CP violation in *b*-hadron decays: Experiments

- How to measure *CP* violation in *B* decays
- A tour of the unitarity triangle
- The future
- The history of the KM paper
- How LHCb was designed

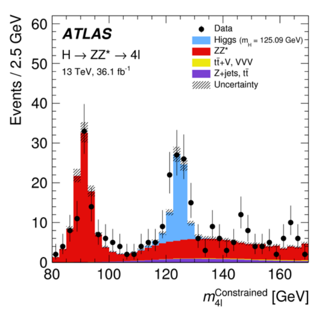
You won't get all.

30/03/2026 — Topical lectures
[indico]

Patrick Koppenburg
Nikhef

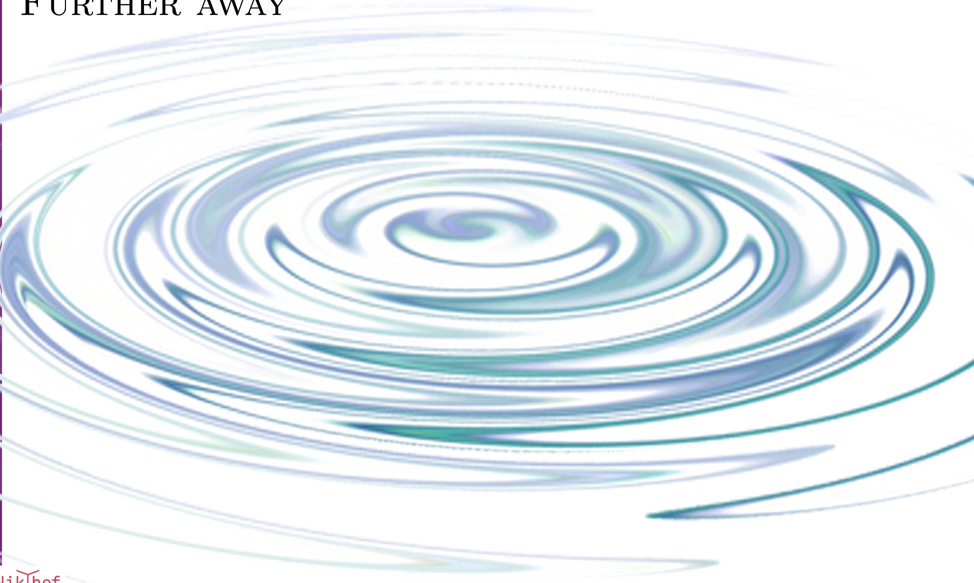
Near

Near



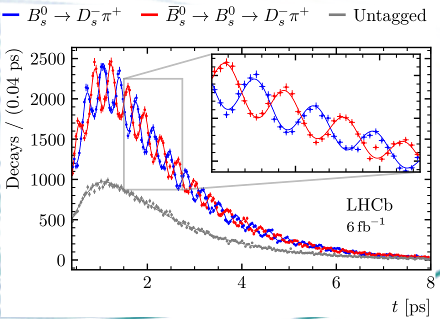
ATLAS
H → ZZ* → 4l
13 TeV, 36.1 fb-1
Data
Higgs (mH = 125.09 GeV)
ZZ*
tt̄+V, VVV
Z+jets, tt̄
Uncertainty
Events / 2.5 GeV
0
10
20
30
40
50
60
80
100
120
140
160
m4l Constrained [GeV]

Further away

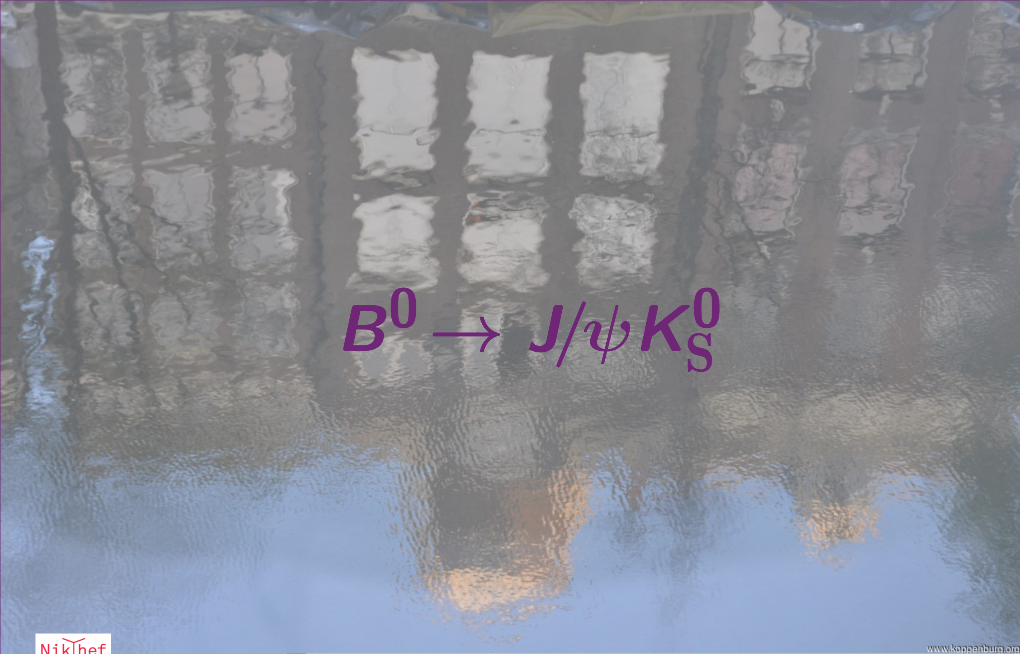


[B]

Further away



[B]

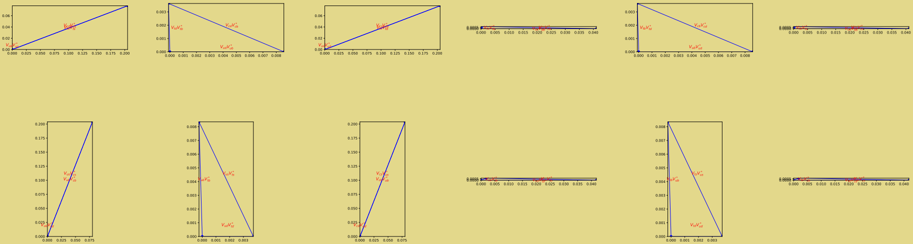


$B^0 \to J/\psi K^0_S$

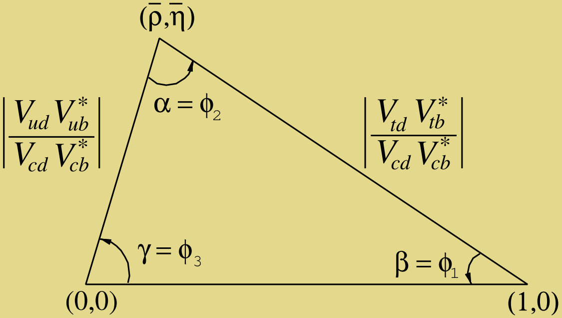
CKM Unitarity Triangles

$$V^\dagger V = \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

You can multiply any row with any (other) column and get a triangle

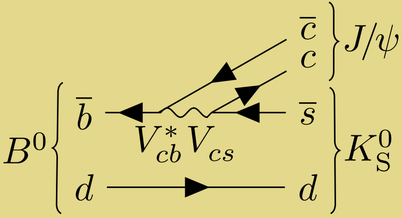


“The” CKM Unitarity Triangle



$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$

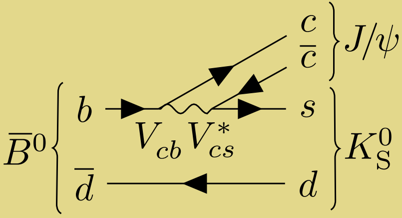
CP violation in $B^0 \to J/\psi K^0_S$



$B^0 \to J/\psi K^0_S$

Amplitude $\propto V_{cb} V^*_{cs}$

➜ Probability $\propto |V_{cb} V^*_{cs}|^2$



$\bar{B}^0 \to J/\psi K^0_S$

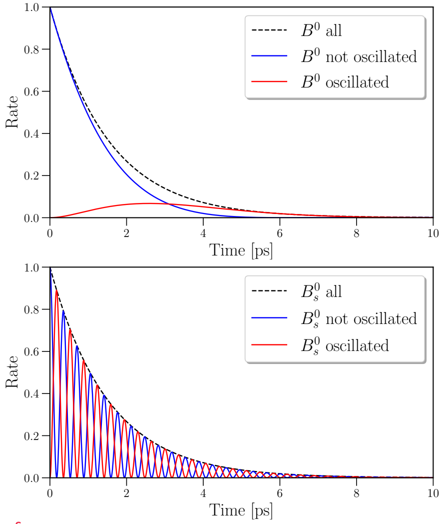
Amplitude $\propto V^*_{cb} V_{cs}$

➜ Probability $\propto |V^*_{cb} V_{cs}|^2$

[B]

The amplitudes are different complex numbers, but the probabilities are the same. Why is there CP violation?

Neutral meson mixing



Weakly decaying neutral mesons will exhibit mixing. The two flavour eigenstates P and $\overline{P}$ will mix into a heavy P_H and a light P_L state

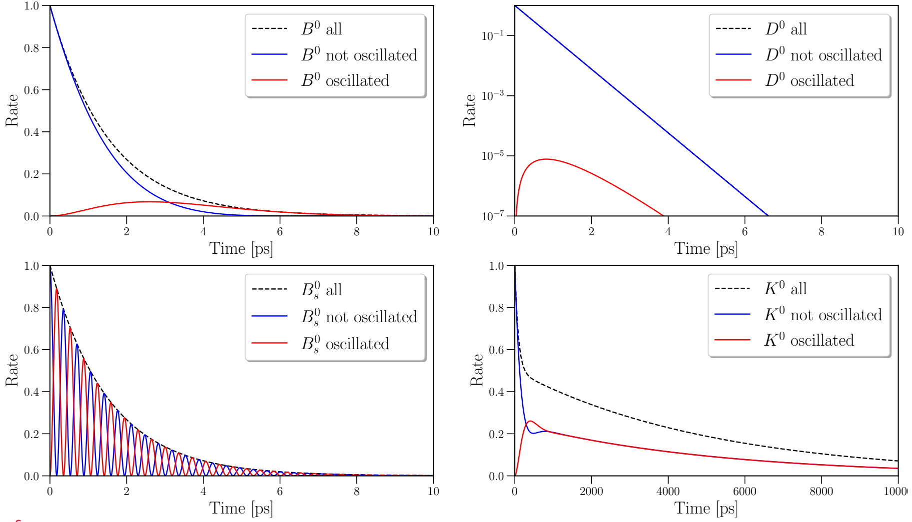
$$|P_\mathrm{L,H}\rangle = p\,|P\rangle \pm q\,\left|\overline{P}\right\rangle .$$

They will oscillate between P and $\overline{P}$ and decay following the lifetimes of P_H and P_L.

The B_s^0 goes considerably faster than the B^0

[B]

Neutral meson mixing

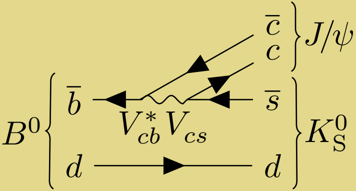


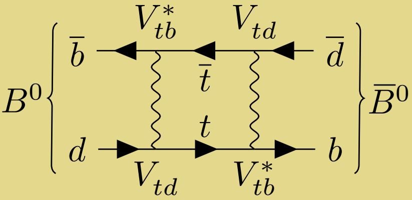
[B]

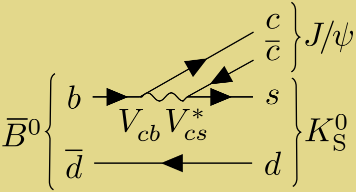
CP violation in $B^0 \to J/\psi K^0_S$

$B^0 \to J/\psi K^0_S$ can proceed directly or after oscillation. Amplitudes are

$$\mathcal{A}(\text{dir}) \propto V_{cb}^* V_{cs}$$
$$\mathcal{A}(\text{oscil}) \propto V_{td} V_{td}^* V_{tb} V_{td}^* V_{cb} V_{cs}^*$$
$$\mathcal{A}(\text{tot}) \propto V_{cb}^* V_{cs} + V_{td} V_{td}^* V_{tb} V_{td}^* V_{cb} V_{cs}^*$$

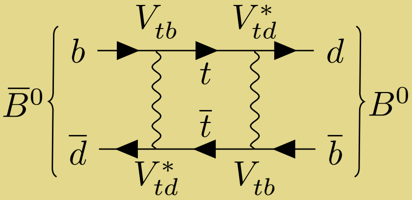


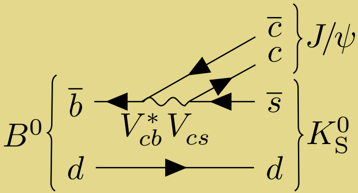




[B]

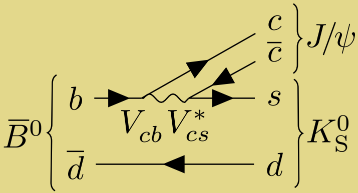
CP violation in $B^0 \to J/\psi K^0_S$





$\overline{B}^0 \to J/\psi K^0_S$ can proceed directly or after oscillation. Amplitudes are

$$\bar{A}(\text{dir}) \propto V_{cb} V^*_{cs}$$
$$\bar{A}(\text{oscil}) \propto V_{td} V^*_{td} V_{tb} V^*_{td} V^*_{cb} V_{cs}$$
$$\bar{A}(\text{tot}) \propto V_{cb} V^*_{cs} + V_{td} V^*_{td} V_{tb} V^*_{td} V^*_{cb} V_{cs}$$

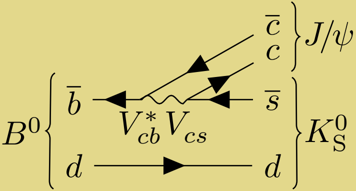


[B]

CP violation in $B^0 \to J/\psi K^0_S$

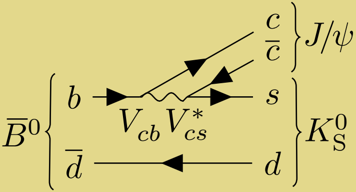
$B^0 \to J/\psi K^0_S$ can proceed directly or after oscillation. Amplitudes are

$$\mathcal{A}(\text{dir}) \propto V_{cb}^* V_{cs}$$
$$\mathcal{A}(\text{oscil}) \propto V_{td} V_{td}^* V_{tb} V_{td}^* V_{cb} V_{cs}^*$$
$$\mathcal{A}(\text{tot}) \propto V_{cb}^* V_{cs} + V_{td} V_{td}^* V_{tb} V_{td}^* V_{cb} V_{cs}^*$$

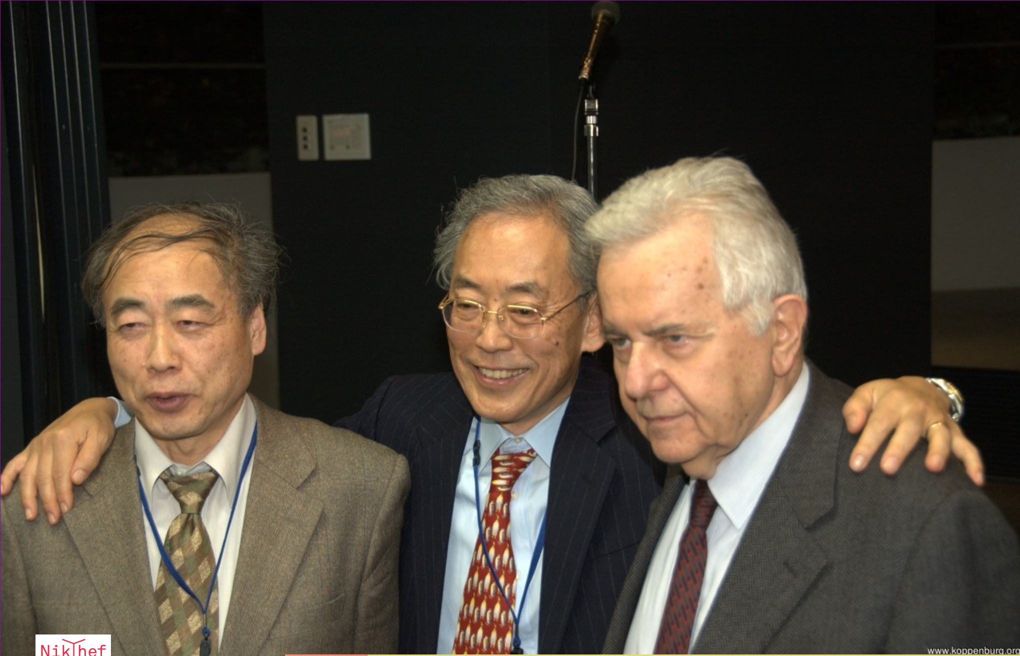


$\bar{B}^0 \to J/\psi K^0_S$ can proceed directly or after oscillation. Amplitudes are

$$\bar{\mathcal{A}}(\text{dir}) \propto V_{cb} V_{cs}^*$$
$$\bar{\mathcal{A}}(\text{oscil}) \propto V_{td} V_{td}^* V_{tb} V_{td}^* V_{cb}^* V_{cs}$$
$$\bar{\mathcal{A}}(\text{tot}) \propto V_{cb} V_{cs}^* + V_{td} V_{td}^* V_{tb} V_{td}^* V_{cb}^* V_{cs}$$



[B]


www.koppenburg.org

Enters A. Ichiro Sanda

An official website of the United States Government Here's how you know

Full image

ASHTON B. **CARTER**

Former Secretary of Defense

Ashton B. Carter served as the 25th Secretary of Defense.

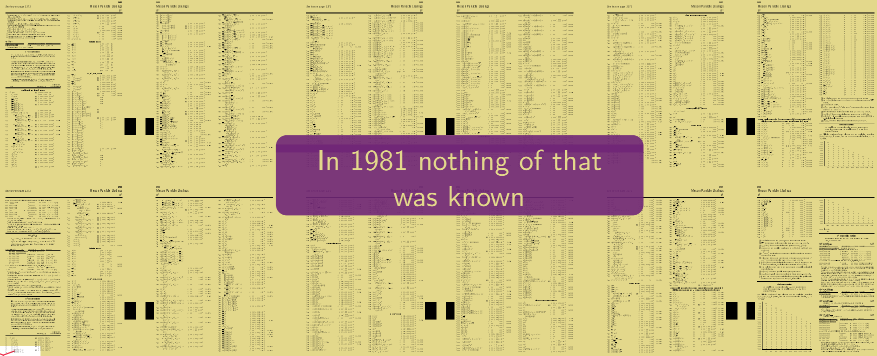
Secretary Carter has spent more than three decades leveraging his knowledge of science and technology, global strategy and policy as well as his deep dedication to the men and women of the Department of Defense to make our nation and the world a safer place. He has done so in direct and indirect service of eleven secretaries of defense in both Democratic and Republican Administrations. Whether in government, academia, or the private sector, Secretary Carter has been guided by pragmatism and his belief in the boundless opportunities of the United States and has worked tirelessly to contribute to the ideas, policies, and innovations that assure our global leadership.

All Biographies

Sanda's idea

The major differences between the K and B systems are

1. The mass eigenstates are close and thus the lifetimes are the same
2. B have many many decay modes. Many.

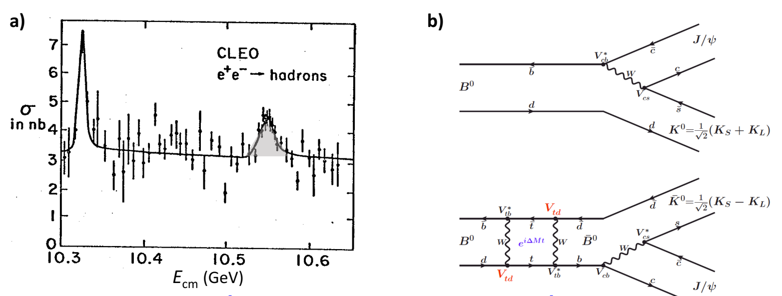


In 1981 nothing of that was known

Sanda's idea

The idea is

$$\mathcal{A}^{CP}_{B\to f_{CP}}(\tau) = \frac{\bar{\Gamma}_{\bar{B}^0\to f_{CP}}(\tau) - \Gamma_{B^0\to f_{CP}}(\tau)}{\bar{\Gamma}_{\bar{B}^0\to f_{CP}}(\tau) + \Gamma_{B^0\to f_{CP}}(\tau)} = -\xi_{CP}\sin(2\beta)\sin(\Delta m_B\tau),$$



[Olsen, KM'50 proceedings, arXiv:2309.06042]

Sanda's idea

To be practical the idea needs

1. Lots of B:

$$\mathcal{F}_{K^0_S J/\psi} < \underbrace{\mathcal{B}(B^0 \to J/\psi K^0_S)}_{\sim 10^{-3}} \underbrace{\mathcal{B}(J/\psi \to \ell^+\ell^-)\mathcal{B}(K^0_S \to \pi^+\pi^-)}_{\sim 10^{-1}} \underbrace{(\epsilon_{\rm trk})^4 \epsilon_{\rm eff}^{\rm tag}}_{\sim 10^{-1}} \approx 10^{-5}$$

2. Large B mixing: Need a large m_t to get rapid oscillations and a long lifetime, *i.e.*V_{cb} needs to be small and V_{ub} even smaller.
3. The time sequence of the two B decays needs to be distinguished. At the $\Upsilon(4S)$ $\gamma\beta = 0.062$ and $\gamma\beta c\tau = 28\,\mu$m. Not enough.

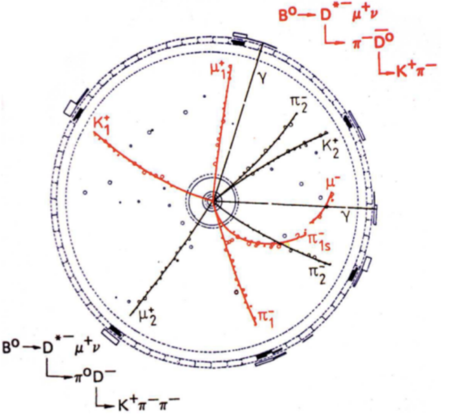
But three miracles occurred! [Olsen, KM'50 proceedings, arXiv:2309.06042]

Three miracles

Miracle 1: *B* mixing at DESY

This implied that the top quark mass was very large. [ARGUS, PLB 192 (1987) 245]

Also, the large *B* lifetime implied a small V_{cb} and V_{ub} [MAC, PRL 51 (1983) 1022]



Three miracles

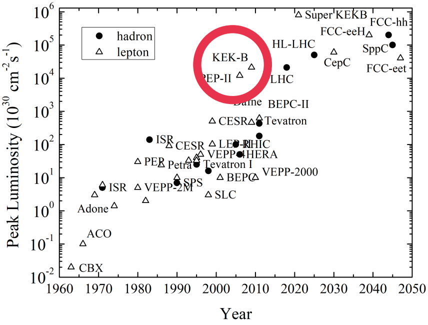
Miracle 1: *B* mixing at DESY

This implied that the top quark mass was very large. [ARGUS, PLB 192 (1987) 245]

Also, the large *B* lifetime implied a small V_{cb} and V_{ub} [MAC, PRL 51 (1983) 1022]

Miracle 2: Large (lumi)

Advances in beam dynamics allowed for three orders of magnitude improvements of e^+e^- luminosities



Three miracles

Miracle 1: B mixing at DESY

This implied that the top quark mass was very large. [ARGUS, PLB 192 (1987) 245]

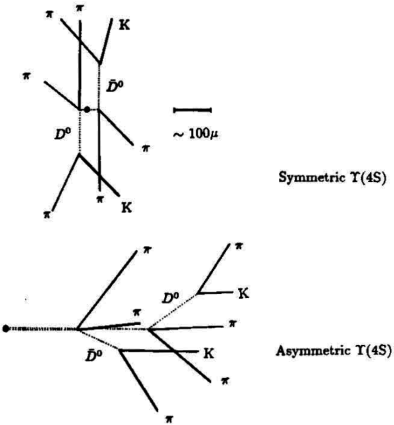
Also, the large B lifetime implied a small V_{cb} and V_{ub} [MAC, PRL 51 (1983) 1022]

Miracle 2: Large (lumi)

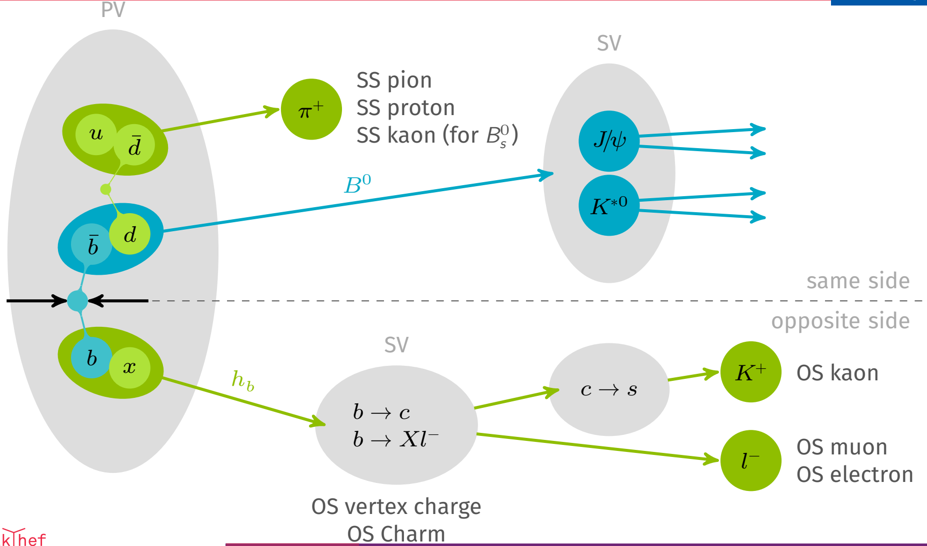
Advances in beam dynamics allowed for three orders of magnitude improvements of e^+e^- luminosities

Miracle 3: asymmetric B factory

Pierre Oddone invents the asymmetric B factory [Oddone, eConf C870126 (1987) 423]



Flavour Tagging at the LHC



[B]

Flavour Tagging

We start with a sample of N B and $\bar{B}$ mesons. We need flavour tagging to know their flavour at origin.

N^{tag} of those have a tagging decision, with $\eta = \frac{N^{\text{tag}}}{N}$. The remaining $N^{\text{tag}} - N$ are not useful for *CP* violation but may be used for other observables.

The fraction of wrongly tagged B is ω

$$N_B^{\text{tag}} = \eta(1-\omega)N_B + \eta\omega N_{\bar{B}}$$
$$N_{\bar{B}}^{\text{tag}} = \eta(1-\omega)N_{\bar{B}} + \eta\omega N_B$$

The *CP* asymmetry is

$$A^{CP}_{\text{meas}} = \frac{N_B^{\text{tag}} - N_{\bar{B}}^{\text{tag}}}{N_B^{\text{tag}} + N_{\bar{B}}^{\text{tag}}} = (1-2\omega)\underbrace{\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}}_{=A^{CP}_{\text{true}}} \quad \rightarrow \quad A^{CP}_{\text{true}} = \frac{A^{CP}_{\text{meas}}}{1-2\omega}$$

[B]

Flavour Tagging

The CP asymmetry is

$$A^{CP}_{\text{meas}} = \frac{N^{\text{tag}}_{B} - N^{\text{tag}}_{\bar{B}}}{N^{\text{tag}}_{B} + N^{\text{tag}}_{\bar{B}}} = (1-2\omega)\underbrace{\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}}_{=A^{CP}_{\text{true}}} \rightarrow \quad A^{CP}_{\text{true}} = \frac{A^{CP}_{\text{meas}}}{1-2\omega}$$

To correctly measure A^{CP} it is necessary to know ω.

The uncertainty is

$$\Delta A^{CP}_{\text{true}} = \frac{\Delta A^{CP}_{\text{meas}}}{1-2\omega} = \frac{1}{1-2\omega}\sqrt{\frac{(1-A^{CP}_{\text{true}})^2}{N^{\text{tag}}}} = \frac{1}{1-2\omega}\sqrt{\frac{(1-A^{CP}_{\text{true}})^2}{\eta N}}$$
$$= \frac{1}{\sqrt{\eta}(1-2\omega)}\Delta A^{CP}_{\text{true}}$$

[B] The effect of the imperfect tagging is the same as reducing the sample by a factor

$$\eta_{\text{eff}} = \eta(1-2\omega)^2$$

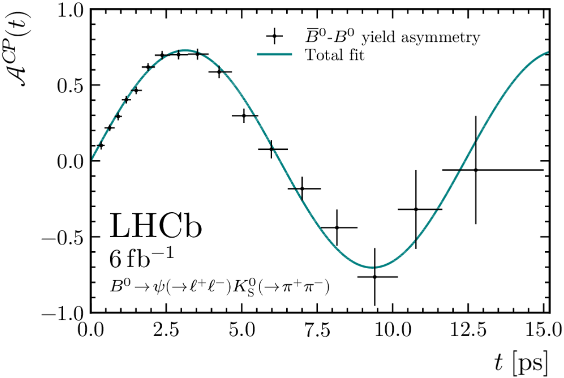
Flavour Tagging

To correctly measure A^{CP} it is necessary to know ω.

The wrong-tag fraction is calibrated on self-tagging control samples.

The measured *CP* asymmetry (*i.e.* $\sin 2\beta$) is proportional to the oscillation amplitude. A wrong value of $\sqrt{\eta}(1-2\omega)$ directly translates into a bias.

[LHCb, PRL 132 (2024) 021801, arXiv:2309.09728]

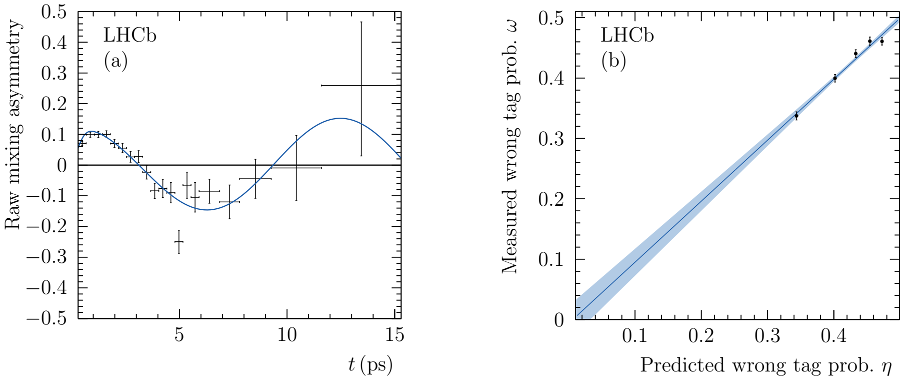


[B]

Flavour Tagging

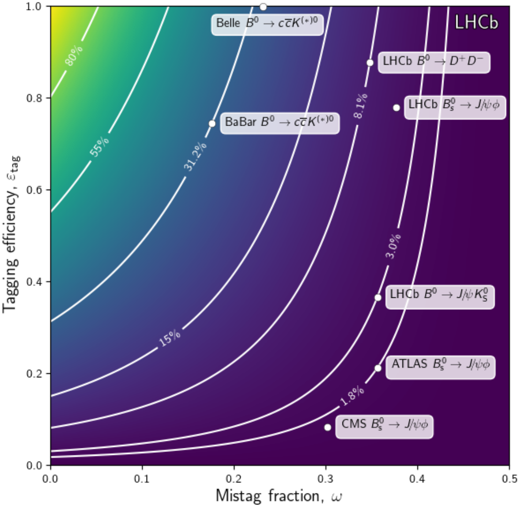
To correctly measure A^{CP} it is necessary to know ω.

