Solving Beautiful Puzzles

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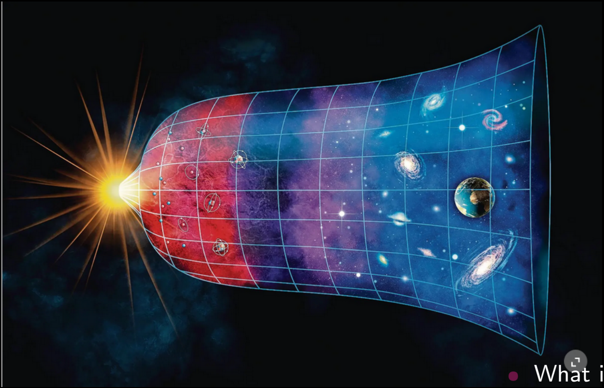
Maastricht University & Nikhef

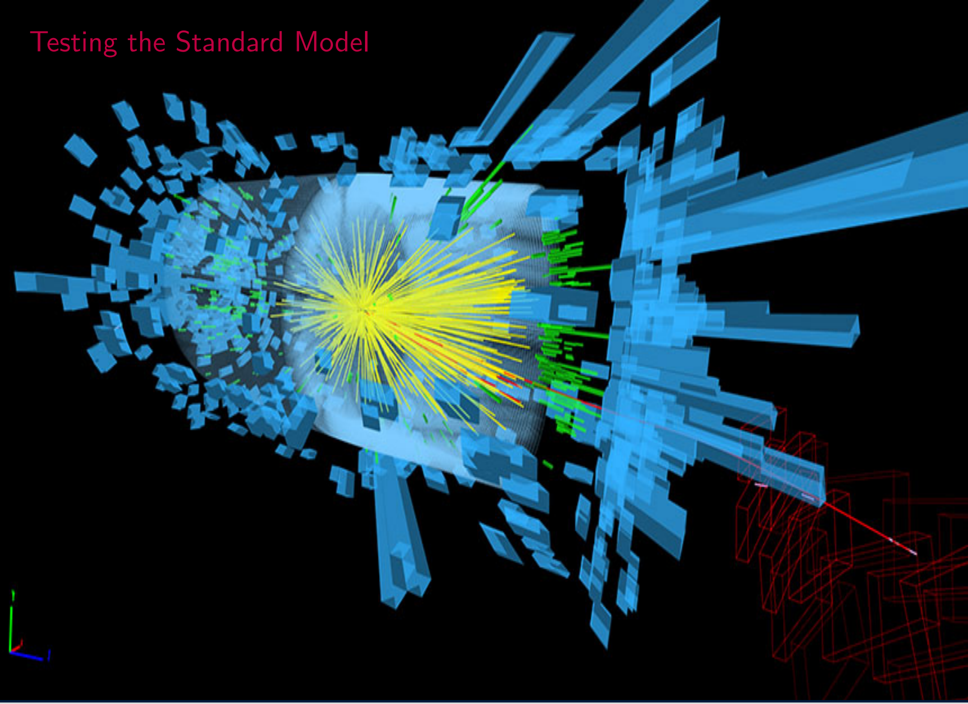
= Studying beauty meson decays at the highest precision =

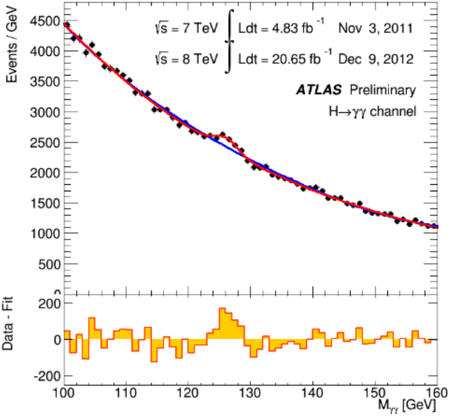
Universal Questions



- What is the structure of matter and interactions?
- Size of fundamental parameters?
- Matter versus antimatter?
- Fine tuning of parameters?
- What is dark matter?

Testing the Standard Model

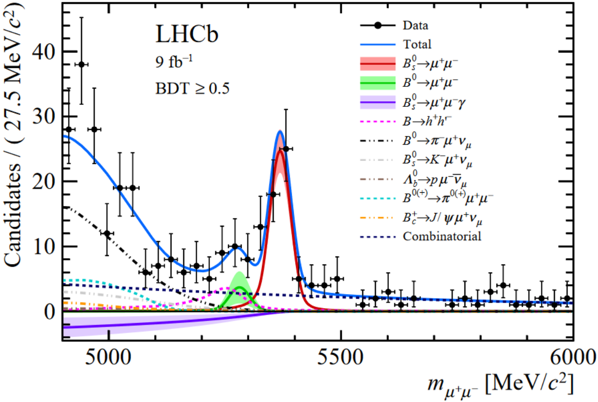




Energy frontier

Higher energy allows to probe higher new mass scales

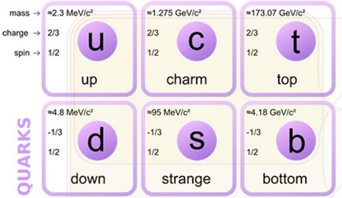
LHCb Collaboration [Phys. Rev. Lett. 128, (2022) 041801]



Precision frontier

Tiny deviations from SM predictions constrain effects of New Physics

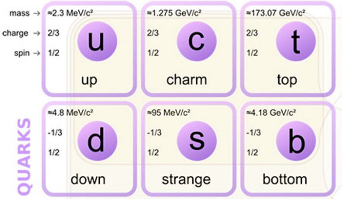
Precision frontier



Flavour Physics

Precision studies of heavy particle transitions!

Precision frontier



Flavour Physics

Precision studies of heavy particle transitions!

Flavour sector itself already quite puzzling!

The Flavour Puzzle

- Flavour symmetry broken by Yukawa couplings to the Higgs field
- Origin of mixing between families described by unitary CKM matrix
- Visualized by unitary triangles

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The Flavour Puzzle

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- Origin of mixing between families described by unitary CKM matrix
- Visualized by unitary triangles
- Dominant source of CP violation (antiparticle-particle asymmetry)

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The Flavour Puzzle

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CP violation in the SM = peculiar!

- CKM Mechanism is the dominant source of CP violation

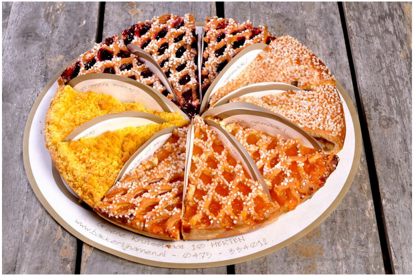
  $\rightarrow$ established by fit to unitarity triangle

- Possible strong CP violation via QCD θ term strongly constrained
- Remains one of the puzzles of the SM!

Why Flavour?

Understanding of Flavour unsatisfactory:

- 22 (out of 27) free parameters from Yukawa sector
- Hierarchy of the CKM matrix
- Three Families
- Hierarchy of masses
- CKM versus PMNS
- Nature of Neutrinos
- CP violation



Visit us in Maastricht and discover your favorite flavour!

Why Flavour?

- Huge amounts of data available and more coming thanks to B-factories, LHCb, Atlas and CMS!
- Very many different types decays
- Probe weak, strong and electromagnetic interaction $=$ need excellent understanding of them*

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How to find New Physics?

