Highlights on BSM searches with flavor physics

Olcyr Sumensari

IJCLab (Orsay)

PhysTeV 2025, Les Houches

The Precision Frontier

- The **Standard Model** is an **EFT** at low energies of a more fundamental theory that is yet unknown:

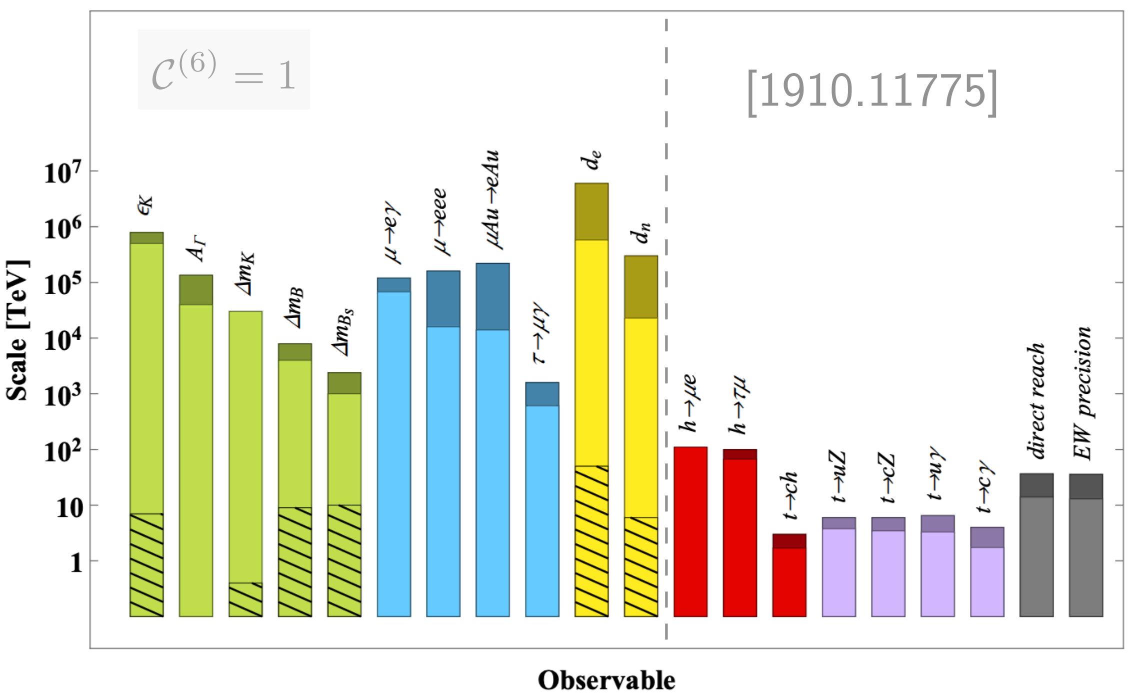
  ⇒ Hierarchy and flavor problems remain unanswered, *among other problems.*

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

- The absence of NP signals at the LHC suggests a **mass gap** between $v_{\rm EW}$ and $\Lambda_{\rm NP} \gtrsim \mathcal{O}(\text{TeV})$.

  ⇒ **Precision physics** is **key to push the boundaries** of the SM.

  ⇒ Historically, precision measurements were fundamental to **guide theory and experiment**: *(i) GIM mechanism; (ii) CPV in K-$\overline{K}$ mixing and CKM mechanism; (iii) top and Higgs masses...*



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

Precision flavor measurements can also be essential in **guiding** the **effort beyond the SM**

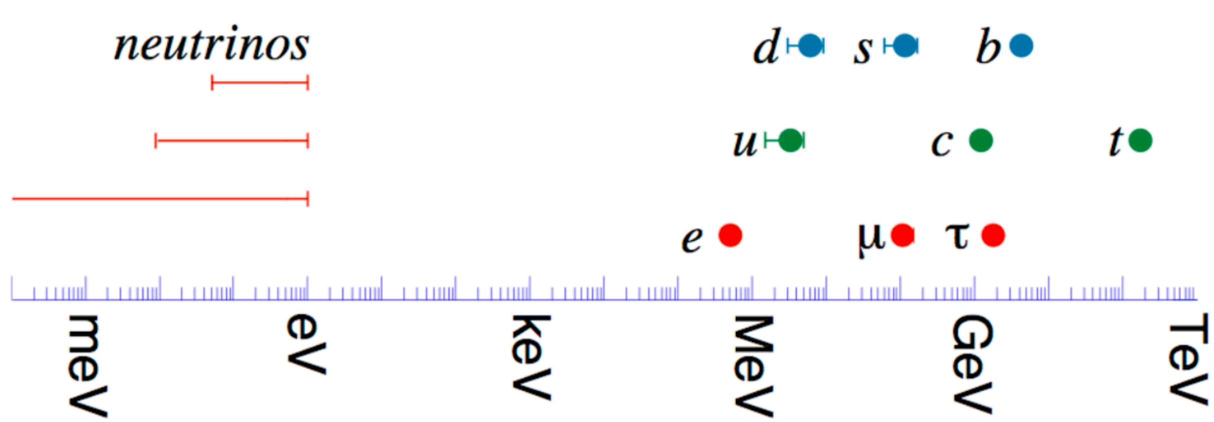
What is the origin of flavor?

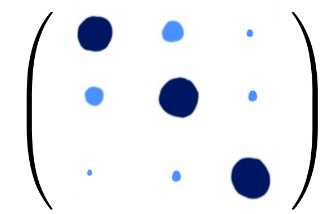
- Flavor sector **loose** in the SM:

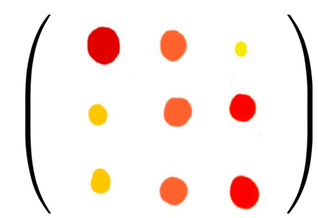
  ⇒ 13 free parameters (masses and quark mixing) — *fixed by data.*

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

  ⇒ These (many) parameters exhibit hierarchical structures that we do not understand.



$V_{\rm CKM} =$ 

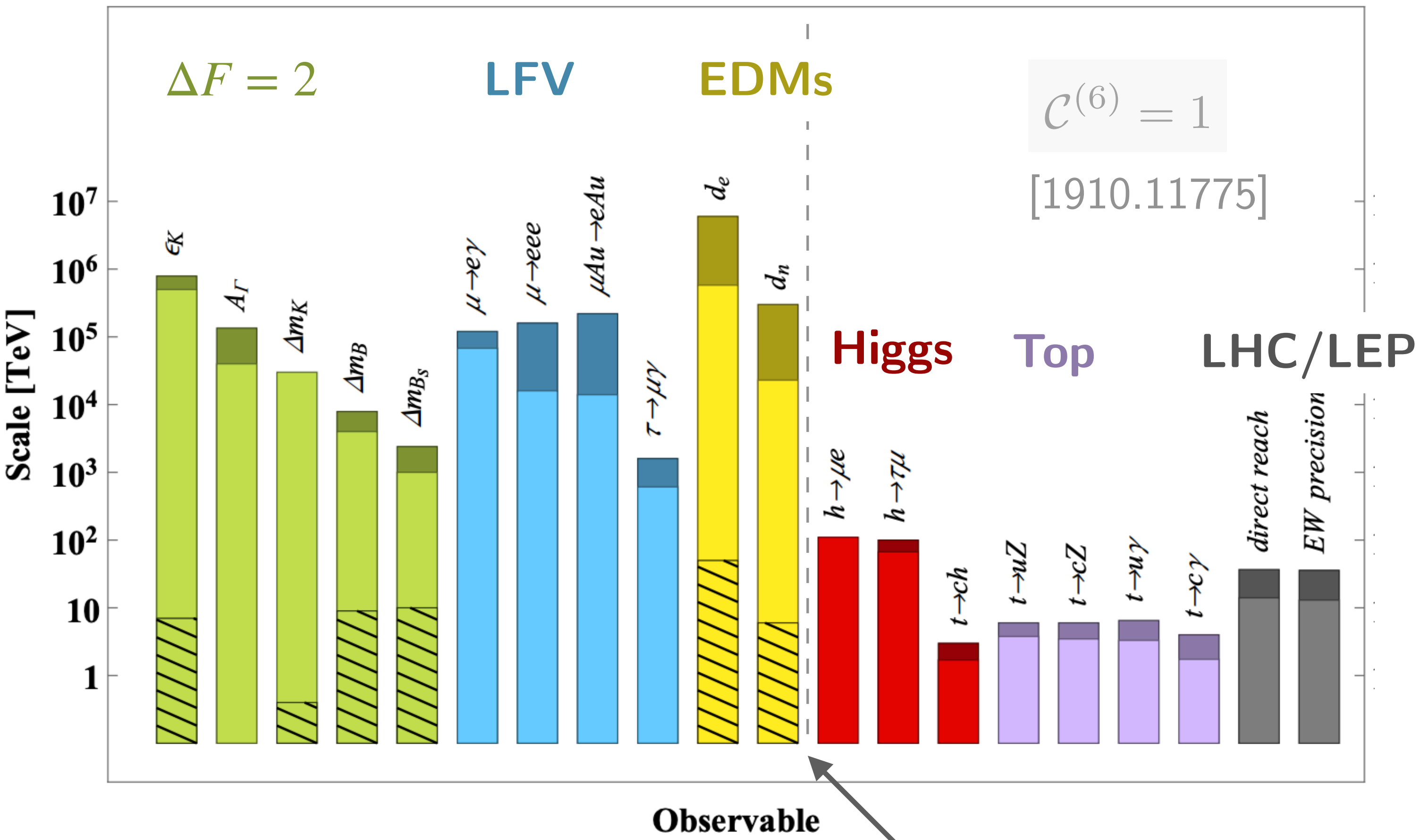
$V_{\rm PMNS} =$ 

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

BSM particles related to the **flavor problem** can lead to imprints in low-energy observables — *possibly with non-universal and hierarchical couplings to SM fermions!*

MFV [D'Ambrosio et al. '02], $U(2)^5$ [Barbieri et al. '11,'15]...
see also [Faroughy et al. ',20], [Greljo et al. '22]

New physics flavor problem?



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

Hatched: Minimal Flavor Violation (MFV)

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

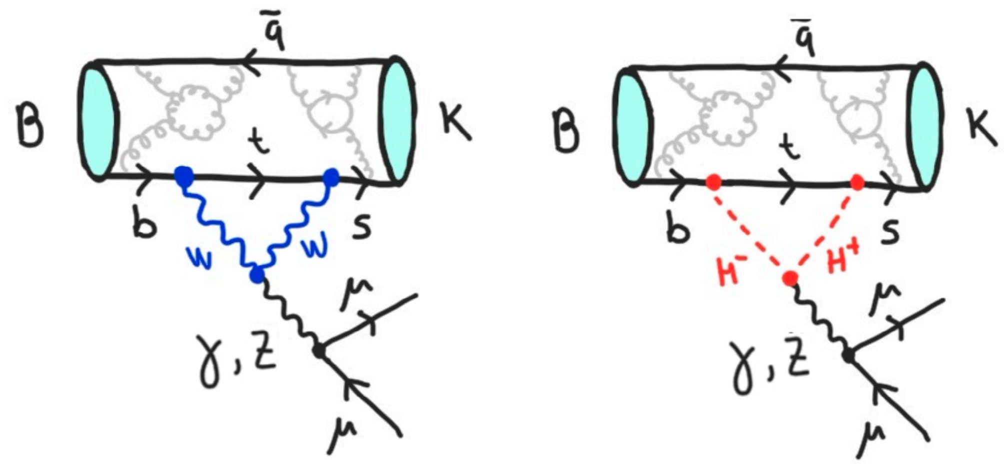
⇒ **Flavor violation** needs to be **protected** to **suppress rare/forbidden** processes.

⇒ Examples: *MFV*, or *flavor symmetries* such as $U(2)^5$.

[D'Ambrosio et al. '02], [Barbieri et al. '11]

Flavor observables and hadronic uncertainties

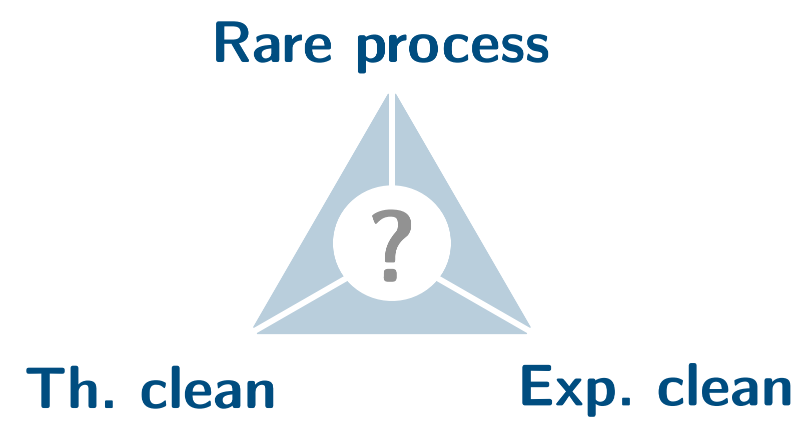
e.g.,



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

Look for observables:

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



$\Rightarrow$ **Challenging task! LFU tests** are a **good example**:

$$R_{H_c} = \frac{\mathcal{B}(H_b \to H_c \tau\nu)}{\mathcal{B}(H_b \to H_c \mu\nu)} \qquad\qquad R_{H_s} = \frac{\mathcal{B}(H_b \to H_s \mu\mu)}{\mathcal{B}(H_b \to H_s ee)} \qquad \cdots$$

$B_{(s)} \to D_{(s)},\ B^*_{(s)} \to D^*_{(s)},\ B_c \to J/\psi,\ \Lambda_b \to \Lambda_c \ldots$

$B \to K,\ B \to K^*,\ B_s \to \phi,\ \Lambda_b \to \Lambda \ldots$

[Kamenik et al. '08, Fajfer et al. '12] ...

[Hiller et al. '03] ...

Accidental symmetries and forbidden processes

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

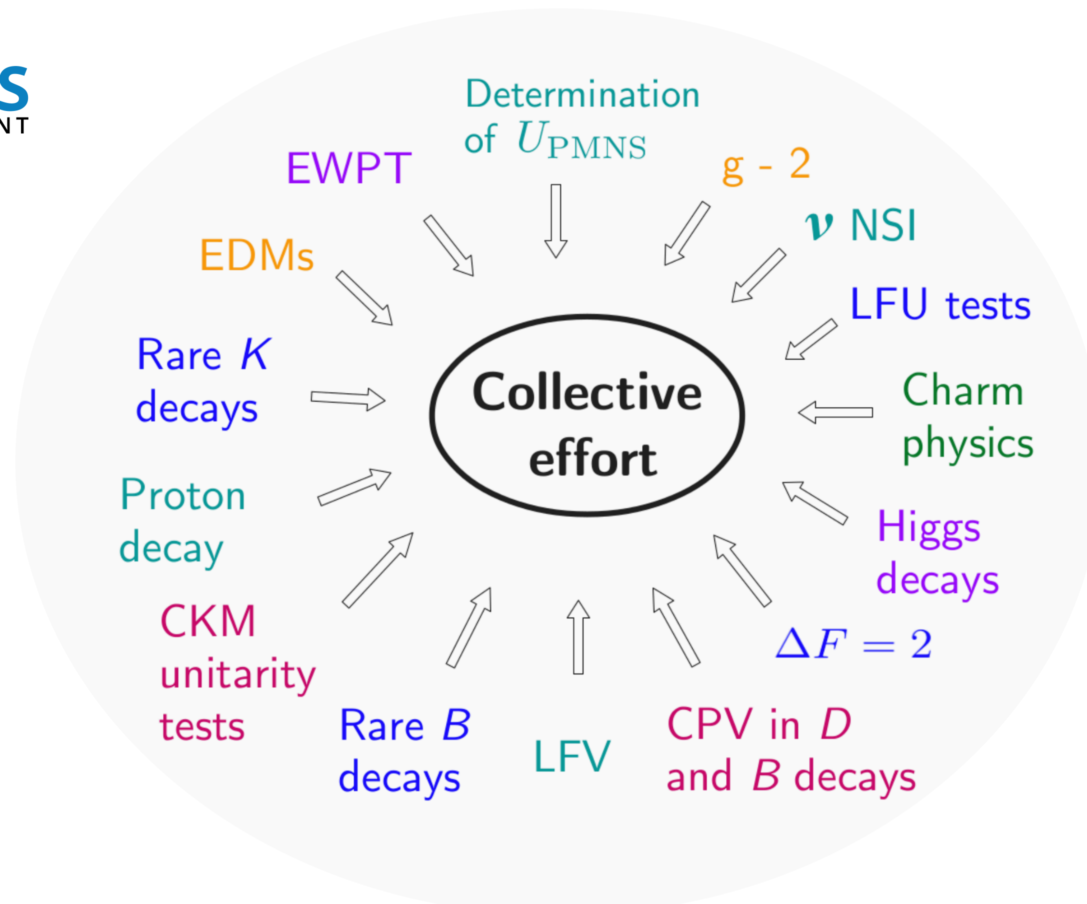
$$U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$$

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):** $\mu \to e\gamma$

<u>Very clean</u> probes of New Physics!

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. CKM-ology

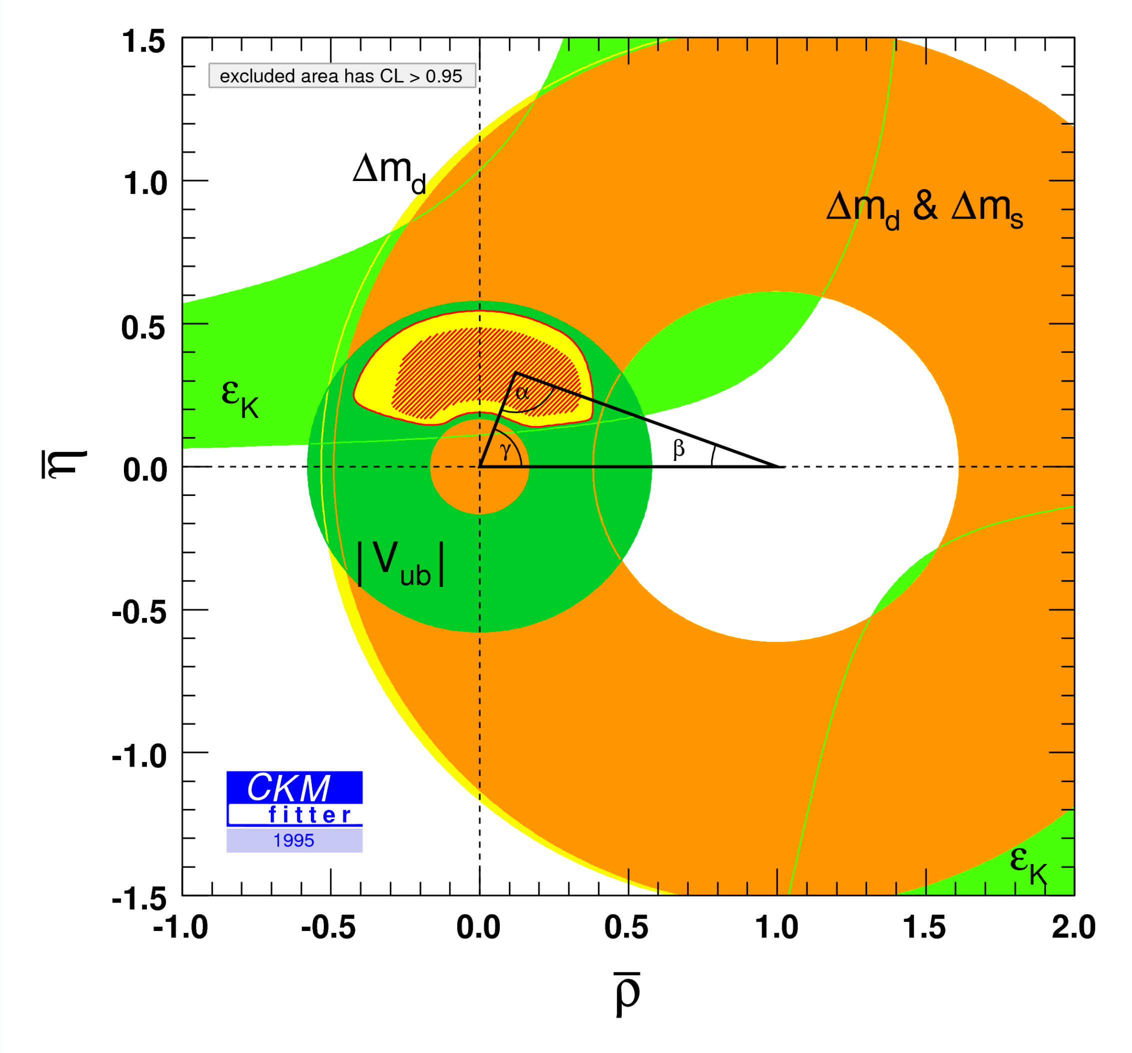
II. Highlights in B-physics

III. Probing flavor at high-p_T

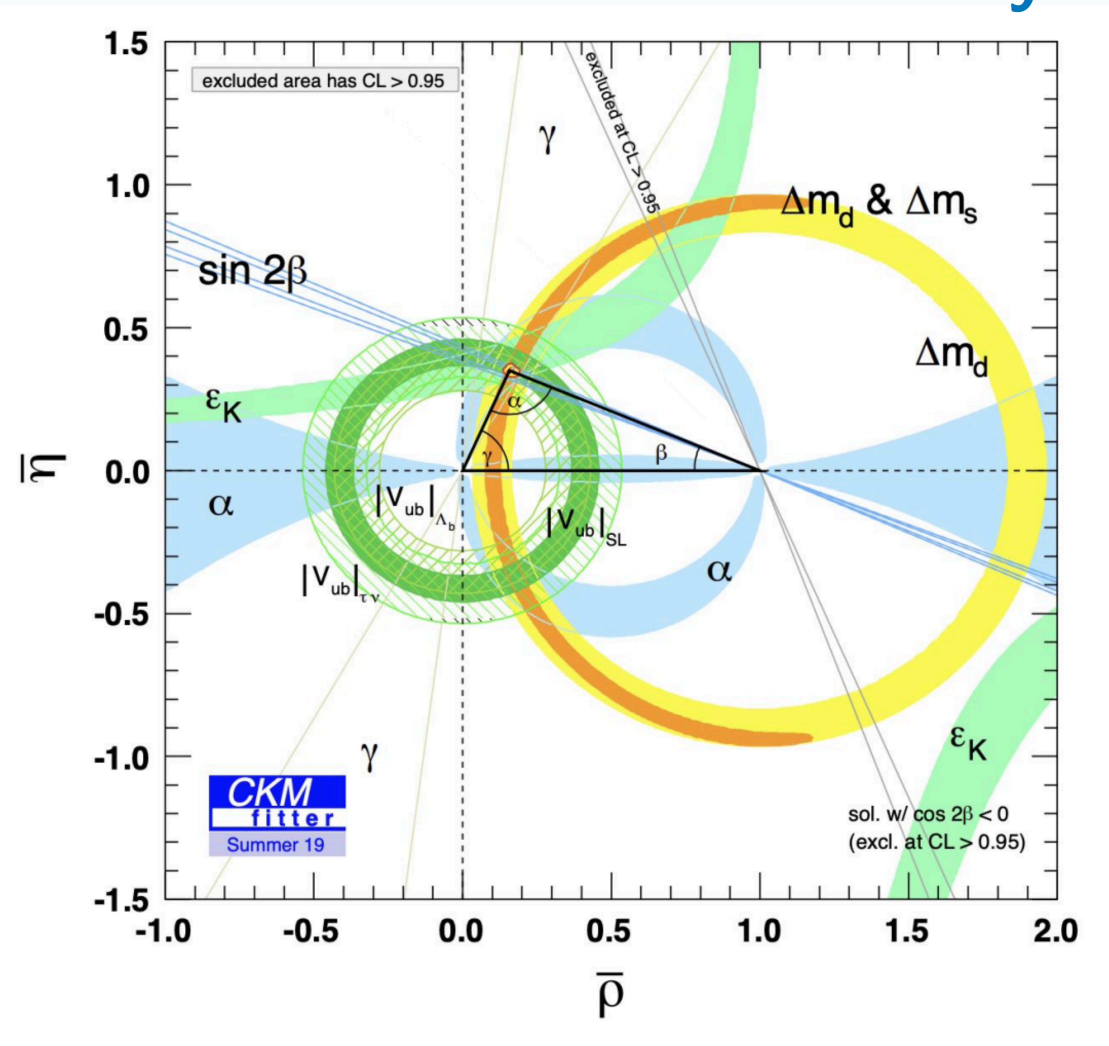
IV. Outlook

I. CKM-ology

1995

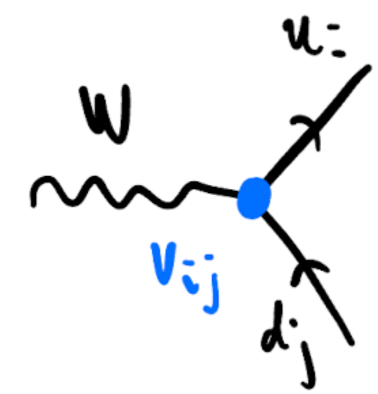


Today



CKM-ology

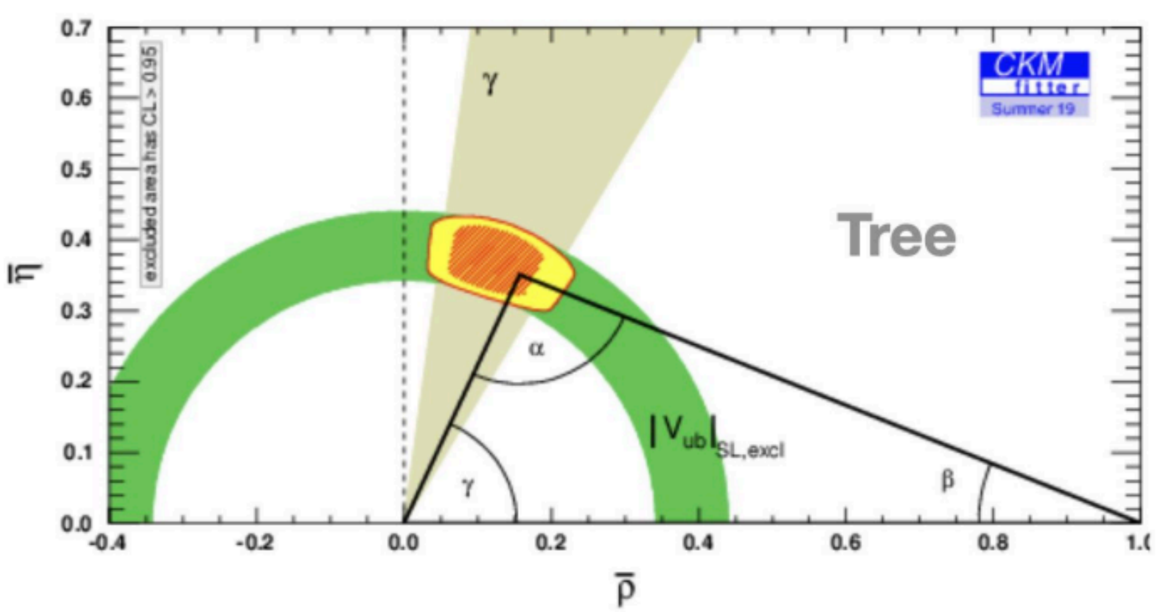
$$\mathcal{L}_{\text{c.c.}} \supset \frac{g}{\sqrt{2}} \left(V_{\text{CKM}}\right)_{ij} \left(\bar{u}_{Li} \gamma^\mu d_{L_j}\right) W^+_\mu + \text{h.c.}$$

