Flavour Physics in 2019

Fundamentals, Challenges, and Opportunities

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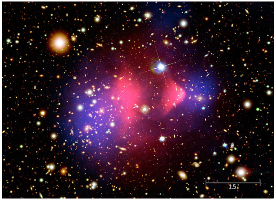
Fundamentals

Flavour at the Heart of Particle Physics?

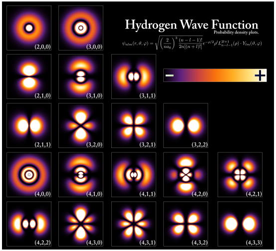
Our job as particle physicists is to determine:

- what are the elementary building blocks of the universe?
- what are the fundamental interactions between them?

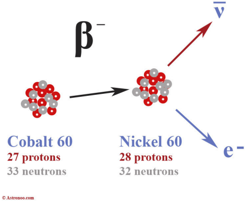
The goal is a uniform description of the building blocks and interactions, which can describe phenomena on very different length and time scales.



$10^{+22}\ m$



$10^{-10}\ m$



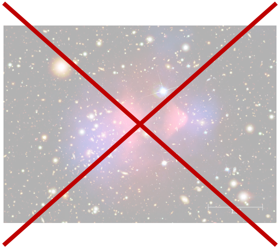
$10^{-19}\ m$

Flavour at the Heart of Particle Physics?

Our job as particle physicists is to determine:

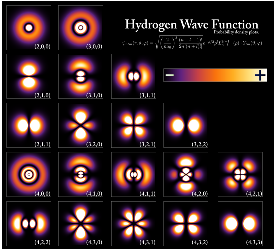
- what are the elementary building blocks of the universe?
- what are the fundamental interactions between them?

To date our best theory is the **Standard Model (SM) of particle physics**.



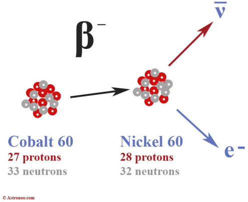
$10^{+22}\ m$

QED

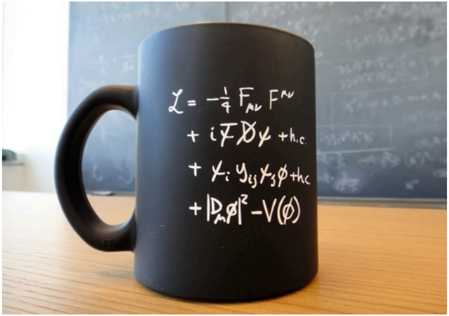


$10^{-10}\ m$

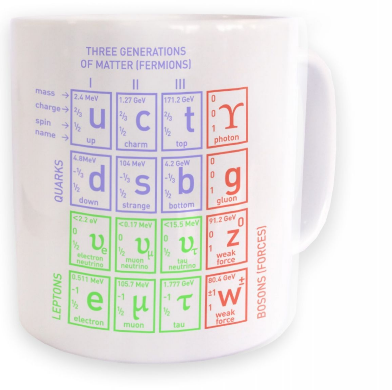
QCD,
weak interaction



$10^{-19}\ m$



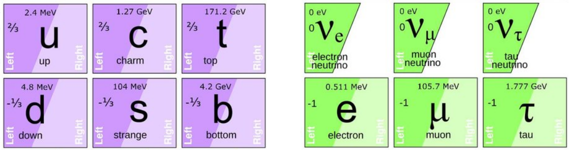
[CERN]



[somethinggeeky.com]

The Standard Model (Flavour Edition)

- matter fields are described in the SM in 3 generations
- the gauge interactions treat the generations universally
- the Higgs field does not!



$$-\mathcal{L} \supset H\,\bar{Q}\,Y_d\,d + H^c\,\bar{Q}\,Y_u\,u + H\,\bar{L}\,Y_e\,e + \text{h.c.}$$

symmetry between and within generations broken by the Yukawa terms

- we can observe quark masses as eigenvalues of $v/\sqrt{2}\,Y_{u,d}$
- we can observe misalignment between u-type and d-type quark fields through changes in the quark family (horizontal jumps)

The misalignment implies that “flavour”
cannot be a conserved quantum number.

Quark Mixing Matrix

The quark Yukawa matrices can be simultaneously diagonalized through bi-unitary transformations

$$\mathrm{diag}(m_u, m_c, m_t) = v/\sqrt{2}\, L_u\, Y_u\, R_u^\dagger$$
$$\mathrm{diag}(m_d, m_s, m_b) = v/\sqrt{2}\, L_d\, Y_d\, R_d^\dagger$$

L_u, L_d unitary matrices applied to the left-handed fields
R_u, R_d unitary matrices applied to the right-handed fields

Generally: misalignment between L_u and L_d

- mass terms can be diagonalized simultaneously
- charged-current terms will be non-diagonal, misaligned by

$$(V_{\text{CKM}})_{ij} = \left(L_u \cdot L_d^\dagger\right)_{ij}$$

the Cabbibo-Kobayashi-Maskawa (CKM) matrix.

