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

Overview and Challenges

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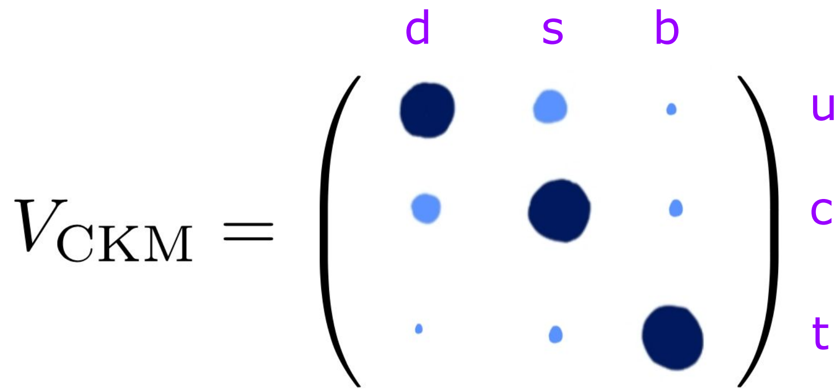
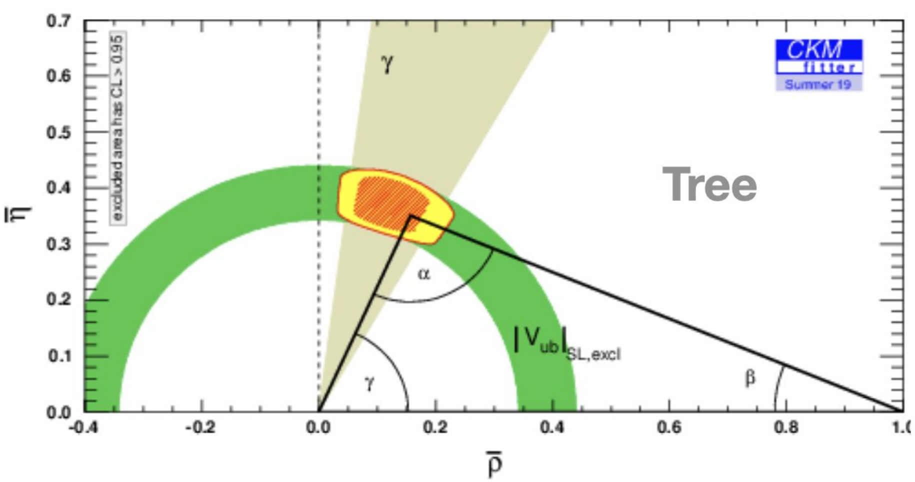
GDR-InF annual meeting, Lyon, 03/11

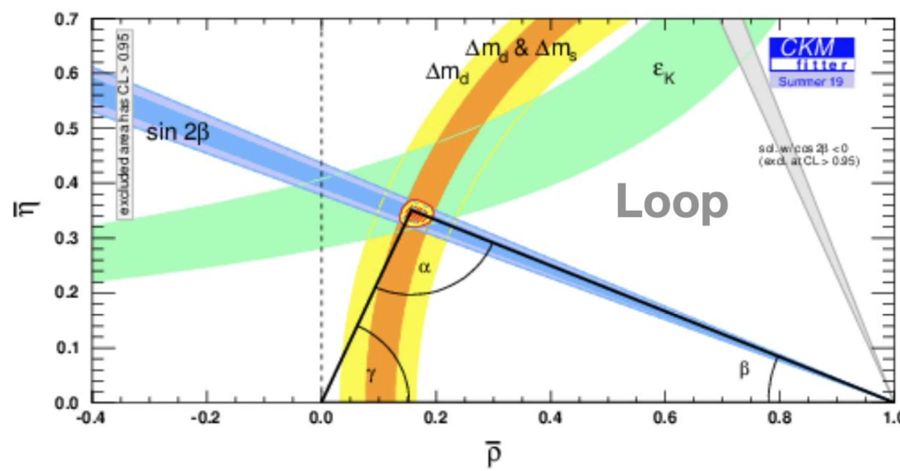
Brief theory overview/challenges

CKM-ology



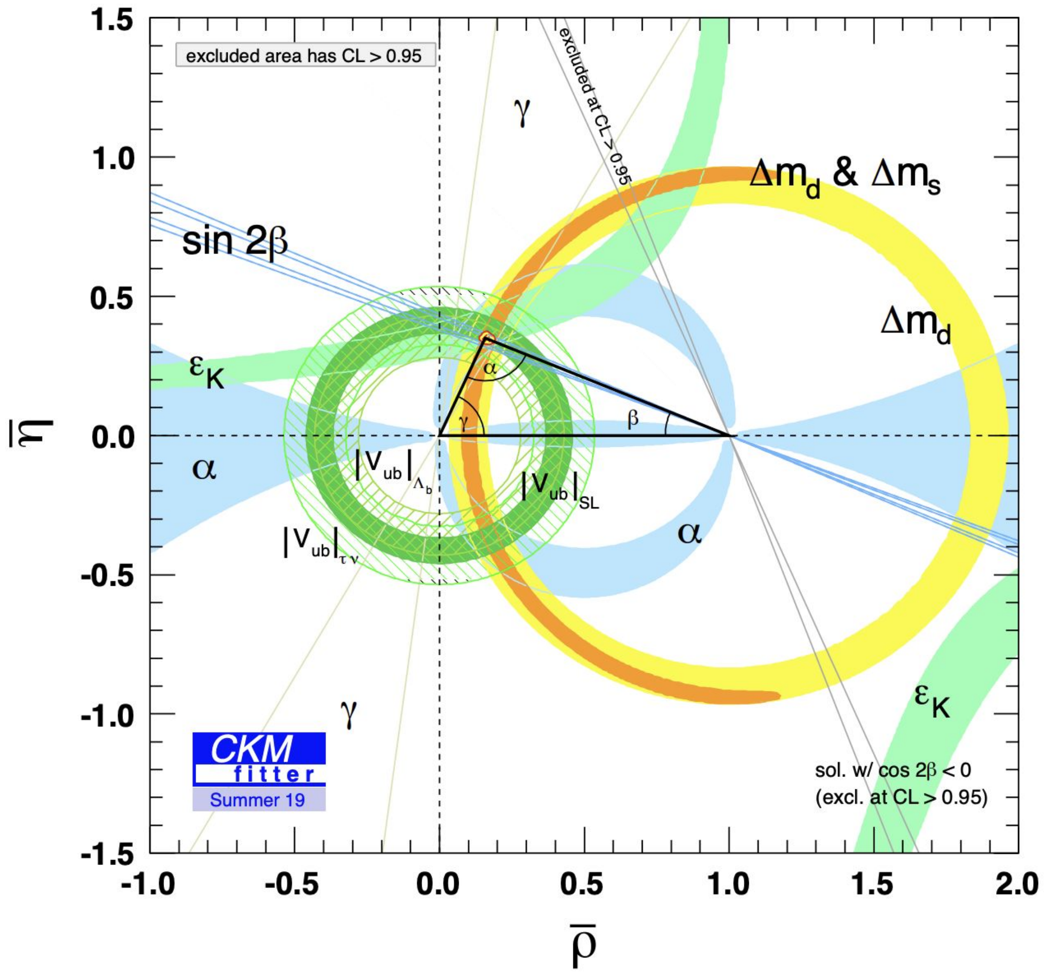
Fix the CKM matrix entries through *tree-level* decays and over-constrain *loop-induced* ones (progress through th. and exp. precision):





See talk by Vincent Tisserand

CKM-ology



Open questions:

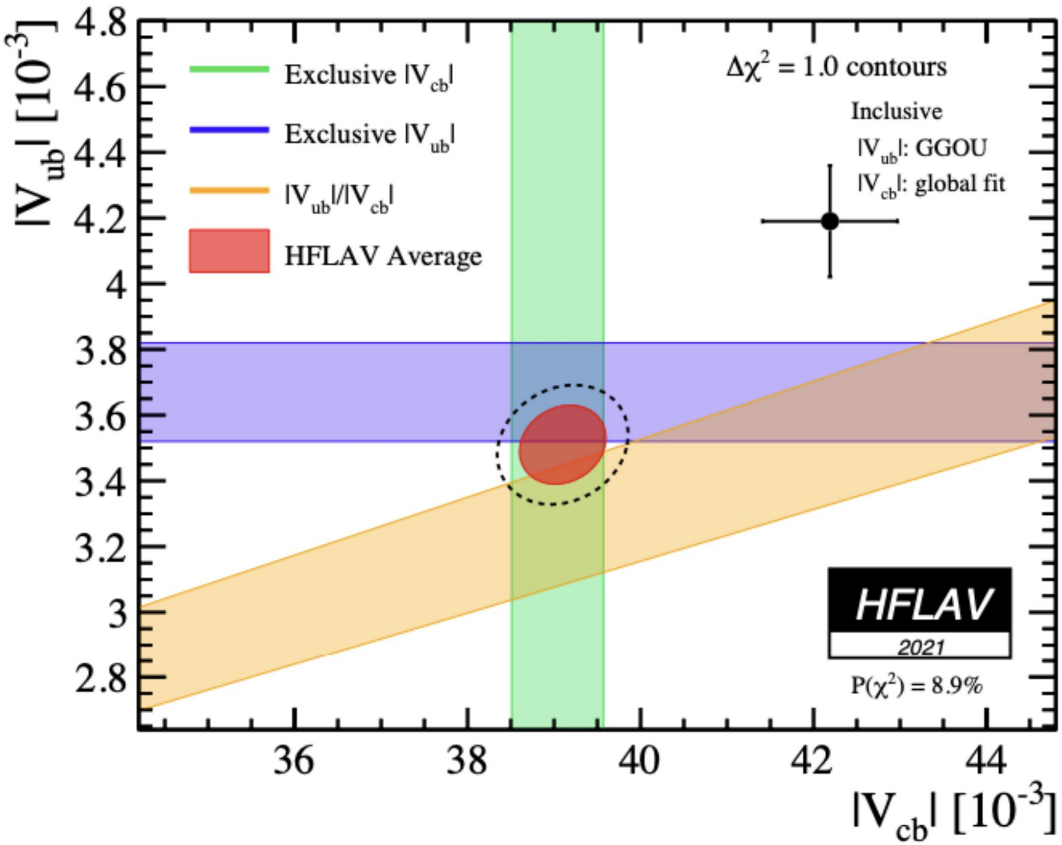
- Exclusive vs. inclusive V_{cb} and V_{ub}.
- Is V_{ud} under control?
- What about V_{us} ($K_{\mu 2}$ vs. K_{l3})?

