Matheus Martines

Universidade de São Paulo (USP)
Laboratoire de Physique des 2 infinis Irène Joliot-Curie (IJClab)

Main research interests

EFTs, Collider Physics, Flavor Physics, BSM Phenomenology, ...

Advisors

Oscar J. P. Éboli (USP) & Olcyr Sumensari (IJCLab)

Hobbies :-)

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

Matheus Martines

Universidade de São Paulo (USP)/Laboratoire de Physique des 2 infinis Irène Joliot-Curie (IJClab)

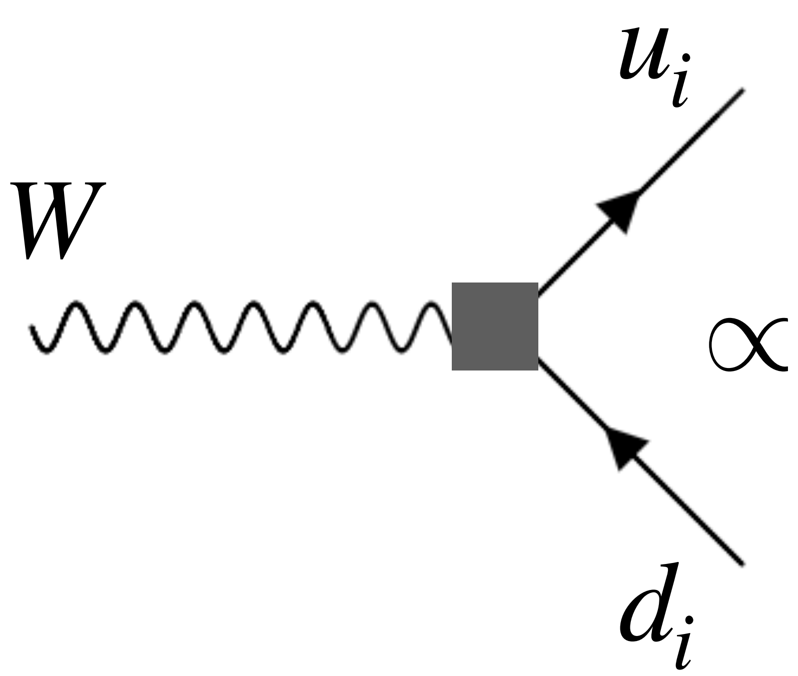
Based on work in progress with O. J. P. Éboli, L. P. S. Leal, and O. Sumensari

Semileptonic Transitions at Different Scales

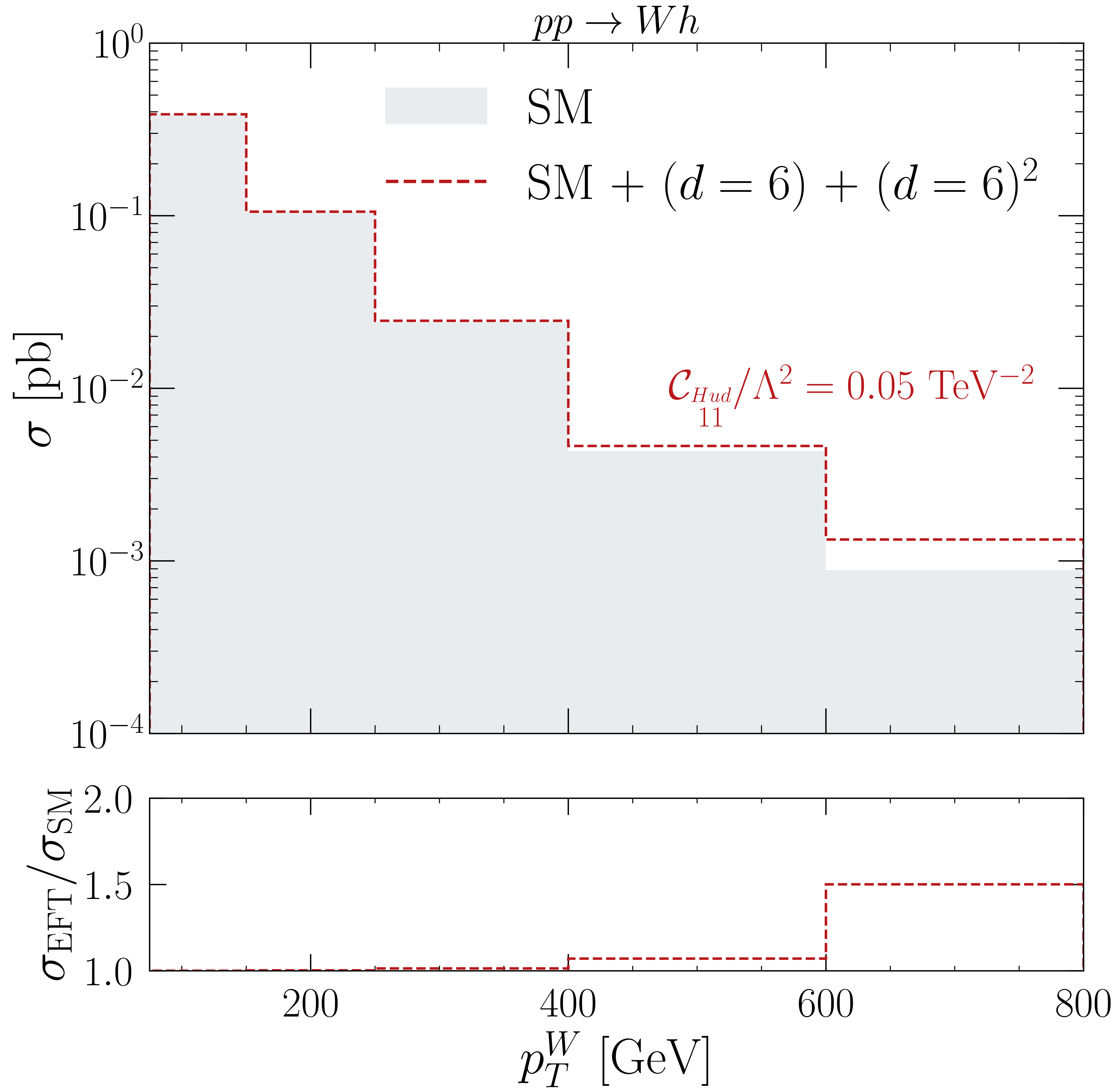
Absence of resonant signals at the LHC. → **Mass gap** between the electroweak scale and the scale of New Physics (NP). → **Effective Field Theories**

Example: Right-Handed Charged Currents at the LHC

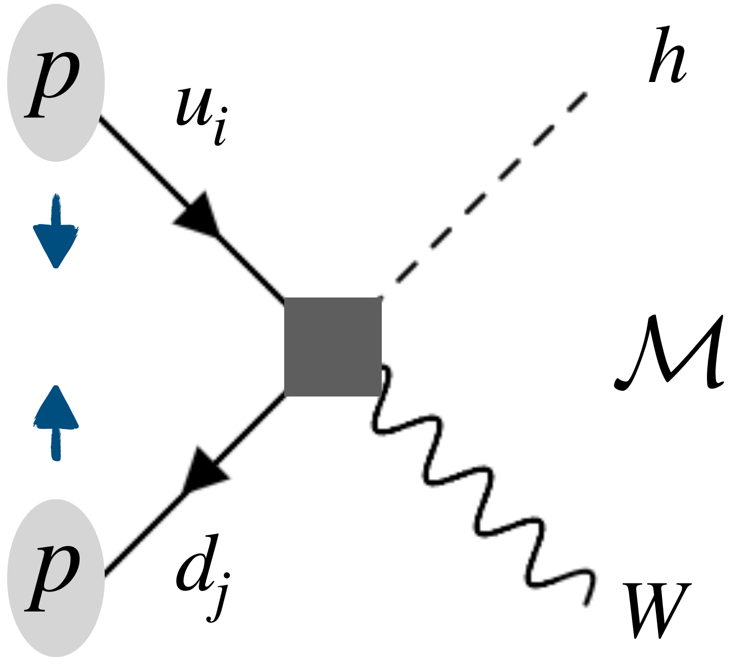
$$\mathcal{O}_{Hud} = (\tilde{H}^\dagger i D_\mu H)(\overline{u}_R \gamma^\mu d_R) + \text{h.c.}$$



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



Energy-enhancement effects



Center of mass energy

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

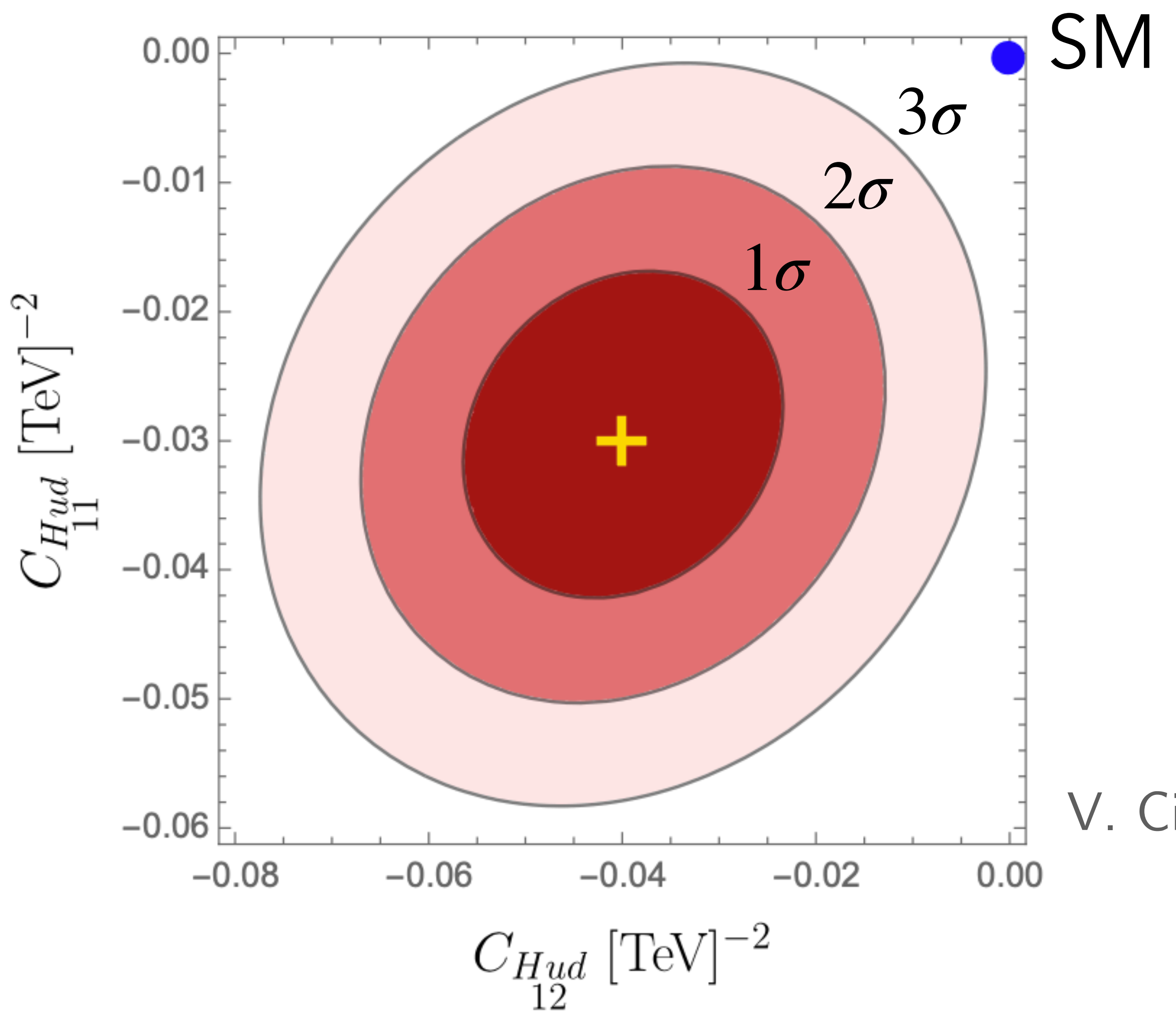
Illustration: First-row CKM unitarity

$$\Delta_{\text{CKM}}^{\text{global}} \equiv |V_{ud}|^2_{\text{global}} + |V_{us}|^2_{\text{global}} + \underbrace{|V_{ub}|^2}_{\simeq 0} - 1 = -0.001\,51(53)$$

~ 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...

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



V. Cirigliano *et al.* [2311.00021]

A. Crivellin *et al.* [2212.06862]

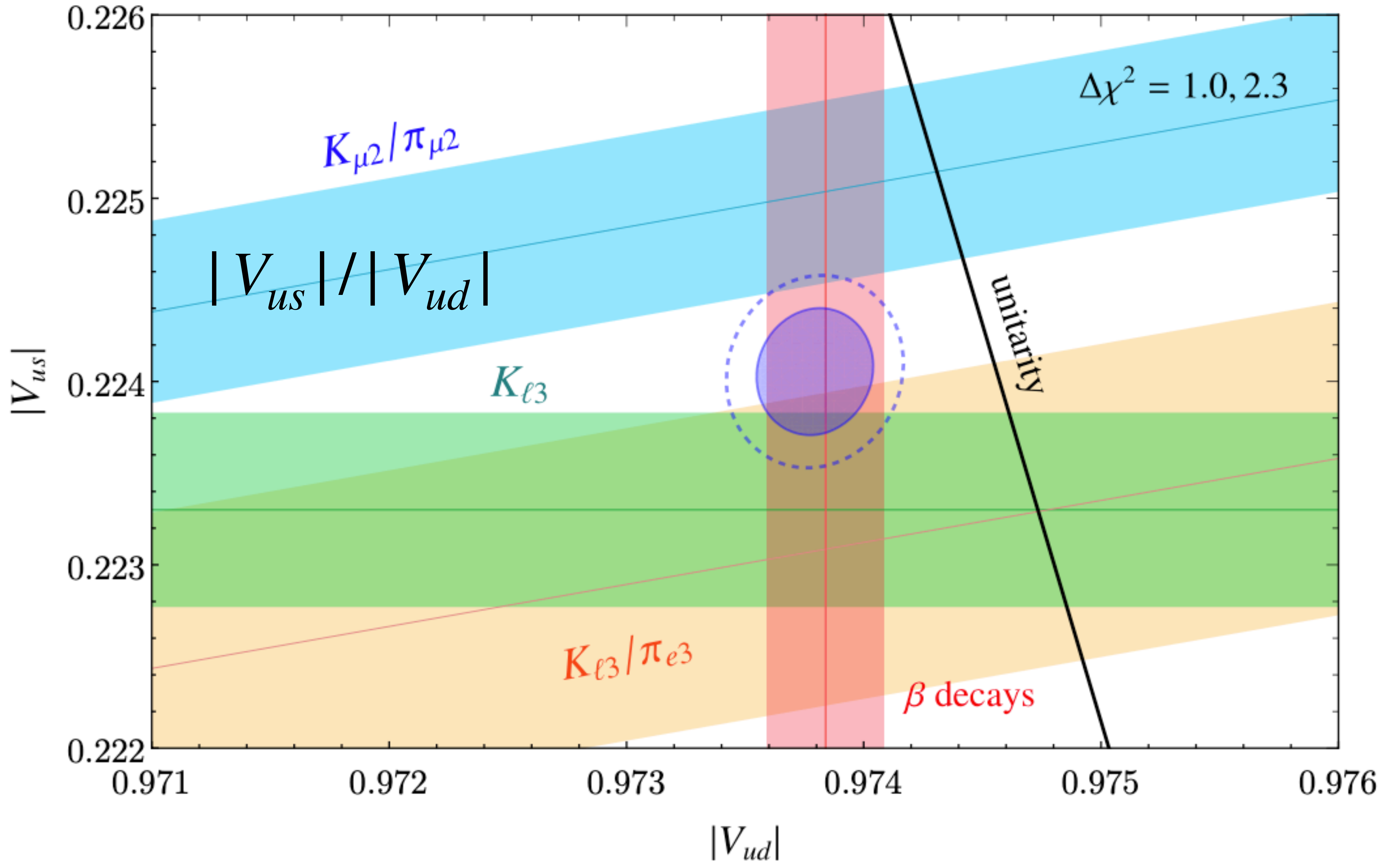
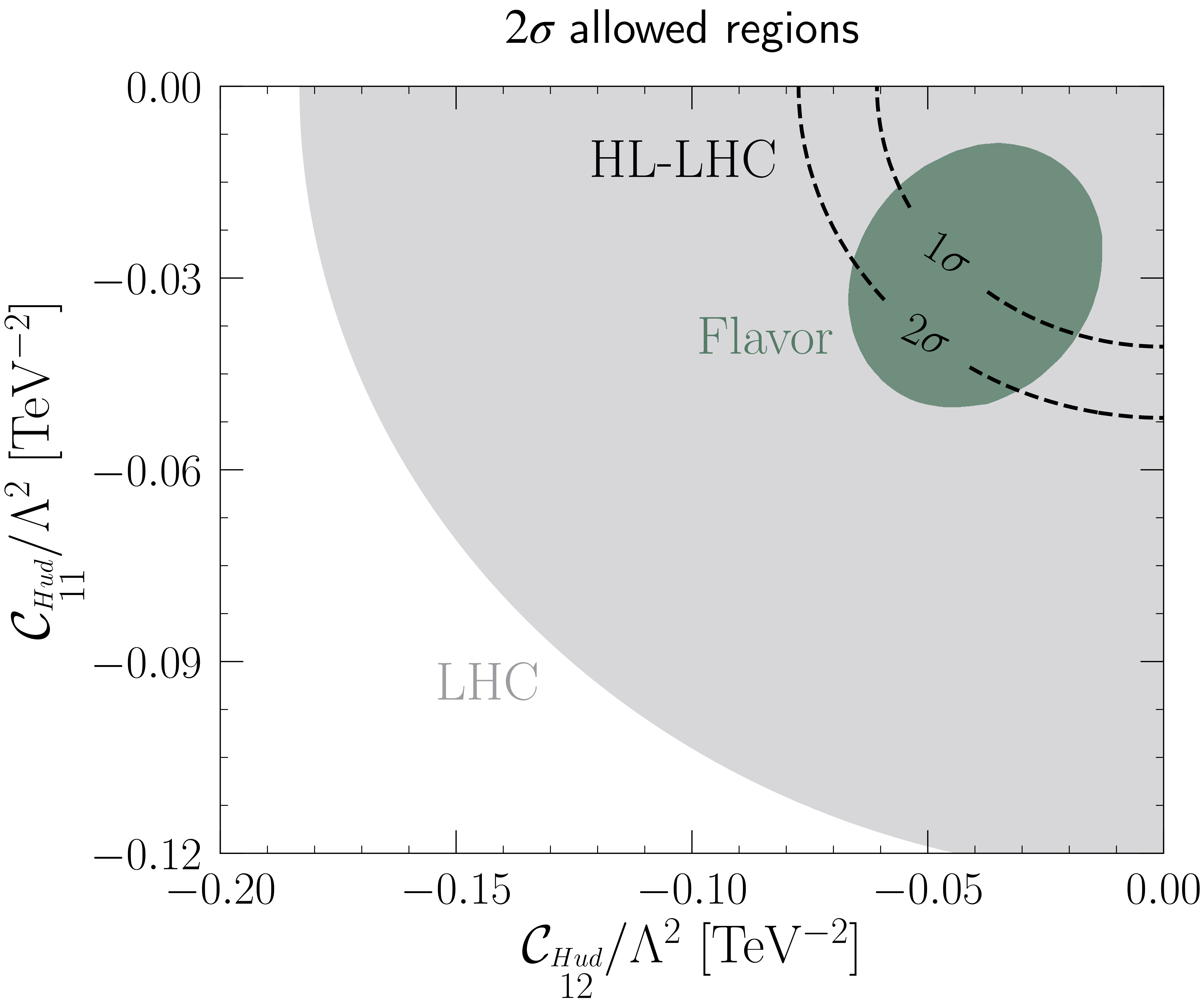


Illustration: First-row CKM unitarity



Flavor limits from **V. Cirigliano *et al.* [2311.00021]**

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.**

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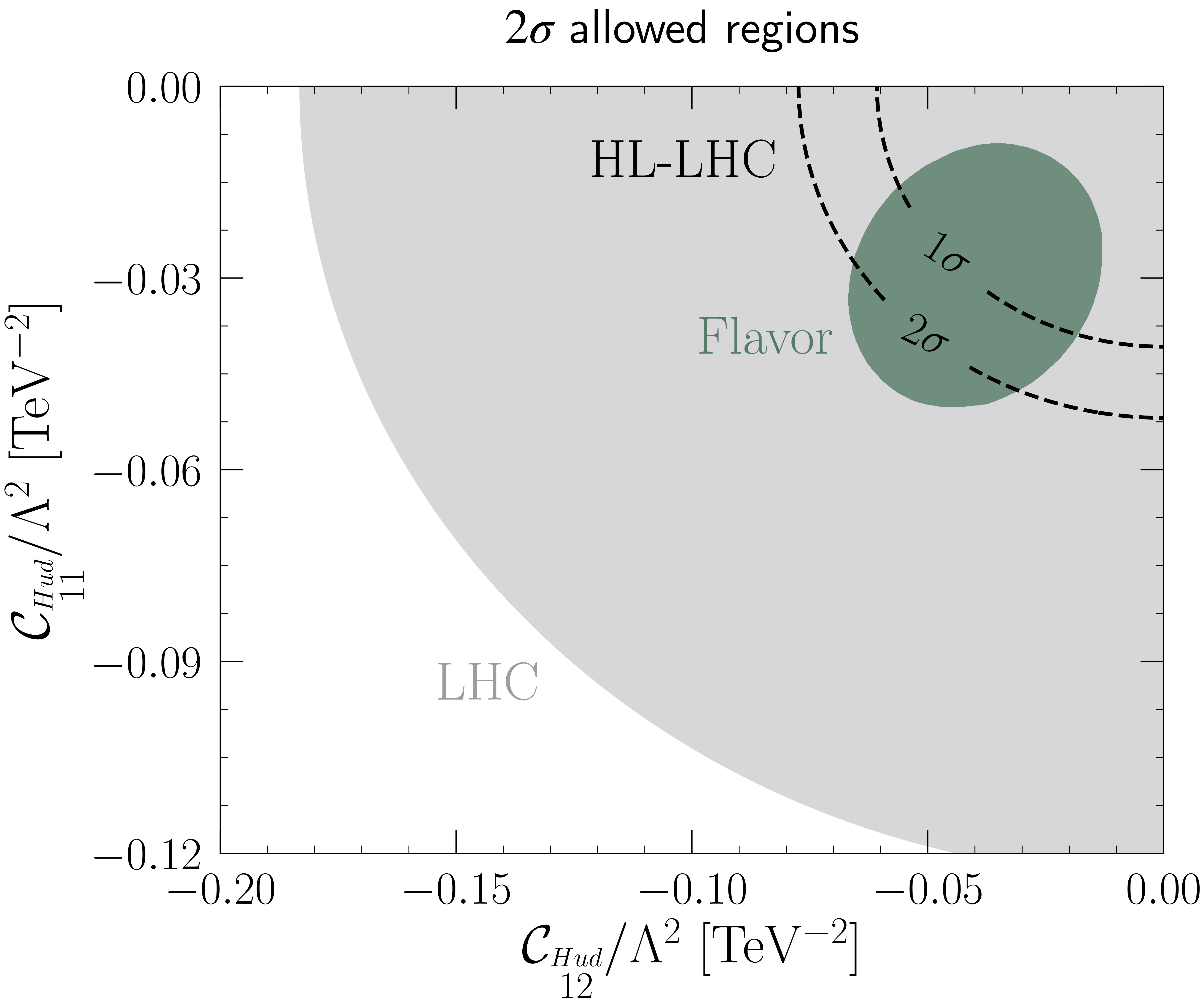

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LHC and HL-LHC limits are dominated by Wh production.

