Universität Zürich[UZH]

Charm Physics Confronts High-p_T Lepton Tails

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Palindromic prime!

Based on 2003.12421

In collaboration with **A. Greljo**, **J. Martin Camalich** and **J. Ruiz-Alvarez**

Higgs and Effective Field Theory - HEFT 2020
Granada, 16 April 2020

The SM flavor puzzle

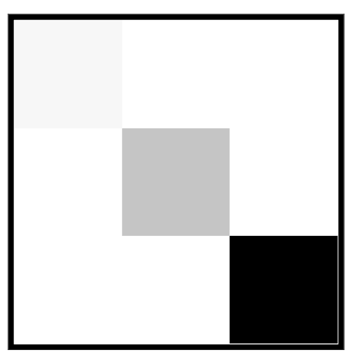
$$\mathscr{L}_{\rm SM} = \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm Yuk}$$

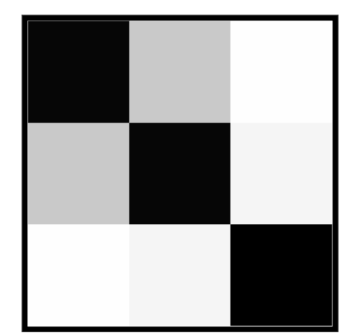
4+2 parameters
(flavor universal)

Flavor non-universal

The SM Yukawa sector is characterized by 13 parameters (for massless neutrinos)
[3 lepton masses + 6 quark masses + 3+1 CKM parameters]

… whose values do not look at all accidental

$M_{u,d,e} \sim$ 

$V_{\rm CKM} \sim$ 

Hints of underlaying symmetry/dynamics?

The SMEFT flavor "problem"

$$\mathscr{L}_{\rm SMEFT} \supset \mathscr{L}_{\rm Gauge} + \mathscr{L}_{\rm Higgs} + \mathscr{L}_{\rm Yuk} + \frac{1}{\Lambda^2}\mathscr{L}^{(6)}$$

4+2 parameters
(flavor universal)

13 parameters
(flavor non-universal)

76 parameters
(if flavor universal)

2499 parameters
(if flavor generic)

[See e.g. 1312.2014]

Approach 1: Assume that possible flavor dynamics is very heavy and impose (strong) flavor assumptions [e.g. $U(3)$ flavor symmetries, Minimal Flavor Violation,…]

Approach 2: Relax flavor assumptions and correlate as many data sets as possible

Low energy/High-p_T data as flavor probes

GeV

Intensity frontier
[Standard approach]

5x more data by '30

50x Belle in '19-'25

+ BES III, NA62, MEG II, Mu3e,…

[Current data: **Flavor anomalies!**]

TeV

High-energy frontier
[Less explored]

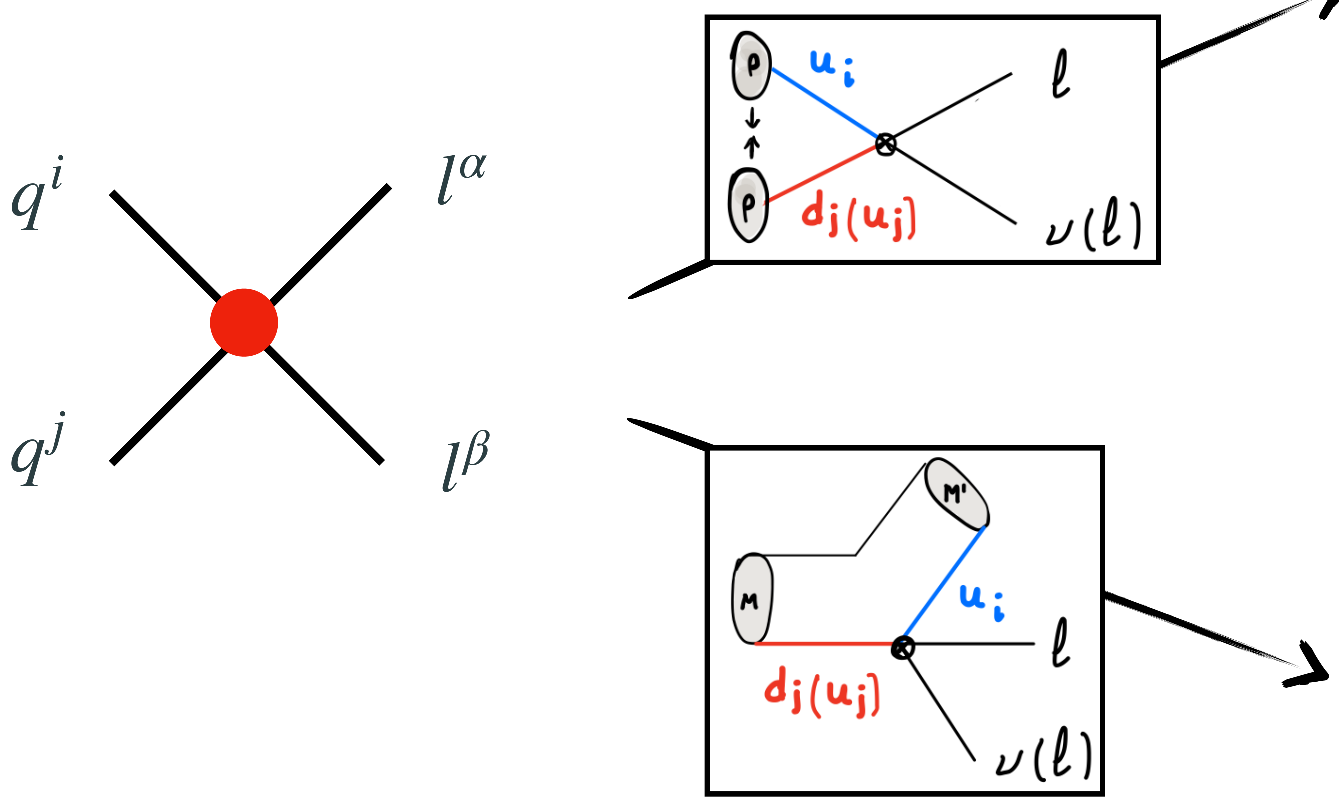
3x more data by '23
20x by '35

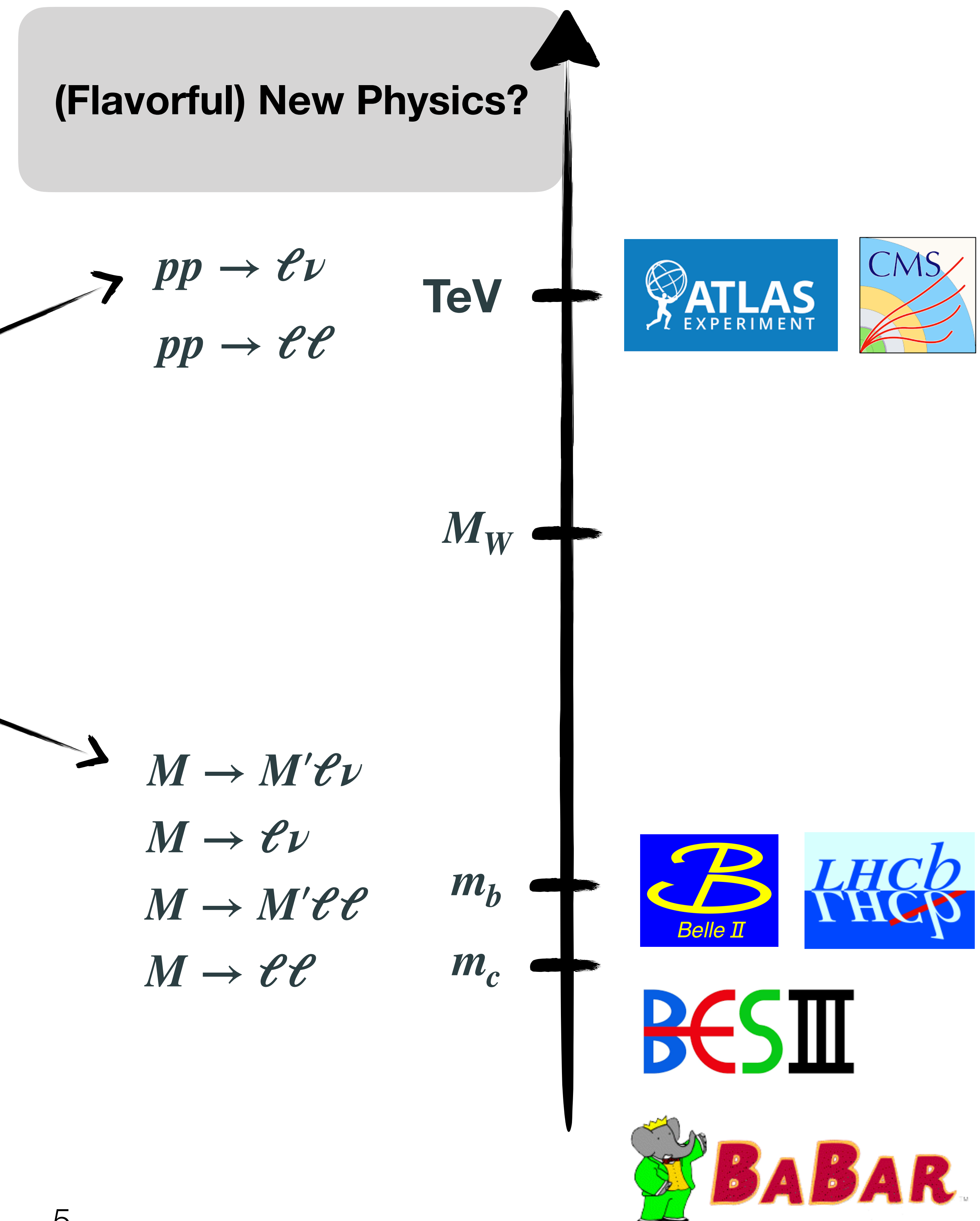
[Current data: **SM-like (at least so far…)**]

