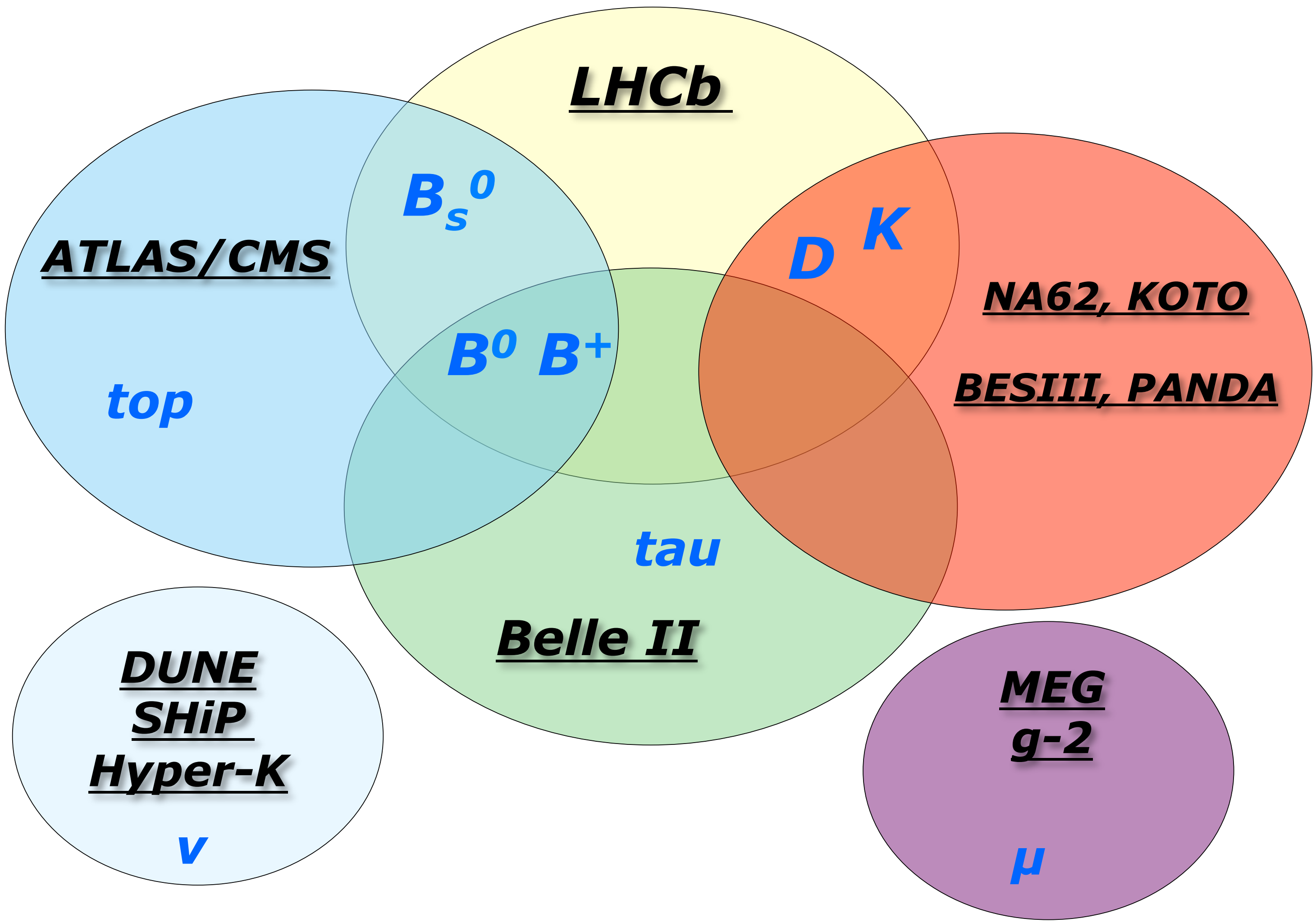
Quark and lepton flavor and plasma

Convenors: A. Mischke, N.T.

ESPP-NL INPUT

5 Oct 2018

Flavour playing field



Target

- *Identify all topics we like to address (draft text available)*
- *Give statements as input for the final recommendations from the Netherlands, starting from the VISTA25 output*

- *WG:* Quark and lepton flavor and plasma
  - B-physics: LHCb II upgrade, Belle II,
  - Muon collider: MEG II, MU2e, g-2,
  - Rare Kaon Decay: NA62, KOTO,
  - Heavy Ion: ALICE
  - Acc. Neutrino: DUNE, SHIP

Outline

- Starting point: Vista25 *(copy-paste)*
- The playing field
- The future: Nikhef priorities

Previous discussions:

- 2012 Texel I: http://agenda.nikhef.nl/conferenceOtherViews.py?view=standard&confId=1793
- 2014 Texel II: http://agenda.nikhef.nl/conferenceDisplay.py?confId=2691
- 2017 Vista25: https://indico.nikhef.nl/event/638/other-view?view=cdsagenda

Vista25: output

- LHCb
  - Study CP violation in B decays, test the CKM paradigm
  - Search for rare decays, in particular $B_d \rightarrow \mu^+\mu^-$ and $B_s \rightarrow \mu^+\mu^-$
  - Search for long lived particles
  - Perform lepton non-universality and lepton flavor violation tests
  - Contribute to detector upgrades for LS2: VELO pixel detector, Scintillating Fiber Tracker, High Level Trigger

- ALICE
  - Determine the elliptic flow of identified particles
  - Study the energy loss of partons in the quark-gluon plasma
  - Measure heavy-quark production
  - Design and build inner silicon tracking detector for installation in LS2

- GOALS OF HL-LHC BEYOND 2022
  - Utilize the rich ATLAS, LHCb and ALICE physics potential of the HL-LHC

Vista25: Inter-experimental – New Research Themes

- NOT explicitly discussed in strategy document but there are several points that implicitly require this
  - Ease the possibility to have inter-experiment activities. Presently very difficult with LHC

- In particular this is linked to the new themes that are suggested to be initiated in the strategy document:
  - Initiate the theme "Global fits to HEP data" to investigate the cohesion of various Standard Model measurements like the old LEP results and recent ATLAS, LHCb and XENON results
  - Initiate the theme 'Neutrino Physics' to increase the cohesion between the Nikhef KM3NeT, DUNE and Auger activities.
  - Initiate the theme 'Dark Matter' to increase the cohesion between ATLAS, LHCb, XENON1T/nT and KM3NeT programme activities.

NEW RESEARCH THEMES GOALS 2017-2022:

→ Initiate the theme 'Neutrino Physics' to increase the cohesion between the Nikhef KM3NeT, DUNE and Auger activities.
→ Initiate the theme 'Dark Matter' to increase the cohesion between ATLAS, LHCb, XENON1T/nT and KM3NeT programme activities.
→ Initiate the theme "Global fits to HEP data" to investigate the cohesion of various Standard Model measurements like the old LEP results and recent ATLAS, LHCb and XENON results.

