MonoTau production at the LHC

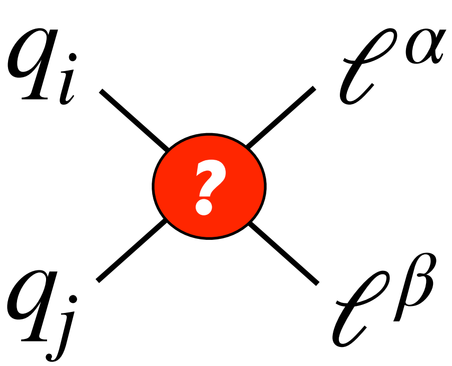
Admir Greljo

Based on: 1811.07920, 2003.12421. See also: 1704.09015, 1609.07138

Snowass-2021 RF05, 23.07.2020

The Scope

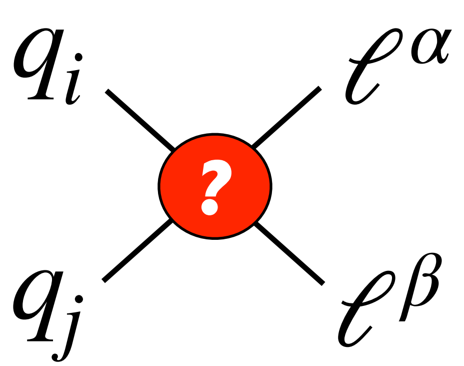
$$\Delta F = 1$$



Today $\alpha = 3$

Opportunities across the scales

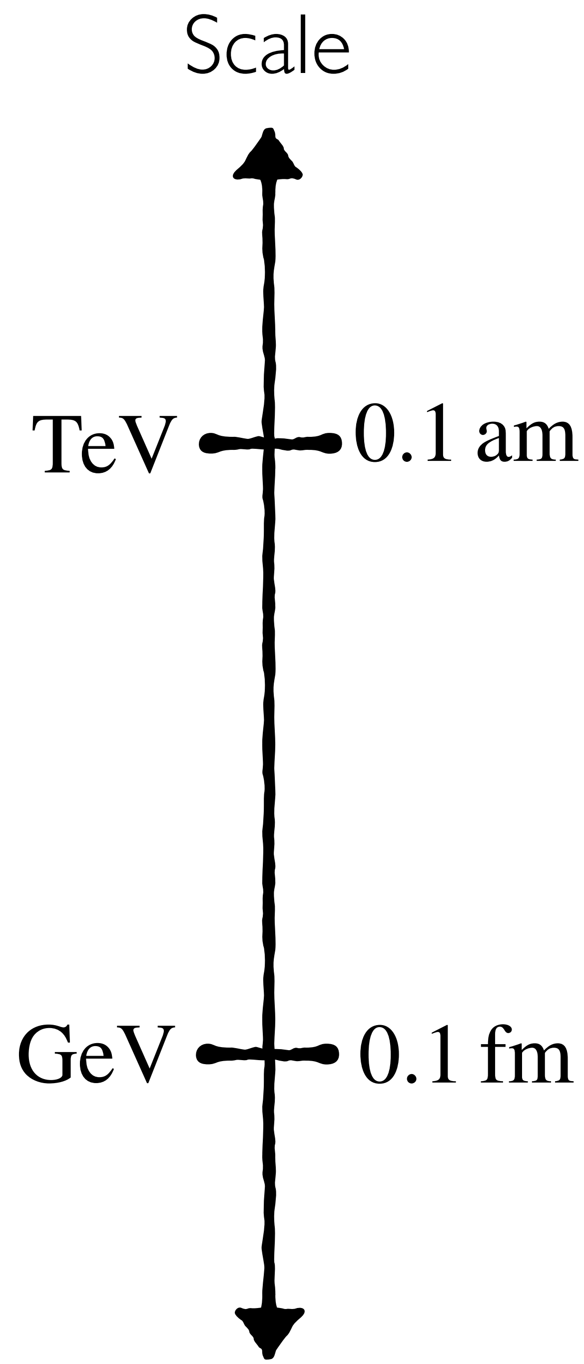
$\Delta F = 1$



Today $\alpha = 3$

Proton collisions

Decays



High-energy frontier

ATLAS EXPERIMENT, CMS

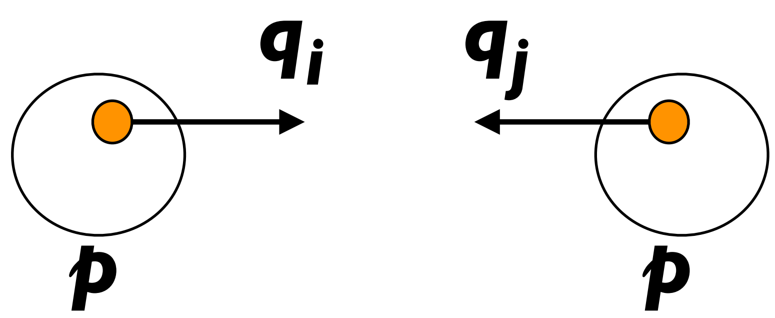
High-intensity frontier

LHCb, Belle II, BESIII

+ NA62, Koto, MEG II, Mu3e, …

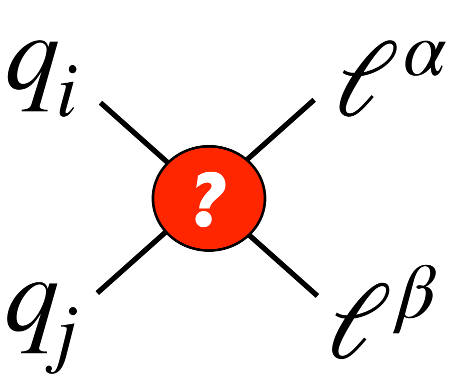
Opportunities across the scales

- Parton distribution functions for five quark flavors; **LHC is a flavor collider.**



- Final state flavor discrimination: *e, mu, TAU, top, b-jet, c-jet, light jet, MET.*

$$\Delta F = 1$$



Today $\alpha = 3$

Decays

GeV — 0.1 fm

High-energy frontier

ATLAS EXPERIMENT, CMS

High-intensity frontier

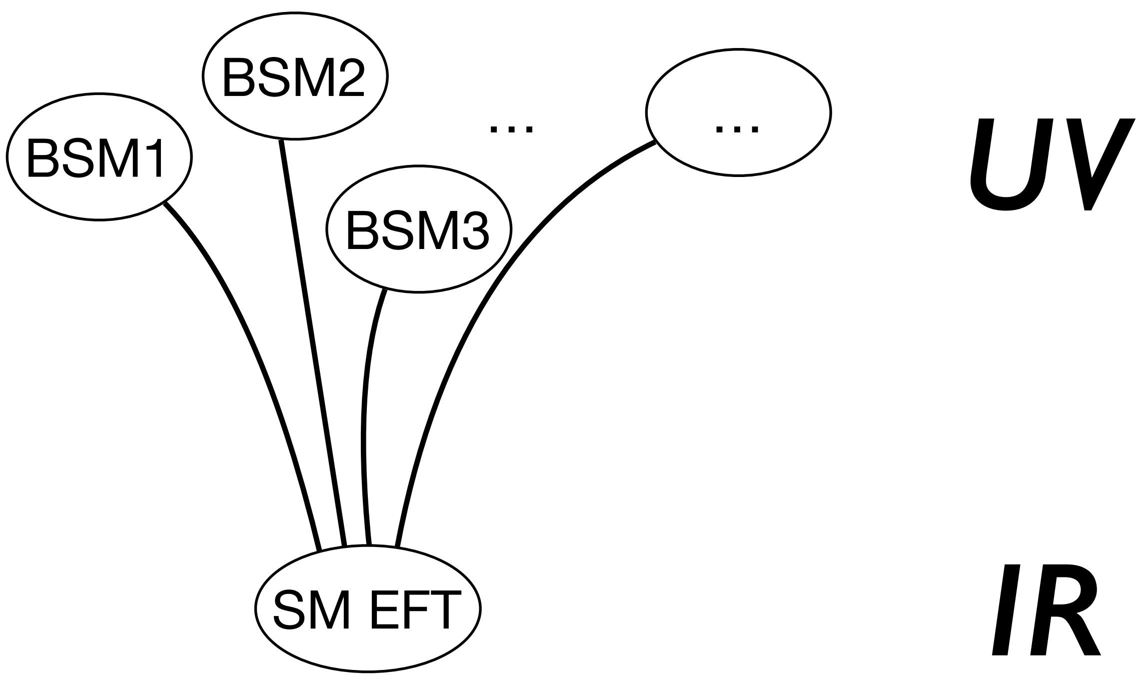
LHCb, Belle II, BESIII

+ NA62, Koto, MEG II, Mu3e, …

Theoretical framework

Warsaw basis: 1008.4884

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



Theoretical framework

2.1 The high-energy effective theory

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

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

(for CC)

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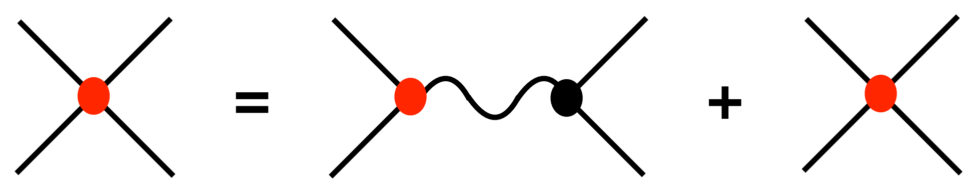
Matching 

