High-pT dilepton tails and Flavour Physics

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Sezione di Trieste

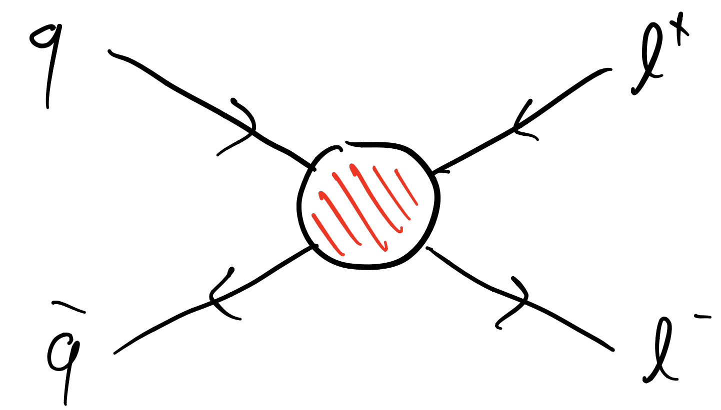
Based on [Greljo, Marzocca 1704.09015]

HEFT 2018 - Mainz University

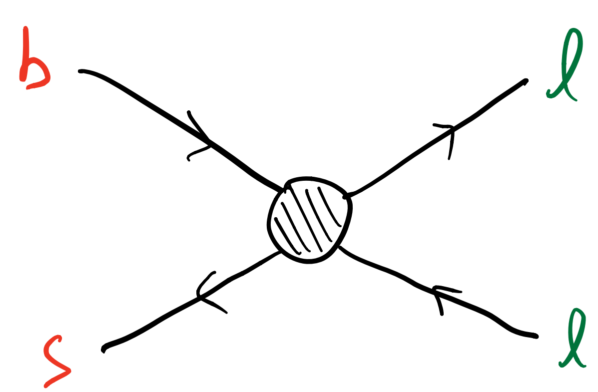
Outline

- Introduction

- SMEFT limits from high-energy dilepton tails



- Application to neutral-current B-physics anomalies



Indirect searches of New Physics

Precision measurements of SM processes can allow to test New Physics at scales not reachable by direct searches.

The SM EFT allows to describe the low-energy effects of heavy New Physics

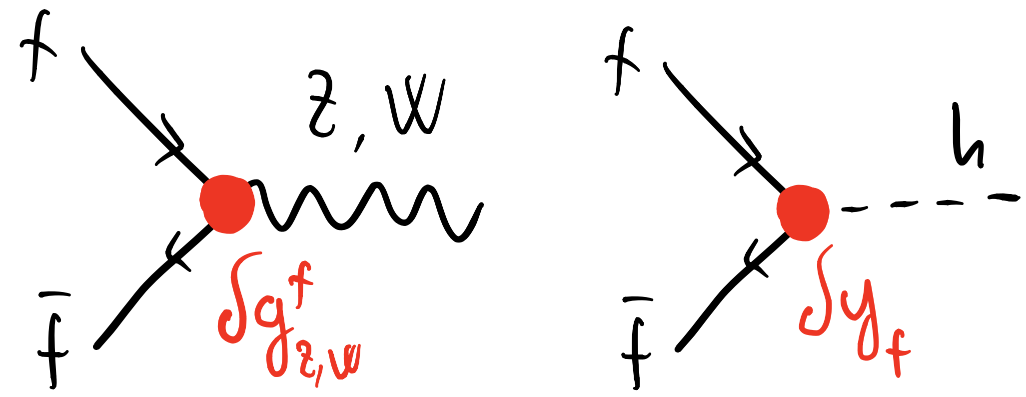
SM + heavy New Physics

$$E, m_Z \ll \Lambda \qquad \mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)}} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots$$

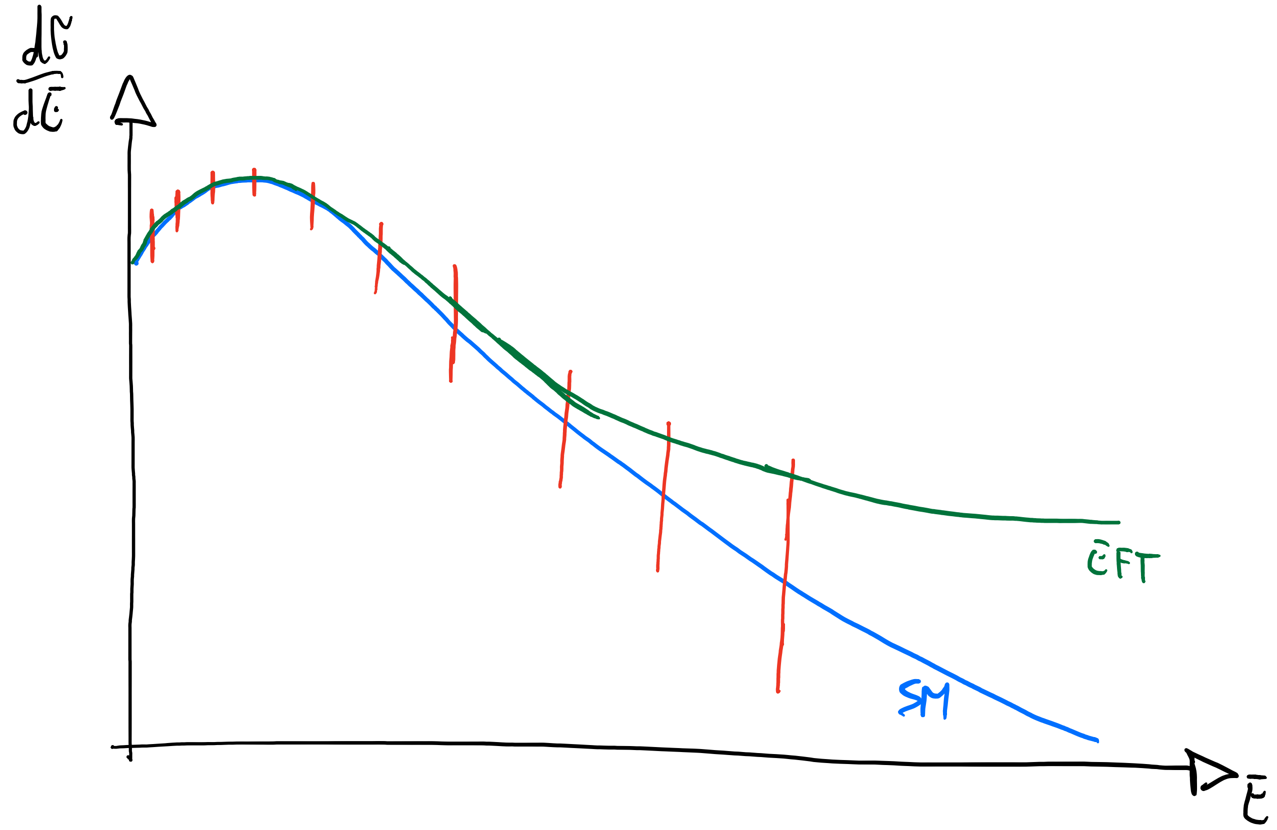
We can describe small deviations from the SM in an expansion of Energy over the mass scale of New Physics.

Two broad strategies for looking for deviations from the SM

1) Deviations in on-shell* couplings between SM particles



2)



Deviations in the tails of differential distributions

$A_{BSM} / A_{SM} \sim E^2$

1) ***Z(W)-pole*** *observables,* ***Higgs*** *couplings,..*

The relative deviation from the SM is: $\delta_{\rm pole} \sim \mathcal{O}\left(g_*^2 \frac{m_Z^2}{\Lambda^2} \right)$ $c_i \sim g_*^2$

LEP-I: $\delta_{\rm pole} \lesssim 10^{-3} \xrightarrow{g_* \sim 1}$ $\mathbf{\Lambda \gtrsim 3\ TeV}$

At LHC these measurements are limited by systematic (incl. theory) uncertainties.

Not much room for improvement beyond ~ (few) % level
[few exceptions, e.g. m_W]

2) *Deviations in the **tails of 2 → 2 processes***

$$\delta_{\rm tail} \sim \mathcal{O}\left(g_*^2 \frac{p^2}{\Lambda^2} \right)$$

$$\delta_{\rm tail} \lesssim 10^{-1} \quad \xrightarrow[g_* \sim 1]{p \,\sim\, 2\ \mathrm{TeV}} \quad \Lambda \gtrsim 6\ \mathrm{TeV}$$

'*Energy helps accuracy'* [see e.g. Farina et al. 1609.08157]

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'*Energy helps accuracy'* [see e.g. Farina et al. 1609.08157]

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

We focus on **operators**
whose interfering amplitude with the SM
grows quadratically with the energy

EFT validity

Ellis, Sanz 1410.7703;
Greljo et al. 1512.06135;
Plehn et al. 1510.03443,1602.05202;
Contino et al. 1604.06444;
Falkowski et al. 1609.06312;
...

