Recent Results in Flavor Physics

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IJCLab (Orsay)

RPP, 26 January, 2024

Flavor physics

- The **Standard Model** is an **effective theory** at low-energies of a more fundamental *(unknown)* theory:

  ⇒ Hierarchy and flavor problems unanswered — *gravity not included.*

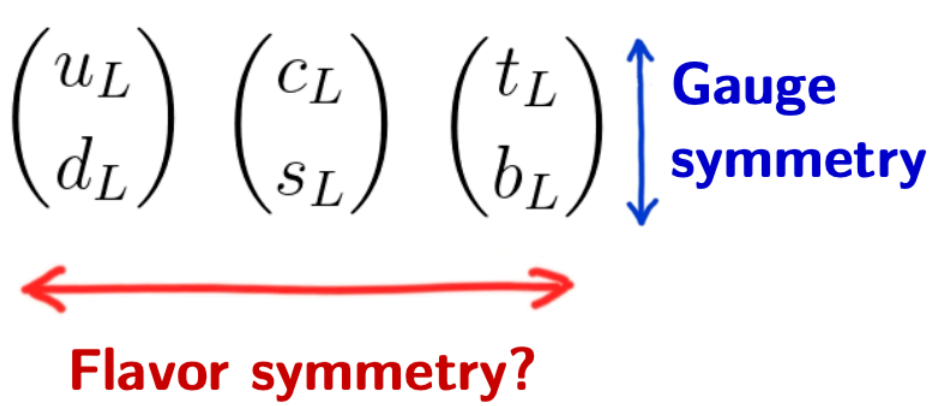
  ⇒ Quest for **physics beyond the SM**!

- *Fermions* appear as three almost *identical replicas*:

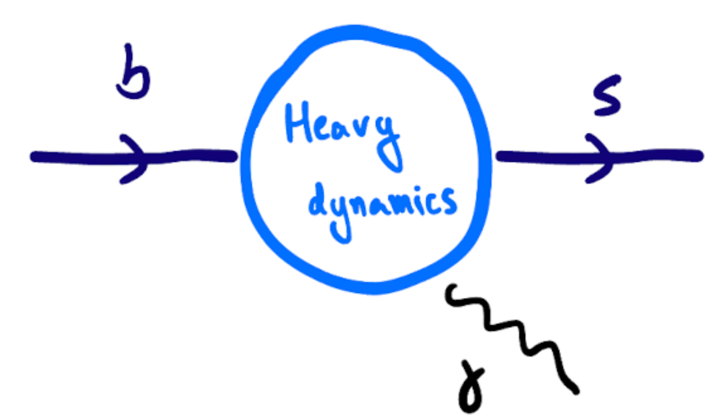
  ⇒ **Flavor physics** is the study of **flavor-changing phenomena** and **CP violation**.

Twofold role of flavor physics:

I. To identify new symmetries:



II. Search of New Physics:



***Through precision!**

I. Origin of flavor?

- Gauge sector of the SM entirely **fixed by symmetry:**

  ⇒ Only a handful of parameters.

  ⇒ Theory renormalizable and verified at the loop level.

- Flavor sector **loose**:

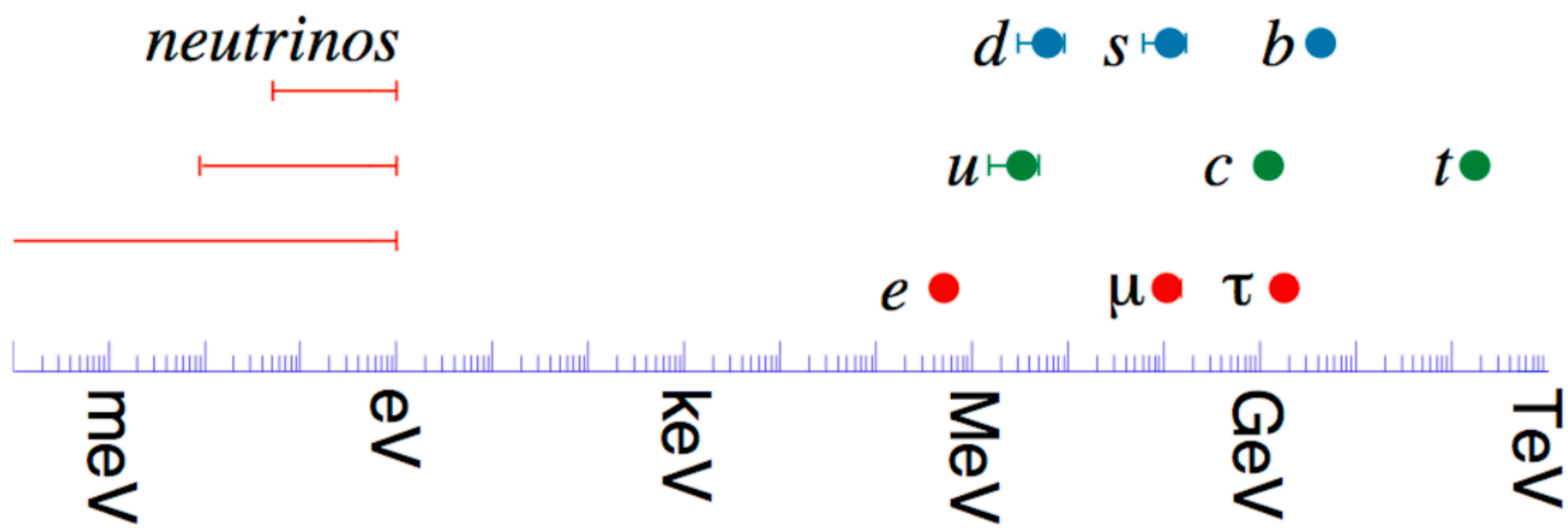
  ⇒ 13 free parameters (masses and quark mixing) — *fixed by data.*

$$\mathcal{L}_{\mathrm{Yuk}} = -Y_d^{ij}\,\overline{Q}_i d_{Rj}\,H - Y_u^{ij}\,\overline{Q}_i u_{Rj}\,\widetilde{H} - Y_\ell^{ij}\,\overline{L}_i e_{Rj}\,H + \mathrm{h.c.}$$

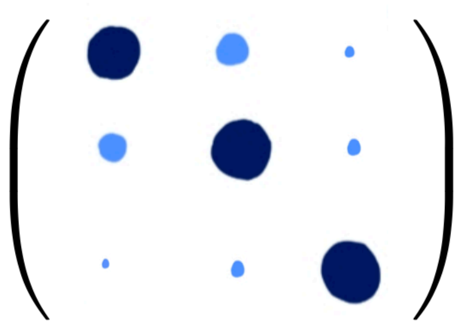
  ⇒ These (many) parameters exhibit a hierarchical structure which we do not understand.

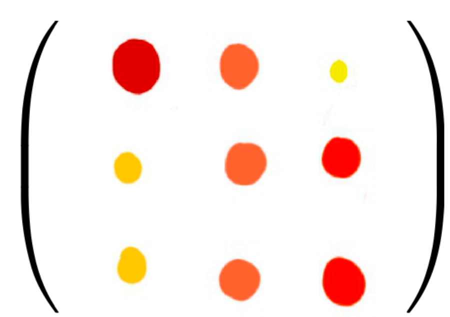
I. Origin of flavor?

- **Striking hierarchy** of fermion masses *[does not look accidental...]*



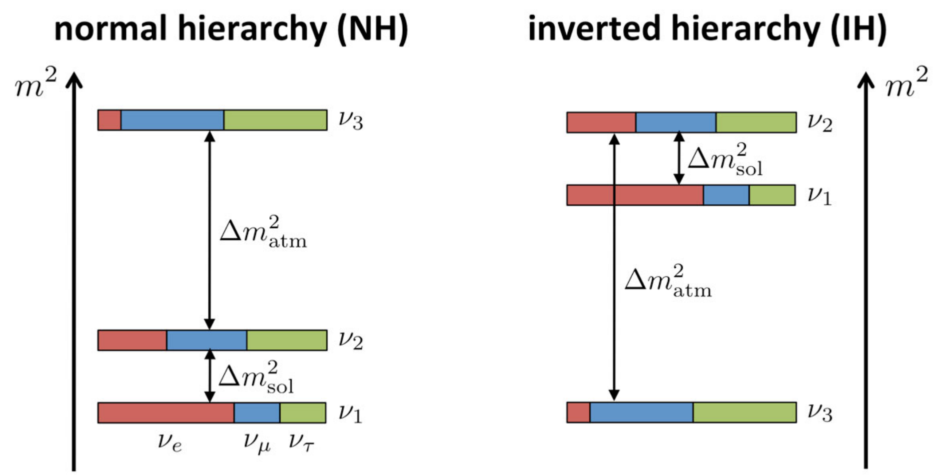
- Why **three families**? Why do **quarks** and **leptons** mix in **different ways**?

$V_{\rm CKM} =$ 

$V_{\rm PMNS} =$ 

How to **explain** the **observed patterns** in terms of **less** and **more fundamental parameters**?

I. Origin of neutrino masses?



Neutrinos are the **least known particles in the SM:**

- What is the **absolute scale** of **neutrino masses**?
- Normal or inverted **ordering**?
- Is ***CP*** violated in the **lepton sector?**
- Majorana or Dirac particles? (i.e., is **lepton number** conserved?)
- ...

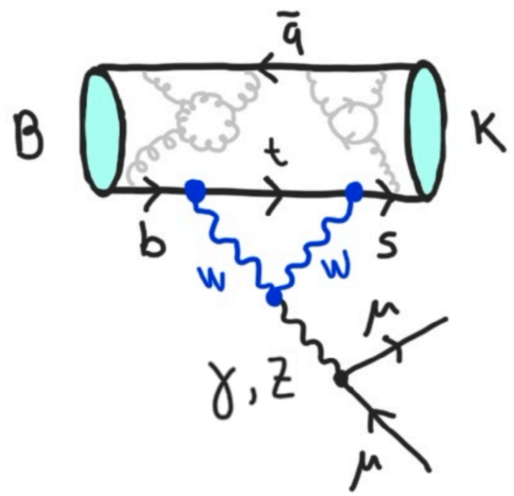
Huge **experimental/theoretical effort** to **answer these questions** and to measure precisely the **PMNS matrix**.

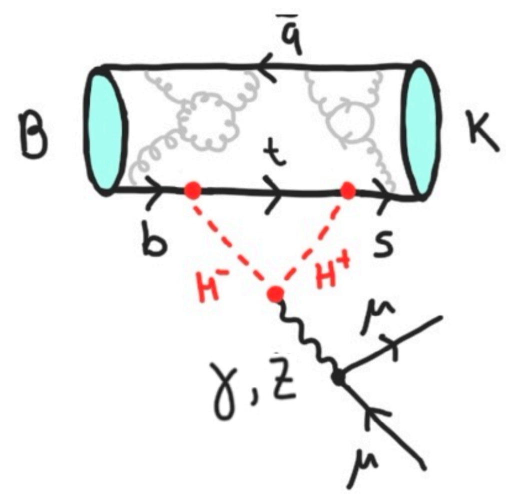
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} & \text{PMNS} & \\ & \text{matrix} & \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

II. Indirect searches of New Physics

i. Search deviations w.r.t. SM predictions:

e.g.,





$$\mathcal{O}_{\text{exp}} = \mathcal{O}_{\text{SM}}\,(1 + \delta_{\text{NP}})$$

Both **exp.** and **theory** must be **precise**!

Look for observables:

- (Highly) sensitive to contributions from New Physics
- Mildly sensitive to hadronic uncertainties
- Accessible in current and/or (near) future experiments.

Rare meson decays are a good example!

II. Indirect searches of New Physics

ii. Search processes forbidden (by accidental symmetries) in the SM

Global symmetry of the SM gauge sector:

$$U(3)^5 \equiv U(3)_Q \times U(3)_L \times U(3)_U \times U(3)_D \times U(3)_E$$

Broken by Yukawas to

$$U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

Examples:

- Proton decay **(BNV)**: $p \to \pi^0 e^+$
- $0\nu\beta\beta$ **(LNV):** $(A,Z) \to (A,Z+2) + 2e^-$
- **L**epton **F**lavor **V**iolation **(LFV):** $\mu \to e\gamma$

Clean probes of New Physics!

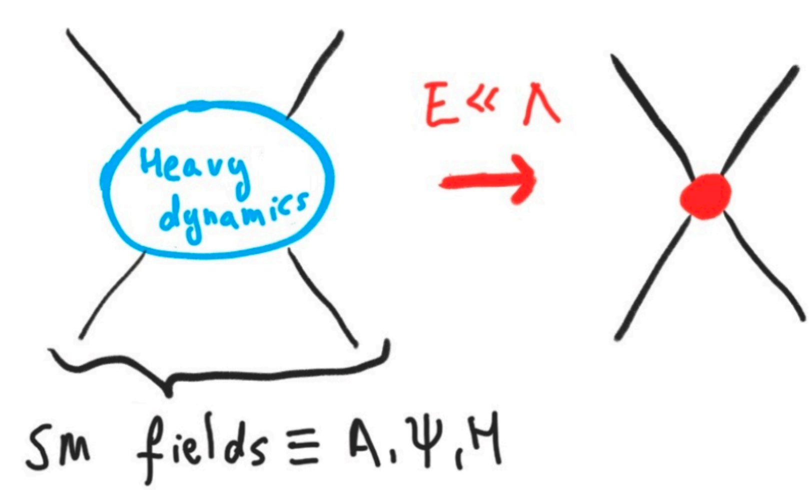
How do we do it?

The SM is an Effective Field Theory (EFT) at low energies of a more fundamental theory which is still unknown:

$$\mathcal{L}_{\text{eff}} = \overbrace{\mathcal{L}_{\text{gauge}}(A,\Psi) + \mathcal{L}_{\text{Higgs}}(A,\Psi,H)}^{\mathcal{L}_{\text{SM}}\ \text{(renormalizable)}} + \underbrace{\sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}_n^{(d)}(A,\Psi,H)}_{\text{Operators of dim} \geq 5 \text{ made of SM fields}}\,,$$

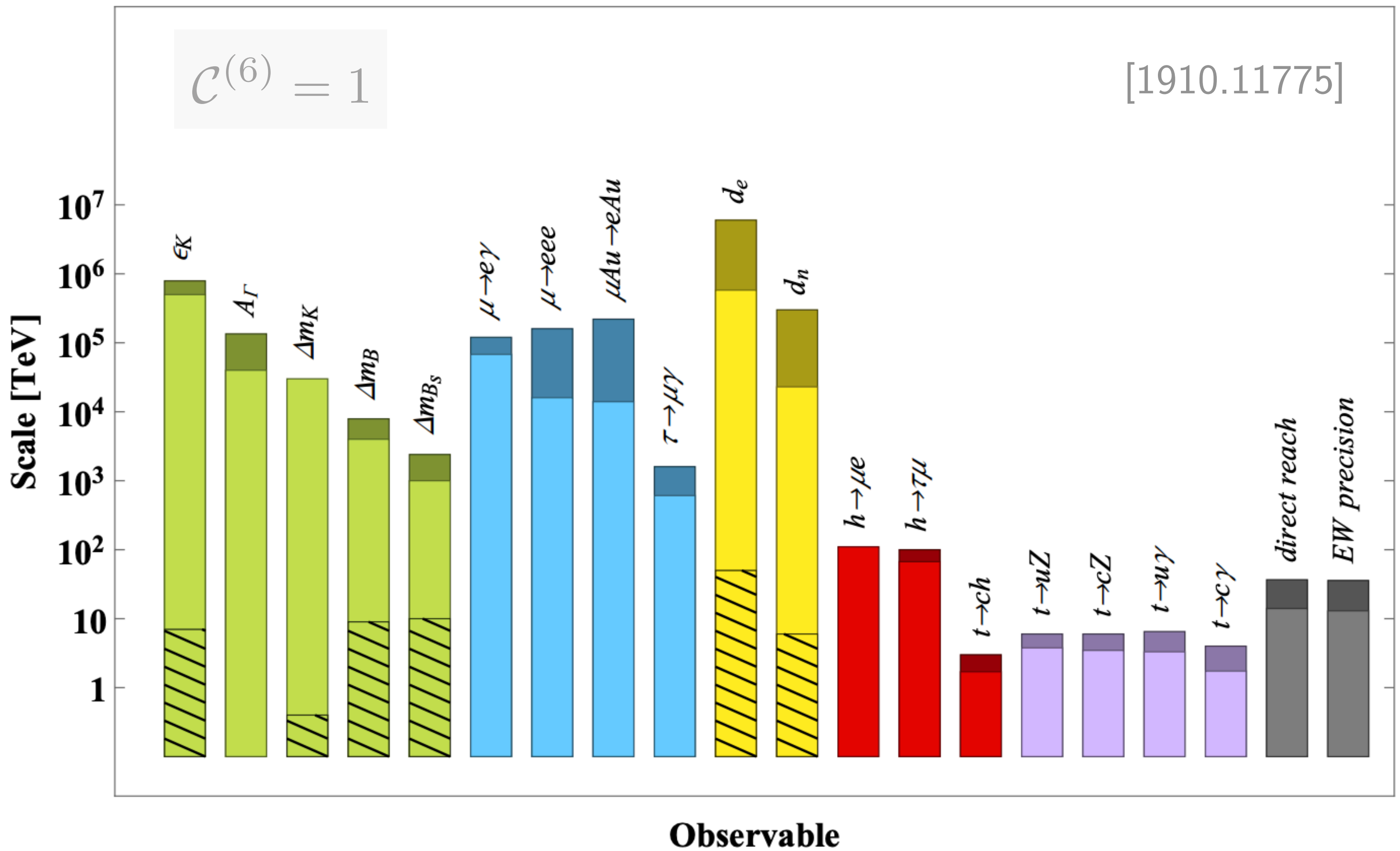
Assumption: $E \ll \Lambda$

Most general description of new physics as long as there is not enough energy to produce the new degrees of freedom.



New physics flavor problem?

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{\mathcal{C}^{(5)}}{\Lambda_L}\mathcal{O}^{(5)} + \sum_i \frac{\mathcal{C}_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \dots$$



Flavor violation needs to be **protected** to **suppress rare/forbidden** processes:

⇒ e.g., *Minimal Flavor Violation*, or *flavor symmetries* such as $U(2)^5$.

⇒ Fundamental input for model building. [D'Ambrosio et al. '02], [Barbieri et al. '11]

Outline

I. Introduction

II. CKM-ology

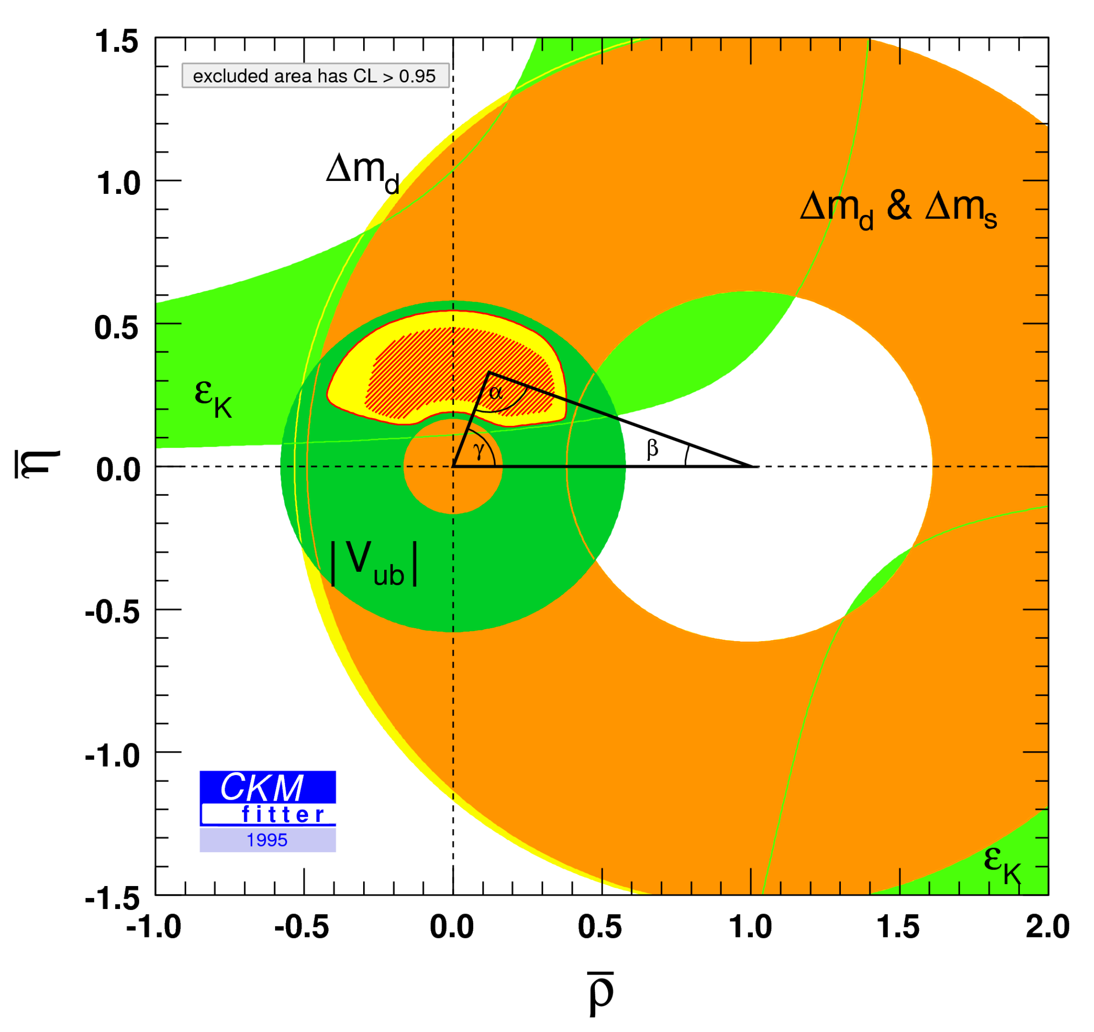
III. Recents results in B-physics*

IV. Outlook

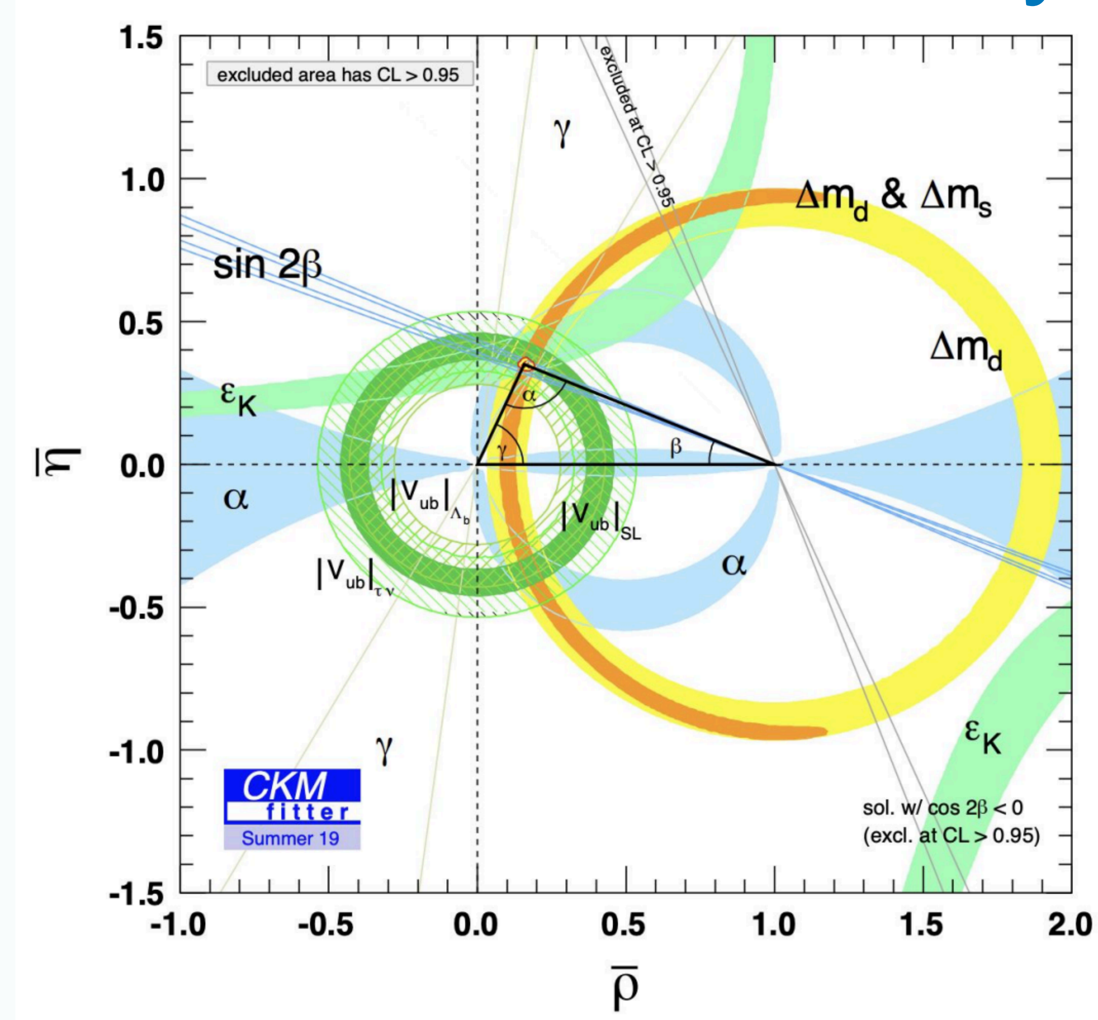
***including the first observation of $B \to K\nu\bar{\nu}$ at Belle-II**

CKM-ology

1995



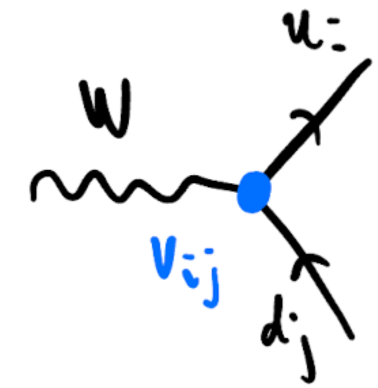
Today



CKM-ology

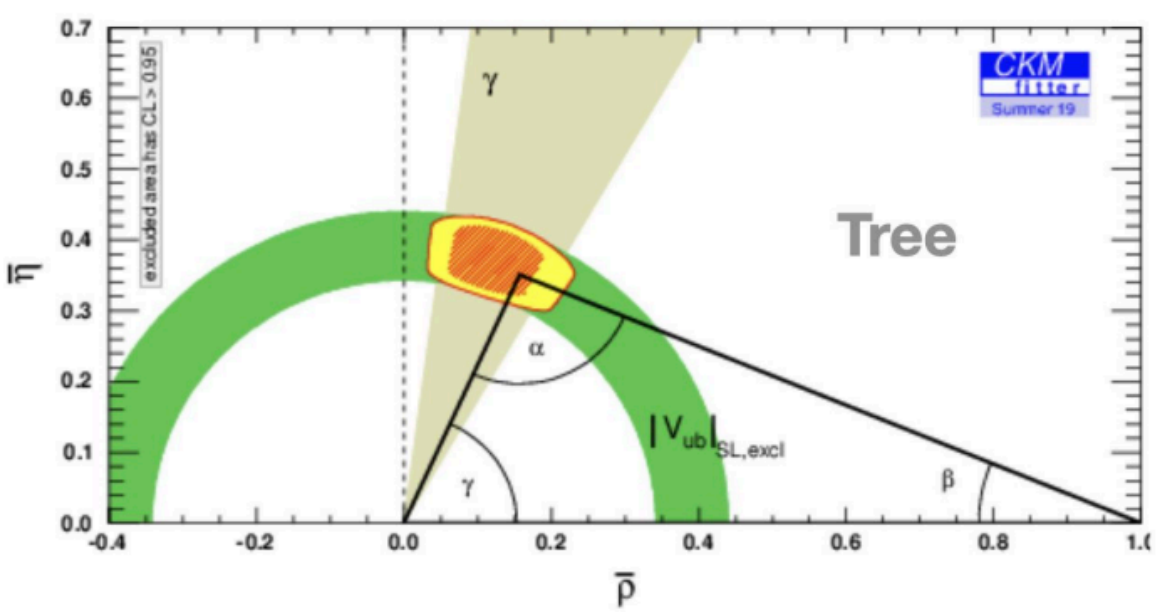
$$\mathcal{L}_{\text{c.c.}} \supset \frac{g}{\sqrt{2}} (V_{\text{CKM}})_{ij} \left(\bar{u}_{Li}\gamma^{\mu} d_{L_j}\right) W^{+}_{\mu} + \text{h.c.}$$

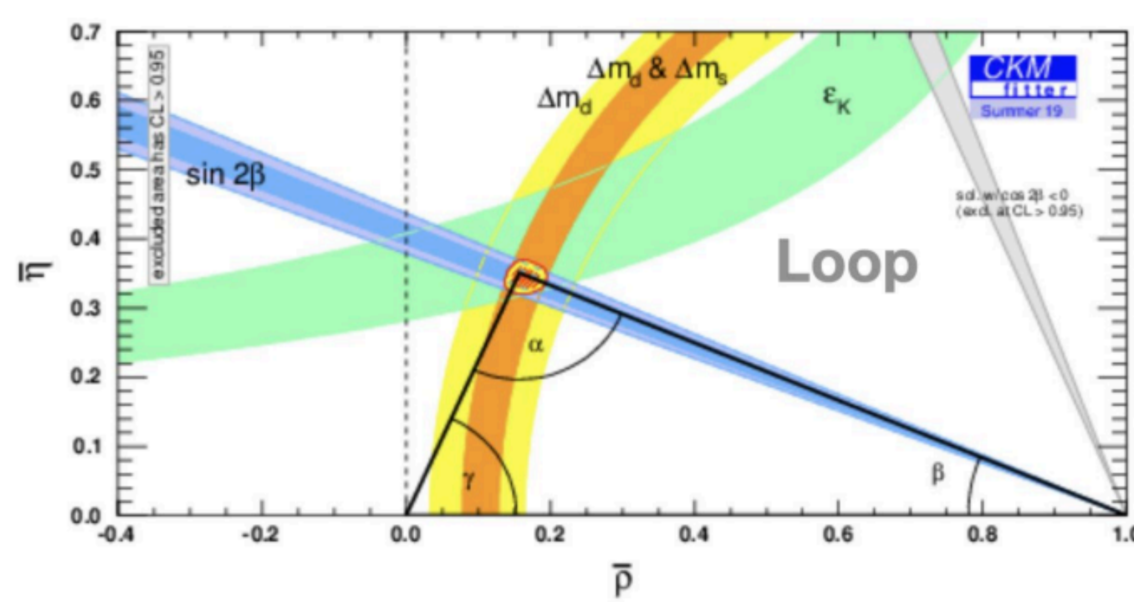
$$V_{\text{CKM}} = U^{\dagger}_{u_L} U_{d_L}$$



Strategy:

Fix the CKM matrix entries through tree-level decays, and over-constrain it with loop-induced processes:



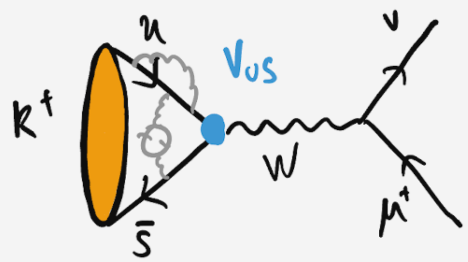


Good agreement! But there are a **few tensions** to be solved (*precision physics is hard!*)

