Connecting flavor at low- and high-p_T in the SMEFT

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

Olcyr Sumensari

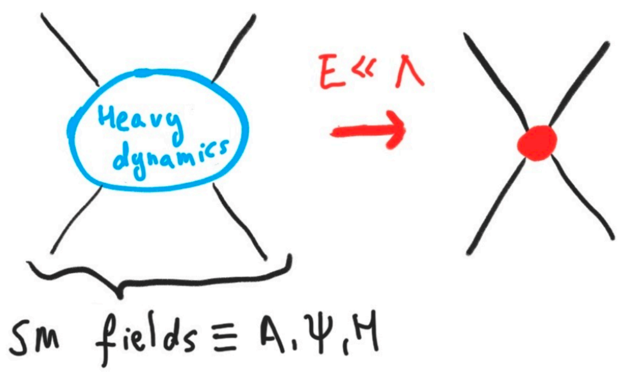
IJCLab (Orsay)

Based on [2207.10756, 2210.11995, ...],
in collaboration with L. Allwicher, D.A. Faroughy, F. Jaffredo and F. Wilsch

Beauty 2023 @ Clermont-Ferrand, 6 July, 2023

Motivation

- **Effective Field Theories (EFTs)** provide the **most general description** of New Physics, provided there is not enough energy to produce them on-shell ($E \ll \Lambda$):



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

Motivation

- **Effective Field Theories (EFTs)** provide the **most general description** of New Physics, provided there is not enough energy to produce them on-shell ($E \ll \Lambda$):

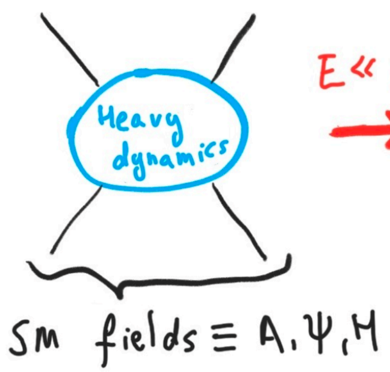
$$\mathcal{L}_{\text{eff}} = \overbrace{\mathcal{L}_{\text{gauge}}(A,\Psi) + \mathcal{L}_{\text{Higgs}}(A,\Psi,H)}^{\mathcal{L}_{\text{SM}}\ \text{(renormalizable)}} + \underbrace{\sum_{d\geq 5} \frac{c_n^{(d)}}{\Lambda^{d-4}} \mathcal{O}_n^{(d)}(A,\Psi,H)}_{\text{Operators of dim}\ \geq 5\ \text{made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

- The **SMEFT** is defined for $\Lambda \gg v_{\text{EW}}$ and is invariant under $SU(3)_c \times SU(2)_L \times U(1)_Y$:

  $\Rightarrow$ *Challenge: $N = 2499$ dim-6 operators that conserve B and L — rich flavor structure!*

Motivation

- **Effective Field Theories (EFTs)** provide the **most general description** of New Physics, provided there is not enough energy to produce them on-shell ($E \ll \Lambda$):



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

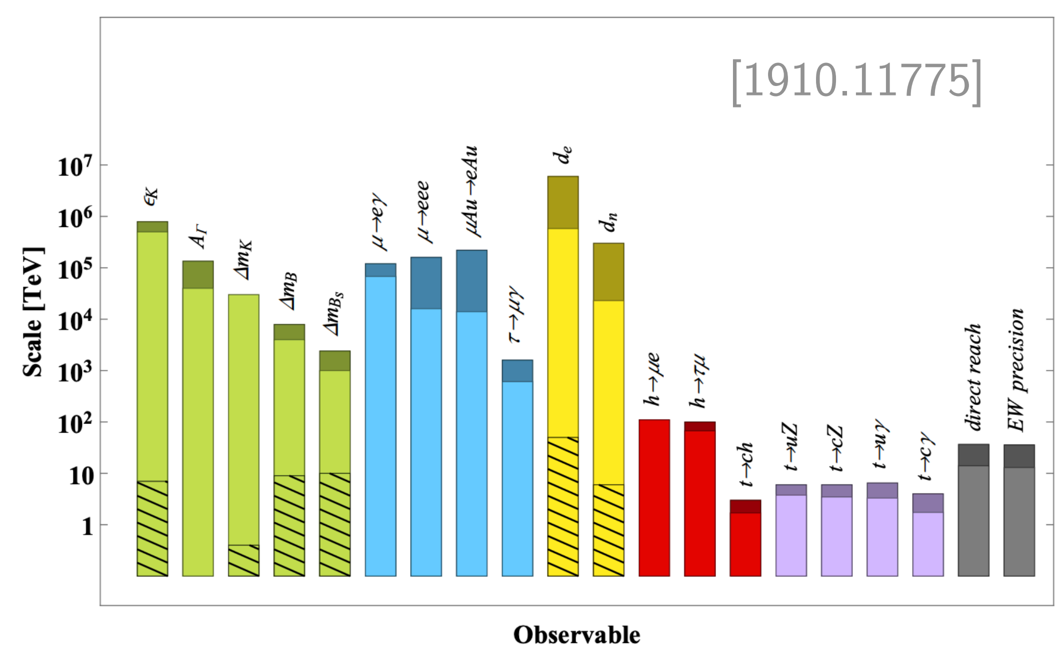
- The **SMEFT** is defined for $\Lambda \gg v_{\rm EW}$ and is invariant under $SU(3)_c \times SU(2)_L \times U(1)_Y$:

  ⇒ *Challenge: $N = 2499$ dim-6 operators that conserve B and L — rich flavor structure!*

- The **best probes** of the **EFT** operators are **rare/forbidden processes** in the SM:

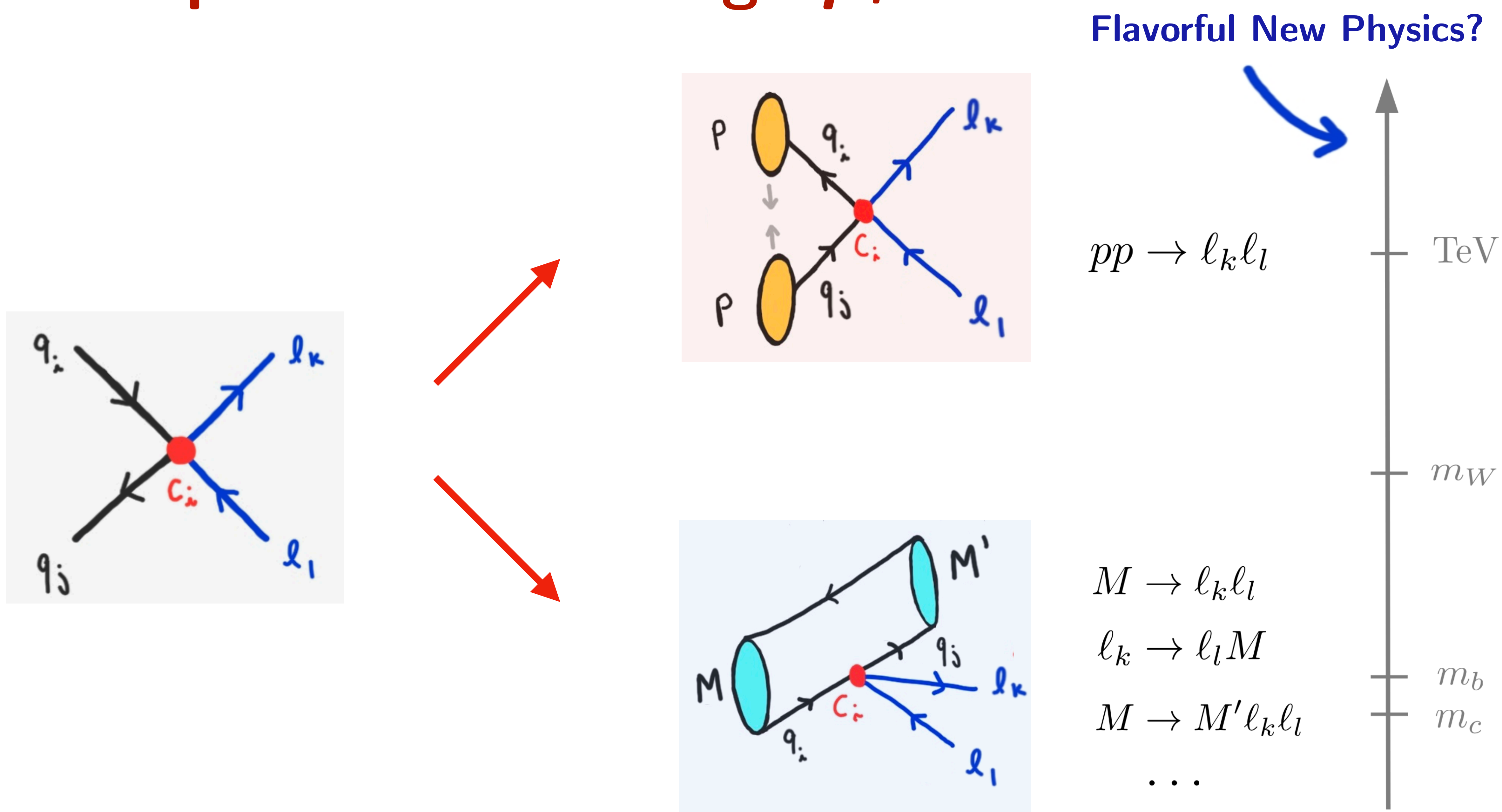
  ⇒ However, these processes can be **suppressed** in **concrete scenarios** *(e.g., MFV, $U(2)^5$ ...)*.

  ⇒ **LHC processes** can be **useful** to probe these types of scenarios (with lower values for Λ)!



This talk: Drell-Yan complementarity to flavor searches

How to probe flavor at high-p_T?



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

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

LHC as a flavor experiment

i) LHC collides quarks with five flavors

Parton luminosities

Partonic cross-section

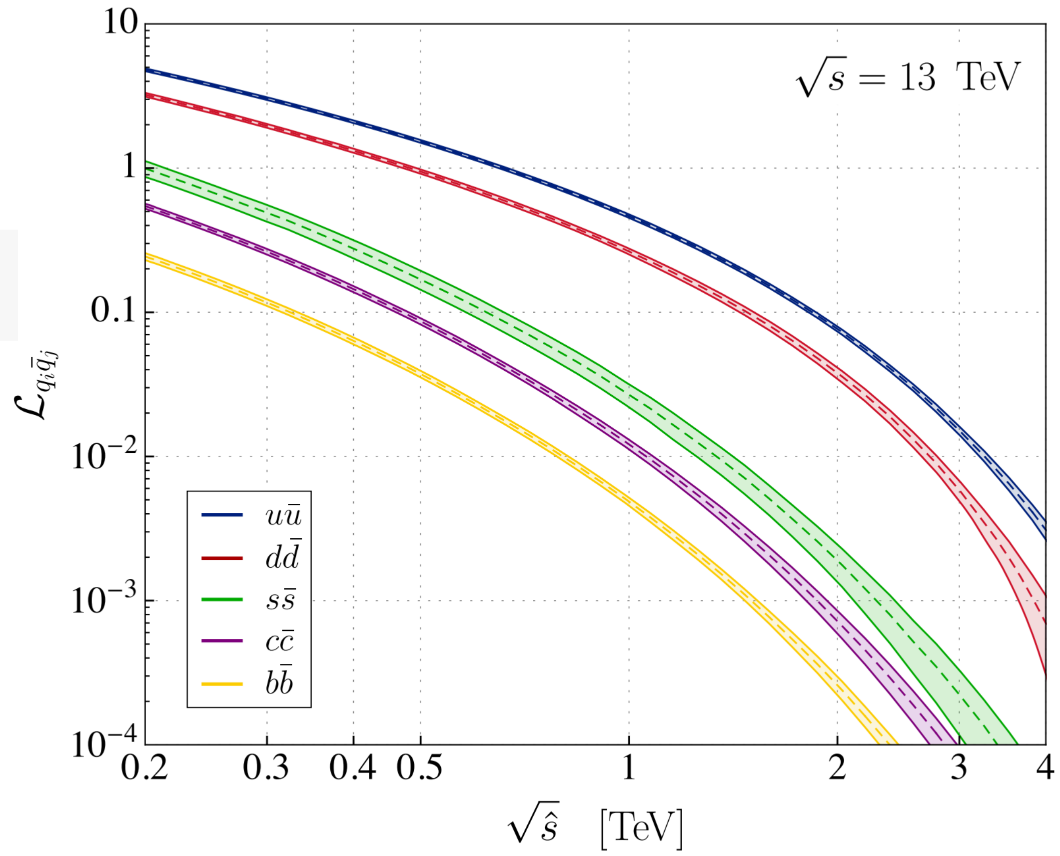
$$\sigma(pp \to \ell\ell') = \sum_{ij} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{q_i\bar{q}_j}(\tau)\, \hat{\sigma}(q_i\bar{q}_j \to \ell\ell')_{\hat{s}=s\tau}$$

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

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

$\sqrt{s} = 13$ TeV

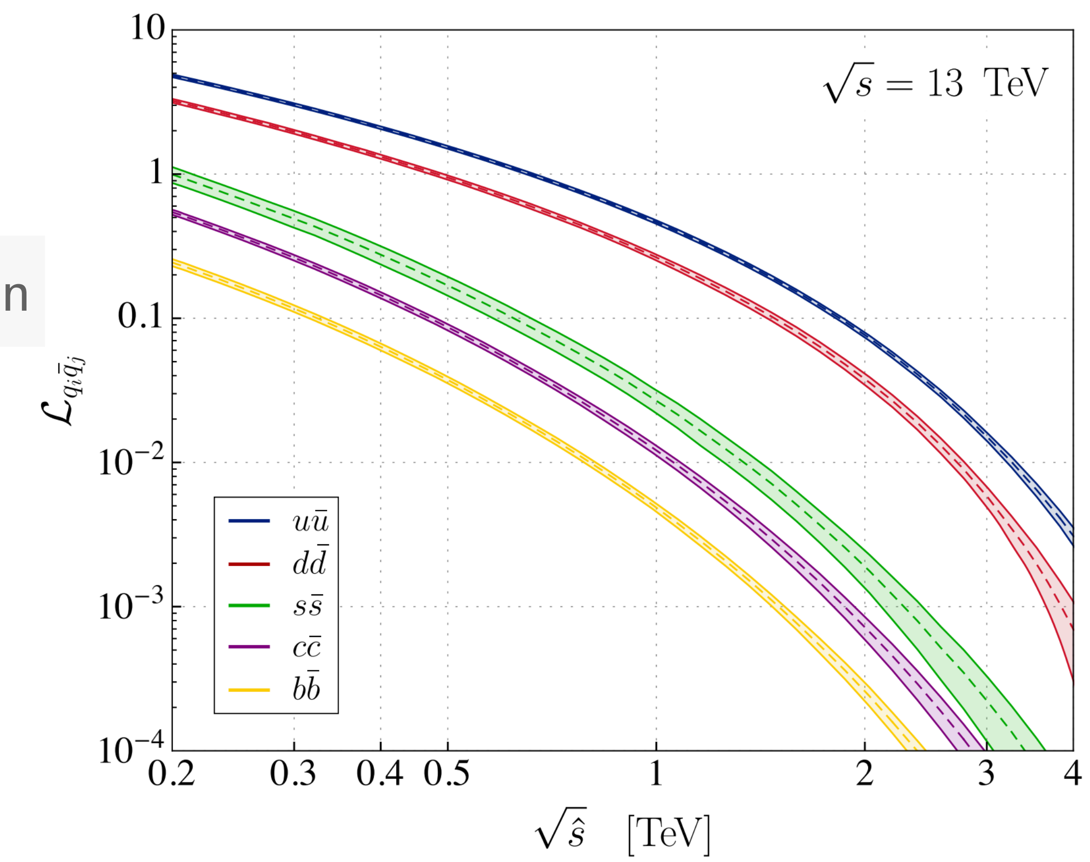
[PDF4LHC15_nnlo_mc]



LHC as a flavor experiment

i) LHC collides quarks with five flavors

[PDF4LHC15_nnlo_mc]



Parton luminosities

Partonic cross-section

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

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

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

$\sqrt{s} = 13$ TeV

ii) Energy helps precision

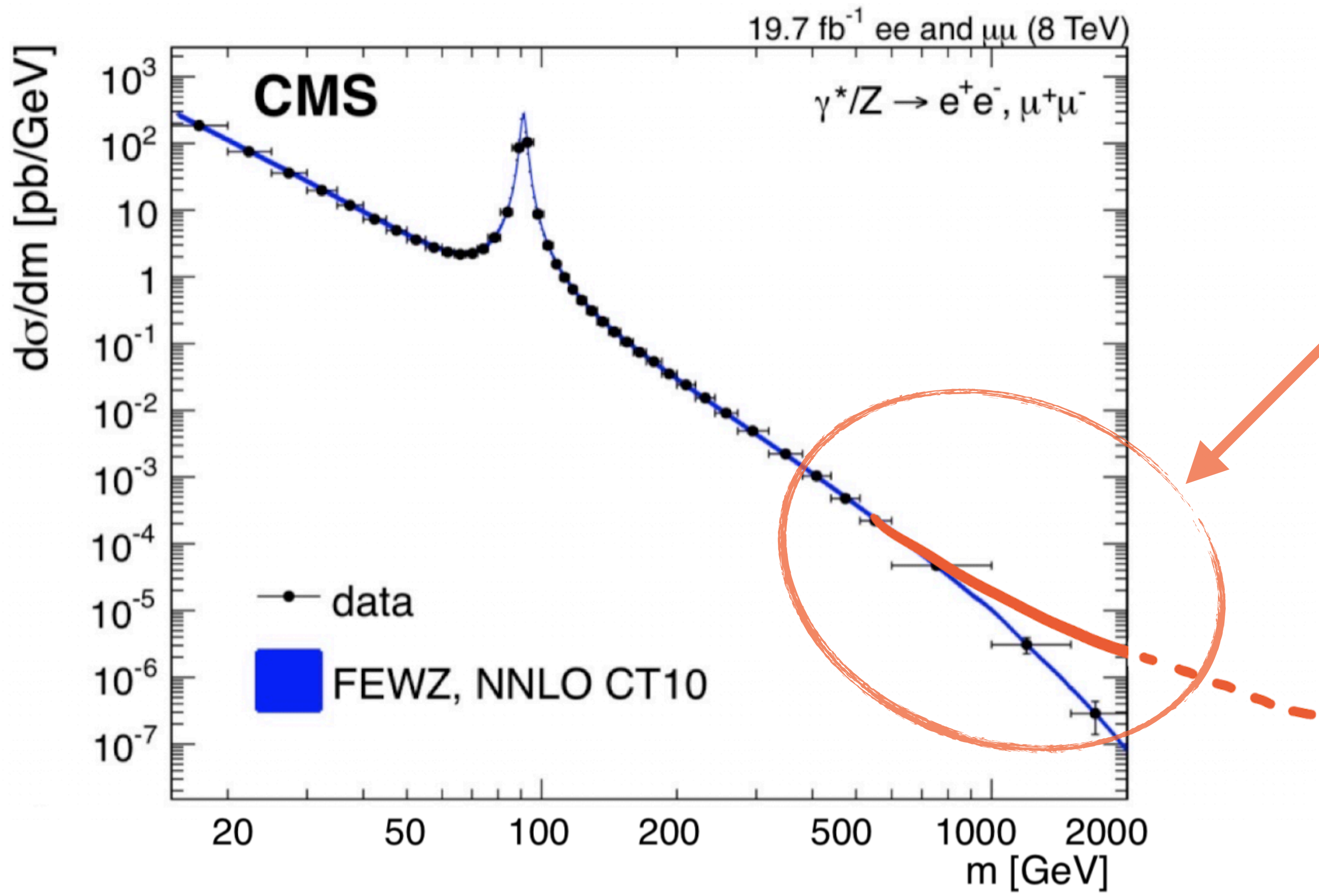
cf. e.g. [Farina et al. '16]

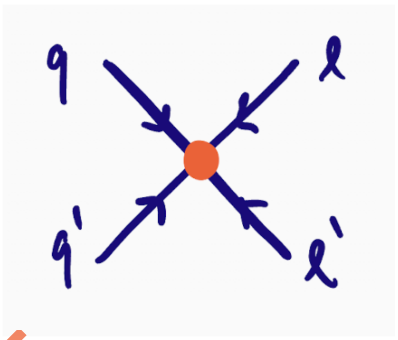
$$\mathcal{L}_{\text{eff}} \supset \frac{\mathcal{C}^{(6)}}{\Lambda^2}\mathcal{O}^{(6)} + \dots \quad \xrightarrow{(\sqrt{\hat{s}} \ll \Lambda)} \quad \hat{\sigma} = \hat{\sigma}_{\text{SM}} + \hat{\sigma}_{\text{int}} + \hat{\sigma}_{\text{NP}^2}$$

