Flavor physics: connecting low- and high-energy searches

Olcyr Sumensari

IJCLab (Orsay)

Based on:

- [Becirevic, Piazza, **OS**. 2301.06990], [Allwicher, Becirevic, Piazza, Rosauro-Alcaraz, **OS.** 2309.02246]
- [Eboli, Leal, Martines, **OS**. 2509.08437], [Becirevic, Martines, Rosauro-Alcaraz, **OS.** 2603.XXXXX]
- [Allwicher, Cornella, Leal, Martines, **OS**. *In preparation*]

IPHC, March 27

Flavor physics

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

  ⇒ Hierarchy and flavor problems unanswered — *among many other problems.*

  ⇒ 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:

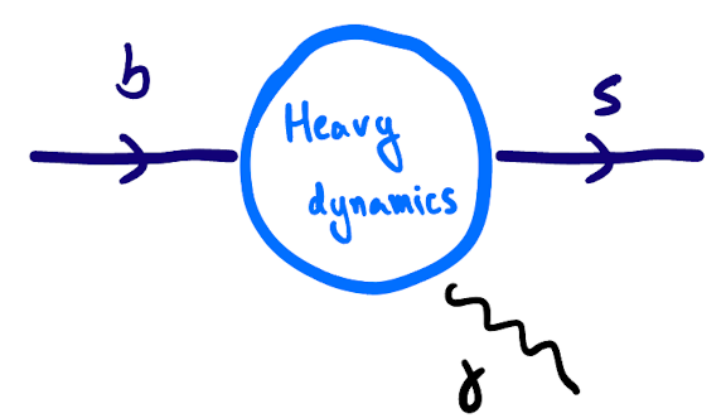
$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \quad \begin{pmatrix} c_L \\ s_L \end{pmatrix} \quad \begin{pmatrix} t_L \\ b_L \end{pmatrix} \updownarrow$$

Gauge symmetry

⟷

Flavor symmetry?

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**:

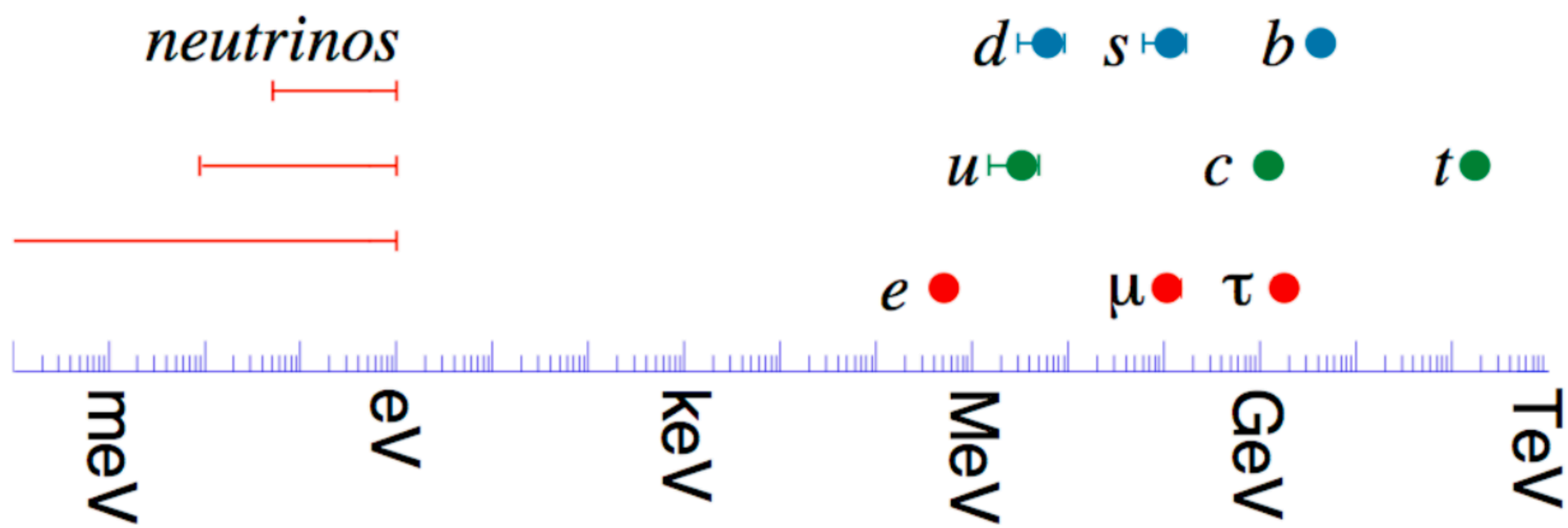
  ⇒ 13 free parameters (masses and quark mixing) — *fixed by data.*

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

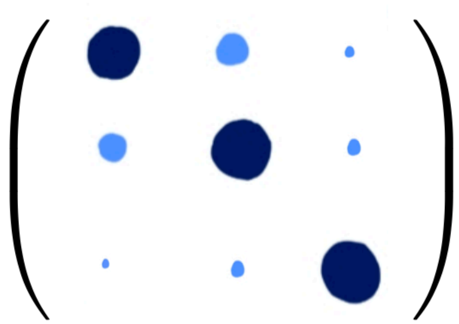
  ⇒ These (many) parameters exhibit a hierarchical structure which we do not understand.

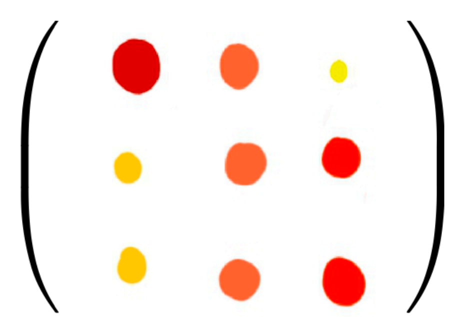
I. Origin of flavor?

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



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

$V_{\mathrm{CKM}} =$ 

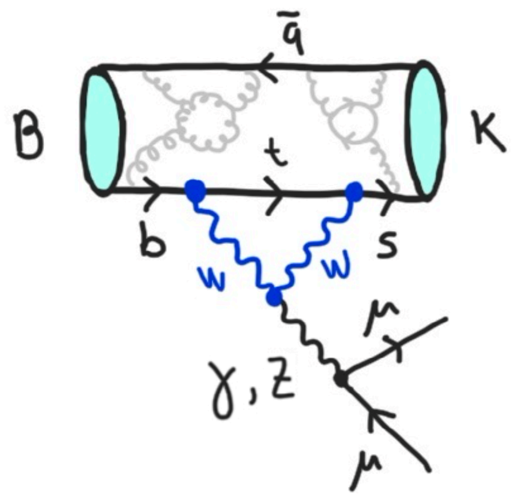
$V_{\mathrm{PMNS}} =$ 

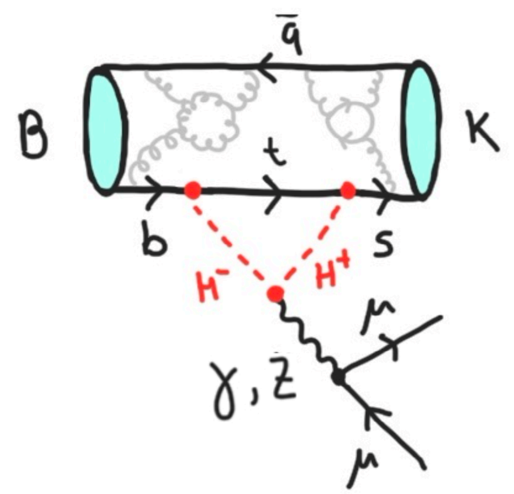
How to **explain** the **observed patterns** in terms of **less** and **more fundamental parameters**?

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.

⇒ **Challenging task!** $B \to K\nu\nu$ 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!

What is experiment telling us?

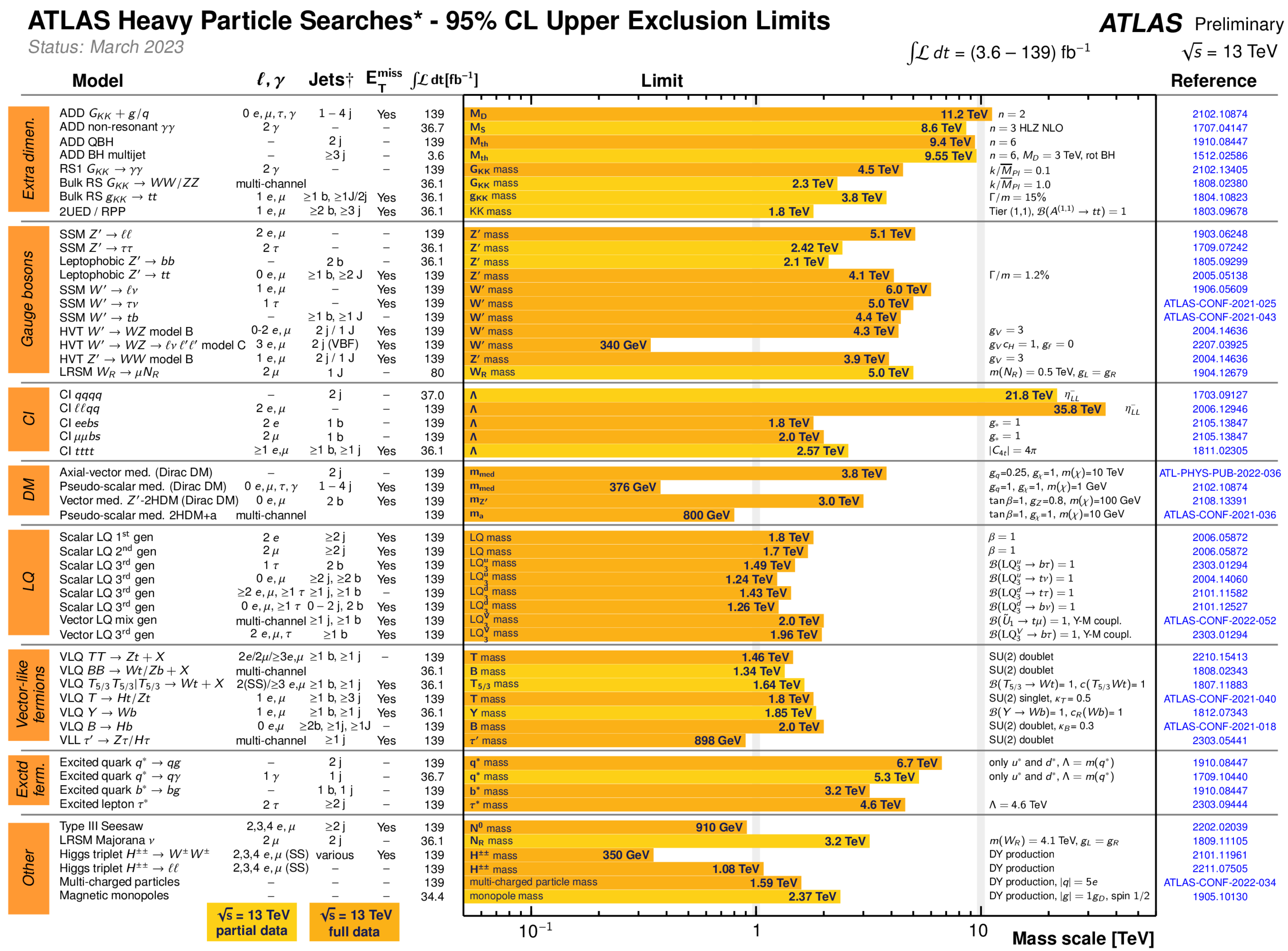
No direct evidence of New Physics…

↓

Presence of a mass gap?

↓

Indirect searches!



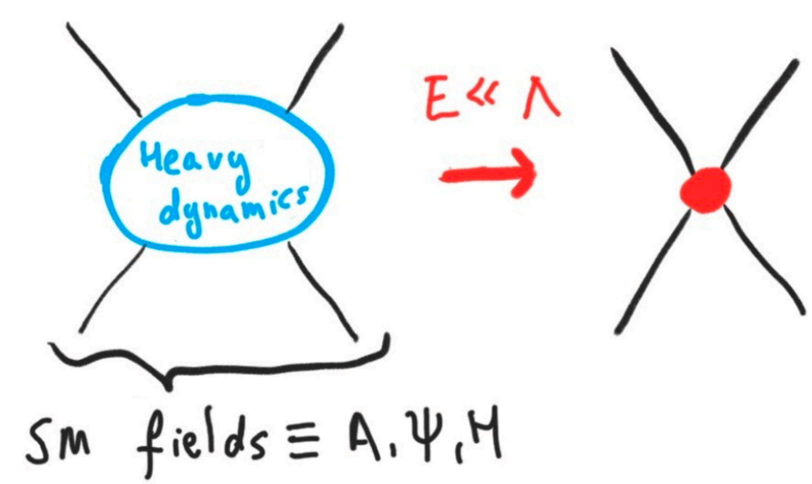
The EFT approach

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

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

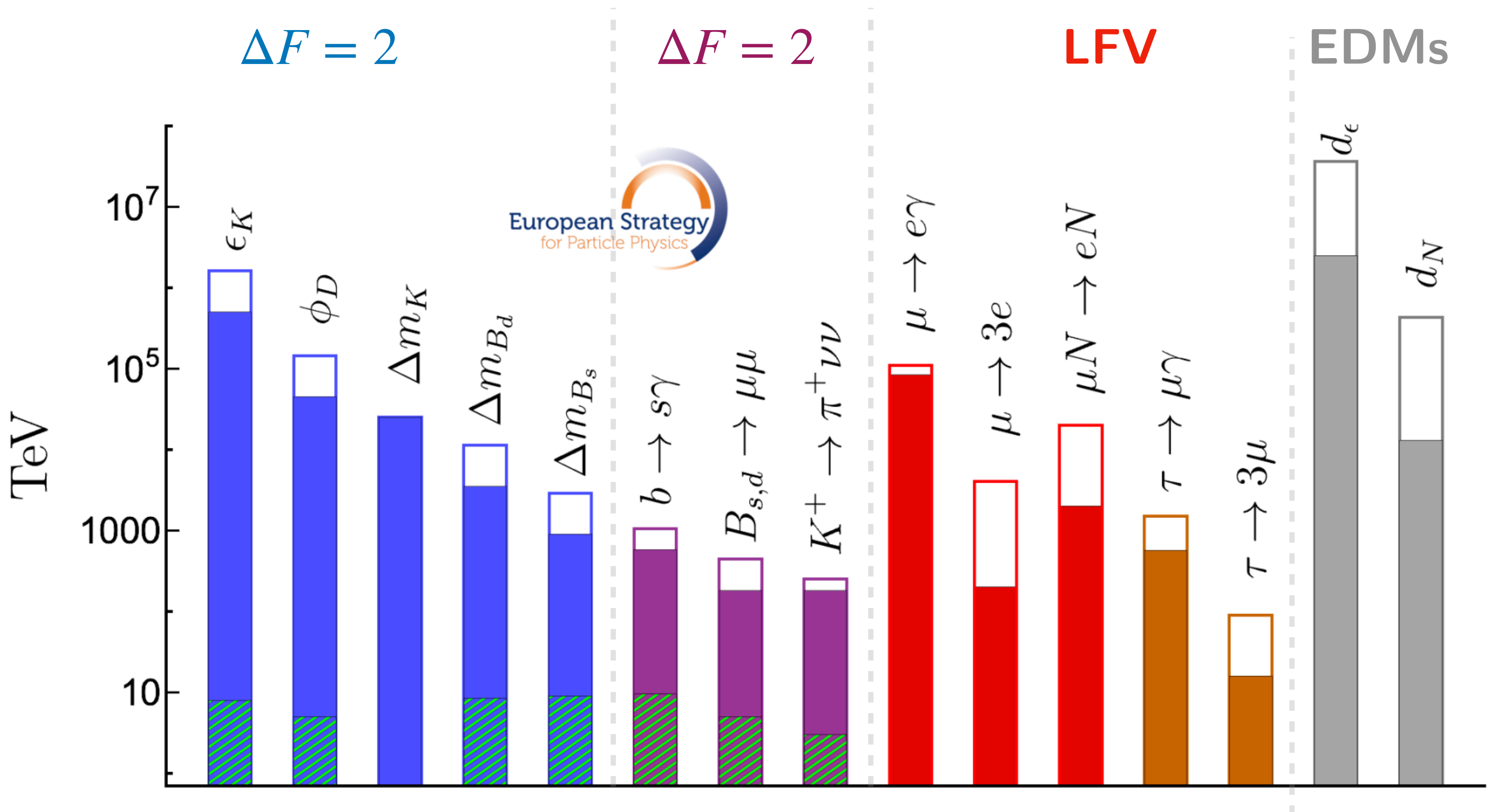
Assumption: $E \ll \Lambda$

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



What is the scale of New Physics?

Flavor physics tells us that **New Physics** is **either heavy**, or has a **non-trivial flavor structure**:



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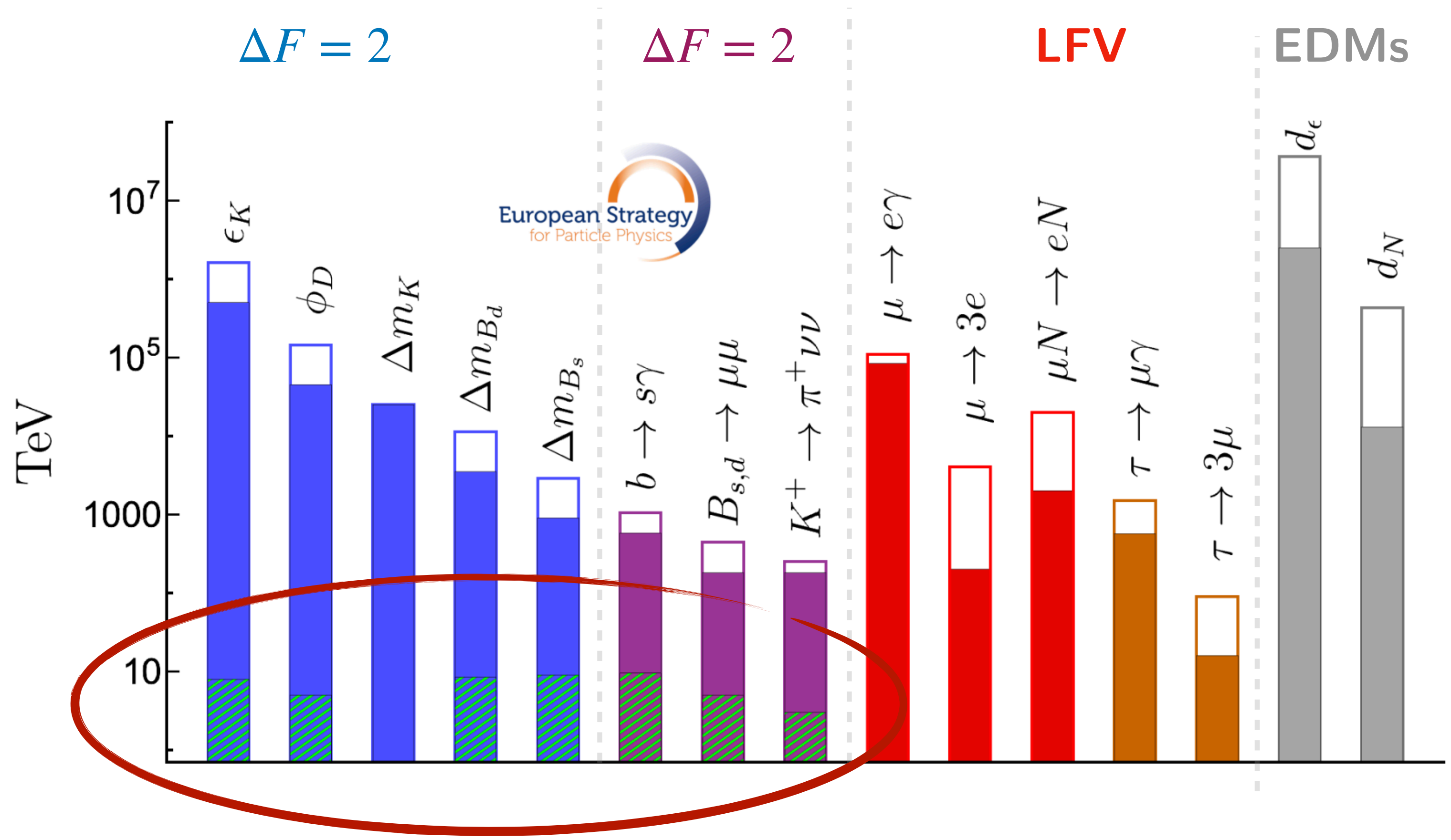


***e.g.*, MFV** (hatched)

$$\frac{\mathcal{C}^{(6)}}{\Lambda^2} = \frac{1}{\Lambda^2}$$

$$\downarrow$$

$$\frac{\mathcal{C}^{(6)}}{\Lambda^2} = \frac{V_{ti} V_{tj}^*}{\Lambda^2}$$

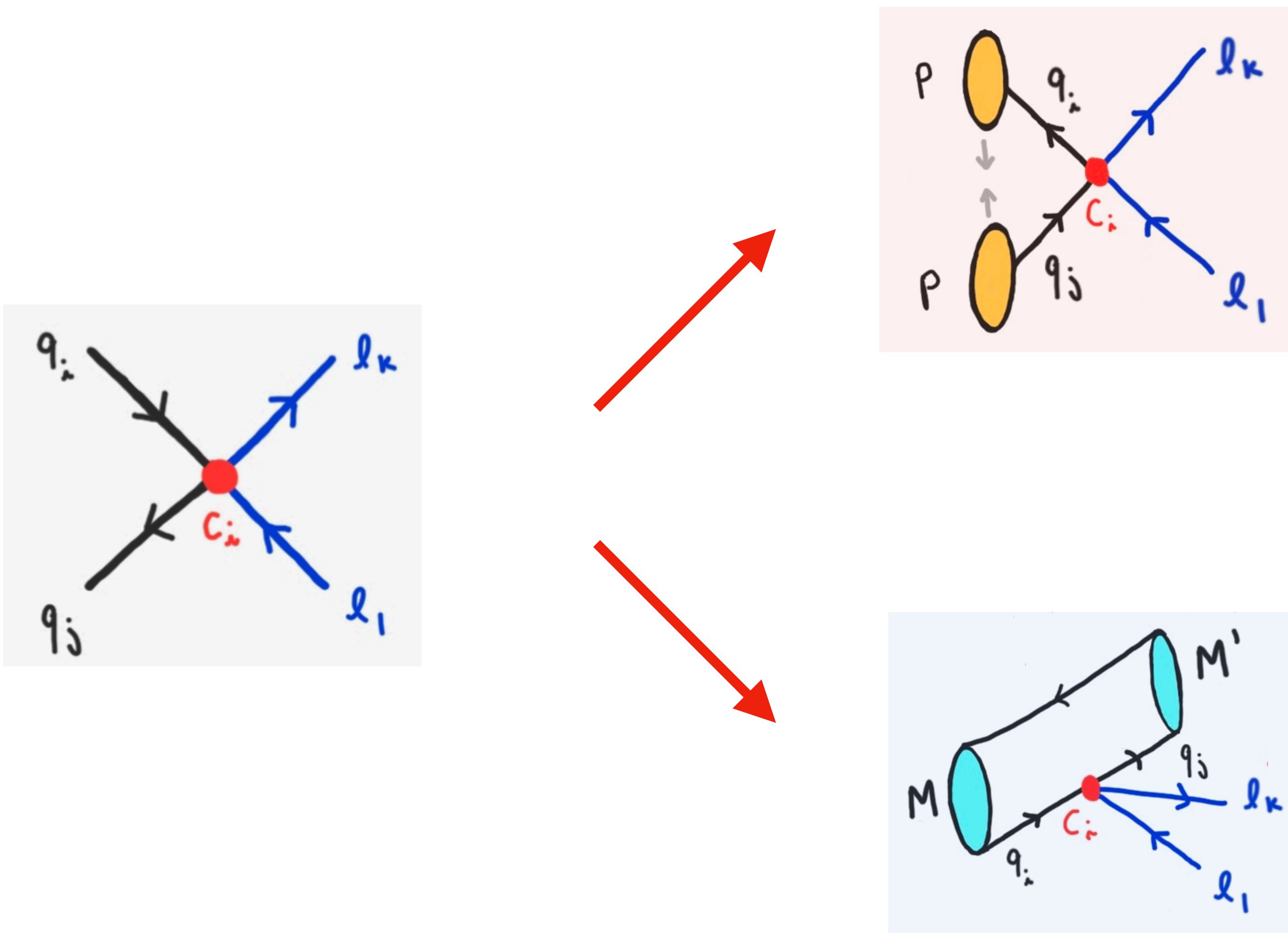
[D'Ambrosio et al. '02]

Non-trivial flavor structures are essential to reconcile **TeV-scale** solutions of the **hierarchy problem** with flavor data — *is there are joint solution of both problems?*

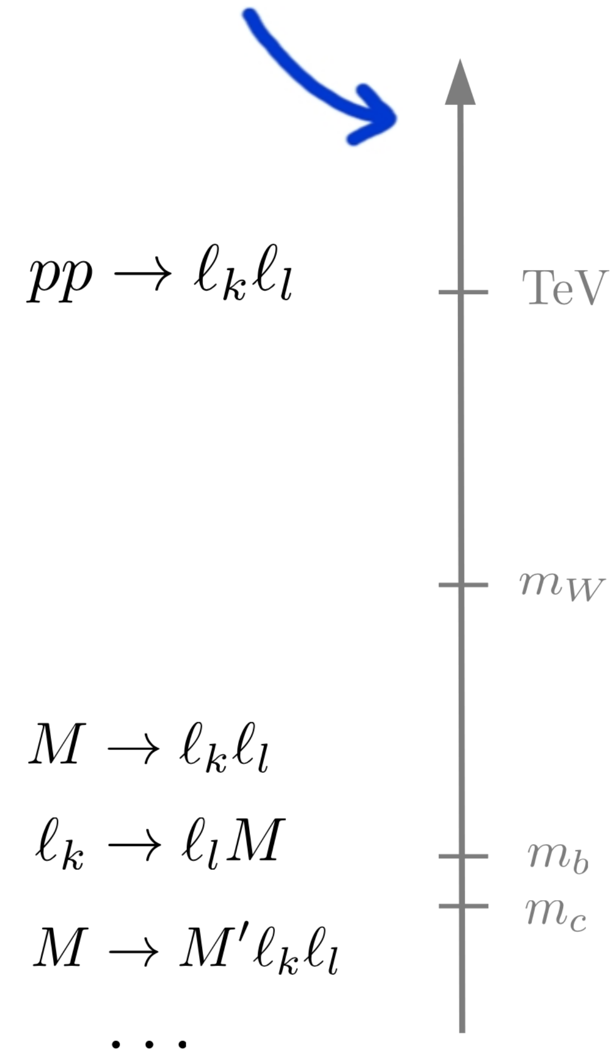
Observables with **3rd-generation fermions** are **very compelling targets** — *accessible at LHC(b) and Belle-II!*

Flavorful EFTs at the LHC

[Angelescu, Faroughy, **OS**. '20], [Allwicher, Faroughy, Jaffredo, **OS**, Wilsch. '22], [Descotes-Genon, Faroughy, Plakias, **OS**, '23]



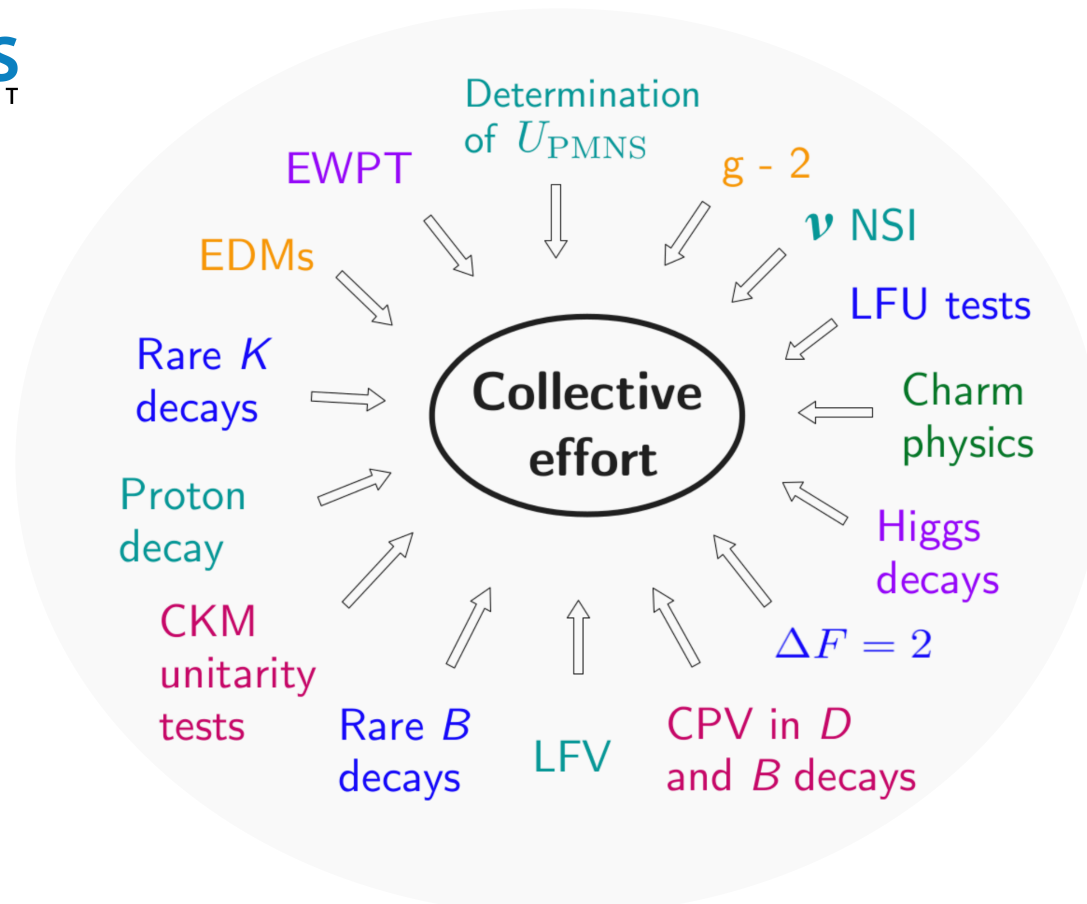
(Flavorful) New Physics?