Many questions to be clarified…

Inclusive vs. exclusive: V_{ub} and V_{cb}

Still an open issue…

[2206.07501]



- Long-standing discrepancy…
- V_{cb} plays an **important role** in the predictions of **FCNC**:

$$|V_{tb}V_{ts}|^2 \simeq |V_{cb}|^2 \left[1 + \mathcal{O}(\lambda^2)\right]$$

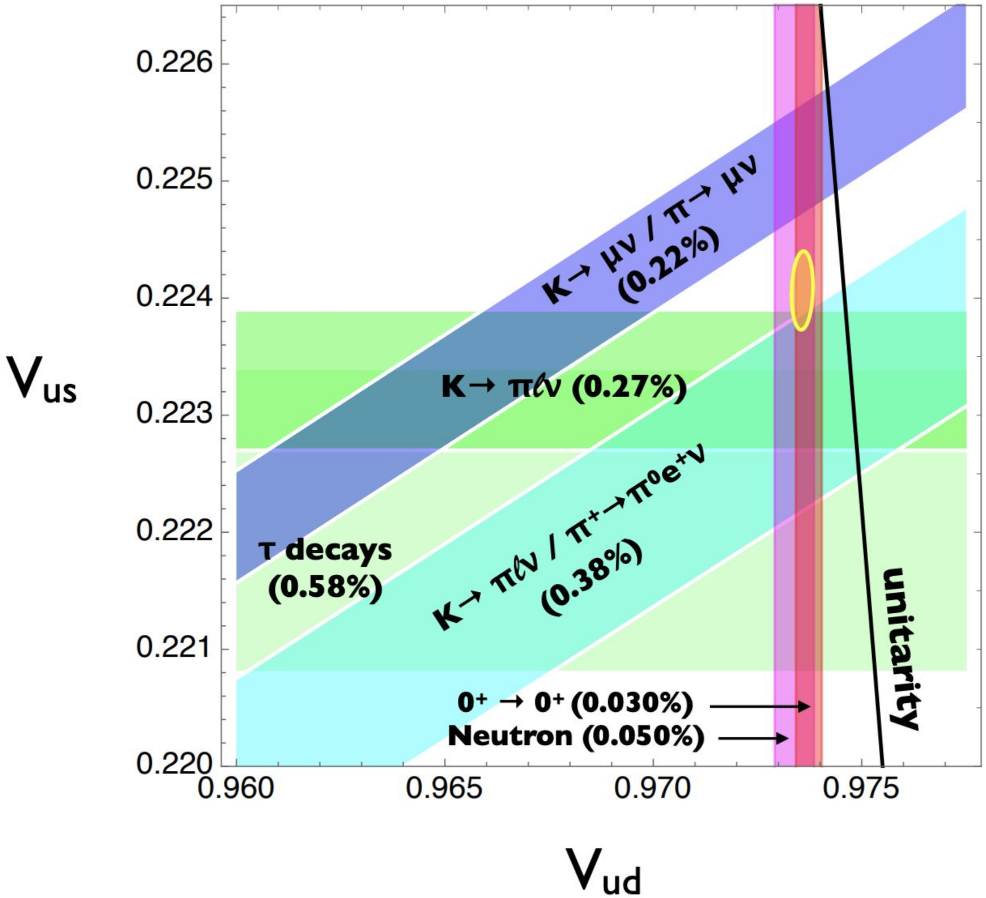
NB. Introduces an *ambiguity* (≈10%) in the SM prediction of *FCNC processes* such as B(B→$K^{(*)}$νν).

See talk by Ludovico Vittorio

First-row CKM unitarity

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \quad (|V_{ub}|^2 \approx 0)$$

[2111.05338]



- Significant discrepancies between nuclear β-decays and (semi)leptonic kaon decays:

  → Are nuclear effects under control?

- Mild deviation from unitarity also in $K_{\mu 2}/\pi_{\mu 2}$ vs. K_{l3}.

  → Need to control radiative corrections! LQCD simulations can already account for QED effects in leptonic π and K decays!

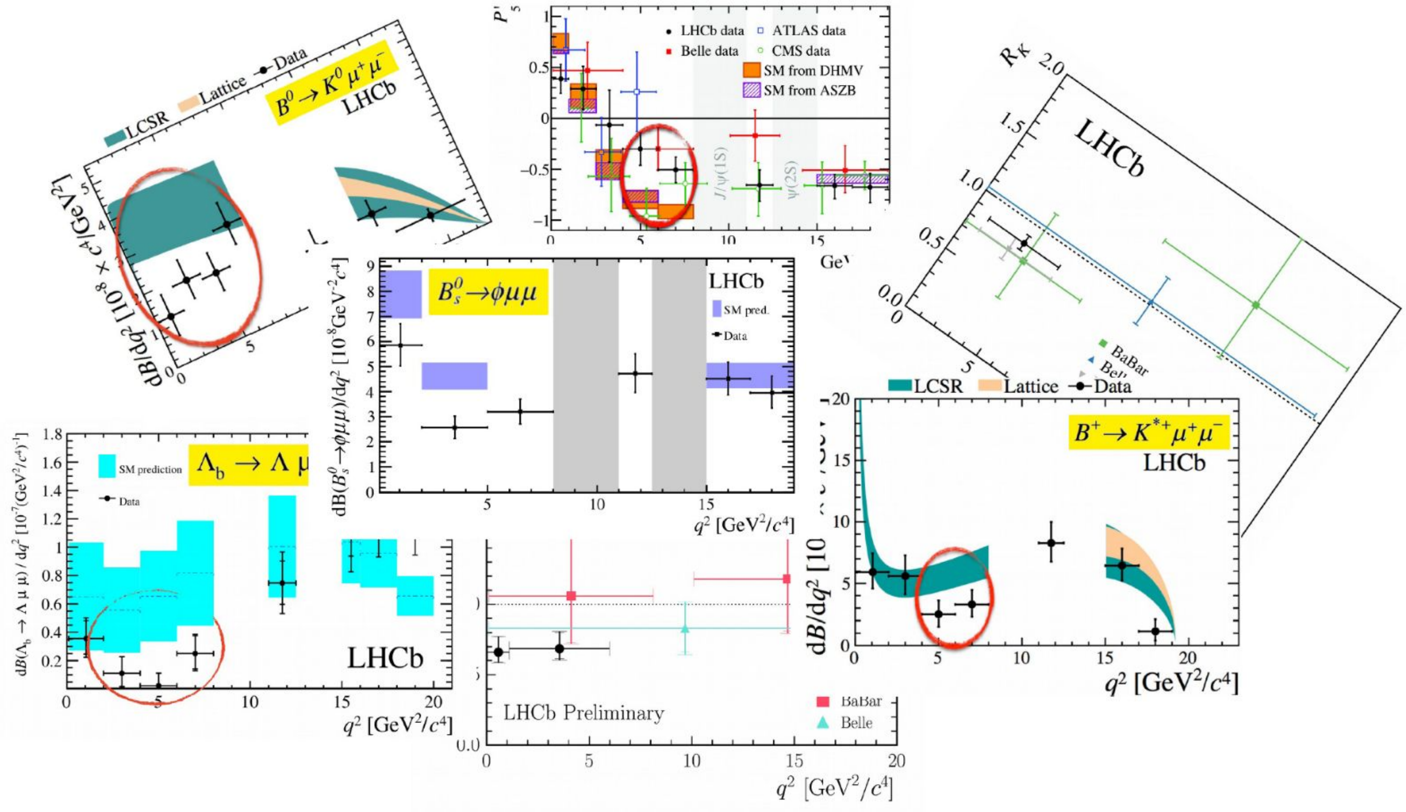
  [1711.06537]

More information (exp. and th.) needed to solve this issue

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), $B_s \to \phi\mu^+\mu^-$, ...

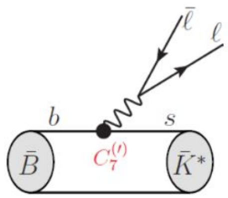


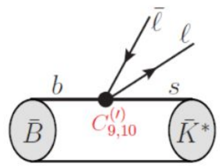
Several small deviations from the SM predictions...