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

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

Indirect searches at the LHC

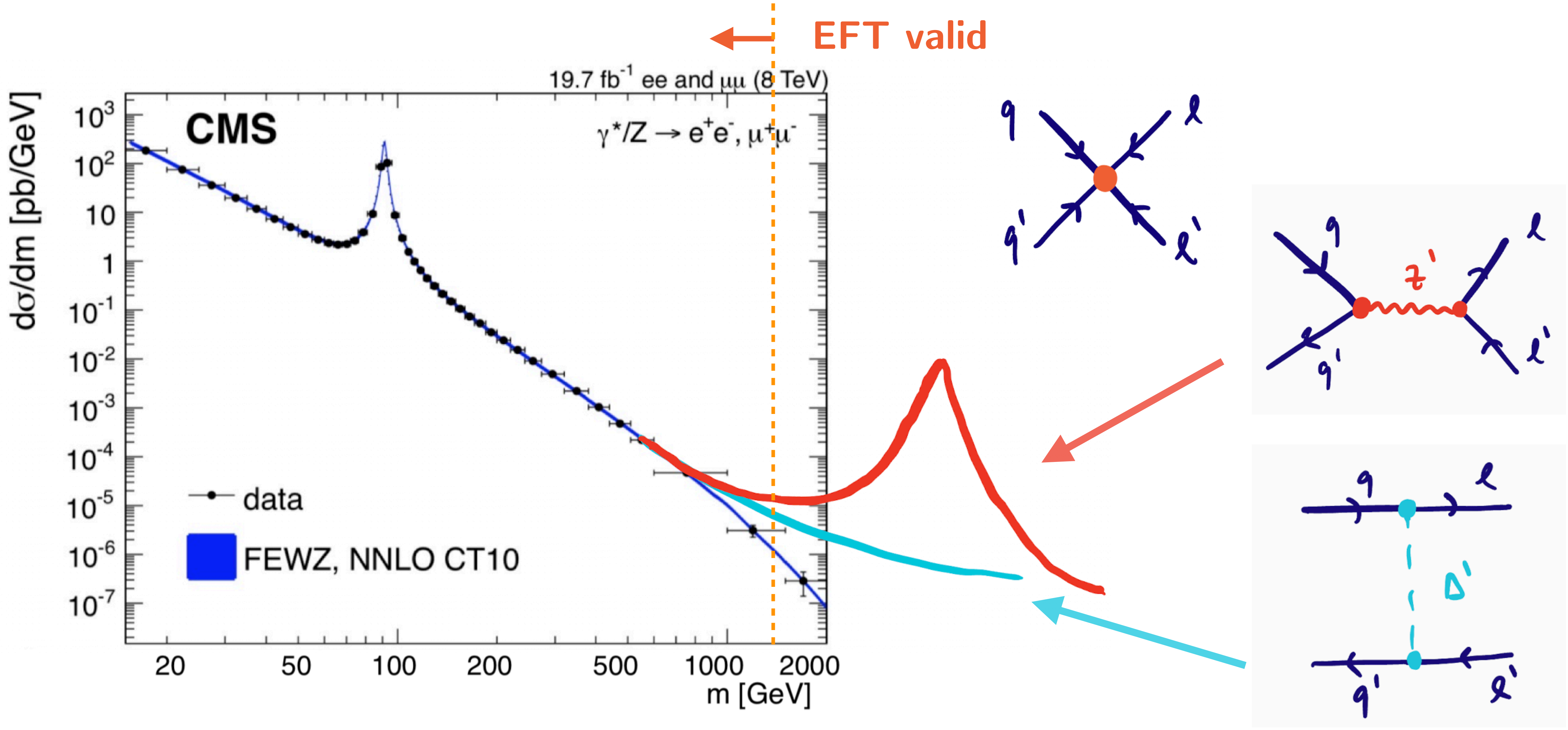




Goal: **Probe flavor transitions** that are **poorly constrained** at **low energies** (e.g., $b \to s\tau\tau$)

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

Indirect searches at the LHC



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

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

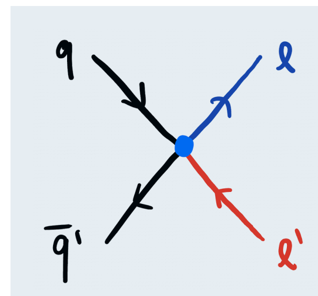
Caveat: EFT must be valid ($E \ll \Lambda$). Otherwise, use explicit model (e.g., leptoquark or Z').

SMEFT and Drell-Yan

SMEFT operators

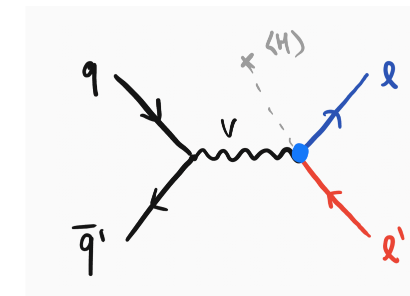
- *Warsaw* basis $d = 6$:   [Buchmuller, Wyler. '85], [Grzadkowski et al. '10]
- Operator classes contributing to $pp \to \ell\ell'$ at tree-level: ψ^4, $\psi^2 XH$, $\psi^2 D^2 H$

i) Four-fermion: ψ^4



	$d=6$	ψ^4
Vector	$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(\bar{q}_i \gamma_\mu q_j)$
Vector	$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j)$
Vector	$\mathcal{O}_{lu}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(\bar{u}_i \gamma_\mu u_j)$
Vector	$\mathcal{O}_{ld}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(\bar{d}_i \gamma_\mu d_j)$
Vector	$\mathcal{O}_{eq}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(\bar{q}_i \gamma_\mu q_j)$
Vector	$\mathcal{O}_{eu}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(\bar{u}_i \gamma_\mu u_j)$
Vector	$\mathcal{O}_{ed}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(\bar{d}_i \gamma_\mu d_j)$
Scalar	$\mathcal{O}_{ledq}$ + h.c.	$(\bar{l}_\alpha e_\beta)(\bar{d}_i q_j)$
Scalar	$\mathcal{O}_{lequ}^{(1)}$ + h.c.	$(\bar{l}_\alpha e_\beta)\varepsilon(\bar{q}_i u_j)$
Tensor	$\mathcal{O}_{lequ}^{(3)}$ + h.c.	$(\bar{l}_\alpha \sigma^{\mu\nu} e_\beta)\varepsilon(\bar{q}_i \sigma_{\mu\nu} u_j)$

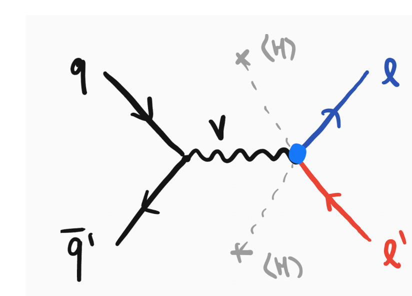
ii) Leptonic dipoles: $\psi^2 XH$



$d=6$	$\psi^2 XH$ + h.c.
$\mathcal{O}_{eW}$	$(\bar{l}_\alpha \sigma^{\mu\nu} e_\beta)\,\tau^I H W^I_{\mu\nu}$
$\mathcal{O}_{eB}$	$(\bar{l}_\alpha \sigma^{\mu\nu} e_\beta)\,H B_{\mu\nu}$

iii) Z/W-coupling modifications: $\psi^2 D^2 H$

$d=6$	$\psi^2 H^2 D$
$\mathcal{O}_{Hl}^{(1)}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(H^\dagger i \overleftrightarrow{D}_\mu H)$
$\mathcal{O}_{Hl}^{(3)}$	$(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(H^\dagger i \overleftrightarrow{D}^I_\mu H)$
$\mathcal{O}_{He}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(H^\dagger i \overleftrightarrow{D}_\mu H)$



NB. Besides operators redefining SM inputs (not energy-enhanced!).

SMEFT operators

- *Warsaw* basis $d = 6$:   [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	# $\mathbb{R}\mathrm{e}$	456	45	48	168	171	44	52
	# $\mathbb{I}\mathrm{m}$	399	25	48	54	63	12	12

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

Too many operators...

SMEFT operators

- *Warsaw* basis $d = 6$: [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

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

Too many operators...

Two possible strategies:

- 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]

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

  ⇒ This talk!

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

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

HighPT

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

References: arXiv:2207.10756, arXiv:2207.10714

Website: https://highpt.github.io

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

Version: 1.0.2

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

Recast procedure:

MadGraph 5 + Pythia + Delphes

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

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

*more to be included (see GitHub page)

Main functionalities:

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

[Aebischer et al. '17]

Low vs high-energy searches

Examples:

- $b \to c\tau\bar{\nu}$ and $b \to s\tau\tau$
- $b \to s\nu\bar{\nu}$ (indirectly)

... with comments on SM predictions.

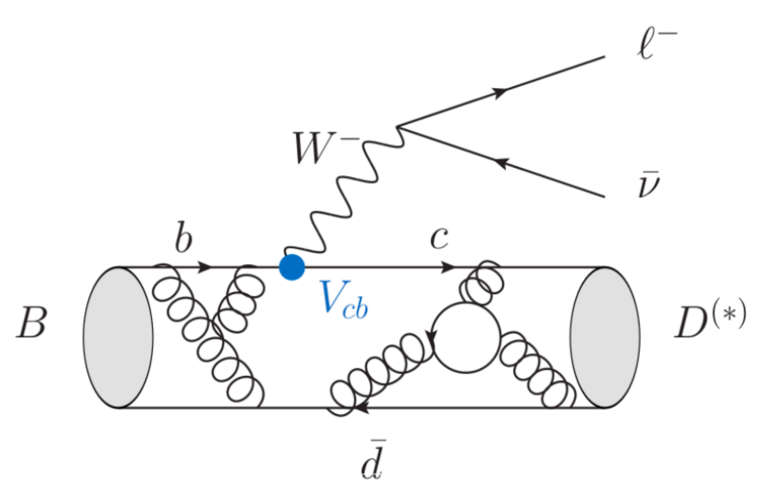
Other examples: See back-up!

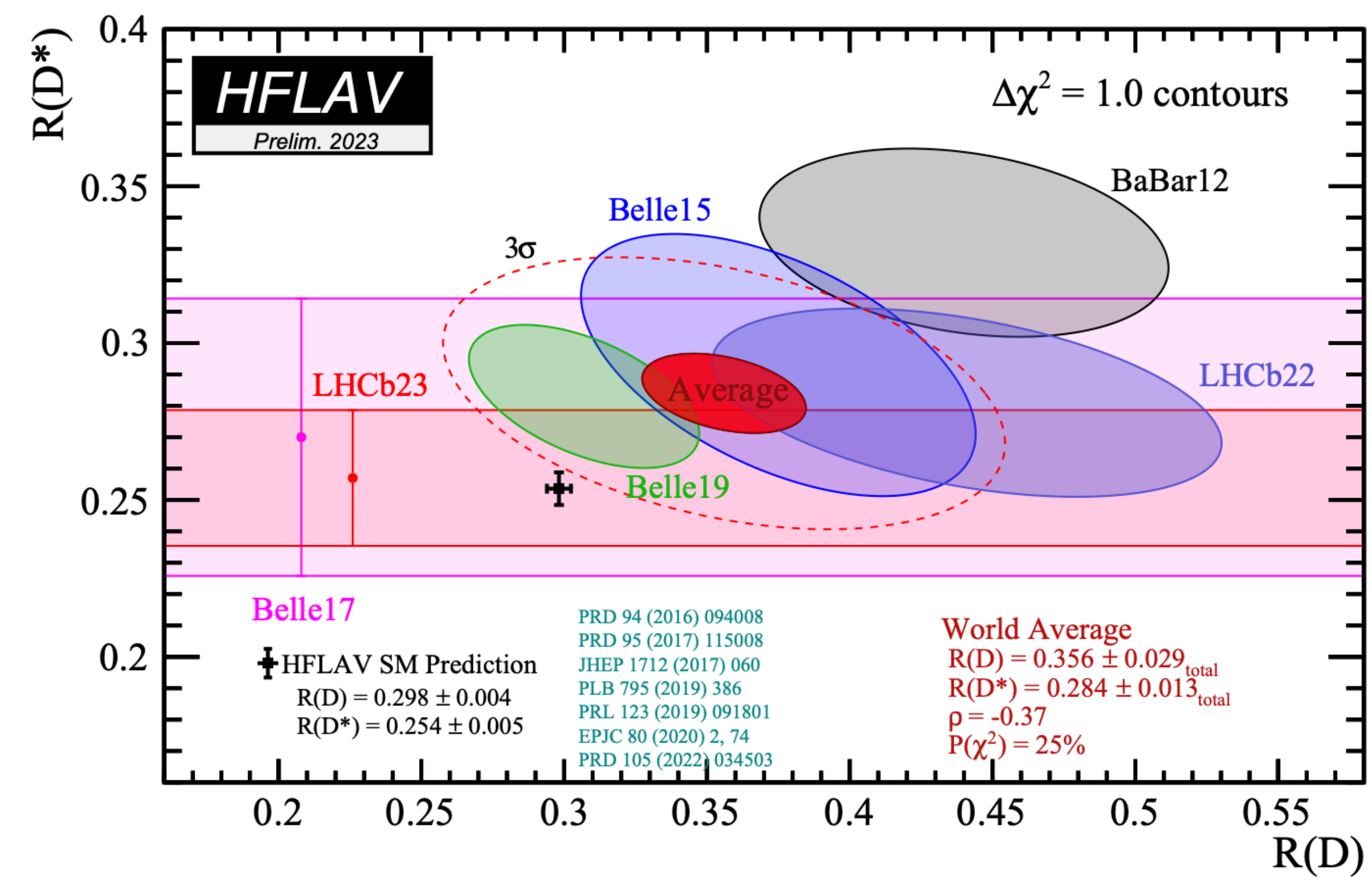
- Charm decays [Fuentes-Martin et al. '20]
- LFV meson decays [Angelescu et al. '20, Descotes-Genon et al. '23]

Example i) $b \to c\tau\bar{\nu}$

See talks by Y. Fan, Fazzini, Lytle and Vos

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



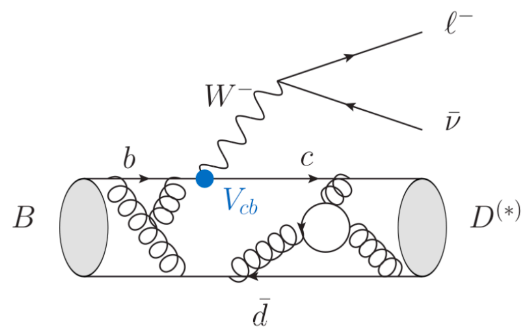


- $R_D^{\rm exp}$ and $R_{D^*}^{\rm exp}$: **dominated by BaBar!**
- LHCb also measured $R_{J/\psi}^{\rm exp}$ and $R_{\Lambda_c}^{\rm exp}$, but with limited precision.
- It can only be accommodated by New Physics with $\Lambda \lesssim 10$ TeV . [Di Luzio et al. '17]

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

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

See talk by Lytle



Known Lorentz factors

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

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

For light (heavy) leptons:

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

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

$$R_D^{\text{latt.}} = 0.293(5)$$

$$R_D^{\text{latt.+exp}} = 0.295(3)$$

[FLAG '21]

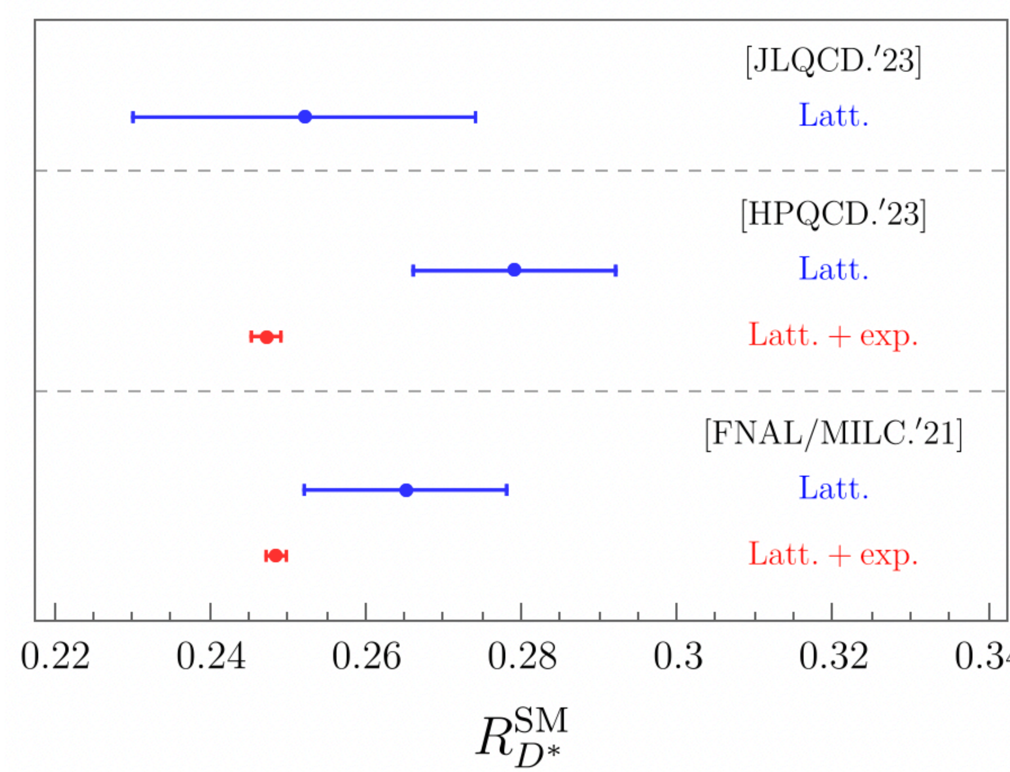
$B \to D^{(*)} l\bar{\nu} \quad (l = e, \mu)$

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

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

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

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



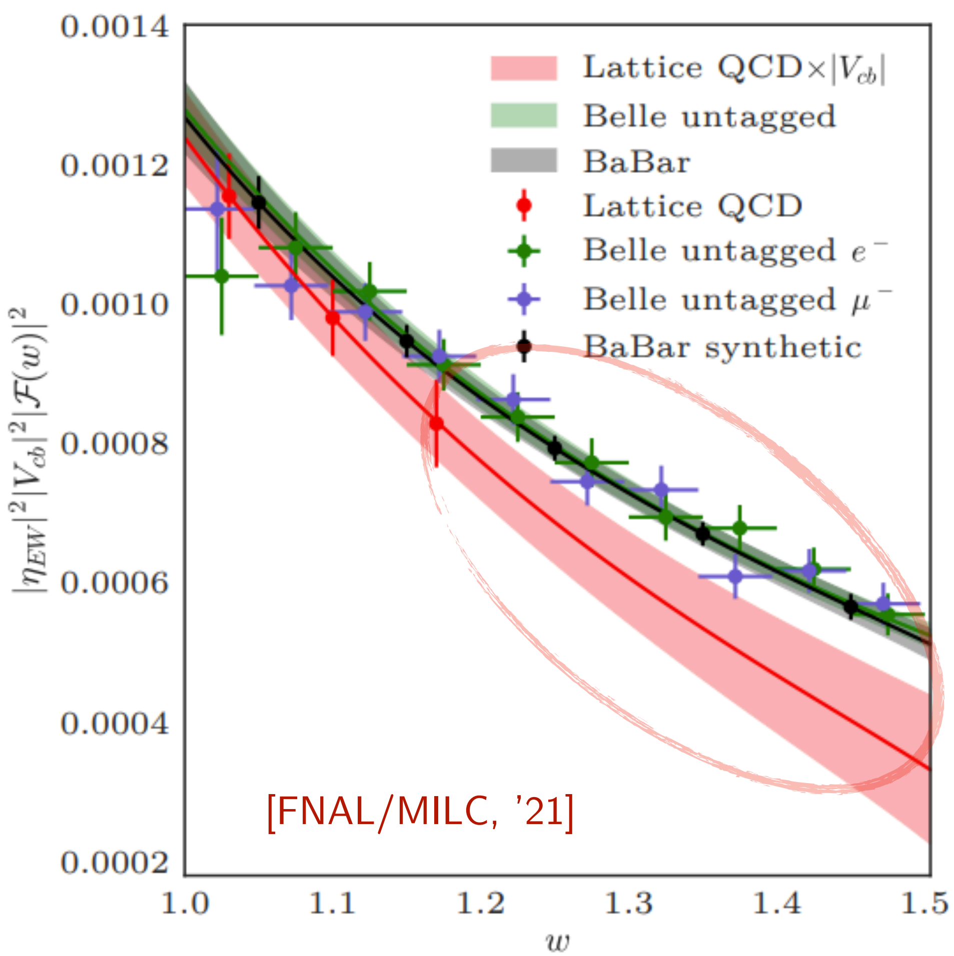
$\approx 2.4\sigma$

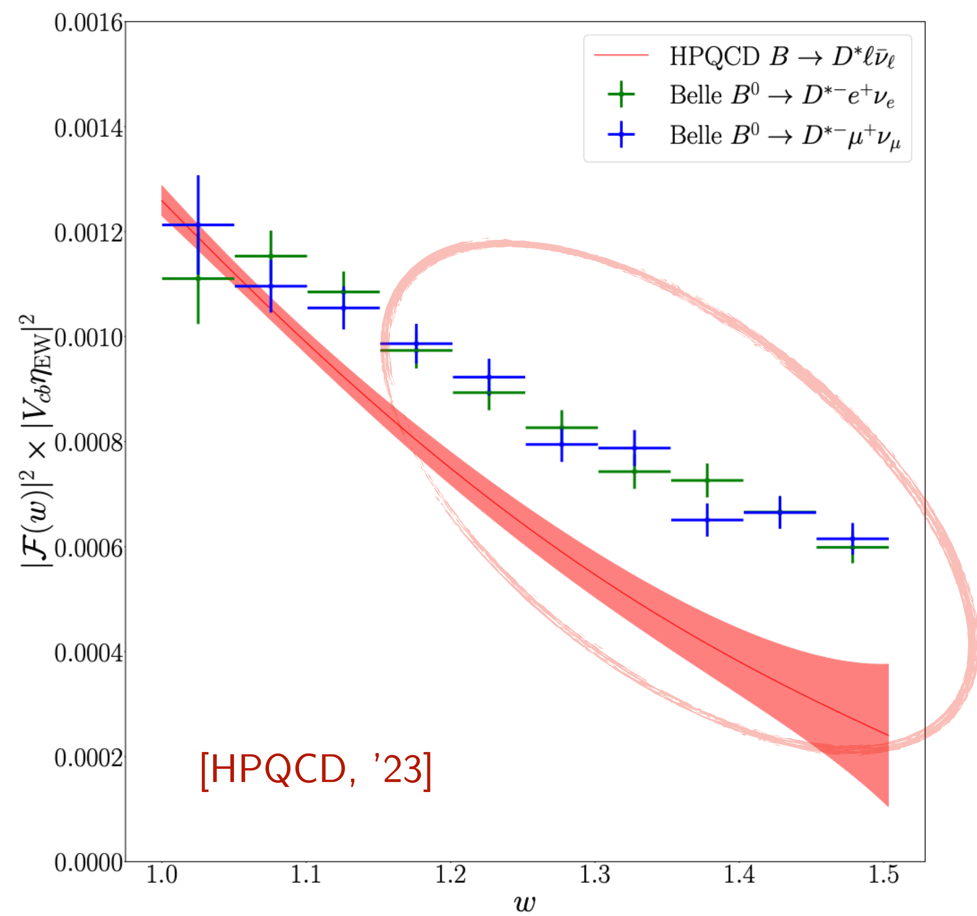
$\approx 1.3\sigma$

[Intermezzo]: Warning!

