Connecting Flavor at Low and High p_T

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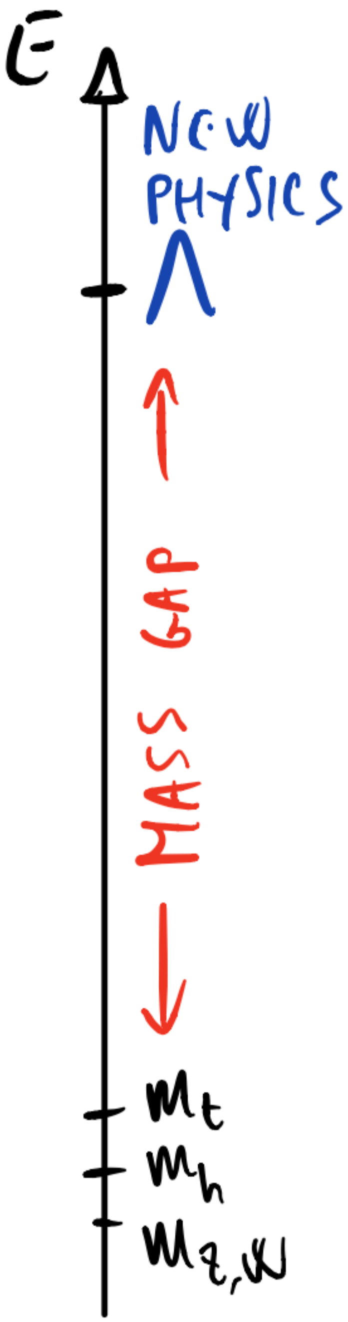
Indirect searches of New Physics

LHC strongly hints to the existence of a **mass gap** between the SM degrees of freedom and the (unknown) mass scale of new states.

Precision measurements can allow to test New Physics at scales not reachable by direct searches

$$E, m_Z \ll \Lambda$$

Indirect searches of New Physics



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$$E, m_Z \ll \Lambda$$

Effective Field Theories allow to describe the low-energy effects of heavy states — expansion in powers of $1/\Lambda$

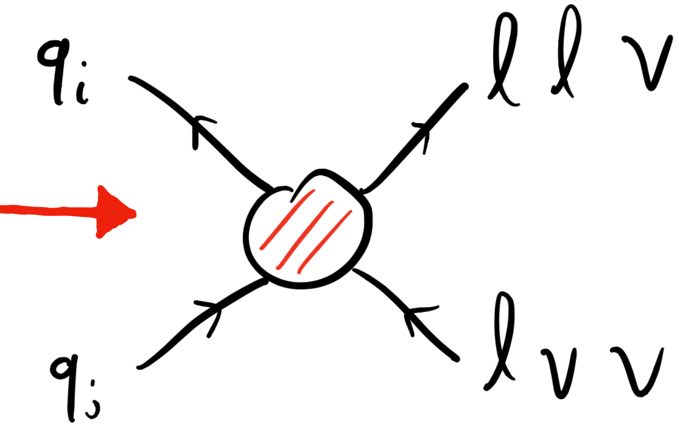
$$\mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \boxed{\sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \dots$$

For this talk, we focus on **four-fermion semi-leptonic** operators

$$\frac{C_{ij}}{\Lambda^2}\left(\bar{q}_i \Gamma_x q_j\right)\left(\bar{f}\Gamma_x f\right) \qquad f = \ell, \nu$$

Semi-leptonic New Physics

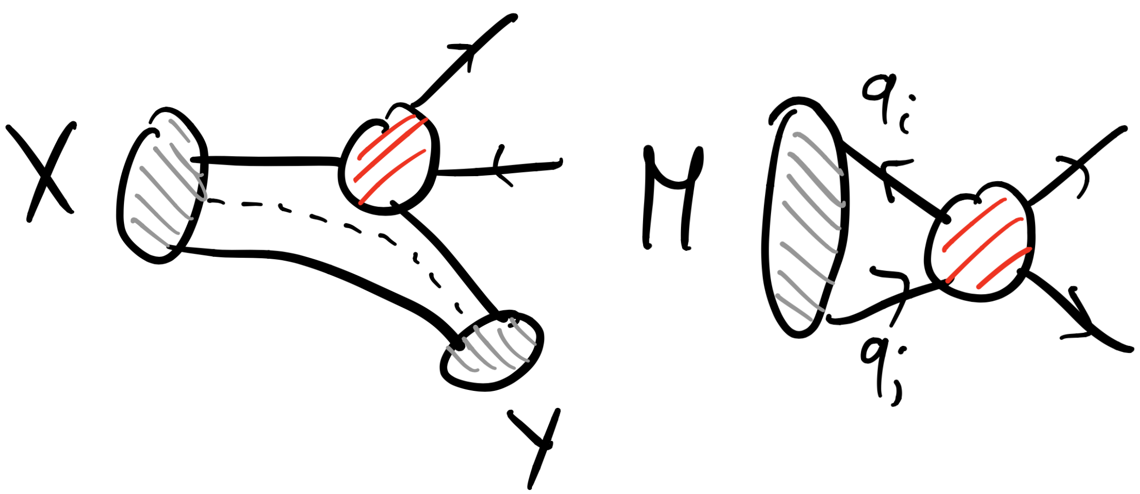
Contact interactions $\frac{c_{ij}}{\Lambda^2}\left(\bar{q}_i \Gamma_x q_j\right)\left(\bar{f}\,\Gamma_x f\right)$ $f = \ell, \nu$



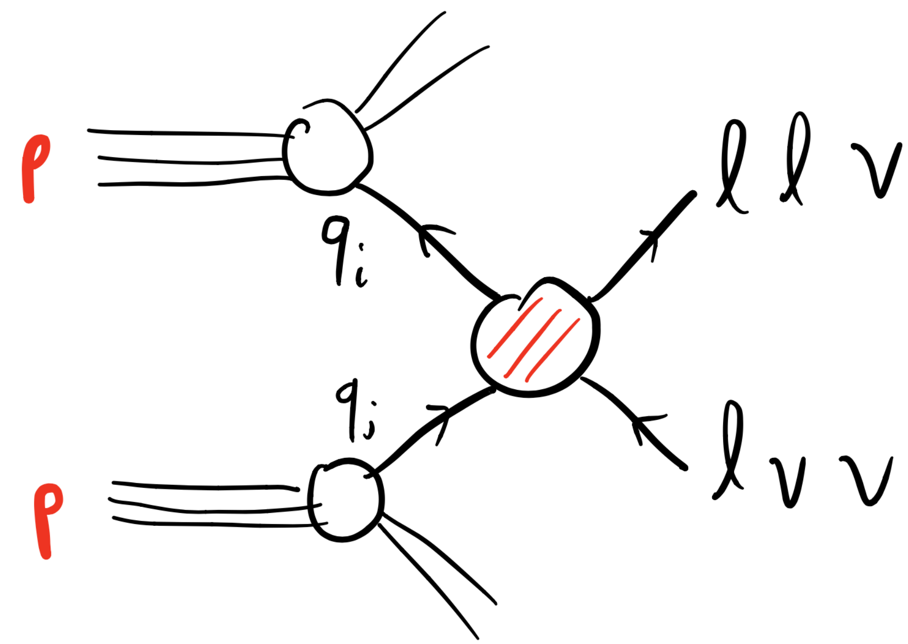
Can be probed at both low and high energies

(semi-)leptonic ΔF=1 decays

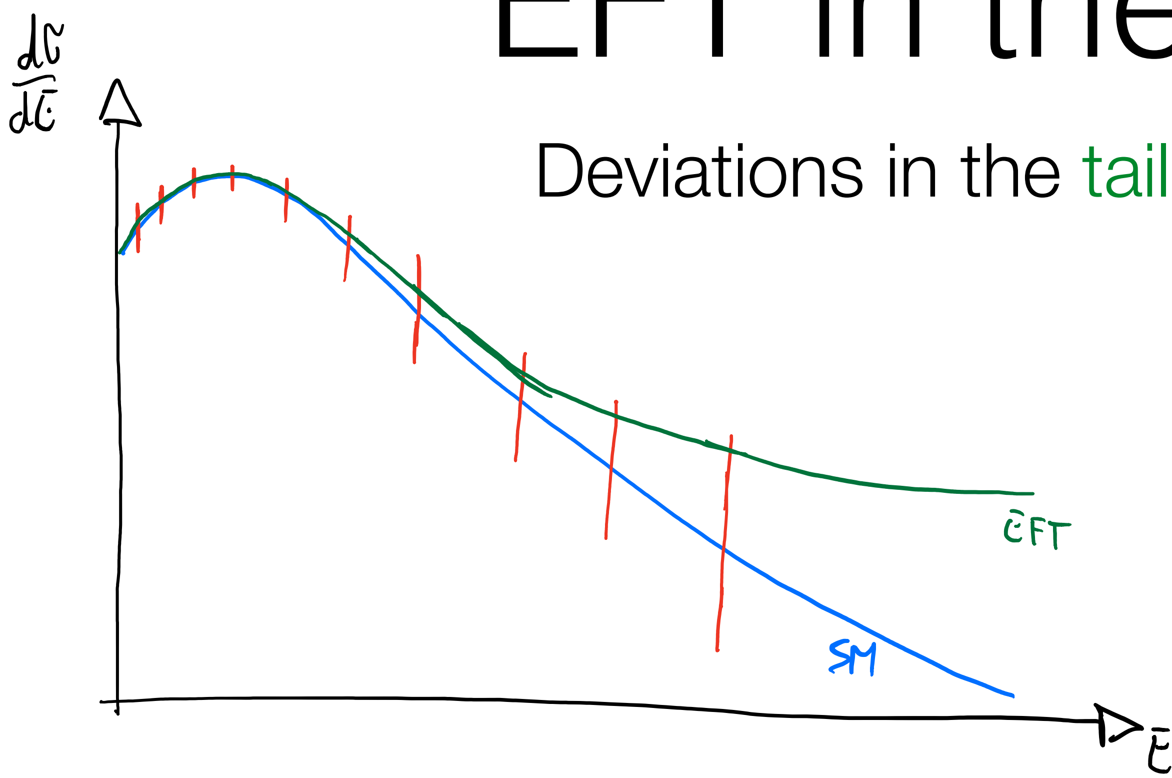
(CC and NC)



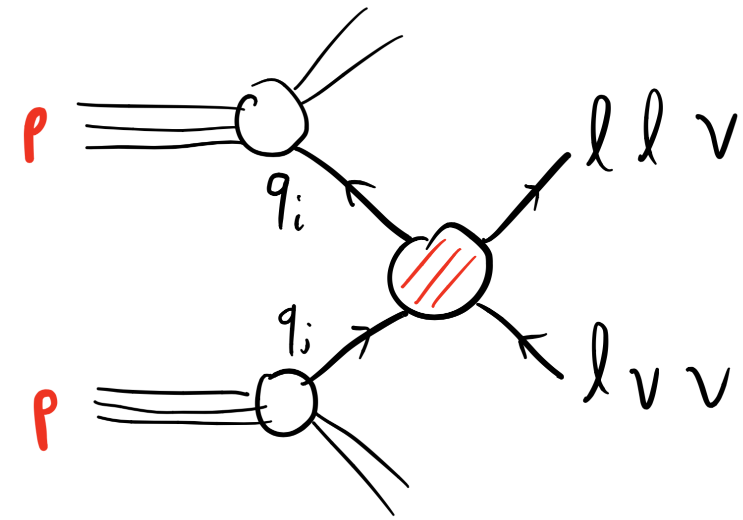
LHC High-pT tails



EFT in the high-pT tails



Deviations in the tails of differential distributions

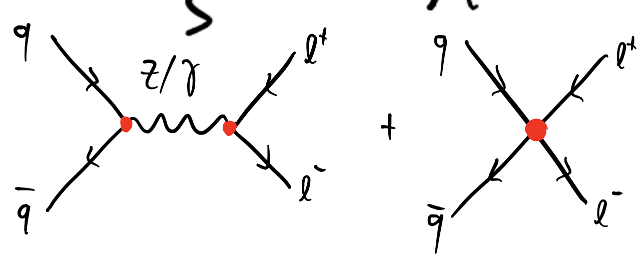


The **EFT contribution** to the scattering amplitude **grows with energy**, compared with the SM.

