Probing flavour non-universality at colliders

David Marzocca

INFN Trieste

The Flavour Path to New Physics - Zurich - 07/06/2025

Flavour Universality

$$\mathcal{L}_{SM}^{gauge} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W^{a\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \mathcal{L}_{g.f.} + \mathcal{L}_{ghosts}$$
$$+ \bar{L}_i i\not{D} L_i + \bar{e}_{R_i} i\not{D} e_{R_i} +$$
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SM **gauge interactions** are **Flavour Universal**:

global symmetry

$$\mathbf{U(3)^5} = U(3)_L \times U(3)_e \times U(3)_Q \times U(3)_u \times U(3)_d$$

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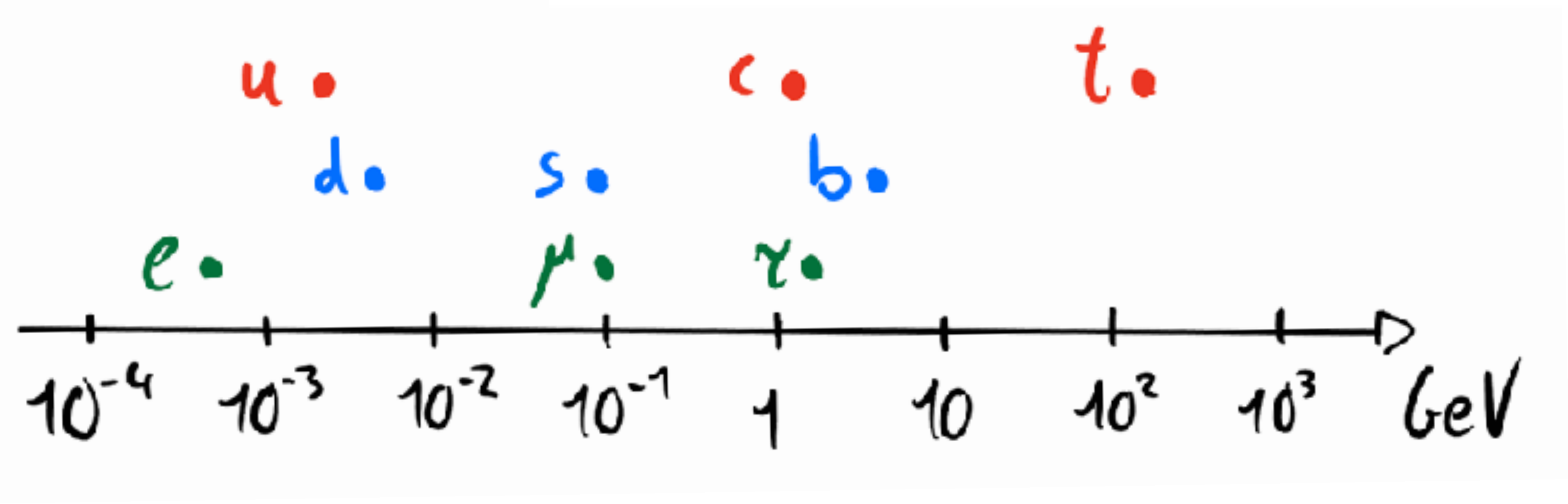
- non-zero and different fermion **masses**
- **Higgs** Yukawa interactions
- **CKM** mixing

* The chiral U(1) components are broken explicitly by anomalies. B+L component broken by non-perturbative EW instantons.

$$\mathcal{L}^{Yuk}_{SM} = - y_e^{ij} \bar{L}'_i e'_j H - y_d^{ij} \bar{Q}'_i d'_j H - y_u^{ij} \bar{Q}'_i u'_j \tilde{H} + h.c.$$



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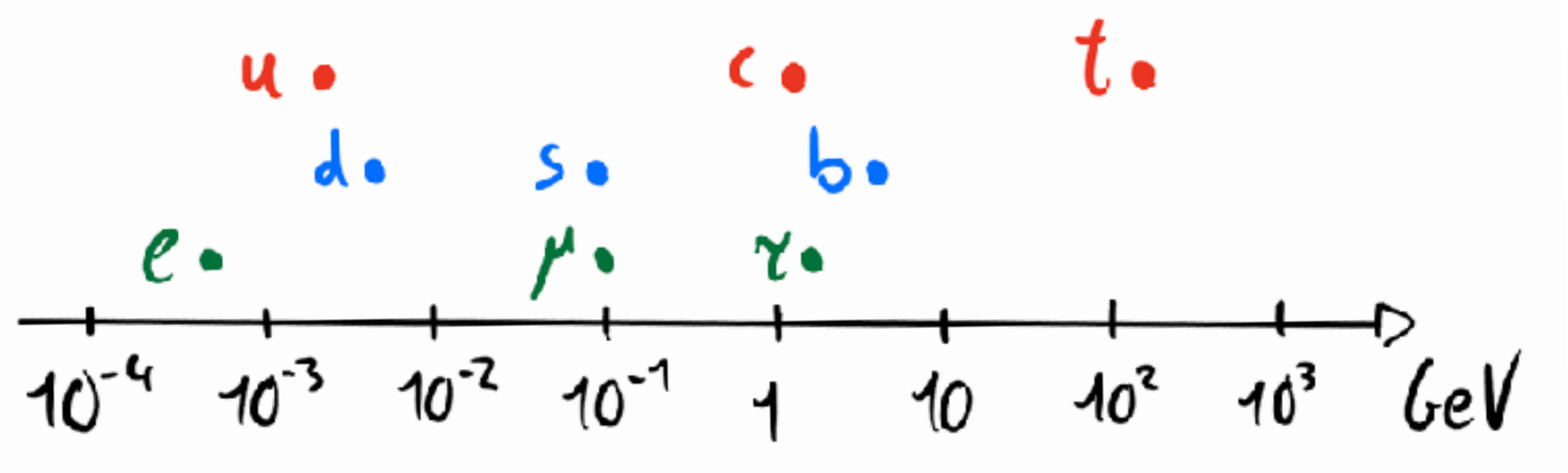

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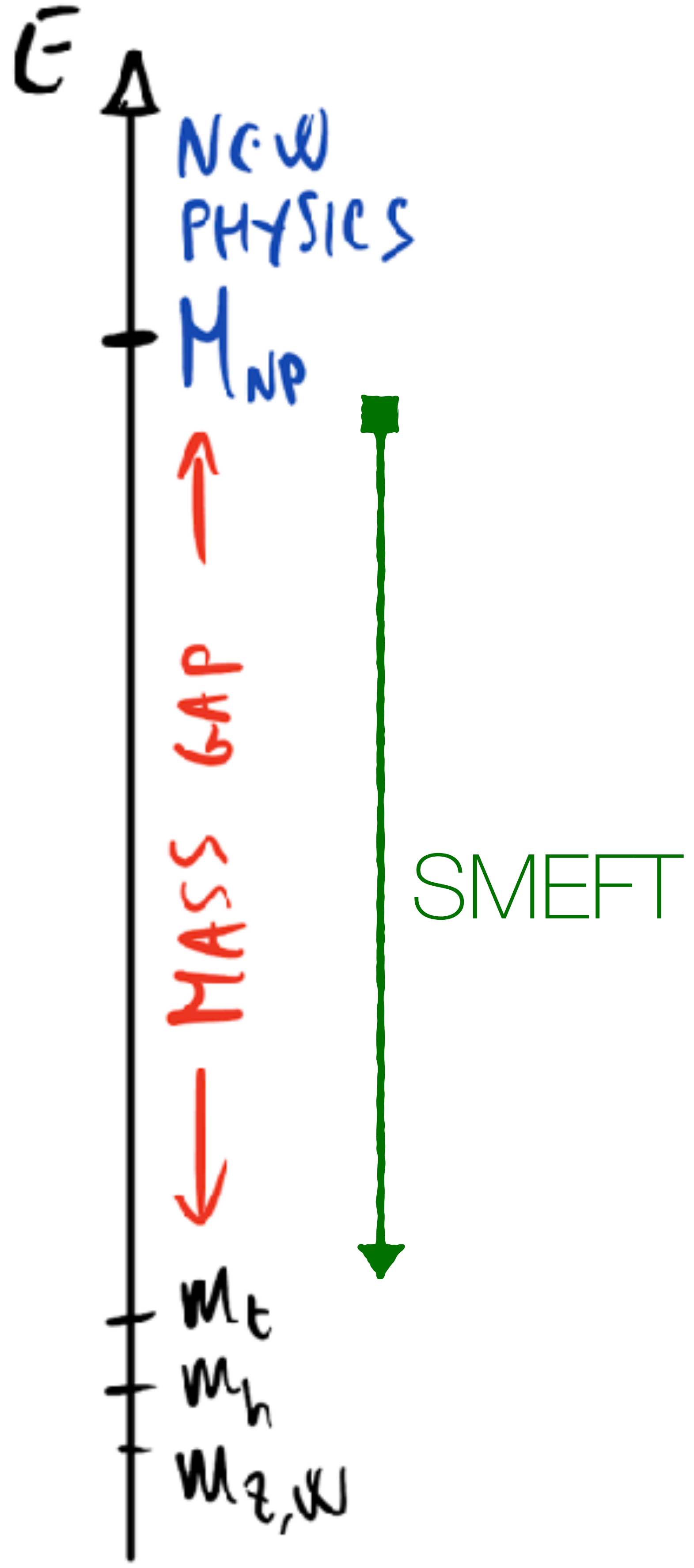
The largest breaking is due to the **top Yukawa $y_t \sim 1$:** $U(3)^5 \rightarrow U(3)^3 \times U(2)_Q \times U(2)_u$

Other breaking terms are small and can be neglected if **fermion mass** effects, **Yukawa interactions**, or **CKM mixing** give small contributions to the process in interest.

Flavour Universality and New Physics

We know that **the Standard Model must be extended at some high energy scale $\mathbf{M}$**.



If we are interested in physics at energies $\mathbf{E} \ll \mathbf{M}$ we can write the low-energy Lagrangian as a series **expanded in powers of $\mathbf{1/M}$**: the **Standard Model Effective Field Theory**.

$$\mathcal{L}^{(d=6)}_{SMEFT} = \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}[\varphi_{SM}]$$

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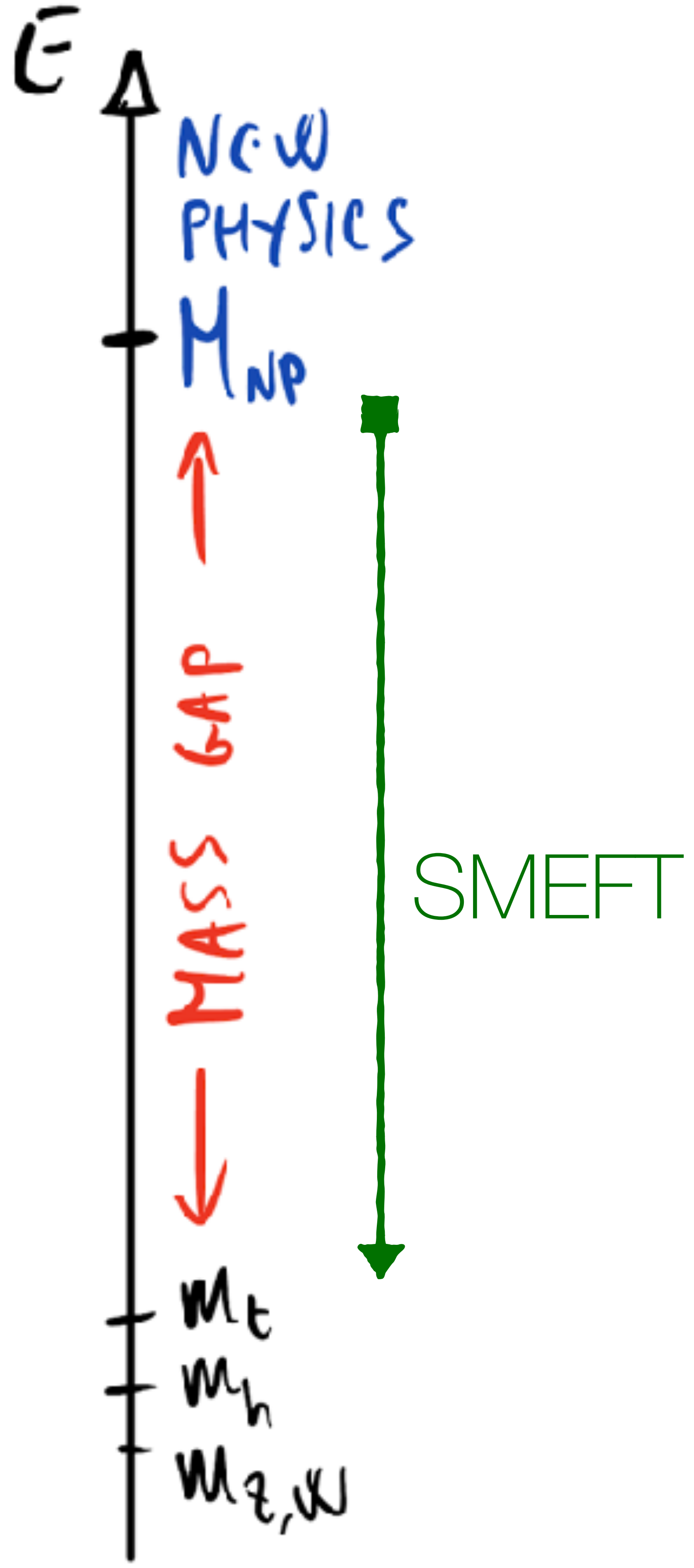

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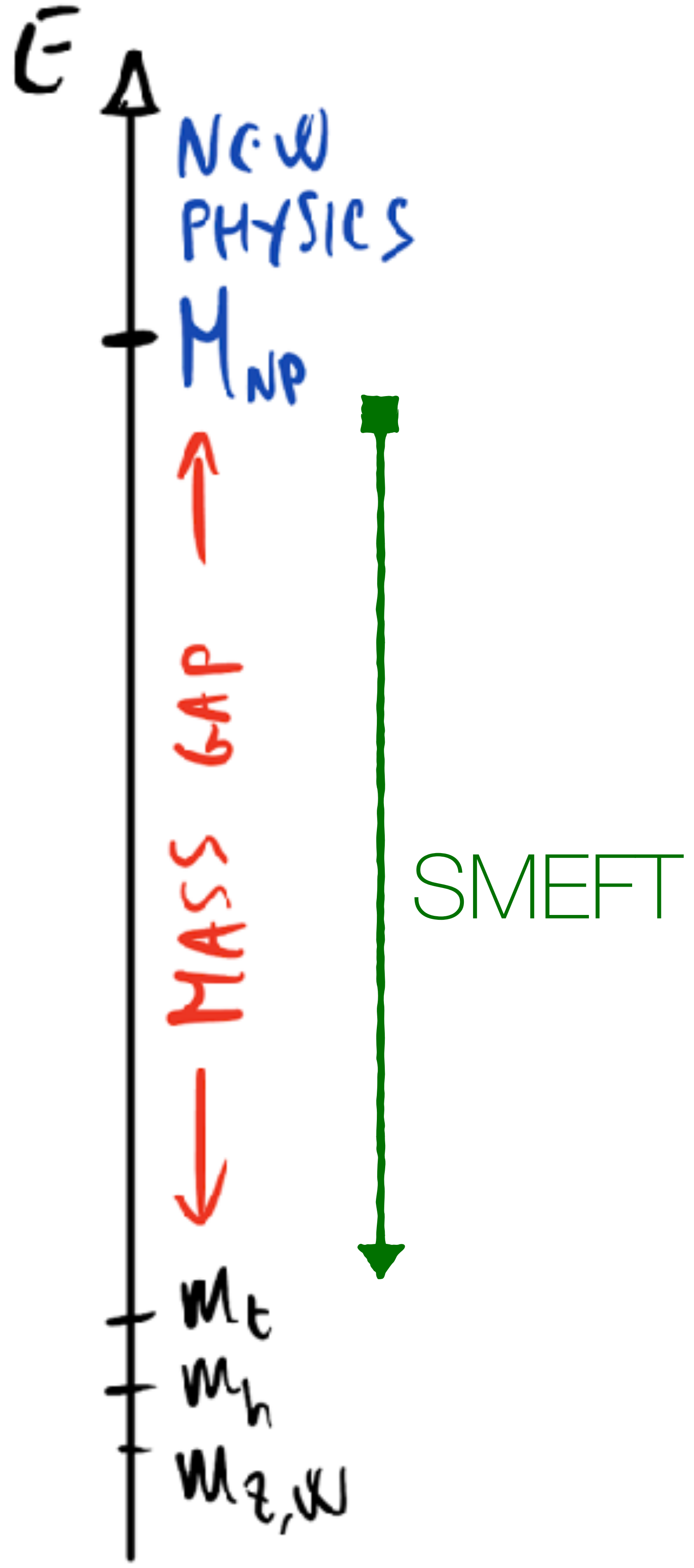

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In our case, **deviations from Flavour Universality** can be expected.
Precision tests of this property of the SM could offer powerful probes of physics BSM.

I define Flavour Universality as invariance under $\mathbf{U(3)^5}$ (or $\mathbf{U(3)^3 \times U(2)_Q \times U(2)_u}$)

The success depends on:
- how good of a symmetry of the SM it is
- how precise (and at which energy) are the experimental tests

Quark Flavour Universality

Flavour universality in the **quark sector**, in practice, is **never a good enough symmetry** since:

- **CKM mixing** between light quarks is not negligible ($\sin \theta_C \sim 0.2$)
- at high-energy colliders, the **PDF of a proton** is flavour non-universal and **light quark jet tagging** not much discriminating
- in low-energy **flavour processes, CKM and quark mass effects are very relevant**.

Indeed, having **New Physics coupled non-universally to quarks is compatible and often preferred**:
e.g. **large couplings to heavy quarks and suppressed couplings to light ones** to avoid LHC direct searches.

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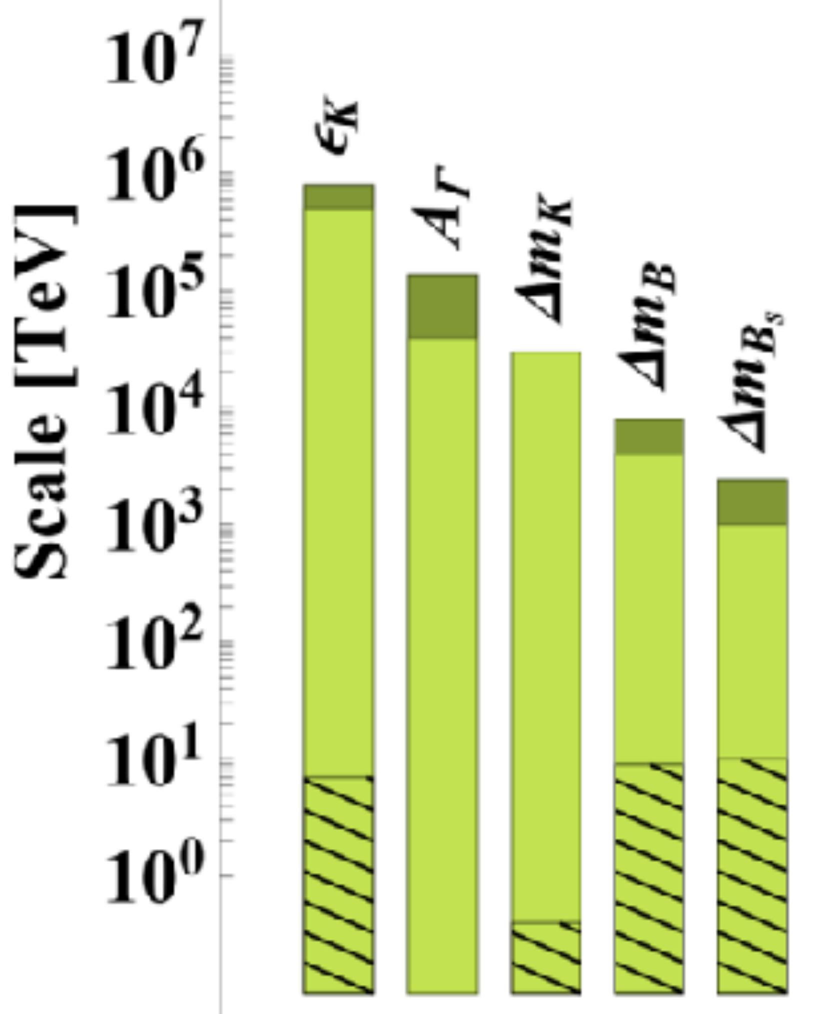
Physics Briefing Book
1910.11775



What is much more **constrained** is the **structure of the flavour-violating** terms: **generic NP requires very high scales**.

Lower NP scales require some ***Flavour protection***,
e.g. CKM-like suppression of flavour-violating interactions (MFV, $U(2)^3$, partial compositeness, etc..)

Quark Flavour Universality

We can then rephrase the question into whether New Physics follows:

MFV-like

(LU, RU in Luca's terms)

$$C_{ij}^{\text{MFV-LIKE}} \sim C \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \delta C_{CKM}$$

vs.

U(2)-like

(pLU, pRU, puRU in Luca's terms)

$$C_{ij}^{\text{U(2)-LIKE}} \sim C \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \delta C_{CKM}$$

Flavour constraints on off-diagonal terms are **similar** in the two cases (in minimally broken cases)

MFV-like has stronger bounds from collider, due to larger couplings to valence quarks in the proton.

So, **U(2)-like** model allow to have an overall **lower New Physics scale** (see e.g. talk by Luca Vecchi).

Non-universal example: top-philic New Physics

Both experimental and theory arguments motivate having **TeV-scale New Physics coupled mostly to the top quark**.

[e.g. review by Franceschini 2301.04407]

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As an exercise, let us **assume heavy NP couples mostly to top quarks**. What **scale** are we probing with **direct** and **indirect** probes?

[0704.1482, 0802.1413, 1109.2357, 1408.0792, 1909.13632, 2012.10456]

Semi-leptonic		Four quarks	
$\mathcal{O}_{lq}^{(1),\alpha\beta}$	$(\bar\ell^\alpha\gamma_\mu\ell^\beta)(\bar q^3\gamma^\mu q^3)$	$\mathcal{O}_{qq}^{(1)}$	$(\bar q^3\gamma^\mu q^3)(\bar q^3\gamma_\mu q^3)$
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$\mathcal{O}_{uG}$	$(\bar q^3\sigma^{\mu\nu}T^A u^3)\tilde H G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u^3\gamma^\mu u^3)$
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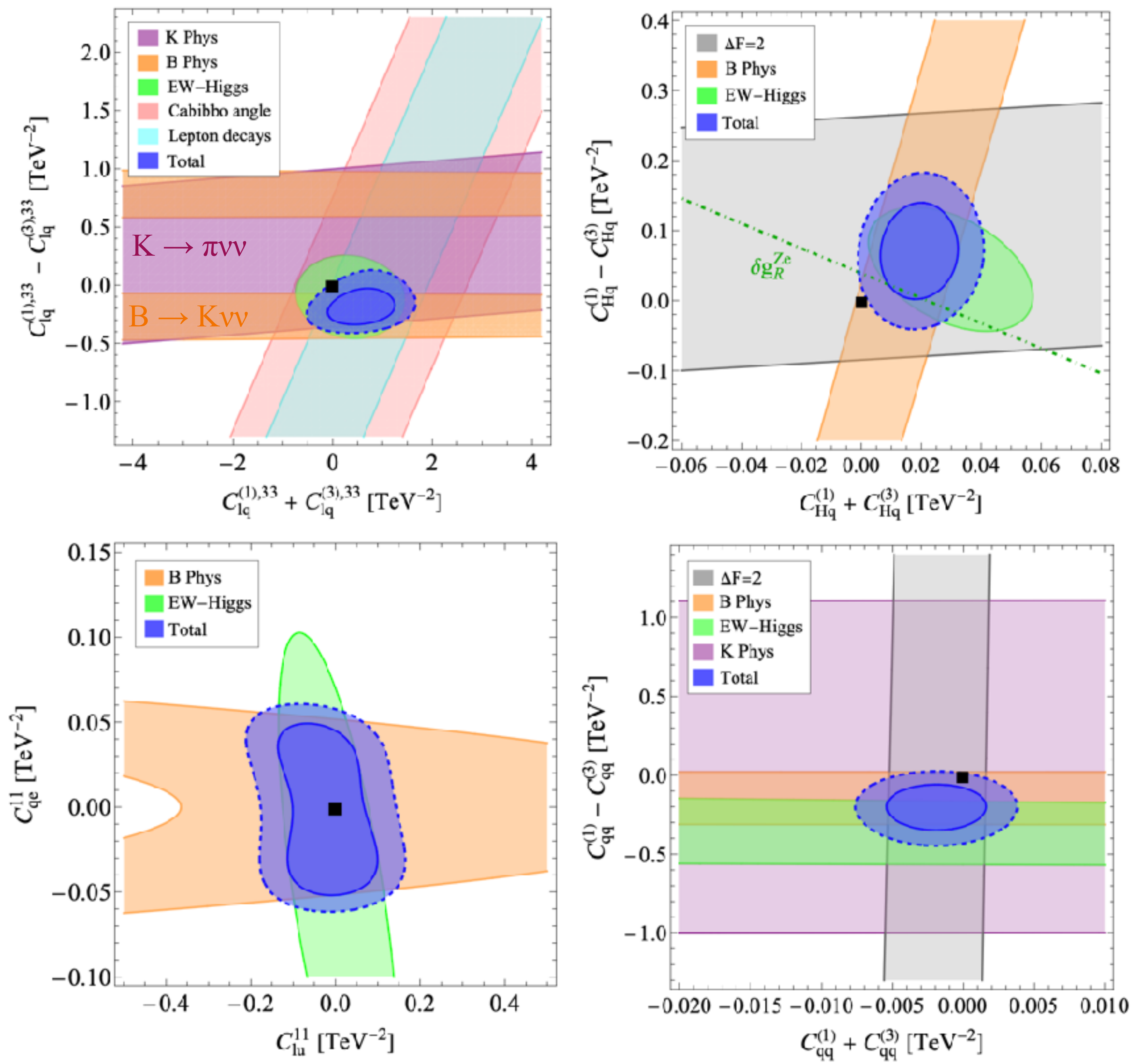
[Garosi, DM, Rodriguez-Sanchez, Stanzione 2310.00047]



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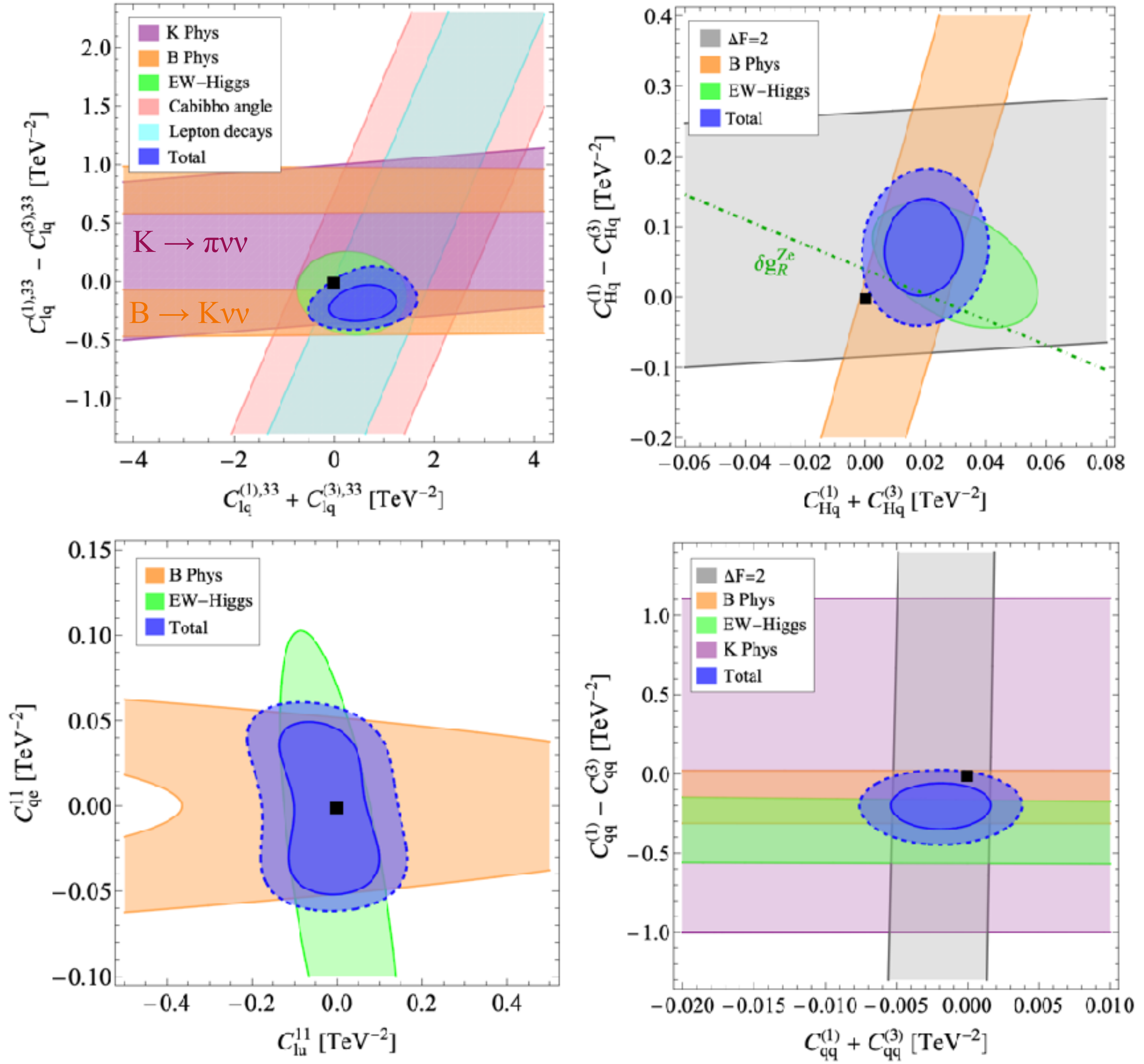
Indirect bounds are in the **few TeV range.**

Exception is $C_{qq}^{(+)}$ that contributes to Bs mixing at tree level.



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How **direct bounds** compare with **indirect** ones? **Indirect are typically much stronger.**

[Garosi, DM, Rodriguez-Sanchez, Stanzione 2310.00047]

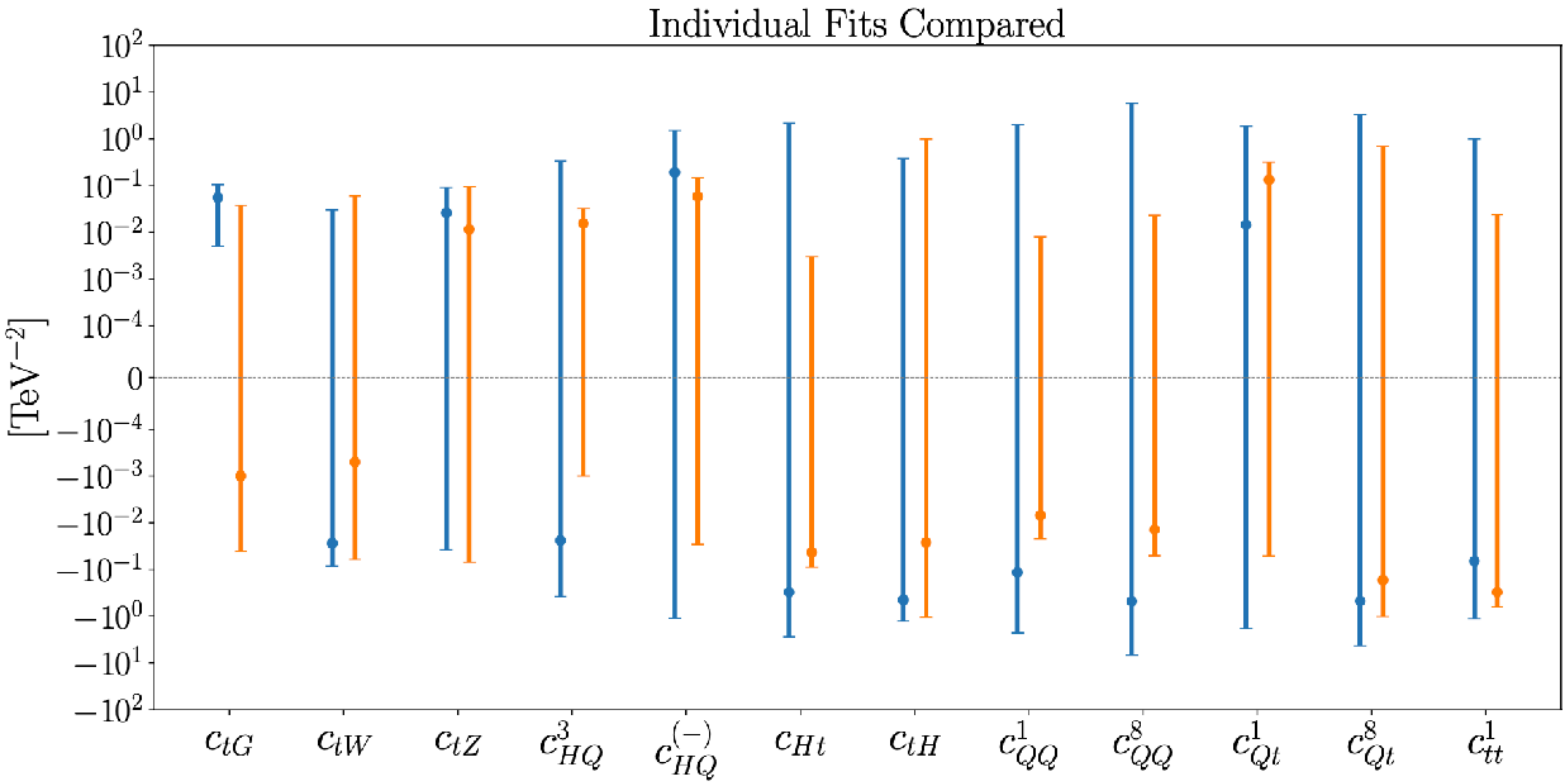
Direct bounds from LHC

top production,
Higgs physics,
diboson production

SMEFiT 2105.00006

Indirect bounds from EW+Flavour

2310.00047



Dipoles

H-top current

top Yukawa

4-top operators

Lepton Flavour Universality

$$U(3)_L \times U(3)_e$$

Lepton Flavour Universality is a much **more interesting property** to test, since:

- **Lepton mixing vanishes** (for massless neutrinos)
- Lepton **masses** are often **negligible** w.r.t. the typical energy of the process $m_\ell \ll E$
- **Yukawa interactions** are also often **negligible**. $y_\ell \ll 1$
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- semi-leptonic hadron CC decays ($K\ell 3$, $D\ell 3$, $R(D^{(*)})$, …)
- semi-leptonic hadron NC decays (R_K, R_{K^*} , …)
- τ decays ($|g_\ell/g_{\ell'}|$)
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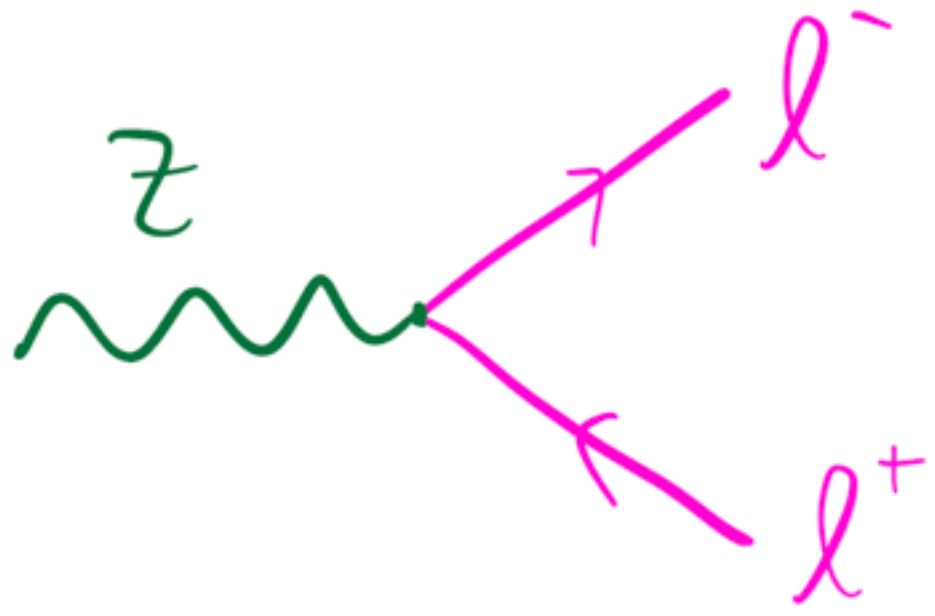
At **colliders** we can probe it via:

- **Z** and **W** leptonic decays
- **Higgs** decays $H \to \ell^+ \ell^- Z$
- High energy **dilepton tails**
- …

LFU in Z decays

Leptonic Z decays allow to test directly universality of gauge interactions with leptons.



