Rare, radiative and semi-leptonic B decays; Charm and Kaon Physics

GdR-inF annual meeting, 6-8 November, Strasbourg

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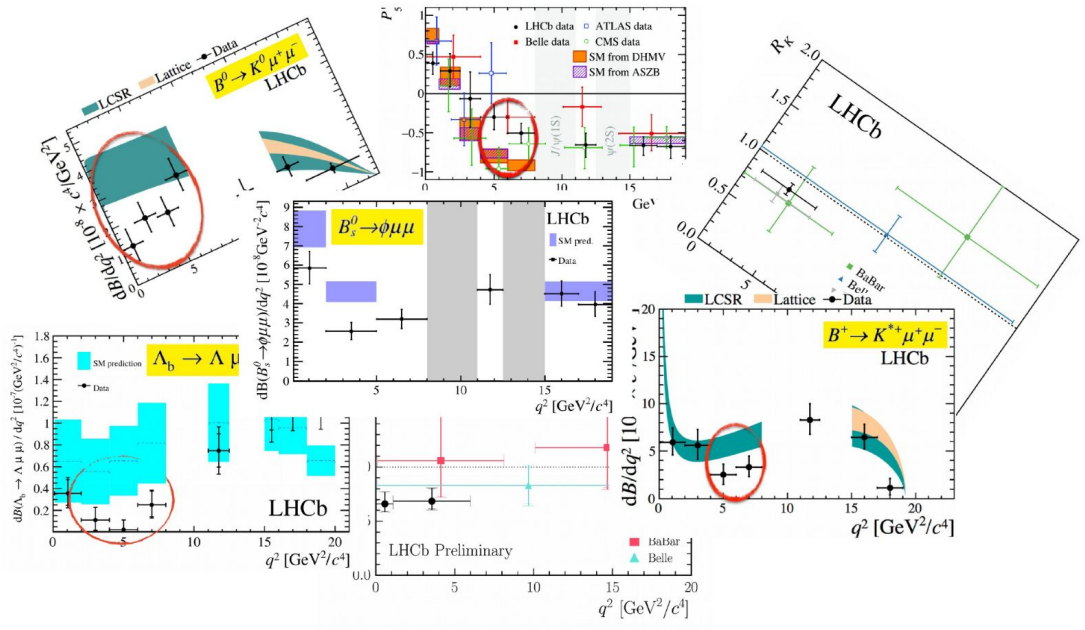
Theoretical overview & challenges

Seeking New Physics with rare *B*-decays

Impressive effort in studying $b \to s\ell\ell$ transitions at LHCb, but also ATLAS, CMS and Belle, with the measurement of a large number of independent branching ratios and angular observables, ratios,...

$B \to K\mu^+\mu^-$, $B \to K^+e^+e^-$, $B \to K^*\mu^+\mu^-$ (F_L, A_{FB}, S_i, P_i), $B_s \to \phi\mu^+\mu^-$, ...

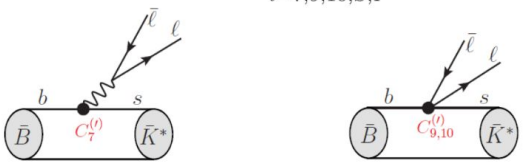


Several small deviations from the SM predictions in BR & angular measurements…

Theoretical Framework: $b \to s\ell\ell$

Effective Hamiltonian has two parts: $\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\rm sl} + \mathcal{H}_{\rm eff}^{\rm had}$

$$\mathcal{H}_{\rm eff}^{\rm sl} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=7,9,10,S,P} C_i^{(\prime)} \mathcal{O}_i^{(\prime)} \Big]$$



$$\langle M\ell\ell|\mathcal{H}_{\rm eff}^{\rm sl}|B\rangle \propto \mathcal{A}_V^\mu\, \bar{u}_\ell\gamma_\mu v_\ell + \mathcal{A}_A^\mu\, \bar{u}_\ell\gamma_\mu\gamma_5 v_\ell + \mathcal{A}_S\, \bar{u}_\ell v_\ell + \mathcal{A}_P\, \bar{u}_\ell\gamma_5 v_\ell$$

local contributions:

$$\mathcal{A}_V^\mu = -\frac{2im_b}{q^2} C_7 \langle M|\bar{s}\,\sigma^{\mu\nu}q_\nu\, P_R\, b|B\rangle + C_9\langle M|\bar{s}\,\gamma^\mu\, P_L\, b|B\rangle$$

$$\mathcal{A}_A^\mu = C_{10}\langle M|\bar{s}\,\gamma^\mu\, P_L\, b|B\rangle$$

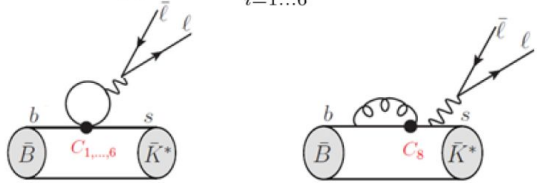
$$\mathcal{A}_{S,P} = C_{S,P}\langle M|\bar{s}\, P_R\, b|B\rangle$$

- 3 form factors for final state $M = K$
- 7 form factors for final state $M = K^*, \phi$

Determined by **Lattice QCD** (high q^2), **Light-Cone Sum Rules** (low q^2) and **combined fit of LCSR + Lattice** (low + high q^2)

Ball et al' '04; Khodjamirian et al. '10; HPQCD '13; Altmannshofer et al. '14; Bharucha et al. '15; MILC '15 ; Horgan et al. '15; Gubernari et al. '18

$$\mathcal{H}_{\rm eff}^{\rm had} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \Big[\sum_{i=1\ldots6} C_i^{(\prime)} \mathcal{O}_i^{(\prime)} + C_8\mathcal{O}_8 \Big]$$



$$\langle M\ell\ell|\mathcal{H}_{\rm eff}^{\rm had}|B\rangle \propto \mathcal{N}^\mu\, \bar{u}_\ell\gamma_\mu v_\ell$$

non-local contributions:

$$\mathcal{H}^\mu = \frac{-16i\pi^2}{q^2} \sum_{i=1,\ldots,6,8} C_i \int dx^4 e^{iq\cdot x} \langle M|T\{j_{\rm em}^\mu(x), O_i(0)\}|B\rangle$$

$$j_{\rm em}^\mu = \sum_q Q_q\, \bar{q}\gamma^\mu q$$

Calculated for low q^2 at **LO in QCD factorization (QCDf)**

Beneke et al '01 and '04

higher powers not fully known ("guesstimated")

