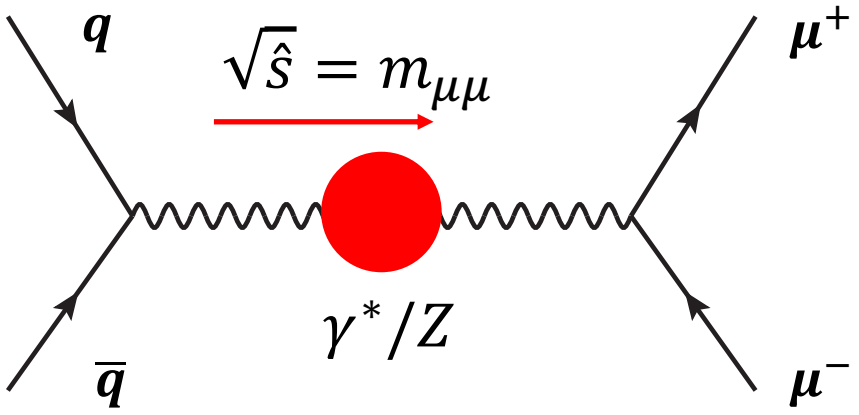
[Flavor] precision in high energy tail

Journal club style – review on selected works

Minho Son
KAIST

Precision in high energy tail



$$\Pi_{VV}(q^2) = \Pi_{VV}^{(0)}(m_Z^2) + \frac{q^2}{\Lambda^2}\Pi_{VV}^{(1)}(m_Z^2) + \cdots$$

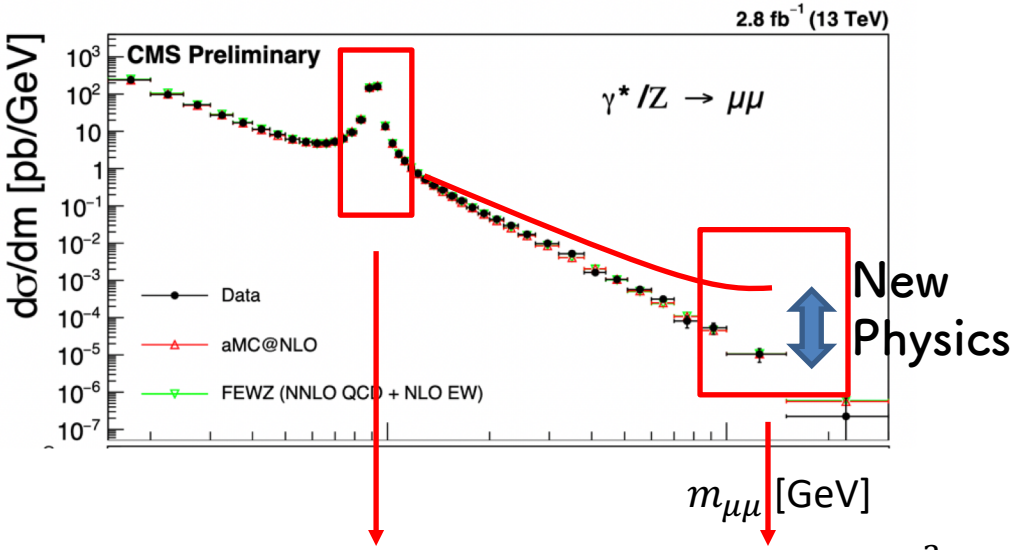
Neutral gauge boson propagator

$$P_N = \begin{bmatrix} \frac{1}{q^2} - \frac{t^2\mathrm{W}+\mathrm{Y}}{m_Z^2} & \frac{t\left(\left(\mathrm{Y}+\hat{\mathrm{T}}\right)c^2+s^2\mathrm{W}-\hat{\mathrm{S}}\right)}{(c^2-s^2)\left(q^2-m_Z^2\right)} + \frac{t(\mathrm{Y}-\mathrm{W})}{m_Z^2} \\ \star & \frac{1+\hat{\mathrm{T}}-\mathrm{W}-t^2\mathrm{Y}}{q^2-m_Z^2} - \frac{t^2\mathrm{Y}+\mathrm{W}}{m_Z^2} \end{bmatrix}$$

Similarly for charged gauge boson propagator

$$P_C = \frac{1+\left(\left(\hat{\mathrm{T}}-\mathrm{W}-t^2\mathrm{Y}\right)-2t^2\left(\hat{\mathrm{S}}-\mathrm{W}-\mathrm{Y}\right)\right)/(1-t^2)}{\left(q^2-m_W^2\right)} - \frac{\mathrm{W}}{m_W^2}$$

Farina, Panico, Pappadopulo, Ruderman, Torre , Wulzer, PLB 17'



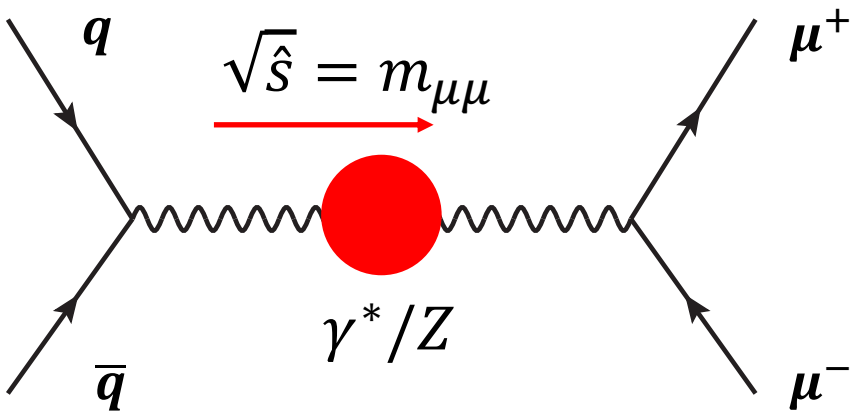
$\bar{c}_i \leq \Delta_{exp} : E \sim v$

$\bar{c}_i \leq \Delta_{exp} \frac{v^2}{E^2}$

Data to Bounds on WCs

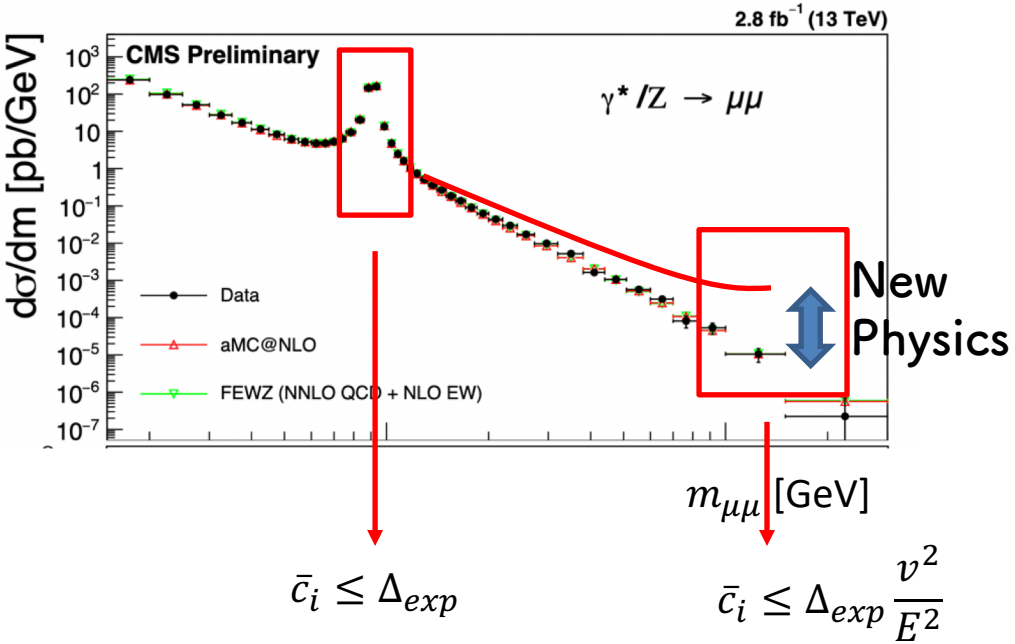
$$\bar{c}_i \frac{E^2}{v^2} \leq \Delta_{exp} \quad \rightarrow \quad \bar{c}_i \leq \Delta_{exp} \frac{v^2}{E^2}$$

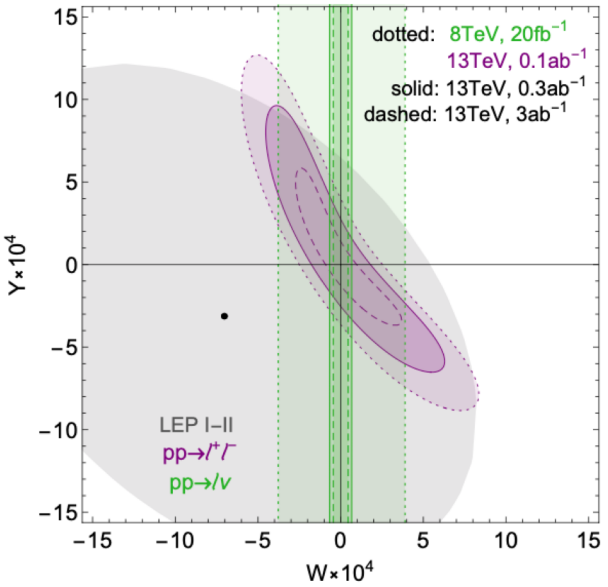
Precision in high energy tail : Drell-Yan



	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	$-\frac{\mathrm{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$	$-\frac{g_1^2\mathrm{Y}}{2m_W^2} J_{Y\,\mu} J_Y{}^\mu$

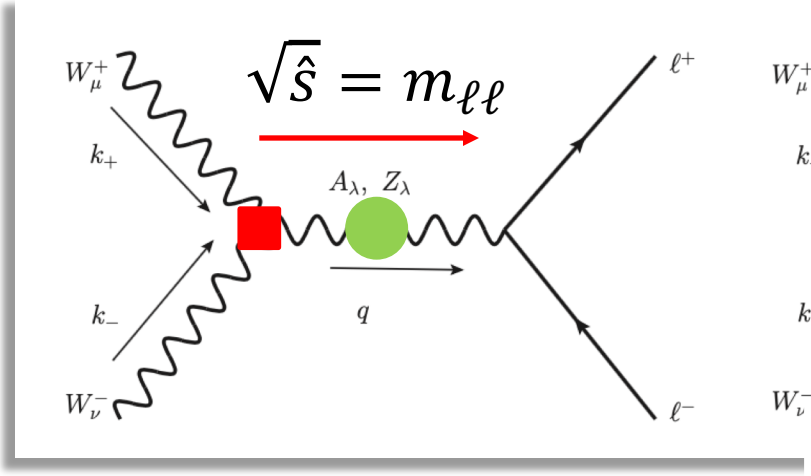
TABLE I. *The parameters* W *and* Y *in their "universal" form (left), and as products of currents related by the equation of motion (right). We dropped corrections to trilinear gauge couplings.*