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Negligible kinematic effects due to lepton masses (0.2% for tau)

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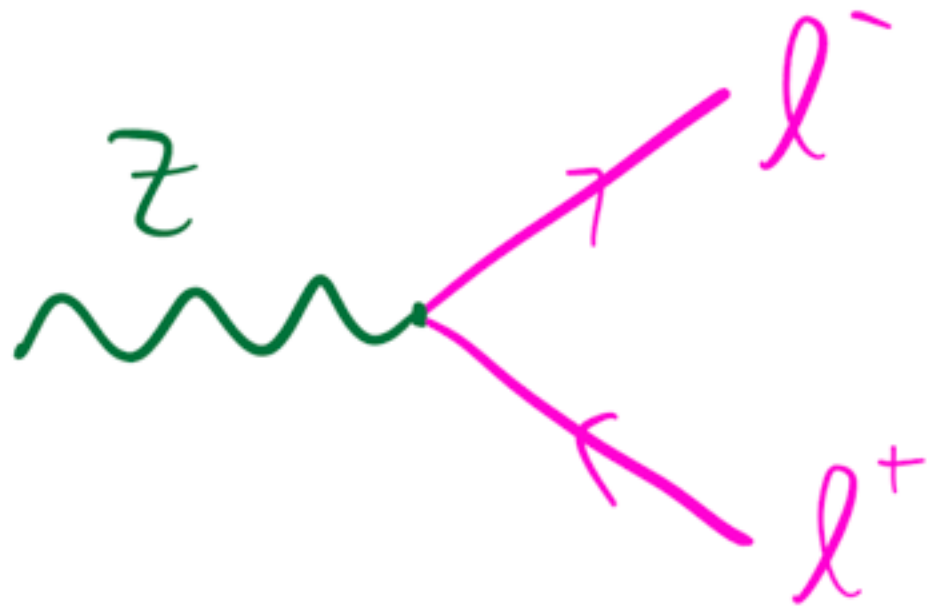

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LEP results (2005)

$$\frac{\Gamma_{\mu\mu}}{\Gamma_{ee}} = \frac{B(Z \to \mu^+\mu^-)}{B(Z \to e^+e^-)} = 1.0009 \pm 0.0028$$

$$\frac{\Gamma_{\tau\tau}}{\Gamma_{ee}} = \frac{B(Z \to \tau^+\tau^-)}{B(Z \to e^+e^-)} = 1.0019 \pm 0.0032$$

Lepton Flavour Universality in Z decays tested at per-mille level

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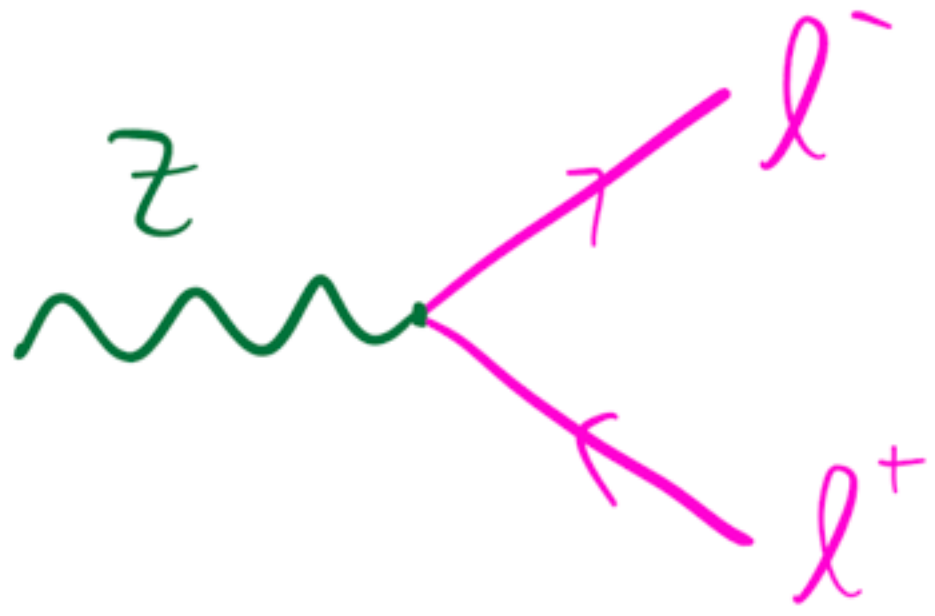

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In terms of effective Z couplings:

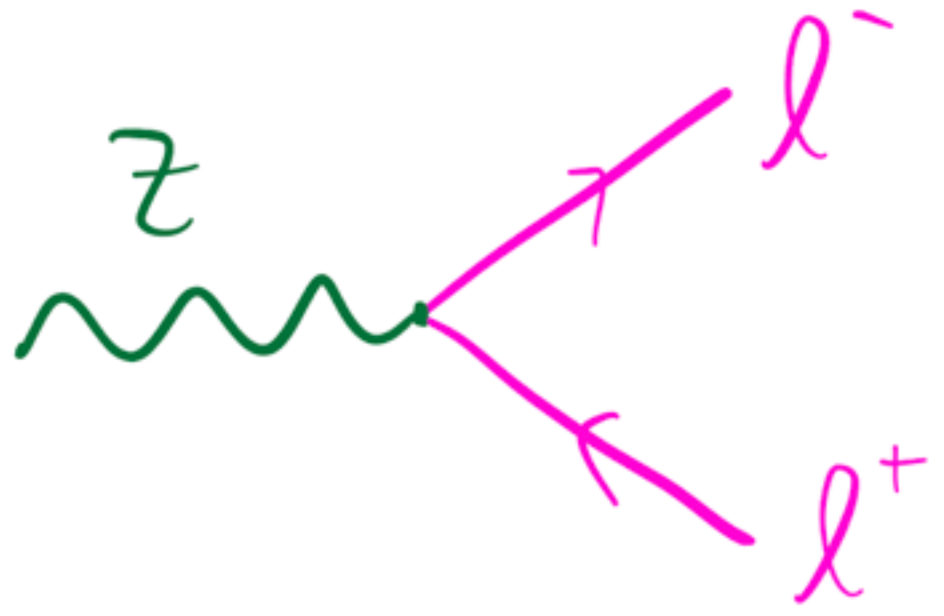
Parameter	Average	Correlations						
		$g_{L\nu}$	g_{Le}	$g_{L\mu}$	$g_{L\tau}$	g_{Re}	$g_{R\mu}$	$g_{R\tau}$
$g_{L\nu}$	+0.5003±0.0012	1.00						
g_{Le}	−0.26963±0.00030	−0.52	1.00					
$g_{L\mu}$	−0.2689±0.0011	0.12	−0.11	1.00				
$g_{L\tau}$	−0.26930±0.00058	0.22	−0.07	0.07	1.00			
g_{Re}	+0.23148±0.00029	0.37	0.29	−0.07	0.01	1.00		
$g_{R\mu}$	+0.2323±0.0013	−0.06	−0.06	0.90	−0.03	−0.09	1.00	
$g_{R\tau}$	+0.23274±0.00062	−0.17	0.04	−0.04	0.44	−0.03	0.04	1.00

$$g_L^{tree} = \sqrt{\rho_0}\,(T_3^f - Q_f \sin^2\theta_W^{tree}) \qquad \rho_0 = 1$$
$$g_R^{tree} = -\sqrt{\rho_0}\,Q_f \sin^2\theta_W^{tree},$$

(includes also asymmetries)

LFU in Z decays

Implications for New Physics



This vertex receives tree-level contribution from the operators:

$$\frac{1}{\Lambda_\ell^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{\ell}\gamma^\mu \ell\right) \qquad \ell = e_R, L_L \qquad \delta g_\ell^Z = -\frac{1}{2}\frac{v^2}{\Lambda_\ell^2}$$

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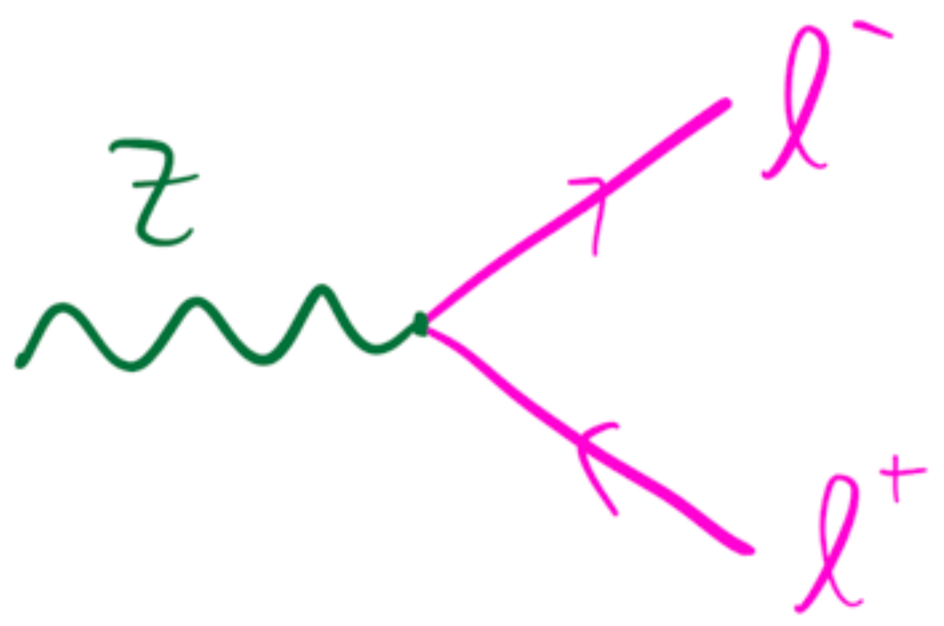

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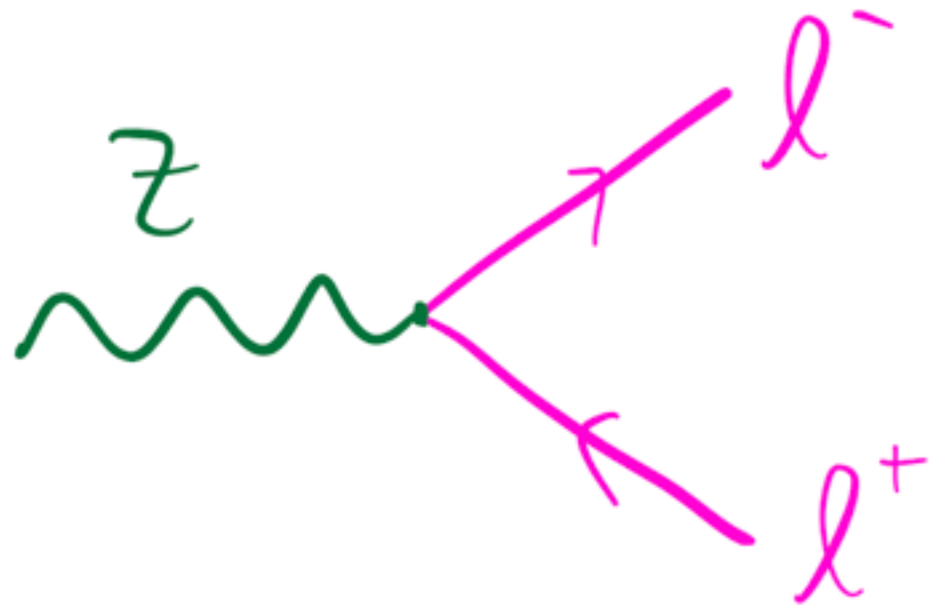

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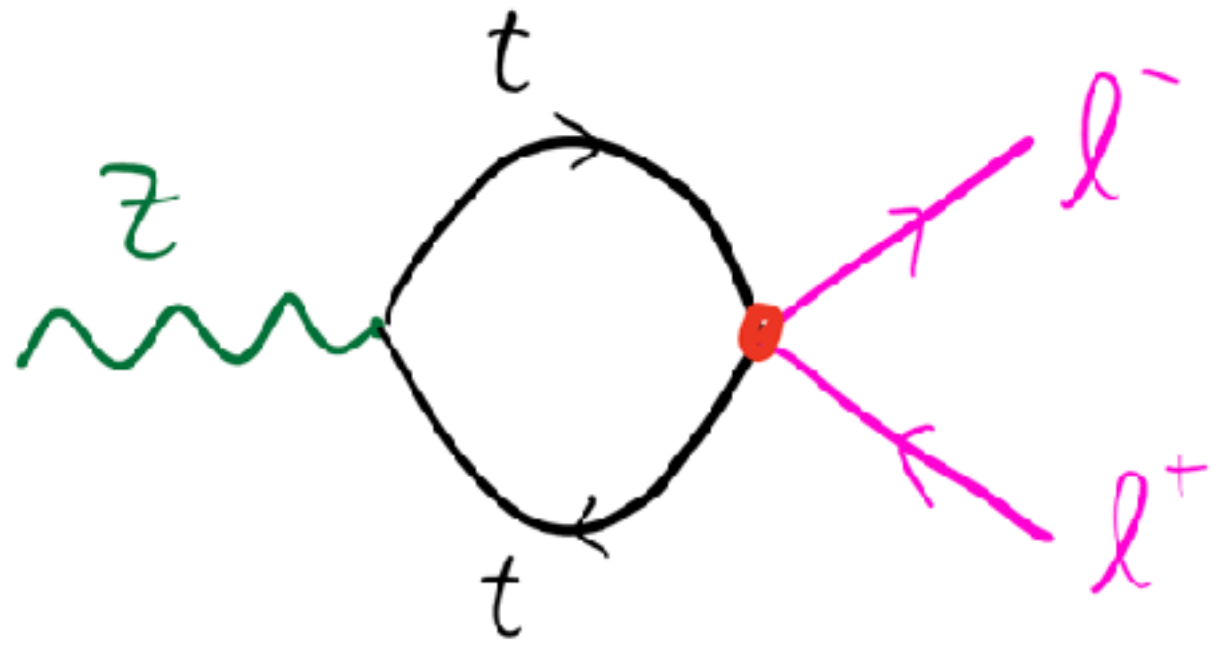
Given the high precision, it can also be sensitive to **loop contributions**.
For instance **top-lepton** semileptonic operators:



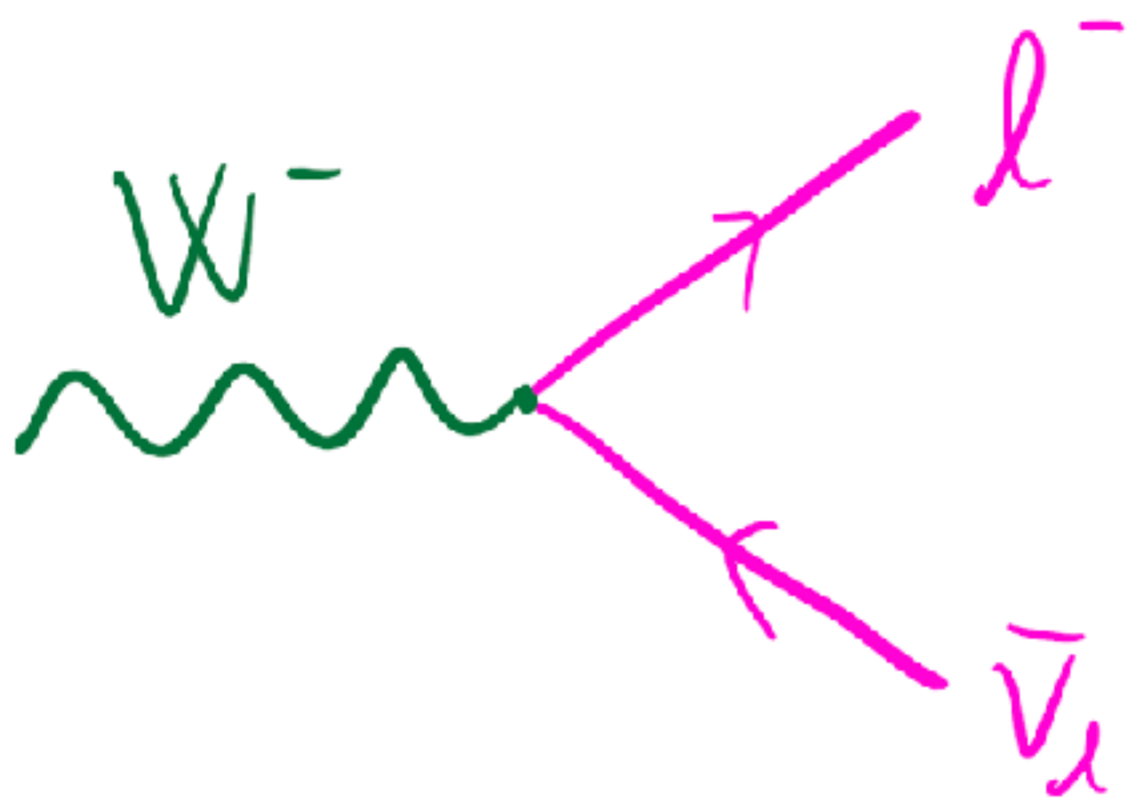
$$\delta g_\ell^Z \sim \frac{N_c}{16\pi^2}\frac{m_t^2}{\Lambda_{t\ell}^2}\log\frac{\mu_{UV}^2}{m_Z^2} \qquad |\Lambda_{t\ell}| \gtrsim 1.8\ \mathrm{TeV}$$

This is a very well known bound in the context of models addressing $R(D^{(*)})$

[Feruglio, Paradisi, Pattori 2016, …]

(this is understood as a RG contribution of the semileptonic operator to the Higgs-lepton operator via top Yukawa)

LFU in W decays



LFU can also be tested in leptonic W decays.

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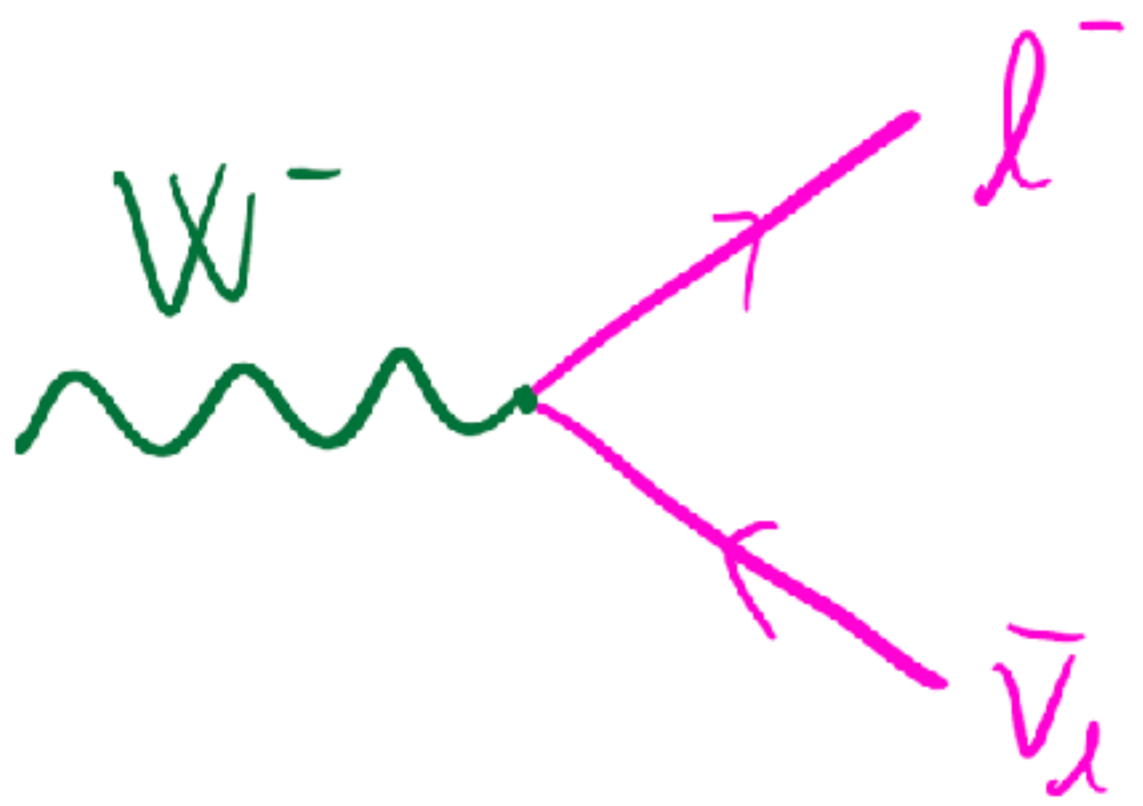

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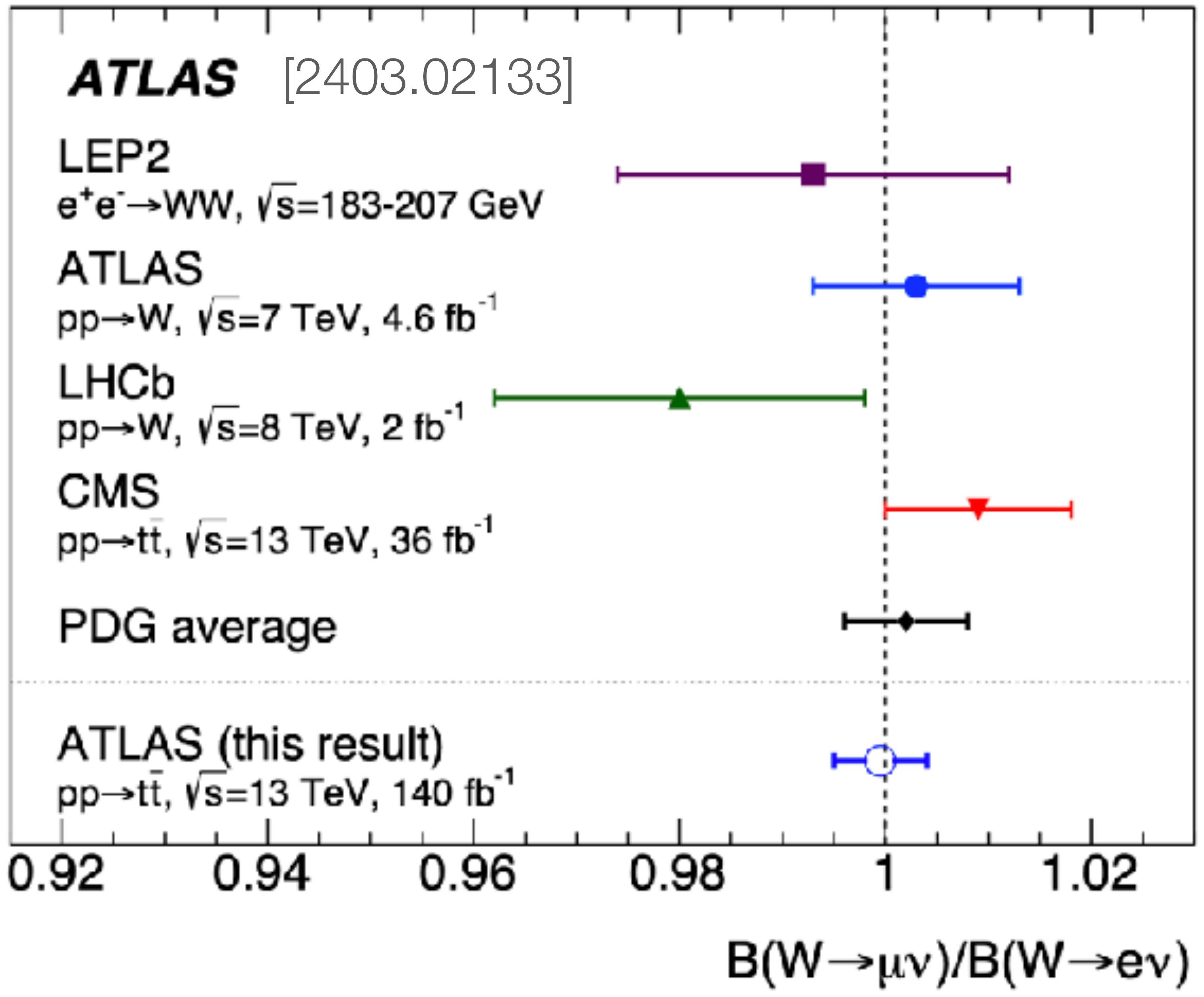
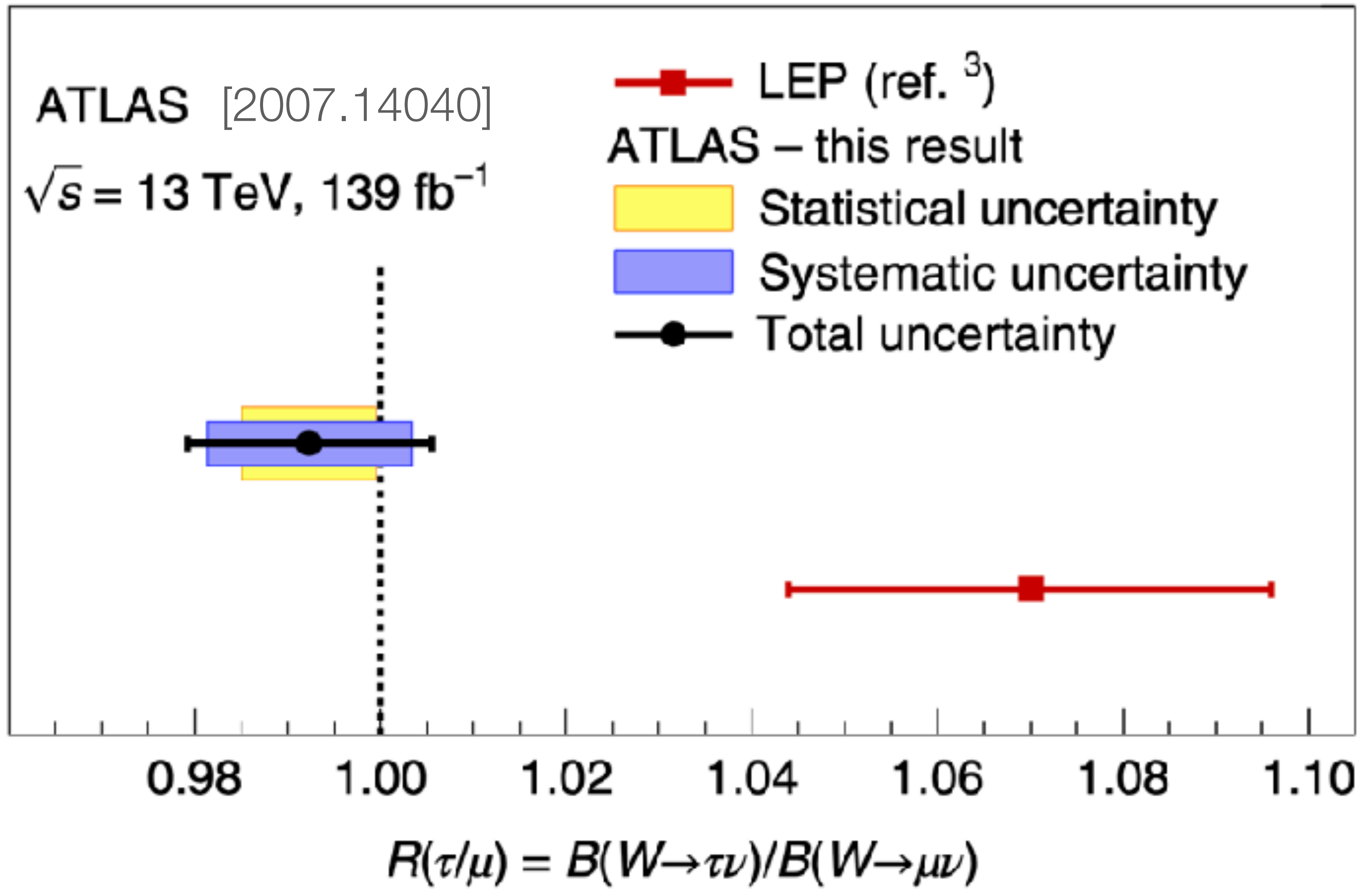
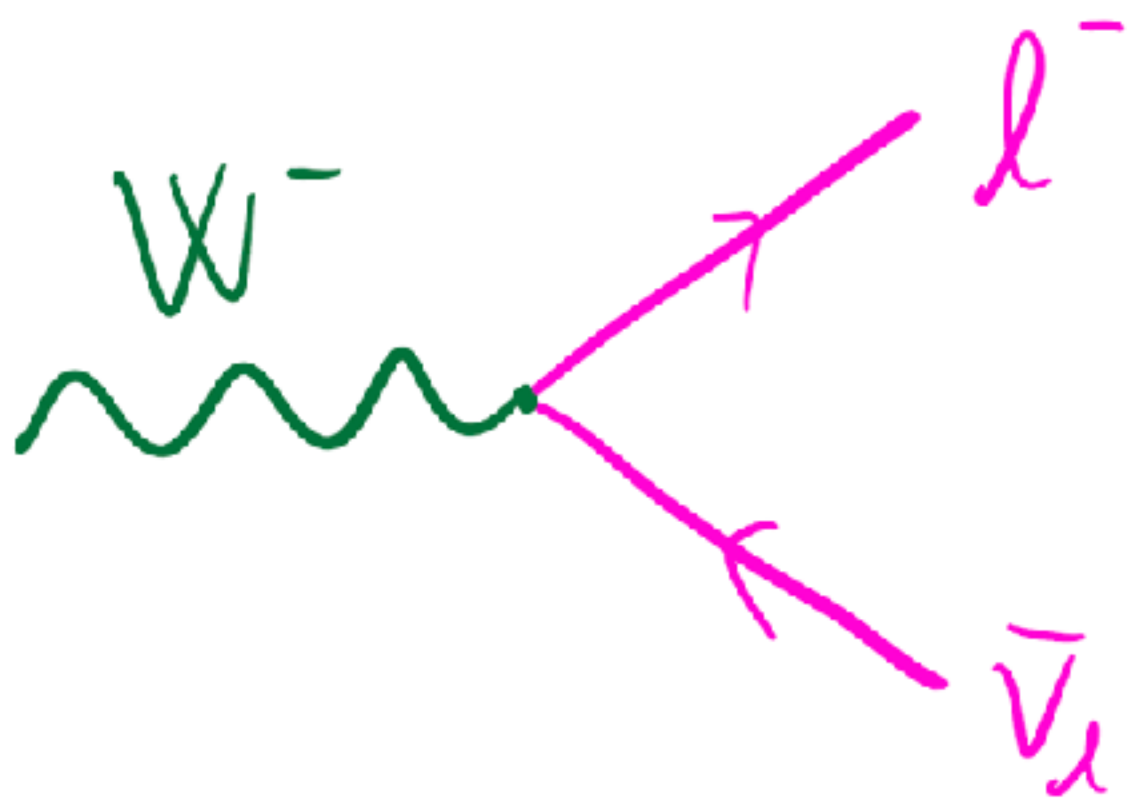
The most stringent constraints now come from ***ATLAS***





$$R_W^{\mu/e} = 0.9995 \pm 0.0045 \qquad R(\tau/\mu) = 0.992 \pm 0.013$$

LFU in W decays



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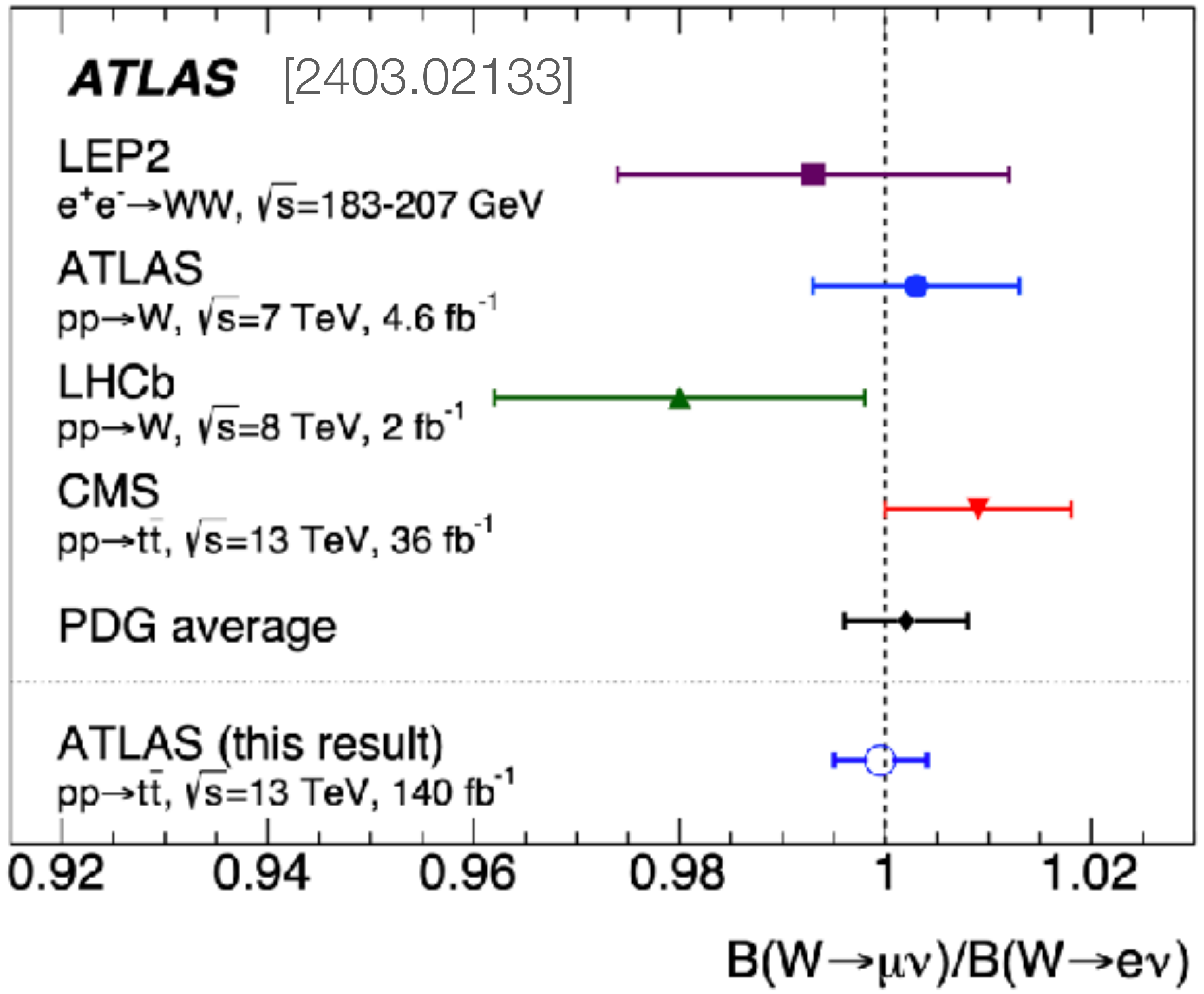