↪ recent progress using **analyticity + experimental data on $b \to sc\bar{c}$** show these corrections should be small

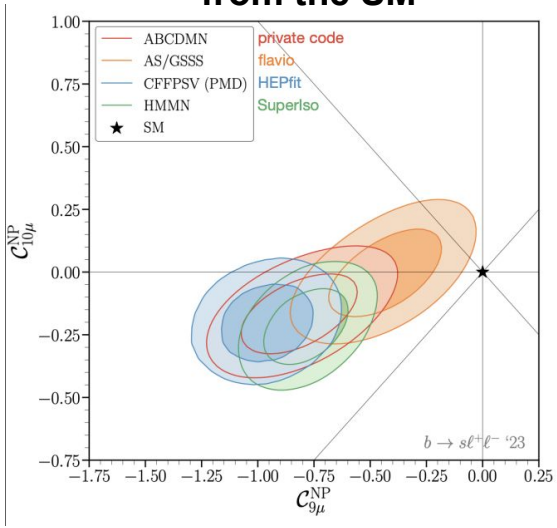
Bobeth et al. '17, Gubernari, et al. '20 and '22

For a review of the status of non-local contribution calculation, talk by M. Reboud at Implications 2023

Global $b \to s\ell\ell$ fits

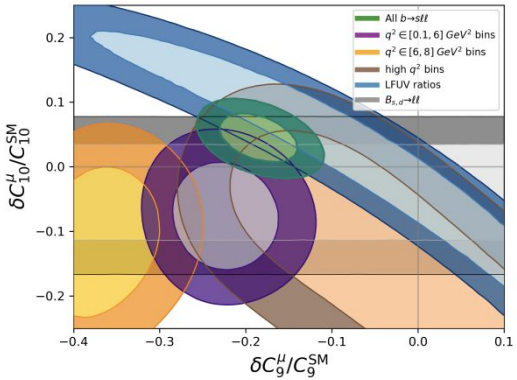
2310.05585

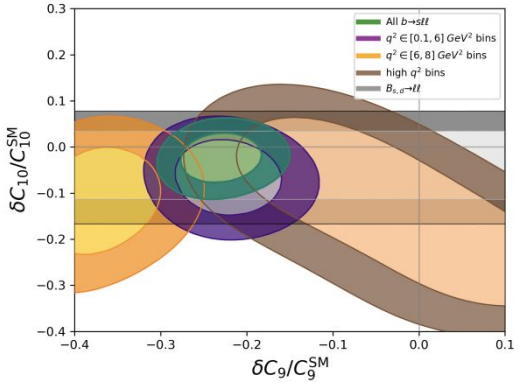
Muon WCs still deviating from the SM

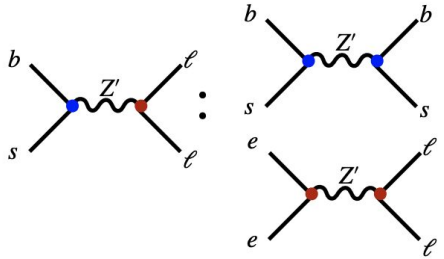


Good agreement between fits even with different statistical frameworks, observable sets, parameterisations and parameters used

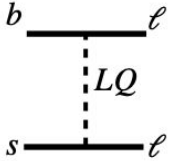
R_K and R_{K^*} now prefer LFU -> implications for models



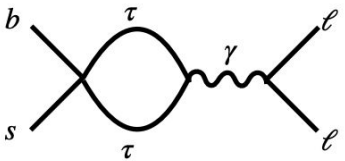




Z' easily be LFU
But stringent complementary constraints (there is wiggle room)



Not that easily LFU because of stringent cLFV constraints, can be done if LQ e.g. lepton-flavored



RG effect, connection with with , also possible through 4q operator

$B_s \to \mu\mu$ and $b \to d\ell\ell$ fits

2210.07221

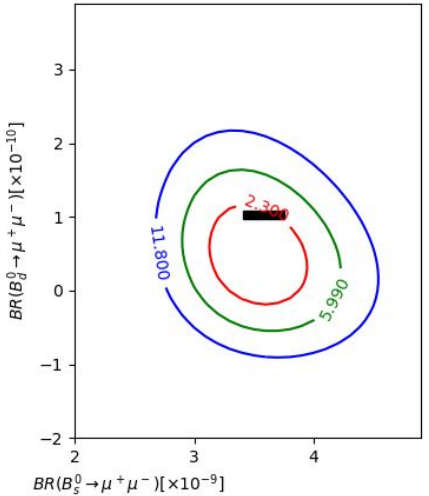
SM prediction: $\mathrm{BR}(B_s \to \mu^+\mu^-) = (3.61 \pm 0.17) \times 10^{-9}$

CMS, July 2022 (CMS-PAS-BPH-21-006)

$$\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{CMS}} = (3.95^{+0.39+0.27+0.21}_{-0.37-0.22-0.19}) \times 10^{-9}$$

combination using the latest measurements:

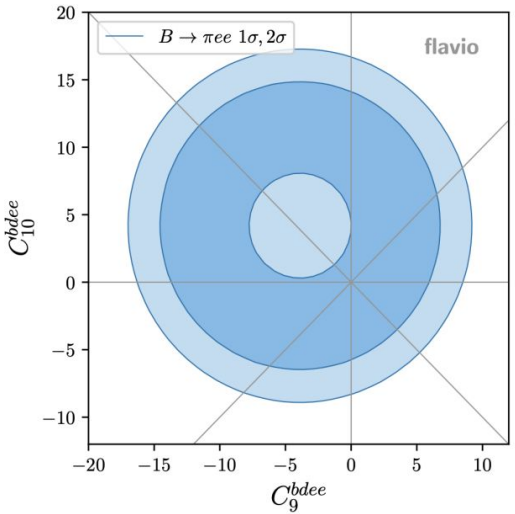
$$\mathrm{BR}(B_s \to \mu^+\mu^-) = 3.52^{+0.32}_{-0.30} \times 10^{-9}$$