$\hat{s} \gg m_W^2$

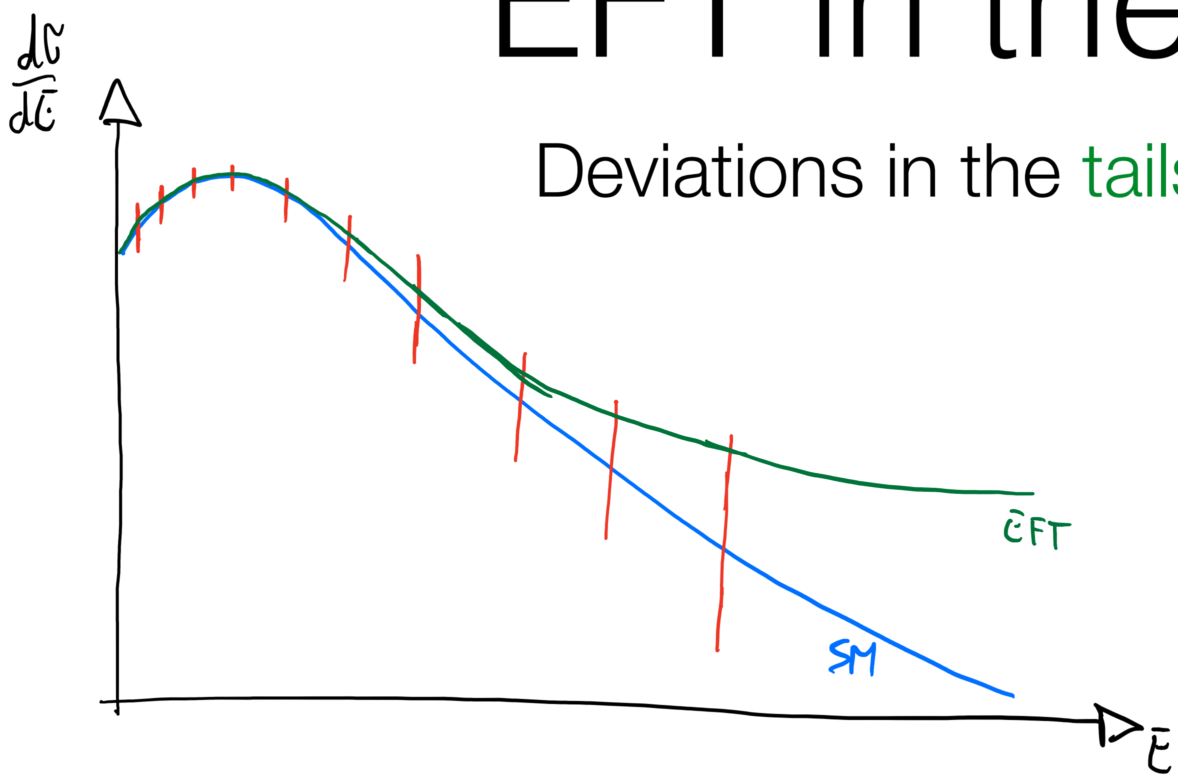
$$\mathcal{A} \sim \frac{g_{SM}^2}{\hat{s}} + \frac{C_{ij}}{\Lambda^2} \sim \mathcal{A}_{SM}\left(1 + \frac{C_{ij}}{g_{SM}^2}\frac{\hat{s}}{\Lambda^2}\right)$$

NP enhancement in high-pT tails

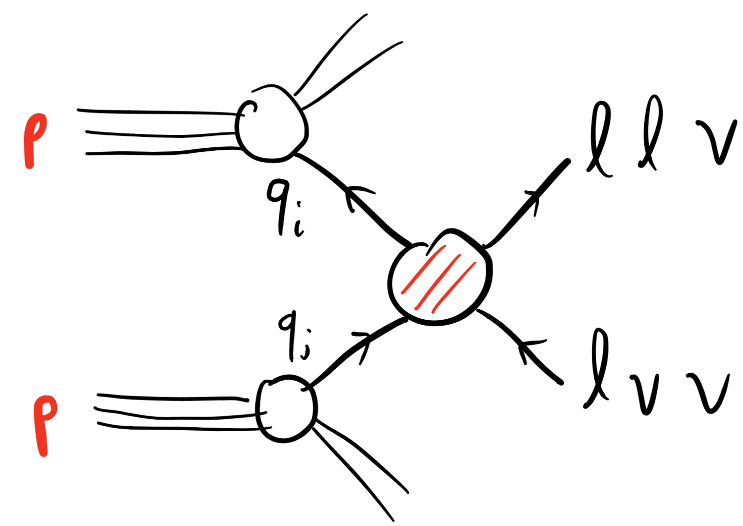


Less precise measurements at high energy can be competitive with very precise ones at low energy.

EFT in the high-pT tails



Deviations in the tails of differential distributions

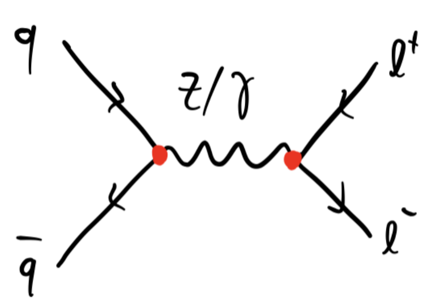


For the differential cross section we have, schematically:

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

Quark luminosity

SM partonic xsec (kinematics)



SM Z, γ, or W couplings $g^2 V_{ij}$ for CC

NP operators interfering with SM

NP operators not interfering with SM (e.g. scalar, tensor, flavor-violating)

EFT in the high-pT tails

With present accuracy, the limits are mainly driven by the **quadratic terms.** *

* see backup slides for implications regarding EFT validity.

Neutral current

$pp \to \ell^+ \ell^-$

Relative deviation from SM

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

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

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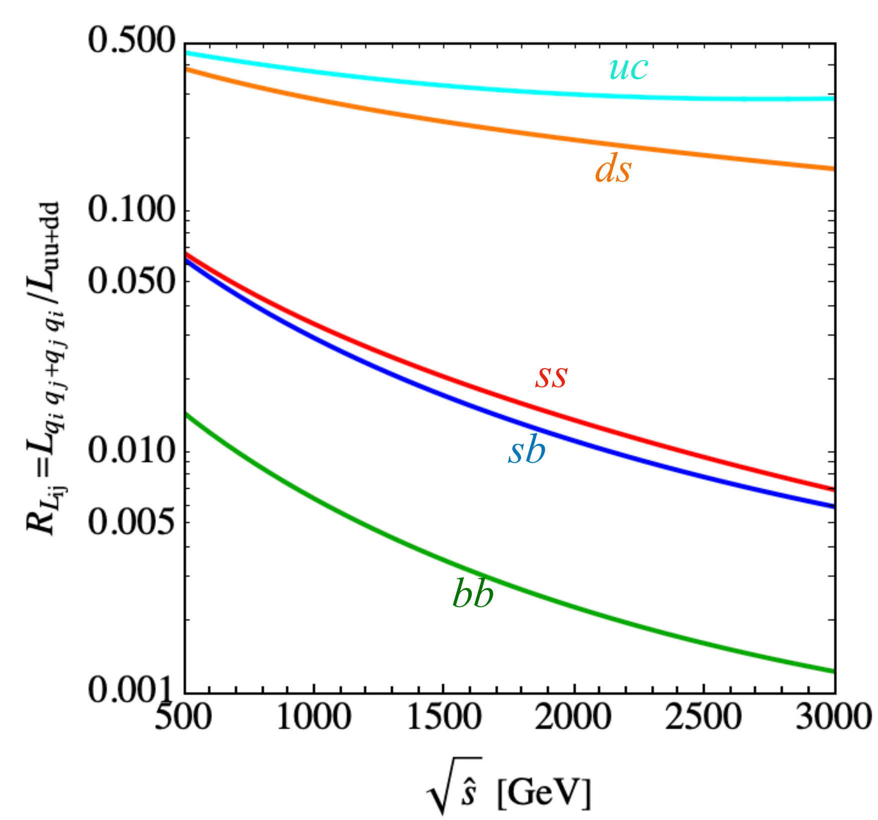
Estimating the reach

A back-of-the-envelope estimate of the bound can be obtained by the ratio of quark luminosities



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

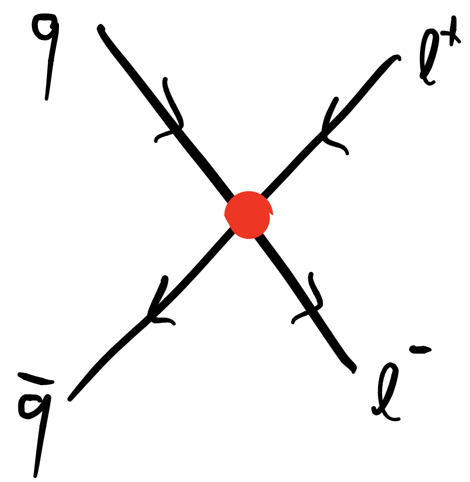
$\Delta\sigma/\sigma \lesssim 10\%$

$g_{SM} \sim 0.4$

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

Limits on semi-leptonic operators

NP above the TeV scale should satisfy SM gauge invariance,
thus the correct EFT to describe it is the SM EFT



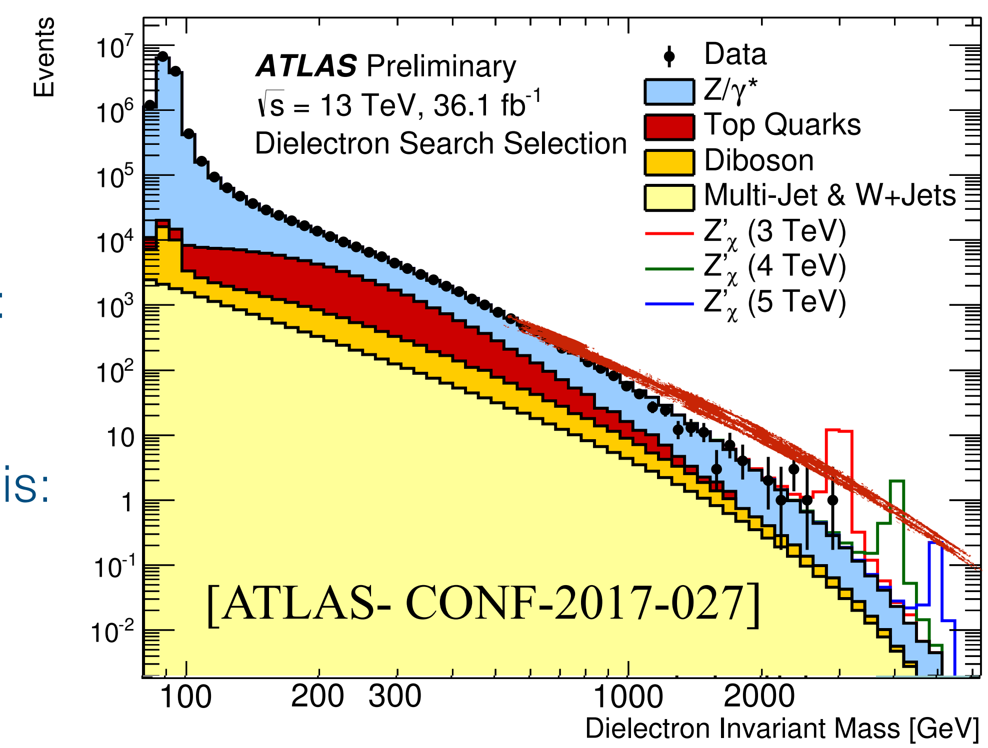
$$\mathcal{L}_{\text{SMEFT}} = \sum_i \frac{C_i}{v^2} \mathcal{O}_i$$

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

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]
- Limits including flavor-violation, recasting ATLAS Drell-Yan 8TeV analysis: [Les Houches 2002.12220 (Sec.2)]



Limits on semileptonic operators

[Greljo, D.M. 1704.09015, Les Houches 2002.12220 (Sec.2)]

Limits in the Warsaw basis, shown here one operator at a time.

