Probing Flavorful EFTs at the LHC

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IJCLab (Orsay)

Based on:

- [D. Bečirević, **MM**, S. Rosauro-Alcaraz, O. Sumensari, 2603.25837]
- [O.J.P. Éboli, L.P.S. Leal, **MM**, O. Sumensari, 2509.08437]

IRN, October 20

The quest for physics beyond the Standard Model

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

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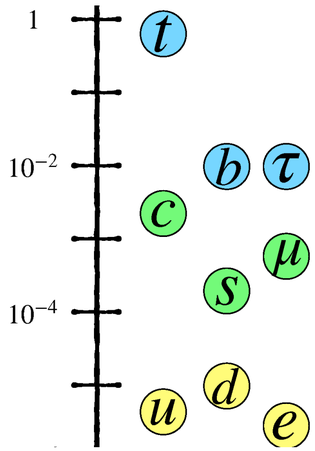
Several questions that **cannot** be answered within the Standard Model:

Hierarchy problem

Flavor puzzle



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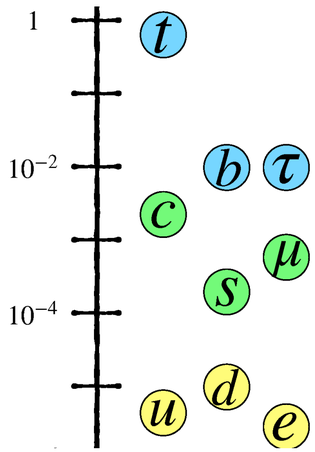


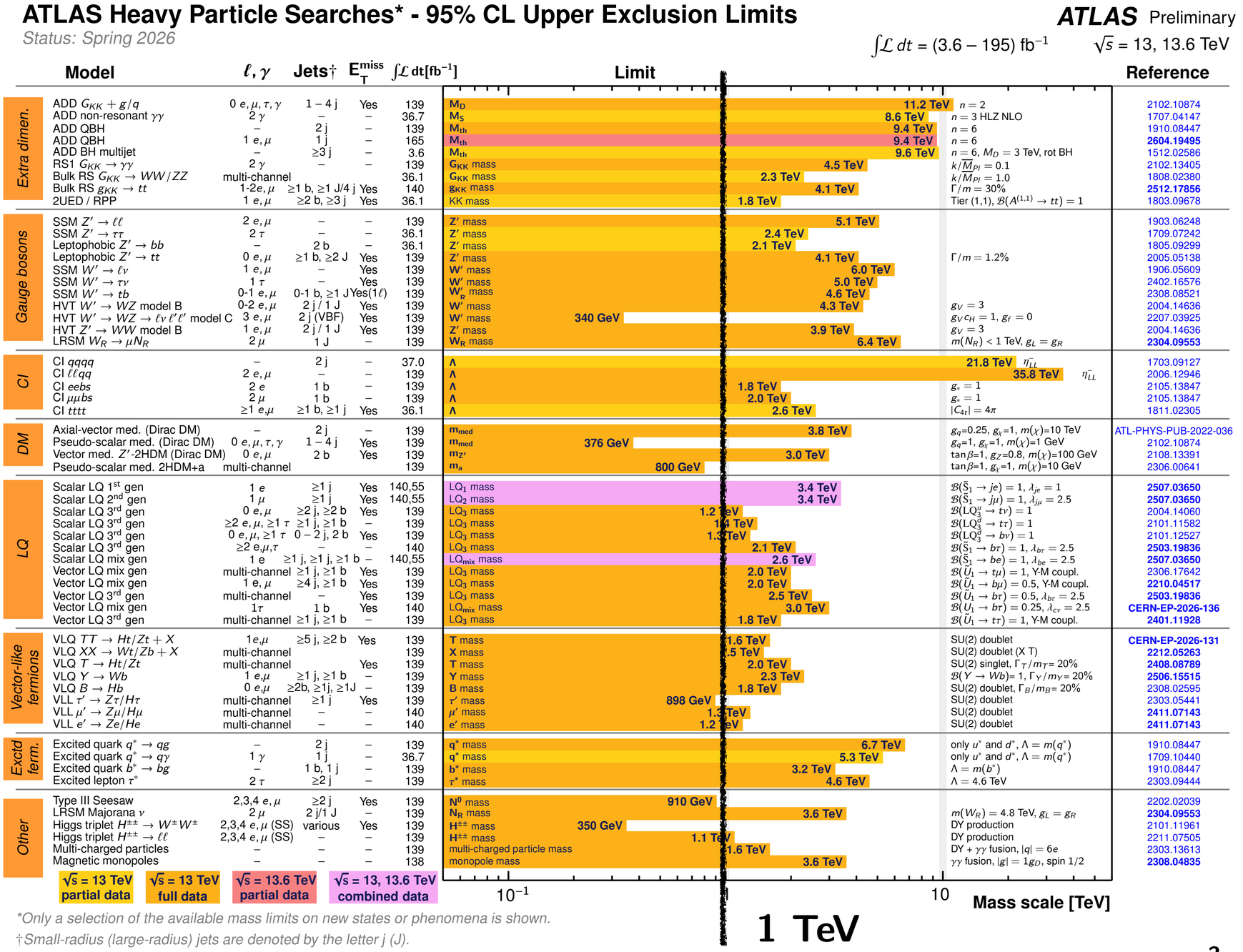
and many more ...

Addressing these fundamental problems **requires** physics **beyond the Standard Model.**

Direct searches

No **direct** evidence of New Physics (NP).

Presence of a **mass gap** between the electroweak scale and the scale of NP.



*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

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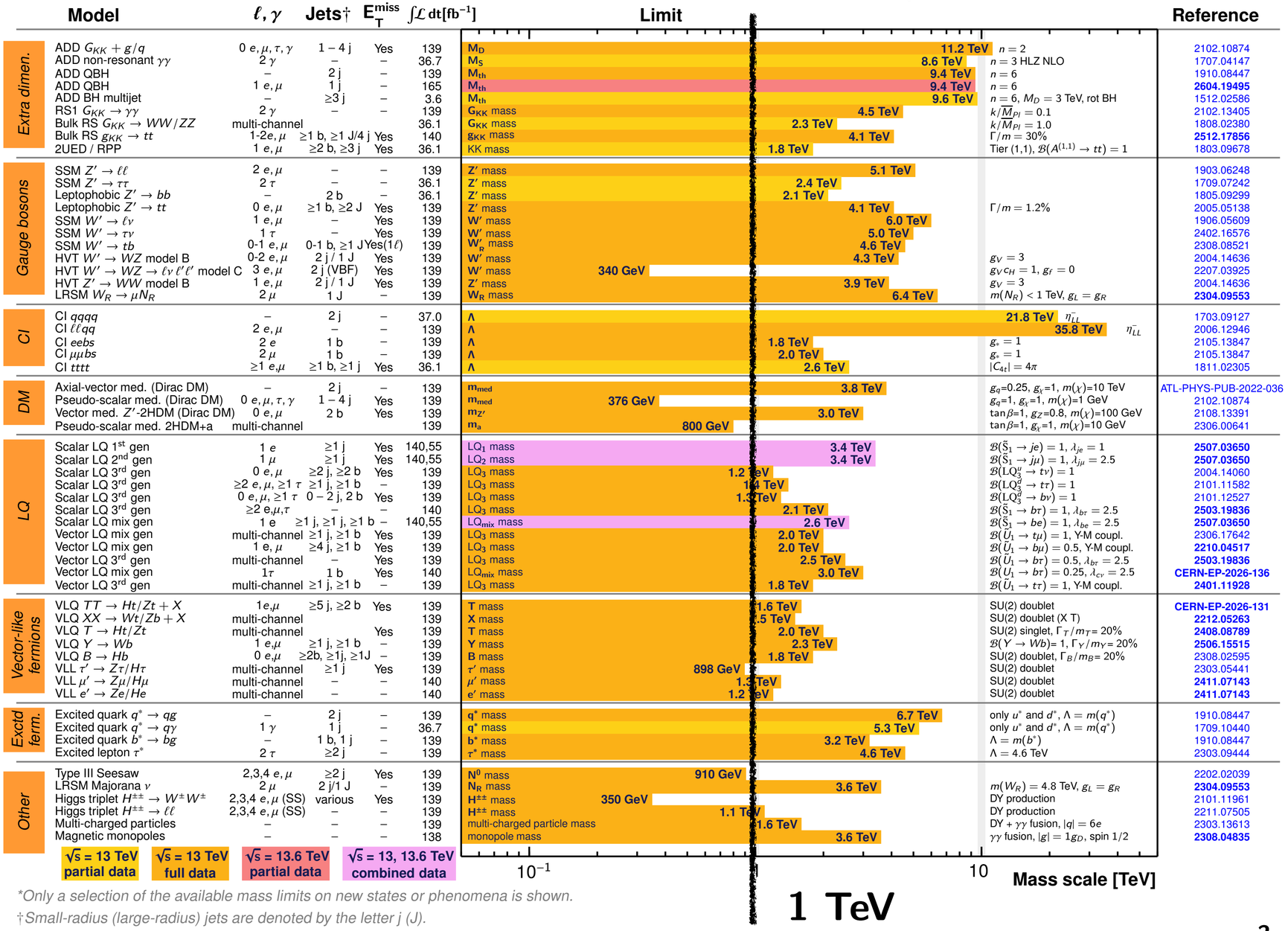
Indirect searches for New Physics.



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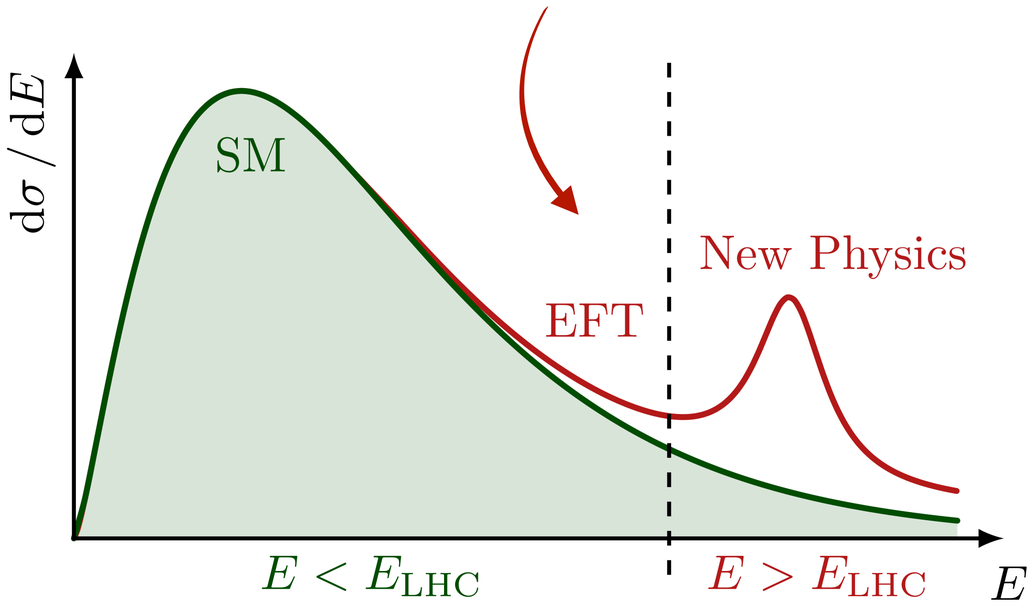
The EFT approach

All possible interactions made of **SM fields** and respecting the **SM gauge symmetries.**

Standard Model EFT (SMEFT)

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}^{(5)} + \frac{1}{\Lambda^2}\mathcal{L}^{(6)} + \frac{1}{\Lambda^3}\mathcal{L}^{(7)} + \frac{1}{\Lambda^4}\mathcal{L}^{(8)} + \dots$$

$$\mathcal{L}^{(d)} = \sum_i c_i \, Q_i^{(d)}$$



- ***New Physics*** *scale* Λ *controls the expansion;*
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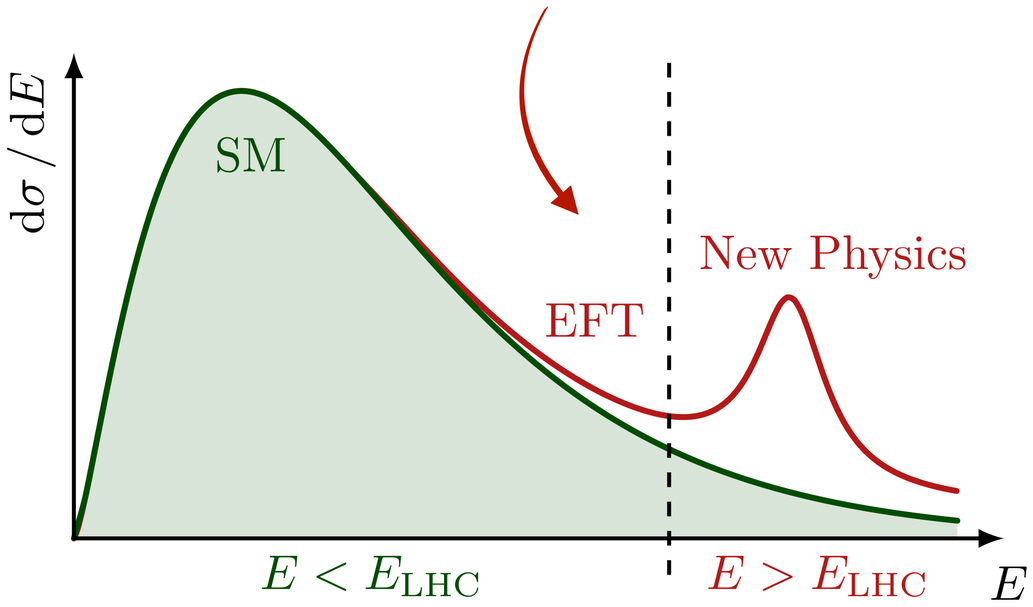

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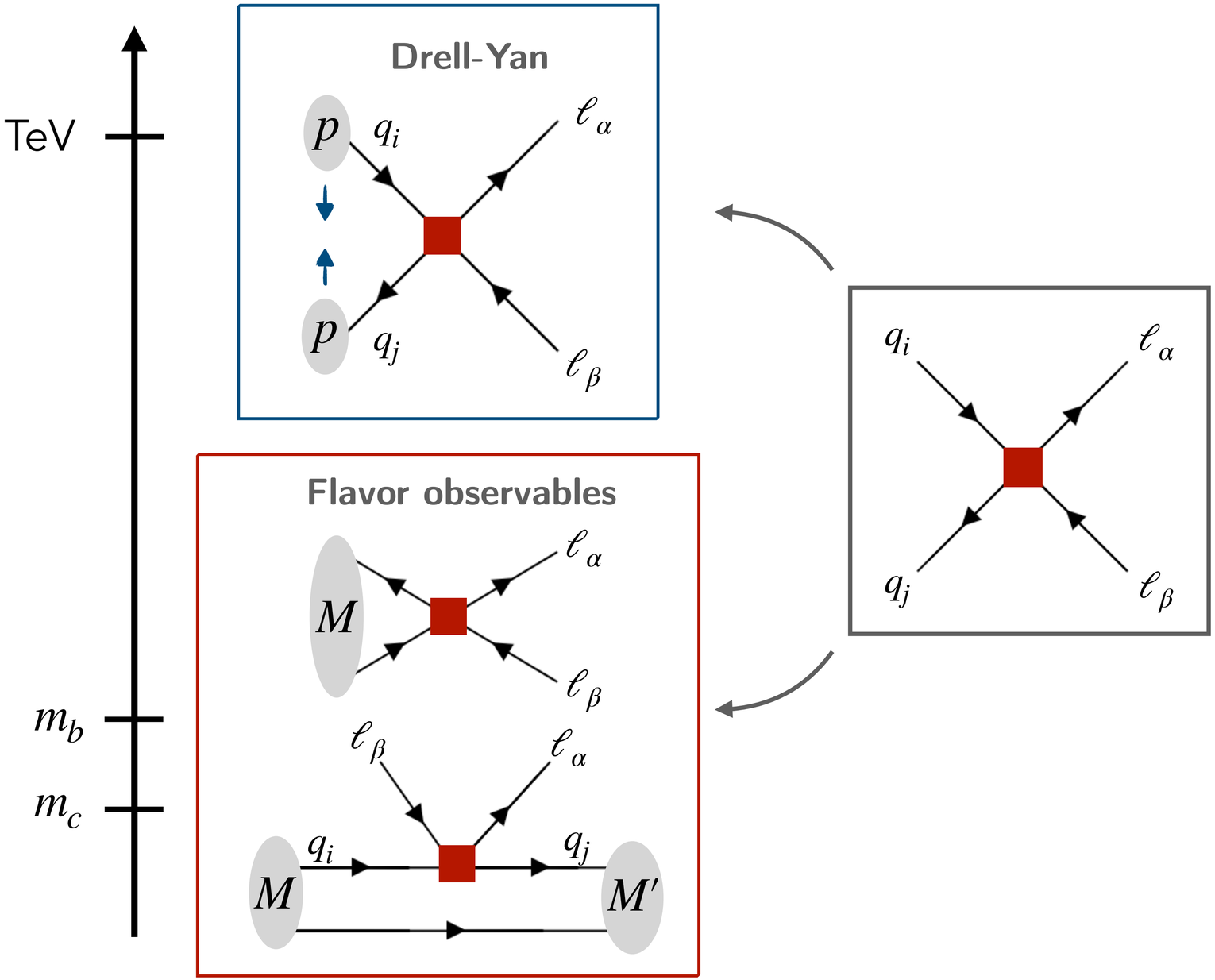
Same class of ***EFT operators*** *can affect processes at* ***different scales.***

e.g. high-energy LHC and low-energy flavor processes.

Synergy between low- and high-energy observables



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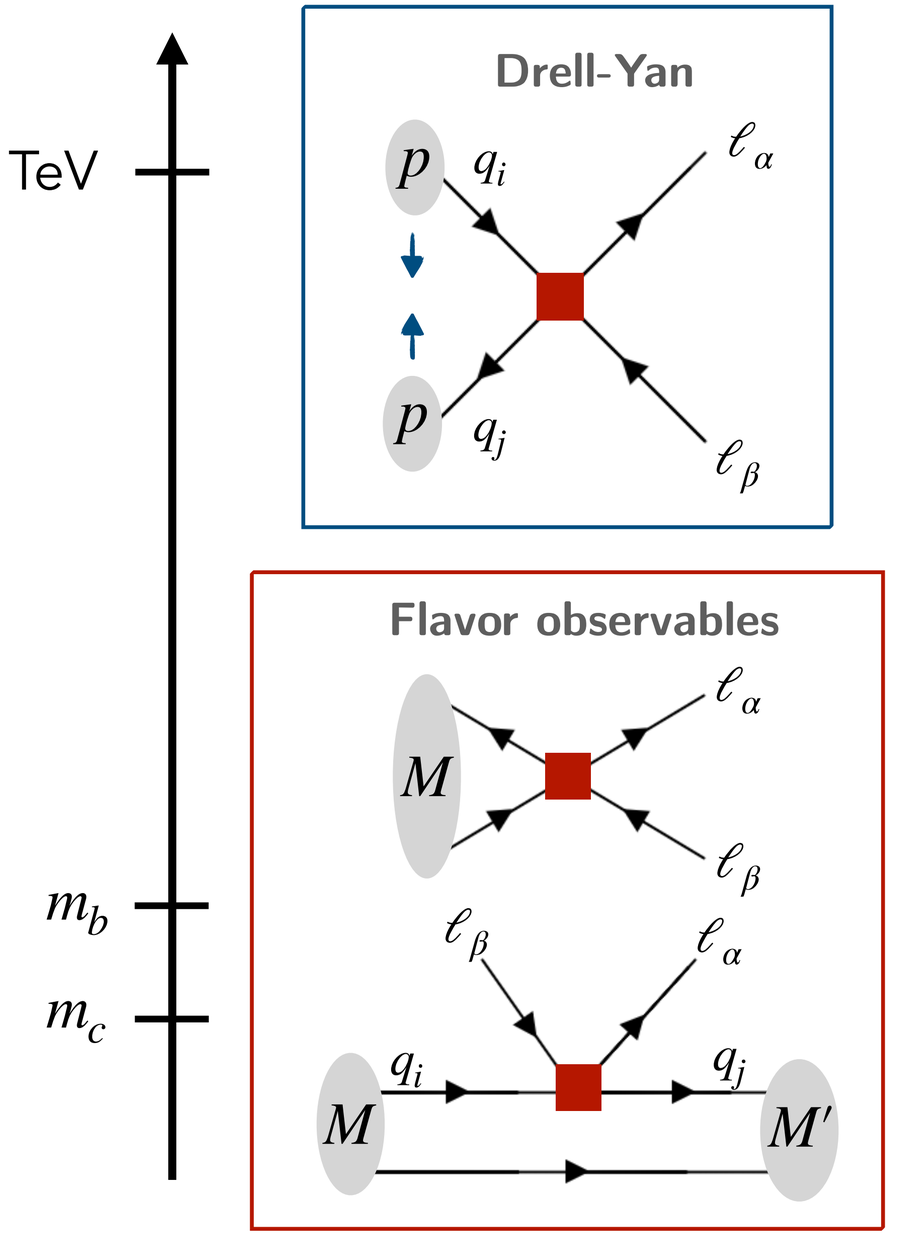
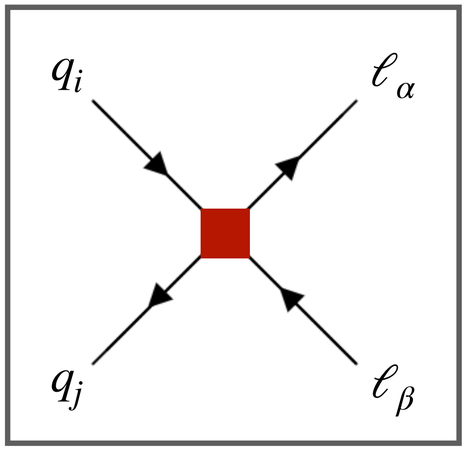
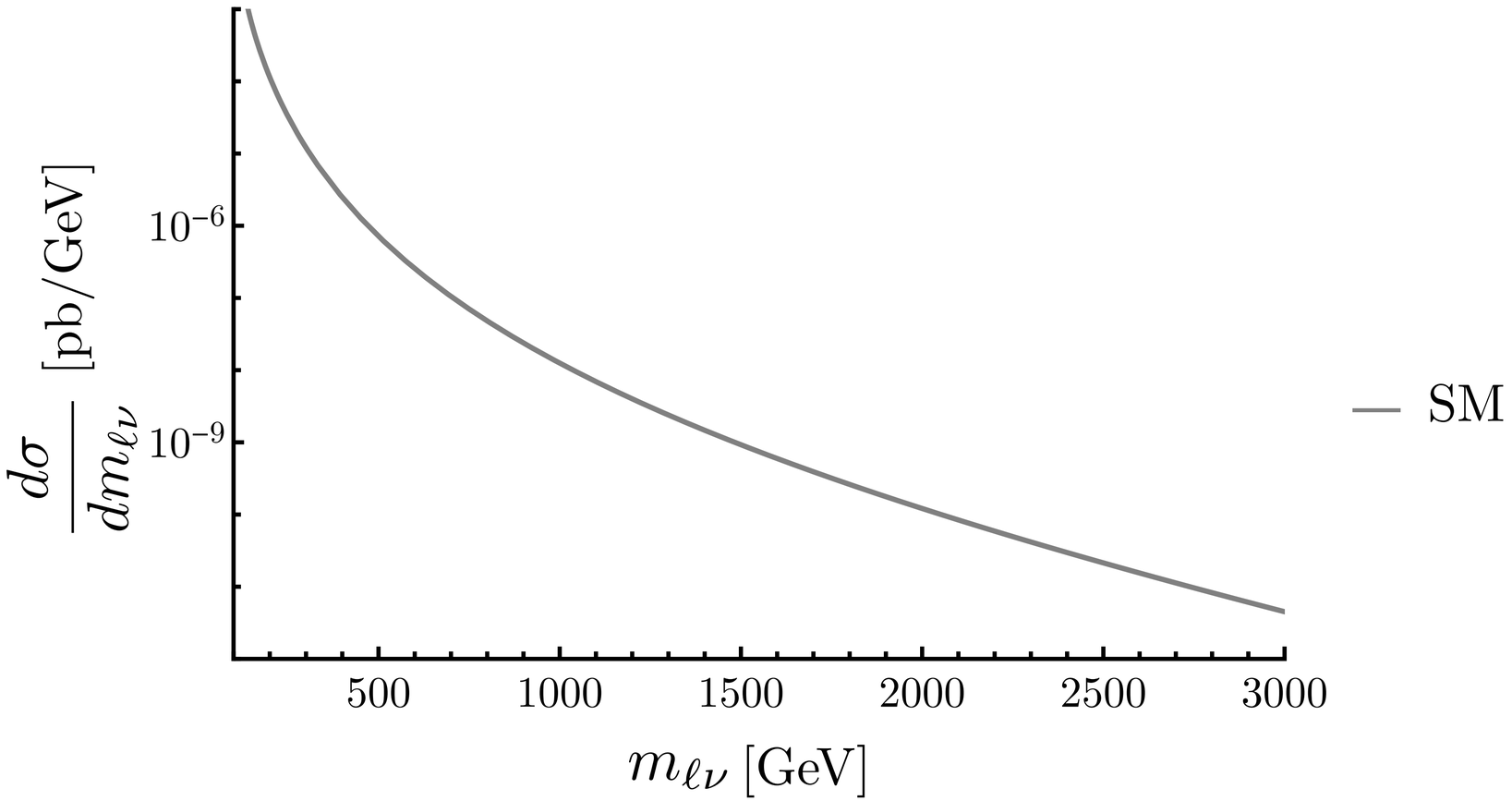


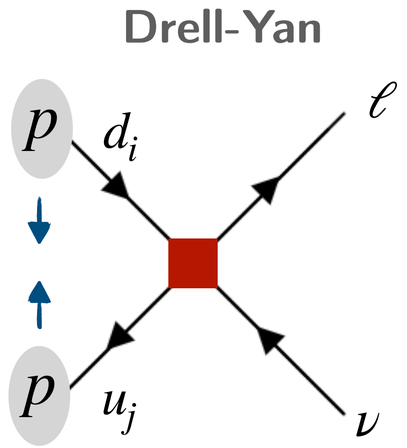


*Can the **LHC** provide **competitive** bounds to those from **flavor**? **Yes!***

D. Becirevic *et al.* [2012.09872], O. Sumensari *et al.* [2312.14070]A. Greljo *et al.* [2306.09401, 2212.10497] ...

High-p_T Drell-Yan tails





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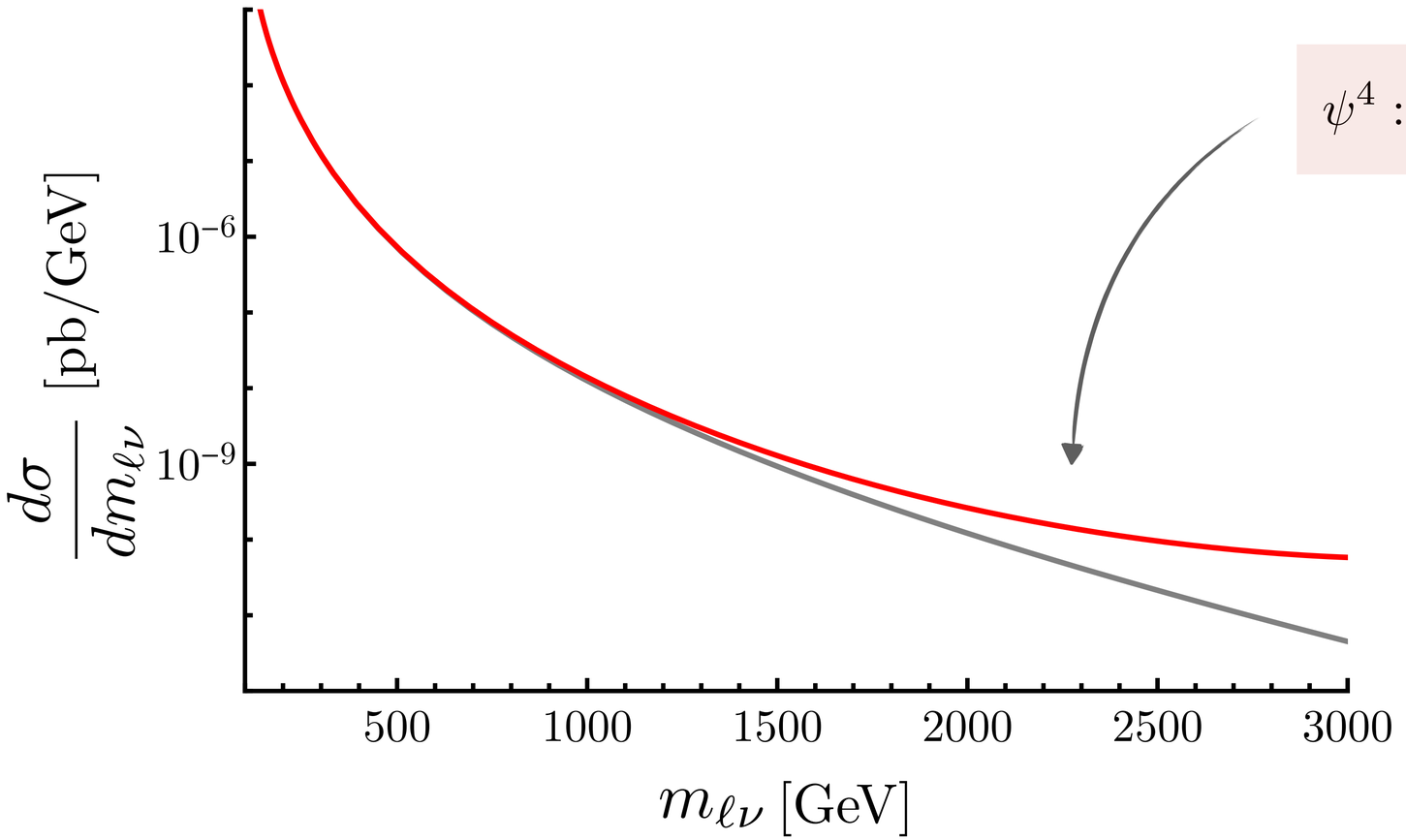
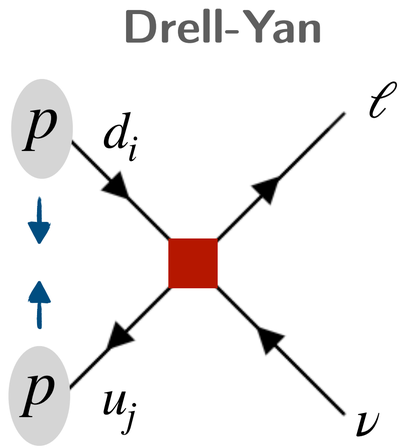


$$\psi^4 : \mathcal{A}^{(6)} \sim E^2/\Lambda^2$$



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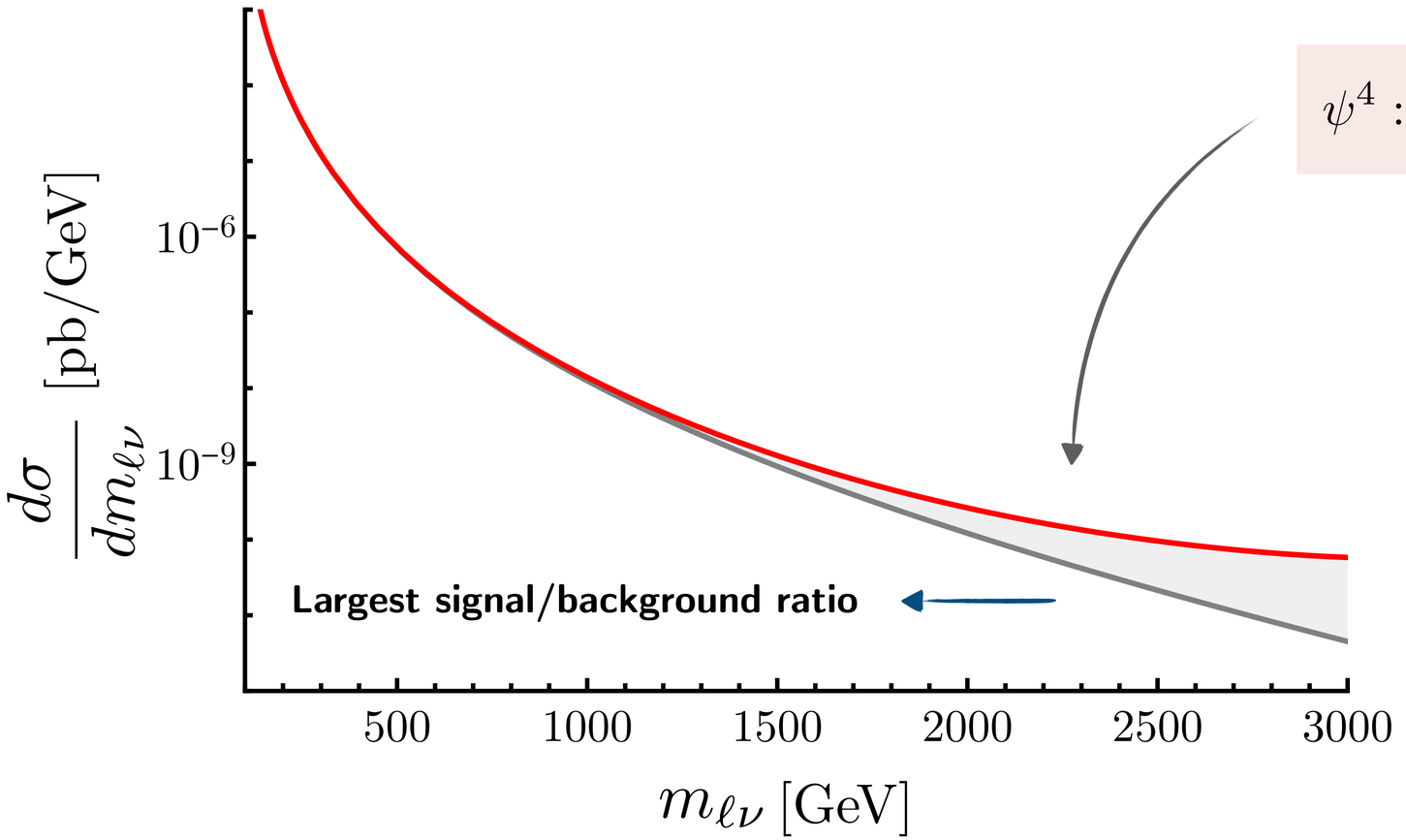

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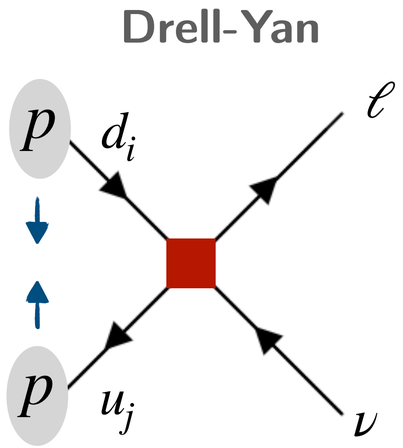
SM

NP



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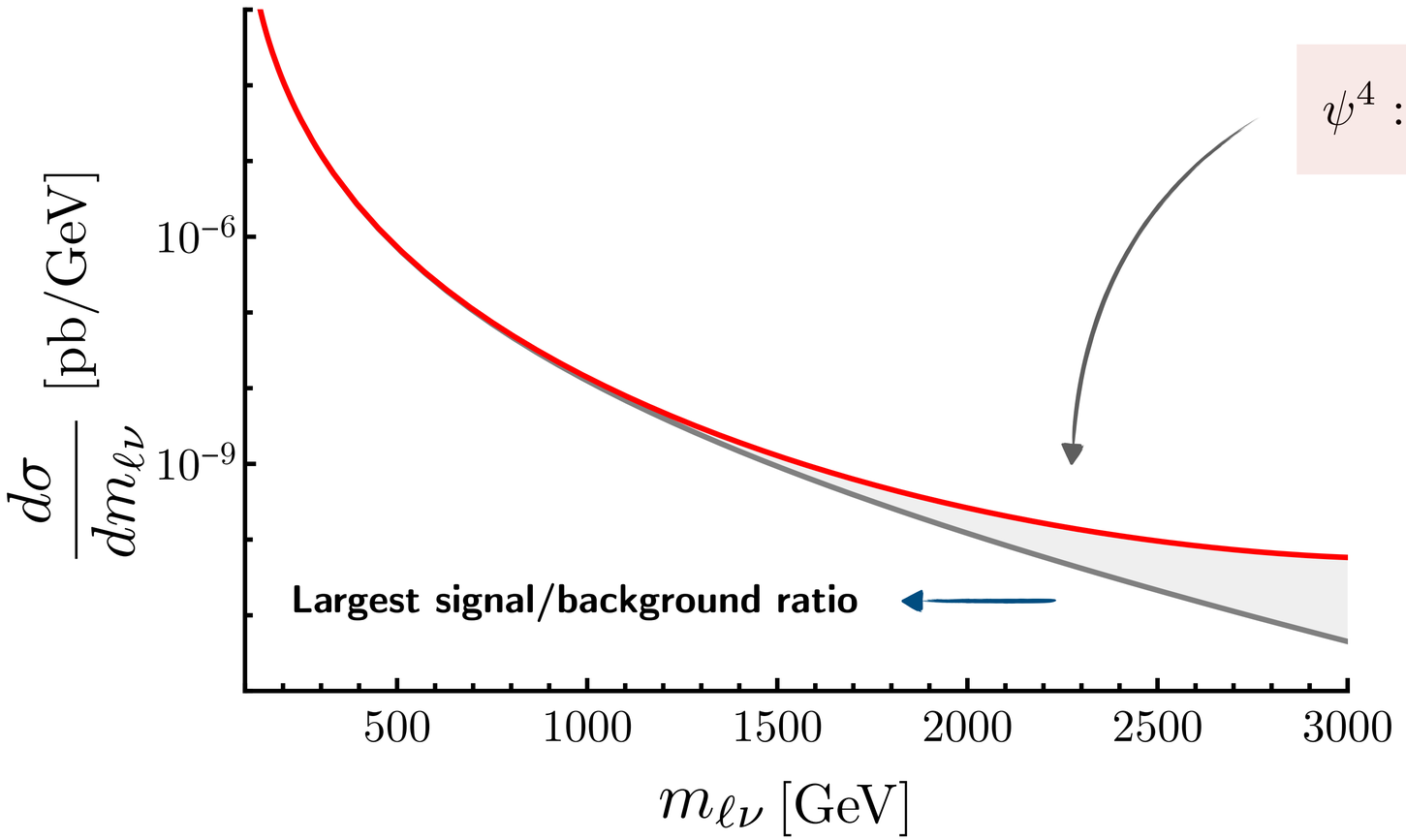

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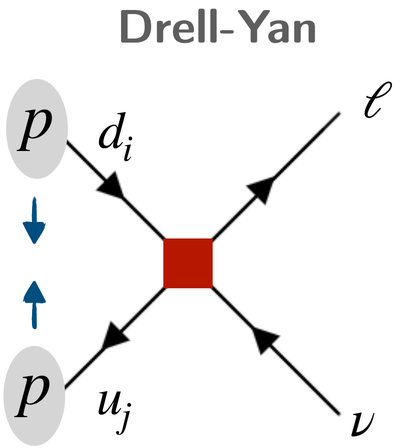

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Energy-enhanced effects in the high-p_T tails.