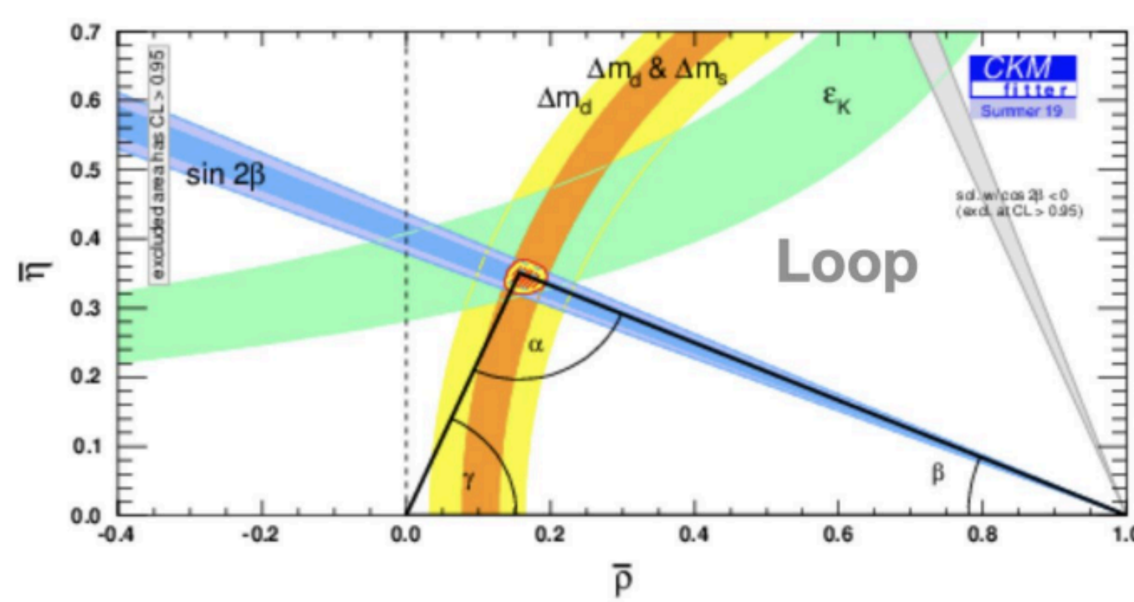


$$V_{\text{CKM}} = U^\dagger_{u_L} U_{d_L}$$

Strategy:

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



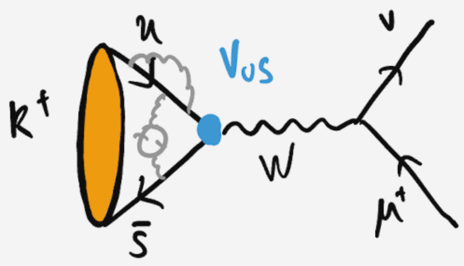


Good agreement! But there are a **few tensions** to be solved (*precision physics is* *hard!*)

Example: kaon decays

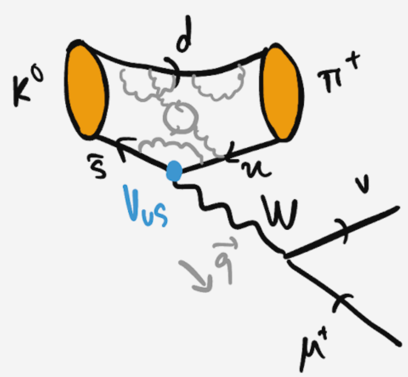
Hadronic uncertainties:

$K \to \mu\nu$



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

$K \to \pi\ell\nu$



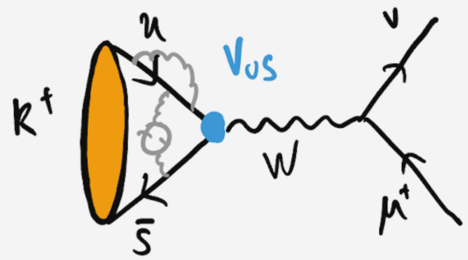
$$\langle \pi^+|\bar{s}\gamma^\mu u|K^0\rangle \propto f_{0,+}(q^2)$$

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

Example: kaon decays

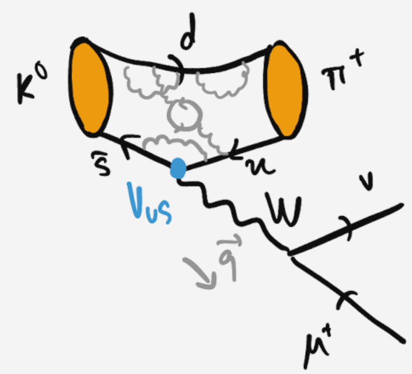
Hadronic uncertainties:

$K \to \mu\nu$



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

$K \to \pi\ell\nu$



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

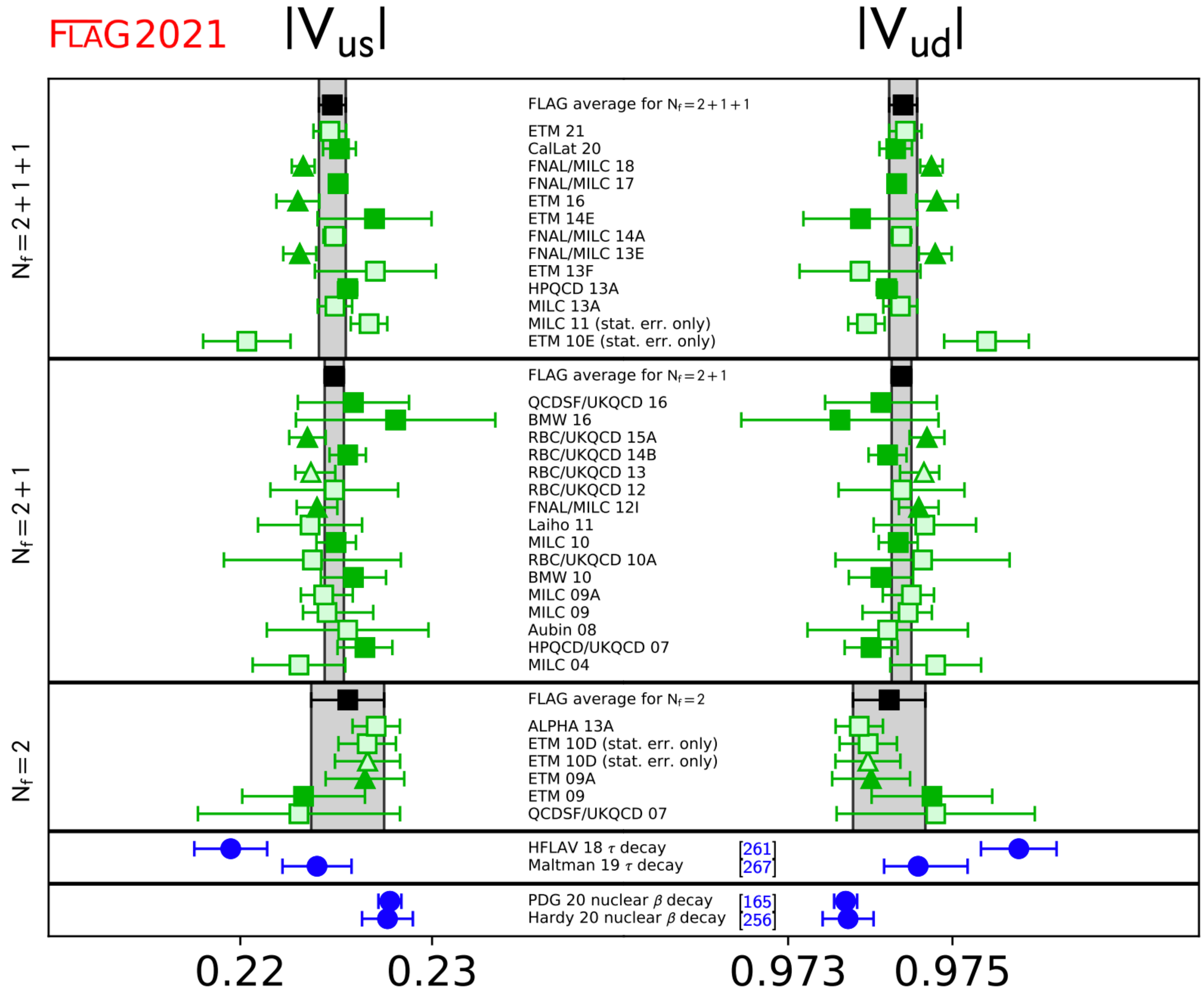
- **Non-perturbative QCD** (Lattice QCD needed) — *cf. FLAG review.*
- **Current precision** requires **radiative** and **isospin-breaking corrections**:

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

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

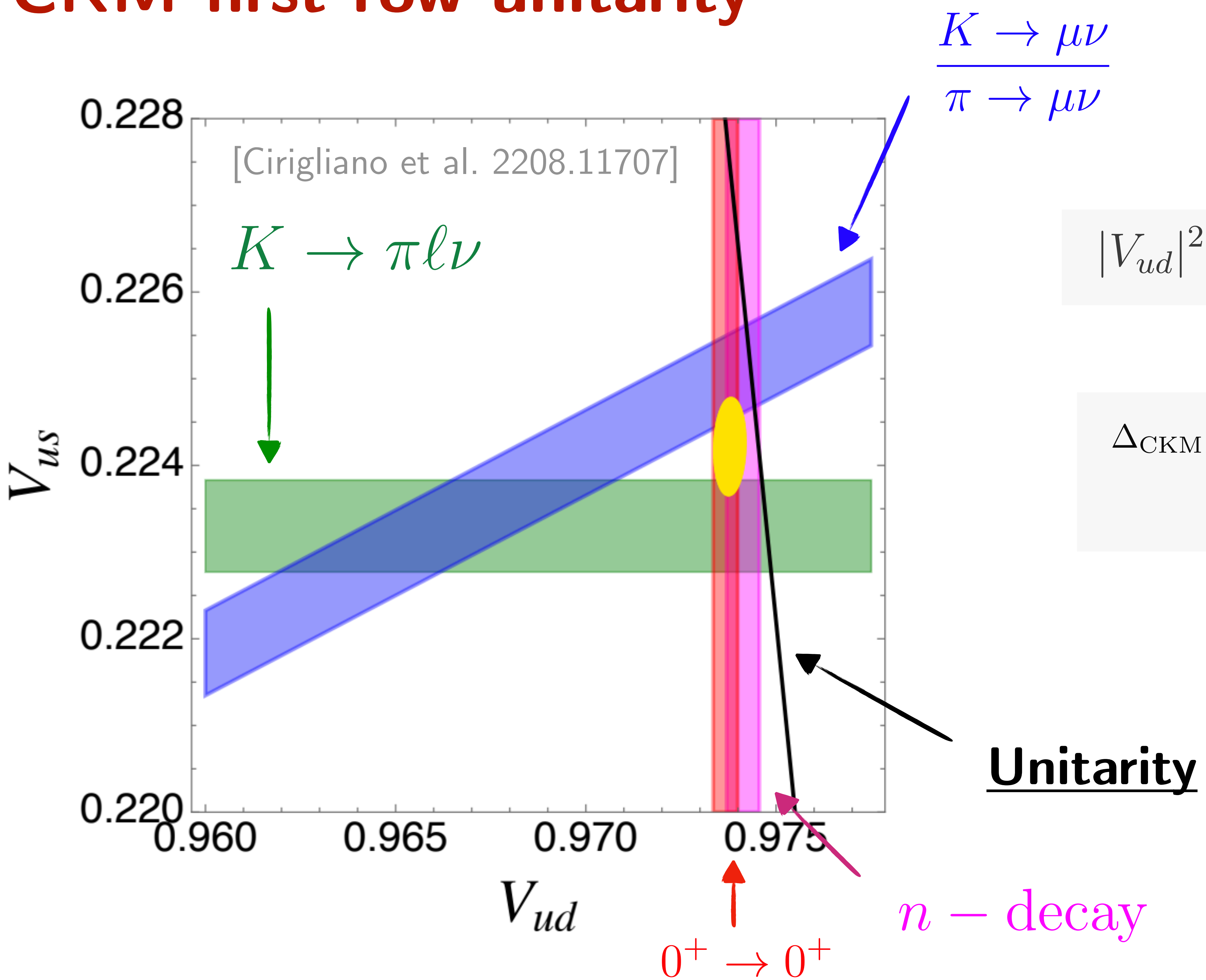
[Di Giusti et al. '17, '18], [Di Carlo et al. '19]...

FLAG


FLAG 2021
$|V_{us}|$
$|V_{ud}|$
$N_f = 2+1+1$
$N_f = 2+1$
$N_f = 2$
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]
0.22
0.23
0.973
0.975

CKM first-row unitarity

see also [Crivellin et al. '22, Belfatto et al. '23]



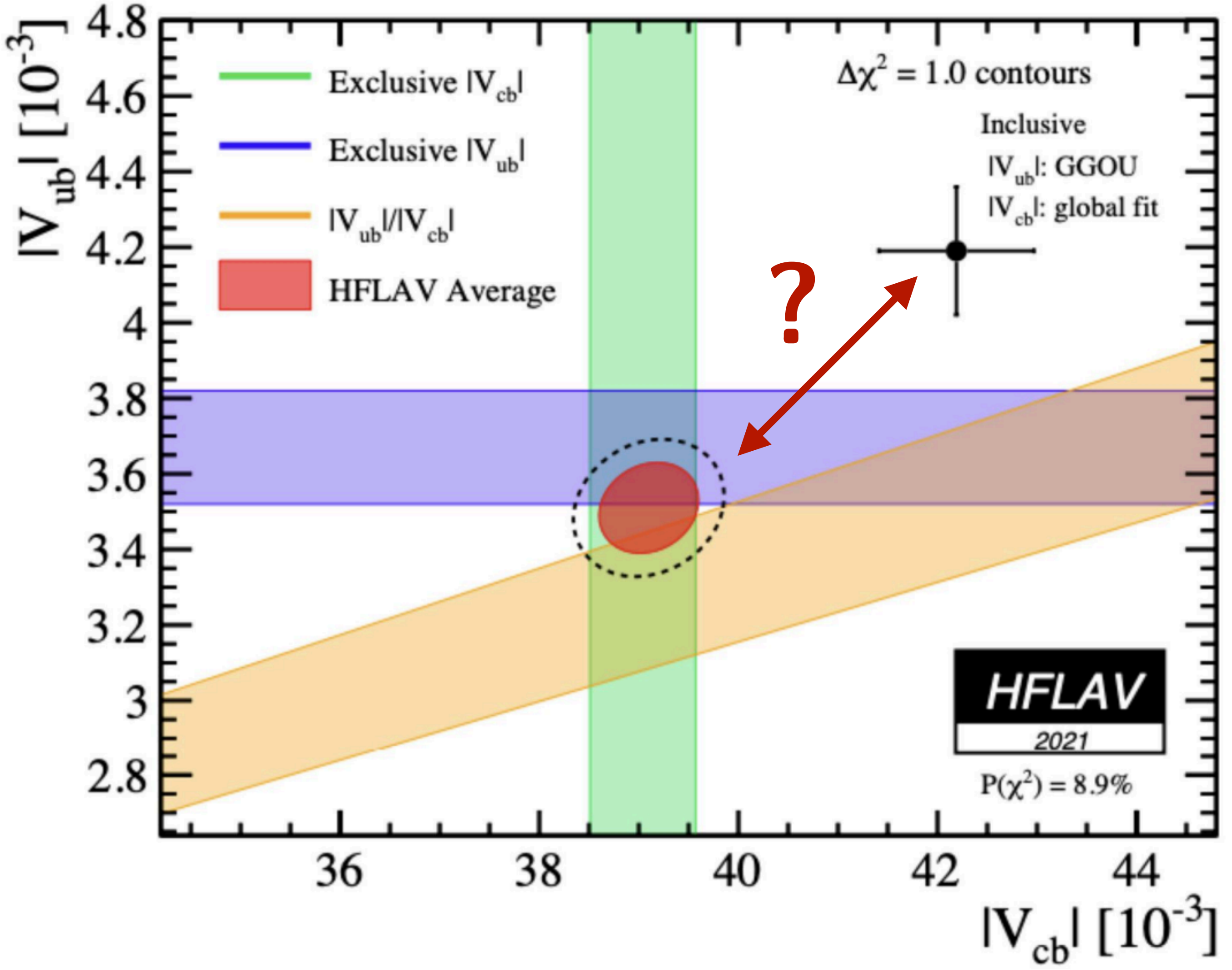
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

≈ 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** will be **fundamental** to solving these (mild) discrepancies! **New exp. inputs** would be **welcome too** (e.g., NA62)!

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



Long-standing discrepancy:

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

$B \to \pi l\nu$

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

$\ldots$

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

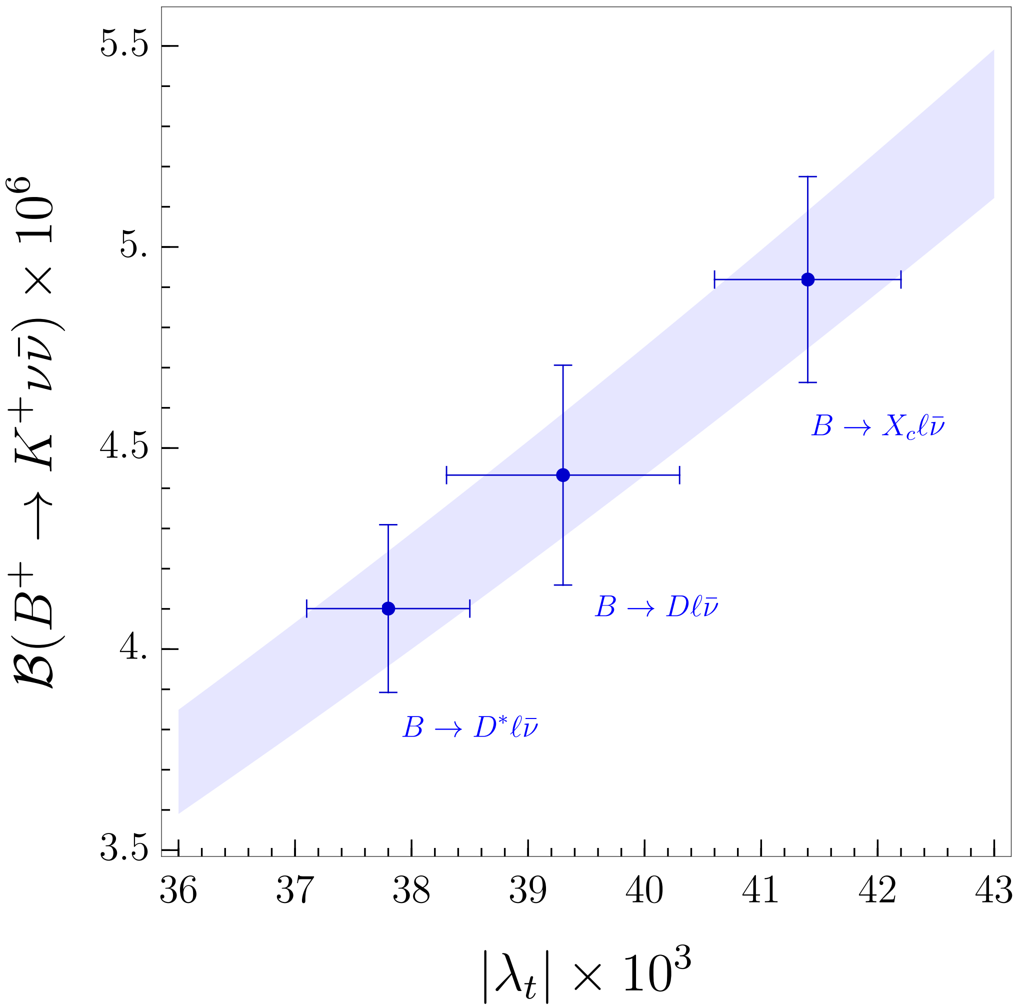
More problematic: V_{cb} plays an **essential role** in the predictions of **FCNCs** through **unitarity**!

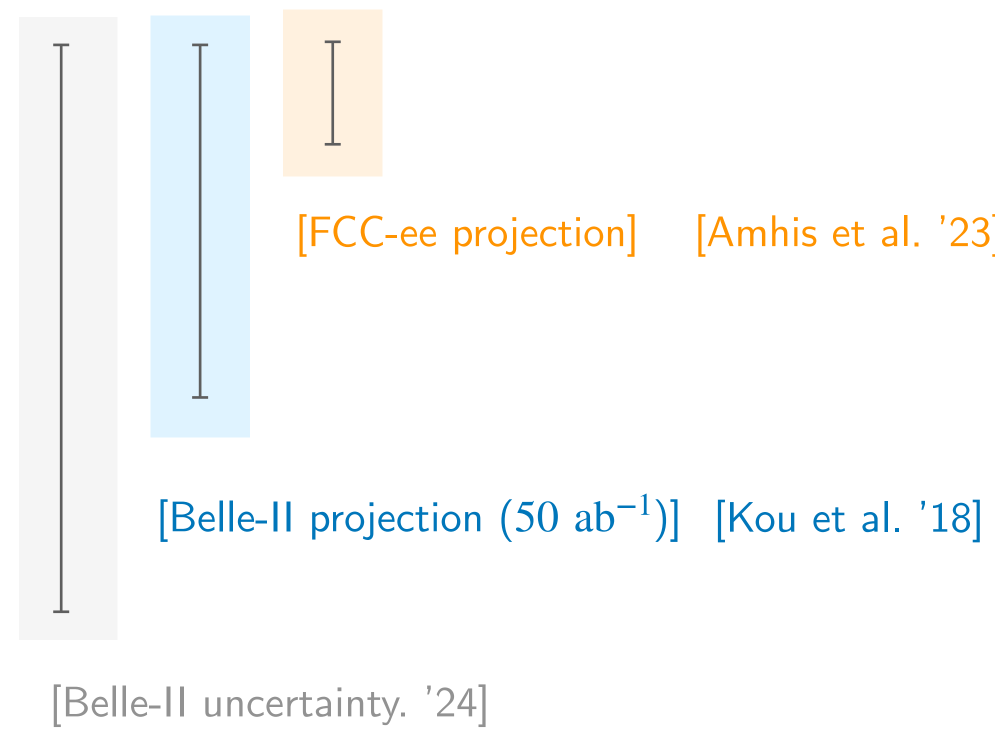
$$|V_{tb}V_{ts}^*| = |V_{cb}|\left[1 + \mathcal{O}(\lambda^2)\right]$$

CKM and theory uncertainties

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

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





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

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

*See [FNAL, '15], [HPQCD, '22] for $B \to K$ FFs

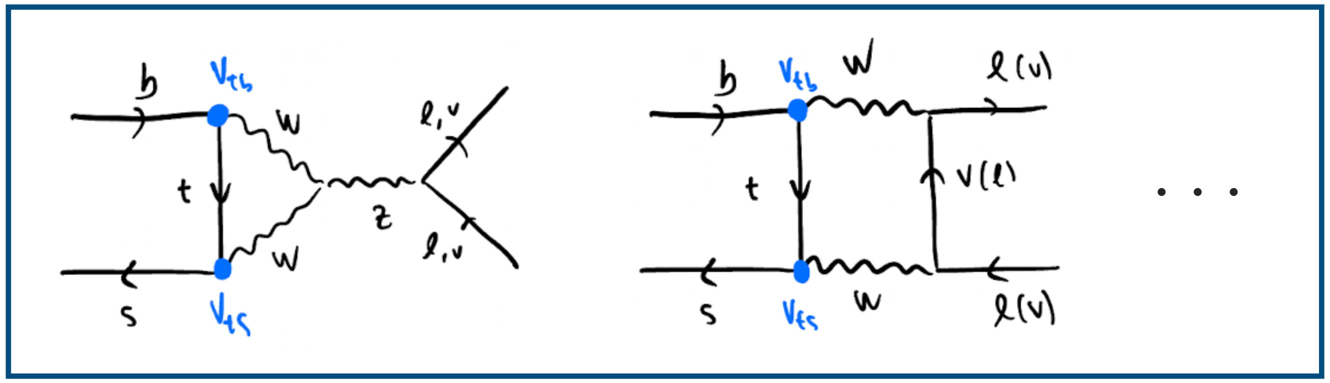
The **ambiguity** in **determining** V_{cb} can be a **bottleneck** for **SM predictions** of **clean FCNC processes** such as $B \to K\nu\bar{\nu}$ and $B_s \to \mu\mu$ in the long term.

II. Highlights in B-physics

[Recap] B-meson decays

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

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



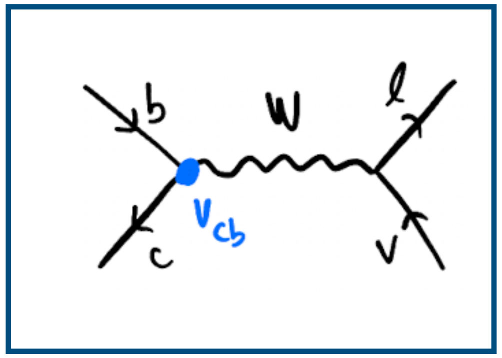
$B \to K^{(*)}\ell\ell$

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

$B_s \to \phi\ell\ell$

$\dots$

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



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

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

$\dots$

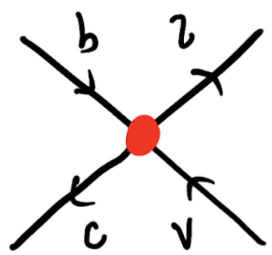
These **processes** are **related** through **gauge invariance** — *within SMEFT and UV models.*

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

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

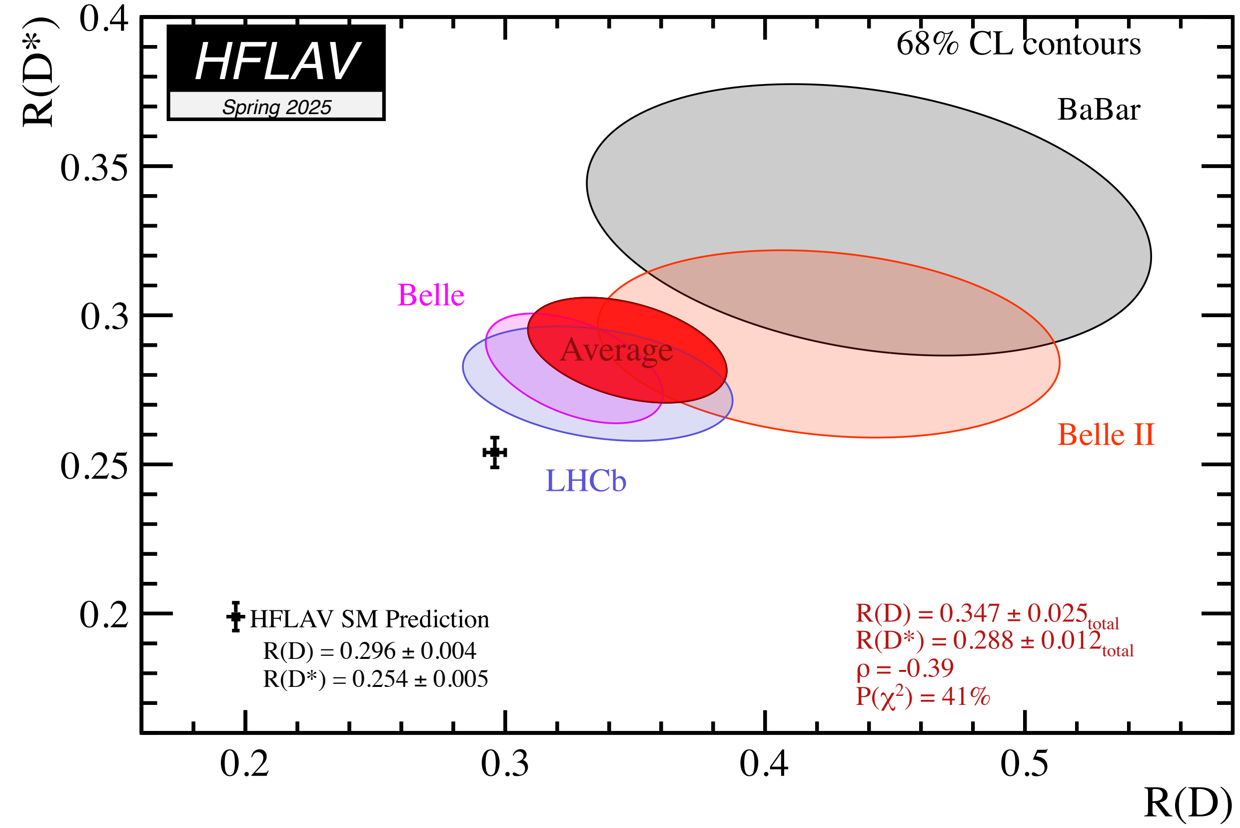
cf. also $R_{J/\psi}$ and R_{Λ_c}

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



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

[Di Luzio et al. '17]

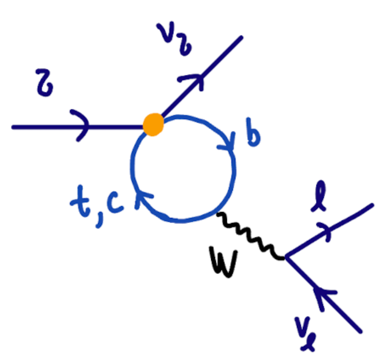


LQCD: [FNAL/MILC, HPQCD]

see also [Bordone et al. '24]

