Testing Flavour at high-p_T

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INFN Trieste

Workshop on HL-LHC and hadron colliders - LNF - 03/10/2024

The Flavour of the Standard Model

Most general renormalisable Quantum Field Theory with given:

- **field content**
- **Poincaré and local (gauge) symmetries:** $SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\mathcal{L}^{SM} = -\frac{1}{4}\sum_A F^A_{\mu\nu} F^{A\mu\nu} - \theta \frac{g_s^2}{32\pi^2} G^A_{\mu\nu} \tilde{G}^{A\mu\nu} + \sum_f \bar{\psi}_f i D_\mu \gamma^\mu \psi_f$$

$$+ |D_\mu H|^2 - V(H) - \left(\bar{\psi}^i_F y^{ij}_F \psi_f H + h.c. \right)$$

	$SU(2)_L \times SU(2)_R$	$SU(3)_c$	$SU(2)_L$	Y
L_i	$(\frac{1}{2}, 0)$	1	2	$-\frac{1}{2}$
e_i	$(0, \frac{1}{2})$	1	1	-1
Q_i	$(\frac{1}{2}, 0)$	3	2	$\frac{1}{6}$
u_i	$(0, \frac{1}{2})$	3	1	$\frac{2}{3}$
d_i	$(0, \frac{1}{2})$	3	1	$-\frac{1}{3}$
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Most of the **richness and complexity** of the Theory comes from the **Yukawa sector:**

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

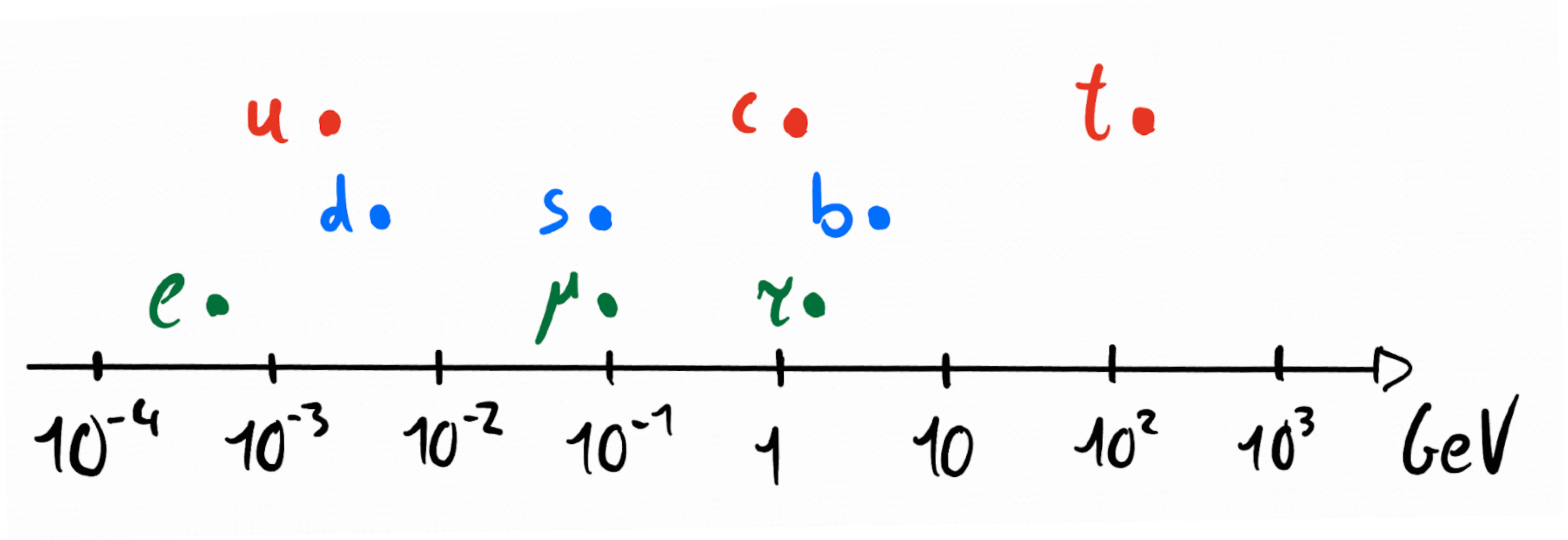
All **lepton masses**, **proton-neutron mass difference**, the **QCD mass gap** (pion mass), $\mathbf{0 < m_e \ll m_{p,n}}$, **CKM** mixing, …

The Flavour of the Standard Model

The **Yukawa sector** also shows a **very peculiar structure**:

- **hierarchical fermion masses**

($m_\nu \sim 10^{-11}$ GeV)



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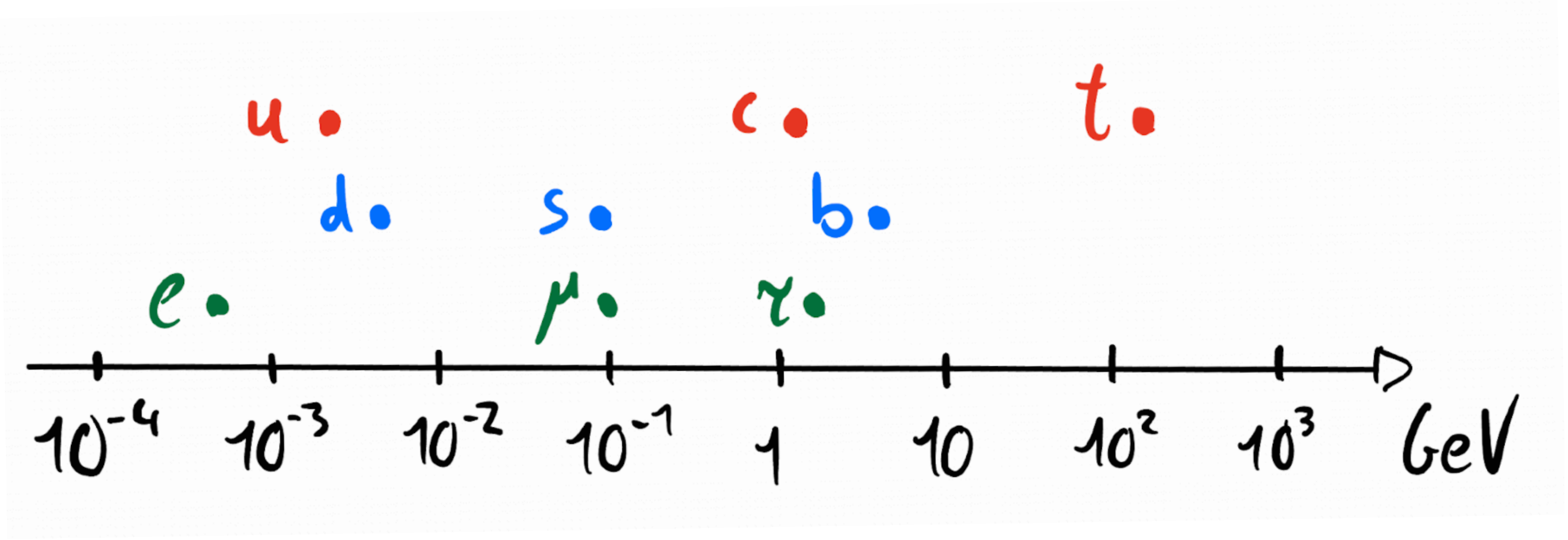
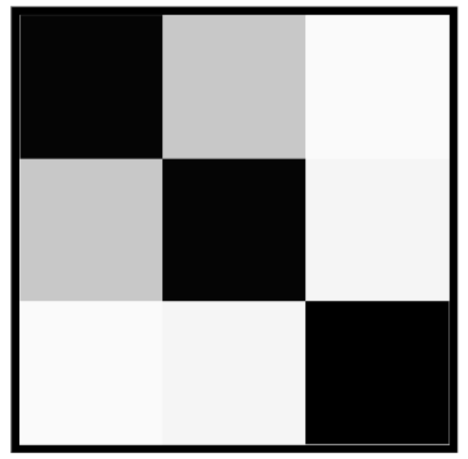


- **hierarchical quark mixing matrix**

$V_{\rm CKM} \sim$



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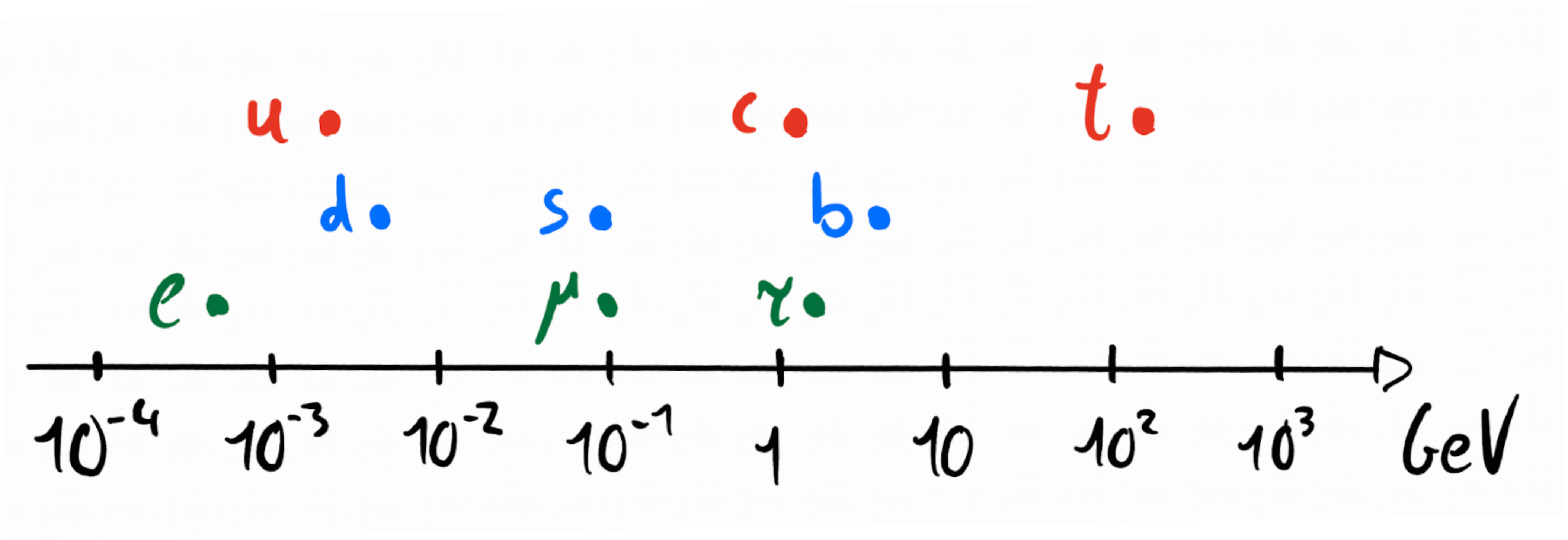

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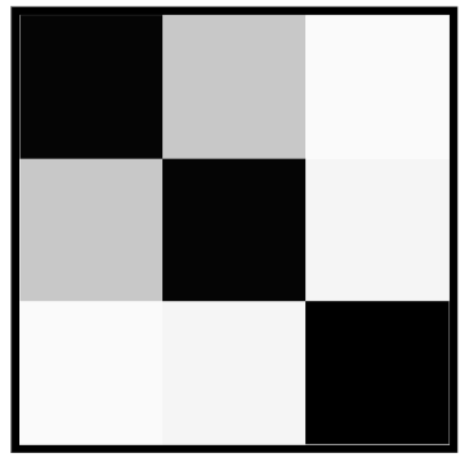
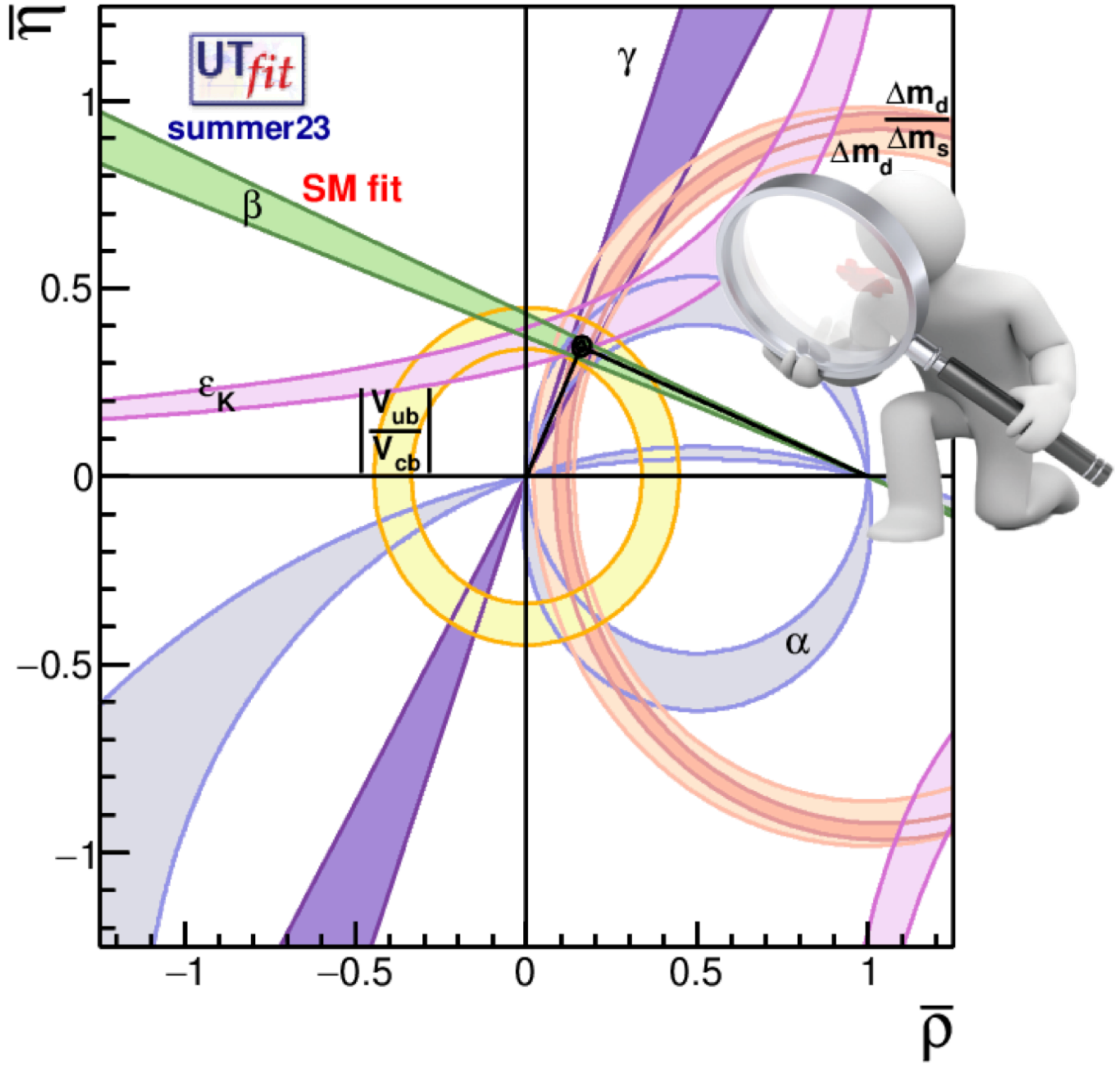


A very predictive and successful structure!

The CKM picture of quark mixing and CP violation has now been tested to an impressive level of precision:



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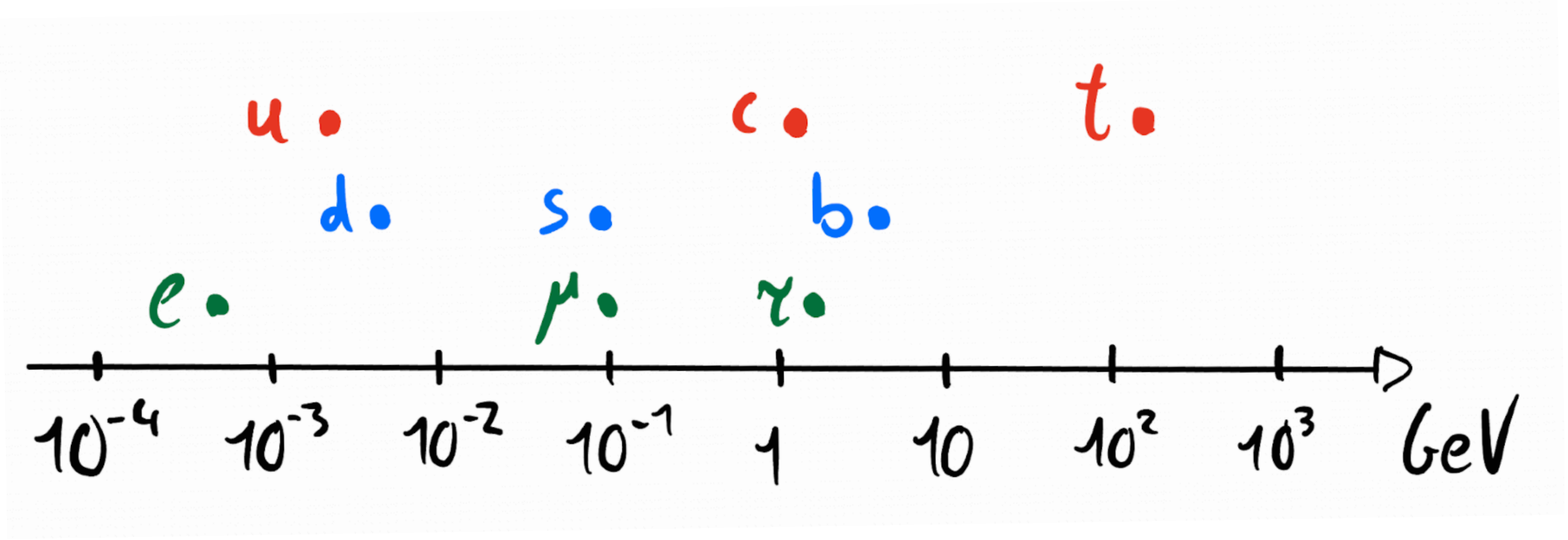

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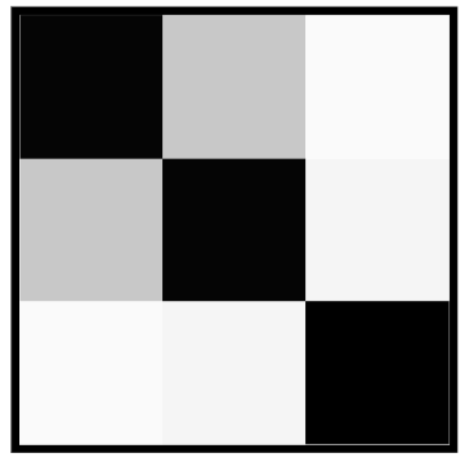
$V_{\rm CKM} \sim$ 

However, **the theory gives no explanation** for these hierarchies.
Is there a more fundamental underlying theory which does?

SM Flavour Puzzle

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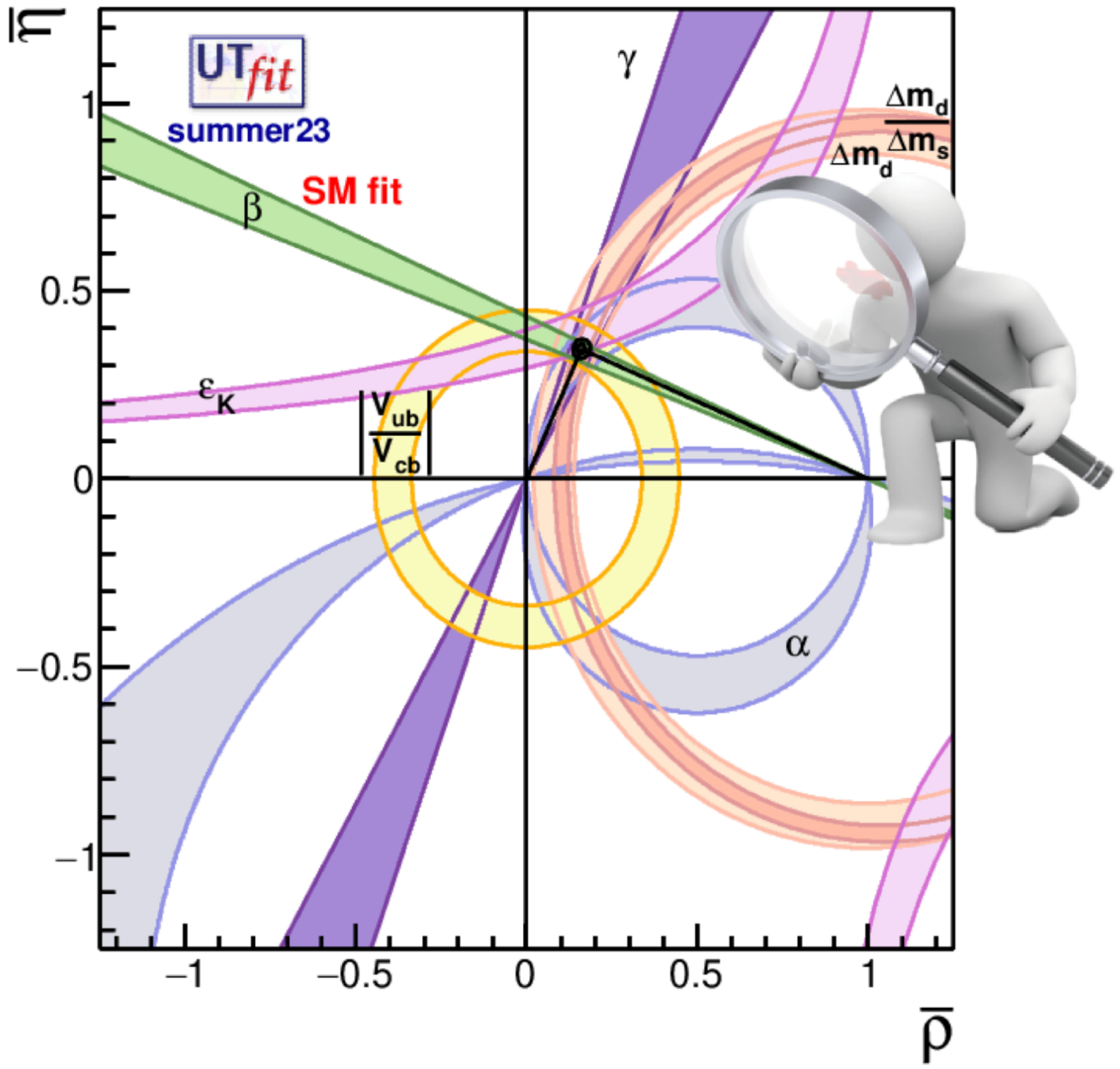
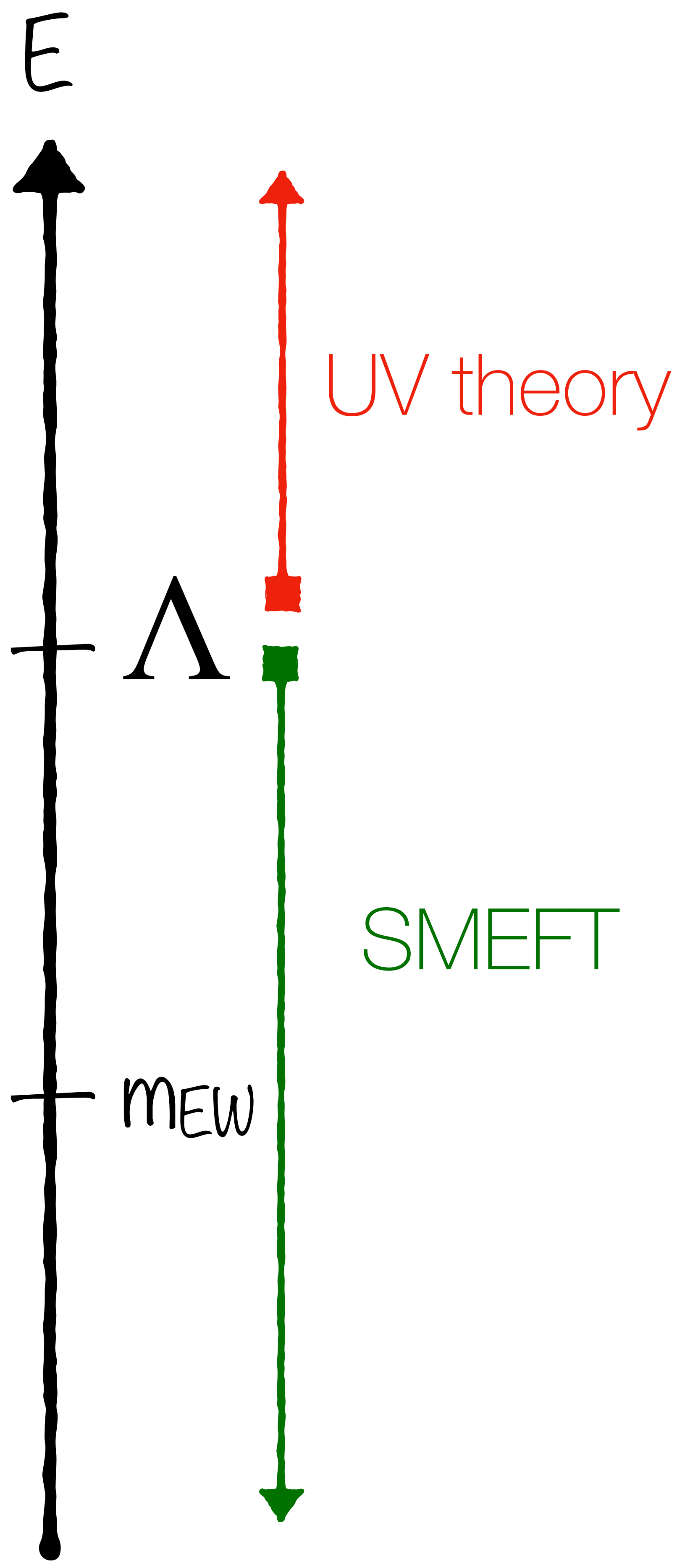


The Standard Model as an EFT



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

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

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(d=4)} + \sum_i \frac{C_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

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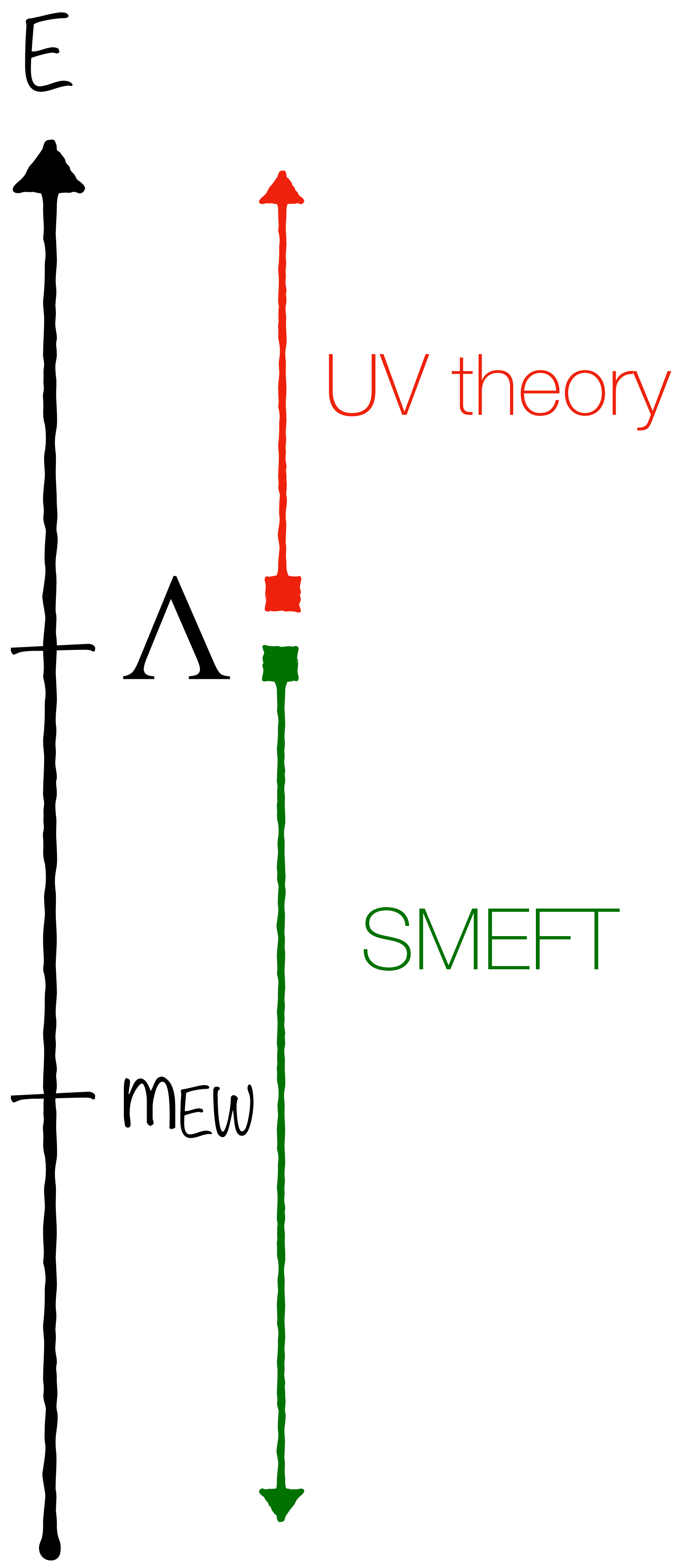

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At **low energies**, the effects from higher-dimension operators are **suppressed** by powers of

$$\left(\frac{E}{\Lambda}\right)^{d-4} \ll 1$$

The **SM** is just the **renormalisable IR remnant of the more fundamental UV theory**.

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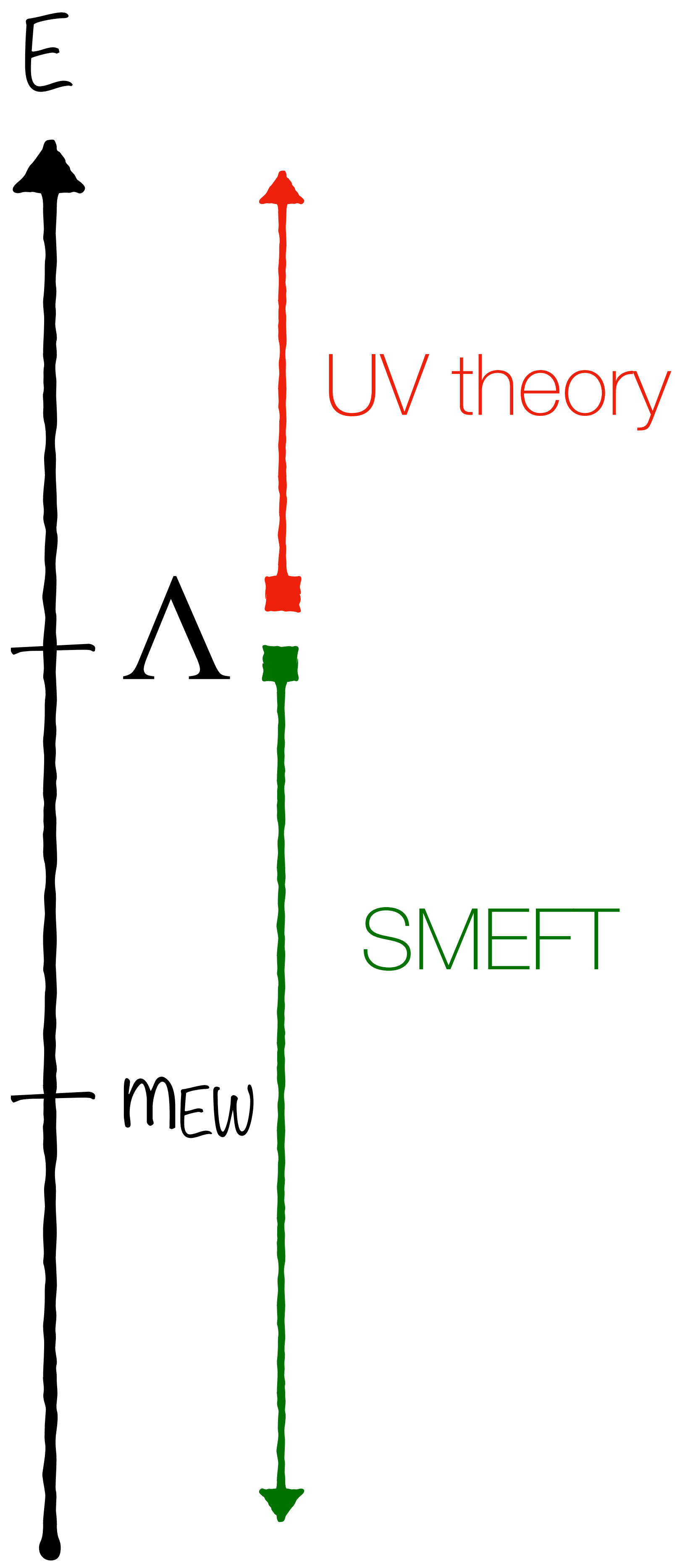

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The limited set of operators allowed at $d \leq 4$ automatically endows the **SM** with **accidental features & symmetries.**

The Standard Model as an EFT

The constrained structure of the Standard Model implies several **accidental features & symmetries**, i.e. properties that arise automatically, not imposed by hand.

Symmetries & conservation laws: conservation of B, L_e, L_μ, L_τ

Custodial symmetry: An approximate global $SU(2)_C$ symmetry in the Higgs sector. Protects the ratio $m_W / (\cos\theta_W m_Z) \approx 1$.

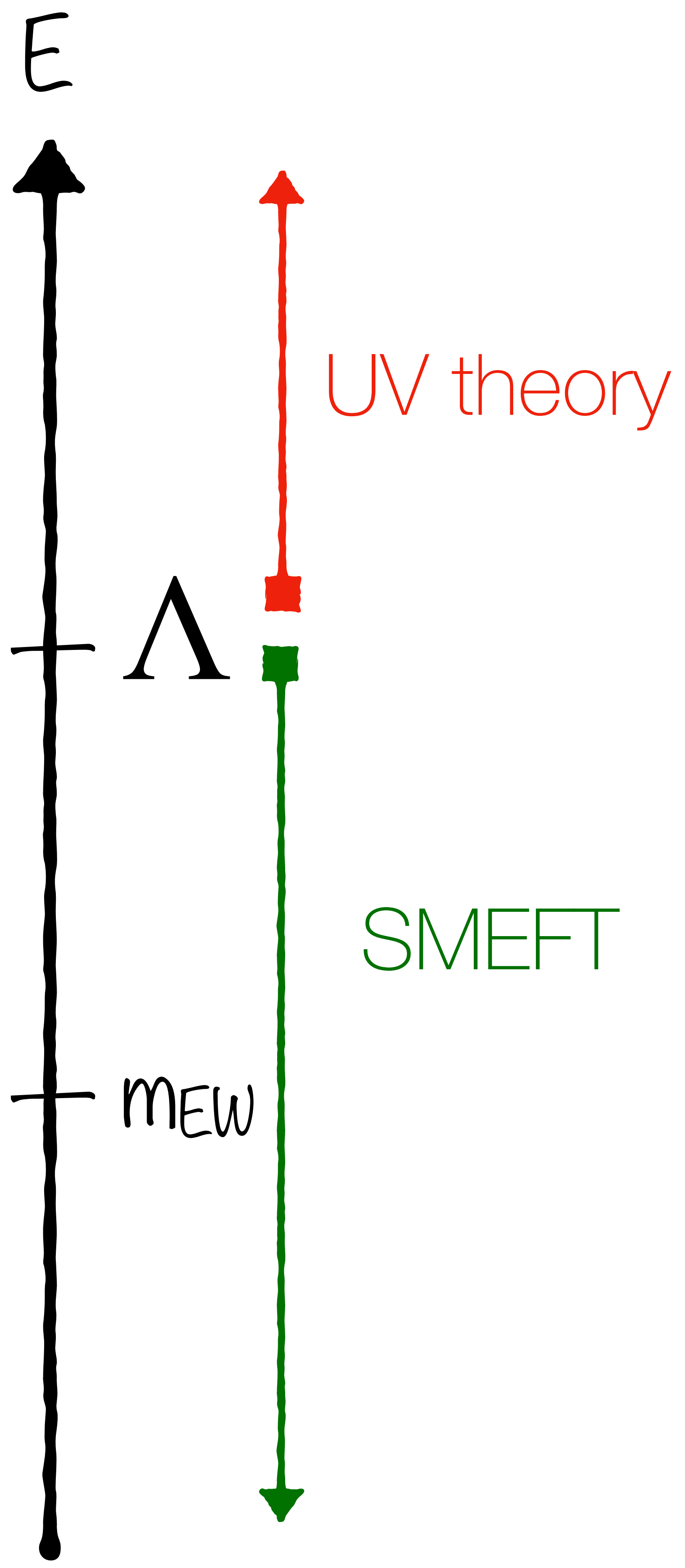
Absence of FCNC at tree-level: Z boson, photon and gluon couple in a flavour-conserving way + Higgs Yukawa couplings are small.