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

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

$$c_i \sim g_*^2$$

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

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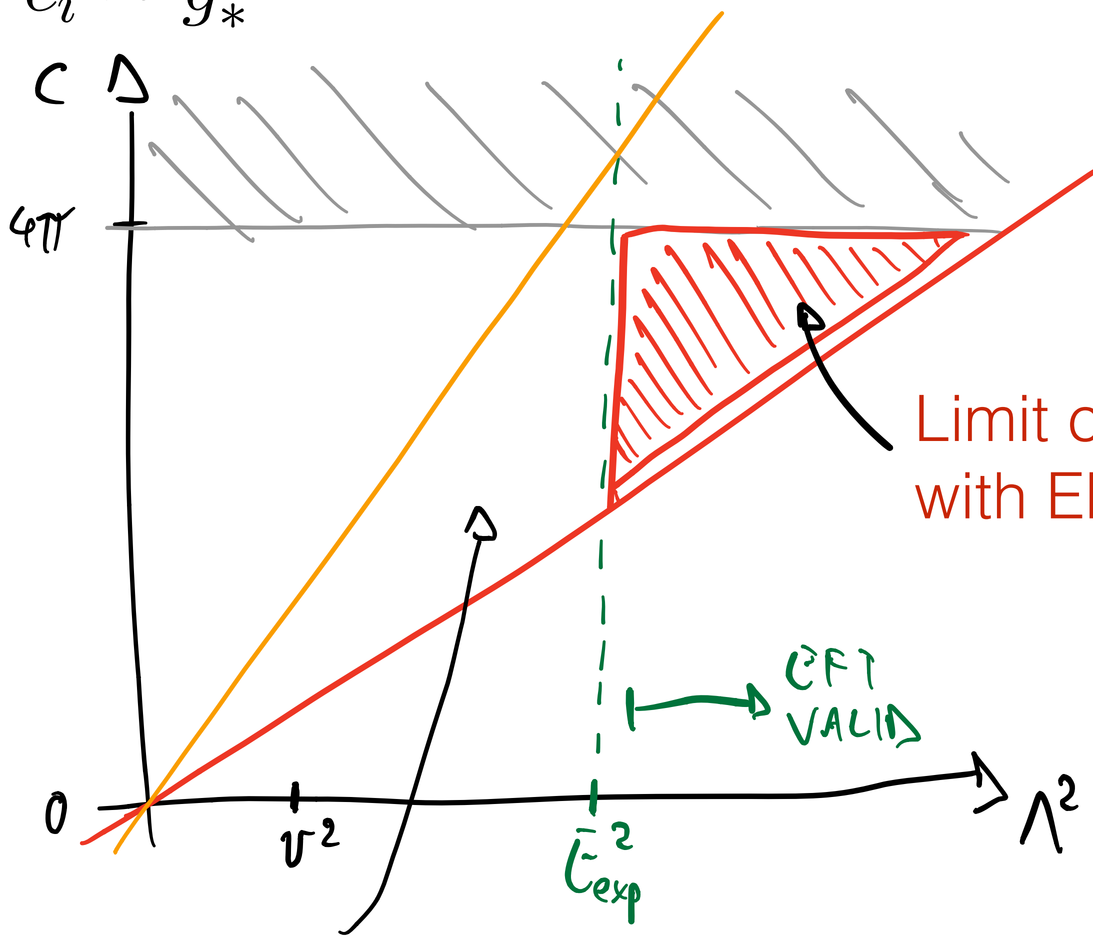


Limit consistent with EFT

This region is possibly excluded by same search, but using a 'direct search' approach.

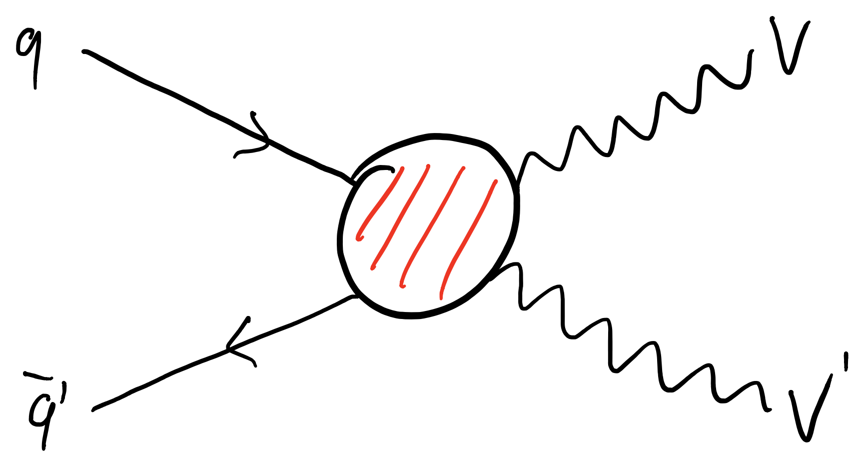
Bad precision at high energy could mean that no scenario is being probed consistently with the EFT.

Increasing the precision enlarges the size of the triangle, accessing more weakly coupled models.

2 → 2 processes at high-p_T

In this talk I will focus on:

Diboson (and VH) production

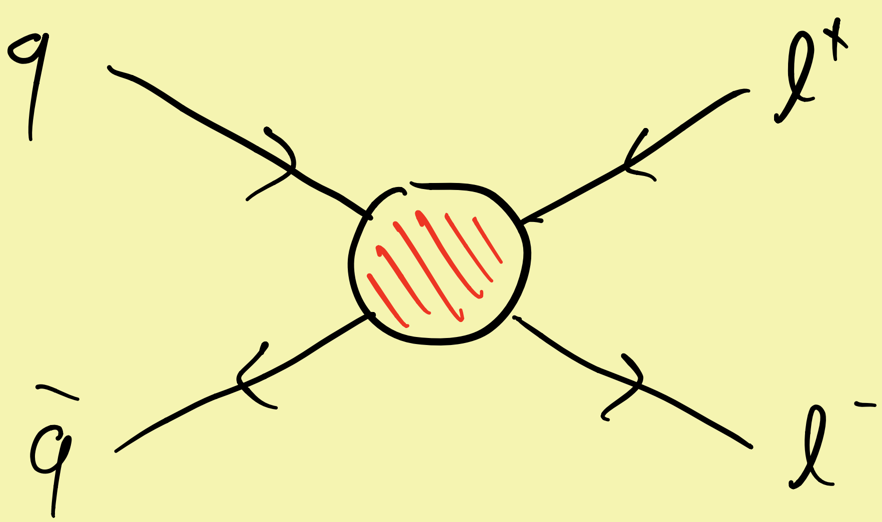


Constraints on
$qqHD_\mu H$ operators.

or anomalous triple-gauge couplings
(aTGC)

See e.g. 1712.01310

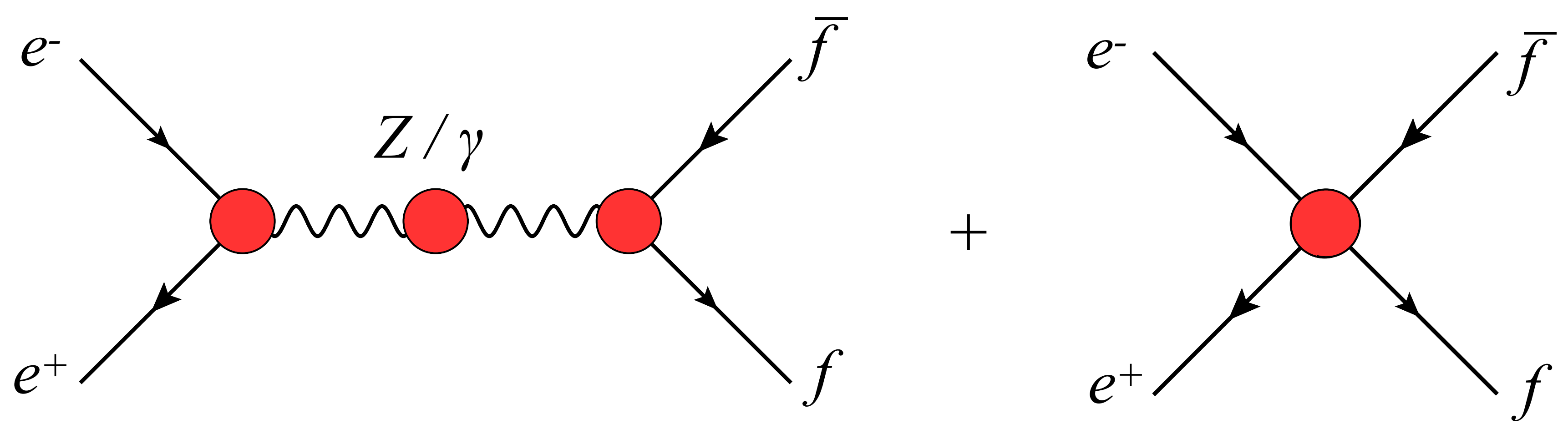
Dilepton production
at high $m_{\ell\ell}$



Constraints on $qq\ell\ell$
four-fermion operators

LEP-2 $f\bar{f}$ data

The Z (or γ) is off-shell



This bounds four-fermion operators

See [Falkowski et al. 1511.07434] for global fit of 4-lepton operators

Assuming "universality" (i.e. only Z,W propagators are affected)

	universal form factor ($\mathcal{L}$)	contact operator ($\mathcal{L}'$)
W	$-\frac{\mathrm{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$	$-\frac{g_2^2\mathrm{W}}{2m_W^2} J_L{}^a_\mu J_L{}^\mu_a$
Y	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$	$-\frac{g_1^2\mathrm{Y}}{2m_W^2} J_Y{}_\mu J_Y{}^\mu$

W and Y parameters of

[Barbieri et al. hep-ph/0405040]

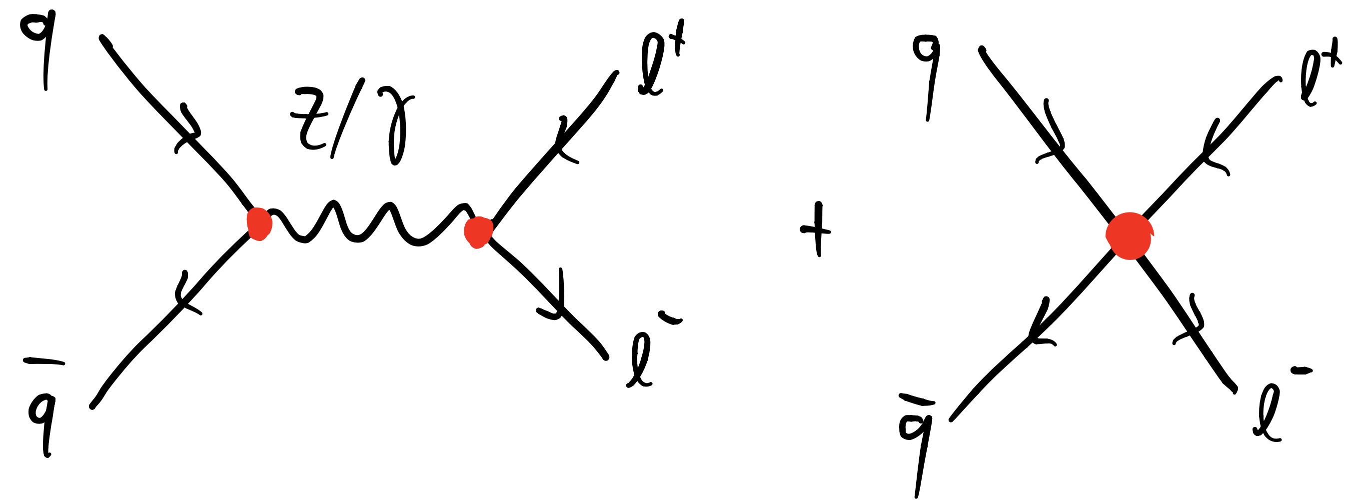
$\sim 10^{-3}$ *precision from LEP*

Dilepton production @ LHC

A very simple process.