The wrong-tag fraction is calibrated on self-tagging control samples. Here $B^0 \to J/\psi K^{*0}(\to K^+\pi^-)$ for $B^0 \to J/\psi K^0_S$ [LHCb, PRL 115 (2015) 031601, arXiv:1503.07089]



[B]

Flavour Tagging performance



Numbers from

LHCb $B^0 \to D^+D^-$
[PRL 117 (2016) 261801, arXiv:1608.06620],

LHCb $B_s^0 \to J/\psi K^+K^-$
[EPJC 79 (2019) 706, arXiv:1906.08356],

LHCb $B^0 \to J/\psi K_S^0$
[PRL 115 (2015) 031601, arXiv:1503.07089],

ATLAS $B_s^0 \to J/\psi\phi$
[ATLAS, arXiv:2001.07115],

CMS $B_s^0 \to J/\psi\phi$
[PLB 757 (2016) 97],

BaBar $B^0 \to J/\psi K_S^0$
[PRD 79, 072009 (2009)],

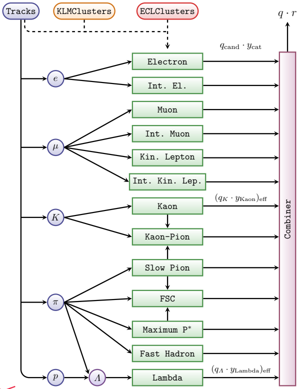
Belle $\sin 2\phi_1$
[NIM A533 (2004) 516].

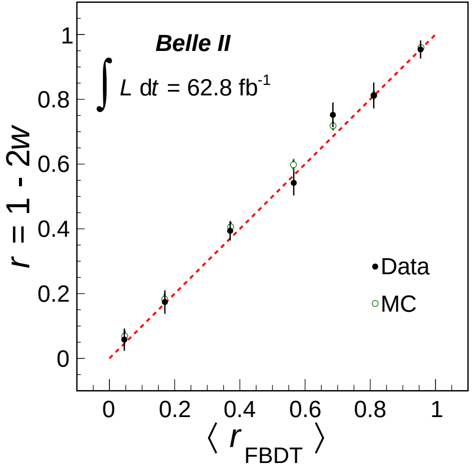
[Belle II, EPJC 82 (2022), arXiv:2110.00790]

Flavour Tagging at Belle II

Tagging power for neutral B mesons:

$$\varepsilon_{\text{eff}}(\text{FBDT}) = (30.0 \pm 1.2 \pm 0.4)\%$$



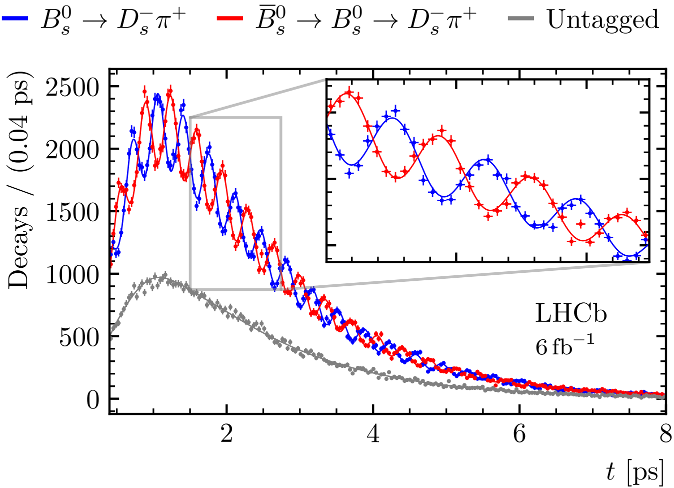


Using $B^0 \to D^{(*)-} h^+$

[B]

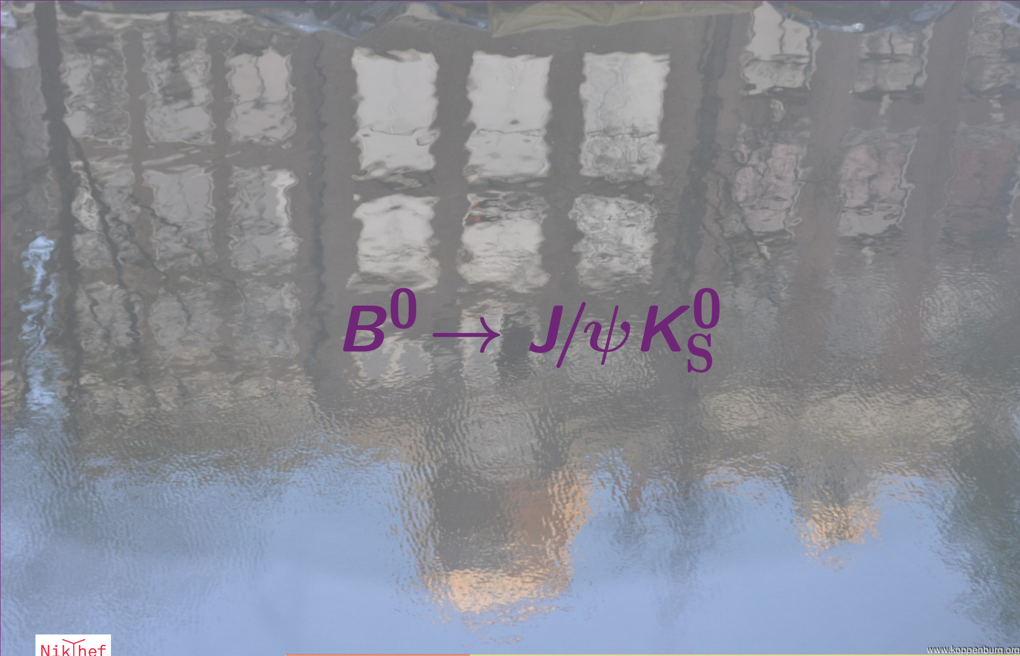
[LHCb, Nature Phys. 18 (2022) 1, arXiv:2104.04421]

Δm_s WITH $B_s^0 \to D_s^- \pi^+$



380k $B_s^0 \to D_s^- \pi^+$ in 6 fb^{-1} Run 2 data ➜ $\Delta m_s = 17.7656 \pm 0.0057\,\text{ps}^{-1}$

$B^0 \to J/\psi K^0_S$

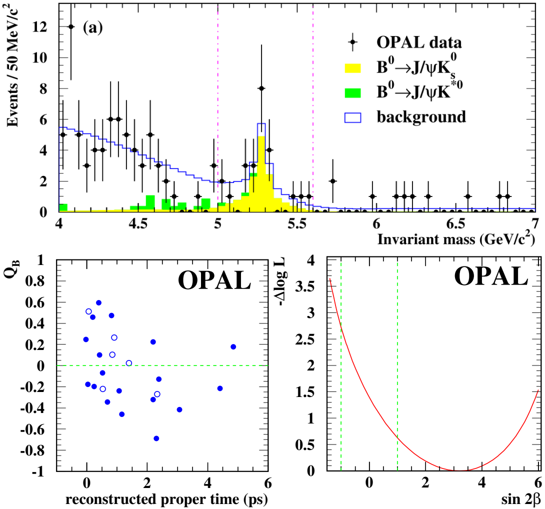


$\sin 2\beta \simeq 3.2$ at OPAL

LEP1 data (1990–94) used

- 24 $B^0 \to J/\psi K^0_S$ with 60% purity
- Tagging: jet charge of opposite jet, jet charge of B^0 jet, opposite side vertex charge

$$\sin 2\beta = 3.2^{+1.8}_{-2.0} \pm 0.5$$

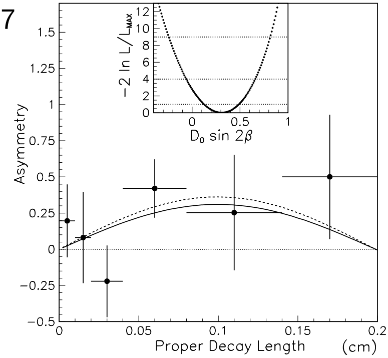


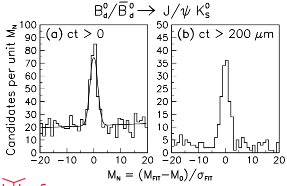
$\sin 2\beta \simeq 1.8$ at CDF

In $110\,\text{pb}^{-1}$ 1992–96 data find 198 ± 17 $B^0 \to J/\psi K^0_S$

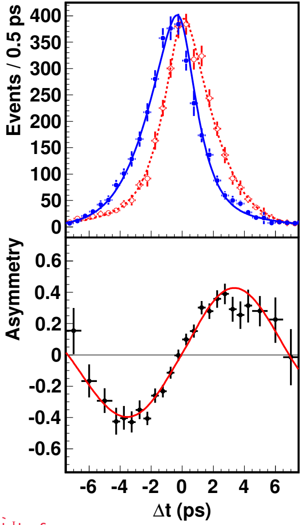
- Use same-side charge taggers ($+1 : B^0$, $-1 : \overline{B}^0$)
- Measure $\mathcal{D}_0 \sin 2\beta = 0.46 \pm 0.19$
- Get dilution from simulation and check on data $\mathcal{D}_0 = 0.166 \pm 0.018 \pm 0.01$

➜ $\sin 2\beta = 1.8 \pm 1.1 \pm 0.3$





Quantum entanglement

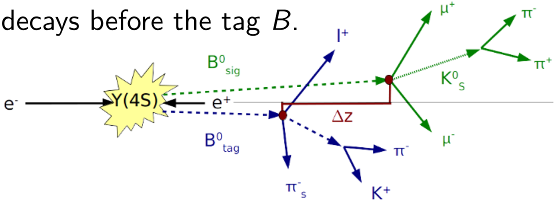


The B^0 and $\bar{B}^0$ originate from a $\Upsilon(4S)$ resonance. They are produced in a quantum-entangled state of a superposition of B^0 and $\bar{B}^0$. The flavour of the one is only fixed once the other decays.

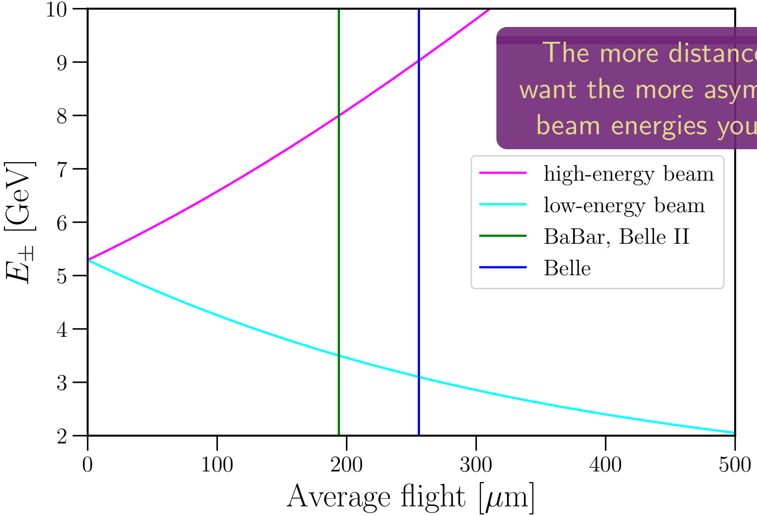
Unlike at the LHC, the clock only starts at the time the other B decays.

➜ The difference in flight time is relevant

- This difference can be negative, if the signal B decays before the tag B.

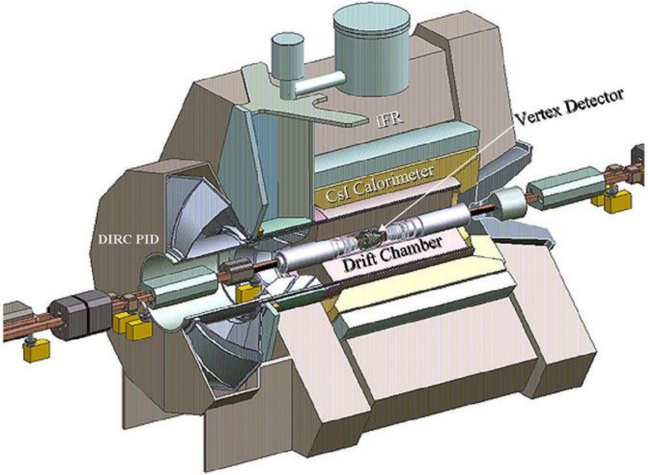


Flight distance and beam energies



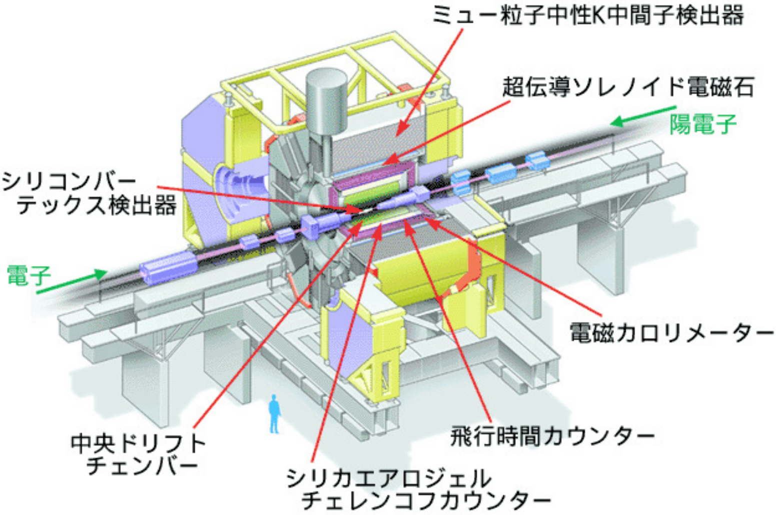
The more distance you want the more asymmetric beam energies you need

BaBar


IFR
Vertex Detector
CsI Calorimeter
DIRC PID
Drift Chamber

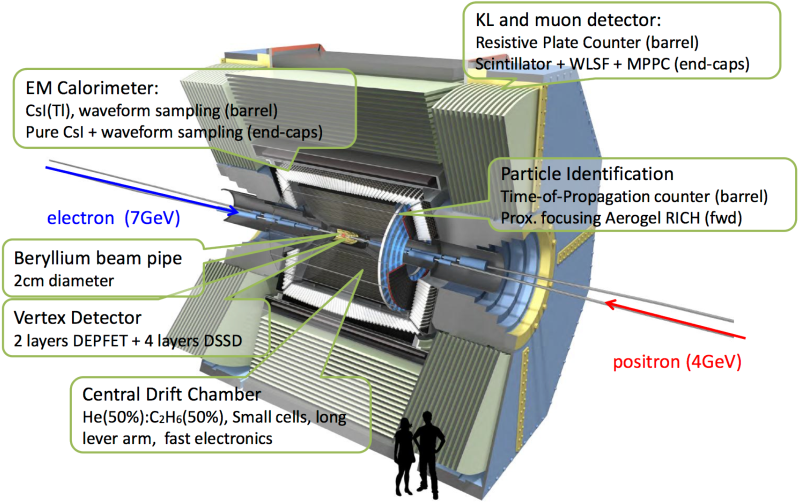
[Belle, NIM A479 (2002) 117]

The Belle Experiment



[PTEP 2019 (2019) 123C01, arXiv:1808.10567]

Belle II



Beam-constrained observables

For B mesons the production process is $e^+e^- \to \Upsilon(4S) \to \bar{B}B$ followed by $B \to XYZ$

The reconstructed mass of the XYZ system must be equal to m_B and the energy in the rest frame to $E^*_{\text{beam}} = \frac{1}{2}\sqrt{s}$.

The second constraint is used by defining

$$\Delta E = E^*_B - E^*_{\text{beam}} = \frac{2p^\mu_B p^{\text{boost}}_\mu - s}{2\sqrt{s}}$$

with p_μ the four-momenta of the B and e^+e^- systems.

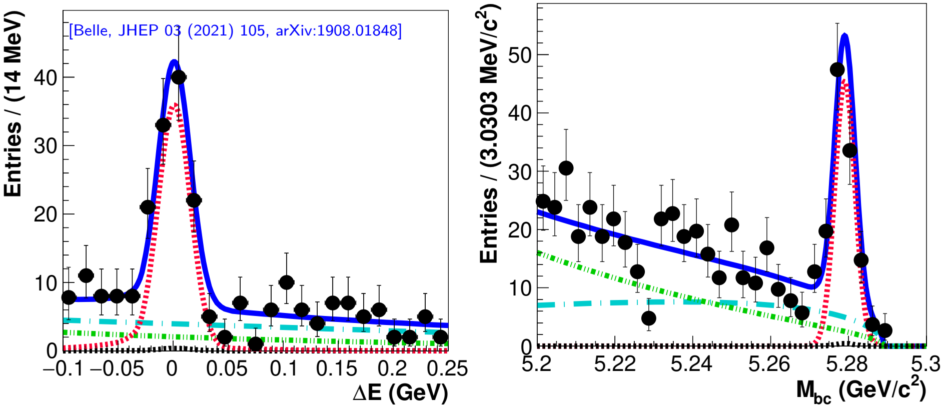
The B mass is also more precisely determined by replacing the measured B energy by the known beam energy

$$M_{\text{bc}} = \sqrt{E^*_{\text{beam}} - p^2_B}.$$

(m_{ES} in BaBar).

A well-reconstructed B should have $(M_{\text{bc}}, \Delta E) = (M_B, 0)$

Beam-constrained observables



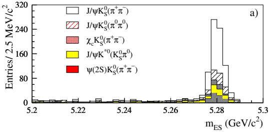
$$\Delta E = E_B^* - E_{\text{beam}}^* = \frac{2p_B^\mu p_\mu^{\text{boost}} - s}{2\sqrt{s}} = m_B, \qquad M_{\text{bc}} = \sqrt{E_{\text{beam}}^* - p_B^2} = 0$$

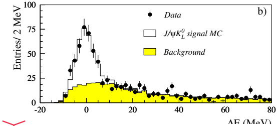
OBSERVATION OF CP VIOLATION IN B^0

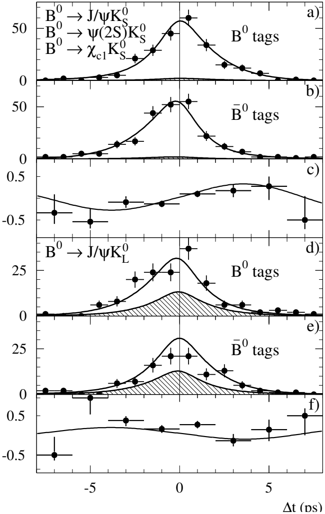
Using 32 million $B\bar{B}$ pairs, BaBar get

$$\sin 2\beta = 0.59 \pm 0.14 \pm 0.05$$

with B^0 decays to $J/\psi K^0_\mathrm{S}$, $\psi(2S)K^0_\mathrm{S}$, $\chi_{c1}K^0_\mathrm{S}$ (CP-odd, 803 events, 80% pure), $J/\psi K^0_\mathrm{L}$ (CP-even) and $J/\psi K^{*0}(K^0_\mathrm{S}\pi^0)$ (mixture).





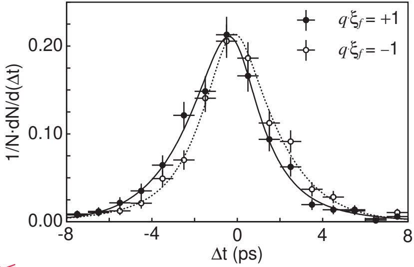


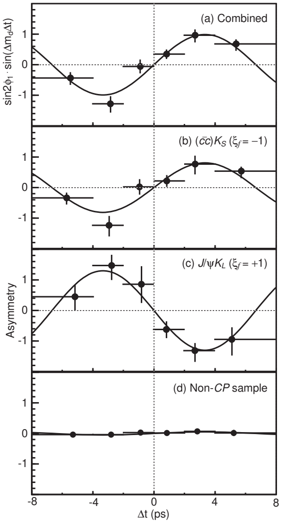
Observation of *CP* violation in B^0

Using 31 million $B\bar{B}$ pairs, Belle get

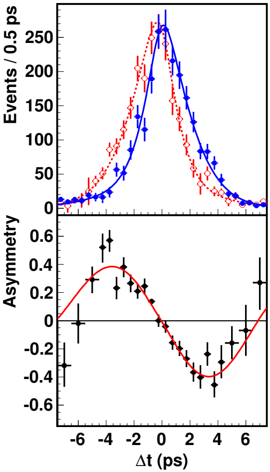
$$\sin 2\beta = 0.99 \pm 0.14 \pm 0.06$$

with B^0 decays to $J/\psi K^0_S$, $\psi(2S)K^0_S$, $\chi_{c1}K^0_S$, $\eta_c K^0_S$ (*CP*-odd, 747 events, 92% pure) and $J/\psi K^0_L$ (*CP*-even, 569 events, 61% pure).

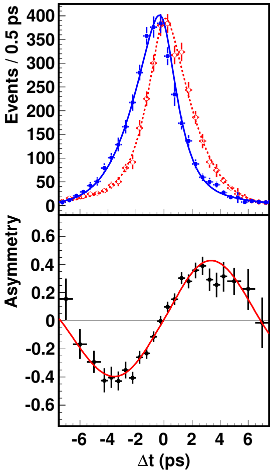




Legacy $\sin 2\beta$

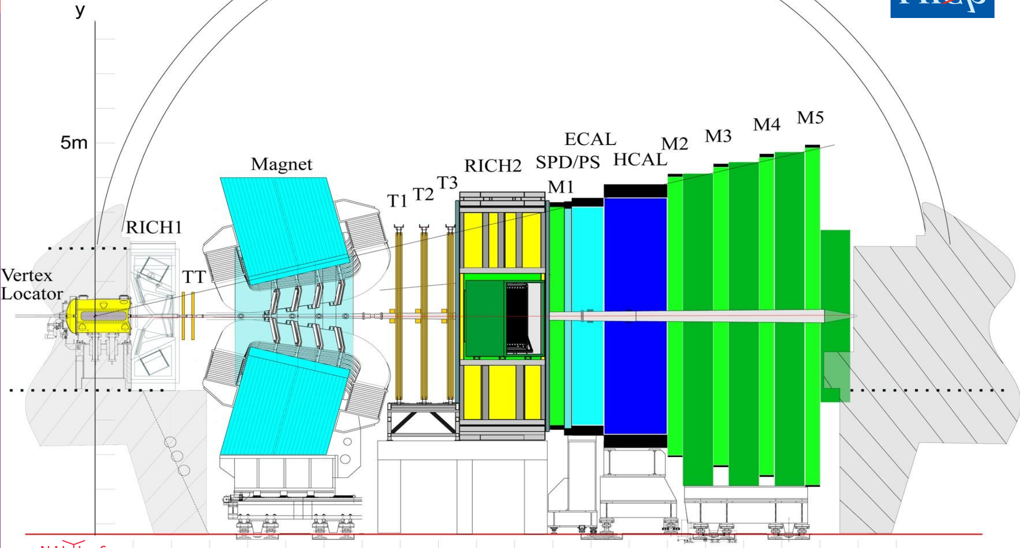


Legacy measurement using $B\to J/\psi K^0_S$, $B\to\psi(2S)K^0_S$ and $B\to J/\psi K^0_L$



$\sin 2\beta = 0.667 \pm 0.023 \pm 0.012 \qquad A_f = 0.006 \pm 0.016 \pm 0.012$

LHCb Legacy 2009–2018

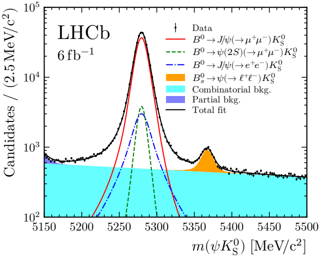


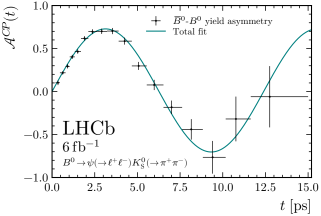
[LHCb, PRL 132 (2024) 021801, arXiv:2309.09728]

$\sin 2\beta$ WITH $B^0 \to J/\psi K^0_S$

Simultaneous fit of 306k $B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$ (82%) 43k $B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S$ (12%) and 24k $B^0 \to J/\psi(\to e^+e^-)K^0_S$ (6%) using 2015–18 data.

$$B^0 \to J/\psi K^0_S : S = 0.716 \pm 0.015 \pm 0.007$$
$$C = 0.010 \pm 0.014 \pm 0.003$$
$$B^0 \to \psi(2S) K^0_S : S = 0.649 \pm 0.053 \pm 0.018$$
$$C = -0.088 \pm 0.048 \pm 0.005$$
$$B^0 \to J/\psi_{ee} K^0_S : S = 0.754 \pm 0.037 \pm 0.008$$
$$C = 0.042 \pm 0.034 \pm 0.008$$
$$\text{Run 2} : S = 0.717 \pm 0.013 \pm 0.008$$
$$C = 0.008 \pm 0.012 \pm 0.003$$





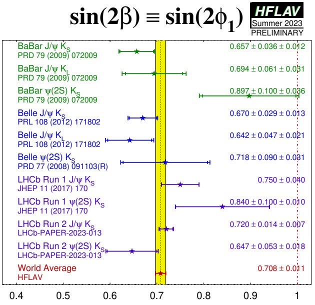
$\sin 2\beta$ WITH $B^0 \to J/\psi K^0_S$

Simultaneous fit of 306k $B^0 \to J/\psi(\to \mu^+\mu^-)K^0_S$ (82%) 43k $B^0 \to \psi(2S)(\to \mu^+\mu^-)K^0_S$ (12%) and 24k $B^0 \to J/\psi(\to e^+e^-)K^0_S$ (6%) using 2015–18 data.

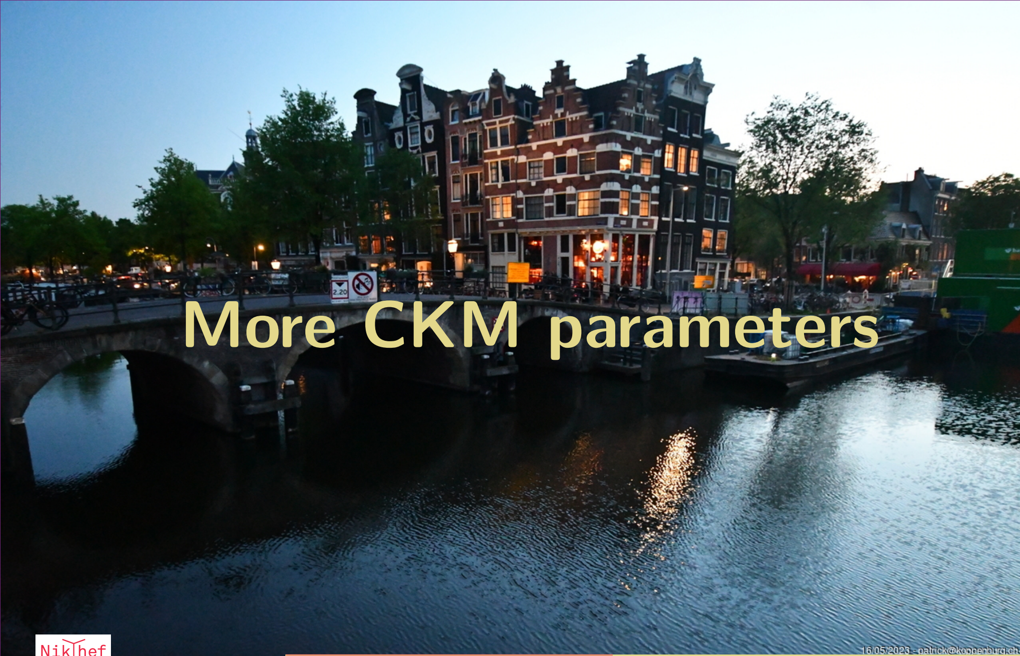
$$\begin{aligned} \text{Run 2}: S &= 0.717 \pm 0.013 \pm 0.008 \\ C &= 0.008 \pm 0.012 \pm 0.003 \\ \text{Run 1}: S &= 0.731 \pm 0.045 \pm 0.020 \\ C &= -0.038 \pm 0.032 \pm 0.005 \end{aligned}$$

[PRL 115 (2015) 031601]

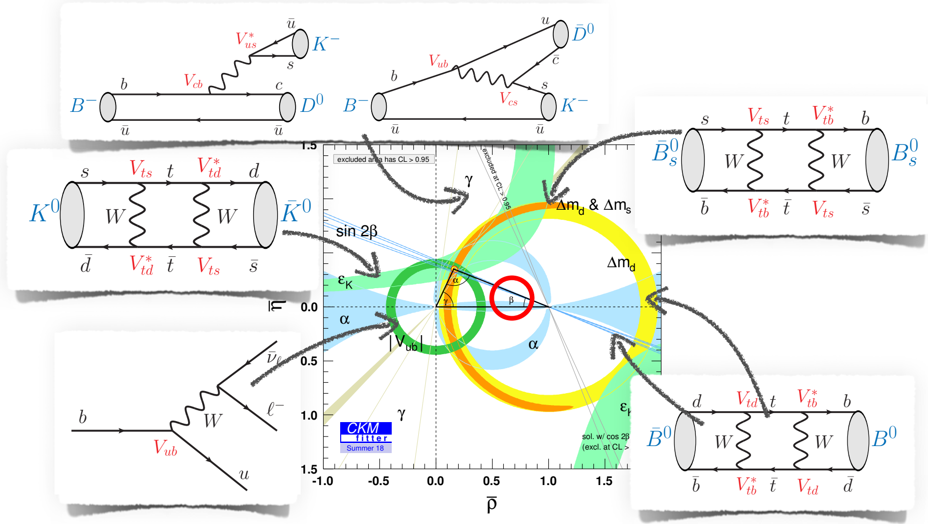
$$\begin{aligned} \text{Run 1\&2}: S &= 0.726 \pm 0.014 \\ C &= 0.010 \pm 0.012 \end{aligned}$$



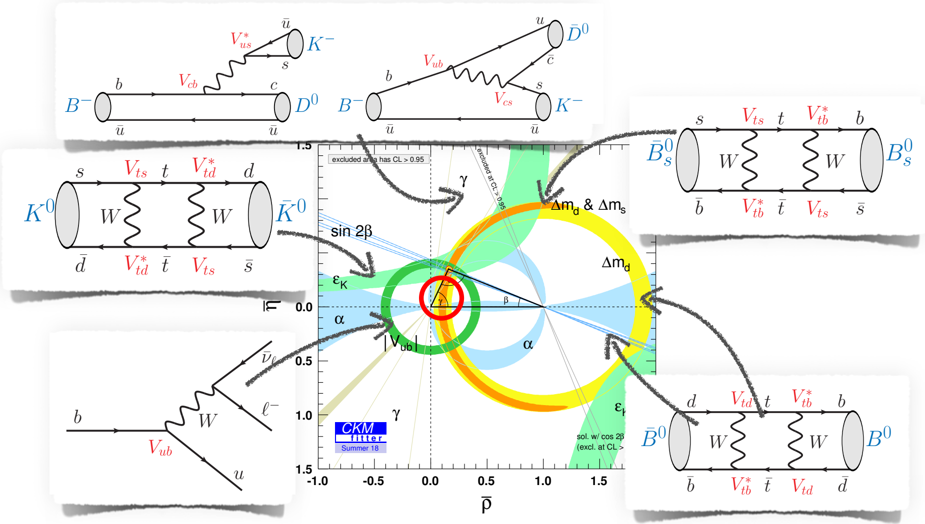
More CKM parameters



CKM fit constraints



CKM FIT CONSTRAINTS

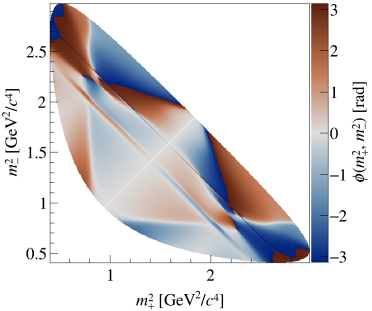


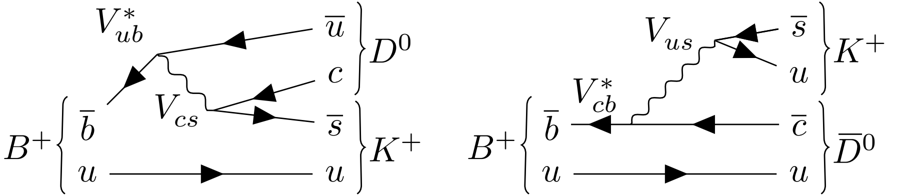
γ from $B^0 \to Dh$ with LHCb+BESIII

Interference of $B^+ \to D^0(K^0_S\pi^+\pi^-)K^+$ and $B^+ \to \overline{D}^0(K^0_S\pi^+\pi^-)K^+$ gives access to $\gamma = \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ (BPGGSZ method).

