Probing Flavorful EFTs via $pp \to Vh$ and $pp \to WV$ at the LHC

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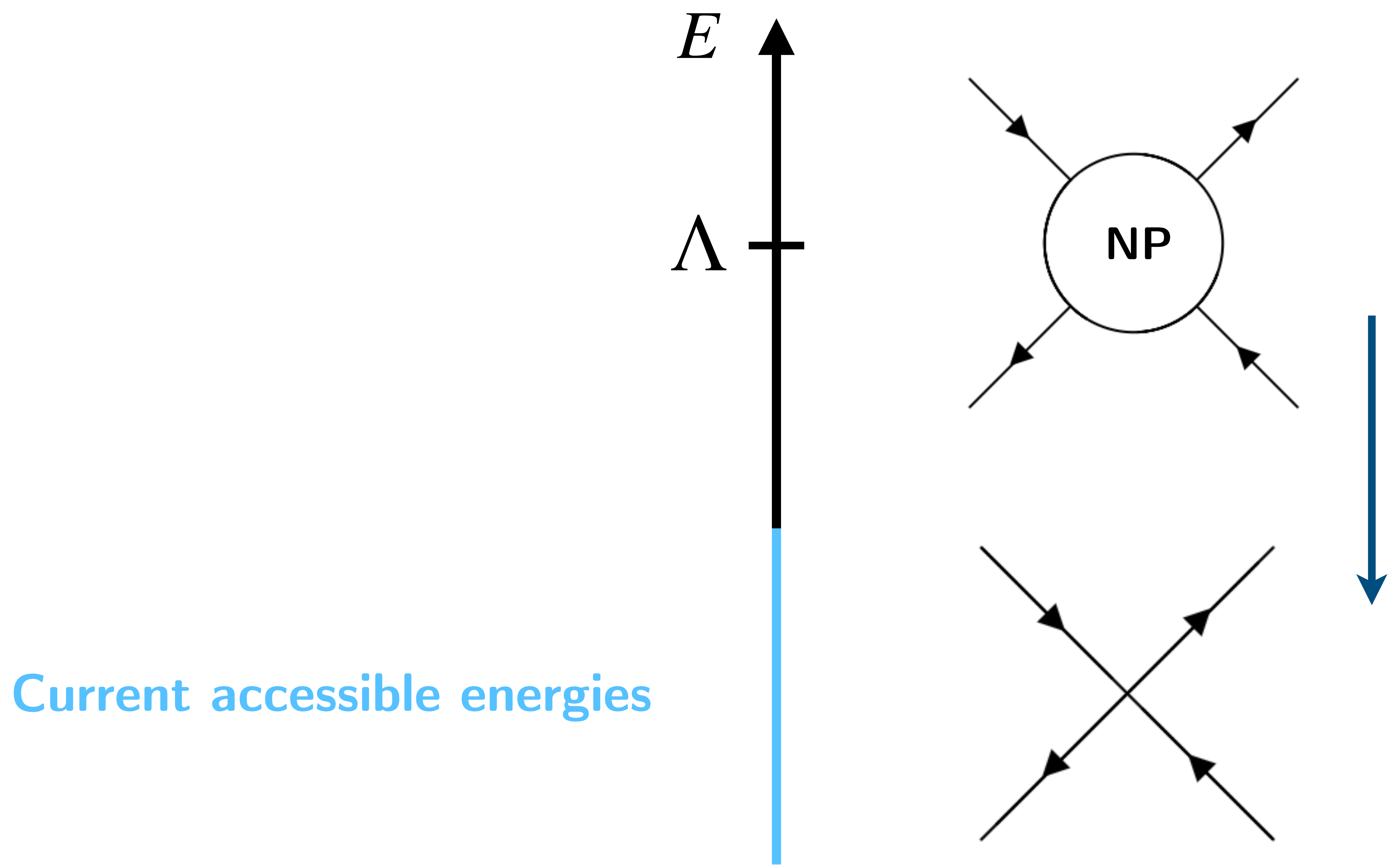
Based on [2509.08437]

In collaboration with O. J. P. Éboli, L. P. S. Leal, and O. Sumensari

Why EFTs?

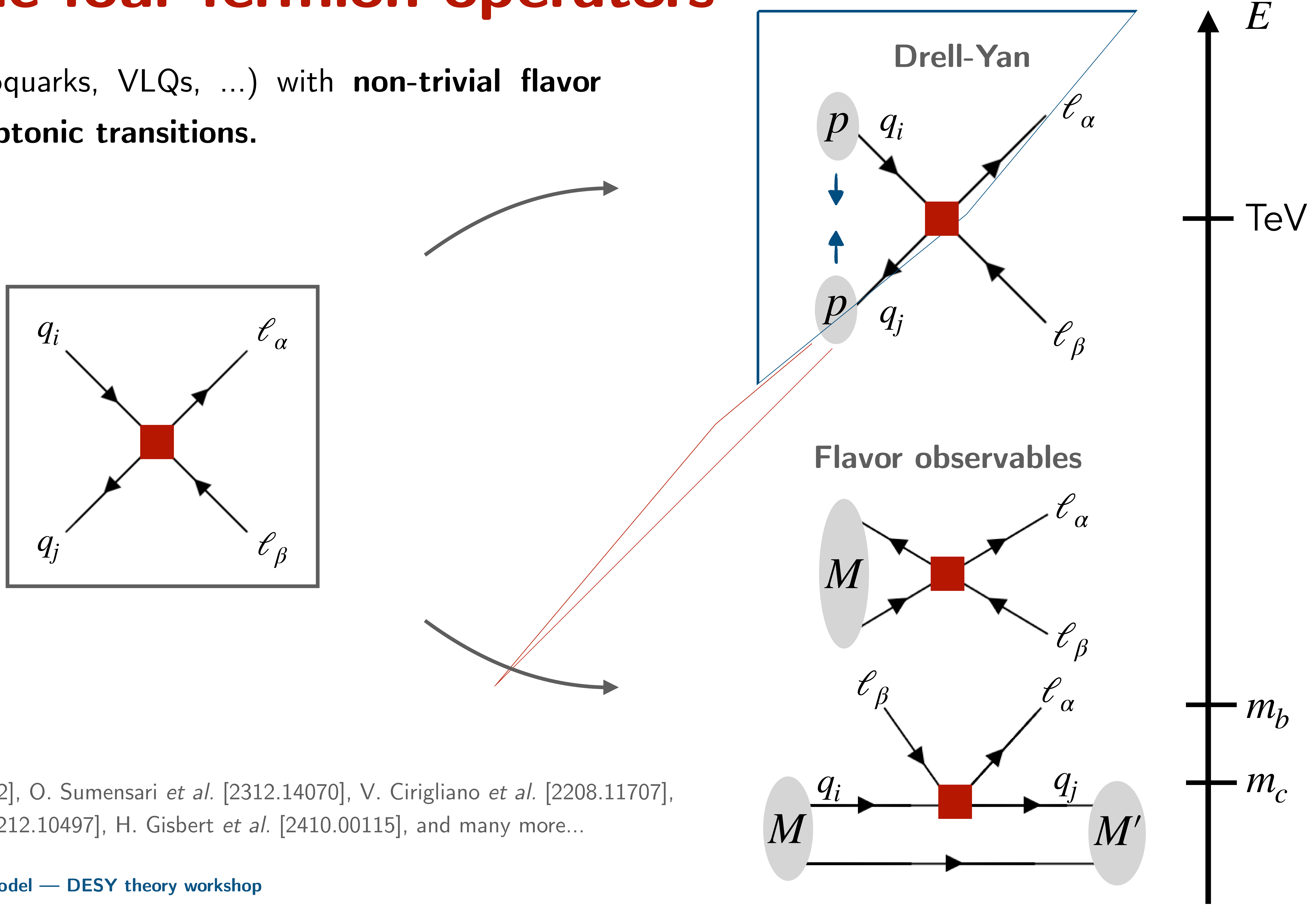
Absence of resonant signals at the LHC. → **Mass gap** between the electroweak scale and the scale of New Physics (NP).

Effective Field Theories (EFTs) can be used to describe the LHC observables in a **model independent way,** provided $E/\Lambda \ll 1$.



Semileptonic four-fermion operators

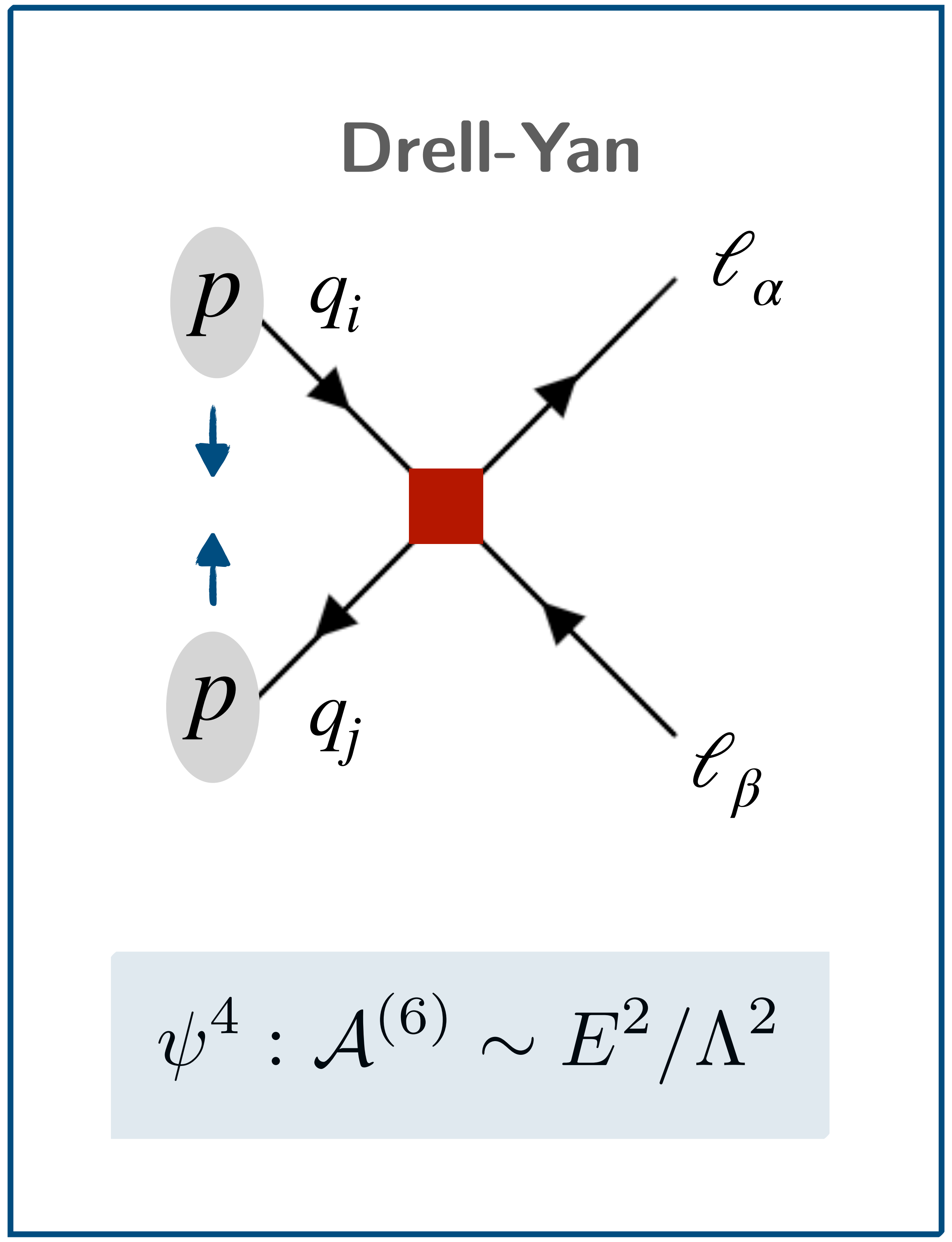
BSM models (Z', leptoquarks, VLQs, ...) with **non-trivial flavor structure** affect **semileptonic transitions.**

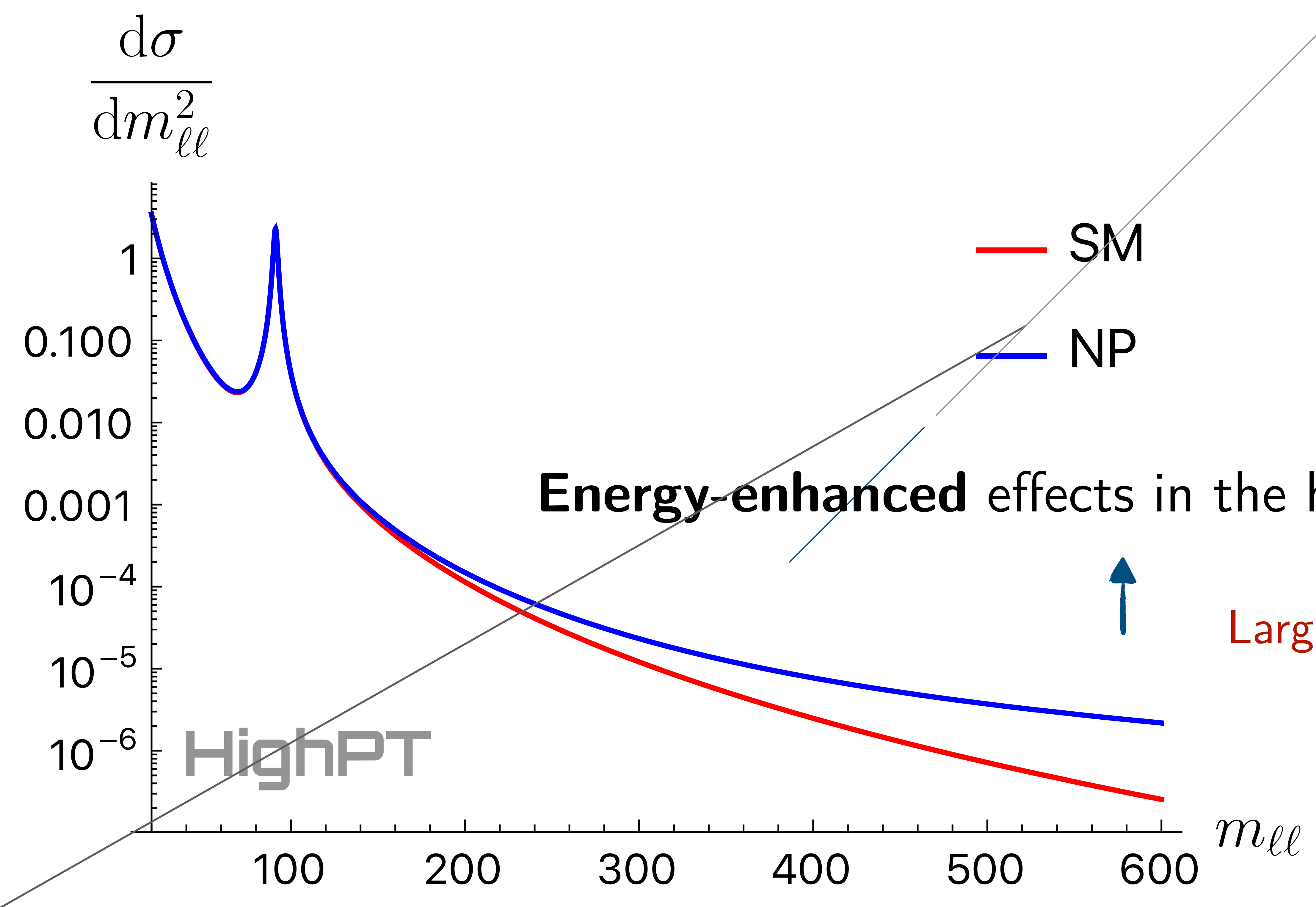


D. Becirevic *et al.* [2012.09872], O. Sumensari *et al.* [2312.14070], V. Cirigliano *et al.* [2208.11707], A. Greljo *et al.* [2306.09401, 2212.10497], H. Gisbert *et al.* [2410.00115], and many more...

High-p_T Drell-Yan tails

DY data can provide constraints that are **competitive** with low-energy flavor observables, despite **PDF suppression**.





Energy-enhanced effects in the high-p_T tails.

Largest signal/background ratio

J. Blas *et al.* [1307.5068], S. Dawson *et al.* [1811.12260], M. Farina *et al.* [1609.08157], L. Allwicher *et al.* [2207.10714, 2412.14162], T. Corbett *et al.* [2503.19962], G. Hiller *et al.* [2502.12250], S. Descostes-Genon *et al.* [2303.07521], A. Angelescu *et al.* [2002.05684], and many more....

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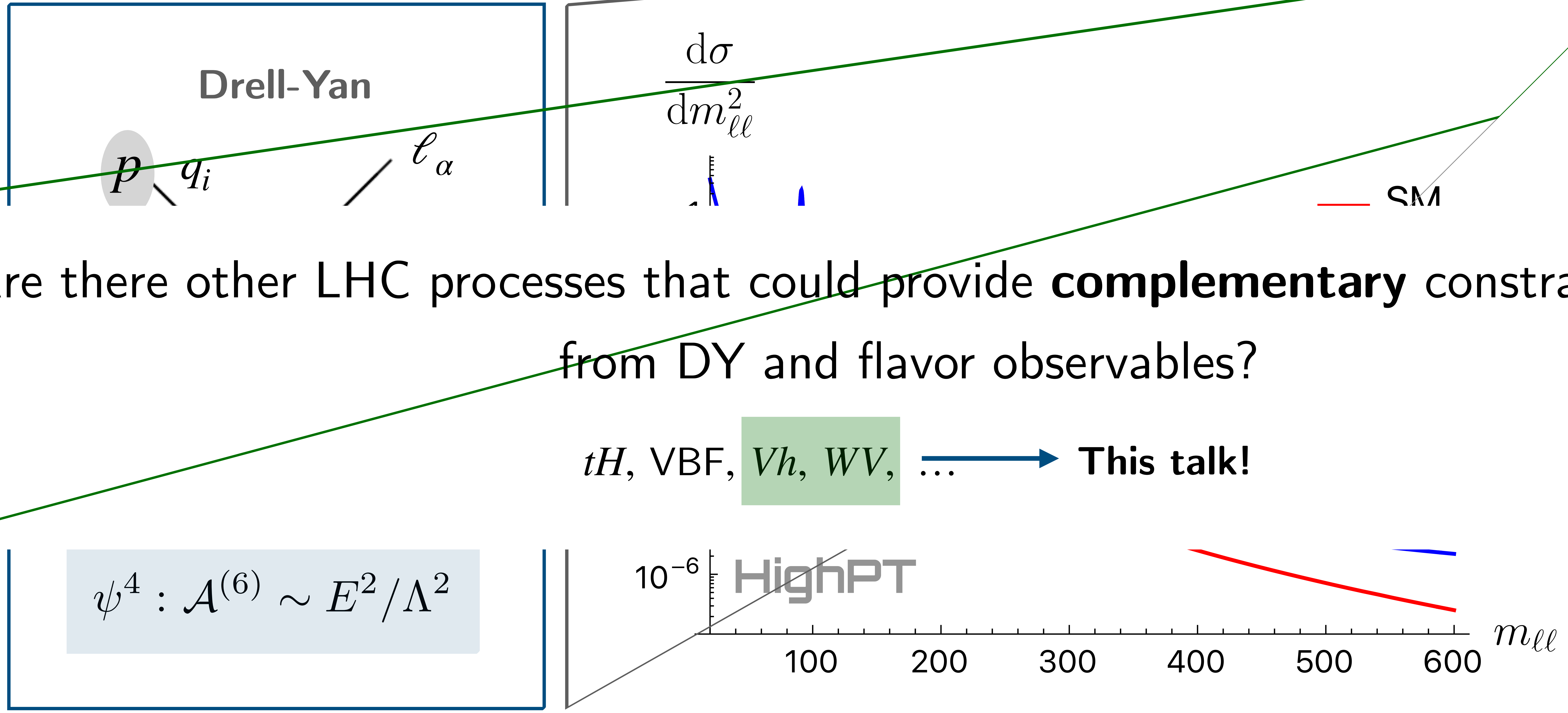


Are there other LHC processes that could provide **complementary** constraints to those from DY and flavor observables?

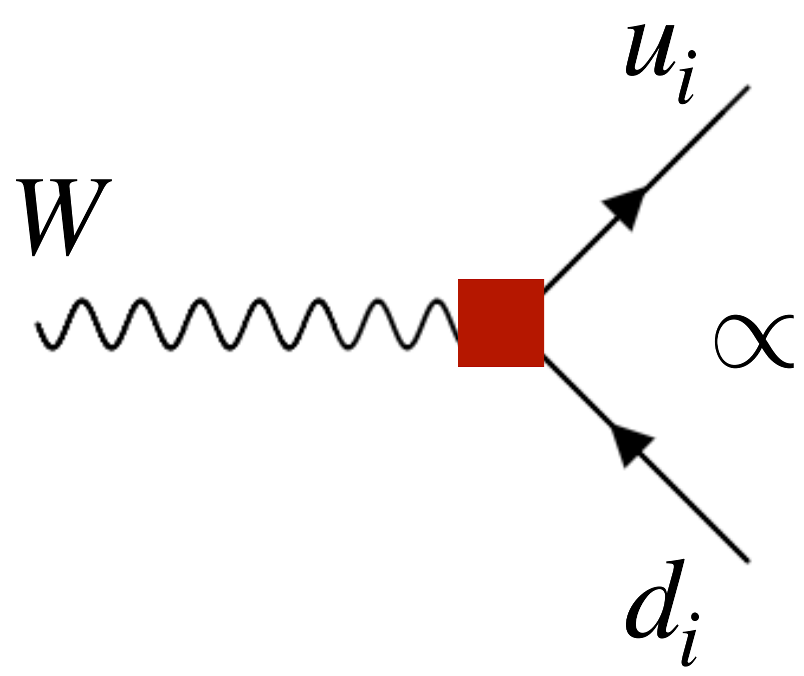
tH, VBF, Vh, WV, … → **This talk!**

tio

J. Blas *et al.* [1307.5068], S. Dawson *et al.* [1811.12260], M. Farina *et al.* [1609.08157], L. Allwicher *et al.* [2207.10714, 2412.14162], T. Corbett *et al.* [2503.19962], G. Hiller *et al.* [2502.12250], S. Descostes-Genon *et al.* [2303.07521], A. Angelescu *et al.* [2002.05684], and many more….