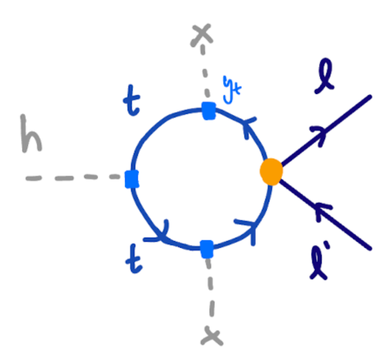
- **SM predictions** are under **reasonable control**, *cf. back-up.*
- **Experimental situation** remains **unclear** — *more data needed!*
- **New physics models** explaining these excesses lead to **signals in τ-related observables**:

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



[Feruglio et al. '16]

$h \to \tau\tau$

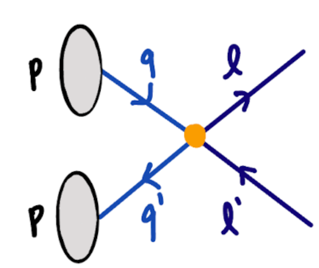


[Feruglio, Paradisi, **OS**. '18]

[Crivellin et al. '20]

$pp \to \tau\tau$

$pp \to \tau\nu$



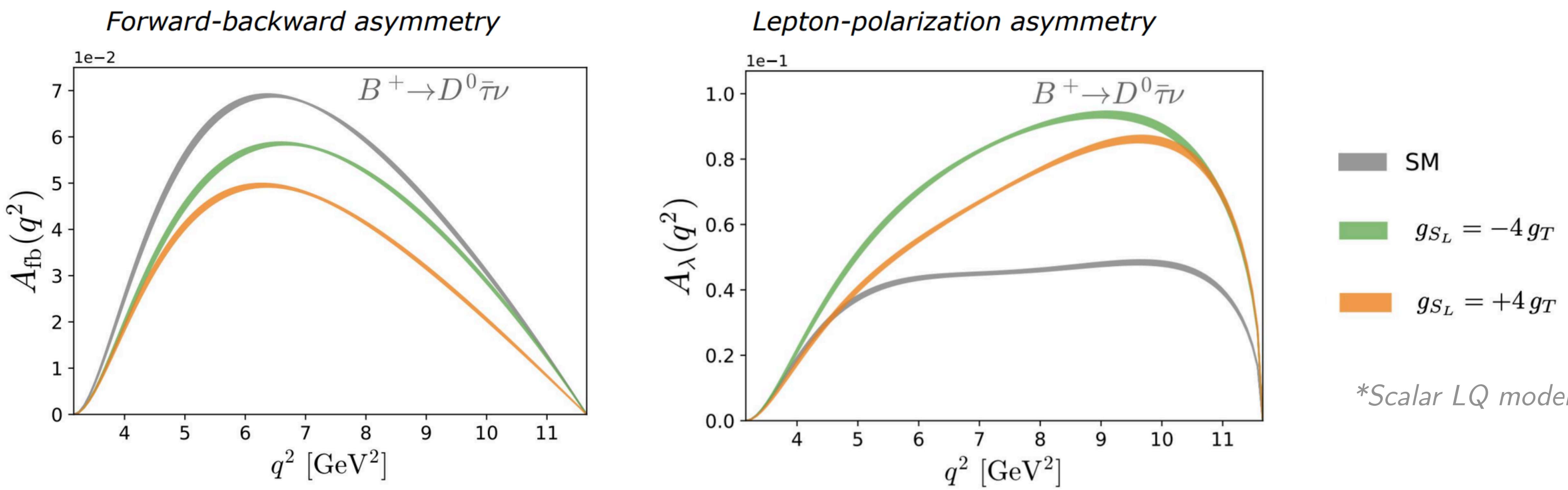
[Faroughy et al. '16]

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

From LFU to angular observables: $b \to c\tau\bar{\nu}$

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

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



*Scalar LQ models

- Many more opportunities in other modes:

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

see e.g. [Becirevic et al. '16, '19]
[Iguro et al. '18], [de Boer et al. '19], [Bobeth et al. '21]

- First exp. studies for specific observables:

$P_\tau^{D^*}$ [Belle. '16, '17]

$F_L^{D^*}$ [Belle. '19], [LHCb. '23]

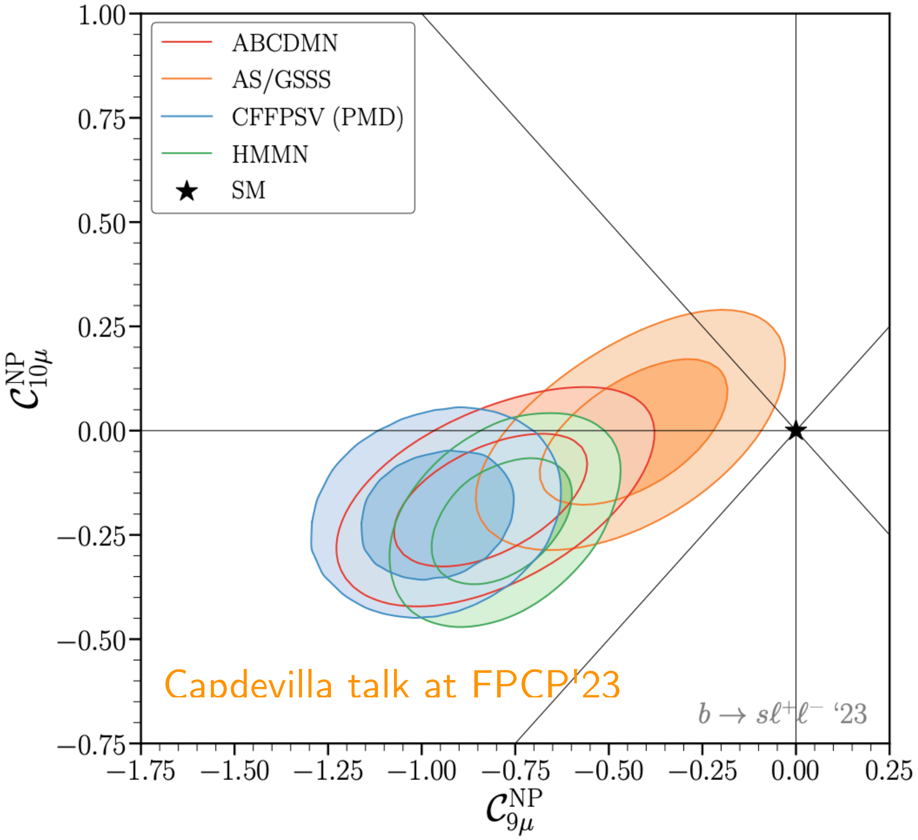
Can we further explore $b \to c\tau\nu$ angular observables?

see [Iguro et al. '24] for discussion

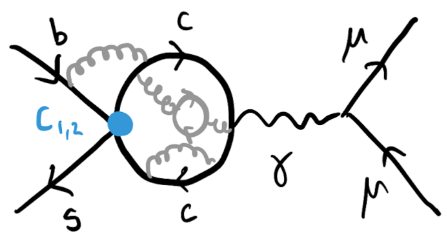
Anomalies in $B \to K^{(*)}\ell\ell$ decays?

- $B \to K^{(*)}\mu\mu$ 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**?



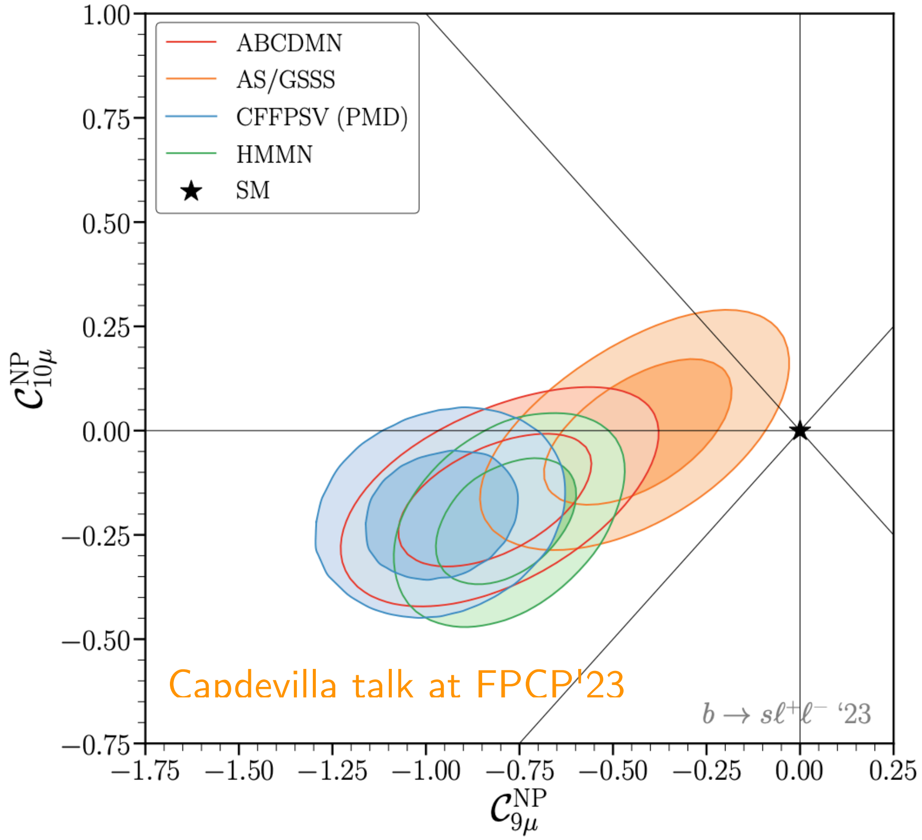
see e.g. [Ciuchini et al'. '21, Gubernari et al. '22, Isidori et al. '24]...

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

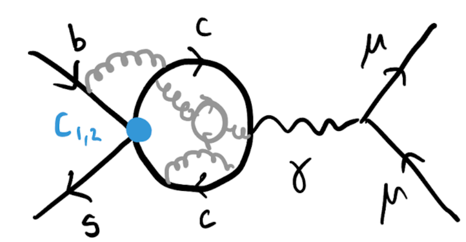
Anomalies in $B \to K^{(*)}\ell\ell$ decays?

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

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



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:

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

[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]

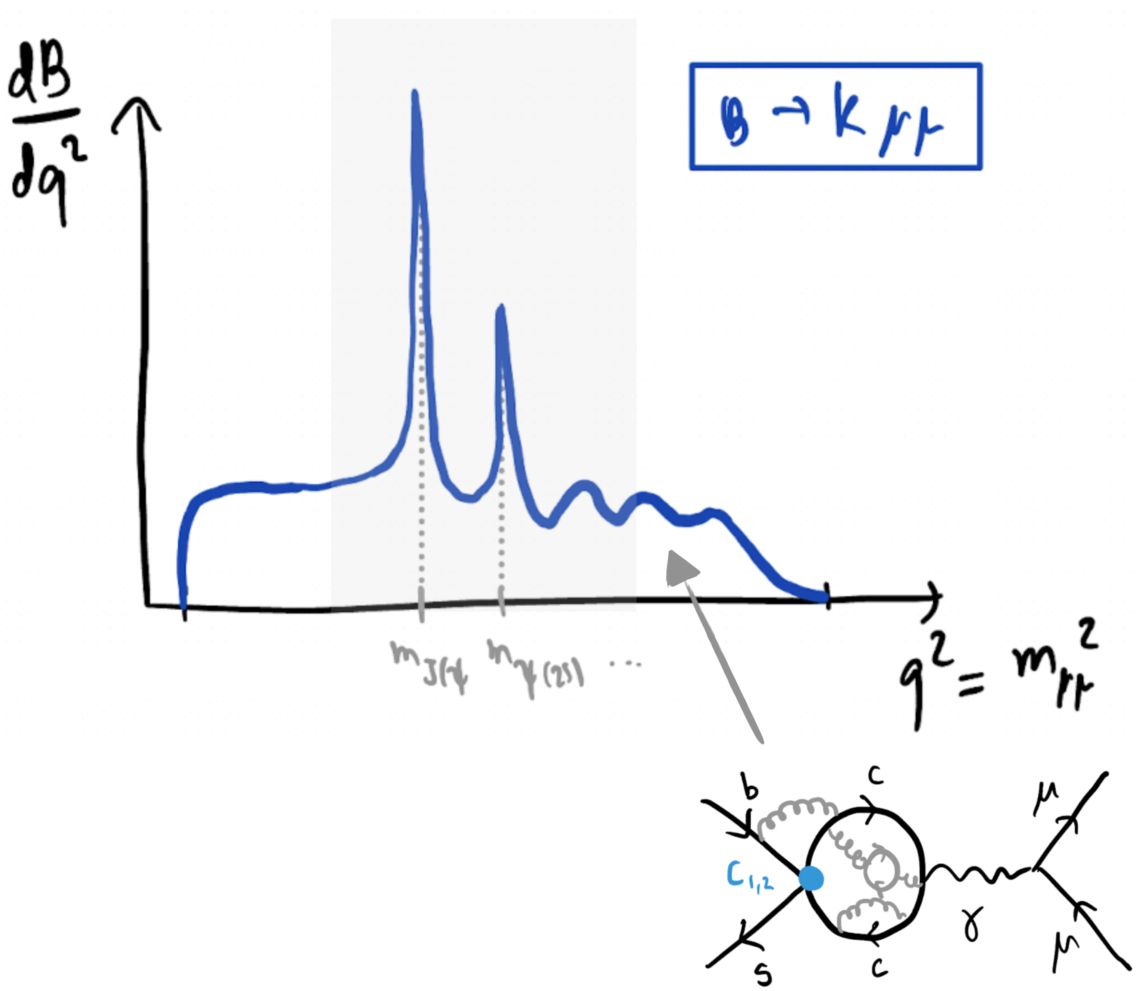
Why to study B-decays with neutrinos?

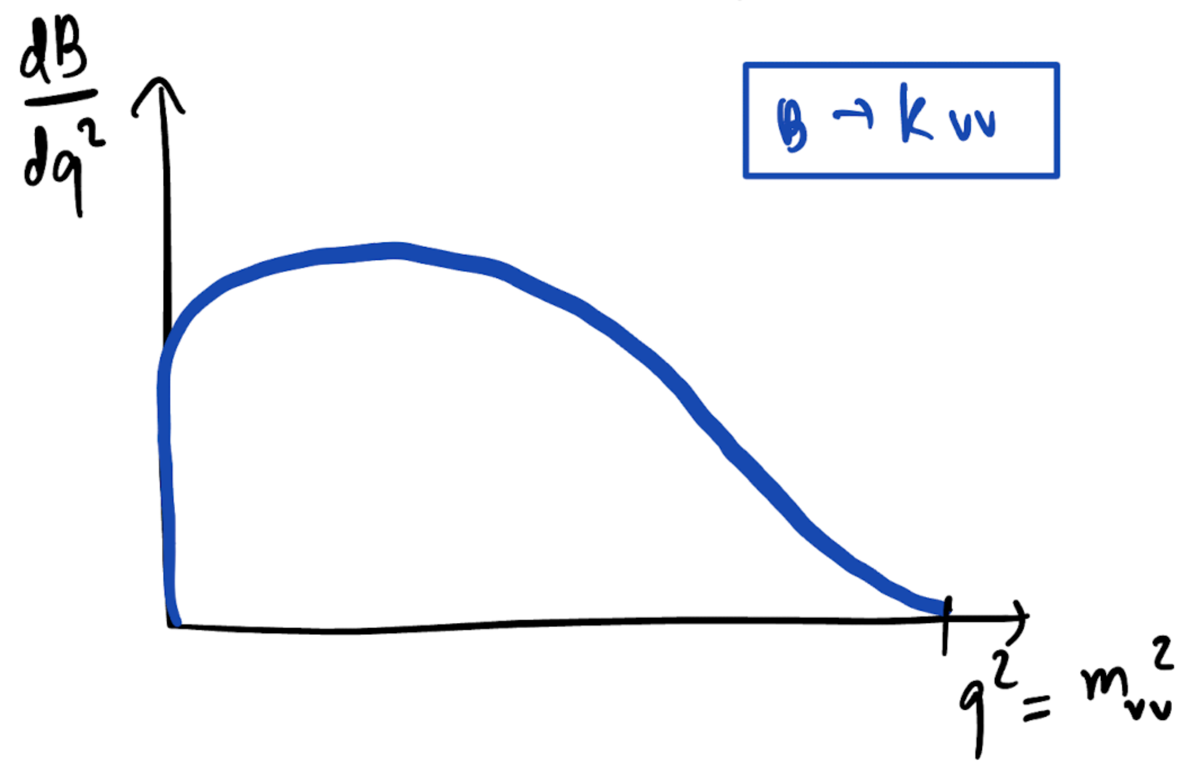
- $B \to K^{(*)}\ell\ell$:

  - *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.*** ✓





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

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

- **Effective Hamiltonian** within the SM:

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

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

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

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

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

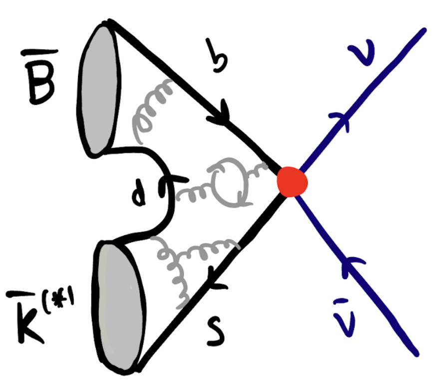
Including NLO QCD and two-loop EW contributions:

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

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

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

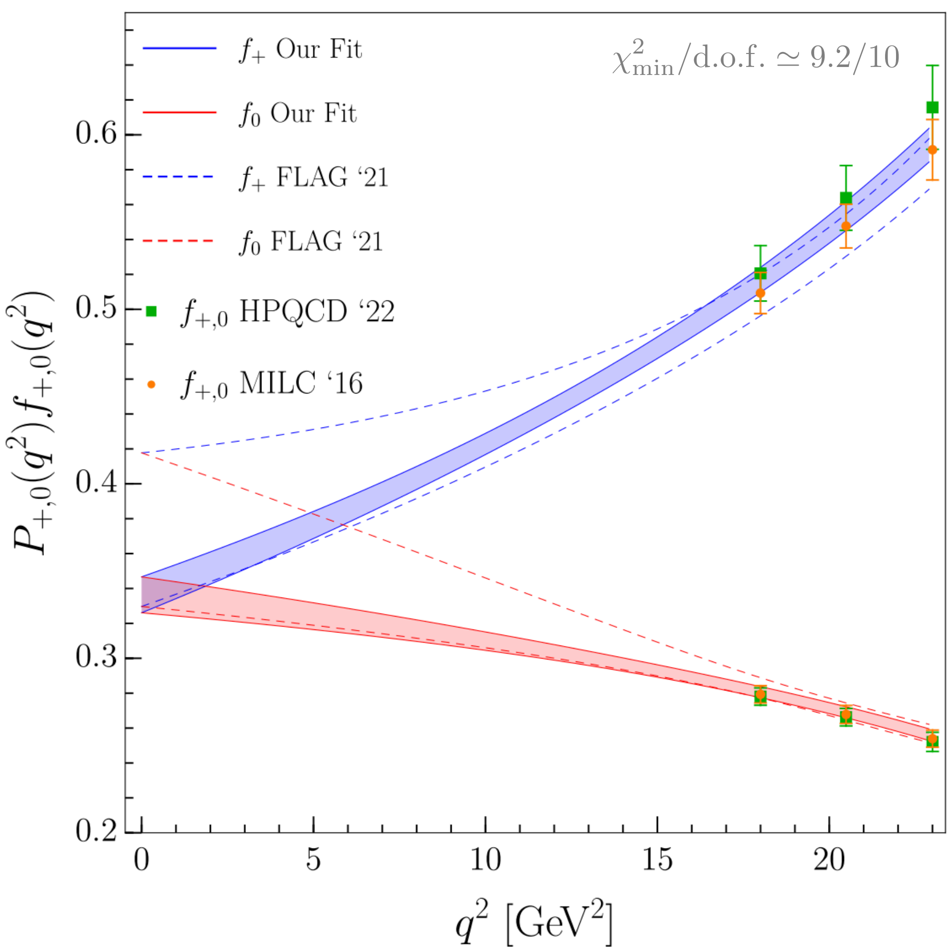
- **Lattice QCD** data available at **nonzero recoil** ($q^2 \neq q^2_{\rm max}$) for all form-factors:

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

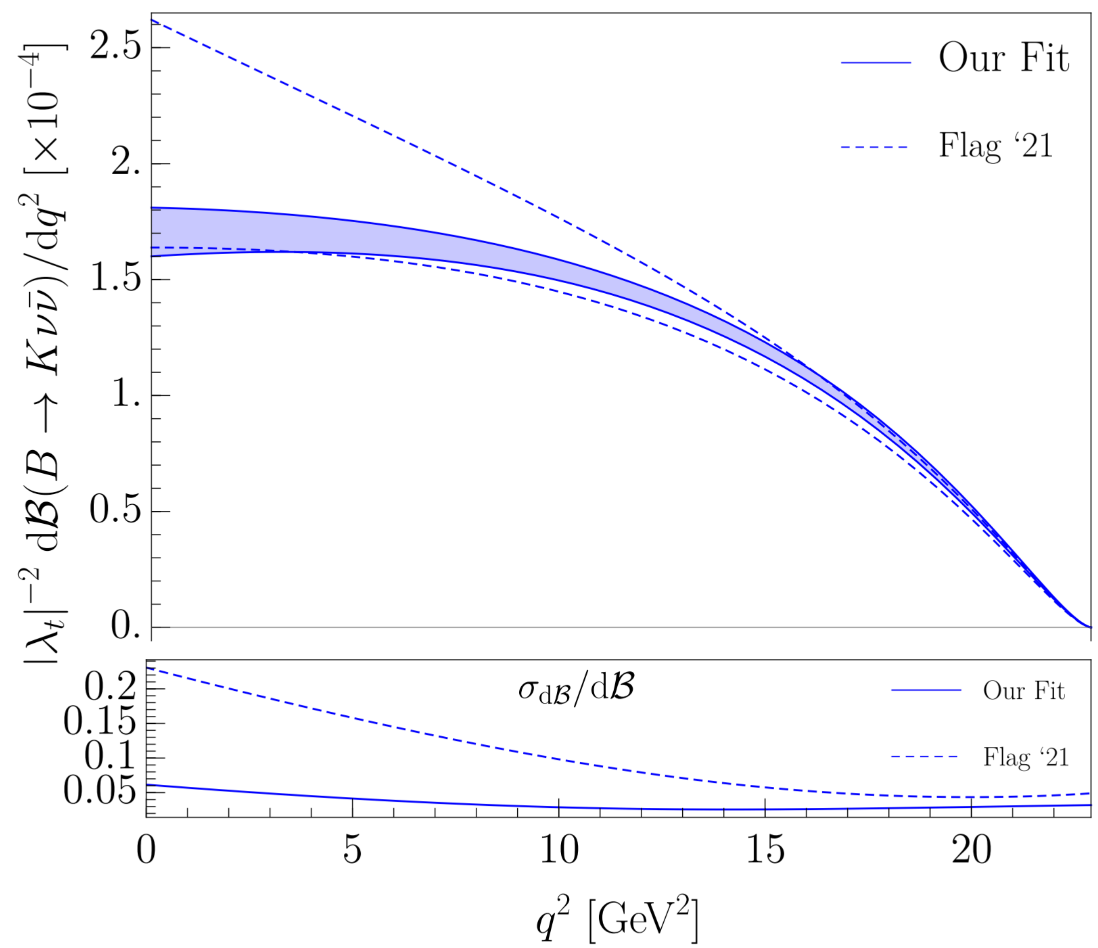
Only form-factor needed for $B \to K\nu\bar{\nu}$!

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

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



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

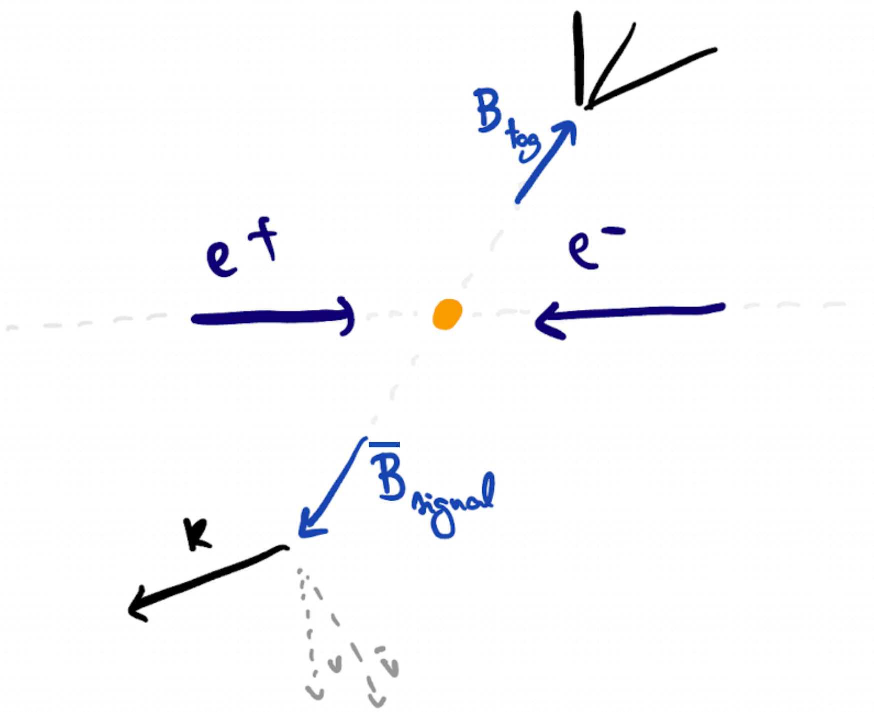


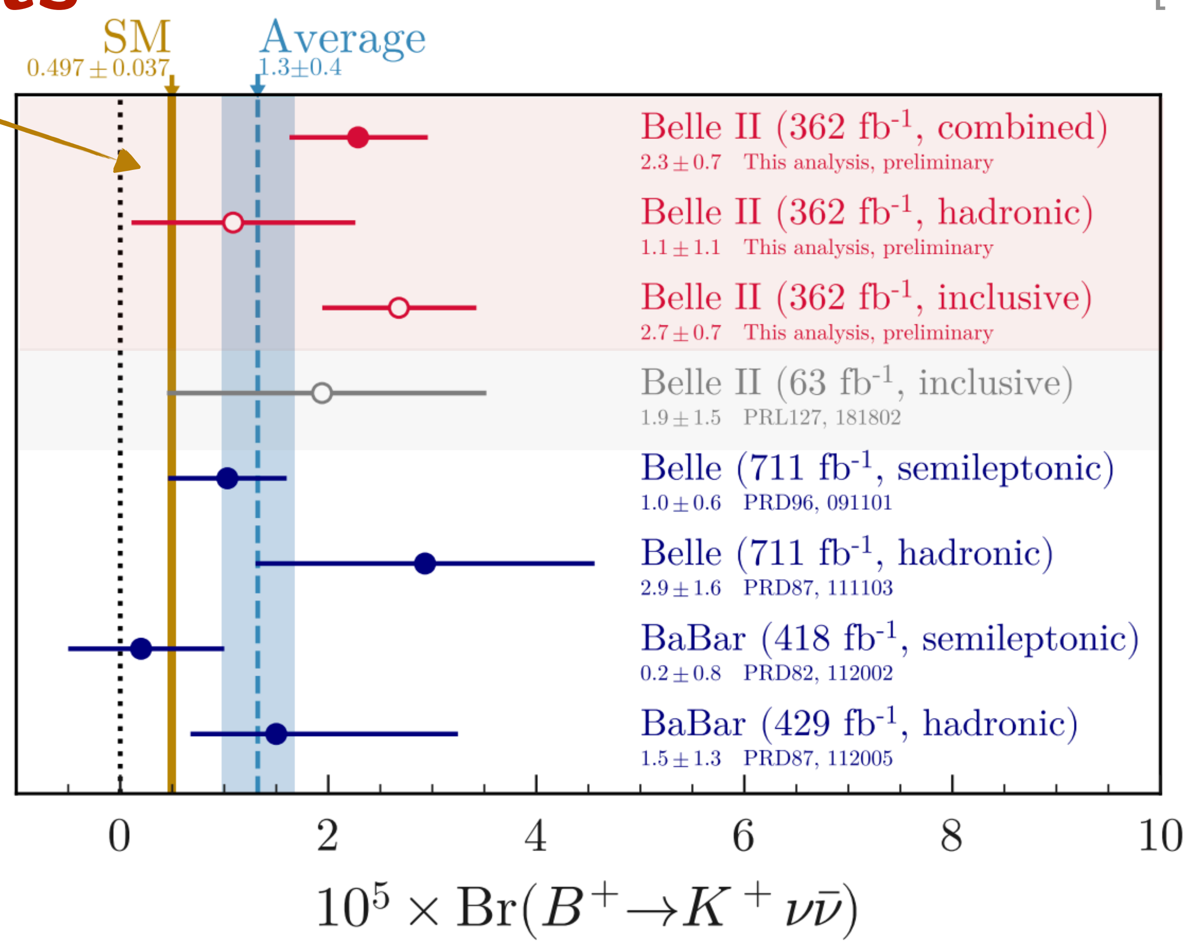
[Becirevic, Piazza, **OS**. 2301.06990]

[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).

