High-p_T Lepton Tails at the LHC and Flavour Physics

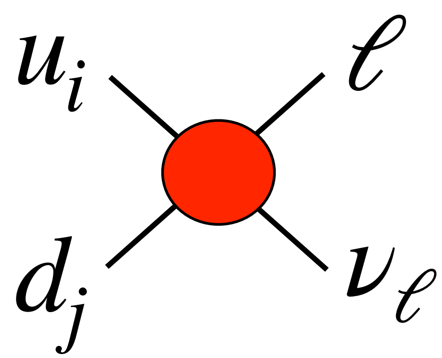
Admir Greljo

Large Hadron Collider (LHC) is delivering an unprecedented amount of data which enables ATLAS and CMS detectors to perform the most precise measurements of the Drell-Yan and mono-lepton high-pT tails. One the one hand, the LHC is a collider of five-quark flavors and several excellent methods of heavy flavor tagging in the final state have recently been developed, while on the other hand, a short distance new physics effects are enhanced at high-pT. Having this in mind, we explore the opportunities and challenges for studying heavy flavour physics in the high-pT tails in years to come.

EPS HEP, 11.7.2019, Ghent

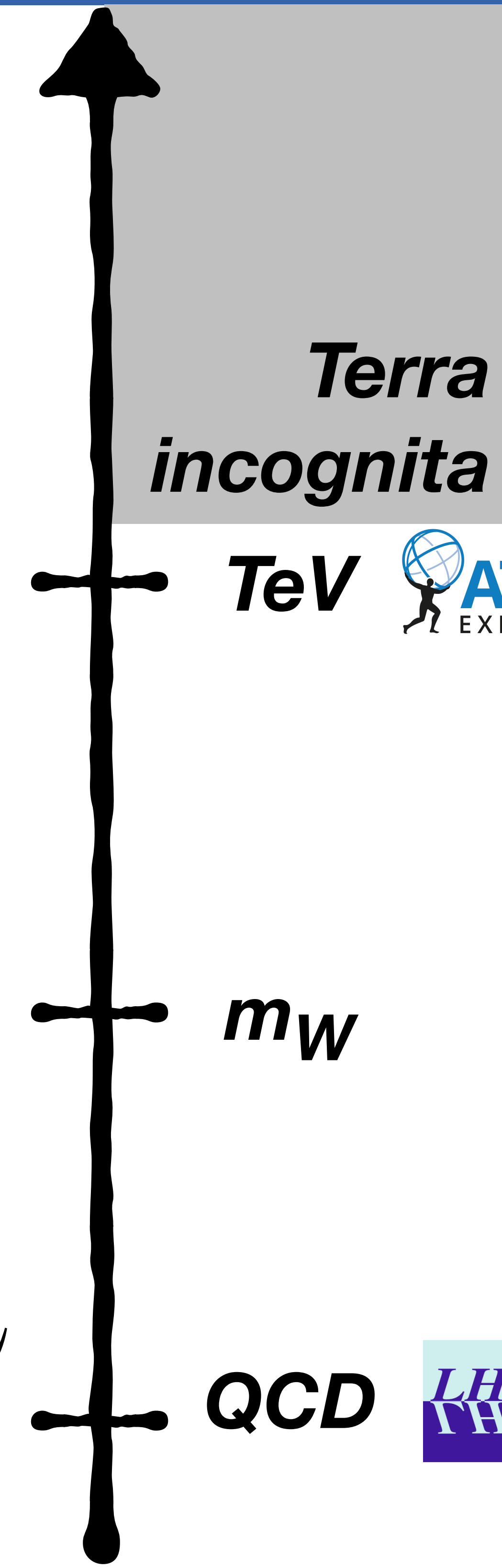
Low/High p_T Interplay

New opportunity: ***Harvesting the large statistics at highest collider energies***



$$pp \to \ell\nu$$

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



- The same underlying 4-point function
  - *albeit different kinematical regime*
- Current status: *Competitive limits at high-p_T*
- Future: ***Improvements at both frontiers***
  (LHCb & Belle II) ⚽ (ATLAS & CMS)

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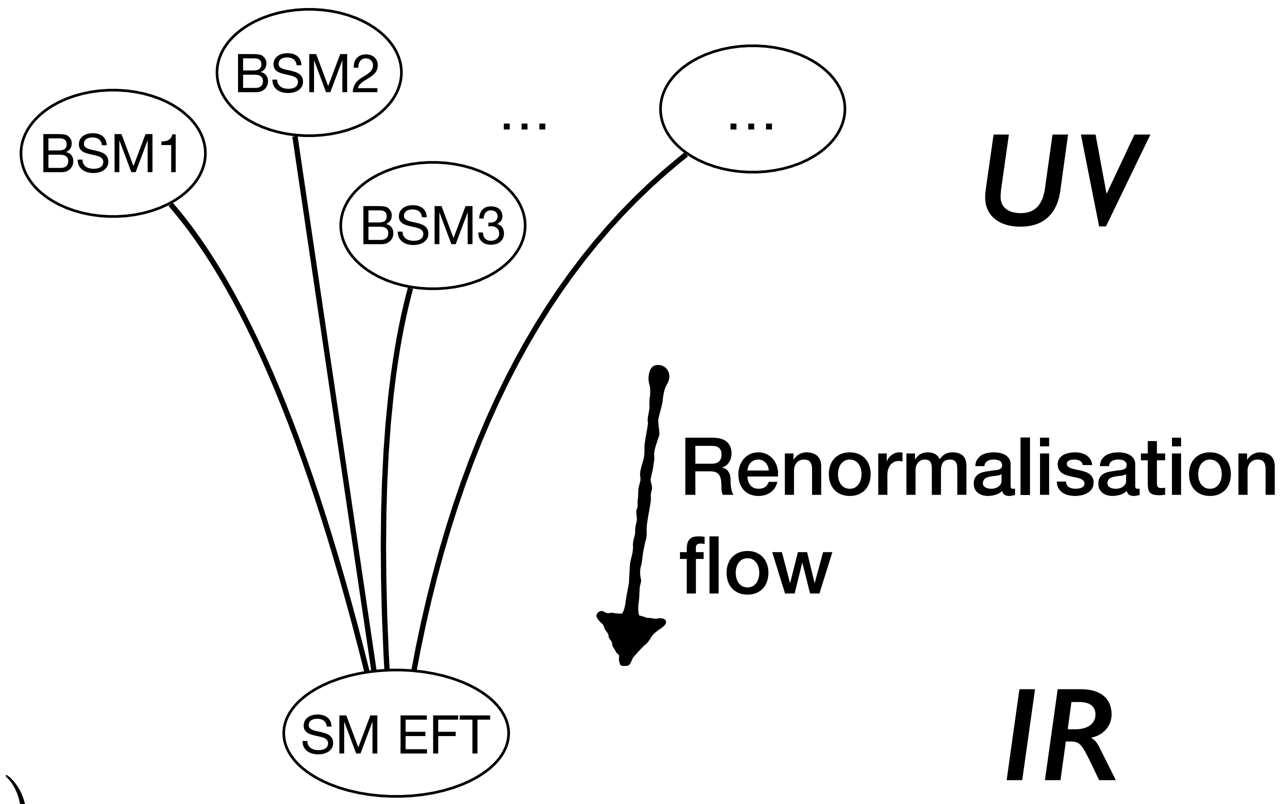


Example: $(\bar{Q}^i_L \gamma_\mu \sigma^a Q^j_L)(\bar{L}^\alpha_L \gamma^\mu \sigma^a L^\beta_L)$

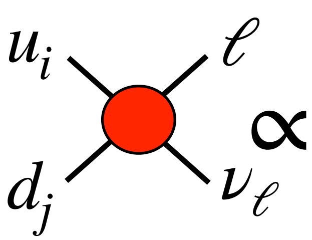
$$\mathscr{L} \supset -\frac{G_F}{\sqrt{2}} V_{ij}\, \epsilon_L \;\; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu \;\times\; \bar{u}_i \gamma^\mu (1-\gamma_5) d_j$$

Low/High p_T Interplay

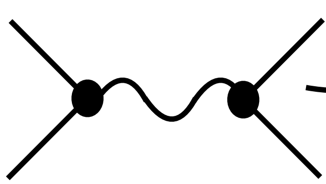
New opportunity: ***Harvesting the large statistics at highest collider energies***

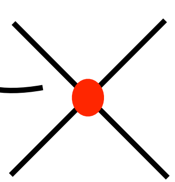
Example:

$(\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j)(\bar{L}_L^\alpha \gamma^\mu \sigma^a L_L^\beta)$



$$\propto V_{ij} \left(\frac{m_W^2}{\hat{s} - m_W^2} - \epsilon_L \right)$$





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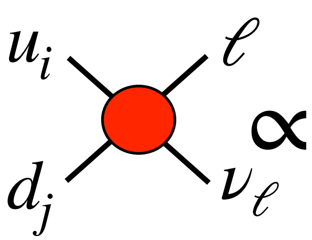

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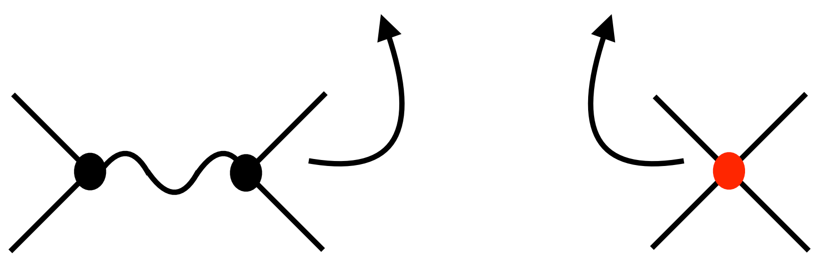


$$\hat{s} \ll m_W^2$$

$$M \to M' \ell \nu \qquad M \to \ell \nu$$

- Correction to observables

$$\sim \left(1 + \epsilon_L\right)^2$$

$$\epsilon_L^{bc\tau\nu} \sim \mathcal{O}(0.1) \qquad \epsilon_L^{cs\tau\nu} \lesssim \mathcal{O}(0.03)$$

*Anomaly

$$\epsilon_L^{bu\tau\nu} \lesssim \mathcal{O}(0.3) \qquad \epsilon_L^{cd\tau\nu} \lesssim \mathcal{O}(0.1)$$