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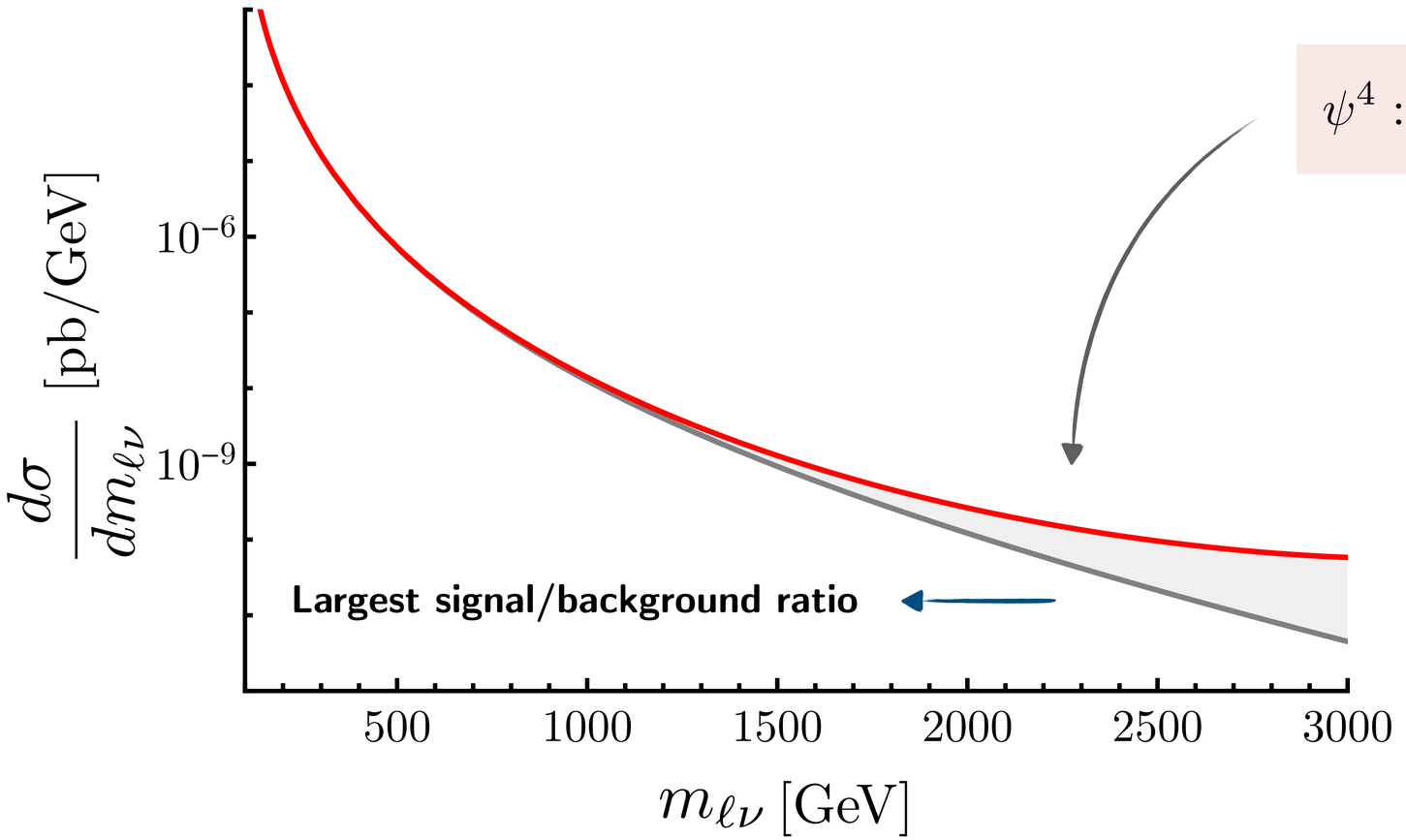
High-p_T Drell-Yan tails

***Example*: constraints on transitions mediated by the **charged current**.**



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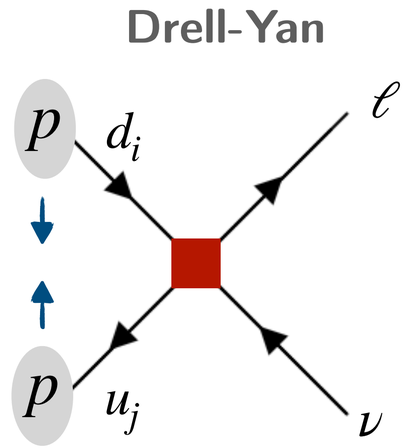

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Low-energy EFT for charged current processes

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- Responsible for leptonic and semileptonic meson decays.

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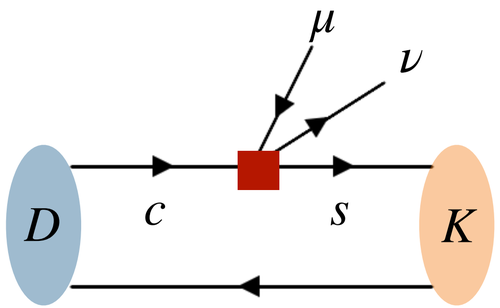

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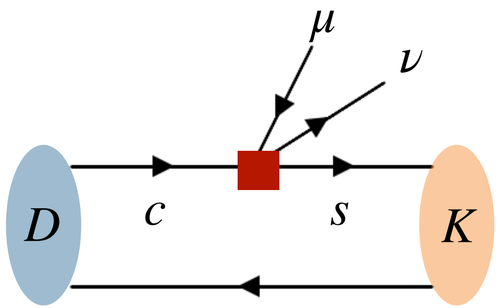

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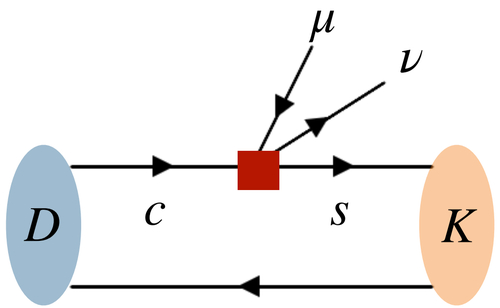

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$$q^2 = (p-k)^2 = (p_\ell + p_\nu)^2$$

- Evaluated using perturbative methods.
- Non-perturbative methods are required, e.g. Lattice QCD.

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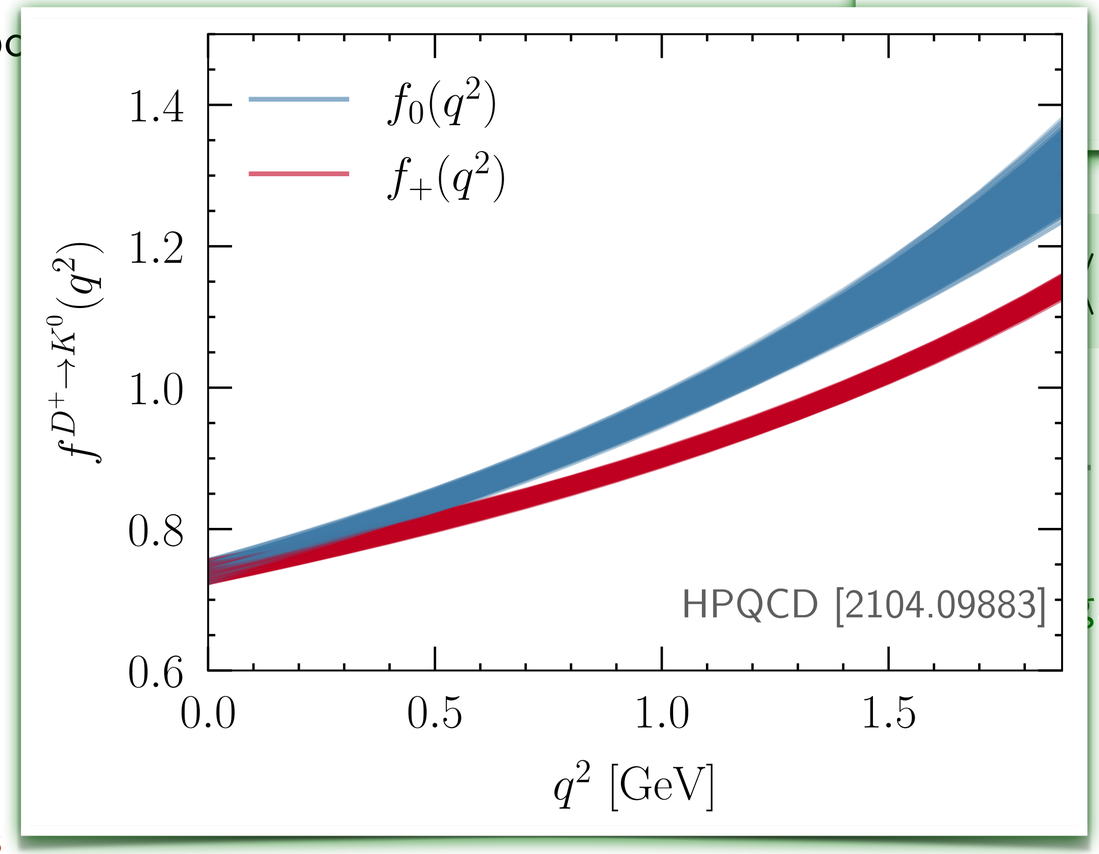

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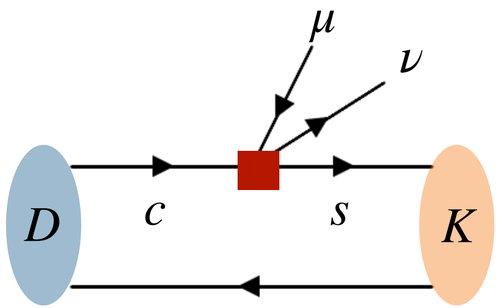

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→ Evaluated using perturbative methods.

→ Non-perturbative methods are required, e.g. Lattice QCD.

→ Encodes information about the underlining microscopic theory.

$$g_S = g_{S_R} + g_{S_L}$$
$$g_V = g_{V_R} + g_{V_L}$$

Low-energy EFT for charged current processes

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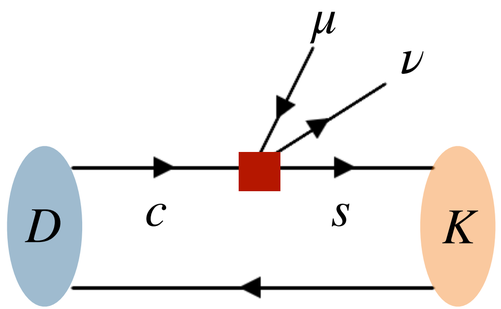
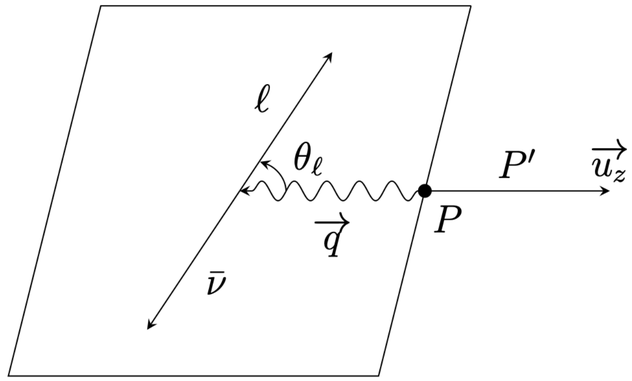


$$\frac{d^2\Gamma}{dq^2 d\cos\theta} = a(q^2) + b(q^2)\cos\theta + c(q^2)\cos^2\theta$$



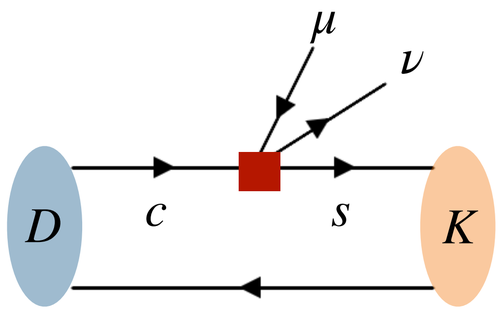
Depend on the Wilson coefficients and the form-factors.

Low-energy EFT for charged current processes

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

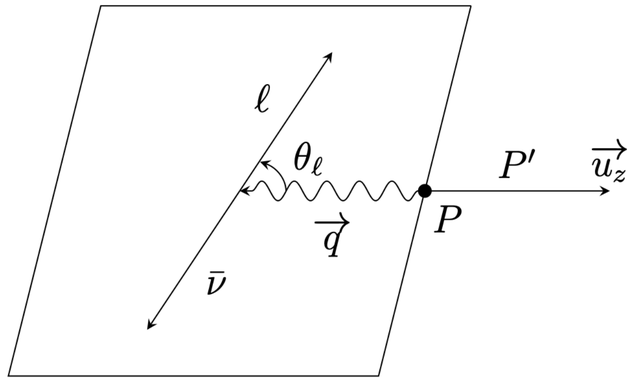
- Responsible for leptonic and **semileptonic** meson decays.

$$g_S = g_{S_R} + g_{S_L}$$
$$g_V = g_{V_R} + g_{V_L}$$



$$\frac{d^2\Gamma}{dq^2 d\cos\theta} = a(q^2) + b(q^2)\cos\theta + c(q^2)\cos^2\theta$$

$$\frac{d\Gamma}{dq^2} \propto a_V(q^2)\,|1+g_V|^2 + a_S(q^2)\,|g_S|^2 + a_{VS}(q^2)\,\text{Re}[(1+g_V)g_S^*] + \ldots$$



*Constrains **vector** and **scalar** couplings.*

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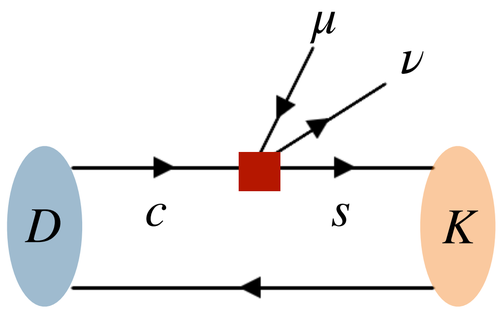

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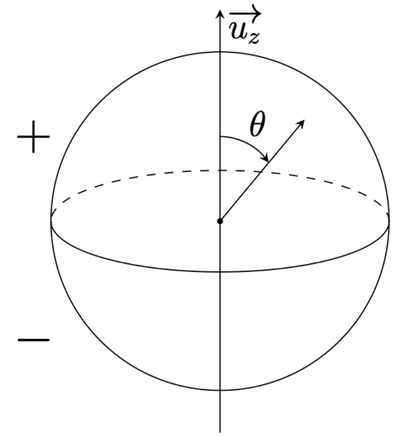
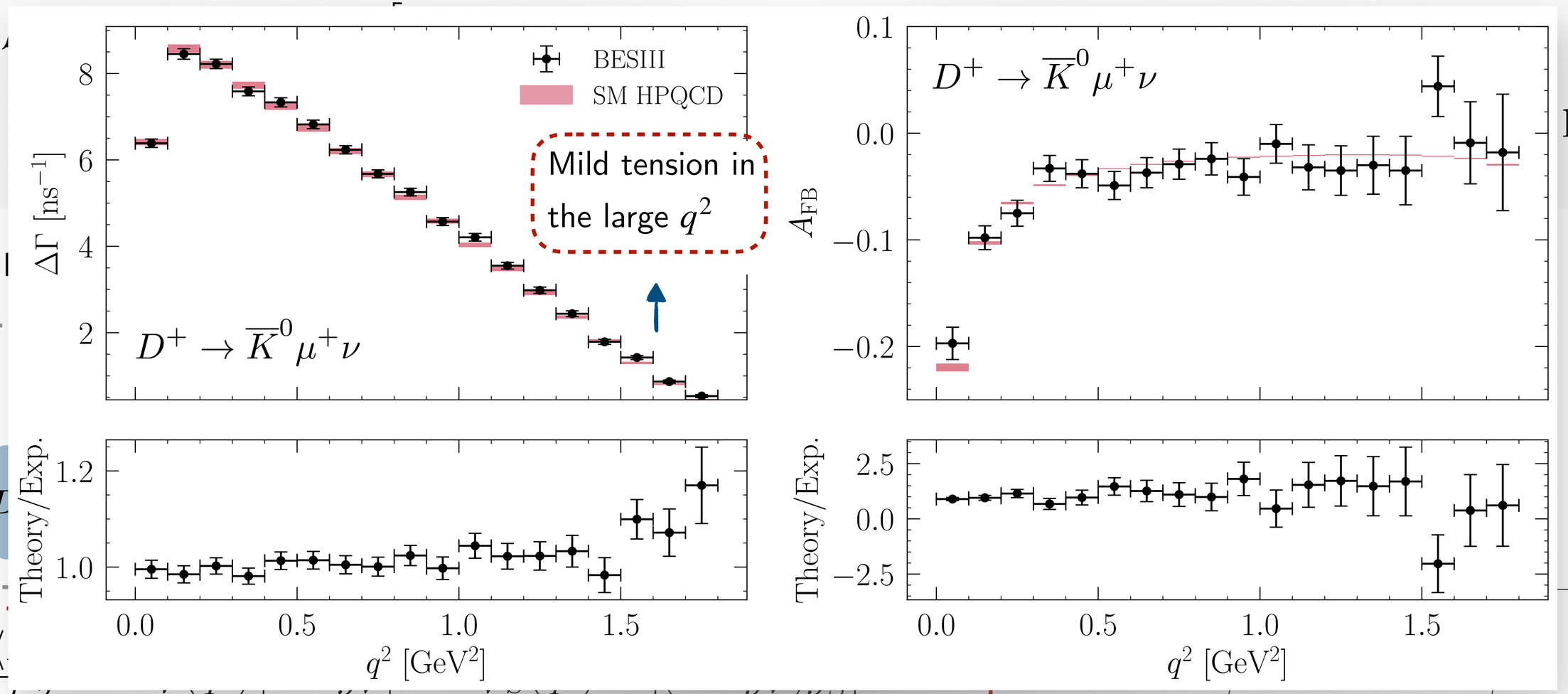


$$\frac{d\langle A_{\text{fb}}\rangle}{dq^2} \propto b_V(q^2)\,|1+g_V|^2 + b_{VS}(q^2)\,\text{Re}[(1+g_V)g_S^*] + \ldots$$

*Constrains the **real part** of the scalar coupling.* [D. Bečirević, F. Jaffredo, A. Peñuelas, O. Sumensari, 2012.09872]

Low-energy EFT for charged current processes



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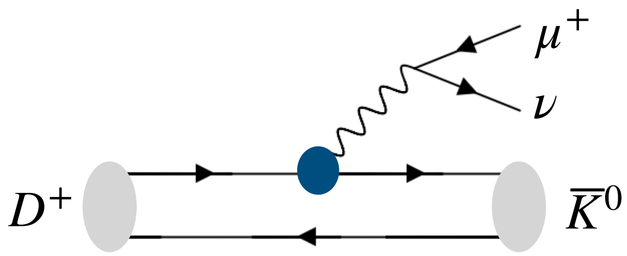
Recently measured by BESIII Collaboration

Testing solutions at the LHC

A **mild tension** with the SM prediction is present in the BESIII differential decay width measurements of the $D \to K\mu\nu$ channels. [2601.21196, 2601.21185]



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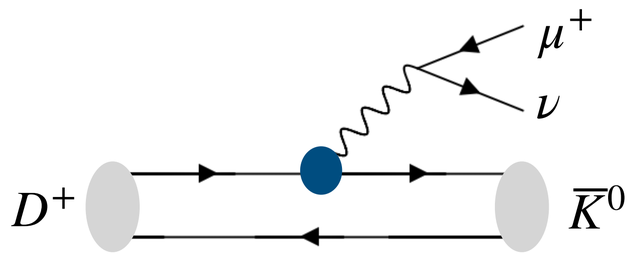

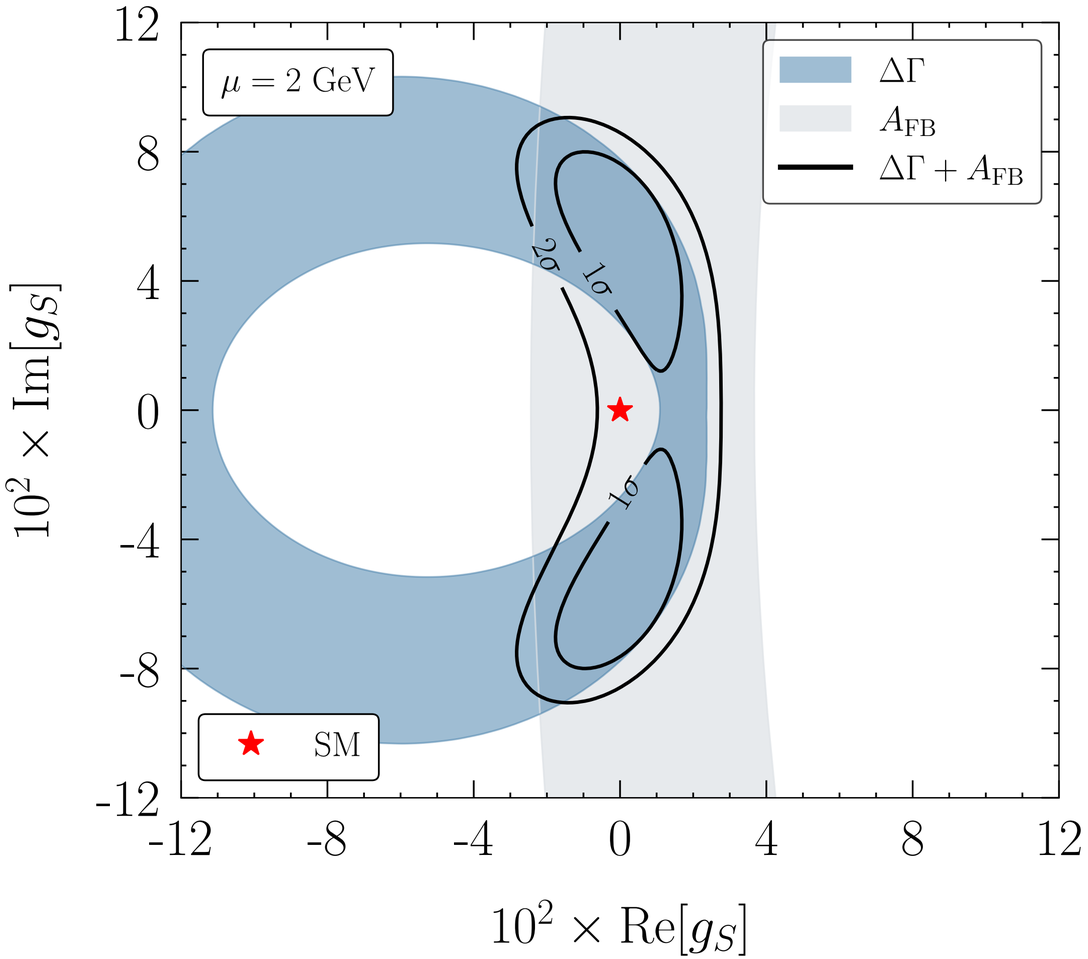

Complex scalar coupling can alleviate the tension.

$$\mathcal{O}_S = (\bar{c}s)(\bar{\mu}_R \nu_L)$$

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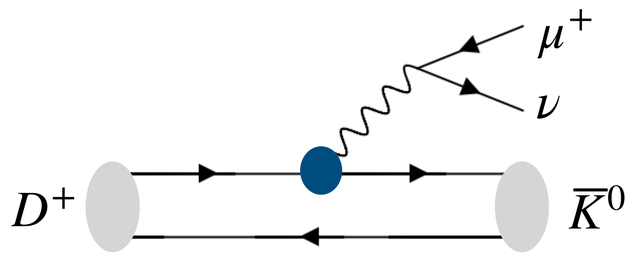

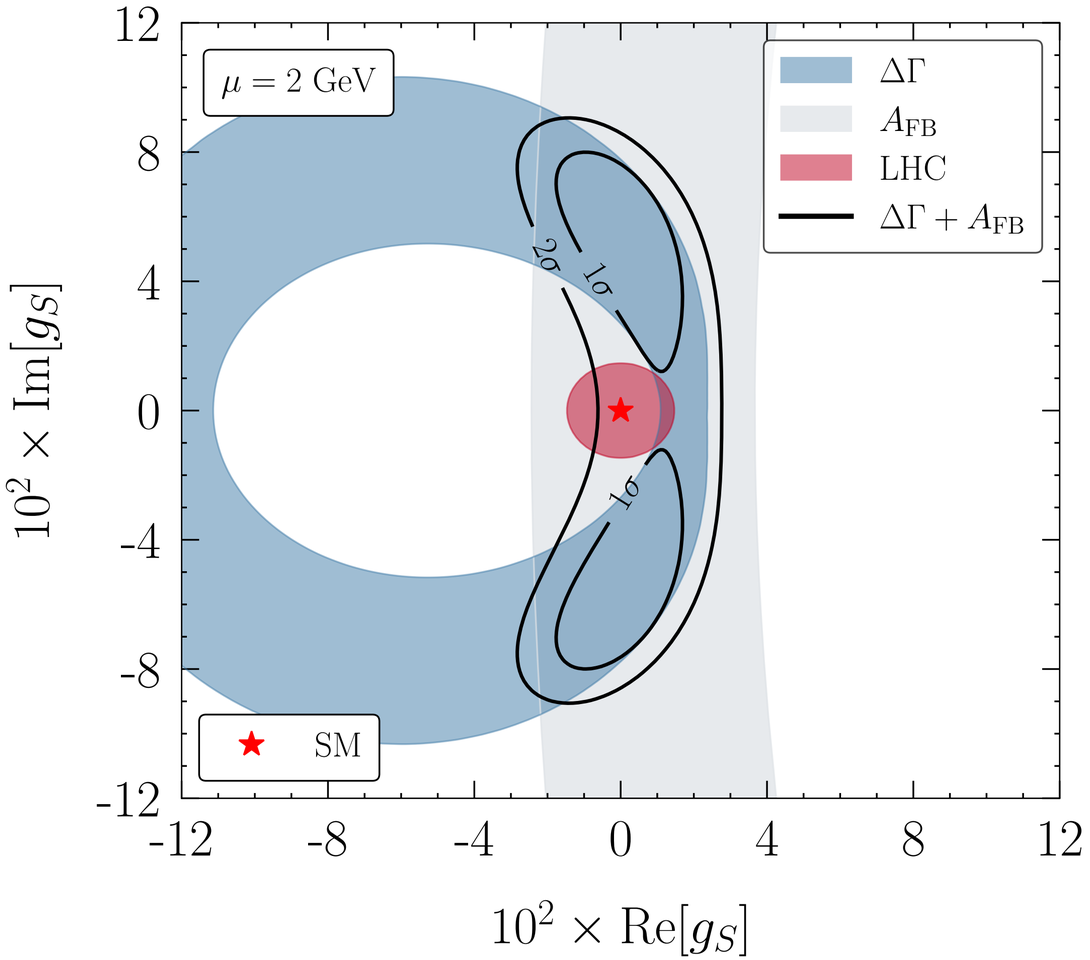

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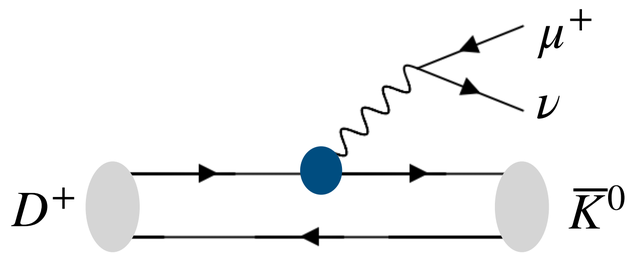

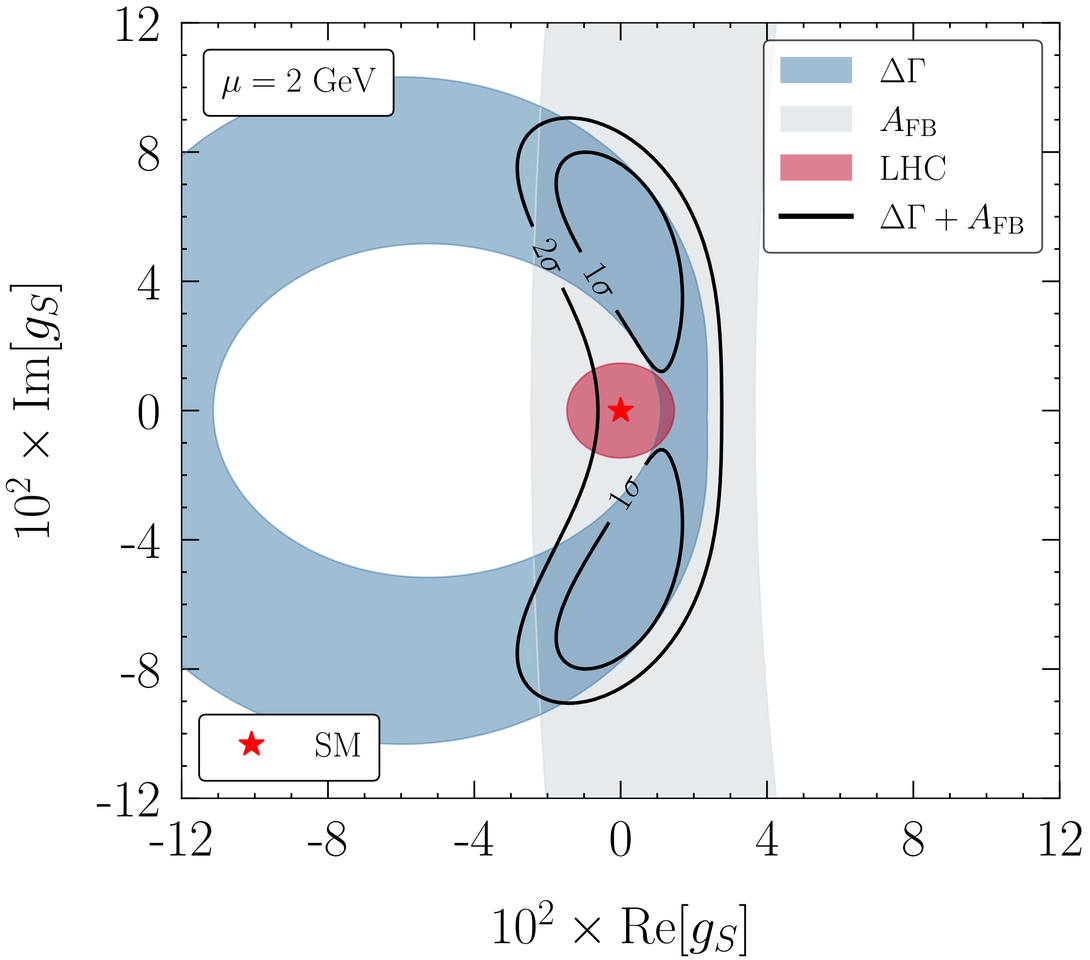

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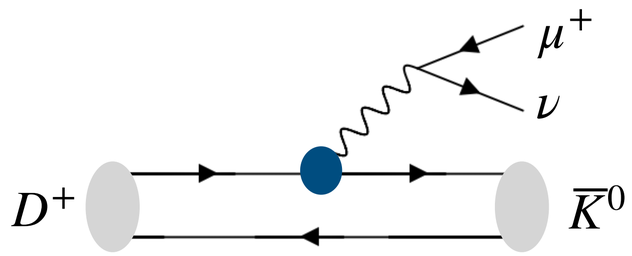

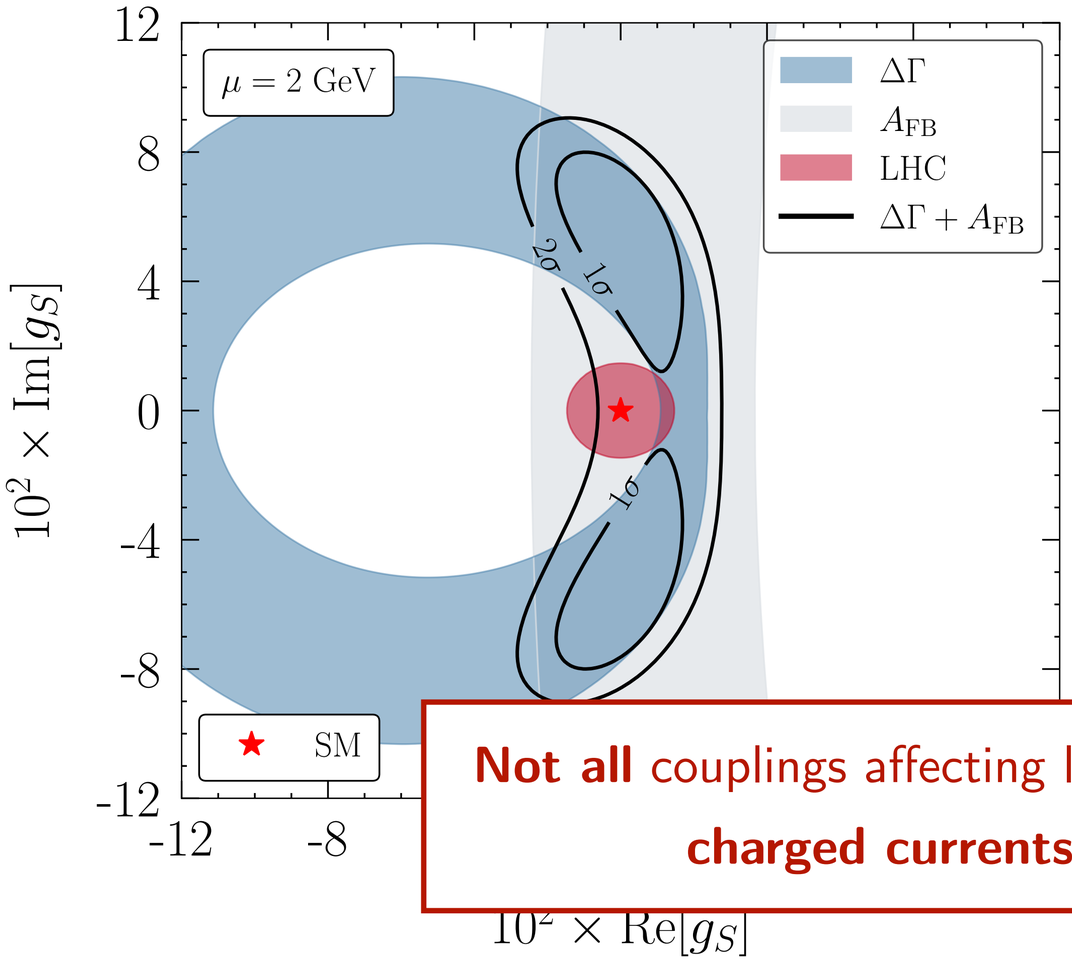

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Not all couplings affecting low-energy **semileptonic transitions** mediated by **charged currents** can be constrained by **Drell-Yan** data.

[D. Becirevic, **MM,** S. Rosauro-Alcaraz, O. Sumensari, 2603.25837]

Low-energy EFT for charged current processes

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Matching with SMEFT @ d=6:

$$g_{V_L}^{ij(\ell)} \propto \frac{v^2}{\Lambda^2}\mathcal{C}^{ij}_{\psi^2H^2D} - \frac{v^2}{\Lambda^2}\mathcal{C}^{ij\ell\ell}_{\psi^4}\,,$$

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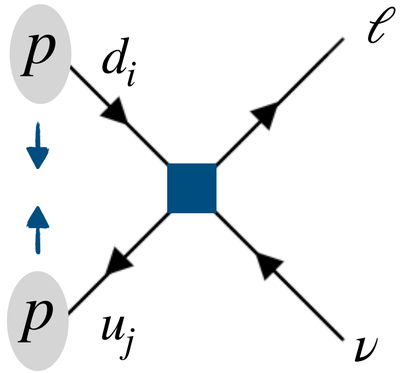
Well constrained by $pp \to \ell\nu$ data

$$\psi^4 : \mathcal{A}^{(6)} \sim E^2/\Lambda^2$$



J. Fuentes-Martín et al. [2003.12421], M. Farina et al. [1609.08157], A. Greljo et al. [2212.10497], A. Angelescu et al. [2002.05684], ...

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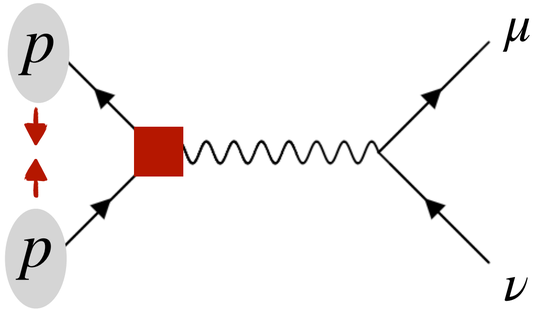
Poorly constrained by $pp \to \ell\nu$ data.

$$\psi^2H^2D:\ \mathcal{M}^{(6)}(u\bar{d}\to\ell^+\nu)\sim v^2/\Lambda^2$$

Only generated by a ψ^2H^2D operator @ d=6.



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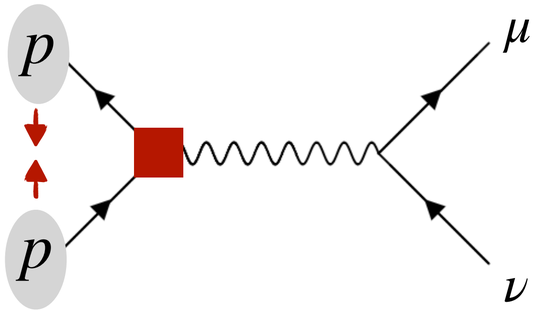
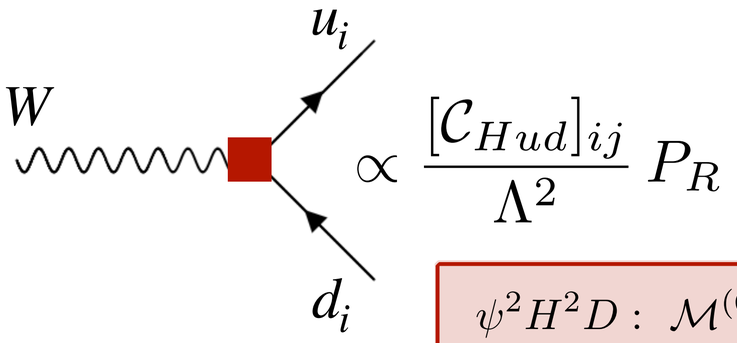


The operators in ψ^2H^2D class can be **energy-enhanced** in **Higgs** production channels.

Example: Right-Handed Charged Currents at the LHC

$$\mathcal{O}_{Hud} = (\tilde{H}^\dagger i D_\mu H)(\overline{u}_R \gamma^\mu d_R) + \text{h.c.}$$



$\psi^2 H^2 D: \ \mathcal{M}^{(6)}(u\bar{d} \to \ell^+ \nu) \sim v^2/\Lambda^2$

Poorly constrained by DY.