Example: kaon decays

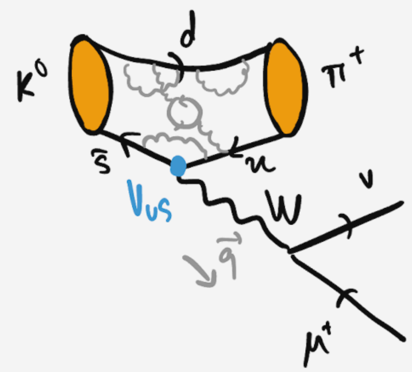
Hadronic uncertainties:

$K \to \mu\nu$



$$\langle 0|\bar{s}\gamma^\mu\gamma_5 u|K^+\rangle \to f_K$$

$K \to \pi\ell\nu$

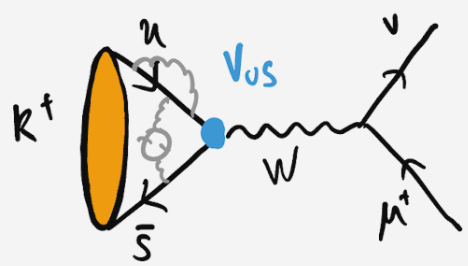


$$\langle \pi^+|\bar{s}\gamma^\mu d|K^0\rangle \to f_{0,+}(q^2)$$

- **Non-perturbative QCD** (Lattice QCD needed) — *cf. FLAG review.*

Example: kaon decays

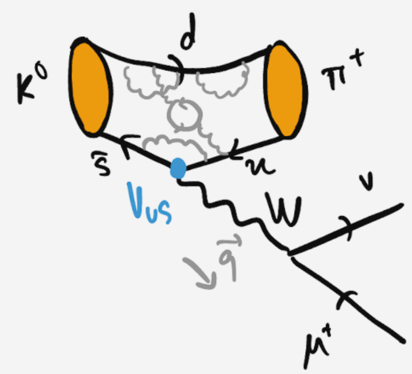
$K \to \mu\nu$



Hadronic uncertainties:

$$\langle 0|\bar{s}\gamma^\mu\gamma_5 u|K^+\rangle \to f_K$$

$K \to \pi\ell\nu$



$$\langle \pi^+|\bar{s}\gamma^\mu u|K^0\rangle \propto f_{0,+}(q^2)$$

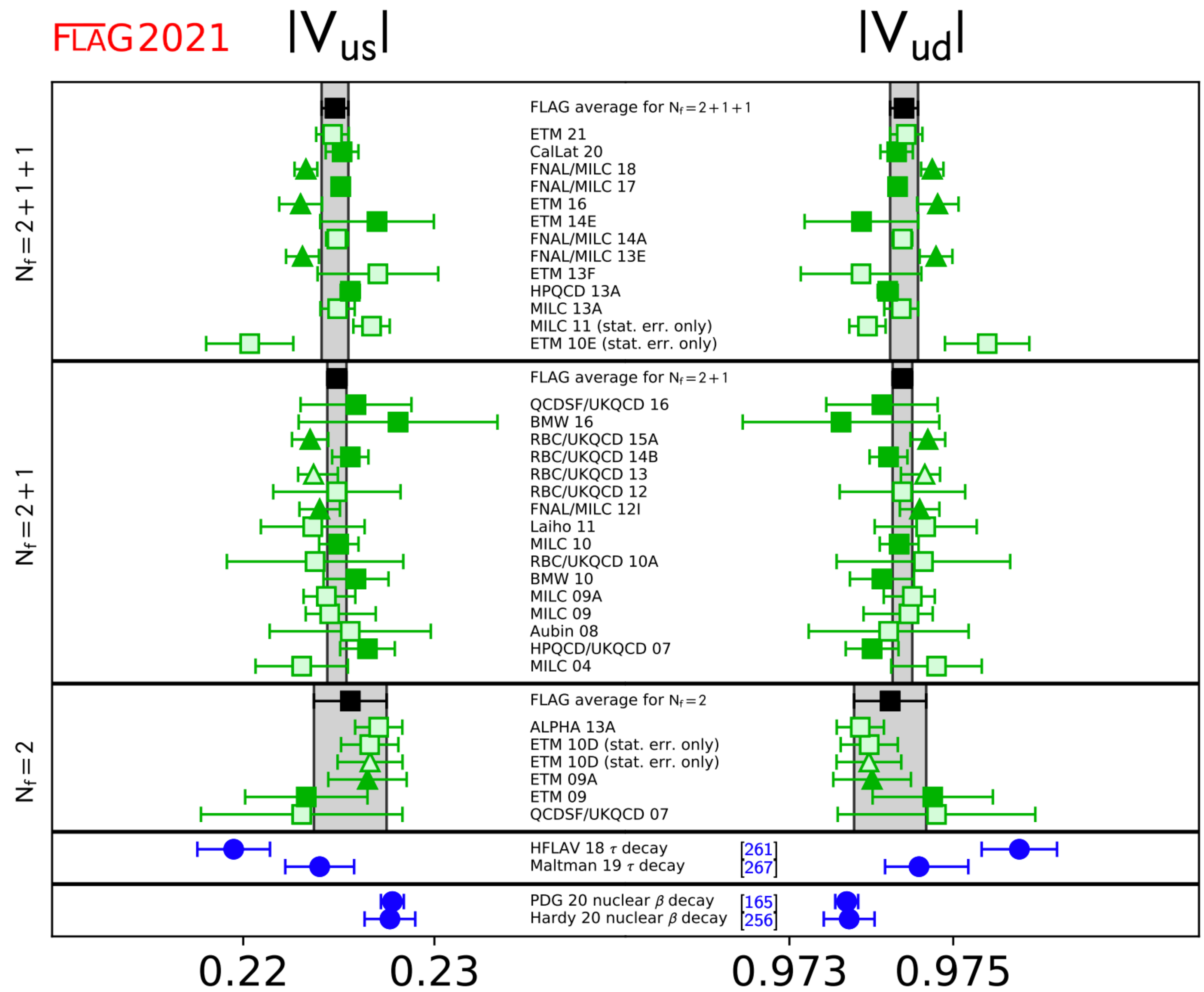
- **Non-perturbative QCD** (Lattice QCD needed) — *cf. FLAG review.*
- **Current precision** requires **radiative** and **isospin-breaking corrections**:

$$\alpha_{\rm em} \approx \frac{1}{137} \quad \text{and} \quad \frac{m_d - m_u}{\Lambda_{\rm QCD}} \approx \mathcal{O}(1\%)$$

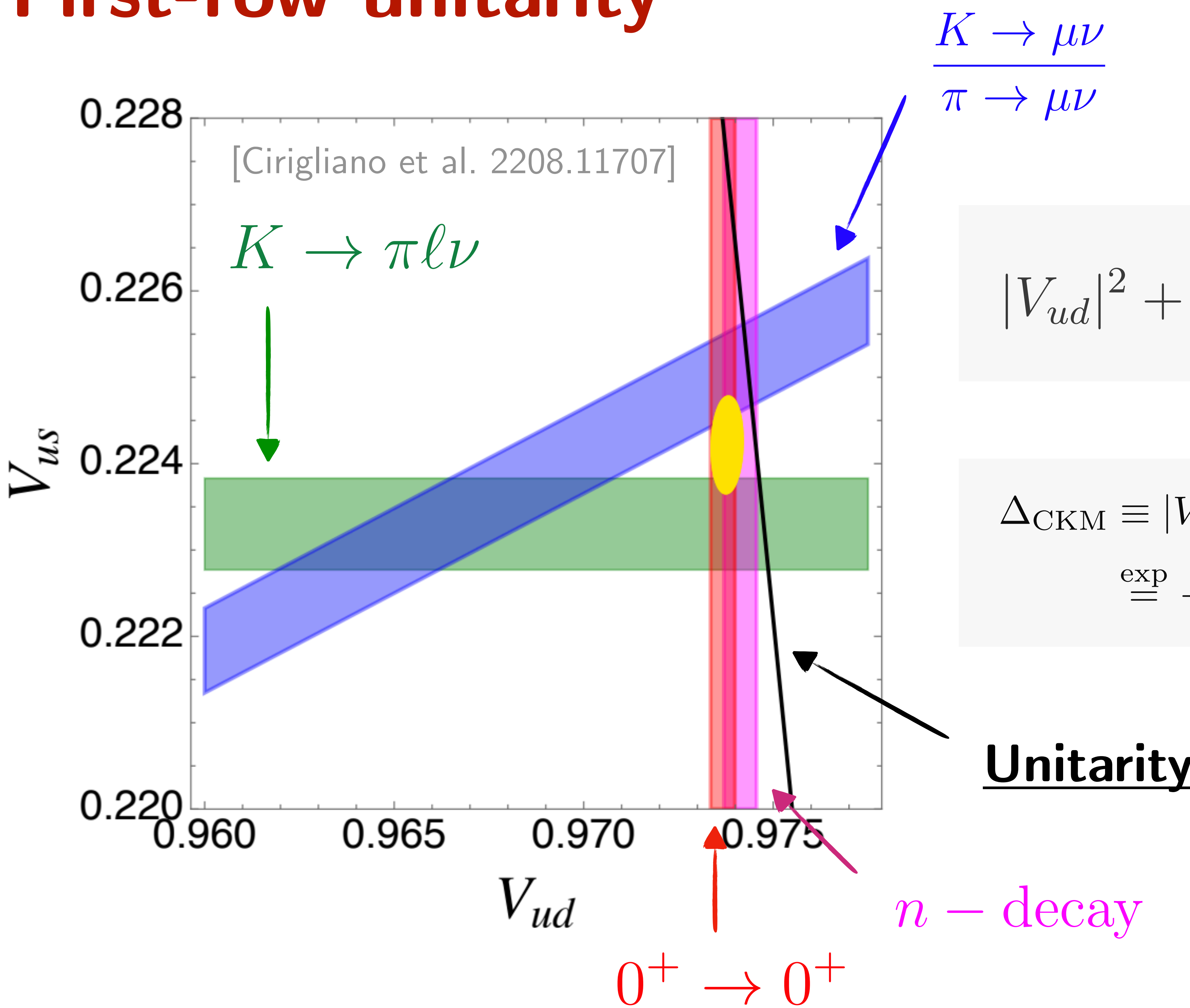
⇒ Included in recent **QCD+QED** simulations of $K(\pi) \to \mu\nu$ on the **lattice**!

[Di Giusti et al. '17, '18], [Di Carlo et al. '19]...

FLAG


FLAG2021
$|V_{us}|$
$|V_{ud}|$
FLAG average for $N_f=2+1+1$
ETM 21
CalLat 20
FNAL/MILC 18
FNAL/MILC 17
ETM 16
ETM 14E
FNAL/MILC 14A
FNAL/MILC 13E
ETM 13F
HPQCD 13A
MILC 13A
MILC 11 (stat. err. only)
ETM 10E (stat. err. only)
FLAG average for $N_f=2+1$
QCDSF/UKQCD 16
BMW 16
RBC/UKQCD 15A
RBC/UKQCD 14B
RBC/UKQCD 13
RBC/UKQCD 12
FNAL/MILC 12I
Laiho 11
MILC 10
RBC/UKQCD 10A
BMW 10
MILC 09A
MILC 09
Aubin 08
HPQCD/UKQCD 07
MILC 04
FLAG average for $N_f=2$
ALPHA 13A
ETM 10D (stat. err. only)
ETM 10D (stat. err. only)
ETM 09A
ETM 09
QCDSF/UKQCD 07
HFLAV 18 τ decay [261]
Maltman 19 τ decay [267]
PDG 20 nuclear β decay [165]
Hardy 20 nuclear β decay [256]
$N_f=2+1+1$
$N_f=2+1$
$N_f=2$
0.22
0.23
0.973
0.975

First-row unitarity



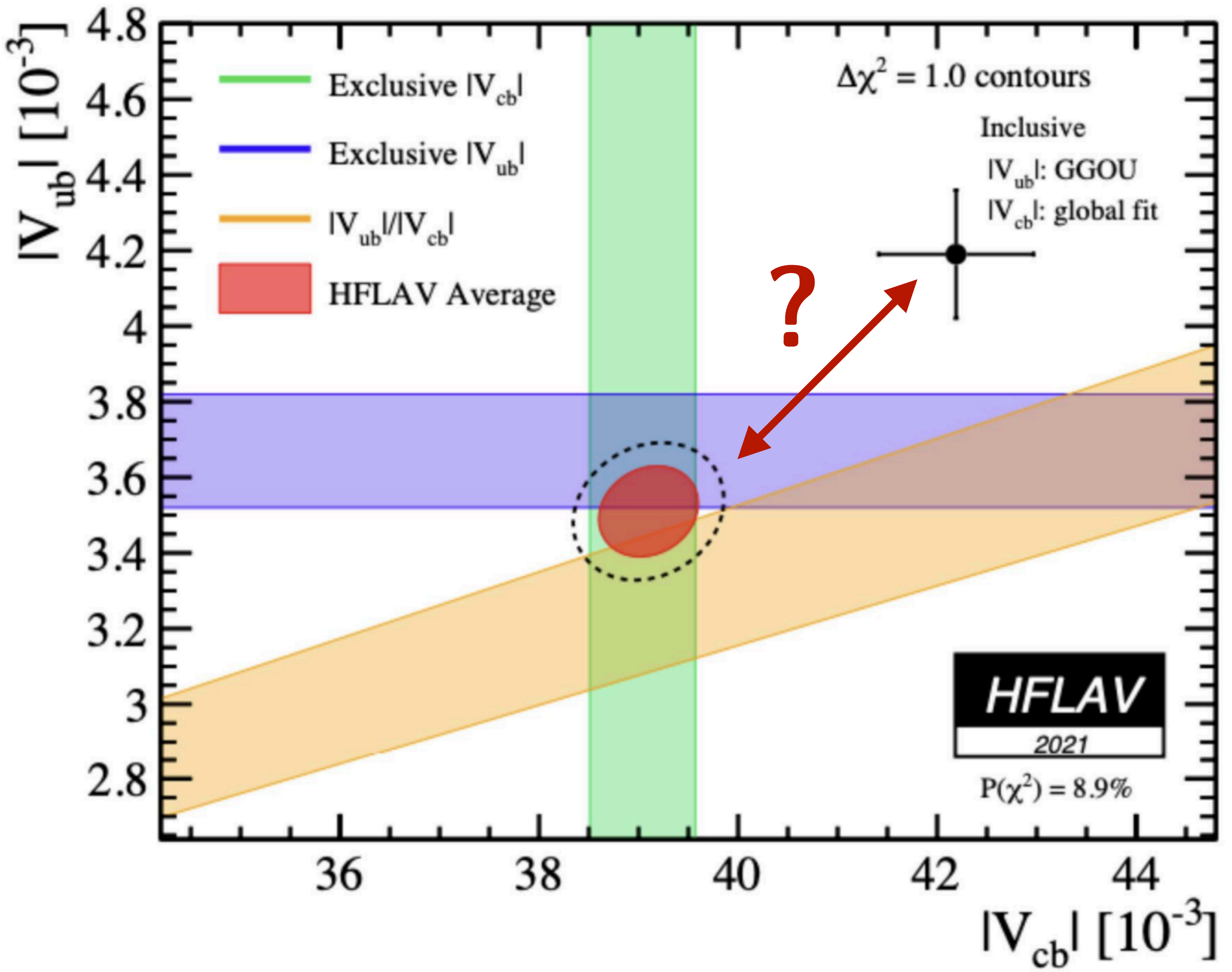
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

($|V_{ub}|^2 \approx 0$)

$$\Delta_{\text{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 \overset{\text{exp}}{=} -0.018(6)$$

Better understanding the hadronic uncertainties is fundamental to solving these (mild) discrepancies!

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



Long-standing discrepancy:

$B \to D^{(*)} l\nu$

$B \to \pi l \nu$

$\dfrac{B_s \to K\mu\nu}{B_s \to D_s \mu\nu}$

$\ldots$

$B \to X_{(c)} l\nu$

More problematic:

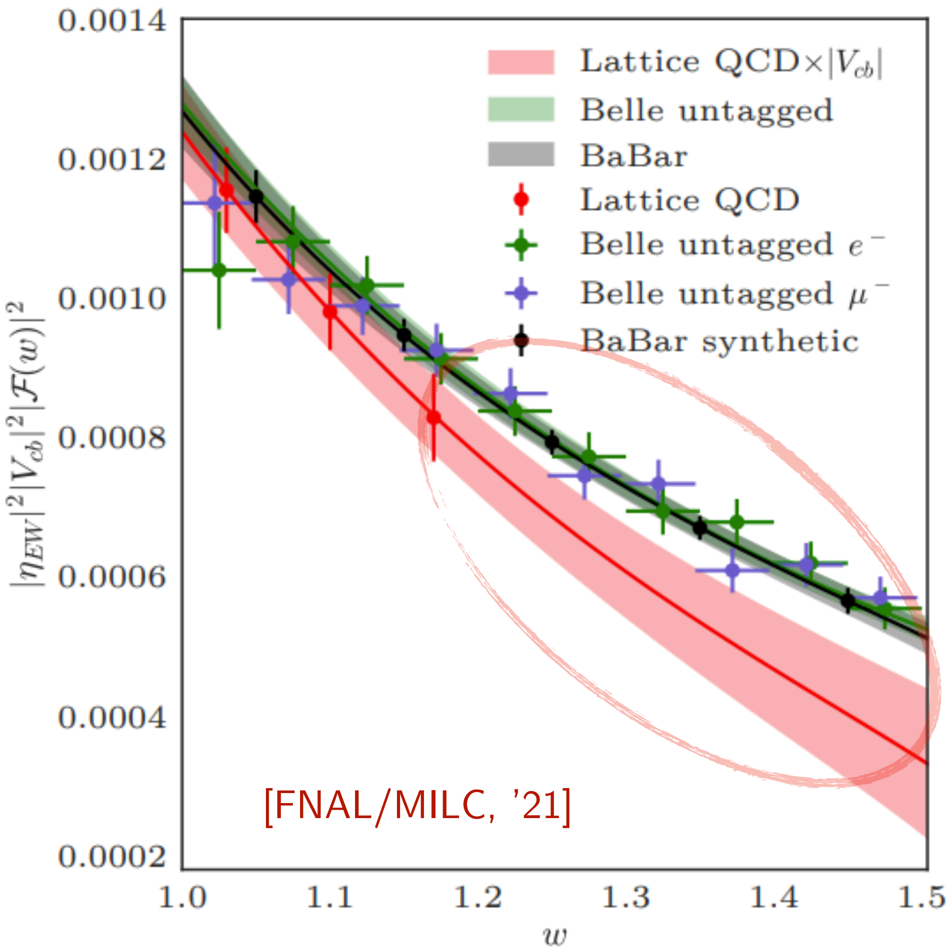
- V_{cb} plays an **essential role** in the predictions of **FCNCs** through **unitarity**:

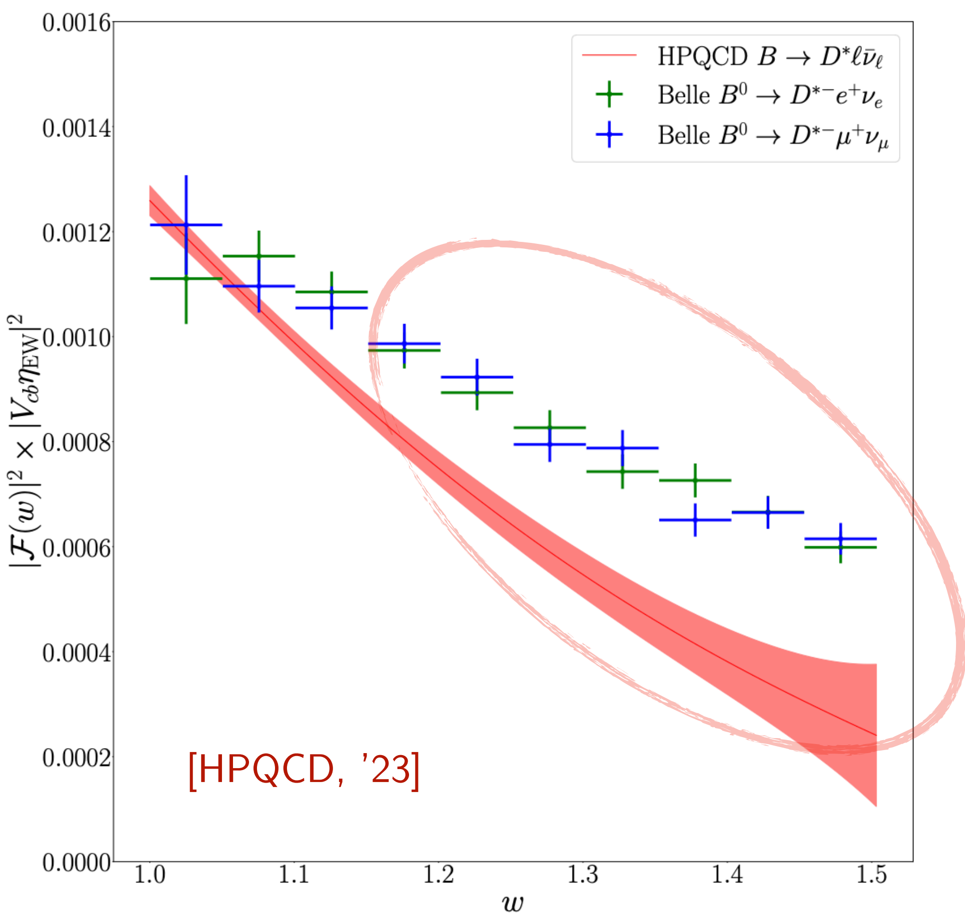
$$|V_{tb}V_{ts}|^2 \simeq |V_{cb}|^2 \left[1 + \mathcal{O}(\lambda^2)\right]$$

- This **ambiguity** needs **to be solved** to **match** the expected **sensitivity of Belle-II!**

[NEW] Warning!

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^*\ell\nu) \propto |V_{cb}|^2\, |\mathcal{F}(w)|^2 \qquad \left[w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2 m_B m_{D^*}} \right]$$





⇒ **Needs clarification** to reliably **extract** $|V_{cb}|$ from $B \to D^*\ell\bar{\nu}$...

NB. Recent JLQCD agrees well with exp. data!

Way out: independent LQCD results + Belle-II data!

Which CKM value?

$$\lambda_t = V_{tb}V_{ts}^*$$

- Using available $b \to c\ell\bar{\nu}$ data:

$$|\lambda_t| \times 10^3 = \begin{cases} 41.4 \pm 0.8\,, & (B \to X_c l\bar{\nu}) \\ 39.3 \pm 1.0\,, & (B \to D l\bar{\nu}) \\ 37.8 \pm 0.7\,, & (B \to D^* l\bar{\nu}) \end{cases}$$

[HFLAV, '22]
[FLAG, '21]
[HFLAV, '22]

… to be compared to CKM global fits:

cf. also [Martinelli et al. '21]

$$|\lambda_t|_{\mathrm{UTfit}} = (41.4 \pm 0.5) \times 10^{-2}$$

$$|\lambda_t|_{\mathrm{CKMfitter}} = (40.5 \pm 0.3) \times 10^{-2}$$

- Alternative strategy: to use $\Delta m_{B_s} \propto f_{B_s}^2 \hat{B}_{B_s} |\lambda_t|^2$

[Buras, Venturini. '21, '22]

$$|\lambda_t| \times 10^3 = \begin{cases} 41.9 \pm 1.0\,, & (N_f = 2+1+1) \\ 39.2 \pm 1.1\,, & (N_f = 2+1) \end{cases}$$

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 256 \pm 6 \text{ MeV} \qquad (N_f = 2+1+1)$$

[HPQCD '19]

$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 274 \pm 8 \text{ MeV} \qquad (N_f = 2+1)$$

[FLAG '21]

There is **not a clear answer** to this **ambiguity** so far.

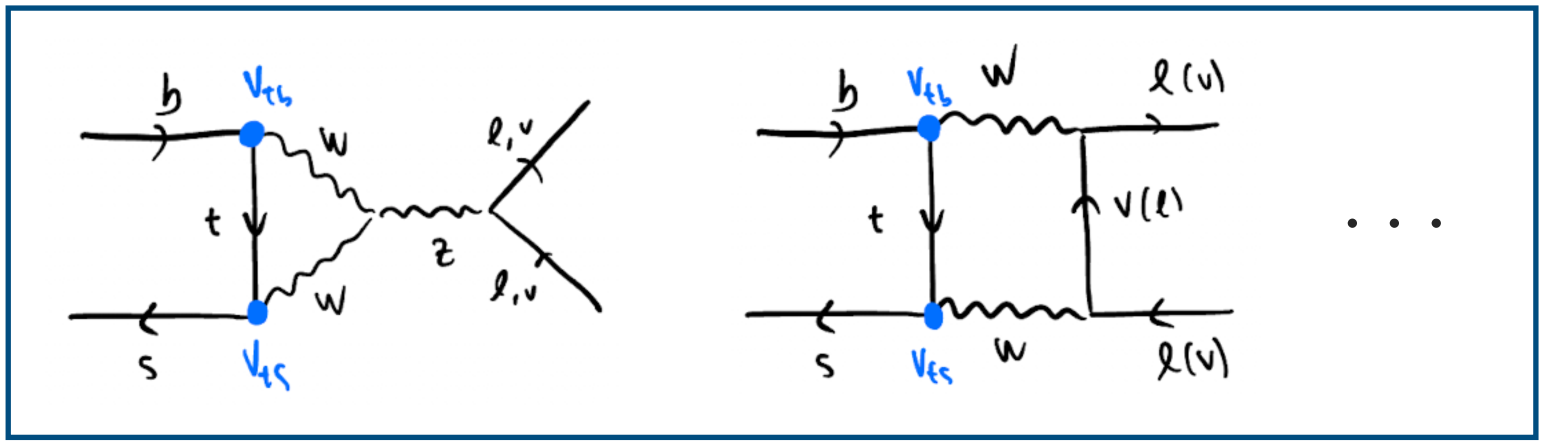
Recent results in B-physics

*emphasis on $B \to K\nu\bar{\nu}$ at Belle-II

[Recap] B-meson decays

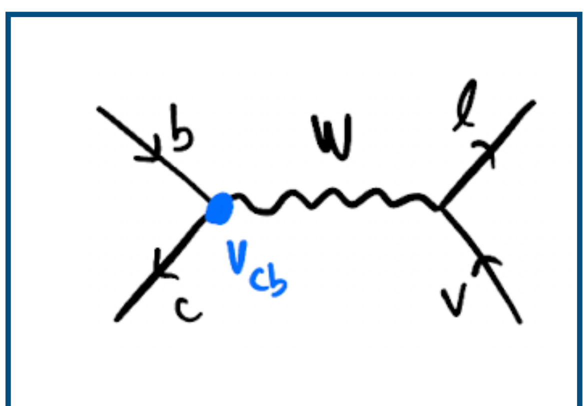
Targets of current experiments (LHCb & Belle-II):

- **Loop-induced decays:** *e.g.*, $b \to s\ell\ell$ and $b \to s\nu\bar{\nu}$



$$B \to K^{(*)}\ell\ell$$
$$B \to K^{(*)}\nu\bar{\nu}$$
$$B_s \to \phi\ell\ell$$
$$\dots$$

- **Tree-level decays:** *e.g.*, $b \to c\tau\bar{\nu}$



$$B \to D^{(*)}\ell\nu$$
$$B_s \to D_s^{(*)}\ell\nu$$
$$\dots$$

⇒ Decays with b-**baryons** are also **available** at LHCb. [Boer et al. '19, Becirevic et al. '22...]

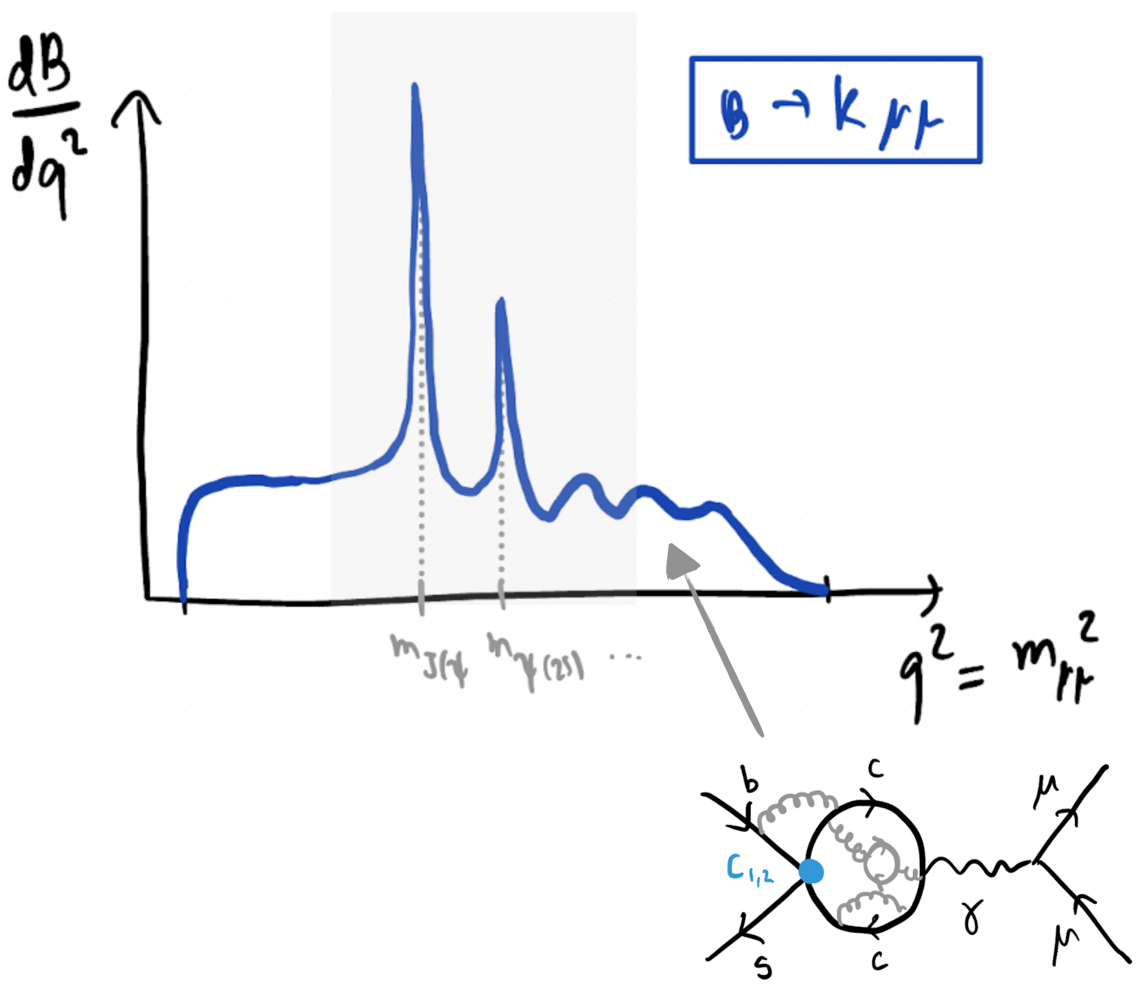
⇒ In both cases, **ratios of observables** can be used to **reduce theoretical uncertainties**.

