CKM 2018 WG3 summary

Rare B, D, K decays

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September 21st, 2018

Rare B decays

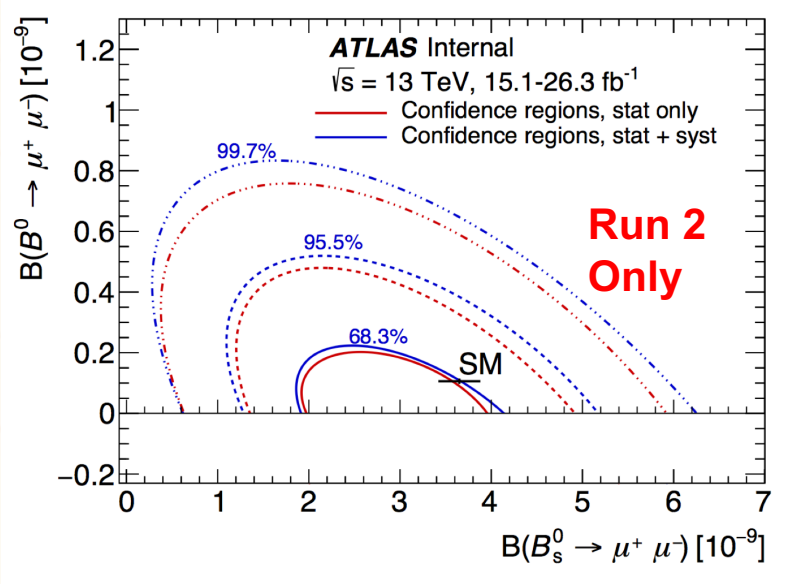
New $B_{(s)} \to \mu^+\mu^-$ result from ATLAS

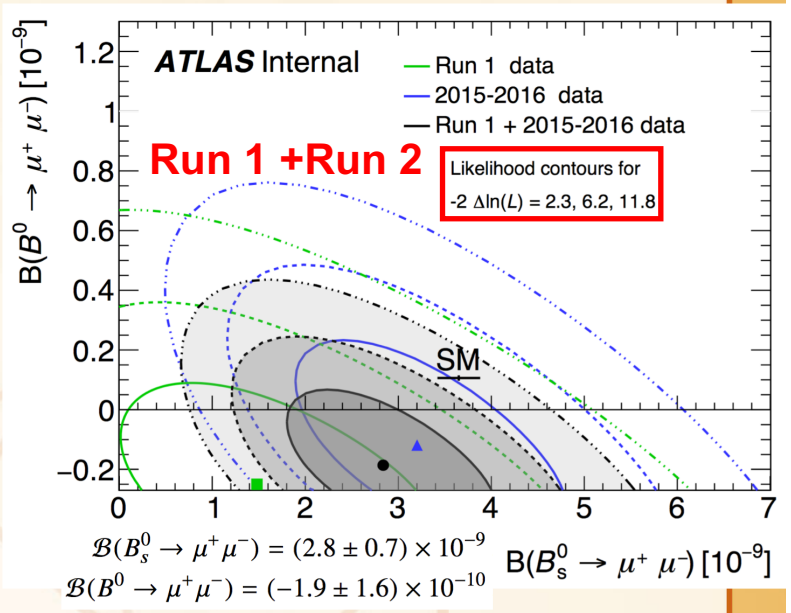
[Alex Cerri]

Run 2 Result and Run 1 Combination

Neyman Contours yield: $\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.21^{+0.96+0.49}_{-0.91-0.30}\right) \times 10^{-9} = \left(3.2^{+1.1}_{-1.0}\right) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) < 4.3 \times 10^{-10}$ @ 95% CL



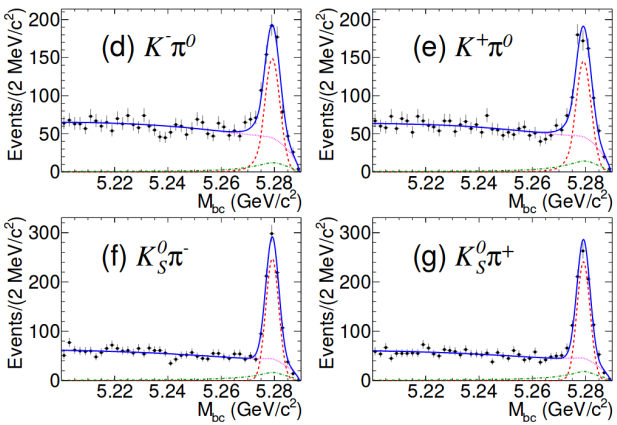


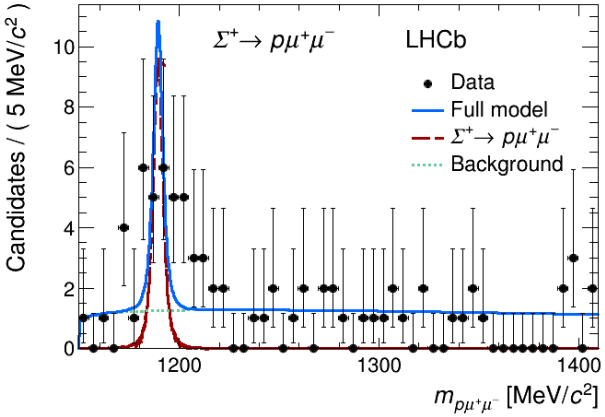
Run 1 + Run 2 (2015+2016) combination:

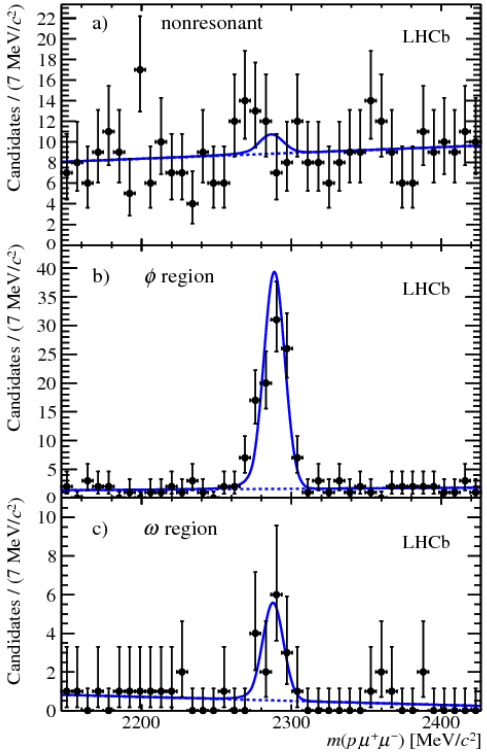
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(2.8^{+0.8}_{-0.7}\right) \times 10^{-9} \quad \mathcal{B}(B^0 \to \mu^+\mu^-) < 2.1 \times 10^{-10}$$

Compatible with SM at 2.4σ

First observations

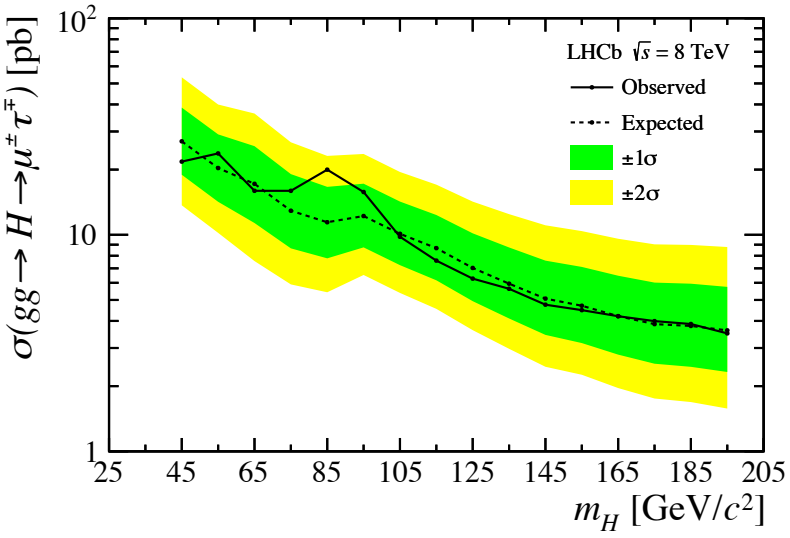


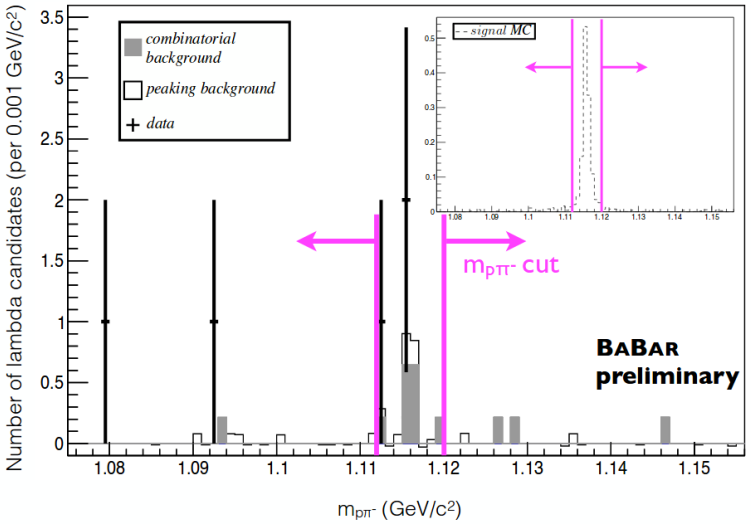




- Belle: Isospin violation in $B \to K^*\gamma$:
  $\Delta_{0+} = (6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%$ (3.1σ) [Tim Gershon]
- LHCb: $\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$ (4.1σ)
  [Giulio Dujany]
- LHCb:
  $\mathcal{B}(\Lambda_c^+ \to p(\omega \to \mu^+\mu^-)) = (9.4 \pm 3.2 \pm 1.0 \pm 2.0) \times 10^{-4}$
  [Giulio Dujany]

Upper limits





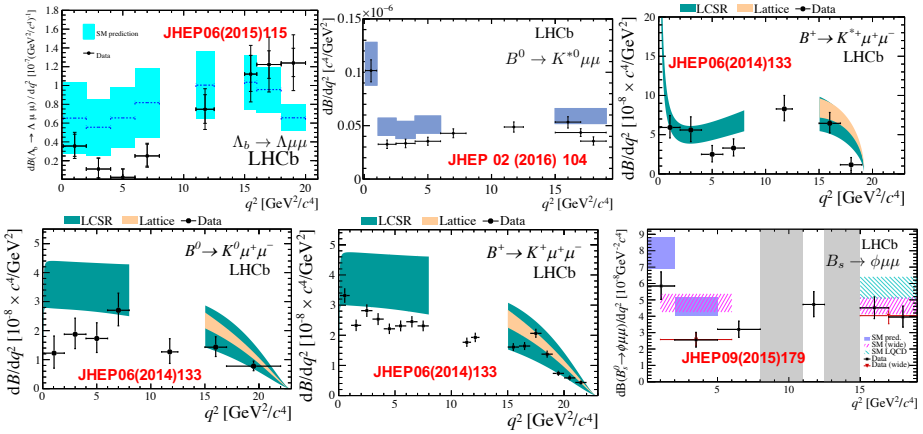
- $\mathcal{B}(B^0 \to e^\pm \mu^\mp) < 5.4 \times 10^{-9}$ (90% CL) [Giulio Dujany]
- $\mathcal{B}(B_s^0 \to e^\pm \mu^\mp) < 1.0 \times 10^{-9}$ (90% CL) [Giulio Dujany]
- $\mathcal{B}(H^0 \to \mu^\pm \tau^\mp) < 26\%$ (for SM Higgs) [Giulio Dujany]
- $\mathcal{B}(B^- \to \Lambda \bar{p} \nu \bar{\nu}) < 3 \times 10^{-5}$ [Tim Gershon]
- All compatible with the Standard Model.