Vista25: Status

- Flavour physics opportunities
  - beauty and charm flavour physics: LHCb Upgrade II, Belle II
  - Kaon flavour physics: KOTO, NA62
  - Muon flavour physics: MEGII, Mu2e, g-2
- Initiatives currently being explored:
  - Exploit HL-LHC potential with LHCb Upgrade II (10x Lumi LHCb upgrade I)
  - Develop pixel detectors with precision time measurement
- DUNE
  - Prepare an extended neutrino physics programme by participating in the protoDUNE programme. The DUNE programme itself starts at FermiLab around 2025.

NEW INITIATIVES GOALS 2017-2022:

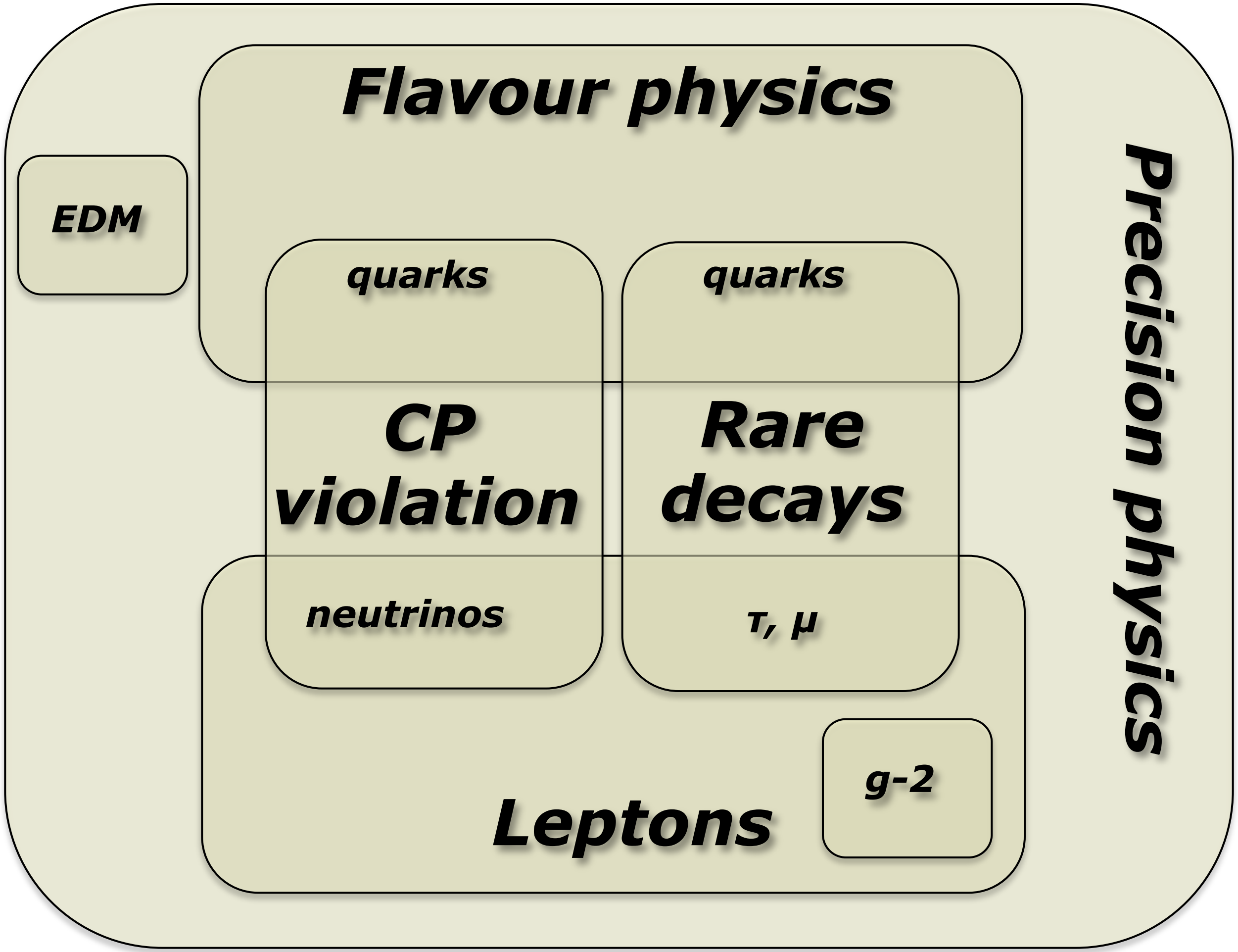
→ Prepare an extended neutrino physics programme by participating in the protoDUNE programme. The DUNE programme itself starts at FermiLab around 2025.

- Future of HI
  - No input from strategy document
- SHiP: searching for very weakly interacting long lived particles at SPS
  - No input from strategy document

Outline

- Starting point: Vista25
- The playing field
- The future: Nikhef priorities

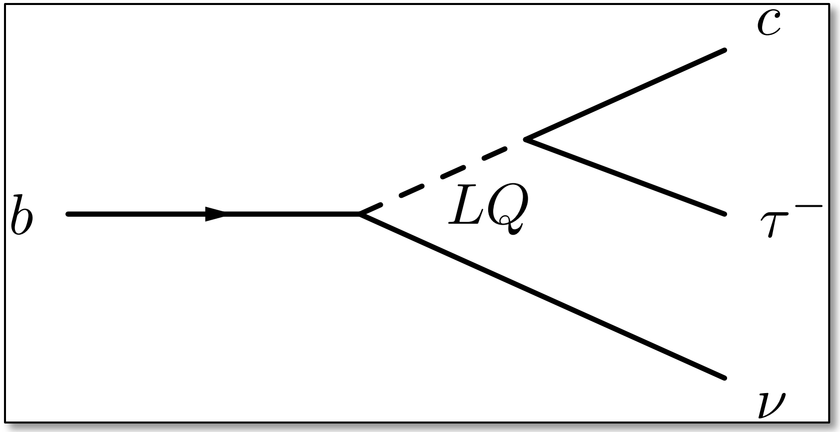
Quarks and Leptons



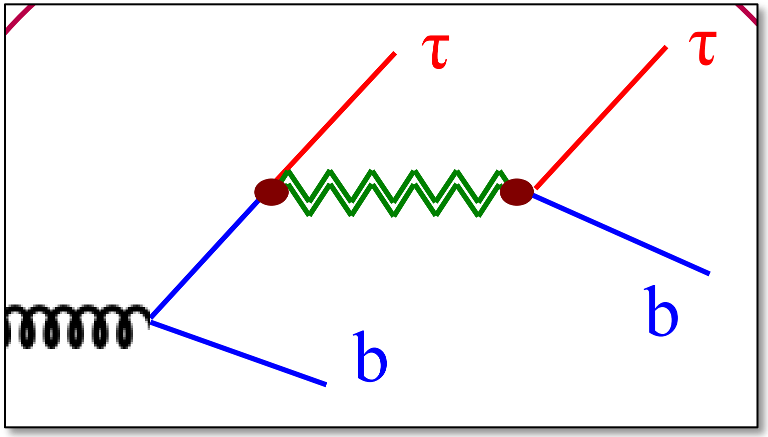
Quarks and Leptons

- Precision measurements to scrutinize the Standard Model
- Precision measurements only way to reach very high mass scales
- Precision measurements are not yet precise enough

Indirect detection: $B^0 \rightarrow D^+ \tau^- \nu$



Direct detection: LQ→ *b-jet* τ^-



Plasma (Starting Statements from Andre Mischke)

- Strongly interacting matter
  - CERN should keep a leading role in the next decade in the
  - characterisation of strongly interacting matter under extreme conditions,
  - Ie. the Quark-Gluon Plasma, which can be studied with high-energy nuclear collisions.