In full generality, at dim-6 in the EFT expansion:

Extra local interactions



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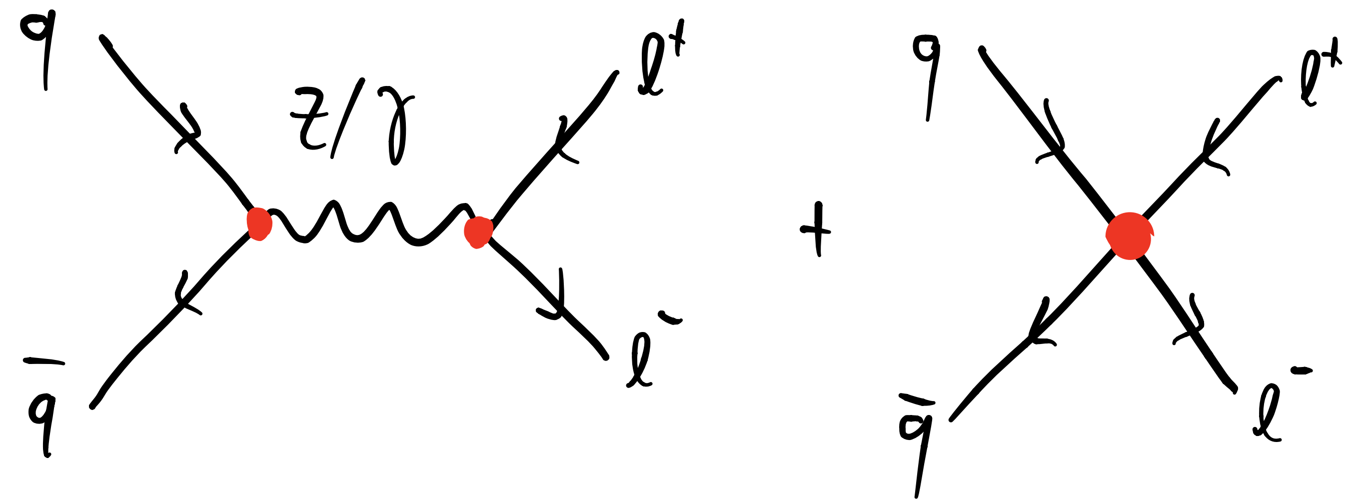

The main observable is the $\ell\ell$ invariant mass distribution.
Don't even need a Lagrangian to describe it:

$$\mathscr{A}(q^i_{p_1}\bar{q}^j_{p_2} \to \ell^-_{p'_1}\ell^+_{p'_2}) = i \sum_{q_L,q_R}\sum_{\ell_L,\ell_R} (\bar{q}^i\gamma^\mu q^j)\,(\bar{\ell}\gamma_\mu\ell)\,F_{q\ell}(p^2)$$

$$F_{q\ell}(p^2) = \delta^{ij}\frac{e^2 Q_q Q_\ell}{p^2} + \delta^{ij}\frac{g_Z^q g_Z^\ell}{p^2 - m_Z^2 + i m_Z \Gamma_Z} + \frac{\epsilon^{q\ell}_{ij}}{v^2}$$

Local interactions, i.e.
4-fermion operators.

[Greljo, D.M. 1704.09015]

Dilepton production @ LHC

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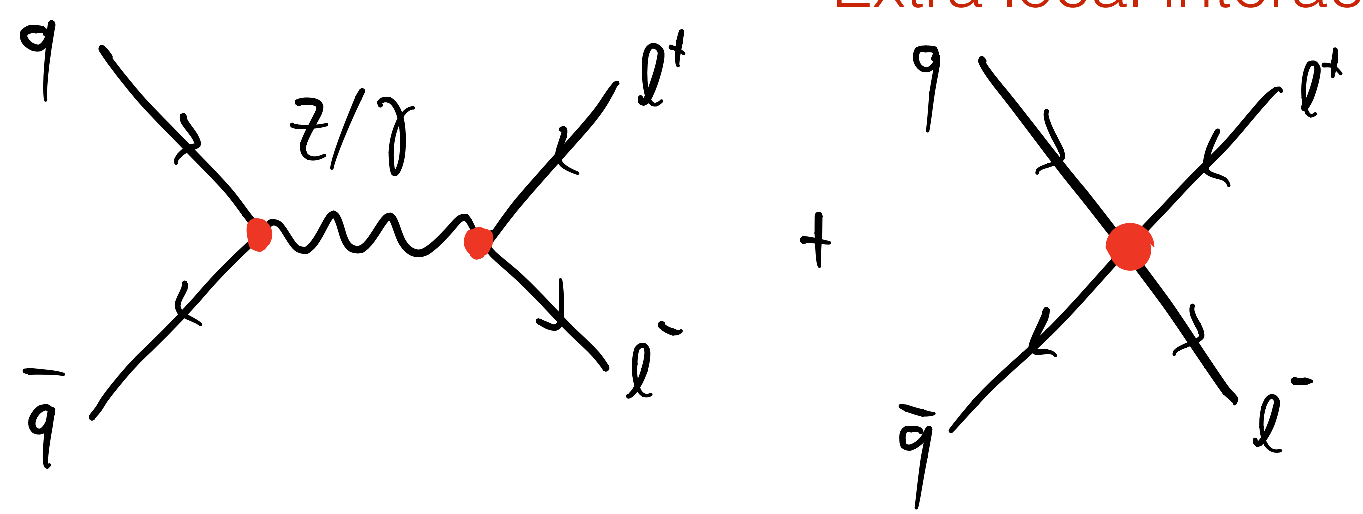

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Local interactions, i.e. 4-fermion operators.

[Greljo, D.M. 1704.09015]

Convolute with parton lumi:

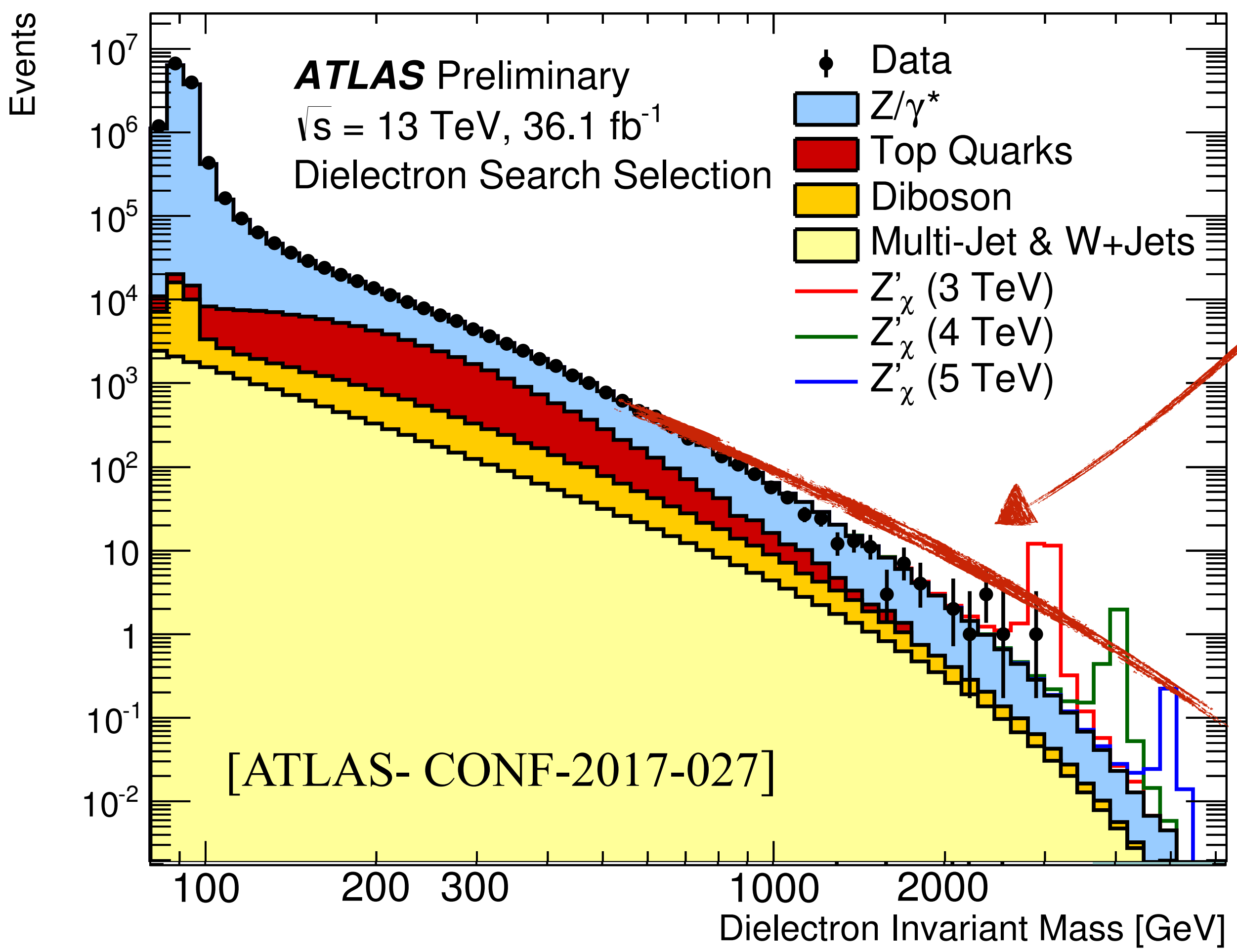
$$\boxed{\frac{d\sigma}{d\tau} = \left(\frac{d\sigma}{d\tau}\right)_{\rm SM} \times \frac{\sum_{q,\ell}\mathscr{L}_{q\bar{q}}(\tau,\mu_F)|F_{q\ell}(\tau s_0)|^2}{\sum_{q,\ell}\mathscr{L}_{q\bar{q}}(\tau,\mu_F)|F^{\rm SM}_{q\ell}(\tau s_0)|^2}}$$

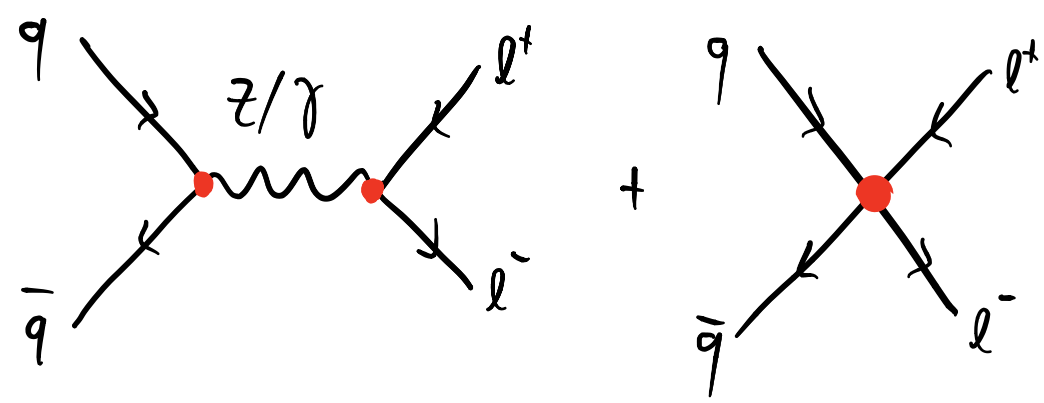
$$\tau \equiv m^2_{\ell^+\ell^-}/s_0$$

Dilepton production @ LHC

$$\frac{d\sigma}{d\tau} = \left(\frac{d\sigma}{d\tau}\right)_{\mathrm{SM}} \times \boxed{\frac{\sum_{q,\ell} \mathscr{L}_{q\bar{q}}(\tau,\mu_F)|F_{q\ell}(\tau s_0)|^2}{\sum_{q,\ell} \mathscr{L}_{q\bar{q}}(\tau,\mu_F)|F_{q\ell}^{\mathrm{SM}}(\tau s_0)|^2}}$$

Just rescale the SM prediction with this factor and compare with the experimental results.