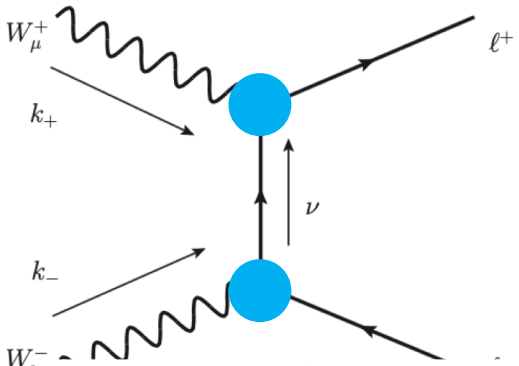




Farina, Panico, Pappadopulo, Ruderman, Torre , Wulzer, PLB 17'

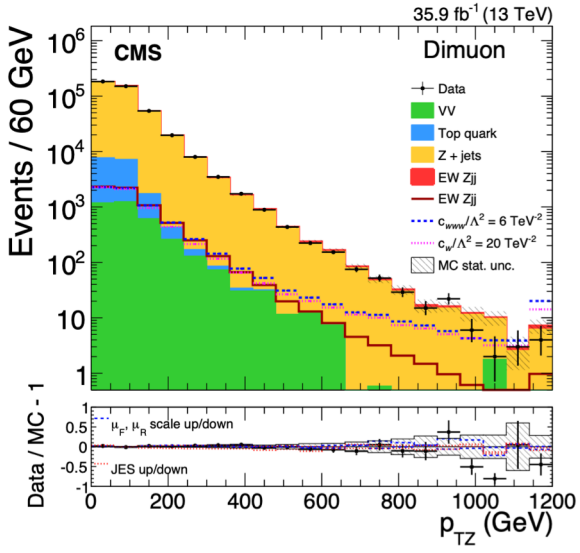
Precision in high energy tail : VBF-Drell-Yan (?)



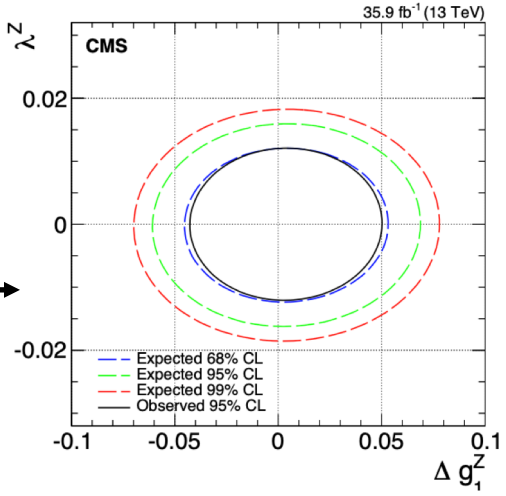


Coupling constant	Expected 95% CL interval	Observed 95% CL interval
λ^Z	$[-0.014, 0.014]$	$[-0.010, 0.010]$
Δg_1^Z	$[-0.053, 0.061]$	$[-0.035, 0.042]$

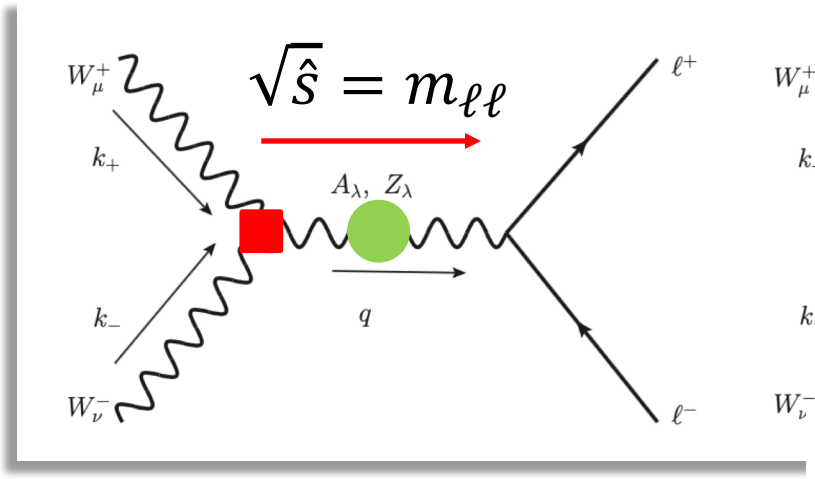
CMS 17' [arXiv:1712.09814]

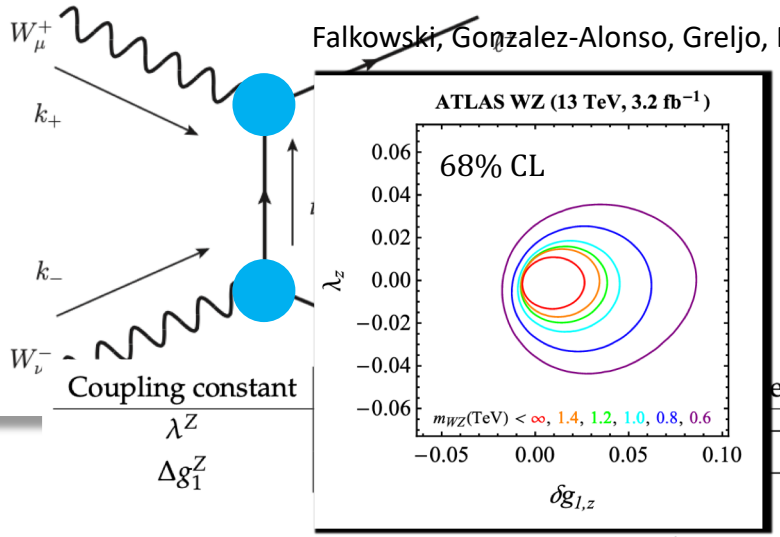


: p_T of Z in m_Z mass window



Precision in high energy tail : VBF-Drell-Yan (?)

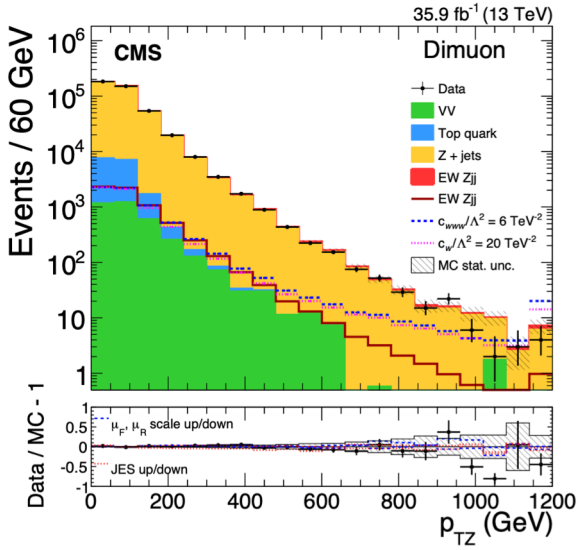




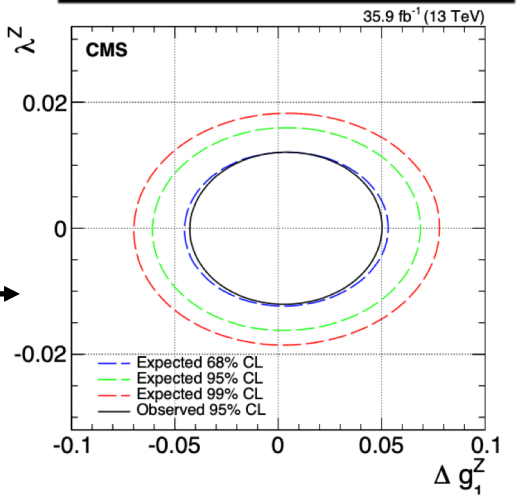
Falkowski, Gonzalez-Alonso, Greljo, Marzocca, **SON** 16‘

ed 95% CL interval
−0.010, 0.010]
−0.035, 0.042]

CMS 17‘ [arXiv:1712.09814]

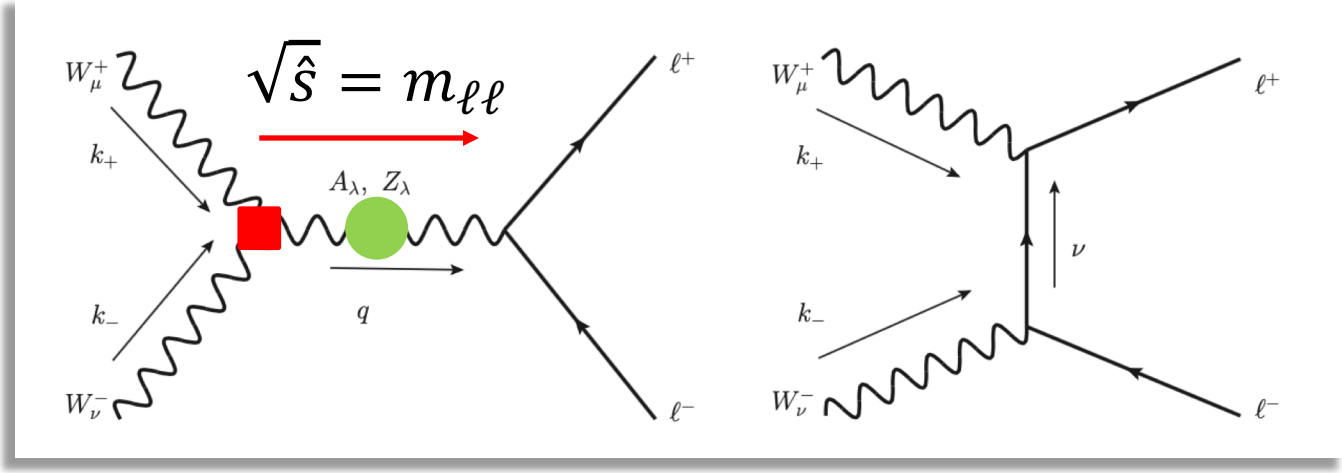


: p_T of Z in m_Z mass window



Precision in high energy tail : VBF-Drell-Yan (?)

Park, **SON**, Ui, Yoo etc in progress



Suppressed Interference between SM and BSM
``Helicity Selection Rule"

$$: \sigma = \sigma^{SM} + \sum \left(\frac{c_i^{(6)}}{\Lambda^2} \sigma_i^{(6\times SM)} + h.c. \right) + \sum \frac{c_i^{(6)} c_j^{(6)*}}{\Lambda^4} \sigma_{ij}^{(6\times 6)} + \cdots$$

- Differential distribution of $m_{\ell\ell}$ might resurrect interference term [Note that sensitivity on WCs are weakened if NP does not interfere with the SM)
- More consistent EFT on data

[Flavor] precision in high-E tail

``Charm"

Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.1242

``Charm Physics Confronts High-pT Lepton Tails"

``Bottom"

Marzocca, Ui, **SON**, JHEP 2020

``Bottom Physics Confronts High-pT Lepton Tails"

Jaffredo 21‘
Endo, Iguro, Kitahara, Takeuchi, Watanabe 21‘
Iguro, Takeuchi, Watanabe 21‘
Greljo, Camalich, Ruiz-Alvarez 18‘
Faroughy, Greljo, Kamenik 16‘
And many more references ...