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

Take aways:

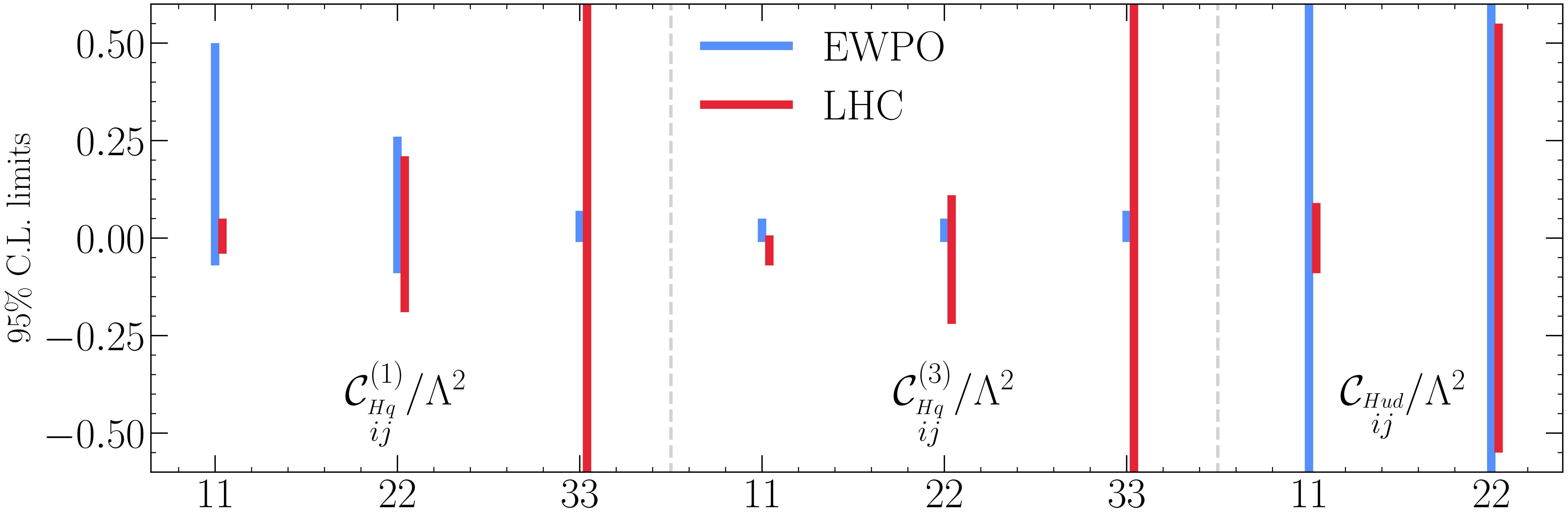
The **HL-LHC** could help clarify **flavor anomalies.**

Also, **HL-LHC** can provide meaningful constraints on several transitions.

Thank you!

Backup

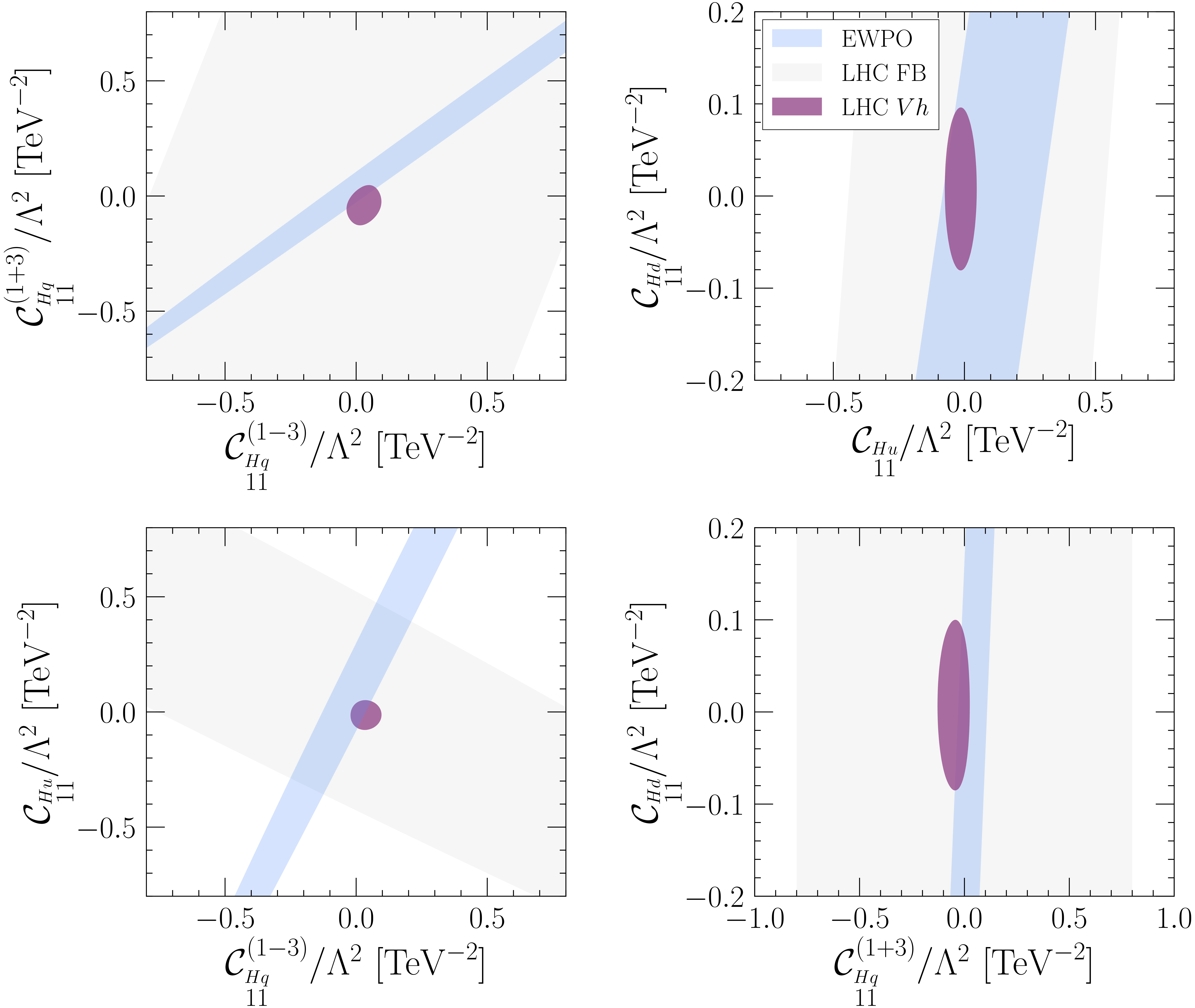
LHC vs EWPO



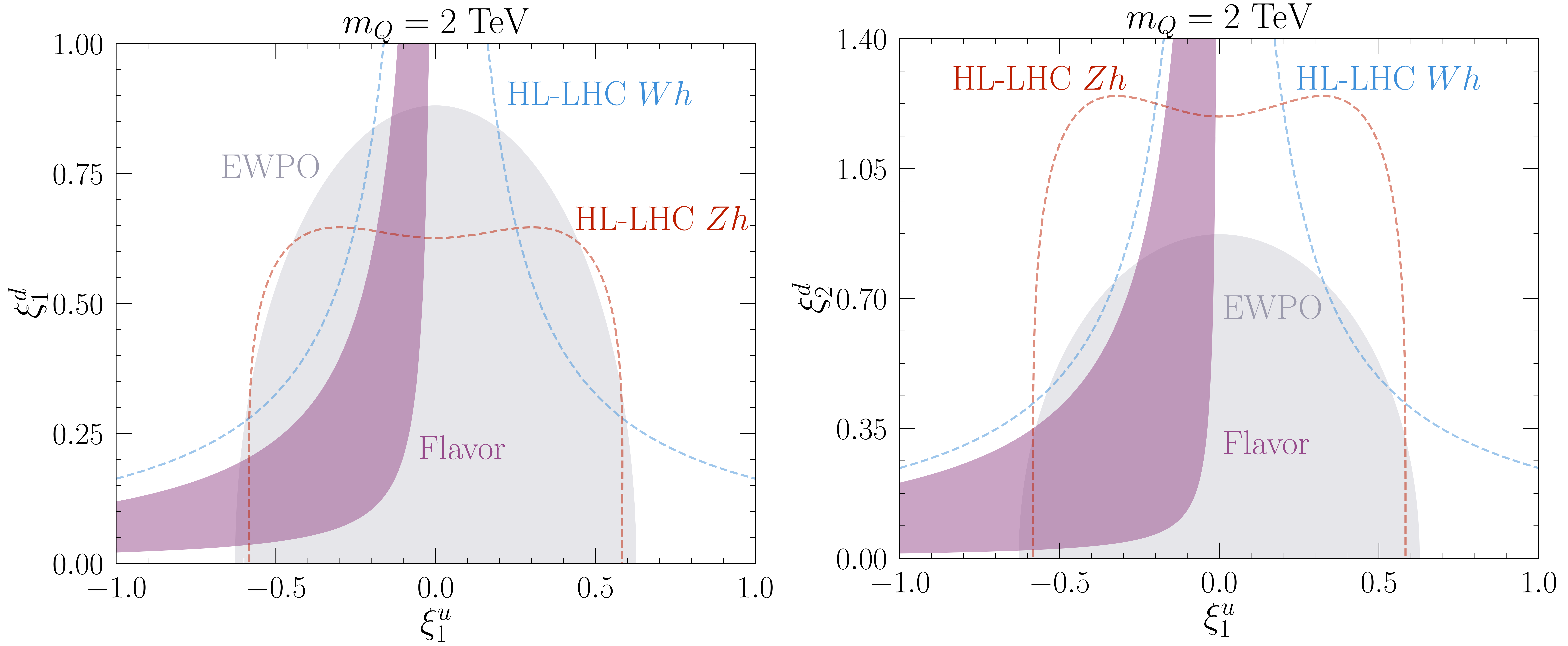
Observable	Measurement	SM prediction
Γ_Z [GeV]	2.4955 ± 0.0023 [61]	2.4941 [62]
$\sigma_{\rm had}$ [nb]	41.4807 ± 0.0325 [61]	41.4923 [63]
R_e	20.8038 ± 0.0497 [61]	20.734 [62]
R_μ	20.7842 ± 0.0335 [61]	20.734 [62]
R_τ	20.7644 ± 0.0448 [61]	20.781 [62]
R_b	0.21629 ± 0.00066 [64]	0.21591 [63]
R_c	0.1721 ± 0.0030 [64]	0.1722 [63]
$A_{\rm FB}^{0,b}$	0.0992 ± 0.0016 [64]	0.1029 [63]
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035 [64]	0.0735 [63]
$\mathcal{A}_b$	0.923 ± 0.020 [64]	0.935 [63]
$\mathcal{A}_c$	0.670 ± 0.027 [64]	0.668 [63]
$\mathcal{A}_s$	0.895 ± 0.091 [64]	0.936 [63]
R_{uc}	0.166 ± 0.009 [65]	0.172 [63]
Γ_W [GeV]	2.085 ± 0.042 [65]	2.087 [63]
${\rm Br}(W \to e\nu)$	0.1071 ± 0.0016 [66]	0.1082 [63]
${\rm Br}(W \to \mu\nu)$	0.1063 ± 0.0015 [66]	0.1082 [63]
${\rm Br}(W \to \tau\nu)$	0.1138 ± 0.0021 [66]	0.1081 [63]

LHC vs EWPO

FB asymmetry limits from V. Bresó-Pla, A. Falkowski, M. González-Alonso [2103.12074]

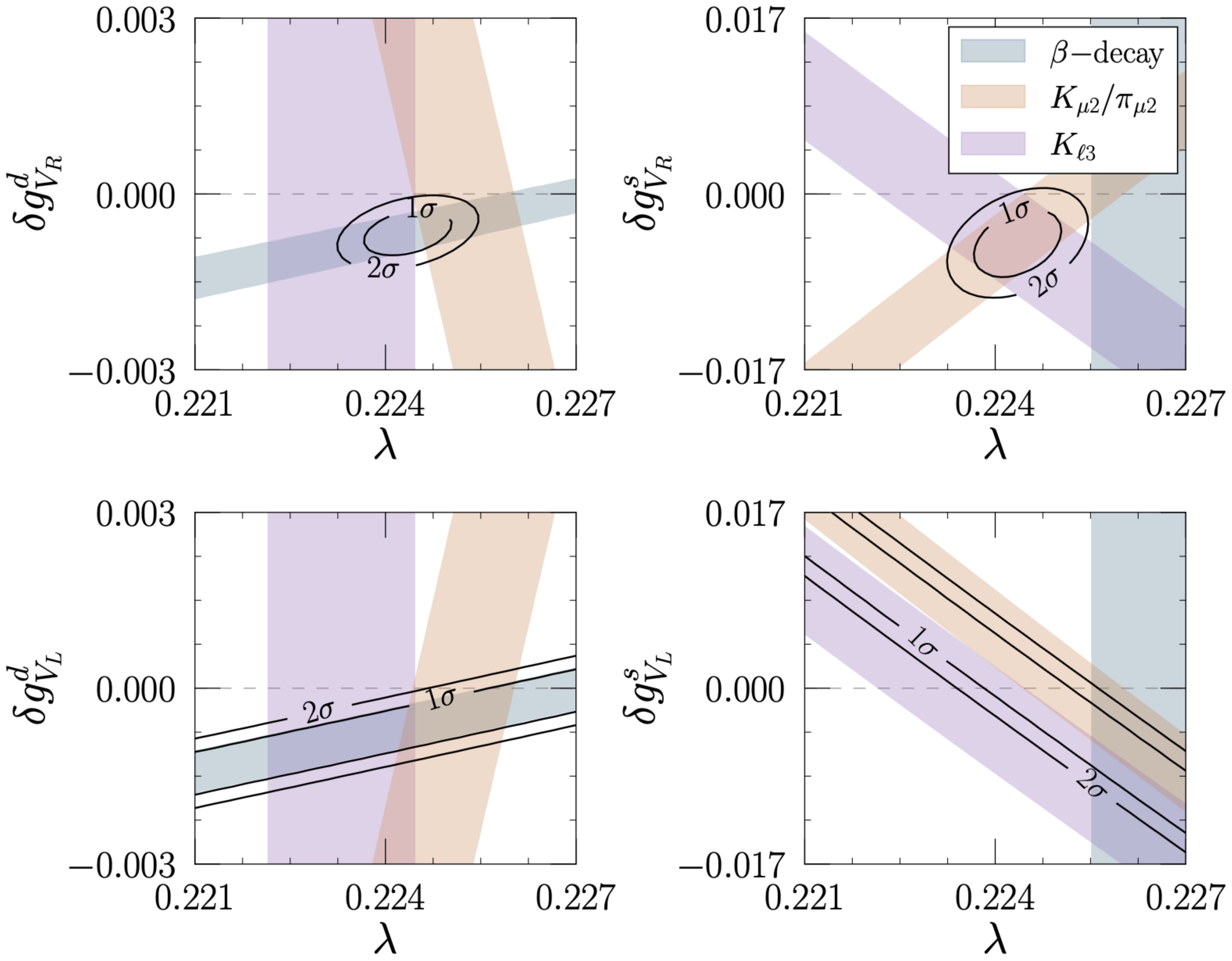


Example: Vector-Like Quark

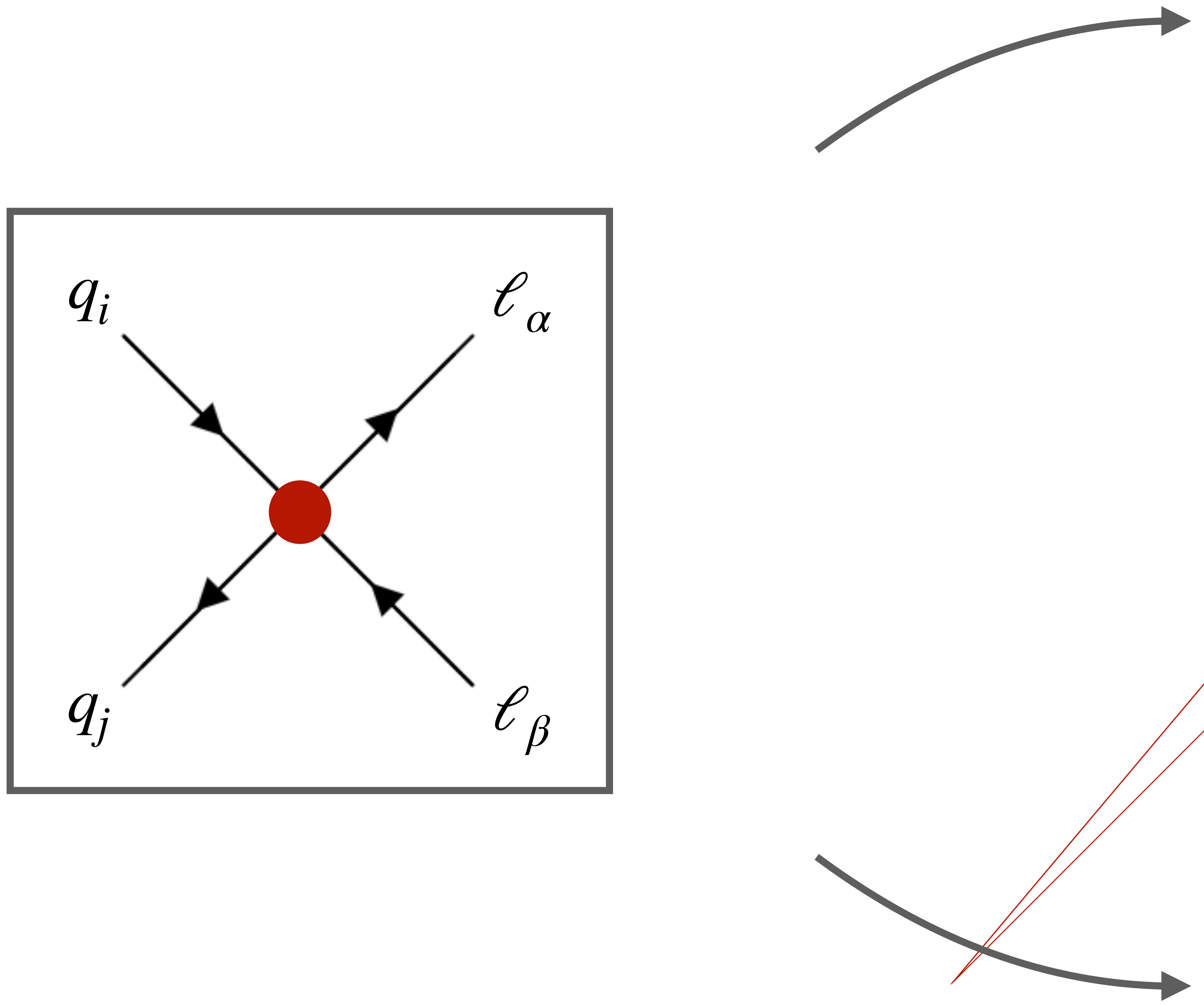


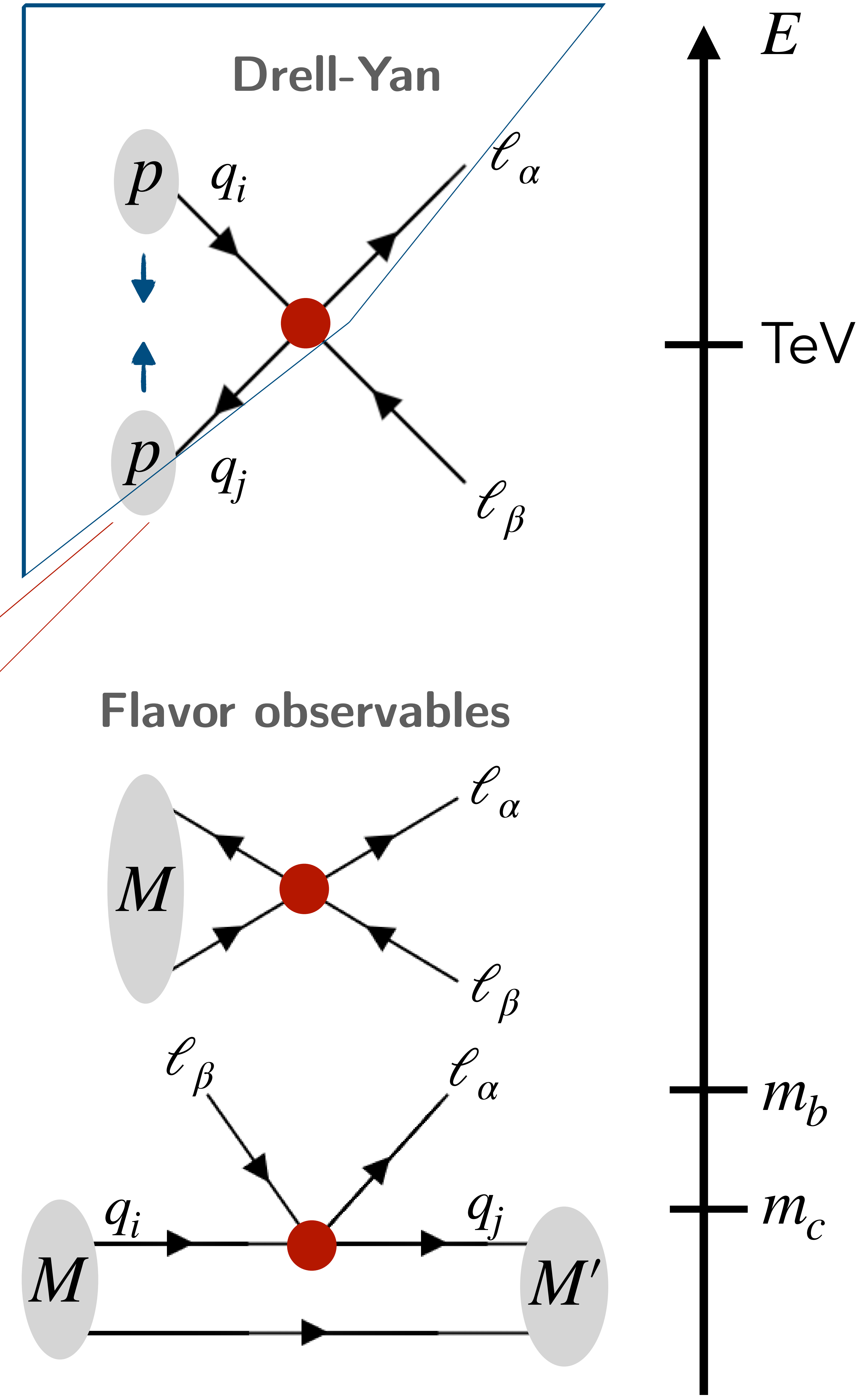
$$\mathcal{L}_{\rm VLQ} \supset -\xi_{fi}^{(u)}\, \overline{\mathcal{Q}}_f \widetilde{H} u_i - \xi_{fi}^{(d)}\, \overline{\mathcal{Q}}_f H d_i + \text{h.c.}\,, \quad \mathcal{Q}_f \sim (\mathbf{3}, \mathbf{2}, 1/6)$$