Example: Right-Handed Charged Currents at the LHC

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



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

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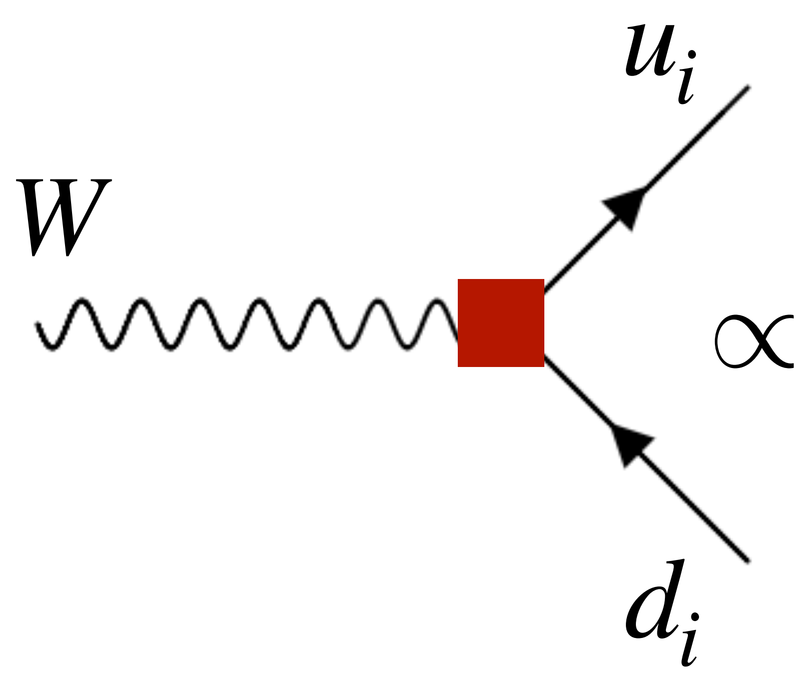

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$\psi^2 H^2 D: \ \mathcal{M}^{(6)}(u\bar{d} \to \ell^+ \nu) \sim v^2/\Lambda^2$

Poorly constrained by DY.

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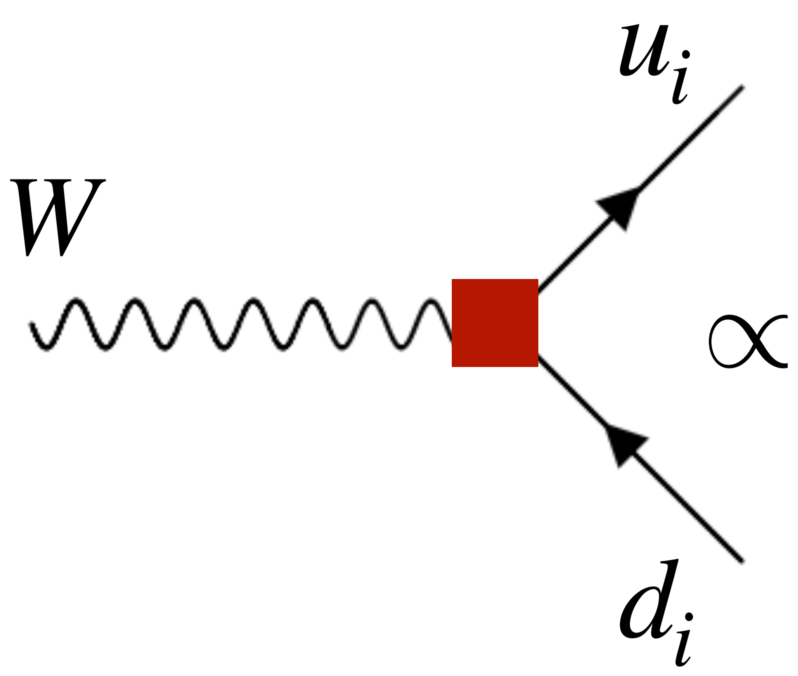

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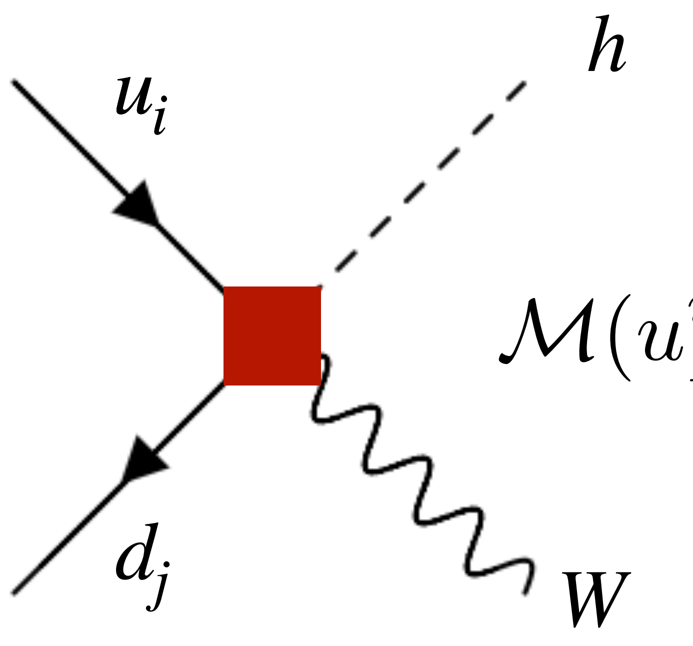

$$\mathcal{M}(u_R^i \, \bar{d}_R^j \to W_0 \, h) = -\frac{i}{\sqrt{2}} \frac{E^2 \sin\theta}{\Lambda^2} \mathcal{C}^*_{\substack{Hud \\ ij}}$$

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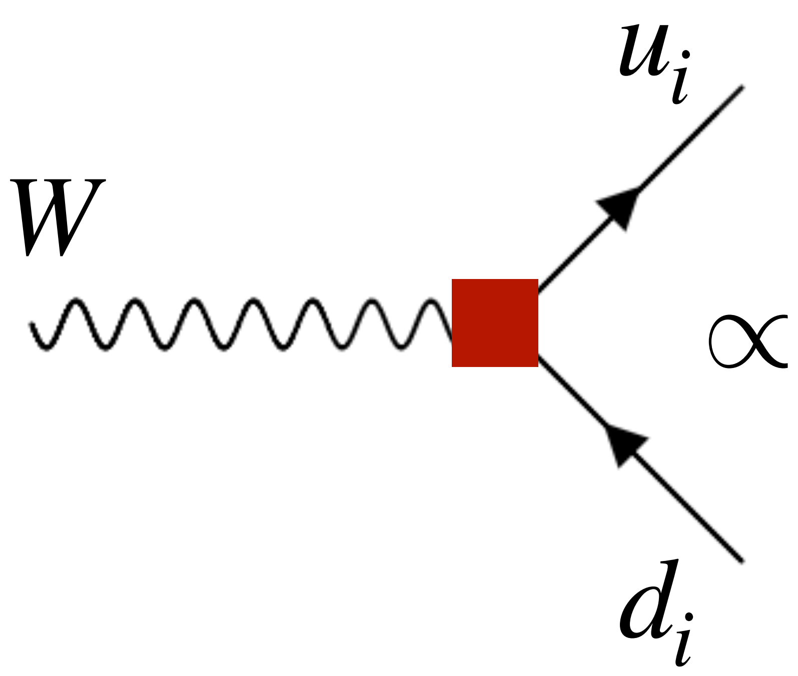

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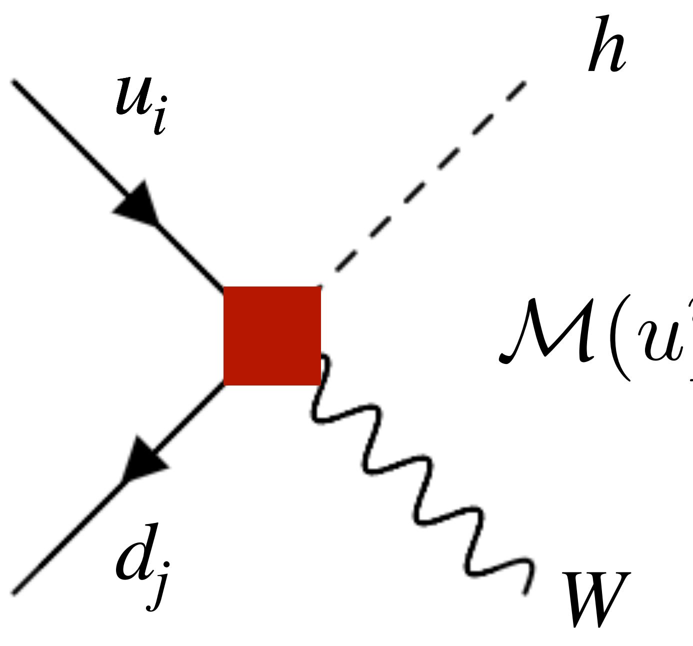

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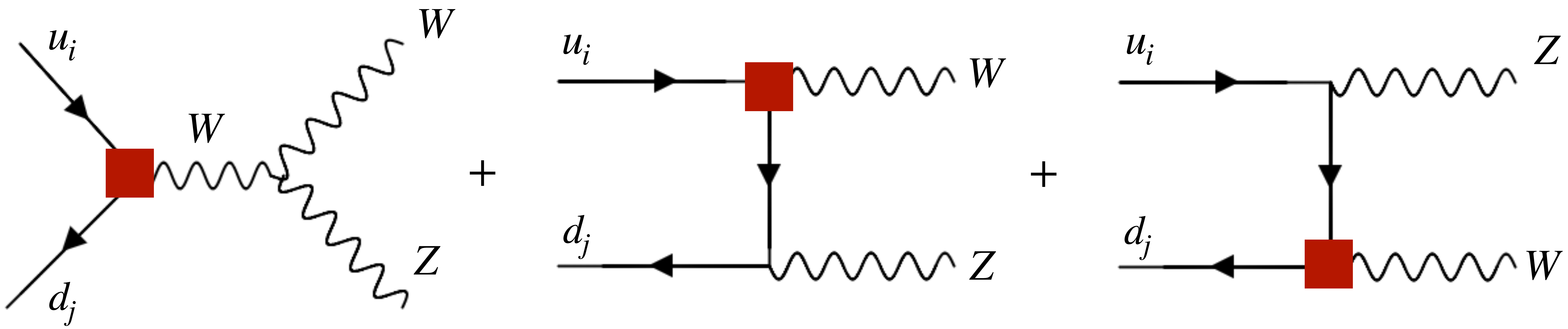
Modifications to the charged current **spoil** the SM cancellations.



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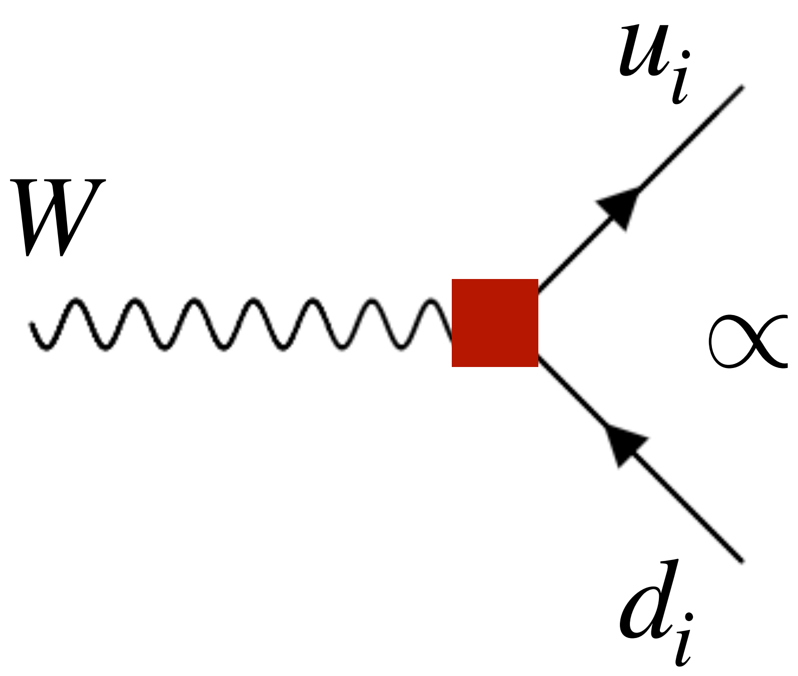

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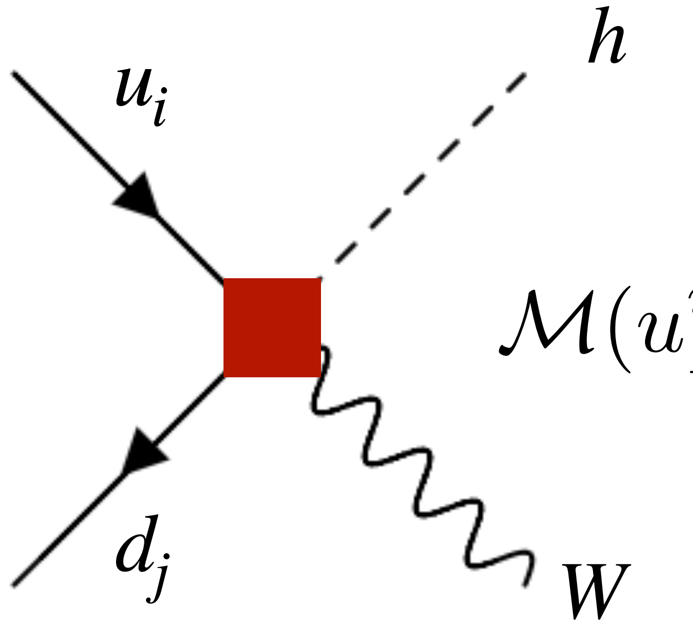

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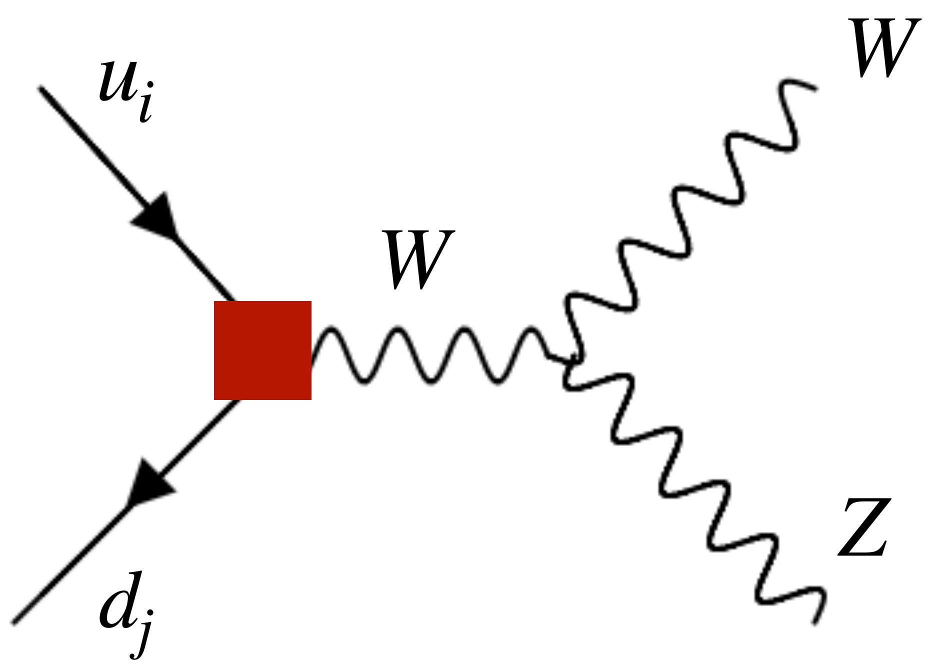

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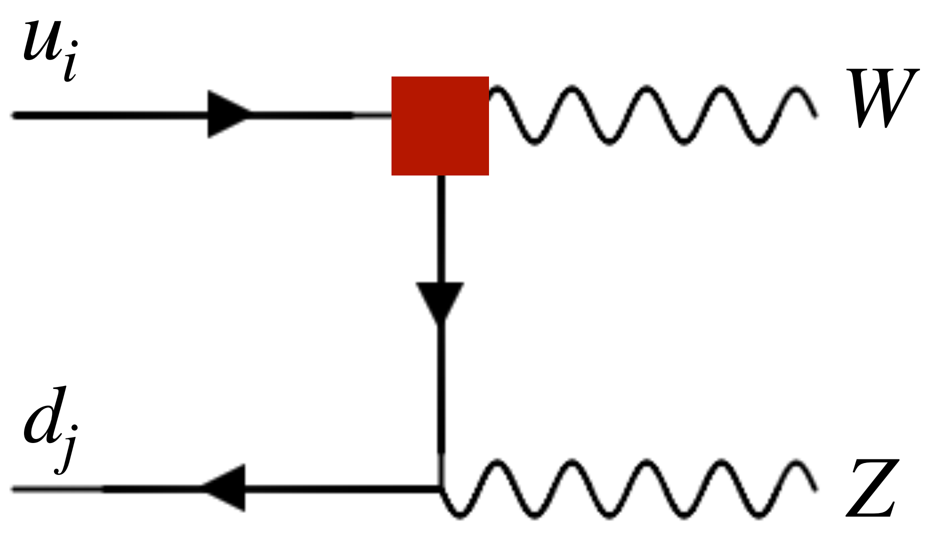

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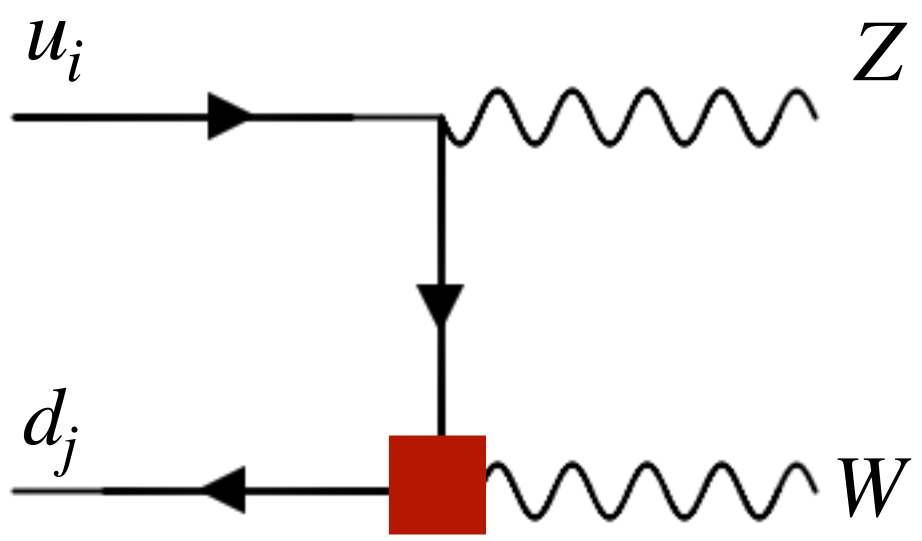

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These amplitudes are related by the **Goldstone Boson Equivalence Theorem**.

Goldstone Boson Equivalence Theorem

See Tao Han's presentation.

In the limit $\widehat{S} \gg m_W^2, m_Z^2$ $\quad \mathcal{M}(q_i\bar{q}_j \to V_0\,V_0') \propto \mathcal{M}(q_i\bar{q}_j \to \phi\,\phi')$

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]

GBs

$$H = \begin{pmatrix} -iw^+ \\ \frac{1}{\sqrt{2}}(v + h + iz) \end{pmatrix}$$

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

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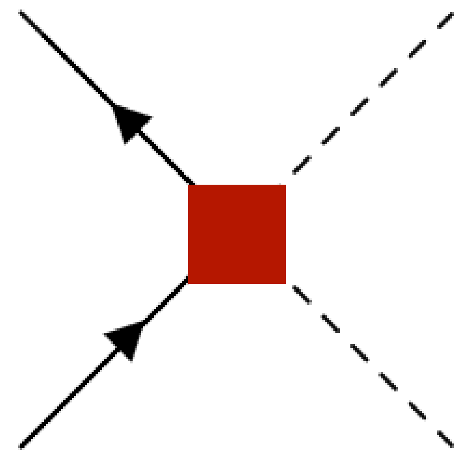

$\propto E^2/\Lambda^2$

→ At energies $E^2 \gg m_W^2$, these amplitudes are related by $SU(2)_L$ **gauge invariance.**

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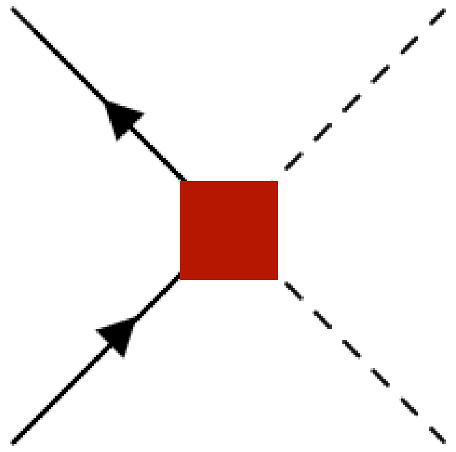

$\propto E^2/\Lambda^2$

→ At energies $E^2 \gg m_W^2$, these amplitudes are related by $SU(2)_L$ **gauge invariance.**