Small CP-violation effects, even though the CP-phase is large: small quark masses and mixing angles.

Lepton-Flavour Universality: SM gauge couplings are generation-independent + Yukawa couplings are small and hierarchical (e.g. $m_{e,\mu} \ll m_b$)

Massless neutrinos: a neutrino mass term is forbidden by gauge symmetries.

The Standard Model as an EFT



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$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM}^{(d\leq 4)} + \frac{C^{(5)}}{\Lambda_{\not L}} \mathcal{O}_W + \sum_i \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}[\varphi_{SM}] + \mathcal{O}(\Lambda^{-4})$$

SM

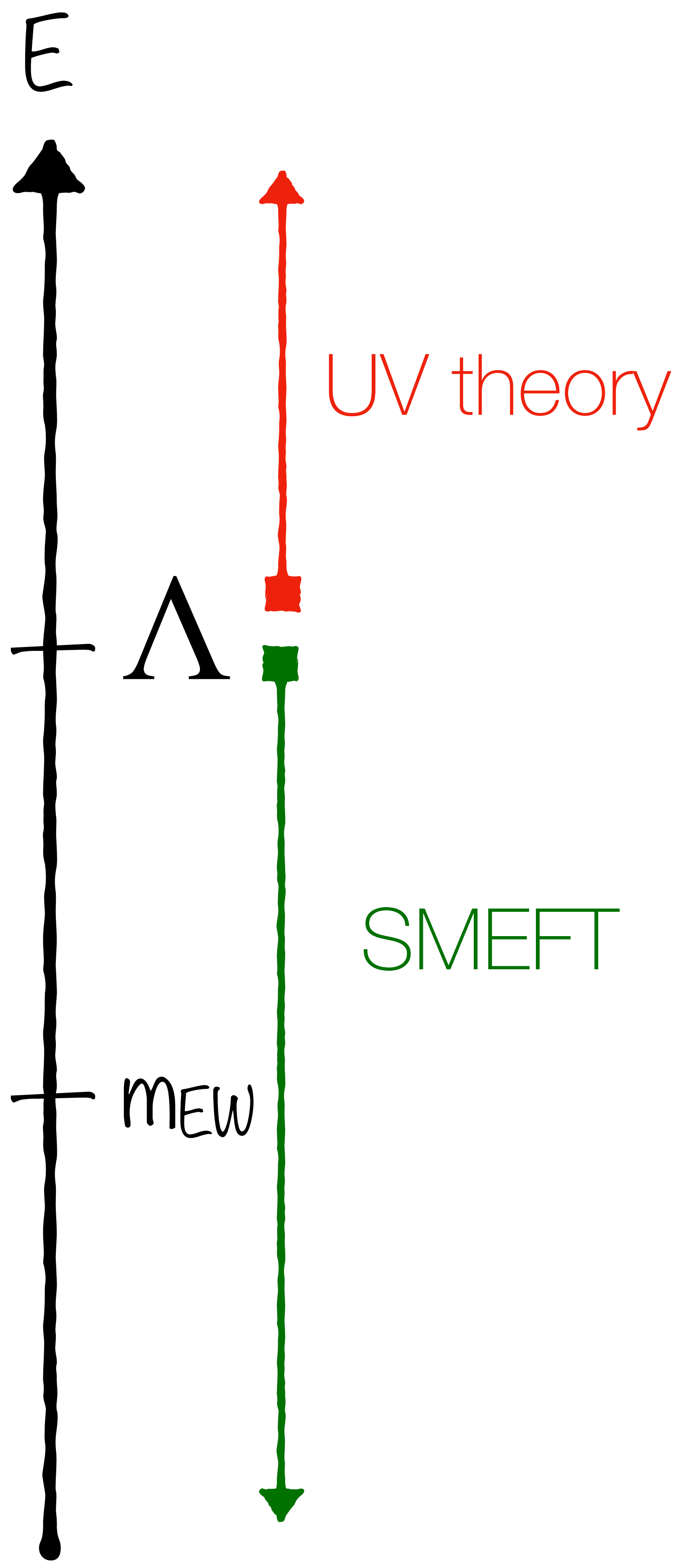
Weinberg operator
→ neutrino masses *

dim-6 SMEFT

higher order effects

* naturally small if the corresponding scale, at which L is violated, is very large. For neutrino pheno see talks by J. Lagoda and E. Resconi

The Standard Model as an EFT



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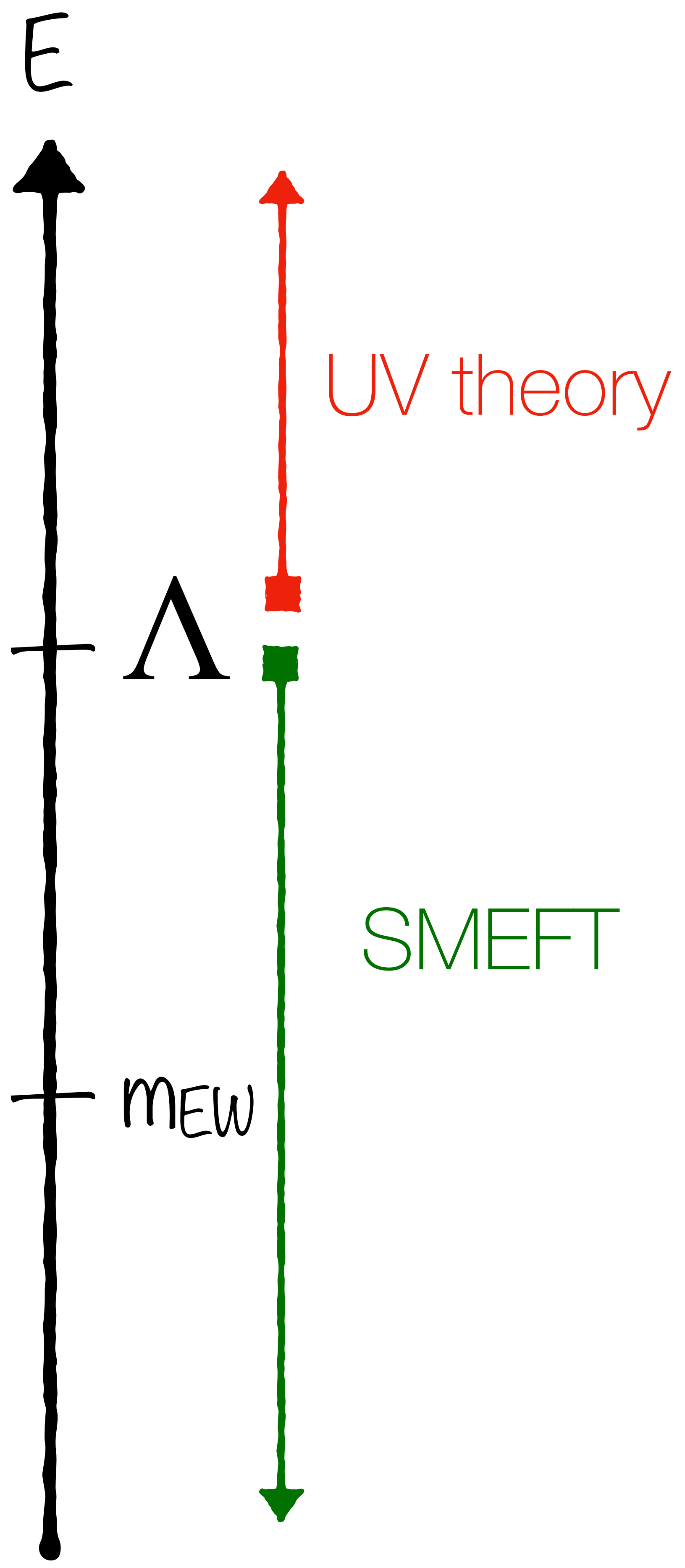

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E.g.: Lepton Flavour Violation,
deviations from LFU,
unsuppressed FCNC and CP effects,
B and L violation, etc..

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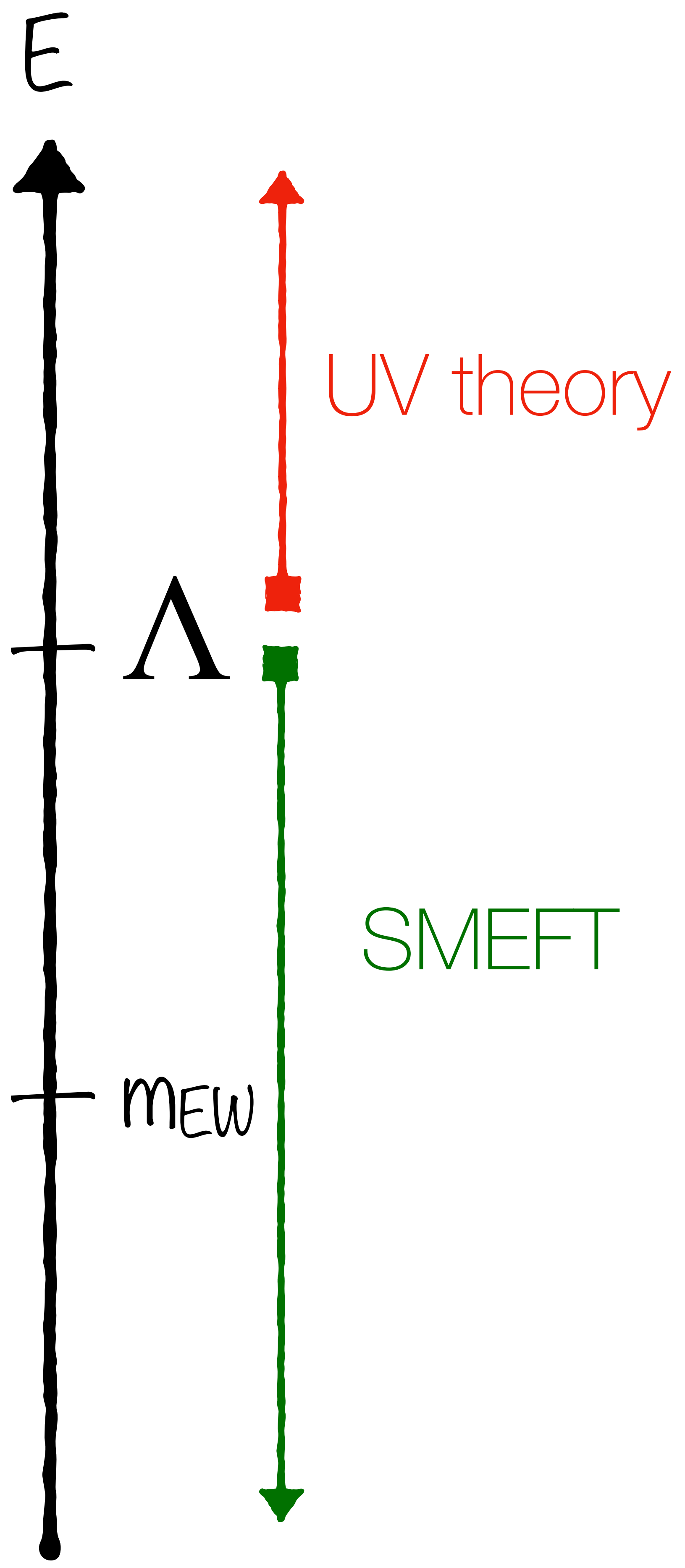

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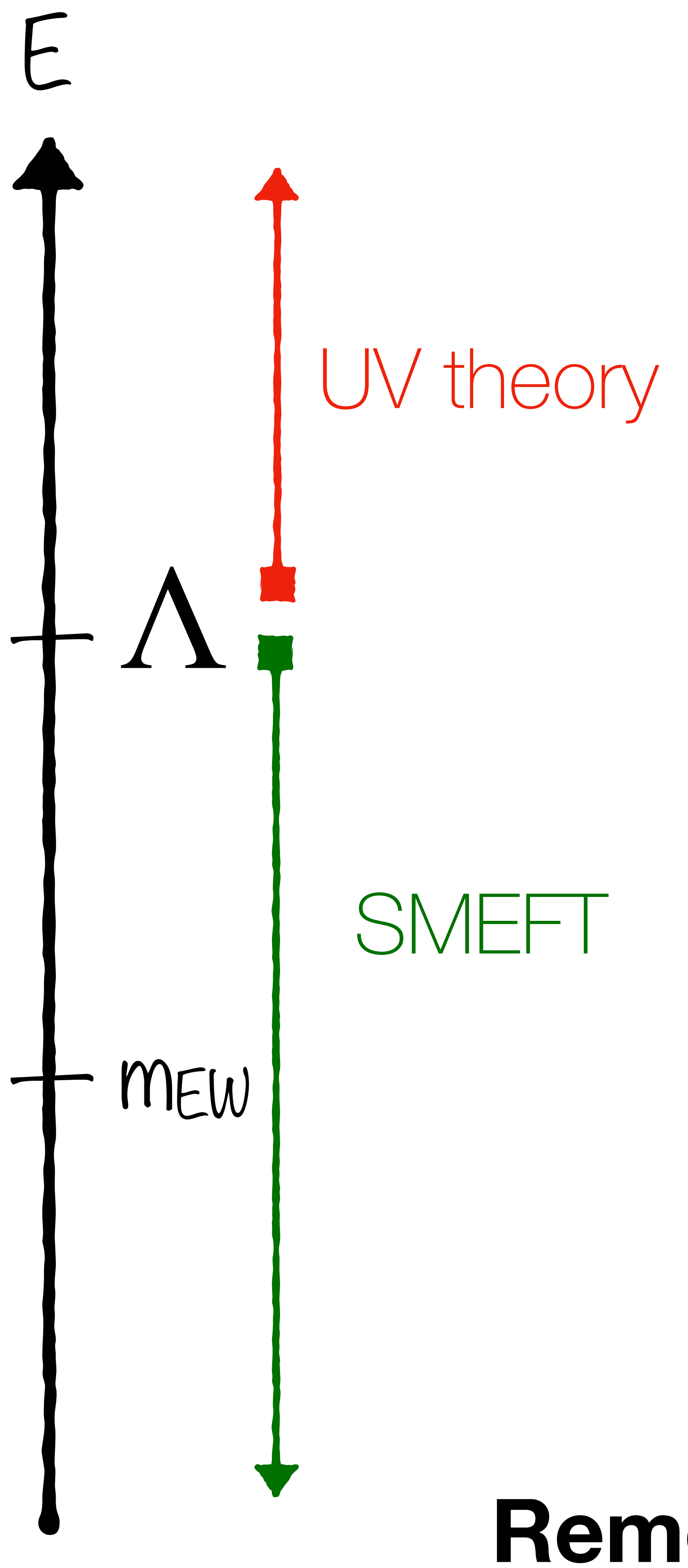

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Remember:

There can be **different scales Λ associated to the violation of different SM properties**: quark flavour, lepton flavour, L and B violation, etc..

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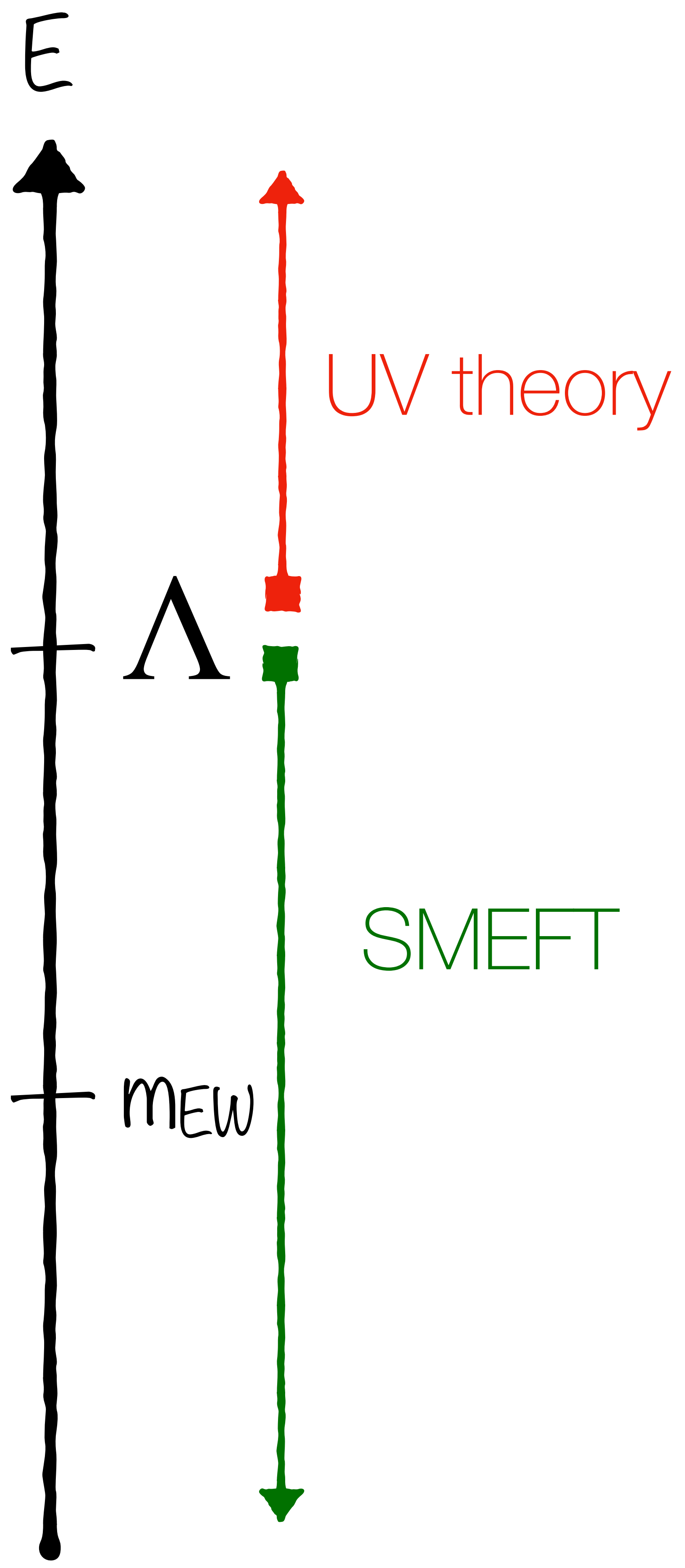

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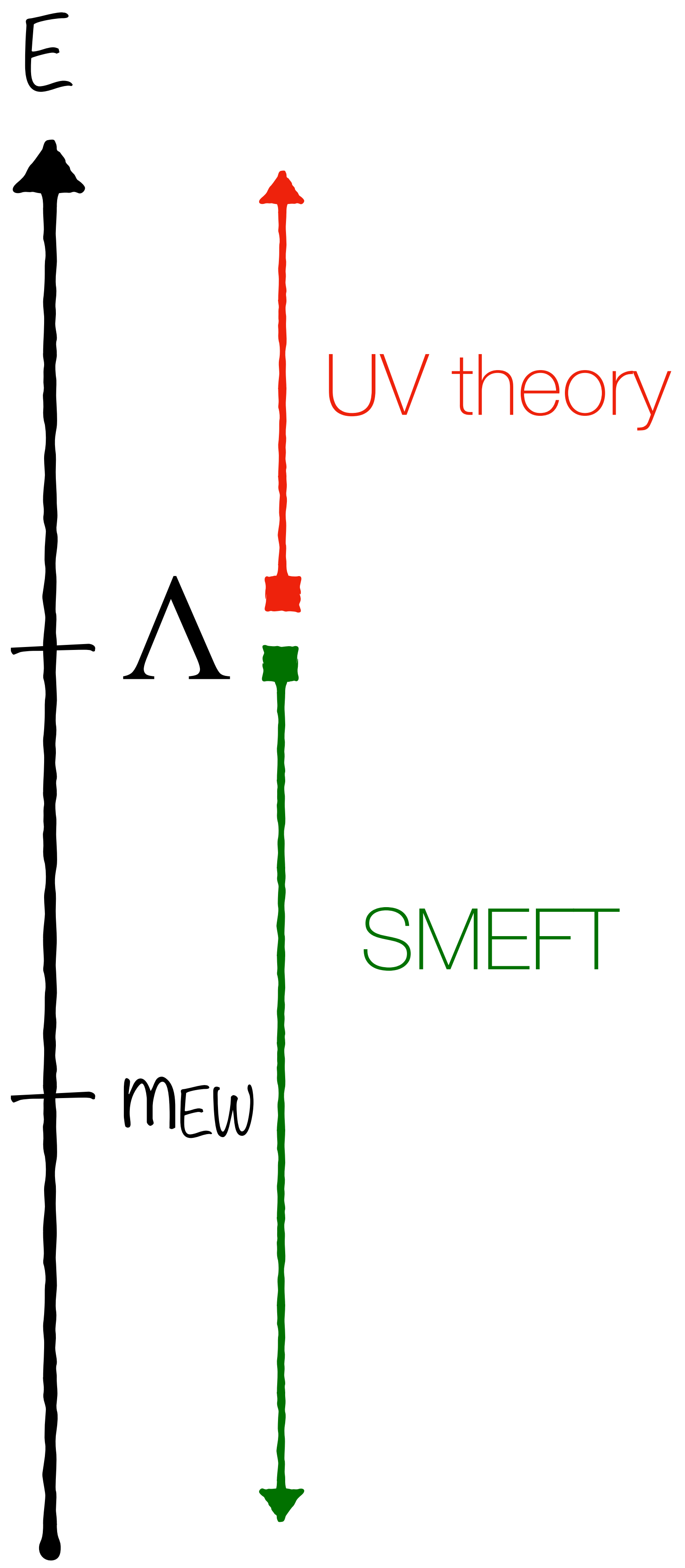

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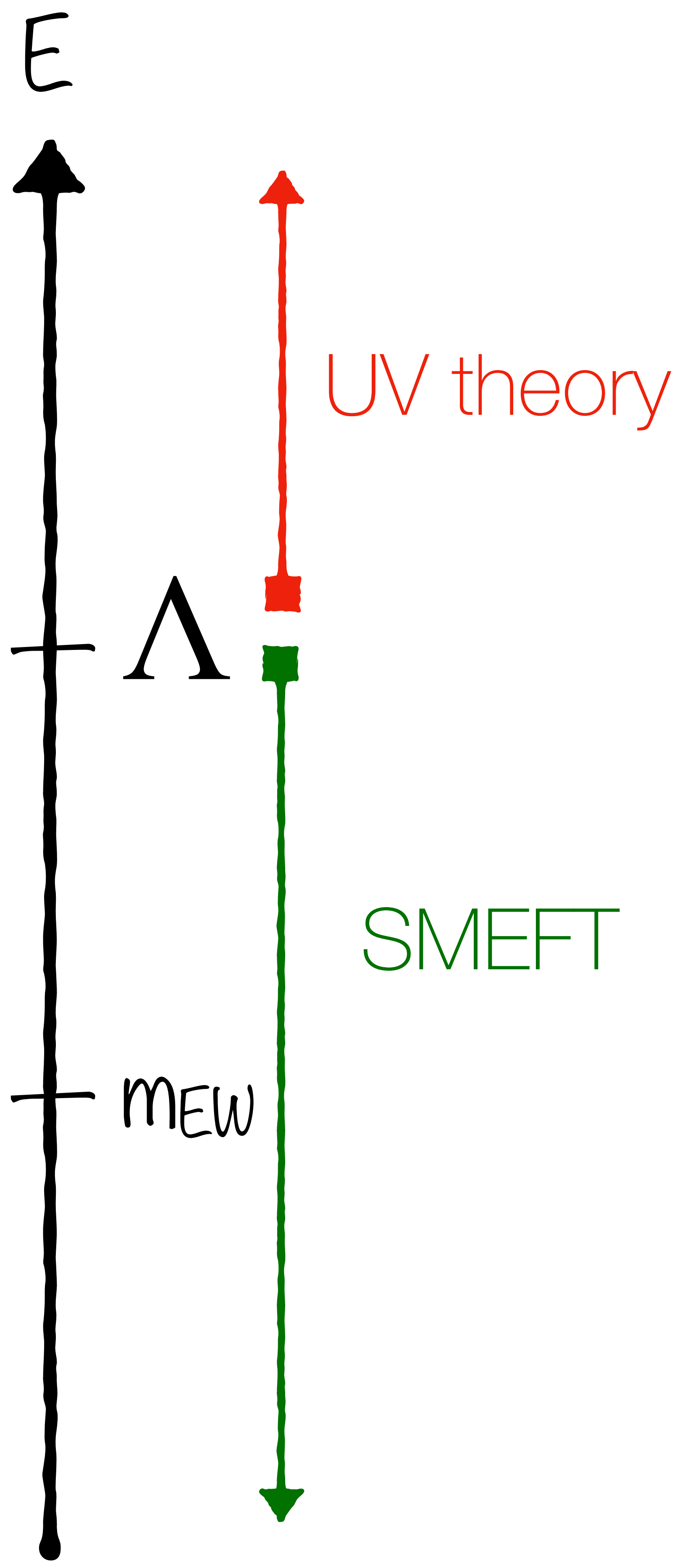

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Motivated Reasons for a **"low"** $\boldsymbol{\Lambda}$:

Hierarchy problem
of the EW scale,

$\boldsymbol{\Lambda \sim \text{TeV}}$

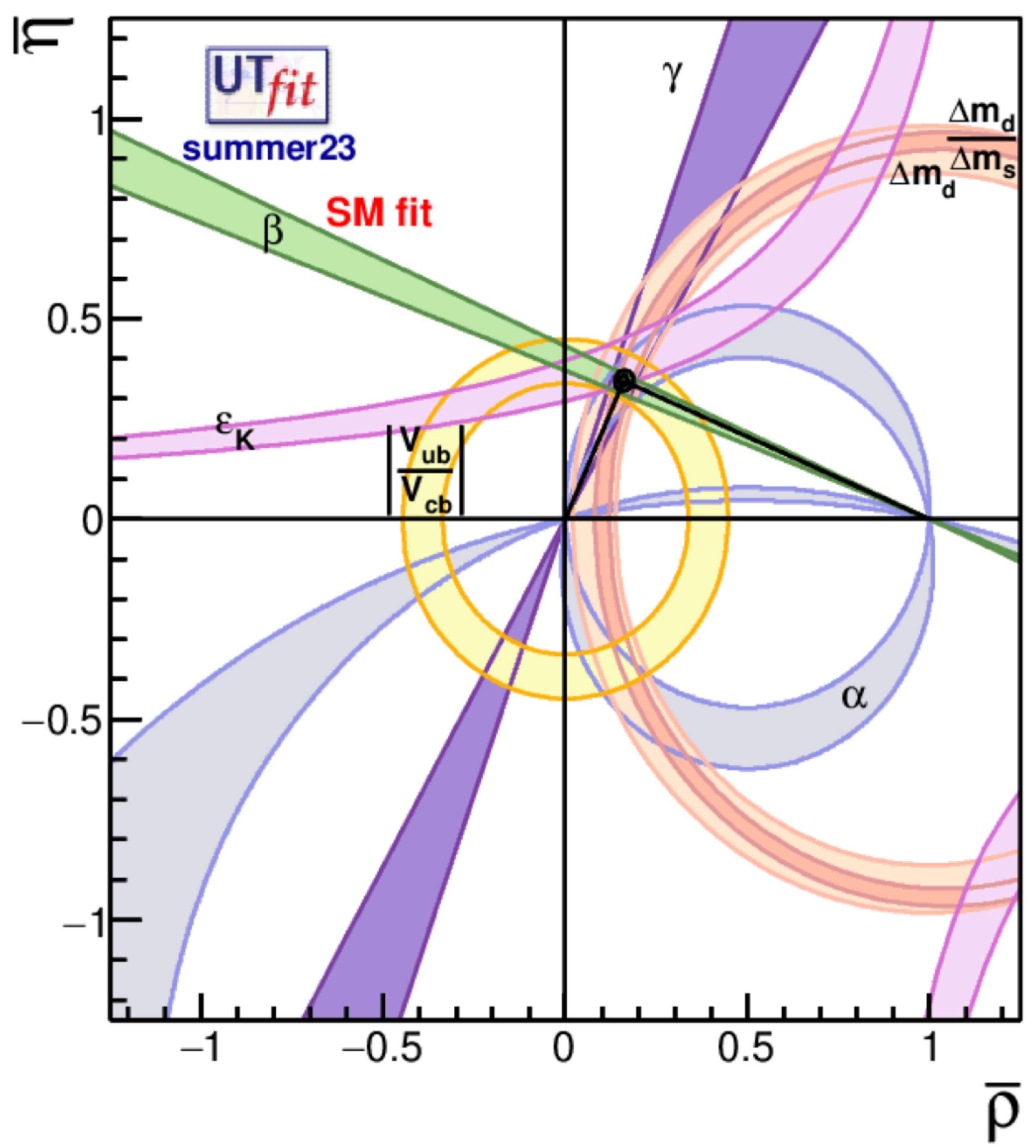
Experimental signatures
of BSM physics (***anomalies***)

$\boldsymbol{\Lambda \sim ?}$ (it depends on the measurement)

WIMP miracle
for Dark Matter

$\boldsymbol{\Lambda \sim 0.1 - O(10)\ \text{TeV}}$

The BSM Flavour Problem



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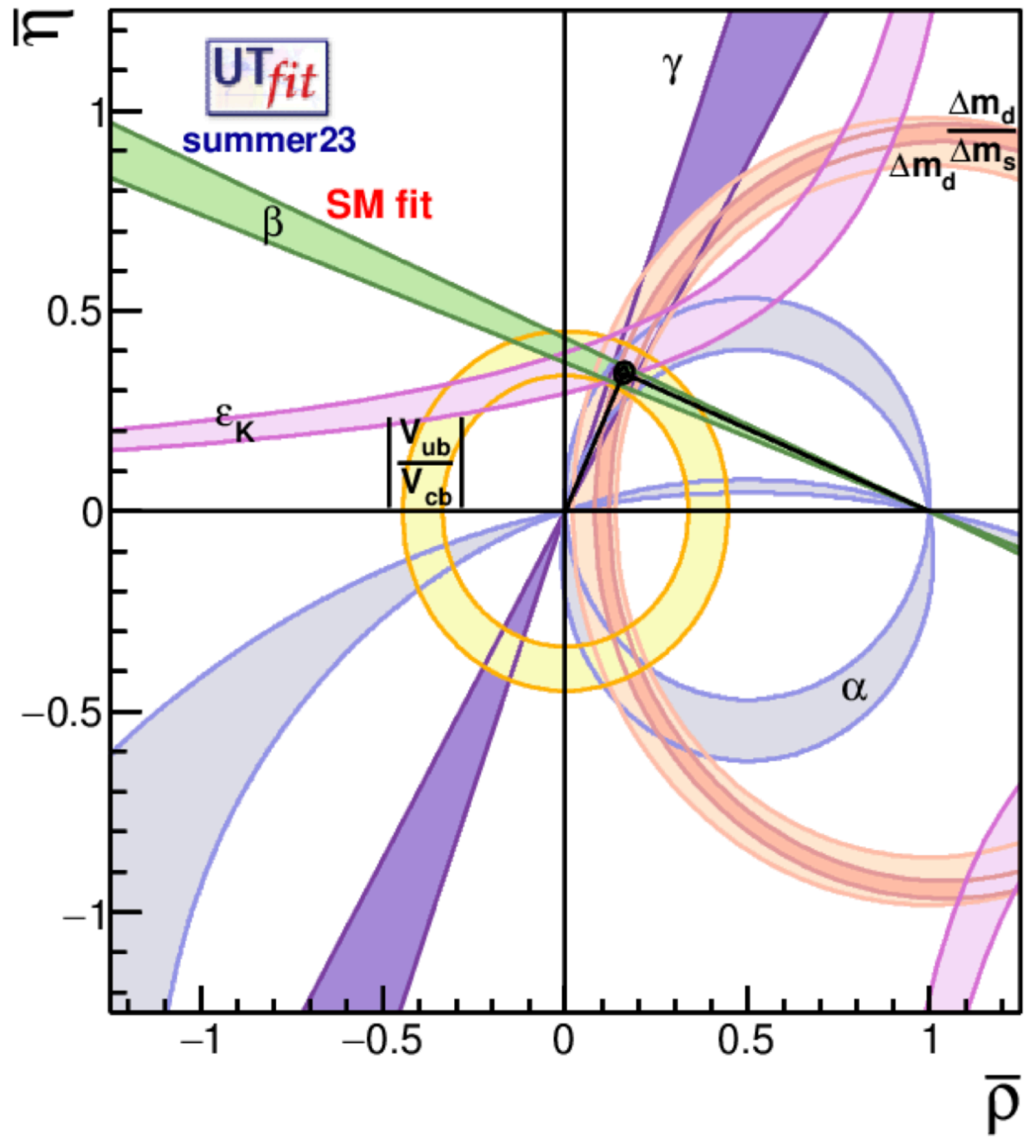

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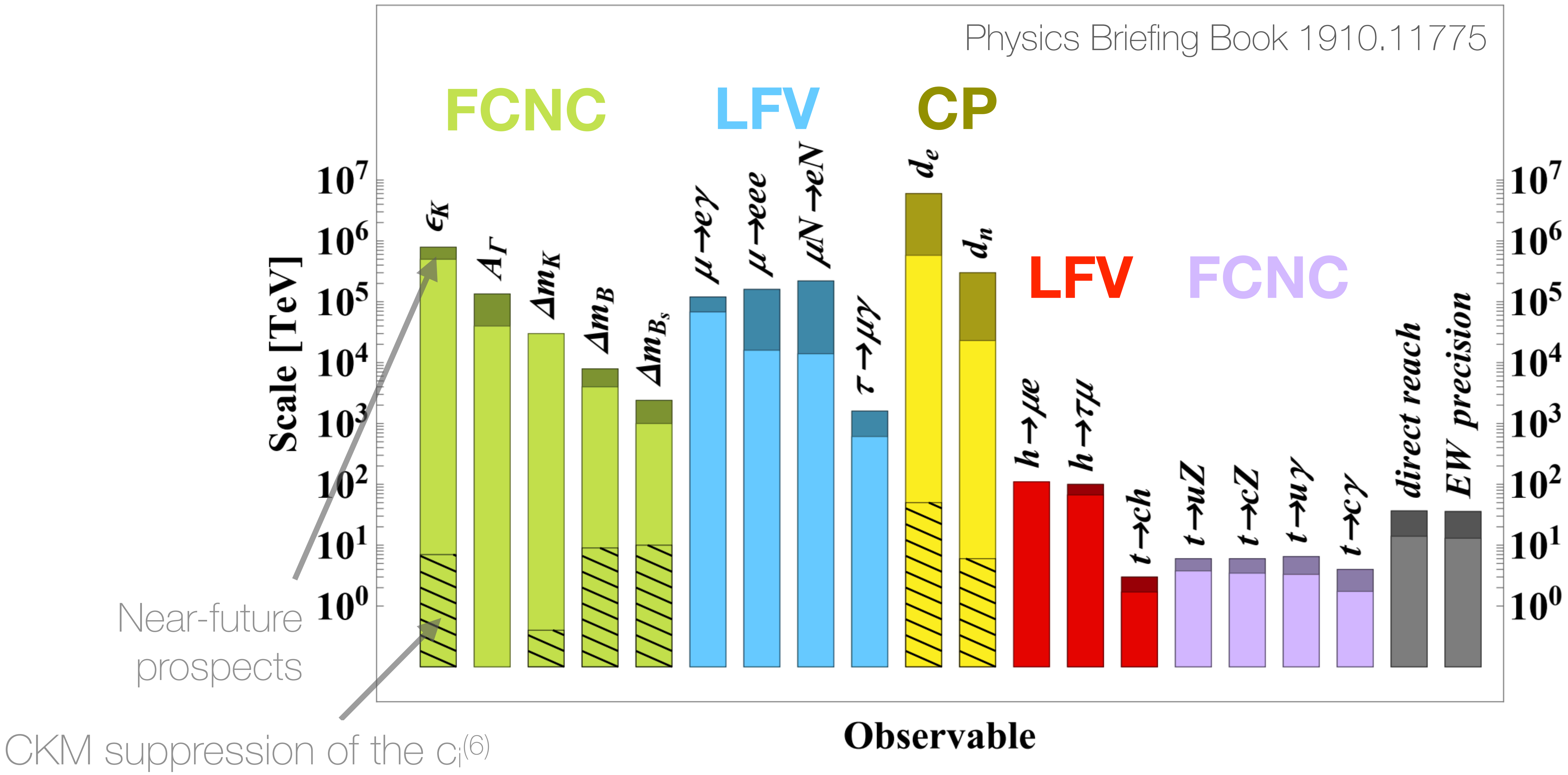
Bounds on Λ (taking $c_i^{(6)} = 1$) from various processes



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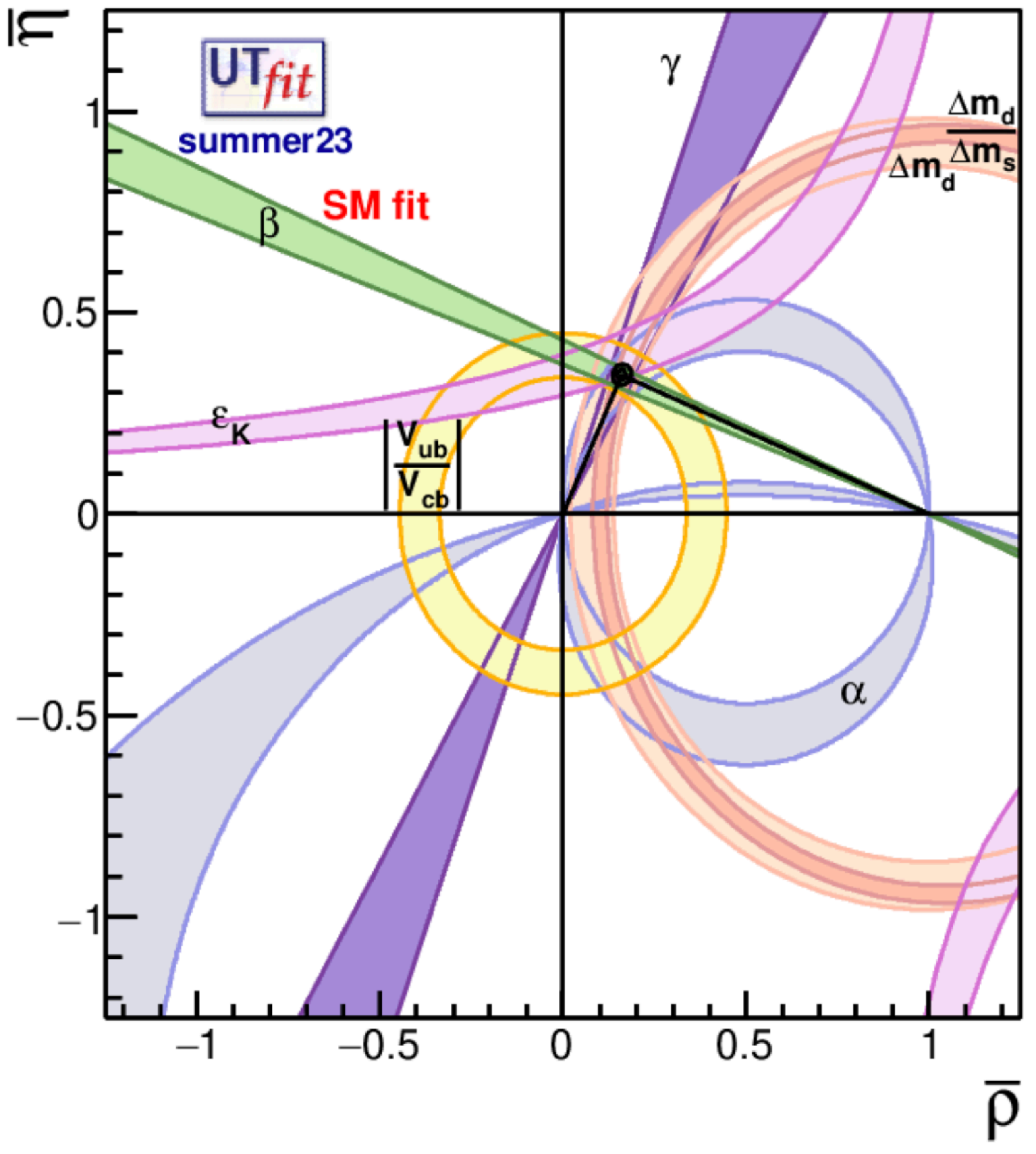

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If New Physics is present **at the TeV scale**, **its flavour structure should be constrained** by some “protecting” principle (symmetry or dynamics): **the BSM Flavour Problem**.