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...).

Recent works on EFTs and DY: 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], [Greljo et al. '22][Grunwald et al. '23], [Hiller et al. '24] ...

Combined effort!



...

...

Flavor physics is a combined effort — *complementary to Higgs/EW and direct searches!*

Rich experimental landscape: *large experiments (with extensive physics program) and small experiments (with specific targets).*

Outline

I. Introduction

II. Seeking New Physics with rare B-decays

III. LHC probes of flavor

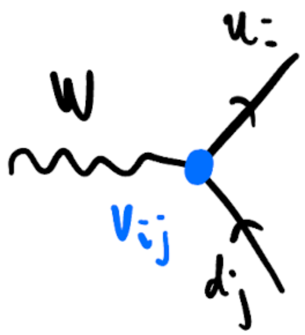
IV. Outlook

Seeking New Physics with rare *B*-decays

- *Reminder: FCNCs in the SM*
- $B \to K\nu\nu$ *in the SM*
- *First lessons from Belle-II data*

Flavor Changing Neutral Currents (FCNCs)

- **FCNCs** are **absent** at **tree-level** in the SM — *i.e., couplings of neutral SM bosons to fermions are flavor diagonal.*
- The only source of **flavor violation** in the SM is the **CKM matrix**:



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

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

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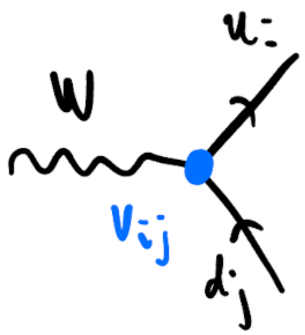

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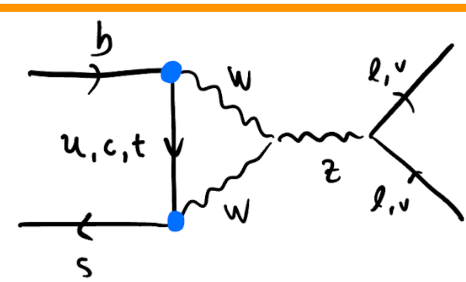
$$V_{\mathrm{CKM}} = U^{\dagger}_{u_L} U_{d_L}$$

$V_{\mathrm{CKM}} =$ 

- **FCNC** processes are **loop-** and **CKM-suppressed**:

- $\Delta F = 1$:

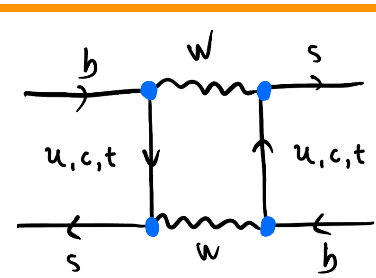


$B \to K^{(*)}\nu\bar{\nu}$

$B \to K^{(*)}\ell\ell$

$\ldots$

- $\Delta F = 2$:



$\Delta m_{B_s} \neq 0$

$\ldots$

⇒ **Rare processes**

⇒ **Sensitive new physics probes!**

- **Reminder**: GIM mechanism

$$\mathcal{M}(b \to s\ell\ell) \propto \sum_{k=u,c,t} V^{*}_{ks} V_{kb}\, \varphi\left(\frac{m_k^2}{m_W^2}\right) \approx \sum_{k=u,c,t} V^{*}_{ks} V_{kb} \frac{m_k^2}{m_W^2}$$

$\varphi(x) = \mathrm{cte} + x + \mathcal{O}(x^2)$

⟶ **Top-quark dominates!**

[Intermezzo]: *"The unbelievably heavy top quark..."*

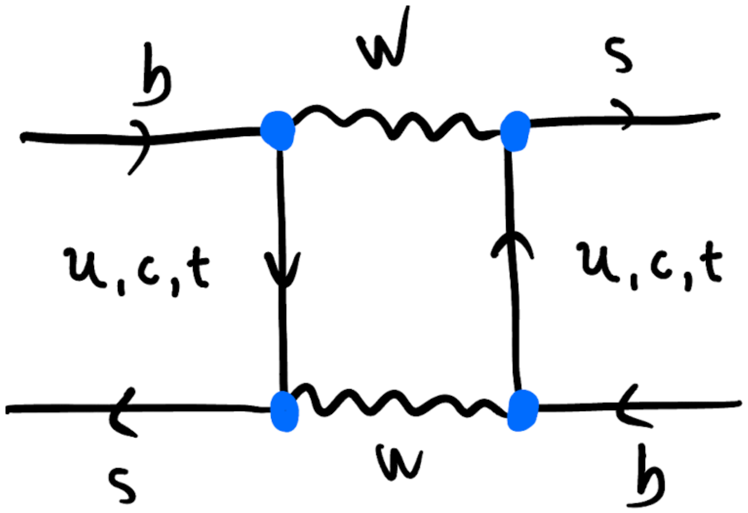
PLB 192 (1987)

OBSERVATION OF B^0–$\bar{B}^0$ MIXING

ARGUS Collaboration

In summary, the combined evidence of the investigation of B^0 meson pairs, lepton pairs and B^0 meson–lepton events on the Υ (4S) leads to the conclusion that B^0–$\bar{B}^0$ mixing has been observed and is substantial.

Parameters	Comments
$r > 0.09$ (90%CL)	this experiment
$x > 0.44$	this experiment
$B^{1/2} f_B \approx f_\pi < 160$ MeV	B meson ($\approx$ pion) decay constant
$m_b < 5$ GeV/c^2	b-quark mass
$\tau < 1.4 \times 10^{-12}$ s	B meson lifetime
$\lvert V_{td} \rvert < 0.018$	Kobayashi–Maskawa matrix element
$\eta_{QCD} < 0.86$	QCD correction factor [a]
$m_t > 50$ GeV/c^2	t quark mass



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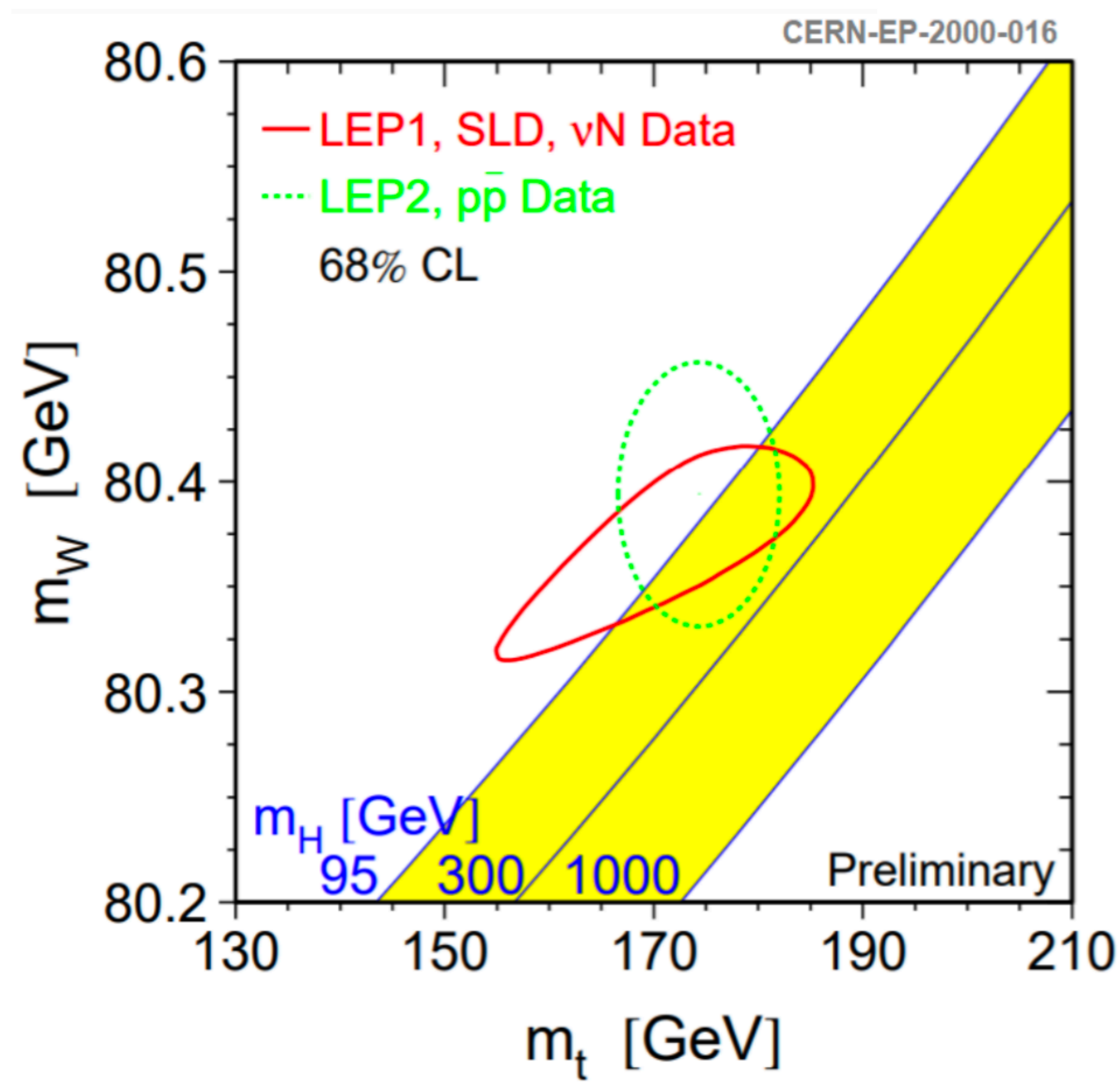
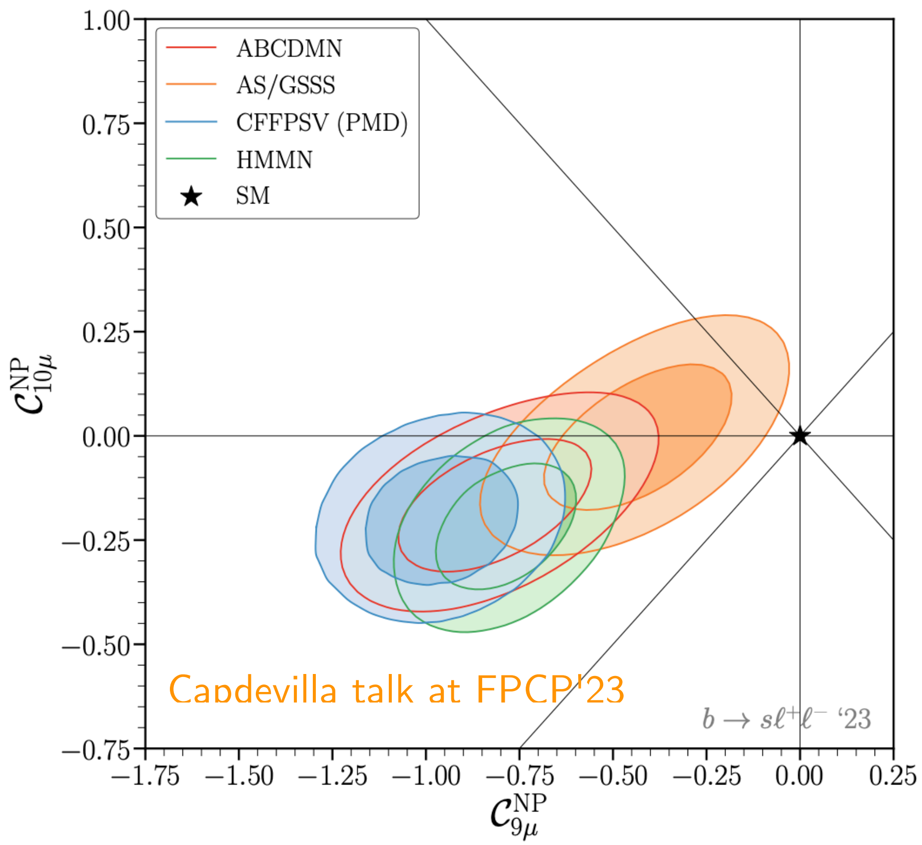


<u>Combined effort</u>: flavor, electroweak and high-energy searches

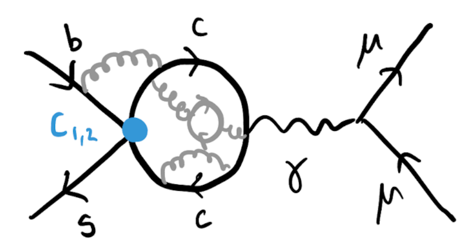
Anomalies in $B \to K^{(*)}\ell\ell$ decays?

- $B \to K^{(*)}\mu\mu$ observables show a preference for $\delta C_{9_\mu} < 0$:

$$\mathcal{O}_{9\ell} = (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_\mu \ell)$$
$$\mathcal{O}_{10\ell} = (\bar{s}_L \gamma^\mu b_L)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$



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



see e.g. [Ciuchini et al'. '21, Gubernari et al. '22, Isidori et al. '24]...

- LFU observables are unaffected by these uncertainties, but (now) in agreement with the SM:

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)} \overset{\text{exp}}{\simeq} 1.0 \pm 0.1 \quad \longrightarrow \quad \frac{|\mathcal{C}_{\not{\text{LFU}}}|}{\Lambda^2} \lesssim (60~\text{TeV})^{-2}$$

[LHCb, '22,'25], cf. backup

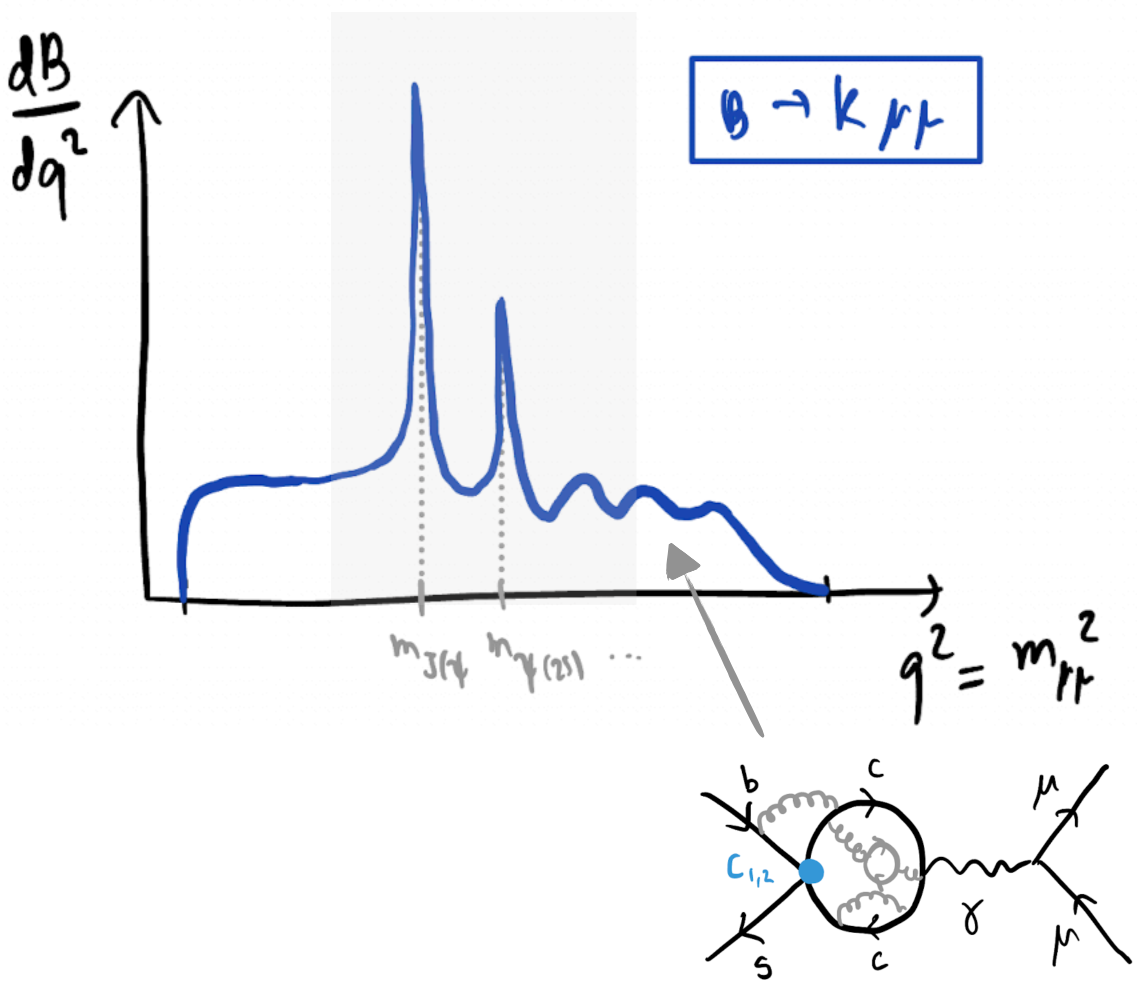
There is still room for exp. improvement before reaching the $\mathcal{O}(1\,\%)$ th. precision of **LFU tests!**

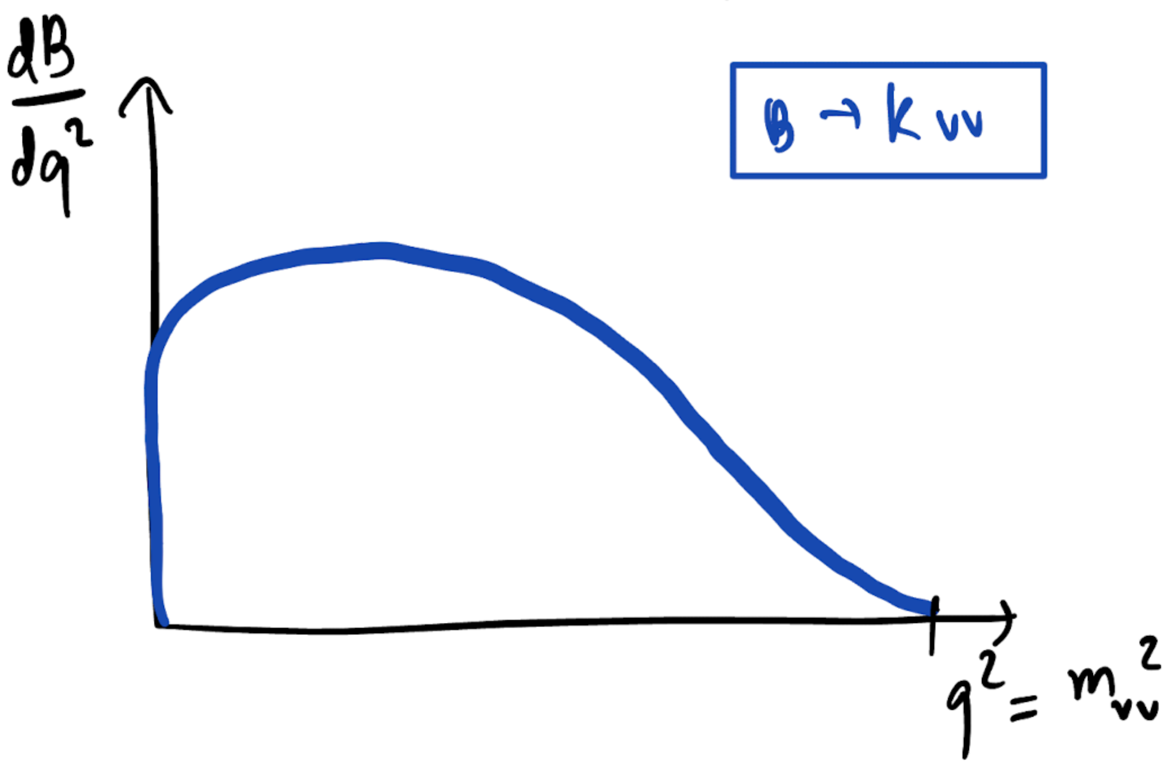
[Bordone et al. '16], [Isidori et al. '20,'22]

Why to study B-decays with neutrinos?