Parametrization of the CKM Matrix (1)

the CKM matrix

- is a 3×3 complex-valued unitary matrix
- is unitary by construction (since $L_{u,d}$ are unitary)

as a quark mixing matrix

- can be redefined such that 5 relative phases are absorbed into the quark field definitions
- has one one global (unobservable) phase

quark mixing in the SM

- can be therefore described in terms of only 4 parameters: 3 angles and 1 complex phase [Kobayashi, Maskawa 1973]

$$\begin{pmatrix} V_{ud}: 1-\frac{\lambda^2}{2} & V_{us}: \lambda & V_{ub}: A\lambda^3(\rho - i\eta) \\ V_{cd}: -\lambda & V_{cs}: 1-\frac{\lambda^2}{2} & V_{cb}: A\lambda^2 \\ V_{td}: A\lambda^3(1-\rho-i\eta) & V_{ts}: -A\lambda^2 & V_{tb}: 1 \end{pmatrix}$$

expansion in $\lambda \simeq 0.2$ up to $\mathcal{O}\left(\lambda^3\right)$

How much information do we require to describe the SM?

gauge sector

- QED gauge coupling $\alpha_e(m_\mu)$,
- weak mixing angle via M_W/M_Z
- QCD gauge coupling $\alpha_s(m_Z)$ 3

Higgs sector

- Higgs vaccum expectation value v
- Higgs quartic coupling λ_4 2

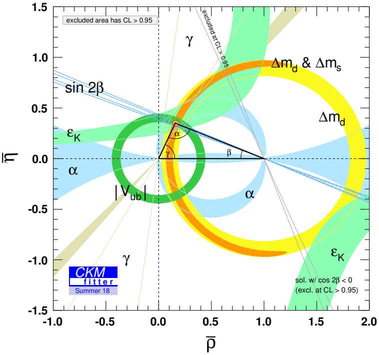
flavour sector

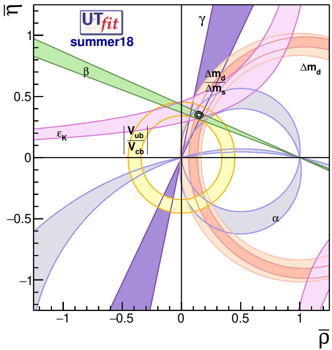
- charged lepton masses m_ℓ 3
- quark masses m_q 6
- CKM parameters λ, A, ρ, η 4

13 / 18 parameters are describing flavour in the SM

only four CKM parameters enter all flavour changing processes

- overconstrain the parameters in a global fit and check:
  - is the CKM matrix unitary?
  - is the CKM matrix the only source of CP violation?





[CKMfitter '18]

[UTfit '18]

CKM Metrology

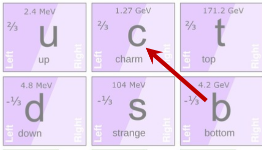
only four CKM parameters enter all flavour changing processes

- overconstrain the parameters in a global fit and check:
  - is the CKM matrix unitary?
  - is the CKM matrix the only source of CP violation?

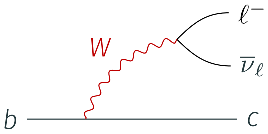
obtain constraints from ...

- tree-level (semi)leptonic decays $c \to sW^* (\to \ell^+ \nu)$
- loop-level neutral-current decays $b \to s\,\{\ell^+\ell^-, \gamma\}$
- tree-level hadronic decays $b \to cW^* (\to s\bar{u})$
- loop-level meson-mixing $(\bar{b}d) \leftrightarrow (\bar{d}b)$

Semileptonic b Decays

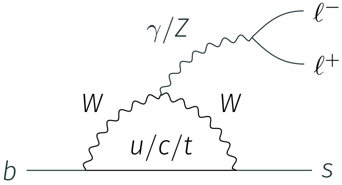


- w/ change of el. charge



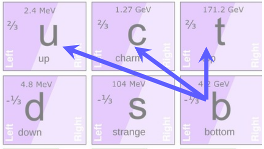
tree level contributions

- w/o change of el. charge

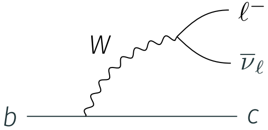


only arises at loop level

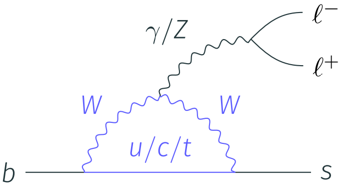
Semileptonic b Decays



- w/ change of el. charge
- w/o change of el. charge



tree level contributions



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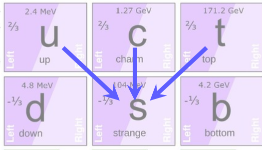
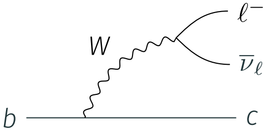
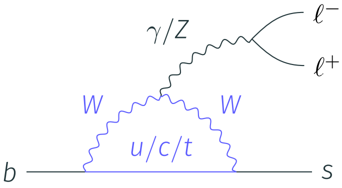