→ 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

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

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

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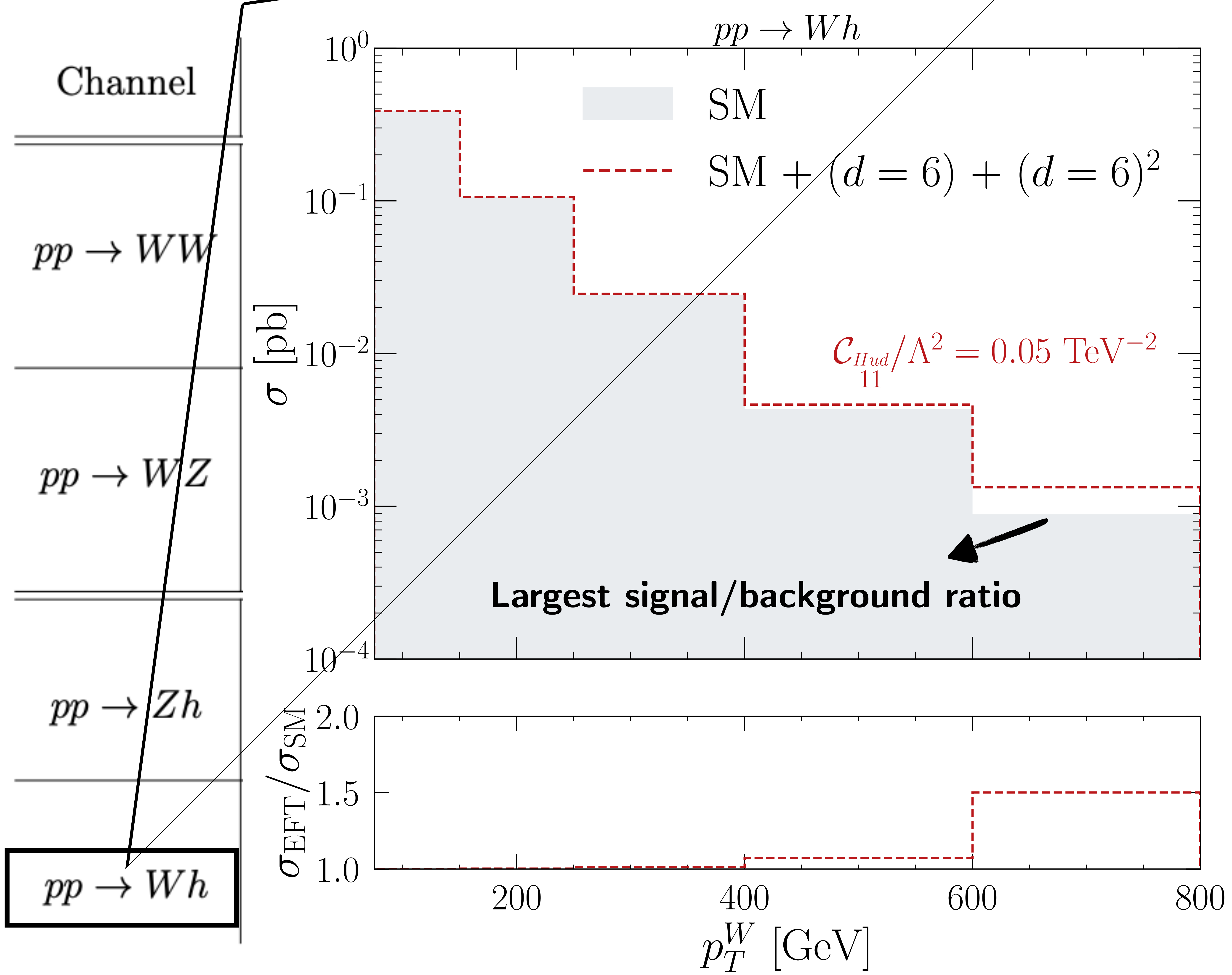
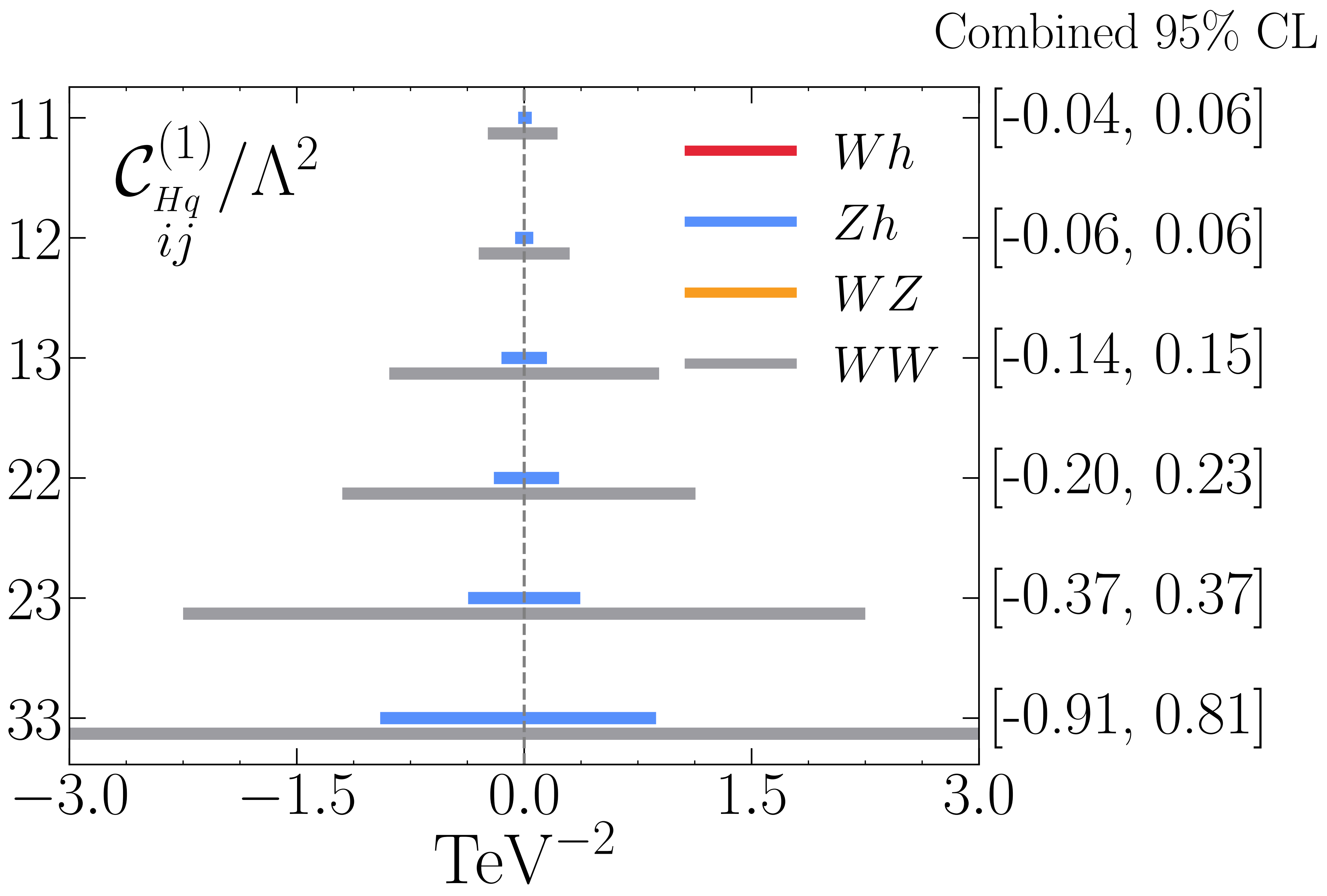
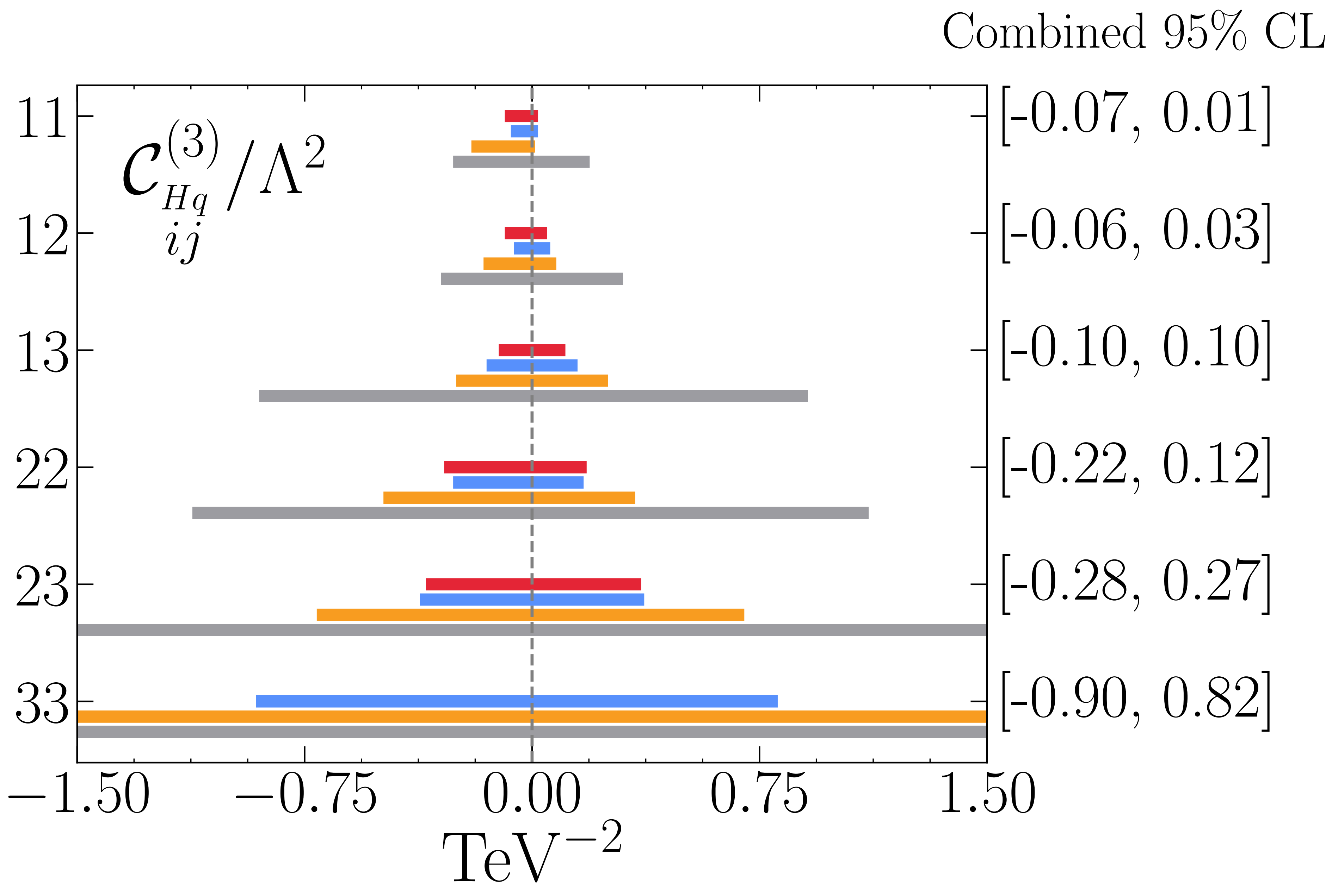
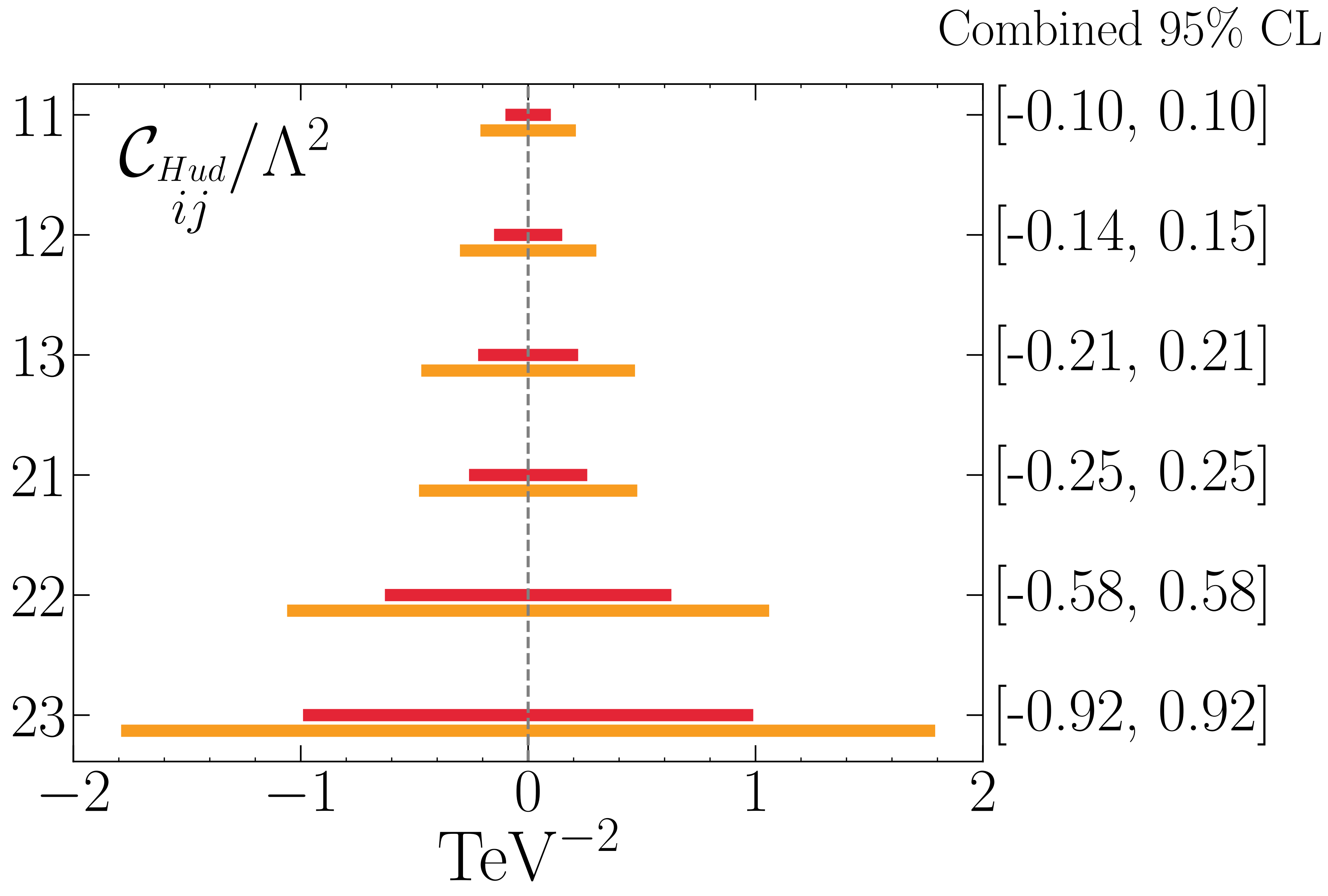


Higgs differential distributions in the format of **Simplified Template Cross-Sections (STXS)** are available. D. De Florian *et al.* [1610.07822]

Single parameter limits



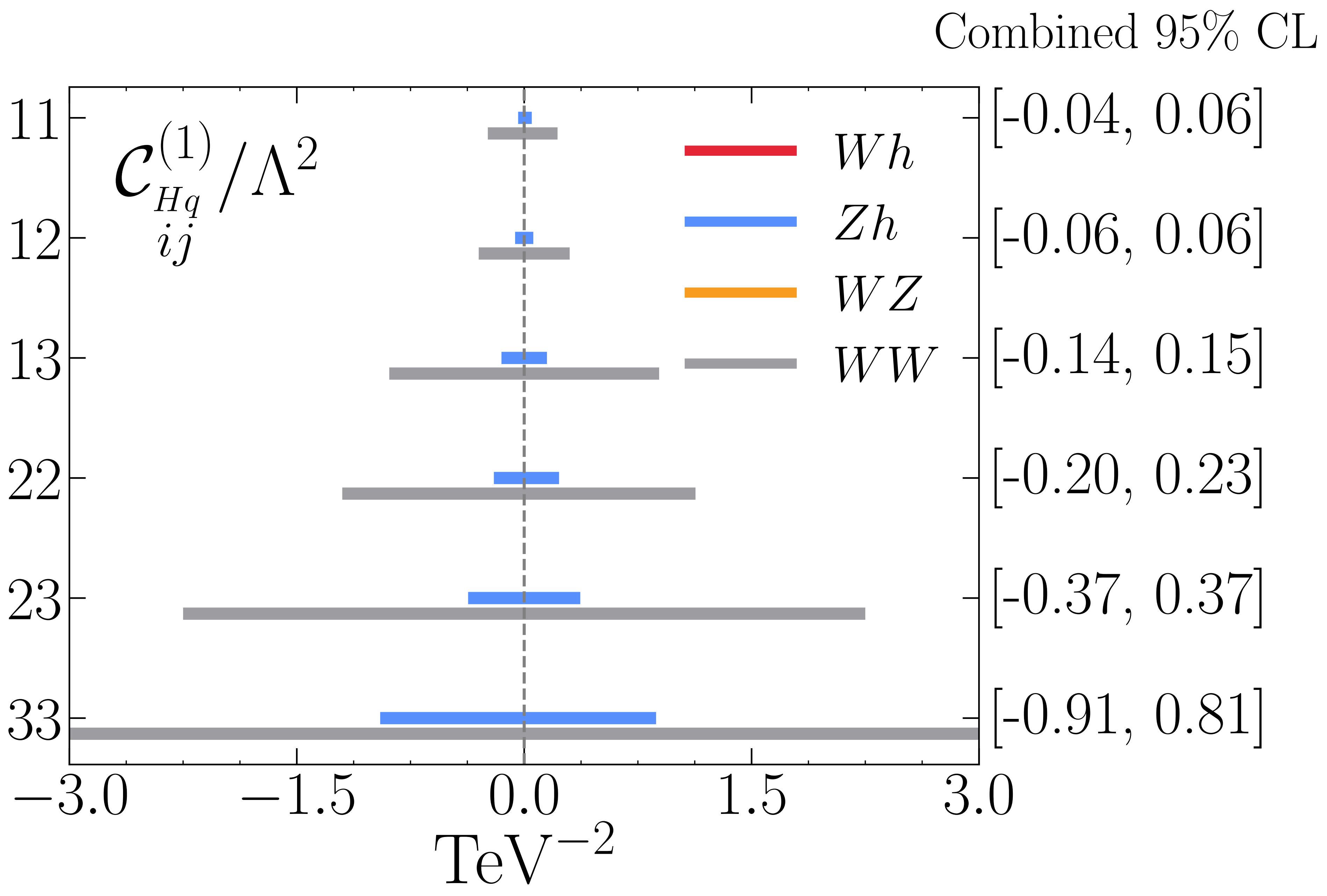


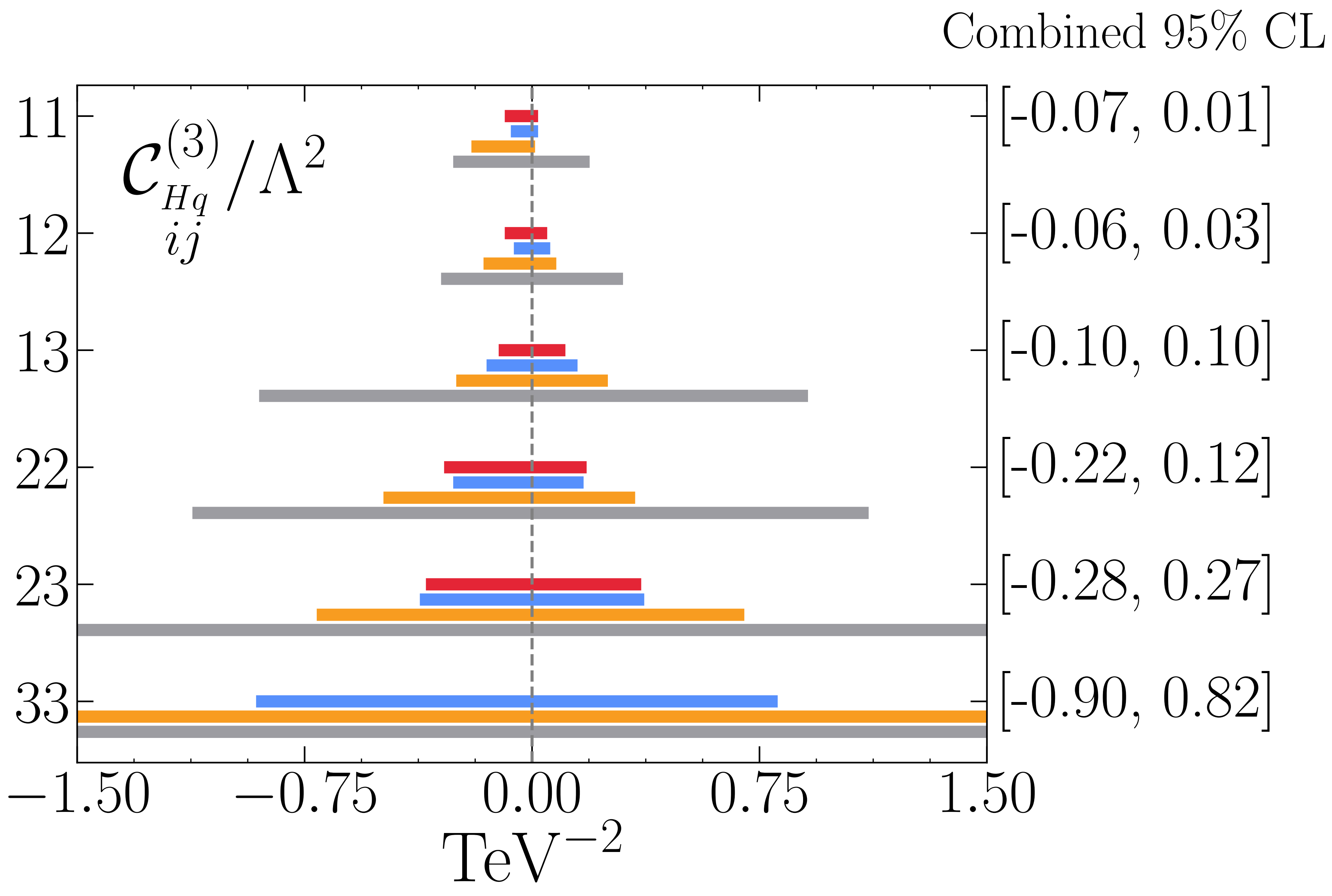


$$\sigma = \sigma_{\text{SM}} + \frac{1}{\Lambda^2}\sigma_{\text{Int}} + \frac{1}{\Lambda^4}\sigma_{\text{NP}^2}$$