Revisiting $B \to K\nu\nu$ in the SM

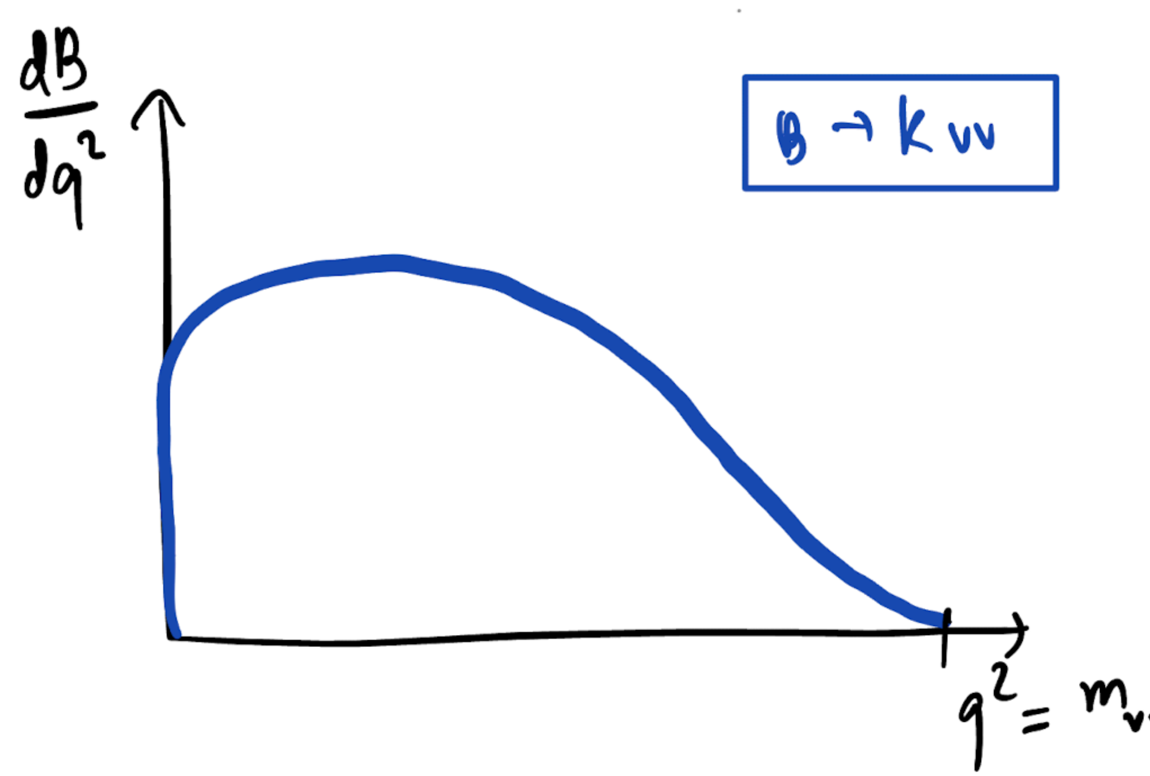
[D. Becirevic, G. Piazza, **OS**, 2301.06990]

Why to study B-decays with neutrinos?

- $B \to K^{(*)}\ell\ell$:
  - *Sensitive to new physics effects.* ✔
  - *Experimentally clean (especially for $\ell = \mu$).* ✔
  - *Many observables (angular distribution).* ✔
  - *Theoretically challenging (non-factorizable contributions...)* ✘



- $B \to K^{(*)}\nu\bar{\nu}$:
  - *Sensitive to new physics effects.* ✔
  - *Exp. more challenging (missing energy).* ✔
  - *Fewer observables.* ✔
  - ***Theoretically cleaner!*** ✔
  - ***Sensitive to operators with τ-leptons.*** ✔



$B \to K\nu\bar{\nu}$ in the SM

- **Effective Hamiltonian** within the SM:

see e.g. [Buras et al. '14]

$$\mathcal{L}_{\rm eff}^{b\to s\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha_{\rm em}}{2\pi}\sum_i C_L^{\rm SM}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu\nu_{Li}) + \text{h.c.}\,,$$

$\lambda_t = V_{tb}V_{ts}^*$

- **Short-distance** contributions known to **good precision**:

$$C_L^{\rm SM} = -X_t/\sin^2\theta_W$$
$$= -6.32(7)$$

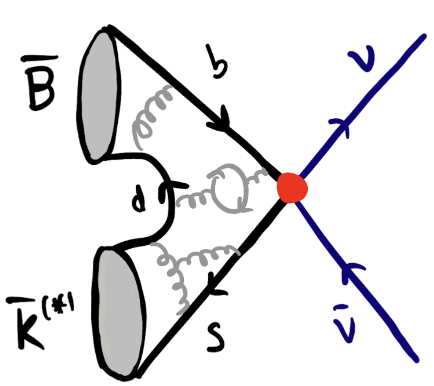
Including NLO QCD and two-loop EW contributions:

$$X_t = 1.462(17)(2)$$

[Buchala et al. '93, '99], [Misiak et al. '99], [Brod et al. '10]

Two main sources of uncertainties:

i) Hadronic matrix-element:



Known Lorentz factors

$$\langle K^{(*)}|\bar{s}_L\gamma^\mu b_L|B\rangle = \sum_a K_a^\mu\,\mathcal{F}_a(q^2)$$

Form-factors (e.g., LQCD)

ii) CKM matrix:

From CKM unitarity:

$$|V_{tb}V_{ts}^*| = |V_{cb}|(1+\mathcal{O}(\lambda^2))$$

Which value to take (incl. vs. excl.)?

Form-factors: $B \to K\nu\bar{\nu}$

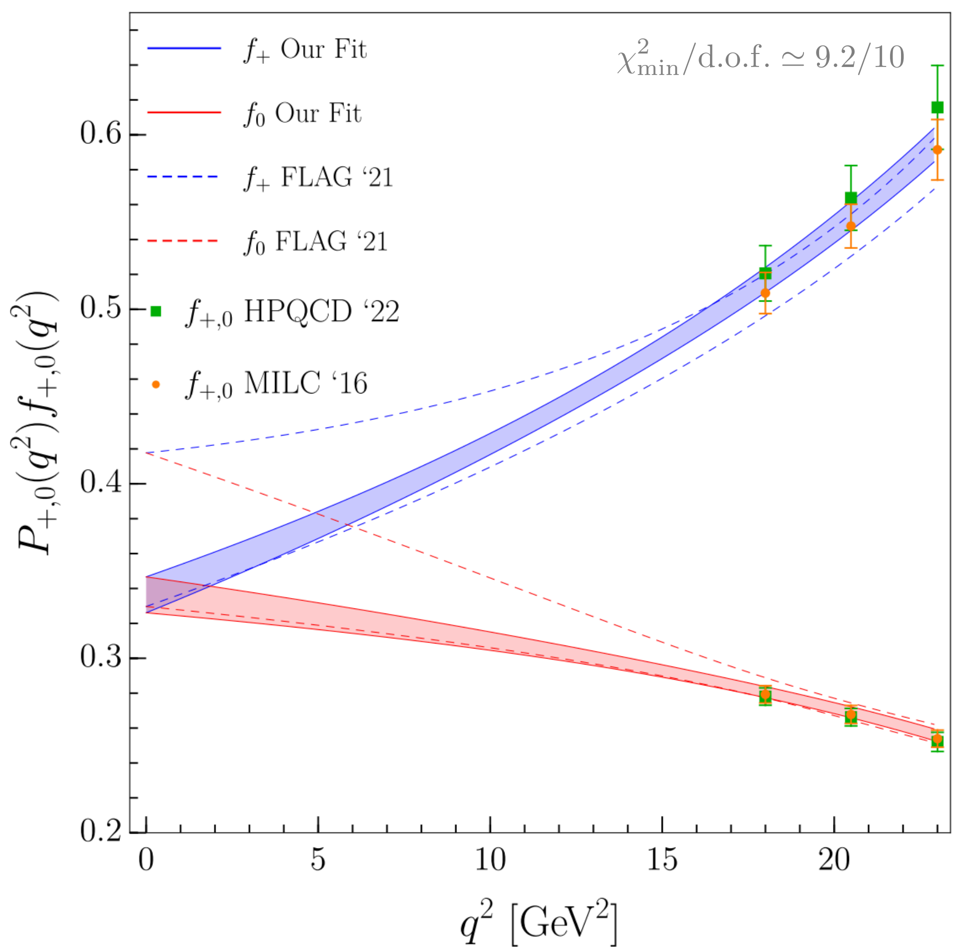
- **Lattice QCD** data available at **nonzero recoil** ($q^2 \neq q^2_{\text{max}}$) for all form-factors:

$$\langle K(k)|\bar{s}\gamma^\mu b|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_K^2}{q^2} q^\mu\right] f_+(q^2) + q^\mu \frac{m_B^2 - m_K^2}{q^2} f_0(q^2)$$

with $f_+(0) = f_0(0)$.

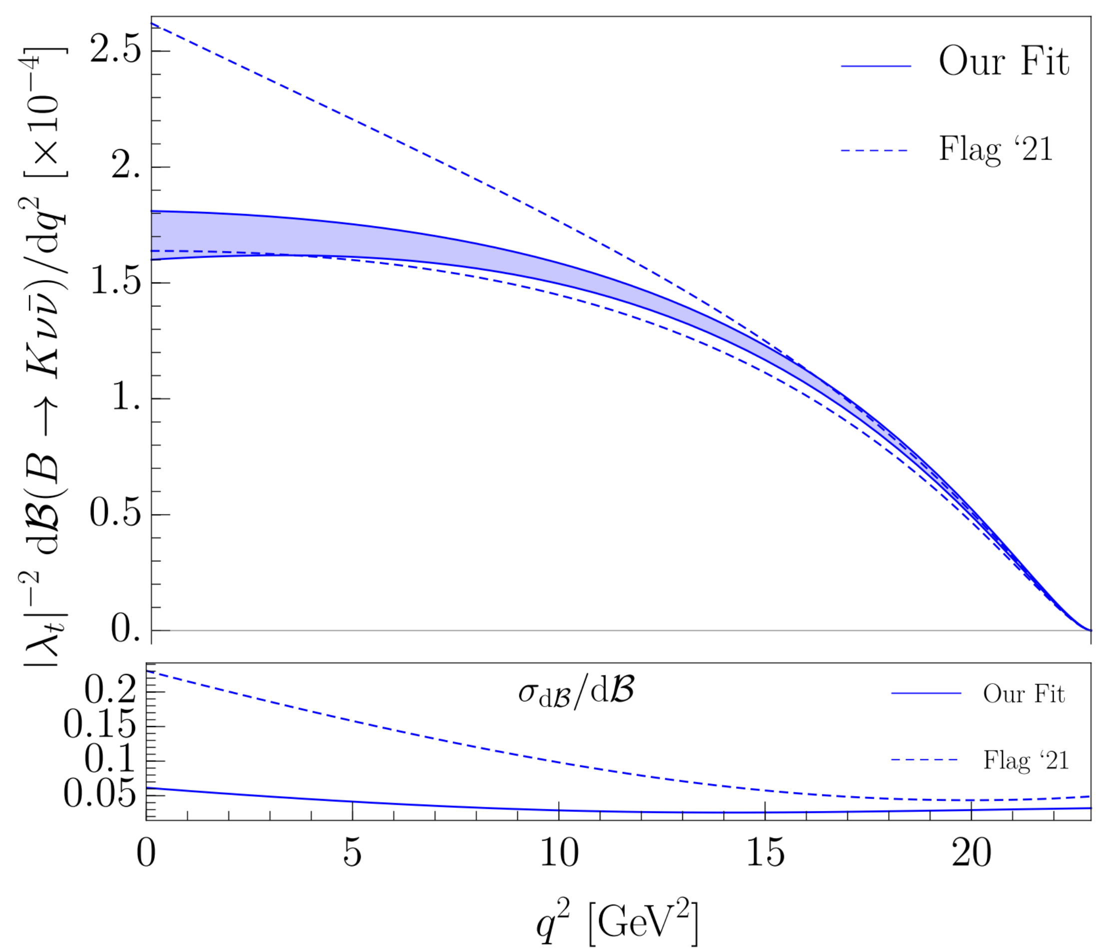
Only form-factor needed for $B \to K\nu\bar{\nu}$!

- **[NEW]** We update the FLAG average by combining [HPQCD '22] results with [FNAL/MILC '16]:



Pole factor:

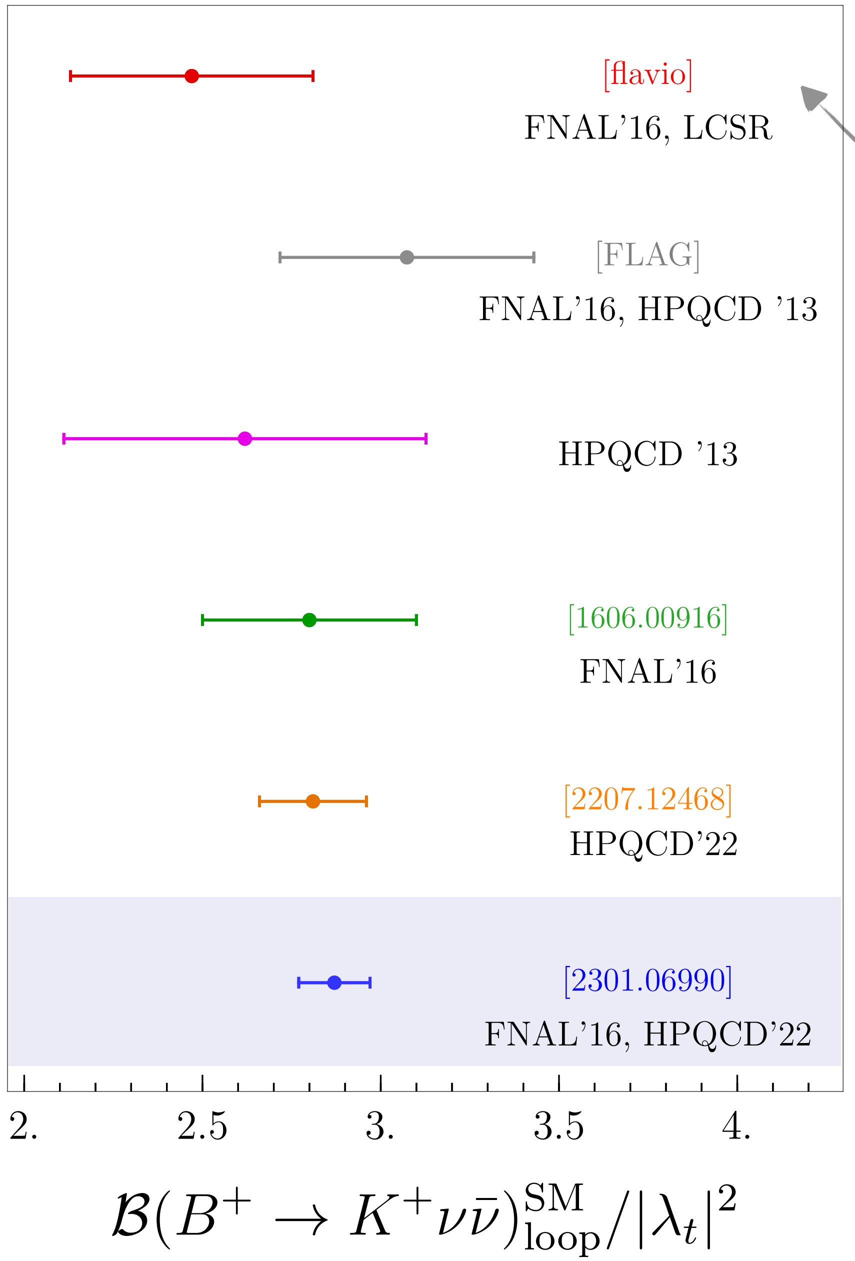
$P_i(q^2) = 1 - q^2/M_i^2$



[Becirevic, Piazza, **OS**. 2301.06990]

Form-factors: $B \to K\nu\bar{\nu}$

**See back-up for proposed tests of these results.*



Form-factors based on Light-Cone Sum Rules (LCSR) lead to smaller branching fractions.

[Bharucha et al. '15, Gubernari et al. '18]

$$\mathcal{B}(B \to K\nu\bar{\nu})^{\rm SM}/|\lambda_t|^2 = \begin{cases} (1.33 \pm 0.04)_{K_S} \times 10^{-3} \\ (2.87 \pm 0.10)_{K^+} \times 10^{-3} \end{cases}$$

[Becirevic, Piazza, **OS**. 2301.06990]

Summary (circa '22)

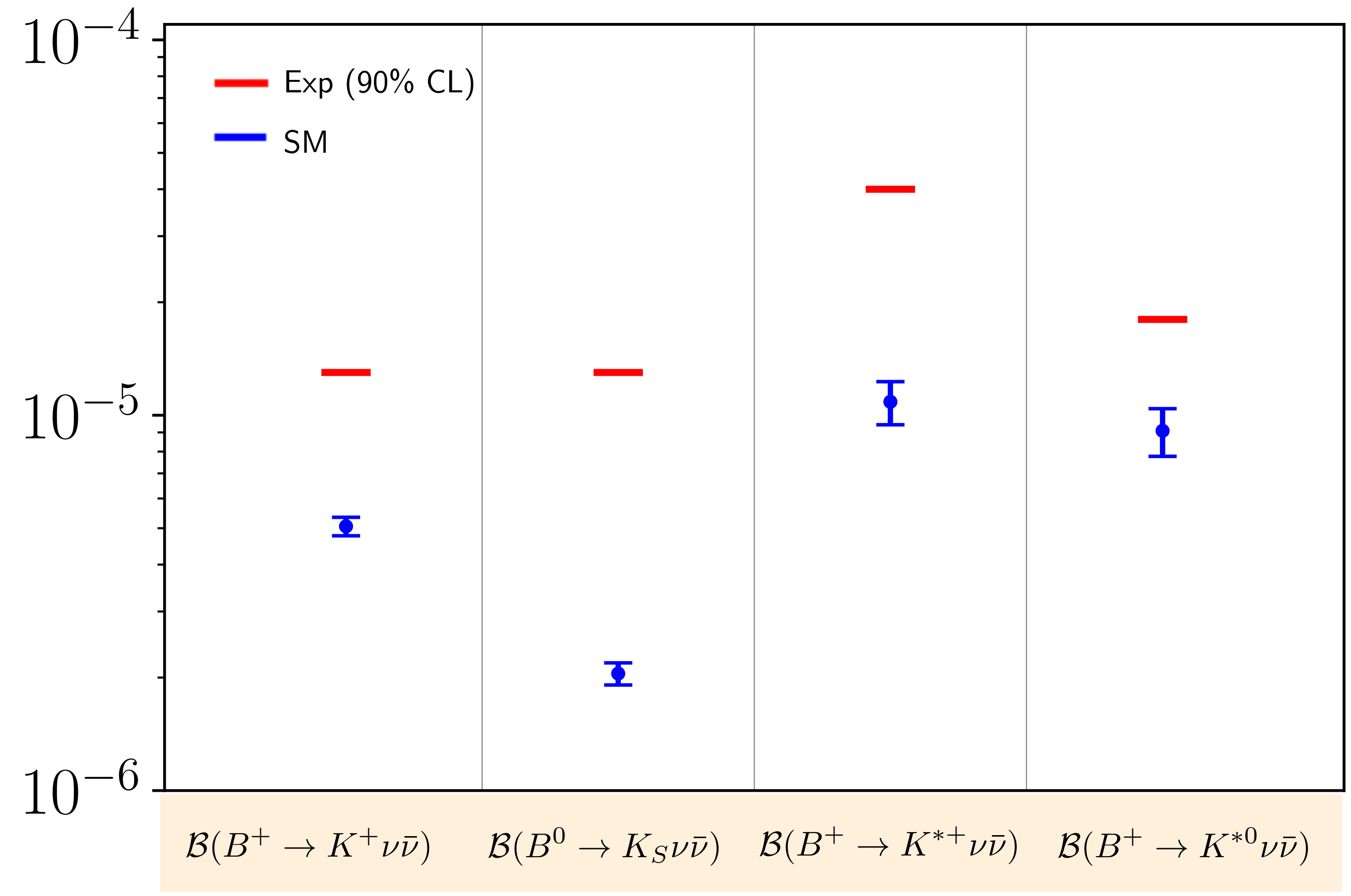
[Belle 1303.3719, 1702.03224]

[BaBar 1009.1529, 1303.7465]

*Using V_{cb} from $B \to D\ell\bar{\nu}$ for illustration

Decay	Branching ratio
$B^+ \to K^+\nu\bar{\nu}$	$(5.06 \pm 0.14 \pm 0.25) \times 10^{-6}$
$B^0 \to K_S\nu\bar{\nu}$	$(2.05 \pm 0.07 \pm 0.12) \times 10^{-6}$
$B^+ \to K^{*+}\nu\bar{\nu}$	$(10.86 \pm 1.30 \pm 0.59) \times 10^{-6}$
$B^0 \to K^{*0}\nu\bar{\nu}$	$(9.09 \pm 1.20 \pm 0.55) \times 10^{-6}$

[Becirevic, Piazza, **OS**. 2301.06990]



Take-home:

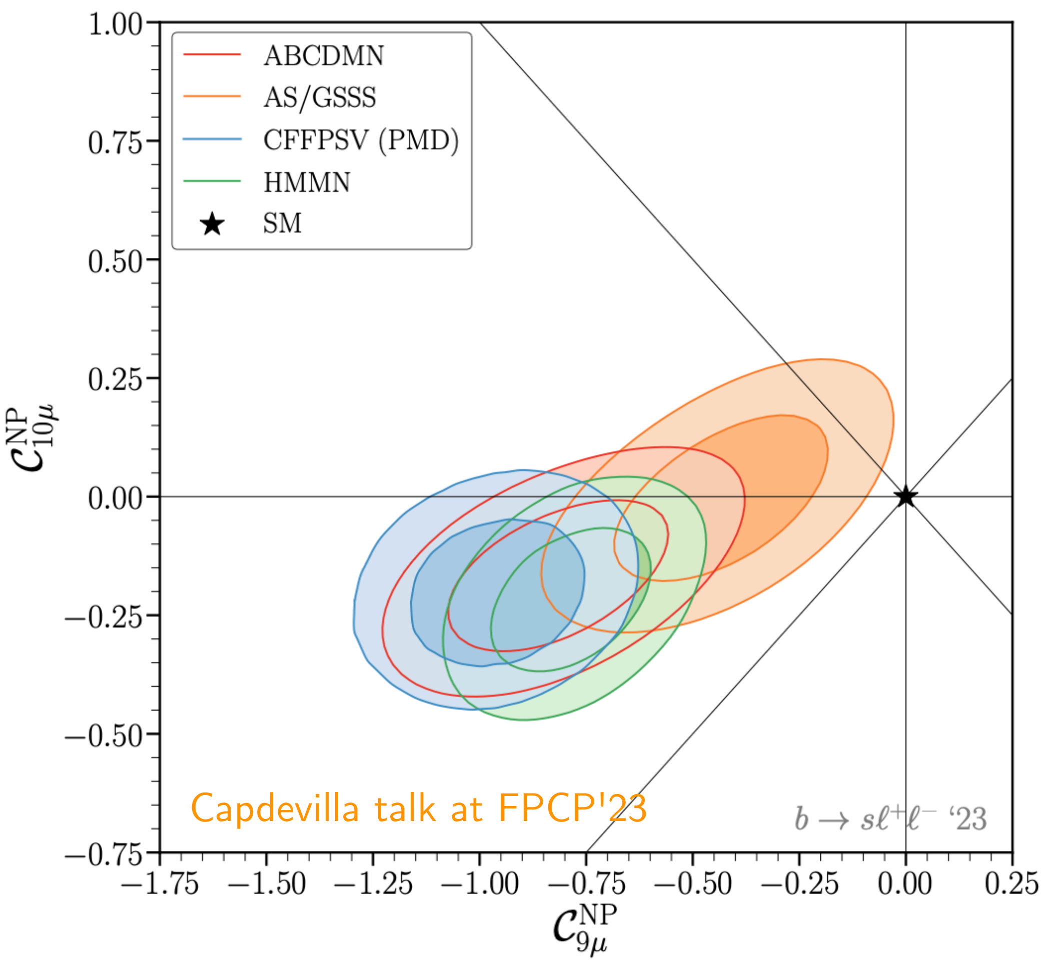
- To remain **cautions** about **hadronic uncertainties** associated to the **form-factors** and the extraction of **CKM** matrix-elements — *non-negligible given the projected Belle-II sensitivity.*
- **Binned measurements** at Belle-II would be a **valuable piece of information** to **test the consistency the SM predictions** (cf. back-up).

[Intermezzo] Anomalies in $B \to K^{(*)}\mu\mu$ decays?

$$\mathcal{L}_{\text{eff}}^{b\to s\ell\ell} = \frac{4G_F}{\sqrt{2}}\lambda_t \sum_\ell \left[C_9^{\ell\ell} \left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu \ell\right) + C_{10}^{\ell\ell} \left(\bar{s}\gamma^\mu P_L b\right)\left(\bar{\ell}\gamma_\mu\gamma_5 \ell\right) + \dots \right] + \text{h.c.}$$

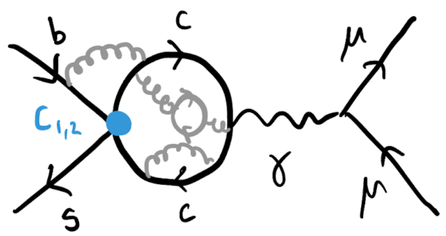
- Angular $B \to K^{(*)}\mu\mu$ observables show a preference for $\delta C_9^{\mu\mu} < 0$:

[Algueró et al. '21, Altmannshofer et al. '21, Hurth et al. '21]



New physics effects or **underestimated hadronic uncertainties**?

see e.g. Ciuchini et al'. '21

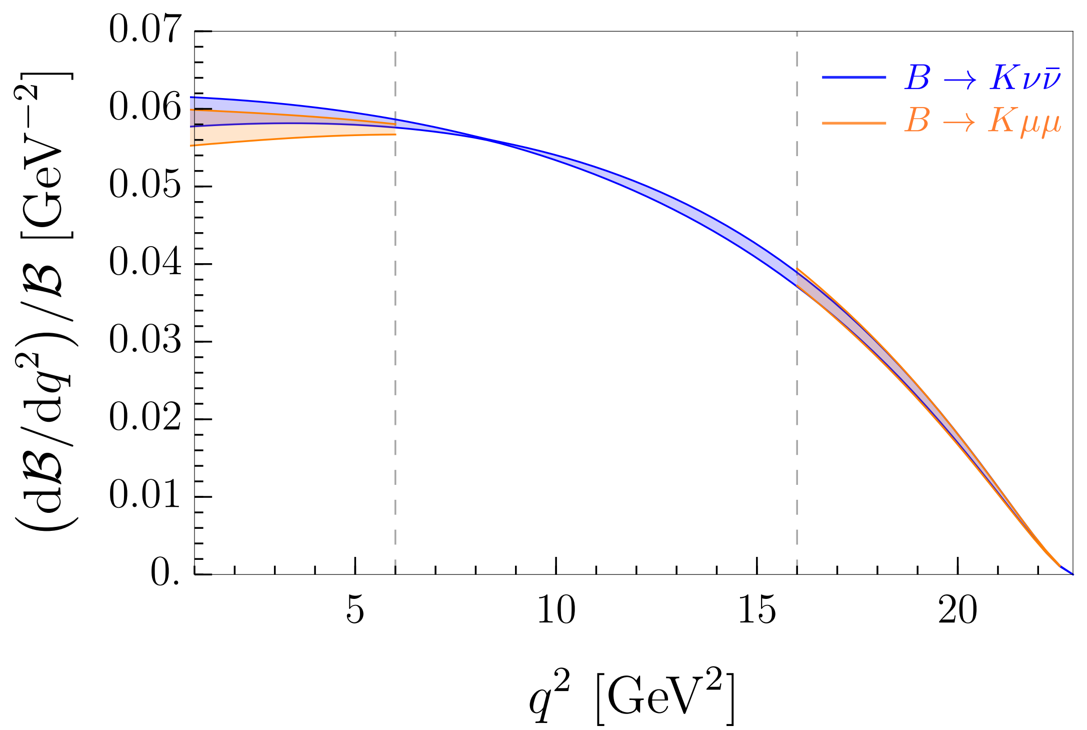


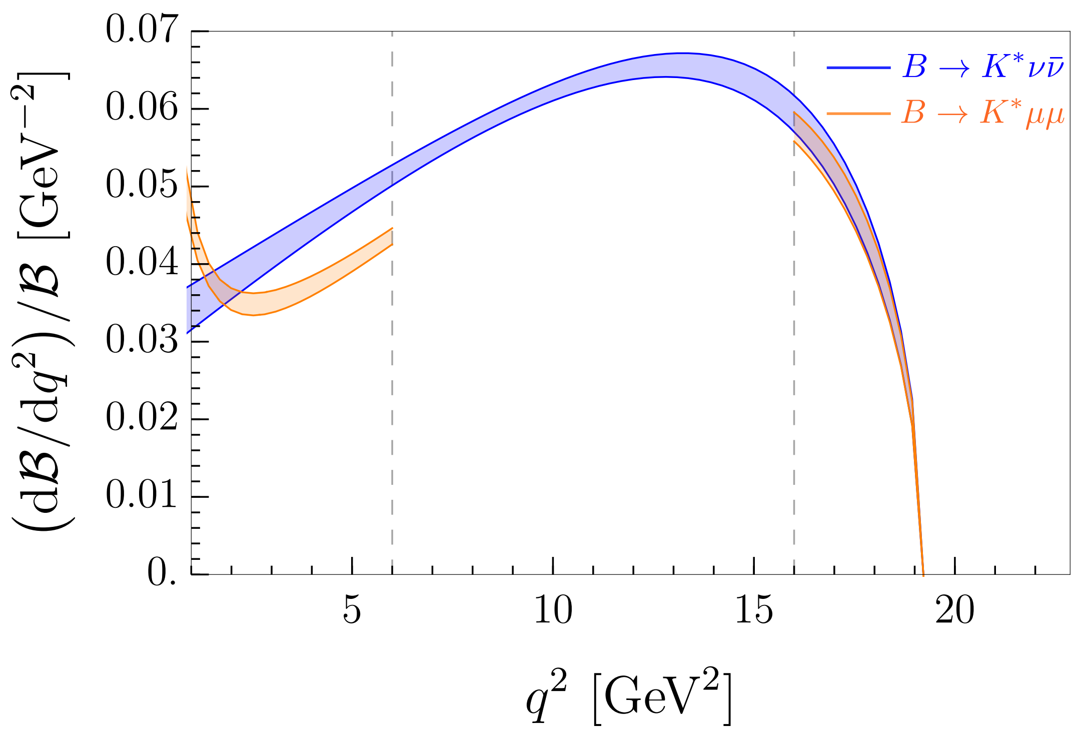
NB. LFU ratios $R_{K^{(*)}} = \mathscr{B}(B \to K^{(*)}\mu\mu)/\mathscr{B}(B \to K^{(*)}ee)$ do not depend on $C_9^{\ell\ell}$, but they are difficult to measure — cf. latest LHCb results, which now agree with the SM predictions.