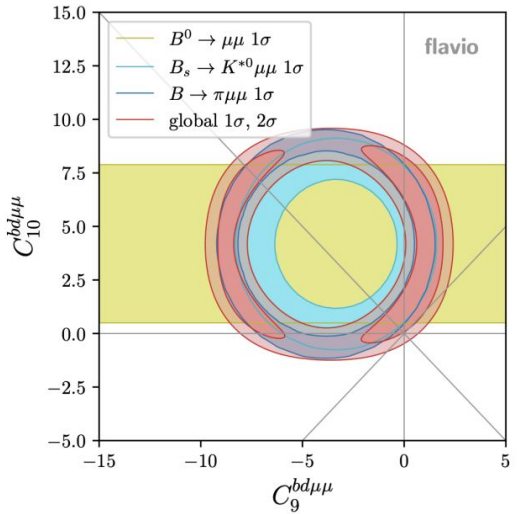


$B \to d\ell\ell$:

- Several semi- and fully leptonic measurements from LHCb, Belle and ATLAS/CMS
- Sizeable room for NP
- Slight preference for negative C_9 (= − C_{10})

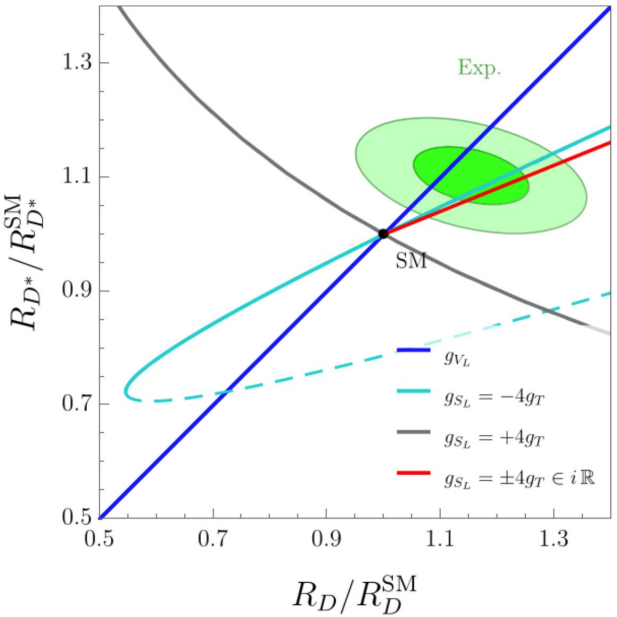
2212.10497





LFU violation in $b \to c\tau\nu$

$$\mathcal{L}_{\text{eff}} = -2\sqrt{2} G_F V_{cb} \Big[(1 + g_{V_L}) (\bar{c}_L \gamma_\mu b_L) (\bar{\ell}_L \gamma_\mu \nu_L) + g_{V_R} (\bar{c}_R \gamma_\mu b_R) (\bar{\ell}_L \gamma_\mu \nu_L) + g_{S_R} (\bar{c}_L b_R) (\bar{\ell}_R \nu_L) + g_{S_L} (\bar{c}_R b_L) (\bar{\ell}_R \nu_L) + g_T (\bar{c}_R \sigma_{\mu\nu} b_L) (\bar{\ell}_R \sigma_{\mu\nu} \nu_L) \Big] + \text{h.c.}$$



- Several scenarios can accommodate data:

  ⇒ *e.g.*, g_{V_L} and $g_{S_L} = \pm 4 g_T$ (at $\mu \approx 1$ TeV).

- More **exp. information** is **needed!**

  i) *e.g., many angular observables:*

  $B \to D\tau\bar{\nu}$ $B \to D^*(D\pi)\tau\bar{\nu}$ $\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\bar{\nu}$

  ii) *Other LFU ratios:*

  $R_{D_s^{(*)}},\ R_{\eta_c},\ R_{J/\psi},\ R_{\Lambda_c},\ \ldots$

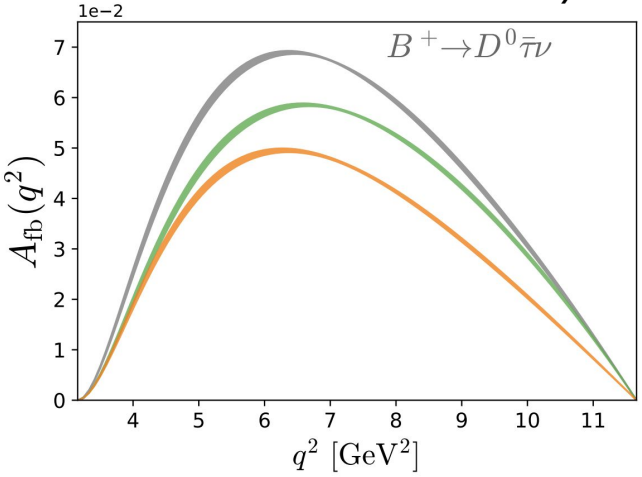
see e.g. [2103.12504]

Angular observables - $b \to c\tau\nu$

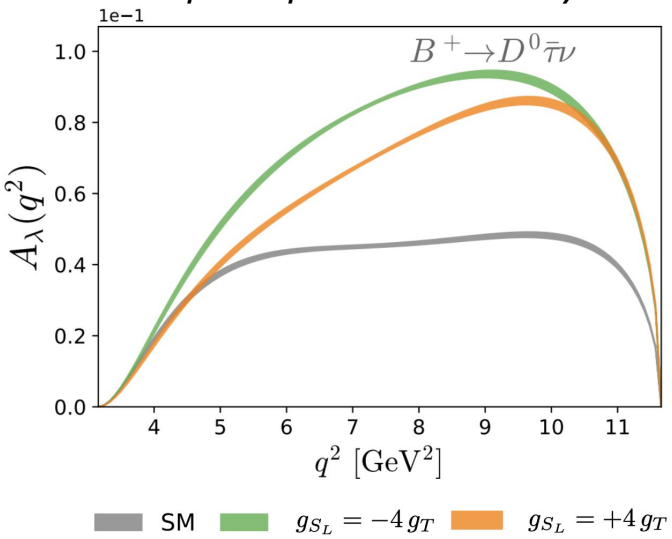
Example: $B \to D\tau\bar{\nu}$

2012.09872

Forward-backward asymmetry



Lepton-polarization asymmetry



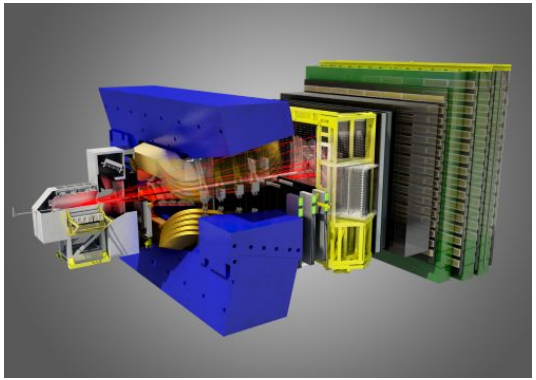
Many more opportunities in other modes:

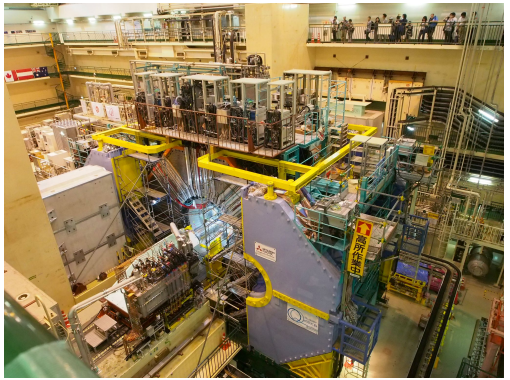
$B \to D^*(\to D\pi)\tau\bar{\nu}$ [1602.03030, 1907.02257, 2104.02094...]