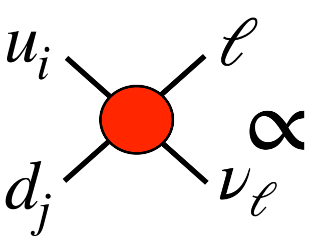
Low/High p_T Interplay

New opportunity: ***Harvesting the large statistics at highest collider energies***

Example:

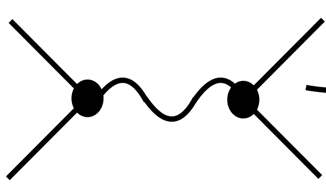
$(\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j)(\bar{L}_L^\alpha \gamma^\mu \sigma^a L_L^\beta)$

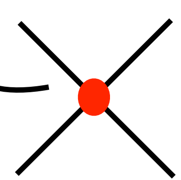
$$pp \to \ell \nu$$



$$\propto V_{ij}\left(\frac{m_W^2}{\hat{s}-m_W^2} - \epsilon_L\right)$$

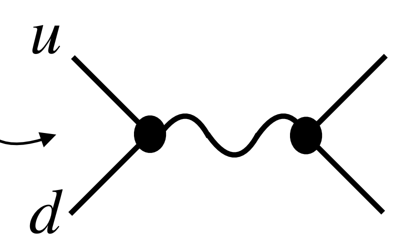
$$\hat{s} \gg m_W^2$$



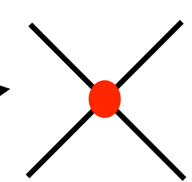


- Correction to observables

$$\frac{\mathcal{L}_{ij} \times |V_{ij}|^2 \times \left(\frac{m_W^2}{\hat{s}} - \epsilon_L\right)^2}{\mathcal{L}_{u\bar{d}+d\bar{u}} \times |V_{ud}|^2 \times \left(\frac{m_W^2}{\hat{s}}\right)^2}$$



Background, Valence quarks



Signal, Heavy flavour

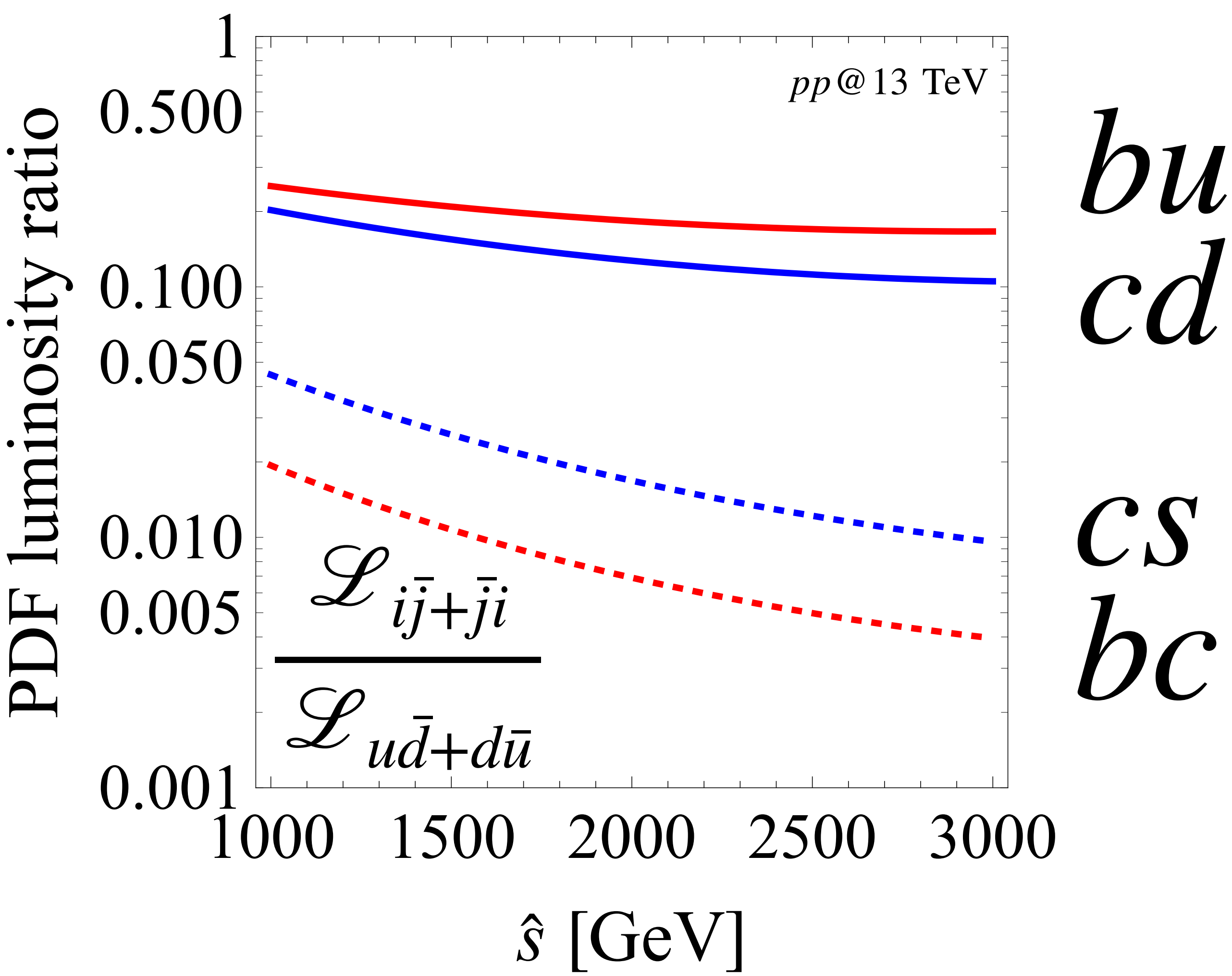
$\mathcal{L}_{ij}$: **Parton luminosity**

...play

...energies

LHC is a ...

...collider of five quark flavours

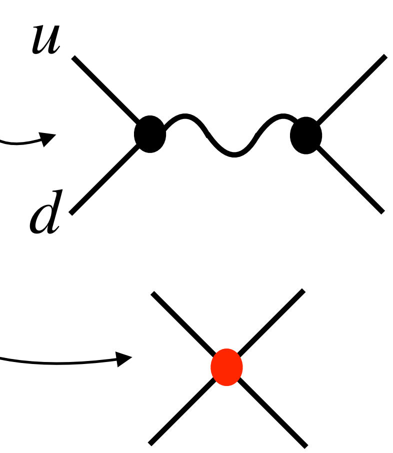


$\times\,|V_{ij}/V_{ud}|^2$ suppression

$$pp \to \ell\nu$$

- Correction to observables

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



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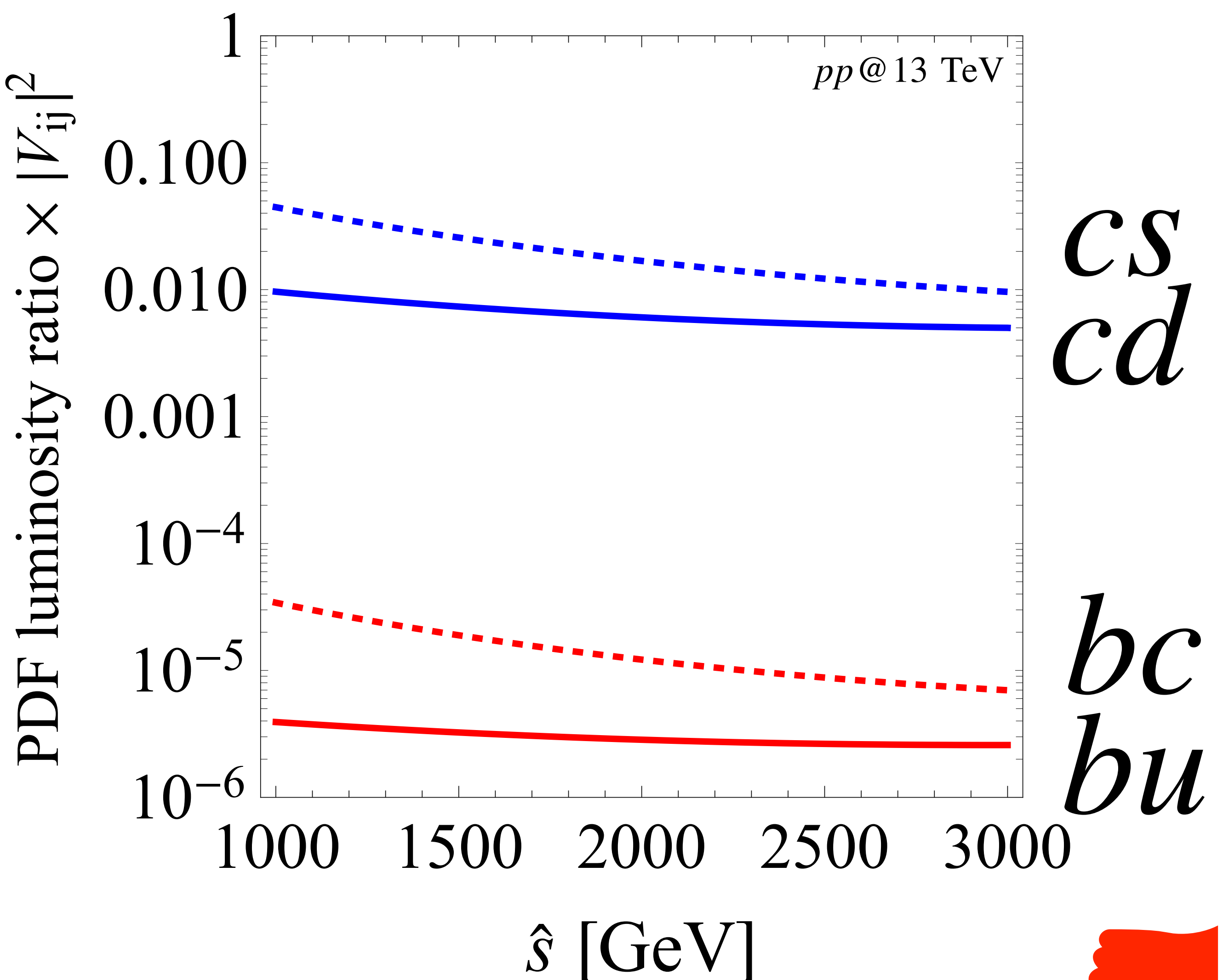
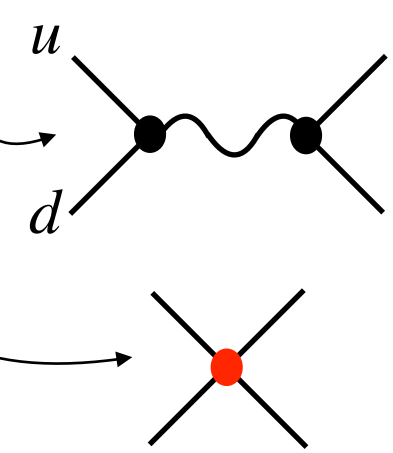