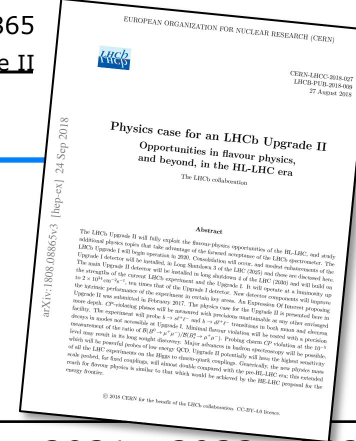
- Neutron star equation of state
  - The Netherlands pursue the measurement of the neutron star equation of state with
  - gravitational wave observations to gain a profound understanding the microscopic physics of dense QCD matter.

- Cooperation with
  - theorists from QCD and
  - gravitational wave physics is essential and
  - should be intensified and extended where possible.

Outline

- Starting point: Vista25
- The playing field
- The future: Nikhef priorities

24 Sep 2018 arXiv:1808.08865
Physics case for an LHCb Upgrade II



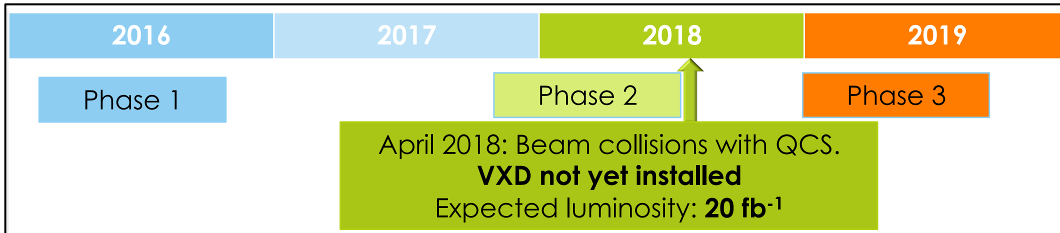
Quarks: Timeline

- LHCb Upgrade I: 2019
- LHCb Upgrade II: 2030

	2019 2020	2021 2022 2023	2024 2025 2026	2027 2028 2029	2030 2031	2032 203+
		Run III		Run IV		Run V
	LS2		LS3		LS4	
	LHCb 40 MHz UPGRADE	$L = 2 \times 10^{33}$	LHCb Consolidation	$L = 2 \times 10^{33}$ $50\ fb^{-1}$	LHCb Ph II UPGRADE *	$L = 2 \times 10^{34}$ $300\ fb^{-1}$
	ATLAS Phase I Upgr	$L = 2 \times 10^{34}$	ATLAS Phase II UPGRADE	HL-LHC $L = 5 \times 10^{34}$	ATLAS	HL-LHC $L = 5 \times 10^{34}$
	CMS Phase I Upgr	$300\ fb^{-1}$	CMS Phase II UPGRADE		CMS	$3000\ fb^{-1}$
Belle II		$5\ ab^{-1}$ $L = 8 \times 10^{35}$	$50\ ab^{-1}$			

LHC schedule: Frederick Bordry, Jun 2015

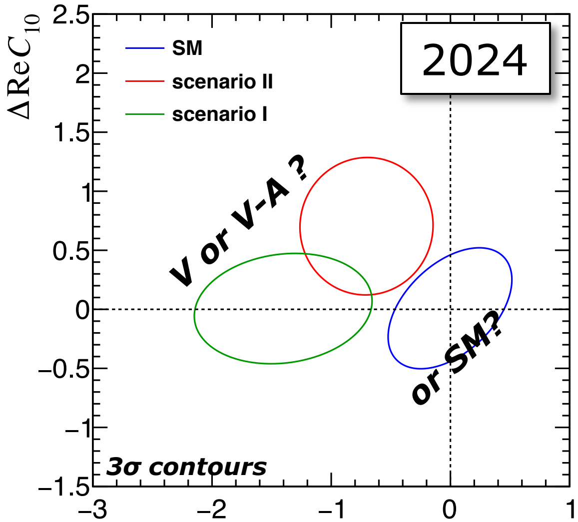
- Belle II
  - $L=5\times10^{33}\ cm^{-2}s^{-1}$ achieved
  - Physics with VXD in 2019