$\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\bar{\nu}$ [1907.12554, 2209.13409]

Experimental overview & challenges

LHCb vs Belle II





- **σ (pp → bb) ~ 144 μb** (13 TeV) in $2 < \eta < 5$
- **3 fb^{-1} at 7-8 TeV + 6 fb^{-1} at 13 TeV**

- Boosted topologies - excellent vertexing (VELO)
- Good PID (RICH, Calo, Muon)
- Access to c & s charges + baryons
- No hermeticity
- Hadronic environment: high backgrounds & low trigger thresholds

- **e^+e^- collisions at 10.58 GeV** (Υ(4S) resonance)
- **~ 430 fb^{-1} collected in total (~360 fb^{-1} in Υ(4S))**

- Clean environment, high trigger efficiency
- Hermetic detector, missing energy recovered
- World-record luminosity ($4.7 \cdot 10^{34}$ cm^{-2} s^{-1})
- Lower production cross-section $\sigma(e^+e^- \rightarrow \Upsilon(4S)) \sim 1$ nb
- Only access to $B^{(+,0)}$ mesons

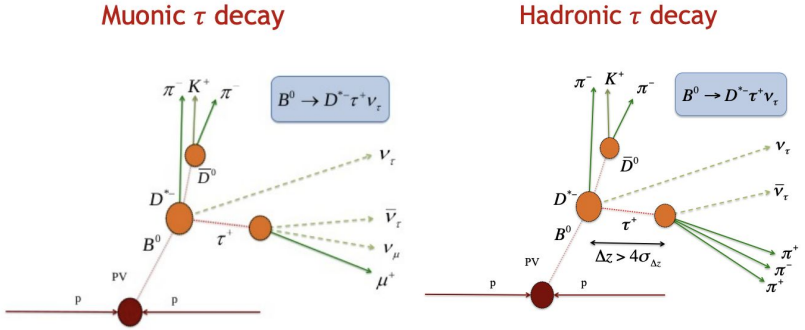
Flavour Changing Charged Currents

RD* updates from Belle II and LHCb

$$R(H_c) = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H_c \tau \bar{\nu}_\tau)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H_c \ell \bar{\nu}_\ell)}{dq^2} dq^2}$$

RD* with hadronic tau decays at LHCb

[Phys. Rev. D108 (2023) 012018]

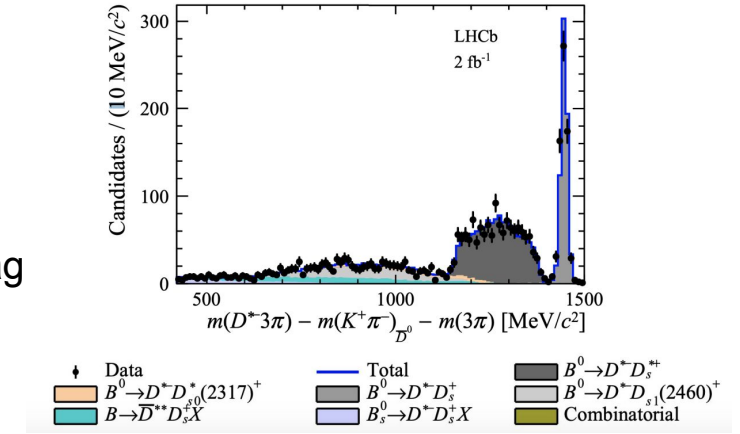


- 2015 + 2016 dataset (2 fb^{-1})
- Signal from 3-D binned template fit to q^2, t_τ and anti-D^+_s BDT
- Background suppression using τ vertex dynamics
- Combined with Run 1 result -> one of the most precise measurements of RD*

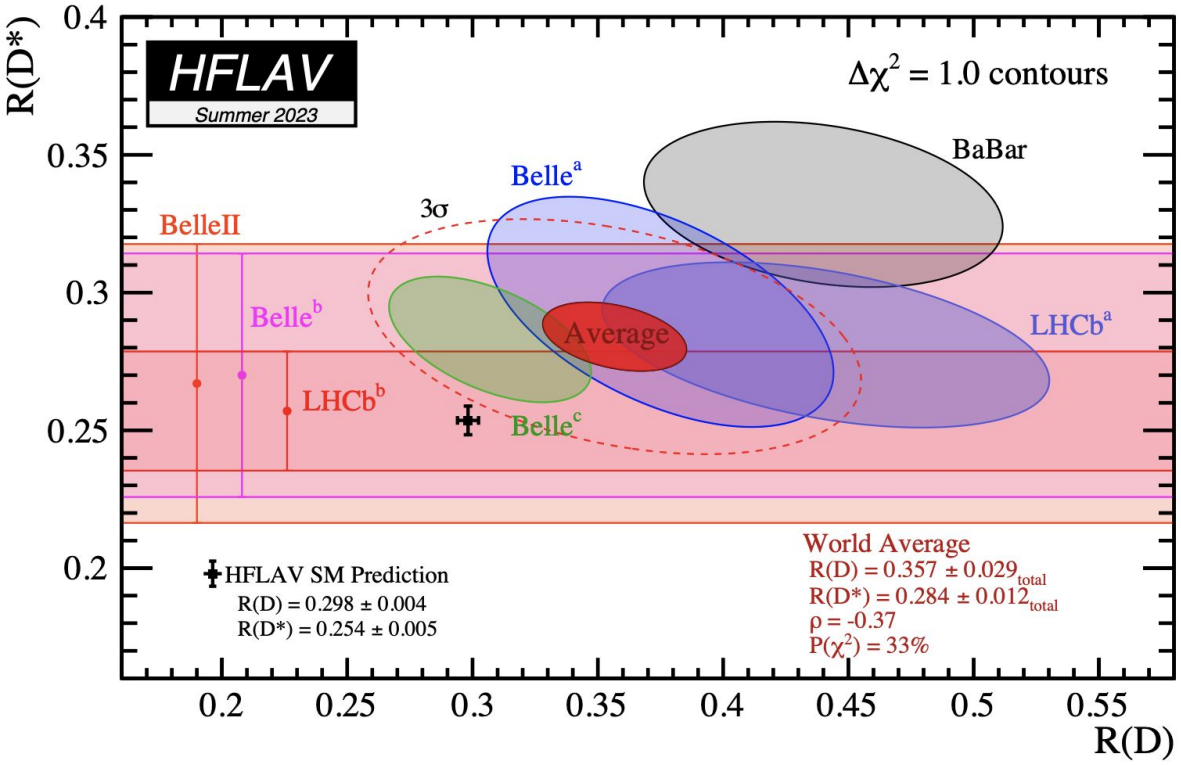
First RD* measurement of Belle II (189 fb^{-1}) Talk at LP2023

