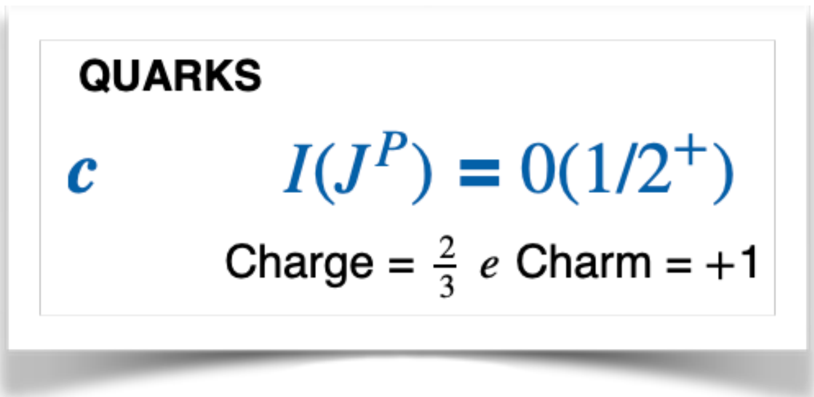
Charm Physics Confronts High-pT Lepton Tails

Admir Greljo

2003.12421

IJPPM, 06.05.2020

Introduction


QUARKS

c $\quad I(J^P) = 0(1/2^+)$

Charge = $\frac{2}{3}$ e Charm = +1

- '70 The GIM mechanism
- '74 November revolution **J/ψ**
- '19 CP violation

- Charm is a cornerstone of the SM
- A unique arena for QCD and Flavor physics

Introduction

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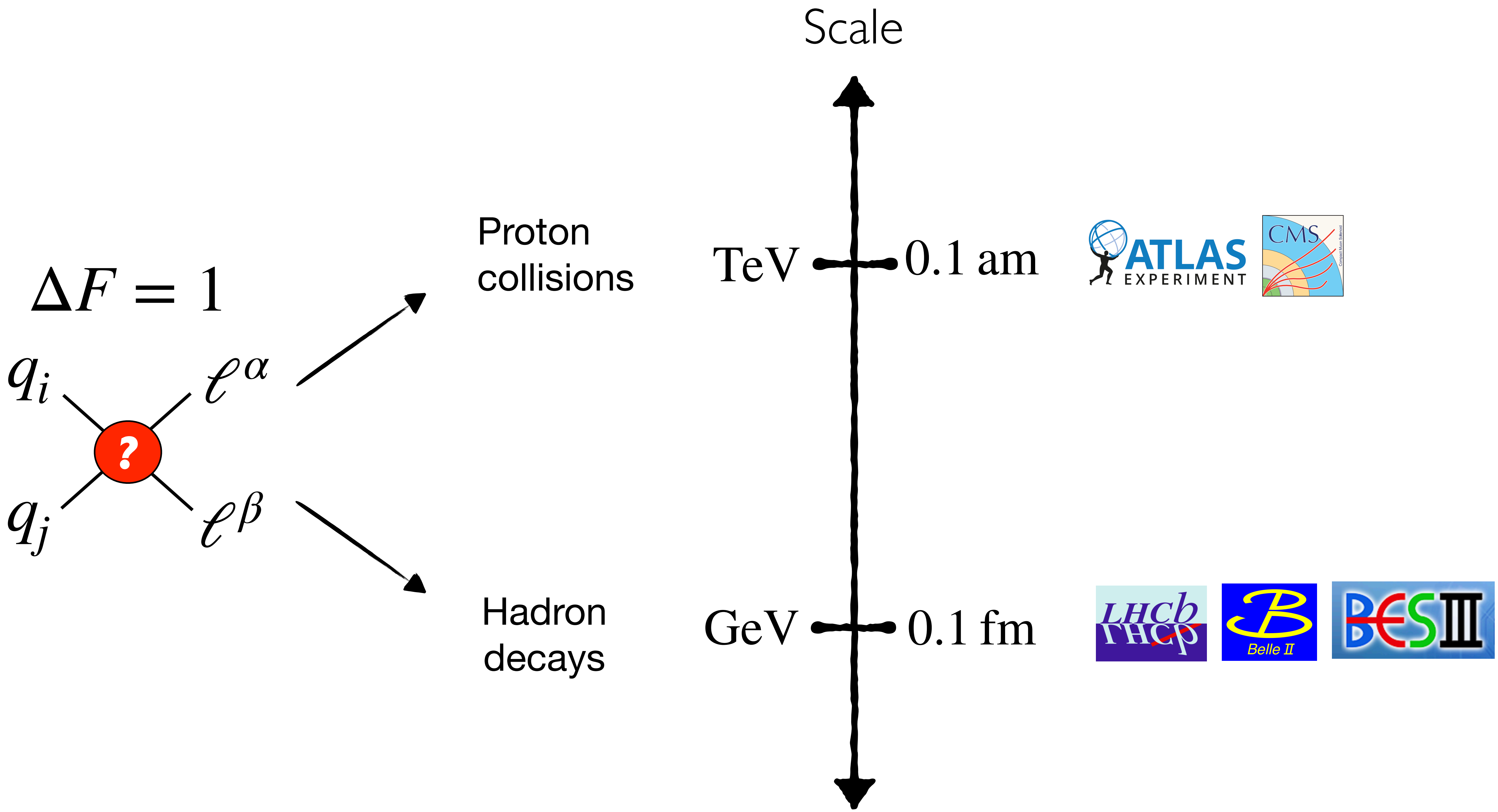
- A unique arena for QCD and Flavor physics

Question: How unique is the charm sector as a probe of <u>New Physics</u> within the zoo of flavor and collider phenomenology? What is the role of charm in a broader quest for a microscopic theory beyond the SM?

Opportunities across the scales



Contemporary experiments

High-energy Frontier

TeV

3 x more luminosity by ’23
20 x by ’35

Harvesting large statistics!

High-intensity Frontier

GeV

5 x more
by ’30

’19 - ’25
50 x Belle

10 x more

Contents

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Javier Fuentes-Martin, Admir Greljo, Jorge Martin Camalich, Jose David Ruiz-Alvarez

2003.12421: *The highlight*

Rare FCNC c → u l+ l- transition

- Tiny SM decay rates:
short-distance contribution negligible, efficient GIM suppression, long-distance dominated
$BR(D^0 \to \mu^+\mu^-) \sim \mathcal{O}(10^{-13})$

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- Take NP solely affecting charm

$$\mathscr{L}_{NP} \approx \frac{\epsilon_V^{\ell\ell}}{15\,\mathrm{TeV}} (\bar{\ell}_R \gamma^\mu \ell_R)(\bar{u}_R \gamma^\mu c_R)$$

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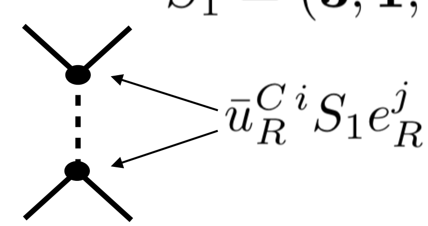
e.g. $S_1 = (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$



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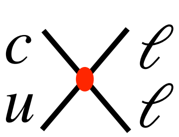
- Calculate

c u > l⁺ l⁻ Drell-Yan 

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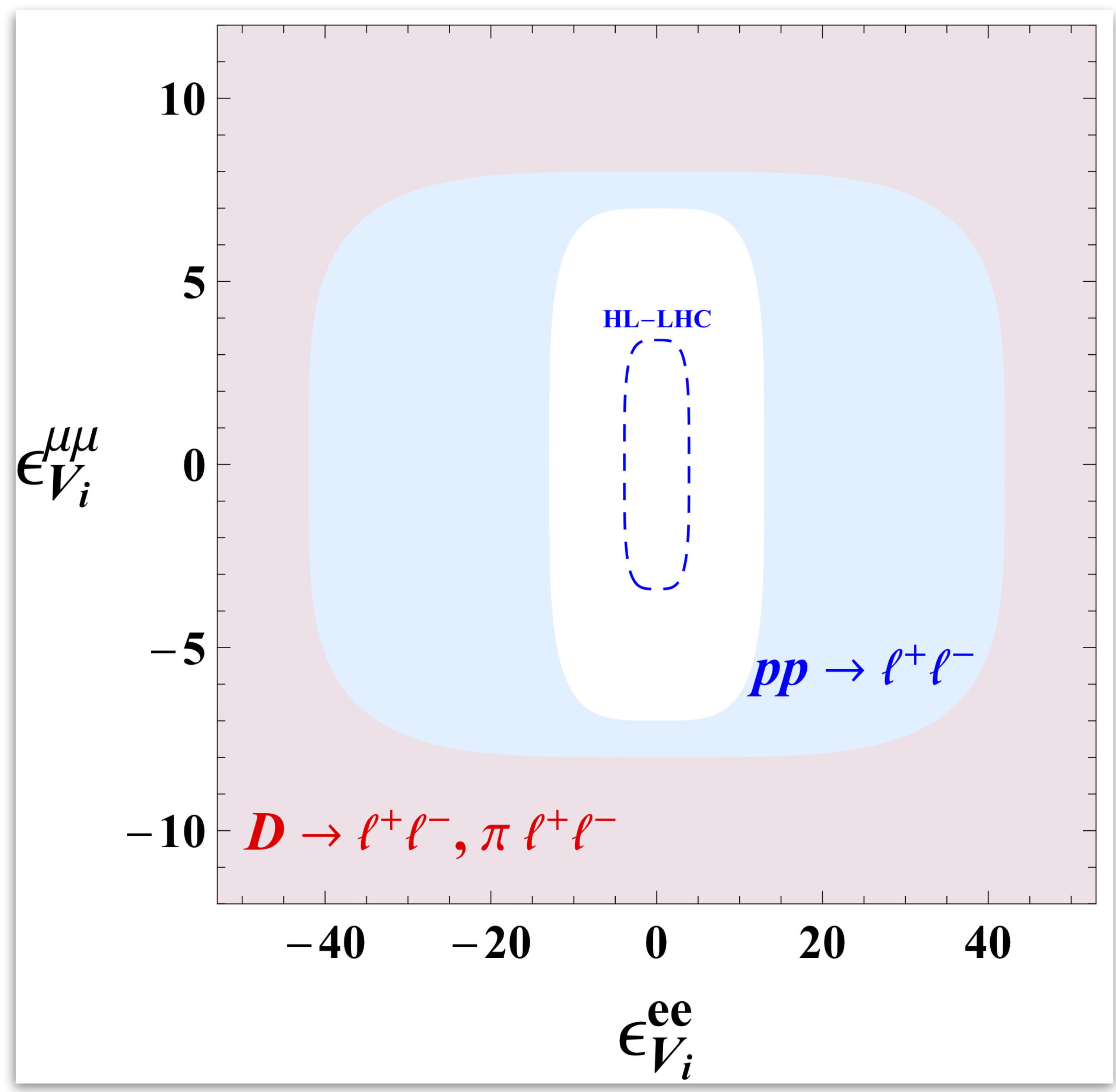

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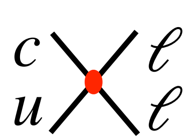
c u > l+ l⁻ Drell-Yan 

Charged currents

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

Theoretical framework

2.2 The low-energy effective theory

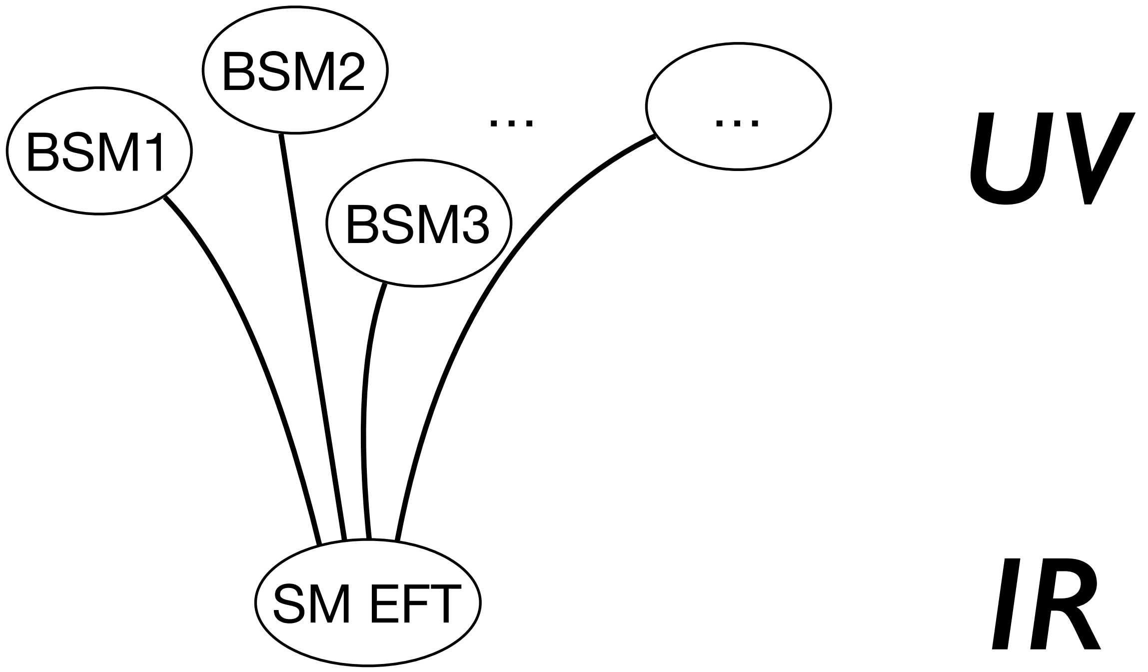
$$\mathcal{L}_{\rm CC} = -\frac{4G_F}{\sqrt{2}} V_{ci} \left[\left(1 + \epsilon^{\alpha\beta i}_{V_L}\right) \mathcal{O}^{\alpha\beta i}_{V_L} + \epsilon^{\alpha\beta i}_{V_R}\, \mathcal{O}^{\alpha\beta i}_{V_R} + \epsilon^{\alpha\beta i}_{S_L}\, \mathcal{O}^{\alpha\beta i}_{S_L} + \epsilon^{\alpha\beta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

$\epsilon^{\alpha\beta i}_{X,SM} = 0$ for all X

$$\begin{aligned}
\mathcal{O}^{\alpha\beta i}_{V_L} &= (\bar{e}^{\alpha}_{L}\gamma_\mu \nu^{\beta}_{L})(\bar{c}_L\gamma^\mu d^i_L)\,, & \mathcal{O}^{\alpha\beta i}_{V_R} &= (\bar{e}^{\alpha}_{L}\gamma_\mu \nu^{\beta}_{L})(\bar{c}_R\gamma^\mu d^i_R)\,,\\
\mathcal{O}^{\alpha\beta i}_{S_L} &= (\bar{e}^{\alpha}_{R}\, \nu^{\beta}_{L})(\bar{c}_R\, d^i_L)\,, & \mathcal{O}^{\alpha\beta i}_{S_R} &= (\bar{e}^{\alpha}_{R}\, \nu^{\beta}_{L})(\bar{c}_L\, d^i_R)\,,\\
\mathcal{O}^{\alpha\beta i}_{T} &= (\bar{e}^{\alpha}_{R}\sigma_{\mu\nu} \nu^{\beta}_{L})(\bar{c}_R\sigma^{\mu\nu} d^i_L)\,.
\end{aligned}$$