Needs the strong phase of $D \to K^0_S\pi^+\pi^-$, which varies over the Dalitz plane.

The same works for $K^0_S K^+K^-$ (lower stats).



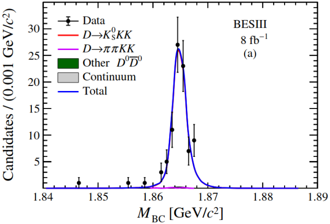


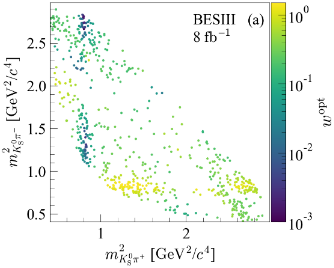
γ FROM $B^0 \to Dh$ WITH LHCB+BESIII

Interference of $B^+ \to D^0(K^0_S\pi^+\pi^-)K^+$ and $B^+ \to \overline{D}^0(K^0_S\pi^+\pi^-)K^+$ gives access to $\gamma = \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ (BPGGSZ method).

Needs the strong phase of $D \to K^0_S\pi^+\pi^-$, which varies over the Dalitz plane.

The strong phase is measured with BESIII data using quantum-correlated D mesons.





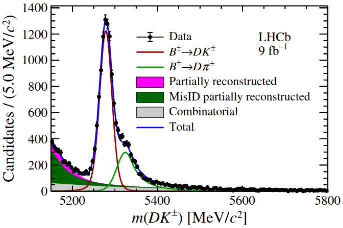
γ FROM $B^0 \to Dh$ WITH LHCB+BESIII

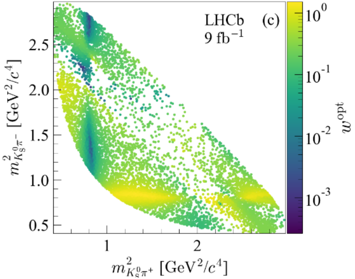
Interference of $B^+ \to D^0(K^0_S\pi^+\pi^-)K^+$ and $B^+ \to \bar{D}^0(K^0_S\pi^+\pi^-)K^+$ gives access to $\gamma = \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ (BPGGSZ method).

Needs the strong phase of $D \to K^0_S\pi^+\pi^-$, which varies over the Dalitz plane.

The strong phase is measured with BESIII data using quantum-correlated D mesons.

This information is then used with B decays from LHCb Run 3 data.





γ FROM $B^0 \to Dh$ WITH LHCB+BESIII

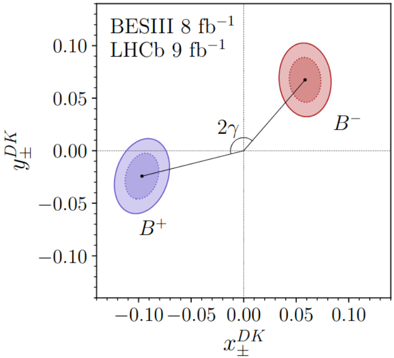
Interference of $B^+ \to D^0(K^0_S\pi^+\pi^-)K^+$ and $B^+ \to \bar{D}^0(K^0_S\pi^+\pi^-)K^+$ gives access to $\gamma = \arg(-V_{ud}V^*_{ub}/V_{cd}V^*_{cb})$ (BPGGSZ method).

Needs the strong phase of $D \to K^0_S\pi^+\pi^-$, which varies over the Dalitz plane.

The strong phase is measured with BESIII data using quantum-correlated D mesons.

This information is then used with B decays from LHCb Run 3 data.

Yielding $\gamma = (71.3 \pm 5.0)^\circ$, in the first LHCb+BESIII publications



γ COMBINATION MATRIX

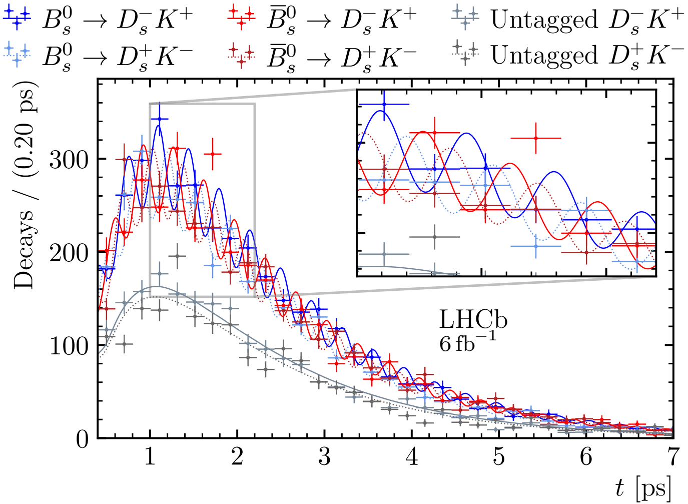
	Time-integrated measurements					
Final states	Dh^+	$D^{*0}h^+$	$DK^0_S\pi^+$	$DK^+\pi^-$	$DK^+\pi^-\pi^-$	DK^{*+}
h^+h^-	**[9 fb^{-1}]**	**[9 fb^{-1}]**	[5 fb^{-1}]	**[9 fb^{-1}]**	[3 fb^{-1}]	**[9 fb^{-1}]**
$h^+\pi^-\pi^+\pi^-$	[3 fb^{-1}]**[9 fb^{-1}]**	**[9 fb^{-1}]**	[5 fb^{-1}]	**[9 fb^{-1}]**		
$h^+h^-\pi^+\pi^-$	**[9 fb^{-1}]**					**[9 fb^{-1}]**
$h^+h^-\pi^0$	**[9 fb^{-1}]**					
$K^0_S h^+h^-$	**[9 fb^{-1}]**[**6 fb^{-1}**]	**[9 fb^{-1}][9 fb^{-1}]**		**[9 fb^{-1}]**		**[9 fb^{-1}]**
$K^0_S K^+\pi^-$	**[9 fb^{-1}]**					

	Time-dependent measurements		
Final states	$D^\mp\pi^\pm$	$B^0_s \to D^\mp_s K^\pm$	$D^\mp_s K^\pm\pi^+\pi^-$
$K^\pm h^+h^-$	[3 fb^{-1}]	N/A	N/A
$h^\pm h^\mp\pi^\pm$	N/A	**[9 fb^{-1}]**	**[9 fb^{-1}]**

Click on lumi to get reference. Last updated with [LHCb-CONF-2025-003]. Items in red or red (Run 3) are not yet included in latest γ combination [LHCb-CONF-2025-003].

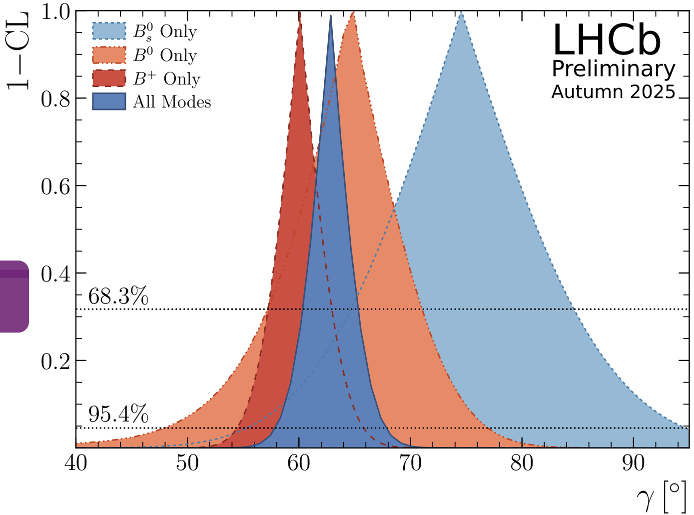
[LHCb, JHEP 03 (2025) 139, arXiv:2412.14074]

$B_s^0 \to D_s^\mp K^\pm$



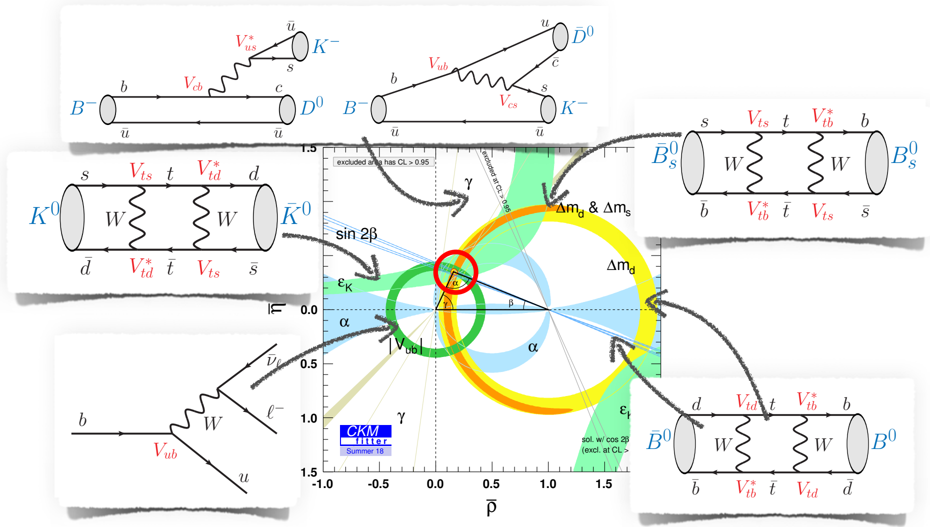
2025 γ combination

$\gamma = (62.8 \pm 2.6)^\circ$

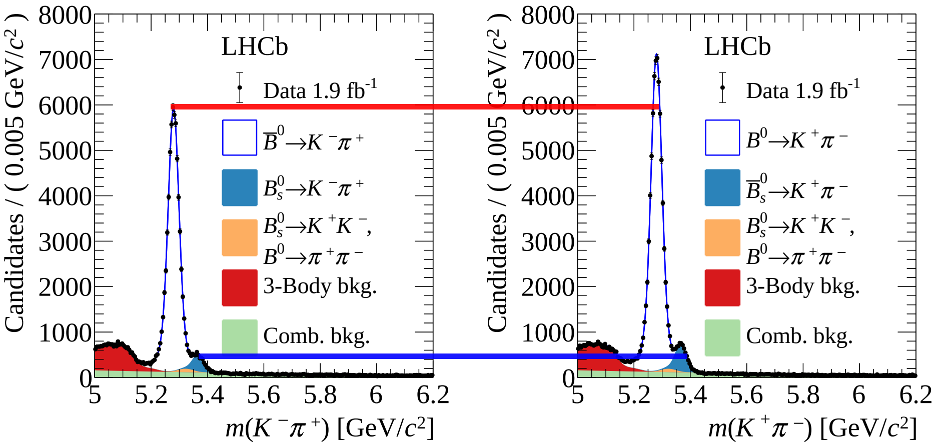


[Jure Zupan, arXiv:1903.05062]

CKM fit constraints



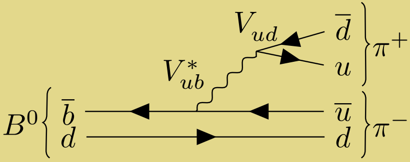
CP VIOLATION IN $B \to h^+ h^-$



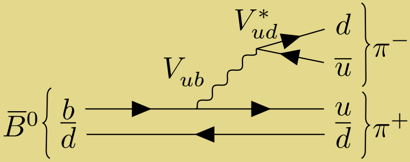
[B]

Large CP violation in charmless B^0 and B^0_s decays (seen in [PRL 110 (2013) 221601])

CP violation in $B^0 \to \pi^+\pi^-$



$B^0 \to \pi^+\pi^-$



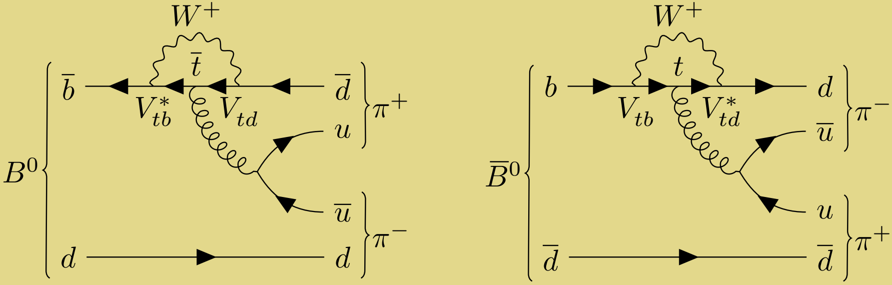
$\overline{B}^0 \to \pi^-\pi^+$

$$\text{Amplitude} \propto V_{us} V_{ub}^* = |V_{us}||V_{ub}|e^{+i\gamma}$$

$$\text{Amplitude} \propto V_{us}^* V_{ub} = |V_{us}^*||V_{ub}|e^{-i\gamma}$$

[B]

CP violation in $B^0 \to \pi^+\pi^-$



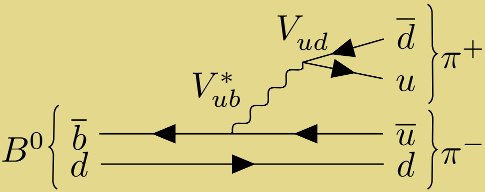
$B^0 \to \pi^+\pi^-$ $\qquad\qquad$ $\bar{B}^0 \to \pi^-\pi^+$

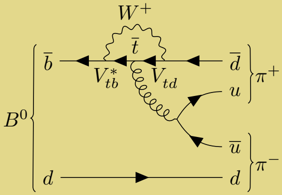
$$\text{Amplitude} \propto V_{tb}^* V_{td} = |V_{tb}^*||V_{td}|e^{-i\beta}$$

$$\text{Amplitude} \propto V_{tb} V_{td}^* = |V_{tb}||V_{td}|e^{+i\beta}$$

[B]

CP violation in $B^0 \to \pi^+\pi^-$





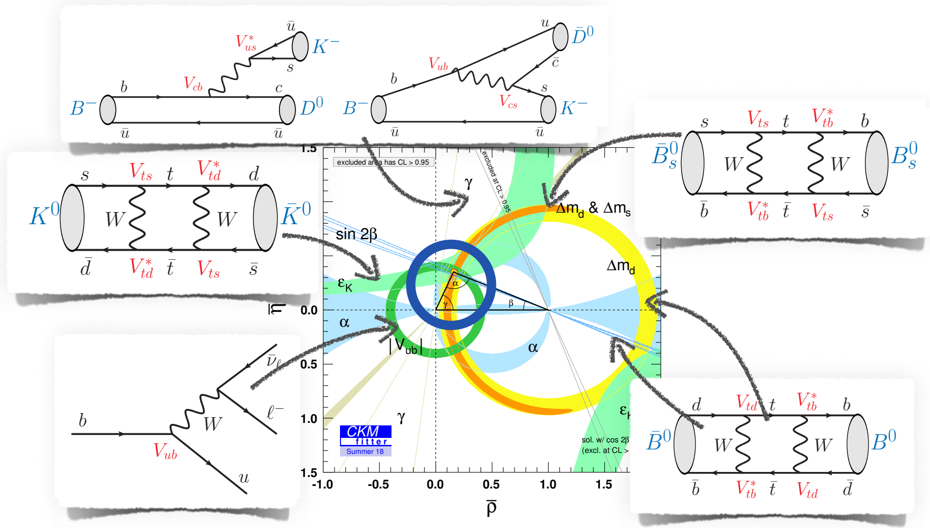
$B^0 \to \pi^+\pi^-$: measures $\gamma + \beta$, or $\pi - \gamma - \beta = \alpha$, assuming unitarity.

- ➜ depending on how New Physics enters, you may or may not be sensitive to it.
- ✗ But in any case it is very difficult to estimate hadronic uncertainties in these $b \to u$ transitions
  - ➜ Check out "$B^0 \to K^-\pi^+$" puzzle

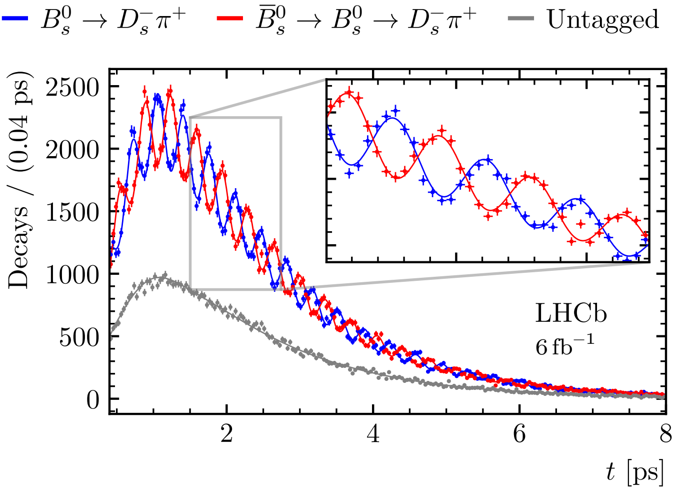
[B]

[Jure Zupan, arXiv:1903.05062]

CKM FIT CONSTRAINTS



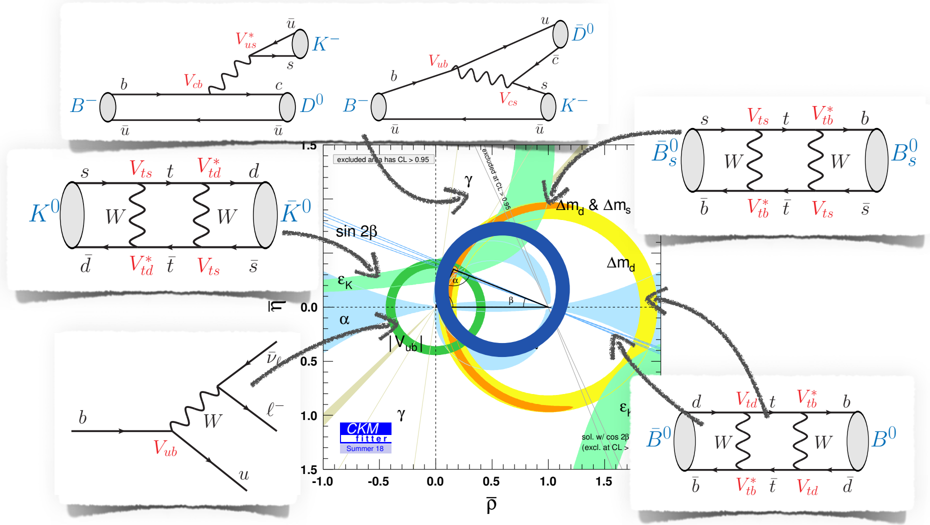
Δm_s WITH $B_s^0 \to D_s^- \pi^+$



380k $B_s^0 \to D_s^- \pi^+$ in 6 fb^{-1} Run 2 data ➜ $\Delta m_s = 17.7656 \pm 0.0057\,\mathrm{ps}^{-1}$

[Jure Zupan, arXiv:1903.05062]

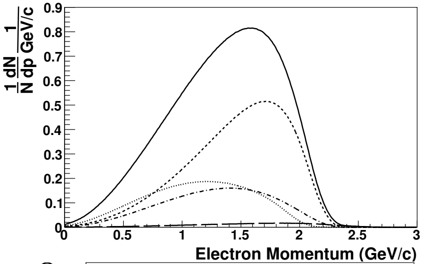
CKM fit constraints

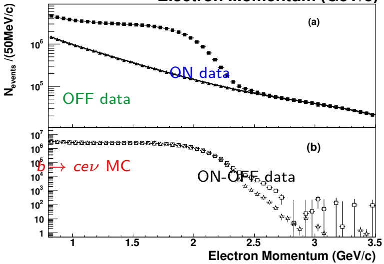


Inclusive V_{ub}

Inclusive $b \to ue\nu$ result by BaBar.

- Full reco tag on other B
- OFF $\Upsilon(4S)$ data subtracted from ON data
  - ➜ Excess of electrons beyond $b \to ce\nu$ kinematical endpoint (2.3 GeV).



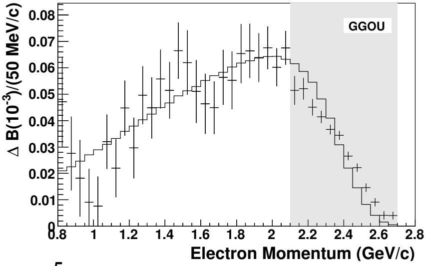


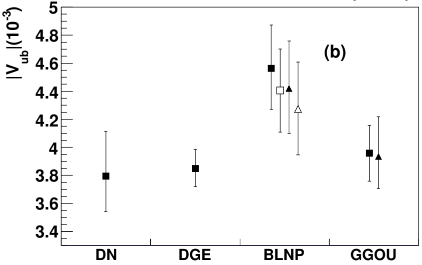
INCLUSIVE V_{ub}

Inclusive $b \to ue\nu$ result by BaBar.

- Full reco tag on other B
- OFF $\Upsilon(4S)$ data subtracted from ON data
  - ➜ Excess of electrons beyond $b \to ce\nu$ kinematical endpoint (2.3 GeV).
- Result depends on model. BaBar favour GGOU model [JHEP 908 10, 058 (2007)]
  - ➜ $|V_{ub}| = (4.0 \pm 0.2) \times 10^{-3}$, closer to the mean of exclusive and inclusive

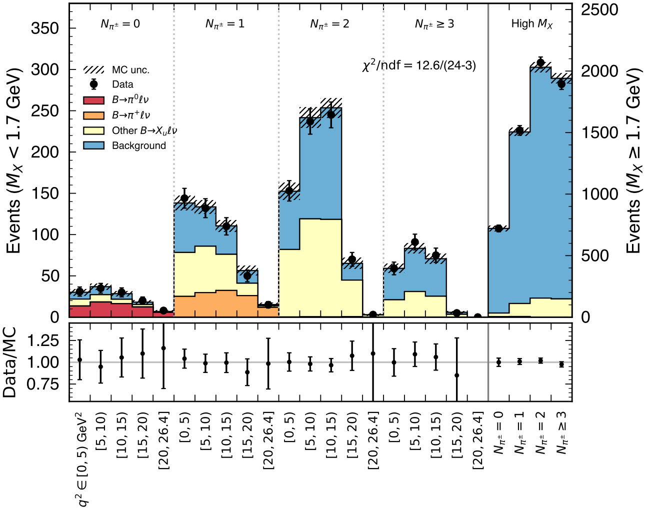
Also new exclusive V_{ub} using D decays to constrain form factors [PRD91 052022 (2015), arXiv:1412.5502].



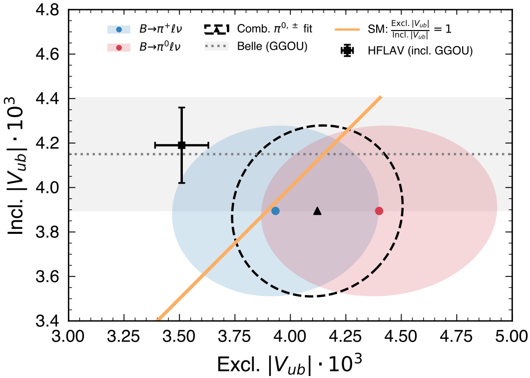


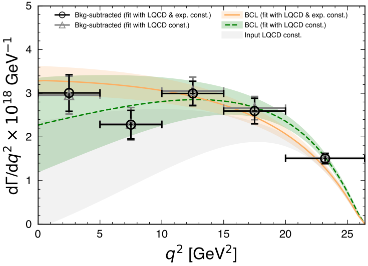
Simultaneous inclusive and exclusive $|V_{ub}|$

Use same selection for $B \to \pi \ell \nu$ and $b \to u \ell \nu$ and determine $|V_{ub}|$ simultaneously for both.



Simultaneous inclusive and exclusive $|V_{ub}|$





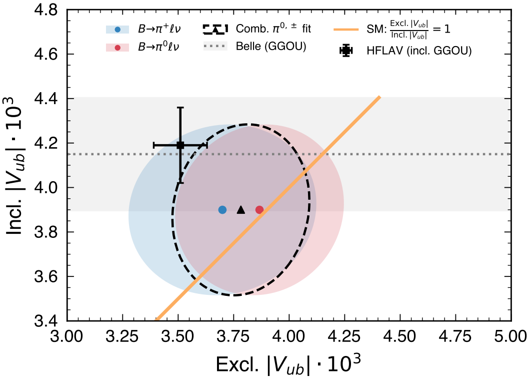
Fit using LQCD form factors

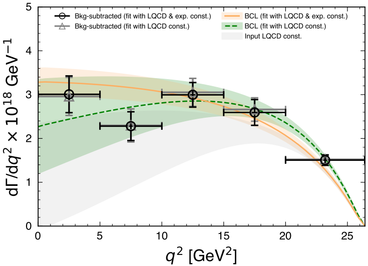
$$\left|V_{ub}^{\text{excl.}}\right| = (4.12 \pm 0.30 \pm 0.18 \pm 0.16) \times 10^{-3}$$

$$\left|V_{ub}^{\text{incl.}}\right| = (3.90 \pm 0.20 \pm 0.32 \pm 0.09) \times 10^{-3}$$

[Belle, PRL 131 (2023) 211801, arXiv:2303.17309]

Simultaneous inclusive and exclusive $|V_{ub}|$





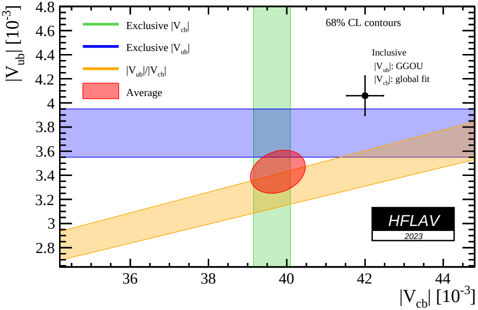
Fit using LQCD+exp form factors

$$\left|V_{ub}^{\text{excl.}}\right| = (3.78 \pm 0.23 \pm 0.16 \pm 0.14) \times 10^{-3}$$

$$\left|V_{ub}^{\text{incl.}}\right| = (3.90 \pm 0.20 \pm 0.32 \pm 0.09) \times 10^{-3}$$

$|V_{ub}|$ AND $|V_{cb}|$

HFLAV

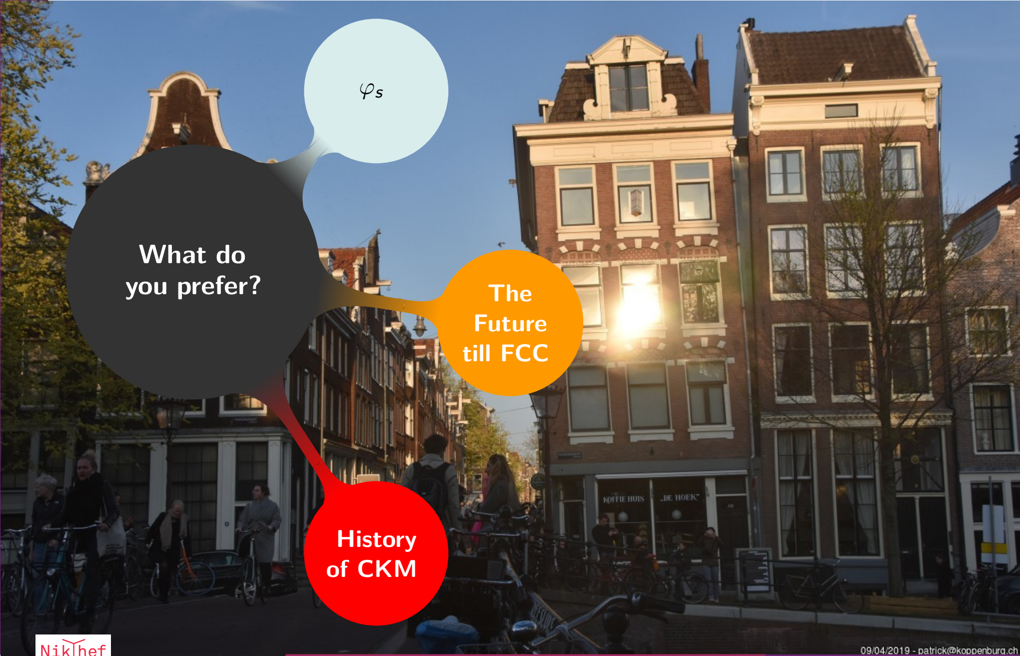


$$|V_{ub}|_{\text{excl}} = (\ 3.43 \pm 0.12) \times 10^{-3} \quad (3\%)$$
$$|V_{cb}|_{\text{excl}} = (39.77 \pm 0.46) \times 10^{-3} \quad (1\%)$$

$$|V_{ub}|_{\text{incl}} = (\ 4.06 \pm 0.16) \times 10^{-3} \quad (3\%)$$
$$|V_{cb}|_{\text{incl}} = (41.97 \pm 0.48) \times 10^{-3} \quad (1\%)$$

Discrepancy between exclusive and inclusive V_{ub} (18%) and V_{cb} (5.5%) determinations. Both more than 3σ.