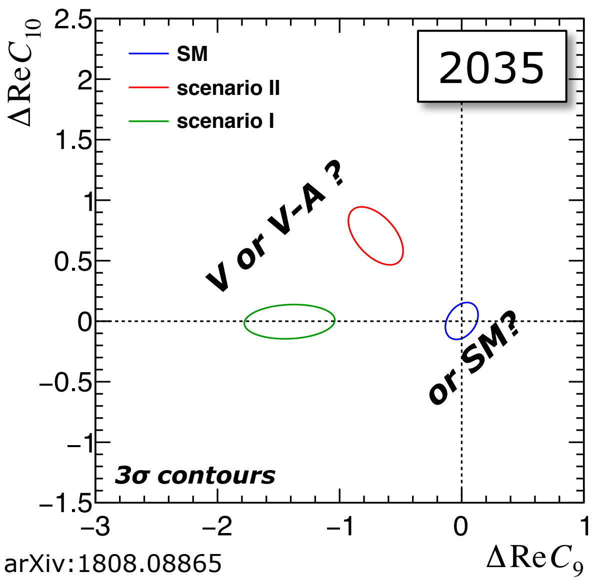


R. Cheaib, Moriond, 12 Mar 2018, arXiv:1802.01366

Quarks: LHCb Upgrade II physics case

NP couplings

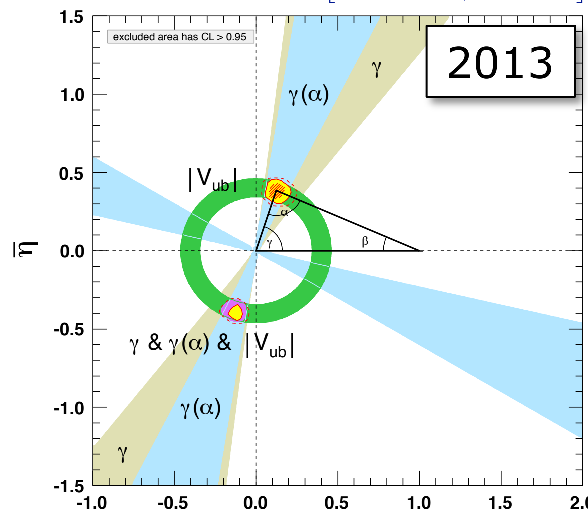




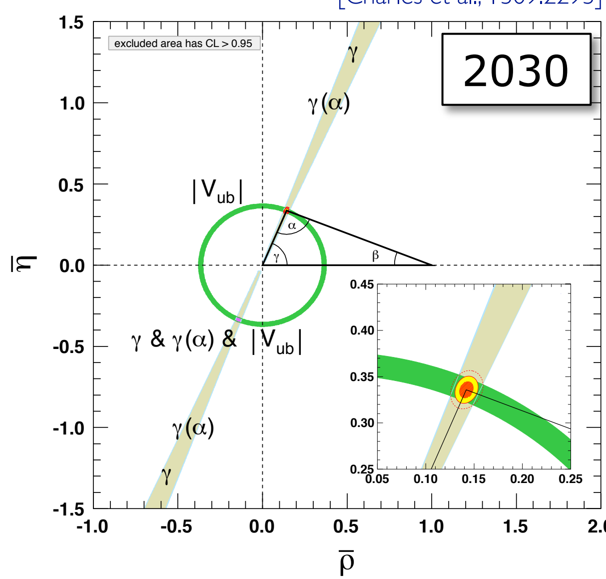
arXiv:1808.08865

CP violation

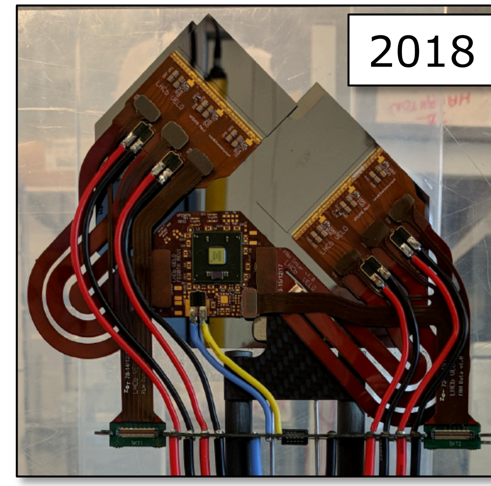
[Charles et al., 1309.2293]

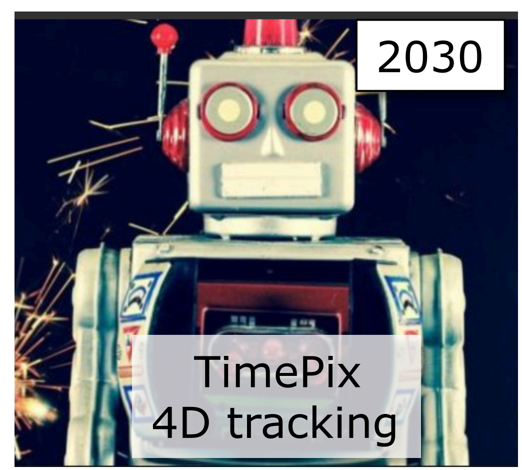


[Charles et al., 1309.2293]

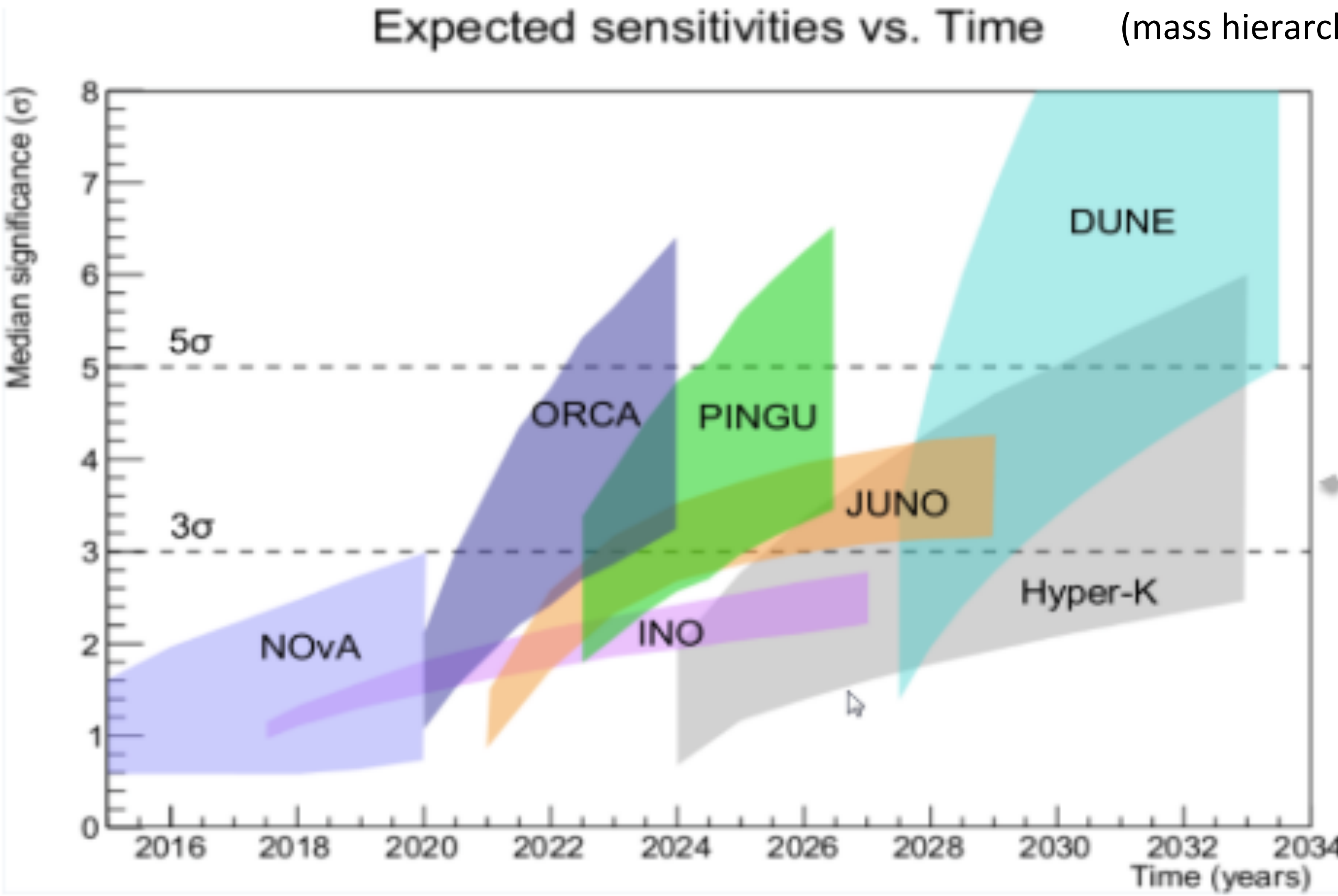


Technology





Leptons: Timeline



(mass hierarchy)

Plasma: Timeline

Future LHC Program

upgrade to full energy 10 x more data	increase in luminosity 10x	high luminosity LHC 100 x more data
LS1 2014	LS2 2019-2020	LS3 2024-2026

2015-2018

goals:

jet, dijets, γ-jet, Z-jet
differentially versus centrality, flow plane, pid
multi-particle correlations, v_n correlations
parton transport and energy loss (jets, heavy-flavor)
color screening quarkonia
low-mass di-leptons, ρ-spectral function, thermal photons
saturation, low-x
collectivity in pA

2021-2023

goals:

jet, dijets, γ-jet, Z-jet, W-jet
differentially versus centrality, flow plane, pid
parton transport and energy loss (jets, heavy-flavor)
color screening quarkonia
low-mass di-leptons, ρ-spectral function, thermal photons
saturation, low-x (new detector?)
t-tbar in heavy-ions

2026-

runs:

pA, PbPb, ArAr

Nikhef priorities 2025 ?