Theoretical framework

2.1 The high-energy effective theory



$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{v^2} \sum_k \mathcal{C}_k\, \mathcal{O}_k$$

Theoretical framework

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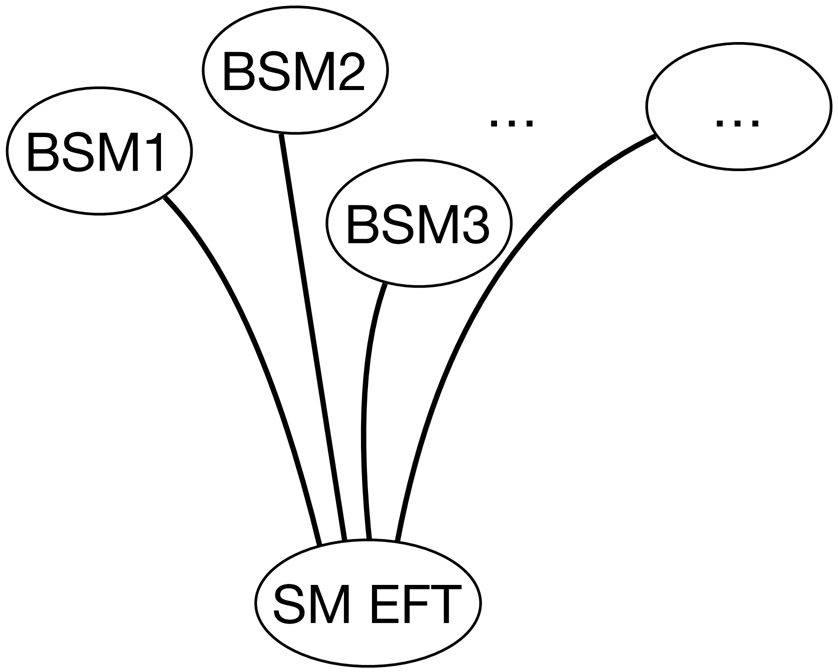


$$\mathcal{L}_{\rm SMEFT} \supset \frac{1}{v^2}\sum_k \mathcal{C}_k\, \mathcal{O}_k$$

- The full list of 4F operators *(*) Warsaw basis*

$$\mathcal{O}_{lq}^{(3)} = (\bar l_L \gamma_\mu \tau^I l_L)(\bar q_L \gamma^\mu \tau^I q_L)\,, \qquad \mathcal{O}_{ledq} = (\bar l_L e_R)(\bar d_R q_L)\,,$$

$$\mathcal{O}_{lequ}^{(1)} = (\bar l_L^p e_R)\epsilon_{pr}(\bar q_L^r u_R)\,, \qquad \mathcal{O}_{lequ}^{(3)} = (\bar l_L^p \sigma_{\mu\nu} e_R)\epsilon_{pr}(\bar q_L^r \sigma^{\mu\nu} u_R)\,,$$

- W vertex correction

$$(\phi^\dagger\, i \overleftrightarrow{D}_\mu^I\, \phi)(\bar q_L \gamma^\mu \tau^I q_L)$$

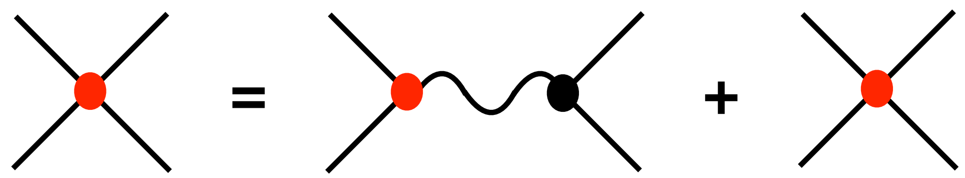
$$(\tilde\phi^\dagger\, i D_\mu \phi)(\bar u_R \gamma^\mu d_R)$$

Theoretical framework

$$\mathcal{O}_{lq}^{(3)} = (\bar{l}_L \gamma_\mu \tau^I l_L)(\bar{q}_L \gamma^\mu \tau^I q_L)\,, \qquad \mathcal{O}_{ledq} = (\bar{l}_L e_R)(\bar{d}_R q_L)\,, \qquad (\phi^\dagger\, i\overleftrightarrow{D}_\mu^I\, \phi)(\bar{q}_L \gamma^\mu \tau^I q_L)$$

$$\mathcal{O}_{lequ}^{(1)} = (\bar{l}_L^p e_R)\epsilon_{pr}(\bar{q}_L^r u_R)\,, \qquad \mathcal{O}_{lequ}^{(3)} = (\bar{l}_L^p \sigma_{\mu\nu} e_R)\epsilon_{pr}(\bar{q}_L^r \sigma^{\mu\nu} u_R)\,, \qquad (\tilde{\phi}^\dagger\, iD_\mu \phi)(\bar{u}_R \gamma^\mu d_R)$$

Matching



$$\mathcal{O}_{V_L}^{\alpha\beta i} = (\bar{e}_L^\alpha \gamma_\mu \nu_L^\beta)(\bar{c}_L \gamma^\mu d_L^i)\,, \qquad \mathcal{O}_{V_R}^{\alpha\beta i} = (\bar{e}_L^\alpha \gamma_\mu \nu_L^\beta)(\bar{c}_R \gamma^\mu d_R^i)\,,$$

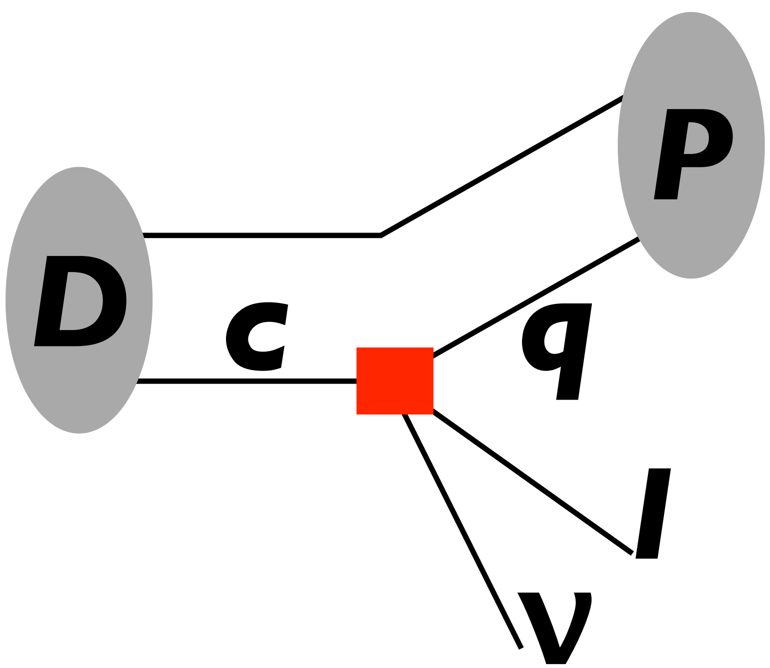
$$\mathcal{O}_{S_L}^{\alpha\beta i} = (\bar{e}_R^\alpha\, \nu_L^\beta)(\bar{c}_R\, d_L^i)\,, \qquad \mathcal{O}_{S_R}^{\alpha\beta i} = (\bar{e}_R^\alpha\, \nu_L^\beta)(\bar{c}_L\, d_R^i)\,,$$

$$\mathcal{O}_{T}^{\alpha\beta i} = (\bar{e}_R^\alpha \sigma_{\mu\nu} \nu_L^\beta)(\bar{c}_R \sigma^{\mu\nu} d_L^i)\,.$$

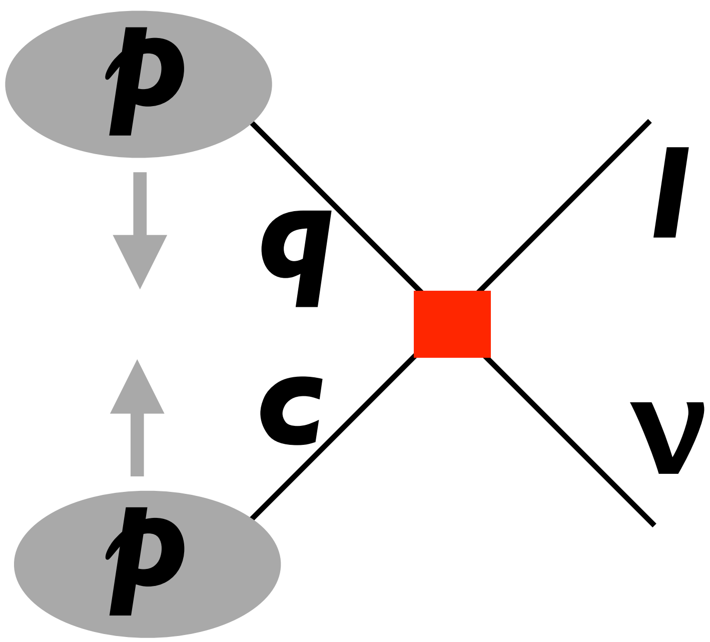
- SMEFT 4F operators match to V_L, S_R, S_L, T but not to V_R
- V_L and V_R receive chirality-preserving *W* vertex corrections
- Effects from chirality-flipping vertex corrections are beyond dim-6 $\bar{\psi}\sigma^{\mu\nu}\psi\,\phi F_{\mu\nu}$
- SMEFT effects in leptonic W couplings, G_F, and CKM determination neglected
- RGEs allow to connect low and high p_T
- RGE effects sizeable for scalar and tensor operators

Caveats beyond this setup will be discussed later

Crossing symmetry



Charmed meson decays



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$$\langle 0 | \bar{q}\sigma^{\mu\nu} q | D \rangle = 0\,, \quad \langle 0 | \bar{q}\gamma^{\mu} q | D \rangle = 0\,, \quad \langle 0 | \bar{q} q | D \rangle = 0$$

  - Leptonic decays sensitive only to axial vector and pseudo scalar operators

$$\epsilon_A^{\alpha\beta i} = \epsilon_{V_R}^{\alpha\beta i} - \epsilon_{V_L}^{\alpha\beta i} \qquad \epsilon_P^{\alpha\beta i} = \epsilon_{S_R}^{\alpha\beta i} - \epsilon_{S_L}^{\alpha\beta i}$$

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$$\mathrm{BR}(D^+ \to \bar{e}^\alpha \nu^\alpha) = \tau_{D^+} \frac{m_{D^+} m_\alpha^2 f_D^2 G_F^2 |V_{cd}|^2 \beta_\alpha^4}{8\pi} \left| 1 - \epsilon_A^{\alpha d} + \frac{m_D^2}{m_\alpha (m_c + m_u)} \epsilon_P^{\alpha d} \right|^2$$

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LQCD: Precise decay constants

$$f_D = 212.0(7)\ \mathrm{MeV}$$
$$f_{D_s} = 249.9(5)\ \mathrm{MeV}$$

[FLAG Review 2019]

Charmed meson decays

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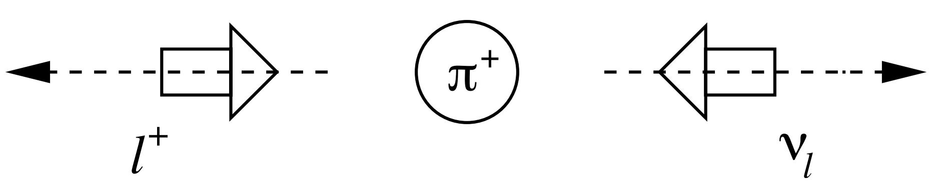
[FLAG Review 2019]

Chirality suppression for the axial vector



$A : \bar{e}_L \gamma^\mu \nu_L \,, \quad P : \bar{e}_R \nu_L$

Charmed meson decays

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

- Leptonic decays: $D_{(s)} \to \bar{e}^\alpha \nu$

i	α	Branching ratios, see PDG
d	e	(*) upper limit, CLEO
	μ	BES3
	τ	BES3
s	e	(*) upper limit, BELLE
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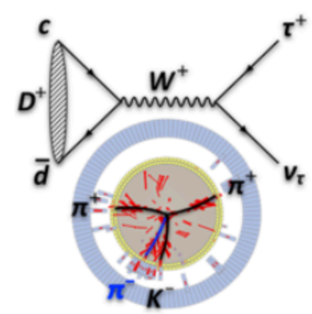
Editors' Suggestion

Observation of the Leptonic Decay $D^+ \to \tau^+ \nu_\tau$

M. Ablikim *et al.* (BESIII Collaboration)

Phys. Rev. Lett. **123**, 211802 (2019) – Published 22 November 2019



The first observation of the two-body decay of a charm meson into a tau and its neutrino allow for a new probe of lepton flavor universality.

Show Abstract +

Charmed meson decays

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

- Leptonic decays: $D_{(s)} \to \bar{e}^\alpha \nu$

i	α	$\epsilon_V^{\alpha i}$	$\epsilon_A^{\alpha i}$	$\epsilon_S^{\alpha i}$	$\epsilon_P^{\alpha i}$	$\epsilon_T^{\alpha i}$
d	e		$[-32,\ 34]$		$[-0.005,\ 0.005]$	
	μ		$[-0.013,\ 0.07]$		$[-0.0024,\ 0.0004]$	
	τ		$[-0.27,\ 0.21]$		$[-0.11,\ 0.15]$	
s	e		$[-27,\ 29]$		$[-0.005,\ 0.004]$	
	μ		$[-0.07,\ 0.02]$		$[-0.0007,\ 0.0022]$	
	τ		$[-0.07,\ 0.014]$		$[-0.008,\ 0.04]$	

95% CL ranges on WCs at 2 GeV (one parameter fit).