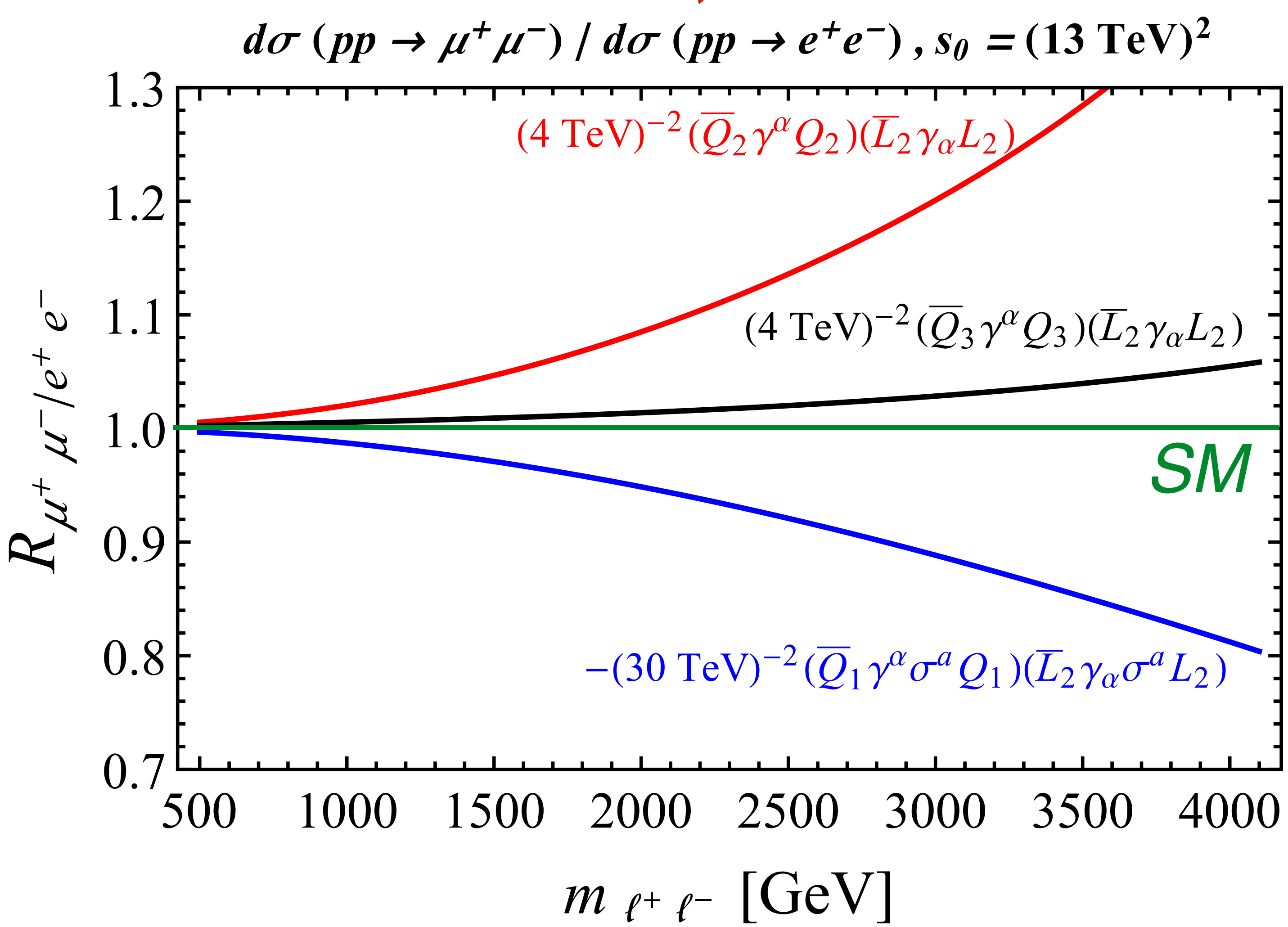




Lepton Flavour Universality ratio

Differential LFU ratio

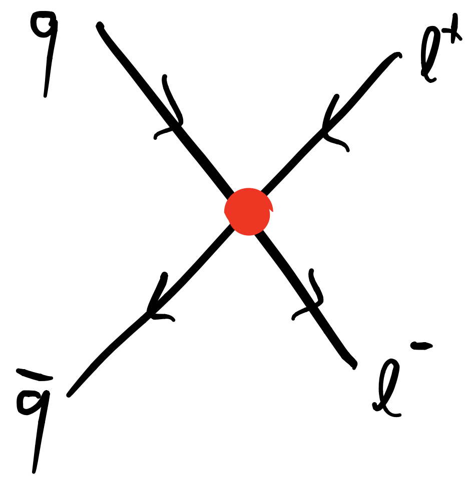
$$R_{\mu^+\mu^-/e^+e^-}(m_{\ell\ell}) \equiv \frac{d\sigma_{\mu\mu}}{dm_{\ell\ell}} \Big/ \frac{d\sigma_{ee}}{dm_{\ell\ell}} = \frac{\sum_{q,\mu} \mathscr{L}_{q\bar{q}}(m_{\ell\ell}^2/s_0, \mu_F)|F_{q\mu}(m_{\ell\ell}^2)|^2}{\sum_{q,e} \mathscr{L}_{q\bar{q}}(m_{\ell\ell}^2/s_0, \mu_F)|F_{qe}(m_{\ell\ell}^2)|^2}$$



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

Tests of LFU are strongly motivated by the B-physics anomalies.

Limits on 36 4-fermion operators



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

Neglecting flavour-violation, in the Warsaw basis there are 36 independent $qq\ell\ell$ ($\ell=e,\mu$) operators which interfere with the SM amplitude (i.e. vector-type) in $pp\to\ell^+\ell^-$.

Having different chiralities and field content, they do not interfere with each other.

Limits on 36 4-fermion operators

[Greljo, D.M. 1704.09015]

Limits in the Warsaw basis, shown here one operator at a time.
We have the complete Likelihood function and checked: no sizable correlations since different operators do not interfere (different flavours and chirality).

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] $\times 10^{-4}$
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$C_{s_R\mu_R}$	[-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] $\times 10^{-3}$

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

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[Greljo, D.M. 1704.09015]

Limits in the Warsaw basis, shown here one operator at a time.
We have the complete Likelihood function and checked: no sizable correlations since different operators do not interfere (different flavours and chirality).

~ 10^{-3} - 10^{-2} *precision now*

$$C = \frac{g_*^2 v^2}{M^2} \xRightarrow{g_* = 1} M \gtrsim 8 \text{ TeV}$$

a *5-10* -fold improvement at HL-LHC

C_i	ATLAS 36.1 fb^{-1}		C_i		
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$C_{c_R e_R}$	[-0.67, 1.27] $\times 10^{-2}$	[-2.59, 4.17] $\times 10^{-3}$	$C_{c_R \mu_R}$	[-1.21, 1.62] $\times 10^{-2}$	[-3.48, 6.32] $\times 10^{-3}$
$C_{b_L L^1}$	[-1.93, 1.19] $\times 10^{-2}$	[-8.62, 4.82] $\times 10^{-3}$	$C_{b_L L^2}$	[-2.61, 2.07] $\times 10^{-2}$	[-11.1, 6.33] $\times 10^{-3}$
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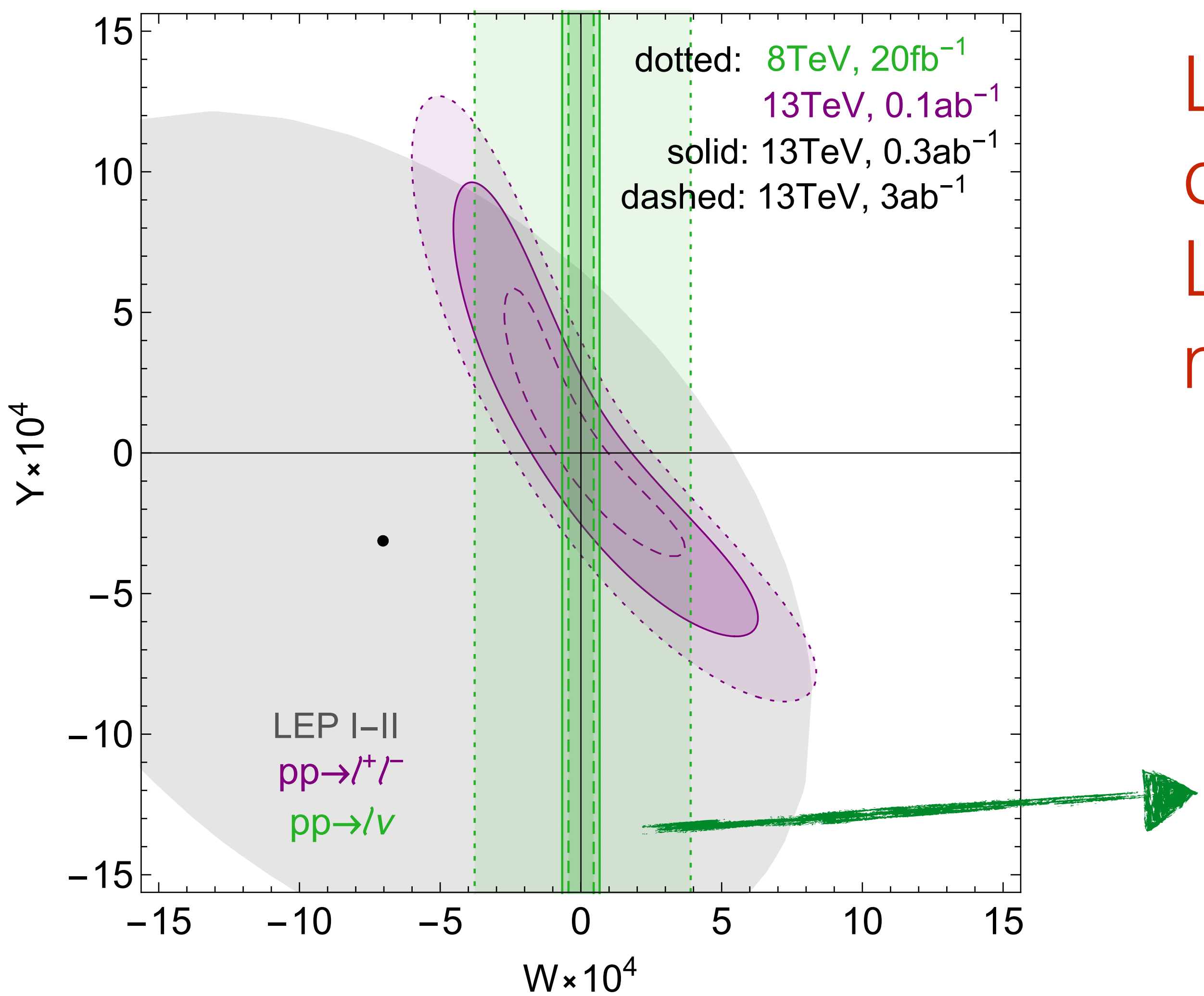
$$C_x \equiv \frac{v^2}{\Lambda^2} c_x$$