- w/ change of el. charge



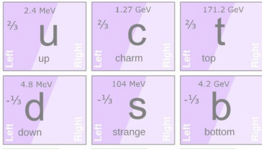
tree level contributions

- w/o change of el. charge

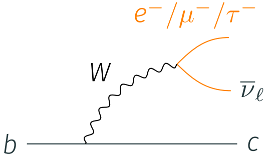


only arises at loop level

Semileptonic b Decays

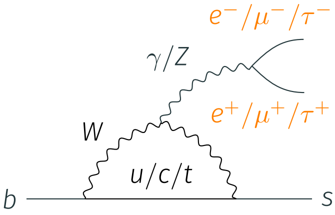


- w/ change of el. charge



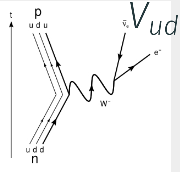
tree level contributions

- w/o change of el. charge



only arises at loop level

in both cases: **lepton-flavour-universal gauge couplings**!

V_{ud} 	V_{us}	V_{ub}
V_{cd}	V_{cs}	V_{cb}
V_{td} ×	V_{ts} ×	V_{tb}

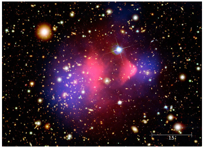
marked with ×: there are no direct measurements of s.l. decays available

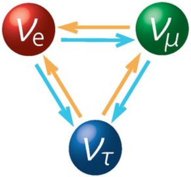
So what is Flavour Physics then?

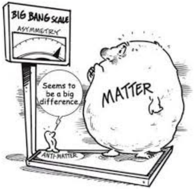
Flavour physics is ...

- ...determining the (flavour-related) majority of SM parameters with the best possible precision
- ...testing the assumptions inherent to the SM, e.g.:
  - the CKM matrix is the only source of flavour change
  - the CKM matrix is the only source of CP violation
  - there are exactly three generations of matter fields
- ...probing indirecly for New Physics by quantifiying the deviations between SM predictions and measurements

since we know New Physics must hide somewhere







Challenges

Why "Anomalies"?

Theory predictions of B-meson decays have been and continue to be tested through several experiments

BaBar at the Stanford Linear Accelerator Center, USA
e^+e^- collisions — stopped in 2008

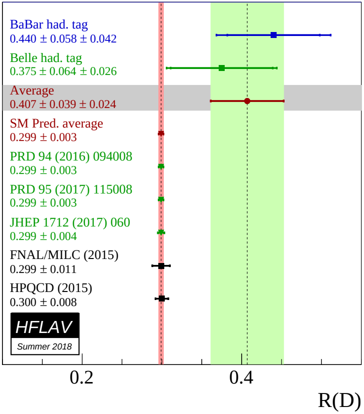
Belle (II) at KEK in Tsukuba, Japan
e^+e^- collisions — Belle data taking stopped in 2010
Belle II data taking (really) from 2019

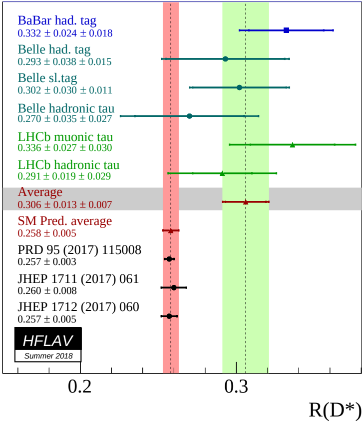
ATLAS,CMS,LHCb at the Large Hadron Collider, CERN
pp collisions — LHC "run 2" ended in 2018
LHC "run 3" planned for 2021
⋮ ⋮ ⋮
LHC "run 5" planned until 2035

Anomalies are those measurements that deviate from the SM theory predictions by more than 2 but less than 5 standard deviations.