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^*\ell\nu) \propto |V_{cb}|^2\,|\mathcal{F}(w)|^2$$

$$\left[w = \frac{m_B^2 + m_{D^*}^2 - q^2}{2m_B m_{D^*}}\right]$$





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

NB. Recent JLQCD agrees well with exp. data!

See talk by Lytle

<u>Way out</u>: independent LQCD results + Belle-II data!

[Intermezzo] How to improve our R_{D^*} predictions?

- Th. uncertainties are related to m_τ (only source of LFU breaking in the SM):

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \ell \bar{\nu}) = \Phi(q^2)\, \omega_\ell(q^2) \left[H_V(q^2)^2 + \frac{m_\ell{}^2}{m_\ell{}^2 + 2q^2} H_S(q^2)^2 \right]$$

$$\underbrace{H_V}_{\propto A_1(q^2),\ A_2(q^2),\ V(q^2)} \qquad \underbrace{H_S}_{\propto A_0(q^2)}$$

- A **simple redefinition** can reduce these uncertainties:

$$R_{D^*}^{(\tau/\mu)} = \frac{\displaystyle\int_{m_\tau^2}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \tau \bar{\nu})}{\displaystyle\int_{m_\mu^2}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \mu \bar{\nu})} \quad \longrightarrow \quad R_{D^*}^{(\tau/\mu)}[q^2_{\mathrm{min}}] = \frac{\displaystyle\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \tau \bar{\nu})}{\displaystyle\int_{q^2_{\mathrm{min}}}^{q^2_{\mathrm{max}}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \mu \bar{\nu})}$$

	Observable	Latt. (FNAL)
Usual definition →	R_{D^*}	0.27(1) [5 %]
Definition with same bins →	$R_{D^*}[m_\tau^2]$	0.343(6) [2 %]

[Intermezzo] How to improve our R_{D^*} predictions?

- Th. uncertainties are related to m_τ (only source of LFU breaking in the SM):

$$\frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \ell \bar{\nu}) = \Phi(q^2)\,\omega_\ell(q^2)\left[H_V(q^2)^2 + \frac{m_\ell{}^2}{m_\ell{}^2 + 2q^2} H_S(q^2)^2\right]$$

$$H_V \propto A_1(q^2),\ A_2(q^2),\ V(q^2) \qquad H_S \propto A_0(q^2)$$

- A **simple redefinition** can reduce these uncertainties:

$$R_{D^*}^{(\tau/\mu)} = \frac{\int_{m_\tau^2}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \tau \bar{\nu})}{\int_{m_\mu^2}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \mu \bar{\nu})} \longrightarrow \widetilde{R}_{D^*}^{(\tau/\mu)}[q^2_{\min}] = \frac{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \tau \bar{\nu})}{\int_{q^2_{\min}}^{q^2_{\max}} \mathrm{d}q^2 \frac{\omega_\tau(q^2)}{\omega_\mu(q^2)} \frac{\mathrm{d}\mathcal{B}}{\mathrm{d}q^2}(B \to D^* \mu \bar{\nu})}$$

[Isidori, **OS**. '20]

	Observable	Latt. (FNAL)
Usual definition →	R_{D^*}	$0.27(1)$ $[5\,\%]$
Definition with same bins →	$R_{D^*}[m_\tau^2]$	$0.343(6)$ $[2\,\%]$
Definition with same bins and re-weighting →	$\widetilde{R}_{D^*}[m_\tau^2]$	$1.080(4)$ $[0.4\,\%]$

NB. QED corrections not included!

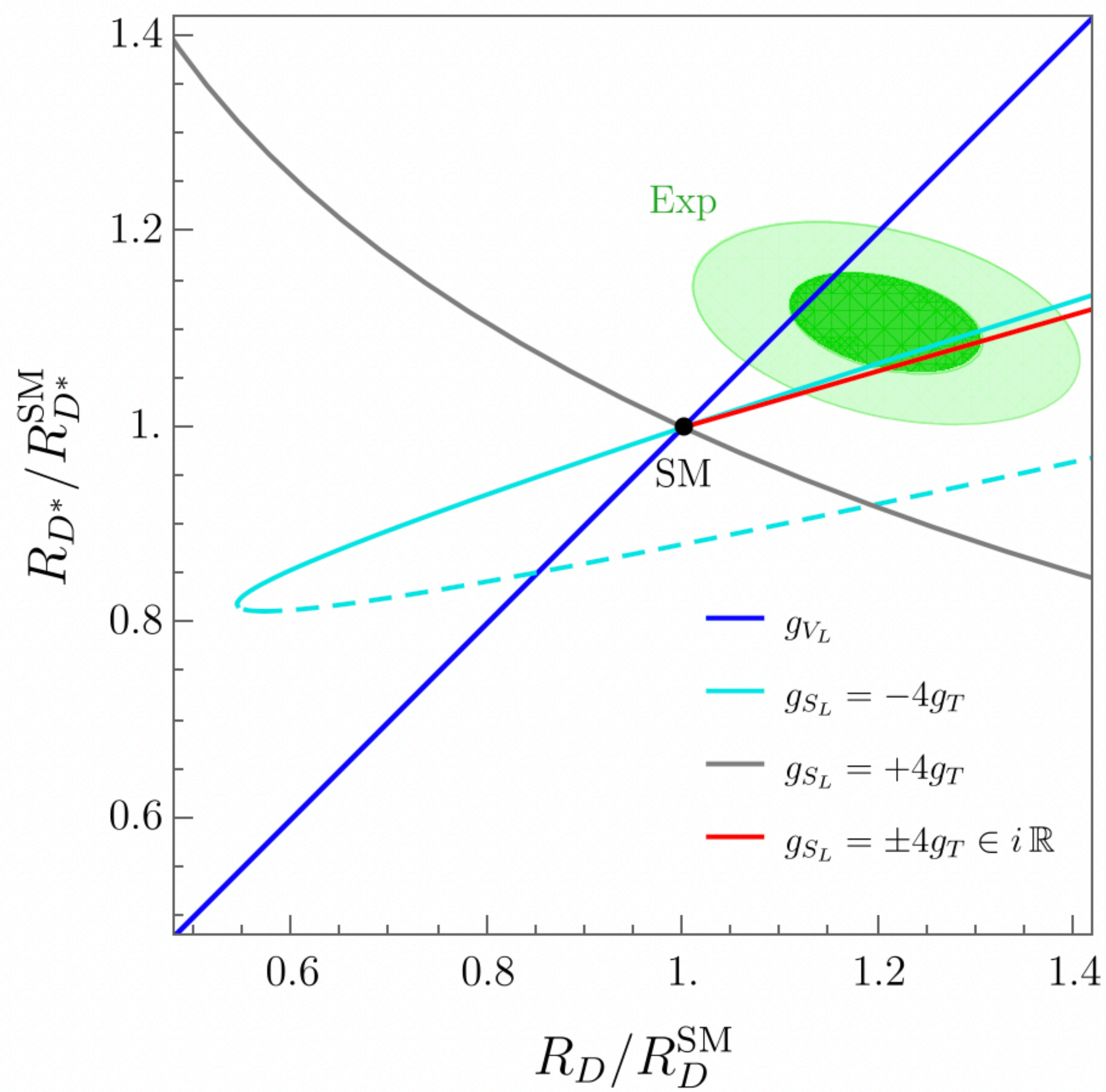
EFT for $b \to c\tau\bar{\nu}$

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

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

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

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

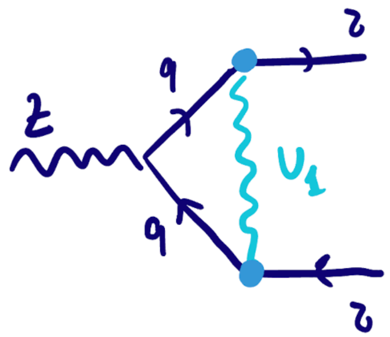


Only scalar/vector **leptoquarks** can **do the job**!

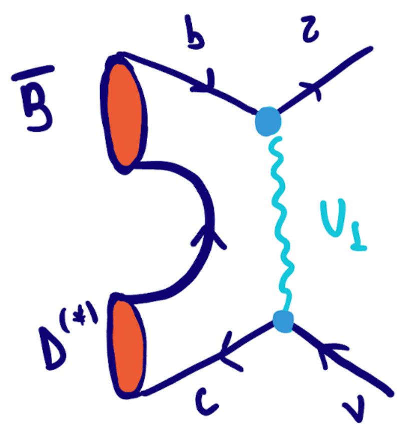
Example: $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$

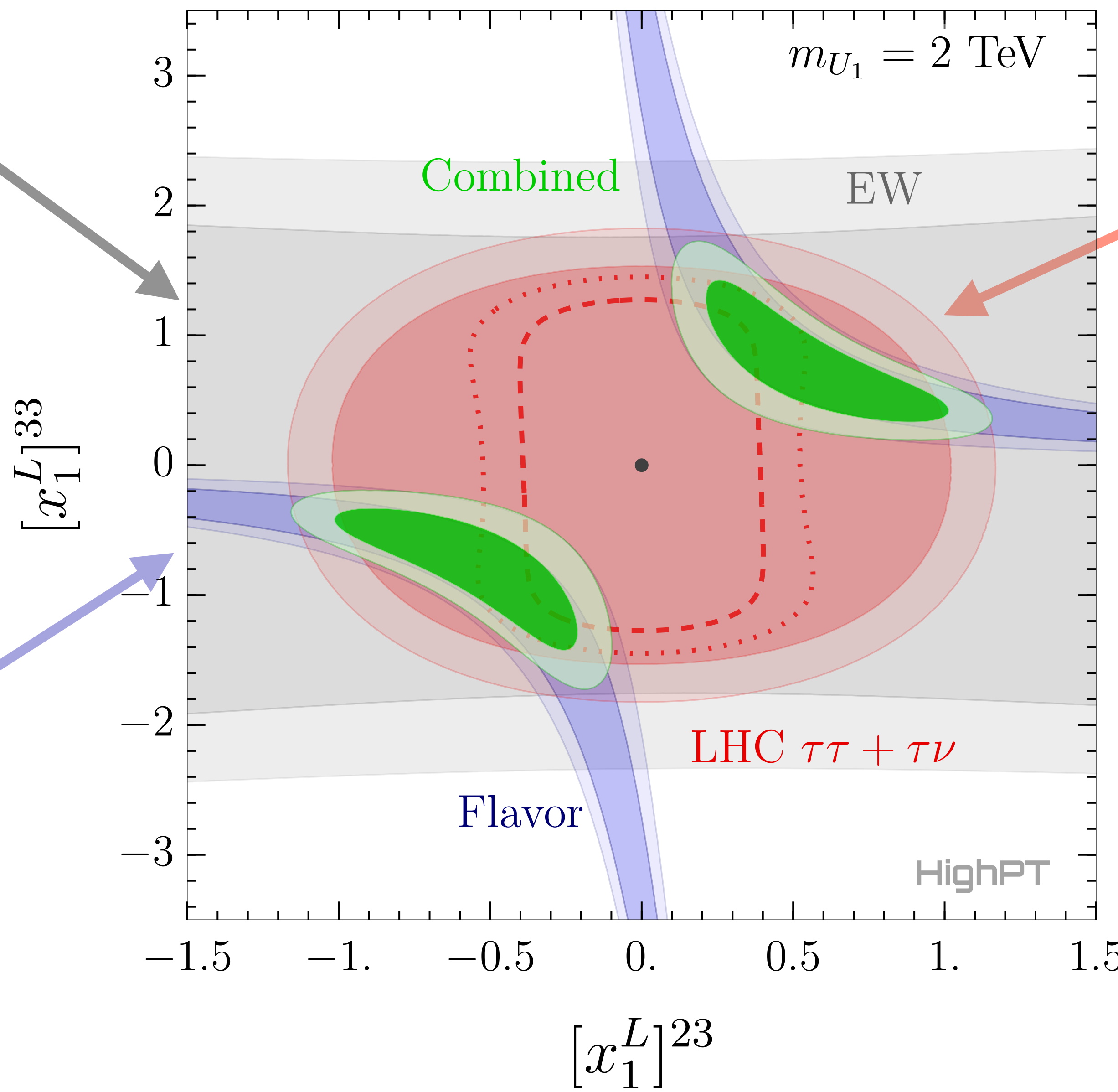
[L. Allwicher, D. Faroughy, F. Jaffredo, **OS**, F. Wilsch. '22]

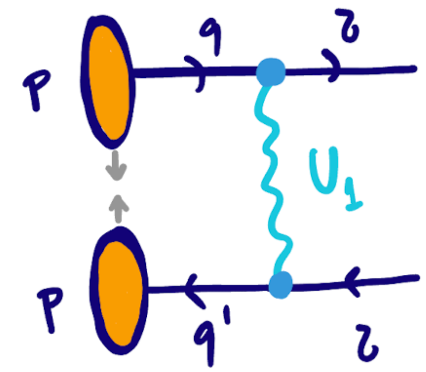
$$\mathcal{L}_{U_1} \supset [x_1^L]_{i\alpha}\, U_1^\mu\, \bar{q}_i \gamma_\mu l_\alpha + \text{h.c.}$$



[Feruglio et al. '16]







First considered by [Eboli, '88]

cf. also [Faroughy et al. '15]

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

*see back-up for the other models!

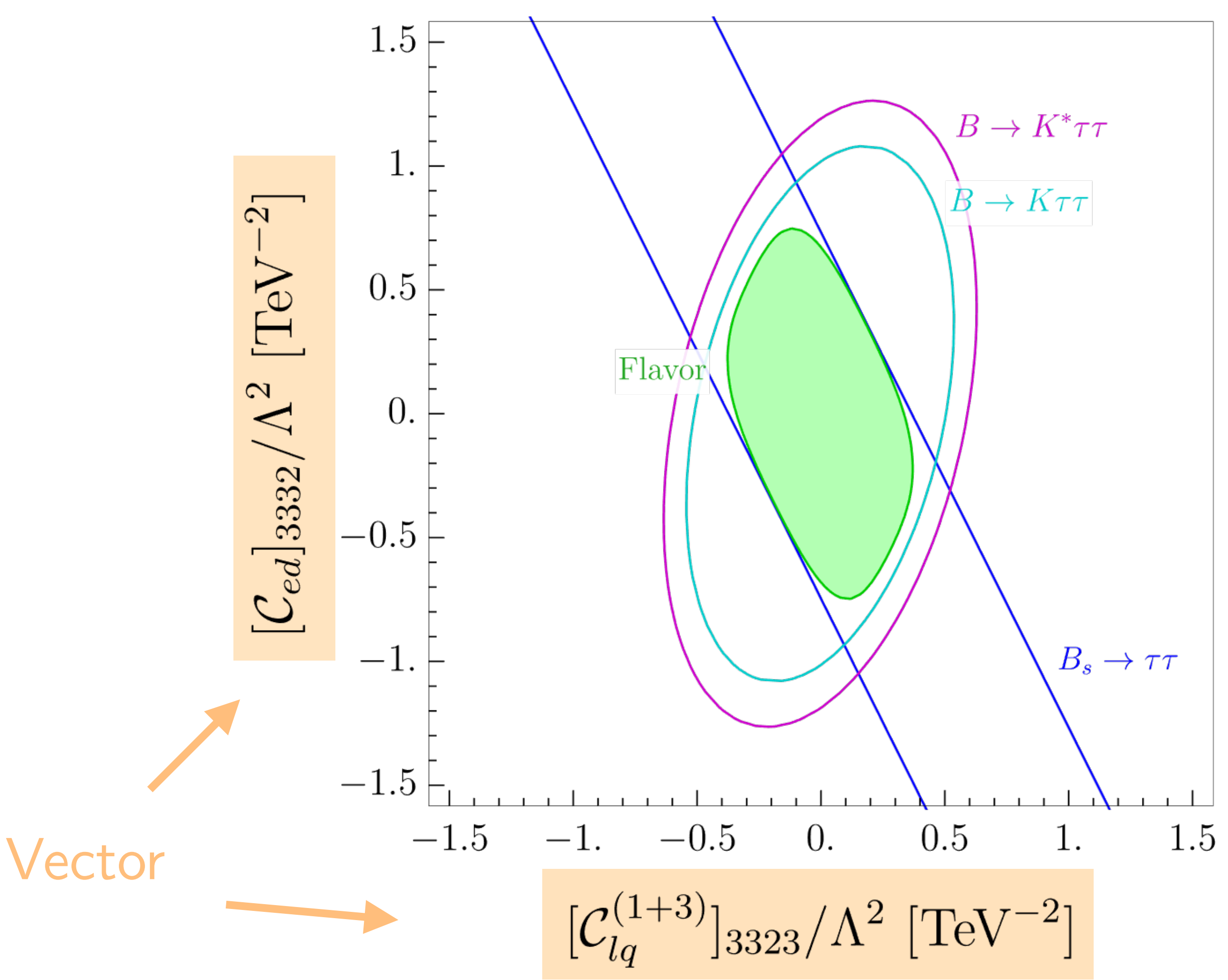
Example ii) $b \to s\tau\tau$

[Allwicher et al., *in preparation*]

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

Upper limits (90%CL.):

$\mathcal{B}(B_s \to \tau\tau) < 6.8 \times 10^{-3}$	[LHCb. '17]		
$\mathcal{B}(B^+ \to K^+\tau\tau) < 2.25 \times 10^{-3}$	[BaBar. '16]	*vs.*	$\mathcal{B}_{\rm SM} \approx 10^{-7}$
$\mathcal{B}(B^0 \to K^{*0}\tau\tau) < 3.1 \times 10^{-3}$	[Belle. '21]		



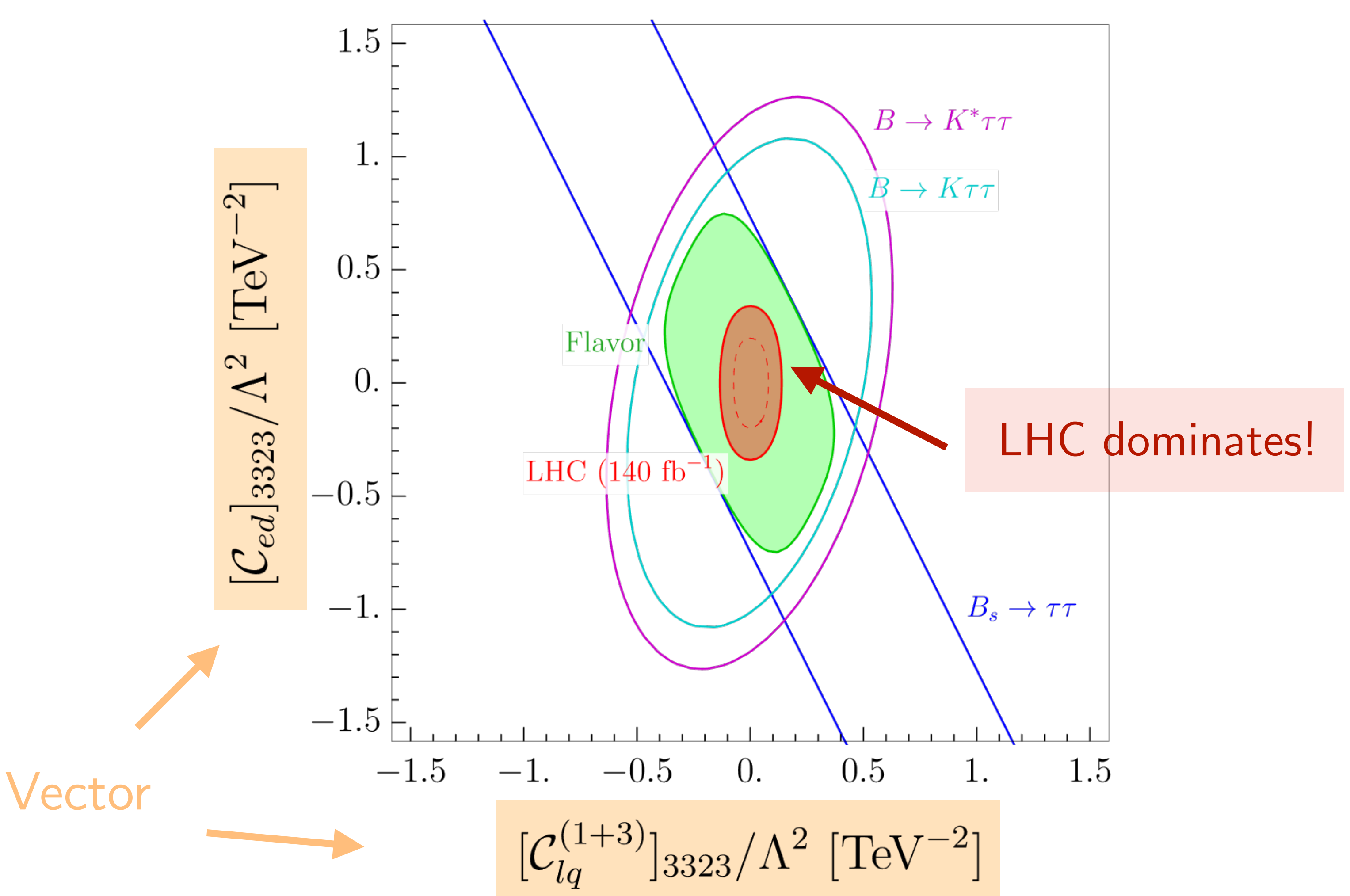
Example ii) $b \to s\tau\tau$

[Allwicher et al., *in preparation*]