[Intermezzo] Remarks on $B \to K^{(*)}\nu\nu$/ $B \to K^{(*)}\mu\mu$

- $B \to K^{(*)}\nu\nu$ and $B \to K^{(*)}\mu\mu$ have a similar decay spectrum away from the narrow $c\bar{c}$ resonances:

[Becirevic, Piazza, **OS**. 2301.06990] [Bartsch et al. '09]





*using 2-loop results for $c\bar{c}$ loops from [Asatryan et al. '09]

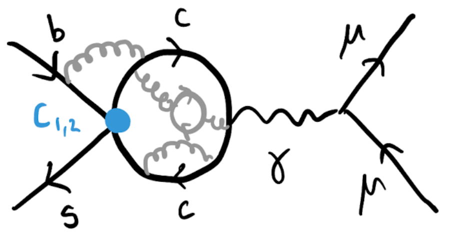
- We can defined the **CKM-free ratio**:

$$\mathcal{R}^{(\nu/l)}_{K^{(*)}}[q_0^2, q_1^2] \equiv \frac{\mathcal{B}(B \to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B \to K^{(*)}ll)}\Bigg|_{[q_0^2, q_1^2]}$$

Ratio of partial branching fractions integrated in the same q^2-bin.

⇒ **Form-factor** uncertainties **cancel out** to a good extent for $q^2 \gg m_\ell^2$.

⇒ Neglecting NP contributions, this ratio can be used to **extract** $C_9^{\mu\mu}$!



- Predictions using perturbative calculation of $c\bar{c}$ loops: [Becirevic, Piazza, **OS**. 2301.06990]

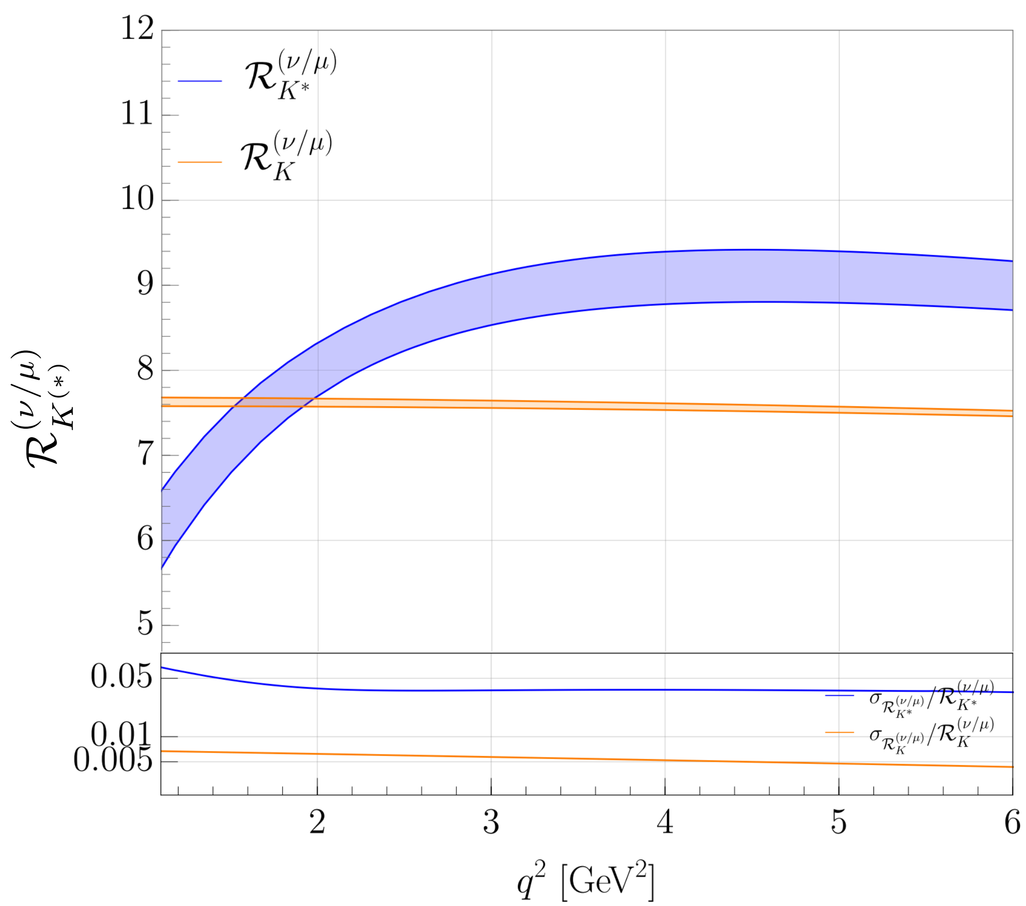
$$\mathcal{R}_K^{(\nu/l)}[1.1,6]\Big|_{\rm SM} = 7.58 \pm 0.04$$

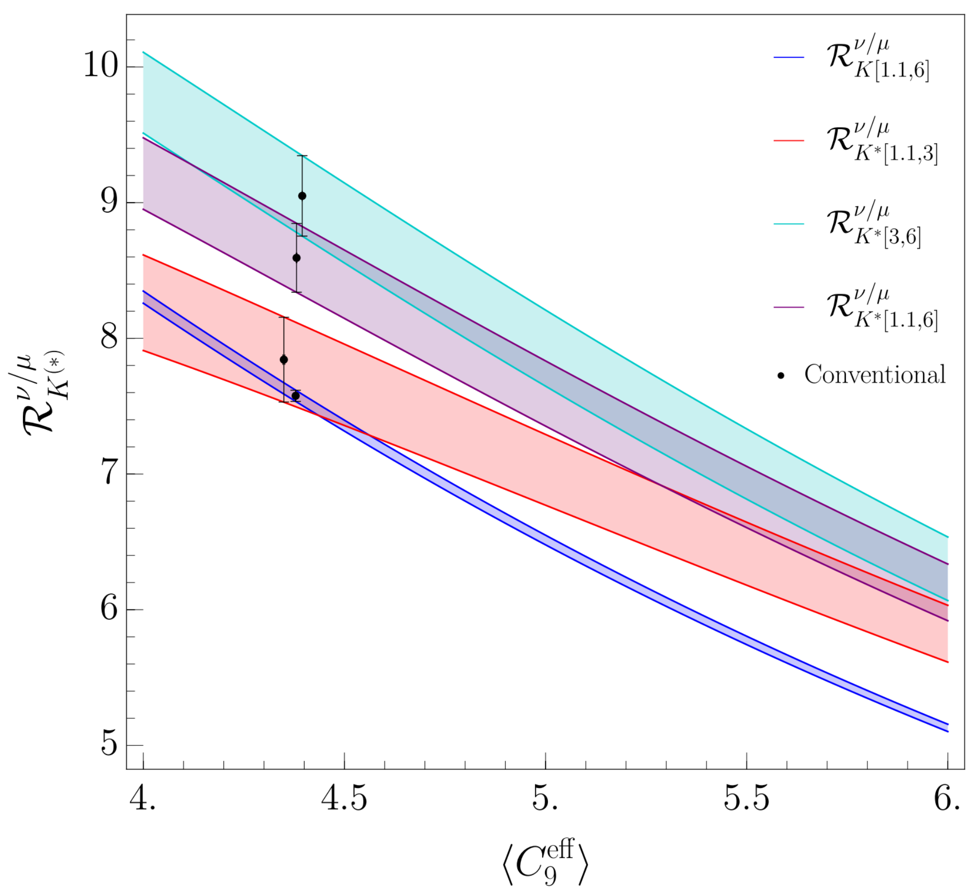
$$\mathcal{R}_{K^*}^{(\nu/l)}[1.1,6]\Big|_{\rm SM} = 8.6 \pm 0.3$$

with the following dependence on $C_9^{\rm eff}$: using [Asatryan et al. '09]

$$\frac{1}{\mathcal{R}_K^{(\nu/l)}[1.1,6]}\Big|_{\rm SM} \simeq \left[7.15 - 0.45 \cdot C_9^{\rm eff} + 0.42 \cdot \left(C_9^{\rm eff}\right)^2\right] \times 10^{-2}$$

$$\frac{1}{\mathcal{R}_{K^*}^{(\nu/l)}[1.1,6]}\Big|_{\rm SM} \simeq \left[9.98 - 1.45 \cdot C_9^{\rm eff} + 0.42 \cdot \left(C_9^{\rm eff}\right)^2\right] \times 10^{-2}$$





Precise measurements could help us to understand the various anomalies in $b \to s\mu\mu$ data.

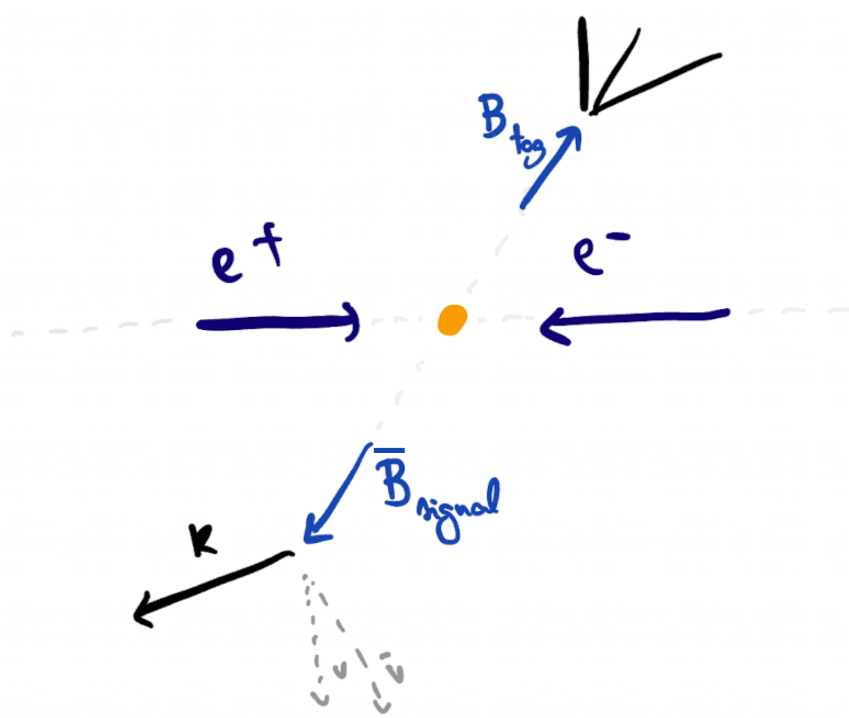
Understanding the first determination of $B \to K\nu\nu$ at Belle-II

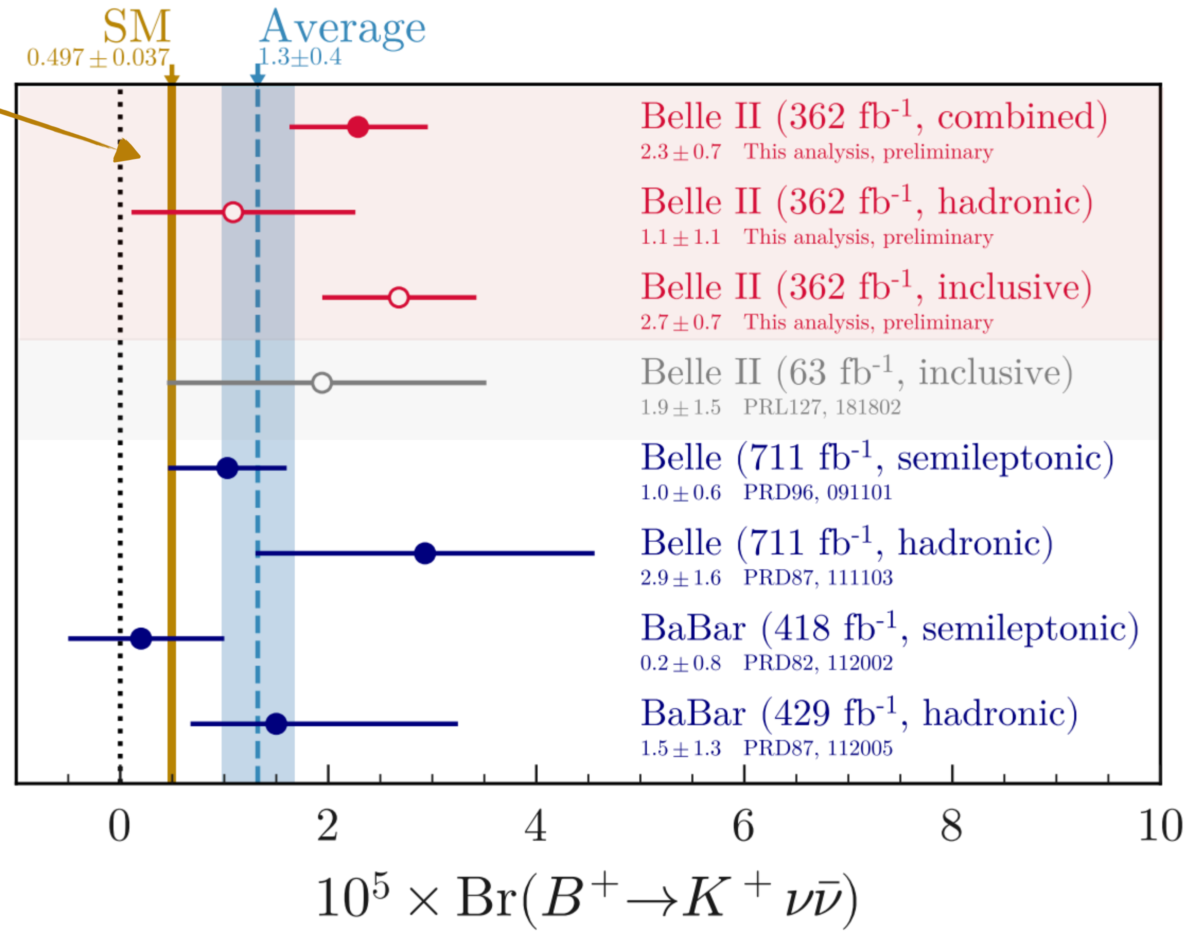
[L. Allwicher, D. Becirevic, G. Piazza, S. Rosauro-Alcaraz, **OS**, 02246]

[NEW] Belle-II results

[Belle-II, 2311.14647]

Theory uncertainty sub-dominant (thus far!)





New Belle-II results

First Belle-II result

$$\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})^{\rm exp} = \left[2.4 \pm 0.5(\mathrm{stat})^{+0.5}_{-0.4}(\mathrm{syst})\right] \times 10^{-5}$$

$\approx 3\sigma$ above the SM prediction

- Only the **incl. method** shows an **excess above background** (and w.r.t. the SM predictions).
- The **had. method** is **compatible** with the **SM** (and with no observed signal).

⇒ More data is needed! Many possible cross-checks *(e.g., $B^0 \to K_S \nu\bar{\nu}$).*

EFT for $b \to s\nu\bar{\nu}$

- Low-energy EFT:

see e.g. [Buras et al. '14]

$$\mathcal{L}_{\text{eff}}^{b\to s\nu\nu} = \frac{4G_F\lambda_t}{\sqrt{2}}\frac{\alpha_{\text{em}}}{2\pi}\sum_{ij}\Big[C_L^{\nu_i\nu_j}(\bar{s}_L\gamma_\mu b_L)(\bar{\nu}_{Li}\gamma^\mu\nu_{Lj}) + C_R^{\nu_i\nu_j}(\bar{s}_R\gamma_\mu b_R)(\bar{\nu}_{Li}\gamma^\mu\nu_{Lj})\Big] + \text{h.c.}\,,$$

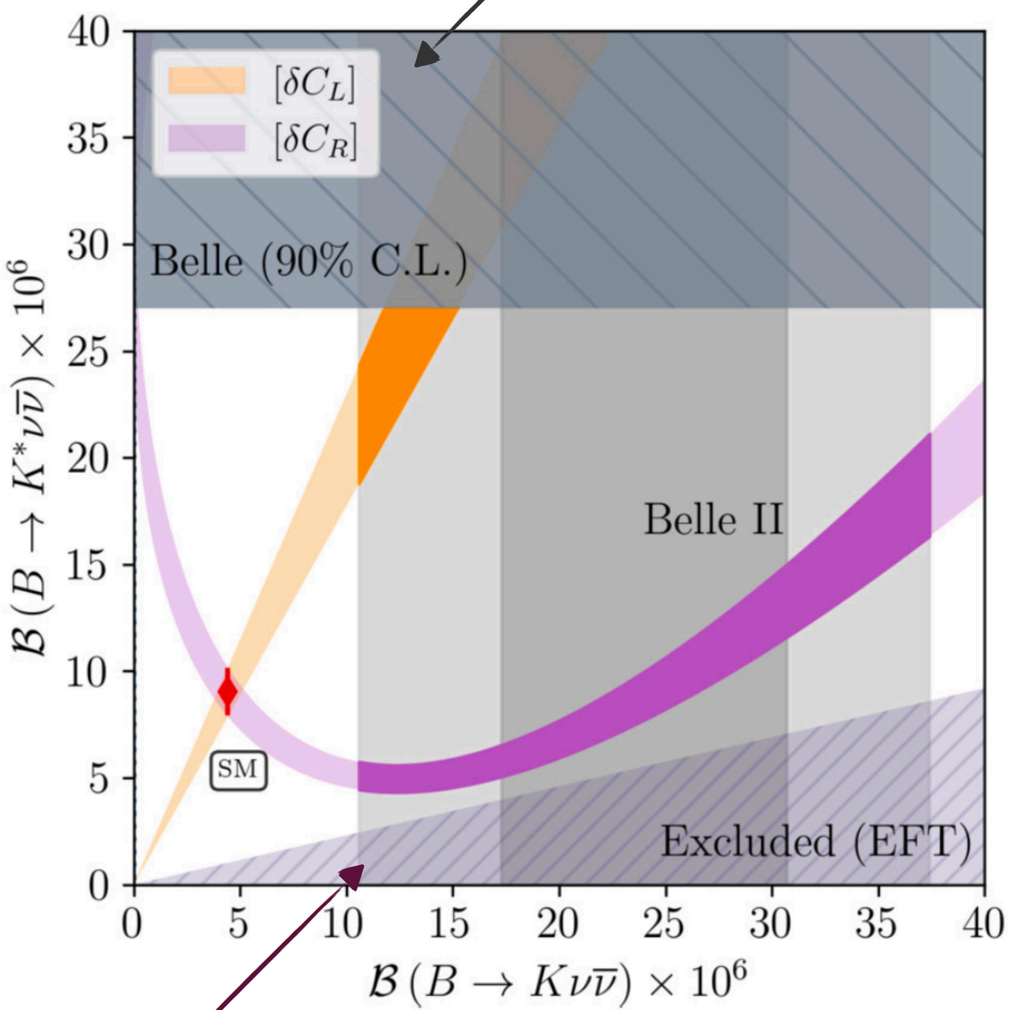
- Complementarity of $B \to K\nu\bar{\nu}$ and $B \to K^*\nu\bar{\nu}$:

$$\frac{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})^{\text{SM}}} = 1 + \sum_i \frac{2\text{Re}[C_L^{\text{SM}}(\delta C_L^{\nu_i\nu_i} + \delta C_R^{\nu_i\nu_i})]}{3|C_L^{\text{SM}}|^2} + \sum_{i,j}\frac{|\delta C_L^{\nu_i\nu_j} + \delta C_R^{\nu_i\nu_j}|^2}{3|C_L^{\text{SM}}|^2} - \eta_{K^{(*)}}\sum_{i,j}\frac{\text{Re}[\delta C_R^{\nu_i\nu_j}(C_L^{\text{SM}}\delta_{ij} + \delta C_L^{\nu_i\nu_j})]}{3|C_L^{\text{SM}}|^2}\,,$$

$\eta_K = 0$
$\eta_{K^*} = 3.5(1)$

[Becirevic, Piazza, **OS**. '22]

Exclusion from Belle/BaBar



Forbidden region in the EFT approach

[Bause et al. '23]

[Allwicher et al (**OS**). '23]

Predictions

[Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

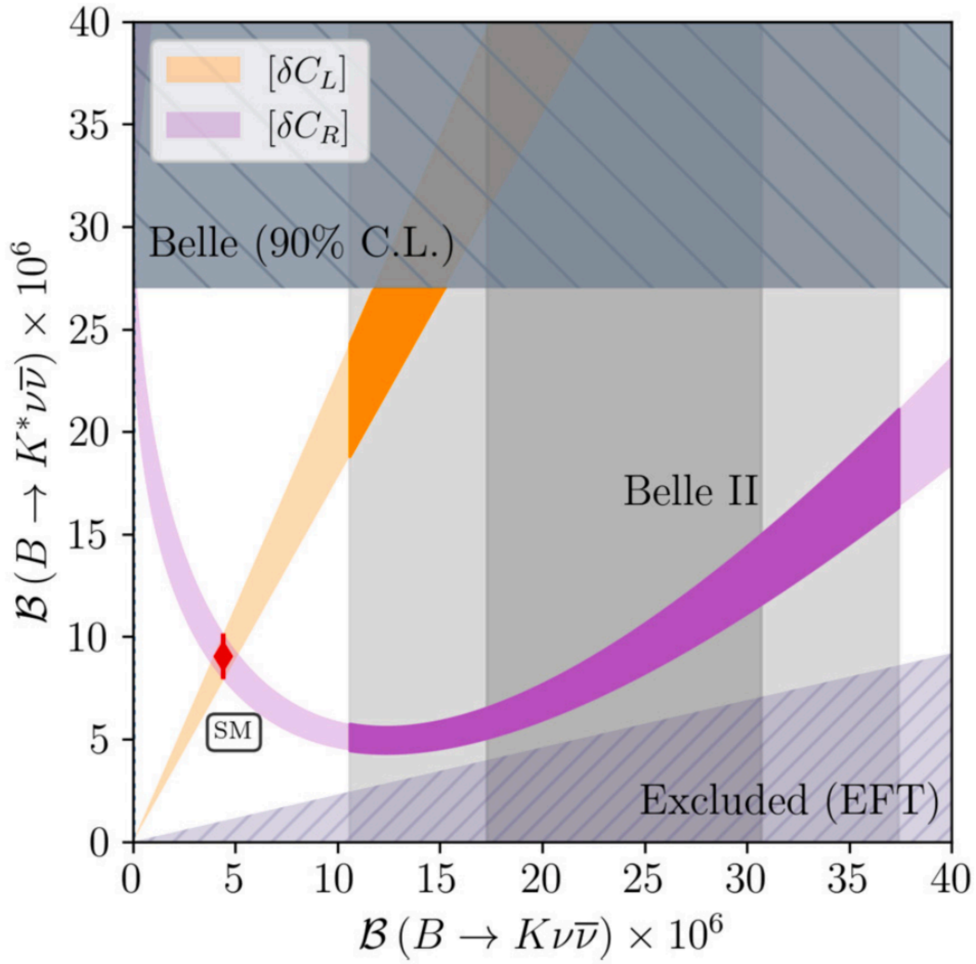
- Another observable to measure is the K^* longitudinal-polarisation asymmetry:

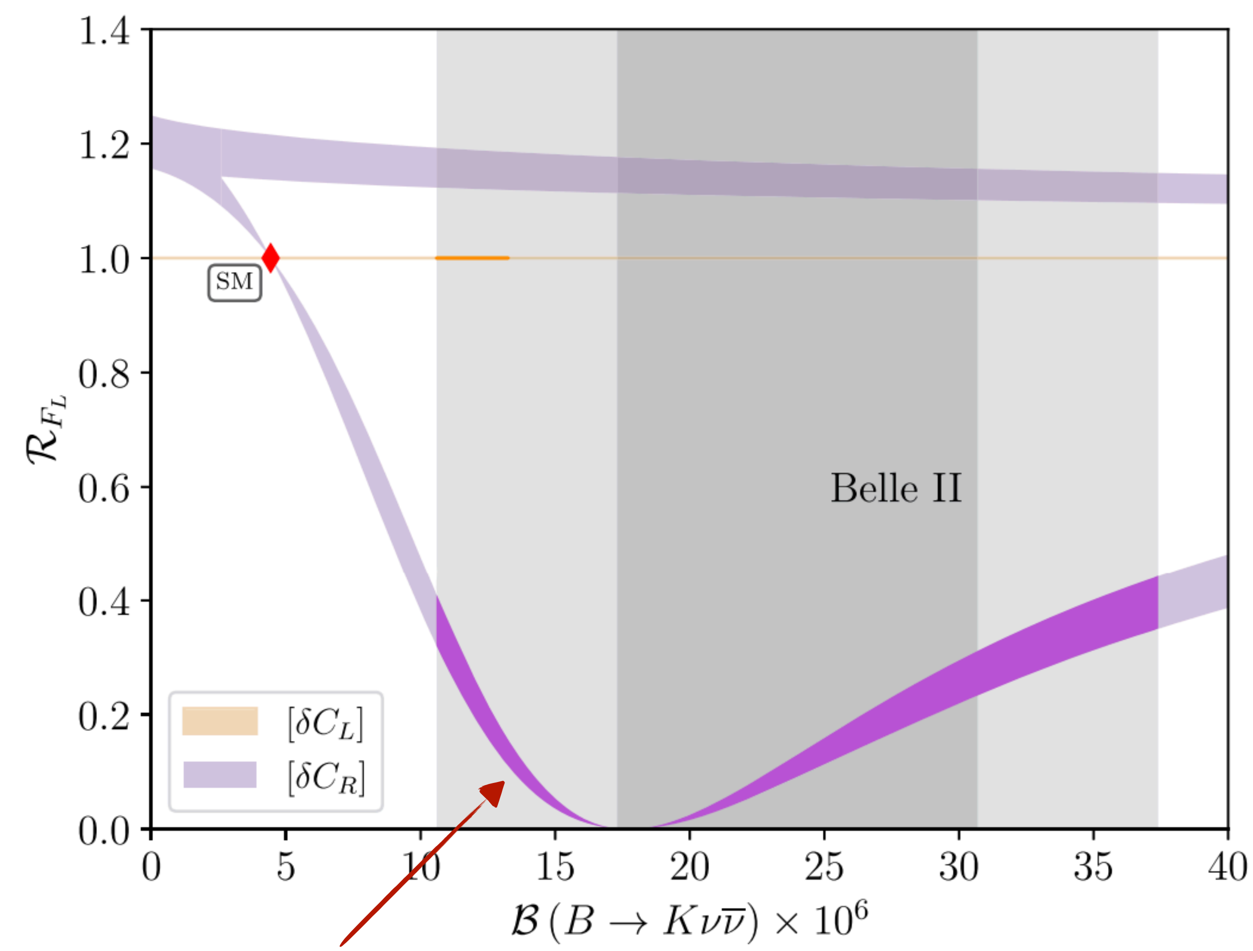
$$F_L \equiv \frac{\Gamma_L(B \to K^* \nu\bar{\nu})}{\Gamma(B \to K^* \nu\bar{\nu})}$$

$$F_L(B \to K^* \nu\bar{\nu})^{\mathrm{SM}} = 0.49(7)$$

$$\mathcal{R}_{F_L} \equiv \frac{F_L}{F_L^{\mathrm{SM}}}$$

[Altmannshofer et al. '09]





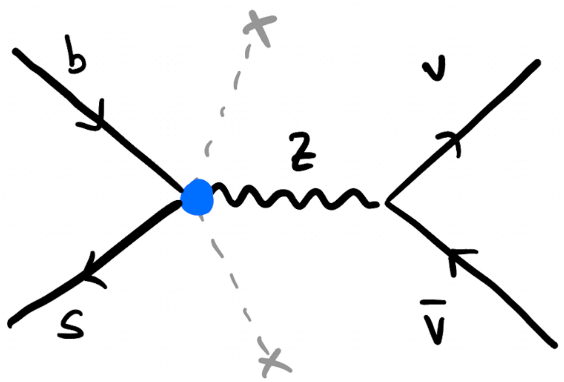
Depletion of SM prediction!

The measurement of $\mathcal{B}(B \to K^* \nu\bar{\nu})$ and $F_L(B \to K^* \nu\bar{\nu})$ would be **model-independent tests** of Belle-II results.

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

- **SMEFT** is formulated for $\Lambda \gg v_{\rm ew}$ with $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant operators.
- Gauge invariance **correlates** $b \to s\nu\bar{\nu}$ with $b \to s\ell\ell$ since $L_i = (\nu_{Li}, \ell_{Li})^T$.
- Two types of $d = 6$ **contributions** at tree-level: [Buchmuller & Wyler. '85, Gradkowski et al. '10]

i) $\psi^2 H^2 D$:

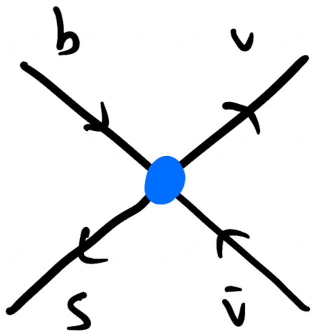


e.g.,

$$\mathcal{O}_{Hl}^{(1)} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$$

Lepton flavor universal!

ii) ψ^4 :



e.g.,

$$\mathcal{O}_{ld} = (\bar{L}\gamma^\mu L)(\bar{d}_R\gamma_\mu d_R)$$

[Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

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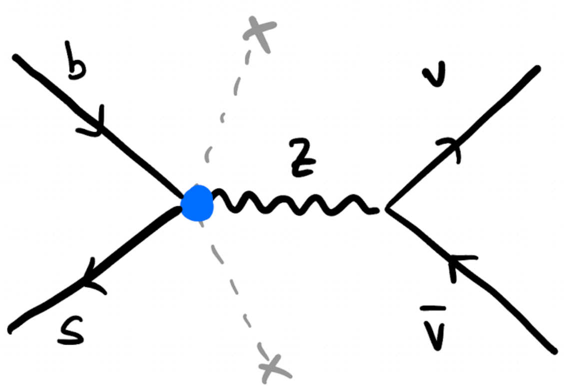
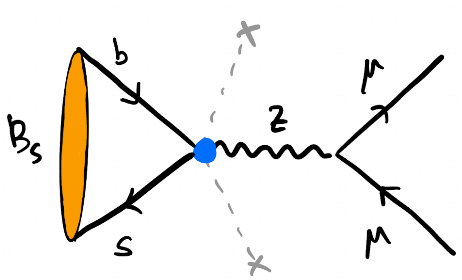


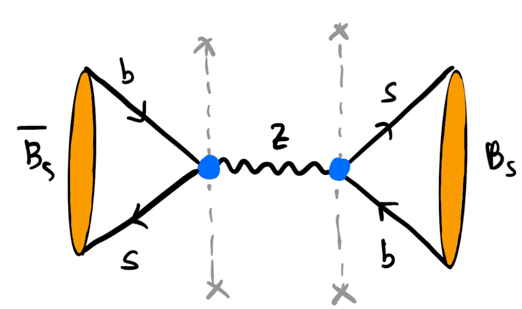
e.g.,

$\mathcal{O}_{Hl}^{(1)} = (H^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}\gamma^\mu L)$

Lepton flavor universal!

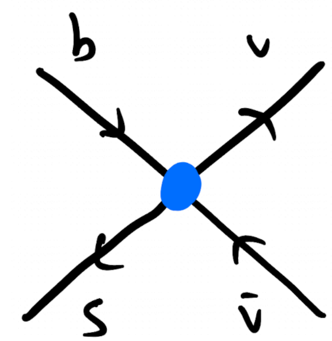
⇒ Severely constrained by $\mathcal{B}(B_s \to \mu\mu)$ and Δm_{B_s} :





✗

ii) ψ^4 :



e.g.,

$\mathcal{O}_{ld} = (\bar{L}\gamma^\mu L)(\bar{d}_R \gamma_\mu d_R)$

⇒ Only viable option!