Tests of Lepton-Flavour-Universality in $b \to c\ell\bar{\nu}$ [HFLAV Sommer 2018]

$$\frac{b \to c\tau\bar{\nu}}{b \to c\mu\bar{\nu}} \quad \to \quad R(X) \equiv \frac{\Gamma\left(\bar{B} \to X\tau\bar{\nu}\right)}{\Gamma\left(\bar{B} \to X\mu\bar{\nu}\right)} \qquad X = D, D^*$$





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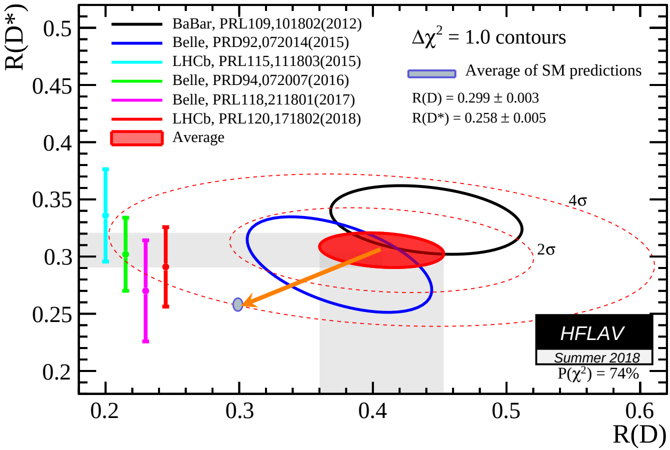
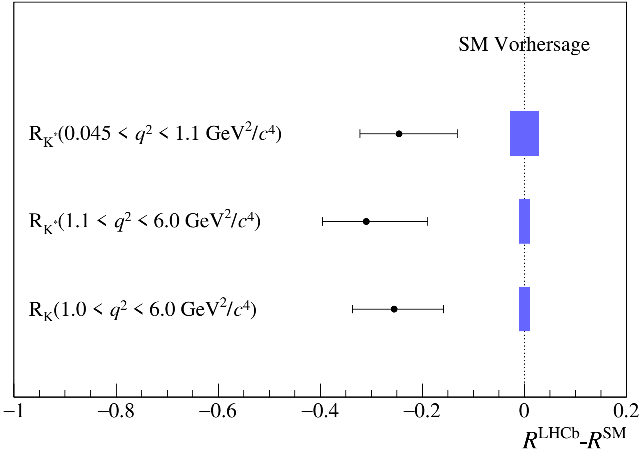


- combined significance: 3.62σ or 1 : 6370

Anomalies in Plots (2)

Tests of Lepton-Flavour-Universalität ($R(X)$), and decay rates, and angular distributions (P_5') in $b \to s\ell^+\ell^-$

[Albrecht,Langenbruch Physik-Journal 2018]



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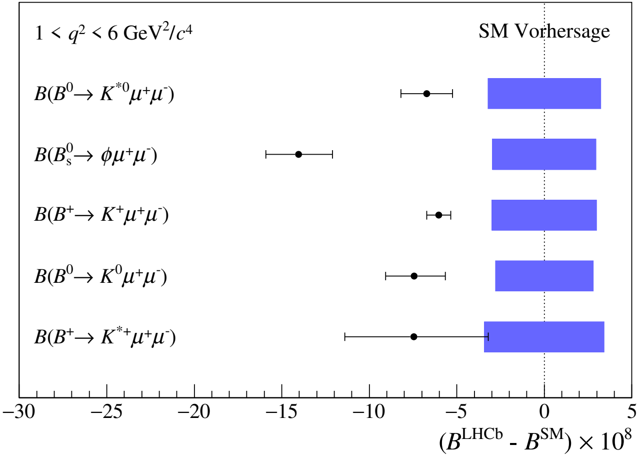

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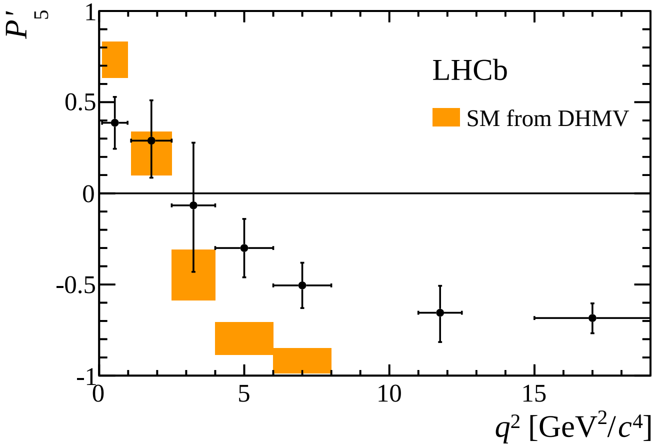
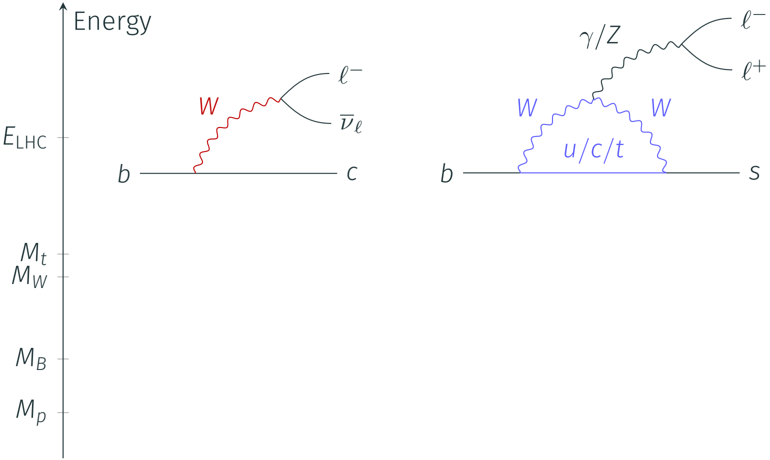