- Hadronic B_{tag} (ML), B_{sig} leptonic τ decays (e/μ)
- Challenges: multiple neutrinos, low stat due to hadronic B-tag

$$R(D^*) = 0.267\ ^{+0.041}_{-0.039}(\text{stat.})\ ^{+0.028}_{-0.033}(\text{syst.})$$



Global RD-RD* picture

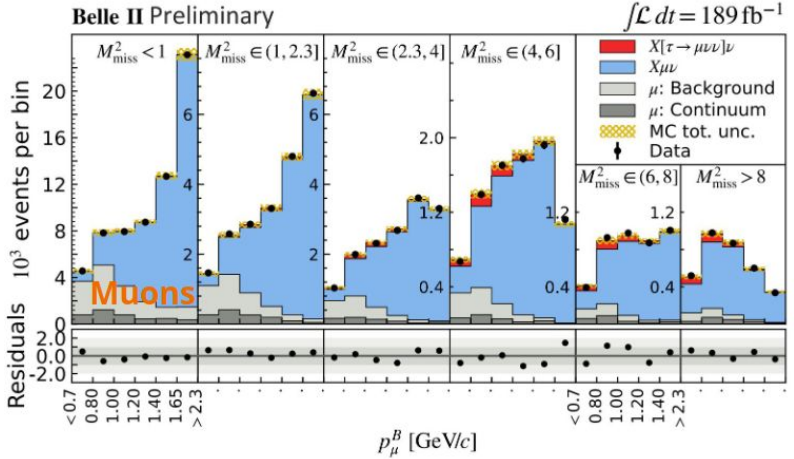


Tension from the SM at 3.3σ

Measurement of R(X) at Belle II

Talk at EPS

$$R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$



- **Inclusive R(X) provides an alternative to R(D$^{(*)}$) measurement**
- Measured for the first time at B factory with both e and μ channels!
- Combined result consistent with SM = 0.223 ± 0.006 but also with R(D$^{(*)}$)

$$R(X_{\tau/e}) = 0.232 \pm 0.020\ (\text{stat}) \pm 0.037\ (\text{syst})$$
$$R(X_{\tau/\mu}) = 0.222 \pm 0.027\ (\text{stat}) \pm 0.050\ (\text{syst})$$

→ ***R(X)* = 0.228 ± 0.016(stat) ± 0.036 (syst)**

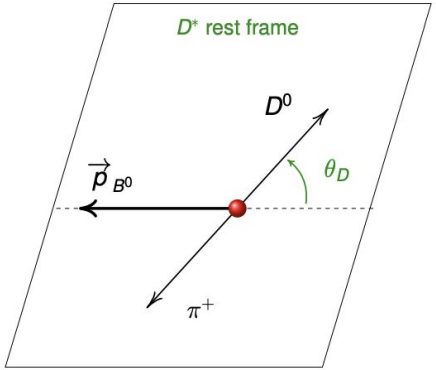
Tackling the angular front

Differential decay rate: $\frac{d^2\Gamma}{dq^2 d\cos\theta_D} = a_{\theta_D}(q^2) + c_{\theta_D}(q^2)\cos^2\theta_D$

D* longitudinal polarization from $B^0 \to D^{*-}\tau^+\nu_\tau$

Longitudinal polarization: $F_L^{D^*}(q^2) = \frac{a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}{3a_{\theta_D}(q^2) + c_{\theta_D}(q^2)}$

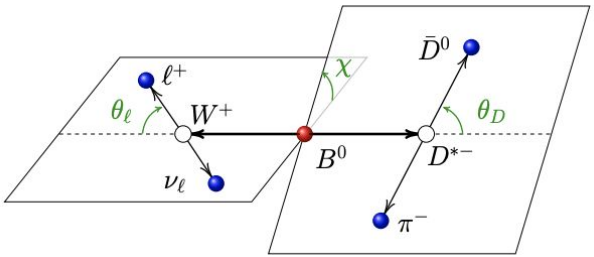
- [LHCB-PAPER-2023-020] in preparation
- State of the art:
  - Theory: [0.441 ± 0.006, 0.457 ± 0.010]
  - Exp: prev. only measured by Belle
- First time by LHCb, using hadronic τ decays (5 fb^{-1})
  - Similar strategy as RD* hadronic
- Measured in two q^2 bins, main systematic from limited template stat.
- $F_L^{D^*} = 0.43 \pm 0.06 \pm 0.03$ - compatible with SM



Full angular analysis:

$$\frac{d^4\Gamma(B^0 \to D^{*-}\ell^+\nu_\ell)}{dq^2 d\cos^2\theta_\ell d\cos\theta_{D^*} d\chi} \propto |V_{cb}|^2 \sum_i \mathcal{H}_i(q^2)\, f_i(\theta_\ell, \theta_{D*}, \chi)$$

