UNIVERSITÄT BERN

SWISS NATIONAL SCIENCE FOUNDATION

Eccellenza, Project-186866

Model building: Where to look?

Admir Greljo

IF anomalies in $b \to s\ell^+\ell^-$ are genuine new physics effect.

20.10.2021, Flavour Anomaly Workshop 2021, CERN

New mass scale?

- The observational evidence of BSM:
  - Neutrino oscillations: $\frac{1}{10^{11}\,\mathrm{TeV}}(LH)(HL)$
  - Cosmo/Astro observations: *Dark Matter*, *Baryon asymmetry*, *Inflation*, etc could be a physics of a very high energy scale (Sci-Fi for colliders)

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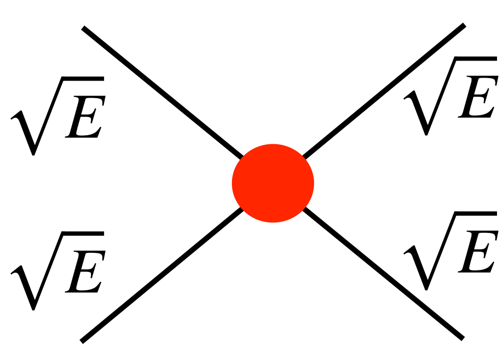
- IF $b \to s\ell^+\ell^-$ anomalies are genuine new physics effect
  $\Longrightarrow$ Major Revolution in HEP

$$\mathscr{L} \supset \frac{1}{(40\ \mathrm{TeV})^2}(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$$ [See talk by Stangl et al]

4-fermion scattering at $E \gg v_{EW}$



$$\mathscr{A} \sim \frac{E^2}{(40\ \mathrm{TeV})^2}$$

$\Longrightarrow$ Violation of perturbative unitary $\lesssim 100\,\mathrm{TeV}$ Di Luzio, Nardecchia; 1706.01868

- Observational evidence!
  (Argument stronger than EW naturalness)

The nightmare scenario

The high-p_T collider nightmare scenario assumptions:

- The only "big" operator in the SMEFT is: $\mathscr{L} \supset \frac{1}{(40\ \mathrm{TeV})^2} (\bar{Q}_2 \gamma^\mu Q_3)(\bar{L}_2 \gamma_\mu L_2)$
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- Top decays are not sensitive:

$\mathscr{L} \supset \frac{1}{(40\ \mathrm{TeV})^2} (\bar{c}_L \gamma^\mu t_L)(\bar{\mu}_L \gamma_\mu \mu_L)$ predicts $\mathscr{B}(t \to c\mu\mu) \sim 10^{-12}$

while

$\mathscr{B}(t \to Zc) \lesssim 10^{-6}$ @ FCC – hh

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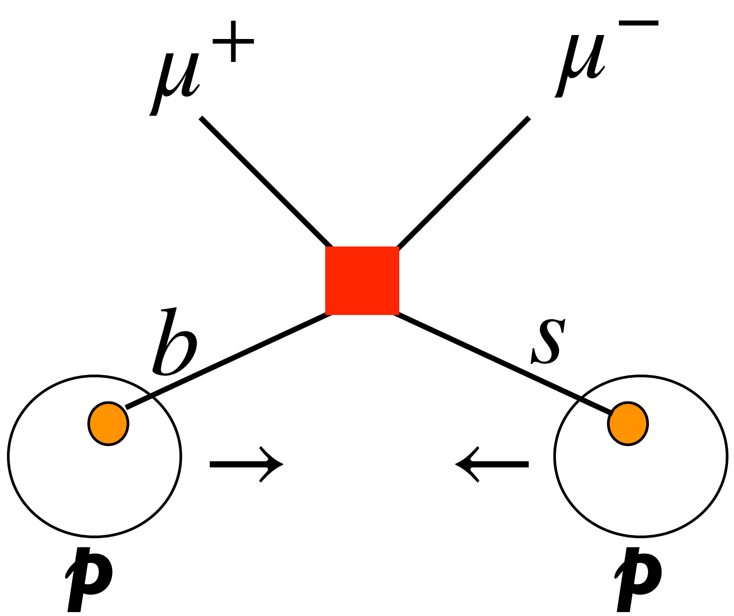
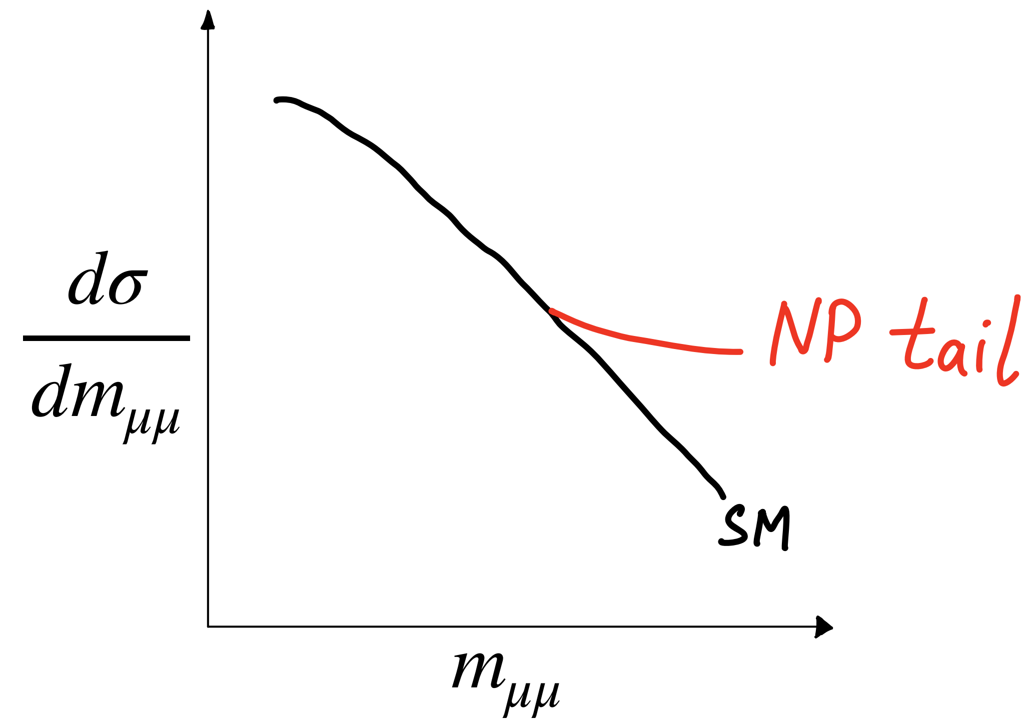
High-mass Drell-Yan tails

AG, Marzocca; 1704.09015



$$\mathscr{A} \sim \frac{E^2}{(40\ \text{TeV})^2}$$

$\Longrightarrow$



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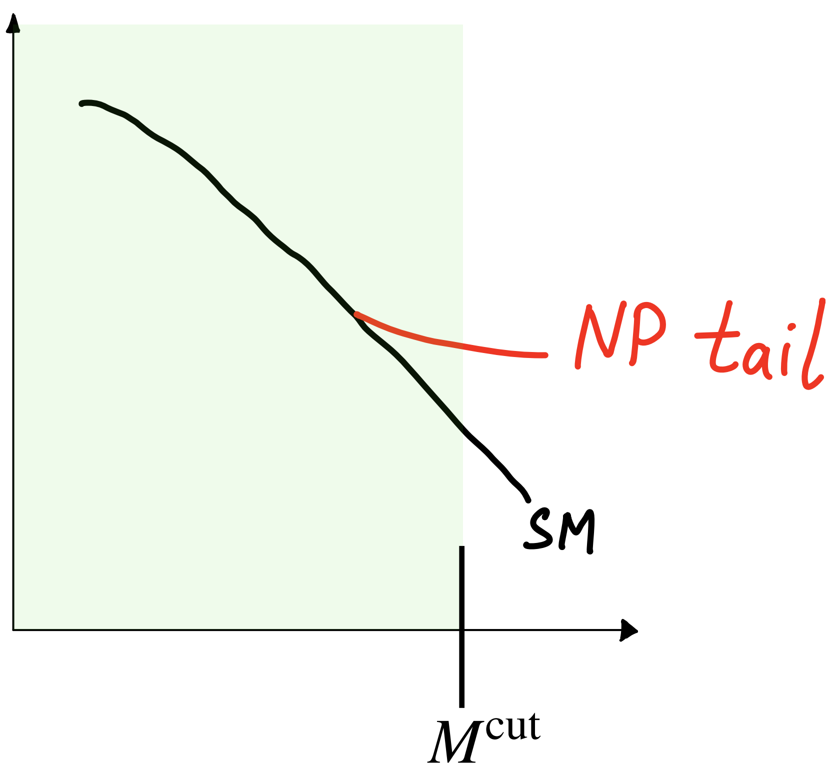

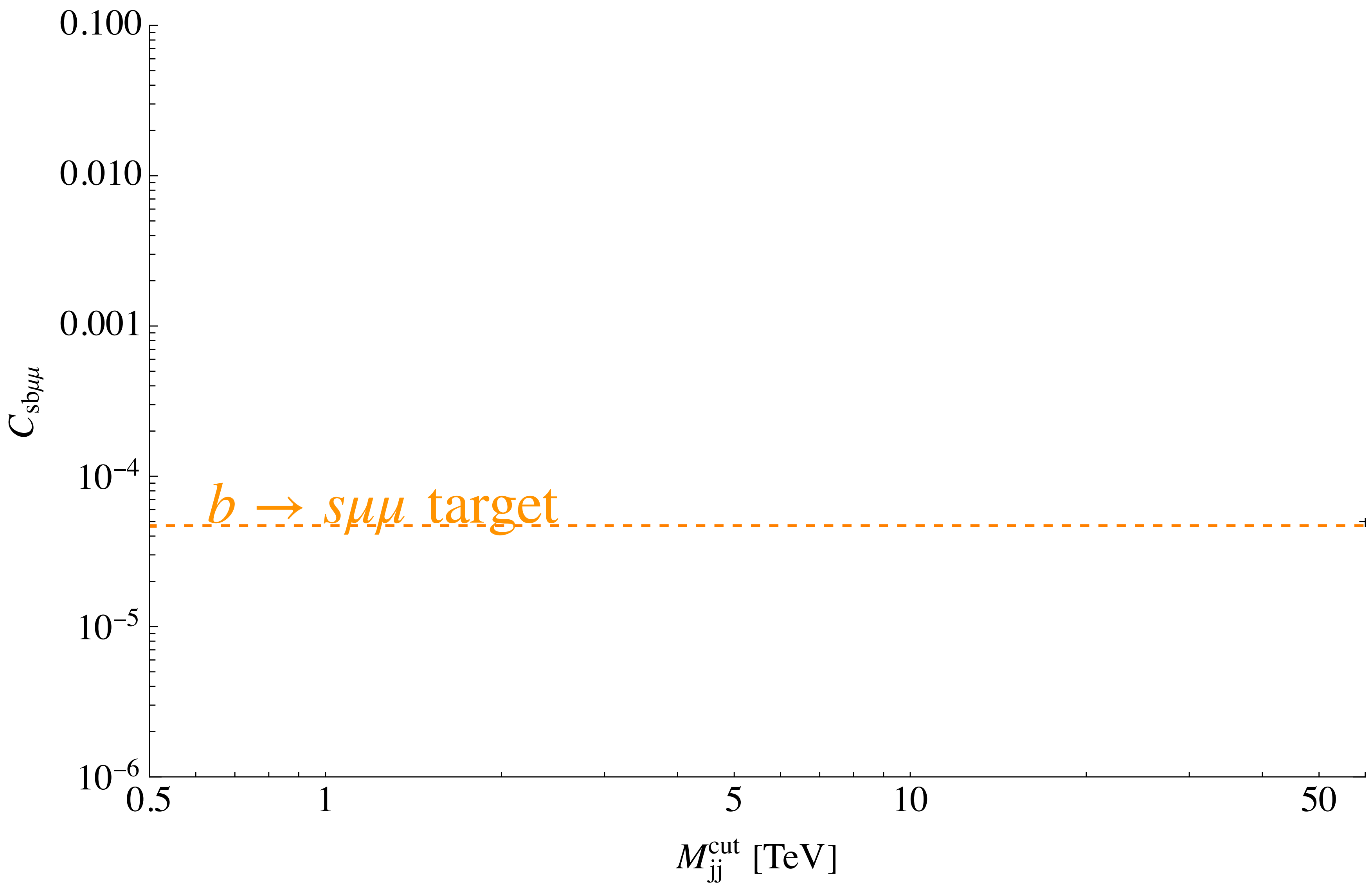

- Consider only the data <u>below</u> M^{cut}
- Valid for $M_{\text{NP}} > M^{\text{cut}}$, otherwise do direct searches

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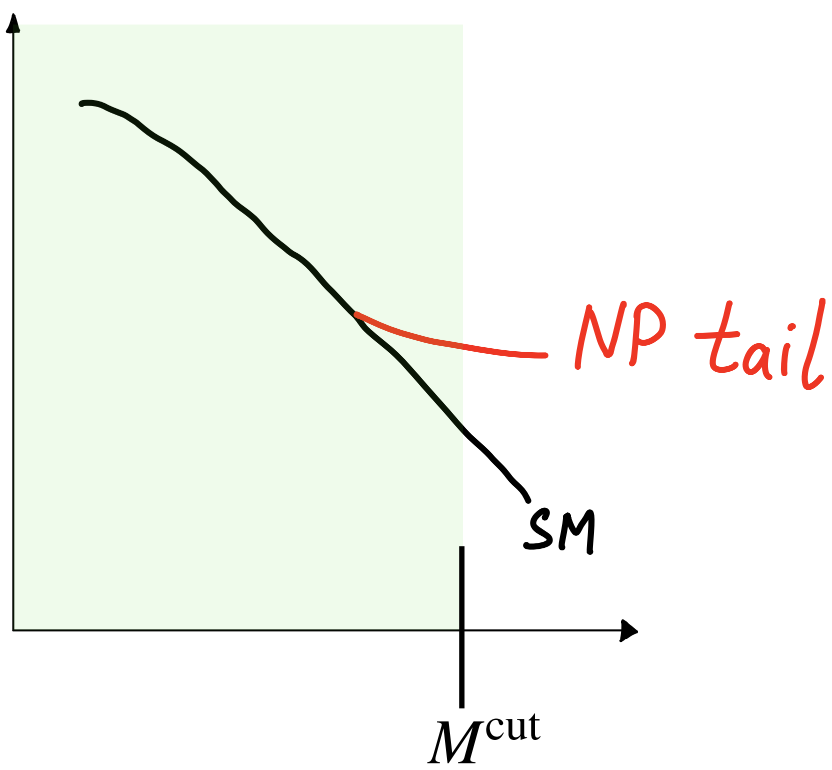

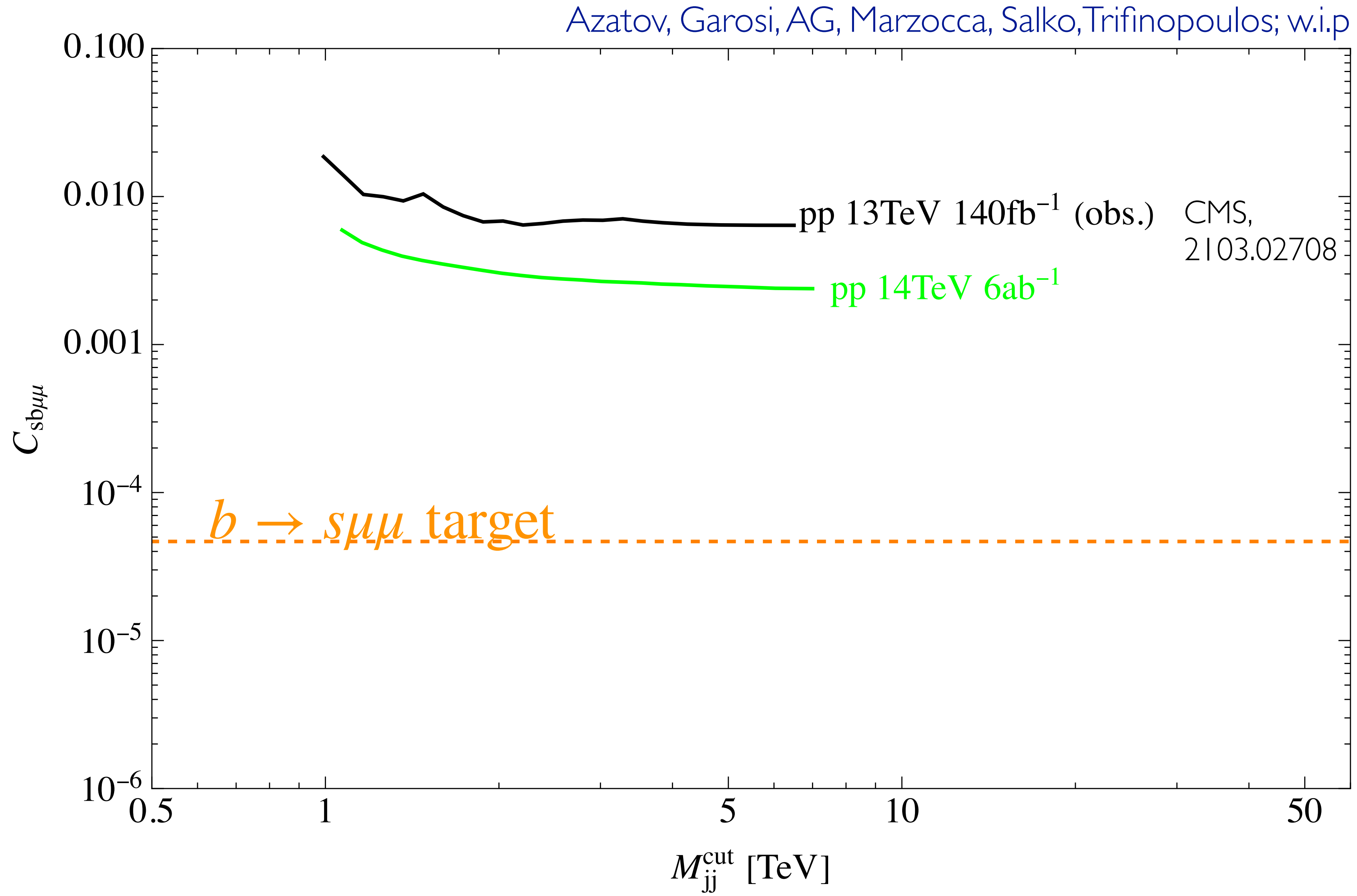

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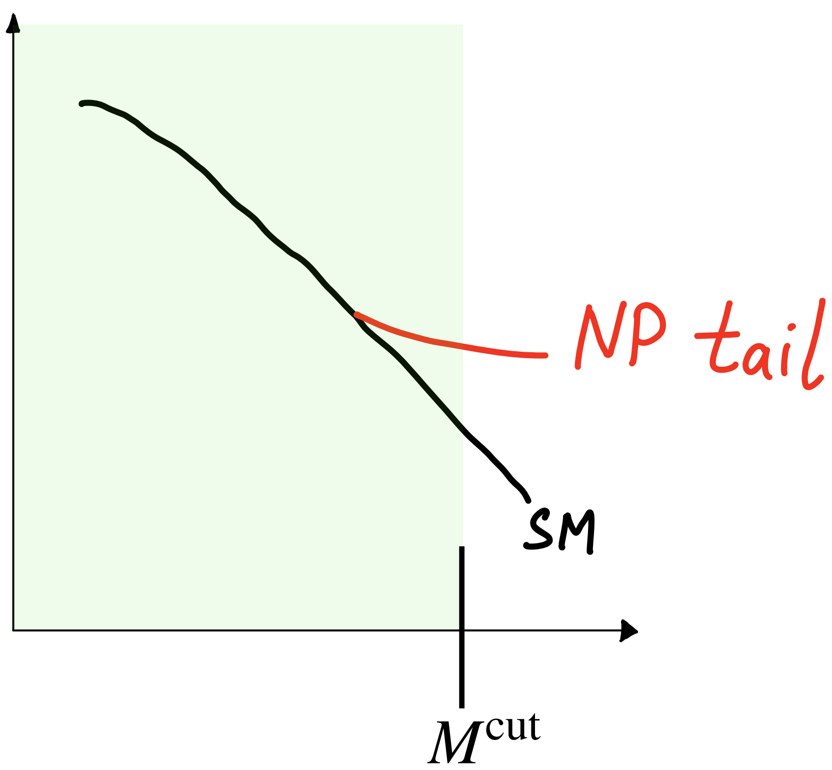
- Hopeless for the LHC.