No sizeable correlations since different operators do not interfere

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] $\times 10^{-5}$
$C_{u_R L^1}$	[-0.19, 1.92] $\times 10^{-3}$	[-1.56, 1.92] $\times 10^{-4}$
$C_{u_R e_R}$	[0.15, 2.06] $\times 10^{-3}$	[-7.89, 8.23] $\times 10^{-5}$
$C_{Q^1 e_R}$	[-0.40, 1.37] $\times 10^{-3}$	[-1.8, 2.85] $\times 10^{-4}$
$C_{d_R L^1}$	[-2.1, 1.04] $\times 10^{-3}$	[-7.59, 4.23] $\times 10^{-4}$
$C_{d_R e_R}$	[-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] $\times 10^{-4}$
$C_{Q^2 e_R}$	[-4.67, 6.34] $\times 10^{-3}$	[-2.11, 3.30] $\times 10^{-3}$
$C_{s_R L^1}$	[-7.4 , 5.9] $\times 10^{-3}$	[-3.96, 2.8] $\times 10^{-3}$
$C_{s_R e_R}$	[-8.17, 5.06] $\times 10^{-3}$	[-3.82, 2.13] $\times 10^{-3}$
$C_{c_R L^1}$	[-0.83, 1.13] $\times 10^{-2}$	[-3.74, 5.77] $\times 10^{-3}$
$C_{c_R e_R}$	[-0.67, 1.27] $\times 10^{-2}$	[-2.59, 4.17] $\times 10^{-3}$
$C_{b_L L^1}$	[-1.93, 1.19] $\times 10^{-2}$	[-8.62, 4.82] $\times 10^{-3}$
$C_{b_L e_R}$	[-1.47, 1.67] $\times 10^{-2}$	[-7.29, 8.99] $\times 10^{-3}$
$C_{b_R L^1}$	[-1.65, 1.49] $\times 10^{-2}$	[-8.86, 7.48] $\times 10^{-3}$
$C_{b_R e_R}$	[-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] $\times 10^{-5}$
$C_{u_R L^2}$	[-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] $\times 10^{-4}$
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$C_{s_R \mu_R}$	[-1.09 , 0.87] $\times 10^{-2}$	[-4.67, 2.73] $\times 10^{-3}$
$C_{c_R L^2}$	[-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] $\times 10^{-3}$
$C_{b_L L^2}$	[-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] $\times 10^{-3}$
$C_{b_R L^2}$	[-2.41, 2.29] $\times 10^{-2}$	[-9.90, 8.68] $\times 10^{-3}$
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$$C_x \equiv \frac{v^2}{\Lambda^2} c_x$$

Limits on semileptonic operators

[Greljo, D.M. 1704.09015, Les Houches 2002.12220 (Sec.2)]

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

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

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

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

Flavour in dimuon tails?

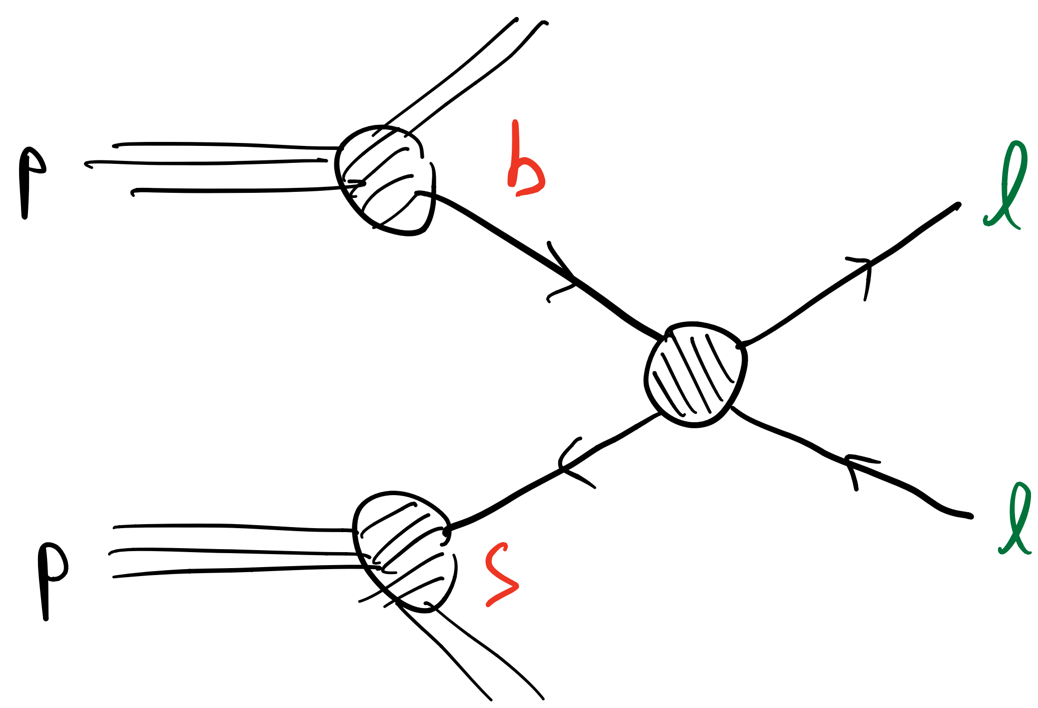
From $b \to s\mu\mu$ transitions
$B \to K^{(*)}\mu\mu$: $R(K^{(*)})$, P_5', ..

D'Amico et al. 1704.05438, Algueró et al. 1903.09578, Alok et al. 1903.09617, Ciuchini et al. 1903.09632, Aebischer et al 1903.10434, …

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

$\Lambda_{bs\mu} \sim 34$ TeV

Can we test this contact interaction directly at the LHC?



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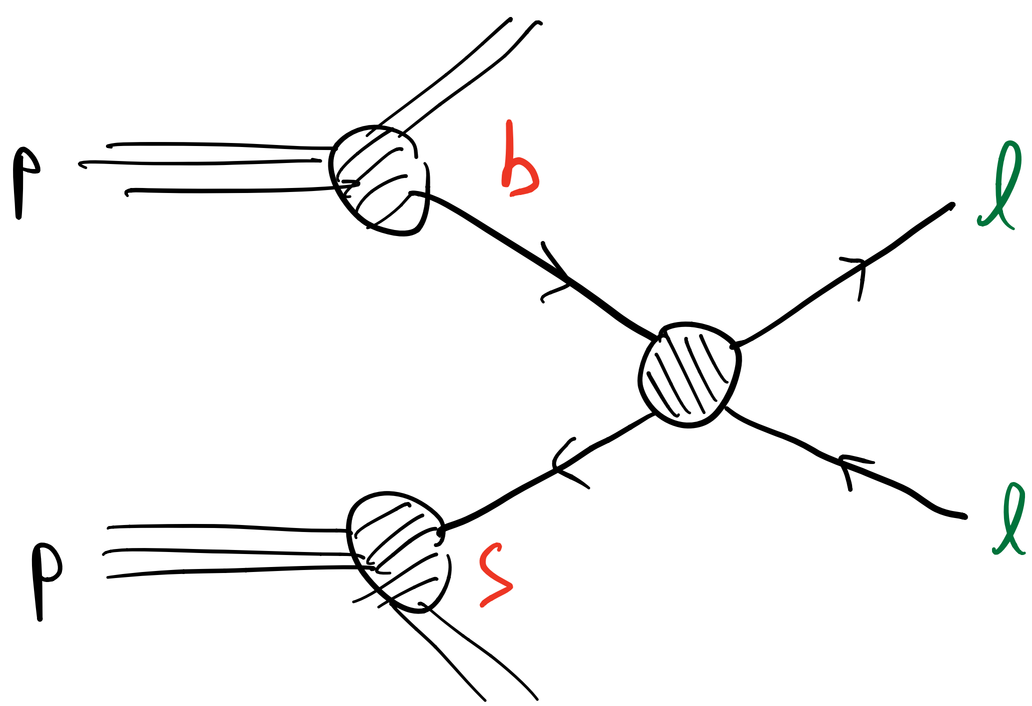


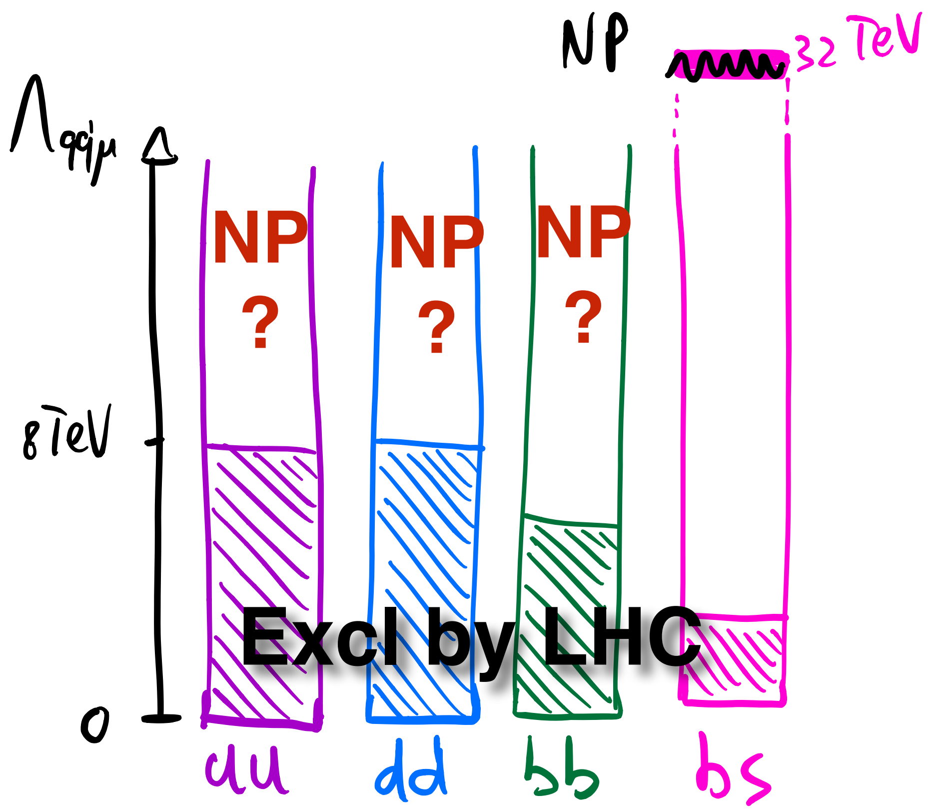
present (future 3ab^{-1}) limits:

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

[Greljo, D.M. 1704.09015,
See also Kohda et al. 1803.07492]

No hope to see this directly…. but…

Flavour in dimuon tails?