Assuming Universality

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

All 4-fermion operators aligned with the W and B currents:

$$-\frac{g_2^2 \mathrm{W}}{2m_W^2} J_{L\,\mu}^{\,a} J_{L\,a}^{\,\mu} \quad -\frac{g_1^2 \mathrm{Y}}{2m_W^2} J_{Y\,\mu} J_Y^{\,\mu}$$



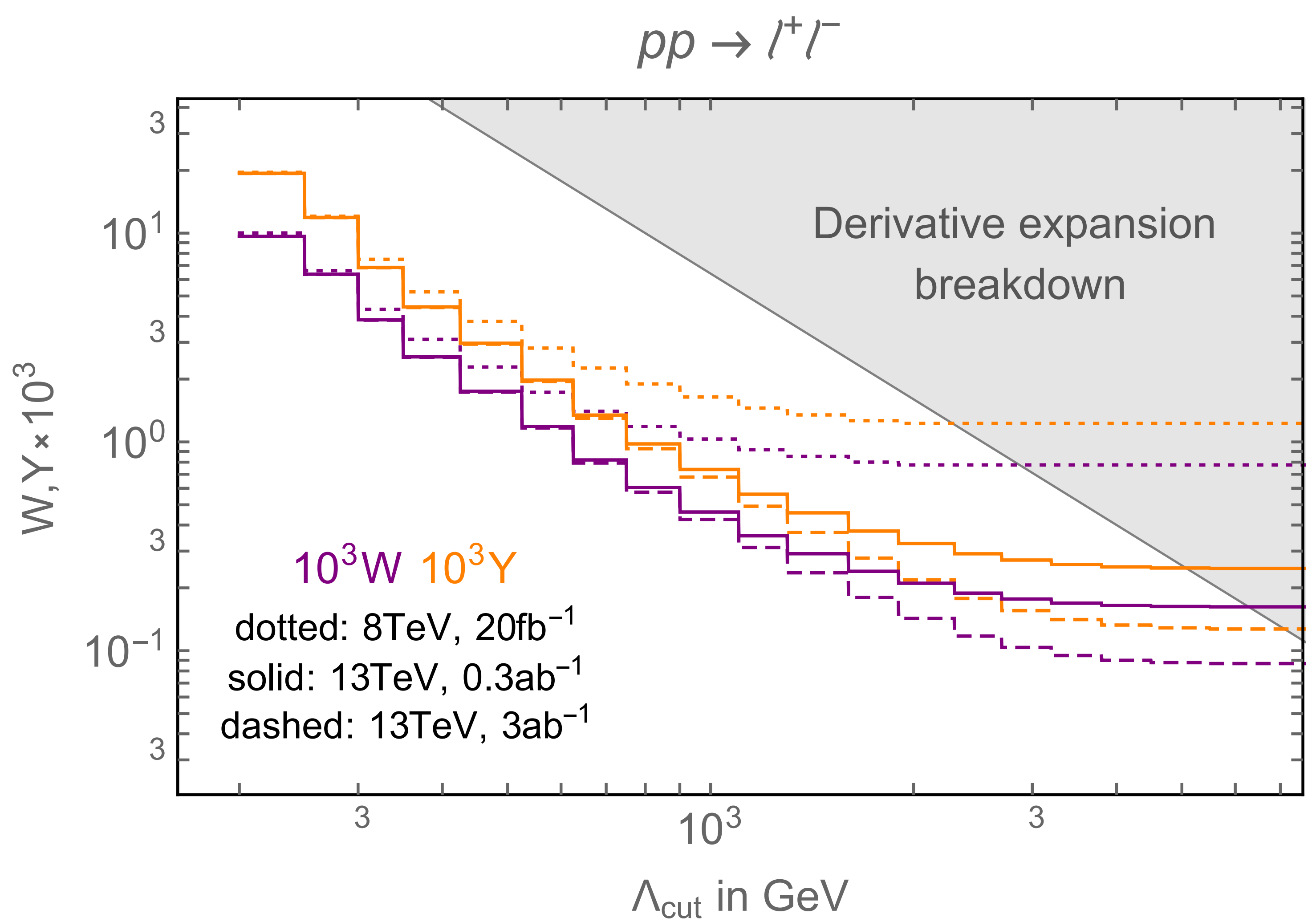
Limits from LHC are already competitive/better than those from LEP and will improve even more with more data.

$pp \to \ell v$ has also potential to provide strong bounds!

Controlling the EFT (II)

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

How do the limits vary when using only events with $m_{\ell\ell} < \Lambda_{\text{cut}}$?



Limits saturate at $\Lambda_{\text{cut}} \sim$ 2-3 TeV at 13TeV.

(more luminosity → more events at high energy)

Application to

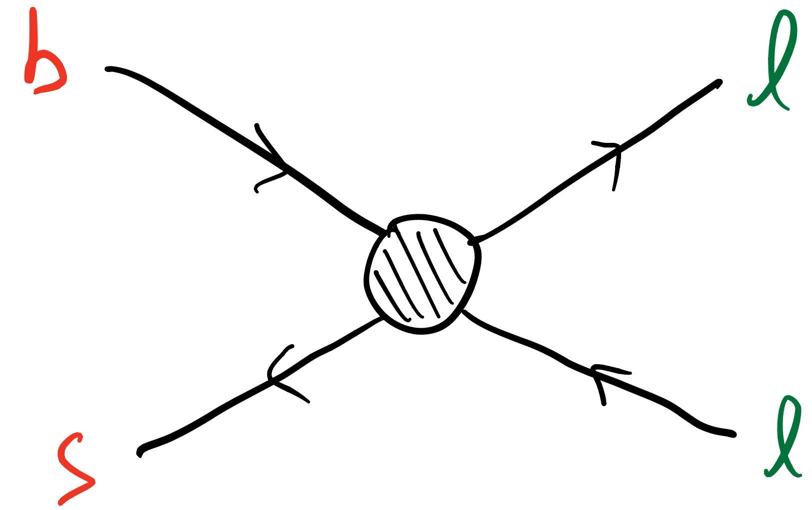
B-physics anomalies

Neutral-current B-anomalies

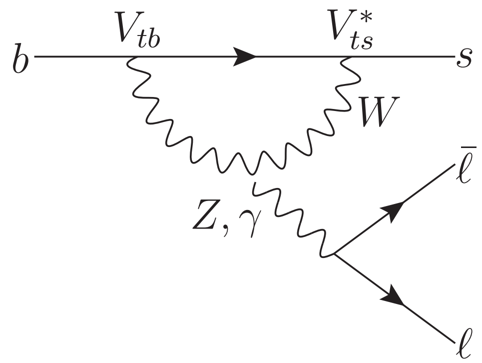
P'$_5$ Angular distributions in μμ in B → K* μμ

> 5σ

Possibly affected by non-perturbative QCD corrections



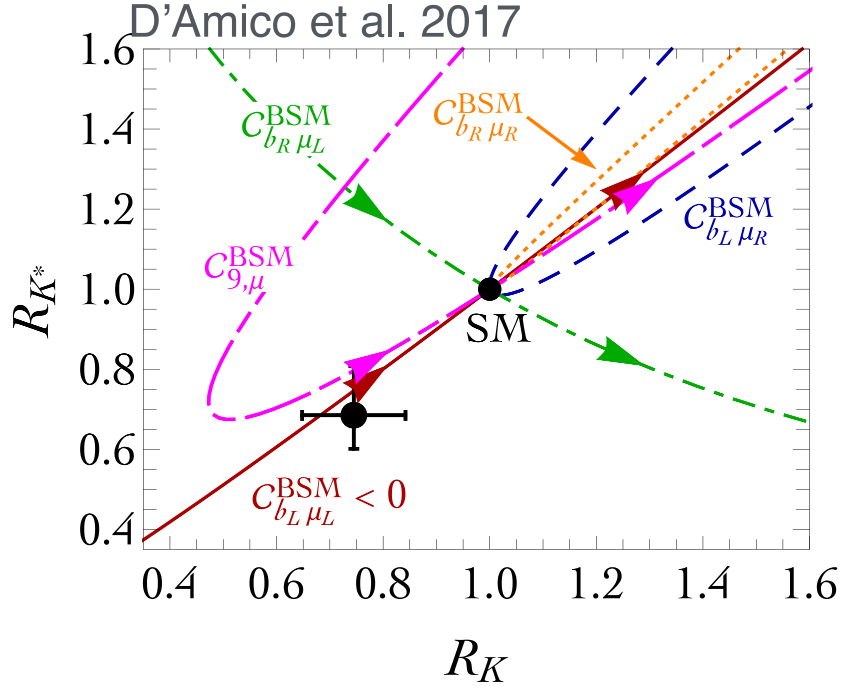
Generated at 1-loop in the SM.