- WIP by LHCb, see more in Bogdan's talk



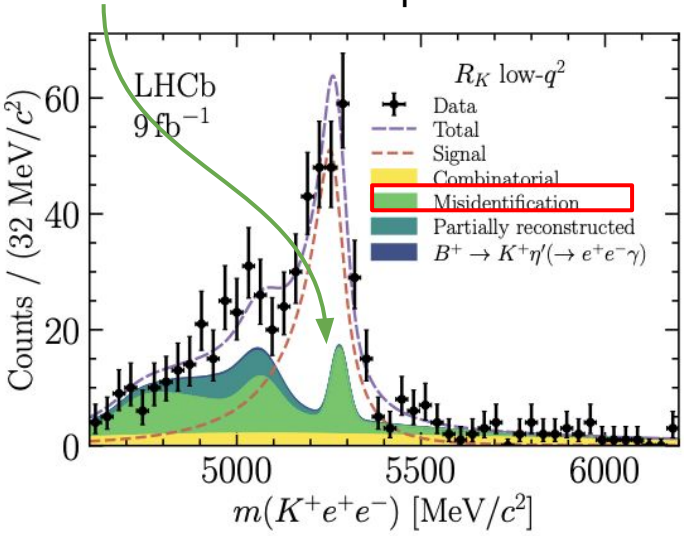
Flavour Changing Neutral Currents

Combined measurement of RK and RK*

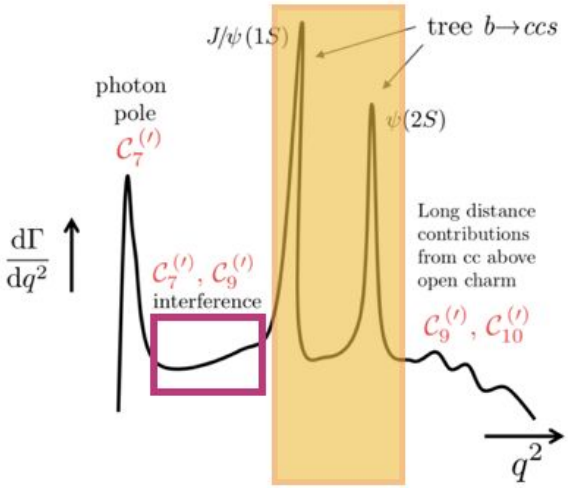
First combined measurement of RK and RK* using full LHCb dataset [arXiv:2212.09153] [arXiv:2212.09152]

Improvements with respect to previous publication [Nat. Phys. 18, 277-282 (2022)]:

- Simultaneous fit & increased statistics
- Better understanding of misID backgrounds:
  - Tighter PID requirements on electrons
  - Residual misID component included in fit



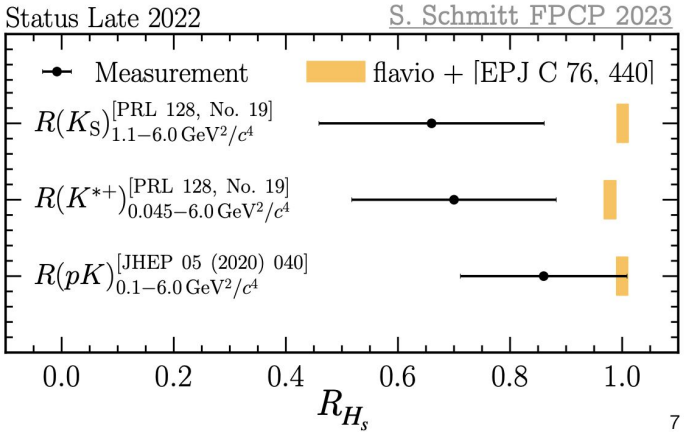
$$R_X = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H\ell_1^+\ell_1^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma(H_b \to H\ell_2^+\ell_2^-)}{dq^2} dq^2}$$

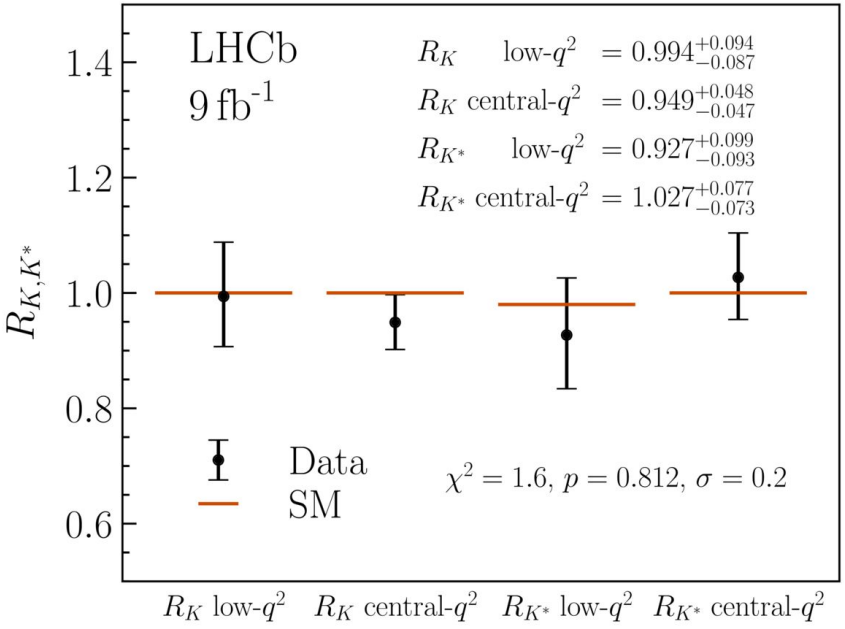


Combined measurement of RK and RK*

- **RK(*) compatible with SM within 5%**

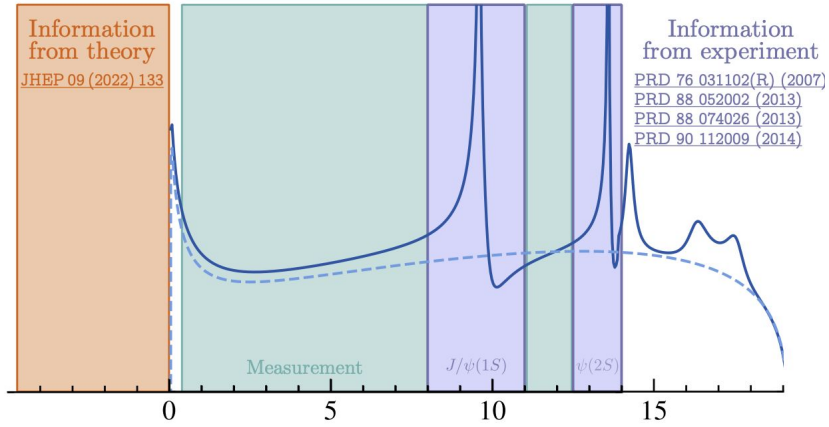
- **Things cooking:**
  - Explore high-q2 region in e/μ
  - b->d l l
  - b->s τ τ
  - Other hadronic channels and angular observables