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]

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

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

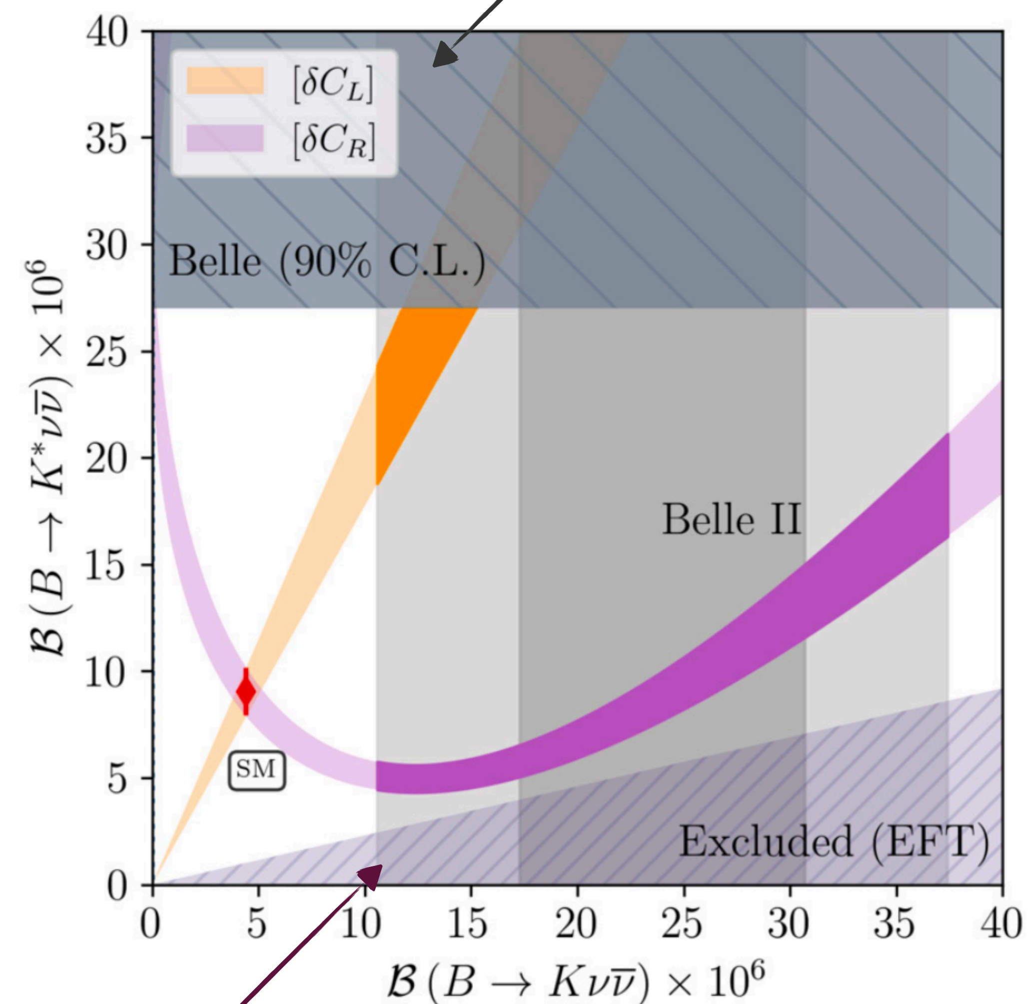
$$\frac{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})}{\mathcal{B}(B\to K^{(*)}\nu\bar{\nu})^{\rm SM}} = 1 + \sum_i \frac{2\text{Re}[C_L^{\rm SM}(\delta C_L^{\nu_i\nu_i} + \delta C_R^{\nu_i\nu_i})]}{3|C_L^{\rm SM}|^2} + \sum_{i,j}\frac{|\delta C_L^{\nu_i\nu_j} + \delta C_R^{\nu_i\nu_j}|^2}{3|C_L^{\rm SM}|^2}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

$\eta_K = 0$

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

[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]

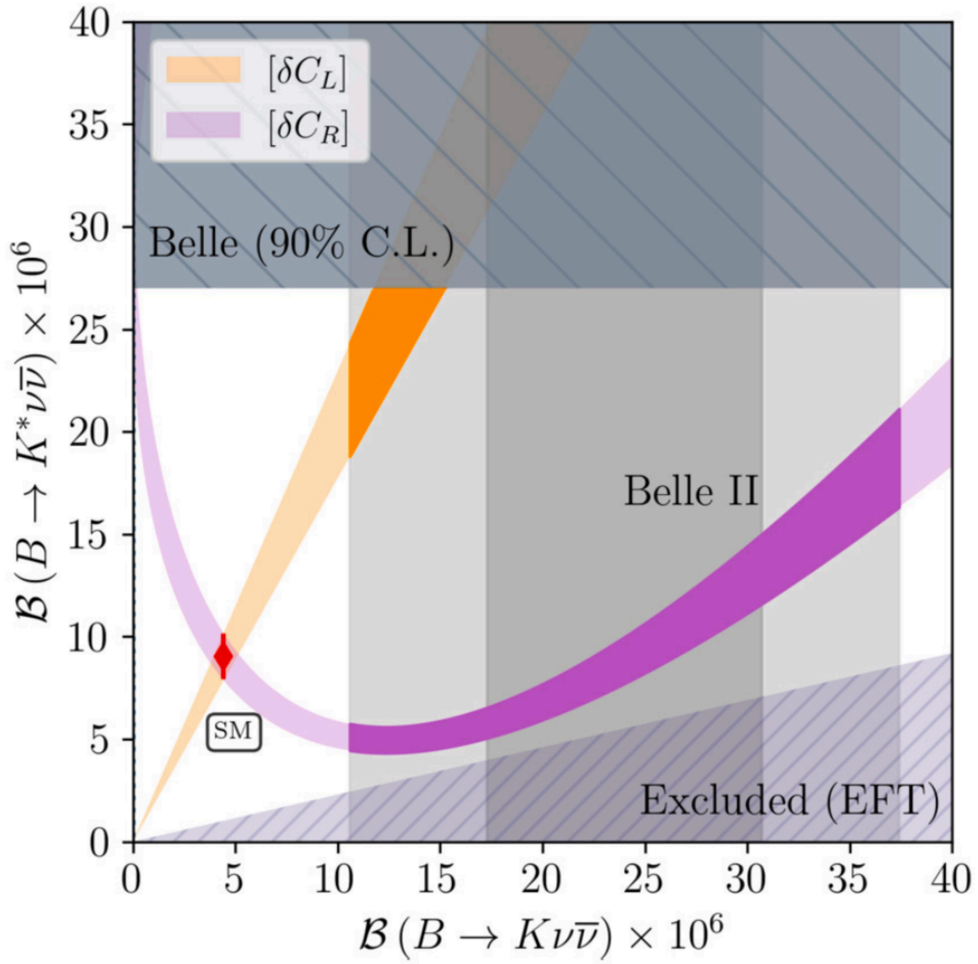
- Another observable to measure is the K^* longitudinal-polarisation asymmetry:

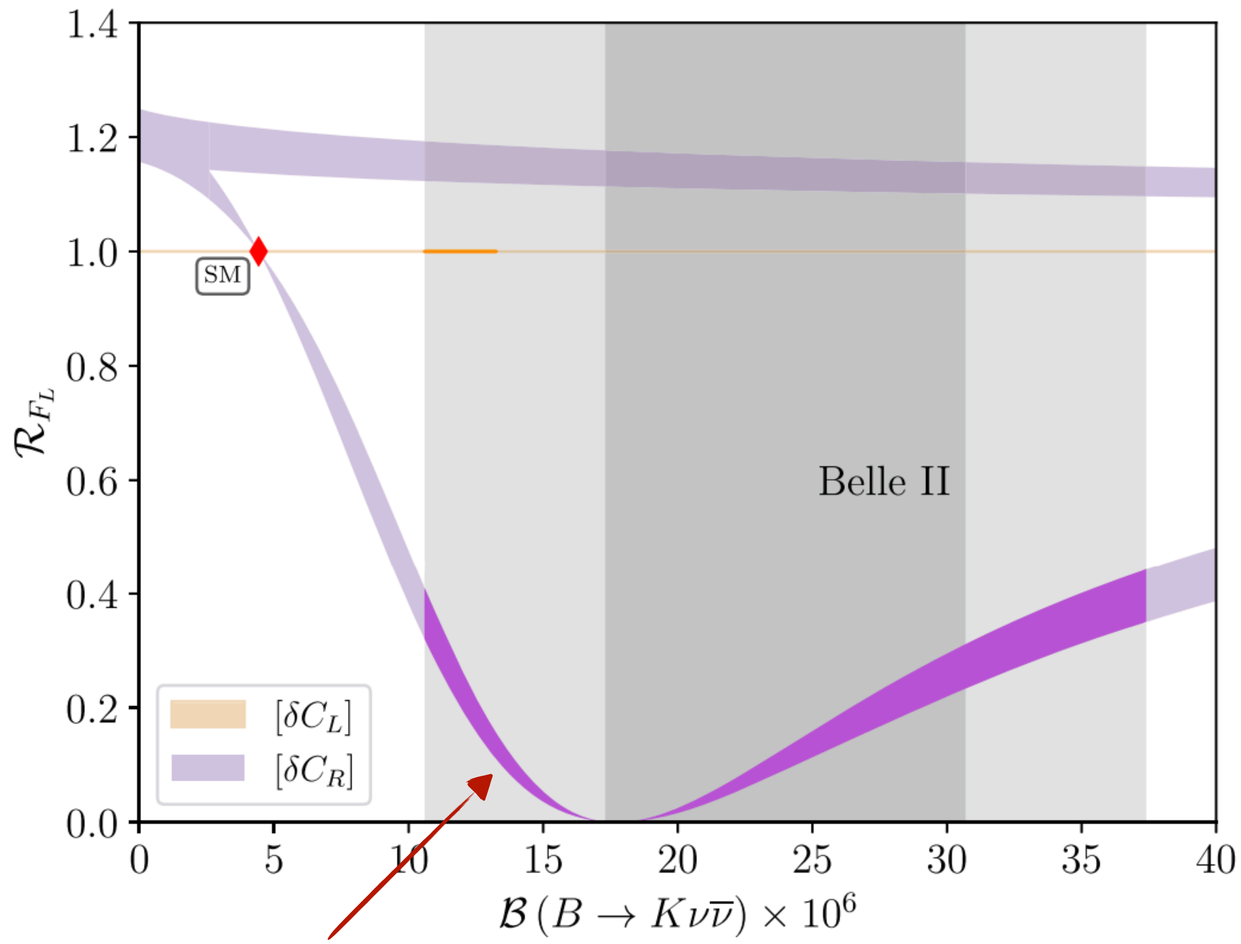
$$F_L \equiv \frac{\Gamma_L(B \to K^*\nu\bar{\nu})}{\Gamma(B \to K^*\nu\bar{\nu})}$$

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

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

[Altmannshofer et al. '09]





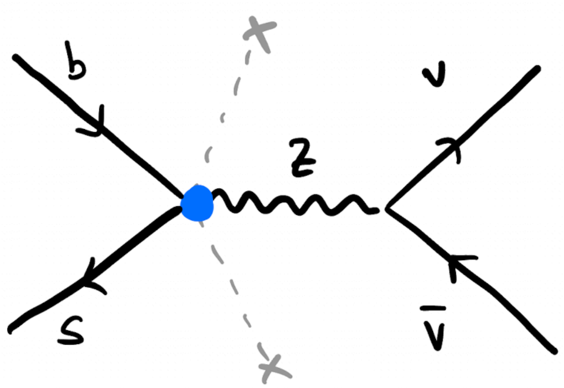
Depletion of SM prediction!

The 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 $\Lambda \gg v_{\text{ew}}$ 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) $\psi^2 H^2 D$:

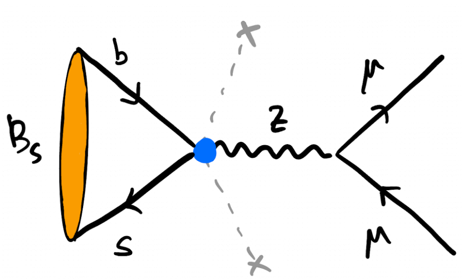


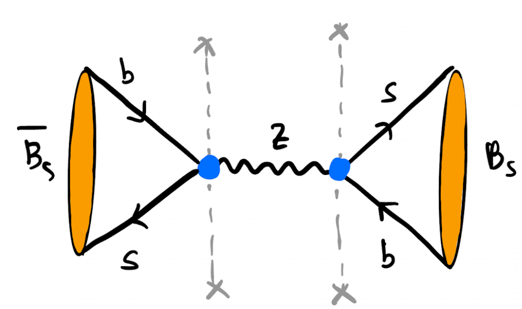
e.g.,

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

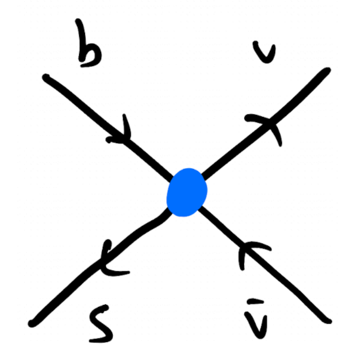
Lepton flavor universal!

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





ii) ψ^4 :



e.g.,

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

$\Rightarrow$ Only viable option!

*with couplings to τ-leptons!

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

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

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

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

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

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

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

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

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

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

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

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

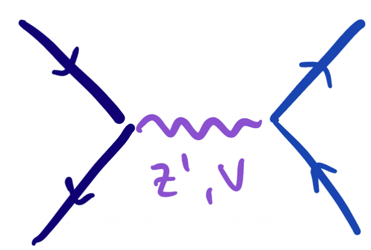
$$[\mathcal{O}_{ld}]_{ijkl} = (\bar{L}_i \gamma^\mu L_j)(\bar{d}_k \gamma_\mu d_l) = (\bar{\ell}_{Li} \gamma^\mu \ell_{Lj})(\bar{d}_{Rk} \gamma_\mu d_{Rl}) + (\bar{\nu}_{Li} \gamma^\mu \nu_{Lj})(\bar{d}_{Rk} \gamma_\mu d_{Rl})$$

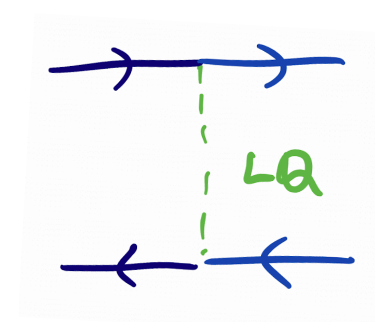
- Correlations for concrete mediators:

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

…

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





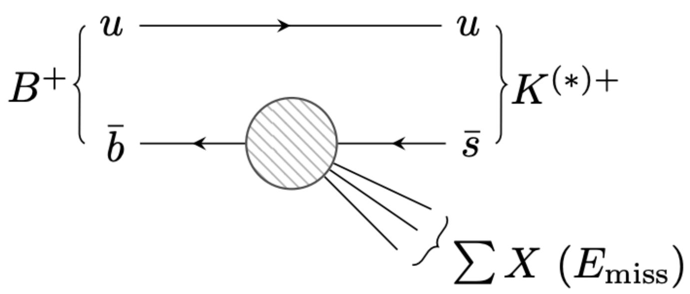
$$\frac{\mathcal{C}}{\Lambda^2} \simeq (5\ \mathrm{TeV})^{-2}$$

*with couplings to τ-leptons!

Hidden sectors?

see e.g. [Izaguirre et al. '17, Gavela et al. **(OS)** '19, Felk et al'. 23, Altmannshofer et al. '23]
[Bauer et al. '21, Alonso-Alvarez et al. '23, He et al. '23, Buras et al. '24]...

- $B \to K + \text{inv}$ is also a probe of light/invisibles particles — different EFT description needed:

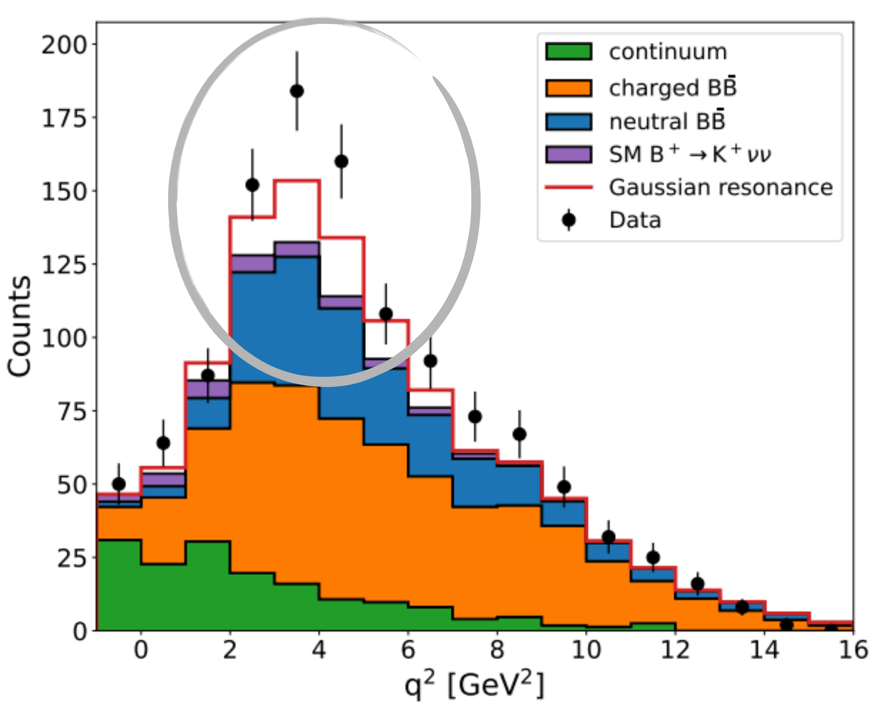


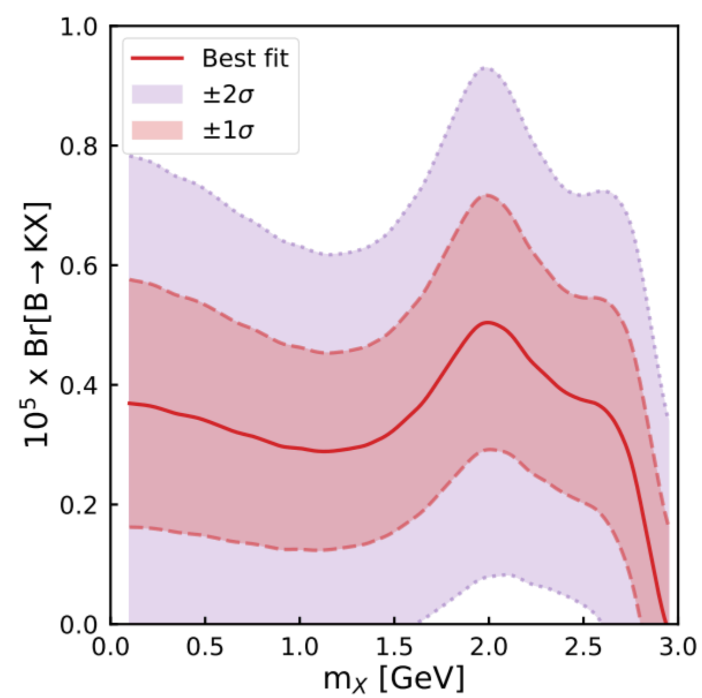
$B \to KX$ $\quad$ $B \to K\nu_L\nu_R$ $\quad$ $B \to K\chi\chi$, $B \to K\phi\phi$ $\quad$ ...

[Kamenik et al. '11, Bolton et al. '24, Rosauro-Alcaraz, Leal. '24]

- If the excess is due to $B \to KX(\to \text{inv})$, where $X \sim (\mathbf{1}, \mathbf{1}, 0)$ is a mediator produced on-shell *(i.e., with $m_X < m_B$),* the main difference would be a **peak** at $q^2 \simeq m_X^2$.

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





Best fit (2.8σ): $m_X \approx 2\ \text{GeV}$

$\mathcal{B}(B \to KX) = (5.1 \pm 2.1) \times 10^{-6}$

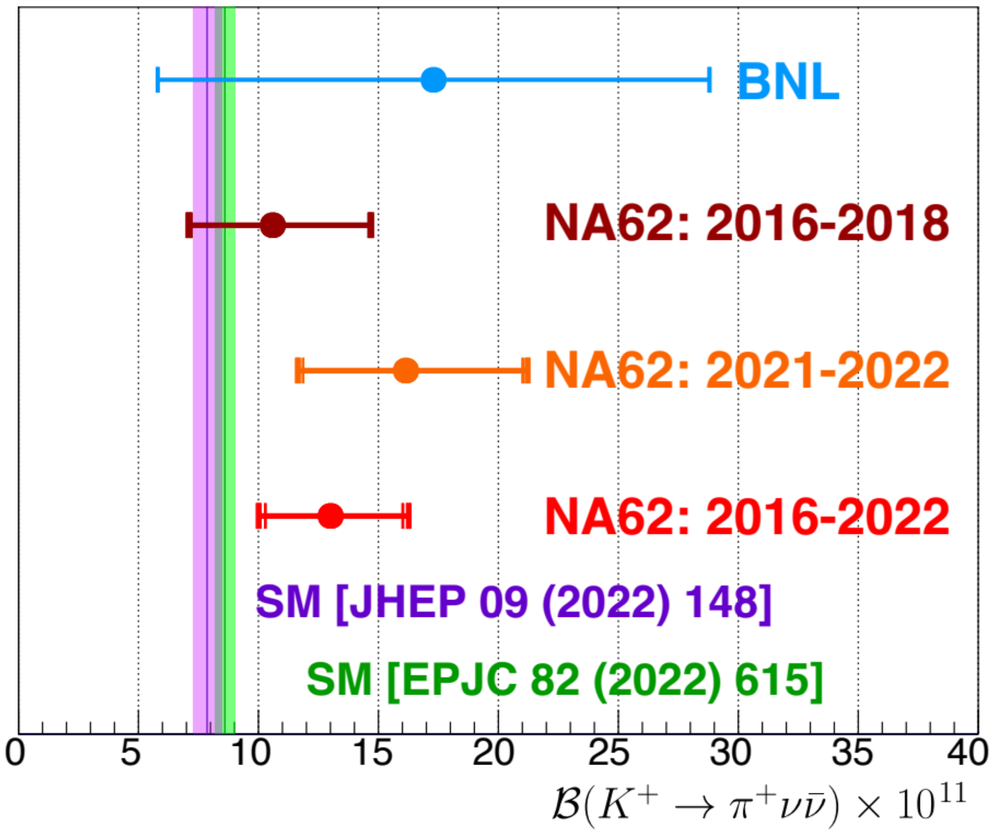
[Altmannshofer et al. '23]

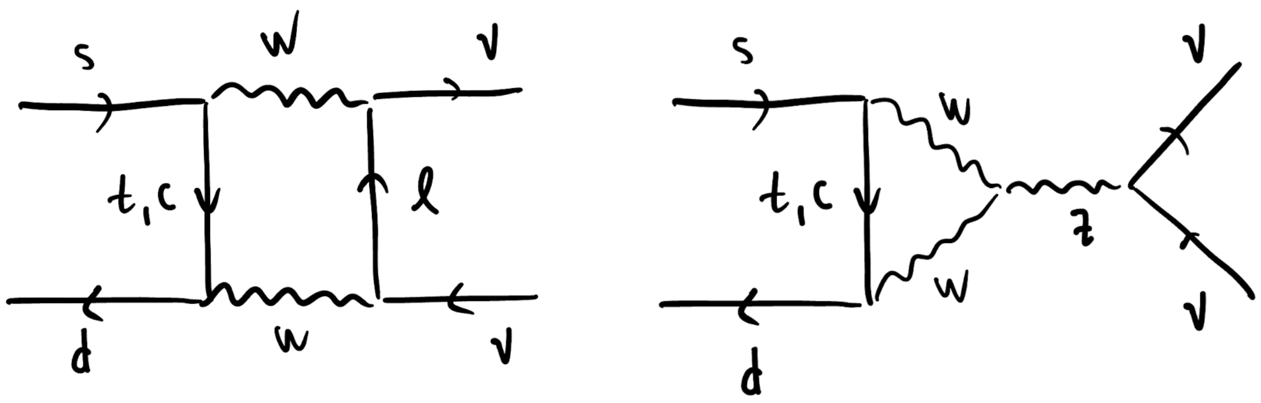
⇒ To be checked by **dedicated searches** at **Belle-II**!

[NEW] $K^+ \to \pi^+ \nu\bar{\nu}$

- **NA62** latest determination of the **theoretically clean** $K^+ \to \pi^+ \nu\bar{\nu}$ mode agrees with the SM at the 2σ level — *complementary to* $B \to K^{(*)}\nu\bar{\nu}$ *within concrete flavor scenarios!*

$$\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})^{\text{exp}} = \left(13.0^{+3.3}_{-3.0}\right) \times 10^{-11}$$





Precise measurements of **both kaon** and B-**meson** decays are **fundamental** to **probe BSM flavor dynamics** — *NA62 run-3 will reach* $\mathcal{O}(15\%)$ *uncertainty...*

$B_s \to \tau\tau$ and $B \to K^{(*)}\tau\tau$

- **Extremely difficult measurement** — *Tera-Z machine* such as FCC-ee needed! [Kamenik et al. '17]

Exp. 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]

$$\mathcal{B}(B^0 \to K^{0*}\tau\tau) < 1.8 \times 10^{-3}$$ [Belle-II. '25]

vs.