- Stringent limits on P operators
- Limits on A depend strongly on the lepton flavour

Charmed meson decays

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

- Semileptonic decays: $D \to \pi(K)\bar{\ell}\nu$
  - QCD invariant under Lorentz symmetry and Parity =>

$$\langle P_i | \bar{q}\gamma^\mu\gamma^5 q | D\rangle = 0\,, \quad \langle P_i | \bar{q}\gamma^5 q | D\rangle = 0$$

  - Semileptonic decays sensitive to <u>vector, scalar and tensor</u> operators

$$\epsilon_V^{\alpha\beta i} = \epsilon_{V_R}^{\alpha\beta i} + \epsilon_{V_L}^{\alpha\beta i} \qquad \epsilon_S^{\alpha\beta i} = \epsilon_{S_R}^{\alpha\beta i} + \epsilon_{S_L}^{\alpha\beta i} \qquad \epsilon_T^{\alpha\beta i}$$

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

Charmed meson decays

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LQCD: Form factors

P	α	$\mathbf{BR_{SM}}$	x_S	x_T	y_S	y_T
π^-	e	$2.65(18)\cdot 10^{-3}$	$1.12(10)\cdot 10^{-3}$	$1.21(15)\cdot 10^{-3}$	2.74(22)	1.14(21)
	μ	$2.61(17)\cdot 10^{-3}$	0.228(19)	0.23(3)	2.73(18)	1.15(22)
K^-	e	$3.48(26)\cdot 10^{-2}$	$1.29(8)\cdot 10^{-3}$	$1.18(11)\cdot 10^{-3}$	2.00(11)	0.69(8)
	μ	$3.39(25)\cdot 10^{-2}$	0.251(16)	0.224(20)	2.00(11)	0.71(8)

(*) interference with the SM is chirally suppressed

Charmed meson decays

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i	α	Branching ratios, see PDG
d	e	BES3 & CLEO e.g. $BR(D^0 \to \pi^- e^+ \nu) = 2.91 \pm 0.04\,\%$
	μ	BES3
	τ	
s	e	BES3 & CLEO
	μ	BES3 e.g. $BR(D^0 \to K^- \mu^+ \nu) = 3.41 \pm 0.04\,\%$
	τ	

Charmed meson decays

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

Semileptonic decays: $D \to \pi(K)\bar{\ell}\nu$

i	α	Branching ratios, see PDG
d	e	BES3 & CLEO e.g. $BR(D^0 \to \pi^- e^+ \nu) = 2.91 \pm 0.04\,\%$
	μ	BES3
	τ	(*) kinematically forbidden
s	e	BES3 & CLEO
	μ	BES3 e.g. $BR(D^0 \to K^- \mu^+ \nu) = 3.41 \pm 0.04\,\%$
	τ	(*) kinematically forbidden

- The largest available phase space $m_{D^+} - m_{\pi^0} \simeq 1.735$ GeV.
- No limits on tauonic V, S, T operators
  [Caveat: Excited resonances or $D_{(s)} \to \tau\nu\gamma$]

Charmed meson decays

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

- Semileptonic decays: $D \to \pi(K)\bar{\ell}\nu$

i	α	$\epsilon_V^{\alpha i}$	$\epsilon_A^{\alpha i}$	$\epsilon_S^{\alpha i}$	$\epsilon_P^{\alpha i}$	$\epsilon_T^{\alpha i}$
	e	$[-0.02,\ 0.11]$		$[-0.29,\ 0.29]$		$[-0.5,\ 0.5]$
d	μ	$[-0.06,\ 0.07]$		$[-0.33,\ 0.17]$		$[-0.6,\ 0.22]$
	τ	$-$		$-$		$-$
	e	$[-0.07,\ 0.08]$		$[-0.29,\ 0.29]$		$[-0.5,\ 0.5]$
s	μ	$[-0.09,\ 0.06]$		$[-0.4,\ 0.16]$		$[-0.9,\ 0.22]$
	τ	$-$		$-$		$-$

95% CL ranges on WCs at 2 GeV (one parameter fit).

- Limits on scalar and tensor operators are weak, dominated by the quadratic contribution.
- Vector operators constrained at the few percent level. Form factor errors relevant.
- Future improvements ~ 3x on the rates at BESIII. Challenge for LQCD to keep up.

Charmed meson decays

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

- Leptonic decays: $D_{(s)} \to \bar{e}^\alpha \nu$
- Semileptonic decays: $D \to \pi(K)\bar{\ell}\nu$

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	$-$	$[-0.07,\ 0.014]$	$-$	$[-0.008,\ 0.04]$	$-$

95% CL ranges on WCs at 2 GeV (one parameter fit).

Charmed meson decays

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

- Leptonic decays: $D_{(s)} \to \bar{e}^\alpha \nu$
- Semileptonic decays: $D \to \pi(K)\bar{\ell}\nu$
- Not considered / future directions
  - D > V, no lattice QCD predictions
  - Baryonic Λc decays, data not precise
  - Kinematic distributions

Charmed meson decays

- In the UV, the relevant operator basis is the "chiral basis" not the "parity basis"

Charmed meson decays

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Vector $\epsilon_{V_L}^{\alpha\beta i}$

$$\mathcal{O}_{lq}^{(3)} = (\bar{l}_L \gamma_\mu \tau^I l_L)(\bar{q}_L \gamma^\mu \tau^I q_L)$$

- Electron: Semileptonic
- Muon: Semileptonic and leptonic comparable
- Tau: Leptonic

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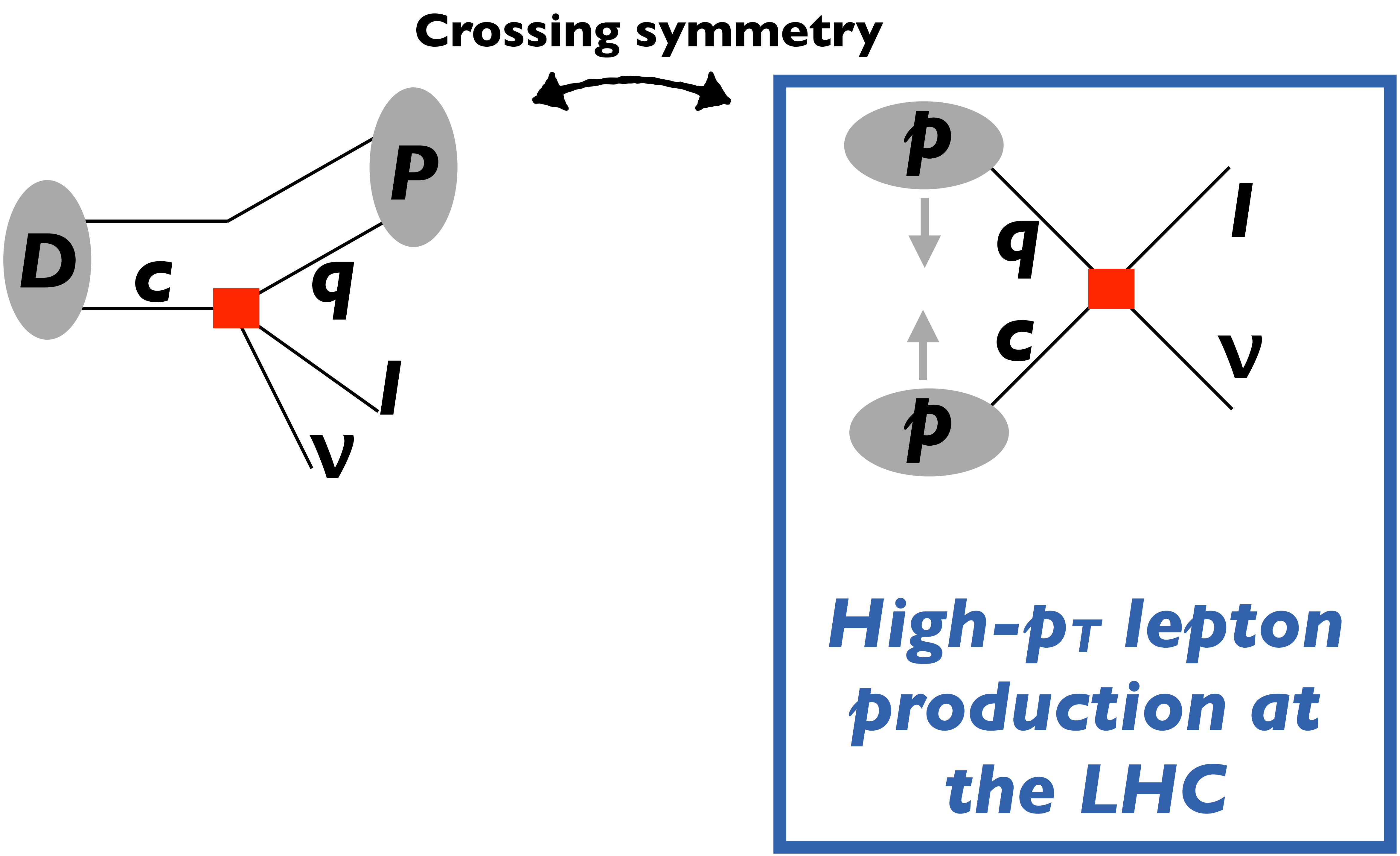
Scalar, Tensor

$$\mathcal{O}_{ledq} = (\bar{l}_L e_R)(\bar{d}_R q_L)\,,$$
$$\mathcal{O}_{lequ}^{(3)} = (\bar{l}_L^p \sigma_{\mu\nu} e_R)\epsilon_{pr}(\bar{q}_L^r \sigma^{\mu\nu} u_R)\,,$$
$$\mathcal{O}_{lequ}^{(1)} = (\bar{l}_L^p e_R)\epsilon_{pr}(\bar{q}_L^r u_R)\,,$$

i	α	$\epsilon_{S_L}^{\alpha i}\ (-\epsilon_{S_R}^{\alpha i}) \times 10^3$	$\epsilon_T^{\alpha i} \times 10^2$
d	e	$[-2.5,\ 2.7]$	$[-1.6,\ 1.5]$
	μ	$[-0.2,\ 1.2]$	$[-0.7,\ 0.13]$
	τ	$[-70,\ 60]$	$[-33,\ 44]$
s	e	$[-2.0,\ 2.2]$	$[-1.3,\ 1.2]$
	μ	$[-1.1,\ 0.3]$	$[-0.2,\ 0.6]$
	τ	$[-19,\ 4.0]$	$[-2.0,\ 12]$

95% CL ranges on WCs at 1 TeV (one parameter fit).

- RGE flow to P operator at low energies


Crossing symmetry
D
c
P
q
l
ν
p
q
c
p
l
ν
High-pT lepton production at the LHC

High-p_T lepton production at the LHC

In the high-energy limit $\sqrt{s} \gg m_W$

W-vertex

Chirality preserving: $\frac{1}{\Lambda^2}\psi^2\phi D\phi$

Chirality flipping: $\frac{1}{\Lambda^2}\psi^2\phi F$

4F $\frac{1}{\Lambda^2}\psi^4$

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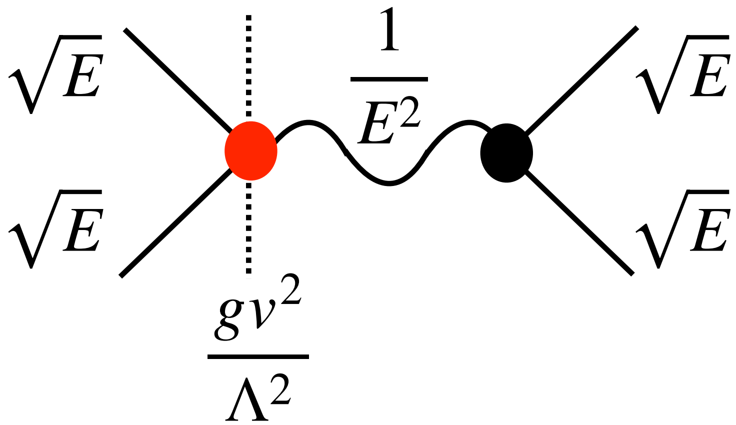
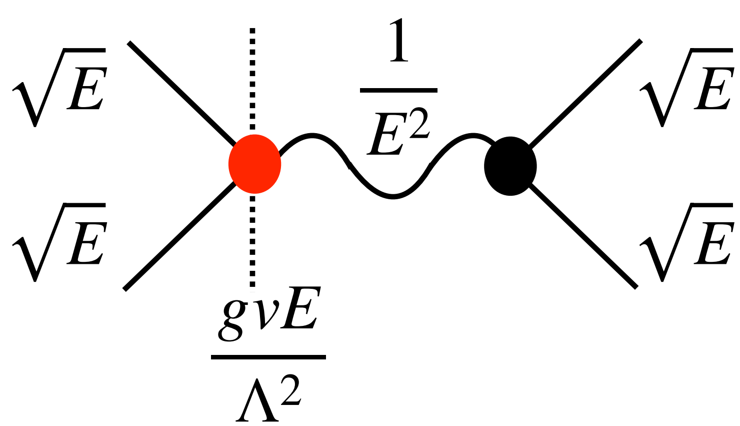


$\mathscr{A} \sim \frac{m_W^2}{\Lambda^2}$

$(\mathscr{A}_{SM} \sim g^2)$

Chirality flipping: $\frac{1}{\Lambda^2}\psi^2\phi F$



$\mathscr{A} \sim \frac{g\sqrt{s}}{\Lambda^2}$

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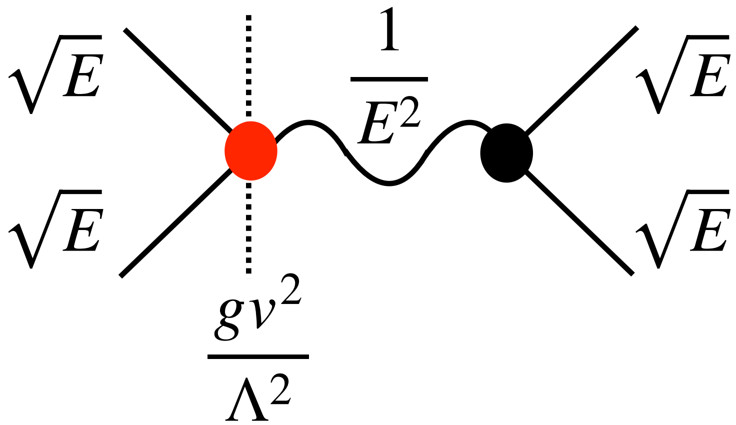

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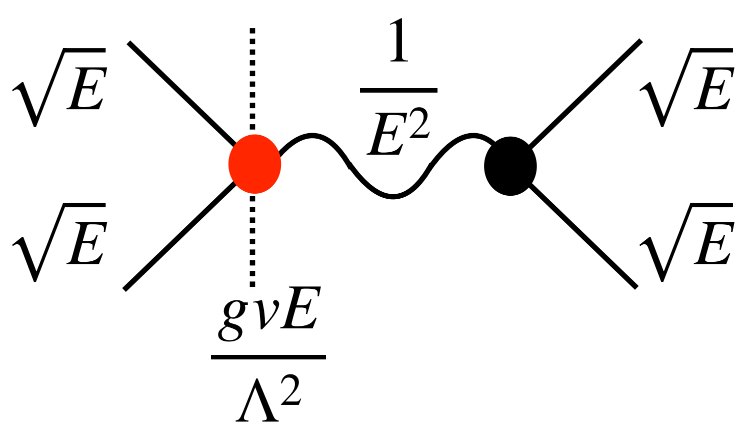
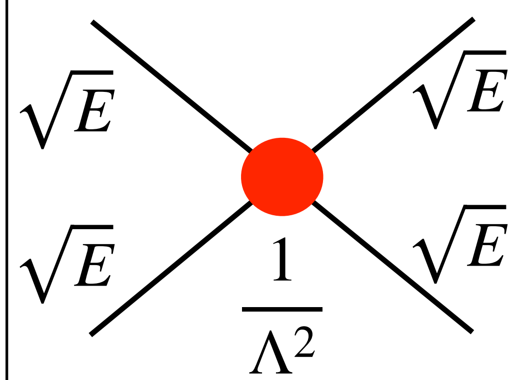


$\mathscr{A} \sim \frac{g\sqrt{s}}{\Lambda^2}$

4F $\frac{1}{\Lambda^2}\psi^4$



$\mathscr{A} \sim \frac{s}{\Lambda^2}$

Dominant

Scattering amplitudes induced by 4F contact interactions grow with energy before the completion kicks in to insure unitarity.

4.1 Short-distance new physics in high-p_T tails

- Partonic level cross section

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

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- In the relativistic limit, chiral fermions act as independent particles with definite helicity.
- Therefore, the interference among operators is achieved only when the operators match the same flavor and chirality for all four fermions.
- The lack of interference tends to increase the cross section in the high-p_T tails, and allows to set bounds on several NP operators simultaneously.
- Different / complementary to charm decays.