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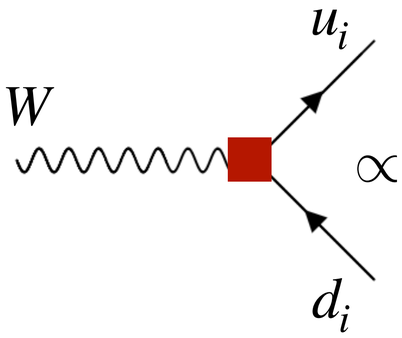

$$\propto \frac{[\mathcal{C}_{Hud}]_{ij}}{\Lambda^2} P_R$$

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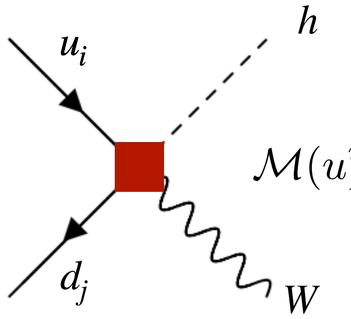
Energy-enhancement effects



$$\mathcal{M}(u_R^i \bar{d}_R^j \to W_0\, h) = -\frac{i}{\sqrt{2}} \frac{E^2 \sin\theta}{\Lambda^2} \mathcal{C}^*_{Hud\ ij}$$

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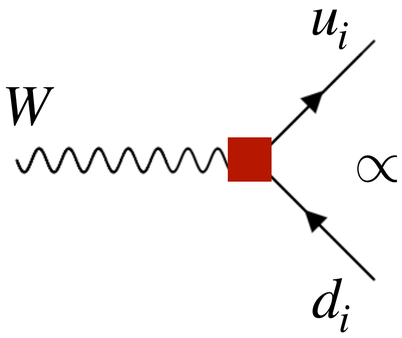

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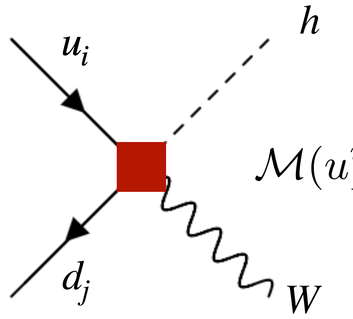

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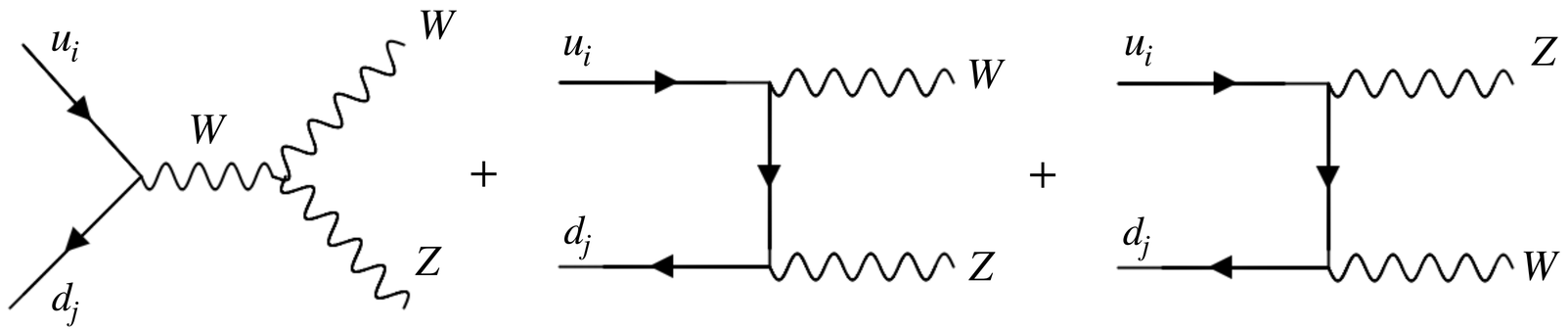

Modifications to the SM couplings **spoil** the cancellations.

$$i\mathcal{M}_{\text{SM}} \simeq i\sqrt{2}\, V_{ij}^* \sin\theta \left[c_W^2 - \left(T^{(u)} - s_W^2 Q^{(u)} \right) + \left(T^{(d)} - s_W^2 Q^{(d)} \right) \right] \frac{E^2}{v^2} = 0$$

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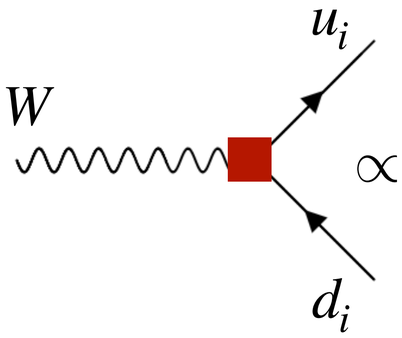

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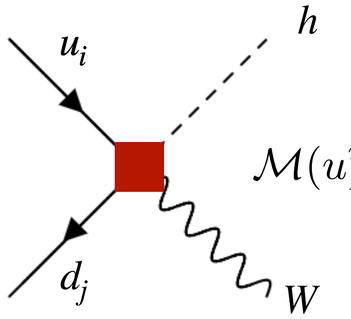
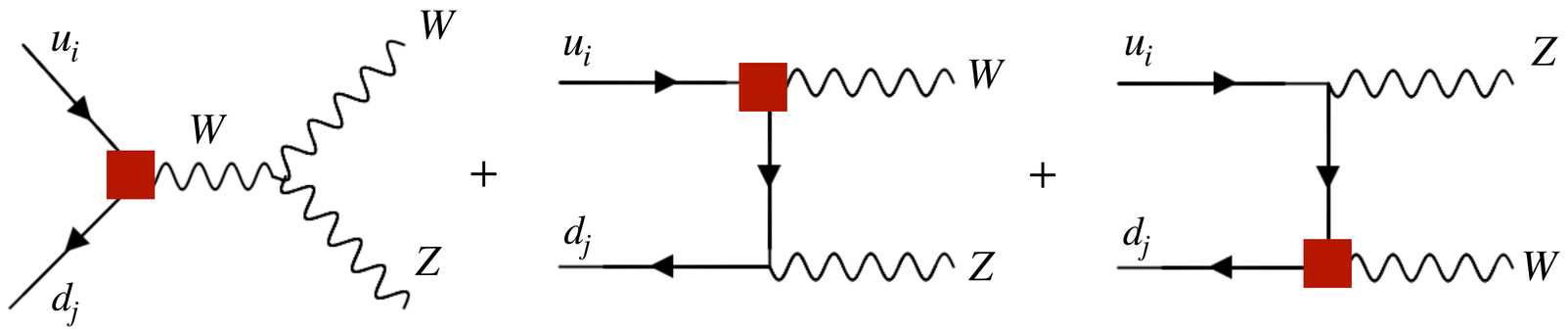


$$\mathcal{M}(u_R^i \bar{d}_R^j \to W_0\, h) = -\frac{i}{\sqrt{2}} \frac{E^2 \sin\theta}{\Lambda^2} \mathcal{C}^*_{Hud\,ij}$$



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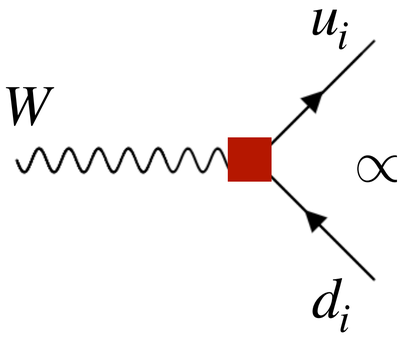
Modifications to the SM couplings **spoil** the cancellations.

Example: Right-Handed Charged Currents at the LHC

$$\mathcal{O}_{Hud} = (\tilde{H}^\dagger i D_\mu H)(\overline{u}_R \gamma^\mu d_R) + \text{h.c.}$$



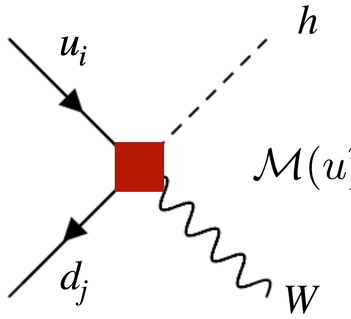
$$\propto \frac{[\mathcal{C}_{Hud}]_{ij}}{\Lambda^2} P_R$$

$\psi^2 H^2 D:\ \mathcal{M}^{(6)}(u\bar{d} \to \ell^+ \nu) \sim v^2/\Lambda^2$

↓

Poorly constrained by DY.

Energy-enhancement effects



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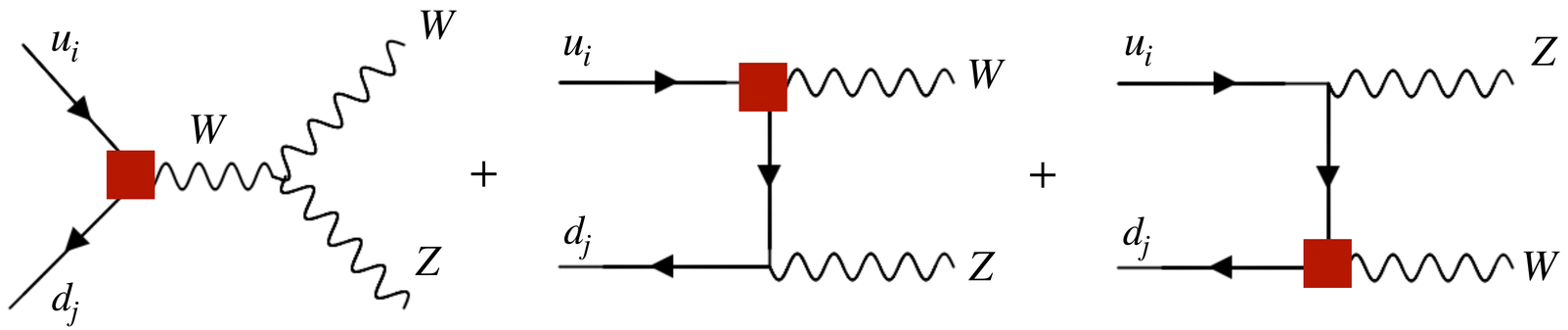

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Modifications to the SM couplings **spoil** the cancellations.

These amplitudes are related by the **Goldstone Boson Equivalence Theorem**.

Goldstone Boson Equivalence Theorem

In the limit $E \gg m_W, m_Z$,

$$\mathcal{M}(q_i \bar{q}_j \to V_0\, V_0') \propto \mathcal{M}(q_i \bar{q}_j \to \phi\, \phi')$$

V_0 → **longitudinal polarization**

ϕ → **Goldstone boson**

B. W. Lee *et al.*, *Phys. Rev. D 16, 1519*, G. J. Gounaris *et al.*, *Phys. Rev. D 34, 3257*, M. Chanowit, *et al.*, *Phys. Rev. D 36, 1490, Nucl.Phys.B 261 (1985) 379-431*, A. Wulzer [1309.6055]

See also R. Franceschini *et al.* [1712.01310]

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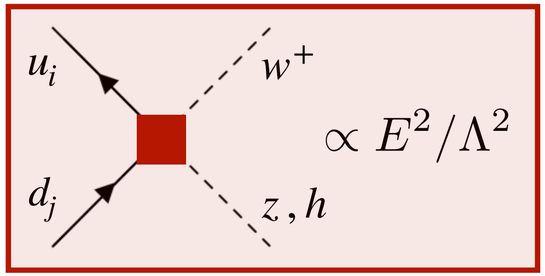

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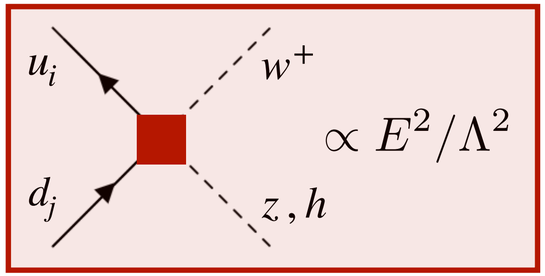

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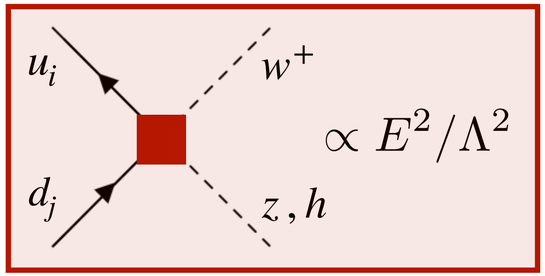

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→ Characteristic of all dim-6 operators modifying **neutral** & **charged** currents.

See also R. Franceschini *et al.* [1712.01310]

Dimension-six Higgs current operators

Only Zh & WW | Only Wh & WZ | Vh and WV

$\mathcal{O}_{\psi^2H^2D}$	Operator
$\mathcal{O}_{Hq}^{(1)}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\bar{q}_i\gamma^\mu q_j\right)$
$\mathcal{O}_{Hq}^{(3)}$	$\left(H^\dagger i\overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_i\gamma^\mu \tau^I q_j\right)$
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Channel	Distribution	Collaboration	N_{obs}	$\mathcal{L}$
$pp \to WW$	$\frac{d\sigma}{dp_T^{\ell\text{lead}}}$	ATLAS	14	36.1 fb^{-1} [42]
	$\frac{dN_{\text{ev}}}{dm_{e\mu}}$	CMS	11	35.9 fb^{-1} [43]
$pp \to WZ$	$\frac{d\sigma}{dm_T^{WZ}}$	ATLAS	12	140 fb^{-1} [44]
	$\frac{1}{\sigma}\frac{d\sigma}{dm_{WZ}}$	CMS	5	137 fb^{-1} [45]
$pp \to Zh$	$\frac{d\sigma}{dp_T^Z}$	ATLAS	5	140 fb^{-1} [30]
		CMS	3	138 fb^{-1} [31]
$pp \to Wh$	$\frac{d\sigma}{dp_T^W}$	ATLAS	5	140 fb^{-1} [30]
		CMS	3	138 fb^{-1} [31]

Kinematic variables related to the **center-of-mass energy.**

Dimension-six Higgs current operators

Only Zh & WW | Only Wh & WZ | Vh and WV

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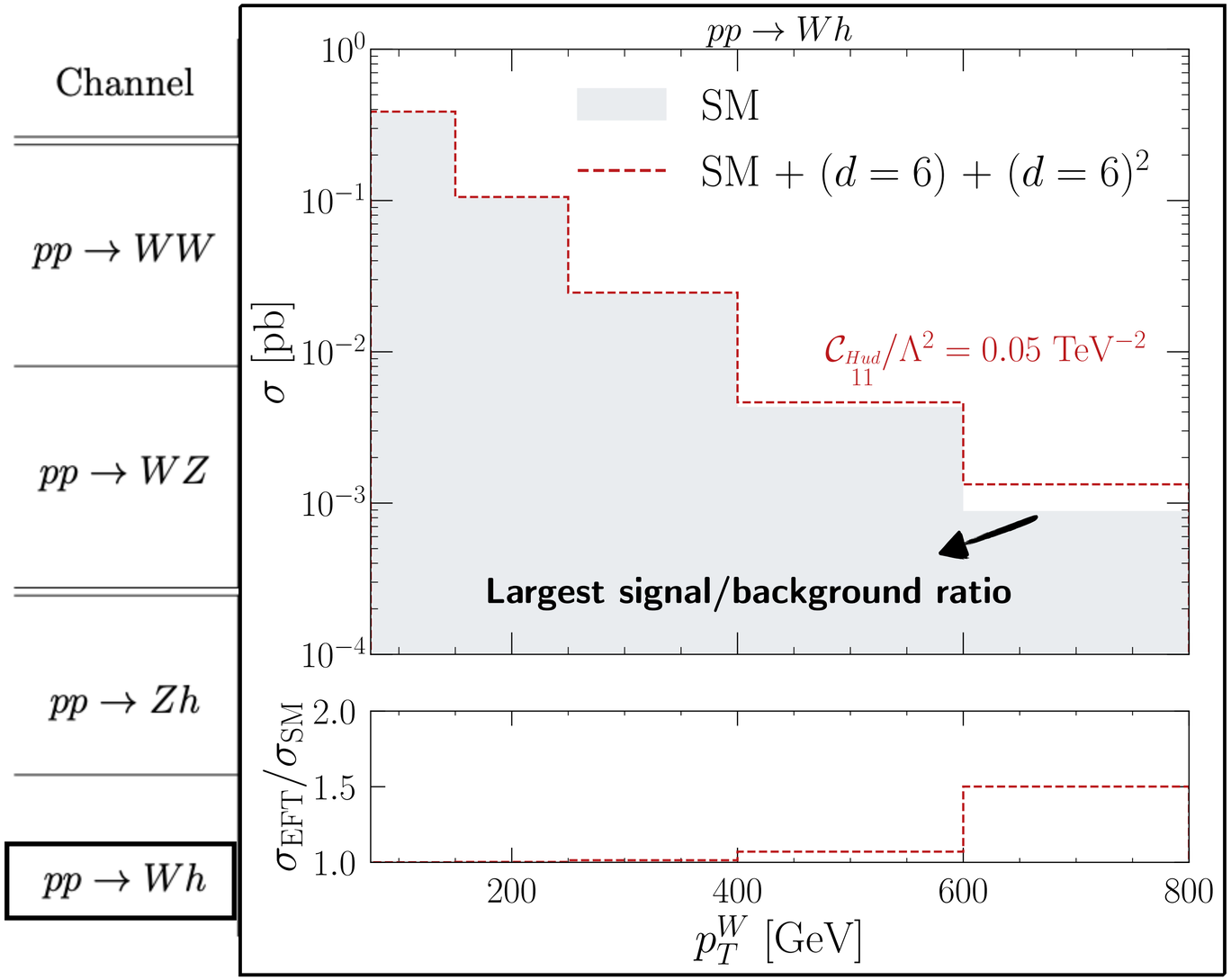
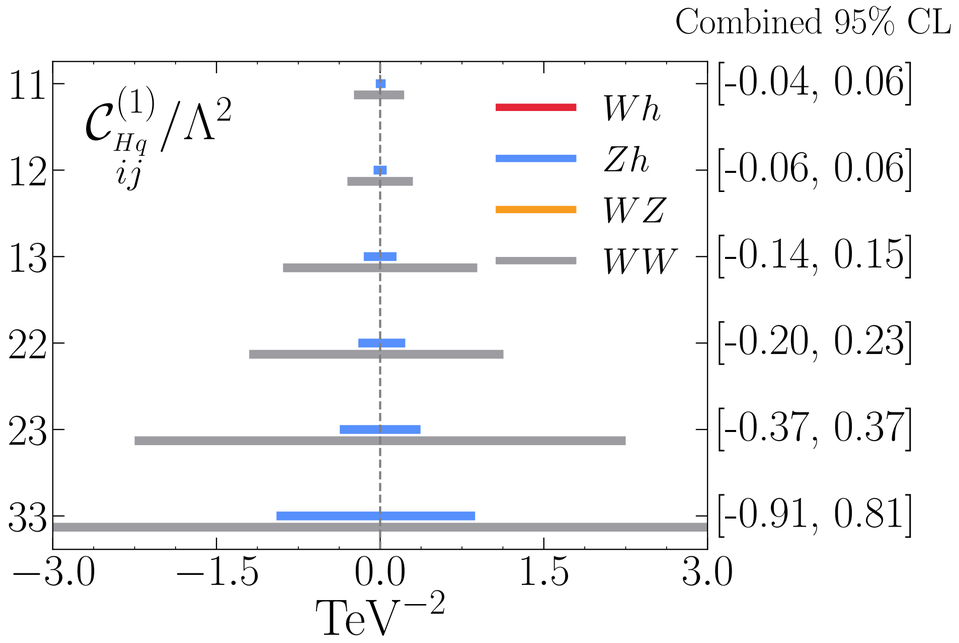
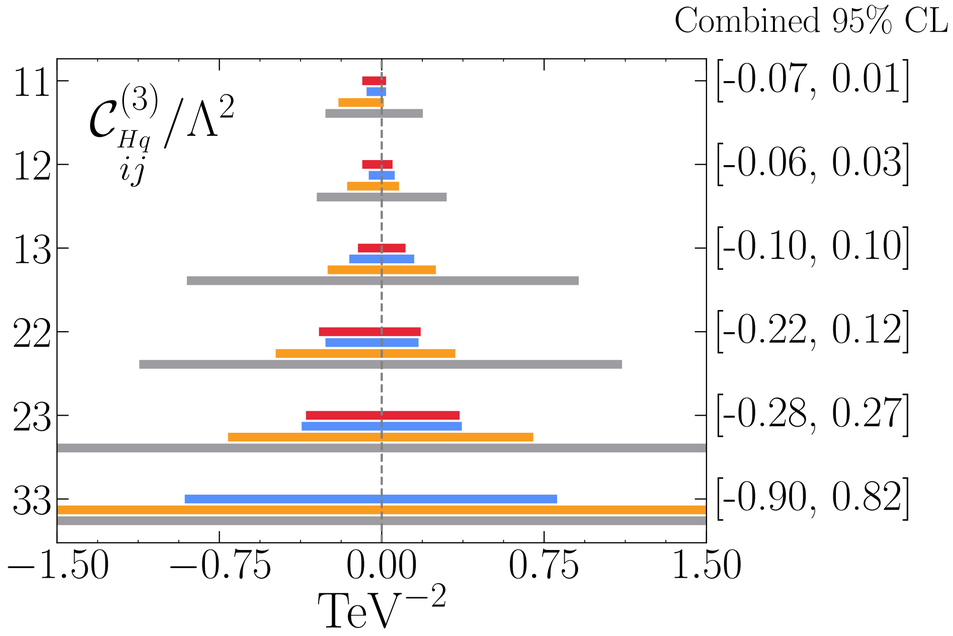
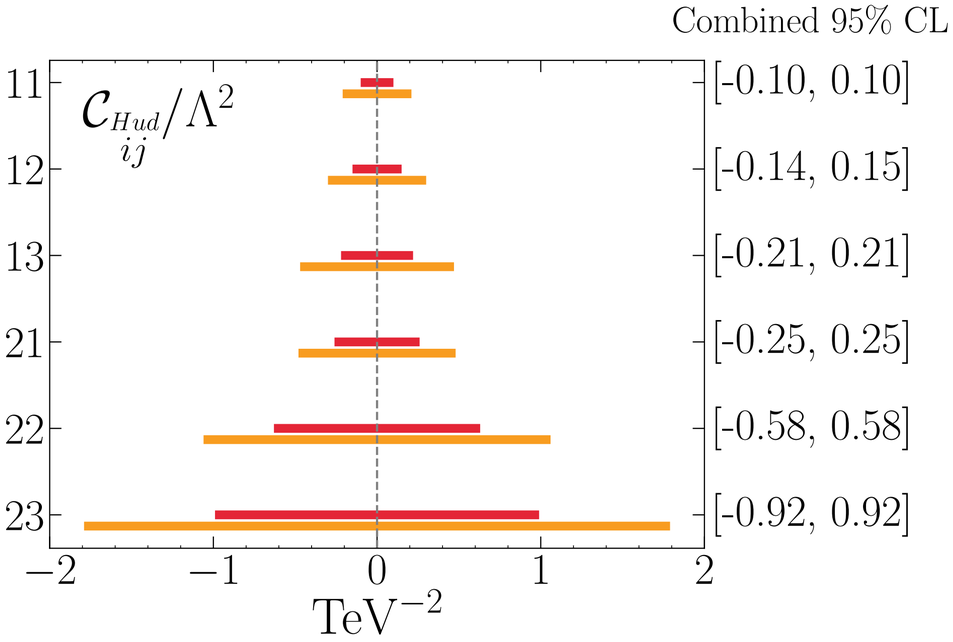


Higgs differential distributions in the format of **Simplified Template Cross-Sections (STXS)** are available. D. De Florian *et al.* [1610.07822]

Single parameter limits







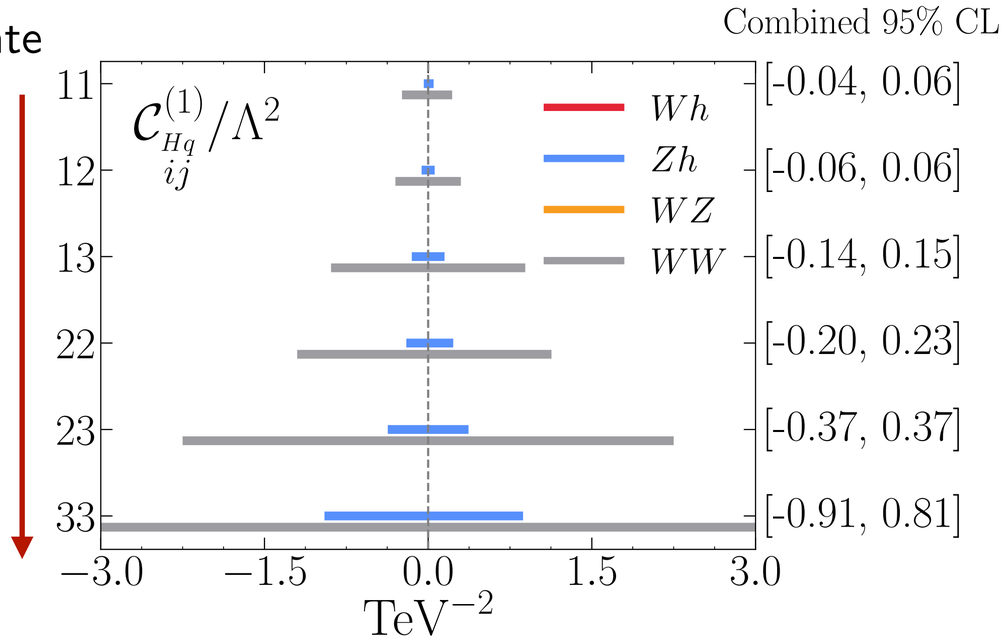
$$\sigma = \sigma_{\rm SM} + \frac{1}{\Lambda^2}\sigma_{\rm Int} + \frac{1}{\Lambda^4}\sigma_{\rm NP^2}$$

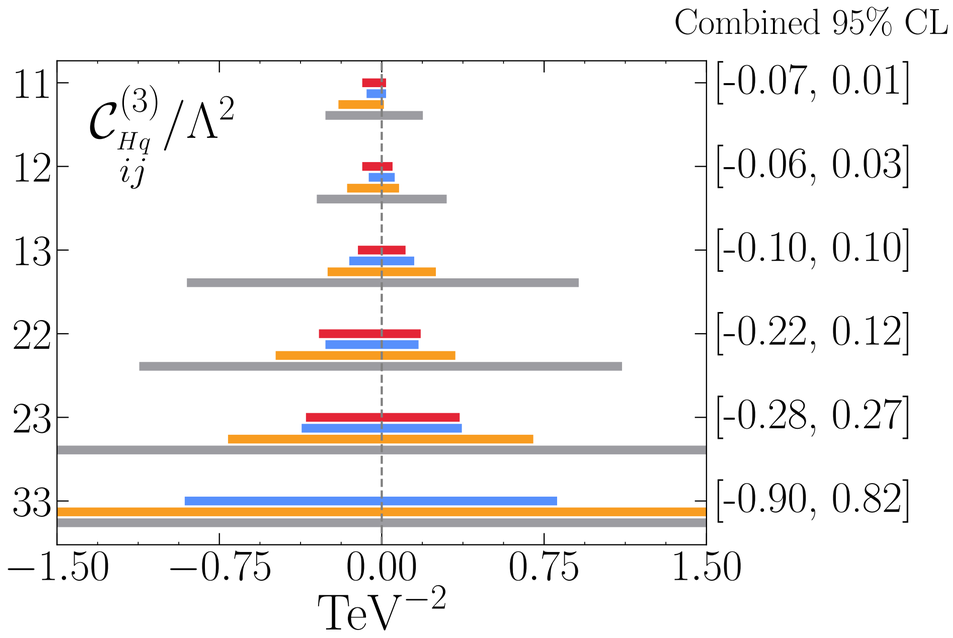
Considering a **single Wilson coefficient at the time.*

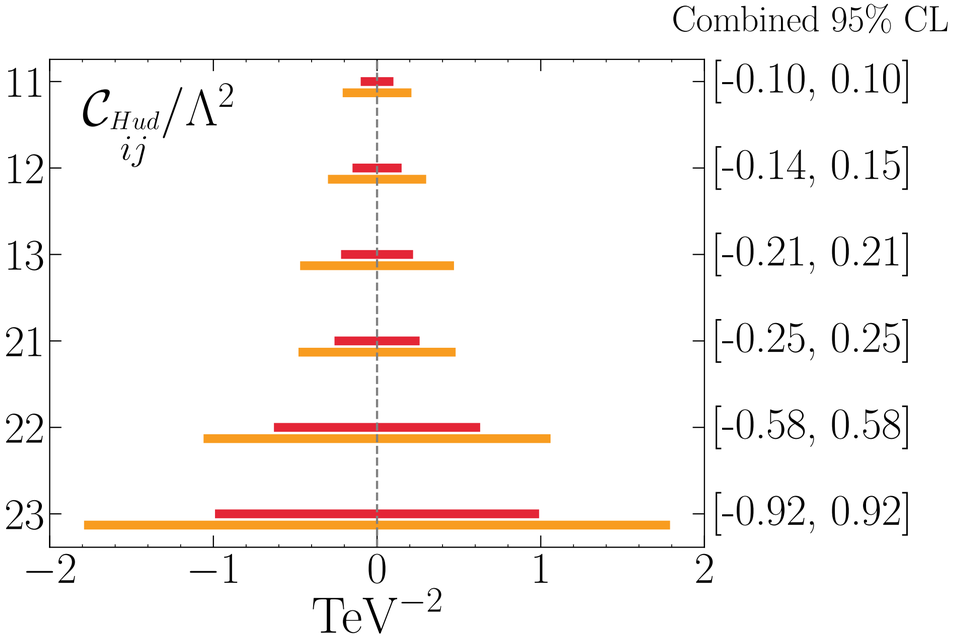
[O. J. P. Éboli, L. P. S. Leal, **MM**, O. Sumensari, 2509.08437]

Single parameter limits

Initial state masses







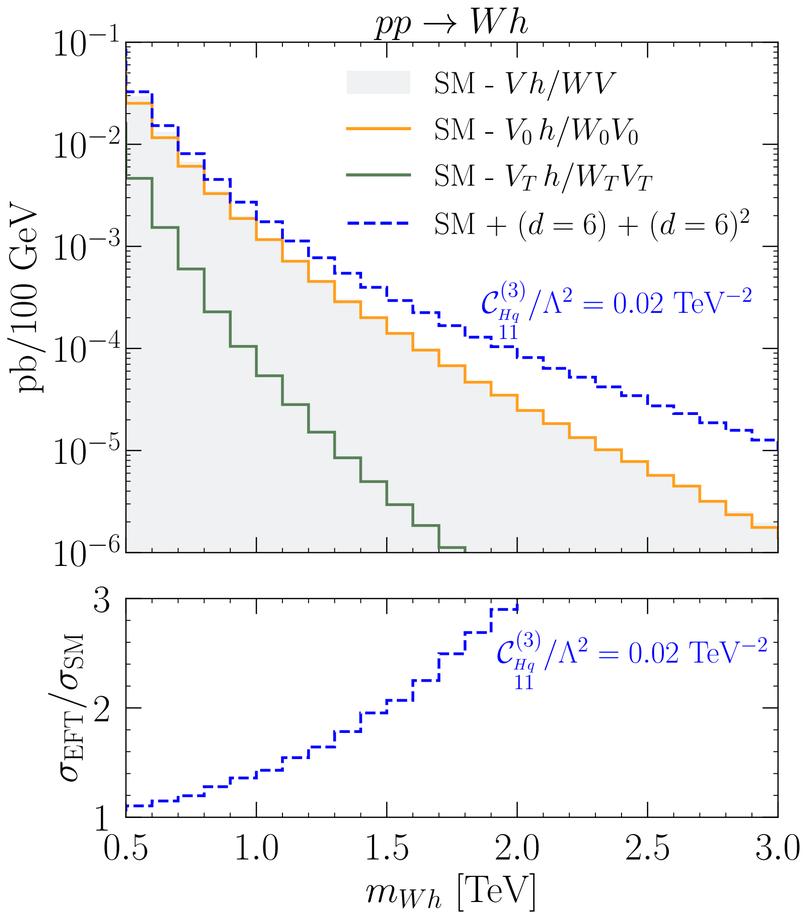
Heavier initial states lead to **weaker** constraints due to **PDF** suppression.

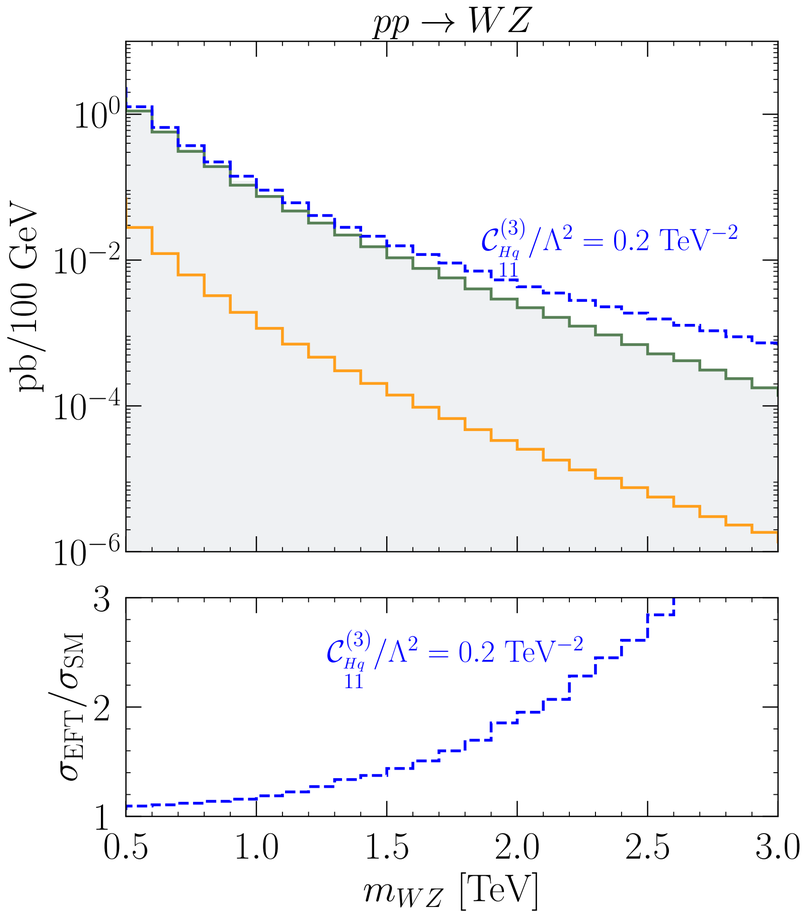
Limits from Vh are a factor of 2 **stronger** than WV when considering Run 2 data.

Considering a **single Wilson coefficient at the time.*

[O. J. P. Éboli, L. P. S. Leal, **MM**, O. Sumensari, 2509.08437]

Differential distributions



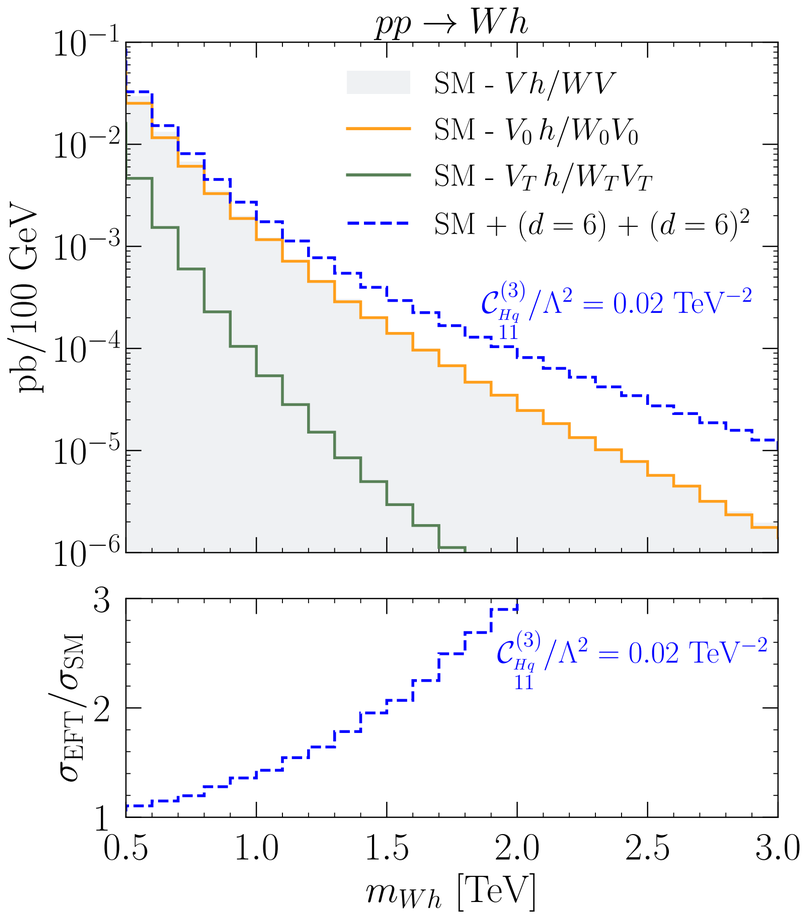


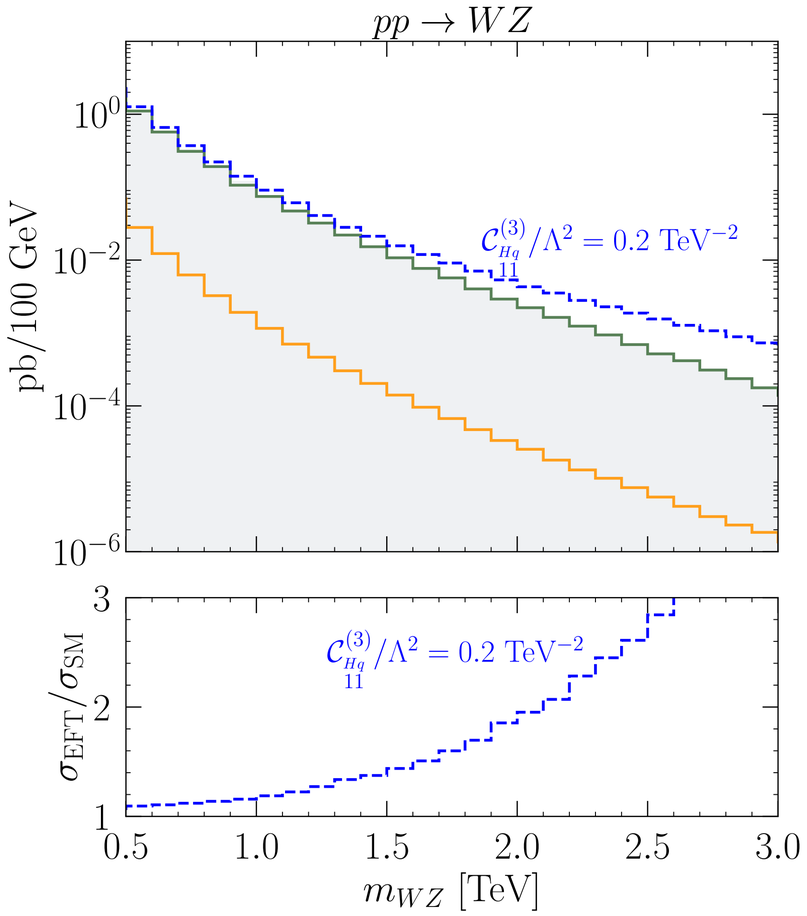
In diboson production channels, **transverse** polarizations **dominate** compared to **longitudinal** modes.