Parametrization for Low-E EFT
: charged current

Following notation of Marzocca, Ui, **SON**, JHEP 2020

$$\mathcal{L}_{EFT} = -\frac{4\,G_F}{\sqrt{2}} V_{ij} \Big[C_{V_L}^{ij\alpha\beta} \mathcal{O}_{V_L}^{ij\alpha\beta} + C_{V_R}^{ij\alpha\beta} \mathcal{O}_{V_R}^{ij\alpha\beta} + C_{SL}^{ij\alpha\beta} \mathcal{O}_{S_L}^{ij\alpha\beta} + C_{SR}^{ij\alpha\beta} \mathcal{O}_{S_R}^{ij\alpha\beta} + C_{TL}^{ij\alpha\beta} \mathcal{O}_T^{ij\alpha\beta} \Big] + h.c.$$

$$\mathcal{O}_{V_L}^{ij\alpha\beta} = (\bar{u}_i \gamma_\mu P_L d_j)(\bar{e}^\alpha P_L \nu^\beta) \qquad \mathcal{O}_{V_R}^{ij\alpha\beta} = (\bar{u}_i \gamma_\mu P_R d_j)(\bar{e}^\alpha P_L \nu^\beta)$$

$$\mathcal{O}_T^{ij\alpha\beta} = (\bar{u}_i \sigma_{\mu\nu} P_L d_j)(\bar{e}^\alpha \sigma^{\mu\nu} P_L \nu^\beta)$$

$$\mathcal{O}_{S_L}^{ij\alpha\beta} = (\bar{u}_i P_L d_j)(\bar{e}^\alpha P_L \nu^\beta) \qquad \mathcal{O}_{S_R}^{ij\alpha\beta} = (\bar{u}_i P_R d_j)(\bar{e}^\alpha P_L \nu^\beta)$$

Switching to notation of Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.1242

(notation: $C = \epsilon$ to match other literature)

``Charm" precision

$$\mathcal{L}_{CC}^{charm} = -\frac{4\,G_F}{\sqrt{2}} V_{ci} \left[\left(1 + \epsilon_{V_L}^{\alpha\beta\, i}\right) \mathcal{O}_{V_L}^{\alpha\beta\, i} + \epsilon_{V_R}^{\alpha\beta\, i} \mathcal{O}_{V_R}^{\alpha\beta\, i} + \epsilon_{S_L}^{\alpha\beta\, i} \mathcal{O}_{S_L}^{\alpha\beta\, i} + \epsilon_{S_R}^{\alpha\beta\, i} \mathcal{O}_{S_R}^{\alpha\beta\, i} + \epsilon_T^{\alpha\beta\, i} \mathcal{O}_T^{\alpha\beta\, i} \right] + h.c.$$

$$= (\bar{c} \gamma_\mu P_L d_i)(\bar{e}^\alpha P_L \nu^\beta)$$

``Bottom" precision

$$\mathcal{L}_{CC}^{Bottom} = -\frac{4\,G_F}{\sqrt{2}} V_{ib} \left[\left(1 + \epsilon_{V_L}^{\alpha\beta\, i}\right) \mathcal{O}_{V_L}^{\alpha\beta\, i} + \epsilon_{V_R}^{\alpha\beta\, i} \mathcal{O}_{V_R}^{\alpha\beta\, i} + \epsilon_{S_L}^{\alpha\beta\, i} \mathcal{O}_{S_L}^{\alpha\beta\, i} + \epsilon_{S_R}^{\alpha\beta\, i} \mathcal{O}_{S_R}^{\alpha\beta\, i} + \epsilon_T^{\alpha\beta\, i} \mathcal{O}_T^{\alpha\beta\, i} \right] + h.c.$$

$$= (\bar{u}_i \gamma_\mu P_L b)(\bar{e}^\alpha P_L \nu^\beta)$$

Uplifting to EWS operators : E.g. b-anomaly

$$q_i \to \left((V^+u)_i, d_i\right)^T = (V^*_{ji}u_j, d_i)^T$$

: from UV origin : PMNS matrix : from CKM matrix

v — $\Delta\mathcal{L}(\Lambda) = -\frac{1}{v^2}\left[C_{lq}^{(3)}\right]_{ijkl}\left(\bar{l}_i\gamma_\mu\sigma^I l_j\right)\left(\bar{q}_k\gamma^\mu\sigma^I q_l\right) + \cdots$

Match to SU(2)xU(1) invariant operators above EW scale

SU(2)xU(1) symmetry spits out more related operators

Rich low-E/collider phenomenology

m_b — B-anomaly : RD, RD*

$$\mathcal{L}_{CC}^{Bottom} = \left(\bar{c}\gamma_\mu P_L b\right)\left(\bar{\tau}P_L\nu_\tau\right)$$

$$= -\frac{4\,G_F}{\sqrt{2}}V_{cb}\left[\left(1 + C_{V_L}^{cb}\right)\mathcal{O}_{V_L}^{cb} + C\,\mathcal{O}_{V_R}^{cb}\right.$$

$$\left. + C_{S_L}^{cb}\,\mathcal{O}_{S_L}^{cb} + C_{S_R}^{cb}\,\mathcal{O}_{S_R}^{cb} + C_T^{cb}\,\mathcal{O}_T^{cb}\right] + h.c.$$

Uplifting to EWS operators : Matching

Match to SU(2)xU(1) invariant operators above EW scale

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

Using convention

$q_i \to \left((V^+u)_i, d_i\right)^T = (V_{ji}^* u_j, d_i)^T$ [or alternatively $q_i \to (u_i, V_{ij}\, d_j)^T$]

$$C_{V_L}^{ij\alpha\beta} = \frac{1}{V_{ij}}\sum_k V_{ik}\left[C_{lq}^{(3)}\right]_{\alpha\beta kj} \quad [\text{ for } \mathcal{O}_{V_L}^{ij\alpha\beta} = (\bar{u}_i\gamma_\mu P_L d_j)(\bar{e}^\alpha P_L \nu^\beta)\ ]$$

$$C_{S_L}^{ij\alpha\beta} = \frac{1}{2V_{ij}}\left[C_{lequ}^{(1)}\right]^*_{\beta\alpha ji}, \quad C_T^{ij\alpha\beta} = \frac{1}{2V_{ij}}\left[C_{lequ}^{(3)}\right]^*_{\beta\alpha ji}$$

[No CKM matrix as down-quark in q_i is selected]

$$C_{S_R}^{ij\alpha\beta} = \frac{1}{2V_{ij}}\sum_k V_{ik}\left[C_{ledq}\right]^*_{\beta\alpha jk}$$

To compare with lit

Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.1242

$$\Delta\mathcal{L}(\Lambda) = \frac{1}{v^2}\Bigg[\left[C_{lq}^{(3)}\right]_{ijkl}(\bar{l}_i\gamma_\mu\sigma^I l_j)(\bar{q}_k\gamma^\mu\sigma^I q_l) + \left[C_{ledq}\right]_{ijkl}(\bar{l}_i^\alpha e_j)(\bar{d}_k q_l^\alpha) + \left[C_{lequ}^{(1)}\right]_{ijkl}(\bar{l}_i^\alpha e_j)\epsilon_{\alpha\beta}\left(\bar{q}_k^\beta u_l\right) + h.c.$$
$$+ \left[C_{lequ}^{(3)}\right]_{ijkl}(\bar{l}_i^\alpha \sigma_{\mu\nu} e_j)\epsilon_{\alpha\beta}\left(\bar{q}_k^\beta \sigma^{\mu\nu} u_l\right) + h.c.$$
$$+ \left[C_{\phi l}^{(3)}\right]_{ij}(\phi^+ D_\mu^I \phi)(\bar{l}_i\sigma^I\gamma^\mu l_j) + h.c.\Bigg]$$

Using convention

$q_i \to (u_i, V_{ij}\, d_j)^T$

``Charm" precision

Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.1242

$$C_{V_L}^{ij\alpha\beta} = -\frac{1}{V_{ij}}\sum_k V_{kj}\left[C_{lq}^{(3)}\right]_{\alpha\beta ik} \quad \to \quad C_{V_L}^{\alpha\beta i} = -\frac{1}{V_{ci}}\sum_j V_{2j}\left[C_{lq}^{(3)}\right]_{\alpha\beta 2j}$$

$$C_{S_L}^{ij\alpha\beta} = -\frac{1}{2V_{ij}}\sum_k V_{kj}\left[C_{lequ}^{(1)}\right]^*_{\beta\alpha ki} \quad \to \quad C_{S_L}^{\alpha\beta i} = -\frac{1}{2V_{ci}}\sum_j V_{ji}\left[C_{lequ}^{(1)}\right]^*_{\beta\alpha j2}$$

$$C_{T}^{ij\alpha\beta} = -\frac{1}{2V_{ij}}\sum_k V_{kj}\left[C_{lequ}^{(3)}\right]^*_{\beta\alpha ki} \quad \to \quad C_{T}^{\alpha\beta i} = -\frac{1}{2V_{ci}}\sum_j V_{ji}\left[C_{lequ}^{(3)}\right]^*_{\beta\alpha j2}$$

$$C_{S_R}^{ij\alpha\beta} = -\frac{1}{2V_{ij}}\left[C_{ledq}\right]^*_{\beta\alpha jk} \quad \to \quad C_{S_R}^{\alpha\beta i} = -\frac{1}{2V_{ci}}\left[C_{ledq}\right]^*_{\beta\alpha i2}$$

$i = c, j \to i, k \to j$

[No CKM matrix as down-quark is right-handed]

[Flavor] precision in high-E tail

``Charm"

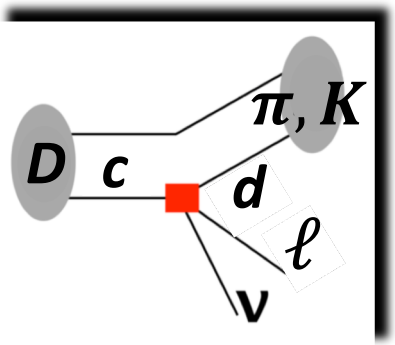
Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.1242

``Charm Physics Confronts High-pT Lepton Tails"

Low-E experiment

: probe through semileptonic decay

$$c \to d^i \bar{e}^\alpha \nu^\beta$$



* sensitivity on WCs are weakened if NP does not interfere with the SM

i	α	$\epsilon_V^{\alpha i}$	$\epsilon_A^{\alpha i}$	$\epsilon_S^{\alpha i}$	$\epsilon_P^{\alpha i}$	$\epsilon_T^{\alpha i}$
d	e	$[-0.02, 0.11]$	$[-32, 34]$	$[-0.29, 0.29]$	$[-0.005, 0.005]$	$[-0.5, 0.5]$
	μ	$[-0.06, 0.07]$	$[-0.013, 0.07]$	$[-0.33, 0.17]$	$[-0.0024, 0.0004]$	$[-0.6, 0.22]$
	τ	–	$[-0.27, 0.21]$	–	$[-0.11, 0.15]$	–
s	e	$[-0.07, 0.08]$	$[-27, 29]$	$[-0.29, 0.29]$	$[-0.005, 0.004]$	$[-0.5, 0.5]$
	μ	$[-0.09, 0.06]$	$[-0.07, 0.02]$	$[-0.4, 0.16]$	$[-0.0007, 0.0022]$	$[-0.9, 0.22]$
	τ	–	$[-0.07, 0.014]$	–	$[-0.008, 0.04]$	–