2.2 The low-energy effective theory

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

$\epsilon_{X,SM}^{\alpha\beta ij} = 0$ for all X

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

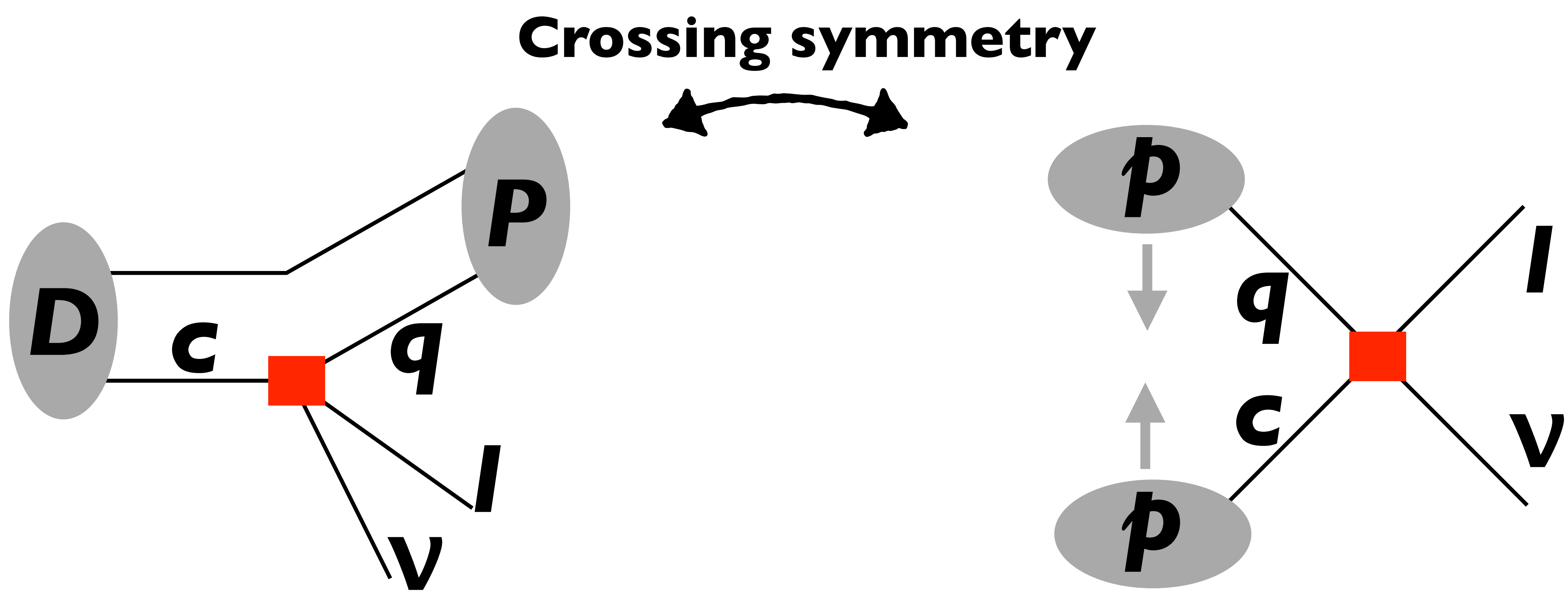
$$\mathcal{O}_{S_L}^{\alpha\beta ij} = (\bar{e}_R^\alpha \nu_L^\beta)(\bar{u}_R^i d_L^j)\,, \qquad \mathcal{O}_{S_R}^{\alpha\beta ij} = (\bar{e}_R^\alpha \nu_L^\beta)(\bar{u}_L^i d_R^j)\,,$$

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

(for CC)

Links

- The EFT allows us to establish links for a generic NP model



- The EFT validity is an important issue (the discussion in the backup).

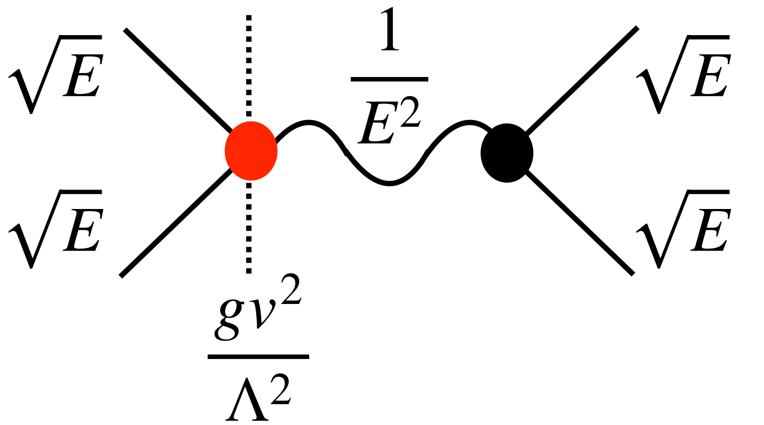
High-p_T lepton production at the LHC

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

$s \sim E^2$

W-vertex

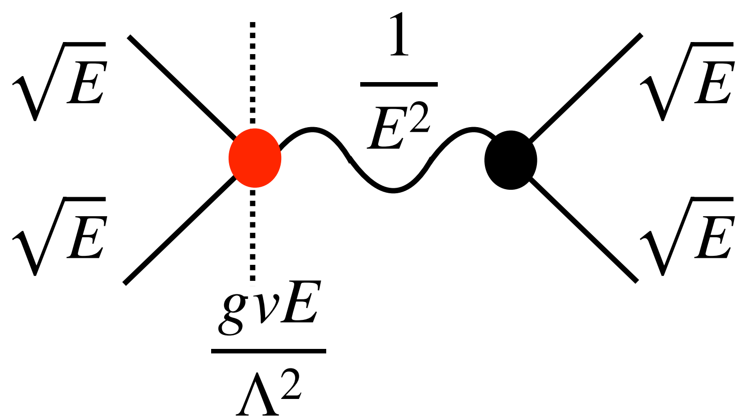
Chirality preserving: $\frac{1}{\Lambda^2}\psi^2\phi D\phi$



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

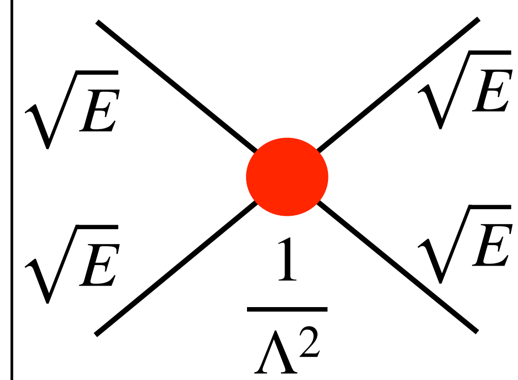
$(\mathscr{A}_{SM} \sim g^2)$

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



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

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.

High-p_T lepton production at the LHC

- 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 from low-energy decays.

Back-of-the-envelope

- 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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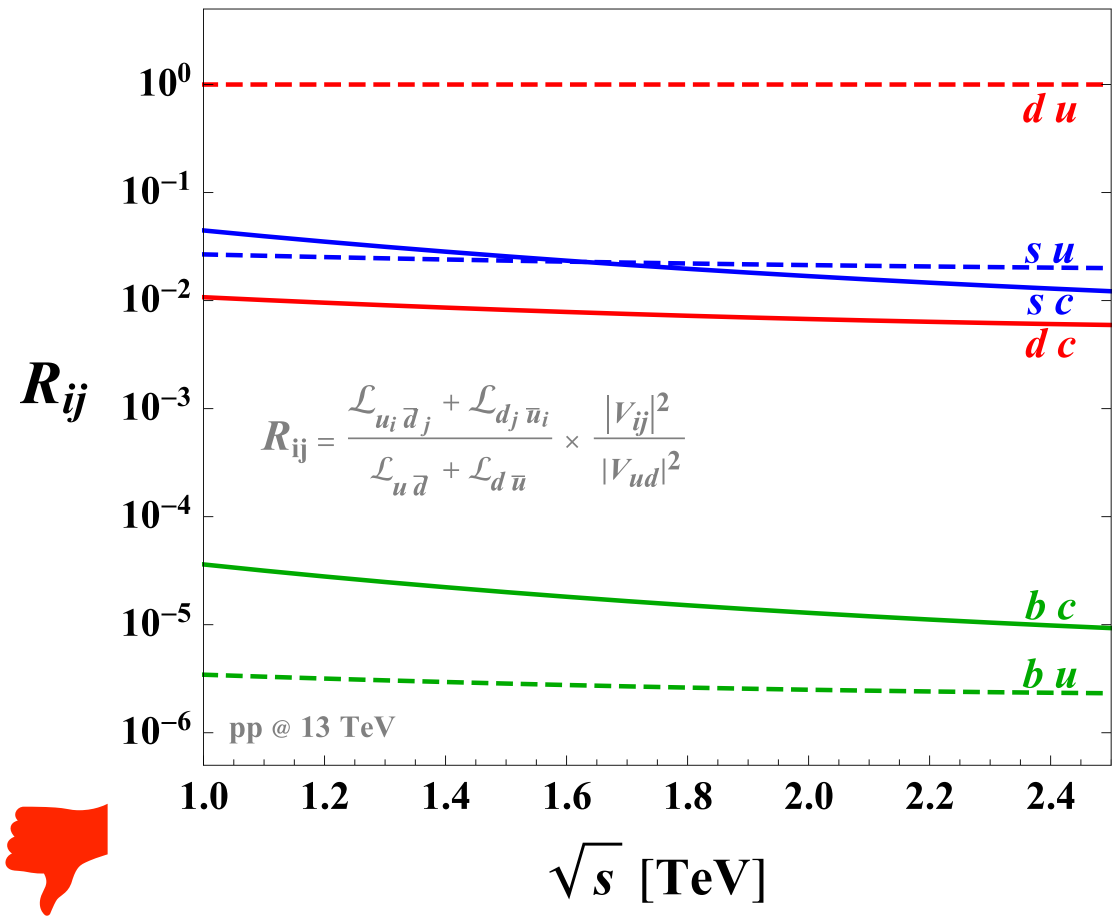