$$pp \to \ell\nu$$

- Correction to observables

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



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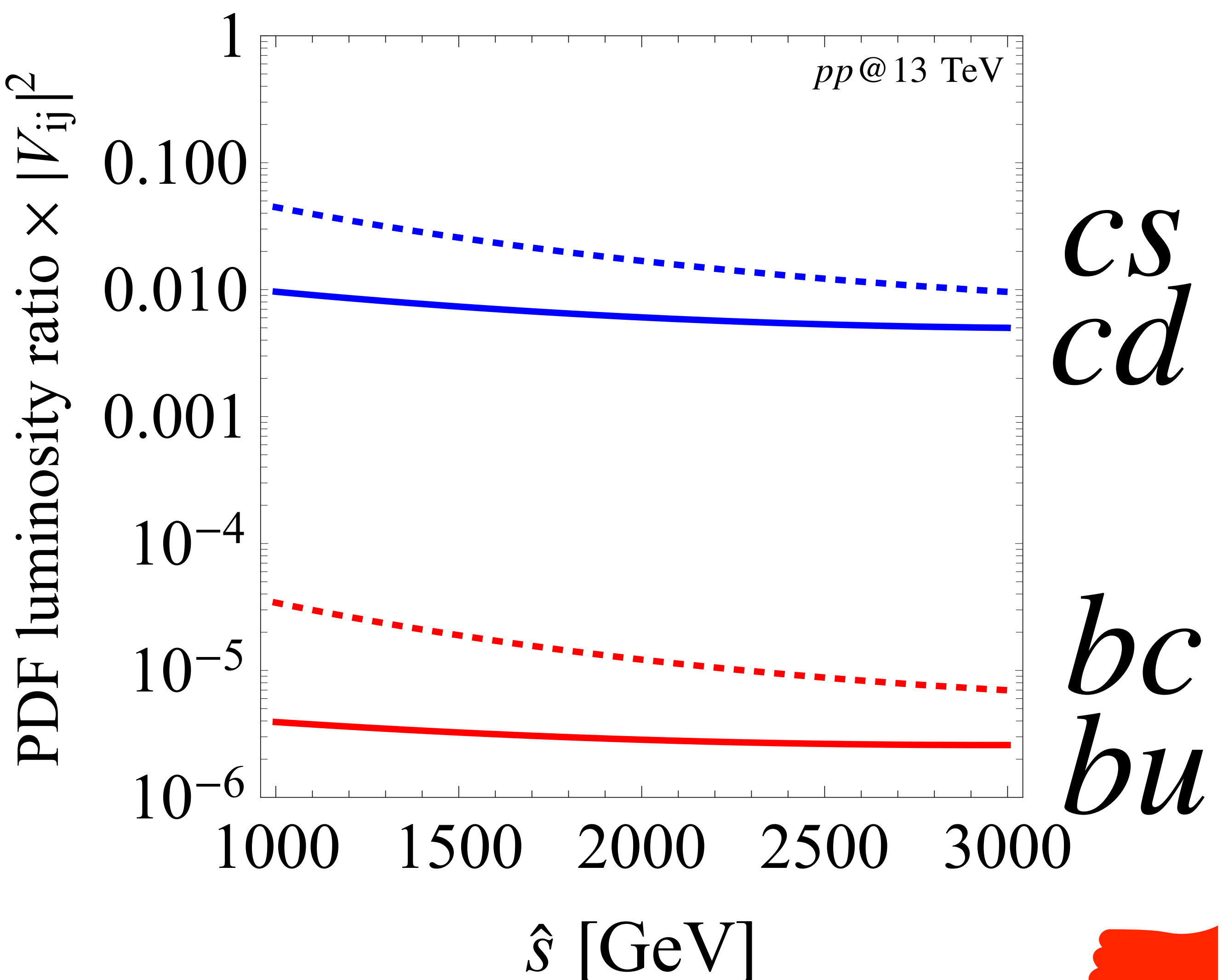

play

energies

$$pp \to \ell \nu$$

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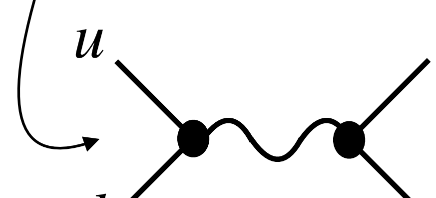
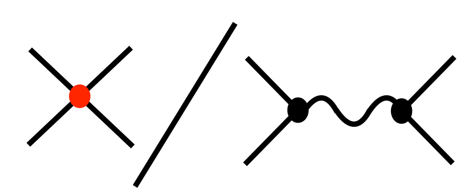


Background, Valence quarks

Energy enhancement

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

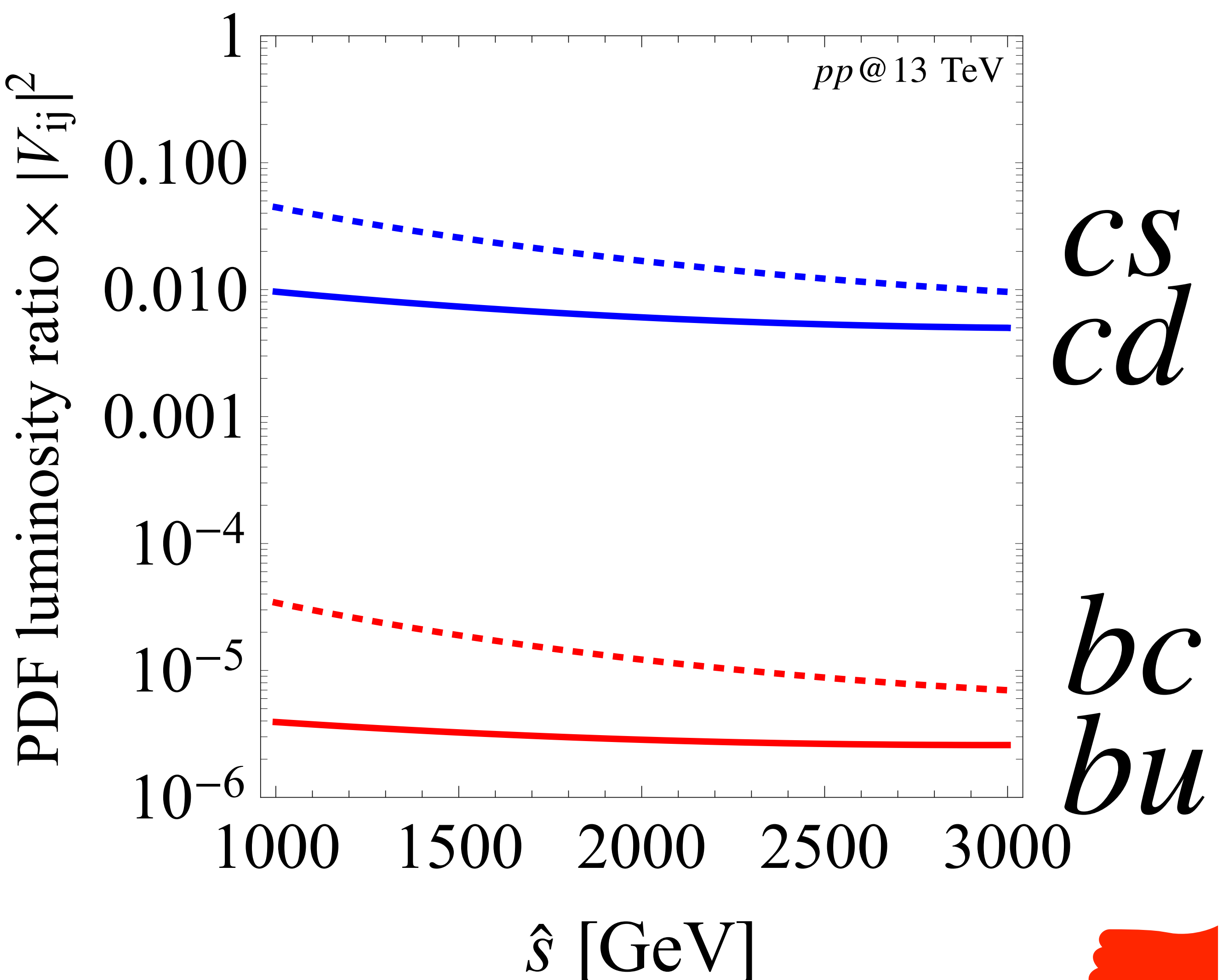
- No interference



play

LHC is a …

…collider of five quark flavours

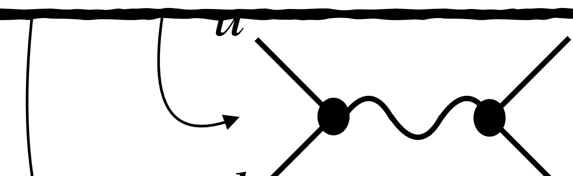


Back of the envelope

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

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

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



Energy enhancement

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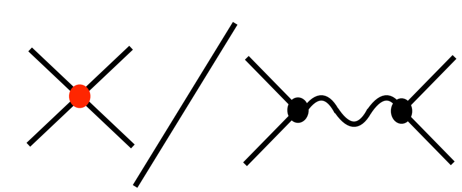
$$\left(\hat{s}/m_W^2\right)^2 \sim \mathcal{O}(10^5)$$