LFU ratios

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

Theoretically clean **~ 4σ**

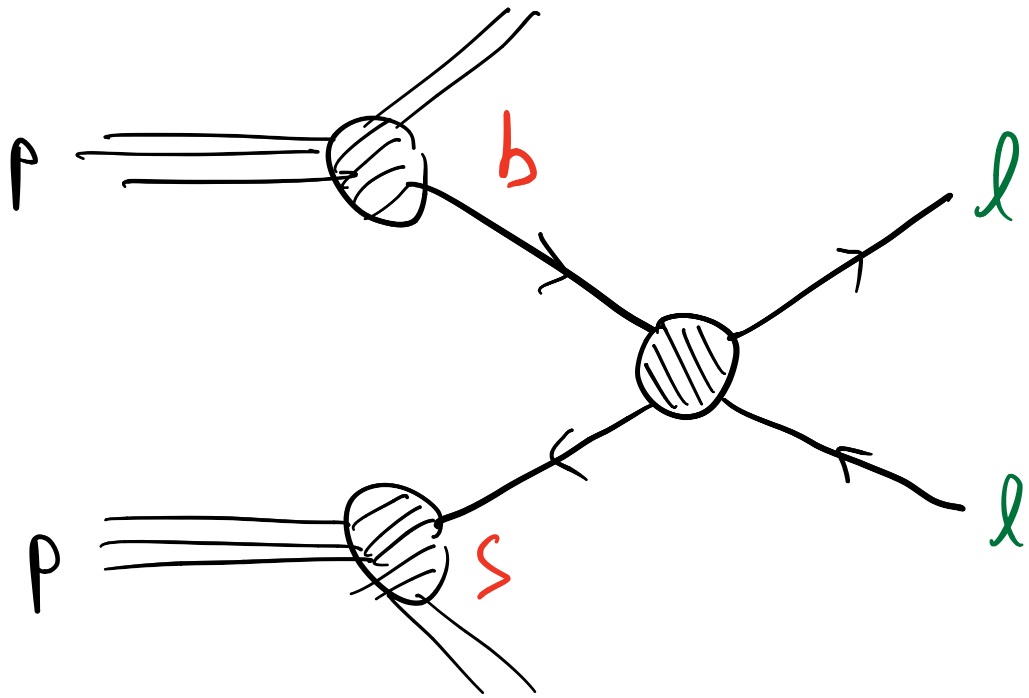


Best New Physics interpretation:

$$\frac{1}{\Lambda_{bs\mu}^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}_L\gamma^\mu\mu_L)$$

$$\Lambda_{bs\mu} \sim 32\ \mathrm{TeV}$$

Flavor in dimuon tails?



Can we test this contact interaction directly at the LHC?

present (future 3ab^{-1}) limits:

$$\Lambda_{bs\mu} > 2.5\ (4.1)\ \text{TeV}$$

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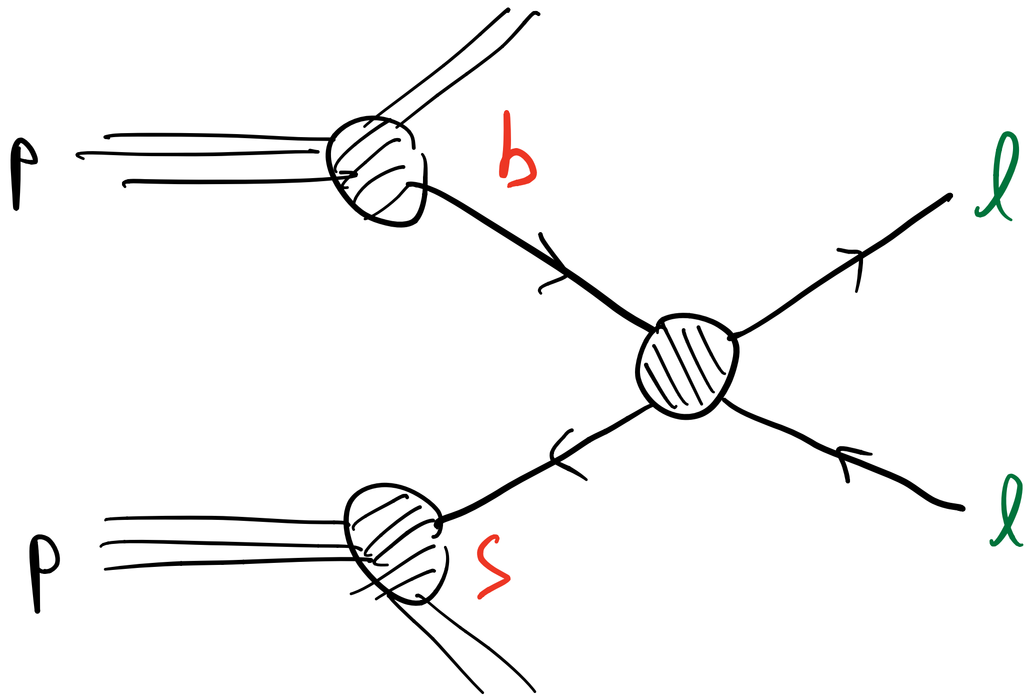

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However

In a most flavour models, this flavour-violating operator is related to flavour-conserving ones, which are less suppressed:

$$\frac{1}{\Lambda^2_{qq\mu}} \left[\lambda^q_{bs} (\bar{s}_L \gamma_\mu b_L) + (\bar{q}_L \gamma_\mu q_L)\right] (\bar{\mu}_L \gamma^\mu \mu_L) \qquad \lambda^\mu_{bs} \ll 1$$

LHC might test this! $\Lambda_{qq\mu} \ll \Lambda_{bs\mu}$

Flavor in dimuon tails?

Instead of working with Λ, I go back to admensional parameters:

$$C_{bs\mu} = \frac{v^2}{\Lambda^2_{bs\mu}}$$

$$\mathscr{L}^{\rm eff} \supset \frac{\mathbf{C}^{U\mu}_{ij}}{v^2}(\bar{u}^i_L \gamma_\mu u^j_L)(\bar{\mu}_L \gamma^\mu \mu_L) + \frac{\mathbf{C}^{D\mu}_{ij}}{v^2}(\bar{d}^i_L \gamma_\mu d^j_L)(\bar{\mu}_L \gamma^\mu \mu_L)$$

$$\mathbf{C}^{U\mu}_{ij} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \quad \mathbf{C}^{D\mu}_{ij} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C^*_{bs\mu} \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$

$$\lambda^q_{bs} \equiv C_{bs\mu}/C_{q\mu}$$

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The flavour structure is predicted in a given model.

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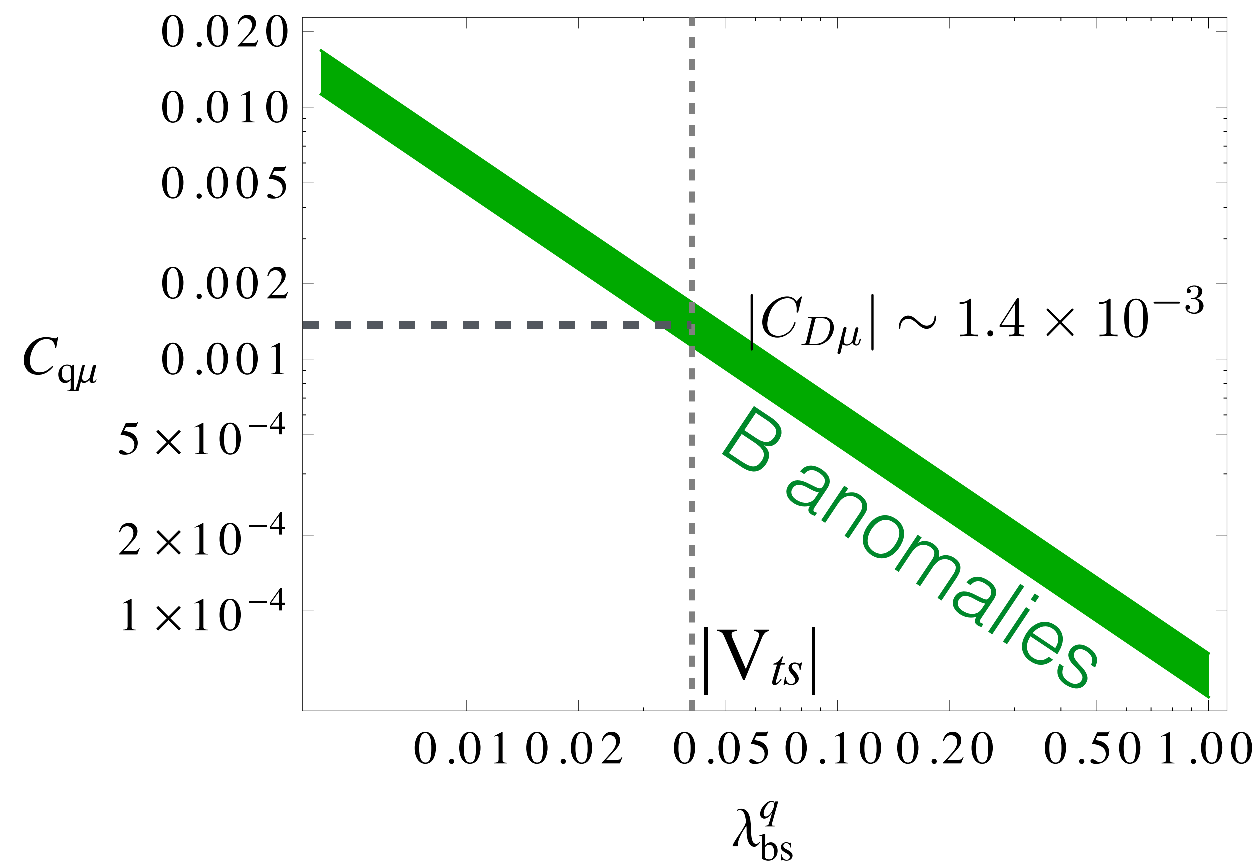

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Minimal Flavour Violation

Assumption: The only breaking of the SU(3)^5 flavour symmetry is via the SM Yukawas.