Crucial to correlate both datasets to pin down any possible (flavorful) new dynamics!

High-p_T flavor studies:

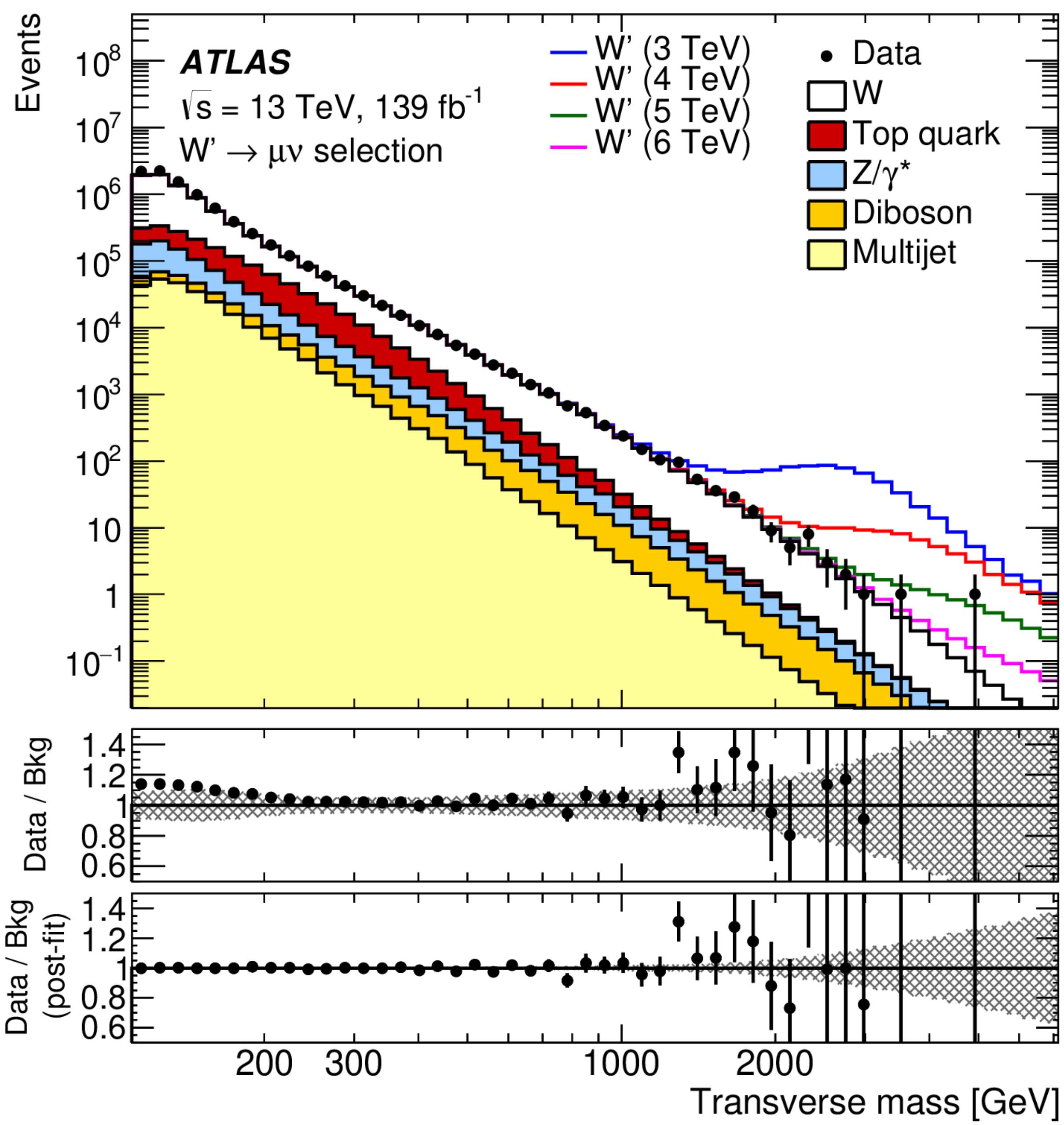
Take advantage of the large statistics at high-energy colliders