✓

[Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

- ψ^4 operators invariant under $SU(2)\times U(1)_Y$:

$b \to s\ell\ell$ | $b \to s\nu\bar{\nu}$

$$\big[\mathcal{O}_{lq}^{(1)}\big]_{ijkl} = \big(\overline{L}_i\gamma^\mu L_j\big)\big(\overline{Q}_k\gamma_\mu Q_l\big)$$
$$\big[\mathcal{O}_{lq}^{(3)}\big]_{ijkl} = \big(\overline{L}_i\gamma^\mu \tau^I L_j\big)\big(\overline{Q}_k\tau^I\gamma_\mu Q_l\big)$$
$$\big[\mathcal{O}_{ld}\big]_{ijkl} = \big(\overline{L}_i\gamma^\mu L_j\big)\big(\overline{d}_k\gamma_\mu d_l\big)$$
$$\big[\mathcal{O}_{eq}\big]_{ijkl} = \big(\overline{e}_i\gamma^\mu e_j\big)\big(\overline{Q}_k\gamma_\mu Q_l\big)$$
$$\big[\mathcal{O}_{ed}\big]_{ijkl} = \big(\overline{e}_i\gamma^\mu e_j\big)\big(\overline{d}_k\gamma_\mu d_l\big)$$

$$\big[\mathcal{O}_{lq}^{(1)}\big]_{ijkl} = \big(\overline{L}_i\gamma^\mu L_j\big)\big(\overline{Q}_k\gamma_\mu Q_l\big) = \big(\overline{\ell}_{Li}\gamma^\mu \ell_{Lj}\big)\big(\overline{d}_{Lk}\gamma_\mu d_{Ll}\big) + \big(\overline{\nu}_{Li}\gamma^\mu \nu_{Lj}\big)\big(\overline{d}_{Lk}\gamma_\mu d_{Ll}\big) + \dots$$

$$\big[\mathcal{O}_{lq}^{(3)}\big]_{ijkl} = \big(\overline{L}_i\gamma^\mu \tau^I L_j\big)\big(\overline{Q}_k\gamma_\mu \tau^I Q_l\big) = \big(\overline{\ell}_{Li}\gamma^\mu \ell_{Lj}\big)\big(\overline{d}_{Lk}\gamma_\mu d_{Ll}\big) - \big(\overline{\nu}_{Li}\gamma^\mu \nu_{Lj}\big)\big(\overline{d}_{Lk}\gamma_\mu d_{Ll}\big) + \dots$$

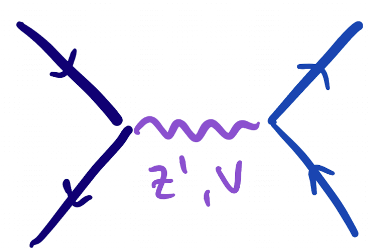
$$\big[\mathcal{O}_{ld}\big]_{ijkl} = \big(\overline{L}_i\gamma^\mu L_j\big)\big(\overline{d}_k\gamma_\mu d_l\big) = \big(\overline{\ell}_{Li}\gamma^\mu \ell_{Lj}\big)\big(\overline{d}_{Rk}\gamma_\mu d_{Rl}\big) + \big(\overline{\nu}_{Li}\gamma^\mu \nu_{Lj}\big)\big(\overline{d}_{Rk}\gamma_\mu d_{Rl}\big)$$

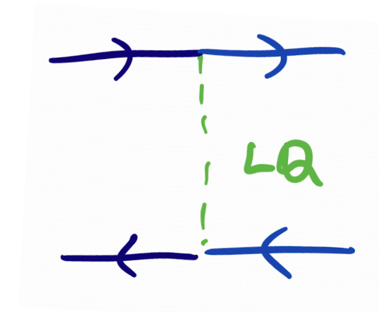
- Correlations for concrete mediators:

  - $Z' \sim (\mathbf{1},\mathbf{1},0)$: $\mathcal{C}_{lq}^{(1)} \neq 0\,, \quad \mathcal{C}_{lq}^{(3)} = 0$
  - $V \sim (\mathbf{1},\ \mathbf{3},\ 0)$: $\mathcal{C}_{lq}^{(1)} = 0\,, \quad \mathcal{C}_{lq}^{(3)} \neq 0$
  - $U_1 \sim (\mathbf{3},\mathbf{1},2/3)$: $\mathcal{C}_{lq}^{(1)} = \mathcal{C}_{lq}^{(3)}$
  - $S_3 \sim (\bar{\mathbf{3}},\mathbf{3},1/3)$: $\mathcal{C}_{lq}^{(1)} = 3\,\mathcal{C}_{lq}^{(3)}$

  ...

$(SU(3)_c,\ SU(2)_L,\ U(1)_Y)$





$$\frac{\mathcal{C}}{\Lambda^2} \simeq (5\ \mathrm{TeV})^{-2}$$

SMEFT for $b \to s\nu\nu$ (and $b \to s\ell\ell$)

- ψ^4 operators invariant under $SU(2) \times U(1)_Y$:

$b \to s\ell\ell$ $\quad$ $b \to s\nu\bar{\nu}$

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i \gamma^\mu L_j)(\overline{Q}_k \gamma_\mu Q_l)$$
$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i \gamma^\mu \tau^I L_j)(\overline{Q}_k \tau^I \gamma_\mu Q_l)$$
$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i \gamma^\mu L_j)(\overline{d}_k \gamma_\mu d_l)$$
$$[\mathcal{O}_{eq}]_{ijkl} = (\overline{e}_i \gamma^\mu e_j)(\overline{Q}_k \gamma_\mu Q_l)$$
$$[\mathcal{O}_{ed}]_{ijkl} = (\overline{e}_i \gamma^\mu e_j)(\overline{d}_k \gamma_\mu d_l)$$

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i \gamma^\mu L_j)(\overline{Q}_k \gamma_\mu Q_l) = (\overline{\ell}_{Li} \gamma^\mu \ell_{Lj})(\overline{d}_{Lk} \gamma_\mu d_{Ll}) + (\overline{\nu}_{Li} \gamma^\mu \nu_{Lj})(\overline{d}_{Lk} \gamma_\mu d_{Ll}) + \dots$$

$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i \gamma^\mu \tau^I L_j)(\overline{Q}_k \gamma_\mu \tau^I Q_l) = (\overline{\ell}_{Li} \gamma^\mu \ell_{Lj})(\overline{d}_{Lk} \gamma_\mu d_{Ll}) - (\overline{\nu}_{Li} \gamma^\mu \nu_{Lj})(\overline{d}_{Lk} \gamma_\mu d_{Ll}) + \dots$$

$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i \gamma^\mu L_j)(\overline{d}_k \gamma_\mu d_l) = (\overline{\ell}_{Li} \gamma^\mu \ell_{Lj})(\overline{d}_{Rk} \gamma_\mu d_{Rl}) + (\overline{\nu}_{Li} \gamma^\mu \nu_{Lj})(\overline{d}_{Rk} \gamma_\mu d_{Rl})$$

Which flavor?

[Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

I) *Couplings to muons* are *tightly constrained* by $\mathcal{B}(B_s \to \mu\mu)$. ✗

II) *LFV couplings* are *constrained* by searches for $\mathcal{B}(B_s \to \ell_i \ell_j)$ and $\mathcal{B}(B \to K^{(*)} \ell_i \ell_j)$. ✗

III) The **only viable option** is coupling to τ's *(due to weak exp. limits on* $b \to s\tau\tau$*)*. ✓

⇒ **Predictions:**

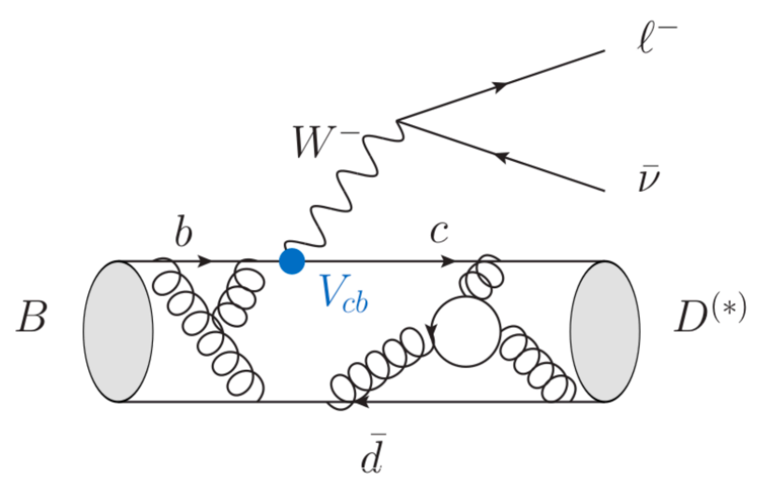
$$\frac{\mathcal{B}(B_s \to \tau\tau)}{\mathcal{B}(B_s \to \tau\tau)^{\rm SM}} \simeq \frac{\mathcal{B}(B \to K^{(*)}\tau\tau)}{\mathcal{B}(B \to K^{(*)}\tau\tau)^{\rm SM}} \simeq 10$$

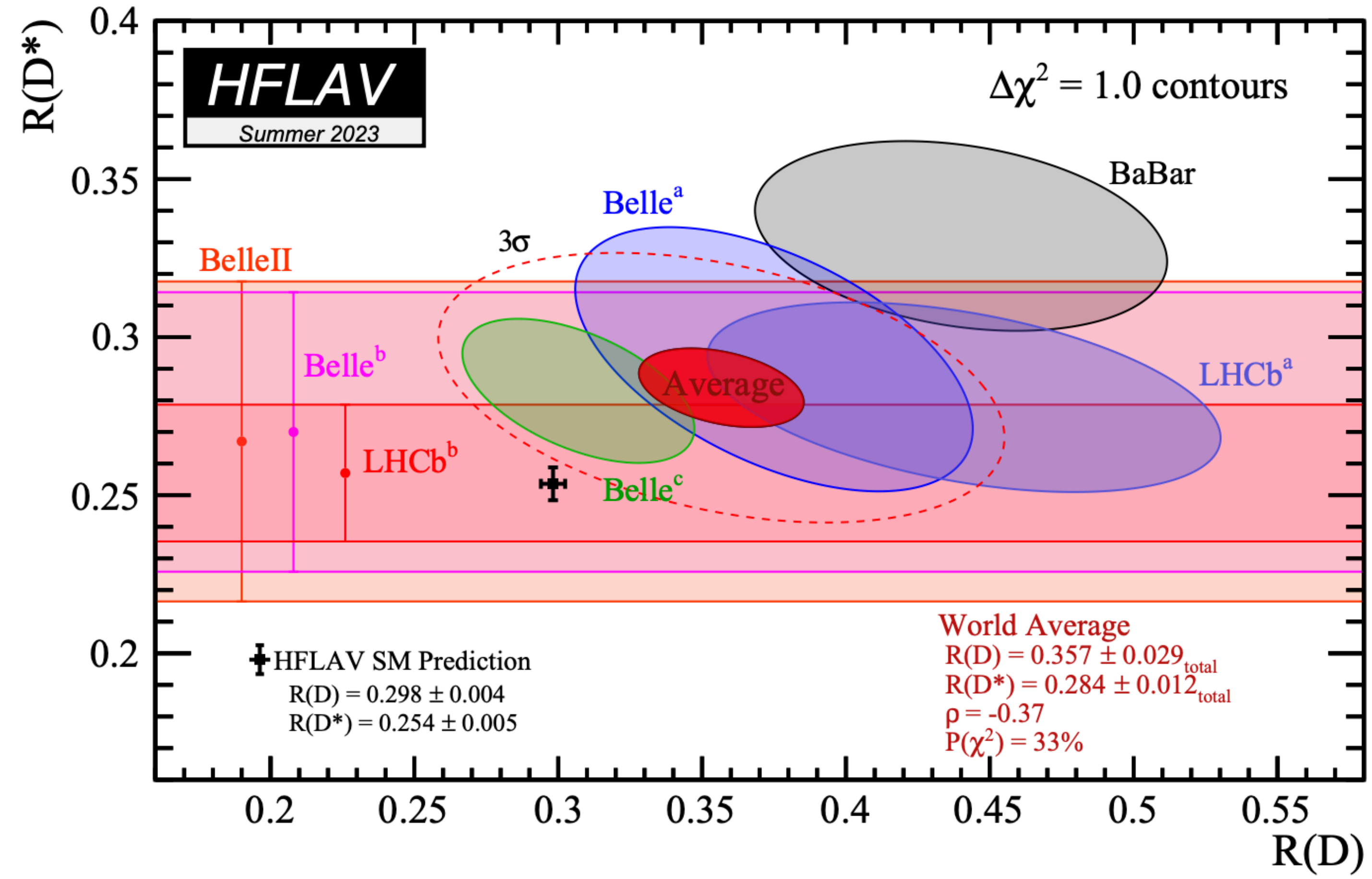
However, **experimentally challenging**...

R_D and R_{D^*}

LFU in $b \to c\tau\bar{\nu}$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\mu\nu)}$$





- R_D^{exp} and $R_{D^*}^{\mathrm{exp}}$: **dominated by BaBar!**
- LHCb also measured $R_{J/\psi}^{\mathrm{exp}}$ and $R_{\Lambda_c}^{\mathrm{exp}}$, but with limited precision.
- SM predictions are under reasonable control (cf. back-up).

Needs urgent clarification from **Belle-II** and **LHCb (run-2)** data!

EFT for $b \to c\tau\bar{\nu}$

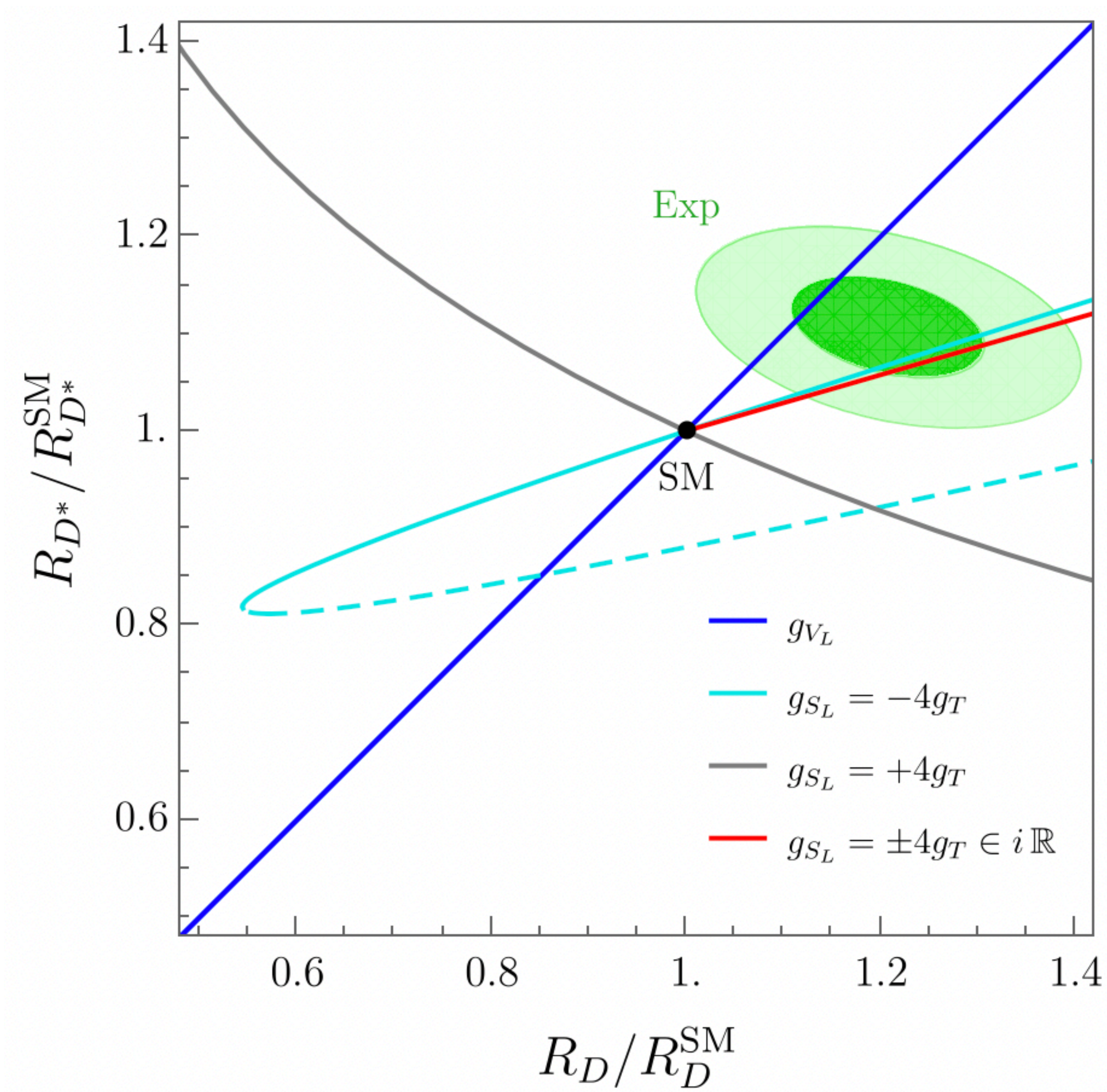
see e.g. [Angelescu, Becirevic, Faroughy, Jaffredo, **OS**, '21]

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

- $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance implies that only g_{V_L}, g_{S_L}, g_{S_R} and g_T can break LFU at $d=6$.

- Few scenarios can accommodate data:
  - $U_1 \sim (\mathbf{3},\mathbf{1},2/3)$: g_{V_L} , g_{S_R}
  - $R_2 \sim (\mathbf{3},\mathbf{2},7/6)$: $g_{S_L} = 4g_T$
  - $S_1 \sim (\bar{\mathbf{3}},\mathbf{1},1/3)$: $g_{S_L} = -4g_T$, g_{V_L}

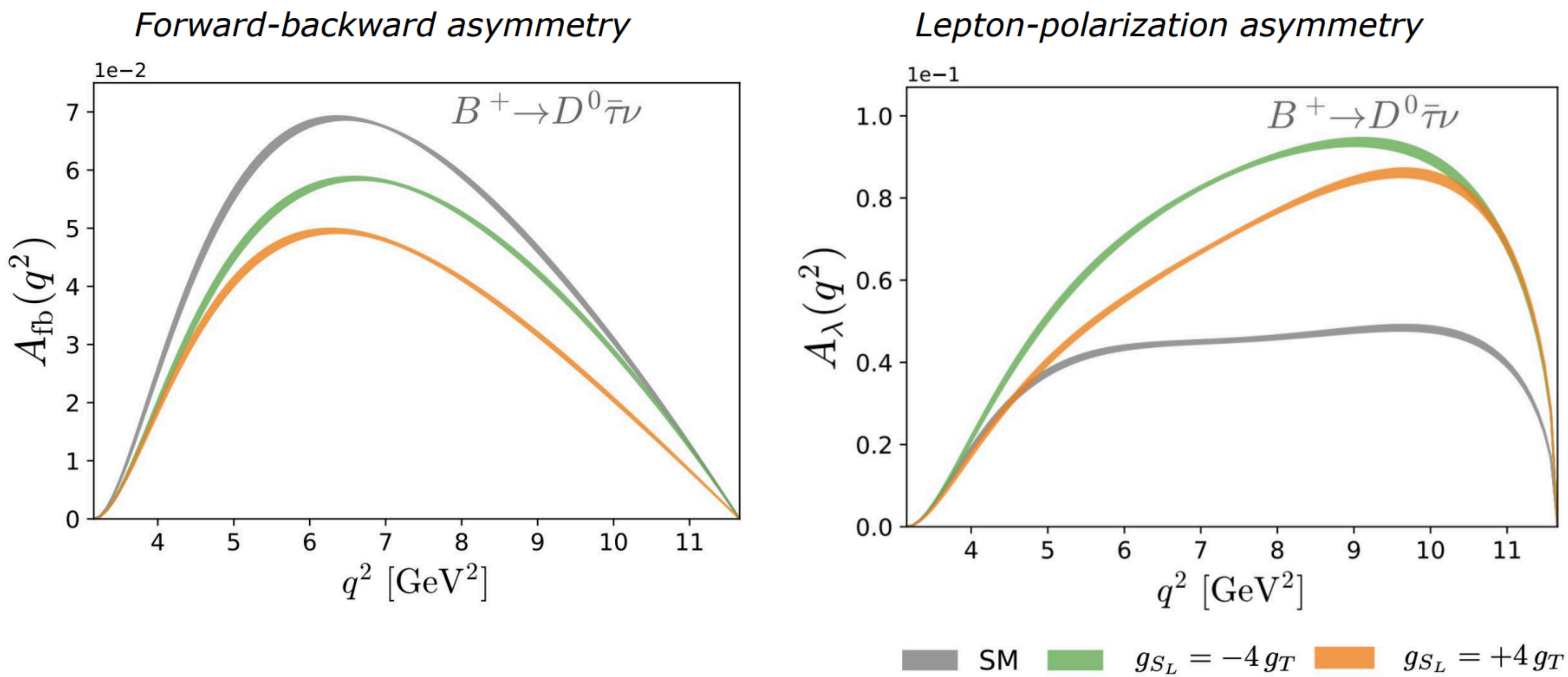
Only scalar/vector **leptoquarks** can **do the job**!



Angular observables: $b \to c\tau\bar{\nu}$

Example: $B \to D\tau\nu$

see e.g. [Becirevic, Jaffredo, Penuelas, **OS**, '21]



- Many more opportunities in other modes:

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

[1602.03030, 1907.02257, 2104.02094...]

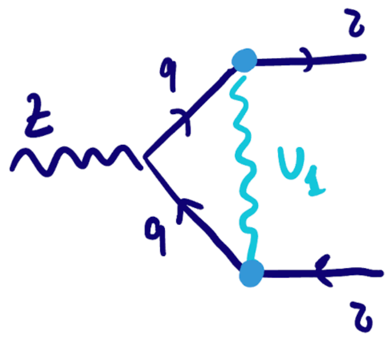
$$\Lambda_b \to \Lambda_c(\to \Lambda\pi)\tau\bar{\nu}$$

[1907.12554, 2209.13409]

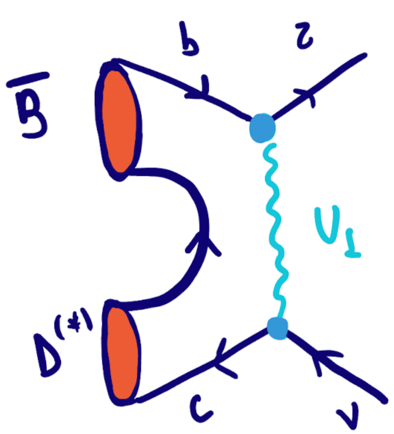
Example: $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

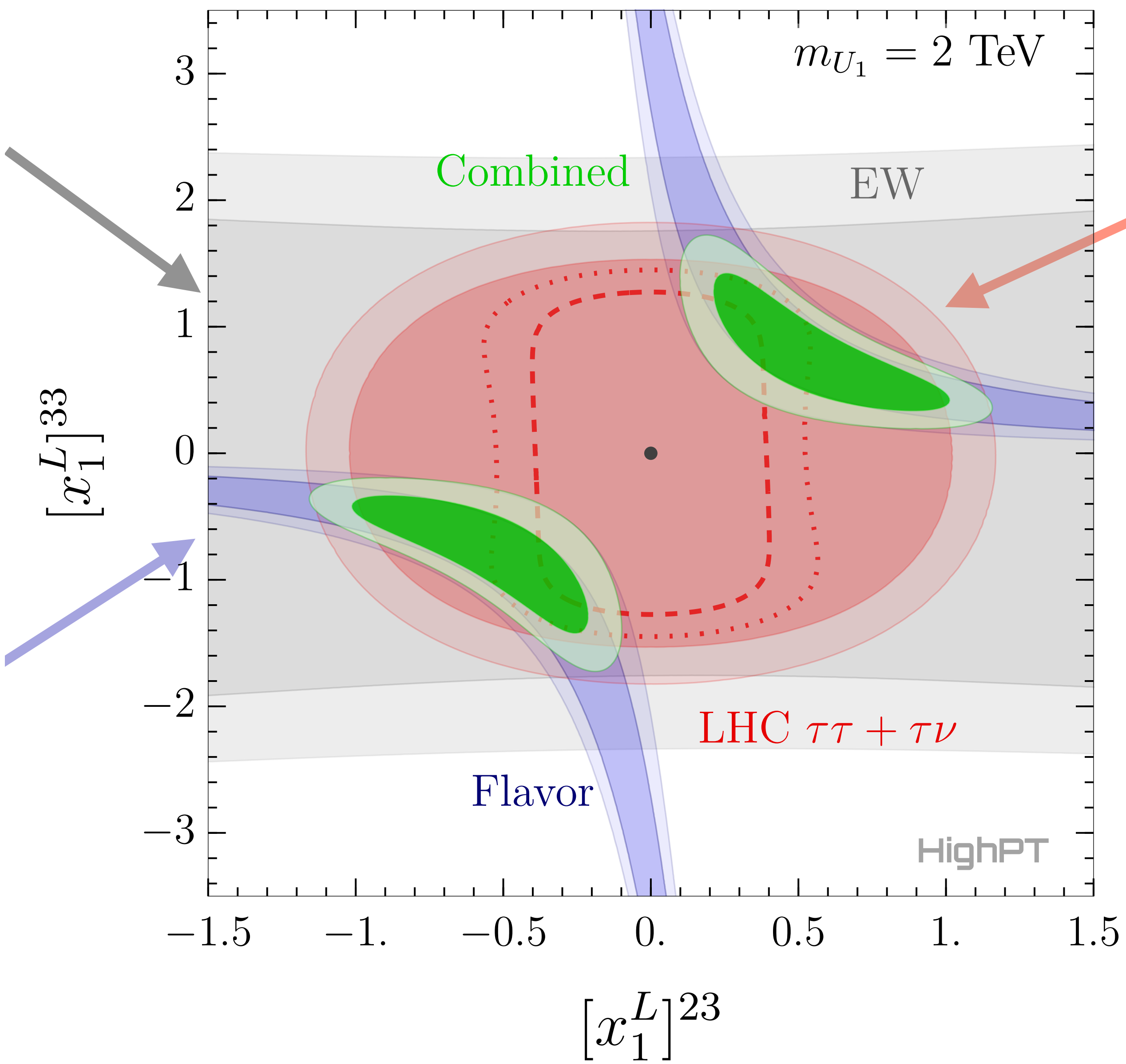
[L. Allwicher, D. Faroughy, F. Jaffredo, **OS**, F. Wilsch. '22]

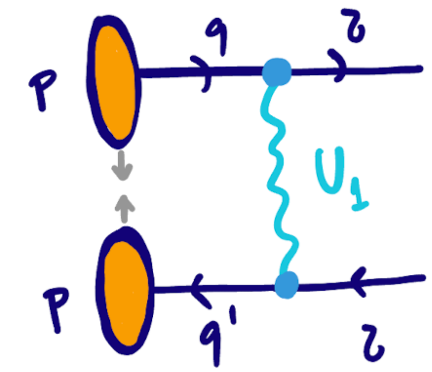
$$\mathcal{L}_{U_1} \supset [x_1^L]_{i\alpha}\, U_1^\mu\, \bar{q}_i \gamma_\mu l_\alpha + \text{h.c.}$$



[Feruglio et al. '16]





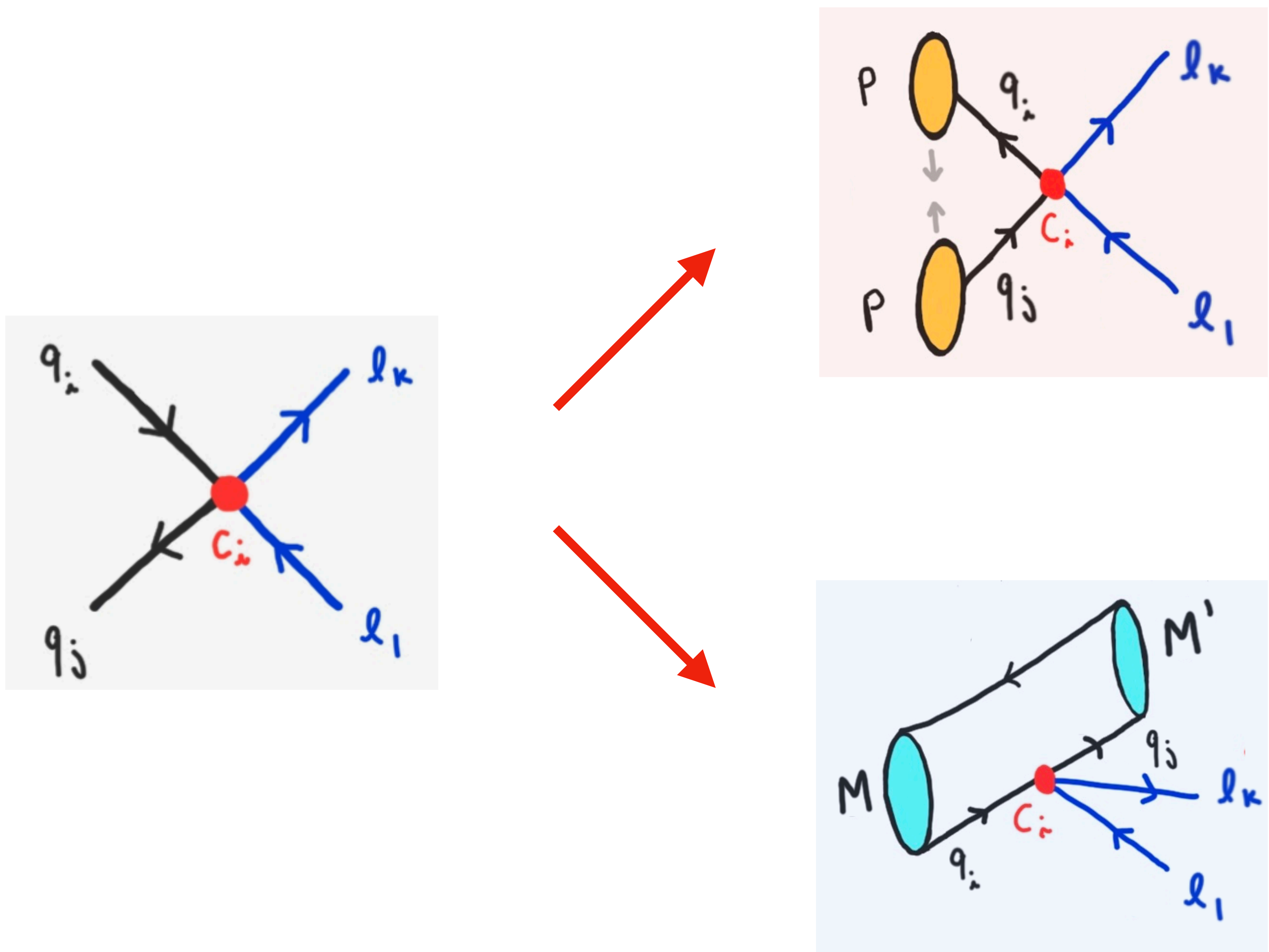


First considered by [Eboli, '88]

cf. also [Faroughy et al. '15]

Complementarity between **LHC data**, **flavor** and **EWPT**

*see back-up for the other models!