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$$|C_{bs\mu}| \sim |V_{tb} V_{ts}^* y_t^2 C_{D\mu}|$$

We get a prediction for $C_{D\mu}$ (which is tested by LHC)

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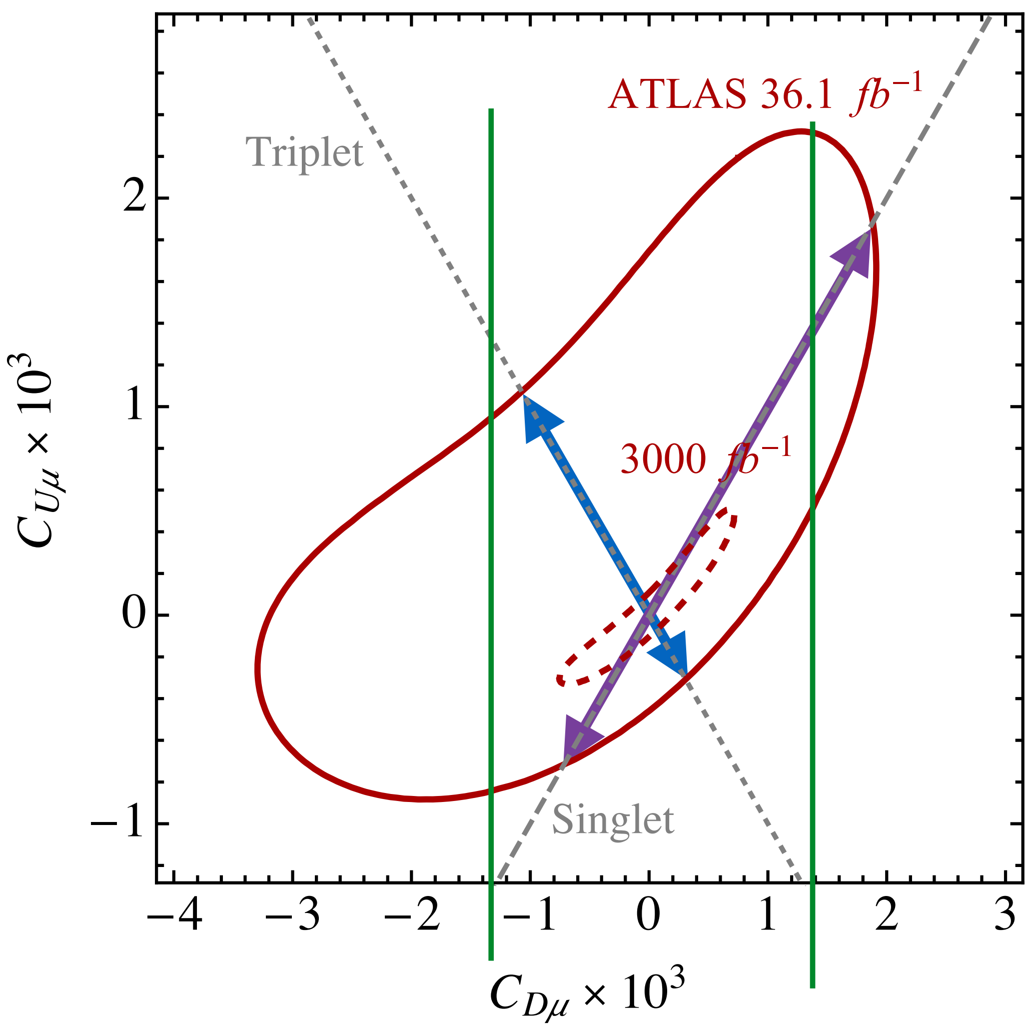

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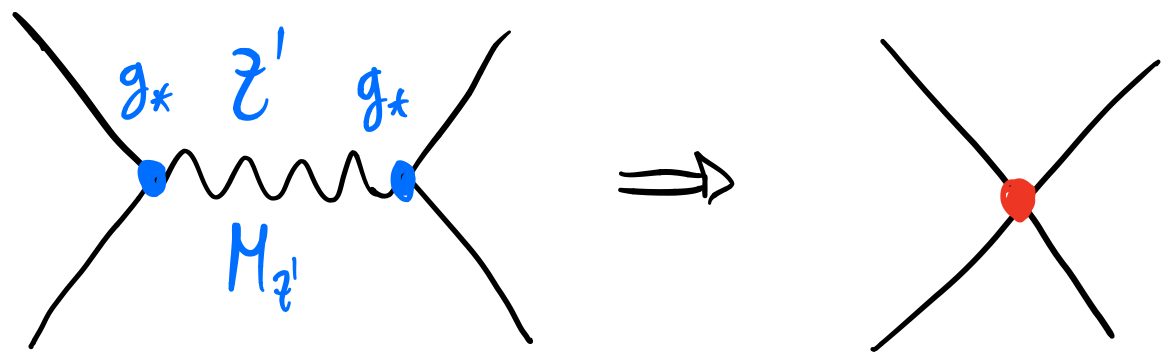
qqμμ operators with valence quarks are tested better than per-mille level.

The MFV solution is already in strong tension with LHC!

Compare to explicit model

Model with a **spin-1 singlet MFV Z'**.



$$\frac{C}{v^2} = -\frac{g_*^2}{M_{Z'}^2}$$

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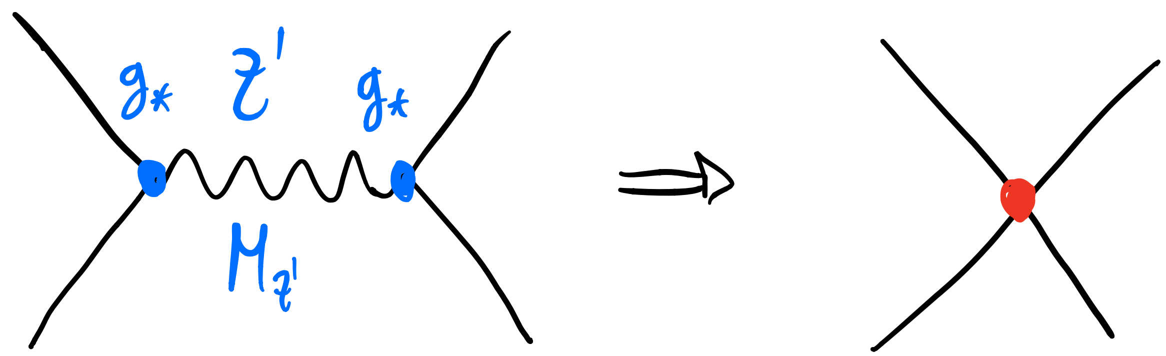
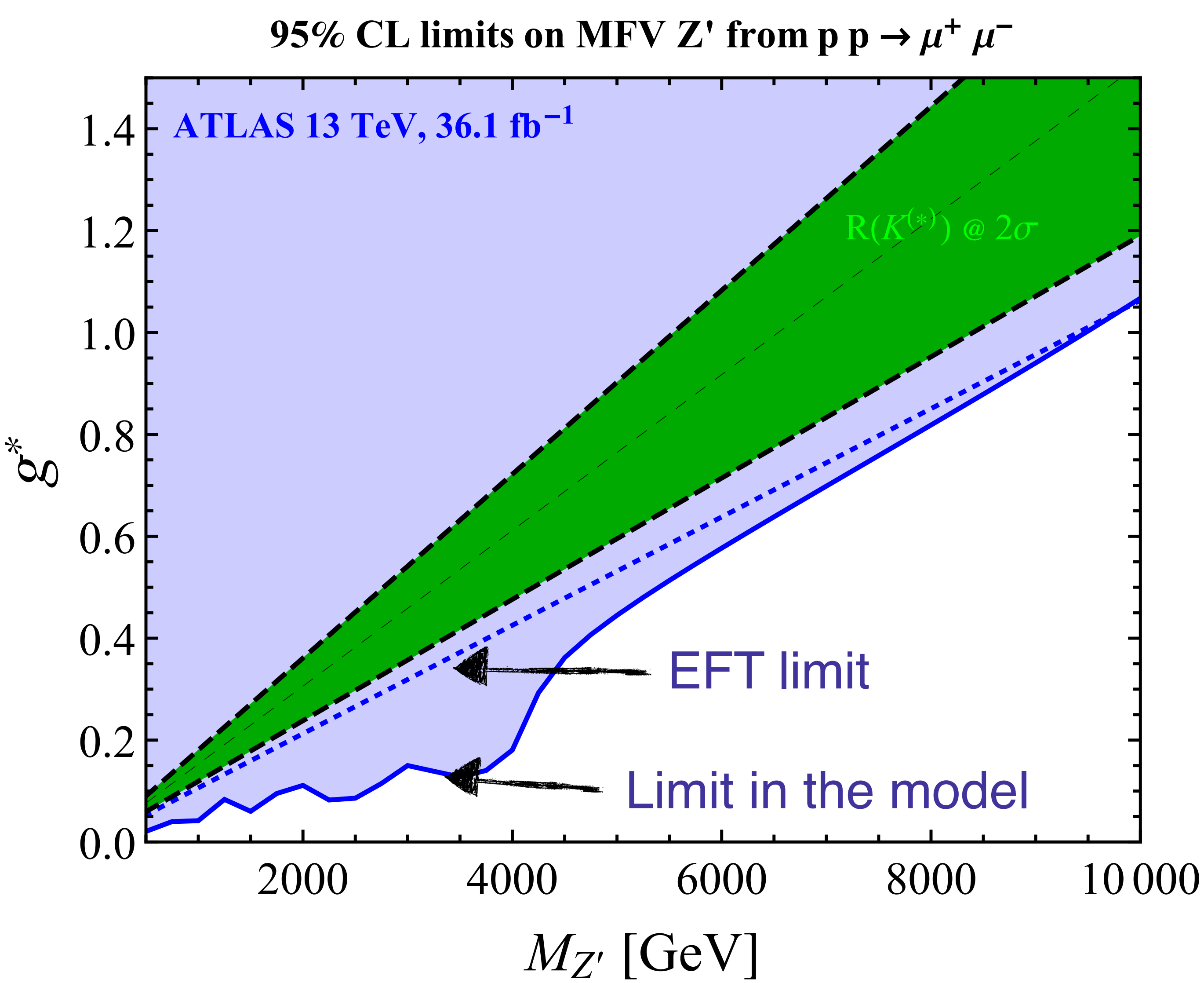


$$\frac{c}{v^2} = -\frac{g_*^2}{M_{Z'}^2}$$



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For $M_{Z'} \gtrsim$ **4-5 TeV** the EFT expansion is OK (still weak coupling).