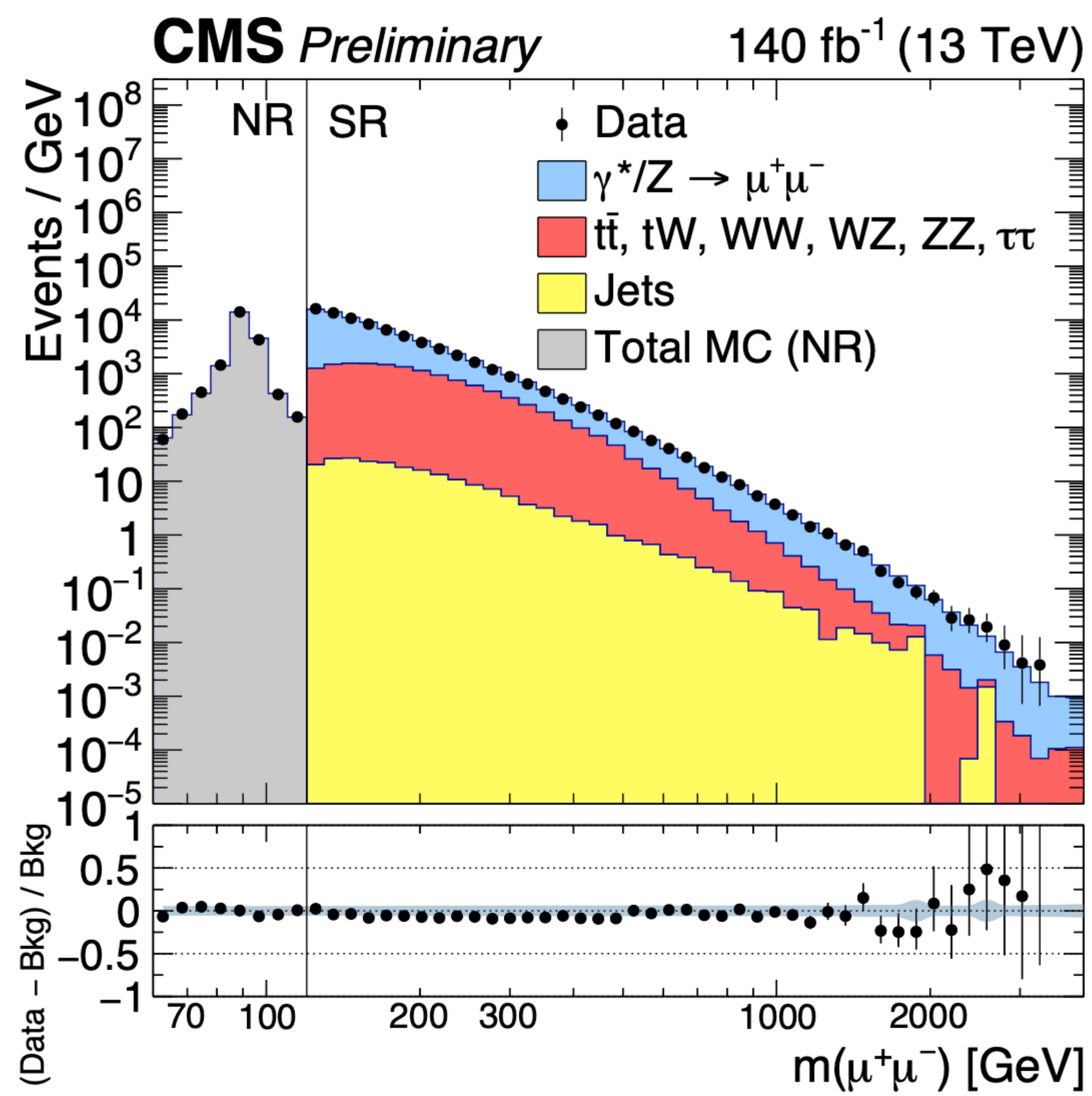




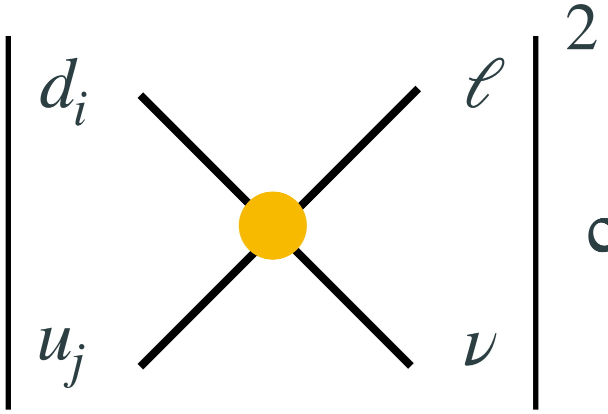
- Same underlaying NP in different kinematical regimes
- **Competitive limits at high-p_T**
- Rather generic/model independent
- Future **improvements at both frontiers**

Strategy: Recast the latest lepton + MET and dilepton searches, and look for New Physics in the tails of the invariant mass distributions (where SM bkg is low)





Example: $(\bar{q}^i_L\gamma_\mu\tau^a q^j_L)(\bar{l}^\alpha_L\gamma_\mu\tau^a l^\beta_L)$



$$\propto |V_{ij}|^2 s \left|\frac{M_W^2}{s-M_W^2} - \epsilon_{V_L}\right|^2$$

$s \ll M_W^2$

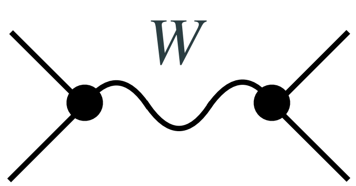
$M \to M'\ell\nu$ $\quad$ $M \to \ell\nu$

- Corrections to observables

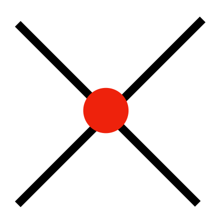
$$\sim |1+\epsilon_{V_L}|^2$$

e.g. $D \to \tau\nu$

$$|\epsilon_{V_L}^{cd\tau\nu_\tau}| \lesssim 0.2$$

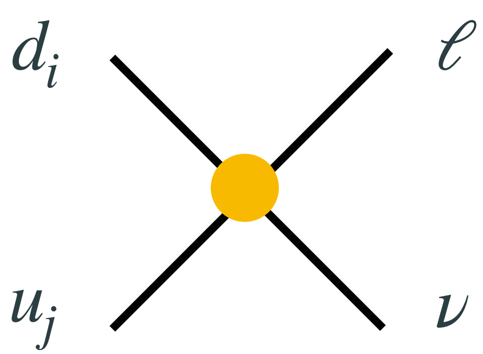


SM



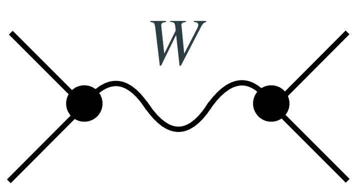
NP

Example: $(\bar{q}_L^i \gamma_\mu \tau^a q_L^j)(\bar{l}_L^\alpha \gamma_\mu \tau^a l_L^\beta)$

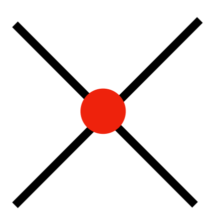


$$\left| \ldots \right|^2 \propto |V_{ij}|^2 s \left| \frac{M_W^2}{s - M_W^2} - \epsilon_{V_L} \right|^2$$

$s \gg M_W^2$



SM

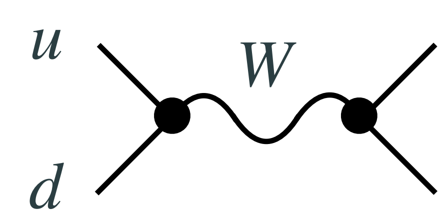


NP

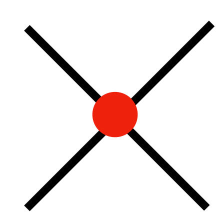
$pp \to \ell\nu$

- Corrections to observables

$$\frac{\mathscr{L}_{ij} \times |V_{ij}|^2 \times \left| \frac{M_W^2}{s} - \epsilon_{V_L} \right|^2}{\mathscr{L}_{u\bar{d}+d\bar{u}} \times |V_{ud}|^2 \times \left(\frac{M_W^2}{s} \right)^2}$$



Background (valence quarks)

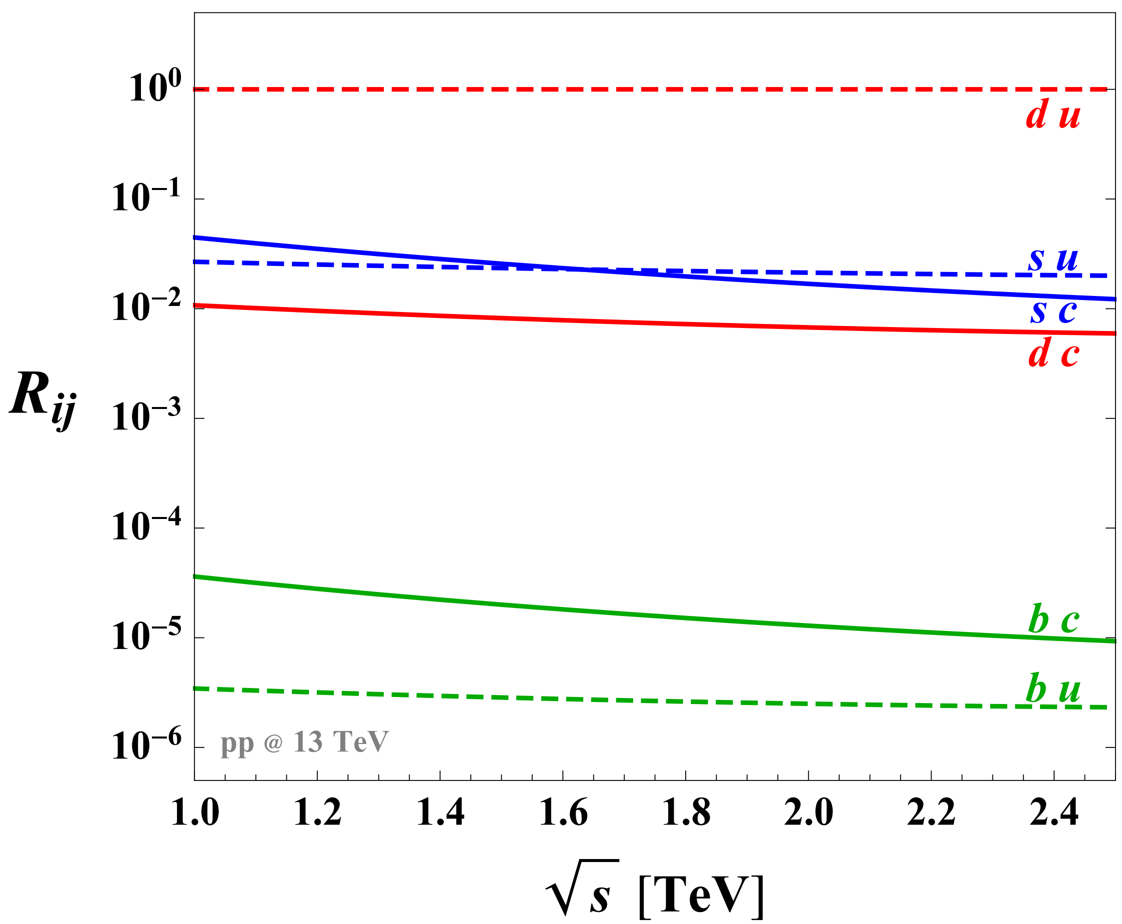


Signal (heavy quarks)

$\mathscr{L}_{ij}$: Parton luminosity

Example: $(\bar{q}^i_L \gamma_\mu \tau^a q^j_L)(\bar{l}^\alpha_L \gamma_\mu \tau^a l^\beta_L)$

LHC is a **five** quark flavor collider



$$R_{ij} = \frac{\mathscr{L}_{i\bar{j}+\bar{i}j} \times |V_{ij}|^2}{\mathscr{L}_{u\bar{d}+\bar{u}d} \times |V_{ud}|^2}$$