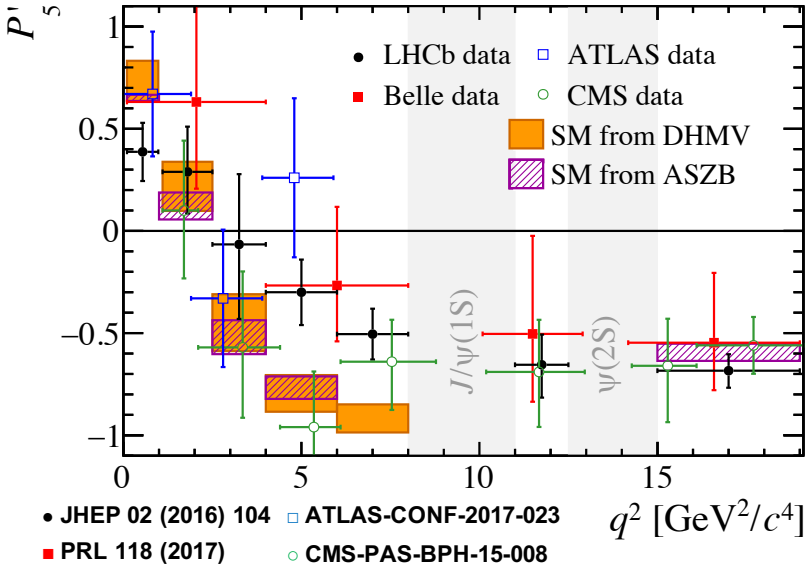
B anomalies:

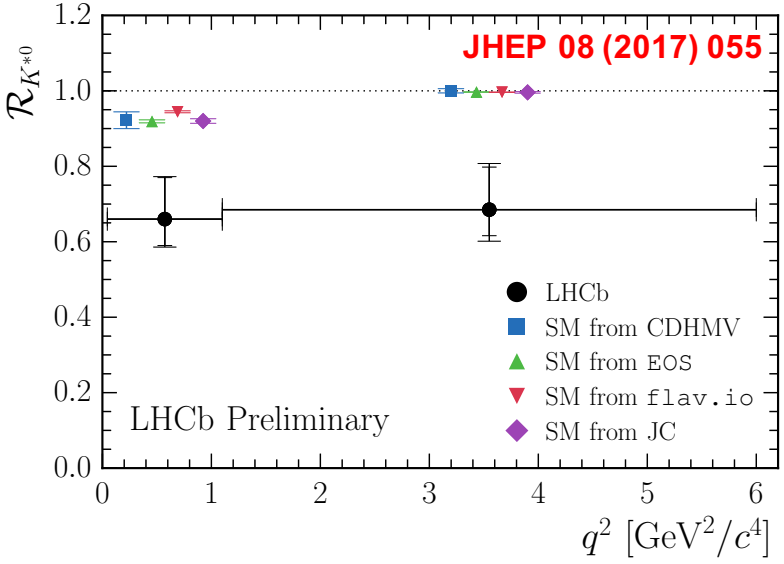
"Gekommen um zu bleiben"?

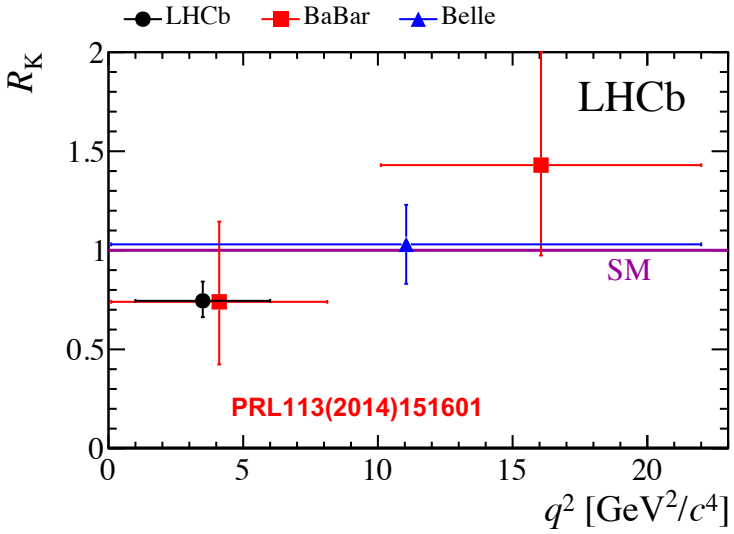
Anomalies

[Gabriela Pomery], [Vitalii Lisovskyi]



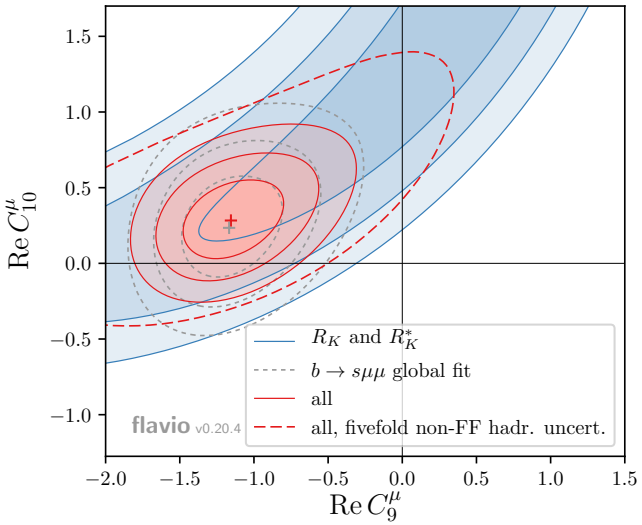


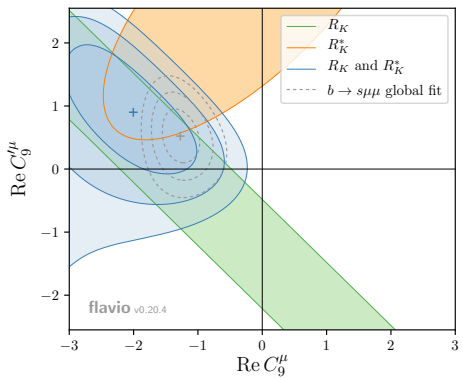




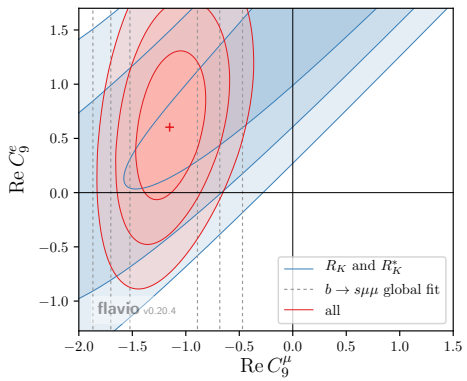
Global fits

[David Straub]





- Right-handed currents not favoured by data

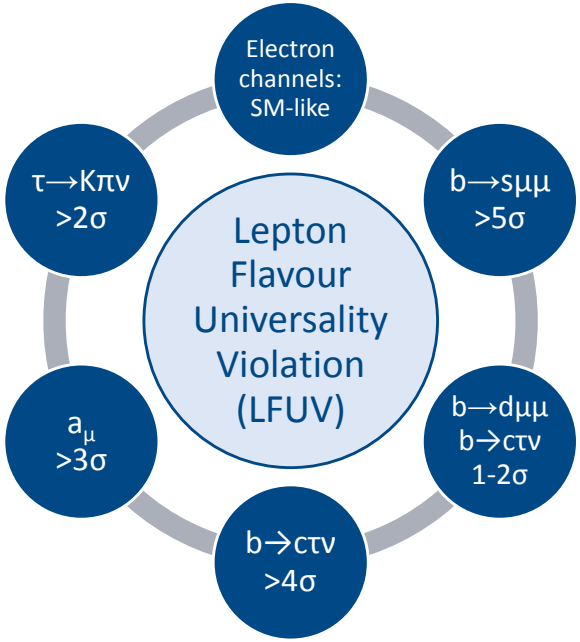


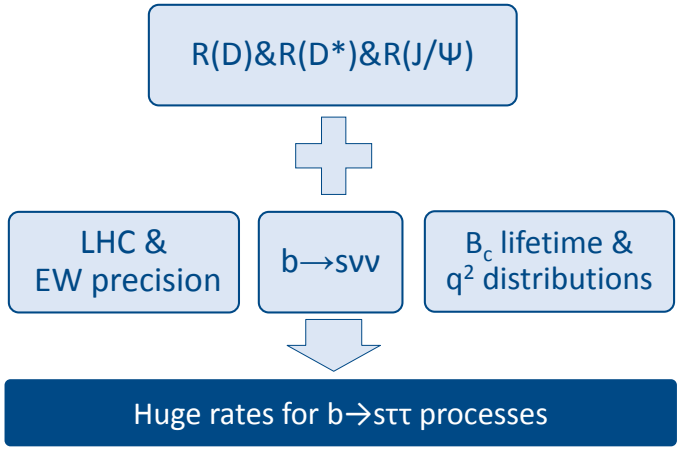
- NP in $b \to s e^+ e^-$ not required by data (but not excluded either)

- Combine branching fractions, angular measurements and $R_{K^{(*)}}$.
- Global fits from $R_{K^{(*)}}$ and $b \to s\mu^+\mu^-$ in excellent agreement.
- No right-handed currents or NP in electrons needed.
- 1D pulls for C_9^{μ}, C_{10}^{μ} around 4σ from SM predictions.
- Lindy effect? "Every additional period of survival implies a longer remaining life expectancy"

Golden Channel: $b \to s\tau\tau$?