SM predictions:

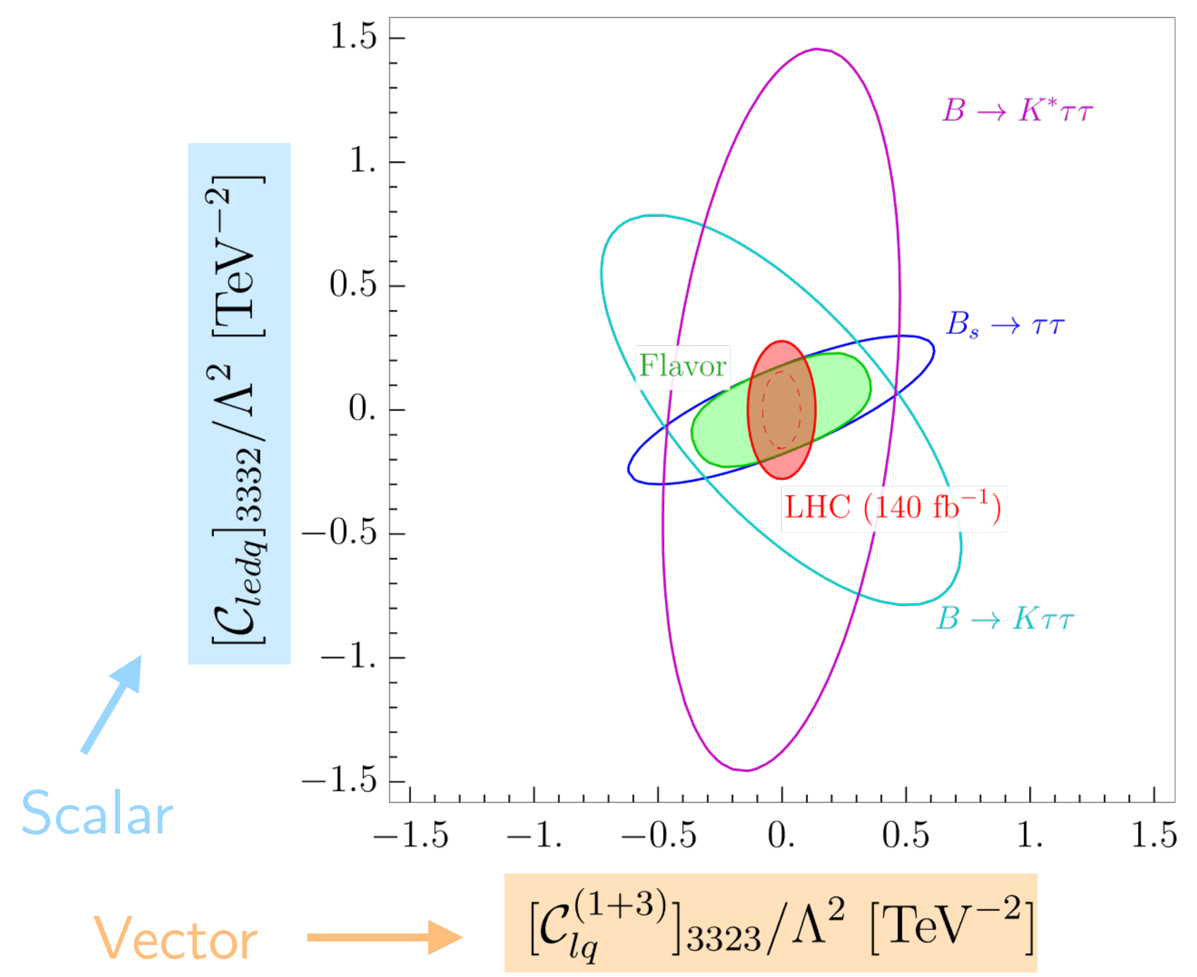
$$\mathcal{B}_{\rm SM} \approx 10^{-7}$$

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

Current reach: $$\frac{|\mathcal{C}_{bs\tau\tau}|}{\Lambda^2} \lesssim (1.3\ \text{TeV})^{-2}$$

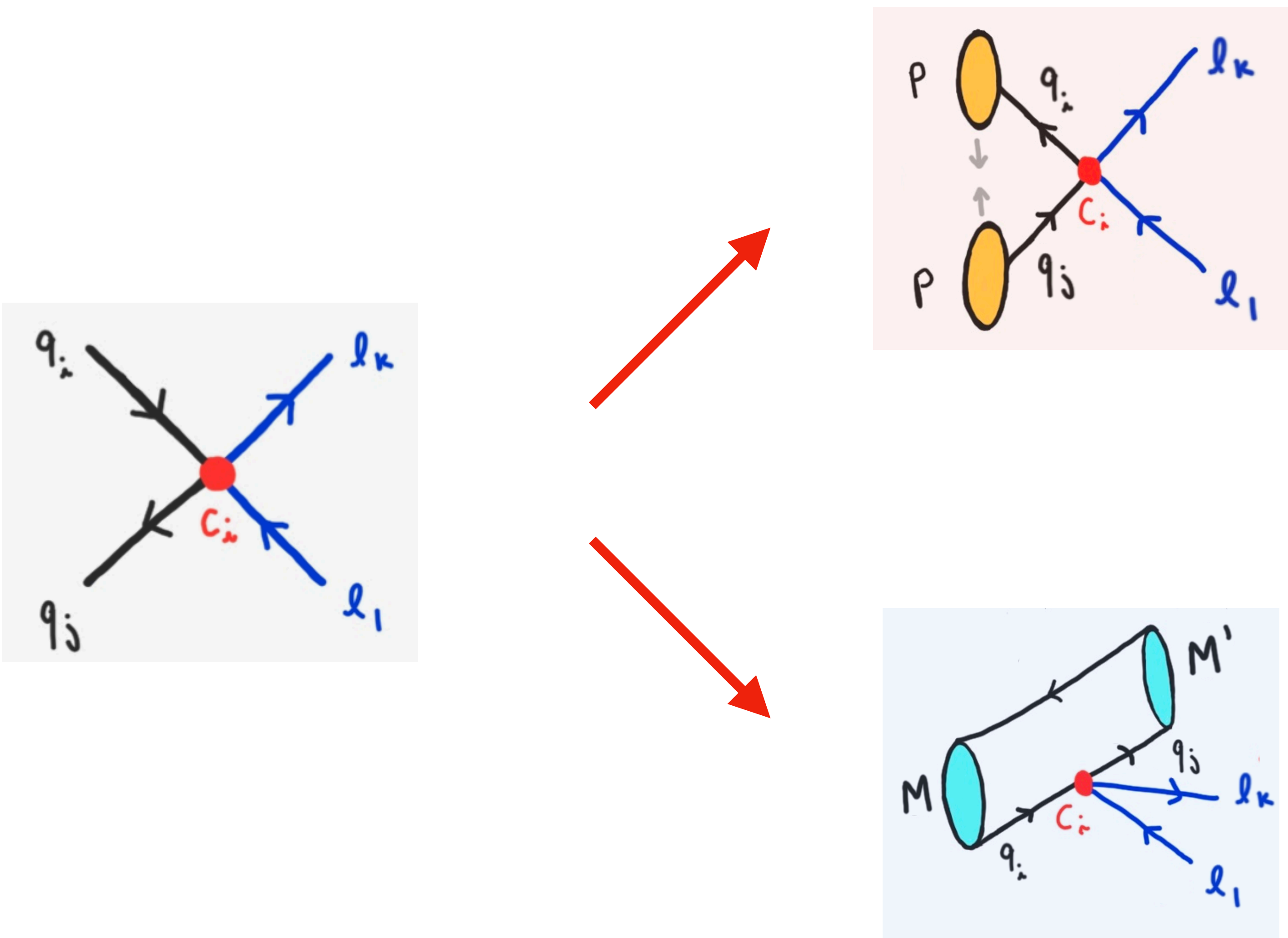
Complementarity to $pp \to \tau\tau$ at the **LHC!**

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



III. Probing flavor at high-p_T

LHC as a flavor experiment



(Flavorful) New Physics?

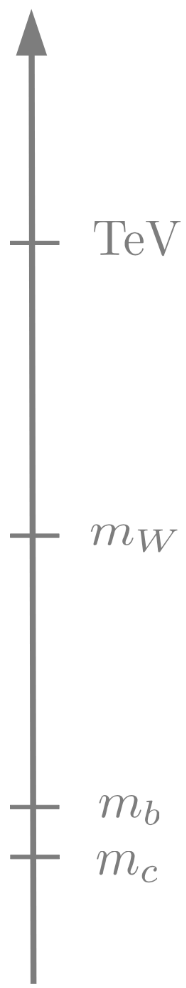
$pp \to \ell_k \ell_l$

$M \to \ell_k \ell_l$

$\ell_k \to \ell_l M$

$M \to M' \ell_k \ell_l$

$\dots$



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] ...

[Angelescu, Faroughy, **OS**. '20], [Allwicher, Faroughy, Jaffredo, **OS**, Wilsch. '22]

LHC as a flavor experiment

i) LHC collides quarks with five flavors

Parton luminosities

Partonic cross-section

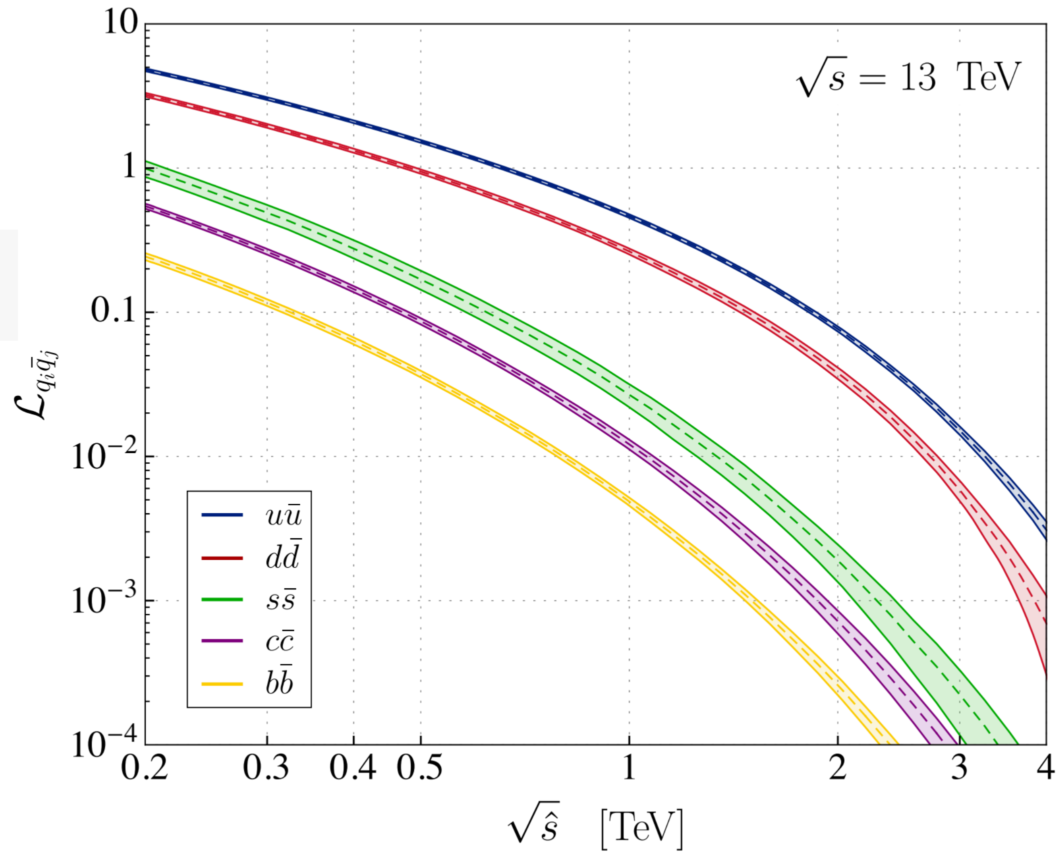
$$\sigma(pp \to \ell\ell') = \sum_{ij} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{q_i\bar{q}_j}(\tau)\, \hat{\sigma}(q_i\bar{q}_j \to \ell\ell')_{\hat{s}=s\tau}$$

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

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

$\sqrt{s} = 13$ TeV

[PDF4LHC15_nnlo_mc]



ii) Energy helps precision

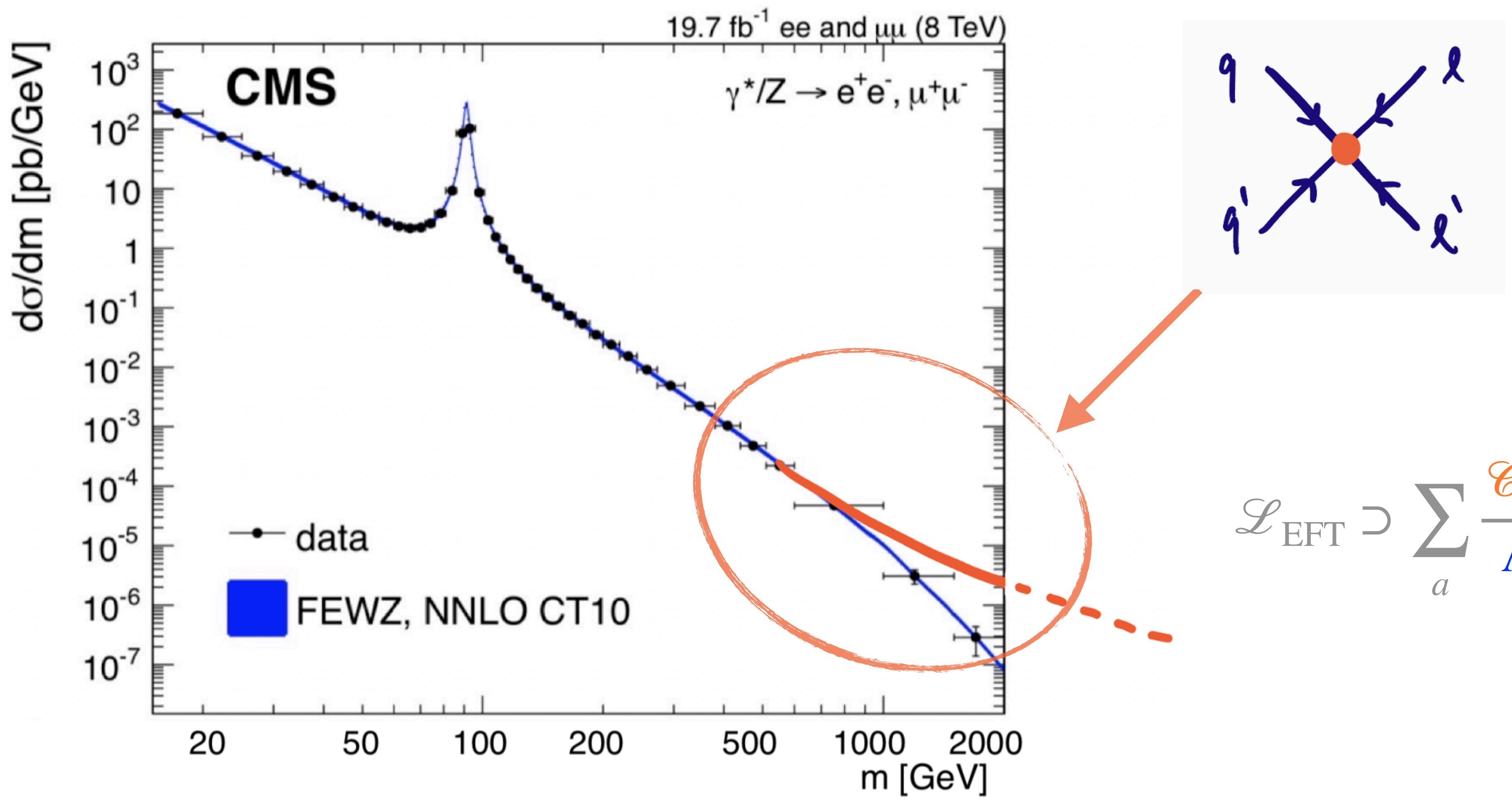
cf. e.g. [Farina et al. '16]

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

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

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

Non-resonant searches at the LHC

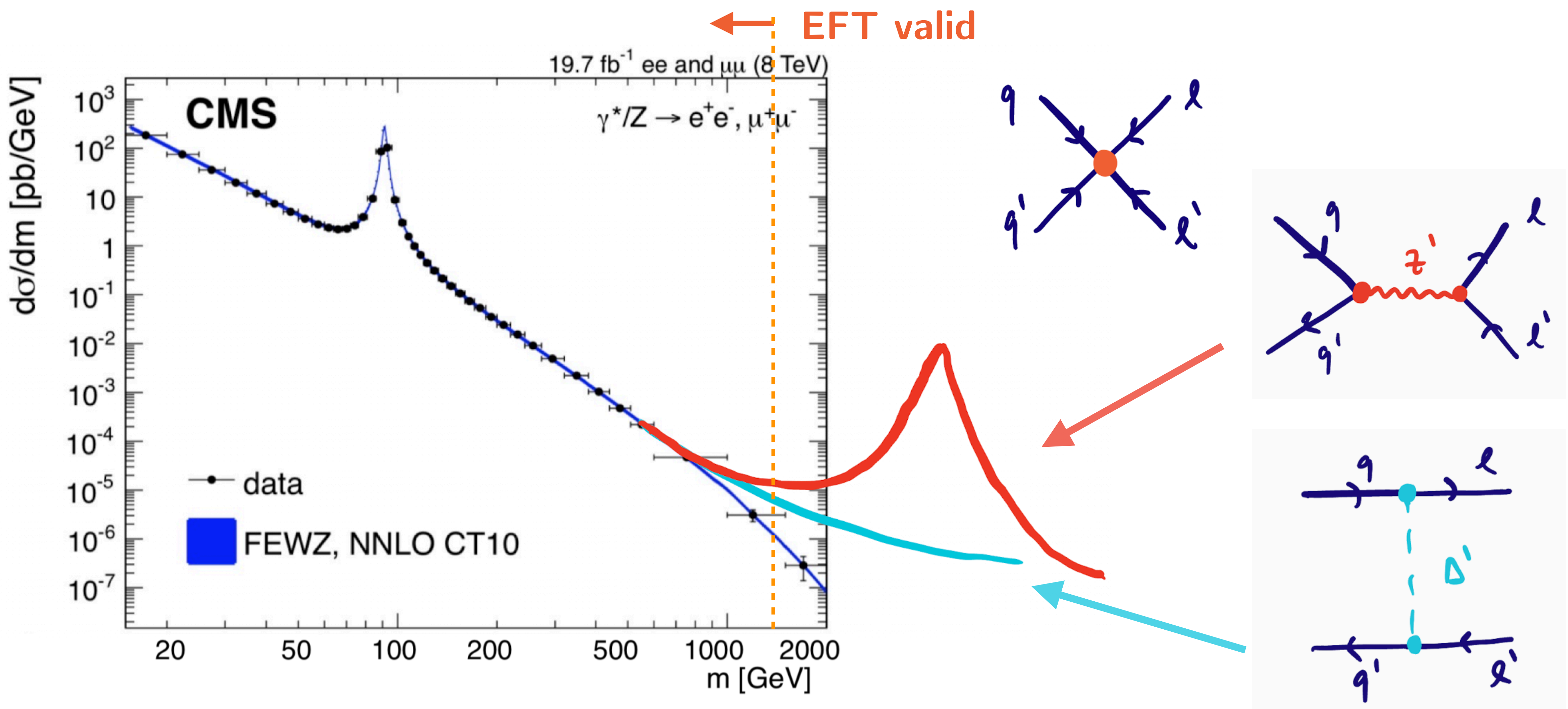


$$\mathscr{L}_{\mathrm{EFT}} \supset \sum_a \frac{\mathcal{C}_a^{(6)}}{\Lambda^2}\, \mathcal{O}_a^{(6)} + \dots$$

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



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!***

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

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^2E^2/Λ^4	v^4/Λ^4	v^2E^2/Λ^4
Parameters	# $\mathbb{R}$e	456	45	48	168	171	44	52
	# $\mathbb{I}$m	399	25	48	54	63	12	12

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

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

Too many operators...

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^2E^2/Λ^4	v^4/Λ^4	v^2E^2/Λ^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...

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*.

<u>Our approach</u>: to automatize!

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

In[5]:= << 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 ($140\ \mathrm{fb}^{-1}$):

$pp \to \tau\tau$	[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:

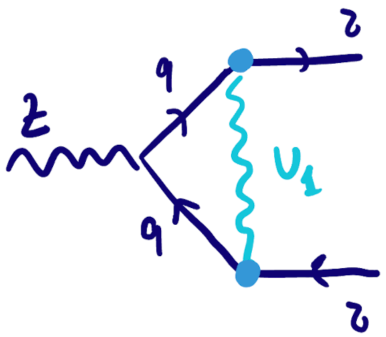
- Consider **SMEFT** ($d \leq 8$) and **specific mediators** (LQs, Z', ...).
- Computes **cross-sections**, **event yields** and **likelihoods** as a function of NP couplings.
- **SMEFT likelihoods** can be exported in the *WCxf* format.

[Aebischer et al. '17]

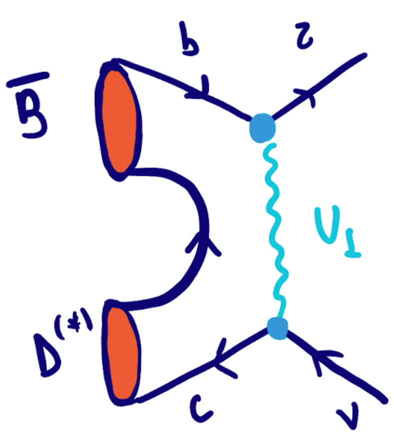
<u>Example</u>: $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

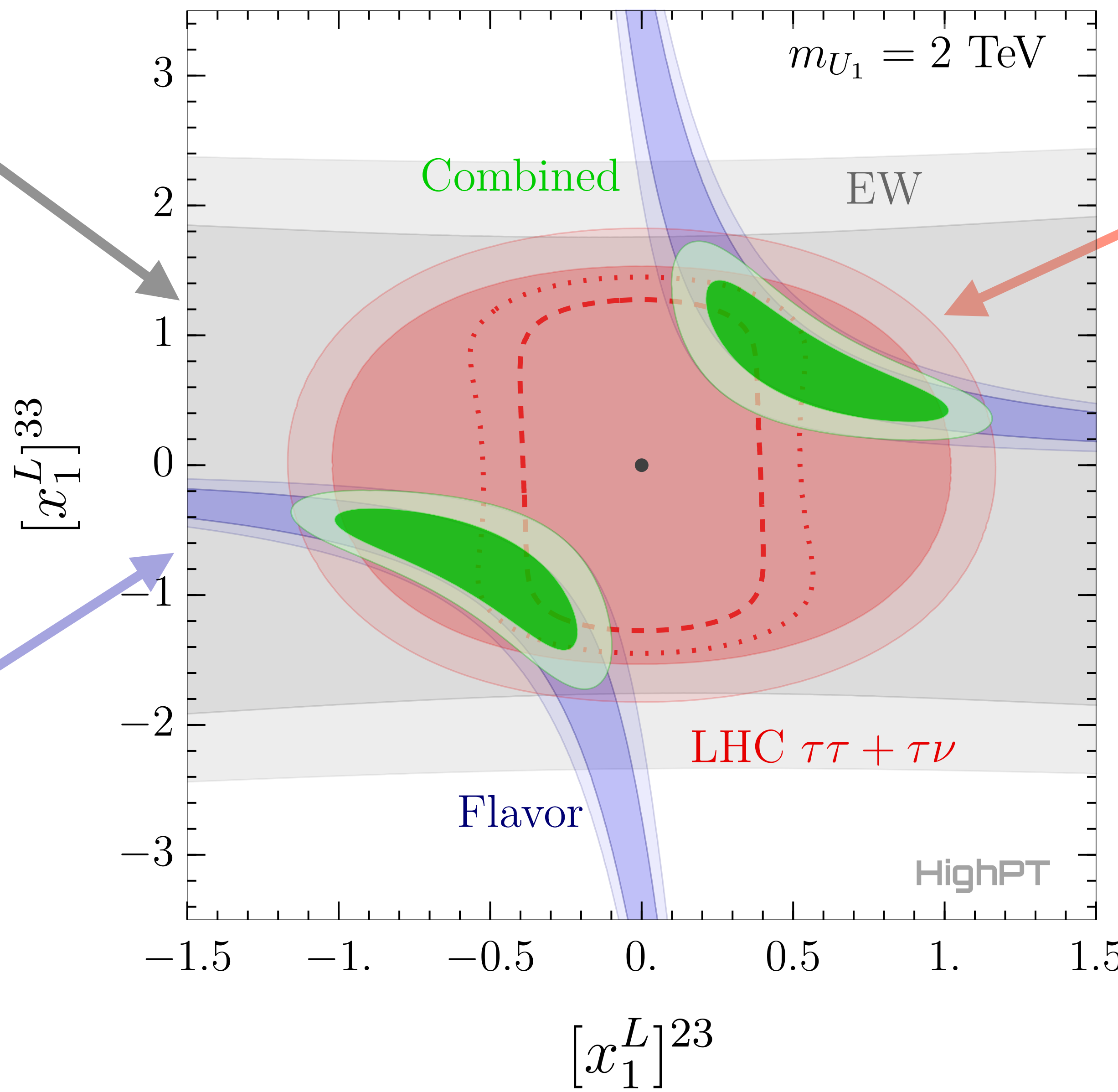
[L. Allwicher, D. Faroughy, F. Jaffredo, **OS**, F. Wilsch. '22]

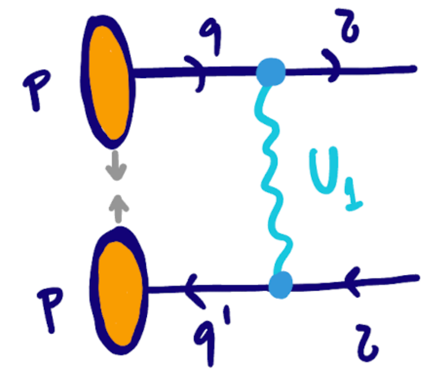
$$\mathcal{L}_{U_1} \supset [x_1^L]_{i\alpha}\, U_1^\mu\, \bar{q}_i \gamma_\mu l_\alpha + \text{h.c.}$$



[Feruglio et al. '16]







First considered by [Eboli, '88]

cf. also [Faroughy et al. '15]

<u>Complementarity</u> between **LHC data**, **flavor** and **EWPT**

Beyond Drell-Yan

[Eboli, Martines, Santos-Leal, **OS**. *In preparation*]

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 @$d=6$:

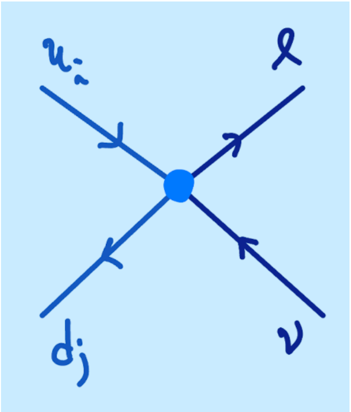
$$g_{V_L}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell} + \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^2DH^2}^{ij}$$

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

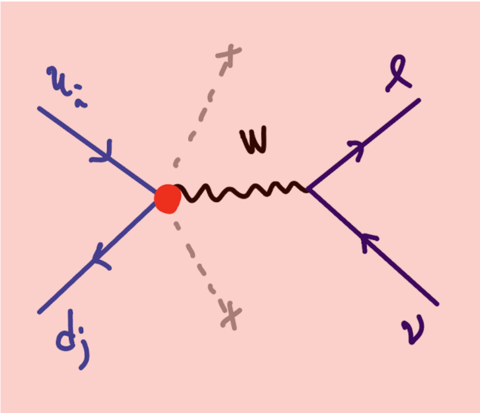
$$g_{S_L}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell}$$

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

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



+



Beyond Drell-Yan

[Eboli, Martines, Santos-Leal, **OS**. *In preparation*]

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 $@d = 6$:

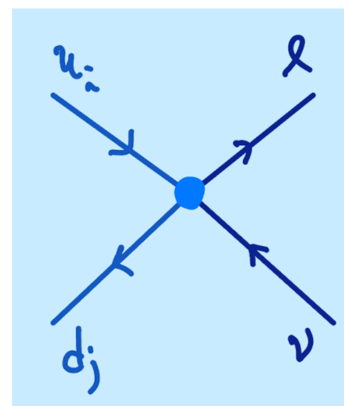
$$g_{V_L}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell} + \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^2 DH^2}^{ij}$$

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

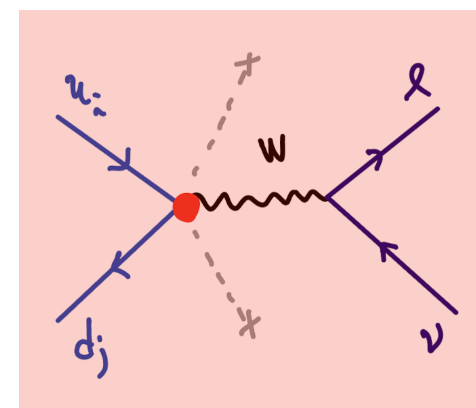
$$g_{S_L}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell}$$

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

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



+



Well-tested by $pp \to \ell\nu$ at high energies:

Suppressed for $E \gg m_W$:

$$\mathcal{M}(u_i\bar{d}_j \to \ell\nu) \simeq \mathcal{M}_{\rm SM}\left[1 + \frac{E^2}{\Lambda^2}\mathcal{C}_{\psi^4} + \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^2 DH^2} + \ldots\right]$$

**expanding on v/E and E/Λ for $v \ll E \ll \Lambda$*

Beyond Drell-Yan

[Eboli, Martines, Santos-Leal, **OS**. *In preparation*]

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 @$d=6$:

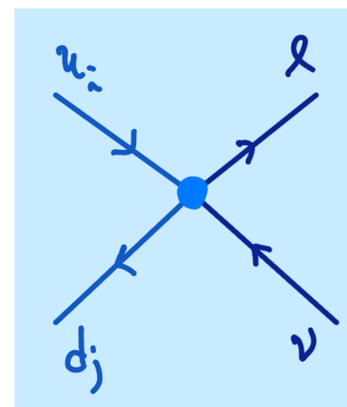
$$g_{V_L}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell} + \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^2DH^2}^{ij}$$

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

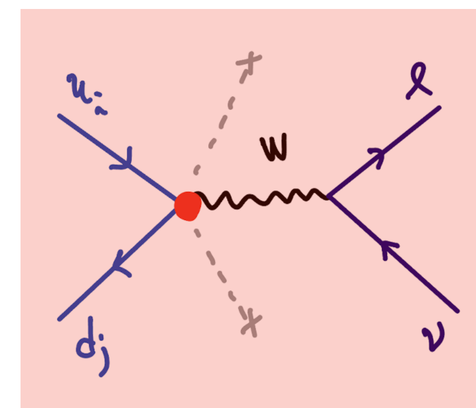
$$g_{S_L}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell}$$

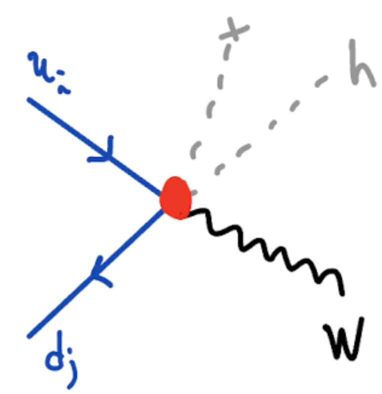
$$g_{S_R}^{ij\ell} \propto \frac{v^2}{\Lambda^2}\mathcal{C}_{\psi^4}^{ij\ell\ell}$$

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



+





But $pp \to VH$ is **energy-enhanced!**

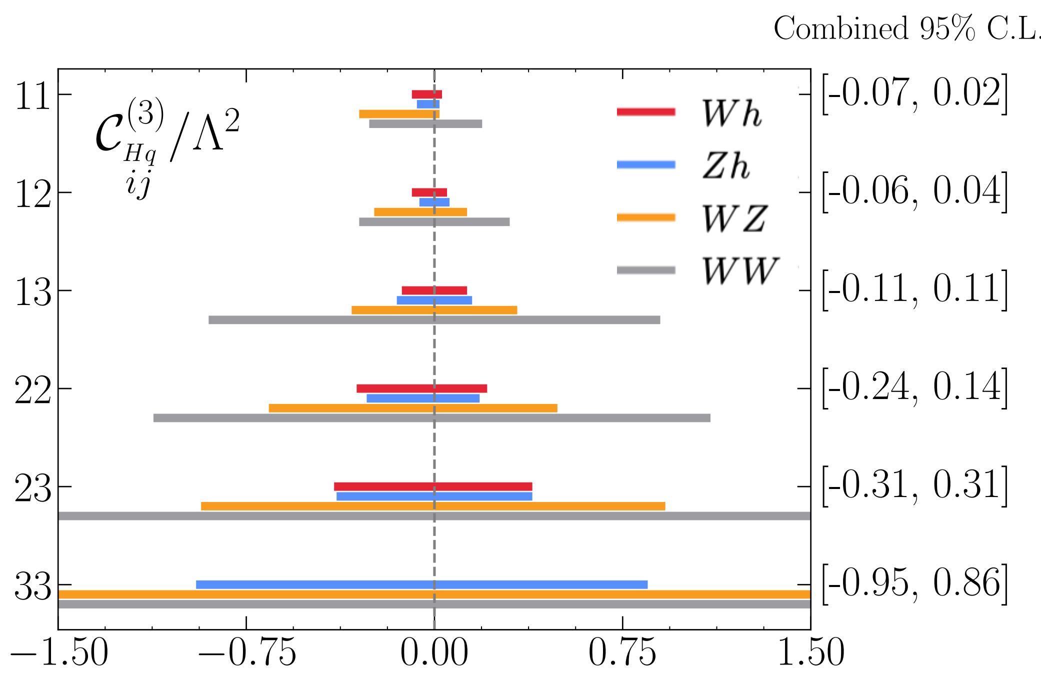
$\Rightarrow$ **Dominant constraints** on **RH currents** (g_{V_R})!