$pp \to \ell\nu$

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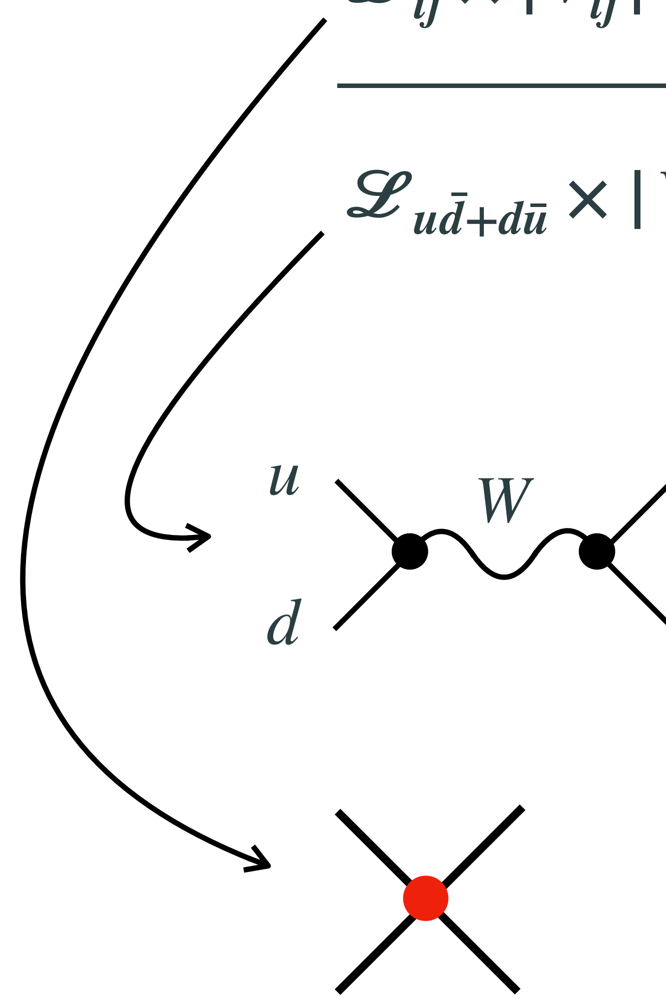
$$\frac{\mathscr{L}_{ij} \times |V_{ij}|^2 \times \left| \frac{M_W^2}{s} - \epsilon_{V_L} \right|^2}{\mathscr{L}_{u\bar{d}+d\bar{u}} \times |V_{ud}|^2 \times \left(\frac{M_W^2}{s} \right)^2}$$



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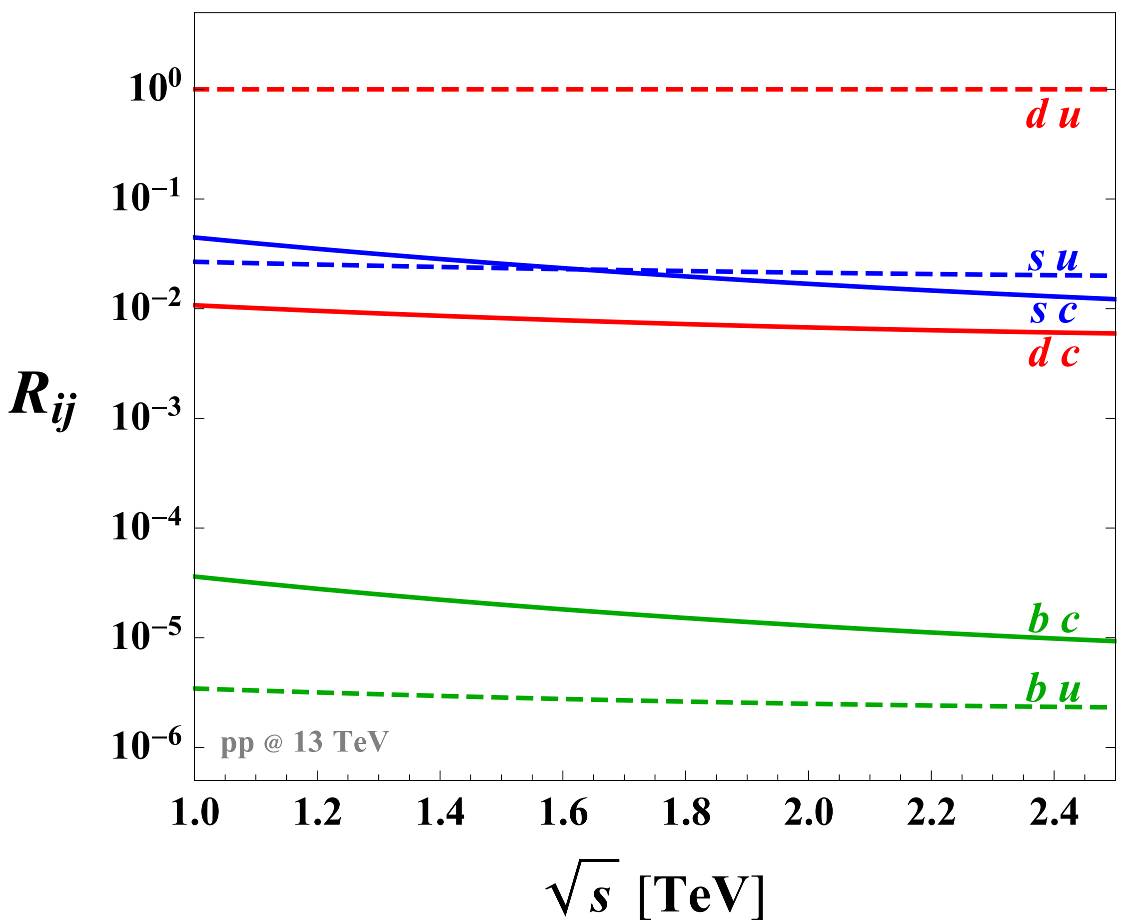

$$R_{ij} = \frac{\mathcal{L}_{i\bar{j}+\bar{i}j} \times |V_{ij}|^2}{\mathcal{L}_{u\bar{d}+\bar{u}d} \times |V_{ud}|^2}$$

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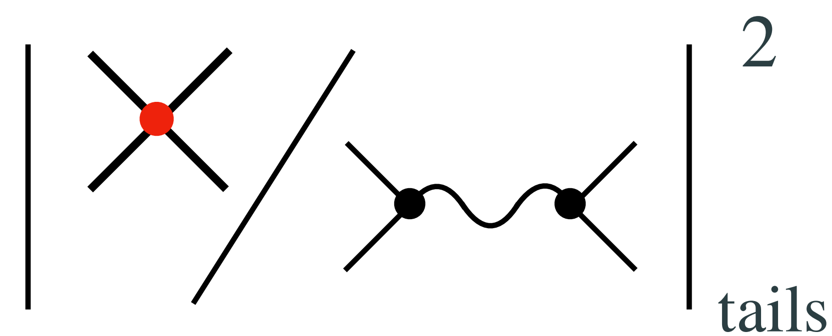

$\lesssim \mathcal{O}(0.1)$

PDF + CKM suppression
$\mathcal{O}(10^{-2})$ for cs, cd

Energy enhancement
$(s/M_W^2)^2 \sim \mathcal{O}(10^5)$

* Neglecting SM interference

Example: $(\bar{q}_L^i \gamma_\mu \tau^a q_L^j)(\bar{l}_L^\alpha \gamma_\mu \tau^a l_L^\beta)$