- $|V_{cb}|$ is a crucial ingredient in many SM predictions.
- ✗ Use of exclusive value would lead to large tensions in $\Delta F = 2$
- In the meantime use V_{cb}-free quantities as $\mathcal{B}(B_s^0 \to \mu^+\mu^-)/\Delta M_s$

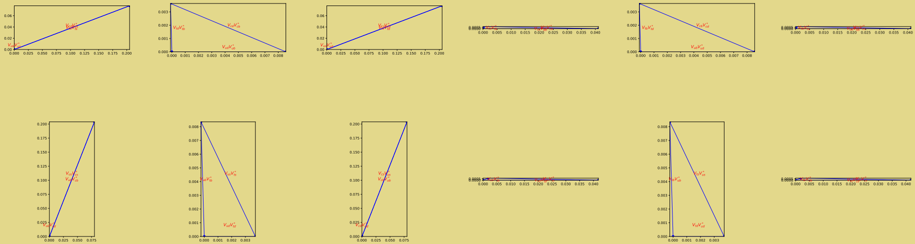

φ_s
What do you prefer?
The Future till FCC
History of CKM
KOFFIE HUIS
„DE HOEK"
09/04/2019 - patrick@koppenburg.ch


φ_s
2.20
16/05/2023 - patrick@koppenburg.ch

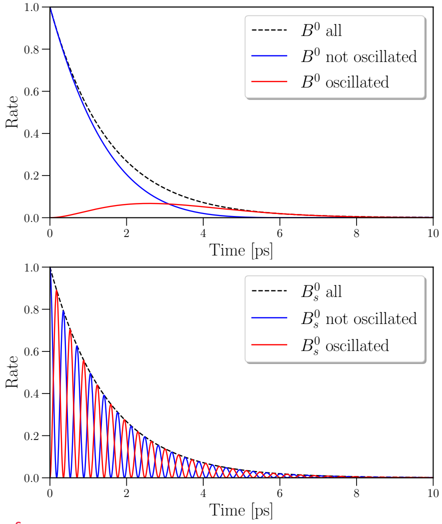
CKM Unitarity Triangles

$$V^\dagger V = \begin{pmatrix} V_{ud}^* & V_{cd}^* & V_{td}^* \\ V_{us}^* & V_{cs}^* & V_{ts}^* \\ V_{ub}^* & V_{cb}^* & V_{tb}^* \end{pmatrix} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

You can multiply any row with any (other) column and get a triangle



Neutral meson mixing



Weakly decaying neutral mesons will exhibit mixing. The two flavour eigentates P and $\overline{P}$ will mix into a heavy P_H and a light P_L state

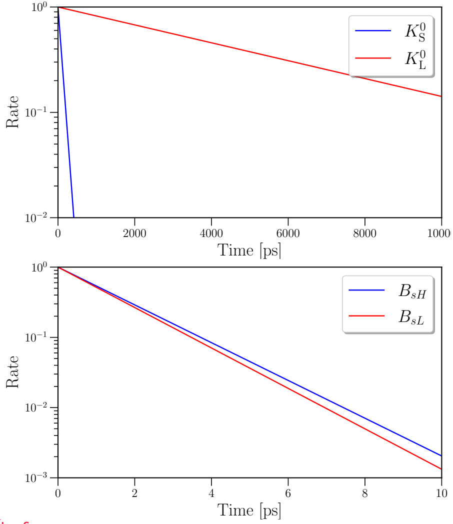
$$|P_\mathrm{L,H}\rangle = p\,|P\rangle \pm q\,\left|\overline{P}\right\rangle .$$

They will oscillate between P and $\overline{P}$ and decay following the lifetimes of P_H and P_L.

The B_s^0 goes considerably faster than the B^0

[B]

Neutral meson mixing



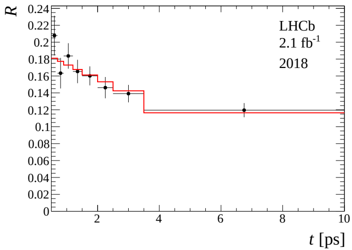
B^0_s and K^0 systems are even more special: they have a significant decay width difference, resulting in different decay times for the heavy (long-lived) and light (short-lived) states.

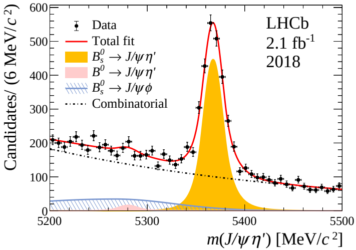
$B_{s\mathrm{L}}$: $CP = +1$, lighter and shorter-lived (1.42 ps)

$B_{s\mathrm{H}}$: $CP = -1$, heavier and longer-lived (1.62 ps)

[B]

$\Delta\Gamma_s$ WITH $B_s^0 \to J/\psi\eta'$

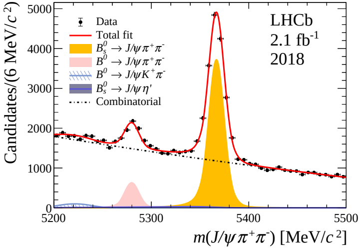




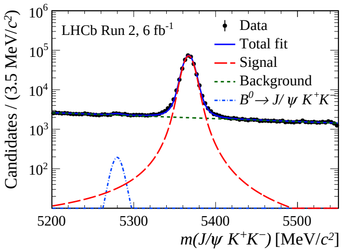
Use $9\,\text{fb}^{-1}$ $B_s^0 \to J/\psi\eta'$ (CP-even) and $B_s^0 \to J/\psi\pi^+\pi^-$ (CP-odd) and get

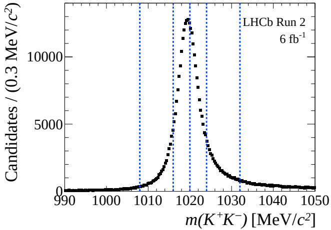
$$\Delta\Gamma_s = 0.087 \pm 0.012 \pm 0.009\,\text{ps}^{-1}$$

consistent with HFlav $\Delta\Gamma_s = 0.074 \pm 0.006$



φ_s IN $B_s^0 \to J/\psi K^+ K^-$

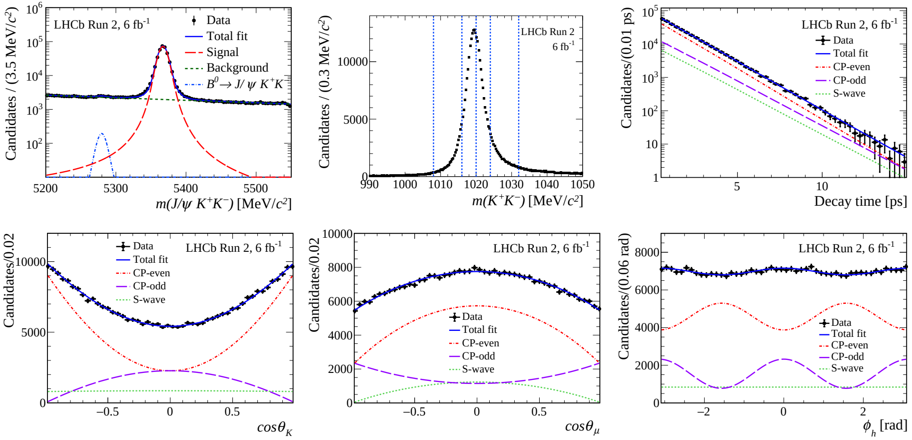




$B_s^0 \to J/\psi(\mu^+\mu^-)\phi(K^+K^-)$ is the golden channel to measure φ_s, the phase between $b \to c\bar{q}s$ and B_s^0 mixing followed by $b \to c\bar{q}s$:

- The signal is very clean. Most backgrounds are peaking: B^0 is vetoed, Λ_b^0 is subtracted using simulation.
  ➜ $350\,800 \pm 700$ B_s^0 in 2015–18 data
- Three polarisation states in the $P \to VV$ process, plus an S-wave contribution from $B_s^0 \to J/\psi K^+K^-$: bin in $m(K^+K^-)$

φ_s IN $B_s^0 \to J/\psi K^+ K^-$



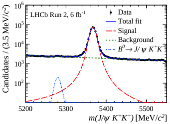
CP-even — *CP*-odd — S-wave

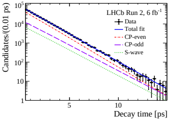
$$\varphi_s = -0.039 \pm 0.022 \pm 0.006\,\text{rad}$$

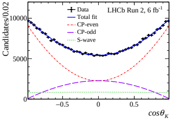
φ_s IN $B_s^0 \to J/\psi K^+ K^-$

Results:

$$\varphi_s = -0.039 \pm 0.022 \pm 0.006\,\text{rad}$$
$$|\lambda| = 1.001 \pm 0.011 \pm 0.005$$
$$\Gamma_s - \Gamma_d = -0.0056\,^{+0.0013}_{-0.0015} \pm 0.0014\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0845 \pm 0.0044 \pm 0.0024\,\text{ps}^{-1}$$
$$\Delta m_s = 17.743 \pm 0.033 \pm 0.009\,\text{ps}^{-1}$$
$$|A_\perp|^2 = 0.2463 \pm 0.0023 \pm 0.0024$$
$$|A_0|^2 = 0.5179 \pm 0.0017 \pm 0.00232$$
$$\delta_\perp - \delta_0 = 2.90 \pm 0.07 \pm 0.05$$
$$\delta_\parallel - \delta_0 = 3.15 \pm 0.06 \pm 0.05\,\text{rad}$$



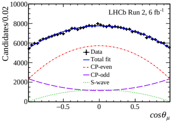


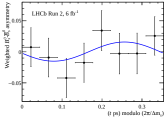


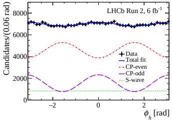
CP-even

CP-odd

S-wave

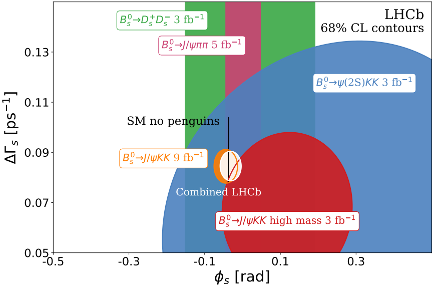


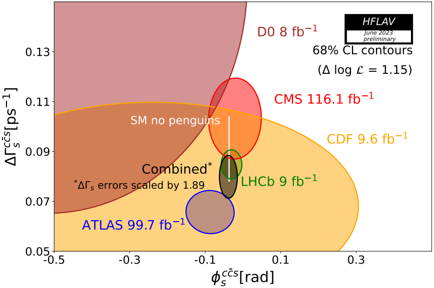




[LHCb, PRL 132 (2024) 051802, arXiv:2308.01468]

φ_s IN $B_s^0 \to J/\psi K^+ K^-$



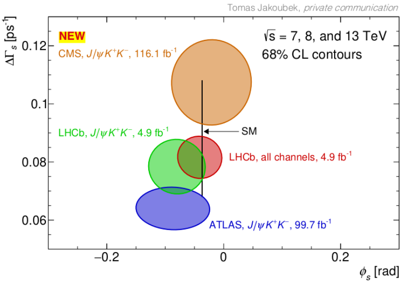


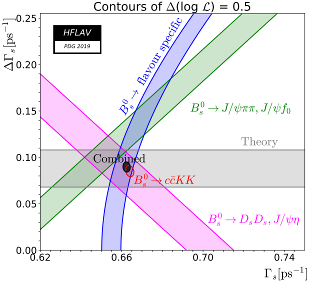
$$\varphi_s = -0.031 \pm 0.018\,\text{rad}$$
$$|\lambda| = 0.990 \pm 0.010$$
$$\Gamma_s = 0.6563 \pm 0.0020\,\text{ps}^{-1}$$
$$\Delta\Gamma_s = 0.0846 \pm 0.0039\,\text{ps}^{-1}$$
$$\Delta m_s = 17.740 \pm 0.027\,\text{ps}^{-1}$$

HFlav [HFlav'23] average with CMS [PLB 816 (2021) 136188], ATLAS [EPJC 81 (2021) 342], D0 [PRD 85 (2012) 032006] and CDF [PRL 109 (2012) 171802]

$$\varphi_s = 0.049 \pm 0.019$$

φ_s AT THE LHC



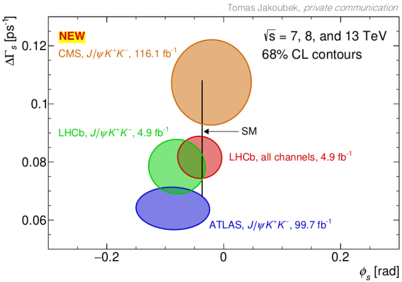


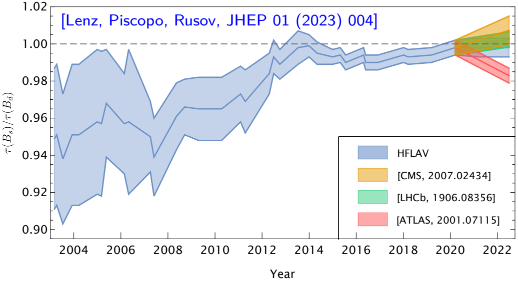
	ATLAS	CMS	LHCb
φ_s	$-0.087 \pm 0.037 \pm 0.021$ rad	-0.074 ± 0.023 rad	-0.080 ± 0.032 rad
$\Delta\Gamma_s$	$0.0657 \pm 0.0043 \pm 0.0037$ ps^{-1}	0.0780 ± 0.0045 ps^{-1}	0.0784 ± 0.0062 ps^{-1}
Γ_s	$0.6703 \pm 0.0014 \pm 0.0018$ ps^{-1}		0.6570 ± 0.0023 ps^{-1}
→ τ_s	1.4930 ± 0.0046 ps	1.522 ± 0.005 ps	1.5312 ± 0.0048 ps

The LHCb and ATLAS values of Γ_s differ by 3.8σ (PDG'18: 1.509 ± 0.004 ps).
$\Delta\Gamma_s$ at CMS and ATLAS also differ by 4σ.

[ATLAS, EPJC 81 (2021) 342] [LHCb, PRL 132 (2024) 051802, arXiv:2308.01468] [CMS, arXiv:2412.19952]

φ_s at the LHC





φ_s	$-0.087 \pm 0.037 \pm 0.021$ rad	-0.074 ± 0.023 rad	-0.080 ± 0.032 rad
$\Delta\Gamma_s$	$0.0657 \pm 0.0043 \pm 0.0037\,\text{ps}^{-1}$	$0.0780 \pm 0.0045\,\text{ps}^{-1}$	$0.0784 \pm 0.0062\,\text{ps}^{-1}$
Γ_s	$0.6703 \pm 0.0014 \pm 0.0018\,\text{ps}^{-1}$		$0.6570 \pm 0.0023\,\text{ps}^{-1}$
➜ τ_s	1.4930 ± 0.0046 ps	1.522 ± 0.005 ps	1.5312 ± 0.0048 ps

The LHCb and ATLAS values of Γ_s differ by 3.8σ (PDG'18: 1.509 ± 0.004 ps).
$\Delta\Gamma_s$ at CMS and ATLAS also differ by 4σ.

[ATLAS, EPJC 81 (2021) 342] [LHCb, PRL 132 (2024) 051802, arXiv:2308.01468] [CMS, arXiv:2412.19952]

φ_s AT THE LHC

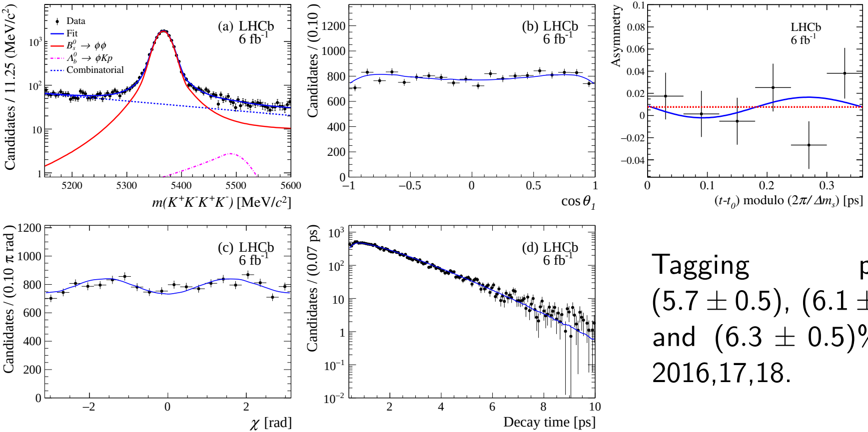
[N. Ellis, Nucl.Phys.Proc.Suppl. 93 (2001) 31]

	ATLAS	CMS	LHCb
$\Delta\Gamma_s$ ($\Delta\Gamma_s/\Gamma_s = 0.15$ input)	12%	8%	9%
Γ_s	0.7%	0.5%	0.6%
A∥	0.8%	0.6%	0.7%
$A_\perp$	3%	2%	2%
$\delta(\phi_s)$ ($x_s = 20$)	0.03	0.014	0.02
$\delta(\phi_s)$ ($x_s = 40$)	0.05	0.03	0.03

Table 1. Estimated precision of parameters determined from fit to $B_s \to J/\psi\phi$ data (3 years ATLAS/CMS, 5 years LHCb).

	ATLAS	CMS	LHCb
φ_s	$-0.087 \pm 0.037 \pm 0.021$ rad	-0.074 ± 0.023 rad	-0.080 ± 0.032 rad
$\Delta\Gamma_s$	$0.0657 \pm 0.0043 \pm 0.0037\,\text{ps}^{-1}$	$0.0780 \pm 0.0045\,\text{ps}^{-1}$	$0.0784 \pm 0.0062\,\text{ps}^{-1}$
Γ_s	$0.6703 \pm 0.0014 \pm 0.0018\,\text{ps}^{-1}$		$0.6570 \pm 0.0023\,\text{ps}^{-1}$
→ τ_s	1.4930 ± 0.0046 ps	1.522 ± 0.005 ps	1.5312 ± 0.0048 ps

Legacy $B_s^0 \to \phi\phi$



Tagging power (5.7 ± 0.5), (6.1 ± 0.7) and $(6.3 \pm 0.5)\%$ for 2016,17,18.

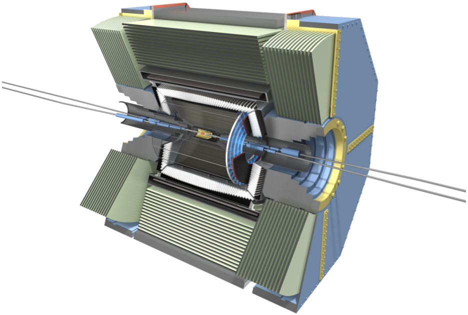
Run 2: $\phi_s^{s\bar{s}s} = -0.04 \pm 0.08 \pm 0.01$,

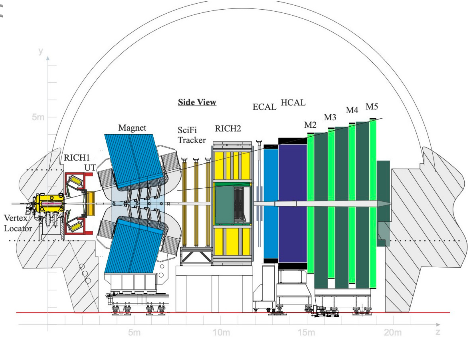
with [PRD 90 (2014) 052011]

$$\phi_s^{s\bar{s}s} = -0.18 \pm 0.09$$

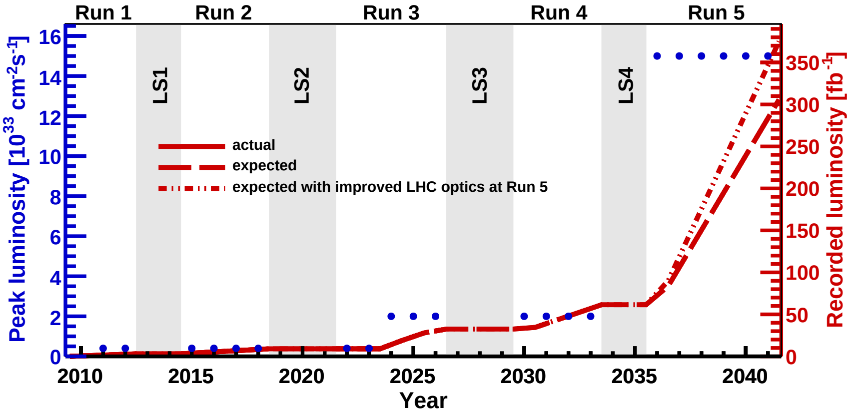
The Future

Flavour Experiments

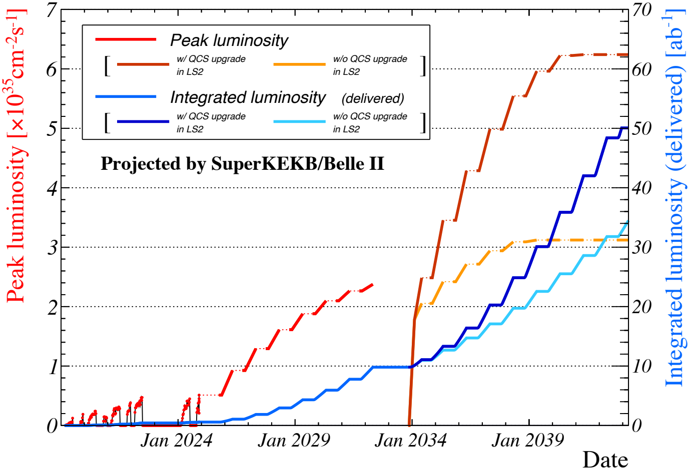




LHCb Upgrade II



Belle II Schedule

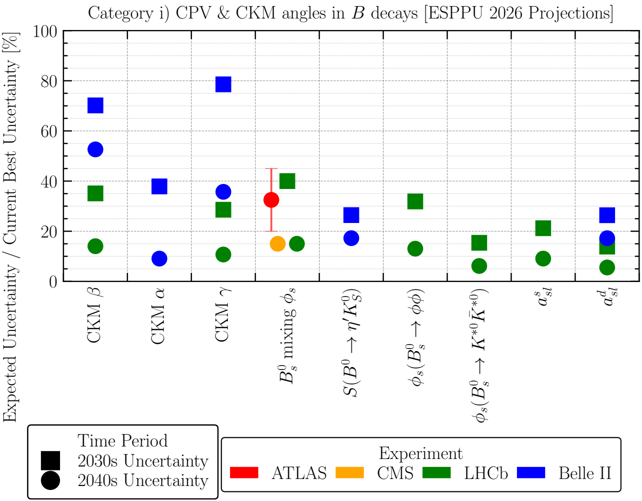


As of Dec 2024

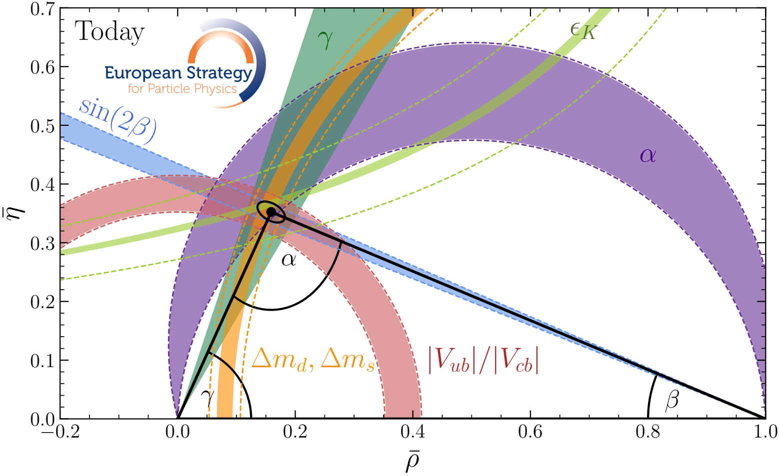
Briefing Book assumes $50\,fb^{-1}$

[ATLAS, Belle II, CMS, LHCb, arXiv:2503.24346]

Heavy Flavour ESPPU input

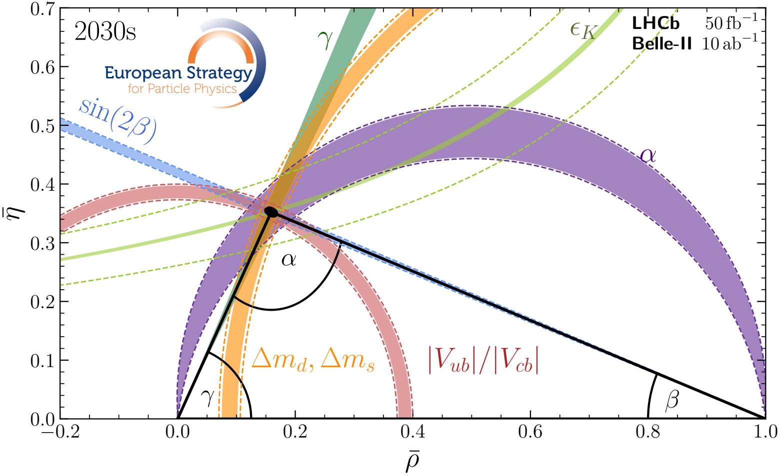


Physics Briefing Book — Flavour

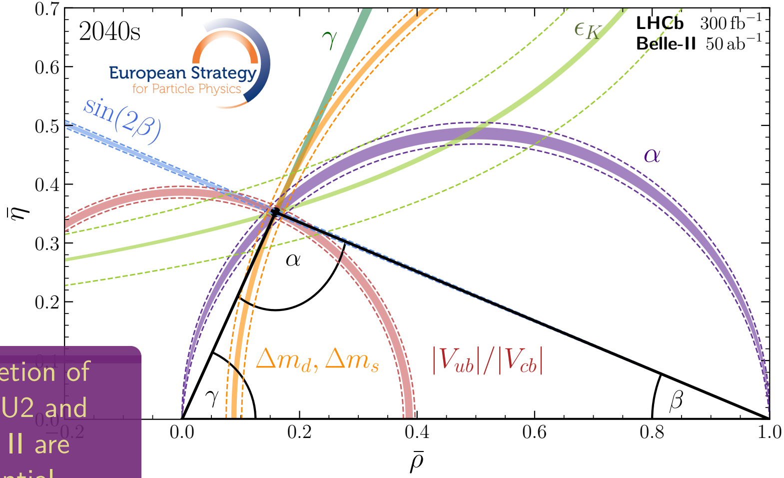


[de Blas *et al.*, arXiv:2511.03883]

Physics Briefing Book — Flavour



Physics Briefing Book — Flavour



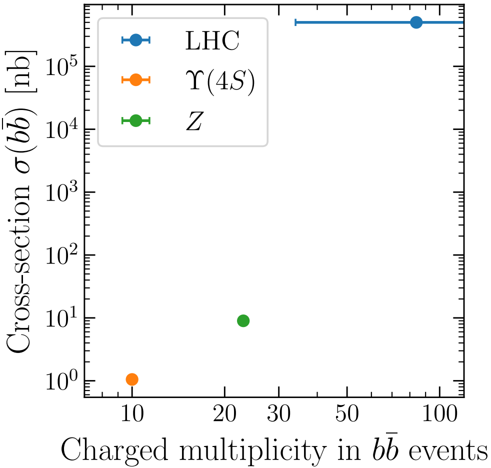
Completion of LHCb U2 and Belle II are essential

What a tera-Z run brings

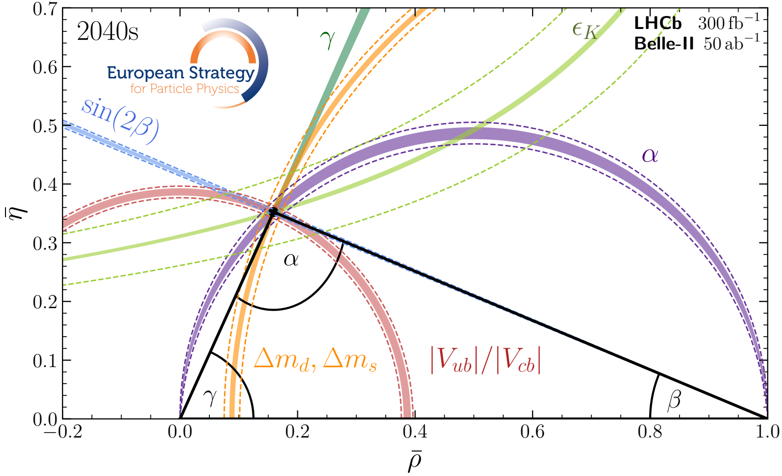
b FROM $\Upsilon(4S)$, Z AND LHC

The $b\overline{b}$ cross-section at the LHC is much (much) higher than at e^+e^-.

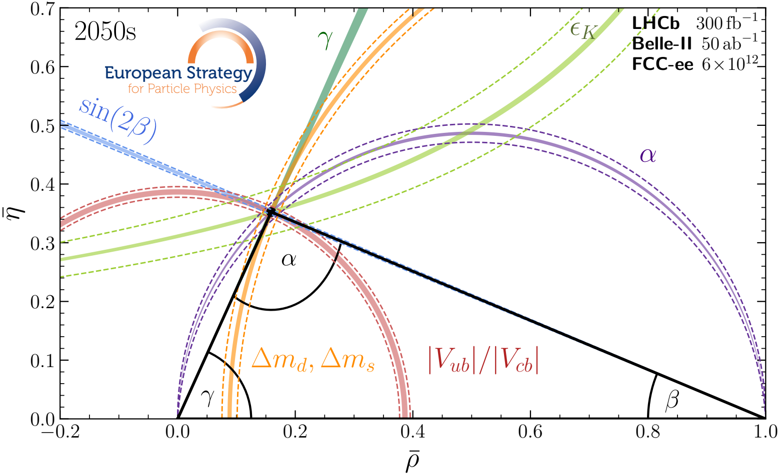
Z are not as clean as $\Upsilon(4S)$, but have a reconstructible primary vertex.