Input from the Netherlands on the
European Strategy for Particle Physics – Update

From a draft version – please provide feedback to the points raised hereunder

Energy and precision frontier

8) The successful realization of the High Luminosity LHC is of highest priority, including upgraded general purpose experiments Atlas and CMS, as well as flavour physics with LHCb and heavy-ion physics with Alice.

11) Any sign of new physics beyond the Standard Model will give direction to the future generation of infrastructure. CERN should take all measures to optimize this potential and intensify the diversity physics program to reach this point.
   - The Netherlands support the construction of the SHIP experiment

Nikhef priorities 2025 ?

- My personal view:

Quarks:
- LHCb UpgradeII
  - Priority
- BelleII
  - Essential to confirm
- NA62, KOTO
  - Interesting, endorse
- BESIII, PANDA
  - Spectroscopy

Leptons:
- DUNE
  - Priority
- SHIP
  - High risk high gain
- Hyper-K

Plasma:
- ALICE
  - Priority
- RHIC
- GSI

- To be clear: my view on the European strategy
  - Not necessarily Nikhef strategy…

Discussion points – fundamental questions

- Quarks
  1) Why are there 3 families of quarks (ie. different mass) ?
  2) Why is there no anti-matter?
  3) Are there additional electro-weak gauge bosons?
  4) Can we find evidence for lepton flavour (universality) violation?
  5) Where are the (NP) flavour changing neutral currents?
- Leptons
  1) Why are there 3 families of leptons? Is there a sterlie neutrino?
  2) What is the amount of CP violation in the neutrino sector?
  3) What is the neutrino mass hierarchy?
  4) Is ν_3 mostly ν_μ or ν_τ ?
  5) New ν properties? (Decay? Magn. moment? CPT violation?)
- Plasma
  1) What is interaction strength between quarks and gluons (in plasma phase) ?
  2) Can a QGP be created in small collision systems, such as p-p and Pb-p ?

Backup slides

Dream Machines (Ch.Quigg)

(21) Can we find evidence of right-handed charged-current interactions? Is nature built on a fundamentally asymmetrical plan, or are the right-handed weak interactions simply too feeble for us to have observed until now, reflecting an underlying symmetry hidden by spontaneous symmetry breaking?

(22) Are there additional electroweak gauge bosons, beyond $W^{\pm}$ and Z?

(23) Is charged-current universality exact? What about lepton-flavor universality?

(24) Where are flavor-changing neutral currents? In the standard model, these are absent at tree level and highly suppressed by the Glashow–Iliopouolos–Maiani mechanism. They arise generically in proposals for physics beyond the standard model, and need to be controlled. And yet we have made no sightings![g] Why not?

(25) Can we find evidence for charged-lepton flavor violation?

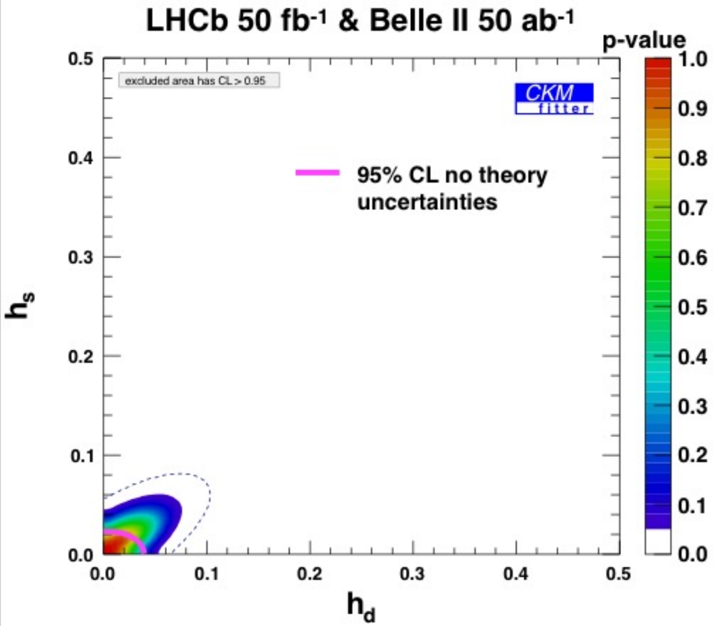
(26) Why are there three families of quarks and leptons? (Is it so?)

From: Chris Quigg, Dream machines, arXiv:1808.06036

Heavy Flavour = Precision search for NP

- Depending on your model, sensitive to multi-TeV scales, eg:

[Charles et al., 1309.2293]



$$M_{12}^q = (M_{12}^q)_{\rm SM}\left(1 + h_q e^{2i\sigma_q}\right)$$

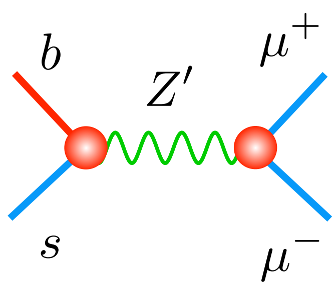
h_q parametrizes magnitude of NP in B_q mixing

$$h_d \lesssim 5\% \quad \Rightarrow \quad \Lambda \gtrsim \begin{cases} 2\cdot 10^3\,\text{TeV}, & \text{anarchic tree} \\ 1.4\,\text{TeV}, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

Heavy Flavour = Precision search for NP

- Depending on your model, sensitive to multi-TeV scales, eg:



$$\mu_{B_s \to \mu^+\mu^-} \simeq 1 \pm \frac{4\pi}{g^2 |V_{tb}^* V_{ts}|^2} \frac{v^2}{\Lambda^2}$$

$\mu_{B\to\mu\mu}$ is ratio BR^{exp}/BR^{SM}

$$\Lambda \gtrsim \frac{v}{\sqrt{0.2}} \times \begin{cases} \dfrac{\sqrt{4\pi}}{g\,|V_{tb}^* V_{ts}|} \\ 1 \end{cases} \simeq \begin{cases} 50\,\text{TeV}\,, & \text{anarchic tree} \\ 0.6\,\text{TeV}\,, & \text{MFV loop} \end{cases}$$

From Uli Haisch, 31 Aug 2016

LHCb Upgrade II

24 Sep 2018 arXiv:1808.08865

- ***Physics case for an LHCb Upgrade II***

  Opportunities in flavour physics and beyond in the HL-LHC era

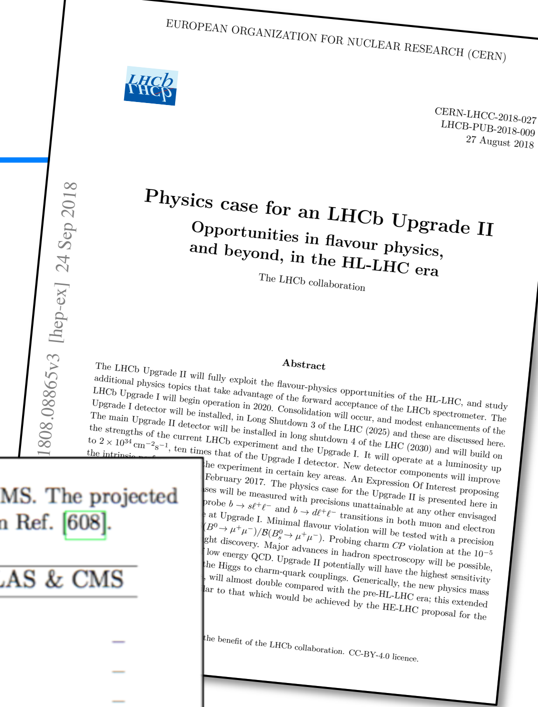


Table 10.1: Summary of prospects for future measurements of selected flavour observables for LHCb, Belle II and Phase-II ATLAS and CMS. The projected LHCb sensitivities take no account of potential detector improvements, apart from in the trigger. The Belle-II sensitivities are taken from Ref. [608].

Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K_S^0$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi\phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K_S^0\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–

The need for more precision

Imagine if Fitch and Cronin had stopped at the 1% level, how much physics would have been missed”

– A.Soni

- “A special search at Dubna was carried out by Okonov and his group. They did not find a single $K_L^0 \to \pi^+\pi^-$ event among 600 decays into charged particles (Anikira et al., JETP 1962). At that stage the search was terminated by the administration of the lab. The group was unlucky.”

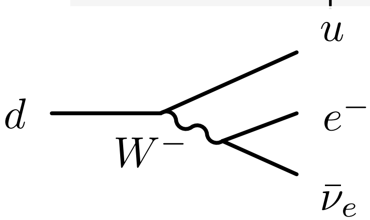
– L.Okun

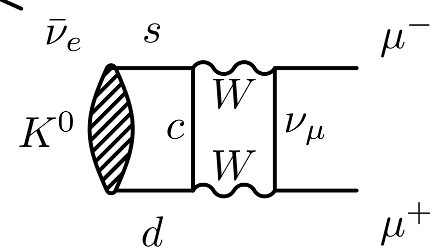
(remember: $B(K_L^0 \to \pi^+\pi^-) \sim 2\ 10^{-3}$)

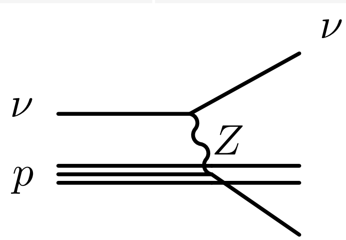
Heavy Flavour = Precision search for NP

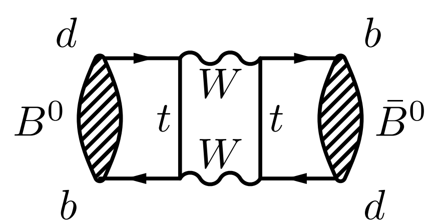
- Historical record of indirect discoveries:

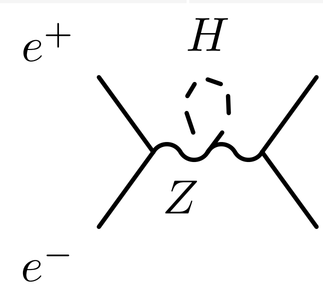
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/72	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?







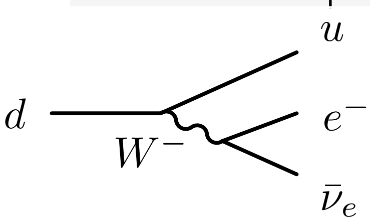


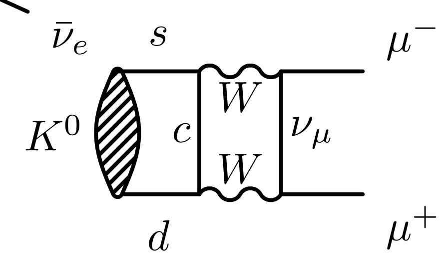


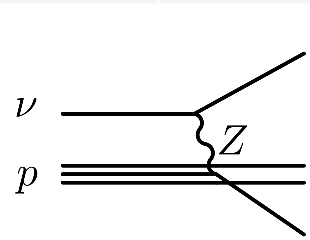
Heavy Flavour = Precision search for NP

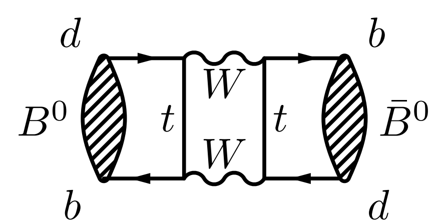
- Direct discoveries rightfully higher valued:

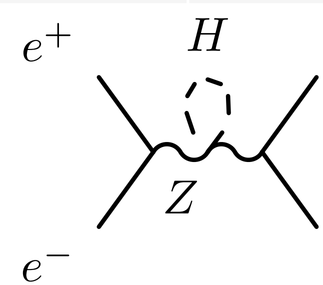
Particle	Indirect			Direct		
ν	β decay	Fermi	1932	Reactor ν-CC	Cowan, Reines	1956
W	β decay	Fermi	1932	$W \to e\nu$	UA1, UA2	1983
c	$K^0 \to \mu\mu$	GIM	1970	J/ψ	Richter, Ting	1974
b	CPV $K^0 \to \pi\pi$	CKM, 3rd gen	1964/	Υ	Ledermann	1977
Z	ν-NC	Gargamelle	1973	$Z \to e^+e^-$	UA1	1983
t	B mixing	ARGUS	1987	$t \to Wb$	D0, CDF	1995
H	e^+e^-	EW fit, LEP	2000	$H \to 4\mu/\gamma\gamma$	CMS, ATLAS	2012
?	**What's next ?**		?			?











Flavour physics has a track record…

GIM mechanism in $K^0 \to \mu\mu$

Weak Interactions with Lepton-Hadron Symmetry*

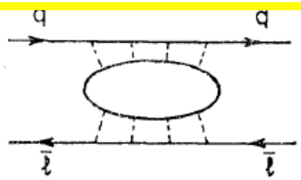
S. L. Glashow, J. Iliopoulos, and L. Maiani†
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02139
(Received 5 March 1970)

We propose a model of weak interactions in which the currents are constructed out of four basic quark fields and interact with a charged massive vector boson. We show, to all orders in perturbation theory, that the leading divergences do not violate any strong-interaction symmetry and the next to the leading divergences respect all observed weak-interaction selection rules. The model features a remarkable symmetry between leptons and quarks. The extension of our model to a complete Yang-Milis theory is discussed.

splitting, beginning at order $G(G\Lambda^2)$, as well as contributions to such unobserved decay modes as $K_2 \to \mu^+ + \mu^-$, $K^+ \to \pi^+ + l + \bar{l}$, etc., involving neutral lepton

We wish to propose a simple model in which the divergences are properly ordered. Our model is founded in a quark model, but one involving four, not three, fundamental fermions; the weak interactions are medi-

new quantum number $\mathcal{C}$ for charm.