Single parameter limits

Initial state masses

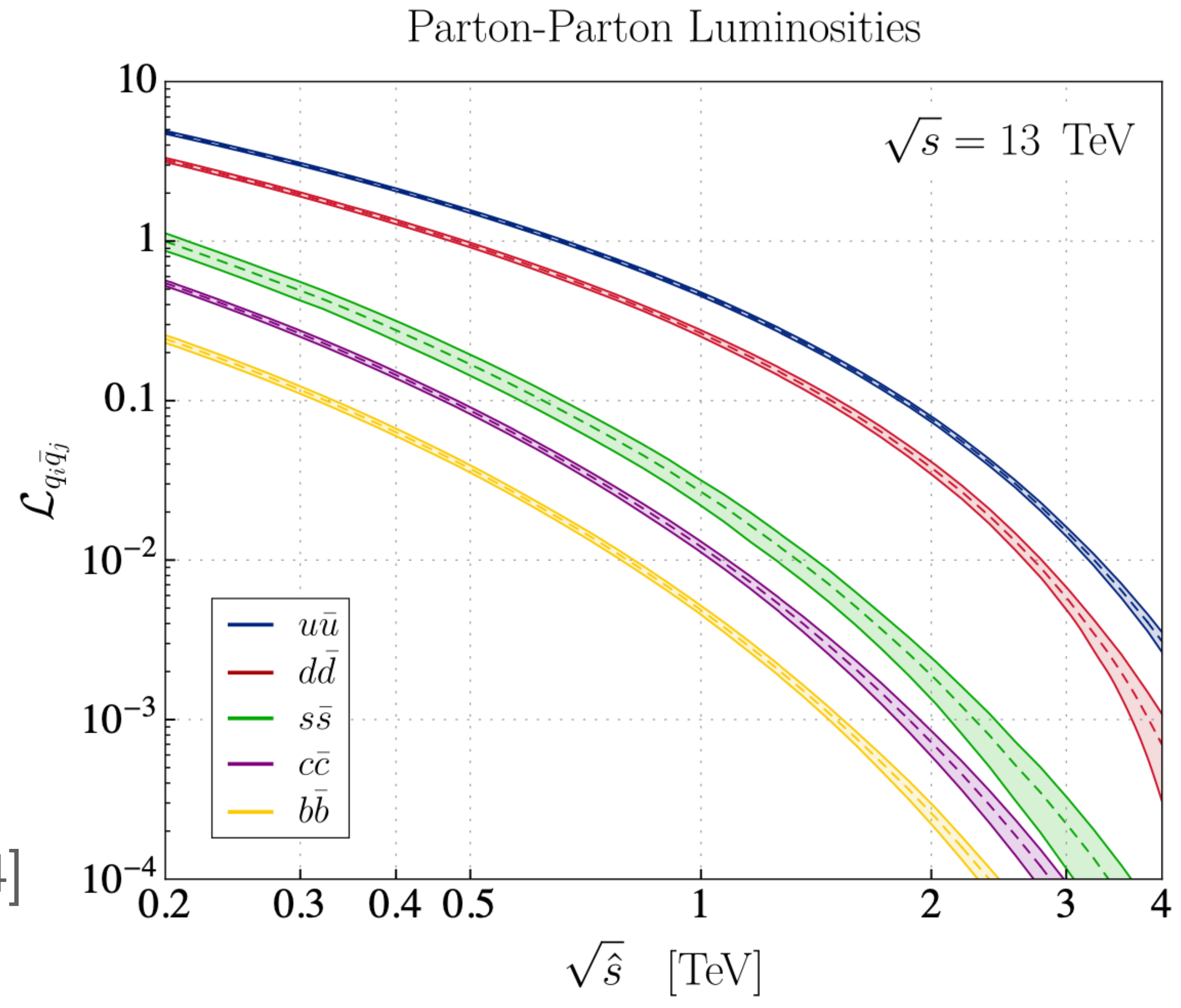




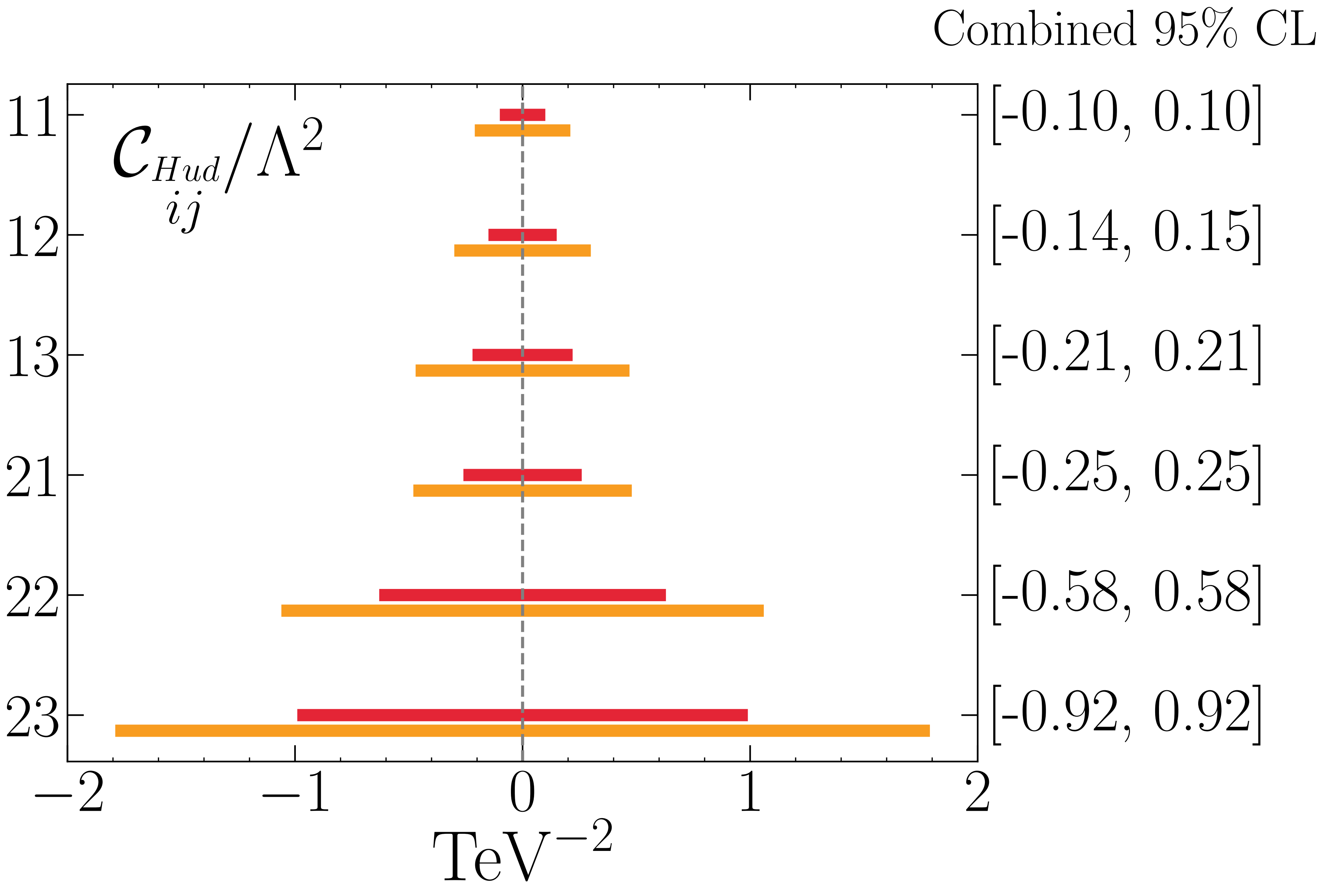
Heavier initial states lead to **weaker** constraints.

PDF suppression.

Quark mass



Angelescu *et al.* [2002.05684]



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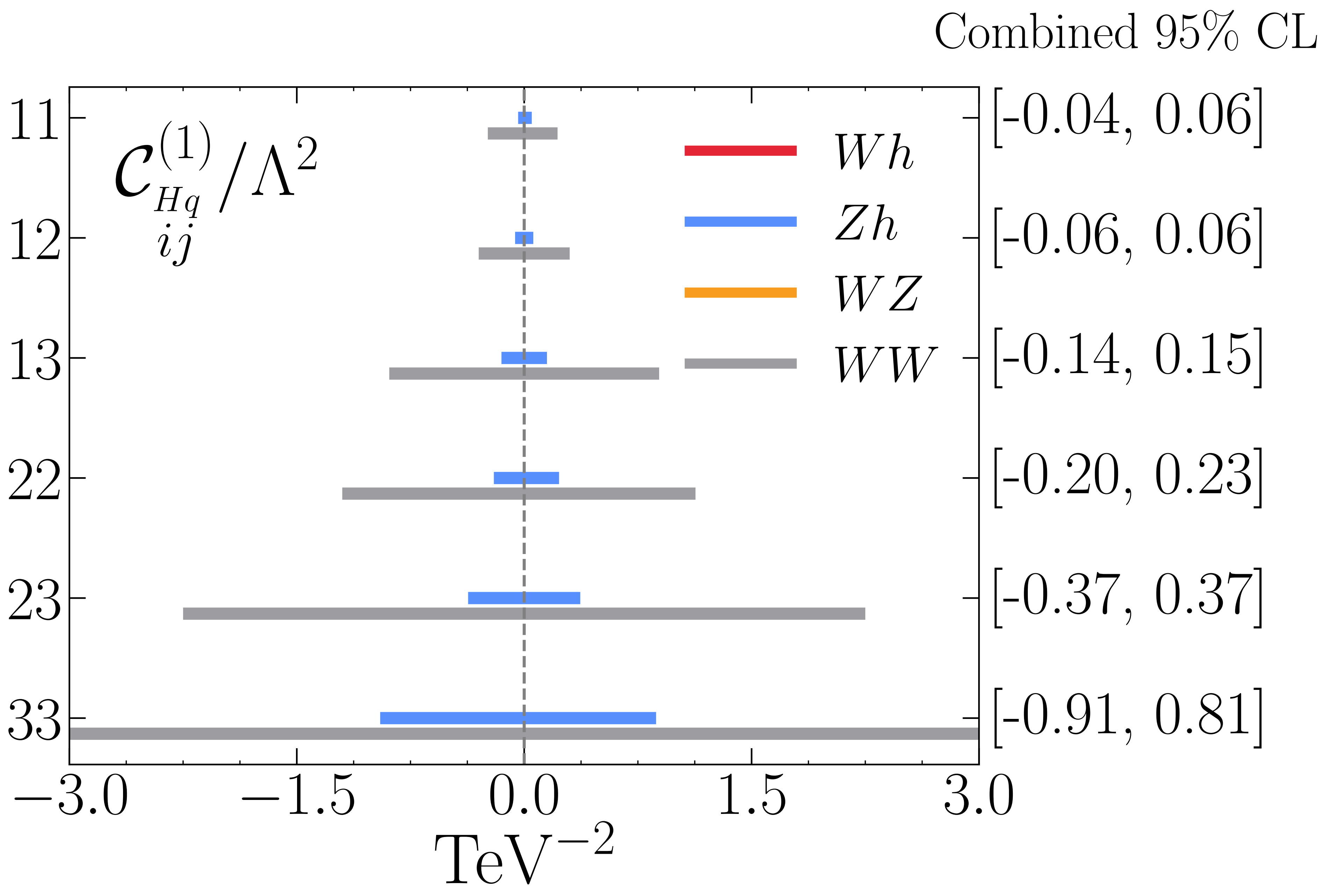
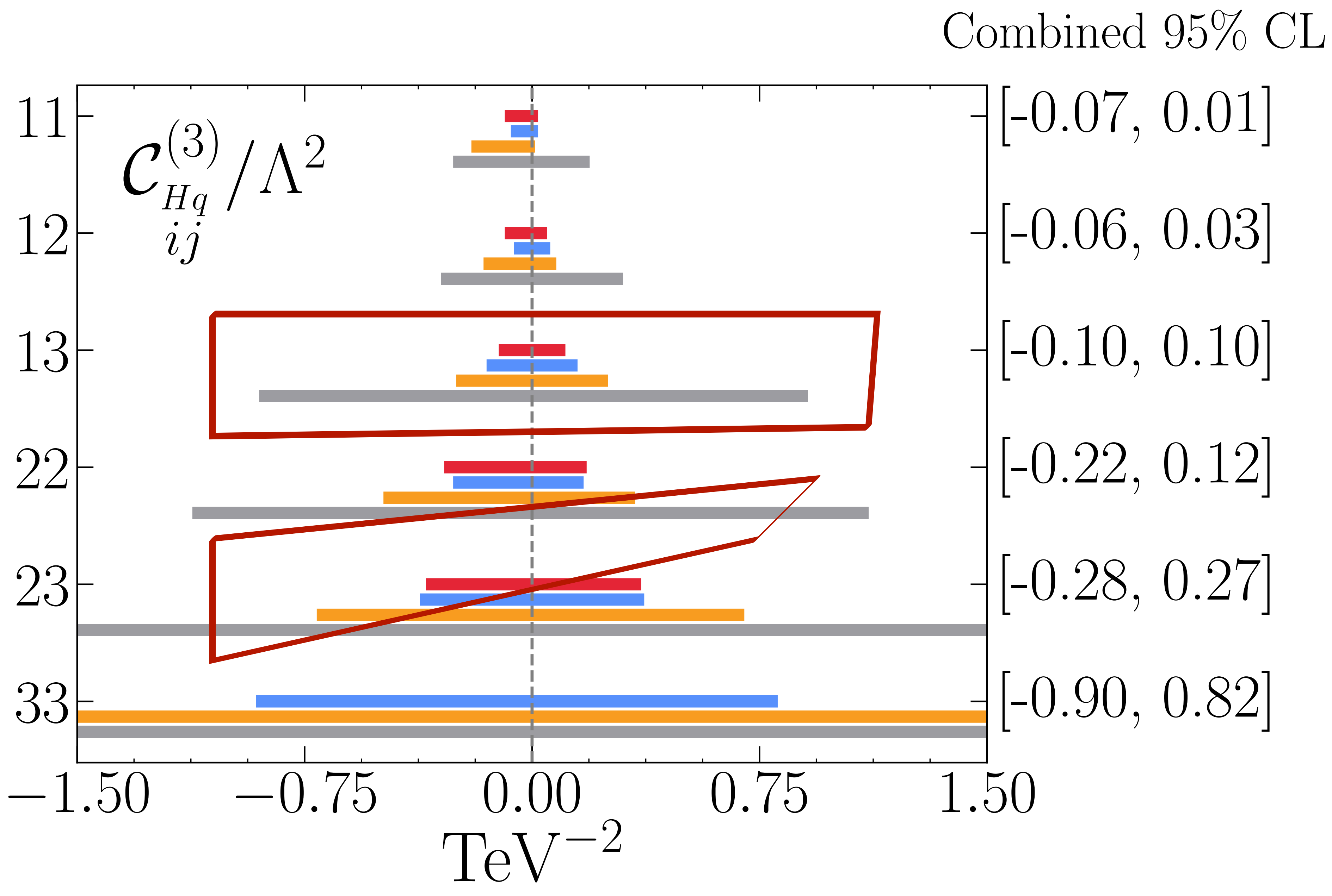
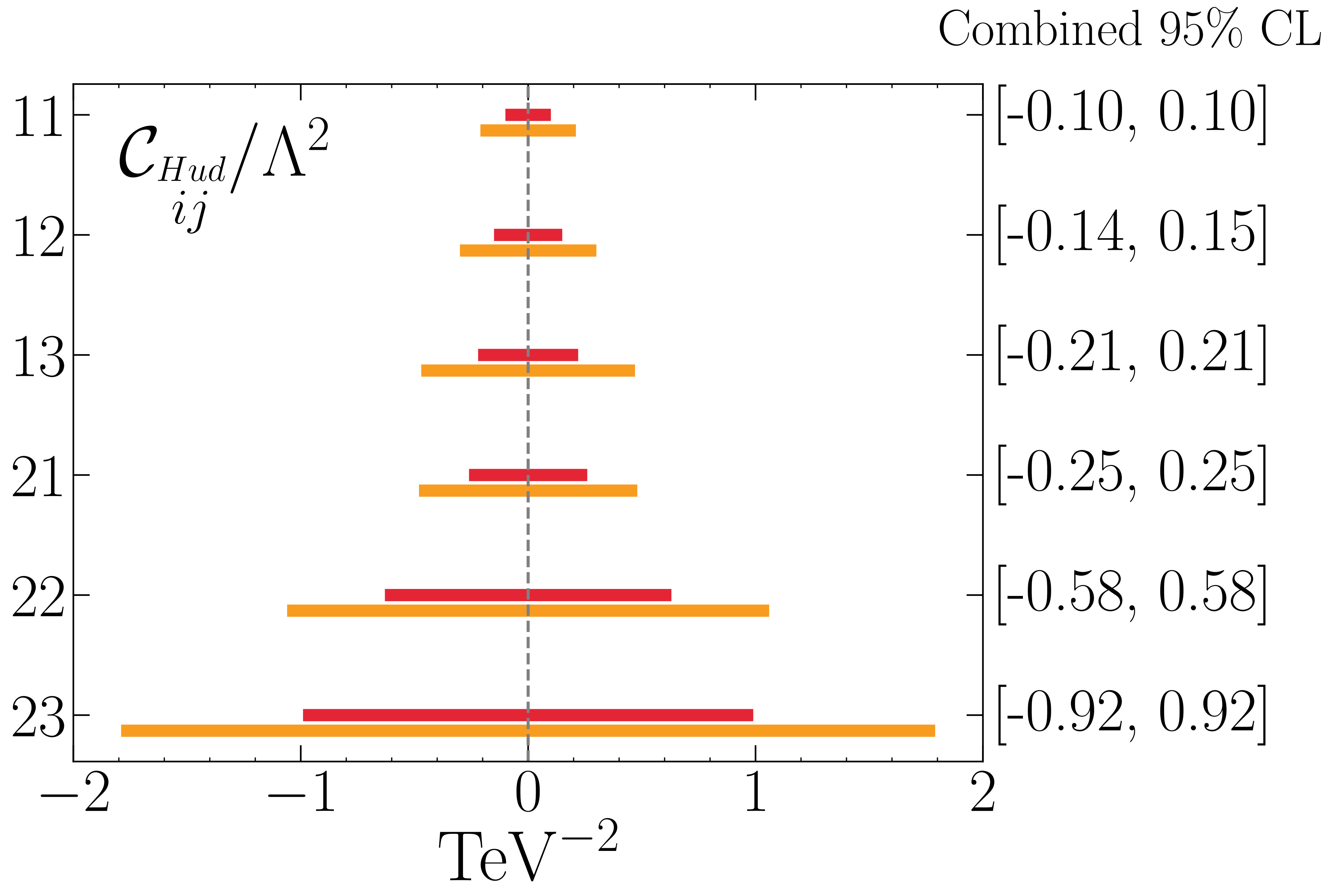
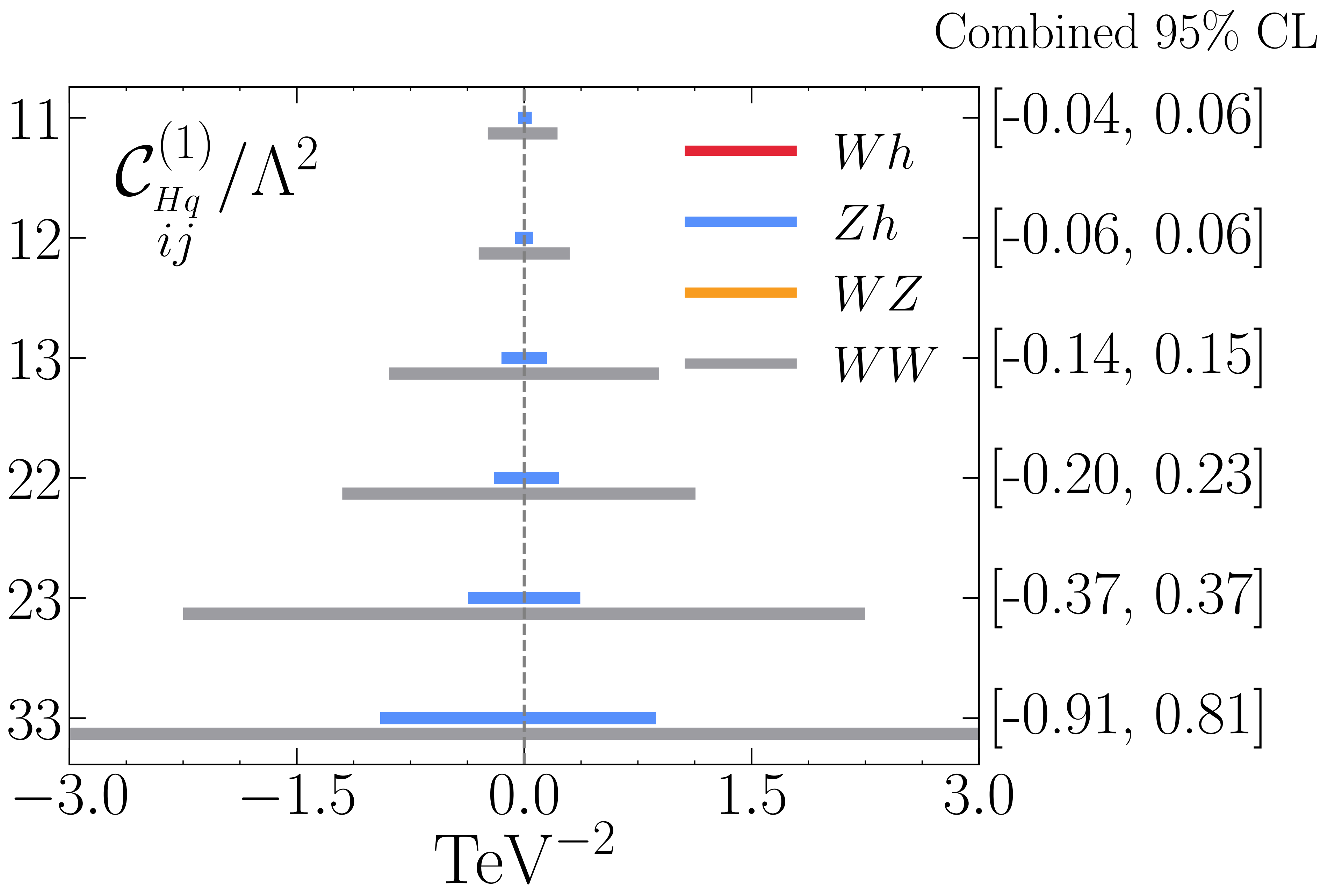