Physics Briefing Book — Flavour

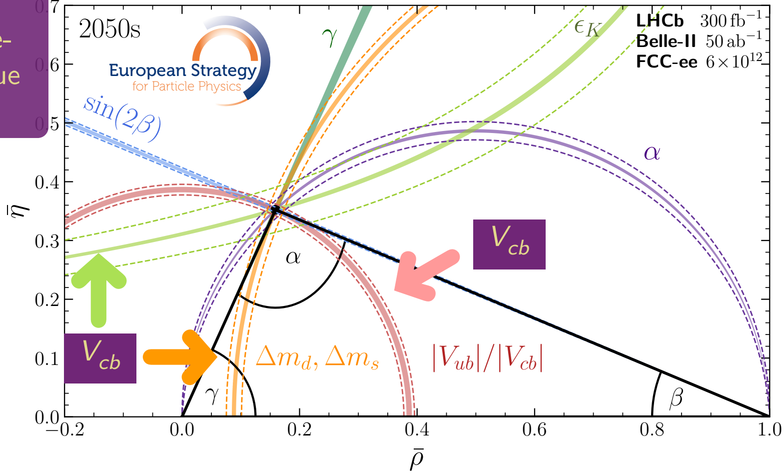


Physics Briefing Book — Flavour

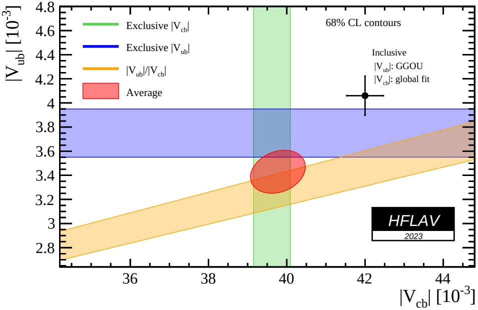


Physics Briefing Book — Flavour

Many improvements due to V_{cb}



$|V_{ub}|$ AND $|V_{cb}|$



$$|V_{ub}|_{\rm excl} = (\ \ 3.43 \pm 0.12) \times 10^{-3} \quad (3\%)$$
$$|V_{cb}|_{\rm excl} = (39.77 \pm 0.46) \times 10^{-3} \quad (1\%)$$
$$|V_{ub}|_{\rm incl} = (\ \ 4.06 \pm 0.16) \times 10^{-3} \quad (3\%)$$
$$|V_{cb}|_{\rm incl} = (41.97 \pm 0.48) \times 10^{-3} \quad (1\%)$$

HFLAV

Discrepancy between exclusive and inclusive V_{ub} (18%) and V_{cb} (5.5%) determinations. Both more than 3σ.

- $|V_{cb}|$ is a crucial ingredient in many SM predictions.
- ✗ Use of exclusive value would lead to large tensions in $\Delta F = 2$
- In the meantime use V_{cb}-free quantities as $\mathcal{B}(B_s^0 \to \mu^+\mu^-)/\Delta M_s$

Above the Z

CKM from WW

Assuming $\mathcal{O}(10^8)$ WW pairs, which comes as a by-product of large $ZH(H)$ samples, or from dedicated WW runs, one measures

$$\mathcal{B}_{ij} = \frac{|V_{ij}|^2}{\sum_{l=u,c;\ m=d,s,b} |V_{lm}|^2} \mathcal{B}_{\text{had}}$$

V_{ub} and V_{cb} are feasible. The others have too high backgrounds from mis-ID.

Present precision on $|V_{cs}|$: 0.6%; on $|V_{cb}|$: 1% with 5% discrepancy.

Number of correctly tagged jets W (before other efficiencies) based on

[Lian *et al.*, arXiv:2310.03440]

V_{ij}	BF	yield
V_{ud}	3.18×10^{-1}	3.2×10^{6}
V_{us}	1.70×10^{-2}	3.4×10^{5}
V_{ub}	4.50×10^{-6}	1.2×10^{2}
V_{cd}	1.70×10^{-2}	3.5×10^{5}
V_{cs}	3.17×10^{-1}	1.3×10^{7}
V_{cb}	5.90×10^{-4}	3.3×10^{4}

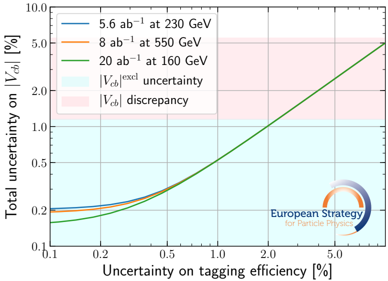
CKM from WW

Assuming $\mathcal{O}(10^8)$ WW pairs, which comes as a by-product of large $ZH(H)$ samples, or from dedicated WW runs, one measures

$$\mathcal{B}_{ij} = \frac{|V_{ij}|^2}{\sum_{l=u,c;\ m=d,s,b} |V_{lm}|^2} \mathcal{B}_{\rm had}$$

The precision is systematically limited by the knowledge of the jet flavour-tagging efficiency, which is calibrated from Z events.

Present precision on $|V_{cs}|$: 0.6%; on $|V_{cb}|$: 1% with 5% discrepancy.



Typical jet-tagging efficiencies ϵ_β^q to tag a β-jet as q-jet

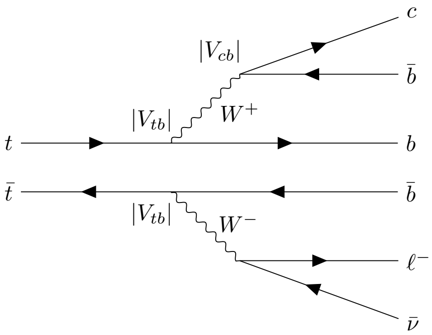
	b	s	c	u	d	g
ϵ_β^b	0.8	0.0001	0.003	0.0005	0.0005	0.007
ϵ_β^c	0.02	0.008	0.8	0.01	0.01	0.01
ϵ_β^s	0.01	0.9	0.1	0.3	0.3	0.2

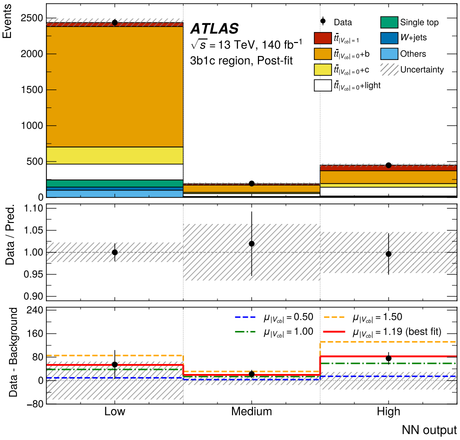
[Robson, Leonidopoulos, de Blas, Koppenburg, List, Maltoni *et al.*, arXiv:2506.15390]

$|V_{cb}|$ FROM TOP

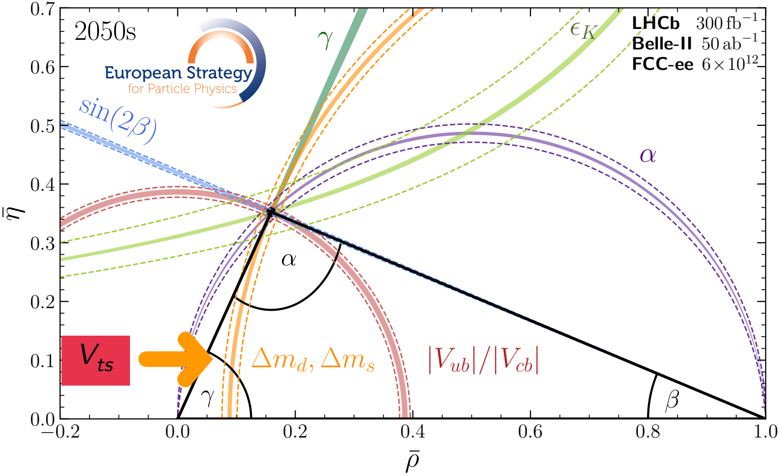
Using $t\bar{t}$ events from Run 2 with $t \to bW^+$ and $W^+ \to \bar{b}c$ on one side and $W^- \to \ell^- \bar{\nu}$ on the other.

$$|V_{cb}| = \left(50\, ^{+\,11}_{-\,14}\right) \times 10^{-3}$$



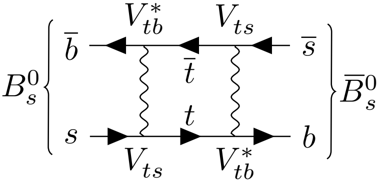


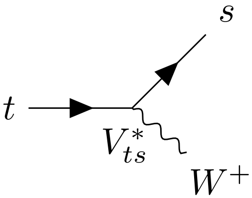
Physics Briefing Book — Flavour

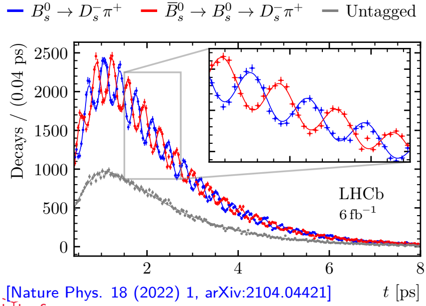


[Robson, Leonidopoulos, de Blas, Koppenburg, List, Maltoni *et al.*, arXiv:2506.15390]

V_{ts} from top quark decays







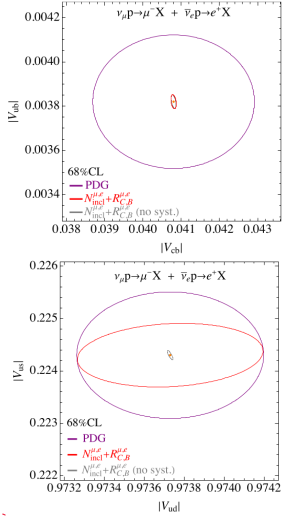
[Nature Phys. 18 (2022) 1, arXiv:2104.04421]

Usually V_{ts} from B_s^0 mixing ➜ 2.2% precision, but assume no new physics

Study was done assuming 2M $t\bar{t}$ pairs. Observation of $t \to sW$ is possible with 15% precision on BF

➜ Precision on V_{ts}: 3.1% [Giappichini *et al.*, 2025]

CKM matrix elements



A 10 TeV muon collider would produce 10^8 W bosons, similar to FCC or LC, giving access to $|V_{cb}|$ and $|V_{cs}|$ [Marzocca, Szewc, Tammaro, JHEP 11 (2024) 017], however without a Z run for calibration.

The $\overline{\nu}_e$ and ν_μ from the straight sections can interact with a 1 ton target as $\nu_\mu p \to \mu^- X$ and alike. The number of DIS events $N^{\mu,e}_{c,b}$ and the ratios

$$R^{\mu,e}_{c,b} = \frac{N^{\mu,e}_{c,b}}{N^{\mu,e}_{\text{incl.}}}$$

get $|V_{cb}|$ and $|V_{ub}|$ to 0.1% and 0.5% precision. Similarly, for the Cabibbo anomaly, $|V_{ud}|$ and $|V_{us}|$ to 3×10^{-4} and 0.2% precision.

Conclusion

- Now the the golden era of *CPV* in the quark sector
- We will either pinpoint to high precision
- Or find cracks in the CKM paradigm

[@koppenburg.ch] [patrick.koppenburg@nikhef.nl]

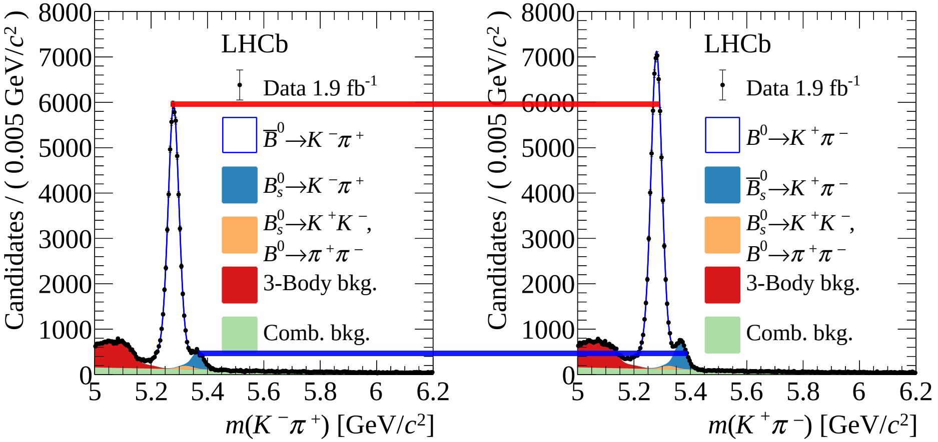

THE
OTHER SIDE
Why do you need a reason?
© 1991 FarWorks, Inc. All rights reserved.

Backup

The KM matrix

11/02/2023 - patrick@koppenburg.ch

CP violation in $B \to h^+h^-$

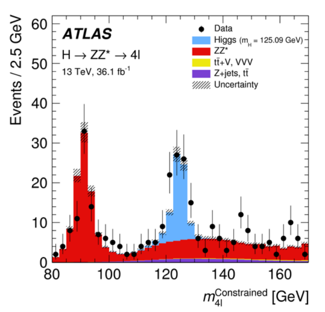


[B]

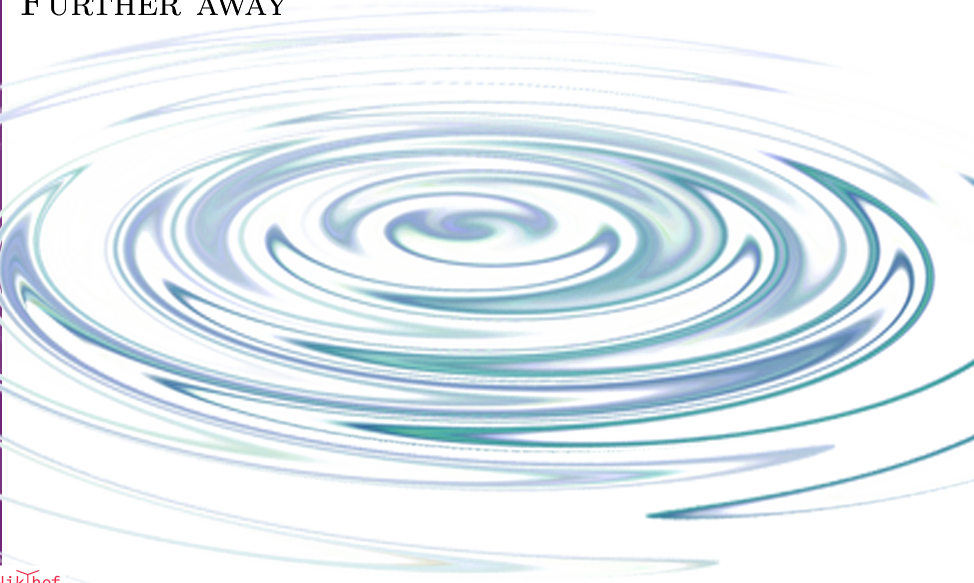
Large CP violation in charmless B^0 and B_s^0 decays (seen in [PRL 110 (2013) 221601])

Near

Near

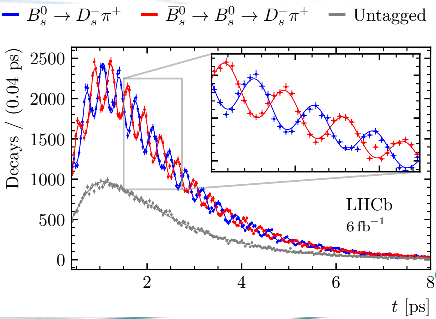

ATLAS
H → ZZ* → 4l
13 TeV, 36.1 fb^-1
Data
Higgs (m_H = 125.09 GeV)
ZZ*
tt̄+V, VVV
Z+jets, tt̄
Uncertainty
Events / 2.5 GeV
0
10
20
30
40
50
60
80
100
120
140
160
m_4l^Constrained [GeV]

Further away



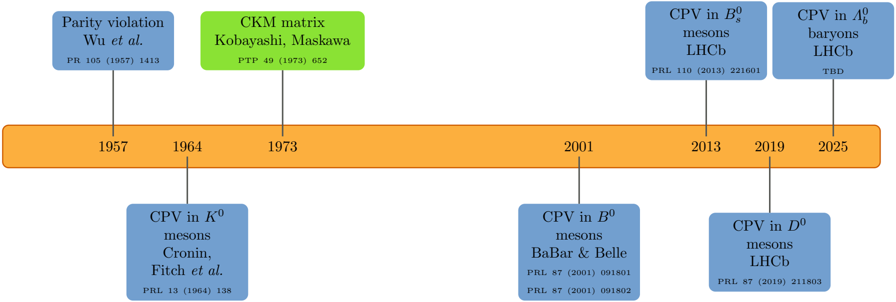
[B]

Further away



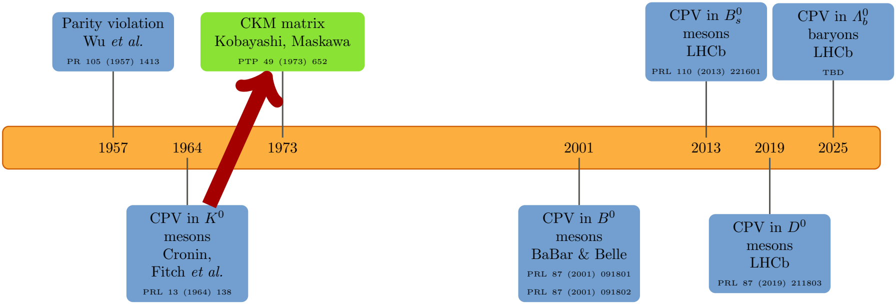
[B]

CP VIOLATION TIMELINE



[B]

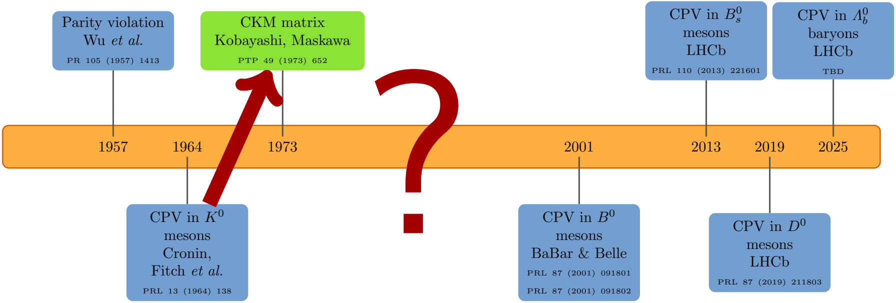
CP violation timeline



- It took nine years to get from CP violation to understanding CP violation

[B]

CP VIOLATION TIMELINE



- It took nine years to get from CP violation to understanding CP violation
- But what happened in the next 28 years?

[B]

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

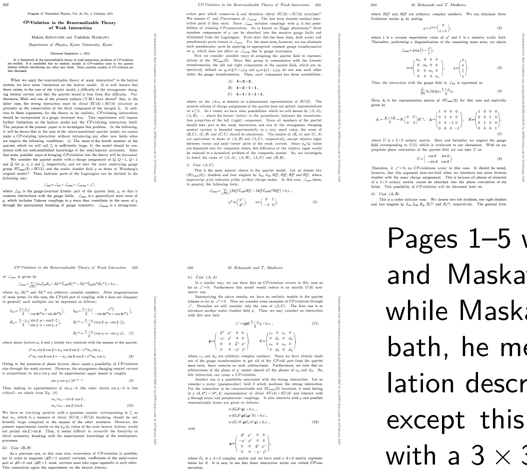
(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-violation exist in the quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

When we apply the renormalizable theory of weak interaction[1)] to the hadron system, we have some

[Olsen, KM'50 proceedings, arXiv:2309.06042] [Kobayashi, Maskawa, Progr. Theo. Phys. 49 (1973) 652]

THE KM MATRIX


652

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

CP-Violation in the Renormalizable Theory of Weak Interaction 653

654 *M. Kobayashi and T. Maskawa*

CP-Violation in the Renormalizable Theory of Weak Interaction 655

656 *M. Kobayashi and T. Maskawa*

Pages 1–5 were null results and Kobayashi and Maskawa were disappointed. Then, while Maskawa was taking his after-dinner bath, he mentally went through the calculation described in the previous paragraph, except this time for a six-quark scenario with a 3×3 flavour-mixing rotation matrix in three dimensions. [Olsen]

First observation of charm?

See one event “6B-23” with two particles decaying likely to $\pi^0\pi^\pm$ and $\pi^0 p$ (?). Mass is around 2 GeV and $\tau \sim 3 \times 10^{-14}$ s.

Kobayashi and Maskawa were aware [Maki, Maskawa, PTP 46 (1971) 1647]

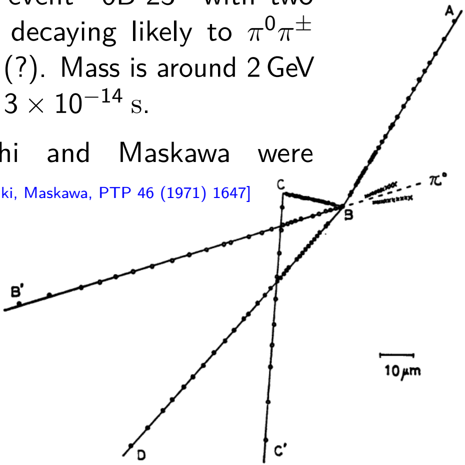


Fig. 3 (c). Z projection.

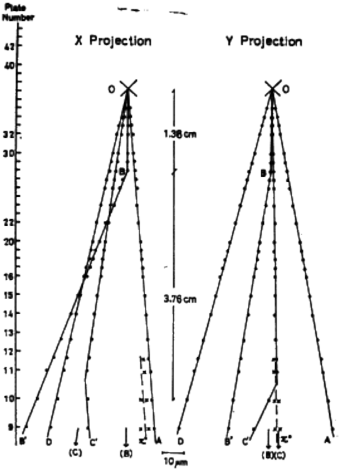
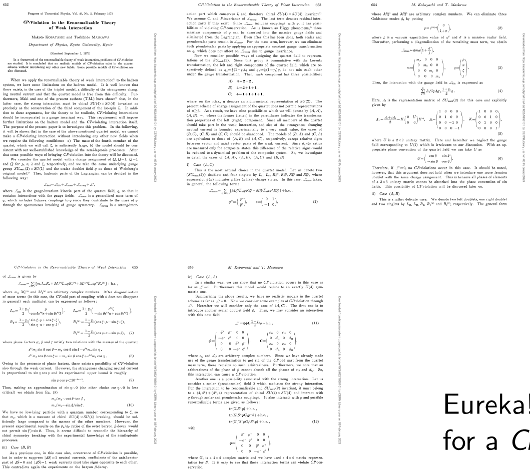


Fig. 3 (a). Fig. 3 (b).

The KM matrix



Next we consider a 6-plet model, another interesting model of CP-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{\text{weak}}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}. \quad (13)$$

Then, we have CP-violating effects through the interference among these different current components. An interesting feature of this model is that the CP-violating effects of lowest order appear only in $\Delta S\neq 0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

So far we have considered only the straightforward extensions of the original Weinberg's model. However, other schemes of underlying gauge groups and/or scalar fields are possible. Georgi and Glashow's model[4] is one of them. We can easily see that CP-violation is incorporated into their model without introducing any other fields than (many) new fields which they have introduced already.

References

1) S. Weinberg, Phys. Rev. Letters **19** (1967), 1264; **27** (1971), 1688.
2) Z. Maki and T. Maskawa, RIFP-146 (preprint), April 1972.
3) P. W. Higgs, Phys. Letters **12** (1964), 132; **13** (1964), 508.
G. S. Guralnik, C. R. Hagen and T. W. Kibble, Phys. Rev. Letters **13** (1964), 585.
4) H. Georgi and S. L. Glashow, Phys. Rev. Letters **28** (1972), 1494.

Downloaded from https://academic.oup.com/ptp/article/49/2/652/1858101 by CERN Library user on 03 February 2023

Eureka! With six quarks there is room for a CP-violating phase!

[Olsen, KM'50 proceedings, arXiv:2309.06042] [Kobayashi, Maskawa, Progr. Theo. Phys. 49 (1973) 652]

The KM matrix

652

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}.$$

(Received September 1, 1972)

should be a cos

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic models of *CP*-vi[...] quartet scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

When we apply the renormalizable theory of weak interaction[1)] to the hadron system, we have some limitations on the hadron model. It is well known that

The KM matrix

$$U = \begin{pmatrix} cc'' & s & cs'' \\ -sc''c' - s''s'z & cc' & -ss''c' + c''s'z \\ -s''c' + sc''s'z^* & -cs'z^* & c''c' + ss''s'z^* \end{pmatrix}$$

[†2] The observation that in a six quark scheme a model of *CP* violation of this type can be constructed has already appeared in the literature, ref. [5]. After completing the paper, I learned that some of the arguments presented here have been independently discussed by S. Pakvasa and H. Sugawara, Hawaii preprint UH-511-204-75, Sept. 1975.

Maiani found the CKM matrix again in 1975 after the charm observation [Maiani, PLB 62 (1976) 183]

[2] M. Kobayashi and K. Maskawa, Prog. Theor. Phys. 49, 652 (1973).

In 1976 Pakvasa and Sugawara (Hawaii) cite it and have another form of the matrix (with a different typo). They also mistype Maskawa's initial. [PRD 14 (1976) 305]

[7] M. Kobayashi and K. Maskawa, Progr. Theor. Phys. 49 (1973) 652.

This typo is then repeated by Ellis, Gaillard, Nanopoulos [NPB 109 (1976) 213]

...ical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

Makoto Kobayashi and Toshihide Maskawa

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of *CP*-violation are studied. It is concluded that no realistic ... scheme without introducing any other new fields. Some possible models of *CP*-violation are also discussed.

When we apply the renormalizable theory of weak interaction[1] to the hadron system, we have some limitations on the hadron model. It is well known that

The KM matrix

652

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

CP-Violation in the Renormalizable Theory of Weak Interaction

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\sin\theta_3 e^{i\delta} \end{pmatrix}.$$

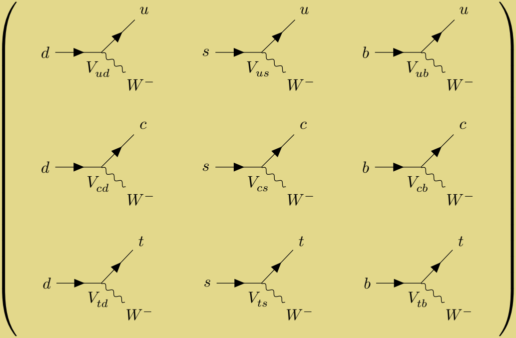
(Received September 1, 1972)

If the phase is the only *CP*-violating phase affecting quarks this picture should be consistent at all levels of precision

→ **Let's check!**

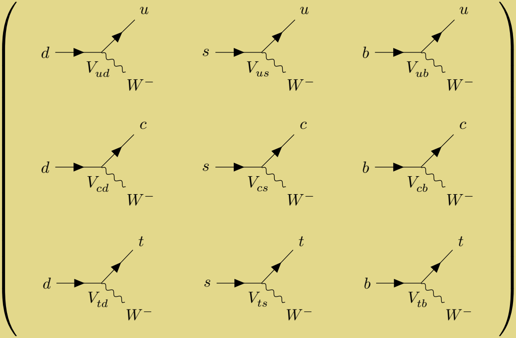
The CKM matrix

$V_{\mathrm{CKM}} =$



The CKM matrix

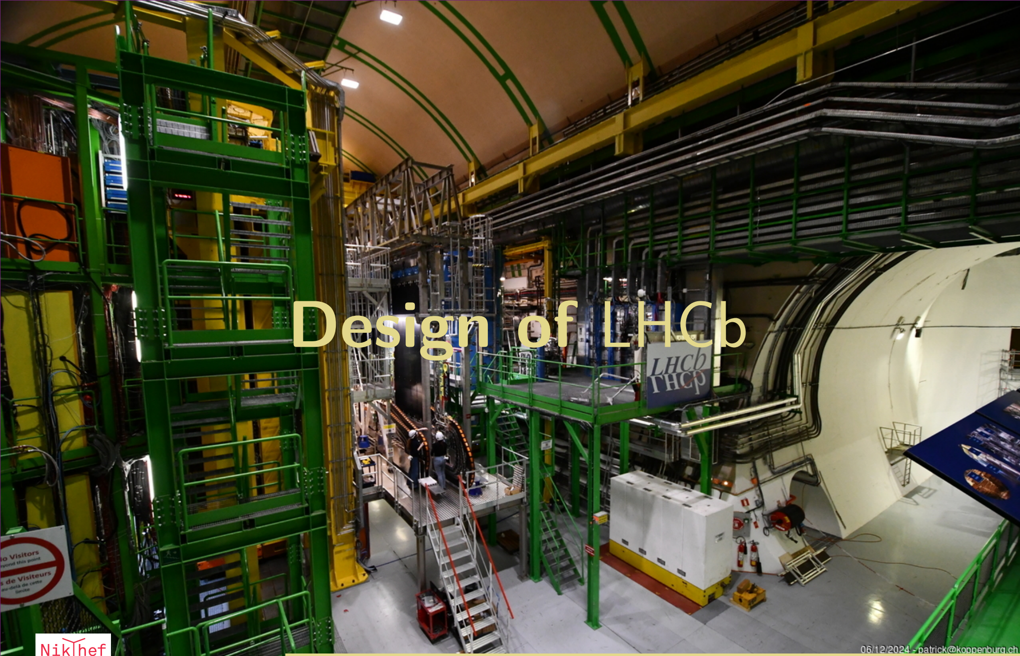
$V_{\text{CKM}} =$



$$=\simeq \begin{pmatrix} 1 & 0.23 & 10^{-4} \\ -0.23 & 1 & 0.04 \\ 10^{-3} & -0.04 & 1 \end{pmatrix}$$

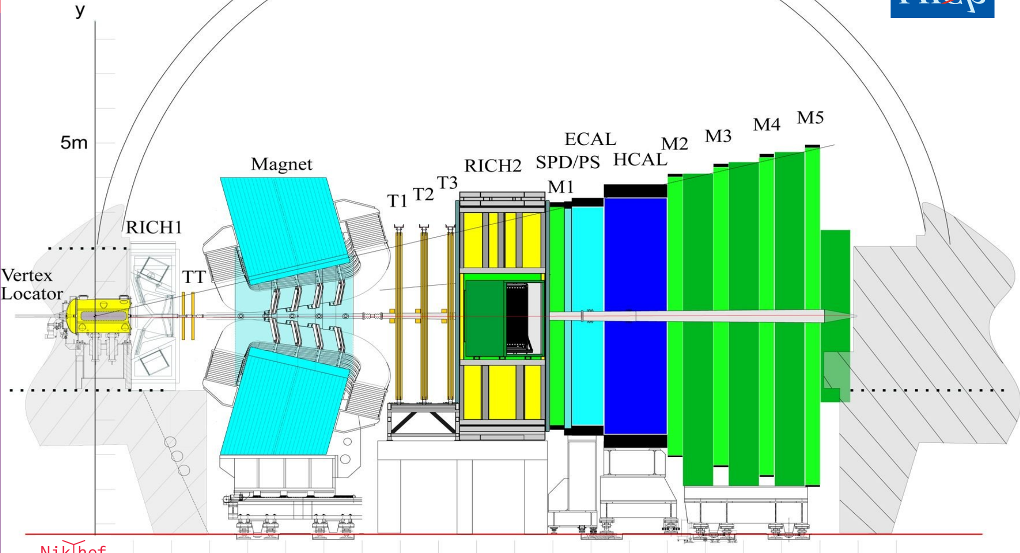
The Higgs and the *W* disagree on what a quark is!