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Found something? = Effective field theory

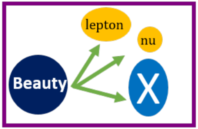
- New physics manifests itself as higher dimensional operators suppressed by scale Λ

$$\mathcal{L} = \mathcal{L}^{\rm SM}_{\rm dim4} + \mathcal{L}_{\rm dim5} + \mathcal{L}_{\rm dim6} + \ldots \qquad \mathcal{L}_{\rm dimn} = \frac{1}{\Lambda^{n-4}} \sum_i C_n^{(i)} \mathcal{O}_n^{(i)}$$

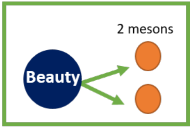
* The key challenge in this endeavour

Types of flavour decays and how to use them

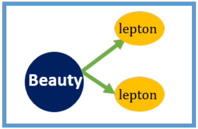
Semileptonic



Non-leptonic



Rare Decays



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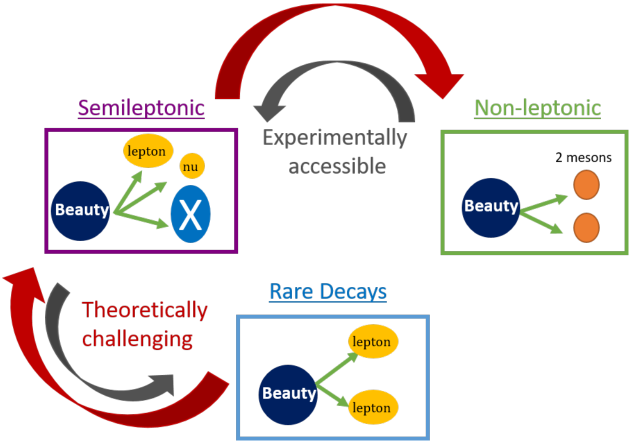

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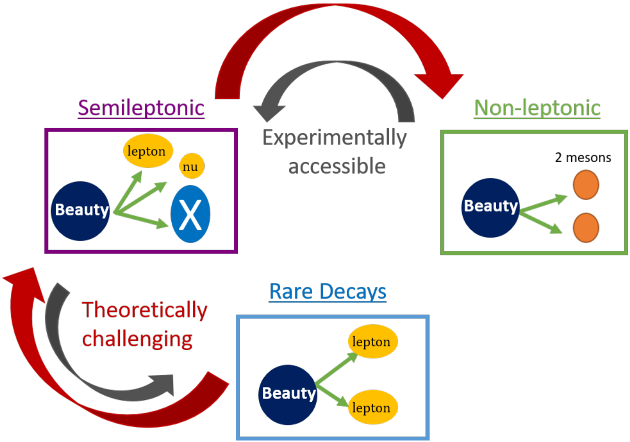

- Complementary decays with different sensitivities to SM and (!) new physics

Reminder: The Particle Physics Zoo...

D meson[20]	D^+	D^-	$c\bar{d}$	1,869.61 ±0.10
D meson[21]	D^0	$\bar{D}^0$	$c\bar{u}$	1,864.84 ±0.07
strange D meson[22]	D_s^+	D_s^-	$c\bar{s}$	1,968.30 ±0.11
B meson[23]	B^+	B^-	$u\bar{b}$	5,279.26 ±0.17
B meson[24]	B^0	$\bar{B}^0$	$d\bar{b}$	5,279.58 ±0.17
Strange B meson[25]	B_s^0	$\bar{B}_s^0$	$s\bar{b}$	5,366.77 ±0.24
Charmed B meson[26]	B_c^+	B_c^-	$c\bar{b}$	6,275.6 ±1.1

Beauty mesons!!

Pion[10]	π^+	π^-	$u\bar{d}$	139.570 18 ±0.000 35
Pion[11]	π^0	Self	$\frac{u\bar{u}-d\bar{d}}{\sqrt{2}}$ [a]	134.9766 ±0.0006
Eta meson[12]	η	Self	$\frac{u\bar{u}+d\bar{d}-2s\bar{s}}{\sqrt{6}}$ [a]	547.862 ±0.018
Eta prime meson[13]	$\eta'(958)$	Self	$\frac{u\bar{u}+d\bar{d}+s\bar{s}}{\sqrt{3}}$ [a]	957.78 ±0.06
Charmed eta meson[14]	$\eta_c(1S)$	Self	$c\bar{c}$	2,983.6 ±0.7
Bottom eta meson[15]	$\eta_b(1S)$	Self	$b\bar{b}$	9,398.0 ±3.2
Kaon[16]	K^+	K^-	$u\bar{s}$	493.677 ±0.016
Kaon[17]	K^0	$\bar{K}^0$	$d\bar{s}$	497.614 ±0.024
K-Short[18]	K_S^0	Self	$\frac{d\bar{s}+s\bar{d}}{\sqrt{2}}$ [e]	497.614 ±0.024[d]
K-Long[19]	K_L^0	Self	$\frac{d\bar{s}-s\bar{d}}{\sqrt{2}}$ [e]	497.614 ±0.024[d]

What do we know about flavour?

- Knowledge is beautifully summarized in the unitary CKM matrix
- All entries unknown $\rightarrow$ phases relevant for CP violation
- Visualized by triangles in the complex plane
- Size and angles from wide range of experimental data!

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

The CP Landscape

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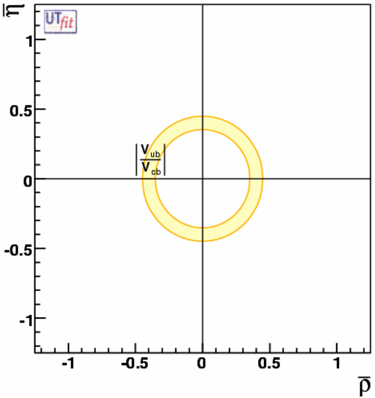

= Exclusive and Inclusive V_{xb} =

Part II of the talk

Zooming into the CP Landscape

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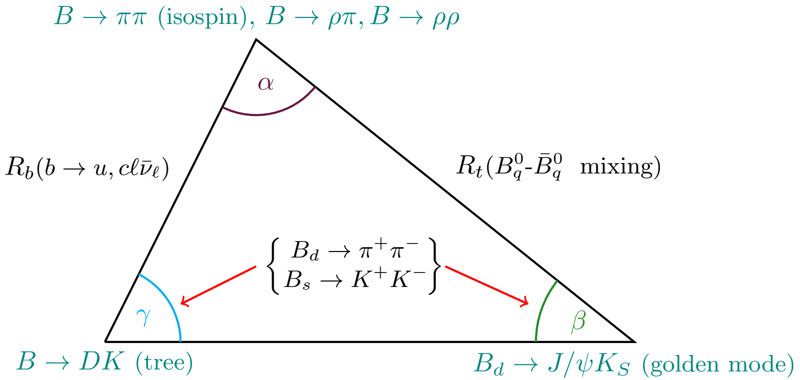

= Part III of the talk =

Flavour symmetries (SU(3), isospin) + many (clean) observables + incredible data set

The CP Landscape

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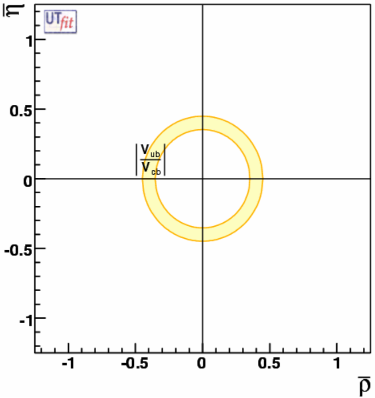

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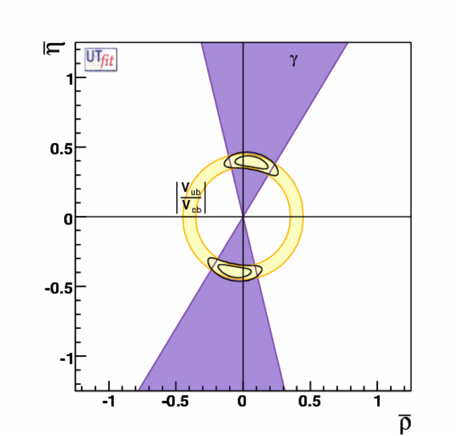

= CP violation in non-leptonic decays =

The CP Landscape

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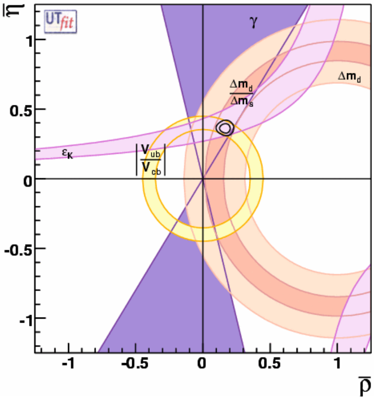
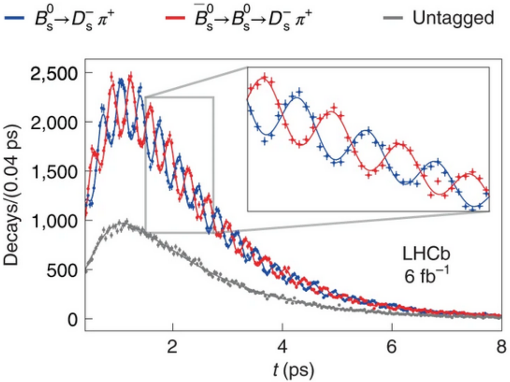