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Energy enhancement

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

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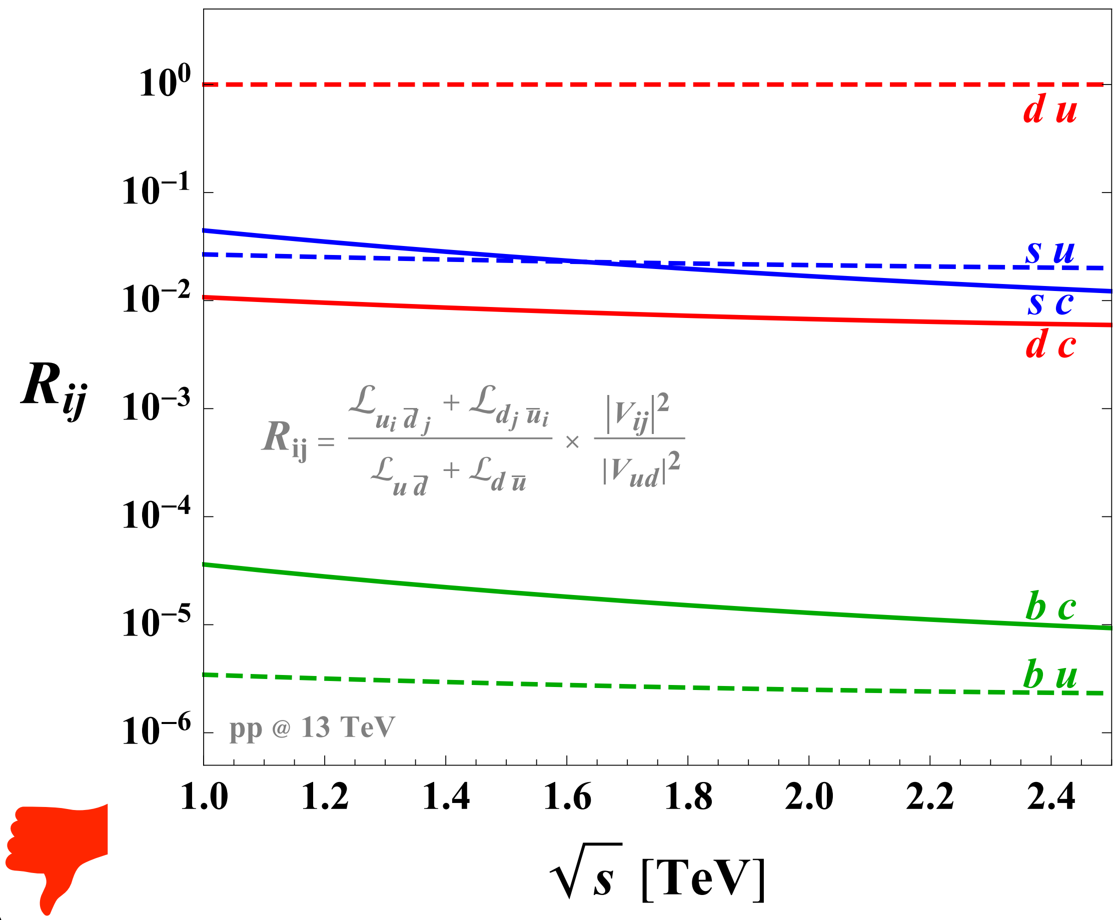

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$d_X = 1, \frac{3}{4}, 4$ for $X = V, S, T$

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

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

Energy enhancement

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

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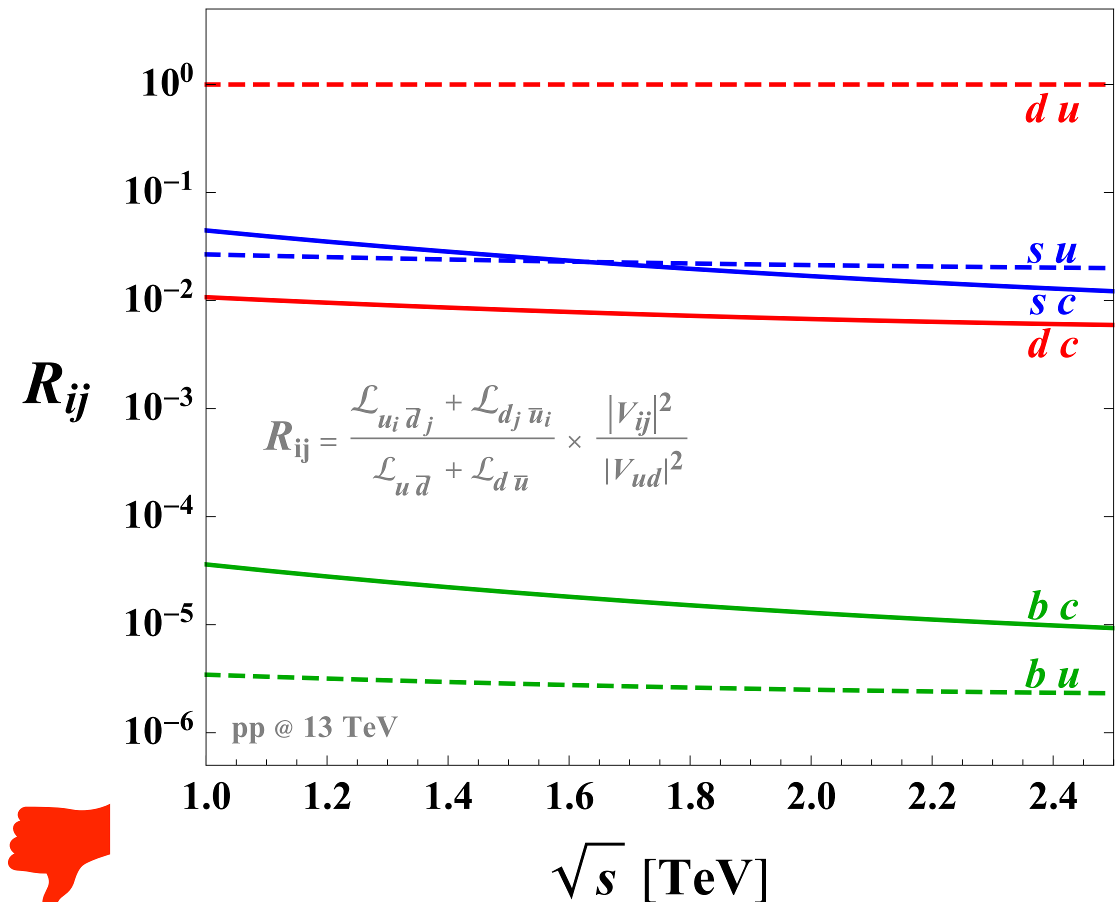
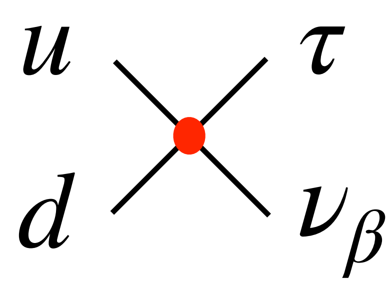
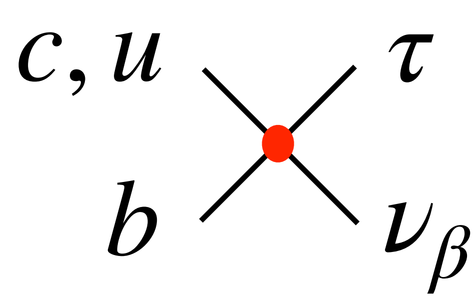


Selected MonoTau references

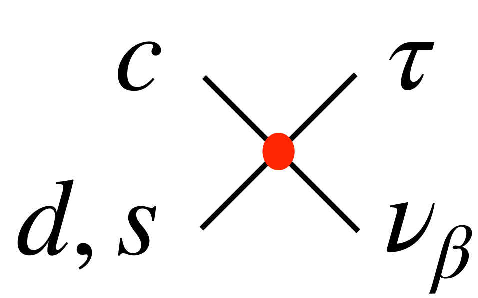
- [Cirigliano, Falkowski, Gonzalez-Alonso, Rodriguez-Sanchez] 1809.01161



- [**Greljo**, Martin-Camalich, Ruiz-Alvarez] 1811.07920



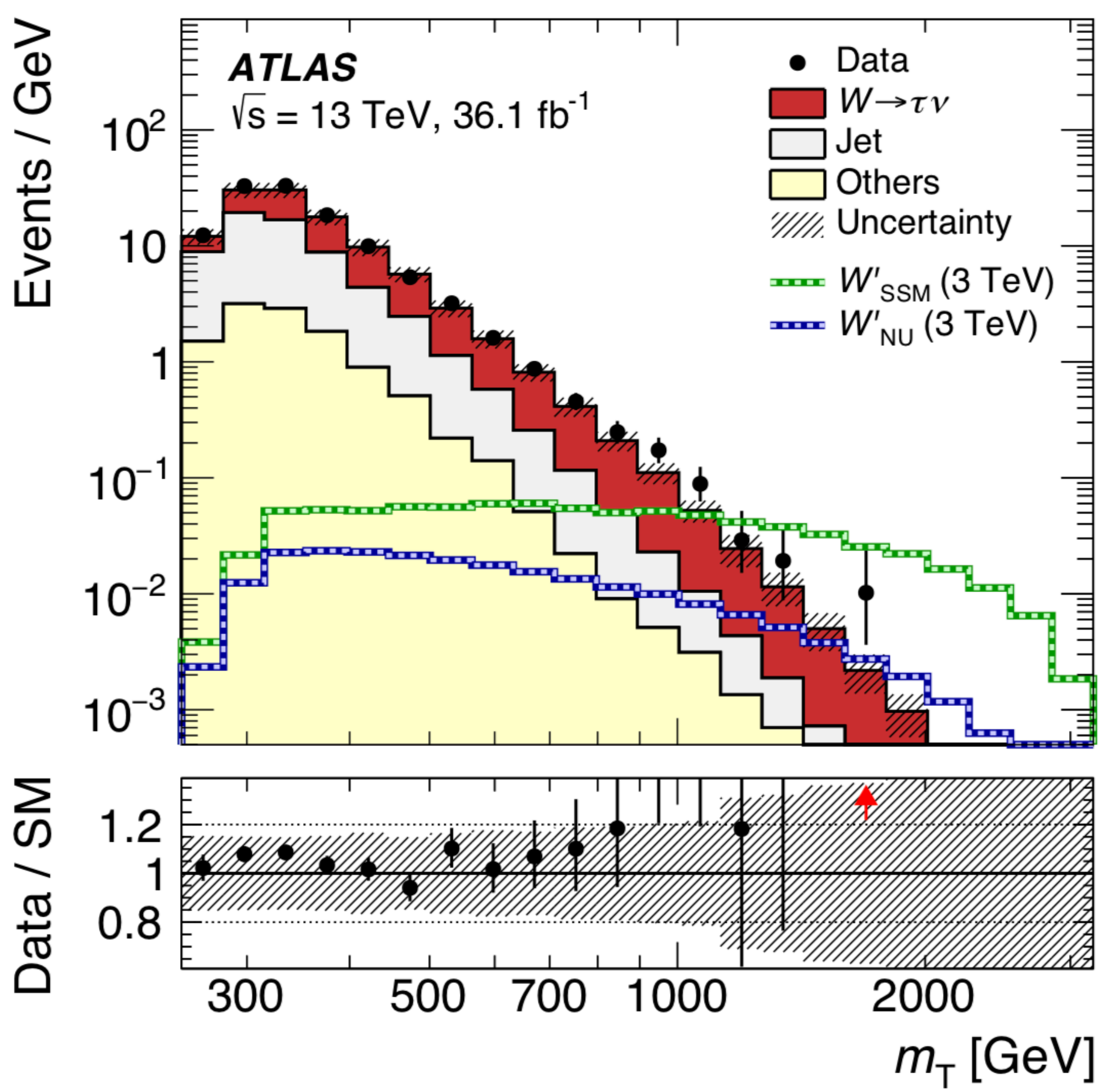
- [Fuentes-Martin, **Greljo**, Martin-Camalich, Ruiz-Alvarez] 2003.12421