Left- vs. Right-handed currents



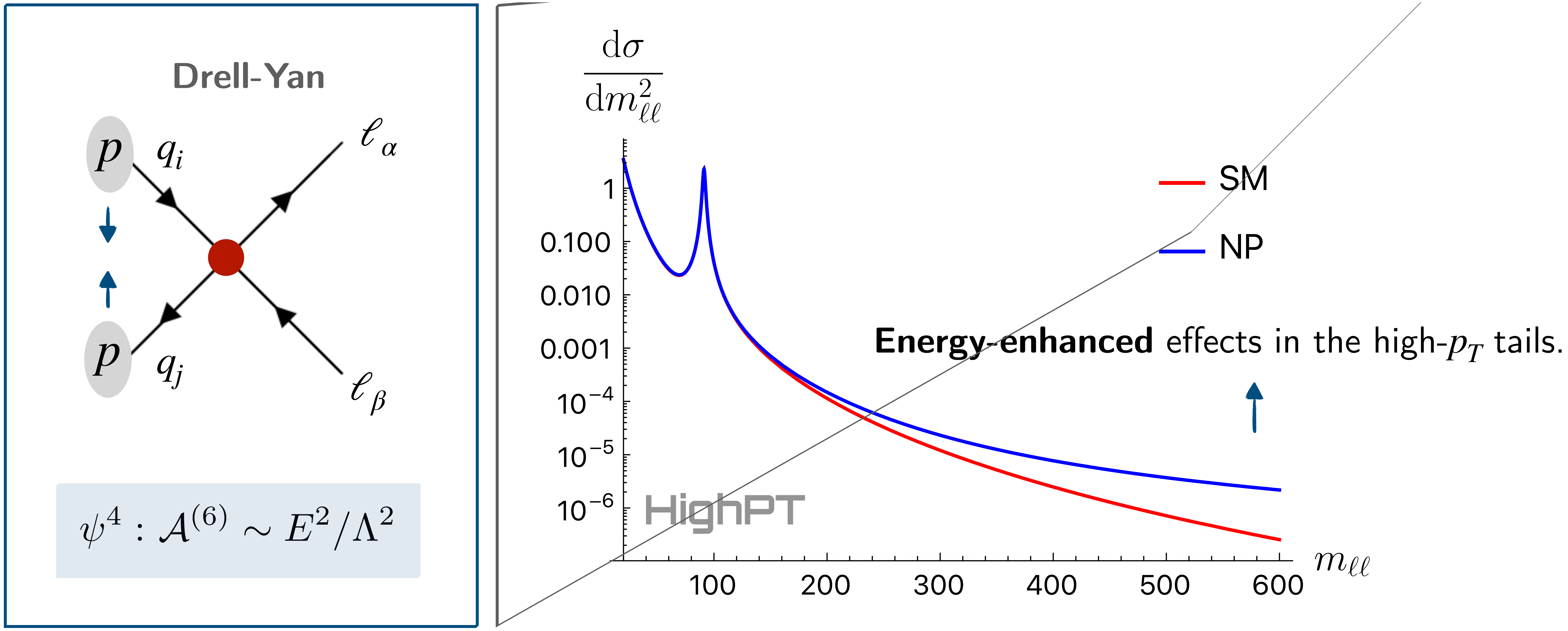
Semileptonic four-fermion operators





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



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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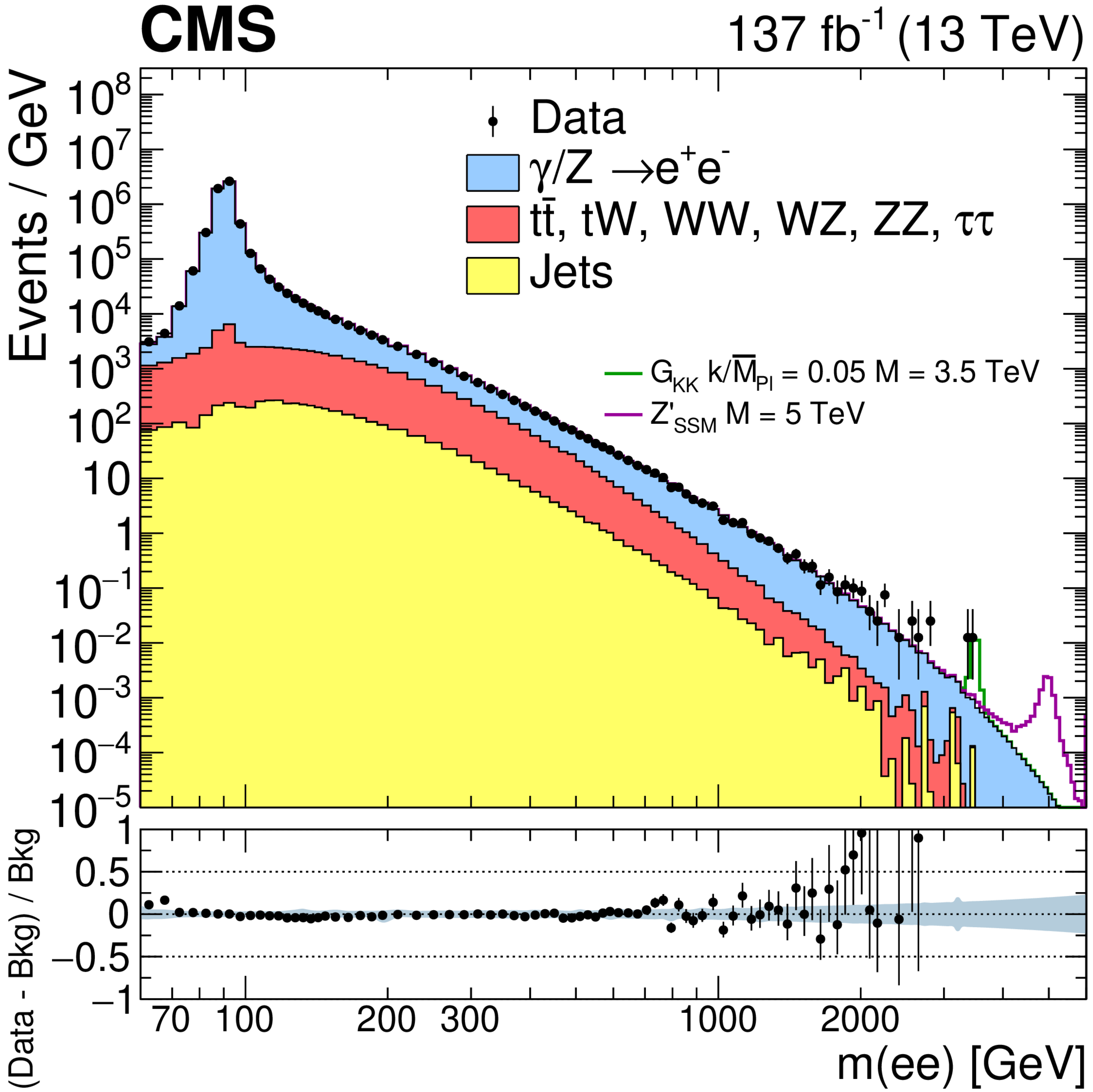
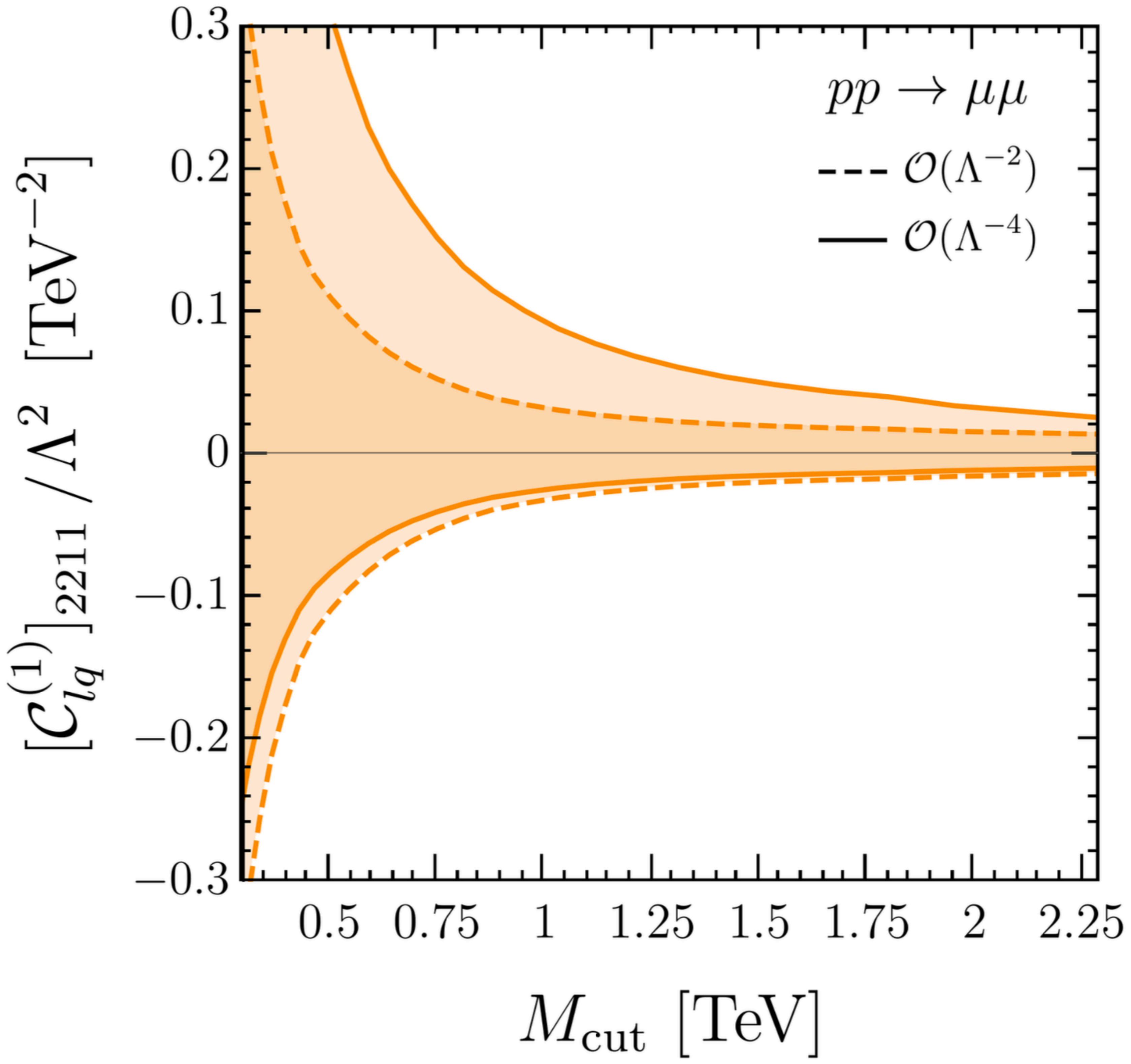


CMS Collaboration [2103.02708]

LHC can measure events with **high** center of mass energy.

Access to **higher energy** bins leads to **stronger constraints**.

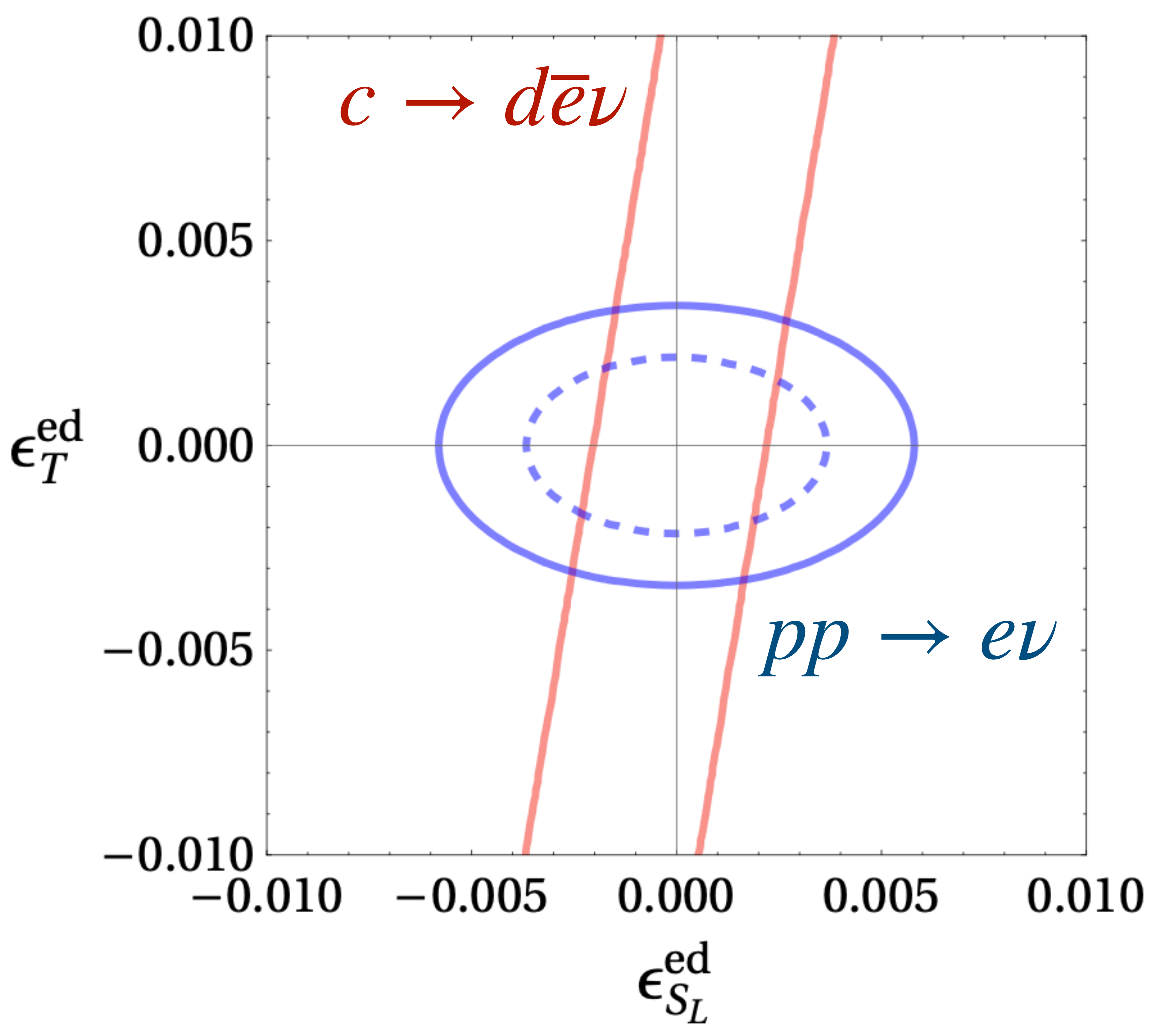
L. Allwicher *et al.* [2207.10714]



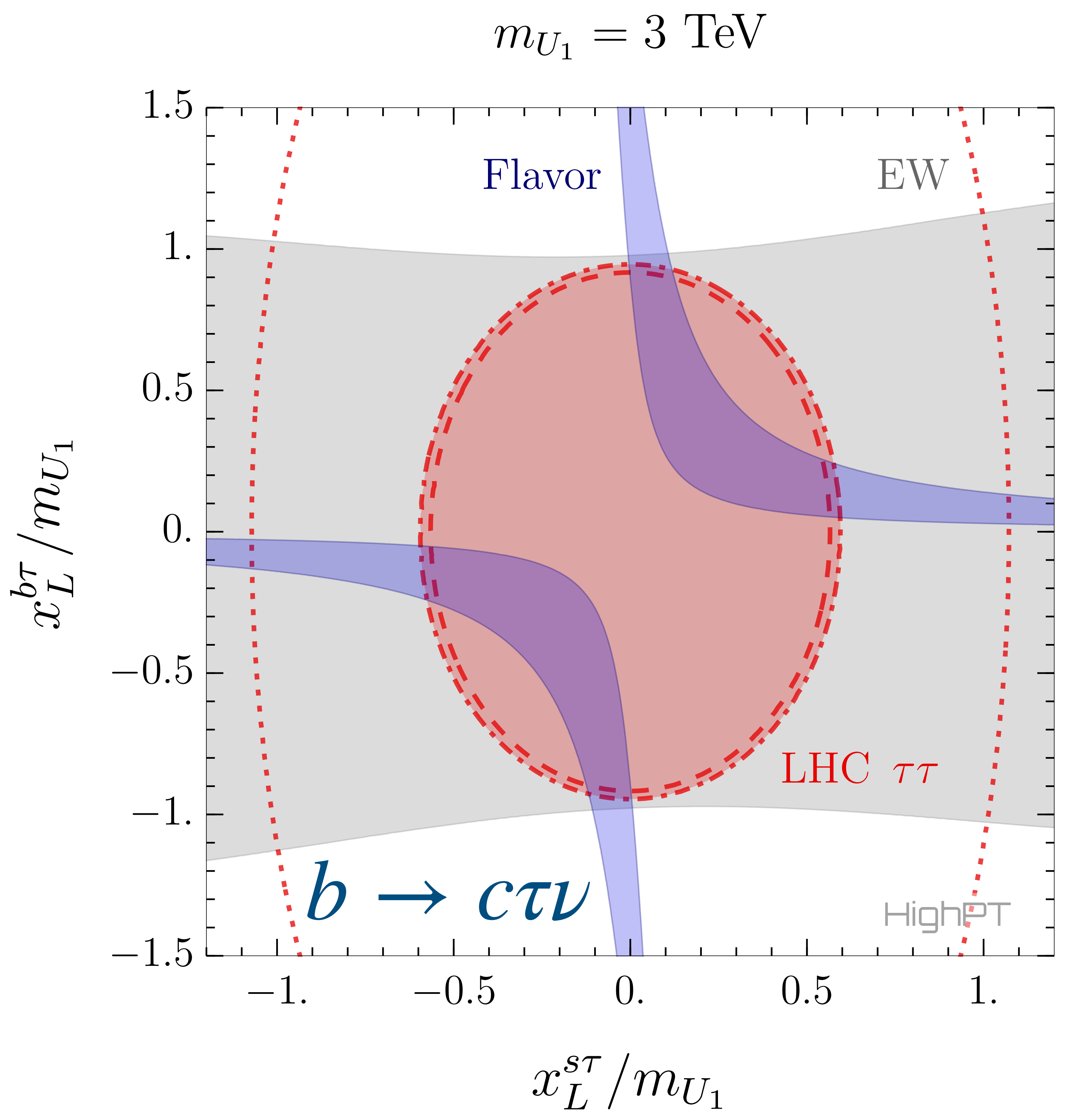
For a discussion on the range of validity of the EFT in the DY channel, see **L. Allwicher et al. [arXiv:2412.14612].**

Combining Flavor and High-p_T DY observables

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



J. Fuentes-Martín, A. Greljo, J. M. Camalich, J. D. Ruiz-Alvarez [2003.12421]



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

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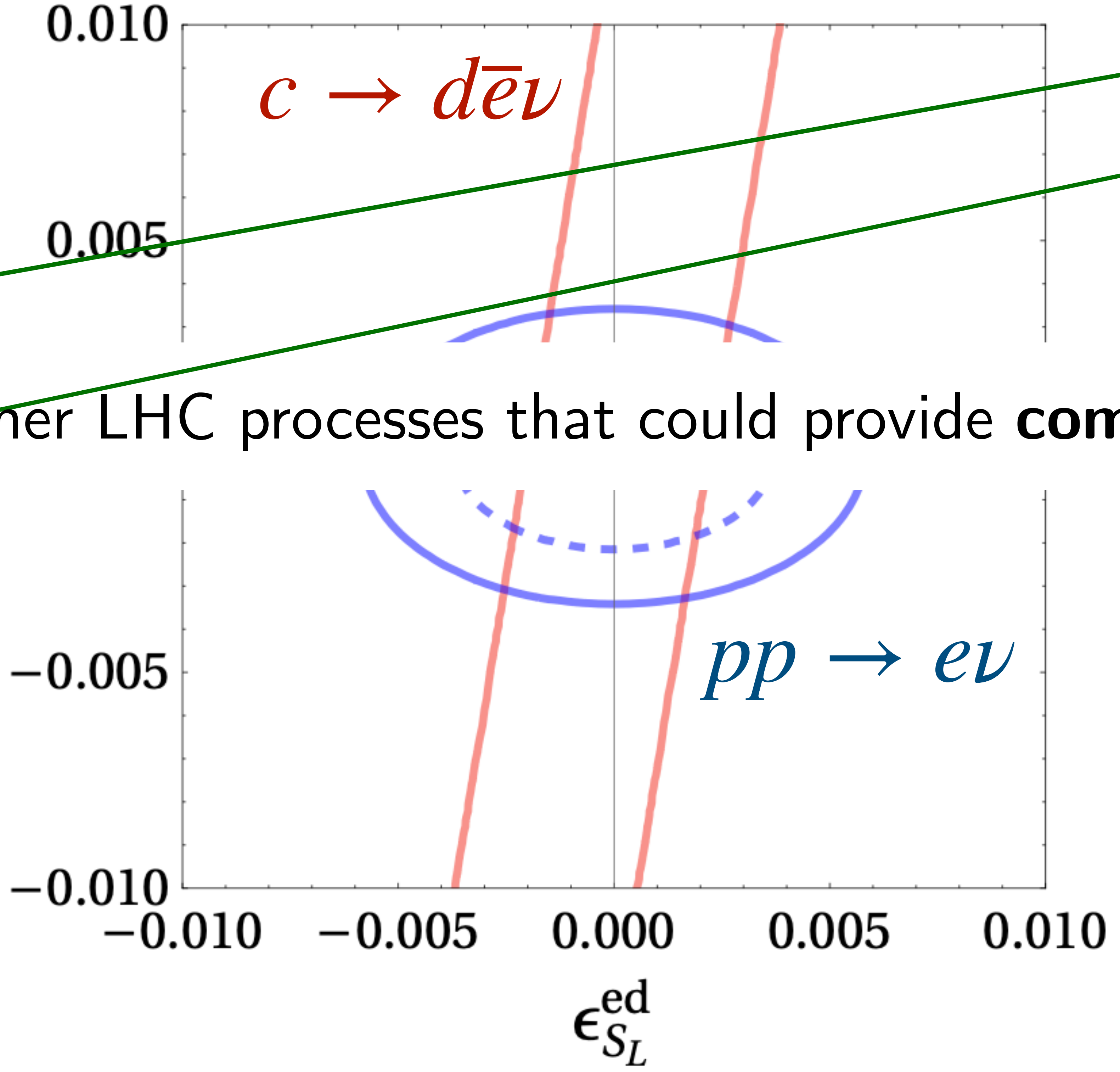