= Kaon and B meson mixing =

$$\bar{\rho} + i\bar{\eta} = -\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}$$

LHCb, Nature 18 1-5 (2022)



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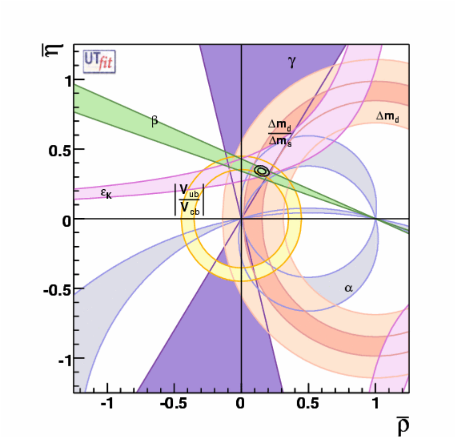

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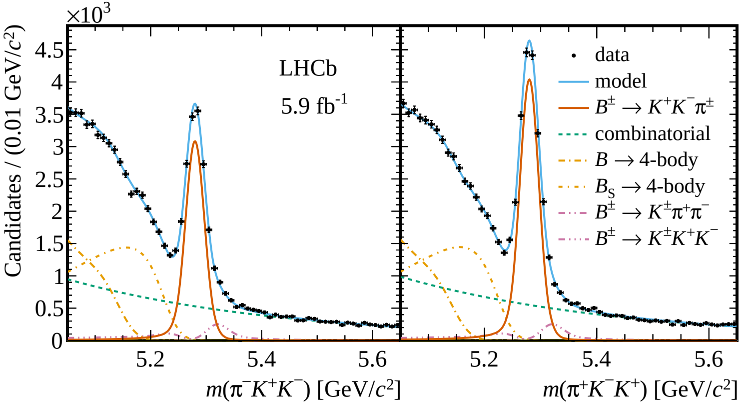
LHCb [2206.07622]



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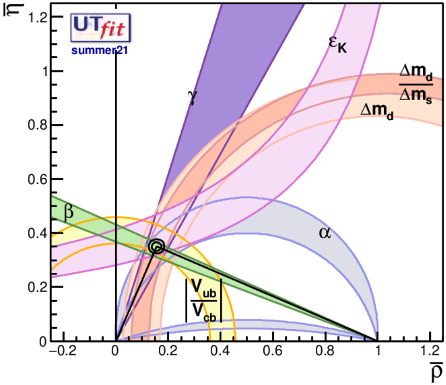

Huge amounts of data + theory advances = Precision frontier

Some cracks are starting to show!

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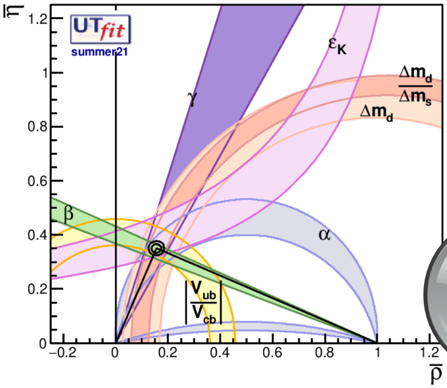

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Hints of New Physics?

Puzzle:

Inconsistency between theory and experiment or between different types of decays

Challenge:

Disentangle SM long-distances effects from the effects of new interactions

Puzzles in semileptonic decays

- Inclusive versus Exclusive
- V_{cb} and V_{ub}
- LFUV in R_D and R_{D*}

Puzzles in nonleptonic decays

- Missing CP violation
- $B \to \pi K$ puzzle
- $B \to D\pi$ puzzle

Puzzles in rare decays

- Anomalies in $b \to s\ell\ell$

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V_{cb} $D\pi$ CPV

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V_{ub} πK

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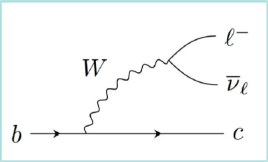
$b \to s$ $R_{D(*)}$

SM or beyond?

Challenge:

Disentangle SM long-distances effects from the effects of new interactions

Quark level process



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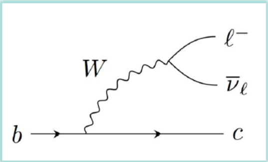
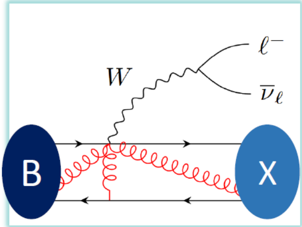


hadronization →

Reality: Bound state



SM or beyond?

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- Reliable theory uncertainties are essential!

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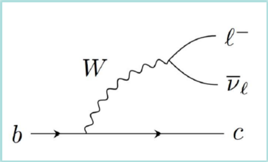

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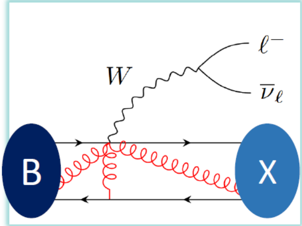

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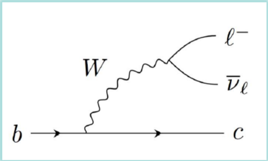

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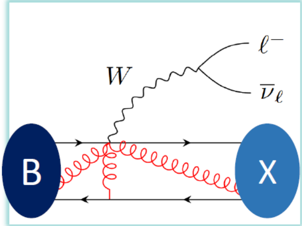
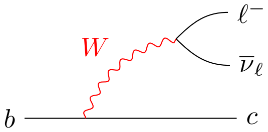


- Reliable theory uncertainties are essential!
- Look for the cleanest observables/methods
- Depends very much on the type of decay!

Puzzles in semileptonic decays: V_{ub} and V_{cb}

Inclusive versus Exclusive decays

Exclusive versus Inclusive Theory



- Theory (Weak interaction): Transitions between quarks/partons

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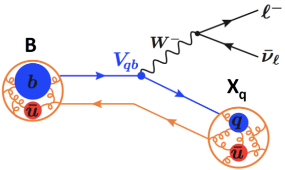
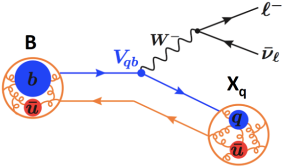


- Theory (Weak interaction): Transitions between quarks/partons
- Observation: Transitions between hadrons

Two options:

- Exclusive decays: pick one final state with the desired quarks ($V_{cb} \to D^{(*)}$ and $V_{ub} \to \pi$)
- Inclusive decays: everything you can think of! (denoted with X_c or X_u)

Exclusive versus Inclusive Theory

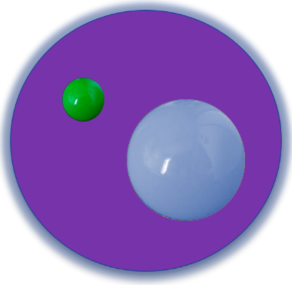


- Theory (Weak interaction): Transitions between quarks/partons

Challenge:

- Dealing with QCD at large distances/small scales
- Parametrize fundamental mismatch in non-perturbative objects
  - Calculable: Lattice or Light-cone sumrules = Exclusive Decays
  - Measurable: from data = Inclusive Decays

The power of beauty



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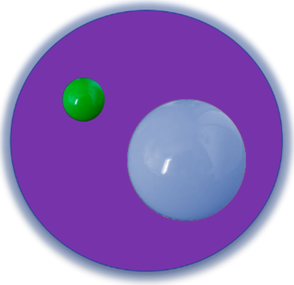
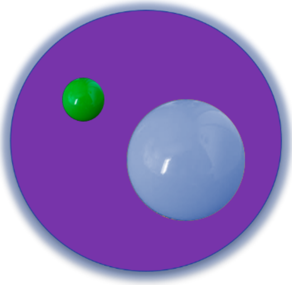