- combined significance? $\to$ need weak effective theory (WET)

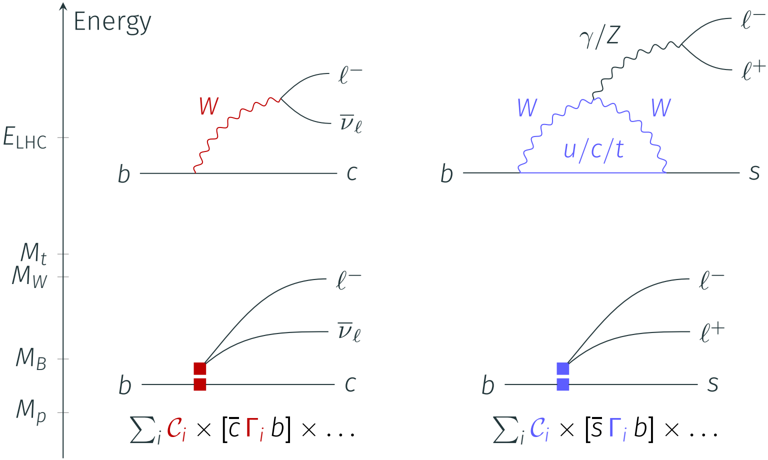
Effective (Quantum) Field Theories

- widely used tool of theoretical physics



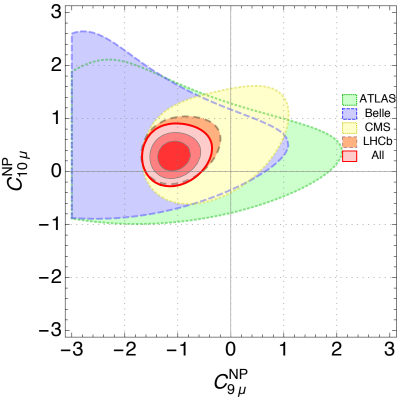
Effective (Quantum) Field Theories

- widely used tool of theoretical physics
- replaces dynamical degrees of freedom (here: t, W, Z) by coefficients $\mathcal{C}_i$ and static structures in local operators (here: Γ_i)



- coefficients $\mathcal{C}$ (over-)constrained through data
- w/o details: 2 coefficients $\mathcal{C}_{9,10}$ numerically dominant
- strong tension between best-fit point and SM prediction

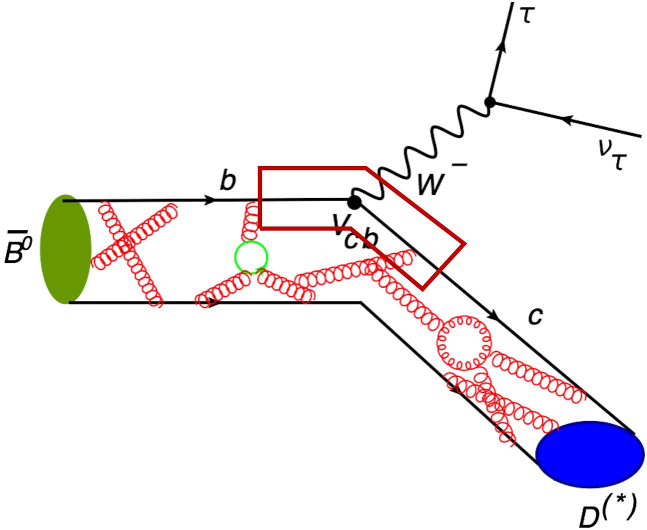
[e.g. Descotes-Genon, Hofer, Matias, Virto 2015]



$$\mathcal{C}_{9,10}^{\text{NP}} \equiv \mathcal{C}_{9,10} - \mathcal{C}_{9,10}^{\text{SM}}$$

- consistent picture across all observ.:
  - decay rates
  - angular distributions
  - LFU ratios
- significance $\sim 5\sigma$ *****
  - no single 5σ measurement!
  - ** form factors
  - *** non-local matrix elements
- tasks
  - E 5σ measurement! (z.B.: R_K)
  - T remove ***** caveats!