Table 2. 95% CL ranges of the WCs of the charged-current operators obtained at the scale $\mu = 2$ GeV from current experimental data on (semi)leptonic $D_{(s)}$-meson decays, assuming them to be real.

$$\epsilon_A = \epsilon_{V_R} - \epsilon_{V_L} \qquad \epsilon_P = \epsilon_{S_R} - \epsilon_{S_L}$$

$$BR(D^+ \to \bar{e}^\alpha \nu^\alpha) = \tau_{D^+} \frac{m_{D^+} m_\alpha^2 f_D^2 G_F^2 |V_{cb}|^2 \beta_\alpha^2}{8\pi} \left| 1 - \epsilon_A^{\alpha d} + \frac{m_D^2}{m_\alpha (m_c + m_u)} \epsilon_P^{\alpha d} \right|^2$$

$$\frac{BR(D \to P_i \bar{l}^\alpha \nu^\alpha)}{BR_{SM}} = \left| 1 + \epsilon_V^{\alpha i} \right|^2 + 2Re\left[(1 + \epsilon_V^{\alpha i})(x_S \epsilon_S^{\alpha i *} + x_T \epsilon_T^{\alpha i *}) \right] + y_S \left| \epsilon_S^{\alpha i} \right|^2 + y_T \left| \epsilon_T^{\alpha i} \right|^2$$

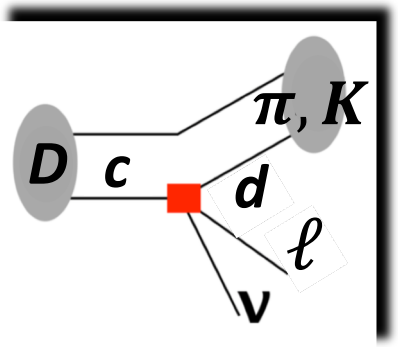
$$\epsilon_V = \epsilon_{V_R} + \epsilon_{V_L} \qquad \epsilon_S = \epsilon_{S_R} + \epsilon_{S_L}$$

- It looks like the precision is driven by linear terms
- Accessible only to linear comb of operators

Low-E experiment

: probe through
semileptonic decay

✓ accessible to only one op



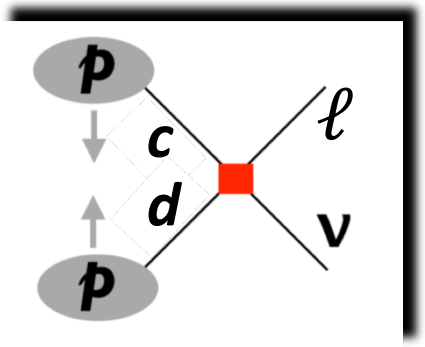
$$\bar{c}_i \frac{\mathcal{O}_i^{(d=6)}}{v^2}$$

$$\bar{c}_i \frac{E^2}{v^2} \leq \Delta_{exp} \quad \rightarrow \quad \bar{c}_i \leq \Delta_{exp} \frac{v^2}{E^2}$$

High-E experiment

: through scattering of
quarks from PDF

✓ accessible to only linear comb of ops



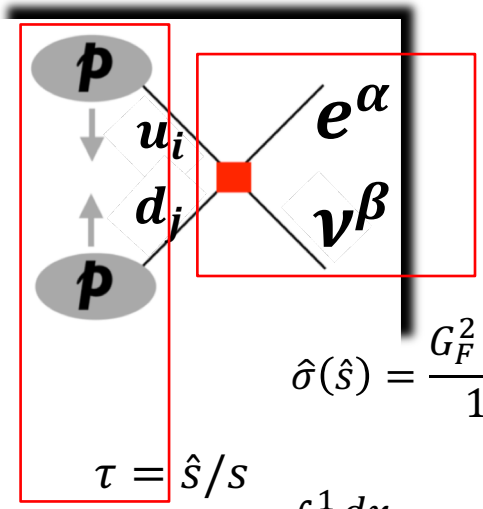
$$\Delta_{exp} \quad \times \quad \frac{v^2}{E^2}$$

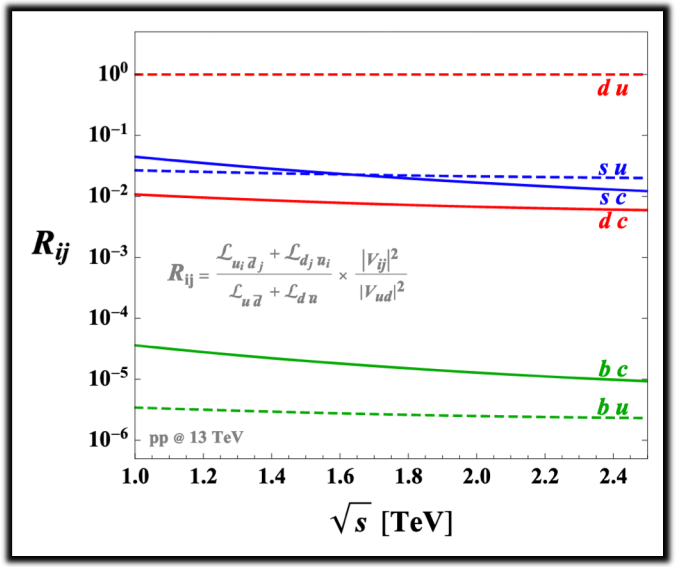
: poor at the LHC : suppression at high–E tail

High-E experiment

: through scattering of quarks from PDF

✓ accessible to only linear comb of ops





$$\hat{\sigma}(\hat{s}) = \frac{G_F^2 |V_{ij}|^2}{18\pi} \hat{s} \left[\left| \delta^{\alpha\beta} \frac{m_W^2}{\hat{s}} - \epsilon_{V_L}^{\alpha\beta ij} \right|^2 + \frac{3}{4} \left(\left| \epsilon_{S_L}^{\alpha\beta ij} \right|^2 + \left| \epsilon_{S_R}^{\alpha\beta ij} \right|^2 \right) + 4 \left| \epsilon_T^{\alpha\beta ij} \right|^2 \right]$$

$$\tau = \hat{s}/s$$

$$\mathcal{L}_{q_i\bar{q}_j}(\tau, \mu_F) = \int_\tau^1 \frac{dx}{x} f_{q_i}(x, \mu_F) f_{\bar{q}_j}(\tau/x, \mu_F)$$

✓ Growing with Energy

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

$$\frac{\Delta\sigma}{\sigma_{SM}} \approx \frac{\left(\mathcal{L}_{u_i\bar{d}_j} + \mathcal{L}_{d_j\bar{u}_i}\right) \times |V_{ij}|^2}{(\mathcal{L}_{u\bar{d}} + \mathcal{L}_{d\bar{u}}) \times |V_{ud}|^2} \times \frac{d_X \cdot \left(\epsilon_{X=V_L,S_{L,R},T}^{\alpha\beta ij}\right)^2}{(m_W^2/\hat{s})^2}$$

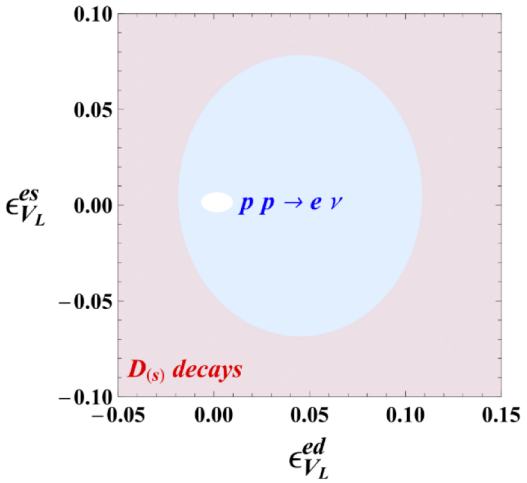
$$\equiv R_{ij}$$

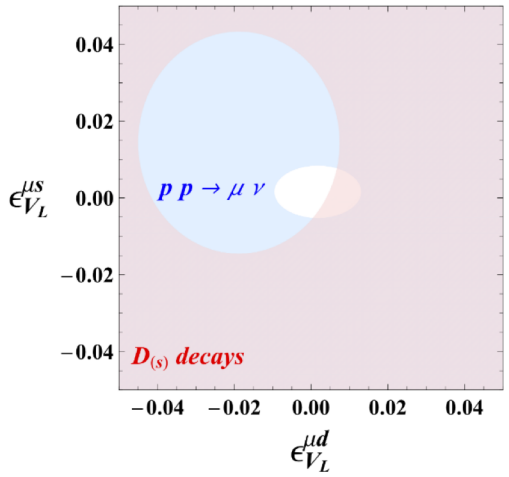
$$d_{X=V_L,S_{L,R},T} = 1, \frac{3}{4}, 4$$

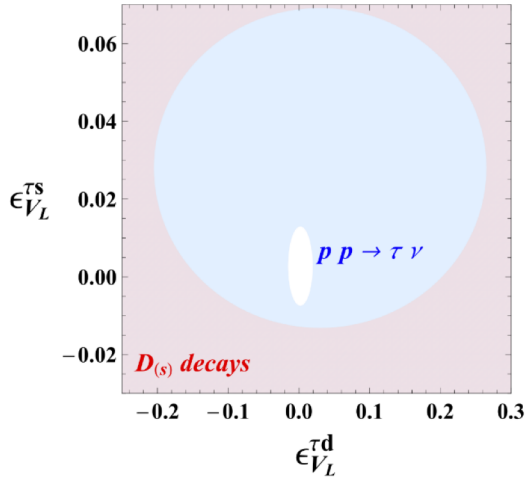
- It looks like the precision is driven by quadratic terms
- Directly accessible to each operator
- Comparison between SM and BSM (comparing between BSMs gives diff aspect)

LHC potential to probe new flavor violating interactions at high energy

Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.1242







$\ell + \nu$:

ATLAS 36.1/fb, CMS 35.9/fb

$\tau + \nu$:

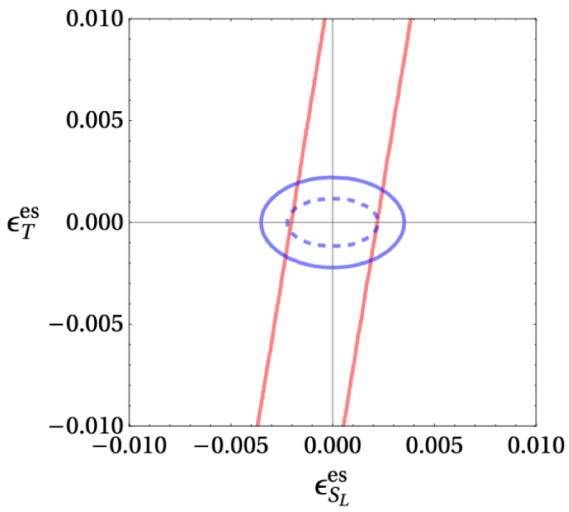
ATLAS 139/fb, CMS 35.9/fb

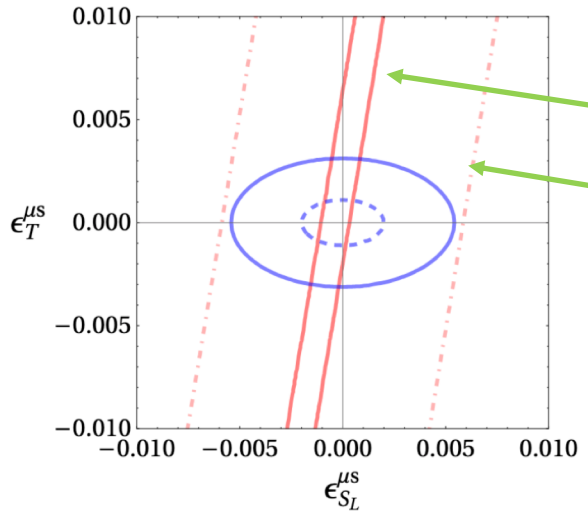
Blue : excluded by High pT @LHC

Pink : excluded by D-meson decays

Figure 2. Exclusion limits at 95% CL on $c \to d(s)\bar{e}^{\alpha}\nu^{\alpha}$ transitions in $(\epsilon^{\alpha\alpha d}_{V_L}, \epsilon^{\alpha\alpha s}_{V_L})$ plane were $\alpha = e$ (top left), $\alpha = \mu$ (top right), and $\alpha = \tau$ (bottom). The region colored in pink is excluded by $D_{(s)}$ meson decays, while the region colored in blue is excluded by high-p_T LHC.