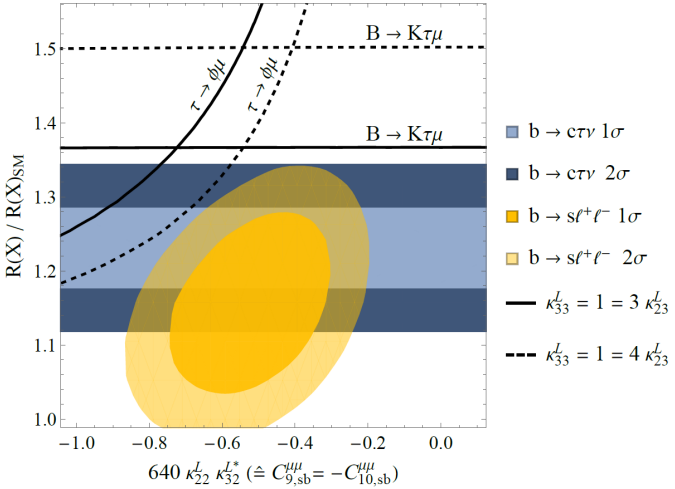
[Andreas Crivellin]





- Models with very large $b \to s\tau\tau$ and LFV just below observation
- Finding $b \to s\tau\tau$ at LHCb/ Belle II would mean New Physics.
- Leptoquarks are most favoured explanation of anomalies.

Perfect agreement with data



Pati-Salam LQ can explain the flavour anomalies

Violation of LFU and BSM physics

[Olcyr Sumensari]

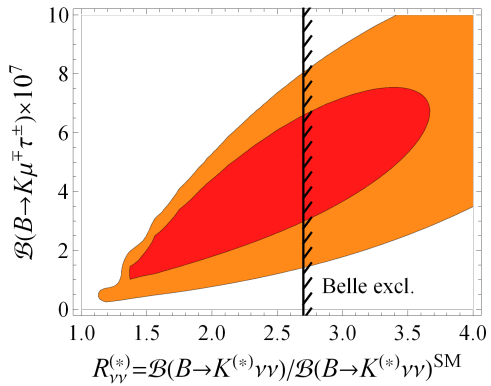
Leptoquarks for $R_{D^{(*)}}$ and $R_{K^{(*)}}$

[Angelescu, Becirevic, Faroughy, OS. 1808.08179]
see also [Greljo et al. '17]

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗*	✗*
$R_2 = (3, 2, 7/6)$	✓	✗*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

- Building a model that can solve all anomalies is a very challenging task!
- Only U_1 can do it, but UV completion needed (more parameters).
  $\Rightarrow$ Possible in Pati-Salam models: [Di Luzio et al. '17, Bordone et al. '17...]
- Two scalar LQs can also do the job (no extra parameters):
  $\Rightarrow$ S_1 and S_3 [Crivellin et al. '17, Marzocca. '18], R_2 and S_3 [Becirevic et al. '18].

Several **distinctive predictions** wrt the SM:



- **Enhancement** of $\mathcal{B}(B \to K\nu\bar{\nu})$ by $\gtrsim 50\%$ wrt to the SM [Belle-II]
- Upper and **lower bounds** on the **LFV** rates: $\mathcal{B}(B \to K\mu\tau) \gtrsim 2 \times 10^{-7}$

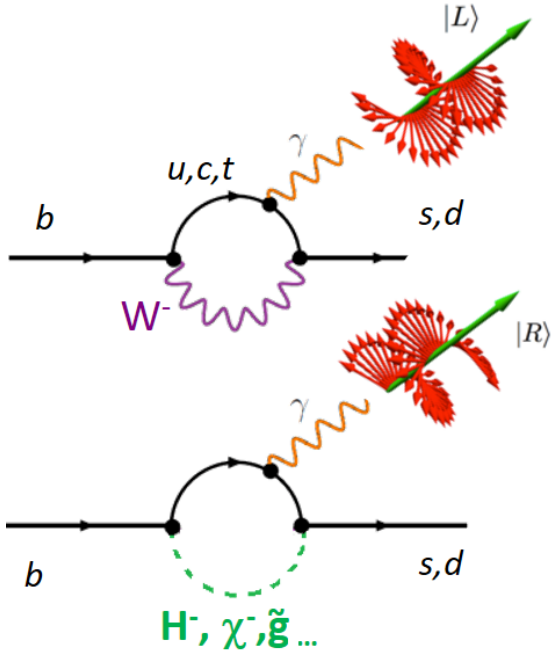
NB. $\mathcal{B}(B \to K^*\mu\tau)/\mathcal{B}(B \to K\mu\tau) \approx 1.8$, $\mathcal{B}(B \to K\mu\tau)/\mathcal{B}(B_s \to \mu\tau) \approx 1.25$
[Becirevic, OS, Zukanovich. 1602.00881]

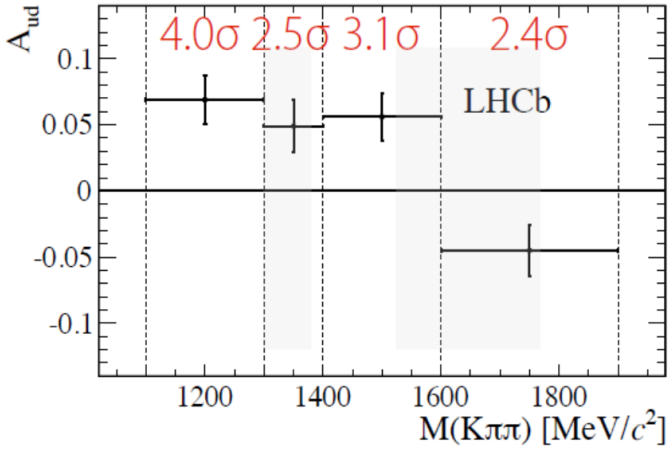
- $R_{D^{(*)}}$ explained by vector, but also by scalar and tensor EFT couplings
- Additional observables favour scalar and vector leptoquarks
- One vector OK (but UV completion needed), but also possible to build models with two scalar LQ
- R_2 and S_3 OK with one complex coupling, with expected enhancement for $B \to K(^*)\ell\ell$, and observable $B \to K\mu\tau$)

Radiative B decays

[Carlos Sanchez Mayordomo]

Photon Polarization

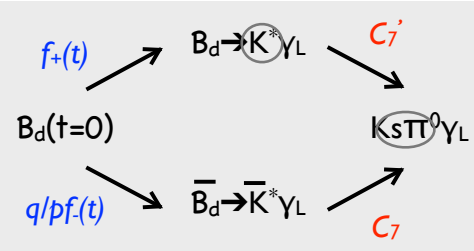




- Photon predominantly left-handed in SM. Different polarization $\rightarrow$ New Physics.
- Can be measured in $B^+ \rightarrow K^+\pi^-\pi^+\gamma$. $K^+\pi^-\pi^+$ spectrum challenging to describe (experimentally and theortically).
- Existence of photon polarization confirmed few years ago, amplitude analysis ongoing.

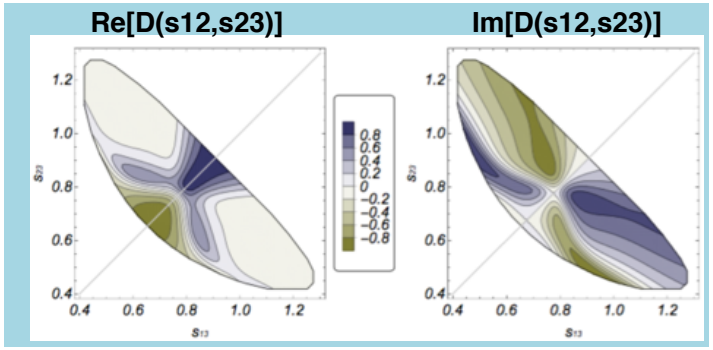
[Carlos Sanchez Mayordomo], [Emi Kou]

Time-dependent radiative analyses

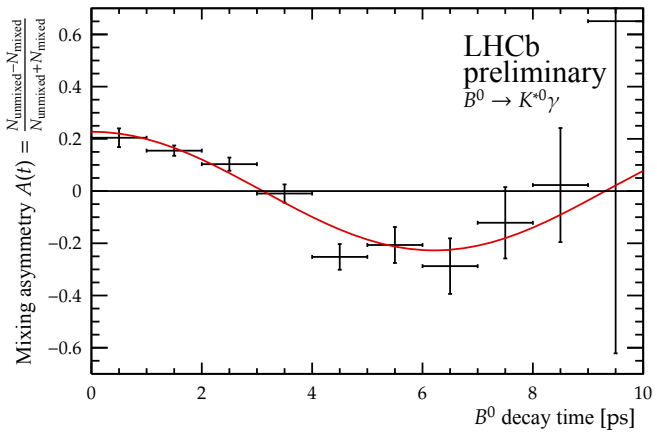


Atwood, Gronau, Soni, PRL 79 (1997)
Atwood, Gershon, Hazumi, Soni, PRD71 (2005)

- In SM C_7' is negligibly small, so the interference does not occur (no CPV).
- Thus, observation of CPV is a signal beyond the SM.



- CPV in $B^0 \to K_{res}\gamma$ decays would be clear sign of new physics.
- Can perform Dalitz analysis of "Dilution factor" to determine Real and Imaginary part of C_7, C_7'



- LHCb used flavour tagging for the first time in a radiative decay, measurement of S_{CP} and A_{CP} in $Bs \to \phi\gamma$ on the way.

Inclusive $B \to X_{d/s}\ell\ell$

Theory for $B \to X_s\gamma$ and $B \to X_s\ell\ell$

[Mikolaj Misiak]

$|C_7|$ from the CP- and isospin-averaged branching ratio of $\bar{B} \to X_s\gamma$ with $E_\gamma > 1.6$ GeV:

$$\mathcal{B}^{\rm exp}_{s\gamma} \times 10^4 = 3.32 \underbrace{\pm 0.15}_{\pm 4.5\%}$$ HFLAV, arXiv:1612.07233, average of Belle, BaBar and CLEO.

$$\mathcal{B}^{\rm SM}_{s\gamma} \times 10^4 = 3.36 \underbrace{\pm 0.23}_{\pm 6.9\%}$$ arXiv:1503.01789, arXiv:1503.01791.

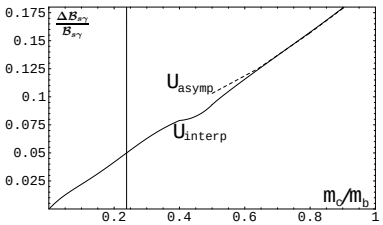
$$\Rightarrow \left|\frac{C_7}{C_7^{\rm SM}}\right| = 0.994 \pm 0.041 \quad (0.15\sigma)$$

Belle II with $50\,{\rm ab}^{-1}$ is going to reach $\pm 2.3\%$ in $\mathcal{B}^{\rm exp}_{s\gamma}$ [naive weighted average of $\pm 3.2\%$, $\pm 4.2\%$ and $\pm 5.7\%$ obtained for $E_\gamma > 1.9$ GeV using different methods in Table 61 of The Belle II Physics Book, arXiv:1808.10567.]

Thus, the TH uncertainty must be reduced.
At present, it consists of four contributions (summed in quadrature):

5% non-perturbative, 3% from the interpolation in m_c,
3% higher order $\mathcal{O}(\alpha_s^3)$, 2% parametric.