- b quark mass is large compared to Λ_{QCD}
- Setting up the Heavy Quark Expansion

The power of beauty



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- Setting up the Heavy Quark Expansion
- Momentum of b quark: $p_b = m_b v + k$, expand in $k \sim iD$

Inclusive Decays

Inclusive $B \to X_c \ell \nu$: Heavy Quark Expansion (HQE)

- b quark mass is large compared to $\Lambda_{\rm QCD}$
- Setting up the HQE: momentum of b quark: $p_b = m_b v + k$, expand in $k \sim iD$
- Optical Theorem $\to$ (local) Operator Product Expansion (OPE)

$$d\Gamma = d\Gamma_0 + \frac{d\Gamma_1}{m_b} + \frac{d\Gamma_2}{m_b^2} + \ldots \qquad d\Gamma_i = \sum_k C_i^{(k)} \left\langle B | O_i^{(k)} | B \right\rangle$$

- $C_i^{(k)}$ perturbative Wilson coefficients
- $\langle B | \ldots | B \rangle$ non-perturbative matrix elements $\to$ string of iD
- operators contain chains of covariant derivatives

$$\langle B|\mathcal{O}_i^{(n)}|B\rangle = \langle B|\bar{b}_v(iD_\mu)\ldots(iD_{\mu_n})b_v|B\rangle$$

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$$\langle B | \mathcal{O}_i^{(n)} | B \rangle = \langle B | \bar{b}_v (iD_\mu) \ldots (iD_{\mu_n}) b_v | B \rangle$$

- HQE parameters extracted from lepton energy, hadronic mass and di-lepton invariant mass moments

Decay rate

Γ_i are power series in $\mathcal{O}(\alpha_s)$

$$\Gamma = \Gamma_0 + \frac{1}{m_b}\Gamma_1 + \frac{1}{m_b^2}\Gamma_2 + \frac{1}{m_b^3}\Gamma_3 \cdots$$

- Γ_0: decay of the free quark (partonic contributions), $\Gamma_1 = 0$
- Γ_2: μ_π^2 kinetic term and the μ_G^2 chromomagnetic moment

$$2M_B\mu_\pi^2 = -\langle B|\bar{b}_v iD_\mu iD^\mu b_v|B\rangle$$
$$2M_B\mu_G^2 = \langle B|\bar{b}_v(-i\sigma^{\mu\nu})iD_\mu iD_\nu b_v|B\rangle$$

- Γ_3: ρ_D^3 Darwin term and ρ_{LS}^3 spin-orbit term

$$2M_B\rho_D^3 = \frac{1}{2}\langle B|\bar{b}_v\left[iD_\mu,[ivD,iD^\mu]\right]b_v|B\rangle$$
$$2M_B\rho_{LS}^3 = \frac{1}{2}\langle B|\bar{b}_v\left\{iD_\mu,\left[ivD,iD_\nu\right]\right\}(-i\sigma^{\mu\nu})b_v|B\rangle$$

- Γ_4: 9 parameters Mannel, Turczyk, Uraltsev, JHEP 1010 (2011) 109
- Γ_5: 18 parameters Mannel, Turczyk, Uraltsev, JHEP 1010 (2011) 109

Moments of the spectrum

BABAR, PRD 68 (2004) 111104; BABAR, PRD 81 (2010) 032003; Belle, PRD 75 (2007) 032005

Predictions cannot be compared directly with the experiment in all regions of phase space!

- Can only predict/describe integrated quantities over a integrated ranges $\rightarrow$ moments of the spectrum

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Charged lepton energy

$$\langle E^n \rangle_{\rm cut} = \frac{\int_{E_\ell > E_{\rm cut}} dE_\ell \, E_\ell^n \, \frac{d\Gamma}{dE_\ell}}{\int_{E_\ell > E_{\rm cut}} dE_\ell \, \frac{d\Gamma}{dE_\ell}}$$

Hadronic invariant mass

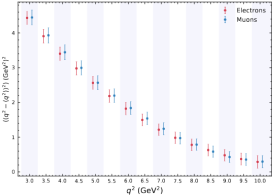
$$\left\langle (M_X^2)^n \right\rangle_{\rm cut} = \frac{\int_{E_\ell > E_{\rm cut}} dM_X^2 \, (M_X^2)^n \, \frac{d\Gamma}{dM_X^2}}{\int_{E_\ell > E_{\rm cut}} dM_X^2 \, \frac{d\Gamma}{dM_X^2}}$$

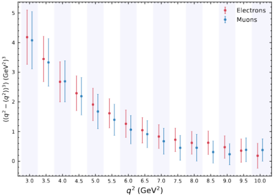
Dilepton momentum

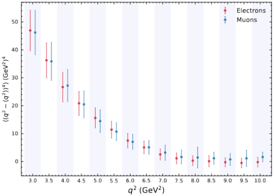
$$\left\langle (q^2) \right\rangle_{\rm cut} = \frac{\int_{q^2 > q^2_{\rm cut}} dq^2 (q^2)^n \, \frac{d\Gamma}{dq^2}}{\int_0 dq^2 \, \frac{d\Gamma}{dq^2}}$$

- Moments up to $n = 3, 4$ and with several energy cuts available
- Experimentally necessary to use lepton energy cut

Belle Collaboration [2109.01685, 2105.08001]



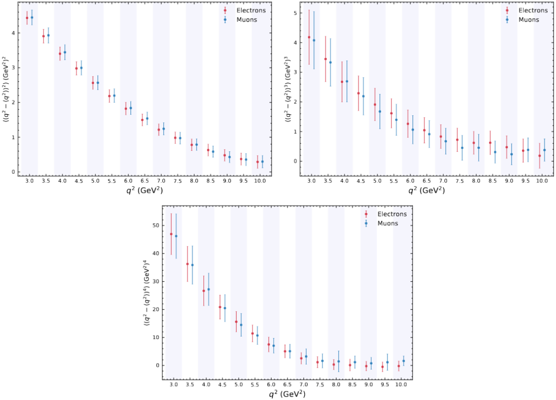




Centralized moments as function of q^2_{cut}

q^2 moments: Belle and Belle II

Belle Collaboration [2109.01685, 2105.08001]



First measurements of inclusive moments since 2009!

Determining V_{cb} and the HQE elements

$$\langle E_\ell^n \rangle, \langle (M_X^2)^n \rangle \qquad \langle (q^2)^n \rangle_{\rm cut}$$

$$\downarrow$$

$$m_b, m_c, \mu_\pi^2, \mu_G^2, \rho_D^3, r_E, r_G, s_E, s_B, s_{qB}, + \cdots$$

$$\downarrow$$

$$\mathrm{Br}(\bar{B} \to X_c \ell \bar{\nu}) \propto \frac{|V_{cb}|^2}{\tau_B} \left[\Gamma_{\mu_3} \mu_3 + \Gamma_{\mu_G} \frac{\mu_G^2}{m_b^2} + \Gamma_{\tilde{\rho}_D} \frac{\tilde{\rho}_D^3}{m_b^3} + \Gamma_{r_E} \frac{r_E^4}{m_b^4} + \Gamma_{r_G} \frac{r_G^4}{m_b^4} + \Gamma_{s_B} \frac{s_B^4}{m_b^4} + \Gamma_{s_E} \frac{s_E^4}{m_b^4} + \Gamma_{s_{qB}} \frac{s_{qB}^4}{m_b^4} \right]$$

$$\downarrow$$

$$V_{cb}$$

State-of-the-art in inclusive $b \to c$

Jezabek, Kuhn, NPB 314 (1989) 1; Melnikov, PLB 666 (2008) 336; Pak, Czarnecki, PRD 78 (2008) 114015; Becher, Boos, Lunghi, JHEP 0712 (2007) 062; Alberti, Gambino, Nandi, JHEP 1401 (2014) 147; Mannel, Pivovarov, Rosenthal, PLB 741 (2015) 290; Fael, Schonwald, Steinhauser, Phys Rev. D 104 (2021) 016003; Fael, Schonwald, Steinhauser, Phys Rev. Lett. 125 (2020) 052003; Fael, Schonwald, Steinhauser, Phys Rev. D 103 (2021) 014005,

$$\Gamma \propto |V_{cb}|^2 m_b^5 \left[\Gamma_0 + \Gamma_0^{(1)} \frac{\alpha_s}{\pi} + \Gamma_0^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \Gamma_0^{(3)} \left(\frac{\alpha_s}{\pi}\right)^3 + \frac{\mu_\pi^2}{m_b^2} \left(\Gamma^{(\pi,0)} + \frac{\alpha_s}{\pi}\Gamma^{(\pi,1)}\right)\right.$$
$$\left. + \frac{\mu_G^2}{m_b^2} \left(\Gamma^{(G,0)} + \frac{\alpha_s}{\pi}\Gamma^{(G,1)}\right) + \frac{\rho_D^3}{m_b^3} \left(\Gamma^{(D,0)} + \Gamma_0^{(1)} \left(\frac{\alpha_s}{\pi}\right)\right) + \mathcal{O}\left(\frac{1}{m_b^4}\right) + \cdots \right)$$