LHC potential to probe new flavor violating interactions at high energy

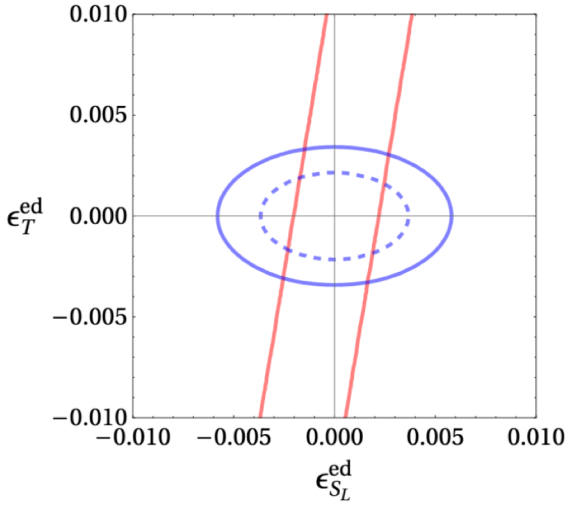


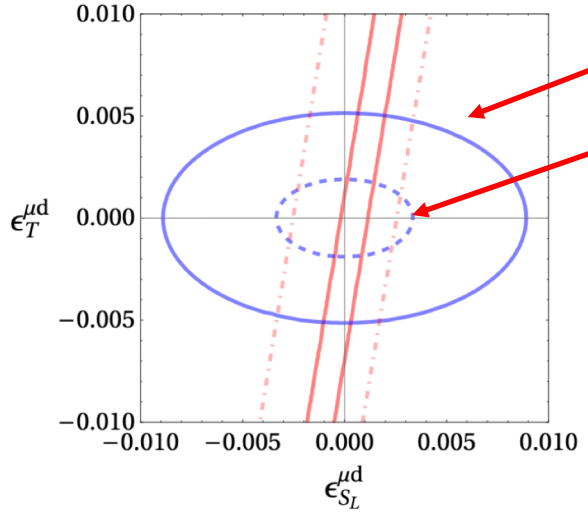


Low-E experiment :
D-meson decays

$\beta = \alpha$

$\beta \neq \alpha$





High-E experiment :

Mono-lepton at LHC

Projection
at HL-LHC

Figure 3. 95% CL regions for the combined fits of $\epsilon_{S_L}^{\alpha\beta i}$ and $\epsilon_T^{\alpha\beta i}$ to the charmed-meson decay data with $\beta = \alpha$ (red solid line) or $\beta \neq \alpha$ (light-red dash-dotted line) and to monolepton LHC data (blue solid line). Projections for the high-luminosity phase of the LHC (3 ab^{-1}), obtained by rescaling the expected limits with luminosity, are represented by dashed ellipses.

Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.1242

LHC potential to probe new flavor violating interactions at high energy

Low-E experiment :

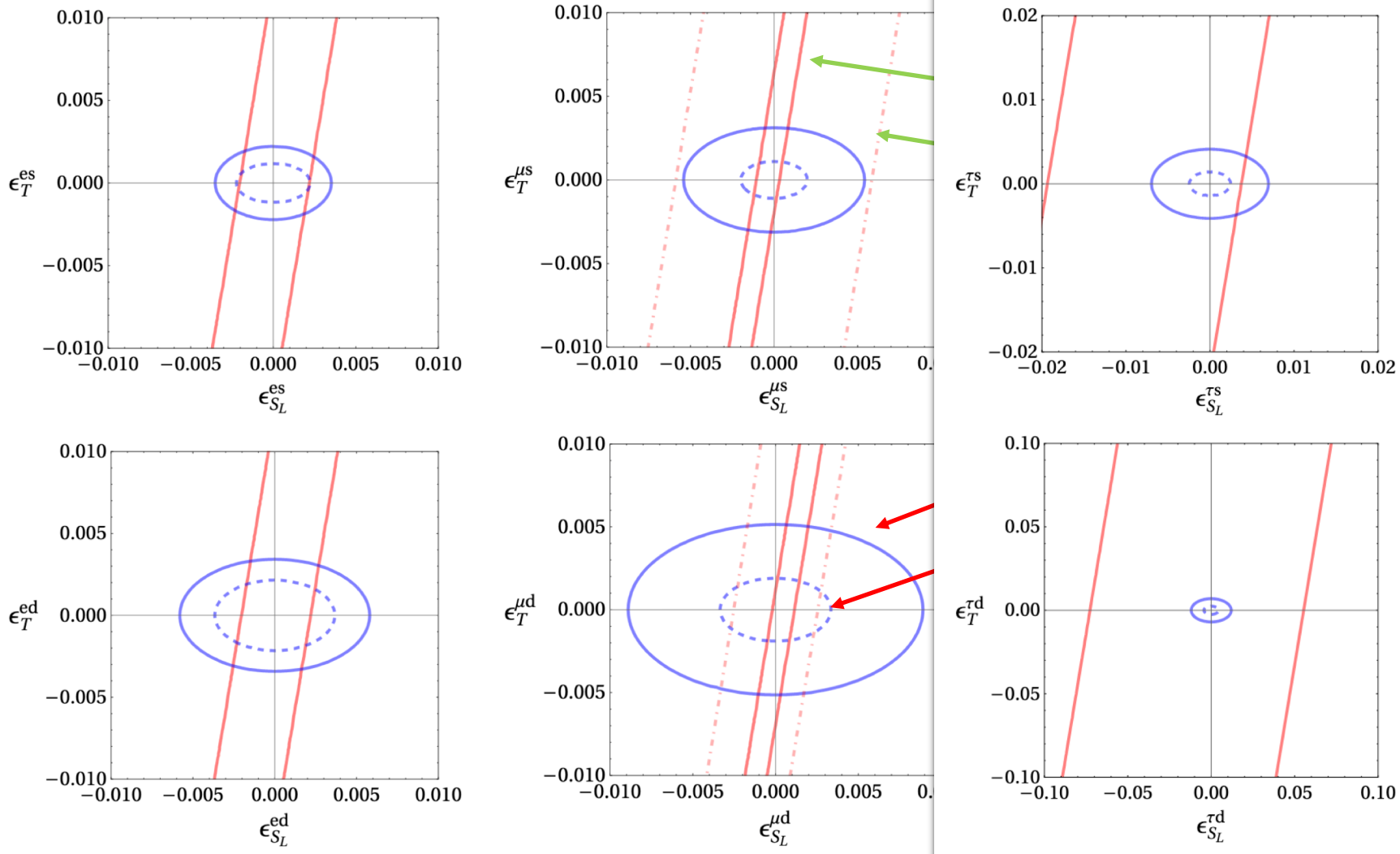


Figure 3. 95% CL regions for the combined fits of $\epsilon_{S_L}^{\alpha\beta i}$ and $\epsilon_T^{\alpha\beta i}$ to the charmed-meson decay data with $\beta = \alpha$ (red solid line) or $\beta \neq \alpha$ (light-red dash-dotted line) and to monolepton LHC data (blue solid line). Projections for the high-luminosity phase of the LHC (3 ab^{-1}), obtained by rescaling the expected limits with luminosity, are represented by dashed ellipses.

Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, 2003.1242

[Flavor] precision in high-E tail

``Bottom"

Marzocca, Ui, **SON**, JHEP 2020

``Bottom Physics Confronts High-pT Lepton Tails"

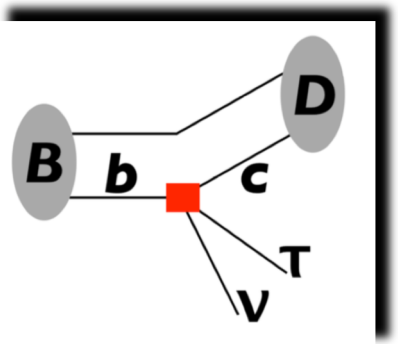
Jaffredo 21‘
Endo, Iguro, Kitahara, Takeuchi, Watanabe 21‘
Iguro, Takeuchi, Watanabe 21‘
Greljo, Camalich, Ruiz-Alvarez 18‘
Faroughy, Greljo, Kamenik 16‘
And many more references ...

