CKM 2021
WG3 Summary
Rare B, D and K decays

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WG3 Sessions: structure

Mon 22 Nov: Rare B decays I

Tue 23 Nov: Rare B decays II

Wed 24 Nov: Radiative B and rare D decays

Joint WG2 & WG3 session

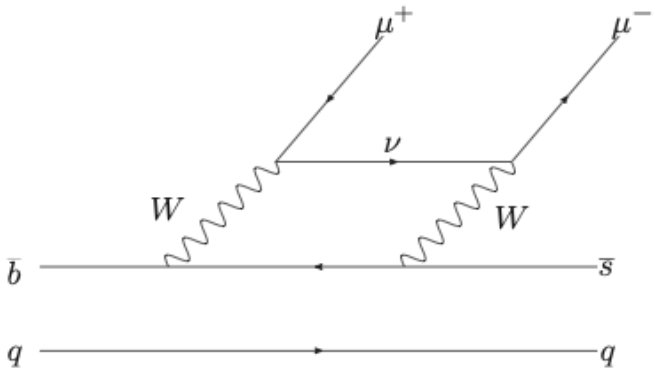
Thu 25 Nov: K decays

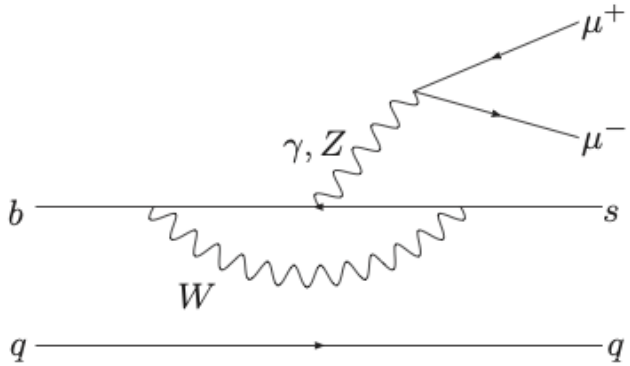
Rare B decays I

- *LHCb results on rare $b \to s\,\ell\ell$ decays* *(Michal Kreps)*
- *EW-penguin decays with missing energy and LFV at Belle II* *(Tao Luo)*
- *Rare $b \to s\,\ell\ell$ decays: progress on QCD uncertainties* *(Danny van Dyk)*
- *Searching for New Physics in rare K and B decays without $|V_{cb}|$ and $|V_{ub}|$ uncertainties* *(Elena Venturini)*

LHCb results on rare b → s ℓℓ decays *(Michal Kreps)*

- In the SM, $b \to sll$ cannot happen at tree level
- FCNC decays through loop diagrams
- SM predicts BF of the order 10^{-6}
- Typically such decays have complex angular structure offering variety of observables
  - Precision of SM prediction varies depending on sensitivity to form factors
- Sensitive probe of NP contribution
- Many intriguing measurements in the past





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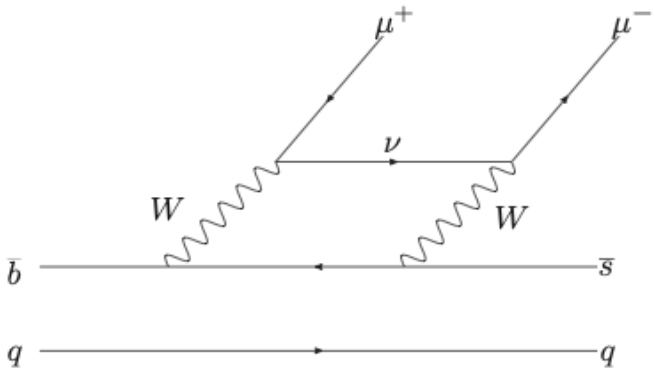
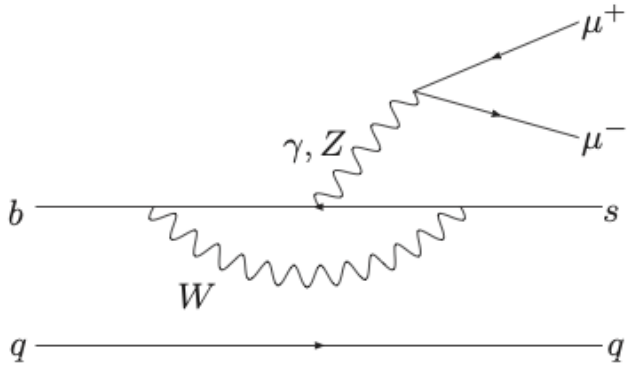
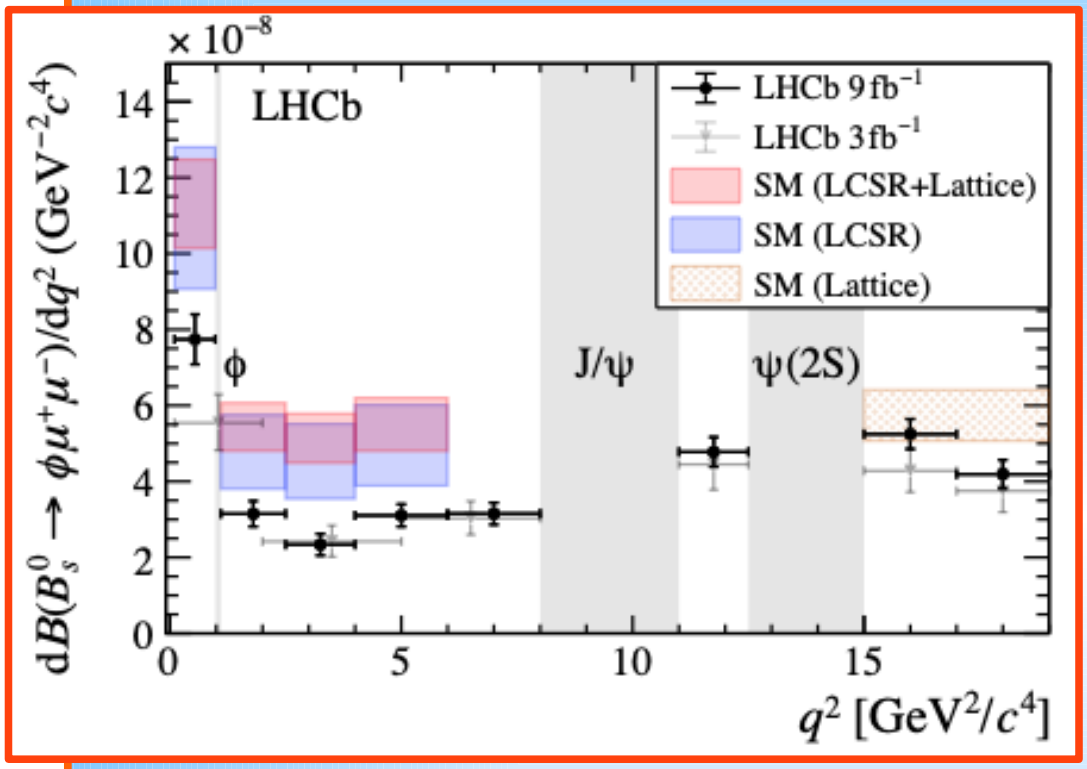
and in the present !





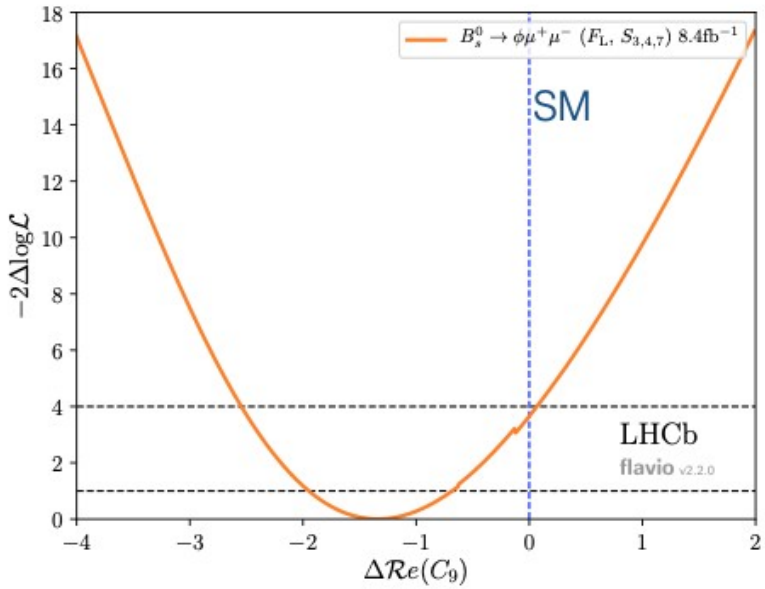
$B_s \to \phi\,\mu\,\mu$: BR



- In q^2 between 1.1 and 6.0 GeV^2 measurement deviates by 3.6σ from the SM (LCSR+Lattice)

$B_s \to \phi\,\mu\,\mu$: angular

- The best fit gives NP contribution $\Delta\mathrm{Re}[C_9] = -1.3^{+0.7}_{-0.6}$
- Preferred by 1.9σ over SM value

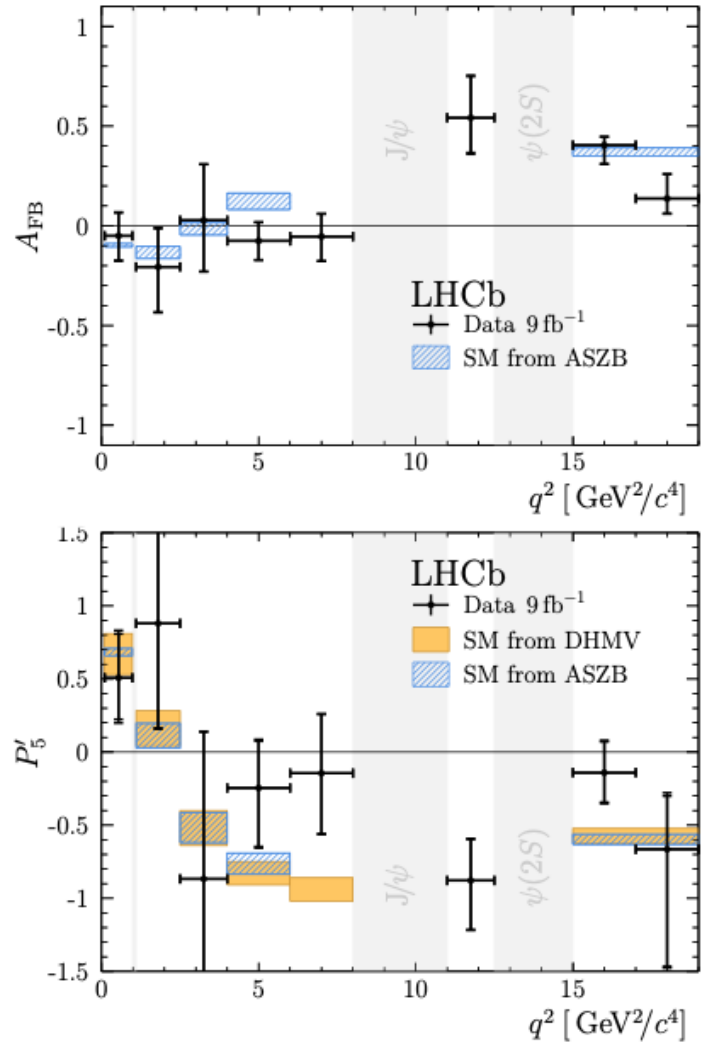


Full set of obs. measured, including T-odd A_8 and A_9

PRL 126, 161802 (2021)

$B^+ \to K^{*+}\mu\mu$ angular analysis

- General pattern observed similar to $B^0 \to K^{*0}\mu\mu$
- Largest local deviation from SM has significance of 3.0σ
- To evaluate consistency with SM, fit for Re[C_9] from measured observables using Flavio
  - Uses subset of q^2 intervals
- Best fit value Re[C_9]=-1.9
- Consistency with SM at 3.1σ



- *In short, tensions persist and these modes are as interesting as ever*
- *Many additional measurements not shown*
  (e.g. photon polarization in $B^0 \to K^{*0}$ ee)
- *New measurements expected*
- *And an upgraded detector*

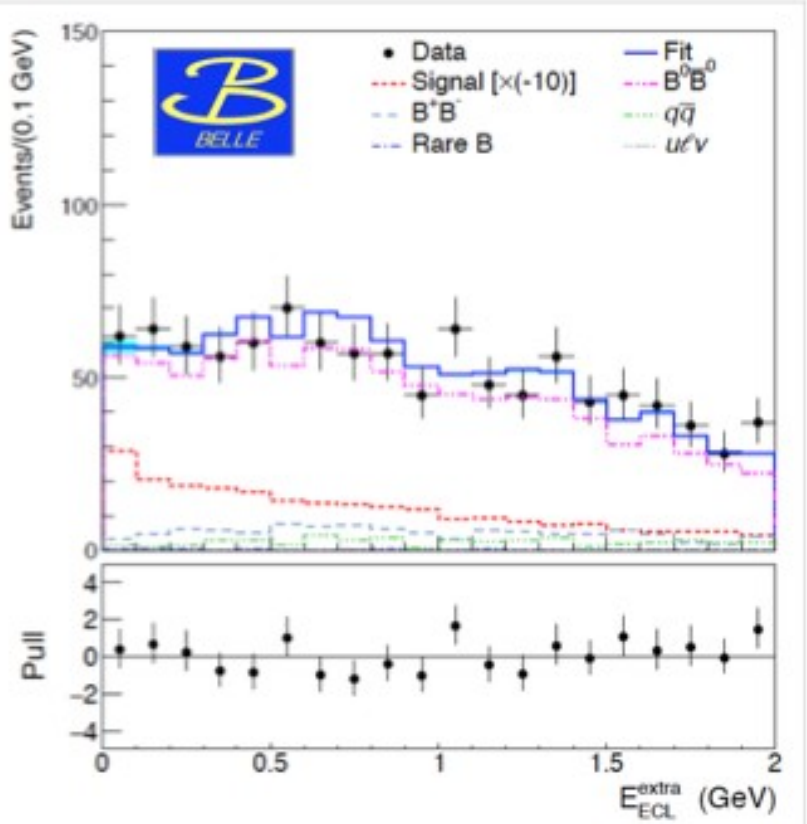
EWP(enguin) decays with E_{miss} and LFV at Belle II (Tao Luo)

- Belle
  - ✓ Search for $B^0 \to K^* \tau^+ \tau^-$ at Belle (arXiv: 2110. 03871)
  - ✓ Search for $B^0_{(d)} \to \tau^{\mp} \ell^{\pm}$ at Belle (arXiv: 2108. 11649)

- Belle II
  - ✓ Search for $B^+ \to K^+ \upsilon \bar{\upsilon}$ at Belle II (Phys. Rev. Lett. 127 (2021) 181802)

EWP(enguin) decays with E_{miss} and LFV at Belle II (Tao Luo)

$B \to K^* \tau \tau$



- E_{ECL}^{extra} is the total energy of the neutral clusters detected in the ECL not associated with either B_{tag} or B_{sig}. "$E_{missing}$"
- The overall selection efficiency, $\epsilon = 1.2\times10^{-5}$
- $N_{sig} = -4.9 \pm 6.0$
- The upper limit:
  - ✓ $\mathcal{B}(B^0 \to K^{*0}\tau^+\tau^-) < 2.0\times10^{-3}$ at 90% C.L.
- The first experimental limit on the decay $B^0 \to K^{*0}\tau^+\tau^-$.