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

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





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

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

- **Effective Hamiltonian** within the SM:

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

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

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

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

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

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]

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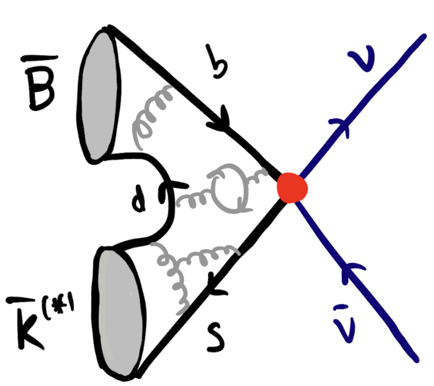
Two main sources of uncertainties:

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

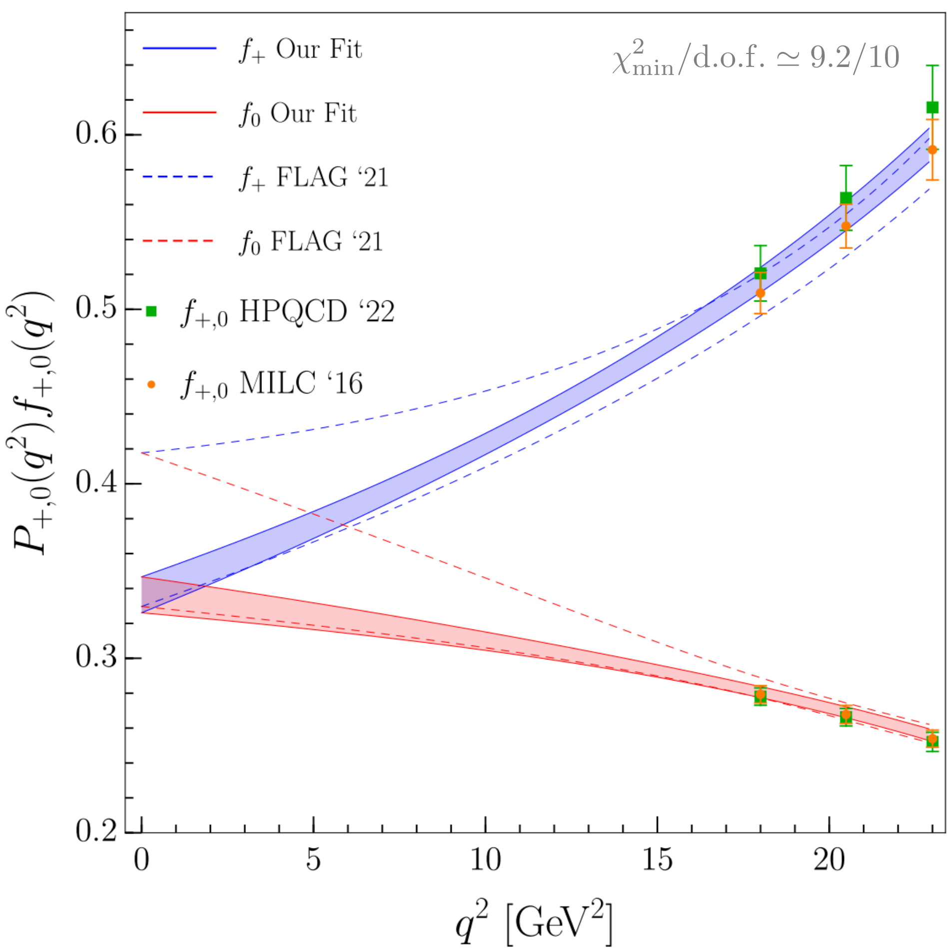
- **Lattice QCD** data available at **nonzero recoil** ($q^2 \neq q^2_{\text{max}}$) for all form-factors:

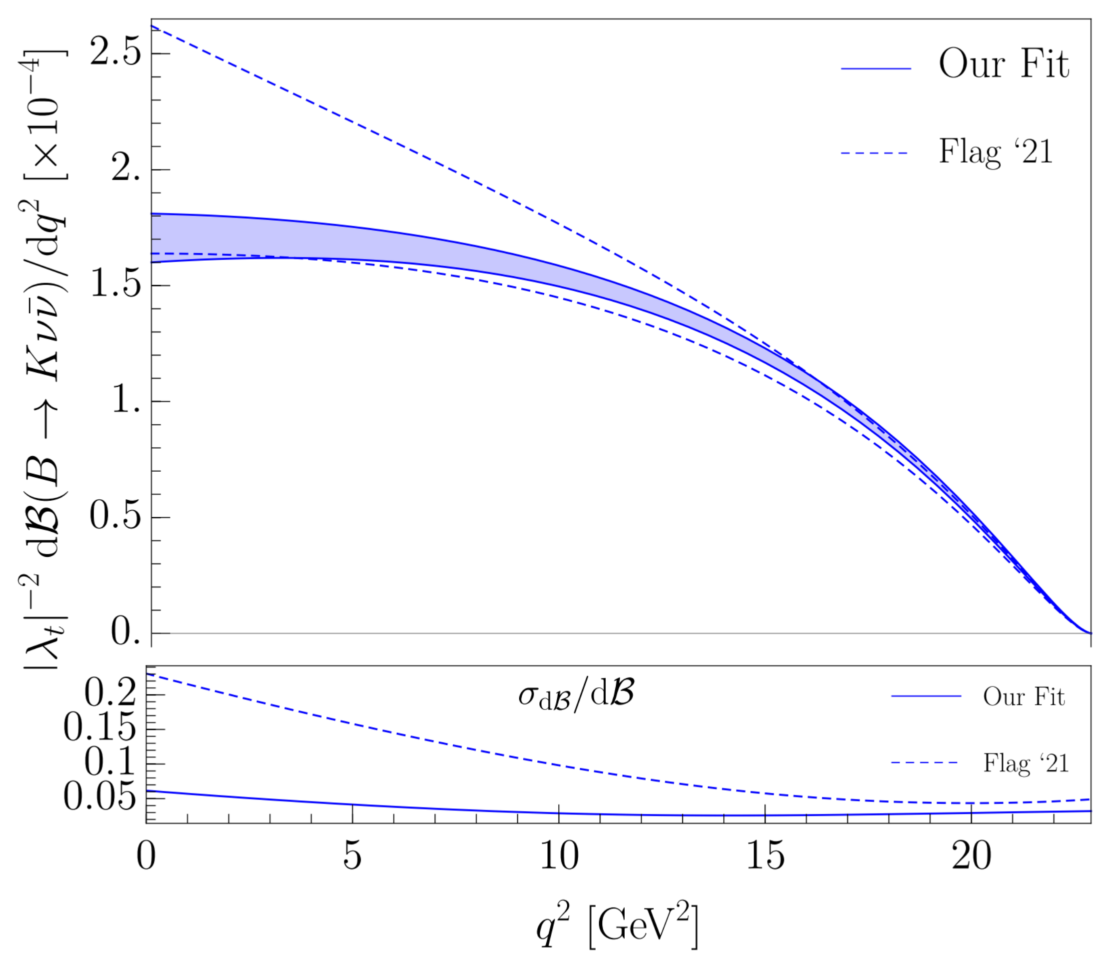
$$\langle K(k)|\bar{s}\gamma^\mu b|B(p)\rangle = \left[(p+k)^\mu - \frac{m_B^2 - m_K^2}{q^2} q^\mu\right] f_+(q^2) + q^\mu \frac{m_B^2 - m_K^2}{q^2} f_0(q^2)$$

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]:





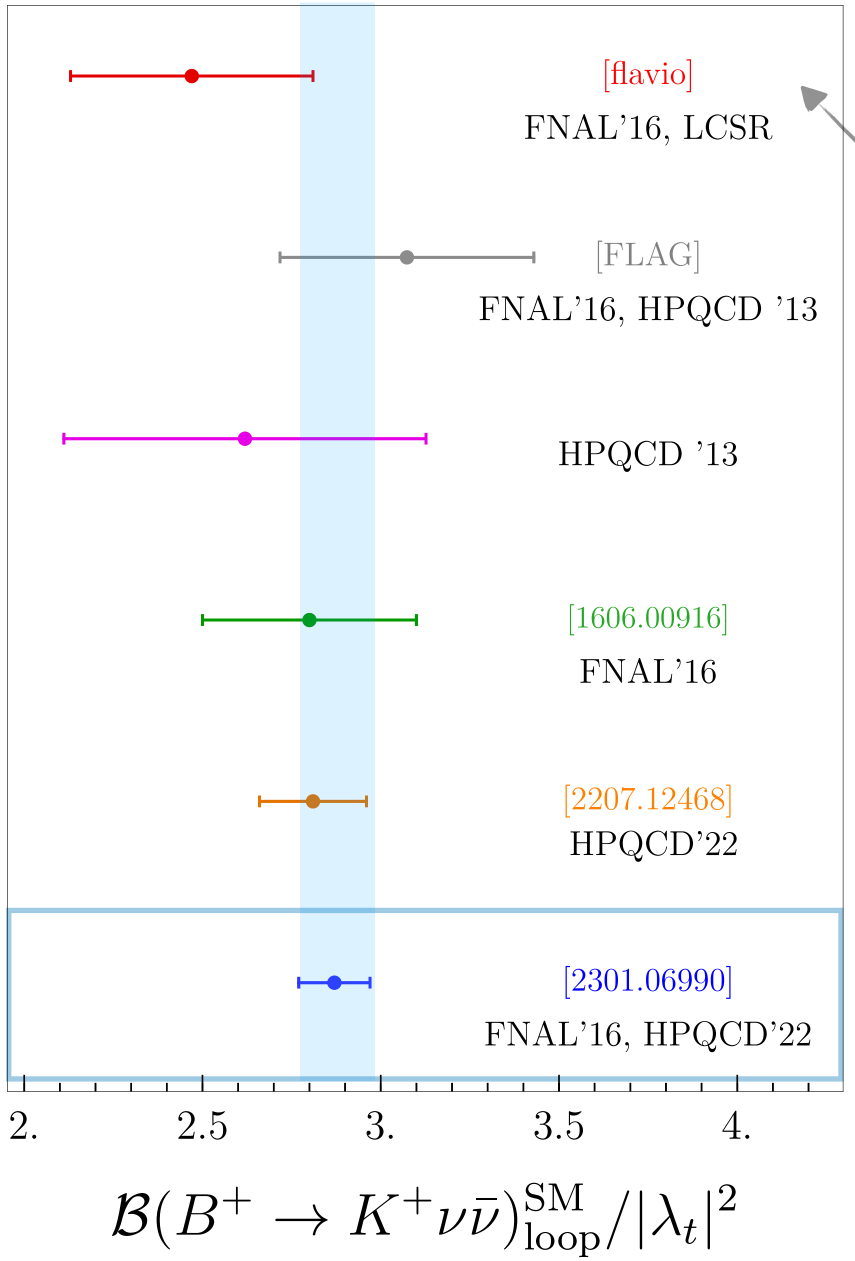
Pole factor:

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

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

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

**Annihilation contributions not included below (see back-up)*



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

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

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

[$\approx 3\,\%$ uncertainty]

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

[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!*

⇒ *New Physics effects would cancel out in this ratio as well — provided that NP is heavy.*

See next slides!

- For instance, 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:

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

Binned measurements at Belle-II would be a **useful cross-check** of the **consistency** of the q^2**-shape** of **SM predictions**.

II. Which CKM value?

See talks by Bona and Dorigo

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

- 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]

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

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

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

[Buras, Venturini. '21, '22]

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

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

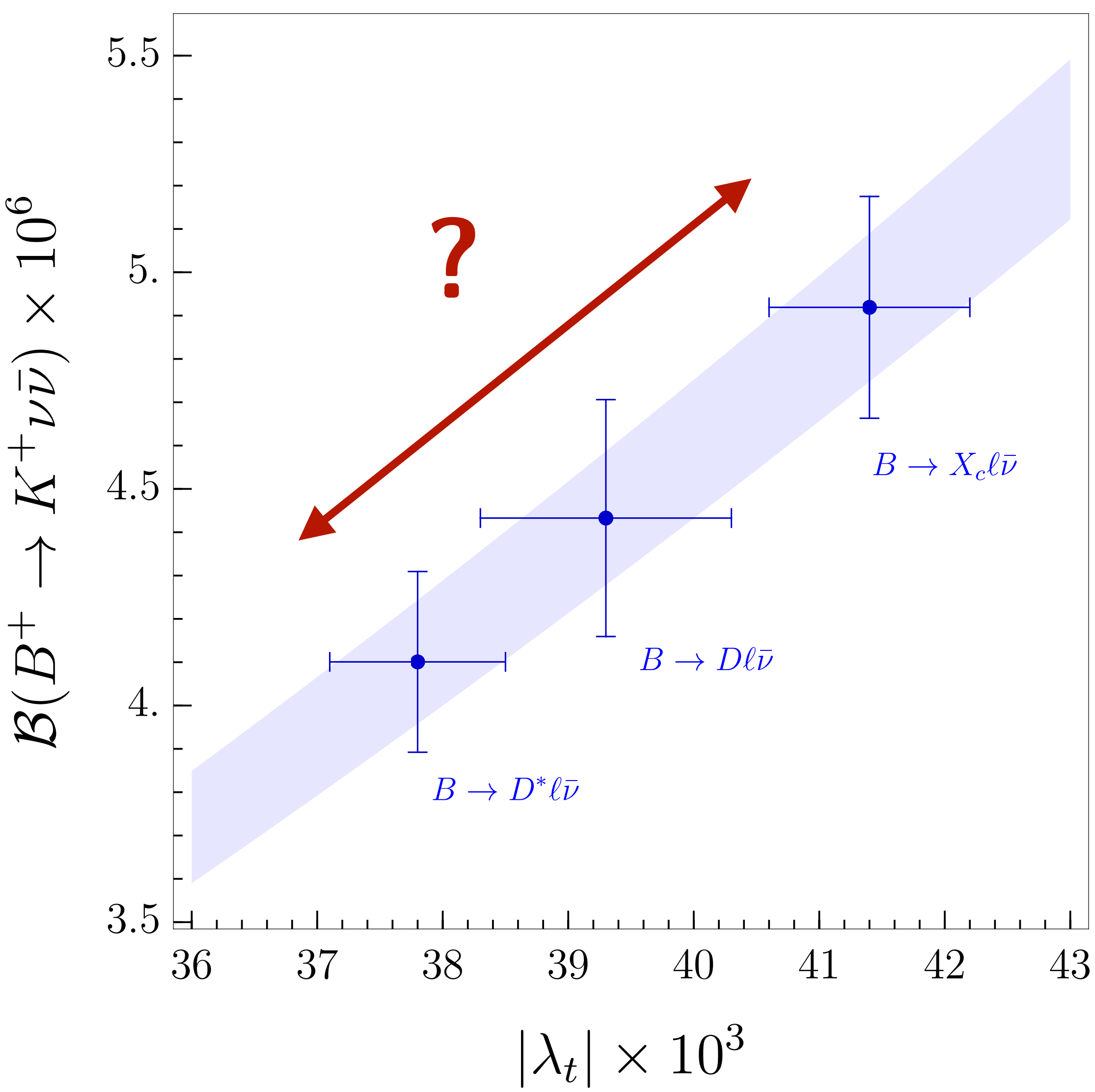
[HPQCD '19]

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

[FLAG '21]

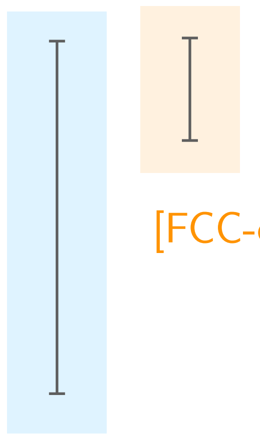
There is **not a clear answer** to this **ambiguity** so far.

CKM and theory uncertainties



[Becirevic, Piazza, **OS**. '23]

see also [Buras et al. '21, '22]



[FCC-ee projection] [Amhis et al. '23]

[Belle-II projection (50 ab^{-1})] [Kou et al. '18]

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

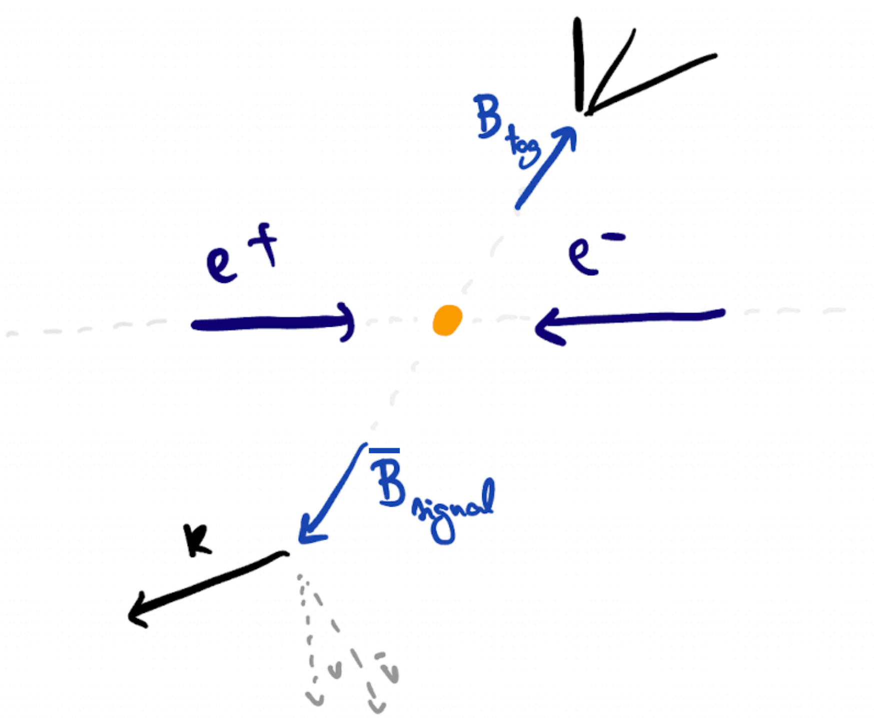
The **ambiguity** in **determining** V_{cb} can be a **bottleneck** for **SM predictions** of **clean FCNC processes** such as $B \to K\nu\bar{\nu}$ [Belle-II] and $B_s \to \mu\mu$ [LHCb, CMS, ATLAS] in the long term.

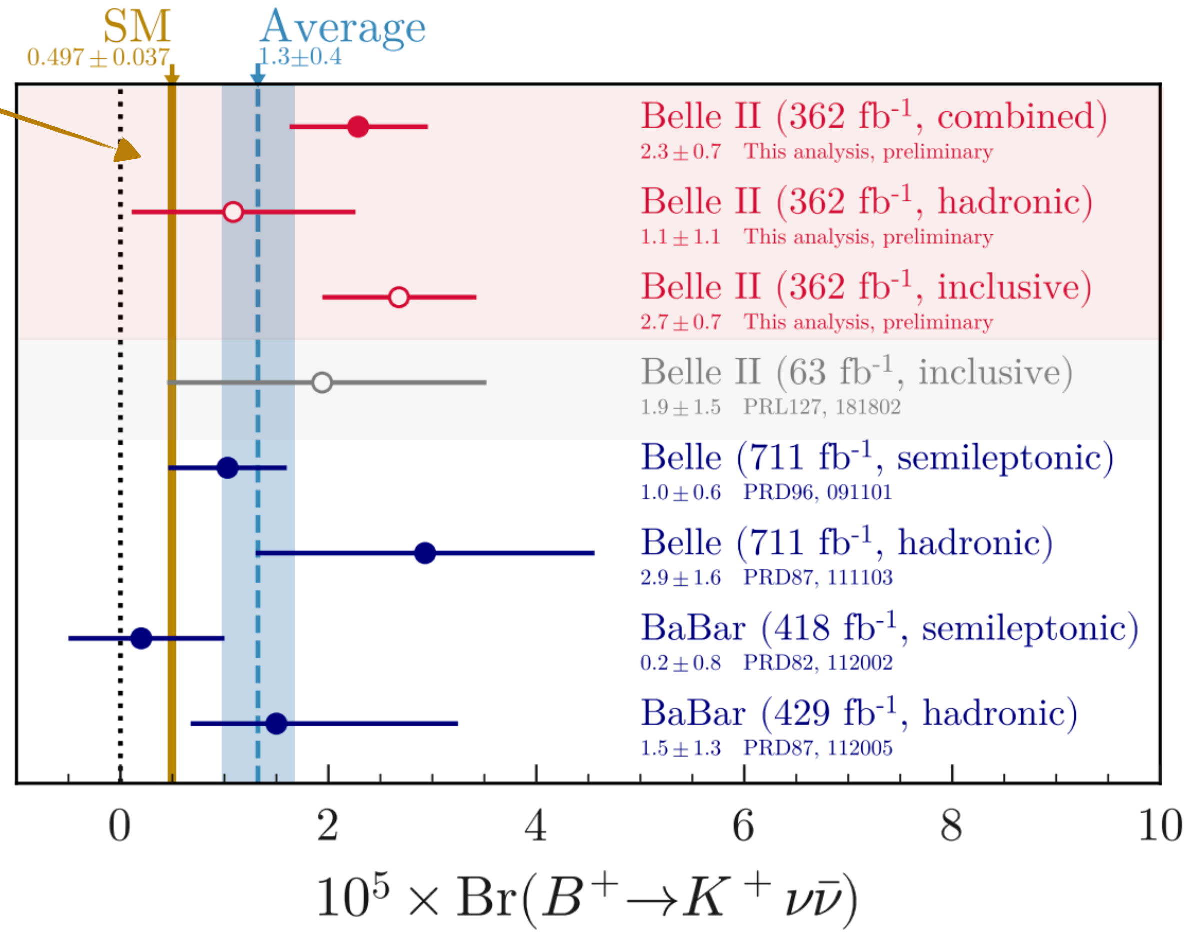
First lessons from Belle-II data

[NEW] Belle-II results

[Belle-II, 2311.14647]

Theory uncertainty sub-dominant (thus far!)





New Belle-II results

First Belle-II result

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

$\approx 3\sigma$ 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).

Several observables to be further explored: $\mathscr{B}(B^0 \to K_S \nu\nu)$, $\mathscr{B}(B \to K^* \nu\nu)$ **and** $F_L(B \to K^* \nu\nu)$

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

- Low-energy EFT:

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

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

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

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

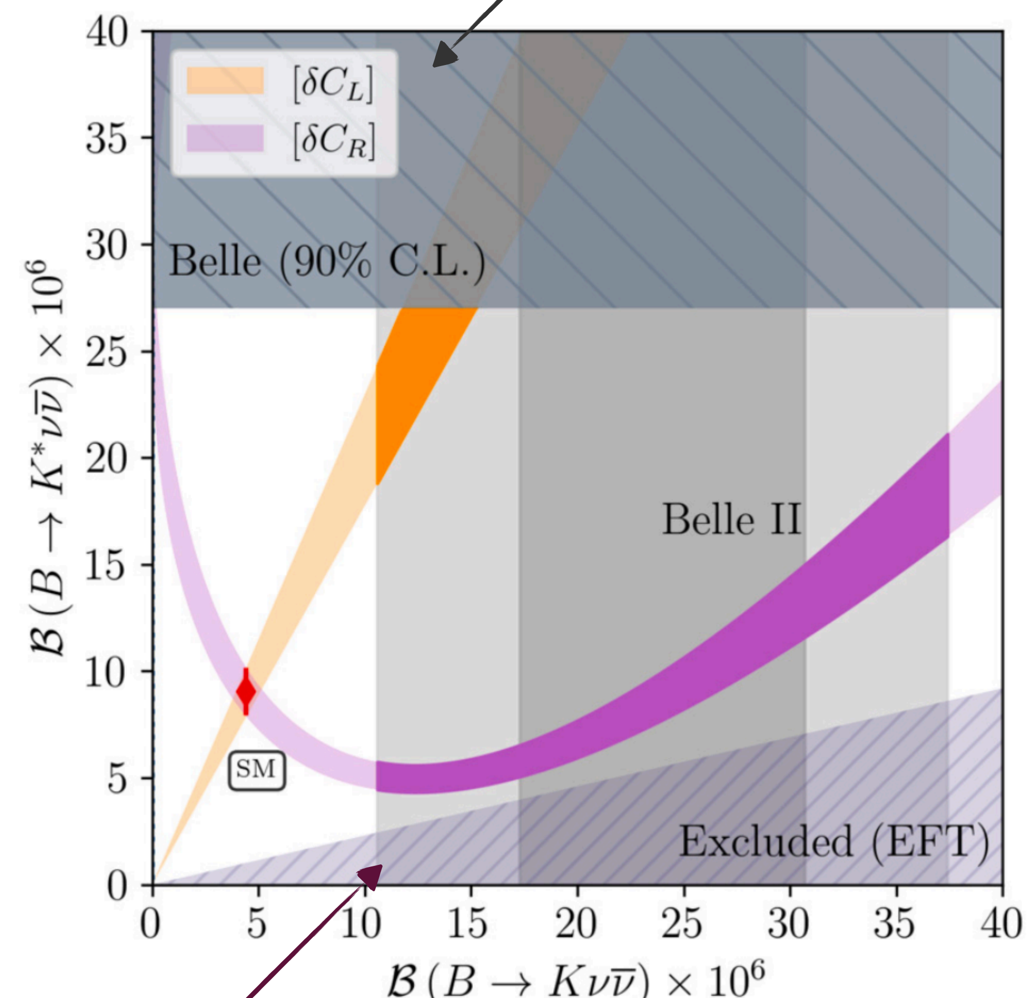
$$\frac{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})^{\rm SM}} = 1 + \sum_i \frac{2\mathrm{Re}[C_L^{\rm SM}(\delta C_L^{\nu_i\nu_i} + \delta C_R^{\nu_i\nu_i})]}{3|C_L^{\rm SM}|^2} + \sum_{i,j}\frac{|\delta C_L^{\nu_i\nu_j} + \delta C_R^{\nu_i\nu_j}|^2}{3|C_L^{\rm SM}|^2}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

$\eta_K = 0$

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

[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]

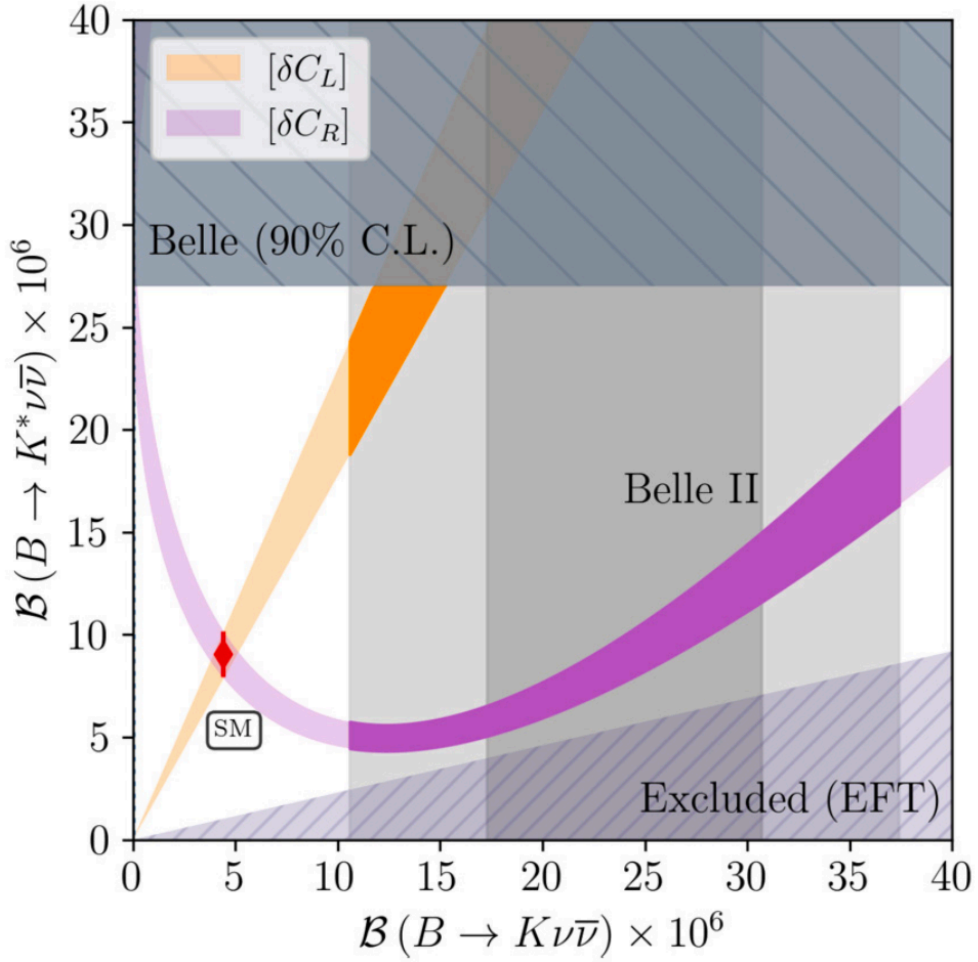
- Another observable to measure is the K^* longitudinal-polarisation asymmetry:

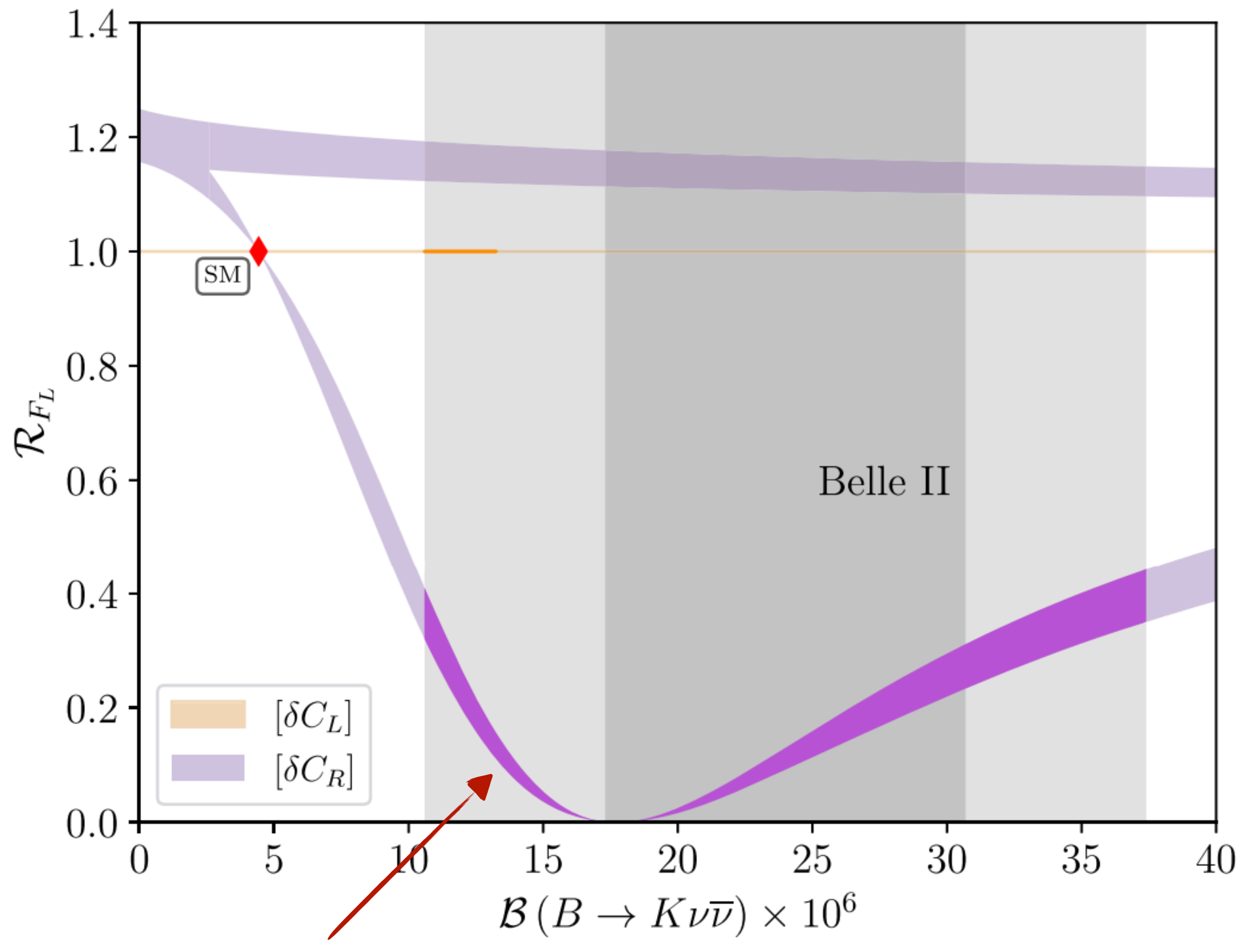
$$F_L \equiv \frac{\Gamma_L(B\to K^*\nu\bar\nu)}{\Gamma(B\to K^*\nu\bar\nu)}$$

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

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

[Altmannshofer et al. '09]





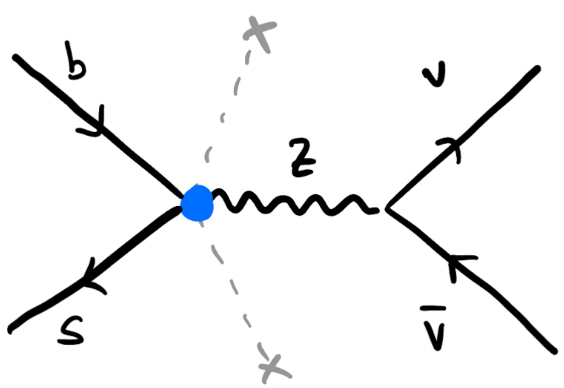
Depletion of SM prediction!

The measurements of $\mathscr{B}(B\to K^*\nu\bar\nu)$ and $F_L(B\to K^*\nu\bar\nu)$ would be **model-independent tests**!

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

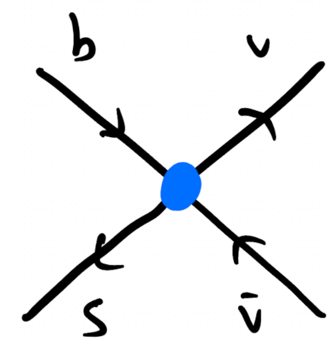


e.g.,

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

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]

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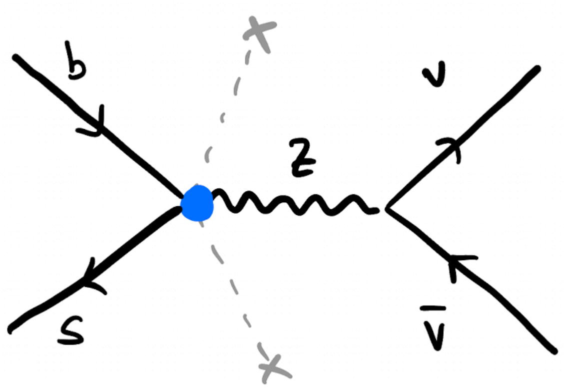
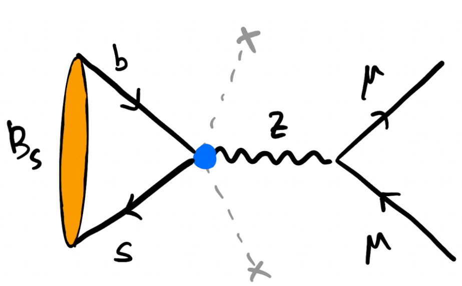


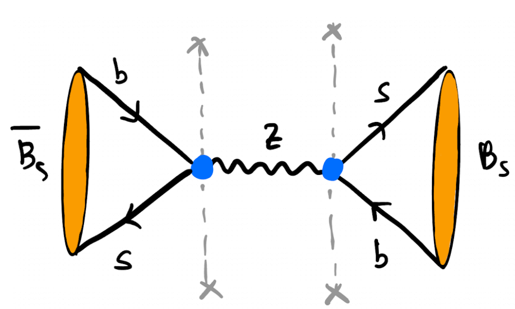
e.g.,

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

Lepton flavor universal!

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





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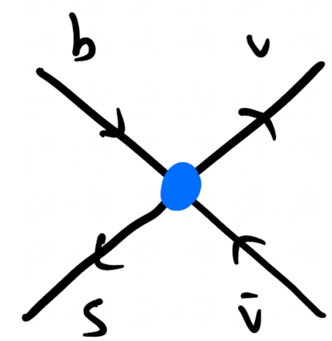

e.g.,

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

$\Rightarrow$ **Only viable option!**

$$\frac{\mathcal{C}_{bs\nu\nu}}{\Lambda^2} \simeq (5\ \text{TeV})^{-2}$$

[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 $SU(2)_L \times U(1)_Y$:

$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{Q}_k\gamma_\mu Q_l)$$

$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\overline{L}_i\gamma^\mu\tau^I L_j)(\overline{Q}_k\tau^I\gamma_\mu Q_l)$$

$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{d}_k\gamma_\mu d_l)$$

$$[\mathcal{O}_{eq}]_{ijkl} = (\overline{e}_i\gamma^\mu e_j)(\overline{Q}_k\gamma_\mu Q_l)$$

$$[\mathcal{O}_{ed}]_{ijkl} = (\overline{e}_i\gamma^\mu e_j)(\overline{d}_k\gamma_\mu d_l)$$

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

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

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

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

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

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

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

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

Which flavor?

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

i. *Couplings to muons* are *tightly constrained* by $\mathcal{B}(B_s \to \mu\mu)$ and $R_{K^{(*)}}$. ✗

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

⇒ **Predictions:**

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

However, **experimentally challenging**...

see e.g. Capdevilla et al. '17

[Intermezzo]: $B_s \to \tau\tau$ and $B \to K^{(*)}\tau\tau$

- **Motivated** by **New Physics** scenarios with **hierarchical flavor structure**; potential explanation of the discrepancies in $b \to s\mu\mu$ data. [Crivellin et al. '18, Cornella et al. '20]
- **But... extremely difficult measurement!**

Exp. (90%CL.):

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

$\mathcal{B}(B^+ \to K^+\tau\tau) < 0.56 \times 10^{-3}$ [Belle-II. '26]

$\mathcal{B}(B^0 \to K^*\tau\tau) < 2.5 \times 10^{-4}$ [LHCb. '25]

vs.

SM predictions:

$\mathcal{B}_{\text{SM}} \approx 10^{-7}$

see e.g. [Capdevilla et al. '17]

Effectively, "null tests" for NP effects given the current exp. sensitivity!

Current reach:

$$\frac{|\mathcal{C}_{bs\tau\tau}|}{\Lambda^2} \lesssim (1.8\ \text{TeV})^{-2}$$

Opportunity for LHC searches with τ-leptons!

see e.g. [Faroughy et al. '16], [Allwicher et al. **(OS)**, 22]

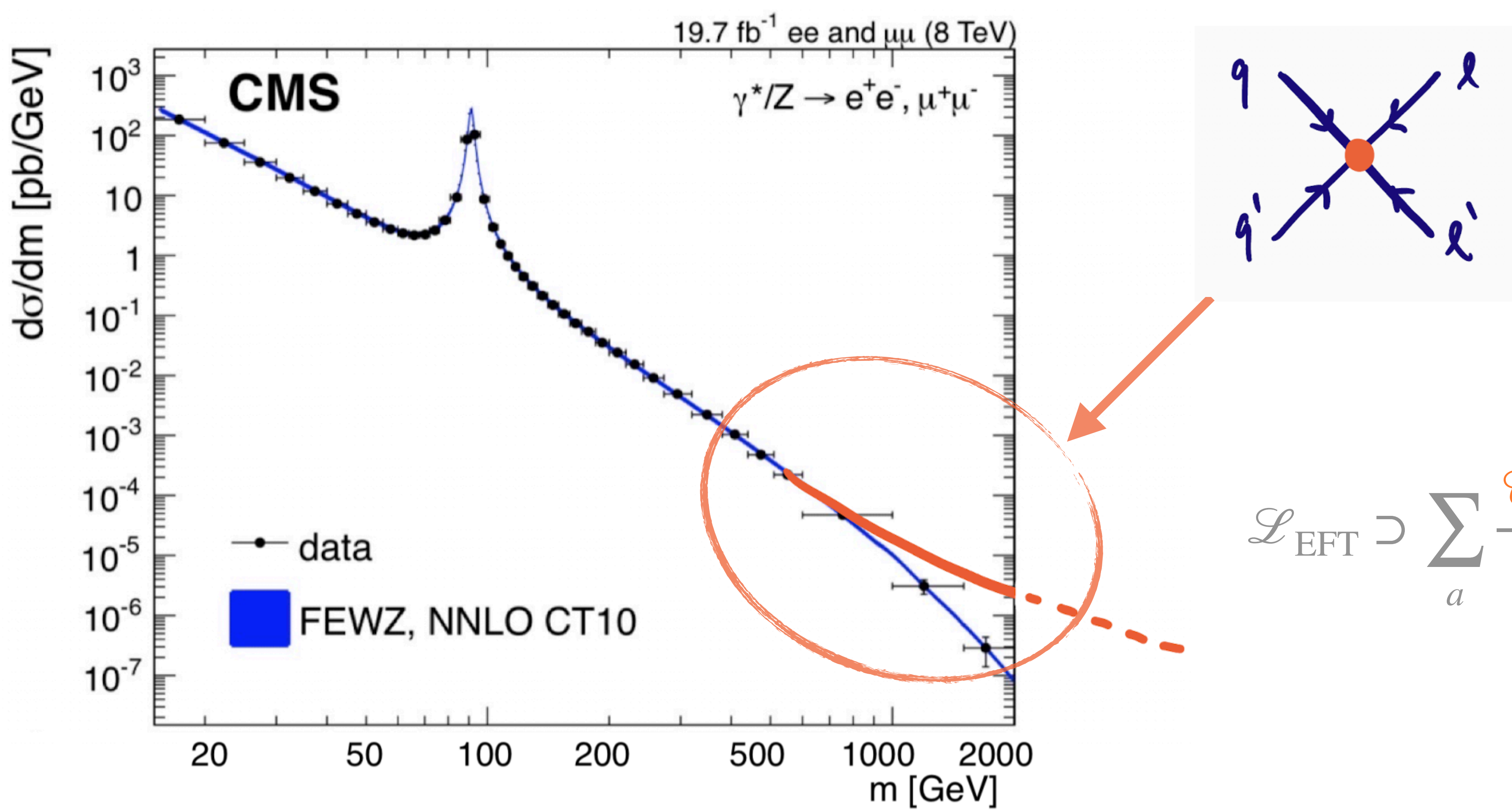
Summary I

- $B \to K^{(*)}\nu\nu$: rather theoretically clean and very sensitive to NP effects — *in particular, to operators with 3rd generation leptons*!
- **Hadronic uncertainties:** nonperturbative QCD effects remain the main obstacle to using low-energy observables to probe new physics — *caution is (always) advised*!
- **Differential distributions:** the precise measurement of $\mathrm{d}\mathcal{B}/\mathrm{d}q^2$ could provide a helpful cross-check of the relevant form-factors, and a potential probe of EFT scenarios with light NP.
- V_{cb}: 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.
- **Belle-II:** More data and further cross-checks are needed to understand the first Belle-II results — *e.g.,* $B^0 \to K_S\nu\bar{\nu}$, $B \to K^*\nu\bar{\nu}$ *and* $F_L(B \to K^*\nu\bar{\nu})$.

Many opportunities to explore physics (B)SM with Belle-II!

LHC probes of flavor

Non-resonant searches at the LHC

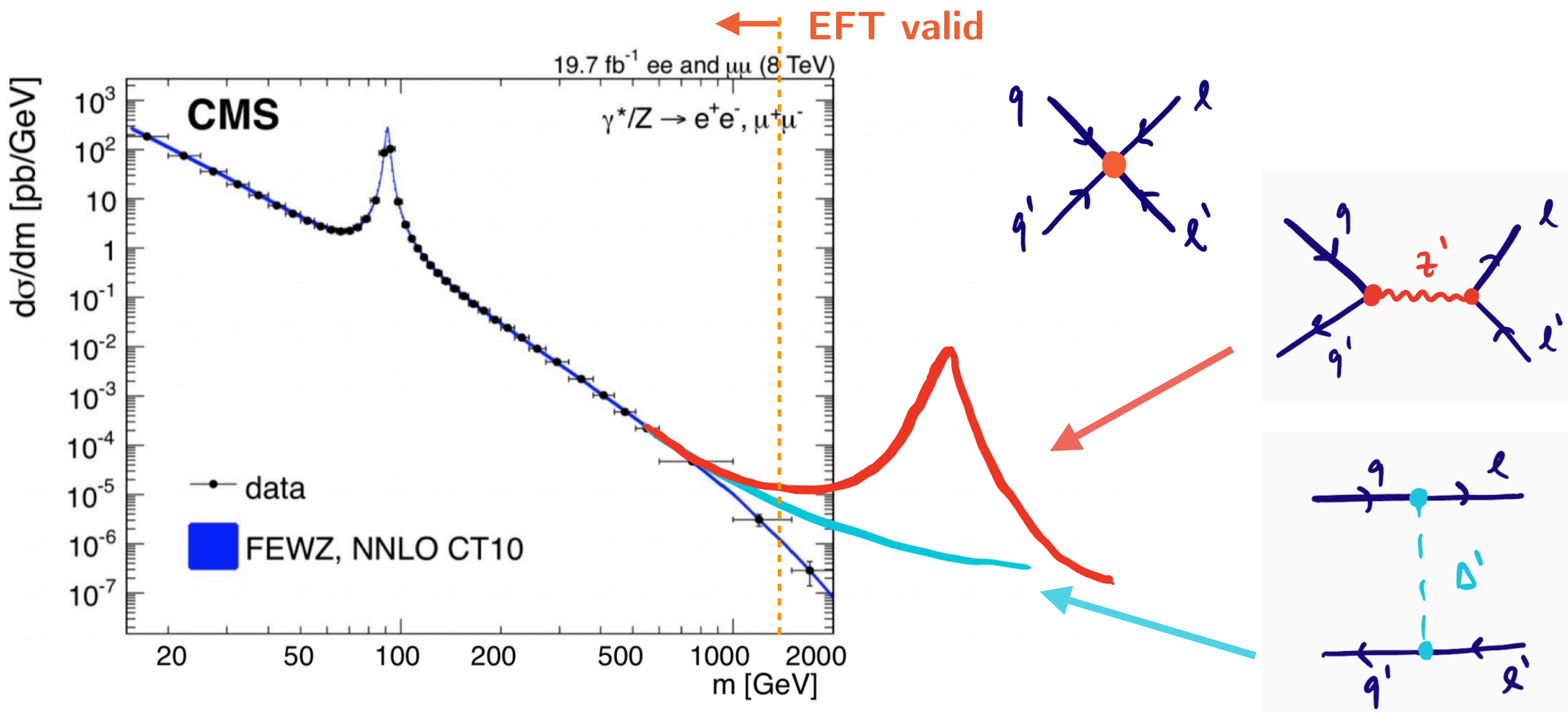


$$\mathscr{L}_{\text{EFT}} \supset \sum_a \frac{\mathscr{C}_a^{(6)}}{\Lambda^2}\mathscr{O}_a^{(6)} + \dots$$

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

Goal: Probe transitions that are **poorly unconstrained** at **low energies** — *including* ***flavor!***

Non-resonant searches at the LHC



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Goal: **Probe transitions** that are **poorly unconstrained** at **low energies** — *including* ***flavor!***

Caveat: Check that the **EFT** is indeed **valid** ($E \ll \Lambda$) — *or, use instead a concrete model.*

LHC as a flavor experiment

i) LHC collides quarks with five flavors

Parton luminosities

Partonic cross-section

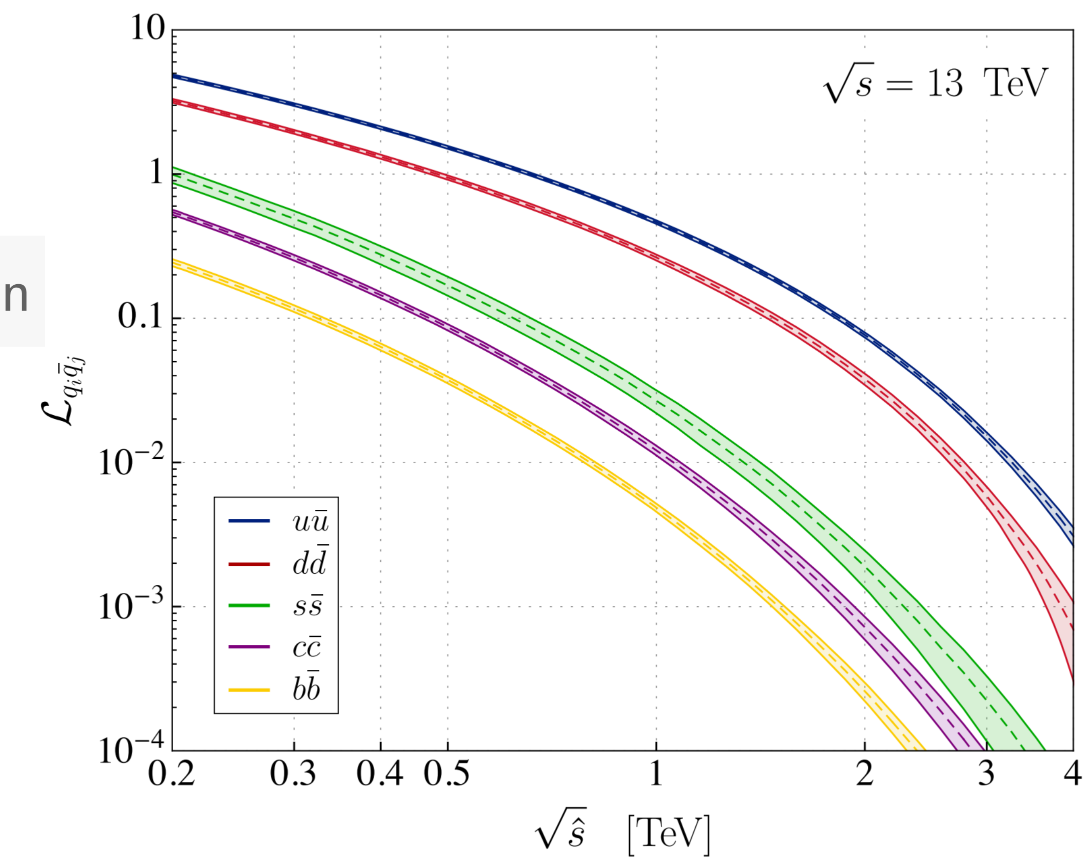
$$\sigma(pp \to \ell\ell') = \sum_{ij} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{q_i \bar{q}_j}(\tau)\, \hat{\sigma}(q_i \bar{q}_j \to \ell\ell')_{\hat{s}=s\tau}$$

$\tau = \hat{s}/s$

$\hat{s} = m_{\ell\ell'}^2$

$\sqrt{s} = 13$ TeV

[PDF4LHC15_nnlo_mc]



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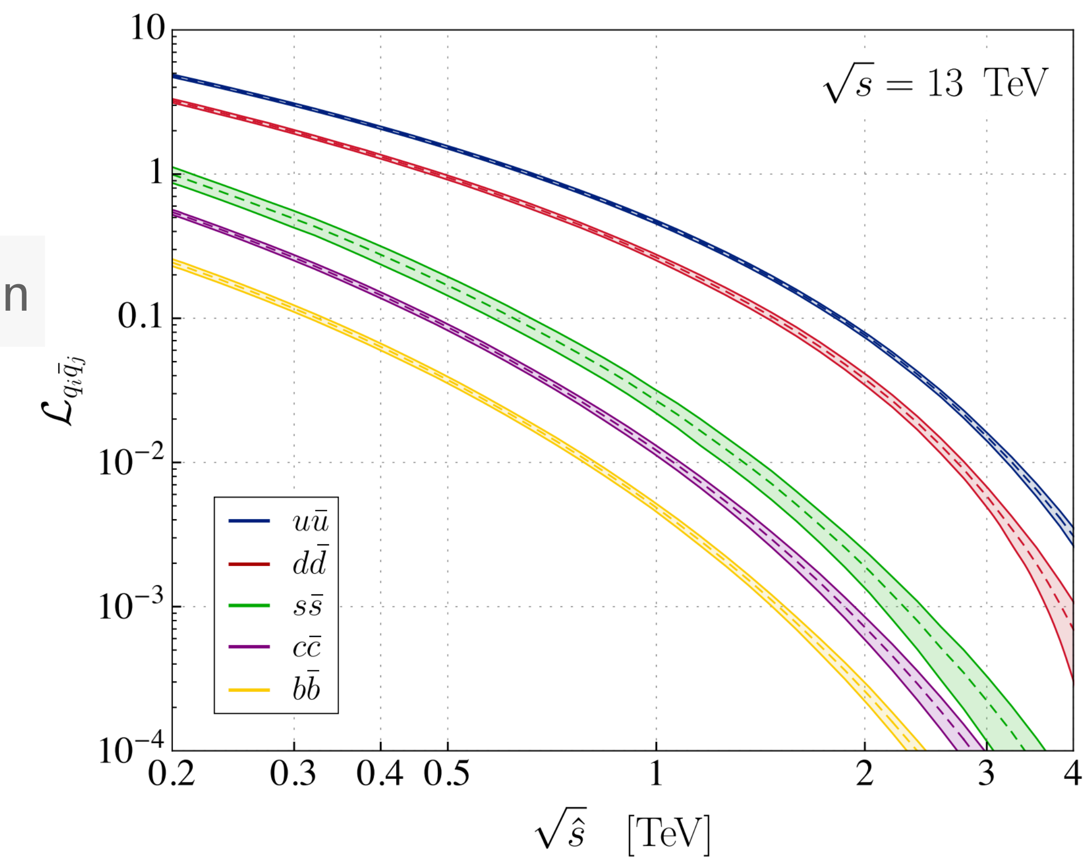

ii) Energy helps precision

cf. e.g. [Farina et al. '16]

$$\mathcal{L}_{\text{eff}} \supset \frac{\mathcal{C}^{(6)}}{\Lambda^2}\mathcal{O}^{(6)} + \ldots \quad \xrightarrow{(\sqrt{\hat{s}} \ll \Lambda)} \quad \hat{\sigma} = \hat{\sigma}_{\text{SM}} + \hat{\sigma}_{\text{int}} + \hat{\sigma}_{\text{NP}^2}$$

$\propto \frac{1}{\hat{s}}$ $\quad \propto \frac{1}{\Lambda^2}\text{Re}(\mathcal{C}^{(6)})$ $\quad \propto \frac{\hat{s}}{\Lambda^4}|\mathcal{C}^{(6)}|^2$

Energy-growth can partially **overcome** heavy-flavor **PDF suppression**.

SMEFT operators

- *Warsaw* basis $d = 6$ (2499 operators...) [Buchmuller, Wyler. '85], [Grzadkowski et al. '10]
- Operator classes contributing to $pp \to \ell\ell'$ at tree-level: ψ^4, $\psi^2 XH$, $\psi^2 D^2 H$

Dimension		$d = 6$			$d = 8$			
Operator classes		ψ^4	$\psi^2 H^2 D$	$\psi^2 XH$	$\psi^4 D^2$	$\psi^4 H^2$	$\psi^2 H^4 D$	$\psi^2 H^2 D^3$
Amplitude scaling		E^2/Λ^2	v^2/Λ^2	vE/Λ^2	E^4/Λ^4	$v^2 E^2/\Lambda^4$	v^4/Λ^4	$v^2 E^2/\Lambda^4$
Parameters	# $\mathbb{Re}$	456	45	48	168	171	44	52
	# $\mathbb{Im}$	399	25	48	54	63	12	12

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

*only $d = 8$ terms interfering with the SM

Too many operators...

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Dimension		$d=6$			$d=8$			
Operator classes		ψ^4	ψ^2H^2D	ψ^2XH	ψ^4D^2	ψ^4H^2	ψ^2H^4D	$\psi^2H^2D^3$
Amplitude scaling		E^2/Λ^2	v^2/Λ^2	vE/Λ^2	E^4/Λ^4	v^2E^2/Λ^4	v^4/Λ^4	v^2E^2/Λ^4
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[Allwicher, Faroughy, Jaffredo, **OS**, Wilsch. '22]

*only $d = 8$ terms interfering with the SM

Too many operators...