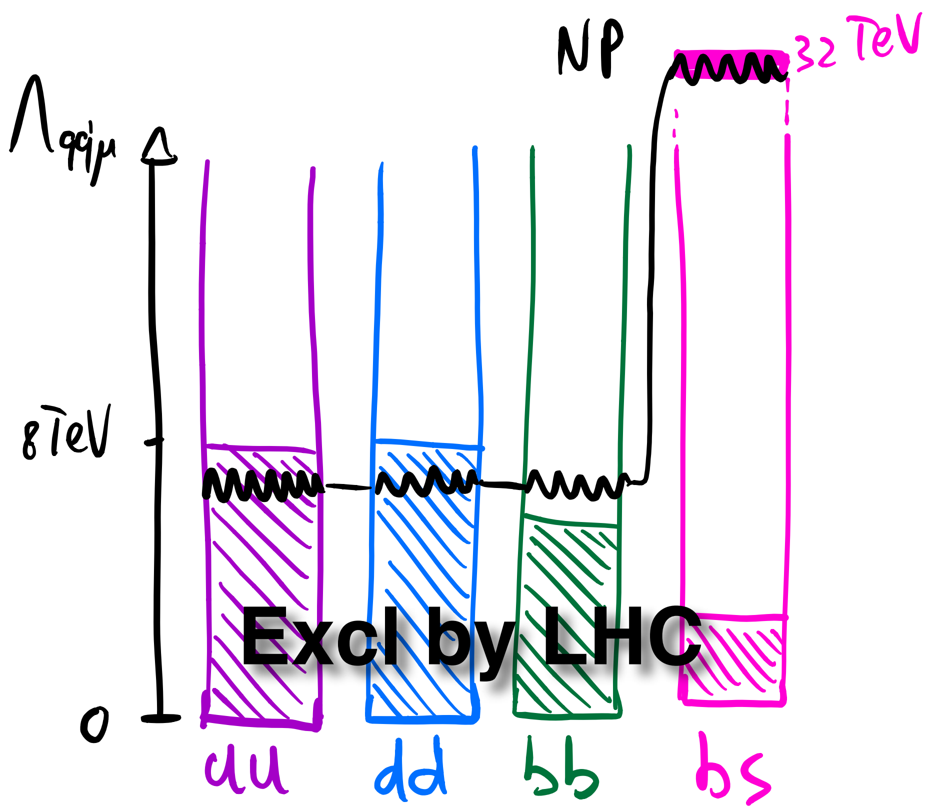


← New Physics for R(K(*))

In most flavour models, this flavour-violating operator is related to flavour-conserving ones via a small coupling

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

Flavour in dimuon tails?



← New Physics for R(K$^{(*)}$)

In most flavour models, this flavour-violating operator is related to flavour-conserving ones via a small coupling

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

$$\lambda^q_{bs} \ll 1 \longleftrightarrow \Lambda_{qq\mu} = \sqrt{\lambda^q_{bs}}\Lambda_{bs\mu} \ll \Lambda_{bs\mu}$$

The NP scale is much lower
In flavour-conserving channels

We can test models which relate the bs coupling to unsuppressed flavour-diagonal ones. e.g. $\lambda^q{}_{bs} \sim \mathrm{V}_{ts}$ in Minimal Flavor Violation

Minimal Flavour Violation

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

$$C_{bs\mu} = \frac{v^2}{\Lambda^2_{bs\mu}}$$ Fixed by R(K$^{(*)}$) fits

$$\mathcal{L} = \frac{C^{D\mu}_{ij}}{v^2}\left(\bar{d}^i_L \gamma_\mu d^j_L\right)\left(\bar{\mu}_L \gamma^\mu \mu_L\right)$$

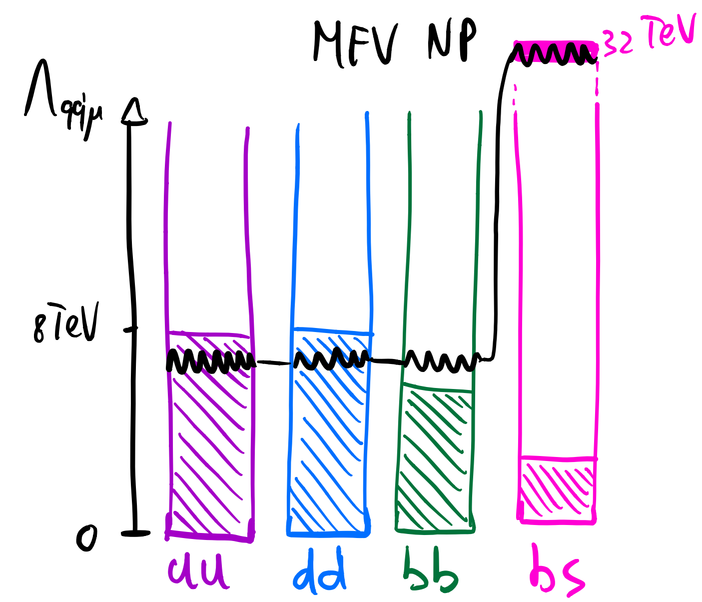
$$C^{D\mu}_{ij} \simeq C_{D\mu}\Big(\delta_{ij} + \overset{O(1)}{a^D}\left(Y_u Y_u^\dagger\right)_{ij} + \dots\Big)$$

$$\simeq C_{D\mu}\left(\delta_{ij} + a^D y_t^2 V_{ti} V^*_{tj} + \dots\right)$$

$$\boxed{|C_{bs\mu}| \sim |C_{D\mu} V_{tb} V^*_{ts}|}$$

We get a prediction for $C_{D\mu}$ (up to O(1) factors)

$$|C_{D\mu}| \sim 1.4 \times 10^{-3}$$
$$\Lambda_{D\mu} \sim 6.4\text{TeV}$$



Minimal Flavour Violation

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

$$C_{bs\mu} = \frac{v^2}{\Lambda^2_{bs\mu}}$$ Fixed by R(K$^{(*)}$) fits

$$\mathcal{L} = \frac{C^{D\mu}_{ij}}{v^2}\left(\bar{d}^i_L \gamma_\mu d^j_L\right)\left(\bar{\mu}_L \gamma^\mu \mu_L\right)$$

$$C^{D\mu}_{ij} \simeq C_{D\mu}\Big(\delta_{ij} + \overset{O(1)}{a^D}\left(Y_U Y_U^\dagger\right)_{ij} + \dots\Big) \simeq C_{D\mu}\left(\delta_{ij} + a^D y_t^2 V_{ti} V^*_{tj} + \dots\right)$$

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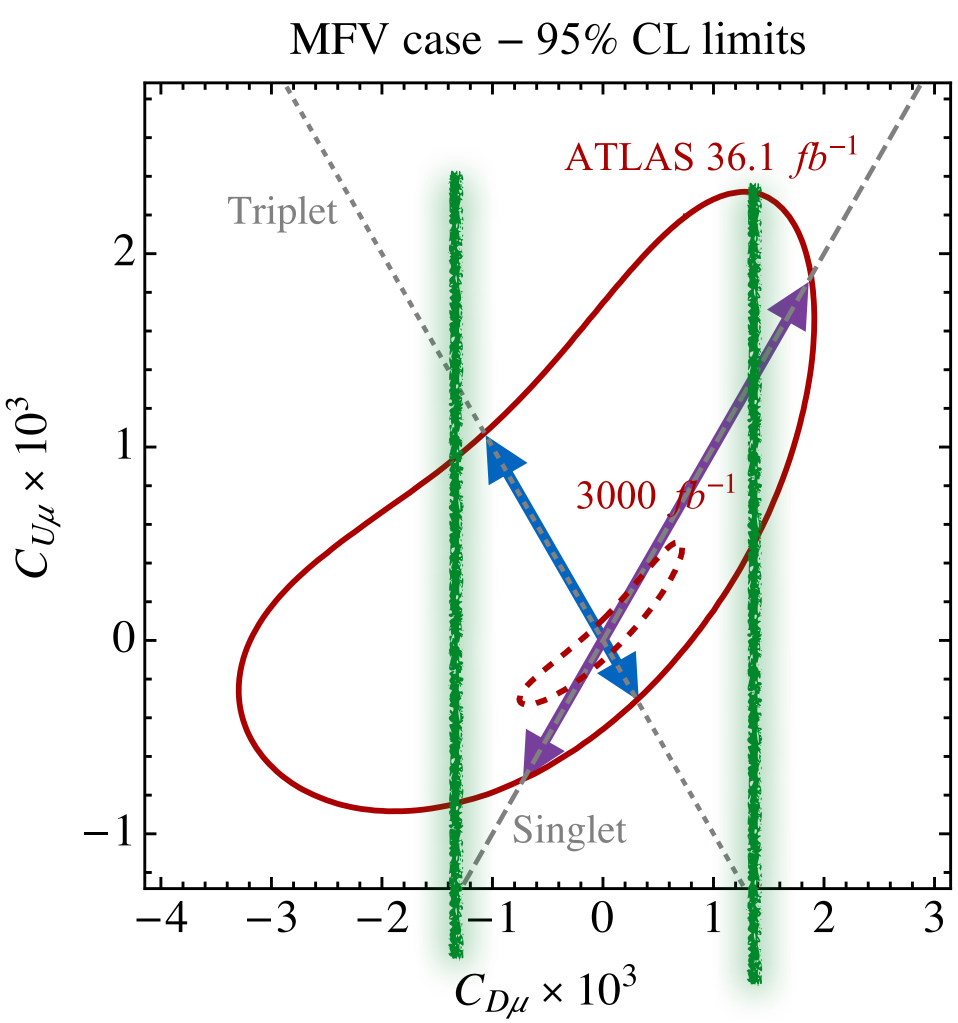

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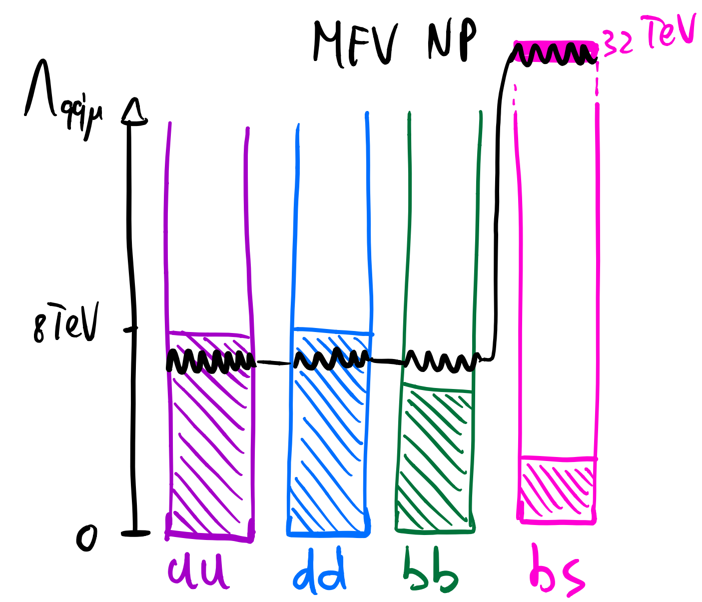
$$|C_{D\mu}| \sim 1.4 \times 10^{-3}$$
$$\Lambda_{D\mu} \sim 6.4\text{TeV}$$