B-decay LFV

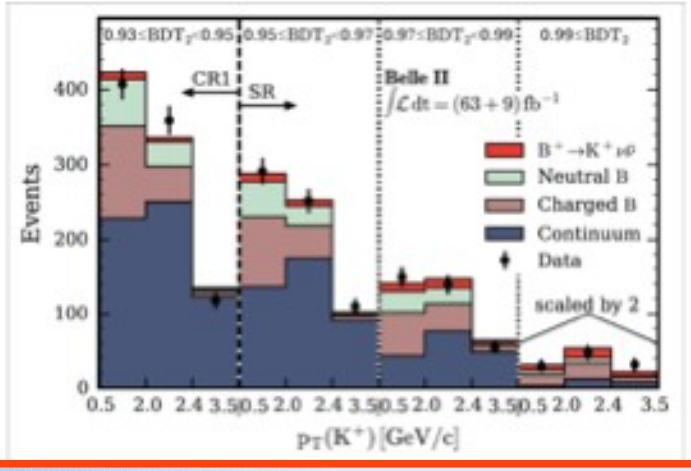
- The upper limits: $\mathcal{B}(B^0 \to \tau\mu) < 1.5\times10^{-5}$, $\mathcal{B}(B^0 \to \tau e) < 1.6\times10^{-5}$ at 90 C.L.
  Electron mode: the most stringent limit to date

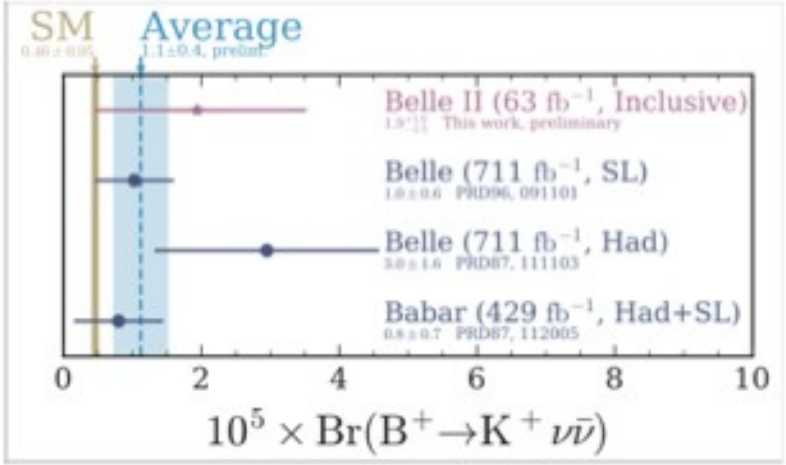
EWP(enguin) decays with E_{miss} and LFV at Belle II (Tao Luo)

$B \to K \nu \bar{\nu}$

$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu}) < 4.1\times10^{-5}$ at 90 C.L

Similar upper limit as Belle and BaBar





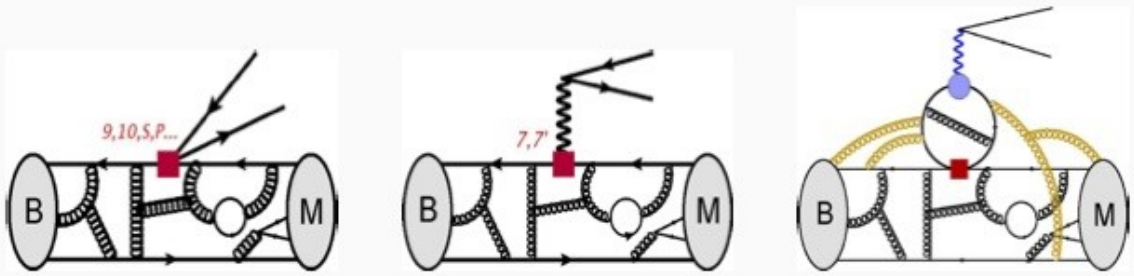
Rare b → s ℓℓ decays: progress on QCD errors (Danny van Dyk)

$$\mathcal{L}_{\rm SM}^{\rm eff} = \mathcal{L}_{\rm QCD} + \mathcal{L}_{\rm QED} + \frac{4G_F}{\sqrt{2}}\left[\lambda_t \sum_i C_i \mathcal{O}_i + \lambda_c \sum_i C_i^c \mathcal{O}_i^c + \lambda_u \sum_i C_i^u \mathcal{O}_i^u\right]$$

$$\mathcal{O}_7 = \frac{e}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R b) F_{\mu\nu} \qquad \mathcal{O}_8 = \frac{g_s}{16\pi^2} m_b (\bar{s}\sigma^{\mu\nu} P_R T^A b) G^A_{\mu\nu}$$

$$\mathcal{O}_9 = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_{10} = \frac{\alpha}{4\pi} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_1^q = (\bar{q}\gamma_\mu P_L b)(\bar{s}\gamma^\mu P_L q) \qquad \mathcal{O}_2^q = (\bar{q}\gamma_\mu P_L T^a b)(\bar{s}\gamma^\mu P_L T^a q)$$



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

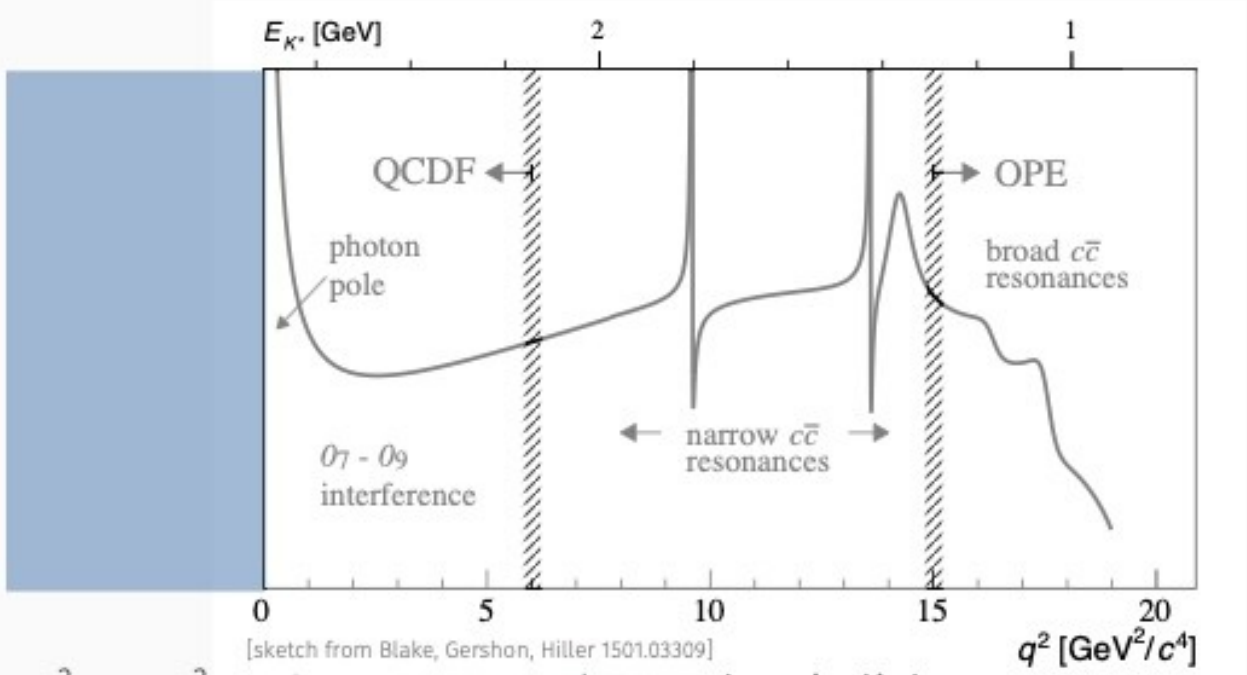
nomenclature of the essential hadronic matrix elements $\qquad q^2 = m_{\ell\ell}^2$

- $\mathcal{F}_\lambda$ local form factors of dimension-three $\bar{s}\gamma^\mu b$ & $\bar{s}\gamma^\mu\gamma_5 b$ currents
- $\mathcal{F}_\lambda^T$ local dipole form factors of dimension-three $\bar{s}\sigma^{\mu\nu} b$ currents
- $\mathcal{H}_\lambda$ nonlocal form factors of dimension-five nonlocal operators

all three needed for consistent description to leading-order in α_e

The elephant in the room

$$\mathcal{H}_\lambda(q^2) = P(\lambda)_\mu \langle H_s | \int d^4x\, e^{iq\cdot x}\, \mathcal{T}\{ J^\mu_{\rm em}(x), [C_1 O_1^c + C_2 O_2^c](0) \} | H_b \rangle$$



[sketch from Blake, Gershon, Hiller 1501.03309]

- $O^c_{1,2} \sim [\bar{s}\Gamma b]\ [\bar{c}\Gamma' c]$

- for $q^2 - 4m_c^2 \ll \Lambda_{\rm had} m_b$, expand T-product in light-cone operators
- leading contributions expressed through local form factors $\mathcal{F}_\lambda$
- correction suppressed by $1/(q^2 - 4m_c^2)$ can by systematically obtained

[Khodjamirian, Mannel, Pivovarov, Wang 2010]

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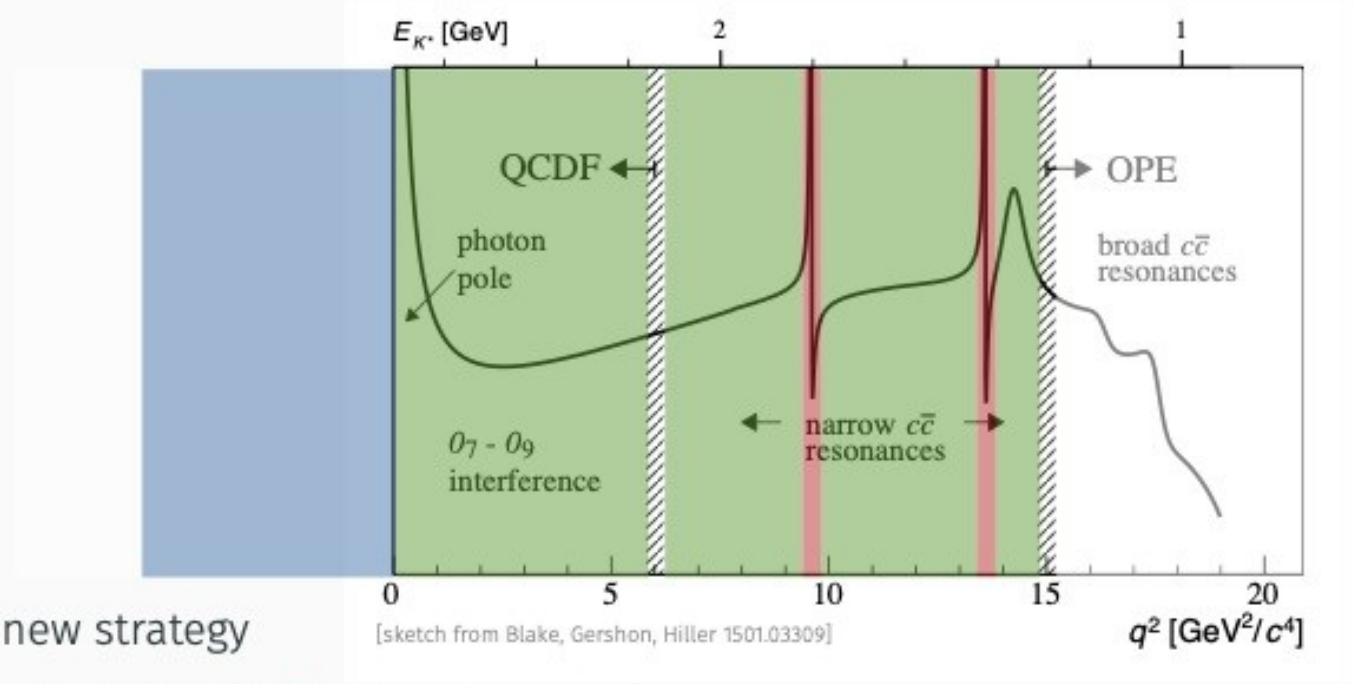

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- $O^c_{1,2} \sim [\bar{s}\Gamma b]\,[\bar{c}\Gamma' c]$

[Bobeth,Chrzaszcz,DvD,Virto '17]

new strategy

- compute $\mathcal{H}_\lambda$ at spacelike q^2
- extrapolate to timelike $q^2 \leq 4M_D^2$ using suitable parametrization
- include information from non-leptonic decays to narrow charmonia J/ψ and $\psi(2S)$

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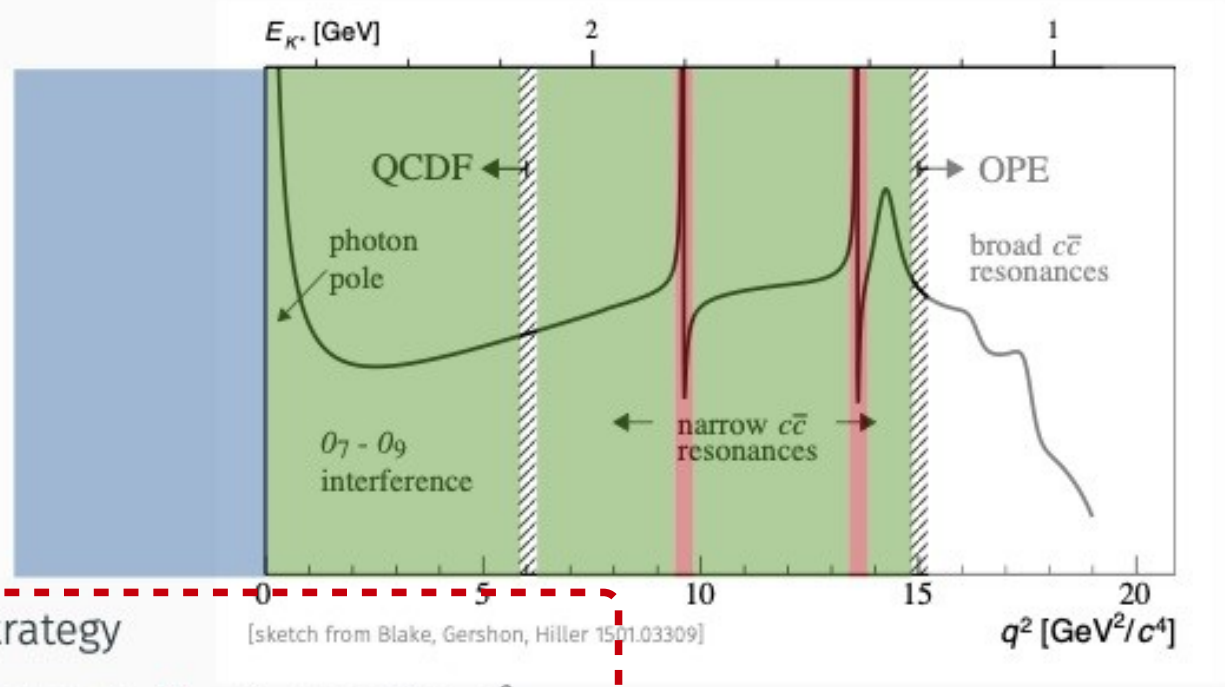

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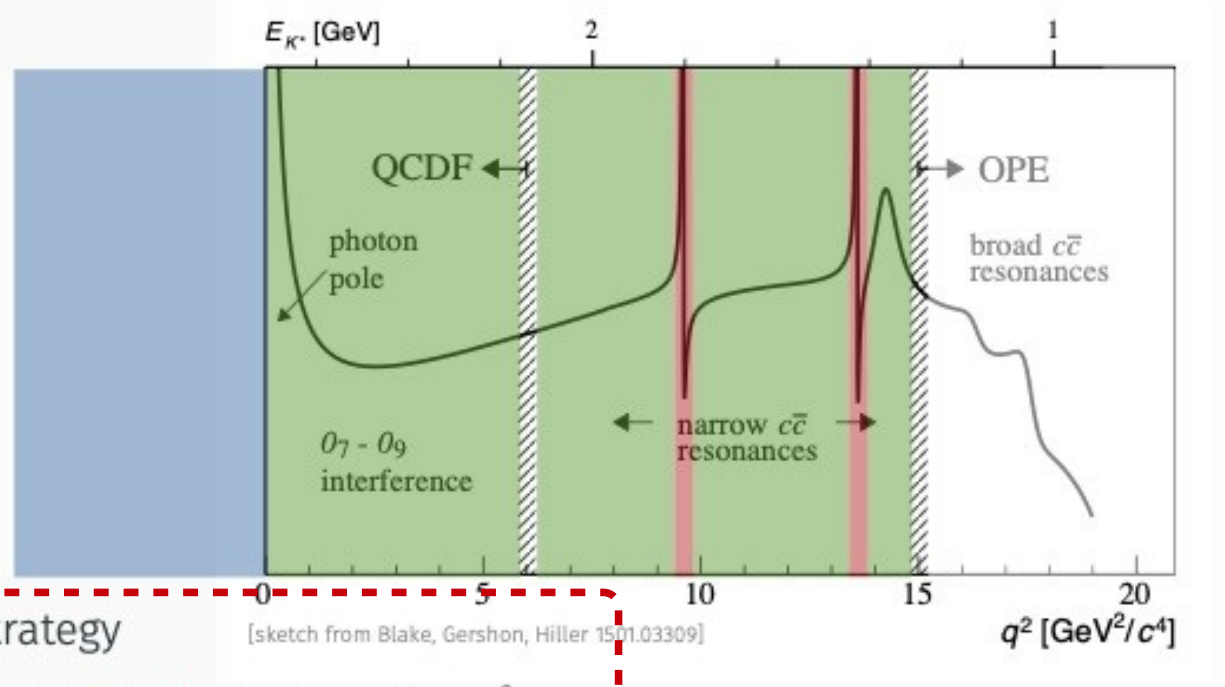