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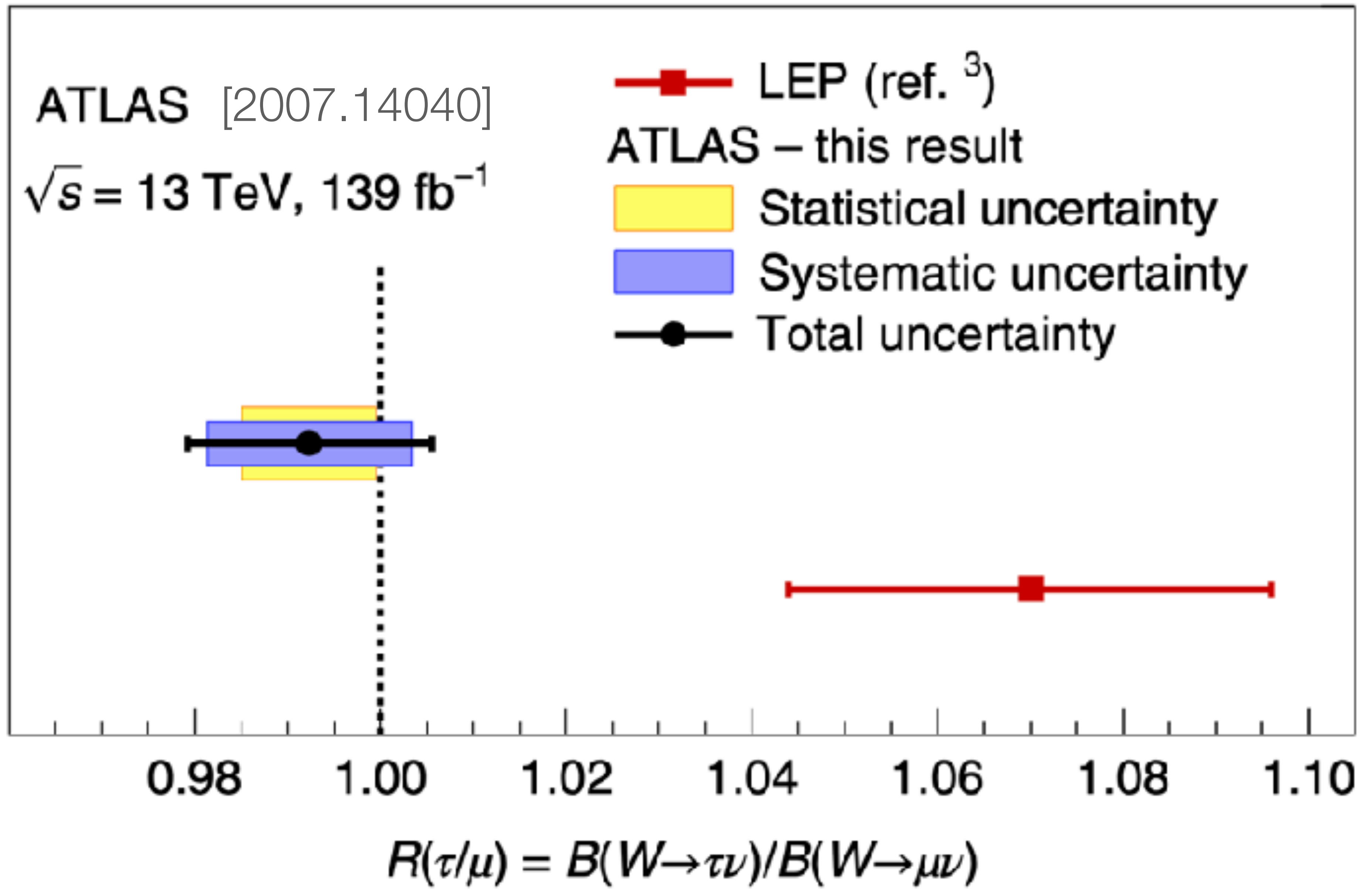


$$R(\tau/\mu) = 0.992 \pm 0.013$$

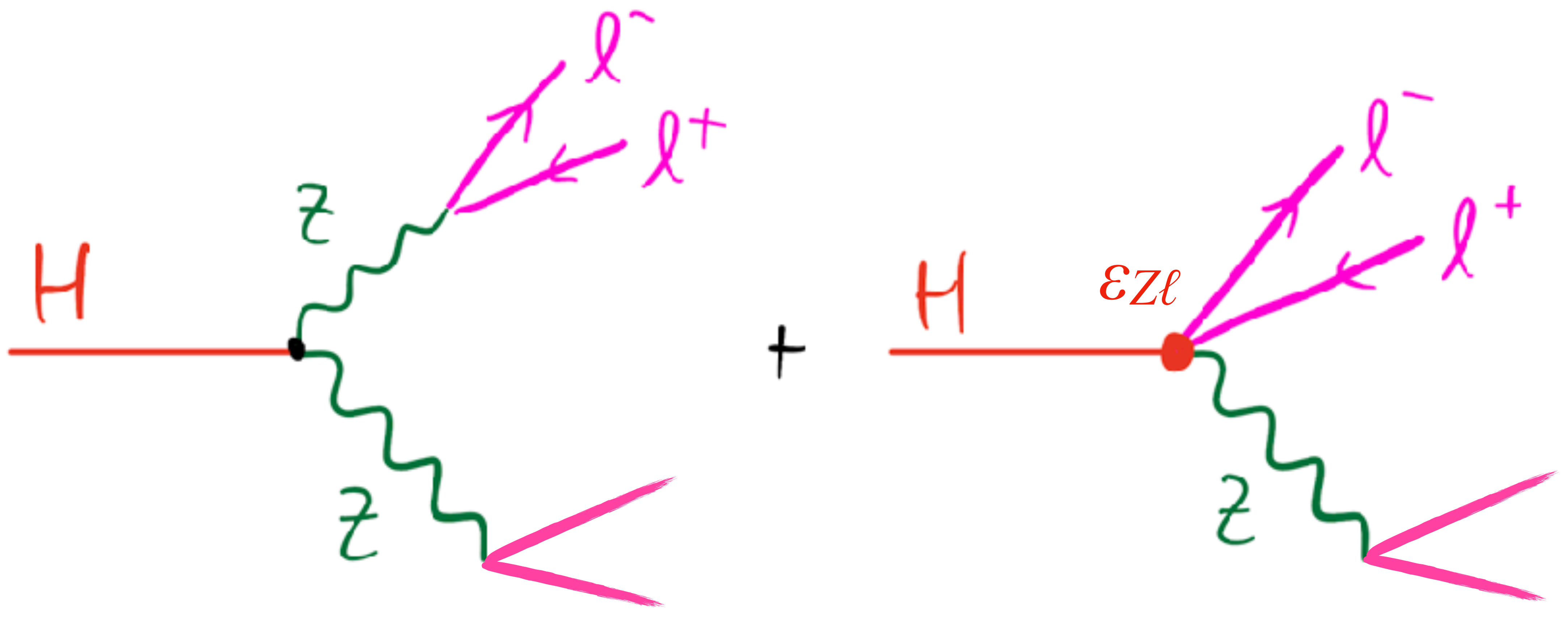
- **few per-mille in μ/e**
- **percent in τ/μ**

$$(H^\dagger \overleftrightarrow{D}^a_\mu H)(\bar{L}\gamma^\mu \sigma^a L)$$

$$|\Lambda^W_{\mu/e}| \gtrsim 2.7\,\text{TeV}$$

$$|\Lambda^W_{\tau/\mu}| \gtrsim 1.7\,\text{TeV}$$

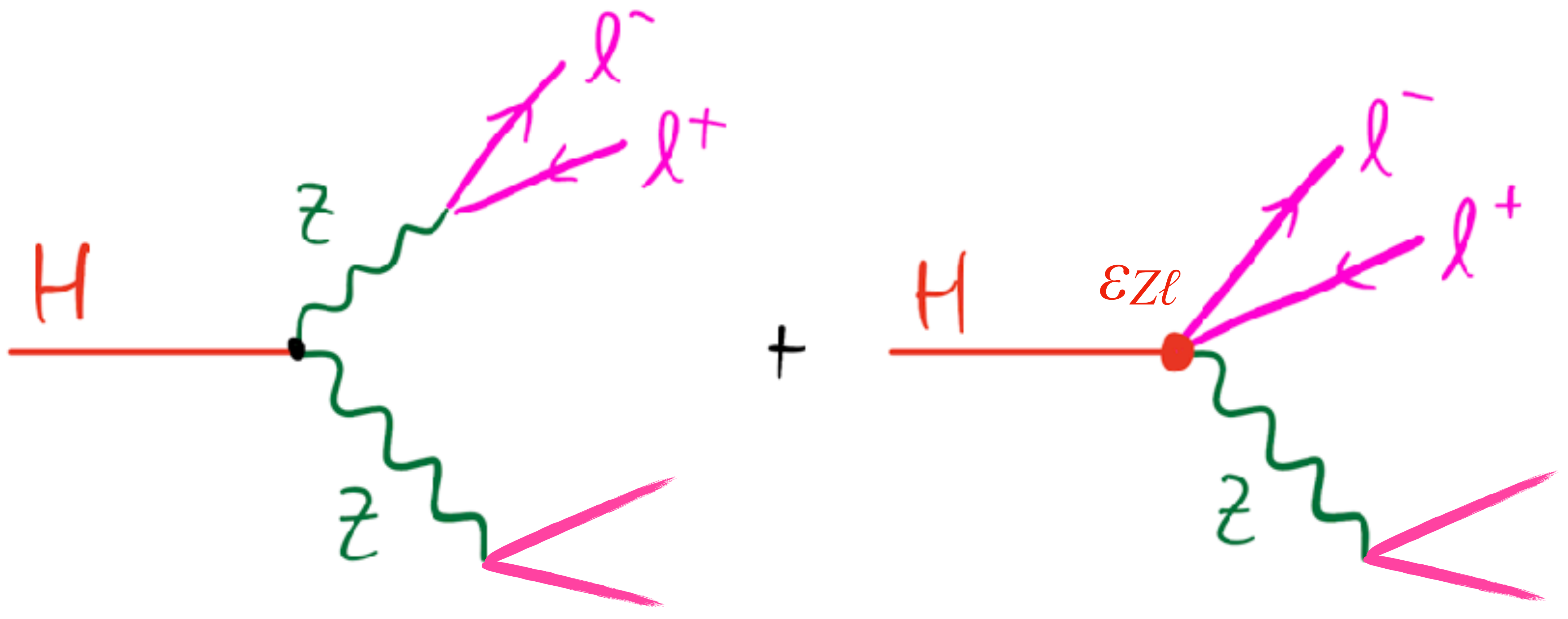
LFU in Higgs decays



Higgs → 4 fermion decays can in principle test deviations from LFU due to **contact interactions**.

1412.6038, 1504.04018, 1808.00965, …

LFU in Higgs decays



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They can be constrained by measuring the different **dilepton invariant mass** dependence [ATLAS 1708.02810]

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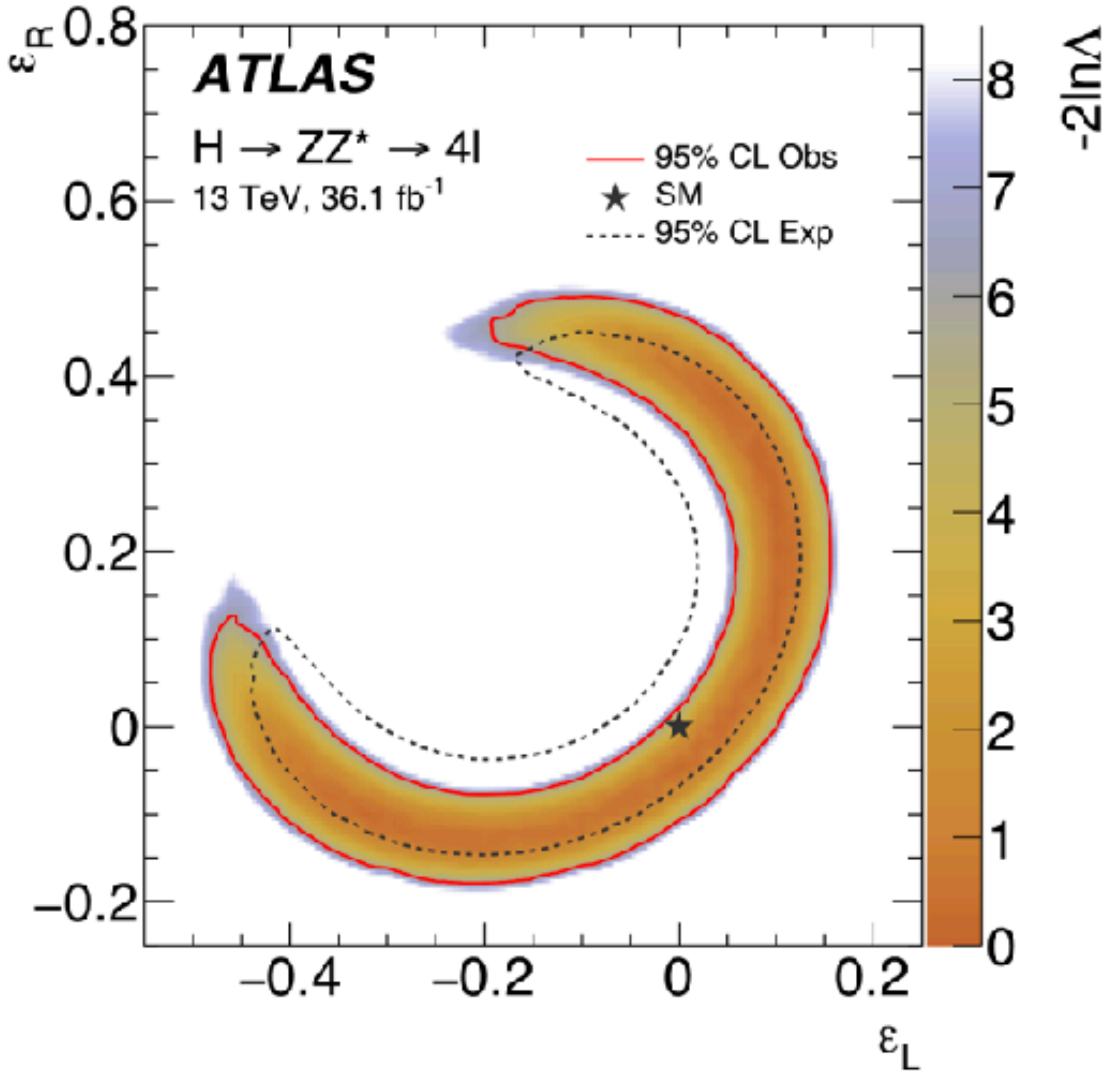

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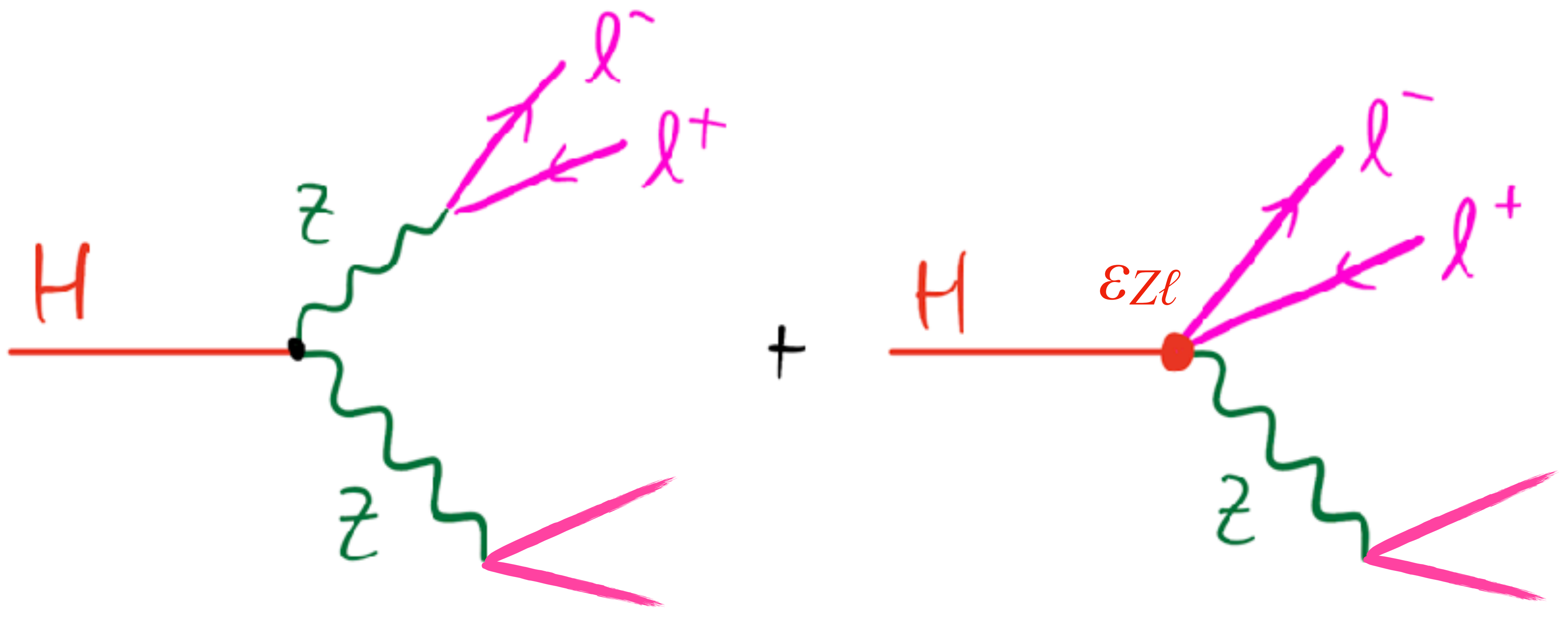

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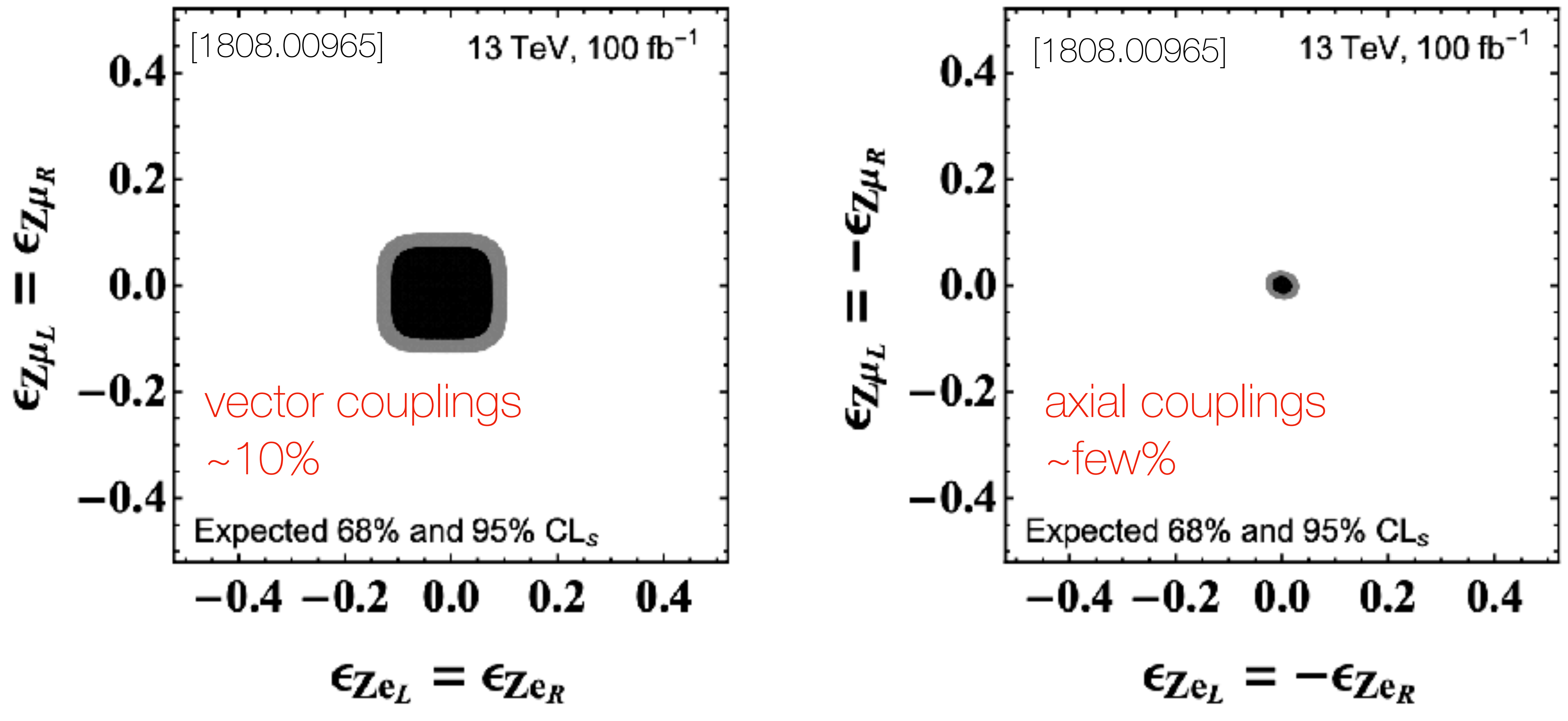
LFU tests: projections [1708.02810, 1808.00965]



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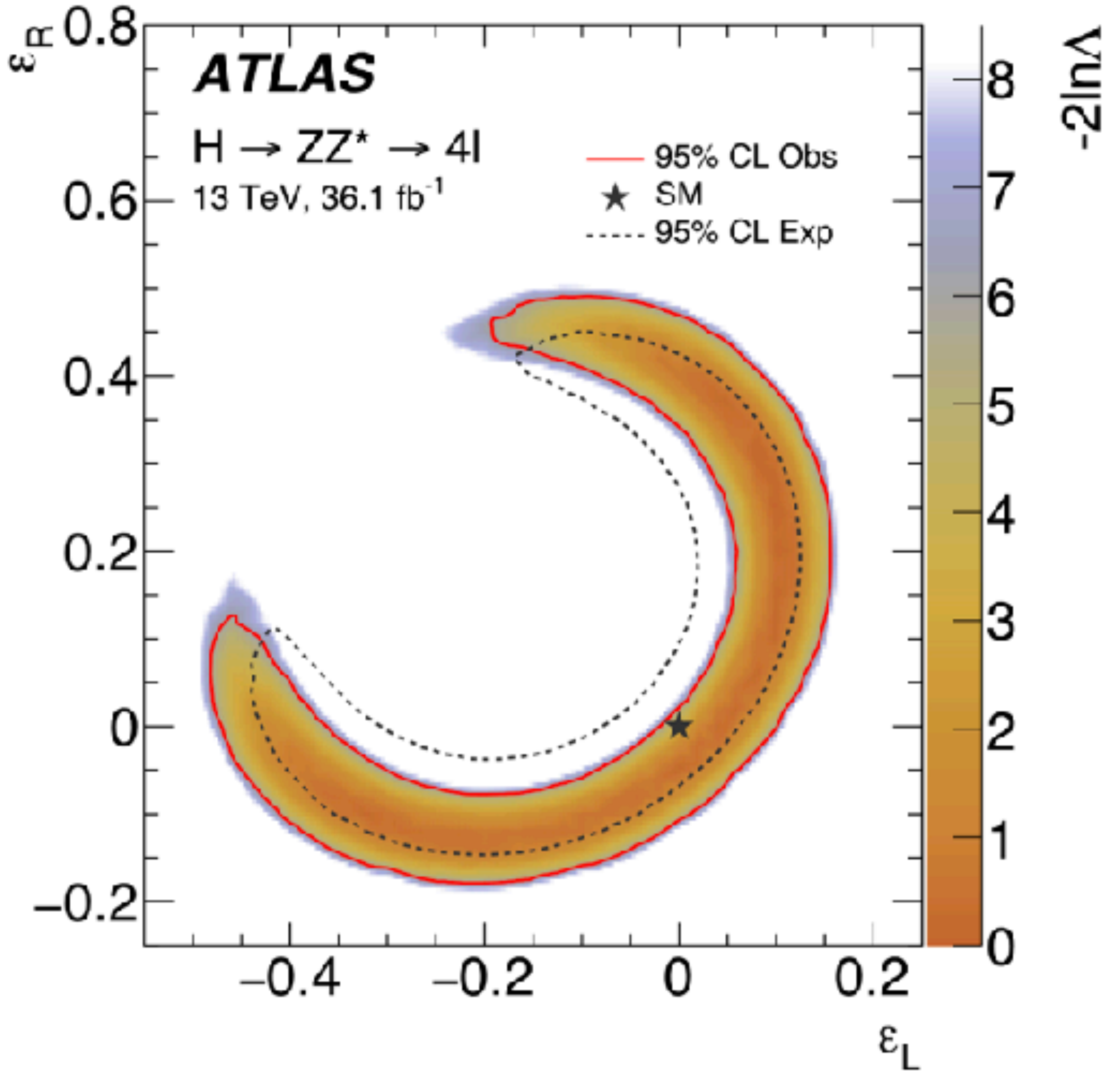

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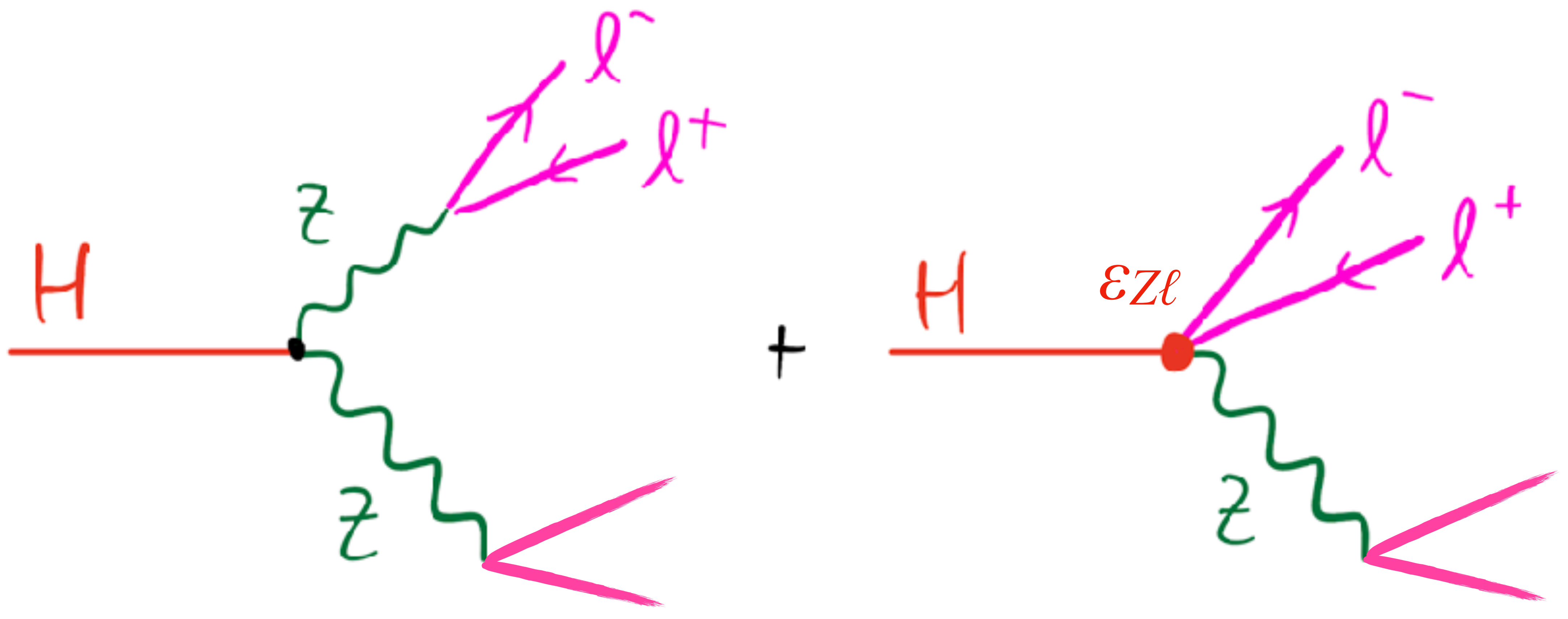

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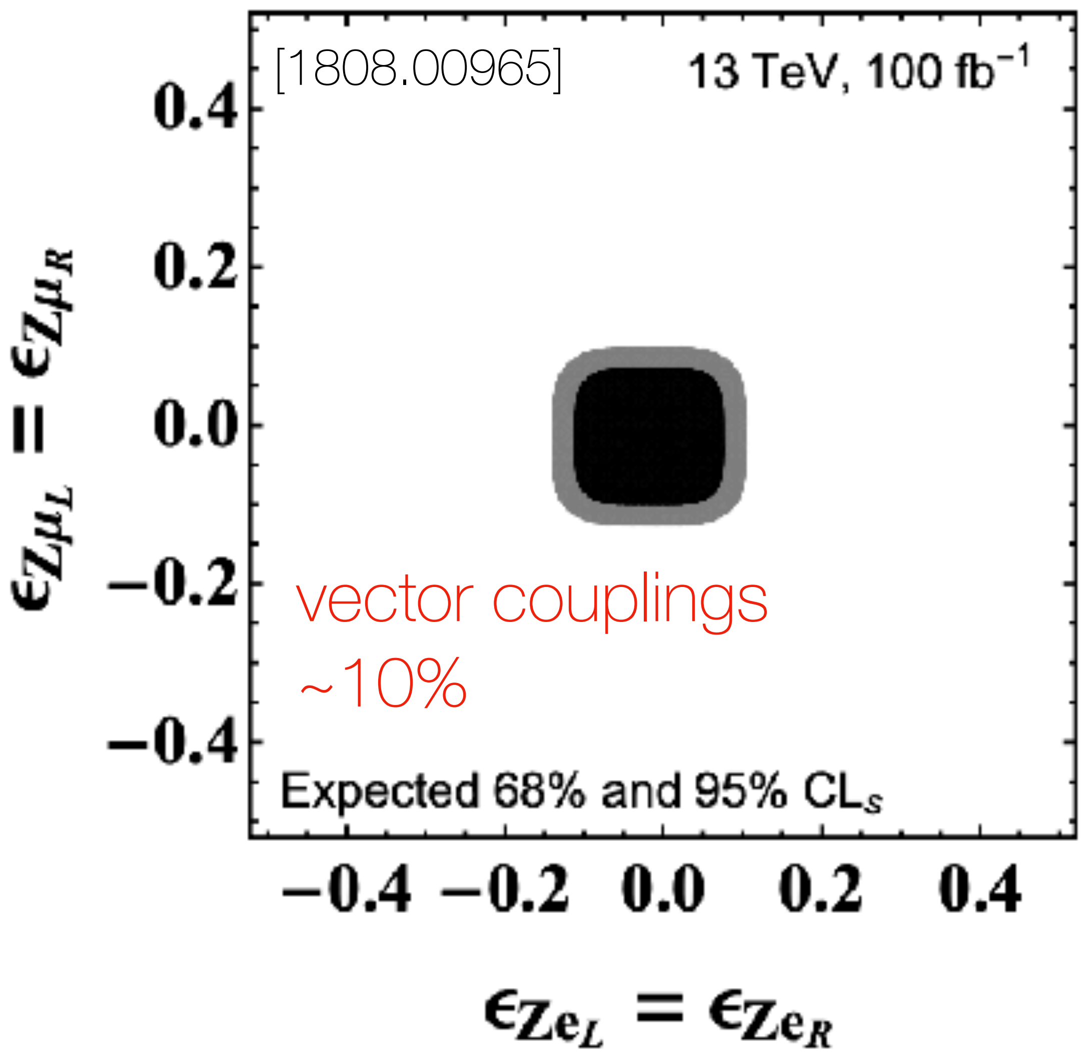
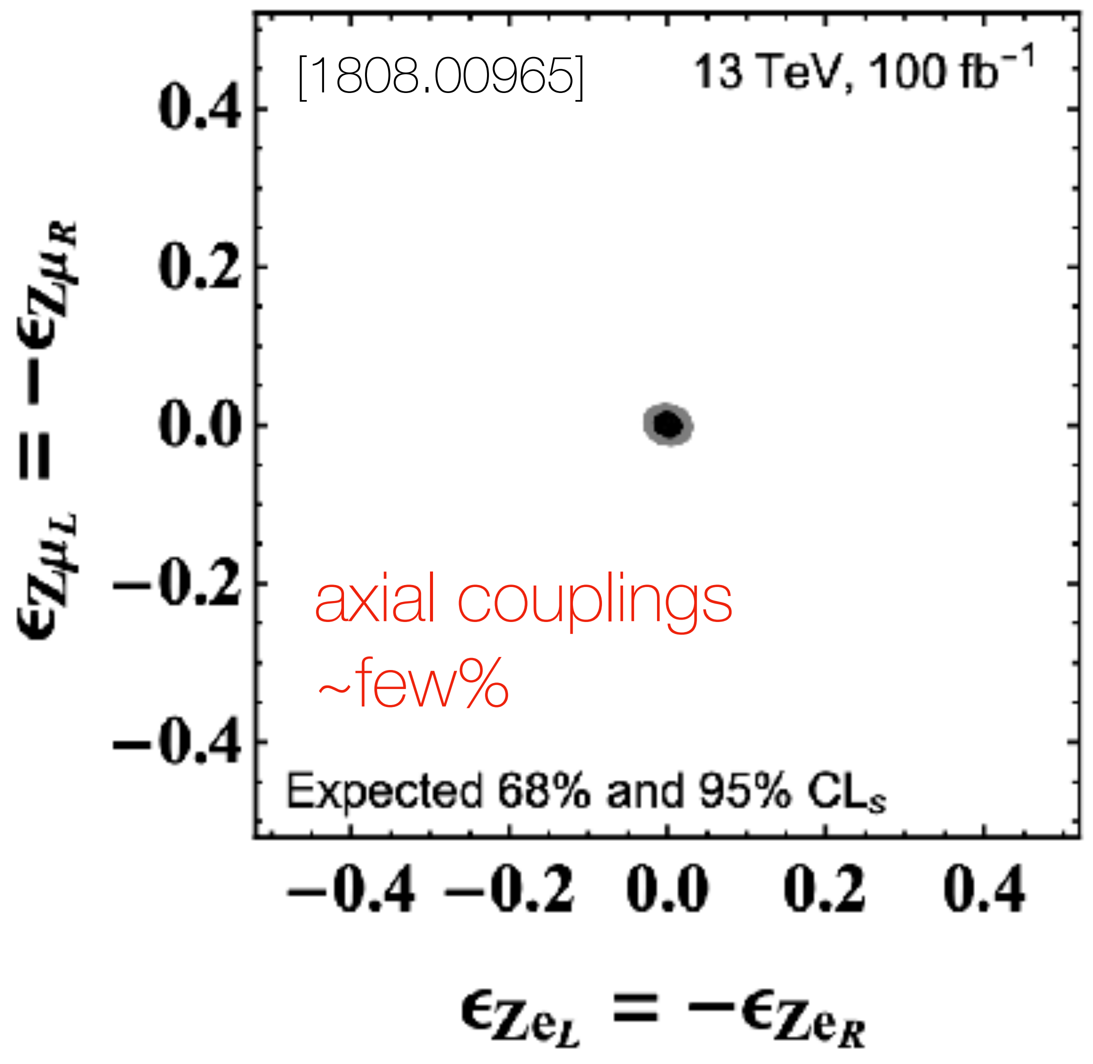




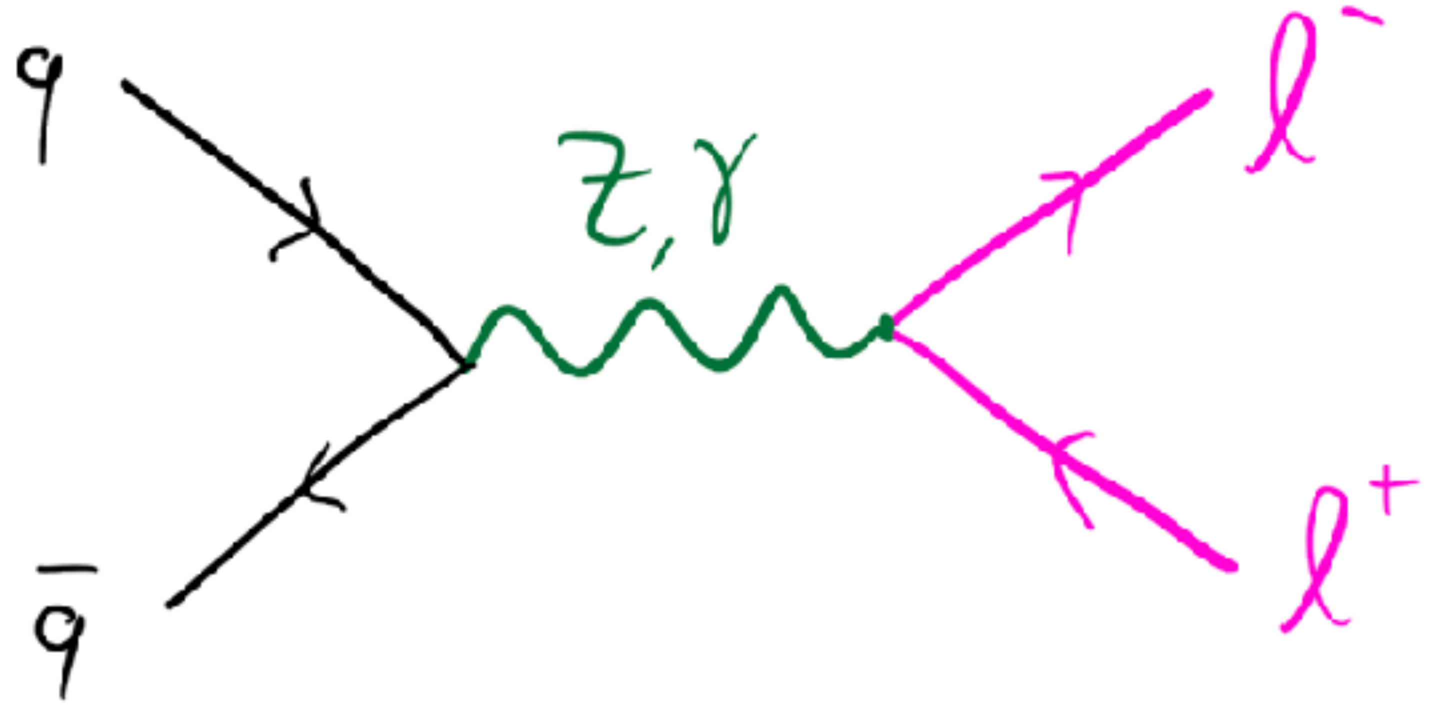
In the SMEFT, deviations from LFU can only be induced (at tree level) by the same operator appearing in Z decays

$$\frac{1}{\Lambda_\ell^2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\left(\bar{\ell}\gamma^\mu \ell\right)$$

$$\left|\varepsilon_{Z\mu} - \varepsilon_{Ze}\right| = \frac{2m_Z}{v}\left|\delta g^Z_\mu - \delta g^Z_e\right| < 10^{-3}$$

So, given the much lower precision attainable in Higgs decays,
no deviations from LFU are expected (assuming SMEFT).