Matrix elements of local operators $\bar{c}\,\Gamma b$ (and $\bar{s}\,\Gamma b$) parametrised through form factors



[Wu 2015]

Hadronic Matrix Elements: Form Factors (1)

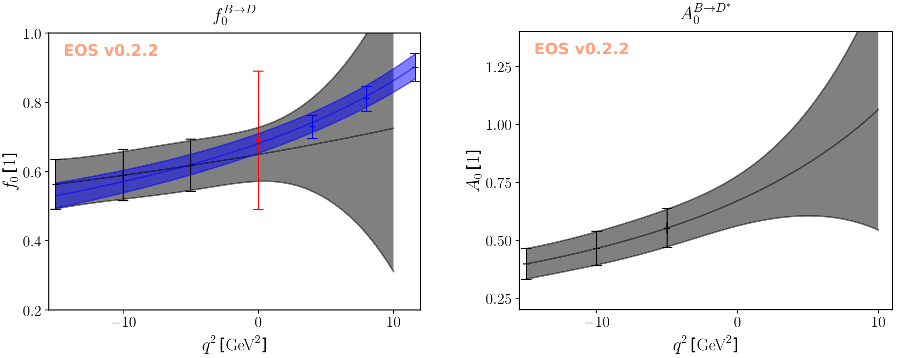
Matrix elements of local operators $\bar{c}\,\Gamma b$ (and $\bar{s}\,\Gamma b$) parametrised through form factors

- functions of momentum transfer (typical notation: q^2)
- 3 independent functions in e.g. $B \to D$ or $B \to K$
- 7 independent funktions in e.g. $B \to D^*$ or $B \to K^*$
- low-energy QCD effects complicate direct calculation; requires numerical simulation (lattice QCD)

alternative: determination through light-cone sum rules with B-meson wave functions

- relatively recent method [Khodjamirian et al 2005,2006,2008] [Feldmann et al. 2008]
- complementary to lattice QCD results
- recent simultaneous analysis of all form factors in $B \to P$ and $B \to V$ transitions, expanding on previous works [Gubernari,Kokulu,DvD 2018]

Hadronic Matrix Elements: Form Factors



[Gubernari,Kokulu,DvD 2018]

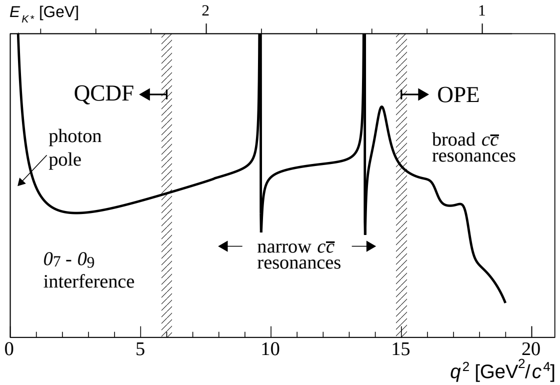
- allows R_D und R_{D^*} predictions independent of $\bar{B} \to D^{(*)}\mu\bar{\nu}$ data
- compatible with $B \to D$ Lattice predictions
- must still be tested in framework of "heavy quark expansion"

[Bordone,Jung,DvD w.i.p.]

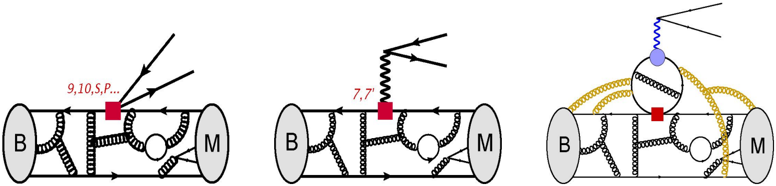
- of relevance indep. of anamolies, since permits precision determinations of SM parameters (i.e.: $|V_{cb}|$, $|V_{ub}|$)

Hadronic Matrix Elements: Non-Local Effects (1)

$B \to K^* \mu^+ \mu^-$ landscape:



[sketch from Blake, Gershon, Hiller 2015]



$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ (C_9 \mp C_{10}) \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[C_7 \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

- non-local: $\mathcal{H}_\lambda(q^2) = i\,\mathcal{P}_\mu^\lambda \int d^4x\, e^{iq\cdot x} \, \langle \bar{M}_\lambda(k) | \, T\{ \mathcal{J}_{\text{em}}^\mu(x), \mathcal{C}_i \mathcal{O}_i(0) \} \, | \bar{B}(q+k) \rangle$

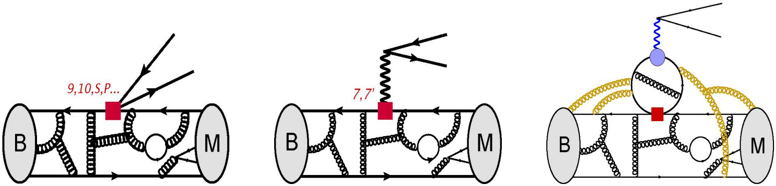
below J/ψ: light-cone OPE [Khodjamirian, Mannel, Pivovarov, Wang 2010]