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Reappraisal of KMPW in

[Gubernari,DvD,Virto '20] see also [Gubernari, Kokulu, DvD '18]

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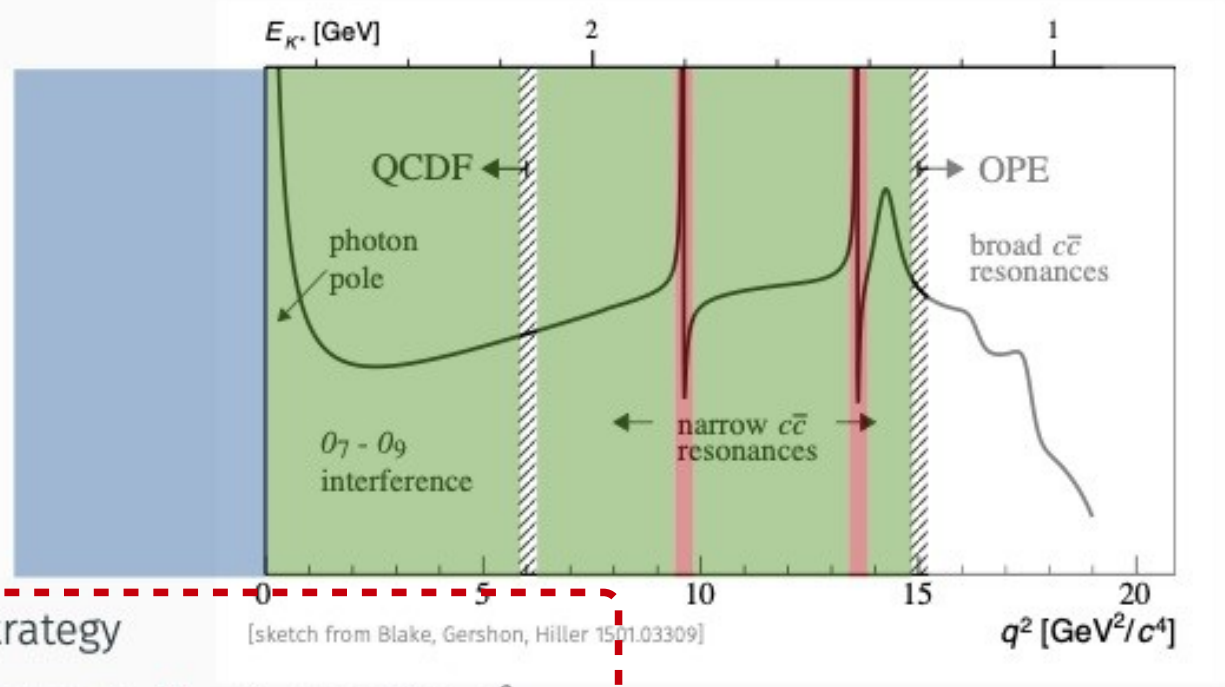

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Global analysis in progress: stay tuned

Searching for NP without V_{cb} and V_{ub} errors (Elena Venturini)

Large uncertainties on K and B decays

- $|V_{cb}|^2 \to 16\,\%$, e.g. in $Br(B_{s,d} \to \mu\mu)$ and $\Delta M_{s,d}$
- $|V_{cb}|^3 \to 24\,\%$, e.g. in $Br(K^+ \to \pi^+\nu\nu)$ and $|\epsilon_K|$
- $|V_{cb}|^4 \to 32\,\%$, e.g. in $Br(K_L \to \pi^0\nu\nu)$ and $Br(K_S \to \mu\mu)$

$$R_{s(d)\mu} \equiv \frac{Br(B_{s(d)} \to \mu^+\mu^-)}{\Delta M_{s(d)}} = C\frac{\tau_{B_{s(d)}}}{\hat{B}_{s(d)}} f(x_t)$$

$$C \downarrow 4.291 \cdot 10^{-10}$$

Idea of:
0303060 [Buras]
2104.09521 [Bobeth, Buras]

$$[R_{s\mu}]_{SM} = \left(2.04^{+0.08}_{-0.06}\right) \cdot 10^{-10}\,\text{ps} \quad \textit{vs} \quad [R_{s\mu}]_{exp} = \left(1.61^{+0.19}_{-0.17}\right) \cdot 10^{-10}\,\text{ps}$$

2.1σ tension with SM

WITHOUT CKM uncertainties

Searching for NP without V_{cb} and V_{ub} errors (Elena Venturini)

Then systematically define $|V_{cb}|$-independent ratios

$$R_5 \equiv \frac{Br(K^+ \to \pi^+\nu\nu)}{[Br(B^+ \to K^+\nu\nu)]^{1.4}} \propto [\sin\gamma]^{1.39} \qquad R_6 \equiv \frac{Br(K^+ \to \pi^+\nu\nu)}{[Br(B^0 \to K^{0*}\nu\nu)]^{1.4}} \propto [\sin\gamma]^{1.39}$$

$$R_7 \equiv \frac{Br(B^+ \to K^+\nu\nu)}{Br(B_s \to \mu\mu)} \propto [F_{B_s}]^{-2} \qquad R_8 \equiv \frac{Br(B^0 \to K^{0*}\nu\nu)}{Br(B_s \to \mu\mu)} \propto [F_{B_s}]^{-2}$$

CKM independent

1.8σ tension SM-exp

$$R_9 \equiv \frac{|\epsilon_K|}{(\Delta M_d)^{1.7}} \propto [\sin\gamma]^{-1.73}[\sin\beta]^{0.87} \qquad R_{10} \equiv \frac{|\epsilon_K|}{(\Delta M_s)^{1.7}} \propto [\sin\gamma]^{1.67}[\sin\beta]^{0.87}$$

$$R_{11} \equiv \frac{Br(K^+ \to \pi^+\nu\nu)}{|\epsilon_K|^{0.82}} \propto [\sin\gamma]^{0.015}[\sin\beta]^{-0.71} \qquad R_{12} \equiv \frac{Br(K_L \to \pi^0\nu\nu)}{|\epsilon_K|^{1.18}} \propto [\sin\gamma]^{0.03}[\sin\beta]^{0.98}$$

Almost depending only on β: accurately determined from $S_{\psi K_S}$

$$R_{s\mu} \equiv \frac{Br(B_s \to \mu\mu)}{\Delta M_s} \propto \text{const} \qquad R_{d\mu} \equiv \frac{Br(B_d \to \mu\mu)}{\Delta M_d} \propto \text{const}$$

CKM independent

$$R_0 \equiv \frac{Br(K^+ \to \pi^+\nu\nu)}{Br(K_L \to \pi^0\nu\nu)^{0.7}} \propto [\sin\beta]^{-1.4} \qquad R_{SL} \equiv \frac{Br(K_S \to \mu\mu)_{SD}}{Br(K_L \to \pi^0\nu\nu)} \propto \text{const}$$

Rare B decays II

- *Rare B decays at CMS and ATLAS* *(Pavel Reznicek)*
- *Very rare B decays* *(Francesco Dettori)*
- *Wilson coefficients and global fits* *(Peter Stangl)*
- *Model-building for rare B-decay anomalies* *(Claudia Cornella)*

Very rare B decays at LHCb (Francesco Dettori)

The $B^0_{d,s} \to \mu^+\mu^-$ decays

Extremely rare decays

- Flavour changing neutral currents
- Helicity suppressed

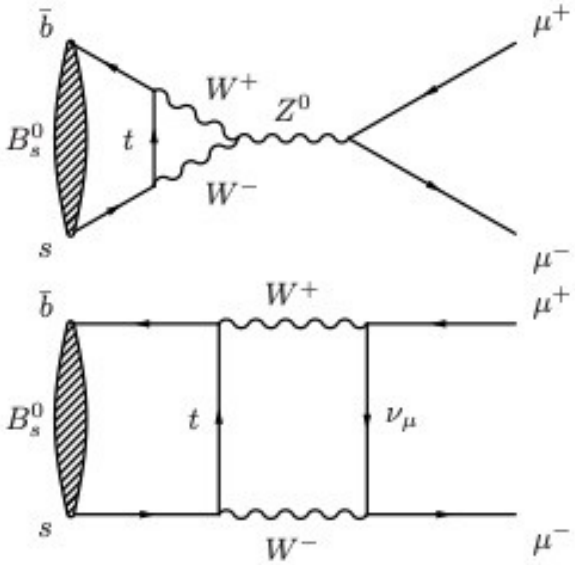
Most recent Standard Model predictions†

$$B(B^0_s \to \mu^+\mu^-) = (3.66 \pm 0.14) \times 10^{-9}$$

$$B(B^0 \to \mu^+\mu^-) = (1.03 \pm 0.05) \times 10^{-10}$$

[Beneke, Bobeth, Szafron, JHEP10(2019) 232]

- Impressively precise predictions
- Any significant deviations from these values is sign of new interactions beyond the SM
- Dominated by parametric uncertainties

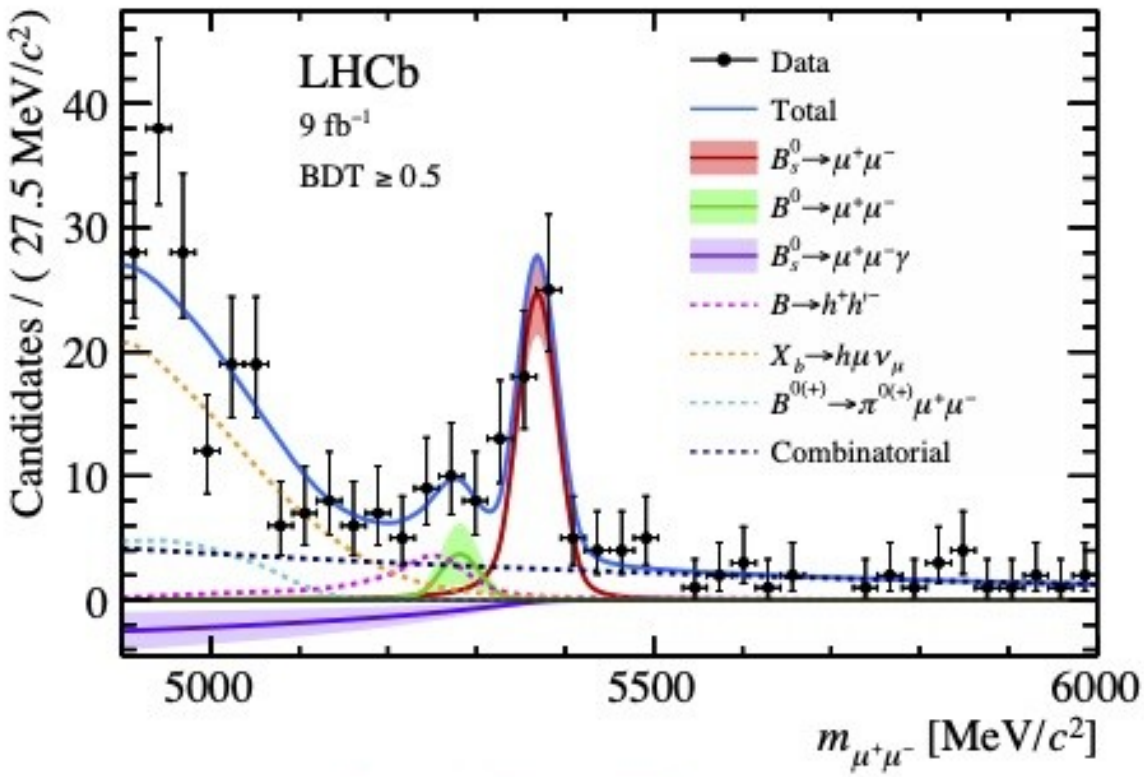


Using the correlation of $\Delta F = 1$ rare decays with $\Delta F = 2$ B mixing, using experimental ΔM values can also be predicted to be:

$$B(B^0_s \to \mu^+\mu^-) = (3.62^{+0.15}_{-0.10}) \times 10^{-9}$$
$$B(B^0 \to \mu^+\mu^-) = (0.99^{+0.05}_{-0.03}) \times 10^{-10}$$

[Buras, Venturini -2109.11032]

Very rare B decays at LHCb (Francesco Dettori)



[LHCb-PAPER-2021-007] [LHCb-PAPER-2021-008]

$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = \left(3.09\,^{+0.46+0.15}_{-0.43-0.11}\right) \times 10^{-9}$

$\mathcal{B}(B^0 \to \mu^+\mu^-) = \left(1.2\,^{+0.8}_{-0.7} \pm 0.1\right) \times 10^{-10} < 2.6 \times 10^{-10}$

$\mathcal{B}(B_s^0 \to \mu^+\mu^-\gamma)_{m_{\mu\mu}>4.9\,\mathrm{GeV}} = (-2.5 \pm 1.4 \pm 0.8) \times 10^{-9} < 2.0 \times 10^{-9}$

No significant signal for $B^0 \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-\gamma$, upper limits at 95%

First world limit on $B_s^0 \to \mu^+\mu^-\gamma$ decay

Very rare B decays at LHCb (Francesco Dettori)

Combined measurement of hadronisation fraction

...and B_s^0 branching fractions

Breaking the recursive problem: combine information of different measurements
Measure production ratios from ratio of decays with known rate (semileptonic) or known rate ratios ($B \to Dh$), and cross-check dependencies with decays of high rate ($B \to J/\psi X$).
Recent LHCb combination $\frac{f_s}{f_d}(13\,\text{TeV}) = 0.2539 \pm 0.0079$

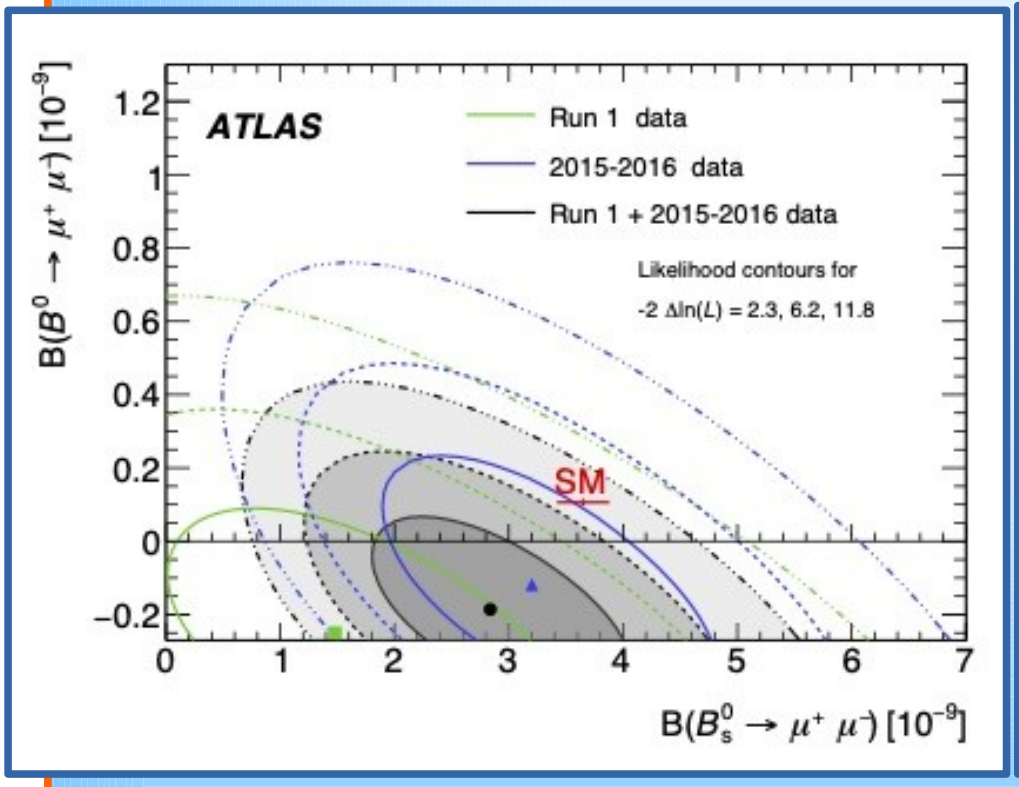
… plus many other measurements that we can't detail unfortunately