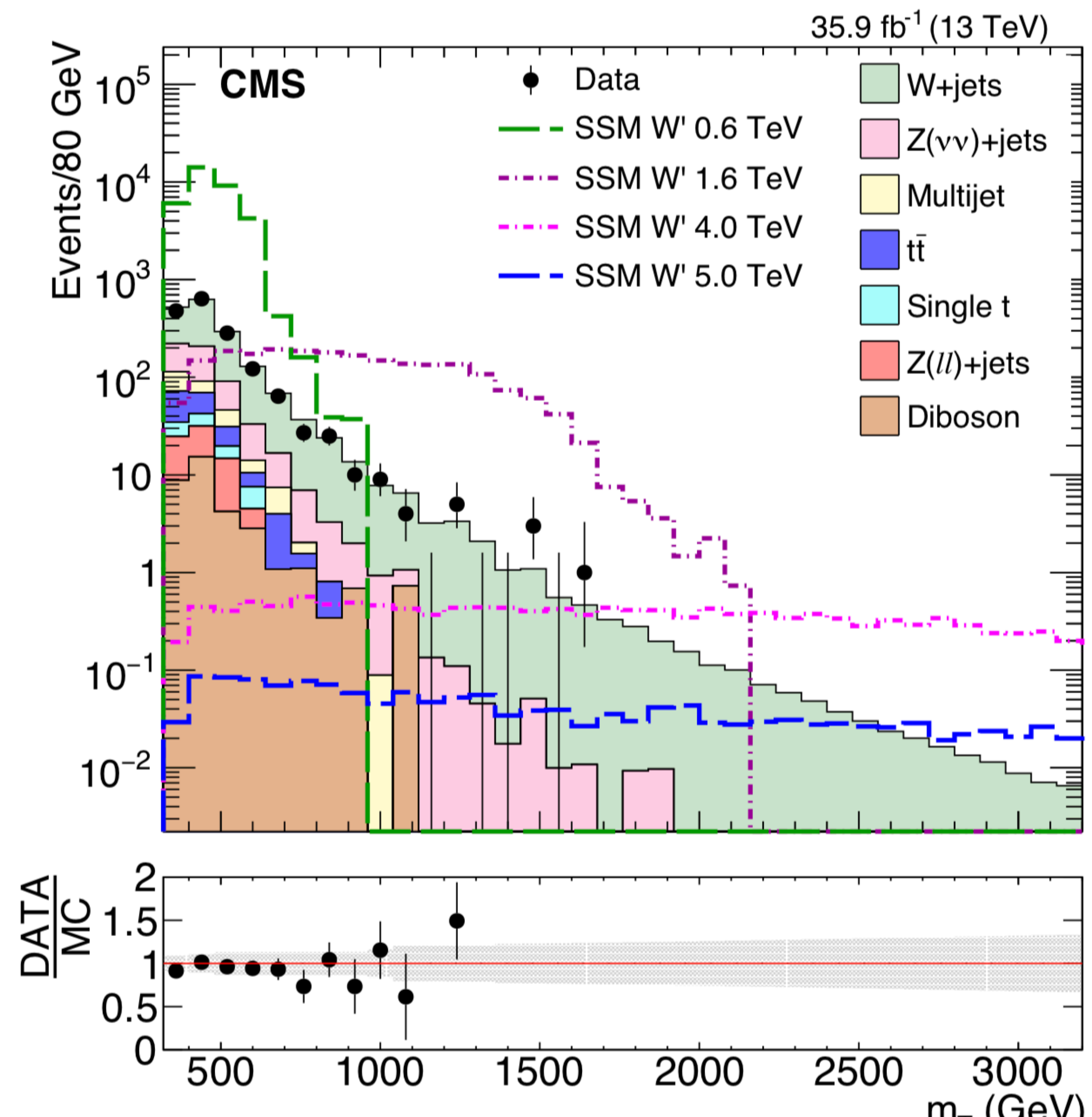


(*) β – flavor index

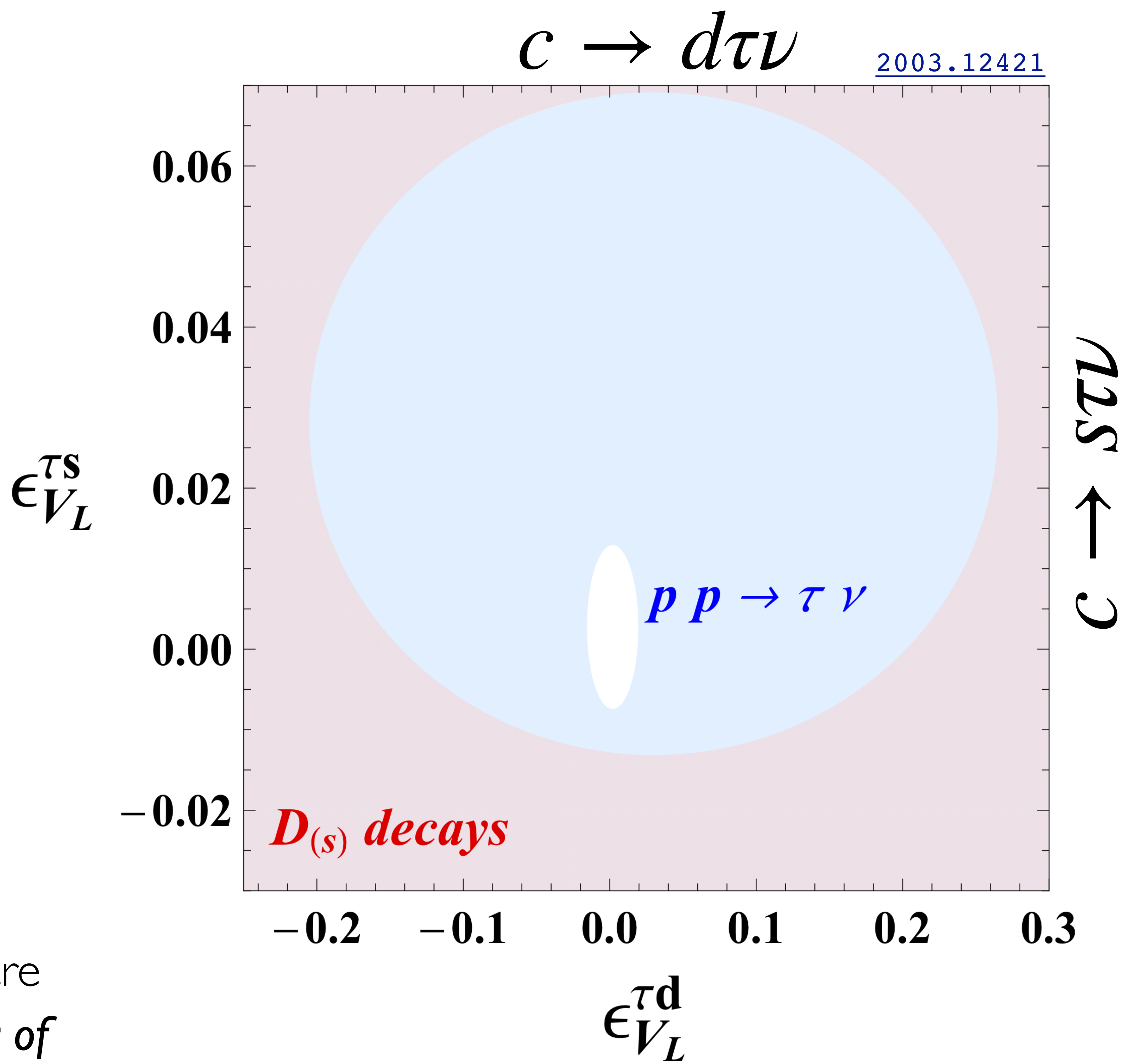
Recast of the existing searches

- We **recast** the available searches fitting the transverse mass distribution at the reconstruction level.
- Full-fledged simulations validated by reproducing the official SM prediction. The SM background systematics included conservatively. The modified frequentist CLs used.