Similar story applies to the bottom precision

Low-E experiment

: probe through semileptonic decay

✓ accessible to only one op



$$\bar{c}_i \frac{\mathcal{O}_i^{(d=6)}}{v^2}$$

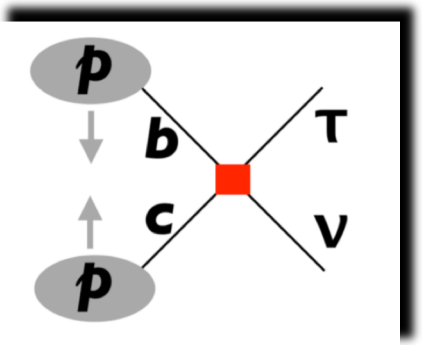
$$\bar{c}_i \frac{E^2}{v^2} \leq \Delta_{exp} \quad \rightarrow \quad \bar{c}_i \leq \Delta_{exp} \frac{v^2}{E^2}$$

: poor at the LHC

High-E experiment

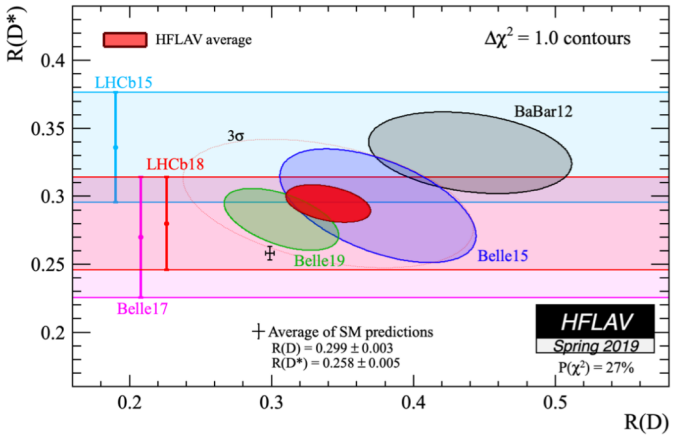
: through scattering of quarks from PDF

✓ accessible to only linear comb of ops



$$\Delta_{exp} \times \frac{v^2}{E^2}$$

: suppression at high–E tail



$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)} \tau \nu_\tau)}{\mathcal{B}(B \to D^{(*)} l \nu_l)}$$

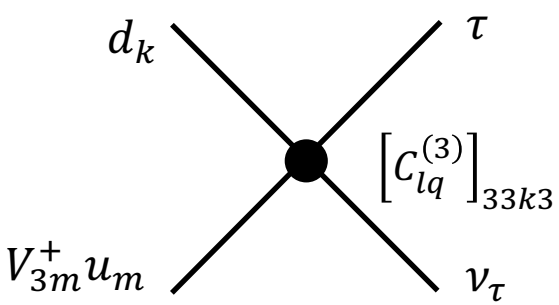
Competition among BSM : diff aspect

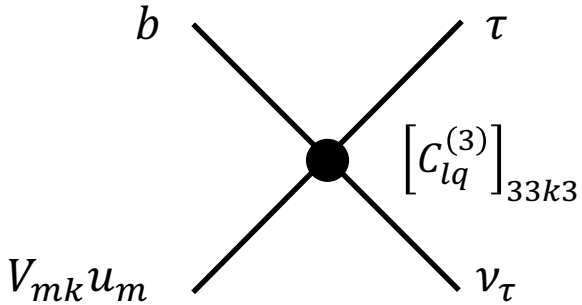
: PMNS matrix ignored for simplicity

$$-\frac{1}{v^2}\left[C_{lq}^{(3)}\right]_{ijkl}(\bar{l}_i\gamma_\mu\sigma^I l_j)(\bar{q}_k\gamma^\mu\sigma^I q_l)$$

$$q_i \to \left((V^+u)_i, d_i\right)^T = (V_{ji}^* u_j, d_i)^T$$

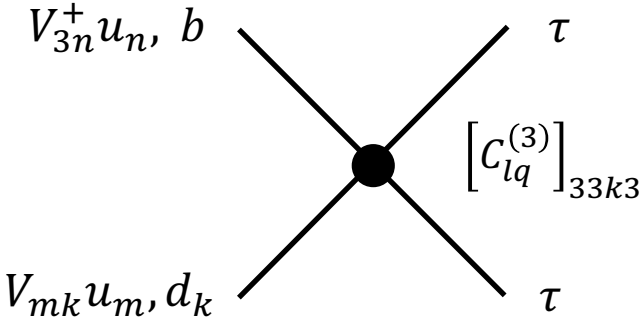
Charged - $\ni \left[C_{lq}^{(3)}\right]_{33k3}$ $[\, 2\, V_{3m}^+(\bar{\nu}_\tau\gamma_\mu\tau)(\bar{d}_k\gamma^\mu u_m) + 2\, V_{mk}(\bar{\tau}\gamma_\mu\nu_\tau)(\bar{u}_m\gamma^\mu b)\,]$

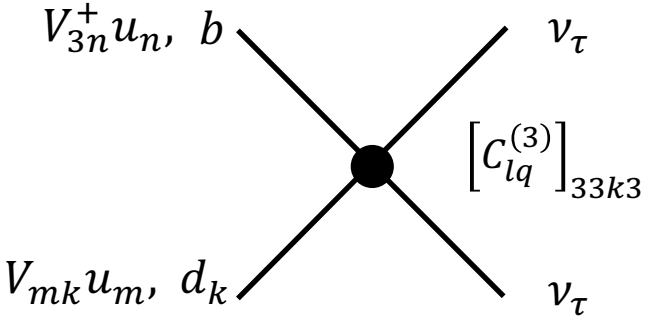




Neutral - $\ni \left[C_{lq}^{(3)}\right]_{33k3}$ $[\, V_{mk}V_{3n}^+(\bar{\nu}_\tau\gamma_\mu\nu_\tau)(\bar{u}_m\gamma^\mu u_n) + (\bar{\tau}\gamma_\mu\tau)(\bar{d}_k\gamma^\mu b)$

$$- V_{mk}V_{3n}^+(\bar{\tau}\gamma_\mu\tau)(\bar{u}_m\gamma^\mu u_n) - (\bar{\nu}_\tau\gamma_\mu\nu_\tau)(\bar{d}_k\gamma^\mu b)\,]$$





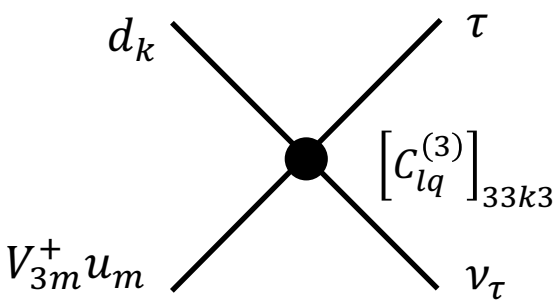
Competition among BSM : diff aspect

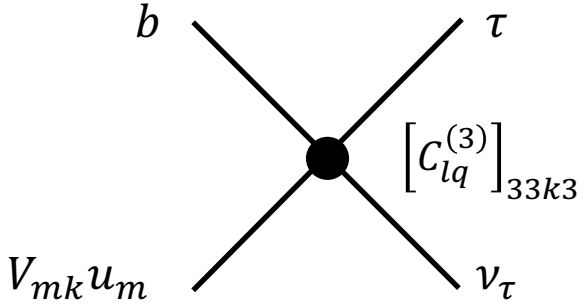
: PMNS matrix ignored for simplicity

$$-\frac{1}{v^2}\left[C_{lq}^{(3)}\right]_{ijkl}(\bar{l}_i\gamma_\mu\sigma^I l_j)(\bar{q}_k\gamma^\mu\sigma^I q_l)$$

$$q_i \to \left((V^+u)_i, d_i\right)^T = (V_{ji}^* u_j, d_i)^T$$

Charged - $\ni \left[C_{lq}^{(3)}\right]_{33k3}$ [$2\,V_{3m}^+(\bar{\nu}_\tau\gamma_\mu\tau)(\bar{d}_k\gamma^\mu u_m) + 2\,V_{mk}(\bar{\tau}\gamma_\mu\nu_\tau)(\bar{u}_m\gamma^\mu b)$]





``Charm", ``Strange", ``Bottom", ``Top" precisions are complementry

$$\mathcal{L}_{CC}^{Bottom} = -\sum_{f=u,c,t}\left[\frac{2\mathcal{C}_{fb}}{v^2}(\bar{\tau}\gamma_\mu\nu_\tau)(\bar{f}\gamma^\mu b) + \frac{2\mathcal{C}_{fs}}{v^2}(\bar{\tau}\gamma_\mu\nu_\tau)(\bar{f}\gamma^\mu s) + \frac{2\mathcal{C}_{fd}}{v^2}(\bar{\tau}\gamma_\mu\nu_\tau)(\bar{f}\gamma^\mu d)\right]$$

$$\mathcal{C}_{fb} = \left[C_{lq}^{(3)}\right]_{3333} V_{fb} + \left[C_{lq}^{(3)}\right]_{3323} V_{fs} + \left[C_{lq}^{(3)}\right]_{3313} V_{fd}$$

$$\mathcal{C}_{fs} = \left[C_{lq}^{(3)}\right]_{3323} V_{fb}\,, \qquad \mathcal{C}_{fd} = \left[C_{lq}^{(3)}\right]_{3313} V_{fb}$$

Let us look at closely BSM terms

$$\mathcal{C}_{fb} = \left[C_{lq}^{(3)}\right]_{3333} V_{fb} + \left[C_{lq}^{(3)}\right]_{3323} V_{fs} + \left[C_{lq}^{(3)}\right]_{3313} V_{fd}\,, \quad \mathcal{C}_{fs} = \left[C_{lq}^{(3)}\right]_{3323} V_{fb}\,, \quad \mathcal{C}_{fd} = \left[C_{lq}^{(3)}\right]_{3313} V_{fb}$$

Flavor aligned

$$\mathcal{L}_{CC}^{Bottom} = -(\bar{\tau}\gamma_\mu \nu_\tau)\left[\frac{2\left[C_{lq}^{(3)}\right]_{3333} V_{cb} + 2\left[C_{lq}^{(3)}\right]_{3323} V_{cs} + 2\left[C_{lq}^{(3)}\right]_{3313} V_{cd}}{v^2}(\bar{c}\gamma^\mu b)\right.$$

$$+ 2\,\frac{\left[C_{lq}^{(3)}\right]_{3333} V_{cb}}{v^2}(24.9\,(\bar{t}\gamma^\mu b) + 0.09\,(\bar{u}\gamma^\mu b))$$

$$+ 2\,\frac{\left[C_{lq}^{(3)}\right]_{3323} V_{cs}}{v^2}(0.04\,(\bar{t}\gamma^\mu b) + 0.24\,(\bar{u}\gamma^\mu b) + 1.03(\bar{t}\gamma^\mu s) + 0.04(\bar{c}\gamma^\mu s) + 0.004(\bar{u}\gamma^\mu s))$$

$$\left. + 2\,\frac{\left[C_{lq}^{(3)}\right]_{3313} V_{cd}}{v^2}(0.04\,(\bar{t}\gamma^\mu b) + 4.22\,(\bar{u}\gamma^\mu b) + 4.34(\bar{t}\gamma^\mu d) + 0.17(\bar{c}\gamma^\mu d) + 0.015(\bar{u}\gamma^\mu d))\right]$$

$$\frac{V_{ub}}{V_{cb}} : \frac{V_{us}}{V_{cs}} : \frac{V_{ud}}{V_{cd}}$$

$\kappa_{C_{LQk3}}$ = 0.09 : 0.24 : 4.22

Double Bonus:
Higher PDF &
Large CKM enhancement

Flavor alignment vs misalignment :

$U(2)_F$ flavor symmetry, broken only by SM Yukawa

Fuentes-Martin, Isidori, Pages, Yamamoto 19'

$$\left[C_{lq}^{(3)}\right]_{3313} = c_V \lambda V_{31}^*\,, \quad \left[C_{lq}^{(3)}\right]_{3323} = c_V \lambda V_{32}^*$$

$$\left[C_{lq}^{(3)}\right]_{3333} = c_V V_{33}^*$$

$$\mathcal{C}_{cb} = c_V V_{33}^* V_{cb}(1-\lambda)$$

$$\mathcal{C}_{ub} = c_V V_{33}^* V_{ub}(1-\lambda)$$

$$\frac{V_{ub}}{V_{cb}} \sim 0.09$$

Greljo, Camalich, Ruiz-Alvarez 18'
Faroughy, Greljo, Kamanik 16' etc

Competition among BSM : probing UV structure

Focusing on `cb' and `ub' initial states

Interference term

~ 0.09

$$\mathcal{C}_{cb}\mathcal{L}_{cb}\hat{\sigma}^{cb}_{SM-EFT} + \mathcal{C}_{ub}\mathcal{L}_{ub}\hat{\sigma}^{ub}_{SM-EFT} = (4.22, 0.24, 0.09)$$

$$\sim \mathcal{C}_{cb}\mathcal{L}_{cb}\hat{\sigma}^{cb}_{SM-EFT}\left[1 + \frac{V_{ub}}{V_{cb}} \cdot \frac{\mathcal{L}_{ub}}{\mathcal{L}_{cb}} \cdot \frac{C^{ub}}{C^{cb}}\right]$$