Effect of the interpolated $\mathcal{O}(\alpha_s^2)$ contribution on the branching ratio:



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SM predictions for $\mathcal{B}(\bar{B} \to X_s\ell^+\ell^-) \times 10^6$ with $q^2 \in [1,6]$ GeV and no cut on M_{X_s}:

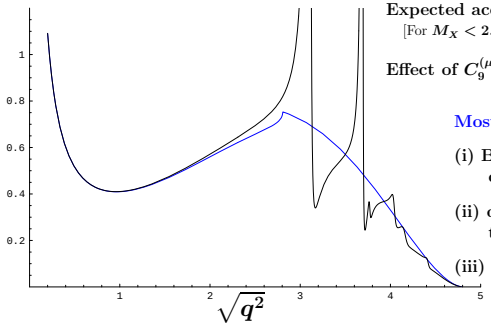
1.64 ± 0.11, $\ell = e$
1.59 ± 0.11, $\ell = \mu$ } parametric and perturbative uncert. only [Huber, Lunghi, MM, Wyler, hep-ph/0512066]

1.67 ± 0.10, $\ell = e$
1.62 ± 0.09, $\ell = \mu$ } param. update + Krüger-Sehgal, [Huber, Hurth, Lunghi, arXiv:1503.04849]
PLB380 (1996) 199
PRD55 (1997) 2799

The corresponding semi-inclusive experimental results:

$1.93^{+0.54}_{-0.51}$, $\ell = e$
$0.66^{+0.88}_{-0.80}$, $\ell = \mu$ } $= 1.60^{+0.48}_{-0.45}$, Babar, arXiv:1312.5364, $471 \times 10^6 B\bar{B}$, extrapolated from $M_X < 1.8$ GeV.

$1.49^{+0.65}_{-0.58}$, Belle, hep-ex/0503044, $152 \times 10^6 B\bar{B}$.



Expected accuracy at Belle II with $50\,{\rm ab}^{-1}$: $\sim \pm 6.5\%$.
[For $M_X < 2.0$ GeV, Table 64 of The Belle II Physics Book, arXiv:1808.10567]

Effect of $C_9^{(\mu)\rm NP} = -C_{10}^{(\mu)\rm NP} = -0.67$: $\mathcal{B} \searrow \sim 30\%$.

Most recent contributions on the theory side:

(i) Benzke, Hurth, Turczyk, arXiv:1705.10366, charm loops & resolved photons → next slides.

(ii) de Boer, arXiv:1707.00988, two loops analytically.

(iii) Huber, Qin, Vos, arXiv:1806.11521, five body & pheno update → next speaker. [Qin Qin]

5

- $B \to X_s\gamma$ ($B \to X_s\ell\ell$) strong contraints on C_7 (C_9, C_{10}), with interesting experimental prospects (Belle II)
- Effect of cut on E_γ or M_{X_s} difficult to tackle (local OPE + SCET), introducing shape functions to be modelled/fitted experimentally
- $B \to X_s\gamma$: charm loops induce m_c dependence, significant source of uncertainty, difficult analytic computation, now under control

Five-particle contributions to $B \to X_{d/s}\ell\ell$

[Qin Qin]

pieces in $\mathcal{B}(\bar{B} \to X_d \ell^+\ell^-)$ $(\times 10^{-8})$	$q^2 \in [1, 3.5]$ GeV^2	$[3.5, 6]$ GeV^2	$[1, 6]$ GeV^2
$R(s)$ (LO+NLO+NNLO)	3.79	3.05	6.84
five-particle	0.092	0.003	0.095

pieces in $\mathcal{B}(\bar{B} \to X_d \ell^+\ell^-)$ $(\times 10^{-8})$	$q^2 > 14.4$ GeV^2
$R(s)$ (LO+NLO+NNLO)	1.46
five-particle	≈ 0

pieces in $\mathcal{B}(\bar{B} \to X_s \ell^+\ell^-)$ $(\times 10^{-6})$	$q^2 \in [1, 3.5]$ GeV^2	$[3.5, 6]$ GeV^2	$[1, 6]$ GeV^2
$R(s)$ (LO+NLO+NNLO)	0.86	0.70	1.56
five-particle	2×10^{-4}	5×10^{-6}	2×10^{-4}

- Ongoing effort to increase the accuracy of $B \to X_{d/s}\ell\ell$.
- Studied five-particle contributions: $b \to d/s\ell\ell u\bar{u}$.
- Effect negligible in $b \to d$ transitions, but seizable effects in $b \to s$ transitions.

Probably the longest formula at CKM 2018

[Qin Qin]