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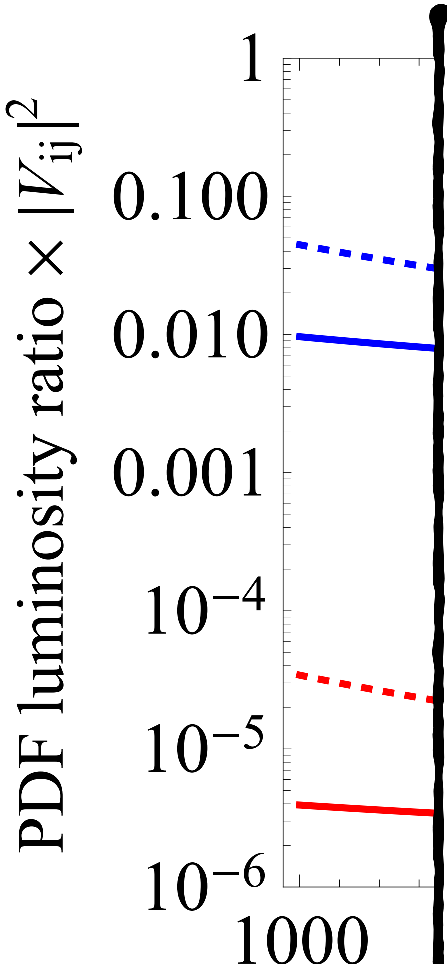


play

Back of the envelope

(0.1)

$\mathcal{O}(0.01)$

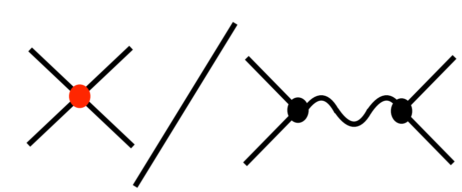
$\mathcal{O}(0.01)$

und,
quarks

ement

ice

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



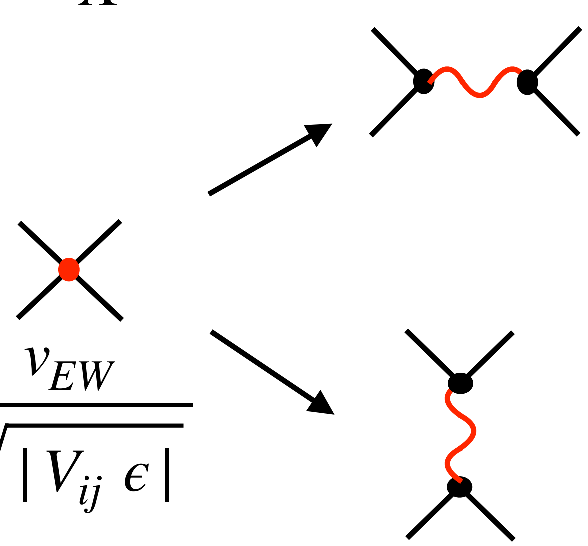
EFT validity

[consider explicit models]

$$\hat{s} \lesssim M_X^2$$

If $\hat{s} \sim M_X^2$

$$\Lambda_{eff} = \frac{v_{EW}}{\sqrt{|V_{ij}\,\epsilon|}}$$

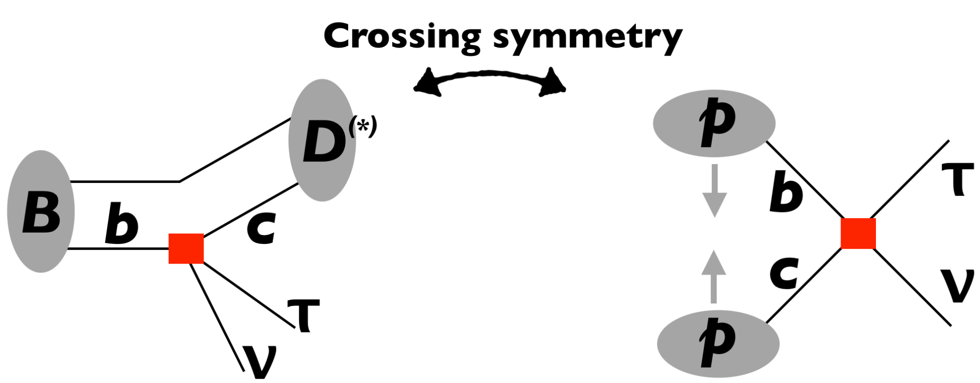


- EFT bounds are overly conservative
- EFT bounds are a good proxy

Exploration

- In the context of SMEFT / explicit benchmark models

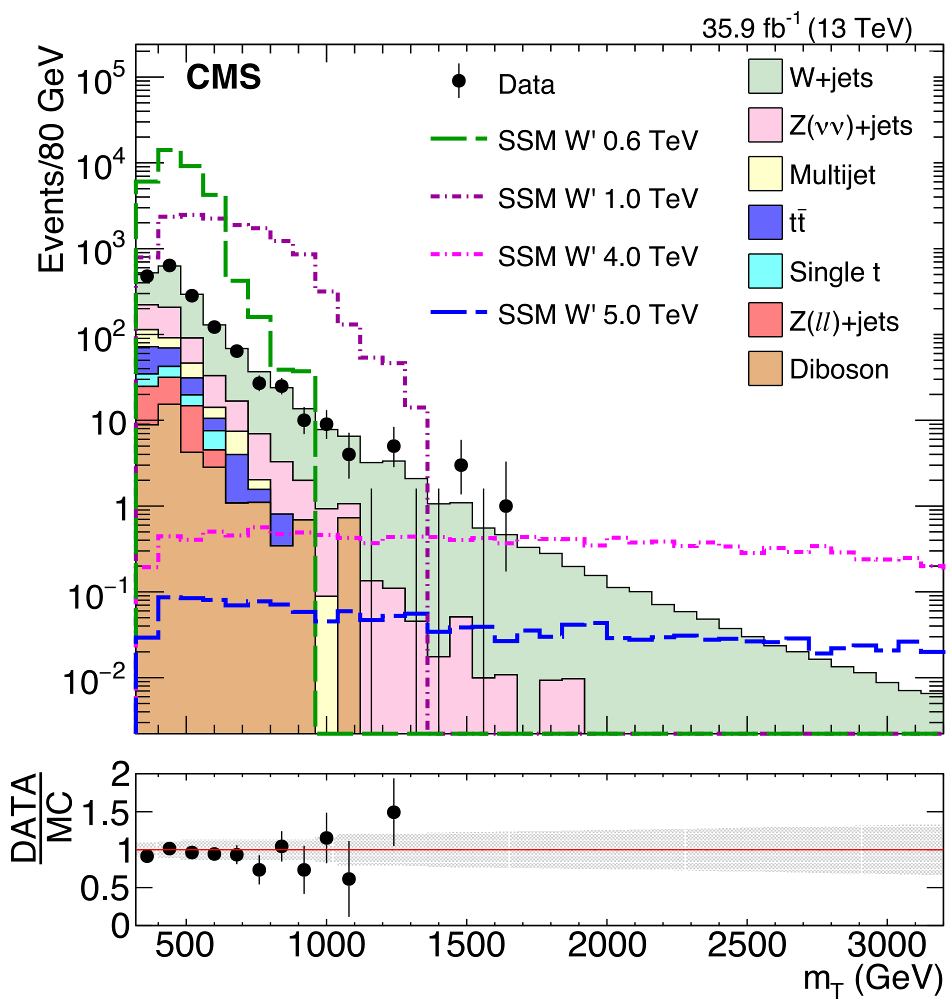
B-decays	High-p$_T$ Tails	Reference
$b \to s \mu \bar{\mu}$ *(ee)	$pp \to \ell^+ \ell^-$	[AG, Marzocca] 1704.09015
$b \to c \tau \bar{\nu}_\tau$	$pp \to \tau \nu$	[AG, Martin Camalich, Ruiz-Alvarez] 1811.07920
	$pp \to \tau^+ \tau^-$	[Faroughy, AG, F. Kamenik] 1609.07138