The nightmare scenario



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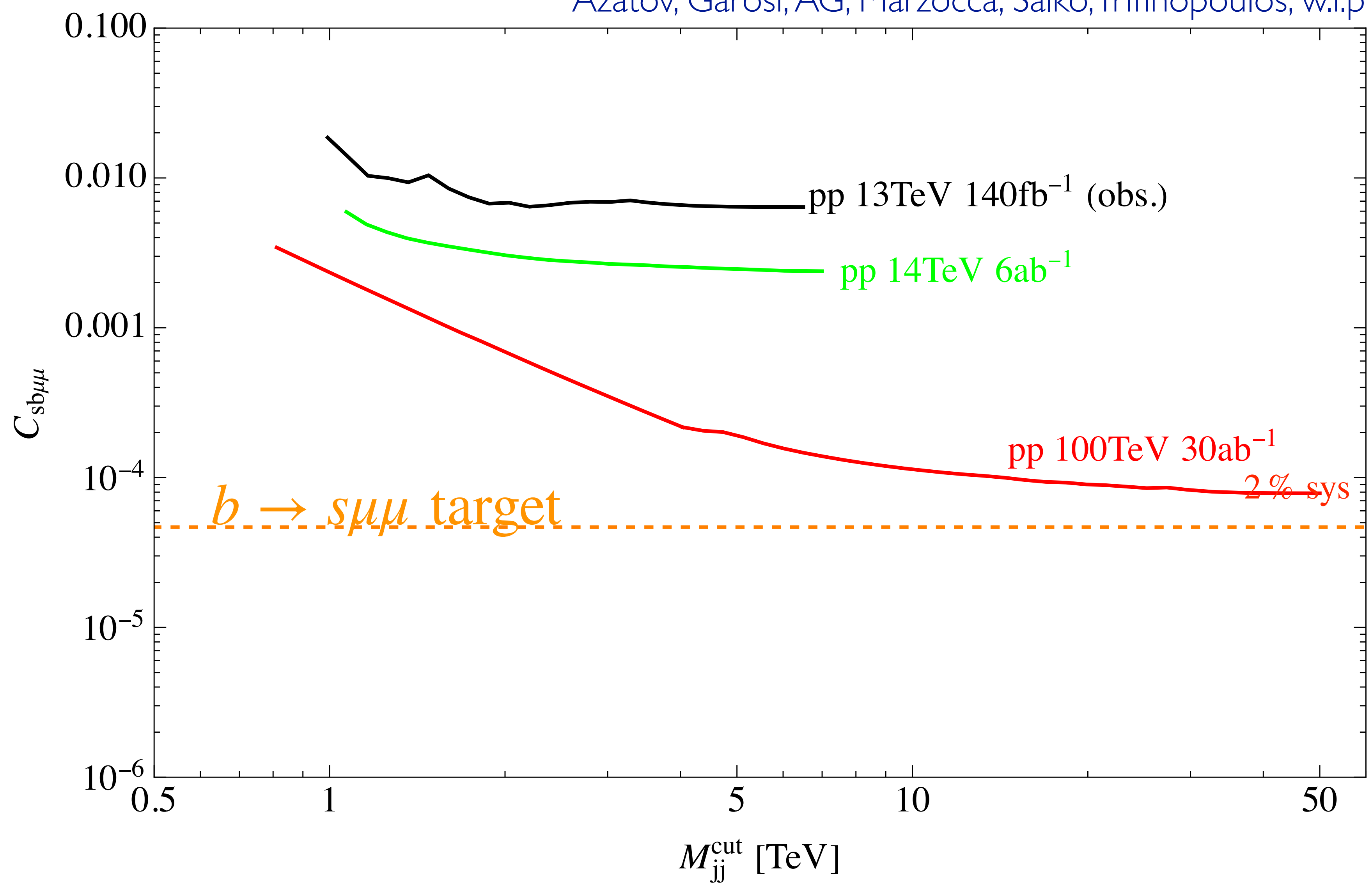
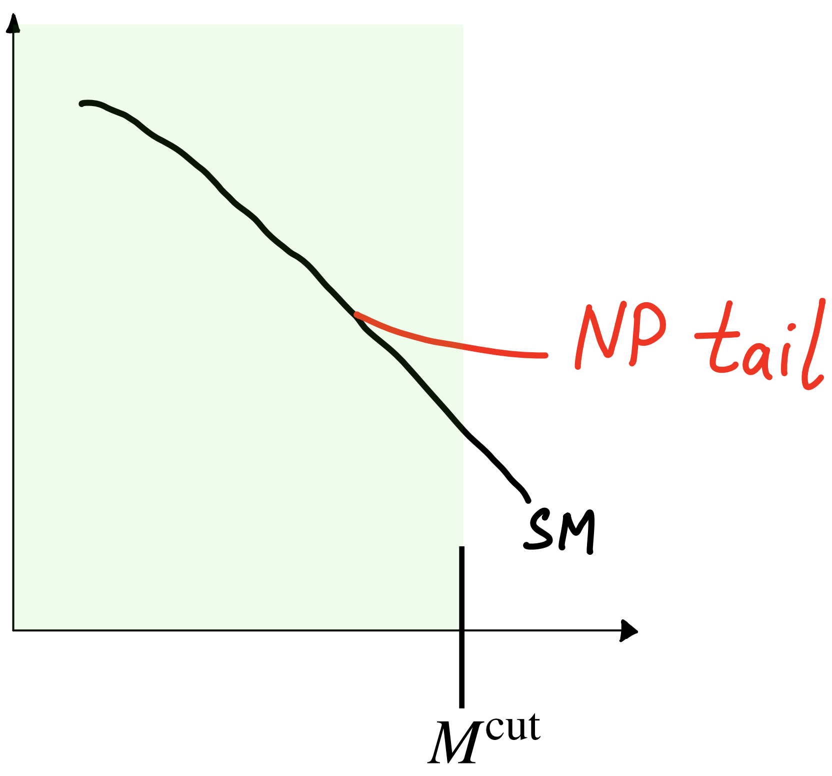
Azatov, Garosi, AG, Marzocca, Salko, Trifinopoulos; w.i.p



- Possible improvements to this analysis; angular kinematics, soft b-jet, etc.

The nightmare scenario



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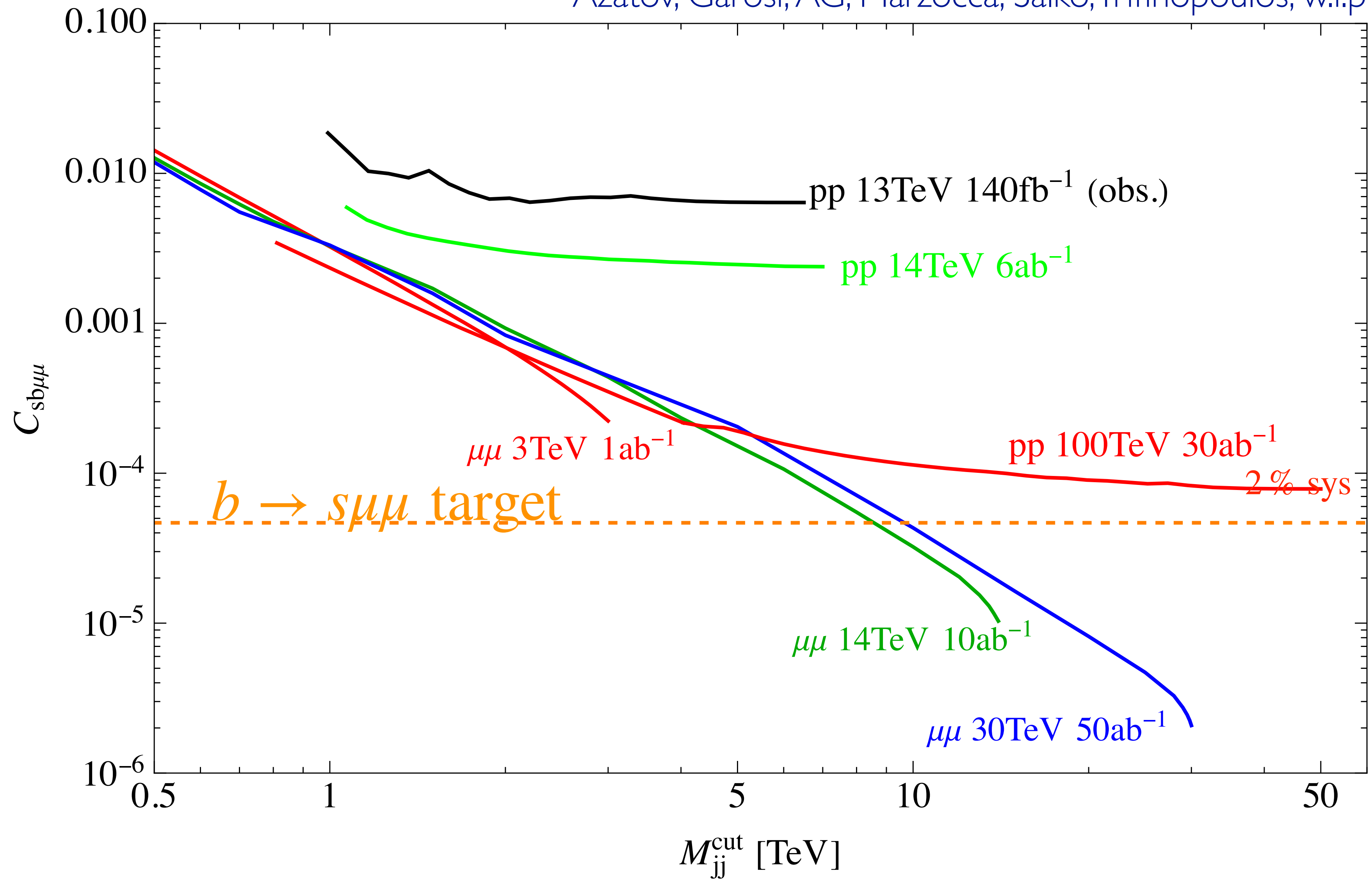

- In $M_{\text{NP}} \gtrsim 10\,\text{TeV}$, future colliders will likely catch the tail.

Reasonable scenario?

- However, the scale indicated from the perturbative unitary tends to be overly pessimistic

  - Example I

Weak interactions $\rightarrow$ $G_F \sim (250\ \mathrm{GeV})^{-2}$ $\qquad G_F \sim \frac{g_w^2}{m_W^2}$ $\qquad m_W \approx 80\,\mathrm{GeV}$

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  - Example 2

    "Super-weak" interaction [L. Wolfenstein]:

$$\frac{e^{i\delta}}{\Lambda^2}(\bar{s}\,\Gamma\,d)^2 \qquad \frac{1}{\Lambda^2} \sim (10^4\ \mathrm{TeV})^{-2} \sim \frac{(G_F\, m_t V_{ts} V_{td})^2}{4\pi^2} \qquad m_t \approx 170\,\mathrm{GeV}$$

[Taken from Isidori]

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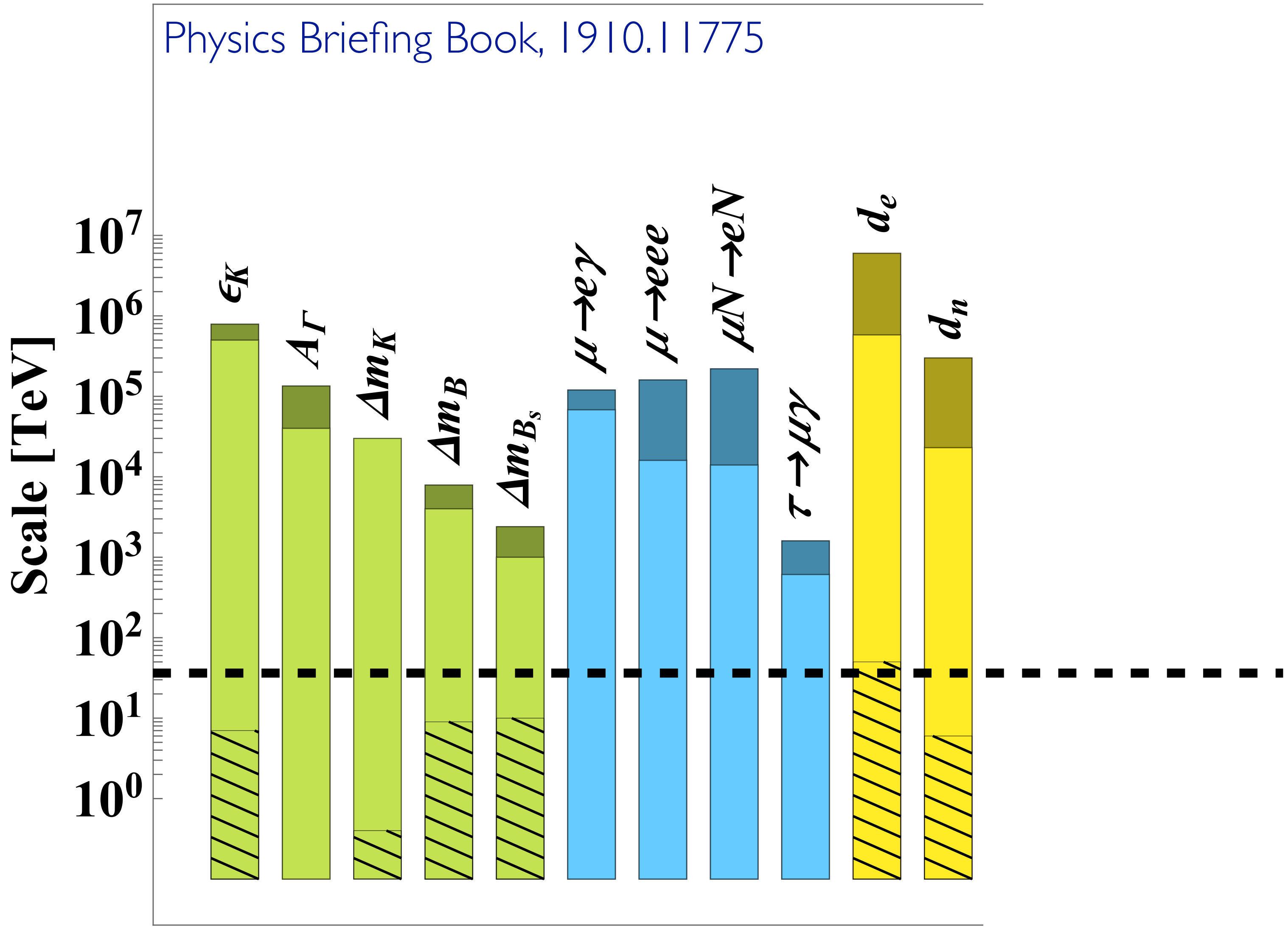
    [Taken from Isidori]

- In $b \to s\ell\ell$ case, $\mathscr{L} \supset \frac{1}{(40\ \text{TeV})^2}(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$
- $40\,\text{TeV}$ could be "*a mirage*"
  $\Longrightarrow$ opportunities at high-p_T LHC

Flavour violation

- General argument against high-scale strongly-coupled UV completion:



- Integrating our composite resonance tends to generate many operators in the SMEFT, in particular, 4Q and 4L FCNC.
- A consistent theory should have a well-defined flavour symmetry and a symmetry breaking pattern (eg. MFV, U(2), partial compositeness, etc).
- Thus, $3_q \to 2_q$ transition should carry a corresponding flavour spurion suppression.