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



- High-p_T limits are almost ***an order of magnitude*** stronger

(*) For $\nu \neq \nu_\tau$ low-p_T weaker, high-p_T unchanged

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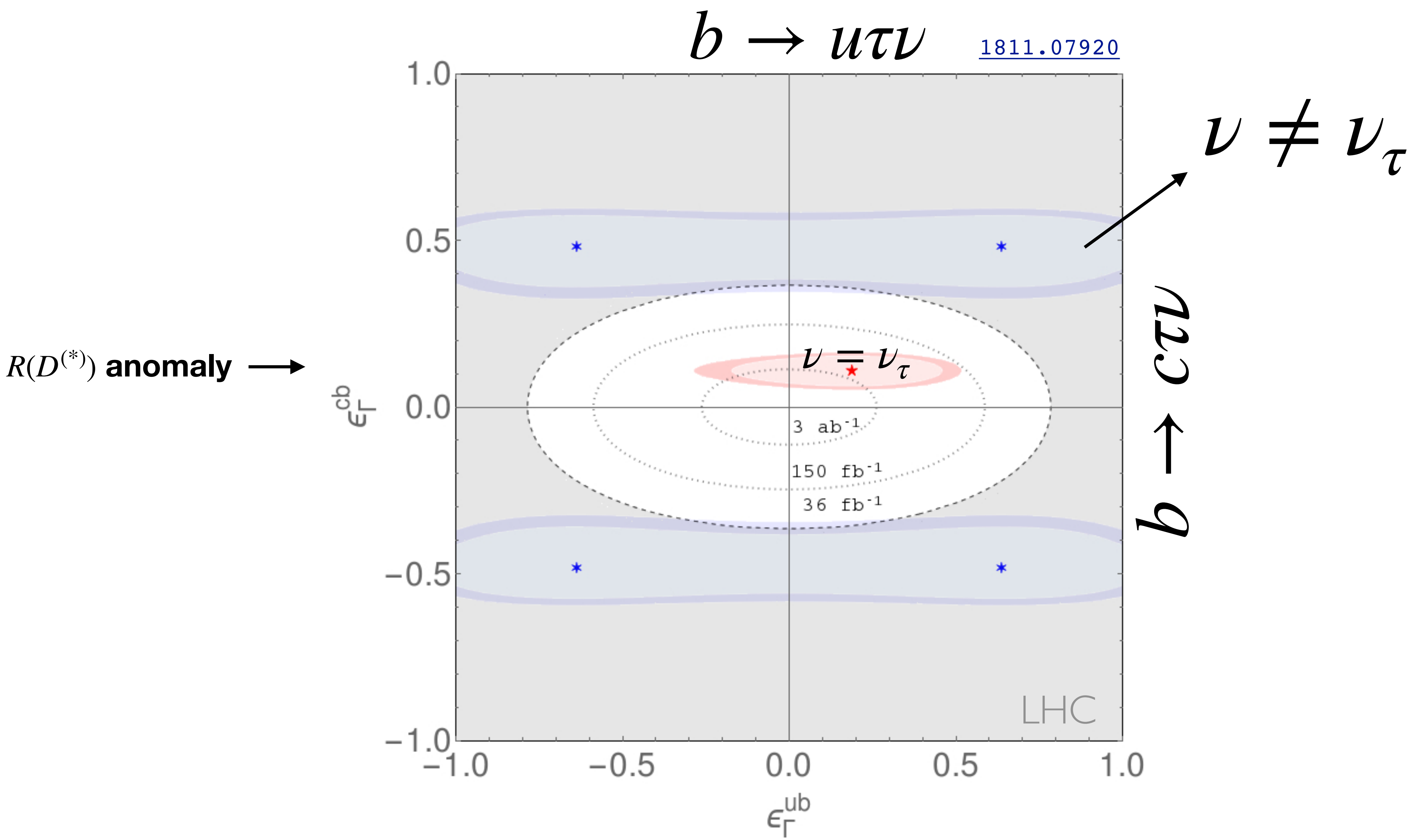

Updated by Jorge Martin Camalich for Portoroz 2019

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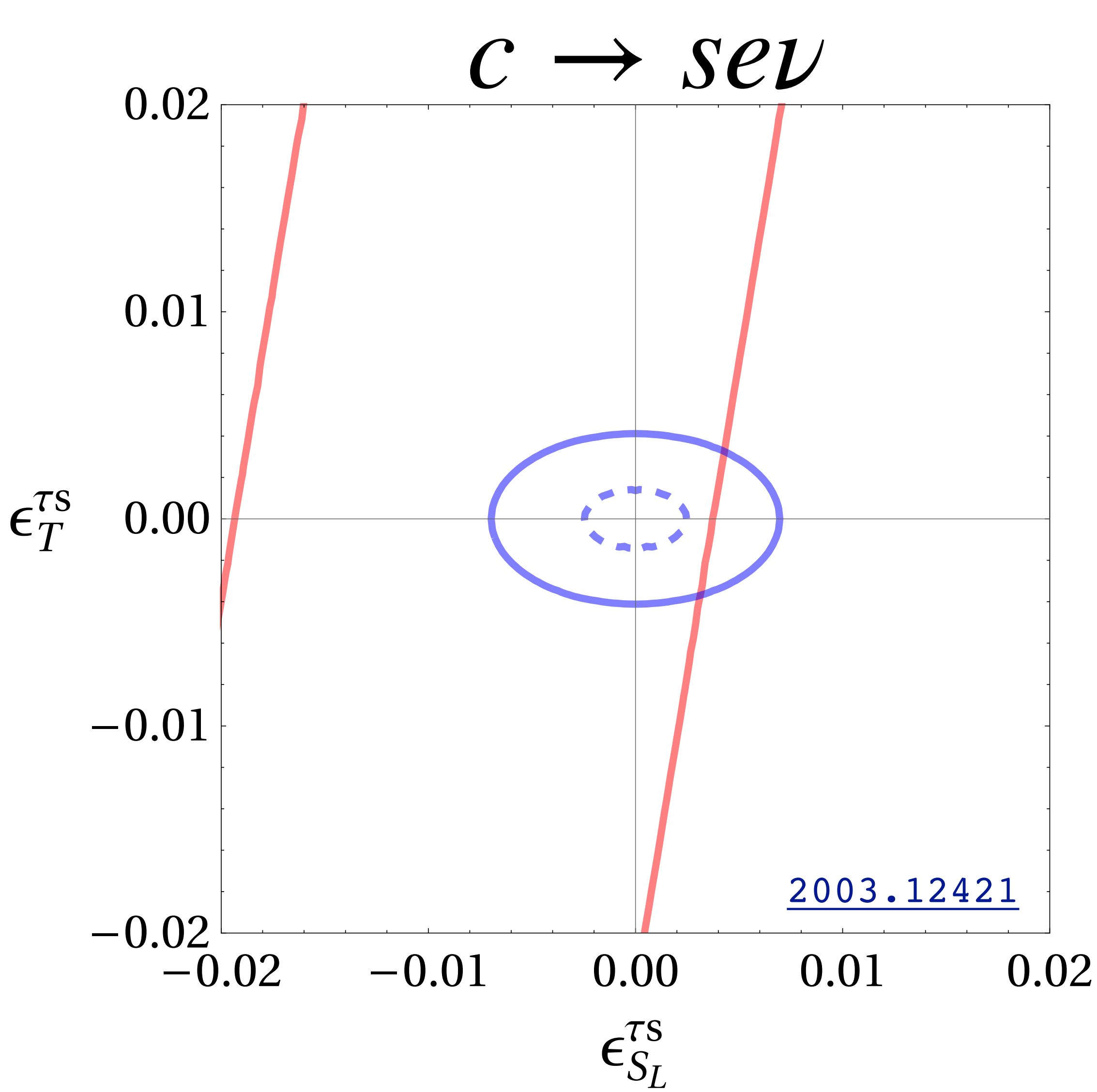
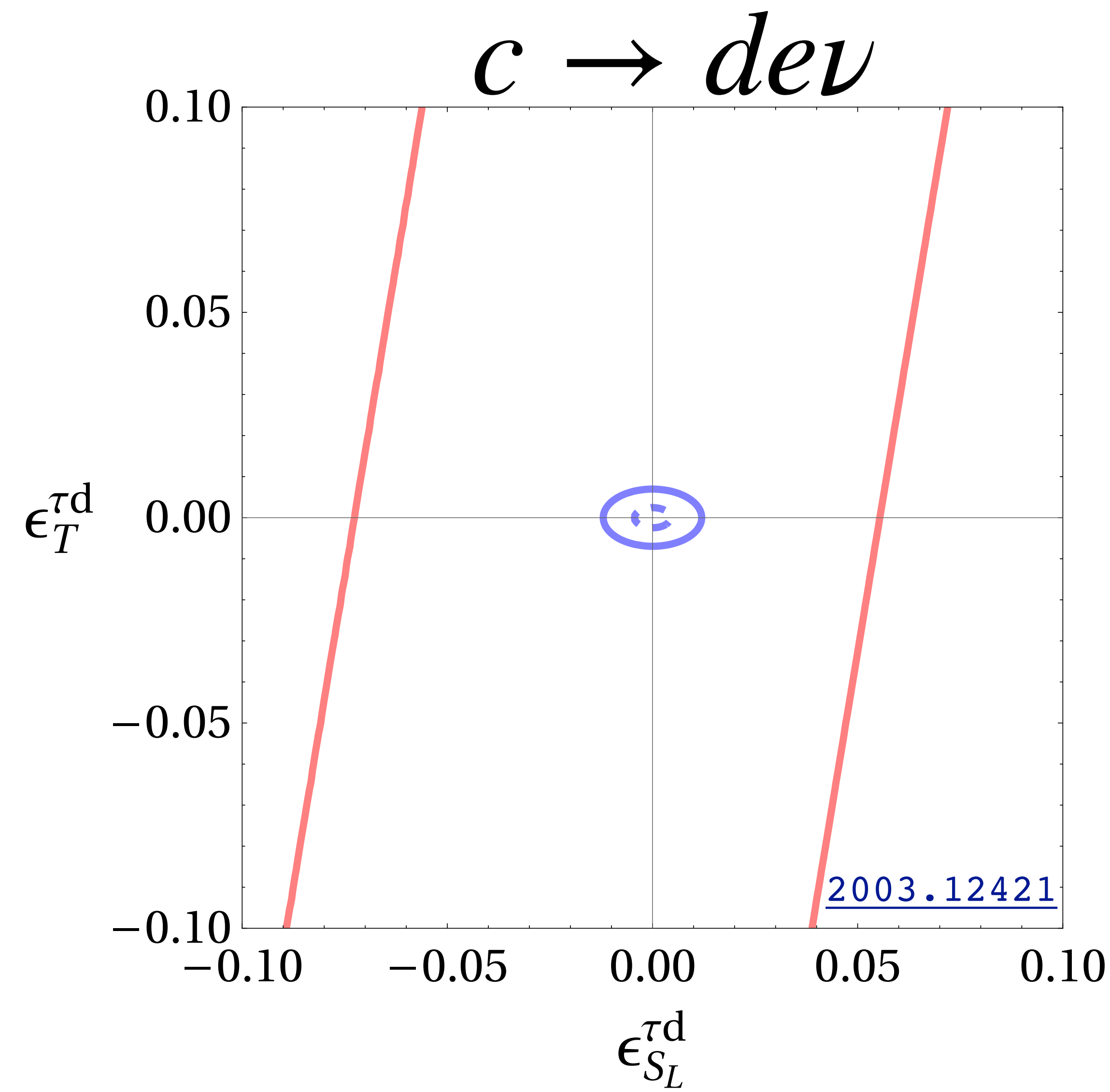
NP in

$$\mathcal{O}^{(1)}_{lequ} = (\bar{l}^p_L e_R)\epsilon_{pr}(\bar{q}^r_L u_R)$$ <> scalar

$$\mathcal{O}^{(3)}_{lequ} = (\bar{l}^p_L \sigma_{\mu\nu} e_R)\epsilon_{pr}(\bar{q}^r_L \sigma^{\mu\nu} u_R)$$ <> tensor





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Theoretical predictions

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 ~ 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.