$pp \to \ell_k \ell_l$

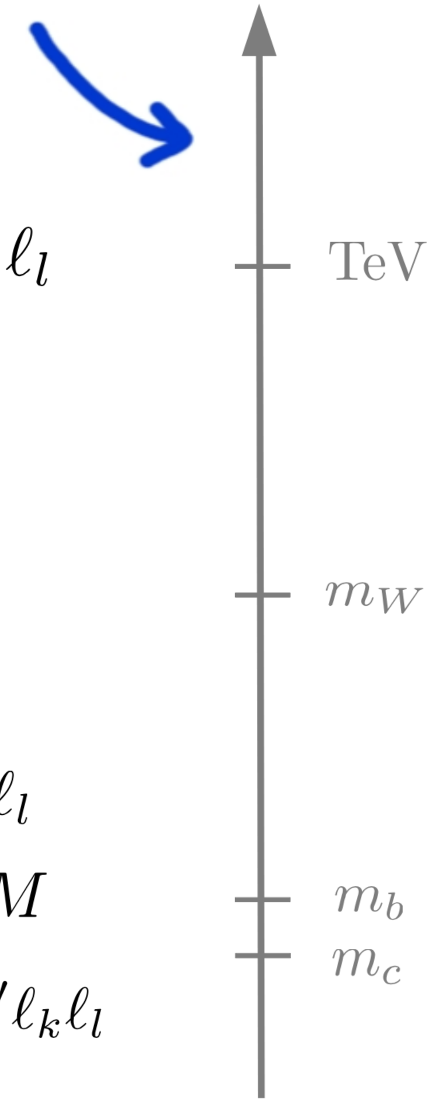
$M \to \ell_k \ell_l$

$\ell_k \to \ell_l M$

$M \to M' \ell_k \ell_l$

...

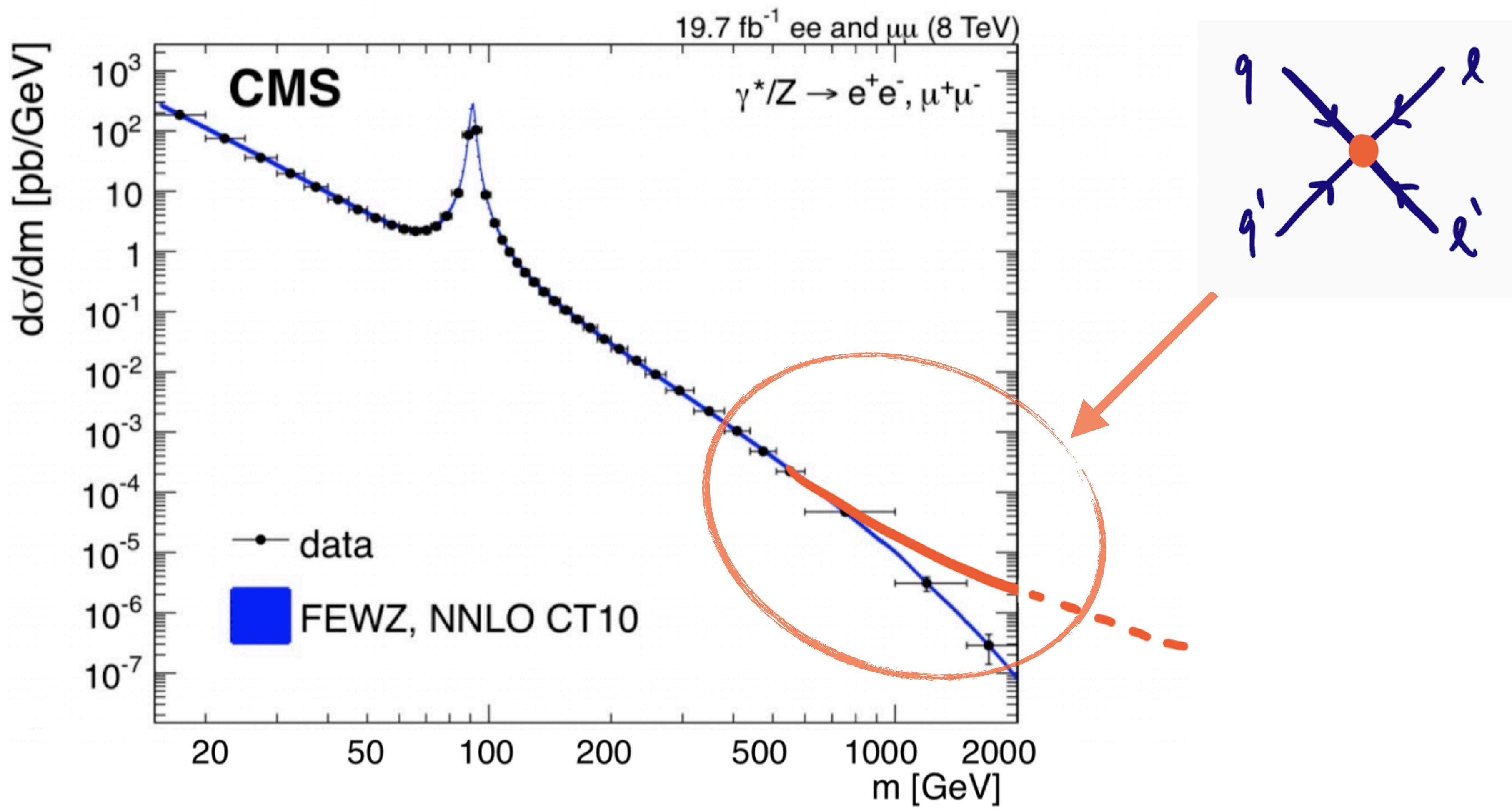
Flavorful New Physics?



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

Many works on EFTs and Drell-Yan: Cirigliano et al. '12, '18], [de Blas et al. '13], [Farina et al. '16], [Dawson et al. '18, '21], [Greljo et al. '18], [Shepherd et al. '18], [Fuentes-Martín et al. '20], [Marzocca et al. '20], [Endo et al. '21], [Boughezal et al. '21], [Angelescu et al. '20], [Allwicher et al. '23]...

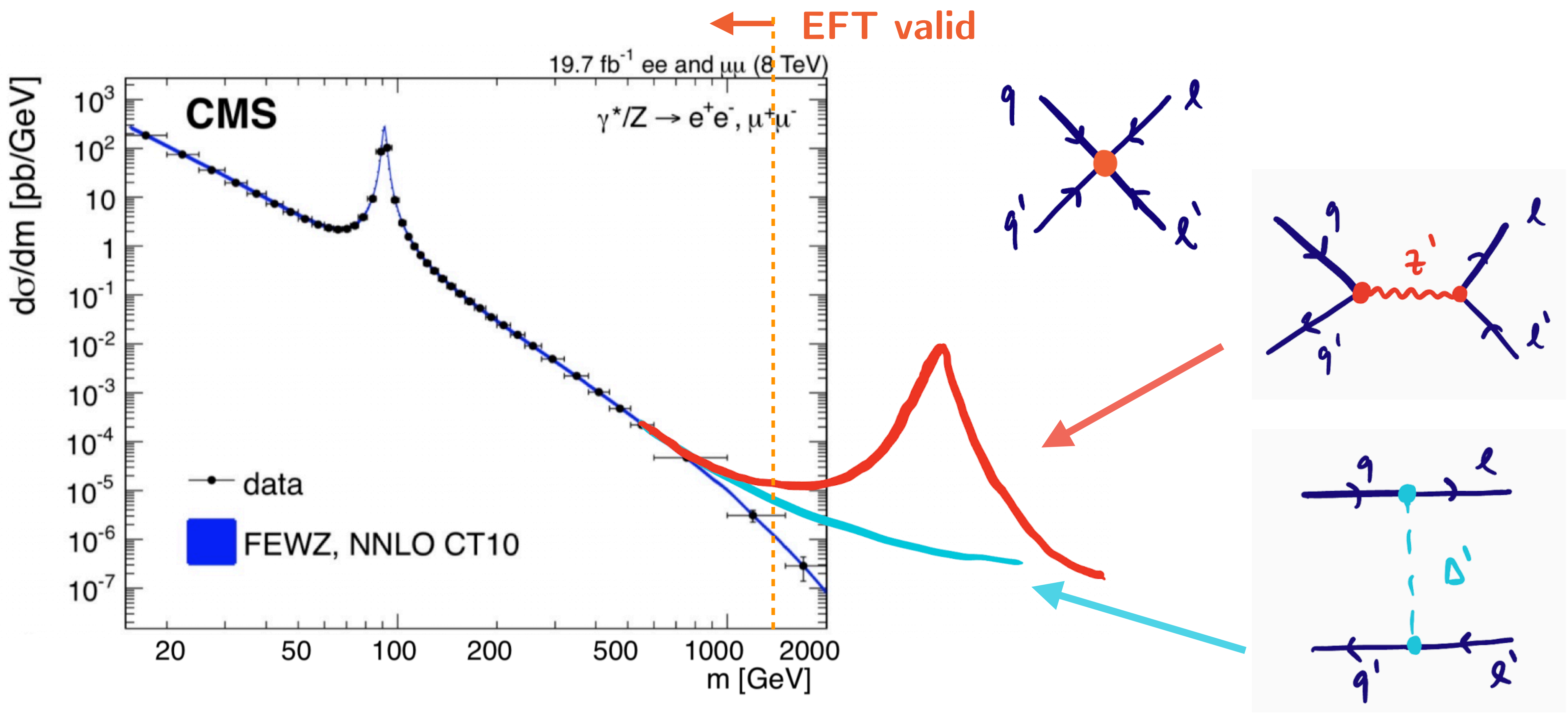
[Intermezzo] Probing flavor at the LHC



Goal: **Probe flavor transitions** that are **poorly constrained** at **low energies** (e.g., $b \to s\tau\tau$)

Strategy: Recast **di-lepton searches** and look for **NP effects** in the **tails** of the **invariant-mass** distributions (where S/B is large).

[Intermezzo] Probing flavor at the LHC



Goal: Probe flavor transitions that are **poorly constrained** at **low energies** (e.g., $b \to s\tau\tau$)

Strategy: Recast **di-lepton searches** and look for **NP effects** in the **tails** of the **invariant-mass** distributions (where S/B is large).

Caveat: EFT must be valid ($E \ll \Lambda$). Otherwise, use explicit model (e.g., leptoquark or Z').

HighPT: A Tool for high-p_T Drell-Yan Tails Beyond the SM

```
In[5]:= << HighPT`
```

HighPT

Authors: Lukas Allwicher, Darius A. Faroughy, Florentin Jaffredo, Olcyr Sumensari, and Felix Wilsch

References: arXiv:2207.10756, arXiv:2207.10714

Website: https://highpt.github.io

HighPT is free software released under the terms of the MIT License.

Version: 1.0.2

Reinterpretation of latest **LHC Drell-Yan** searches for **New Physics** scenarios with **general flavor structure**.

Recast procedure:

MadGraph 5 + Pythia + Delphes

Searches available ($140\ \mathrm{fb}^{-1}$):

$pp \to \tau\tau$	[arXiv:2002.12223]
$pp \to ee,\ \mu\mu$	CMS-PAS-EXO-19-019
$pp \to \tau\nu$	ATLAS-CONF-2021-025
$pp \to e\nu,\ \mu\nu$	[arXiv:1906.05609]
$pp \to e\mu,\ e\tau,\ \mu\tau$	[arXiv:2205.06709]

*more to be included (see GitHub page)

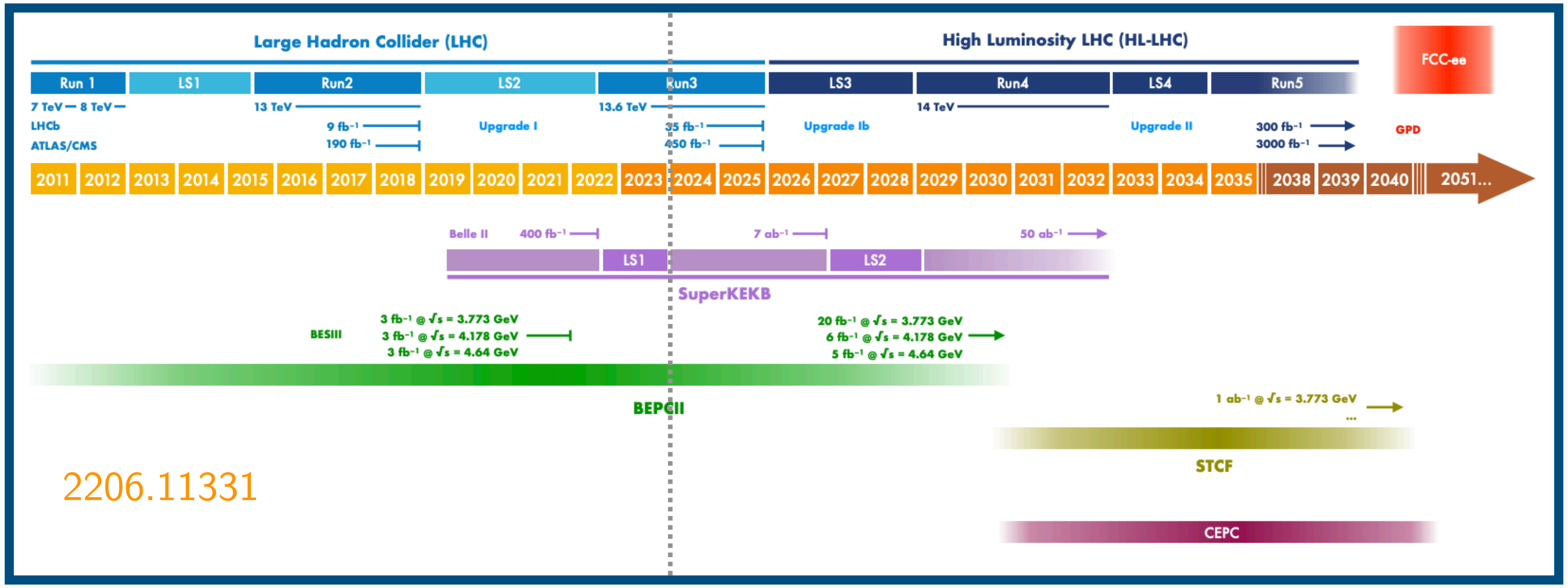
Main functionalities:

- Consider **SMEFT** ($d \leq 8$) and **specific mediators** (LQs, Z', ...).
- Computes **cross-sections**, **event yields** and **likelihoods** as a function of NP couplings.
- **SMEFT likelihoods** can be exported in the *WCxf* format.

[Aebischer et al. '17]

Outlook

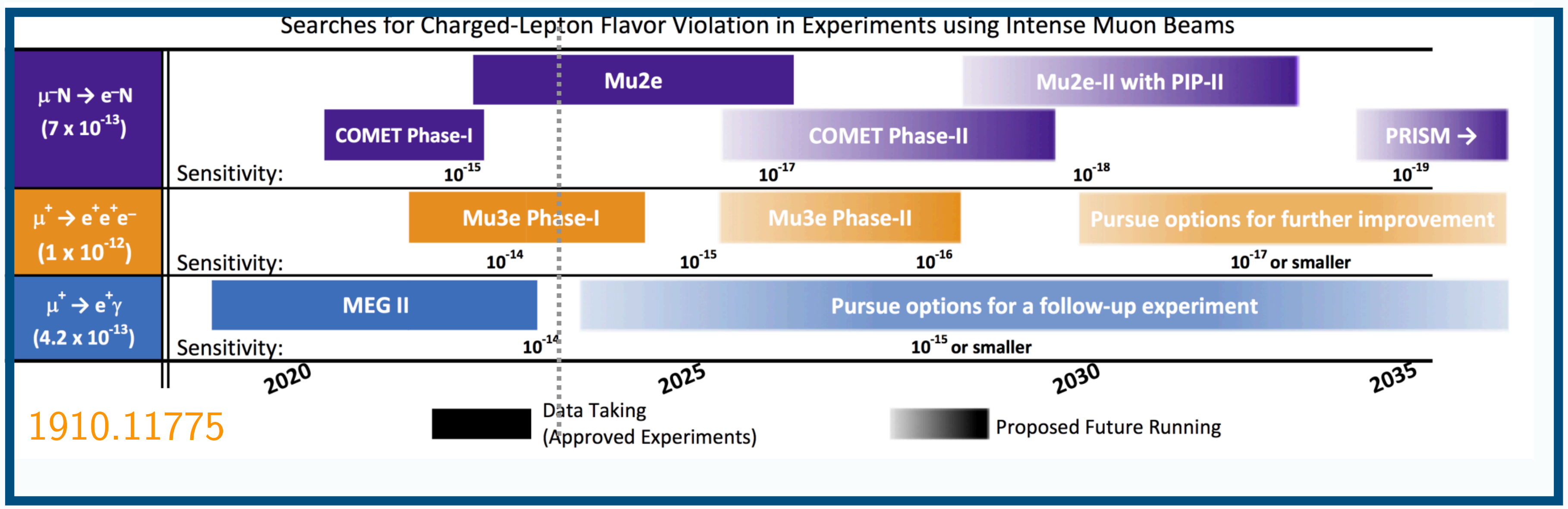
Outlook



LHCb

Belle-II

BES-III

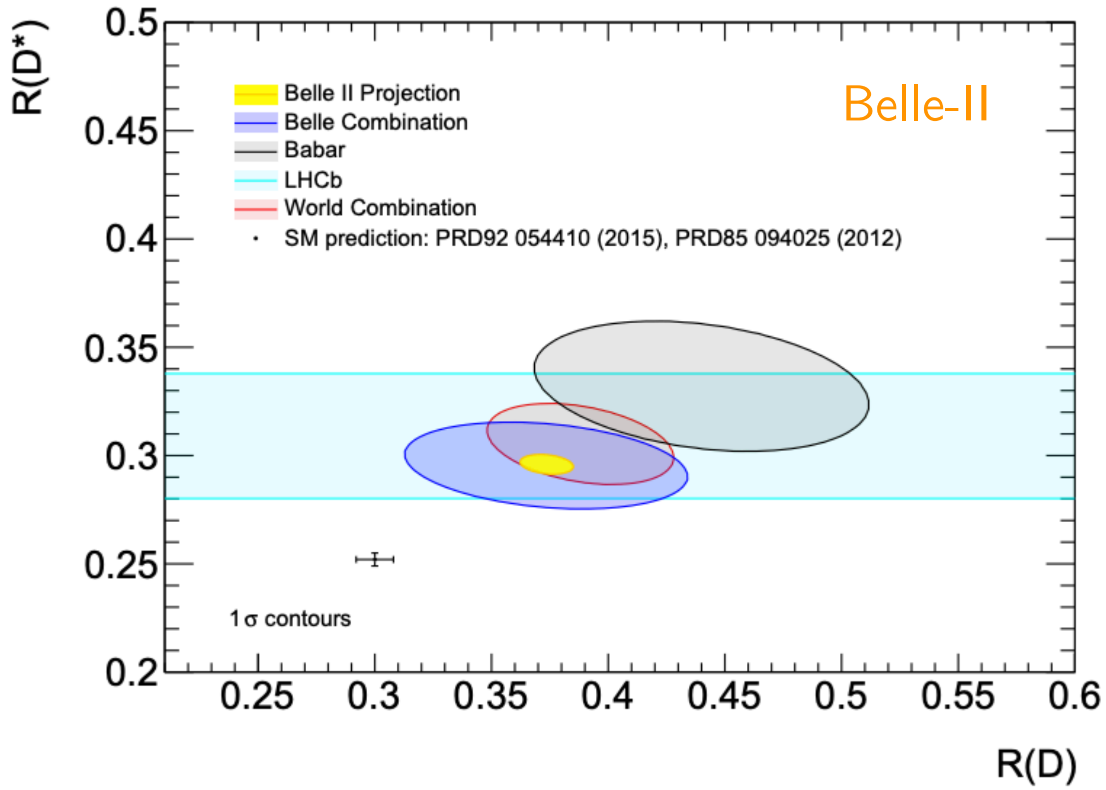


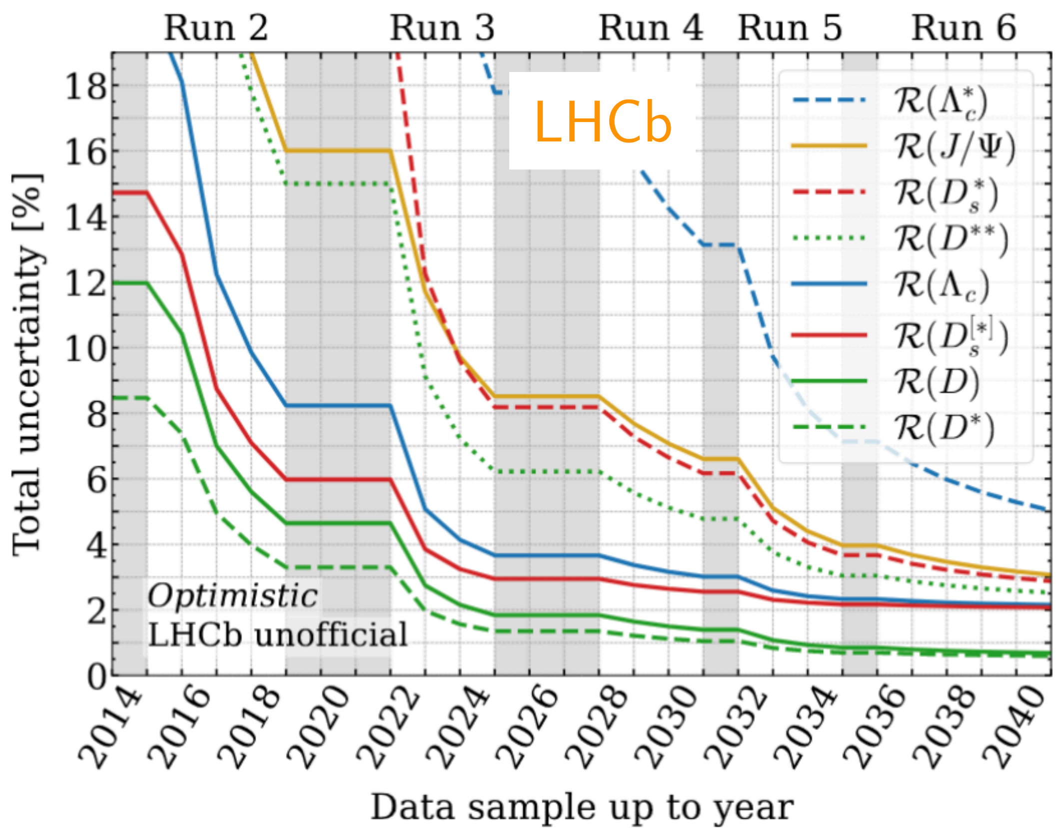
LFV

- + Kaon physics (NA62 and KOTO)
- + EDM experiments & Muon g-2 at Fermilab
- + Huge effort in the neutrino sector
- + ...

B-**physics**: Belle-II and LHCb

Improved data will have the potential **to resolve persisting anomalies** such $R_{D^{(*)}}$:





[Rev. Mod. Phys. 94, 015003 (2022)]

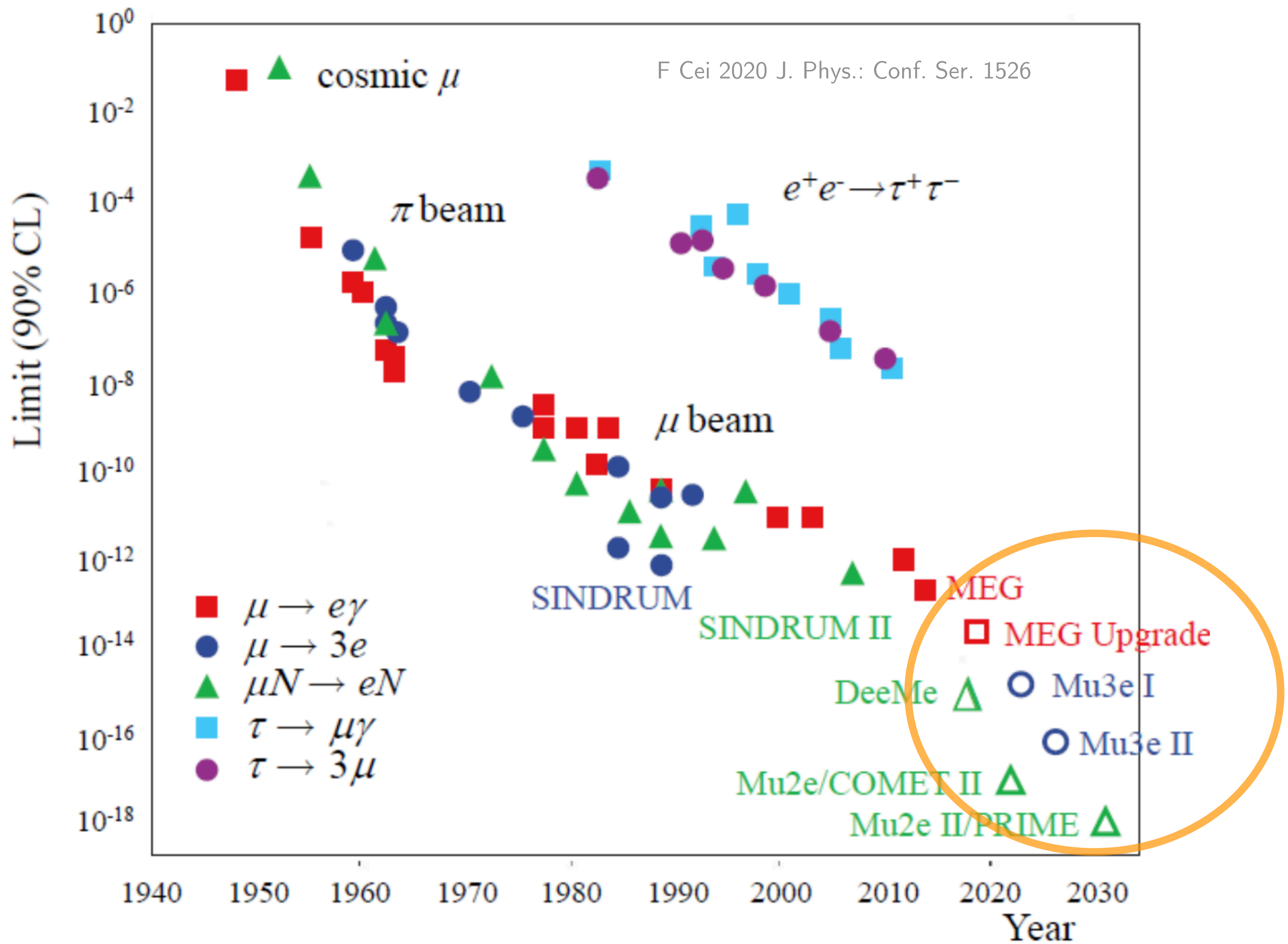
⇒ They will also provide **valuable inputs** to **determine** better V_{ub} and V_{cb} :

Observables	Belle (2017)	Belle II 5 ab^{-1}	Belle II 50 ab^{-1}
$\lvert V_{cb}\rvert$ incl.	$42.2 \cdot 10^{-3} \cdot (1 \pm 1.8\%)$	1.2%	–
$\lvert V_{cb}\rvert$ excl.	$39.0 \cdot 10^{-3} \cdot (1 \pm 3.0\%_{\rm ex.} \pm 1.4\%_{\rm th.})$	1.8%	1.4%
$\lvert V_{ub}\rvert$ incl.	$4.47 \cdot 10^{-3} \cdot (1 \pm 6.0\%_{\rm ex.} \pm 2.5\%_{\rm th.})$	3.4%	3.0%
$\lvert V_{ub}\rvert$ excl. (WA)	$3.65 \cdot 10^{-3} \cdot (1 \pm 2.5\%_{\rm ex.} \pm 3.0\%_{\rm th.})$	2.4%	1.2%
$\mathcal{B}(B \to \tau\nu)$ $[10^{-6}]$	$91 \cdot (1 \pm 24\%)$	9%	4%
$\mathcal{B}(B \to \mu\nu)$ $[10^{-6}]$	< 1.7	20%	7%
$R(B \to D\tau\nu)$ (Had. tag)	$0.374 \cdot (1 \pm 16.5\%)$	6%	3%
$R(B \to D^*\tau\nu)$ (Had. tag)	$0.296 \cdot (1 \pm 7.4\%)$	3%	2%

Belle-II physics book

Lepton Flavor Violation $\mu \to e$

An **impressive progress** is expected in the next years in $\mu \to e$ **experiments**:

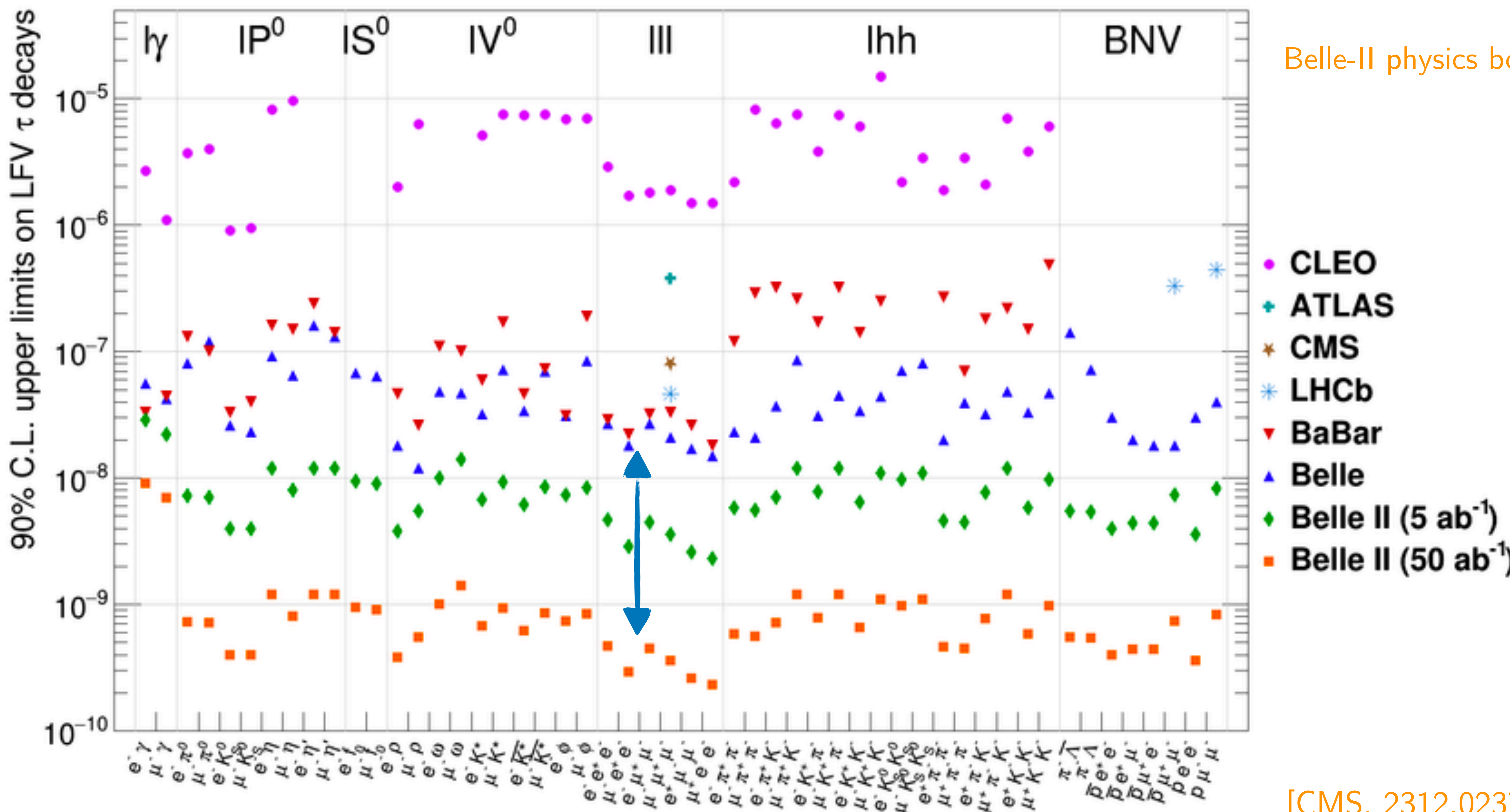


⇒ **Very clean probes of new physics!**

Lepton Flavor Violation

τ-decays

Belle-II will also **improve** the **sensitivity** on $\tau \to e$ and $\tau \to \mu$ decays by a **factor** $\mathcal{O}(10)$:



Belle-II physics book

[CMS, 2312.02371]

[NEW] CMS obtained $\mathrm{Br}(\tau \to 3\mu) < 2.4 \times 10^{-8}$ (90%CL.) — comparable to BaBar/Belle!