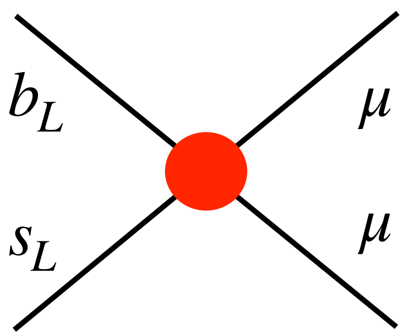
$$b \to s\ell^+\ell^-$$

$$3_q \to 2_q \quad |V_{ts}| \approx 0.04$$

$$\mathscr{L} \supset \frac{|V_{ts}|}{(8\ \text{TeV})^2}(\bar{s}_L\gamma^\mu b_L)(\bar{\mu}_L\gamma_\mu\mu_L)$$

$$\Longrightarrow \text{Scale} \lesssim 20\,\text{TeV}$$

Mediators



[See talk by Renner]

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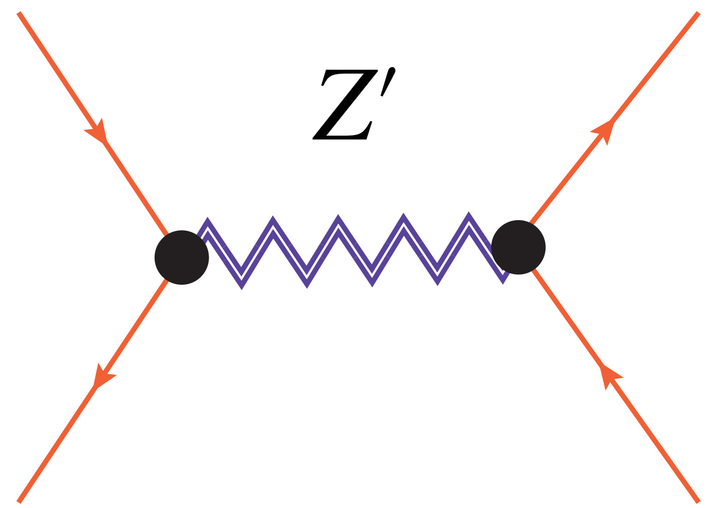
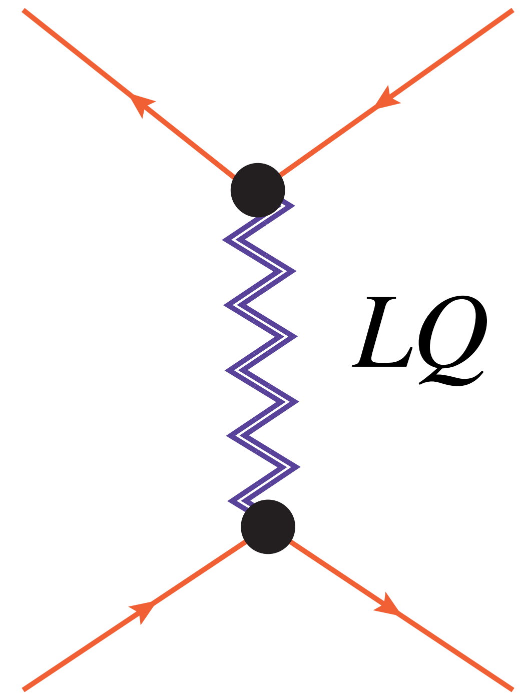
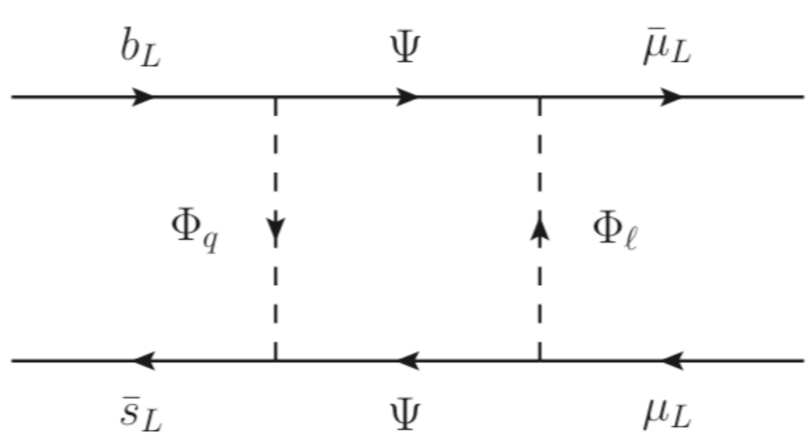


or



This talk

or



+ other loop models

$$\mathcal{L} \supset \frac{1}{16\pi^2}\frac{|V_{ts}|}{(0.6\ \text{TeV})^2}(\bar s_L \gamma^\mu b_L)(\bar\mu_L \gamma_\mu \mu_L)$$

See for example:
Arcadi, Calibbi, Fedele, Mescia, 2104.03228

Models: Class I

The mediator mainly couples to muons

[or at least as much as to tau leptons]

$$g_\tau \lesssim g_\mu$$

This talk

Models: Class II

The mediator dominantly couples to taus

$$g_\tau \gg g_\mu$$

Models: Class I

$$g_\tau \lesssim g_\mu$$

Examples

- Z' of $U(1)_{L_\mu - L_\tau}$, $U(1)_{B-3L_\mu}$, $U(1)_{B_3 - L_\mu}$, etc

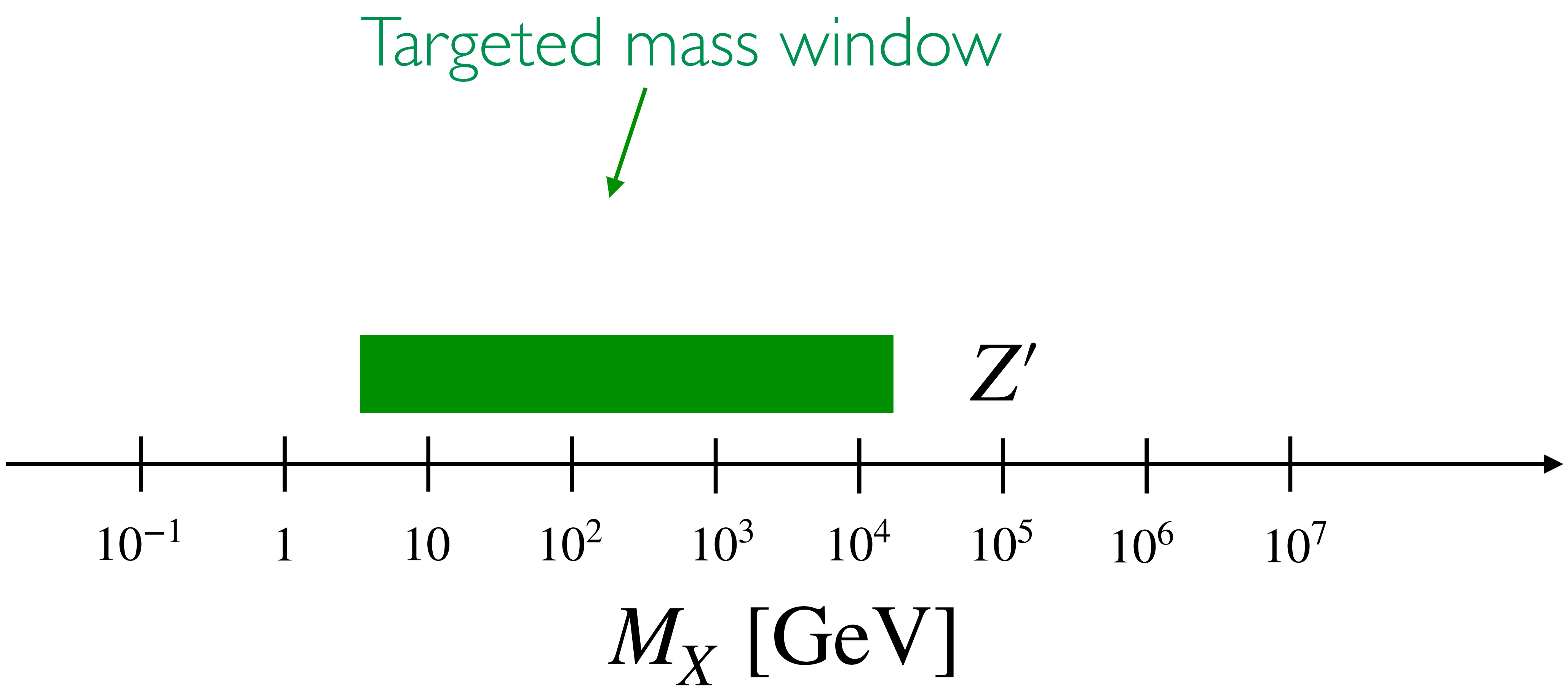
Altmannshofer, Gori, Pospelov, Yavin; 1403.1269,
Crivellin, D'Ambrosio, Heeck; 1501.00993,
Celis, Fuentes-Martin, Jung, Serodio; 1505.03079,
Crivellin, Fuentes-Martin, AG, Isidori; 1611.02703,
Alonso, Cox, Han, Yanagida; 1705.03858,
Bonilla, Modak, Srivastava, Valle; 1705.00915,
Ellis, Fairbairn, Tunney; 1705.03447;
Allanach, Davighi; 1809.01158,
Altmannshofer, Davighi, Nardecchia; 1909.02021,
Allanach; 2009.02197,
+ many more …

- LQ charged under $U(1)_X$ gauge symmetry such that it couples only to μ but not e, τ.
- The accidental symmetry is $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ and $LQ \equiv (-1/3, 0,\ -1, 0)$

Hambye, Heeck; 1712.04871
Davighi, Kirk, Nardecchia, 2007.15016
AG, Stangl, Thomsen, 2103.13991
AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

Class I

Z' models: general remarks



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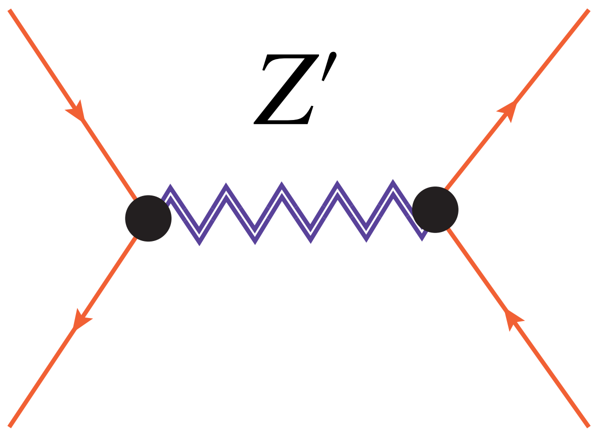
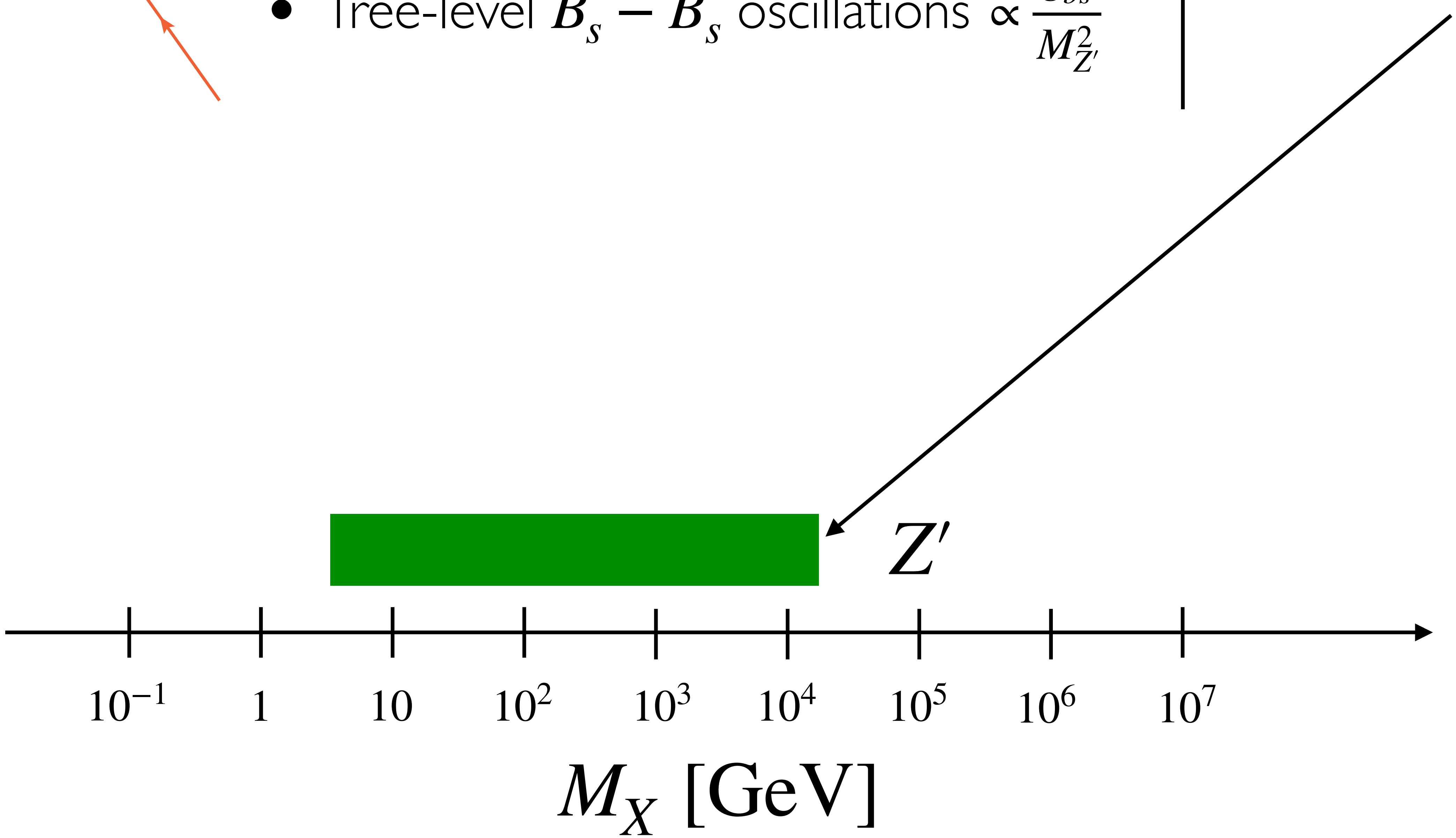


- Tree-level $b \to s\ell\ell$ $\frac{1}{(40\,\text{TeV})^2} = \frac{g_{bs} g_{\mu\mu}}{M_{Z'}^2}$
- Tree-level $B_s - \bar{B}_s$ oscillations $\propto \frac{g_{bs}^2}{M_{Z'}^2}$

$$\Longrightarrow \sqrt{4\pi} \gtrsim g_{\mu\mu} > \frac{M_{Z'}}{5\,\text{TeV}}$$



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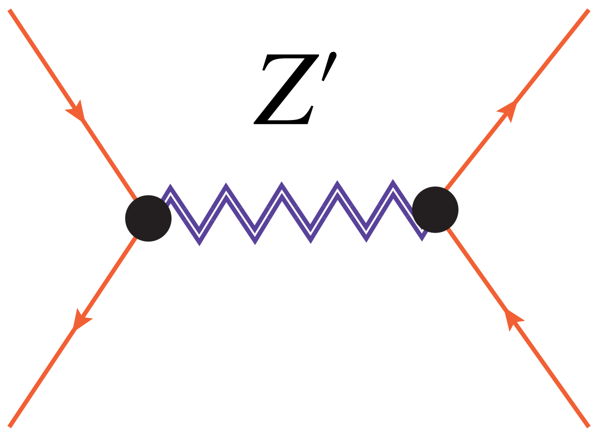