Design of LHCb



The Large Hadron Collider at CERN

LHCb Legacy 2009–2018



LHCb detector design

Acceptance

Mass and momentum resolution

Impact parameter and time resolution

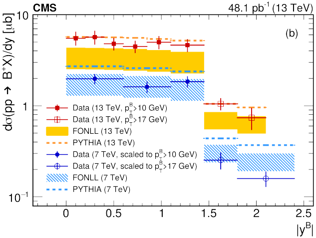
Particle identification

LHCb detector design: Acceptance

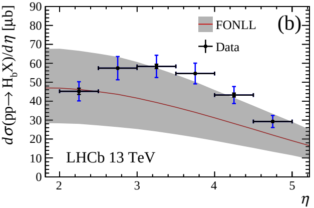
Acceptance: Light particles tend to be closer to the beam pipe. It's cheaper to instrument the forward region than 4π.

$$\ln \frac{\sqrt{s}}{m_X} \geq \eta(X)$$

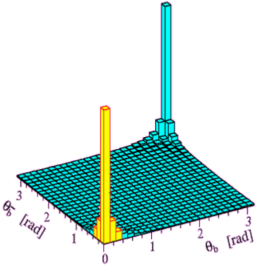
For Higgs at 13.6 TeV it's 4.7 while for B it's 7.9.



[CMS, PLB 771 (2017) 435]

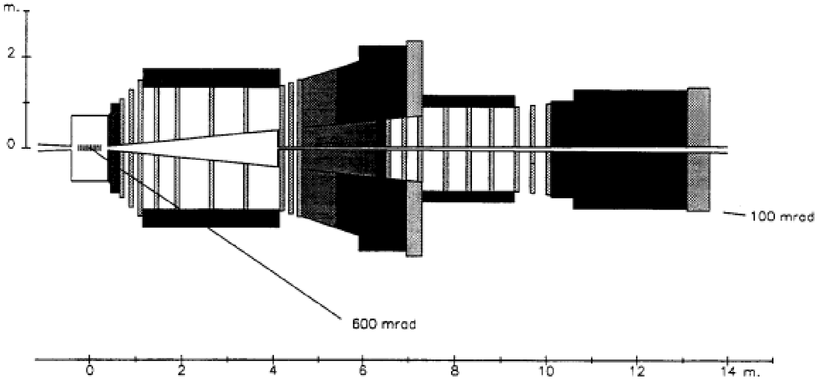


[PRL 118 (2017) 052002, arXiv:1612.05140]



LHCb detector design: Acceptance

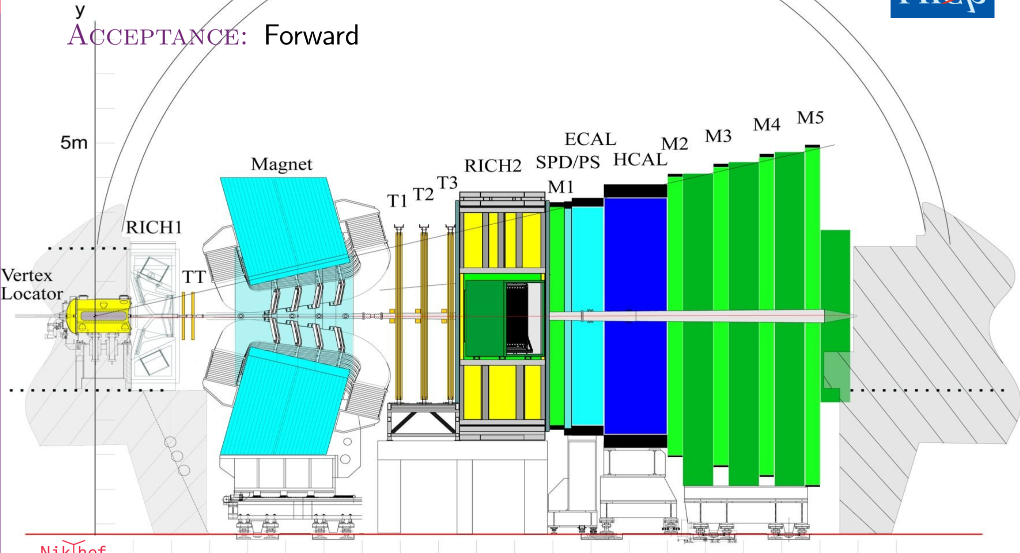
Acceptance: Forward



COBEX LOI LHCC-93-50 (1993)

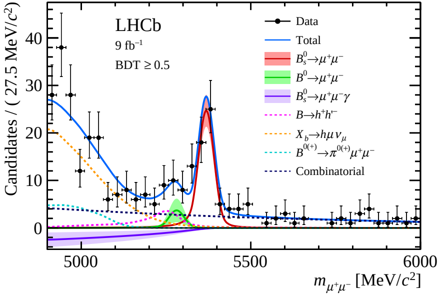
LHCb detector design: Acceptance

Acceptance: Forward

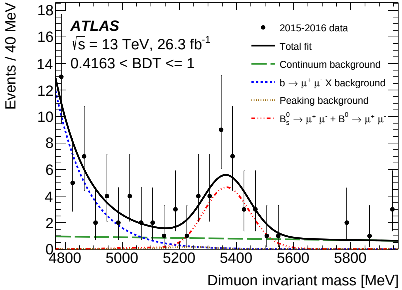


LHCb DETECTOR DESIGN: p RESOLUTION

MASS RESOLUTION: Better resolution translates into better S–B discrimination. But at the minimum we want to resolve the B_s^0 and B^0.



[PRL 128 (2022) 041801, arXiv:2108.09284]



[ATLAS, JHEP 04 (2019) 098]

LHCb DETECTOR DESIGN: p RESOLUTION

MASS RESOLUTION: Better resolution translates into better S–B discrimination. But at the minimum we want to resolve the B_s^0 and B^0.

$$\begin{pmatrix} \sqrt{p_x^2 + p_z^2 + m^2} \\ p_x \\ 0 \\ p_z \end{pmatrix} = \begin{pmatrix} \sqrt{p_a^2 + m_a^2} \\ p_a \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} \sqrt{p_b^2 + m_b^2} \\ p_b \cos\theta \\ 0 \\ p_b \sin\theta \end{pmatrix}$$

where p_a defines the x direction and y is at an angle θ. This leads to

$$m = \sqrt{m_a^2 + m_b^2 - 2 p_a p_b \cos\theta + 2\sqrt{m_a^2 + p_a^2}\sqrt{m_b^2 + p_b^2}}$$

$$\frac{\partial m}{\partial p_a} = \frac{1}{m}\left(p_a \frac{\sqrt{m_b^2 + p_b^2}}{\sqrt{m_a^2 + p_a^2}} - p_b \cos\theta \right) \qquad \frac{\partial m}{\partial \theta} = \frac{1}{m} p_a p_b \sin\theta$$

LHCb DETECTOR DESIGN: p RESOLUTION

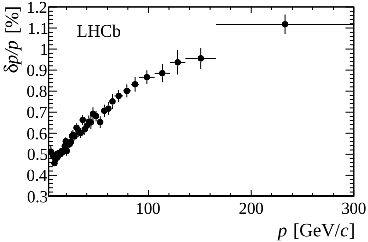
MASS RESOLUTION: Better resolution translates into better S–B discrimination. But at the minimum we want to resolve the B_s^0 and B^0.

$$m = \sqrt{m_a^2 + m_b^2 - 2p_a p_b \cos\theta + 2\sqrt{m_a^2 + p_a^2}\sqrt{m_b^2 + p_b^2}}$$

$$\frac{\partial m}{\partial p_a} = \frac{1}{m}\left(p_a \frac{\sqrt{m_b^2 + p_b^2}}{\sqrt{m_a^2 + p_a^2}} - p_b \cos\theta\right)$$

Plugging in $p_a = p_b = 30\,\text{GeV}$ gets $\theta = 0.18$ for $B_s^0 \to \mu^+\mu^-$

- 3σ B_s^0-B^0 separation ➜ $\leq 30\,\text{MeV}$ resolution
- which translates into $\leq 0.55\%$ p resolution.

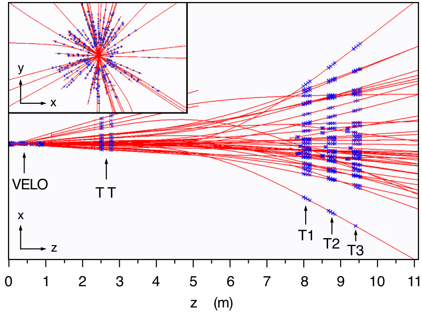


LHCb detector design: p resolution

Mass resolution: Better resolution translates into better S–B discrimination. But at the minimum we want to resolve the B_s^0 and B^0.

➜ Need $\delta p/p \sim 0.5\%$

- In a dipole field the momentum is obtained from the angle of the track before and after the magnet



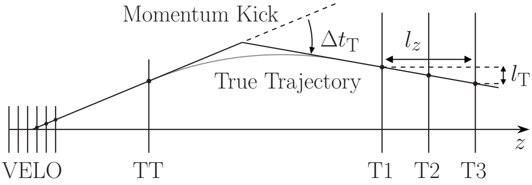
LHCb detector design: p resolution

Mass resolution: Better resolution translates into better S–B discrimination. But at the minimum we want to resolve the B_s^0 and B^0.

➜ Need $\delta p/p \sim 0.5\%$

- In a dipole field the momentum is obtained from the angle of the track before and after the magnet

$$\Delta\vec{p} = p\Delta t_{\mathrm{T}} \qquad t_{\mathrm{T}} = l_{\mathrm{T}}/l_z \qquad \rightarrow \qquad \frac{\sigma_p}{p} \simeq \frac{\sigma_{l_{\mathrm{T}}}}{l_{\mathrm{T}}}$$



Many handles

1. Hit resolution ➜ $\sigma_{l_{\mathrm{T}}}$
2. Tracking volume l_z
3. B field, and
4. level-arm z ➜ Δt_{T} ➜ $\frac{l_{\mathrm{T}}}{l_z}$

Legacy LHCb: $\sigma_{l_{\mathrm{T}}} \sim 200\,\mu\mathrm{m}$, $l_z \sim 2\,\mathrm{m}$, $\int B \mathrm{d}l_z = 4\,\mathrm{Tm}$

LHCb DETECTOR DESIGN: p RESOLUTION

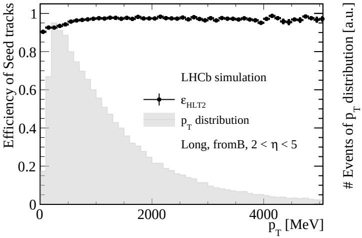
MASS RESOLUTION: Better resolution translates into better S–B discrimination. But at the minimum we want to resolve the B_s^0 and B^0.

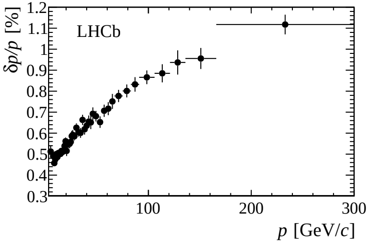
➜ Need $\delta p/p \sim 0.5\%$

- In a dipole field the momentum is obtained from the angle of the track before and after the magnet

✔ In the upgraded LHCb the SciFi provides 100 µm resolution

[LHCb-DP-2022-002, arXiv:2305.10515]





LHCb DETECTOR DESIGN: p RESOLUTION

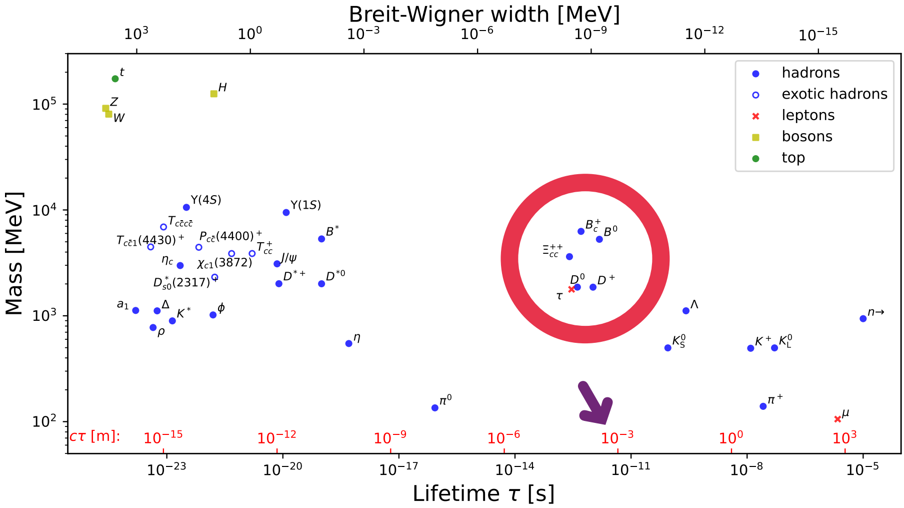
MASS RESOLUTION: Better resolution translates into better S–B discrimination. But at the minimum we want to resolve the B_s^0 and B^0.

$$m = \sqrt{m_a^2 + m_b^2 - 2p_a p_b \cos\theta + 2\sqrt{m_a^2 + p_a^2}\sqrt{m_b^2 + p_b^2}}$$

Let's now assume $p_i \gg m_i$ and θ is small

$$m \simeq \sqrt{p_a p_b}\sqrt{2(1-\cos\theta)} \simeq \sqrt{p_a p_b}\,\frac{\theta}{2}$$

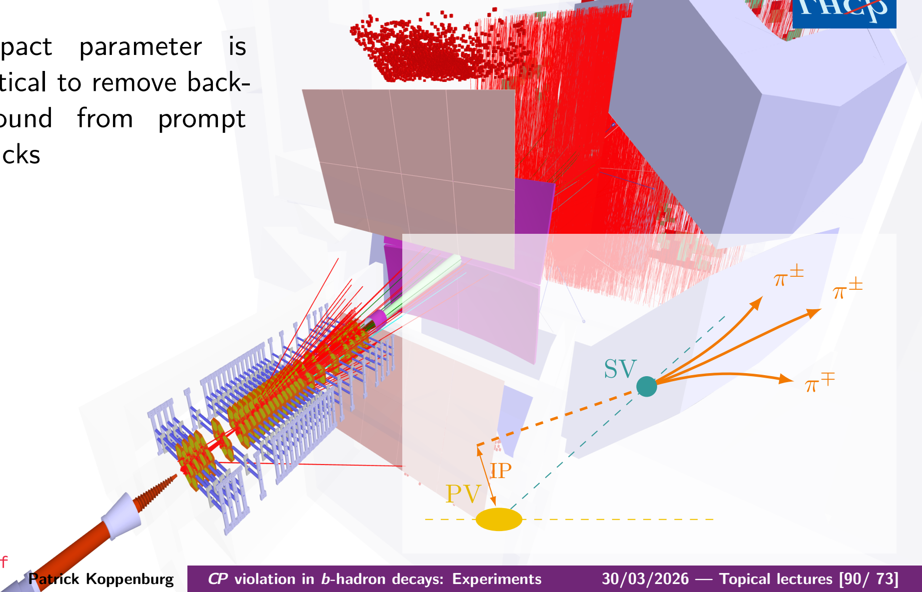
Lifetimes and widths of selected particles



[LHCb, Int. J. Mod. Phys. A 30 (2015) 1530022, arXiv:1412.6352] [De Bruyn, 2015]

LHCb detector design: Impact parameter

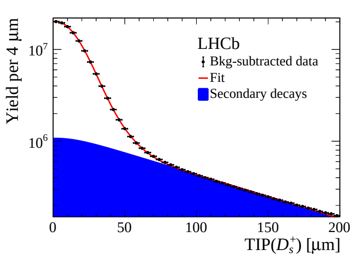
Impact parameter is critical to remove background from prompt tracks

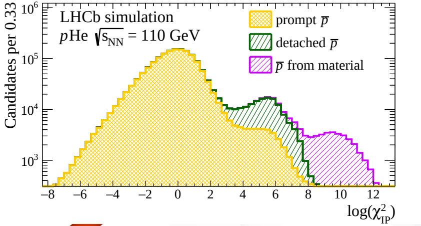


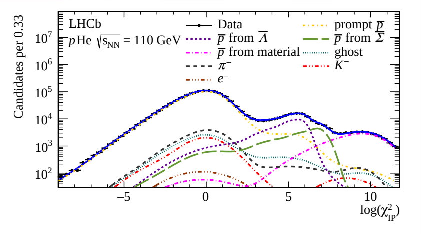
[LHCb, Int. J. Mod. Phys. A 30 (2015) 1530022, arXiv:1412.6352] [De Bruyn, 2015]

LHCb detector design: Impact parameter

Impact parameter is critical to remove background from prompt tracks

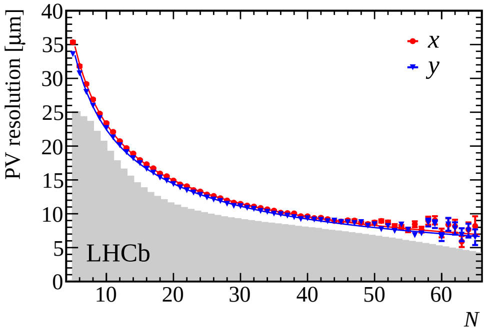


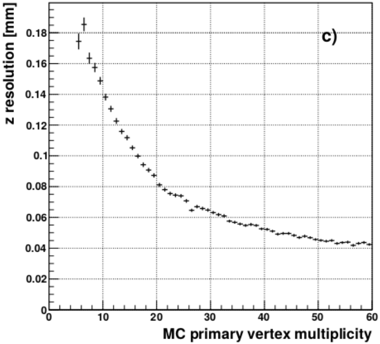




LHCb detector design: Impact parameter

IP resolution depends on "track resolution" and "PV resolution", which depends on "track resolution" for N tracks.





[LHCb, Int. J. Mod. Phys. A 30 (2015) 1530022, arXiv:1412.6352] [De Bruyn, 2015]

LHCb detector design: Impact parameter

IP is the length of the $\vec{\mathrm{IP}}$ vector. Let's look at the x component

$$\mathrm{IP}_x = x - x_{\mathrm{PV}} - (z - z_{\mathrm{PV}}) t_x$$

where t_x is the slope of the track in x

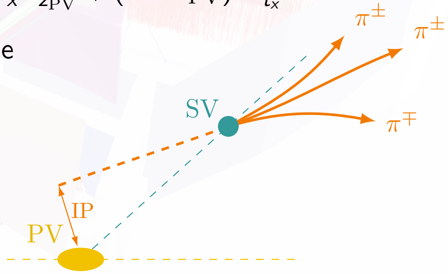
$$\sigma^2_{\mathrm{IP_x}} = \sigma^2_x + \sigma^2_{x_{\mathrm{PV}}} + t_x^2 \sigma^2_{z_{\mathrm{PV}}} + (z - z_{\mathrm{PV}})^2 \sigma^2_{t_x}$$

The last term dominates due to multiple scattering.

$$(z - z_{\mathrm{PV}}) \propto 1/t \qquad \text{(Geometry)}$$

$$\sigma_t \propto 1/p \qquad \text{(Mult. Scat.)}$$

$$\frac{1}{t}\frac{1}{p} = \frac{1}{p_{\mathrm{T}}}$$



LHCb detector design: Impact parameter

IP is the length of the $\vec{\text{IP}}$ vector. Let's look at the x component

$$\text{IP}_x = x - x_{\text{PV}} - (z - z_{\text{PV}})t_x$$

where t_x is the slope of the track in x

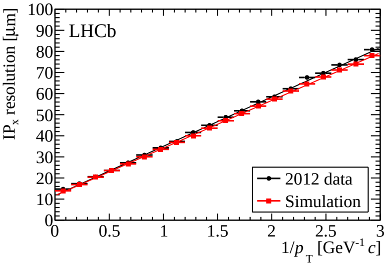
$$\sigma^2_{\text{IP}_x} = \sigma^2_x + \sigma^2_{x_{\text{PV}}} + t^2_x \sigma^2_{z_{\text{PV}}} + (z - z_{\text{PV}})^2 \sigma^2_{t_x}$$

The last term dominates due to multiple scattering.

$$(z - z_{\text{PV}}) \propto 1/t \quad \text{(Geometry)}$$

$$\sigma_t \propto 1/p \quad \text{(Mult. Scat.)}$$

$$\frac{1}{t}\frac{1}{p} = \frac{1}{p_{\text{T}}}$$



LHCb detector design: decay time

One infers the **decay time *t*** of a given candidate particle from the measured **flight distance *l***

$$ct = \gamma l$$

It follows a decaying exponential. The **lifetime τ** of a particle is the average decay time.

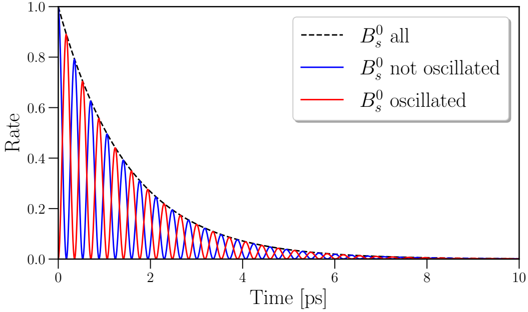
LHCb DETECTOR DESIGN: DECAY TIME

One infers the **decay time t** of a given candidate particle from the measured **flight distance l**

$$ct = \gamma l$$

A better time resolution helps for measuring decay times, but is crucial for resolving oscillations

- The B_s^0 sets the strongest constraints
- $\Delta m_s = 17.8\,\text{ps}^{-1}$
  - ➜ $1/\Delta m_s = 56\,\text{fs}$
    - We did not know this in 2000 ➜ LHCb is overdesigned for time resolution.



LHCb DETECTOR DESIGN: DECAY TIME

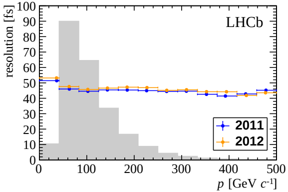
One infers the **decay time *t*** of a given candidate particle from the measured **flight distance *l***

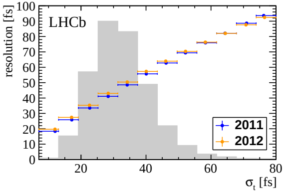
$$ct = \gamma l$$

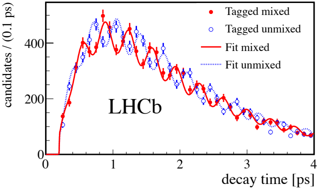
The resolution is

$$\sigma_t^2 = \left(\frac{m}{p}\right)^2 \sigma_l^2 + \left(\frac{t}{p}\right)^2 \sigma_p^2$$

The resolution σ_l relates to that on IP and PV. At low p multiple scattering dominates. At high p the opening angle is small and detector resolution matters most.

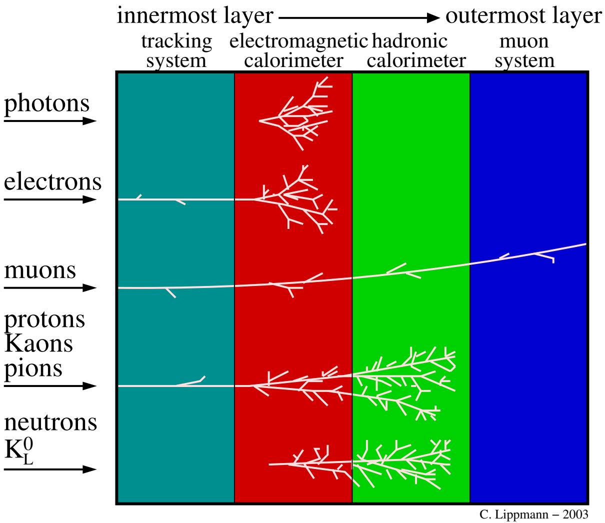




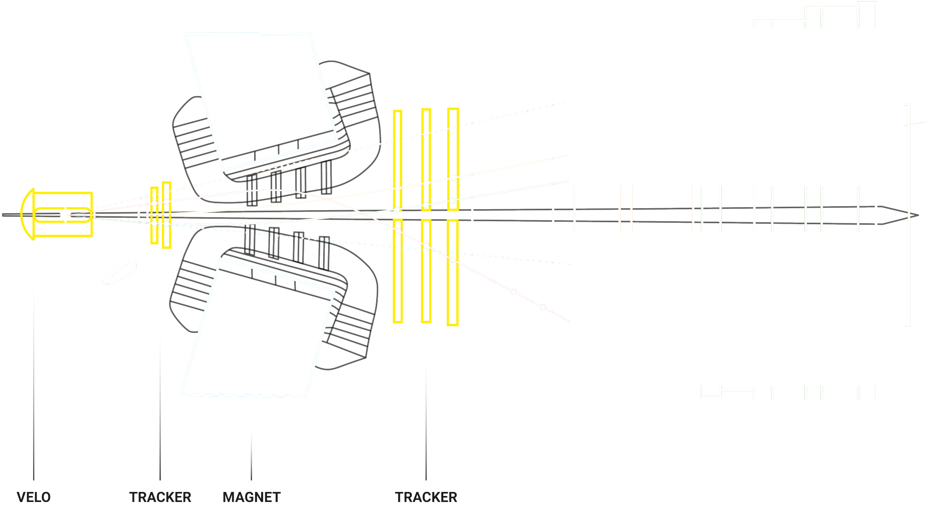


PID

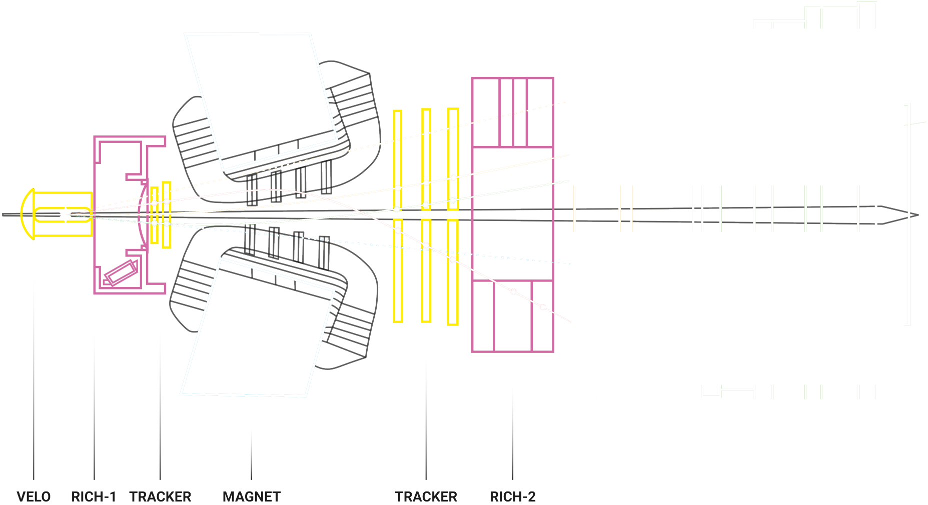
Detector design is imposed by physics. Not much of a choice here.