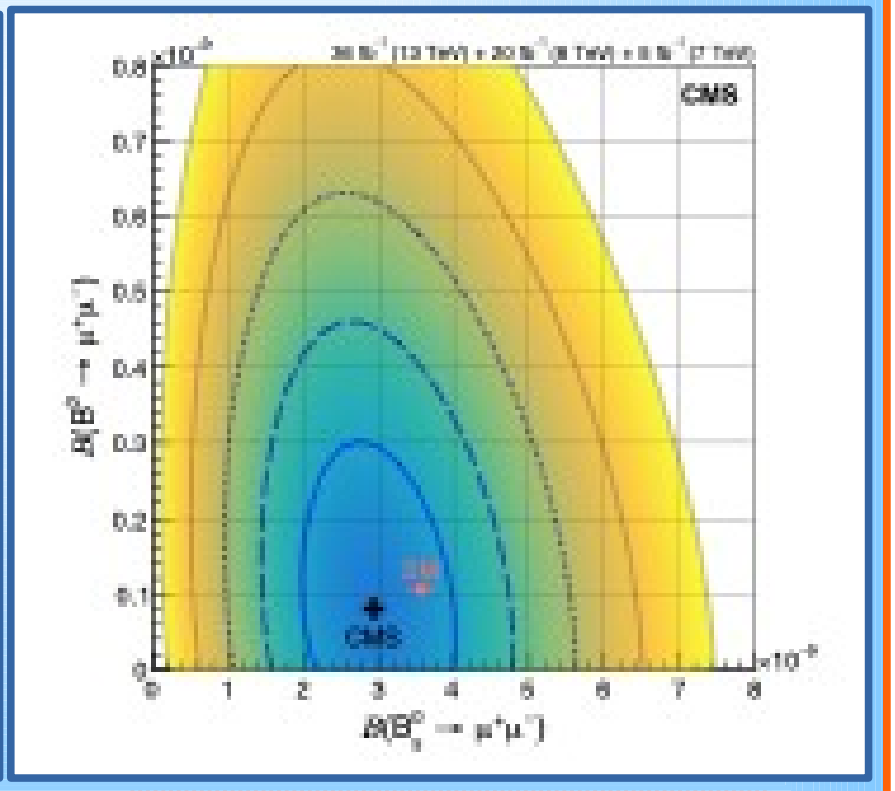
- $\tau_{\text{eff}}(B_s^0 \to \mu^+\mu^-) = 2.07 \pm 0.29 \pm 0.03\,\text{ps}$
- Updated $B_{(s)}^0 \to \mu^+\mu^-\mu^+\mu^-$search
  - First search for $B \to aa$ with mass also around 1 GeV
  - Strong constraints on all branching fractions
- Search for $B^0 \to \phi\mu^+\mu^-$ decays leads world best limit

Rare B decays at CMS and ATLAS *(Pavel Reznicek)*

- Program focused mostly on muonic final states, fully reconstructable; exceptions exist:
  - CMS B-parking Run 2 data collecting huge unbiased ($\sim 10^{10}$) *b*-hadron events
  - Di-electron triggers in Run 2 at ATLAS

$B_s \rightarrow \mu\ \mu$



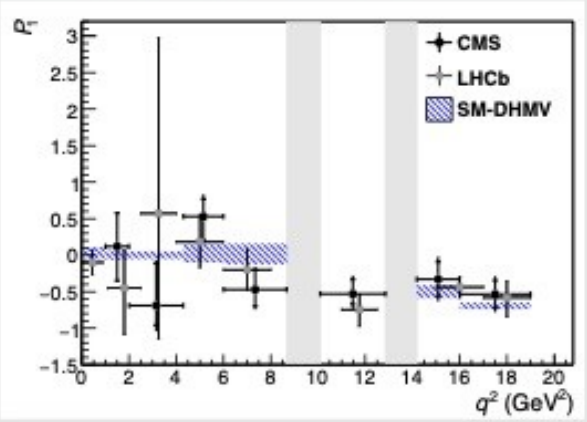


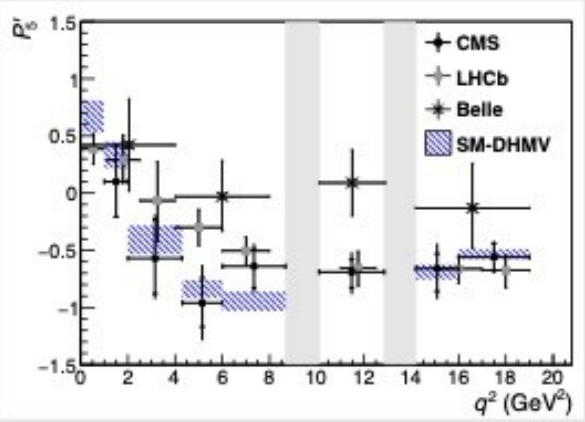
Eff. lifetime measured as well !

Rare B decays at CMS and ATLAS (Pavel Reznicek)

$B^0 \to K^{*0}\mu\mu$: Results (CMS, ATLAS)

CMS: P_1, P_5', A_{FB}, F_L; full q^2 range

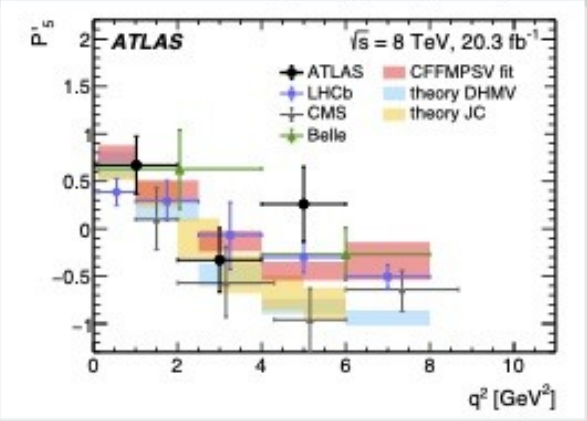


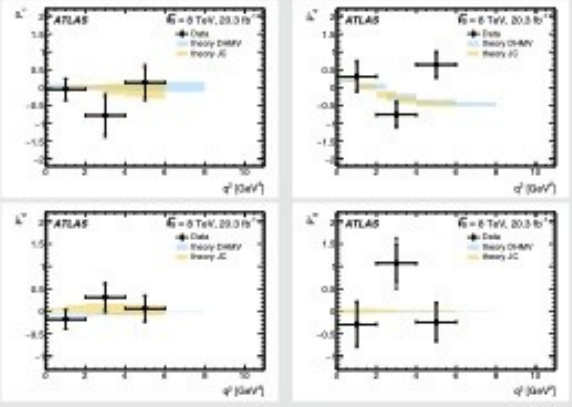


- Consistent with SM predictions

Source	$P_1(\times 10^{-3})$	$P_5'(\times 10^{-3})$
Simulation mismodeling	1–33	10–23
Fit bias	5–78	10–120
Finite size of simulated samples	29–73	31–110
Efficiency	17–100	5–65
$K\pi$ mistagging	8–110	6–66
Background distribution	12–70	10–51
Mass distribution	12	19
Feed-through background	4–12	3–24
F_L, F_S, A_S uncertainty propagation	0–210	0–210
Angular resolution	2–68	0.1–12
Total	100–230	70–250

ATLAS: P_1, P_4', P_5', P_6', P_8', F_L; low q^2 range only





- P_5' and P_4' deviation of 2.7σ in $q^2 = (4-6)\,\mathrm{GeV}^2$ following direction of the LHCb deviation
- But still compatible with SM prediction

Wilson Coefficients and global fits *(Peter Stangl)*

Setup

- Quantify agreement between theory and experiment by χ^2 function

$$\chi^2(\vec{C}) = \left(\vec{O}_{\text{exp}} - \vec{O}_{\text{th}}(\vec{C})\right)^{\mathsf{T}} \left(C_{\text{exp}} + C_{\text{th}}(\vec{C})\right)^{-1} \left(\vec{O}_{\text{exp}} - \vec{O}_{\text{th}}(\vec{C})\right) .$$

- **theory errors** and **correlations** in covariance matrix $\boldsymbol{C}_{\text{th}}$
- **experimental errors** and available **correlations** in covariance matrix $\boldsymbol{C}_{\text{exp}}$
- Theory errors depend on new physics (NP) Wilson coefficients $\boldsymbol{C}_{\text{th}}(\vec{C})$ *NEW*

Altmannshofer, PS, arXiv:2103.13370

- $\Delta\chi^2$ and pull

$$\text{pull}_{1D} = 1\sigma \cdot \sqrt{\Delta\chi^2}\,, \qquad \text{where } \Delta\chi^2 = \chi^2(\vec{0}) - \chi^2(\vec{C}_{\text{best fit}})\,.$$

$$\text{pull}_{2D} = 1\sigma, 2\sigma, 3\sigma, \ldots \quad \text{for} \quad \Delta\chi^2 \approx 2.3, 6.2, 11.8, \ldots$$

- New physics scenarios in **Weak Effective Theory (WET)** at scale 4.8 GeV

Wilson Coefficients and global fits *(Peter Stangl)*

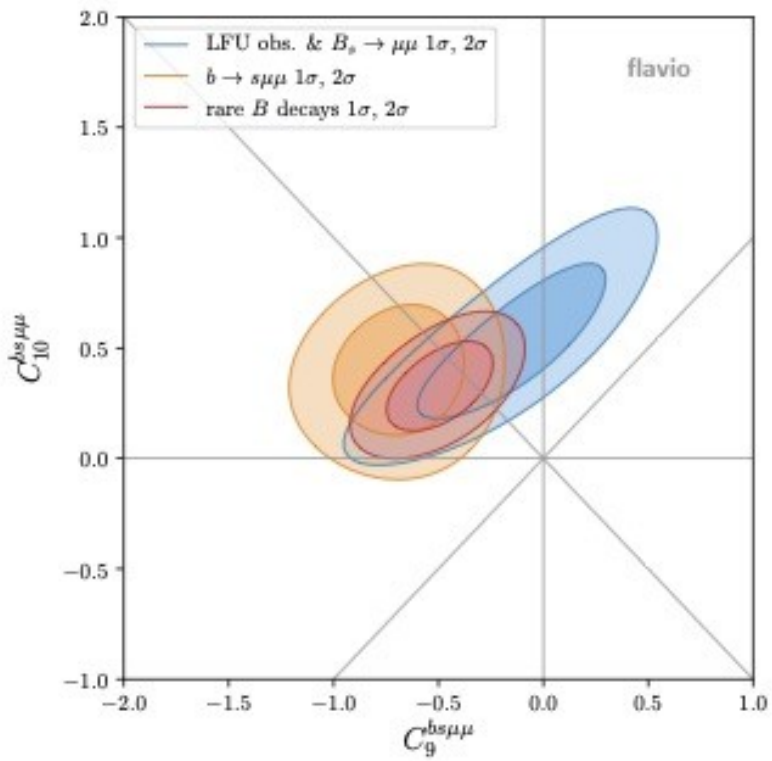
Scenarios with a single Wilson coefficients

	Wilson coefficient	$b \to s\mu\mu$ best fit	$b \to s\mu\mu$ pull	LFU, $B_s \to \mu\mu$ best fit	LFU, $B_s \to \mu\mu$ pull	all rare B decays best fit	all rare B decays pull
NP err.	$C_9^{bs\mu\mu}$	$-0.70^{+0.21}_{-0.22}$	**3.3σ**	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.71^{+0.15}_{-0.15}$	**5.1σ**
	$C_{10}^{bs\mu\mu}$	$+0.45^{+0.22}_{-0.23}$	1.9σ	$+0.60^{+0.14}_{-0.14}$	**4.7σ**	$+0.54^{+0.12}_{-0.12}$	4.8σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.55^{+0.13}_{-0.13}$	**3.8σ**	$-0.35^{+0.08}_{-0.08}$	**4.6σ**	$-0.39^{+0.07}_{-0.07}$	**5.6σ**
SM err.	$C_9^{bs\mu\mu}$	$-0.83^{+0.22}_{-0.20}$	**3.6σ**	$-0.74^{+0.20}_{-0.21}$	4.1σ	$-0.77^{+0.15}_{-0.15}$	**5.3σ**
	$C_{10}^{bs\mu\mu}$	$+0.45^{+0.21}_{-0.20}$	2.3σ	$+0.60^{+0.14}_{-0.14}$	**4.7σ**	$+0.54^{+0.12}_{-0.12}$	4.9σ
	$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	$-0.60^{+0.17}_{-0.18}$	**3.8σ**	$-0.35^{+0.08}_{-0.08}$	**4.6σ**	$-0.39^{+0.07}_{-0.07}$	**5.6σ**

Visible effect of theory errors depending on new physics, in particular for $C_9^{bs\mu\mu}$

Wilson Coefficients and global fits (Peter Stangl)

Scenarios with two Wilson coefficients



WET at 4.8 GeV

Combination of $B_s \to \mu^+\mu^-$ and LFU observables (R_K, R_{K^*}, $D_{P_{4',5'}}$)

- LFU obs. & $B_s \to \mu\mu$: very clean theory prediction, insensitive to universal $C_9^{\text{univ.}}$
- $b \to s\mu\mu$ sensitive to univ. coeff. possibly afflicted by underestimated hadr. uncert.
- Agreement between $b \to s\mu\mu$ observables and R_K & R_{K^*} could be further improved by **LFU** contribution to $\boldsymbol{C_9^{\text{univ.}}}$

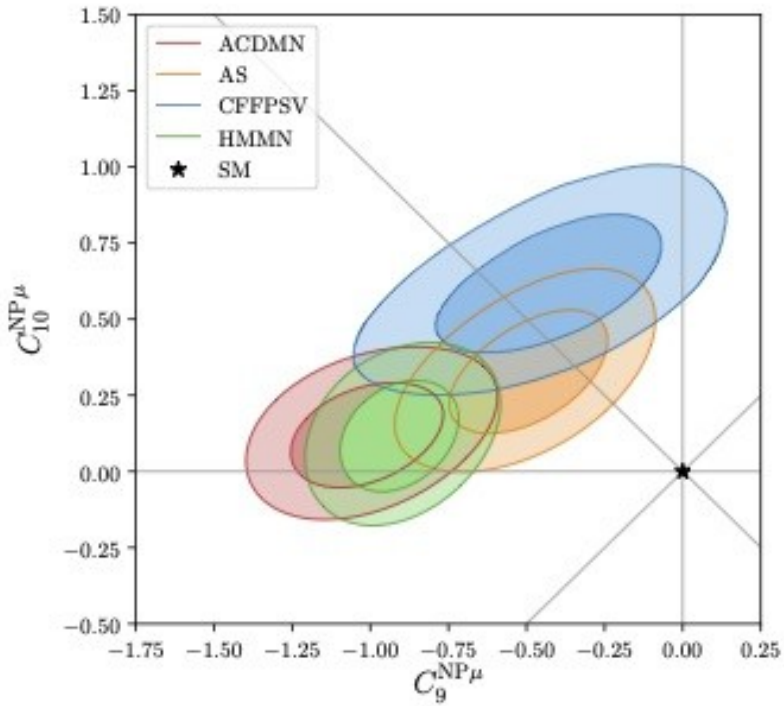
possible connection to $b \to c\ell\nu$ anomalies
see backup slides and talk by Claudia Cornella

Global fit in $C_9^{bs\mu\mu}$-$C_{10}^{bs\mu\mu}$ plane prefers negative $C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$