Unbinned amplitude analysis of $B^0 \to K^{0*}\mu^+\mu^-$

Analysis concept: include charm loops in the measurement to understand whether anomalies can be accounted for from QCD



non-local hadronic matrix elements "charm-loop"

- Perform q^2 unbinned amplitude analysis
  - model *local* vs *non-local* contributions

$$\mathcal{A}_\lambda^{L,R} = \mathcal{N}_\lambda \left\{ \left[(\mathcal{C}_9 \pm \mathcal{C}'_9) \mp (\mathcal{C}_{10} \pm \mathcal{C}'_{10}) \right] \mathcal{F}_\lambda(q^2) + \frac{2 m_b M_B}{q^2} \left[(\mathcal{C}_7 \pm \mathcal{C}'_7) \mathcal{F}_\lambda^T(q^2) - 16\pi^2 \frac{M_B}{m_b} \mathcal{H}_\lambda(q^2) \right] \right\}$$

$\lambda = \perp, \parallel, 0$

Wilson coeff. — Form Factors

[CKM slides]

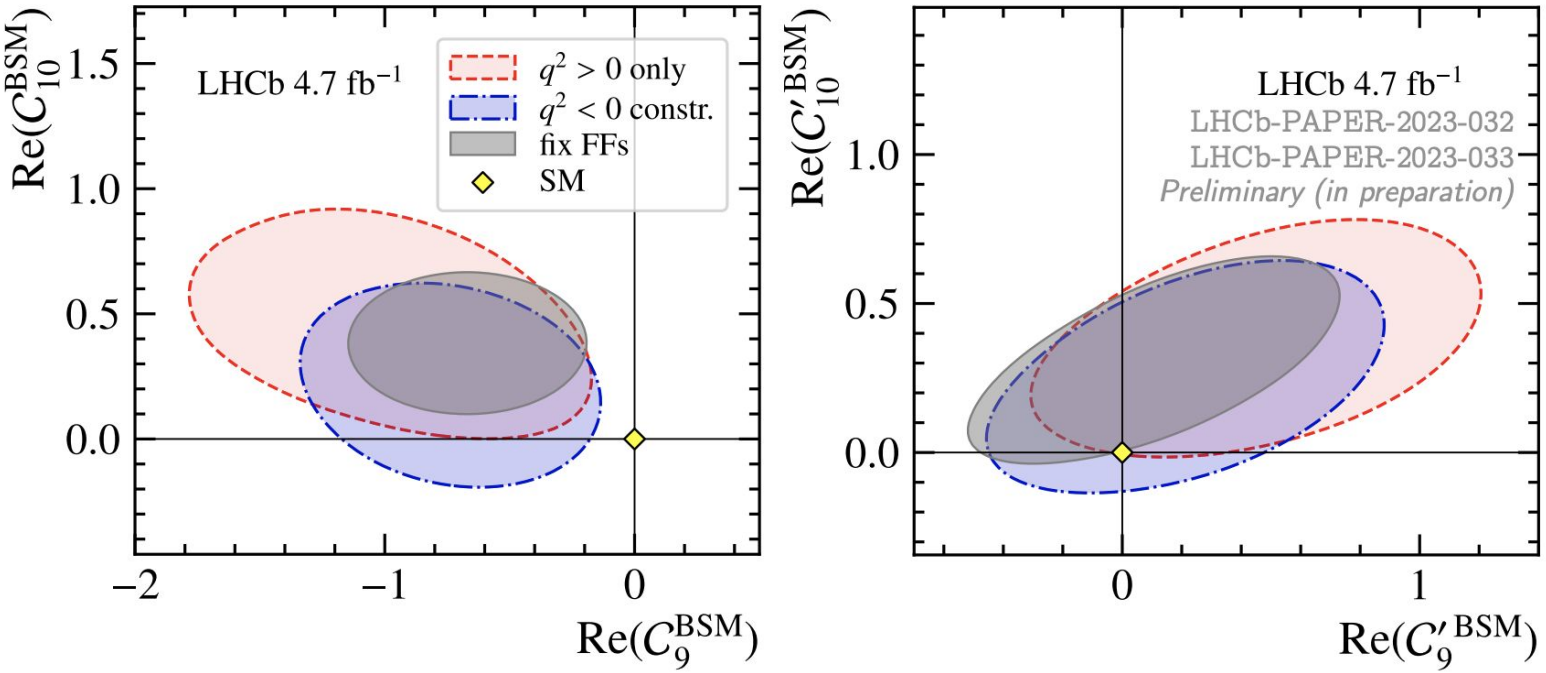
polynomial expansion — JHEP 09 (2022) 133

$$\mathcal{H}_\lambda(z) = \frac{1 - z z^*_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z^*_{\psi(2S)}}{z - z_{\psi(2S)}} \times \ldots \times \sum_n \alpha_{\lambda,n} z^n$$

- **Fit 5-D differential decay rate!**
  - $q^2, m^2_{K\pi}, \cos\theta_\ell, \theta_K, \phi$

Slide from A. Mauri CKM '23

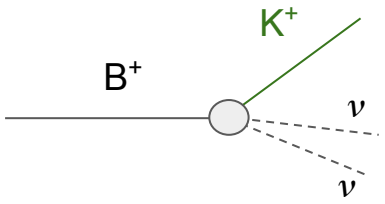
Unbinned amplitude analysis of $B^0 \to K^{0*} \mu^+ \mu^-$

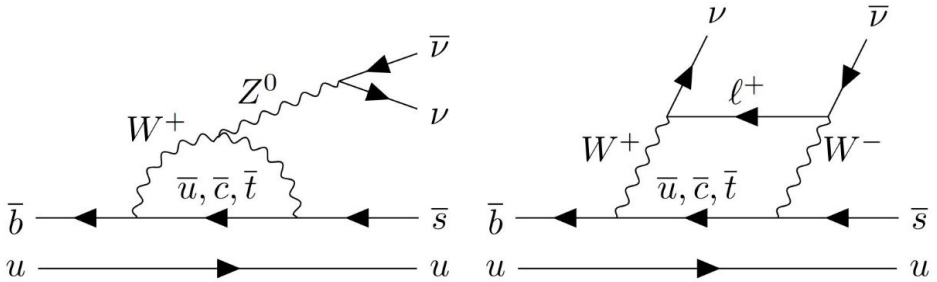


Data — SM tension ~1.9 σ in C9 , glonsl tension ~1.4 σ

$B^+ \to K^+ \nu \nu$ in Belle II

- FCNC suppressed by GIM mechanism: **BR_{SM} ~ 5 x 10^{-6}**
- One charged track in the final state: reconstruction of missing energy is crucial





- Belle II recently reported a new measurement using 362 fb^{-1}
- **France heavily involved (Strasbourg group)**

Dedicated talk this afternoon!