High-Energy dilepton tails



The production of lepton pairs at high-energy colliders is **mediated by gauge interactions**:
Flavour Universal in the SM

$$\sigma_{tot}(pp \to e^+ e^-)_{SM} = \sigma_{tot}(pp \to \mu^+ \mu^-)_{SM} = \sigma_{tot}(pp \to \tau^+ \tau^-)_{SM}$$

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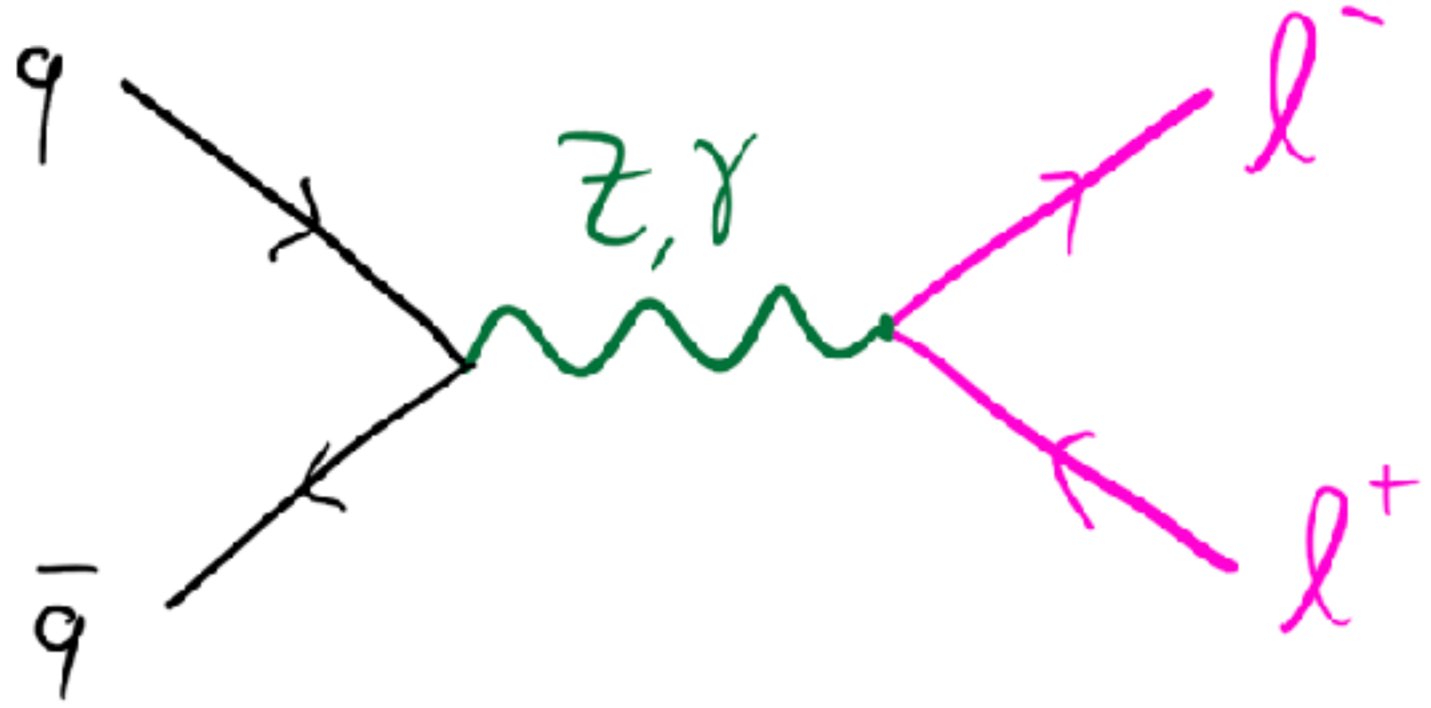

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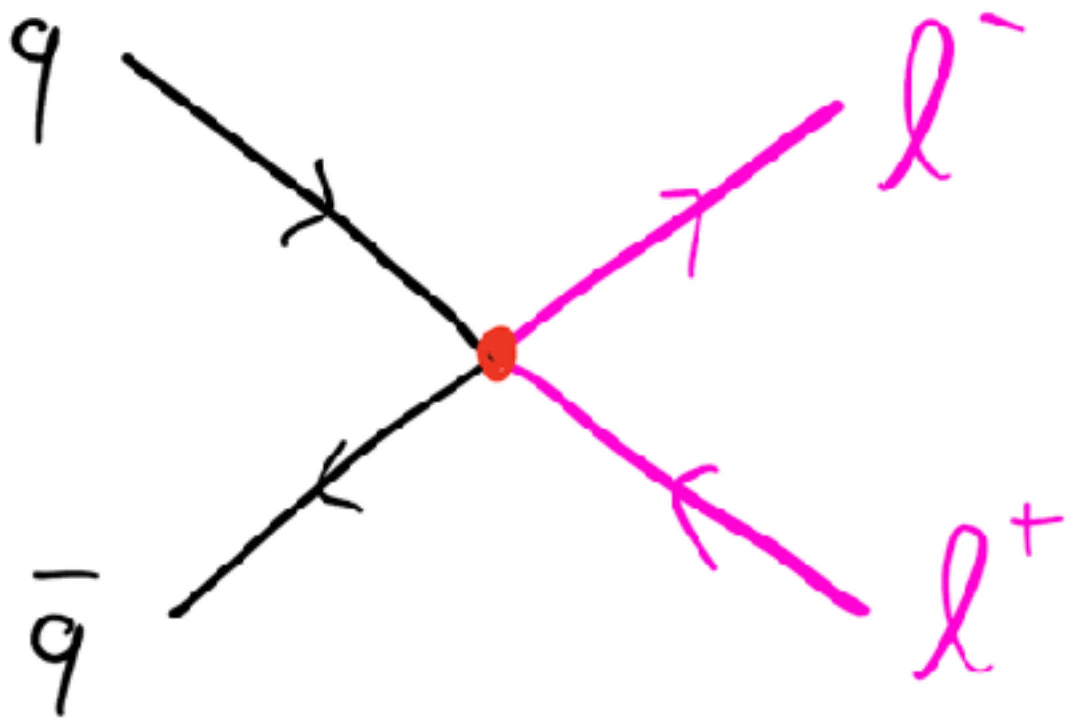

New Physics can affect different flavours in different way, **violating LFU**.
In the **EFT approach** we could have contributions from semileptonic operators of different lepton flavours:

$$(\bar{q}\gamma_\mu P_{L,R}\, q)(\bar{\ell}\gamma^\mu P_{L,R}\, \ell)$$

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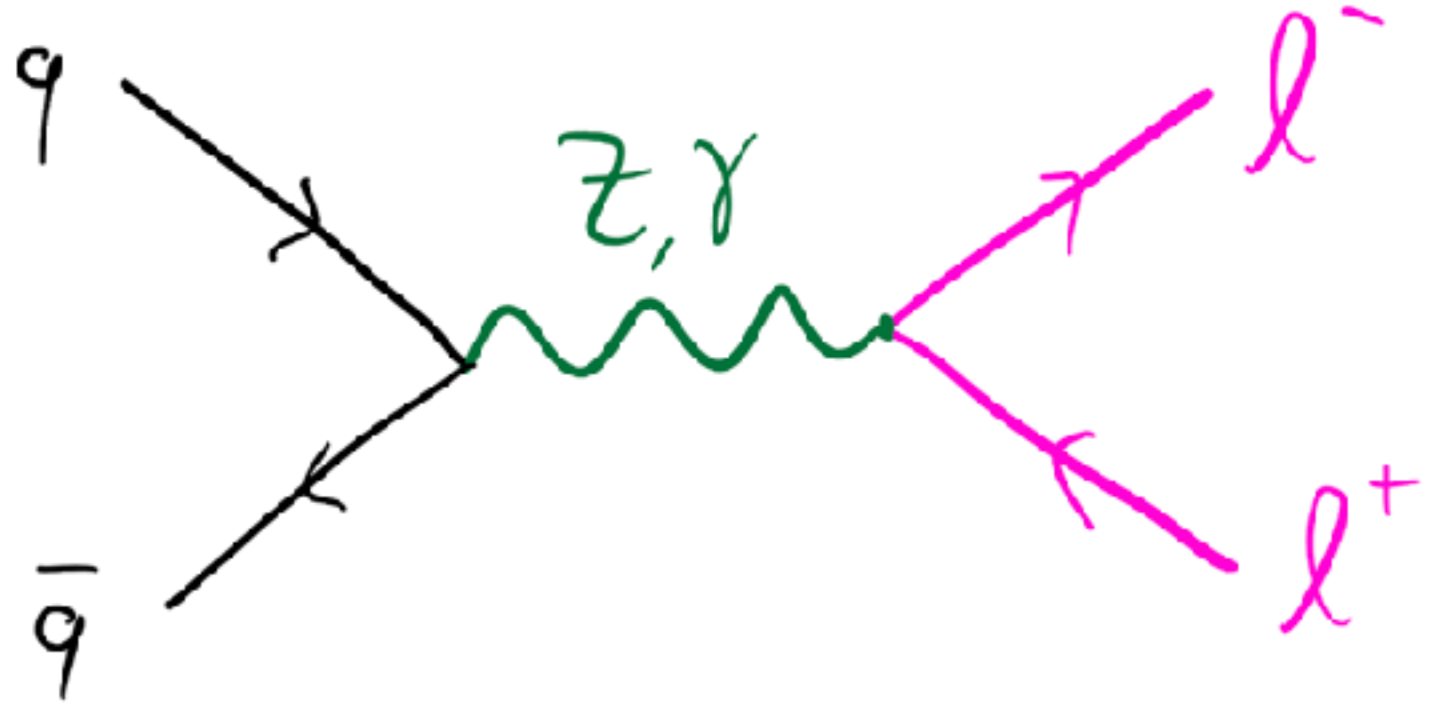

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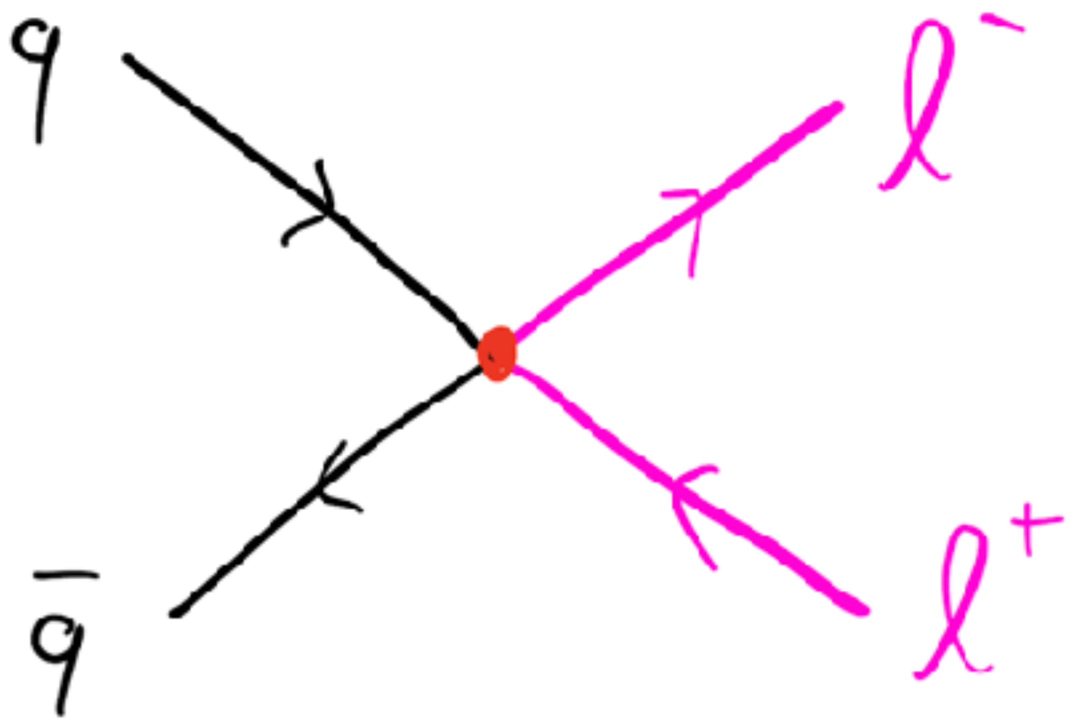

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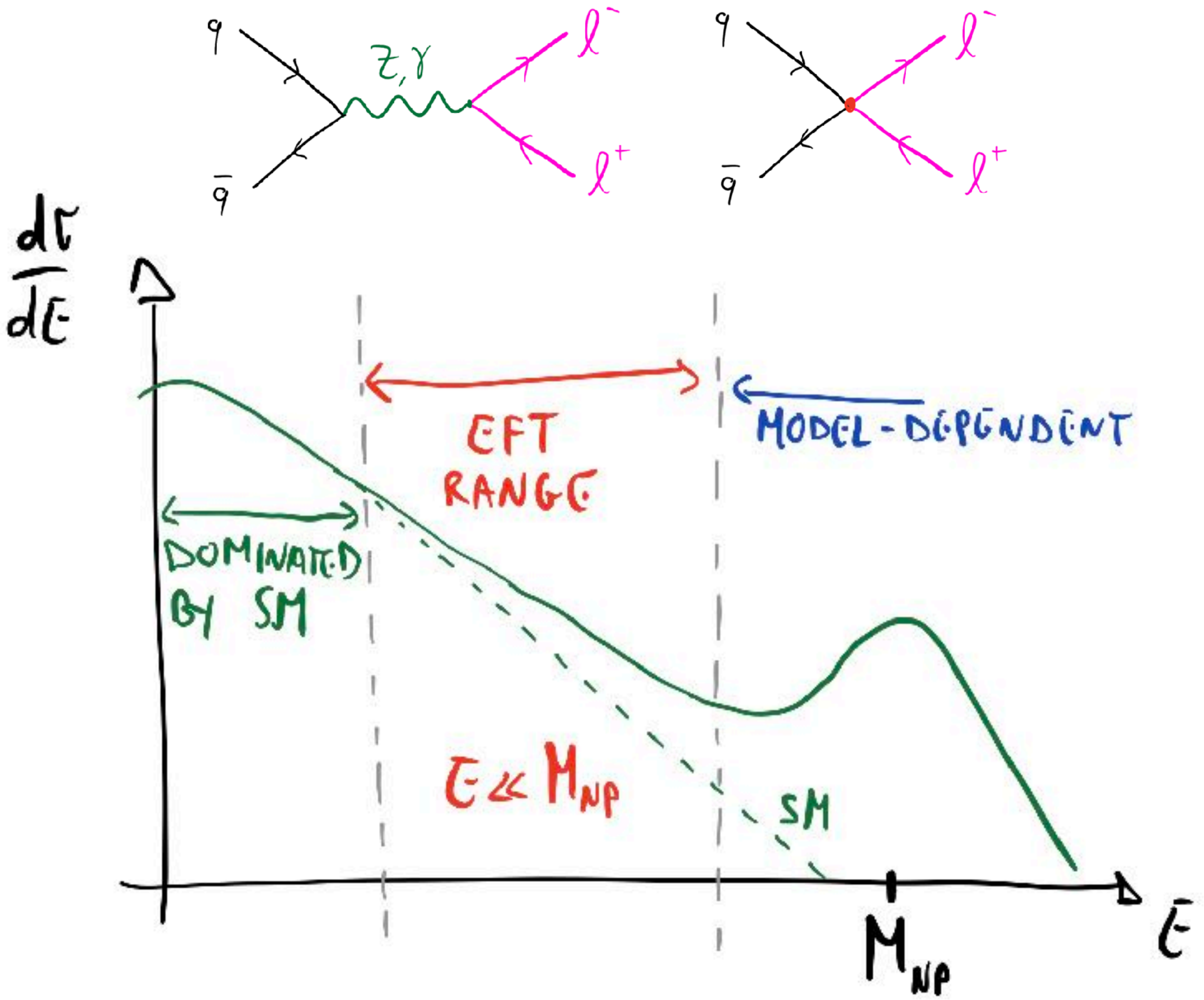
Muons and electrons have similar analysis workflows (although different reconstructions), so can be **compared more directly**.
Taus decay inside the detector and the resulting neutrinos affect their reconstruction & backgrounds. They are studied separately from other leptons.

High-Energy dilepton tails

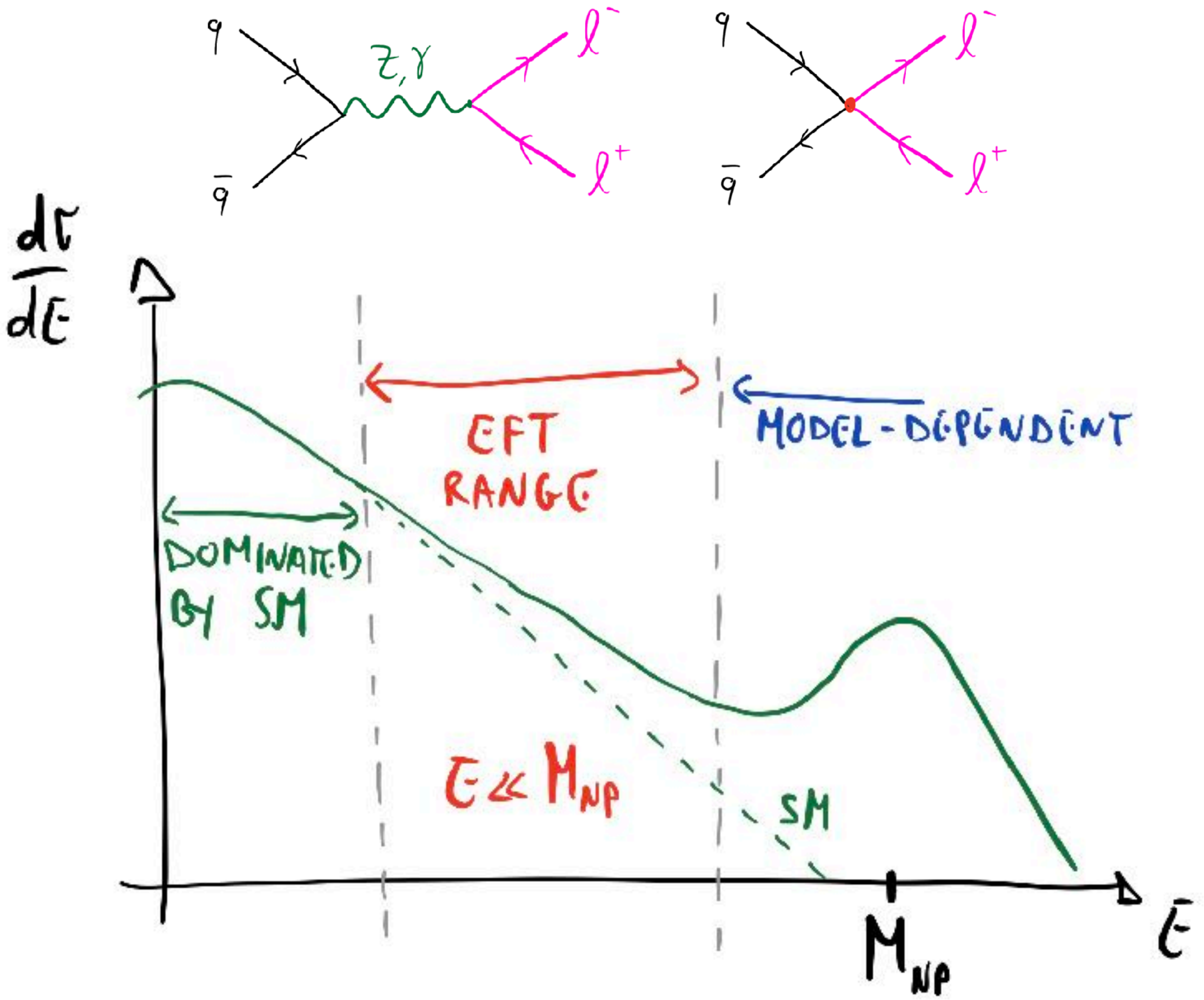


The **effect of heavy New Physics grows with the energy** until the scale of new states is reached.

$$m_{EW} \ll E \ll M_{NP}$$

$$\mathcal{A} \sim \frac{g_{SM}^2}{E^2} + \frac{c_{ij}}{M_{NP}^2} \sim \mathcal{A}_{SM}\left(1 + \frac{c_{ij}}{g_{SM}^2}\frac{E^2}{M_{NP}^2}\right)$$

High-Energy dilepton tails



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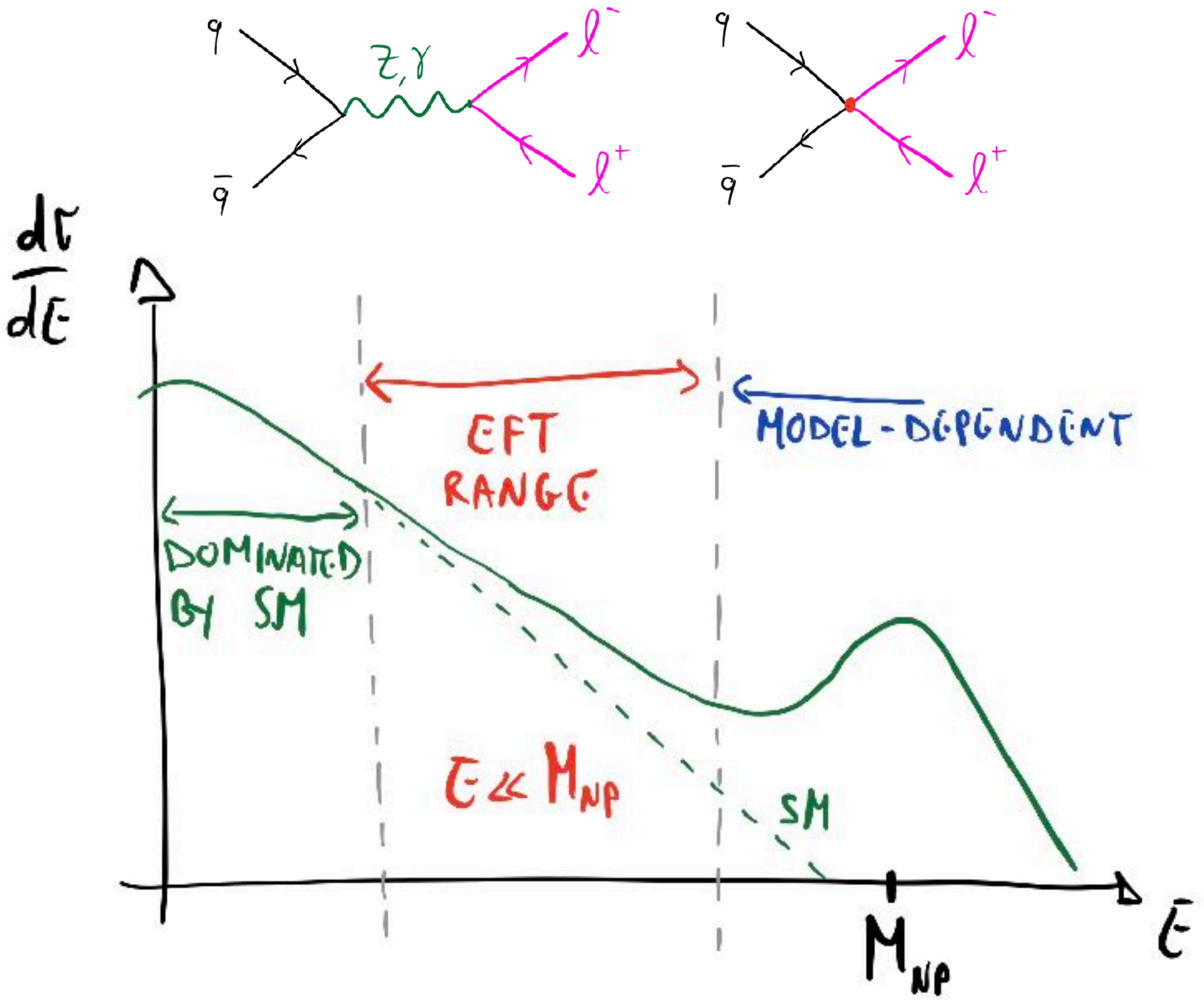

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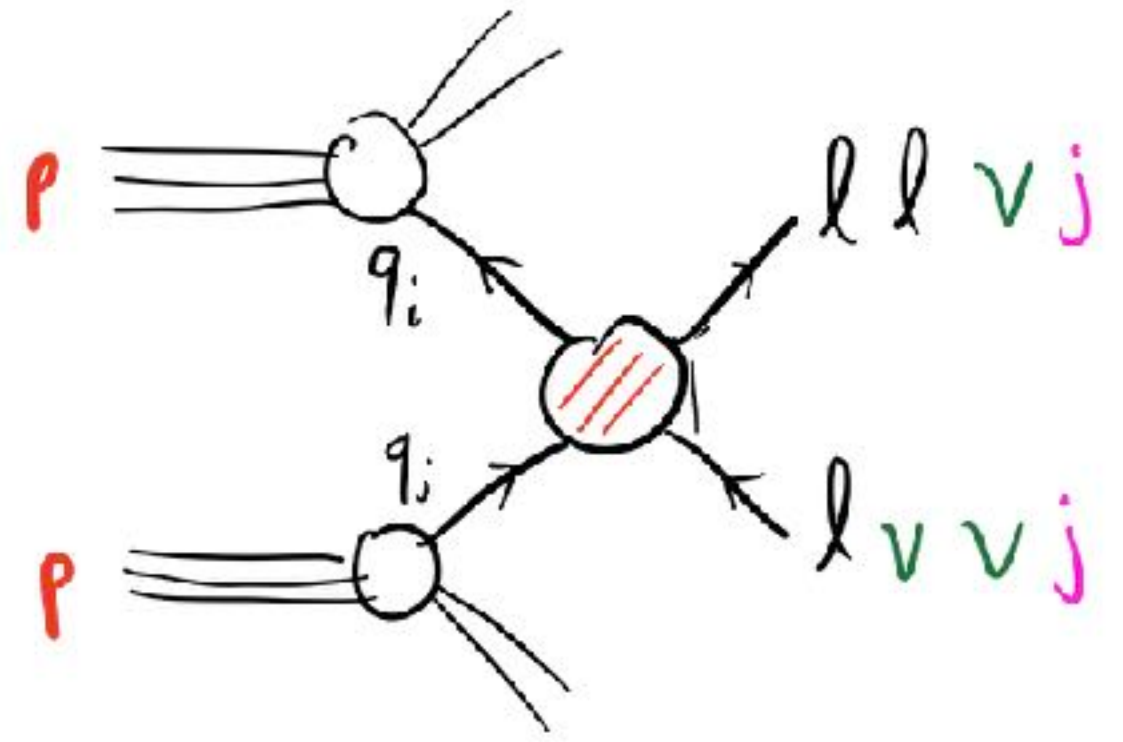
Expected reach:

At LHC: $\delta_{\text{tail}} \lesssim 10^{-1}$ $\xrightarrow{p \sim 2\ \text{TeV}}$ $\boldsymbol{\Lambda \gtrsim 6\ \text{TeV}}$

Less precise measurements at high energy can be competitive with very precise ones at low energy.

[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer 1609.08157, etc..]

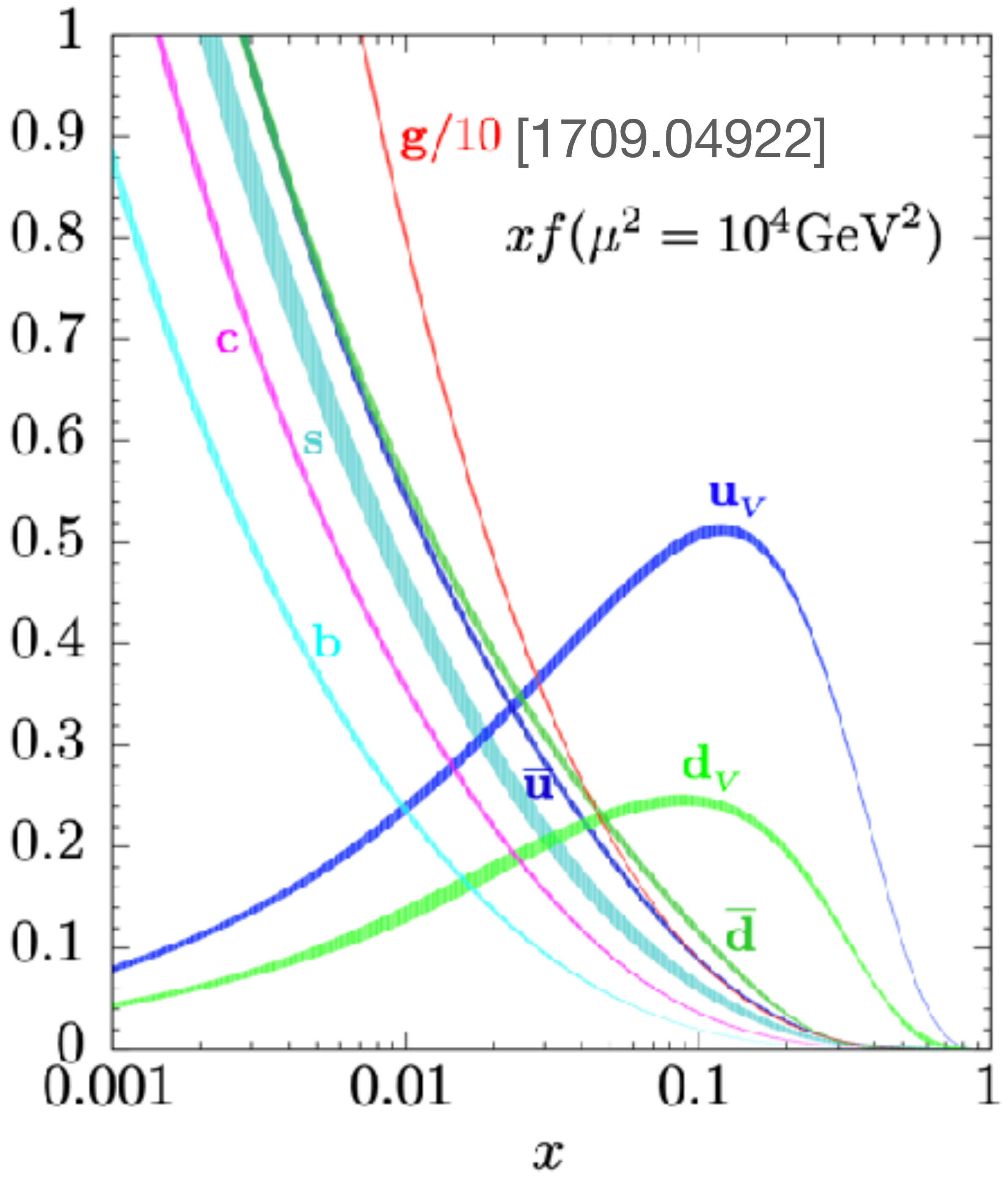
LHC as a “Flavor collider”



The differential cross section is approximately

$$\frac{d\sigma}{d\hat{s}}(\hat{s}) \sim \mathcal{L}_{\bar{q}_i q_j}(\hat{s})\, \sigma_{SM}(\hat{s})\left(\left| g^2_{SM}\,\delta_{ij} + C_{ij}\,\frac{\hat{s}}{M^2} \right|^2 + \kappa \left| \tilde{C}_{ij}\,\frac{\hat{s}}{M^2} \right|^2 \right)$$

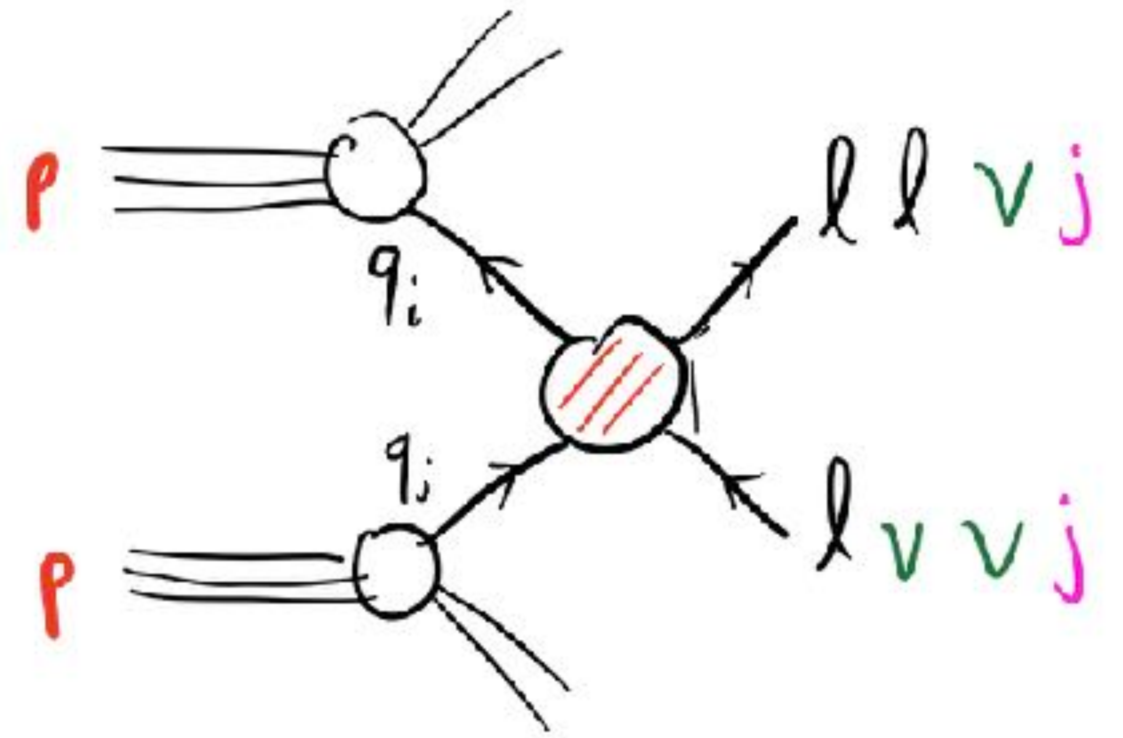
Protons contain all flavors



$$\mathcal{L}_{\bar{q}_i q_j}(\hat{s},\mu_F) = \int_{\hat{s}/s_0}^{1} \frac{dx}{x}\, \underbrace{f_{\bar{q}_i}(x,\mu_F)\, f_{q_j}\!\left(\frac{\hat{s}/s_0}{x},\mu_F\right)}_{\text{PDF}}$$

quark-antiquark luminosities

LHC as a “Flavor collider”