11/04 -12/04 in Orsay

Topical workshop on LFV decays of the tau

11 Apr 2024, 09:00 → 12 Apr 2024, 18:00 Europe/Paris

210/1-114 - Salle des Séminaires (IJCLab)

Asmaa Abada-Zeghal (Pôle Théorie IJCLAB), Damir Becirevic (IJCLab - Pôle Théorie), Olcyr Sumensari (IJCLab)

https://indico.ijclab.in2p3.fr/e/tauLFV

Thursday, 11 April

10:00 → 10:30	$\tau\to 3\ell$ at hadron colliders Speaker: Federica Simone (Bari U./INFN)	30m	210/1-114 - Salle des Séminai...
10:30 → 11:00	$\tau\to 3\ell$ at Belle-II Speaker: Justine Serrano (CPPM)	30m	210/1-114 - Salle des Séminai...
11:00 → 11:30	Coffee Break	30m	
11:30 → 12:00	Effective field theory description of LFV decays Speaker: Marco Ardu (Valencia U., IFIC)	30m	210/1-114 - Salle des Séminai...
14:30 → 15:00	New Physics models giving rise to LFV (seesaw mechanism inspired) Speaker: Enrique Fernandez Martinez (UAM/IFT-Madrid)	30m	210/1-114 - Salle des Séminai...
15:00 → 15:30	New Physics models giving rise to LFV (involving leptoquarks) Speaker: Nejc Košnik (IJS, Ljubljana)	30m	210/1-114 - Salle des Séminai...
15:30 → 16:00	Coffee Break	30m	
16:00 → 16:30	New Physics models giving rise to LFV (general considerations) Speaker: Shaikh Saad (U. Basel)	30m	210/1-114 - Salle des Séminai...

Friday, 12 April

10:00 → 10:30	$\tau\to\ell$+hadron decays at Belle II Speaker: Laura Zani (INFN, Rome3)	30m	210/1-114 - Salle des Séminai...
10:30 → 11:00	Hadronic issues in LFV decays of τ	30m	210/1-114 - Salle des Séminai...
11:00 → 11:30	Coffee Break	30m	
11:30 → 12:00	Constraints on the decays from the High-p_T studies at LHC Speaker: Felix Wilsch (RWTH Aachen U.)	30m	210/1-114 - Salle des Séminai...

INTENSITY frontier GDR-InF

cnrs NUCLÉAIRE & PARTICULES

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis

Summary

- **Precision frontier:** fundamental to seek new physics particles that cannot be produced on-shell at the LHC — *complementary approach*!

- **Hadronic uncertainties:** QCD remains the main obstacle to using low-energy observables to probe new physics — *caution is advised*!

- V_{cb} **and** V_{ub} **:** theory and exp. progress is needed to solve this issue — *needed to fix the parametric uncertainties of rare decays in the SM...* Belle-II data and new LQCD results will be essential.

- $B \to K\nu\nu$**:** Theoretically clean and a helpful tool to constrain (B)SM physics. More data and further cross-checks are needed to understand the first Belle-II results — *e.g.,* $B^0 \to K_S\nu\bar{\nu}$ *and* $B \to K^*\nu\bar{\nu}$.

- **LHC:** Drell-Yan processes at high energies are also complementary probes of flavor-physics operators — *valuable inputs for flavor model-building.*

Many **opportunities** to **explore** physics **(B)SM** in current/future flavor experiments!

Thank you!

Back-up

EFT for $b \to s\ell\ell$

$$\mathcal{L}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \left[\sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i + \sum_{7,8,9,10,P,S} \Big(C_i(\mu)\mathcal{O}_i + C_i'(\mu)\mathcal{O}_i' \Big) \right] + \text{h.c.}$$

- **Semileptonic operators:**

$$\mathcal{O}_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

$$\mathcal{O}_S^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\ell)$$

$$\mathcal{O}_P^{(\prime)} = (\bar{s} P_{R(L)} b)(\bar{\ell}\gamma_5 \ell)$$

- Dimension-6 *tensor operator* is *not allowed* by $SU(2)_L \times U(1)_Y$.

[Buchmuller, Wyler. '85]

- *(Pseudo)scalar operators* are *tightly constrained* by

$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{exp}} = (2.85 \pm 0.22) \times 10^{-9}$$

[Our exp. average: CMS, ATLAS, LHCb]

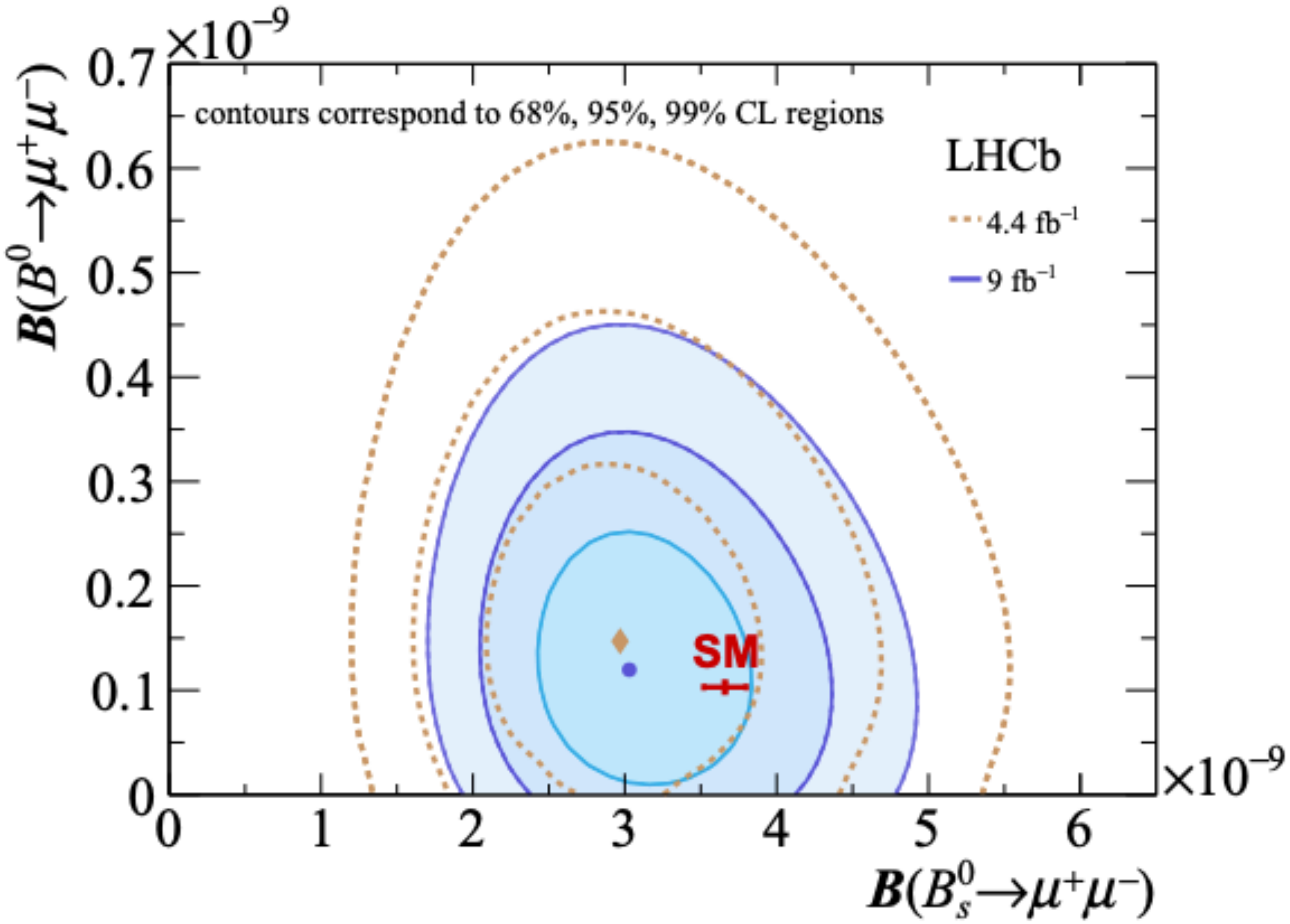
$$\overline{\mathcal{B}}(B_s \to \mu\mu)^{\text{SM}} = (3.66 \pm 0.14) \times 10^{-9}$$

[Beneke et al. '19]

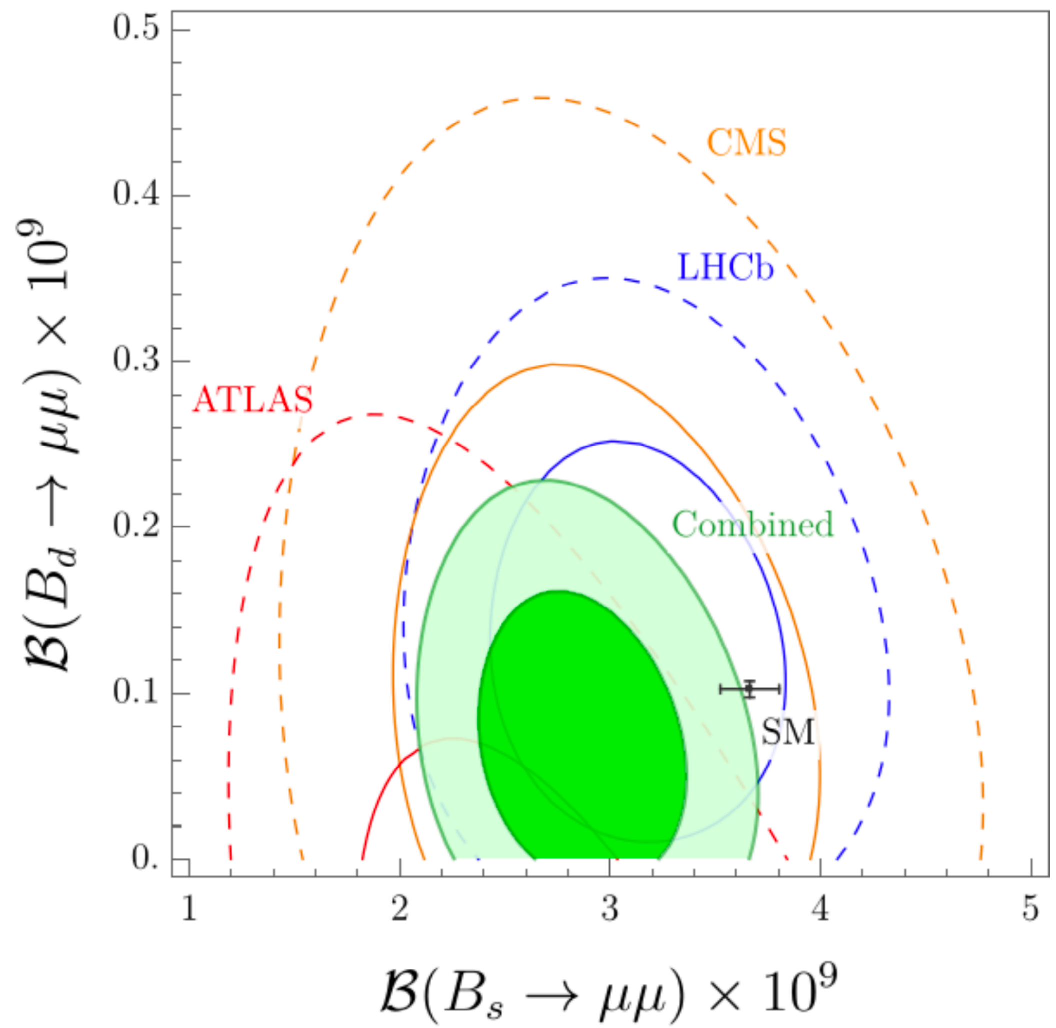
$B_s \to \mu\mu$

[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**. '21]

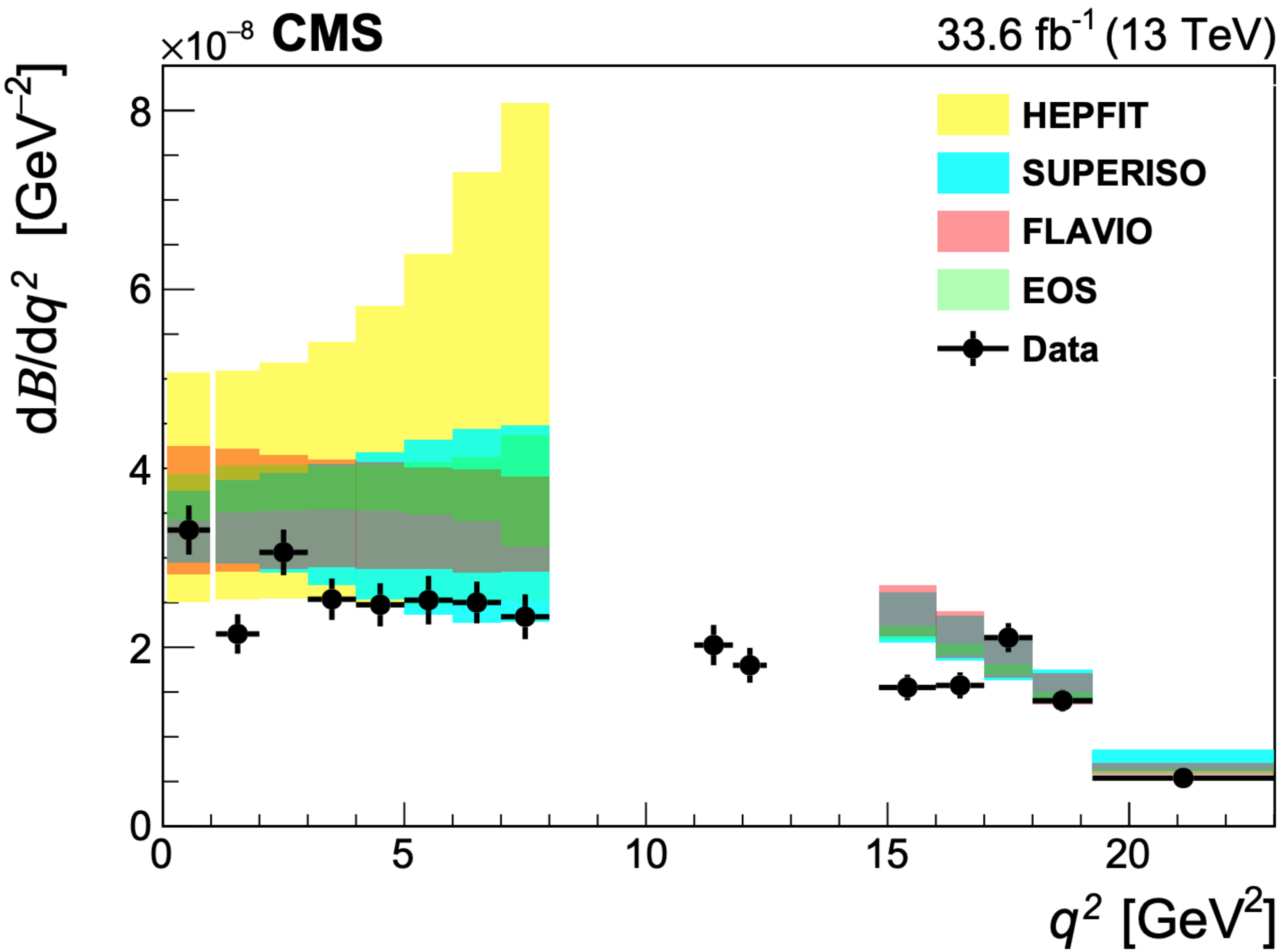
[LHCb '21]



[Our exp. average: CMS, ATLAS, LHCb]

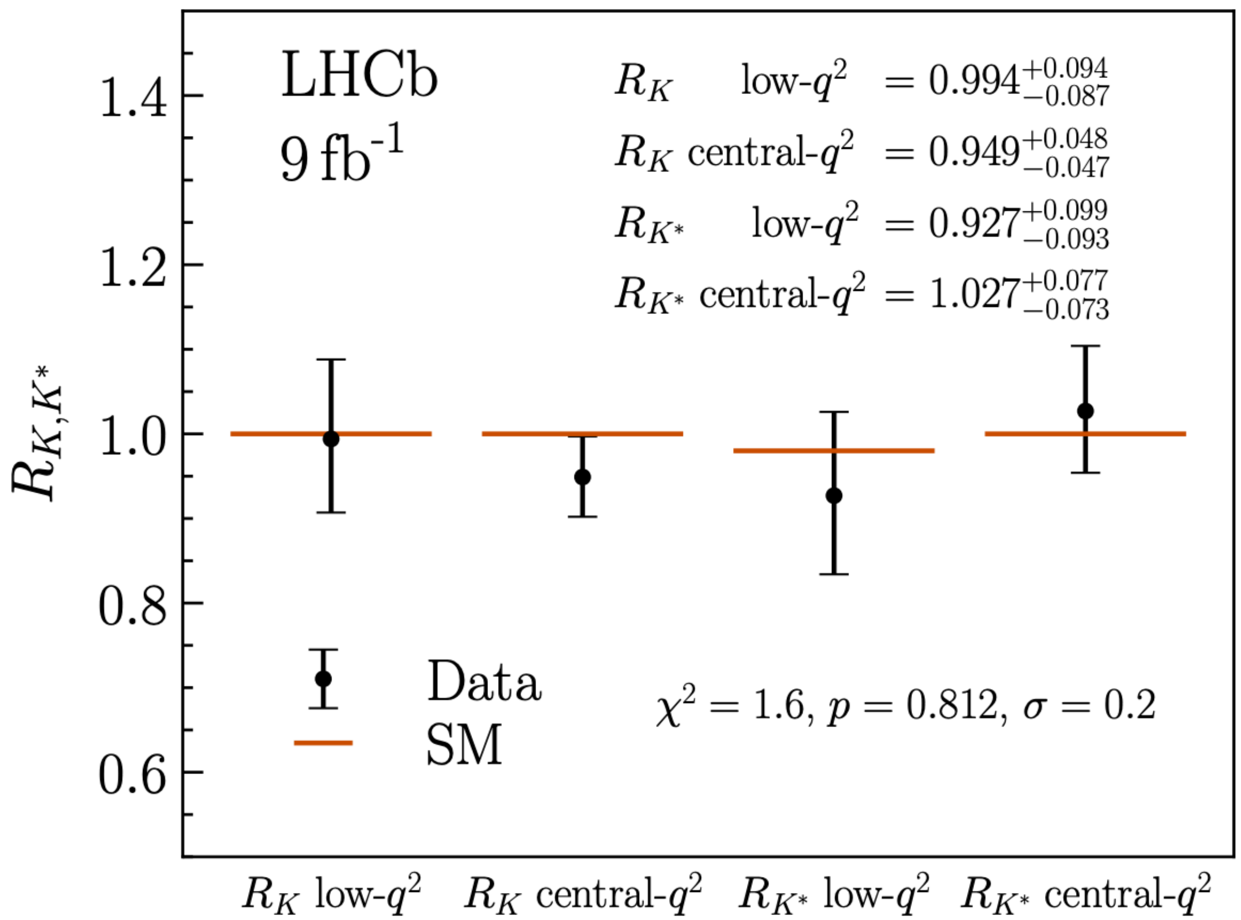


- **Good agreement** between **LHCb** results and the SM predictions;
- Small deficit in the exp. average — *due to ATLAS measurement*.


CMS
33.6 fb^{-1} (13 TeV)
$\times 10^{-8}$
dB/dq^2 [GeV^{-2}]
q^2 [GeV^2]
HEPFIT
SUPERISO
FLAVIO
EOS
Data
0
2
4
6
8
0
5
10
15
20

[Intermezzo] Lepton Flavor Universality violation?

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\bigg|_{q^2\in[q_0^2,q_1^2]}$$



LFU ratios are independent of $C_9^{\ell\ell} \equiv C_9^{ee} = C_9^{\mu\mu}$, thus being **theoretically clean**. However, LHCb data now **agrees** with the **SM predictions**.

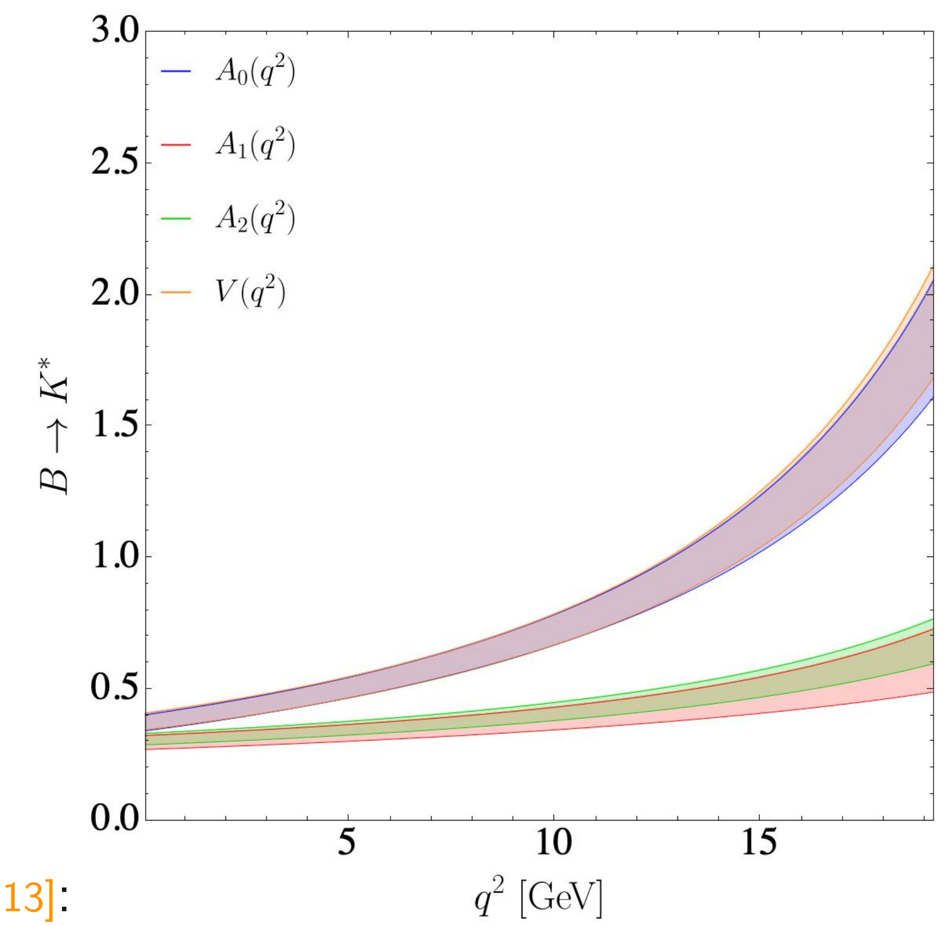
Constraints on **LFU violation**:

$$\frac{|\mathcal{C}_{\not{\text{LFU}}}|}{\Lambda^2} \lesssim (60\ \text{TeV})^{-2}$$

Form-factors: $B \to K^* \nu\bar{\nu}$

- $B \to K^* \nu\bar{\nu}$ decays are **more challenging** for several reasons:

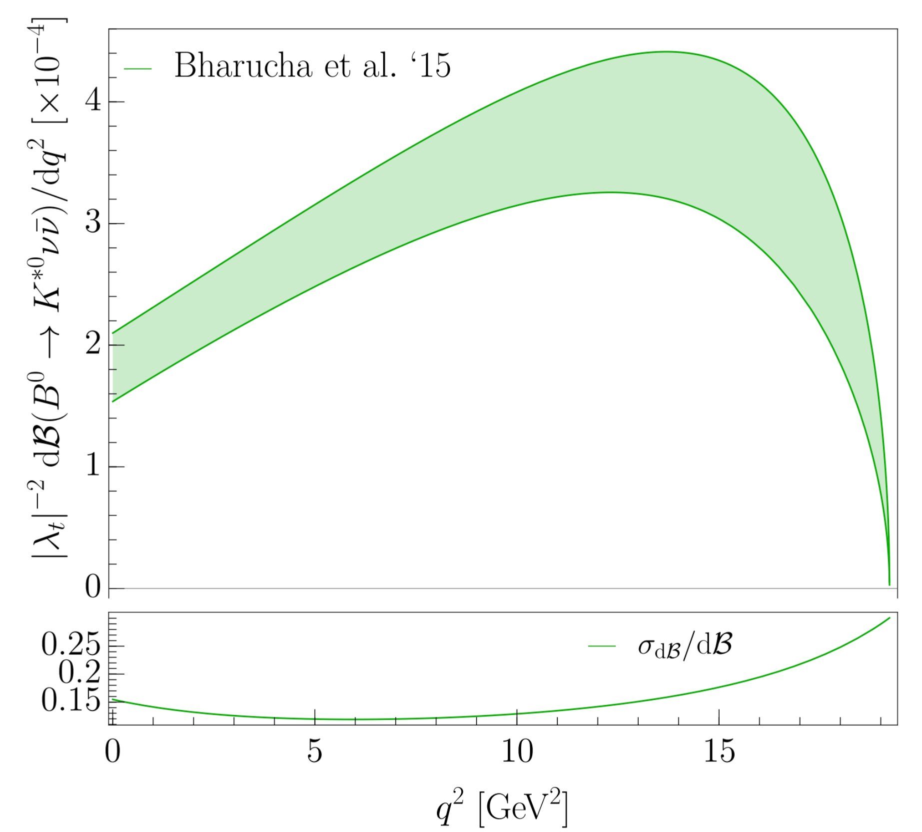
$$\langle \bar{K}^*(k)|\bar{s}\gamma_\mu(1-\gamma_5)b|\bar{B}(p)\rangle = \varepsilon_{\mu\nu\rho\sigma}\varepsilon^{*\nu}p^\rho k^\sigma \frac{2V(q^2)}{m_B+m_{K^*}}$$
$$- i\varepsilon^*_\mu (m_B+m_{K^*})A_1(q^2)$$
$$+ i(p+k)_\mu(\varepsilon^*\cdot q)\frac{A_2(q^2)}{m_B+m_{K^*}}$$
$$+ iq_\mu(\varepsilon^*\cdot q)\frac{2m_{K^*}}{q^2}\left[A_3(q^2)-A_0(q^2)\right],$$



- We use LCSR (+LQCD) results from [Bharucha et al. '15, Horgan et al. '13]:

$$\mathcal{B}(B\to K^*\nu\bar{\nu})^{\rm SM}/|\lambda_t|^2 = \begin{cases}(5.9\pm0.8)_{K^{*0}}\times 10^{-3}\\(6.4\pm0.9)_{K^{*+}}\times 10^{-3}\end{cases}$$

[$\approx 15\,\%$ uncertainty]



⇒ Relatively small uncertainties, **but are they accurate**?

[Intermezzo]: Cross-check of $f_+^{B\to K}(q^2)$

- SM predictions depend on the **extrapolation** of the LQCD **form-factors to low** q^2 values — **parameterisation dependent?**

  ⇒ How can we **test the shape** of the **extrapolated** LQCD **form-factors**?