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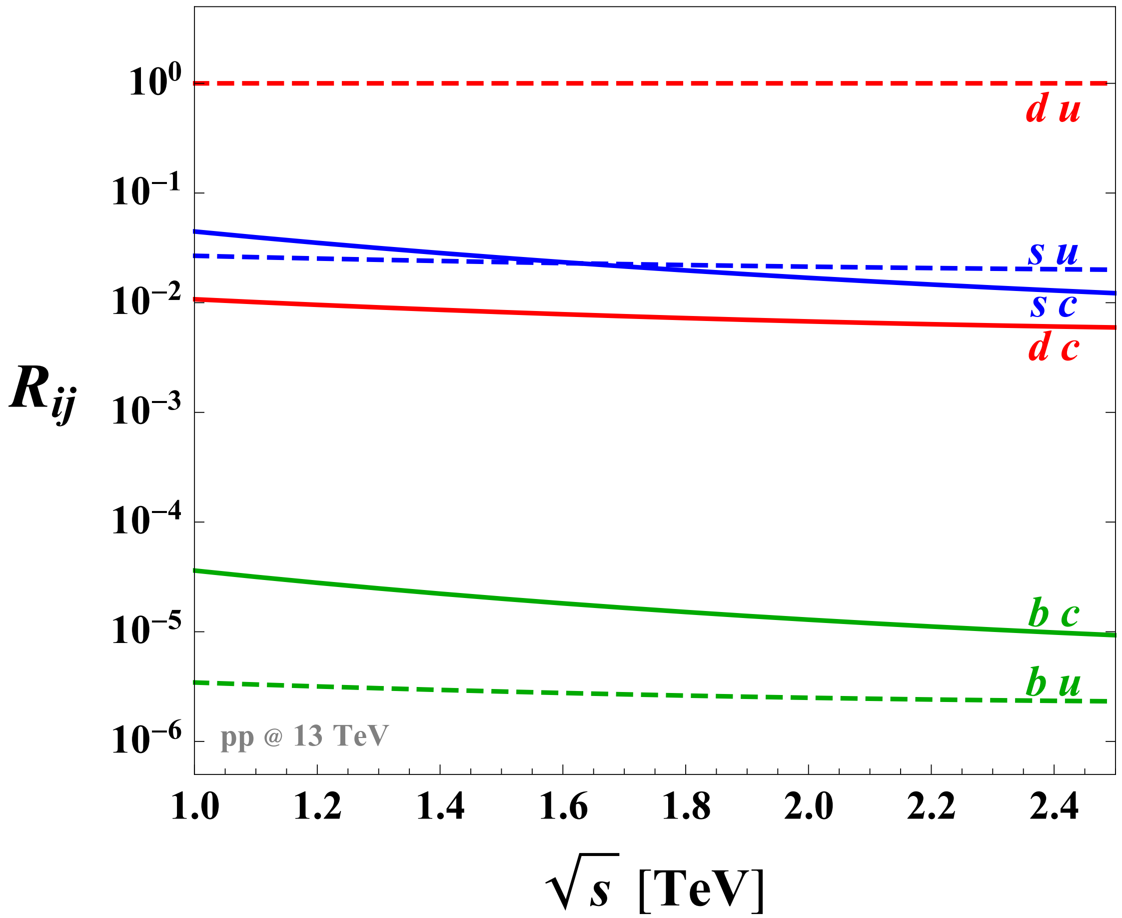


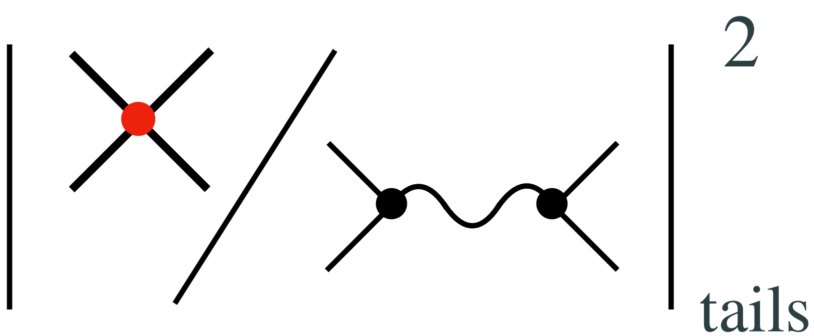
$$R_{ij} = \frac{\mathcal{L}_{i\bar{j}+\bar{i}j} \times |V_{ij}|^2}{\mathcal{L}_{u\bar{d}+\bar{u}d} \times |V_{ud}|^2}$$

$$pp \to \ell\nu$$

Back of the envelop estimates

$\epsilon_{V_L}^{bc} \lesssim \mathcal{O}(0.1)$ $\epsilon_{V_L}^{cs} \lesssim \mathcal{O}(0.01)$

$\epsilon_{V_L}^{bu} \lesssim \mathcal{O}(1)$ $\epsilon_{V_L}^{cd} \lesssim \mathcal{O}(0.01)$



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EFT for $c \to d(s)\ell\nu$ transitions

N.B.: Contributions from possible NP in G_F and V_{ci} are small compared to the precision achieved in charm

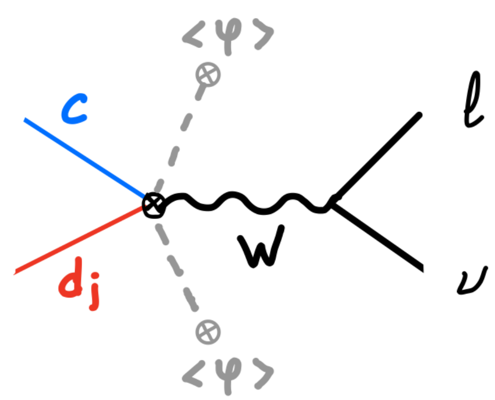
$$\mathcal{L}_{\rm CC} = -\frac{4G_F}{\sqrt{2}} V_{ci} \Big[(1+\epsilon_{V_L}^{\alpha\beta i})\,(\bar\ell_L^\alpha \gamma_\mu \nu_L^\beta)(\bar c_L \gamma^\mu d_L^i) + \epsilon_{V_R}^{\alpha\beta i}\,(\bar\ell_L^\alpha \gamma_\mu \nu_L^\beta)(\bar c_R \gamma^\mu d_R^i) + \epsilon_{S_L}^{\alpha\beta i}\,(\bar\ell_R^\alpha \nu_L^\beta)(\bar c_R d_L^i)$$
$$+ \epsilon_{S_R}^{\alpha\beta i}\,(\bar\ell_R^\alpha \nu_L^\beta)(\bar c_L d_R^i) + \epsilon_T^{\alpha\beta i}\,(\bar\ell_R^\alpha \sigma_{\mu\nu} \nu_L^\beta)(\bar c_R \sigma_{\mu\nu} d_L^i) \Big]$$

The SM + 5 New Physics Wilson coefficients for each transition (90 NP parameters)

Matching to the high-energy theory (SMEFT):

- RGE-induced operator mixing: $\epsilon_{S_L}^{\alpha\beta i}(2\,\mathrm{GeV}) \approx 2.1\,\epsilon_{S_L}^{\alpha\beta i}(\mathrm{TeV}) - 0.3\,\epsilon_T^{\alpha\beta i}(\mathrm{TeV})$
- ϵ_{V_R} is not generated by 4-fermion operators (no enhancement at high-p_T)

$$\mathcal{O}_{\varphi ud} = (\tilde\varphi^\dagger\, iD_\mu\, \varphi)(\bar u_R \gamma^\mu d_R)$$



Lepton flavor universal
(-16 NP parameters)

$D_{(s)}$ decays vs high-p_T data: Charged currents

e.g. $c \to s(d)\tau\nu$ [See 2003.12421 for the rest]

High-p_T LHC limits ($pp \to \ell\nu$)

$$c \to s\tau\nu$$

	$\lvert\epsilon_{V,A}\rvert$	$\lvert\epsilon_{S,P}\rvert$	$\lvert\epsilon_T\rvert$
ATLAS + CMS	0.009	0.018	0.004

$$c \to d\tau\nu$$

	$\lvert\epsilon_{V,A}\rvert$	$\lvert\epsilon_{S,P}\rvert$	$\lvert\epsilon_T\rvert$
ATLAS + CMS	0.016	0.031	0.007

Low-energy limits

$$\mathcal{B}(D_s \to \tau\nu) = (5.55 \pm 0.24)\,\%$$

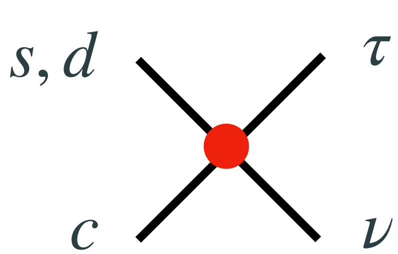
$\lvert\epsilon_A\rvert \lesssim 0.042$ $\lvert\epsilon_P\rvert \lesssim 0.024$

$$\mathcal{B}(D \to \tau\nu) = (1.20 \pm 0.27) \times 10^{-3}$$

$\lvert\epsilon_A\rvert \lesssim 0.24$ $\lvert\epsilon_P\rvert \lesssim 0.13$

Phase-space suppression

$$m_D - m_\tau \approx 90 \text{ MeV}$$

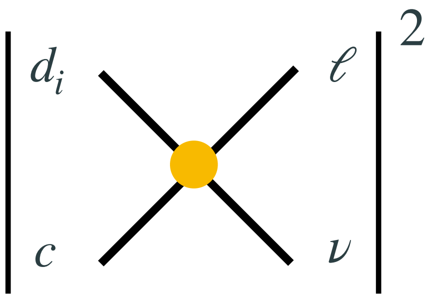


High-p_T beats low energy!