R. Franceschini *et al.* [1712.01310]

Differential distributions

*Examples where **Higgs** and **DY** data are important.*





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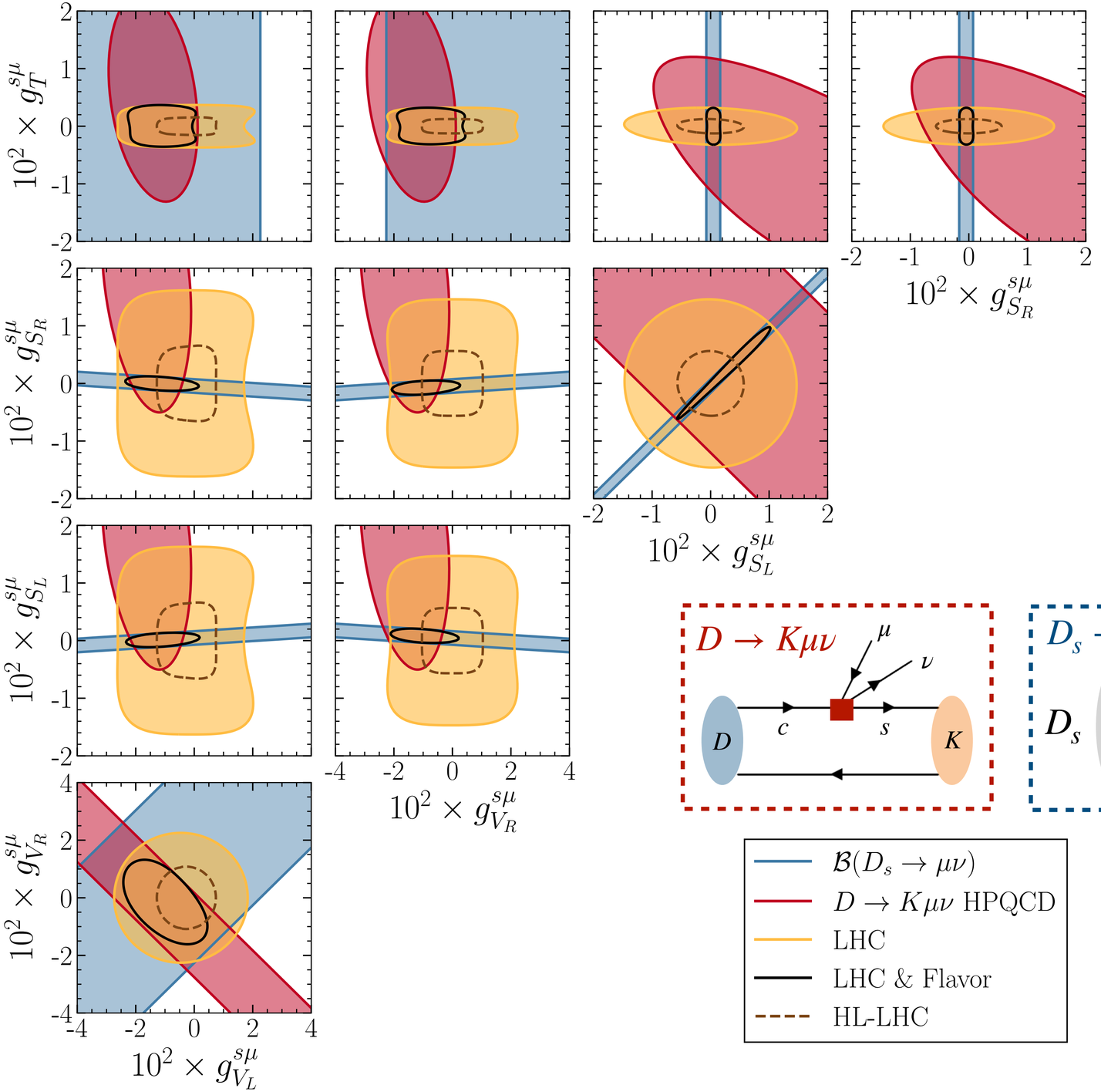
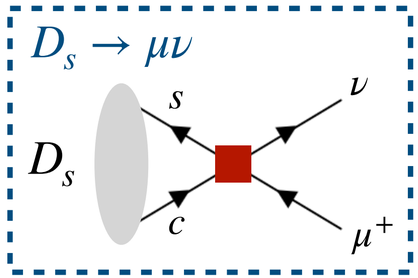
LHC & Flavor I: $c \to s\mu\nu$

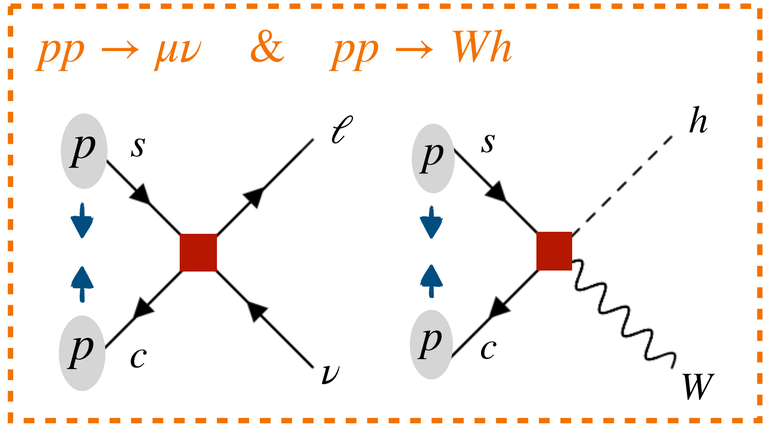


Assuming all coefficients to be **real**.

DY & VH data allows to constrain **all** parameter space.

All scenarios are **consistent** with the **SM** within 2σ.





[D. Becirevic, **MM,** S. Rosauro-Alcaraz, O. Sumensari, 2603.25837]

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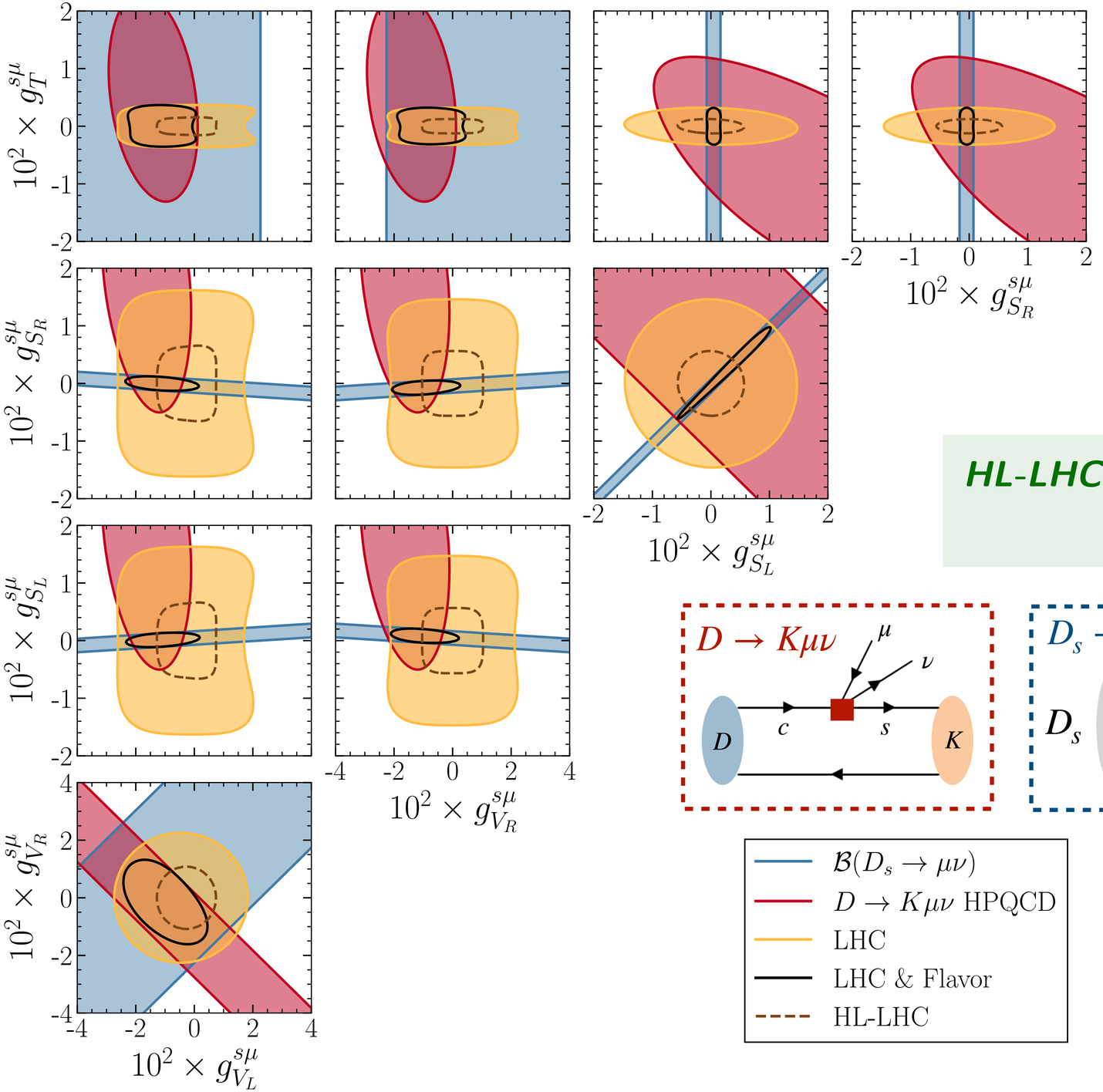

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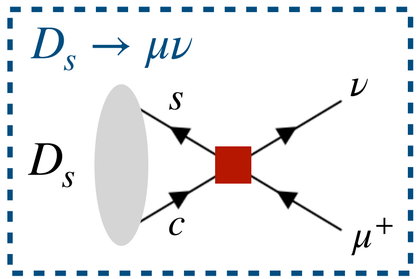
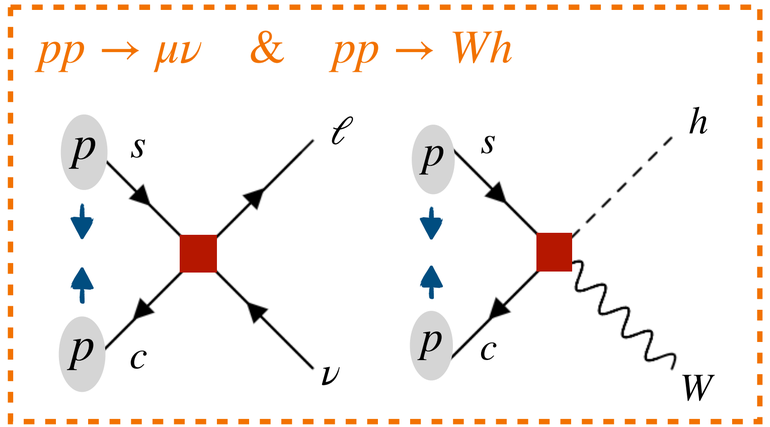
***HL-LHC** will further **improve** the limits on **charged-current** interactions.*



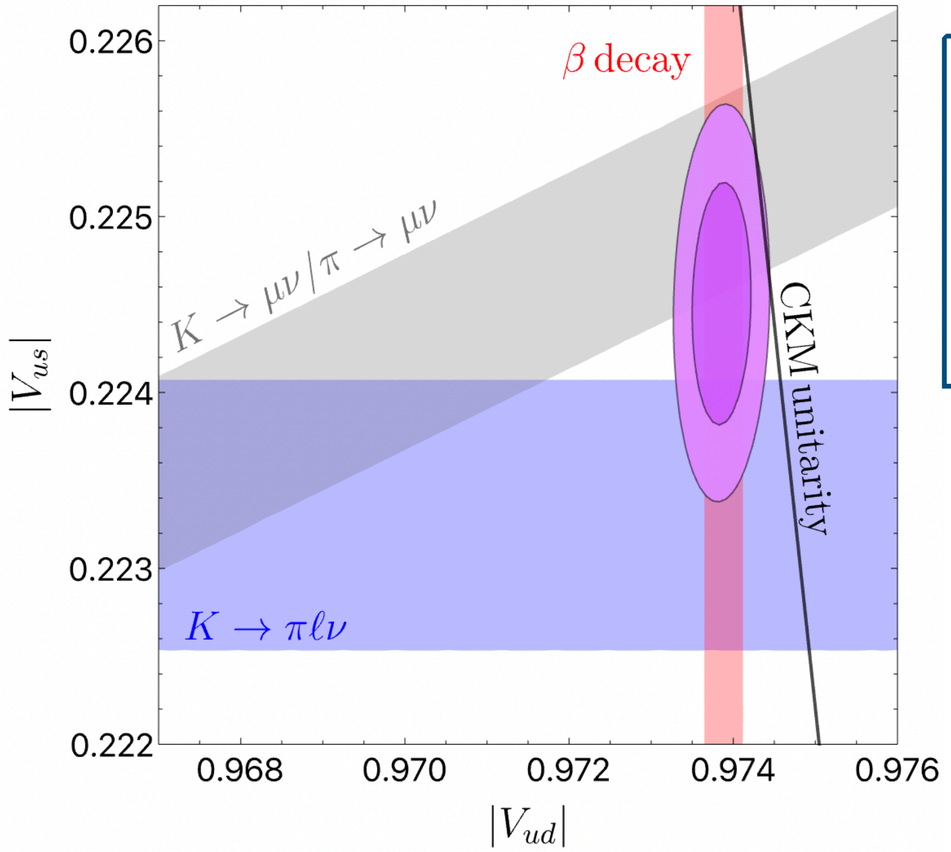


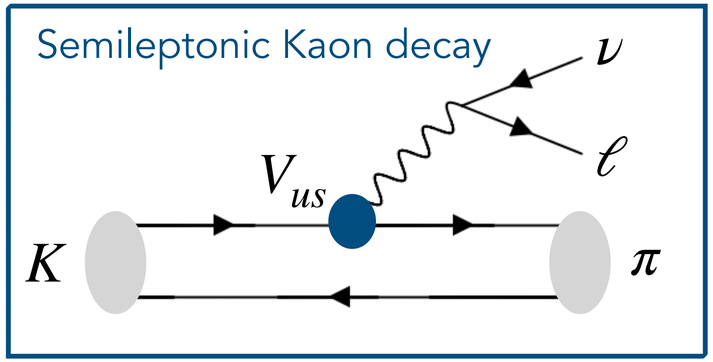
[D. Becirevic, **MM,** S. Rosauro-Alcaraz, O. Sumensari, 2603.25837]

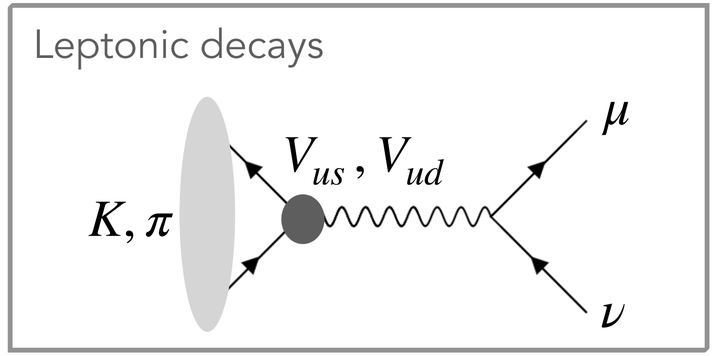
LHC & Flavor II: First-row CKM unitarity

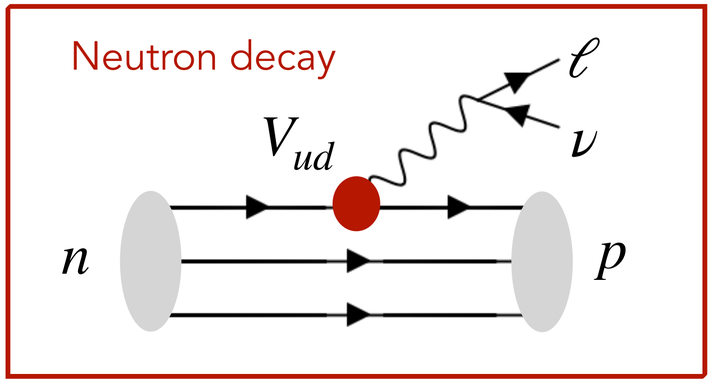
$$\Delta^{\text{global}}_{\text{CKM}} \equiv |V_{ud}|^2_{\text{global}} + |V_{us}|^2_{\text{global}} + |V_{ub}|^2 - 1 = -0.001\,51(53)$$ ~ 3σ tension with **CKM** unitarity.

A. Crivellin *et al.* [2212.06862], [2008.01113], B. Belfatto *et al.* [1906.02714], Y. Grossman *et al.* [1911.07821], M. Kirk [2008.0113], A. K. Alok *et al.* [2108.05614], and many more...









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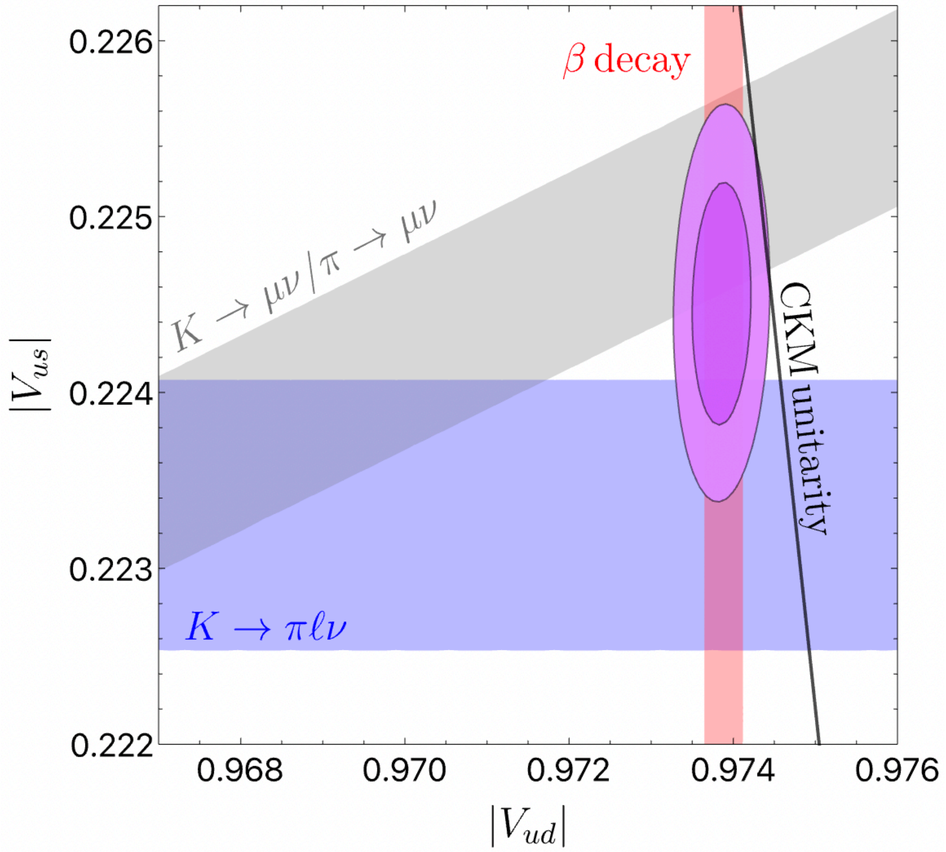
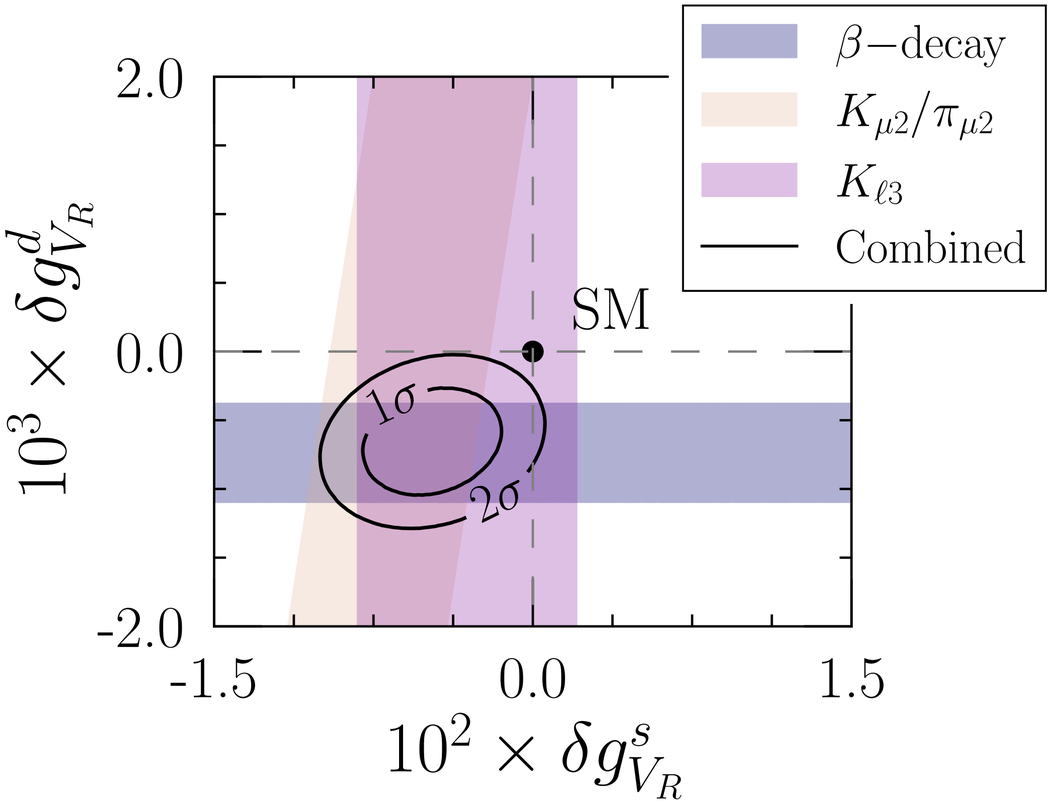
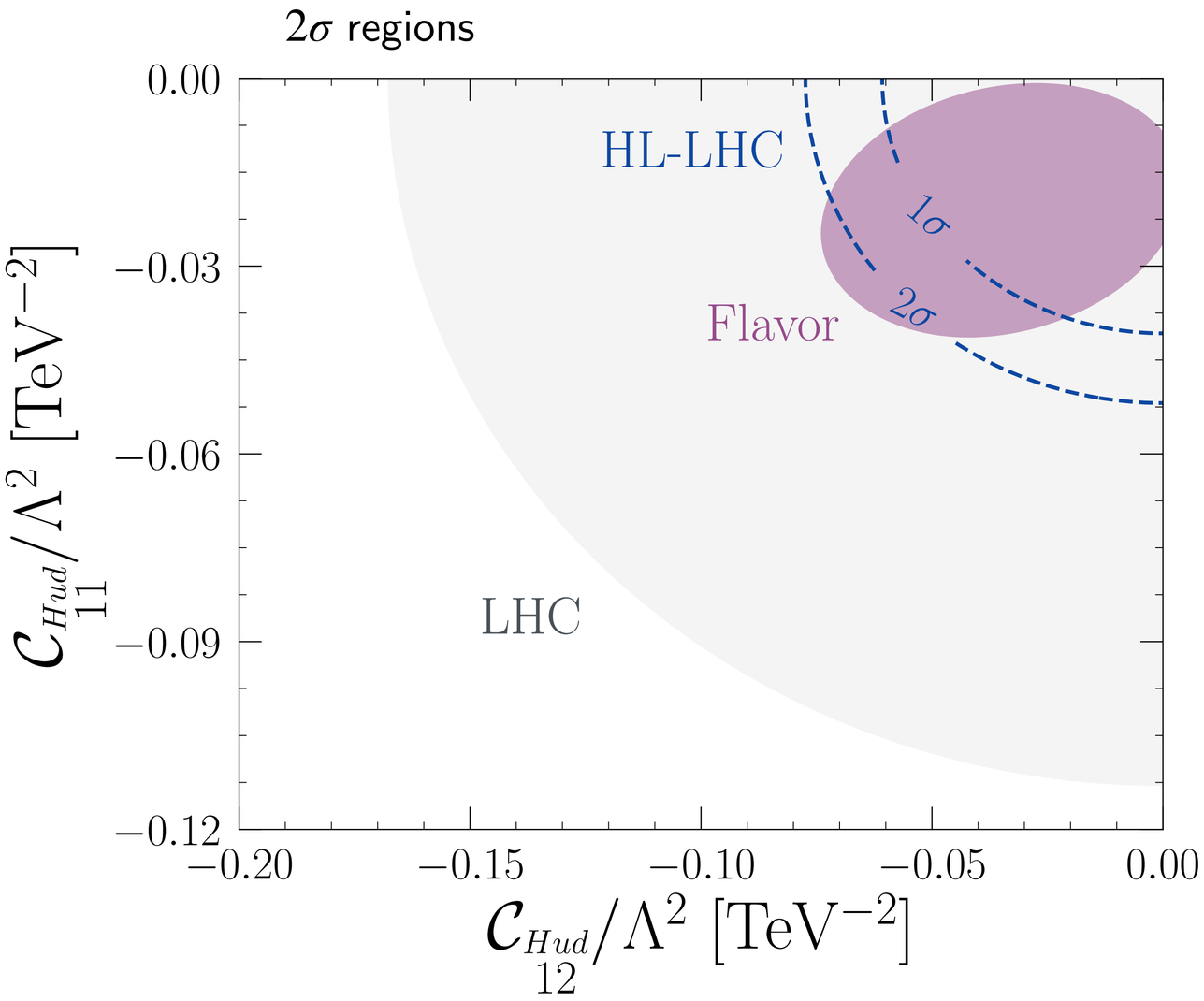


Assuming the discrepancy arises from NP, **RH CC** could offer a viable explanation. V. Cirigliano *et al.* [2208.11707]



[O. J. P. Éboli, L. P. S. Leal, **MM**, O. Sumensari, 2509.08437]

LHC & Flavor II: First-row CKM unitarity



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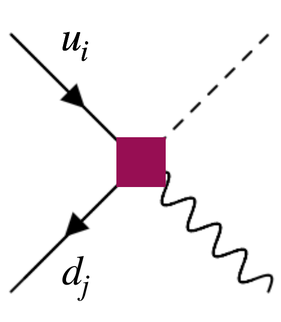
LHC and HL-LHC limits are dominated by Wh production.

HL-LHC has the potential to provide constraints that are **competitive** with those from **flavor observables.**



$$\mathcal{M}(u_R^i\,\overline{d}_R^j \to W_0\,h) = -\frac{i}{\sqrt{2}}\frac{E^2\sin\theta}{\Lambda^2}\mathcal{C}^*_{Hud\,ij}$$

Summary

LHC data offer **complementary constraints** to low-energy processes, benefiting from **energy-enhanced** effects in the high-p_T tails.

Diboson (**VV**) and Higgs-associated (**VH**) production processes can **probe** Wilson coefficients that are **poorly constrained** by Drell–Yan data.

The **combination** of **DY** and **VH** production allows to constrain all couplings affecting **charged-current** interactions.

Soon to be implemented in ***HighPT Mathematica*** package. [github.com/HighPT/HighPT]

*The **HL-LHC** could help clarify **flavor anomalies**, such as the Cabibbo angle anomaly, and provide meaningful constraints on several transitions.*

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Thank you!

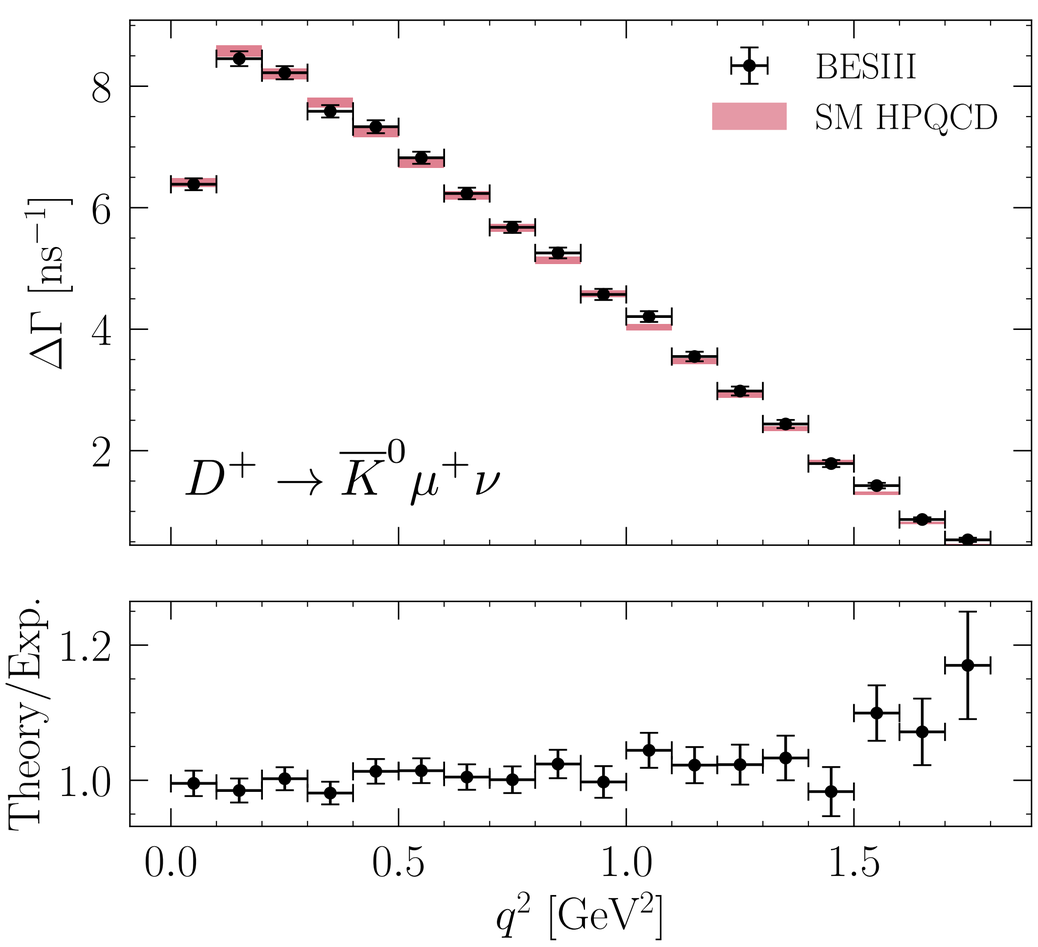
Backup

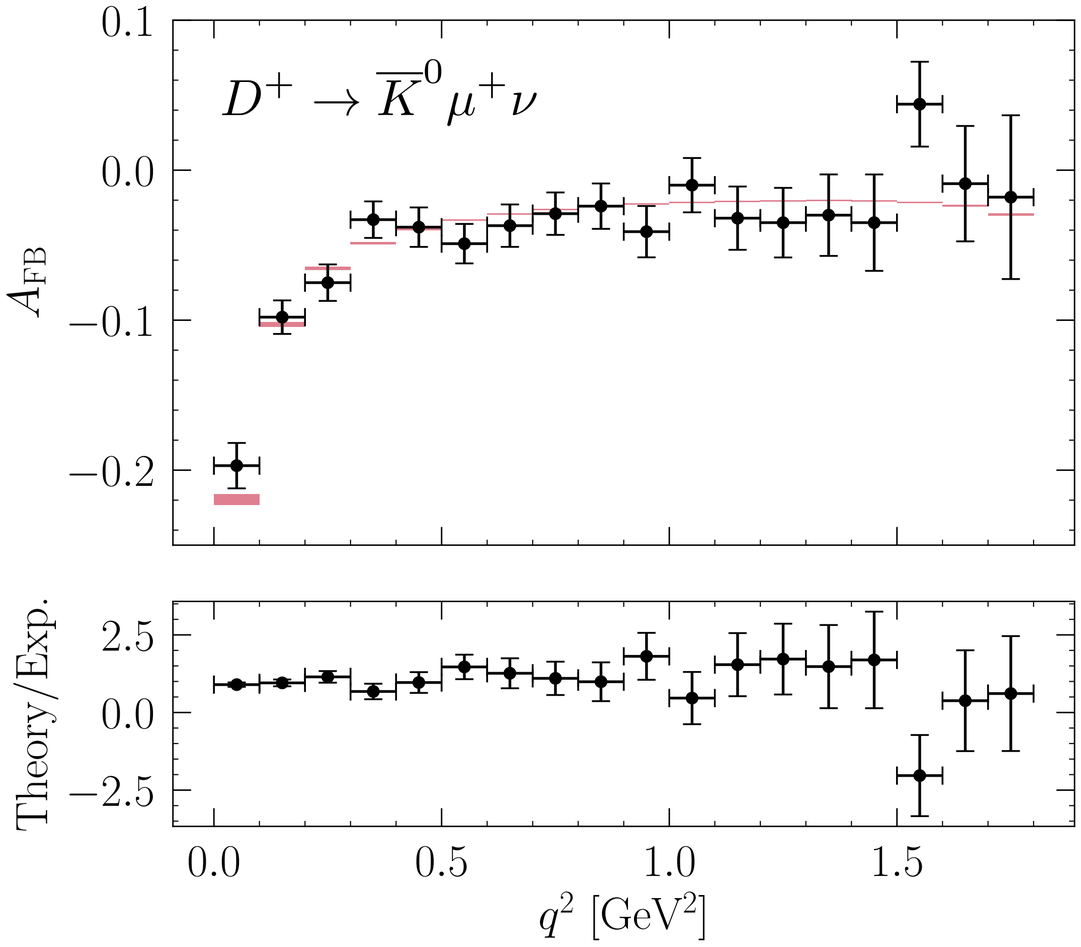
Interpreting the results on exclusive $c \to s\mu\nu$ modes

Illustration II: BESIII measurements on $c \to s\mu\nu$ modes

BESIII measurements on total branching ratio and forward-backward asymmetry are **consistent** with the SM prediction. [2601.21196, 2601.21185]

Mild tension present in the q^2 distribution.





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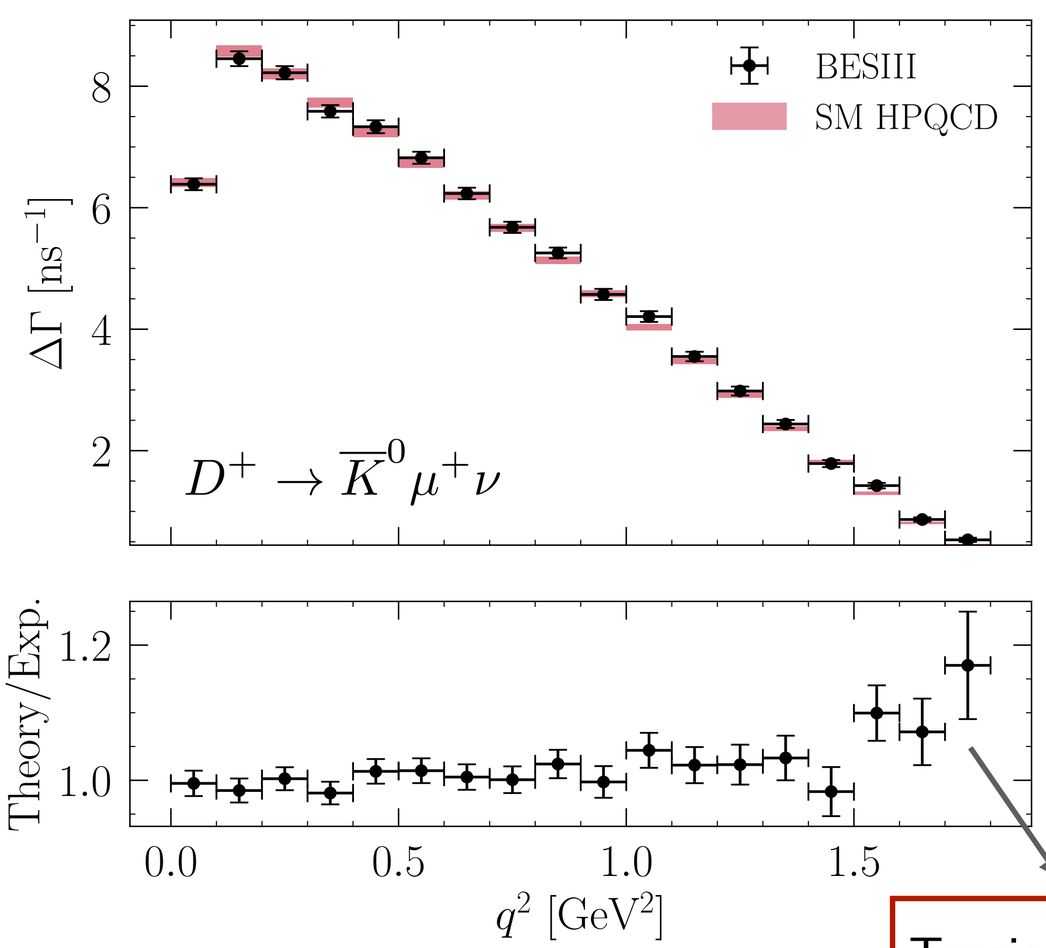

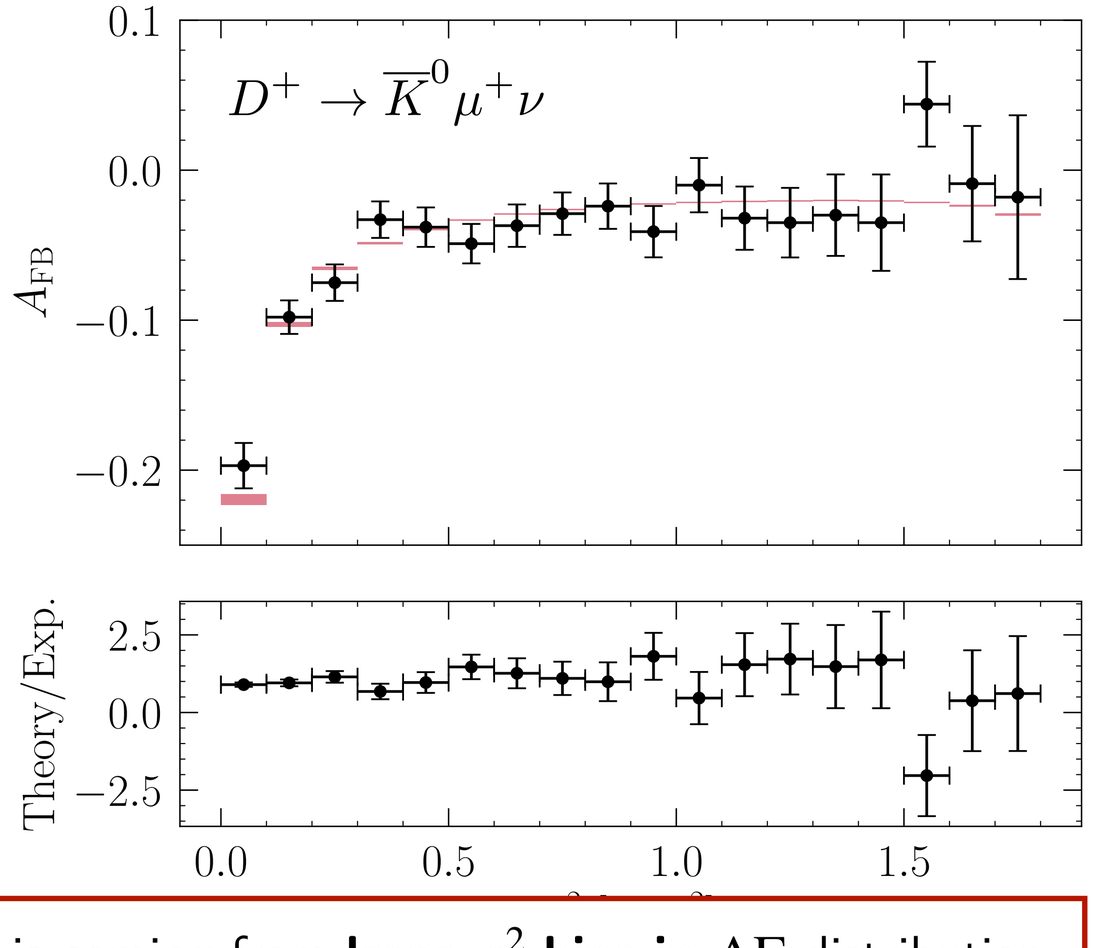

Tension is coming from **large q^2 bins in $\Delta\Gamma$** distribution.