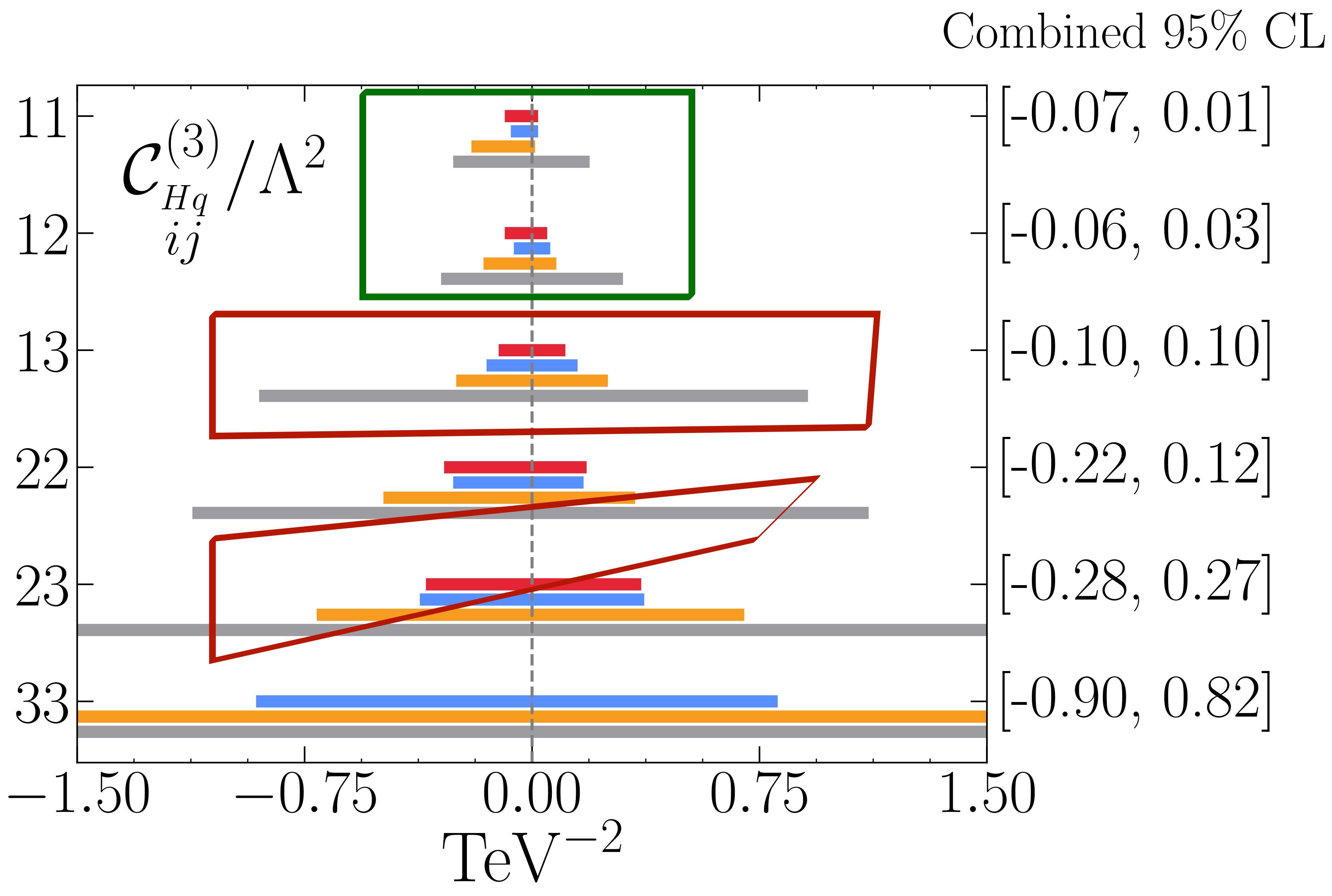


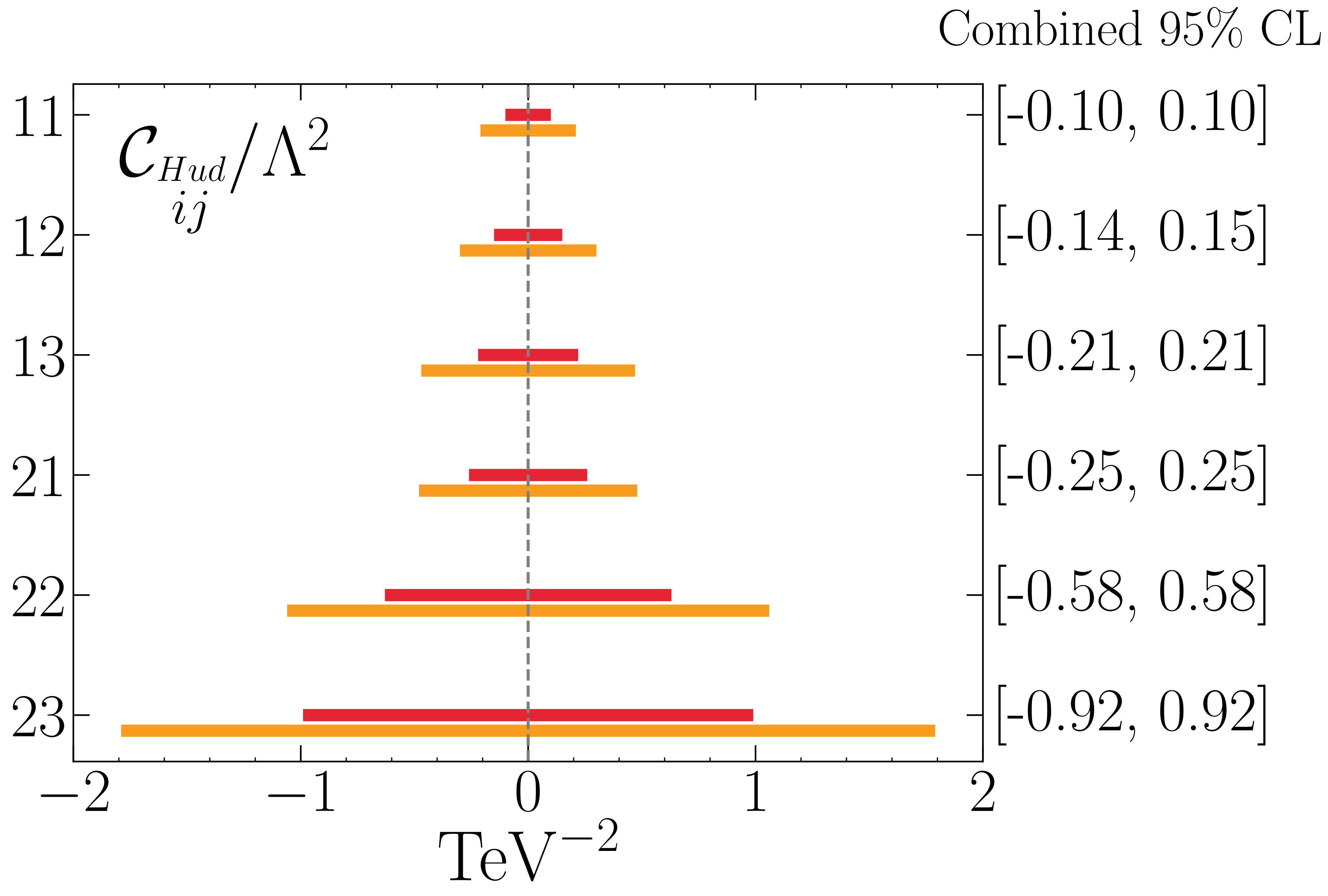


For initial states with **heavy and different-flavor** quarks, the **quadratic** terms drive the limits.

Single parameter limits







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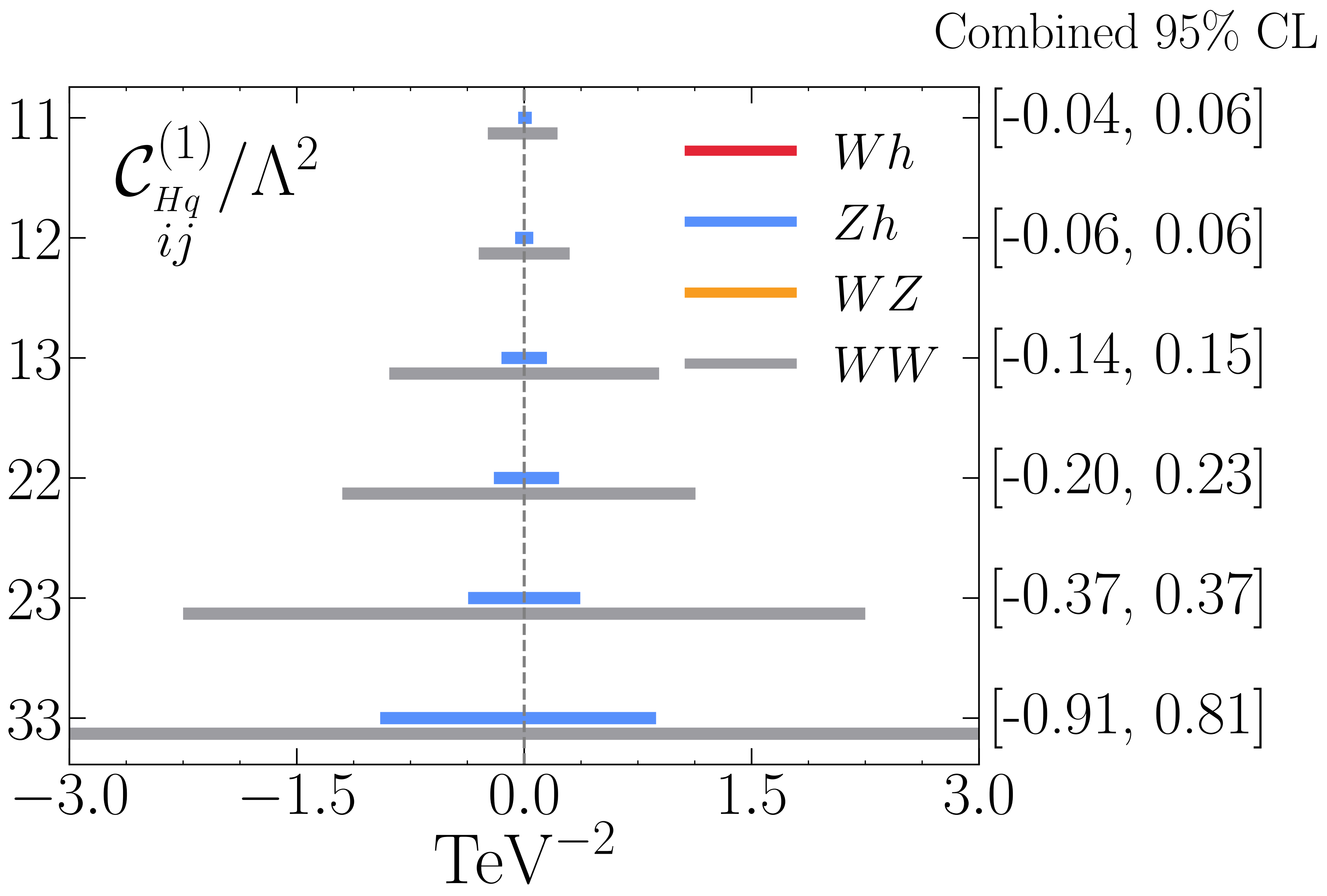
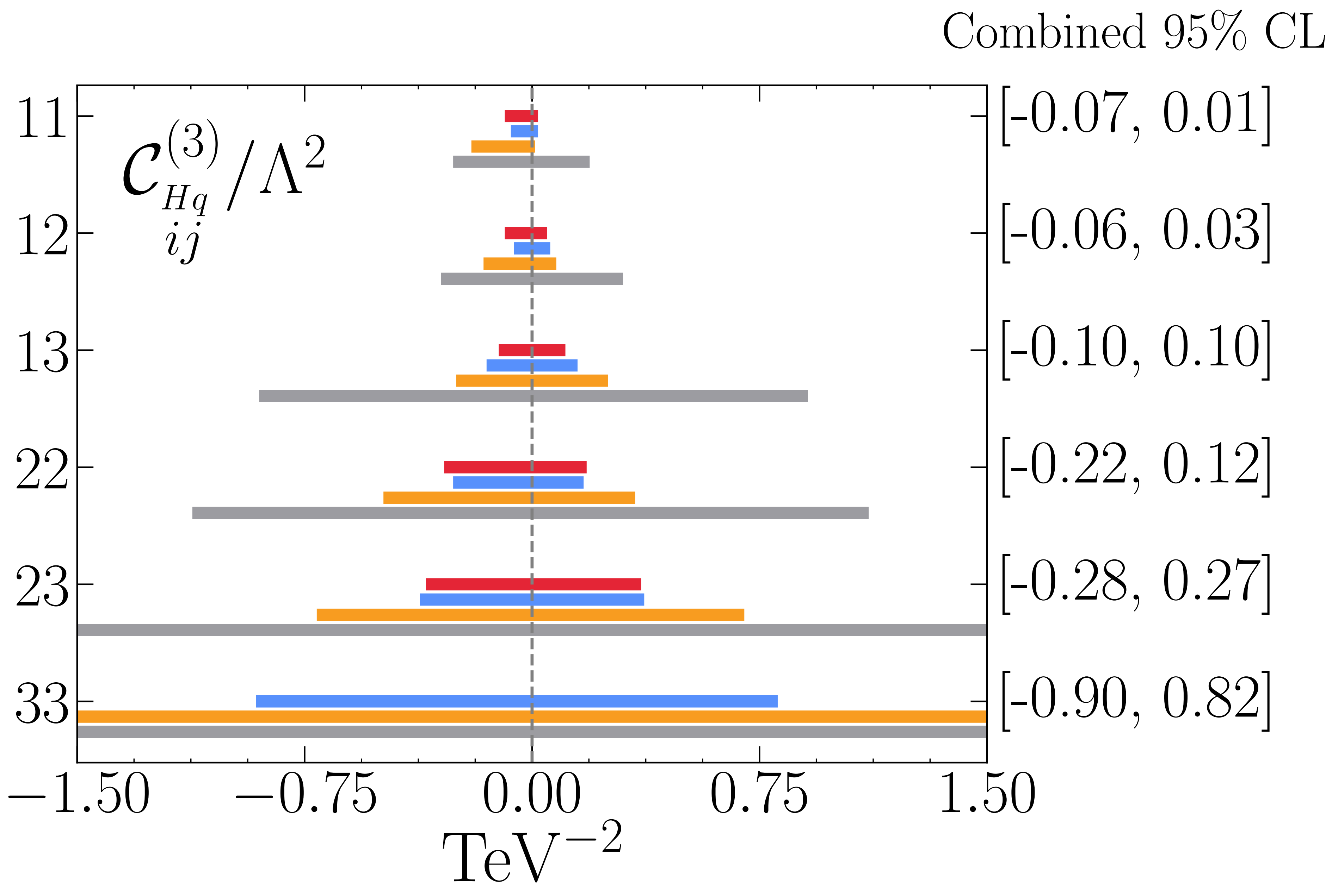
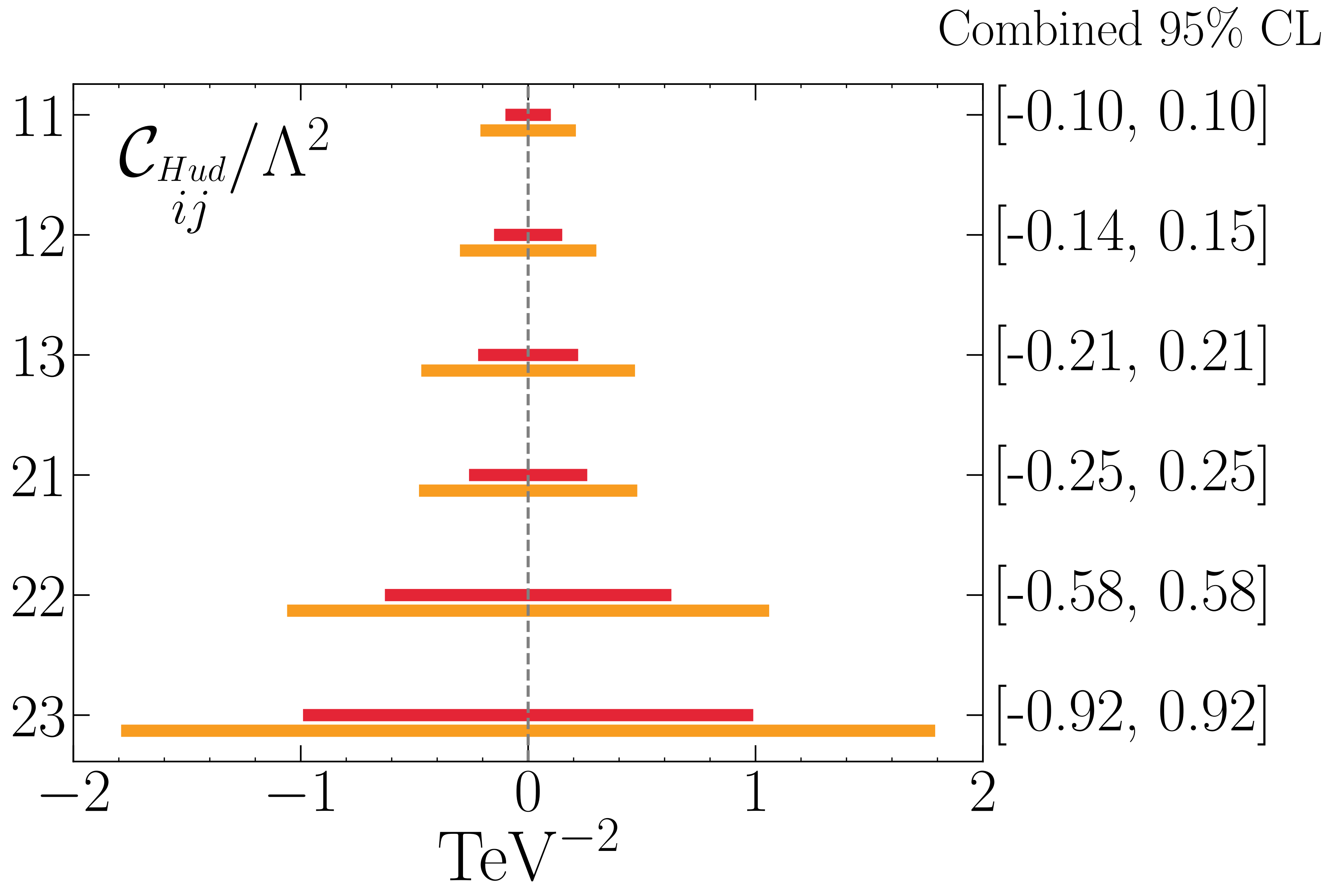
For **same-flavor or light initial** states, the **interference** can lead to asymmetric confidence intervals.

Single parameter limits

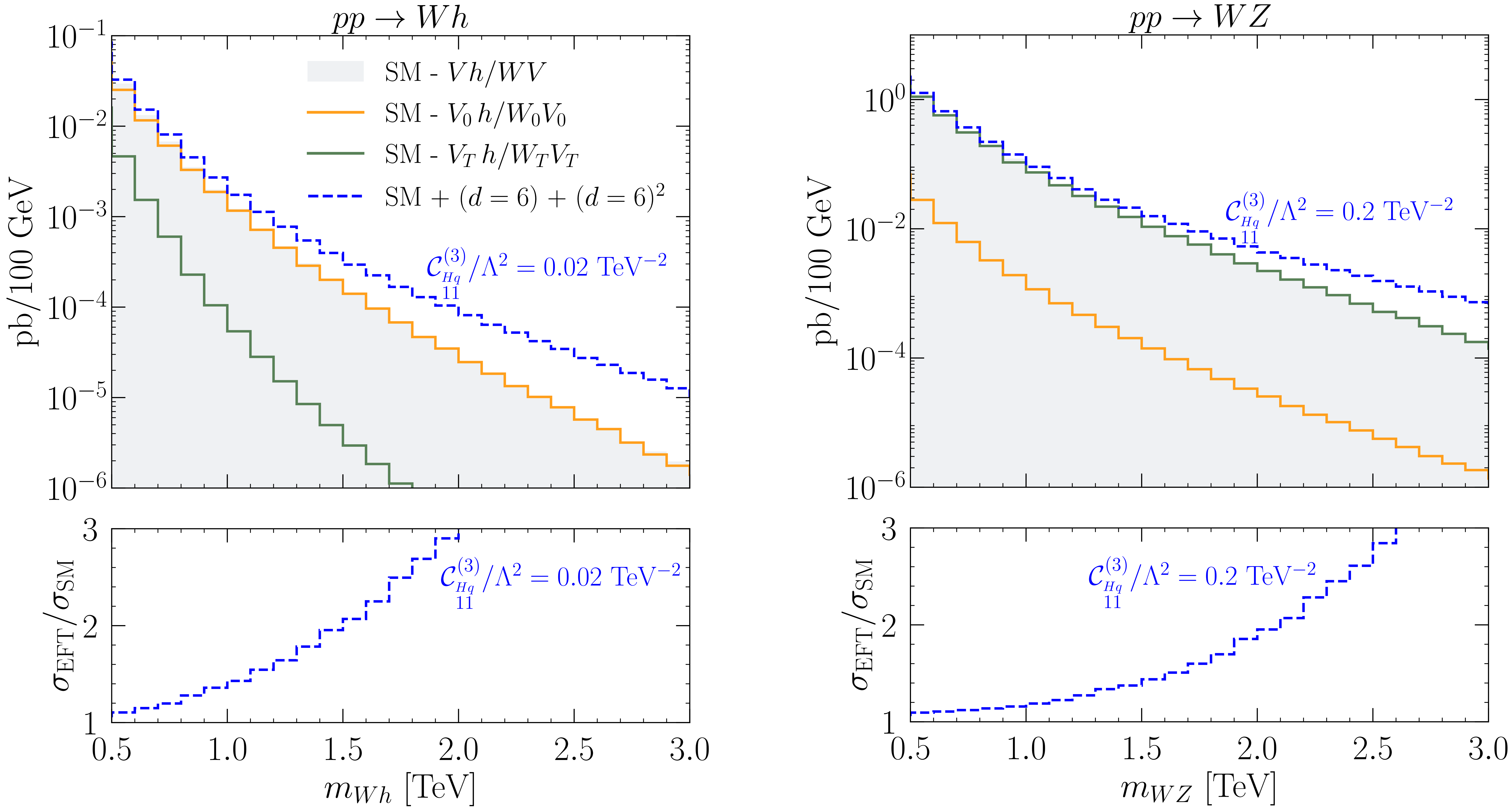






Limits from Vh are **stronger** than WV at the moment.

Differential distributions



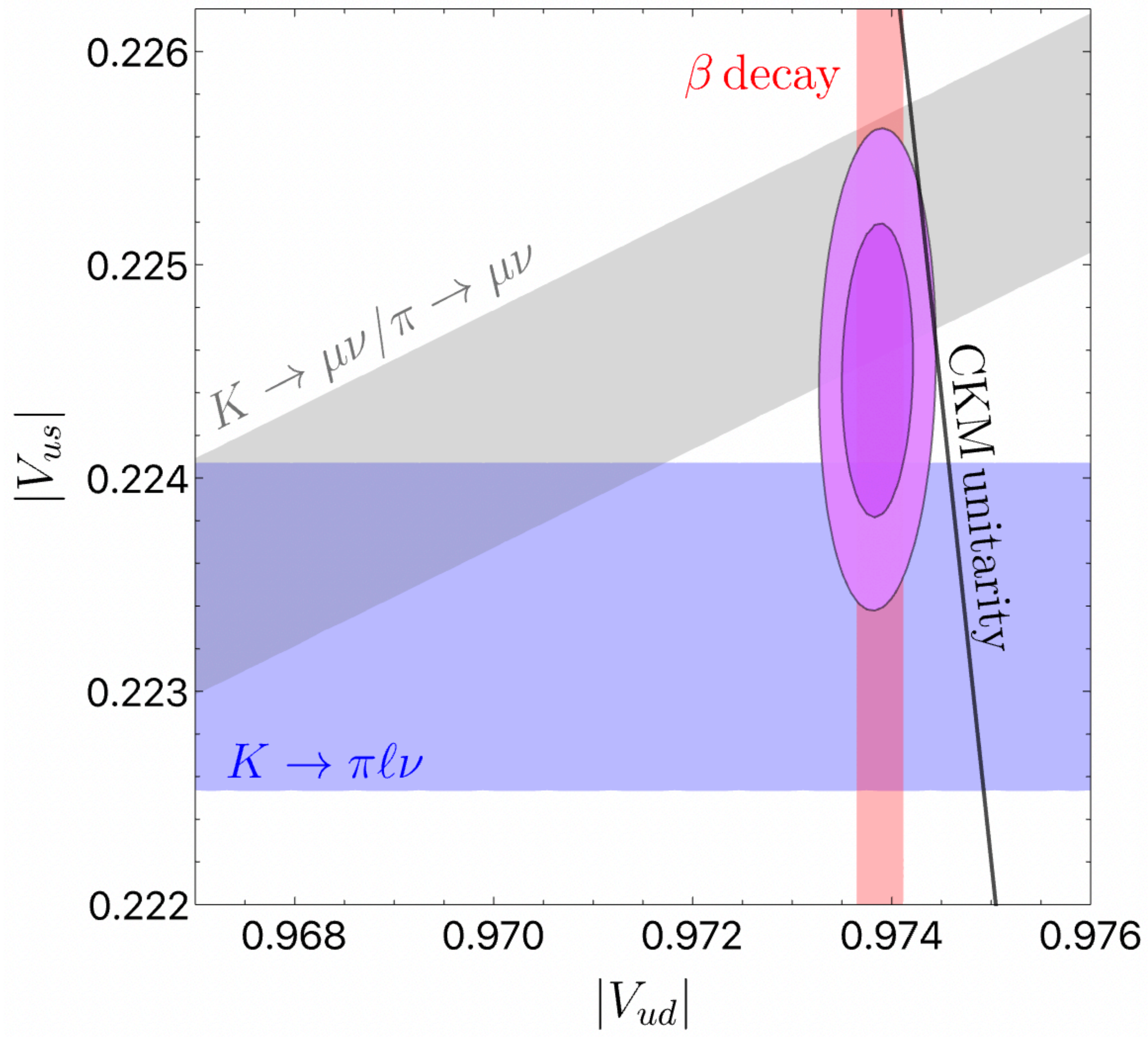
In diboson production channels, **transverse** polarizations **dominate** compared to **longitudinal** modes.

R. Franceschini *et al.* [1712.01310]

Illustration: 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...



(thanks Luighi!)