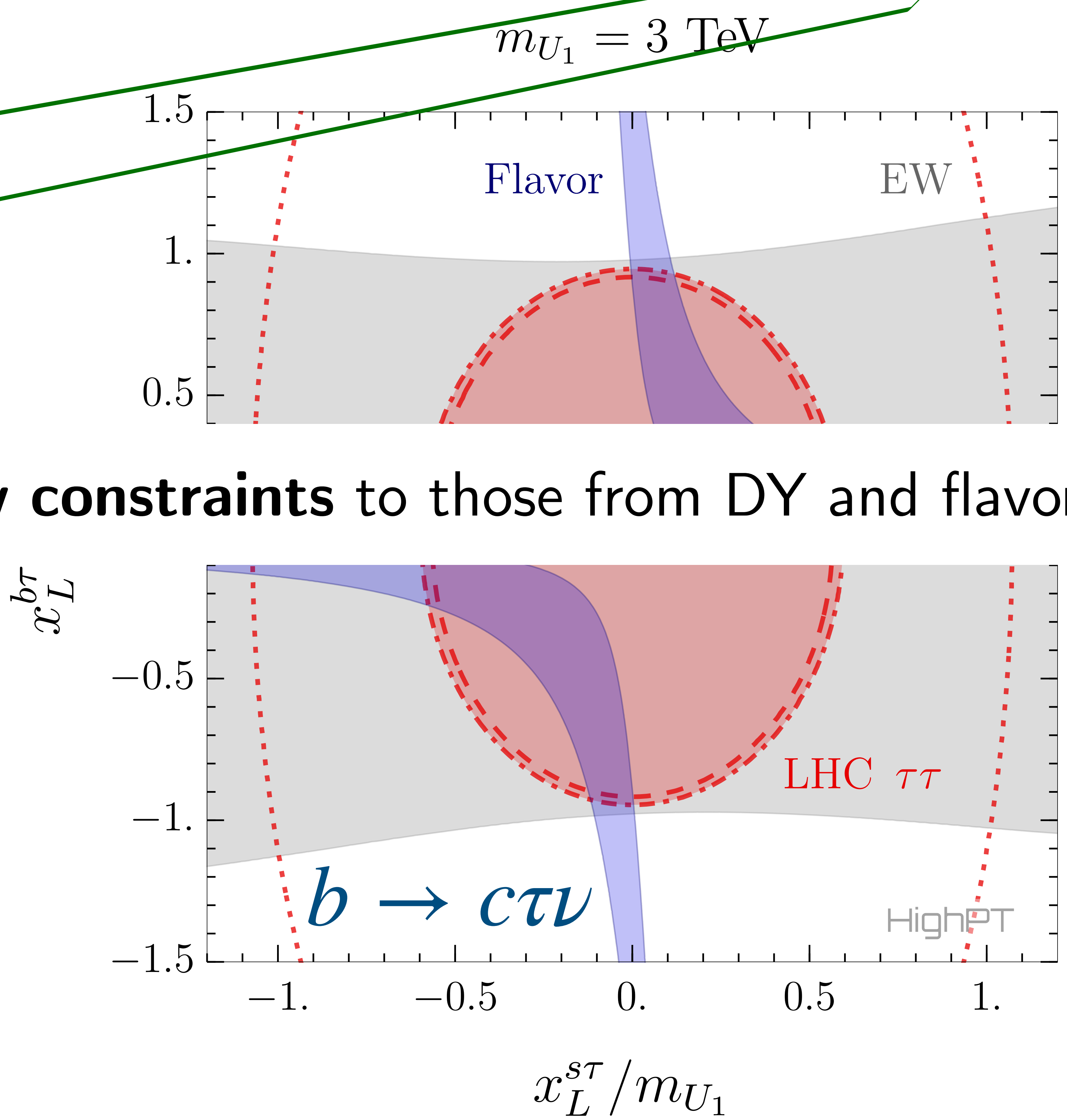

Are there other LHC processes that could provide **complementary constraints** to those from DY and flavor observables?

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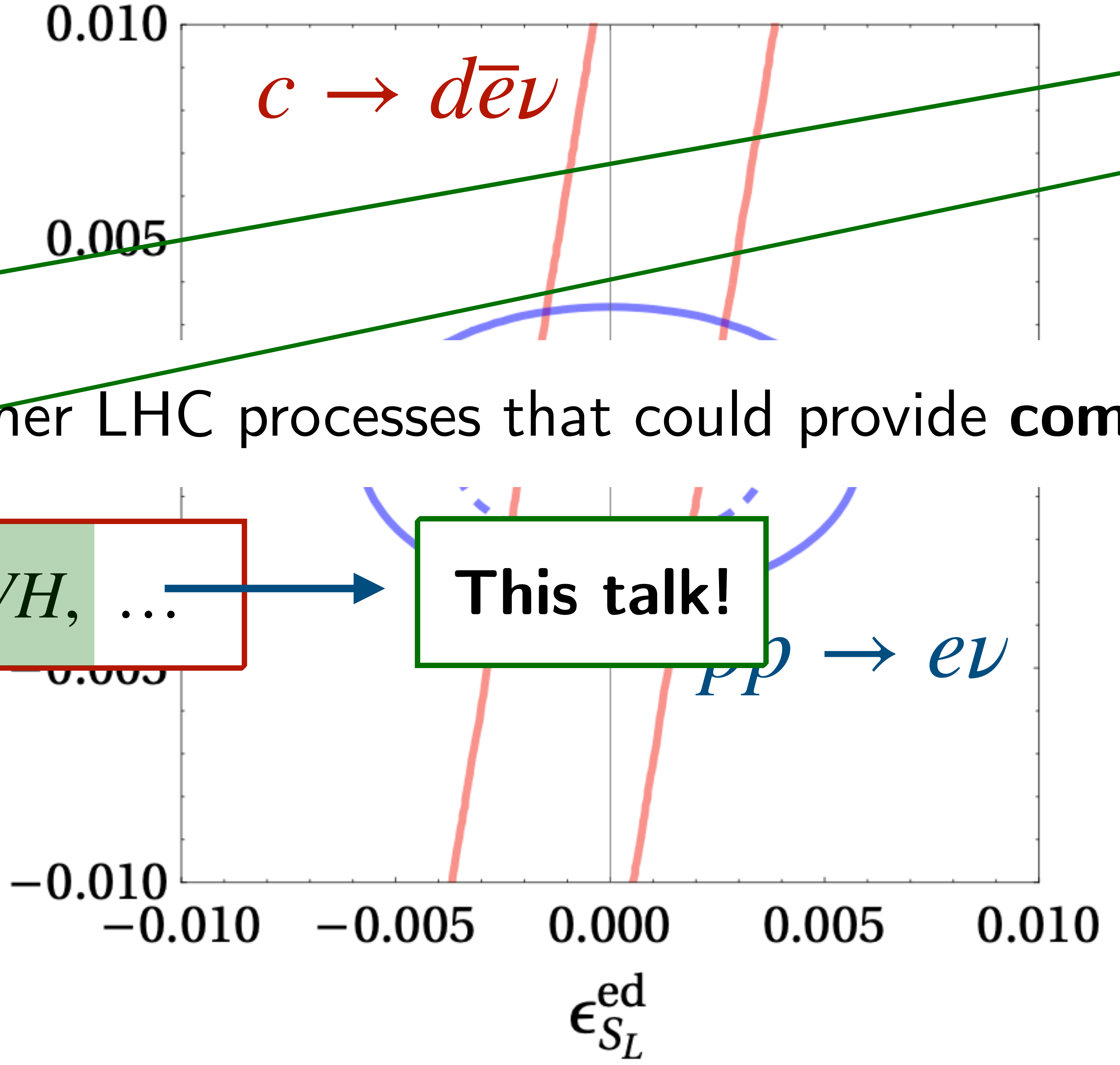

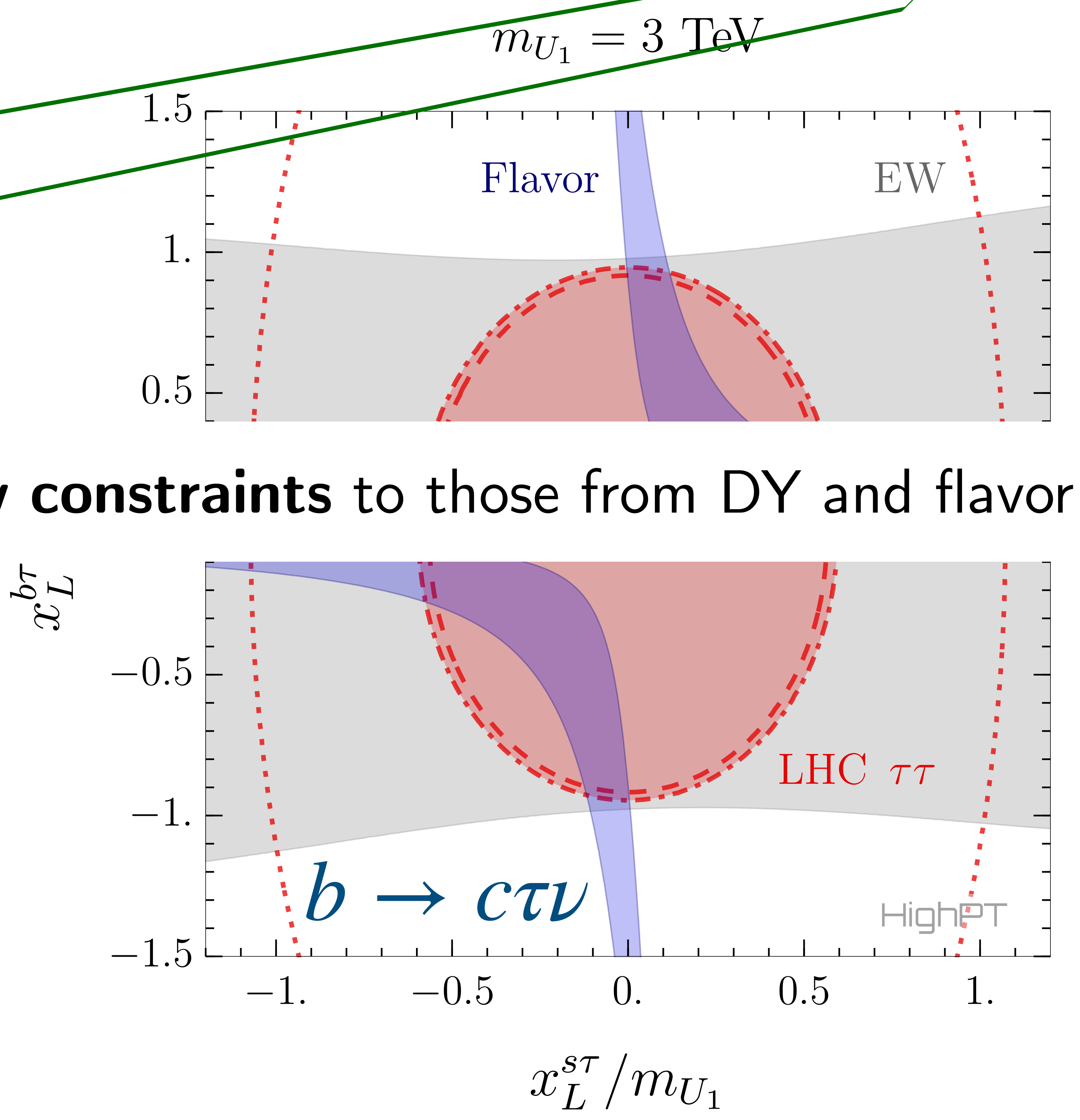

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tH, VBF, VH, … → **This talk!**

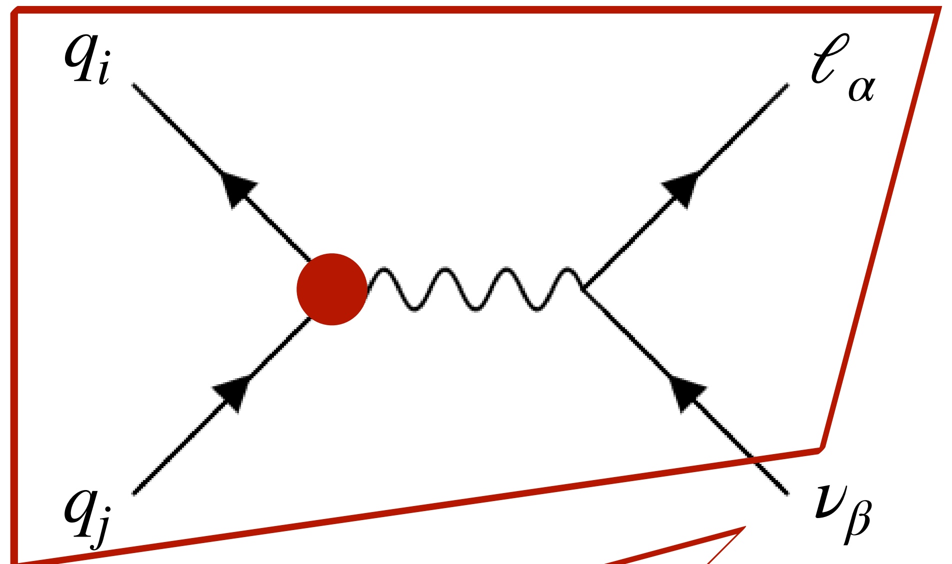
J. Fuentes-Martín, A. Greljo, J. M. Camalich, J. D. Ruiz-Alvarez [2003.12421]

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

Example: Right-Handed Charged Currents at the LHC

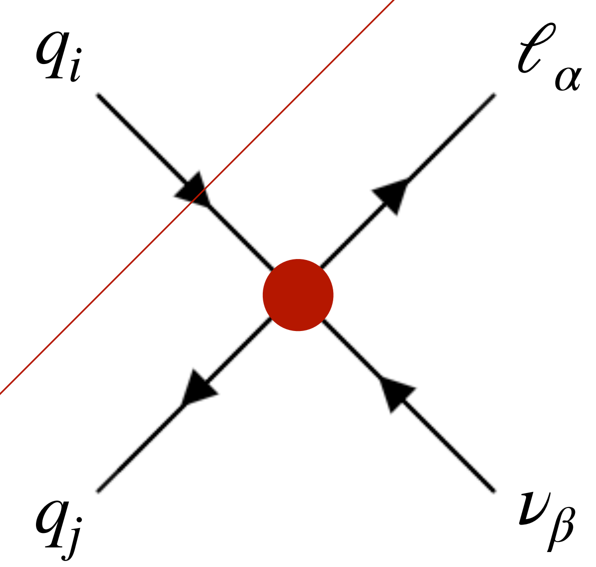
Assuming a linear realization of the $SU(2)_L \times U(1)_Y$ gauge symmetry.

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



- **Lepton flavor universal**

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



- Affects **leptonic** and **semi-leptonic** meson decays.

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

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

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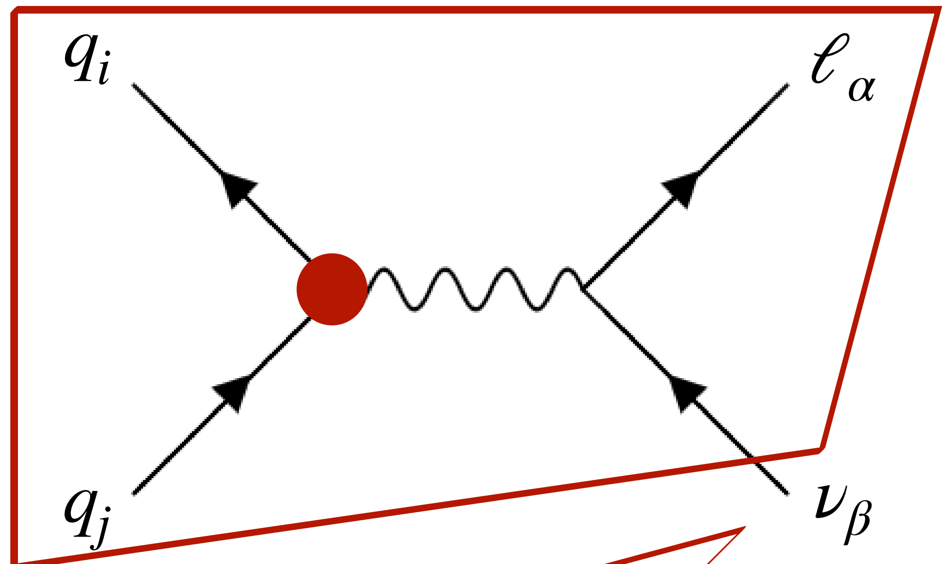

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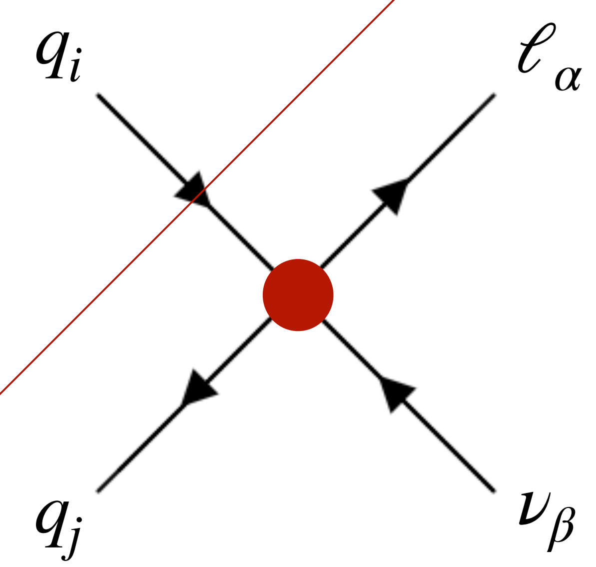

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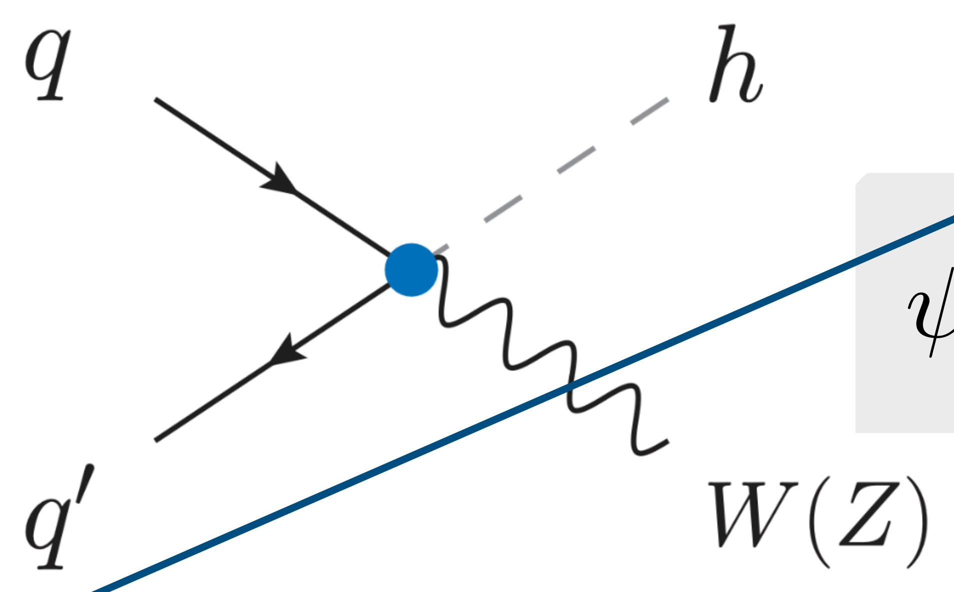
Alternative: ***Vh* production data.**

Dimension-six Higgs current operators

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

B. Grzadkowski *et al.* [1008.4884]

Only Zh | Only Wh | Wh and Zh



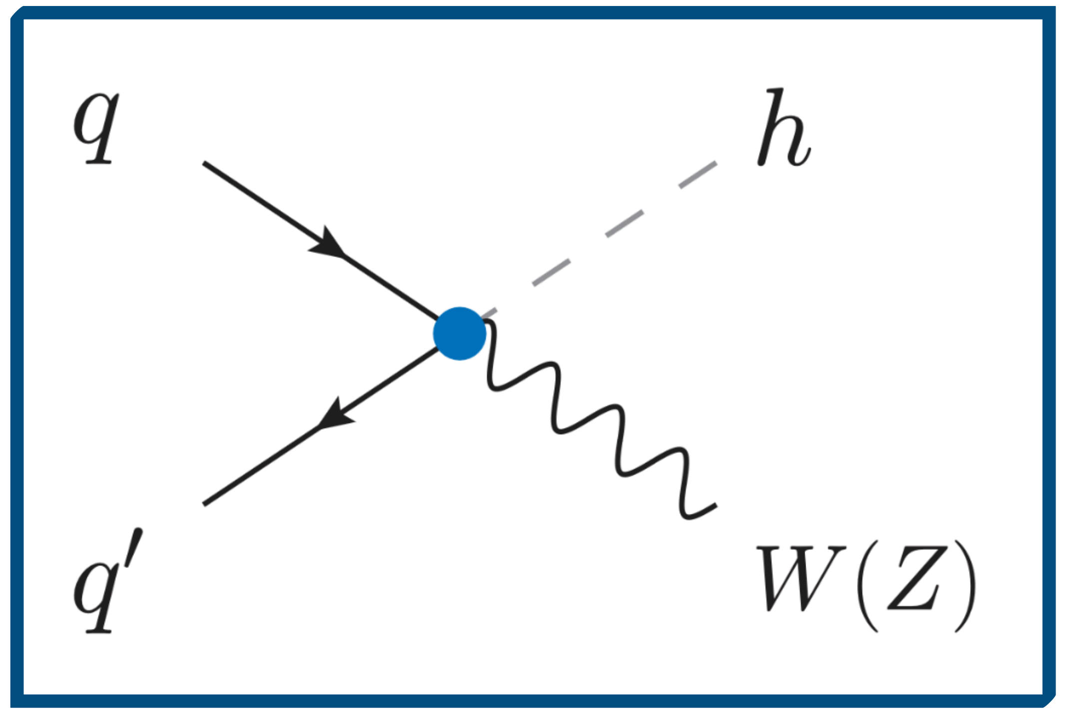
$$\psi^2 H^2 D: \ \mathcal{M}^{(6)}(qq' \to hV) \sim E^2/\Lambda^2$$

Already pointed out by S. Alioli, V. Cirigliano *et al.* [1703.04751]

Using the Higgs **Signal Strengths** measurements.

$$\frac{\sigma(pp \to Vh) \times B^{h\to X}}{(\sigma(pp \to Vh) \times B^{h\to X})_{\text{SM}}}$$