→ the $c^{(6)}$ coefficients should be suppressed.

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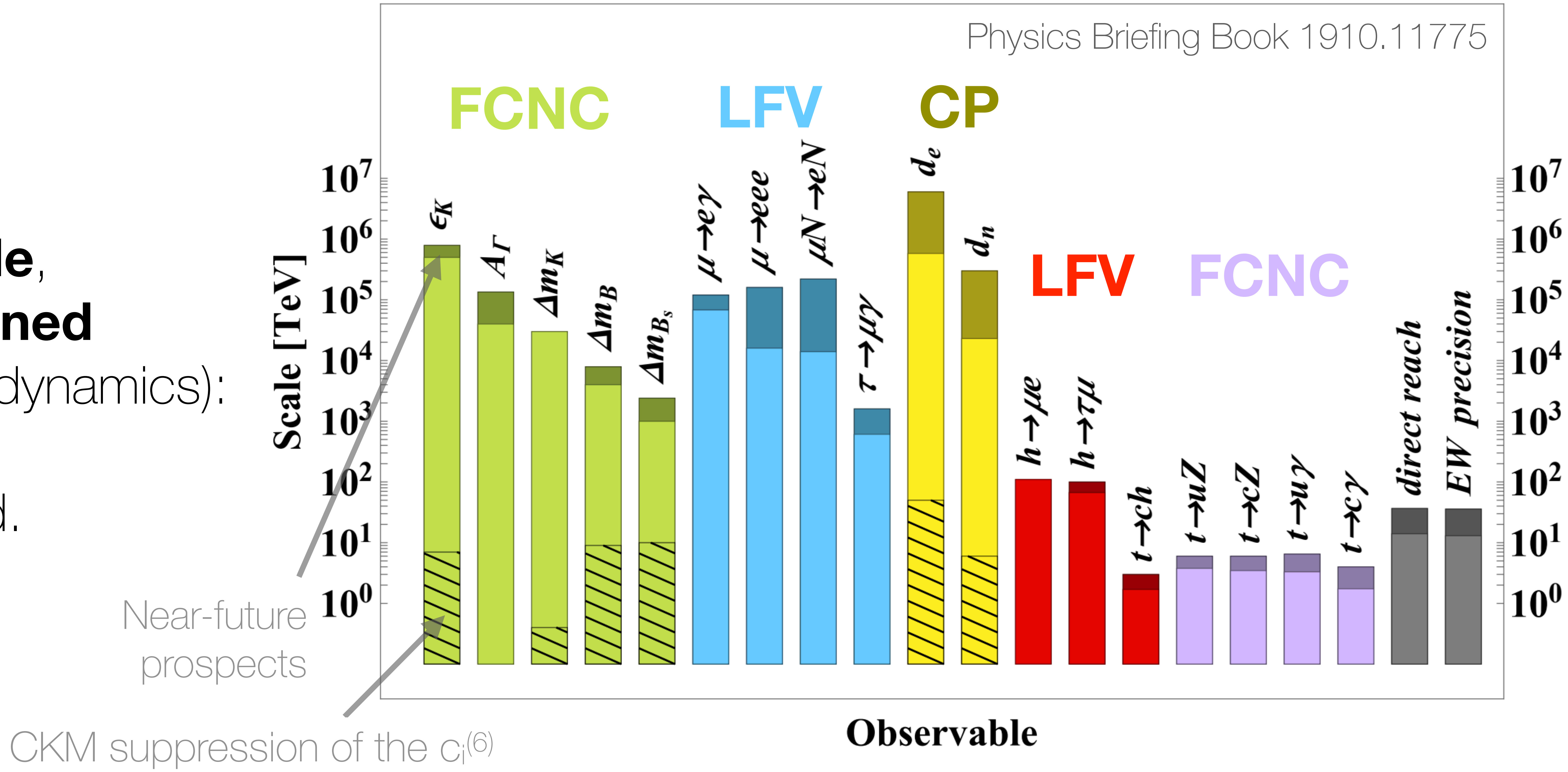

The BSM Flavour Problem

Let us consider the hypothetical case $\Lambda \sim 1$ - 10 TeV

- Solutions to the Hierarchy Problem
- Reach of present/future colliders
- Experimental anomalies

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With this low scale, **flavour-violating operators should be suppressed**, e.g. by small CKM elements.

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Typically, a good **flavour structure for a quark-current operator** $\mathcal{O}_{ij} \propto (\bar{d}_i \gamma_\mu d_j) \ldots$ is:

$$C_{ij} \sim \begin{pmatrix} \varepsilon_1 & \lambda^5 & \lambda^3 \\ \lambda^5 & \varepsilon_2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \qquad \lambda \sim \sin\vartheta_c$$

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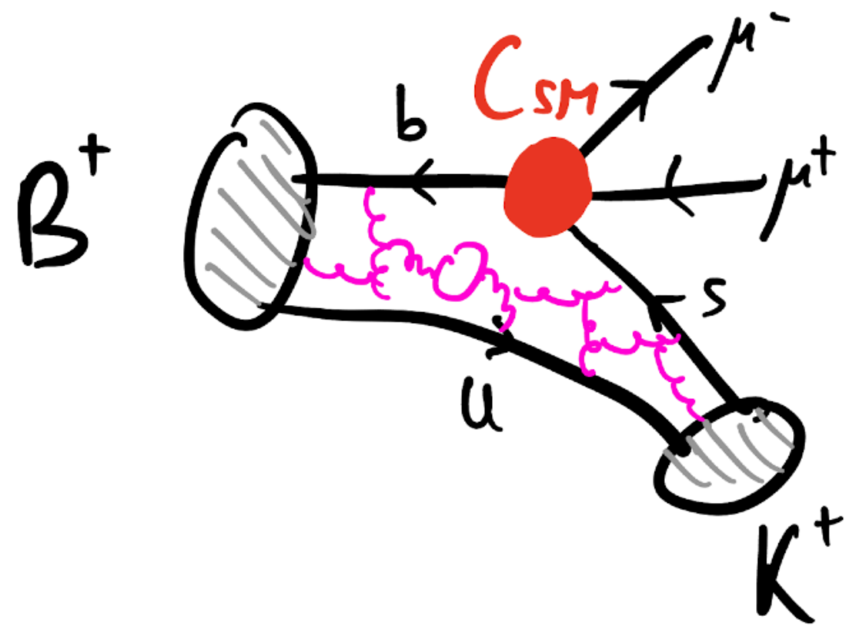
$\varepsilon_{1,2}$:
- **U(2)**-like: $\varepsilon_{1,2} \ll 1$
- **MFV**-like: $\varepsilon_{1,2} \sim 1$

Probing New Physics with flavour

Consider a **rare low-energy process in the SM**
Short-distance low-energy EFT coefficient

$$C_{SM} \sim \frac{\lambda_{SM}}{v^2} \qquad \lambda_{SM} \ll 1$$

Example: $C^{sb}_{SM} \sim \frac{\alpha}{4\pi} \frac{V_{ts} V_{tb}}{v^2}$



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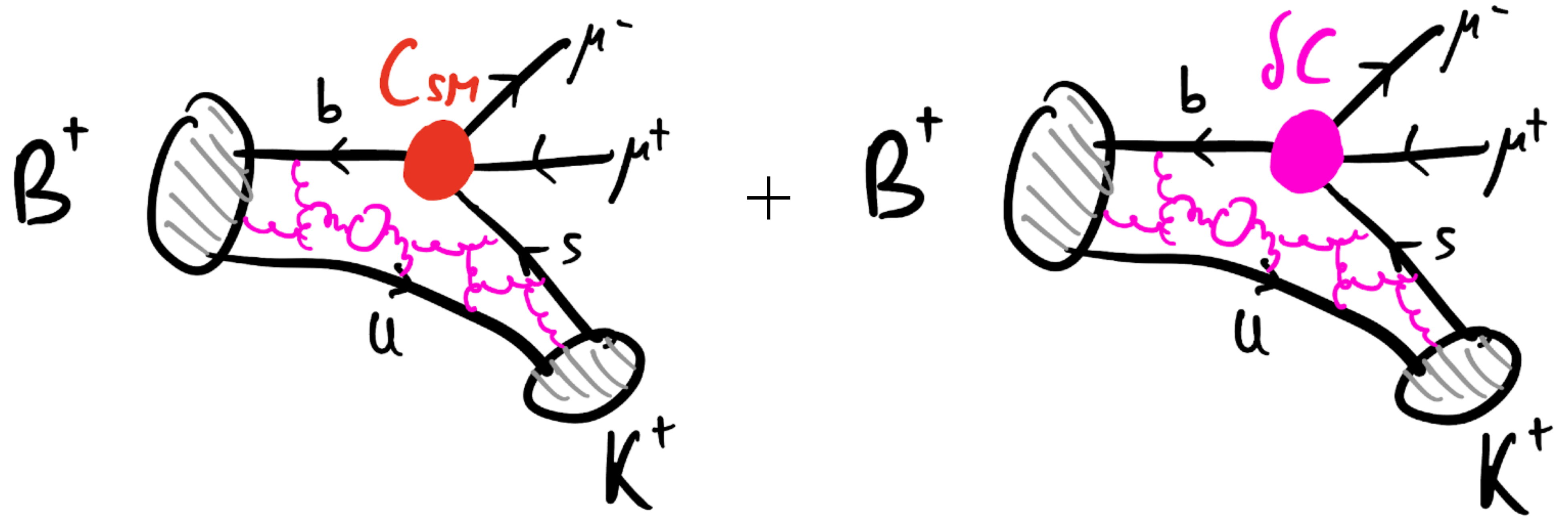

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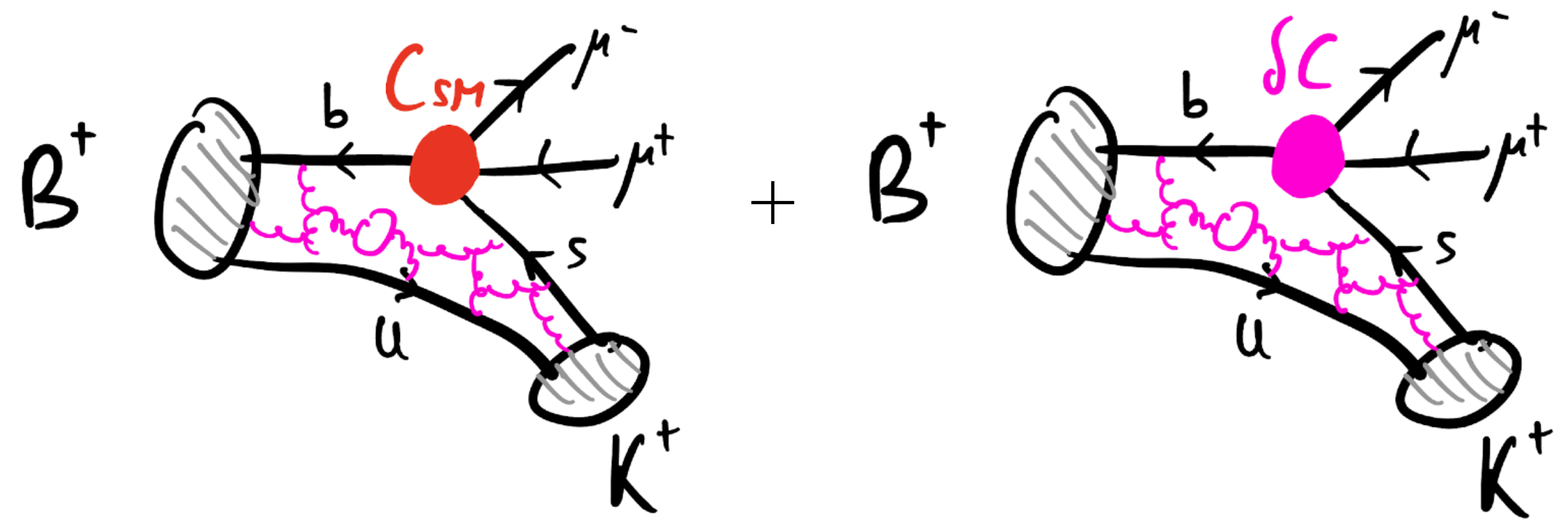

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$$\frac{\delta C}{C_{SM}} \sim \frac{c}{\lambda_{SM}} \frac{v^2}{\Lambda^2}$$

Relative **deviation in the short-distance coefficient**

Measuring this precisely puts strong constraints on the **EFT combination c/Λ^2**,
the **better the smallest λ_{SM}** is.

Probing New Physics with flavour

Typical EFT scales probed by different low-energy flavour physics measurements:

$R(K^{(*)})$

$$C_{sb\mu\mu} \lesssim \frac{1}{(50\ \mathrm{TeV})^2}$$

$K^+ \to \pi^+ \nu\nu$

$$C_{sd\nu\nu} \lesssim \frac{1}{(80\ \mathrm{TeV})^2}$$

$B^+ \to K^+ \nu\nu$

$$C_{sb\nu\nu} < \frac{1}{(8.6\ \mathrm{TeV})^2}$$

$R(D^{(*)})$

$$C_{bc\nu\tau} \sim \frac{1}{(4\ \mathrm{TeV})^2}$$

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$R(D^{(*)})$: $C_{bc\nu e} \sim \frac{1}{(4\ \text{TeV})^2}$

Assuming the **CKM-like flavour structure** (i.e. MFV, $U(2)^3$, etc..):

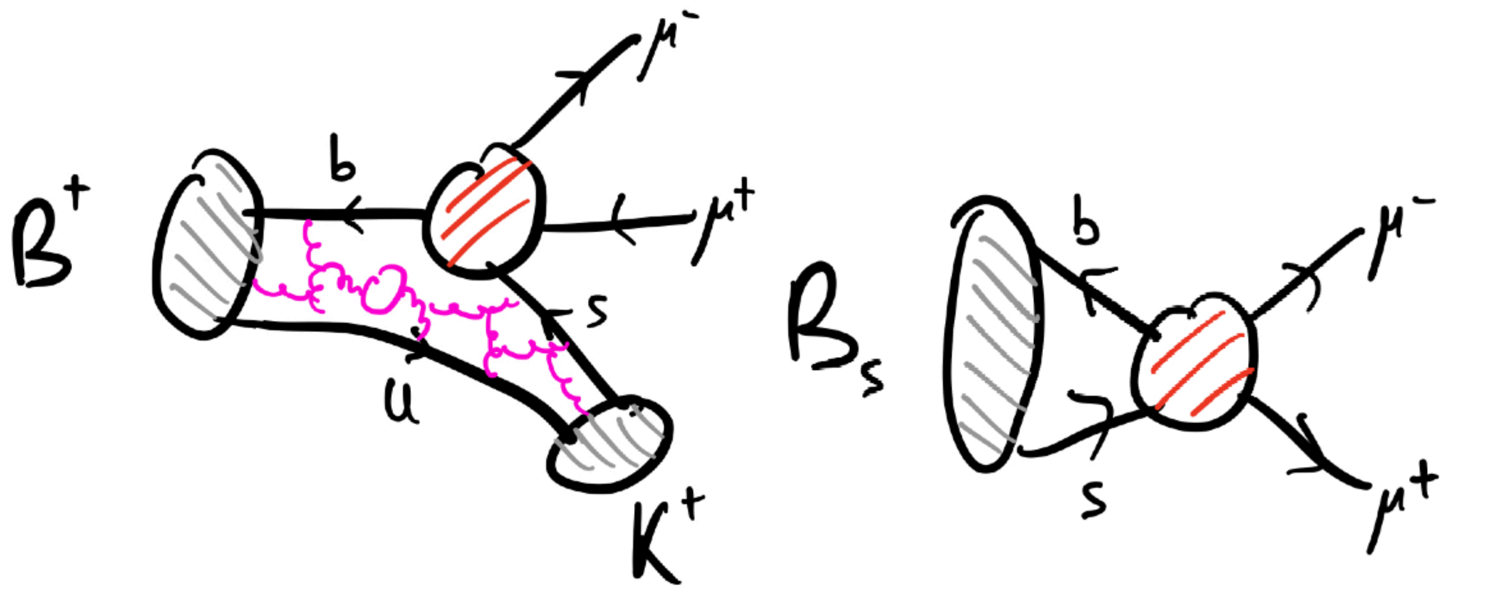
$$C_{sb\mu\mu} \sim \frac{V_{ts} V_{tb}}{\Lambda_\mu^2} \qquad C_{sd\nu\nu} \sim \frac{V_{ts} V_{td}}{\Lambda^2} \qquad C_{sb\nu\nu} \sim \frac{V_{ts} V_{tb}}{\Lambda^2} \qquad C_{bc\nu e} \sim \frac{V_{cb} V_{tb}}{\Lambda^2}$$

The bounds on the scale go down to $\Lambda \sim O(1)$ **TeV** for **all** (except $\Lambda_\mu \sim 10$ TeV)

See also: Bordone, Buttazzo, Isidori, Monnard [1705.10729], Borsato, Gligorov, Guadagnoli, Martinez Santos, Sumensari [1808.02006], Fajfer, Kosnik, Vale-Silva [1802.00786], DM, Trifinopoulos, Venturini [2106.15630]

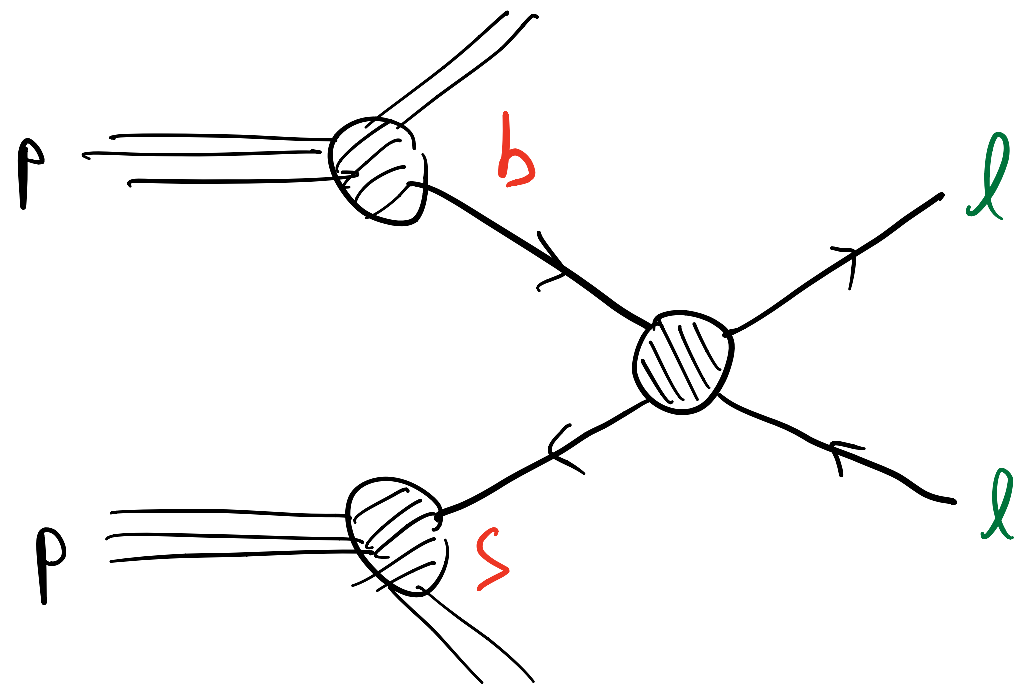
From low to high energy

Meson decays



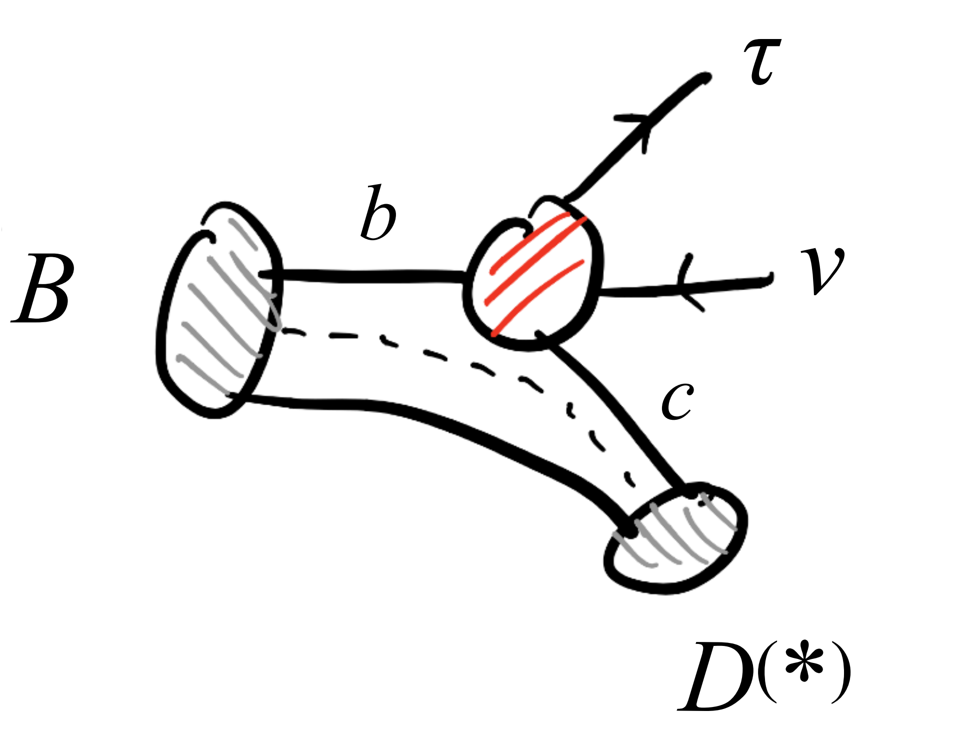
Crossing symmetry

Drell-Yan tail



[Greljo, DM 1704.09015]

If $\mathbf{m_{EW} < E_{\ell\ell} \ll M_{NP}}$ we can use an EFT approach



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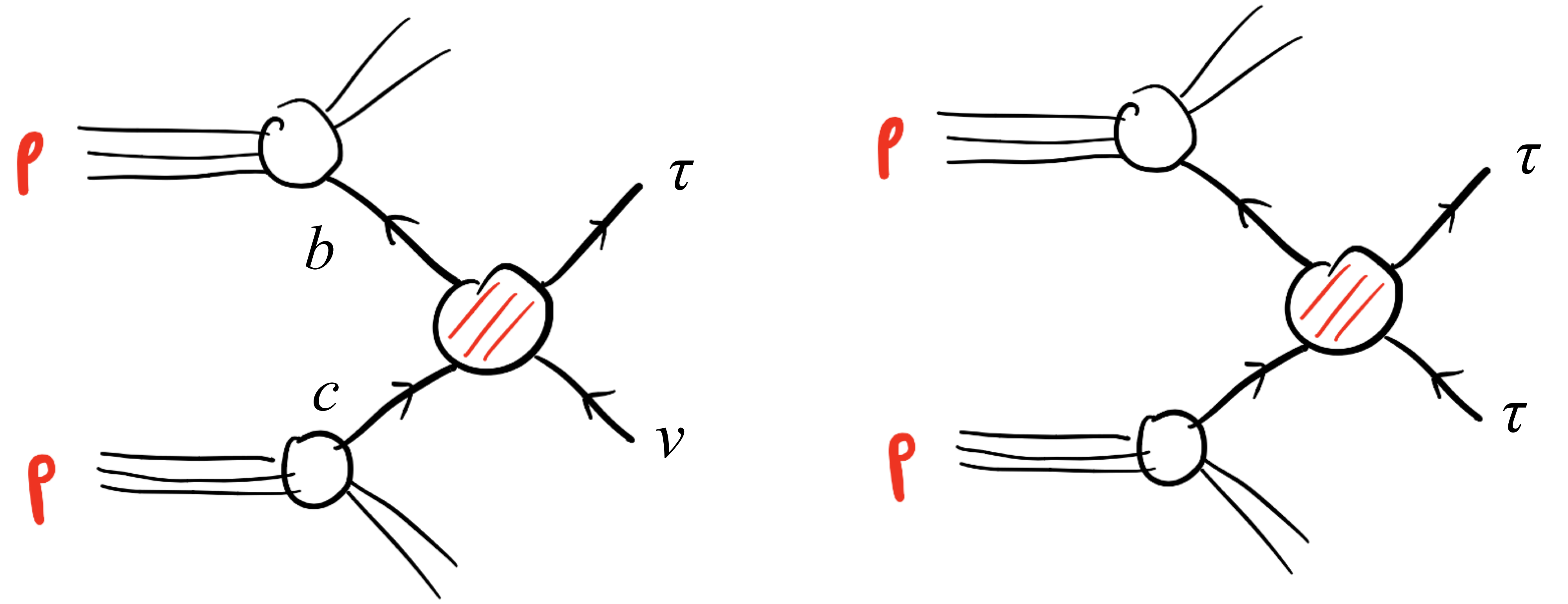
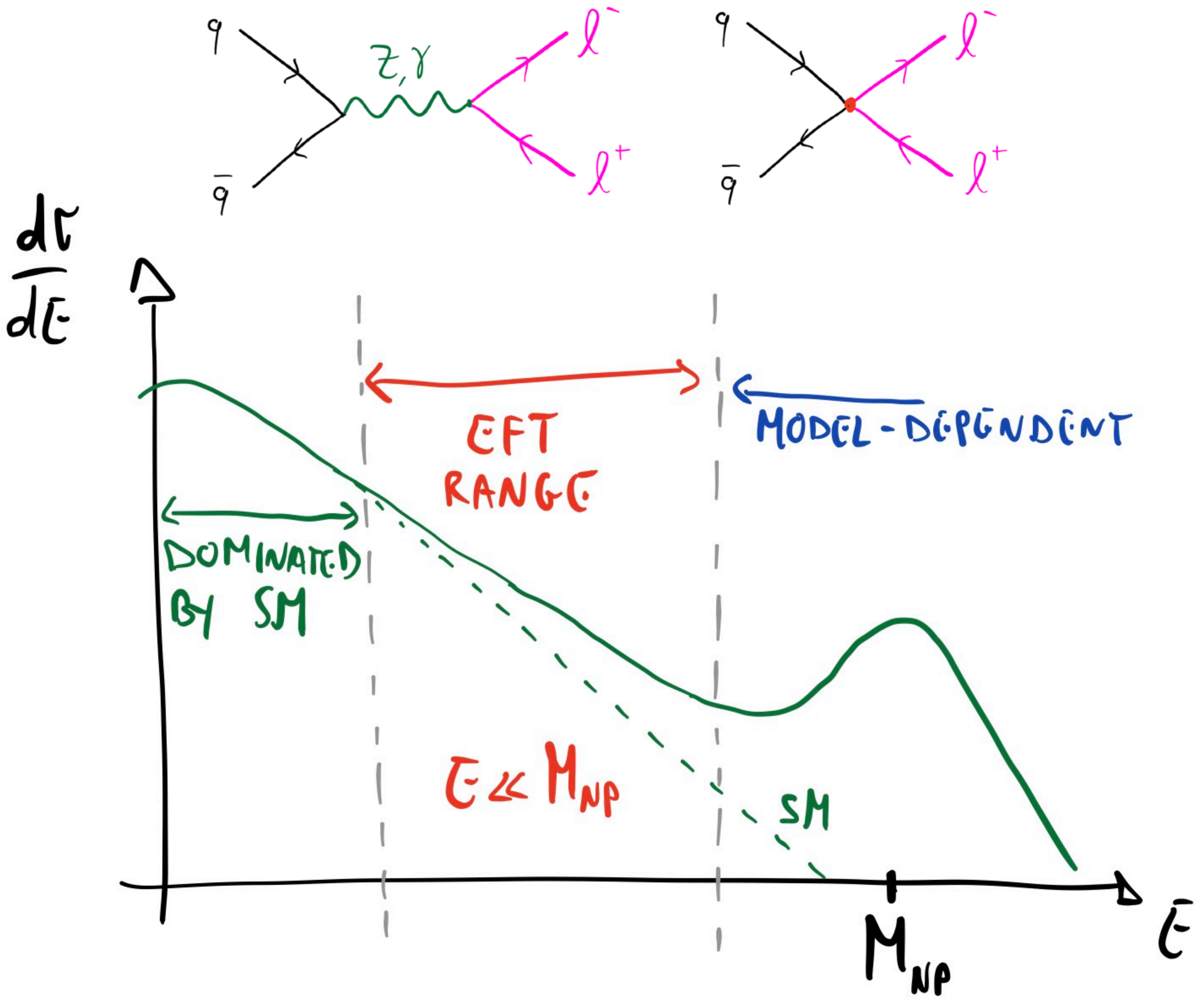


[Greljo, Camalich, Ruiz-Alvarez 1811.07920]
[DM, Min, Son, 2008.07541]

[Faroughy, Greljo, Kamenik 1609.07138]

Now also a public tool: *HighpT*: [2207.10714, 2207.10756]

High-Energy dilepton tails

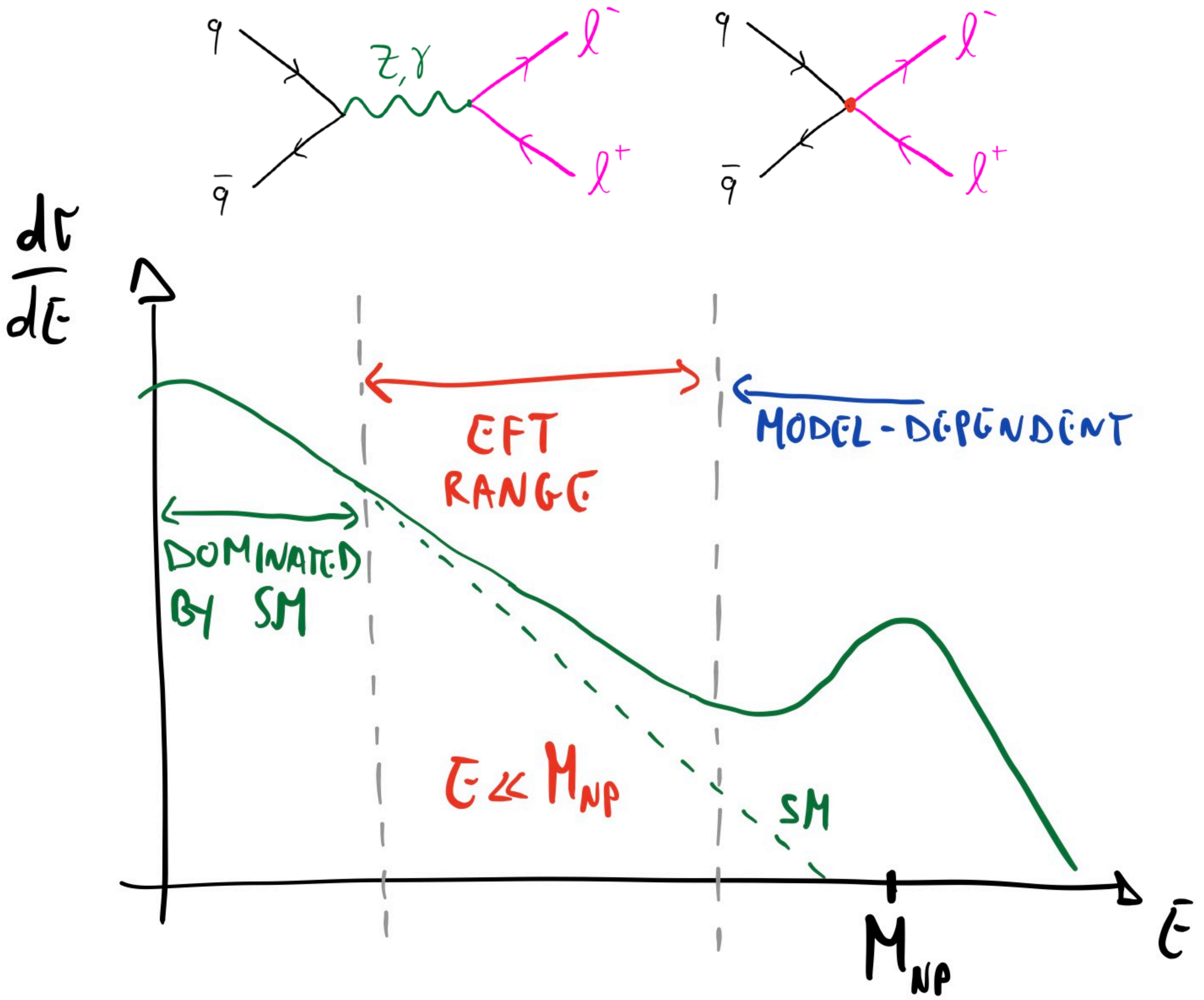


The **effect of heavy New Physics grows with the energy** until the scale of new states is reached.