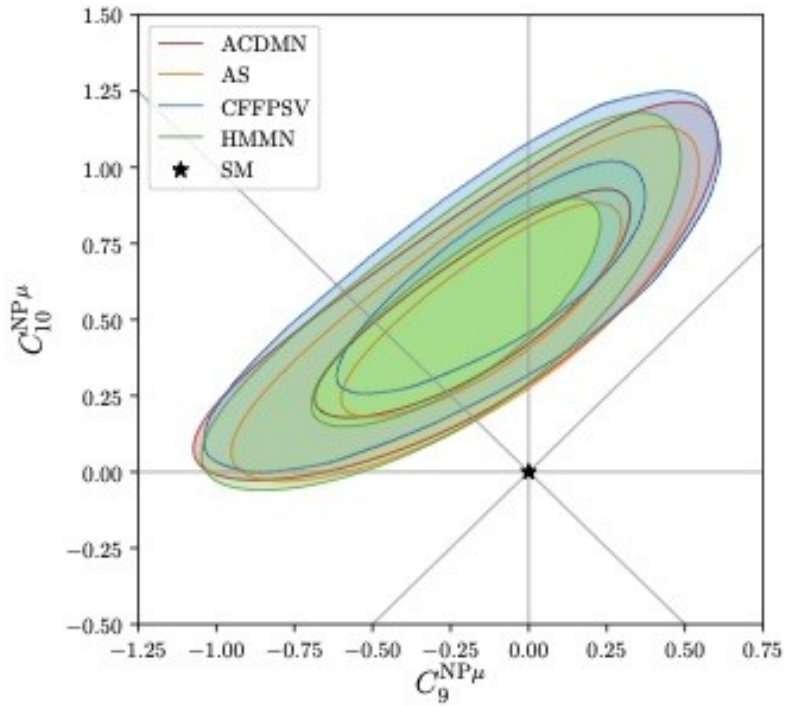
Wilson Coefficients and global fits (Peter Stangl)

Robustness of global fits

Capdevila, Fedele, Neshatpour, PS



global fit



fit to LFU observables + $B_s \to \mu\mu$

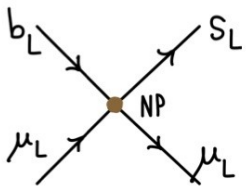
ACDMN (Algueró, Capdevila, Descotes-Genon, Matias, Novoa-Brunet), arXiv:2104.08921
AS (Altmannshofer, PS), arXiv:2103.13370
CFFPSV (Ciuchini, Fedele, Franco, Paul, Silvestrini, Valli), arXiv:2011.01212
HMMN (Hurth, Mahmoudi, Martínez-Santos, Neshatpour), arXiv:2104.10058

Wilson Coefficients and global fits (Peter Stangl)

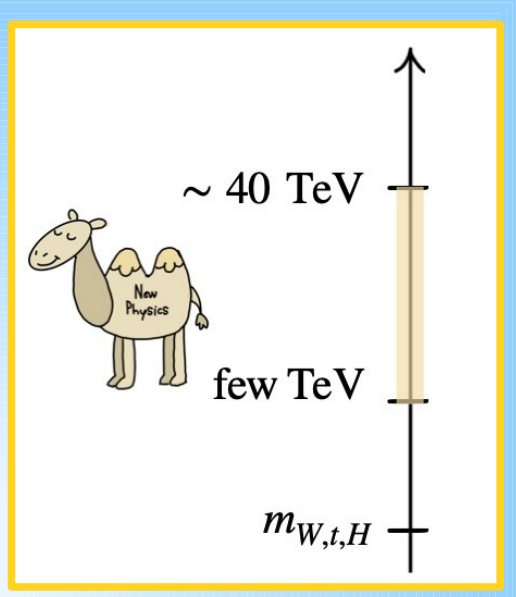
Apologies for having to skip other interesting aspects, including

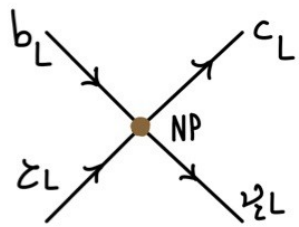
- global fits in the SMEFT
- global fits within Leptoquark models
- specific models of muonic anomalies

Model-building for the anomalies (Claudia Cornella)

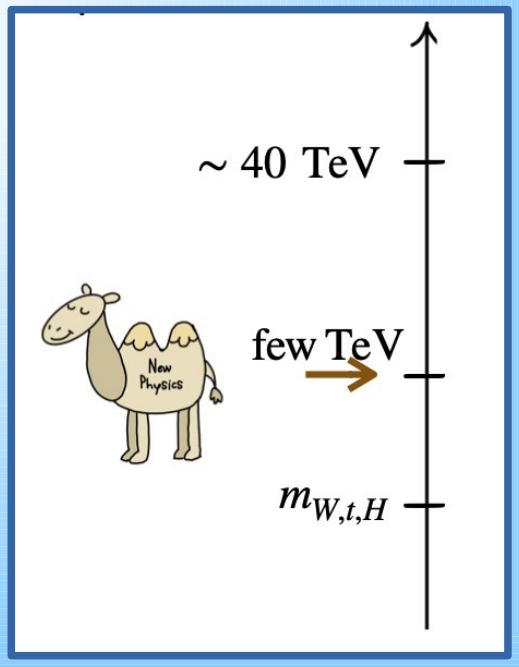


$$\sim 4 \times 10^{-5}\, G_F \quad \Rightarrow \quad \frac{g_{\rm NP}^2}{\Lambda^2} \sim \frac{1}{(40\ \text{TeV})^2}$$





$$\sim 10^{-2}\, G_F$$



Model-building for the anomalies (Claudia Cornella)

Why both?

No obvious connection. Why combine both anomalies in a single NP framework?

$b \to sll$	$SU(2)_L$	$b \to cl\nu$
$(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$	$\longleftrightarrow$	$(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)$

⇒ Minimal sol: **left-handed NP in semi-leptonic operators** (RH currents also possible)

- Three possibilities for a combined explanation:
  - $S_1 + S_3$ [Crivellin et al 1703.09226; Buttazzo et al. 1706.07808; Marzocca 1803.10972...]
  - $R_2 + S_3$ [Bečirević et al., 1806.05689]
  - $U_1 \sim (3, 1, 2/3)$ [di Luzio et al., 1708.08450; Calibbi et al., 1709.00692; Bordone, CC, et al. 1712.01368; Barbieri, Tesi 1712.06844; Heck,Teresi 1808.07492…]

✓ no $b \to s\nu\bar{\nu}$ at tree level

Model-building for the anomalies (Claudia Cornella)

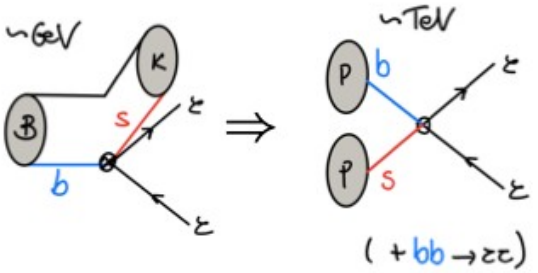
Low-energy predictions for the U_1

- large $b \to s\tau\tau$
- large τ/μ LFV in $b \to s\tau\mu$ and τ decays

High-pT bounds for the U_1

The same interaction can be probed in **di-tau tails**.

Expected excess in $pp \to \tau^+\tau^-$! [Faroughy et al, 1609.07138]

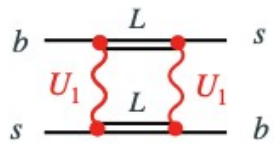


Model-building for the anomalies (Claudia Cornella)

UV-sensitive low-energy observables

[Selimovic et al., 2009.11296]
[CC, Fuentes et al., 2103.16558]

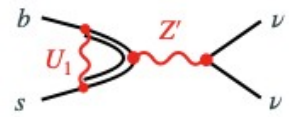
- B_s-$\bar{B}_s$ mixing

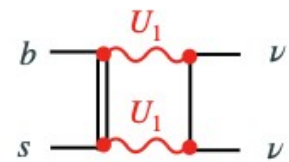


$$\frac{C_{bs}^{\text{NP-tree}}}{C_{bs}^{\text{SM}}} \propto \left(\beta_L^{s\tau *}\right)^2 M_L^2$$

$\rightarrow U(2)_q$ breaking (for $R_{D^{(*)}}$)

- $B \to K\nu\bar{\nu}$





UV-completing the U_1: the gauge path

$\mathcal{G}_{4321} = SU(4) \times SU(3)' \times SU(2)_L \times U(1)'$ $\quad$ $4321/\text{SM} \ni U_1, Z', G' \sim (8,1,0)$

✓ $SU(4)$ decorrelated from $SU(3)_c$. High-pT problem solved for $g_4 \gg g_1, g_3$

✓ both Z' and U_1 can be flavor non-universal

[Georgi and Y. Nakai, 1606.05865;
Diaz, Schmaltz, Zhong, 1706.05033;
Di Luzio, Greljo, Nardecchia, 1708.08450]

Radiative B and rare D decays

- *On the $\overline{B} \to X_s \gamma$ accuracy* *(Abdur Rehman)*
- *Radiative B decays at LHCb* *(Carla Marin Benito)*
- *Radiative B decays at Belle & Belle II* *(Markus Roerken)*
- *Rare D decays at LHCb* *(Davide Brundu)*
- *Rare D decays at BES III* *(Liang Sun)*

On the $\overline{B} \to X_s \gamma$ accuracy (Abdur Rehman)

Branching fraction, HFLAV [arXiv: 1909.12524]

$\mathcal{B}_{s\gamma}$: CP- and isospin-averaged BR of $\bar{B} \to X_s\gamma$ and $B \to X_s\gamma$

$\bar{B} = B^-(b\bar{u})$ or $\bar{B}^0(b\bar{d})$

$$\mathcal{B}_{s\gamma}^{\rm exp} = (3.32 \pm 0.15) \cdot 10^{-4} \qquad (\text{for } E_\gamma > 1.6\,\text{GeV})$$

(4.5%)

Background grows for smaller E_γ! Average CLEO, BELLE and BABAR with $E_0 \in [1.7, 2.0]$ GeV. Then, extrapolate to $E_0 = 1.6$ GeV $\simeq m_b/3$.

THEORY: E_0 should be large ($\sim m_b/2$) but not too close to the endpoint ($m_b - 2E_0 \gg \Lambda_{\rm QCD}$), $E_0 = 1.6$ GeV is now conventional.

On the $\overline{B} \to X_s\,\gamma$ accuracy (Abdur Rehman)

The matrix elements can be "effectively" evaluated in perturbation theory.

$$\mathcal{B}(\bar{B} \to X_s\gamma)_{E_\gamma > E_0} = \mathcal{B}(\bar{B} \to X_c e\bar{\nu})_{\rm exp} \left|\frac{V_{tb}V_{ts}^*}{V_{cb}}\right|^2 \frac{6\alpha_{\rm em}}{\pi\, C} \Big[\underbrace{P(E_0)}_{\sim 96\%}^{\text{perturbative}} + \underbrace{N(E_0)}_{\sim 4\%}^{\text{non-perturbative}}\Big]$$

$$\Gamma(b \to X_s^p\gamma)_{E_\gamma > E_0} \simeq N \sum_{i,j=1}^{8} C_i(\mu_b) C_j(\mu_b)\, \hat{G}_{ij}(E_0, \mu_b)$$

This talk $G_{27}^{(2)}(z)$: (an interference of $\mathcal{Q}_2$ and $\mathcal{Q}_7$ operators) for arbitrary charm quark mass

On the $\overline{B} \to X_s\,\gamma$ accuracy (Abdur Rehman)

Updated SM predictions for $\mathcal{B}_{s\gamma}$ and $R_\gamma \equiv \mathcal{B}_{(s+d)\gamma}/\mathcal{B}_{c\ell\bar{\nu}}$

Mikolaj Misiak, Abdur Rehman, Matthias Steinhauser
JHEP 114 (2020) 175 [arXiv: 2002.01548]

Mikolaj Misiak *et al.*
[arXiv:1503.01789]

$$\mathcal{B}_{s\gamma}^{\rm SM} = (3.40 \pm \overset{\pm 5.0\%}{0.17}) \times 10^{-4} \longleftarrow (3.36 \pm \overset{\pm 6.9\%}{0.23}) \times 10^{-4}$$

$$R_\gamma = (3.35 \pm \underset{\pm 4.8\%}{0.16}) \times 10^{-3} \longleftarrow (3.31 \pm \underset{\pm 6.7\%}{0.22}) \times 10^{-3}$$

Belle-II: Better accuracy is expected, $\sim 2.6\%$; [arXiv:1808.10567]

Radiative B decays at LHCb *(Carla Marin Benito)*

PRL 123 (2019) 081802

Photon polarization in $B_s \to \phi\gamma$

Time dependent decay rate for f_{CP} states gives access to photon polarization:

$$\Gamma(t) \propto e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_{(s)}}{2}\right) - \mathcal{A}^{\Delta}\sinh\left(\frac{\Delta\Gamma_{(s)}}{2}\right) \pm \mathcal{C}_{CP}\cos\left(\Delta m_{(s)}t\right) \mp \mathcal{S}_{CP}\sin\left(\Delta m_{(s)}t\right)\right]$$

Accessible from decay time distribution

Require knowledge of the B_s flavour at production

in terms of Wilson coefficients:

$$\mathcal{A}^{\Delta}_{\phi\gamma} \simeq \frac{\mathrm{Re}(e^{-i\phi_s}C_7\,C_7')}{|C_7|^2+|C_7'|^2} \qquad S_{\phi\gamma} \simeq \frac{\mathrm{Im}(e^{-i\phi_s}C_7\,C_7')}{|C_7|^2+|C_7'|^2}$$

$$S_{\phi\gamma} = 0.43 \pm 0.30 \pm 0.11$$
$$C_{\phi\gamma} = 0.11 \pm 0.29 \pm 0.11$$
$$\mathcal{A}^{\Delta}_{\phi\gamma} = -0.67\,^{+0.37}_{-0.41} \pm 0.17$$

First measurement in B_s system

Radiative B decays at LHCb *(Carla Marin Benito)*

First observation of $\Lambda^0_b \to \Lambda\gamma$

Using 2016 dataset (1.7 fb^{-1})

Significance of 5.6σ → First observation!