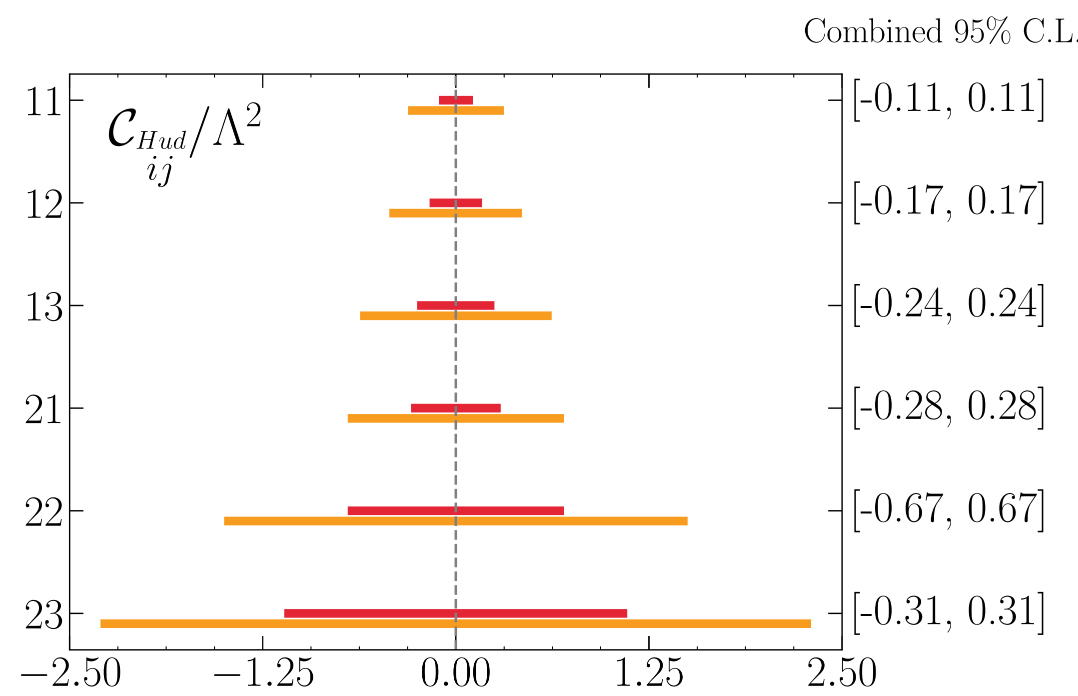
Beyond Drell-Yan (preliminary)

[Eboli, Martines, Santos-Leal, **OS**. *In preparation*]

See also [Alioli et al. '17]

- Recast of CMS/ATLAS searches for $pp \to Vh$ and $pp \to WV$, with $V = W, Z$ *[cf. back-up]* — *related through Goldstone equivalence theorem:* [ATLAS, 2410.19161], [CMS, 2312.07562]...





$$\mathcal{O}^{(3)}_{\substack{Hq\\ij}} = \left(H^\dagger \overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_i \gamma^\mu \tau^I q_j\right)$$

$$\mathcal{O}_{\substack{Hud\\ij}} = \left(H^\dagger D_\mu H\right)\left(\bar{u}_i \gamma^\mu d_j\right) + \text{h.c.}$$

Limits extracted using **STXS data** are $\approx 10\times$ **stronger** than those from signal-strength data.

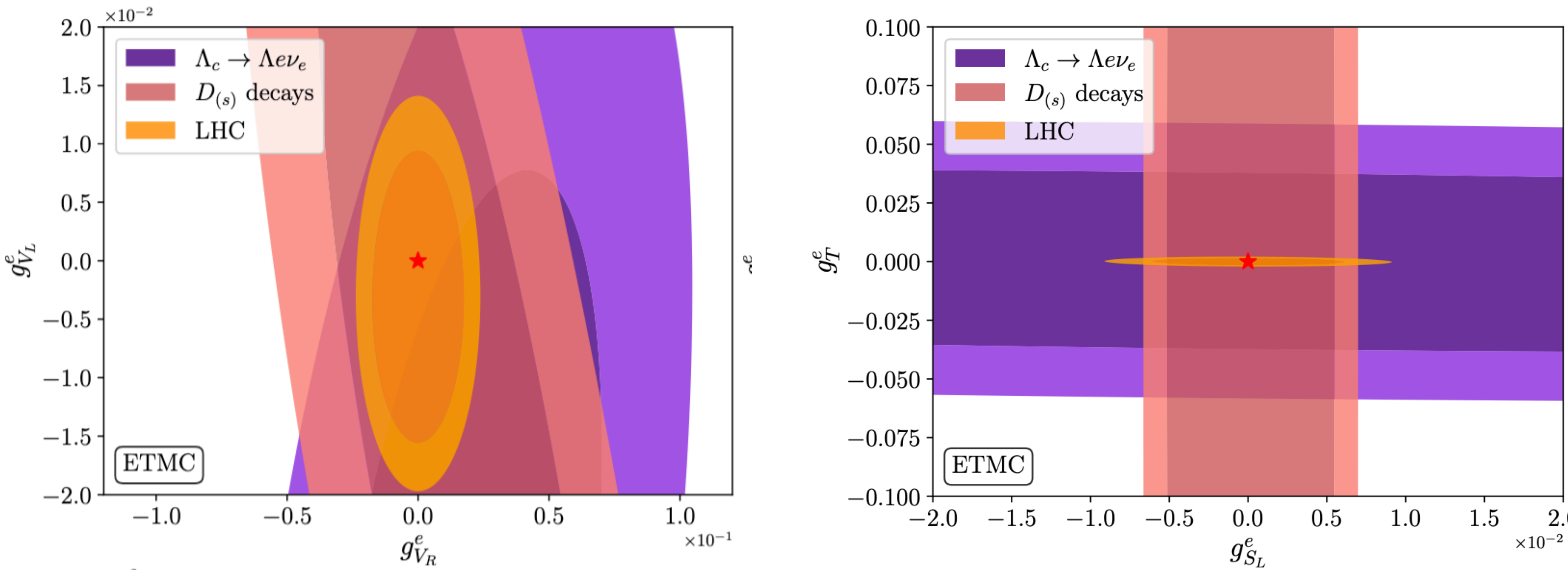
Already useful limits (competitive with flavor/EW data) — *to be improved at HL-LHC!*

Beyond Drell-Yan (preliminary)

Example: $c \to s e \nu$

[Becirevic, Martines, Rosauro-Alcaraz, **OS**. *In preparation*]

See also [Camalich et al. '20] for DY limits

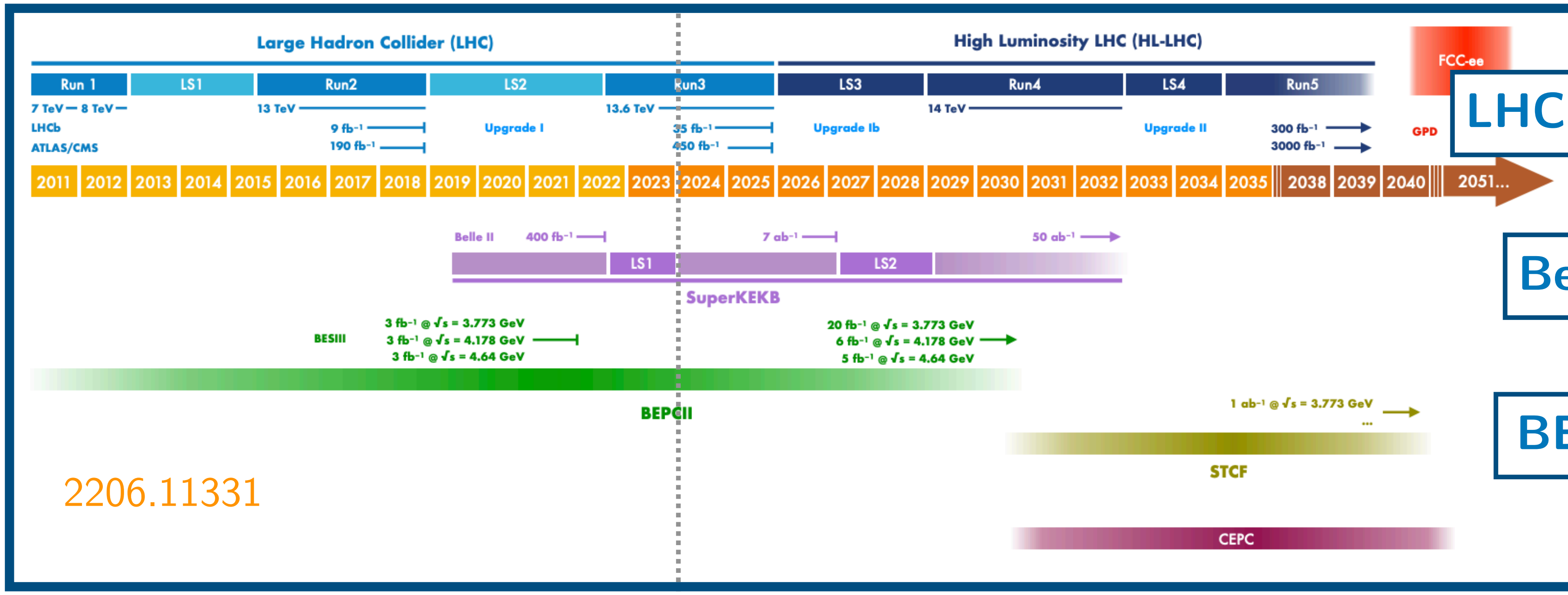


These LHC limits leave **little room** for **BSM effects** in $c \to d\ell\nu$ and $c \to s\ell\nu$ transitions — *charm semileptonic decays are rather laboratories to test (L)QCD calculations!*

*See back-up

Summary/Outlook

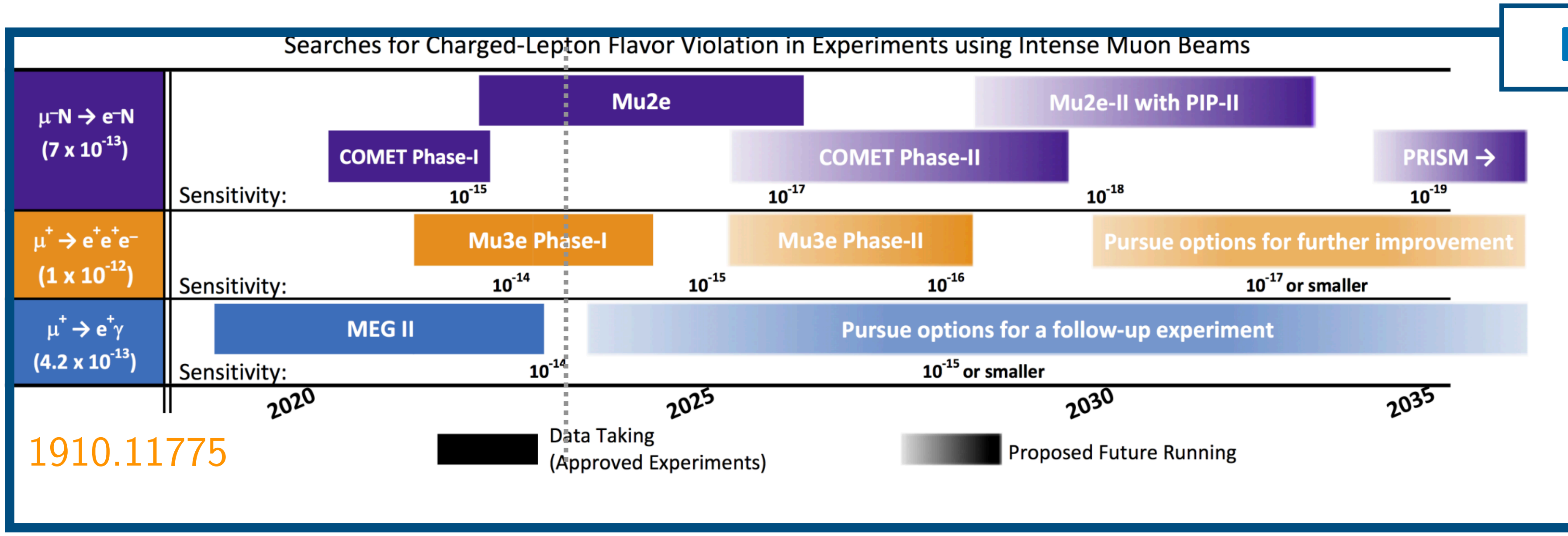
Summary/Outlook



LHCb/CMS

Belle-II

BES-III

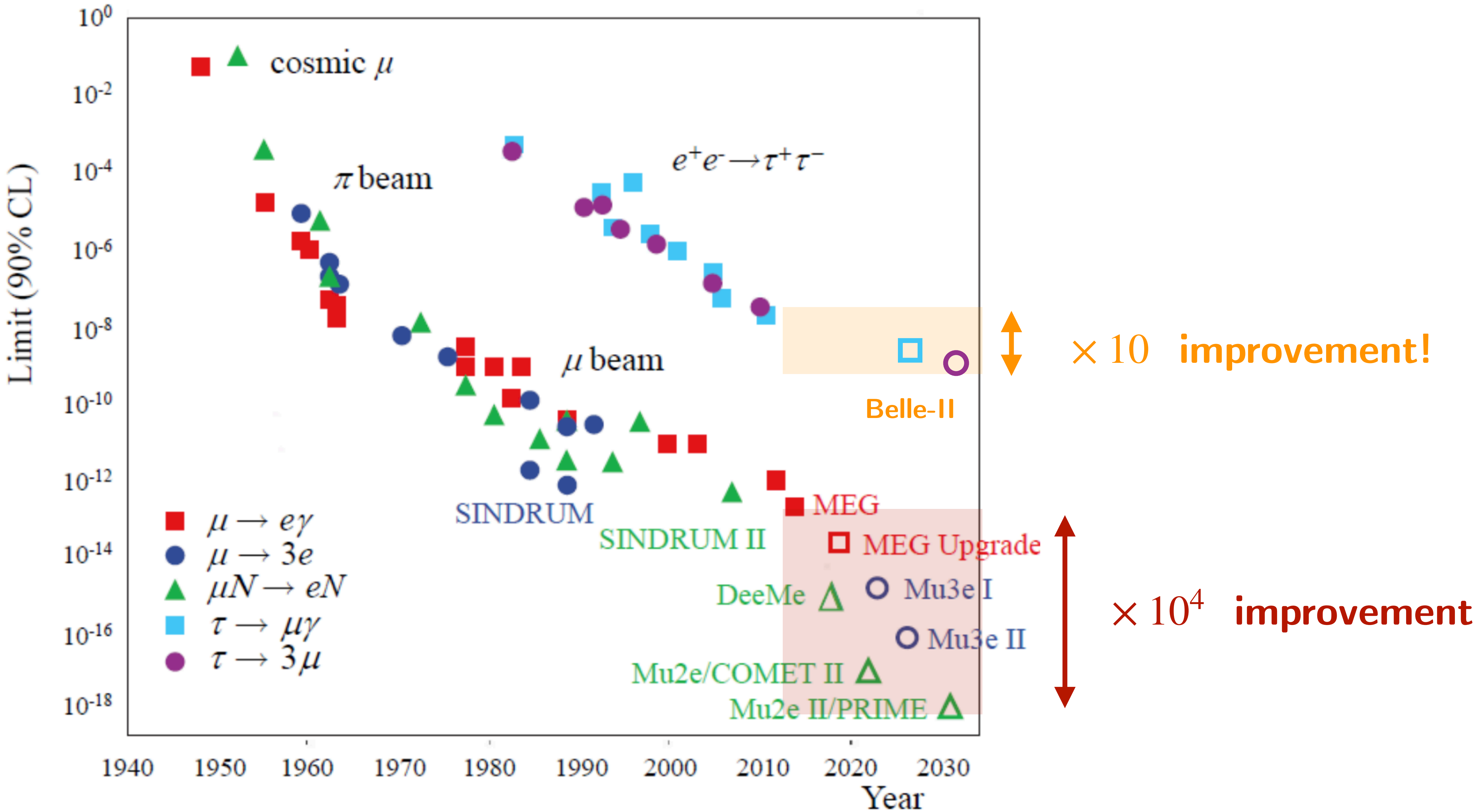


LFV

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

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

Lepton Flavor Violation



Significant experimental progress is expected in **the near future** — *many opportunities!*

Summary/Outlook

Marginal increase in energy, but $\approx 20\times$ luminosity!

Questions/Challenges — mid/long term

I. How to resolve the V_{ub} & V_{cb} problems? The *parametric uncertainty* from CKM will soon become a *bottleneck*...

II. LQCD progress can also open new directions for exploration — *what to expect in the mid- long-term?*

III. Current exp. precision in certain observables (EDMs) is already sensitive to two-loop contributions from EFTs, but *two-loop RGEs* are *not fully known yet*...

First steps in [Fuentes-Martin, '24], [Aebischer et al. '25], [Naterop et al. '25]

IV. What is the best strategy to extract flavor limits from LHC data (EFT validity...)?

[Allwicher et al. '24]

V. Are there other relevant probes of flavor-changing transitions at high-p_T?

VI. New theoretical approaches to the flavor problem?

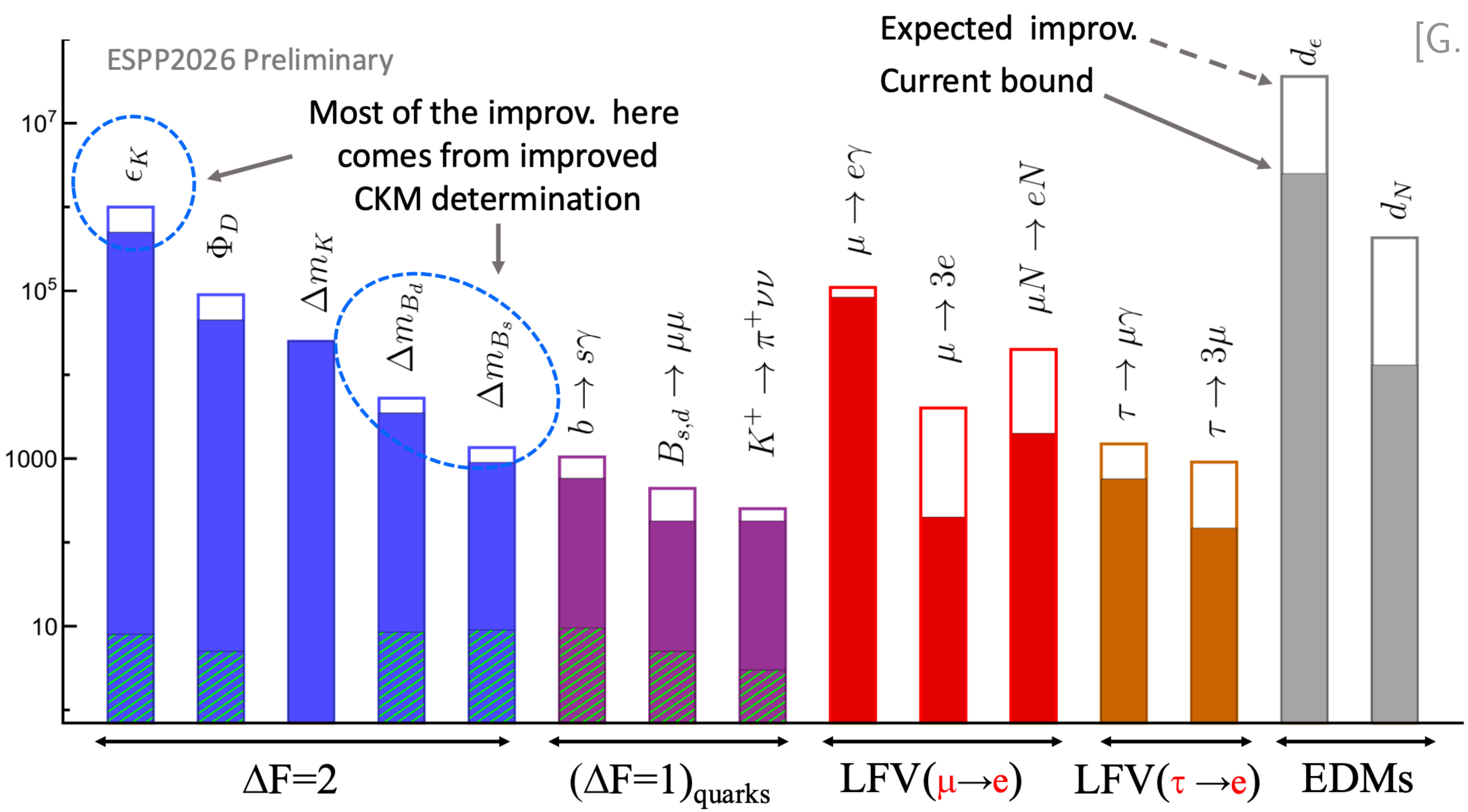
VII. What are the opportunities for flavor physics in future high-energy experiments?

Flavor-physics at future experiments

Particle production (10^9)	$B^0/\overline{B}^0$	B^+/B^-	$B_s^0/\overline{B}_s^0$	$B_c^+/\overline{B}_c^-$	$\Lambda_b/\overline{\Lambda}_b$	$c\overline{c}$	$\tau^+\tau^-$
Belle II	27.5	27.5	n/a	n/a	n/a	65	45
FCC-ee	620	620	150	4	130	600	170

[FCC Snowmass Summary, 2203.06520]

[G. Isidori talk at ESPPU]



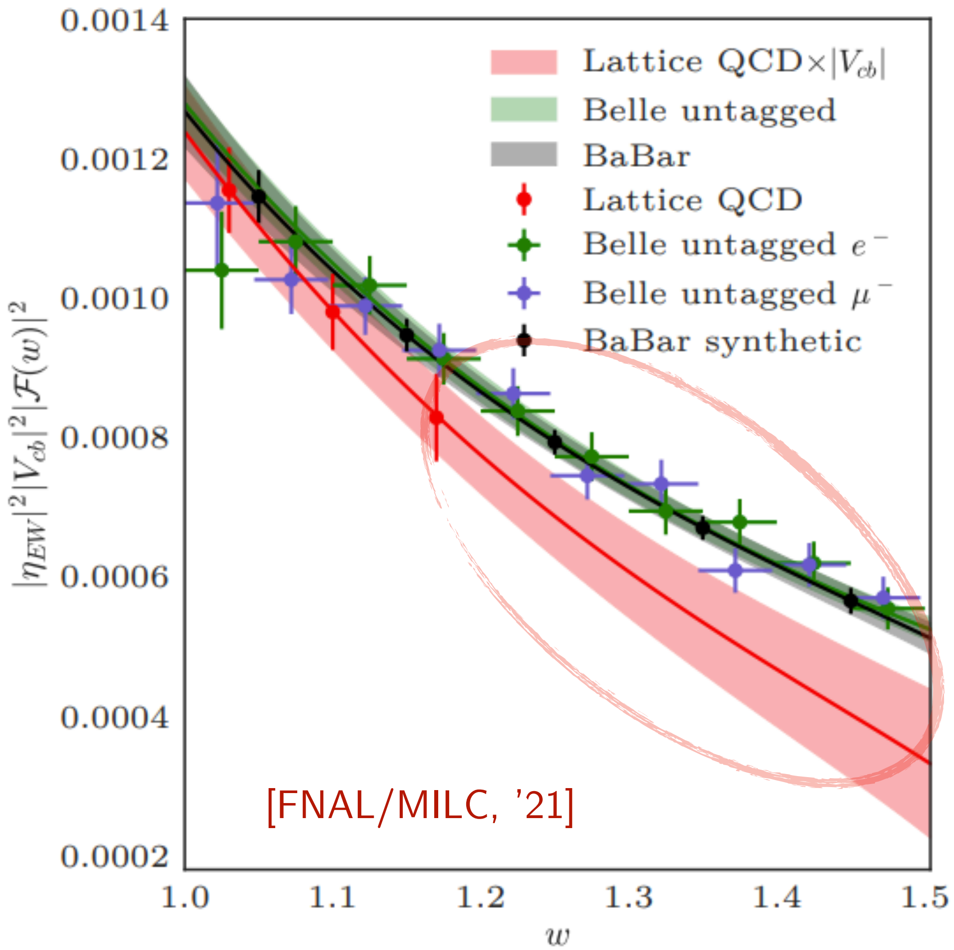
Thank you!