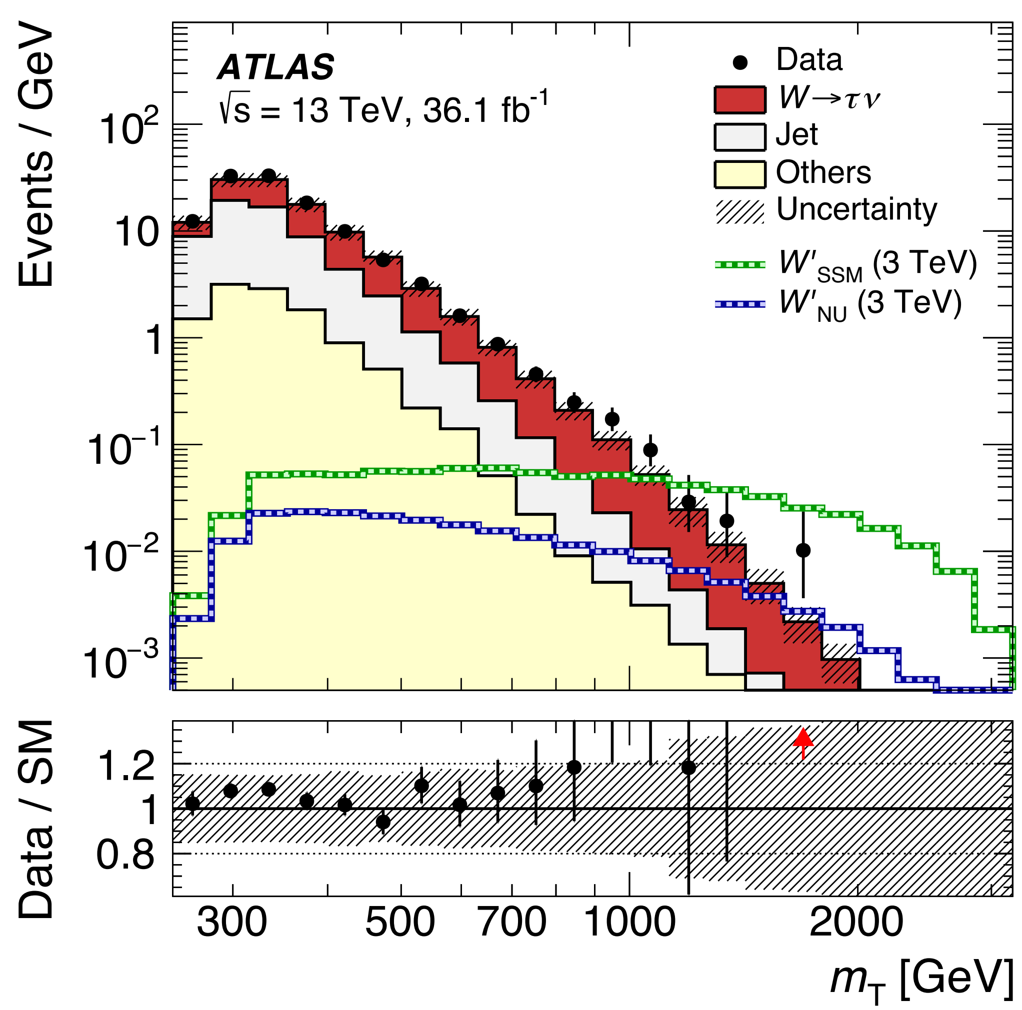


[AG, Martin Camalich, Ruiz-Alvarez]
Phys.Rev.Lett. 122 (2019) no.13, 131803

- We recast the latest hadronic Tau + MET searches

MadGraph5 AMC@NLO v2.6.1 > Pythia 8 v8.230 > Delphes v3.4.1



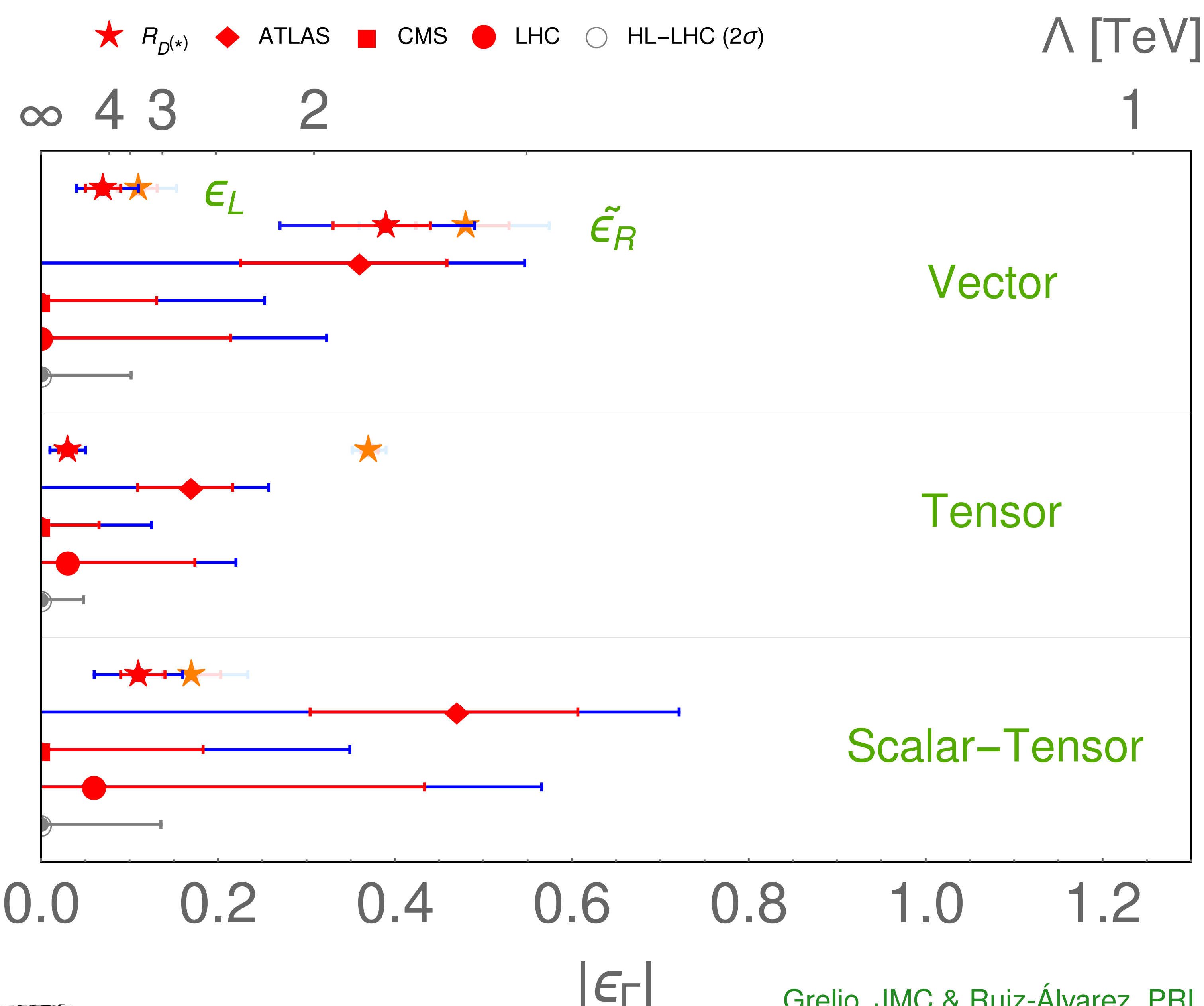


$$pp \to \tau\nu$$

$$\mathcal{L}_{\text{LEEFT}} \supset -\frac{2V_{kl}}{v^2}\Big[\Big(1+\epsilon_L^{kl\tau}\Big)\bar{\tau}\gamma_\mu P_L\nu_\tau \cdot \bar{u}_k\gamma^\mu P_L d_l + \epsilon_R^{kl\tau}\bar{\tau}\gamma_\mu P_L \nu_\tau \cdot \bar{u}_k \gamma^\mu P_R d_l$$
$$+\epsilon_T^{kl\tau}\,\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau \cdot \bar{u}_k\sigma^{\mu\nu}P_L d + \epsilon_{S_L}^{kl\tau}\bar{\tau}P_L\nu_\tau \cdot \bar{u}_k P_L d_l + \epsilon_{S_R}^{kl\tau}\bar{\tau}P_L\nu_\tau \cdot \bar{u}_k P_R d_l\Big] + \text{h.c.},$$

$$\Lambda = v/\sqrt{|V_{cb}||\epsilon_\Gamma|}$$

* 1σ (red) and 2σ (blue) ranges on the absolute value of the WCs of semi-tauonic cb transitions at μ = mb



A lot of room for improvements:
- b-tag,
- tau charge-asymetries,
- rapidity distribution,
- polarization.

Greljo, JMC & Ruiz-Álvarez, PRL122, 131803 (updated)

$$\boxed{pp \to \tau\nu}$$

[For simplified-mediator models see backup slides]

Summary

- We propose the exploration of the High-p_T tails in the context of flavour physics.

- We argue that such analyses could be competitive to the traditional low-energy probes.

- The plethora of tails to be looked at

  $$p\,p \to \tau\nu,\ \tau\tau,\ \mu\mu,\ ee,\ \tau\mu,\ \tau e,\ tb,\ bb,\ tt,\ jj$$

  and optimised in the context of an exhaustive set of flavourful SM EFT four-fermion contact interactions, and simplified single-mediator models featuring either a broad s-channel resonance, or a non-resonant t-channel.