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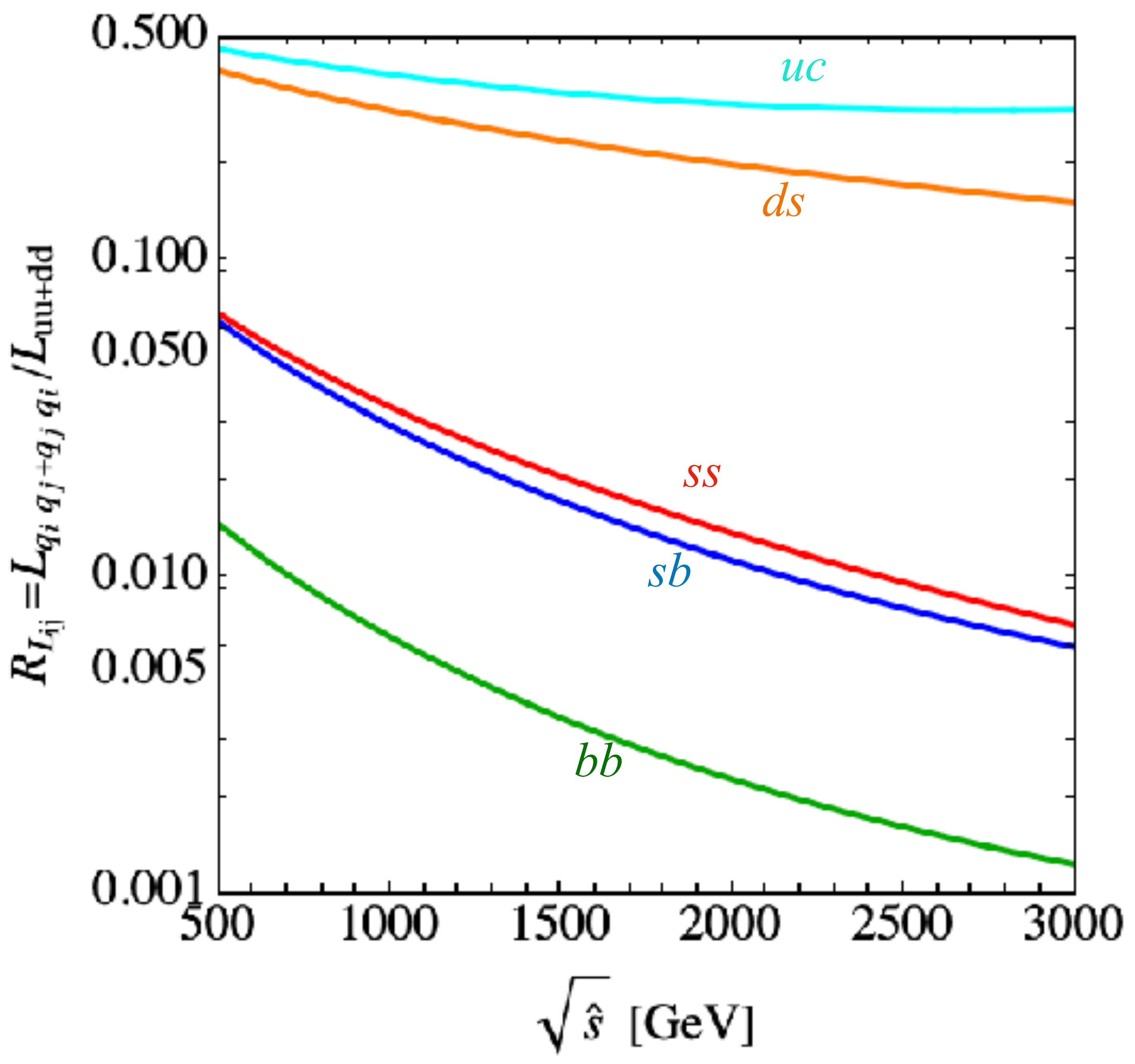
$$\frac{d\sigma}{d\hat{s}}(\hat{s}) \sim \mathcal{L}_{\bar{q}_i q_j}(\hat{s})\, \sigma_{SM}(\hat{s}) \left(\left| g_{SM}^2 \delta_{ij} + C_{ij} \frac{\hat{s}}{M^2} \right|^2 + \kappa \left| \tilde{C}_{ij} \frac{\hat{s}}{M^2} \right|^2 \right)$$

Let us estimate the reach of high-p_T tails

Relative deviation in a bin, due to EFT (assuming quadratic terms are dominant)

$$\frac{C_{ij}}{M^2} \equiv \frac{\epsilon_{ij}}{v^2}$$

$$\frac{\Delta\sigma}{\sigma_{SM}}(\hat{s}) \sim \underbrace{\frac{\mathcal{L}_{\bar{q}_i q_j} + \mathcal{L}_{\bar{q}_j q_i}}{\mathcal{L}_{\bar{d}d} + \mathcal{L}_{\bar{u}u}}}_{R_{\mathcal{L}_{ij}}} \left| \frac{\epsilon_{ij}}{g_{SM}^2} \frac{\hat{s}}{v^2} \right|^2$$



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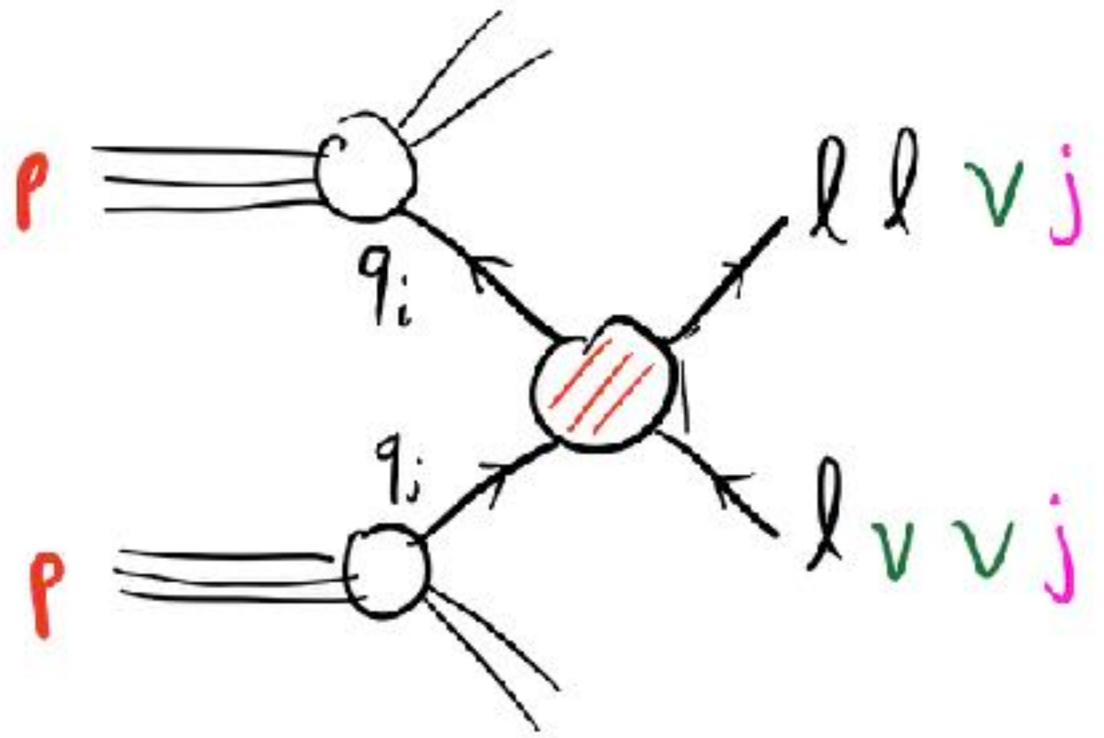

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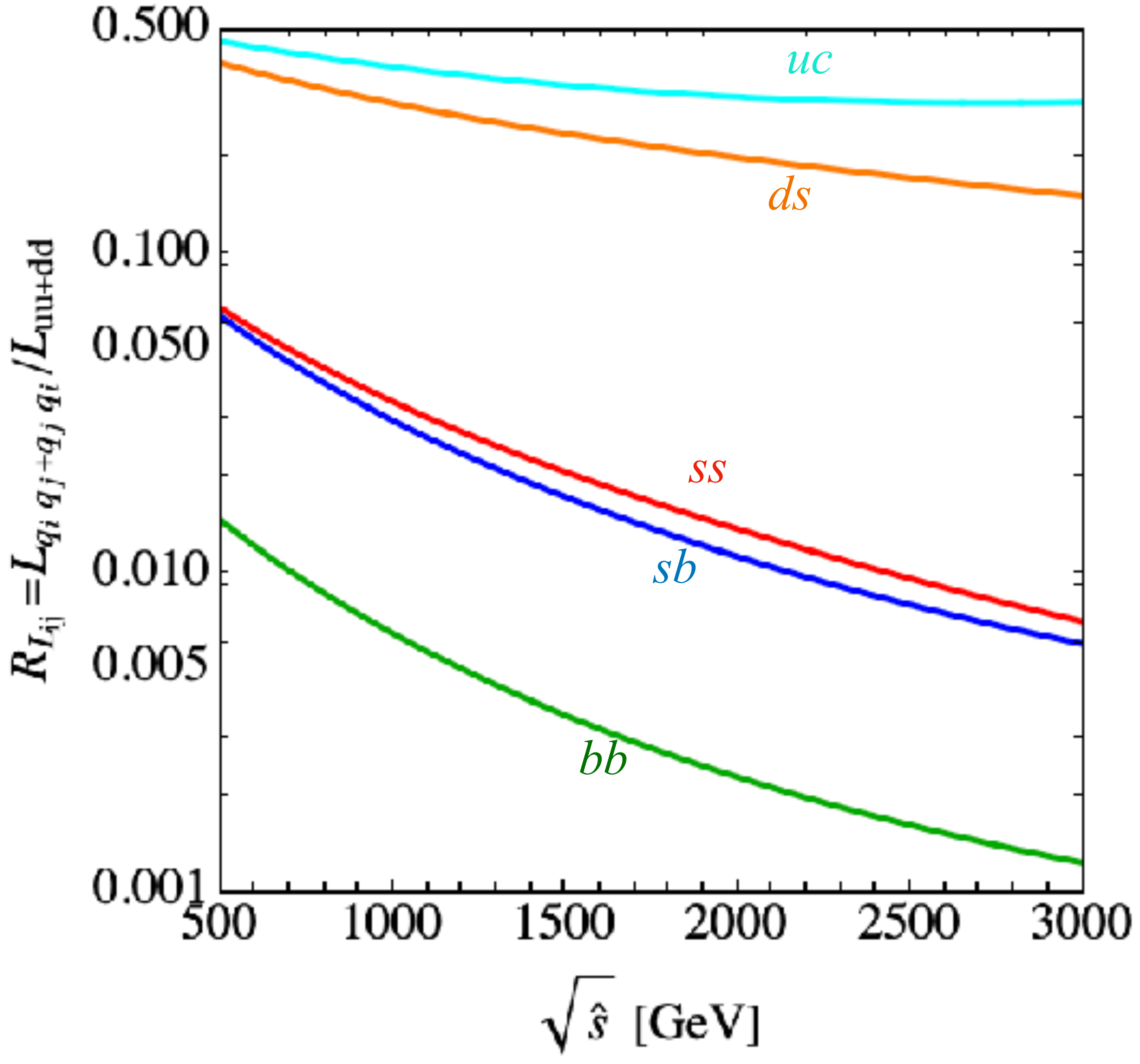


Example:

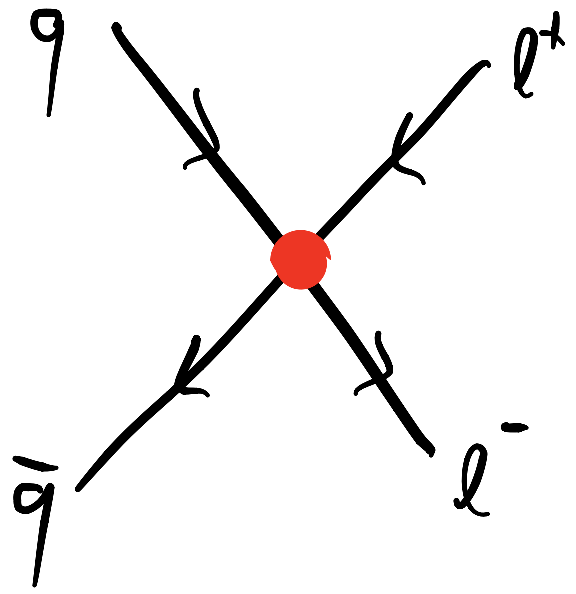
$\hat{s} = (2\ \text{TeV})^2$

$\Delta\sigma/\sigma \lesssim 10\%$

$g_{SM} \sim 0.4$

$$R_{\mathcal{L}_{ij}} = \begin{cases} 1 \to \varepsilon \lesssim 10^{-4} & M/\sqrt{c} \gtrsim 8.5\ \text{TeV} \\ 0.1 \to \varepsilon \lesssim 10^{-3} & M/\sqrt{c} \gtrsim 5\ \text{TeV} \\ 0.01 \to \varepsilon \lesssim 10^{-2} & M/\sqrt{c} \gtrsim 3\ \text{TeV} \end{cases}$$

Di-lepton tails at LHC



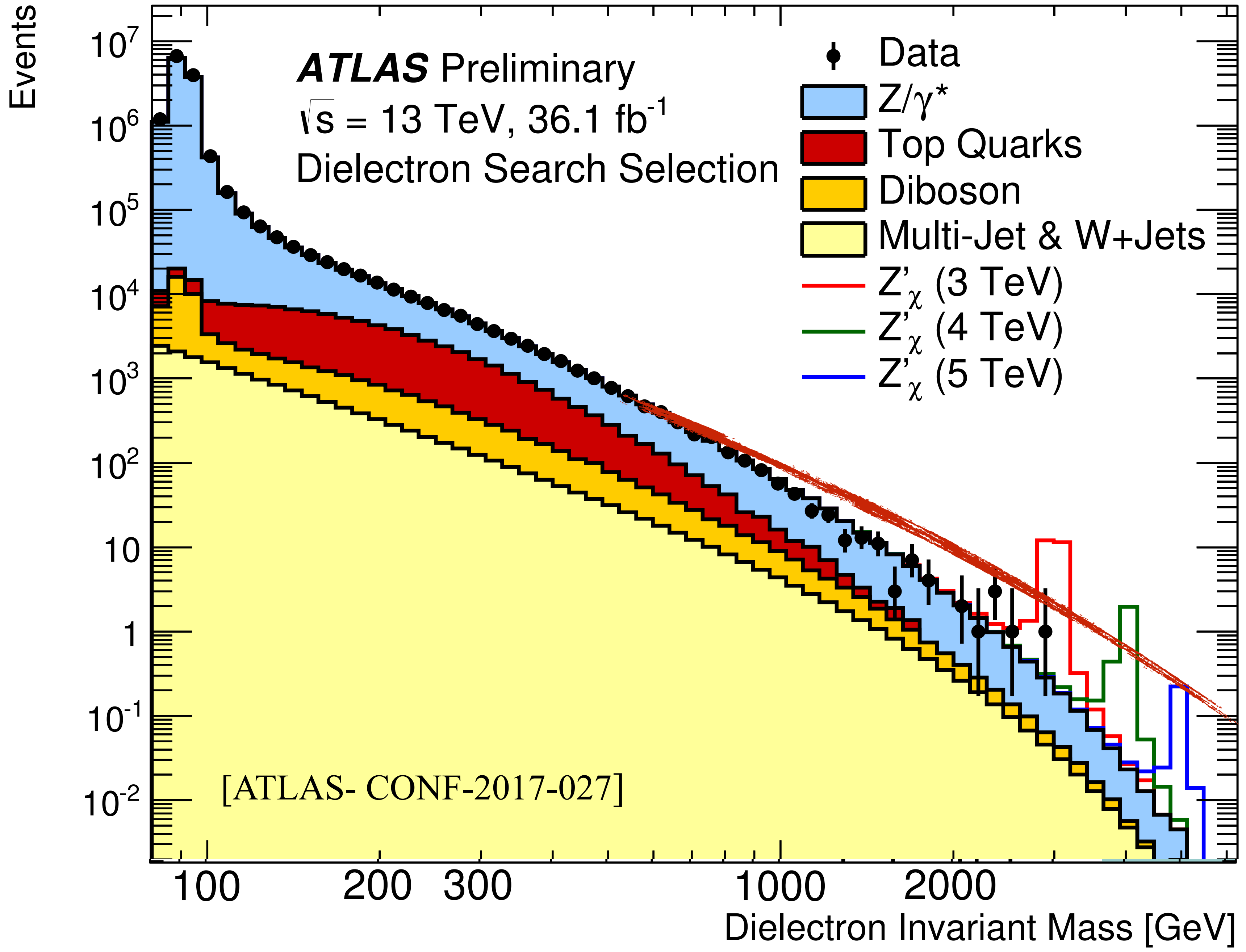
$$\mathcal{L}_{\rm SMEFT} = \sum_i \frac{C_i}{v^2}\mathcal{O}_i$$

$$C_x \equiv \frac{v^2}{\Lambda^2} c_x$$

Operators interfering with SM:

$(\mathcal{O}_{lq}^{(1)})_{\alpha i} = (\bar{l}_\alpha \gamma_\mu l_\alpha)(\bar{q}_i \gamma^\mu q_i)$	$(\mathcal{O}_{lq}^{(3)})_{\alpha i} = (\bar{l}_\alpha \gamma_\mu \sigma^a l_\alpha)(\bar{q}_i \gamma^\mu \sigma^a q_i)$
$(\mathcal{O}_{qe})_{i\alpha} = (\bar{q}_i \gamma^\mu q_i)(\bar{e}_\alpha \gamma^\mu e_\alpha)$	
$(\mathcal{O}_{lu})_{\alpha i} = (\bar{l}_\alpha \gamma_\mu l_\alpha)(\bar{u}_i \gamma^\mu u_i)$	$(\mathcal{O}_{ld})_{\alpha i} = (\bar{l}_\alpha \gamma_\mu l_\alpha)(\bar{d}_i \gamma^\mu d_i)$
$(\mathcal{O}_{eu})_{\alpha i} = (\bar{e}_\alpha \gamma_\mu e_\alpha)(\bar{u}_i \gamma^\mu u_i)$	$(\mathcal{O}_{ed})_{\alpha i} = (\bar{e}_\alpha \gamma_\mu e_\alpha)(\bar{d}_i \gamma^\mu d_i)$

Limits on flavor-conserving operators, recasting ATLAS 13TeV analysis: [Greljo, D.M. 1704.09015]



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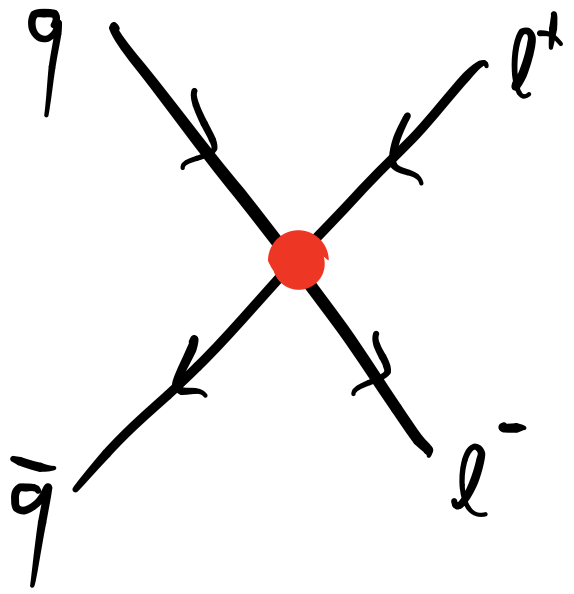

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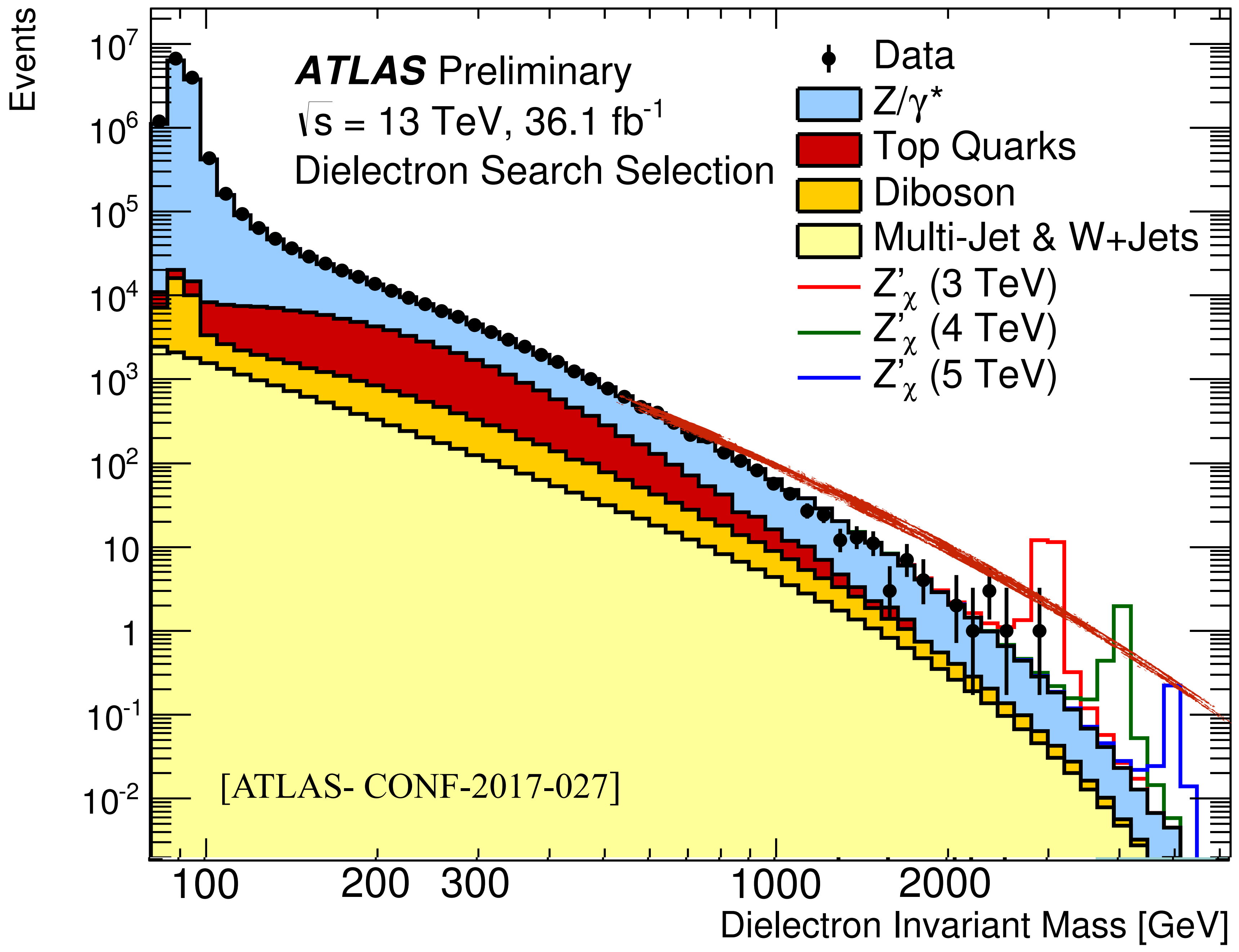
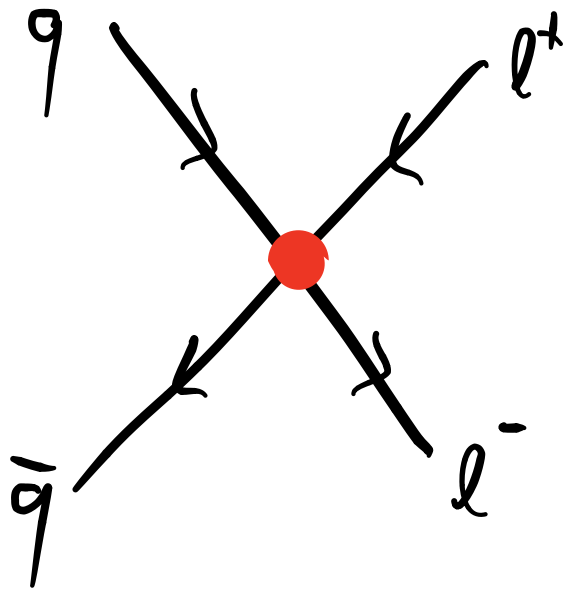


C_i	ATLAS 36.1 fb^{-1}	3000 fb^{-1}
$C^{(1)}_{Q^1L^1}$	[-0.0, 1.75] $\times 10^{-3}$	[-1.01, 1.13] $\times 10^{-4}$
$C^{(3)}_{Q^1L^1}$	[-8.92, -0.54] $\times 10^{-4}$	[-3.99, 3.93] $\times 10^{-5}$
$C_{u_RL^1}$	[-0.19, 1.92] $\times 10^{-3}$	[-1.56, 1.92] $\times 10^{-4}$
$C_{u_Re_R}$	[0.15, 2.06] $\times 10^{-3}$	[-7.89, 8.23] $\times 10^{-5}$
$C_{Q^1e_R}$	[-0.40, 1.37] $\times 10^{-3}$	[-1.8, 2.85] $\times 10^{-4}$
$C_{d_RL^1}$	[-2.1, 1.04] $\times 10^{-3}$	[-7.59, 4.23] $\times 10^{-4}$
$C_{d_Re_R}$	[-2.55, 0.46] $\times 10^{-3}$	[-3.37, 2.59] $\times 10^{-4}$
$C^{(1)}_{Q^2L^1}$	[-6.62, 4.36] $\times 10^{-3}$	[-3.31, 1.92] $\times 10^{-3}$
$C^{(3)}_{Q^2L^1}$	[-8.24, 2.05] $\times 10^{-3}$	[-8.87, 7.90] $\times 10^{-4}$
$C_{Q^2e_R}$	[-4.67, 6.34] $\times 10^{-3}$	[-2.11, 3.30] $\times 10^{-3}$
$C_{s_RL^1}$	[-7.4 , 5.9] $\times 10^{-3}$	[-3.96, 2.8] $\times 10^{-3}$
$C_{s_Re_R}$	[-8.17, 5.06] $\times 10^{-3}$	[-3.82, 2.13] $\times 10^{-3}$
$C_{c_RL^1}$	[-0.83, 1.13] $\times 10^{-2}$	[-3.74, 5.77] $\times 10^{-3}$
$C_{c_Re_R}$	[-0.67, 1.27] $\times 10^{-2}$	[-2.59, 4.17] $\times 10^{-3}$
$C_{b_LL^1}$	[-1.93, 1.19] $\times 10^{-2}$	[-8.62, 4.82] $\times 10^{-3}$
$C_{b_Le_R}$	[-1.47, 1.67] $\times 10^{-2}$	[-7.29, 8.99] $\times 10^{-3}$
$C_{b_RL^1}$	[-1.65, 1.49] $\times 10^{-2}$	[-8.86, 7.48] $\times 10^{-3}$
$C_{b_Re_R}$	[-1.73, 1.40] $\times 10^{-2}$	[-9.38, 6.63] $\times 10^{-3}$

C_i	ATLAS 36.1 fb^{-1}	3000 fb^{-1}
$C^{(1)}_{Q^1L^2}$	[-5.73, 14.2] $\times 10^{-4}$	[-1.30, 1.51] $\times 10^{-4}$
$C^{(3)}_{Q^1L^2}$	[-7.11, 2.84] $\times 10^{-4}$	[-5.25, 5.25] $\times 10^{-5}$
$C_{u_RL^2}$	[-0.84, 1.61] $\times 10^{-3}$	[-2.00, 2.66] $\times 10^{-4}$
$C_{u_R\mu_R}$	[-0.52, 1.36] $\times 10^{-3}$	[-1.04, 1.08] $\times 10^{-4}$
$C_{Q^1\mu_R}$	[-0.82, 1.27] $\times 10^{-3}$	[-2.25, 4.10] $\times 10^{-4}$
$C_{d_RL^2}$	[-2.13, 1.61] $\times 10^{-3}$	[-8.98, 5.11] $\times 10^{-4}$
$C_{d_R\mu_R}$	[-2.31, 1.34] $\times 10^{-3}$	[-4.89, 3.33] $\times 10^{-4}$
$C^{(1)}_{Q^2L^2}$	[-8.84, 7.35] $\times 10^{-3}$	[-3.83, 2.39] $\times 10^{-3}$
$C^{(3)}_{Q^2L^2}$	[-9.75, 5.56] $\times 10^{-3}$	[-1.43, 1.15] $\times 10^{-3}$
$C_{Q^2\mu_R}$	[-7.53, 8.67] $\times 10^{-3}$	[-2.58, 3.73] $\times 10^{-3}$
$C_{s_RL^2}$	[-1.04 , 0.93] $\times 10^{-2}$	[-4.42, 3.33] $\times 10^{-3}$
$C_{s_R\mu_R}$	[-1.09 , 0.87] $\times 10^{-2}$	[-4.67, 2.73] $\times 10^{-3}$
$C_{c_RL^2}$	[-1.33, 1.52] $\times 10^{-2}$	[-4.58, 6.54] $\times 10^{-3}$
$C_{c_R\mu_R}$	[-1.21, 1.62] $\times 10^{-2}$	[-3.48, 6.32] $\times 10^{-3}$
$C_{b_LL^2}$	[-2.61, 2.07] $\times 10^{-2}$	[-11.1, 6.33] $\times 10^{-3}$
$C_{b_L\mu_R}$	[-2.28, 2.42] $\times 10^{-2}$	[-8.53, 10.0] $\times 10^{-3}$
$C_{b_RL^2}$	[-2.41, 2.29] $\times 10^{-2}$	[-9.90, 8.68] $\times 10^{-3}$
$C_{b_R\mu_R}$	[-2.47, 2.23] $\times 10^{-2}$	[-10.5, 7.97] $\times 10^{-3}$

Di-lepton tails at LHC



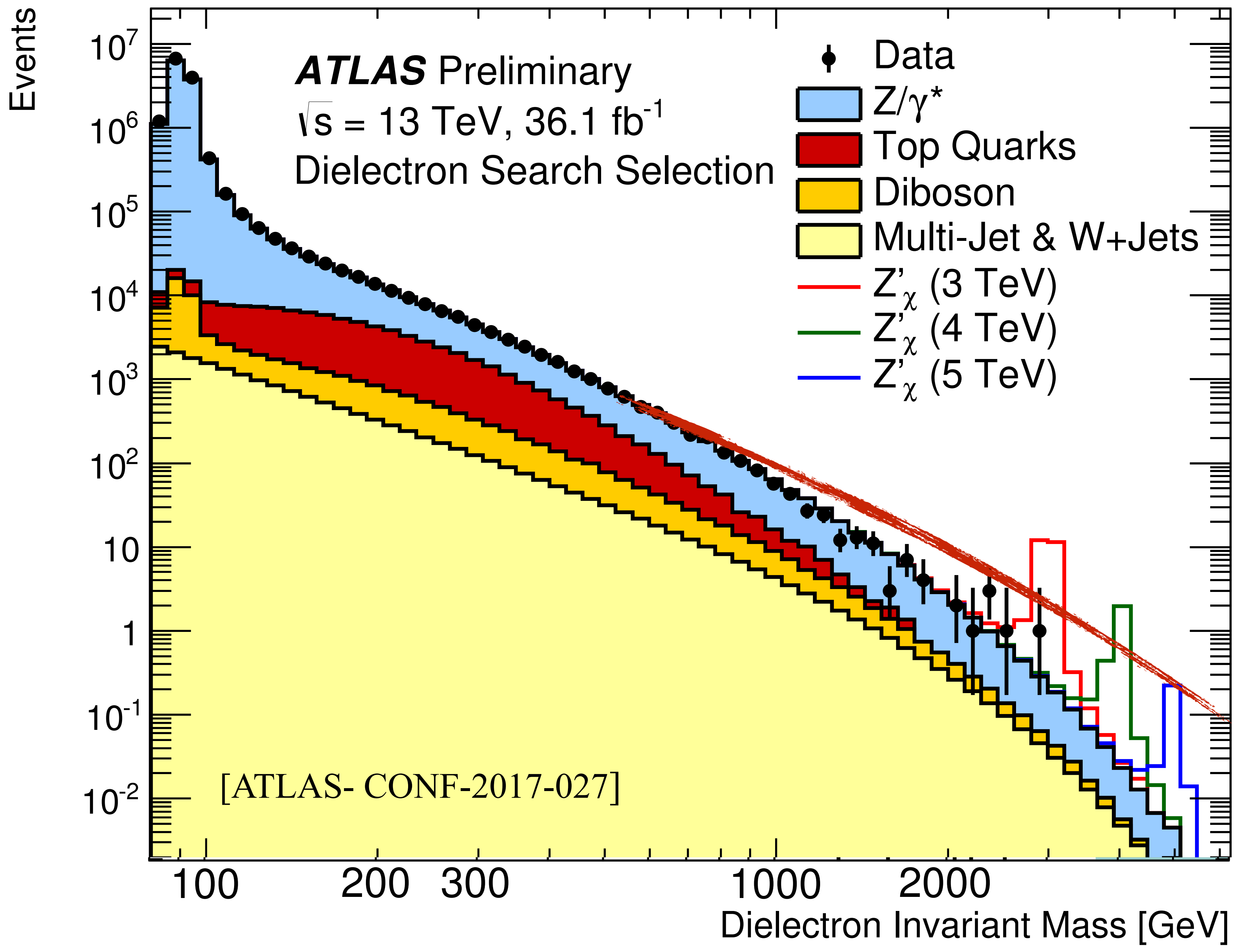
$$\mathcal{L}_{\rm SMEFT} = \sum_i \frac{C_i}{v^2}\mathcal{O}_i$$

$$C_x \equiv \frac{v^2}{\Lambda^2} c_x$$

Operators interfering with SM:

$(\mathcal{O}^{(1)}_{lq})_{\alpha i} = (\bar{l}_\alpha\gamma_\mu l_\alpha)(\bar{q}_i\gamma^\mu q_i)$	$(\mathcal{O}^{(3)}_{lq})_{\alpha i} = (\bar{l}_\alpha\gamma_\mu\sigma^a l_\alpha)(\bar{q}_i\gamma^\mu\sigma^a q_i)$
$(\mathcal{O}_{qe})_{i\alpha} = (\bar{q}_i\gamma^\mu q_i)(\bar{e}_\alpha\gamma^\mu e_\alpha)$	
$(\mathcal{O}_{lu})_{\alpha i} = (\bar{l}_\alpha\gamma_\mu l_\alpha)(\bar{u}_i\gamma^\mu u_i)$	$(\mathcal{O}_{ld})_{\alpha i} = (\bar{l}_\alpha\gamma_\mu l_\alpha)(\bar{d}_i\gamma^\mu d_i)$
$(\mathcal{O}_{eu})_{\alpha i} = (\bar{e}_\alpha\gamma_\mu e_\alpha)(\bar{u}_i\gamma^\mu u_i)$	$(\mathcal{O}_{ed})_{\alpha i} = (\bar{e}_\alpha\gamma_\mu e_\alpha)(\bar{d}_i\gamma^\mu d_i)$

Limits on flavor-conserving operators, recasting ATLAS 13TeV analysis: [Greljo, D.M. 1704.09015]



C_i	ATLAS 36.1 fb^{-1}	3000 fb^{-1}
$C^{(1)}_{Q^1L^1}$	[-0.0, 1.75] $\times 10^{-3}$	[-1.01, 1.13] $\times 10^{-4}$
$C^{(3)}_{Q^1L^1}$	[-8.92, -0.54] $\times 10^{-4}$	
$C_{u_RL^1}$	[-0.19, 1.92] $\times 10^{-3}$	
$C_{u_Re_R}$	[0.15, 2.06] $\times 10^{-3}$	
$C_{Q^1e_R}$	[-0.40, 1.37] $\times 10^{-3}$	
$C_{d_RL^1}$	[-2.1, 1.04] $\times 10^{-3}$	
$C_{d_Re_R}$	[-2.55, 0.46] $\times 10^{-3}$	
$C^{(1)}_{Q^2L^1}$	[-6.62, 4.36] $\times 10^{-3}$	
$C^{(3)}_{Q^2L^1}$	[-8.24, 2.05] $\times 10^{-3}$	
$C_{Q^2e_R}$	[-4.67, 6.34] $\times 10^{-3}$	
$C_{s_RL^1}$	[-7.4 , 5.9] $\times 10^{-3}$	
$C_{s_Re_R}$	[-8.17, 5.06] $\times 10^{-3}$	
$C_{c_RL^1}$	[-0.83, 1.13] $\times 10^{-2}$	
$C_{c_Re_R}$	[-0.67, 1.27] $\times 10^{-2}$	
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Approximately:

$\Lambda/\sqrt{c_i} \gtrsim$ 7 TeV 1st gen.
3.5 TeV 2nd gen.
2.5 TeV 3rd gen.