Glashow, Iliopoulos, Maiani, Phys.Rev. D2 (1970) 1285

CP violation, $K_L^0 \to \pi\pi$

27 July 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

This Letter reports the results of experimental studies designed to search for the 2π decay of the K_2^0 meson. Several previous experiments have

three-body decays of the K_2^0. The presence of a two-pion decay mode implies that the K_2^0 meson is not a pure eigenstate of CP. Expressed as $K_2^0 = 2^{-1/2}[(K_0 - \bar{K}_0) + \epsilon(K_0 + \bar{K}_0)]$ then $|\epsilon|^2 \cong R_T \tau_1 \tau_2$

Christenson, Cronin, Fitch, Turlay, Phys.Rev.Lett. 13 (1964) 138-140

$B^0 \leftrightarrow \bar{B}^0$ mixing

DESY 87-029
April 1987

OBSERVATION OF B^0-$\bar{B}^0$ MIXING

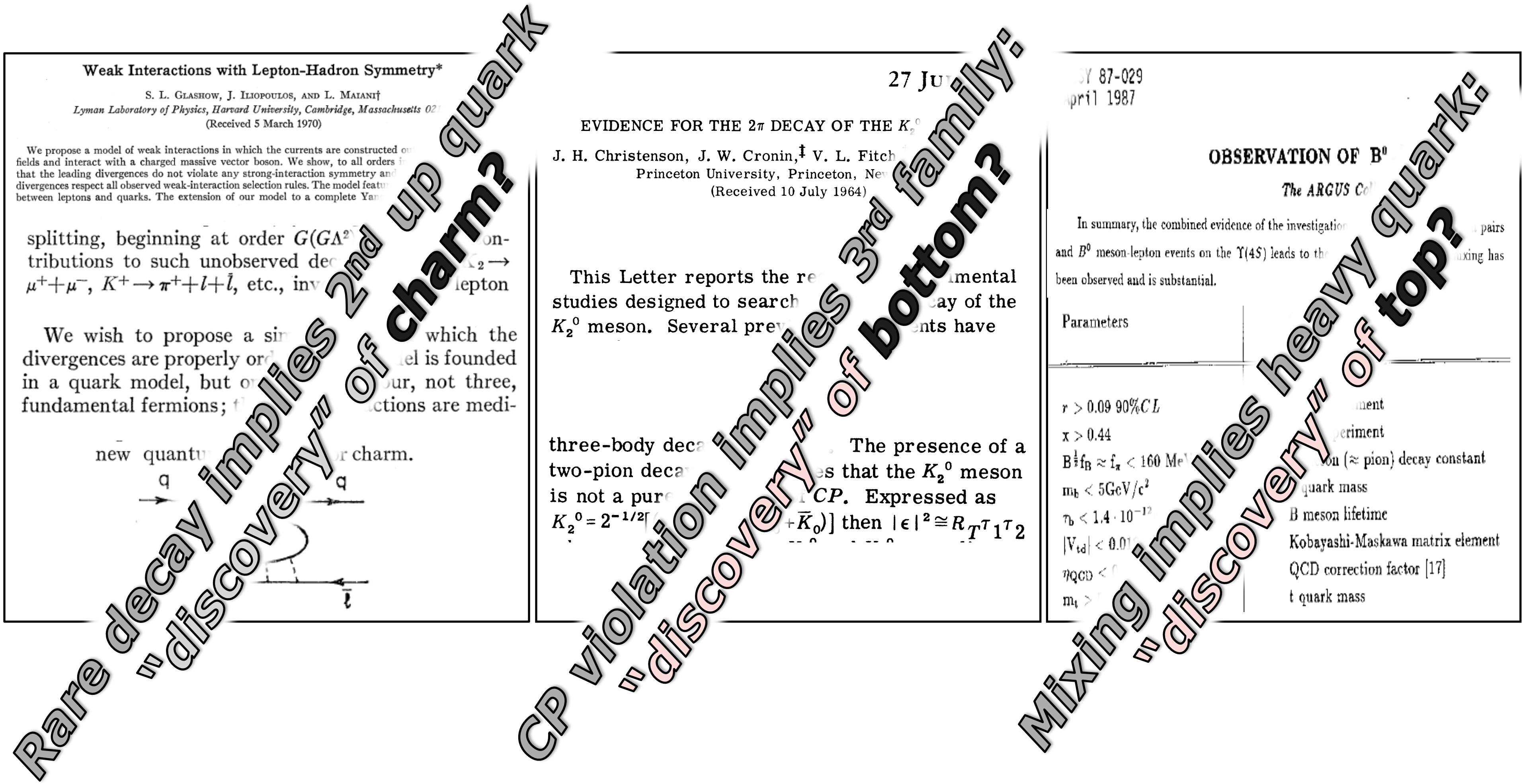
The ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson-lepton events on the $\Upsilon(4S)$ leads to the conclusion that B^0-$\bar{B}^0$ mixing has been observed and is substantial.

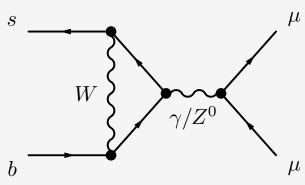
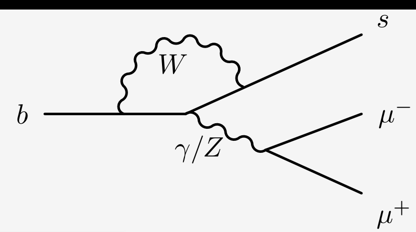
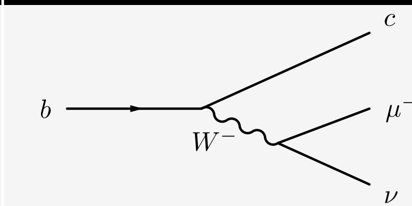
Parameters	Comments
$r > 0.09$ 90% CL	This experiment
$x > 0.44$	This experiment
$B^{\frac{1}{2}} f_B \approx f_\pi < 160$ MeV	B meson (≈ pion) decay constant
$m_b < 5\,\mathrm{GeV}/c^2$	b-quark mass
$\tau_b < 1.4 \cdot 10^{-12}$ s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi-Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [17]
$m_t > 50\,\mathrm{GeV}/c^2$	t quark mass

ARGUS Coll. Phys.Lett.B192:245,1987

Flavour physics has a track record…



References – Rare Decays

	Flavour Changing Neutral Current			Charged Current
	Leptonic	**Mesonic**	**Baryonic**	**Semi-leptonic**
				
Strange	*LHCb, 1706.00758*	*NA62, Moriond 2018* *KOTO, ICHEP 2018*	*LHCb, 1712.08606*	
Charm	*LHCb, 1305.5059,* *LHCb, 1512.00322*	*LHCb, 1707.08377* *LHCb, 1806.10793* *BESIII, 1710.02278* *BESIII, 1802.09752* *BESIII, 1802.04057*	*LHCb, 1712.07938*	
Beauty	*CMS, 1307.5025* *LHCb&CMS, 1411.4413* *LHCb, 1703.05747* *LHCb, 1710.04333* *LHCb, 1703.02508*	*BaBar, 1204.3933 (RK)* *BaBar, 1508.07960 (Ang)* *Belle, 0904.0770 (RK)* *Belle, 1612.05014 (Q5')* *CMS, 1507.08126 (Ang, B^0)* *CMS, 1710.02846 (Ang, B^0)* *CMS, 1806.00636 (Ang, B^+)* *ATLAS, 1805.04000 (B^0)* *LHCb, 1403.8044 (BR(B^0))* *LHCb, 1406.6482 (R_K)* *LHCb, 1512.04442 (Ang)* *LHCb, 1506.08777 (BR(B_s))* *LHCb, 1612.06764 (phase)* *LHCb, 1612.07818 (scalar search)* *LHCb, 1705.05802 (R_K*)* *LHCb, 1804.07167 (B_s^0)*	*LHCb, 1503.07138* *LHCb, 1701.08705* *LHCb, 1703.00256*	*BaBar, 1205.5442* *Babar, 1303.0571* *Belle, 1607.07923* *Belle, 1612.00529* *Belle, 1709.00129* *Belle, 1803.06444* *LHCb, 1506.08614* *LHCb, 1708.08856* *LHCb, 1709.02505*