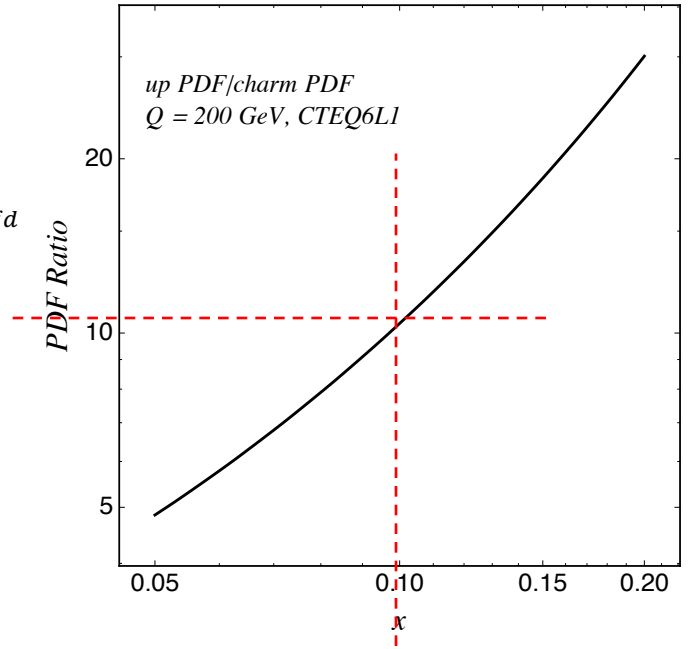
$$\mathcal{C}_{fb} = \left[C^{(3)}_{lq}\right]_{3333} V_{fb} + \left[C^{(3)}_{lq}\right]_{3323} V_{fs} + \left[C^{(3)}_{lq}\right]_{3313} V_{fd}$$

Quadratic term

$$|\mathcal{C}_{cb}|^2\mathcal{L}_{cb}\hat{\sigma}^{cb}_{EFT^2} + |\mathcal{C}_{ub}|^2\mathcal{L}_{ub}\hat{\sigma}^{ub}_{EFT^2}$$

$$\sim |\mathcal{C}_{cb}|^2\mathcal{L}_{cb}\hat{\sigma}^{cb}_{EFT^2}\left[1 + \frac{\mathcal{L}_{ub}}{\mathcal{L}_{cb}} \cdot \frac{|C^{ub}|^2}{|C^{cb}|^2}\right]$$

up PDF/charm PDF
Q=200GeV, CTEQ6L1



$\sim$ 140 GeV at 13 TeV

(peak value of our SM simulation)

[Flavor] precision in high-E tail

``Bottom"

Marzocca, Ui, **SON**, JHEP 2020

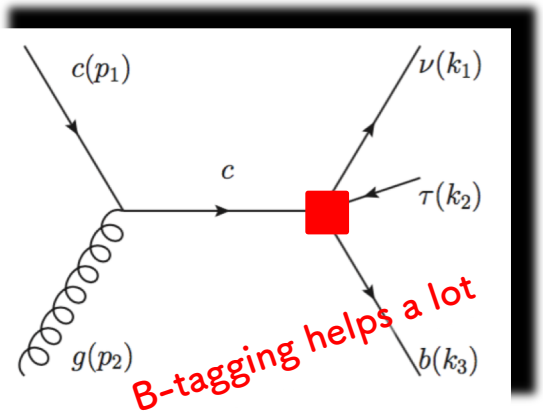
``Bottom Physics Confronts High-pT Lepton Tails"

+ Flavor-tagging

Marzocca, Ui, **SON**, JHEP 2020

``Bottom-flavored Mono-Tau Tails at the LHC"

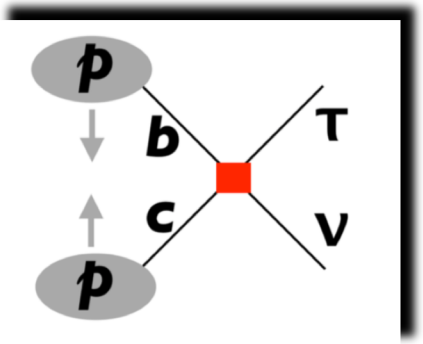
Bottom-flavored Mono-Tau Tails at the LHC

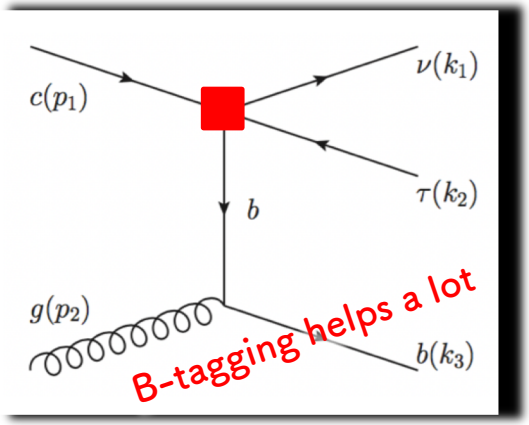


High-E experiment

: through scattering of quarks from PDF

- ✓ accessible to only linear comb of ops



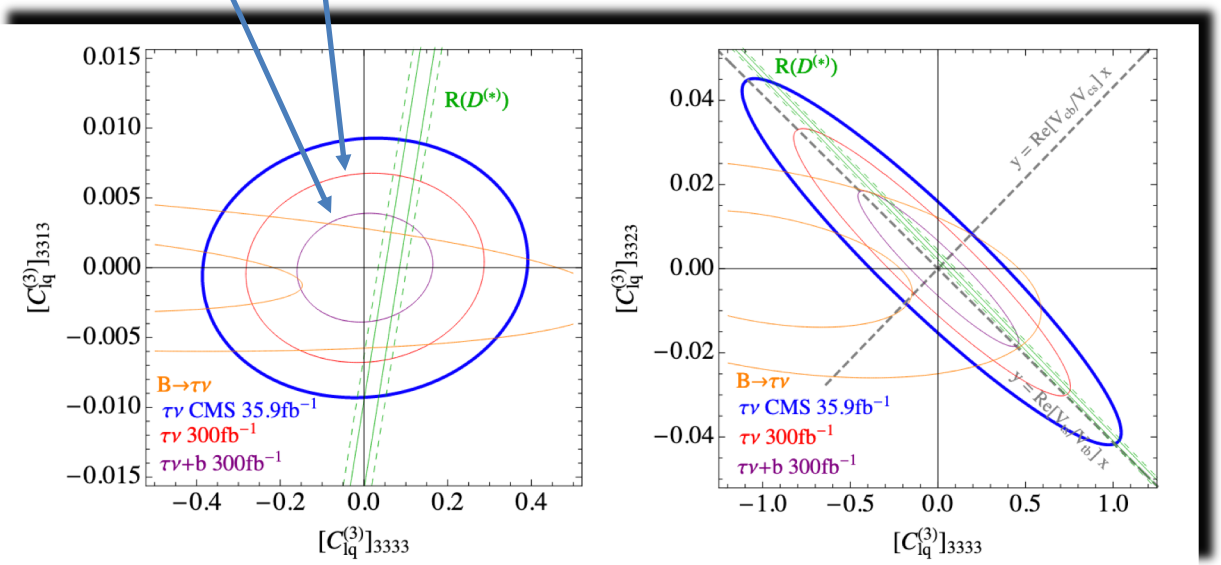


Marzocca, Ui, SON JHEP 2020

Without b-tagging

With b-tagging

- ✓ B-tagging has equivalent benefit as increasing luminosity by 10x

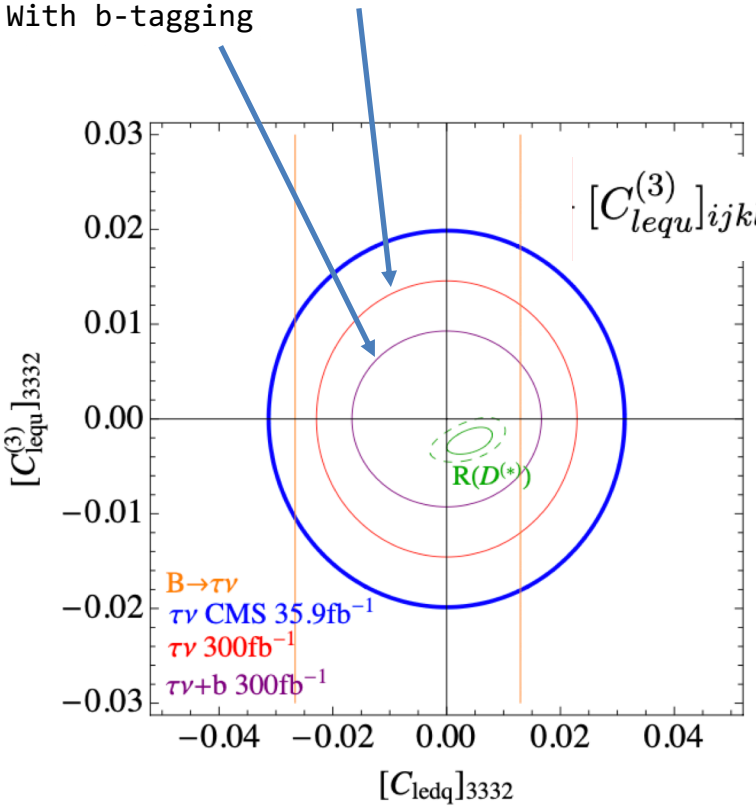


$$-\sum_{f=u,c,t}\left[\frac{2\mathcal{C}_{fb}}{v^2}(\bar{\tau}\gamma_\mu\nu_\tau)(\bar{f}\gamma^\mu b)+\cdots\right]$$