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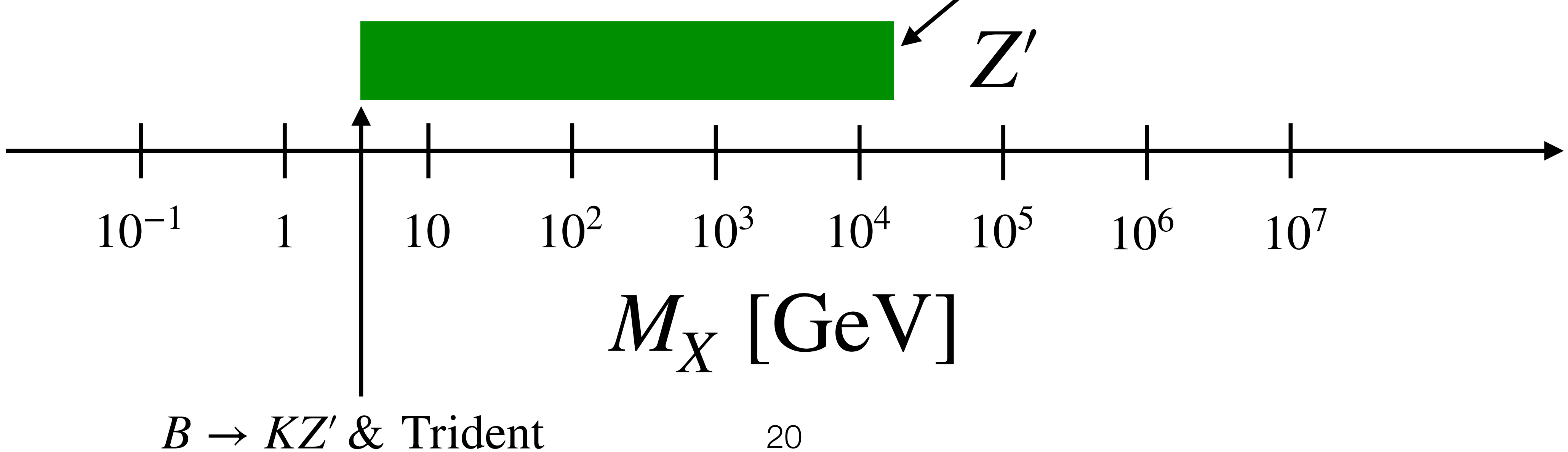
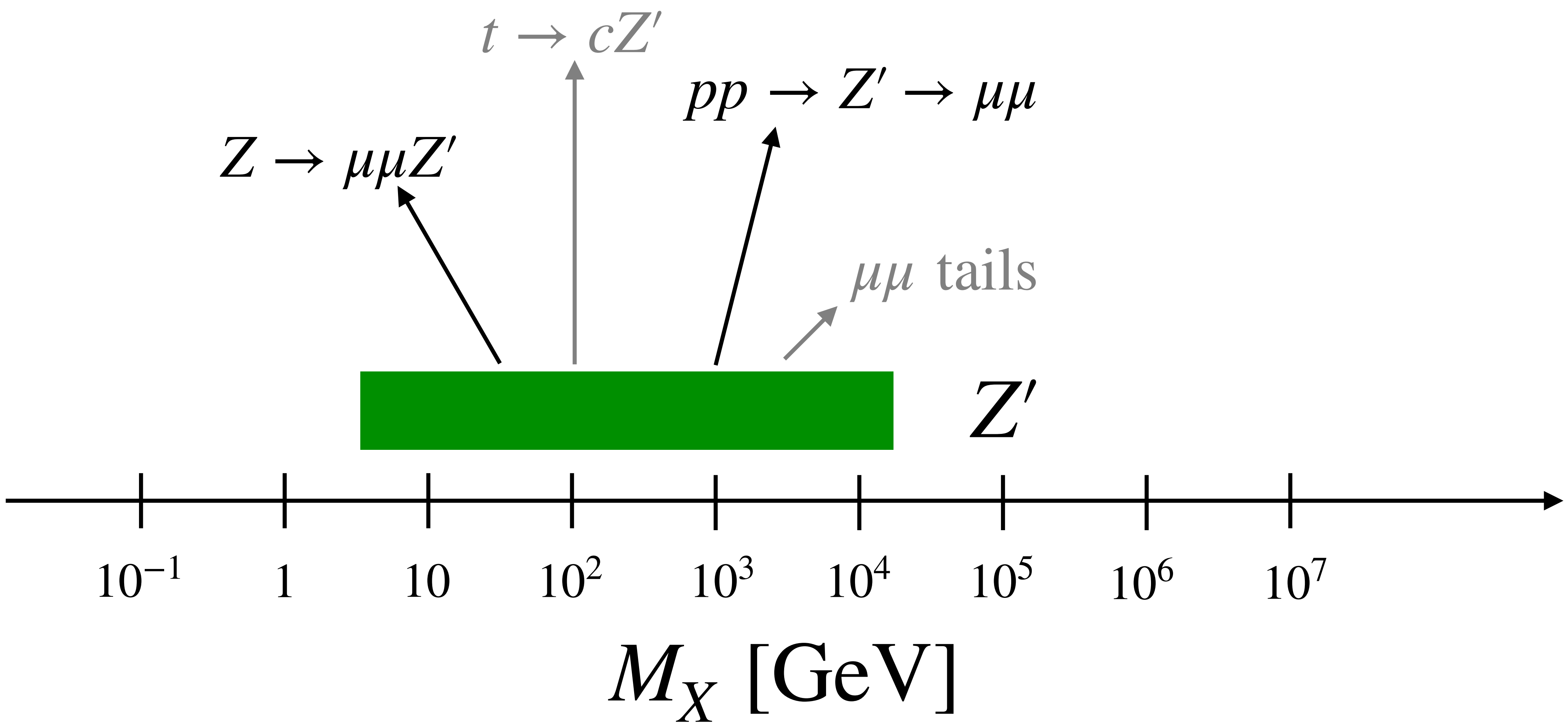


Class I

Z' models: general remarks

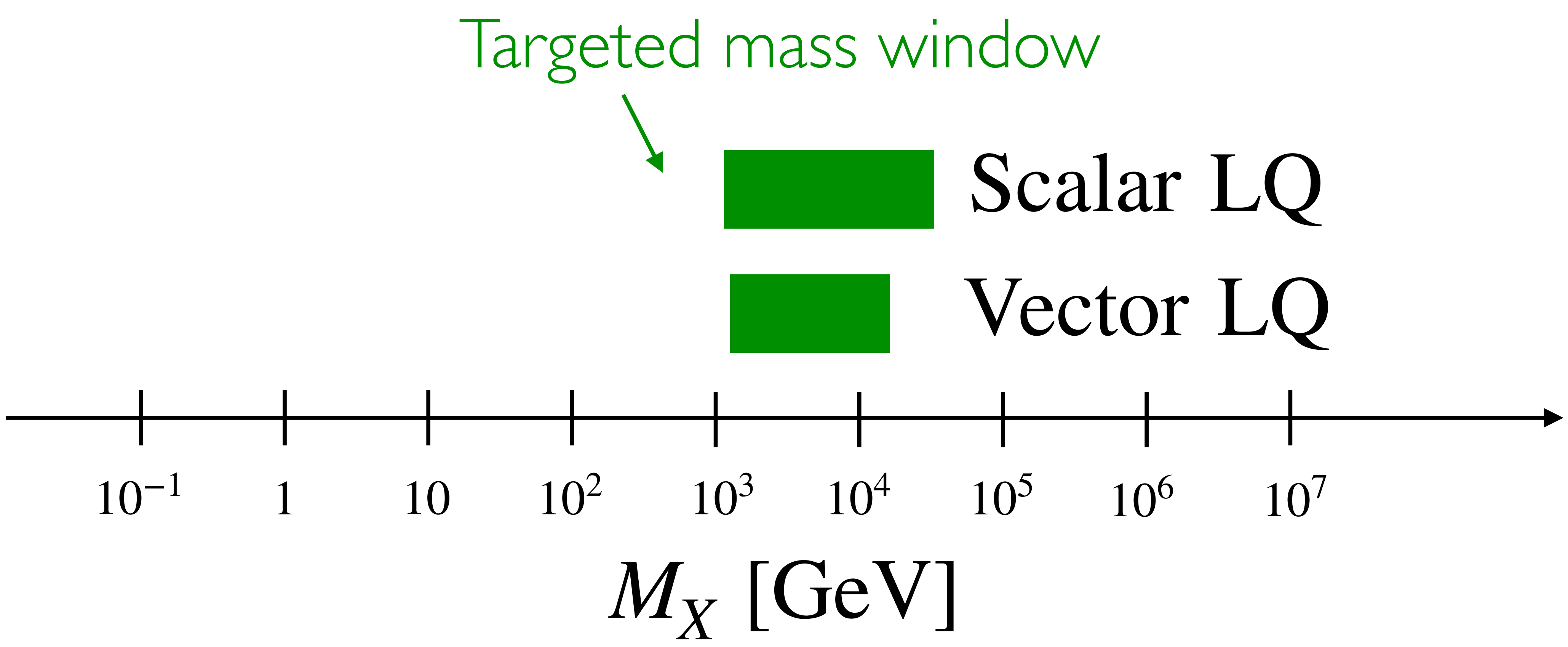
Signatures:



[Explicit models in the Backup]

Class I

LQ models: general remarks

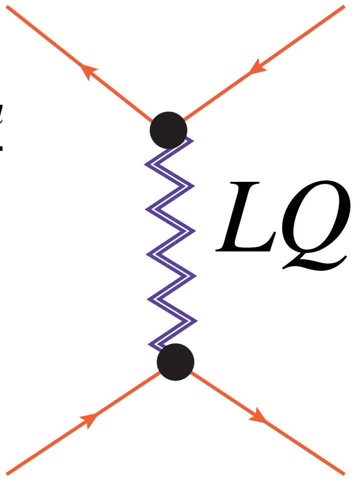


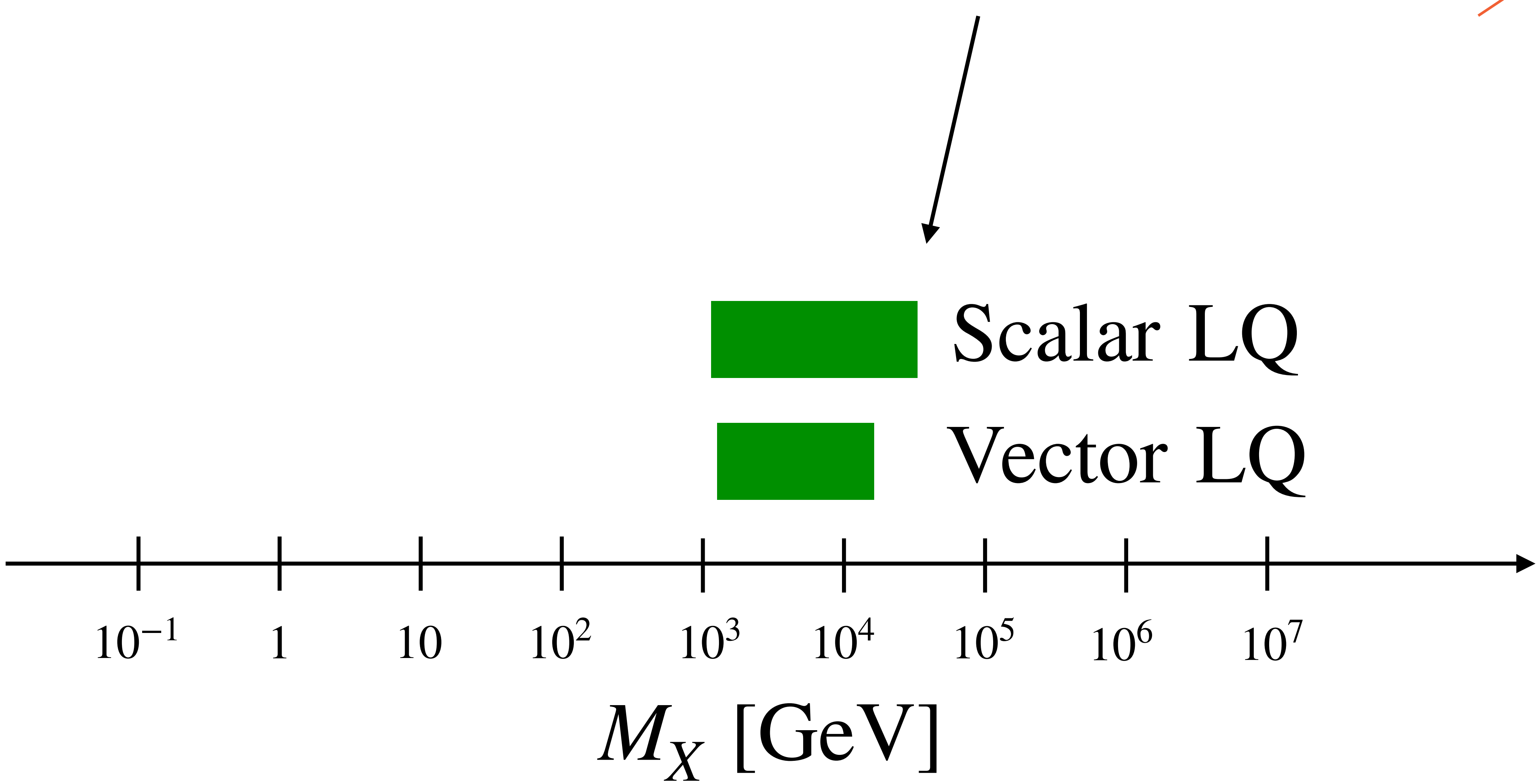
[Explicit models in the Backup]

Class I

LQ models: general remarks

- Tree-level $b \to s\ell\ell$ $\quad \dfrac{1}{(40\,\text{TeV})^2} = \dfrac{g_{b\mu}g_{s\mu}}{M_{Z'}^2}$
- One-loop $B_s - \bar{B}_s$ oscillations. Vector LQ comes with the Z'.





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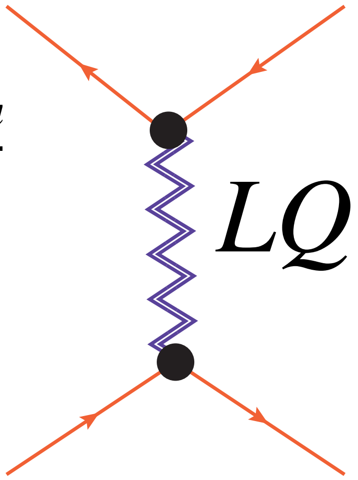
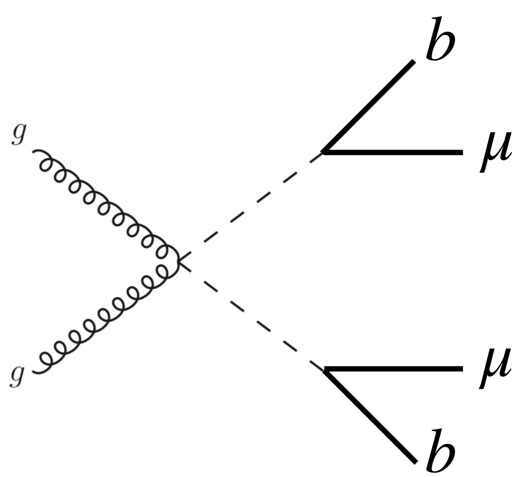
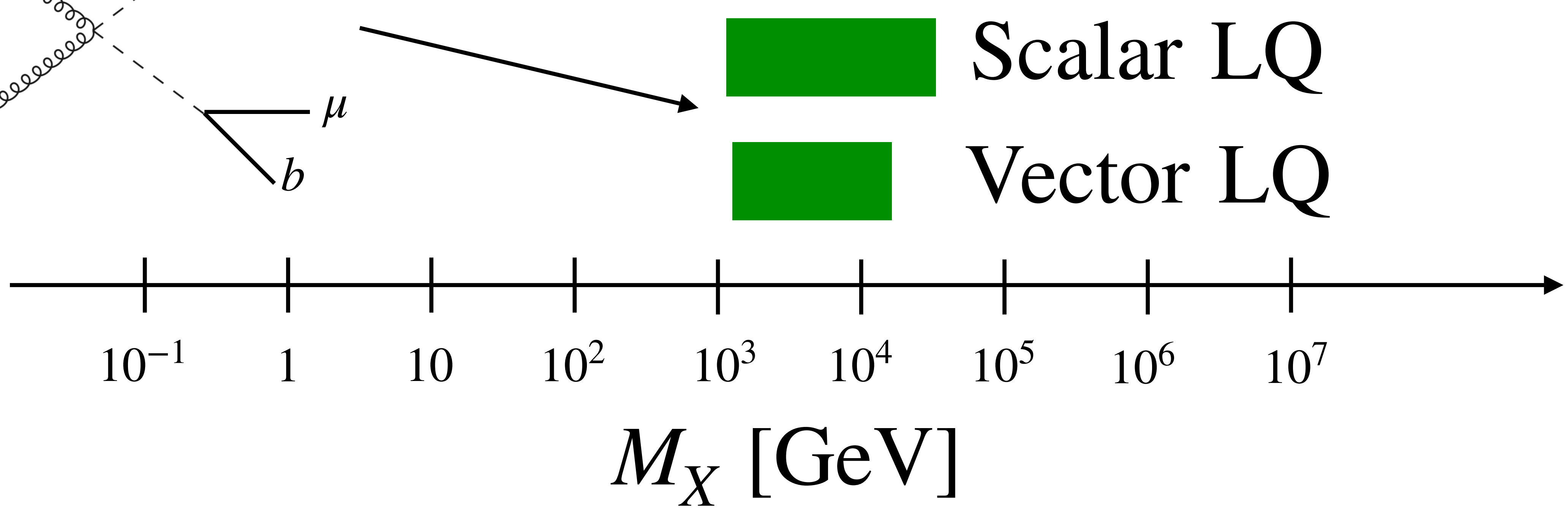


- LHC bounds: LQ pair production $m_{LQ} \gtrsim 1\,\mathrm{TeV}$





[Explicit models in the Backup]

Models: Class II

The mediator dominantly couples to taus

$$g_\tau \gg g_\mu$$

Class II

Third-generation dominance

- Since $m_\tau \gg m_\mu$, perhaps: $\mathscr{L} \supset \frac{|V_{ts}|}{(2\ \mathrm{TeV})^2} \frac{m_\mu}{m_\tau} (\bar{s}_L \gamma^\mu b_L)(\bar{\mu}_L \gamma_\mu \mu_L)$

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$\Longrightarrow$ $\delta R_{D^{(*)}} = \mathcal{O}(\%)$ (Remarkable!)

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- Collider implications:
New physics mostly coupled to third generation

$$\mathscr{L} \supset \frac{1}{(2\ \mathrm{TeV})^2} (\bar{b}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \tau_L)$$

$\Longrightarrow$ Scale $\lesssim 5\,\mathrm{TeV}$

high-p_T LHC!

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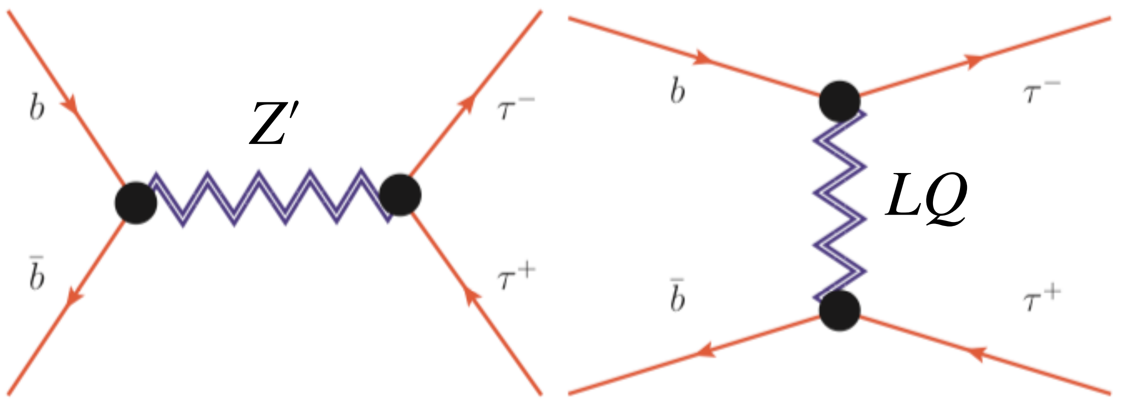

Faroughy, AG, Kamenik; 1609.07138

Class II

The 4321 *model*

- Pati-Salam vector leptoquark model

$\mathrm{SU}(4)_3 \times \mathrm{SU}(3)_{1+2} \times [\ \mathrm{SU}(2)_L \times \mathrm{U}(1)'\ ]$

ψ_3 $\psi_{1,2}$

$\rightarrow$ LQ [U_1] + Z' + G'

SM

Di Luzio, Greljo, Nardecchia, '17

1708.08450,
1712.01368,
1802.04274,
1805.09328,
1808.00942,
1903.11517,
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. . .