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

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

High-Energy dilepton tails



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EFT enhancement in high-pT tails

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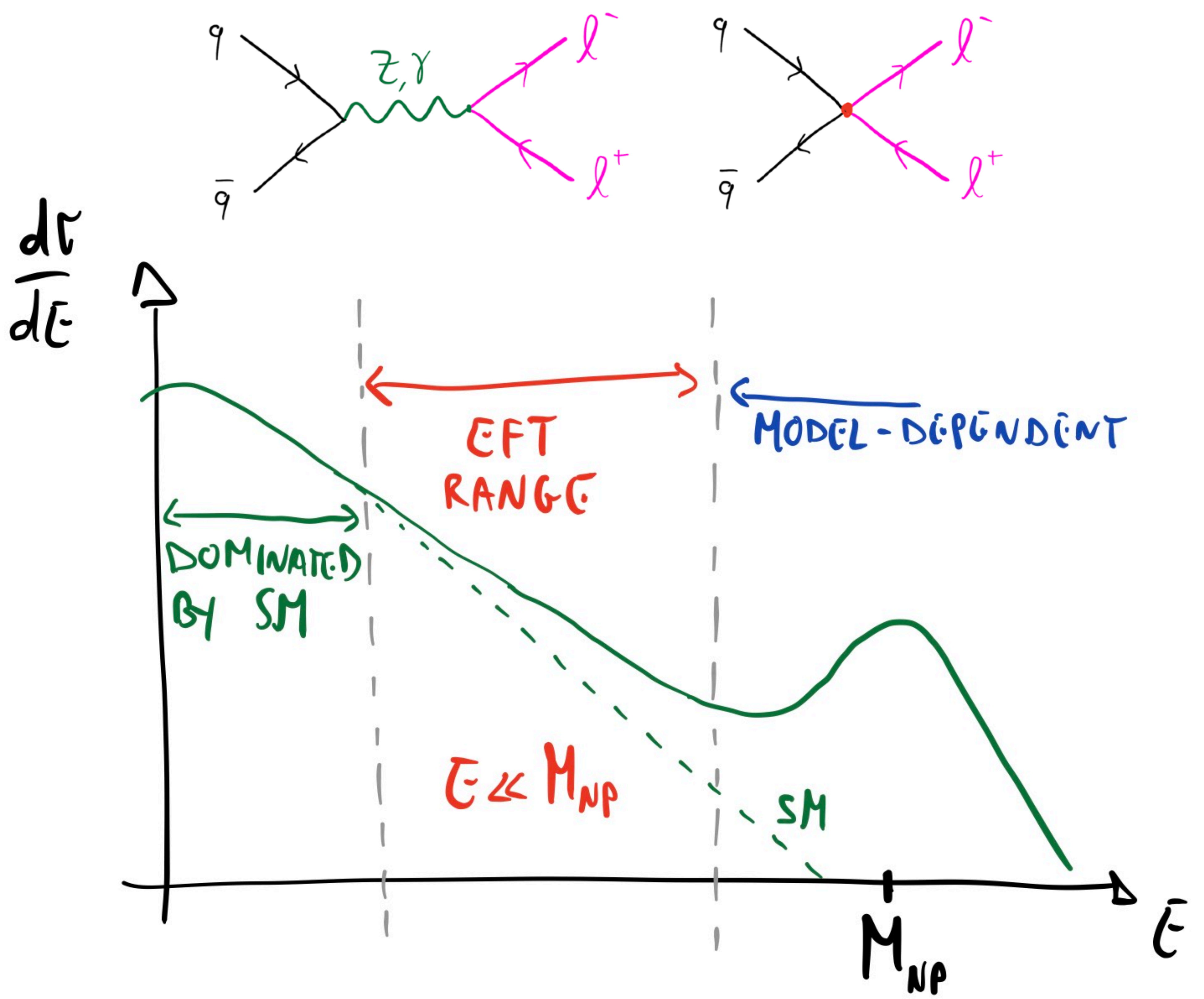
vs.

$$\frac{\delta C}{C_{SM}} \sim \frac{c}{\lambda_{SM}}\,\frac{v^2}{\Lambda^2}$$

SM less suppressed

High-Energy dilepton tails



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

vs.

$$\frac{\delta C}{C_{SM}} \sim \frac{C}{\lambda_{SM}}\frac{v^2}{\Lambda^2}$$

SM less suppressed

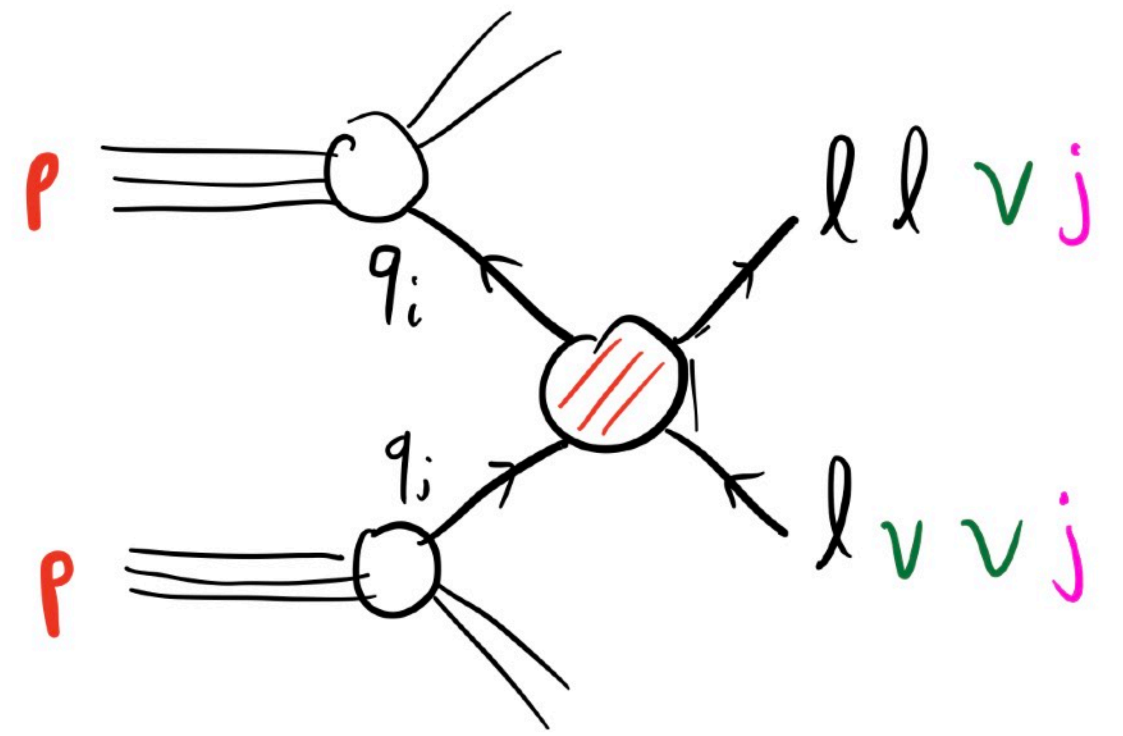
Expected reach:

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

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..]

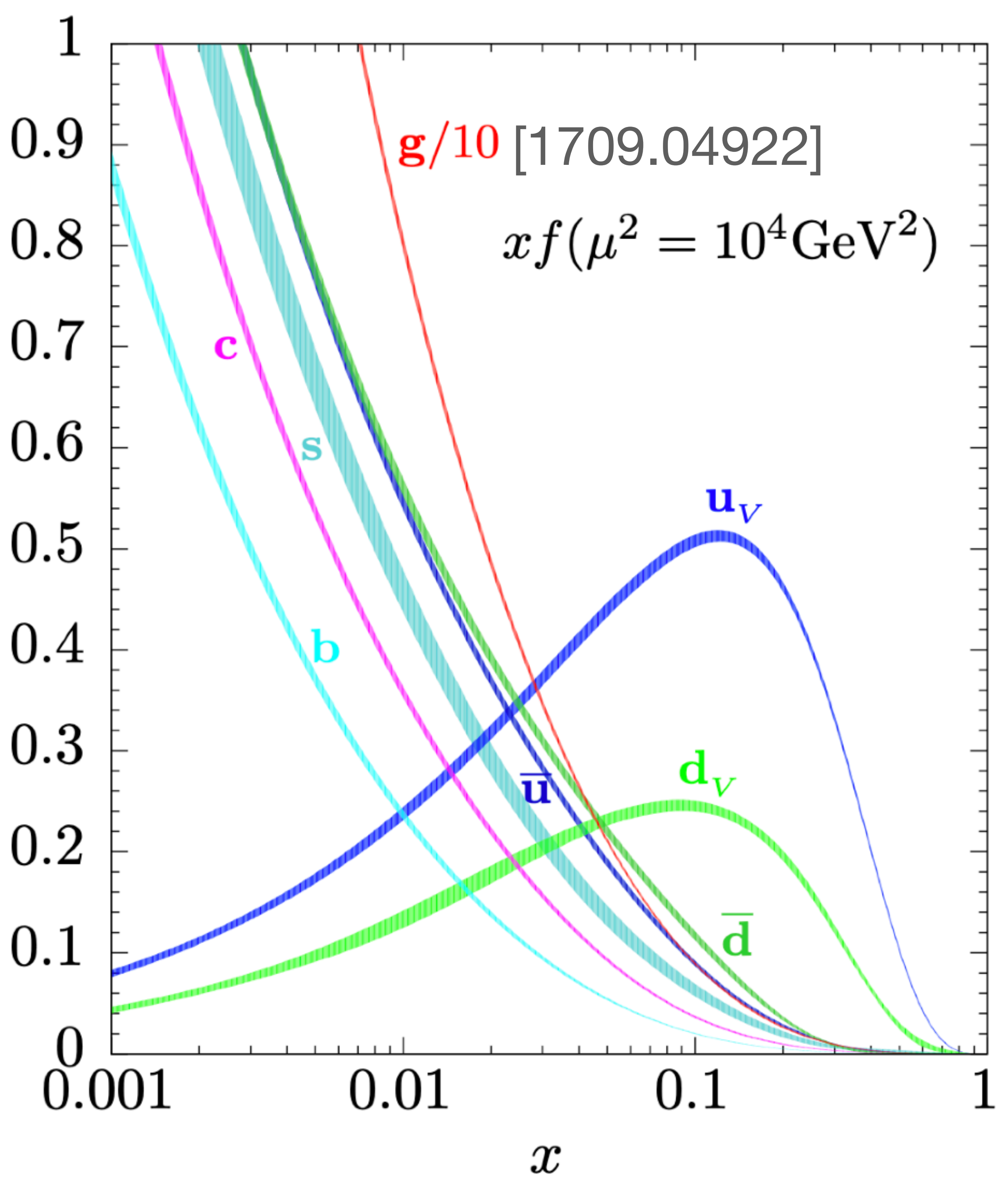
(HL-)LHC as a "Flavor collider"



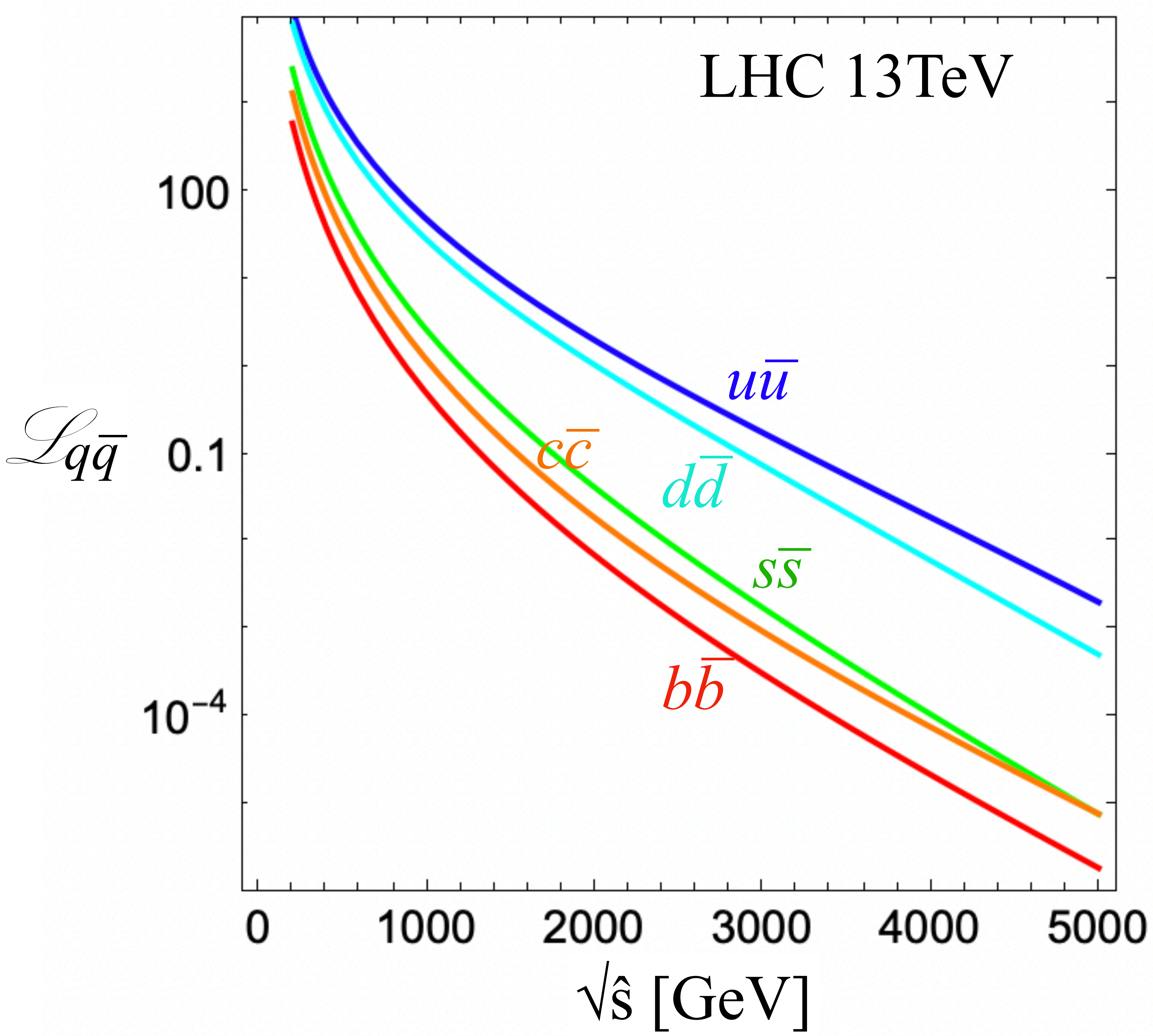
The differential cross section is approximately

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

Protons contain all flavors

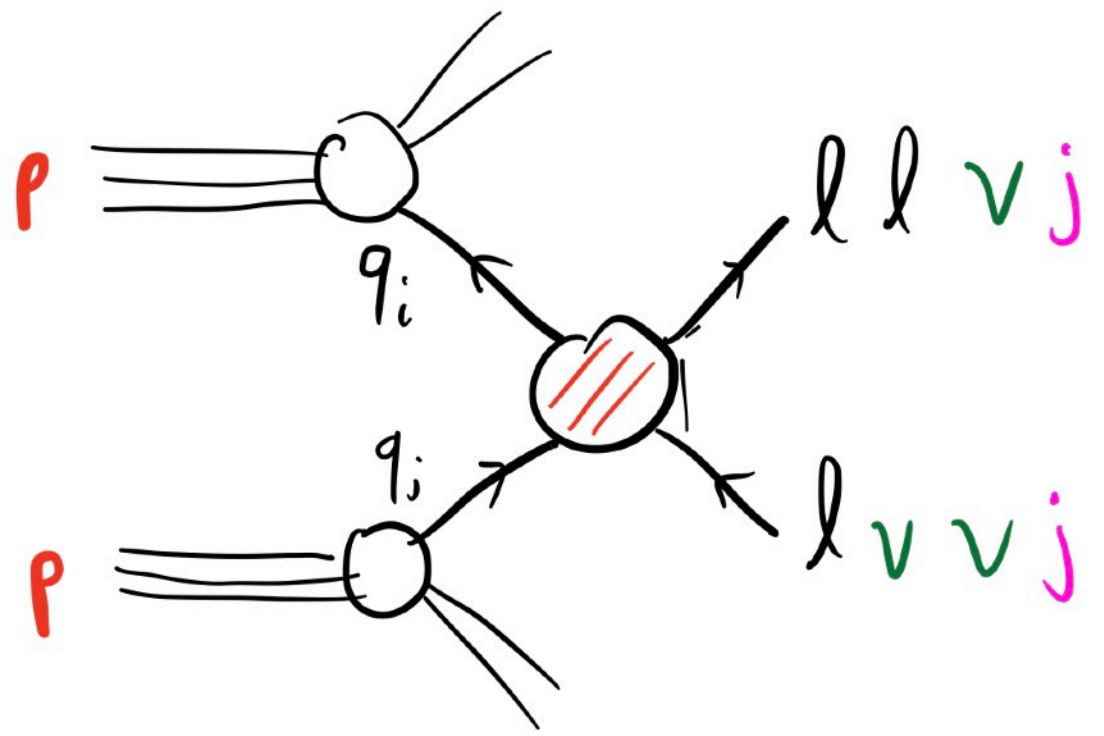


quark-antiquark luminosities



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

(HL-)LHC as a “Flavor collider”



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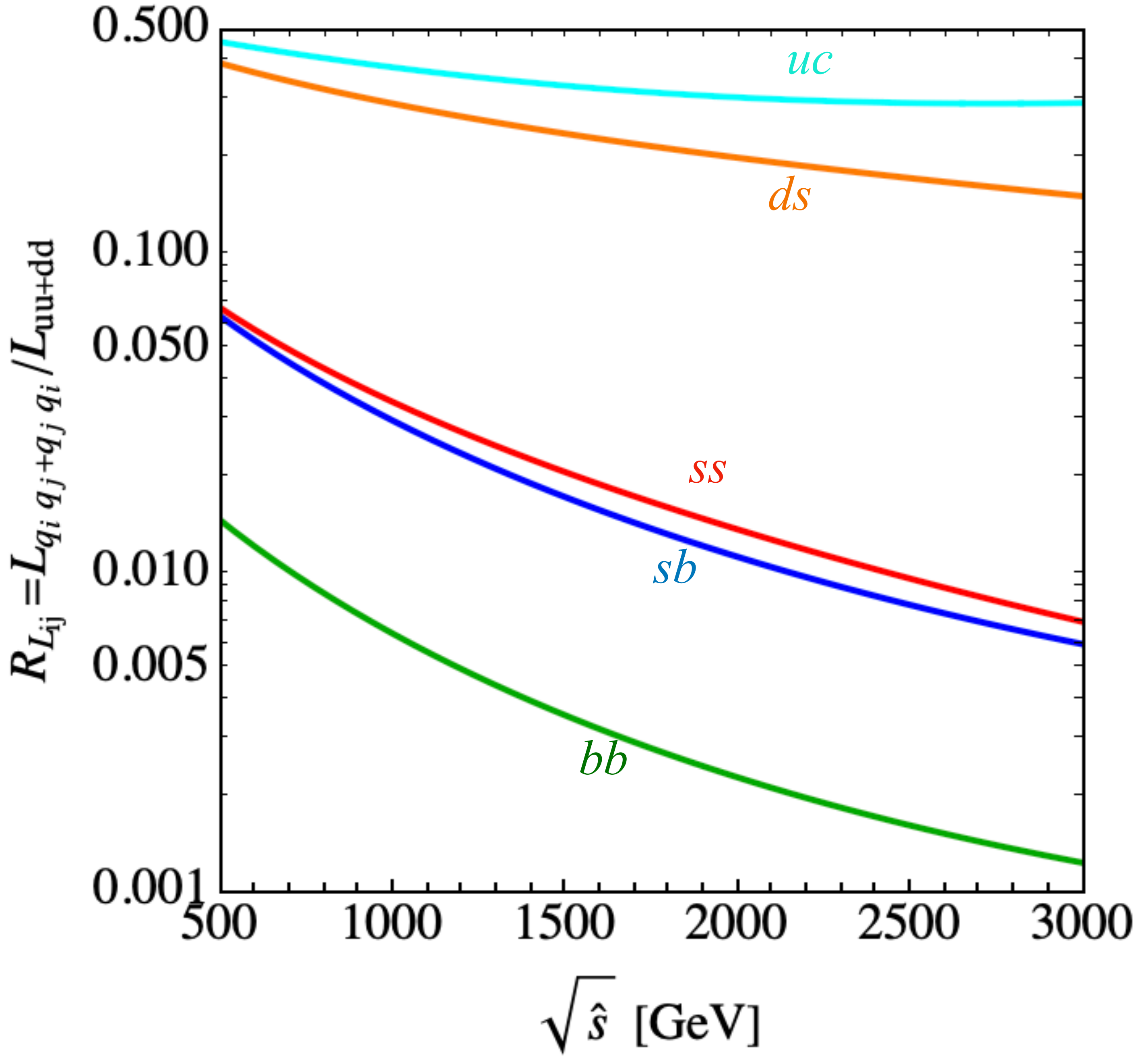
Let us estimate the reach of high-p_T tails

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

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

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



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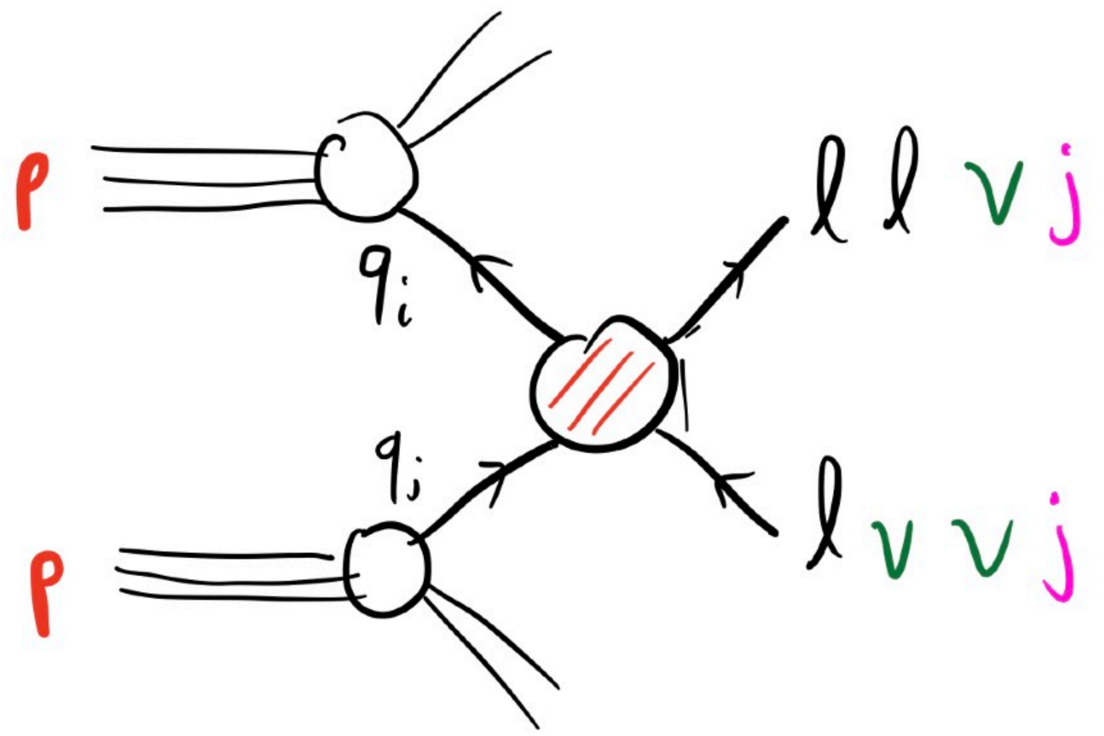

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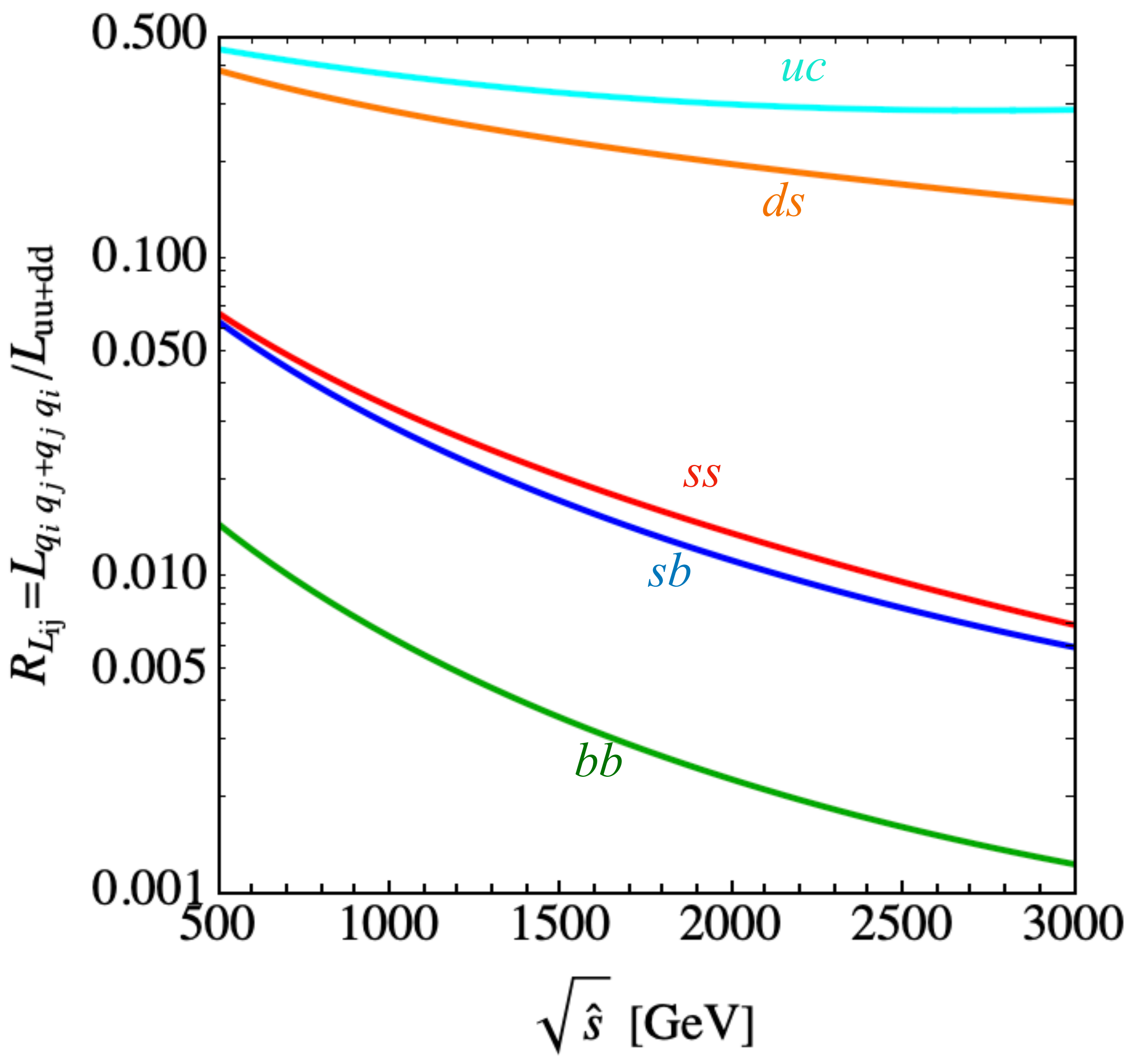


Example:

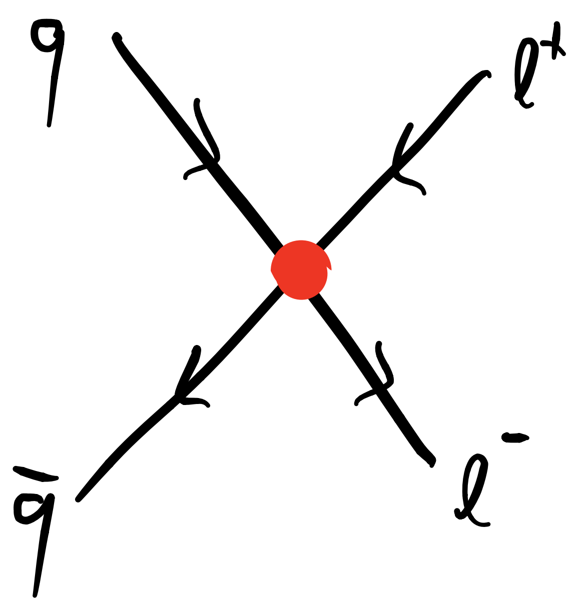
$\hat{s} = (2\ \text{TeV})^2$

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

$g_{SM} \sim 0.4$

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

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:

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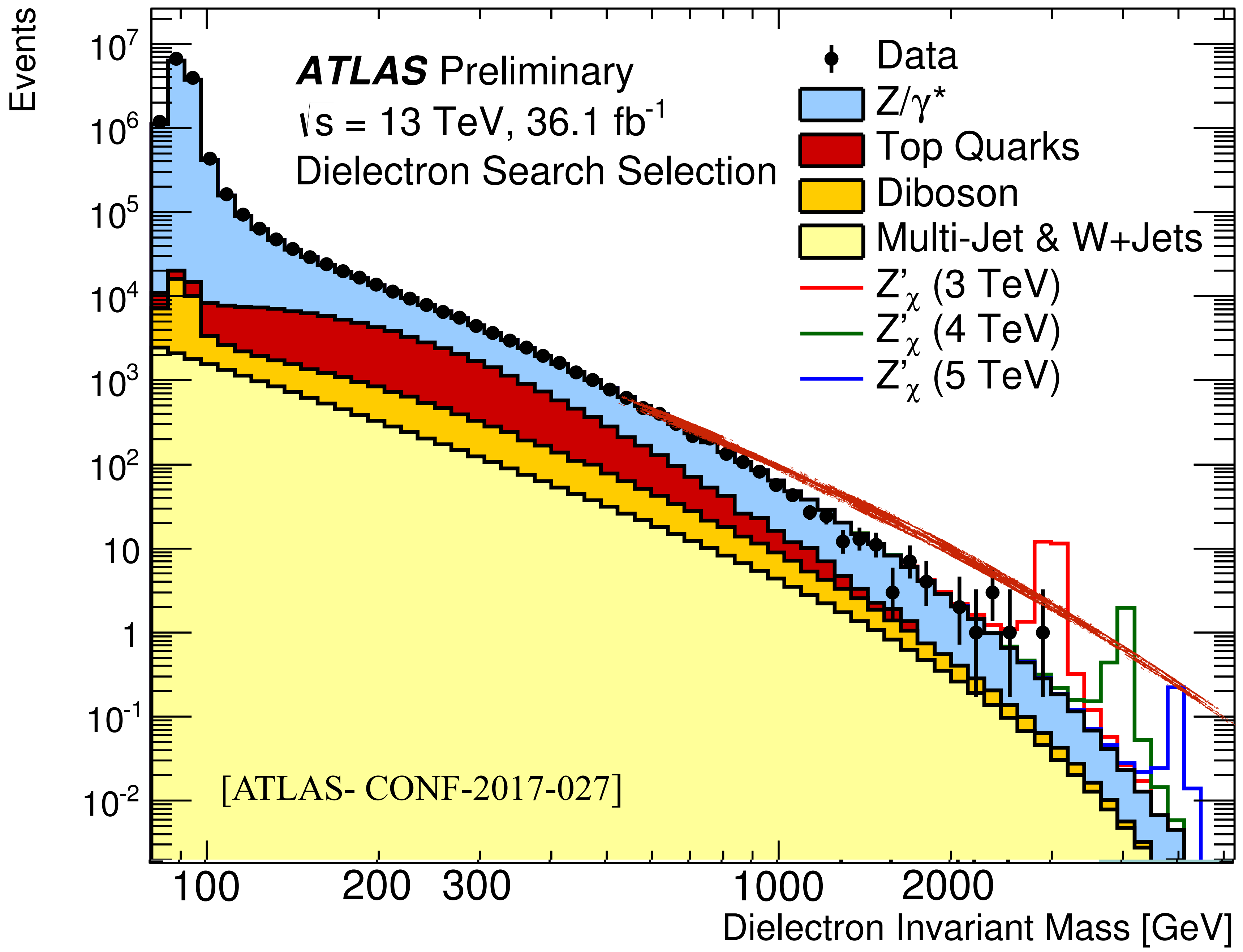
$(\mathcal{O}_{eu})_{\alpha i} = (\bar{e}_\alpha \gamma_\mu e_\alpha)(\bar{u}_i \gamma^\mu u_i)$	$(\mathcal{O}_{ed})_{\alpha i} = (\bar{e}_\alpha \gamma_\mu e_\alpha)(\bar{d}_i \gamma^\mu d_i)$

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



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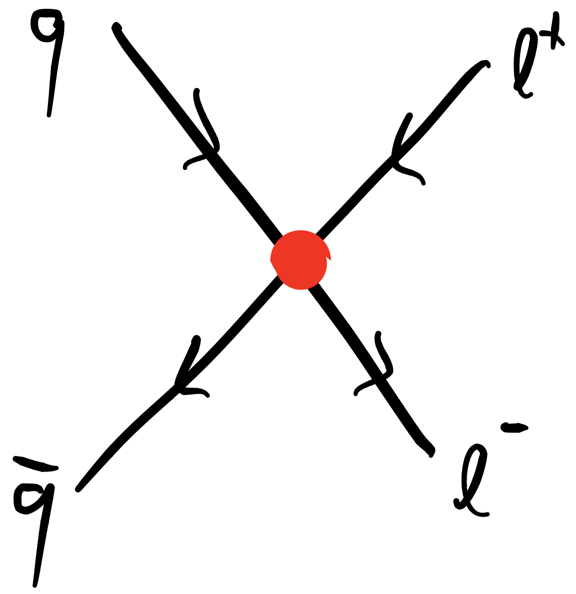

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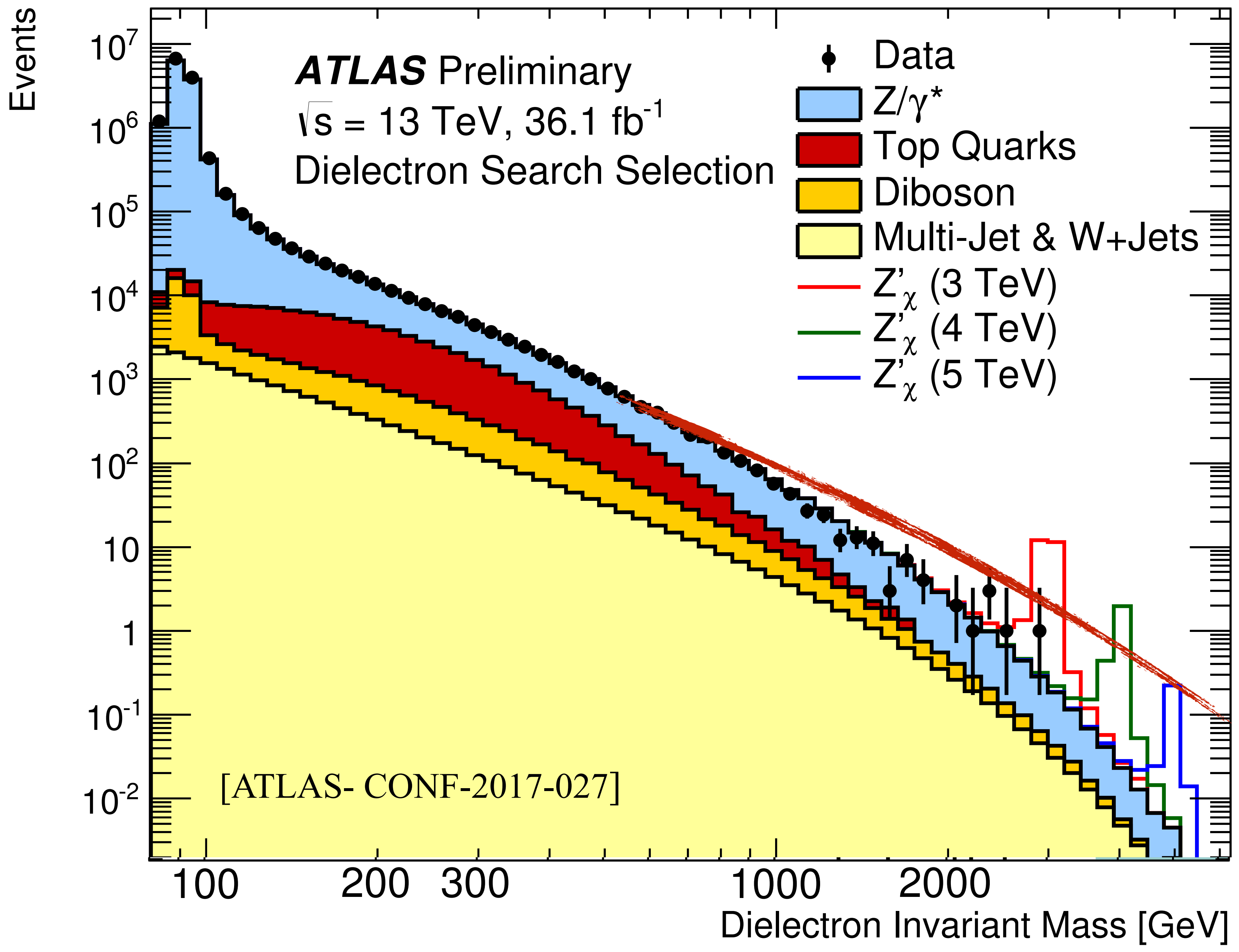
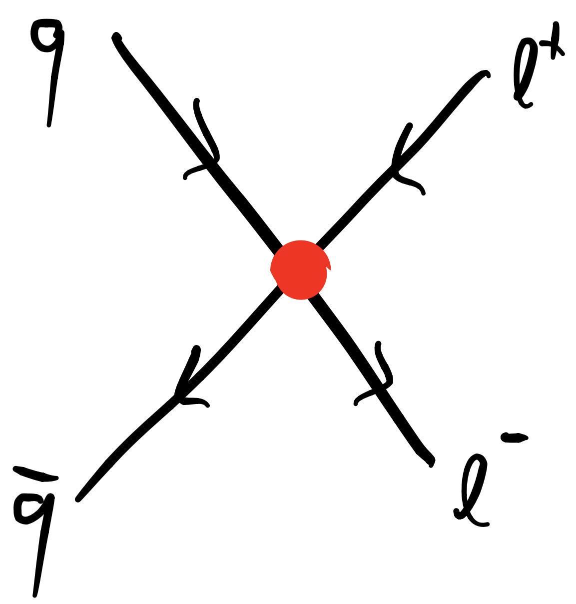