Usual strategies:

i) To invoke a *flavor symmetry* (*e.g.*, MFV, $U(2)^5$...) or a specific model.

see e.g. [Grunwald et al. '23, Greljo et al. '23]

ii) To focus on a *specific transition* and/or *subset of operators*.

Our approach: to automatize!

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.

MadGraph 5 + Pythia + Delphes

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

$pp \to \tau\tau$	[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]

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

[Allwicher, Cornella, Martines, **OS**, Wilsch. *In preparation*]

Vector

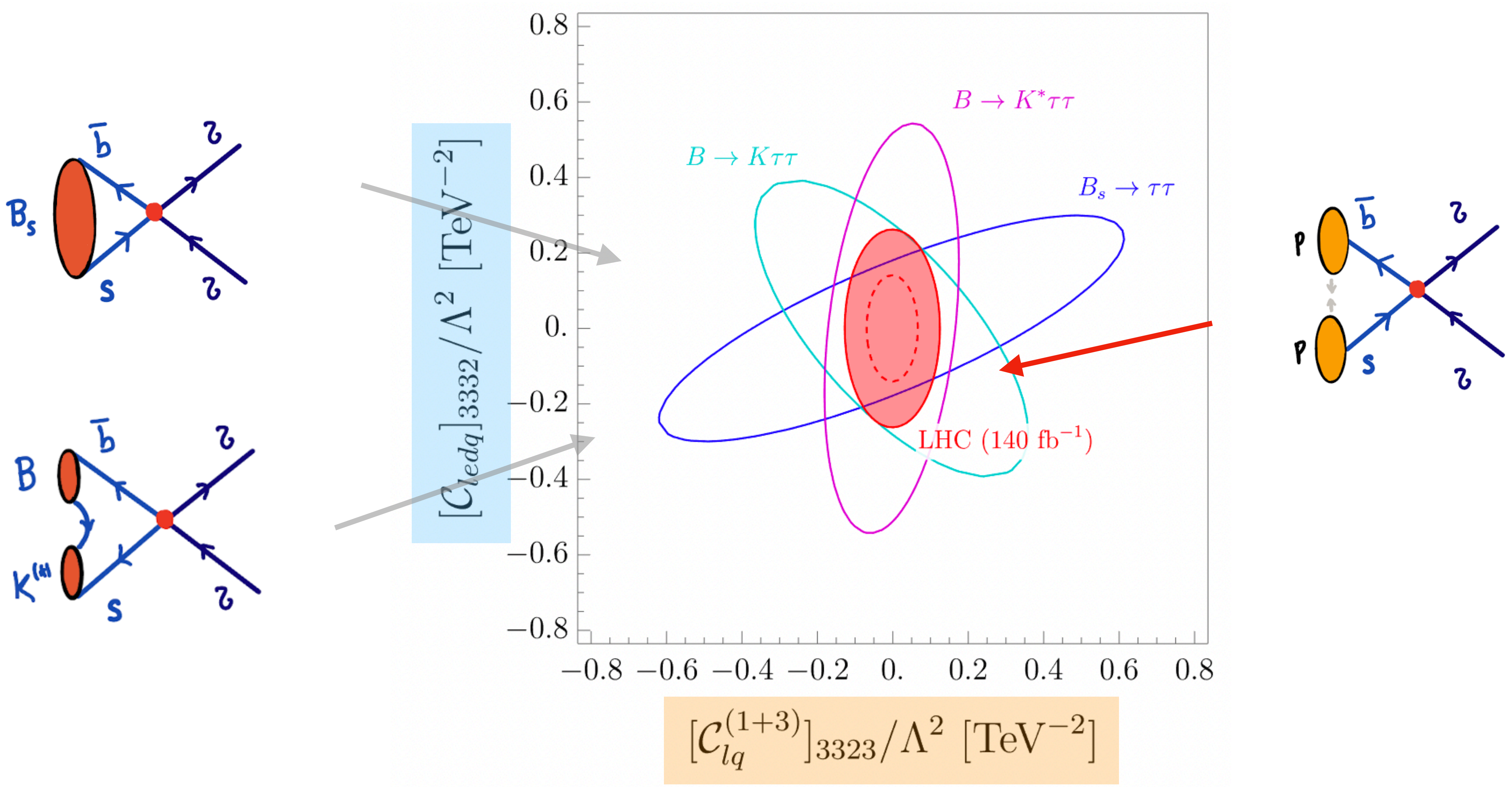
$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\bar{l}_i\gamma^\mu l_j)(\bar{q}_k\gamma_\mu q_l)$$

$$[\mathcal{O}_{lq}^{(3)}]_{ijkl} = (\bar{l}_i\gamma^\mu\tau^I l_j)(\bar{q}_k\gamma_\mu\tau^I q_l)$$

Scalar

$$[\mathcal{O}_{ledq}]_{ijkl} = (\bar{l}_i e_j)\epsilon(\bar{d}_k q_l) + \text{h.c.}$$

$$\dots$$

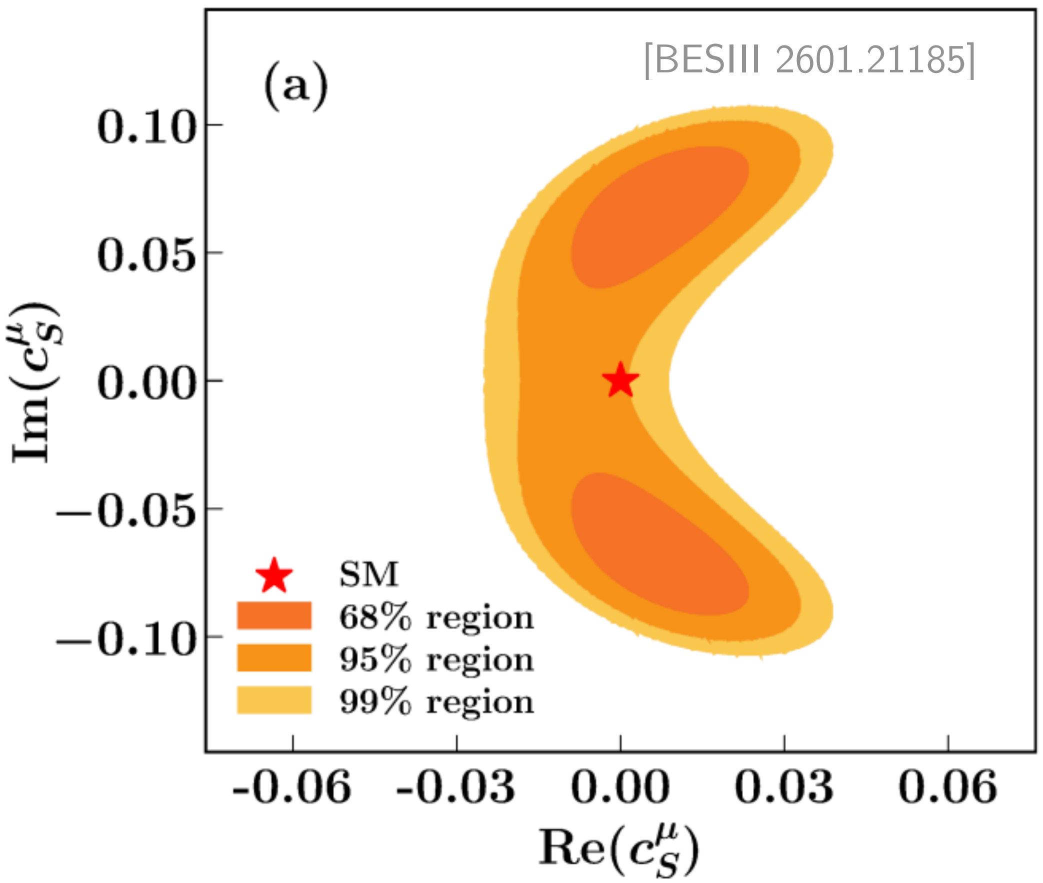


LHC provides competitive constraints — *to be improved at HL-LHC!*

Example II: charm semileptonic decays

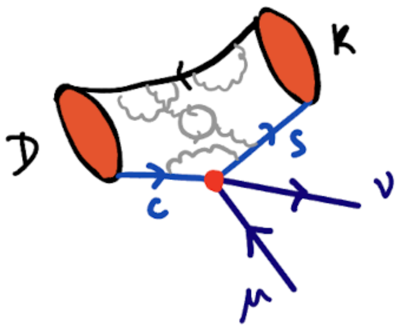
[Becirevic, Martines, Rosauro-Alcaraz, **OS**. *2605.XXXXX*]

Differential distributions of $D \to K\mu\nu$ decays show **mild discrepancies** wrt the SM:



$$O_S = (\bar{c}s)(\bar{\mu}_R \nu_L)$$

$c \to s\mu\nu$



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[Becirevic, Martines, Rosauro-Alcaraz, **OS**. 2603.XXXXX]

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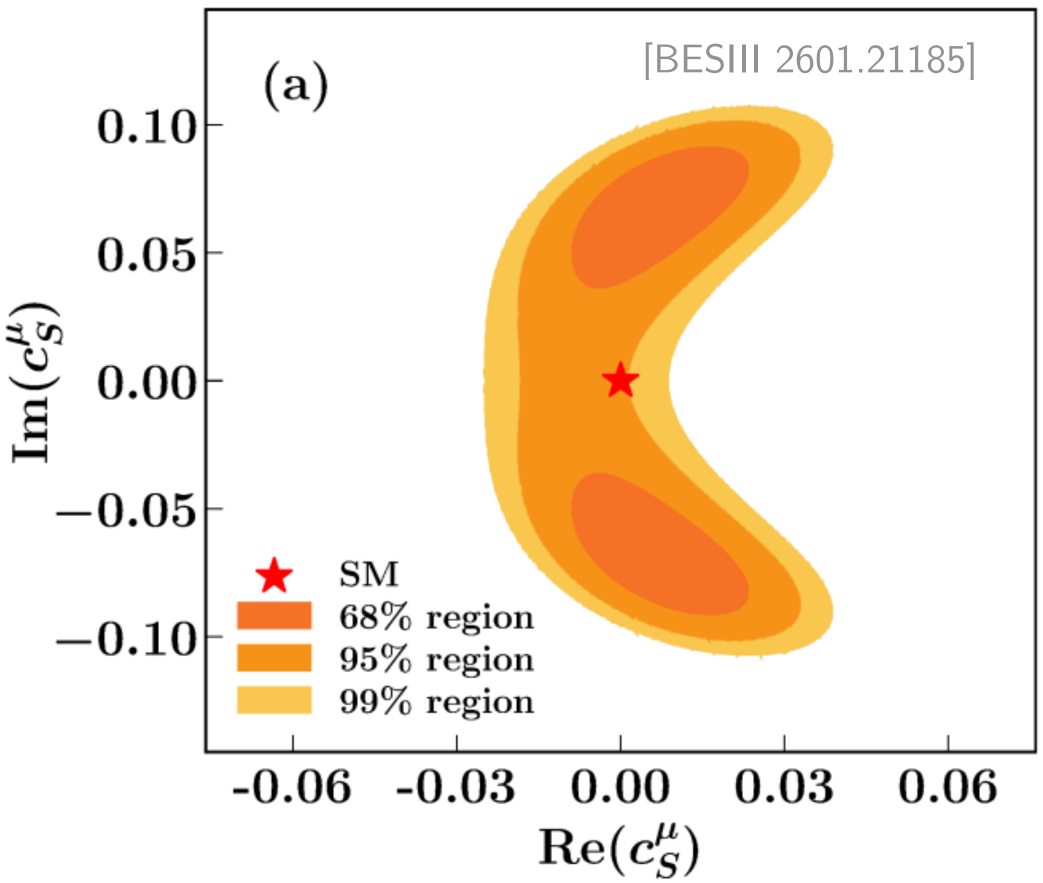
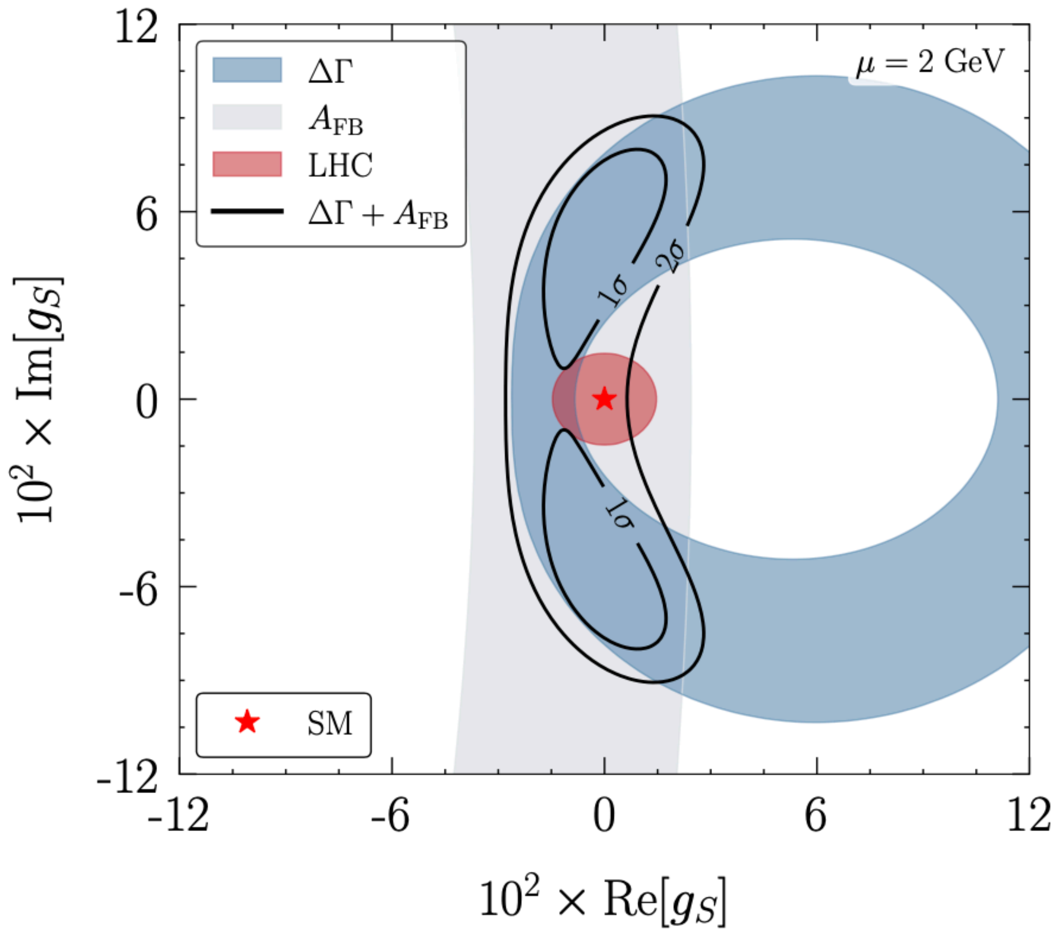
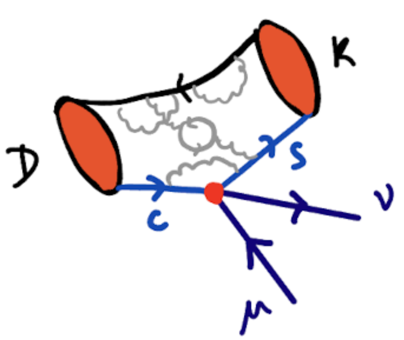
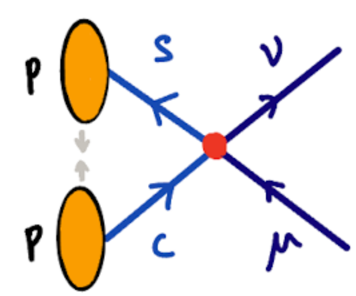




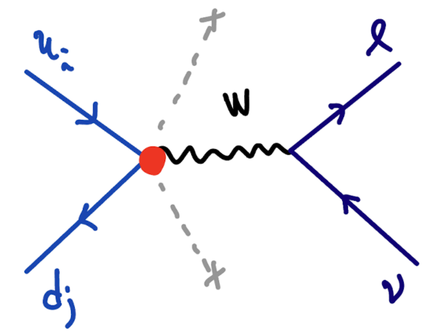
$c \to s\mu\nu$





Another example of the impact of LHC searches on flavor studies

Example III: right-handed currents

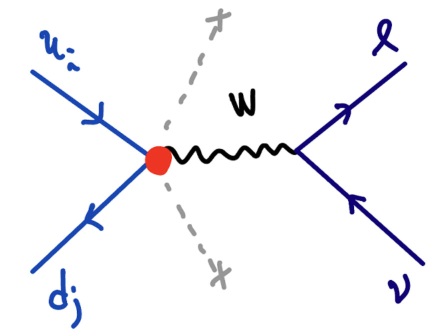


Charged-current RH operators are necessarily of type $\psi^2 D H^2$:

$$\left[\mathcal{O}_{Hud}\right]_{ij} = \left(H^\dagger D_\mu H\right)\left(\bar{u}_i \gamma^\mu d_j\right) + \text{h.c.} \longrightarrow \mathcal{L}_{\text{LEFT}} \supset g_{V_R}^{ij} \left(\bar{u}_{Ri}\gamma_\mu d_{Rj}\right)\left(\bar{\ell}_L \gamma^\mu \nu_L\right) + \text{h.c.}$$

⇒ **Suppressed contributions** to $pp \to \ell\nu$ at high-p_T due to W-boson propagator.

Example III: right-handed currents



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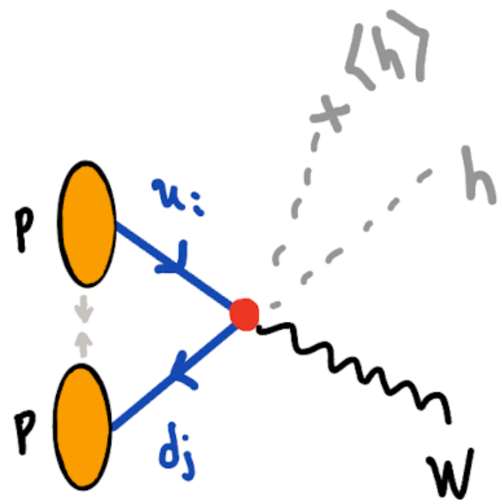
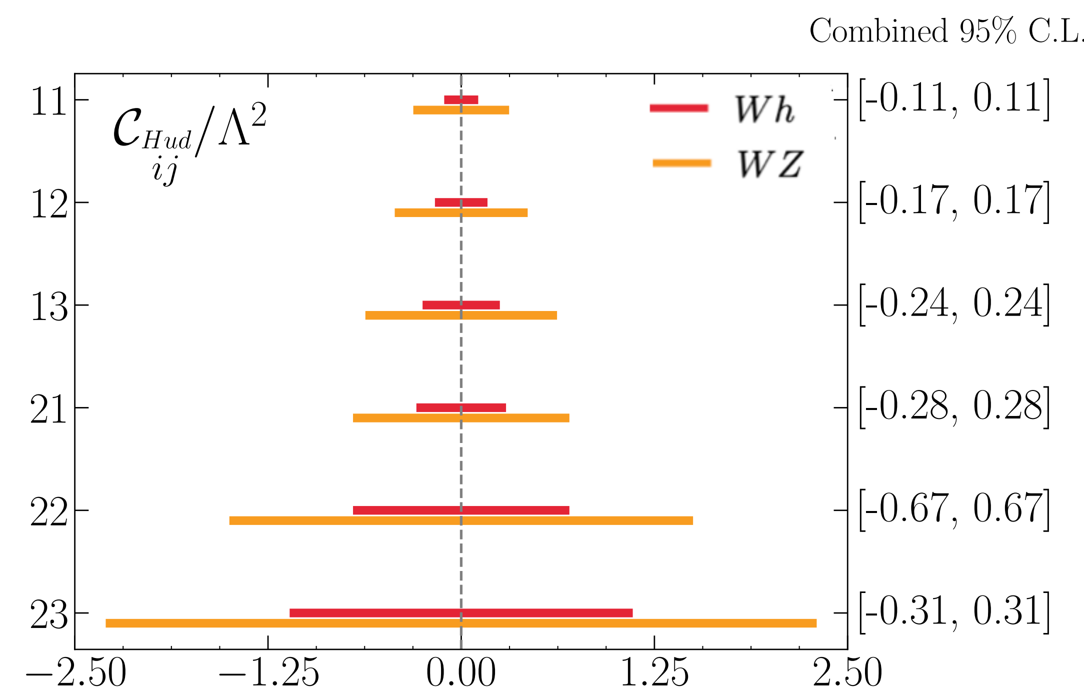
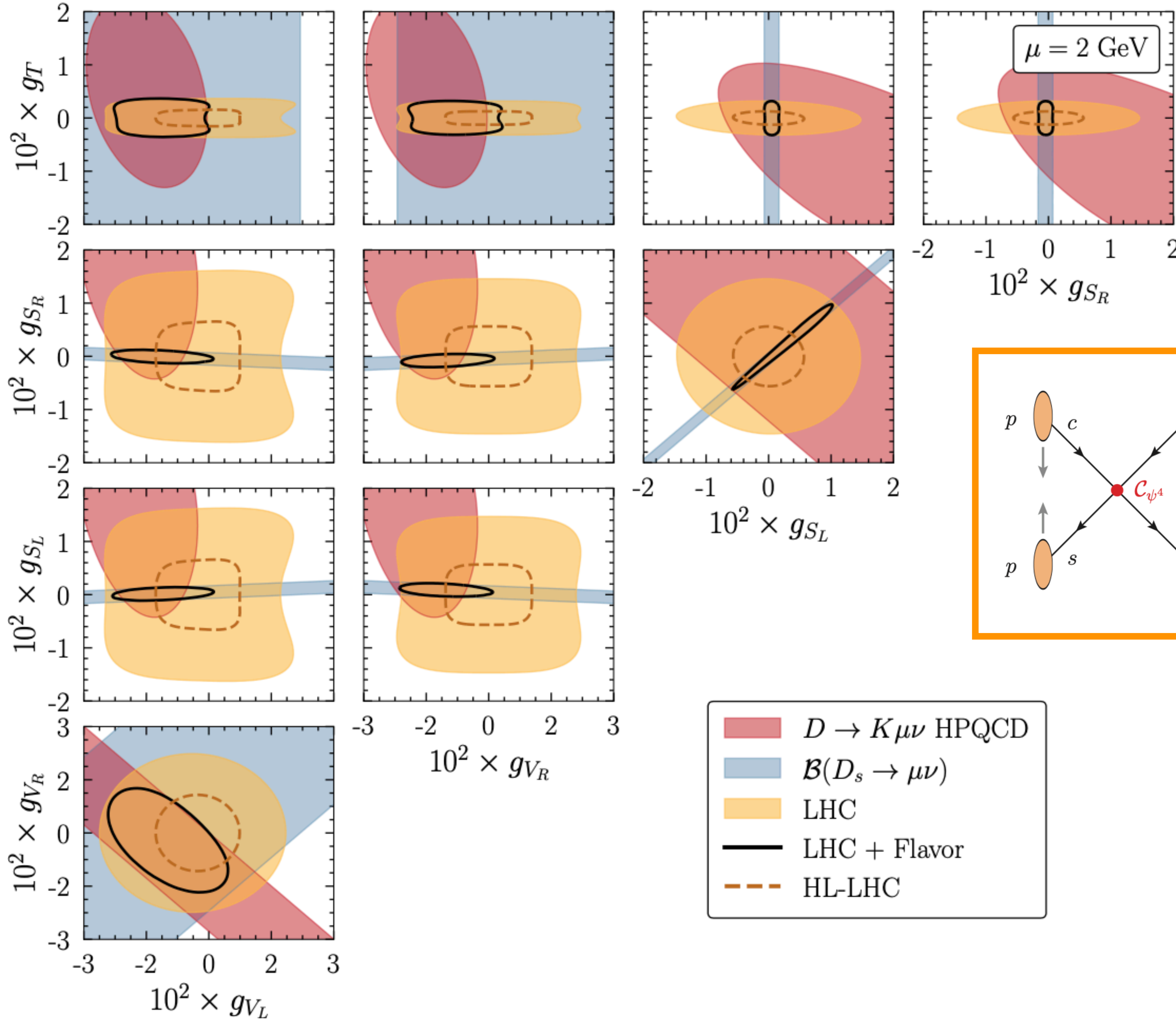
⇒ **Suppressed contributions** to $pp \to \ell\nu$ at high-p_T due to W-boson propagator.