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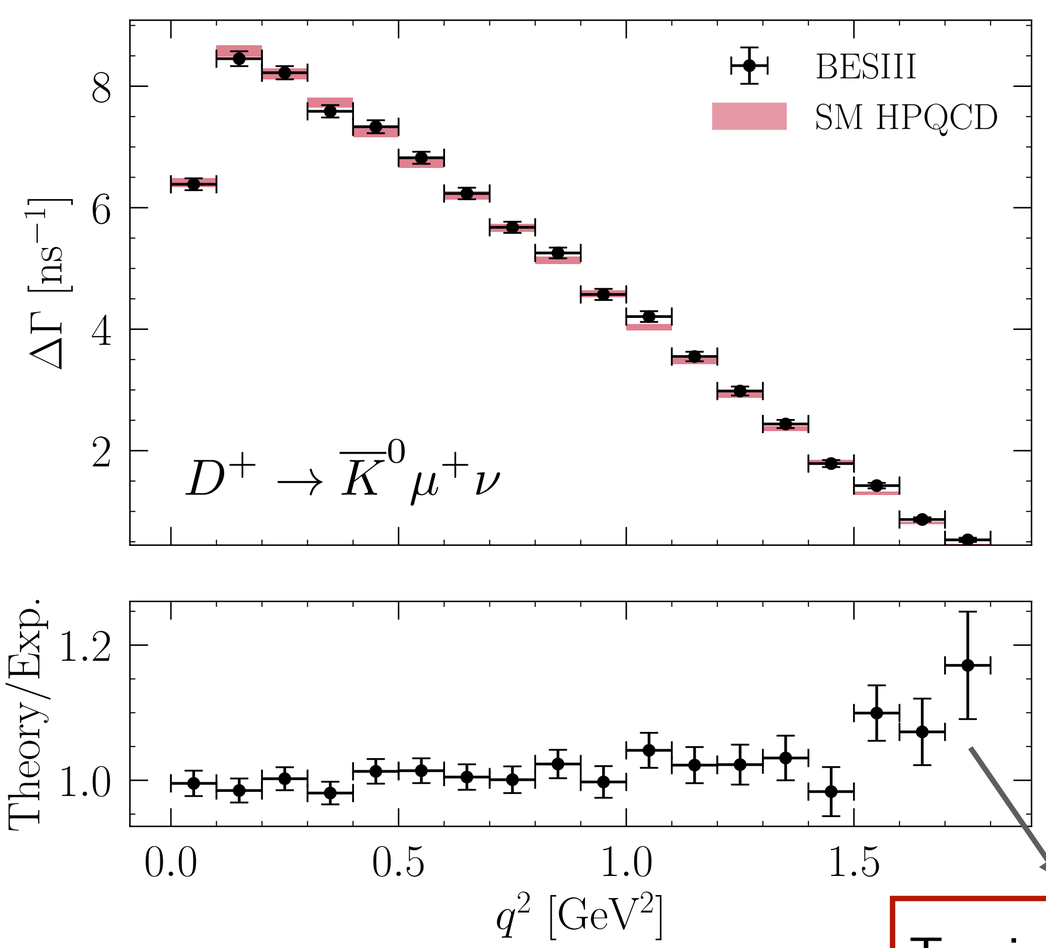
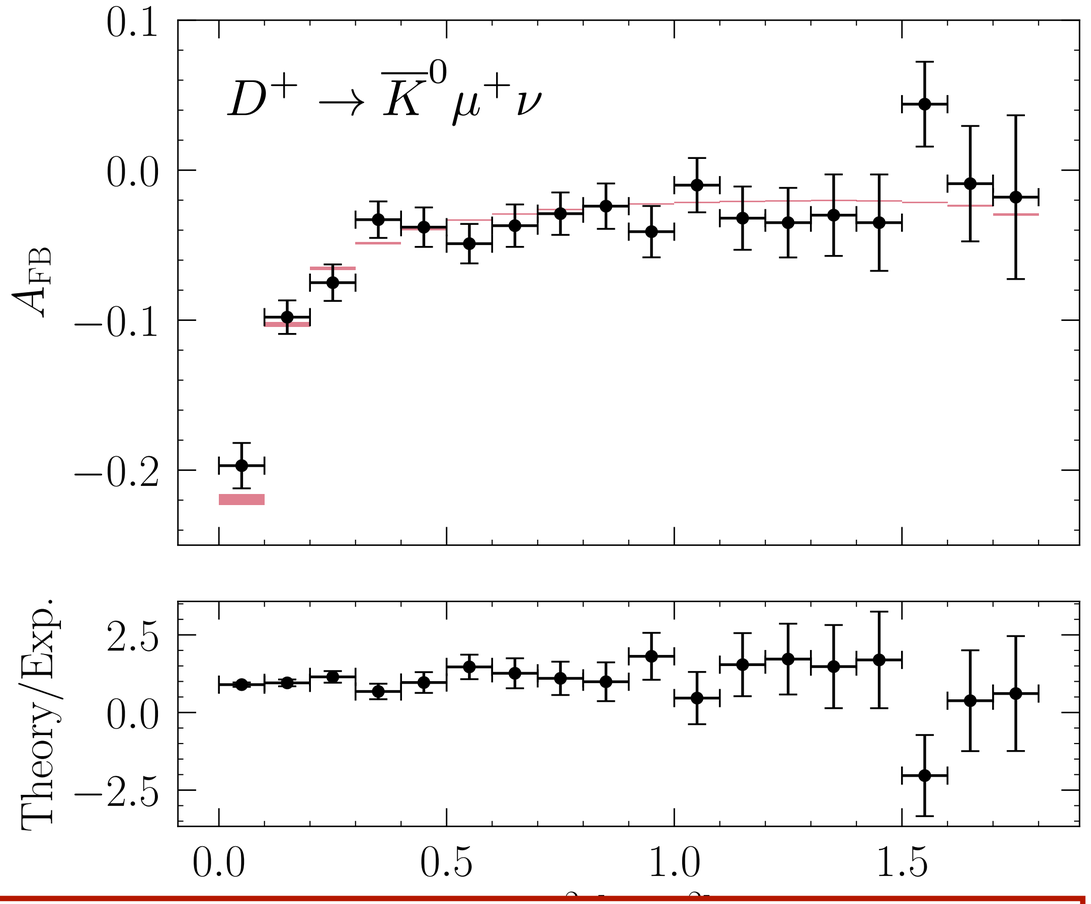
Which **EFT operators** could alleviate this tension?





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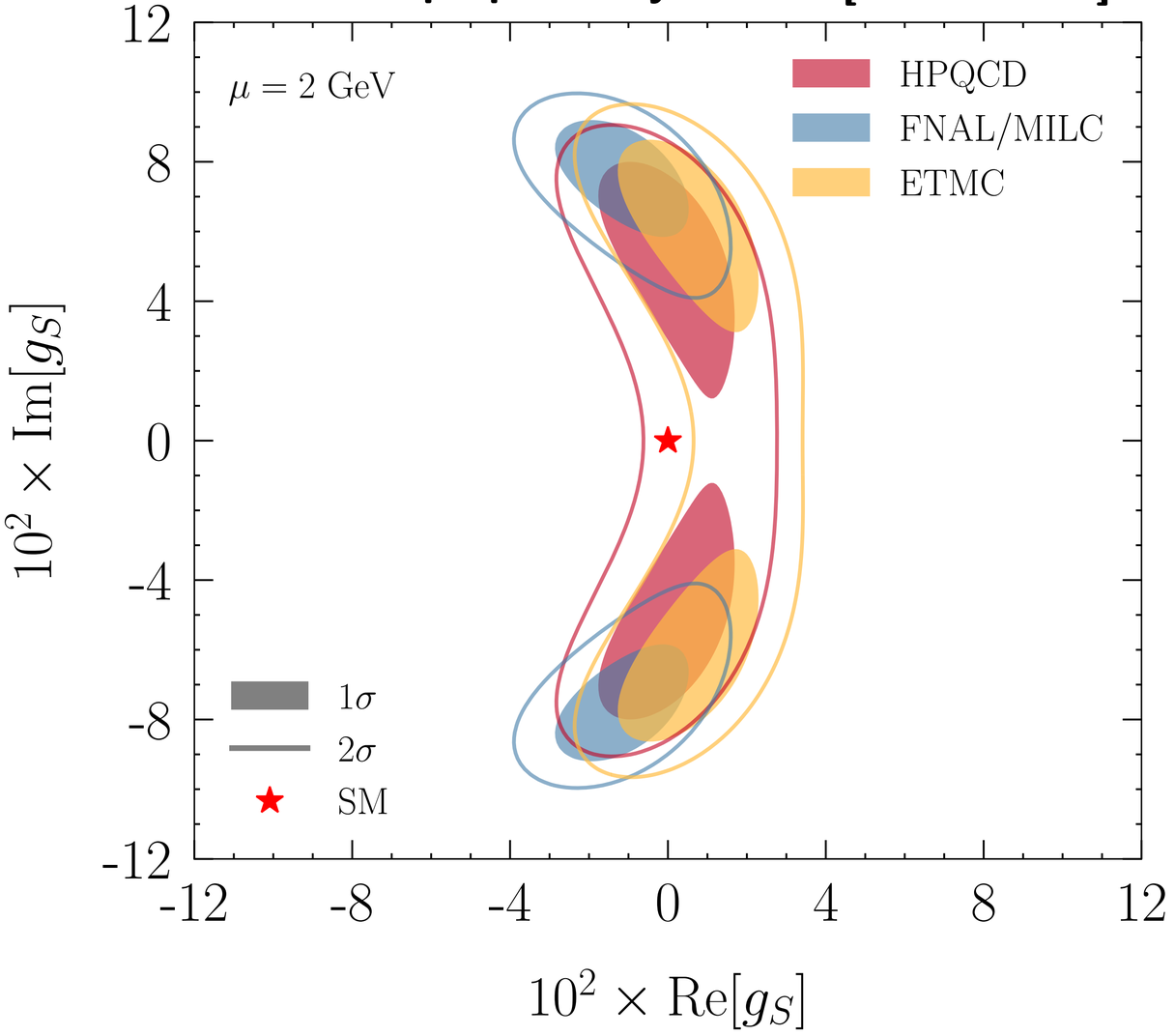
Complex scalar coupling

Solution proposed by BESIII [2601.21185]



[D. Becirevic,, **MM,** S. Rosauro-Alcaraz, O. Sumensari, 2603.25837]

Complex scalar coupling can alleviate the tension.

The tension is present regardless of the **form-factor parametrization.**

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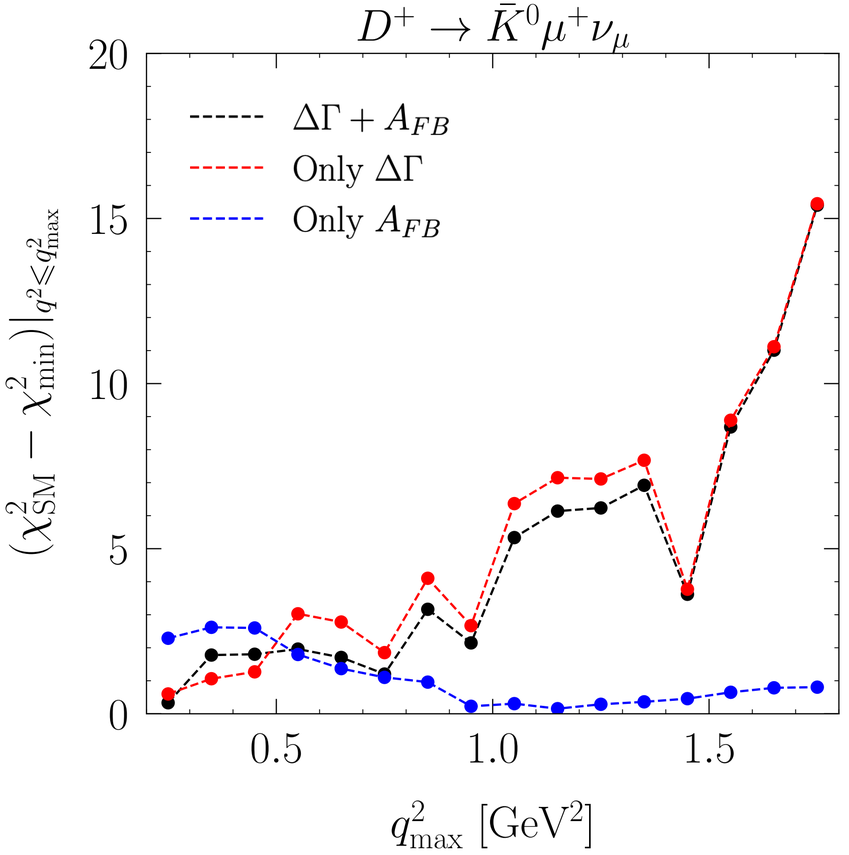

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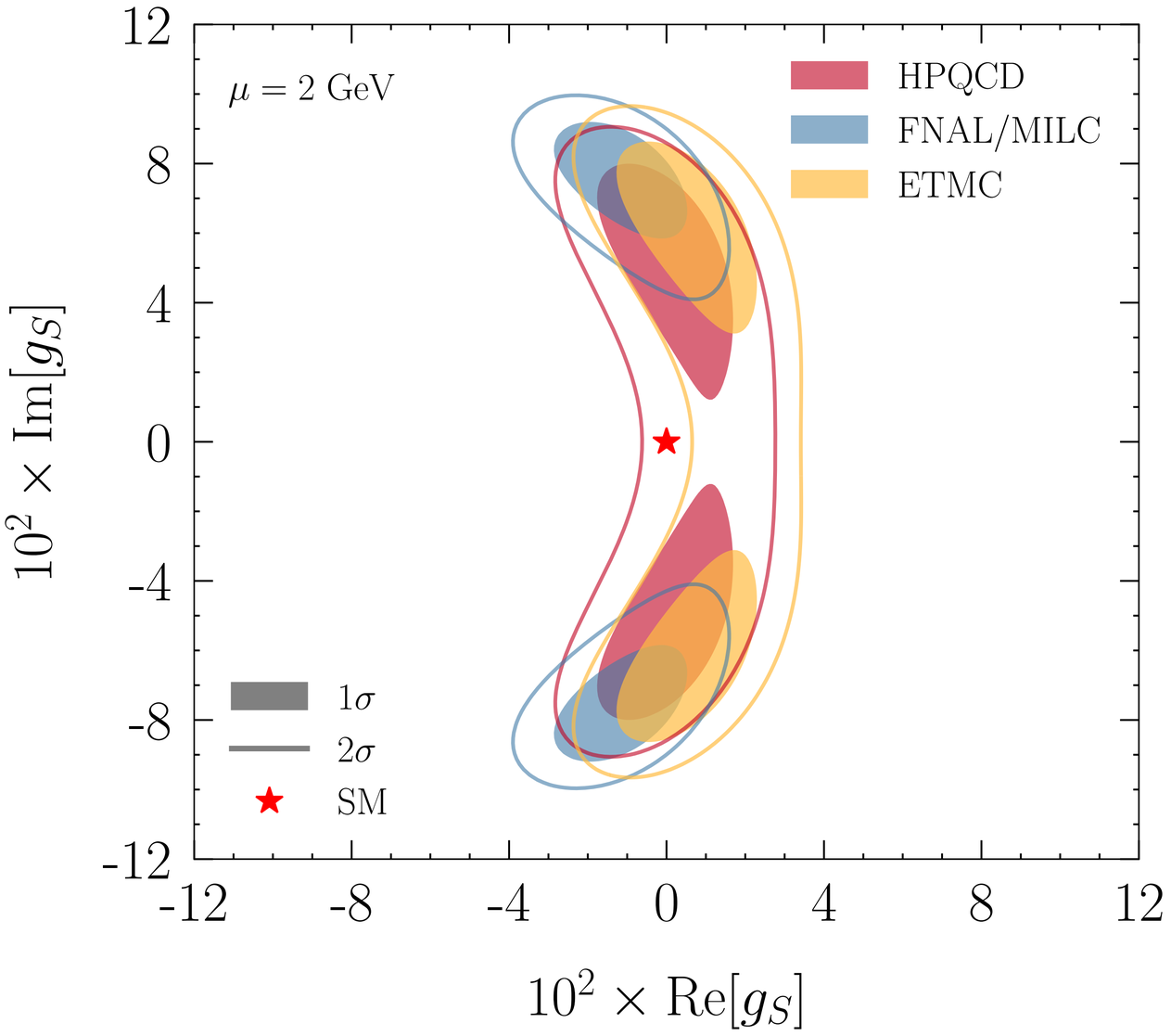

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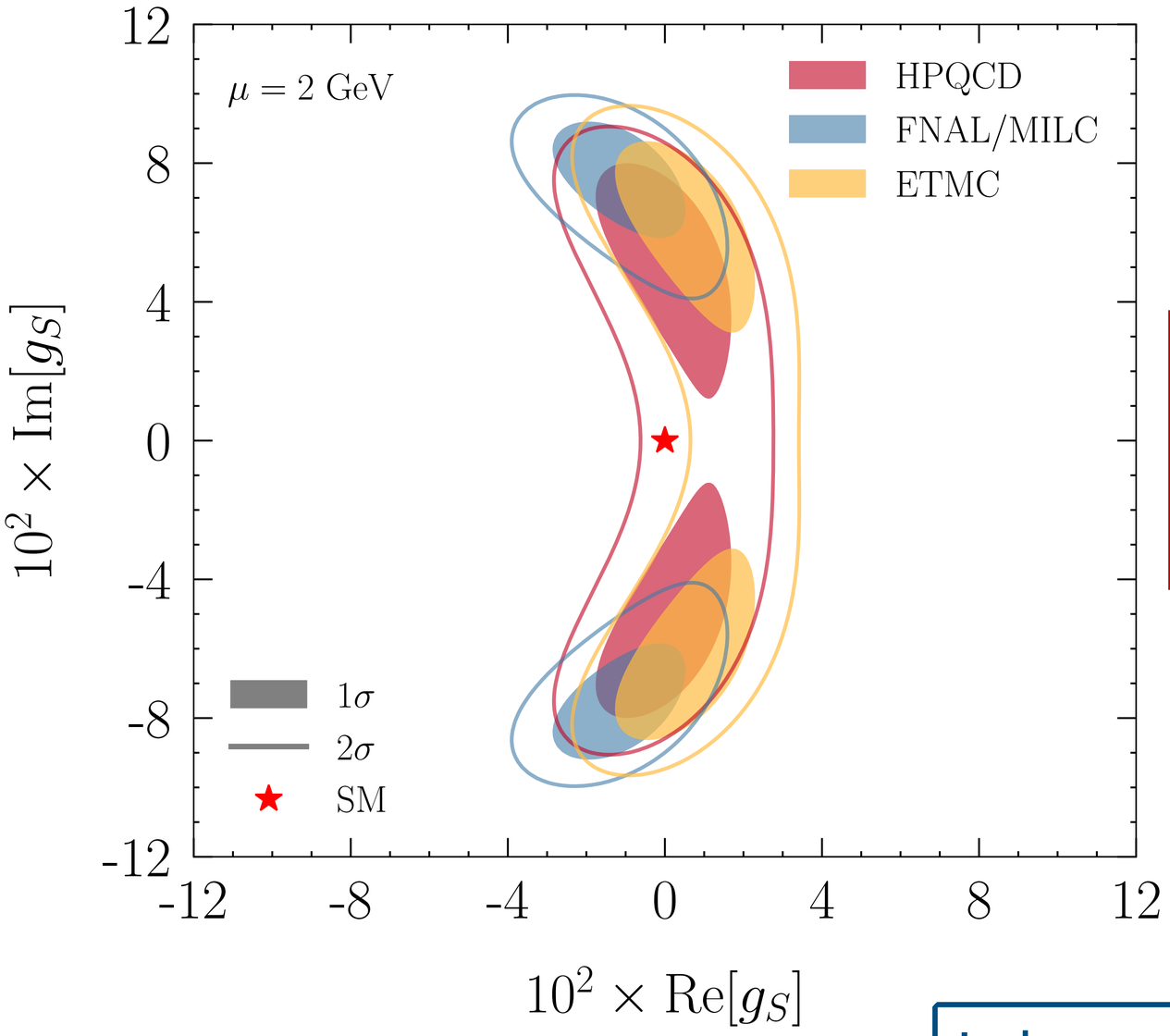

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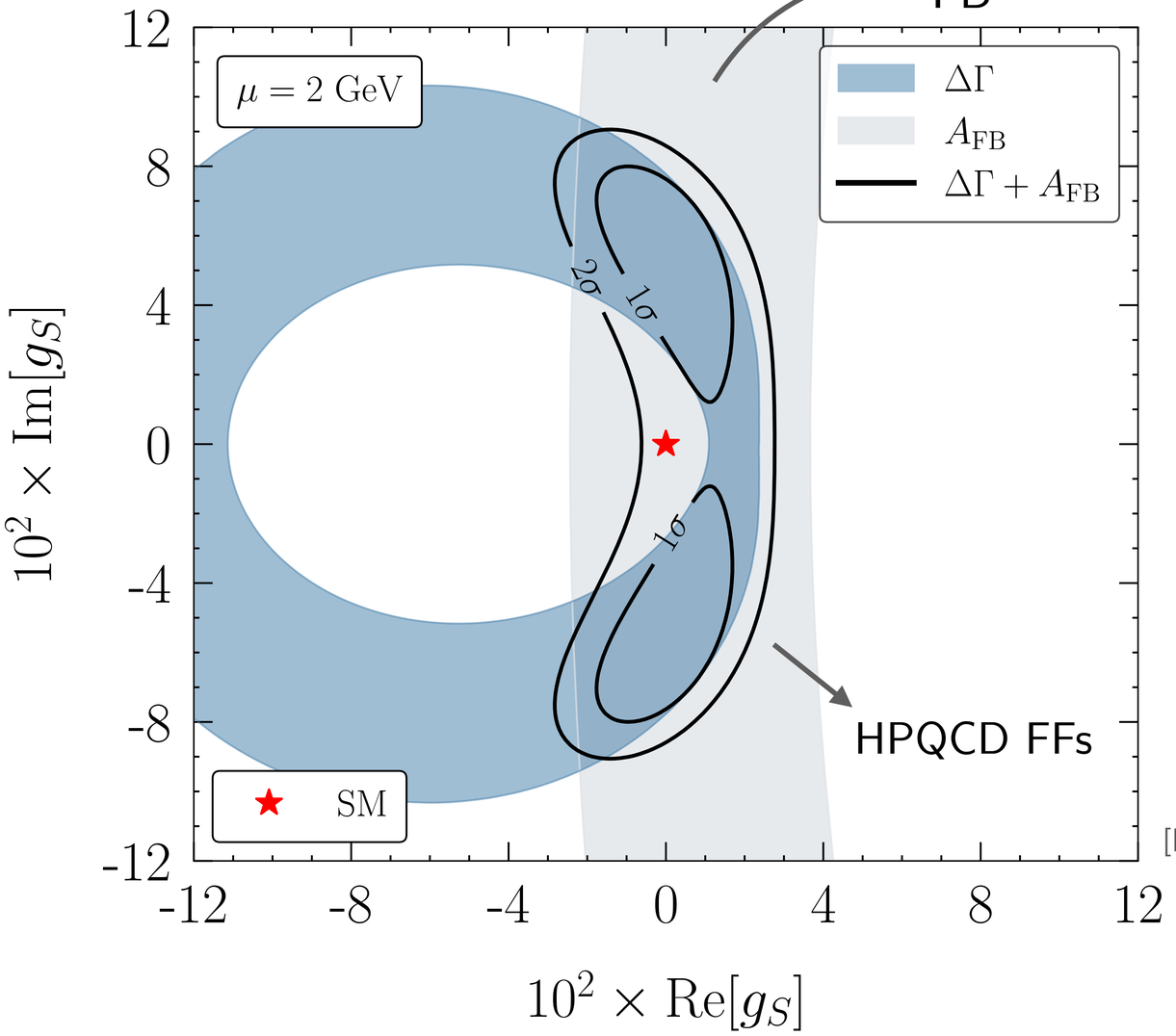
Is the proposed solution consistent with high-p_T bounds?

Complex scalar coupling



$A_{\rm FB}$ is **linearly** sensitive to the real part of the **scalar** coupling.

D. Becirevic et al. [2012.09872], S. Fajfer et al. [1502.07488]

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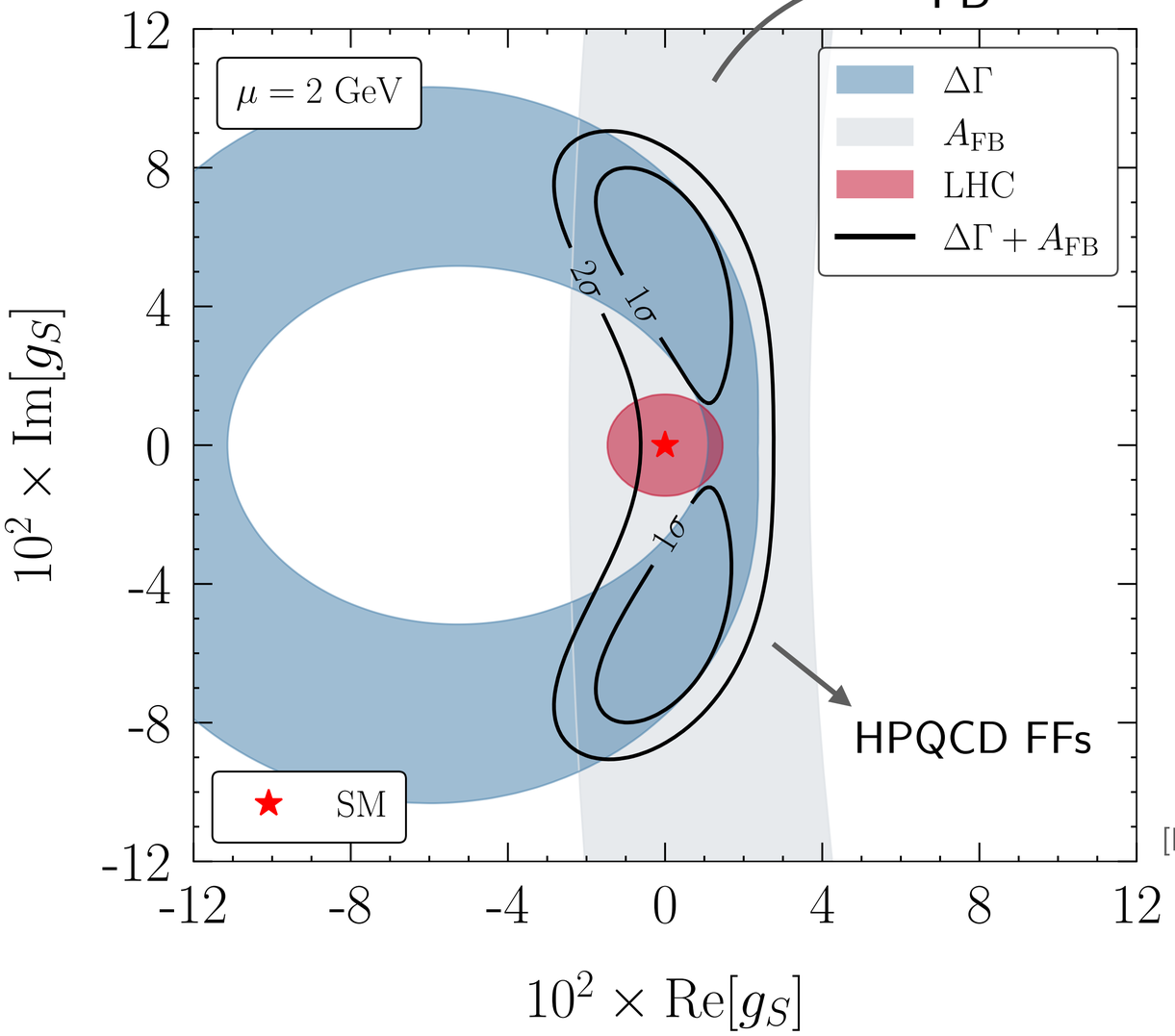

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- **High-**p_T bounds provides stringent constraints, **excluding** the 1σ preferred region.

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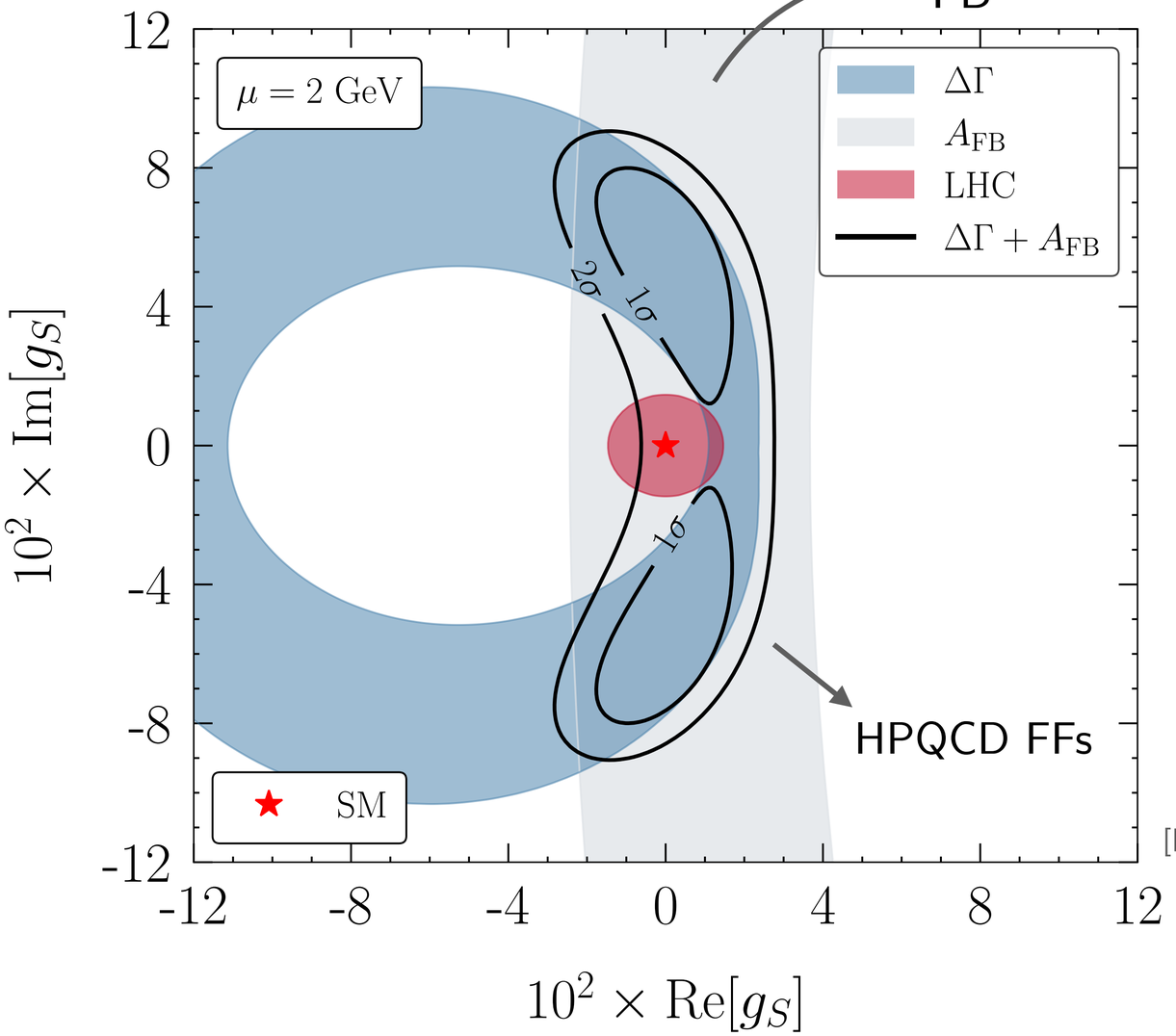

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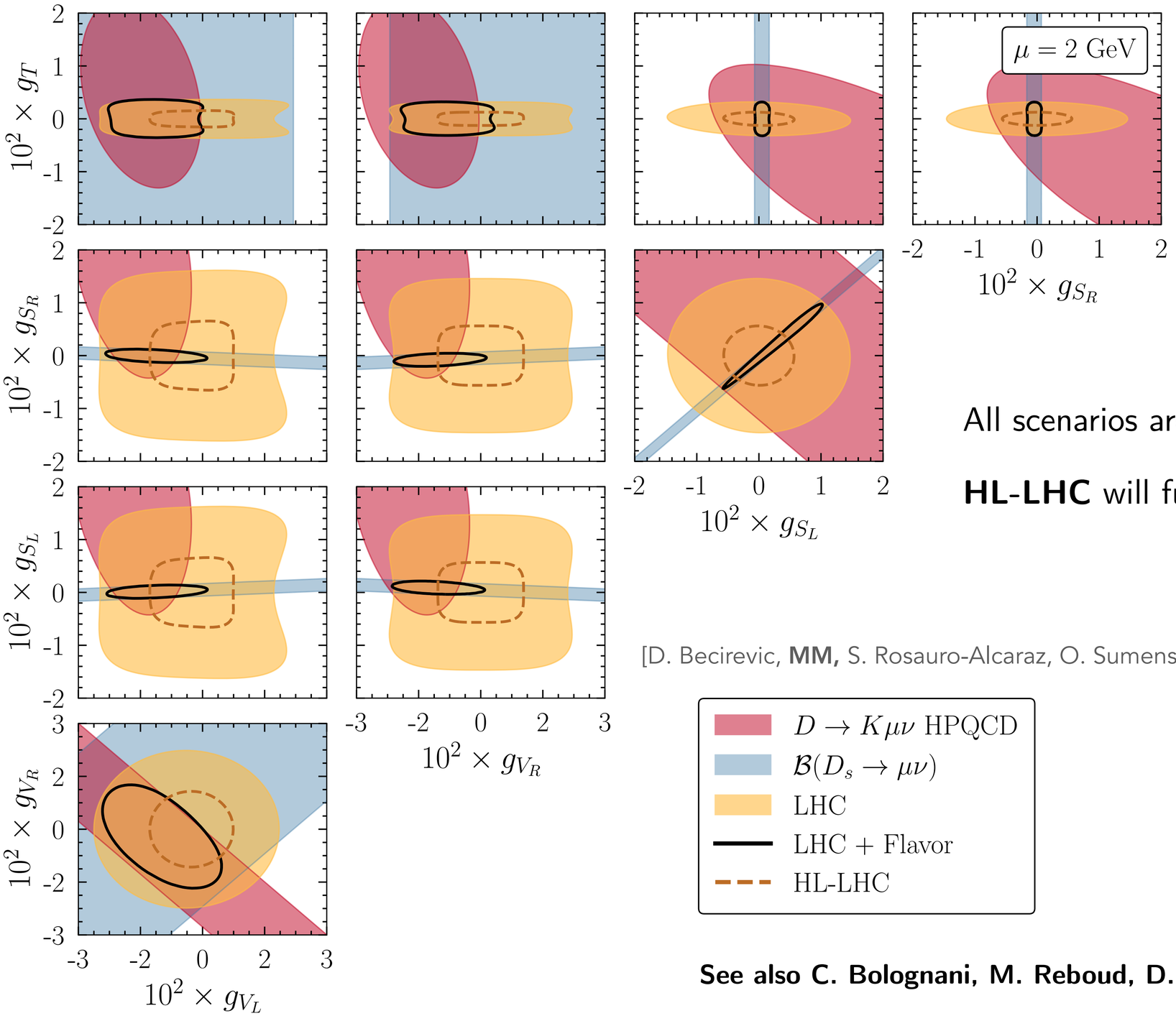
Which other scenarios are possible?

[D. Becirevic, **MM,** S. Rosauro-Alcaraz, O. Sumensari, 2603.25837]

Real couplings



All scenarios are **consistent** with the **SM** within 2σ.

HL-LHC will further improve the limits on CC interactions.