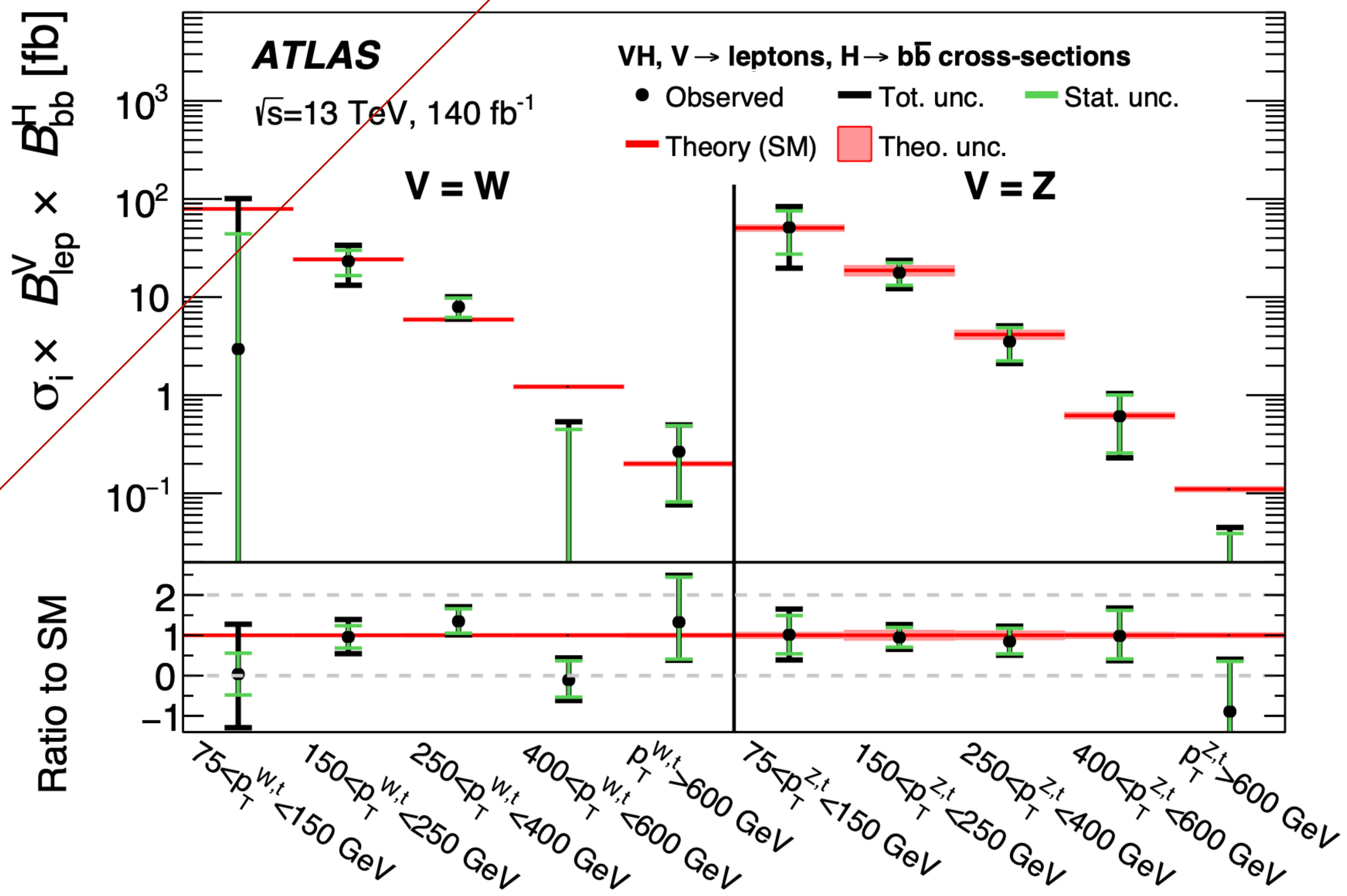
STXS data for Vh production



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

Limits extracted using STXS data can be a factor of 10 stronger compared with those from SS data. CMS Collaboration [2411.16907]

ATLAS Collaboration [2410.19611]



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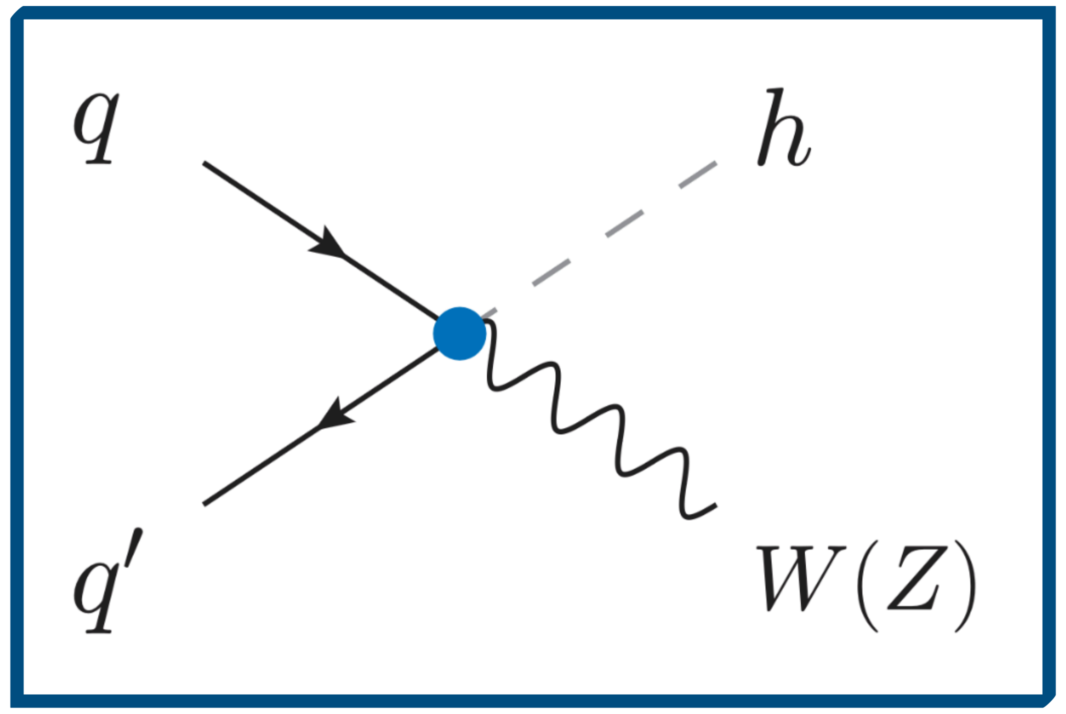

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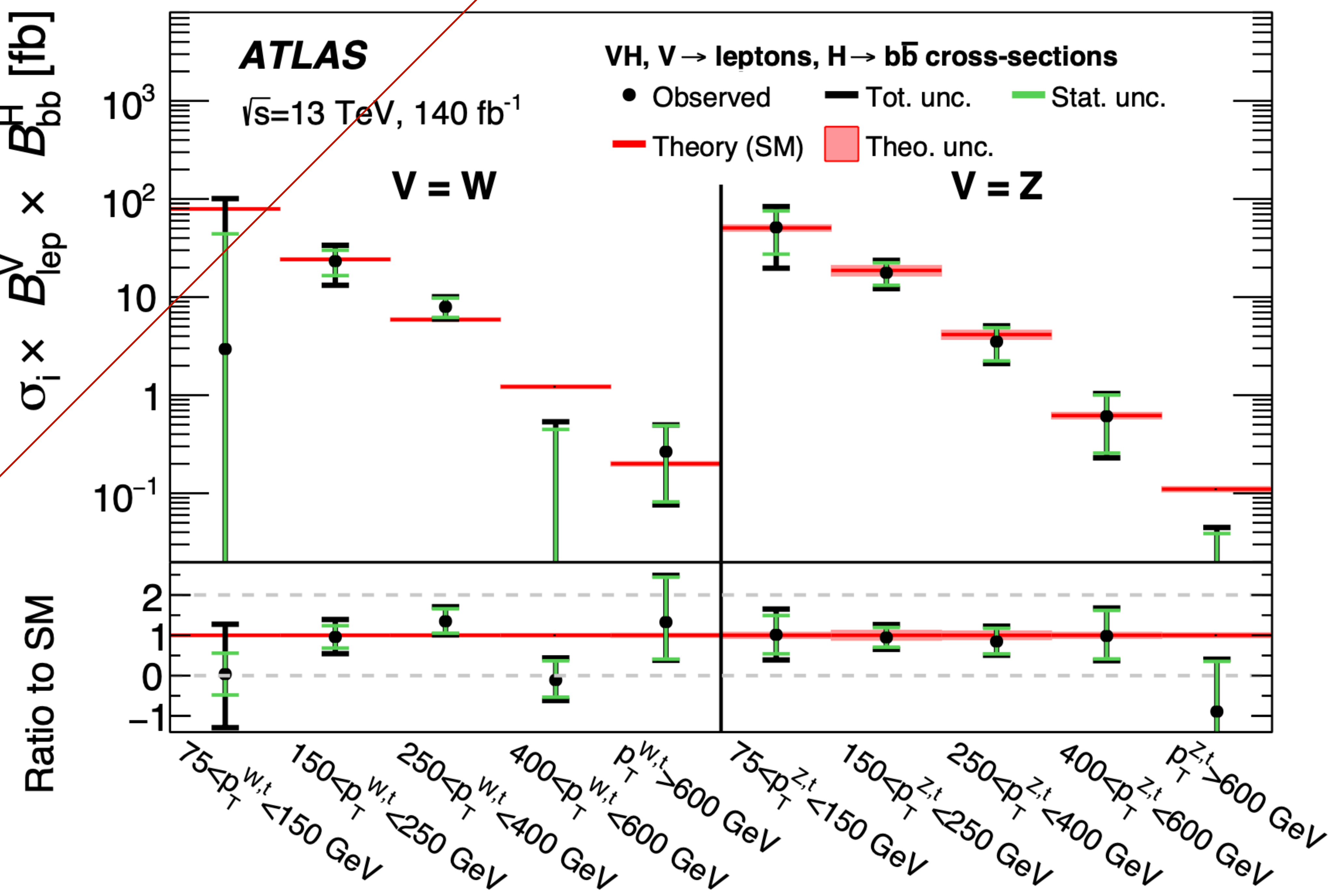
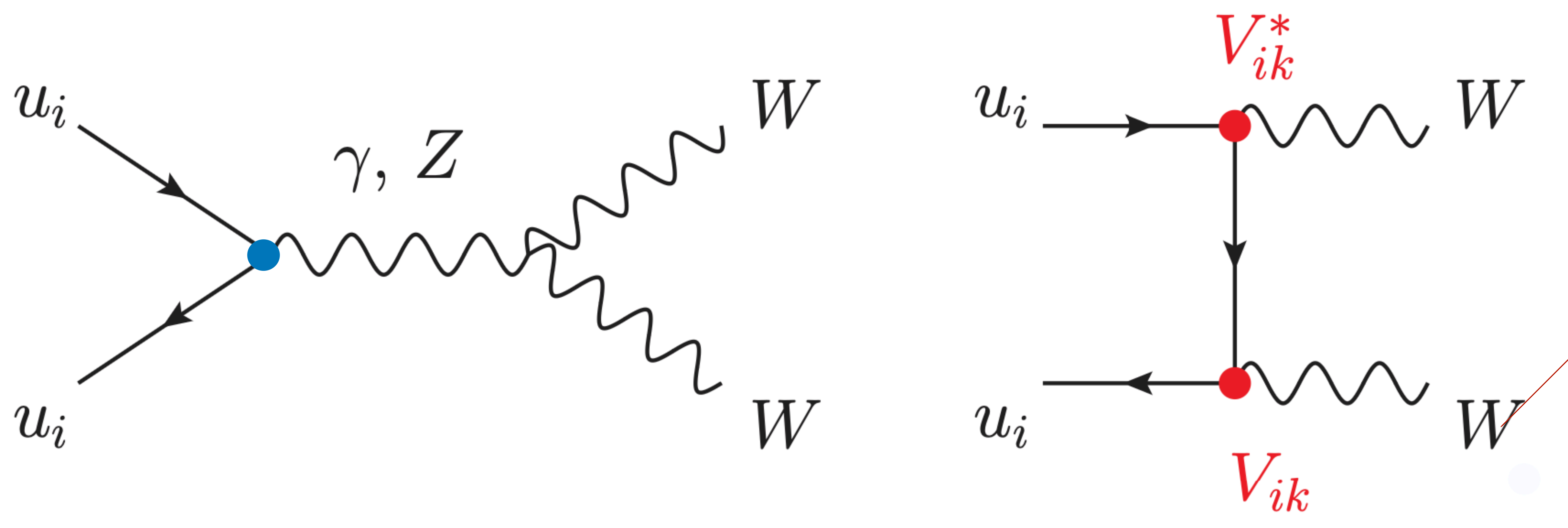


$W_L V_L$ **production** presents the same high-energy behavior.

Diboson production



CKM is unitary

SM prediction for W_0W_0 production

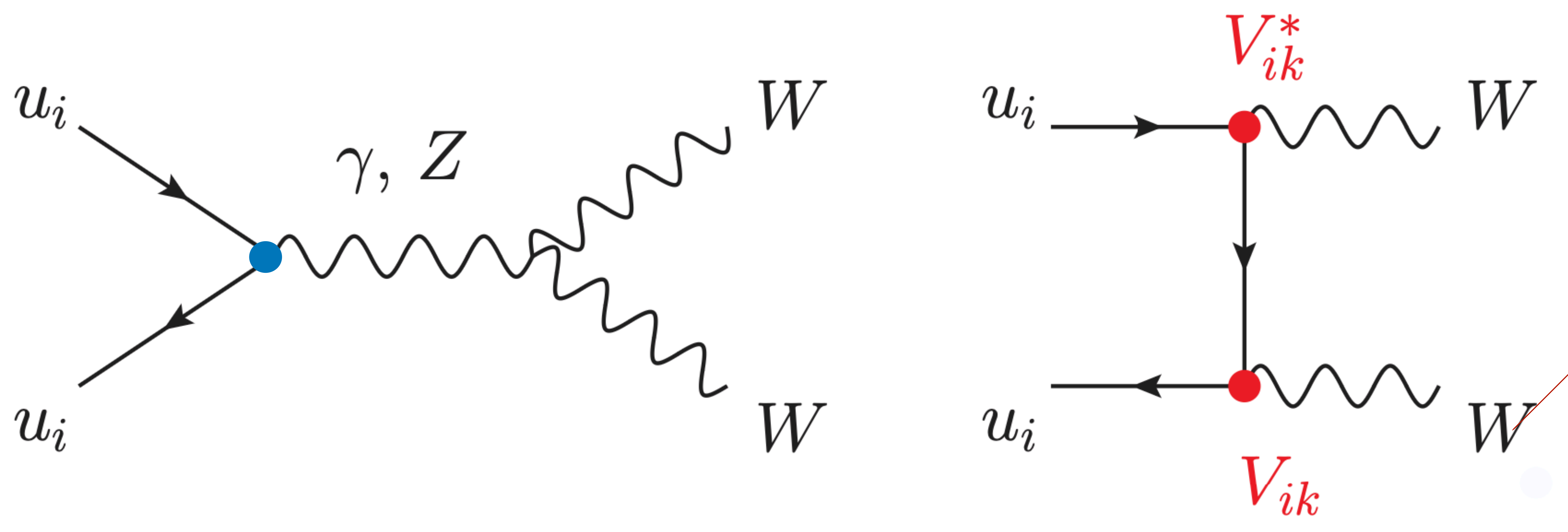
$$\mathcal{M}(u_i\bar{u}_j \to W_0W_0) \overset{\text{SM}}{=} i\widehat{S}\,\frac{e^2\sin\theta}{2m_W^2}\left[Q_q\,\delta_{ij} + \frac{1}{s_W^2}(T_q^3 - s_W^2 Q_q)\,\delta_{ij} - \frac{T_q^3}{s_W^2}(V^\dagger\cdot V)ij\right] + \mathcal{O}(\hat{s}^0)\,,$$

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

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

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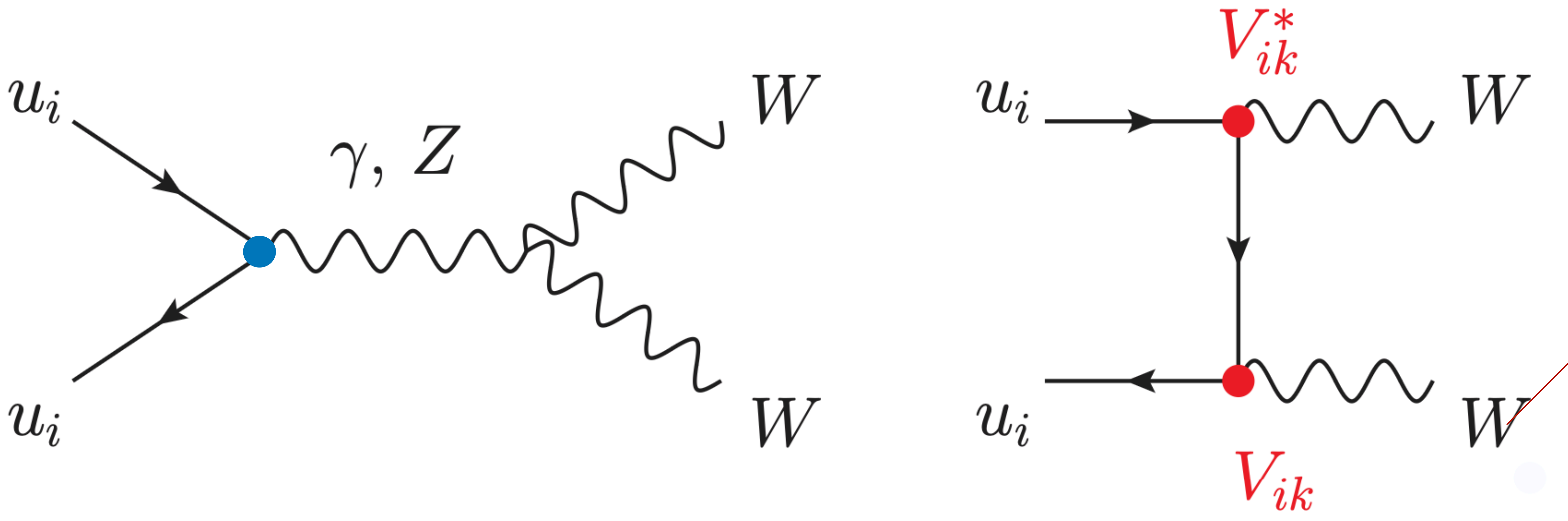

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SM prediction for W_0W_0 production

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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**

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]

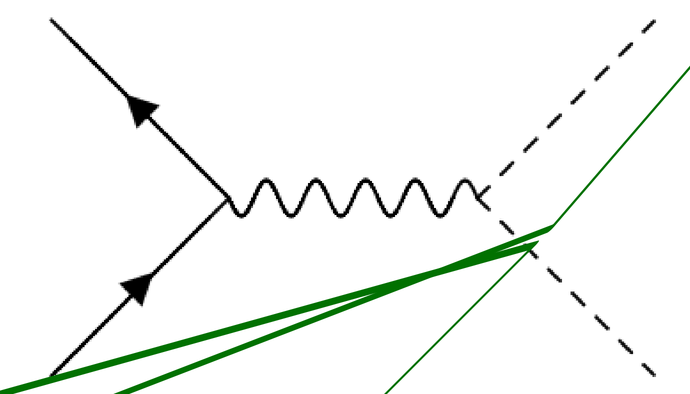
High-energy amplitudes

Goldstone Boson Equivalence Theorem

In the limit $\hat{S} \gg m_W^2, m_Z^2$ $\qquad \mathcal{M}(qq' \to V_0 V_0') \sim \mathcal{M}(qq' \to \phi\phi')$

GBs

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]



SM case

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

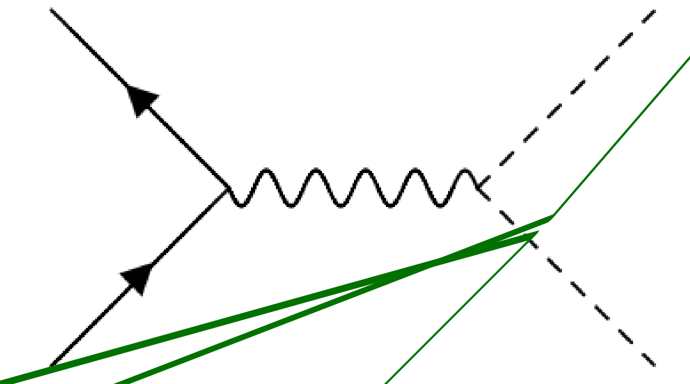
High-energy amplitudes

Goldstone Boson Equivalence Theorem

In the limit $\widehat{S} \gg m_W^2,\, m_Z^2$ $\qquad \mathcal{M}(qq' \to V_0 V_0') \sim \mathcal{M}(qq' \to \phi\phi')$

GBs

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]



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At dimension $d = 6$, for neutral processes

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

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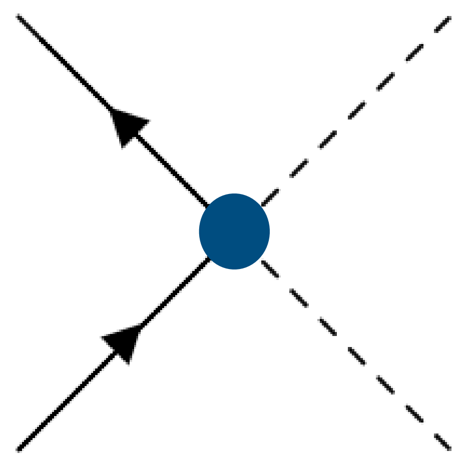
Weak basis



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

$\mathcal{C}^{(1\pm3)}_{Hq} = \mathcal{C}^{(1)}_{Hq} \pm \mathcal{C}^{(3)}_{Hq}$ $\quad$ *WW* and *Zh* probe the **same combination** of couplings.

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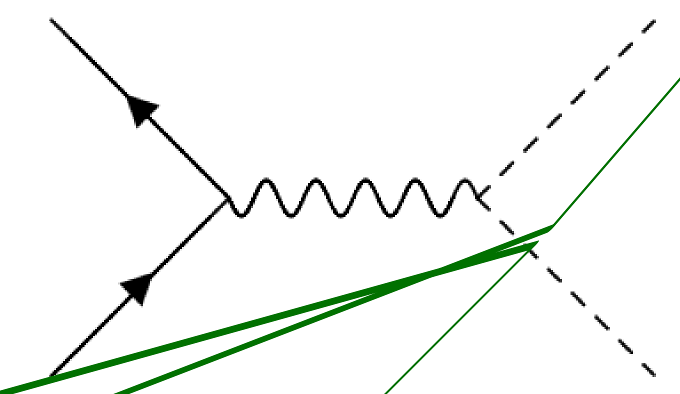

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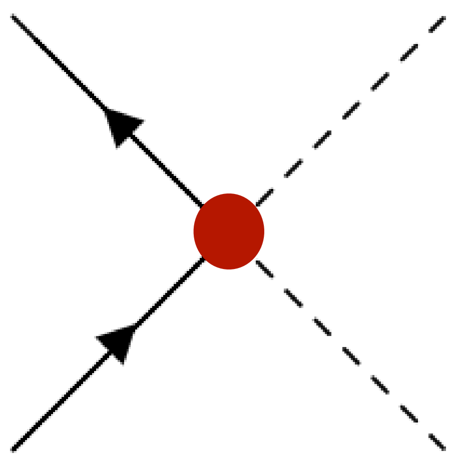

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WZ and Wh probe the **same combination** of couplings.