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

Upper limits (90%CL.):

$\mathcal{B}(B_s \to \tau\tau) < 6.8 \times 10^{-3}$	[LHCb. '17]		
$\mathcal{B}(B^+ \to K^+\tau\tau) < 2.25 \times 10^{-3}$	[BaBar. '16]	*vs.*	$\mathcal{B}_{\rm SM} \approx 10^{-7}$
$\mathcal{B}(B^0 \to K^{*0}\tau\tau) < 3.1 \times 10^{-3}$	[Belle. '21]		



Example ii) $b \to s\tau\tau$

[Allwicher et al., *in preparation*]

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

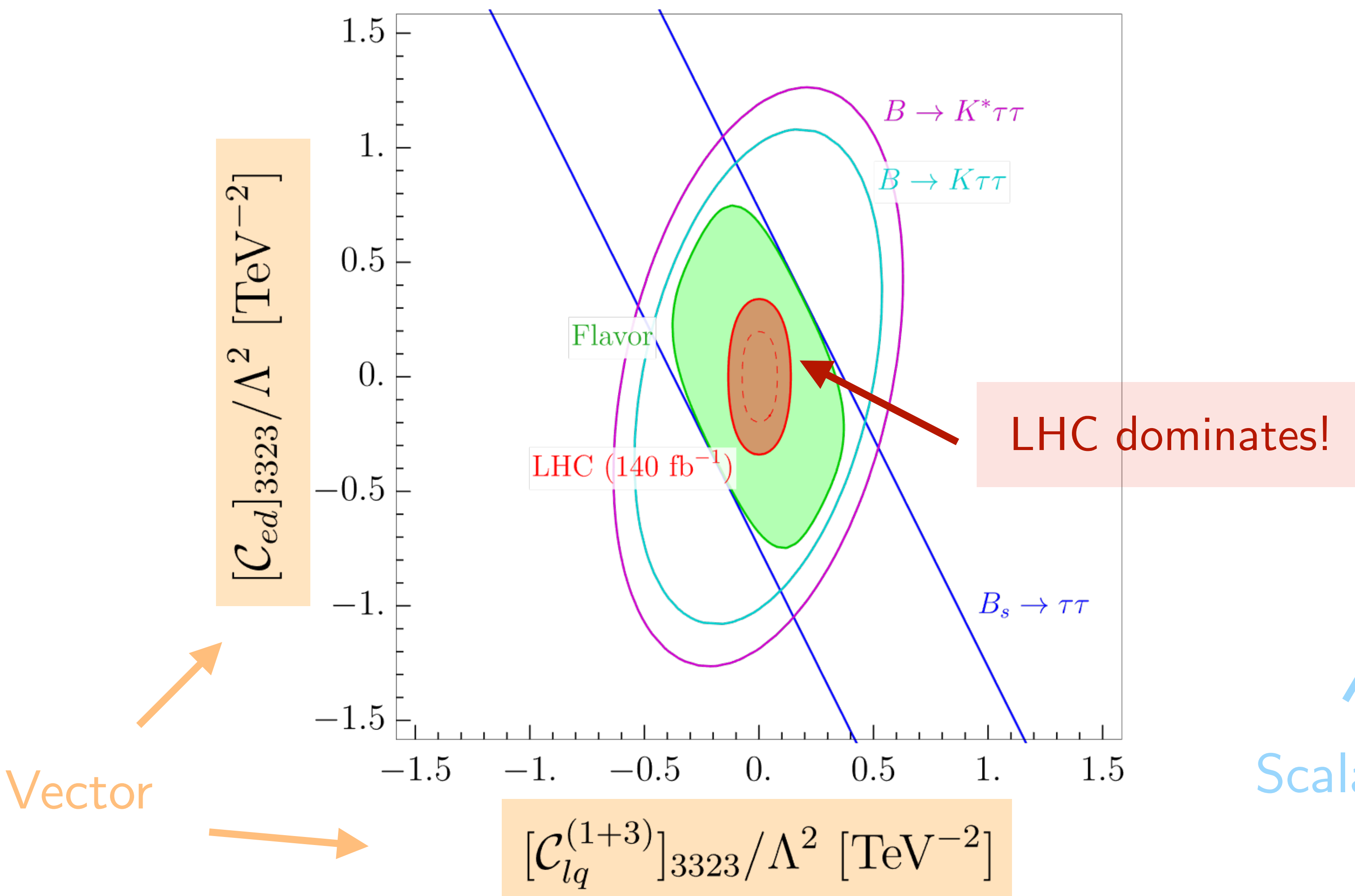
Upper limits (90%CL.):

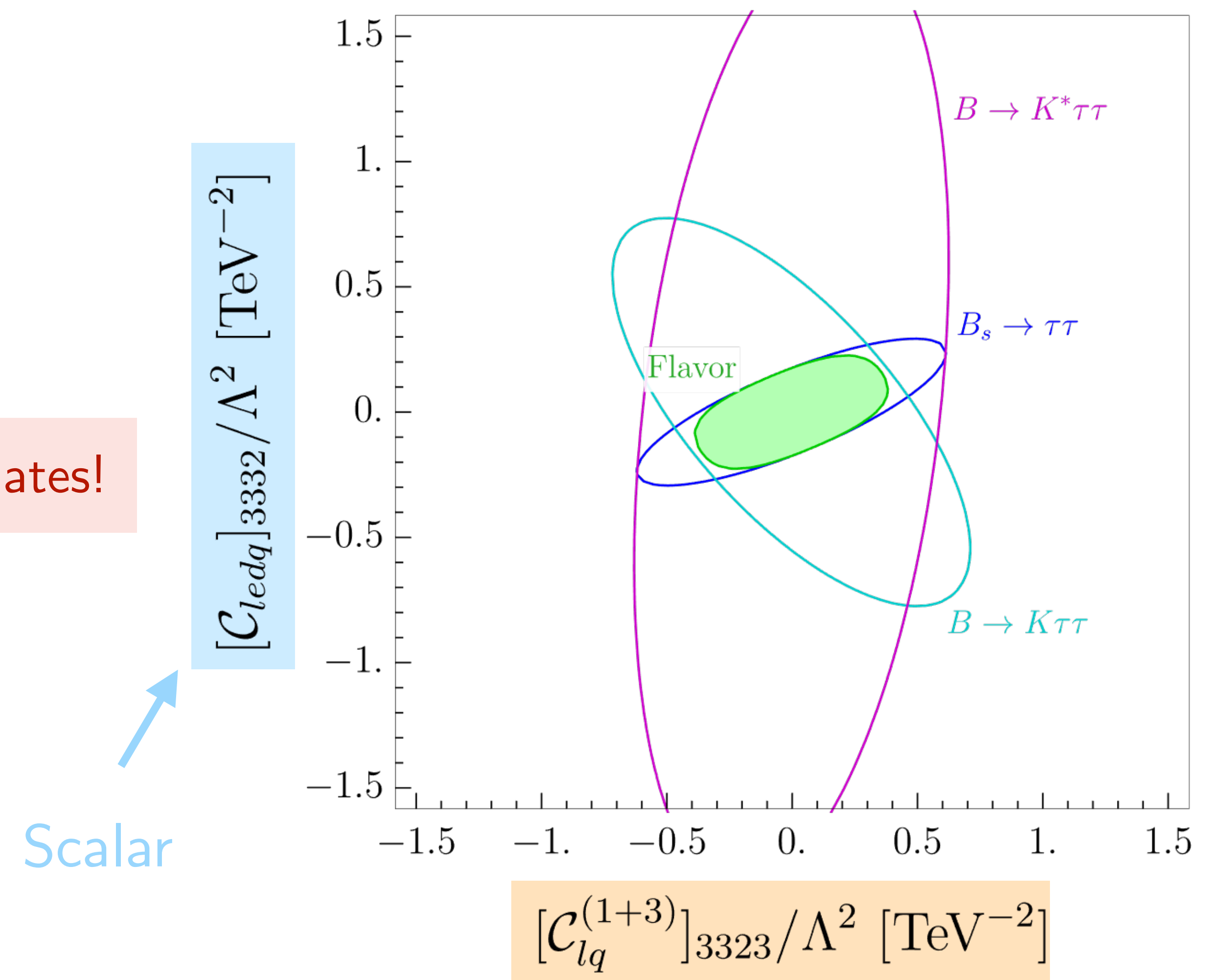
$$\mathcal{B}(B_s \to \tau\tau) < 6.8 \times 10^{-3}$$ [LHCb. '17]

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

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

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





Example ii) $b \to s\tau\tau$

[Allwicher et al., *in preparation*]

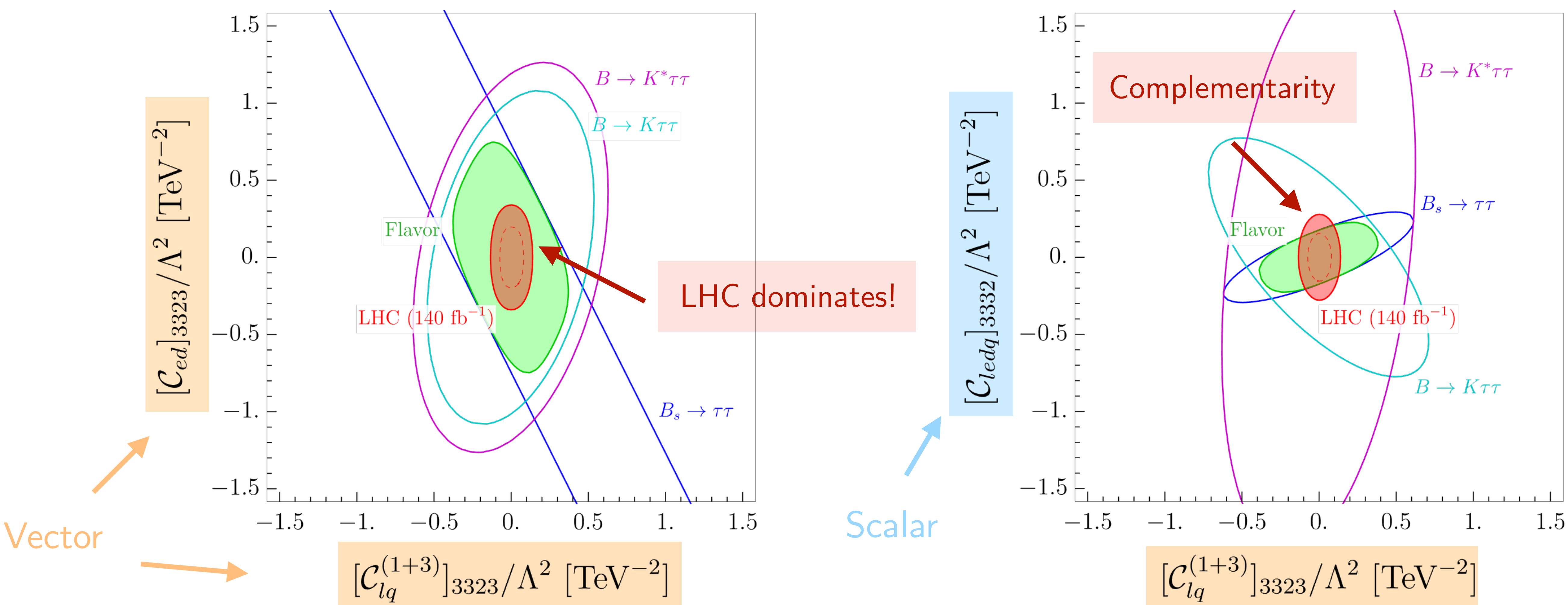
- Related to $b \to c\tau\bar{\nu}$ for some operators through $SU(2)_L$ **invariance**, $L_i = (\nu_{Li}, \ell_{Li})^T$.
- **Extremely difficult measurement** at low-energies!

Upper limits (90%CL.):

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

$\mathcal{B}(B^+ \to K^+\tau\tau) < 2.25 \times 10^{-3}$ [BaBar. '16] *vs.* $\mathcal{B}_{\rm SM} \approx 10^{-7}$

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



Example ii) $b \to s\tau\tau$

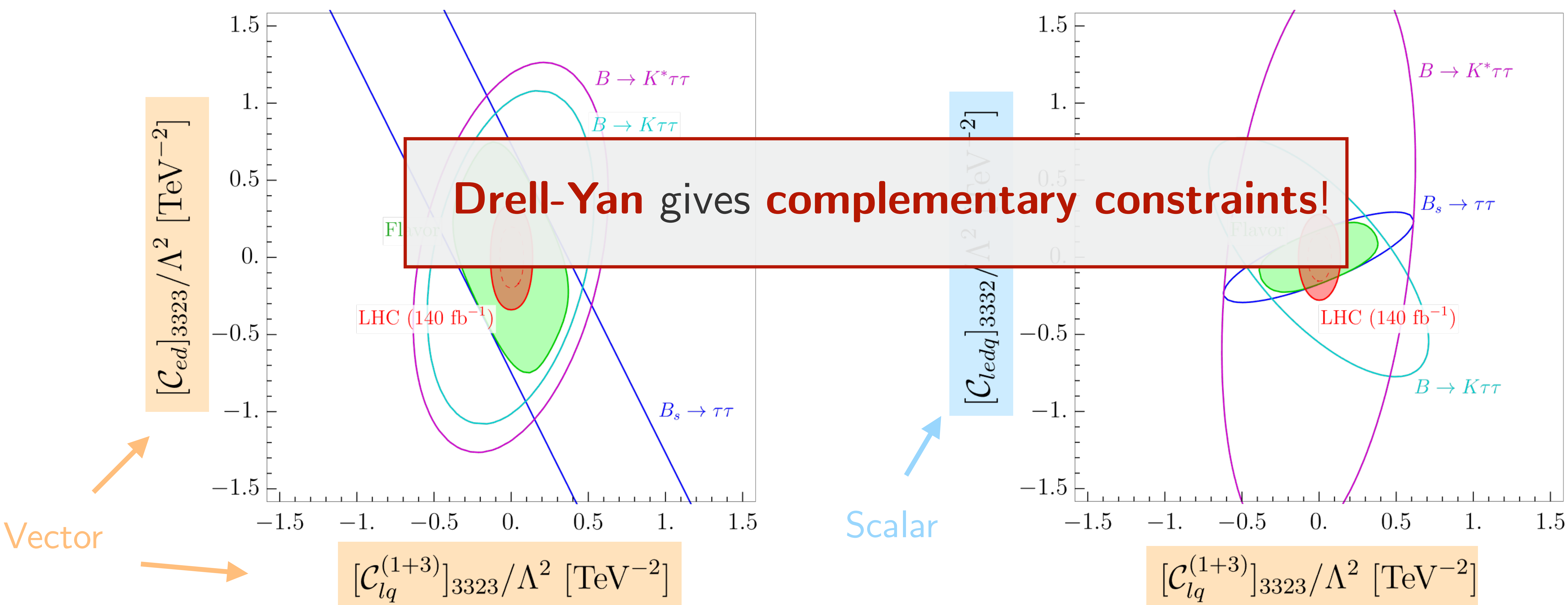
[Allwicher et al., *in preparation*]

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

Upper limits (90%CL.):

$\mathcal{B}(B_s \to \tau\tau) < 6.8 \times 10^{-3}$	[LHCb. '17]
$\mathcal{B}(B^+ \to K^+\tau\tau) < 2.25 \times 10^{-3}$	[BaBar. '16]
$\mathcal{B}(B^0 \to K^{*0}\tau\tau) < 3.1 \times 10^{-3}$	[Belle. '21]

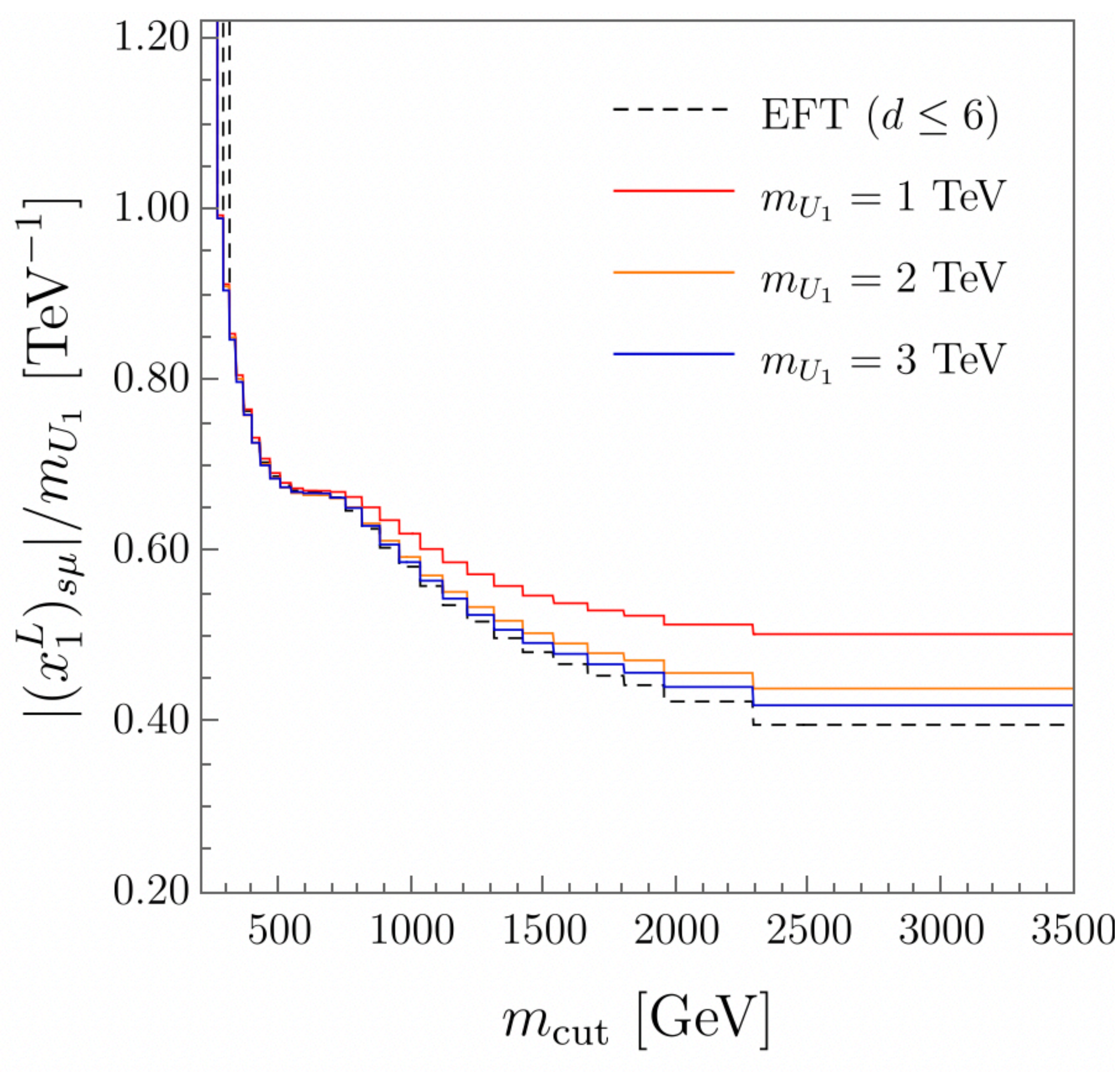
vs. $\mathcal{B}_{\rm SM} \approx 10^{-7}$