* In all cases but $\epsilon_P^{e\ell i,\mu\ell i}$

Complementarity between low energy and high-p_T

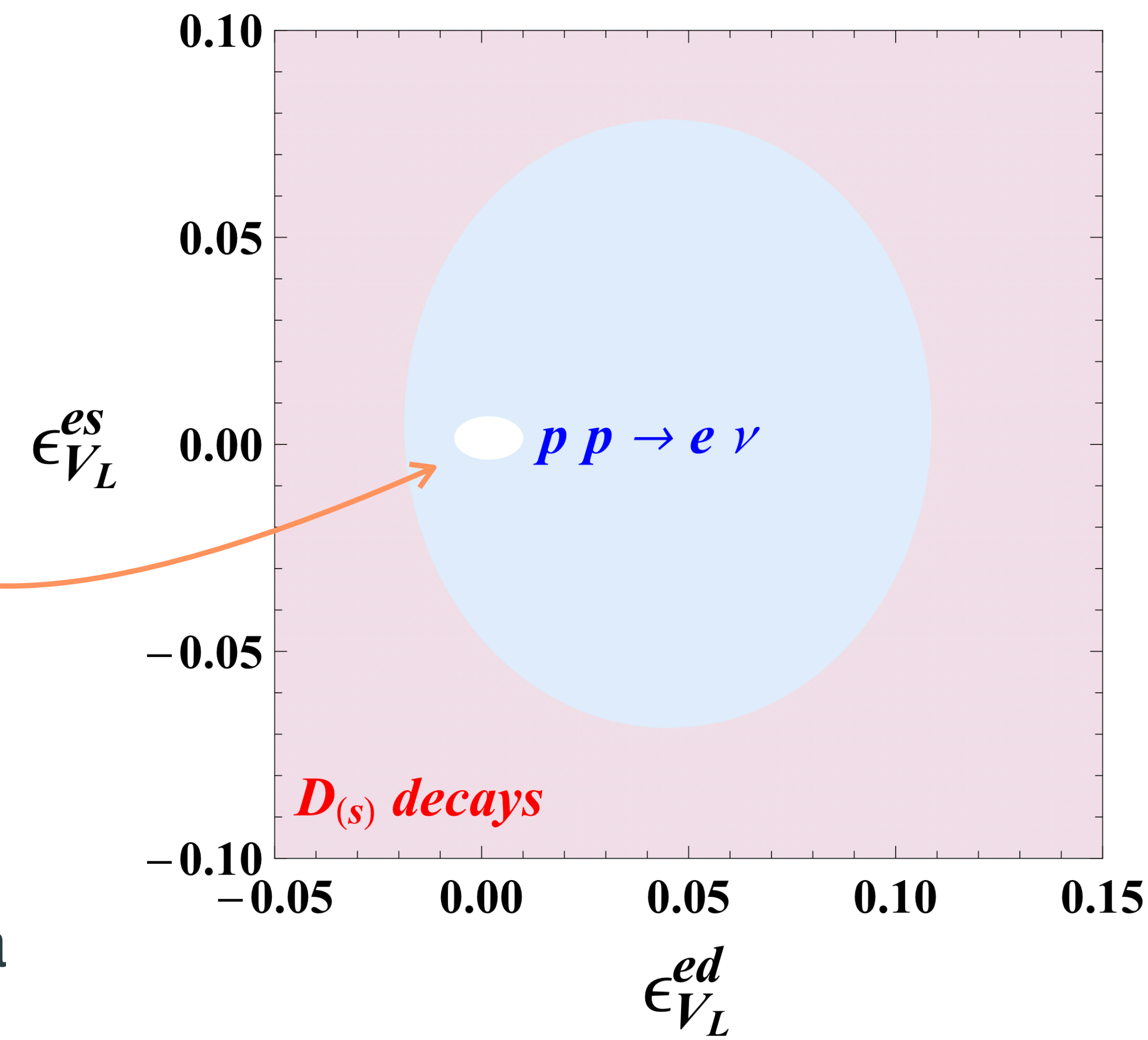
$$\mathscr{L}_W \supset \frac{g}{\sqrt{2}} V_{ci} \left(1 + \delta g^{ci}_{L,R}\right) \bar{c}\gamma^\mu P_{L,R}\, d_i\, W^+_\mu$$



$$\propto s \left| \frac{M_W^2}{s - M_W^2}\left(1 + \delta g^{ci}_{L,R}\right) - \epsilon^{\ell i}_{V_L} \right|^2$$

No energy growing at large s

Strong constraints from high-p_T



Combining $pp \to \ell\nu$ with low-energy flavor data

$$\delta g^{ci}_{L,R} \lesssim \text{few} \times 10^{-2}$$

Competitive with LEP and LHC on-shell W production!

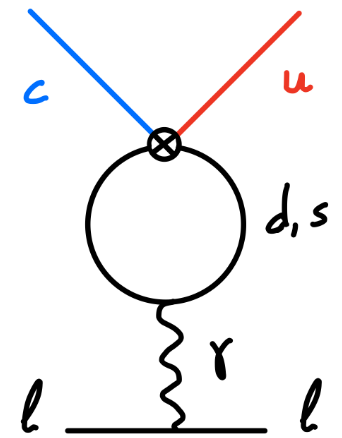
EFT for rare $c \to u\ell\ell^{(\prime)}$ transitions

$$\mathscr{L}_{\rm NC} = \frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\lambda_c\Big[\epsilon^{\alpha\beta}_{V_{LL}}(\bar\ell^{\alpha}_L\gamma_\mu\ell^{\beta}_L)(\bar u_L\gamma^\mu c_L) + \epsilon^{\alpha\beta}_{V_{LR}}(\bar\ell^{\alpha}_L\gamma_\mu\ell^{\beta}_L)(\bar u_R\gamma^\mu c_R) + \epsilon^{\alpha\beta}_{S_{LL}}(\bar\ell^{\alpha}_R\ell^{\beta}_L)(\bar u_R c_L)$$
$$+\epsilon^{\alpha\beta}_{S_{LR}}(\bar\ell^{\alpha}_R\ell^{\beta}_L)(\bar u_L c_R)+\epsilon^{\alpha\beta}_{T_L}(\bar\ell^{\alpha}_R\sigma_{\mu\nu}\ell^{\beta}_L)(\bar u_R\sigma_{\mu\nu}c_L) + (L\leftrightarrow R)\Big]$$

10 New Physics Wilson coefficients for each transition (90 NP parameters)

SM short-distance extremely GIM suppressed

Main SM contributions due to long-distance effects



Matching to the high-energy theory (SMEFT):

- RGE-induced operator mixing: $\epsilon^{\alpha\beta i}_{S_{LL,RR}}(2\,{\rm GeV}) \approx 2.1\,\epsilon^{\alpha\beta i}_{S_{LL,RR}}({\rm TeV}) - 0.5\,\epsilon^{\alpha\beta i}_{T_{L,R}}({\rm TeV})$
- Some Wilson coefficient are absent: $\epsilon^{\alpha\beta}_{S_{LR}} = \epsilon^{\alpha\beta}_{S_{RL}} = 0$ (-18 NP parameters)

Rare D decays vs high-p_T data: Neutral currents

High-p_T LHC limits ($pp \to \ell\ell$)

	$\vert\epsilon_{V_i}^{\ell\ell}\vert$	$\vert\epsilon_{S_{LL,RR}}^{\ell\ell}\vert$	$\vert\epsilon_{T_{L,R}}^{\ell\ell}\vert$
$c \to uee$	13	32	5.2
$c \to u\mu\mu$	7.0	17	2.8
$c \to u\tau\tau$	25	60	11

Limits will improve by a factor $2-3$ with full HL-LHC statistics
[assuming statistically dominated errors]

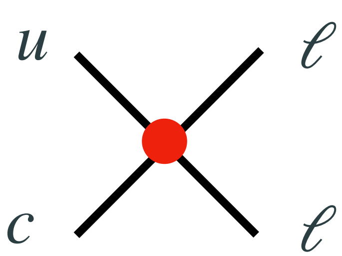
Low-energy limits [Bause et al., 1909.11108]
[from $D \to \pi\ell\ell$, $D \to \ell\ell$]

$$|\epsilon_{V_i}^{ee}| \lesssim 42, \quad |\epsilon_{S_{LL,RR}}^{ee}| \lesssim 1.5, \quad |\epsilon_{T_{L,R}}^{ee}| \lesssim 66$$

$$|\epsilon_{V_i}^{\mu\mu}| \lesssim 8, \quad |\epsilon_{S_{LL,RR}}^{\mu\mu}| \lesssim 0.4, \quad |\epsilon_{T_{L,R}}^{\mu\mu}| \lesssim 9$$

$D \to \tau\tau, \tau\mu$, forbidden by phase space ($m_D - m_\tau \approx 90\,\text{MeV}$)

Improvements limited by SM long-distance effects [except for $D \to \ell\ell$ or SM null tests]



Again, high-p_T beats low energy!