Normalising to the well-known $B^0 \to K^*\gamma$:

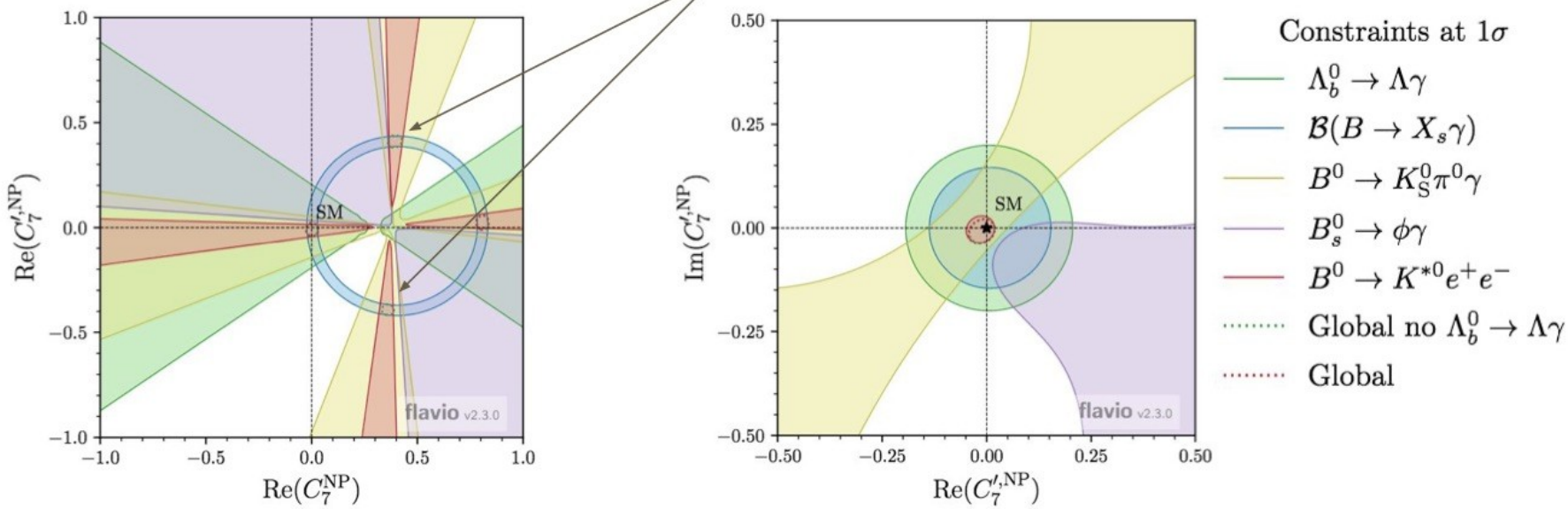
$$\mathcal{B}(\Lambda_b^0 \to \Lambda\gamma) = (7.1 \pm 1.5 \pm 0.6 \pm 0.7) \times 10^{-6}$$

Radiative B decays at LHCb *(Carla Marin Benito)*

arXiv:2111.10194

Photon polarisation in $\Lambda^0_b \to \Lambda\gamma$

New constraints on C_7 and C'_7: discard 2 so-far allowed solutions



Radiative B decays at Belle & Belle II (Markus Roehrken)

Exclusive

- Belle measurement with fill dataset (711 fb^{-1}):
  - 3% precision on BF CP asymmetry consistent with zero and SM prediction
  - first evidence of isospin asymmetry at 3.1σ

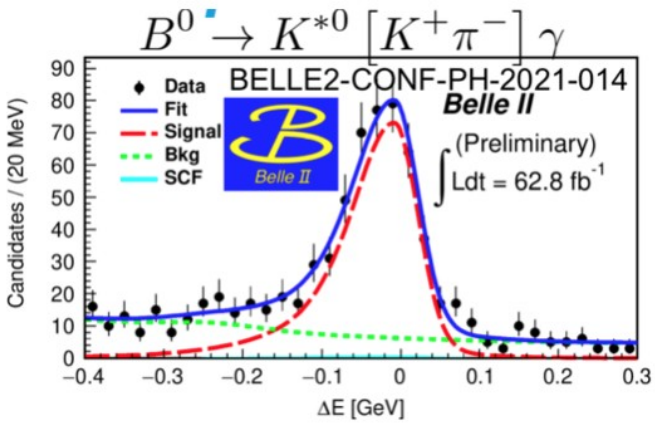
Belle with $772 \times 10^6\ B\bar{B}$ PRL **119**, 191802 (2017)

$$\mathcal{B}(B^0 \to K^{*0}\gamma) = (3.96 \pm 0.07 \pm 0.14) \times 10^{-5},$$
$$\mathcal{B}(B^+ \to K^{*+}\gamma) = (3.76 \pm 0.10 \pm 0.12) \times 10^{-5},$$
$$A_{CP}(B^0 \to K^{*0}\gamma) = (-1.3 \pm 1.7 \pm 0.4)\%,$$
$$A_{CP}(B^+ \to K^{*+}\gamma) = (+1.1 \pm 2.3 \pm 0.3)\%,$$
$$A_{CP}(B \to K^{*}\gamma) = (-0.4 \pm 1.4 \pm 0.3)\%,$$
$$\Delta_{0+} = (+6.2 \pm 1.5 \pm 0.6 \pm 1.2)\%,$$
$$\Delta A_{CP} = (+2.4 \pm 2.8 \pm 0.5)\%,$$
$$\bar{A}_{CP} = (-0.1 \pm 1.4 \pm 0.3)\%,$$

- Preliminary Belle II (62.8 fb^{-1}) consistent with expectation:

Mode	$\mathcal{B}_{\rm meas}$ $[10^{-5}]$
$B^0 \to K^{*0}[K^+\pi^-]\gamma$	$4.5 \pm 0.3 \pm 0.2$
$B^0 \to K^{*0}[K^0_S\pi^0]\gamma$	$4.4 \pm 0.9 \pm 0.6$
$B^+ \to K^{*+}[K^+\pi^0]\gamma$	$5.0 \pm 0.5 \pm 0.4$
$B^+ \to K^{*+}[K^0_S\pi^+]\gamma$	$5.4 \pm 0.6 \pm 0.4$

[BELLE2-CONF-PH-2021-014]



- Prospects at Belle II (62.8 fb^{-1}) :

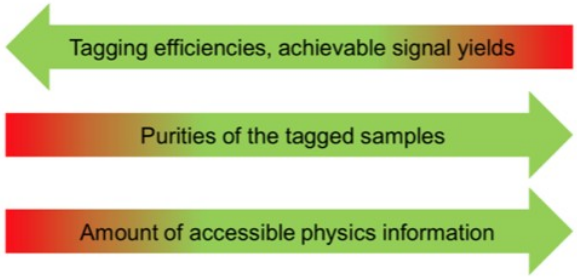
Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\Delta_{0+}(B \to K^*\gamma)$	2.0%	0.70%	0.53%
$A_{CP}(B^0 \to K^{*0}\gamma)$	1.7%	0.58%	0.21%
$A_{CP}(B^+ \to K^{*+}\gamma)$	2.4%	0.81%	0.29%
$\Delta A_{CP}(B \to K^*\gamma)$	2.9%	0.98%	0.36%
$S_{K^{*0}\gamma}$	0.29	0.090	0.030

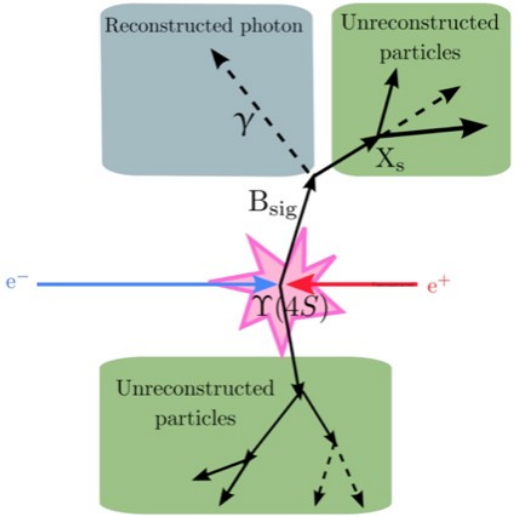
[The Belle II Physics Book, BELLE2-PAPER-2018-001]

Radiative B decays at Belle & Belle II (Markus Roehrken)

Inclusive

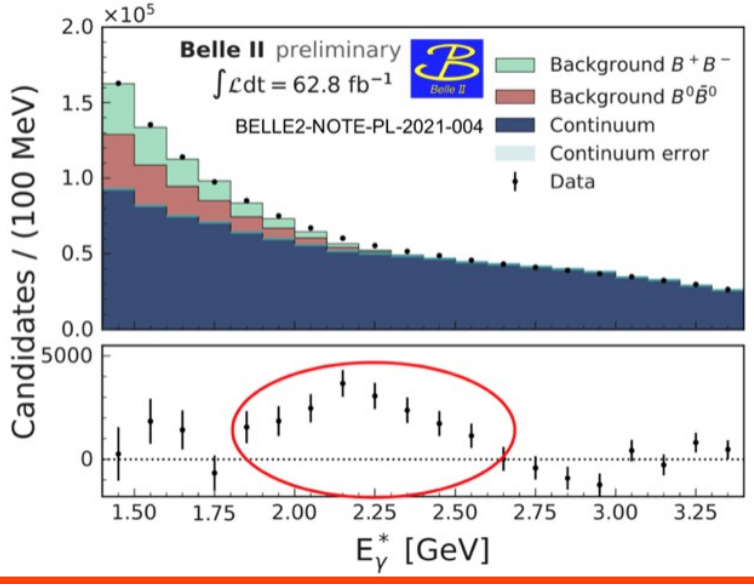
- B → Xs γ reconstruction at B factories, how to:





Fully inclusive, no tagging	Lepton tagging	Semileptonic tagging	Hadronic tagging
$B \to$ anything	$B \to lX$	$B \to \bar{D}^{(*)} l\nu n\pi$	$B \to$ hadrons, e.g. $B \to \bar{D}^{(*)}\, n\pi$
$\epsilon \approx \mathcal{O}(10\%)$	$\epsilon \approx \mathcal{O}(1\%)$	$\epsilon \approx \mathcal{O}(0.2\%)$	$\epsilon \approx \mathcal{O}(0.1\%)$

- Belle/Belle II status and Belle II prospects

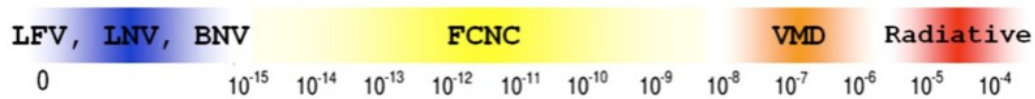


Observables	Belle 0.71 ab^{-1}	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\mathrm{Br}(B \to X_s\gamma)^{\text{lep-tag}}_{\text{inc}}$	5.3%	3.9%	3.2%
$\mathrm{Br}(B \to X_s\gamma)^{\text{had-tag}}_{\text{inc}}$	13%	7.0%	4.2%
$\mathrm{Br}(B \to X_s\gamma)_{\text{sum-of-ex}}$	10.5%	7.3%	5.7%
$\Delta_{0+}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.1%	0.81%	0.63%
$\Delta_{0+}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	9.0%	2.6%	0.85%
$A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	1.3%	0.52%	0.19%
$A_{CP}(B^0 \to X_s^0\gamma)_{\text{sum-of-ex}}$	1.8%	0.72%	0.26%
$A_{CP}(B^+ \to X_s^+\gamma)_{\text{sum-of-ex}}$	1.8%	0.69%	0.25%
$A_{CP}(B \to X_{s+d}\gamma)^{\text{lep-tag}}_{\text{inc}}$	4.0%	1.5%	0.48%
$A_{CP}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	8.0%	2.2%	0.70%
$\Delta A_{CP}(B \to X_s\gamma)_{\text{sum-of-ex}}$	2.5%	0.98%	0.30%
$\Delta A_{CP}(B \to X_{s+d}\gamma)^{\text{had-tag}}_{\text{inc}}$	16%	4.3%	1.3%

[Belle II Physics Book, arXiv:1808.10567]

Rare D decays at LHCb *(Davide Brundu)*

- Plethora of D decay modes, from forbidden to not-so-rare, to search for new physics effect



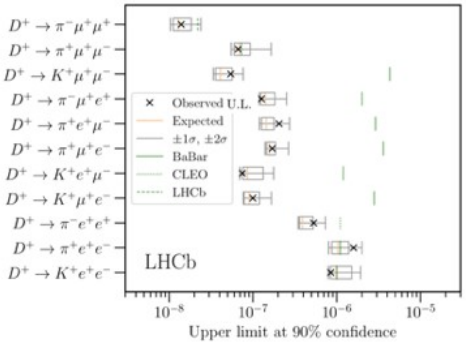
Search for NP in branching fractions

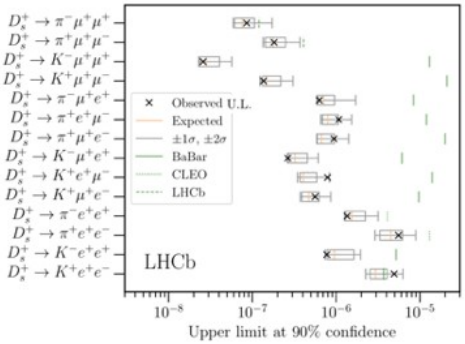
- search for $D^0 \to \mu^+\mu^-$ [PLB 725 15-24 (2013)]
- **search for $D^+_{(s)} \to h^+\ell^+\ell^-$** **[JHEP 06 44 (2021)]**
- search for $D^0 \to \pi^+\pi^-\mu^+\mu^-$ [PLB 728 234-243 (2014)]
- observation of $D^0 \to K^-\pi^+\mu^+\mu^-$ [PLB 757 558-567 (2016)]
- search for $\Lambda_c^+ \to p\mu^+\mu^-$ [PRD 97 091101 (2018)]
- observation of $D^0 \to h^+h^-\mu^+\mu^-$ [PRL 119 181805 (2017)]

Search for NP based on symmetries

- search for $D^0 \to \mu^+e^-$ [PLB 754 167 (2016)]
- **search for $D^+_{(s)} \to h^-\ell^+\ell'^+$** **[JHEP 06 44 (2021)]**
- search for CPV and angular asymmetries in $D^0 \to h^+h^-\mu^+\mu^-$ [PRL 121 091801 (2018)]
- **full angular analysis and search for CPV in $D^0 \to h^+h^-\mu^+\mu^-$** **arXiv:2111.03327 [hep-ex]**

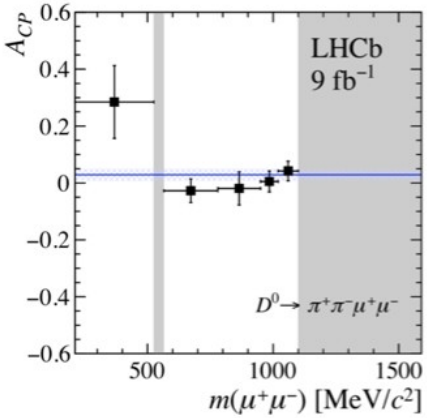
- $D_{(s)}^+ \to h^+ \ell^+\ell^-$ [JHEP 06 44 (2021)]

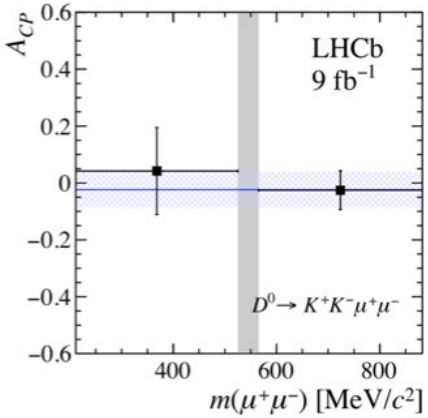




- No evidence for signal, large improvement on BF wrt previous measurement

- $D^0 \to h^+ h^- \ell^+\ell^-$ arXiv:2111.03327
  - angular analysis and CP asymmetry measurement to test SM





- Agreement with SM prediction

New updates are coming very soon (D^0 4-body decays with electrons in the final state, update on D^0 3-body decays presented today, update of $D^0 \to \mu^+\mu^-$).

Rare D decays at BES III (Liang Sun)

- Majorana neutrino indirect search with $D \to K\pi e^+e^+$

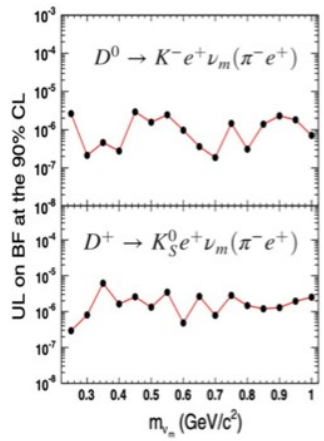
  [PRD 99, 112002 (2019)]

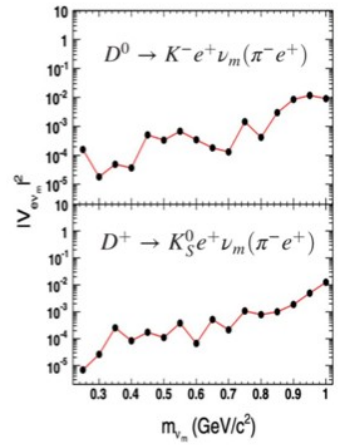
  - BF Upper limits @ 90% CL are determined:

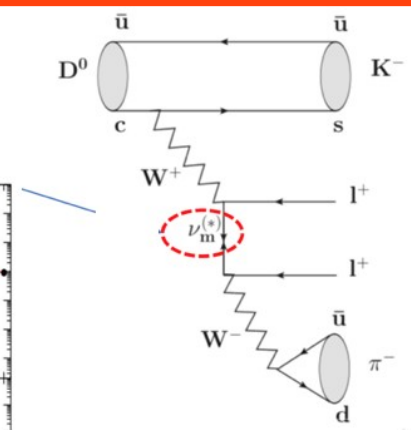
Channels	Upper Limit
$D^0 \to K^-\pi^-e^+e^+$	2.8×10^{-6}
$D^+ \to K_S^0\pi^-e^+e^+$	3.3×10^{-6}
$D^+ \to K^-\pi^0e^+e^+$	8.5×10^{-6}

$$\int_0^{\mathcal{B}_{UL}} L(\mathcal{B})d\mathcal{B} = 0.9$$

First searches on both channels so far!