- We propose to measure:

  [Becirevic, Piazza, **OS**. 2301.06990]

$$r_{\text{low/high}} = \frac{\mathcal{B}(B\to K\nu\bar{\nu})_{\text{low}-q^2}}{\mathcal{B}(B\to K\nu\bar{\nu})_{\text{high}-q^2}}$$

⇒ *Independent of λ_t and the form-factor normalisation, as well as of NP contributions.*

NB. w/o ν_R

- Using the bins $(0, q^2_{\text{max}}/2)$ vs. $(q^2_{\text{max}}/2, q^2_{\text{max}})$:

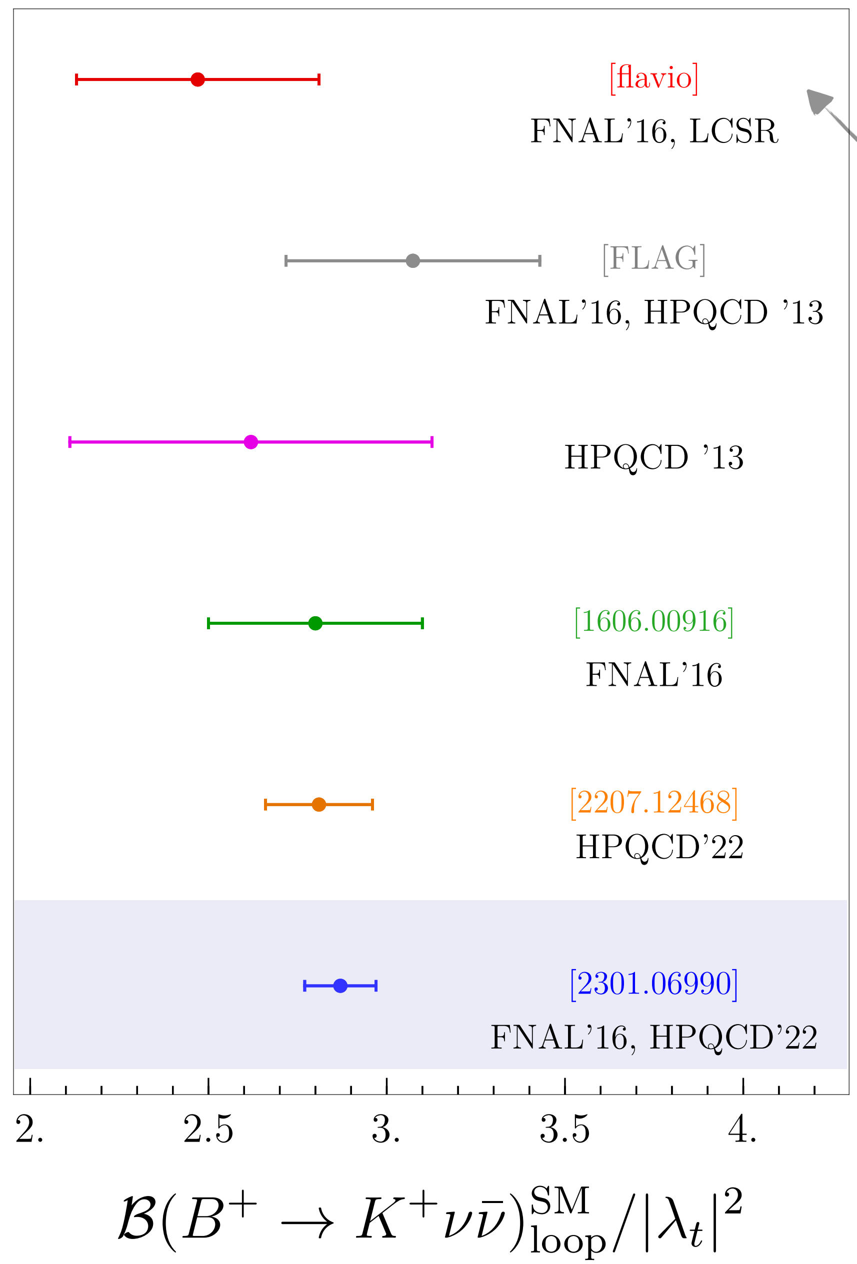
$$r_{\text{low/high}} = 1.91 \pm 0.06$$

e.g, using (old) FLAG average:

$$r_{\text{low/high}} = 2.15 \pm 0.26$$

Form-factors: $B \to K\nu\bar{\nu}$

**Annihilation contributions not included below (see next slides)!*



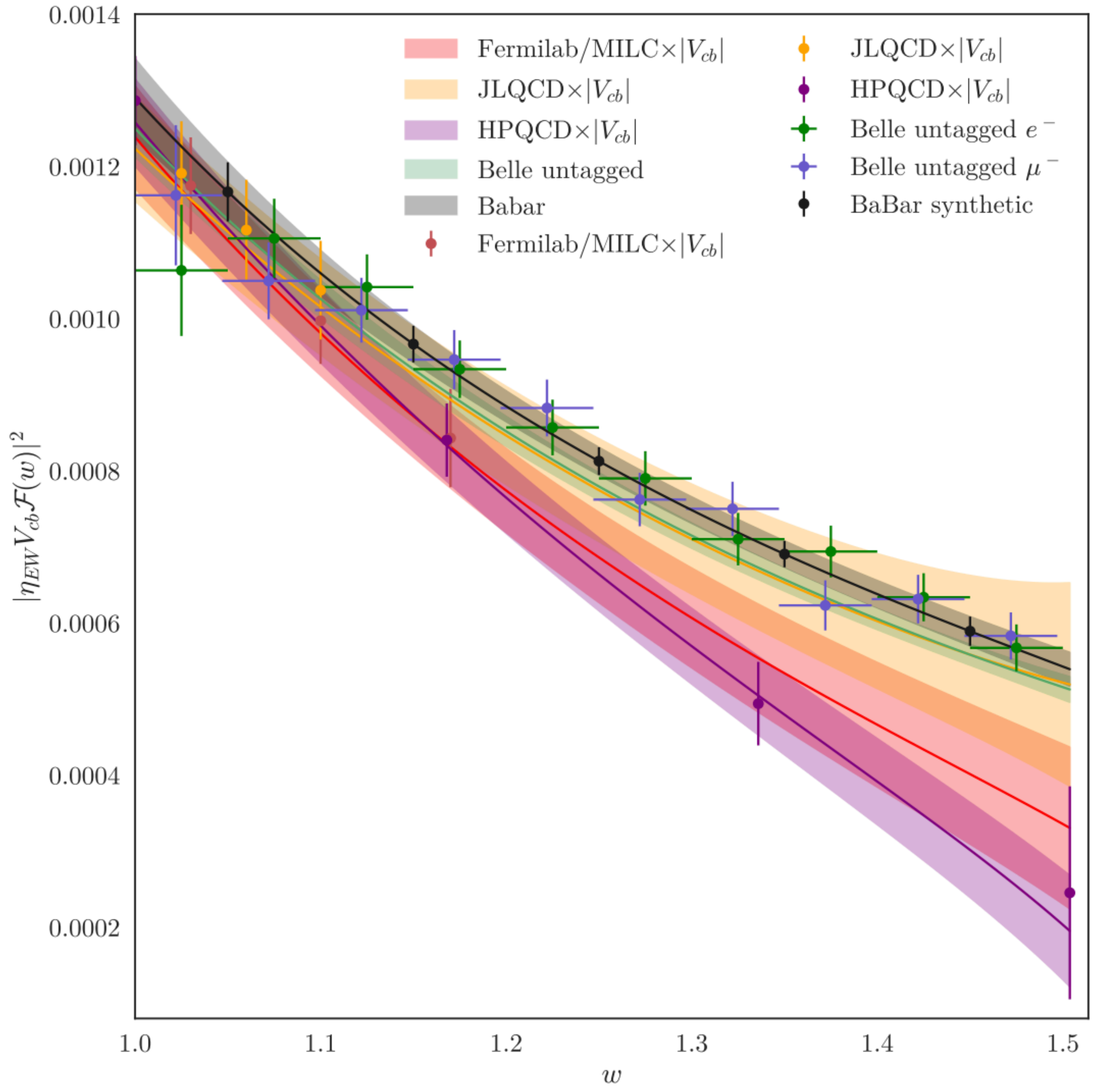
Form-factors based on Light-Cone Sum Rules (LCSR) lead to smaller branching fractions.

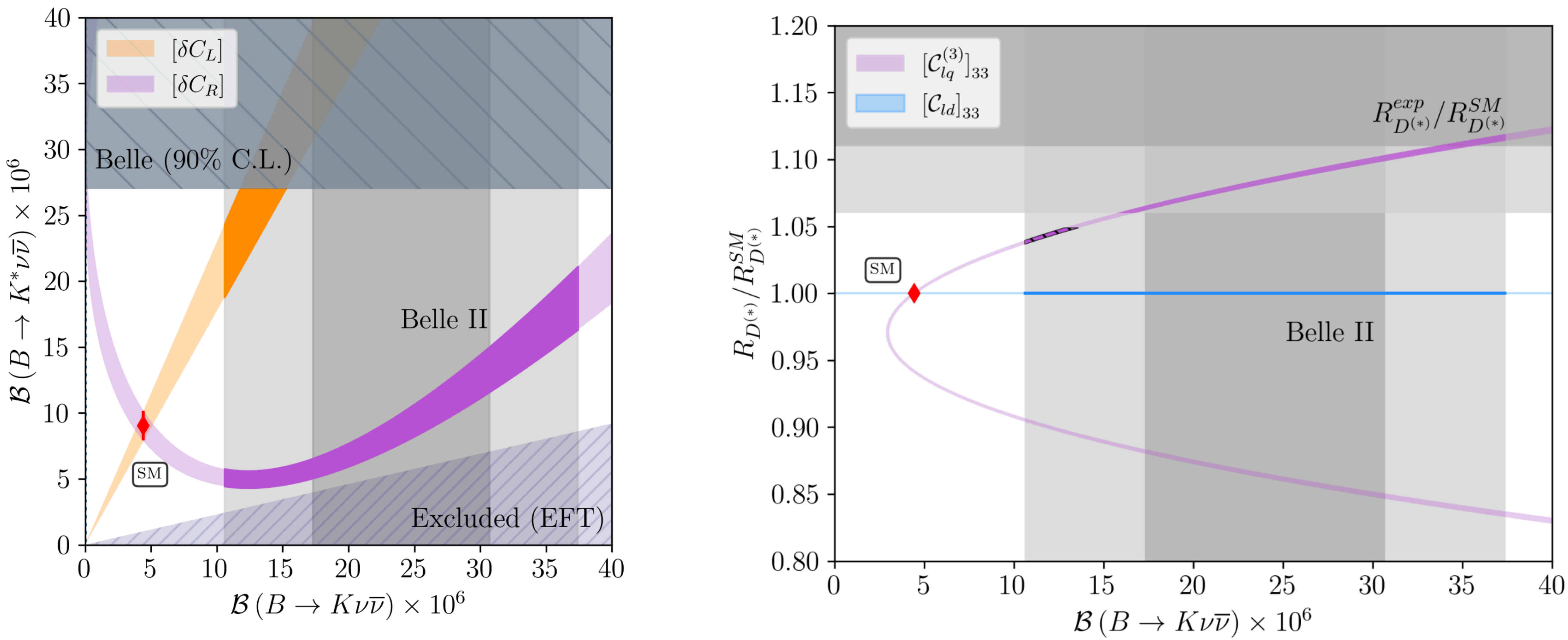
[Bharucha et al. '15, Gubernari et al. '18]

$$\mathcal{B}(B \to K\nu\bar{\nu})^{\rm SM}/|\lambda_t|^2 = \begin{cases} (1.33 \pm 0.04)_{K_S} \times 10^{-3} \\ (2.87 \pm 0.10)_{K^+} \times 10^{-3} \end{cases}$$

[Becirevic, Piazza, **OS**. 2301.06990]

Comparison from A. Lytle talk





$[\delta C_L]$
$[\delta C_R]$
Belle (90% C.L.)
Belle II
SM
Excluded (EFT)
$\mathcal{B}(B \to K^* \nu\bar{\nu}) \times 10^6$
$\mathcal{B}(B \to K \nu\bar{\nu}) \times 10^6$
$[\mathcal{C}_{lq}^{(3)}]_{33}$
$[\mathcal{C}_{ld}]_{33}$
$R^{exp}_{D^{(*)}}/R^{SM}_{D^{(*)}}$
SM
Belle II
$R_{D^{(*)}}/R^{SM}_{D^{(*)}}$
$\mathcal{B}(B \to K \nu\bar{\nu}) \times 10^6$

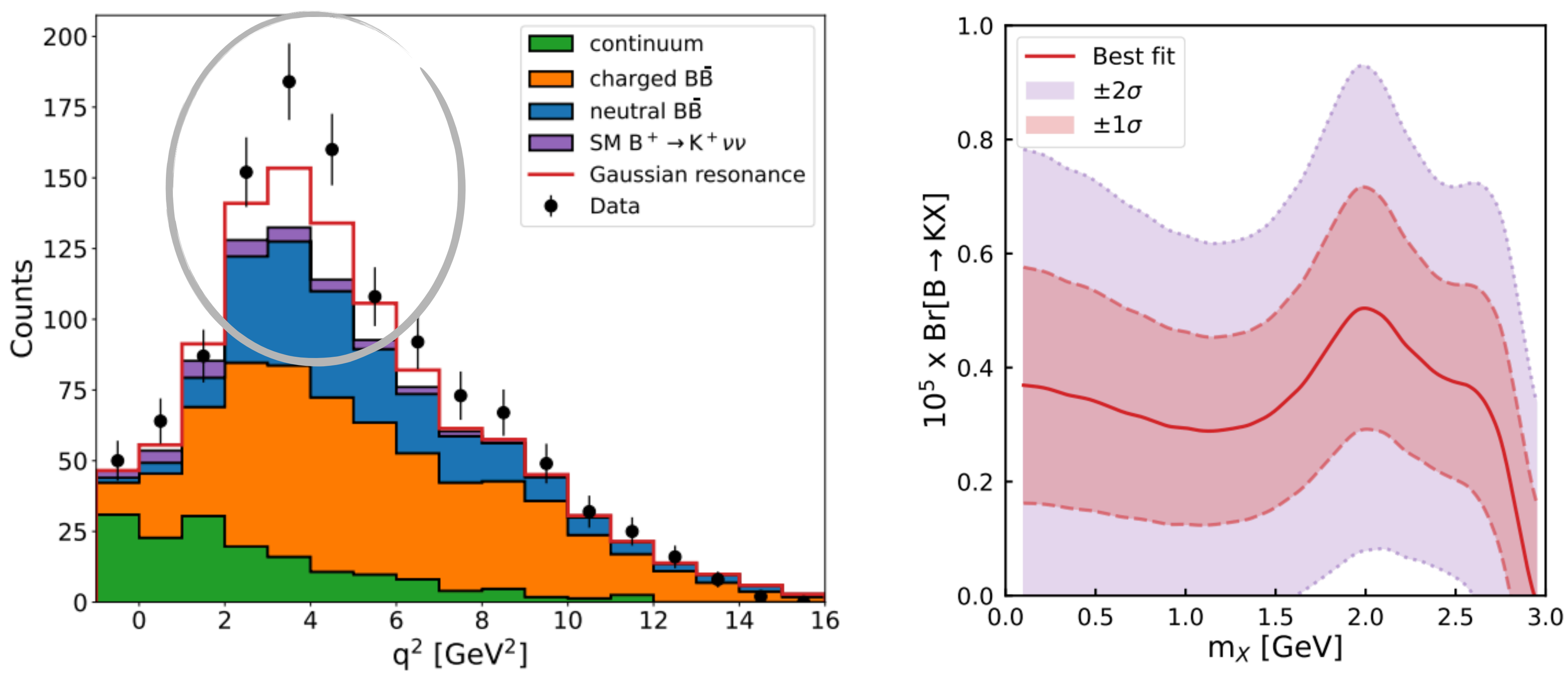
Hidden sectors?

[Altmannshofer et al. '23]

- What if the excess is due to $B \to KX(\to \text{inv})$, where $X \sim (\mathbf{1}, \mathbf{1}, 0)$ is a light mediator produced on-shell *(i.e., with $m_X < m_B$)*?

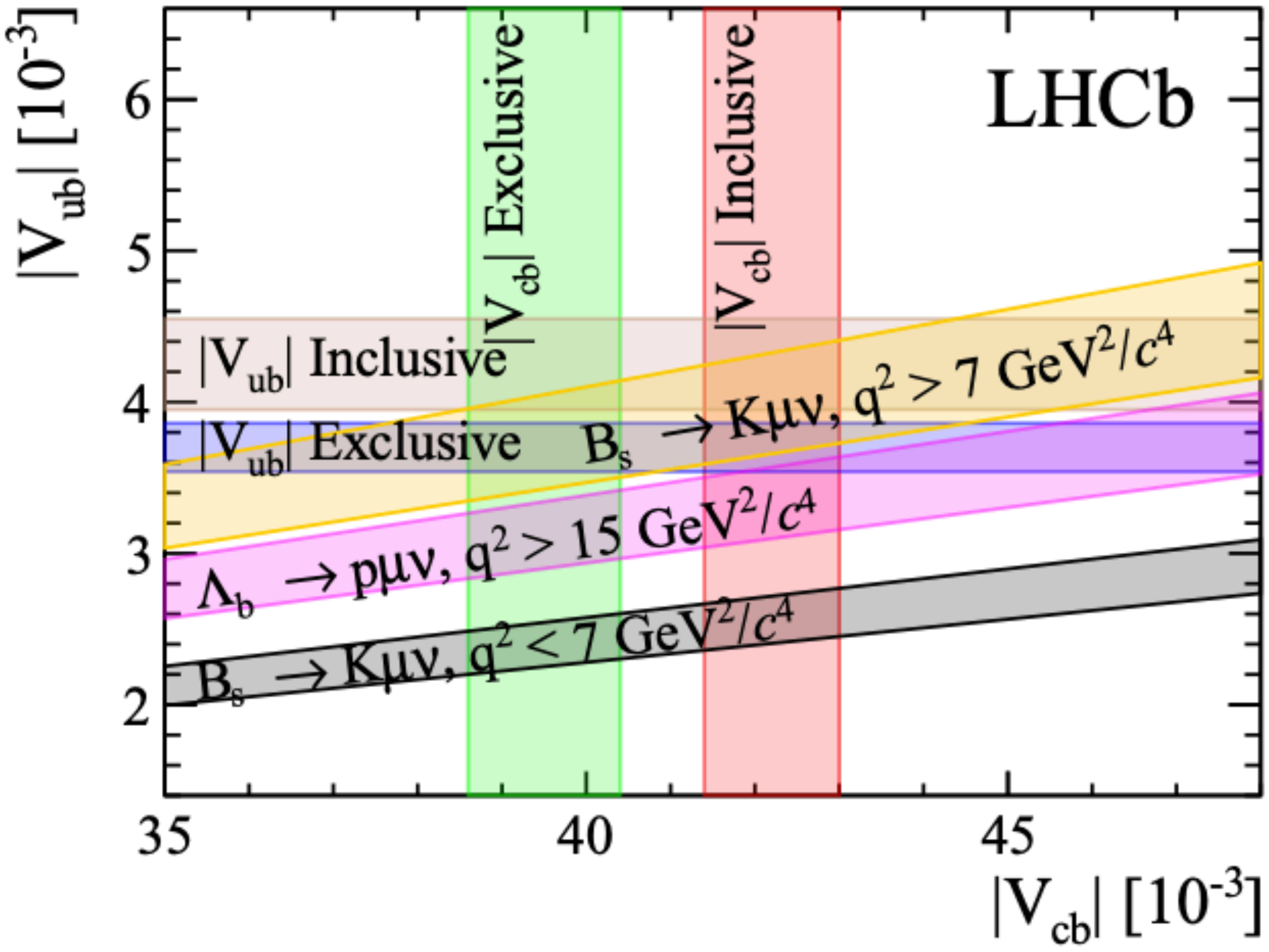
- The main difference would be a **peak** in the **q^2-distributions** at $q^2 \simeq m_X^2$, smeared by the detector resolution.

- **Good fit** to Belle-II data **too** since the excess is mostly localised (**within large uncertainties!**):



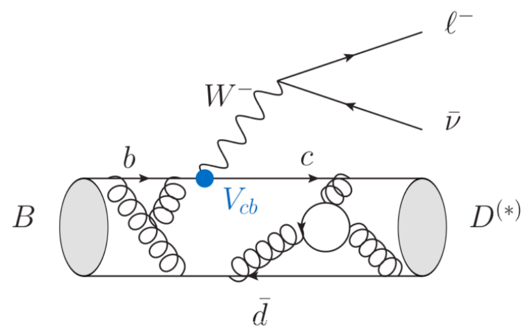
- Best fit (2.8σ): $m_X \approx 2$ GeV $\qquad \mathcal{B}(B \to KX) = (5.1 \pm 2.1) \times 10^{-6}$

$\Rightarrow$ To be checked by **dedicated searches**!


LHCb
|V_ub| Inclusive
|V_ub| Exclusive
|V_cb| Exclusive
|V_cb| Inclusive
B_s → Kμν, q² > 7 GeV²/c⁴
Λ_b → pμν, q² > 15 GeV²/c⁴
B_s → Kμν, q² < 7 GeV²/c⁴
|V_ub| [10⁻³]
|V_cb| [10⁻³]
35
40
45
2
3
4
5
6

[Intermezzo]: $B \to D^{(*)}\ell\bar{\nu}$ in the SM

See talk by Lytle



Known Lorentz factors

$$\langle D^{(*)}|\bar{c}_L\gamma^\mu b_L|B\rangle = \sum_a K_a^\mu \mathcal{F}_a(q^2)$$

Form-factors (from lattice, exp...)

For light (heavy) leptons:

- $B \to D$: one (two) form-factors with $f_0(0) = f_+(0)$ at $q^2 = 0$;

  $\Rightarrow$ Lattice QCD at $q^2 \neq q^2_{\rm max}$ for both form-factors. [MILC/Fermilab '15, HPQCD '15]

$$R_D^{\rm latt.} = 0.293(5) \qquad R_D^{\rm latt.+exp} = 0.295(3)$$

[FLAG '21]

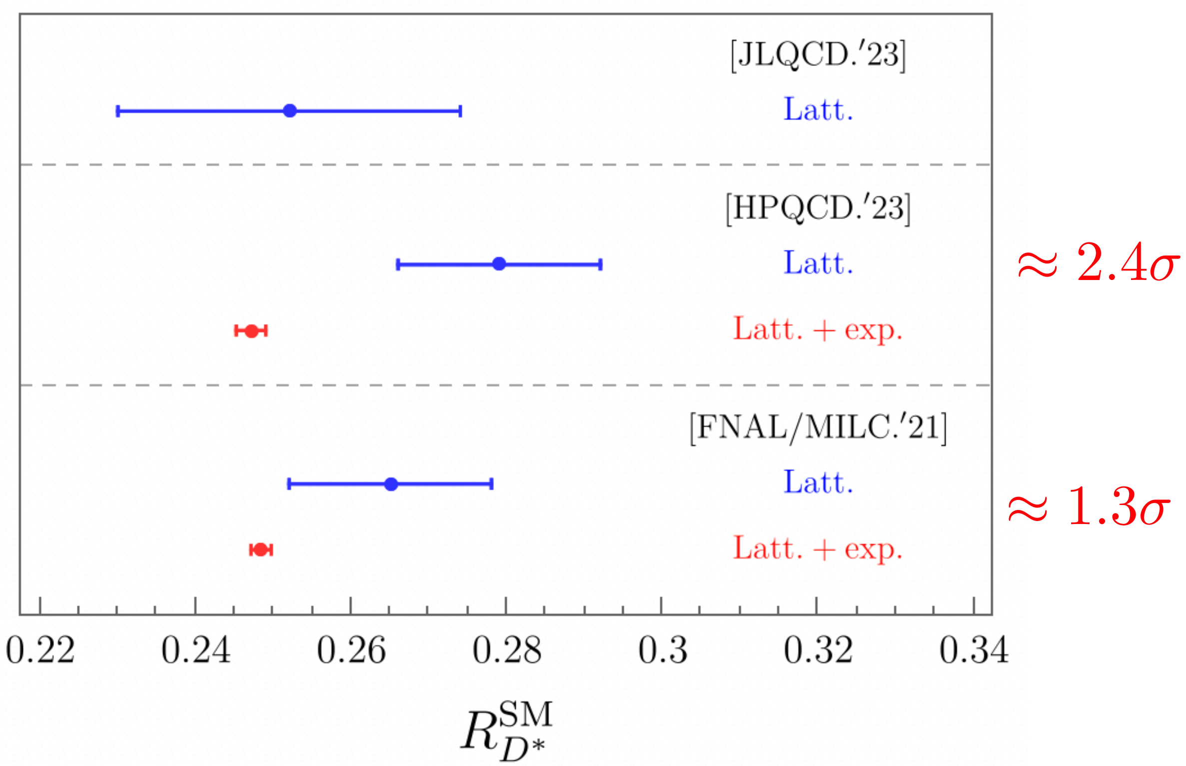
$B \to D^{(*)} l\bar{\nu} \quad (l = e, \mu)$

- $B \to D^*$: three (four) form-factors;

  $\Rightarrow$ **[NEW]** First lattice results at $q^2 \neq q^2_{\rm max}$!

  $\Rightarrow$ Tensions with $B \to D^*\ell\bar{\nu}$ exp. data...

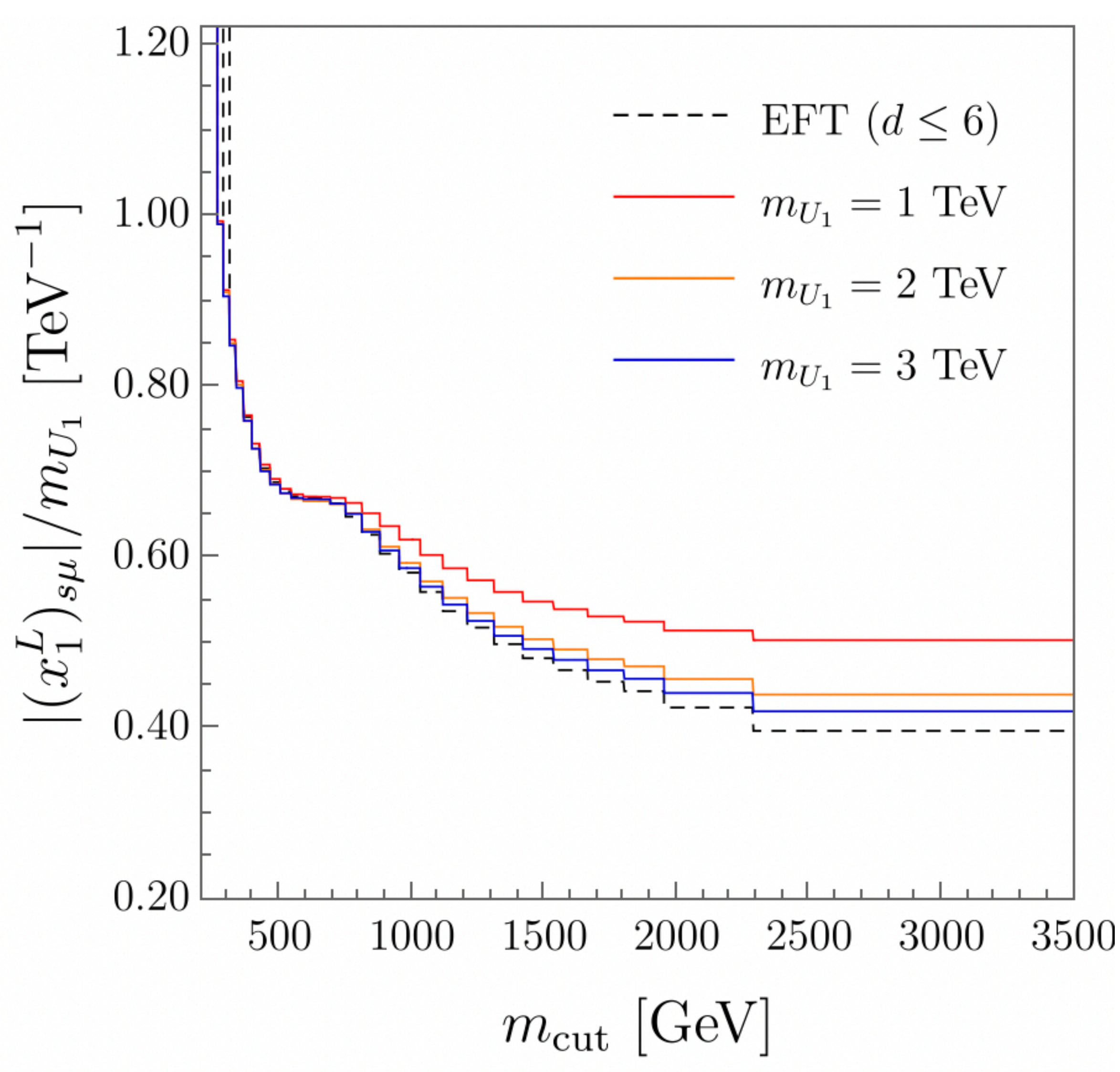
  ... for [MILC/Fermilab '21, HPQCD '23]

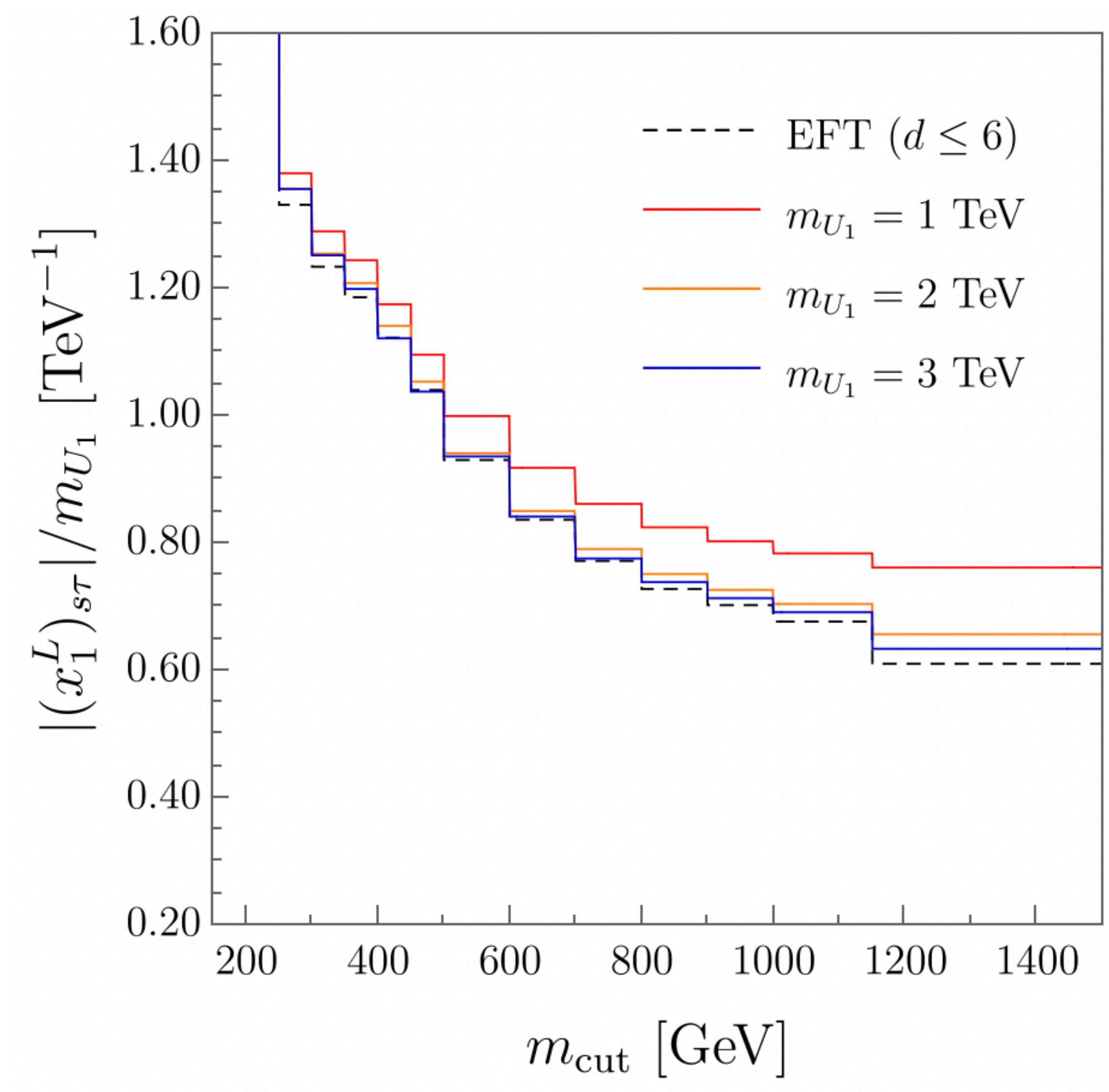


EFT vs. concrete models

[Allwicher et al., *in preparation*]

Examples: $pp \to \mu\mu$ $pp \to \tau\tau$





The **EFT reproduces** well the **leptoquark models** for $M \gtrsim 2$ TeV .

NB. The convergence is slower for s-channel mediators.

Example: $b \to s\tau\tau$

[Allwicher et al., *in preparation*]

- Related to $b \to c\tau\bar{\nu}$ for some operators through $SU(2)_L$ **invariance**, $L_i = (\nu_{Li}, \ell_{Li})^T$.
- **Extremely difficult measurement** at low energies!

Upper limits (90%CL.):

$$\mathcal{B}(B_s \to \tau\tau) < 6.8 \times 10^{-3}$$ [LHCb. '17]

$$\mathcal{B}(B^+ \to K^+\tau\tau) < 2.25 \times 10^{-3}$$ [BaBar. '16]

$$\mathcal{B}(B^0 \to K^{*0}\tau\tau) < 3.1 \times 10^{-3}$$ [Belle. '21]

vs. $\mathcal{B}_{\rm SM} \approx 10^{-7}$