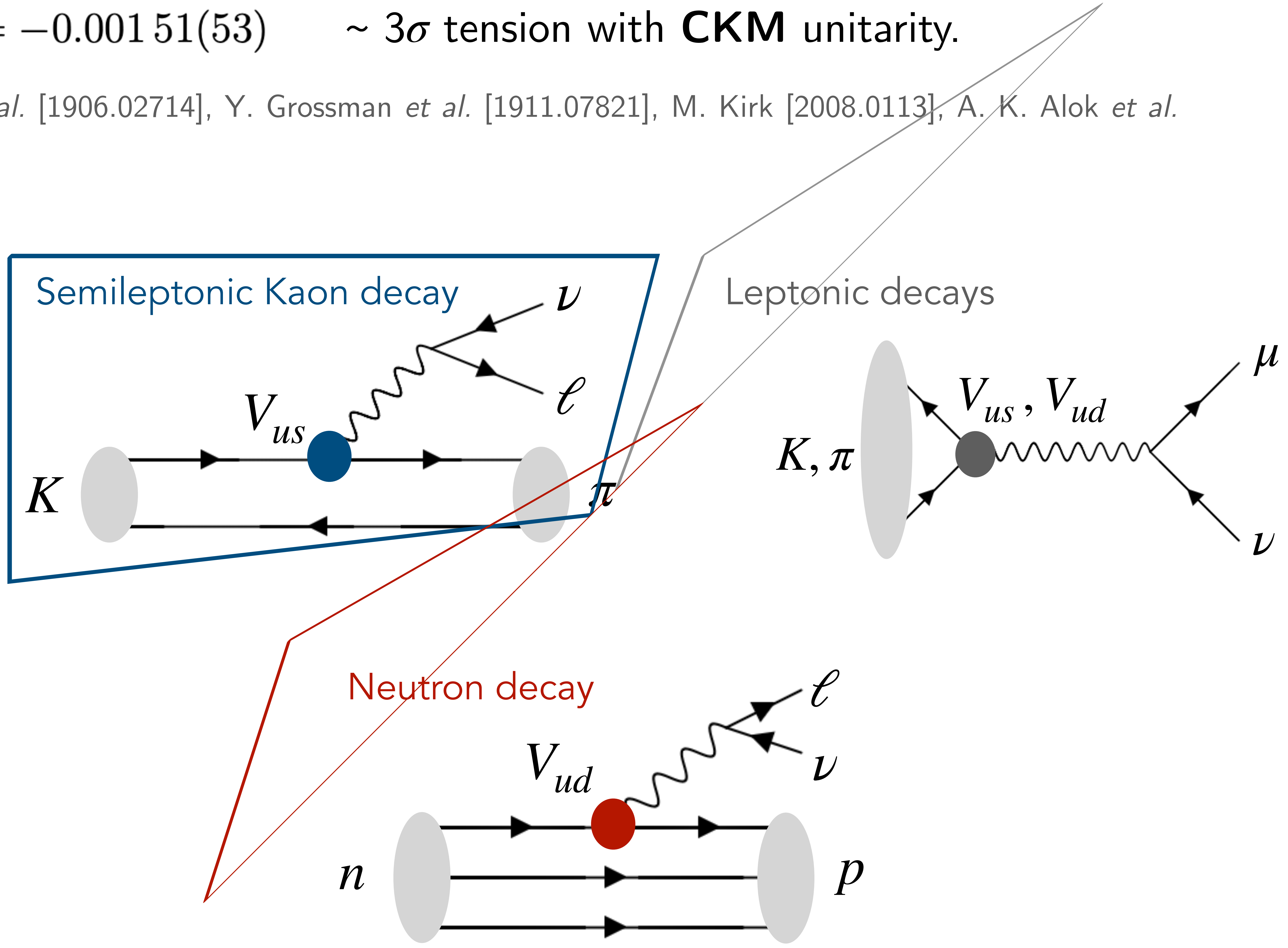
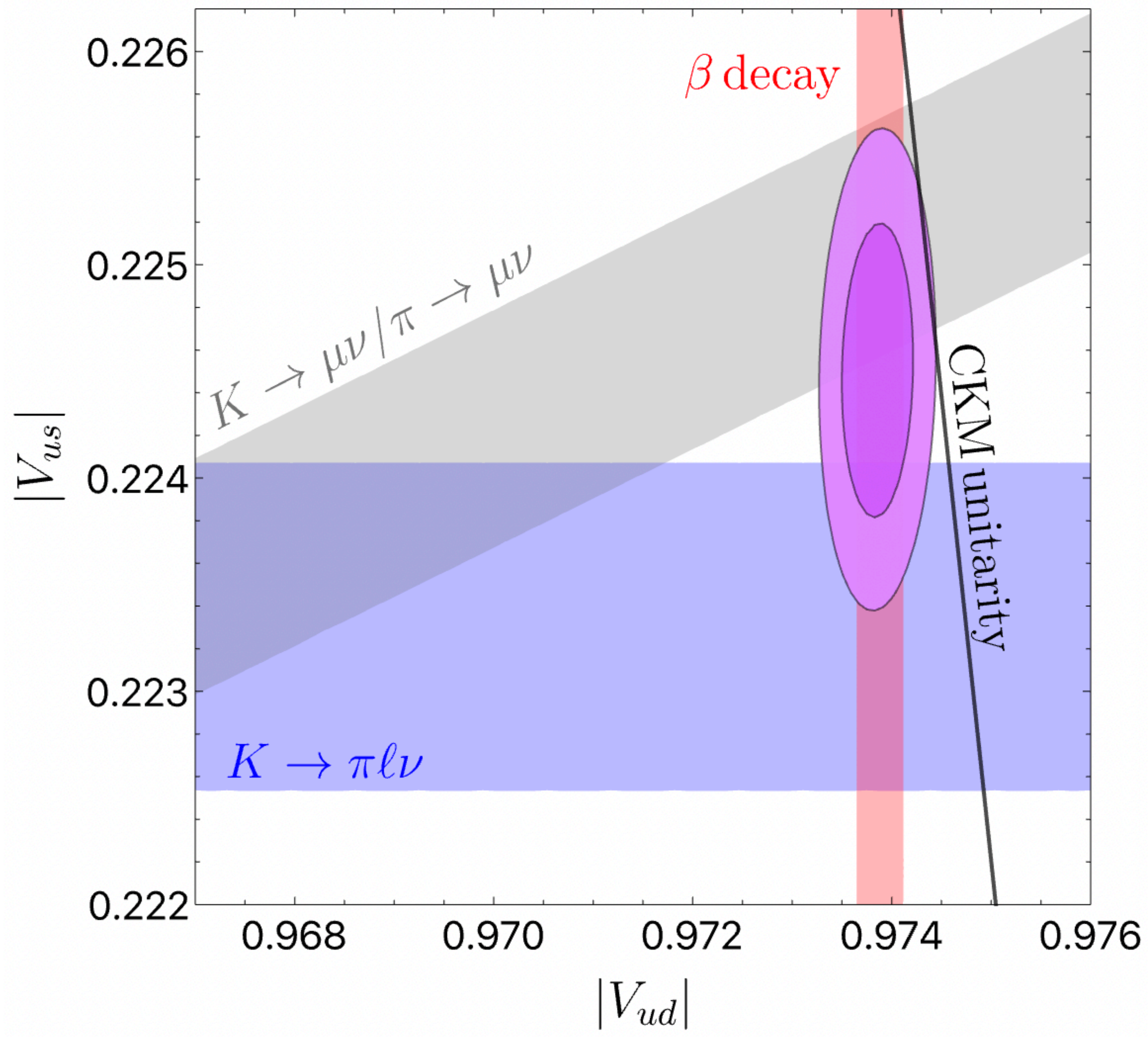


Illustration: First-row CKM unitarity

$$\Delta_{\rm CKM}^{\rm global} \equiv |V_{ud}|^2_{\rm global} + |V_{us}|^2_{\rm global} + |V_{ub}|^2 - 1 = -0.001\,51(53)$$

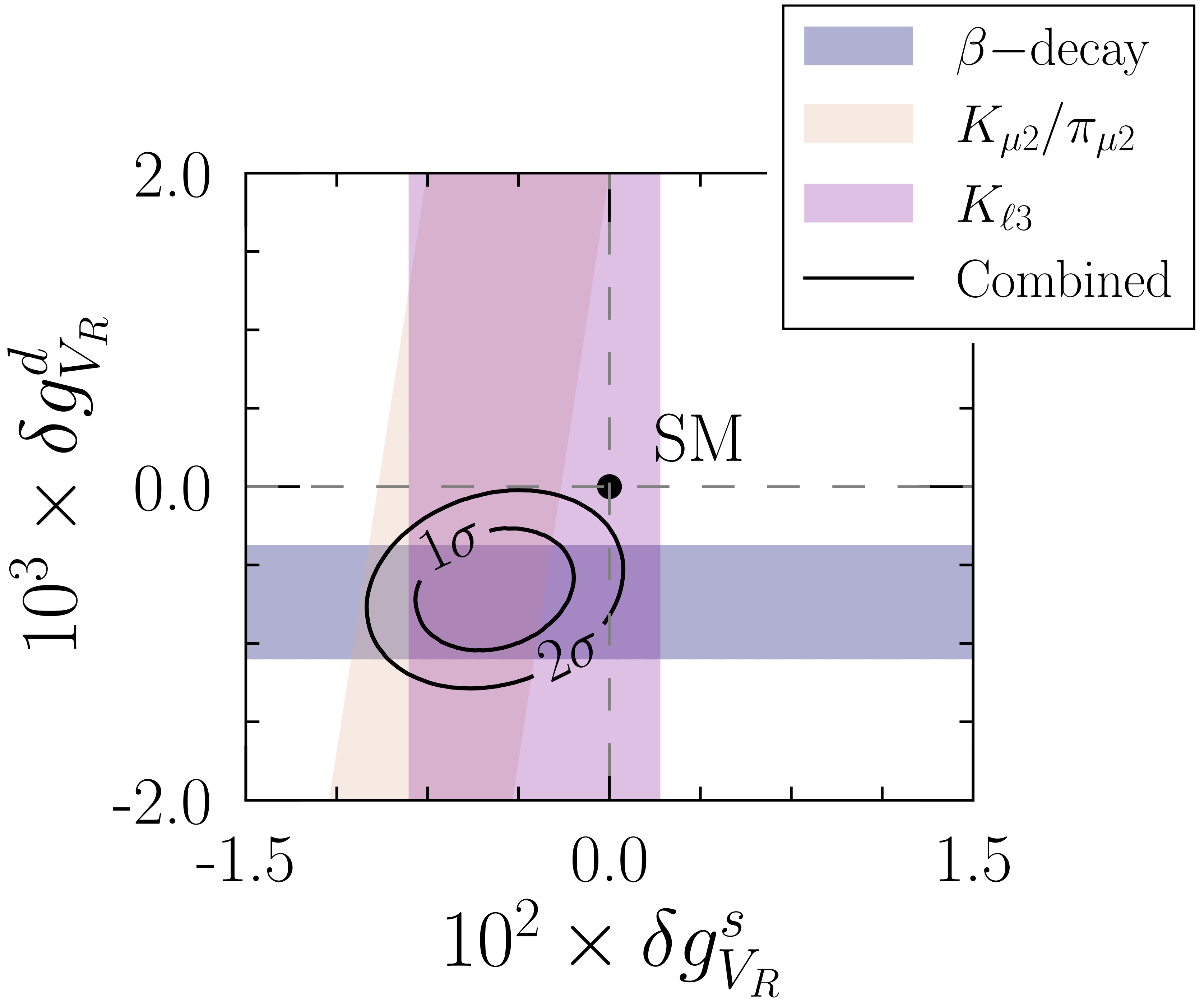
~ 3σ tension with **CKM** unitarity.

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...



(thanks Luighi!)

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



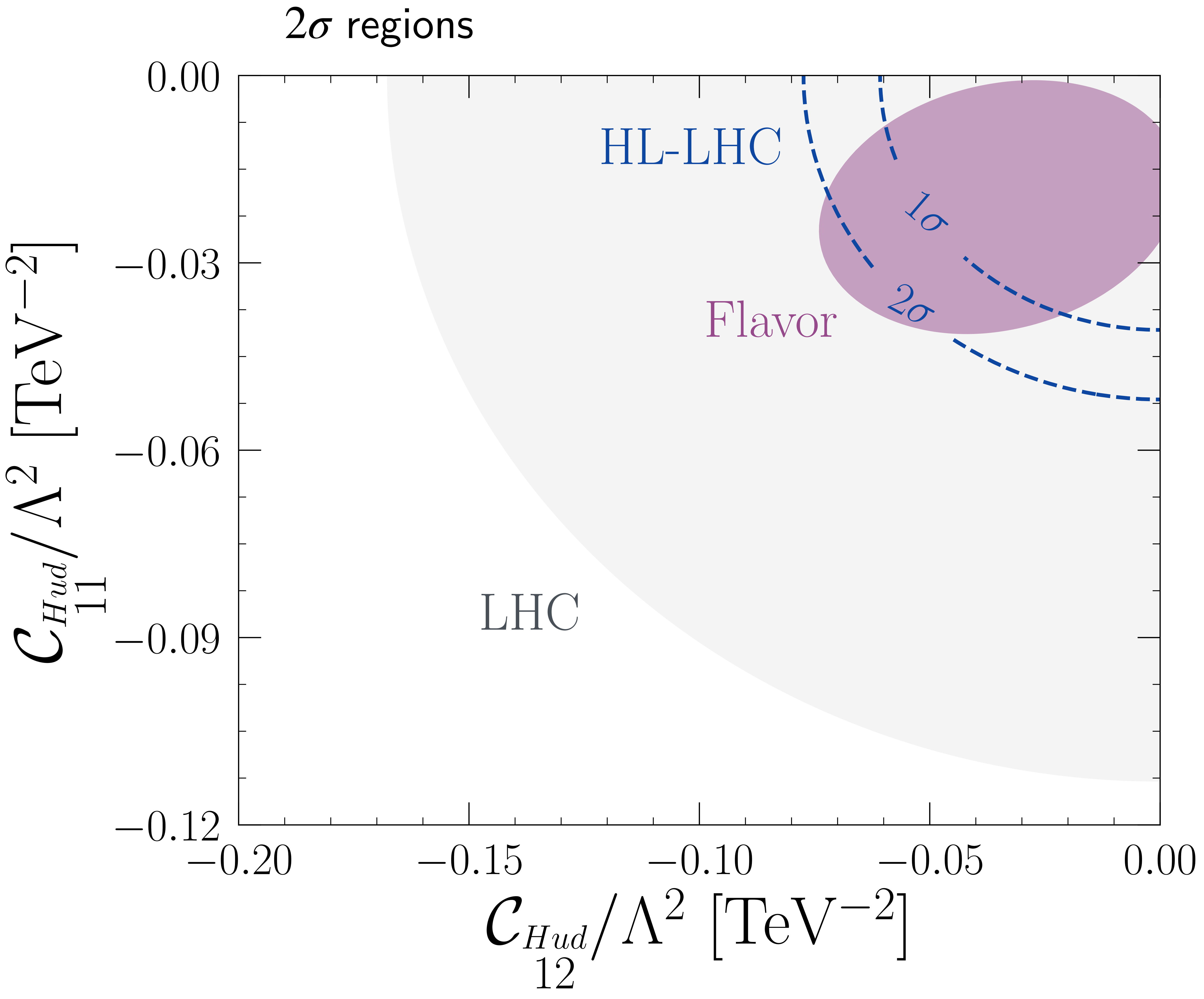
$$(\widetilde{H}^\dagger i D_\mu H)(\overline{u}_R \gamma^\mu d_R) + \text{h.c.}$$

↓ Integrating out the W boson

$$(\overline{u}_R \gamma_\mu d_R)(\overline{\ell}_L \gamma^\mu \nu_L)$$

$$\delta g^q_{V_R} = \frac{v^2}{2\Lambda^2} \frac{1}{V_{uq}} \mathcal{C}_{Hud}_{1q}$$

Illustration: First-row CKM unitarity



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.**

Conclusions

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 **weakly constrained** by Drell–Yan data.

- Soon to be implemented in HighPT [github.com/HighPT/HighPT]

We extract limits on the Wilson coefficients of Higgs–current operators, without imposing flavor assumptions, using LHC Run 2 data on VV and VH production.

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

Conclusions

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

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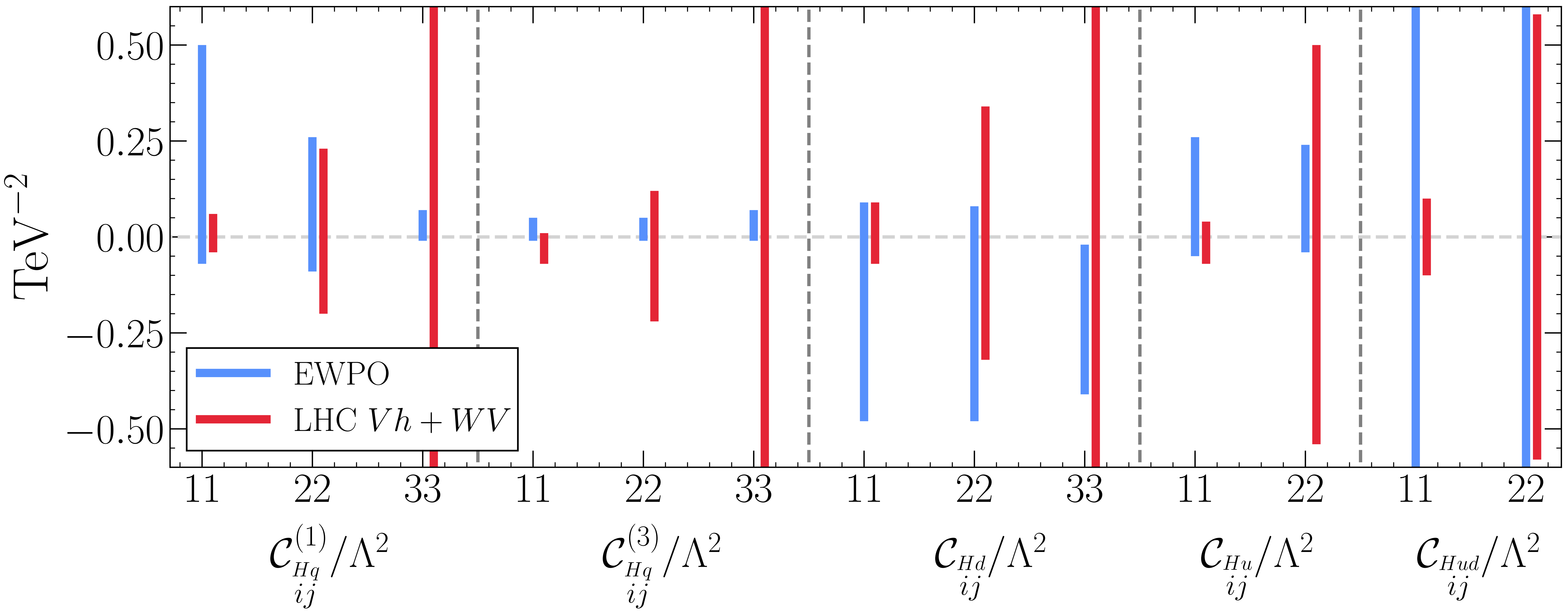
Thank you!

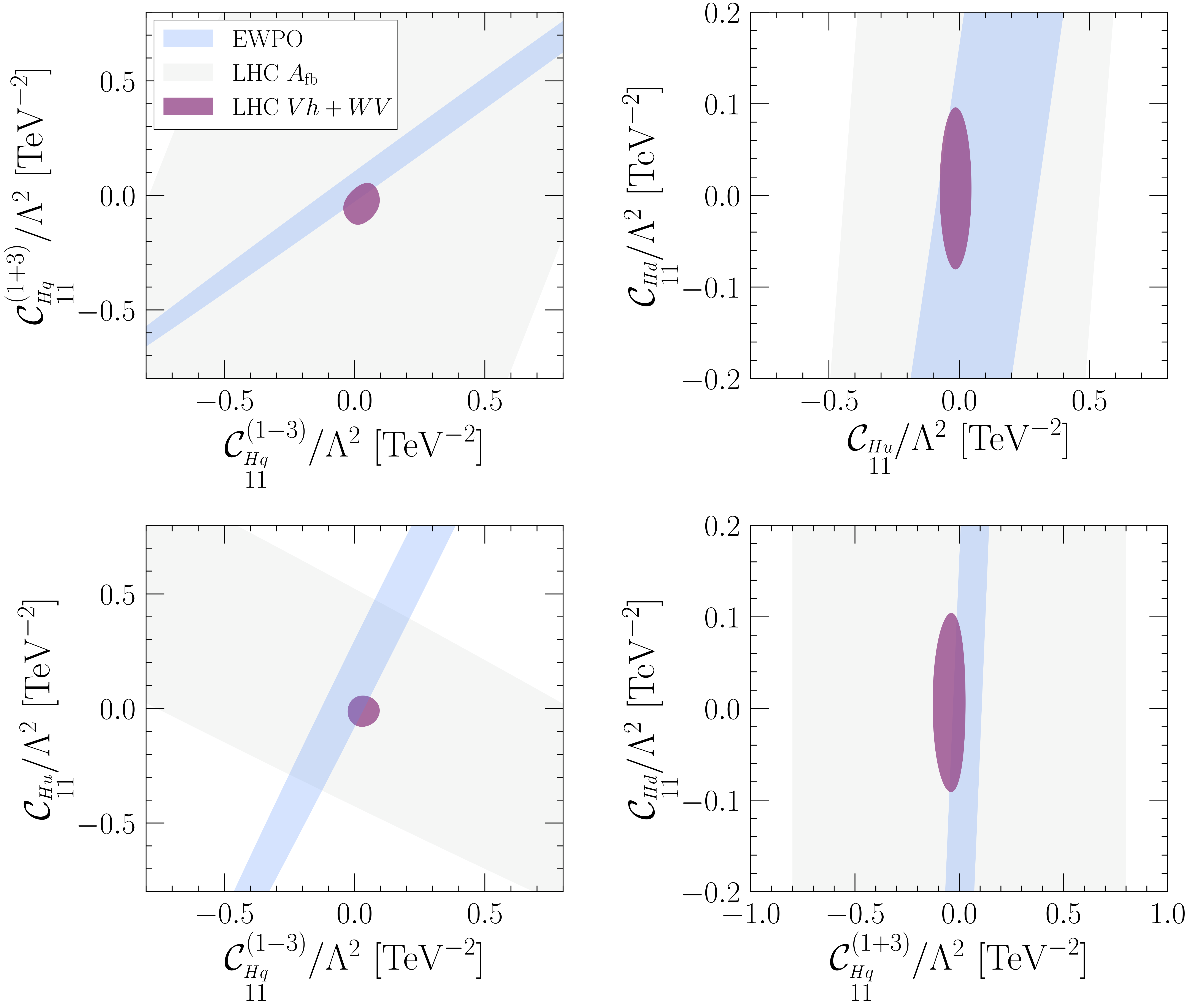
Backup

Confronting LHC with EWPO



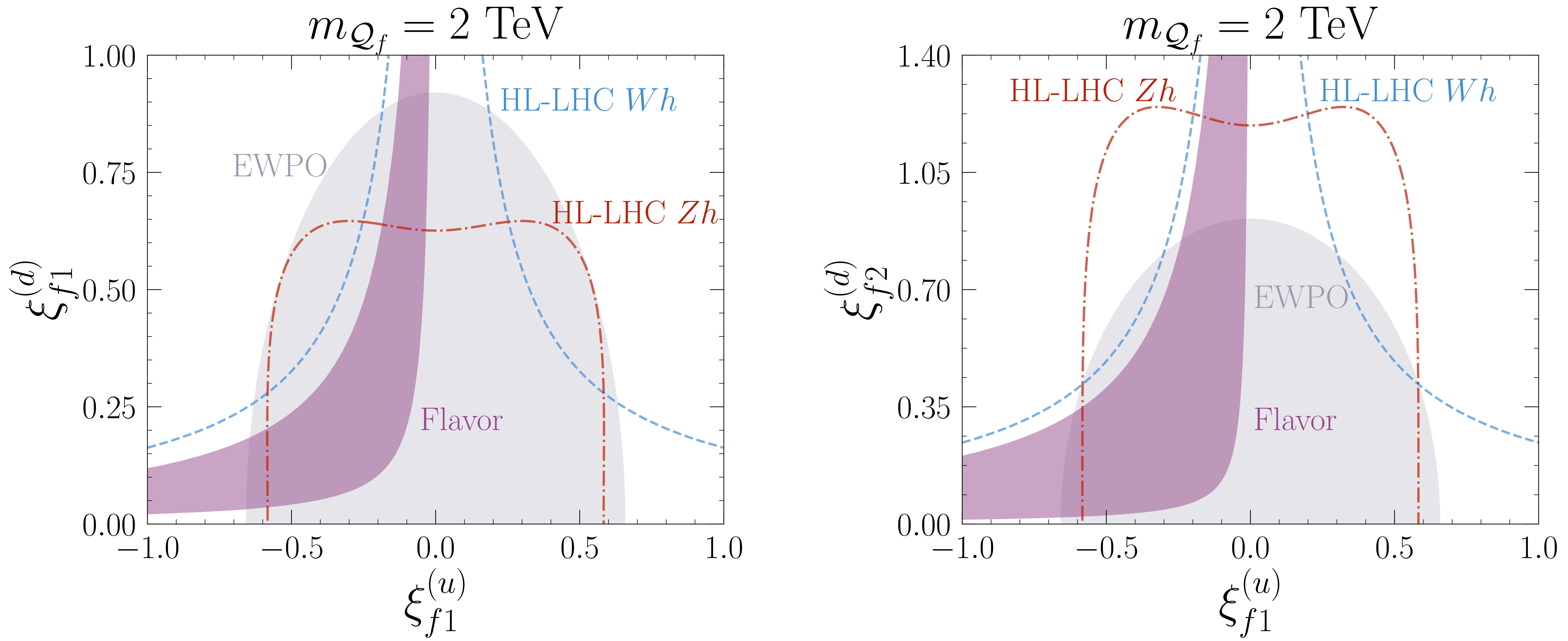
Considering a single non vanishing coefficient at a time.