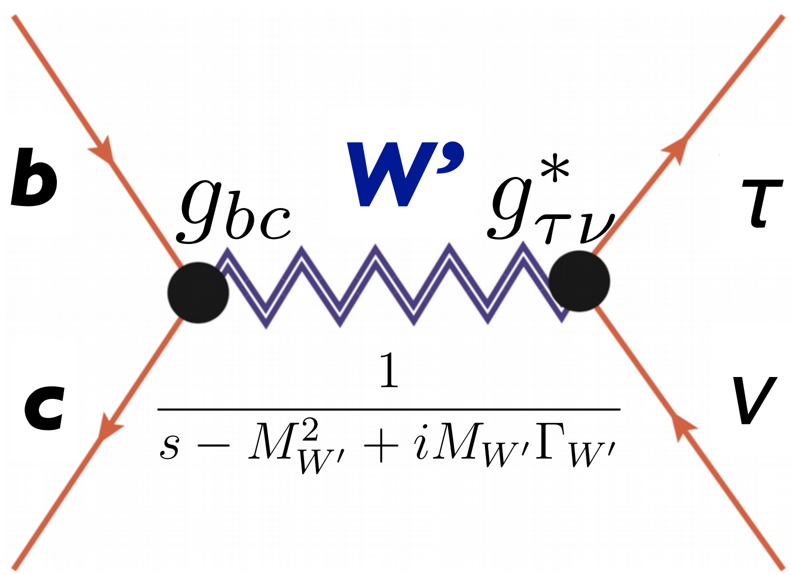
Backup

W' model

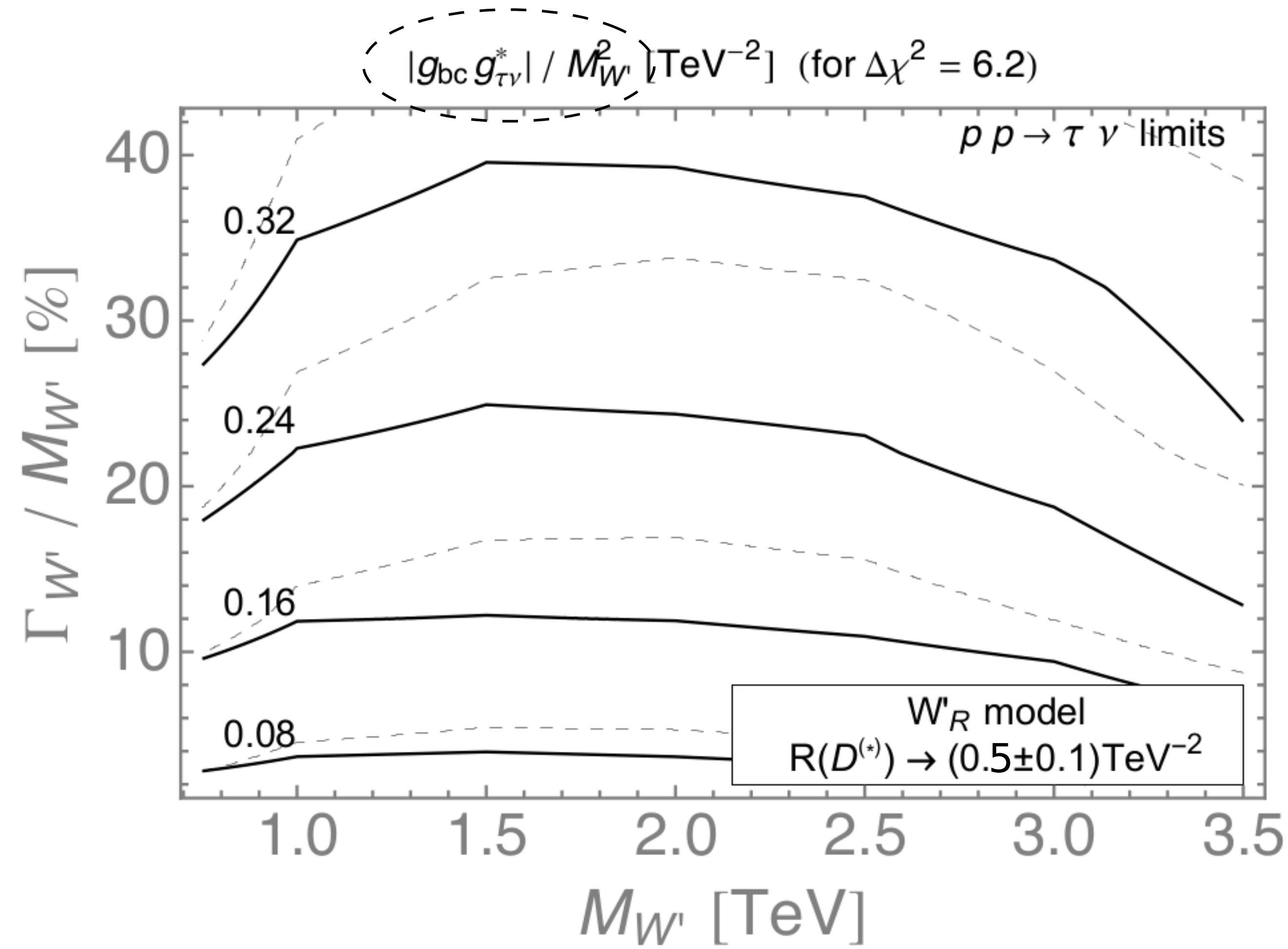
$$\mathcal{L} \supset g_{bc}\,\bar{c}\gamma^\mu P_{L,R} b\, W'_\mu + g_{\tau\nu}\,\bar{\nu}\gamma^\mu P_{L,R}\tau\, W'_\mu + \text{h.c.}$$

RH W' models:
[Asadi, Buckley, Shih] 1804.04135
[AG, Robinson, Shakya, Zupan] 1804.04642

LH W' models:
[AG, Isidori, Marzocca] 1506.01705
$pp \to \tau^+\tau^-$ [Faroughy, AG, F. Kamenik] 1609.07138



- Upper limit on the Wilson coefficient from MonoTau



*Very wide resonances indicate the loss of predictivity

- Three parameters (in full generality)
- Event shape depends on $\Gamma_{W'}$ and $M_{W'}$
- Normalisation controlled by: $g_{bc}g^*_{\tau\nu}$

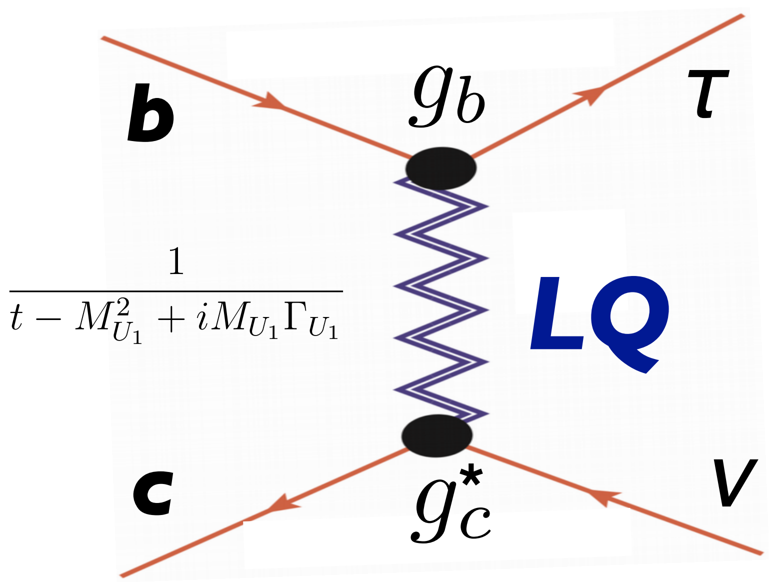
$$\boxed{pp \to \tau\nu}$$

LQ model

$$\mathcal{L} \supset g_c\, \bar{c}\gamma_\mu P_{L,R}\nu\, U_1^\mu + g_b\, \bar{b}\gamma_\mu P_{L,R}\tau\, U_1^\mu$$

LH U_1 model:
[Buttazzo, AG, Isidori, Marzocca] 1706.07808

RH U_1 model:
[Robinson, Shakya, Zupan] 1807.04753

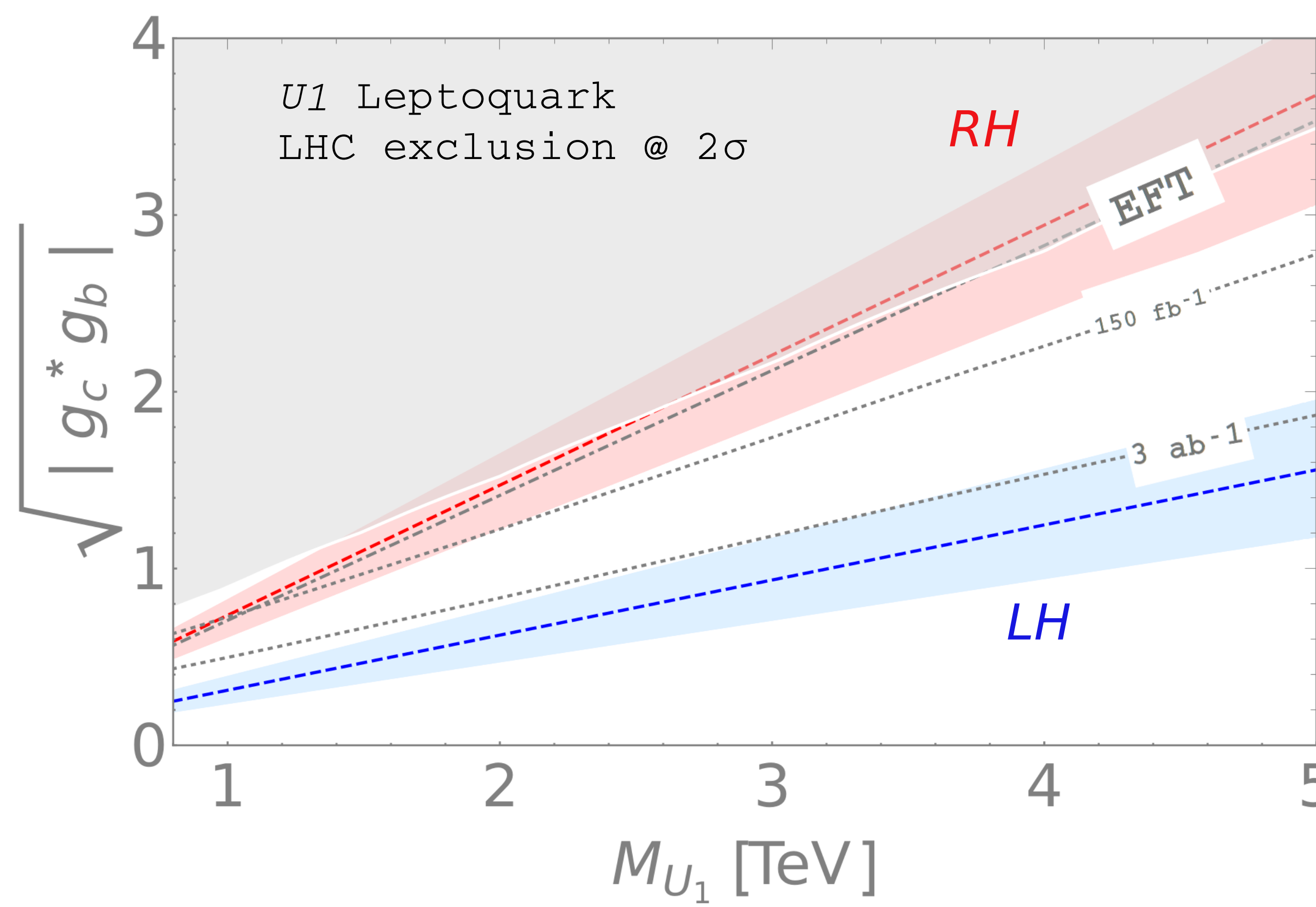


- Smooth distortion of the distribution
- The total width effects negligible
- Two parameters (in full generality)