C_i	ATLAS 36.1 fb^{-1}	3000 fb^{-1}
$C^{(1)}_{Q^1L^1}$	[-0.0, 1.75] $\times 10^{-3}$	[-1.01, 1.13] $\times 10^{-4}$
$C^{(3)}_{Q^1L^1}$	[-8.92, -0.54] $\times 10^{-4}$	[-3.99, 3.93] $\times 10^{-5}$
$C_{u_RL^1}$	[-0.19, 1.92] $\times 10^{-3}$	[-1.56, 1.92] $\times 10^{-4}$
$C_{u_Re_R}$	[0.15, 2.06] $\times 10^{-3}$	[-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



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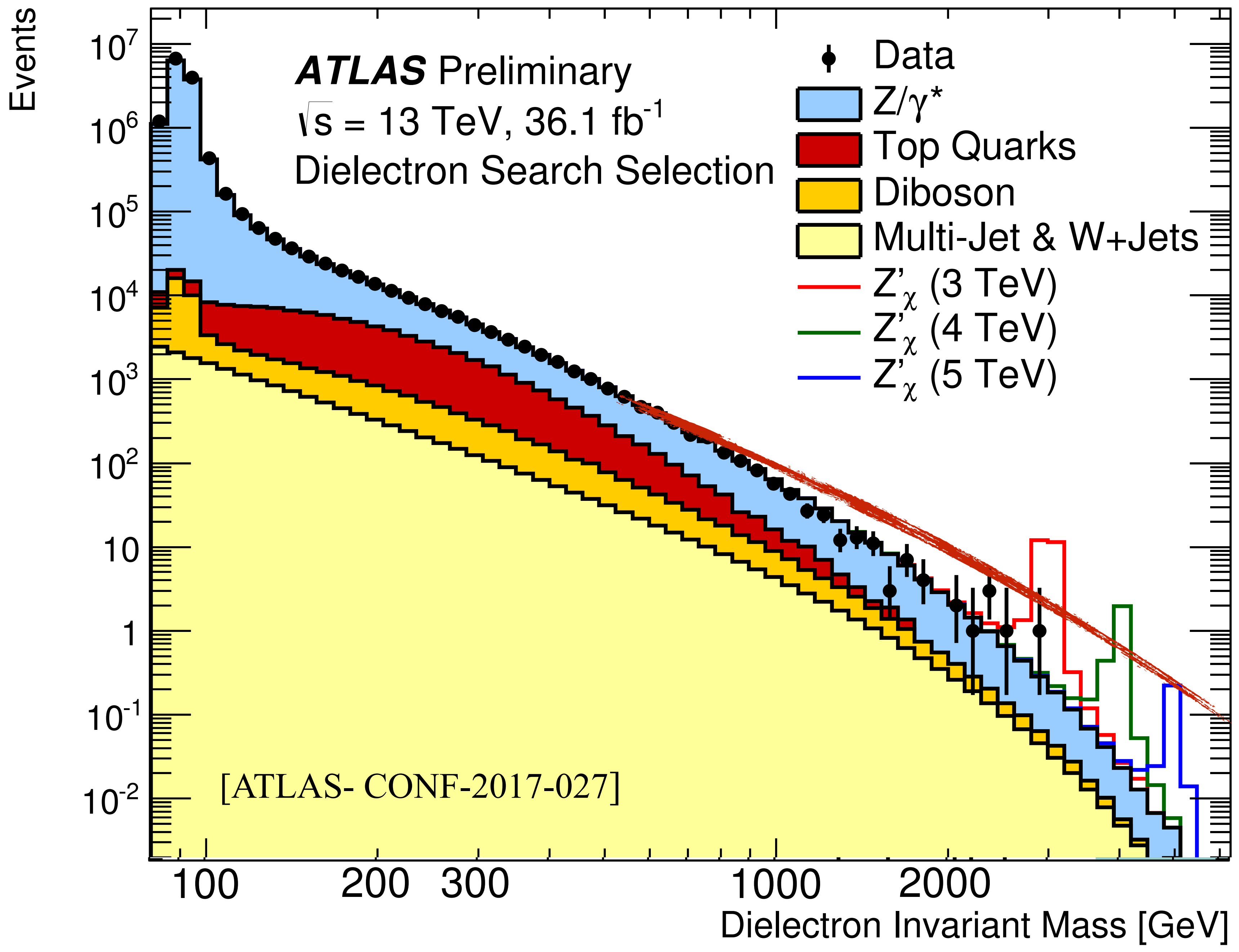

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Approximately:

$\Lambda/\sqrt{c_i} \gtrsim$ 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]

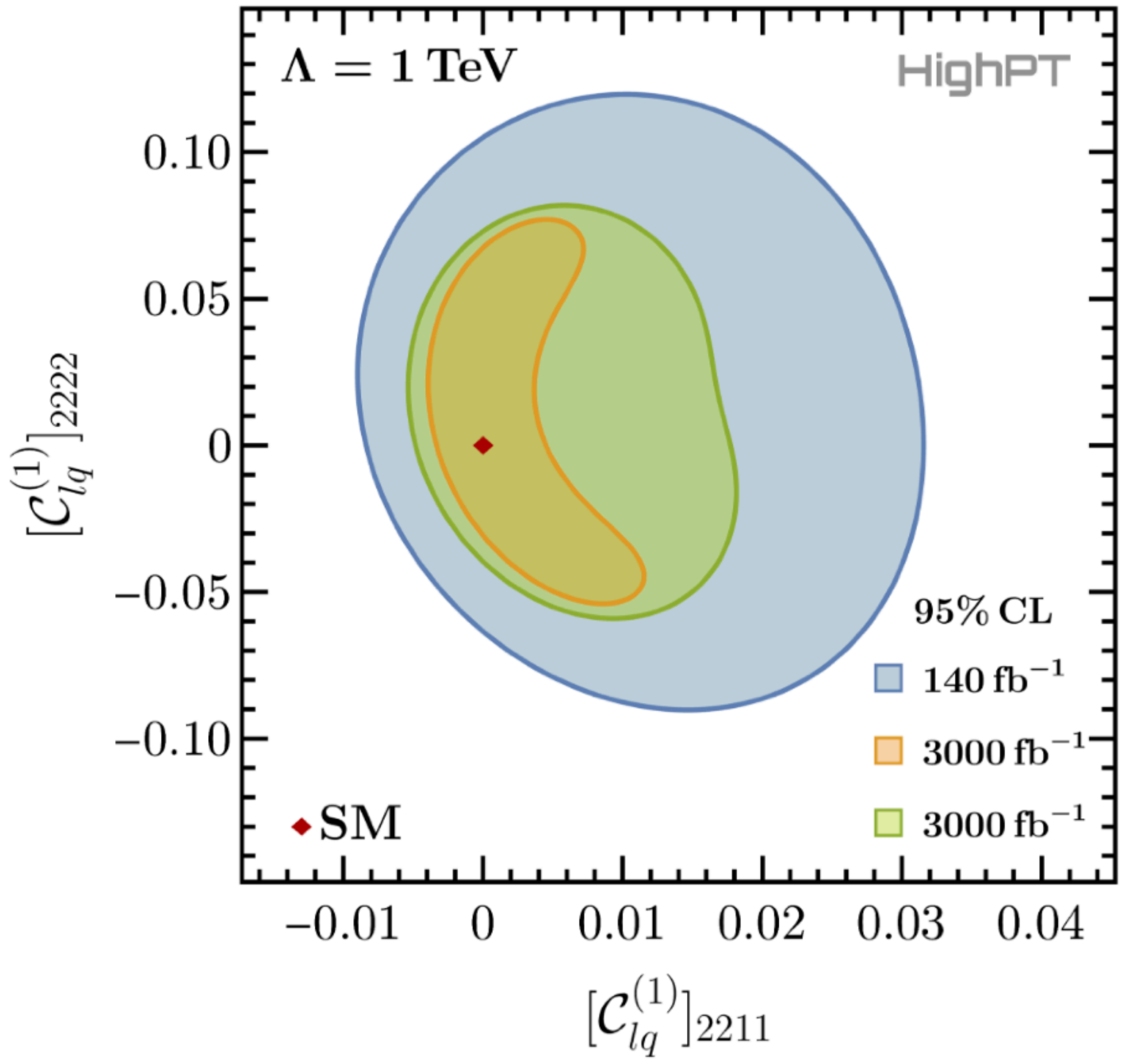
Implemented analyses with NC and CC channels with muons and electrons and ~140 fb^{-1} of luminosity. All relevant SMEFT operators included.

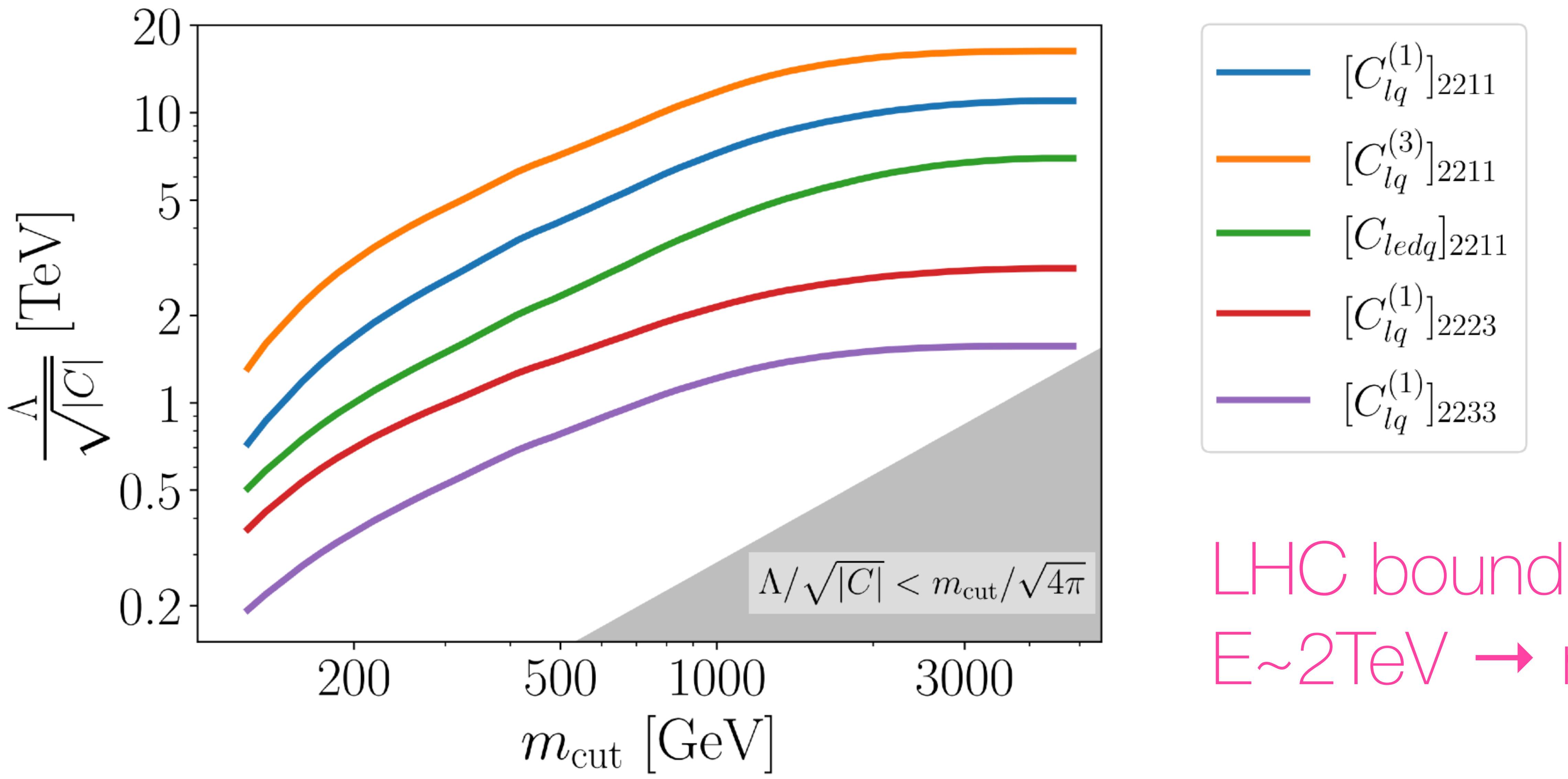
HighPT

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.

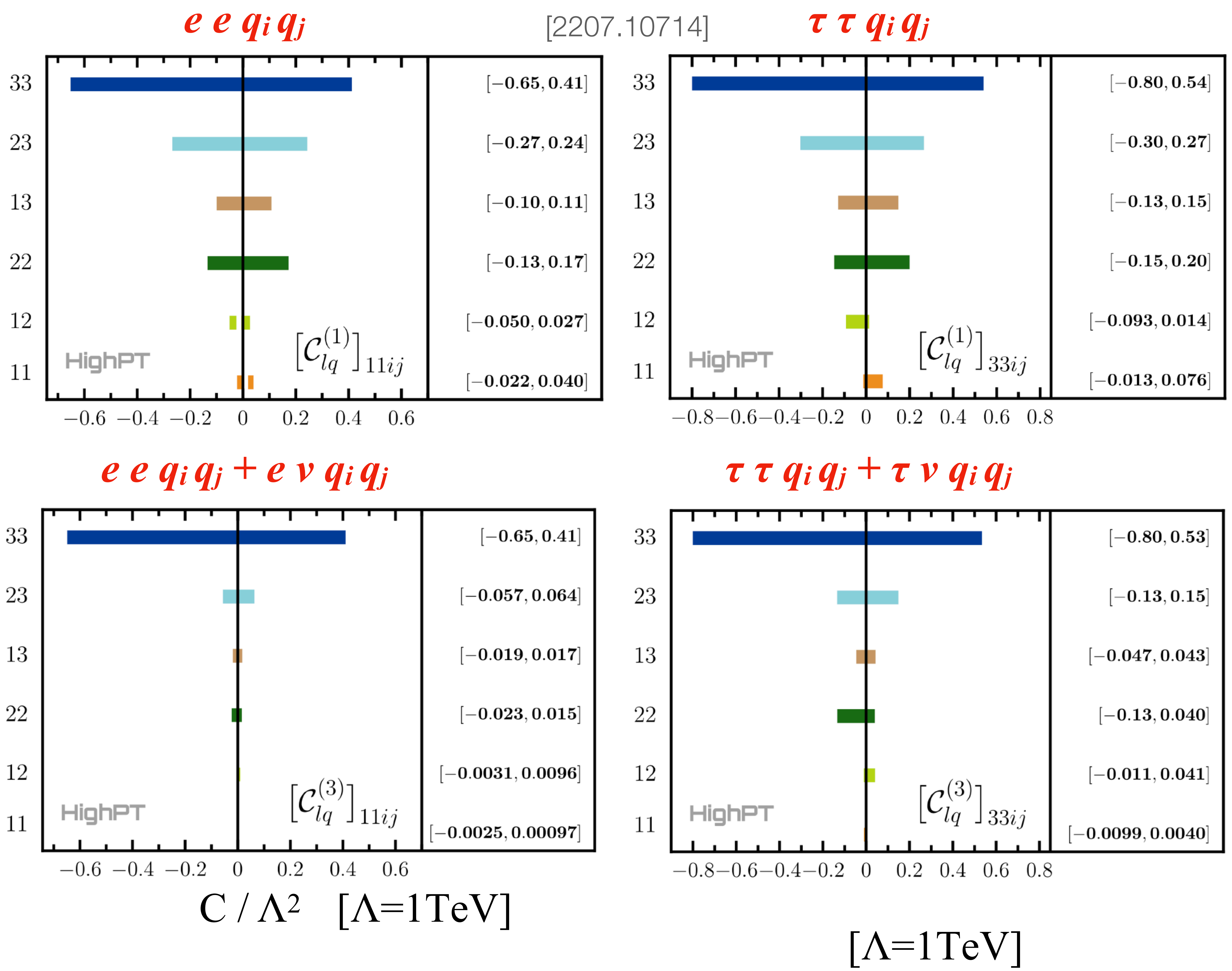




LHC bounds saturate at E~2TeV → relevant scale.

Di-lepton tails at LHC

[Faroughy, Greljo, Kamenik 1609.07138; Greljo et al. 1811.07920; DM, Min, Son 2008.07541; Allwicher et al. 2207.10714, Greljo et al 2212.10497]



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.

Stronger constraints for light quarks, due to PDF enhancement, as seen before.

LFU in dilepton tails

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

[Greljo, D.M. 1704.09015]

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

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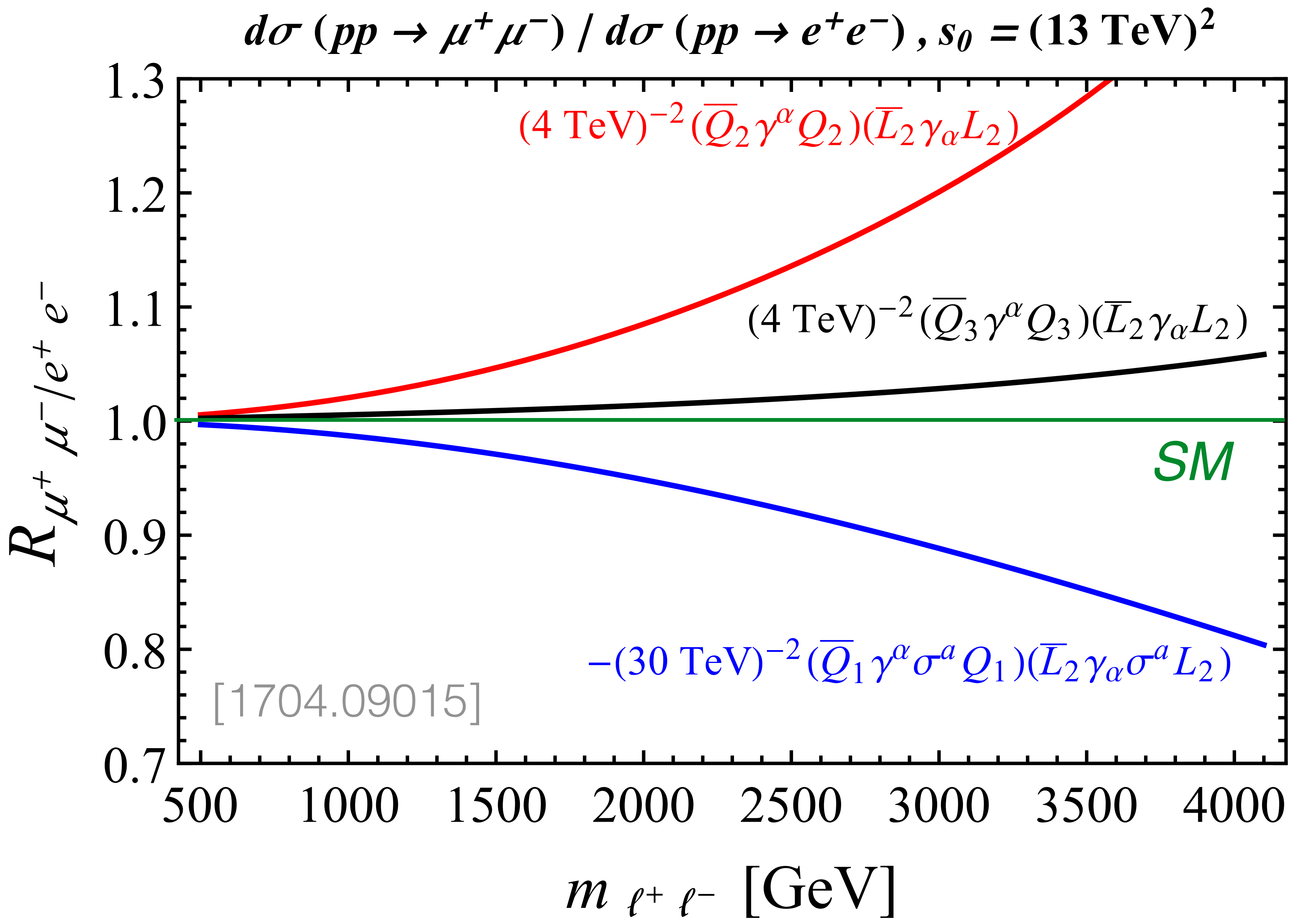

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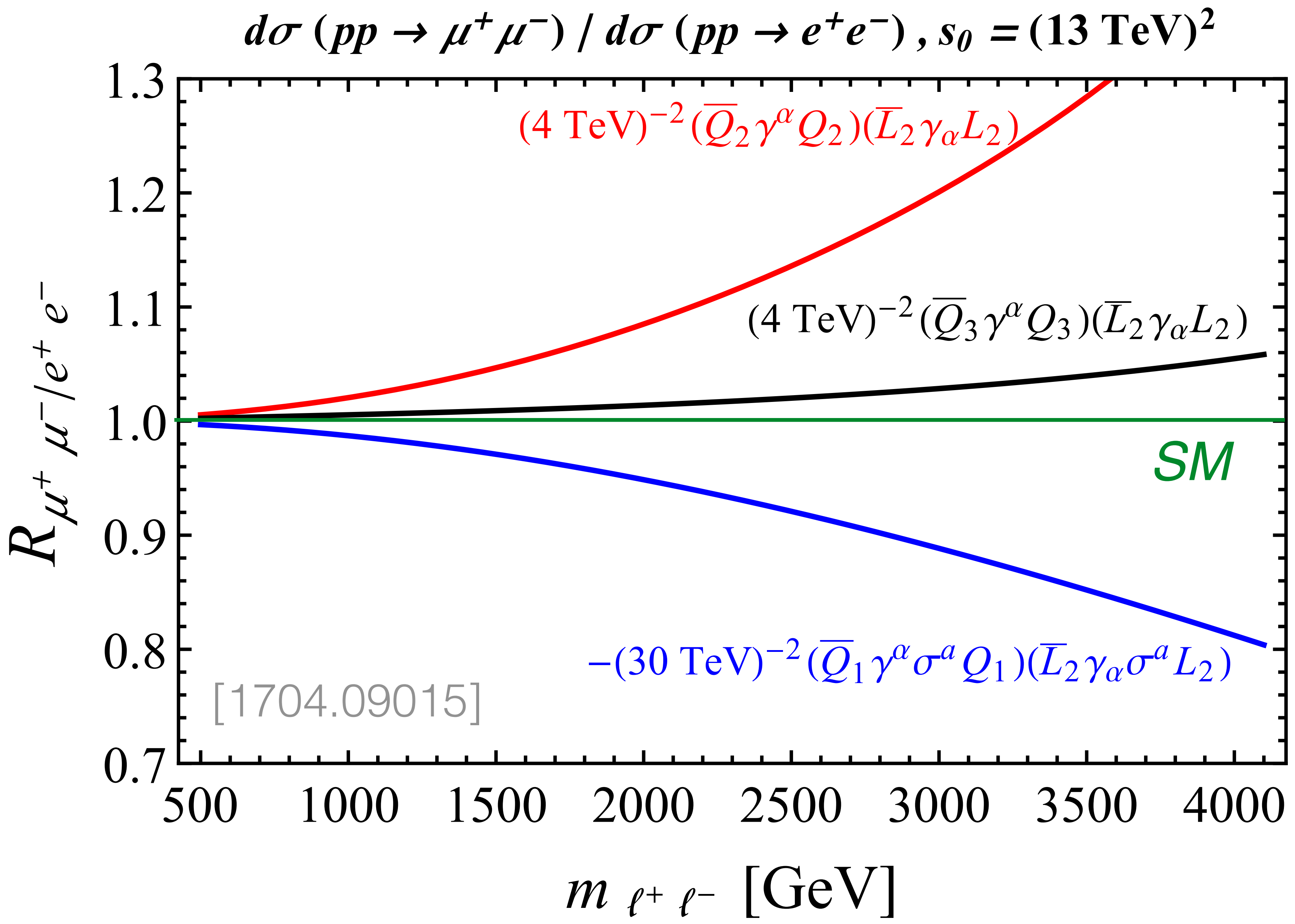
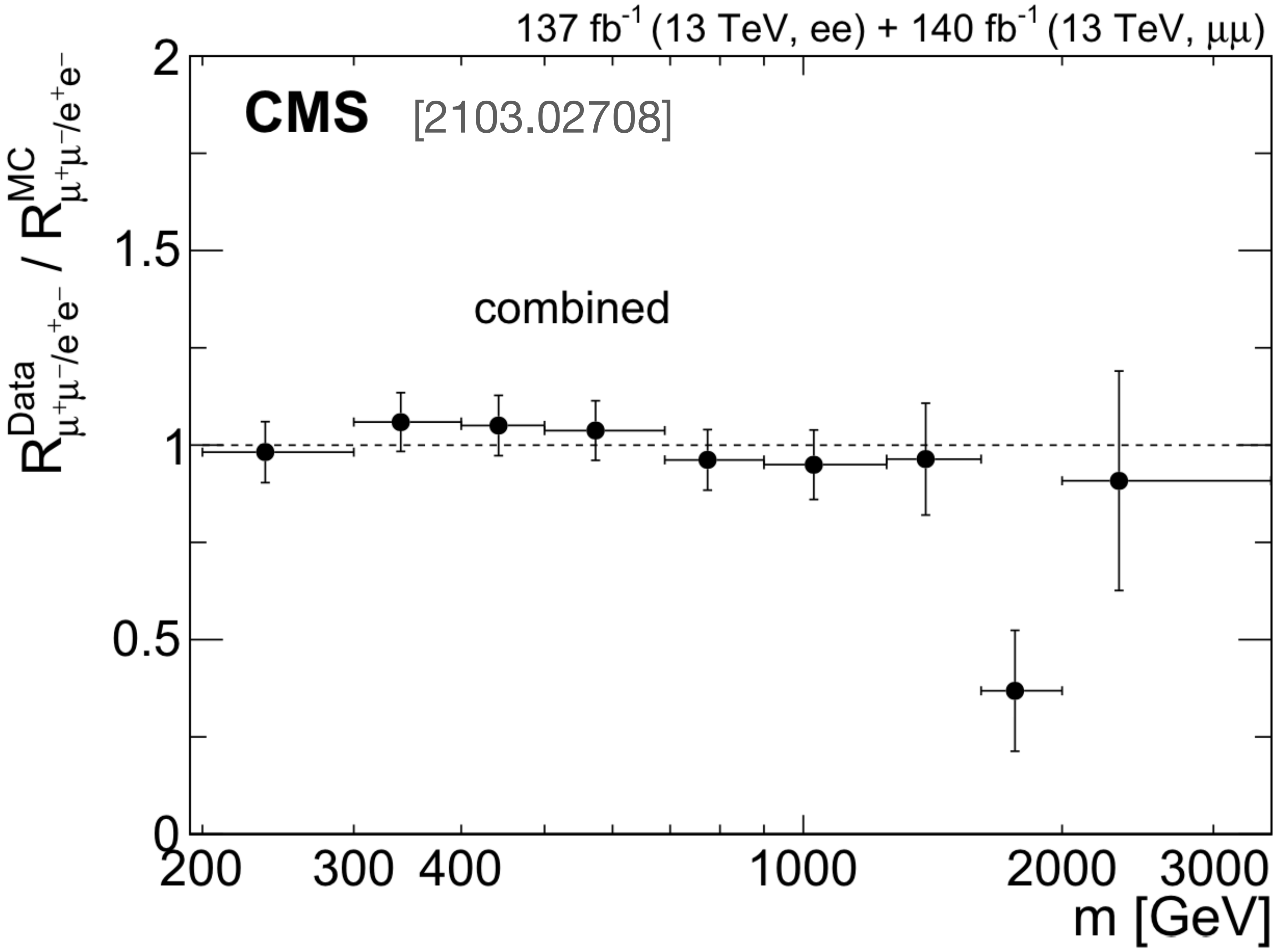
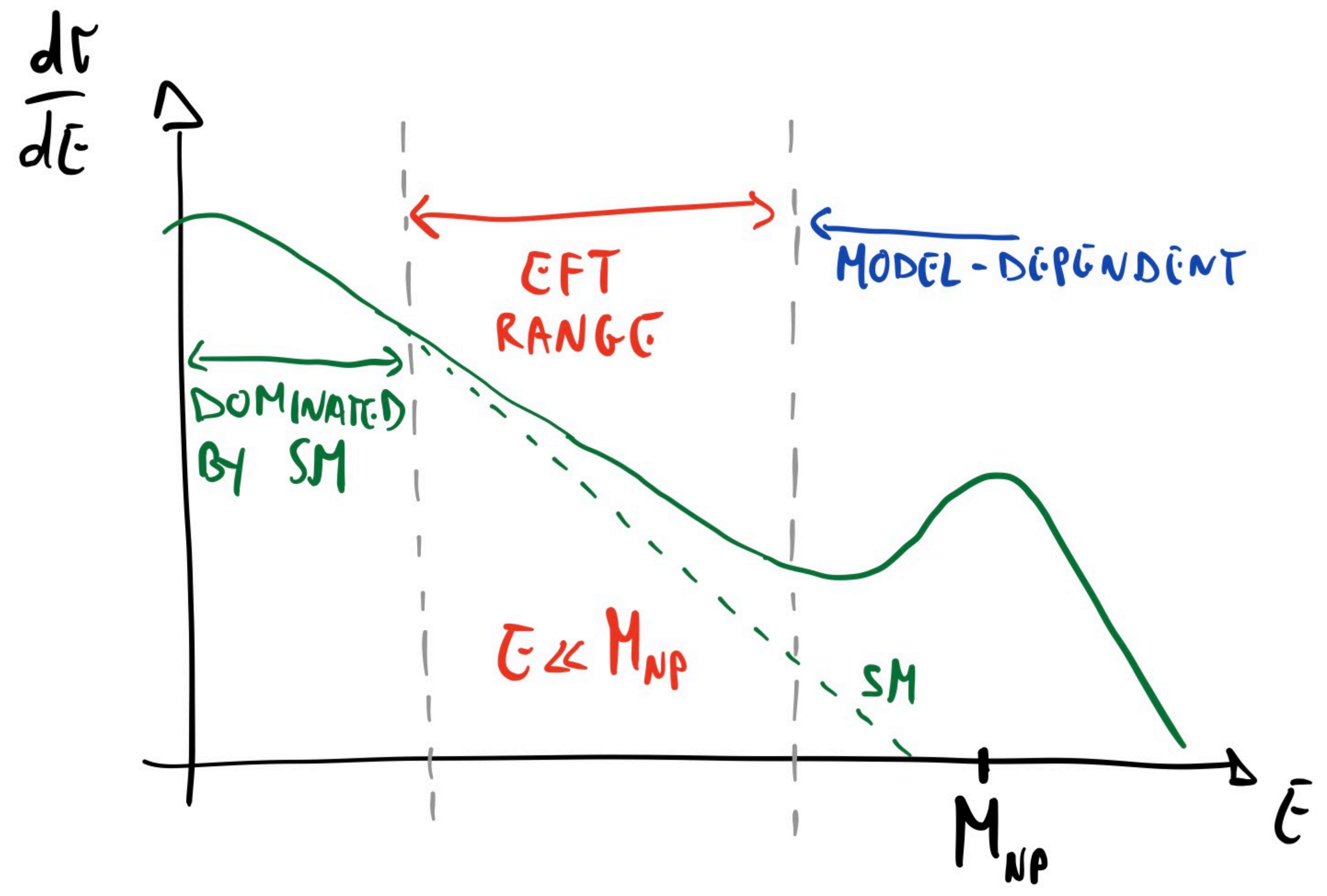


with real data →



EFT validity



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

With 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).