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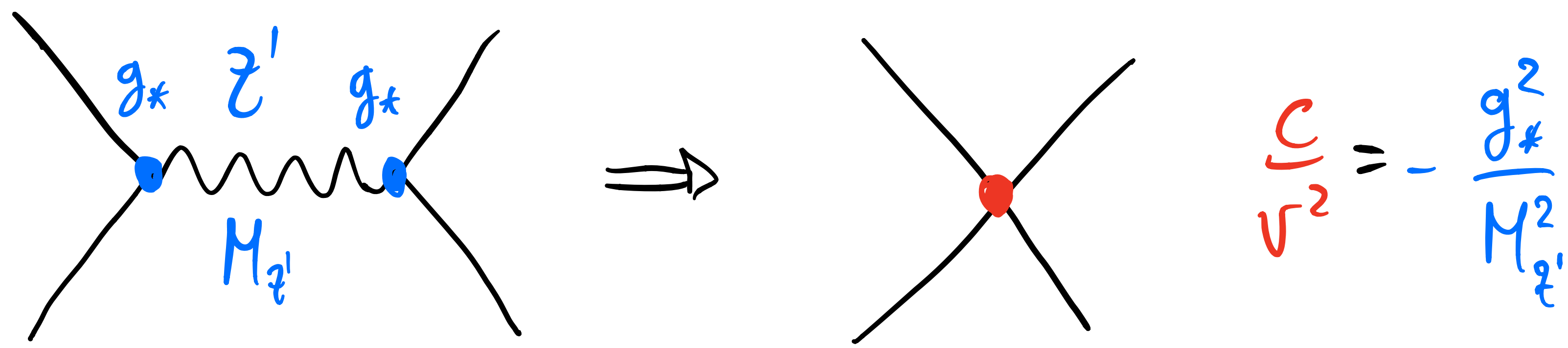

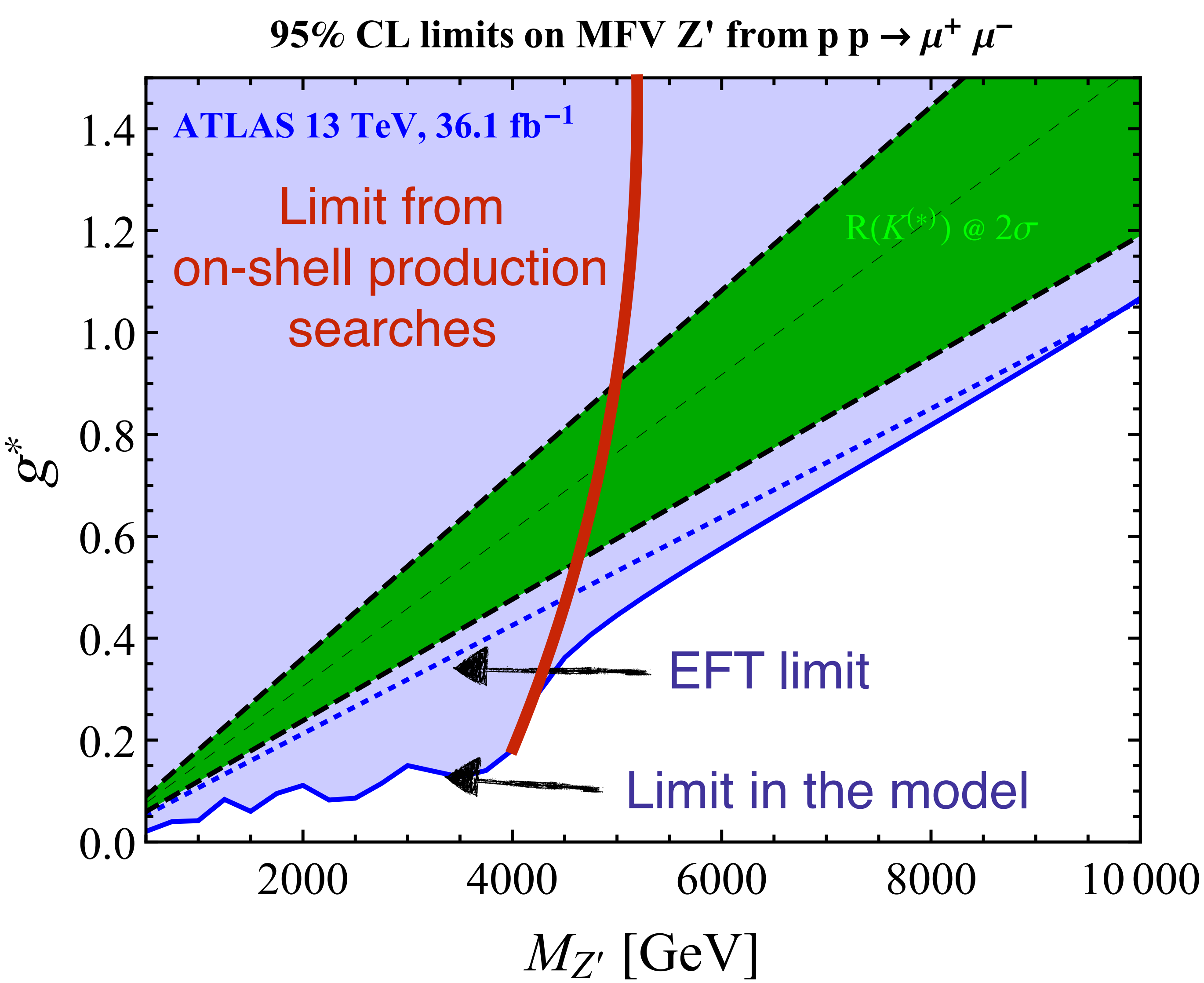

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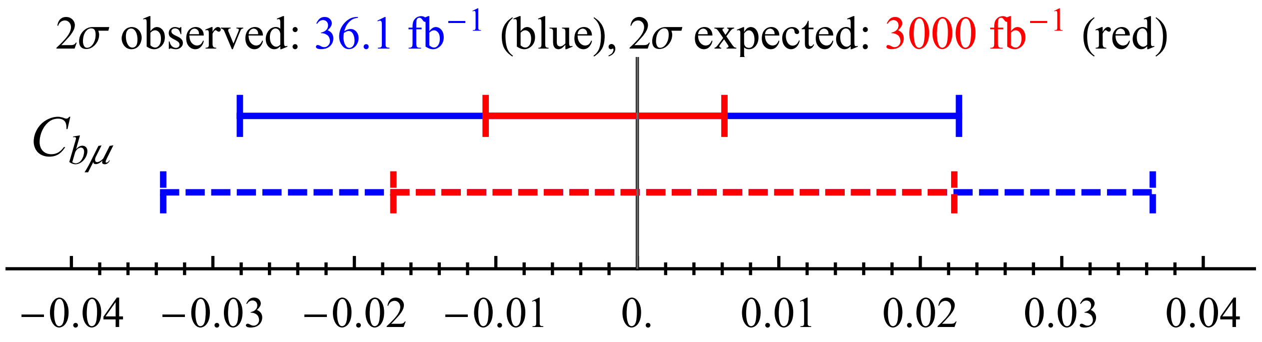
U(2) symmetry

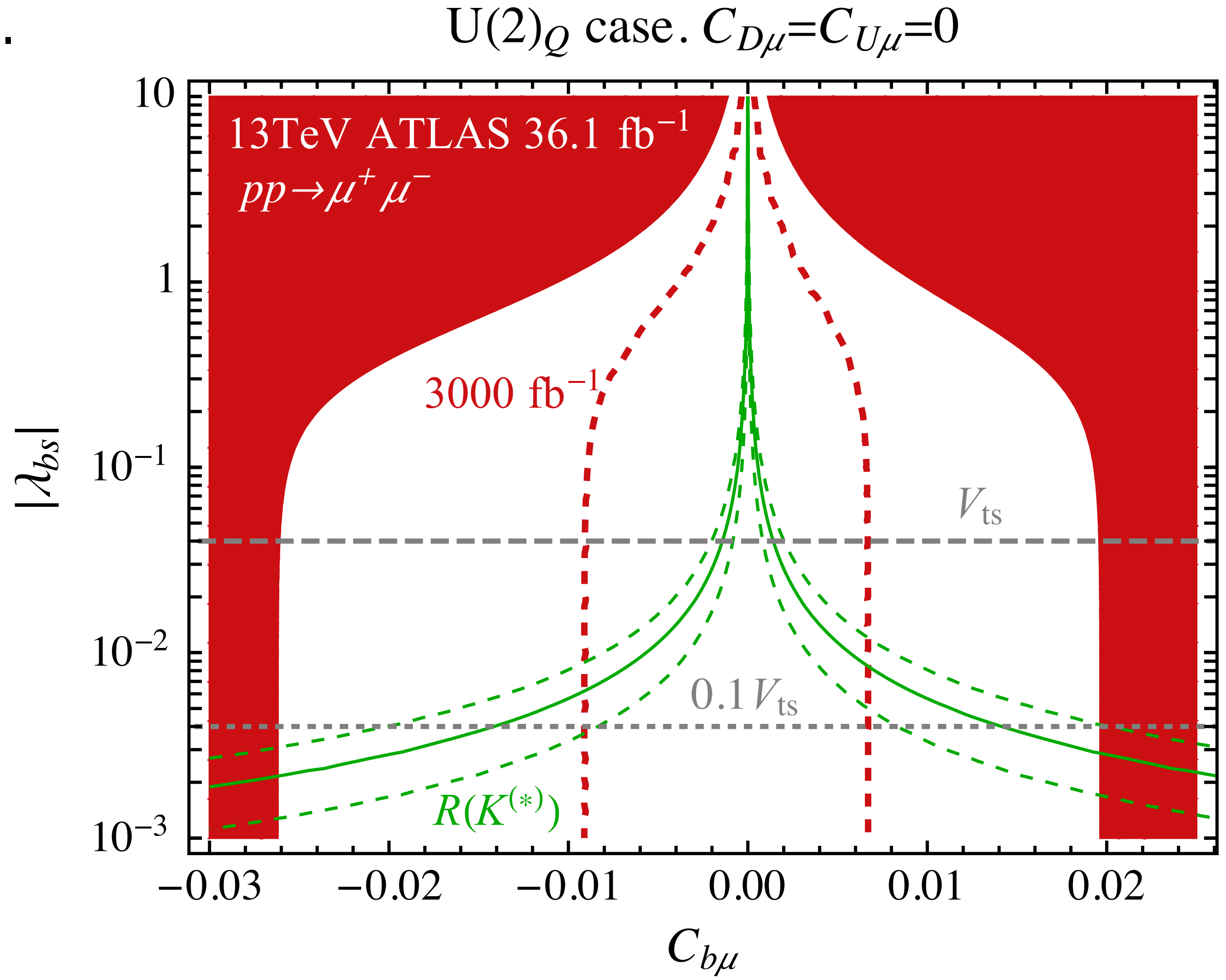
In this case one assumes that light generations do not couple directly to NP.
Only $C_{b\mu}$ is relevant

$$C_{bs\mu} \sim V_{ts}\, C_{b\mu} \longrightarrow C_{b\mu} \sim 1.4 \times 10^{-3}$$

The present and future limits on the bottom operator are instead at the percent level.



For general λ_{bs}



Conclusions

- LHC measurements of **high-p_T tails** of 2 → 2 processes offer **strong probes of new physics**,
  complementing (and often surpassing) limits derived from LEP.

- Care must be taken to understand the typical energy scale of the experiment and making sure that, at the interpretation level,

$$E_{exp} \ll \Lambda_{NP}$$

- This allows us to probe mass scales often higher than the reach of direct searches.

- The limits are already relevant for models addressing B-anomalies.

Thank you!

Backup