* Except for $\epsilon_{S_{LL,RR}}^{ee,\,\mu\mu,\,e\mu}$

Beyond charm decays: PDF rescaling

Estimates on $\Delta S = 1$ and $\Delta B = 1$ rare transitions from PDF rescaling of $\Delta C = 1$ limits (similar signal acceptance)

$$|\epsilon_X^{\alpha\beta ji}| = |\epsilon_X^{\alpha\beta uc}| \frac{\lambda_c}{|V_{ti}V_{tj}^*| \sqrt{L_{ij:cu}}}$$

Flavor rescaling

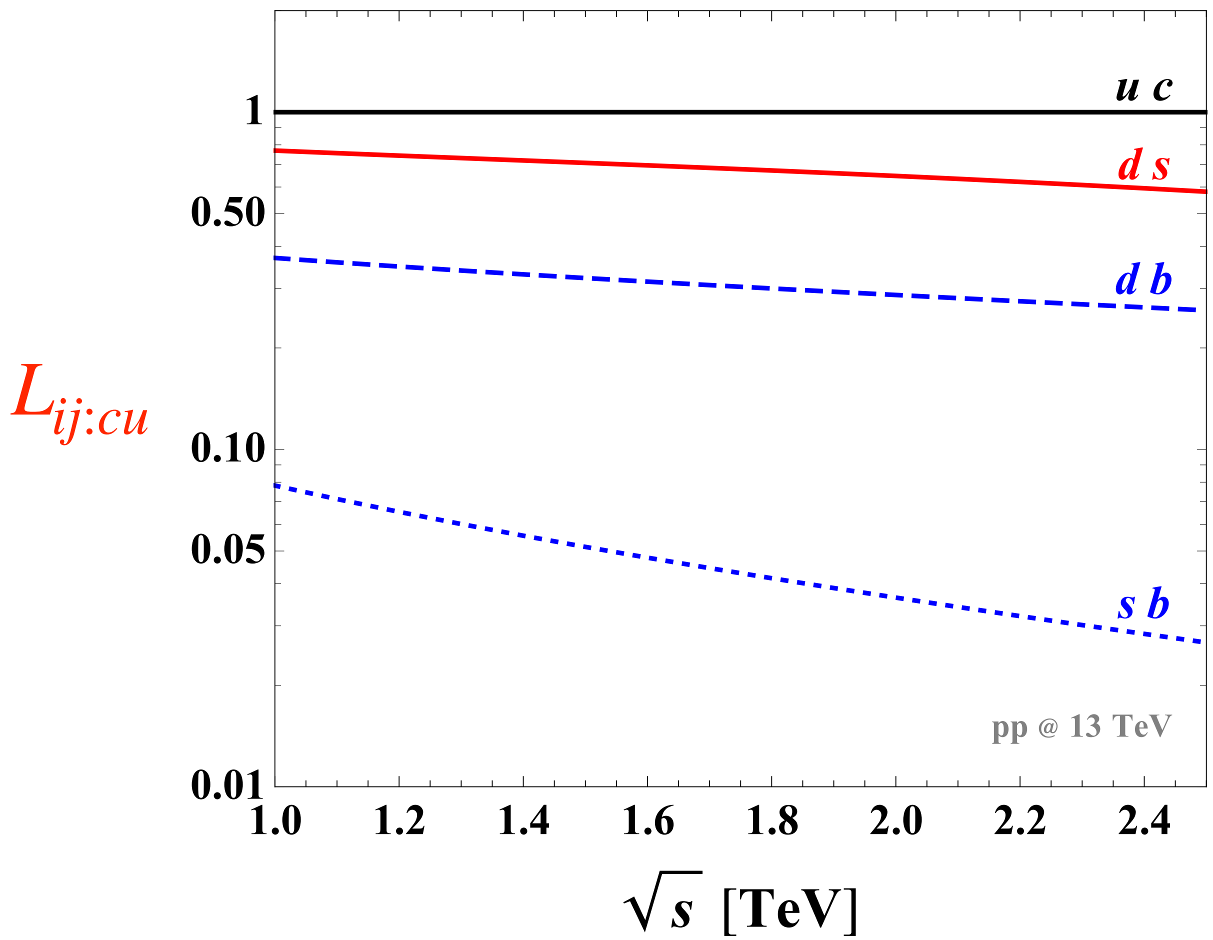
PDF rescaling

$$L_{ij:cu} = \frac{\mathscr{L}_{d_i\bar{d}_j} + \mathscr{L}_{d_j\bar{d}_i}}{\mathscr{L}_{c\bar{u}} + \mathscr{L}_{u\bar{c}}}$$

$$|\epsilon_X^{\alpha\beta db}| \approx 40\,|\epsilon_X^{\alpha\beta uc}|$$

$$|\epsilon_X^{\alpha\beta sb}| \approx 20\,|\epsilon_X^{\alpha\beta uc}|$$

$$|\epsilon_X^{\alpha\beta ds}| \approx 700\,|\epsilon_X^{\alpha\beta uc}|$$



e.g. $b \to s\tau\tau$

$$\mathscr{B}(B \to K\tau\tau) < 2.68 \times 10^{-3}$$

$$\epsilon_{V_{LL}}^{\tau\tau sb} < 990$$

$pp \to \tau\tau$ from uc with PDF rescaling

$$\epsilon_{V_{LL}}^{\tau\tau sb} < 420$$

Most sensitive bin $\sqrt{s} \sim [1{,}1.5]$ TeV

Constraints from $SU(2)_L$ invariance

Example: $(\bar{q}^i_L \gamma_\mu \tau^a q^j_L)(\bar{l}^\alpha_L \gamma_\mu \tau^a l^\beta_L)$ $[C^{(3)}_{lq}]$

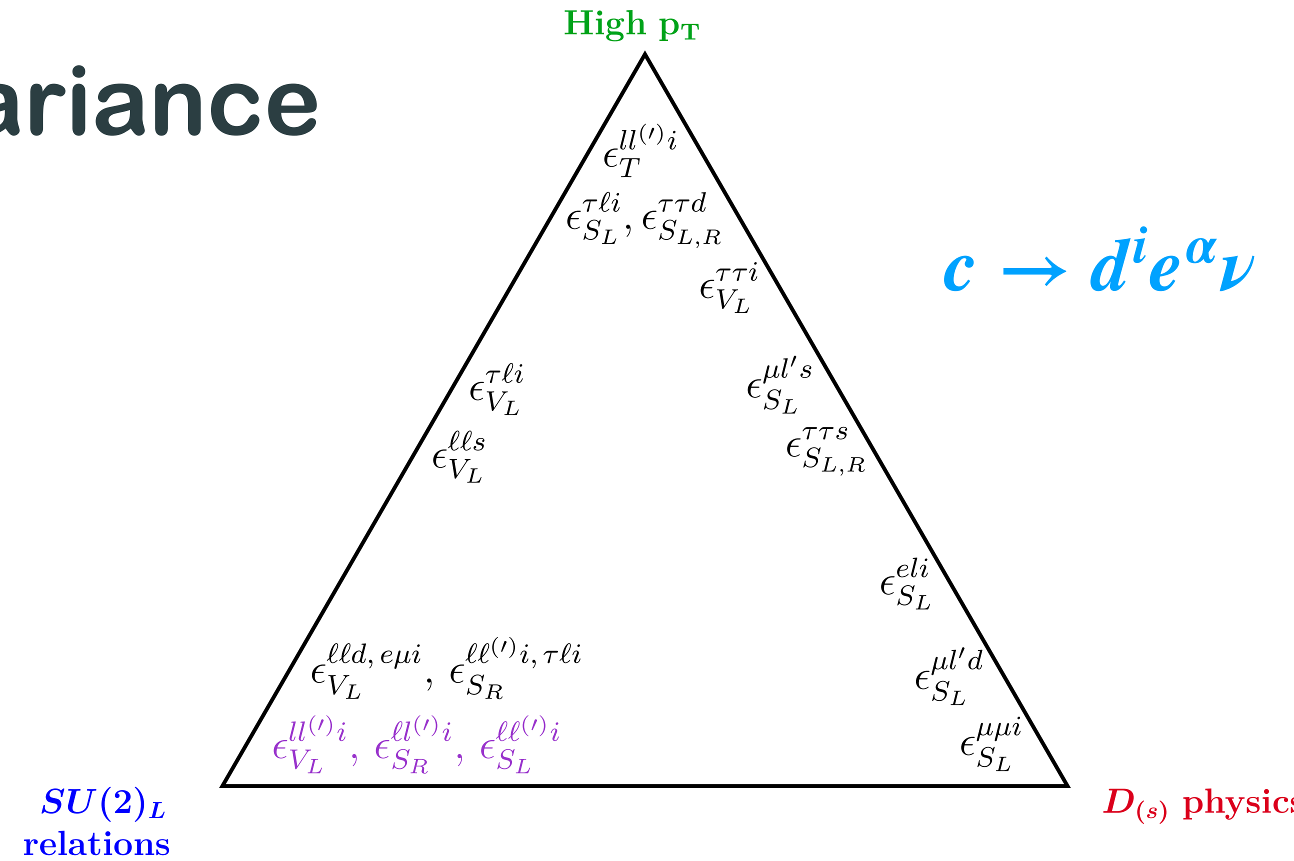
$$q^i_L = \begin{pmatrix} V_u^{ij}\, u^j_L \\ V_d^{ij}\, d^j_L \end{pmatrix} \qquad l^\alpha_L = \begin{pmatrix} \nu^\alpha_L \\ e^\alpha_L \end{pmatrix}$$