5-10 -fold improvement at HL-LHC

Di-lepton tails at LHC

More recent developments

Tool included in **flavio**.

[Greljo, Salko, Smolkovic, Stangl 2212.10497]

Implemented analyses with NC and CC channels with muons and electrons and ~140 fb^{-1} of luminosity. All relevant SMEFT operators included.

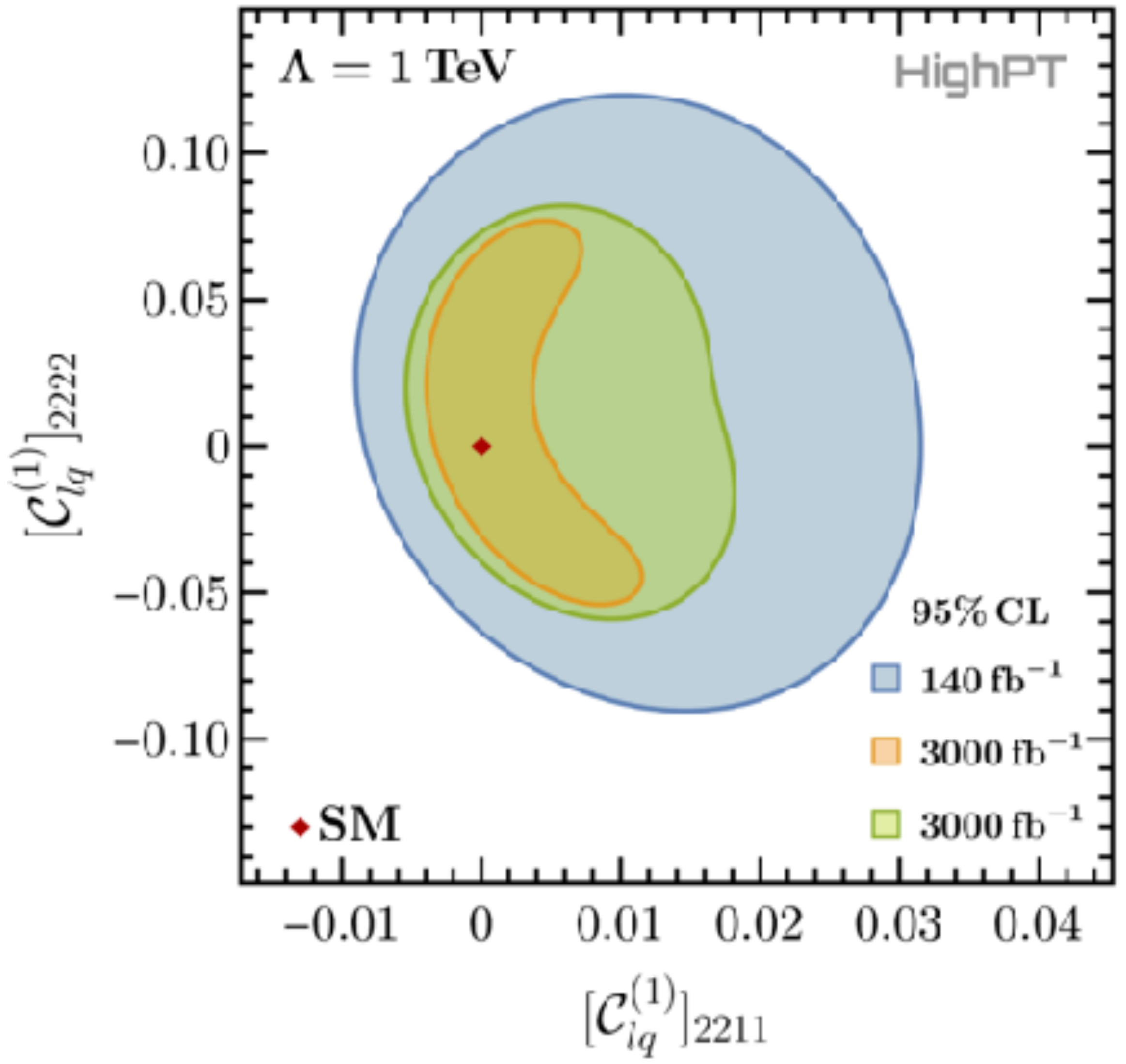
HighPT

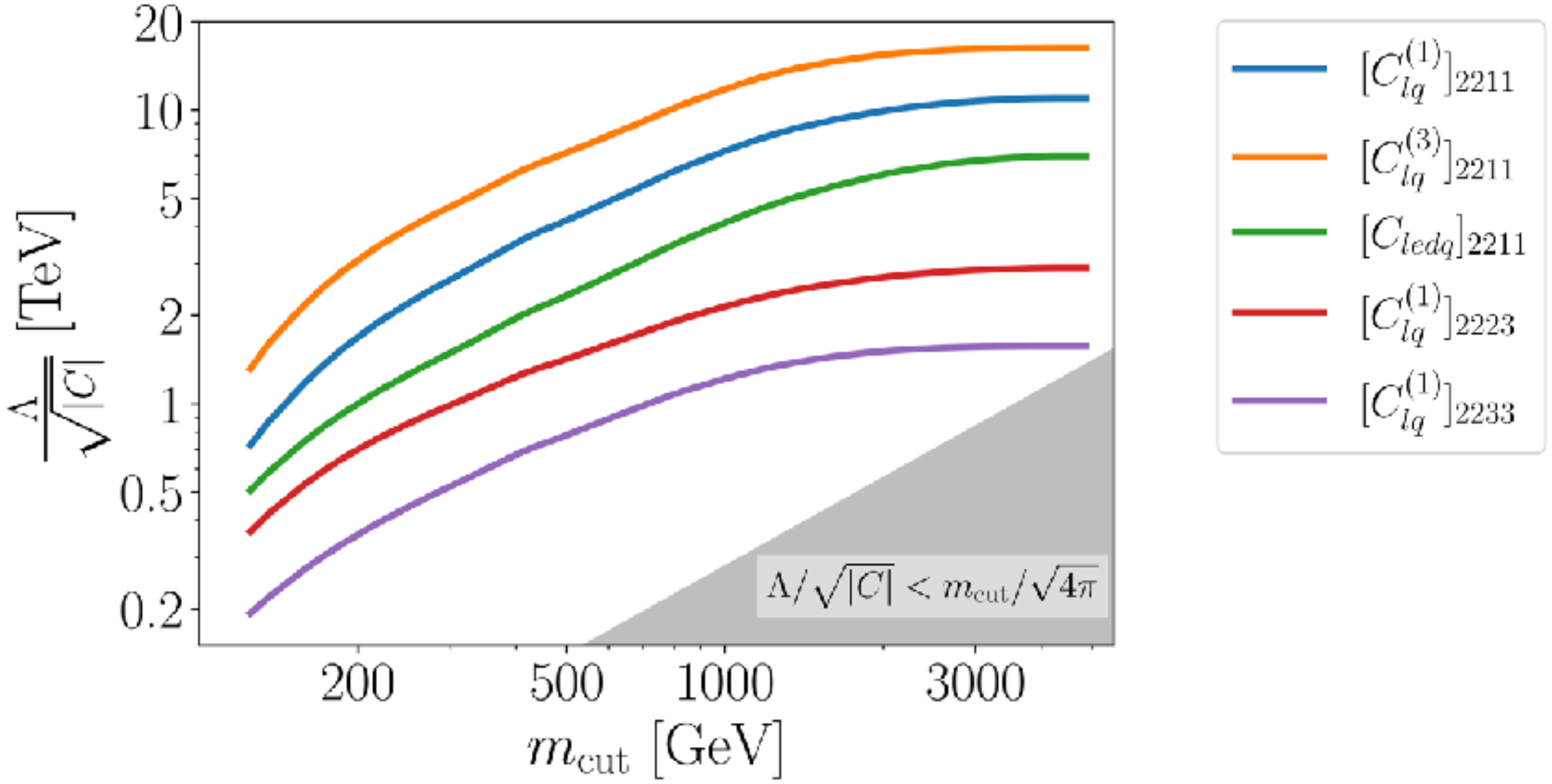
Mathematica package.

[Allwicher, Faroughy, Jaffredo, Sumensary, Wilsch 2207.10714, 2207.10756]

Implemented analyses with NC and CC channels with muons, electrons, and taus. and ~140 fb^{-1} of luminosity.

All relevant SMEFT operators included, plus also some explicit mediator models.





LFU in High-Energy dilepton tails

To test directly deviations from LFU we can define the **differential LFU ratio**:

[Greljo, D.M. 1704.09015]

$$R_{\mu^+\mu^-/e^+e^-}(m_{\ell\ell}) \equiv \frac{d\sigma_{\mu\mu}}{dm_{\ell\ell}} \Big/ \frac{d\sigma_{ee}}{dm_{\ell\ell}}$$

QCD and EW corrections are flavour universal: such ratios will reduce theory uncertainties in the SM prediction (including pdf).

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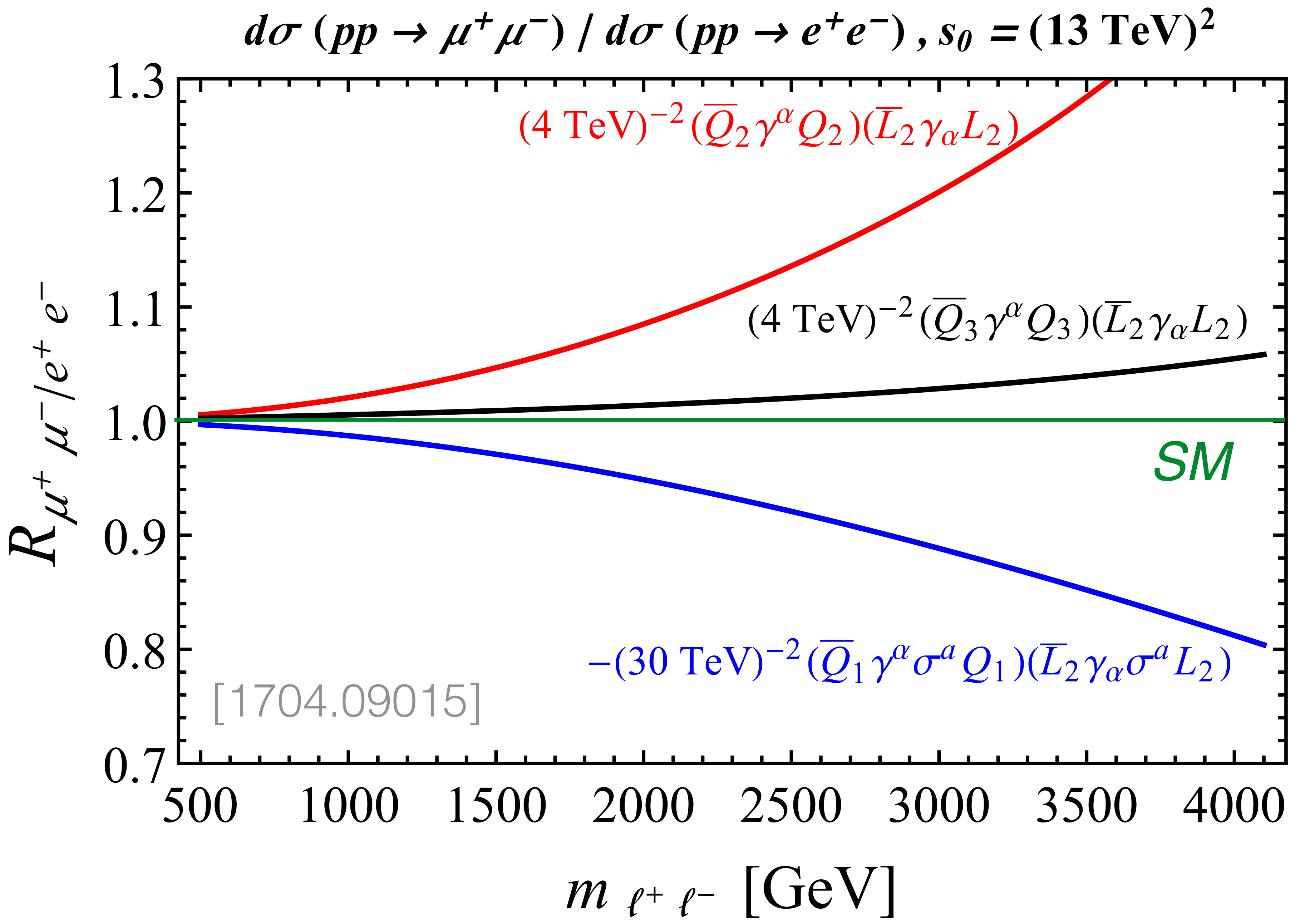

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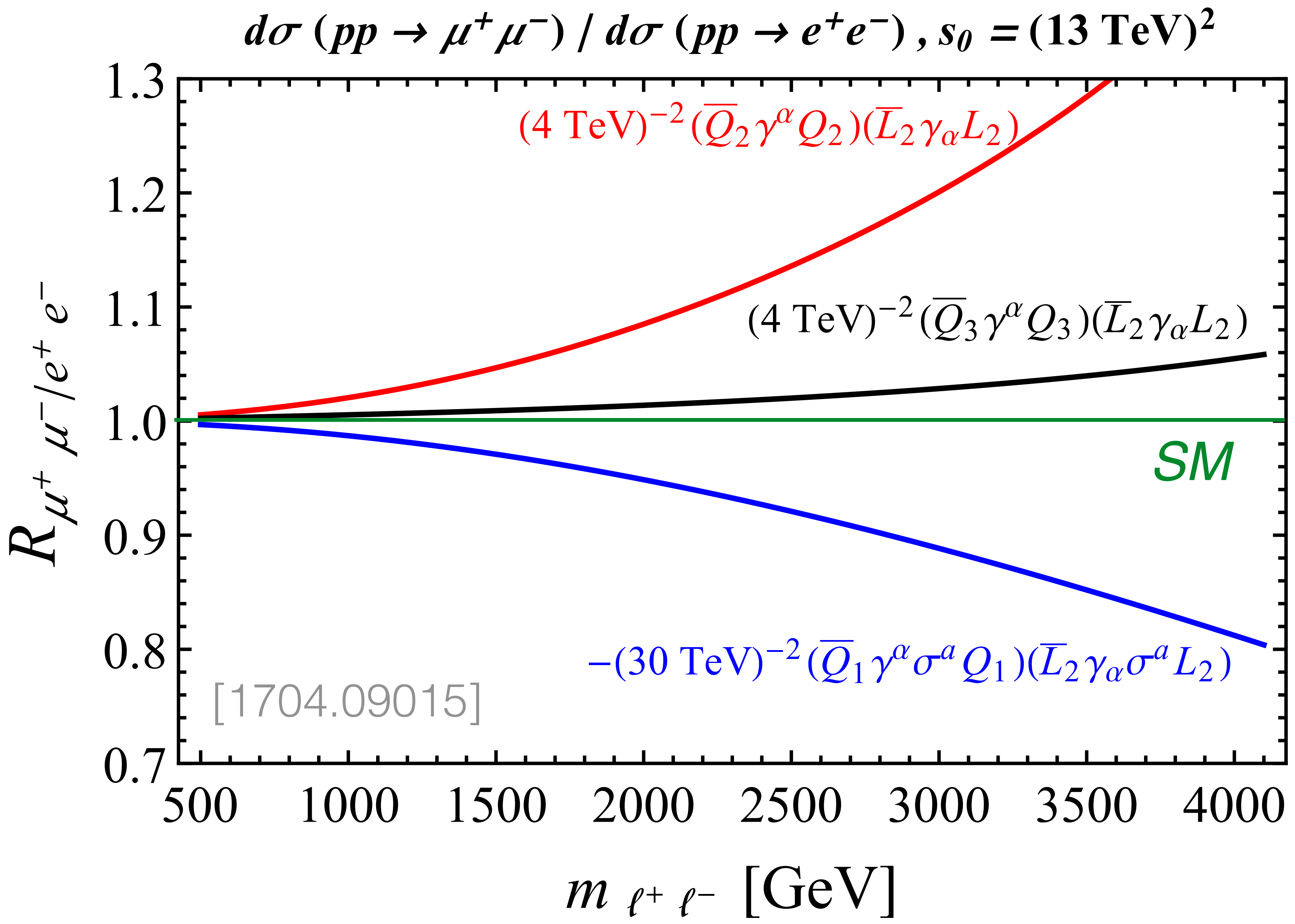

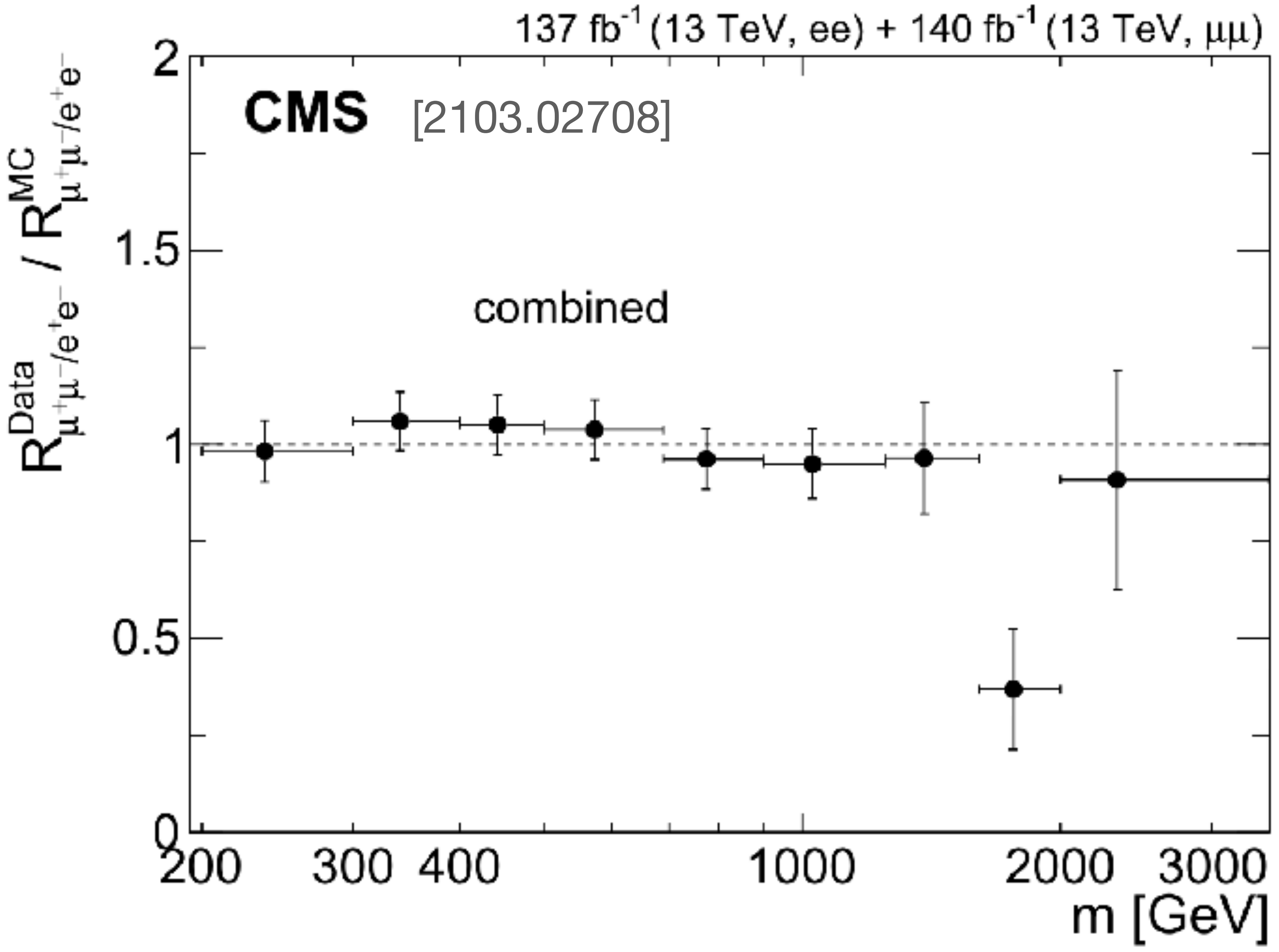

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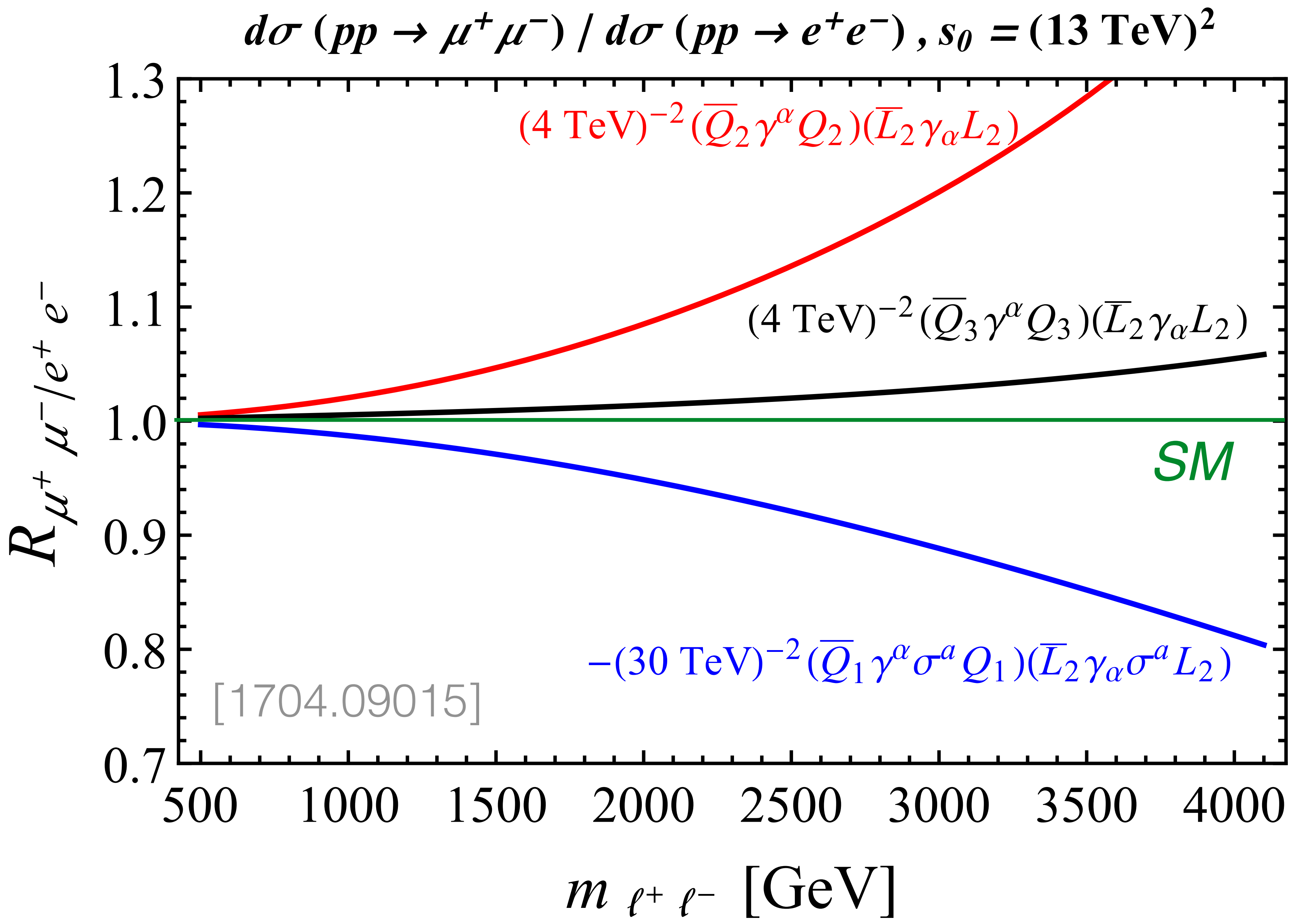
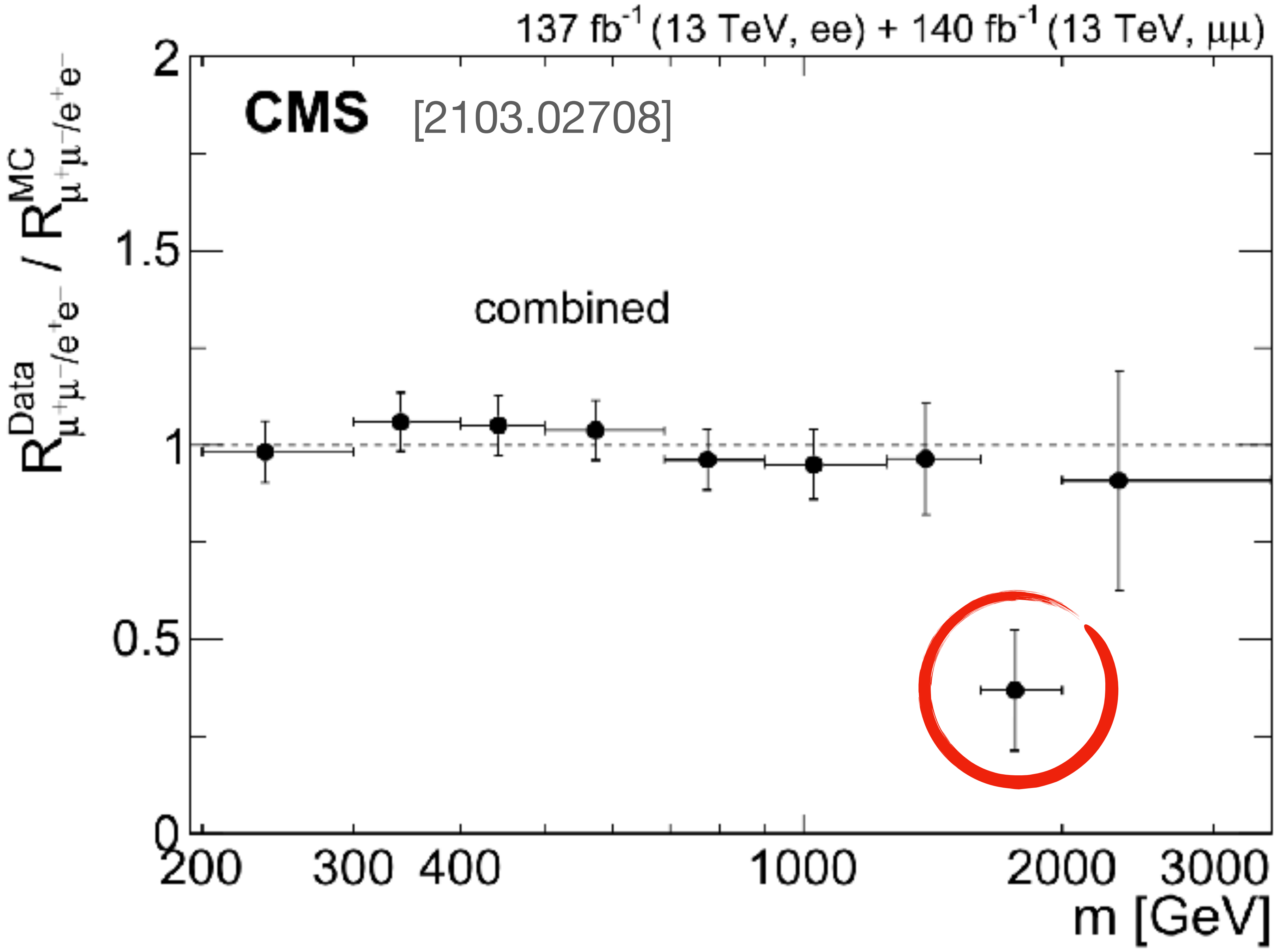
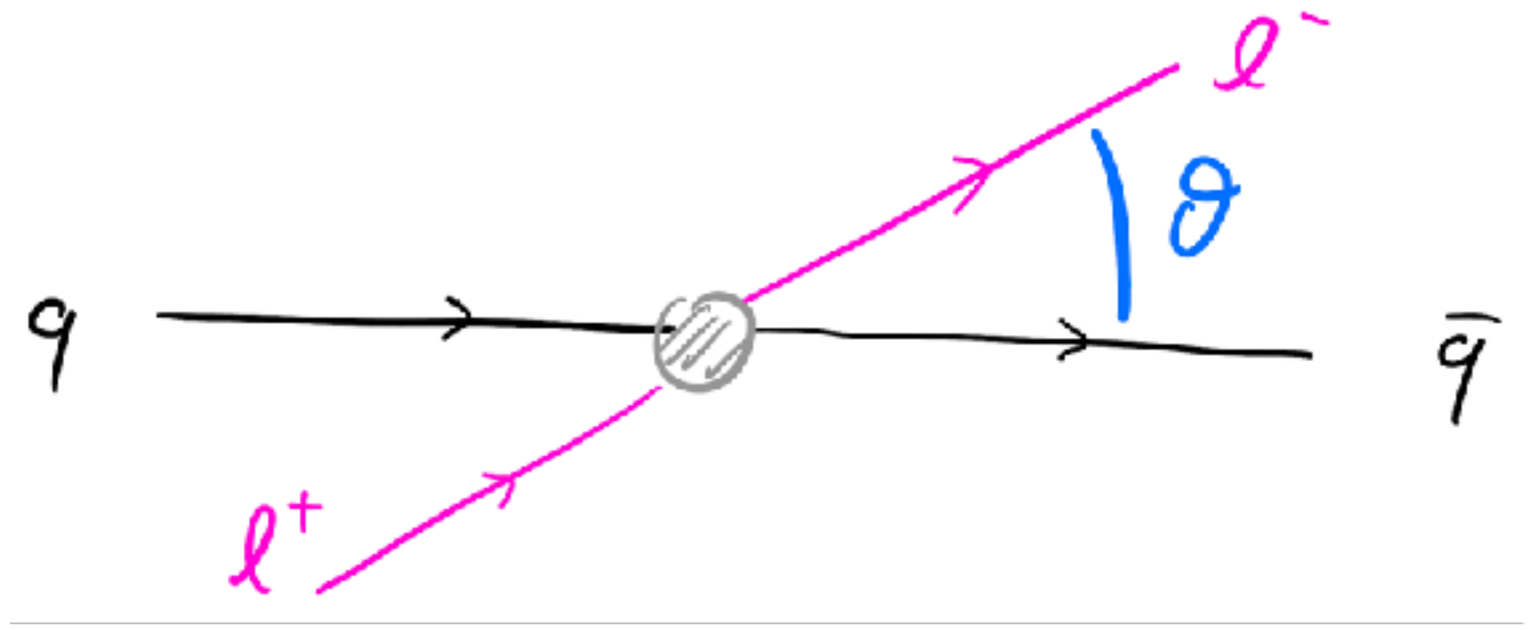




~4σ at face value. The deviation is due to an excess in the electron channel.

LFU in dilepton forward-backward asymm.

Allow reduced systematic uncertainties related to the reconstruction and identification of high-momentum leptons.