- Include terms up to $1/m_b^3$* see also Gambino, Healey, Turczyk [2016]
- α_s^3 to total rate and kinetic mass Fael, Schonwald, Steinhauser [2020, 2021]
- $\alpha_s \rho_D^3$ for total rate Mannel, Pivovarov [2020]

E_ℓ, M_X moments:

$$|V_{cb}|^{\rm BCG}_{\rm incl} = (42.16 \pm 0.51) \times 10^{-3}$$

q^2 moments*:

$$|V_{cb}|^{q^2}_{\rm incl} = (41.79 \pm 0.57) \times 10^{-3}$$

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First combined fit available Finauri, Gambino [2310.20324] + in progress [KKV, Bernlochner, Prim, Fael]

Gambino, Schwanda, PRD 89 (2014) 014022; Alberti, Gambino et al, PRL 114 (2015) 061802; Bordone, Capdevila, Gambino, Phys.Lett.B 822 (2021) 136679; Bernlochner, Welsch, Fael, Olschewsky, Persson, van Tonder, KKV [2205.10274]

Towards the ultimate precision in inclusive V_{cb}

$$\Gamma \propto |V_{cb}|^2 m_b^5 \left[\Gamma_0 + \Gamma_0^{(1)} \frac{\alpha_s}{\pi} + \Gamma_0^{(2)} \left(\frac{\alpha_s}{\pi}\right)^2 + \Gamma_0^{(3)} \left(\frac{\alpha_s}{\pi}\right)^3 + \frac{\mu_\pi^2}{m_b^2} \left(\Gamma^{(\pi,0)} + \frac{\alpha_s}{\pi}\Gamma^{(\pi,1)}\right)\right.$$
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Challenge:

- Include higher-order $1/m_b$ and α_s corrections
- Proliferation of non-perturbative matrix elements
  - 4 up to $1/m_b^3$
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Can we include higher order term and get even higher precision?!

The advantage of q^2 moments

Mannel, KKV, JHEP 1806 (2018) 115; Fael, Mannel, KKV, JHEP 02 (2019) 177

Reparametrization invariant quantities:

- Setting up the HQE: momentum of b quark: $p_b = m_b v + k$, expand in $k \sim iD$
- Choice of v not unique: Reparametrization invariance (RPI)

$$v_\mu \to v_\mu + \delta v_\mu$$

$$\delta_{RP}\ v_\mu = \delta v_\mu \ \text{ and } \ \delta_{RP}\ iD_\mu = -m_b \delta v_\mu$$

- links different orders in $1/m_b \to$ reduction of parameters
- up to $1/m_b^4$: 8 parameters (previous 13)

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== q^2 moments enable (?) a full extraction up to $1/m_b^4$ ==

q^2 moments only analysis

Bernlochner, Welsch, Fael, Olschewsky, Persson, van Tonder, KKV [2205.10274]

First q^2 moment analysis with $1/m_b^4$:

$$|V_{cb}|^{q^2}_{\mathrm{incl}} = (41.69 \pm 0.63) \times 10^{-3}$$

- Shifts V_{cb} minimally downwards
- Higher order coefficients important to check convergence of the HQE

$$r_E^4 = (0.02 \pm 0.34) \cdot 10^{-1}\mathrm{GeV}^4 \quad r_G^4 = (-0.21 \pm 0.69)\mathrm{GeV}^4$$

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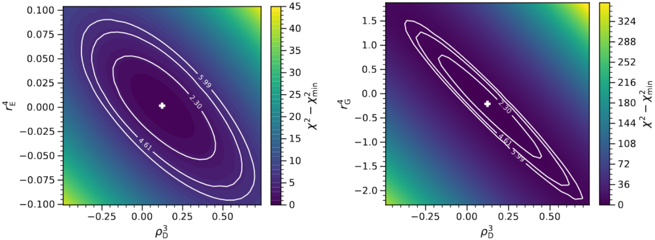

Exclusive V_{cb}

$B \to D$ and $B \to D^*$

- Form factors extracted from lattice, LC sumrules (+data)
- Knowledge on the q^2 dependence crucial
- BGL Boyd, Grinstein,Lebed or CLN/HQE Caprini, Lellouch, Neubert parametrization
  - Start of many discussions Gambino, Jung, Schacht, Bordone, van Dyck, Gubernari, ...
  - BGL: model independent parametrization using analyticity
  - CLN*: uses HQE at $1/m_b$ + assumptions *justified at time of introduction
- Recent combination: Bernlochner, Prim, Robinson, KKV [invited review]

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- Different lattice determinations seem to agree reasonably well..

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- New experimental and lattice data needed!

What about V_{ub}?

The challenge of V_{ub}

Exclusive $B \to \pi \ell \nu$

- Only one form factor, several lattice calculations: $|V_{ub}|_{\text{excl}} = (3.75 \pm 0.20) \times 10^{-3}$

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- Introduce non-perturbative shape functions ($\sim$ parton DAs in DIS)
- Moments of shape functions can be linked to HQE parameters in $b \to c$
- Different frameworks: BLNP, GGOU, DGE, ADFR

Aritmic average of all available measurements: [Bernlochner, Prim, Robinson, KKV [2402.xx]]

$$|V_{ub}|_{\rm incl} = (4.19 \pm 0.22) \cdot 10^{-3}$$

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$$|V_{ub}|_{\text{incl}} = (4.19 \pm 0.22) \cdot 10^{-3}$$

Puzzle! Update of the inclusive description necessary! Lange, Mannel, KKV [in progress]

Ratios of V_{cb} and V_{ub}: a B_s puzzle

Bolognani, van Dyk, KKV [2308.0437]
LHCb [2012.05143], Khodjamirian, Rusov [2017]

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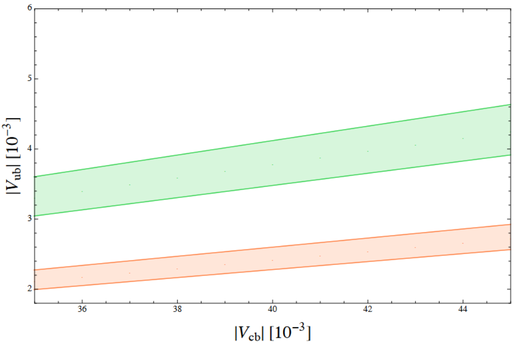


LHCb high q^2 ratio: FF_K determined with LQCD

LHCb low q^2 ratio: FF_K determined with LCSR

$$\left|\frac{V_{ub}}{V_{cb}}\right|_{\text{low } q^2} = 0.061 \pm 0.004$$

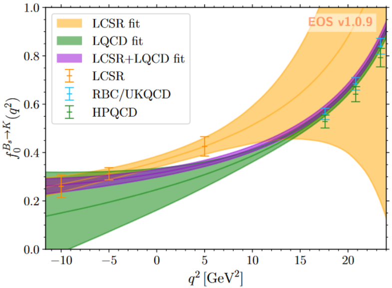
$$\left|\frac{V_{ub}}{V_{cb}}\right|_{\text{high } q^2} = 0.095 \pm 0.008$$

3.8σ

A puzzle in B_s decays?