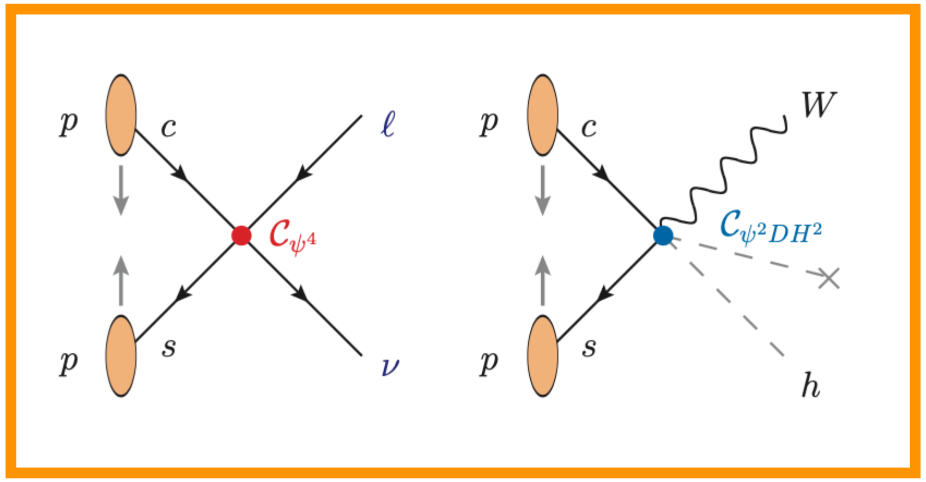
⇒ But... **energy-enhanced** contributions to $pp \to Wh$! [Eboli, Leal, Martines, OS. '25]





Already useful limits (competitive with flavor/EW data) — *to be improved at HL-LHC!*


$10^2 \times g_T$
$10^2 \times g_{S_R}$
$10^2 \times g_{S_L}$
$10^2 \times g_{V_R}$
$10^2 \times g_{V_L}$
$\mu = 2$ GeV
$D \to K\mu\nu$ HPQCD
$\mathcal{B}(D_s \to \mu\nu)$
LHC
LHC + Flavor
HL-LHC

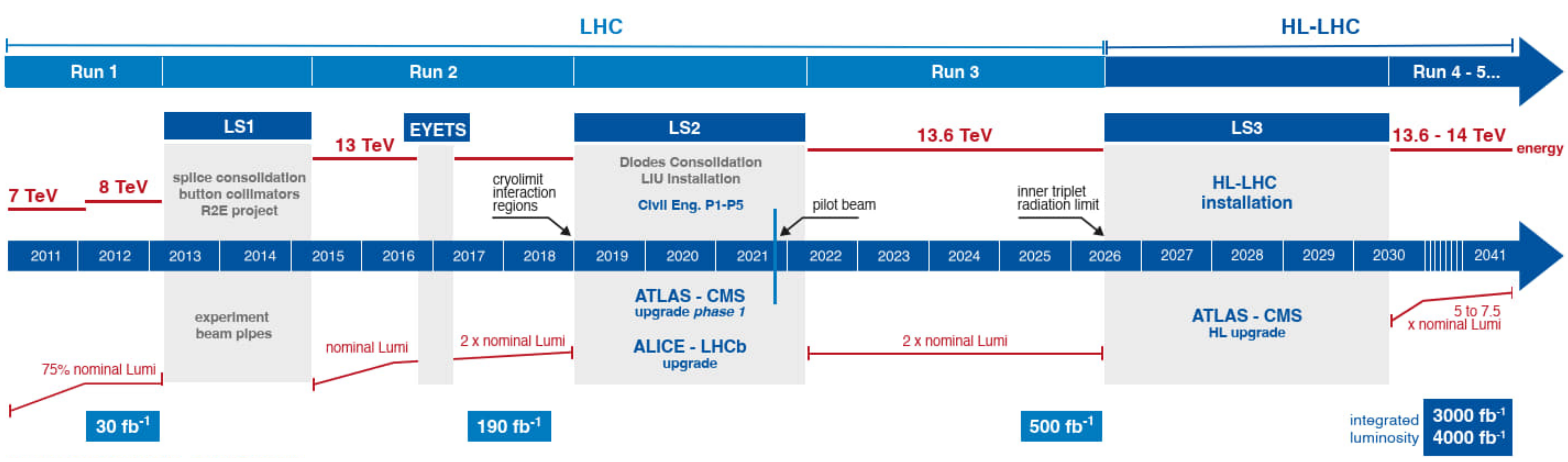

p
c
s
ℓ
ν
$\mathcal{C}_{\psi^4}$
W
h
$\mathcal{C}_{\psi^2 DH^2}$

Summary II

- **Drell-Yan:** complementary to low-energy flavor observables and particularly useful if New Physics couples to τ-leptons.

- $pp \to Vh$: current precision already allows us to test operators with 2nd and 3rd generation quarks — *complementary to flavor and electroweak observables.*

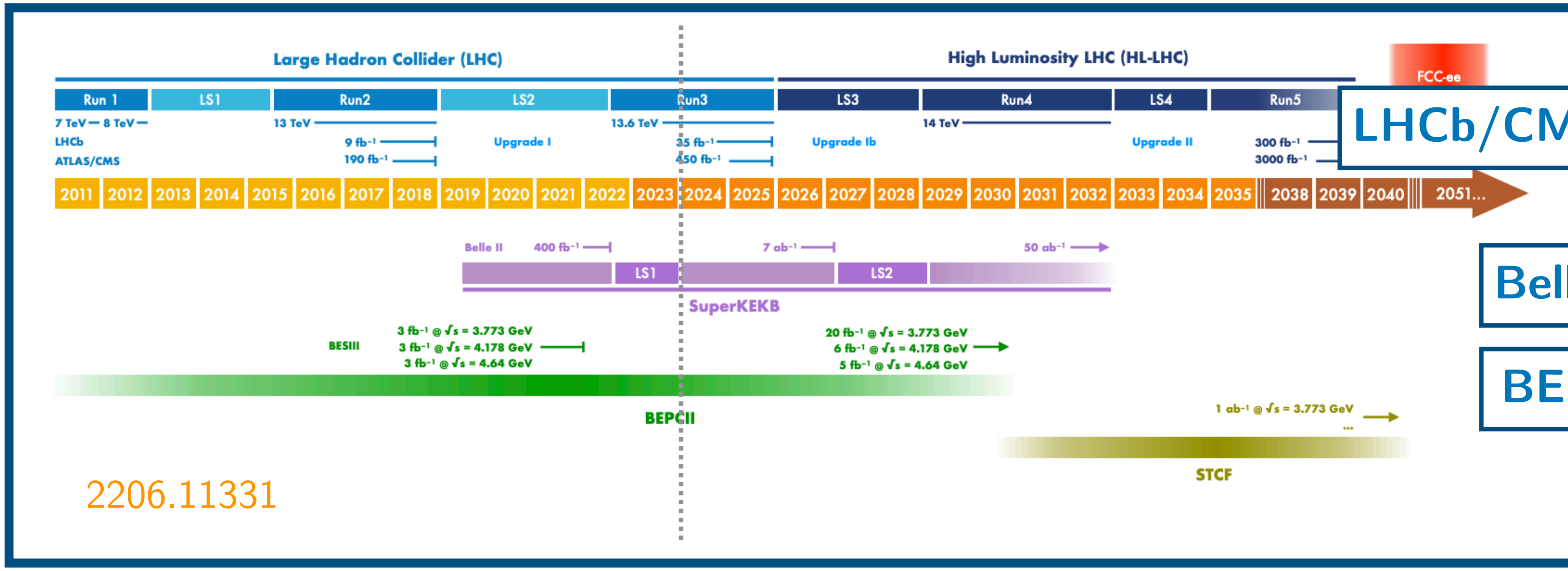
- **HL-LHC:** marginal increase in energy, but $\times 20$ more luminosity — *helpful for probing EFTs at the tails of the distributions!*



Many opportunities to improve the current limits and to explore new observables!

Outlook

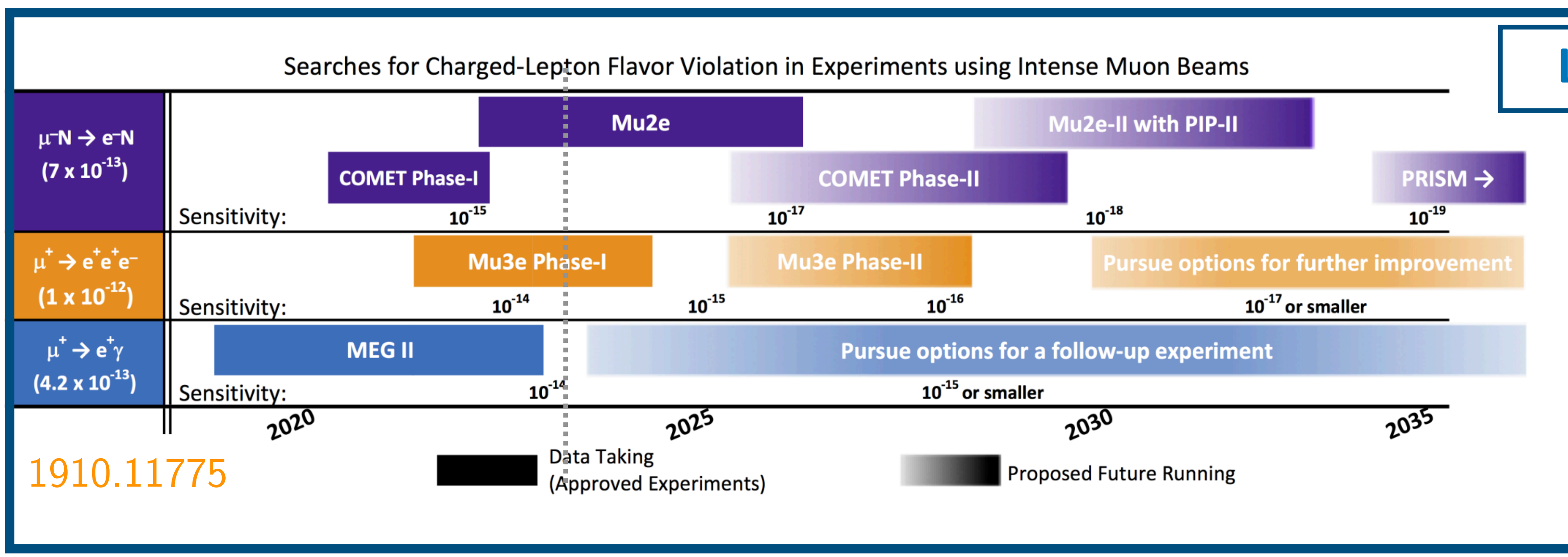
Experimental landscape



LHCb/CMS/ATLAS

Belle-II

BES-III



LFV

- \+ Kaon physics
- \+ EDMs
- \+ Many ν exps.
- \+ ...

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

Don't forget...

1958

Long-lived Neutral *K* Mesons*

M. Bardon, K. Lande, and L. M. Lederman

Columbia University, New York, New York, and Brookhaven National Laboratories, Upton, New York

and

William Chinowsky

Brookhaven National Laboratories, Upton, New York

BR($K_L \to \pi^+ \pi^-$) < 0.6 %

Volume 6, Number 10 PHYSICAL REVIEW LETTERS 1961

DECAY PROPERTIES OF K_2^0 MESONS*

D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov
Joint Institute of Nuclear Research, Moscow, U.S.S.R.
(Received April 20, 1961)

BR($K_L \to \pi^+ \pi^-$) < 0.3 %

« At that stage the search was terminated by administration of the Lab."
[Okun, hep-ph/0112031]

Volume 13, Number 4 PHYSICAL REVIEW LETTERS 1964

EVIDENCE FOR THE 2π DECAY OF THE K_2^0 MESON*†

J. H. Christenson, J. W. Cronin,‡ V. L. Fitch,‡ and R. Turlay§
Princeton University, Princeton, New Jersey
(Received 10 July 1964)

BR($K_L \to \pi^+ \pi^-$) = $(2 \pm 0.4)\ 10^{-3}$

CP violation discovery !

ESPPU2026 - Open Symposium (Venice, June 2025) - Marie-Helene Schune - Flavour WG report

[MH. Schune at ESPPU26 Open Symposium]

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Volume 6, Number 10 PHYSICAL REVIEW LETTERS 1961 1

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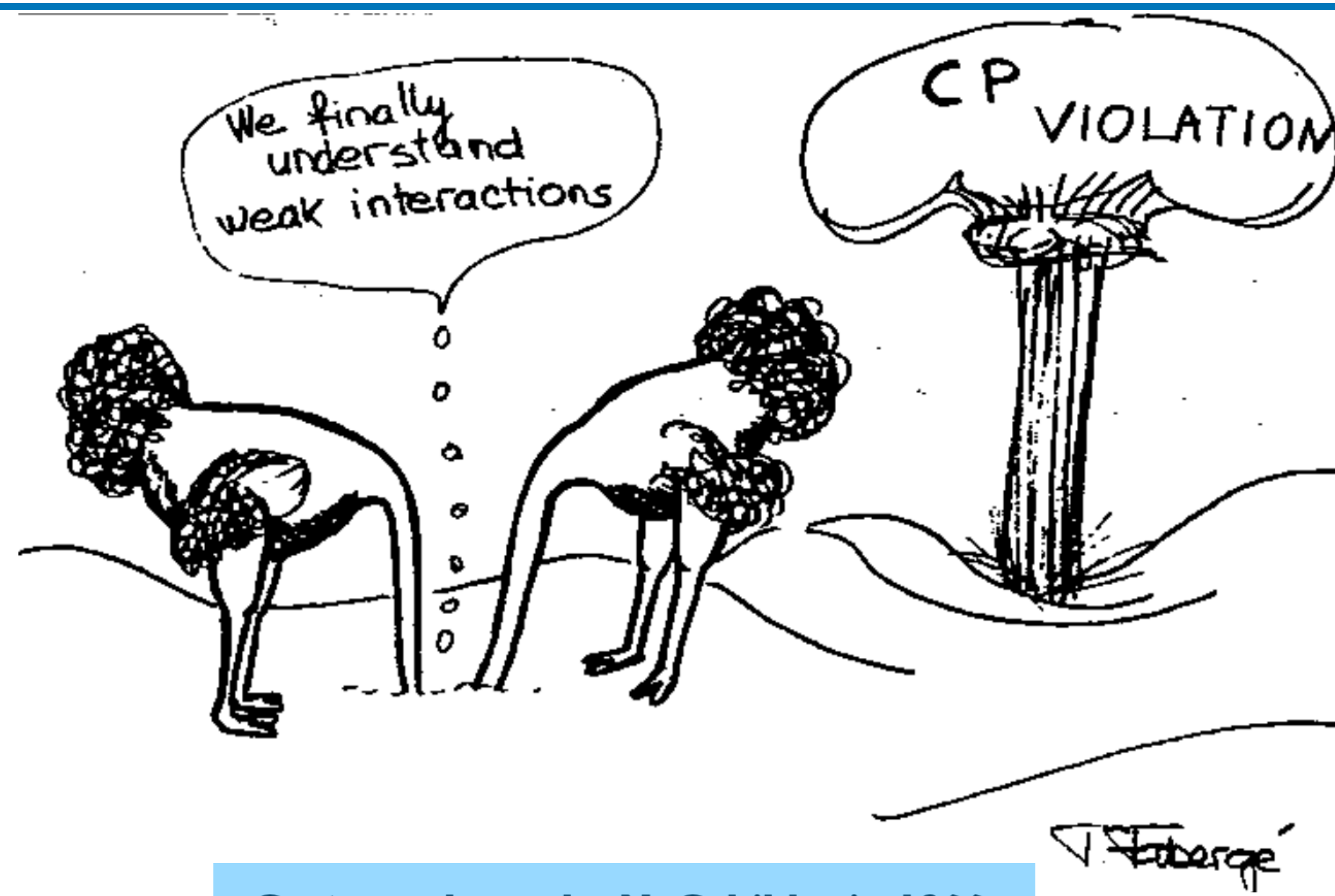
ESPPI



Cartoon shown by N. Cabibbo in 1966…

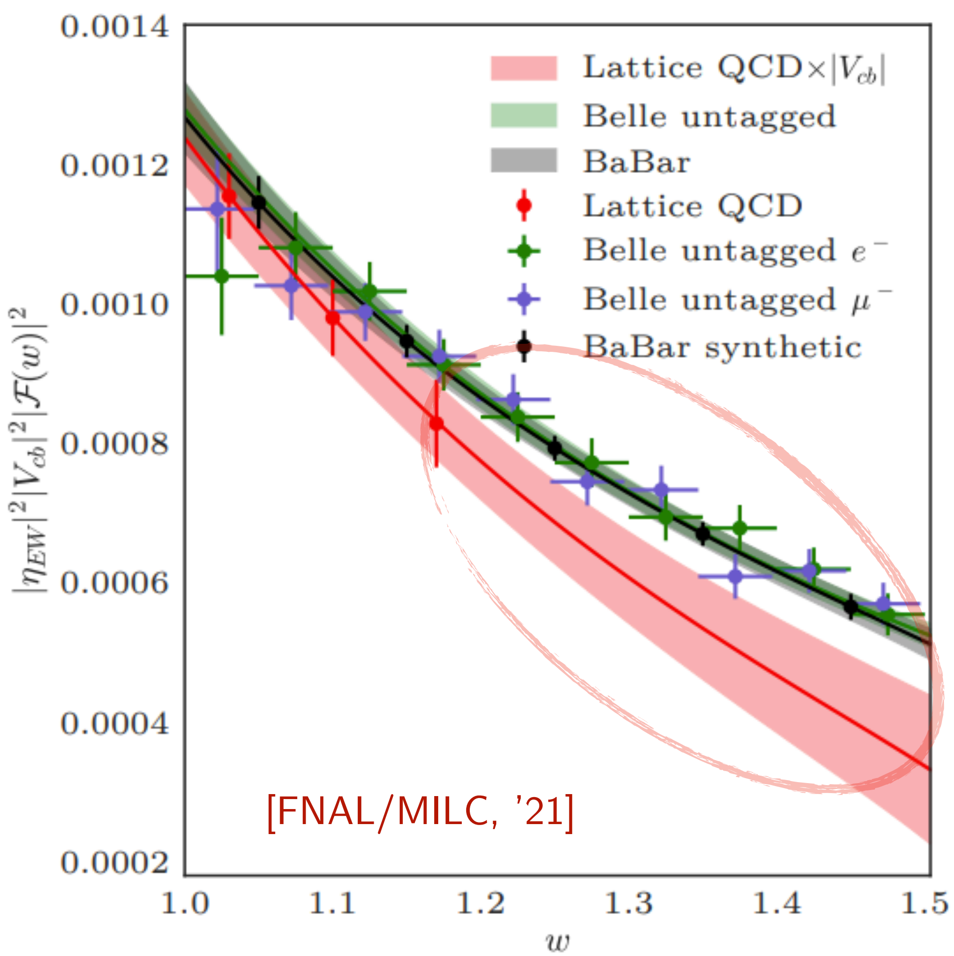
Thank you!

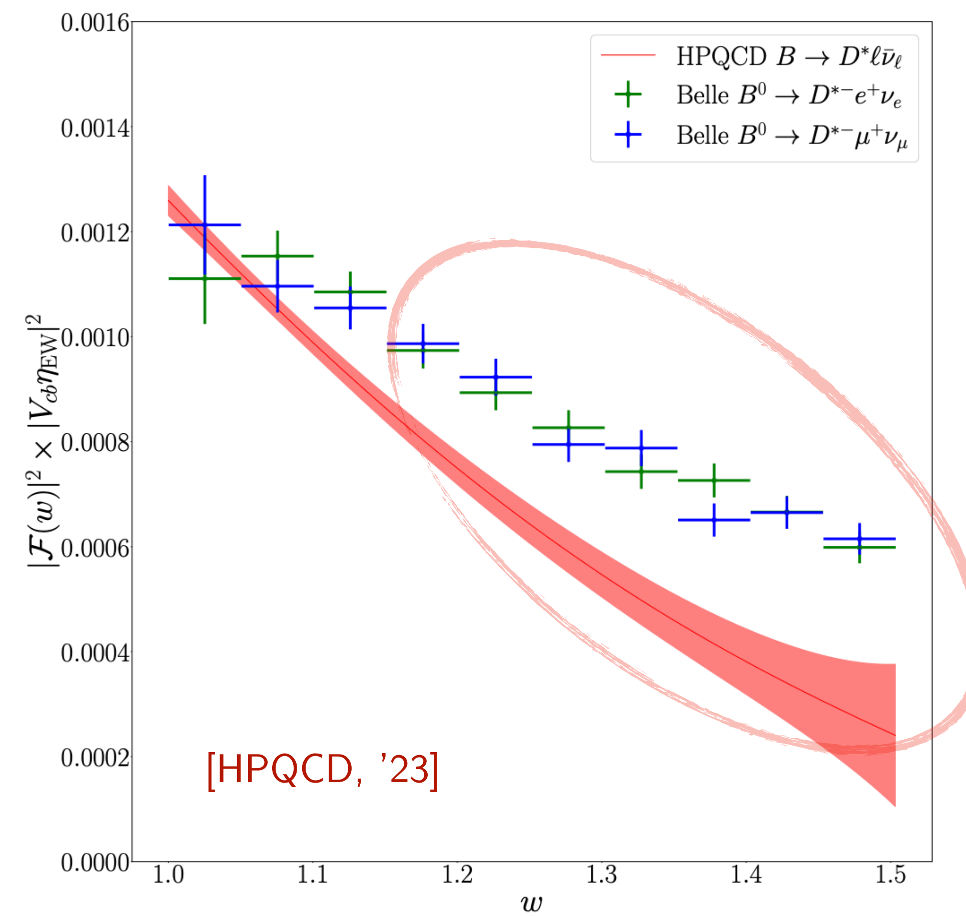
Back-up

[NEW] Warning!

see [Bordone et al. '24]

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





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

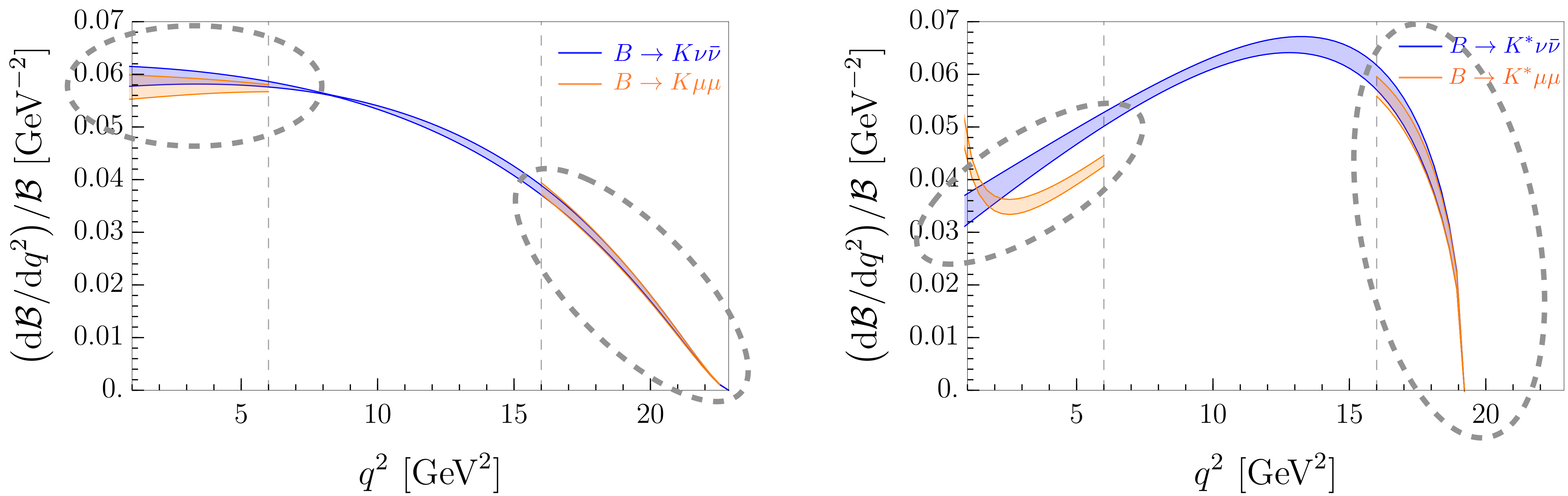
NB. JLQCD agrees well with exp. data, *albeit* with larger uncertainties — cf. back-up!

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

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]

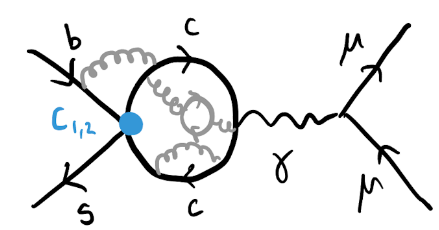


*using 2-loop results for $c\bar{c}$ loops from [Asatryan et al. '09]

- 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.

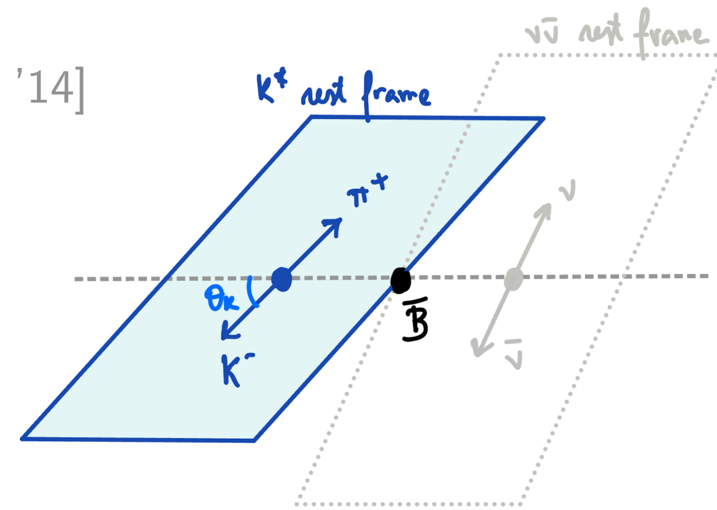


⇒ **Form-factor** uncertainties **cancel out** to a good extent for $q^2 \gg m_\ell^2$.

⇒ Neglecting NP contributions, this ratio can be used to **directly probe** $C_9^{\mu\mu}$ — *independently of form-factors!*

$F_L(B \to K^* \nu\nu)$

[Altmannshofer et al. '09, Buras et al. '14]



- The $B \to K^*(\to K\pi)\nu\nu$ distribution reads

$$\frac{d^2\Gamma}{dq^2 d\cos\theta_K} = \frac{3}{2}\frac{d\Gamma_L}{dq^2}\cos^2\theta_K + \frac{3}{4}\frac{d\Gamma_T}{dq^2}\sin^2\theta_K$$

⇒ **Longitudinal** (Γ_L) and **transverse** (Γ_T) polarization fractions can be extracted from data.

- Two independent observables:

$$\frac{d\Gamma}{dq^2} \equiv \frac{d\Gamma_L}{dq^2} + \frac{d\Gamma_T}{dq^2} \qquad F_L \equiv \frac{d\Gamma_L}{dq^2} \Big/ \frac{d\Gamma}{dq^2}$$

⇒ **The longitudinal polarization fraction** (F_L) is a **ratio**, thus independent of the CKM matrix (λ_t) and less sensitive to form-factors uncertainties.

$$\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})^{\rm SM} = (9.1 \pm 1.3 \pm 0.6) \times 10^{-6}$$

FF CKM

$$F_L(B^0 \to K^{*0}\nu\bar{\nu})^{\rm SM} = 0.49 \pm 0.04$$

FF

⇒ **Clean probe** of **New Physics** effects!