[LQ collider physics in the Backup]

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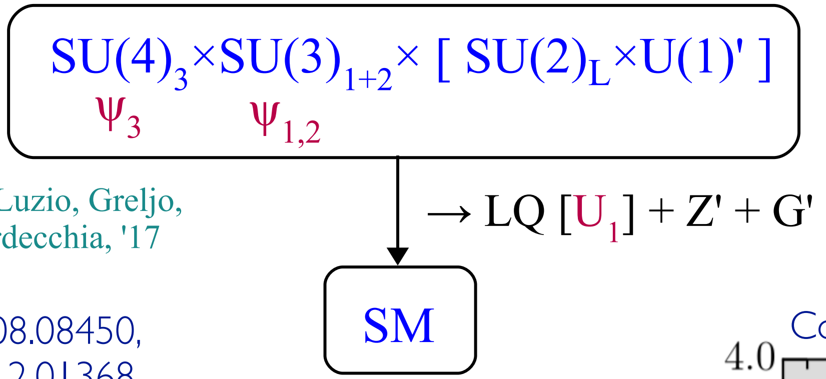
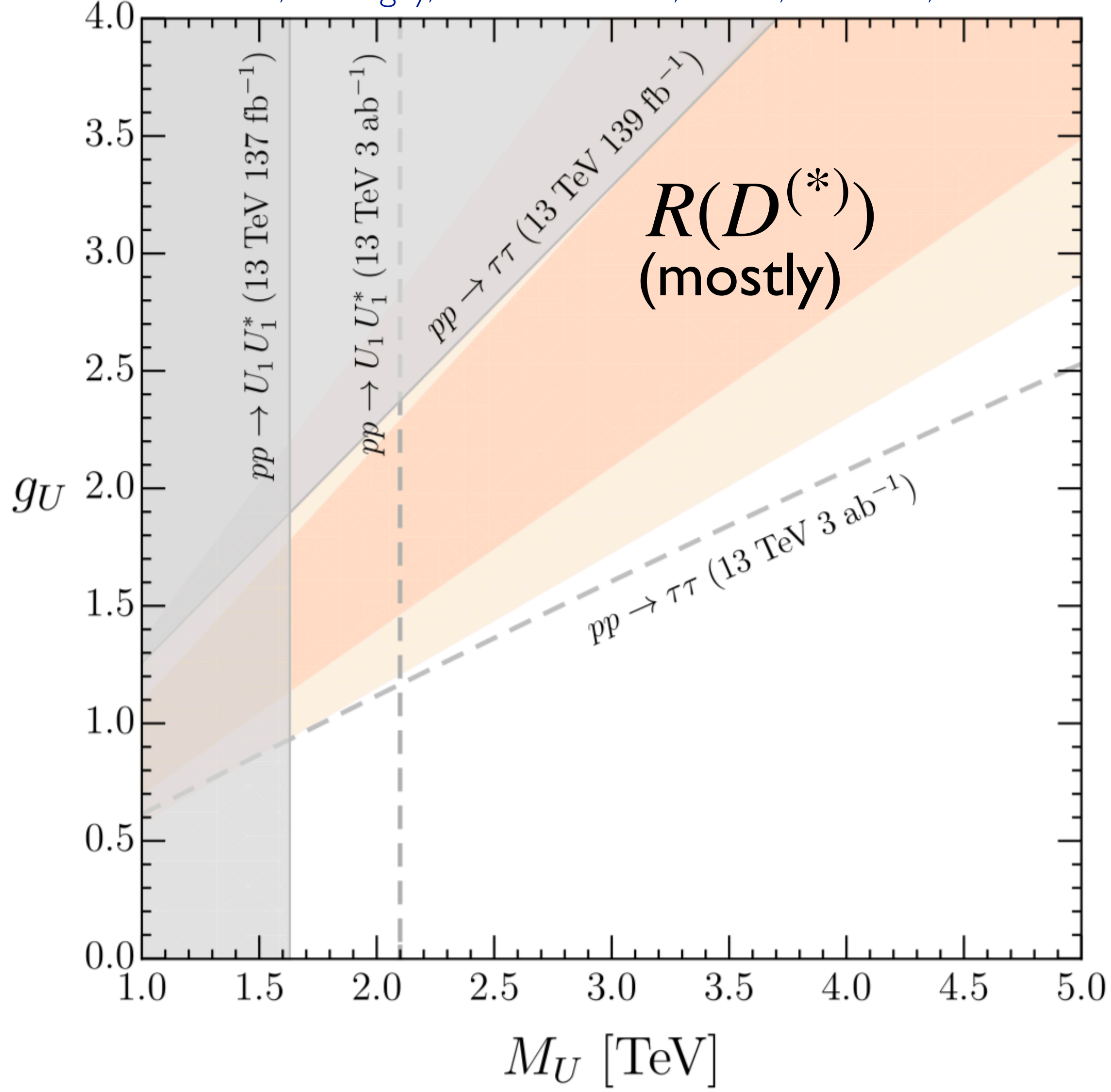


Di Luzio, Greljo, Nardecchia, '17

1708.08450, 1712.01368, 1802.04274, 1805.09328, 1808.00942, 1903.11517, 1910.13474, 2004.11376, …

Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558



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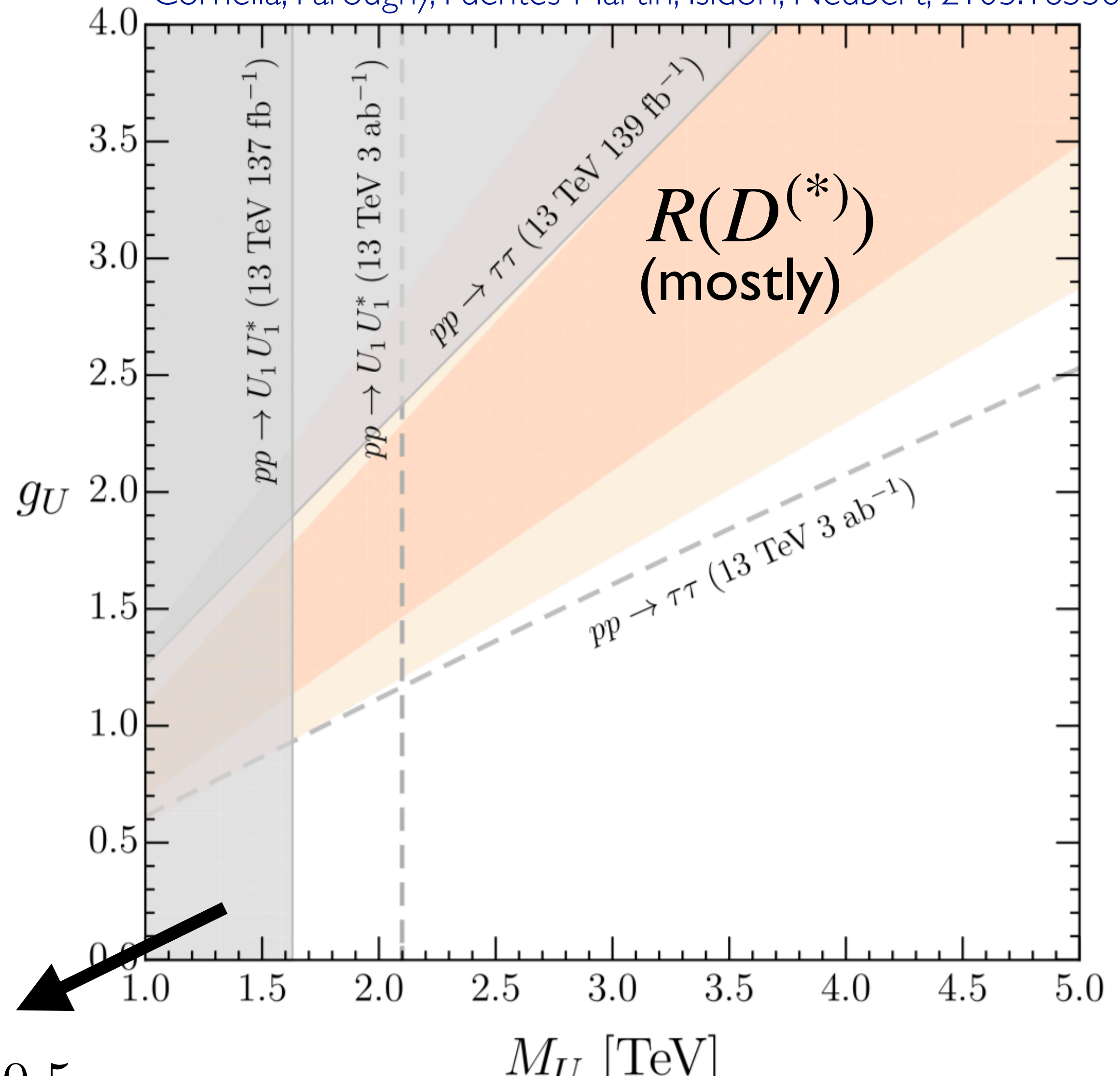


Pair production

$\mathcal{B}(U \to t\nu) \approx \mathcal{B}(U \to b\tau) \approx 0.5$

[LQ collider physics in the Backup]

Class II

The 4321 *model*

- Pati-Salam vector leptoquark model

$SU(4)_3 \times SU(3)_{1+2} \times [\, SU(2)_L \times U(1)' \,]$

ψ_3 $\psi_{1,2}$

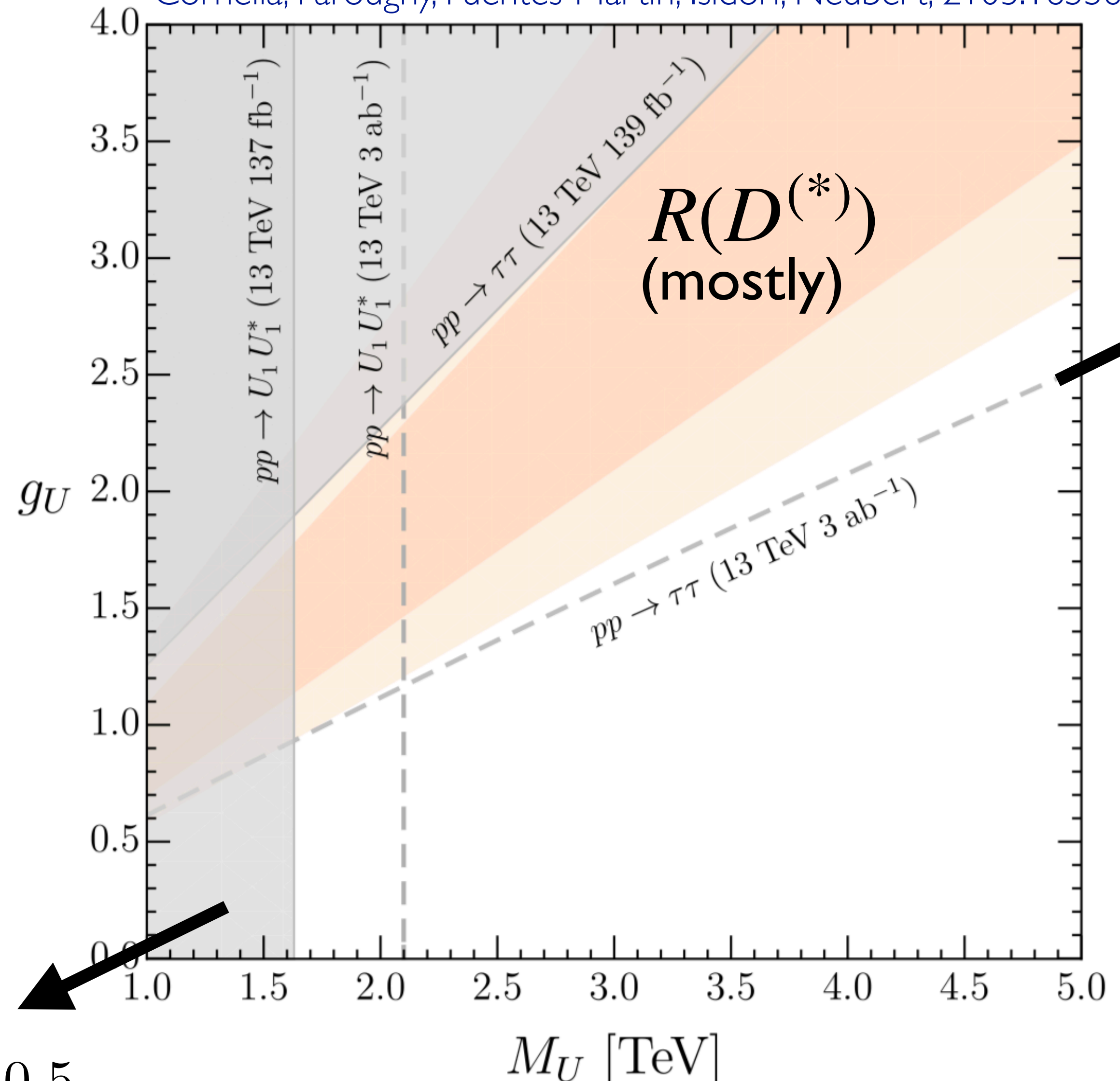
$\rightarrow$ LQ $[U_1]$ + Z' + G'

SM

Di Luzio, Greljo, Nardecchia, '17

1708.08450,
1712.01368,
1802.04274,
1805.09328,
1808.00942,
1903.11517,
1910.13474,
2004.11376,
…

Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert, 2103.16558



$b\bar{b} \to \tau^+\tau^-$
LQ t-channel
@ HL-LHC

Pair production

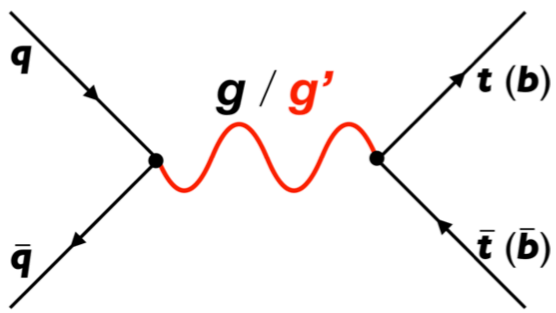
$\mathcal{B}(U \to t\nu) \approx \mathcal{B}(U \to b\tau) \approx 0.5$

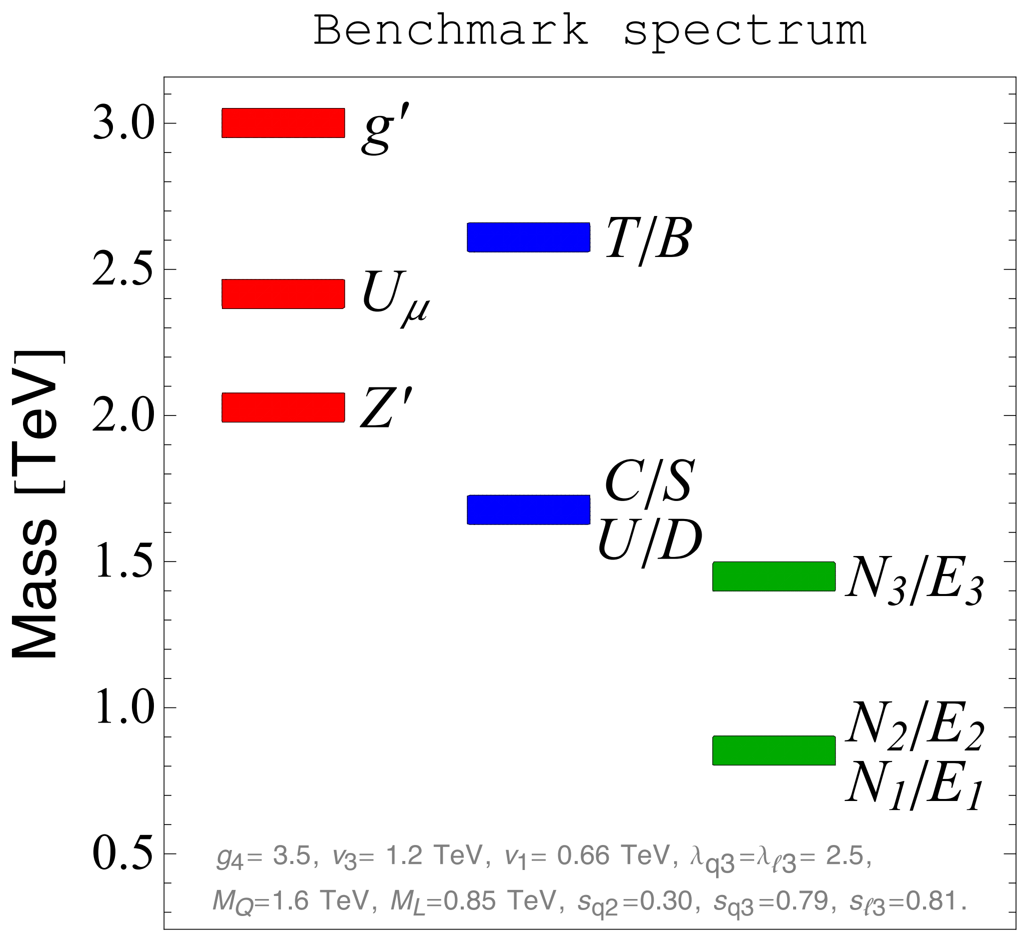
[LQ collider physics in the Backup]