LHC distributions

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

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

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

MadGraph@NLO

↓

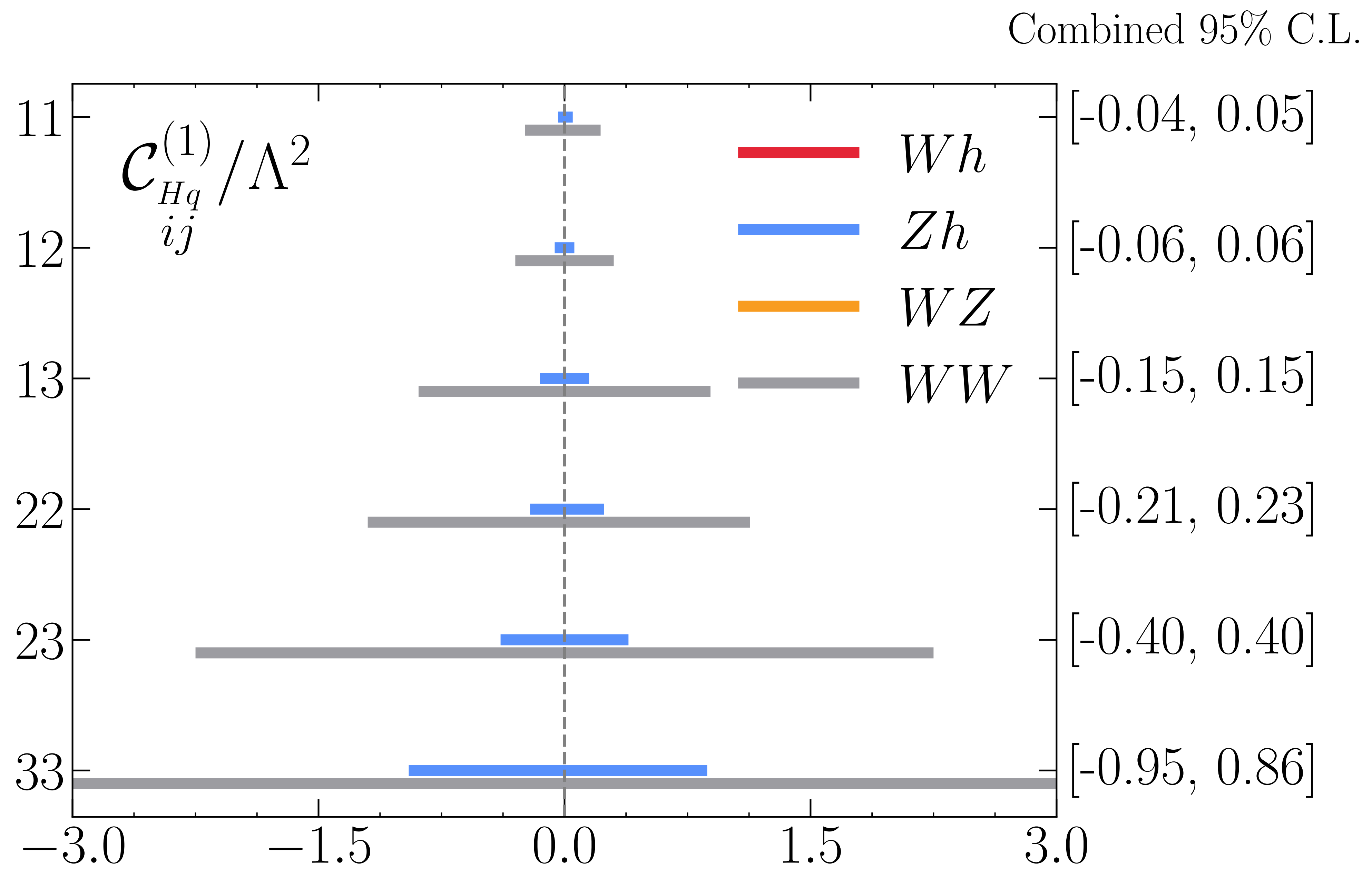
Pythia8

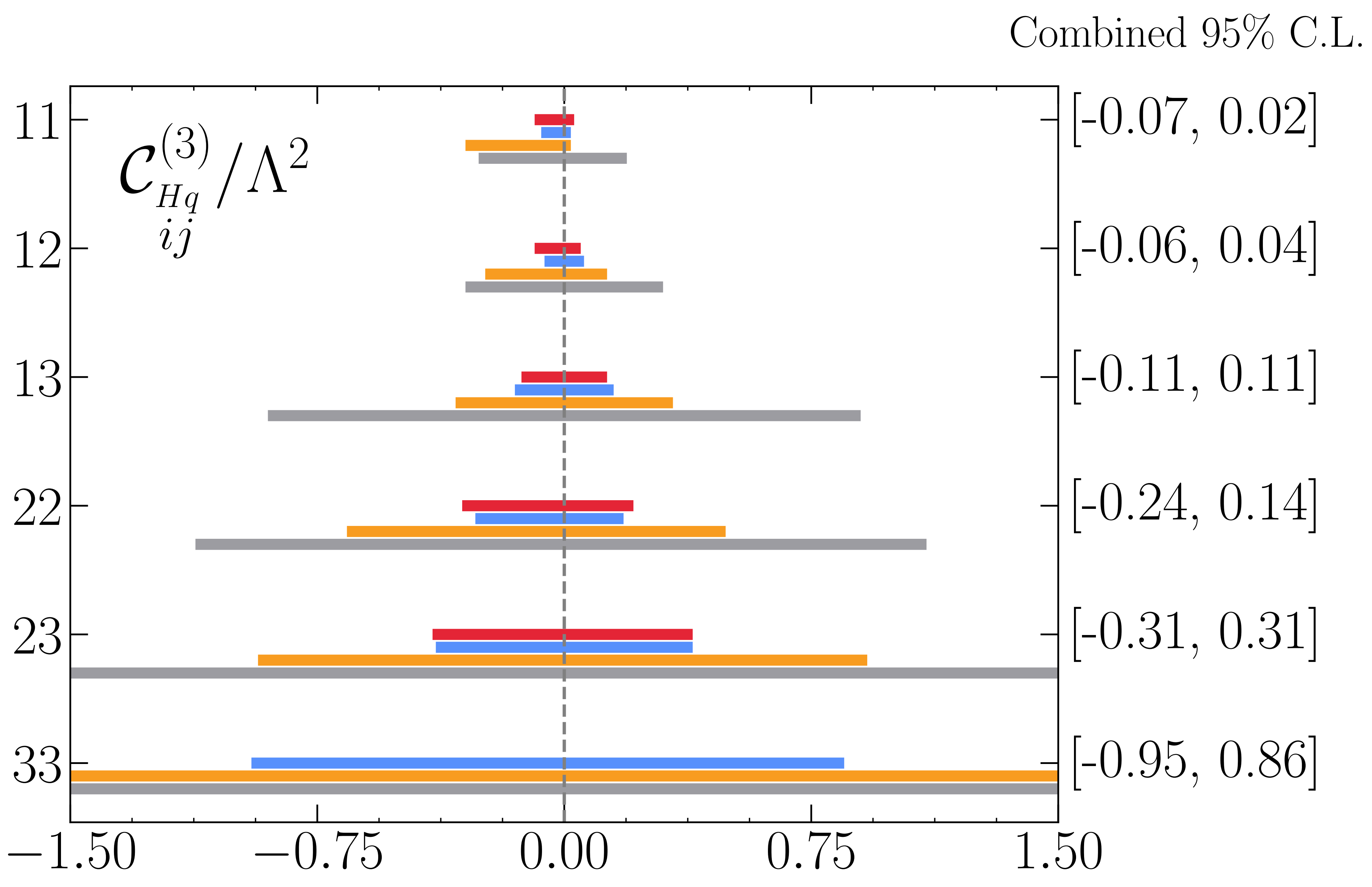
↓

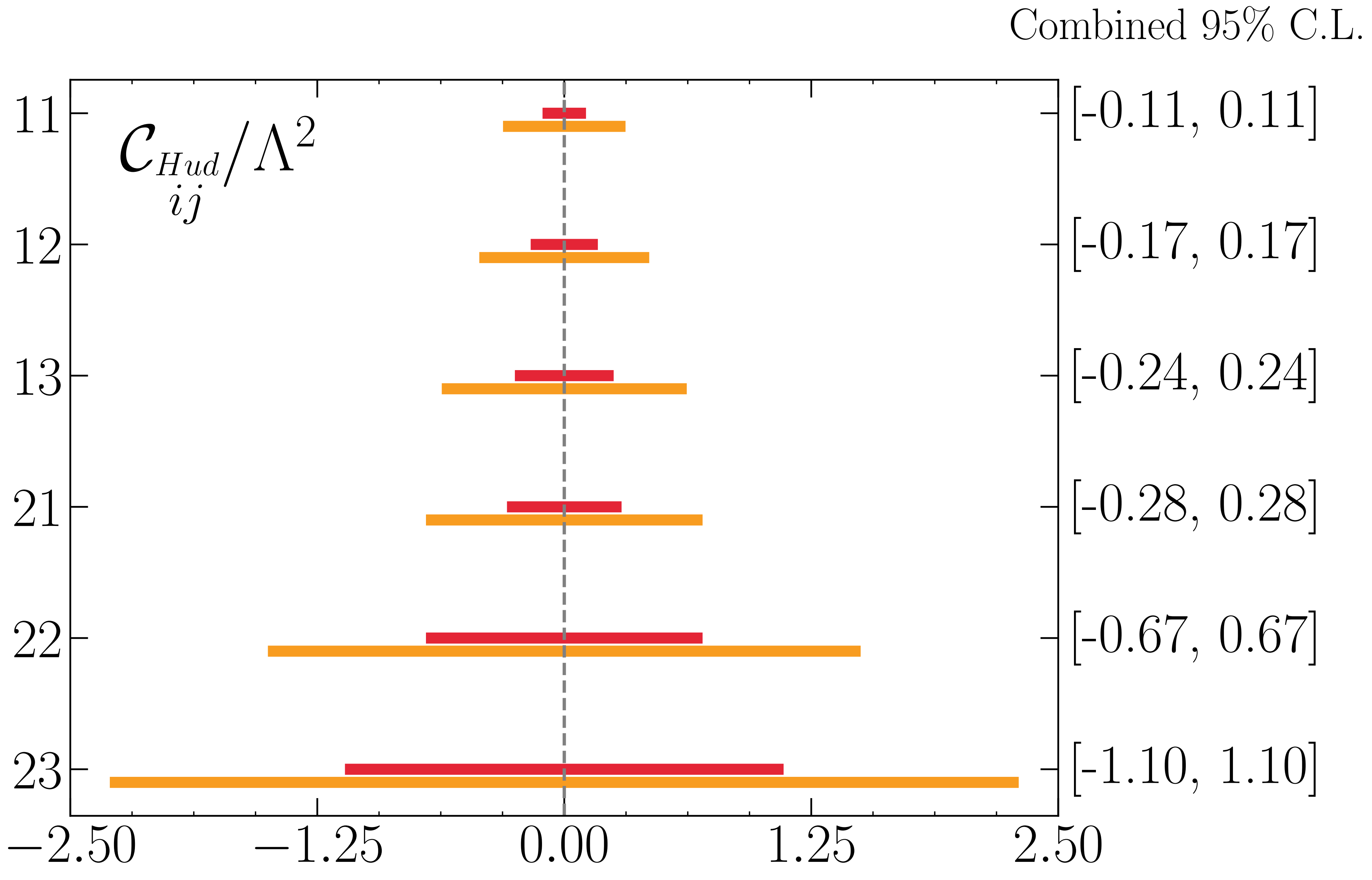
Delphes

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

Single parameter limits (preliminary)



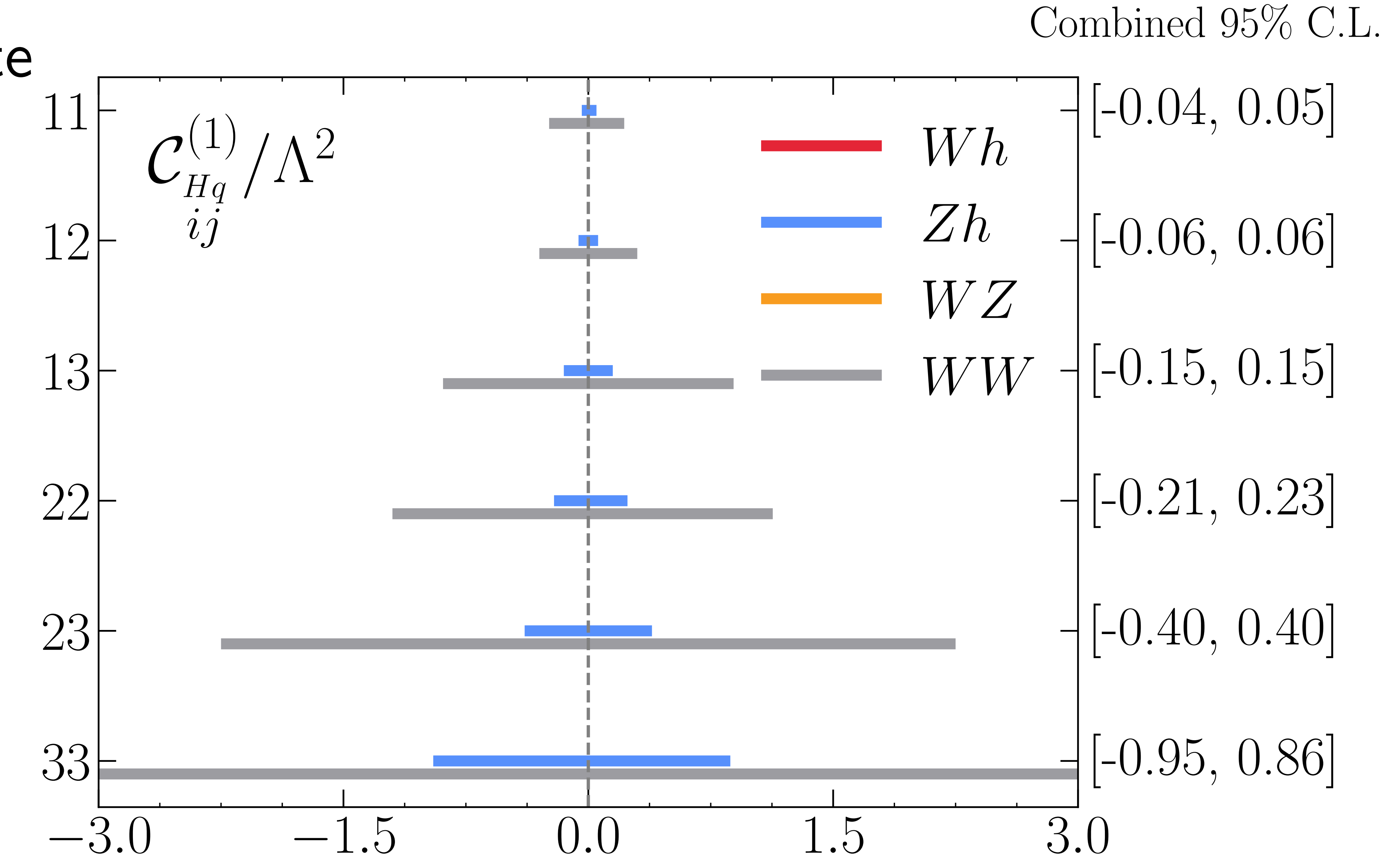


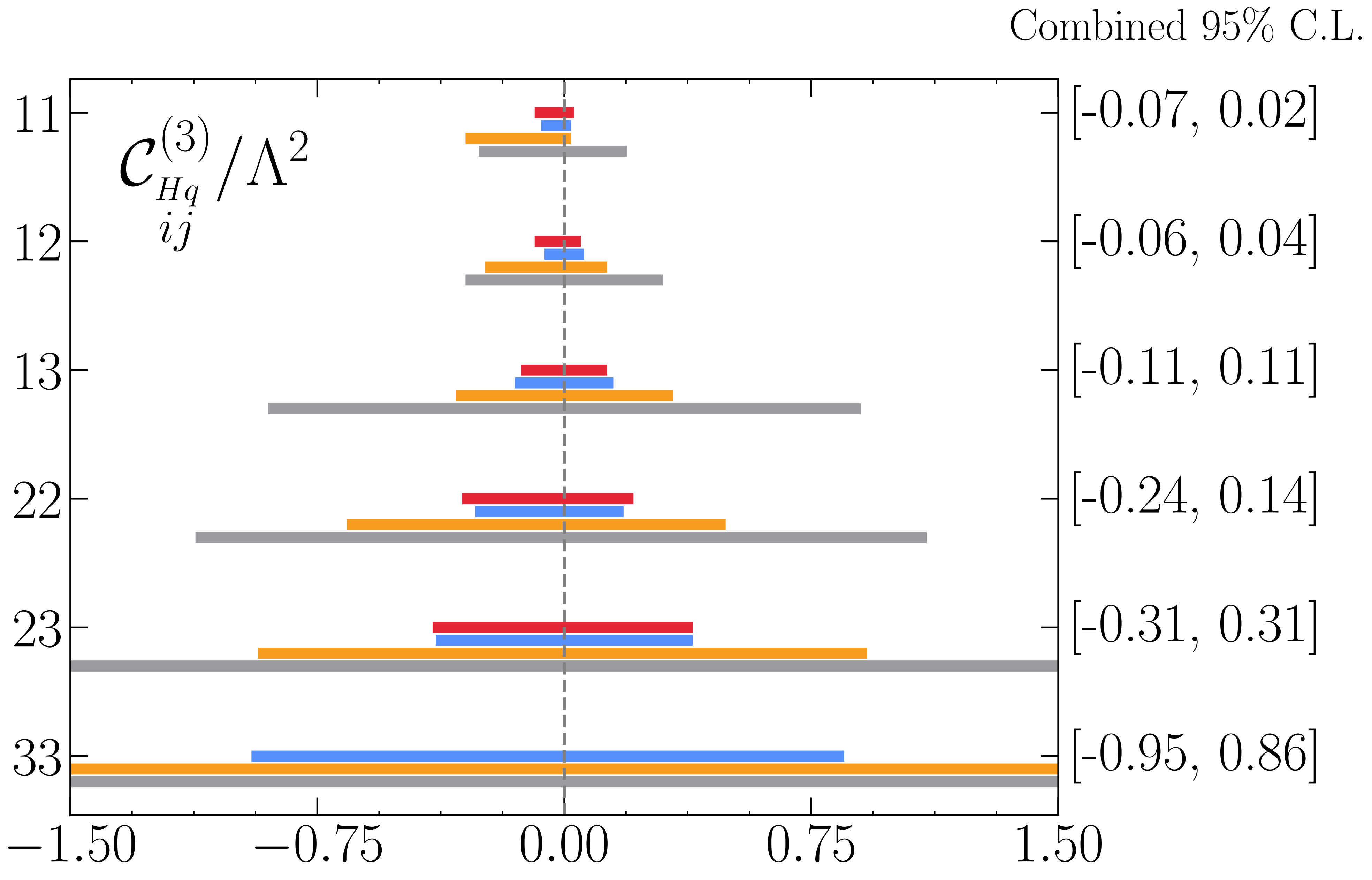


$$\sigma = \sigma_{\text{SM}} + \frac{1}{\Lambda^2}\sigma_{\text{Int}} + \frac{1}{\Lambda^4}\sigma_{\text{NP}^2}$$

Single parameter limits (preliminary)