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

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

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





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

local contributions:

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

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

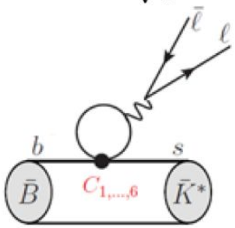
$$\mathcal{A}_{S,P} = C_{S,P} \langle M|\bar s\, P_R\, b|B\rangle$$

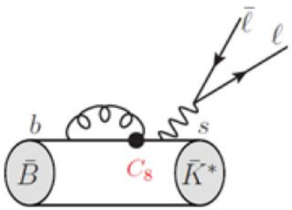
- 3 form factors for final state $M = K$
- 7 form factors for final state $M = K^*, \phi$

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

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





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

non-local contributions:

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

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

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

See talks by Meril Reboud and Aleks Smolkovic

Lepton Flavor Universality Violation?

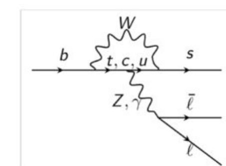
- **Well-tested** property of the SM **gauge sector**, which is *broken by Yukawas*:

$$g_V \equiv g_V^{\ell}$$

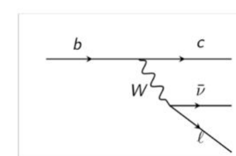
[LEP, τ-decays]

- Several discrepancies have been observed in ***b*-hadron** decays:

$$R_{K^{(*)}} = \left.\frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\right|_{q^2 \in [q^2_{\rm min}, q^2_{\rm max}]} \qquad \& \qquad R_{K^{(*)}}^{\rm exp} < R_{K^{(*)}}^{\rm SM}$$



$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell \in (e,\mu)} \qquad \& \qquad R_{D^{(*)}}^{\rm exp} > R_{D^{(*)}}^{\rm SM}$$



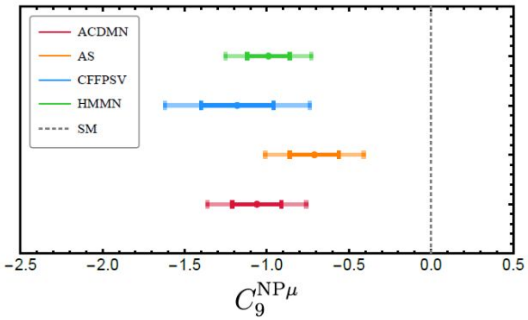
[LHCb, *B-factories*]

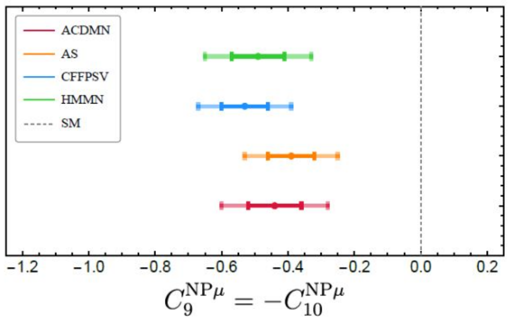
<u>Theoretically clean</u> observables! See talk by Saad Nabeebaccus

Needs clarification (Belle-II and LHCb run-II)

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

One dimensional fits:





ACDMN: M. Algueró, B. Capdevila, S. Descotes-Genon, J. Matias, M. Novoa-Brunet arXiv:2104.08921

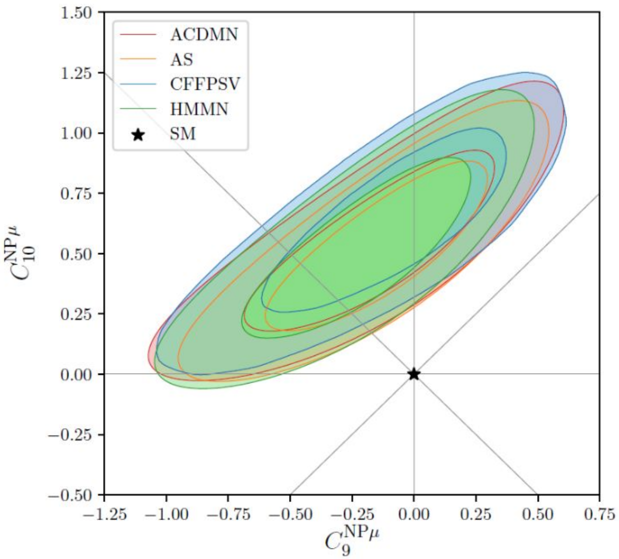
AS: W. Altmannshofer, P. Stangl arXiv:2103.13370

CFFPSV: M. Ciuchini, M. Fedele, E. Franco, A. Paul, L. Silvestrini, M. Valli arXiv:2011.01212

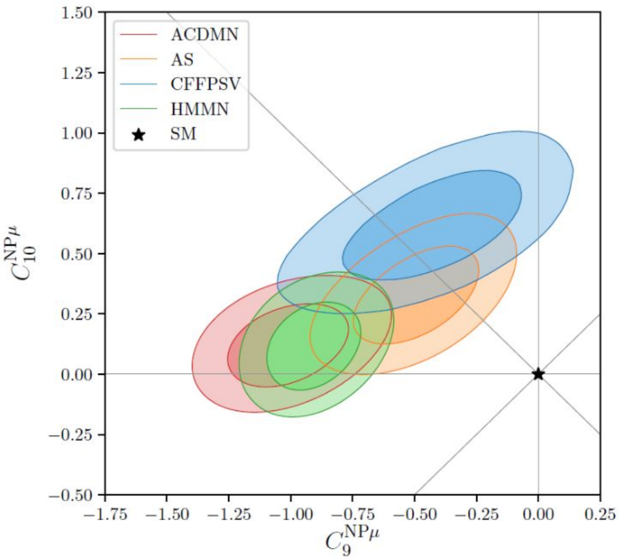
HMMN: T. Hurth, F. Mahmoudi, D. Martínez-Santos, S. Neshatpour arXiv:2104.10058

Two dimensional fits:

Clean observables



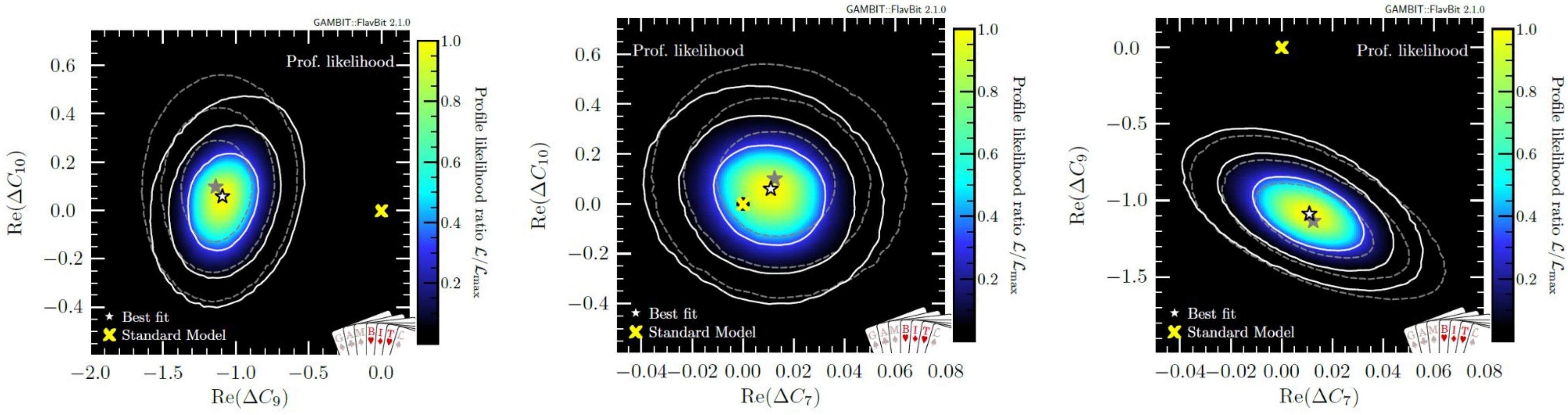
All observables



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

2D fits to angular observables and branching ratios (No LFUV ratios):

with the assumption of 10% power corrections



GAMBIT, J. Bhom et al., Eur.Phys.J.C 81 (2021) 12, 1076

- Contour lines: 1, 2 and 3σ confidence regions.
- SM prediction: yellow cross.
- Grey contours: when the theory covariance is approximated by its value in the SM, across the entire parameter space.