Class II

The 4321 model

- Third-generation high-p_T signatures



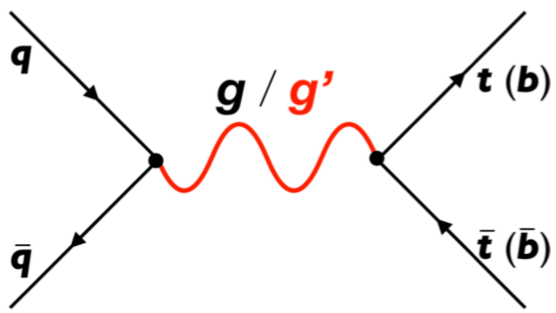


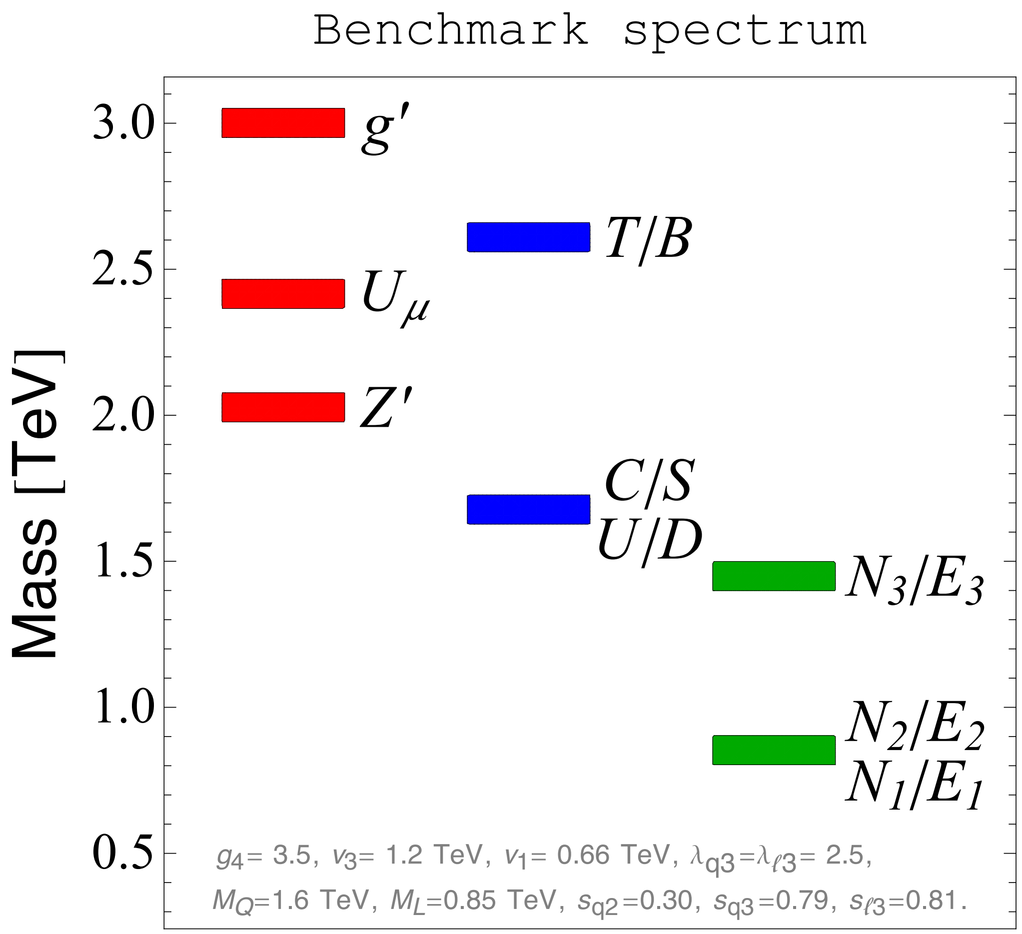
Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner; 1808.00942

Class II

The 4321 model

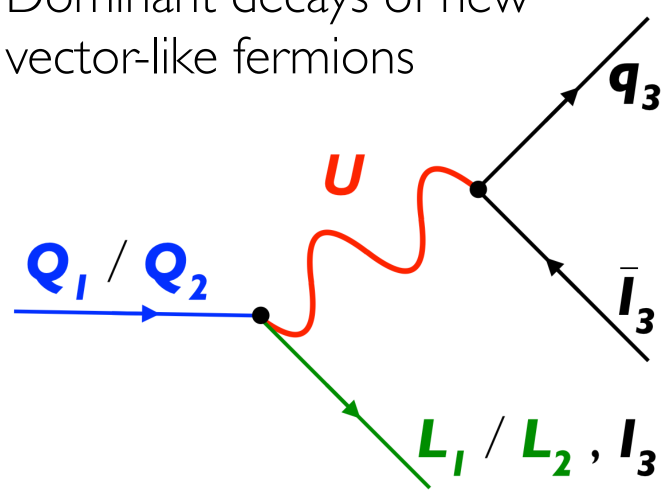
- Third-generation high-p_T signatures





Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner; 1808.00942

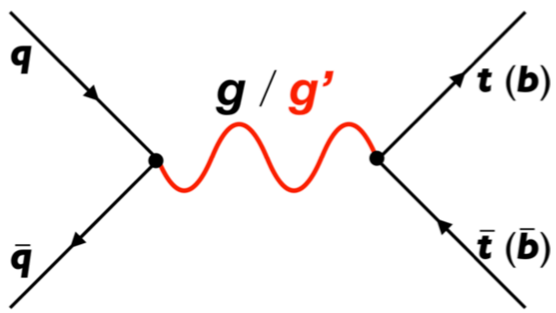
Dominant decays of new vector-like fermions



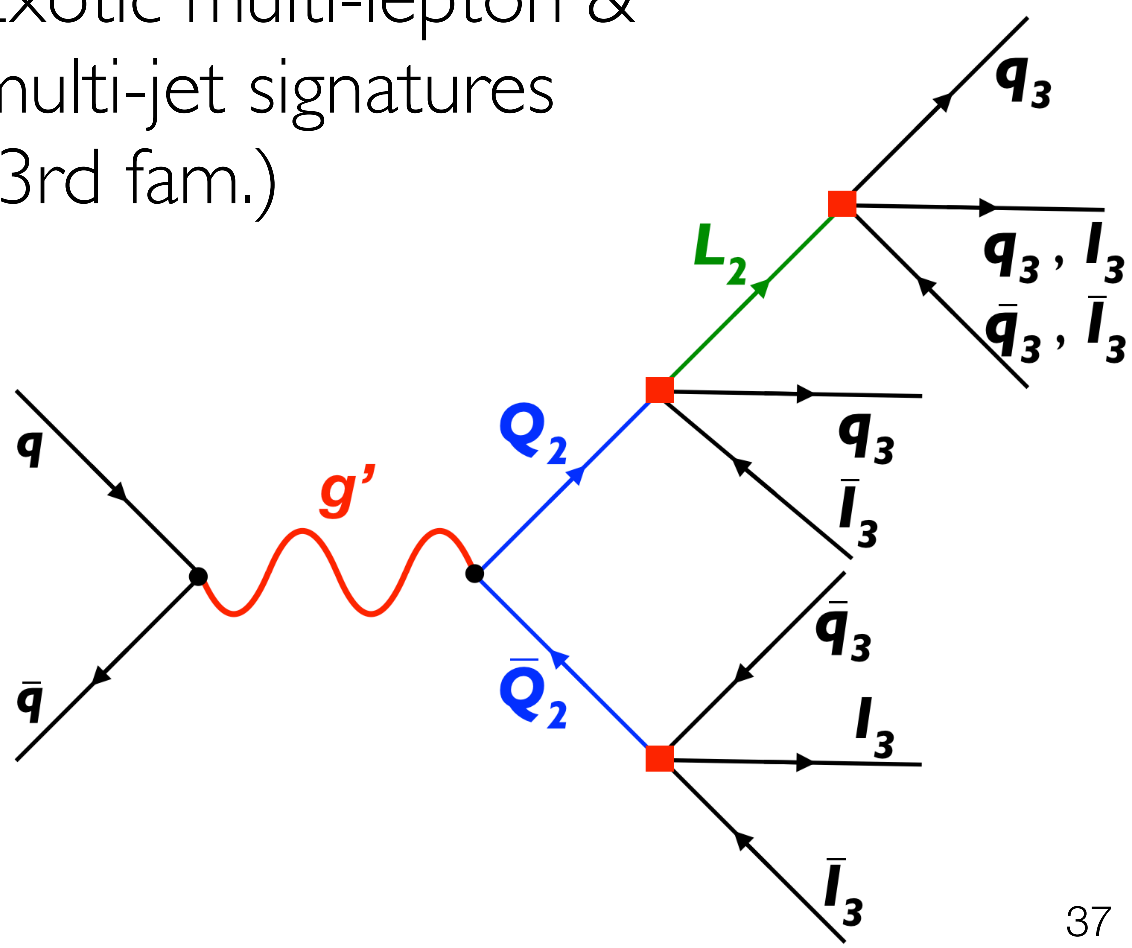
Class II

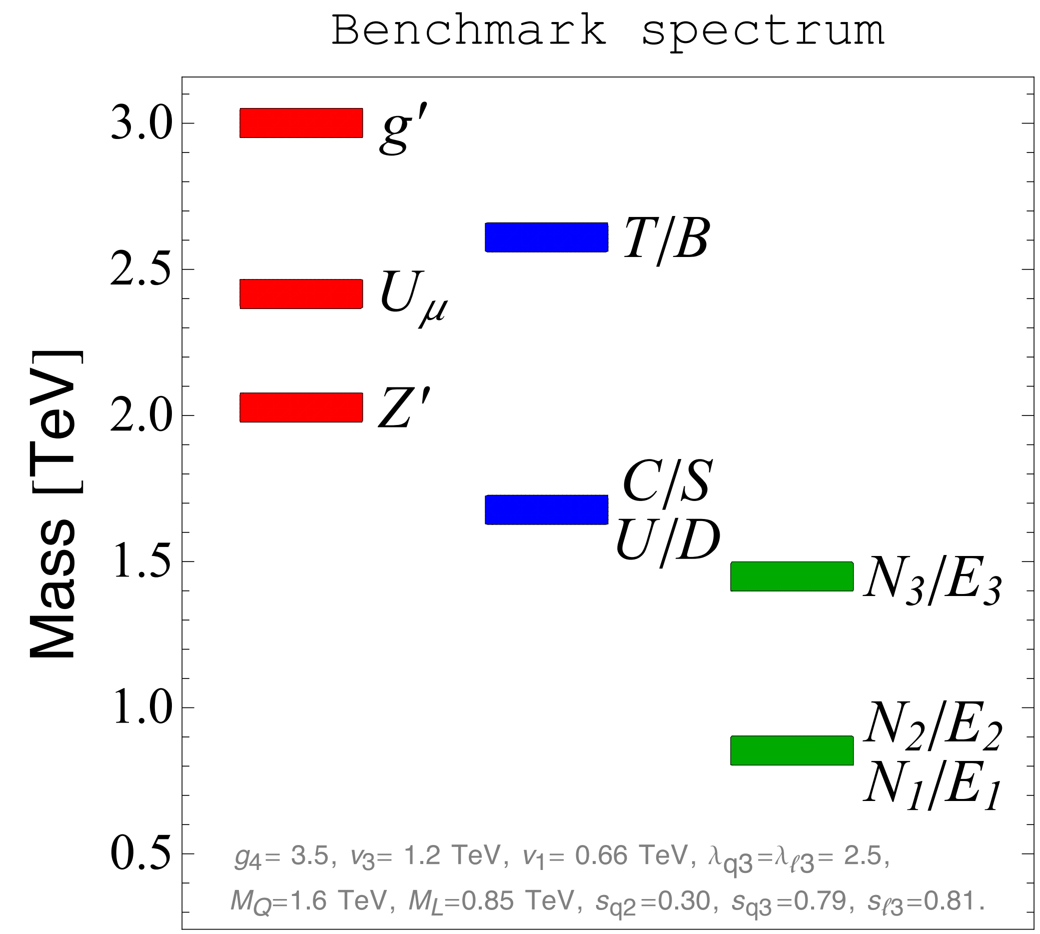
The 4321 *model*

- Third-generation high-p_T signatures



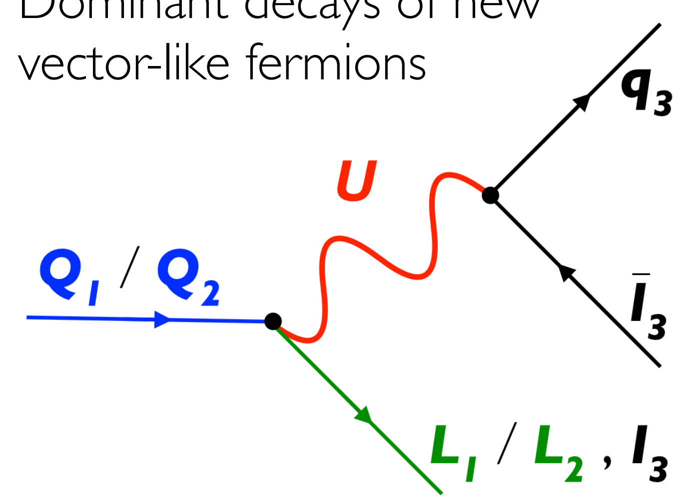
- Exotic multi-lepton & multi-jet signatures (3rd fam.)





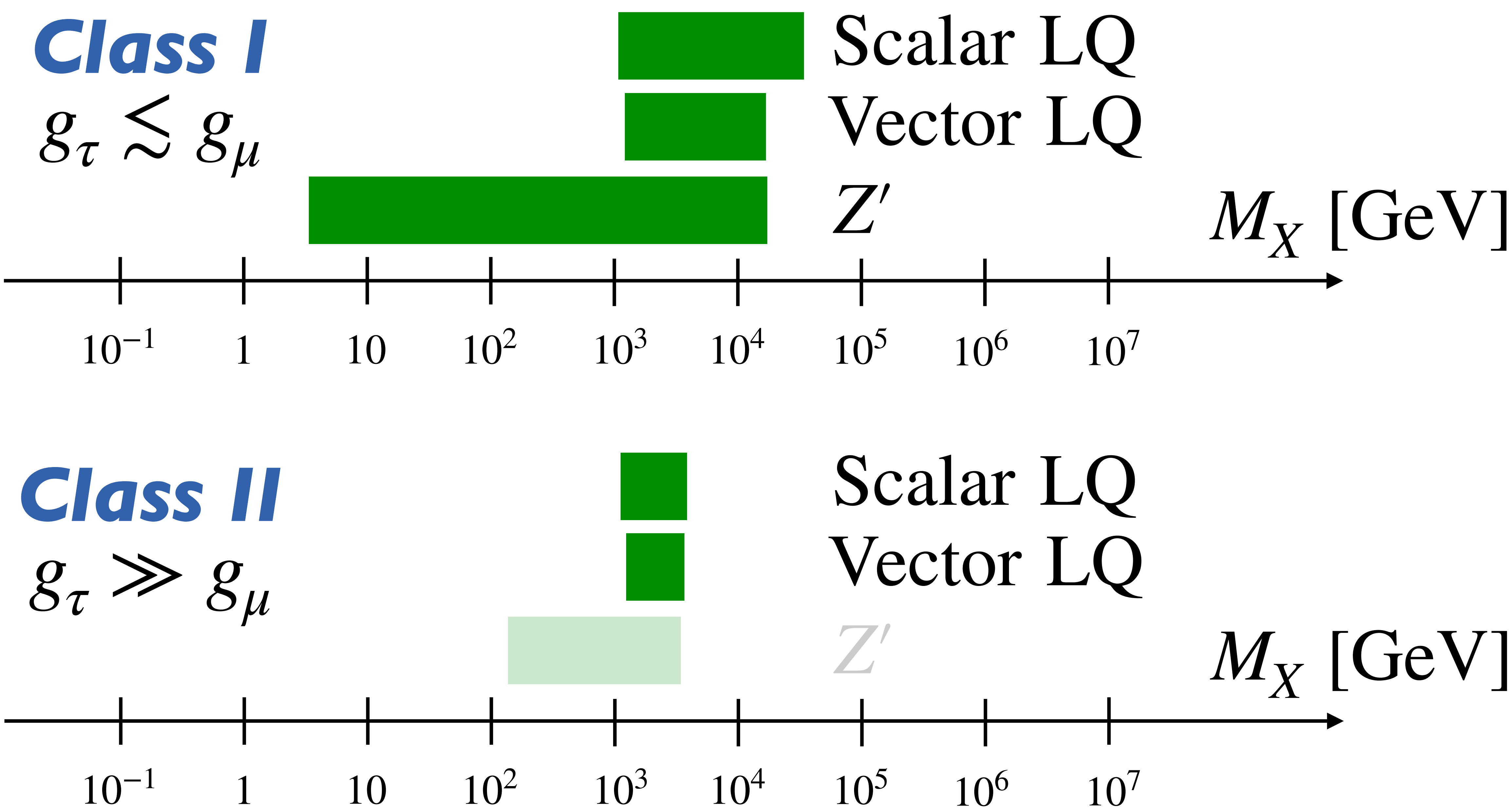
Di Luzio, Fuentes-Martin, AG, Nardecchia, Renner; 1808.00942

Dominant decays of new vector-like fermions



Summary

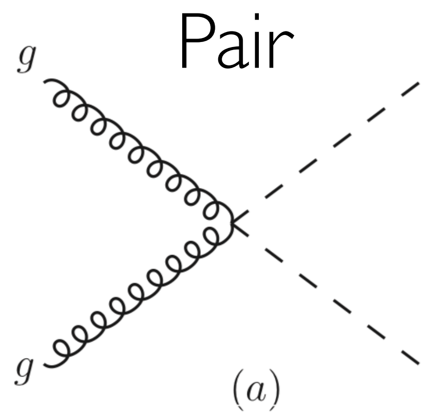
- $b \to s\ell\ell$ collider targets: Where to look?