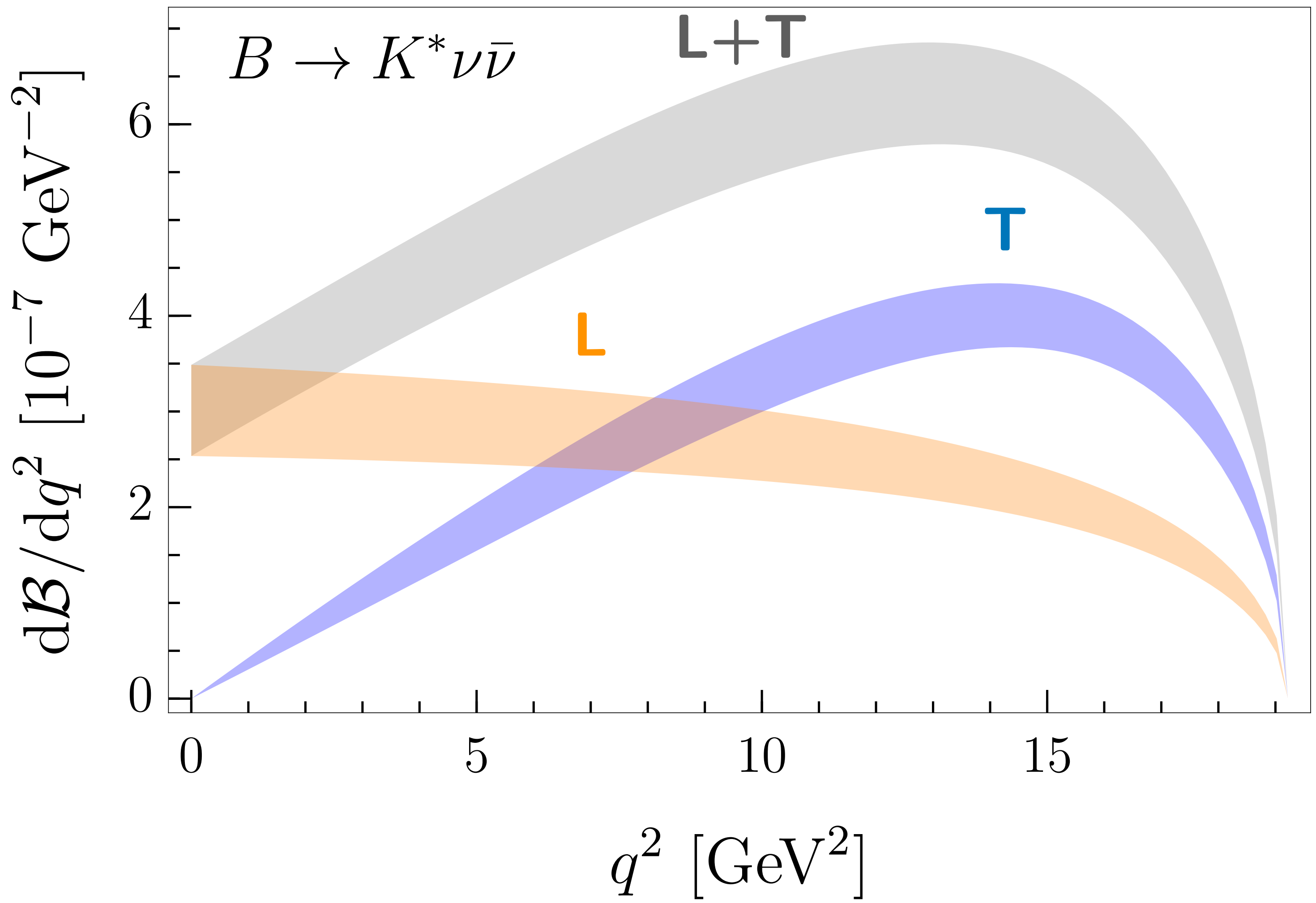
[Allwicher, Becirevic, Piazza, Rousaro-Alcaraz **OS**. '23]

$F_L(B \to K^* \nu\nu)$

$$F_L \equiv \frac{\mathrm{d}\Gamma_L}{\mathrm{d}q^2} \Big/ \frac{\mathrm{d}\Gamma}{\mathrm{d}q^2}$$

$$\frac{\mathrm{d}\Gamma_L}{\mathrm{d}q^2} \propto |C_L - C_R|^2 A_{12}(q^2)^2$$

$$\frac{\mathrm{d}\Gamma_T}{\mathrm{d}q^2} \propto |C_L - C_R|^2 A_1(q^2)^2 + \# |C_L + C_R|^2 V(q^2)^2$$



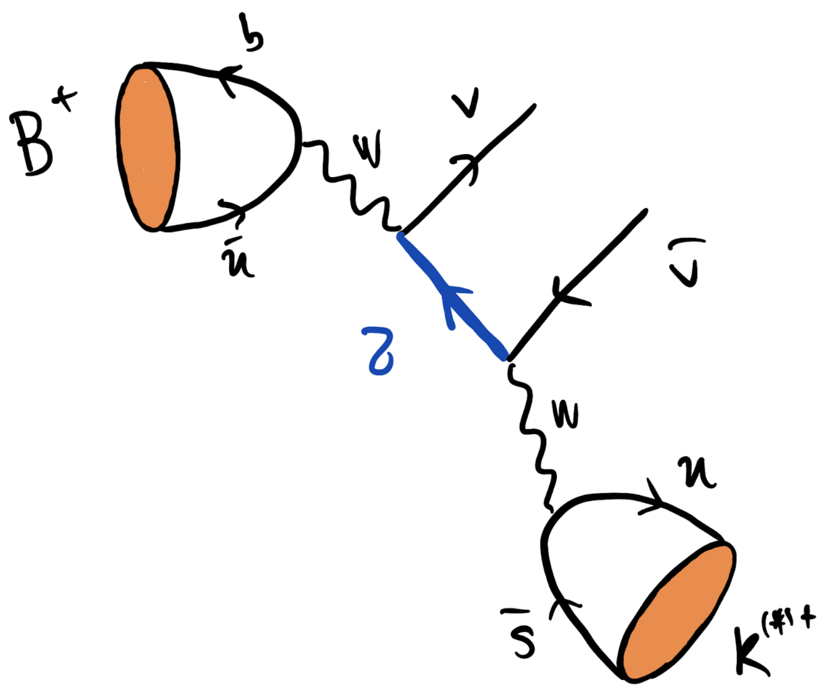
Contributions from **LH operators** ($\delta C_L \neq 0$) **cancel out** in F_L.

This observable is **sensitive** to **right-handed currents** ($\delta C_R \neq 0$)!

Weak-annihilation contributions

[Kamenik, Smith. '09]

- **To keep in mind**: decay modes with **charged mesons** are affected by **tree-level** weak **annihilation contributions**.



$$m_{K^{(*)+}} \leq m_\tau \leq m_B$$

- Using *narrow-width* approximation:

$$\mathcal{B}(B^+ \to K^{(*)+}\nu\bar{\nu}) \simeq \mathcal{B}(B^+ \to \tau^+\bar{\nu})\,\mathcal{B}(\tau^+ \to K^{(*)+}\nu)$$

- *Non-negligible* contributions:

$$\frac{\mathcal{B}(B^+ \to K^+\nu\bar{\nu})_{\text{tree}}}{\mathcal{B}(B^+ \to K^+\nu\bar{\nu}))_{\text{loop}}} \simeq 14\ \%$$

$$\frac{\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu})_{\text{tree}}}{\mathcal{B}(B^+ \to K^{*+}\nu\bar{\nu}))_{\text{loop}}} \simeq 11\ \%$$

$\Rightarrow$ They *cannot be removed* by a *simple kinematical cut*...

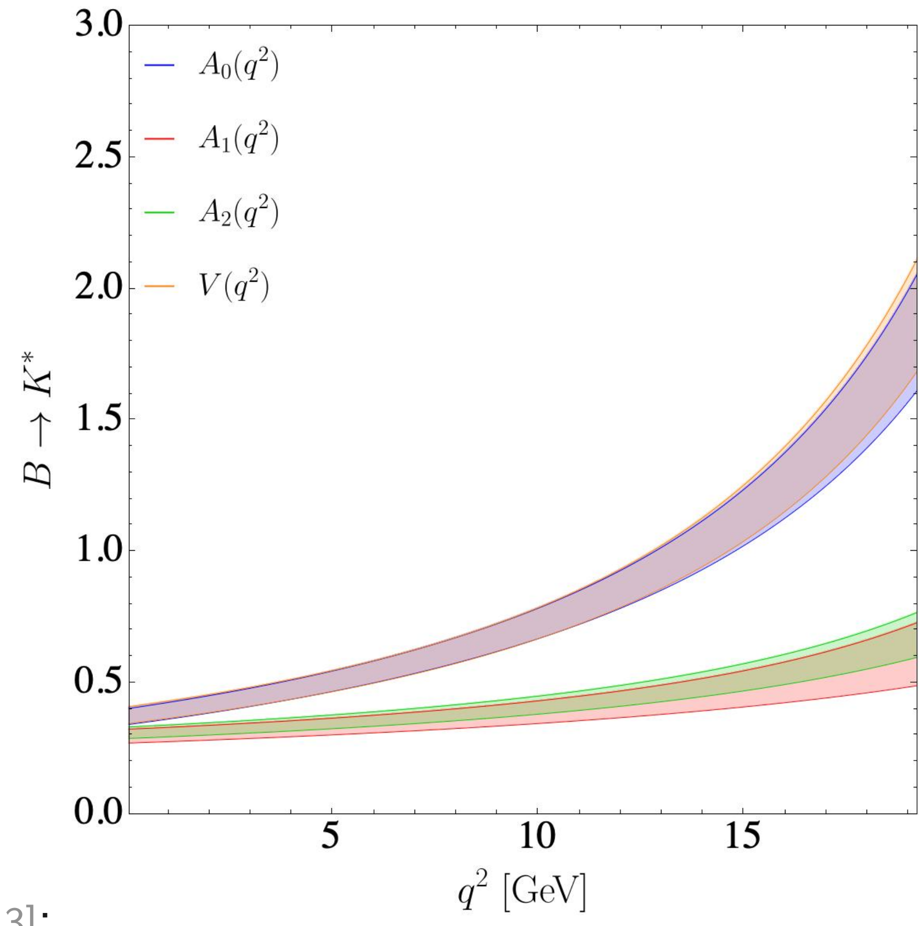
Belle-II: These contributions are treated as a **background.**

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

See talk by van Dyk

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

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

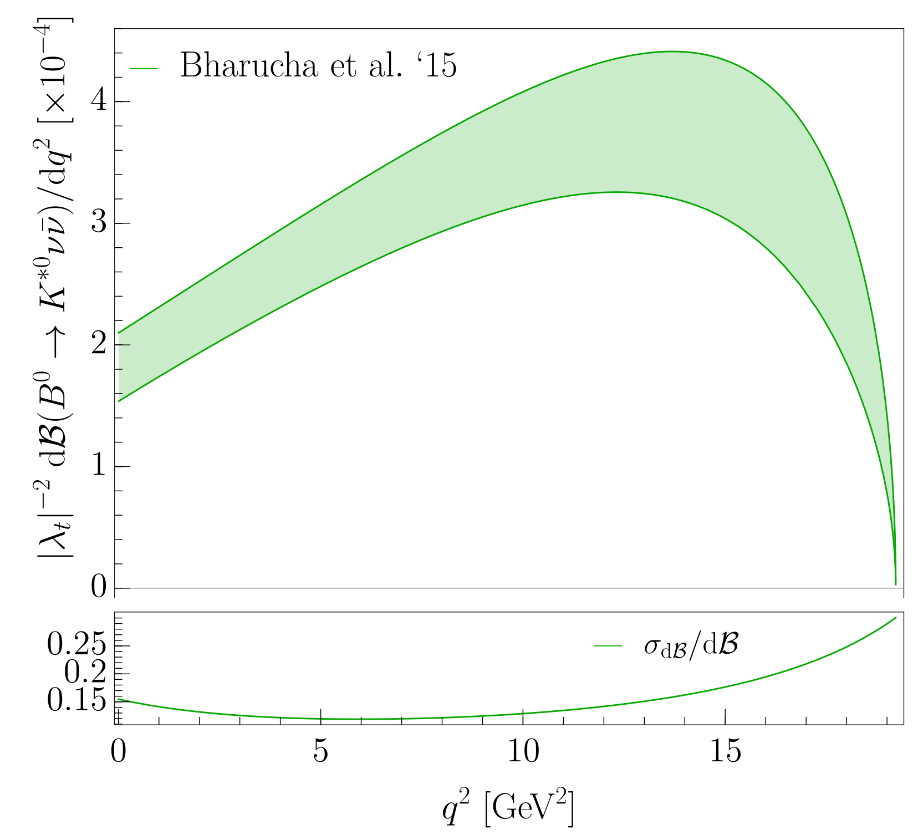


- We use LCSR (+LQCD) results from [Bharucha et al. '15, Horgan et al. '13]:

See also [Gubernari et al. '23]

$$\mathcal{B}(B \to K^*\nu\bar{\nu})^{\rm SM}/|\lambda_t|^2 = \begin{cases}(5.9 \pm 0.8)_{K^{*0}} \times 10^{-3}\\(6.4 \pm 0.9)_{K^{*+}} \times 10^{-3}\end{cases}$$

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



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

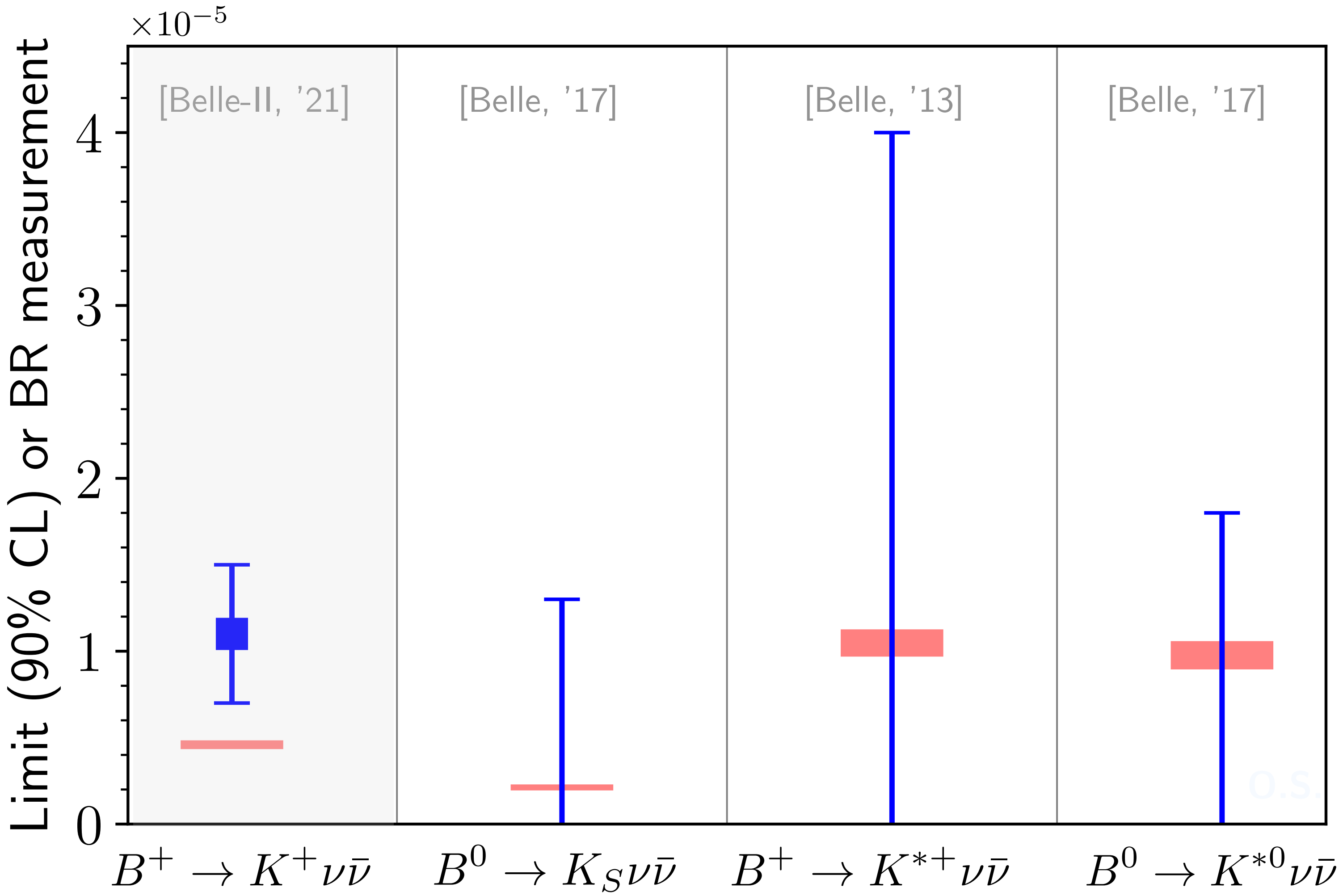
SM predictions

Decay	Branching ratio
$B^+ \to K^+ \nu\bar{\nu}$	$(4.44 \pm 0.14 \pm 0.27) \times 10^{-6}$
$B^0 \to K_S \nu\bar{\nu}$	$(2.05 \pm 0.07 \pm 0.12) \times 10^{-6}$
$B^+ \to K^{*+} \nu\bar{\nu}$	$(9.79 \pm 1.30 \pm 0.60) \times 10^{-6}$
$B^0 \to K^{*0} \nu\bar{\nu}$	$(9.05 \pm 1.25 \pm 0.55) \times 10^{-6}$

FF CKM

*Using V_{cb} $[B \to D\ell\bar{\nu}]$ for illustration — *the central value changes by* $-7\,\%$ *or* $+10\,\%$ *if we use* $B \to D^*\ell\bar{\nu}$ *or* $B \to X_c\ell\bar{\nu}$*, respectively.*

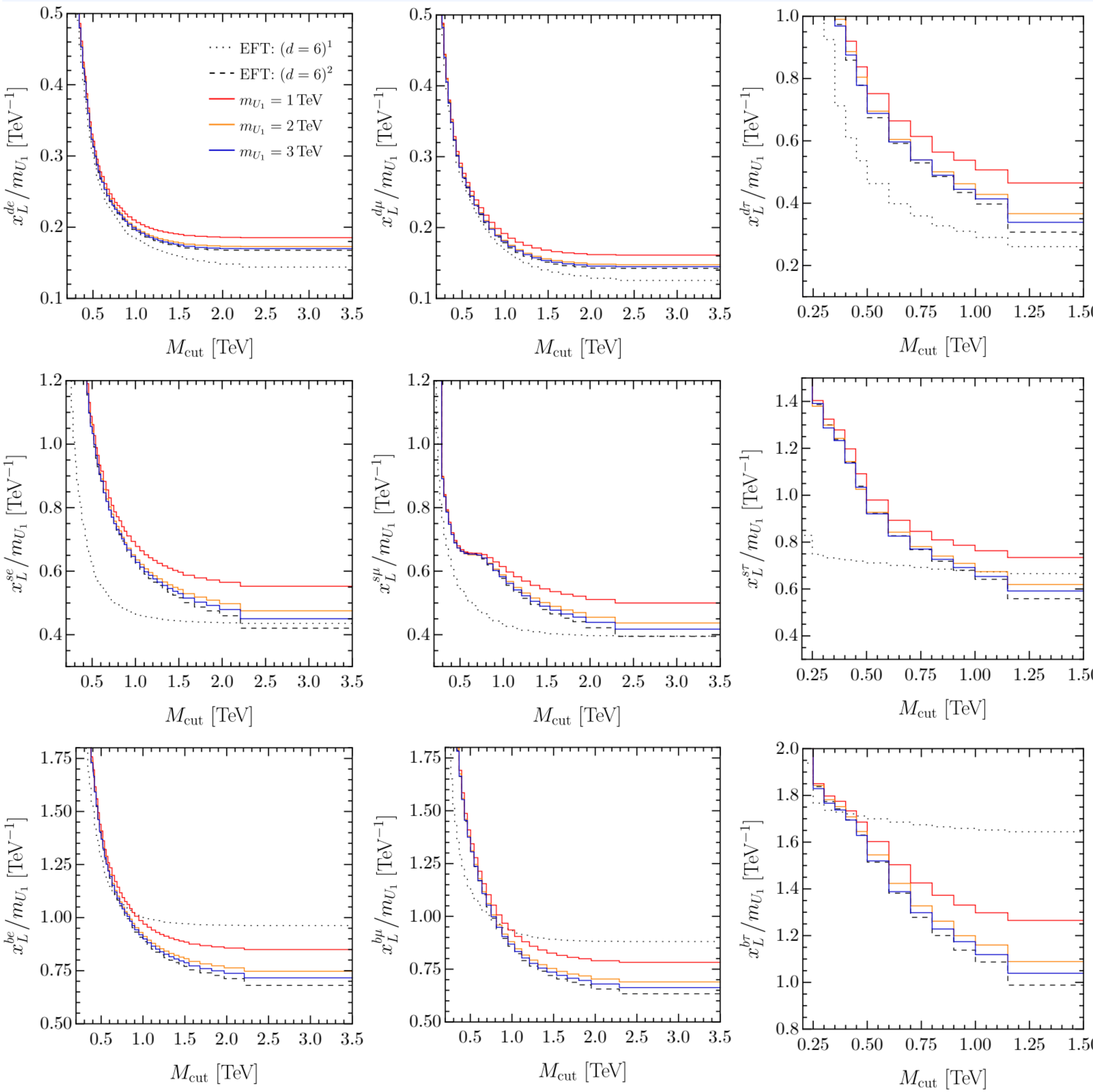
[Becirevic, Piazza, **OS**. 2301.06990]



Take-home:

- To remain **cautious** about **hadronic uncertainties** associated with the **form-factors** and the **CKM** values extracted from data — *non-negligible given the projected Belle-II sensitivity.*
- **Binned measurements** at Belle-II would be **valuable** for **testing** the $B \to K^{(*)}$ **form factors**.

See next slides!



EFT: $(d=6)^1$
EFT: $(d=6)^2$
$m_{U_1} = 1\,\text{TeV}$
$m_{U_1} = 2\,\text{TeV}$
$m_{U_1} = 3\,\text{TeV}$
x_L^{de}/m_{U_1} [TeV^{-1}]
$x_L^{d\mu}/m_{U_1}$ [TeV^{-1}]
$x_L^{d\tau}/m_{U_1}$ [TeV^{-1}]
x_L^{se}/m_{U_1} [TeV^{-1}]
$x_L^{s\mu}/m_{U_1}$ [TeV^{-1}]
$x_L^{s\tau}/m_{U_1}$ [TeV^{-1}]
x_L^{be}/m_{U_1} [TeV^{-1}]
$x_L^{b\mu}/m_{U_1}$ [TeV^{-1}]
$x_L^{b\tau}/m_{U_1}$ [TeV^{-1}]
M_{cut} [TeV]

EFT convergence — resonant mediator

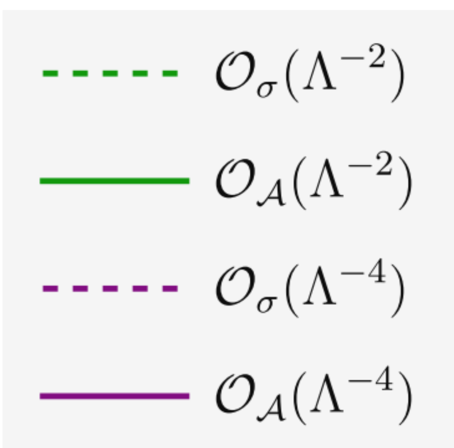
- EFT cross-section computed with different orders in Λ^{-1} and normalized to the full model.
- Example: $Z' \sim (\mathbf{1},\mathbf{1},0)$

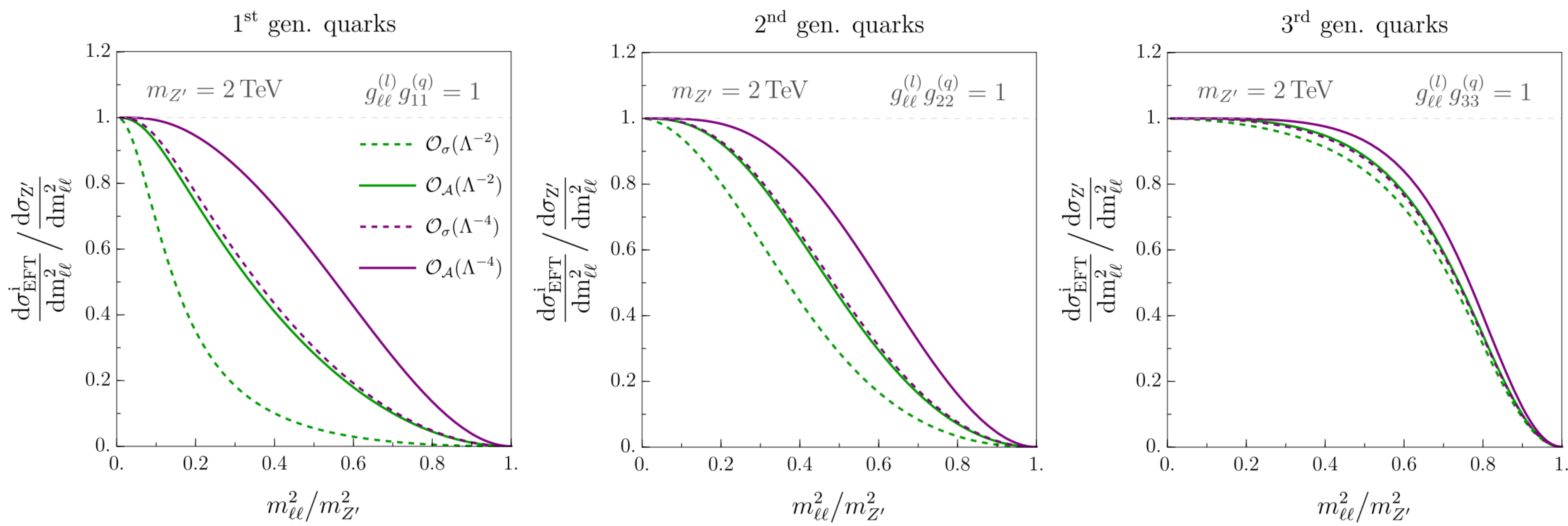
$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} + \frac{m_{Z'}^2}{2} Z'_\mu Z'^{\,\mu} + J^\mu Z'_\mu$$

$$J_\mu = g_{ij}^{(q)}\, \bar{q}_i \gamma_\mu q_j + g_{\alpha\beta}^{(l)}\, \bar{l}_\alpha \gamma_\mu l_\beta$$