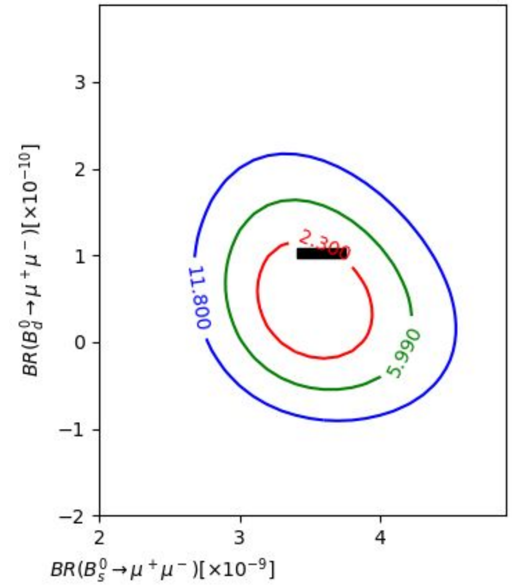
Large negative contributions to C_9 are favoured

[NEW] $B_s \to \mu\mu$ and $b \to s\ell\ell$ fits

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)

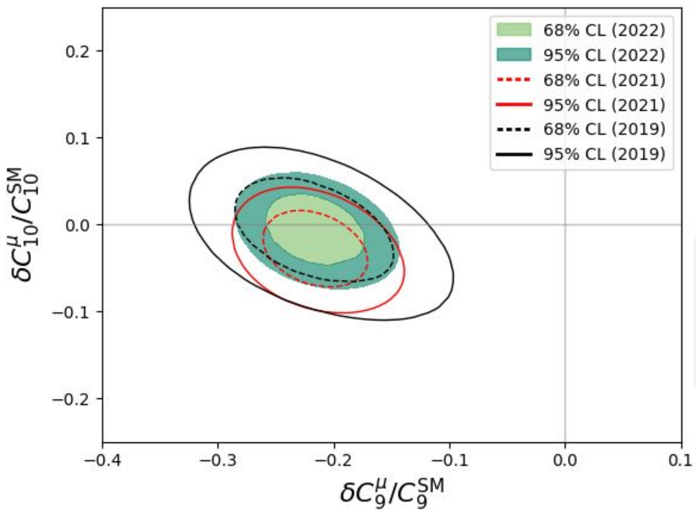
$$\mathrm{BR}(B_s \to \mu^+\mu^-)^{\mathrm{CMS}} = (3.95^{+0.39+0.27+0.21}_{-0.37-0.22-0.19}) \times 10^{-9}$$



combination using the latest measurements:

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

2210.07221



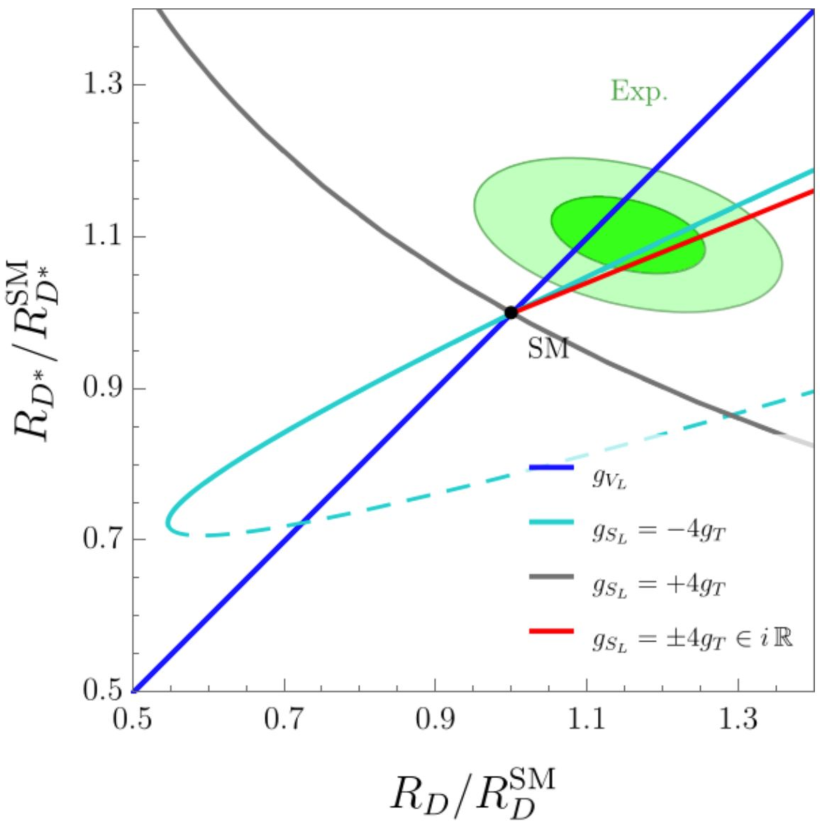
2019: Run I results

2021: (partial) Run II updates, mainly for $B \to K^*\mu^+\mu^-$, R_K and $B_s \to \mu^+\mu^-$ (LHCb)

2022: current situation
(partial) Run II updates, mainly for $B_s \to \mu^+\mu^-$ (CMS), $R_{K^{*+}}$, $R_{K_S^0}$ and $B_s \to \phi\mu^+\mu^-$

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

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



see e.g. [2103.12504]

- Several scenarios can accommodate data:

  $\Rightarrow$ *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:*

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

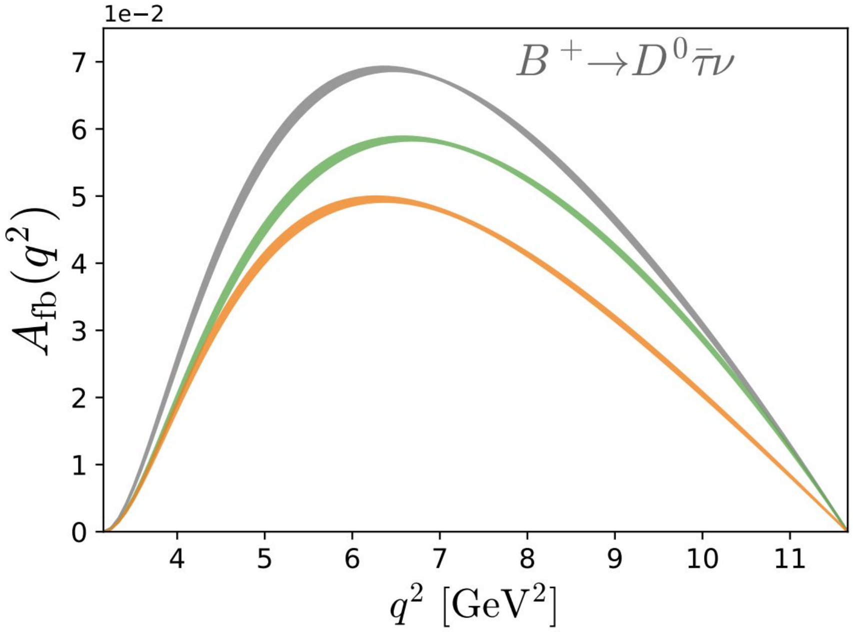
  ii) *Other LFU ratios:*

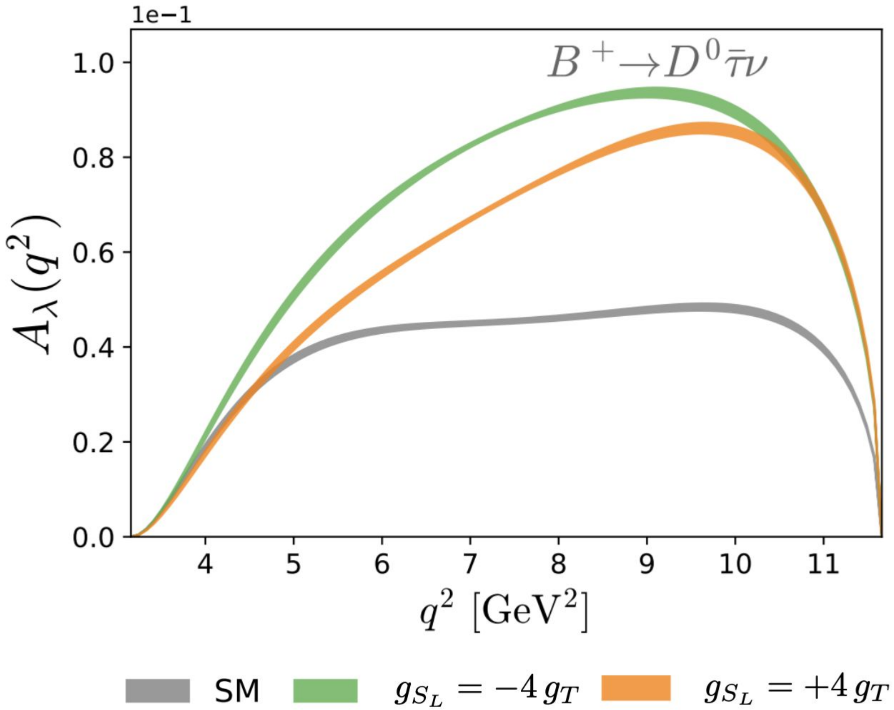
  $R_{D_s^{(*)}},\ R_{\eta_c},\ R_{J/\psi},\ R_{\Lambda_c},\ \ldots$

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:

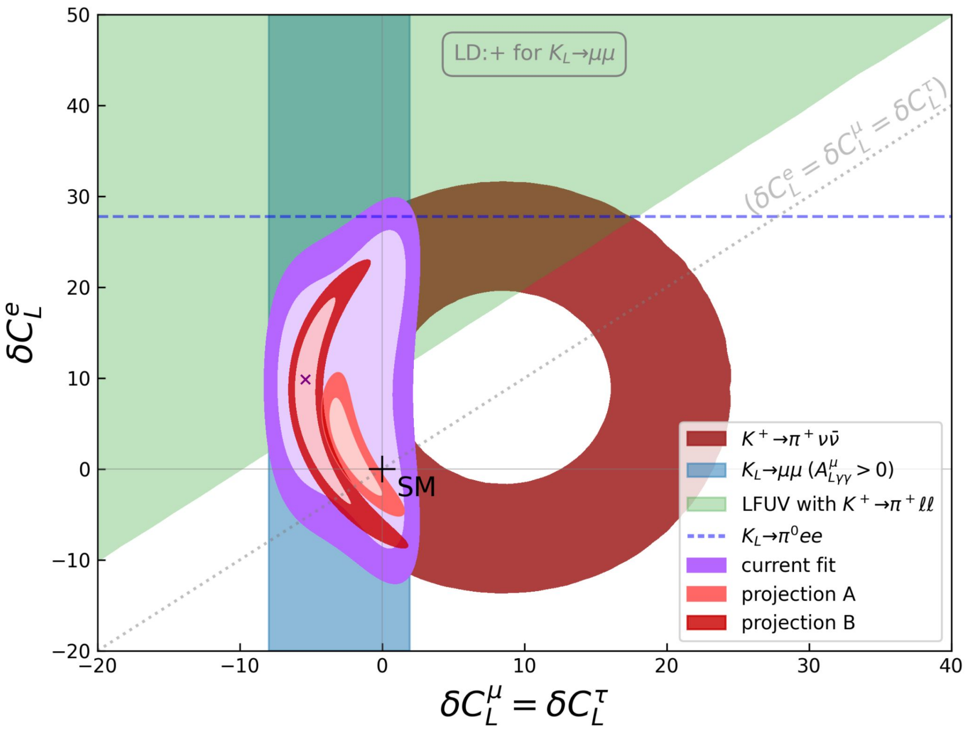
$B \to D^*(\to D\pi)\tau\bar{\nu}$ [1602.03030, 1907.02257, 2104.02094...]

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

From *B*-physics to kaons

It is natural to expect that the NP effects in *B*-meson decays would also impact operators contributing to kaon decays. [1705.10729, 1802.00786, 2005.03734, 2206.14748]...

Global picture: [2206.14748]



Relevant operators:

$$O_9^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10}^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$O_L^\ell = (\bar{s}\gamma_\mu P_L d)\,(\bar{\nu}_\ell\,\gamma^\mu (1-\gamma_5)\,\nu_\ell)$$

Projection A: Assuming SM as the central values

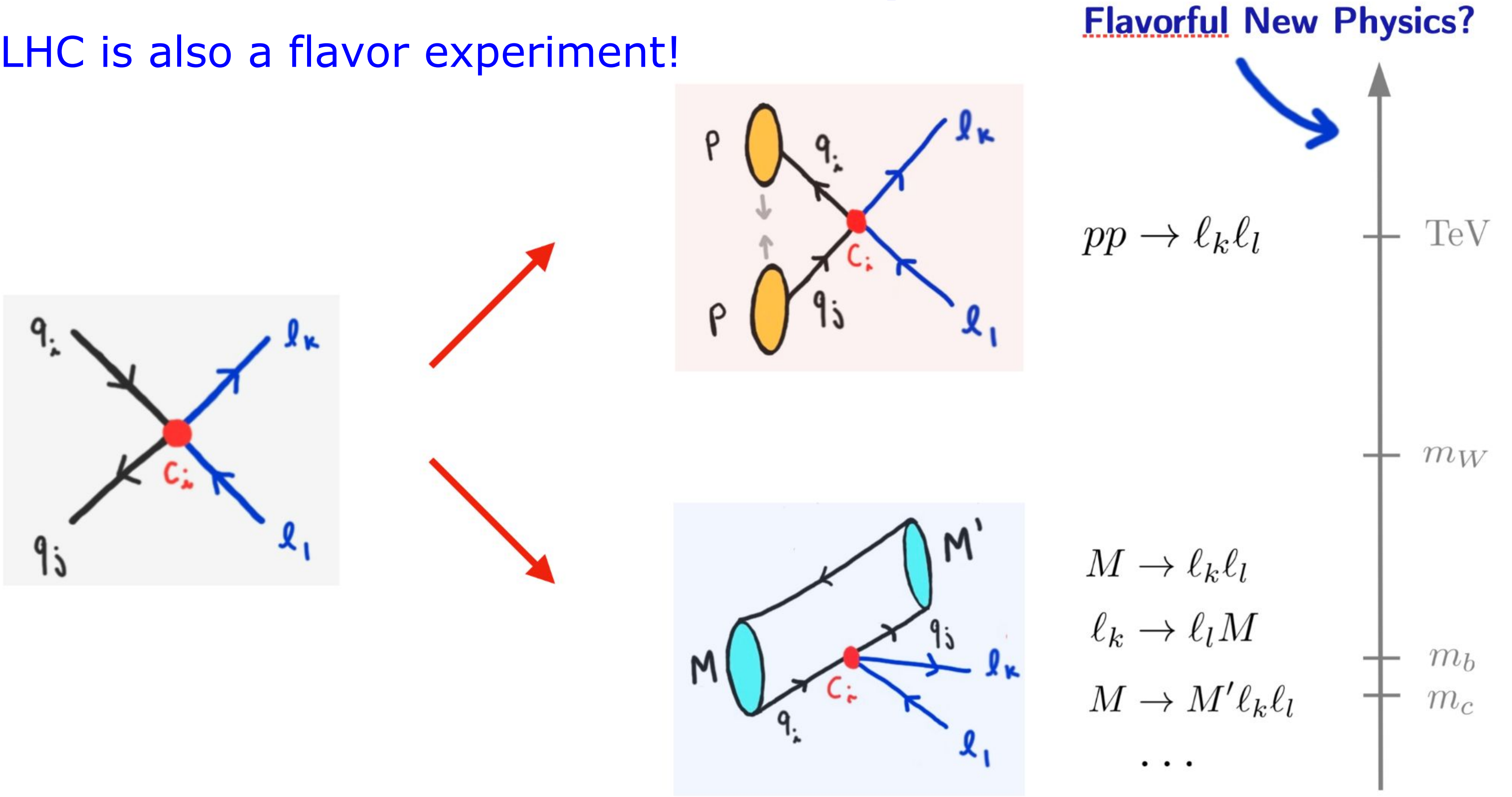
Projection B: Assuming the best-fit values from the current fits as the central values

→ **Effective probe of NP in the muon sector!**

Need to achieve a better accuracy in the theoretical computation of $K_L \to \mu\mu$

Flavor physics at high-p_T

LHC is also a flavor experiment!

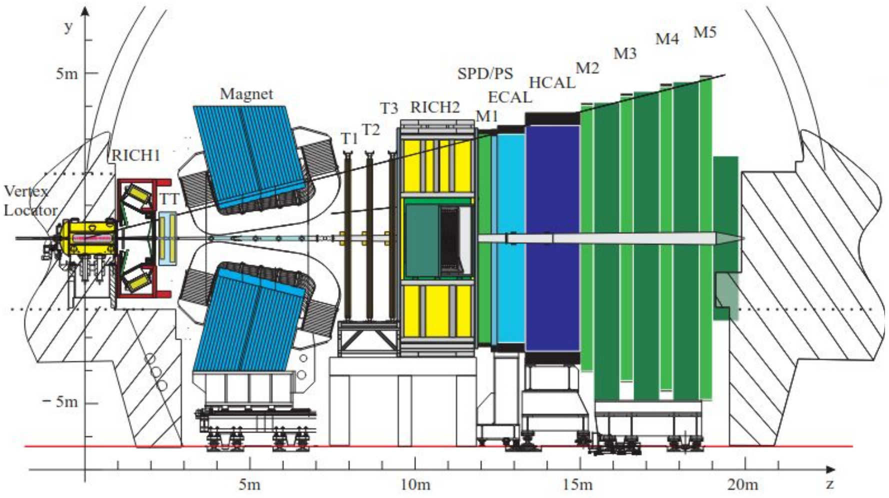


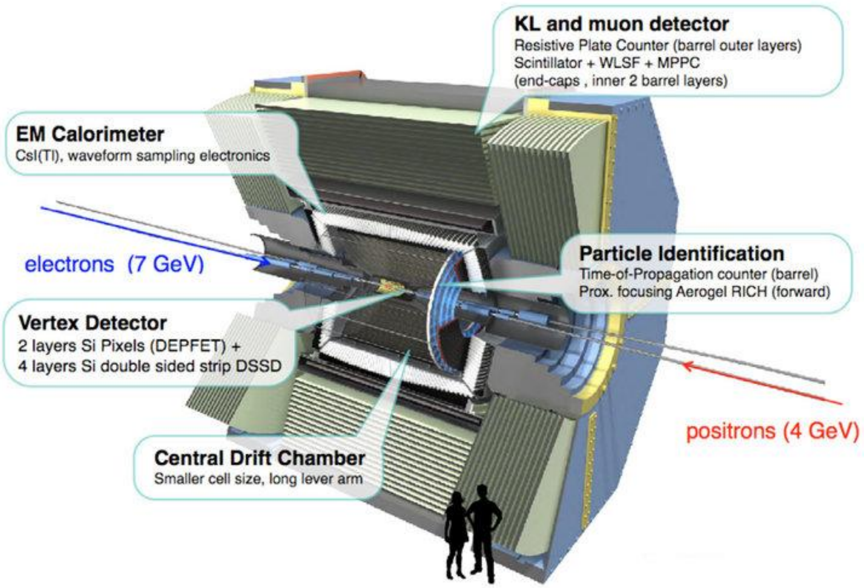
High-p_T searches (CMS and ATLAS) **can probe** the **same operators** constrained by **flavor-physics experiments** (NA62, KOTO, BES-III, LHCb, Belle-II...).