- leading (local) terms as in QCD factorisation [Beneke, Feldmann, Seidel 2001&2004]
- next-to-leading terms from light-cone sum rules [Khodjamirian, Mannel, Pivovarov, Wang 2010]

above the $\psi(2S)$: local OPE in $1/m_b$ and $1/\sqrt{q^2}$; $q^2 = m^2(\mu\mu)$

- OPE in HQET operators [Grinstein, Pirjol 2004]
- OPE in QCD operators [Beylich, Buchalla, Feldmann 2011]

Hadronic Matrix Elements: Non-Local Effects (2)



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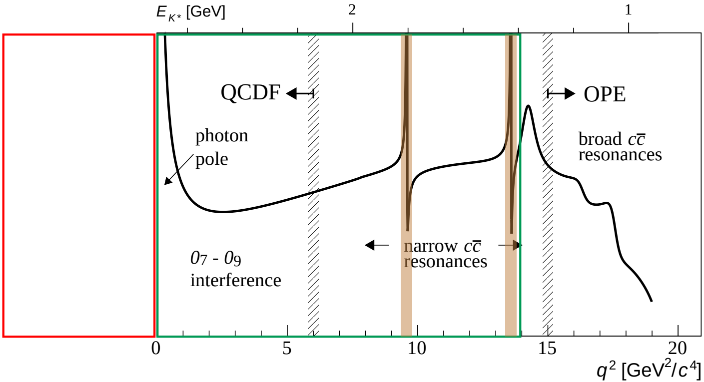
- OPE in QCD operators [Beylich, Buchalla, Feldmann 2011]

Strategy



[sketch from Blake, Gershon, Hiller 2015]

- calculate non-local matrix elements at $q^2 < 0$
- extrapolate to $q^2 > 0$ via some type of analytic continuation
- constrain two narrow resonances at $q^2 > 0$ from data on $B \to \psi_n K^*$

Non-local Effects in $B \to K^* \mu^+ \mu^-$

- new idea to parametrize non-local effects based on analyticity properties

[Bobeth, Chrzaszcz, van Dyk, Virto 2017]

- includes theory predictions and experimental data simultaneously

some details for actual parametrisation

- parametrize the ratios $\mathcal{H}_\lambda(q^2)/\mathcal{F}_\lambda(q^2)$
- poles for subthreshold resonances J/ψ, $\psi(2S)$
- rest: power series in parameter z, which has correct analyticity properties
- the poles should not modify the asymptotic behaviour at $|q^2| \to \infty$

$$\mathcal{H}_\lambda(z) = \frac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \hat{\mathcal{H}}_\lambda(z)$$

$$\hat{\mathcal{H}}_\lambda(z) = \left[\sum_{k=0}^{K} \alpha_k^{(\lambda)} z^k\right] \mathcal{F}_\lambda(z)$$

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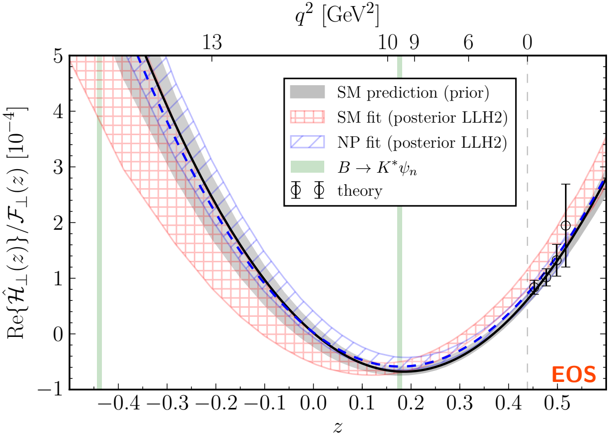

- parametrisation does not provide enough freedom in the SM fit in order to deviate substantially from the prior

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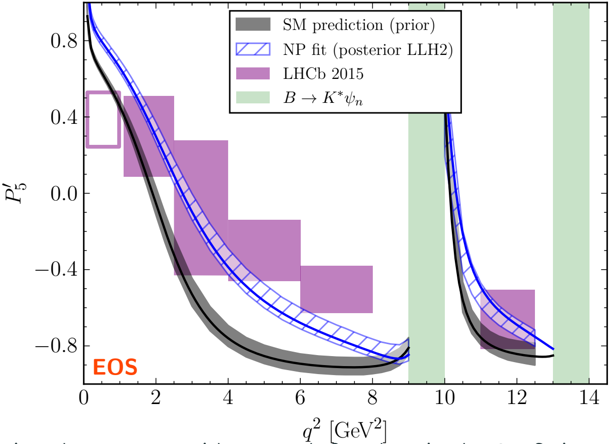
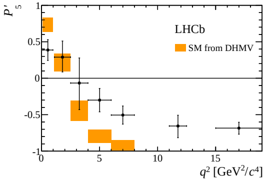


- parametrisation does not provide enough freedom in the SM fit in order to deviate substantially from the prior

So ...?