$$M_{U_1} \qquad g_b g_c^*$$

$$\boxed{pp \to \tau\nu}$$

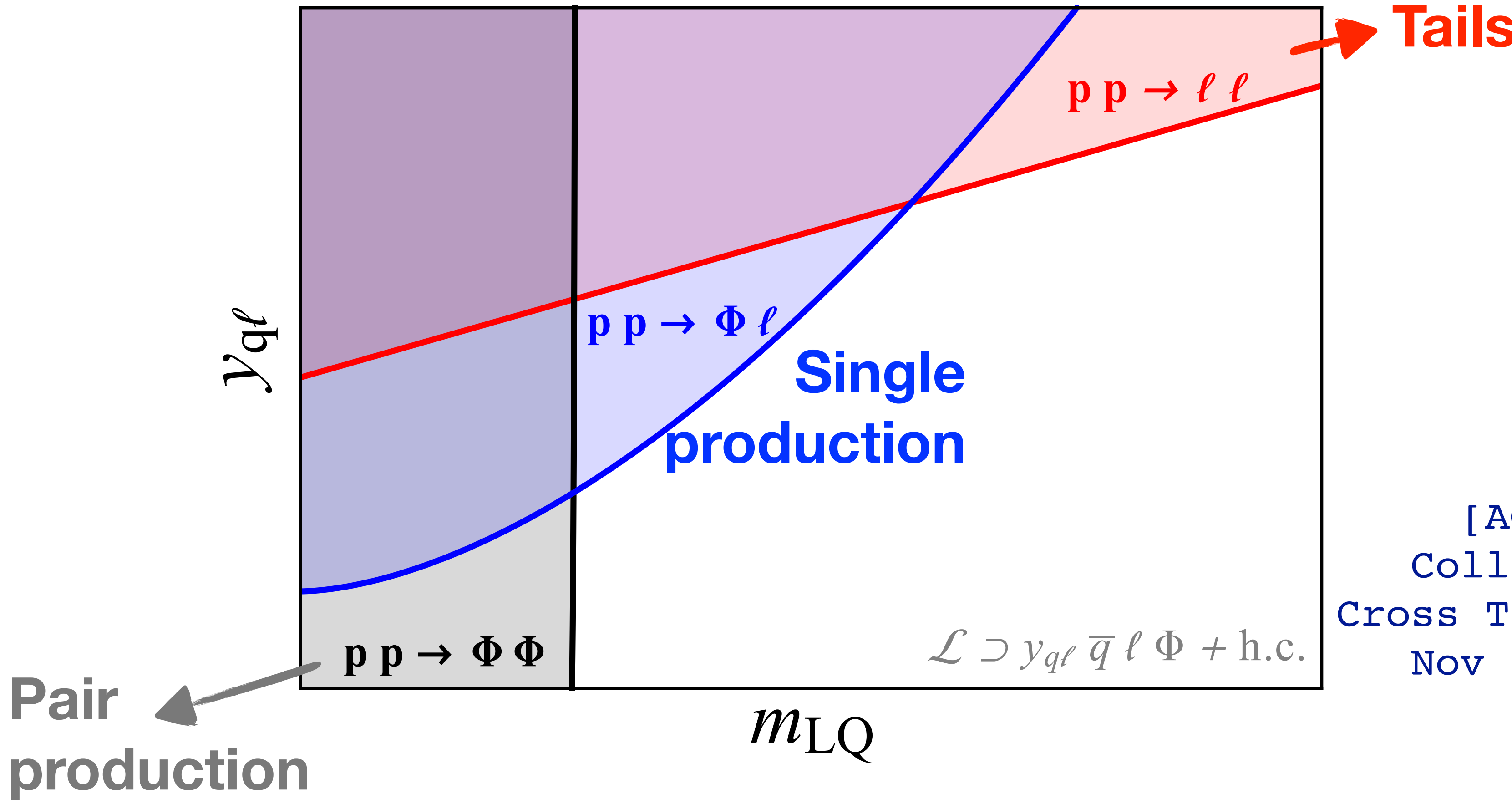
From B-decays



*Good agreement with the EFT results for the heavy LQ

The LQ intermezzo

Leptoquark Toolbox: [Doršner, AG] 1801.07641



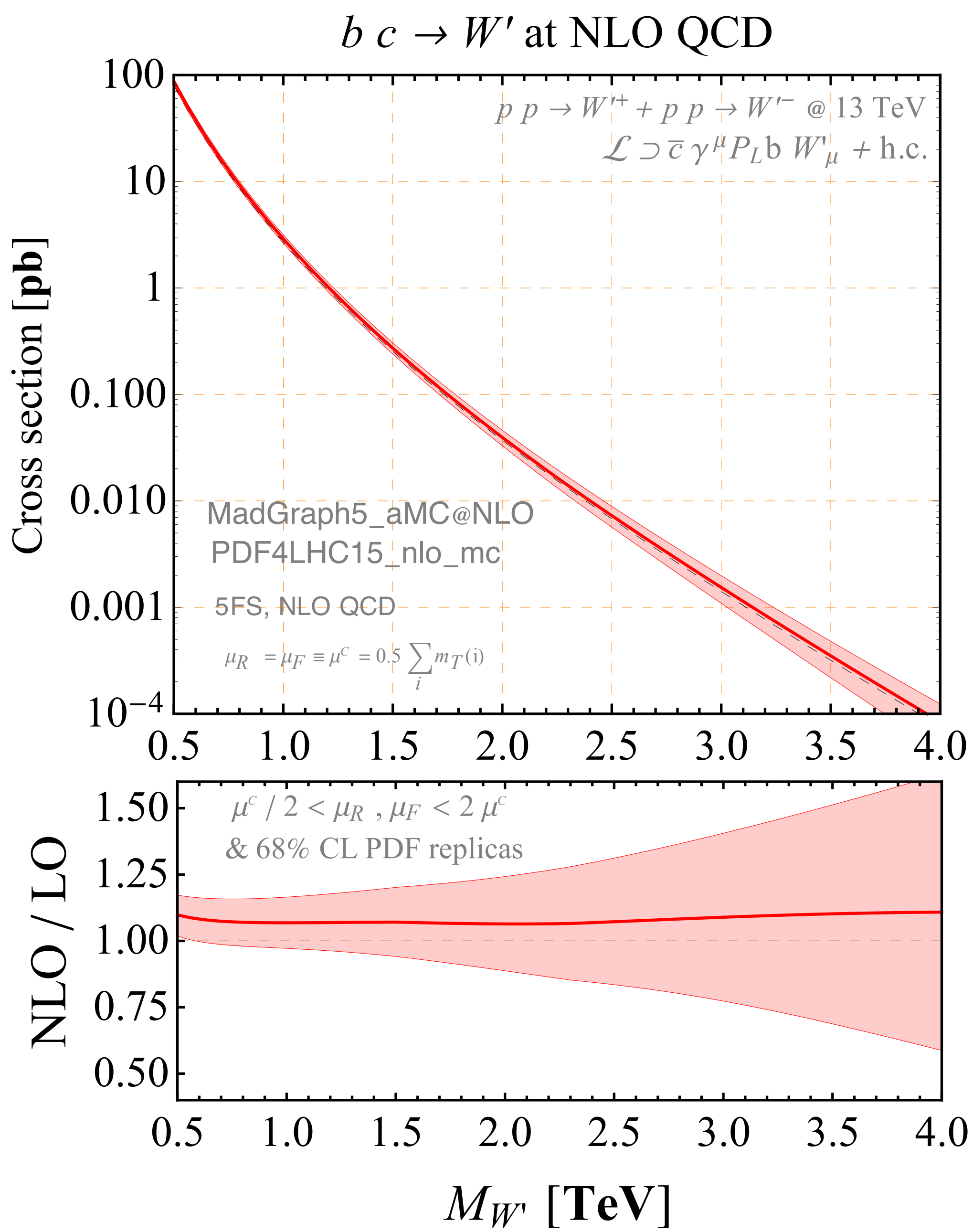
[AG] @ Collider Cross Talk, Nov 2017

Complementarity!

See also [Doršner, Fajfer, AG, Košnik, F. Kamenik] Phys.Rept. 641 (2016) 1-68

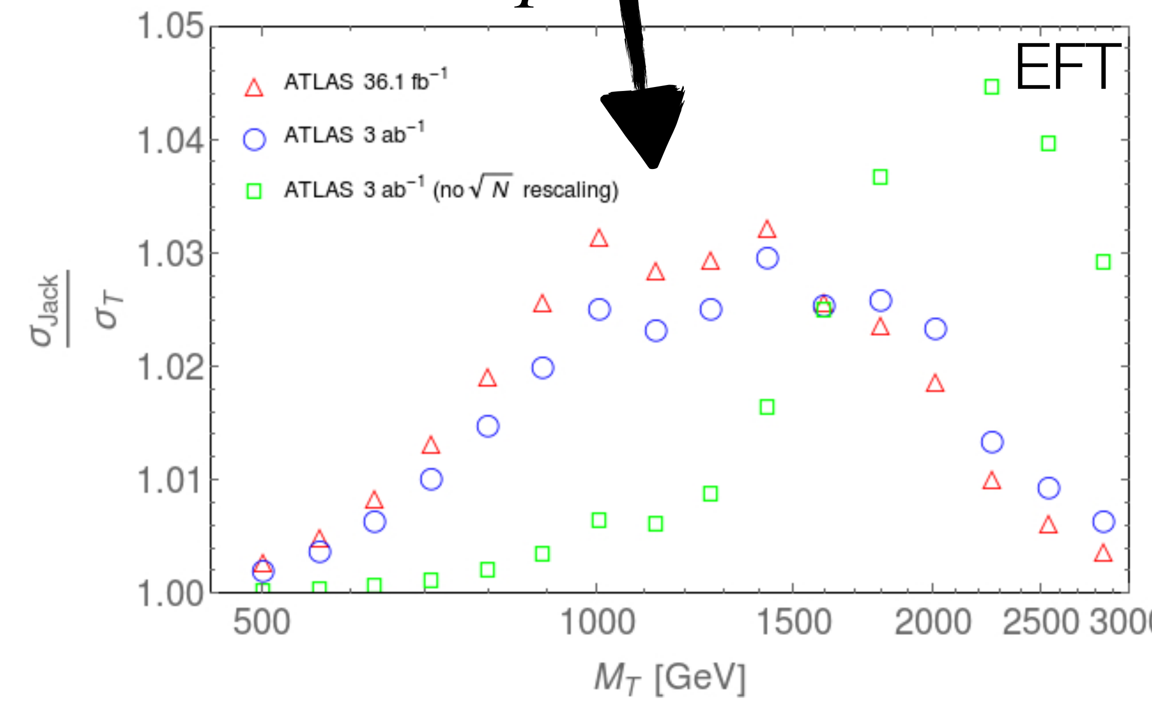
Consolidation

- Signal prediction @ NLO QCD



- The most sensitive bins

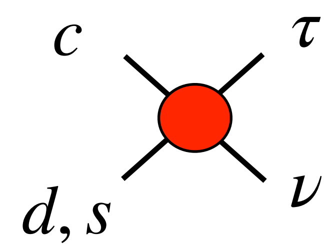
$\hat{s} > M_T^2$



- Systematic uncertainties fully included
- PDFs not effected by this NP
- MC tools available upon request

$$\boxed{pp \to \tau\nu}$$

Connection to D-meson physics



- Preliminary LHC limits

$$cs \to \tau\nu$$

	Vector	Scalar	Tensor
LHC combined	0.009	0.015	0.004

$$cd \to \tau\nu$$

Data set	Vector	Scalar	Tensor
LHC combined	0.015	0.025	0.008

- Looking at the PDG

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

$$\epsilon_L \lesssim 0.03 \qquad \epsilon_S \lesssim 0.02$$

$$\mathscr{B}(D \to \tau\nu) < 1.2 \times 10^{-3}$$

$$\epsilon_L \lesssim 0.09 \qquad \epsilon_S \lesssim 0.05$$

- Phase space suppression

$$m_{D^\pm} - m_\tau \approx 90 \text{ MeV}$$

High-pT beats Low-pT!