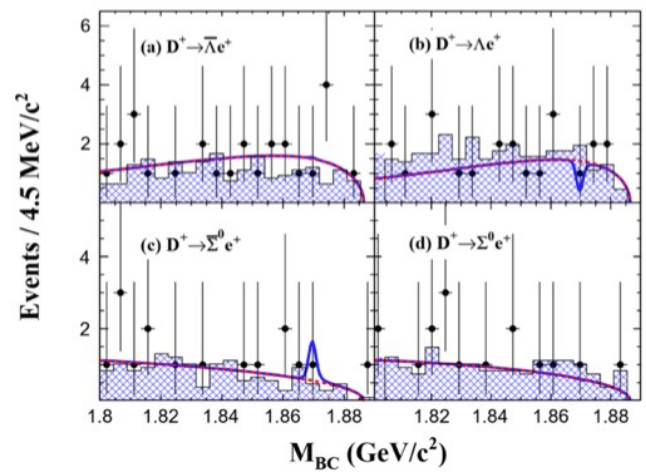
- Testing Baryon number violation with $D^+ \to \Lambda\,(\Sigma_0)e$ [PRD 101, 031102 (2020)]

BF Upper limits @ 90% CL are determined:

Channels	Upper Limit
$D^+ \to \Lambda\, e^+$	1.1×10^{-6}
$D^+ \to \bar{\Lambda}\, e^+$	6.5×10^{-7}
$D^+ \to \Sigma^0\, e^+$	1.7×10^{-6}
$D^+ \to \bar{\Sigma}^0\, e^+$	1.3×10^{-6}

$$\int_0^{\mathcal{B}_{UL}} L(\mathcal{B})d\mathcal{B} = 0.9$$

First searches



- More analyses on rare/forbidden decays are on the way:
  - A wide range of topics: invisible final states, LNV, BNV, FCNC, etc.
  - Still great potentials on D_s^+ and Λ_c^+ decays
- More $\psi(3770)$ data: $\int \mathcal{L} \sim 20$ fb^{-1} in a few years [Chin. Phys. C 44, 040001 (2020)]

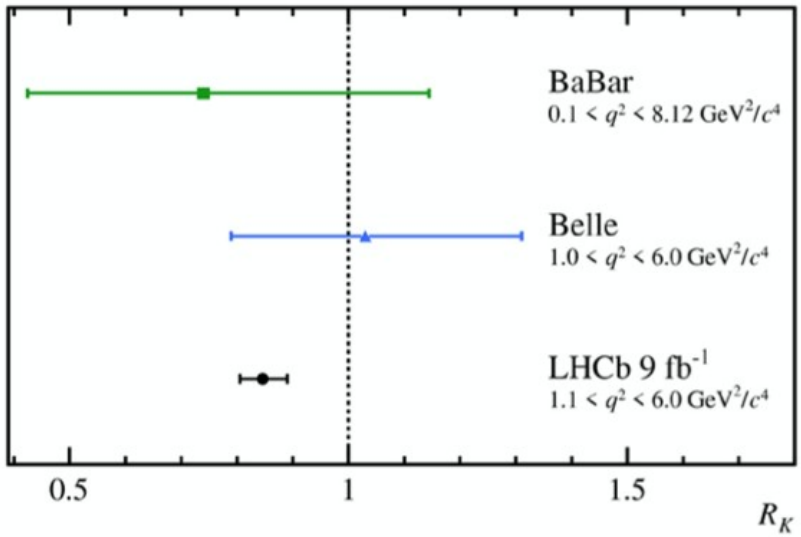
Joint WG2 & WG3 session

- *R(D(*)) at LHCb* *(Luke Scantlebury-Smead)* [covered by WG2]
- *$R_{K(*)}$ at LHCb and Belle II* *(Renato Quagliani)*
- *QED corrections: open challenges* *(Robert Szafron)*
- *On the $R_{K(*)}$ theory error* *(Saad Nabeebaccus)*

$R_{K(*)}$ at LHCb and Belle II (Renato Quagliani)

$R_{K(*)}$ at LHCb

$$R_K(1.1 < q^2 < 6) = 0.846\ ^{+0.042}_{-0.039}\ (\text{stat})\ ^{+0.013}_{-0.012}\ (\text{syst})$$



- **3.1σ from SM**
- Same test at resonances also performed

$$r_{J/\psi} = 0.981 \pm 0.020(stat + sys)$$

$$R_{\psi(2S)} = 0.997 \pm 0.011(stat + sys)$$

	q^2 [0.045,1.1] GeV^2 / c^4	q^2 [1.1,6] GeV^2 / c^4
$R(K^{*0})$	$0.66^{+0.11}_{-0.07} \pm 0.03$	$0.69^{+0.11}_{-0.07} \pm 0.05$
	2.1-2.3 σ below SM	2.4-2.5 σ below SM

$R_{K(*)}$ at LHCb and Belle II (Renato Quagliani)

More R's at LHCb

$$R(pK) = 0.86^{+0.14}_{-0.11} \pm 0.05$$

$$R_{K^0_S} = 0.66^{+0.20}_{-0.15}(\text{stat})^{+0.02}_{-0.04}(\text{syst})$$

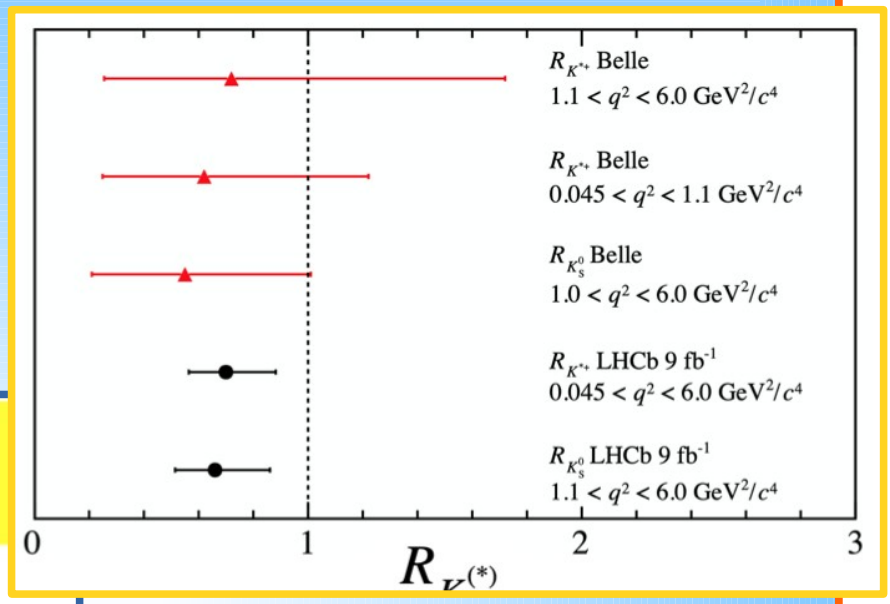
$[1.1 < q^2/\text{GeV}^2 < 6.0]$

Significance w.r.t SM: 1.5σ

$$R_{K^{*+}} = 0.70^{+0.18}_{-0.13}(\text{stat})^{+0.03}_{-0.04}(\text{syst})$$

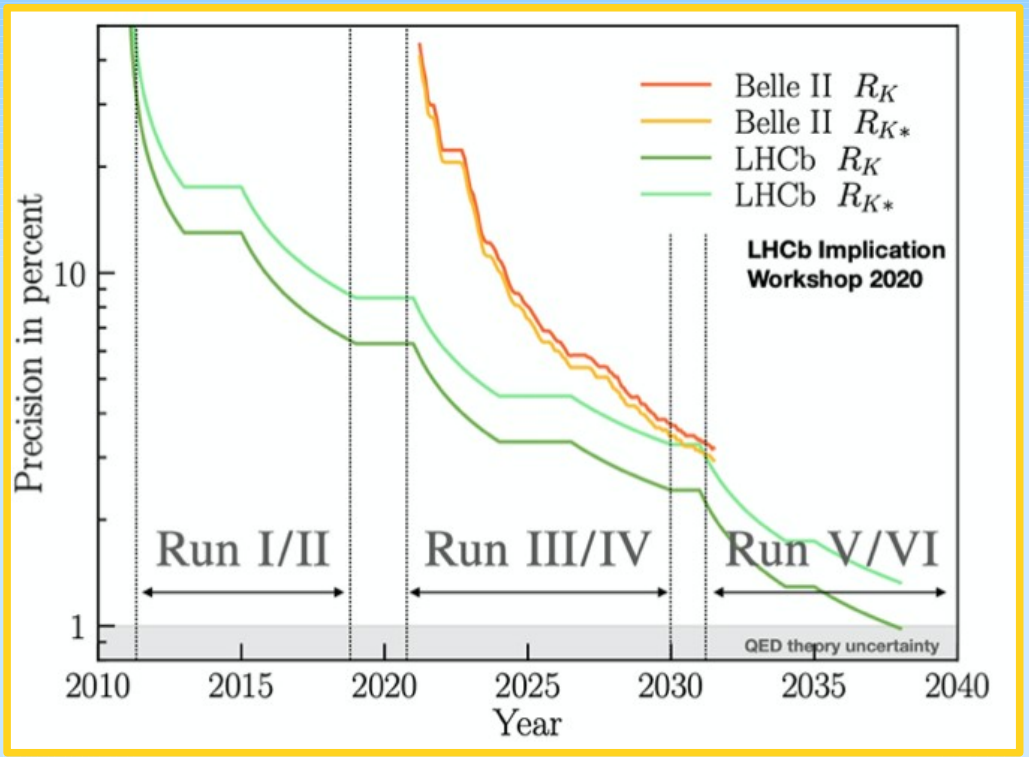
$[0.045 < q^2/\text{GeV}^2 < 6.0]$

Significance w.r.t SM: 1.4σ



Same enticing pattern everywhere

$R_{K(*)}$ at LHCb and Belle II (Renato Quagliani)



R_{Xs} at Belle II

- **Promising expectations for inclusive $B \to X_s \ell \ell$ at Belle II**

Observables	Belle (0.71 ab^{-1})	Belle II (5 ab^{-1})	Belle II (50 ab^{-1})
R_{X_s} ([1.0, 6.0] GeV$^2/c^4$)	32%	12%	4.0%
R_{X_s} ([> 14.4] GeV$^2/c^4$)	28%	11%	3.4%

On the $R_{K(*)}$ theory error (Saad Nabeebaccus)

Why are QED corrections to $\bar{B} \to \bar{K}\ell^+\ell^-$ important?

Expected to be small, since $\frac{\alpha}{\pi} \approx 2 \cdot 10^{-3}$.

Due to kinematic effects however, QED corrections are enhanced to $\mathcal{O}(\frac{\alpha}{\pi}) \ln \hat{m}_\ell \gtrsim 2 - 3\,\%$ [*Note:* $\hat{m}_\ell \equiv \frac{m_\ell}{m_B}$].

Bordone et al. (1605.07633) already performed a calculation to estimate QED corrections to R_K, working in single differential in q^2.

More general study in Isidori, Nabeebaccus, Zwicky (+ work in progress)

- We work with *full matrix elements* (real and virtual), starting from an *EFT Lagrangian description*. Hence, we can capture effects beyond collinear $\ln \hat{m}_\ell$ terms, such as $\ln \hat{m}_K$ which are not necessarily small.

On the $R_{K^{(*)}}$ theory error (Saad Nabeebaccus)

Q: Do we miss any $\ln \hat{m}_\ell$ contributions due to structure dependence, by doing an EFT calculation?

A: No, gauge invariance ensures that there are no such additional contributions. [Sec. 3.4, Isidori, SN, Zwicky '20]

However, using the EFT analysis, we do *not* capture $\ln \hat{m}_K$ effects, which are not so small.

$\Longrightarrow$ *Structure Dependent Contributions: LCSR approach* [Ongoing].

- $\bar{B} \to \bar{K}\ell^+\ell^-$ differential distribution through Monte Carlo: Check PHOTOS and investigate effects of charmonium resonances [Ongoing].

QED corrections: open challenges (Robert Szafron)

Phenomenology

1. *Structure dependent corrections for semi-leptonic heavy-to-light and* $R_K^{(*)}$ *ratios*

$$\Delta^R_{\rm QED} = \frac{1+\Delta^\mu_{\rm QED}}{1+\Delta^e_{\rm QED}} \sim \frac{1+\mathcal{O}(\alpha)\mathcal{O}\left(\frac{m_\mu^2}{\Lambda^2_{\rm QCD}}\right)\mathcal{O}\left(\ln\frac{m_\mu^2}{\dots}\right)}{1+\mathcal{O}(\alpha)\mathcal{O}\left(\frac{m_e^2}{\Lambda^2_{\rm QCD}}\right)\mathcal{O}\left(\ln\frac{m_e^2}{\dots}\right)} = 1+\mathcal{O}(\alpha)\mathcal{O}\left(\ln\frac{m_\mu^2}{\dots}\right)$$

Worst case scenario: additional few % uncertainty from structure dependent corrections!

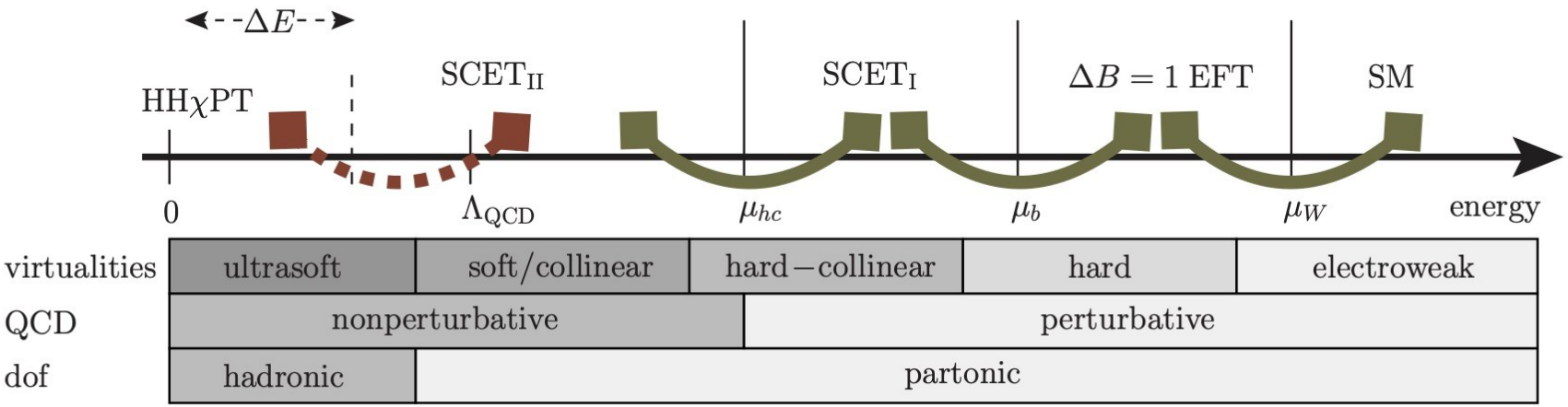
2. *Lattice evaluation of QED corrections for heavy mesons: complementary to the EFT approach*

$$\ln\frac{m_\mu}{\Delta E} \sim 2.5; \qquad \ln\frac{m_B}{m_\mu} \sim 4; \qquad \ln\frac{m_B}{\Lambda_{\rm QCD}} \sim 3; \qquad \dots$$

QED corrections: open challenges (Robert Szafron)

Theory

1. *Non-perturbative matching between point-like EFT and microscopic description*



2. *Non-perturbative soft matrix elements in QCD×QED (LCDA)*
3. *Dedicated Monte Carlo for QED compatible with EFT description above* $\Lambda_{\rm QCD}$
4. *Going beyond leading power in* $1/M_B$ *expansion*

Rare K session

- *Review of* $K \to \pi\nu\bar{\nu}$ *(Yu-Chen Tung)*
- *Rare K decays (Evgueni Goudzovski)*
- *LQCD status of* ϵ'/ϵ , ϵ_K , $K \to \pi\nu\bar{\nu}$ *(Mattia Bruno)*
- ϵ'/ϵ *in the SM & beyond (Andrzej Buras)*
- $K \to \pi\nu\bar{\nu}$ *and B anomalies (David Marzocca)*

Review of $K \to \pi\nu\bar{\nu}$ (Yu-Chen Tung)

	$K^+ \to \pi^+\nu\bar{\nu}$	$K_L \to \pi^0\nu\bar{\nu}$
BR_{SM}	$(8.4\pm1.0)\times10^{-11}$	$(3.4\pm0.6)\times10^{-11}$

[Buras et al, JHEP 1511]

- NA62 provided the current best measurement on $BR(K^+ \to \pi^+\nu\bar{\nu})$.
  - $BR(K^+ \to \pi^+\nu\bar{\nu}) = [10.6^{+4.0}_{-3.4}(stat) \pm 0.9(syst)] \times 10^{-11}$ at $68\,\%\,C.L.$ [JHEP06.093]
- NA62 RUN-II data-taking resumed in July 2021.
  - Expect to achieve O(10%) statistical precision on $BR(K^+ \to \pi^+\nu\bar{\nu})$ by LS3.
- KOTO 2015 data results set the current current best limit on $BR(K_L \to \pi^0\nu\bar{\nu})$.
  - $BR(K_L \to \pi^0\nu\bar{\nu}) < 3.0 \times 10^{-9}$ at $90\,\%\ C.L.$ [PRL.122.021802]
- KOTO expects to improve the S.E.S. to $O(10^{-11})$ by 2026.
- New experiments, KOTO Step-II and KLEVER, are planned, both aiming to measure $BR(K_L \to \pi^0\nu\bar{\nu})$ with $O(10^{-13})$ S.E.S.