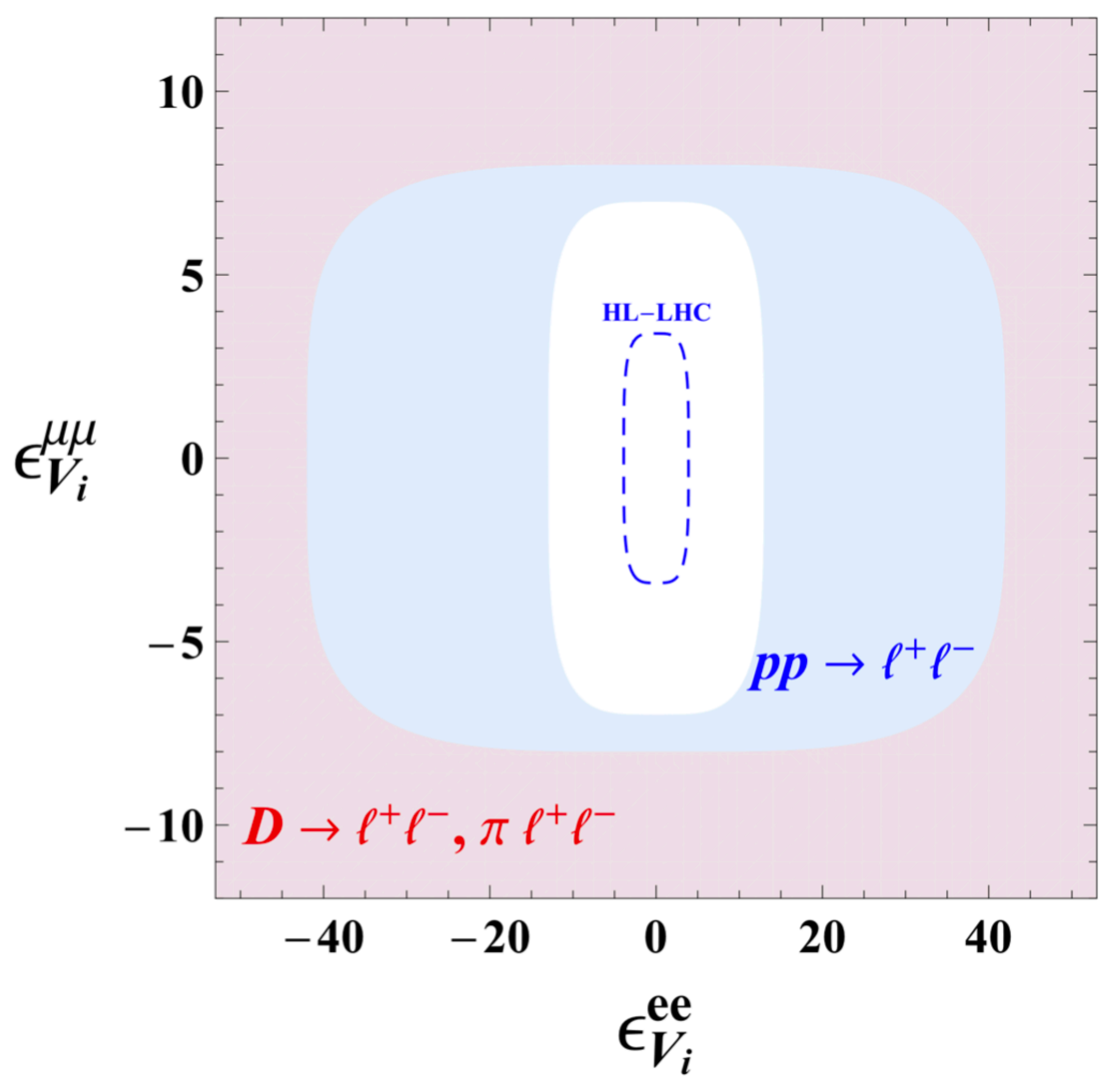
The MFV solution is already in tension with LHC!

Charm physics vs. dilepton tails

[Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez 2003.12421]

$c \longrightarrow u\, \ell^+ \ell^-$

Due to larger theory and experimental uncertainties, FCNC decays in charm are less precise than those in the Kaon or Bottom sector.



Limits from high-energy tails at LHC are thus competitive with those from decays,

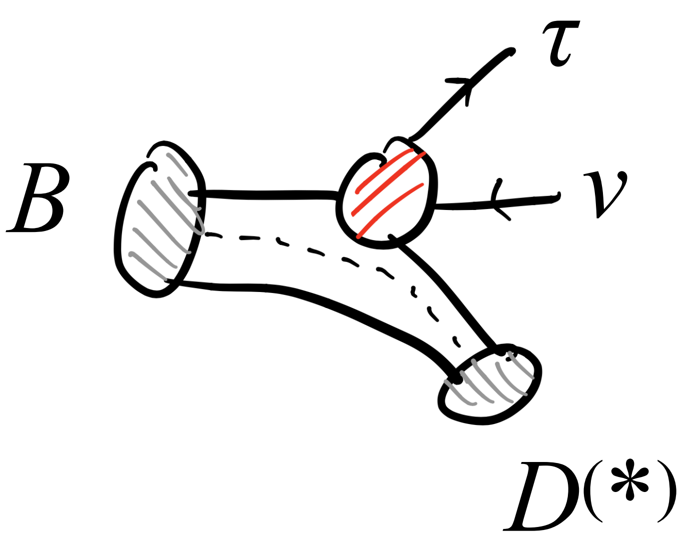
except in the case of scalar operators due to the chiral enhancement in leptonic D^0 decays.

Charged Current $\quad u_i\, d_i \to \tau\, \nu$

[Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez 1811.0792, 2003.12421; D.M., Min, Son, 2008.07541]

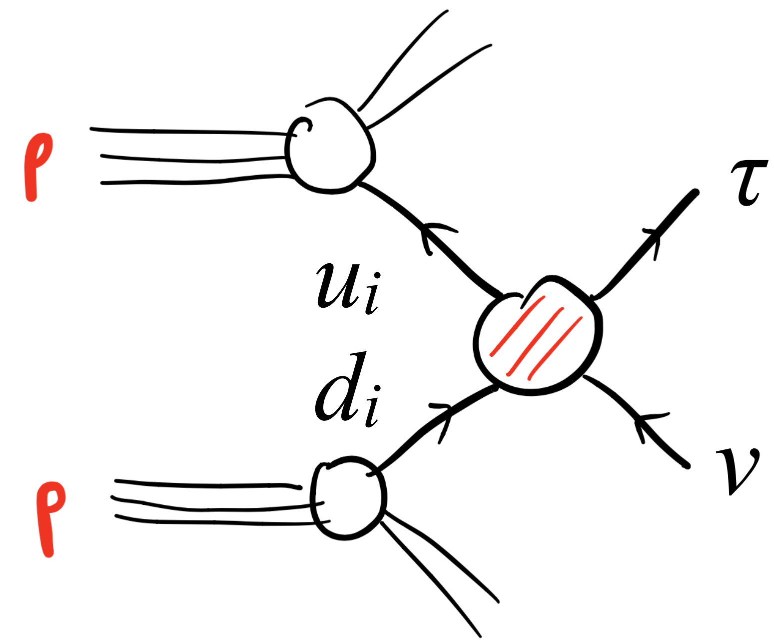
This channel is particularly interesting now due to the

connection with R(D(*))



$$\mathcal{L}_{\rm BSM} = \frac{2c}{\Lambda^2}(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau) + h.c.$$

if $c = 1 \quad \to \quad \mathbf{\Lambda_{R(D)} \sim 4.5\ TeV}$



Can LHC mono-tau tails test this?

$$\frac{\Delta\sigma}{\sigma_{SM}}(\hat{s}) \sim \frac{\mathcal{L}_{\bar{u}_i d_j} + \mathcal{L}_{\bar{d}_i u_j}}{\mathcal{L}_{\bar{u}d} + \mathcal{L}_{\bar{d}u}} \left| \frac{\epsilon_{ij} V_{ij}}{g^2_{SM} V_{ud}} \frac{\hat{s}}{v^2} \right|^2 \qquad \frac{C_{ij}}{\Lambda^2} = \frac{\epsilon_{ij} V_{ij}}{v^2}$$

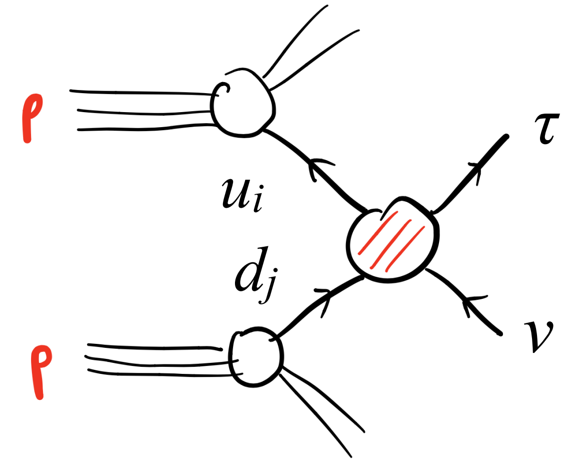
Mono-tau tails

[Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez 1811.0792, 2003.12421; D.M., Min, Son, 2008.07541]

LHC mono-tau tails probes all quark flavours except top.

Different flavours and chiralities do not interfere: can put limits on all operators.

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



Mono-tau tails

[Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez 1811.0792, 2003.12421; D.M., Min, Son, 2008.07541]

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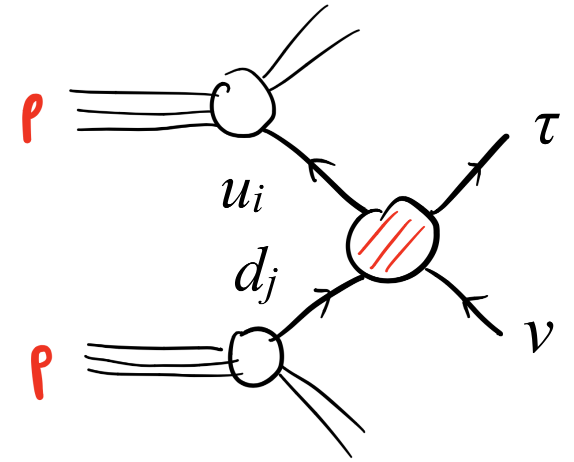
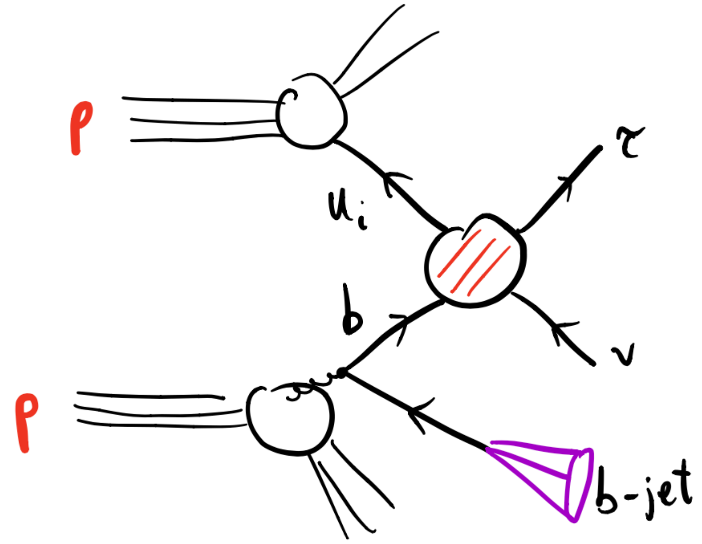


The sensitivity to operators involving a b-quark can be improved by adding a b-jet tagging.



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

How big is the improvement?