New in 2018

CKM and PMNS matrix

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

vs

$$\begin{bmatrix} |d'\rangle \\ |s'\rangle \\ |b'\rangle \end{bmatrix} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} \begin{bmatrix} |d\rangle \\ |s\rangle \\ |b\rangle \end{bmatrix}.$$

- A completely different hierarchy ?!

$$U_{MNSP} \approx \begin{pmatrix} 0.85 & 0.53 & 0 \\ -0.37 & 0.60 & 0.71 \\ -0.37 & 0.60 & -0.71 \end{pmatrix}$$

$$V_{CKM} = \begin{pmatrix} 0.97428 & 0.2253 & 0.00347 \\ 0.2252 & 0.97345 & 0.0410 \\ 0.00862 & 0.0403 & 0.999152 \end{pmatrix}$$

CKM and PMNS matrix

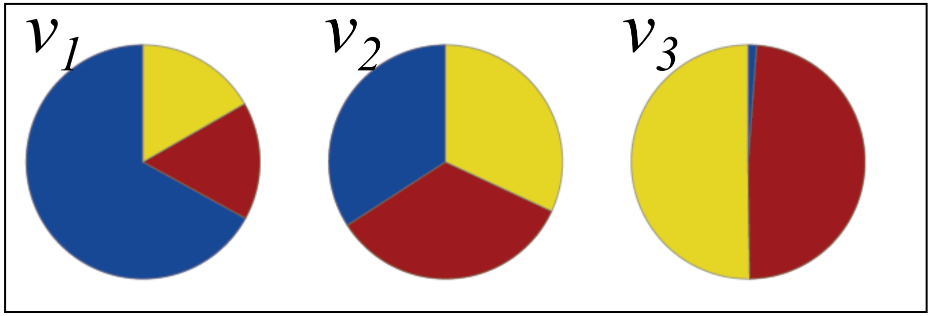
$$\begin{bmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{bmatrix} = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix}\begin{bmatrix}\nu_1\\ \nu_2\\ \nu_3\end{bmatrix}$$

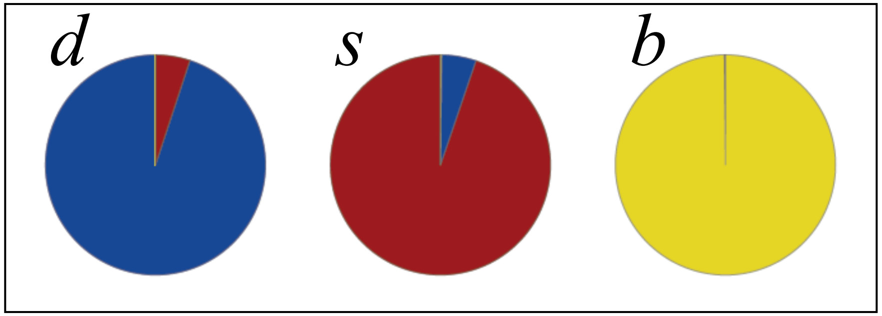
vs

$$\begin{bmatrix}|d'\rangle\\ |s'\rangle\\ |b'\rangle\end{bmatrix} = \begin{bmatrix}V_{ud} & V_{us} & V_{ub}\\ V_{cd} & V_{cs} & V_{cb}\\ V_{td} & V_{ts} & V_{tb}\end{bmatrix}\begin{bmatrix}|d\rangle\\ |s\rangle\\ |b\rangle\end{bmatrix}.$$

- A completely different hierarchy ?!

$$\begin{pmatrix}|U_{e1}|^2 & |U_{e2}|^2 & |U_{e3}|^2\\ |U_{\mu1}|^2 & |U_{\mu2}|^2 & |U_{\mu3}|^2\\ |U_{\tau1}|^2 & |U_{\tau2}|^2 & |U_{\tau3}|^2\end{pmatrix} \approx \begin{pmatrix}\frac{2}{3} & \frac{1}{3} & 0\\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2}\\ \frac{1}{6} & \frac{1}{3} & \frac{1}{2}\end{pmatrix}$$

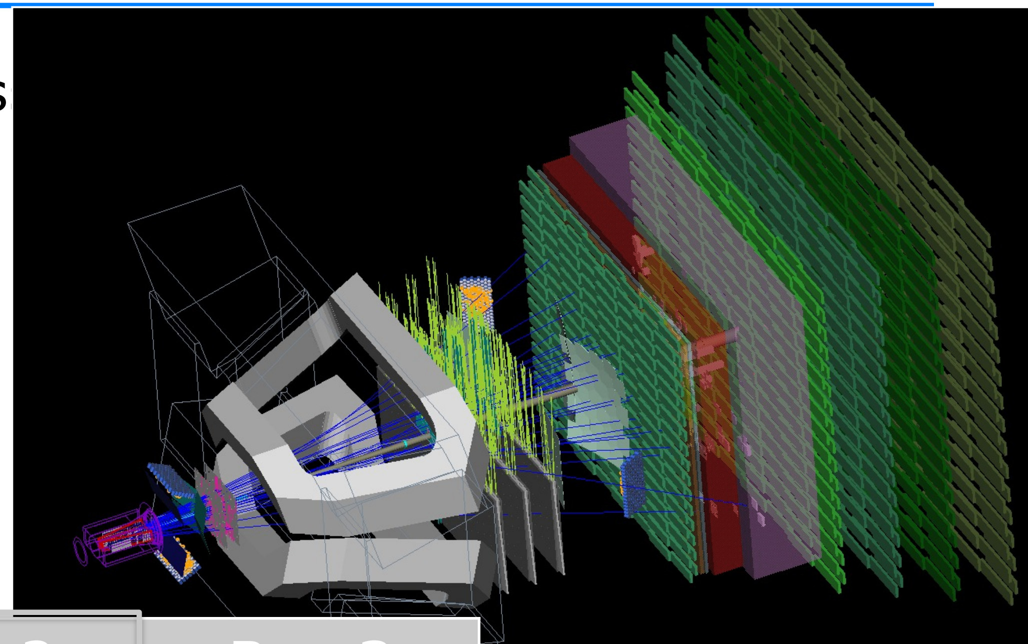




See eg. PhD thesis R. de Adelhart Toorop

LHC and LHCb

- First LHC run: big succes



	Run-1	Run-2	Run-3
Year	2010 - 2012	2015 - 2018	2021 - 2030
Energy	7-8 TeV	13 TeV	14 TeV
Lumi	3 fb^{-1}	7 fb^{-1}	50 fb^{-1}
Nr(B)	10^{12}	$3.5x10^{12}$	$50x10^{12}$

5,000,000,000,000 B-mesons produced