See talk by Felix Wilsch!

Experimental challenges and new results

LHCb vs Belle II





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

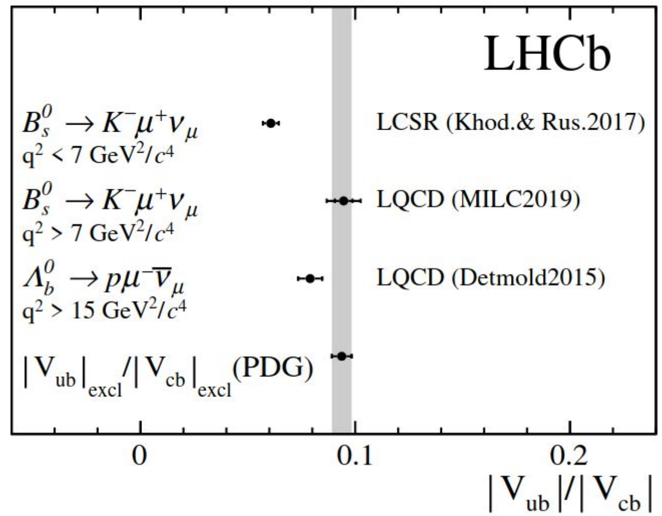
- **e^+e^- collisions at 10.58 GeV** ($\Upsilon(4S)$ resonance)
- **~ 430 fb^{-1} collected**

- **High vertex resolution** (VELO)
- **Good PID capabilities** (RICH, Calo, Muon)
- Hadronic environment, low trigger efficiency
- Forward detector, no hermiticity

- **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 $\sigma(e^+e^- \to Y(4S)) \sim 1$ nb

Recent results and prospects for V_{ub} and V_{cb}

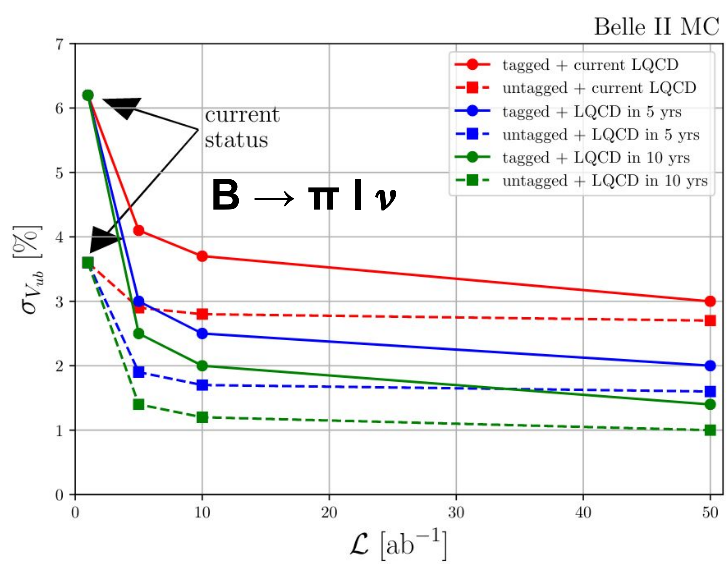
- LHCb measured the **ratio $|V_{ub}|/|V_{cb}|$** [arXiv:2012.05143]
  - Exclusive $B^0_s \to K^- \mu^+ \nu$ and $\Lambda^0_b \to p \mu^- \nu$
  - Expected **precision of ≲ 1%** with full LHCb dataset (300 fb^{-1}) [arXiv:1808.08865]



- … and **$|V_{cb}|$ with exclusive $B^0_s \to D^{(*)-}_s \mu^+ \nu$** [arXiv:2001.03225]
  - $|V_{cb}|_{CLN} = (41.4 \pm 0.6 \pm 0.9 \pm 1.2) \cdot 10^{-3}$
  - $|V_{cb}|_{BGL} = (42.3 \pm 0.8 \pm 0.9 \pm 1.2) \cdot 10^{-3}$

- Recent measurements also by Belle II:
  - **$|V_{ub}|$ from $B \to \pi e \nu$**: $|V_{ub}| = (3.88 \pm 0.45) \times 10^{-3}$
  - **$|V_{cb}|$ from $B \to D^* l \nu$**: $|V_{cb}| = (37.9 \pm 2.7) \times 10^{-3}$
  - **$|V_{cb}|$ from $B \to X_c l \nu$**: $|V_{cb}| = (41.69 \pm 0.63) \times 10^{-3}$

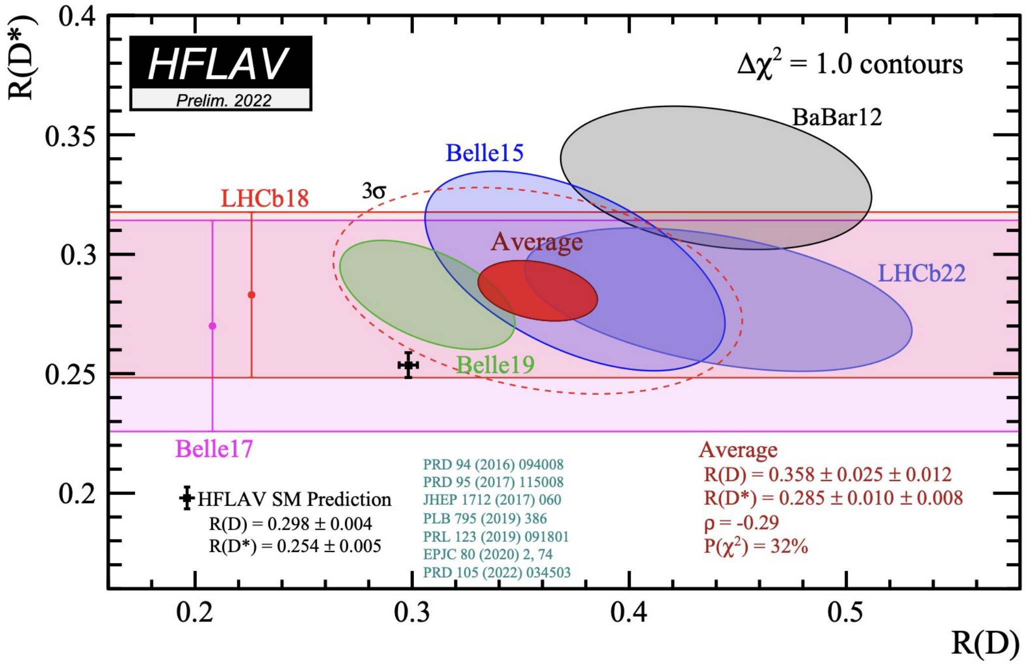
- Expected **precision of $O(1\%)$** with full Belle II dataset (50 ab^{-1})



[arXiv:1808.10567]

R(D) and R(D*) measurement at LHCb

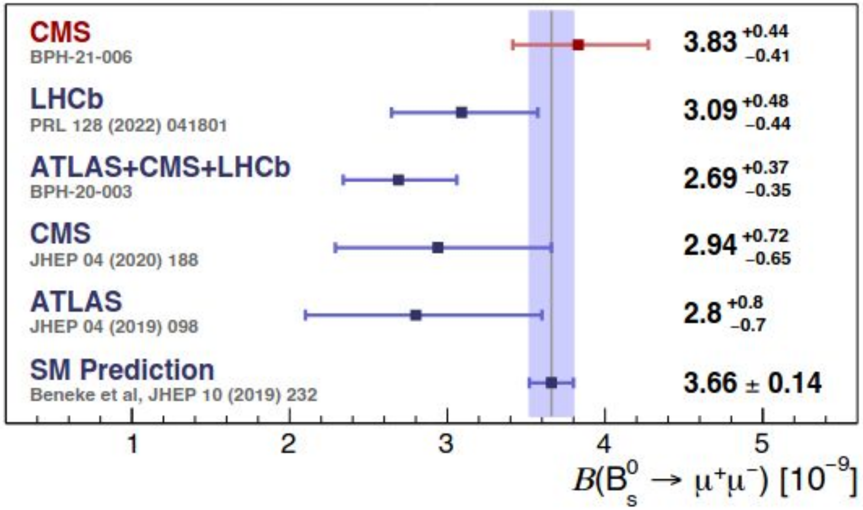
- First R(D) and R(D*) combined measurement at a hadronic machine (3 fb^{-1})
- Main challenges:
  - Missing energy from neutrinos, no narrow peak → three-dimensional fit in E_μ, $m^2_{missing}$, q^2
  - Background from partially reconstructed and misidentified B decays
  - Generation and validation of simulated samples
- **1.9 (3.2) σ agreement** between this measurement (new average) and SM prediction



- Run 2 measurement ongoing in this and other channels
- **See talk by Gaya Benane!**

$B^0_{(s)} \rightarrow l^+ l^- (\gamma)$

- Recent updates from LHCb and CMS on $B^0_{(s)} \rightarrow \mu^+\mu^- (\gamma)$
- **See talk by Camille Normand!**



- Upper limits on $B^0_{(s)} \rightarrow e^+e^-$ and $B^0_{(s)} \rightarrow \tau^+\tau^-$ provided by LHCb