[D. Becirevic, **MM,** S. Rosauro-Alcaraz, O. Sumensari, 2603.25837]

See also C. Bolognani, M. Reboud, D. Van Dyk, K. Keri Vos [2407.06145]

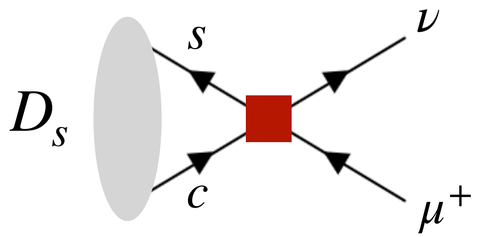
Low-energy EFT for charged current processes

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

- Responsible for **leptonic** and semileptonic meson decays.

$$g_A \equiv g_{V_R} - g_{V_L}$$
$$g_S \equiv g_{S_R} - g_{S_L}$$

decay constant



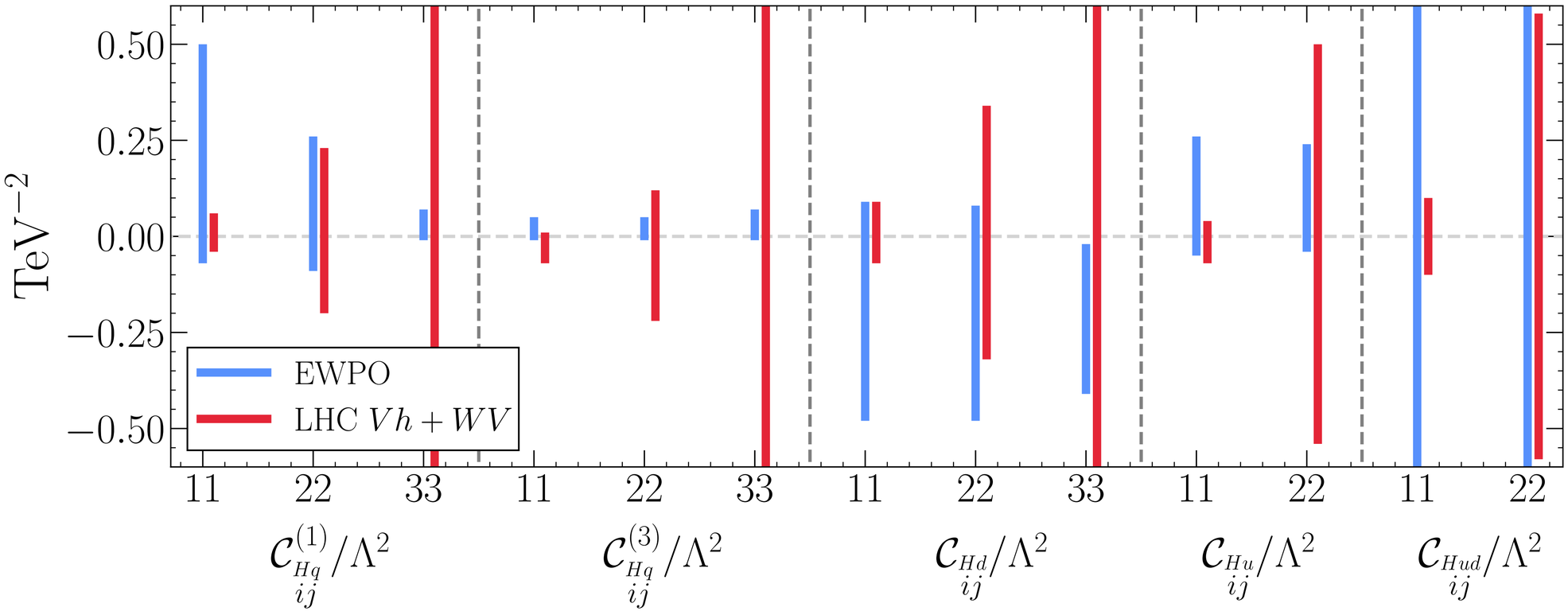
$$\mathcal{B}(D_s \to \mu\nu) = \tau_{D_s}\frac{G_F^2|V_{cs}|^2 f_{D_s}^2 m_{D_s} m_\mu^2}{8\pi}\left|1 - g_A + g_P\frac{m_{D_s}^2}{m_\mu(m_c+m_s)}\right|^2$$

Helicity suppressed

*Constraints on **axial** and **pseudoscalar** couplings.*

Probing Flavorful EFTs at the LHC

Confronting LHC with EWPO

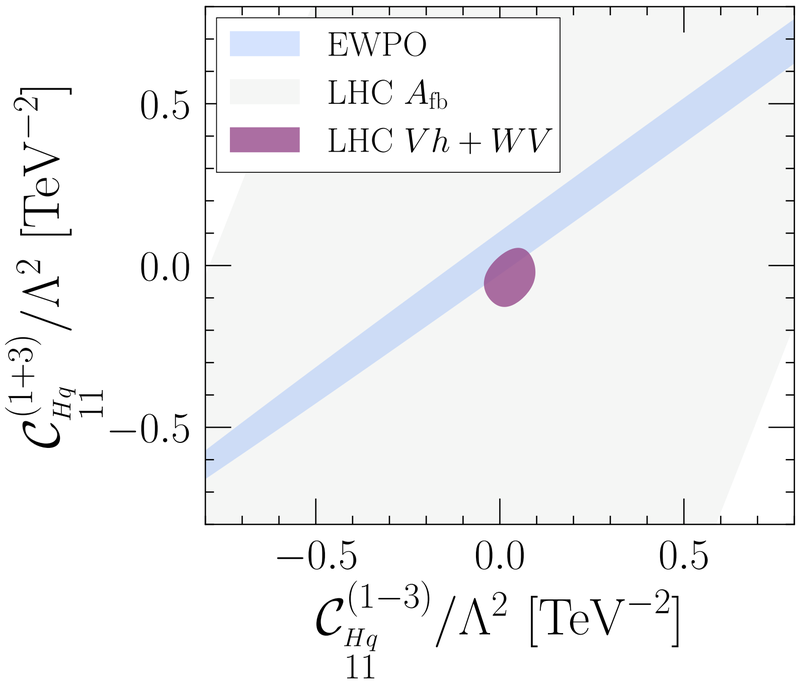


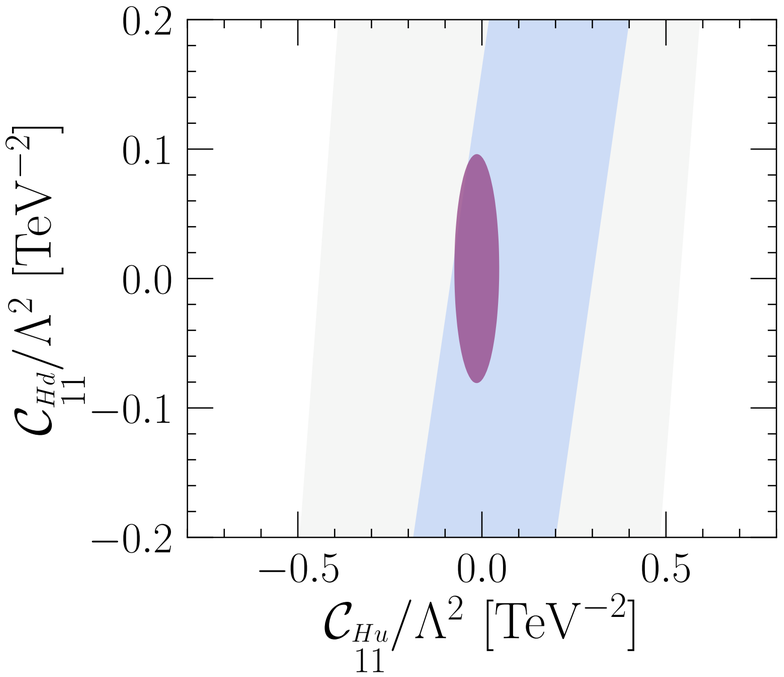
Considering a **single non vanishing** coefficient at a time.

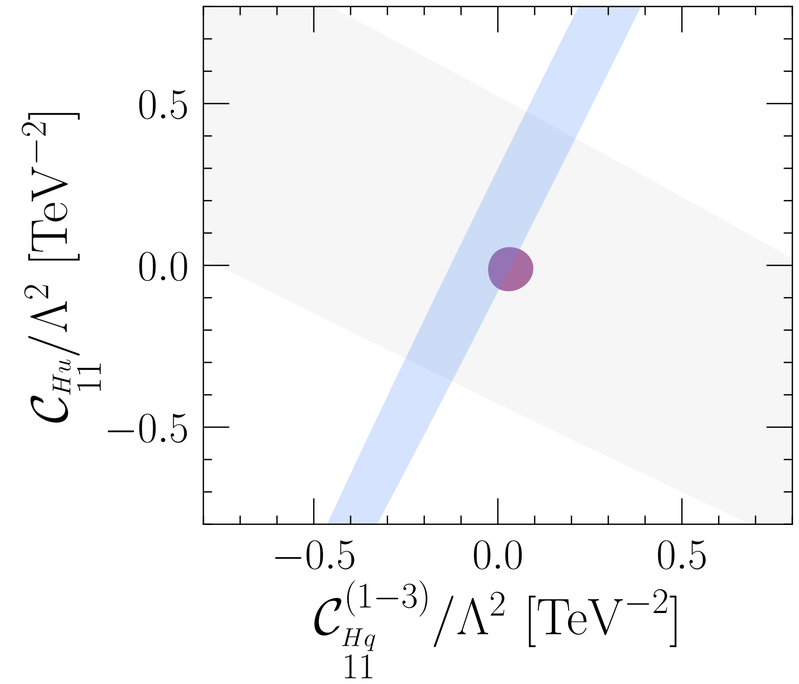
Confronting LHC with EWPO

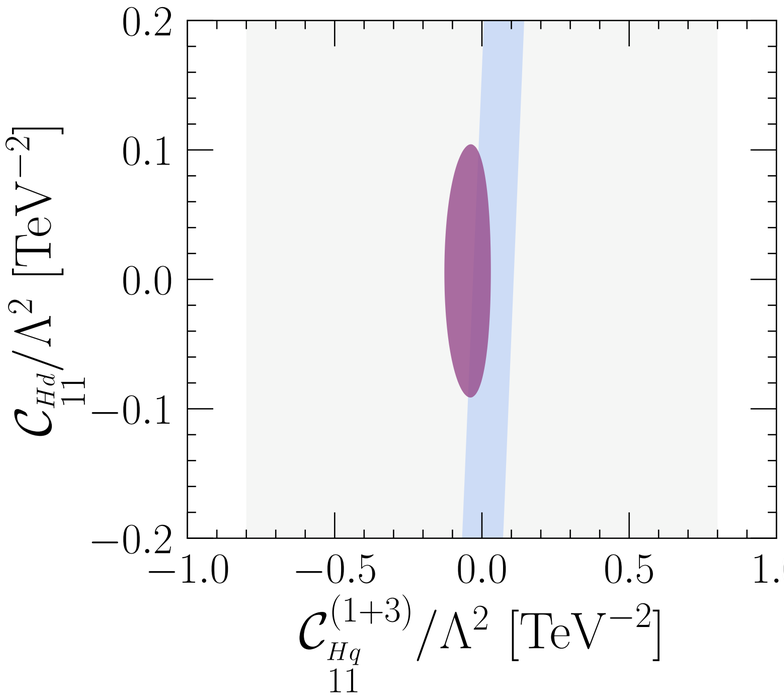
Vh production **breaks** the blind-directions present in the **EWPO** involving the **first generation of quarks.**

Forward-backward asymmetry limits taken from V. Bresó-Pla et al.[2103.12074].

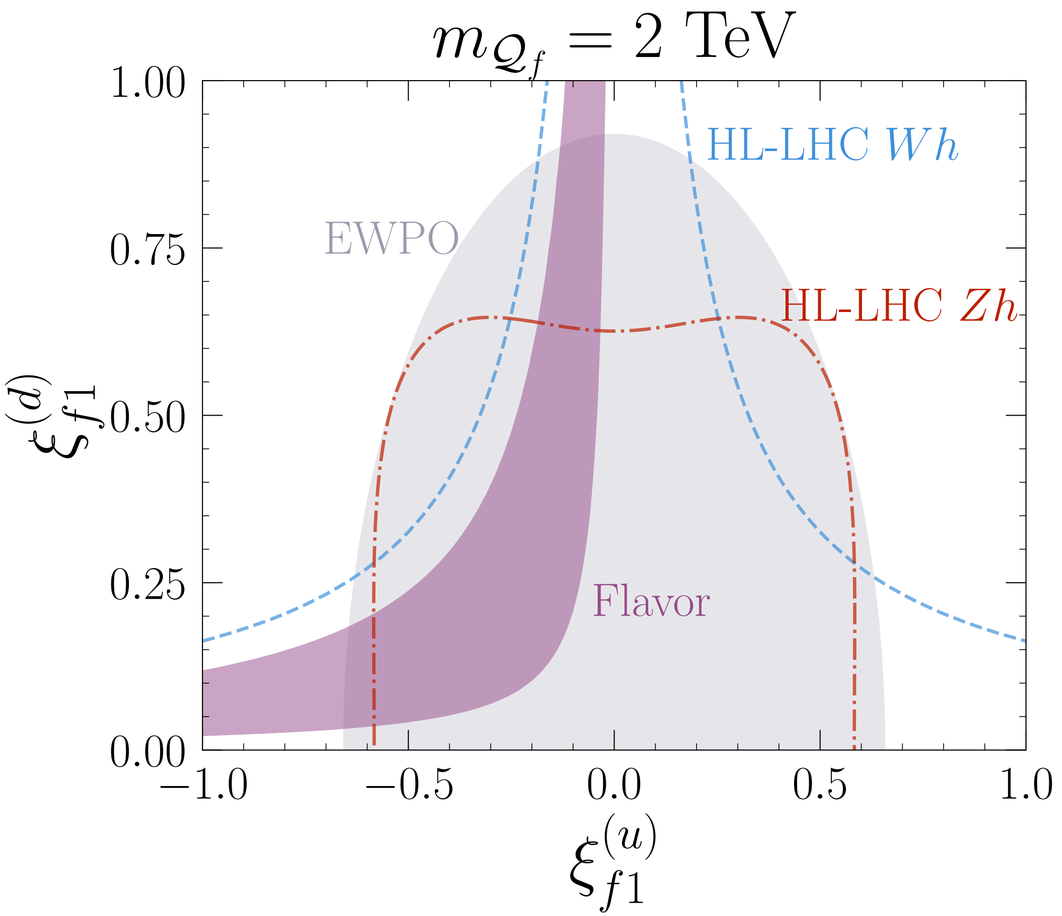


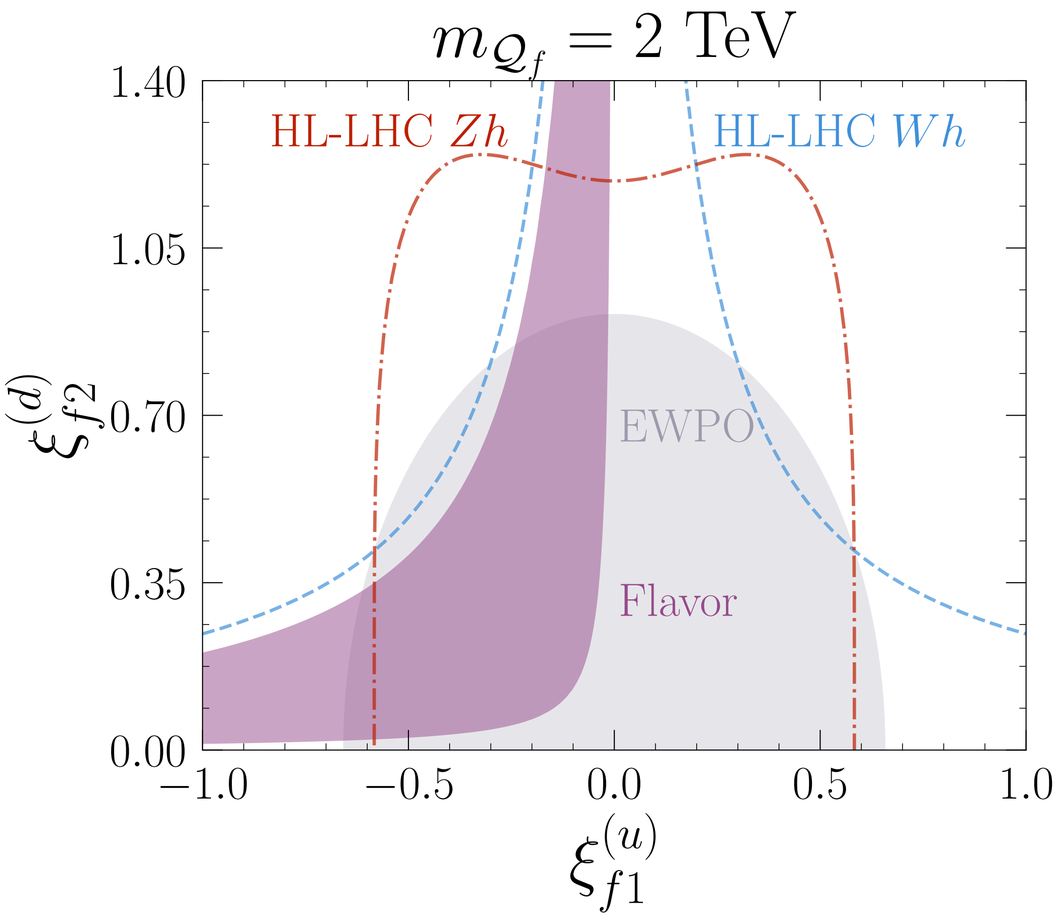






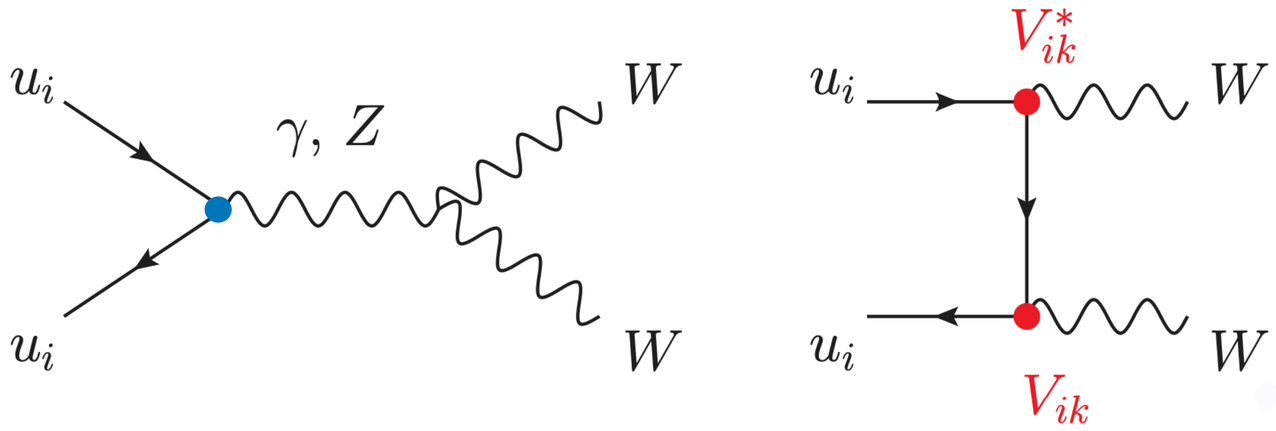
Limits on VLQs





$$\mathcal{L}_{\rm VLQ} \supset -\xi^{(u)}_{fi}\,\overline{\mathcal{Q}}_f \widetilde{H} u_i - \xi^{(d)}_{fi}\,\overline{\mathcal{Q}}_f H d_i + \text{h.c.}$$

Diboson production



SM prediction for W_0W_0 production

$$\mathcal{M}(u_i\bar{u}_j \to W_0W_0) \overset{\text{SM}}{=} i\widehat{S}\,\frac{e^2\sin\theta}{2m_W^2}\left[Q_q\,\delta_{ij} + \frac{1}{s_W^2}(T_q^3 - s_W^2 Q_q)\,\delta_{ij} - \frac{T_q^3}{s_W^2}(V^\dagger\cdot V)ij\right] + \mathcal{O}(\hat{s}^0)\,,$$

CKM is unitary

Center of mass energy

t-channel

s-channel Z

s-channel γ

C. Grojean, M. Montull, M. Riembau [1810.05149]

R. Franceschini, G. Panico, A. Pomarol, F. Riva, A. Wulzer [1712.01310]

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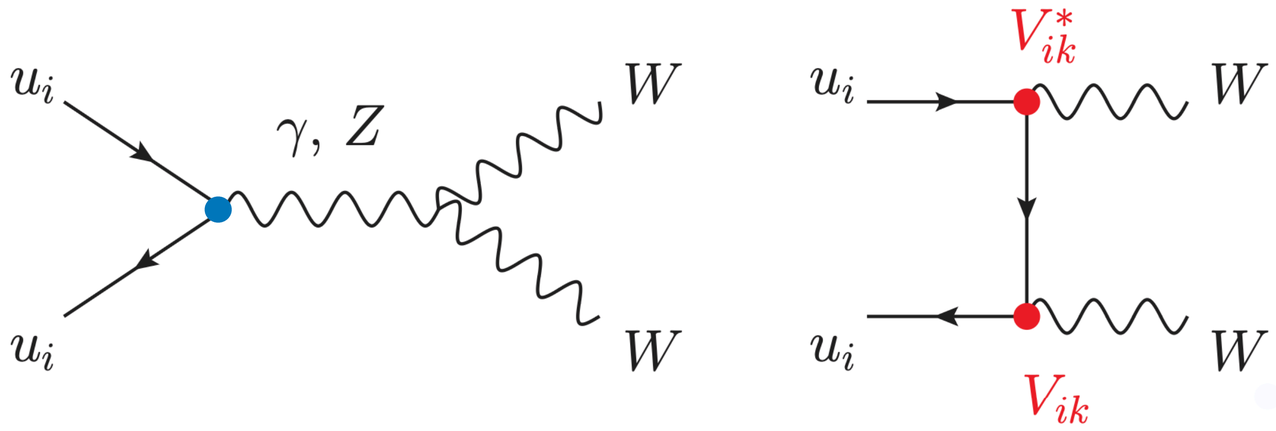

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Modifications to the Z and W couplings can **spoil** the SM cancellation.

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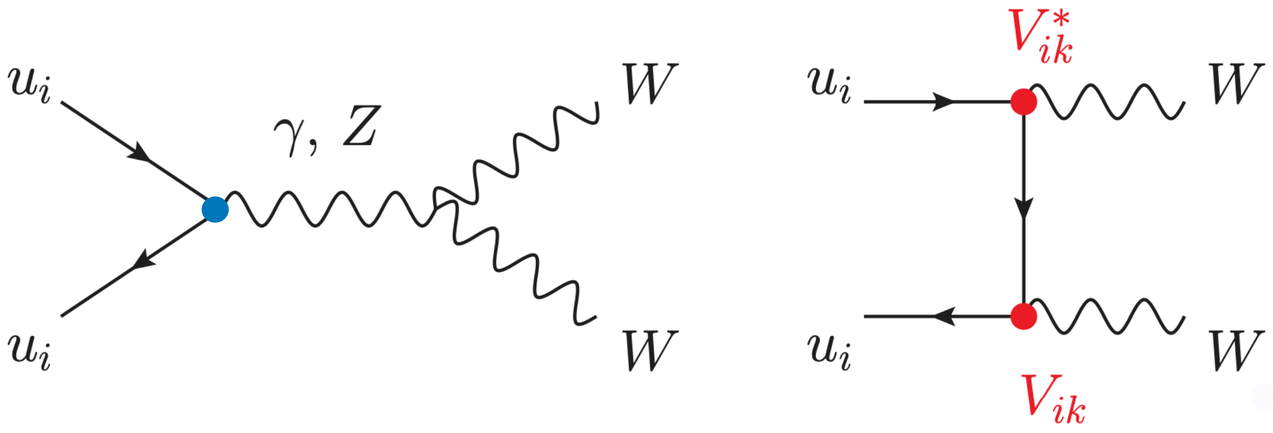

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s-channel Z
s-channel γ

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Modifications to the Z and W couplings can **spoil** the SM cancellation.

At high-energies, $\mathcal{M}(qq' \to W_0V_0) \sim \mathcal{M}(qq' \to hV_0')$ → **Goldstone Boson Equivalence Theorem**

B. W. Lee *et al.*, *Phys. Rev. D 16, 1519*, G. J. Gounaris *et al.*, *Phys. Rev. D 34, 3257*, M. Chanowit, *et al.*, *Phys. Rev. D 36, 1490, Nucl.Phys.B 261 (1985) 379-431*, A. Wulzer [1309.6055]

High-energy amplitudes

At dimension $d = 6$, for neutral processes

$$\mathcal{M}(u_L^i \bar{u}_L^j \to W_0^- W_0^+) = -c_W \mathcal{M}(d_L^i \bar{d}_L^j \to Z_0 h) = -i \frac{\widehat{S} \sin\theta}{\Lambda^2} \mathcal{C}_{Hq\,ij}^{(1+3)},$$

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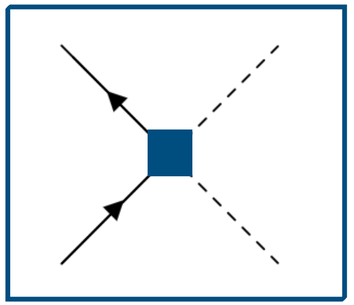
WW and Zh probe the **same combination** of couplings.

Weak basis



$$\mathcal{C}_{Hq}^{(1\pm3)} = \mathcal{C}_{Hq}^{(1)} \pm \mathcal{C}_{Hq}^{(3)}$$

$\mathcal{O}_{\psi^2 H^2 D}$	Operator
$\mathcal{O}_{Hq}^{(1)}$	$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{q}_i \gamma^\mu q_j\right)$
$\mathcal{O}_{Hq}^{(3)}$	$\left(H^\dagger i \overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_i \gamma^\mu \tau^I q_j\right)$
$\mathcal{O}_{Hu}$	$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{u}_i \gamma^\mu u_j\right)$
$\mathcal{O}_{Hd}$	$\left(H^\dagger i \overleftrightarrow{D}_\mu H\right)\left(\bar{d}_i \gamma^\mu d_j\right)$
$\mathcal{O}_{Hud}$	$\left(\widetilde{H}^\dagger i D_\mu H\right)\left(\bar{u}_i \gamma^\mu d_j\right) + \text{h.c.}$

High-energy amplitudes

At dimension $d = 6$, for charged processes

$$-c_W\,\mathcal{M}(u_L^i \bar{d}_L^j \to W_0 Z_0) = \mathcal{M}(u_L^i \bar{d}_L^j \to W_0 h) = -i\sqrt{2}\,\frac{\widehat{S}\,\sin\theta}{\Lambda^2}\mathcal{C}^{(3)}_{\substack{Hq\\ij}},$$

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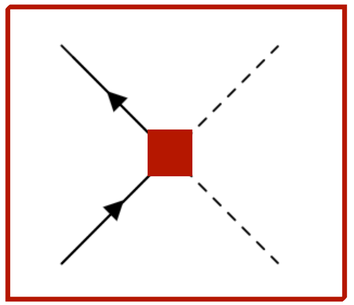

$\mathcal{O}_{\psi^2H^2D}$	Operator
$\mathcal{O}^{(1)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\bar{q}_i\gamma^\mu q_j\right)$
$\mathcal{O}^{(3)}_{Hq}$	$\left(H^\dagger i\overleftrightarrow{D}^I_\mu H\right)\left(\bar{q}_i\gamma^\mu \tau^I q_j\right)$
$\mathcal{O}_{Hu}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\bar{u}_i\gamma^\mu u_j\right)$
$\mathcal{O}_{Hd}$	$\left(H^\dagger i\overleftrightarrow{D}_\mu H\right)\left(\bar{d}_i\gamma^\mu d_j\right)$
$\mathcal{O}_{Hud}$	$\left(\widetilde{H}^\dagger i D_\mu H\right)\left(\bar{u}_i\gamma^\mu d_j\right) + \text{h.c.}$

On the validity of Drell-Yan tails

EFT validity of Drell-Yan tails

LHC EFT WG note:
Truncation, validity, uncertainties

See also
T. Corbett [2405.04570]
I. Brivio et al. [2201.04974]
S. Dawson et al. [2205.01561]
T. Kim, A. Martin [2203.11976]
R. Contino et al. [1604.06444]
T. Cohen et al. [2111.09895]
T. Corbett et al. [2503.19962]
and more.

Main questions

1. How accurate is the EFT description of DY?
2. Whenever the EFT expansion is valid, which terms of the EFT series should be considered?

Our work

A **direct comparison** between the **EFT** and concrete **UV models**, considering different truncations of the EFT series.

↳ Level of agreement between UV model and EFT in different kinematic ranges.

↳ Comparison of limits from the UV model and EFT.

↳ Benefit: not relying on general methods.

[L. Allwicher, D. A. Faroughy, MM, O. Sumensari, F. Wilsh, 2024]

Factors that can play an important role

The **initial quark flavors** (i. e., PDFs)

light vs. heavy quarks.

The **topology** of the **NP contribution**

s- or $t-$channel mediator.

The **experimental sensitivity**

Depends on the available kinematic information and signal region.

Drell-Yan cross-section — PDF importance

See F. Wilsch presentation [link].

Amplitudes for $q_i\bar{q}_j \to \ell_\alpha \bar{\ell}_\beta$ consistent with $SU(3)_c \times U(1)_{em}$

$$\mathcal{A}(\bar{q}_i q_j \to \ell^-_\alpha \ell^+_\beta) = \frac{1}{v^2} \sum_{\Gamma\otimes\Gamma'} \mathcal{F}^{\alpha\beta ij}_{\Gamma,\Gamma'} \left(\bar{\ell}_\alpha \Gamma \ell_\beta\right)\left(\bar{q}_i \Gamma' q_j\right)$$

$$\Gamma \otimes \Gamma' \in \{P_X \otimes P_Y\,, \gamma_\mu P_X \otimes \gamma^\mu P_Y\,, \sigma_{\mu\nu} P_X \otimes \sigma^{\mu\nu} P_X\}$$

$$X, Y \in \{L, R\}$$

$$\mathcal{F}^{\alpha\beta ij}_{\Gamma,\Gamma'} \equiv \mathcal{F}^{\alpha\beta ij}_{\Gamma,\Gamma'}(\hat{s}, \hat{t})$$

Includes **contact-interactions** and/or **pole contributions**.

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Hadronic LHC cross-section:

Parton Luminosities/PDFs

$$\sigma(pp \to \ell^-_\alpha \ell^+_\beta) = \frac{1}{48\pi v^4} \sum_{\Gamma\otimes\Gamma'} \sum_{i,j} \int \frac{\mathrm{d}\hat{s}}{s} \int_{-\hat{s}}^{0} \mathrm{d}\hat{t}\, \mathcal{L}_{\bar{q}_i q_j}\, \mathcal{M}_{\Gamma,\Gamma'} \left|\mathcal{F}^{\alpha\beta ij}_{\Gamma,\Gamma'}\right|^2$$

$$\mathcal{L}_{\bar{q}_i q_j}(\hat{s}) \equiv \int_{\hat{s}/s}^{1} \frac{\mathrm{d}x}{x} \left[f_{\bar{q}_i}(x, \mu_F) f_{q_j}\left(\frac{\hat{s}}{sx}, \mu_F\right) + (\bar{q}_i \leftrightarrow q_j) \right]$$

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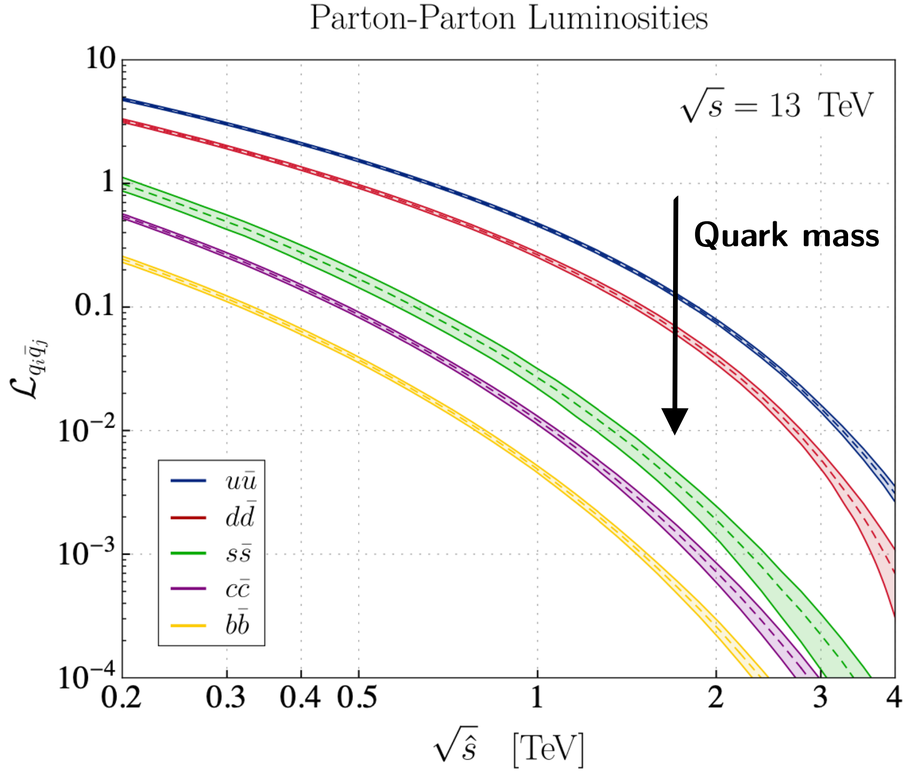

Angelescu, Faroughy, Sumensari [2002.05684]

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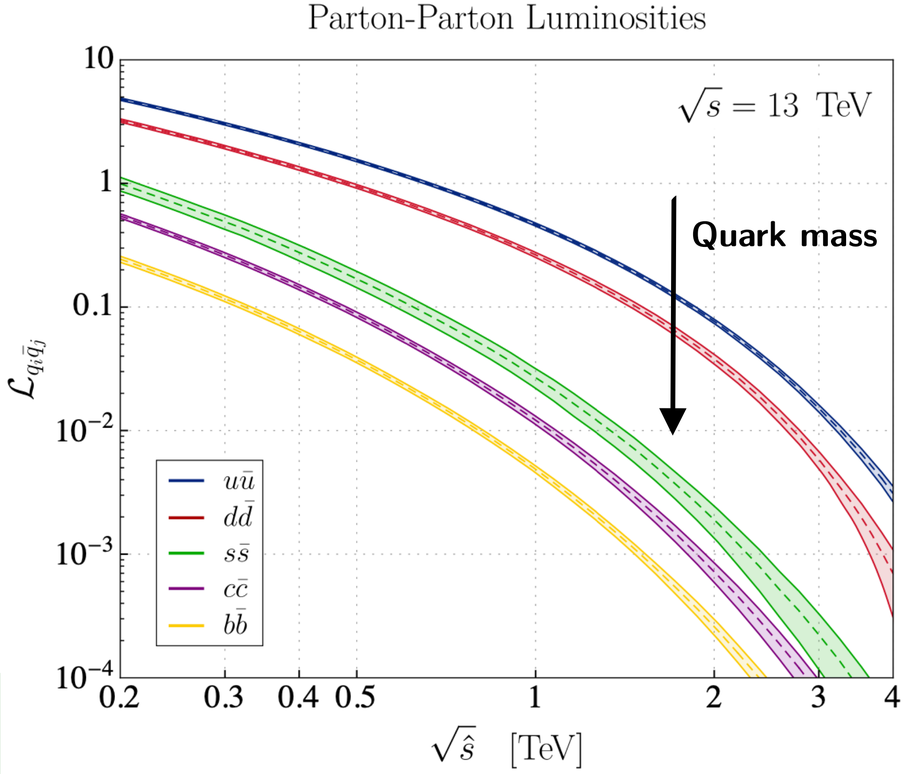
The **flavor of the initial quarks** can impact the convergence of the EFT.



Angelescu, Faroughy, Sumensari [2002.05684]

EFT convergence — resonant mediator

Example 1:

$Z' \sim (\mathbf{1}, \mathbf{1}, \mathbf{0})$

(*s*-channel)

Integrating out the heavy Z' at tree-level

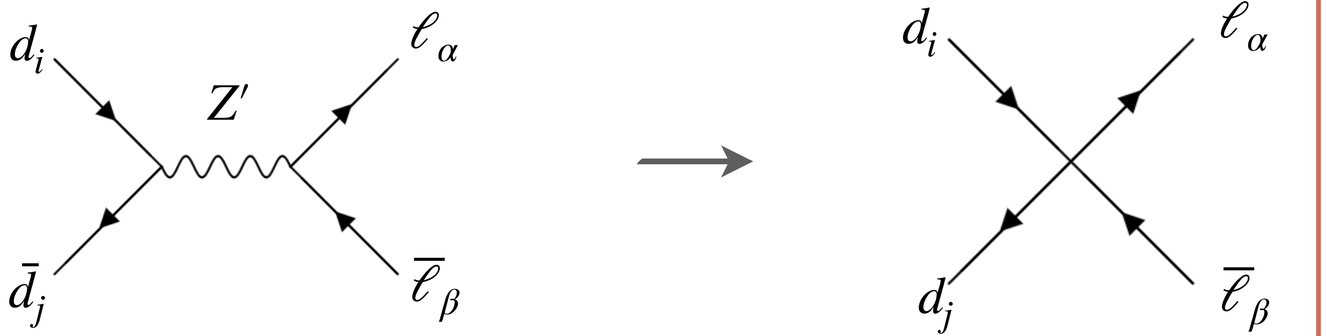
$$\mathcal{L}_{Z'} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\,\mu\nu} + \frac{m^2_{Z'}}{2} Z'_{\mu} Z'^{\,\mu} + J^{\mu} Z'_{\mu}$$

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

$$\longrightarrow \quad \mathcal{L}^{Z'}_{\text{eff}} \supset -\frac{J_{\mu} J^{\mu}}{2m^2_{Z'}} - \frac{1}{2m^4_{Z'}} (D_{\mu} J_{\nu})(D^{\mu} J^{\nu}) + \ldots$$

q and $l \longrightarrow$ quark and lepton doublets.

Example:

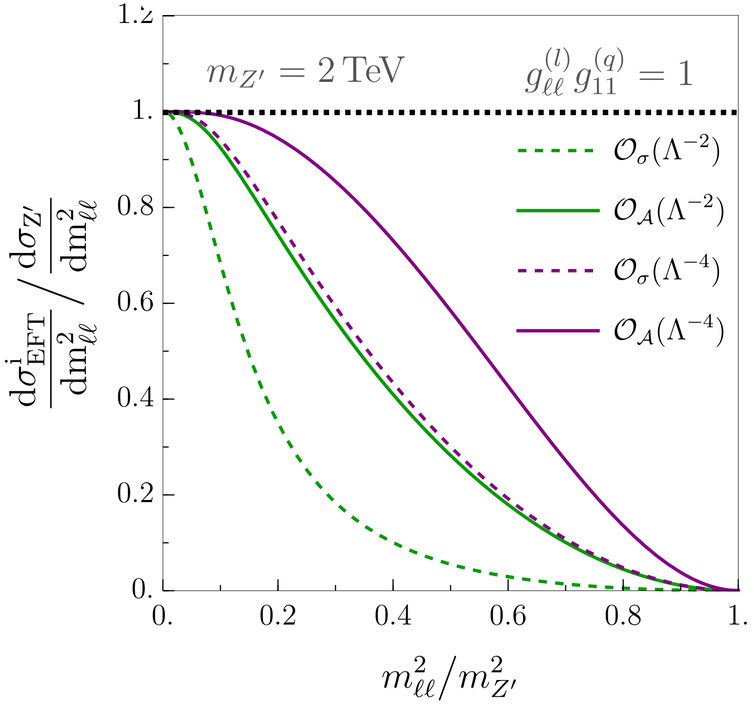


EFT convergence — resonant mediator

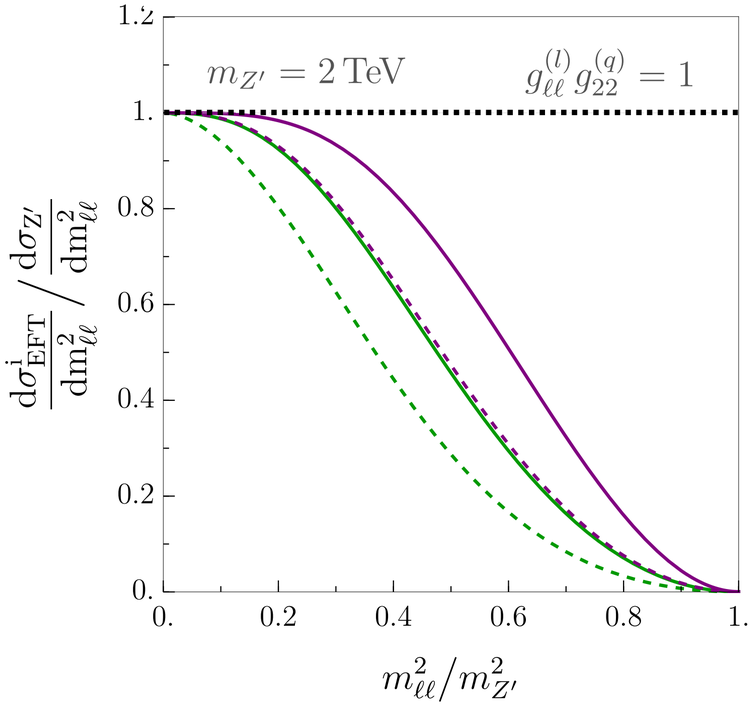
EFT parton-level cross-section computed in different orders in Λ^{-1} and normalized to the full model.