$$
\begin{aligned}
&\frac{1}{s3^2} 8 e^4 QL^2 \Bigg(-\frac{Qu^2 (1-u1) \big(s2\, t2 (-s3+t2-t3) - s3\, t2\, t3 + 2 t2^2 t3 - 2 t2\, t3^2 + 2\, p3p4\, t2 (s3-t2+2 t3) + s3^2 u1 - s3\, t2\, u1 + 2 s3\, t3\, u1 - 2 t2\, t3\, u1 + 2 t3^2 u1\big)}{t2^2} - \frac{Qd^2 (1-u1) \big(-8\, p3p4^2 (s2-u1) + (s2-s3)(s2(t2-t3) - s3\, u1) + p3p4 \big(4 s2^2 + 4 s3\, u1 - 2 s2 (s3+t2-2 t3+2 u1)\big)\big)}{s2^2} - \\
&\frac{1}{s2\, t2} Qd\, Qu (1-u1) \big(8\, p3p4^2 (s3-t2) + s2^2 (t2-t3) + s2 \big(t2^2 + t2 (t3-2 u1) + (s3-2 t3)(t3-u1)\big) - 2\, p3p4 (s2 (s3-t2-2 t3) + (t2-2 t3)(t2-2 u1) + s3 (-t2+4 t3+2 u1)) - s3 \big(t2 (t3+u1) - 2 \big(t3^2 - t3\, u1 + u1^2\big)\big)\big) + \frac{1}{(-1+s1-s3+u1+u2)^2} \\
&Qd^2 (s2-s3+t2-u1) \big(4 + 6\, p3p4 - 2 s1 + 3 s2 - 2 s3 - s1^2 + s3 + s1\, s2\, s3 + 6 t2 + s1^2 t2 + 3 s3\, t2 - 3 t3 - s1^2 t3 - 3 s3\, t3 + s1\, s3\, t3 - 6 u1 - s2\, u1 + 2 s3\, u1 - 3 s1\, s3\, u1 + s2\, s3\, u1 - 5 t2\, u1 + 2 s1\, t2\, u1 + 4 t3\, u1 - 2 s1\, t3\, u1 + s3\, t3\, u1 + 2 u1^2 - 2 s3\, u1^2 + t2\, u1^2 - t3\, u1^2 - 2 u2 - s2\, u2 + 3 s3\, u2 - 2 s1\, s3\, u2 + s2\, s3\, u2 - 5 t2\, u2 + \\
&2 s1\, t2\, u2 + 4 t3\, u2 - 2 s1\, t3\, u2 + s3\, t3\, u2 + 2 u1\, u2 - 3 s3\, u1\, u2 + 2 t2\, u1\, u2 - 2 t3\, u1\, u2 - s3\, u2^2 + t2\, u2^2 - t3\, u2^2 - 6 u3 - 5 s2\, u3 + s1\, s2\, u3 + 6 s3\, u3 - 2 s1\, s3\, u3 + s2\, s3\, u3 - 7 t2\, u3 + 3 s1\, t2\, u3 - s3\, t2\, u3 + 2 t3\, u3 - 2 s1\, t3\, u3 + 2 s3\, t3\, u3 + 8 u1\, u3 - 2 s1\, u1\, u3 + s2\, u1\, u3 - 2 s3\, u1\, u3 + 3 t2\, u1\, u3 - 2 t3\, u1\, u3 - \\
&2 u1^2 u3 + 2 u2\, u3 + s2\, u2\, u3 - 2 s3\, u2\, u3 + 3 t2\, u2\, u3 - 2 t3\, u2\, u3 - 2 u1\, u2\, u3 + 2 u3^2 + 2 s2\, u3^2 - 2 s3\, u3^2 + 2 t2\, u3^2 - 2 u1\, u3^2 + s1 (-s2+3 s3-5 t2+4 t3+2 u1+2 u3) + 2\, p3p4 (s1-s3+u1+u2)(s1+u1+u2+2 u3) - 2\, p3p4 (4 s1-3 s3+4 u1+4 u2+2 u3)\big) + \frac{1}{(-1+s1-s2+s3-t2+u1+u2)^2} \\
&Qu^2 (s2-s3+t2-u1) \big(4 - 6\, p3p4 - 2 s1 + 5 s2 + s2^2 - 4 s3 - s1^2 s3 - s2\, s3 + s1\, s2\, s3 + 2 t2 + s1^2 t2 - s2\, t2 - s1\, s2\, t2 + 2 s3\, t2 - 2 t2^2 + s1\, t2^2 + 3 t3 - s1^2 t3 + 3 s2\, t3 + s1\, s2\, t3 - 3 s3\, t3 + s1\, s3\, t3 + 3 t2\, t3 - 3 s1\, t2\, t3 + 2 s1\, t3^2 - 6 u1 - 3 s2\, u1 + 2 s3\, u1 - s1\, s3\, u1 + t2\, u1 + s2\, t2\, u1 - s3\, t2\, u1 + \\
&t2^2 u1 - 4 t3\, u1 - s2\, t3\, u1 + s3\, t3\, u1 - t2\, t3\, u1 + 2 u1^2 - t2\, u1^2 + t3\, u1^2 - 2 u2 - s2\, u2 + 3 s3\, u2 - 2 s1\, s3\, u2 + s2\, s3\, u2 - 3 t2\, u2 + 2 s1\, t2\, u2 - s2\, t2\, u2 + t2^2 u2 + 2 t3\, u2 - 2 s1\, t3\, u2 + s2\, t3\, u2 + s3\, t3\, u2 - 3 t2\, t3\, u2 + 2 t3^2 u2 + 2 u1\, u2 - s3\, u1\, u2 - s3\, u2^2 + t2\, u2^2 - t3\, u2^2 + 8\, p3p4^2 (s1+u2) - 6 u3 - 7 s2\, u3 + \\
&s1\, s2\, u3 - s2^2 u3 + 6 s3\, u3 - 2 s1\, s3\, u3 + s2\, s3\, u3 - 5 t2\, u3 + 3 s1\, t2\, u3 - s3\, t2\, u3 + t2^2 u3 - 2 t3\, u3 - 2 s1\, t3\, u3 - 2 s2\, t3\, u3 + 2 s3\, t3\, u3 - 2 t2\, t3\, u3 + 8 u1\, u3 - 2 s1\, u1\, u3 + 3 s2\, u1\, u3 - 2 s3\, u1\, u3 + t2\, u1\, u3 + 2 t3\, u1\, u3 - 2 u1^2 u3 + 2 u2\, u3 + s2\, u2\, u3 - 2 s3\, u2\, u3 + 3 t2\, u2\, u3 - 2 t3\, u2\, u3 - 2 u1\, u2\, u3 + 2 u3^2 + \\
&2 s2\, u3^2 - 2 s3\, u3^2 + 2 t2\, u3^2 - 2 u1\, u3^2 + s1 (-s2+3 s3-3 t2+2 t3+2 u1+2 u3) + p3p4 (-4 s1-6 s2+6 s3-6 t2+8 u1-4 u2+4 u3) + 2\, p3p4 \big(s1^2 - s3\, u1 + t2\, u1 - u1^2 - s3\, u2 + 3 t2\, u2 - 4 t3\, u2 + u2^2 - s1 (s2+s3-3 t2+4 t3-2 u2-2 u3) - 2 s3\, u3 + 2 t2\, u3 - 2 u1\, u3 + 2 u2\, u3 + s2 (u1-u2+2 u3)\big)\Big) - \\
&\frac{1}{t2 (1-s1+s3-u1-u2)} Qd\, Qu \big(s3^2 + 6\, p3p4 (s3-t2) - 8\, p3p4^2 t2 - s2\, t2 + s2^2 t2 - s1\, s3\, t2 + s1\, s2\, s3\, t2 - 4 t2^2 + 2 s1\, t2^2 - s1\, s2\, t2^2 + s3\, t2^2 - 2 t2^3 + s1\, t2^3 + 3 s2\, t3 + s1\, s3\, t3 + s3^2 t3 + 6 t2\, t3 - 2 s1\, t2\, t3 + s1\, s2\, t2\, t3 - 5 s3\, t2\, t3 + s1\, s3\, t2\, t3 + 5 t2^2 t3 - 3 s1\, t2^2 t3 + 2 s3\, t3^2 - \\
&2 t2\, t3^2 + 2 s1\, t2\, t3^2 + s3 (2 t2-3 t3-2 u1) + s1\, s2\, s3\, u1 - s2^2 s3\, u1 + 4 s3^2 u1 - 2 s1\, s3^2 u1 + s2\, s3^2 u1 + 4 t2\, u1 - 2 s1\, t2\, u1 - s1\, s2\, t2\, u1 - 9 s3\, t2\, u1 + 3 s1\, s3\, t2\, u1 + 8 t2^2 u1 - 3 s1\, t2^2 u1 - s2\, t2^2 u1 - s3\, t2^2 u1 + t2^3 u1 - 6 t3\, u1 + 2 s1\, t3\, u1 + s1\, s2\, t3\, u1 + 8 s3\, t3\, u1 - 3 s1\, s3\, t3\, u1 - s2\, s3\, t3\, u1 + \\
&s3^2 t3\, u1 - 13 t2\, t3\, u1 + 5 s1\, t2\, t3\, u1 + s2\, t2\, t3\, u1 + s3\, t2\, t3\, u1 - 3 t2^2 t3\, u1 + 2 t3^2 u1 - 2 s1\, t3^2 u1 + 2 t2\, t3^2 u1 + 5 s3\, u1^2 - s1\, s3\, u1^2 + 3 s2\, s3\, u1^2 - 3 s3^2 u1^2 - 6 t2\, u1^2 + 2 s1\, t2\, u1^2 - s2\, t2\, u1^2 + 6 s3\, t2\, u1^2 - 3 t2^2 u1^2 + 8 t3\, u1^2 - 2 s1\, t3\, u1^2 + s2\, t3\, u1^2 - 3 s3\, t3\, u1^2 + 5 t2\, t3\, u1^2 - 2 t3^2 u1^2 - \\
&3 s3\, u1^3 + 2 t2\, u1^3 - 2 t3\, u1^3 - s2^2 s3\, u2 - 2 s3\, t2\, u2 + s2\, s3\, t2\, u2 + 2 t2^2 u2 - s2\, t2^2 u2 - s3\, t2^2 u2 + t2^3 u2 + s3\, t3\, u2 - 2 s2\, s3\, t3\, u2 - 2 t2\, t3\, u2 + s2\, t2\, t3\, u2 + 3 s3\, t2\, t3\, u2 - 3 t2^2 t3\, u2 - 2 s3\, t3^2 u2 + 2 t2\, t3^2 u2 + 2 s3\, u1\, u2 + 3 s2\, s3\, u1\, u2 - 2 s3^2 u1\, u2 - 2 t2\, u1\, u2 - s2\, t2\, u1\, u2 + 5 s3\, t2\, u1\, u2 - \\
&3 t2^2 u1\, u2 + 2 t3\, u1\, u2 + s2\, t3\, u1\, u2 - 3 s3\, t3\, u1\, u2 + 5 t2\, t3\, u1\, u2 - 2 t3^2 u1\, u2 - 3 s3\, u1^2 u2 + 2 t2\, u1^2 u2 - 2 t3\, u1^2 u2 + 8\, p3p4^2 (s1\, t2 - (s3-t2)(u1+u2)) - s2^2 t2\, u3 - 2 s3\, t2\, u3 + s2\, s3\, t2\, u3 + 2 t2^2 u3 - s3\, t2^2 u3 + t2^3 u3 + 2 s3\, t3\, u3 - 4 t2\, t3\, u3 - 2 s2\, t2\, t3\, u3 + 2 s3\, t2\, t3\, u3 - 2 t2^2 t3\, u3 + \\
&2 s3\, u1\, u3 + 2 s2\, s3\, u1\, u3 - 2 s3^2 u1\, u3 - 2 t2\, u1\, u3 - s2\, t2\, u1\, u3 + 4 s3\, t2\, u1\, u3 - 3 t2^2 u1\, u3 + 4 t3\, u1\, u3 + 4 s2\, t3\, u1\, u3 - 4 s3\, t3\, u1\, u3 + 6 t2\, t3\, u1\, u3 - 2 s3\, u1^2 u3 + 2 t2\, u1^2 u3 - 4 t3\, u1^2 u3 + s2 \big(s3^2 + t2^2 + s1 (t2-t3) + t2\, t3 + 3 t2\, u1 - 6 t3\, u1 + t2\, u2 - t3\, u2 - s3 (3 t2-3 t3+4 u1+u2) - 2 t3\, u3\big) - \\
&2\, p3p4 \big(s3^2 u1 + 2 s3\, t2\, u1 - 3 t2^2 u1 - 2 s3\, t3\, u1 + 4 t2\, t3\, u1 - s3\, u1^2 + 2 t2\, u1^2 - 2 t3\, u1^2 + s1 \big(s2\, t2 + s3\, t2 - 3 t2^2 + 4 t2\, t3 - s3\, u1 + 2 t2\, u1 - 2 t3\, u1\big) + 3 s3\, t2\, u2 - 3 t2^2 u2 - 4 s3\, t3\, u2 + 4 t2\, t3\, u2 - s3\, u1\, u2 + 2 t2\, u1\, u2 - 2 t3\, u1\, u2 + 2 s3\, t2\, u3 - 2 t2^2 u3 + 2 t2\, u1\, u3 - s2 (s3\, u1 + 2 t3\, u1 + 2 s3\, u2 - t2\, u2 + 2 t2\, u3)\big)\Big) - \\
&\frac{1}{s2 (1-s1+s2-s3+t2-u1-u2)} Qd\, Qu \big(2 s2^2 + s2^3 - s1\, s2^2 t2 + s1\, s2\, t2^2 - s1\, s3\, t2^2 + s1\, s2^2 t3 - s1\, s2\, s3\, t3 - 3 s1\, s2\, t2\, t3 + 2 s1\, s3\, t2\, t3 + 2 s1\, s2\, t3^2 - 2 s1\, s3\, t3^2 - 6\, p3p4 (2 s2-s3+t2-2 u1) + 8\, p3p4^2 (s2+t2-u1) + s1\, s2\, s3\, u1 + 2 s2^2 t2\, u1 + s1\, s3\, t2\, u1 - 3 s2\, s3\, t2\, u1 + s3^2 t2\, u1 + \\
&2 s2\, t2^2 u1 - s3\, t2^2 u1 - 2 s2^2 t3\, u1 + s1\, s3\, t3\, u1 + 3 s2\, s3\, t3\, u1 - s3^2 t3\, u1 - 2 s2\, t2\, t3\, u1 + s3\, t2\, t3\, u1 - s1\, s3\, u1^2 - s2\, s3\, u1^2 + s3^2 u1^2 - 2 s2\, t2\, u1^2 + 2 s2\, t3\, u1^2 - s3\, t3\, u1^2 + s3\, u1^3 - s2 (4 s3+t2-3 t3+2 u1) + s3 (s3-3 t3+4 u1) + s2^2 s3\, u2 - s2^2 t2\, u2 + s2\, t2^2 u2 + s2^2 t3\, u2 + s2\, s3\, t3\, u2 - 3 s2\, t2\, t3\, u2 + \\
&2 s2\, t3^2 u2 - s2\, s3\, u1\, u2 - s3\, t2\, u1\, u2 + s3\, t3\, u1\, u2 + s3\, u1^2 u2 + 8\, p3p4^2 (s1 (s2-s3-u1) + u1 (s3-t2+u1-u2) + s2 (-u1+u2)) - s3^2 u3 + s2^2 s3\, u3 - s2\, s3\, t2\, u3 + s2\, t2^2 u3 - 2 s2^2 t3\, u3 + 2 s2\, s3\, t3\, u3 - 2 s2\, t2\, t3\, u3 + 3 s2^2 u1\, u3 - 4 s2\, s3\, u1\, u3 + 2 s3^2 u1\, u3 + s2\, t2\, u1\, u3 - 2 s3\, t2\, u1\, u3 + 2 s2\, t3\, u1\, u3 - \\
&2 s2\, u1^2 u3 + 2 s3\, u1^2 u3 - s2^2 (2 s3+2 t2-4 t3+3 u1+2 u3) + s3 \big(t2\, t3 - 2 t3^2 + s1 (-t2+t3) + s3 (t2-t3-4 u1) + 3 t2\, u1 + 2 t3\, u1 - 5 u1^2 + t3\, u2 - 2 u1\, u2 + 2 t3\, u3 - 2 u1\, u3\big) + s2 \big(-3 t2^2 + s1 (t2-t3) + 4 t2\, t3 + 2 t2\, u1 - 5 t3\, u1 + 2 u1^2 + t2\, u2 - t3\, u2 - 2 t3\, u3 + 2 u1\, u3 + s3 (2 t2-5 t3+8 u1+u2+2 u3)\big) + \\
&2\, p3p4 \big(-5 s2^2 + s3^2 + t2^2 + 2 s3\, t3 - 2 t2\, t3 + s1 (2 s2-s3+t2-2 u1) - 8 s3\, u1 + 6 t2\, u1 + 2 t3\, u1 - 8 u1^2 - s3\, u2 + t2\, u2 - 2 u1\, u2 - 2 s3\, u3 + 2 t2\, u3 - 4 u1\, u3 + s2 (4 s3-4 t2-2 t3+13 u1+2 u2+4 u3)\big) - 2\, p3p4 \big(s1 \big(s2^2 + s3 (2 t2-4 t3-u1) + s2 (-s3-3 t2+4 t3+u1) + u1 (3 t2-2 (t3+u1))\big) + \\
&s2^2 (-3 u1+u2-2 u3) + s2 \big(-2 t3\, u1 + 5 u1^2 + 4 t3\, u2 + u1\, u2 + 6 u1\, u3 + s3 (4 u1+u2+2 u3) - t2 (2 u1+3 u2+2 u3)\big) - u1 \big(s3^2 - t2^2 + t2 (2 t3-u1-3 u2-4 u3) + s3 (-2 t3+3 u1+u2+4 u3) + 2 (t3 (-u1+u2) + u1 (u1+u2+2 u3))\big)\big)\Big) - \\
&\frac{1}{s2 (1-s1+s3-u1-u2)} Qd^2 \big(2 s2^2 + s2^3 - s1\, s2^2 t2 + s1\, s2\, t2^2 - s1\, s3\, t2^2 + s1\, s2^2 t3 - s1\, s2\, s3\, t3 - 3 s1\, s2\, t2\, t3 + 2 s1\, s3\, t2\, t3 + 2 s1\, s2\, t3^2 - 2 s1\, s3\, t3^2 - 6\, p3p4 (2 s2-s3+t2-2 u1) + s1\, s2\, s3\, u1 - s2^2 t2\, u1 + s1\, s3\, t2\, u1 - s2\, s3\, t2\, u1 + s3^2 t2\, u1 + \\
&s2\, t2^2 u1 - s3\, t2^2 u1 - s2\, s3\, t3\, u1 + s3^2 t3\, u1 - 2 s2\, t2\, t3\, u1 + s3\, t2\, t3\, u1 - s1\, s3\, u1^2 - s2\, s3\, u1^2 + s3^2 u1^2 - 2 s2\, t2\, u1^2 + 2 s2\, t3\, u1^2 - s3\, t3\, u1^2 + s3\, u1^3 - s2 (4 s3+t2-3 t3+2 u1) + s3 (s3-3 t3+4 u1) + s2^2 s3\, u2 - s2^2 t2\, u2 + s2\, t2^2 u2 + s2^2 t3\, u2 + s2\, s3\, t3\, u2 - 3 s2\, t2\, t3\, u2 + \\
&2 s2\, t3^2 u2 - s2\, s3\, u1\, u2 - s3\, t2\, u1\, u2 + s3\, t3\, u1\, u2 + s3\, u1^2 u2 + 8\, p3p4^2 (s1 (s2-s3-u1) + (s2-u1)(u1+u2)) + s2^2 (-2 s3+t2+t3-3 u1-2 u3) - s2^3 u3 + s2^2 s3\, u3 - s2\, s3\, t2\, u3 + s2\, t2^2 u3 - 2 s2^2 t3\, u3 + 2 s2\, s3\, t3\, u3 - 2 s2\, t2\, t3\, u3 + 3 s2^2 u1\, u3 - 4 s2\, s3\, u1\, u3 + 2 s3^2 u1\, u3 + s2\, t2\, u1\, u3 - 2 s3\, t2\, u1\, u3 + 2 s2\, t3\, u1\, u3 - \\
&2 s2\, u1^2 u3 + 2 s3\, u1^2 u3 - s2^2 (2 s3+2 t2-4 t3+3 u1+2 u3) + s3 \big(s1 (-t2+t3) + s3 (t2-t3-2 u1) + 2 t2\, u1 - 3 u1^2 + t3\, u2 - 2 u1\, u2 + 2 t3\, u3 - 2 u1\, u3\big) + s2 \big(-2 t2^2 + s1 (t2-t3) - 2 s3\, t3 - 2 t3^2 + 5 s3\, u1 - 3 t3\, u1 + 2 u1^2 + s3\, u2 - t3\, u2 + t2 (5 t3+u2) + 2 s3\, u3 - 2 t3\, u3 + 2 u1\, u3\big) + 2\, p3p4 \big(-s2^2 + s3^2 + s3\, t2 - 2 s3\, t3 + s1 (2 s2-s3+t2-2 u1) - 6 s3\, u1 + 8 t2\, u1 - 2 t3\, u1 - 8 u1^2 - s3\, u2 + t2\, u2 - 2 u1\, u2 - 2 s3\, u3 + 2 t2\, u3 - 4 u1\, u3 + s2 (s3-5 t2+4 t3+9 u1+2 u2+4 u3)\big) + \\
&2\, p3p4 \big(s1 \big(s2^2 + s3 (2 t2-4 t3-u1) + s2 (-s3-3 t2+4 t3+u1) + u1 (3 t2-2 (t3+u1))\big) + s2^2 (u1+u2-2 u3) + s2 \big(4 t3\, u1 + u1^2 + 4 t3\, u2 + u1\, u2 + 6 u1\, u3 + s3 (u1+u2+2 u3) - t2 (3 u1+3 u2+2 u3)\big) - u1 \big(s3^2 + s3 (-t2+2 t3+u1+u2+4 u3) - t2 (3 u1+3 u2+4 u3) + 2 (t3 (u1+u2) + u1 (u1+u2+2 u3))\big)\big)\Big)\Bigg)
\end{aligned}
$$