$\sigma_F: \cos\vartheta > 0$

$\sigma_B: \cos\vartheta < 0$

$$A_{\mathrm{FB}} = \frac{\sigma_{\mathrm{F}} - \sigma_{\mathrm{B}}}{\sigma_{\mathrm{F}} + \sigma_{\mathrm{B}}}$$

In pp collisions the angle is measured w.r.t. the direction of the longitudinal momentum of the dilepton system (since typically valence quarks carry more momentum than antiquarks)

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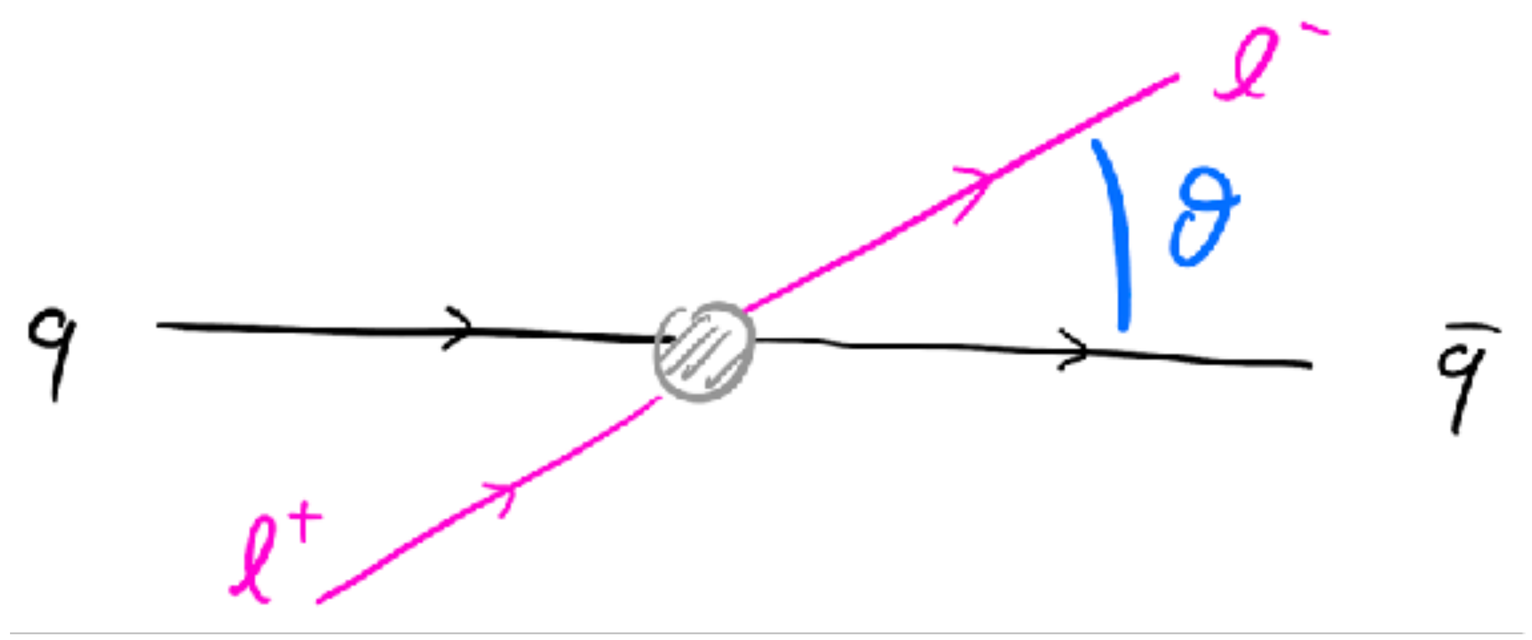

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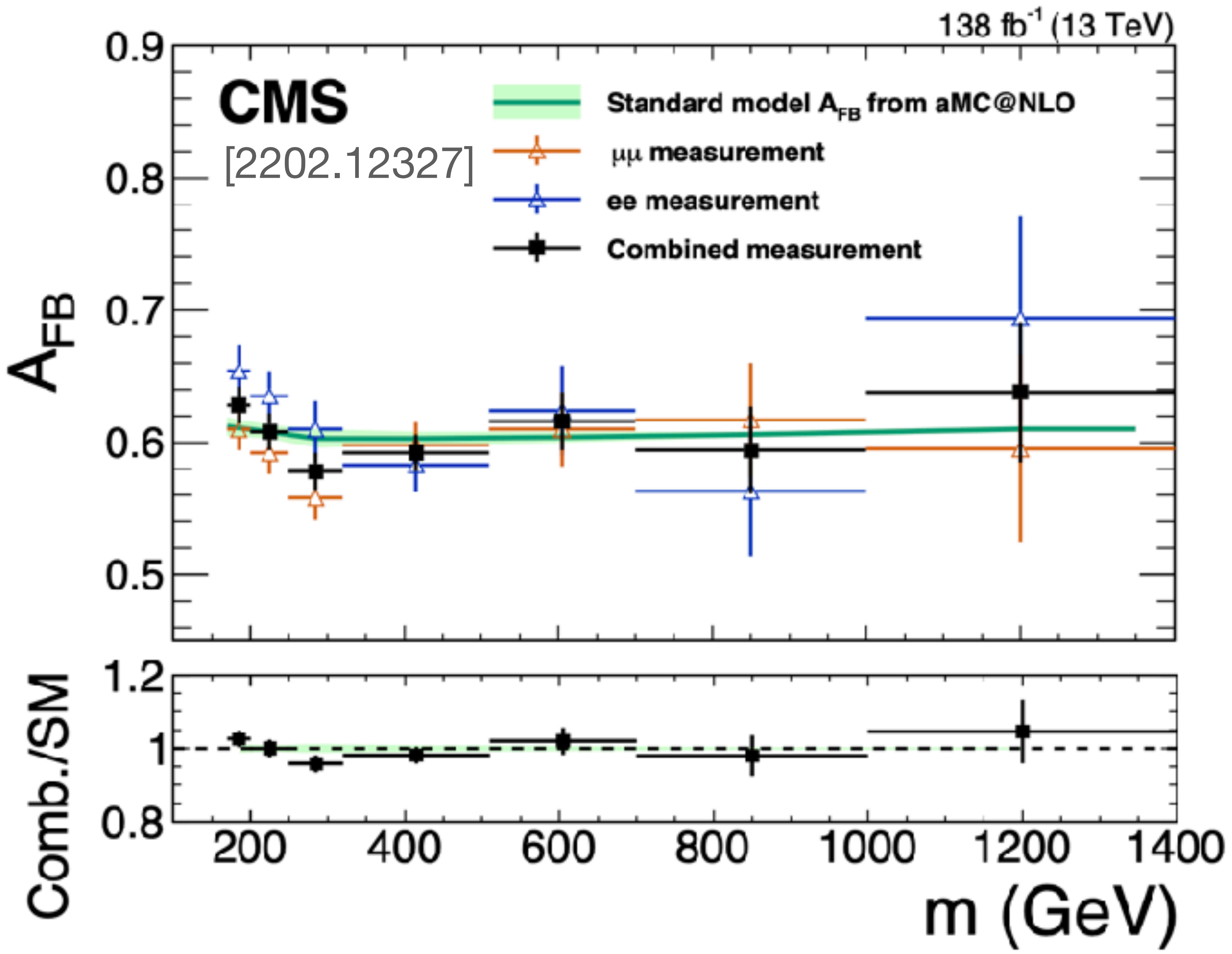
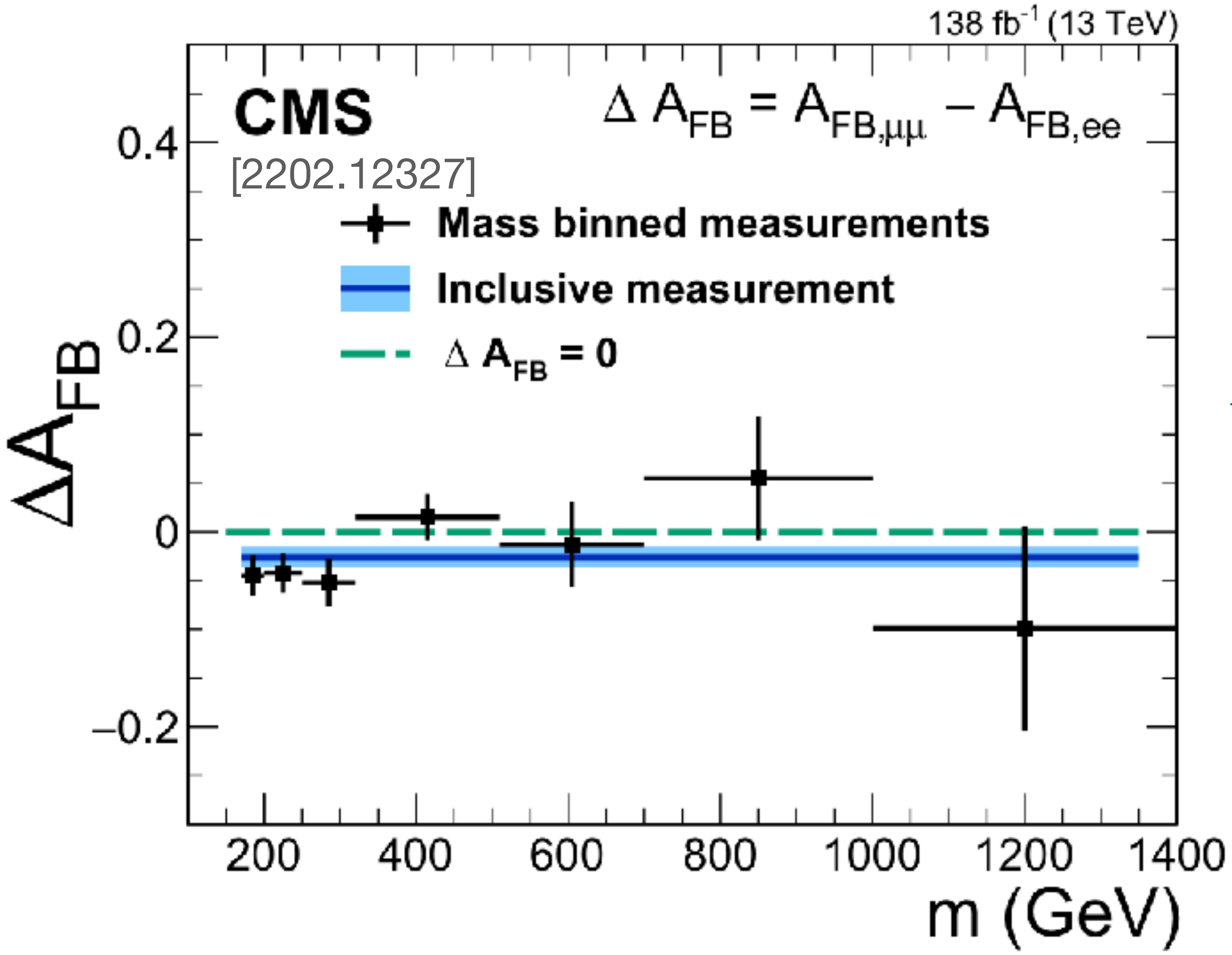


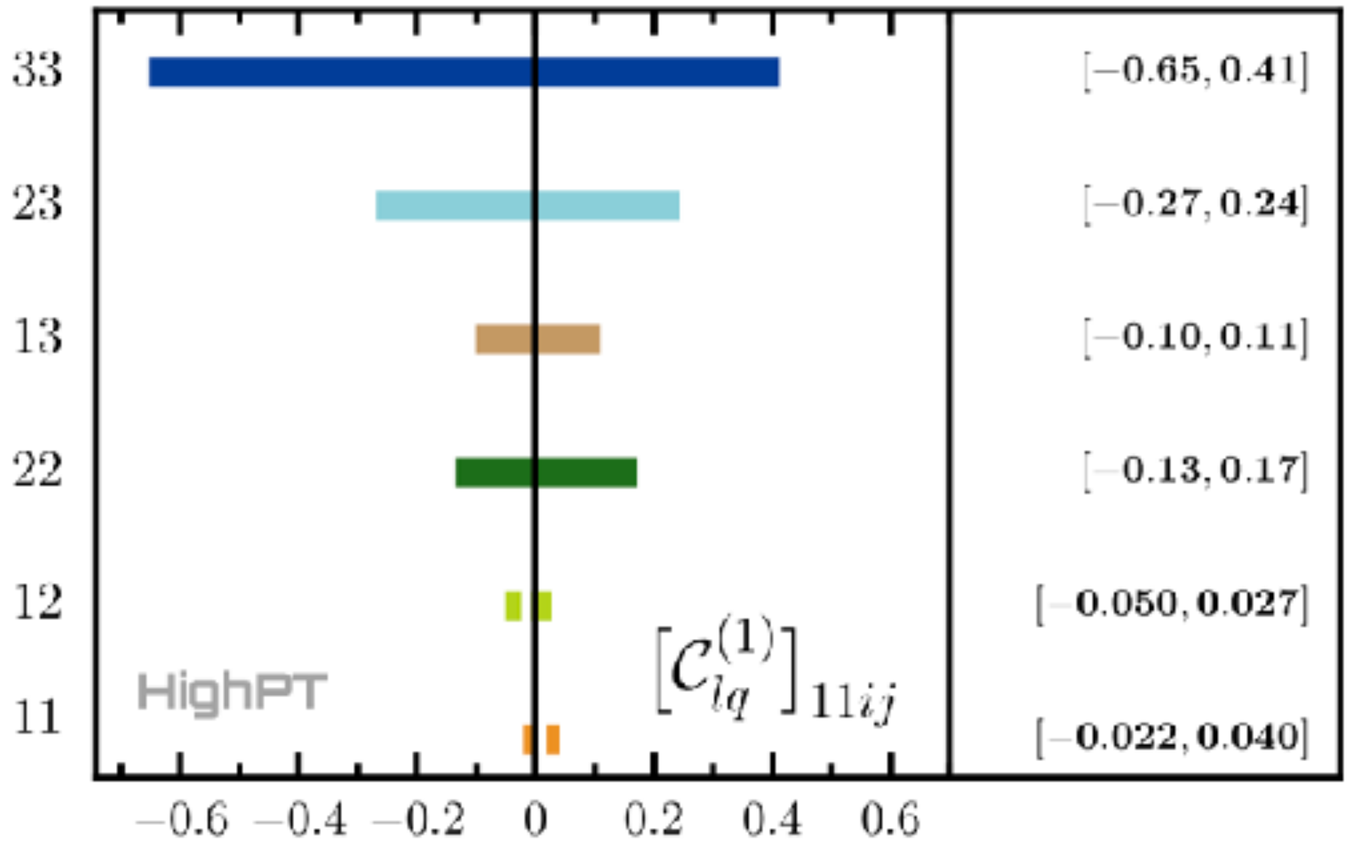


The deviation in the inclusive measurement is ~2.4σ.
Seems mostly due to low energy bins.

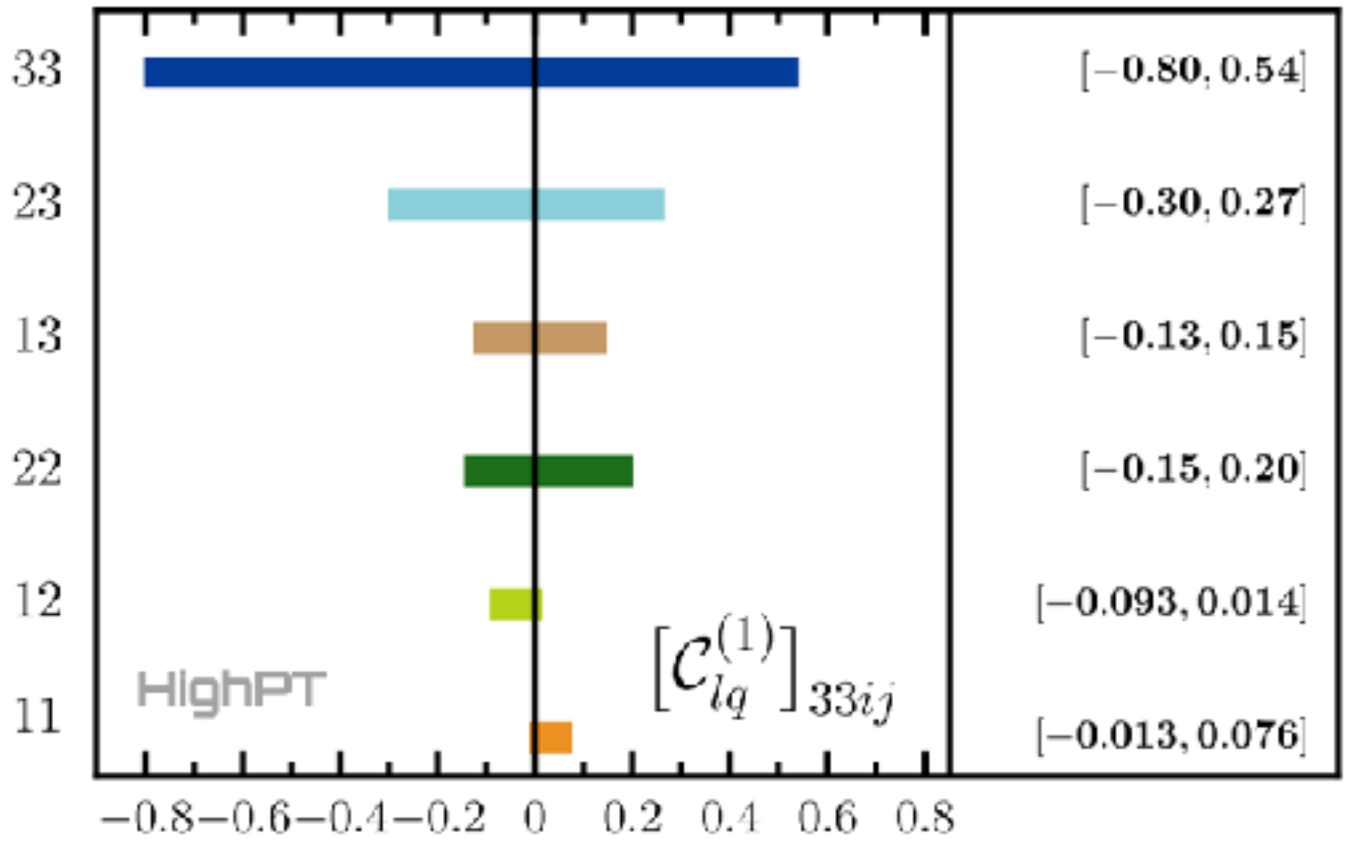
di-tau and mono-tau tails

[Faroughy, Greljo, Kamenik 1609.07138; Greljo et al. 1811.07920; DM, Min, Son 2008.07541; Allwicher et al. 2207.10714]

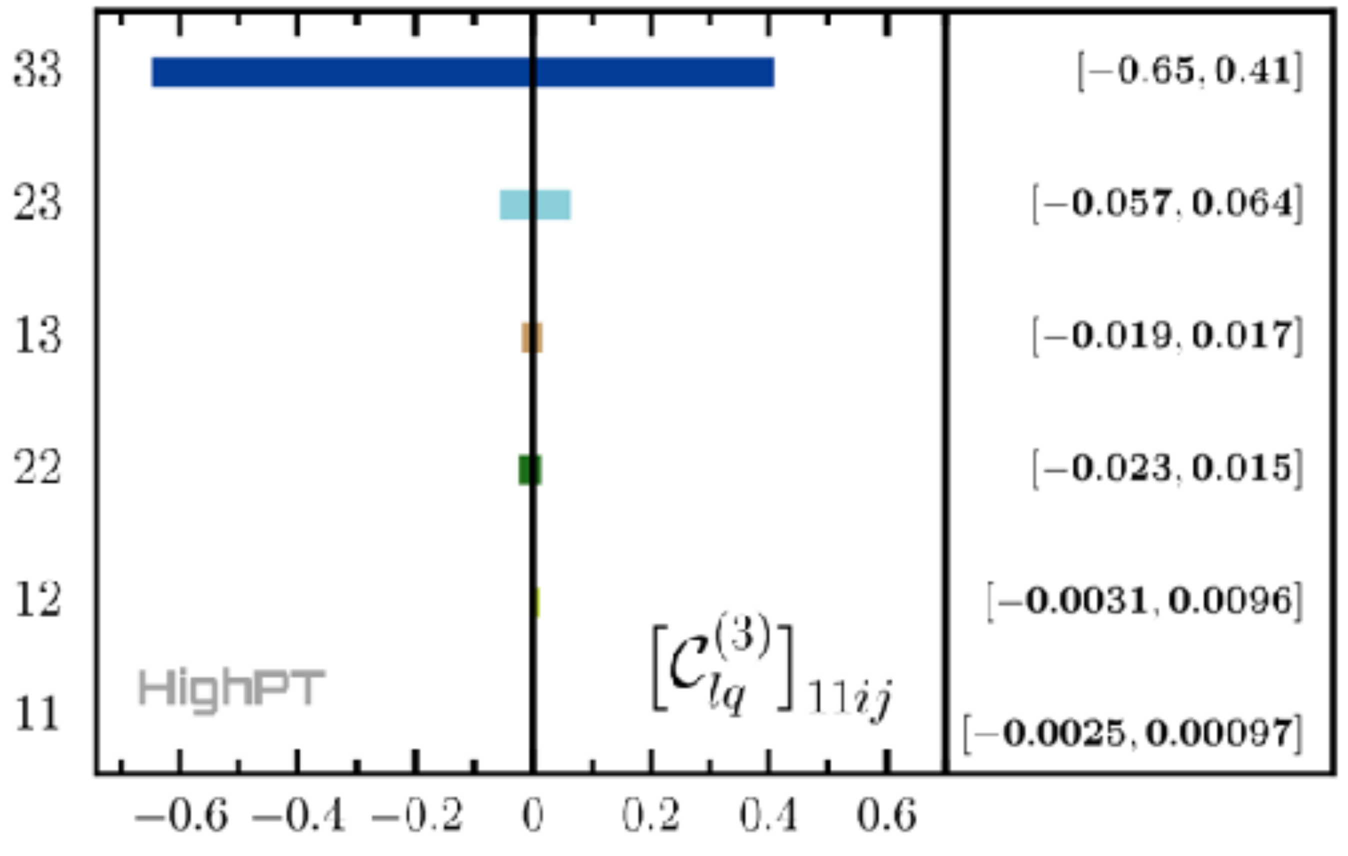
$e\, e\, q_i\, q_j$



$\tau\, \tau\, q_i\, q_j$



$e\, e\, q_i\, q_j + e\, \nu\, q_i\, q_j$



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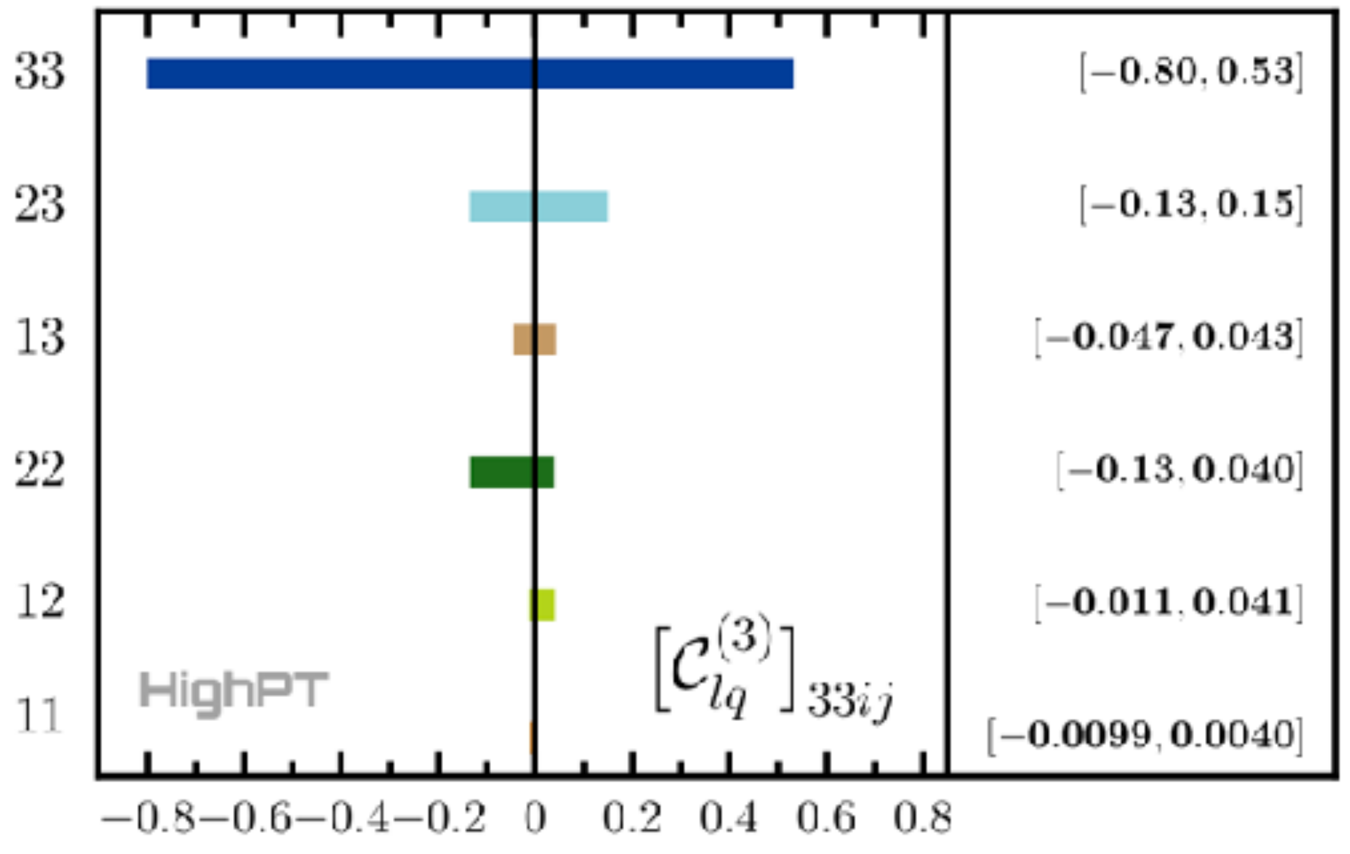


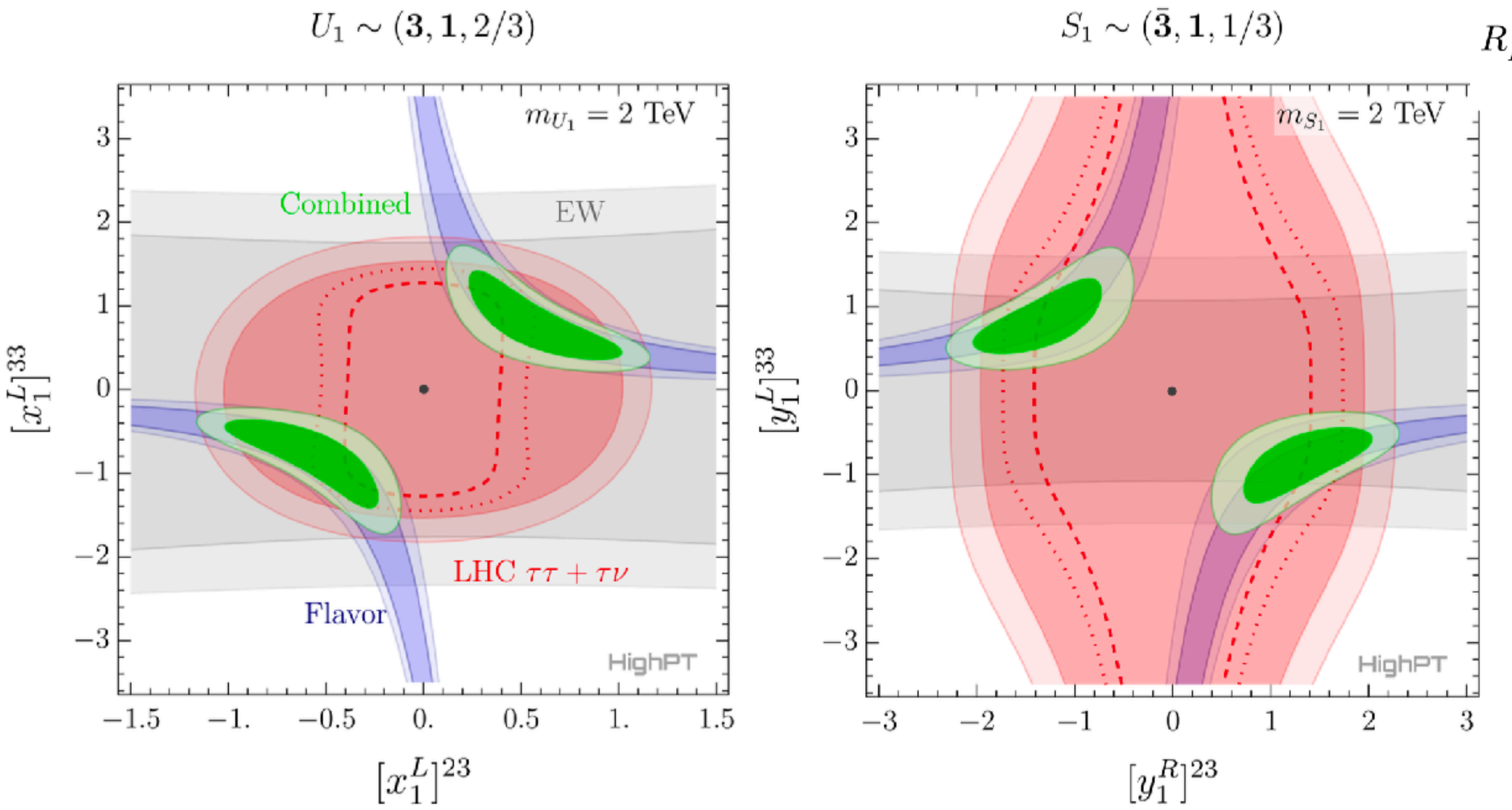
C / Λ^2 Λ=1TeV

Taus present more experimental challenges in regards to their reconstruction and backgrounds.

This implies slightly larger uncertainties and therefore somewhat weaker constraints on New Physics.

Application: LQ and R(D(*))

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



[<too many papers to cite them all> + Allwicher, Faroughy, Jaffredo, Sumensary, Wilsch 2207.10714]

Electroweak measurements (mainly Z → ττ, νν) and high-pT di-tau tails put strong constraints on models addressing the LFU violation in charged-current B decays.

Conclusions

Flavour Universality is an accidental property of SM gauge interactions.

In the **quark sector** it is broken at O(1) by the top Yukawa and Cabibbo angle,
also broken in the initial states by PDFs of a proton or hadron flavours.

Rather than testing "universality" in the quark sector it is perhaps more interesting to test whether New Physics follows **MFV-like or U(2)-like** structures (second one favoured for TeV New Physics).

Lepton Flavour Universality is a much better symmetry and it is precisely tested at high energy by:

- **Z and W** leptonic decays (per-mille level): **few TeV** bounds on **Higgs-lepton current** operators.

- **high-pT dilepton tails**: **multi-TeV** bounds on **semileptonic** operators with all quark combinations.

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Thank you!

Backup

Non-universal example: top-philic New Physics

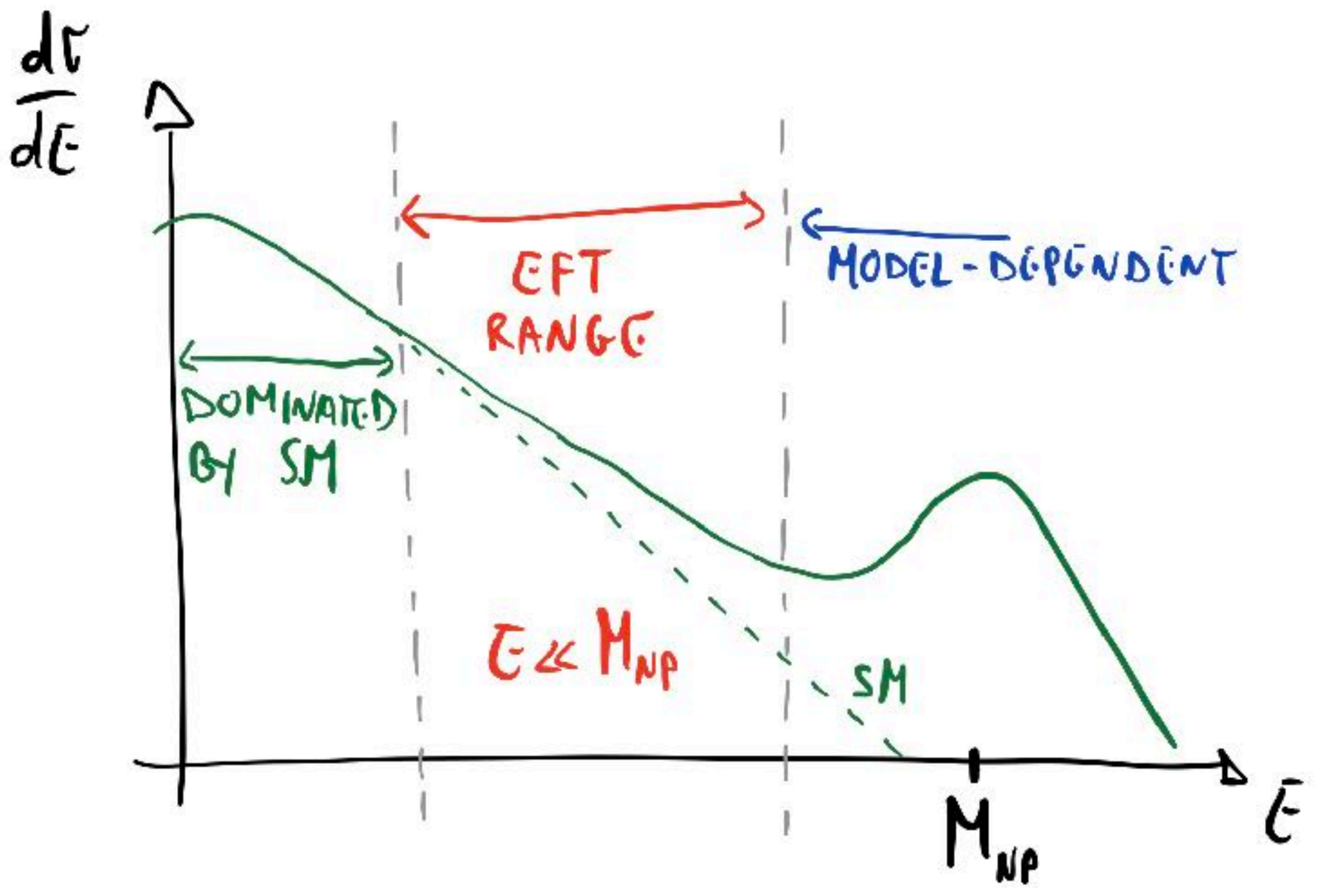
One-parameter fits from our global analysis of indirect constraints on top quark operators.
In the third column we report the observable giving the dominant constraint in each case.

Wilson	Global fit [TeV^{-2}]	Dominant
$C_{qq}^{(+)}$	$(-1.9 \pm 2.3) \times 10^{-3}$	ΔM_s
$C_{qq}^{(-)}$	$(-2.0 \pm 1.0) \times 10^{-1}$	$B_s \to \mu\mu$
$C_{qu}^{(1)}$	$(1.3 \pm 1.0) \times 10^{-1}$	ΔM_s
$C_{qu}^{(8)}$	$(-1.7 \pm 4.4) \times 10^{-1}$	ΔM_s
C_{uu}	$(-3.0 \pm 1.7) \times 10^{-1}$	$\delta g_{L,11}^{Ze}$
$C_{Hq}^{(+)}$	$(18.7 \pm 8.8) \times 10^{-3}$	$B_s \to \mu\mu$
$C_{Hq}^{(-)}$	$(5.8 \pm 4.5) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
C_{Hu}	$(-4.3 \pm 2.3) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
C_{uB}	$(-0.6 \pm 2.0) \times 10^{-2}$	$c_{\gamma\gamma}$
C_{uG}	$(-0.1 \pm 2.0) \times 10^{-2}$	c_{gg}
C_{uH}	$(-0.3 \pm 5.2) \times 10^{-1}$	$C_{uH,33}$
C_{uW}	$(-0.1 \pm 3.1) \times 10^{-2}$	$c_{\gamma\gamma}$

Wilson	Global fit [TeV^{-2}]	Dominant
$C_{lq}^{(+),11}$	$(2.4 \pm 3.5) \times 10^{-3}$	R_K
$C_{lq}^{(+),22}$	$(-4.0 \pm 3.4) \times 10^{-3}$	R_K
$C_{lq}^{(+),33}$	$(7.2 \pm 4.4) \times 10^{-1}$	g_τ / g_i
$C_{lq}^{(-),11}$	$(10.9 \pm 7.6) \times 10^{-2}$	$R_{K^{(*)}}^{\nu}$
$C_{lq}^{(-),22}$	$(-6.0 \pm 7.0) \times 10^{-2}$	$R_{K^{(*)}}^{\nu}$
$C_{lq}^{(-),33}$	$(-1.8 \pm 1.0) \times 10^{-1}$	$R_{K^{(*)}}^{\nu}$
C_{lu}^{11}	$(-1.7 \pm 7.0) \times 10^{-2}$	$\delta g_{L,11}^{Ze}$
C_{lu}^{22}	$(-4.3 \pm 1.8) \times 10^{-1}$	$\delta g_{L,22}^{Ze}$, R_K
C_{lu}^{33}	$(0.5 \pm 2.4) \times 10^{-1}$	$\Delta g_{L,33}^{Ze}$
C_{qe}^{11}	$(-0.7 \pm 3.9) \times 10^{-2}$	R_{K^*}
C_{qe}^{22}	$(12.1 \pm 9.2) \times 10^{-3}$	$B_s \to \mu\mu$
C_{qe}^{33}	$(2.2 \pm 2.4) \times 10^{-1}$	$\delta g_{R,33}^{Ze}$

Wilson	Global fit [TeV^{-2}]	Dominant
C_{eu}^{11}	$(5.0 \pm 8.1) \times 10^{-2}$	$\Delta {g_R^{Ze}}_{11}$
C_{eu}^{22}	$(4.8 \pm 2.1) \times 10^{-1}$	$\Delta {g_R^{Ze}}_{22}$
C_{eu}^{33}	$(-2.3 \pm 2.5) \times 10^{-1}$	$\Delta {g_R^{Ze}}_{33}$
$C_{lequ}^{(1),11}$	$(0.4 \pm 1.0) \times 10^{-2}$	$(g-2)_e$
$C_{lequ}^{(1),22}$	$(1.8 \pm 1.6) \times 10^{-2}$	$C_{eH\,22}$
$C_{lequ}^{(1),33}$	$(8.0 \pm 9.1) \times 10^{-2}$	$C_{eH\,33}$
$C_{lequ}^{(3),11}$	$(-0.6 \pm 1.5) \times 10^{-5}$	$(g-2)_e$
$C_{lequ}^{(3),22}$	$(-19.3 \pm 8.1) \times 10^{-5}$	$(g-2)_\mu$
$C_{lequ}^{(3),33}$	$(-7.0 \pm 7.8) \times 10^{-1}$	$C_{eH\,33}$

EFT validity



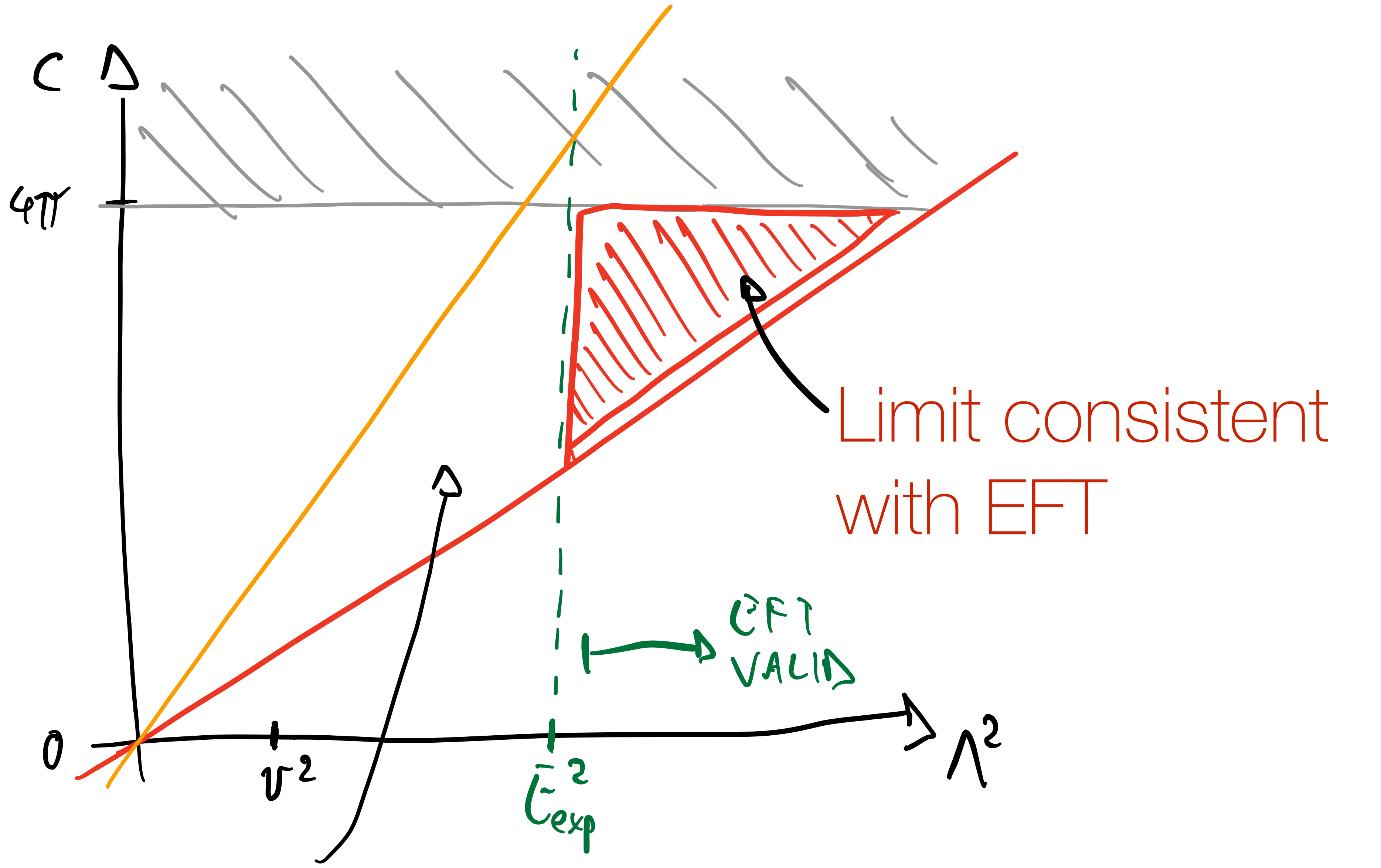
The EFT description is only valid if $E \ll M_{NP}$.