Confronting LHC with EWPO



- Limits from forward-backward asymmetry taken from V. Bresó-Pla et al.[2103.12074].

Limits on VLQs

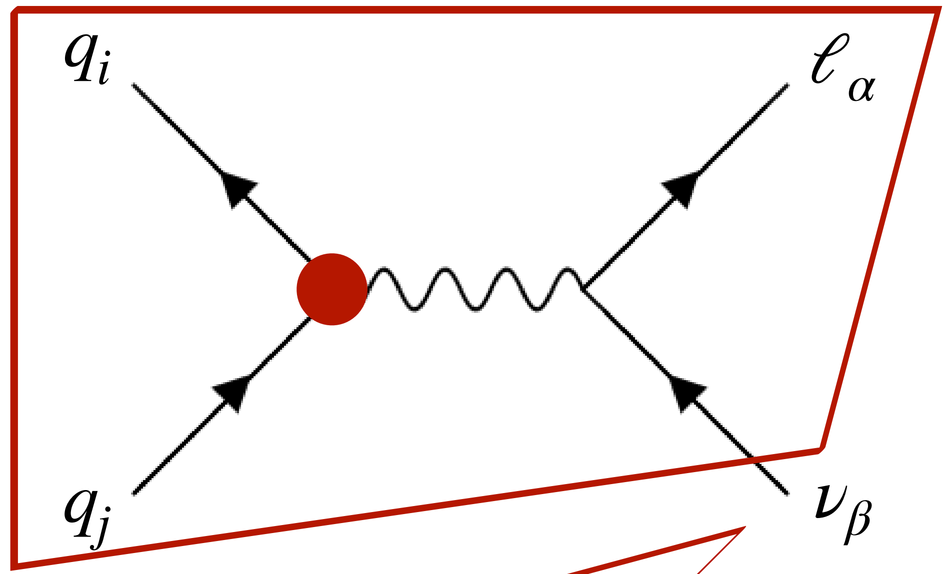


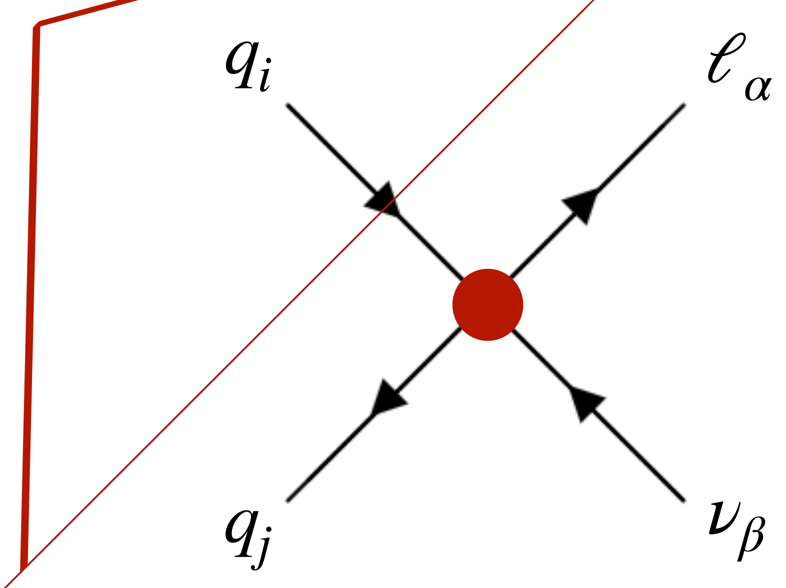
$$\mathcal{L}_{\text{VLQ}} \supset -\xi^{(u)}_{fi}\,\overline{\mathcal{Q}}_f \widetilde{H} u_i - \xi^{(d)}_{fi}\,\overline{\mathcal{Q}}_f H d_i + \text{h.c.}$$

Example: Right-Handed Charged Currents at the LHC

SMEFT ~TeV $(\widetilde{H}^\dagger i D_\mu H)(\overline{u}_R \gamma^\mu d_R) + \text{h.c.}$

Low-energy EFT (LEFT) ~GeV $(\overline{u}_R \gamma_\mu d_R)(\overline{\ell}_L \gamma^\mu \nu_L)$





- **Lepton flavor universal**
- Affects **leptonic** and **semi-leptonic** meson decays.

SMEFT operator that give rise to **right-handed charged-currents** are **poorly** constrained by DY data.

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

Alternative: ***Vh* production data.**

LHC distributions

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]

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

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

MadGraph@NLO

↓

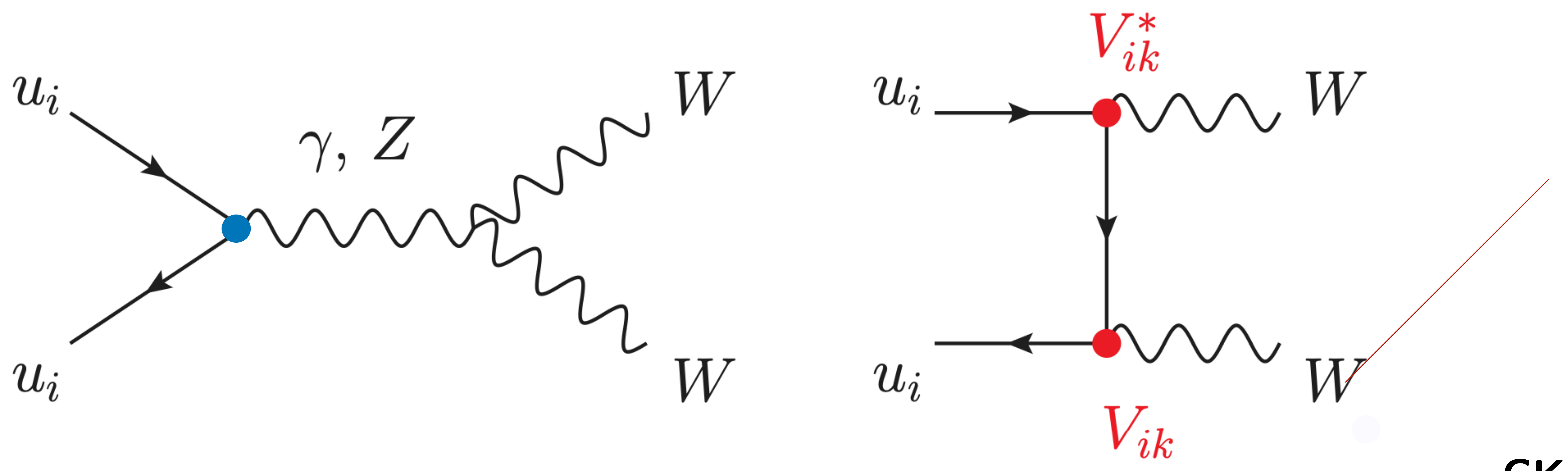
Pythia8

↓

Delphes

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

Diboson production



CKM is unitary

SM prediction for W_0W_0 production

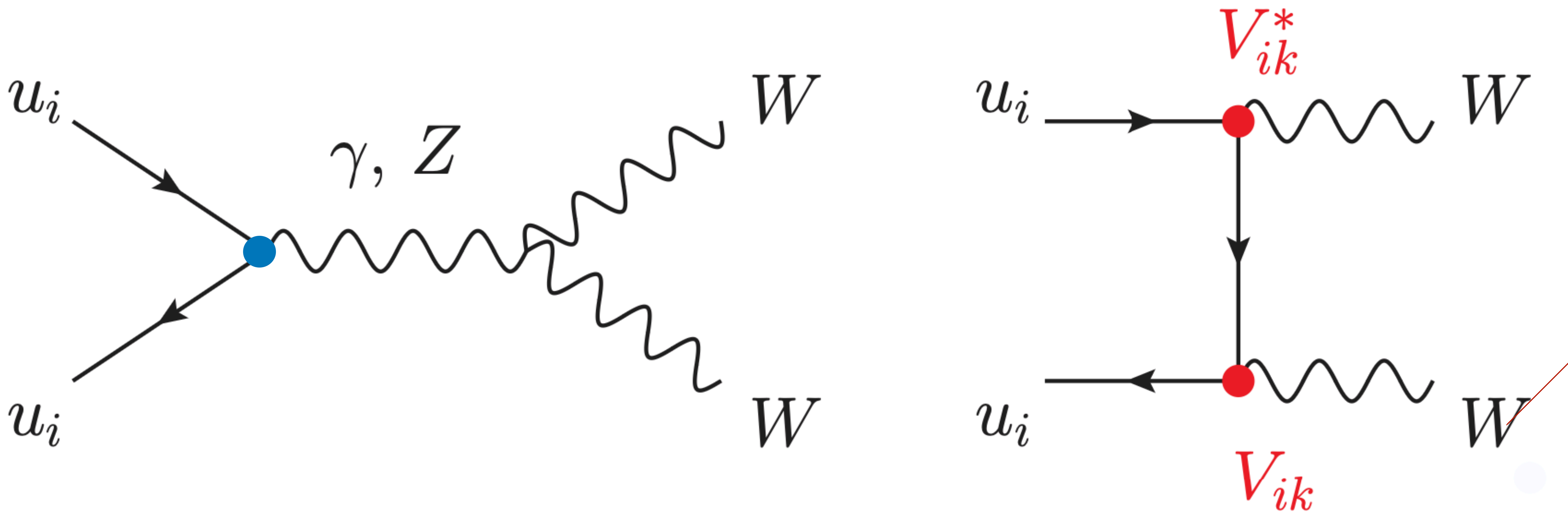
$$\mathcal{M}(u_i\bar{u}_j \to W_0W_0) \overset{\text{SM}}{=} i\widehat{S}\,\frac{e^2\sin\theta}{2m_W^2}\left[Q_q\,\delta_{ij} + \frac{1}{s_W^2}(T_q^3 - s_W^2 Q_q)\,\delta_{ij} - \frac{T_q^3}{s_W^2}(V^\dagger\cdot V)ij\right] + \mathcal{O}(\hat{s}^0)\,,$$

t-channel
s-channel Z
s-channel γ

Center of mass energy

C. Grojean, M. Montull, M. Riembau [1810.05149]
R. Franceschini, G. Panico, A. Pomarol, F. Riva, A. Wulzer [1712.01310]
T. Corbett, O. J. P. Éboli, M. C. Gonzalez-Garcia [1705.09294]

Diboson production



CKM is unitary

SM prediction for $W_0 W_0$ production

$$\mathcal{M}(u_i \bar{u}_j \to W_0 W_0) \overset{\text{SM}}{=} i\widehat{S}\,\frac{e^2 \sin\theta}{2m_W^2}\left[Q_q\,\delta_{ij} + \frac{1}{s_W^2}(T_q^3 - s_W^2 Q_q)\,\delta_{ij} - \frac{T_q^3}{s_W^2}(V^\dagger \cdot V)ij\right] + \mathcal{O}(\hat{s}^0)\,,$$

t-channel
s-channel Z
s-channel γ

Center of mass energy

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

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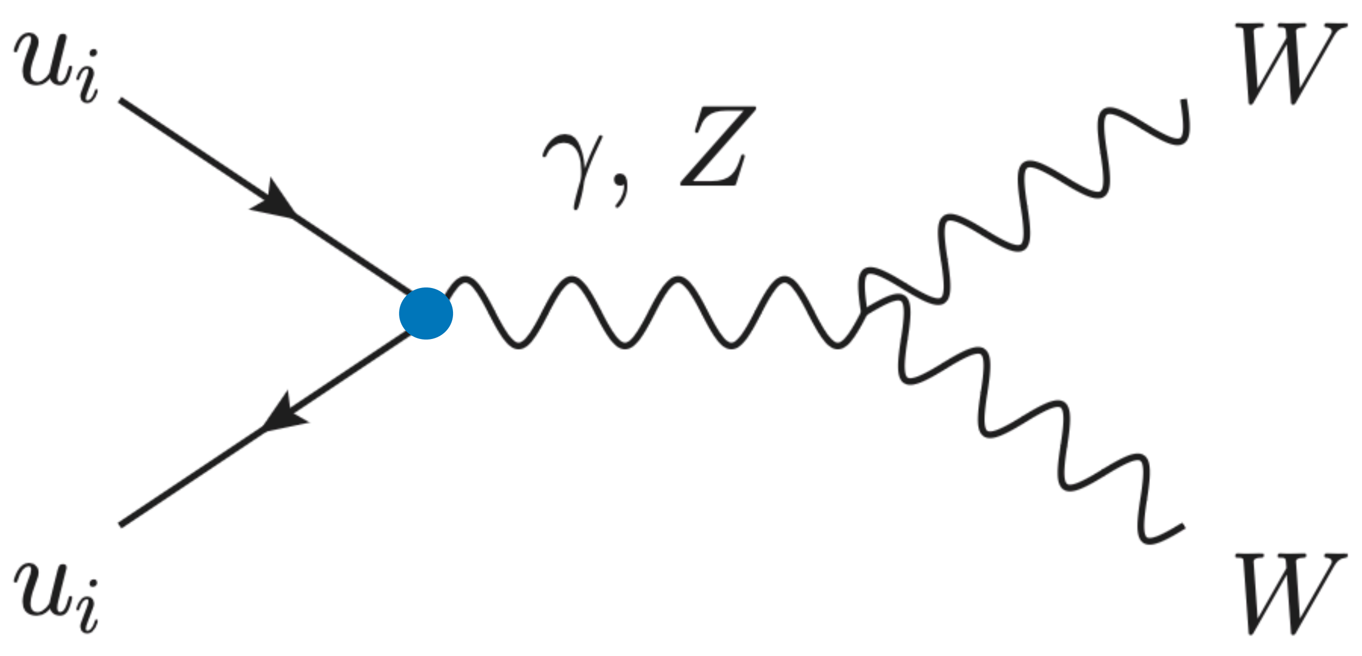

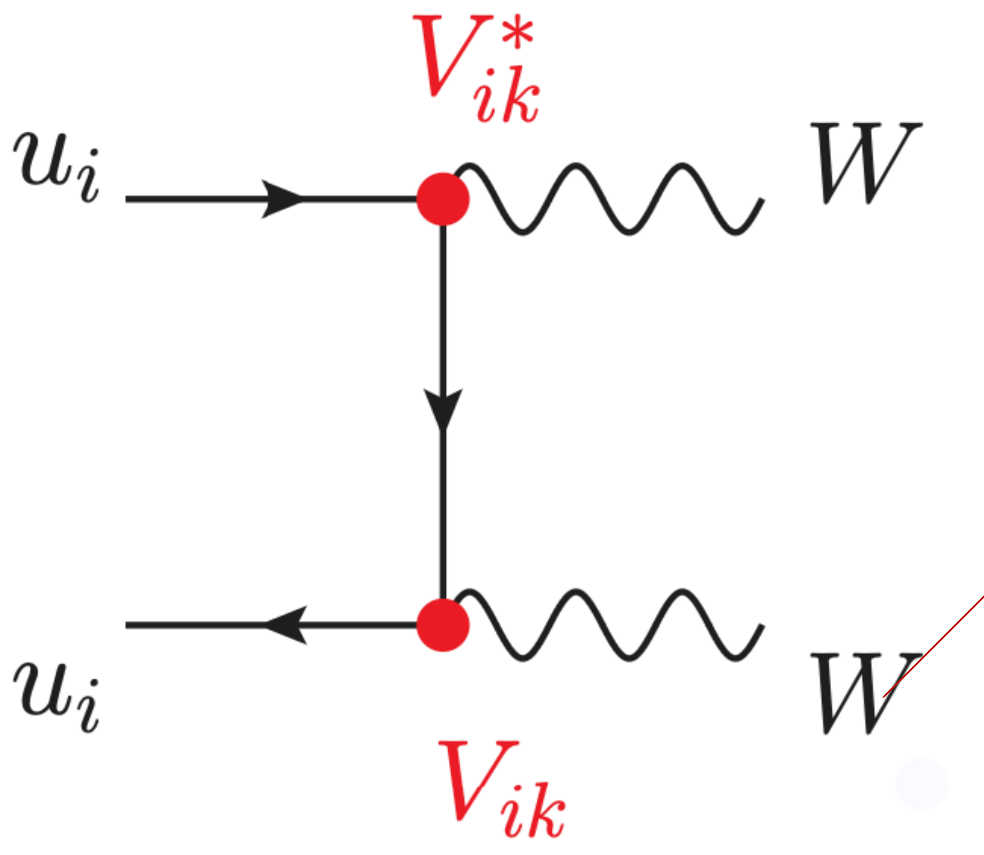

CKM is unitary

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t-channel
s-channel Z
s-channel γ

Center of mass energy

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

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

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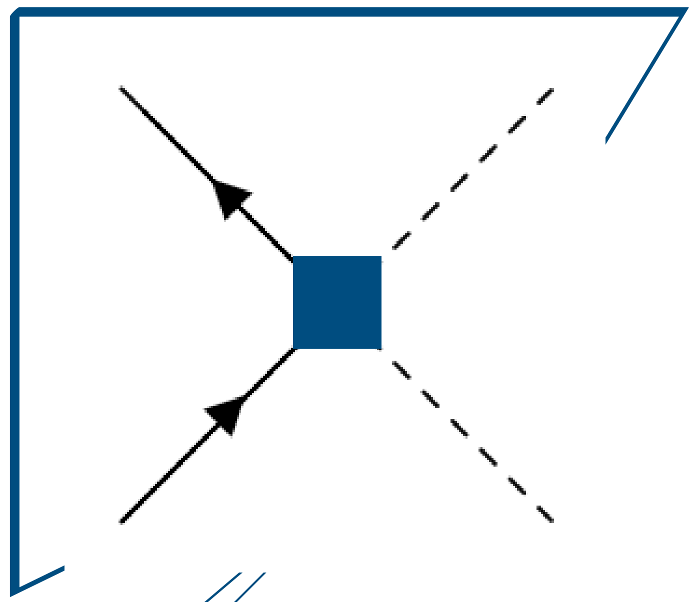
WW and Zh probe the **same combination** of couplings.

Weak basis



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

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

High-energy amplitudes

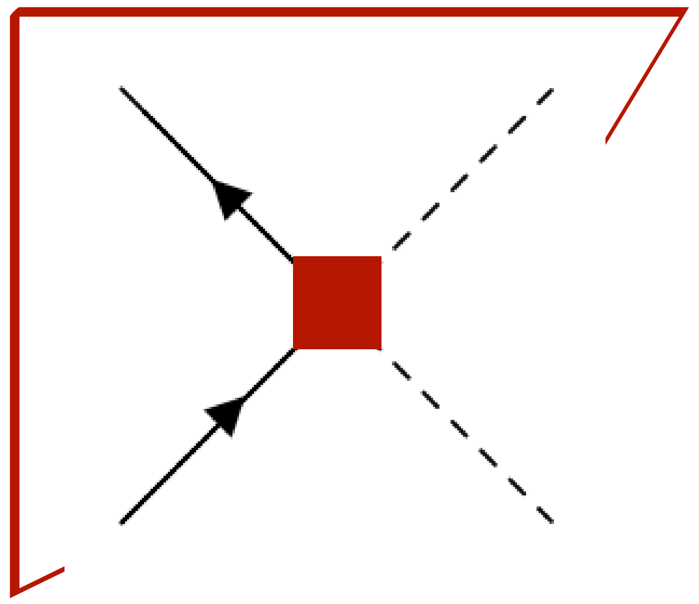
At dimension $d = 6$, for charged processes

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

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

WZ and Wh probe the **same combination** of couplings.