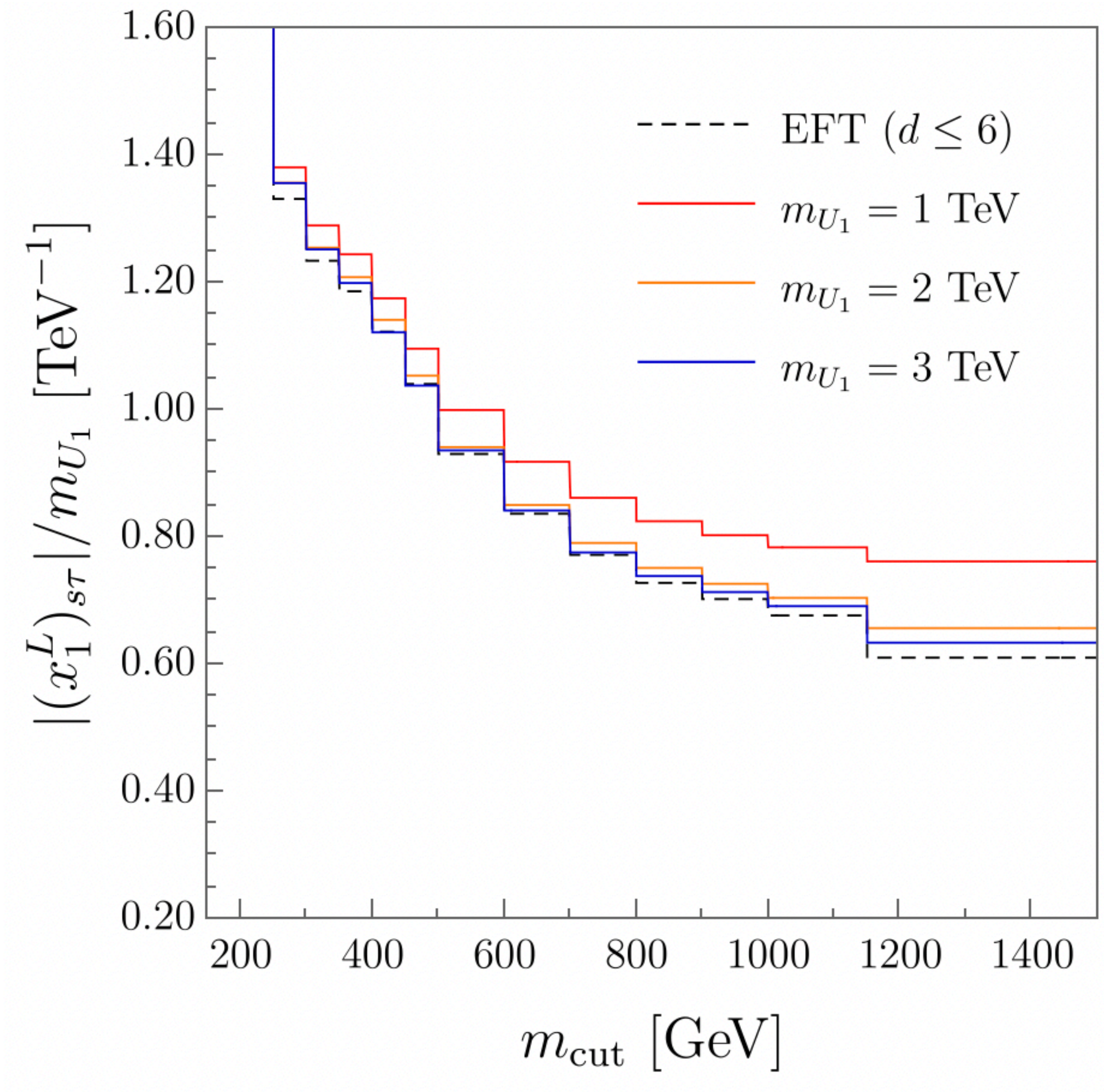


EFT vs. concrete models

[Allwicher et al., *in preparation*]

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





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

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

Low vs high-energy searches

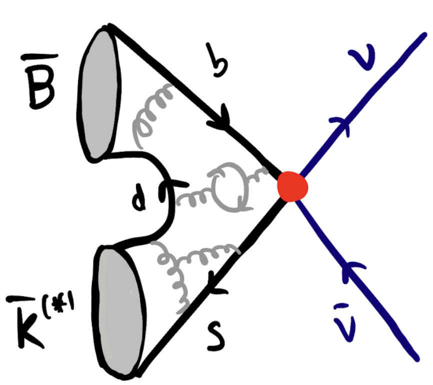
Examples:

- $b \to c\tau\bar{\nu}$ and $b \to s\tau\tau$
- $b \to s\nu\bar{\nu}$ (indirectly)

Example iii) $b \to s\nu\bar{\nu}$ (indirectly...)

- $B \to K^{(*)}\nu\bar{\nu}$ decays **will be soon measured** by the first time by **Belle-II**.
- They **cannot be directly probed** at the **LHC** (in an efficient way...), but they are constrained indirectly by e.g. $pp \to \ell\ell$ via gauge invariance, $L_i = (\nu_{Li}, \ell_{Li})^T$.
- These decays are **(rather) clean**:
  - No contributions from *infamous $c\bar{c}$ loops*. [Buchala et al. '93, '99], [Misiak et al. '99], [Brod et al. '10]
  - *Short-distance* contributions are known to *good precision*.
- Two **main sources** of **theoretical uncertainty**:

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:

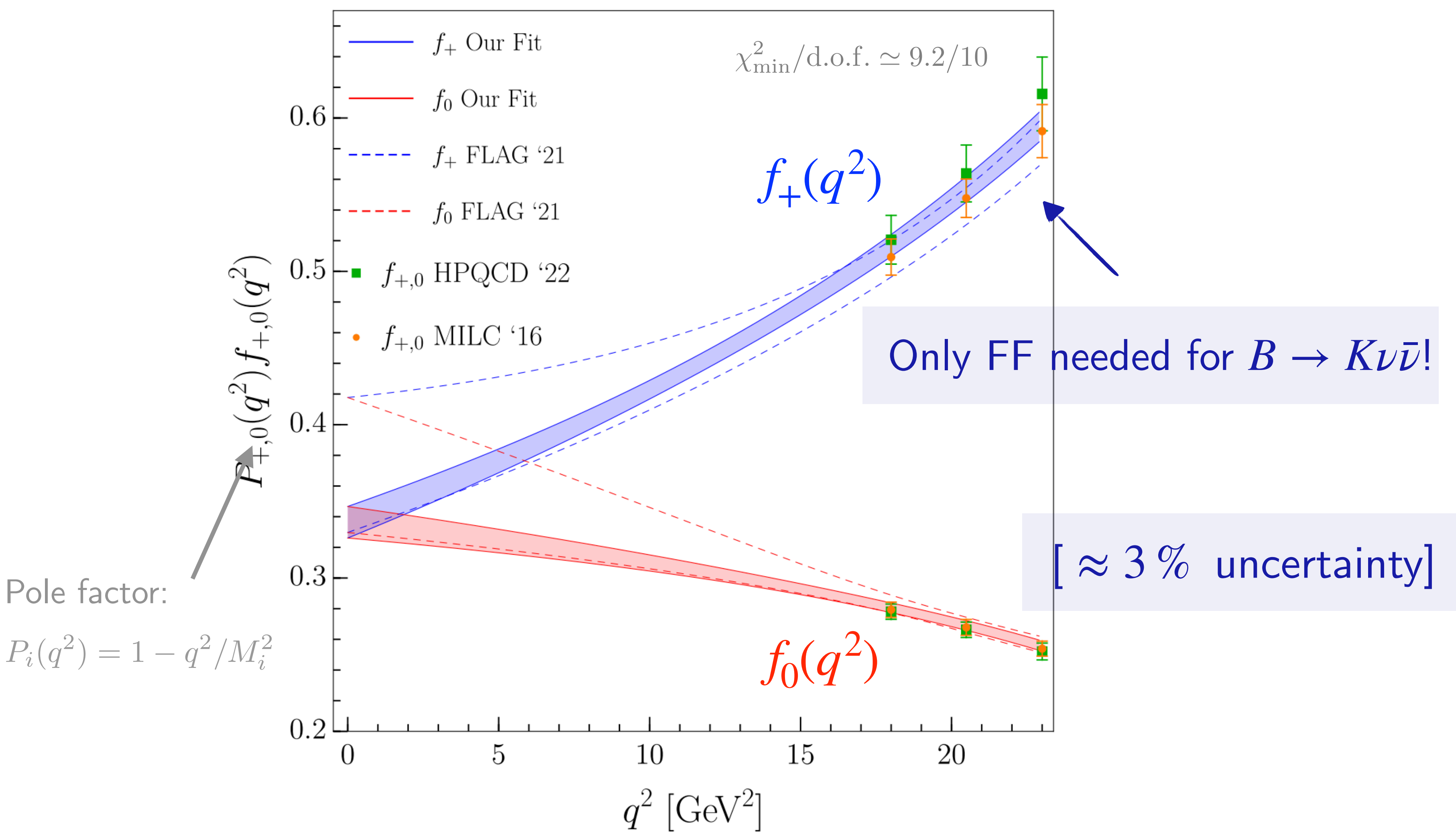
$$|V_{tb}V_{ts}^*| = |V_{cb}|(1+\mathcal{O}(\lambda^2))$$

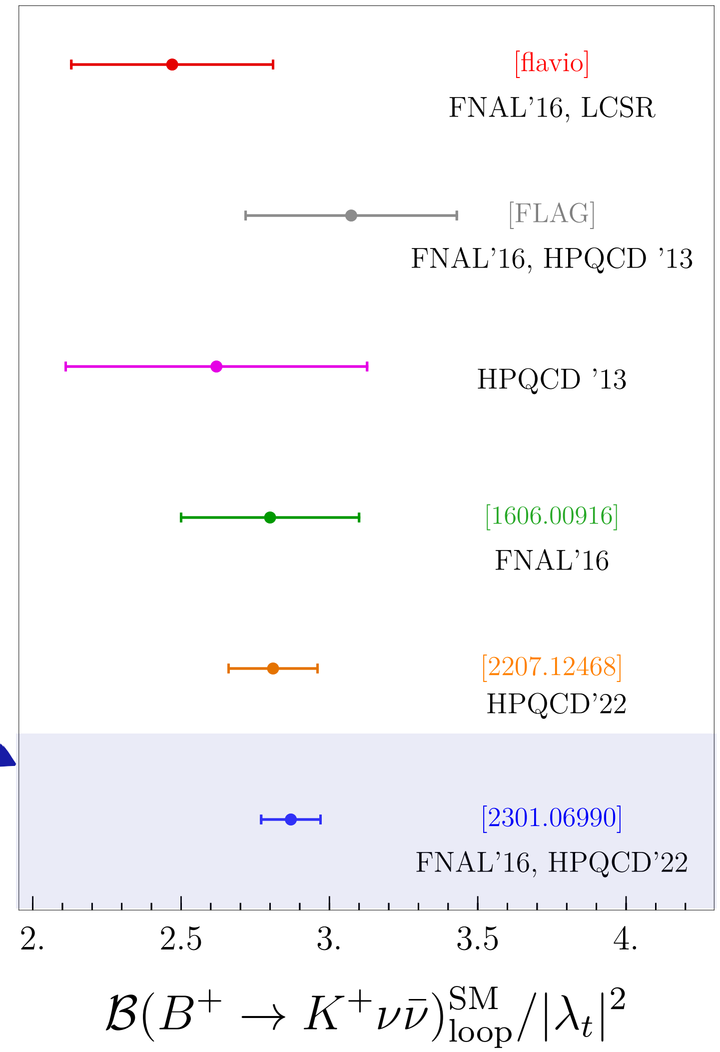
Which value to take (incl. vs. excl.)?

[Intermezzo]: $B \to K^{(*)}$ form-factors

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

- $B \to K$: precise **LQCD** data available at **nonzero recoil** ($q^2 \neq q^2_{max}$):





- $B \to K^*$: more challenging for several reasons...

See talks by Mahmoudi and Reboud

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

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

[$\approx 15\,\%$ uncertainty; *accurate?*]

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

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

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

- We propose to measure: [Becirevic, Piazza, **OS**. 2301.06990]

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

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

NB. w/o ν_R

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

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

e.g, using (old) FLAG average:

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

[Intermezzo]: Which CKM value?

Se talk by K. Vos

- 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.

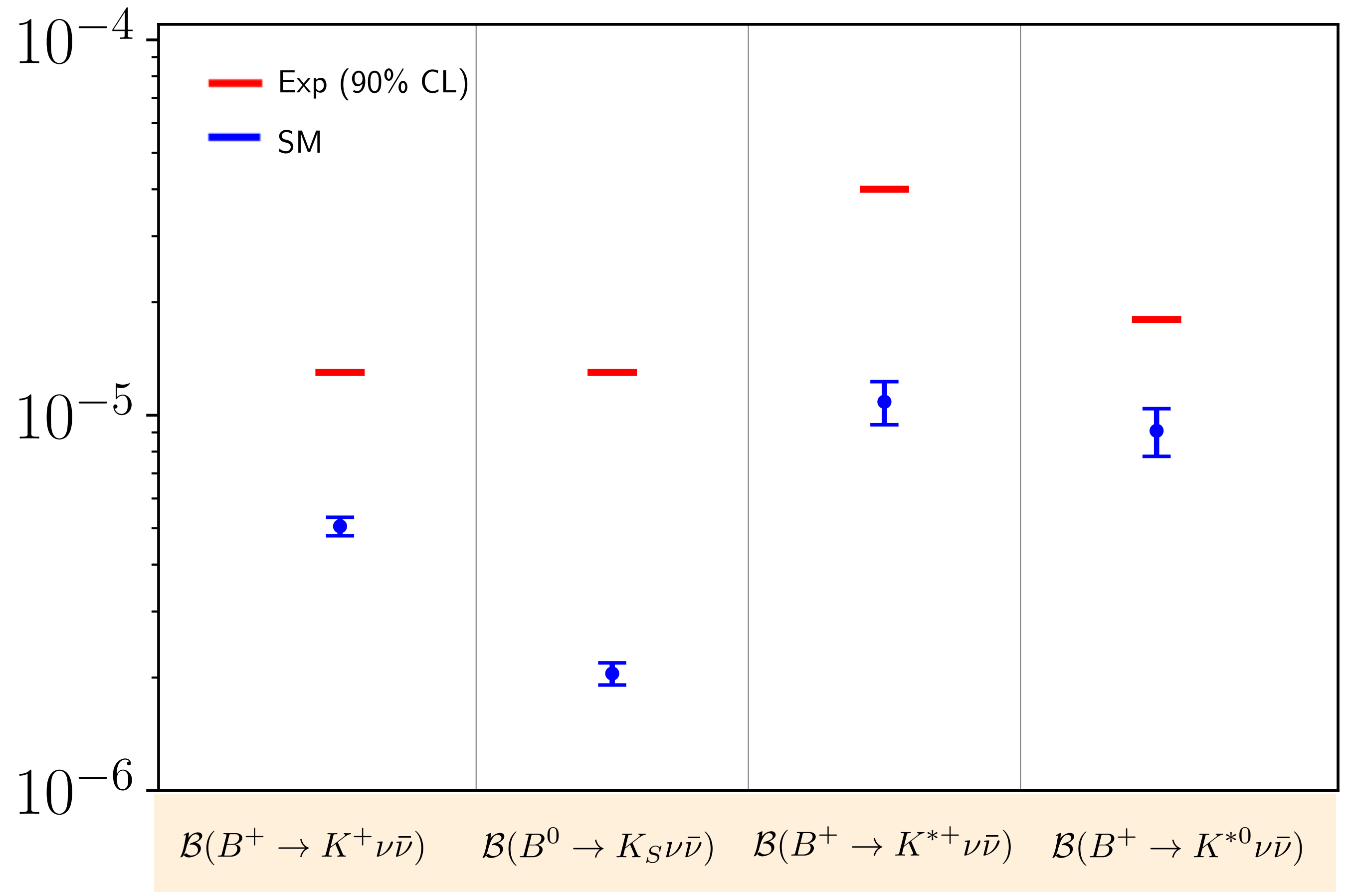
*Using V_{cb} from $B \to D\ell\bar{\nu}$ for illustration

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

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

[Belle 1303.3719, 1702.03224]

[BaBar 1009.1529, 1303.7465]



Take-home:

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

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

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

- Low-energy EFT:

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

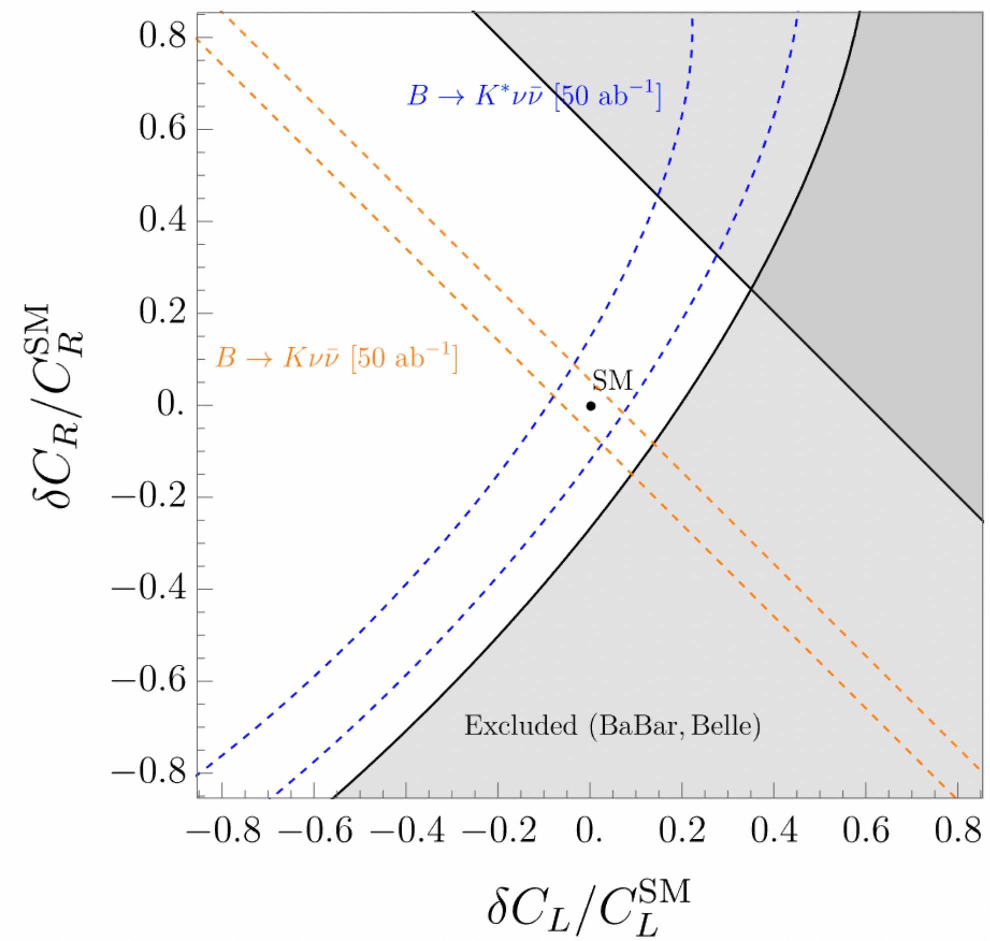
- Complementarity of $B\to K\nu\bar{\nu}$ and $B\to K^*\nu\bar{\nu}$:

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

$\eta_K = 0$

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

Example: $\delta C_{L(R)}^{\nu_i\nu_j} = \delta_{ij}\,\delta C_{L(R)}$



NB. $F_L(B\to K^*\nu\bar{\nu}) \leftrightarrow \mathcal{B}(B\to K\nu\bar{\nu}),\ \mathcal{B}(B\to K^*\nu\bar{\nu})$

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

- EFT invariant under $SU(2) \times U(1)_Y$ $[\psi^4]$:

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

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

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

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

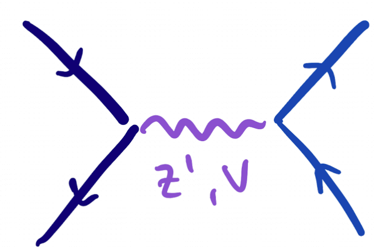
$$[\mathcal{O}_{ld}]_{ijkl} = (\overline{L}_i\gamma^\mu L_j)(\overline{d}_k\gamma_\mu d_l) = (\overline{\ell}_{Li}\gamma^\mu\ell_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl}) + (\overline{\nu}_{Li}\gamma^\mu\nu_{Lj})(\overline{d}_{Rk}\gamma_\mu d_{Rl})$$

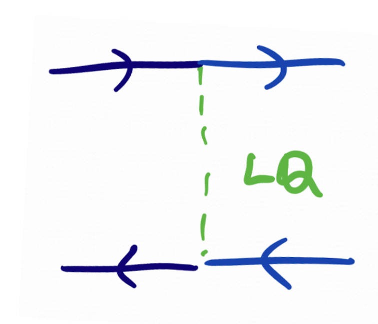
- Correlations for concrete mediators:

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

…

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





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

- EFT invariant under $SU(2) \times U(1)_Y$ $[\psi^4]$:

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

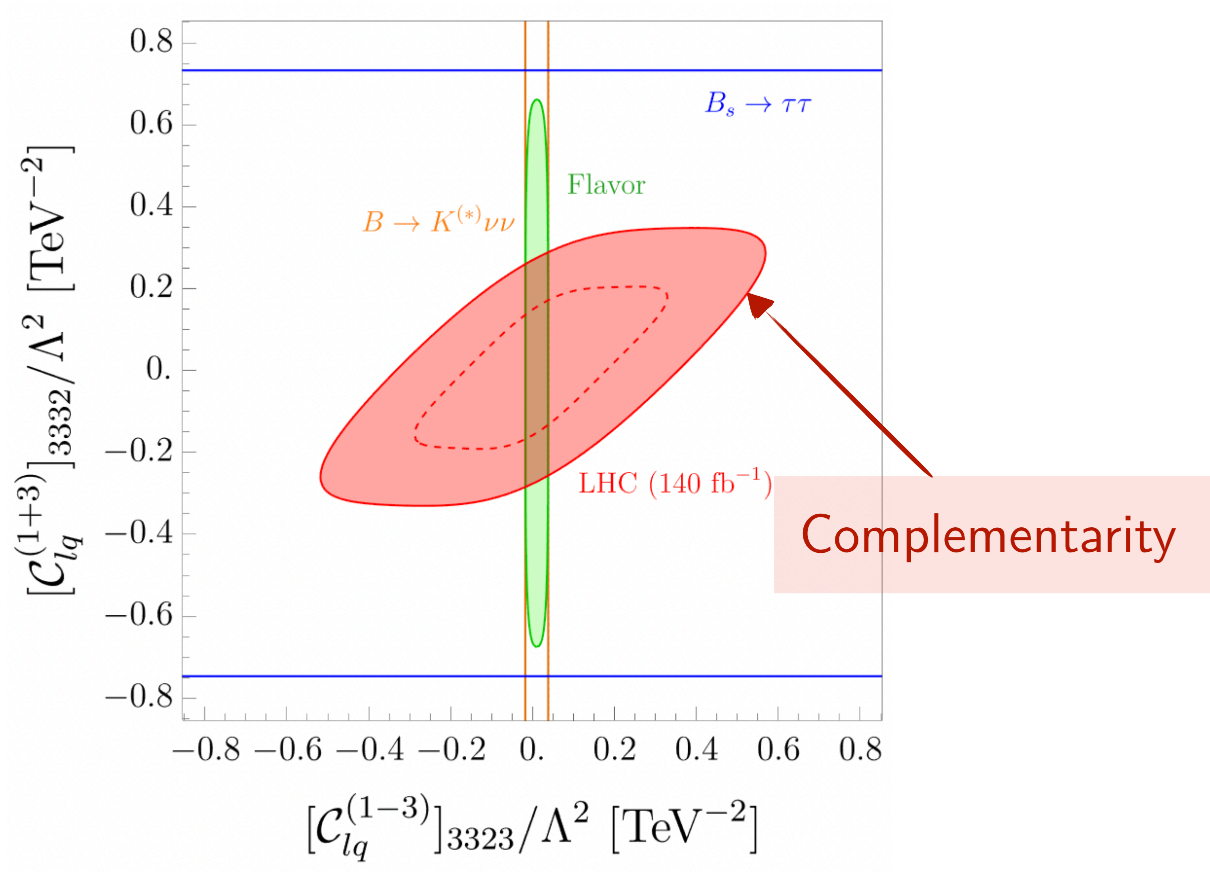
$b \to s\ell\ell$ | $b \to s\nu\bar{\nu}$

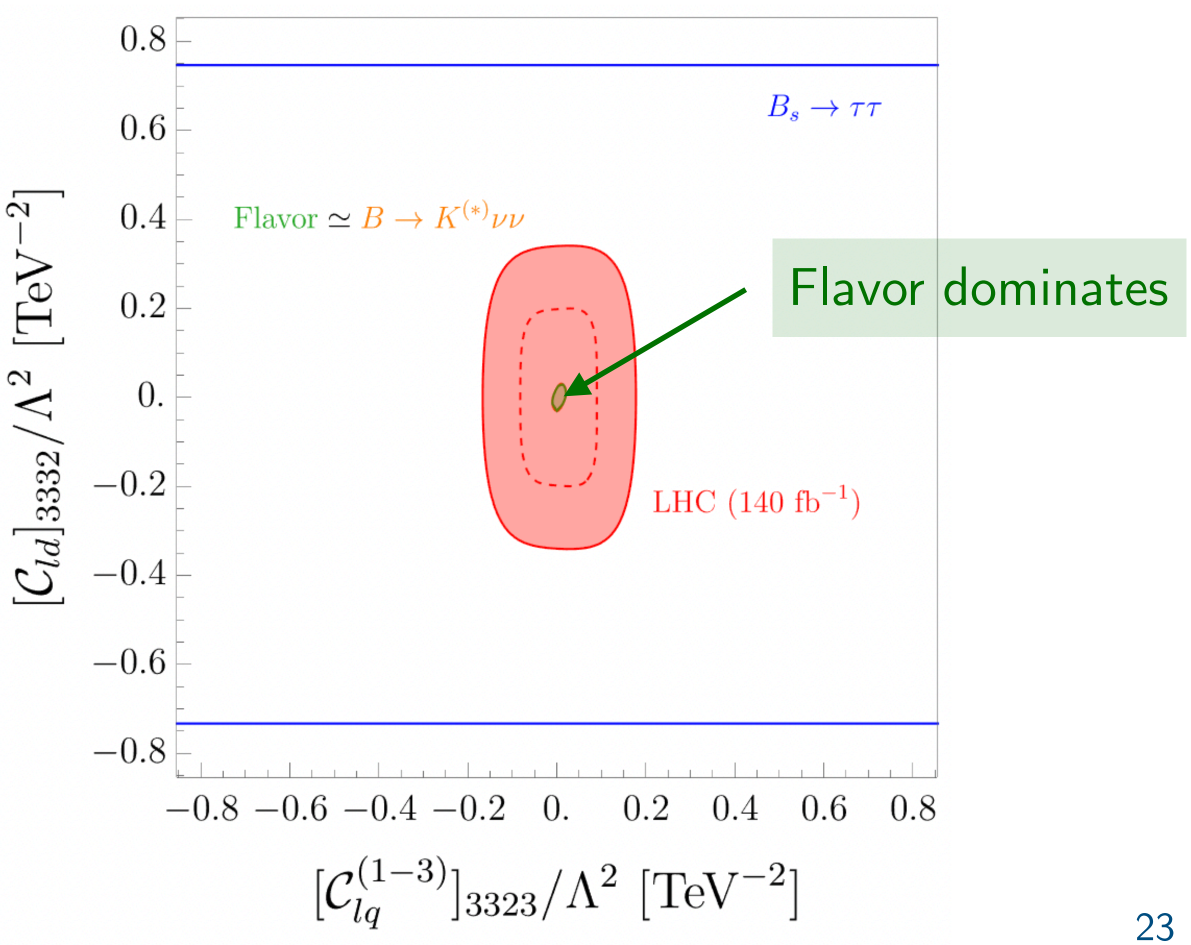
$$[\mathcal{O}_{lq}^{(1)}]_{ijkl} = (\overline{L}_i \gamma^\mu L_j)(\overline{Q}_k \gamma_\mu Q_l) = (\overline{\ell}_{Li} \gamma^\mu \ell_{Lj})(\overline{d}_{Lk} \gamma_\mu d_{Ll}) + (\overline{\nu}_{Li} \gamma^\mu \nu_{Lj})(\overline{d}_{Lk} \gamma_\mu d_{Ll}) + \ldots$$

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

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

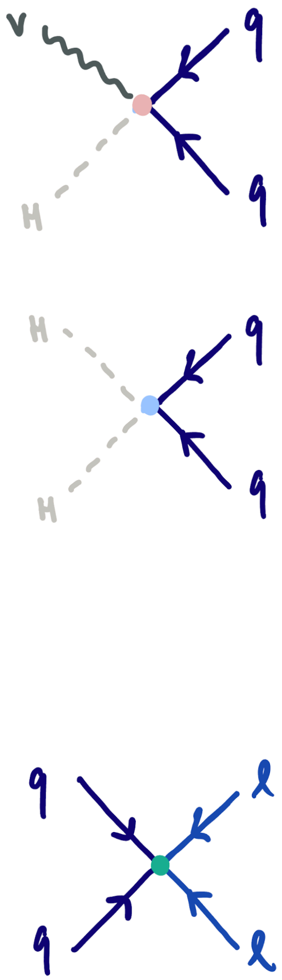
- Unique access to operators with τ_L:

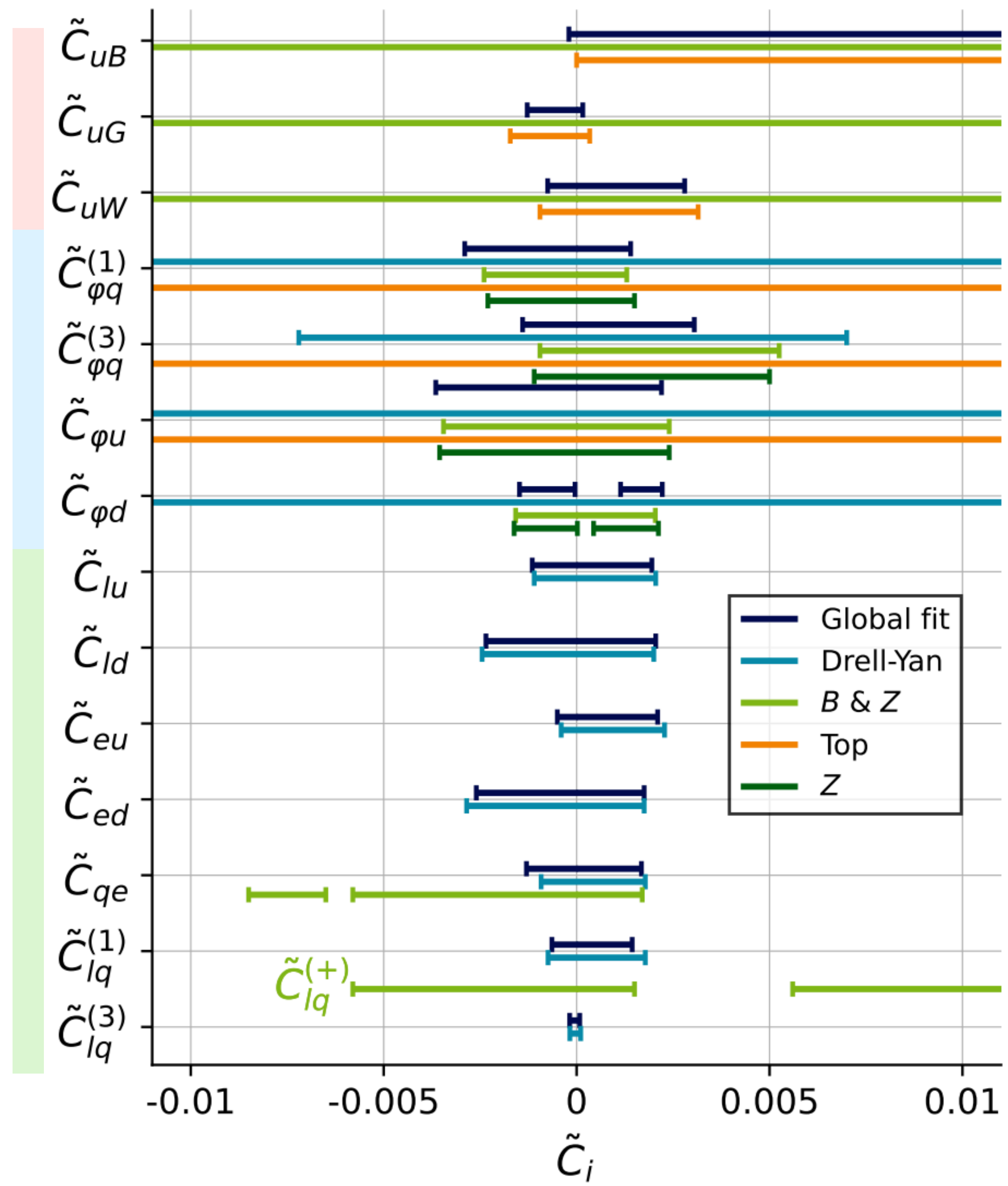




Beyond semileptonic operators

- First steps towards **(flavorful) SMEFT analyses — within MFV**:





[Grunwald. 2304.12837]

NB. In agreement with our Drell-Yan reinterpretations

Synergy between **electroweak**, **flavor** and **LHC** observables

See also [Greljo et al. '23]

Summary & Outlook

Summary & Outlook

- Semileptonic operators can modify the $pp \to \ell_i \ell_j$ tails currently studied at the LHC.
- These high-p_T observables can be more constraining than their low-energy counterparts for specific transitions and sets of operators.
- Complete flavor likelihood for high-p_T Drell-Yan production at LHC has been derived, for the first time, and implemented in the Mathematica package `HighPT`:

http://highpt.github.io/

- Several improvements are planned:
  - Implementation of more LHC searches and observables (e.g., A_{fb});
  - Inclusion of NLO corrections and PDF uncertainties in the signal simulation.
- Combining low- and high-energy observables is fundamental: *work in progress* to derive the complete SMEFT likelihood!

Thank you!

Back-up

Partonic cross-section

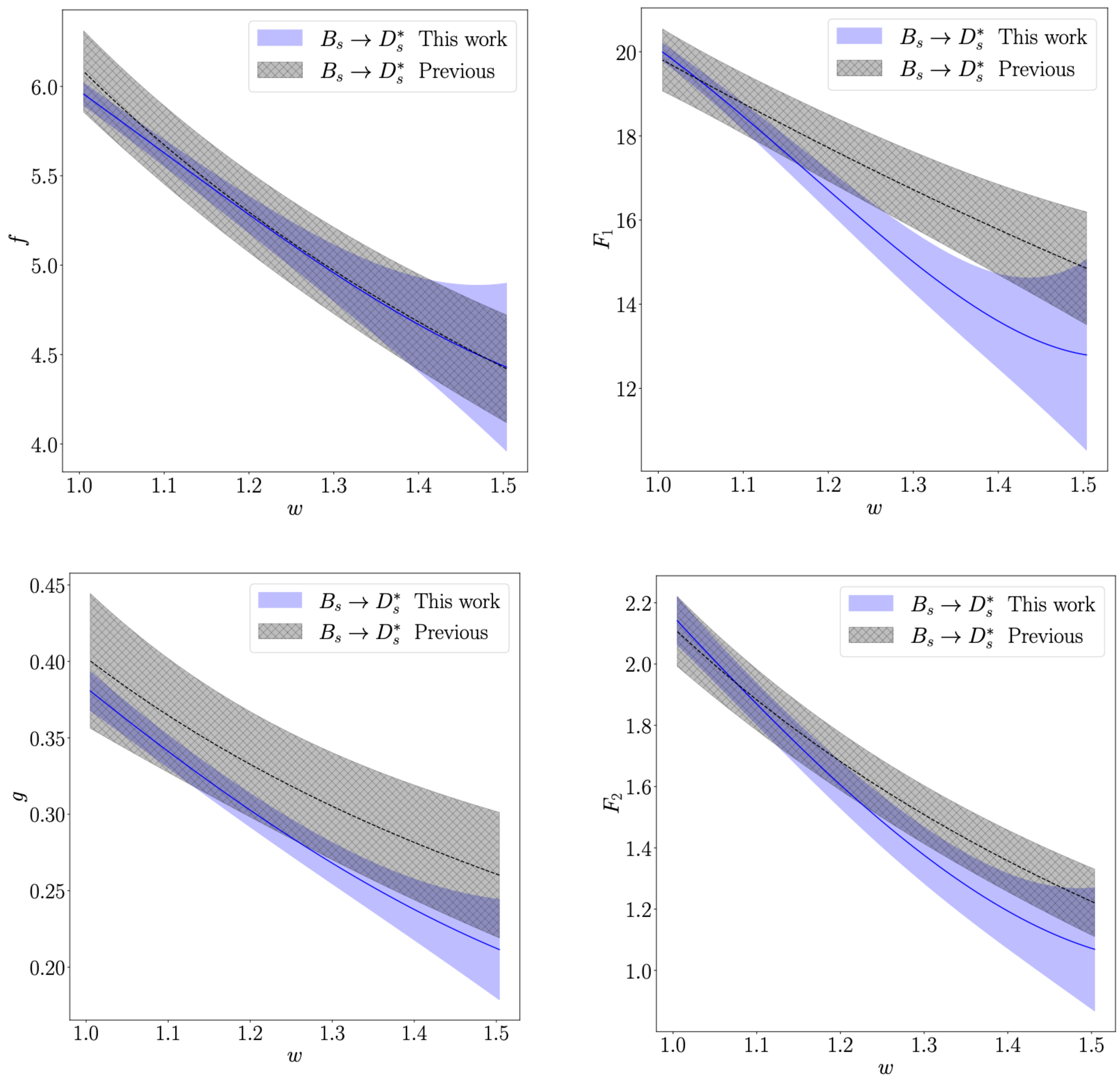
[L. Allwicher, D. Faroughy, F. Jaffredo, **OS**, Wilsch. '22]

$$\hat{\sigma}(\bar{q}_i q'_j \to \bar{\ell}_\alpha \ell'_\beta;\, \hat{s}) = \frac{1}{16\pi}\frac{1}{\hat{s}^2}\int_{\hat{t}_-}^{\hat{t}_+} \mathrm{d}\hat{t}\, \overline{\left|[\mathcal{A}]_{\alpha\beta ij}\right|^2}$$
$$= \frac{1}{48\pi v^4}\int_{\hat{t}_-}^{\hat{t}_+} \mathrm{d}\hat{t} \sum_{X,Y}\sum_{I,J} M_{IJ}^{XY}\big(\hat{s},\hat{t}\big)\left[\mathcal{F}_I^{XY}\big(\hat{s},\hat{t}\big)\right]_{\alpha\beta ij}\left[\mathcal{F}_J^{XY}\big(\hat{s},\hat{t}\big)\right]^*_{\alpha\beta ij}$$

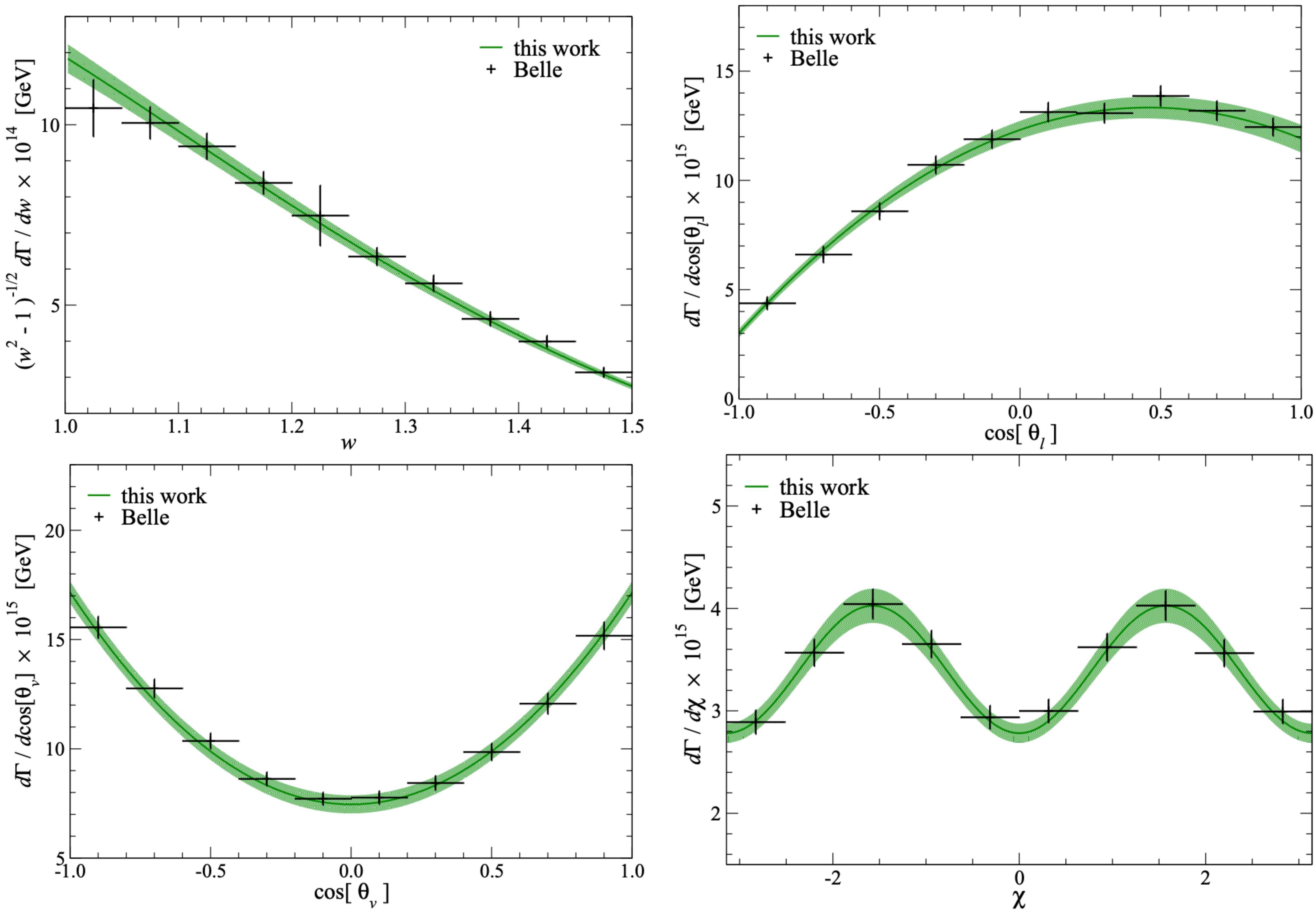
$$\begin{aligned} M_{VV}^{XY}(\omega) &= (1+2\omega)\delta^{XY} + \omega^2\,,\\ M_{SS}^{XY} &= 1/4\,,\\ M_{ST}^{XY}(\omega) &= -(1+2\omega)\delta^{XY}\,,\\ M_{TT}^{XY}(\omega) &= 4(1+2\omega)^2\delta^{XY}\,,\\ M_{DD}^{XY}(\omega) &= -\omega(1+\omega)\,,\end{aligned}$$

with $\omega = \hat{t}/\hat{s} = \frac{1}{2}(\cos\theta^* - 1)$.