- In all cases!

[Fuentes-Martin, AG, Martin Camalich, Ruiz-Alvarez] w.i.p

$b \to u$
transitions

Data set	Vector	Scalar	Tensor
LHC combined	0.72	1.23	0.34
LHC (150 fb^{-1})	0.48	0.84	0.23
HL-LHC	0.21	0.37	0.10

$$B^0 \to \pi^- \tau^+ \nu$$

$$-1.25 \lesssim \epsilon_T^{ub} \lesssim 0.57$$

$$-1.75 \lesssim \epsilon_{S_L}^{ub} + \epsilon_{S_R}^{ub} \lesssim 0.94$$

*No anomaly here. The comparison of the upper limits from the High-pT tails (left) and B-decays (right).

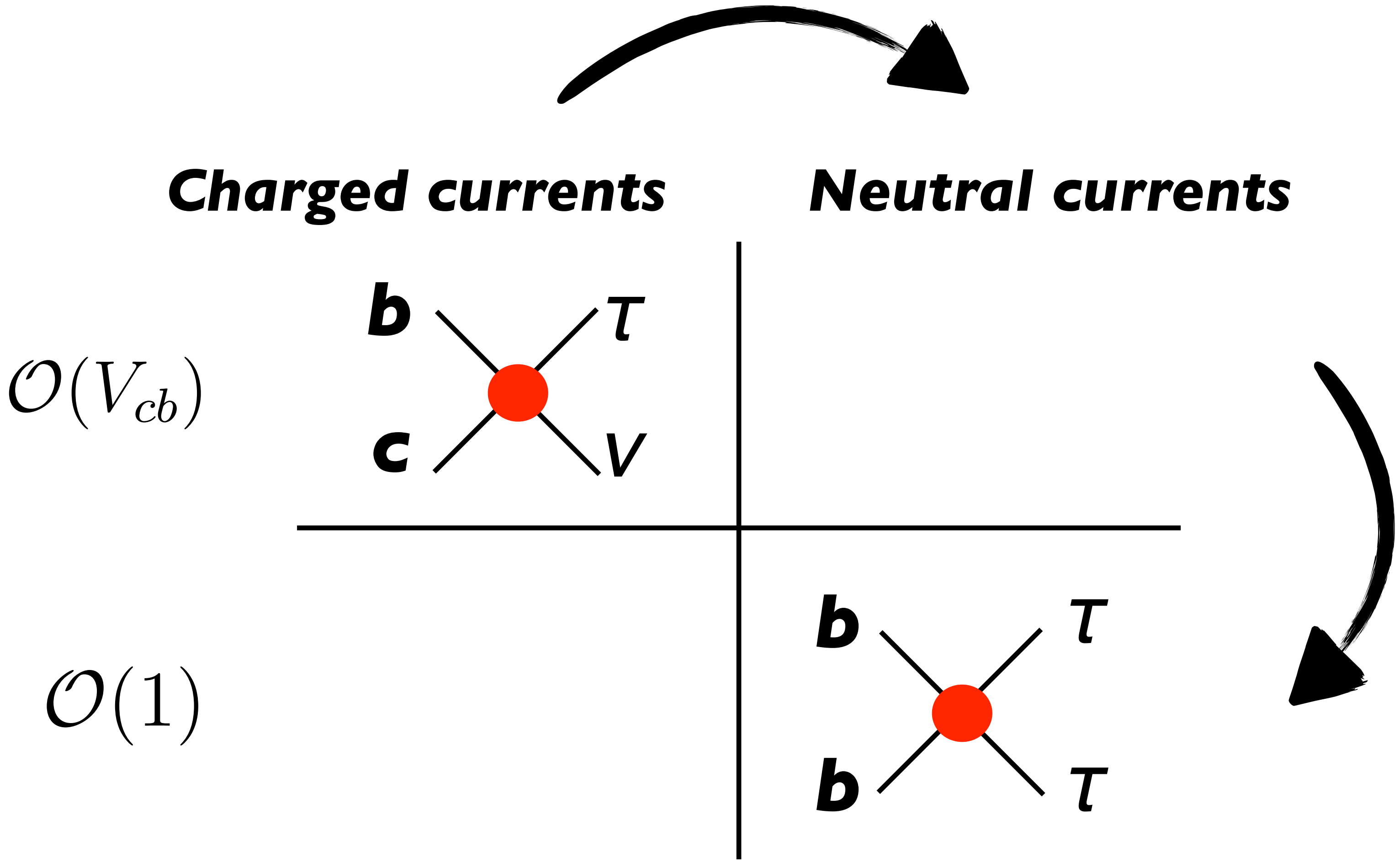
$$\boxed{pp \to \tau\nu}$$

[AG, Martin Camalich, Ruiz-Alvarez] 1811.07920

DiTau vs B decays

[Faroughy, AG, F. Kamenik]
1609.07138

- *$SU(2)_L$ gauge symmetry*



- *Flavour Structure*

- ***Generically, CKM enhanced DiTau!*** $pp \to \tau^+\tau^-$
  - Better than Upsilon decays

- ***One of the main obstacles to NP explanation of anomalies in $B \to D^{(*)}\tau\nu$***
- ***However, still some model dependence unlike MonoTau***

*typically

DiTau beats MonoTau

Recent example:

Vector LQ model

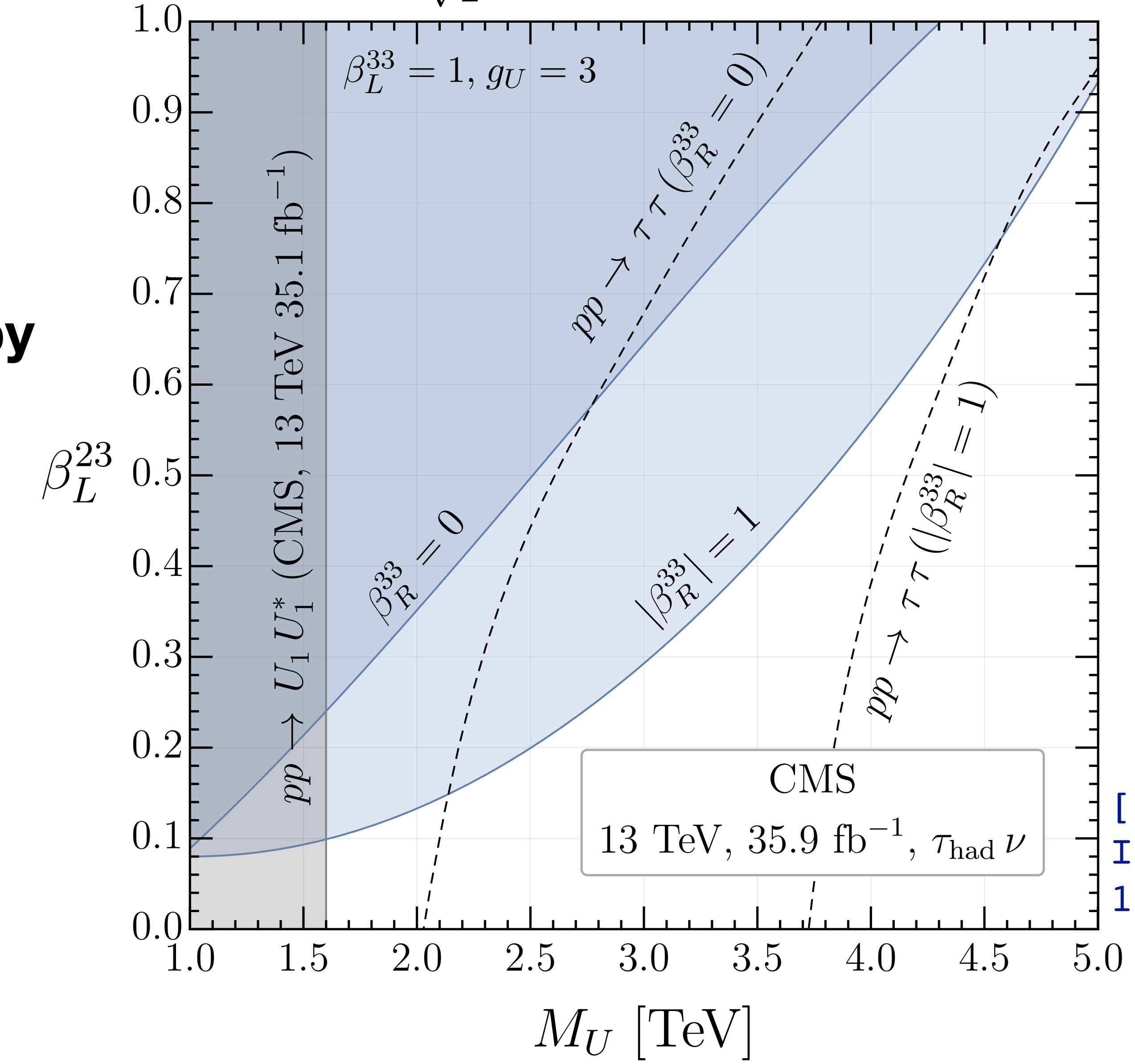
$$\frac{(\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_L)}{(\bar{b}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\tau_L)}$$

This ratio is controlled by

Natural expectation:

$\mathcal{O}(V_{cb})$

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}}[U_1^\mu(\beta_L^{ij}\,\bar{q}_L^i\gamma_\mu\ell_L^j + \beta_R^{ij}\,\bar{d}_R^i\gamma_\mu e_R^j)$$



[Baker, Fuentes-Martin, Isidori, Konig] 1901.10480

- Two different scenarios considered
- In both cases, DiTau beats MonoTau in the natural parameter space