Initial state masses

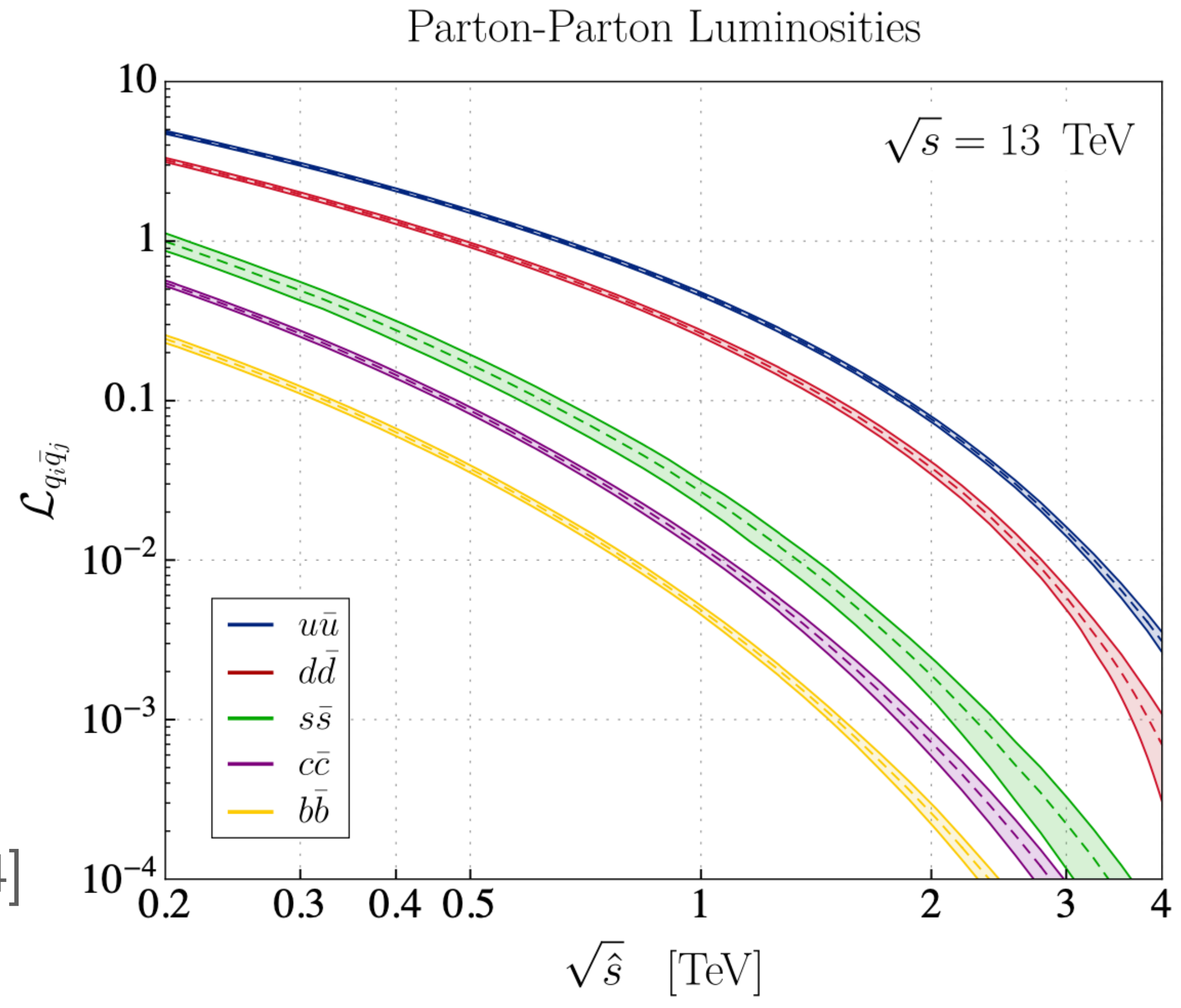




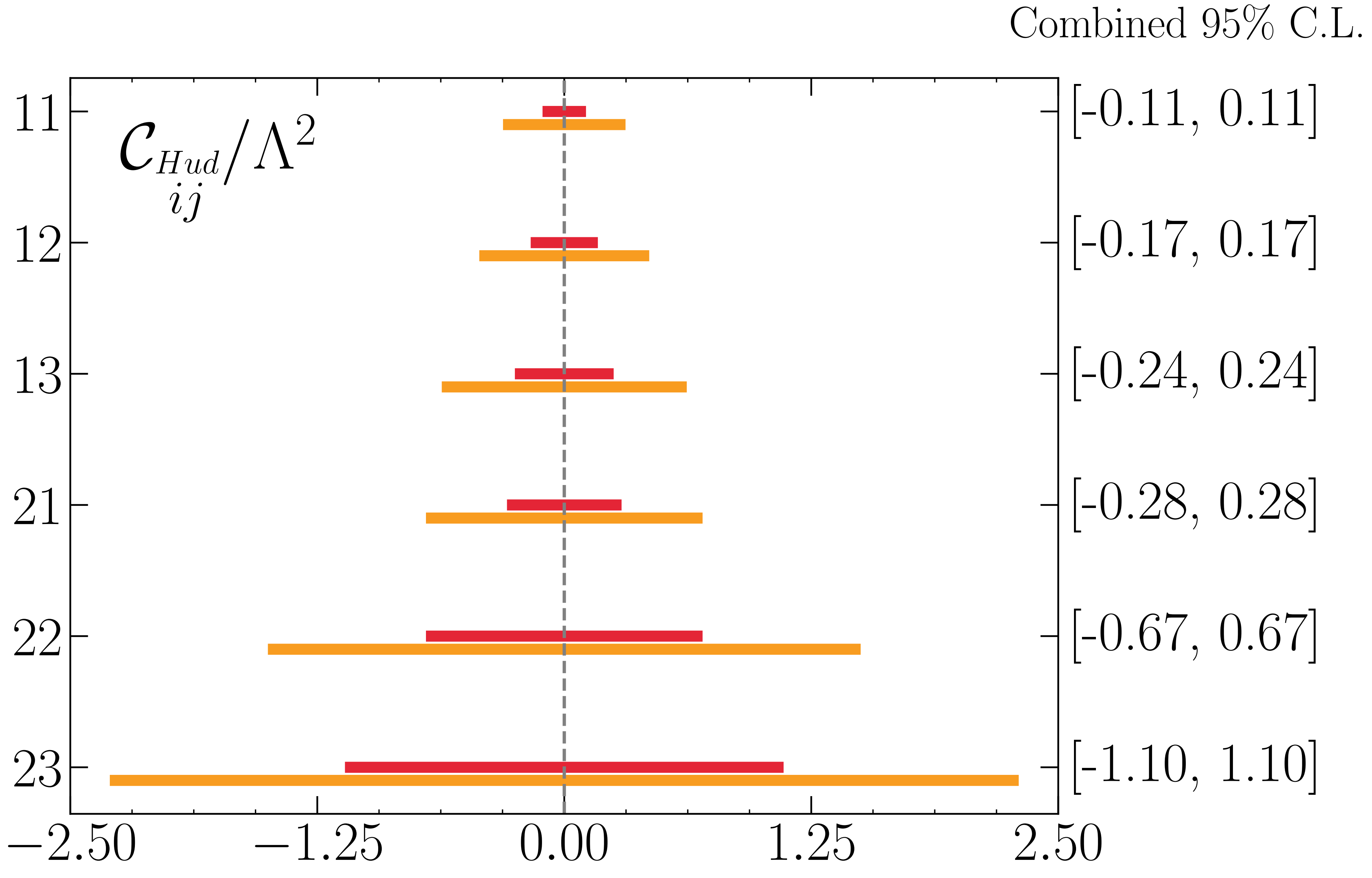
Heavier initial states lead to **weaker** constraints.

PDF suppression.

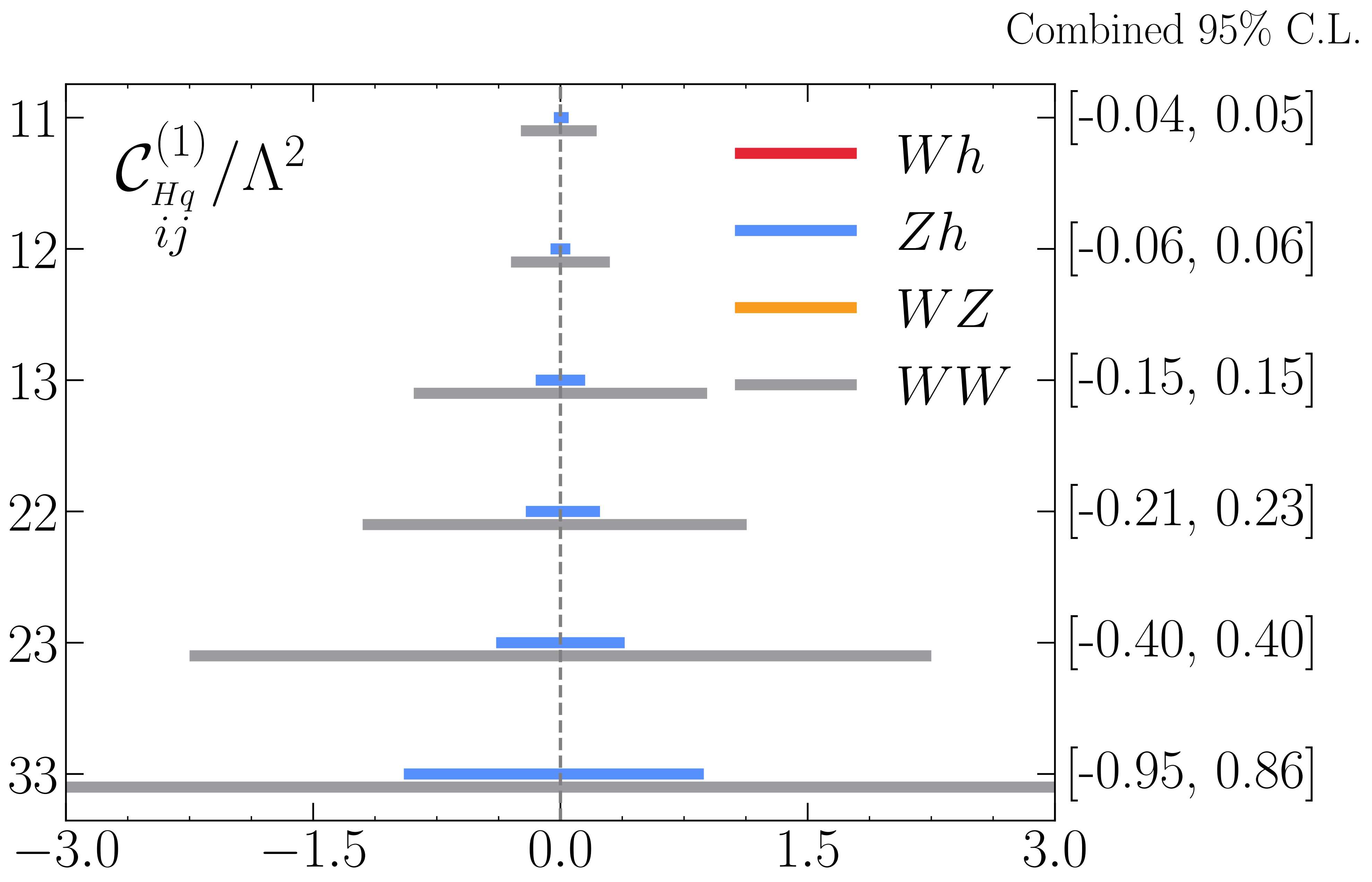
Quark mass

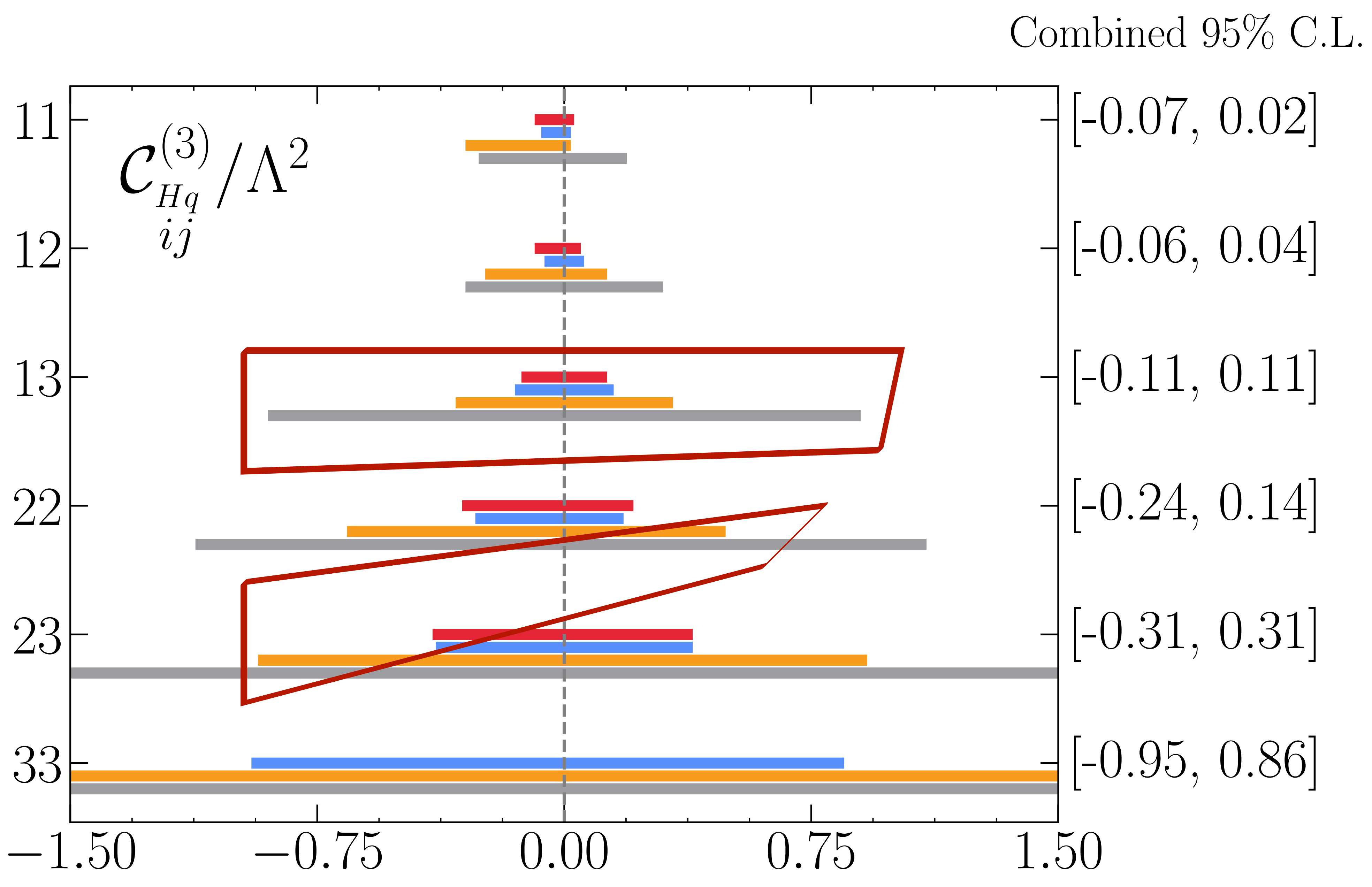


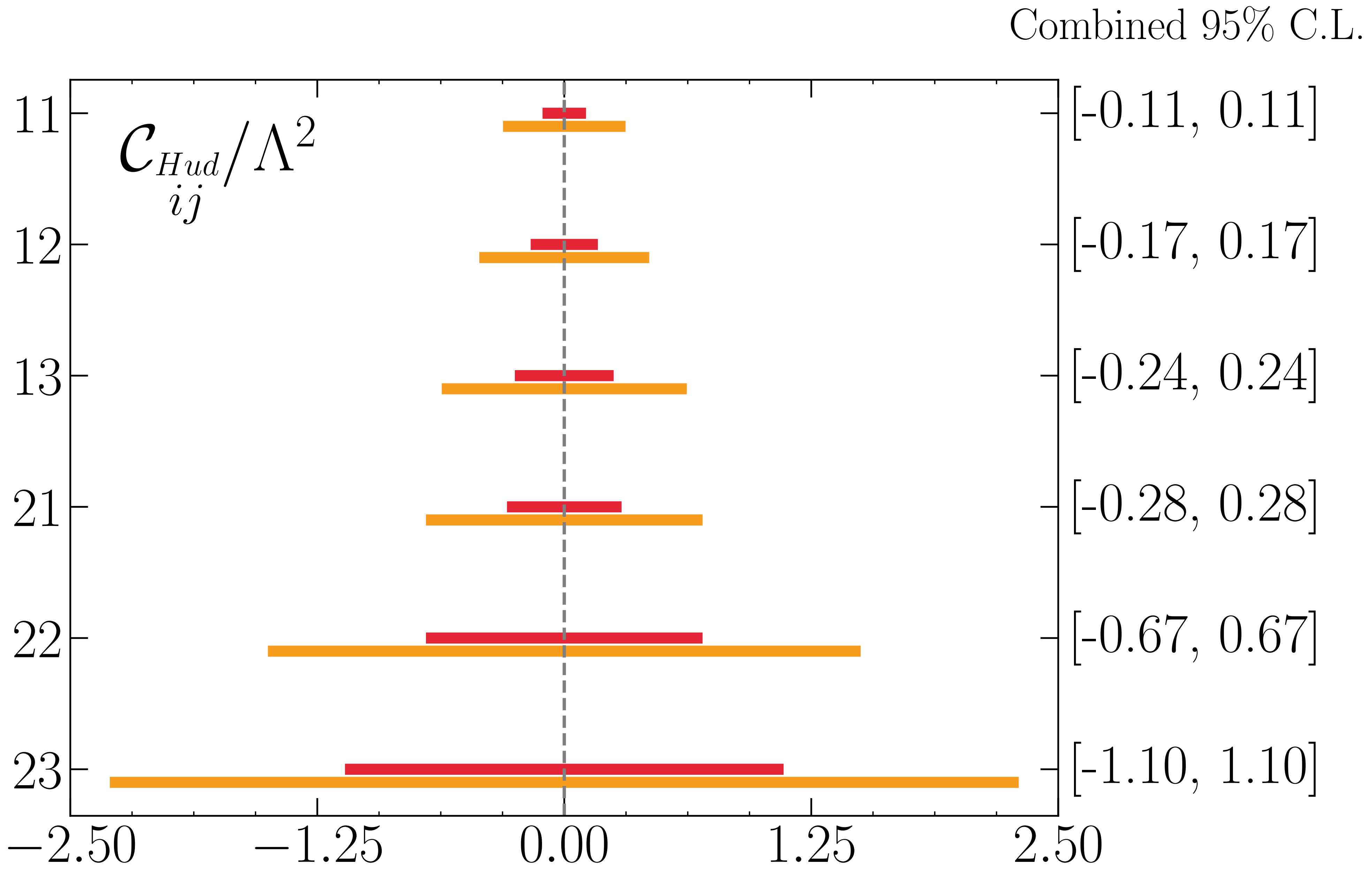
Angelescu *et al.* [2002.05684]



Single parameter limits (preliminary)





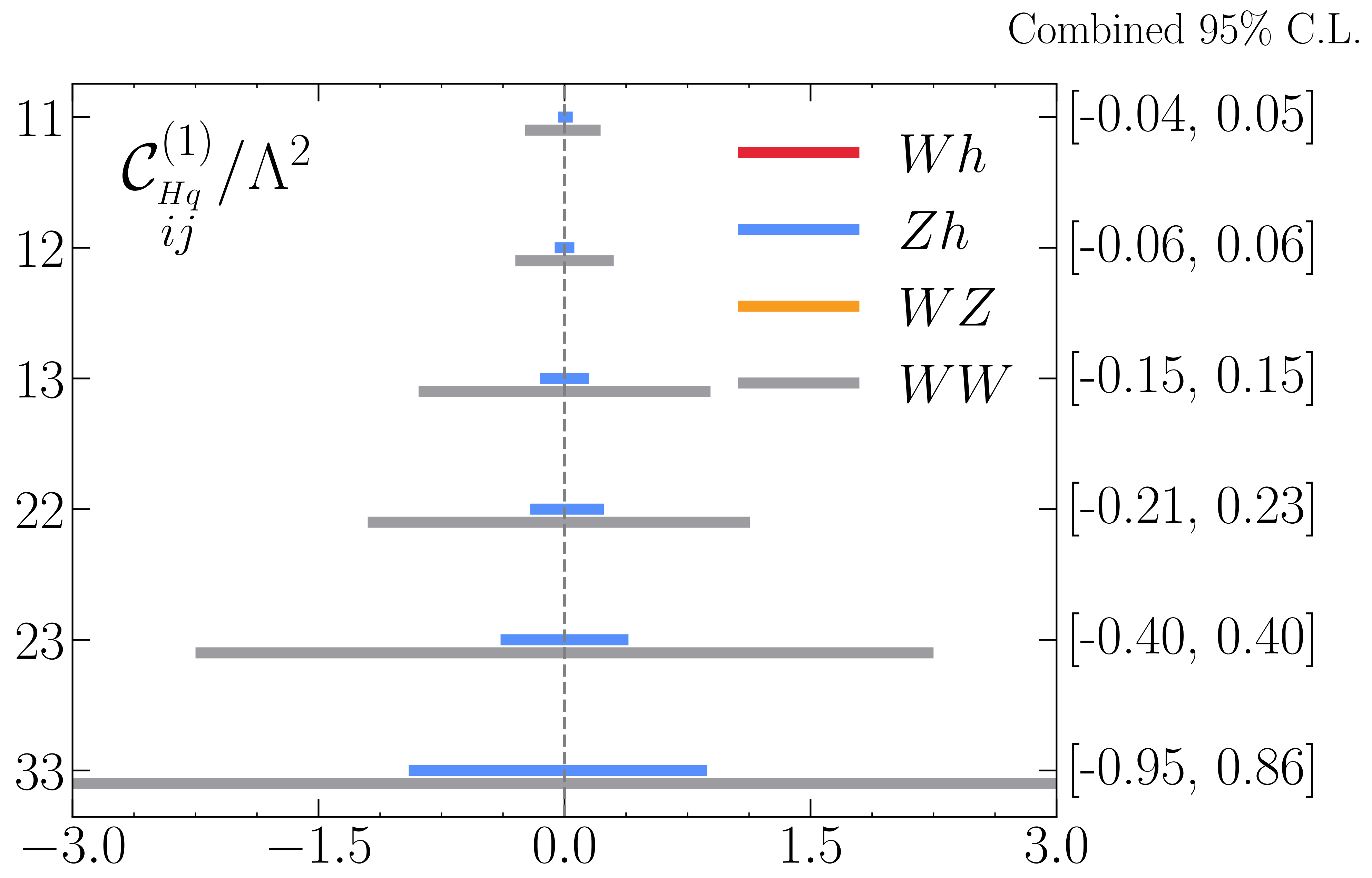


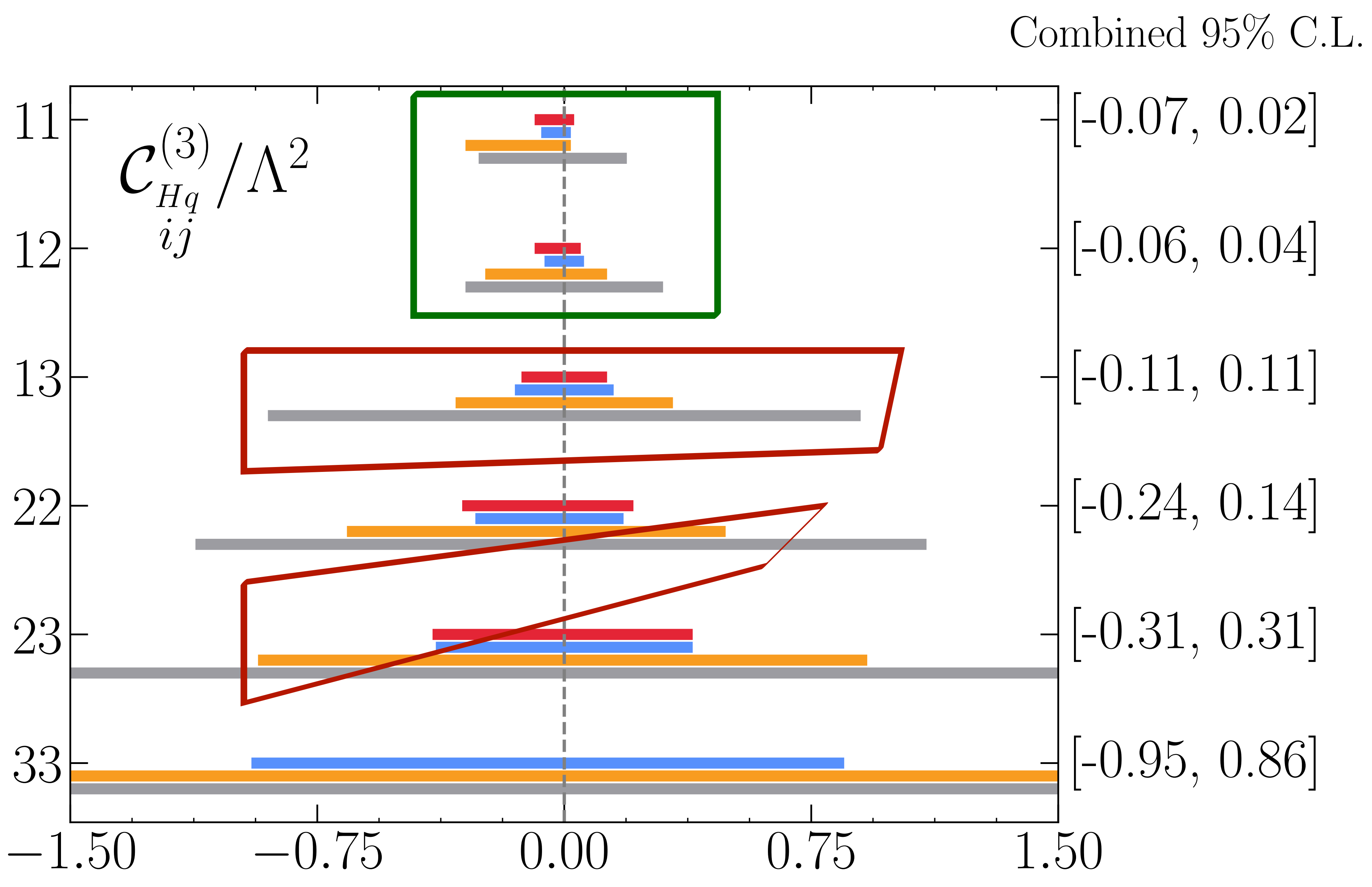
For initial states with **heavy and different-flavor** quarks, the **quadratic** terms drive the limits.