Rare K decays (Evgueni Goudzovski)

- Recent results on hidden-sector mediator production and other BSM physics in kaon decays:
  - ✓ extension of the $K^+ \to \pi^+ \nu\nu$ analysis: search for $K^+ \to \pi^+ X$ and $\pi^0 \to inv$;
  - ✓ searches for $K^+ \to \ell^+ N$ and $K^+ \to \mu^+ \nu X$ decays;
  - ✓ searches for LNV/LFV K^+ and π^0 decays (six modes so far).

Expected background: 0.91±0.41 evt
Candidates observed: 1
$BR(K^+ \to \pi^- \mu^+ \mu^+) < 4.2 \times 10^{-11}$ at 90% CL

Expected background: 0.43±0.09 evt
Candidates observed: 0
$BR(K^+ \to \pi^- e^+ e^+) < 5.3 \times 10^{-11}$ at 90% CL

NEW!

Expected background: 0.044±0.020 evt
Candidates observed: 0
$BR(K^+ \to \pi^- \pi^0 e^+ e^+) < 8.5 \times 10^{-10}$ at 90% CL
First search for this mode.

K^+ decays in FV: $(1.33 \pm 0.02) \times 10^{12}$
Expected background: 1.07±0.20 evt
Candidates observed: 0
$BR(K^+ \to \pi^- \mu^+ e^+) < 4.2 \times 10^{-11}$ at 90% CL

Expected background: 0.92±0.34 evt
Candidates observed: 2
$BR(K^+ \to \pi^+ \mu^- e^+) < 6.6 \times 10^{-11}$ at 90% CL
$BR(\pi^0 \to \mu^- e^+) < 3.2 \times 10^{-10}$ at 90% CL

based on world's largest decay samples:
- ✓ $K^+ \to \pi^+ \mu^+ \mu^-$ analysis based on 28k candidates;
- ✓ $K^+ \to \pi^0 e^+ \nu\gamma$ analysis based on 130k candidates.

LQCD status of ϵ'/ϵ , ϵ_K , $K \to \pi\nu\bar{\nu}$ (Mattia Bruno)

ϵ'/ϵ

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \frac{\omega}{\sqrt{2}|\varepsilon|}\mathrm{Re}\left[ie^{i(\delta_2-\delta_0-\phi_\varepsilon)}\right]\left[\frac{\mathrm{Im}\,A_2}{\mathrm{Re}\,A_2} - \frac{\mathrm{Im}\,A_0}{\mathrm{Re}\,A_0}\right]$$

1. use $\omega, \mathrm{Re}\,A_0, \mathrm{Re}\,A_2$ from experiment
2. phases either from dispersive or lattice, no difference
3. take $\mathrm{Im}\,A_2$ from previous LQCD [RBC/UKQCD '15]
4. take $\mathrm{Im}\,A_0$ from new work [RBC/UKQCD '20]

$\mathrm{Re}\,(\varepsilon'/\varepsilon) = 21.7(2.6)(6.2)(5.0) \cdot 10^{-4}$ from lattice [RBC/UKQCD '20]
$\mathrm{Re}\,(\varepsilon'/\varepsilon) = 16.6(2.3) \cdot 10^{-4}$ from experiment

Errors:
(2.6) statistical, (6.2) systematic, (5.0) isospin-breaking

LQCD status of ϵ'/ϵ , ϵ_K , $K \to \pi\nu\bar{\nu}$ (Mattia Bruno)

Δm_K & ϵ_K

Δm_K

$\Delta m_K^{\rm exp} = 3.483(6) \cdot 10^{-12}$ MeV

first numerical results only in PoS [Wang Lattice '18 '19]

preliminary results at $m_\pi^{\rm phys} \to \Delta m_K = 6.7(1.7) \cdot 10^{-12}$ MeV

dominated by discr. errors from charm

$m_\pi^{\rm phys} \to$ large $L \oplus$ charm $\to$ fine a: challenging

---

ε_K

$|\varepsilon_K^{\rm exp}| = 2.228(11) \cdot 10^{-3}$

conference papers, latest $\varepsilon_K^{\rm LD} = 0.17(1) \cdot 10^{-3}$ [Bai Lattice '16]

significant amount of Wick contractions and topologies

preliminary results at $m_\pi \simeq 390$ MeV, unphys. charm

approx 5% consistent w/ expectation but requires improvements

LQCD status of ϵ'/ϵ , ϵ_K , $K \to \pi\nu\bar{\nu}$ (Mattia Bruno)

$K \to \pi\nu\bar{\nu}$

$K \to \pi\bar{\nu}\nu$

FCNC ideal probes for new physics effects

mostly dominated by short-distance effects, QCD input from $K_{\ell 3}$

current theory predictions around 10 % [Buras et al '15]

LD effects potentially up to 6% in $K^+ \to \pi^+\bar{\nu}\nu$

exploratory calculation at unphys. kinematics [RBC/UKQCD '17 '18]

cancellation of WW vs Z-exchange $\to$ will survive at $m_\pi^{\rm phys}$?

2nd calculation $m_\pi \simeq 170$ MeV, unphys. charm [RBC/UKQCD '19]

small mom. dependence, clarified role of intermediate $(\pi\pi)$

ε´/ε Controversy

2015-2020

$$(\varepsilon'/\varepsilon)_{exp} = (16.6 \pm 2.3) \cdot 10^{-4}$$

(NA48, KTeV)

$$(\varepsilon'/\varepsilon)_{SM} = (14 \pm 5) \cdot 10^{-4}$$

Chiral Perturbation Theory (Pich et al)

No Anomaly

★ $$(\varepsilon'/\varepsilon)_{SM} = (5 \pm 2) \cdot 10^{-4}$$

Hep-arxiv: 2101.00020

Insight from Dual QCD + NNLO QCD

(AJB + Gérard)

Anomaly

$$(\varepsilon'/\varepsilon)_{SM} = (21.7 \pm 8.4) \cdot 10^{-4}$$

RBC – UKQCD

No Anomaly

Important Message for Non-Experts to take Home

RBC-UKQCD collaboration and ChPT Experts do not claim that there is no New Physics in ε´/ε. But as of 2021 their methods are not sufficiently powerful to see an anomaly in ε´/ε.

Dual QCD approach, even if approximate, can much faster see the underlying dynamics, even analytically. Both in ε´/ε and the ΔI = ½ rule !!

Main Homework for Coming Years

RBC-UKQCD :
- a) Isospin breaking and QED Corrections (including η-η' mixing)
- b) Inclusion of charm

ChPT :
- a) Matching to short distance (L_5)
- b) Better inclusion of η-η' mixing (L_7)

DQCD : Final state interactions

Inclusion of NNLO QCD to QCD Penguins

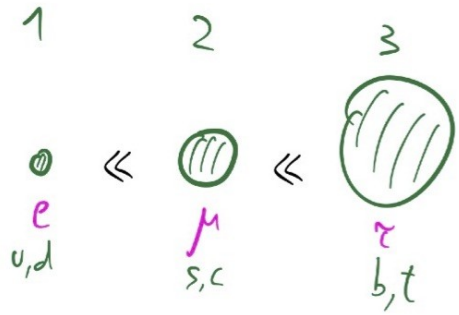
BSM hadronic matrix elements from LQCD

known only from DQCD

Contributions from other LQCD Groups

Ishizuka et al 1809.03893; Hernandez et al. 2003.10293

EFT level



The hierarchy in NP couplings to the three generations, same as hierarchy in SM fermion masses, suggests a possible $U(2)^5$ flavor structure

$$G_F = U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$$

Assuming **minimal breaking** of the flavor symmetry:

$$R(D^{(*)}): \; C_{bc\tau\nu} \sim \frac{1}{(4\,\text{TeV})^2} \sim V_{cb}\,\frac{g_{b\tau}^2}{M^2}$$

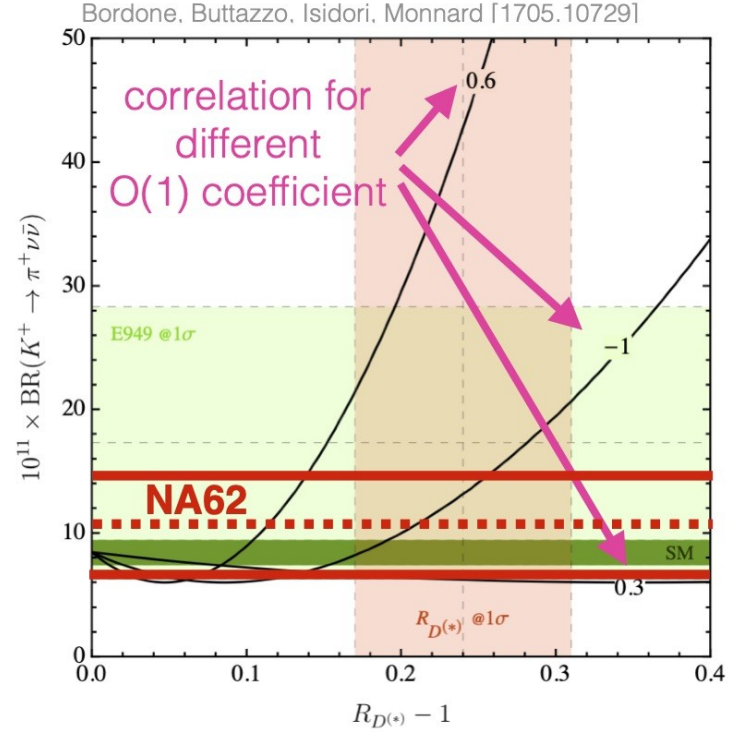
Effect in **K→πνν** $\Rightarrow$ $C_{sd\nu_\tau\nu_\tau} \sim V_{td}V_{ts}\,\frac{g_{b\tau}^2}{M^2} \sim \frac{1}{(42\,\text{TeV})^2}$

same order as the NA62 bound!

$$C_{sd\nu_\tau\nu_\tau} \in \left[-\frac{1}{(50\,\text{TeV})^2}, \frac{1}{(81\,\text{TeV})^2}\right] \text{ @ } 95\%\text{ CL}$$

A **UV model** is required to fix the O(1) coefficients.

Bordone, Buttazzo, Isidori, Monnard [1705.10729]



$K \to \pi\nu\bar{\nu}$ and B anomalies (David Marzocca)

Leptoquarks + $U(2)^5$

$S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$,
$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

LQ couplings to LH fermions:

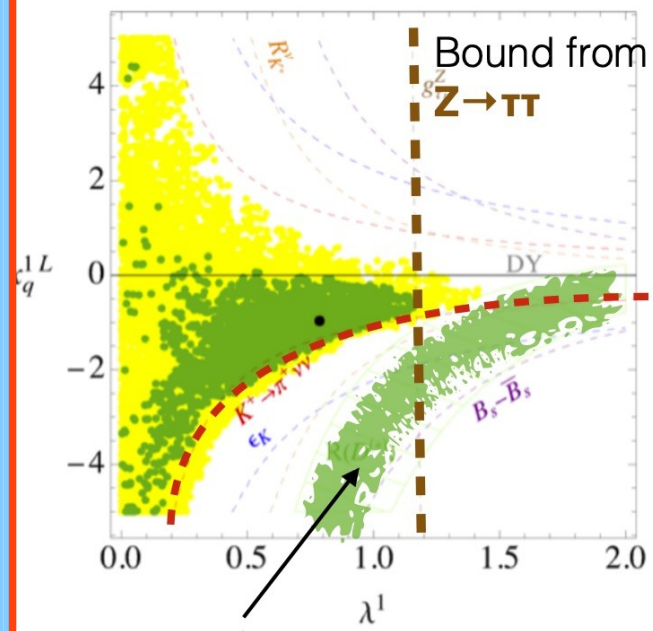
$$\lambda^{1(3)L} = \lambda^{1(3)} \begin{pmatrix} x_{q\ell}^{1(3)} s_e V_\ell V_{td} & x_{q\ell}^{1(3)} V_\ell V_{td} & x_q^{1(3)} V_{td} \\ x_{q\ell}^{1(3)} s_e V_\ell V_{ts} & x_{q\ell}^{1(3)} V_\ell V_{ts} & x_q^{1(3)} V_{ts} \\ x_\ell^{1(3)} s_e V_\ell & x_\ell^{1(3)} V_\ell & 1 \end{pmatrix}$$

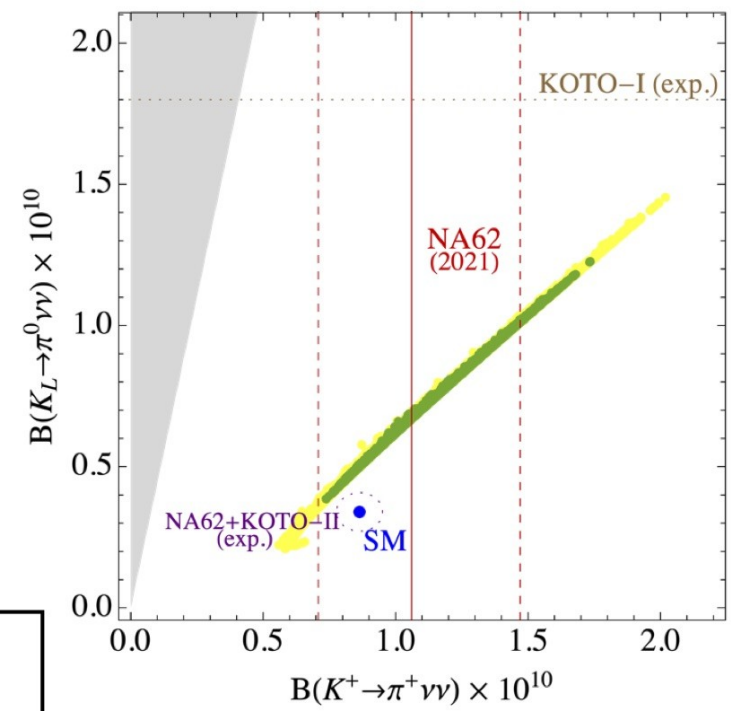
S. Trifinopoulos, E. Venturini, D. Marzocca [2106.15630]

Exact relations (selection rules)

$$\lambda_{d\alpha}^{1(3)L} = \lambda_{s\alpha}^{1(3)L} \frac{V_{td}}{V_{ts}}$$

$$\lambda_{ie}^{1(3)L} = \lambda_{i\mu}^{1(3)L} \sin\vartheta_e$$





R(D(*)) can only be **addressed at 2σ** due to the combination of the **constraints** from **Z→ττ** and **K⁺→π⁺ νν**