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

[arXiv:2003.03999]

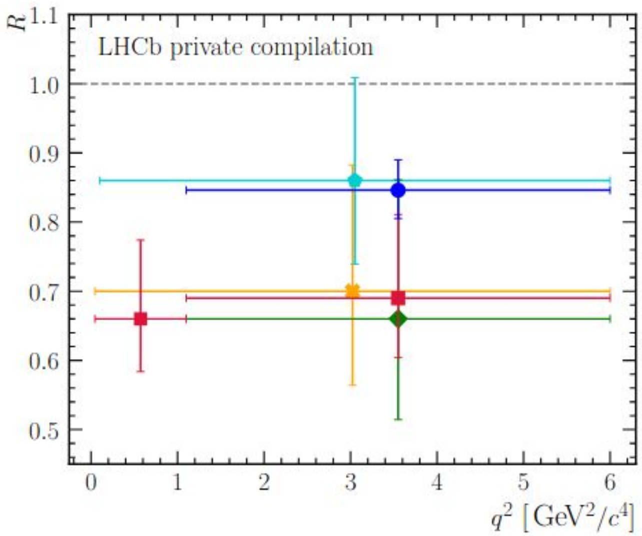
$$\bar{\mathcal{B}}(B^0 \to \tau^+ \tau^-) < 2.1 \cdot 10^{-3} \text{ at } 95\% \text{ CL},$$
$$\bar{\mathcal{B}}(B^0_s \to \tau^+ \tau^-) < 6.8 \cdot 10^{-3} \text{ at } 95\% \text{ CL}.$$

[arXiv:1703.02508]

- **See talk by Gilberto Tetlalmatzi-Xolocotzi!**

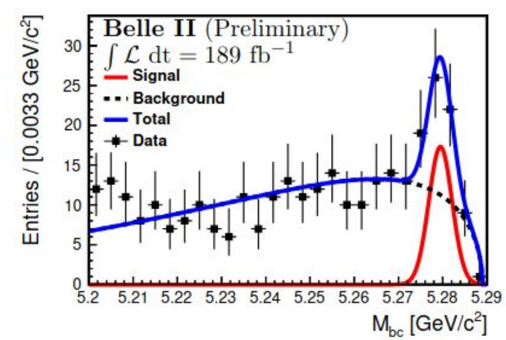
LFU tests in rare decays

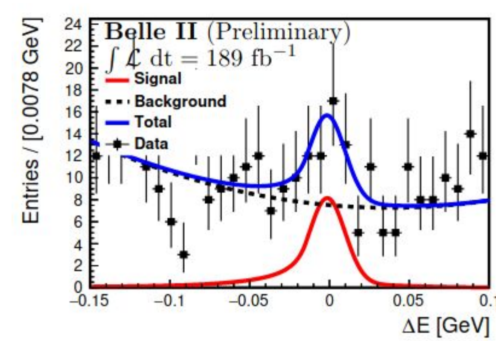
- Several LFU tests in b-hadron decays performed at LHCb
- *R(K)* shows **3.1 σ discrepancy w.r.t. SM** predictions
- Overall trend observed in LFU ratios, *updated measurements ongoing*



- First measurement of $B \to K^* \, l^+ l^-$ branching ratios at Belle II
- Results in agreement with world average, *updates ongoing*

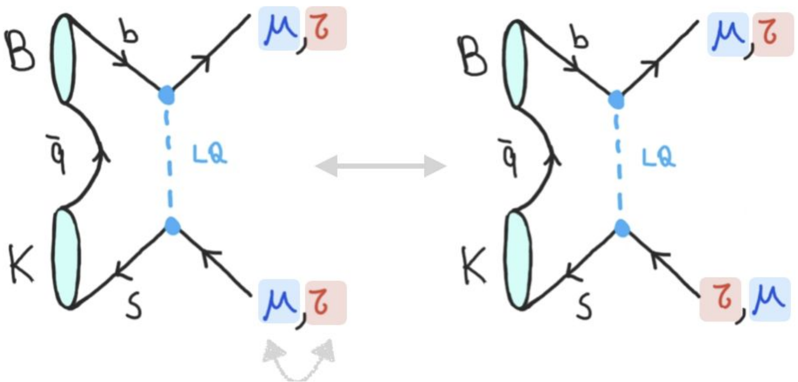
$$\mathcal{B}(B \to K^*(892)\mu^+\mu^-) = (1.19 \pm 0.31 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*(892)e^+e^-) = (1.42 \pm 0.48 \pm 0.09) \times 10^{-6},$$
$$\mathcal{B}(B \to K^*(892)\ell^+\ell^-) = (1.25 \pm 0.30 \pm^{+0.08}_{-0.07}) \times 10^{-6},$$





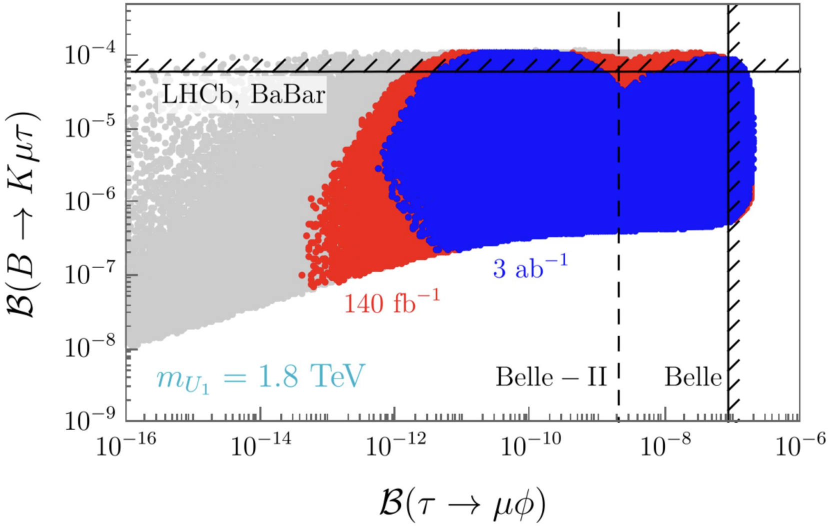
Lepton Flavor Violation

- From **LFUV** to **LFV**:



[1411.0565, 1602.00881...]

Example: $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$



[2103.12504]

- New **limits on LFV modes** @ 90 % (95 %) CL:

[arXiv:2207.04005]

$B^0_s \to \phi$ μ e — $\mathcal{B}(B^0_s \to \phi\mu^\pm e^\mp) < 16.0 \times 10^{-9}$ (19.8×10^{-9})

$B^0 \to K^{*0}$ μ e — $\mathcal{B}(B^0 \to K^{*0}\mu^\pm e^\mp) < 10.1 \times 10^{-9}$ (11.7×10^{-9}),

[arXiv:2209.09846]

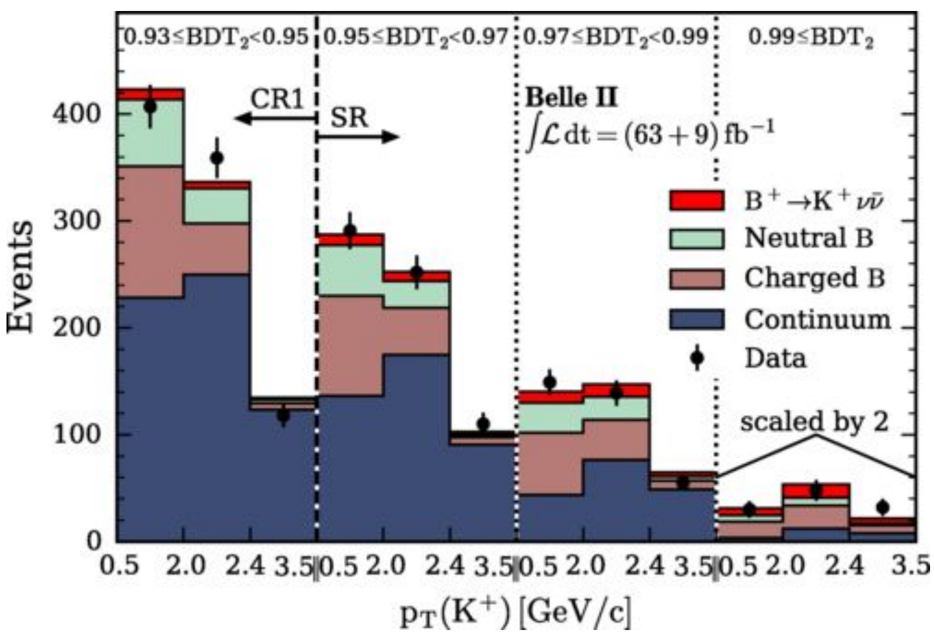
$B^0 \to K^{*0}$ τ μ —
$\mathcal{B}(B^0 \to K^{*0}\tau^+\mu^-) < 1.0\ (1.2) \times 10^{-5}$
$\mathcal{B}(B^0 \to K^{*0}\tau^-\mu^+) < 8.2\ (9.8) \times 10^{-6}$

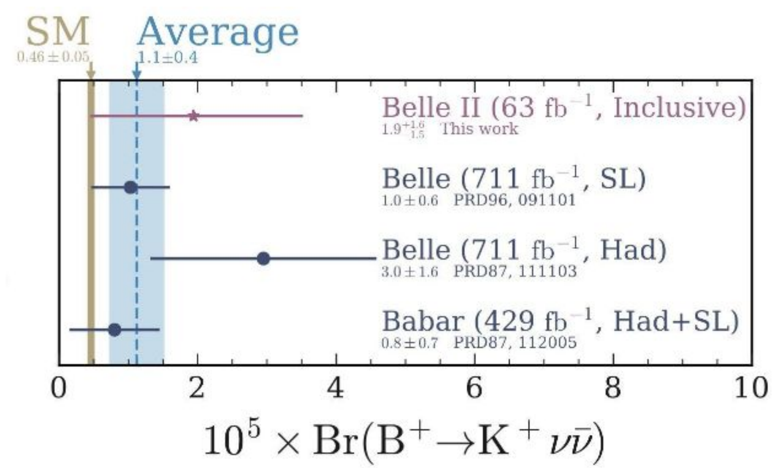
- No sign of LFV yet, we keep searching!