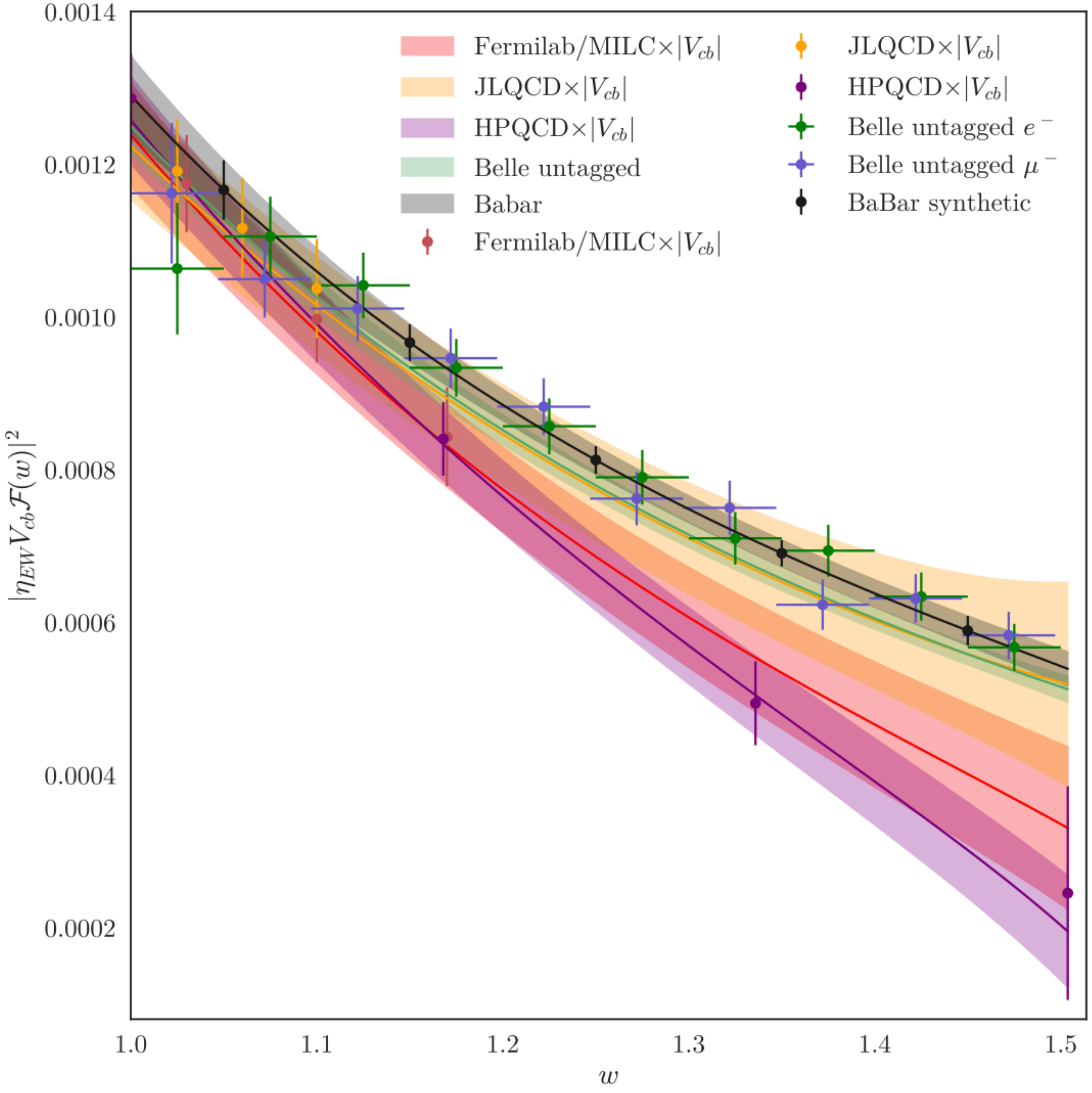
[HPQCD. '2304.03137]



[JLQCD. 2306.05657]

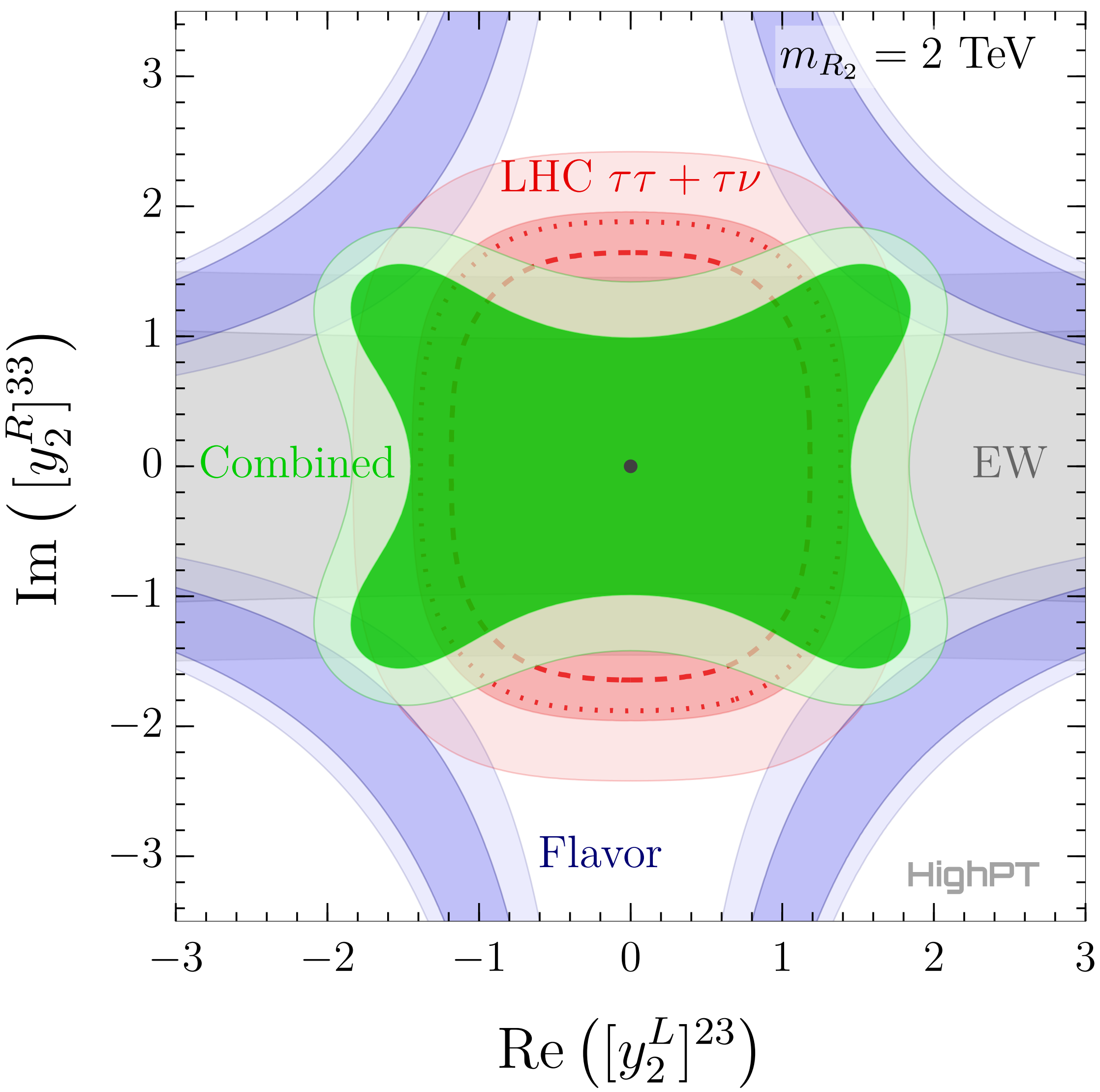


Comparison from A. Lytle talk

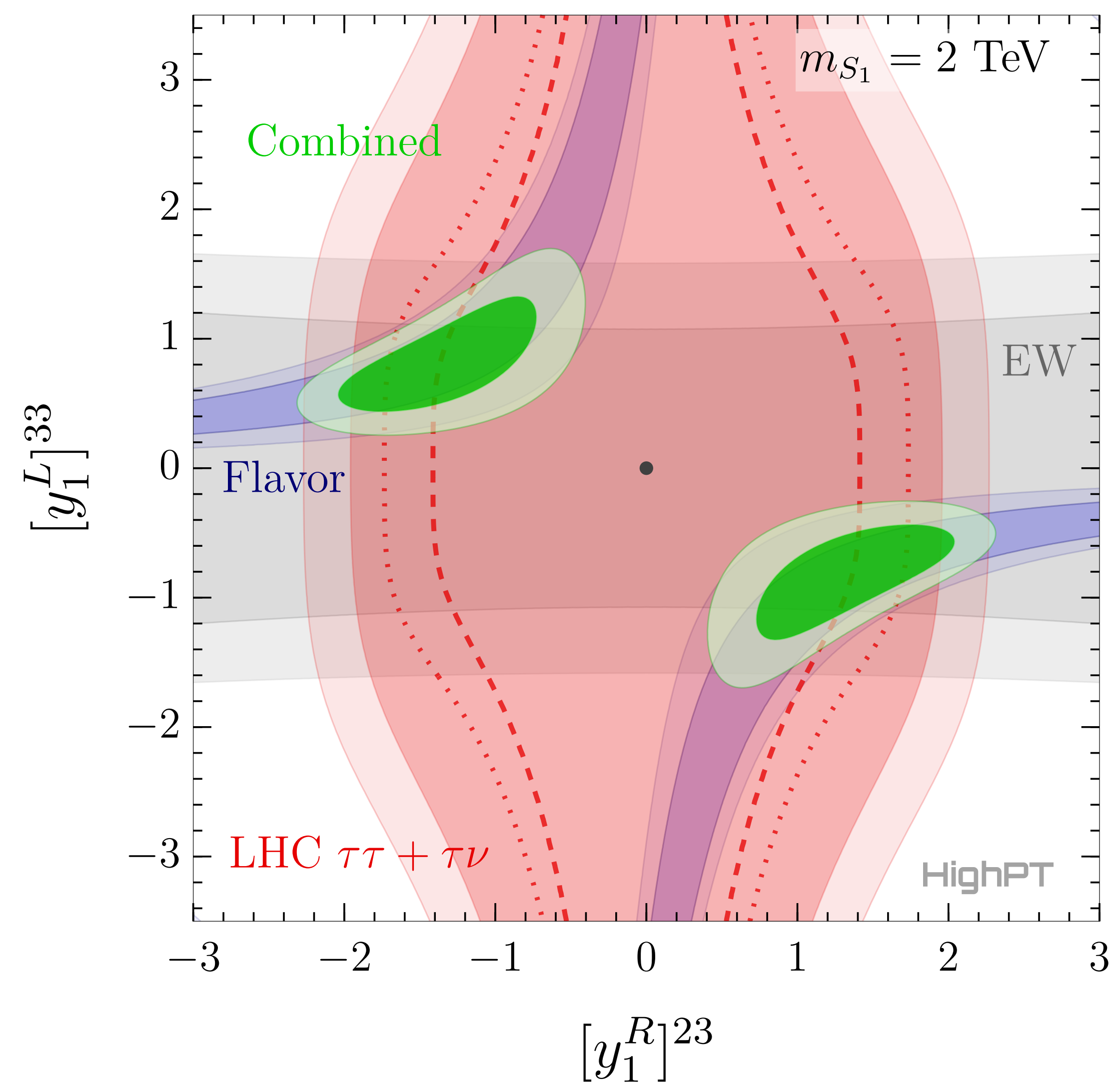


[L. Allwicher, D. Faroughy, F. Jaffredo, **OS**, F. Wilsch. '22]

$R_2 \sim (\mathbf{3}, \mathbf{2}, 7/6)$

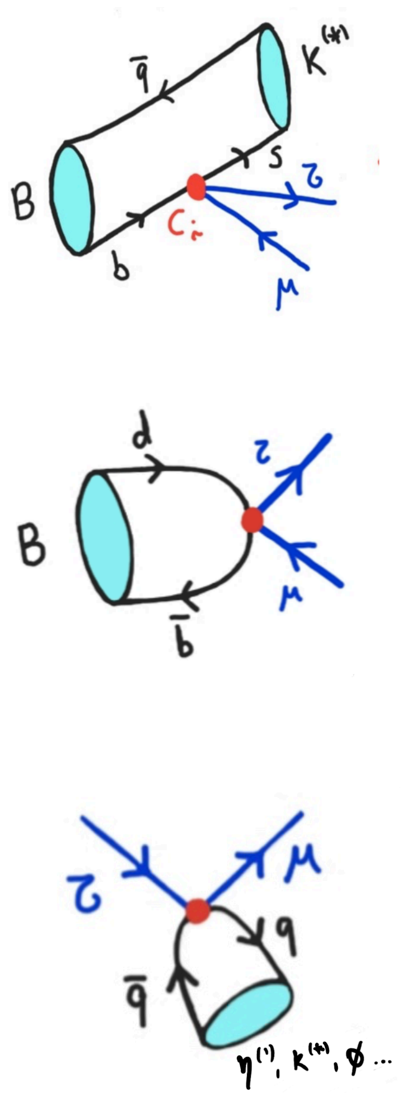


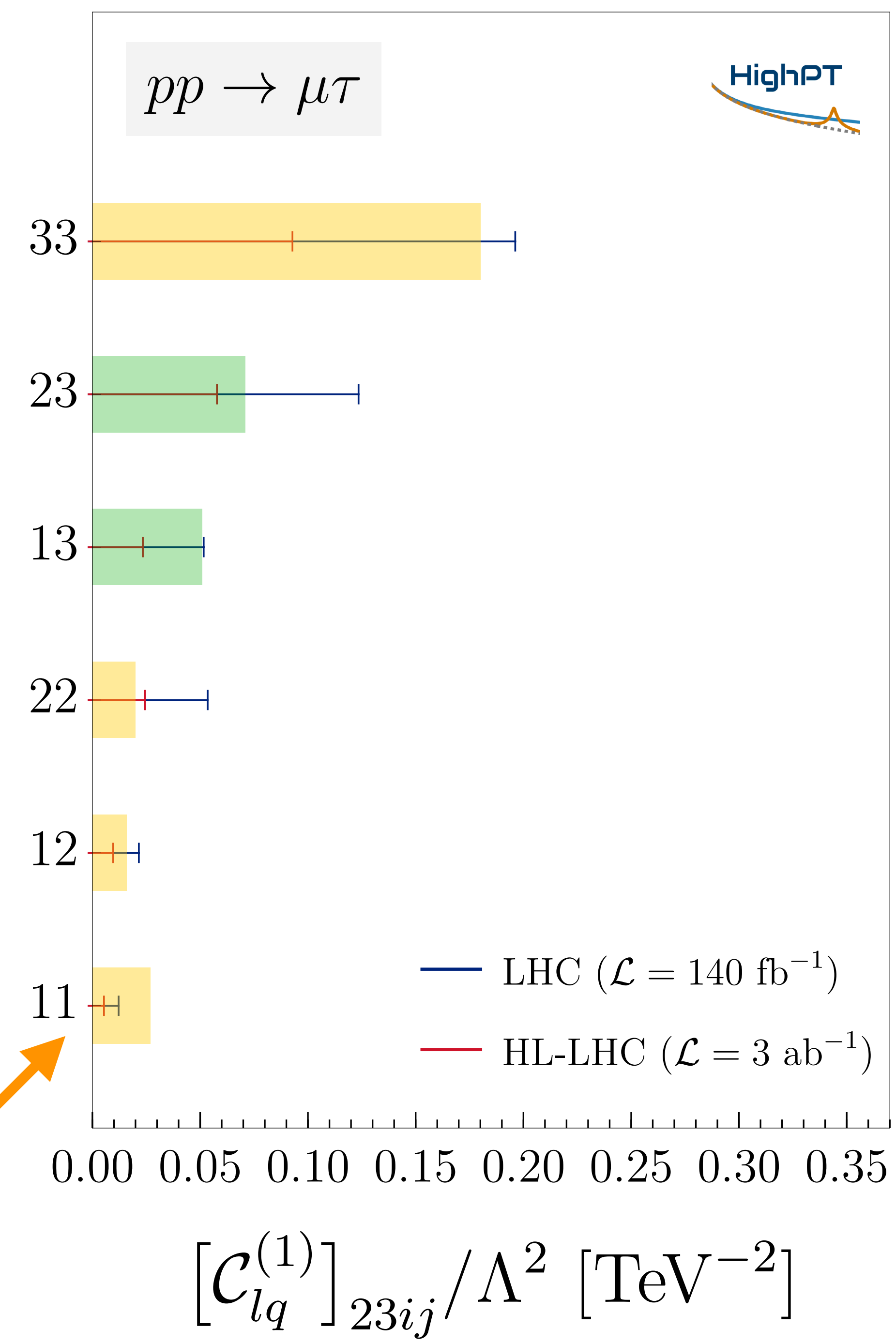
$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$

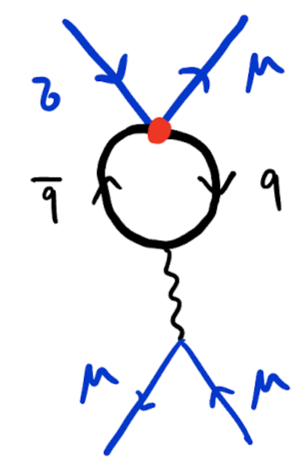


Lepton Flavor Violation (LFV)

For a left-handed operator: $[\mathcal{O}_{lq}^{(1)}]_{klij} = (\bar{l}_k \gamma^\mu l_l)(\bar{q}_i \gamma_\mu q_j)$





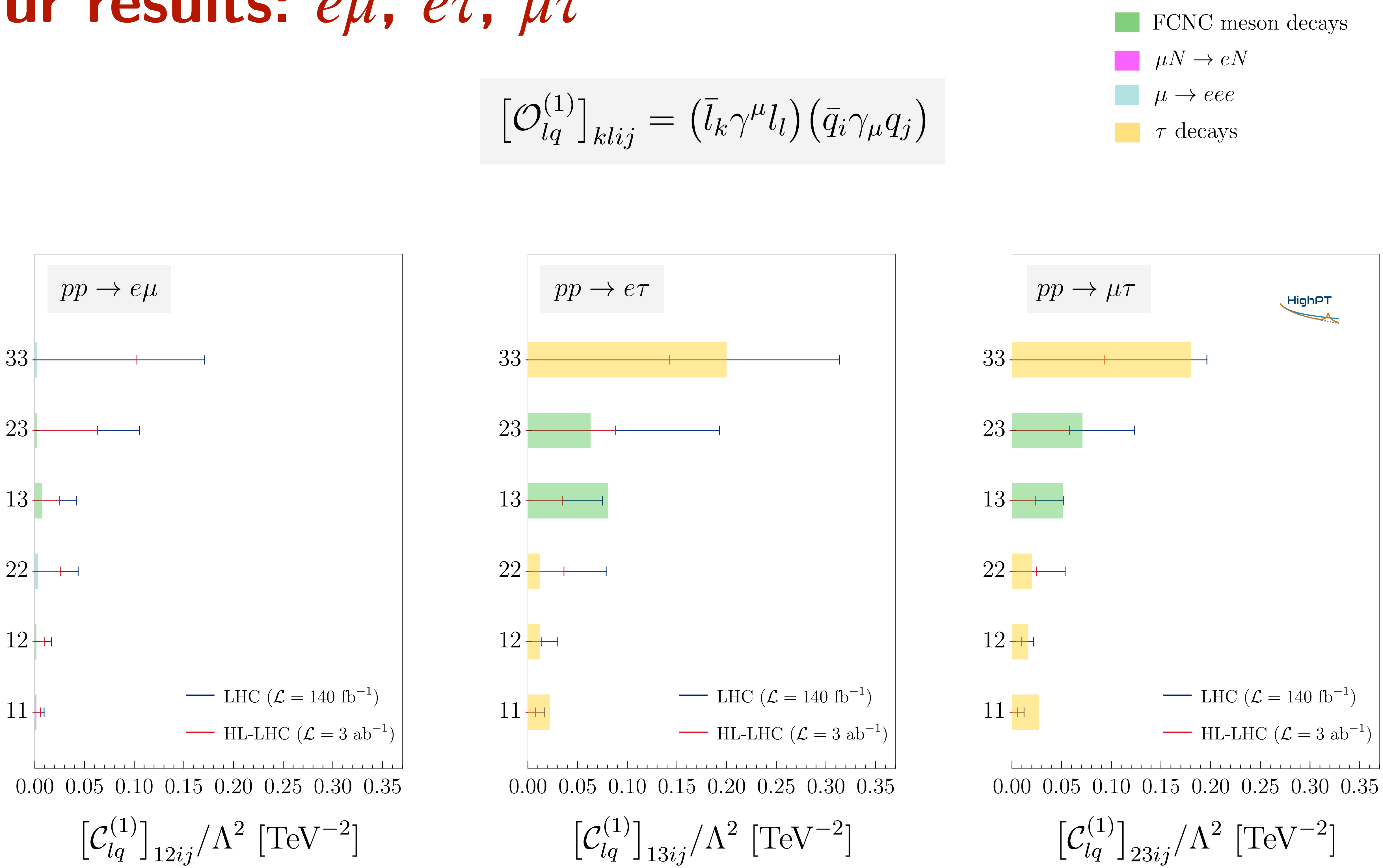


Quark-flavor indices: *i,j*

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

Our results: $e\mu$, $e\tau$, $\mu\tau$

$$\left[\mathcal{O}_{lq}^{(1)}\right]_{klij} = \left(\bar{l}_k \gamma^\mu l_l\right)\left(\bar{q}_i \gamma_\mu q_j\right)$$