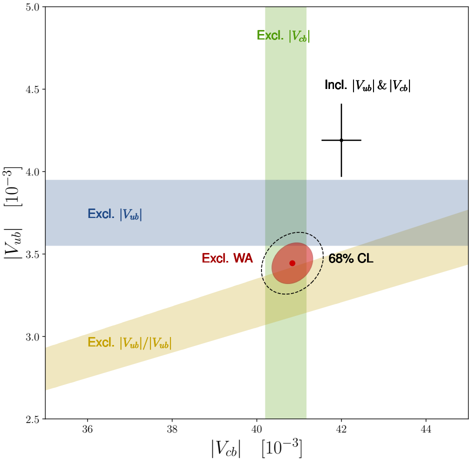
Bolognani, van Dyk, KKV [2308.0437]
LHCb [2012.05143], Khodjamirian, Rusov [2017]

- Recent update: New form factor predictions combining lattice and light-cone sumrule information
- Puzzle becomes less: 1.9σ difference



$$q^2 < 7\text{GeV}^2 \rightarrow \frac{|V_{ub}|}{|V_{cb}|} = 0.0681 \pm 0.004 \qquad q^2 > 7\text{GeV}^2 \rightarrow \frac{|V_{ub}|}{|V_{cb}|} = 0.0801 \pm 0.005$$

Inclusive versus Exclusive semileptonic decays



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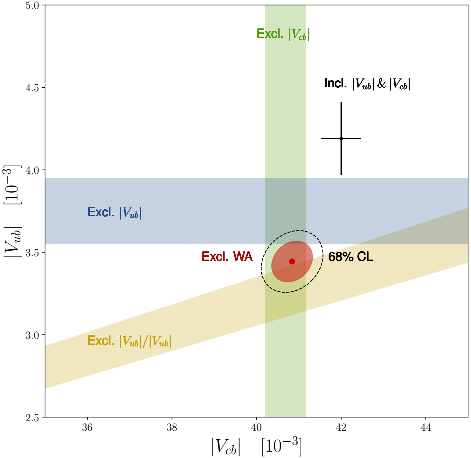
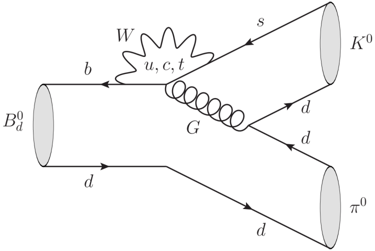


- Not very likely this is New Physics Jung, Straub [2018]
- New data on its way: stay tuned!

Puzzles in nonleptonic decays

The challenge of nonleptonic B decays

- Nonleptonic decays are important probes of CP violation
  - Direct CP violation due to different strong and weak phases
  - Mixing-induced CP violation in neutral decays probe mixing phase $\phi_{d,s}$
  - Sensitivity to NP in loops (penguins)



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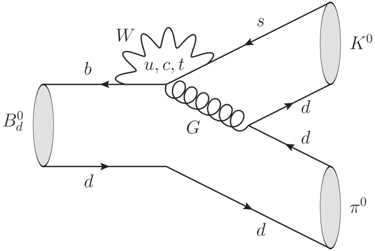
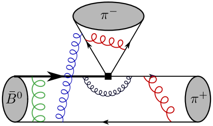


Challenge: Calculation of Hadronic matrix elements

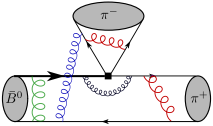
How to handle nonleptonic B decays?



QCD Factorization Beneke, Buchalla, Neubert, Sachrajda

- Disentangle perturbative (calculable) and non-perturbative dynamics using HQE
- Include QED corrections Beneke, Boer, Toelstede, KKV [2020]

How to handle nonleptonic B decays?



QCD Factorization Beneke, Buchalla, Neubert, Sachrajda

- Disentangle perturbative (calculable) and non-perturbative dynamics using HQE
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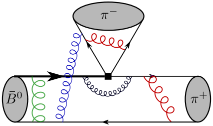

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Checking the consistency of the data extremely important!

$B \to \pi K$ puzzle

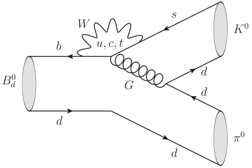
e.g. Buras, Fleischer, Recksiegel, Schwab. Jaeger, Pirjol, Zupan, Rosner, Datta, London

(Longstanding) Puzzling patterns in $B \to \pi K$ data

- Penguin dominated; Electroweak penguins contribute at same level as tree!

$$\delta(\pi K) \equiv A_{\rm CP}(\pi^0 K^-) - A_{\rm CP}(\pi^+ K^-)$$

- LHCb measurement LHCb Collaboration, PRL 126, 091802 [2021]
  - $\delta(\pi K)^{\rm exp} = (11.5 \pm 1.4)\%$
  - 8σ from 0



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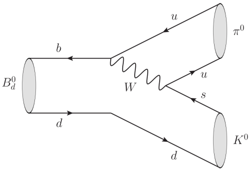

- Do we expect zero? No!
  - Color-suppressed tree contributes
  - $\delta(\pi K)^{\rm QCDF} = (2.1^{+2.8}_{-4.6})\%$ [Bell, Beneke, Huber, Li]
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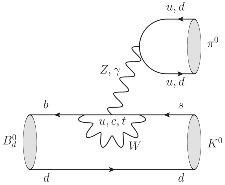

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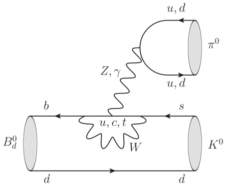

Need measurement of mixing-induced CP asymmetry to solve the puzzle!

New puzzles in B_s decays?

LHCb [2012.05319], Fleischer, Jaarsma, KKV, JHEP 02 (2023) 081 [2211.08346]

- First observation of CP violation in penguin dominated $B_s \to K^- K^+$ [LHCb]
    - Allows determination of γ and ϕ_s
    - Interesting to compare loops with tree!
- Updated measurements of CP asymmetries for other $B \to hh$ modes [LHCb]

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New Puzzle?

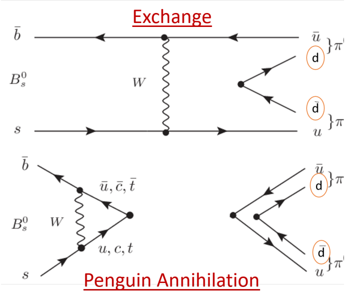
$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_s^0 \to K^- K^+) - \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d^0 \to \pi^- K^+) = 0.089 \pm 0.031$$
$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d^0 \to \pi^- \pi^+) - \mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_s^0 \to K^- \pi^+) = -0.095 \pm 0.040$$

- Modes only differ by their spectator quark!
- Can exchange and penguin annihilation contributions cause this?

Suppressed contributions?

LHCb [2012.05319], Fleischer, Jaarsma, KKV, JHEP 02 (2023) 081 [2211.08346]

- Exchange and Penguin Annihilation usually neglected
- Justified with current data?



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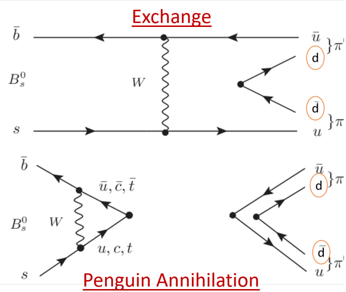

- The difference in the direct CP asymmetries can be accommodated by exchange and penguin annihilation effects at the level of (20–30)%.
- No anomalously enhanced rescattering effects

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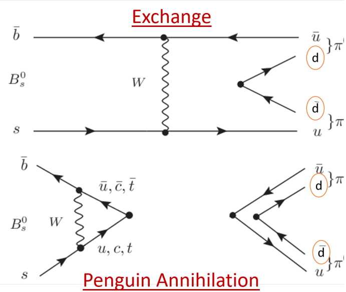

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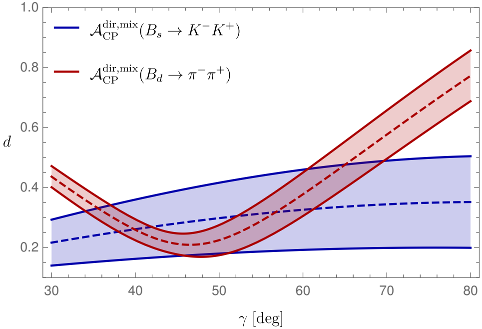
- CP asymmetries in the $B_s^0 \to \pi^-\pi^+$, $B_d^0 \to K^-K^+$ system would provide even more info!