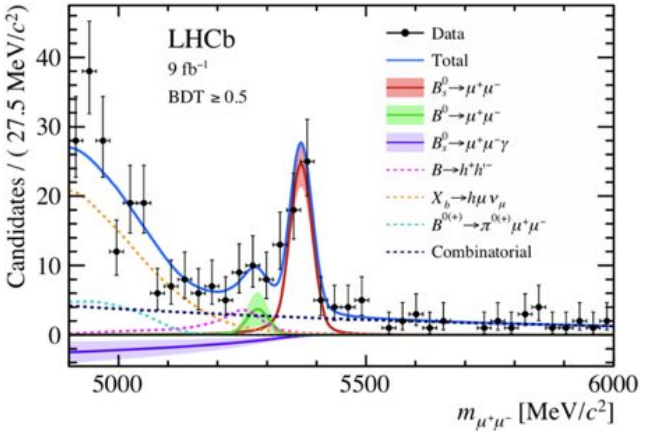
Ultra-rare and radiative decays

Ultra-rare and radiative decays

- $B^0_{(s)} \to l^+ l^- (\gamma)$:
  - LHCb [PRL128 (2022) 041801] and CMS [2212.10311] provided legacy measurements last year in the dimuon mode
  - World's best measurement from CMS
  - LHCb upper limits on $B^0_{(s)} \to e^+e^-$ [arXiv:2003.03999] and $B^0_{(s)} \to \tau^+\tau^-$ [arXiv:1703.02508]

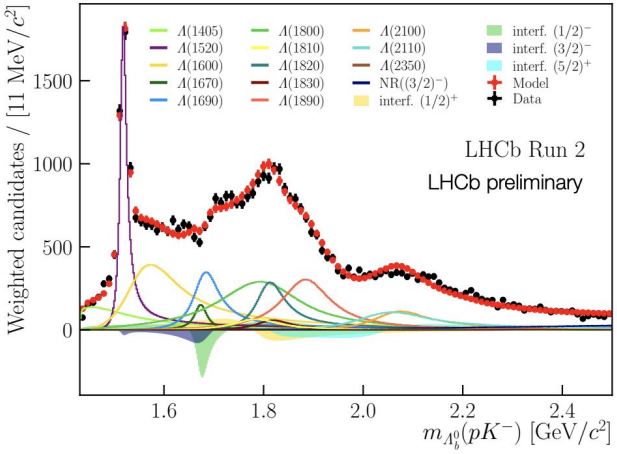
$$\bar{\mathcal{B}}(B^0 \to e^-e^+) < 3.0 \cdot 10^{-9} \text{ at } 95\% \text{ CL}, \quad \bar{\mathcal{B}}(B^0 \to \tau^+\tau^-) < 2.1 \cdot 10^{-3} \text{ at } 95\% \text{ CL},$$
$$\bar{\mathcal{B}}(B^0_s \to e^-e^+) < 11.2 \cdot 10^{-9} \text{ at } 95\% \text{ CL}. \quad \bar{\mathcal{B}}(B^0_s \to \tau^+\tau^-) < 6.8 \cdot 10^{-3} \text{ at } 95\% \text{ CL}.$$

  - LHCb working on $B^0_{(s)} \to l^+ l^- \gamma$, see talk from Irene



[LHCb-PAPER-2023-036 in preparation]

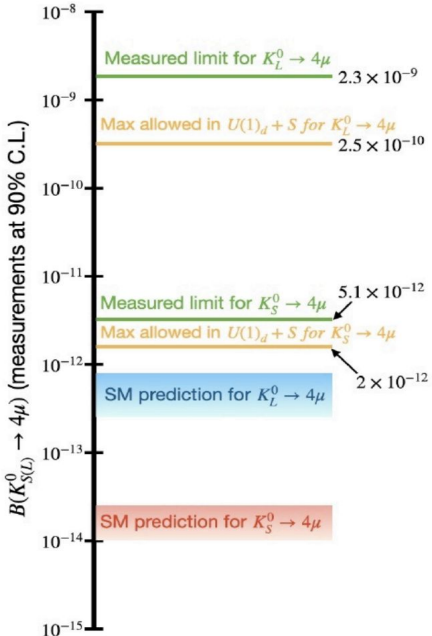
- **Amplitude analysis of Λb→pKγ:**
  - Motivation: explore resonance structure of pK spectrum up to heavier states
  - Best model containing dominant contributions from Λ(1800), Λ(1600), Λ(1890) and Λ(1520)
  - Uncertainty dominated by external inputs to amplitude model



Beyond the B-sector: Rare charm and Kaon physics

- **Rare charm searches at LHCb:**
  - Search for $D^0 \to \mu^+\mu^-$: $\mathcal{B}(D^0 \to \mu^+\mu^-) < 3.1 \times 10^{-9}$ at 90% CL 🇫🇷 1305.5059
  - Search for $D^{*0}(2007) \to \mu^+\mu^-$: $\mathcal{B}(D^{*0} \to \mu^+\mu^-) < 2.6 \times 10^{-8}$ at 90% CL 2304.01981
  - Work on electron modes (BF 🇫🇷) ongoing

- **Rare Kaon decay searches at LHCb:**
  - K_s-> 2μ: UL on B(K_s-> 2μ) < 2.1 x 10^{-10} (2 o.o.m above SM prediction) Phys. Rev. Lett. **125**, 231801
  - New: $K_{s(L)}$->4μ: $\mathcal{B}(K_S^0 \to \mu^+\mu^-\mu^+\mu^-) < 5.1 \times 10^{-12}$, $\mathcal{B}(K_L^0 \to \mu^+\mu^-\mu^+\mu^-) < 2.3 \times 10^{-9}$ Phys. Rev. D **108**, L031102
  - Main limitation from Run1/2 hardware trigger (L0) - removed for Run 3



Conclusions

- **Rare, radiative and semi-leptonic B decays offer rich phenomenology, from MeV to TeV range, complementary to direct searches of NP**
- **Charm and Kaon physics offer important complementarity**
- **LHCb & Belle II continue exploring the intensity frontier**
- **Exciting experimental results coming out!**

Thank you for your attention!

Backup

Global b->sll fit with and without Rx