Most of the bounds from $D_{(S)}$ mesons decays depend on interference terms among different WCs, and it becomes difficult to break flat directions without additional observables.

4.1 Short-distance new physics in high-p_T tails

- Five quark flavors accessible in the incoming proton PDFs

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

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- The relative correction to the x-section in the tail

$$\frac{\Delta\sigma}{\sigma} \approx R_{ij} \times \frac{d_X \, \epsilon_X^2}{\left(m_W^2/s\right)^2}$$

$$R_{ij} \equiv \frac{(\mathcal{L}_{u_i \bar{d}_j} + \mathcal{L}_{d_j \bar{u}_i}) \times |V_{ij}|^2}{(\mathcal{L}_{u\bar{d}} + \mathcal{L}_{d\bar{u}}) \times |V_{ud}|^2}$$

$d_X = 1, \frac{3}{4}, 4$ for $X = V, S, T$

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PDF and CKM suppression

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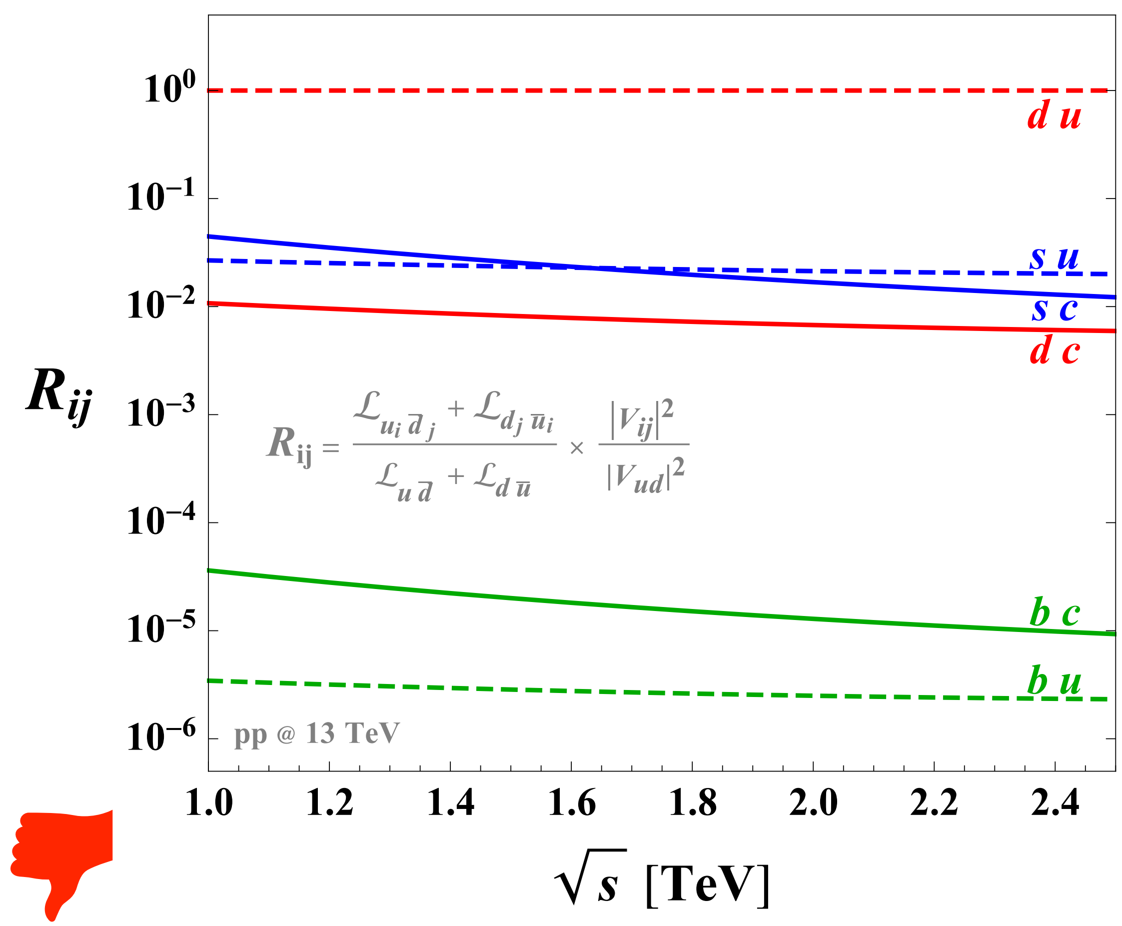

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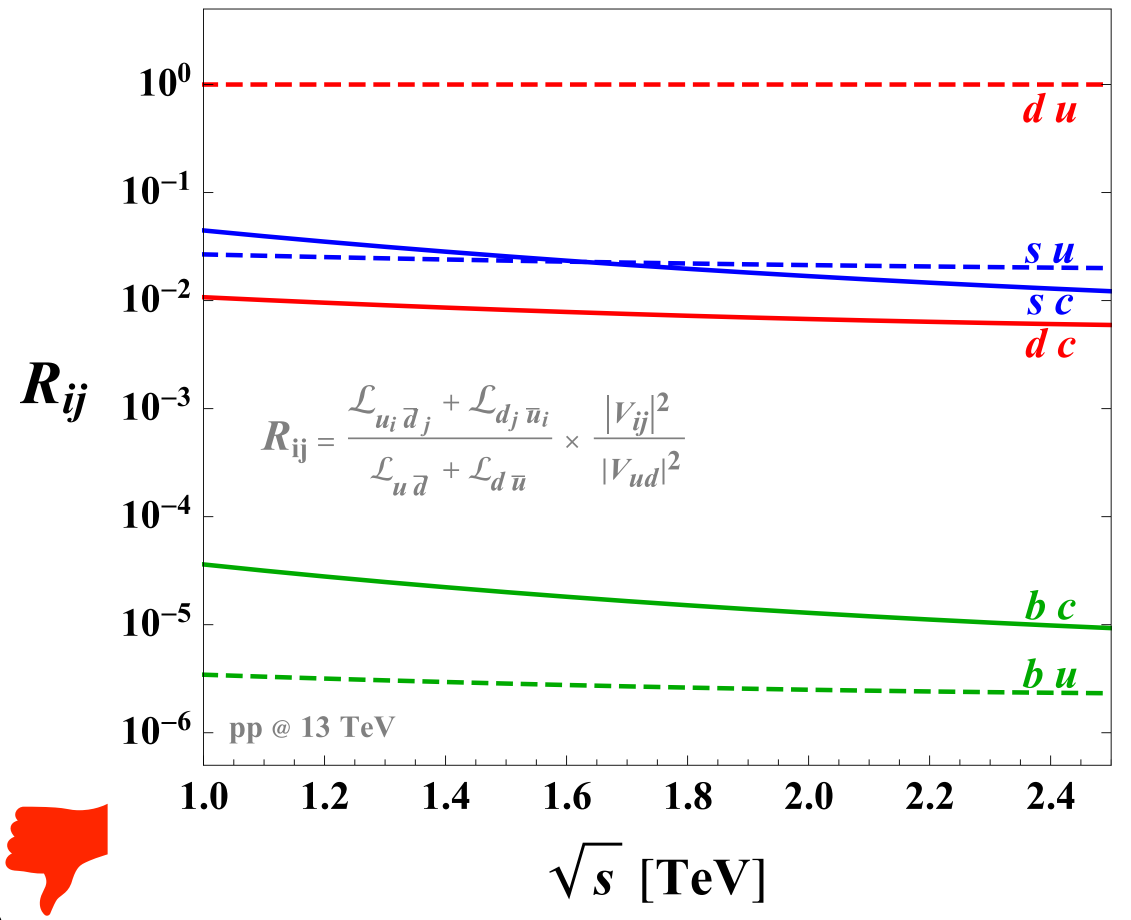
$d_X = 1, \frac{3}{4}, 4$ for $X = V, S, T$

Energy enhancement

$$\left(s/m_W^2\right)^2 \sim \mathcal{O}(10^5)$$

PDF and CKM suppression

$$R_{ij} \equiv \frac{(\mathcal{L}_{u_i \bar{d}_j} + \mathcal{L}_{d_j \bar{u}_i}) \times |V_{ij}|^2}{(\mathcal{L}_{u\bar{d}} + \mathcal{L}_{d\bar{u}}) \times |V_{ud}|^2}$$



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$d_X = 1, \frac{3}{4}, 4$ for $X = V, S, T$

$$\left|\Delta\sigma/\sigma\right|_{tails} \lesssim \mathcal{O}(0.1)$$

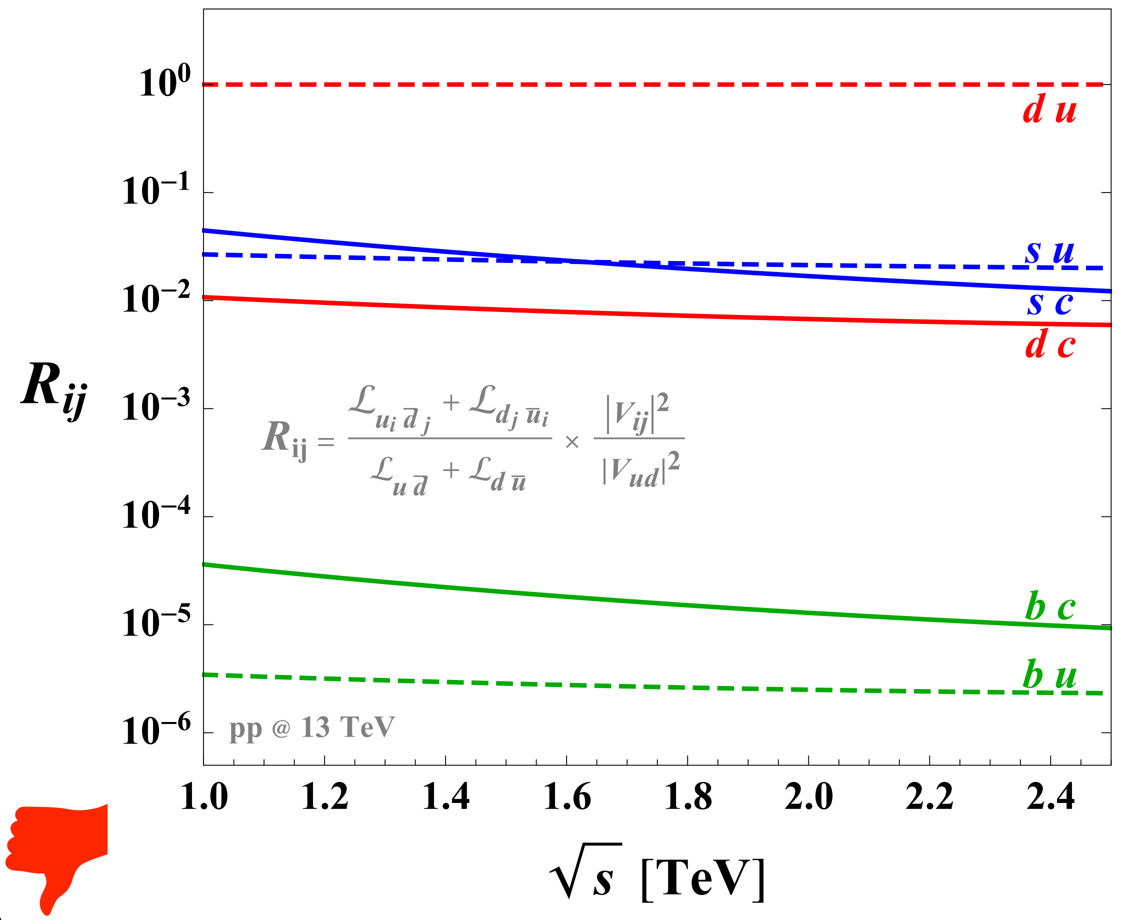
e.g. $\rightarrow\ \epsilon_L^{cs} \lesssim \mathcal{O}(0.01)$

Energy enhancement

$$\left(s/m_W^2\right)^2 \sim \mathcal{O}(10^5)$$

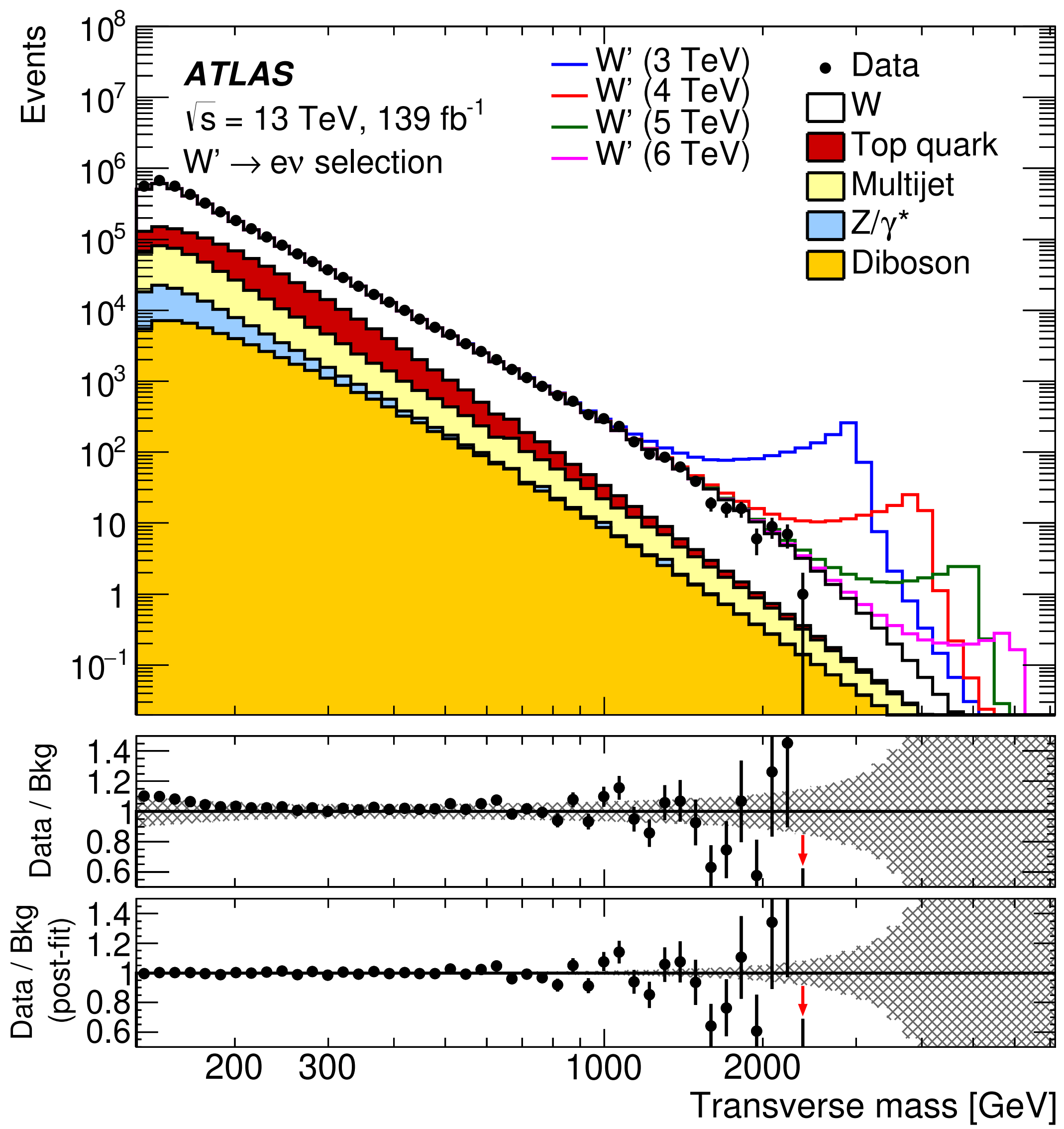
PDF and CKM suppression

$$R_{ij} \equiv \frac{(\mathcal{L}_{u_i\bar{d}_j} + \mathcal{L}_{d_j\bar{u}_i}) \times |V_{ij}|^2}{(\mathcal{L}_{u\bar{d}} + \mathcal{L}_{d\bar{u}}) \times |V_{ud}|^2}$$



4.2 Recast of the existing experimental searches

- Charged (and neutral) Drell-Yan is extremely well measured at the LHC.
- We recast the available searches fitting the transverse mass distribution at the reco level.