From EFTs to physical observables

Problem to solve:

$$\max_{\vec{\mathcal{C}}}\left\{\mathcal{O}(\vec{\mathcal{C}})\,,\quad \text{with}\quad \chi^2_{\rm LHC}(\vec{\mathcal{C}})\leq \chi^2_{\rm min}+\Delta\chi^2\right\}$$

$\mathcal{O}\equiv$ *Branching fraction of a low-energy LFV*

$\vec{\mathcal{C}}\equiv$ *Vector of Wilson coefficients*

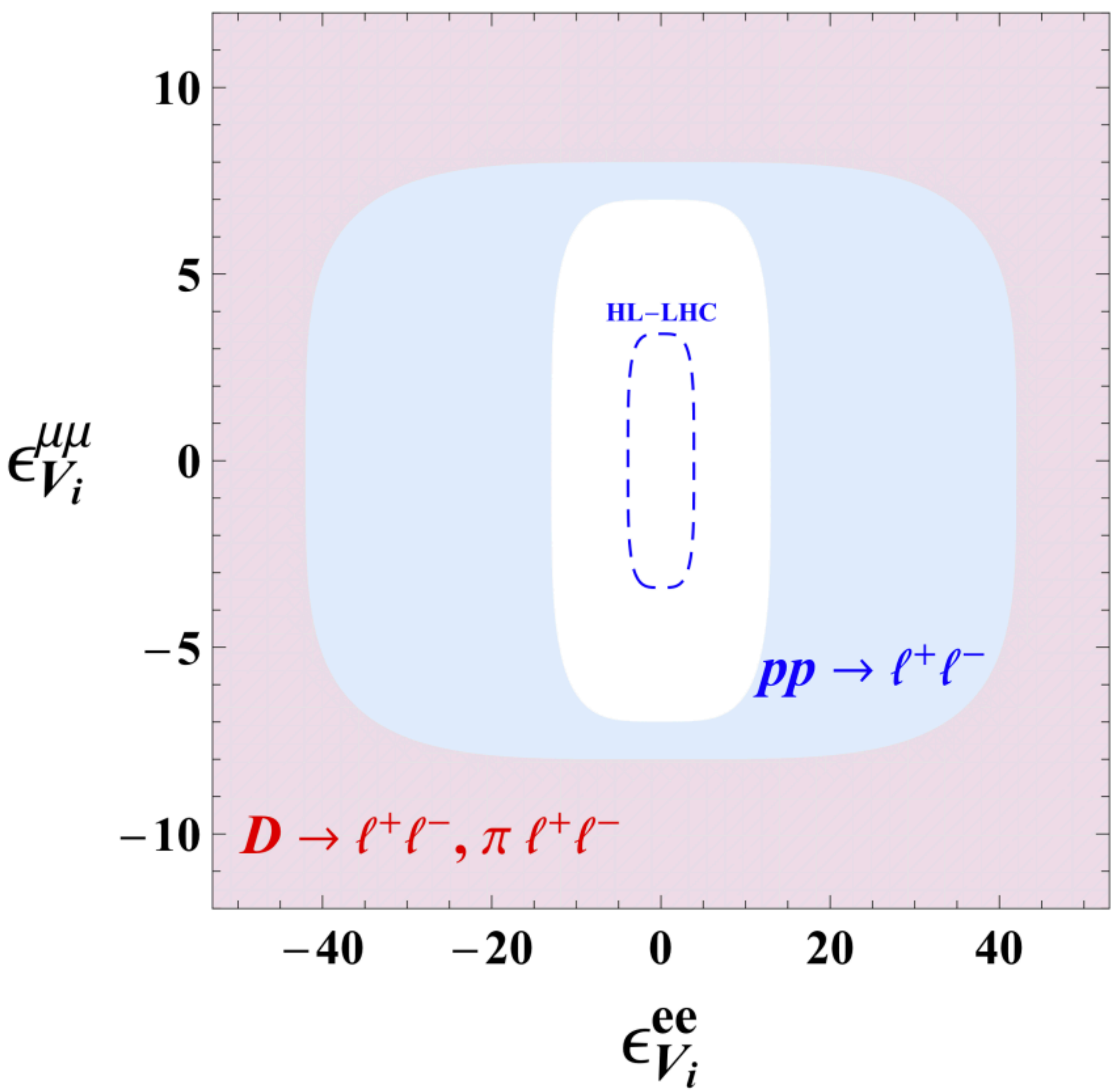
Observable	LHC (140 fb^{-1})	HL-LHC (3 ab^{-1})	Exp. limit
$\mathcal{B}(B^0\to\mu^\pm\tau^\mp)$	8×10^{-4}	1.7×10^{-4}	1.4×10^{-5}
$\mathcal{B}(B^+\to\pi^+\mu^\pm\tau^\mp)$	1.1×10^{-4}	2×10^{-5}	9.4×10^{-5}
$\mathcal{B}(B_s\to K_S^0\mu^\pm\tau^\mp)$	4×10^{-5}	8×10^{-6}	–
$\mathcal{B}(B^0\to\rho\mu^\pm\tau^\mp)$	7×10^{-5}	1.5×10^{-5}	–
$\mathcal{B}(B_s\to\mu^\pm\tau^\mp)$	8×10^{-3}	1.7×10^{-3}	4.2×10^{-5}
$\mathcal{B}(B^+\to K^+\mu^\pm\tau^\mp)$	9×10^{-4}	1.9×10^{-4}	3.9×10^{-5}
$\mathcal{B}(B^0\to K^{*0}\mu^\pm\tau^\mp)$	4×10^{-4}	1.0×10^{-4}	–
$\mathcal{B}(B_s\to\phi\mu^\pm\tau^\mp)$	5×10^{-4}	1.0×10^{-4}	–

[Descotes-Genon, Faroughy, Plakias, **OS**. '23]

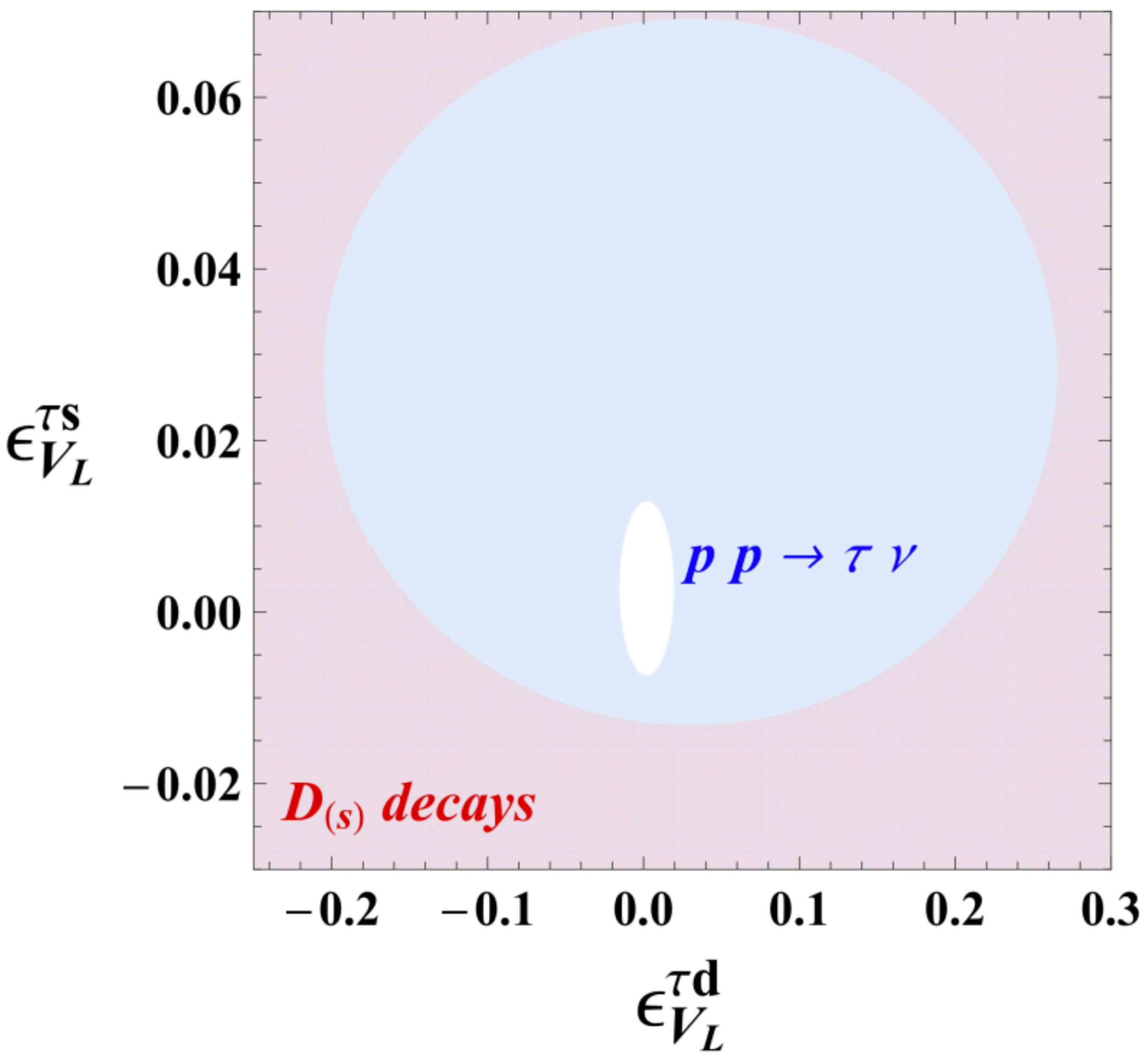
Charm physics

[Fuentes-Martin et al. '20]

$c \to u\ell\ell$



$c \to d(s)\ell\nu$



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

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

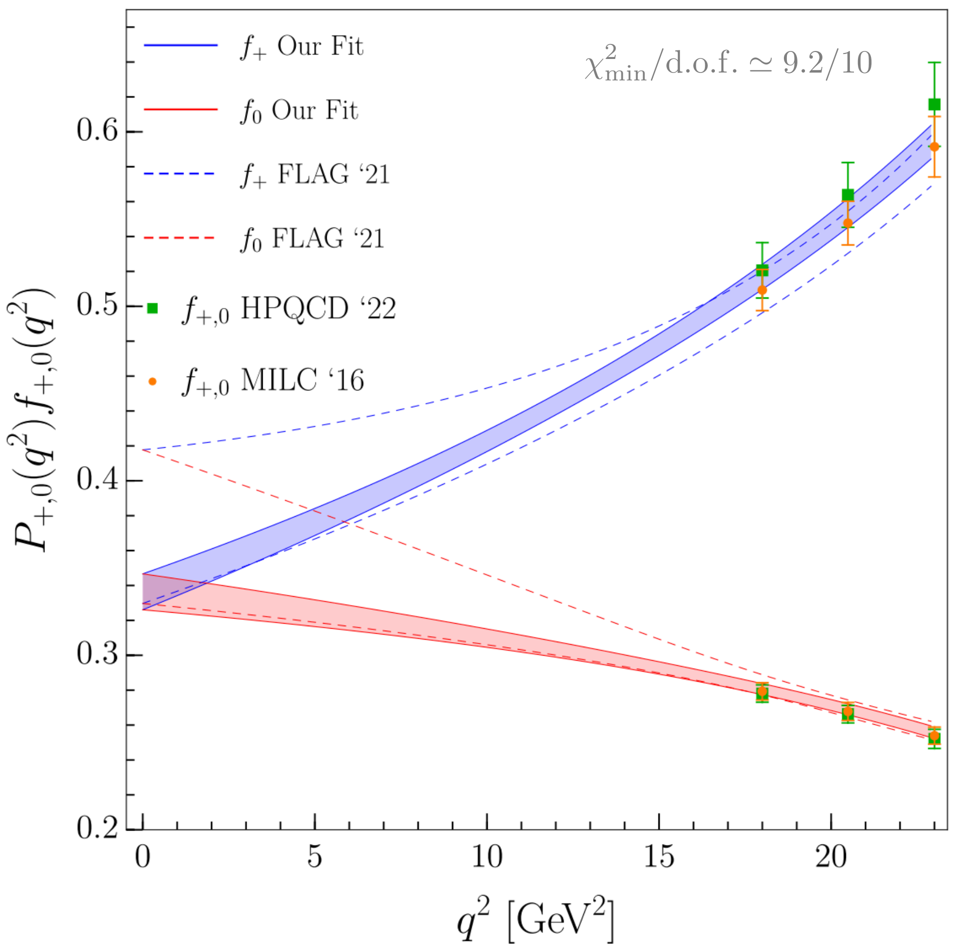
- **Lattice QCD** data available at **nonzero recoil** $(q^2 \neq q^2_{\rm max})$ for all form-factors:

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

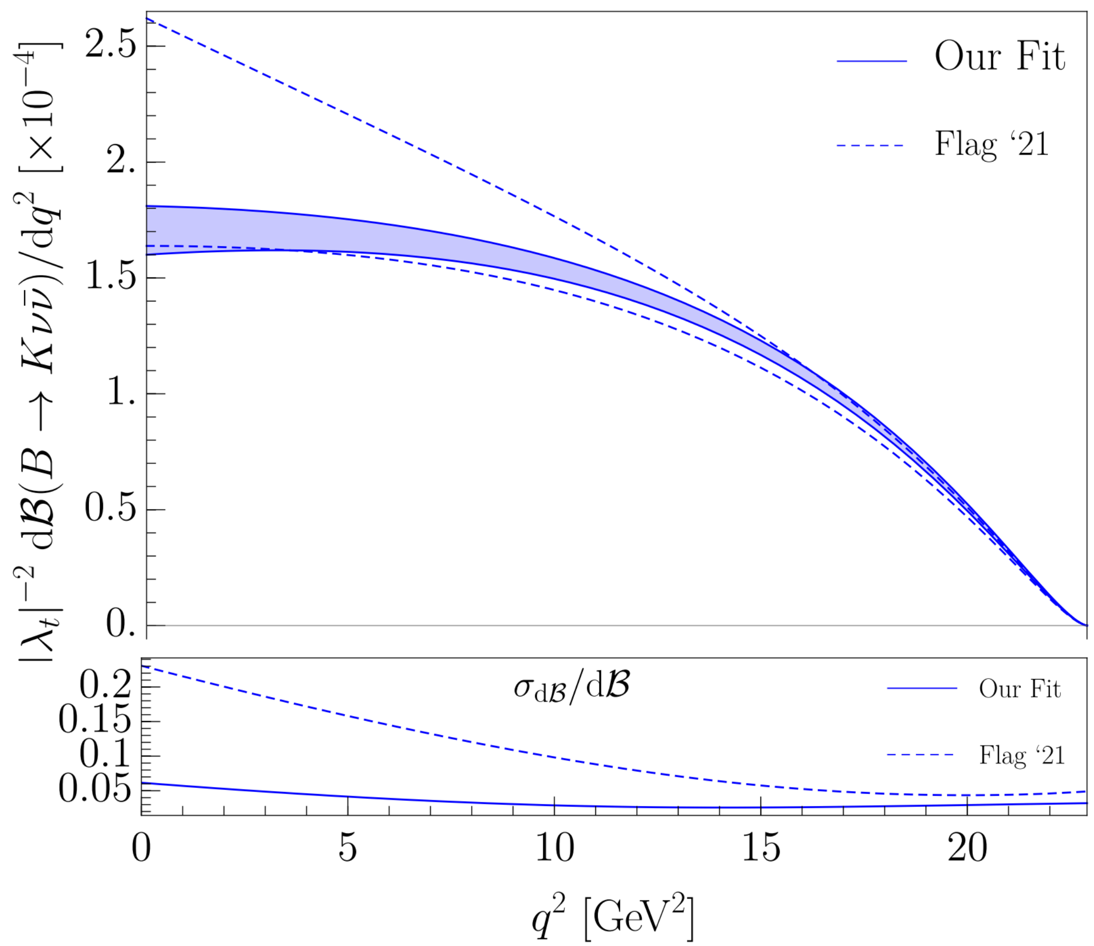
with $f_+(0) = f_0(0)$.

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

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



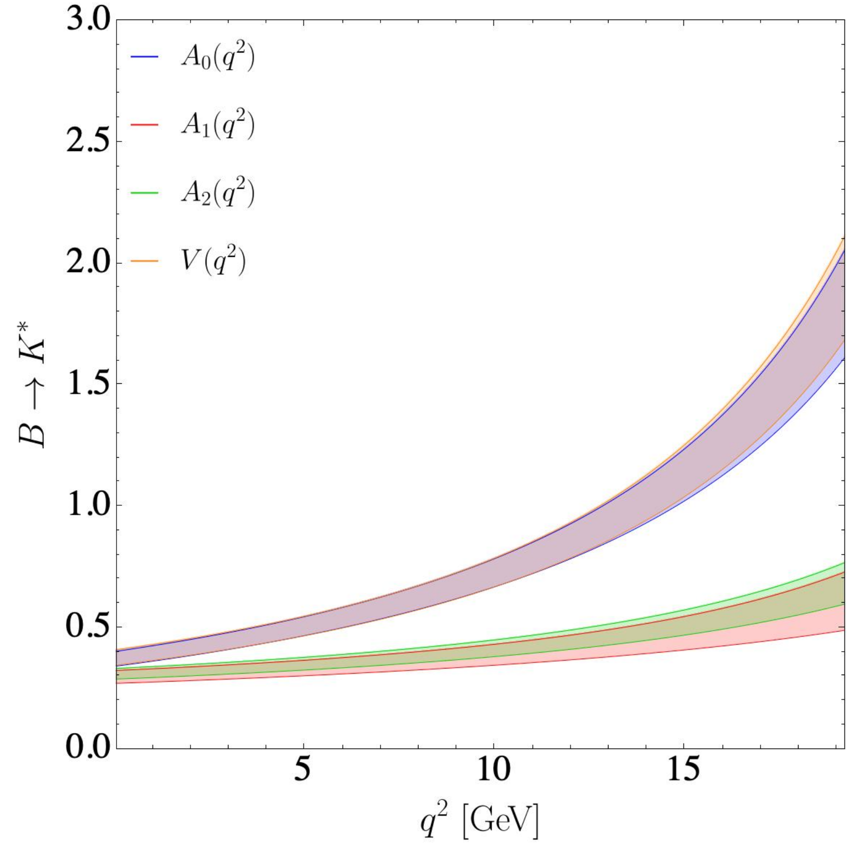
Pole factor:
$P_i(q^2) = 1 - q^2$



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

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

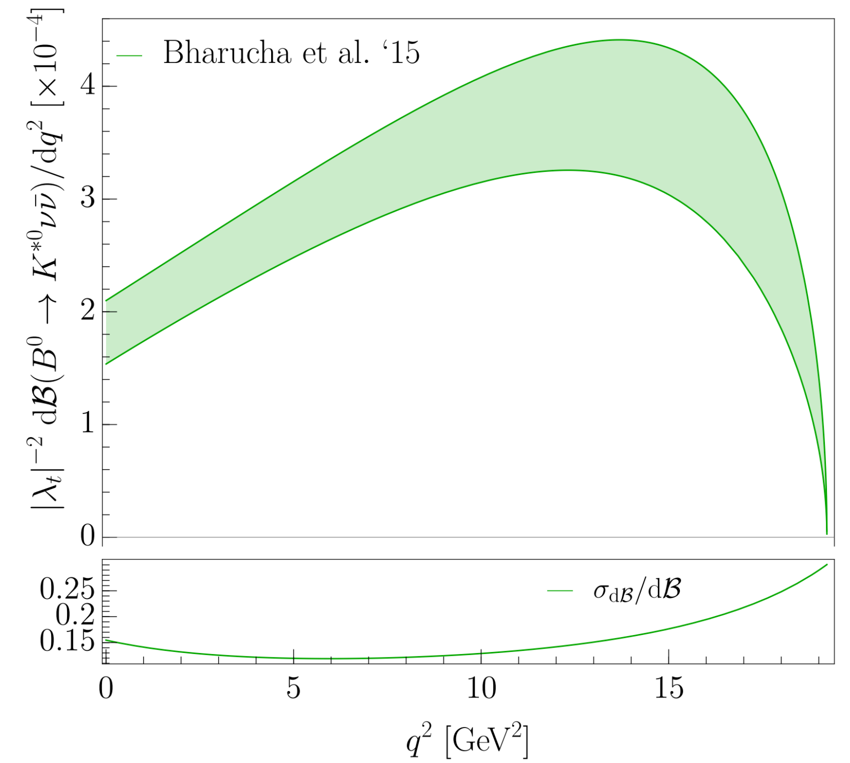
$$
\begin{aligned}
\langle \bar{K}^*(k)|\bar{s}\gamma_\mu(1-\gamma_5)b|\bar{B}(p)\rangle = \varepsilon_{\mu\nu\rho\sigma}\varepsilon^{*\nu}p^\rho k^\sigma \frac{2V(q^2)}{m_B+m_{K^*}} \\
- i\varepsilon^*_\mu(m_B+m_{K^*})A_1(q^2) \\
+ i(p+k)_\mu(\varepsilon^*\cdot q)\frac{A_2(q^2)}{m_B+m_{K^*}} \\
+ iq_\mu(\varepsilon^*\cdot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



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

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

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



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