The LHCb detector

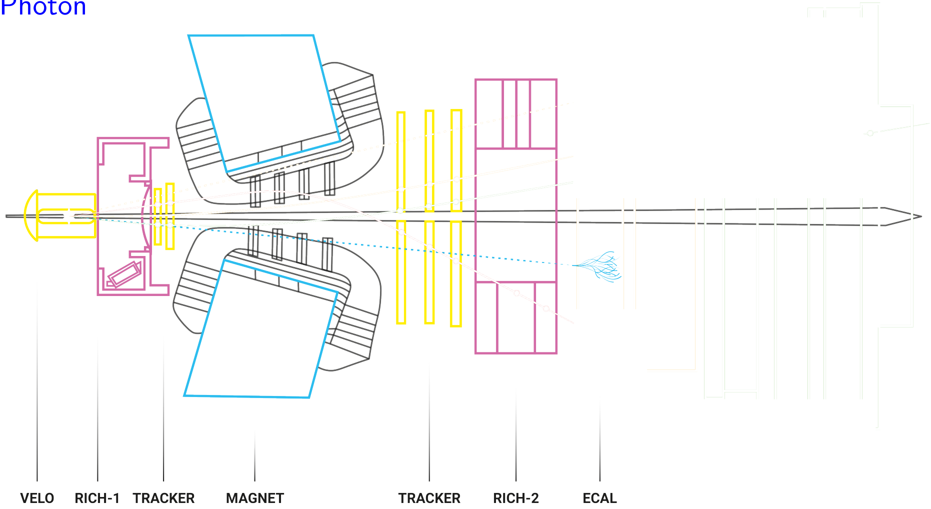


The LHCb detector



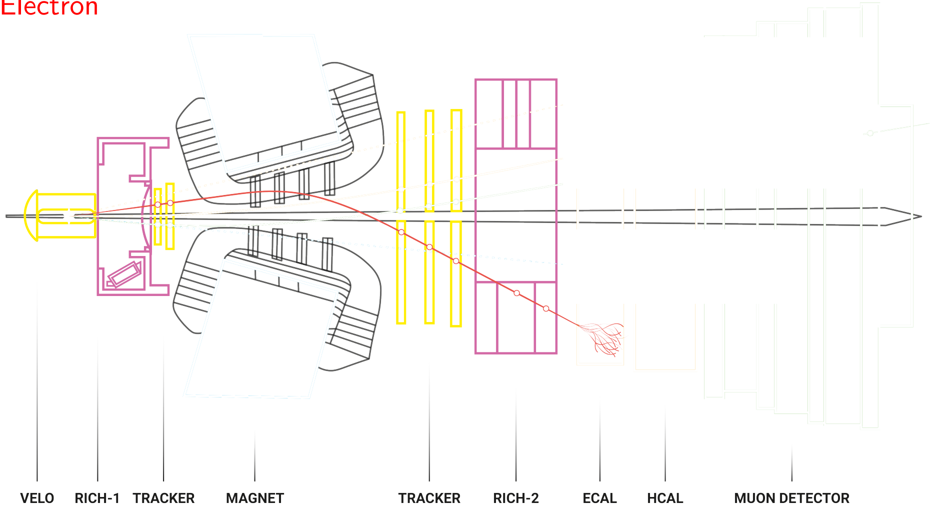
The LHCb detector

Photon



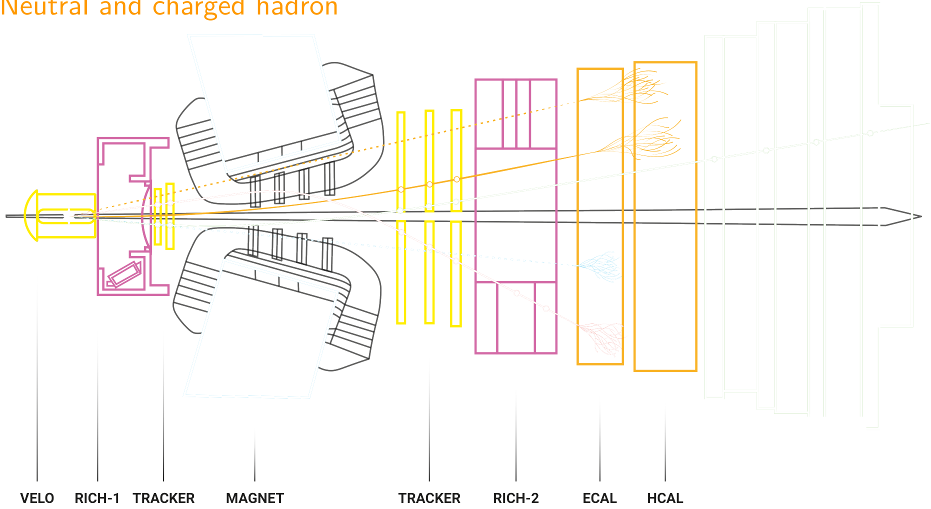
The LHCb detector

Electron



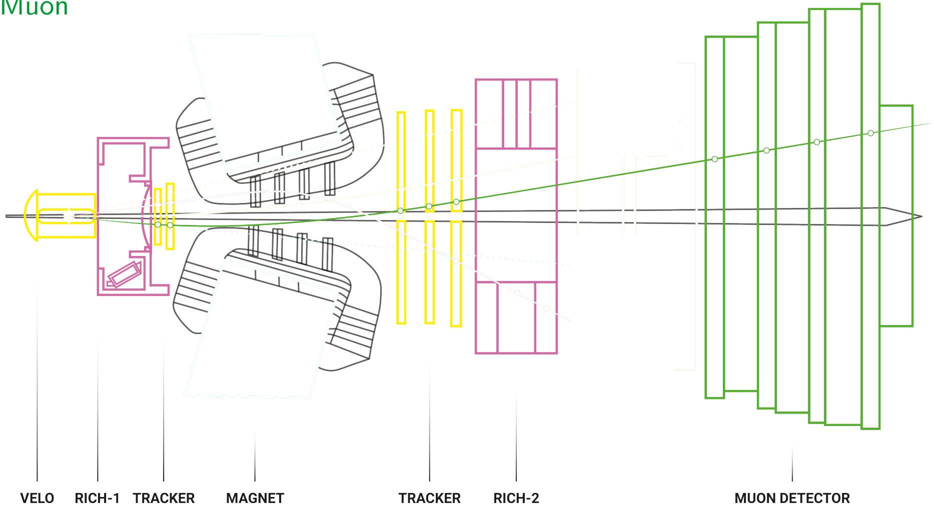
THE LHCb DETECTOR

Neutral and charged hadron



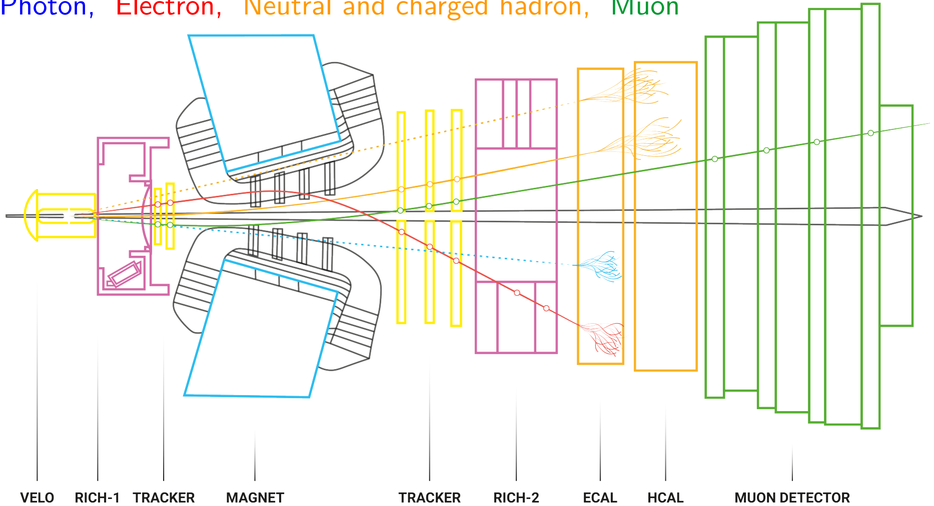
The LHCb detector

Muon

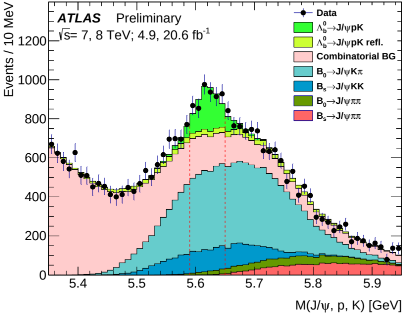


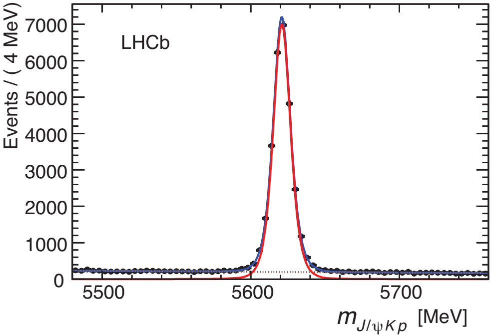
The LHCb detector

Photon, Electron, Neutral and charged hadron, Muon



$P_{c\bar{c}}$ states at ATLAS





With Run 1 data, ATLAS find 2270 ± 300 $\Lambda_b^0 \to J/\psi pK^-$ decays

- With Run 1 data ($3\,\text{fb}^{-1}$), LHCb see $26\,000 \pm 170$ with hardly any background [LHCb, PRL 115 (2015) 072001, arXiv:1507.03414]

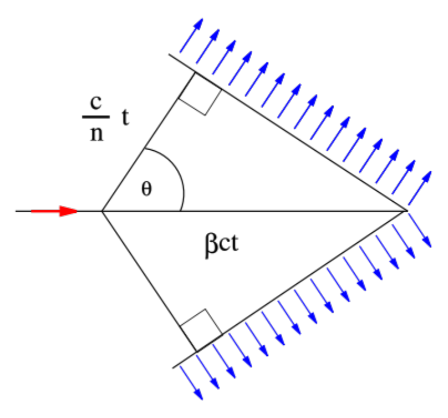
Cherenkov

Cherenkov radiation is emitted by charged particles crossing a transparent medium at a speed higher than the speed of light *in that medium*.

$$v = \frac{c}{n}$$

➜ Like boom of a supersonic aircraft.

Cherenkov



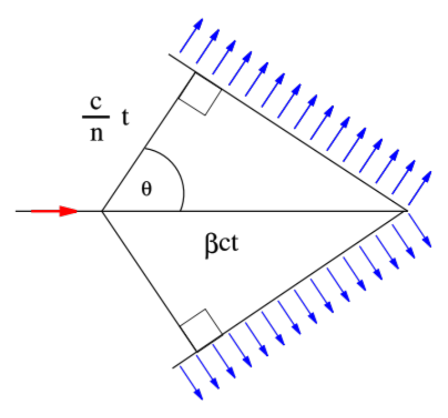
Cherenkov radiation is emitted by charged particles crossing a transparent medium at a speed higher than the speed of light *in that medium*.

$$v = \frac{c}{n}$$

➜ Like boom of a supersonic aircraft.

[Cherenkov, Dokl.Akad.Nauk SSSR 2 (1934) 8, 451]

Cherenkov



Cherenkov radiation is emitted by charged particles crossing a transparent medium at a speed higher than the speed of light *in that medium*.

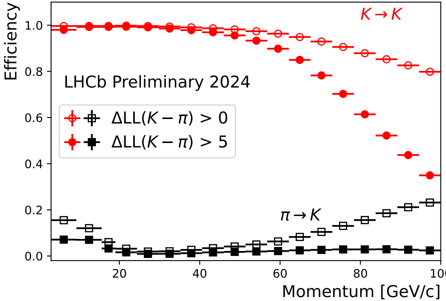
$$v = \frac{c}{n}$$

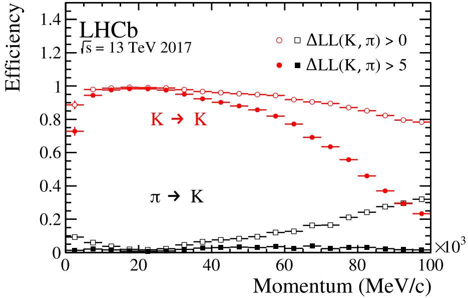
➜ Like boom of a supersonic aircraft.

- The emission angle depends on the speed of the particle.
- From the speed and the momentum one can work out the mass. Hence the identity!

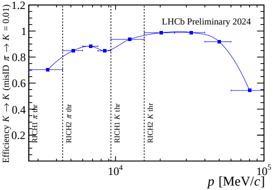
[FIGURE-2024-031]

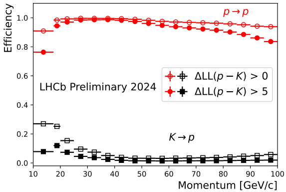
Run 3 figures: PID



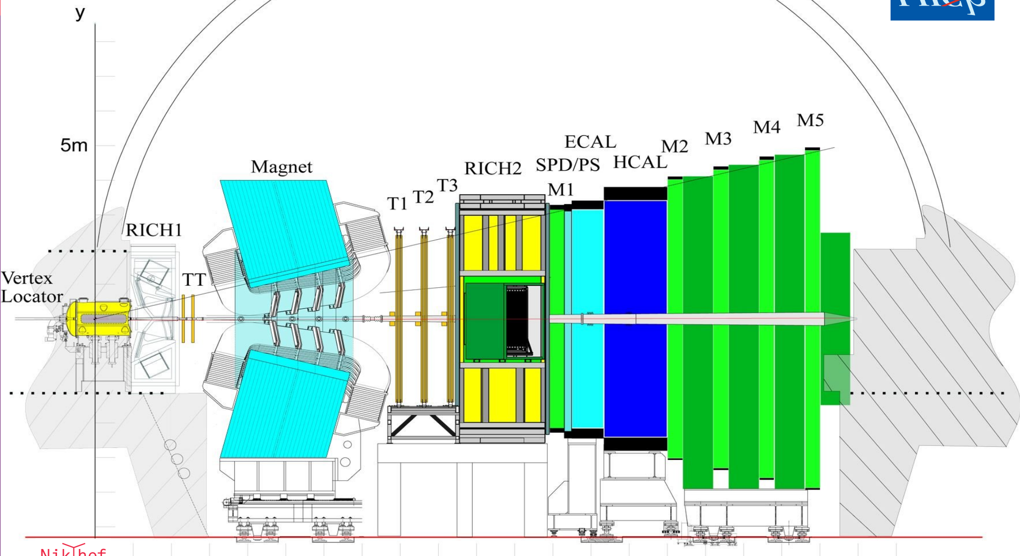


[LHCb-DP-2021-004, arXiv:2205.13400]

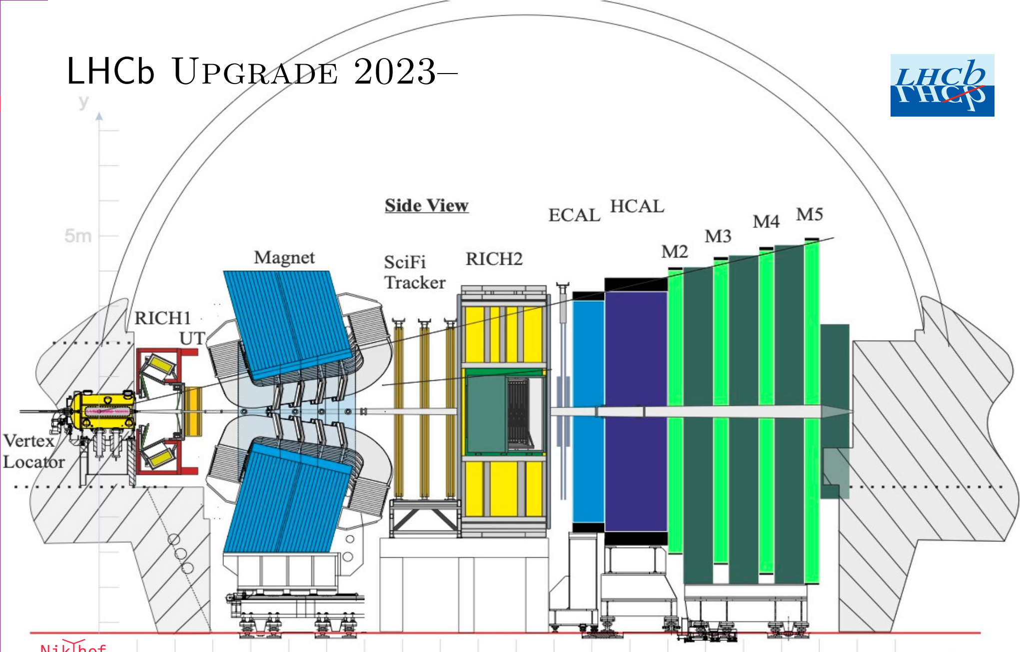




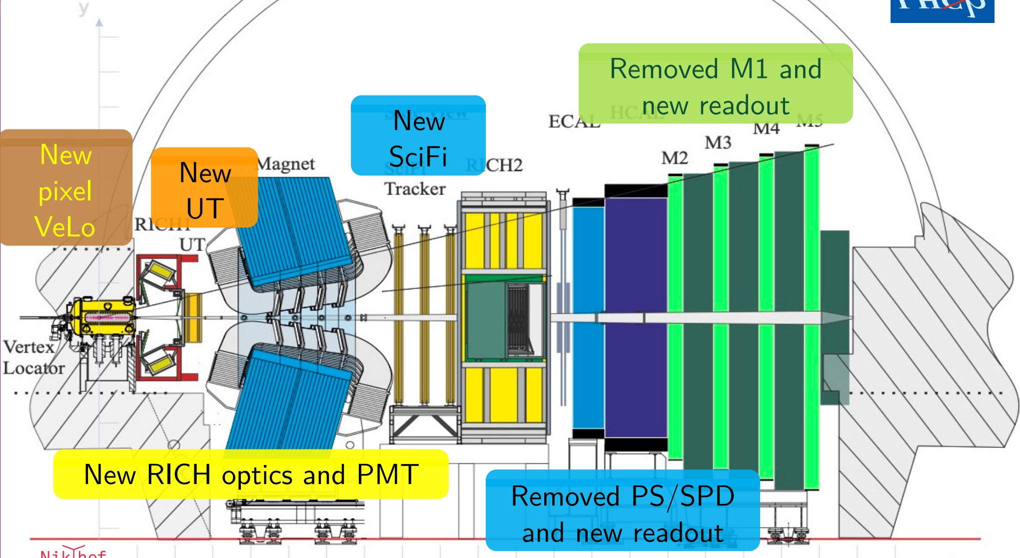
LHCb Legacy 2009–2018



LHCb Upgrade 2023–

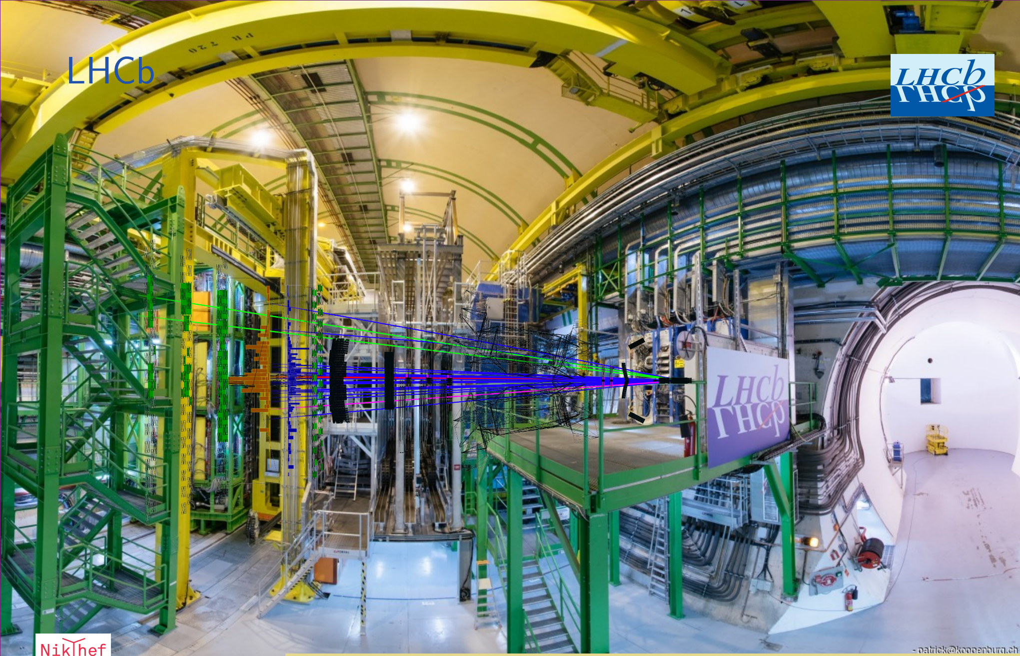


LHCb Upgrade 2023–



LHCb

LHCb



The Large Hadron Collider at CERN

$B^0 \to K^+\pi^-$

You learned from Niels' lecture that

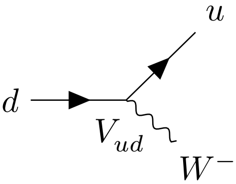
- *CPV* comes from the imaginary phase of the CKM matrix
- You need at least two interfering processes with different *CP*-even and different *CP*-odd phases

➜ Skip some slides

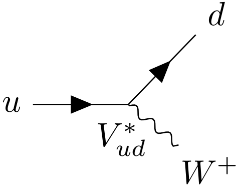
www.koppenburg.org

CP violation

Particles:



$A \propto V_{ud}$

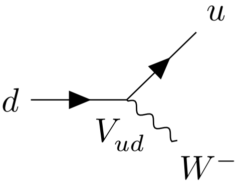


$A \propto V_{ud}^*$

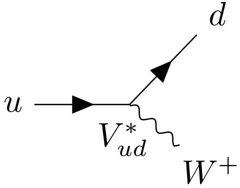
[B]

CP violation

Particles:

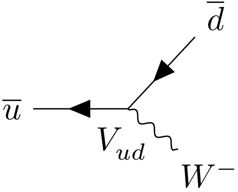


$A \propto V_{ud}$

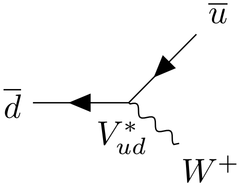


$A \propto V^*_{ud}$

Antiparticles:



$A \propto V_{ud}$



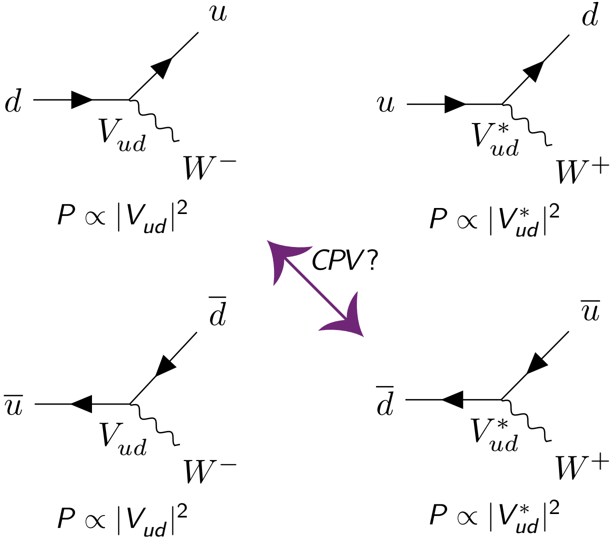
$A \propto V^*_{ud}$

[B]

CP VIOLATION

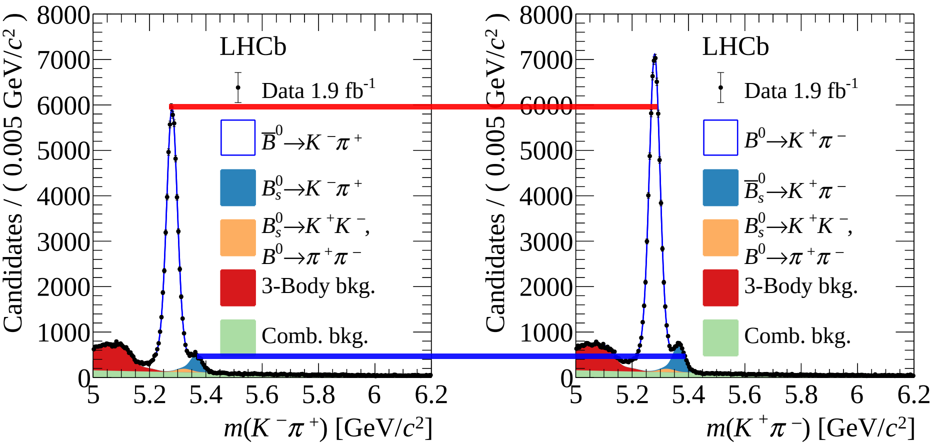
Particles:

Antiparticles:



[B]

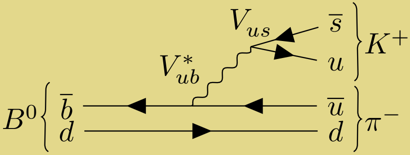
CP violation in $B \to h^+h^-$



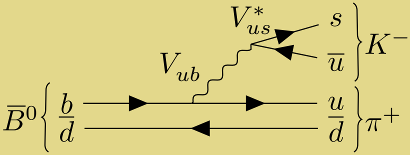
[B]

Large CP violation in charmless B^0 and B_s^0 decays (seen in [PRL 110 (2013) 221601])

CP violation in $B^0 \to K^+\pi^-$



$B^0 \to K^+\pi^-$



$\overline{B}^0 \to K^-\pi^+$

Amplitude $\propto V_{ub}^* V_{us}$

➜ Probability $\propto |V_{ub}^* V_{us}|^2$

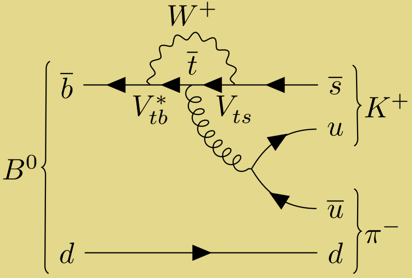
Amplitude $\propto V_{ub} V_{us}^*$

➜ Probability $\propto |V_{ub} V_{us}^*|^2$

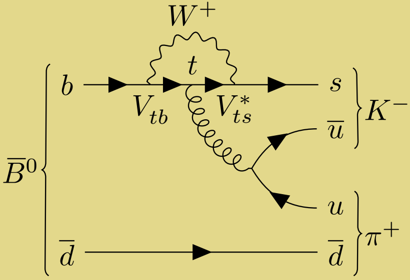
[B]

The amplitudes are different complex numbers, but the probabilities are the same. Why is there CP violation?

CP violation in $B^0 \to K^+\pi^-$



$B^0 \to K^+\pi^-$



$\overline{B}^0 \to K^-\pi^+$

Amplitude $\propto V_{tb}^* V_{ts}$

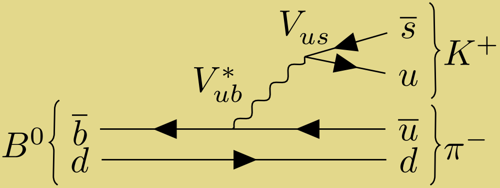
➜ Probability $\propto |V_{tb}^* V_{ts}|^2$

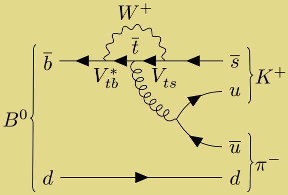
Amplitude $\propto V_{tb} V_{ts}^*$

➜ Probability $\propto |V_{tb} V_{ts}^*|^2$

[B]

CP violation in $B^0 \to K^+\pi^-$

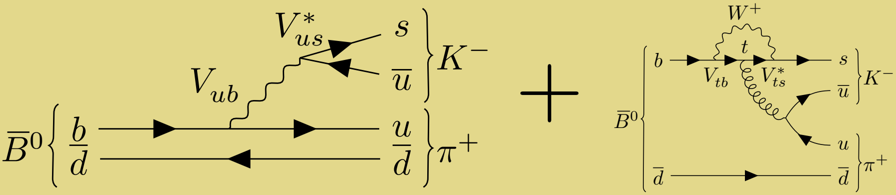




$$B^0 \to K^+\pi^- : \; A \propto V_{ub}^* V_{us} + V_{tb}^* V_{ts} \quad \rightarrow \quad P \propto |V_{ub}^* V_{us} + V_{tb}^* V_{ts}|^2$$

[B]

CP violation in $B^0 \to K^+\pi^-$

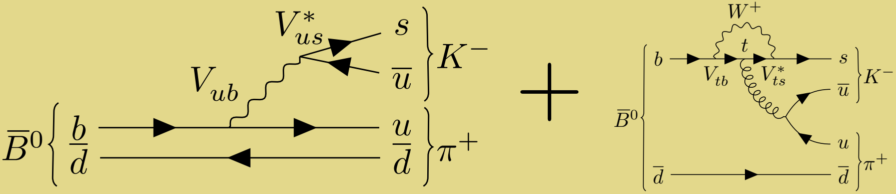


$$B^0 \to K^+\pi^- : \; A \propto V_{ub}^* V_{us} + V_{tb}^* V_{ts} \quad \rightarrow \quad P \propto |V_{ub}^* V_{us} + V_{tb}^* V_{ts}|^2$$

$$\overline{B}^0 \to K^-\pi^+ : \; \bar{A} \propto V_{ub} V_{us}^* + V_{tb} V_{ts}^* \quad \rightarrow \quad \bar{P} \propto |V_{ub} V_{us}^* + V_{tb} V_{ts}^*|^2$$

[B]

CP violation in $B^0 \to K^+\pi^-$



$$B^0 \to K^+\pi^- : \ A \propto V_{ub}^* V_{us} + V_{tb}^* V_{ts} \quad \to \quad P \propto |V_{ub}^* V_{us} + V_{tb}^* V_{ts}|^2$$

$$\overline{B}^0 \to K^-\pi^+ : \ \bar{A} \propto V_{ub} V_{us}^* + V_{tb} V_{ts}^* \quad \to \quad \bar{P} \propto |V_{ub} V_{us}^* + V_{tb} V_{ts}^*|^2$$

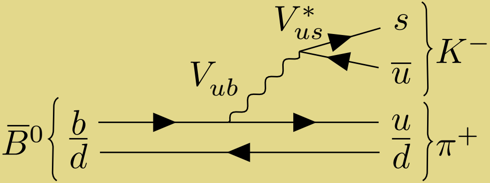
$$P \propto |V_{ub}^* V_{us}|^2 + |V_{tb}^* V_{ts}|^2 + 2|V_{ub}^* V_{us}||V_{tb}^* V_{ts}| \cos(+\delta_{\mathrm{T}} + +\delta_{\mathrm{P}})$$

$$\bar{P} \propto |V_{ub}^* V_{us}|^2 + |V_{tb}^* V_{ts}|^2 + 2|V_{ub}^* V_{us}||V_{tb}^* V_{ts}| \cos(-\delta_{\mathrm{T}} + -\delta_{\mathrm{P}})$$

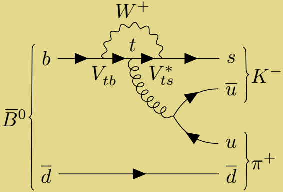
[B]

That's the same thing. Still no *CPV*!

CP violation in $B^0 \to K^+\pi^-$



+



$$B^0 \to K^+\pi^- : \; A \propto e^{i\phi_\mathrm{T}} V^*_{ub} V_{us} + e^{i\phi_\mathrm{T}} V^*_{tb} V_{ts} \quad \to \quad P \propto |e^{i\phi_\mathrm{T}} V^*_{ub} V_{us} + e^{i\phi_\mathrm{P}} V^*_{tb} V_{ts}|^2$$

$$\overline{B}^0 \to K^-\pi^+ : \; \bar{A} \propto e^{i\phi_\mathrm{T}} V_{ub} V^*_{us} + e^{i\phi_\mathrm{P}} V_{tb} V^*_{ts} \quad \to \quad \bar{P} \propto |e^{i\phi_\mathrm{T}} V_{ub} V^*_{us} + e^{i\phi_\mathrm{P}} V_{tb} V^*_{ts}|^2$$

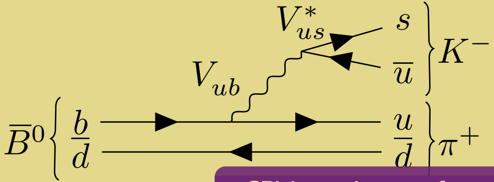
$$P \propto |e^{i\phi_\mathrm{T}} V^*_{ub} V_{us}|^2 + |e^{i\phi_\mathrm{P}} V^*_{tb} V_{ts}|^2 + 2|V^*_{ub} V_{us}||V^*_{tb} V_{ts}| \cos(\phi_\mathrm{T} + \delta_\mathrm{T} + \phi_\mathrm{P} + \delta_\mathrm{P})$$

$$\bar{P} \propto |e^{i\phi_\mathrm{T}} V^*_{ub} V_{us}|^2 + |e^{i\phi_\mathrm{P}} V^*_{tb} V_{ts}|^2 + 2|V^*_{ub} V_{us}||V^*_{tb} V_{ts}| \cos(\phi_\mathrm{T} - \delta_\mathrm{T} + \phi_\mathrm{P} - \delta_\mathrm{P})$$

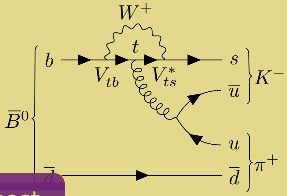
[B]

With *CP*-even phases it works!