Channel	Statistics [fb^{-1}]	Experiment
$\tau\nu$	36	CMS
	36	ATLAS
$e\nu$, $\mu\nu$	139	ATLAS
	36	ATLAS
	36	CMS
$\tau\tau$	36	ATLAS
$\tau\tau$, $e\mu$, $e\tau$, $\mu\tau$	2.2	CMS
ee, $\mu\mu$	139	ATLAS
	140	CMS
	36	CMS
	36	ATLAS
$e\mu$, $e\tau$, $\mu\tau$	36	ATLAS
	36	ATLAS

[Available data]

- Full-fledged simulations validated by reproducing the official SM prediction. The SM background systematics included conservatively. The modified frequentist CLs method used.

4.2 Recast of the existing experimental searches

i	α	$\epsilon_{V_L}^{\alpha\alpha i} \times 10^2$	$\lvert\epsilon_{V_L}^{\alpha\beta i}\rvert \times 10^2$ ($\alpha \neq \beta$)	$\lvert\epsilon_{S_{L,R}}^{\alpha\beta i}(\mu)\rvert \times 10^2$		$\lvert\epsilon_{T}^{\alpha\beta i}(\mu)\rvert \times 10^3$	
				$\mu = 1$ TeV	$\mu = 2$ GeV	$\mu = 1$ TeV	$\mu = 2$ GeV
d	e	$[-0.52, 0.86]$	0.67 (0.42)	0.72 (0.46)	1.5 (0.96)	4.3 (2.7)	3.4 (2.2)
	μ	$[-0.85, 1.2]$	1.0 (0.38)	1.1 (0.42)	2.3 (0.86)	6.6 (2.4)	5.2 (1.9)
	τ	$[-1.4, 1.8]$	1.6 (0.68)	1.5 (0.55)	3.1 (1.1)	8.7 (3.1)	6.9 (2.5)
s	e	$[-0.28, 0.59]$	0.42 (0.26)	0.43 (0.28)	0.91 (0.57)	2.8 (1.5)	2.2 (1.2)
	μ	$[-0.46, 0.78]$	0.63 (0.23)	0.68 (0.25)	1.4 (0.52)	4.0 (1.4)	3.1 (1.1)
	τ	$[-0.65, 1.2]$	0.93 (0.40)	0.87 (0.31)	1.8 (0.65)	5.2 (1.8)	4.1 (1.5)

95% CL ranges on WCs. Naive HL-LHC projection in ().

4.2 Recast of the existing experimental searches

i	α	$\epsilon_{V_L}^{\alpha\alpha i} \times 10^2$	$\lvert\epsilon_{V_L}^{\alpha\beta i}\rvert \times 10^2$ $(\alpha \neq \beta)$	$\lvert\epsilon_{S_{L,R}}^{\alpha\beta i}(\mu)\rvert \times 10^2$ $\mu = 1$ TeV	$\mu = 2$ GeV	$\lvert\epsilon_{T}^{\alpha\beta i}(\mu)\rvert \times 10^3$ $\mu = 1$ TeV	$\mu = 2$ GeV
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95% CL ranges on WCs. Naive HL-LHC projection in ().

- Similar results for **d** and **s** - strange PDF versus Cabibo squared.
- Approx all limits O(0.01).
- $\epsilon_{V_L}^{\alpha\beta i} \; : \; \epsilon_{S_{L,R}}^{\alpha\beta i} \; : \; \epsilon_{T}^{\alpha\beta i} \approx 1 : \frac{2}{\sqrt{3}} : \frac{1}{2}$
- Quadratic terms dominates the limits also for V_L.
- The most sensitive bins fall in the range [1 - 1.5] TeV
- Dedicated future analysis: angular dependence, lepton charge asymmetry, etc.

4.1 Short-distance new physics in high-p_T tails

How well do we know the bckg?

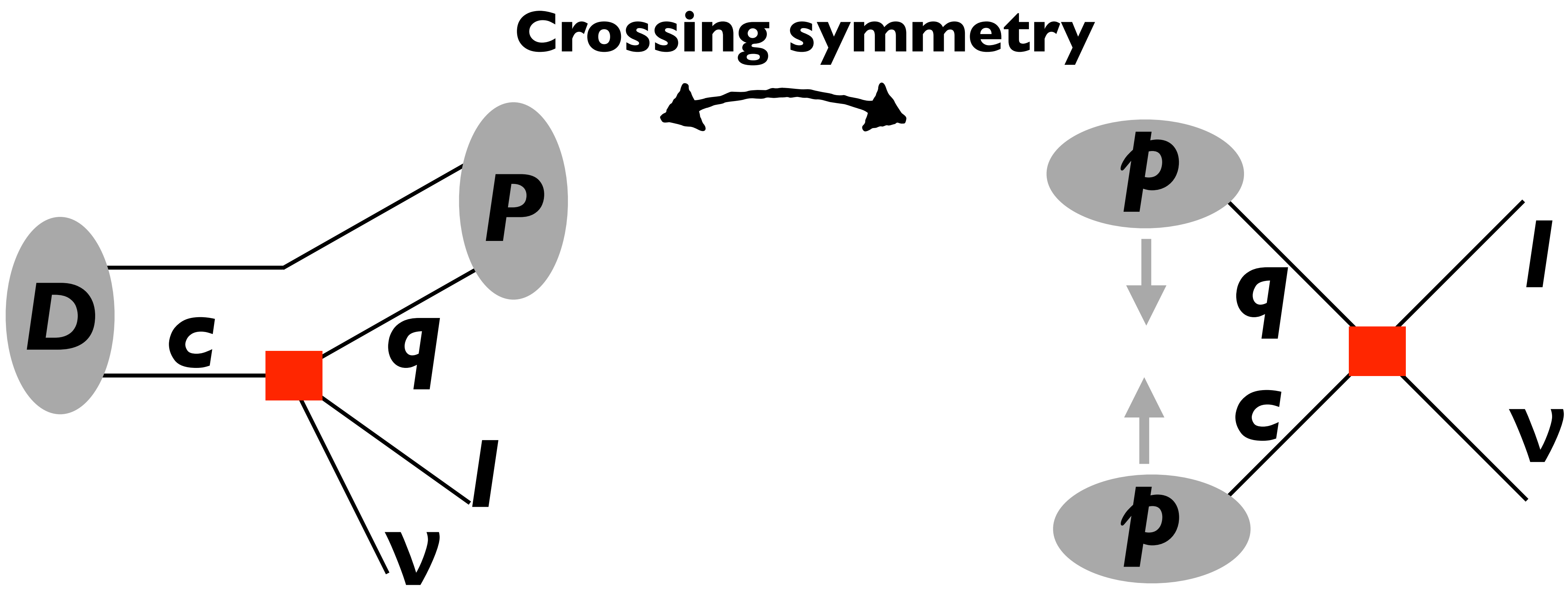
- The SM prediction (NNLO QCD + NLO EW) suffices the experimental precision.

How well do we know the signal?

- The uncertainty on the signal prediction from NLO QCD and PDF replicas estimated to be $\sim$ 10 % on the rate in the most sensitive bin. Electroweak corrections at the similar level. $\Delta\epsilon_X/\epsilon_X \approx 0.5\,\Delta\sigma/\sigma$

How well do we know PDFs?

- The PDF determination assumes the SM. The impact of the Drell-Yan data in the global PDF fit is small at the moment. The issue is there in the future.



Interplay between low and high energy

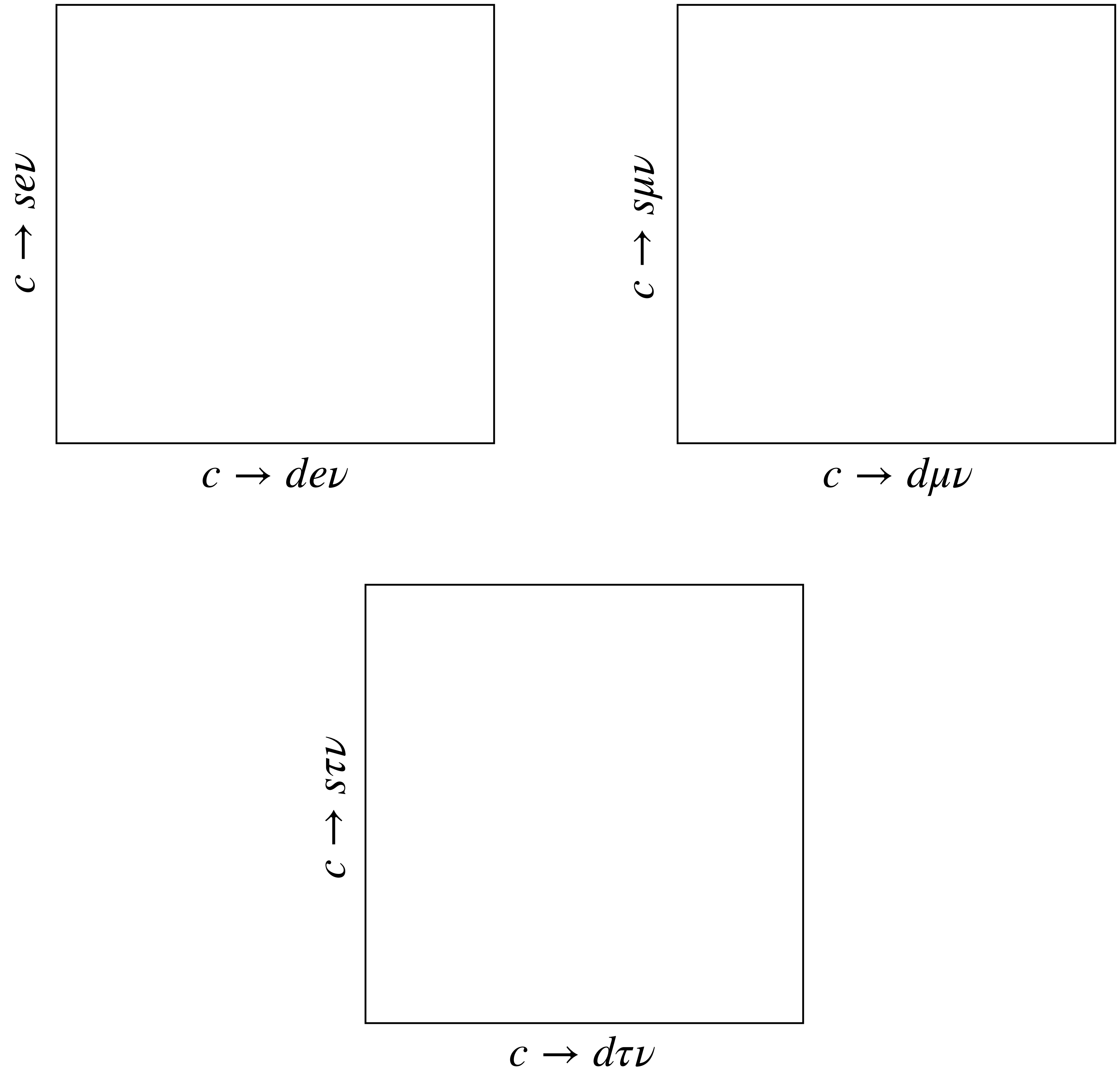
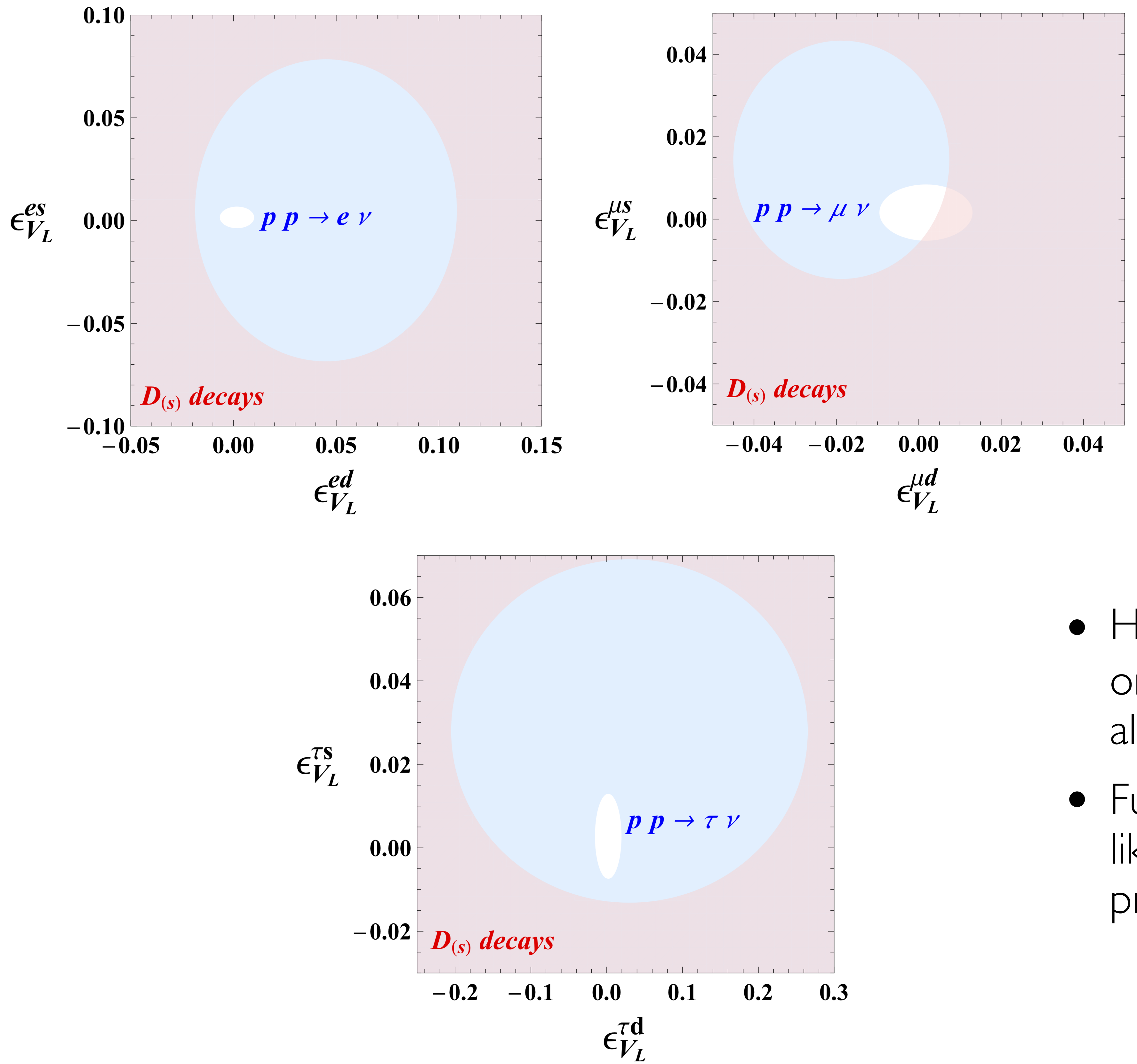