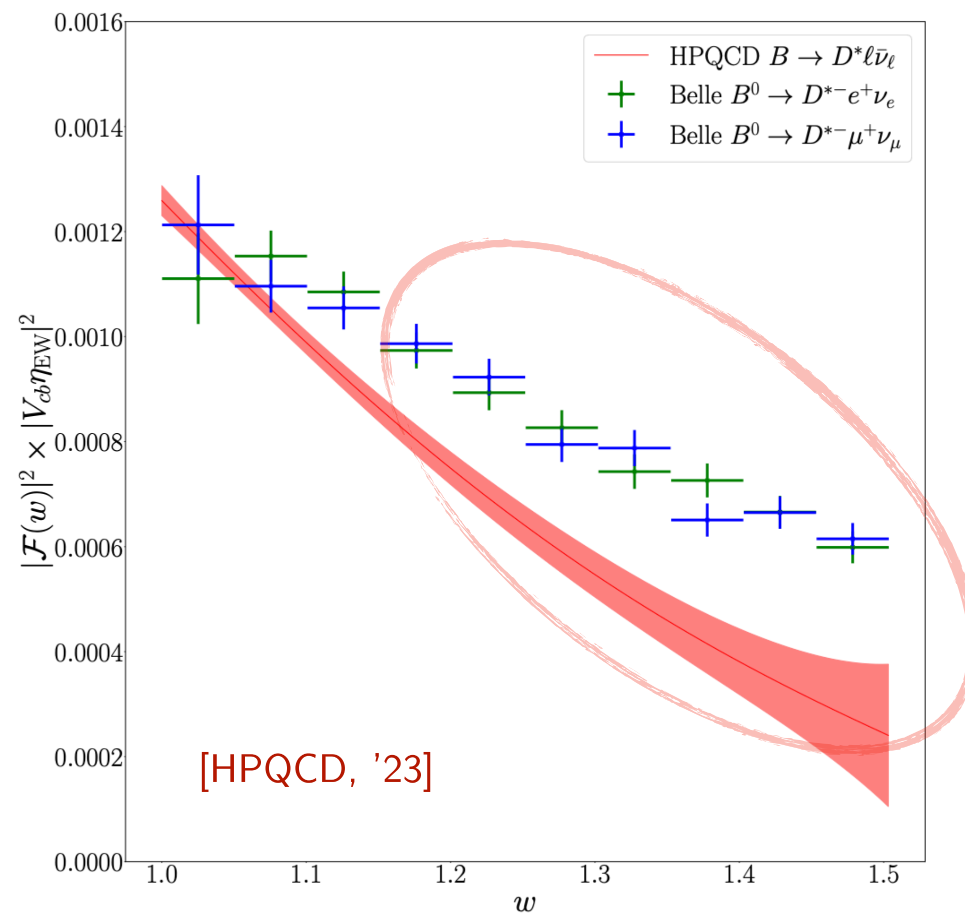
Back-up

[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!

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]

$$|\lambda_t|_{\mathrm{UTfit}} = (41.4 \pm 0.5) \times 10^{-2} \qquad |\lambda_t|_{\mathrm{CKMfitter}} = (40.5 \pm 0.3) \times 10^{-2}$$

- Alternative strategy: to use $\Delta m_{B_s} \propto f_{B_s}^2 \hat{B}_{B_s} |\lambda_t|^2$ [Buras, Venturini. '21, '22]

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

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

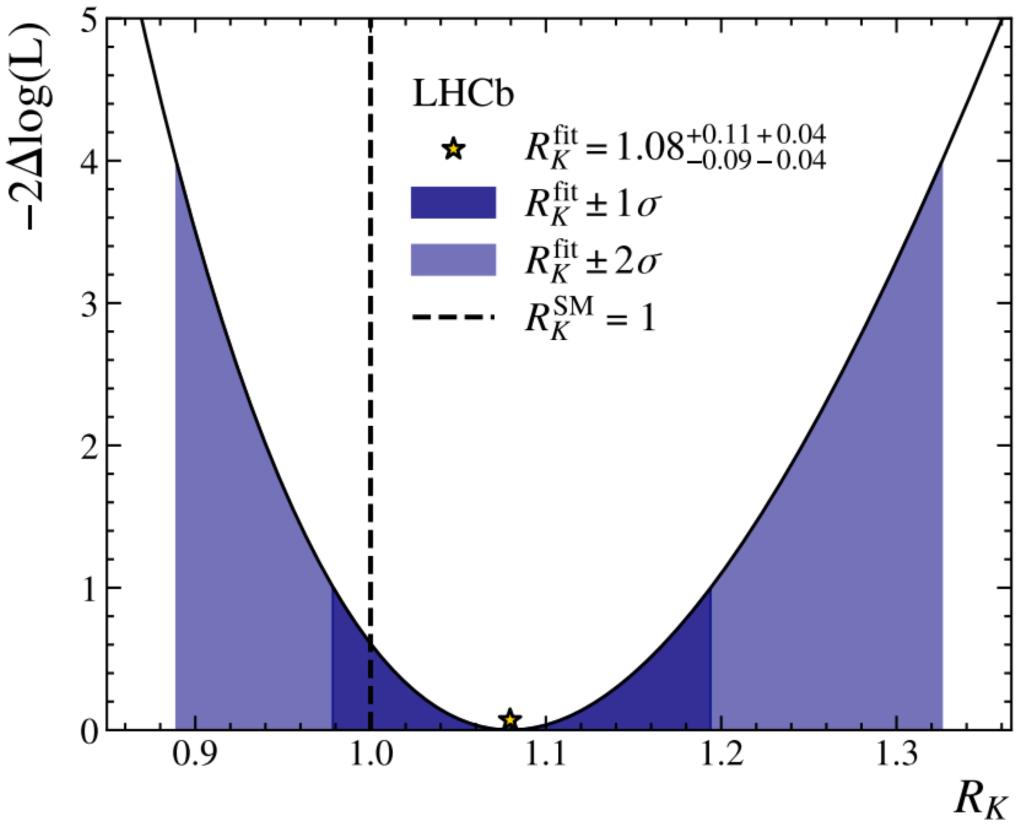
[HPQCD '19]

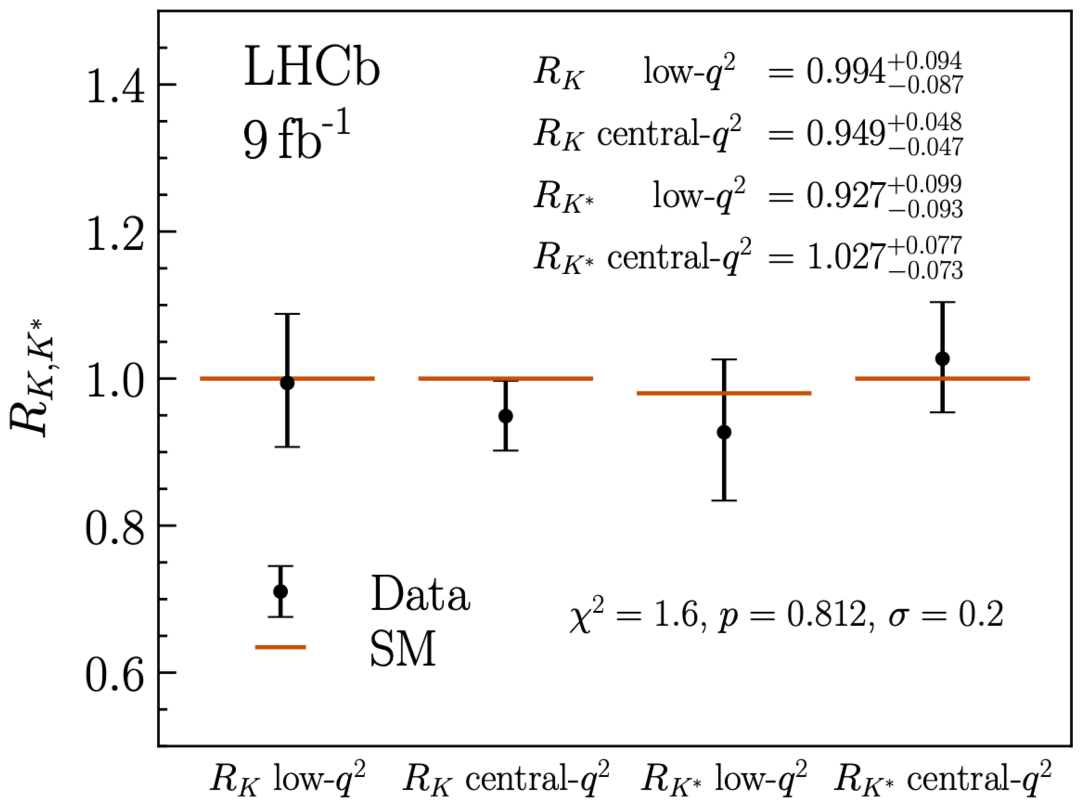
$$f_{B_s}\sqrt{\hat{B}_{B_s}} = 274 \pm 8 \text{ MeV} \qquad (N_f = 2+1)$$

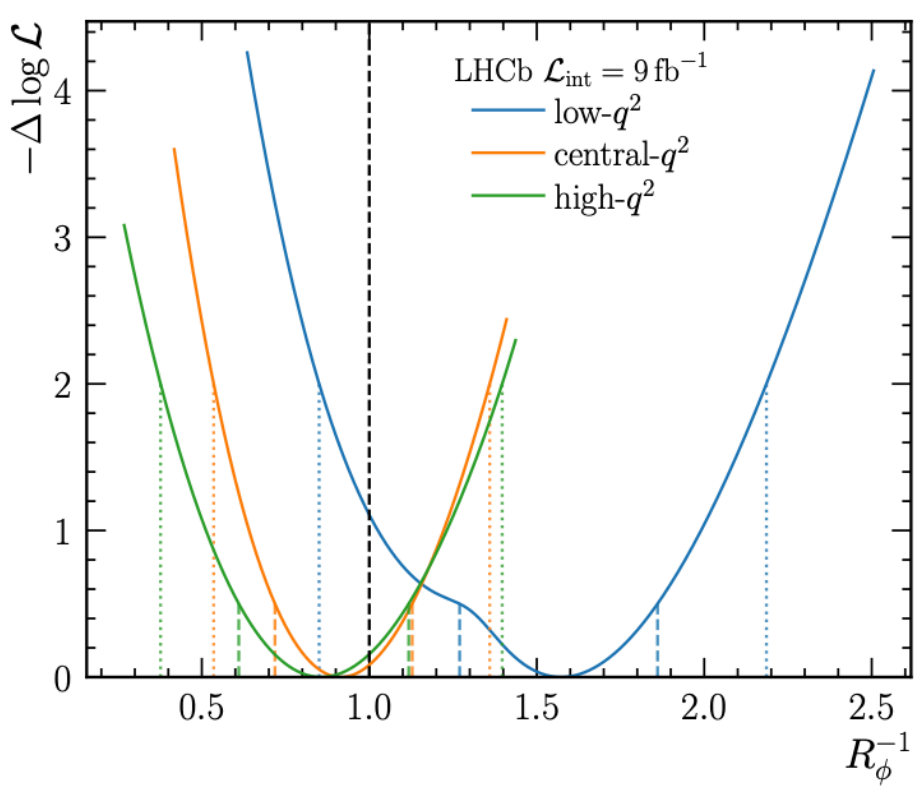
[FLAG '21]

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

LFU in $b \to s\ell\ell$ [LHCb]



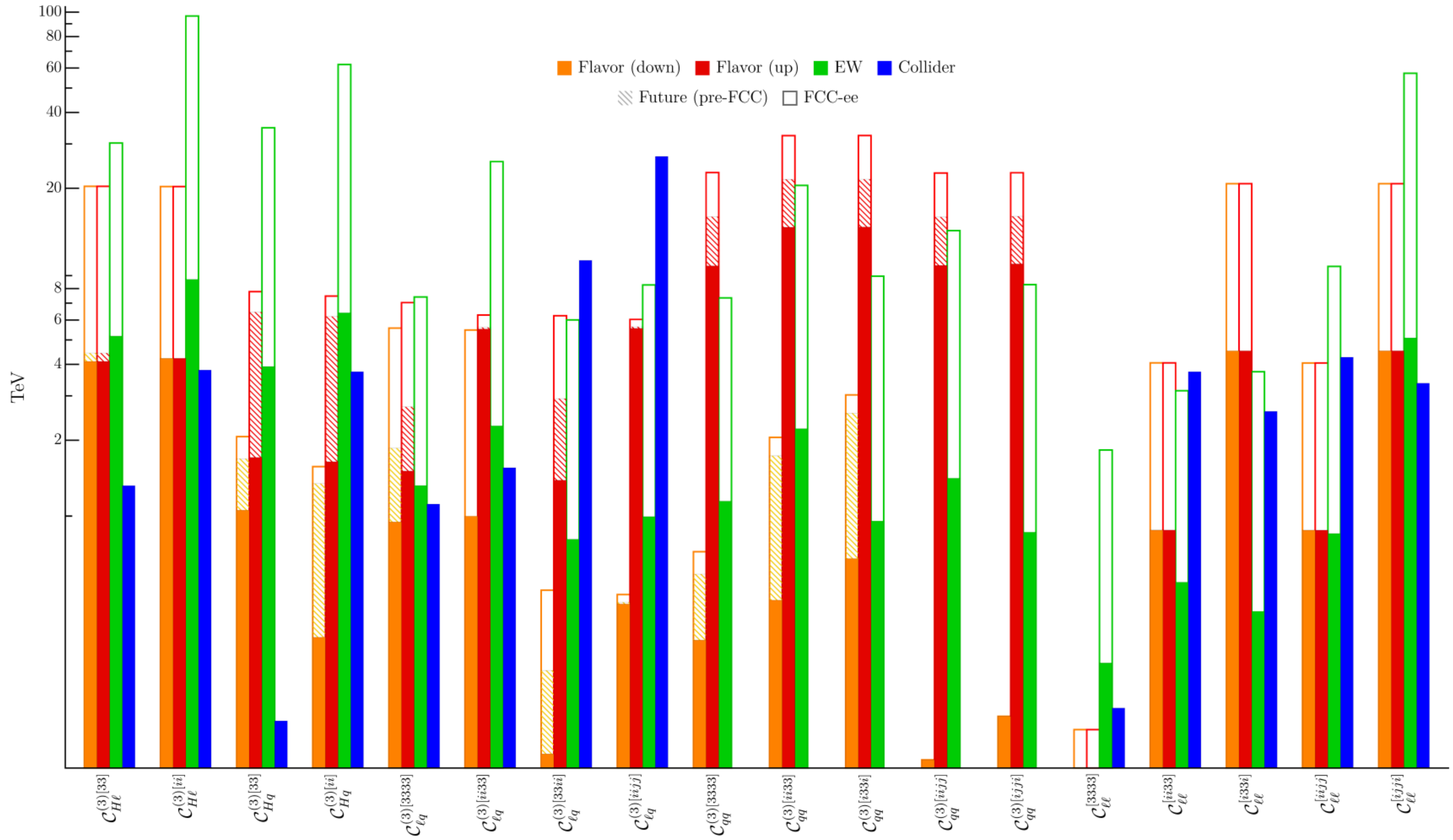




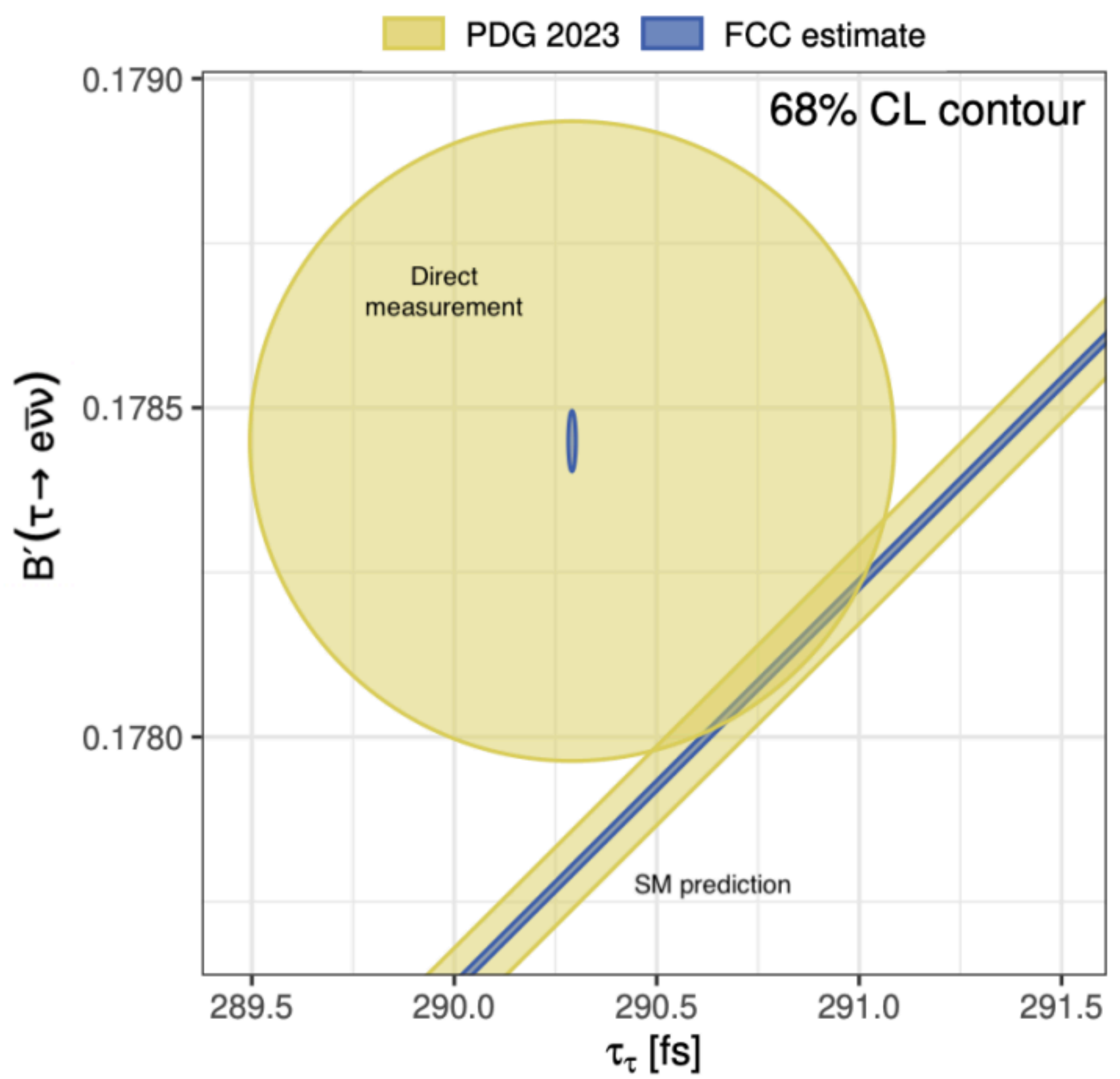
Combining flavor data with EW/Higgs

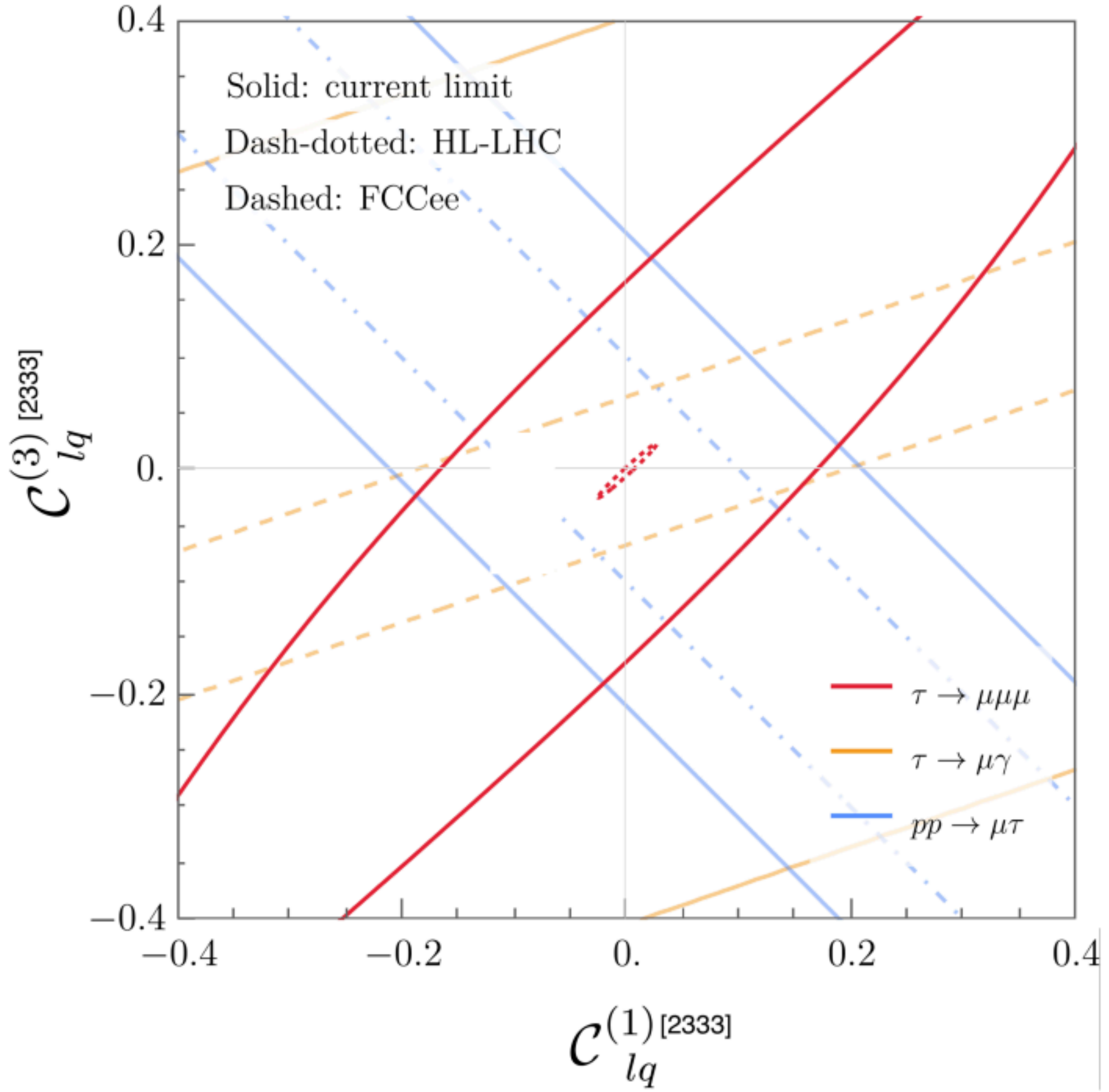
Example: FCC-ee projections for $U(2)^5$

[Allwicher et al. '25]



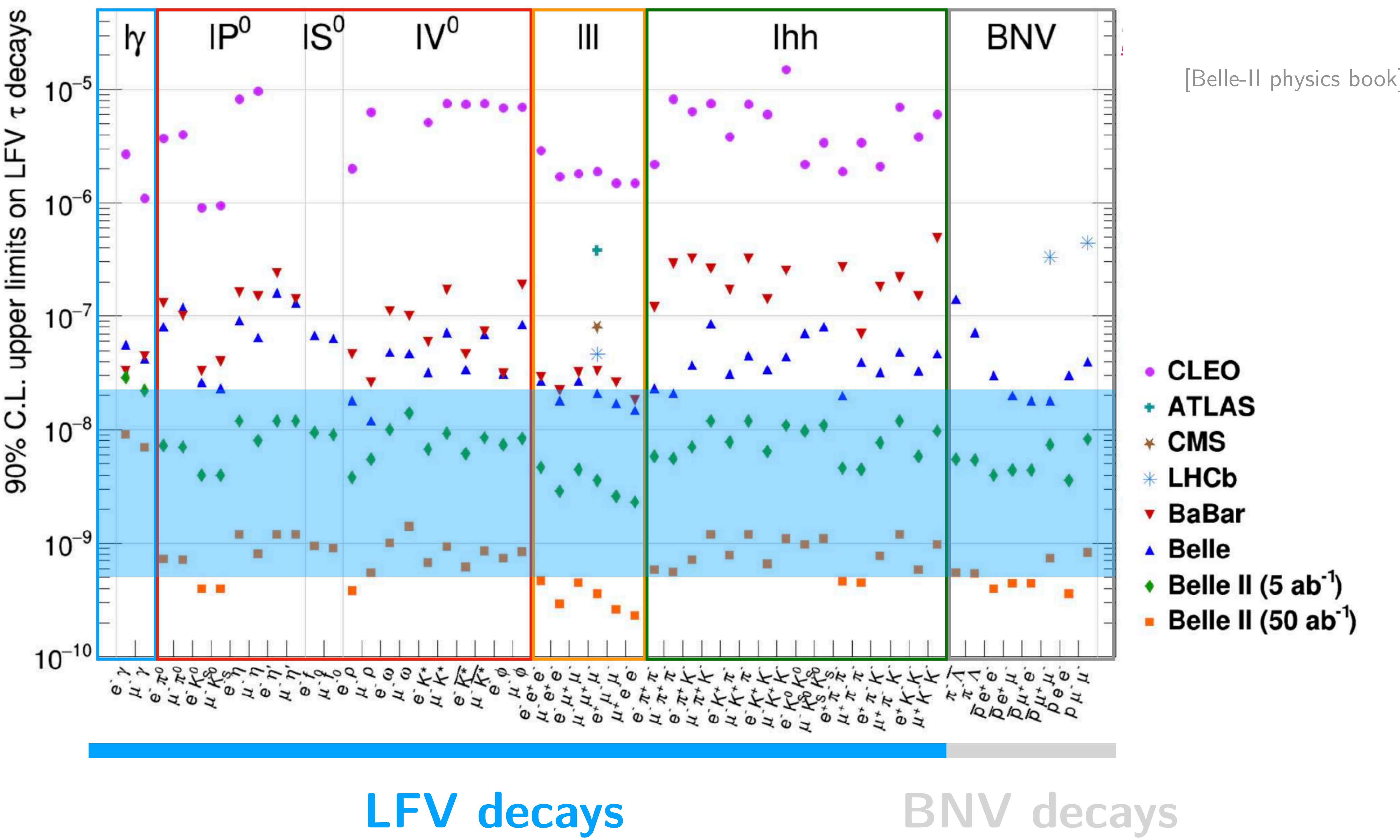
FCCee projections: τ-physics





Belle-II and τ-decays

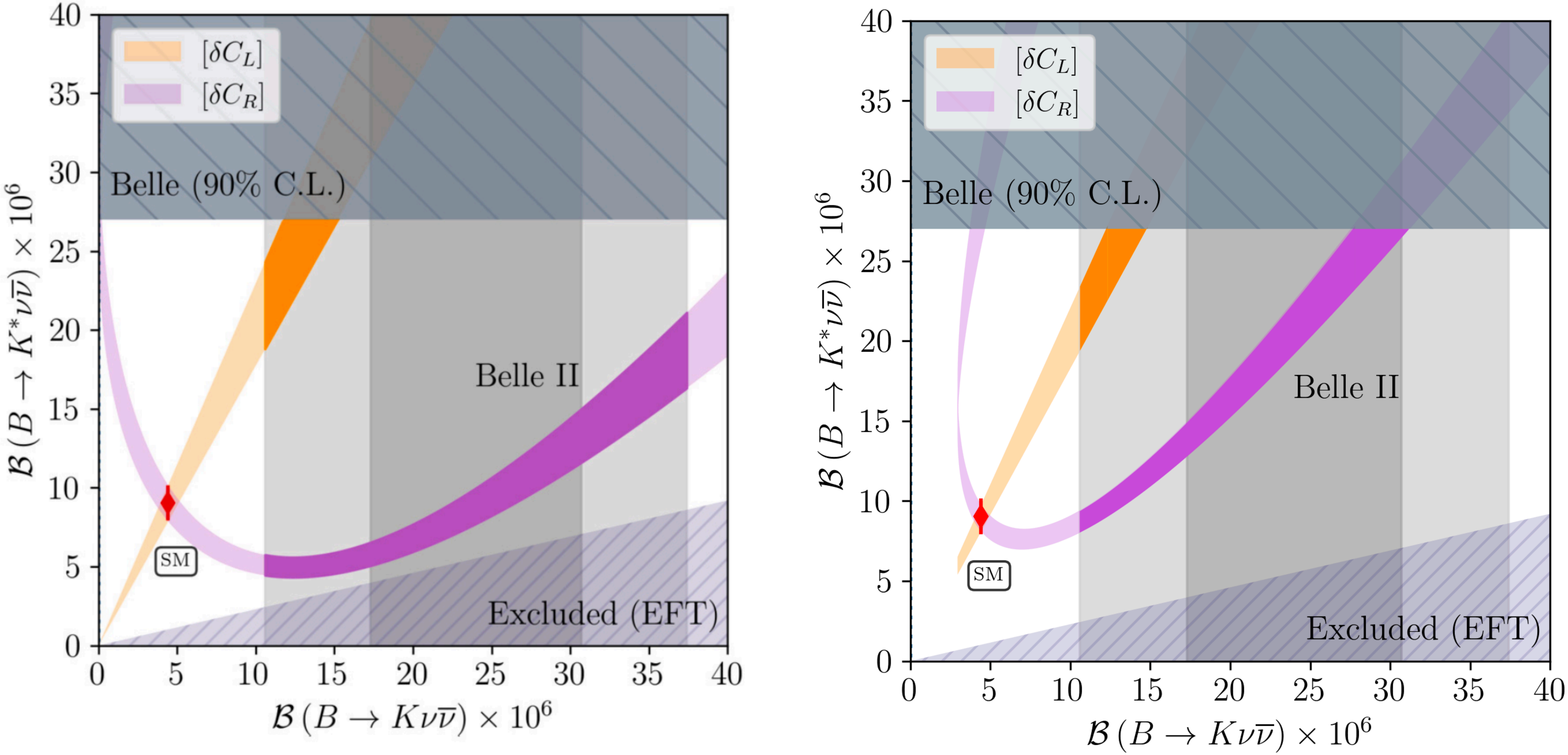
Belle-II will **improve** the **sensitivity** on $\tau \to e$ and $\tau \to \mu$ decays by a **factor** $\mathcal{O}(10)$:



[Belle-II physics book]

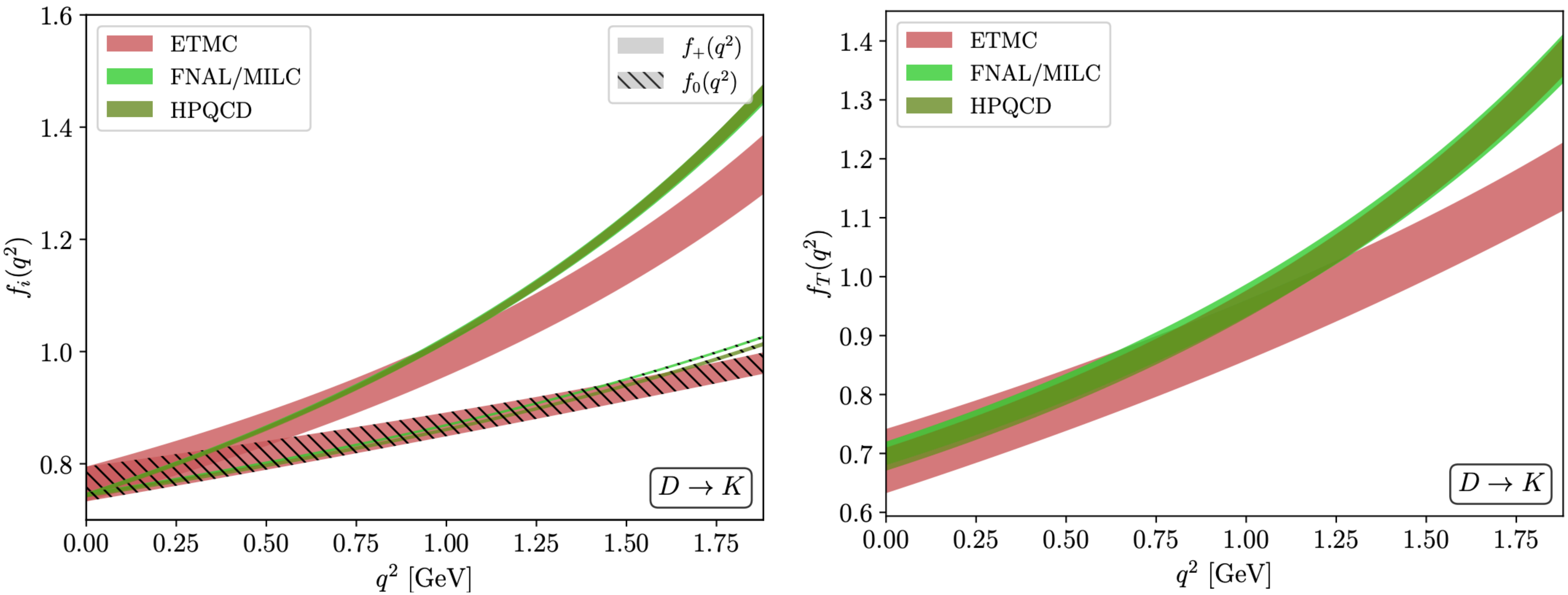
LFU vs. single-flavor

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



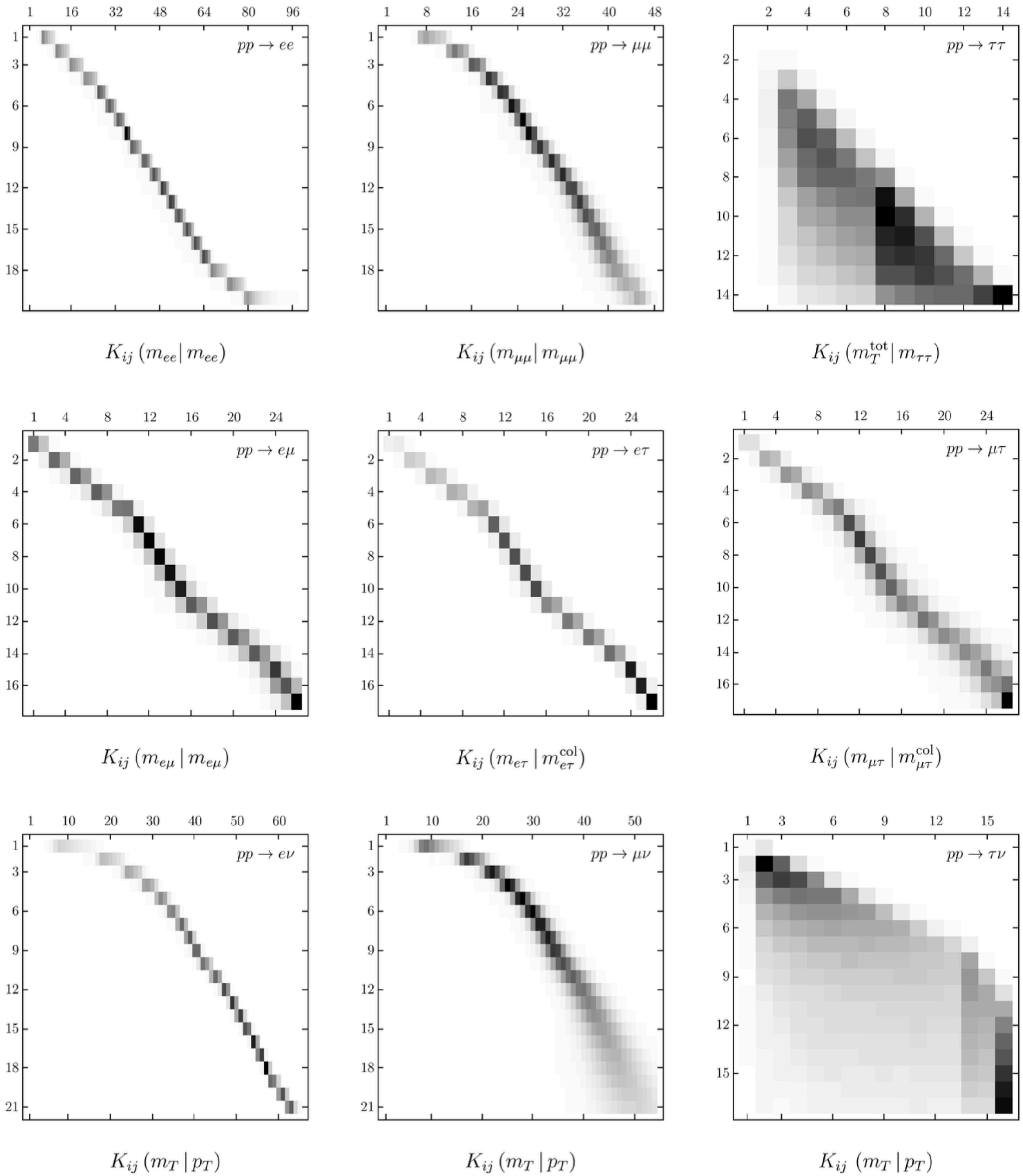
Semileptonic charm decays

$D \to K\ell\nu:$ $\langle K(k)|\bar{c}\gamma_\mu s|D(p)\rangle \propto f_+(q^2), f_0(q^2)$ $\langle K(k)|\bar{c}\gamma_\mu\gamma_5 s|D(p)\rangle = 0$ $\langle K(k)|\bar{c}\sigma_{\mu\nu} s|D(p)\rangle \propto f_T(q^2)$



More work needed to understand the differences (lattice artefacts)

Process	Experiment	Luminosity	Ref.	$x_{\rm obs}$	x
$pp \to \tau\tau$	ATLAS	$139\,\mathrm{fb}^{-1}$	[85]	$m_T^{\rm tot}(\tau_h^1, \tau_h^2, \not{E}_T)$	$m_{\tau\tau}$
$pp \to \mu\mu$	CMS	$140\,\mathrm{fb}^{-1}$	[86]	$m_{\mu\mu}$	$m_{\mu\mu}$
$pp \to ee$	CMS	$137\,\mathrm{fb}^{-1}$	[86]	m_{ee}	m_{ee}
$pp \to \tau\nu$	ATLAS	$139\,\mathrm{fb}^{-1}$	[87]	$m_T(\tau_h, \not{E}_T)$	$p_T(\tau)$
$pp \to \mu\nu$	ATLAS	$139\,\mathrm{fb}^{-1}$	[88]	$m_T(\mu, \not{E}_T)$	$p_T(\mu)$
$pp \to e\nu$	ATLAS	$139\,\mathrm{fb}^{-1}$	[88]	$m_T(e, \not{E}_T)$	$p_T(e)$
$pp \to \tau\mu$	CMS	$138\,\mathrm{fb}^{-1}$	[89]	$m_{\tau_h\mu}^{\rm col}$	$m_{\tau\mu}$
$pp \to \tau e$	CMS	$138\,\mathrm{fb}^{-1}$	[89]	$m_{\tau_h e}^{\rm col}$	$m_{\tau e}$
$pp \to \mu e$	CMS	$138\,\mathrm{fb}^{-1}$	[89]	$m_{\mu e}$	$m_{\mu e}$



$pp \to ee$
$pp \to \mu\mu$
$pp \to \tau\tau$
$K_{ij}\,(m_{ee}|\,m_{ee})$
$K_{ij}\,(m_{\mu\mu}|\,m_{\mu\mu})$
$K_{ij}\,(m_T^{\rm tot}|\,m_{\tau\tau})$
$pp \to e\mu$
$pp \to e\tau$
$pp \to \mu\tau$
$K_{ij}\,(m_{e\mu}\,|\,m_{e\mu})$
$K_{ij}\,(m_{e\tau}\,|\,m_{e\tau}^{\rm col})$
$K_{ij}\,(m_{\mu\tau}\,|\,m_{\mu\tau}^{\rm col})$
$pp \to e\nu$
$pp \to \mu\nu$
$pp \to \tau\nu$
$K_{ij}\,(m_T\,|\,p_T)$
$K_{ij}\,(m_T\,|\,p_T)$
$K_{ij}\,(m_T\,|\,p_T)$

Is the EFT description justified?

[Brivio et al. '22]

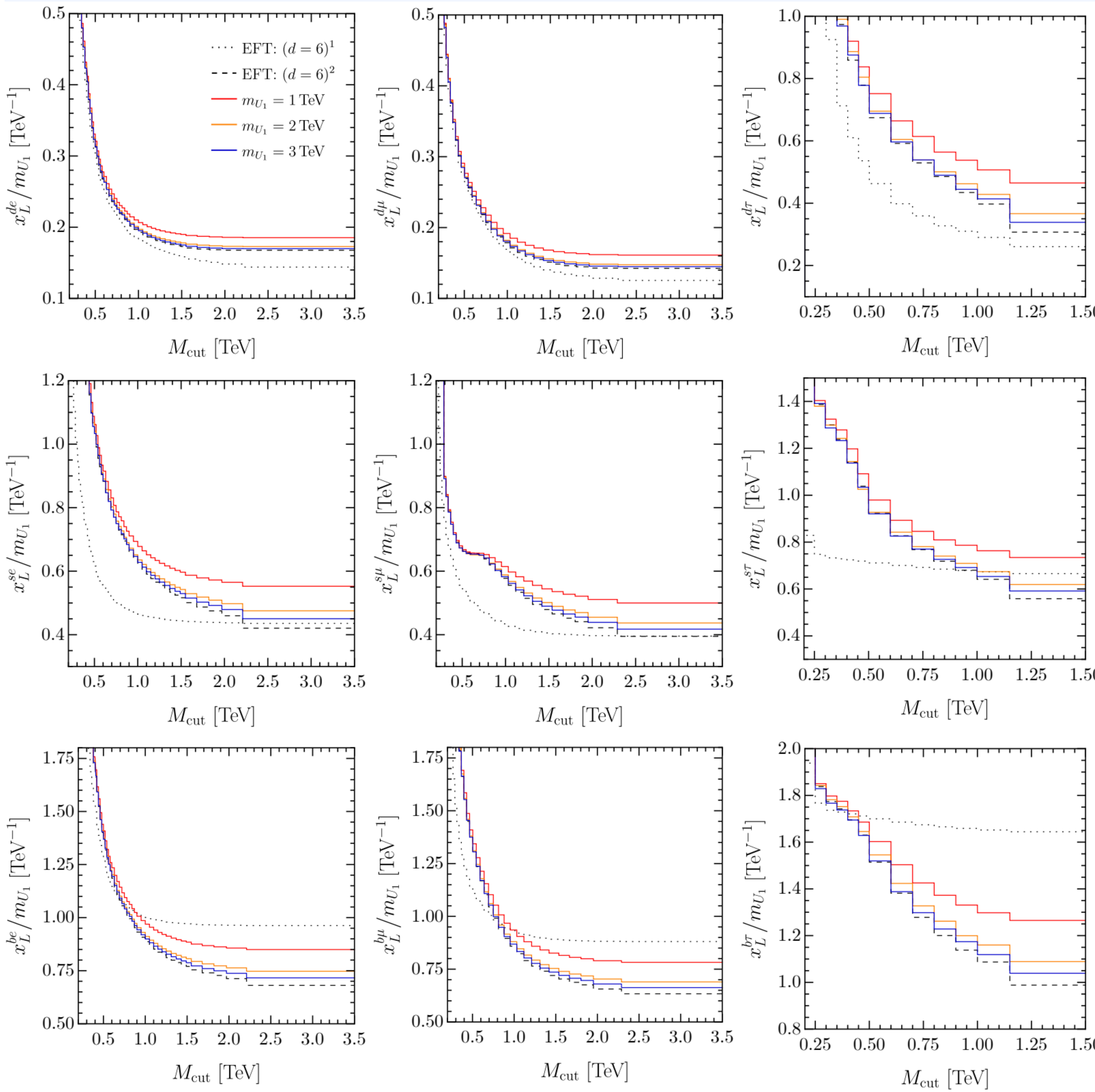
The main caveat of collider bounds on EFTs is that events can have invariant mass in the $\mathcal{O}(1\ \mathrm{TeV})$ range.

Are we indeed probing $\mathcal{C}^{(6)}/\Lambda^2$ with $|\mathcal{C}^{(6)}| \lesssim 4\pi$ and $\Lambda \gg E$?

The answer depends on **several factors**:

- The **experimental sensitivity** — *channels with τ's and MET are harder.*
- The **initial quark flavors** (i.e., PDFs)— *light vs. heavy quarks.*
- The **topology** of the underlying **NP contribution** — *resonant or non-resonant.*

The definite answer is <u>model</u> and <u>process-dependent</u>



EFT: $(d=6)^1$
EFT: $(d=6)^2$
$m_{U_1} = 1\,\mathrm{TeV}$
$m_{U_1} = 2\,\mathrm{TeV}$
$m_{U_1} = 3\,\mathrm{TeV}$
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: $Z' \sim (\mathbf{1},\mathbf{1},0)$

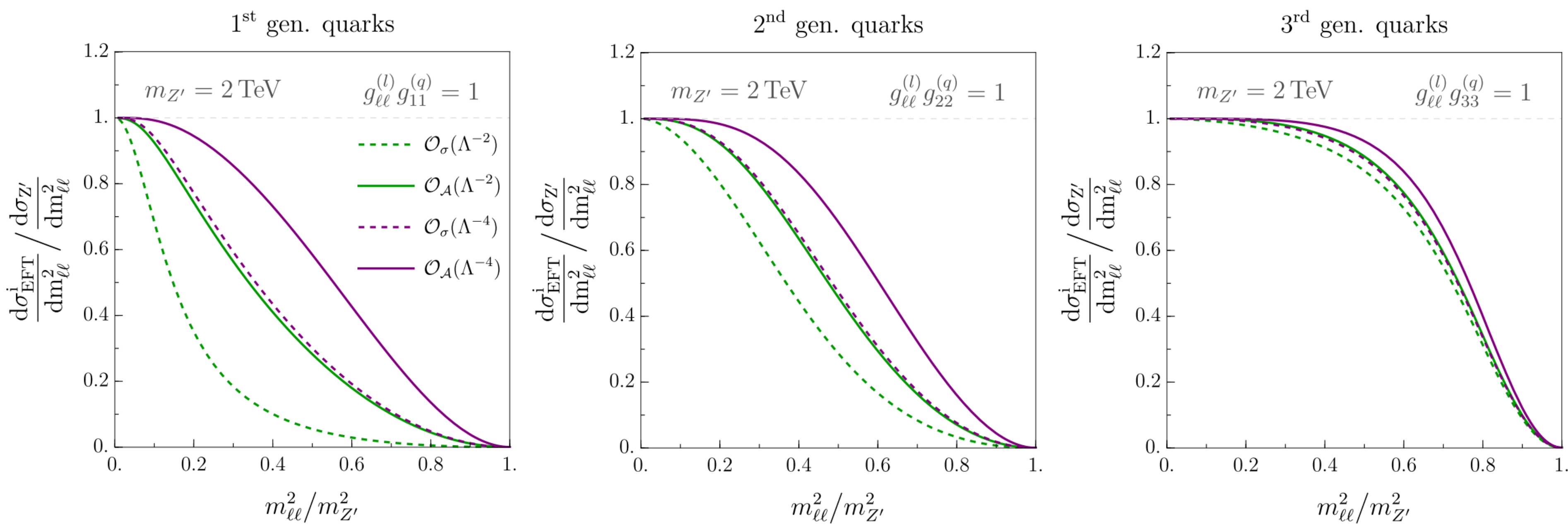
$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} + \frac{m_{Z'}^2}{2} Z'_\mu Z'^{\,\mu} + J^\mu Z'_\mu$$

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

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

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

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



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

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

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

EFT convergence — resonant mediator

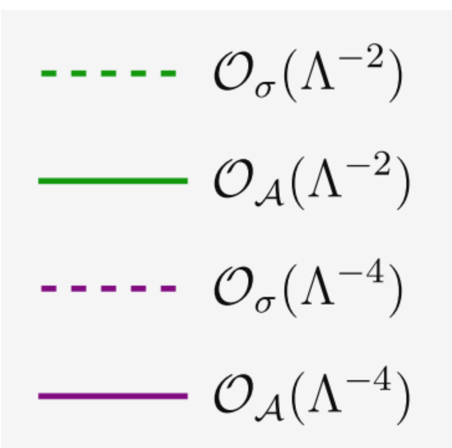
- EFT cross-section computed with different orders in Λ^{-1} and normalized to the full model.
- Example: $Z' \sim (\mathbf{1},\mathbf{1},0)$

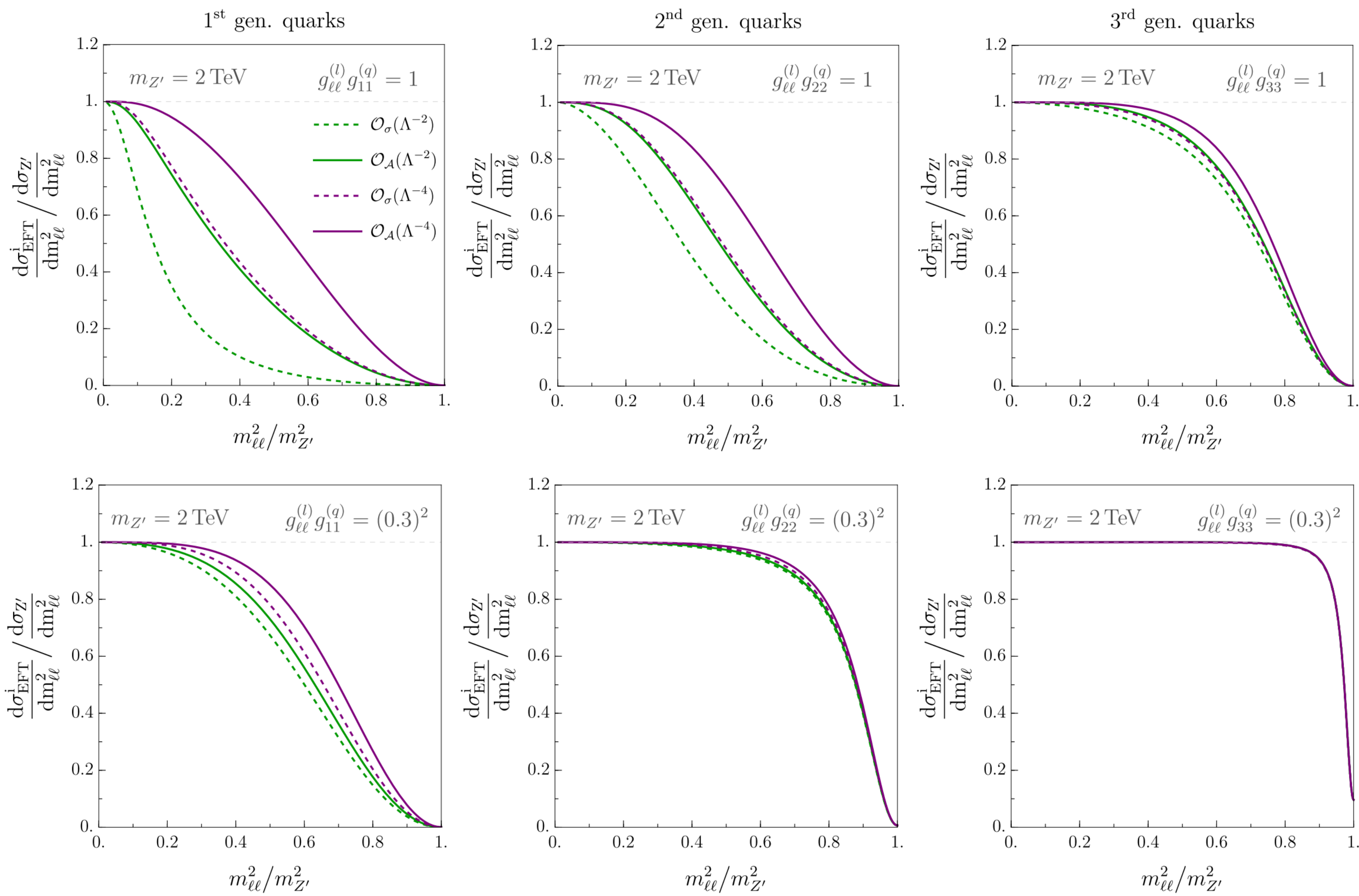
$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} + \frac{m_{Z'}^2}{2} Z'_\mu Z'^{\,\mu} + J^\mu Z'_\mu$$

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

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

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





*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

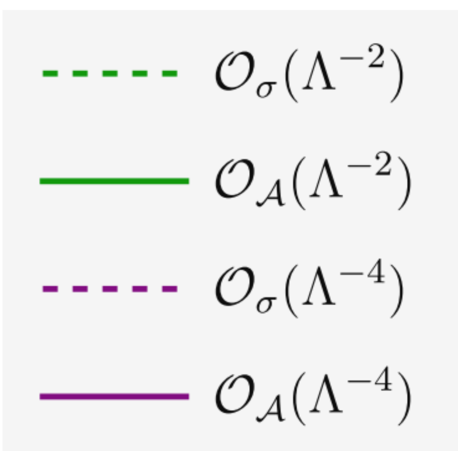
- EFT cross-section computed with different orders in Λ^{-1} and normalized to the full model.
- Example: $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

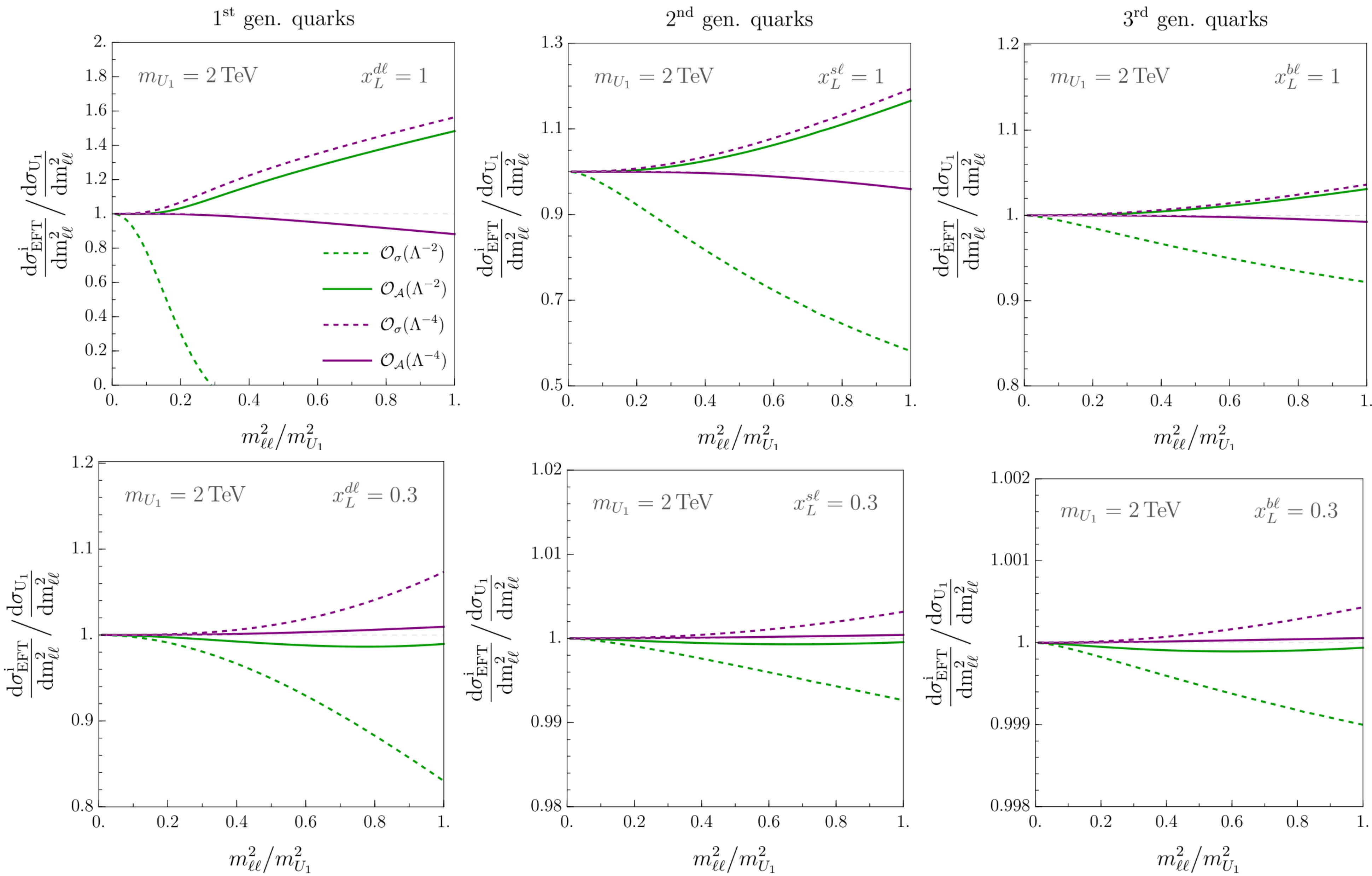
$$\mathcal{L}_{U_1} \supset -\frac{1}{2} U_{1\,\mu\nu}^{\dagger} U_1^{\mu\nu} + m_U^2\, U_1^{\mu\,\dagger} U_{1\,\mu} + (J_\mu^\dagger U_1^\mu + \text{H.c.})$$

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

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

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





*Neglecting the width

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

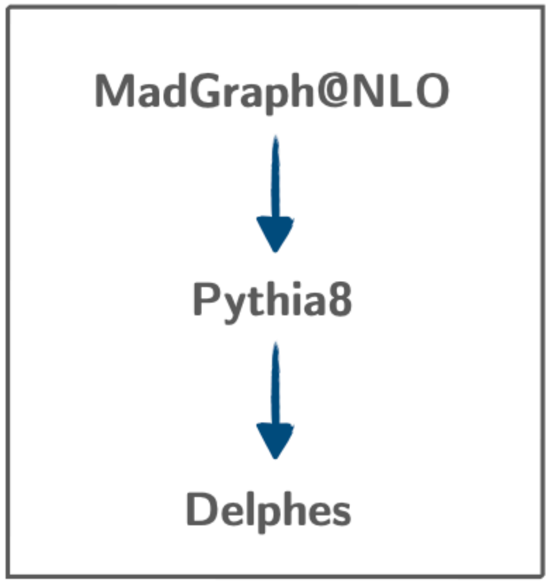
[Allwicher, Faroughy, Martines, **OS**, Wilsch. '24]

$pp \to VH$

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

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

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



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