Search for the $B \to K \nu \nu$ decay

[arXiv:2104.12624]

- Crucial **complementarity to $b \to s\, l^+ l^-$** searches
- **Golden channel** for Belle II:
  - Missing energy from neutrinos → full reconstruction of the event needed
  - Expected **O(10%) uncertainty with 50 ab^{-1}** → Approaching precision regime!



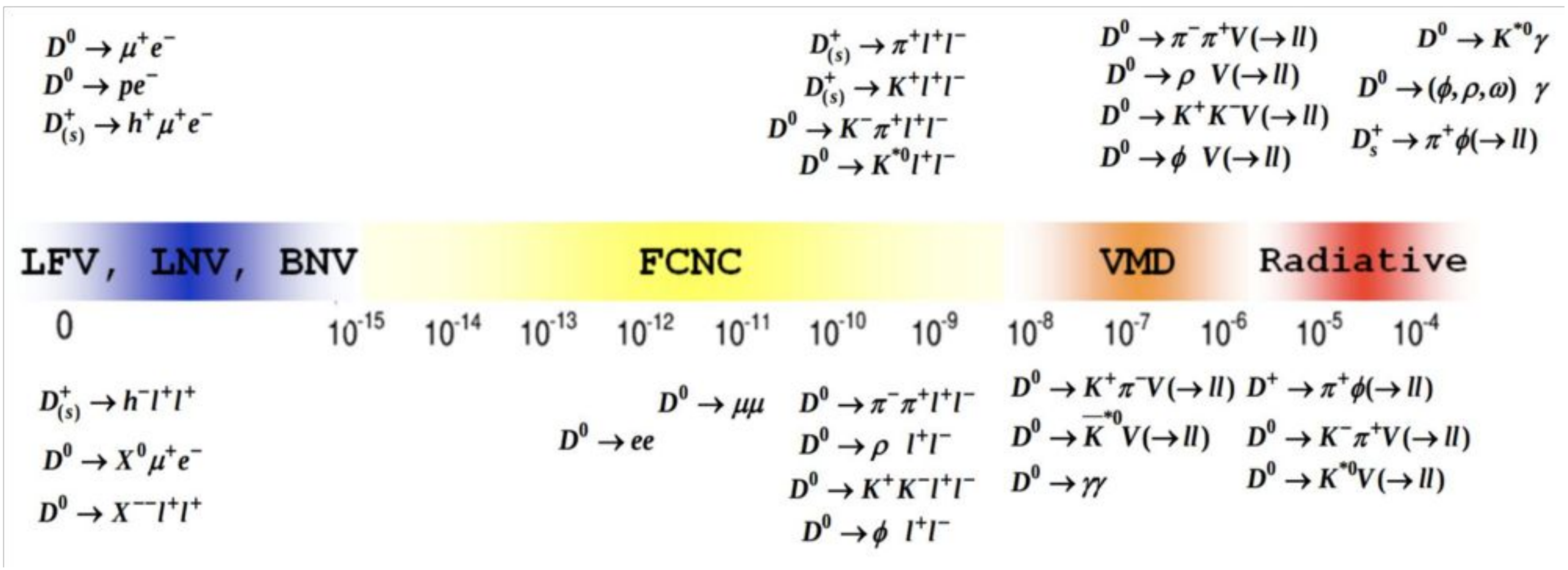


$\mathcal{B}(B^+ \to K^+ \nu \nu) < 4.1 \times 10^{-5}$ @ 90 % CL

- Updated measurements ongoing in several channels!
- **See talk by Lucas Martel and Jacopo Cerasoli!**

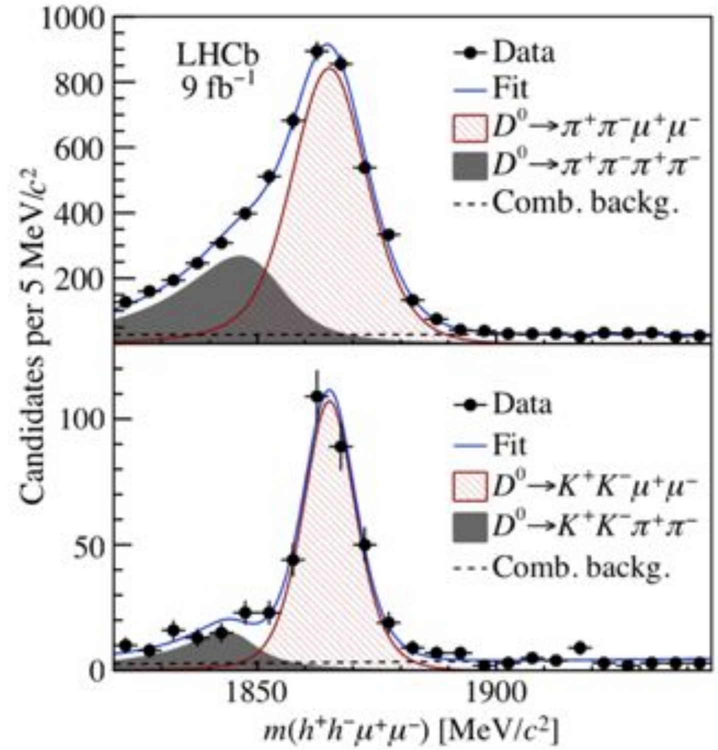
Rare charm decays

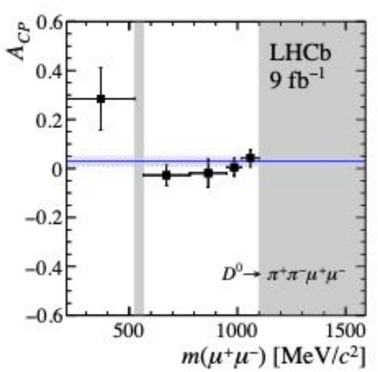
- Probing $c \rightarrow u$ type FCNC - **complementarity to B physics!**
- Charm scale not too far from Λ_{QCD} & resonant D contributions
  - Accurate theoretical predictions are challenging
  - Test SM consistency / search for NP through clean observables & null tests
- Very suppressed in the SM due to GIM and CKM suppressions
  - Rich spectrum of channels from forbidden and ultra-rare to less rare / resonant

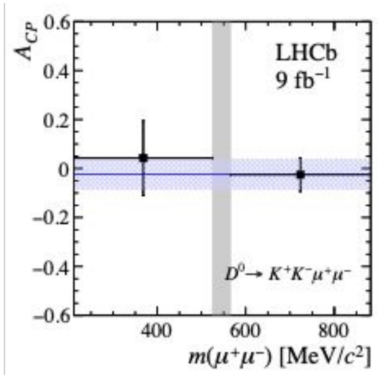


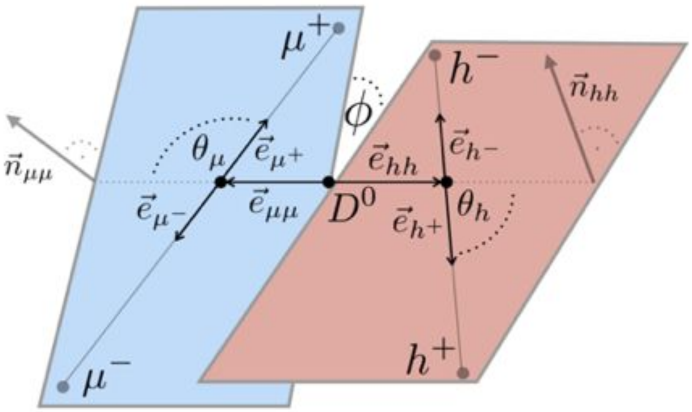
Rare charm decays

- **Complementarity with b → s l^+ l^-** searches
- LHCb has produced world leading measurements in muon modes:
- First observation (h=π,K) with 2012 data (2 fb^{-1}) [Phys. Rev. Lett. 119, 181805]
- Measurement of selected angular and CP asymmetries with Run 1 + 2016 data (5 fb^{-1}) [Phys. Rev. Lett. 121, 091801]
- And first full angular analysis of a rare charm decay -> search for CP violation! [Phys.Rev.Lett. 128 (2022) 22, 221801]









- **What about electron channels? → See talk by Alessandro Scarabotto!**

Summary

- **Rare, radiative and semi-leptonic B decays are rich channels**
- **Charm and Kaon physics offer important complementarity**
- **Rich phenomenology, from MeV to TeV range**
- **Exciting experimental results coming out!**

Thank you!