Figure 2. Exclusion limits at 95% CL on $c \to d(s)\bar{e}^\alpha \nu^\alpha$ transitions in $(\epsilon_{V_L}^{\alpha\alpha d}, \epsilon_{V_L}^{\alpha\alpha s})$ plane were $\alpha = e$ (top left), $\alpha = \mu$ (top right), and $\alpha = \tau$ (bottom). The region colored in pink is excluded by $D_{(s)}$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

$$\boxed{\mathcal{O}_{lq}^{(3)} = (\bar{l}_L \gamma_\mu \tau^I l_L)(\bar{q}_L \gamma^\mu \tau^I q_L)}$$



- High-p_T limits are almost an order of magnitude stronger for all transitions
- Future projections from BESIII likely not competitive with future projections from the HL-LHC

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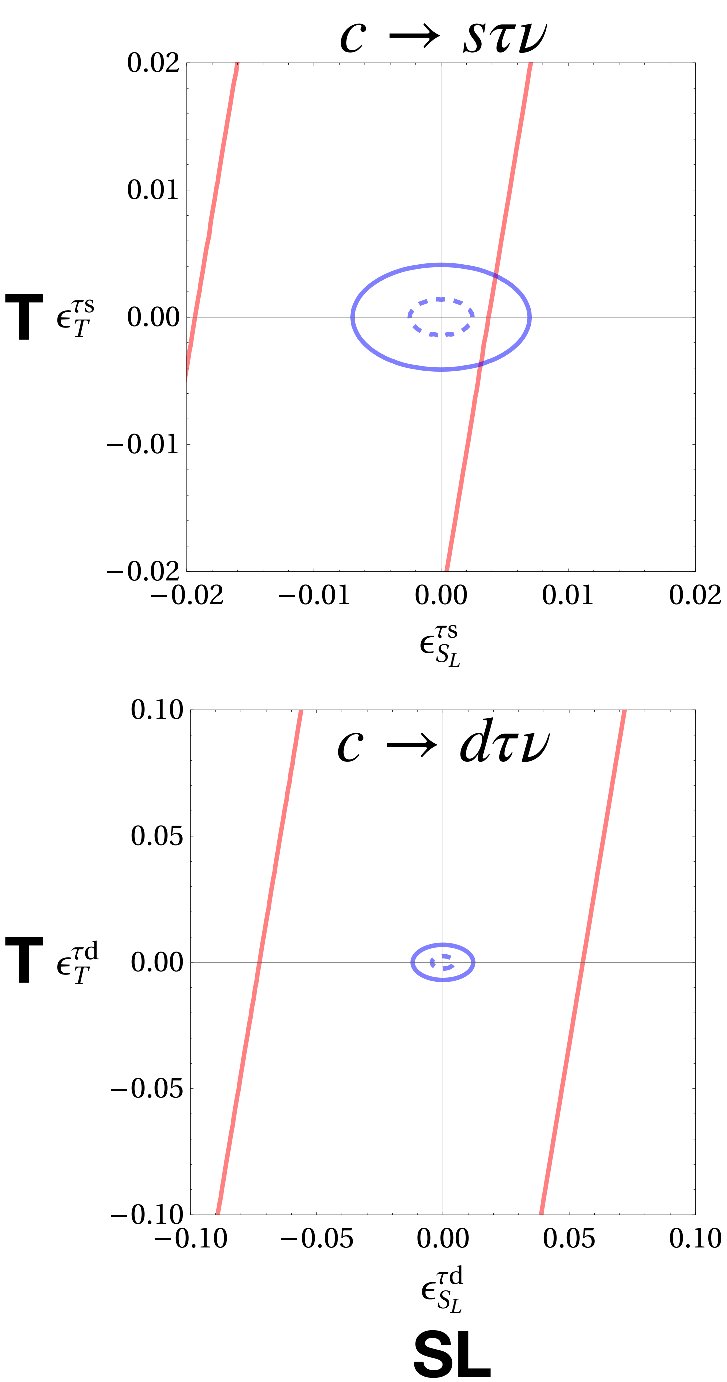
Figure 3. 95% CL regions for the combined fits of $\epsilon_{S_L}^{\alpha\beta i}$ and $\epsilon_{T}^{\alpha\beta i}$ to the charmed-meson decay data with $\beta = \alpha$ (red solid line) or $\beta \neq \alpha$ (light-red dash-dotted line) and to monolepton LHC data (blue solid line). Projections for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

$$\boxed{\begin{aligned} \mathcal{O}_{lequ}^{(1)} &= (\bar{l}_L^p e_R)\epsilon_{pr}(\bar{q}_L^r u_R) \\ \mathcal{O}_{lequ}^{(3)} &= (\bar{l}_L^p \sigma_{\mu\nu} e_R)\epsilon_{pr}(\bar{q}_L^r \sigma^{\mu\nu} u_R) \end{aligned}}$$

- Tau: High-p_T more sensitive



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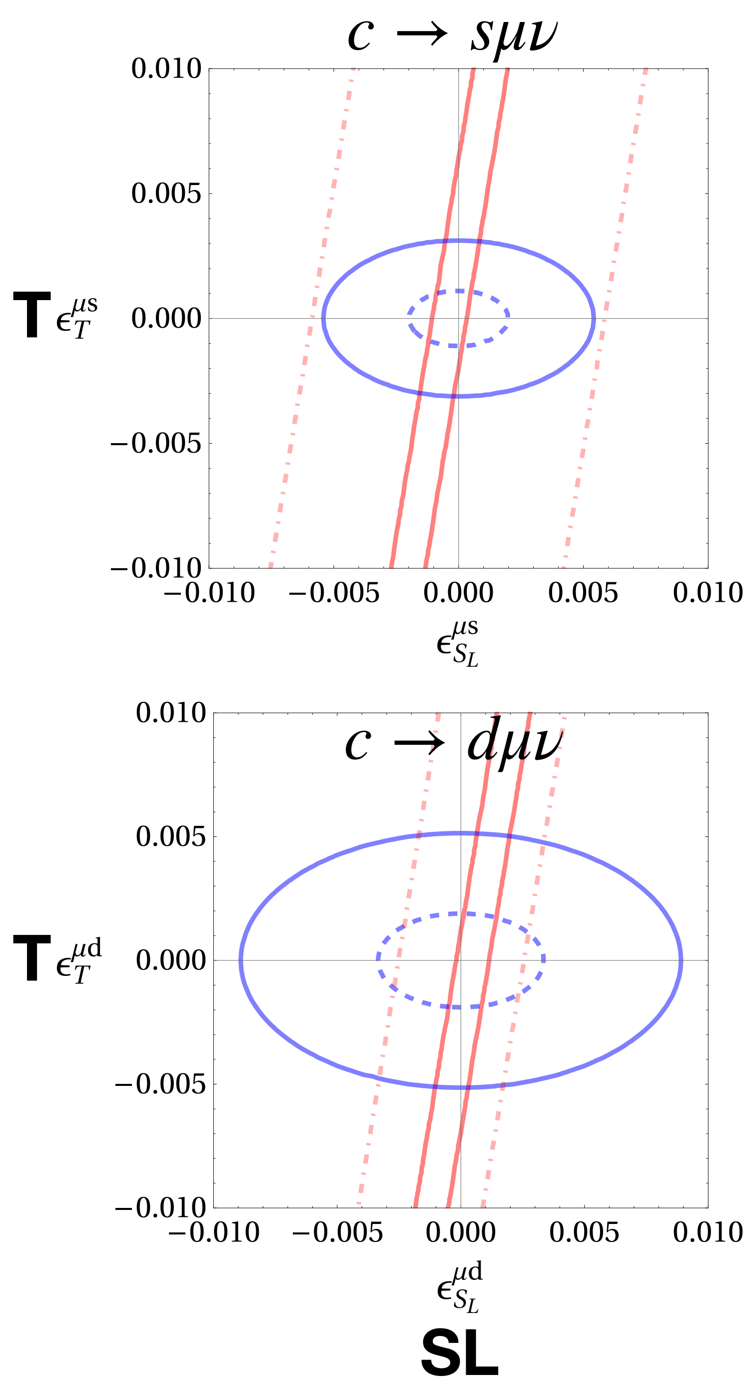

- Muon: P low-pT, S high-pT

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.

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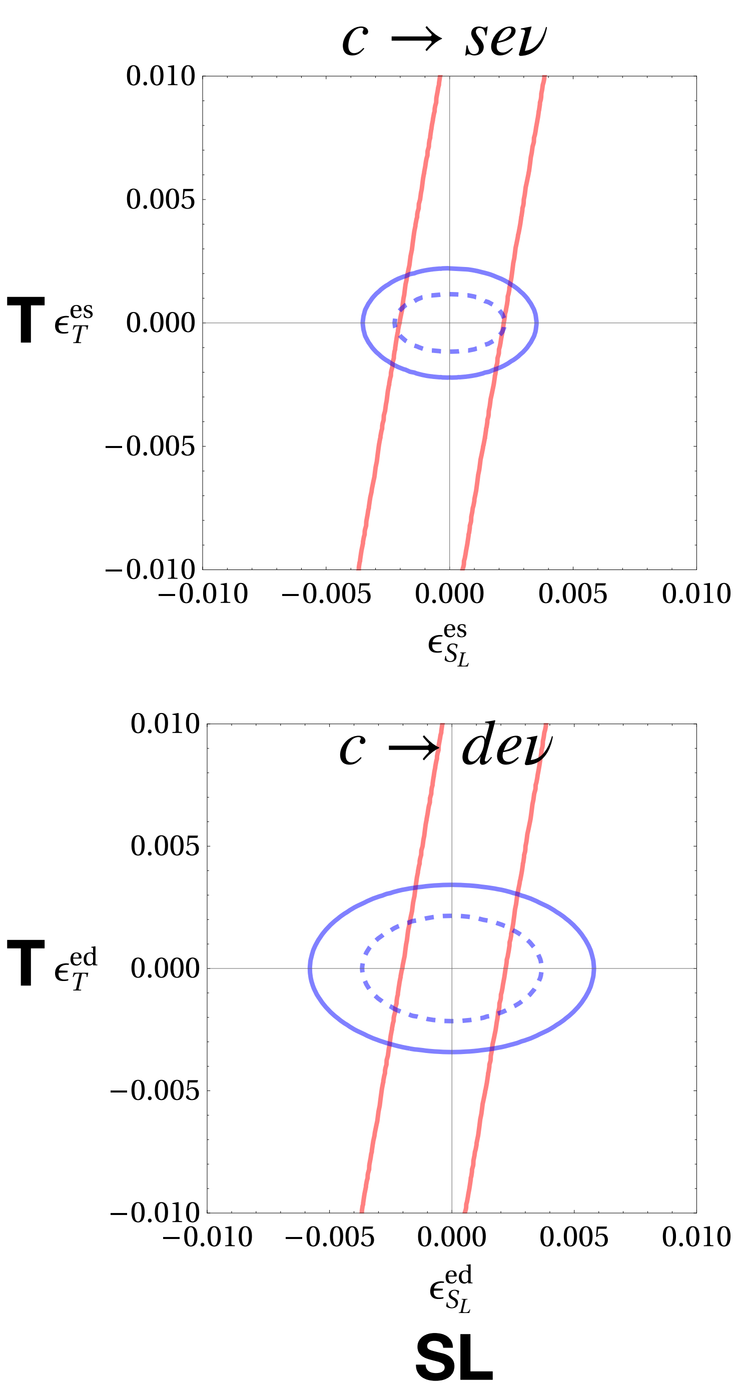

- Electron: P competitive

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  Different scaling with s, only a partial cancellation possible.

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Dominant term

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(*) A single tree-level s-channel resonance exchange predicts

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A significant cancellation would require a peculiar NP scenario.

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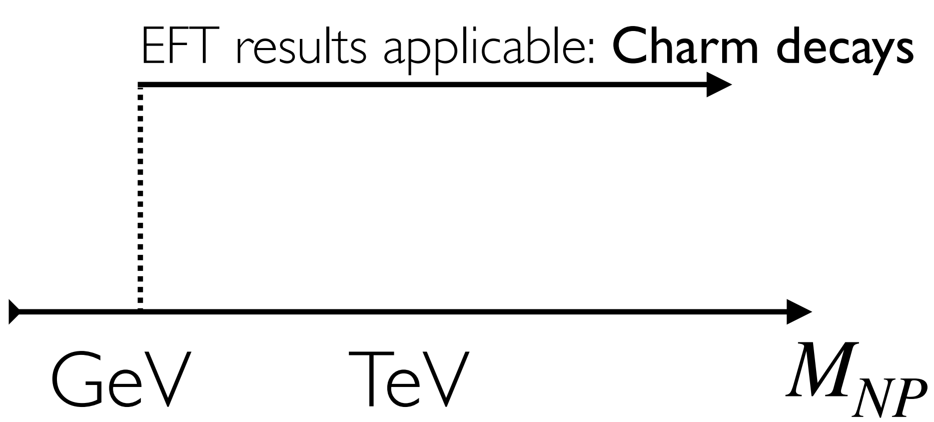

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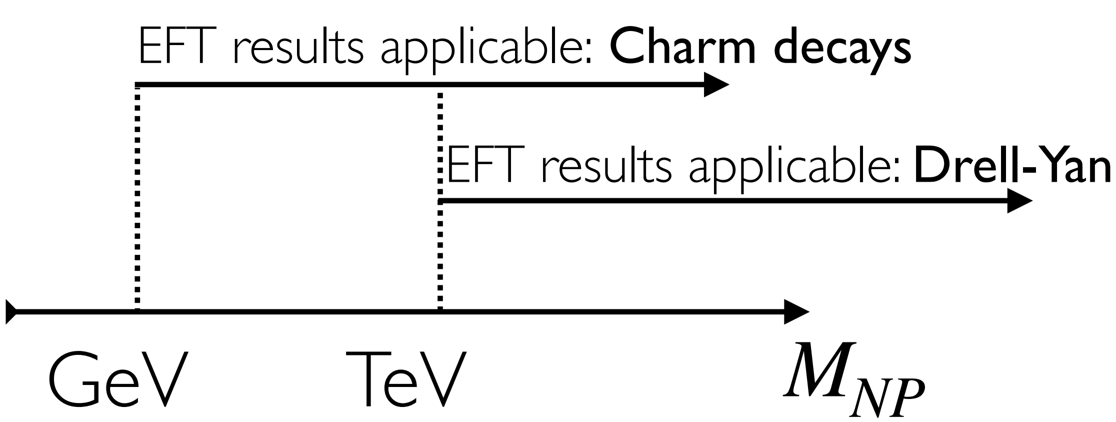