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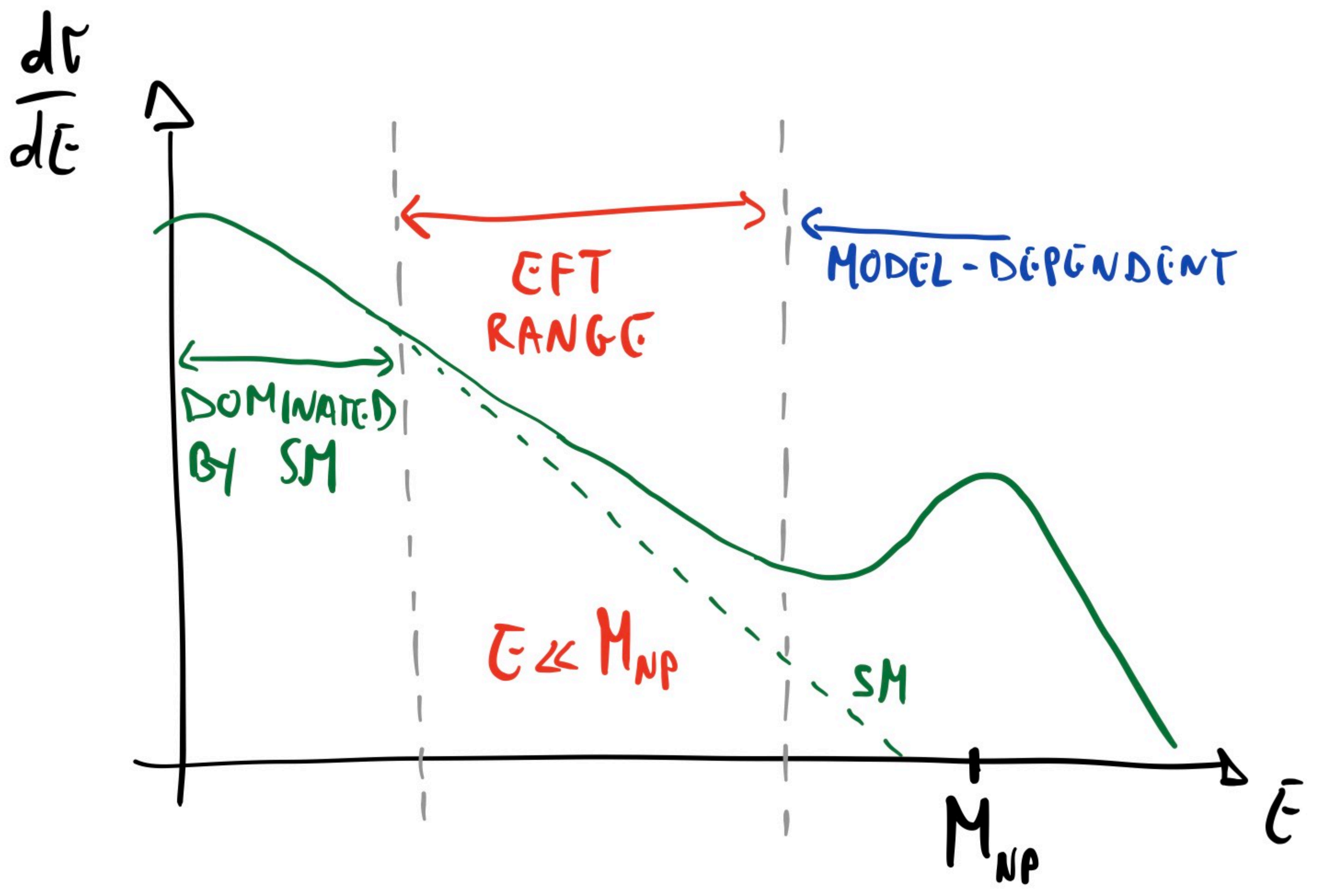

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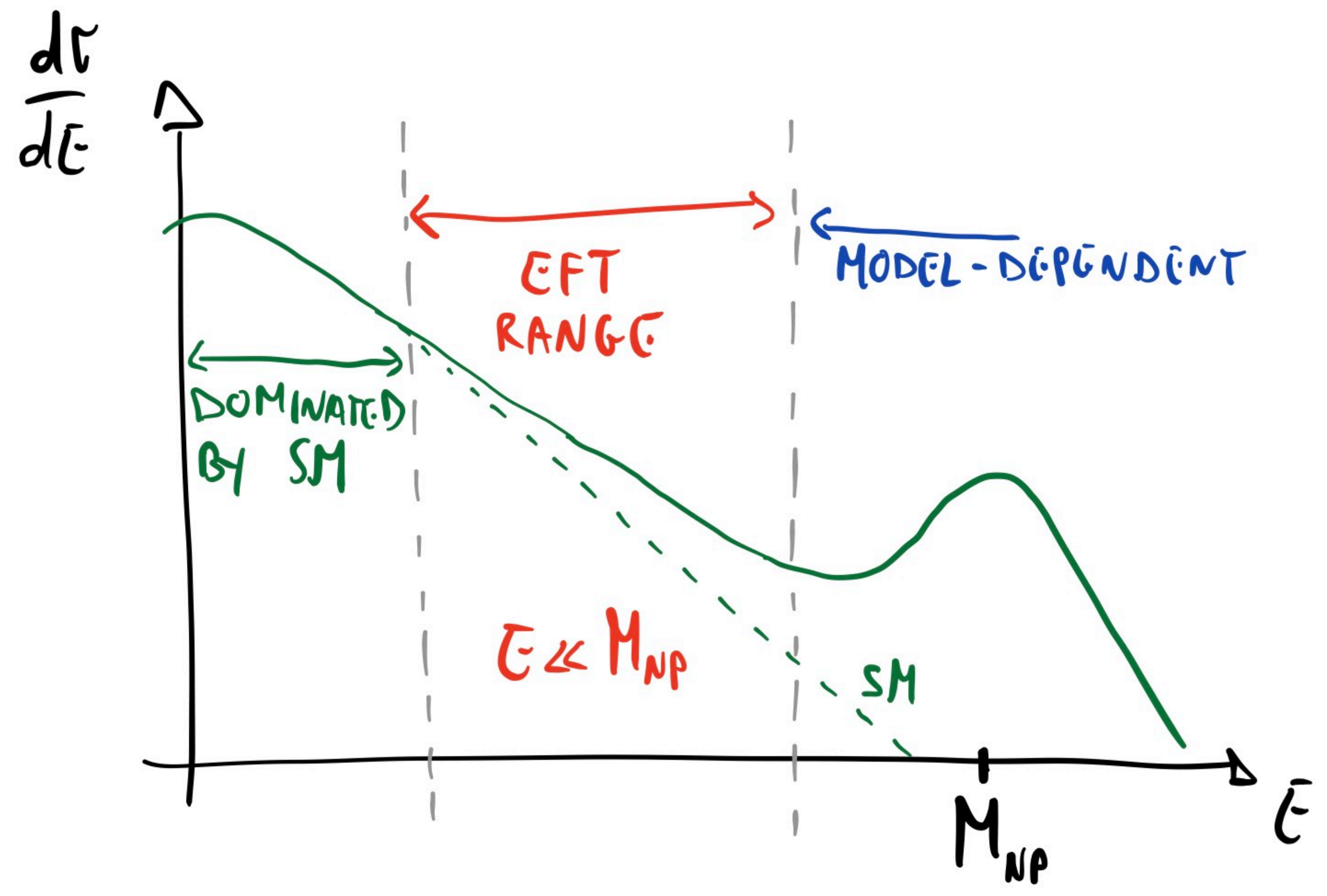

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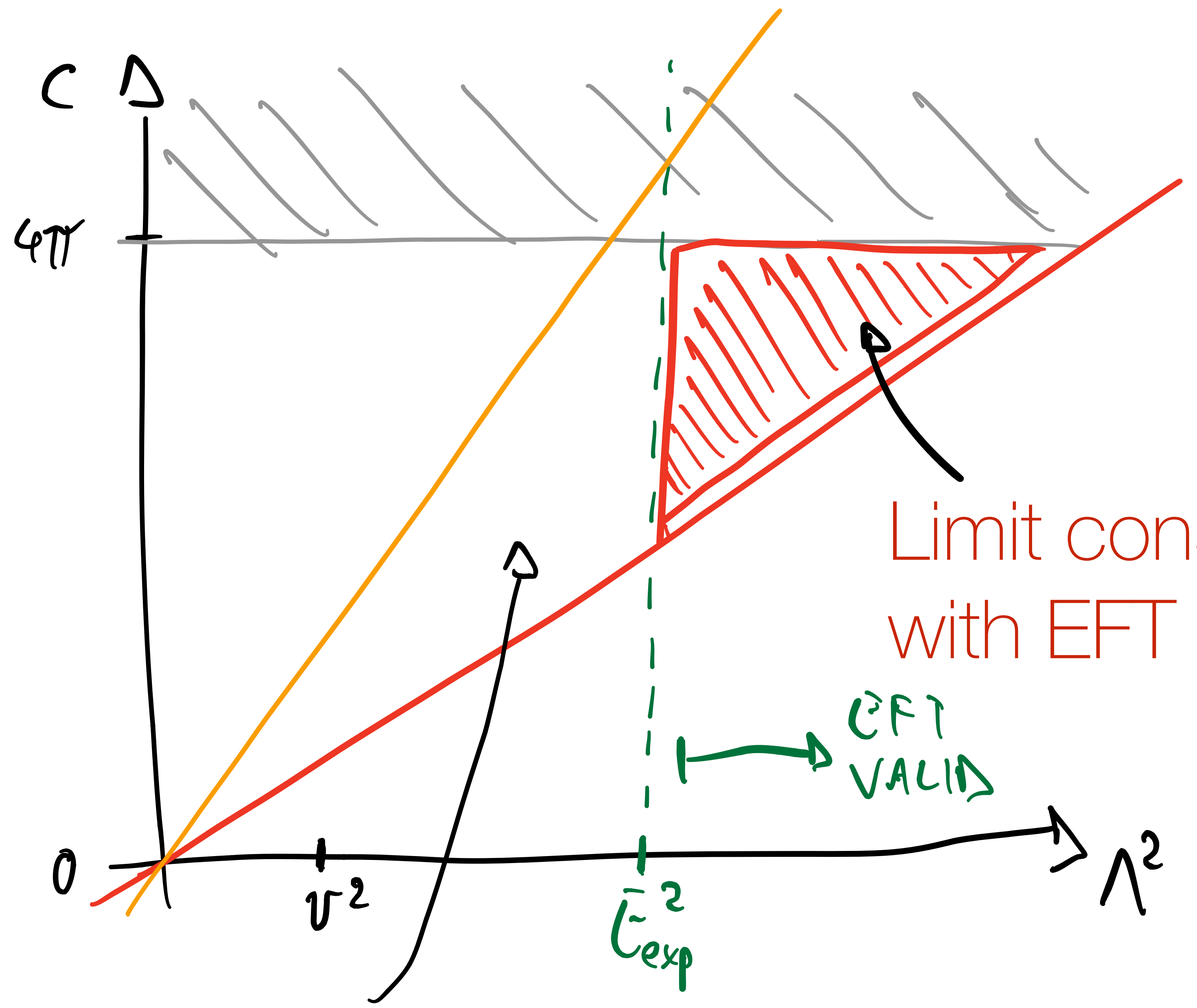
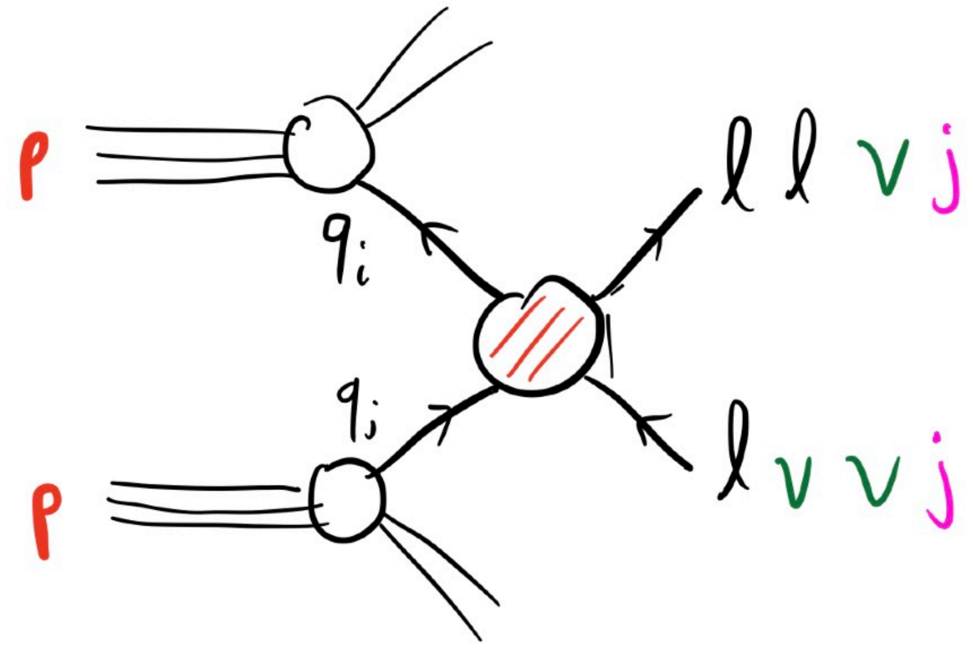
$$\begin{cases} c < \frac{\Lambda^2}{v^2}\,\delta_{prec.} \\ c \lesssim 4\pi \\ \Lambda \gg E_{exp} \end{cases}$$



Limit consistent with EFT

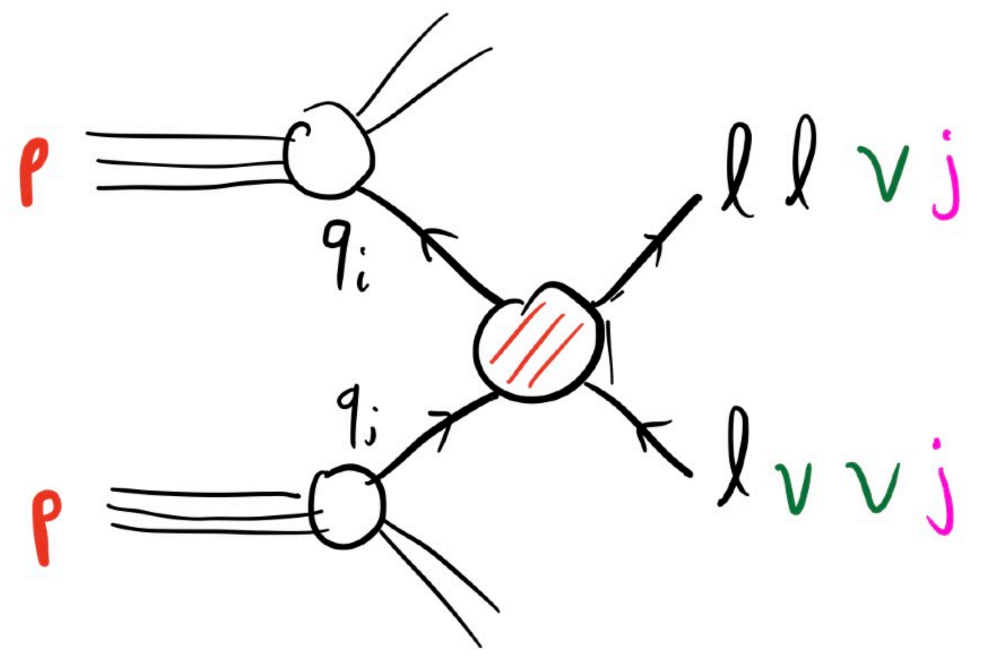
This region is possibly excluded by same search, but a 'direct search' approach should be used with the specific model.



Using high-p_T for Flavour

Option 1)
Constraining directly the flavour-violating couplings

	$R(D^{(*)})$	$R(K^{(*)})$	$B^+ \to K^+ \nu\nu$	$K^+ \to \pi^+ \nu\nu$
Low-E	$C_{bc\nu\tau} \sim \frac{1}{(4\,\text{TeV})^2}$	$C_{sb\mu\mu} \lesssim \frac{1}{(50\,\text{TeV})^2}$	$C_{sb\nu\nu} < \frac{1}{(8.6\,\text{TeV})^2}$	$C_{sd\nu\nu} \lesssim \frac{1}{(80\,\text{TeV})^2}$



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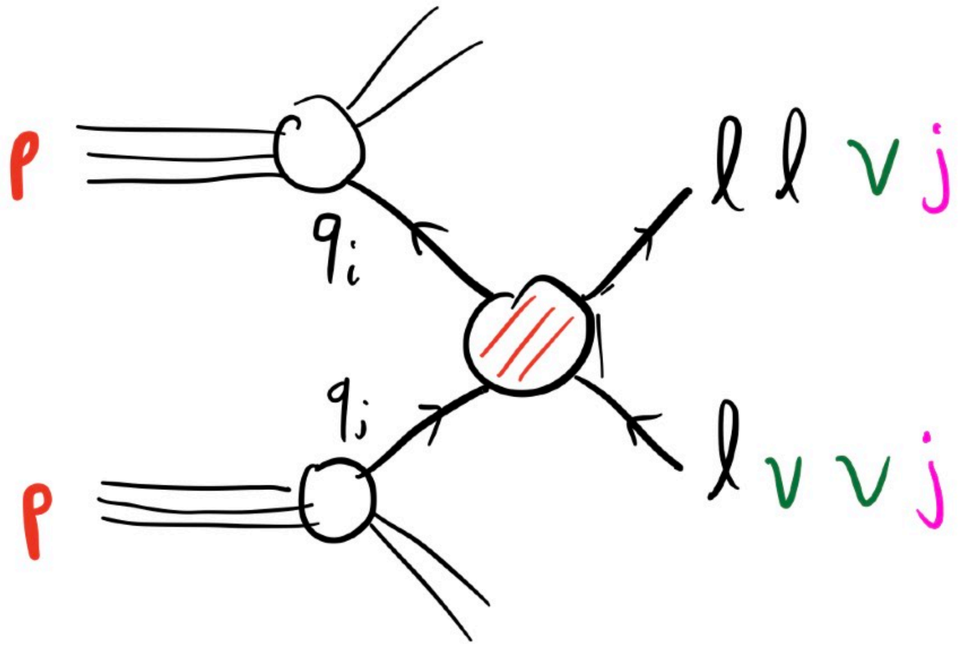
High-p_T(*)	$C_{bc\tau\nu} \lesssim (3\,\text{TeV})^{-2}$	$C_{sb\mu\mu} \lesssim (2\,\text{TeV})^{-2}$		$C_{sd\ell\ell/} \lesssim (6\text{-}10\,\text{TeV})^{-2}$

Good prospects to obtain complementary measurements for **charged-current processes like $R(D^{(*)})$**,
No hope to compete directly with rare FCNC ones at (HL-)LHC.

(*) These numbers are approximate. Precise ones depend on the specific gauge and flavour structures.



Using high-p_T for Flavour

Option 2)
Constraining the flavour-diagonal contributions

	$R(D^{(*)})$	$R(K^{(*)})$	$B^+ \to K^+ \nu\nu$	$K^+ \to \pi^+ \nu\nu$
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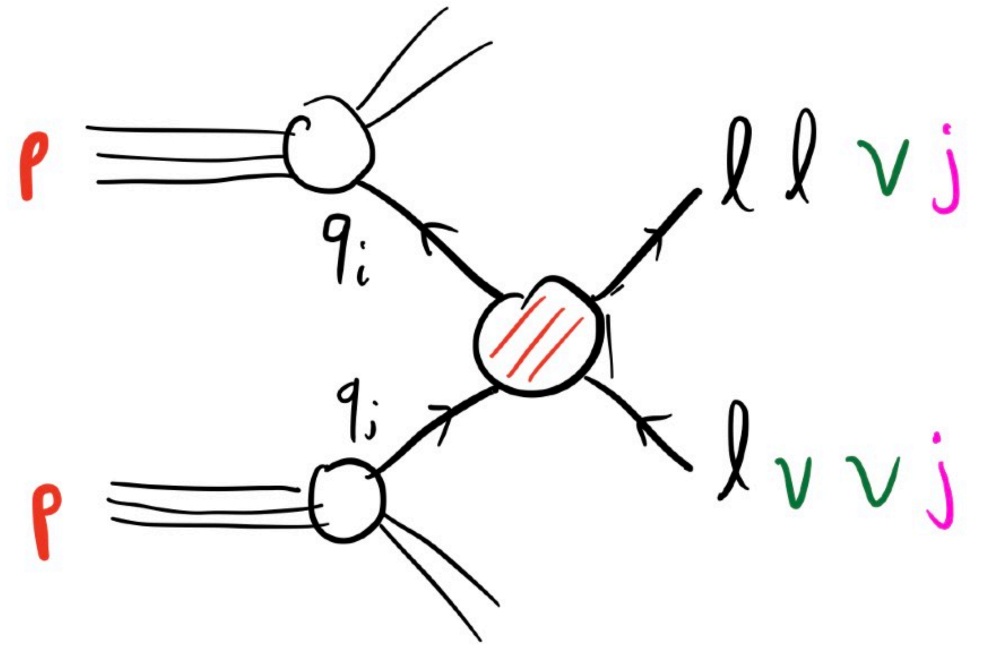
Assuming the **CKM-like flavour structure** (i.e. MFV, U(2)3, etc..):

$$C_{ij} \sim \begin{pmatrix} \varepsilon_1 & \lambda^5 & \lambda^3 \\ \lambda^5 & \varepsilon_2 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

$$C_{bc\nu e} \sim \frac{V_{cb} V_{tb}}{\Lambda^2} \qquad C_{sb\mu\mu} \sim \frac{V_{ts} V_{tb}}{\Lambda_\mu^2} \qquad C_{sb\nu\nu} \sim \frac{V_{ts} V_{tb}}{\Lambda^2} \qquad C_{sd\nu\nu} \sim \frac{V_{ts} V_{td}}{\Lambda^2}$$

$\Lambda \sim O(1)$ TeV and **$\Lambda_\mu \sim 10$ TeV**



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$\Lambda \sim O(1)$ **TeV** and $\Lambda_\mu \sim 10$ TeV

High-p_T

$[C^{(3)}_{\ell q}]_{3311} \lesssim (15\ \text{TeV})^{-2}$

$[C^{(3)}_{\ell q}]_{3322} \lesssim (5\ \text{TeV})^{-2}$

$[C^{(3)}_{\ell q}]_{3333} \lesssim (1.4\ \text{TeV})^{-2}$

$[C^{(3)}_{\ell q}]_{2211} \lesssim (24\ \text{TeV})^{-2}$

$[C^{(3)}_{\ell q}]_{2222} \lesssim (8\ \text{TeV})^{-2}$

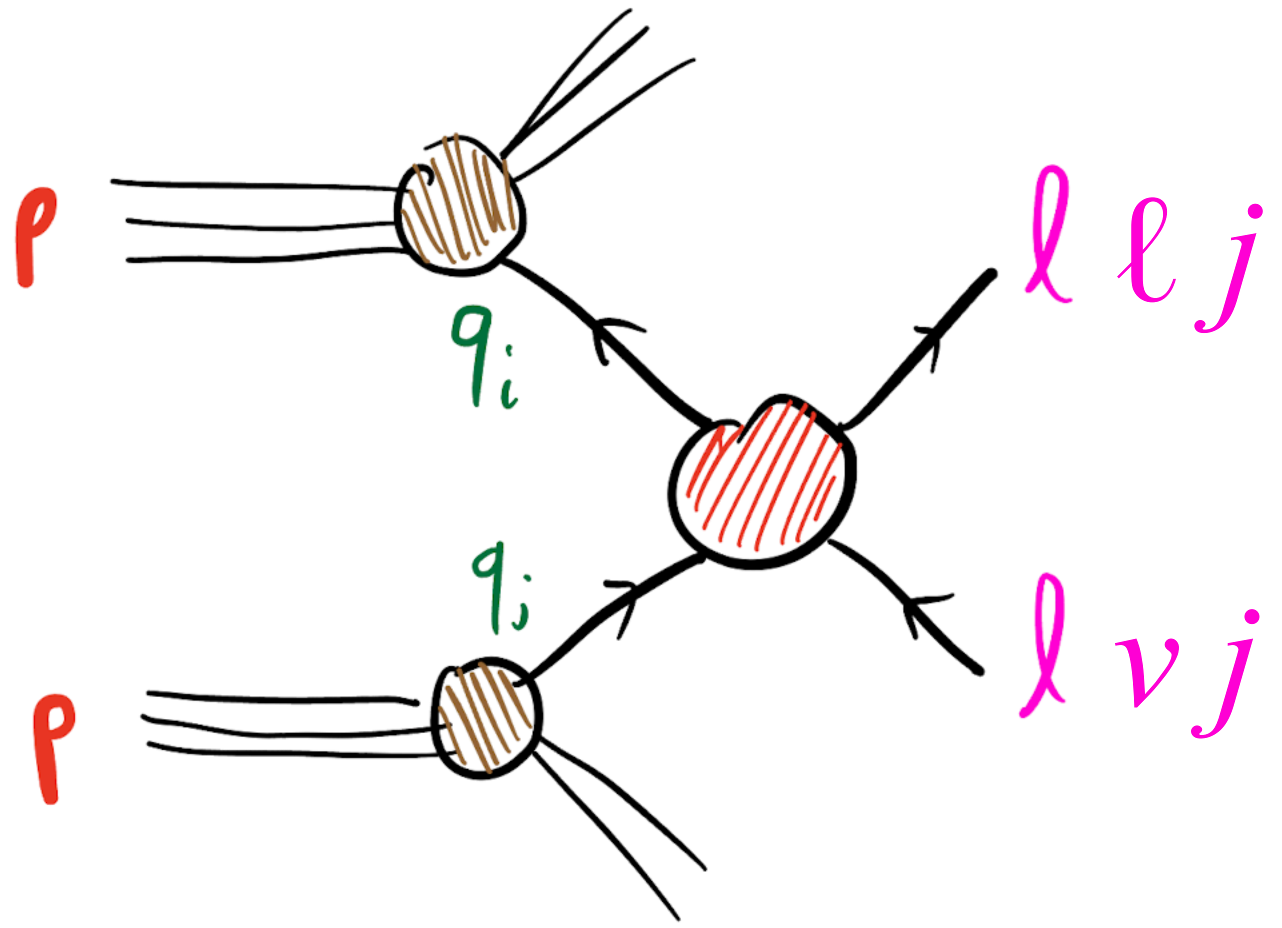
$[C^{(3)}_{\ell q}]_{2233} \lesssim (2\ \text{TeV})^{-2}$

A non-universal structure like U(2)^3 allows to relax the high-p_T constraints.

High-p_T Flavour at Future Colliders

Hadron Colliders

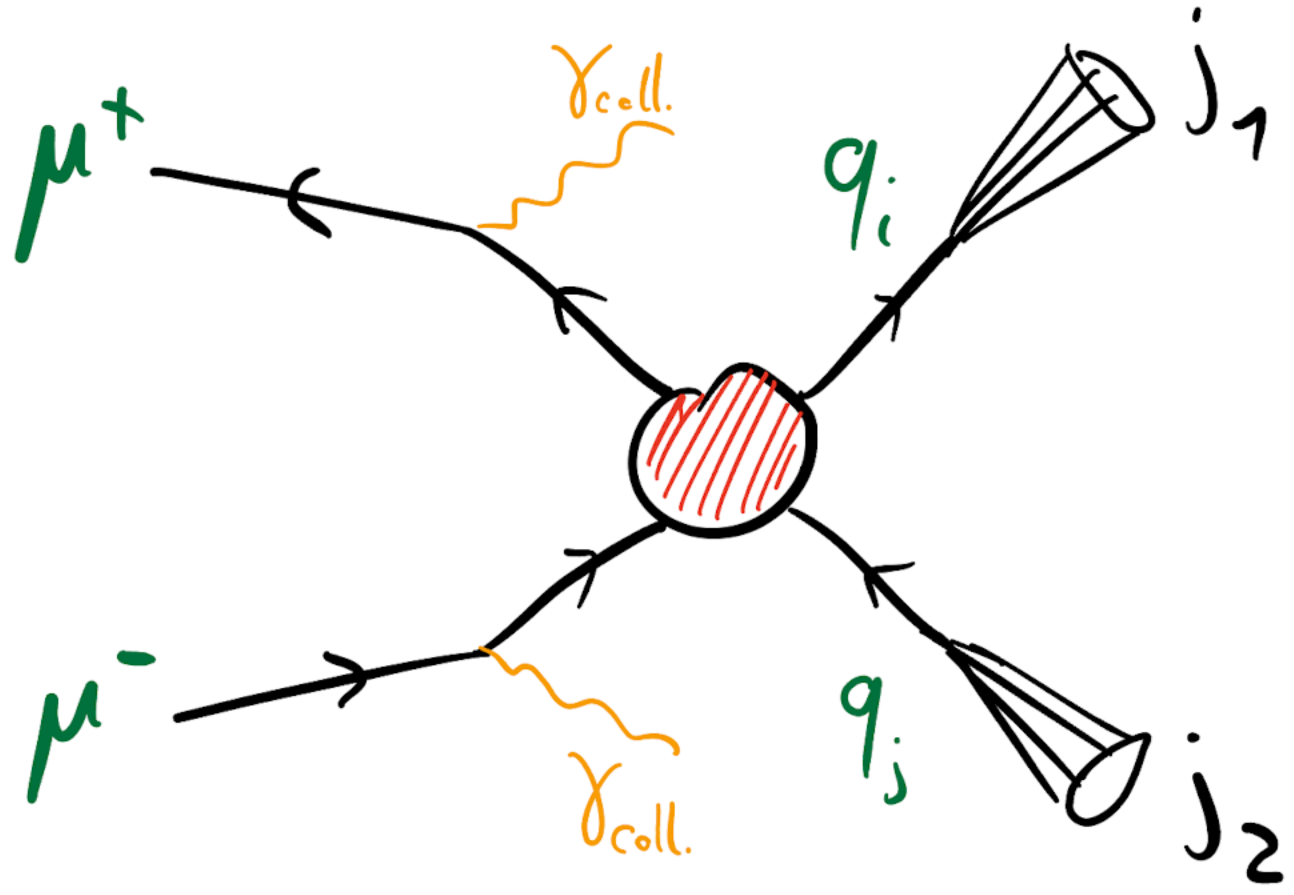
Drell-Yan



- (+) All quark flavors available in PDFs
- (+) Possibility to use jet tagging to improve signal
- (-) q-$\bar{q}$ PDFs suppressed at large $\sqrt{s}$
- (+) All possible leptonic final states available
- (+) Possibility to test 4q interactions

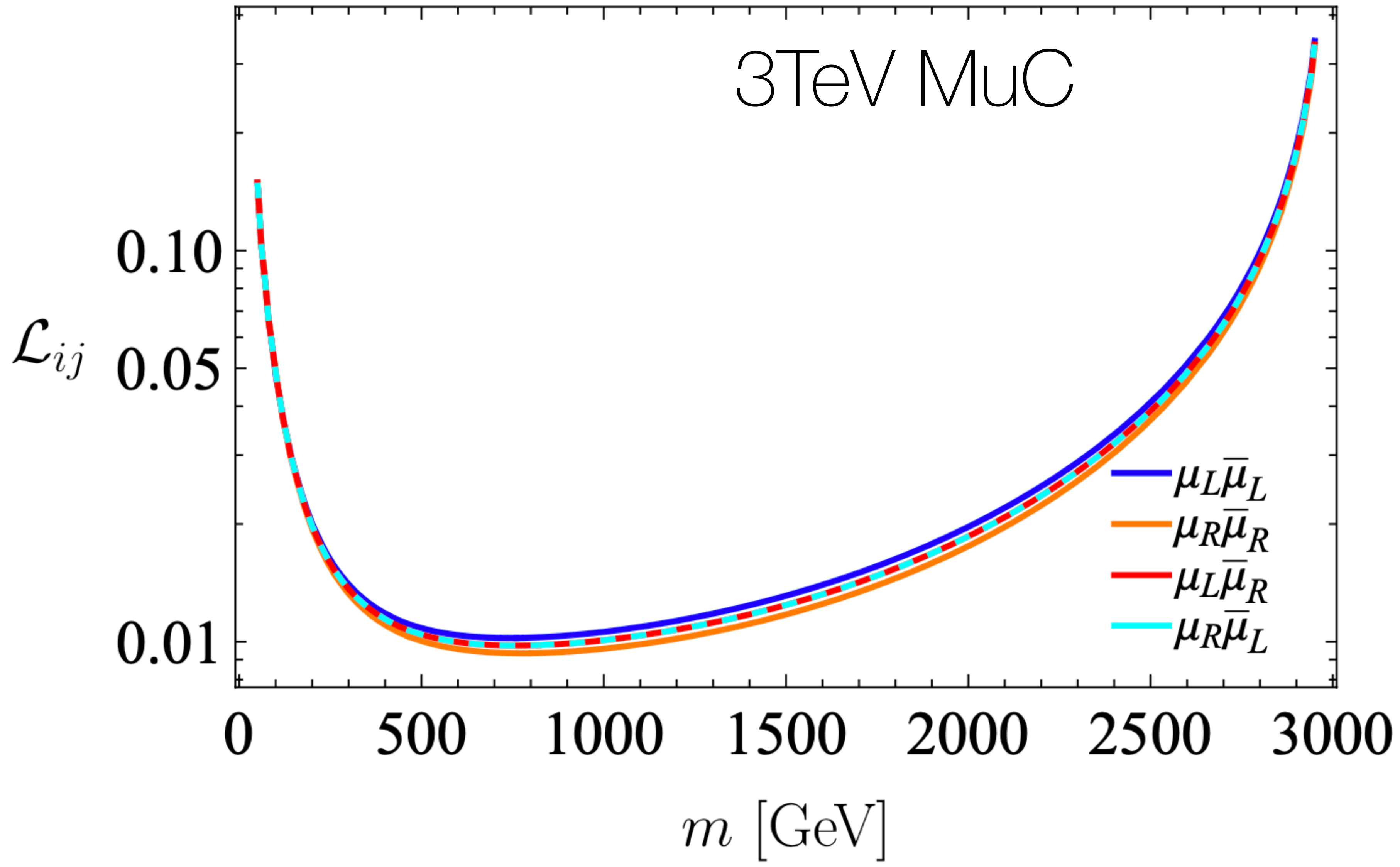
Muon Colliders

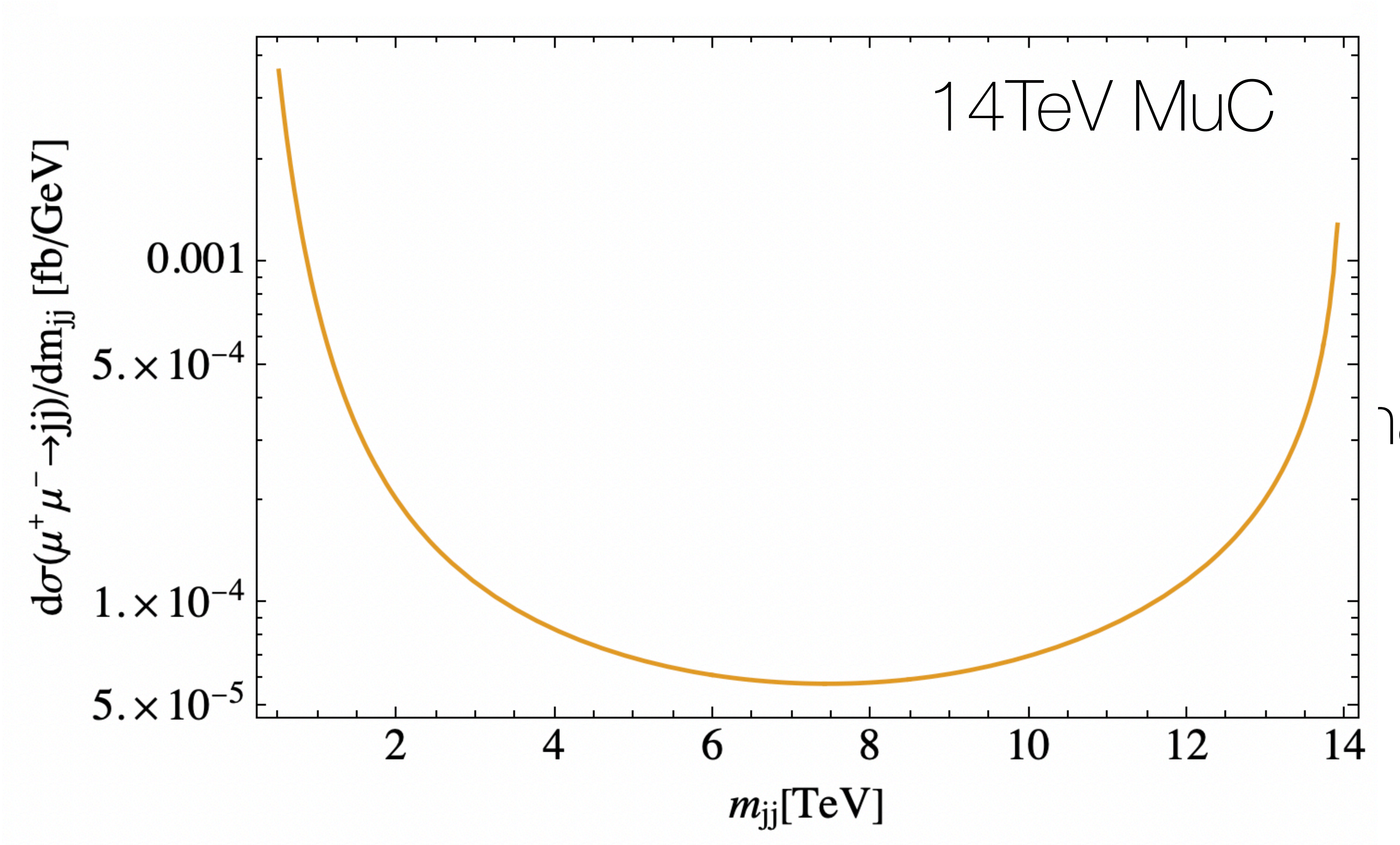
"Inverse Drell-Yan"



- (+) All quark flavors available in final state jets.
- (+) Possibility to use jet tagging to improve signal
- (+) $\mu^+\mu^-$ PDF enhanced at $\sqrt{s} = E_{collider}$.
- (-) Only $\mu^+\mu^-$ initial state viable at large energy
- (+) Possibility to test $\mu\mu\ell\ell'$ interactions.