A. Greljo, S. Iranipour, Z. Kassabov, M. Madison, J. Moore, J. Rojo, MU, C. Voisey in progress

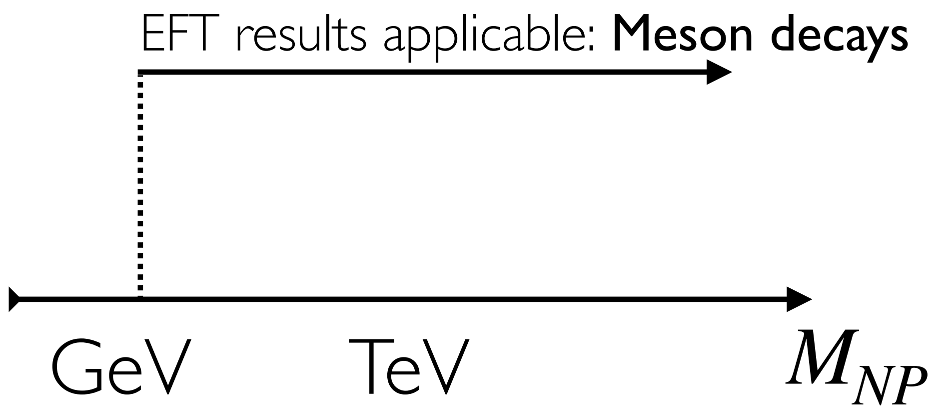
…the final topic

⚠ *EFT validity*

[Backup]

EFT validity

- EFT expansion parameter s/M_{NP}^2



EFT validity

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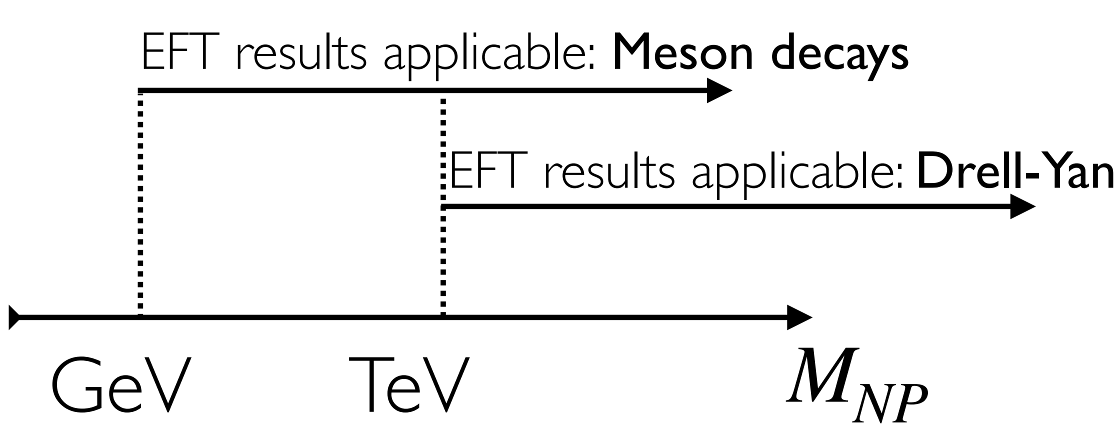
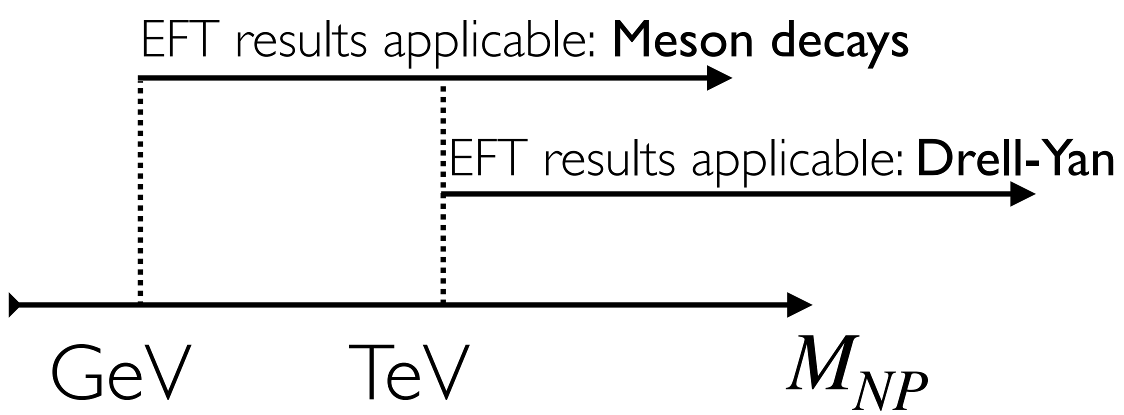


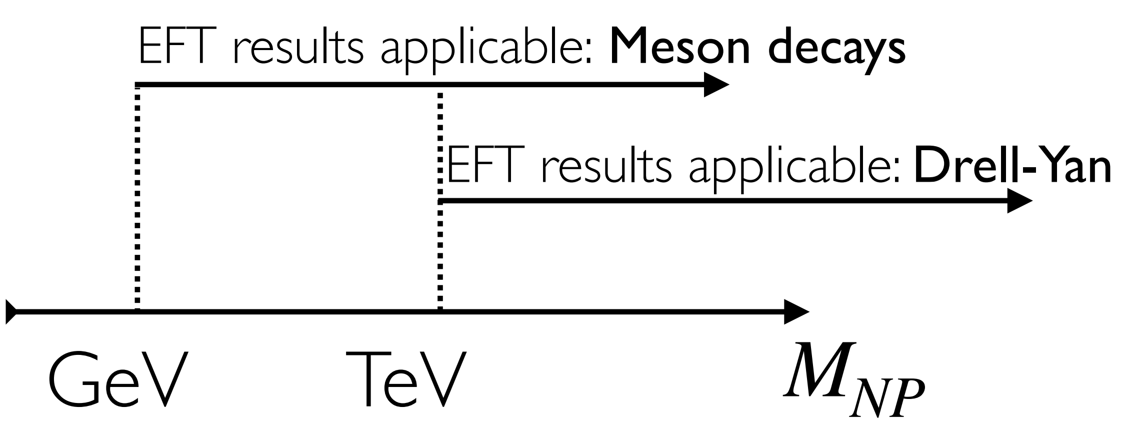
EFT validity

- EFT expansion parameter s/M_{NP}^2
- Perturbative unitarity suggests that the largest scales currently probed are at most few x 10 TeV for strongly coupled theories.

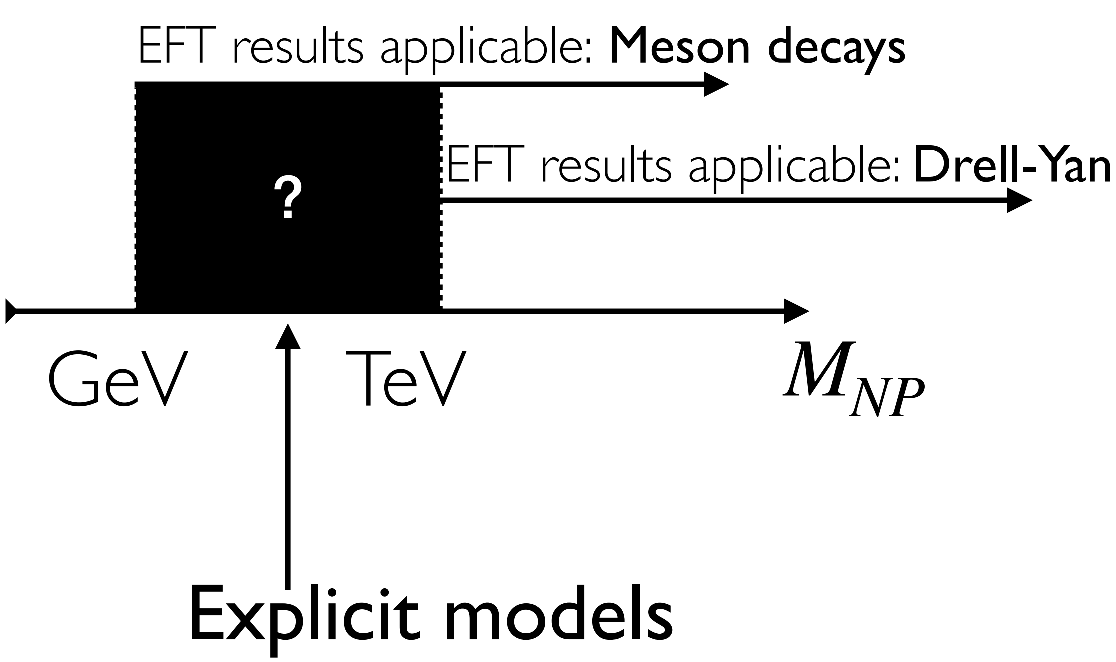


EFT validity

- EFT expansion parameter s/M_{NP}^2
- Perturbative unitarity suggests that the largest scales currently probed are at most few x 10 TeV for strongly coupled theories.
- Any suppression in the matching, such as loop, weak coupling, or flavor spurion, brings the actual NP mass scale down.