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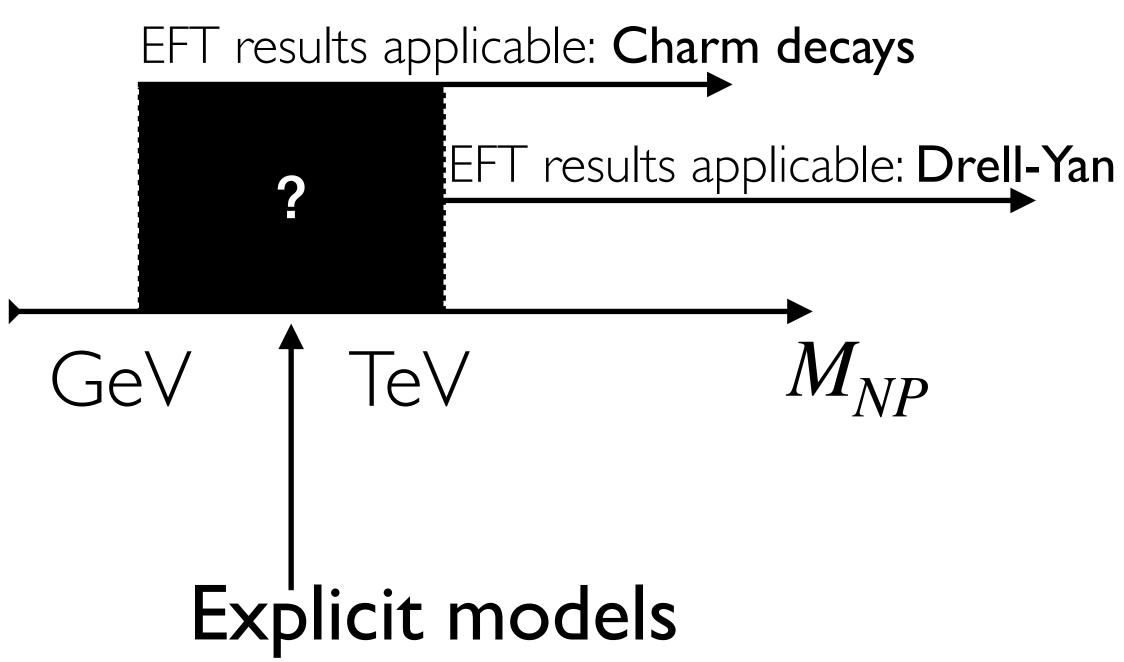

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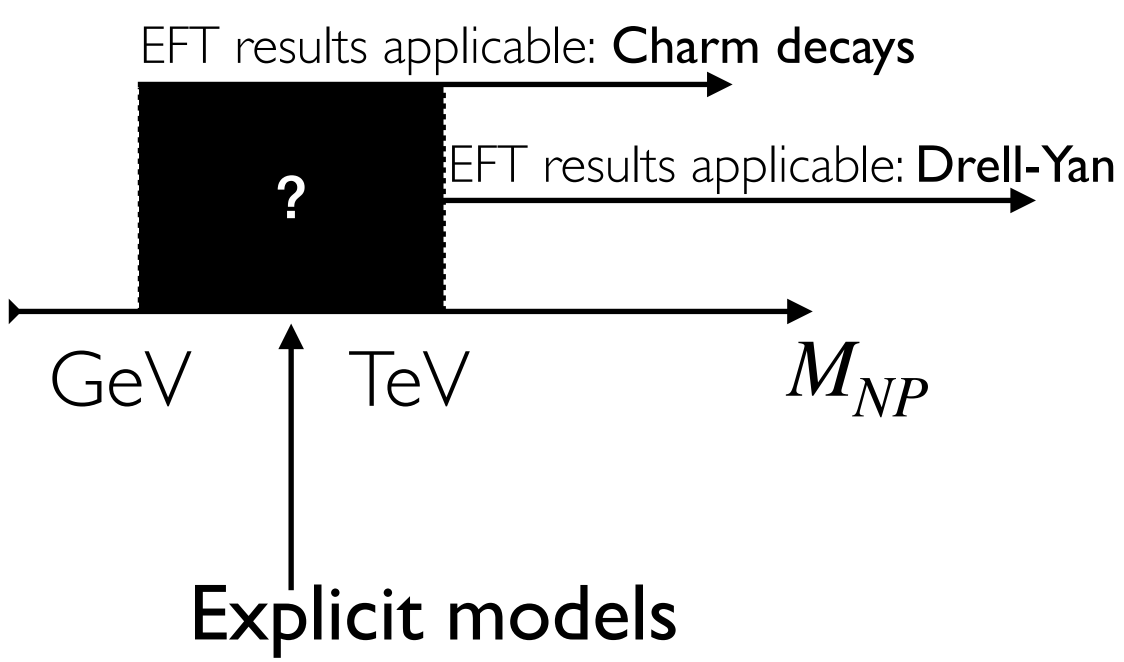
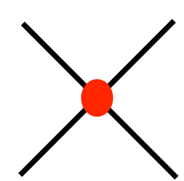


Tree-level UV completions



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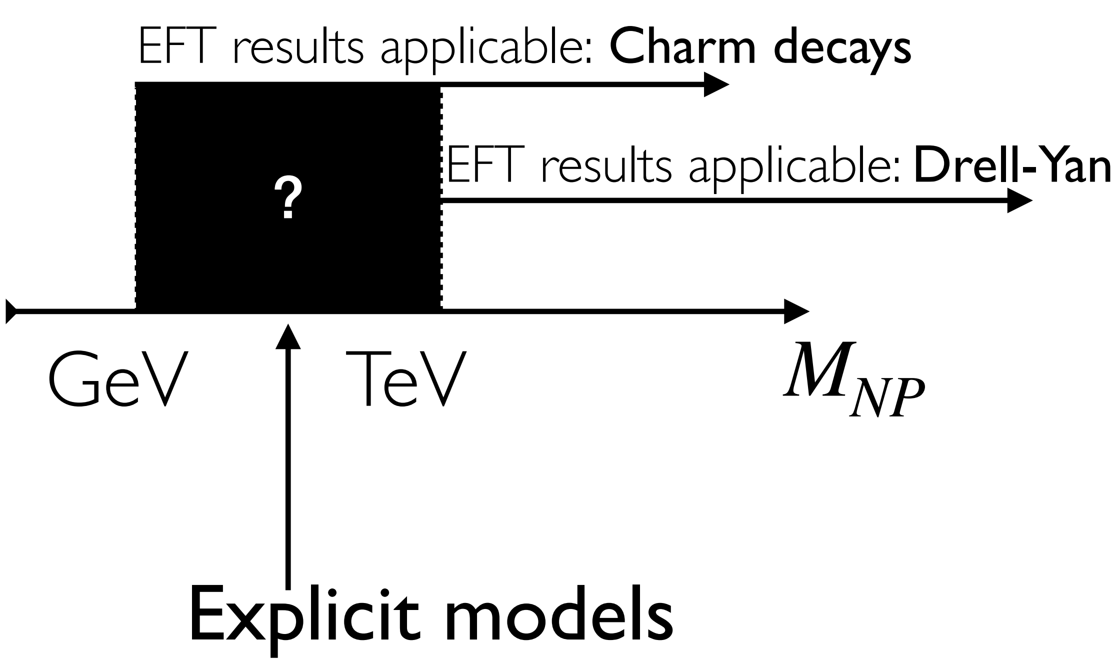
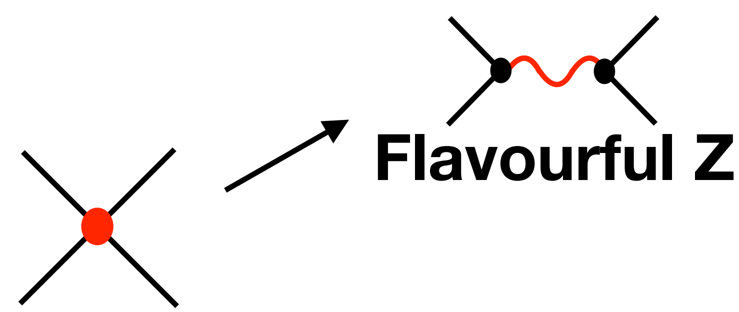


Tree-level UV completions

s-channel



- EFT bounds are overly conservative

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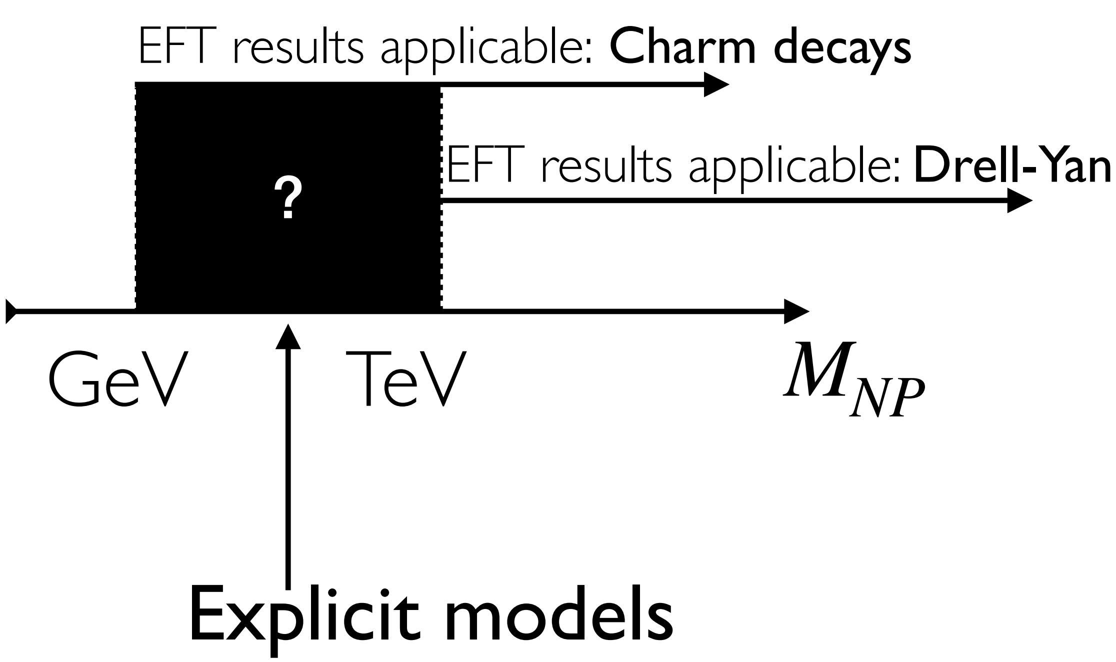

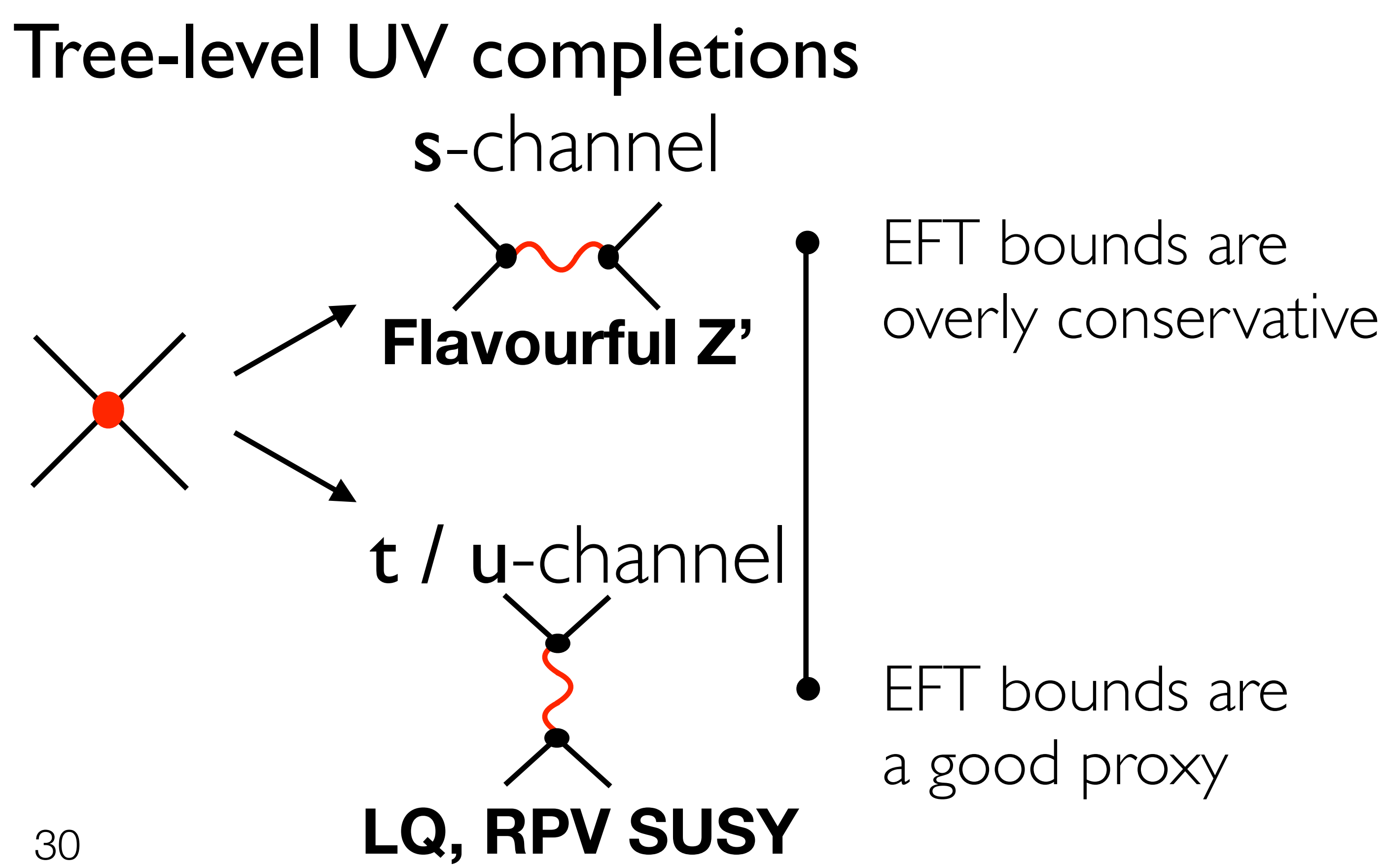

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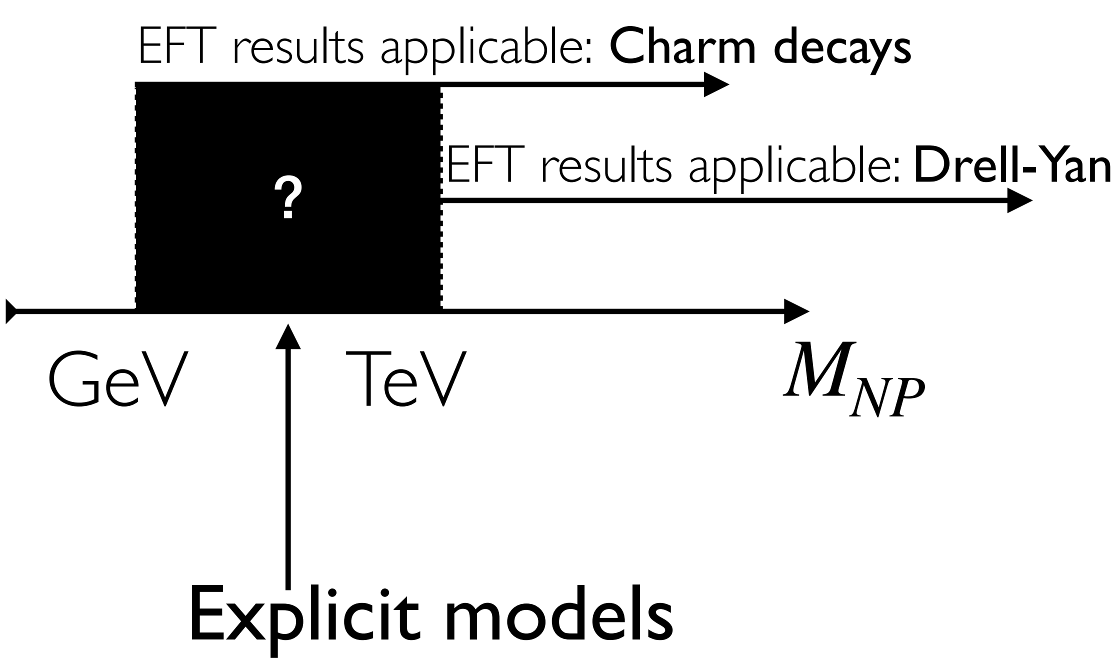