Amplitude truncation $\equiv \mathcal{O}_{\mathcal{A}}$

Cross-section truncation $\equiv \mathcal{O}_\sigma$





$$\hat{\sigma} \propto \left| \mathcal{A}_{\text{SM}} + \frac{\mathcal{A}_6}{\Lambda^2} + \frac{\mathcal{A}_{6\times 6} + \mathcal{A}_8}{\Lambda^4} + \mathcal{O}_{\mathcal{A}}(\Lambda^{-6}) \right|^2$$

$$= \underbrace{\underbrace{|\mathcal{A}_{\text{SM}}|^2 + \frac{2\text{Re}\,(\mathcal{A}_{\text{SM}}^* \mathcal{A}_6)}{\Lambda^2} + \frac{|\mathcal{A}_6|^2}{\Lambda^4}}_{\mathcal{O}_{\mathcal{A}}(\Lambda^{-2})} + \frac{2\text{Re}\,(\mathcal{A}_{\text{SM}}^* \mathcal{A}_{6\times 6} + \mathcal{A}_{\text{SM}}^* \mathcal{A}_8)}{\Lambda^4} + \frac{2\text{Re}\,(\mathcal{A}_6^* \mathcal{A}_{6\times 6} + \mathcal{A}_6^* \mathcal{A}_8)}{\Lambda^6} + \frac{|\mathcal{A}_{6\times 6}|^2 + |\mathcal{A}_8|^2}{\Lambda^8}}_{\mathcal{O}_{\mathcal{A}}(\Lambda^{-4})} + \dots\,,$$

[Allwicher, Faroughy, Martines, **OS**, Wilsch. '24]

EFT convergence — resonant mediator

- EFT cross-section computed with different orders in Λ^{-1} and normalized to the full model.
- Example: $Z' \sim (\mathbf{1},\mathbf{1},0)$

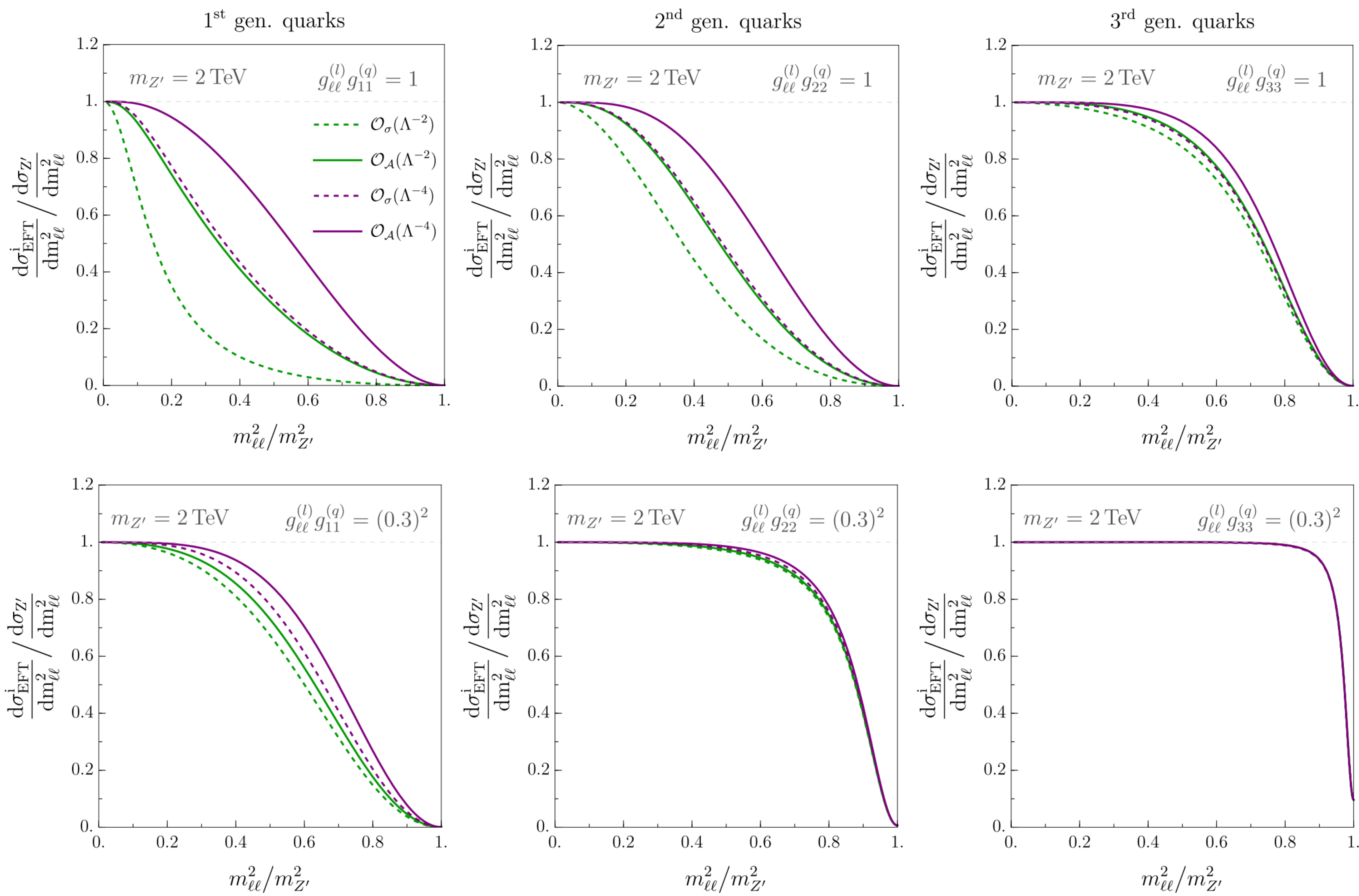
$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} + \frac{m_{Z'}^2}{2} Z'_\mu Z'^{\,\mu} + J^\mu Z'_\mu$$

$$J_\mu = g_{ij}^{(q)}\, \bar{q}_i \gamma_\mu q_j + g_{\alpha\beta}^{(l)}\, \bar{l}_\alpha \gamma_\mu l_\beta$$

Amplitude truncation $\equiv \mathcal{O}_{\mathcal{A}}$

Cross-section truncation $\equiv \mathcal{O}_{\sigma}$

- - - - $\mathcal{O}_\sigma(\Lambda^{-2})$
—— $\mathcal{O}_{\mathcal{A}}(\Lambda^{-2})$
- - - - $\mathcal{O}_\sigma(\Lambda^{-4})$
—— $\mathcal{O}_{\mathcal{A}}(\Lambda^{-4})$



Neglecting the width

$$\frac{1}{\hat{s} - m_{Z'}^2} \overset{x<1}{=} -\frac{1}{m_{Z'}^2} \sum_{n=0}^{\infty} x^n$$

$$x \equiv \frac{\hat{s}}{m_{Z'}^2} > 0$$

[Allwicher, Faroughy, Martines, **OS**, Wilsch. '24]

EFT convergence — non-resonant mediator

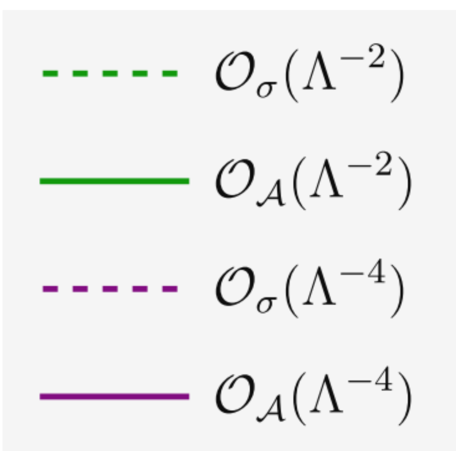
- EFT cross-section computed with different orders in Λ^{-1} and normalized to the full model.
- Example: $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

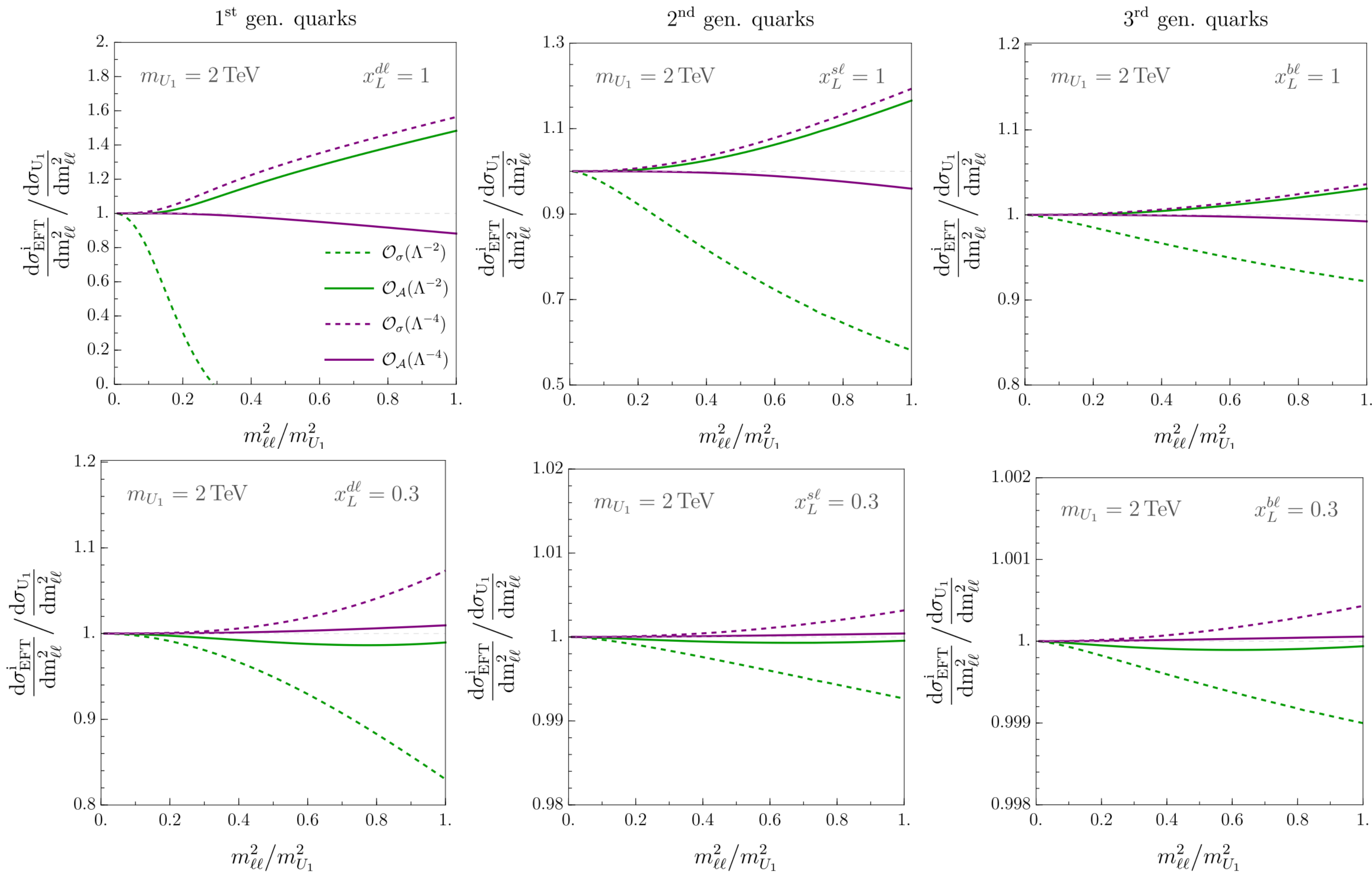
$$\mathcal{L}_{U_1} \supset -\frac{1}{2} U_{1\,\mu\nu}^{\dagger} U_1^{\mu\nu} + m_U^2\, U_1^{\mu\,\dagger} U_{1\,\mu} + (J_\mu^\dagger U_1^\mu + \mathrm{H.c.})$$

$$J_\mu^\dagger = x_L^{i\alpha}\, \bar{q}_i \gamma_\mu l_\alpha$$

Amplitude truncation $\equiv \mathcal{O}_{\mathcal{A}}$

Cross-section truncation $\equiv \mathcal{O}_{\sigma}$





Neglecting the width

$$\frac{1}{\hat{t} - m_{U_1}^2} \overset{y<1}{=} -\frac{1}{m_{U_1}^2} \sum_{n=0}^{\infty} (-1)^n y^n \qquad y \equiv -\frac{\hat{t}}{m_{U_1}^2} > 0$$

[Allwicher, Faroughy, Martines, **OS**, Wilsch. '24]

$pp \to VH$

Channel	Distribution	Collaboration	$N_{\rm obs}$	Luminosity
$pp \to WW$	$\dfrac{d\sigma}{dp_T^{\ell{\rm lead}}}$	ATLAS	14	$36.1\ {\rm fb}^{-1}$ [33]
	$\dfrac{dN_{\rm ev}}{dm_{e\mu}}$	CMS	11	$35.9\ {\rm fb}^{-1}$ [34]
$pp \to WZ$	$\dfrac{d\sigma}{dm_T^{WZ}}$	ATLAS	6	$36.1\ {\rm fb}^{-1}$ [35]
	$\dfrac{1}{\sigma}\dfrac{d\sigma}{dm_{WZ}}$	CMS	5	$137\ {\rm fb}^{-1}$ [36]
$pp \to Zh$	$\dfrac{d\sigma}{dp_T^Z}$	ATLAS	5	$140\ {\rm fb}^{-1}$ [37]
		CMS	3	$138\ {\rm fb}^{-1}$ [38]
$pp \to Wh$	$\dfrac{d\sigma}{dp_T^W}$	ATLAS	5	$140\ {\rm fb}^{-1}$ [37]
		CMS	3	$138\ {\rm fb}^{-1}$ [38]

$W^+W^- + Zh$ $\quad$ $WZ + Wh$

$\mathcal{C}_{Hq}^{(1)},\ \mathcal{C}_{Hd},\ \mathcal{C}_{Hu}$ | $\mathcal{C}_{Hq}^{(3)}$ | $\mathcal{C}_{Hud}$

MadGraph@NLO

↓

Pythia8

↓

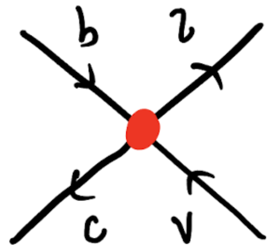
Delphes

$$q_i = \begin{pmatrix} (V^\dagger u)_{Li} \\ d_{Li} \end{pmatrix}$$

LFU in $b \to c\ell\nu$

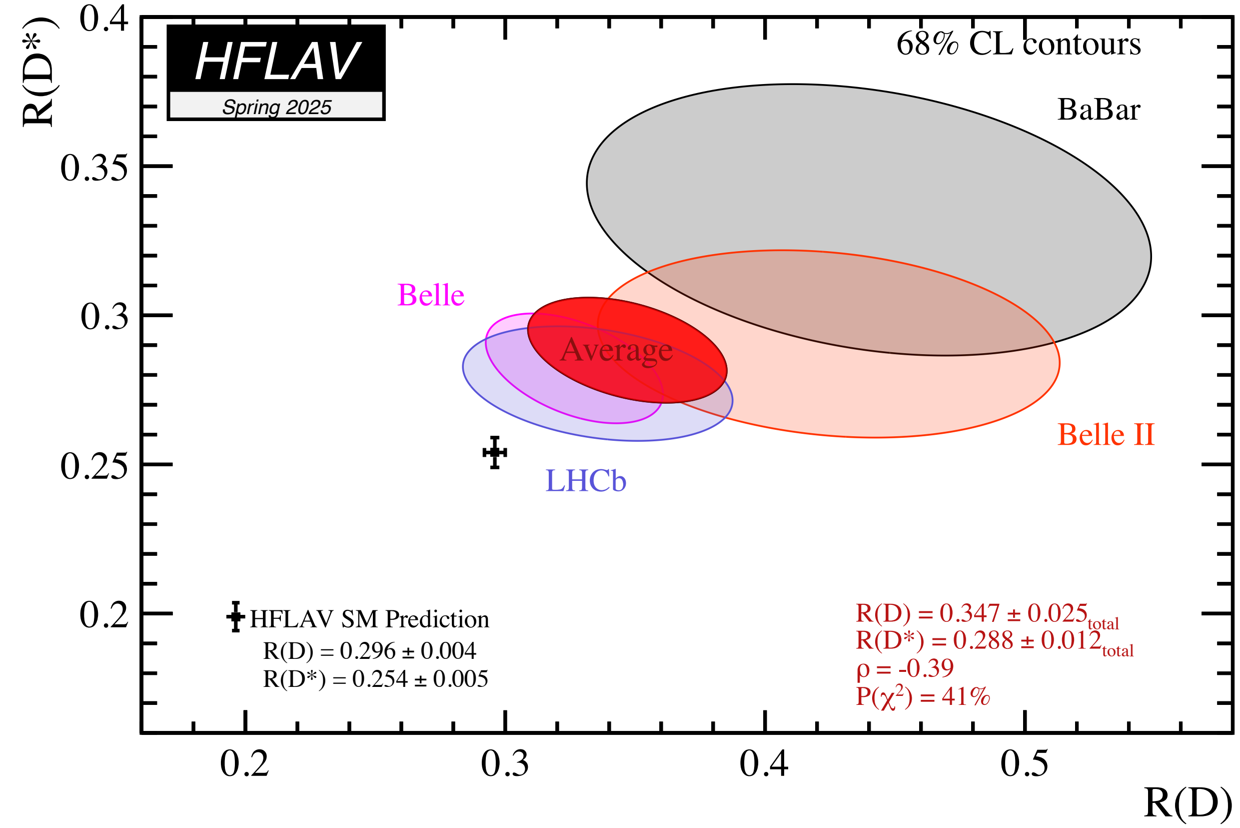
cf. also $R_{J/\psi}$ *and* R_{Λ_c}

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



$\Rightarrow$ $\Lambda/|\mathscr{C}| \lesssim$ few TeV

[Di Luzio et al. '17]

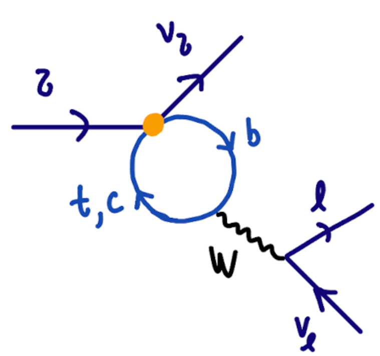


LQCD: [FNAL/MILC, HPQCD]

see also [Bordone et al. '24]

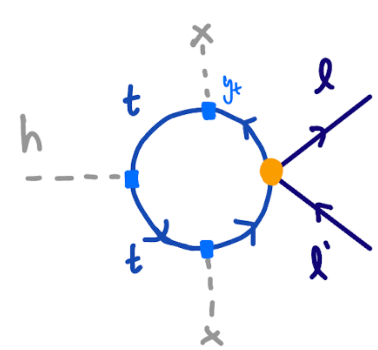
- **SM predictions** are under **reasonable control**, *cf. back-up.*
- **Experimental situation** remains **unclear** — *more data needed!*
- **New physics models** explaining these excesses lead to **signals in τ-related observables**:

$\tau \to \ell\nu\bar{\nu}$



[Feruglio et al. '16]

$h \to \tau\tau$

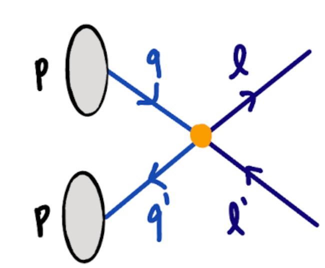


[Feruglio, Paradisi, **OS**. '18]

[Crivellin et al. '20]

$pp \to \tau\tau$

$pp \to \tau\nu$



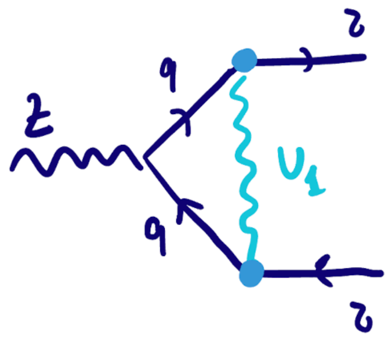
[Faroughy et al. '16]

[Allwicher et al. **(OS)**, 21]

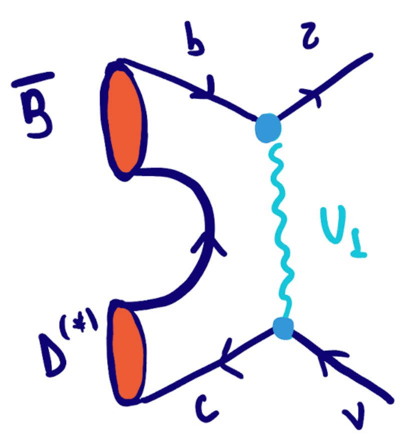
Example I: $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

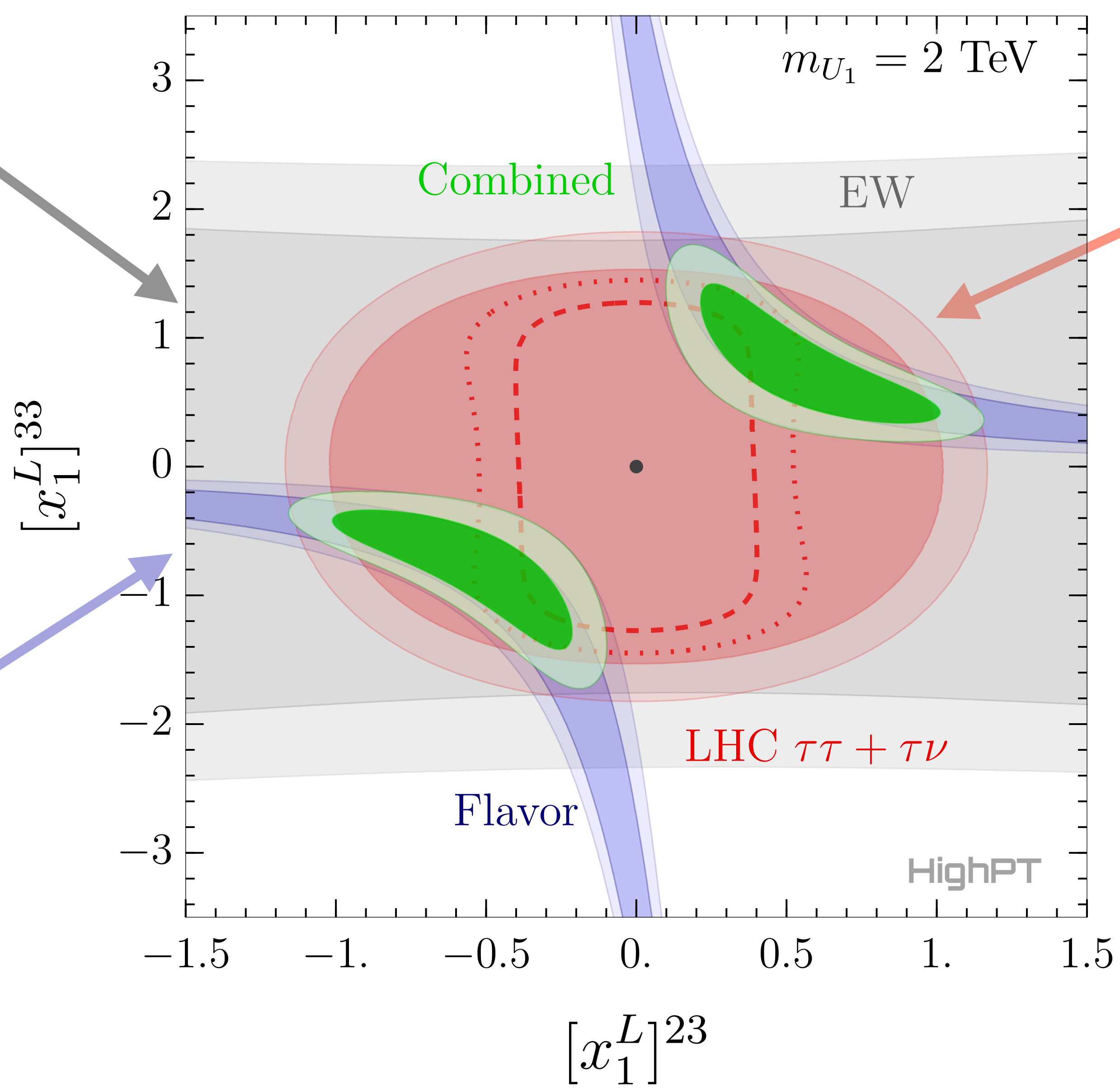
[L. Allwicher, D. Faroughy, F. Jaffredo, **OS**, F. Wilsch. '22]

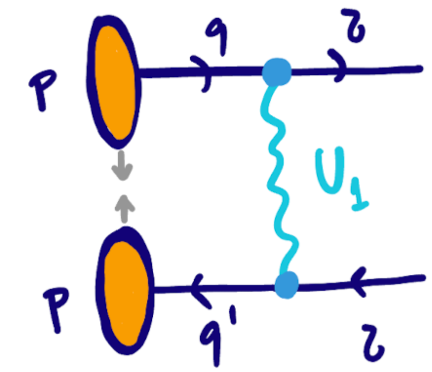
$$\mathcal{L}_{U_1} \supset [x_1^L]_{i\alpha}\, U_1^\mu\, \bar{q}_i \gamma_\mu l_\alpha + \text{h.c.}$$



[Feruglio et al. '16]







First considered by [Eboli, '88]

cf. also [Faroughy et al. '15]

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

Charged-current transition:

$$\mathcal{L}_{\rm LEFT} = -2\sqrt{2}G_F V_{ij}\Big[\big(1+g_{V_L}^{ij\,\ell}\big)\big(\bar{u}_{Li}\gamma_\mu d_{Lj}\big)\big(\bar{\ell}_L\gamma^\mu\nu_L\big) + g_{V_R}^{ij\,\ell}\big(\bar{u}_{Ri}\gamma_\mu d_{Rj}\big)\big(\bar{\ell}_L\gamma^\mu\nu_L\big)$$
$$+ g_{S_L}^{ij\,\ell}\big(\bar{u}_{Ri}d_{Lj}\big)\big(\bar{\ell}_R\nu_L\big) + g_{S_R}^{ij\,\ell}\big(\bar{u}_{Li}d_{Rj}\big)\big(\bar{\ell}_R\nu_L\big) + g_T^{ij\,\ell}\big(\bar{u}_{Ri}\sigma_{\mu\nu}d_{Lj}\big)\big(\bar{\ell}_R\sigma^{\mu\nu}\nu_L\big)\Big] + \text{h.c.}$$

Matching to SMEFT @$d=6$:

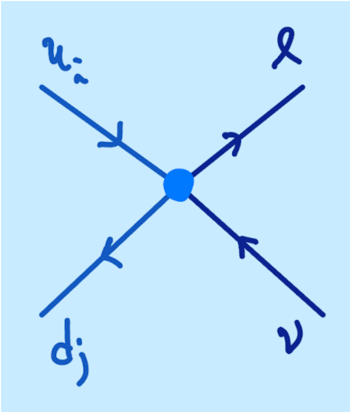
$$g_{V_L}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell} + \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^2 DH^2}^{ij}$$

$$g_{V_R}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^2 DH^2}^{ij\ell\ell}$$

$$g_{S_L}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell}$$

$$g_{S_R}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell}$$

$$g_T^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell}$$



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