High-p_T Flavour at Future Colliders





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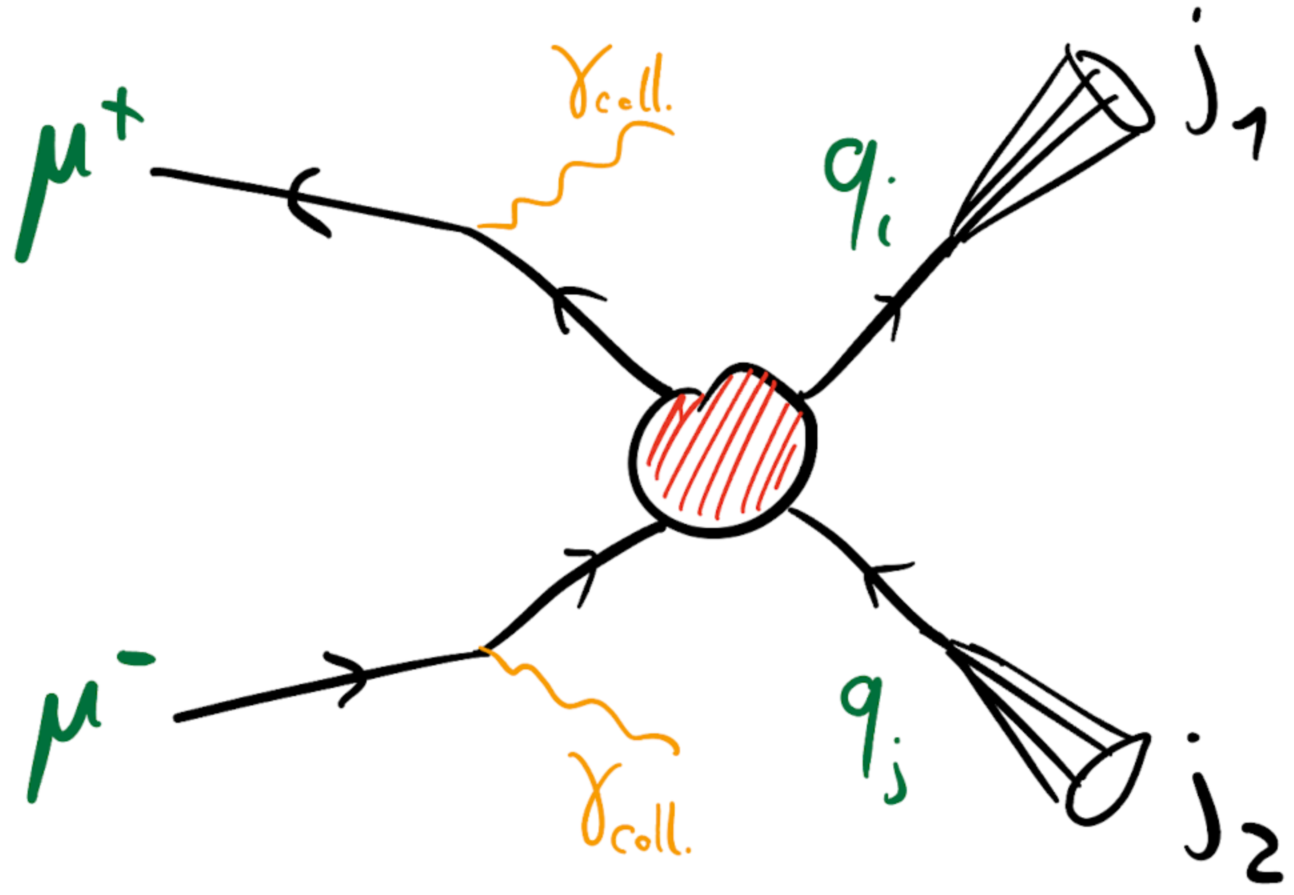

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High-p$_T$ Flavour at Future Colliders

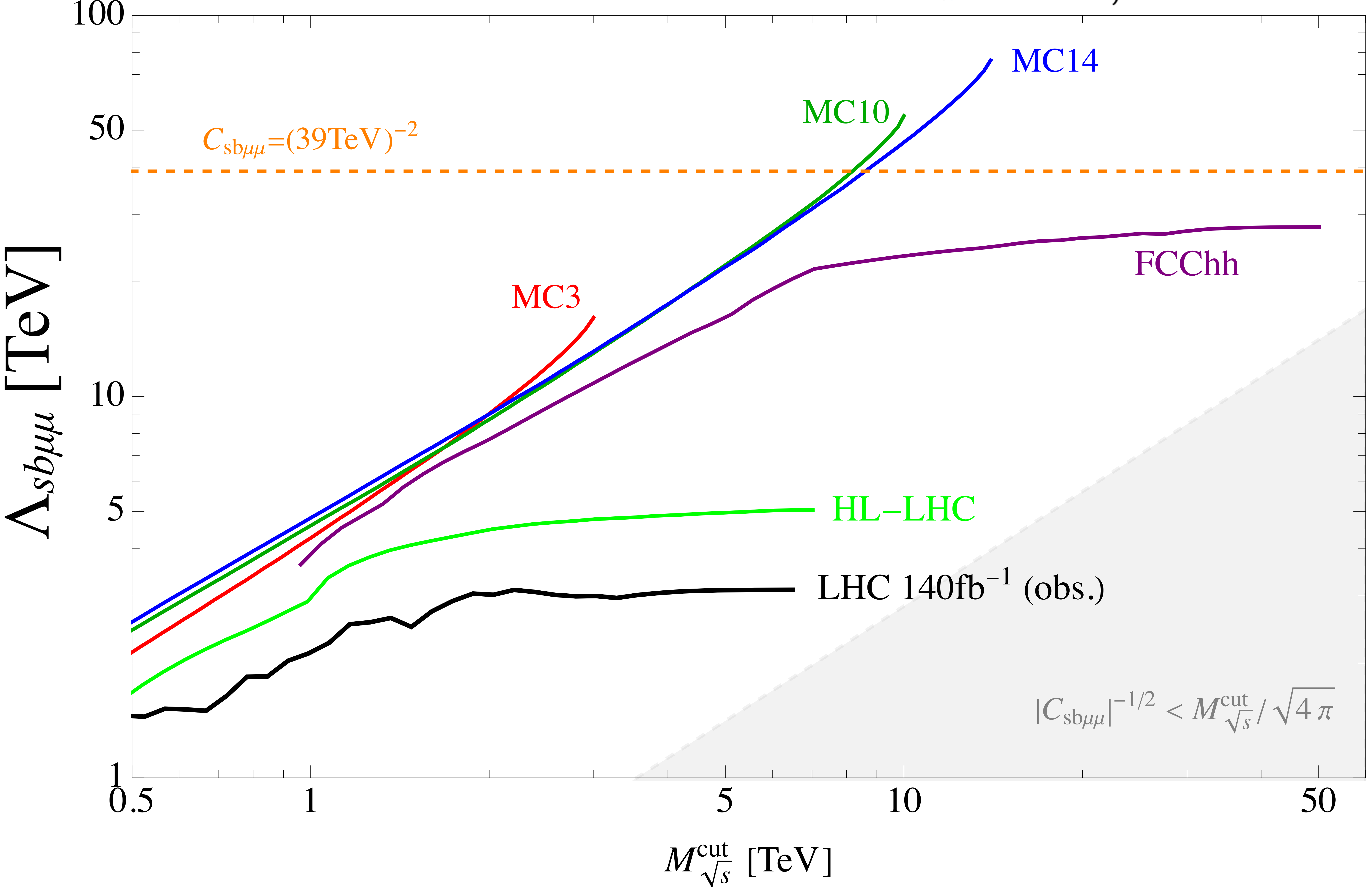
95%CL limits as function of the invariant mass cut.

s b μ μ

$$\mathcal{L}_{LEFT} = C_{s_L b_L \mu_L \mu_L} (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}_L \gamma^\mu \mu_L)$$

EFT scale

$C_x = 1 / \Lambda_x^2$



Azatov, Garosi, Greljo, DM, Salko, Trifinopoulos [2205.13552]

High-p_T Flavour at Future Colliders

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b b μ μ

$$\mathcal{L}_{EFT} = C_{bb\mu\mu} \left(\bar{b}_L \gamma_\alpha b_L\right)\left(\bar{\mu}_L \gamma^\alpha \mu_L\right)$$

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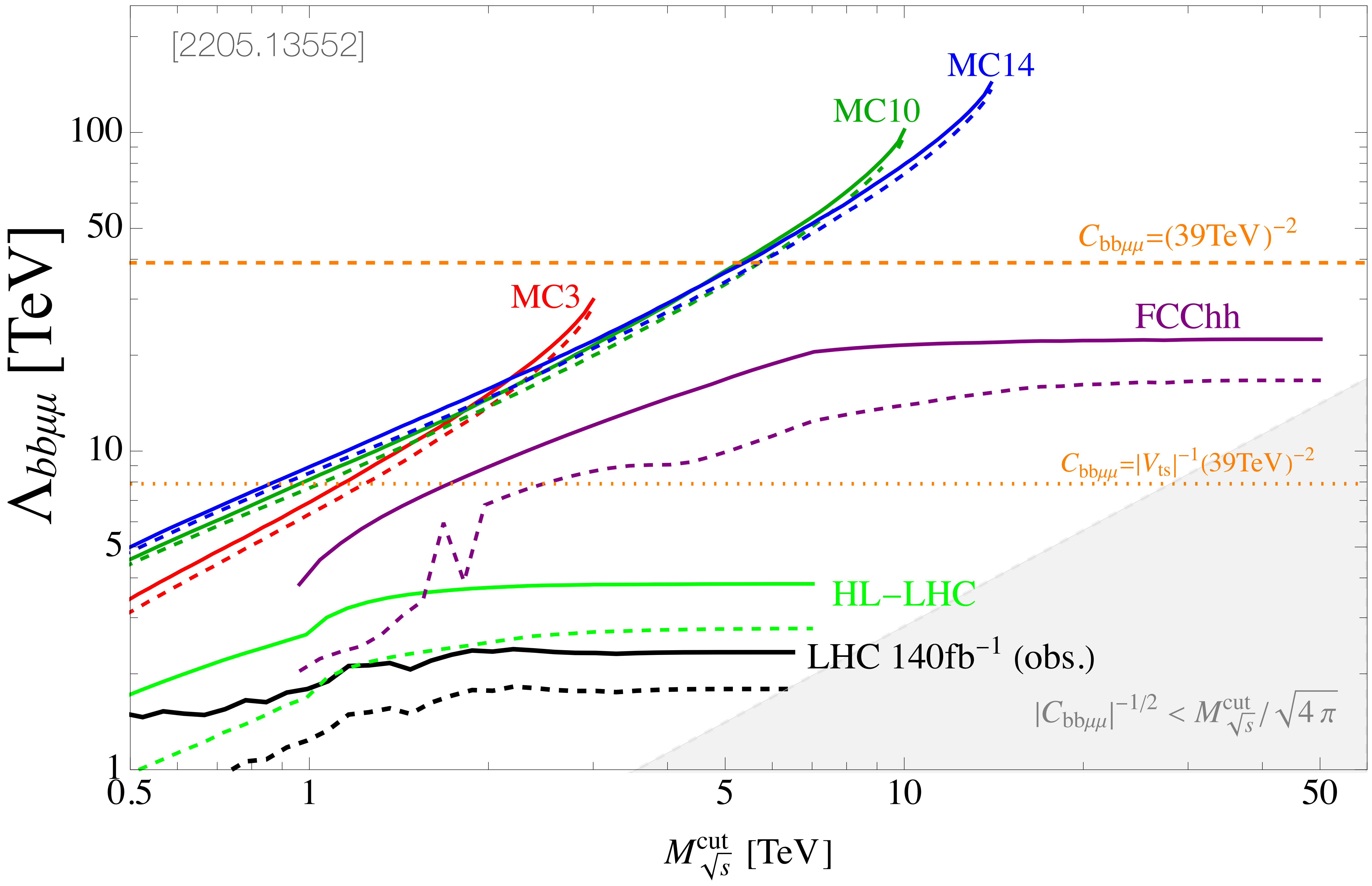


Solid: positive C

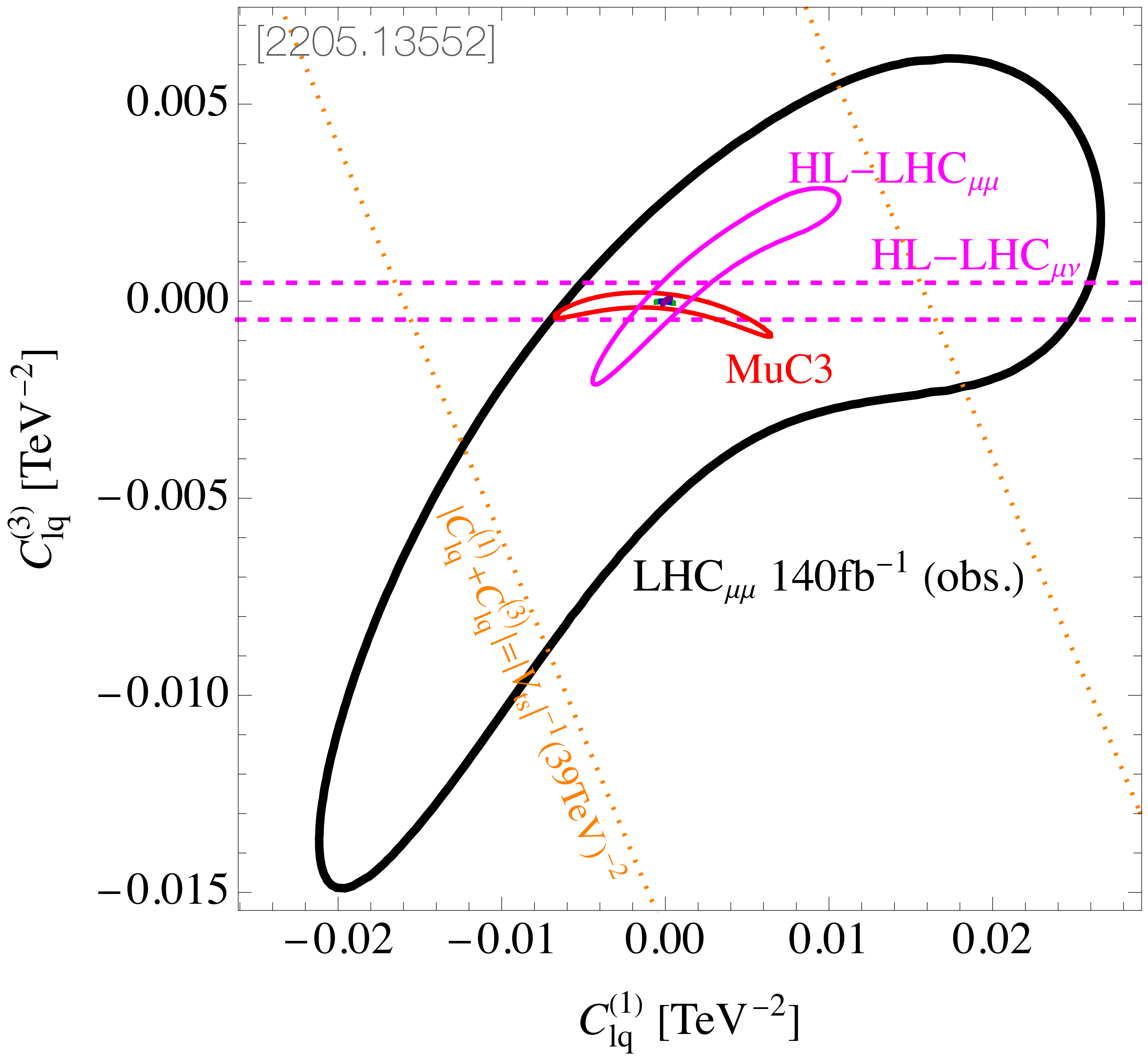
Dashed: negative C

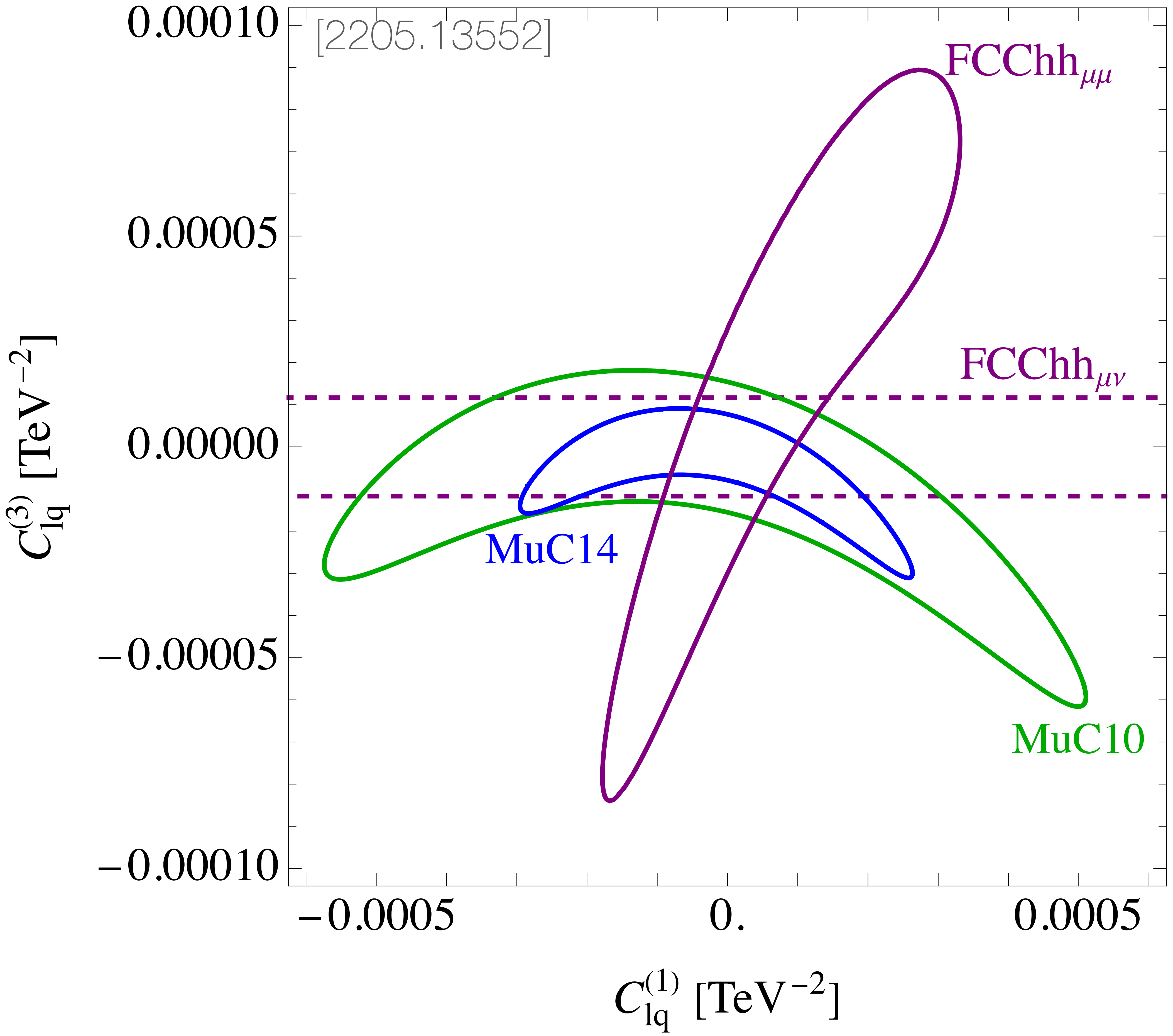
High-p_T Flavour at Future Colliders

Flavour Universal

$$\mathcal{L}_{\rm SMEFT} \supset [C^{(1)}_{\ell q}]_{22ij}(\bar{L}^2_L\gamma_\alpha L^2_L)(\bar{Q}^i_L\gamma^\alpha Q^j_L) + [C^{(3)}_{\ell q}]_{22ij}(\bar{L}^2_L\gamma_\alpha\sigma^a L^2_L)(\bar{Q}^i_L\gamma^\alpha\sigma^a Q^j_L)$$

$$[C^{(1)}_{lq}]_{22ij} = C^{(1)}_{lq}\delta_{ij} \text{ and } [C^{(3)}_{lq}]_{22ij} = C^{(3)}_{lq}\delta_{ij}$$





Conclusions

Probing rare flavour-violating processes allows to test large New Physics scales.

If NP is present at the TeV scale, its **flavour structure should be hierarchical**: Flavour Problem.

A complementary tool for testing such New Physics is by looking for **deviations in the high-p_T tails** of Drell-Yan dilepton and mono-lepton production. Effects due to heavy NP are **enhanced by E^2/M^2**.

Typical **LHC bounds range from O(1) to O(10) TeV**, depending if the operator involves heavy or light quarks. This offers very **good constraints for MFV-type** scenarios, slightly worse for U(2)-like setups.

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Thank you!

Backup

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.

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

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

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

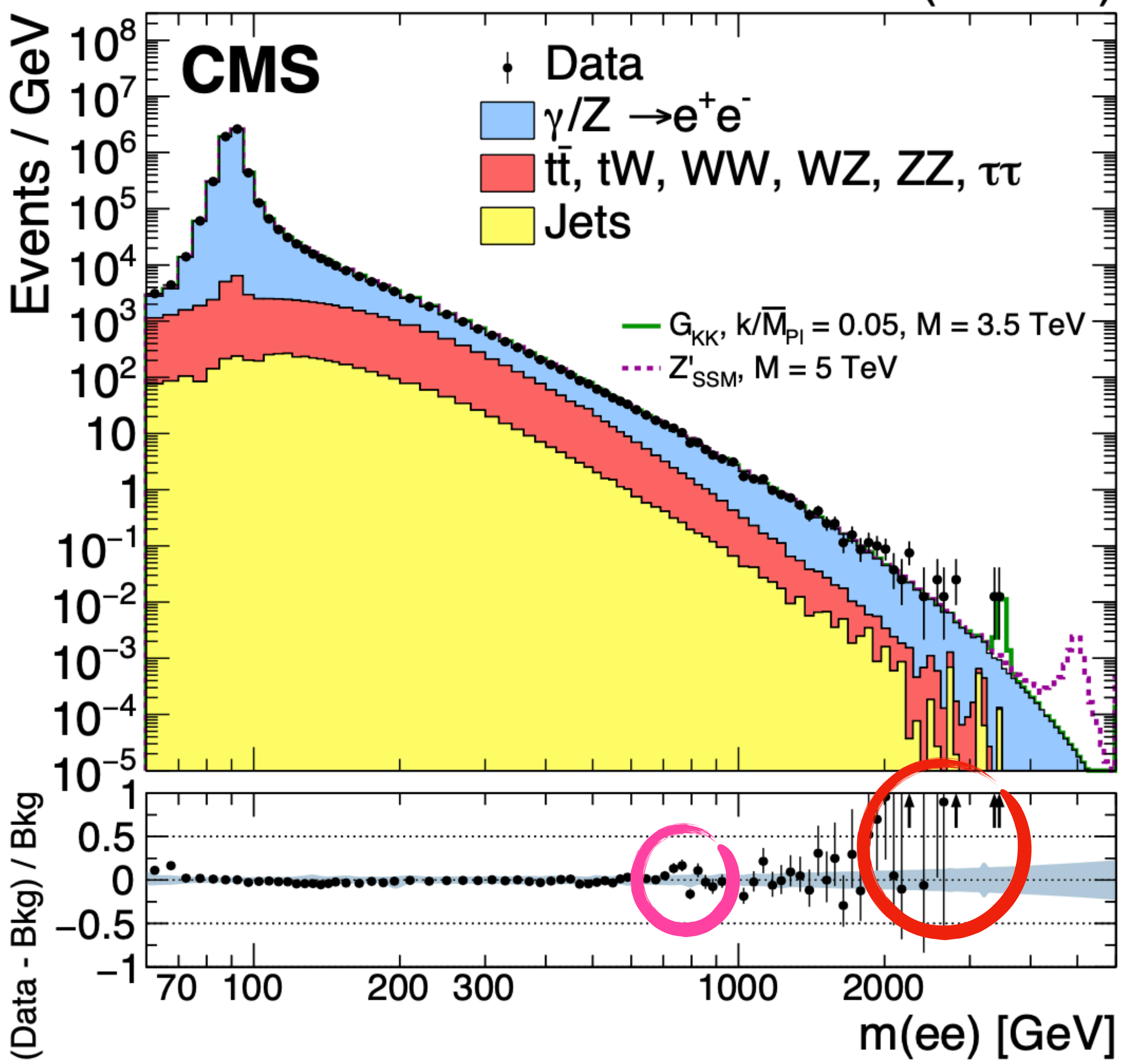
The dim-8 interference is necessarily smaller than dim-6 interference if $C^{(8)} \leq C^{(6)}$

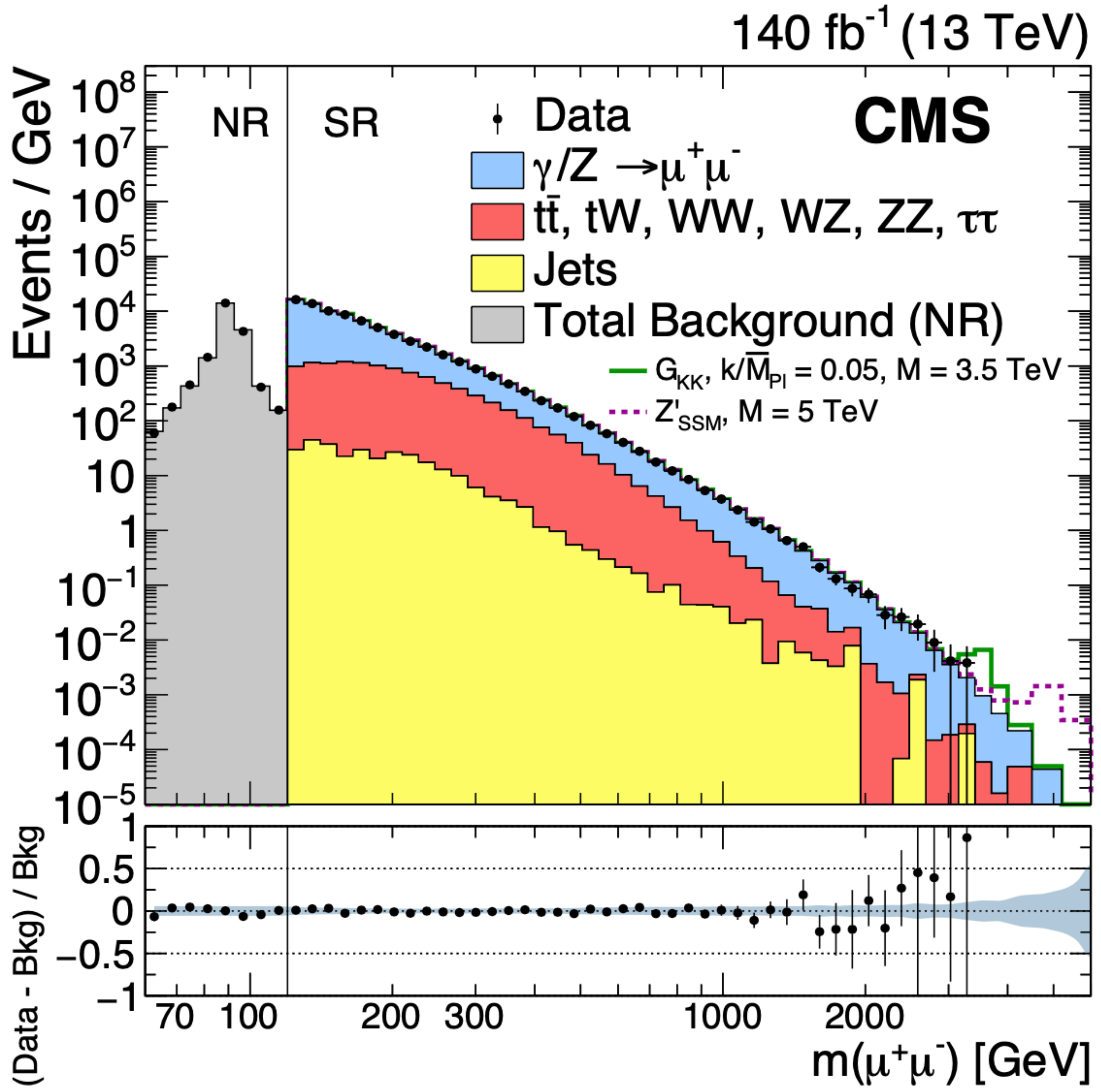
since $s \ll M_{NP}^2$. For a single mediator $C^{(8)} = C^{(6)} \sim g_{NP}^2$

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

CMS di-electron excess

[2103.02708]

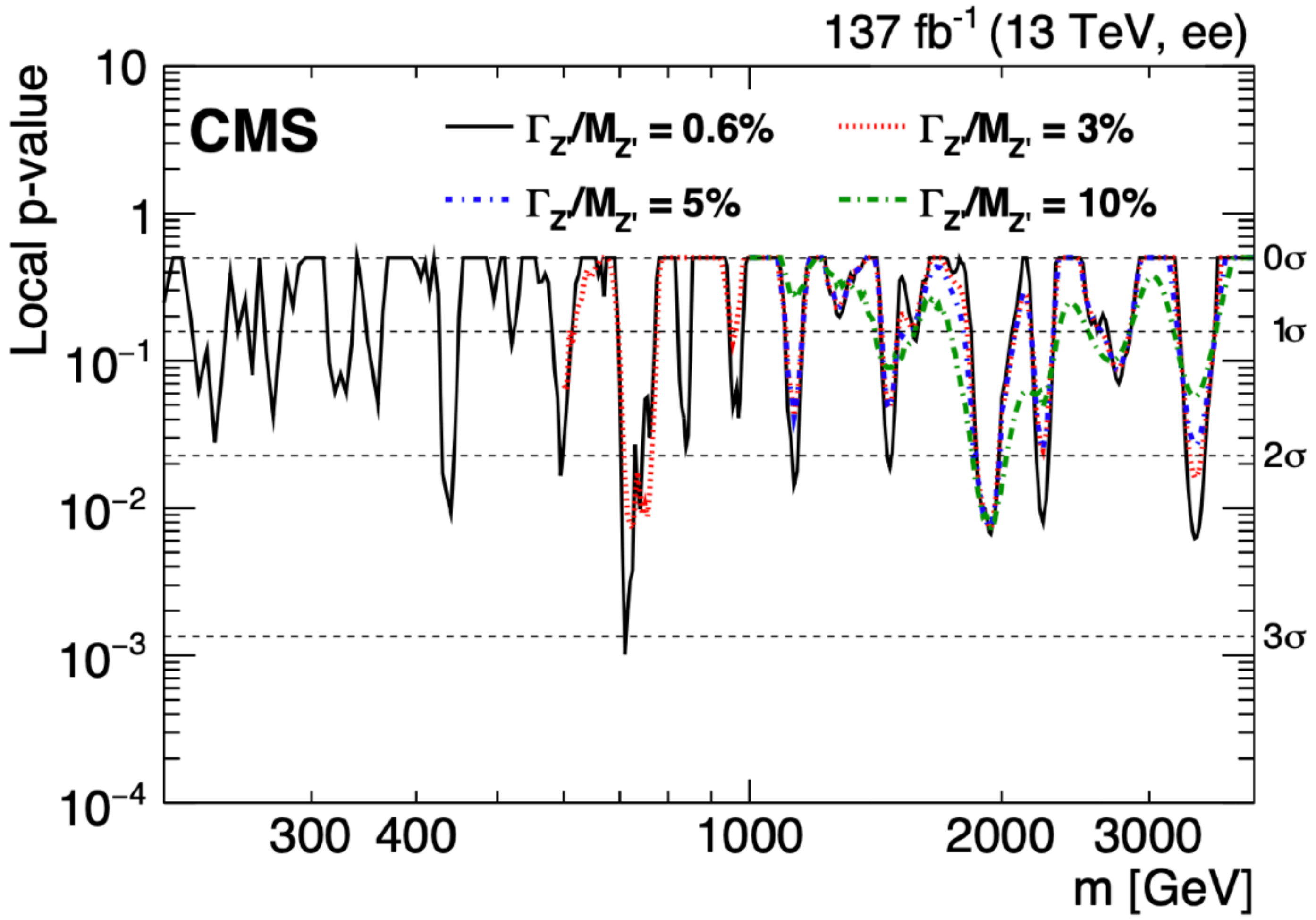




m_{ee} range [GeV]	Observed yield	Total background
60–120	28194452	28200000 ± 710000
120–400	912504	942000 ± 37000
400–600	16192	16400 ± 770
600–900	3756	3660 ± 190
900–1300	704	696 ± 47
1300–1800	135	131 ± 12
>1800	44	29.2 ± 3.6

$m_{\mu\mu}$ 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.



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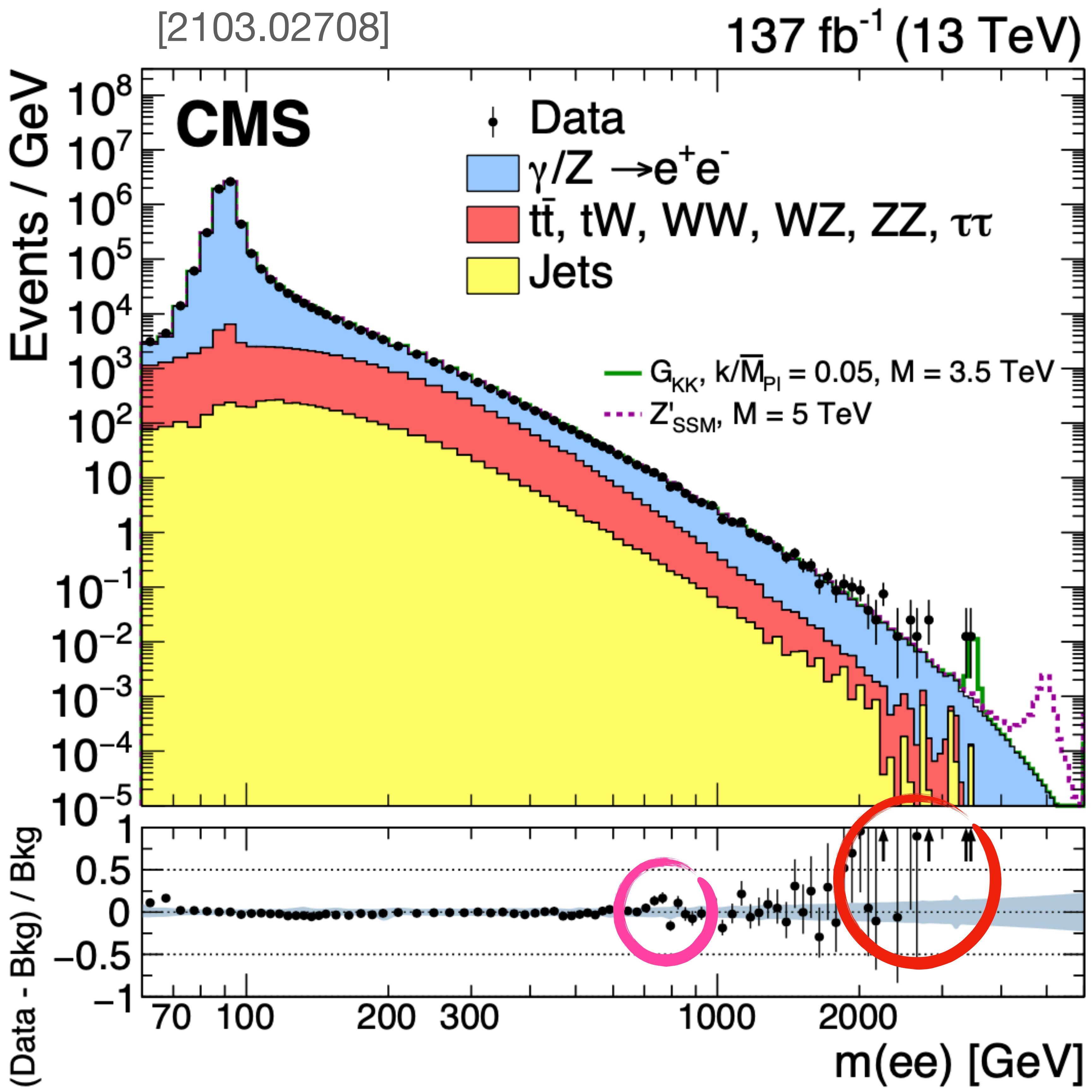
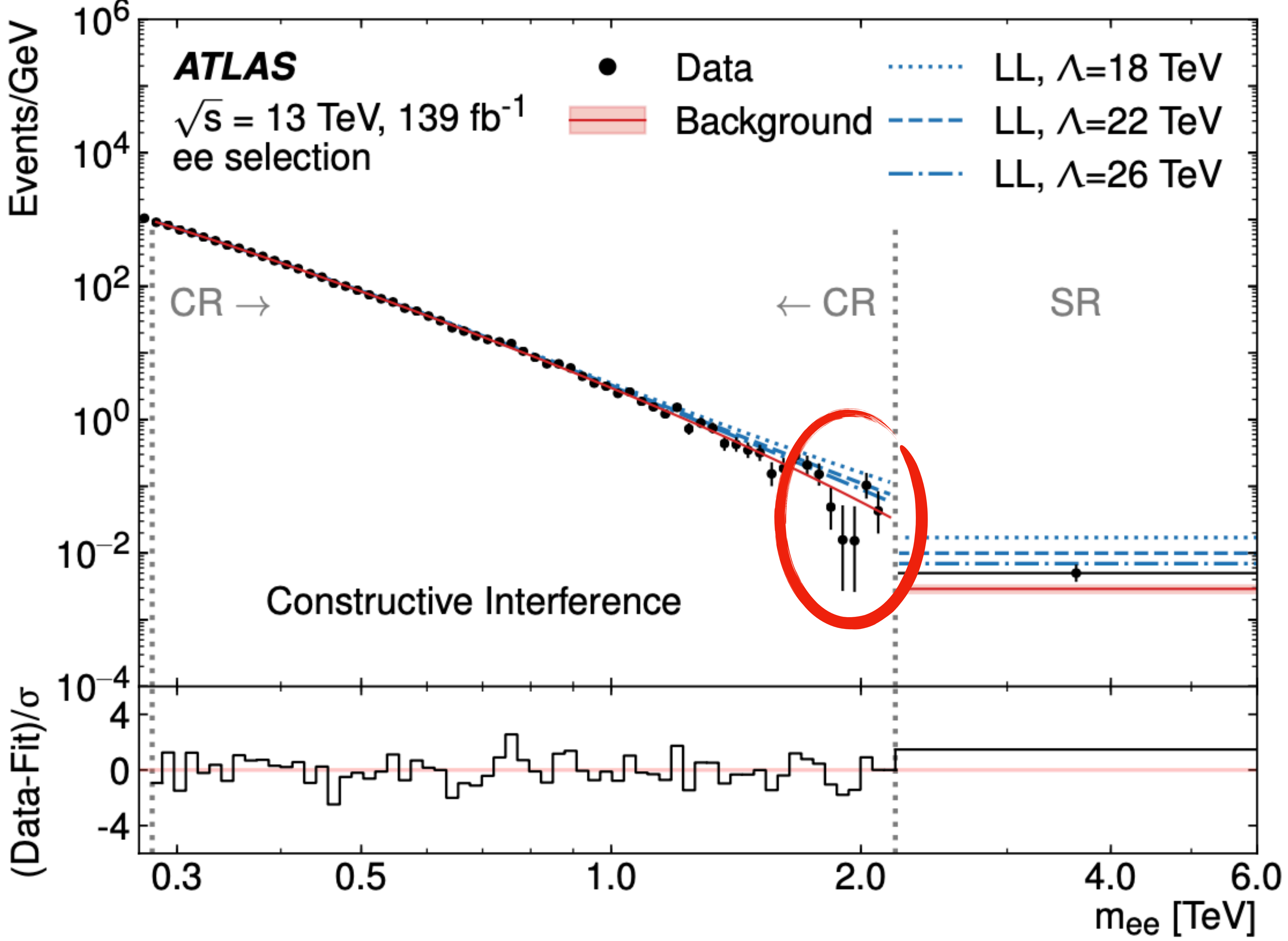