↓

In charged channels, the interference term suffers from **PDF** and **CKM** **suppression**.

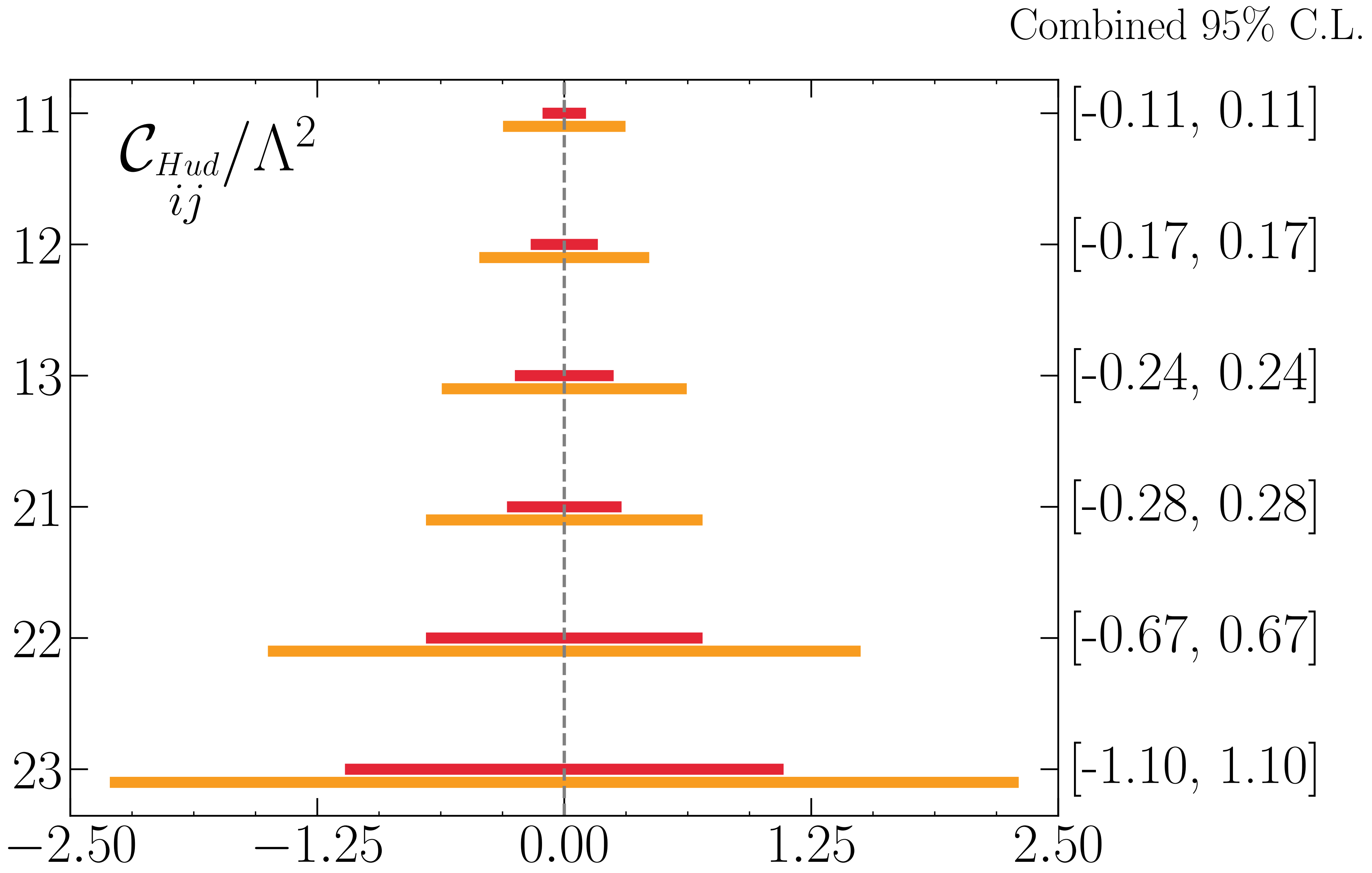
Single parameter limits (preliminary)





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

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



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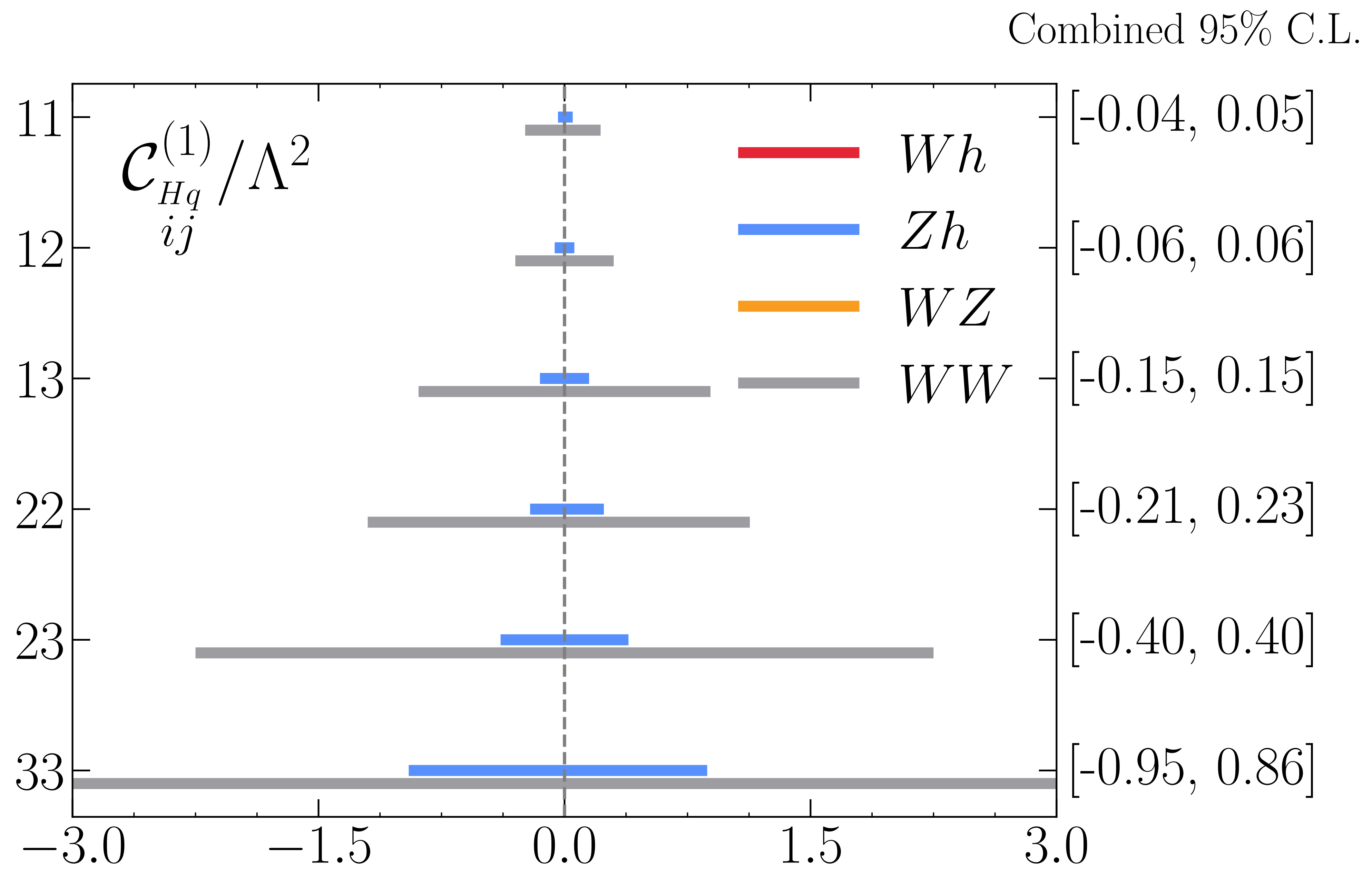
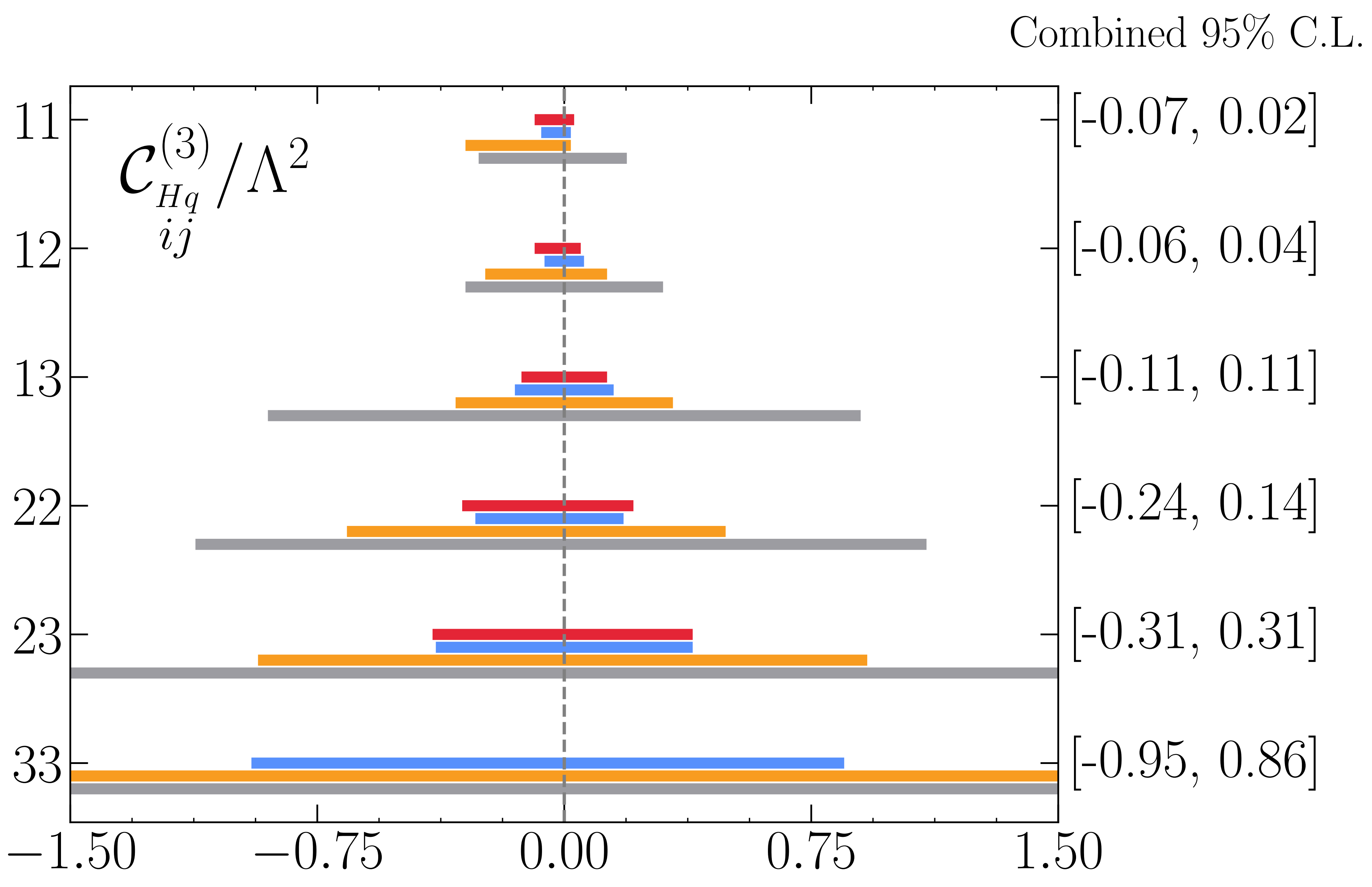
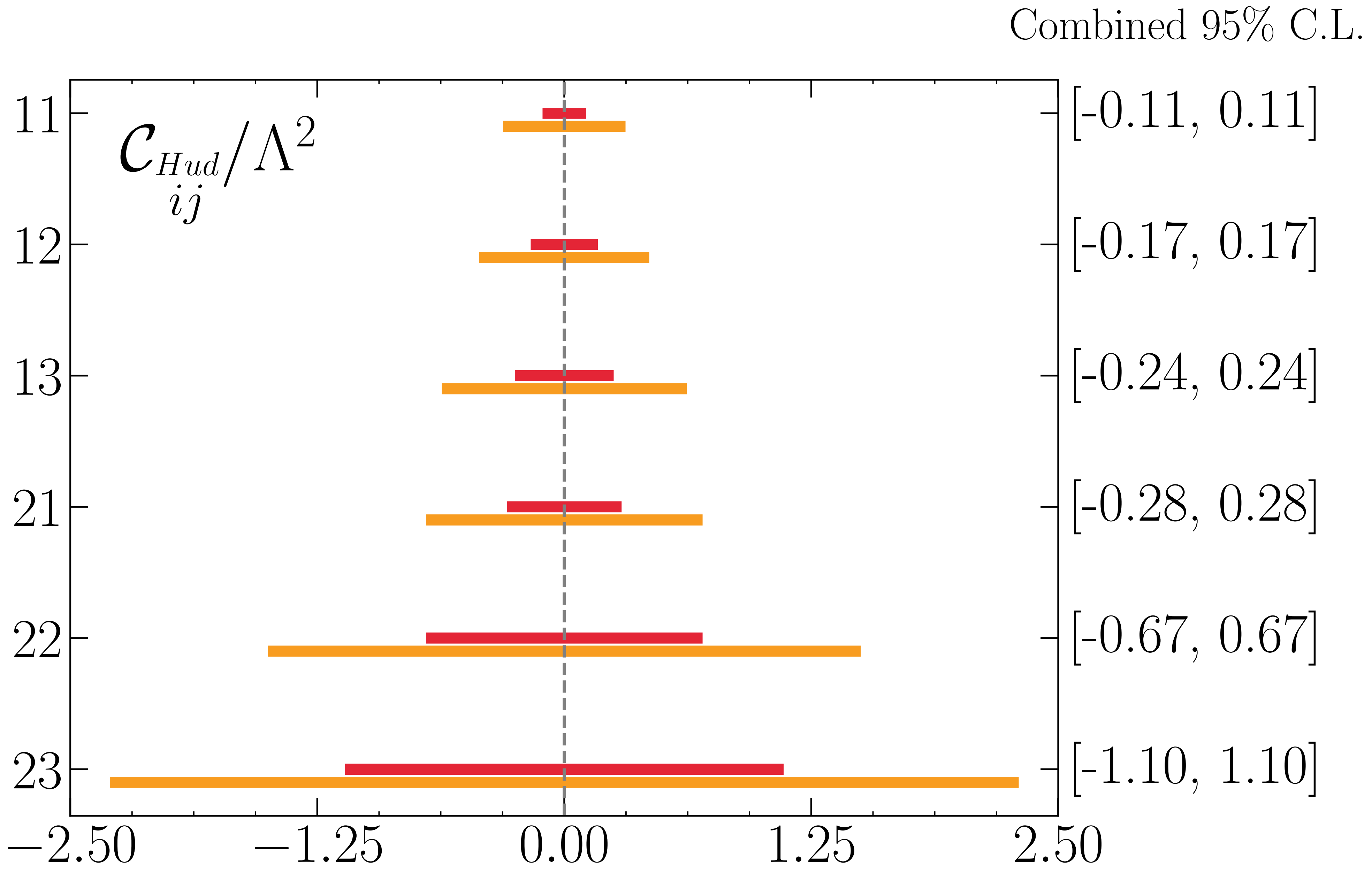
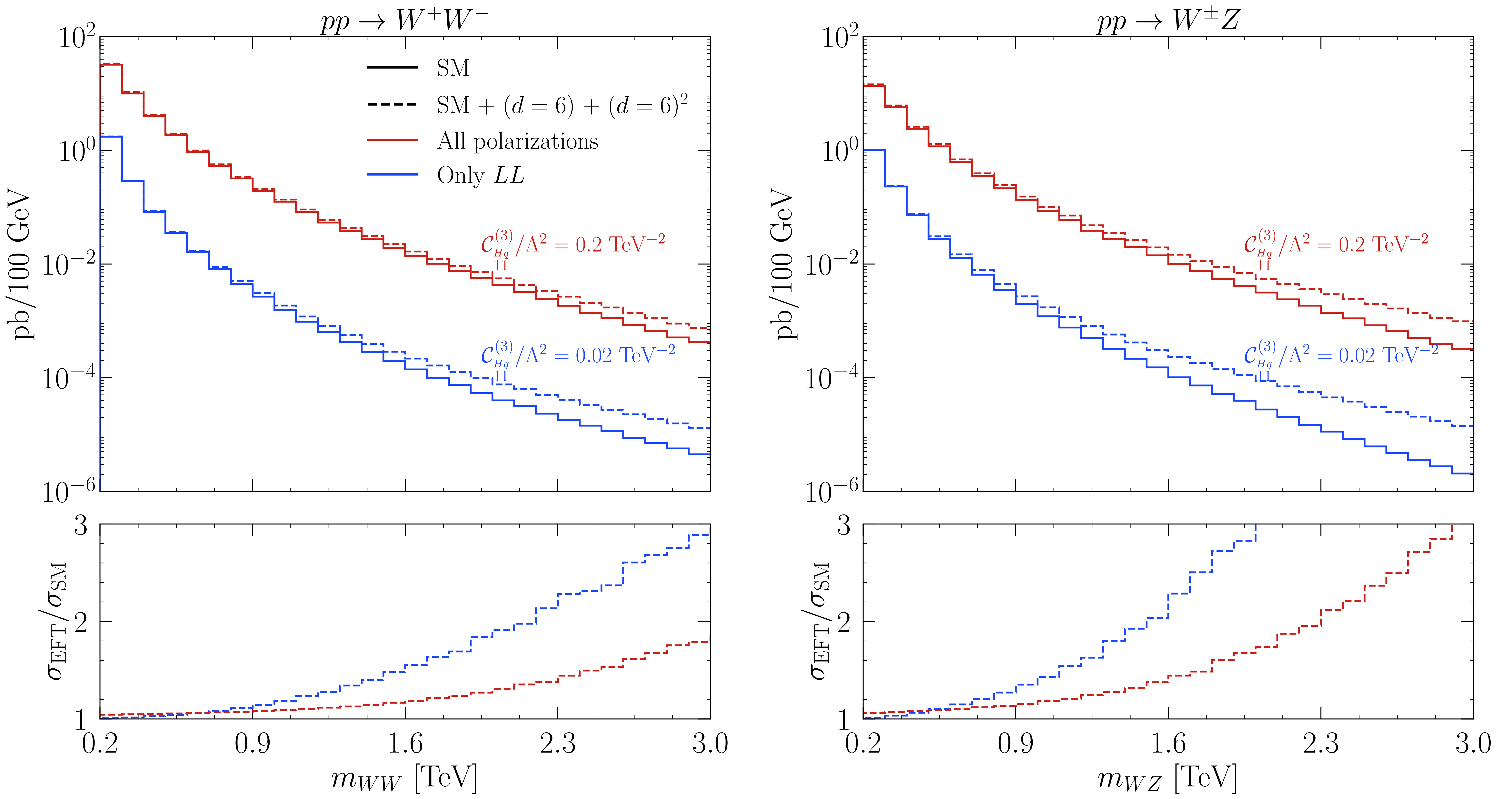






Limits from Vh are **stronger** than WV at the moment.

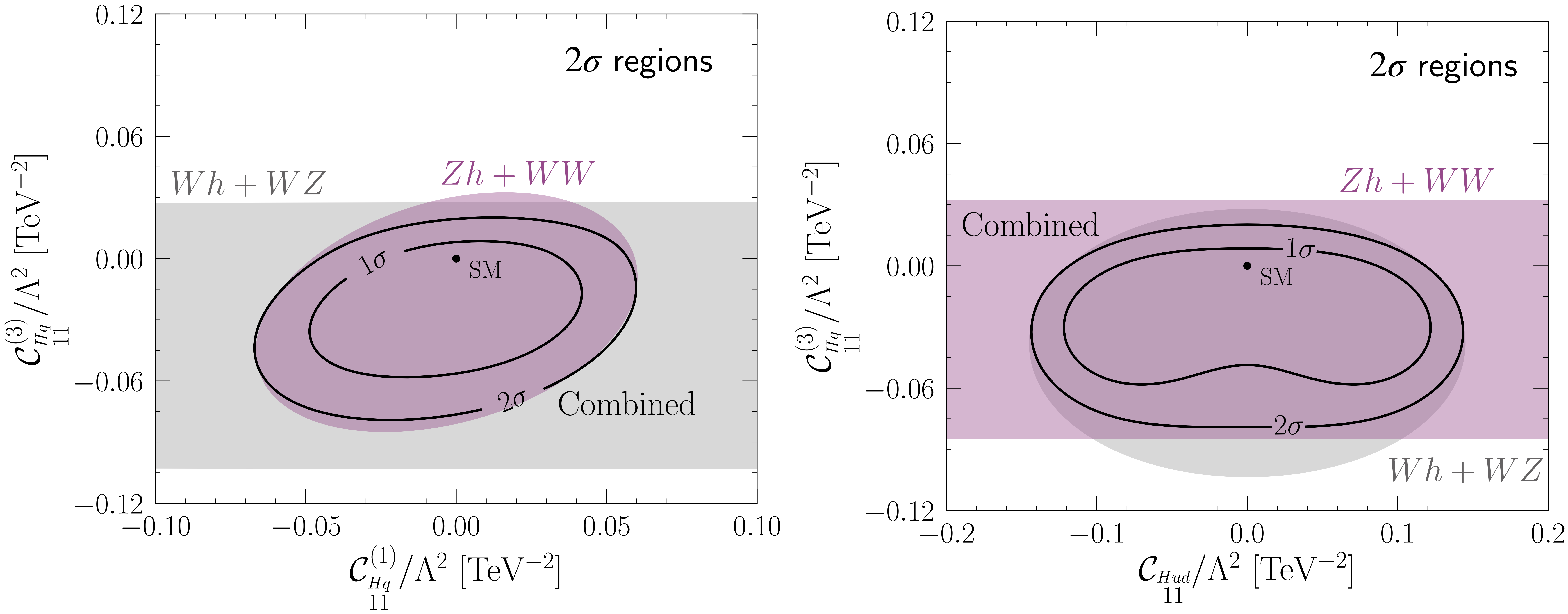
Parton-level distributions



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

R. Franceschini *et al.* [1712.01310]

Neutral vs. Charged channels (preliminary)



Combination of both **neutral** and **charged** processes is important to constrain the parameter space.

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.

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Thank you!