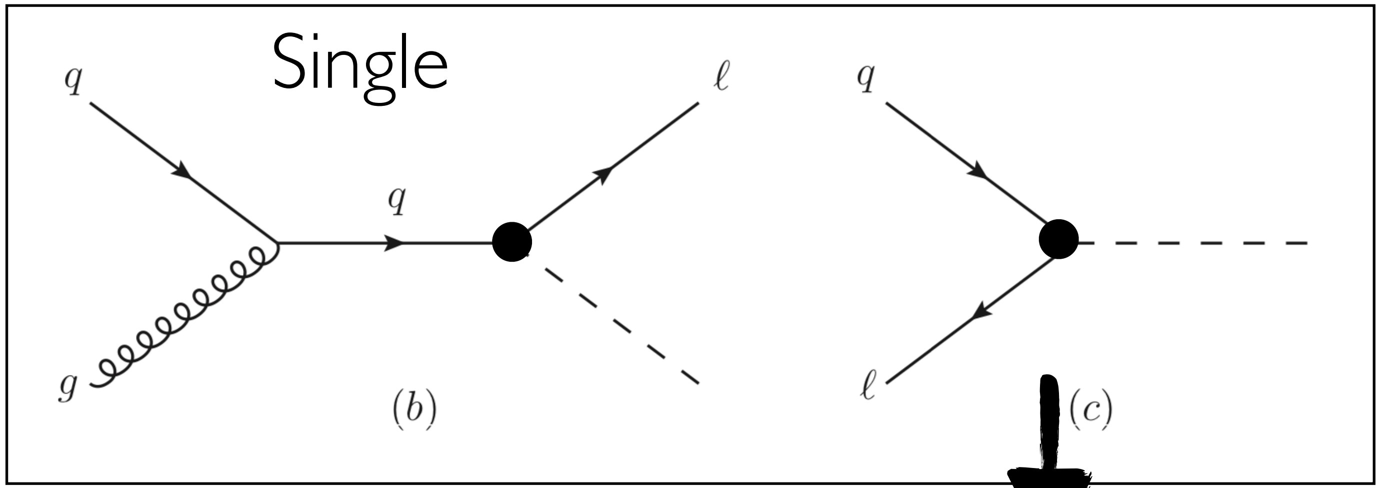


Backup

LQ collider physics: Large coupling

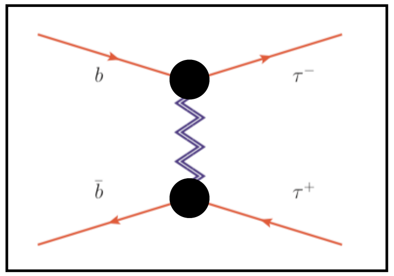
On-shell:





$\sigma \propto y^2$

Off-shell:



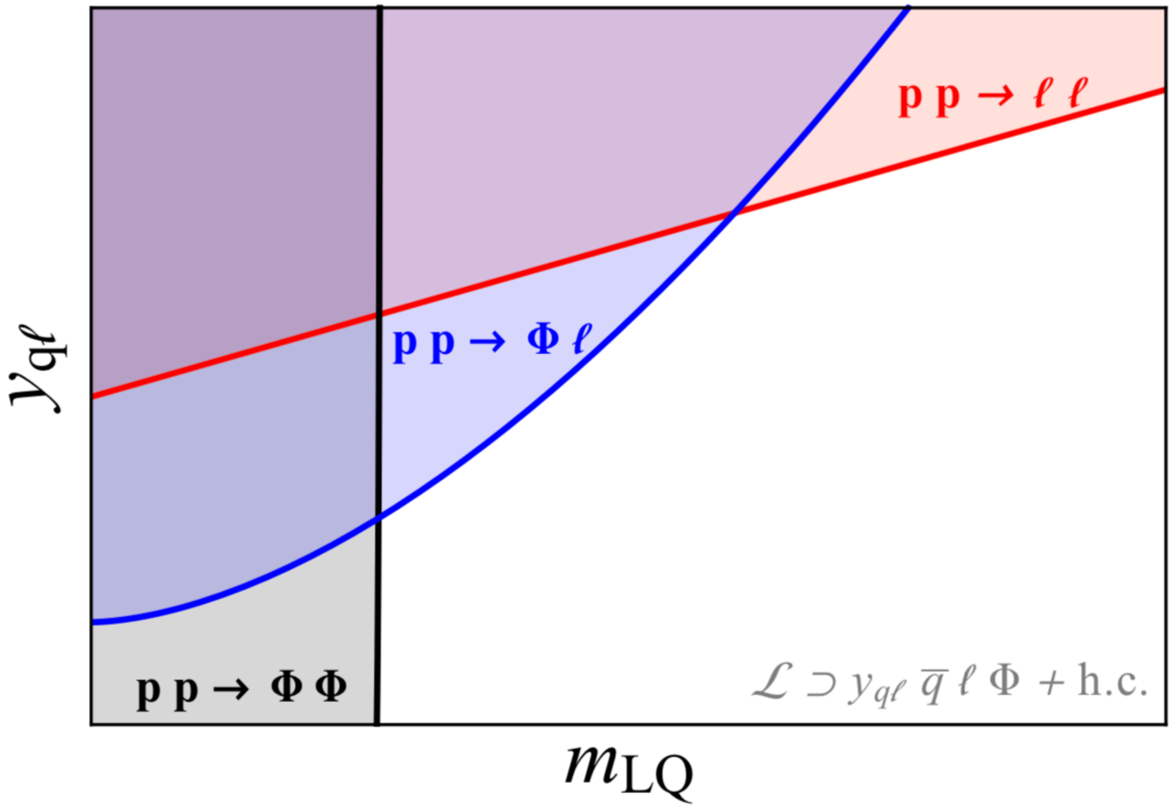
$\sigma \propto y^4$

Resonant LQ production

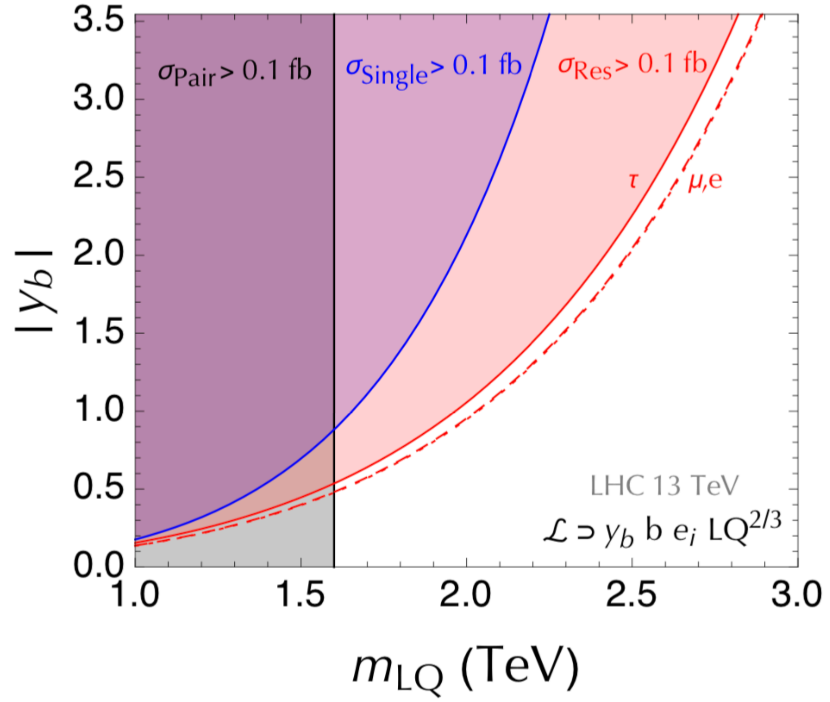
$pp \to \Phi$

Buonocore, Haisch, Nason, Tramontano, Zanderighi; 2005.06475
Haisch,Polesello; 2012.11474
AG, Selimovic; 2012.02092

Dorsner, AG; 1801.07641



AG, Selimovic; 2012.02092



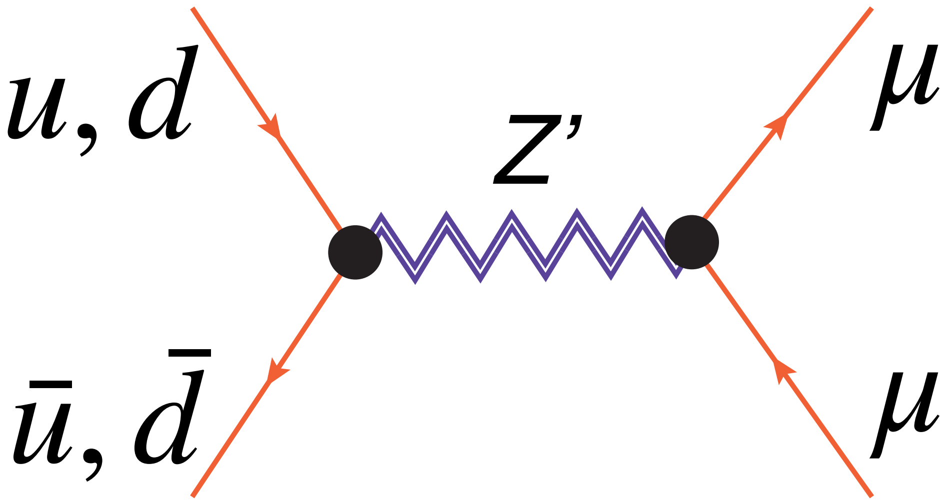
Quark-universal Z' models

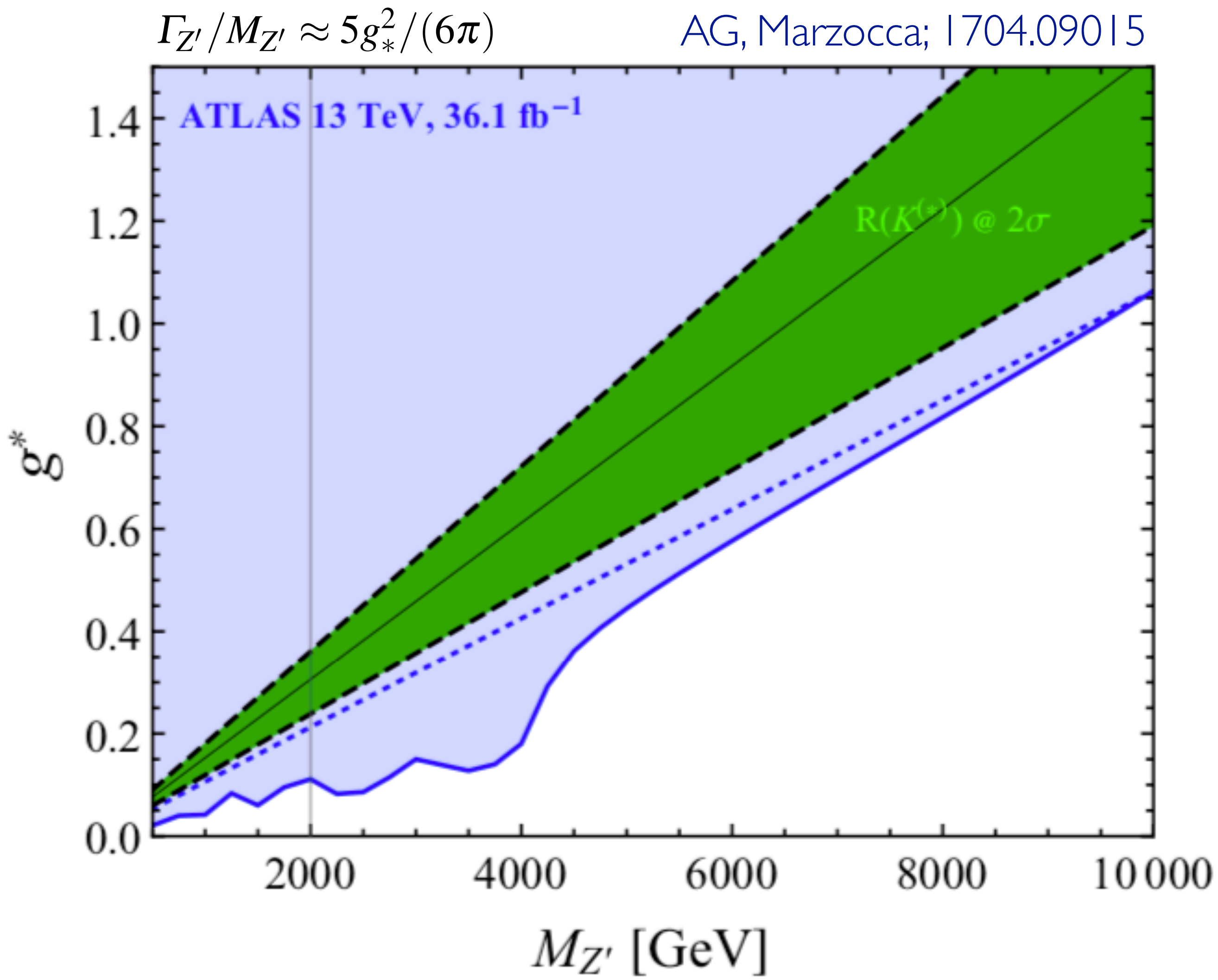
- Z'-quark interactions are of the form

$$g_{Q_L} = g^* \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & V_{ts} \\ 0 & V_{ts}^* & 1 \end{bmatrix} \qquad g_{L_L}^{22} = g^*$$

- For example gauged $U(1)_{B-3L_\mu}$, etc.

- Production from valence quarks:





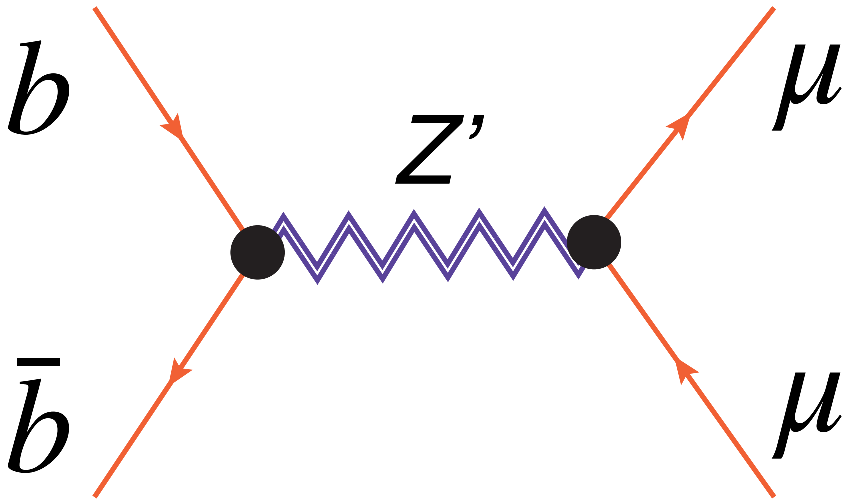
3rd-gen-quark Z' models

- Z'-quark interactions are of the form:

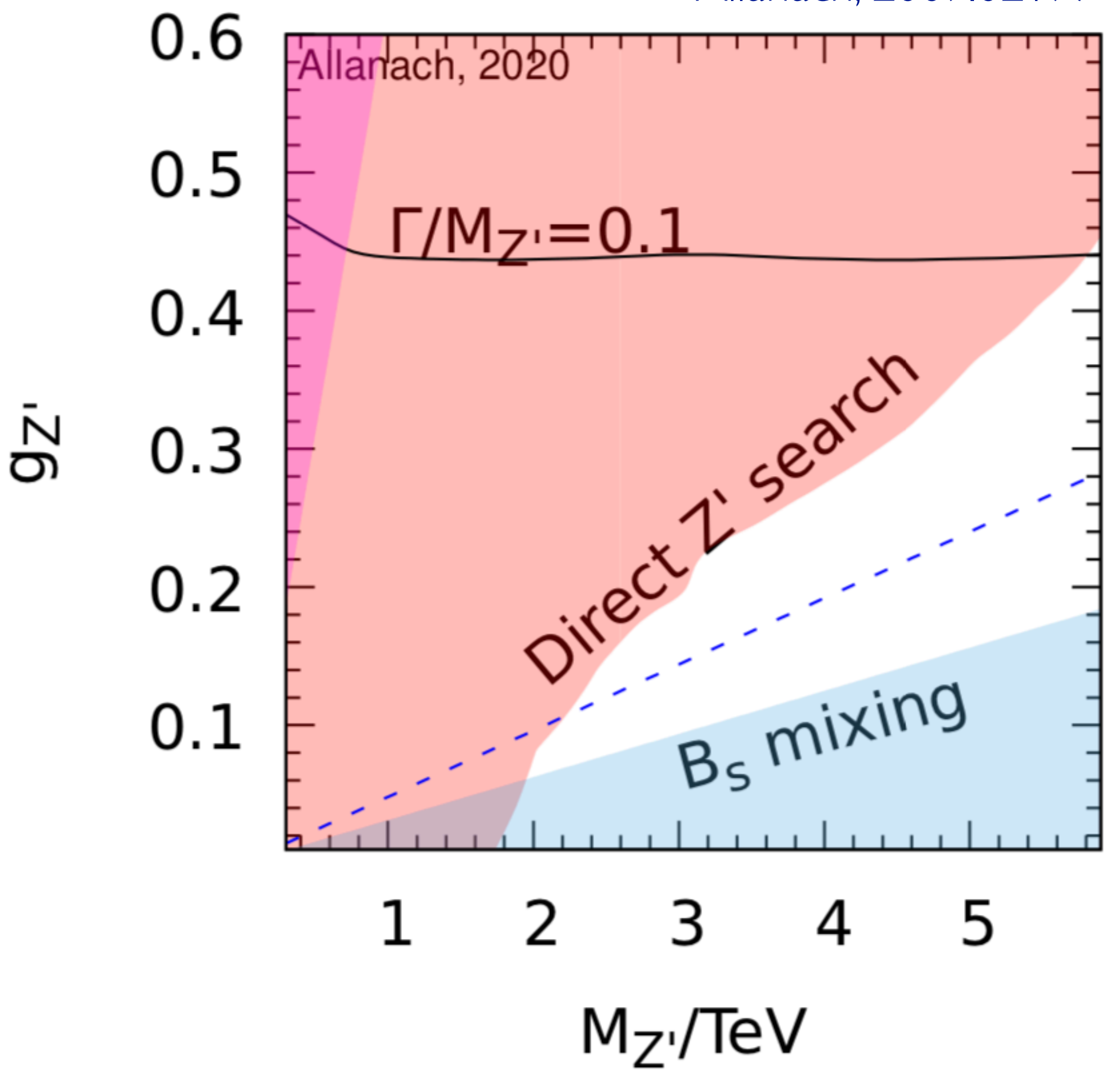
$$g_q = g^* \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & V_{ts} \\ 0 & V_{ts}^* & 1 \end{bmatrix}$$

- For example gauged $U(1)_{B_3-L_\mu}$, etc.