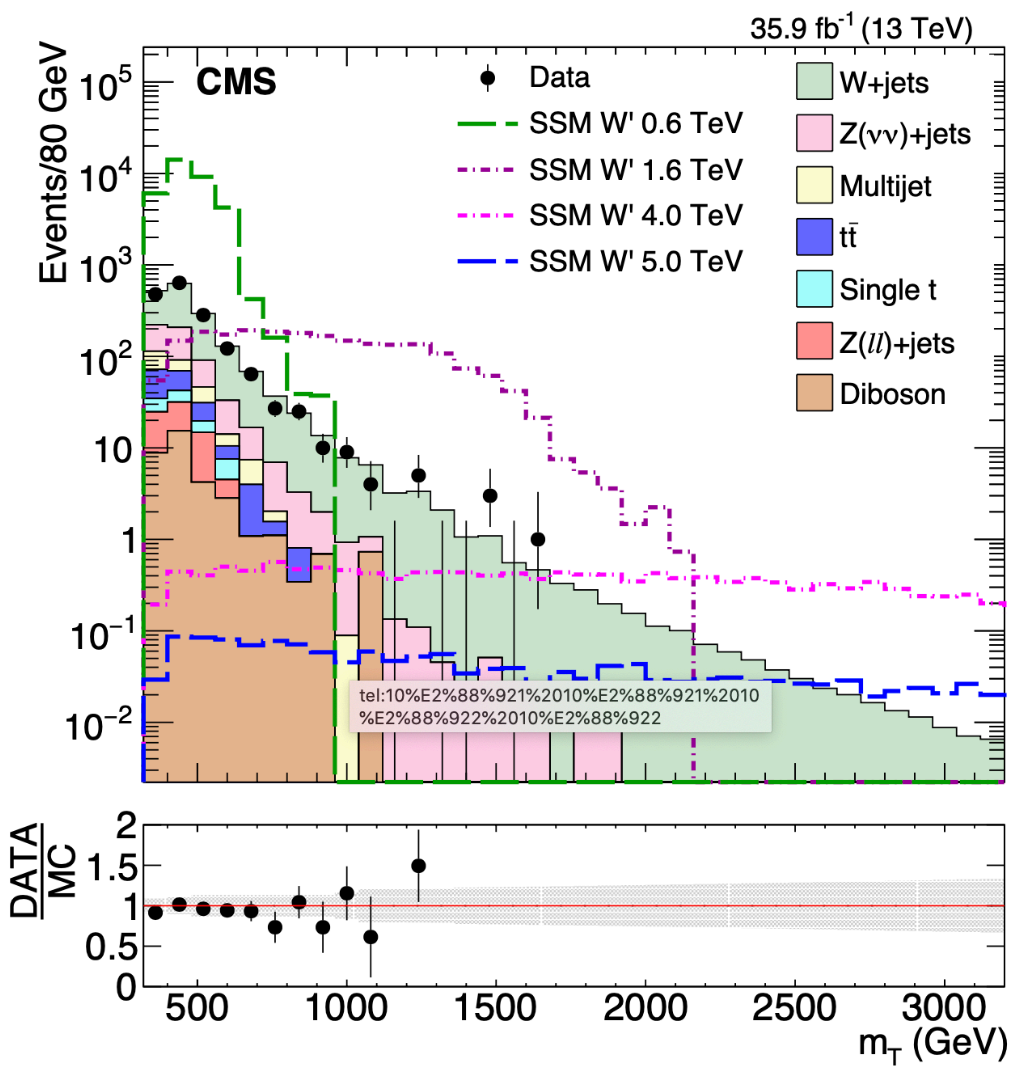
Analysis details

We recast CMS $\tau\nu$ analysis at 13 TeV and 35.9fb^{-1} [1807.11421]

$$p_T(\tau) > 80 \text{ GeV} \,, \quad |\eta(\tau)| < 2.1 \,, \quad p_T^{miss} > 200 \text{ GeV} \qquad 0.7 < p_T^\tau / p_T^{miss} < 1.3 \,, \quad \Delta\phi(\vec{p}_T^{\,\tau}, \vec{p}_T^{\,miss}) > 2.4$$

Bins in “transverse mass"

$$m_T = \sqrt{2 p_T^\tau p_T^{miss} [1 - \cos\Delta\phi(\vec{p}_T^{\,\tau}, \vec{p}_T^{\,miss})]}$$



For each bin we get the xsection:

$$\sigma = \sigma_{SM} + C_X^{ij}\, \sigma_{SM-EFT}^{ij,X} + (C_X^{ij})^2\, \sigma_{EFT^2}^{ij,X}$$

… which we use to build the likelihood

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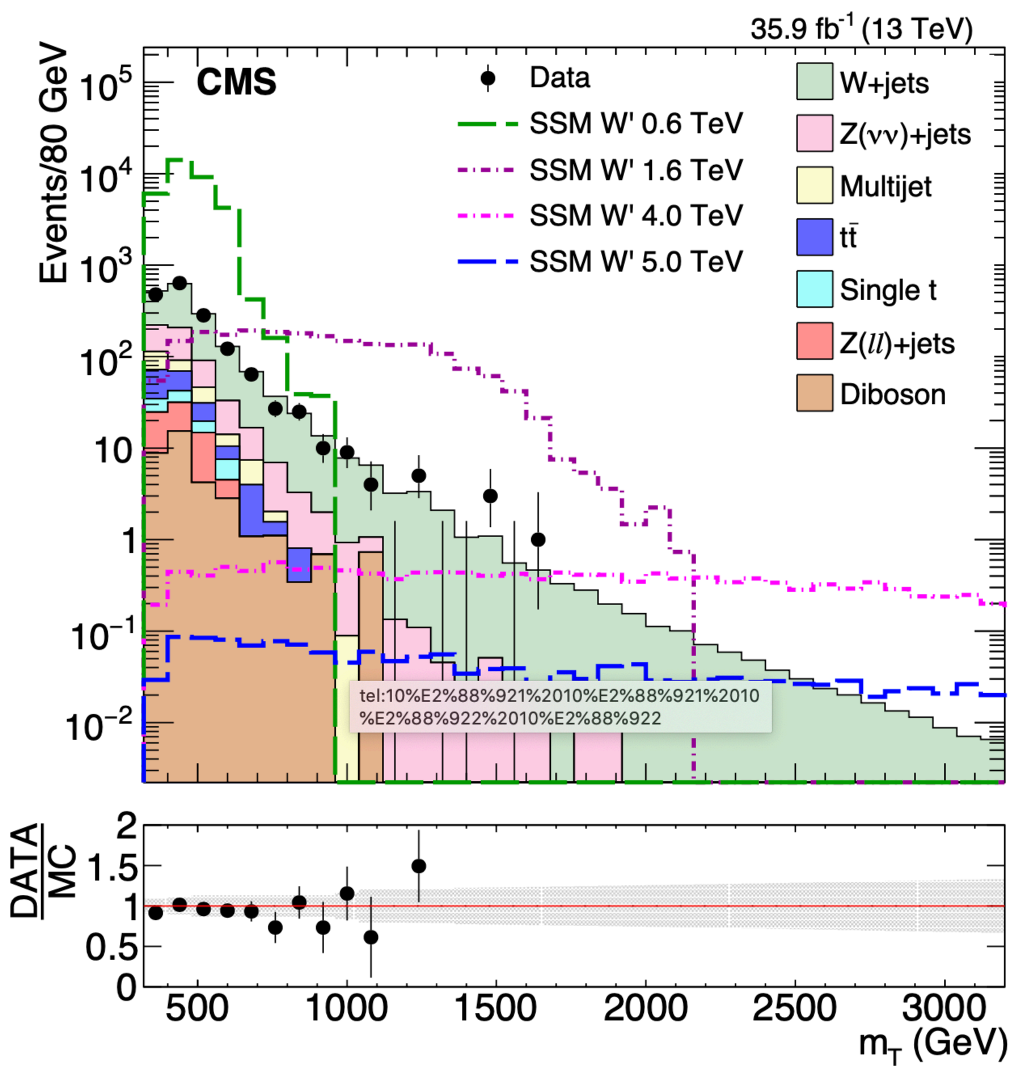

For each bin we get the xsection:

$$\sigma = \sigma_{SM} + C_X^{ij}\, \sigma_{SM-EFT}^{ij,X} + (C_X^{ij})^2\, \sigma_{EFT^2}^{ij,X}$$

… which we use to build the likelihood

After validating with CMS $\tau\nu$ analysis, we devise **our own $\tau\nu$+b analysis**

$$p_T(\tau) > 70\ \text{GeV}\ , \quad |\eta(\tau)| < 2.1\ , \quad p_T^{miss} > 150\ \text{GeV}$$

$$p_T(b) > 20\ \text{GeV}\ , \quad |\eta(b)| < 2.5\ , \quad N_j \leq 4$$

$$0.7 < p_T^\tau / p_T^{miss} < 1.3\ , \quad \Delta\phi(\vec{p}_T^{\,\tau}, \vec{p}_T^{\,miss}) > 2.4$$

EFT limits and prospects

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

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

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

By comparing

3rd and 4th columns:

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

EFT limits and prospects

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

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}
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$\lvert C_{SR}^{22}\rvert$	9.7×10^{-3}	7.5×10^{-3}	–
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$\lvert C_{T}^{11}\rvert$	8.5×10^{-4}	6.5×10^{-4}	–
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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

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

By comparing

3rd and 4th columns:

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

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

The best-fit for the anomaly is for

$$C_{VLL}^{cb}(\text{TeV}) = 0.068 \pm 0.017$$

In order to probe this directly HL-LHC and further optimisation is needed.

Flavor at Low vs. High Energy

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

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^{11}_{VLL}	$[-0.40, 3.2] \times 10^{-3}$	3.1×10^{-4}	–
C^{12}_{VLL}	$[-0.78, 1.1] \times 10^{-2}$	9.0×10^{-3}	–
C^{13}_{VLL}	$[-2.1, 2.1]$	1.6	0.93
C^{21}_{VLL}	$[-1.4, 1.8] \times 10^{-2}$	1.4×10^{-2}	–
C^{22}_{VLL}	$[-0.73, 1.2] \times 10^{-2}$	1.5×10^{-3}	–
C^{23}_{VLL}	$[-0.33, 0.34]$	$[-0.25, 0.26]$	$[-0.14, 0.15]$

$\tau \to \nu\pi$ $\quad C^{ud}_{VLL} \in [-9.2, 1.6] \times 10^{-3}$

$\tau \to \nu K$ $\quad C^{us}_{VLL} \in [-2.8, -0.02] \times 10^{-2}$

$B \to \tau\nu$ $\quad C^{ub}_{VLL}(m_b) \in [-0.13, 0.41]$

charm $\quad C^{cd}_{VLL} \in [-0.21, 0.27]$

$\quad C^{cs}_{VLL} \in [-1.4, 7.0] \times 10^{-2}$.

$R(D^{(*)})$ $\quad C^{cb}_{VLL}(\text{TeV}) = 0.068 \pm 0.017$

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

semileptonic τ decays [A. Pich 1310.7922]

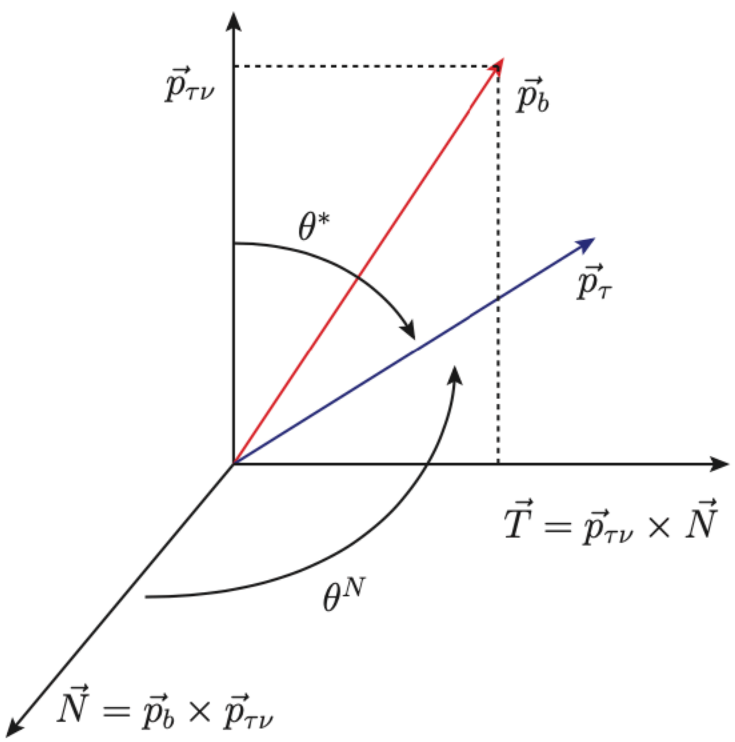
and **charm physics** [for more details on this see Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.12421]