CP violation in $B^0 \to K^+\pi^-$



+



$B^0 \to K^+\pi^-$: $A \propto e^{i\phi_\mathrm{T}} V^*_{ub} V_{us} + e^{i\phi_\mathrm{P}} V^*_{tb} V_{ts}$ → $P \propto |e^{i\phi_\mathrm{T}} V^*_{ub} V_{us} + e^{i\phi_\mathrm{P}} V^*_{tb} V_{ts}|^2$

$\overline{B}^0 \to K^-\pi^+$: $\bar{A} \propto e^{i\phi_\mathrm{T}} V_{ub} V^*_{us} + e^{i\phi_\mathrm{P}} V_{tb} V^*_{ts}$ → $\bar{P} \propto |e^{i\phi_\mathrm{T}} V_{ub} V^*_{us} + e^{i\phi_\mathrm{P}} V_{tb} V^*_{ts}|^2$

CPV needs interference of at least **two** diagrams with different CP-odd **and** different CP-even phases

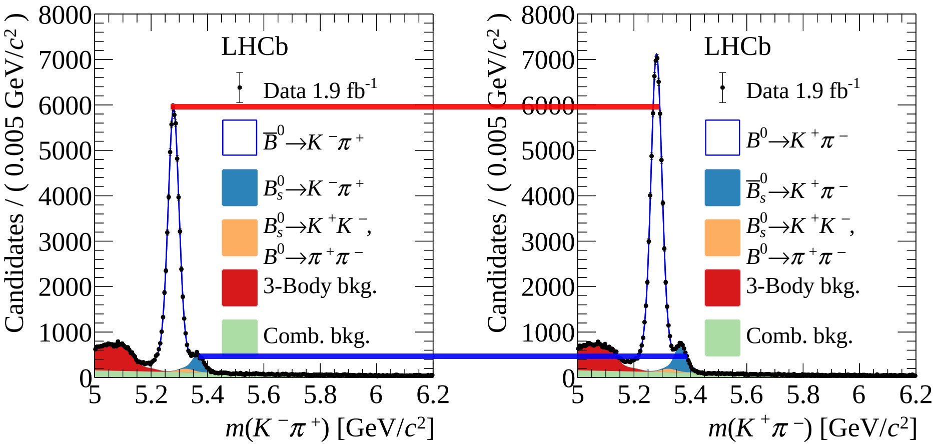
$$P \propto |e^{i\phi_\mathrm{T}} V^*_{ub} V_{us}|^2 + |e^{i\phi_\mathrm{P}} V^*_{tb} V_{ts}|^2 + 2|V^*_{ub} V_{us}||V^*_{tb} V_{ts}| \cos(\phi_\mathrm{T} + \delta_\mathrm{T} + \phi_\mathrm{P} + \delta_\mathrm{P})$$
$$\bar{P} \propto |e^{i\phi_\mathrm{T}} V^*_{ub} V_{us}|^2 + |e^{i\phi_\mathrm{P}} V^*_{tb} V_{ts}|^2 + 2|V^*_{ub} V_{us}||V^*_{tb} V_{ts}| \cos(\phi_\mathrm{T} - \delta_\mathrm{T} + \phi_\mathrm{P} - \delta_\mathrm{P})$$

[B]

With CP-even phases it works!

[LHCb, JHEP 03 (2021) 075, arXiv:2012.05319]

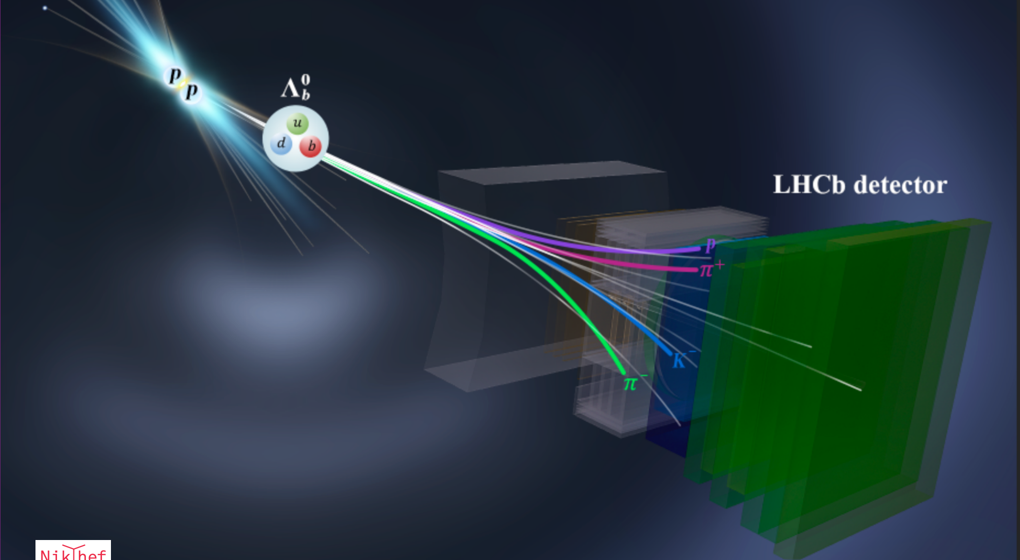
CP violation in $B \to h^+ h^-$



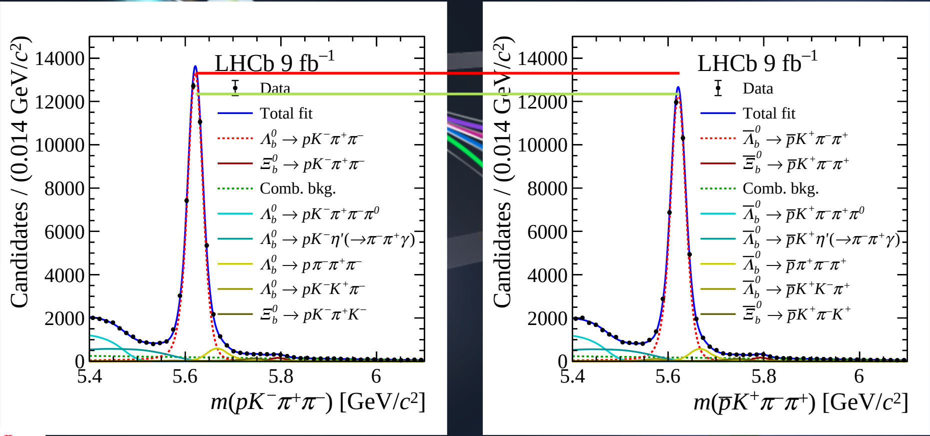
[B]

Large CP violation in charmless B^0 and B_s^0 decays (seen in [PRL 110 (2013) 221601])

Observation of *CPV* in baryon decays



Observation of *CPV* in baryon decays



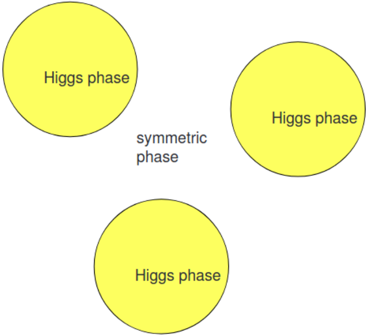
CPV INTRO

Flavour Physics is a complicated part of the SM

1. It's certainly a complex part of the SM
2. Many imaginary phases
3. Different bases to express quark states (Higgs disagrees with W)
4. Oscillations, mass eigenstates with different lifetimes and masses
5. Many particles involved, K, B, J/ψ, ...
6. Loads of decay modes (PDG'24 lists 586 for B^0)
7. Historical development not most pedagogical
8. Useless jargon: "direct", "indirect" *CPV* *etc.*

[Cohen, Kaplan, Nelson, PLB 263 (1991) 86]

Sakharov Conditions



Size of the critical bubble:

$R \sim (\alpha_W T_c)^{-1}$

$T_c \sim 100$ GeV

Bubble size at percolation:

$\sim 10^{-6}$ cm.

Sakharov Conditions

1. Symmetric phase: $\langle\phi^\dagger\phi\rangle \simeq \mathbf{0} \rightarrow$ fermions are almost massless and B-nonconservation is rapid.

2. Higgs phase: $\langle\phi^\dagger\phi\rangle \neq \mathbf{0} \rightarrow$ fermions are massive and B-nonconservation is exponentially suppressed.

$\Downarrow$

Fermions interact in a CP-violating way (reflected and transmitted) with the surface of the bubble

$\Downarrow$

Baryon asymmetry of the Universe after EW phase transition.

The SM Higgs Lagrangian

$$\mathcal{L}_{\text{Higgs}} = \underbrace{|D\phi|^2}_{} + \underbrace{(y_{jk}\bar{\psi}_j\psi_k\phi + \text{h.c.})}_{} - \underbrace{V(\phi^\dagger\phi)}_{}$$

gauge interactions, HWW, HZZ couplings well tested after LHC	Yukawa interactions, $Hf\bar{f}$, CKM, CPV, studied since 2018	Higgs potential, HHH, $HHHH$ couplings, not yet tested
	"5th force"	"6th force"

Puzzles:

Yukawa part: flavour puzzle, no obvious symmetry, only source of CPV

Higgs potential: $V = V_0 - \mu^2(v+H)^2 + \lambda(v+H)^4$

μ relates to the hierarchy problem, λ to the metastability of the Universe, V to the fine-tuning of the cosmological constant

$$L_{SM} = L_{Kinetic} + L_{Higgs} + L_{Yukawa}$$

Recap

$$-L_{Yuk} = Y_{ij}^{d} (\overline{u_L^I}, \overline{d_L^I})_i \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} d_{Rj}^I + \ldots$$

$$L_{Kinetic} = \frac{g}{\sqrt{2}} \overline{u_{Li}^I} \gamma^\mu W_\mu^- d_{Li}^I + \frac{g}{\sqrt{2}} \overline{d_{Li}^I} \gamma^\mu W_\mu^+ u_{Li}^I + \ldots$$

Diagonalize Yukawa matrix Y_{ij}

- Mass terms
- Quarks rotate
- Off diagonal terms in charged current couplings

$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix} \to V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$-L_{Mass} = (\bar{d}, \bar{s}, \bar{b})_L \cdot \begin{pmatrix} m_d & & \\ & m_s & \\ & & m_b \end{pmatrix} \cdot \begin{pmatrix} d \\ s \\ b \end{pmatrix}_R + (\bar{u}, \bar{c}, \bar{t})_L \cdot \begin{pmatrix} m_u & & \\ & m_c & \\ & & m_t \end{pmatrix} \cdot \begin{pmatrix} u \\ c \\ t \end{pmatrix}_R + \ldots$$

$$L_{CKM} = \frac{g}{\sqrt{2}} \overline{u_i} \gamma^\mu W_\mu^- V_{ij} \left(1 - \gamma^5\right) d_j + \frac{g}{\sqrt{2}} \overline{d_j} \gamma^\mu W_\mu^+ V_{ij}^* \left(1 - \gamma^5\right) u_i + \ldots$$

CKM Parametrisations

The first parametrisations of the CKM matrix were done before the elements were measured.

Harari set requirements [Harari, Leurer, PLB 181 (1986) 123]

1. There should be a simple relation between the most directly measurable matrix elements V_{ij} and the quark mixing angles.
2. The matrix elements above the diagonal, which correspond to kinematically allowed decay processes that are directly measurable, should have the simplest possible expressions.
3. If possible, the *CP* violating phase should be linked to only one angle, and preferably the sine of that angle.

Two parametrisations achieved this: Chau-Keung [Chau, Keung, PRL 53 (1984) 1802] and Wolfenstein [Wolfenstein, PRL 51 (1983) 1945].

CKM Parametrisations

The Chau-Keung parametrisation is exactly unitary [Chau, Keung, PRL 53 (1984) 1802]

$$V_{\text{CKM}} = \overbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}^{\theta_{23} \text{ about } d''} \overbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}}^{\theta_{13} \text{ about } s' \text{ (incl. } \delta)} \overbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}^{\theta_{12} \text{ about } b}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

This is the PDG parametrisation. We now have [PDG]

$$\theta_{12} = 13.09^\circ \pm 0.03^\circ \quad \theta_{23} = 2.32^\circ \pm 0.04^\circ$$
$$\theta_{13} = 0.207^\circ \pm 0.007^\circ \quad \delta = 68.53^\circ \pm 0.51^\circ.$$

CKM Parametrisations

The Wolfenstein parametrisation is approximate

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4),$$

with $\lambda = \sin\theta_{\mathrm{C}}$ and $A \sim 0.8$ accounts for the suppression between V_{cb} and V_{cd}.
Using the Buras convention [Buras et al, PRD 50 (1994) 3433, arXiv:hep-ph/9403384]

$$\lambda \equiv s_{12} = \frac{|V_{us}|}{\sqrt{|V_{ud}|^2 + |V_{us}|^2}}$$

$$A\lambda^2 \equiv s_{23} = \lambda \frac{|V_{cb}|}{|V_{us}|} \qquad A\lambda^3(\rho - i\eta) \equiv s_{13} e^{i\delta} = V_{ub}^*.$$

V_{ub} is the same as in the Chau and Keung parameterizations, and the higher corrections to V_{us} and V_{cb} start at $\mathcal{O}(\lambda^7)$ and $\mathcal{O}(\lambda^8)$, respectively.

CKM Parametrisations

The Wolfenstein parametrisation is approximate

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4),$$

Buras [Buras et al, PRD 50 (1994) 3433, arXiv:hep-ph/9403384] also defines

$$\bar\rho + i\bar\eta = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*} \quad \rightarrow \quad \bar\rho = \rho(1-\frac{\lambda^2}{2}) + \mathcal{O}(\lambda^4) \quad \text{and} \quad \bar\eta = \eta(1-\frac{\lambda^2}{2}) + \mathcal{O}(\lambda^4)$$

and we have [PDG]

$$\lambda = 0.22650 \pm 0.00048 \qquad A = 0.790\,^{+0.017}_{-0.012}$$

$$\bar\rho = 0.141\,^{+0.016}_{-0.017} \qquad \bar\eta = 0.357 \pm 0.011$$

Jarlskog invariant

The total amount of *CP* violation is

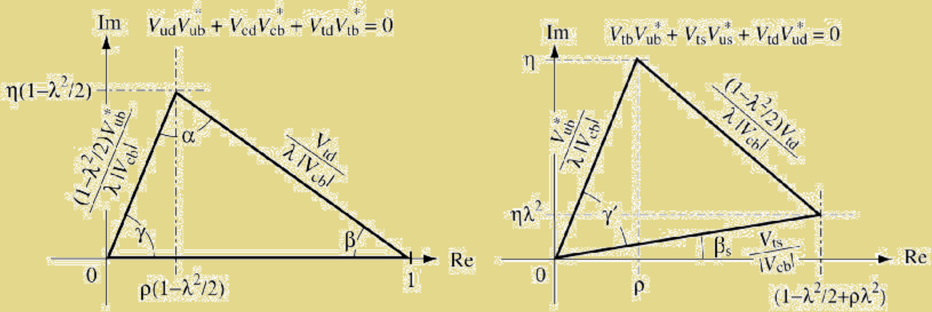
$$\underbrace{J}_{3\times10^{-5}} \times \underbrace{\frac{P_u P_d}{M^{12}}}_{10^{-14}}$$

with $J \simeq \lambda^6 A^2 \eta \sim 3 \times 10^{-5}$ the double of the area of the unitarity triangles,

$$P_u = (m_c^2 - m_u^2)(m_t^2 - m_c^2)(m_t^2 - m_u^2)$$
$$P_d = (m_s^2 - m_d^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)$$

and $M \sim 100\,\text{GeV}$ the EW scale.

"The" CKM Unitarity Triangles



$$V_{\rm CKM} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|e^{-i\beta_s} & |V_{tb}| \end{pmatrix}$$

[B]

Flavour Tagging

We start with a sample of N B and $\bar{B}$ mesons. We need flavour tagging to know their flavour at origin.

N^{tag} of those have a tagging decision, with $\eta = \frac{N^{\text{tag}}}{N}$. The remaining $N^{\text{tag}} - N$ are not useful for CP violation but may be used for other observables.

The fraction of wrongly tagged B is ω

$$N_B^{\text{tag}} = \eta(1-\omega)N_B + \eta\omega N_{\bar{B}}$$
$$N_{\bar{B}}^{\text{tag}} = \eta(1-\omega)N_{\bar{B}} + \eta\omega N_B$$

The CP asymmetry is

$$A_{\text{meas}}^{CP} = \frac{N_B^{\text{tag}} - N_{\bar{B}}^{\text{tag}}}{N_B^{\text{tag}} + N_{\bar{B}}^{\text{tag}}} = (1-2\omega)\underbrace{\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}}_{=A_{\text{true}}^{CP}} \quad \rightarrow \quad A_{\text{true}}^{CP} = \frac{A_{\text{meas}}^{CP}}{1-2\omega}$$

[B]

Flavour Tagging

The *CP* asymmetry is

$$A^{CP}_{\text{meas}} = \frac{N^{\text{tag}}_{B} - N^{\text{tag}}_{\bar{B}}}{N^{\text{tag}}_{B} + N^{\text{tag}}_{\bar{B}}} = (1-2\omega)\underbrace{\frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}}}_{=A^{CP}_{\text{true}}} \quad \rightarrow \quad A^{CP}_{\text{true}} = \frac{A^{CP}_{\text{meas}}}{1-2\omega}$$

To correctly measure A^{CP} it is necessary to know ω.

The uncertainty is

$$\Delta A^{CP}_{\text{true}} = \frac{\Delta A^{CP}_{\text{meas}}}{1-2\omega} = \frac{1}{1-2\omega}\sqrt{\frac{(1-A^{CP}_{\text{true}})^2}{N^{\text{tag}}}} = \frac{1}{1-2\omega}\sqrt{\frac{(1-A^{CP}_{\text{true}})^2}{\eta N}}$$
$$= \frac{1}{\sqrt{\eta}(1-2\omega)}\Delta A^{CP}_{\text{true}}$$

[B] The effect of the imperfect tagging is the same as reducing the sample by a factor

$$\eta_{\text{eff}} = \eta(1-2\omega)^2$$

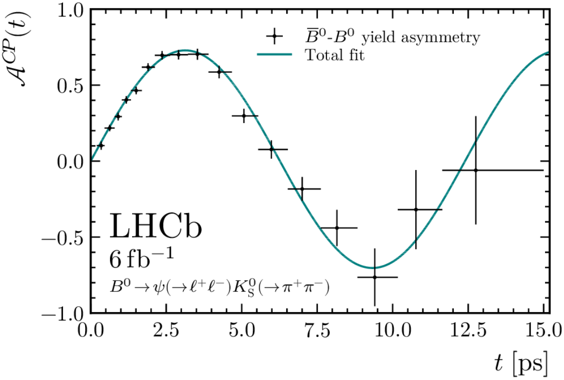
Flavour Tagging

To correctly measure A^{CP} it is necessary to know ω.

The wrong-tag fraction is calibrated on self-tagging control samples.

The measured *CP* asymmetry (*i.e.* $\sin 2\beta$) is proportional to the oscillation amplitude. A wrong value of $\sqrt{\eta}(1-2\omega)$ directly translates into a bias.

[LHCb, PRL 132 (2024) 021801, arXiv:2309.09728]

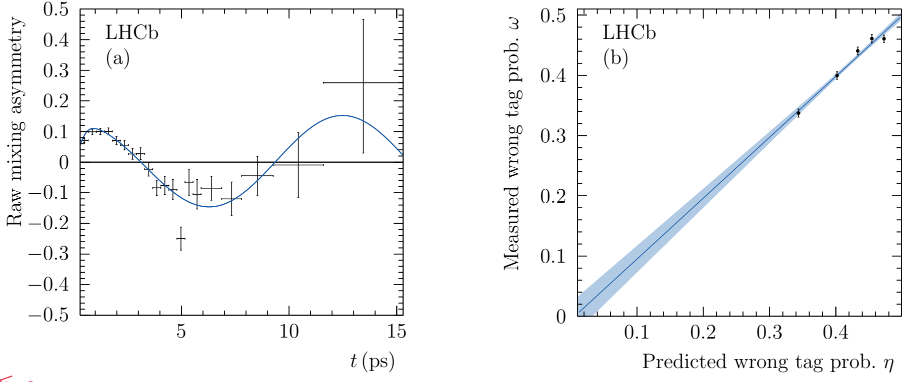


[B]

Flavour Tagging

To correctly measure A^{CP} it is necessary to know ω.

The wrong-tag fraction is calibrated on self-tagging control samples. Here $B^0 \to J/\psi K^{*0}(\to K^+\pi^-)$ for $B^0 \to J/\psi K^0_S$ [LHCb, PRL 115 (2015) 031601, arXiv:1503.07089]

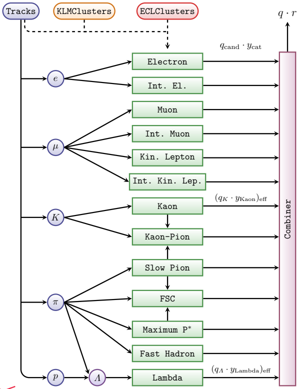


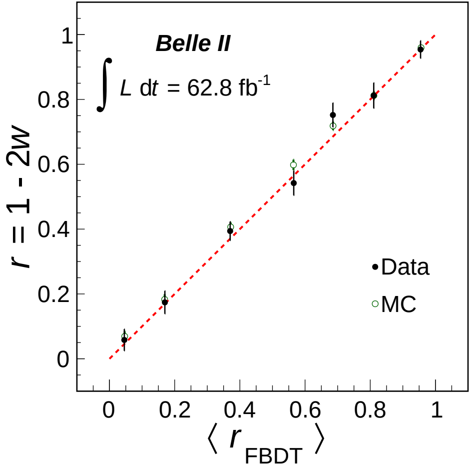
[B]

Flavour Tagging at Belle II

Tagging power for neutral B mesons:

$$\varepsilon_{\text{eff}}(\text{FBDT}) = (30.0 \pm 1.2 \pm 0.4)\%$$

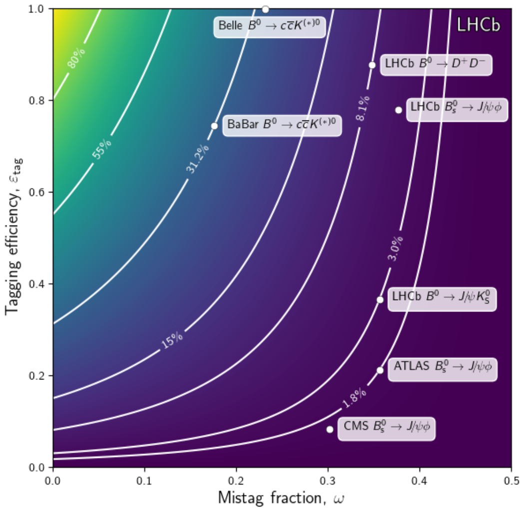


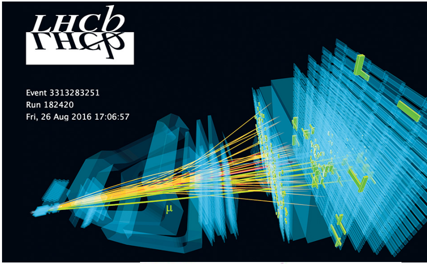


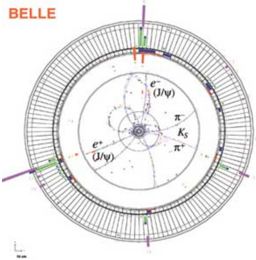
Using $B^0 \to D^{(*)-} h^+$

[B]

Flavour Tagging performance







Mixing

$$i\frac{\partial}{\partial t}\psi = H\psi \quad \text{with} \quad \psi(t) = a(t)\left|P\right\rangle + b(t)\left|\bar{P}\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$H = \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix}$$

Look at P=proton and $\bar{P}$= antiproton. Nothing happens. $a = 1, b = 0$

Mixing

$$i\frac{\partial}{\partial t}\psi = H\psi \quad \text{with} \quad \psi(t) = a(t)\left|P\right\rangle + b(t)\left|\overline{P}\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$H = \begin{pmatrix} M & 0 \\ 0 & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & 0 \\ 0 & \Gamma \end{pmatrix}$$

Same for P=neutron. Except it decays.

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(|a(t)|^2 + |b(t)|^2\right) = -\begin{pmatrix} a(t)^* & b(t)^* \end{pmatrix}\begin{pmatrix} \Gamma & 0 \\ 0 & \Gamma \end{pmatrix}\begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

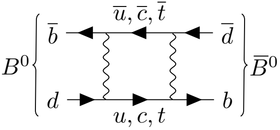
Mixing

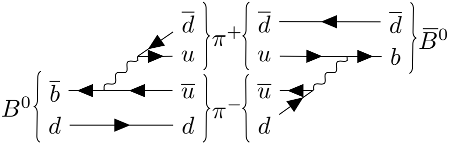
$$i\frac{\partial}{\partial t}\psi = H\psi \quad \text{with} \quad \psi(t) = a(t)\left|P\right\rangle + b(t)\left|\overline{P}\right\rangle \equiv \begin{pmatrix} a(t) \\ b(t) \end{pmatrix}$$

$$H = \begin{pmatrix} M & M_{12} \\ M_{12}^* & M \end{pmatrix} - \frac{i}{2}\begin{pmatrix} \Gamma & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma \end{pmatrix}$$

The $P{=}B^0$ ($\overline{b}d$) and the $\overline{B}^0$ ($b\overline{d}$) mix, because "everything not forbidden is compulsory" [Gell-Mann].

M_{12} catches off-shell diagrams, like boxes. Γ_{12} is generated by physical states to which both B^0 and $\overline{B}^0$ decay, like $\pi^+\pi^-$.





Mixing

$$i\frac{\partial}{\partial t}\psi = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\psi$$

➜ $|P_1\rangle = p\left|P^0\right\rangle - q\left|\overline{P}^0\right\rangle \qquad |P_2\rangle = p\left|P^0\right\rangle + q\left|\overline{P}^0\right\rangle$

with masses and widths

$$m_1 + \frac{i}{2}\Gamma_1 = M - \mathcal{R}F - \frac{i}{2}\Gamma - \mathcal{I}F$$

$$m_2 + \frac{i}{2}\Gamma_2 = M + \mathcal{R}F - \frac{i}{2}\Gamma + \mathcal{I}F$$

$$\text{with } F = \sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

Mixing

$$i\frac{\partial}{\partial t}\psi = \begin{pmatrix} M - \frac{i}{2}\Gamma & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M - \frac{i}{2}\Gamma \end{pmatrix}\psi$$

$$\rightarrow \quad |P_1\rangle = p\left|P^0\right\rangle - q\left|\overline{P}^0\right\rangle \qquad |P_2\rangle = p\left|P^0\right\rangle + q\left|\overline{P}^0\right\rangle$$

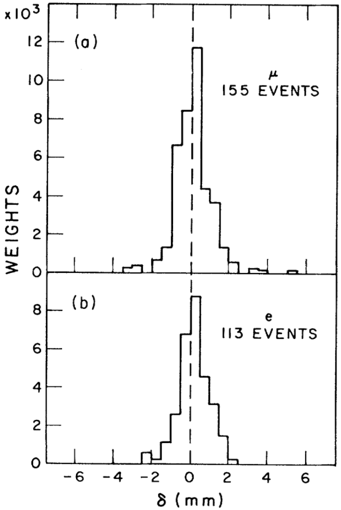
with masses and widths differences

$$\Delta m = 2\mathcal{R}\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

$$\Delta\Gamma = 4\mathcal{I}\sqrt{\left(M_{12} - \frac{i}{2}\Gamma_{12}\right)\left(M_{12}^* - \frac{i}{2}\Gamma_{12}^*\right)}$$

The two mass eigenstates have different masses and lifetimes. Δm is the oscillation frequency.

Long B lifetime measured at PEP

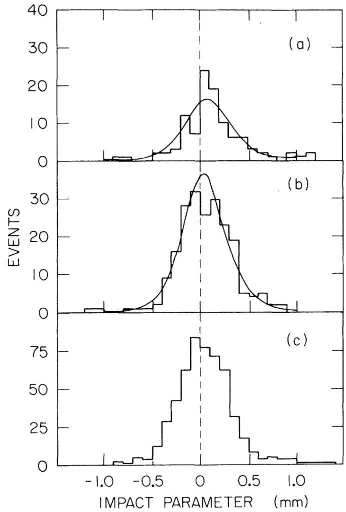


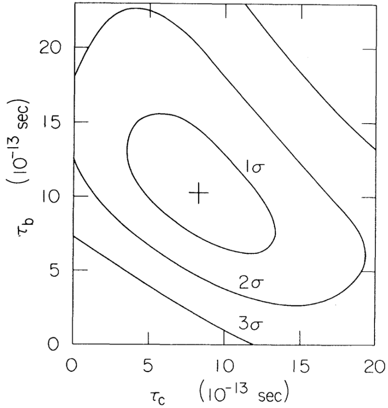
$$\tau_b = (1.8 \pm 0.6 \pm 0.4)\,\text{ps}$$

[MARK, PRL 51 (1983) 1316] (now 1.5 ps)

That's a factor three more than the c lifetime, which was a big surprise.

Long B lifetime measured at PEP





$$\tau_b = (1.20\,{}^{+0.45}_{-0.36} \pm 0.30)\ \text{ps}$$

[MARK, PRL 51 (1983) 1316] (now 1.5 ps)

Long B lifetime measured at PEP

The textbook expression of the muon lifetime adapted for $b \to c$ transitions reads

$$\Gamma_b = \frac{1}{\tau_b} = |V_{cb}|^2 \frac{G_\mathrm{F}^2 m_b^5 c^4}{192\pi^3\hbar^7}(2_\mathrm{quarks} \times 3_\mathrm{colours} + 3_\mathrm{leptons}),$$

[Olsen, KM'50 proceedings, arXiv:2309.06042]

with

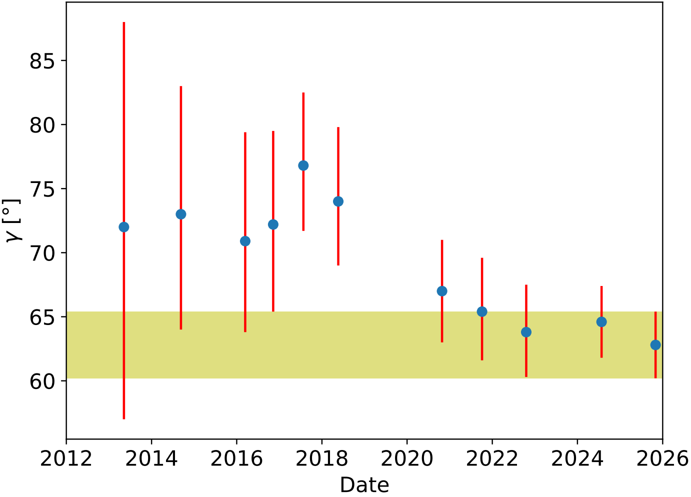
$$\tau_b = (1.8 \pm 0.6 \pm 0.4)\,\mathrm{ps}$$ [MAC, PRL 51 (1983) 1022]

$$\tau_b = (1.20\,^{+\,0.45}_{-\,0.36} \pm 0.30)\,\mathrm{ps}$$ [MARK, PRL 51 (1983) 1316]

you get

$$|V_{cb}| \simeq 0.04 \qquad (\text{now } 0.04053)$$

γ HISTORY



[Kwok, Polonsky, Lukashenko,Aebischer, Kilminster, arXiv:2506.08089]

$B_s^0 \to \phi\mu^+\mu^-$ AT FCC

This study demonstrates that FCC-ee enables first-time access to CP -sensitive observables previously beyond experimental reach.

The LHCb sensitivity is studied in [Schmitt *et al.*, arXiv:2510.17646]