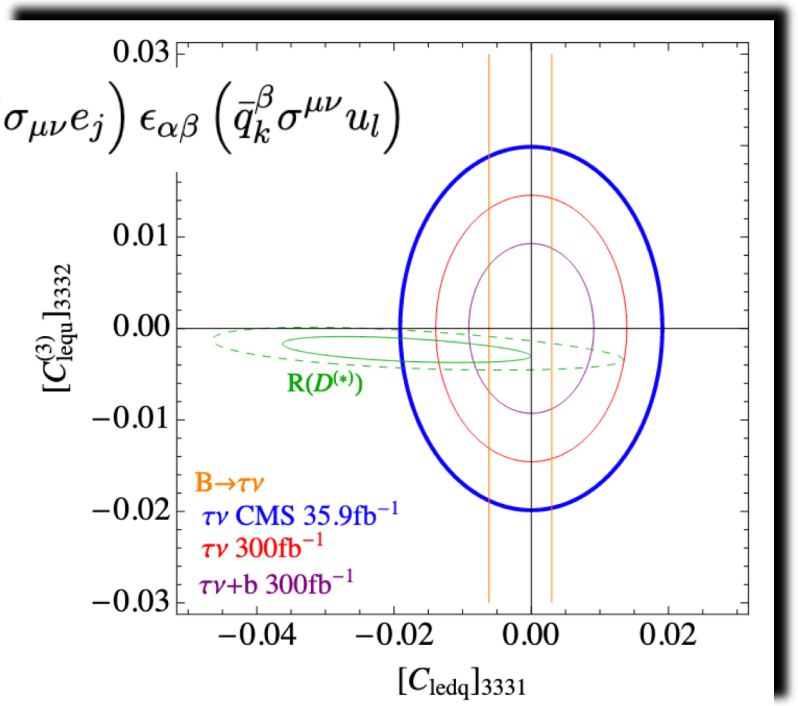
$$\mathcal{C}_{fb}=\left[C_{lq}^{(3)}\right]_{3313}V_{fd}+\left[C_{lq}^{(3)}\right]_{3323}V_{fs}+\left[C_{lq}^{(3)}\right]_{3333}V_{fb}$$

Without b-tagging

With b-tagging



$$[C^{(3)}_{lequ}]_{ijkl} \left(\bar{l}_i^{\alpha} \sigma_{\mu\nu} e_j\right) \epsilon_{\alpha\beta} \left(\bar{q}_k^{\beta} \sigma^{\mu\nu} u_l\right)$$



$$[C_{ledq}]_{ijkl} \left(\bar{l}_i^{\alpha} e_j\right) \left(\bar{d}_k q_l^{\alpha}\right)$$

✓ B-tagging has equivalent benefit as increasing luminosity by 10x

Something to keep it mind/to consider in the EFT approach

1. Validity of EFT

s-channel mediator

$$\frac{g_*^2}{(s - m_{NP}^2)^2} \gtrsim \frac{g_*^2}{m_{NP}^2} = \frac{1}{\Lambda^2}$$

: EFT leads to weaker bounds

t-channel mediator

$$\frac{g_*^2}{(t - m_{NP}^2)^2} \lesssim \frac{g_*^2}{m_{NP}^2}$$

: EFT leads to stronger bounds

dim6*dim6 vs SM*dim8

2. Charge asymmetry

SM Background

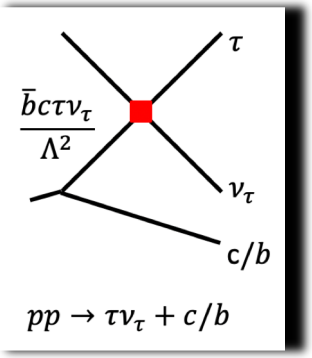
$$pp \to W^{\pm *} \to \tau^{\pm} \nu$$

$$[\, pp \to (W^{+*})\tau^{+}\nu > pp \to (W^{-*})\tau^{-}\nu \,]$$

$$\frac{N(\tau^+)}{N(\tau^-)} > 2$$

VS

EFT contribution



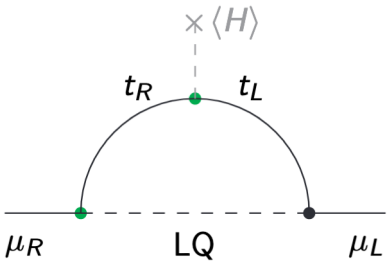
$$\frac{N(\tau^+)}{N(\tau^-)} = 1$$

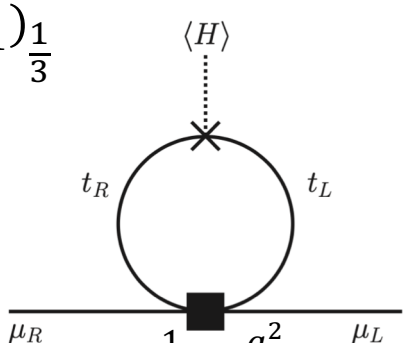
Muon g-2 in high energy tail

: collider probe of LQ/EFT-based muon g-2

Collider probe of LQ/EFT-based muon g-2

$SU(2)_L$ singlet scalar Leptoquark : $(S_1)_{\frac{1}{3}}$





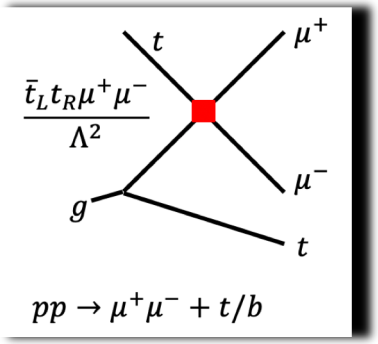
$$\sim \frac{1}{\Lambda^2} \approx \frac{g_{LQ}^2}{m_{LQ}^2}$$

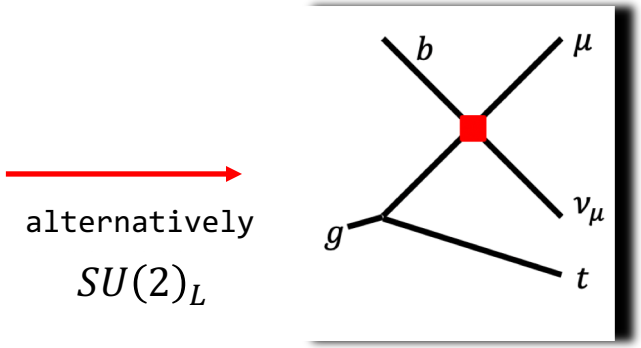
$$(g-2)_\mu : \quad \frac{a_\mu}{m_\mu} \sim \frac{1}{16\pi^2}\frac{m_\mu}{\Lambda^2} \times \frac{m_t}{m_\mu}$$

$$\mathcal{L}_{S_1 LQ} = -\left(h_L^{ij}\overline{q^c}_i \epsilon L_j + h_R^{ij}\overline{u^c}_i e_j\right) S_1 + h.c.$$

$$\rightarrow \quad \mathcal{L}_{EFT} = -\frac{1}{2m_{S_1}^2} h_L^{ij} h_R^{kl\,*} \left[(\bar{u}_k q_i)(\bar{e}_l L_j) - \frac{1}{4}(\bar{u}_k \sigma^{\mu\nu} q_i)(\bar{e}_l \sigma^{\mu\nu} L_j)\right] + h.c.$$

Collider probe





$$pp \to \mu\nu_\tau + t\,(+b)$$

$2 \to 3$ (or $2 \to 4$) process

The END

Leptoquark UV-completion

$SU(2)_L$ singlet vector: U_1^μ

$$\mathcal{L}_{U_1} = h_L^{ij}\left(\bar{u}_i\gamma_\mu P_L \nu_j + \bar{d}_i\gamma_\mu P_L e_j\right)U_1^\mu + h_R^{ij}\left(\bar{d}_i\gamma_\mu P_R e_j\right)U_1^\mu + h.c.$$

$$C_{V_L}^{cb} = \frac{\sqrt{2}}{4G_F V_{cb}}\frac{(Vh_L)^{23}h_L^{*33}}{M_{LQ}^2}\,, \quad C_{S_R}^{cb} = -\frac{\sqrt{2}}{4G_F V_{cb}}\frac{2(Vh_L)^{23}h_R^{*33}}{M_{LQ}^2}$$

$SU(2)_L$ doublet scalar: $\mathcal{R}$

$$\mathcal{L}_{R_2} = \left(h_L^{ij}\bar{u}_i P_L \nu_j + h_R^{ij}\bar{d}_i P_R e_j + \tilde{h}_L^{ij}\bar{d}_i P_L e_j\right)R_2^{2/3} + h.c.$$

$$C_{V_R}^{cb} = \frac{\sqrt{2}}{4G_F V_{cb}}\frac{h_L^{23}\tilde{h}_L^{*33}}{2M_{LQ}^2}\,, \qquad C_{S_L}^{cb} = \frac{\sqrt{2}}{4G_F V_{cb}}\frac{h_L^{23}h_R^{*33}}{2M_{LQ}^2}\,, \qquad C_{S_L}^{cb} = +4C_T^{cb}$$

$$\mathcal{L} = \left(g_1^{ij}\bar{u}_i R_2 \epsilon L^j + \tilde{g}_1^{ij}\bar{L}_j \epsilon \tilde{R}_2^+ d_R^i + g_2^{ij}\bar{e}_R^j q_L^i R_2^+ + h.c.\right) + \lambda\,\mathrm{Tr}(\mathcal{R}^+\mathcal{H})\mathrm{Tr}(\mathcal{H}^+\mathcal{R})$$

$$\mathcal{R} = \left(\tilde{R}_2, R_2\right) = (3,2,2)_{2/3} \qquad \mathcal{H} = \left(\tilde{H}, H\right)$$

$U(1)_X$

$SU(2)_R \times U(1)_X \to U(1)_Y$ $\qquad$ $U(1)_{EM}$

$$(R_2)_{7/6} = \begin{pmatrix} R_2^{5/3} \\ R_2^{2/3} \end{pmatrix}\,, \quad \left(\tilde{R}_2\right)_{1/6} = \begin{pmatrix} \tilde{R}_2^{2/3} \\ \tilde{R}_2^{-1/3} \end{pmatrix}$$

$SU(2)_L$ singlet scalar : $(S_1)_{\frac{1}{3}}$

$$\mathcal{L} = -\left(h_L^{ij}\overline{q^c}_i \epsilon L_j + h_R^{ij}\overline{u^c}_i e_j\right)S_1 + h.c.$$

$$C_{V_L}^{cb} = \frac{\sqrt{2}}{4G_F V_{cb}} \frac{h_L^{33}(Vh_L^*)^{23}}{2M_{LQ}^2}, \qquad C_{S_L}^{cb} = -\frac{\sqrt{2}}{4G_F V_{cb}} \frac{h_L^{33} h_R^{*23}}{2M_{LQ}^2} = -4C_T$$

$SU(2)_L$ triplet scalar : $(S_3)_{\frac{1}{3}}$

$$\mathcal{L} = -\left(h_L^{ij}\overline{q^c}_i \epsilon L_j + h_R^{ij}\overline{u^c}_i e_j\right)S_1 - \lambda_{3L}^{ij}\overline{q^c}_i \epsilon \sigma^a L_j S_3^a + h.c.$$

$$\mathcal{L}_{ueeu} = \frac{1}{2m_{S_1}^2} h_R^{ij} h_R^{kl\,*} (\bar{u}_k \gamma^\mu u_i)(\bar{e}_k \gamma^\mu e_i)$$

$$\mathcal{L}_{qleu} = -\frac{1}{2m_{S_1}^2} h_L^{ij} h_R^{kl\,*} \left[(\bar{u}_k q_i)(\bar{e}_l L_j) - \frac{1}{4}(\bar{u}_k \sigma^{\mu\nu} q_i)(\bar{e}_l \sigma^{\mu\nu} L_j)\right] + h.c.$$