Initial Quark Flavor

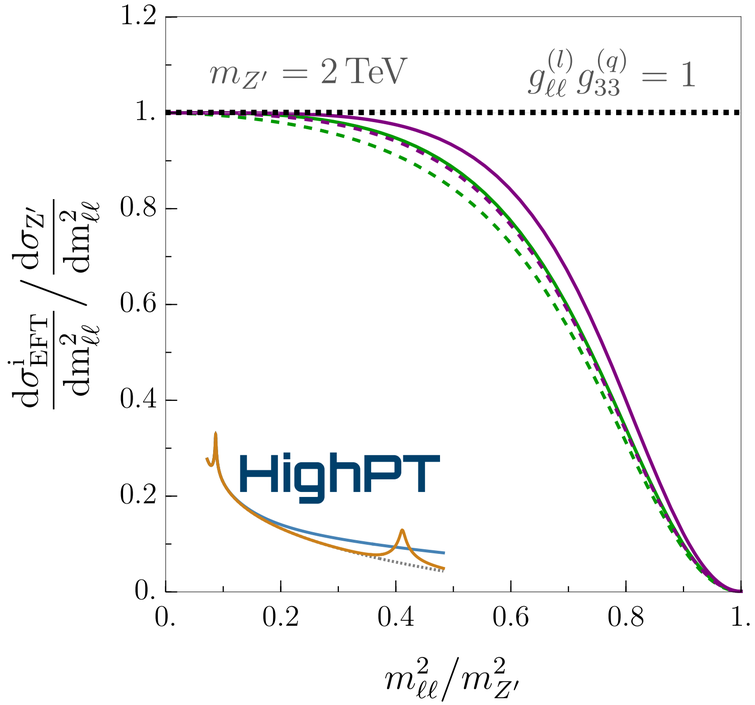
1st gen. quarks



2nd gen. quarks



3rd gen. quarks



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

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

$$\frac{1}{1 - x_V^{-1}} = -\sum_{n=1}^{\infty} x_V^n$$

$$x_V \equiv \hat{s}/m^2_{Z'}$$

*neglecting the width.

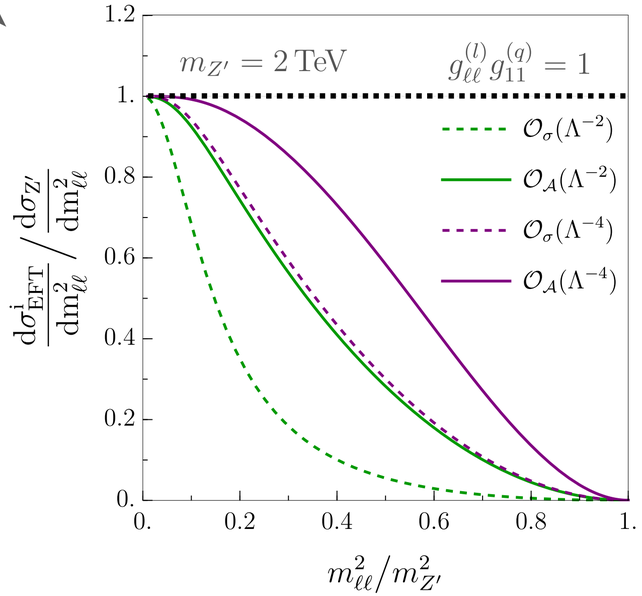
Initial Quark Flavor

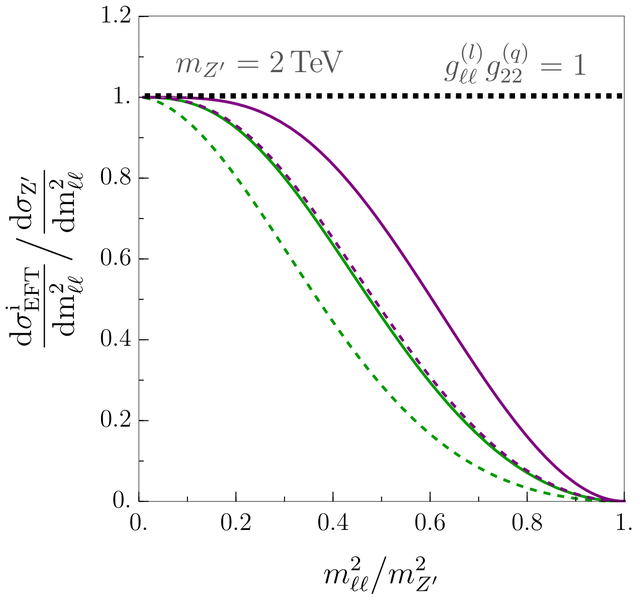
Coupling size

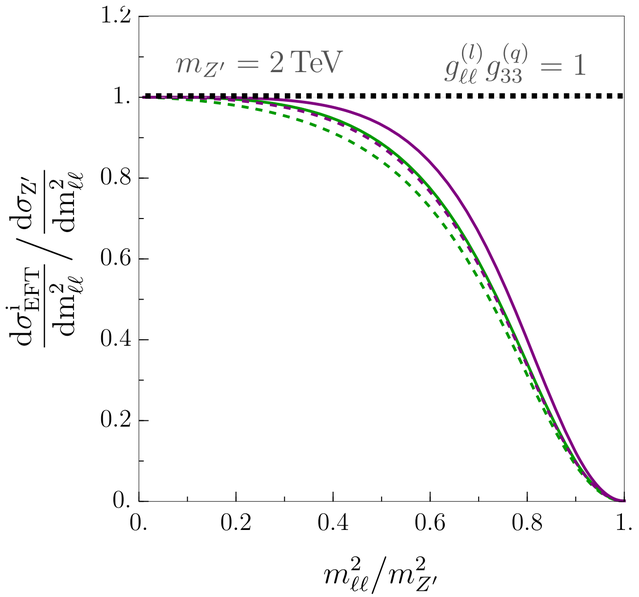
1st gen. quarks

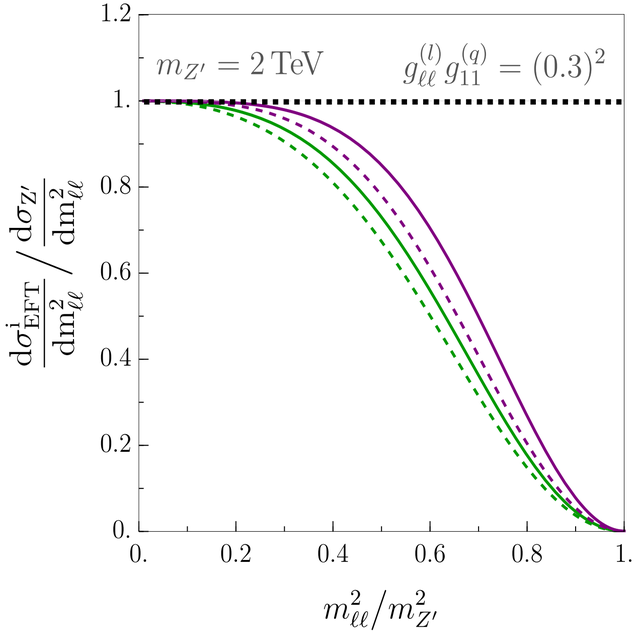
2nd gen. quarks

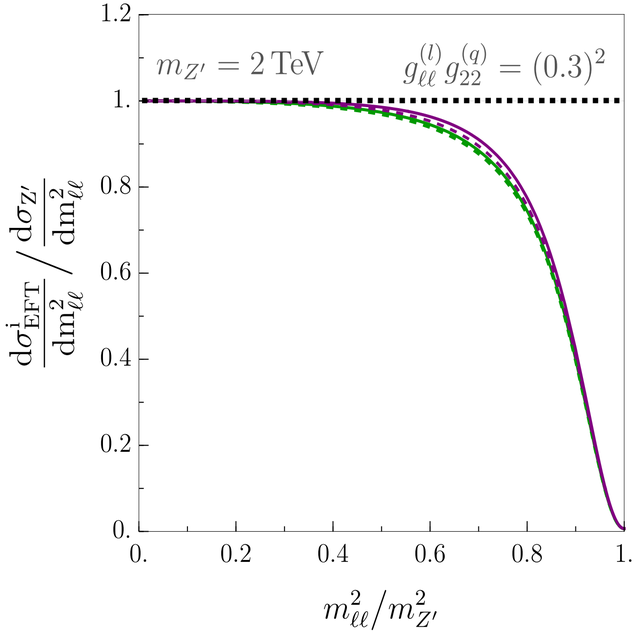
3rd gen. quarks

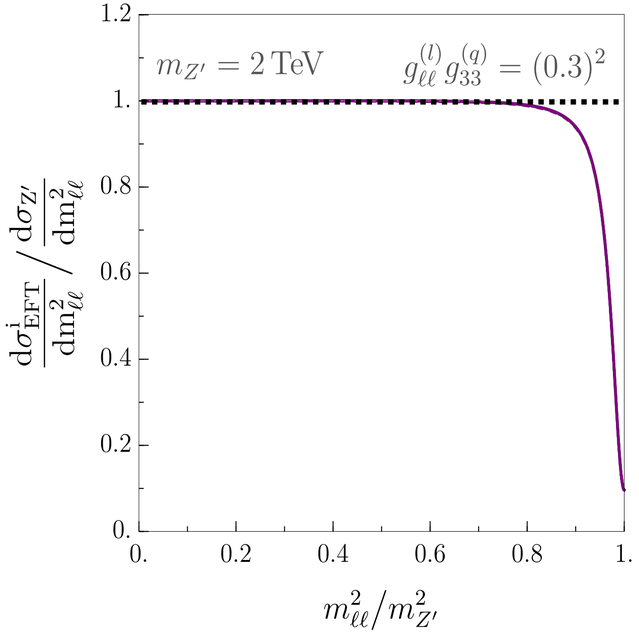












EFT convergence — non-resonant mediator

Example 2:

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

(t-channel)

Integrating out the heavy U_1 at **tree-level**.

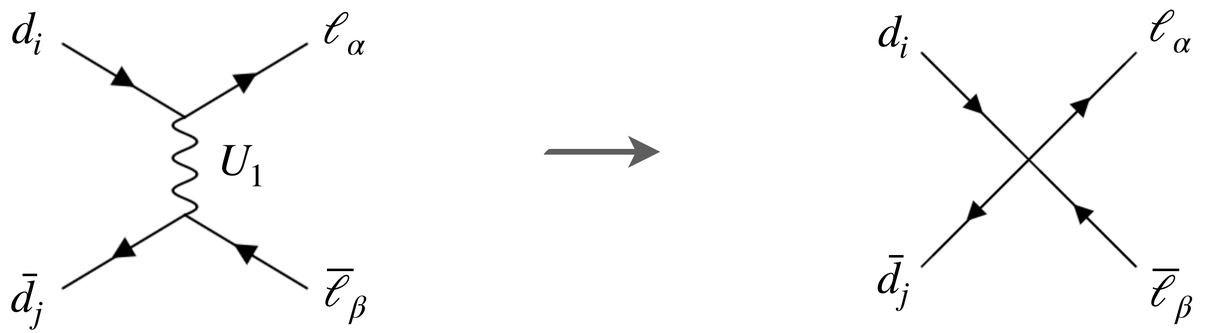
$$\mathcal{L}_{U_1} \supset -\frac{1}{2} U_{1\mu\nu}^{\dagger} U_1^{\mu\nu} + m_U^2 \, U_1^{\mu\dagger} U_{1\mu} + (J_\mu^{\dagger} U_1^{\mu} + \text{h.c.})$$

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

$$\longrightarrow \quad \mathcal{L}_{\text{eff}}^{U_1} \supset -\frac{J_\mu^{\dagger} J^\mu}{m_{U_1}^2} - \frac{1}{m_{U_1}^4} (D_\mu J_\nu)^{\dagger} (D^\mu J^\nu) + \frac{1}{m_{U_1}^4} (D_\mu J_\nu)^{\dagger} (D^\nu J^\mu) + \ldots$$

q and l ⟶ quark and lepton doublets.

Example:

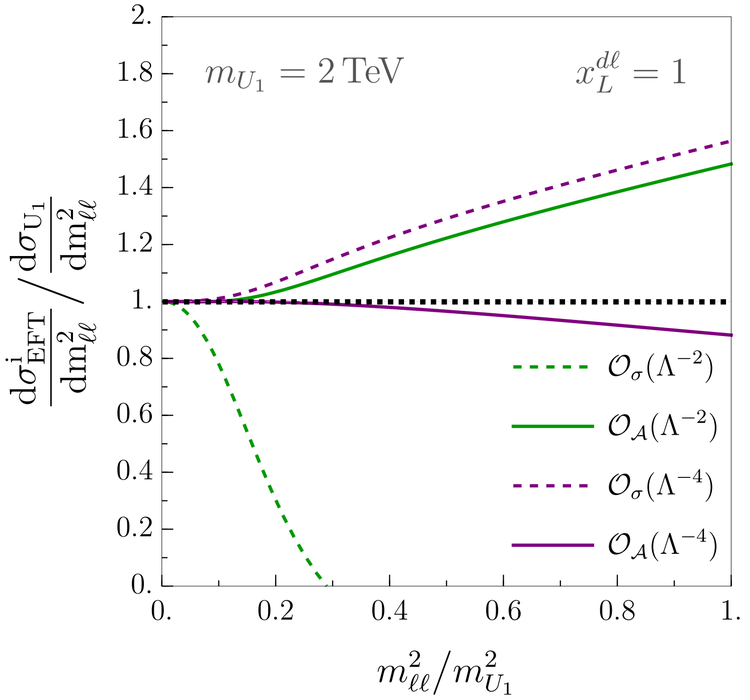


EFT convergence — non-resonant mediator

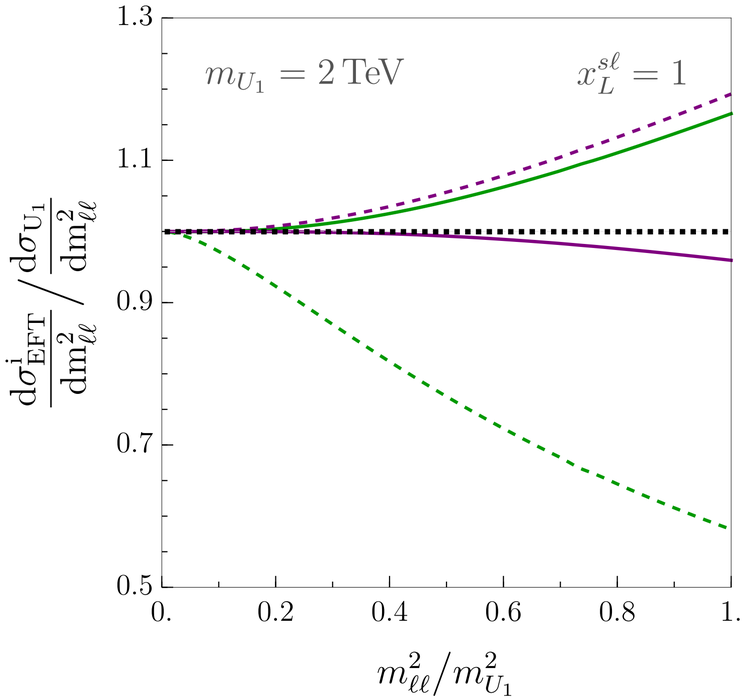
EFT parton-level cross-section computed in different orders in Λ^{-1} and normalized to the full model.

Initial Quark Flavor

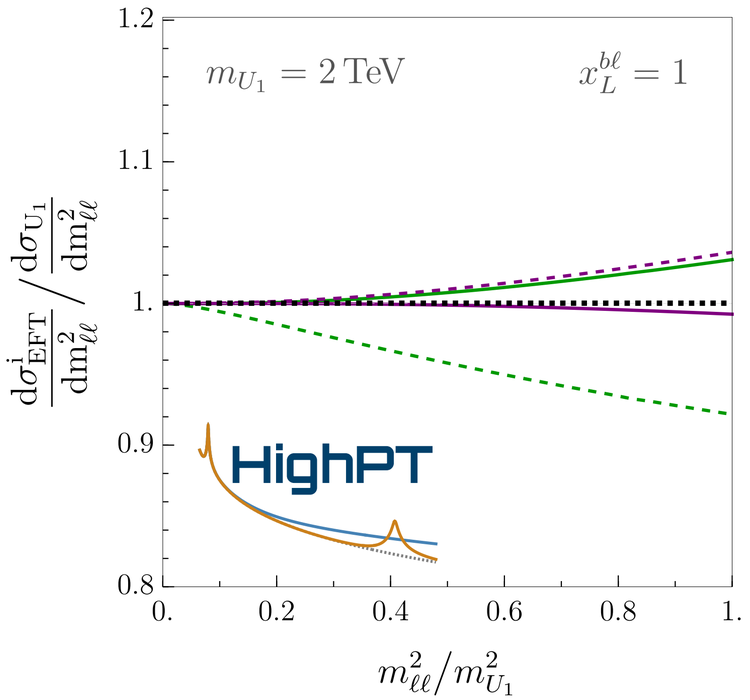
1st gen. quarks



2nd gen. quarks



3rd gen. quarks



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$$\frac{1}{1 - x_V^{-1}} = -\sum_{n=1}^{\infty} (-1)^n x_V^n$$

$$x_V \equiv -\frac{t}{m^2_{U_1}} > 0$$

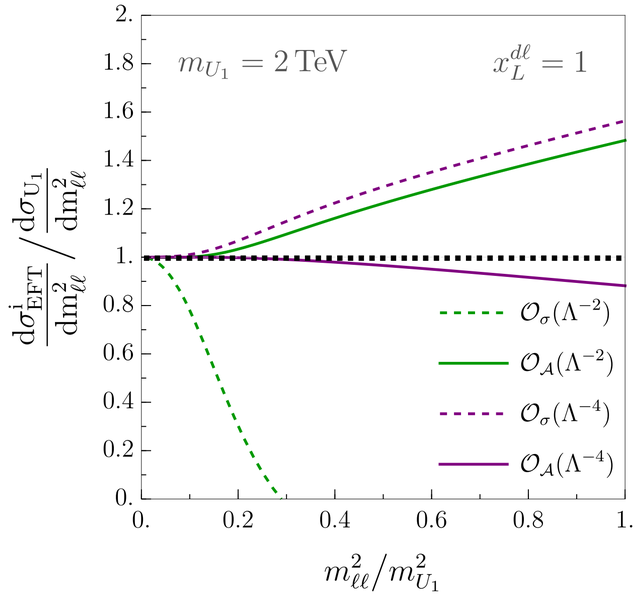
Initial Quark Flavor

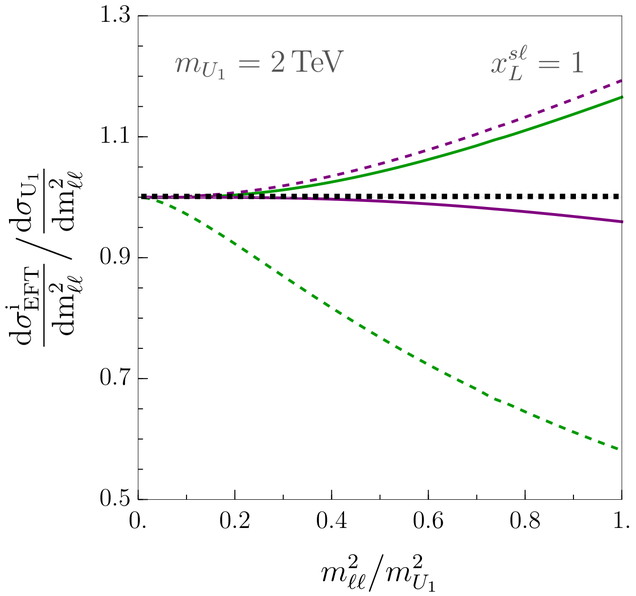
Coupling size

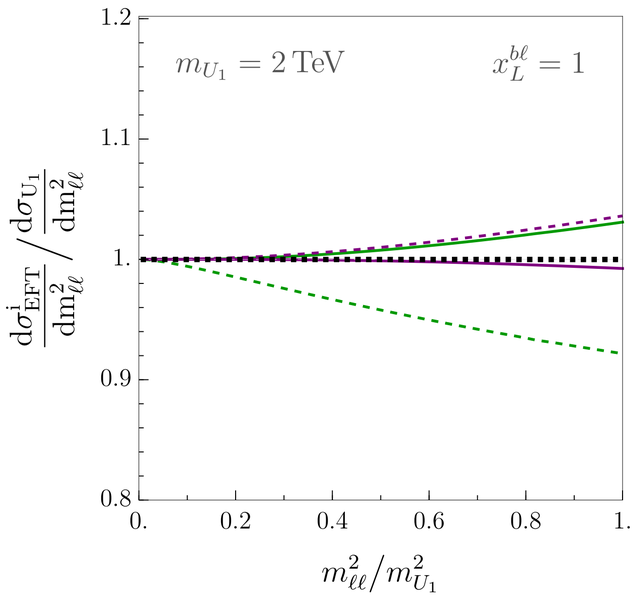
1st gen. quarks

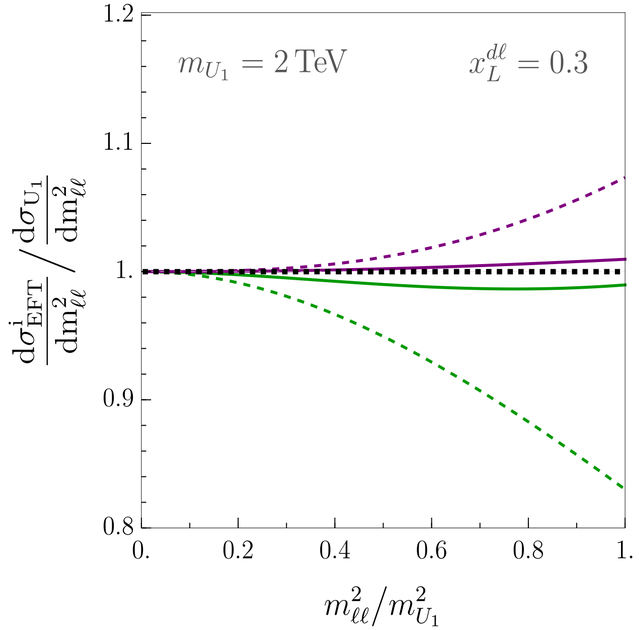
2nd gen. quarks

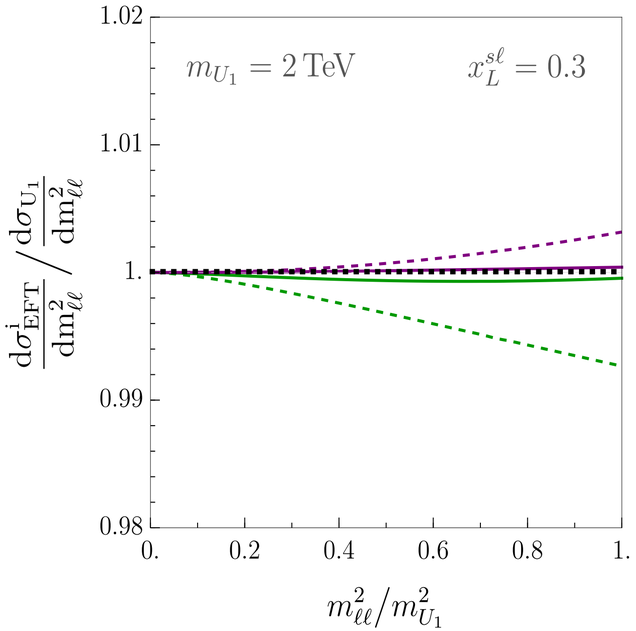
3rd gen. quarks

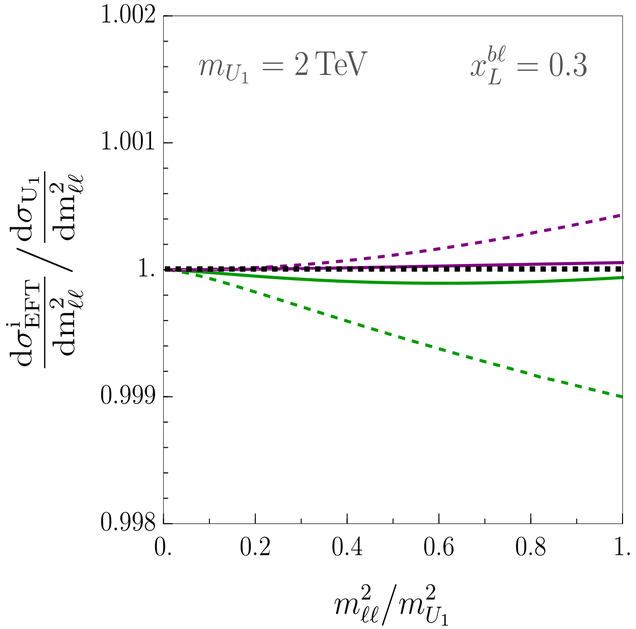












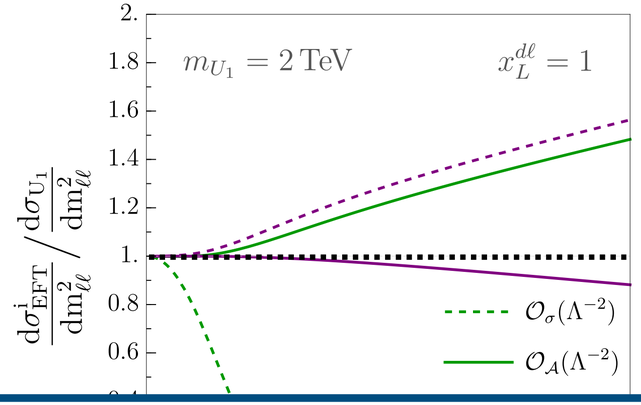
Initial Quark Flavor

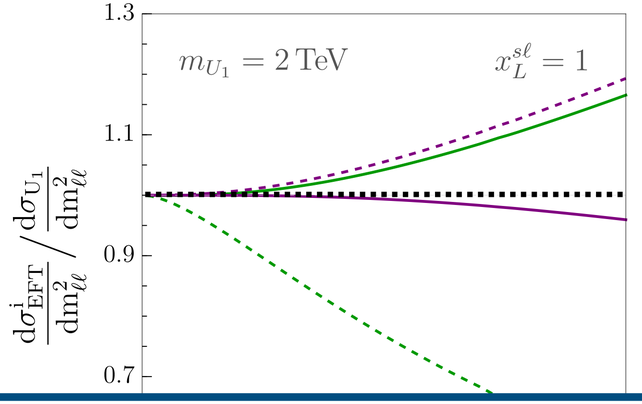
Coupling size

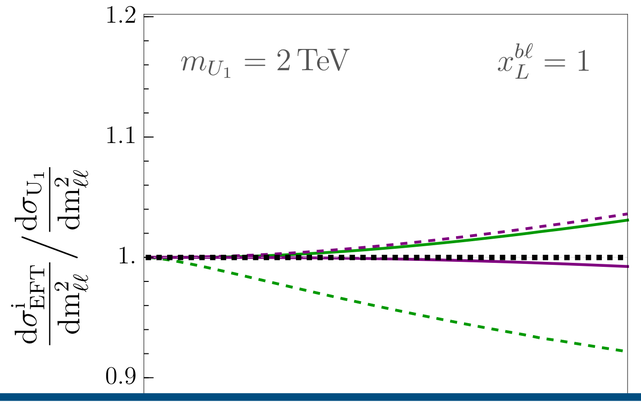
1st gen. quarks

2nd gen. quarks

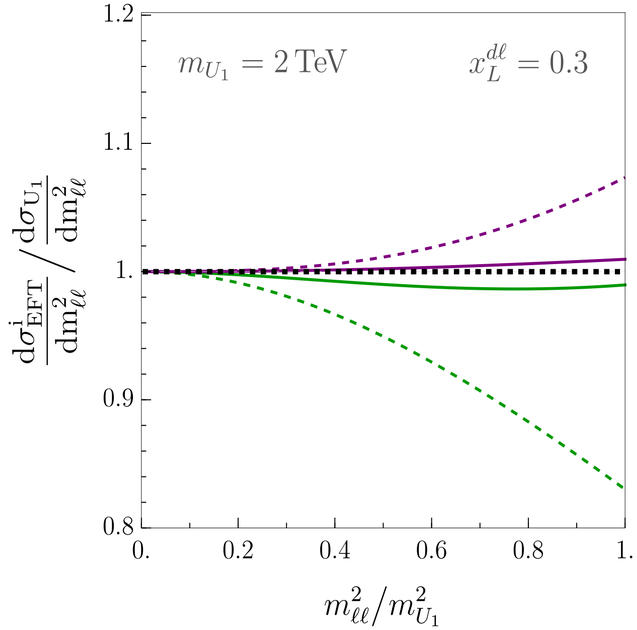
3rd gen. quarks

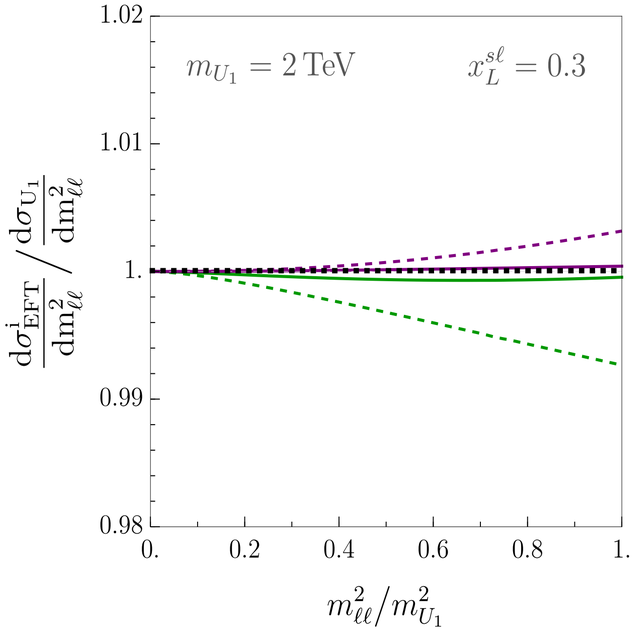


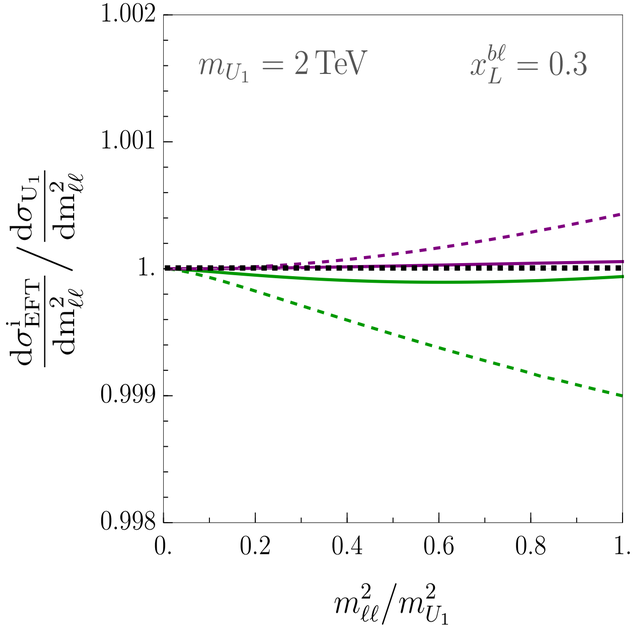




In all cases, the EFT appears to converge better towards the model when **truncating the series on amplitude level.**



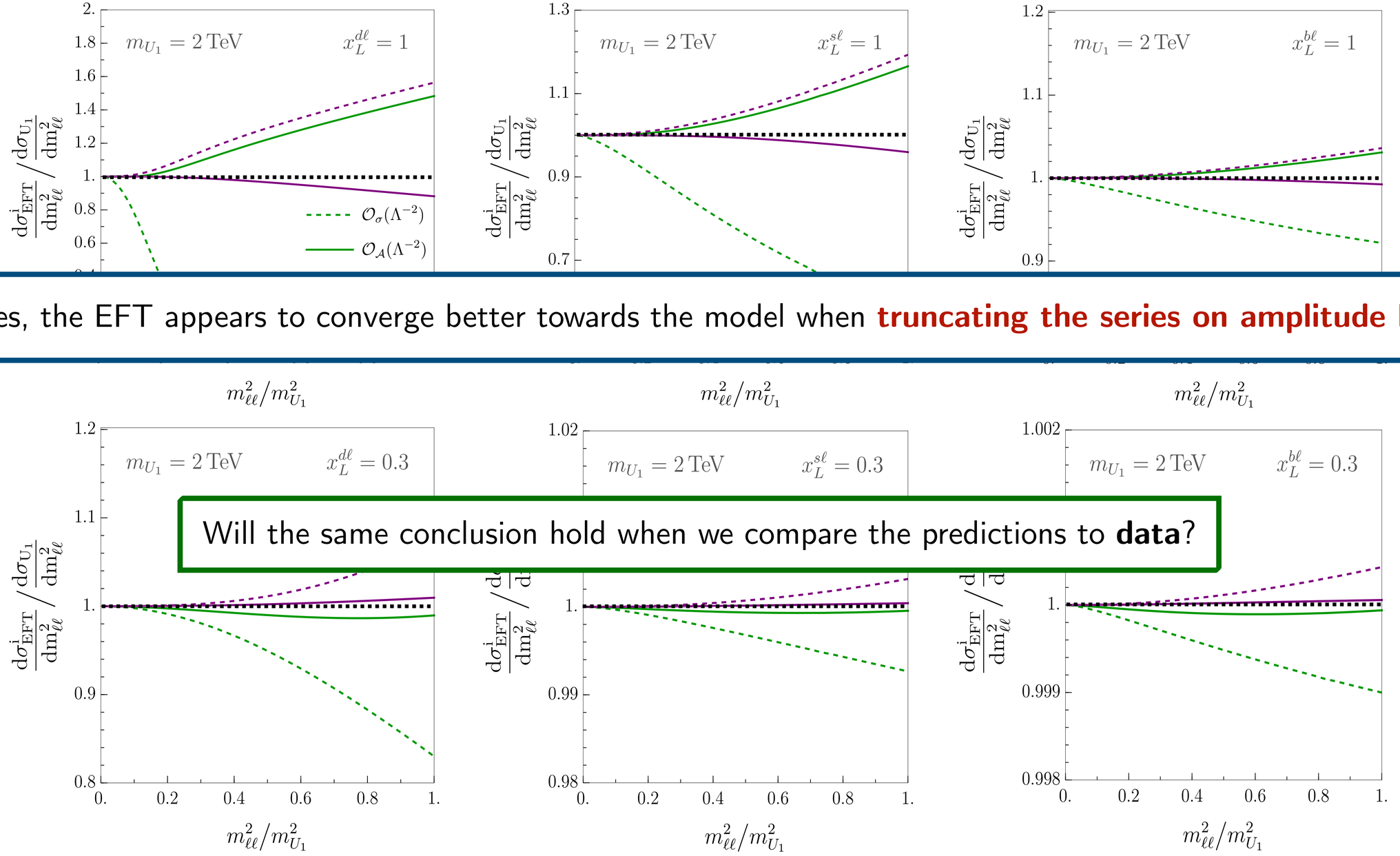




Initial Quark Flavor

Coupling size

1st gen. quarks | **2nd gen. quarks** | **3rd gen. quarks**



In all cases, the EFT appears to converge better towards the model when **truncating the series on amplitude level.**

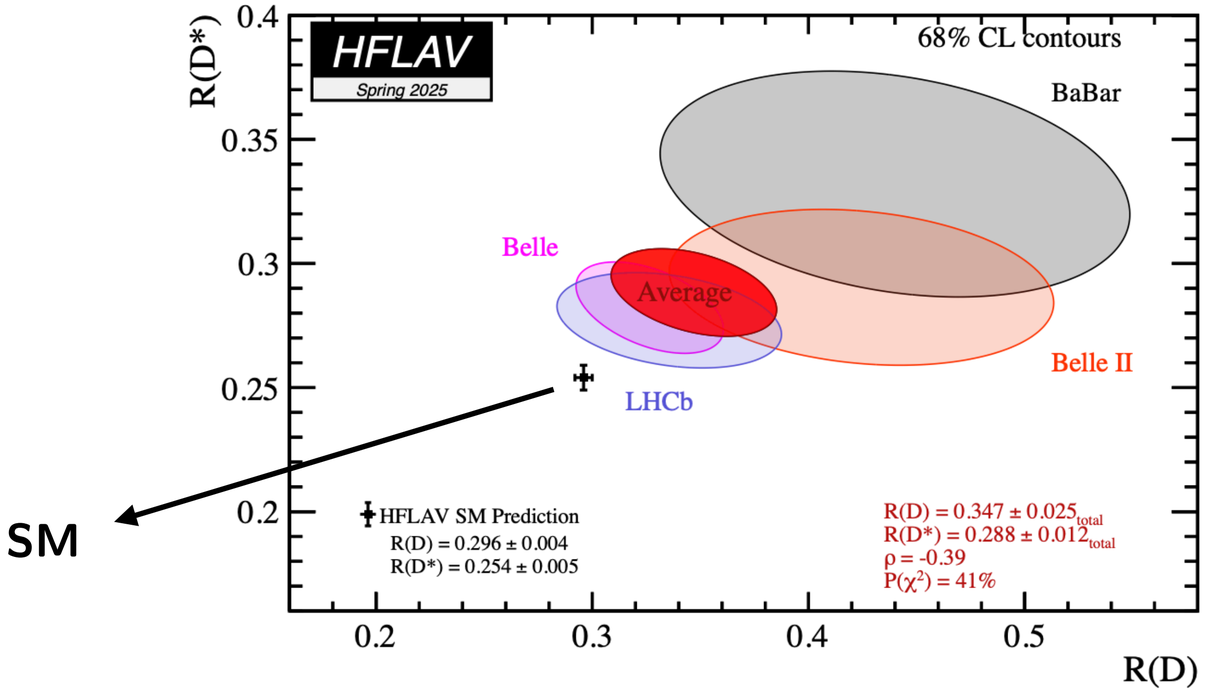
Will the same conclusion hold when we compare the predictions to **data**?

Example: low vs. high-p_T constraints

Motivation:

$$R_D^{\text{exp}} = 0.342 \pm 0.026\,, \qquad R_{D^*}^{\text{exp}} = 0.287 \pm 0.012$$

In combination, 3σ above the average SM predictions.