Weak basis



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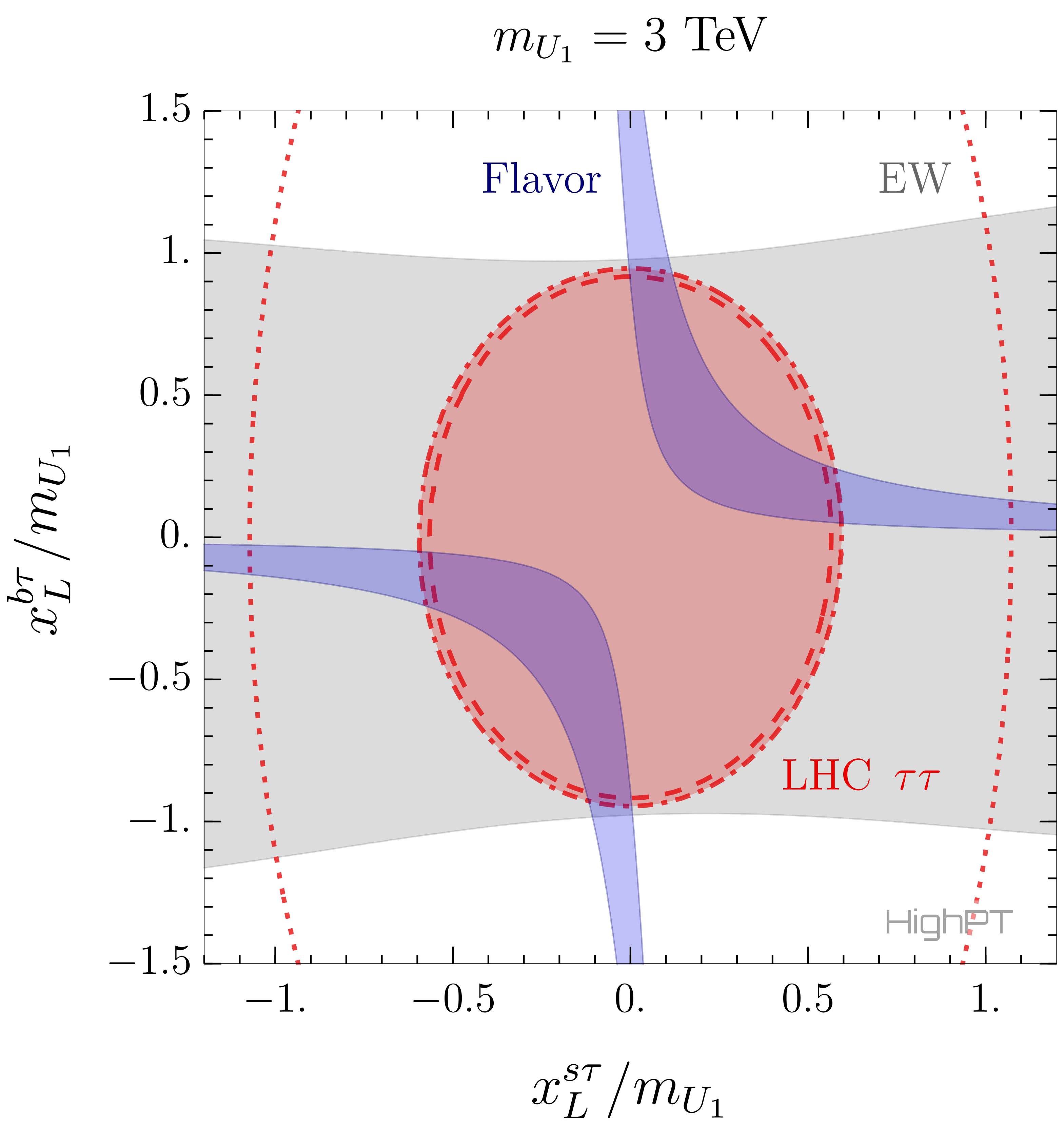
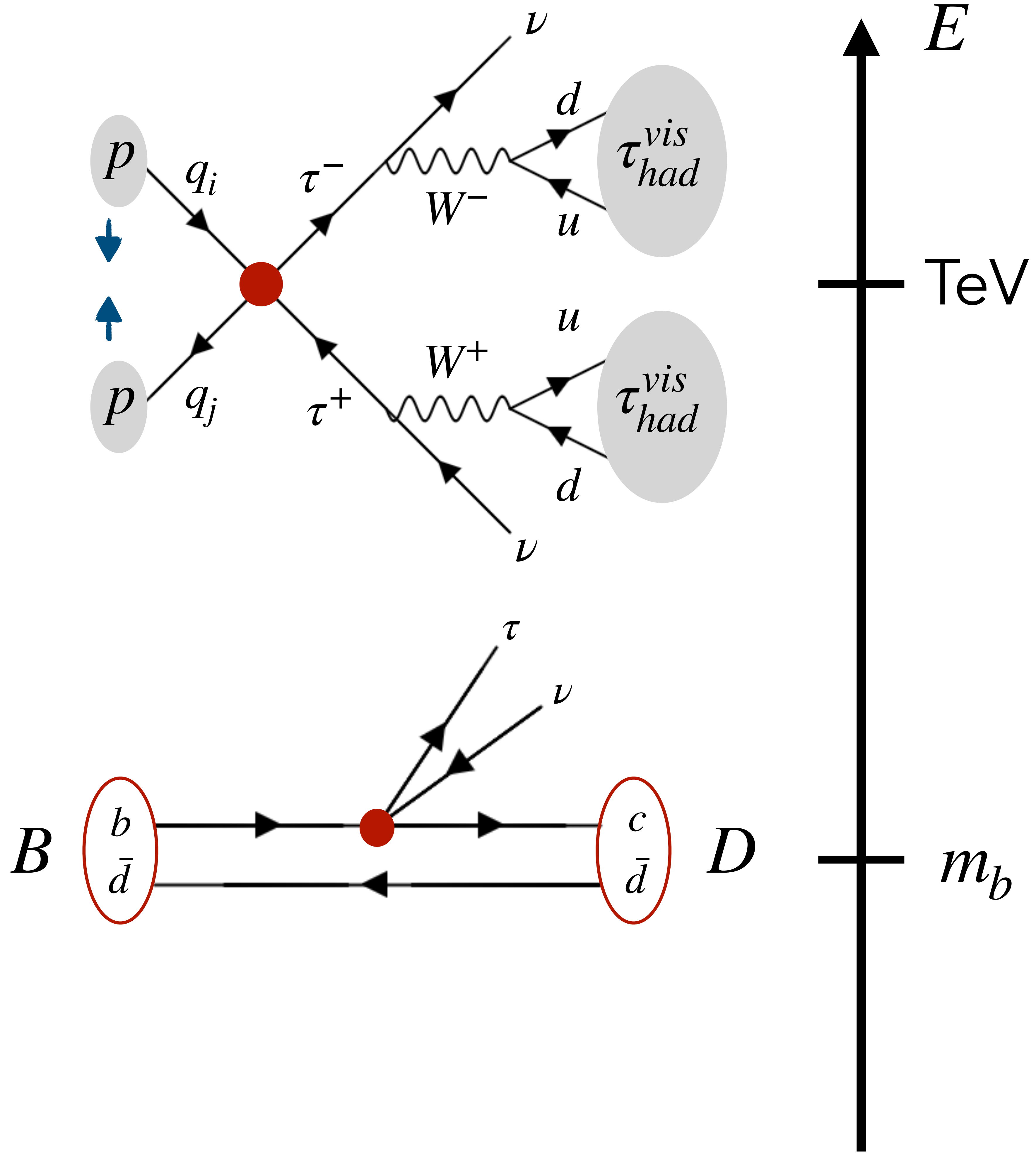
Combining Flavor and High-p_T DY observables

DY data can provide constraints that are **competitive** with low-energy flavor observables, despite **PDF suppression**.



$$\mathcal{L} \supset x_L^{i\alpha} \, (\bar{q}_i \gamma^\mu l_\alpha) \, U_1^\mu + \text{h.c.}$$



L. Allwicher, D. A. Faroughy, **M. M.**, O. Sumensari, F. Wilsch [2412.14612]

See also J. Fuentes-Martín *et al.* [2003.12421], A. Greljo *et al.* [2212.10497], ...

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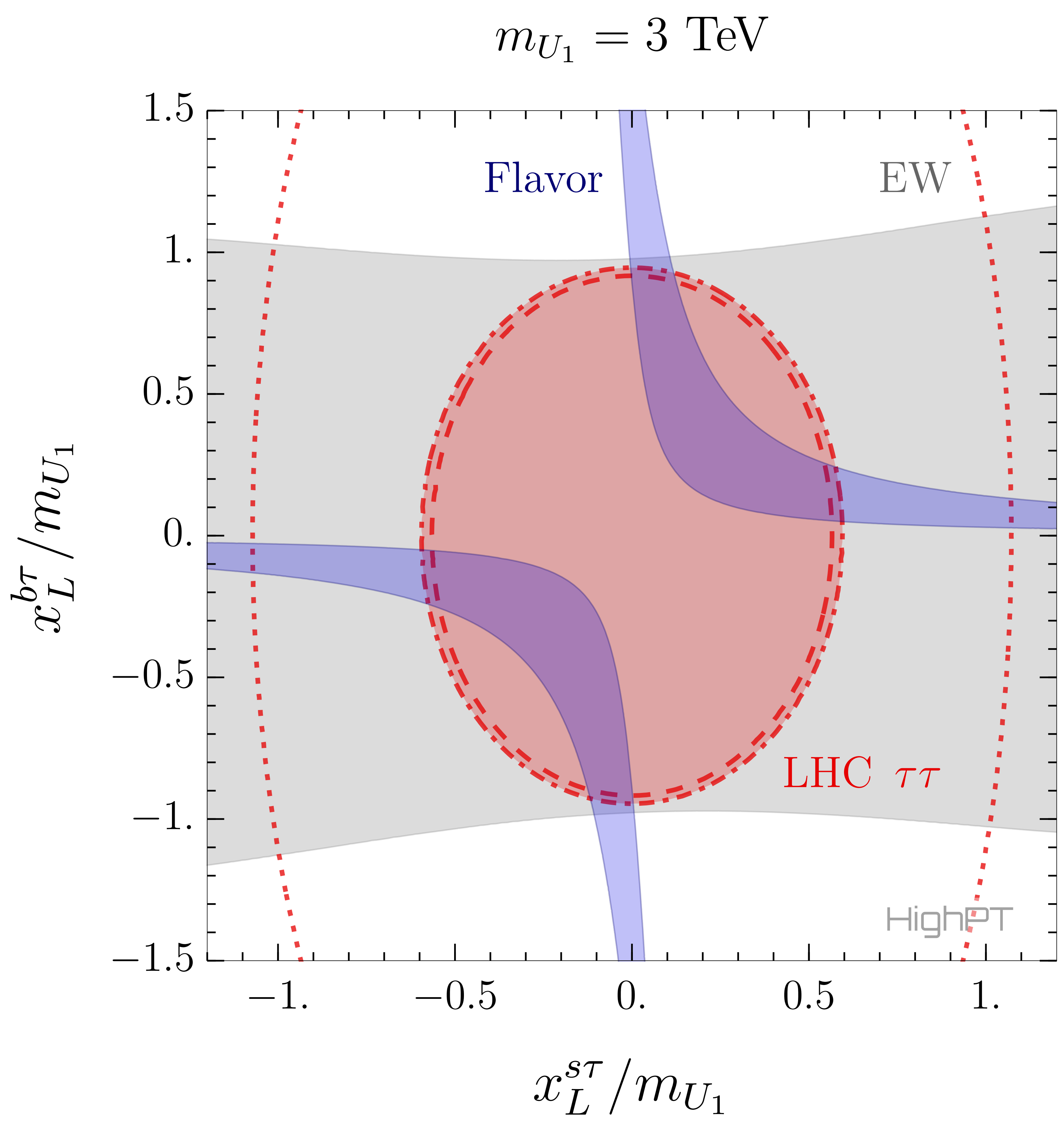


Are there other LHC processes that could provide **complementary constraints** to those from DY and flavor observables?

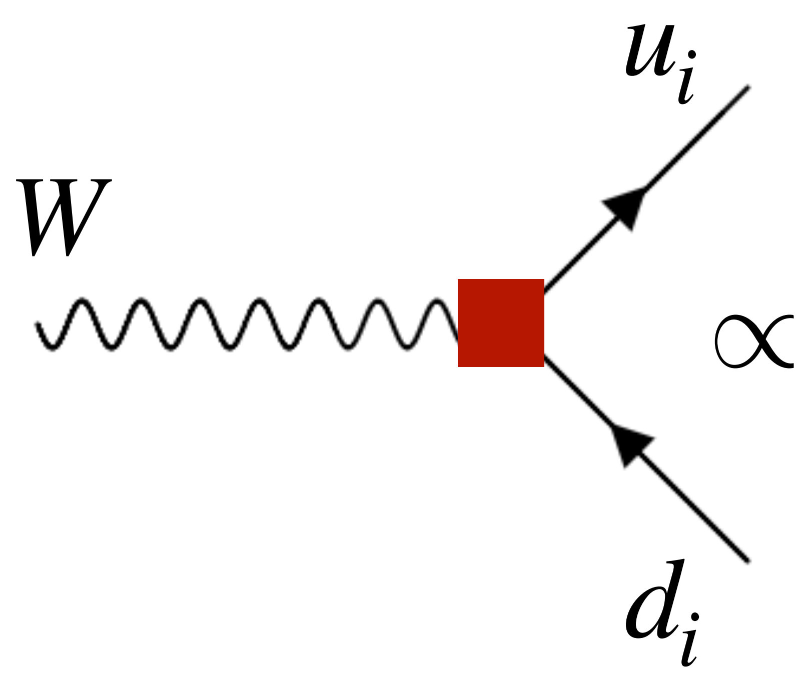
tH, VBF, Vh, WV, … → **This talk!**

L. Allwicher, D. A. Faroughy, **M. M.**, O. Sumensari, F. Wilsch [2412.14612]

See also J. Fuentes-Martín *et al.* [2003.12421], A. Greljo *et al.* [2212.10497], …

Example: Right-Handed Charged Currents at the LHC

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

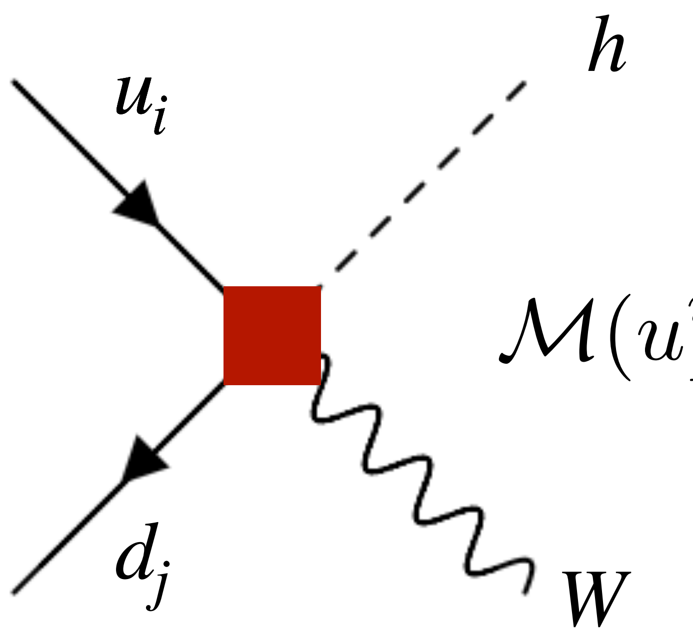


$$\propto \frac{[\mathcal{C}_{Hud}]_{ij}}{\Lambda^2} P_R$$

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

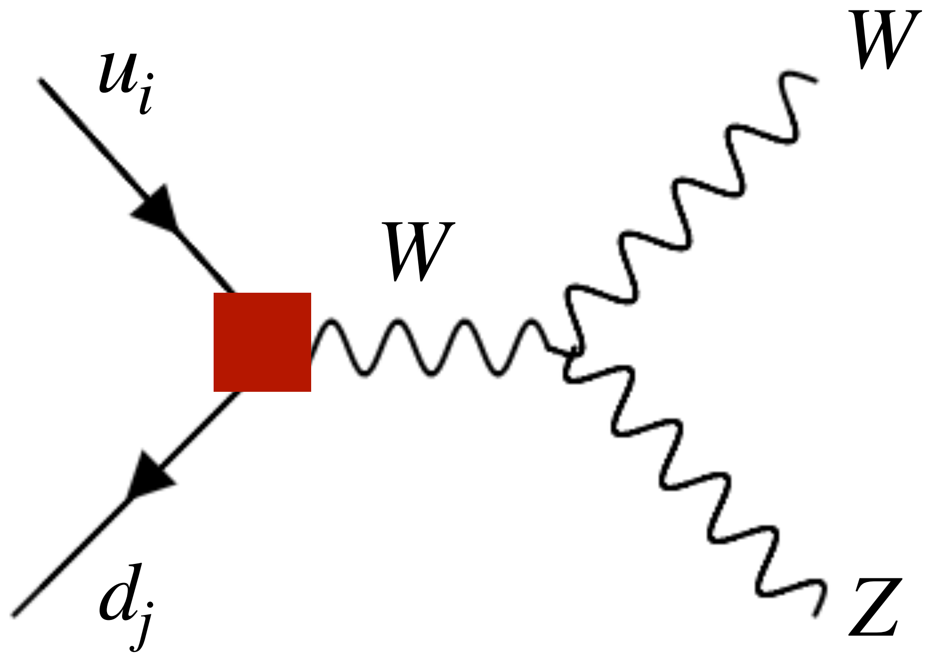
Poorly constrained by DY.

Energy-enhancement effects

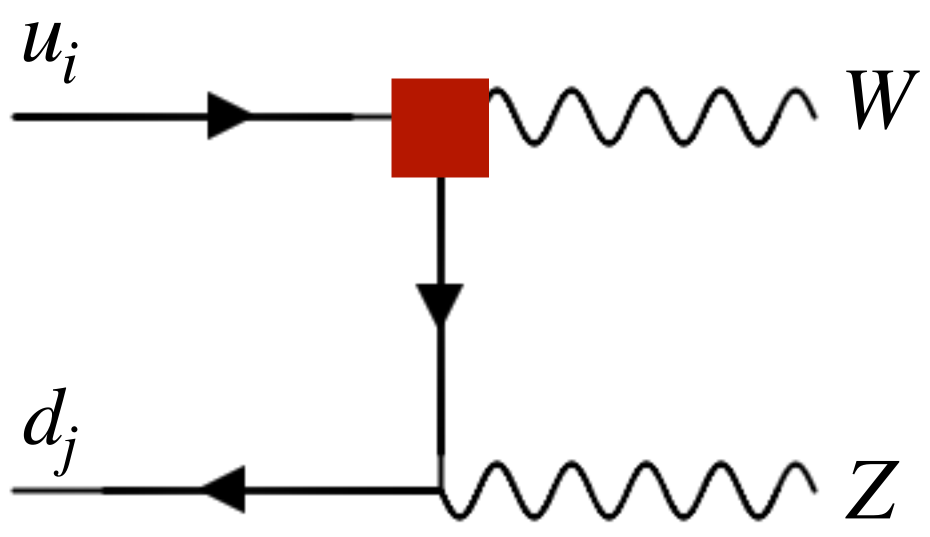


$$\mathcal{M}(u_R^i \bar{d}_R^j \to W_0\, h) = -\frac{i}{\sqrt{2}} \frac{E^2 \sin\theta}{\Lambda^2} \mathcal{C}^*_{\substack{Hud\\ij}}$$

Modifications to the charged current **spoil** the SM cancellations.



$+$



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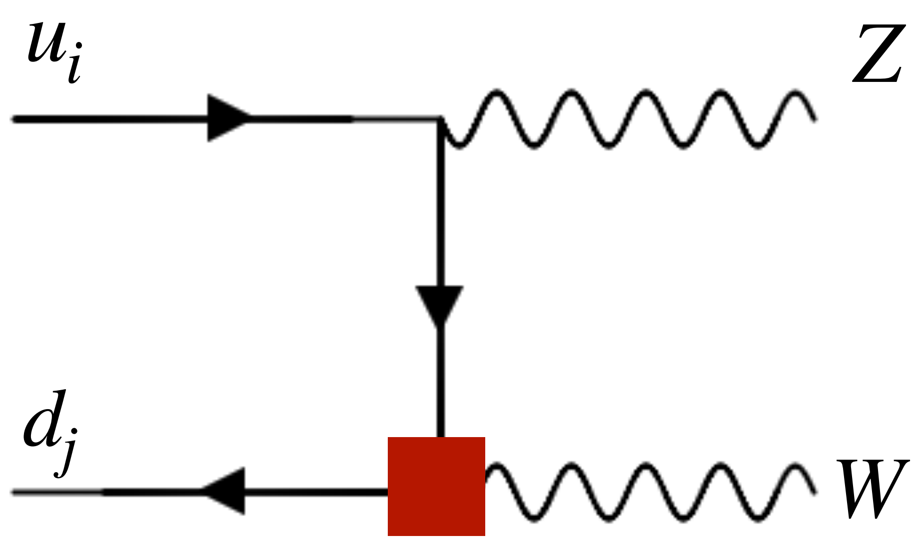
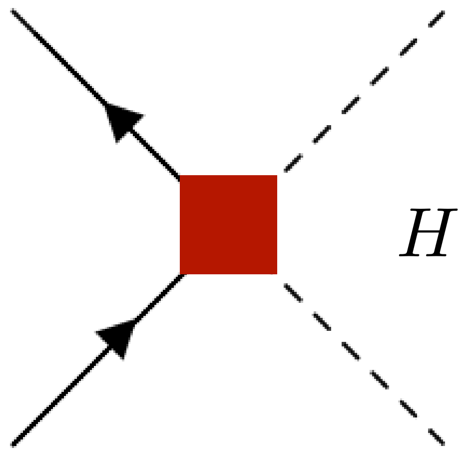


$$\mathcal{M}(u_R^i \bar{d}_R^j \to W_0\, Z_0) = -\frac{i}{\sqrt{2}} \frac{E^2 \sin\theta}{\Lambda^2} \mathcal{C}^*_{\substack{Hud\\ij}}$$

Goldstone Boson Equivalence Theorem

B. W. Lee *et al.*, *Phys. Rev. D 16, 1519*, G. J. Gounaris *et al.*, *Phys. Rev. D 34, 3257*, and many more...

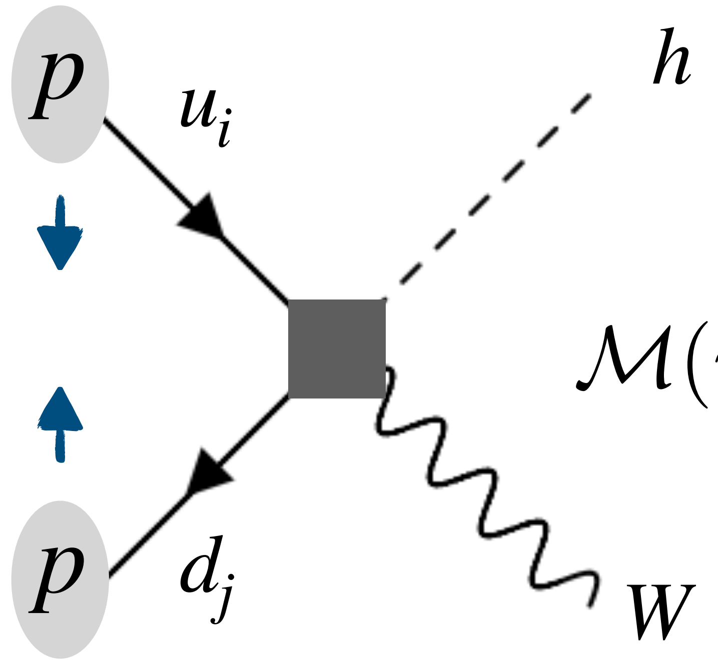


$$H = \begin{pmatrix} -iw^+ \\ \frac{1}{\sqrt{2}}(v + h + iz) \end{pmatrix}$$

Example: Right-Handed Charged Currents at the LHC

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

Energy-enhancement effects at the tails



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

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

Higgs differential distributions in the format of **Simplified Template Cross-Sections (STXS)** are available.

D. De Florian *et al.* [1610.07822]