By our EFT measurements we can only access the combination c_i/M^2_{NP},
→ to assess the validity of the EFT an input from a specific UV-completion is needed, for example the size of the NP couplings (c_i).

Any experimental limit in the EFT approach will be on the combination

$$v^2 \frac{C}{\Lambda^2} < \delta_{prec.}$$

$$\begin{cases} C < \frac{\Lambda^2}{v} \delta_{prec.} \\ C \lesssim 4\pi \\ \Lambda \gg E_{exp} \end{cases}$$



This region is possibly excluded by same search, but a 'direct search' approach should be used with the specific model.

Quadratic vs. Linear fit

The EFT expansion is valid only if
the energy scale the experiment is **below** the NP mass scale

$$s \ll M_{NP}^2$$

What about ***dim-8*** interference w.r.t |***dim-6***|^2 terms?

take e.g. $$\mathcal{L}_{EFT} = \frac{C^{(6)}}{M_{NP}^2}(\bar{\mu}_L\gamma_\mu\mu_L)(\bar{d}_L\gamma^\mu d_L) + \frac{C^{(8)}}{M_{NP}^4}(\bar{\mu}_L\gamma_\mu\mu_L)\partial^2(\bar{d}_L\gamma^\mu d_L)$$

$$\hat{\sigma}(s) \sim \hat{\sigma}_{SM}(s)\left|1 + \frac{C^{(6)}}{g_{SM}^2}\frac{s}{M_{NP}^2} + \frac{C^{(8)}}{g_{SM}^2}\left(\frac{s}{M_{NP}^2}\right)^2\right|^2$$

$$= \hat{\sigma}_{SM}(s)\left[1 + 2\frac{C^{(6)}}{g_{SM}^2}\frac{s}{M_{NP}^2} + \frac{(C^{(6)})^2}{g_{SM}^4}\left(\frac{s}{M_{NP}^2}\right)^2 + 2\frac{C^{(8)}}{g_{SM}^2}\left(\frac{s}{M_{NP}^2}\right)^2 + \dots\right]$$

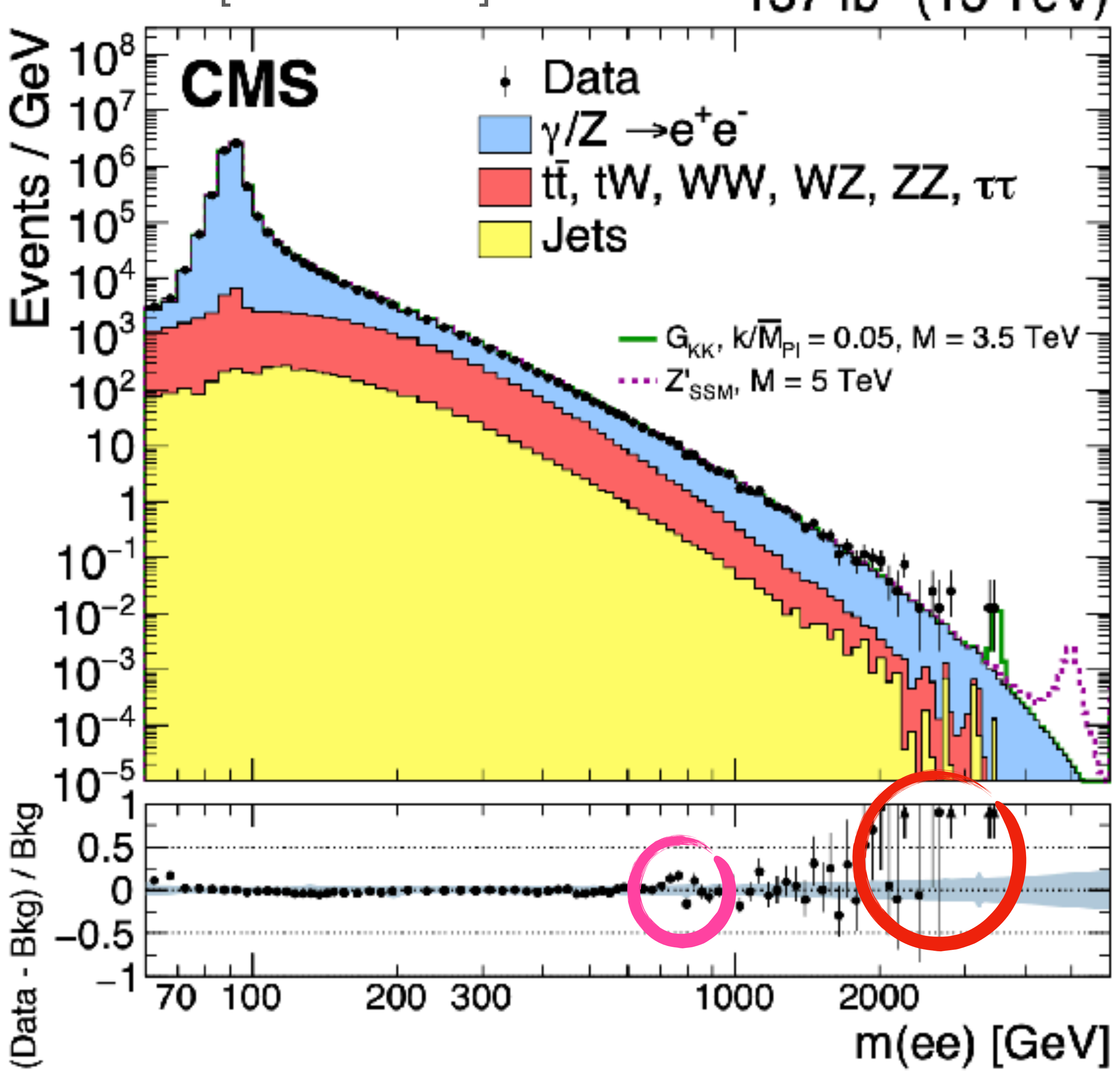
The dim-8 interference is necessarily smaller than dim-6 interference if $C^{(8)} \lesssim C^{(6)}$

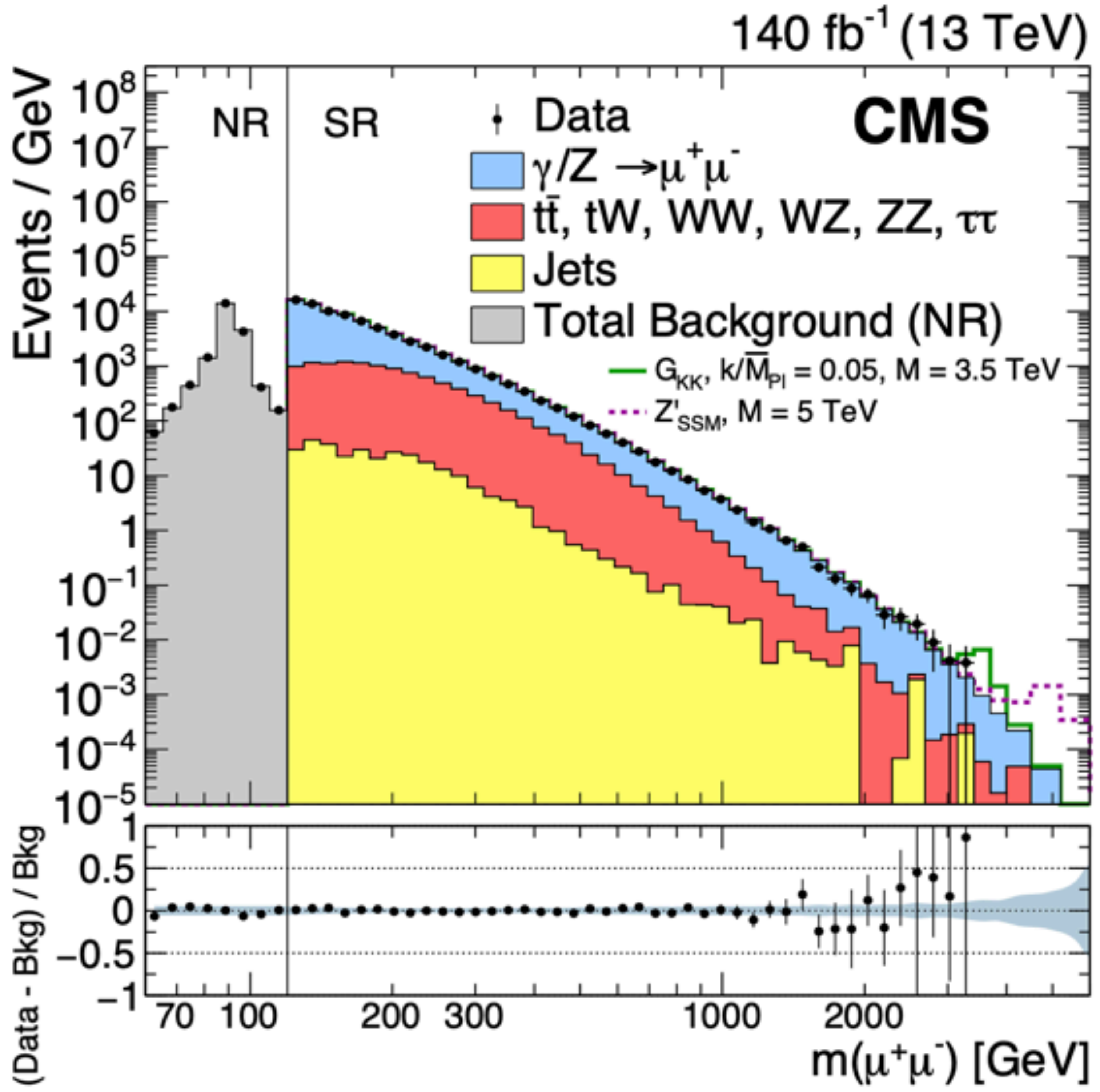
since $s \ll M_{NP}^2$. For a single mediator $C^{(8)} = C^{(6)} \sim g_{NP}^2$

[See discussion in Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez 2003.12421]

CMS di-electron excess

[2103.02708]

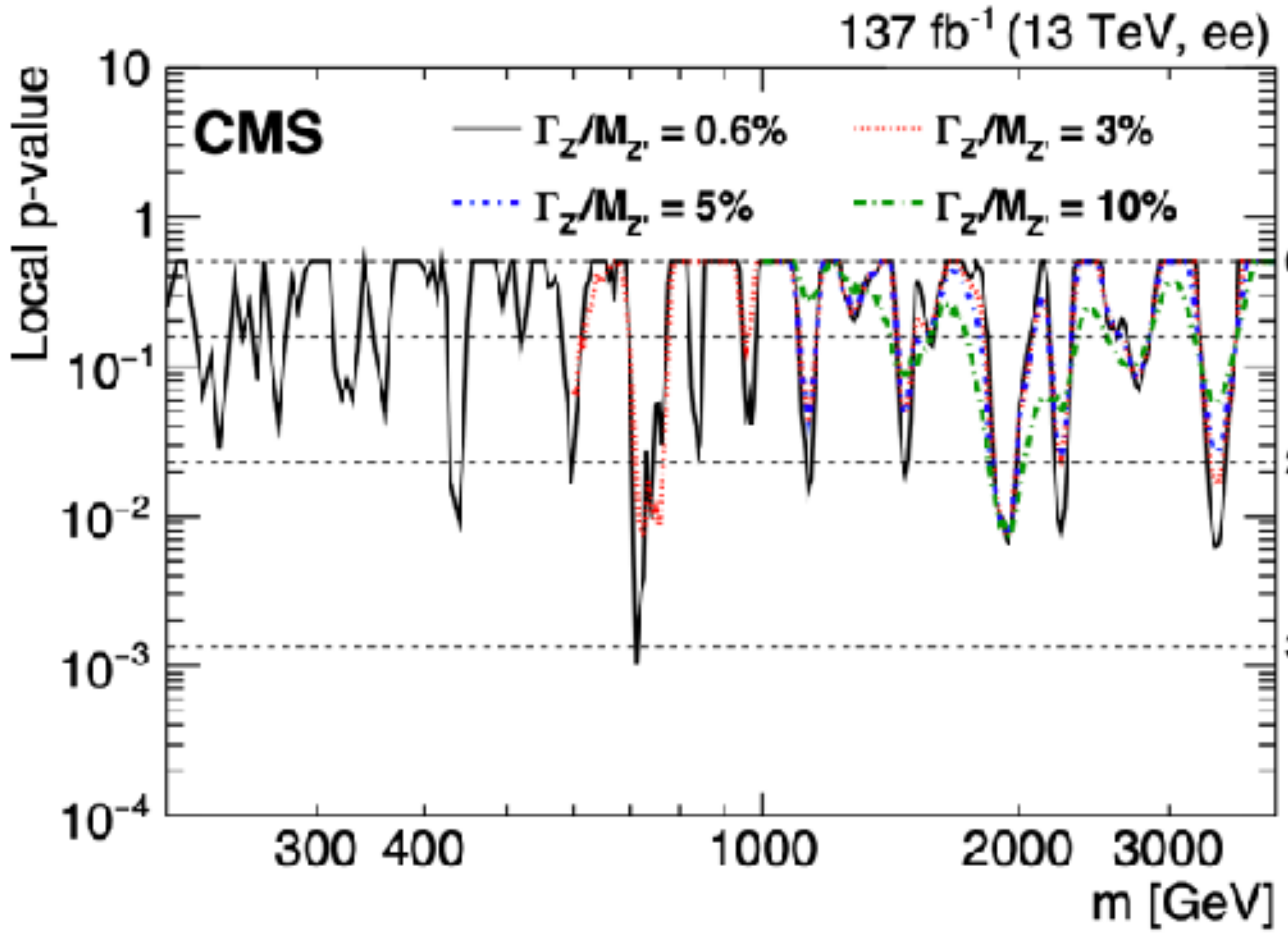




m_{ee} range [GeV]	Observed yield	Total background
60–120	28194452	28200000 ± 710000
120–400	912504	942000 ± 37000
400–600	16192	16400 ± 770
600–900	3756	3660 ± 190
900–1300	704	696 ± 47
1300–1800	135	131 ± 12
>1800	44	29.2 ± 3.6

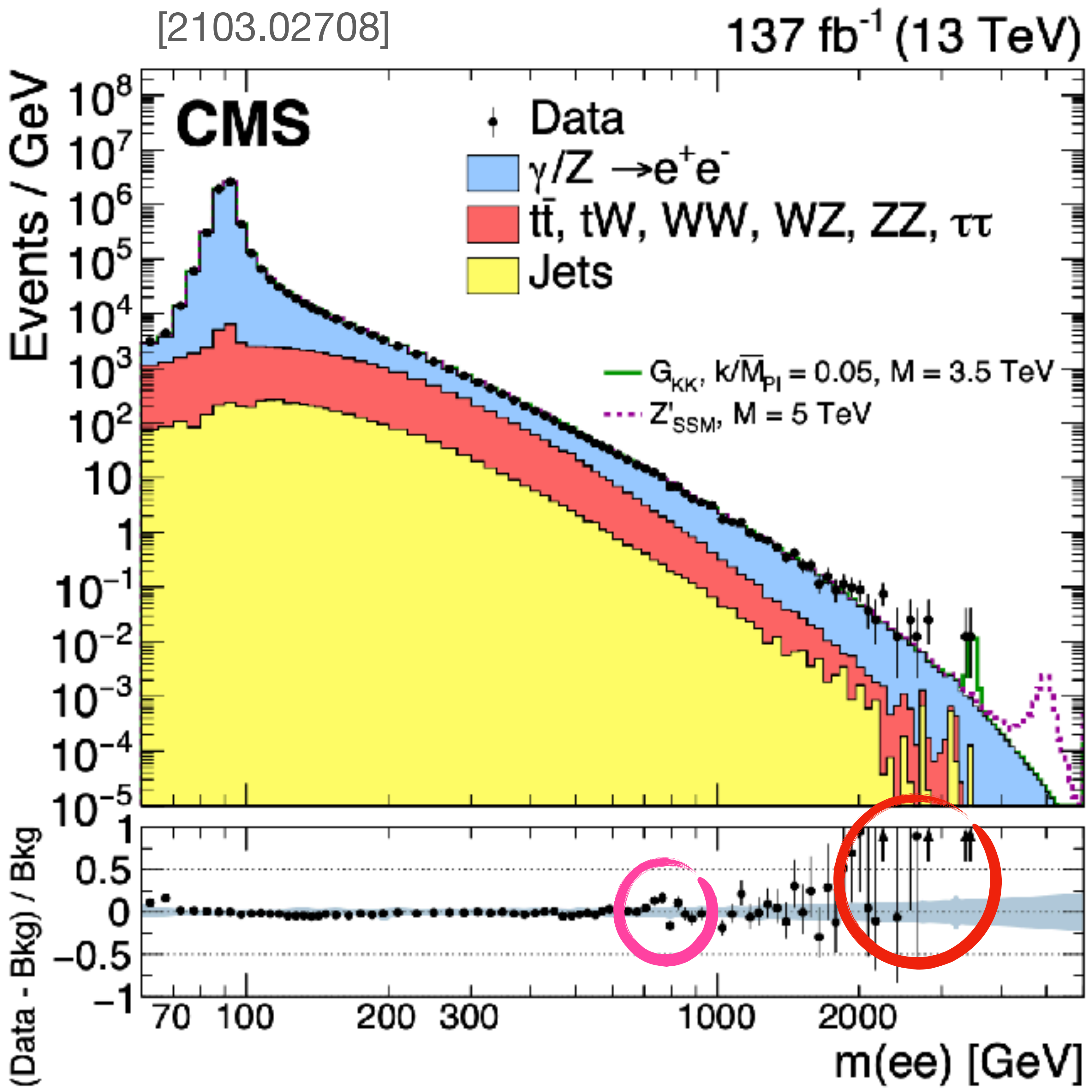
$m_{\mu\mu}$ range [GeV]	Observed yield	Total background
60–120	164075	166000 ± 9360
120–400	977714	1050000 ± 60400
400–600	24041	26100 ± 1580
600–900	5501	5610 ± 337
900–1300	996	1050 ± 65
1300–1800	183	195 ± 13
>1800	42	44.3 ± 3.4

Electron excess at 700GeV:
local 3.1σ,
global in the whole mass range -1.4σ,
global in the vicinity 0.9σ.

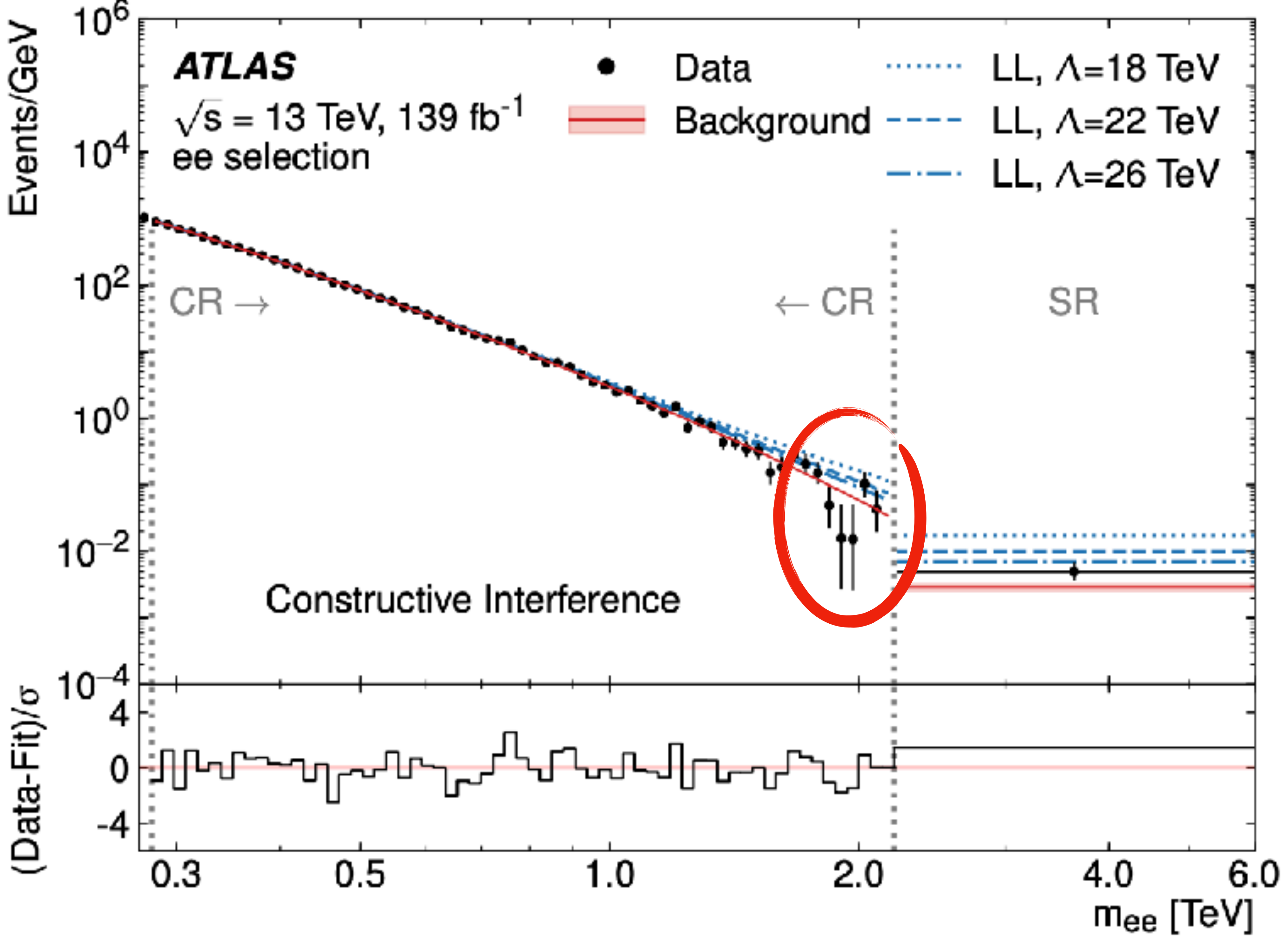


CMS di-electron excess

[2103.02708]



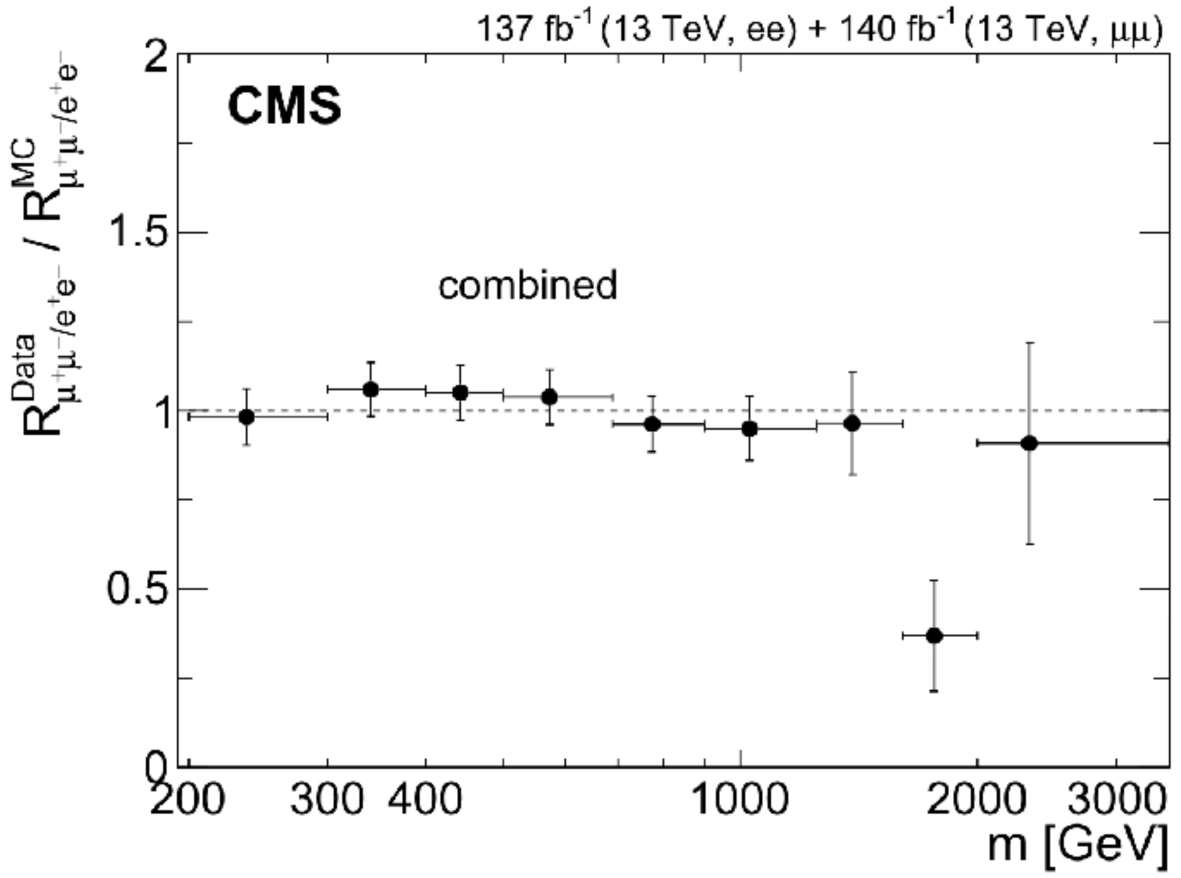
[2006.12946]

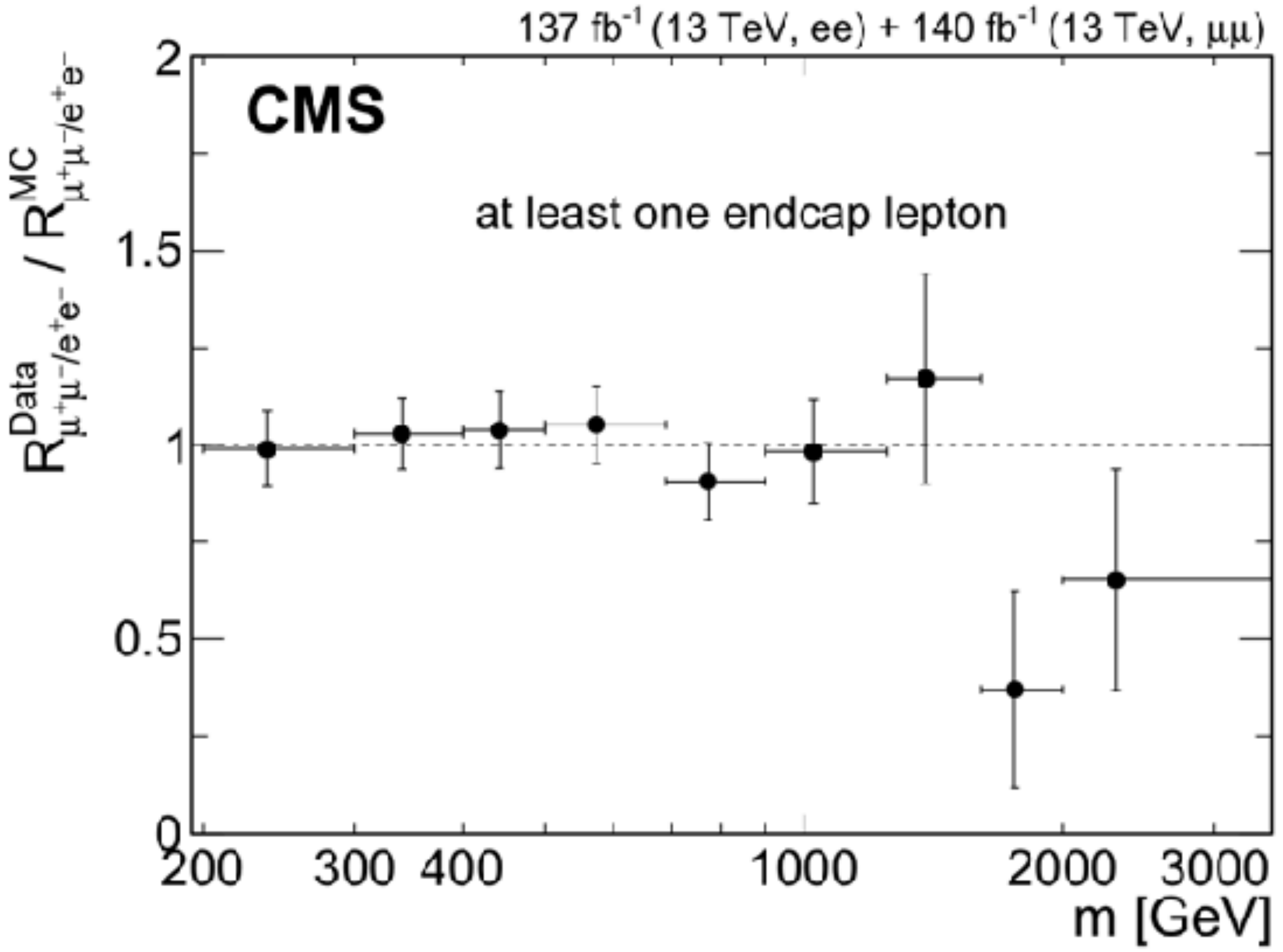


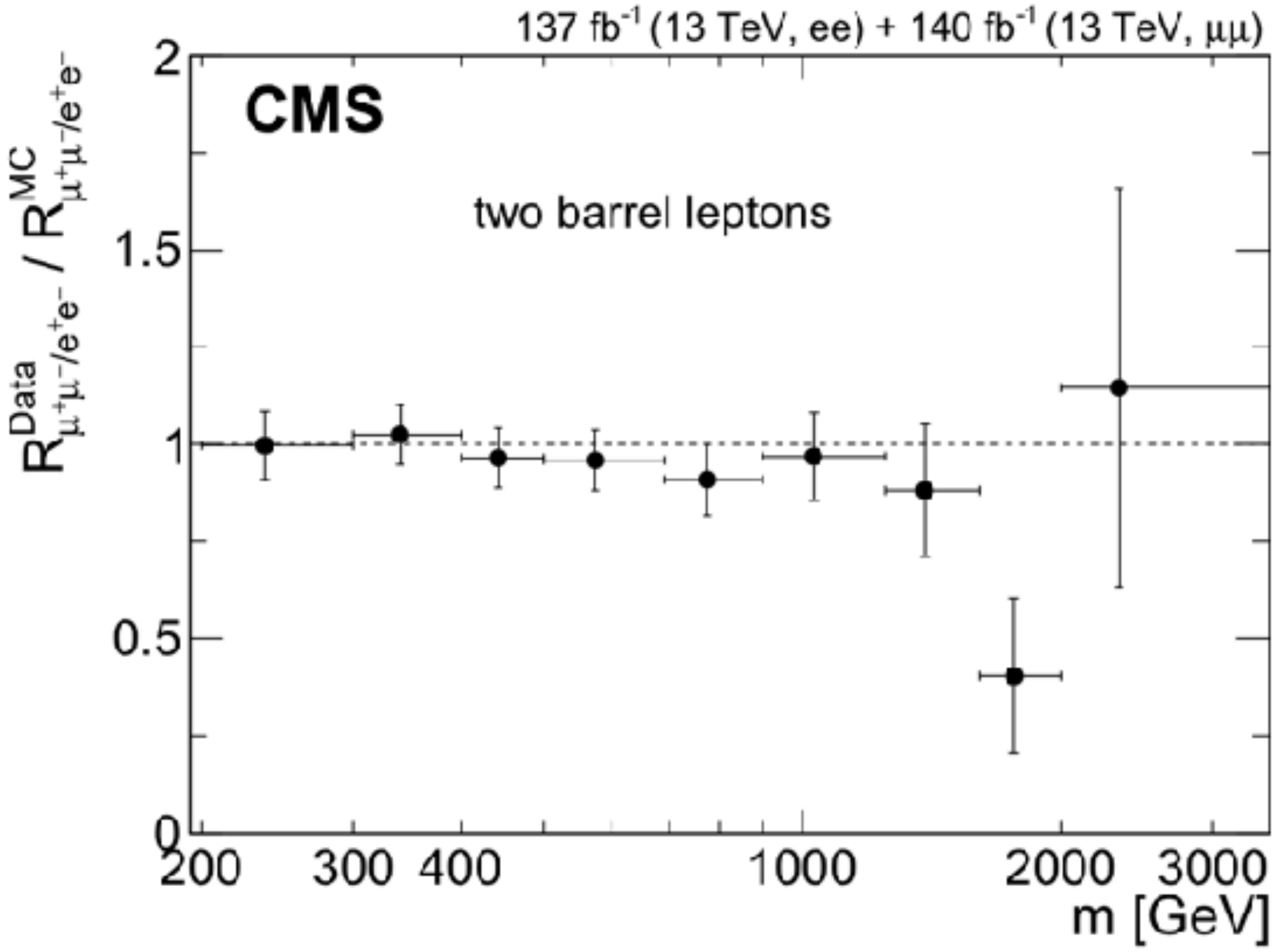
CMS di-electron excess

[CMS 2103.02708]

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(q\bar{q} \to e^+e^-)/dm_{\ell\ell}}$$







"At very high masses, the statistical uncertainties are large. Here, some deviations from unity are observed, caused by the slight excess in the dielectron channel discussed above. A χ^2 test for the mass range above 400 GeV is performed.
The resulting χ^2/dof values are 11.2/7 for the events with two barrel leptons, 9.4/7 for those with at least one lepton in the endcaps, and 17.9/7 for the combined distribution. These correspond to one-sided *p*-values of 0.130 and 0.225, and **0.012**, respectively."

The dimuon and dielectron invariant mass spectra are corrected for the detector effects and, for the first time in this kind of analysis, compared at the TeV scale. No significant deviation from lepton flavor universality is observed. [CMS 2103.02708]