Charged mediators
$M_{\mathrm{NP}} \gtrsim \mathcal{O}(100\,\mathrm{GeV})$
Coloured mediators even more

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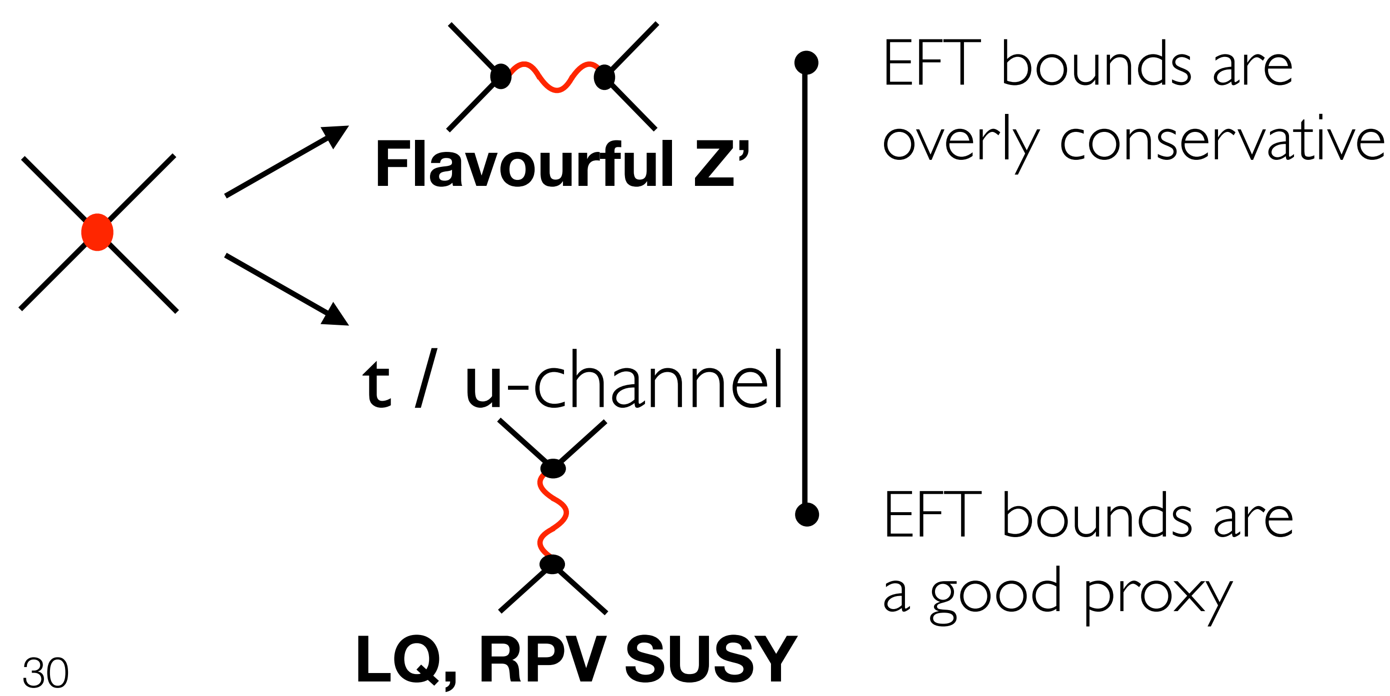

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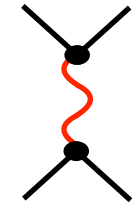
- *To conclude, the comparison of low- and high-p_T data within an EFT framework is a useful exercise even if the EFT validity is not guaranteed.*
- *If high-p_T provides stronger limits relative to the ones derived from low-p_T, this will also hold in a generic NP model barring tuned cancellations.*



LQ, RPV SUSY

- EFT bounds are a good proxy

Explicit models

Neutral currents

$$c \to u\, e^{\alpha} \bar{e}^{\beta}$$

- Exercise repeated, see 2003.12421

Constraints from SU(2) gauge invariance

$$q_L^i = \begin{pmatrix} V_u^{ij} u_L^j \\ V_d^{ij} d_L^j \end{pmatrix}, \; V = V_u^\dagger V_d \qquad\qquad l_L^\alpha = \begin{pmatrix} \nu_L^\alpha \\ e_L^\alpha \end{pmatrix},$$

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Example

$$\boxed{\mathcal{O}_{lq}^{(3)} = (\bar{l}_L \gamma_\mu \tau^I l_L)(\bar{q}_L \gamma^\mu \tau^I q_L)}$$

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\end{aligned}$$

$i)$ Charged-current $d_i \to u\ell\nu$ and $\tau \to d_i u\nu$ transitions (1st line),

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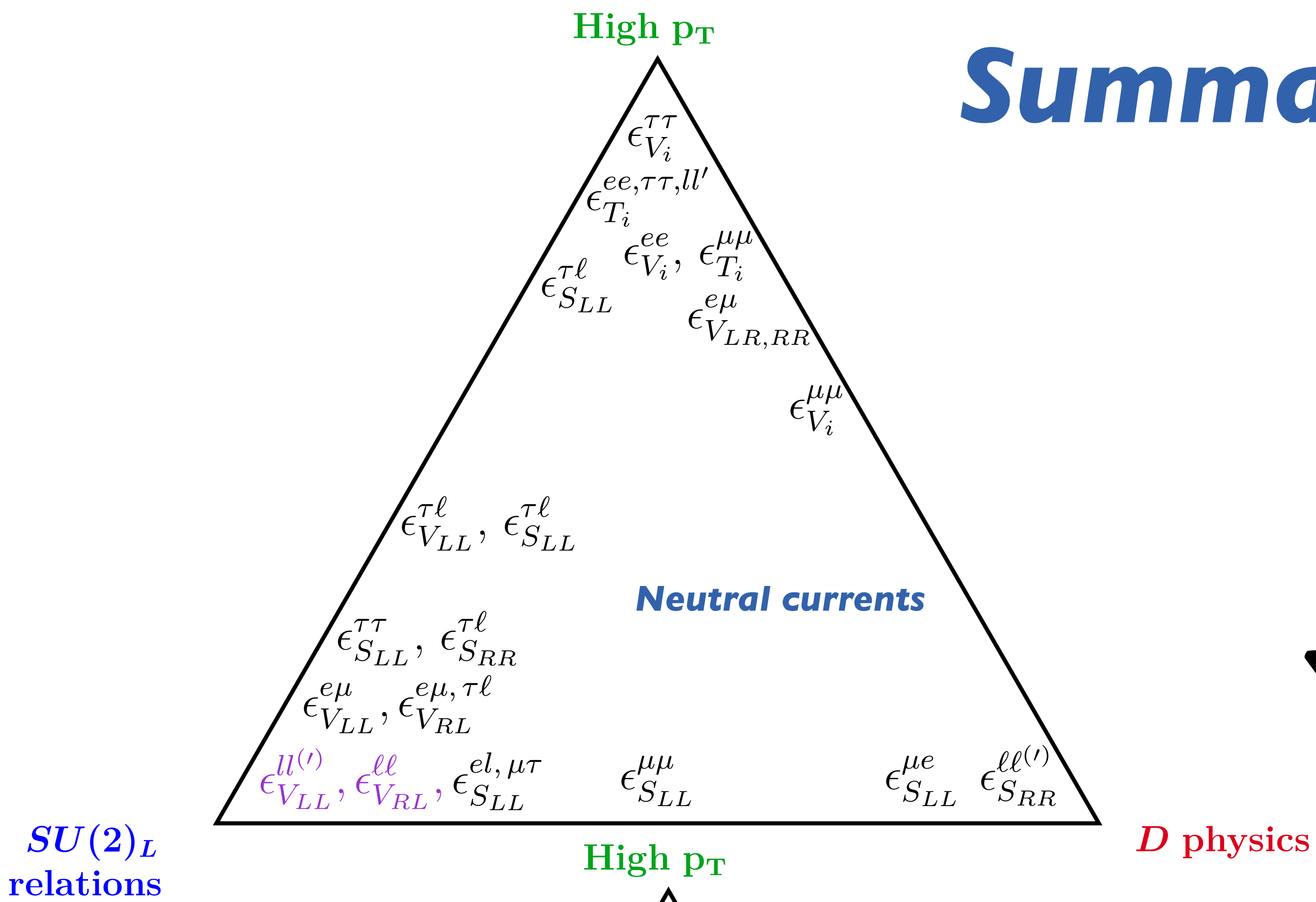
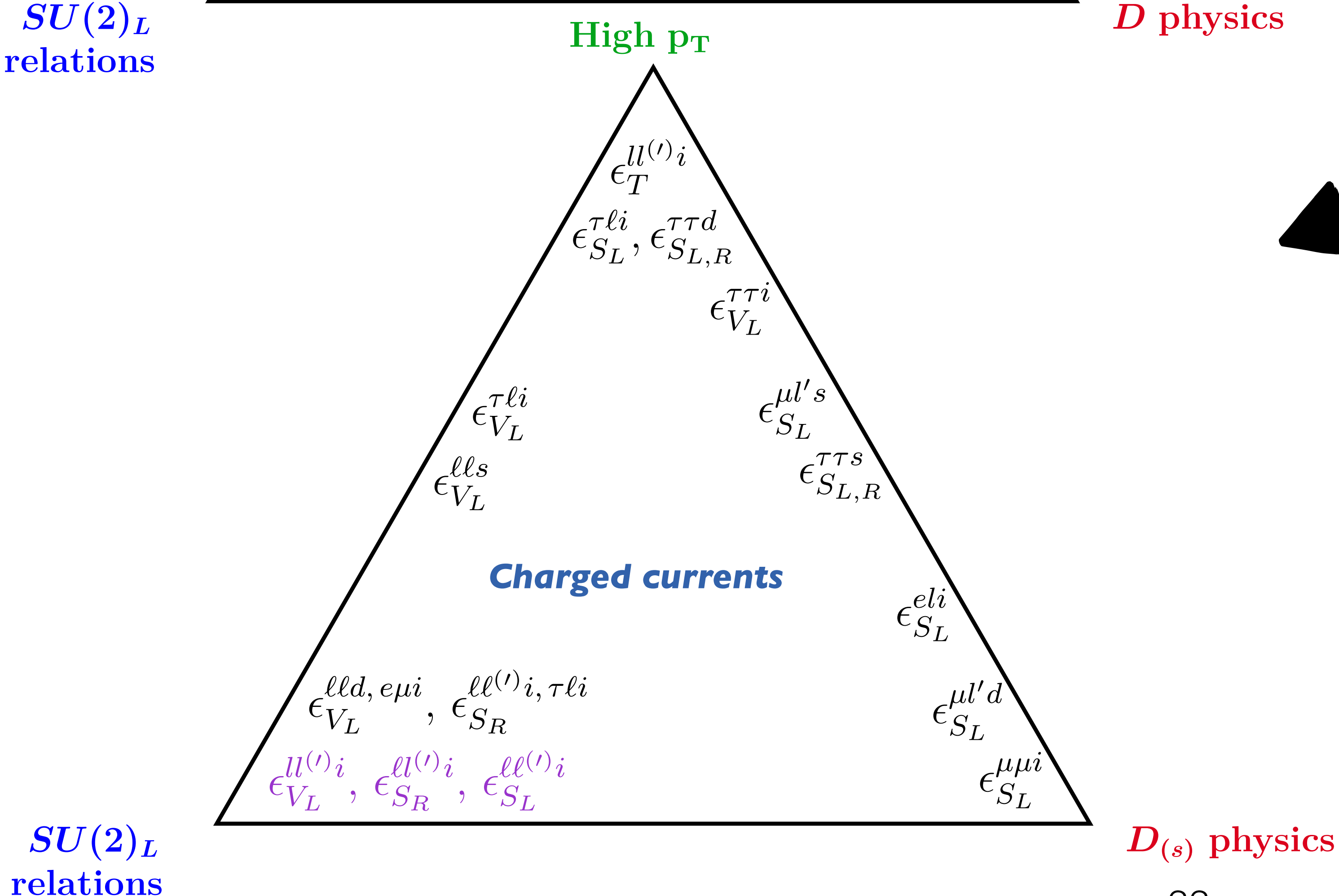
Counterexample

$$\boxed{\mathcal{O}_{eu} = (\bar{e}_R \gamma^\mu e_R)(\bar{u}_R \gamma^\mu u_R)}$$

Summary





We systematically went through all options

$$\mathcal{O}_{LQ}^{(1)} = (\bar{L}\gamma_\mu L)(Q\gamma^\mu Q)\,, \qquad \mathcal{O}_{LQ}^{(3)} = (\bar{L}\gamma_\mu \tau^I L)(Q\gamma^\mu \tau^I Q)\,,$$
$$\mathcal{O}_{eu} = (\bar{e}\gamma_\mu e)(\bar{u}\gamma^\mu u)\,, \qquad \mathcal{O}_{Lu} = (\bar{L}\gamma_\mu L)(\bar{u}\gamma^\mu u)\,,$$
$$\mathcal{O}_{Qe} = (\bar{Q}\gamma^\mu Q)(\bar{e}\gamma_\mu e)\,, \qquad \mathcal{O}_{LedQ} = (\bar{L}\gamma_\mu e)(\bar{d}\gamma^\mu Q)\,,$$
$$\mathcal{O}_{LeQu}^{(1)} = (\bar{L}^p e)\epsilon_{pr}(\bar{Q}^r u)\,, \qquad \mathcal{O}_{LeQu}^{(3)} = (\bar{L}^p \sigma_{\mu\nu} e)\epsilon_{pr}(\bar{Q}^r \sigma^{\mu\nu} u)\,,$$

D(s) decays, high-p_T lepton tails and $SU(2)_L$ relations chart the space of the SMEFT affecting semi(leptonic) charm flavor transitions.

The end

I apologise for missing citations, see the reference list of 2003.12421