Possible Future Improvements

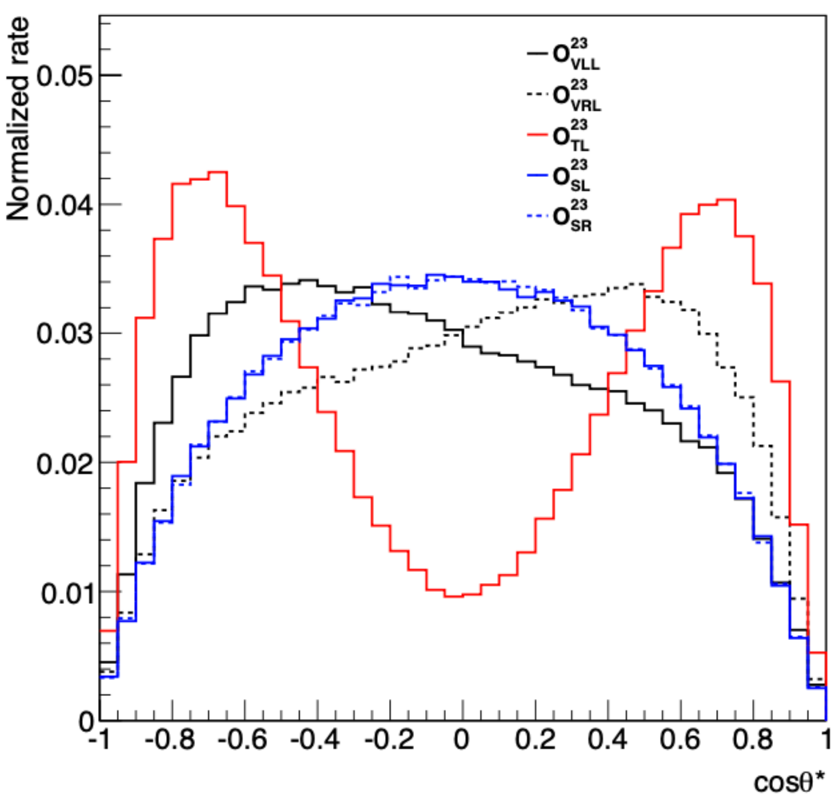
[D.M., Min, Son, 2008.07541]

LHC limits on mono-tau tails can be improved by
increased statistics and lower systematic (and theory) uncertainties,
finer binning at large mT,
and study of **angular distributions**:

$$pp \to \tau\, \nu\, b$$



From partonic events:



Conclusions

High-energy tails of scattering processes at LHC can provide strong tests for New Physics heavier than the direct-searches reach.

The limits in both neutral-current and charged-current channels are complementary with those coming from low-energy flavour measurements

Our recasts are available in terms of the general χ^2 functions of all EFT coefficients:

- $pp \to \mu\mu/ee$: ATLAS Drell-Yan analysis at 8TeV, 20.3fb^{-1} [https://arxiv.org/abs/2002.12220]
  https://people.sissa.it/~dmarzocc/dileptonATLAS8TeVchiSQ.zip
- $pp \to \tau\nu$: CMS 13TeV, 35.9fb^{-1} ancillary files in arXiv https://arxiv.org/abs/2008.07541

Backup

EFT Validity

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

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

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

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

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

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

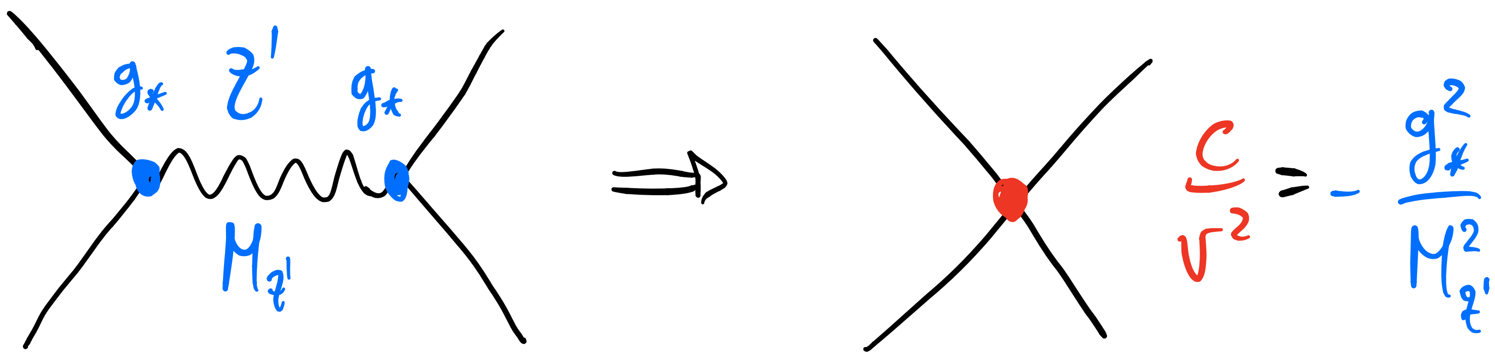
The dim-8 interference is necessarily smaller than dim-6 interference if $C^{(8)} \lesssim C^{(6)}$

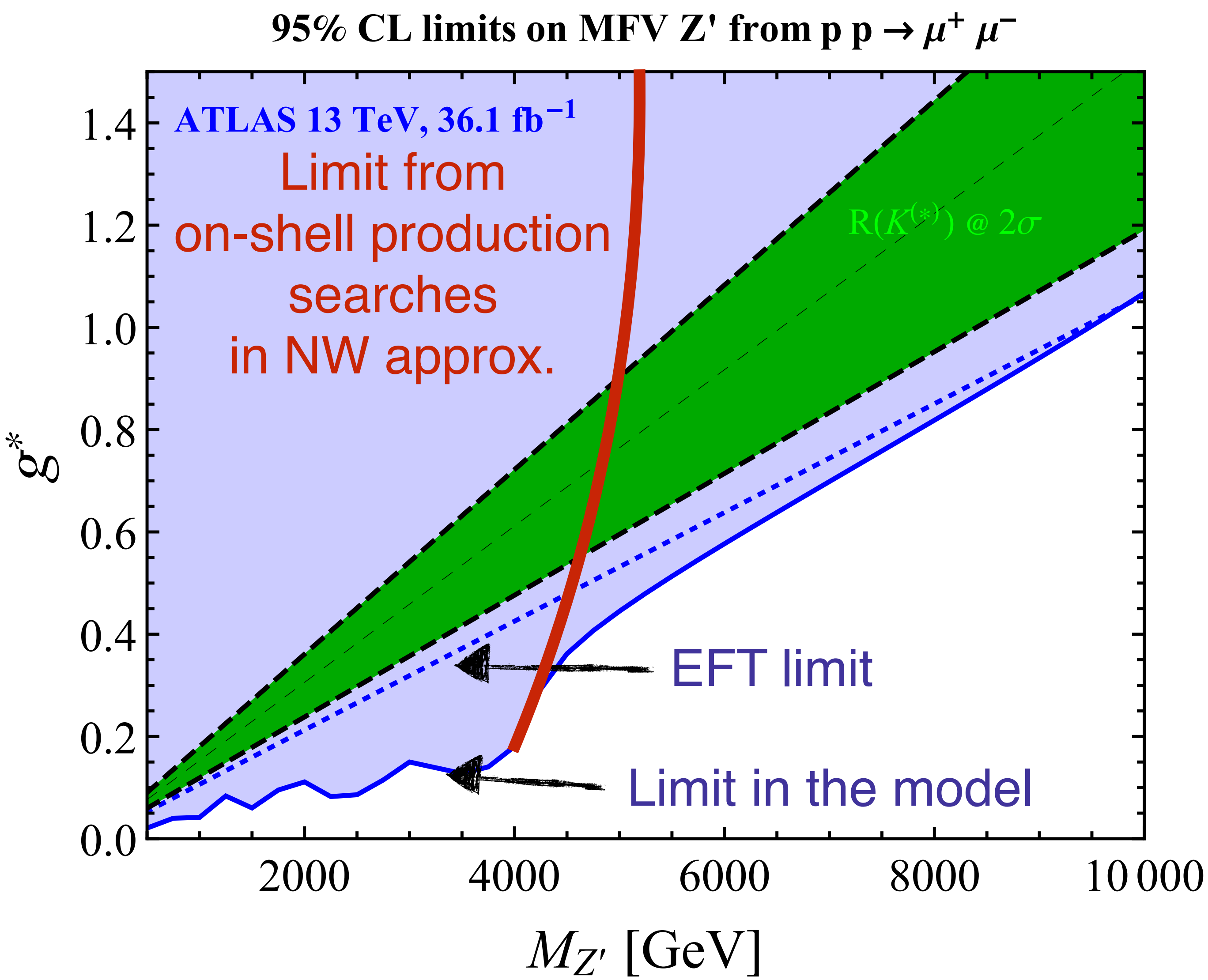
since $s \ll M_{NP}^2$. For a single mediator $C^{(8)} = C^{(6)} \sim g_{NP}^2$

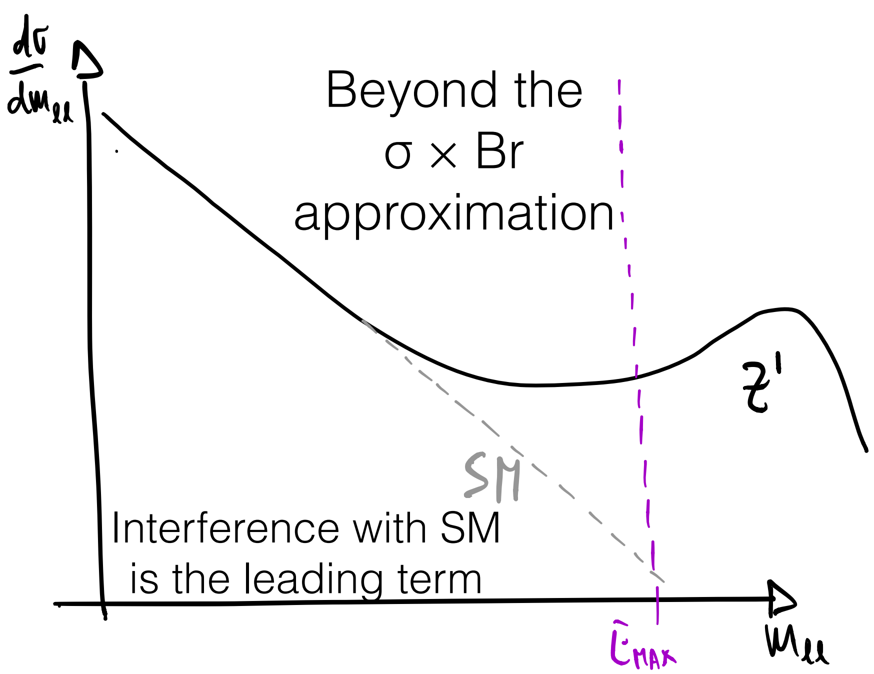
[See discussion in Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez 2003.12421]

Compare to explicit model

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







Such an explanation of the anomalies, with $\lambda_{bs} = V_{ts}$, is **excluded for any mass**.