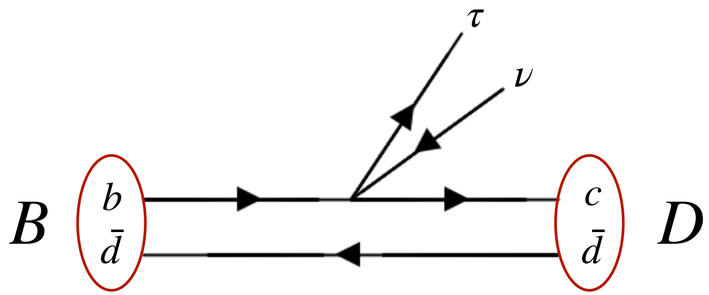


SM

Measured at LHCb and B-factories

Sw. Banerjee et al. [2411.18639]

$$R_{D^{(*)}} = \left.\frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}l\bar{\nu})}\right|_{\ell \in \{e,\ \mu\}}$$



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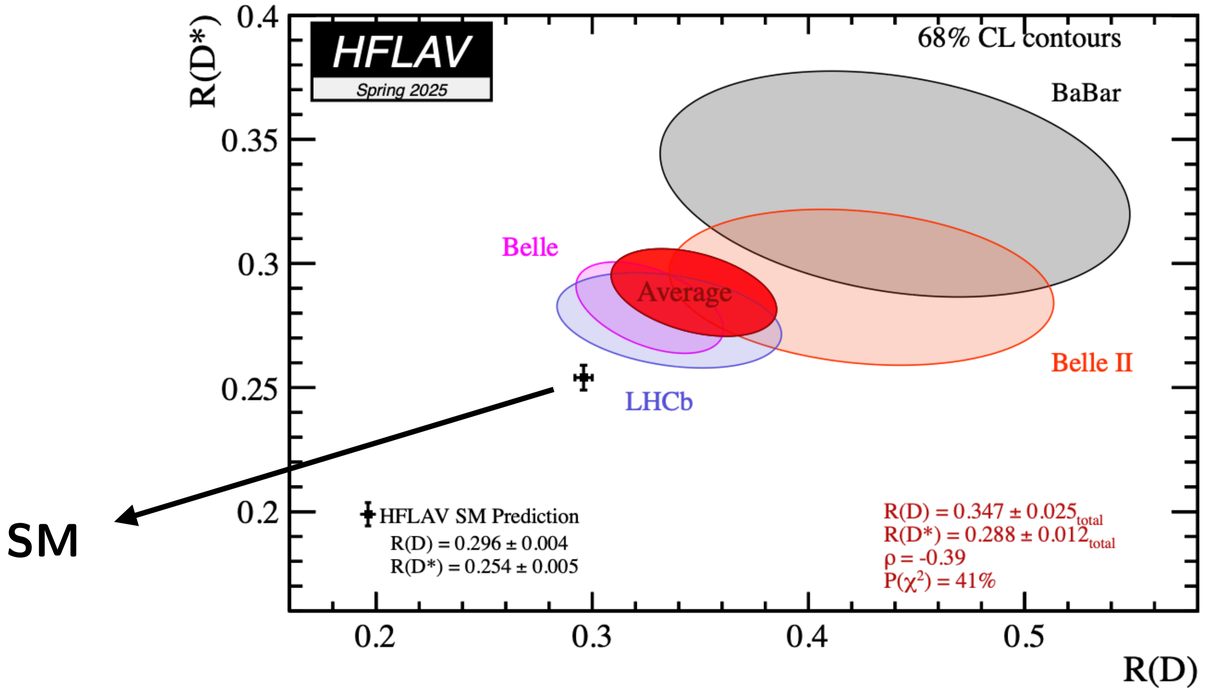

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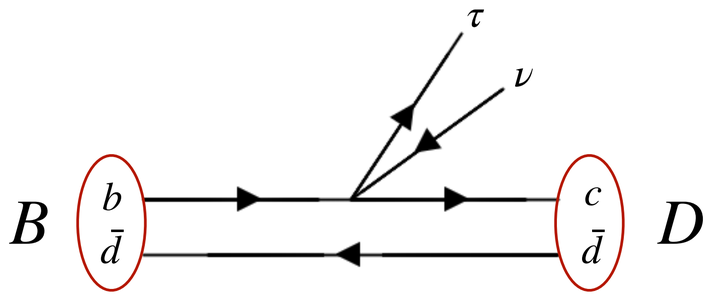

Vector leptoquarks can provide a good solution for the discrepancies.

D. Buttazzo et al. [1706.07808], A. Angelescu et al. [1808.08179], C. Cornella et al. [1903.11517], and more.

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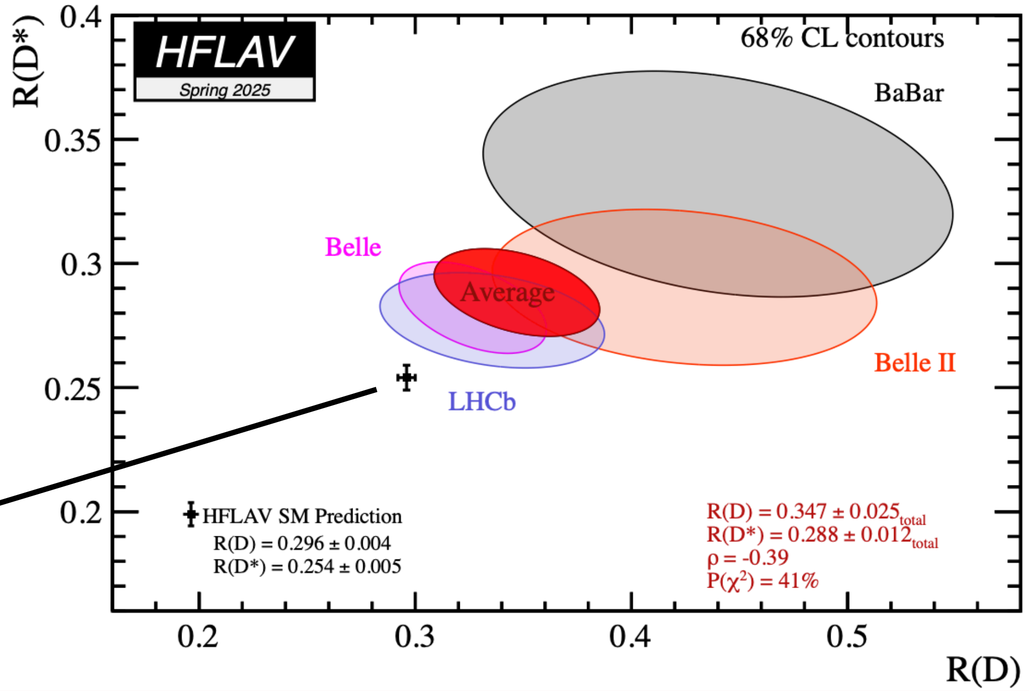

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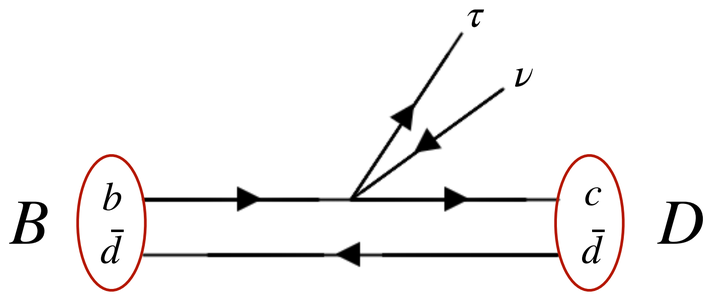

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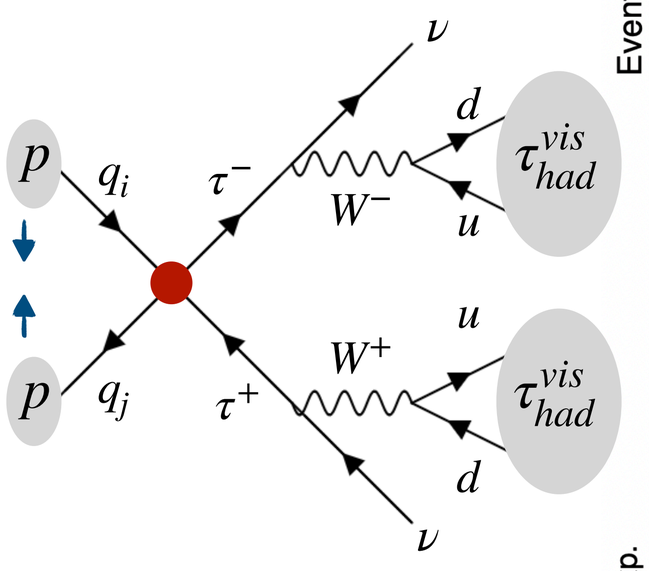
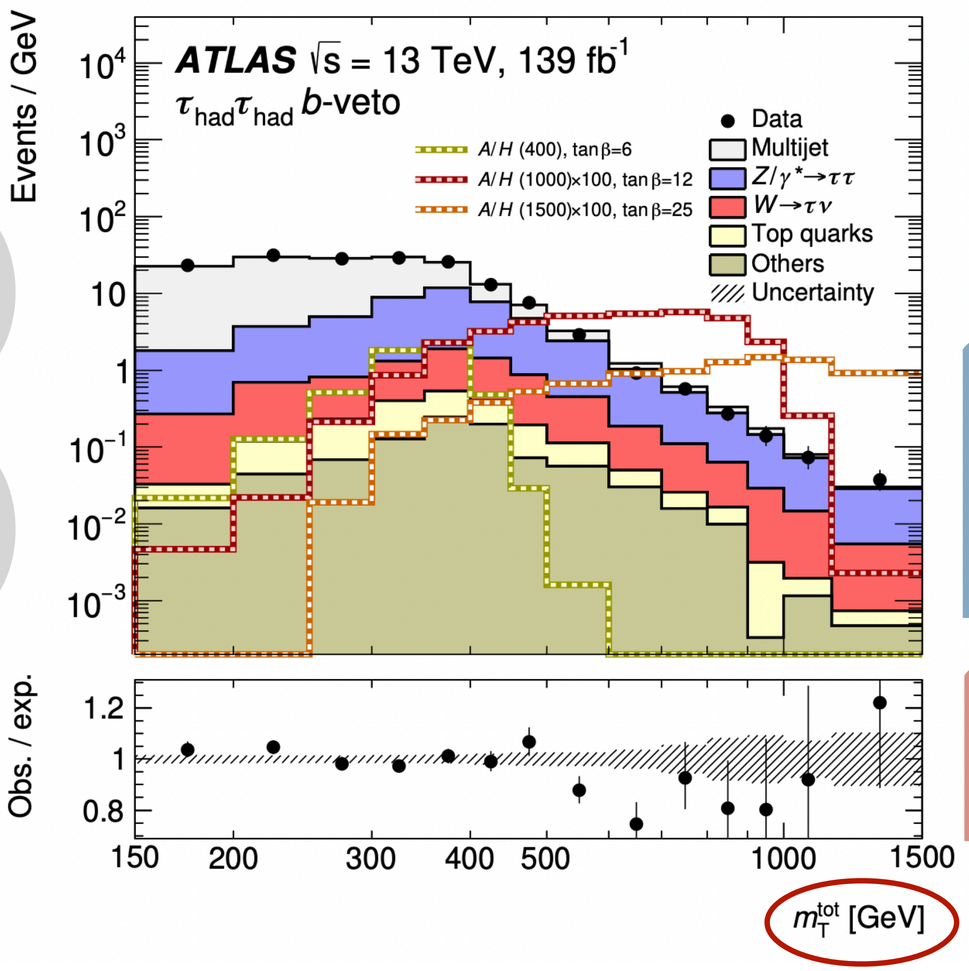
High-p_T DY tails are **complementary** to low-energy observables, and allows the study of the **EFT validity**.

Experimental search for the analysis

Recast of $pp \to \tau\tau$ ATLAS search [G. Aad et al. [2002.12223]].





Allwicher, Faroughy, Wilsch, Jaffredo, Sumensari [2207.10741], [2207.10756]

Observables convoluted with

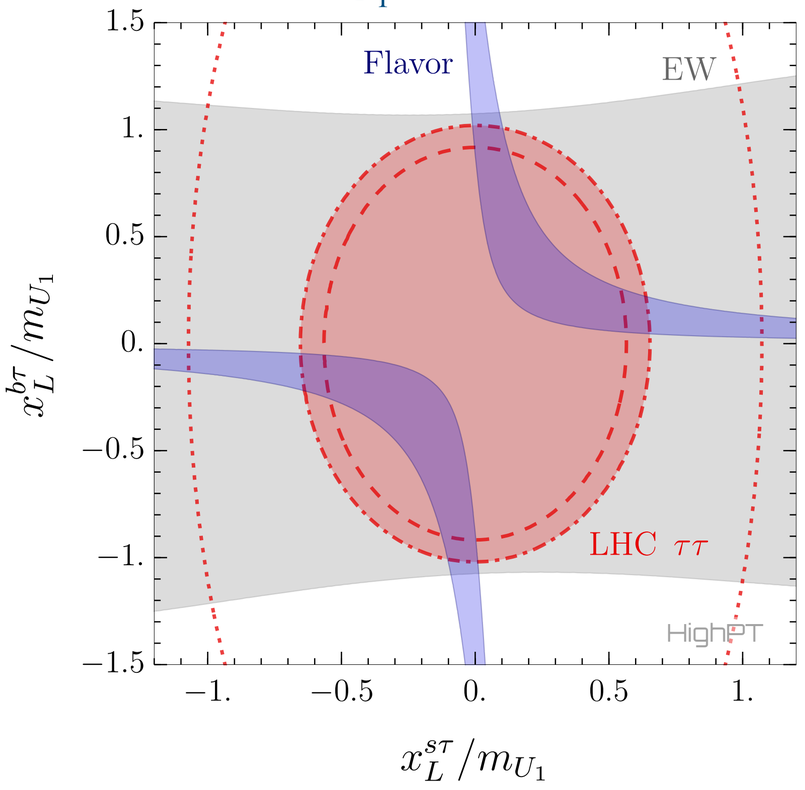
- Parton Shower and Hadronization — **Pythia8**.
- Detector simulation — **Delphes**.

Not possible to fully reconstruct the kinematics of the events.

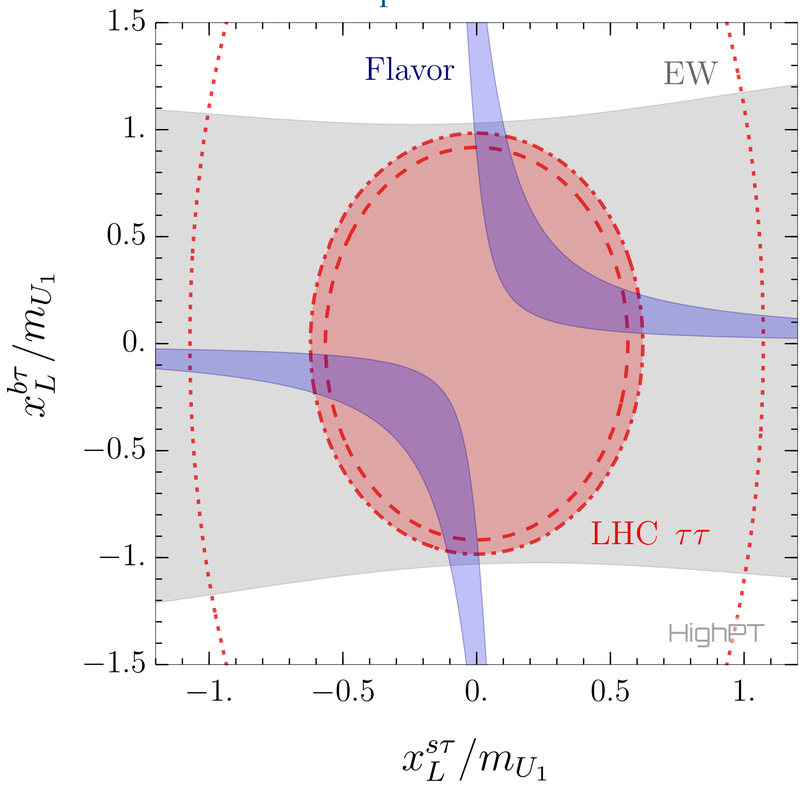
Example: low vs. high-p_T constraints

m_{U_1}

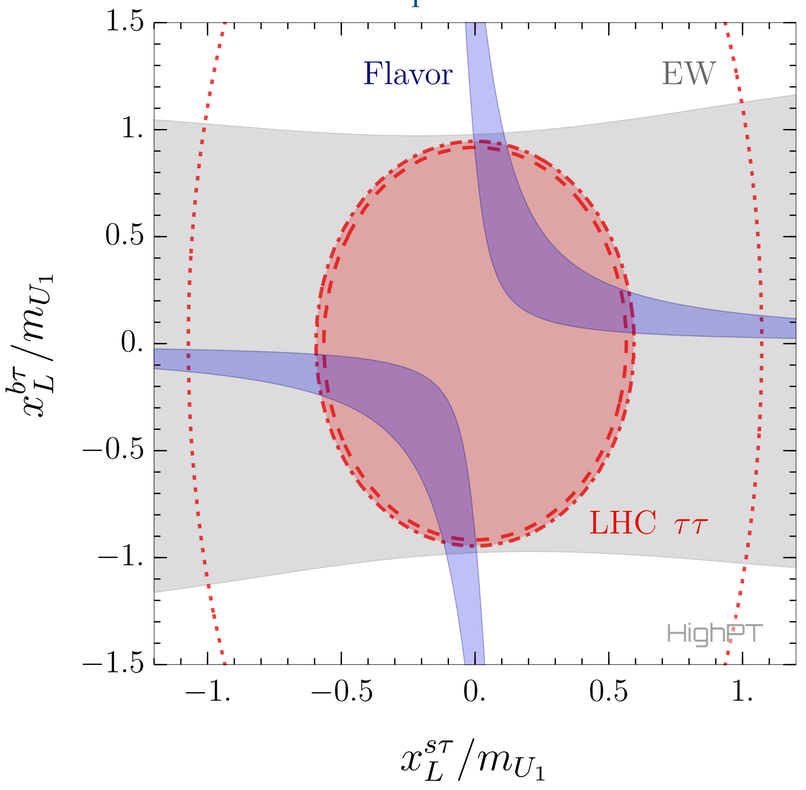
$m_{U_1} = 1.5$ TeV



$m_{U_1} = 2$ TeV



$m_{U_1} = 3$ TeV



Flavor observables

$$\frac{R_{D^{(*)}}}{R_{D^{(*)}}^{\rm SM}} \simeq 1 - \frac{v^2}{\Lambda^2}{\rm Re}\left(\frac{1}{V_{cb}^*}[\mathcal{C}_{lq}^3]_{3323} + [\mathcal{C}_{lq}^3]_{3333}\right) = 1 + \frac{v^2}{2m_{U_1}^2}{\rm Re}\left(\frac{x_L^{s\tau}x_L^{b\tau\,*}}{V_{cb}^*} + |x_L^{b\tau}|^2\right)$$

Example: low vs. high-p_T constraints

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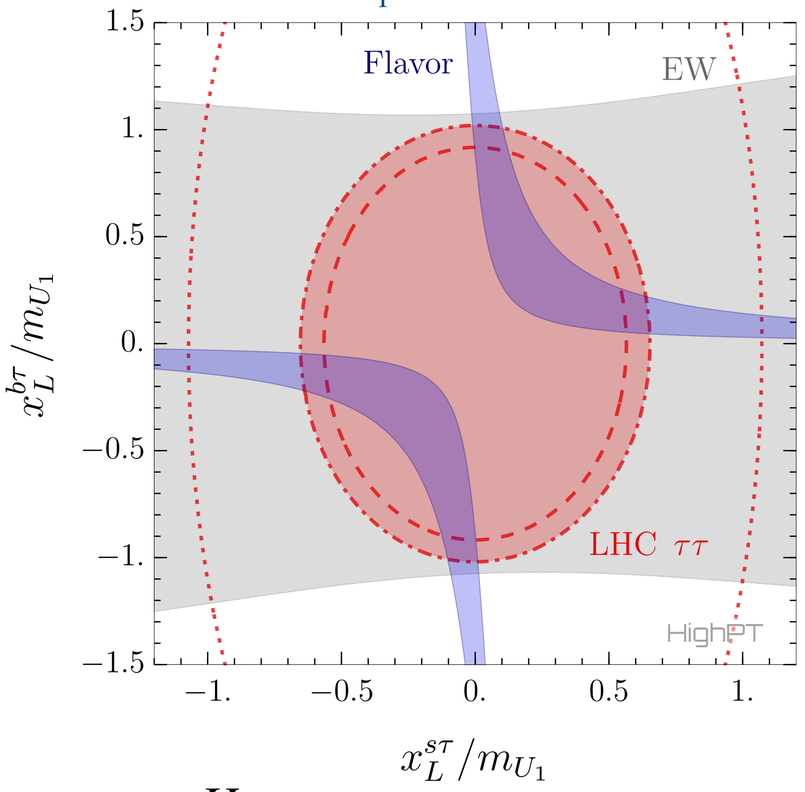

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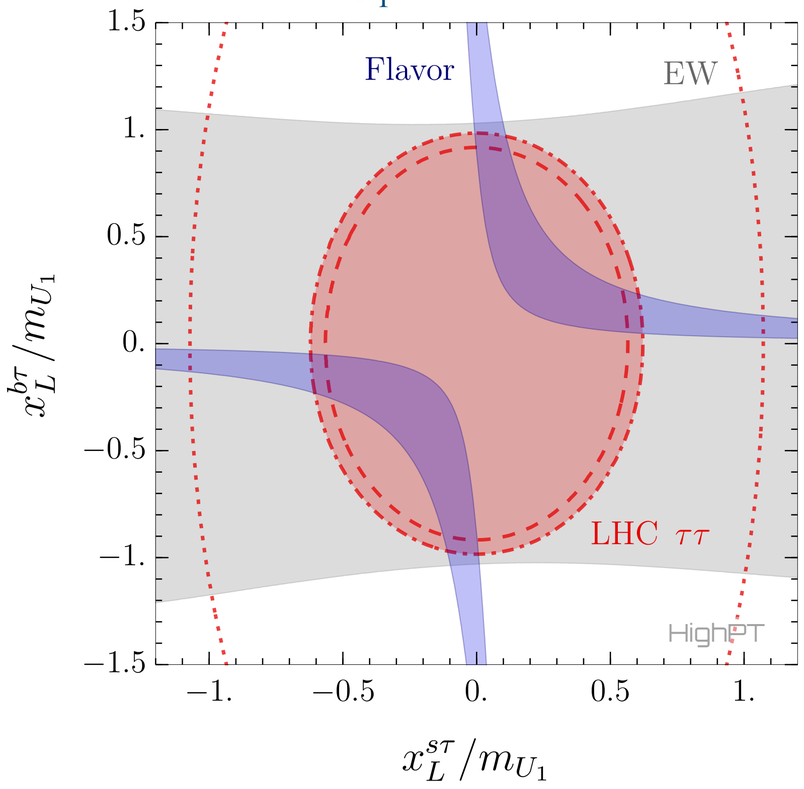

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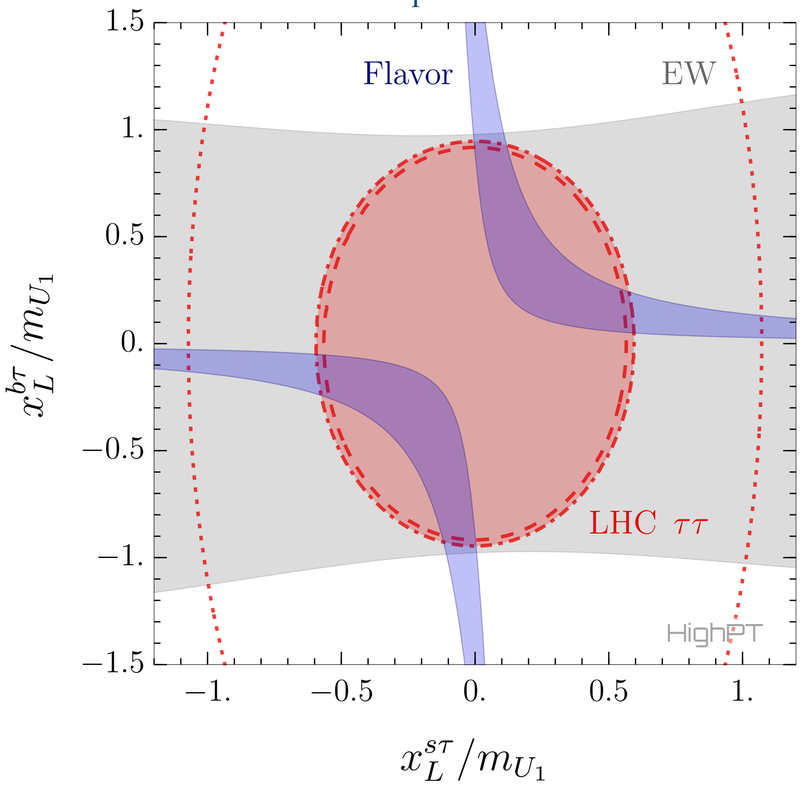

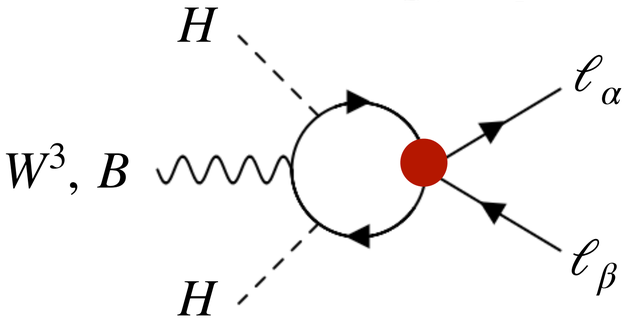

Largest effect in EWPO comes from $Z\nu\bar{\nu}$ vertex corrections

$$\delta g_L^\nu \propto [\mathcal{C}_{Hl}^{(1-3)}]_{33}(m_Z) \simeq \frac{6|y_t|^2}{16\pi^2}\log\frac{m_Z}{\Lambda}[\mathcal{C}_{lq}^{(1+3)}]_{3333} = \frac{6|y_t|^2}{16\pi^2}\log\left[-\frac{m_Z}{m_{U_1}}\frac{|x_L^{b\tau}|^2}{2}\right]$$

Inputs taken from V. Bresó-Pla, A. Falkowski and M. González-Alonso [2103.12074].

RGEs- E. E. Jenkins et al [1308.2627], [1310.4838], [1312.2014].

Example: low vs. high-p_T constraints

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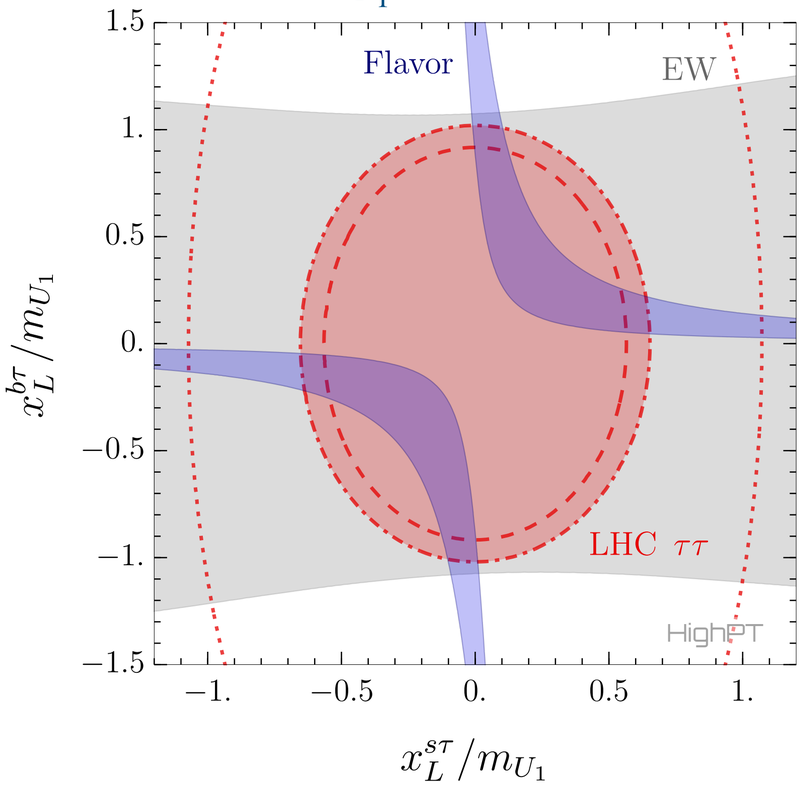

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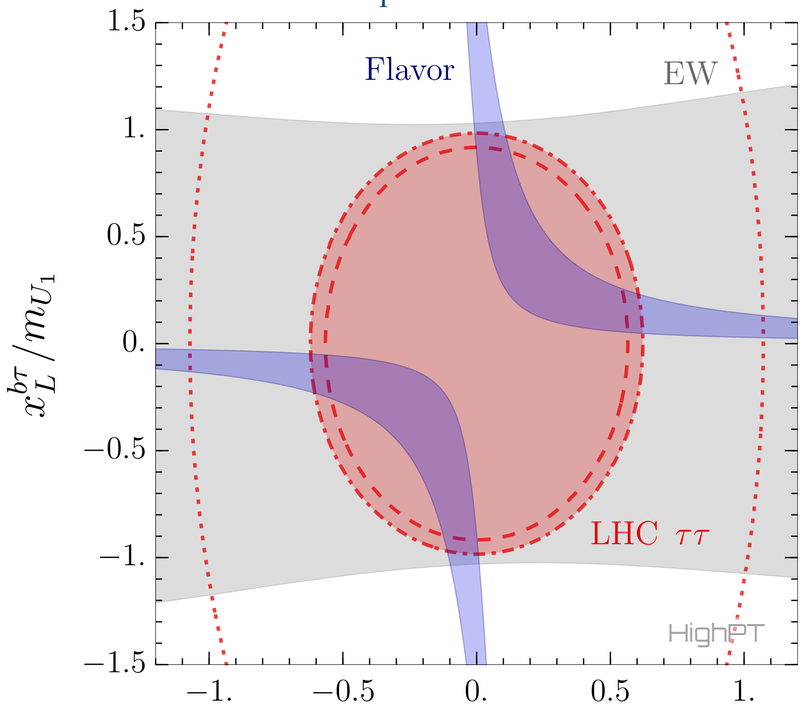

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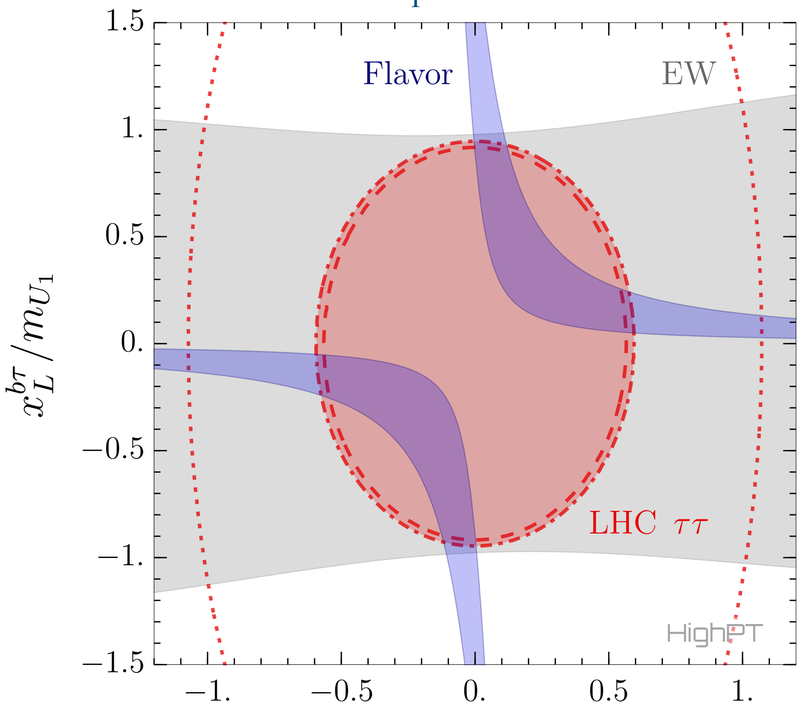


$\mathcal{O}_\sigma(\Lambda^{-2})$ Full model

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

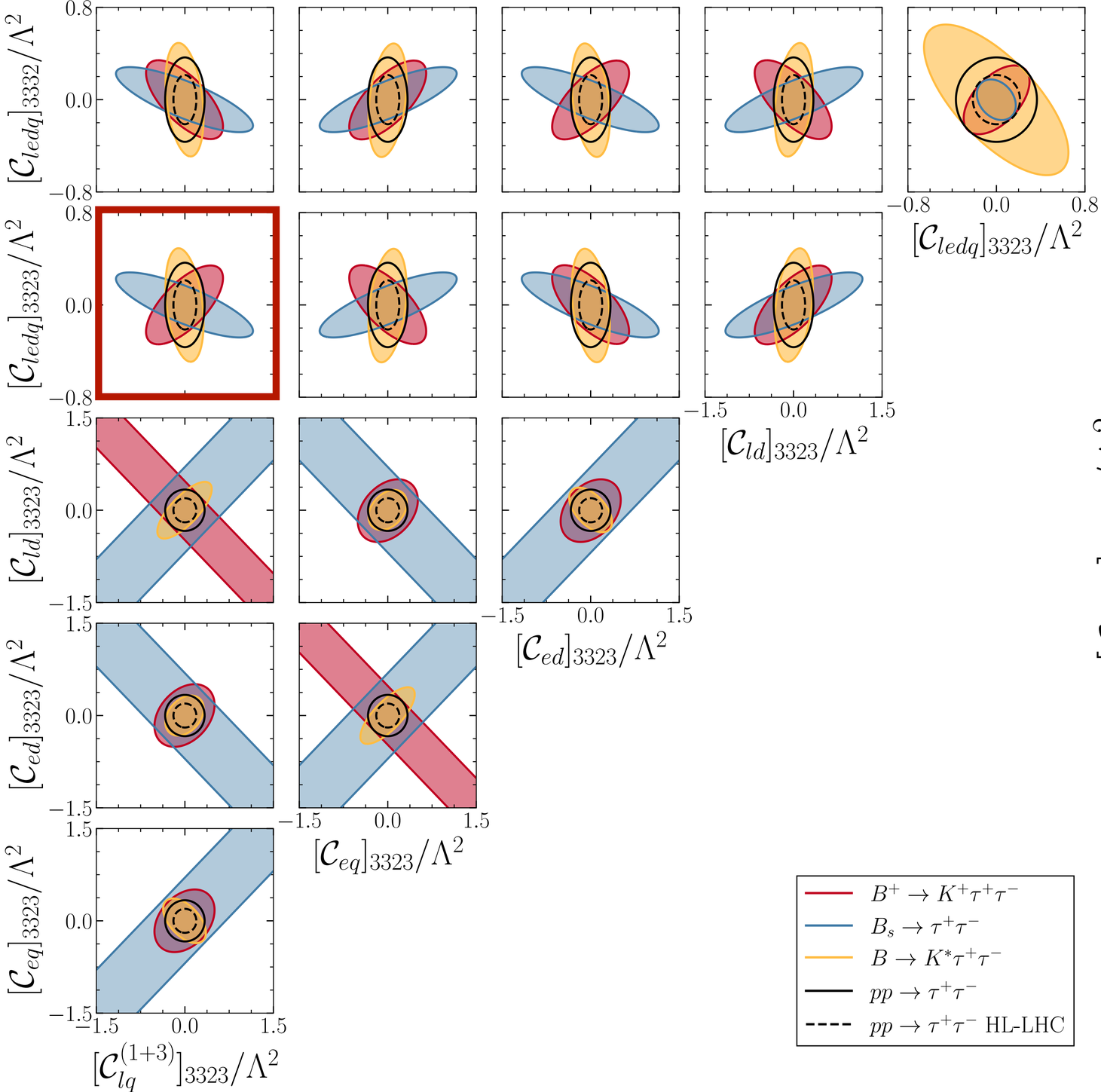
$\mathcal{O}_\mathcal{A}(\Lambda^{-4})$

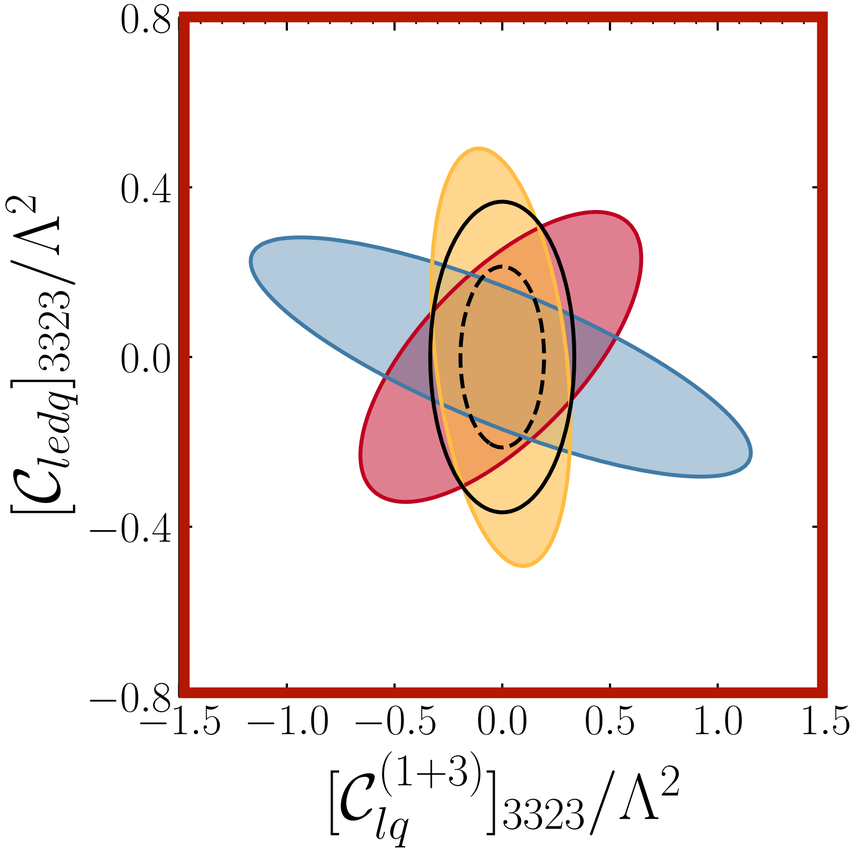
High-p_T DY tails - $pp \to \tau\tau$

- The EFT series has alternating signs, which helps with its convergence.
- $\mathcal{O}_\mathcal{A}(\Lambda^{-2})$: EFT series exhibits ~10% difference from the model for $m_{U_1} = 1.5$ TeV.
- $\mathcal{O}_\mathcal{A}(\Lambda^{-4})$: EFT is an excellent approximation for the model.

Rare decays

$b \to s\tau\tau$ transitions





[L. Allwicher, D. A. Faroughy, MM, O. Sumensari, F. Wilsh, In preparation]