D decays:
Plain SM or smoking guns of NP?

D decays and NP

[Svjetlana Fajfer]

Motivation

B meson puzzles → Solution by New Physics

B meson puzzles → Tests of Lepton flavour universality

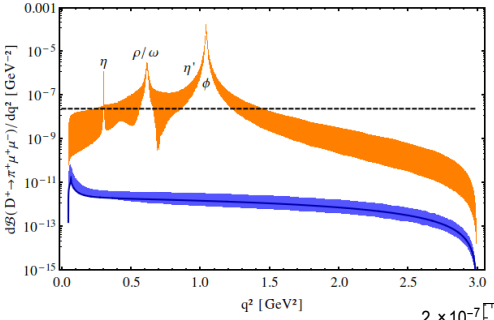
$(g\text{-}2)_\mu$ discrepancy SM prediction and experimental result

How about charm?

- In experiments producing B mesons there are always D mesons;
- Charm offers tests of possible NP in up sector at low-energies;
- If NP couples to weak doublets of quarks, CKM connects it with charm sector.
- Lattice QCD made progress for charm meson coupling constants and some form-factors
- Can one see NP in charm decays not being present in B meson ?

NP constraints from rare D decays

[Svjetlana Fajfer]

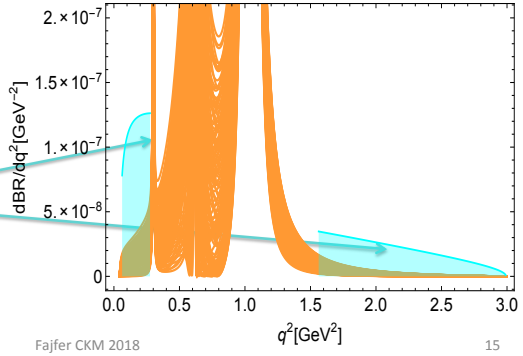


SM prediction: Long distance contributions most important!
peaks at ρ,ω,φ and η resonances

$$D \to \pi V \to \pi l^+ l^-$$

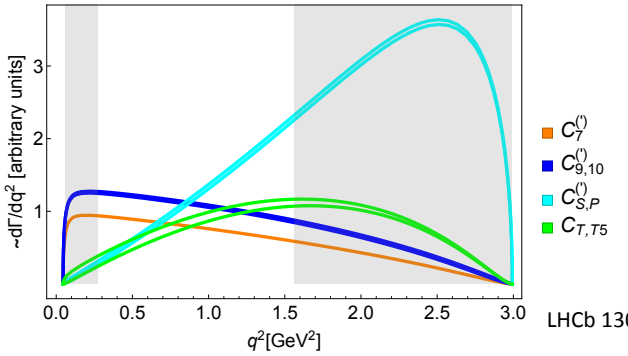
de Boer, Hiller, 1510.00311,
SF and Kosnik, 1510.00965

LHCb bound- assumption – constant amplitude
LHCb 1304.6365



(SF and Kosnik, 1510.00965)

Maximally allowed values of the Wilson coefficients in the low and high energy bins according to LHCb 1304.6365 :



LHCb 1304.6365

$$\mathrm{BR}(\pi^+\mu^+\mu^-)_{\mathrm{I}} \equiv \mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[0.0625,0.276]\ \mathrm{GeV}^2} < 2.5\times 10^{-8}$$

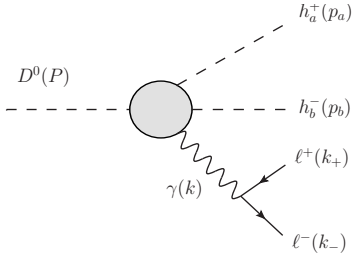
$$\mathrm{BR}(\pi^+\mu^+\mu^-)_{\mathrm{II}} \equiv \mathrm{BR}(D^+ \to \pi^+\mu^+\mu^-)_{q^2\in[1.56,4.00]\ \mathrm{GeV}^2} < 2.9\times 10^{-8}$$

- $D + B$ mesons : strong constraints on leptoquark models (favoured by B-anomalies), but also Z' models and 2HDM
- Analysis of rare decays possible in terms of effective Hamiltonian
- Constraints on short-distance physics from $Br(D^0 \to \mu\mu)$ and $Br(D \to \pi\mu\mu)$, and also from Lepton Flavour Universality in $D \to \pi\mu\mu$

$D \to PP\ell\ell$ decays

[Oscar Cata]

Long distances



- Bremsstrahlung: pure QED effects, calculable with Low's theorem:

$$\mathcal{M}_b(D^0 \to h_1^+ h_2^- \gamma) = 2e \left[\frac{p_1 \cdot \epsilon}{2p_1 \cdot q + q^2} - \frac{p_2 \cdot \epsilon}{2p_2 \cdot q + q^2} \right] \mathcal{M}(D^0 \to h_1^+ h_2^-)$$

- Resonant contributions (dominant effects, estimated at $\sim 10^{-6}$). [Burdman et al'02].
  For comparison, short distance SM contribution estimated at $\sim 10^{-9}$. [Bigi et al'11].
- Charge radius (suppressed, not discussed in this talk).