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

EFT in the high-pT tails

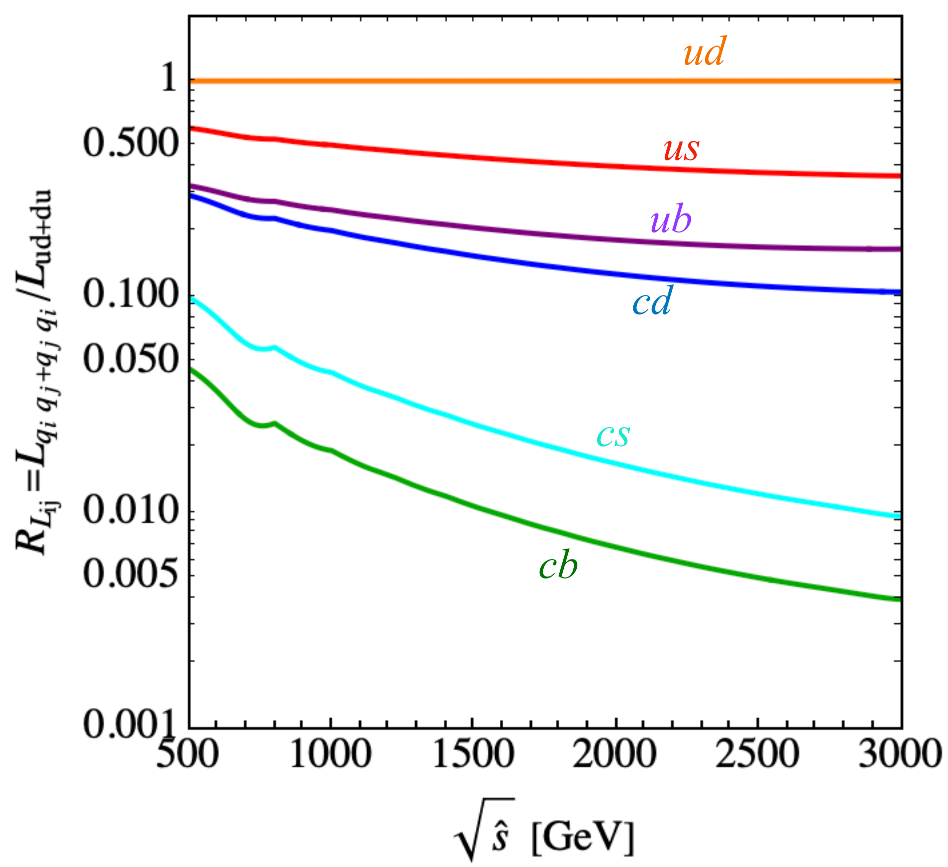
Estimating the reach

Presently, the limits are dominated by the quadratic terms.

Charged-current

$pp \to \ell \nu$

$$\frac{\Delta\sigma}{\sigma_{SM}}(\hat{s}) \sim \frac{\mathcal{L}_{\bar{u}_i d_j} + \mathcal{L}_{\bar{d}_i u_j}}{\mathcal{L}_{\bar{u} d} + \mathcal{L}_{\bar{d} u}} \left| \frac{\epsilon_{ij} V_{ij}}{g^2_{SM} V_{ud}} \frac{\hat{s}}{v^2} \right|^2 \qquad \frac{C_{ij}}{\Lambda^2} \equiv \frac{\epsilon_{ij} V_{ij}}{v^2}$$



SMEFT limits

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

NP above the TeV scale should satisfy SM gauge invariance.

Operator in the SMEFT framework (we use the Warsaw basis)

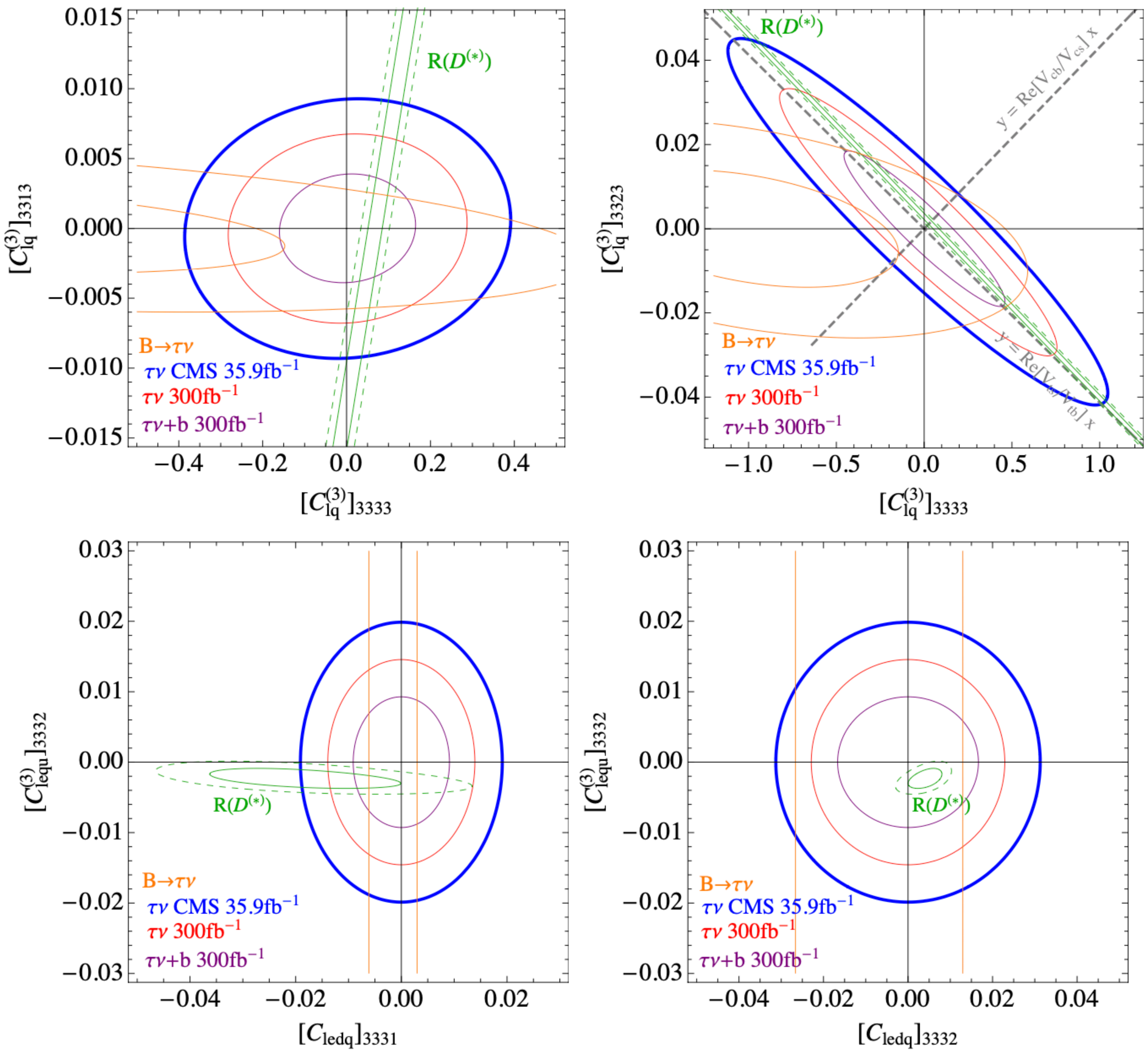
SMEFT coeff.	CMS ($\mathcal{L}$=35.9 fb^{-1})	$\tau\nu$ - $\mathcal{L}$=300 fb^{-1}	$\tau\nu b$ - $\mathcal{L}$=300 fb^{-1}
$[C_{lq}^{(3)}]_{3311}$	$[-0.39, 3.2] \times 10^{-3}$	3.1×10^{-4}	–
$[C_{lq}^{(3)}]_{3312}$	$[-1.1, 2.6] \times 10^{-3}$	$[-0.85, 2.2] \times 10^{-3}$	–
$[C_{lq}^{(3)}]_{3313}$	$[-7.9, 7.9] \times 10^{-3}$	$[-6.1, 6.0] \times 10^{-3}$	3.5×10^{-3}
$[C_{lq}^{(3)}]_{3322}$	$[-4.8, 8.8] \times 10^{-3}$	$[-3.5, 7.1] \times 10^{-3}$	–
$[C_{lq}^{(3)}]_{3323}$	$[-1.3, 1.4] \times 10^{-2}$	$[-1.0, 1.1] \times 10^{-2}$	5.8×10^{-3}
$[C_{lq}^{(3)}]_{3333}$	$[-0.33, 0.33]$	$[-0.25, 0.26]$	$[-0.14, 0.15]$
$\lvert[C_{lequ}^{(1)}]_{3311}\rvert$	2.9×10^{-3}	2.2×10^{-3}	–
$\lvert[C_{lequ}^{(1)}]_{3312}\rvert$	7.2×10^{-3}	5.5×10^{-3}	–
$\lvert[C_{lequ}^{(1)}]_{3321}\rvert$	4.4×10^{-3}	3.4×10^{-3}	–
$\lvert[C_{lequ}^{(1)}]_{3322}\rvert$	1.9×10^{-2}	1.5×10^{-2}	–
$\lvert[C_{lequ}^{(1)}]_{3331}\rvert$	1.6×10^{-2}	1.2×10^{-2}	0.80×10^{-2}
$\lvert[C_{lequ}^{(1)}]_{3332}\rvert$	2.8×10^{-2}	2.2×10^{-2}	1.5×10^{-2}
$\lvert[C_{lequ}^{(3)}]_{3311}\rvert$	1.7×10^{-3}	1.3×10^{-3}	–
$\lvert[C_{lequ}^{(3)}]_{3312}\rvert$	4.2×10^{-3}	3.2×10^{-3}	–
$\lvert[C_{lequ}^{(3)}]_{3321}\rvert$	2.5×10^{-3}	1.9×10^{-3}	–
$\lvert[C_{lequ}^{(3)}]_{3322}\rvert$	1.1×10^{-2}	0.87×10^{-2}	–
$\lvert[C_{lequ}^{(3)}]_{3331}\rvert$	0.93×10^{-2}	0.71×10^{-2}	0.42×10^{-2}
$\lvert[C_{lequ}^{(3)}]_{3332}\rvert$	1.7×10^{-2}	1.3×10^{-2}	0.83×10^{-2}
$\lvert[C_{ledq}]_{3311}\rvert$	3.0×10^{-3}	2.3×10^{-3}	–
$\lvert[C_{ledq}]_{3312}\rvert$	6.5×10^{-3}	5.0×10^{-3}	–
$\lvert[C_{ledq}]_{3313}\rvert$	0.17	0.13	–
$\lvert[C_{ledq}]_{3321}\rvert$	4.5×10^{-3}	3.5×10^{-3}	–
$\lvert[C_{ledq}]_{3322}\rvert$	1.4×10^{-2}	1.1×10^{-2}	–
$\lvert[C_{ledq}]_{3323}\rvert$	0.42×10^{-3}	0.32	–
$\lvert[C_{ledq}]_{3331}\rvert$	1.6×10^{-2}	1.2×10^{-2}	0.81×10^{-2}
$\lvert[C_{ledq}]_{3332}\rvert$	2.7×10^{-2}	2.0×10^{-2}	1.5×10^{-2}
$\lvert[C_{ledq}]_{3333}\rvert$	0.66×10^{-3}	0.51	0.37

$$\mathcal{L}_{\rm SMEFT}^{\rm dim6} \supset -\frac{1}{v^2}\Big[[C_{lq}^{(3)}]_{ijkl}\left(\bar{l}_i\gamma_\mu\sigma^I l_j\right)\left(\bar{q}_k\gamma^\mu\sigma^I q_l\right) + [C_{ledq}]_{ijkl}\left(\bar{l}_i^\alpha e_j\right)\left(\bar{d}_k q_l^\alpha\right) + [C_{lequ}^{(1)}]_{ijkl}\left(\bar{l}_i^\alpha e_j\right)\epsilon_{\alpha\beta}\left(\bar{q}_k^\beta u_l\right) + \text{h.c.} + [C_{lequ}^{(3)}]_{ijkl}\left(\bar{l}_i^\alpha\sigma_{\mu\nu}e_j\right)\epsilon_{\alpha\beta}\left(\bar{q}_k^\beta\sigma^{\mu\nu}u_l\right) + \text{h.c.}\Big] \, ,$$

$$q_i = (V_{ji}^* u_L^j, d_L^i)$$

SMEFT limits

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



Due to CKM misalignment, each operator induces correlated effects with different quark flavors.

The limit from mono-tau tails can in some cases be complementary to limits from low-energy processes.