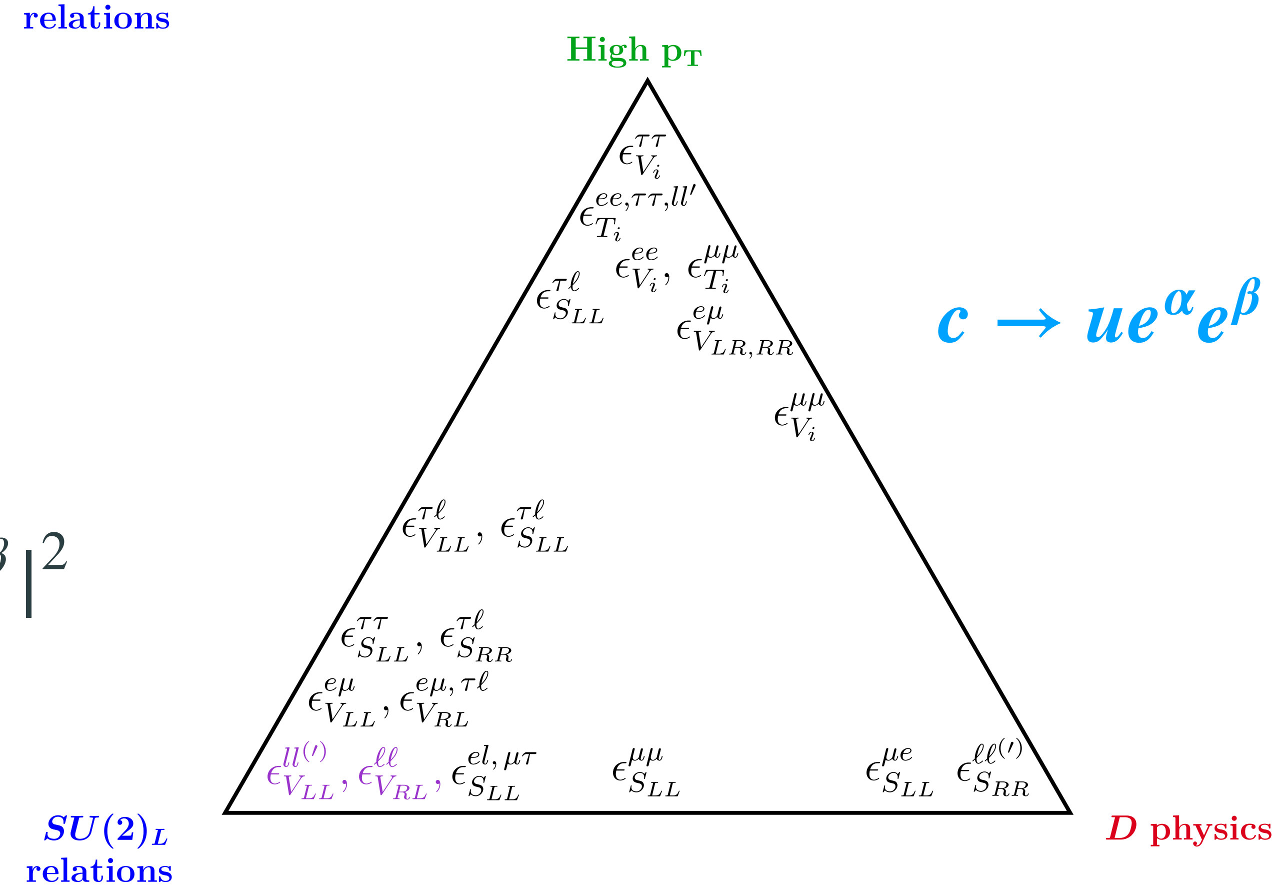
Contributions not only to $\Delta C = 1$
(correlations with other observables)

Sometimes they can be avoided e.g.

$$\mathscr{B}(K \to \pi \nu\nu) \propto |\, V_d^{*is}\, V_d^{jd}\, [C^{(3)}_{lq} - C^{(1)}_{lq}]^{ij\alpha\beta}\,|^2$$

Tuned BSM scenarios or underlaying dynamical mechanisms





$\ell = e, \mu$ $\qquad l = e, \mu, \tau$

If $V_d \approx V_{\rm CKM}$ and no WC cancellations

Possible caveats to the high-p_T constraints

★ $(dim\,6)^2$ vs $\mathrm{SM} \times dim\,8$

$$\hat{\sigma}(s) = \frac{G_F^2 |V_{ci}|^2}{18\pi}\, s \left[\frac{m_W^4}{s^2} - 2\left(\frac{m_W^2}{s} \mathrm{Re}(\epsilon_{V_L}^{(6)}) + \frac{m_W^2}{M_{\mathrm{NP}}^2} \mathrm{Re}(\epsilon_{V_L}^{(8)}) \right) + |\epsilon_{V_L}^{(6)}|^2 \right] + \mathcal{O}\left(\frac{1}{M_{\mathrm{NP}}^6} \right)$$

- $\mathrm{SM} \times dim\,8$ subdominant if $\epsilon_{V_L}^{(6)} \approx \epsilon_{V_L}^{(8)}$ (as expected with tree-level mediators), since $s < M_{\mathrm{NP}}^2$ by assumption
- Not a problem for LFV or neutral currents (SM extremely GIM suppressed)

★ NP mediator masses below the EFT validity range

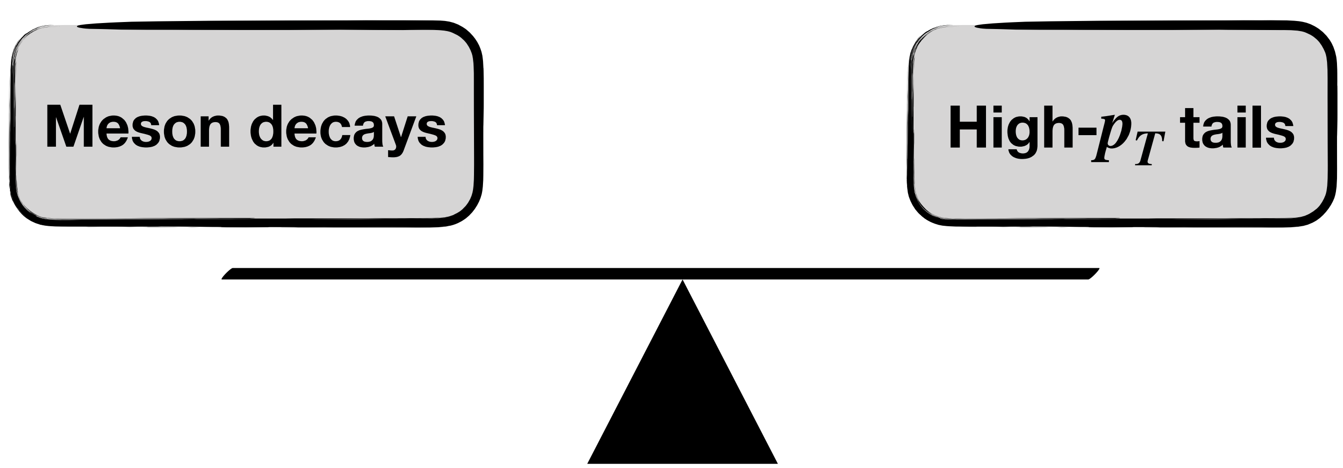
- Unlikely for charged currents (direct searches on pair produced mediators), possible in neutral current (e.g. Z' could avoid direct searches)
- Even when the EFT validity is not guaranteed, limits offer relevant information in a larger kinematical regime [s-channel (resonant) vs t/u-channel (good estimate)]

Conclusions

- Non-resonant high-p_T searches offer an alternative flavor probe (PDF suppression can be overcome by the energy growing)

- NP in (semi)leptonic charm decays scrutinized by high-p_T Drell-Yan data (and in other (semi)leptonic decays as well, e.g. $b \to s\tau\tau$)

- Interesting complementarity between charm physics and high-p_T (e.g. W vertex corrections)



¡Gracias!