EFT validity



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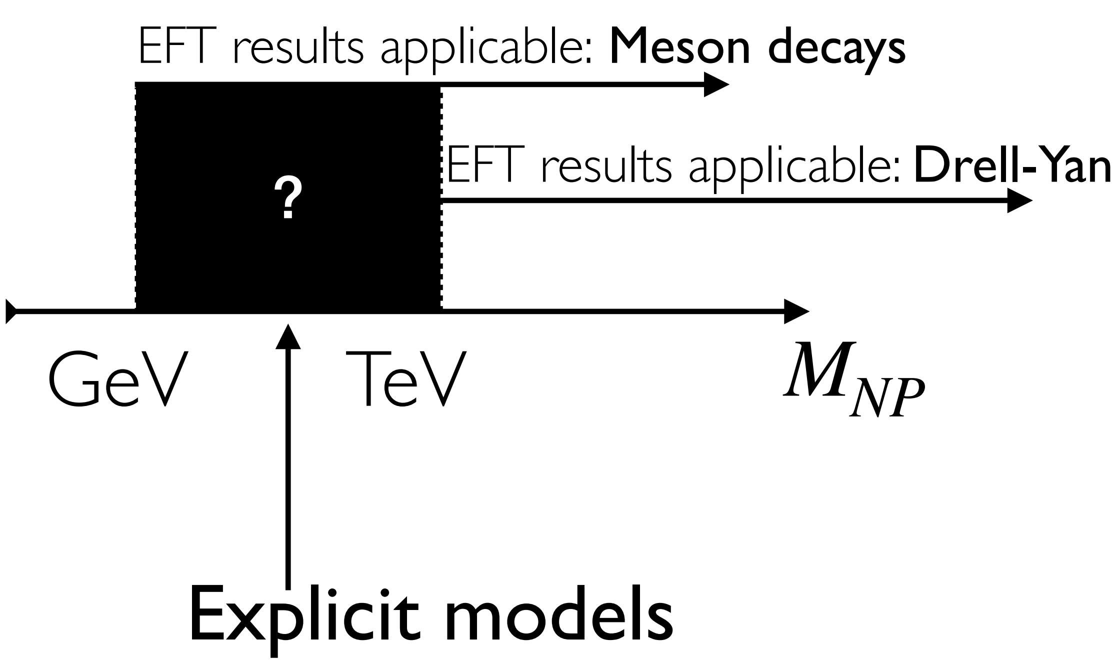
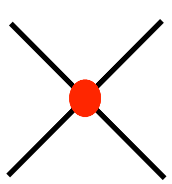


Tree-level UV completions



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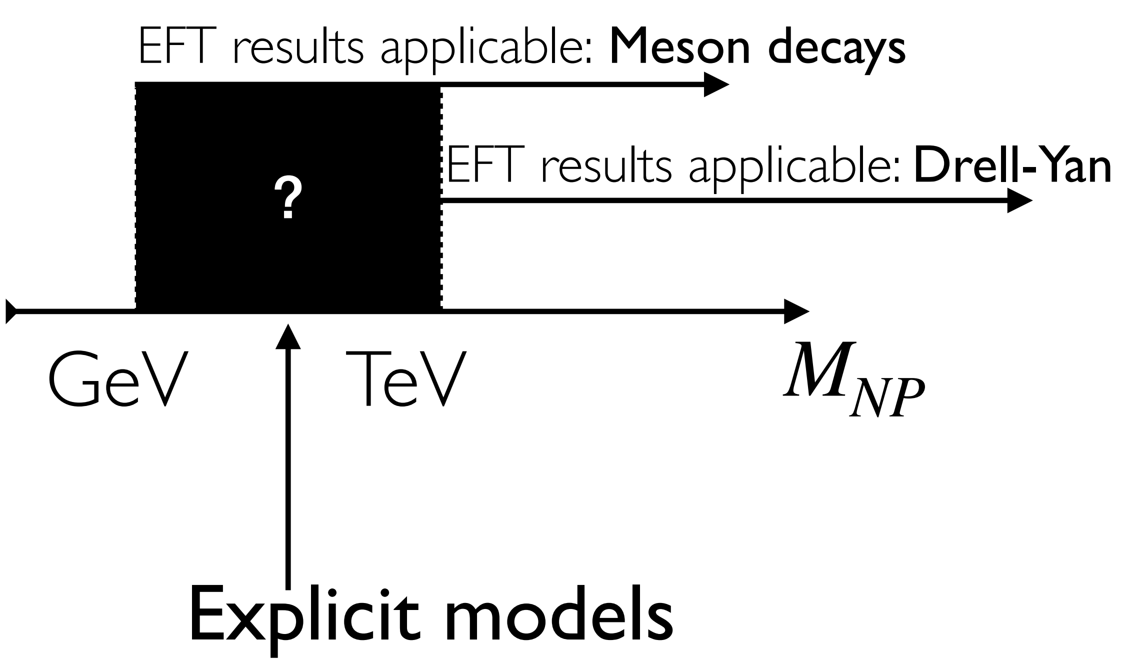
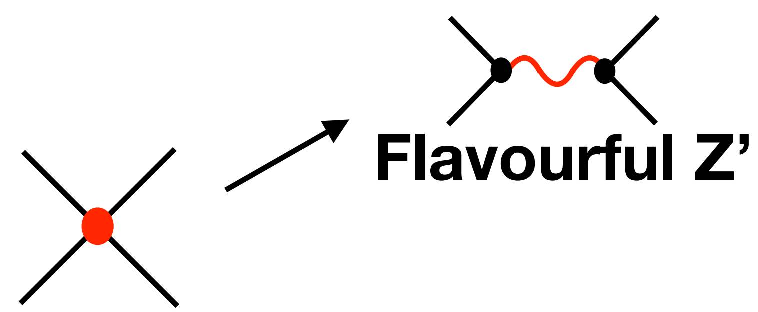