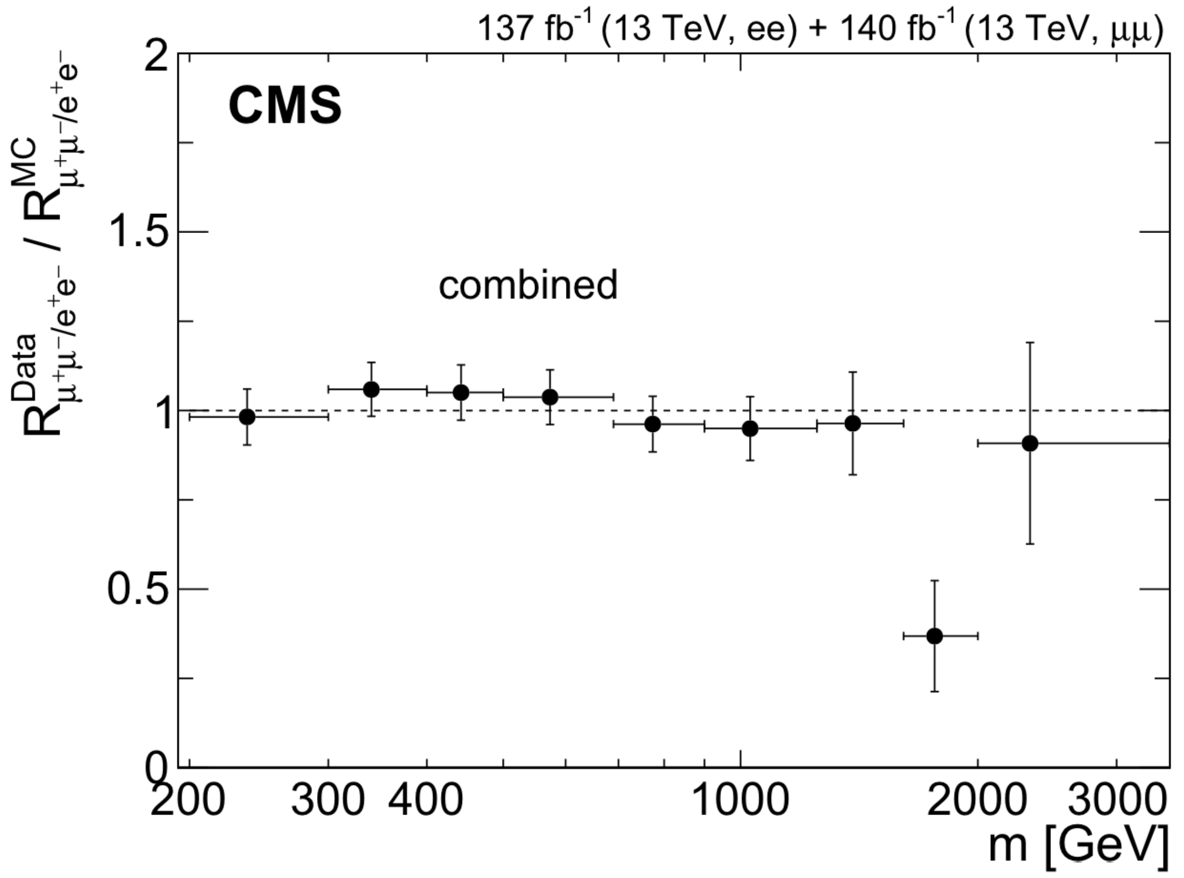
[2006.12946]

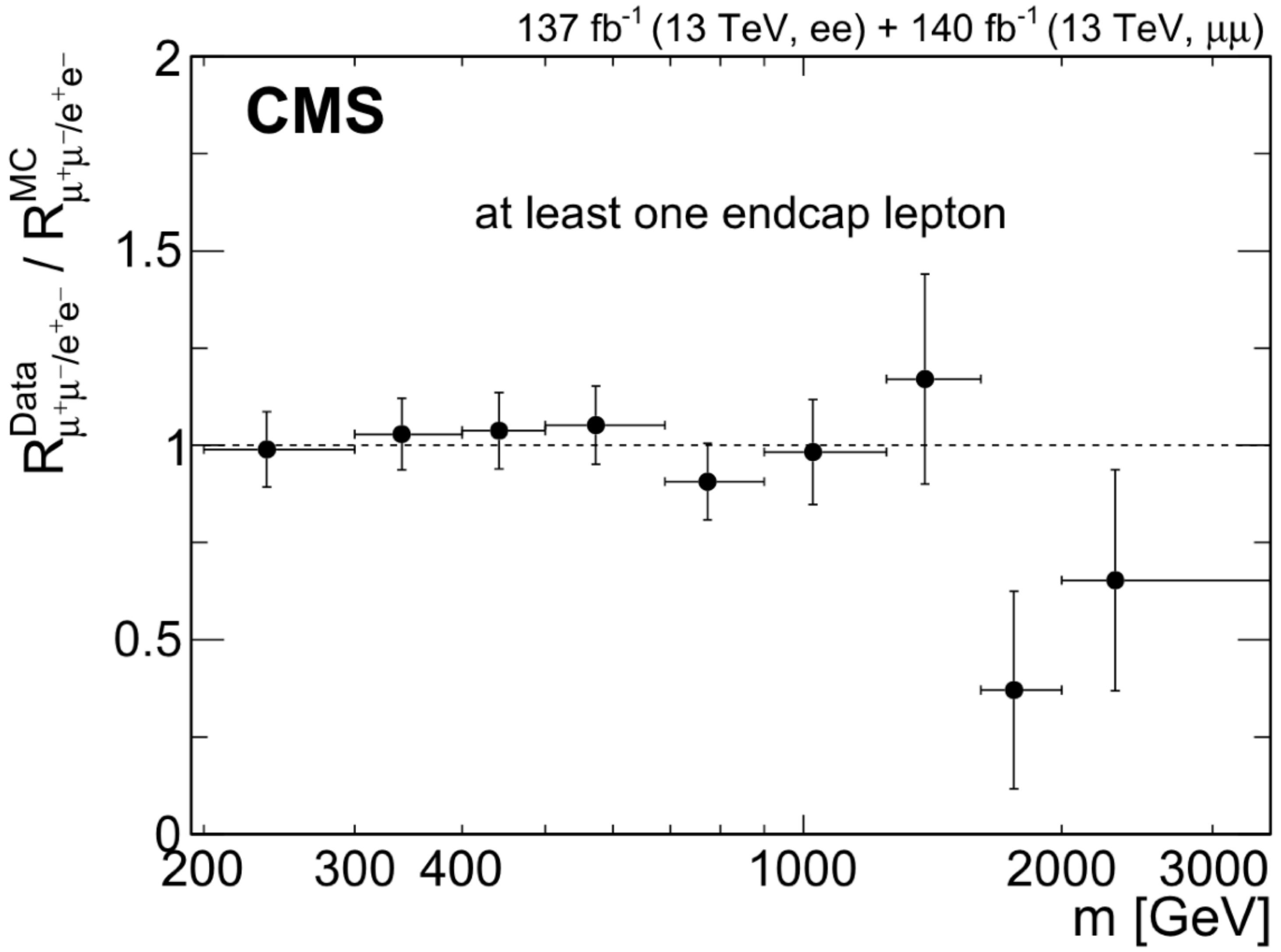


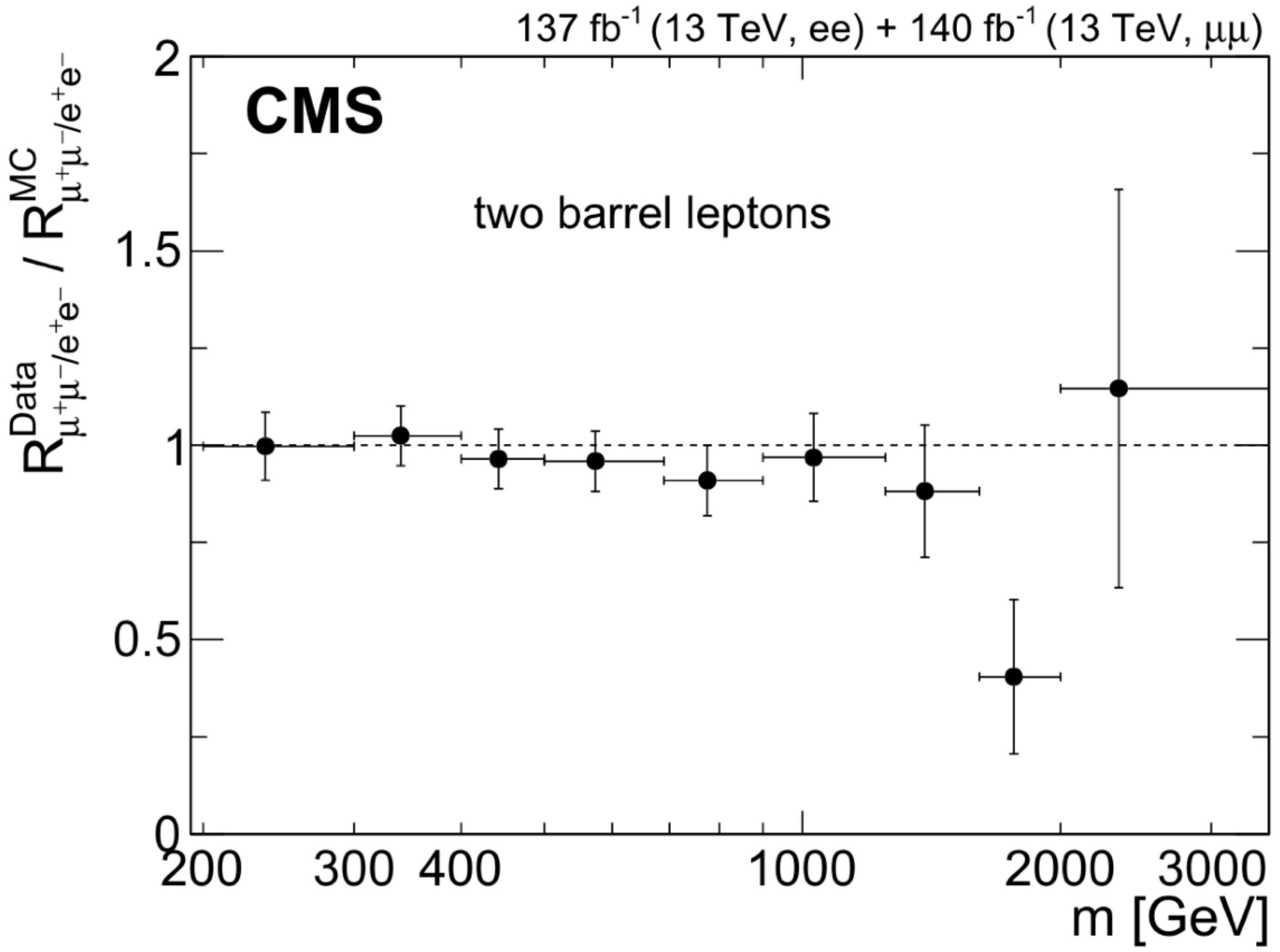
CMS di-electron excess

[CMS 2103.02708]

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







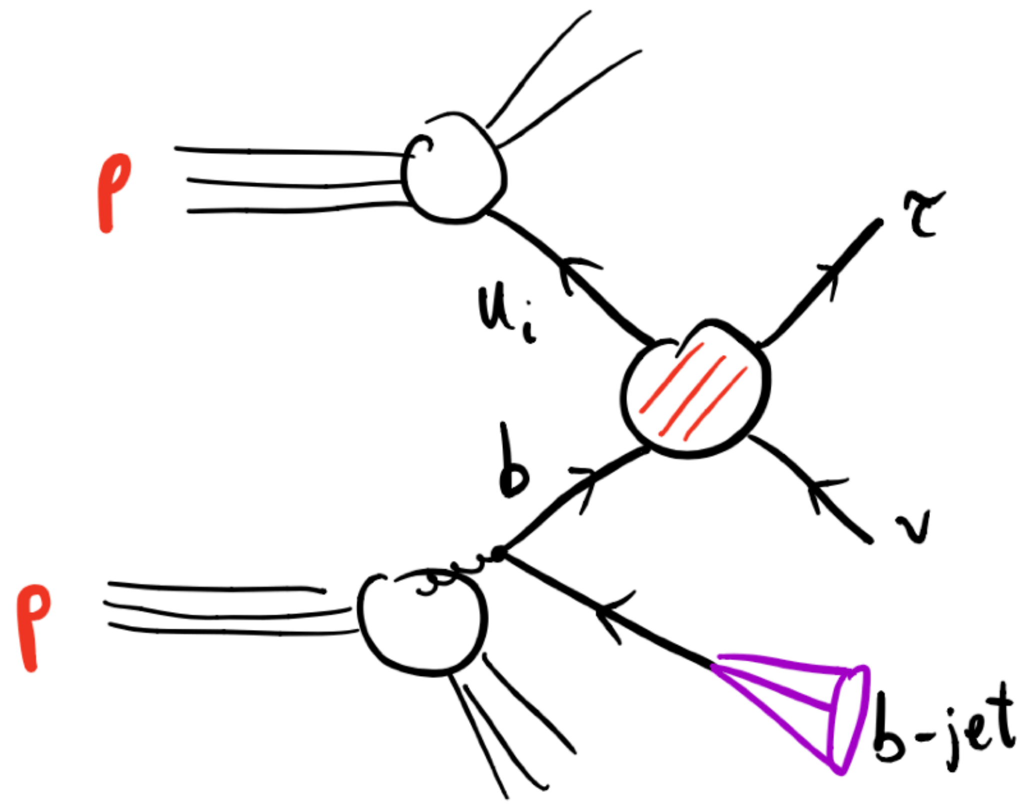
"At very high masses, the statistical uncertainties are large. Here, some deviations from unity are observed, caused by the slight excess in the dielectron channel discussed above. A χ^2 test for the mass range above 400 GeV is performed.
The resulting χ^2/dof values are 11.2/7 for the events with two 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]

Mono-tau tails at LHC

[DM, Min, Son, 2008.07541]

Optimise the sensitivity to $b \to c\,\tau\,\nu$ operators requiring **b-jet tagging**:



- Improves the Signal/Background ratio
- Selects only operators with b-quark

By comparing 3rd and 4th columns:

b-tagging improves the limits by at least ~30%

95%CL limits

EFT coeff.	CMS ($\mathcal{L}$=35.9 fb^{-1})	$\tau\nu$ - $\mathcal{L}$=300 fb^{-1}	$\tau\nu b$ - $\mathcal{L}$=300 fb^{-1}
$\lvert C_{SL}^{11}\rvert$	1.5×10^{-3}	1.1×10^{-3}	–
$\lvert C_{SL}^{12}\rvert$	9.8×10^{-3}	7.5×10^{-3}	–
$\lvert C_{SL}^{13}\rvert$	2.2	1.7	1.1
$\lvert C_{SL}^{21}\rvert$	1.6×10^{-2}	1.2×10^{-2}	–
$\lvert C_{SL}^{22}\rvert$	9.8×10^{-3}	7.5×10^{-3}	–
$\lvert C_{SL}^{23}\rvert$	0.33	0.26	0.18
$\lvert C_{SL}^{23}\rvert = 4\lvert C_T^{23}\rvert$	0.31	0.24	0.17
$\lvert C_{SR}^{11}\rvert$	1.5×10^{-3}	1.1×10^{-3}	–
$\lvert C_{SR}^{12}\rvert$	9.9×10^{-3}	7.5×10^{-3}	–
$\lvert C_{SR}^{13}\rvert$	2.2	1.7	1.1
$\lvert C_{SR}^{21}\rvert$	1.6×10^{-2}	1.2×10^{-2}	–
$\lvert C_{SR}^{22}\rvert$	9.7×10^{-3}	7.5×10^{-3}	–
$\lvert C_{SR}^{23}\rvert$	0.33	0.26	0.19
$\lvert C_T^{11}\rvert$	8.5×10^{-4}	6.5×10^{-4}	–
$\lvert C_T^{12}\rvert$	5.5×10^{-3}	4.2×10^{-3}	–
$\lvert C_T^{13}\rvert$	1.3	0.97	0.57
$\lvert C_T^{21}\rvert$	9.4×10^{-3}	7.2×10^{-3}	–
$\lvert C_T^{22}\rvert$	5.8×10^{-3}	4.5×10^{-3}	–
$\lvert C_T^{23}\rvert$	0.20	0.16	0.099
C_{VLL}^{11}	$[-0.40, 3.2]\times10^{-3}$	3.1×10^{-4}	–
C_{VLL}^{12}	$[-0.78, 1.1]\times10^{-2}$	9.0×10^{-3}	–
C_{VLL}^{13}	$[-2.1, 2.1]$	1.6	0.93
C_{VLL}^{21}	$[-1.4, 1.8]\times10^{-2}$	1.4×10^{-2}	–
C_{VLL}^{22}	$[-0.73, 1.2]\times10^{-2}$	1.5×10^{-3}	–
C_{VLL}^{23}	$[-0.33, 0.34]$	$[-0.25, 0.26]$	$[-0.14, 0.15]$
$\lvert C_{VRL}^{11}\rvert$	1.5×10^{-3}	1.1×10^{-3}	–
$\lvert C_{VRL}^{12}\rvert$	9.6×10^{-3}	7.3×10^{-3}	–
$\lvert C_{VRL}^{13}\rvert$	2.1	1.6	0.94
$\lvert C_{VRL}^{21}\rvert$	1.6×10^{-2}	1.2×10^{-2}	–
$\lvert C_{VRL}^{22}\rvert$	9.6×10^{-3}	7.4×10^{-3}	–
$\lvert C_{VRL}^{23}\rvert$	0.33	0.26	0.15

Flavor at High vs. Low Energy

[D.M., Min, Son, 2008.07541]

$$\mathcal{L}_{\text{eff}}^{\text{CC}} = -\mathcal{H}_{\text{eff}}^{\text{CC}} = -\frac{4G_f V_{ij}}{\sqrt{2}}\Big[C_{VLL}^{ij}(\bar{u}_i\gamma_\mu P_L d_j)(\bar{\tau}\gamma^\mu P_L\nu_\tau) + C_{VRL}^{ij}(\bar{u}_i\gamma_\mu P_R d_j)(\bar{\tau}\gamma^\mu P_L\nu_\tau) + C_{SL}^{ij}(\bar{u}_i P_L d_j)(\bar{\tau}P_L\nu_\tau) + C_{SR}^{ij}(\bar{u}_i P_R d_j)(\bar{\tau}P_L\nu_\tau) + C_T^{ij}(\bar{u}_i\sigma_{\mu\nu}P_L d_j)(\bar{\tau}\sigma^{\mu\nu}P_L\nu_\tau)\Big] + h.c.\ .$$

How do these **LHC limits compare with bounds from low energy**?

Let us focus for simplicity on LL operators.

EFT coeff.	CMS ($\mathcal{L}$=35.9 fb^{-1})	$\tau\nu$ - $\mathcal{L}$=300 fb^{-1}	$\tau\nu b$ - $\mathcal{L}$=300 fb^{-1}
C_{VLL}^{11}	$[-0.40, 3.2]\times 10^{-3}$	3.1×10^{-4}	–
C_{VLL}^{12}	$[-0.78, 1.1]\times 10^{-2}$	9.0×10^{-3}	–
C_{VLL}^{13}	$[-2.1, 2.1]$	1.6	0.93
C_{VLL}^{21}	$[-1.4, 1.8]\times 10^{-2}$	1.4×10^{-2}	–
C_{VLL}^{22}	$[-0.73, 1.2]\times 10^{-2}$	1.5×10^{-3}	–
C_{VLL}^{23}	$[-0.33, 0.34]$	$[-0.25, 0.26]$	$[-0.14, 0.15]$

- τ→νπ: $C_{VLL}^{ud} \in [-9.2, 1.6]\times 10^{-3}$
- τ→νK: $C_{VLL}^{us} \in [-2.8, -0.02]\times 10^{-2}$
- B→τν: $C_{VLL}^{ub}(m_b) \in [-0.13, 0.41]$
- charm: $C_{VLL}^{cd} \in [-0.21, 0.27]$
- charm: $C_{VLL}^{cs} \in [-1.4, 7.0]\times 10^{-2}$.
- R(D(*)): $C_{VLL}^{cb}(\text{TeV}) = 0.068 \pm 0.017$

Mono-tau tails are (or will be in the future) competitive with low-energy limits from

semileptonic τ decays [A. Pich 1310.7922]

and **charm physics** [Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.12421]

Di-tau high-p_T tail

If $R(D^{(*)})$ is addressed by this operator

$$(\bar{b}_L \gamma_\alpha c_L)(\bar{\nu}_\tau \gamma^\alpha \tau_L)$$

$\downarrow$ $SU(2)_L$

A sizeable effect is also induced in at least one of these:

$$(\bar{b}_L \gamma_\alpha s_L)(\bar{\tau}_L \gamma^\alpha \tau_L)$$

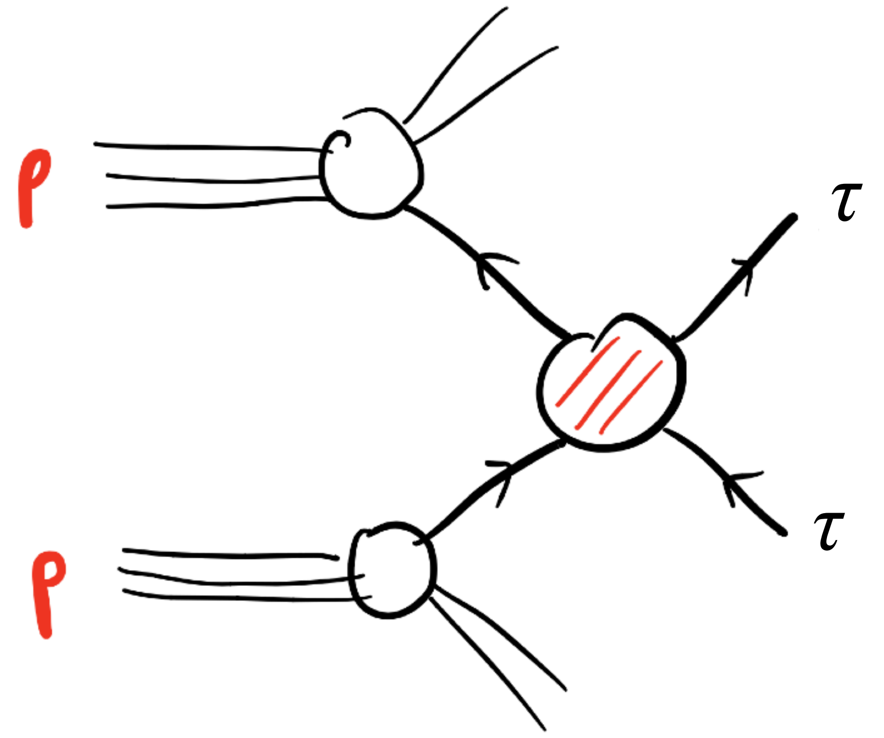
$$(\bar{b}_L \gamma_\alpha b_L)(\bar{\tau}_L \gamma^\alpha \tau_L)$$

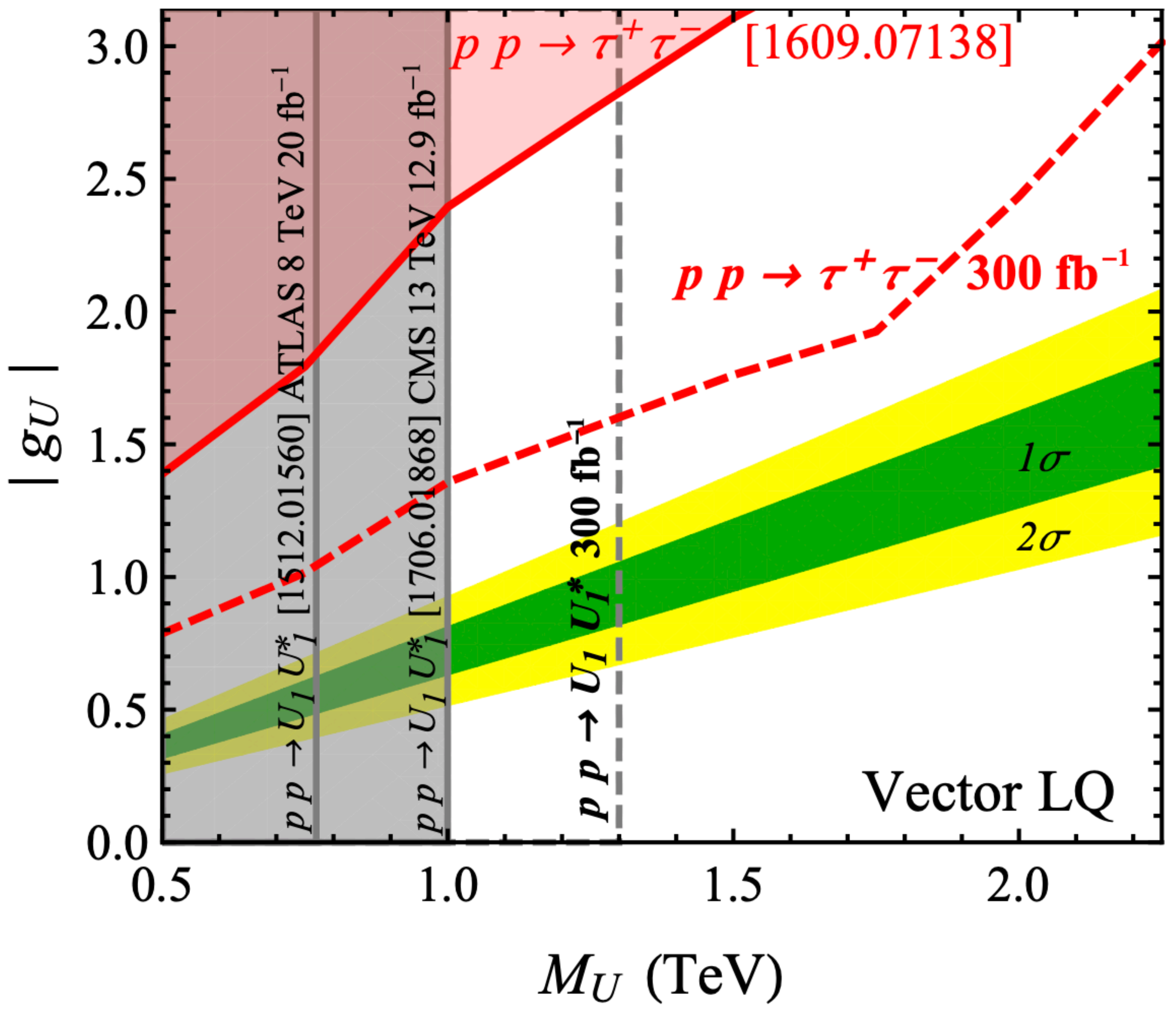
$$(\bar{c}_L \gamma_\alpha c_L)(\bar{\tau}_L \gamma^\alpha \tau_L)$$

[Faroughy, Greljo, Kamenik 1609.07138]

These can be looked for in

ττ high-p_T searches





[Buttazzo, Greljo, Isidori, DM 1706.07808,
see also 1808.08179, 1810.10017 for more general scenarios]

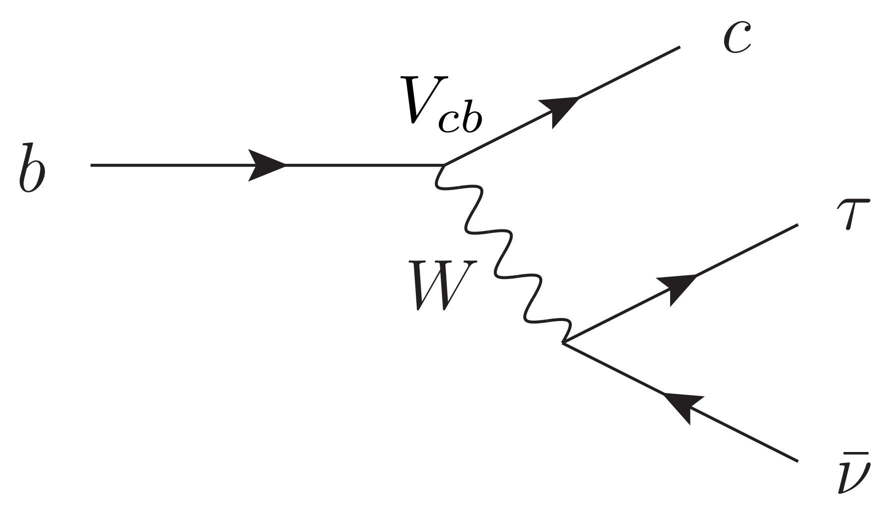
B-anomalies in charged current $b \to c\,\tau\,\bar{\nu}_\tau$

Lepton Flavour Universality

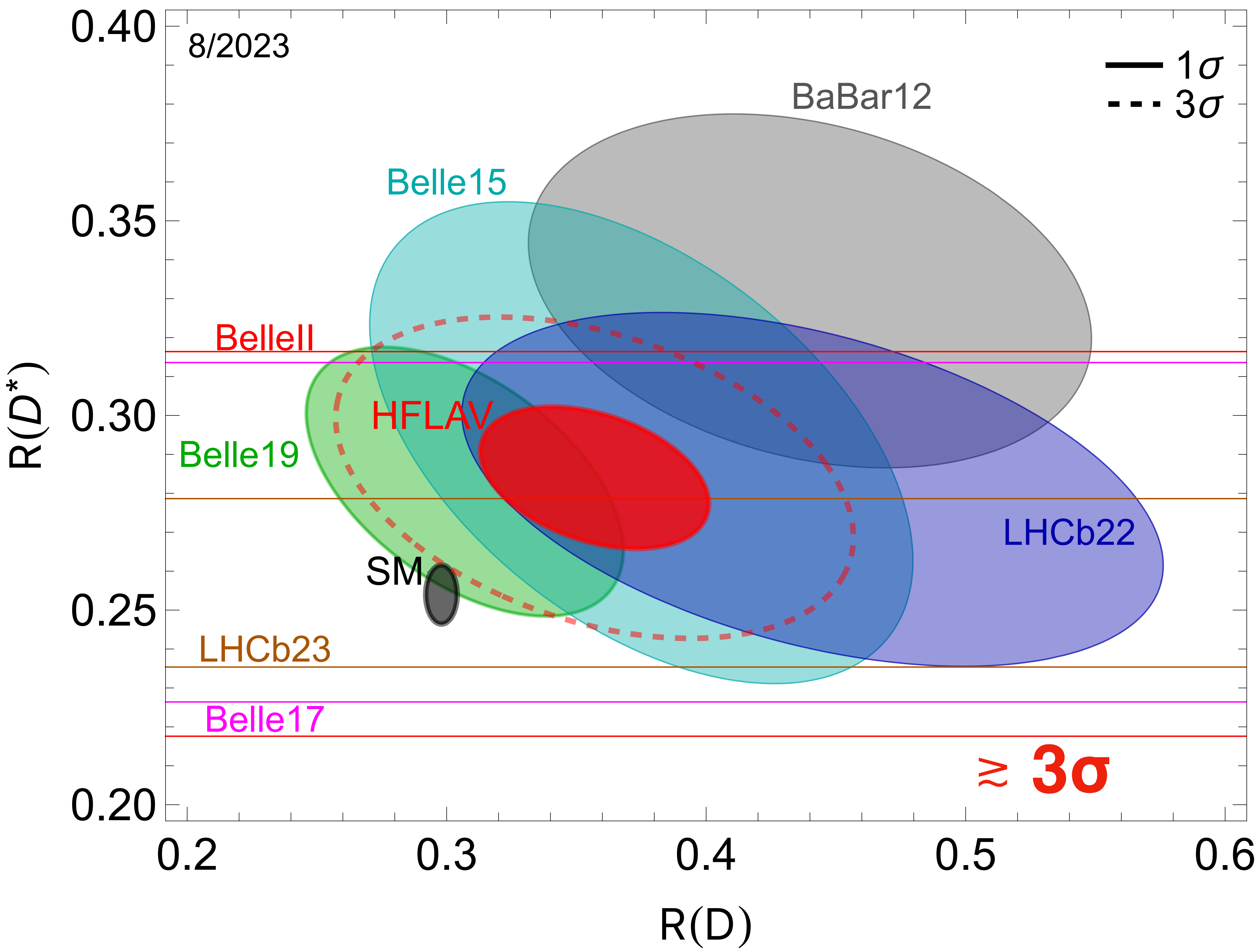
$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)}, \quad R(X) = \frac{\mathcal{B}(B \to X\tau\nu_\tau)}{\mathcal{B}(B \to X\ell\nu_\ell)}$$

$$\ell = \mu, e$$

Tree-level SM process with V_{cb} suppression.



SM prediction under control.



$$R^\tau_{cc} \equiv \frac{R(D)}{R(D)_{SM}} = \frac{R(D^*)}{R(D^*)_{SM}} = \frac{R(X)}{R(X)_{SM}}$$

$$R^\tau_{cc} = 1{,}135 \pm 0{,}034$$

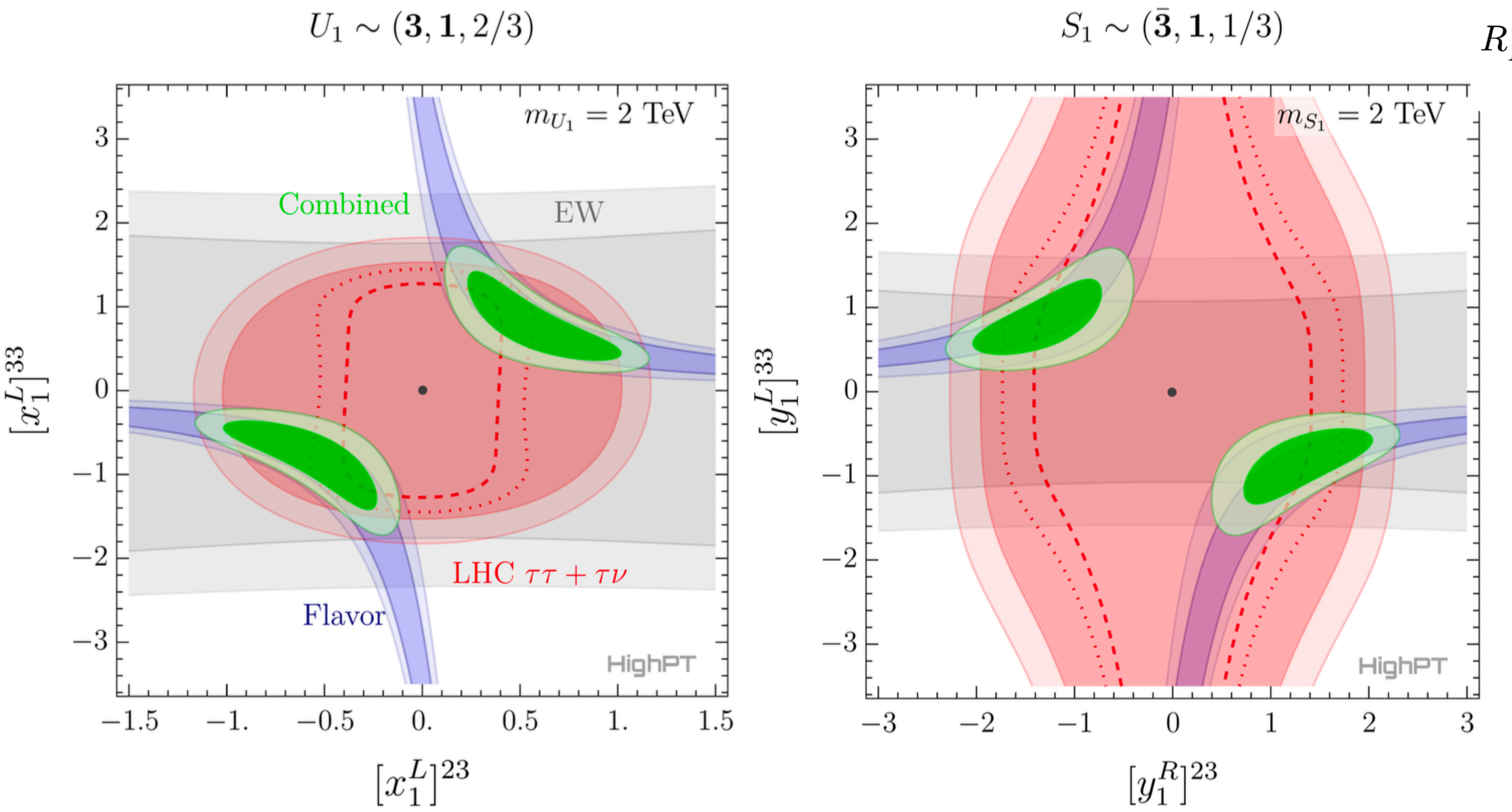
$$\mathcal{L}_{EFT} \supset C^{du\nu\tau}_{ij\tau\tau}\left(\bar{d}_{iL}\gamma_\mu u_{jL}\right)\left(\bar{\nu}_\tau \gamma^\mu \tau_L\right)$$

Corresponds to a **New Physics scale** of

$$C^{R(D^{(*)})}_{cb\tau\nu} \sim (4\,\mathrm{TeV})^{-2}$$

Application: LQ and R(D$^{(*)}$)

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



[<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.