So is this New Physics then?



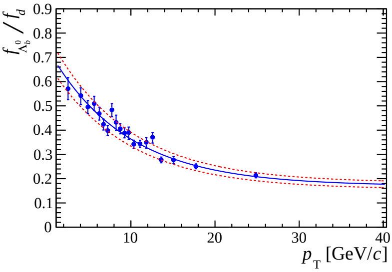
Jury's still out!

- no single 5σ deviation
- so far no theorist confident enough about old physics to claim a New Physics discovery!
- challenging situation indeed!

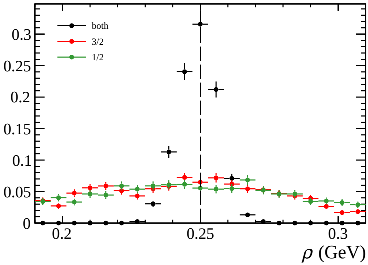
Opportunities

Opportunity: The LHC as a Λ_b^0 Factory

(bdu) with $J^P = 1/2^+$ and $I = 0$



[LHCb 1405.6842]



[Böer et al 2018]

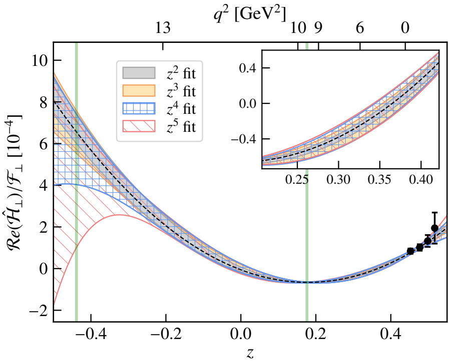
- no anomalies (yet?) with b baryons
- independent “laboratory” to check theory
- QCD factorisation harder to prove than for B mesons [e.g. Feldman,Yip 2011]
- heavy-quark expansion seems to work much better than for mesons

[$\Lambda_b \to \Lambda_c$: Bernlochner,Ligeti,Robinson,Sutcliffe 2018]
[$\Lambda_b \to \Lambda_c^*$: Böer,Bordone,Graverini,Owen,Rotondo,DvD 2018]

Opportunity: Future Combined Analyses (Theory + Experiment)

Sensitivity to non-local parameters in $B \to K^* \mu^+ \mu^-$ from an unbinned fit

[Chrzaszcz, Mauri, Serra, Silva Coutinho, van Dyk 2018]



- cover various benchmark points for the non-local matrix elements
  - includes approached with polynomials up to order z^5
  - uses central theory inputs from pheno analysis

[Bobeth, Chrzaszcz, van Dyk, Virto 2017]

- find sensitivity to z^3 and higher coefficients
- constrain non-local matrix elements well for region $1.1\,\text{GeV}^2 \leq q^2 \leq 9\,\text{GeV}^2$

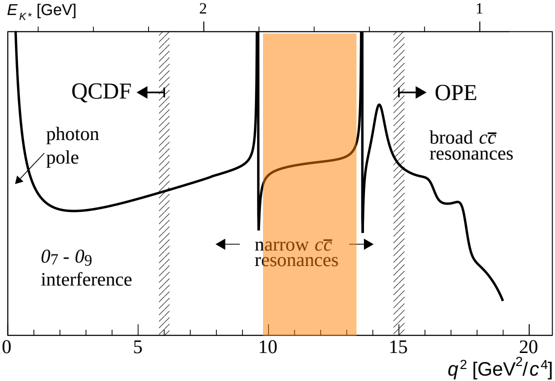
Opportunity: Belle 2 complementary to LHCb

common lore: [Belle 2 Physics Book]

- inclusive $B \to X_s \mu^+ \mu^-$ golden channel for Belle 2
- for exclusive $B \to K^* \mu^+ \mu^-$ LHCb expected to have better precision throughout

measurements in between and close to J/ψ, ψ' resonances difficult for LHCb!

▶ opportunity for Belle 2 to contribute substantially



- C++14 software framework for flavour observables
  - includes Python bindings
- use cases
  - theory predictions
  - Bayesian parameter inference
  - Monte-Carlo simulation of signal events
- open source / binary packages for Debian & Ubuntu

EOS homepage GitHub repository

- available also through the Belle 2 Externals

Summary

Summary

- flavour physics is a corner stone of particle physics (2019 or not!)
- accurate and precise theory predictions within the SM and beyond are important to further our understanding of physics at shortest distances
  - essentiell for the interpretation of the present anomalies
  - even if anomalie are a (statistical) fluke: theory predictions govern precision in the determination of SM parameters
- flavour physics thrives through close collaboration between theory and experiment
  - LHC runs 3 through 5 and Bell 2 will pile up a huge treasure of data
  - will require concerted efforts to fully exploit the data!

Backup Slides