Extracting γ from QCD penguin decays

CKM-angle γ from non-tree decays

Fleischer [1999,2007]; Fleischer, Knegjens [2011]; Fleischer, Malami, Jaarsma, KKV [2016]
Cuichini, Franco, Mishima, Silvestrini [2012], Data from LHCb [2022]Fleischer, Jaarsma, KKV [2211.08346]



- Step 1: Parametrize the decays in terms of tree and penguin + CKM factor γ
- Step 2: Assume U-spin symmetry (d-quark $\to$ s-quark)
- Step 3: CP asymmetries give link penguin parameter d and γ
- Drawback: Limited by U-spin breaking corrections

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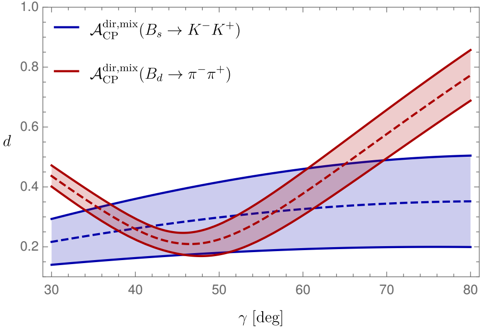

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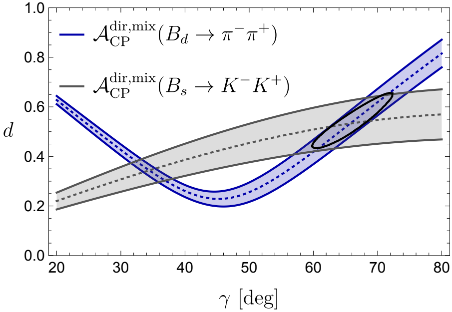

- New! First observation of CP violation in penguin dominated $B_s \to K^+K^-$ LHCb 2022
- New! First determination of γ with only CP asymmetries
- $\gamma = (65^{+7}_{-5})^\circ$ Fleischer, Jaarsma, KKV [2211.08346]
- Agrees with tree determinations: $\gamma = (64.9 \pm 4.5)^\circ$ LHCb [2021] without B_s modes

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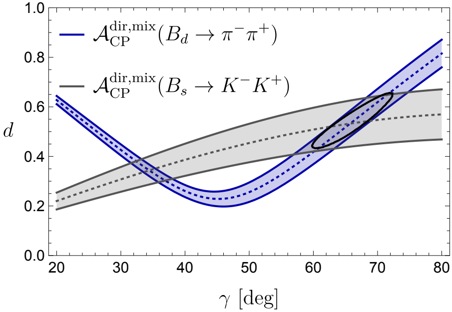

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Solving Beautiful Puzzles

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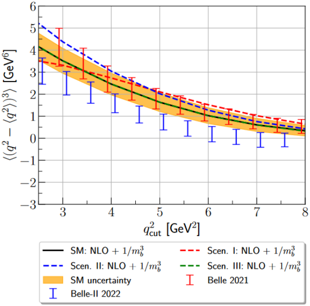
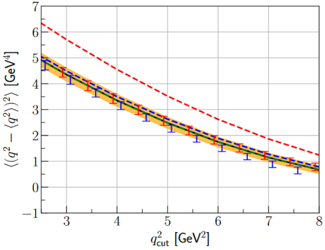
Backup

New Physics?

Fael, Rahimi, KKV [2208.04282]



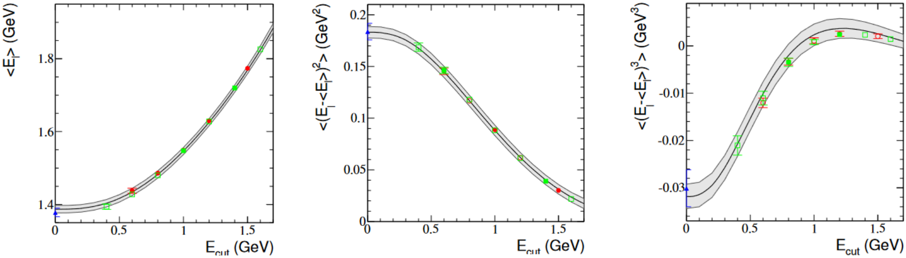


NP Scenarios	C_{V_L}	C_{V_R}	C_{S_R}	C_{S_L}	C_T
I	0	0	1	1	0
II	0	0	0	-1	0.5
III	-1	0.5	0	0	0

- NP would also influence the moments of the spectrum
- What's next? Requires a simultaneous fit of hadronic parameters and NP

Moments of the spectrum

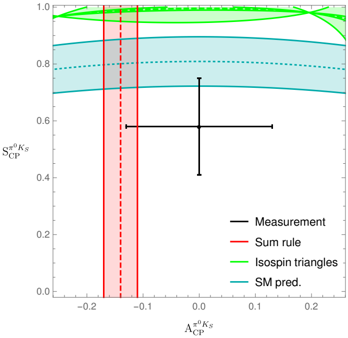
Gambino, Schwanda Phys. Rev. D 89, 014022 (2014)



Isospin Amplitude Triangles

Nir, Quin [1991]; Gronau, Hernandez, London, Rosner [1995]

Fleischer, Jaeger, Pirjol, Zupan [2008]; Fleischer, Jaarsma, KKV [2018]



Mixing-induced CP asymmetry provides new information!

Determination of ϕ_s (I)

Strategy I:

Fleischer, Jaarsma, KKV, JHEP 02 (2023) 081 [2211.08346] (and [1612.07342])

- Use semileptonic decays

$$R_\pi \equiv \frac{\Gamma(B_d^0 \to \pi^-\pi^+)}{|d\Gamma(B_d^0 \to \pi^-\ell^+\nu_\ell)/dq^2|_{q^2=m_\pi^2}} \qquad R_K \equiv \frac{\Gamma(B_s^0 \to K^-K^+)_{\text{theo}}}{|d\Gamma(B_s^0 \to K^-\ell\nu_\ell/dq^2|_{q^2=m_K^2}}$$

- Gives access to hadronic parameters $r_K = (1 + \left(\frac{d'}{\epsilon}\right)^2 + 2d'/\epsilon \cos\theta' \cos\gamma)$
- Use ratios to get favorable structure!

$$r_K = \frac{R_K}{R_\pi}\left(\frac{|V_{ud}|f_\pi}{|V_{us}|f_K}\right)^2 \frac{X_\pi}{X_K}\left(\xi^a_{\text{NF}}\right)^2 r_\pi$$

- $X_{\pi,K}$ ratio of form factor $\to$ input

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- Non-factorisable U-spin-breaking contributions:

$$\xi_{\rm NF}^a \equiv \left|\frac{1+r_P}{1+r'_P}\right|\left|\frac{1+x}{1+x'}\right|\left|\frac{a_{\rm NF}^T}{a_{\rm NF}^{T'}}\right|,$$

- $a_{\rm NF}^T$ tree-level contribution from QCDF

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- $a^T_{\rm NF}$ tree-level contribution from QCDF
- $\xi^a_{\rm NF} = 1.00 \pm 0.07 \to 0.8^\circ$ theoretical uncertainty on $\Delta\phi_{KK}$

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- Experimental input not available!
- Theoretical control over penguin effects excellent!
- $\xi^a_{\rm NF} = 1.00 \pm 0.07$ $\to$ 0.8° theoretical uncertainty on $\Delta\phi_{KK}$

Determination of ϕ_s (II)

Fleischer, Jaarsma, KKV, JHEP 02 (2023) 081 [2211.08346]

Strategy II:

- Use ratio of branching ratios of $B_d \to \pi\pi$ and $B_s \to KK$ decays

$$K \equiv \frac{1}{\epsilon}\left[\frac{m_{B_s}}{m_{B_d}}\frac{\Phi(m_\pi/m_{B_d}, m_\pi/m_{B_d})}{\Phi(m_K/m_{B_s}, m_K/m_{B_s})}\frac{\tau_{B_d}}{\tau_{B_s}}\right]\frac{\mathcal{B}(B_s^0 \to K^- K^+)_{\rm theo}}{\mathcal{B}(B_d^0 \to \pi^-\pi^+)} = 105.3 \pm 9.6$$

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$$\left|\frac{\mathcal{C}}{\mathcal{C}'}\right| = \frac{f_\pi}{f_K}\left[\frac{m_{B_d}^2 - m_\pi^2}{m_{B_s}^2 - m_K^2}\right]\left[\frac{F_0^{B_d\pi}(m_\pi^2)}{F_0^{B_sK}(m_K^2)}\right]\xi_{\rm NF}^a$$

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- Use form factor information: 10% uncertainty
- $\Delta\phi_{KK} = -(4.5 \pm 5.3)^\circ$
- With $\phi_s^{\mathrm{eff}} = -(8.1 \pm 1.9)^\circ \to \phi_s = -(3.6 \pm 5.7)^\circ$

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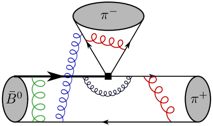
Remarkable agreement with $B^0_s \to J/\psi\phi$ determination: $\phi_s = -(4.2 \pm 1.4)^\circ$

How to handle nonleptonic B decays?



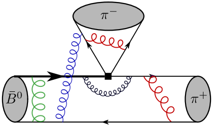
QCD Factorization
Beneke, Buchalla, Neubert, Sachrajda

- Disentangle perturbative (calculable) and non-perturbative dynamics using HQE
- Systematic expansion in α_s and $1/m_b$ (studied up to α_s^2) Bell, Beneke, Huber, Li

$$\langle \pi^+\pi^-|\mathcal{Q}_i|B\rangle = T_i^I \otimes F^{B\to\pi^+} \otimes \Phi_{\pi^-} + T_i^{II} \otimes \Phi_{\pi^-} \otimes \Phi_{\pi^+} \otimes \Phi_B$$

- Non-perturbative form factors and LCDAs
  - from data, lattice or Light-Cone Sum Rules
- No systematic framework to compute power corrections (yet?)
- Strong phases suffer from large uncertainties
- Theoretical challenge: reliable computations of observables
- Include QED corrections Beneke, Boer, Toelstede, KKV [2020]

How to handle nonleptonic B decays?



QCD Factorization Beneke, Buchalla, Neubert, Sachrajda

- Disentangle perturbative (calculable) and non-perturbative dynamics using HQE
- Include QED corrections Beneke, Boer, Toelstede, KKV [2020]

Flavour symmetries (Isospin or $SU(3)$)

- Many studies e.g. Fleischer, Jaarsma, KKV, Malami [2017,2018]
- Global $SU(3)$ fit to $B \to PP$ decays Huber, Tetlalmatzi-Xolocotzi [2111.06418]

The V_{cb} puzzle: Inclusive versus Exclusive decays

Exclusive $B \to D^{(*)}\ell\bar{\nu}$

- Form factor required (only for $B \to D$ available at different kinematic points)
- Different parametrizations for form factors: CLN Caprini, Lellouch, Neubert [1997] and BGL Boyd, Grinstein, Lebed [1995]
  - BGL: model independent based on unitarity and analyticity
  - CLN: Simple parametrization using HQE relations
- Some inconsistencies in the Belle data were pointed out see e.g. van Dyk, Jung, Bordone, Gubernari [2104.02094]

Inclusive $B \to X_c\ell\nu$

- Determined fully data driven including $1/m_b$ power corrections

Recently a lot of attention for the V_{cb} puzzle! Bigi, Schacht, Gambino, Jung, Straub, Bernlochner, Bordone, van Dyk, Gubernari

Stay tuned!

BLNP update - in progress -

Bosch, Lange, Neubert, Paz [2005]
Greub, Neubert, Pecjak [0909.1609]; Beneke, Huber, Li [0810.1230]; Becher, Neubert [2005]

Update of BLNP approach

- Systematic framework: Soft Collinear Effective Theory (SCET)
- Separates the different scales in the problem
- In progress: include known α_s^2 corrections
- Moments of shape functions can be linked to HQE parameters in $b \to c$
  - In progress: include higher-moments
  - kinetic mass scheme as in $b \to c$
- Shape function is non-perturbative and cannot be computed
  - In progress: new flexible parametrization

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In progress:

Gunawardana, Lange, Mannel, Paz, Olschewsky, KKV [in progress]

$|V_{ub}|_{\text{incl}} =$ Stay Tuned!

Shape functions

Bigi, Shifman, Uraltsev, Luke, Neubert, Mannel, $\cdots$

- Leading order shape functions

$$2m_B f(\omega) = \langle B(v)|\bar{b}_v \delta(\omega + i(n \cdot D)) b_v |B(v)\rangle$$

- Charged Lepton Energy Spectrum (at leading order)

$$\frac{d\Gamma}{dy} \sim \int d\omega \theta(m_b(1-y) - \omega) f(\omega)$$

- Moments of the shapefunction are related to HQE ($b \to c$) parameters:

$$f(\omega) = \delta(\omega) + \frac{\mu_\pi^2}{6m_b^2}\delta''(\omega) - \frac{\rho_D^3}{m_b^3}\delta'''(\omega) + \cdots$$

- Shape function is non-perturbative and cannot be computed

Shape functions

Lange, Neubert, Bosch, Paz

- Systematic framework: Soft Collinear Effective Theory (SCET)
- Separates the different scales in the problem

$$d\Gamma = H \otimes J \otimes S$$

  → H: Hard scattering kernel at $\mathcal{O}(m_b)$
  → J: universal Jet function at $\mathcal{O}(\sqrt{m_b \Lambda_{\rm QCD}})$
  → S: Shape function at $\mathcal{O}(\Lambda_{\rm QCD})$
- Framework to include radiative corrections (+ NNLL resummation)
- Introduces 3 subleading shape functions

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- Other approach: OPE with hard-cutoff μ Gambino, Giordano, Ossola, Uraltsev
  - Use pert. theory above cutoff and parametrize the infrared
  - Different definition of the shape functions
- Shape functions have to be parametrized and obtained from data

Flavor symmetries in $B_s^0 \to K^-K^+$ and $B_d \to \pi^-\pi^+$

Fleischer [1999, 2007]; Fleischer, Knegjens [2011]

$$A(B_s \to K^+K^-) = \sqrt{\epsilon} e^{i\gamma} \mathcal{C}' \left[1 + \frac{1}{\epsilon} d' e^{i\theta'} e^{-i\gamma}\right]$$

$$A(B_d \to \pi^+\pi^-) = e^{i\gamma} \mathcal{C} \left[1 - d e^{i\theta} e^{-i\gamma}\right]$$

$$\mathcal{C}' \propto T' + P^{(ut)\prime} + E' + PA^{(ut)\prime} \text{ and } d' e^{i\theta'} \propto \frac{P^{(ct)\prime} + PA^{(ct)\prime}}{T' + P^{(ut)\prime} + E' + PA^{(ut)\prime}}$$

- d and θ penguin parameters [$\epsilon \sim 0.04$]
- Extract hadronic parameters from direct and mixing-induced CP asymmetries

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U-spin symmetry

$$d e^{i\theta} = d' e^{i\theta'}$$

- Or assume $d = d'$ and extract γ
- Limited by U-spin breaking corrections

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- Extract hadronic parameters from direct and mixing-induced CP asymmetries

- Even cleaner extraction of mixing-phase ϕ_s possible Fleischer, Jaarsma, KKV [2211.08346]

New Physics explanation?

- Too many to count: exclusive $B \to D^{(*)}$ in combination with

$$R_{D^{(*)}} = \frac{B \to D^{(*)} \tau\nu}{B \to D^{(*)} \mu\nu}$$

- For inclusive $b \to c$ less analyses
  - RH-current, scalar and tensor NP contributions to rate Jung, Straub [2018]
  - RH-current to moments Feger, Mannel, et. al. [2010]
  - NP for moments KKV, Fael, Rahimi [in progress]