Branching ratios

Decay mode	Bremsstrahlung	Direct emission (E)	Direct emission (M)
$D^0 \to K^-\pi^+e^+e^-$	$9.9 \cdot 10^{-6}$	$6.2 \cdot 10^{-6}$	$4.8 \cdot 10^{-7}$
$D^0 \to \pi^+\pi^-e^+e^-$	$5.3 \cdot 10^{-7}$	$1.3 \cdot 10^{-6}$	$1.3 \cdot 10^{-7}$
$D^0 \to K^+K^-e^+e^-$	$5.4 \cdot 10^{-7}$	$1.1 \cdot 10^{-7}$	$5.0 \cdot 10^{-9}$
$D^0 \to K^+\pi^-e^+e^-$	$3.7 \cdot 10^{-8}$	$1.7 \cdot 10^{-8}$	$1.3 \cdot 10^{-9}$
$D^0 \to K^-\pi^+\mu^+\mu^-$	$8.6 \cdot 10^{-8}$	$6.2 \cdot 10^{-6}$	$4.8 \cdot 10^{-7}$
$D^0 \to \pi^+\pi^-\mu^+\mu^-$	$5.6 \cdot 10^{-9}$	$1.3 \cdot 10^{-6}$	$1.3 \cdot 10^{-7}$
$D^0 \to K^+K^-\mu^+\mu^-$	$3.3 \cdot 10^{-9}$	$1.1 \cdot 10^{-7}$	$5.0 \cdot 10^{-9}$
$D^0 \to K^+\pi^-\mu^+\mu^-$	$3.3 \cdot 10^{-10}$	$1.7 \cdot 10^{-8}$	$1.3 \cdot 10^{-9}$

- Experimental results (LHCb and BaBar): [arXiv:1510.08367; arXiv:1707.08377; arXiv:1808.09680

$$\mathcal{B}(D^0 \to K^-\pi^+\mu^+\mu^-) = (4.17 \pm 0.42) \cdot 10^{-6}$$
$$\mathcal{B}(D^0 \to \pi^+\pi^-\mu^+\mu^-) = (9.64 \pm 0.48 \pm 0.51 \pm 0.97) \cdot 10^{-7}$$
$$\mathcal{B}(D^0 \to K^+K^-\mu^+\mu^-) = (1.54 \pm 0.27 \pm 0.09 \pm 0.16) \cdot 10^{-7}$$
$$\mathcal{B}(D^0 \to K^-\pi^+e^+e^-) = (4.0 \pm 0.5 \pm 0.2 \pm 0.1) \cdot 10^{-6}$$

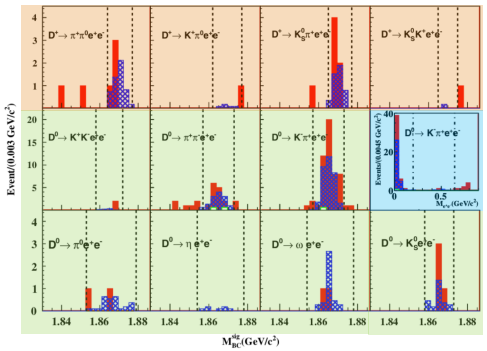
- Good agreement overall. Approximations capture the bulk of the effect.

- $D \to PP\ell\ell$: interplay of short and long distances
- Hadronic description mandatory: Vector dominance and factorisation of weak matrix elements
- Resonance exchange parametrised by form factors $D \to V$ and $V \to \ell\ell$
- Good overall agreement with later LHCb measurements
- Additional contribution from axial resonances ($a_1(1230)$ and $K_1(1272)$) to be included ($\simeq 30\%$ of vector)

Rare D decays at BESIII

[Peter Weidenkaff]

Search for $D \to h\,(h')e^+e^-$



Signal decays	$\mathcal{B}$ ($\times 10^{-5}$)	PDG [9] ($\times 10^{-5}$)
$D^+ \to \pi^+\pi^0 e^+e^-$	<1.4	···
$D^+ \to K^+\pi^0 e^+e^-$	<1.5	···
$D^+ \to K^0_S\pi^+ e^+e^-$	<2.6	···
$D^+ \to K^0_S K^+ e^+e^-$	<1.1	···
$D^0 \to K^-K^+ e^+e^-$	<1.1	<31.5
$D^0 \to \pi^+\pi^- e^+e^-$	<0.7	<37.3
$D^0 \to K^-\pi^+ e^+e^-$	<4.1	<38.5
$D^0 \to \pi^0 e^+e^-$	<0.4	<4.5
$D^0 \to \eta e^+e^-$	<0.3	<11
$D^0 \to \omega e^+e^-$	<0.6	<18
$D^0 \to K^0_S e^+e^-$	<1.2	<11
in $M_{e^+e^-}$ regions:		
[0.00, 0.20) GeV/c^2	<3.0 ($1.5^{+1.0}_{-0.9}$)	···
[0.20, 0.65) GeV/c^2	<0.7	···
[0.65, 0.90) GeV/c^2	<1.9 ($1.0^{+0.5}_{-0.4}$)	···

- UL $\mathcal{O}(10^{-5} \sim 10^{-6})$
- Significant improvements in UL

Phys.Rev.D97, 072015 (2018)

Search for $D^+ \to \gamma e^+ \upsilon_e$

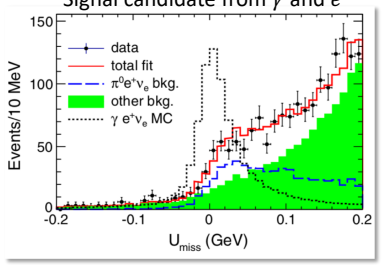
- Strong interaction effects theoretically simple
- SM predictions range from 10^{-6} to 10^{-4}
- Data sample at $D\bar{D}$ threshold: 2.93fb^{-1} @ $\sqrt{s} = 3.773 GeV$

$$BR(D^+ \to \gamma e^+ \upsilon_e) < 3.0 \times 10^{-5}$$

@ 90% C.L.

- Largest systematic from EMC shower model
- More data needed to discriminate th. models

Signal candidate from γ and e^+

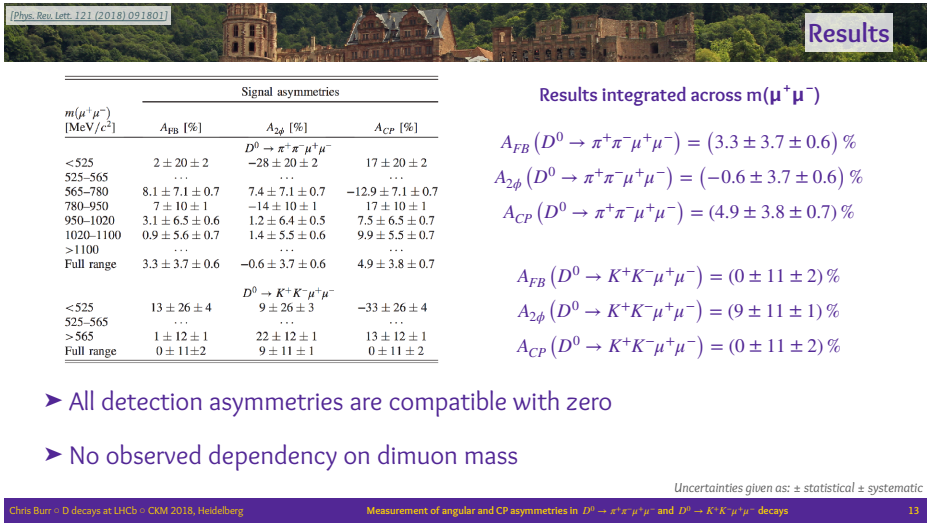


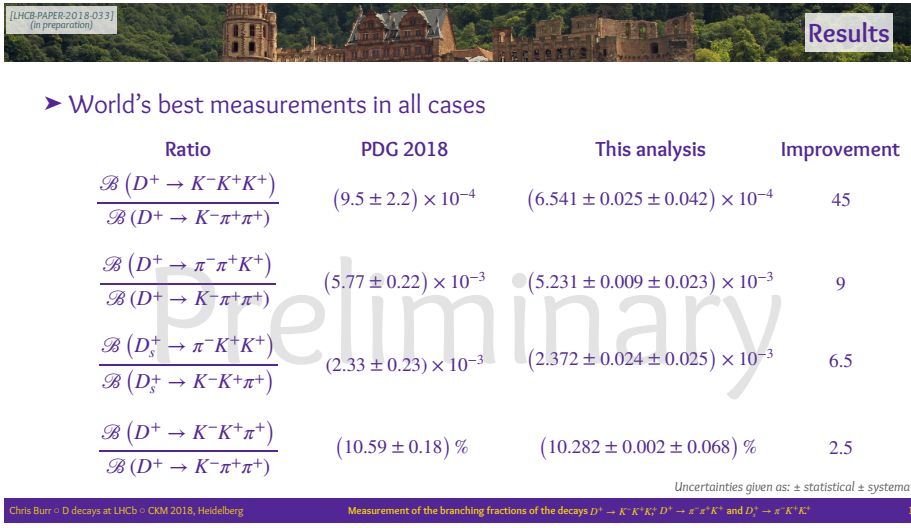
Phys. Rev. D. 95, 071102 (2017)

- Ongoing rich programme at BESIII
- Bounds on $D \to h(h')e^+e^-$ (10^{-5} level) and $D^+ \to \gamma e^+ \nu_e$
- Measurements of $D_s^+ \to p\bar{n}$ and $D \to a_0 e^+ \nu_e$
- Ongoing analyses on $D \to K\pi e^+e^+$, $D \to \pi^0 \nu\bar{\nu}$, baryon/lepton number violation in $D^+ \to \Lambda$ and Σ

Rare D decays at LHCb

[Chris Burr]





- LHCb not only with beauty but also with charm in abundance
- Angular and CP-asymmetries for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ and $D^0 \to K^+K^-\mu^+\mu^-$, potential signals of NP (vanish in SM)
- New: measurements of BRs for $D^+ \to K^-K^+K^+$, $D^+ \to \pi^-\pi^+K^+$, $D_s^+ \to \pi^-K^+K^+$ (significant improvement in all modes !)

K decays: probing NP since 1947

ϵ'/ϵ in and beyond the SM

[Jason Aebischer]

Motivation

$K \to \pi\pi$

ε' : direct CP violation in $K_L \to \pi\pi$
ε : indirect CP violation in $K_L \to \pi\pi$

Measurement hep-ex/0208009, hep-ex/0208007

NA48 and KTeV: $(\varepsilon'/\varepsilon)_{\text{exp}} = (16.6 \pm 2.3) \times 10^{-4}$

SM prediction

Lattice: $(1.4 \pm 6.9) \times 10^{-4}$	RBC-UKQCD: 1502.00263, 1505.07863
$(1.9 \pm 4.5) \times 10^{-4}$	Buras/Gorbahn/Jamin/Jäger:1507.06345
$(1.1 \pm 5.1) \times 10^{-4}$	Kitahara/Nierste/Tremper: 1607.06727
DQCD: $\leq (6 \pm 2.4) \times 10^{-4}$	Buras/Gérard 1507.06326
χPT: $(15 \pm 7) \times 10^{-4}$	Gisbert/Pich 1712.06147