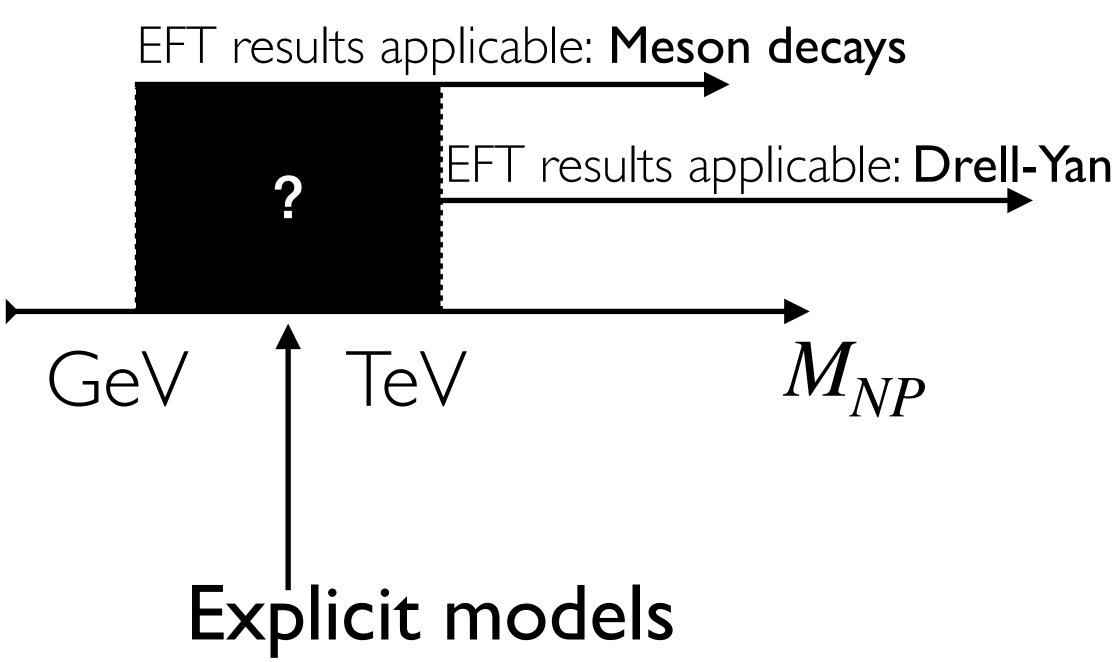
Tree-level UV completions

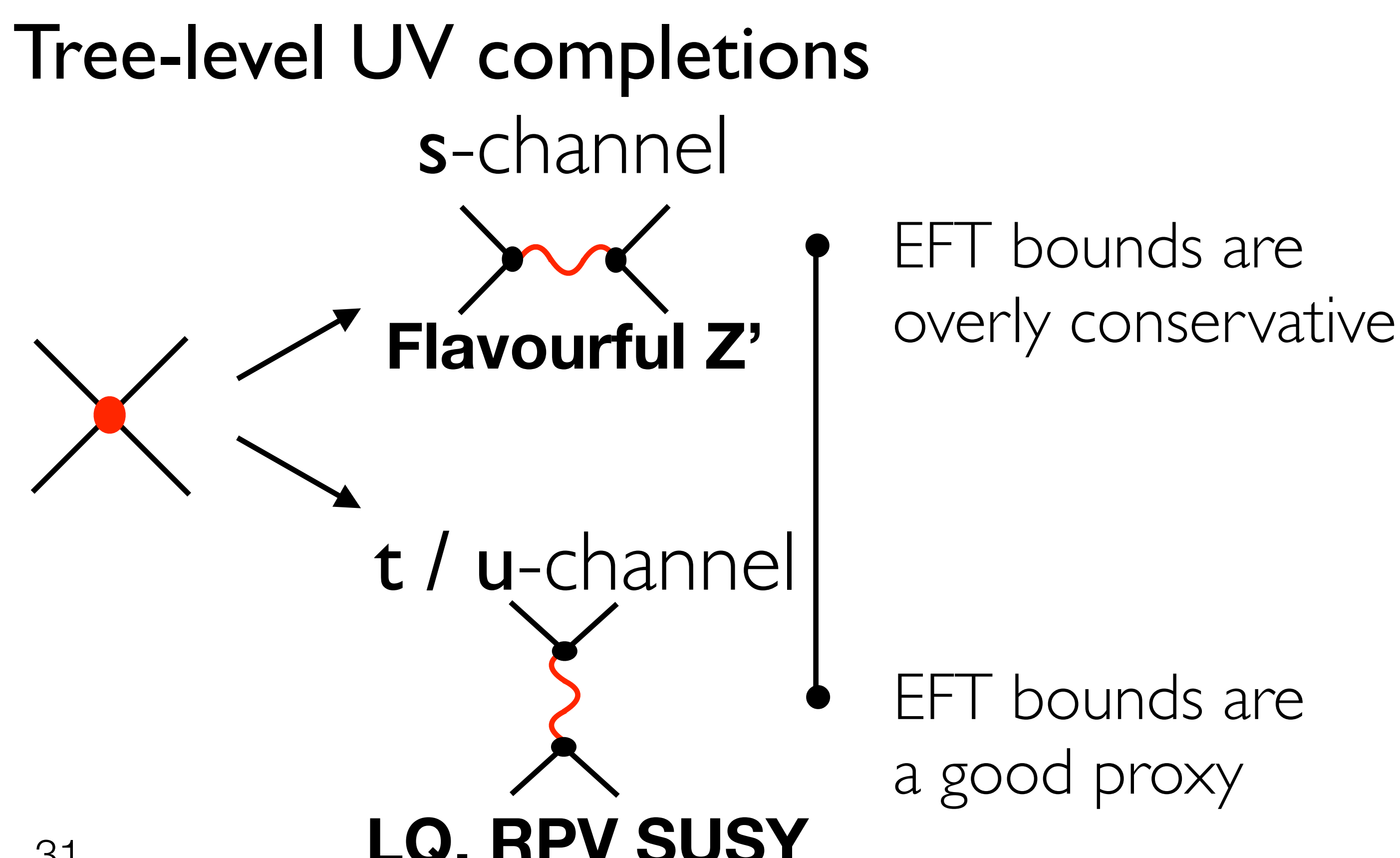
s-channel



- EFT bounds are overly conservative

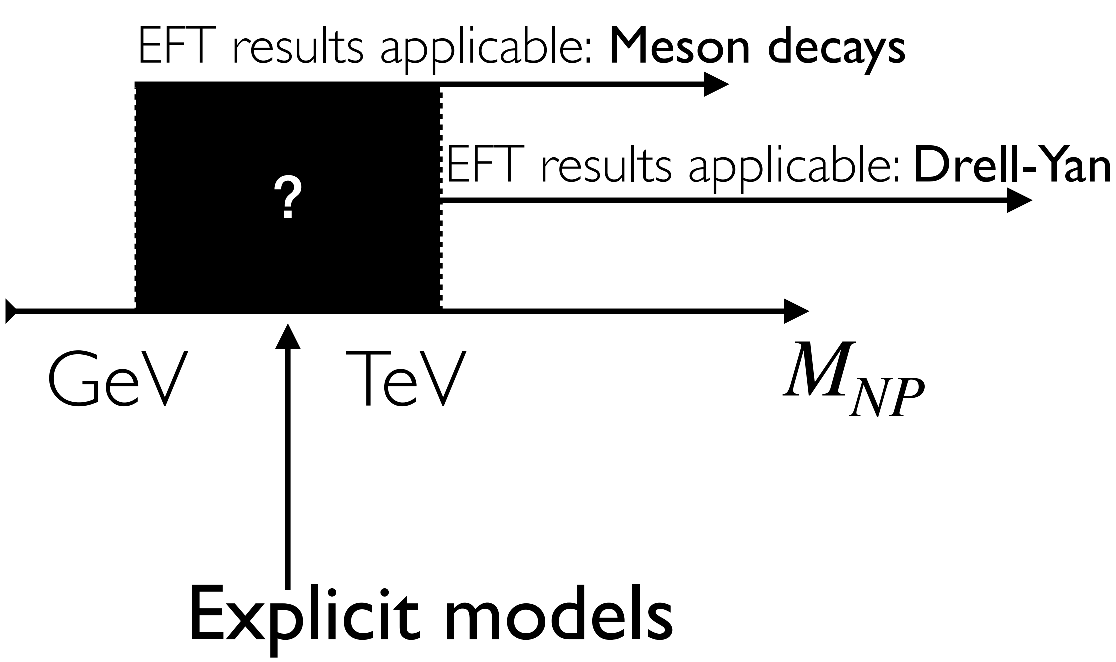
EFT validity





EFT validity

- This EFT exercise is useful even if the EFT validity is not guaranteed.
- If, in the EFT, the high-p_T provides stronger limits, better carefully check the collider pheno of the model.



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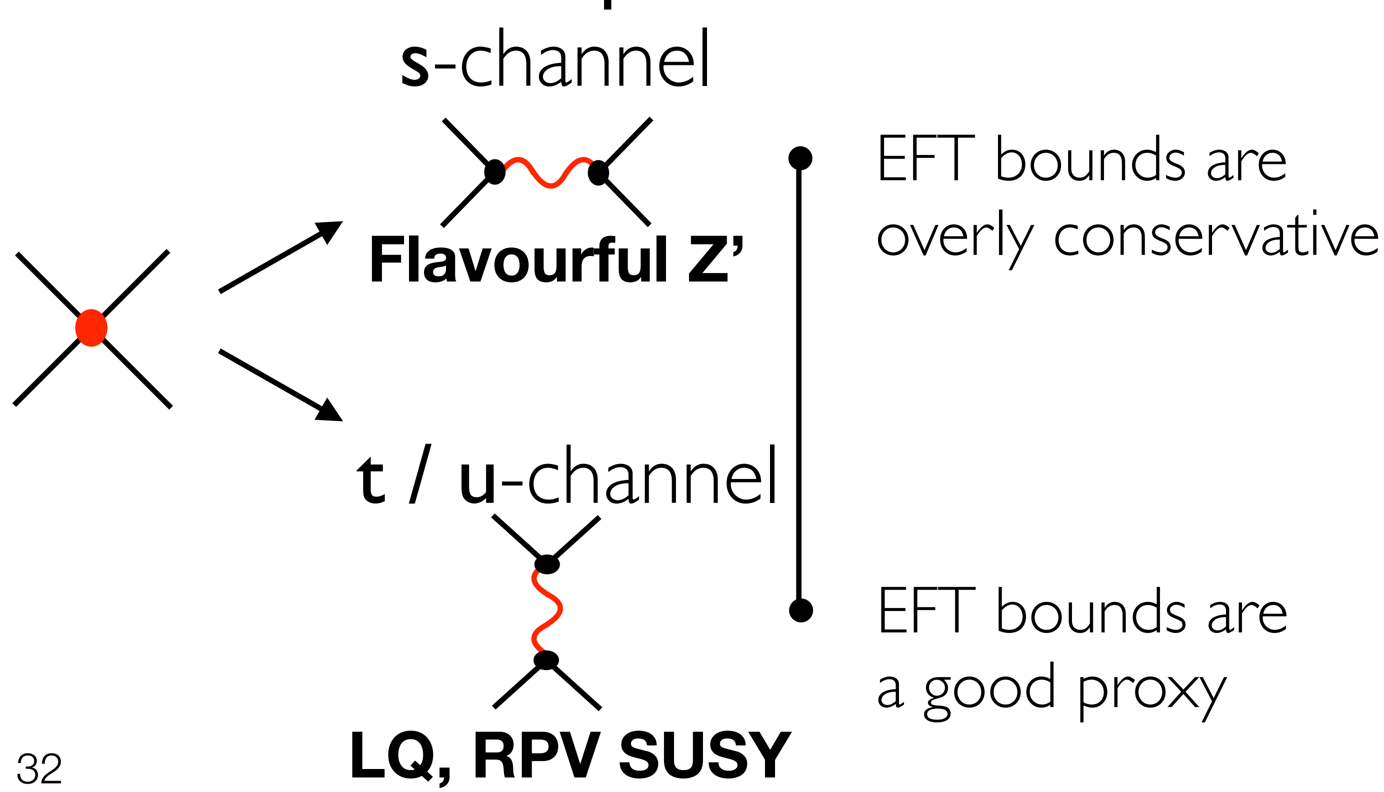
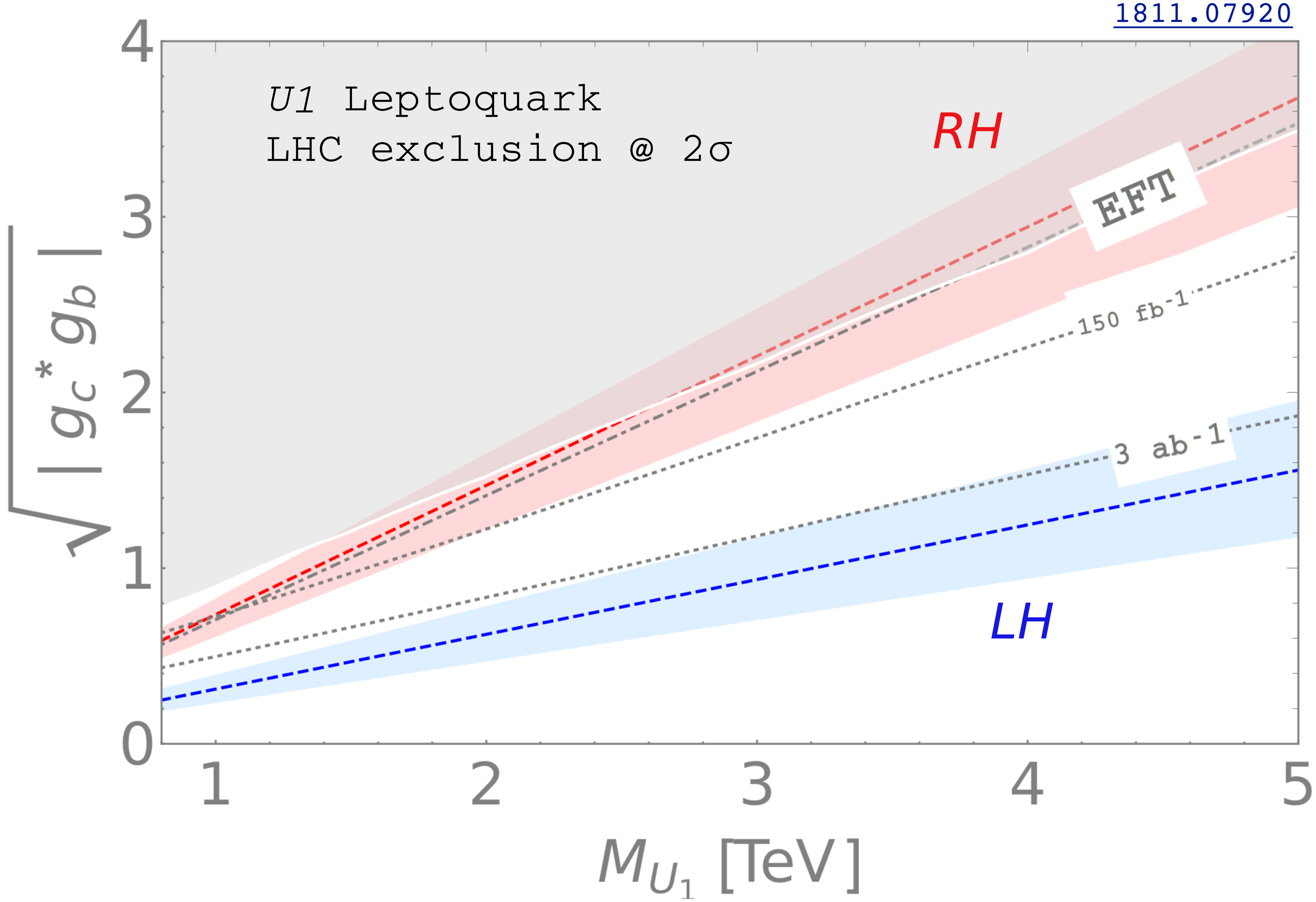


EFT validity

- Explicit model example

1811.07920



EFT validity

- The most sensitive bin analysis

1811.07920