Master formula

JA/Bobeth/Buras/Gérard/Straub:1807.02520

$$\left(\frac{\varepsilon'}{\varepsilon}\right)_{\text{NP}} = \sum_i P_i(\mu_W)\, \text{Im}[C_i(\mu_W) - C_i'(\mu_W)]$$

with

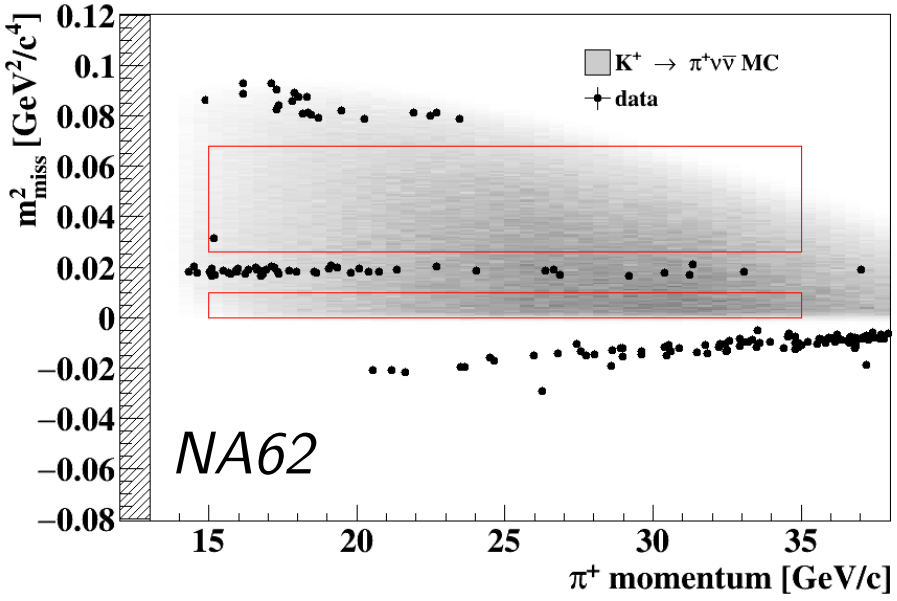
$$P_i(\mu_W) = \sum_j \sum_{I=0,2} p_{ij}^{(I)}(\mu_W, \mu_c) \left[\frac{\langle O_j(\mu_c)\rangle_I}{\text{GeV}^3}\right]$$

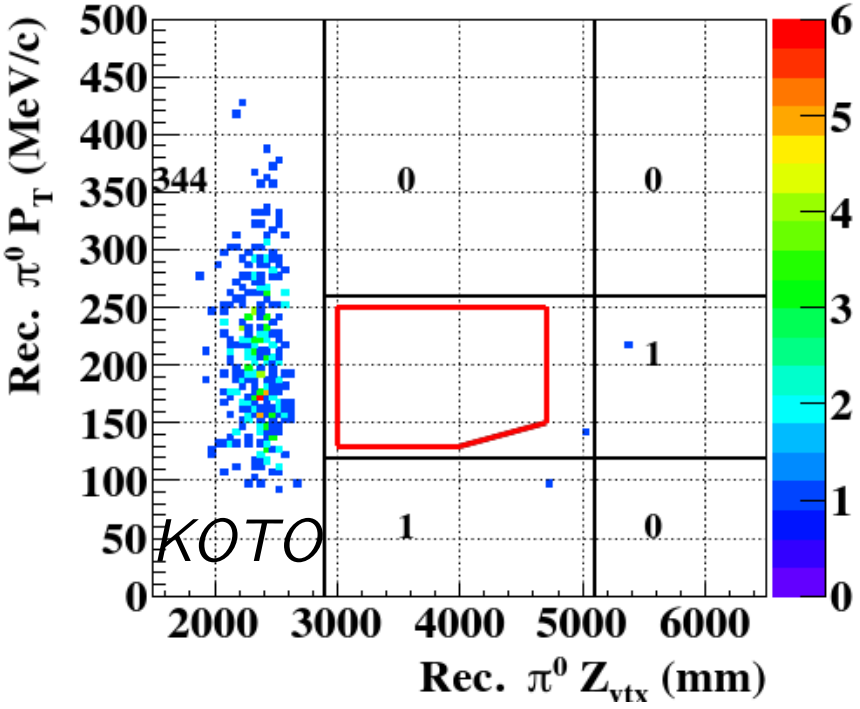
$p_{ij}^{(I)}(\mu_W, \mu_c)$ = Evolution from μ_c to μ_W
$\langle O_j(\mu_c)\rangle_I$ = Hadronic MEs

- Ongoing discussion on the SM computation of ϵ'/ϵ with different approaches (lattice, chiral perturbation theory...)
- Dual QCD: large N_c + meson description + $1/N_c$ corrections
- Master formula to obtain ϵ'/ϵ in SMEFT

Results from NA62/KOTO

[Michal Koval]



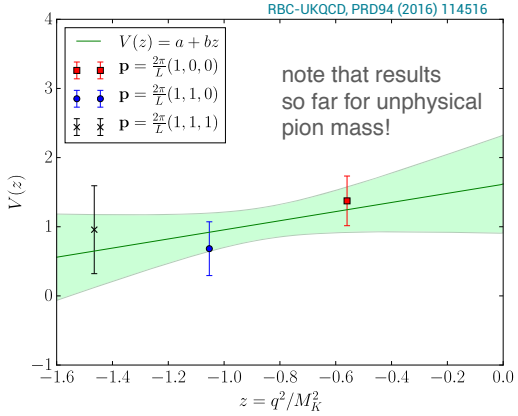


- NA62:
  - One event observed in signal region R2
  - $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95%CL
- KOTO:
  - No signal candidates observed
  - $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) < 3 \times 10^{-9}$ @ 90%CL
- Both results are compatible with the SM

Lattice results on $K \to \pi\nu\bar{\nu}$ and $K \to \pi\ell\ell$ [Andreas Juttner]

$K^+ \to \pi^+ l^+ l^-$ Results exploratory study

RBC-UKQCD, PRD94 (2016) 114516



$V_+(z)=a_+ + b_+ q^2/m_K^2$ our result: $a_+=1.6(7)$, $b_+=0.7(8)$

pheno fit to exp. data: $a_+=-0.58(2)$, $b_+=0.78(7)$

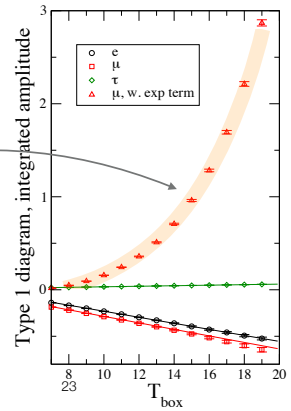
Cirigliano, et. al., Rev. Mod. Phys. 84 (2012) 399

$K^+ \to \pi^+\nu\bar{\nu}$ decay

$$\int_{-T_a}^{T_b} dx_0 \langle \pi^+\nu\bar{\nu}|T\{H_A(x_0)H_B(0)\}|K^+\rangle = \sum_n \left\{ \frac{\langle \pi^+\nu\bar{\nu}|H_A|n\rangle\langle n|H_B|K^+\rangle}{E_n - E_K}\left(1 - e^{(E_K - E_n)T_b}\right) + \frac{\langle \pi^+\nu\bar{\nu}|H_B|n\rangle\langle n|H_A|K^+\rangle}{E_n - E_K}\left(1 - e^{(E_K - E_n)T_a}\right)\right\}$$

intermediate states:

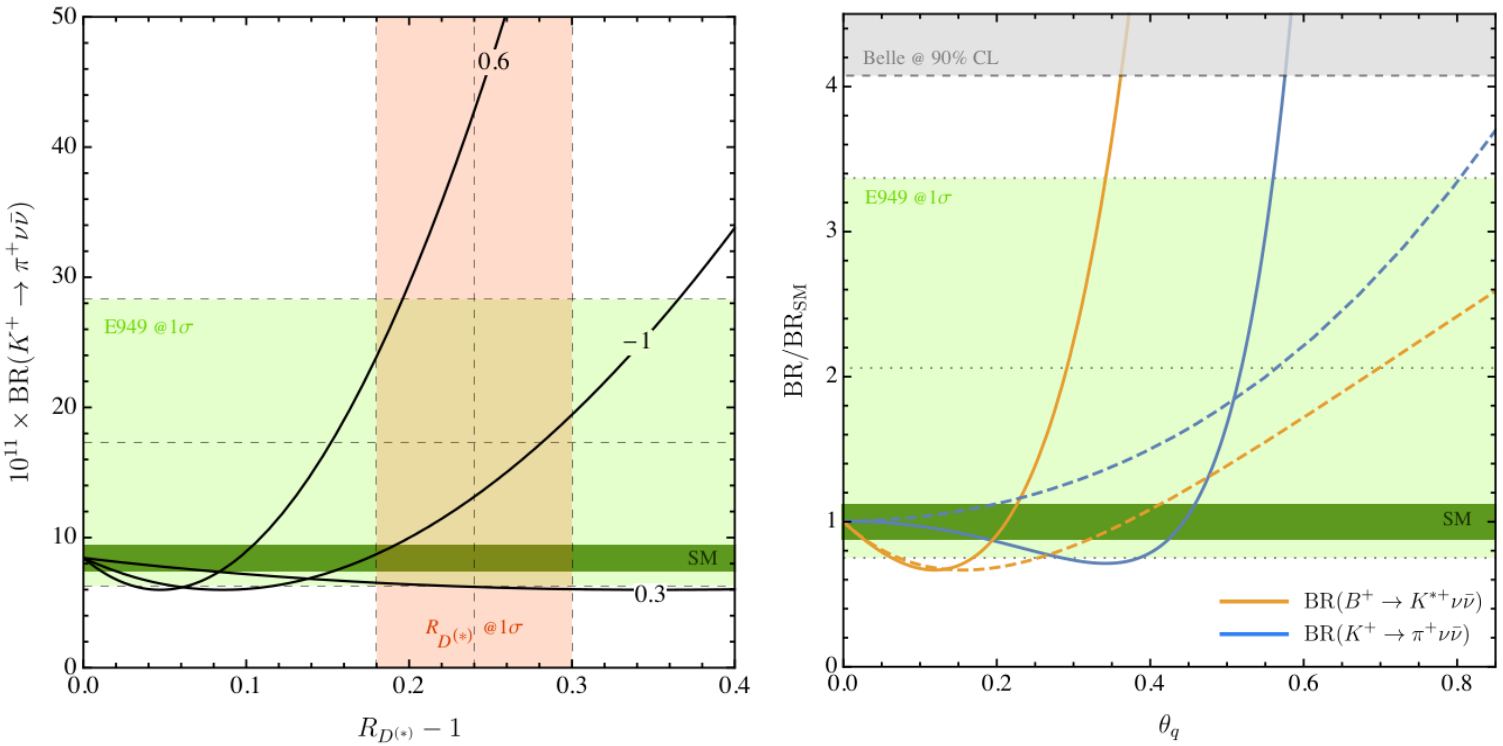
$$|n\rangle = |l^+\nu\rangle, |\pi^0 l^+\nu\rangle, |(\pi^+\pi^0)^{I=2}\rangle$$



- First lattice evaluation of $K^+ \to \pi^+\ell\ell$ form factor
- Intermediate state subtraction and renormalisation are technical challenges that can be managed
- Work in progress towards real-world simulations

Connecting $K \to \pi\nu\bar{\nu}$ and B anomalies

[Marzia Bordone]



- EFT approach based on $U(2)^n$ flavour symmetry
- $s \to d\nu\bar{\nu}$ may distinguish between classes of models within EFT
- Interesting correlations between $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ and
  - $R_{D^{(*)}}$
  - $\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})$
- PS^3 model contains Z' contributing to $K \to \pi\nu\bar{\nu}$ at tree level
  - up to $\sim 20\%$ effects on $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$