- Production from sea quarks:



Allanach; 2009.02197



Z' models: $L_\mu - L_\tau$

- Constraints:

  1. Neutral meson mixing:

$$\sim \frac{g_{bs}^2}{m_{Z'}^2} \lesssim \frac{\left|\frac{M_{12}}{M_{12}^{\rm SM}} - 1\right| / 10\%}{(244\,{\rm TeV})^2}$$

$$\left|\frac{M_{12}}{M_{12}^{\rm SM}} - 1\right| \approx 10\% \quad \Downarrow \quad \frac{g_{\mu\mu}}{m_{Z'}} \gtrsim \frac{1}{5.3\,{\rm TeV}}$$

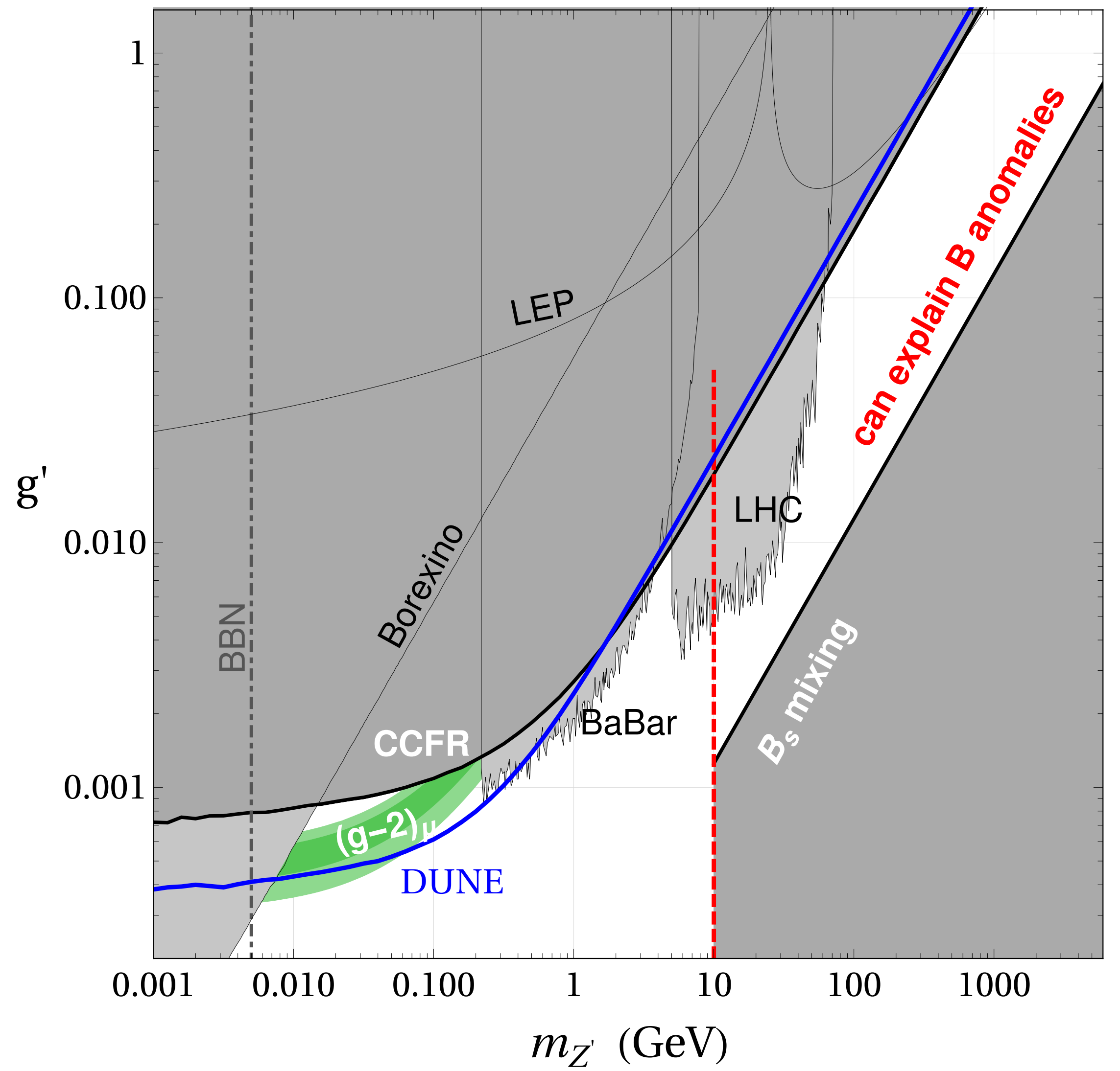
  2. Neutrino trident production $\nu\gamma \to \nu\mu\mu$

$$\frac{g_{\mu\mu}}{m_{Z'}} \lesssim \frac{1}{0.5\,{\rm TeV}}$$

($b \to s\ell\ell$ fit suggests left-handed lepton doublet is involved)

$L_\mu - L_\tau$

Altmannshofer, Gori, Martin-Albo, Sousa, Wallbank 1902.06765



- Simultaneous explanation of $(g-2)_\mu$ not possible

LQ model example

- Scalar LQ

$$\mathscr{L} \supset \eta_{ij}\, Q_L^i L_L^j S_3$$

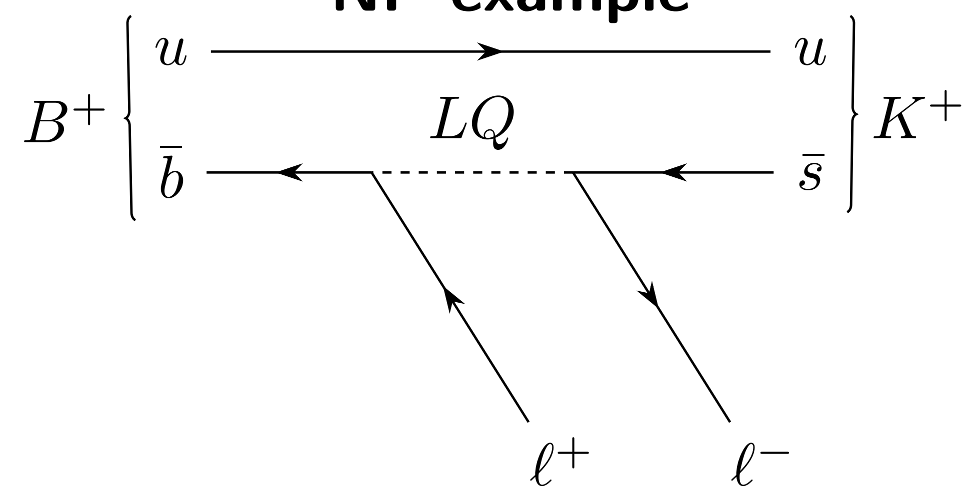
$$\uparrow$$

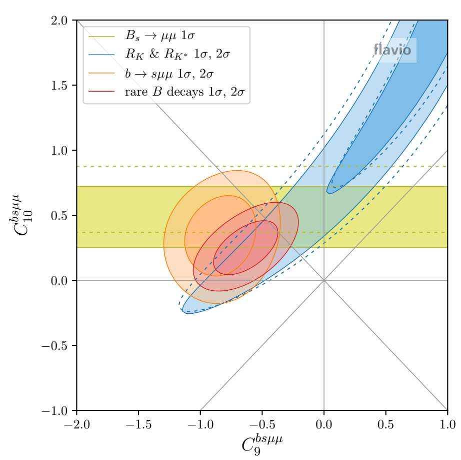
$$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$$

* V-A structure

Hiller, Schmaltz, 1408.1627,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Buttazzo, AG, Isidori, Marzocca; 1706.07808,
Gherardi, Marzocca, Venturini; 2008.09548
+ many more

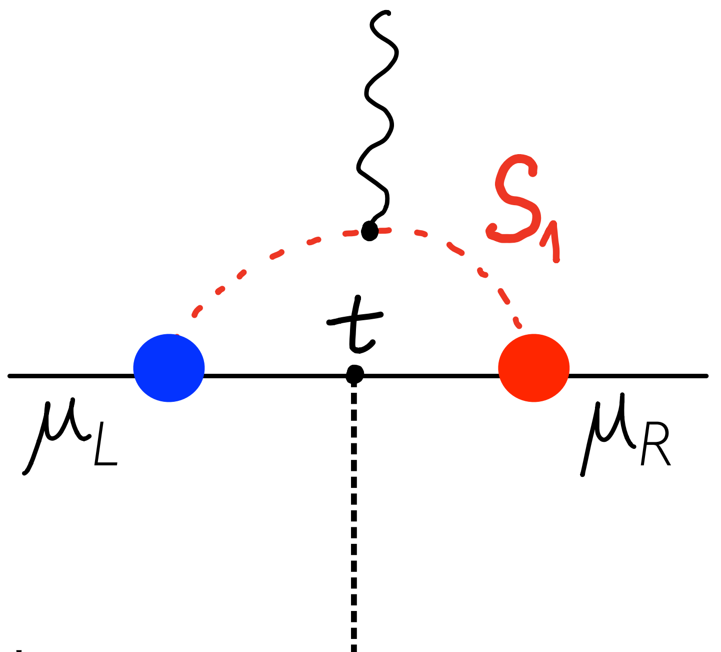
NP example





$$\Longrightarrow \quad \frac{\eta_{b\mu}\eta_{s\mu}}{M_{LQ}^2} \sim \frac{1}{(40\ \text{TeV})^2}$$

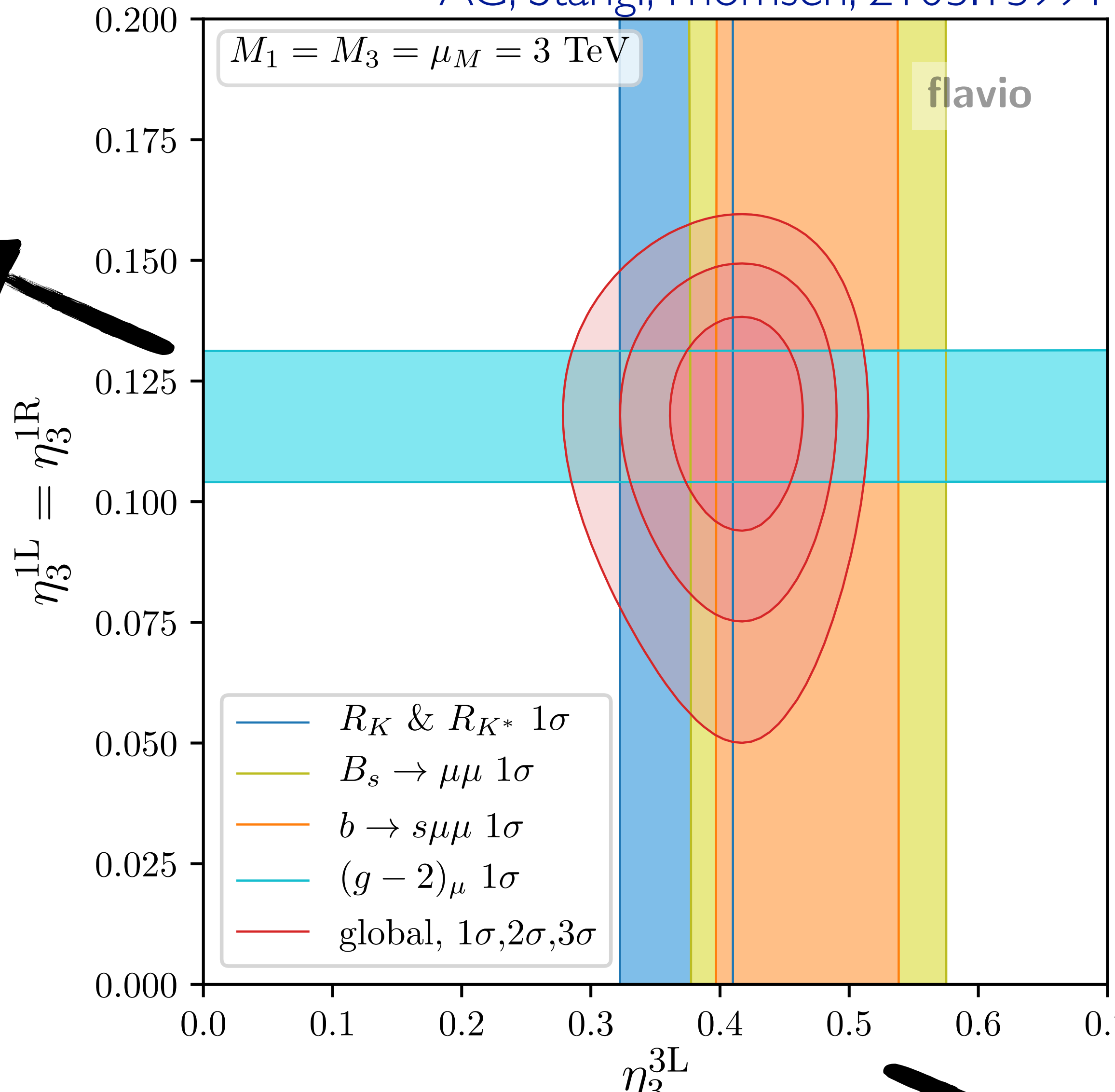
LQ model example



✳ m_t/m_μ enhancement

Queiroz, Shepherd; 1403.2309,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Coluccio Leskow, Crivellin, D'Ambrosio, Müller; 1612.06858
Dorsner, Fajfer, Sumensari; 1910.03877
Gherardi, Marzocca, Venturini; 2008.09548
+ many more

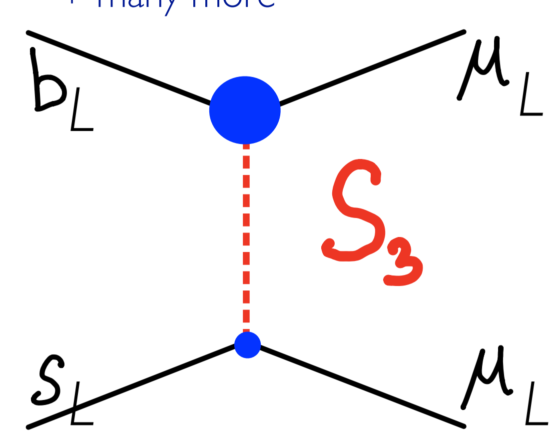
AG, Stangl, Thomsen, 2103.13991



$$\eta_i^{3L} = (V_{td},\, V_{ts},\, 1)\, \eta_3^{3L}$$

✳ V-A structure

Hiller, Schmaltz, 1408.1627,
Dorsner, Fajfer, AG, Kamenik, Kosnik; 1603.04993,
Buttazzo, AG, Isidori, Marzocca; 1706.07808,
Gherardi, Marzocca, Venturini; 2008.09548
+ many more



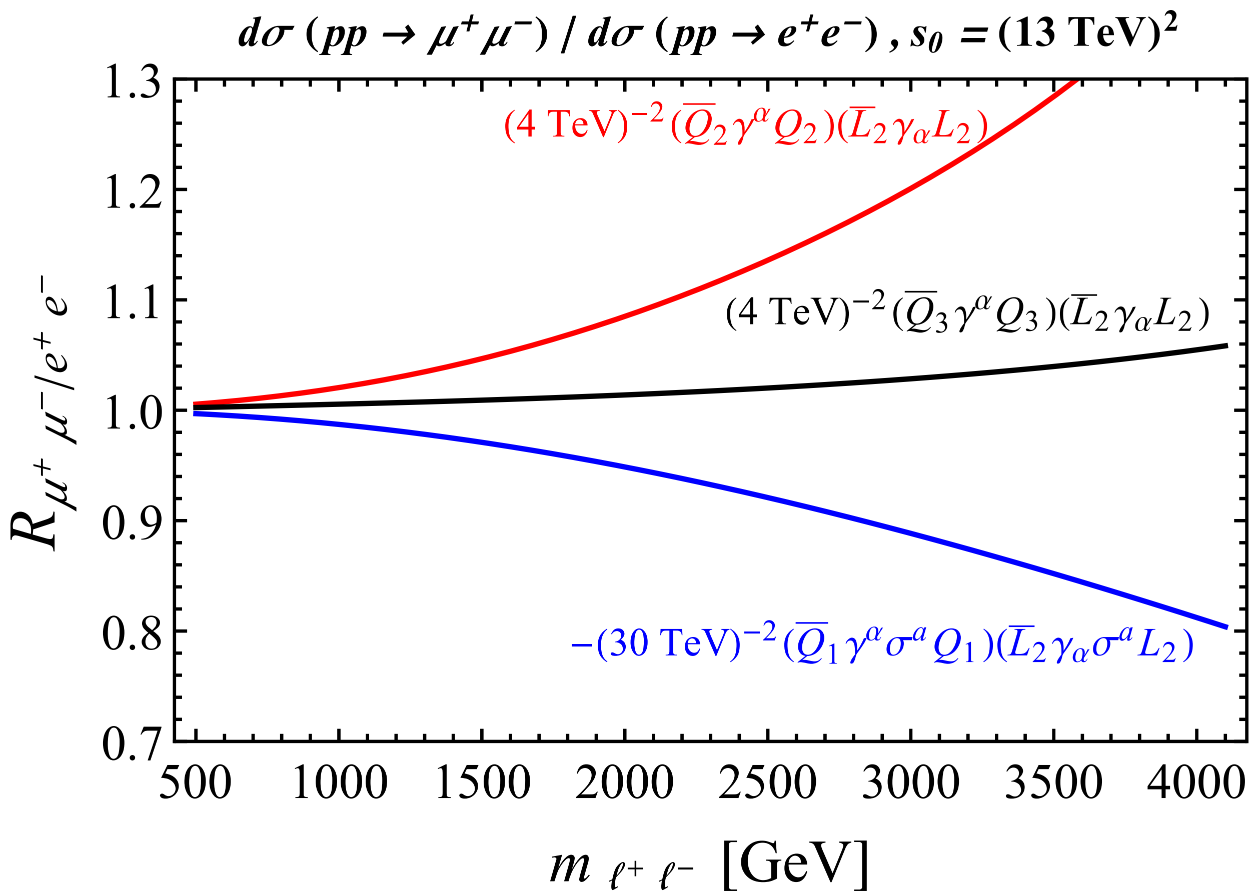
- One-loop matching to SMEFT from 2003.12525
- 399 observables in **smelli** 1810.07698
- EW and flavor opservables, LFV, LFU, magnetic moments, neutral meson mixing, semileptonic and rare B, D, K decays, etc.

LFU tests at High-p_T

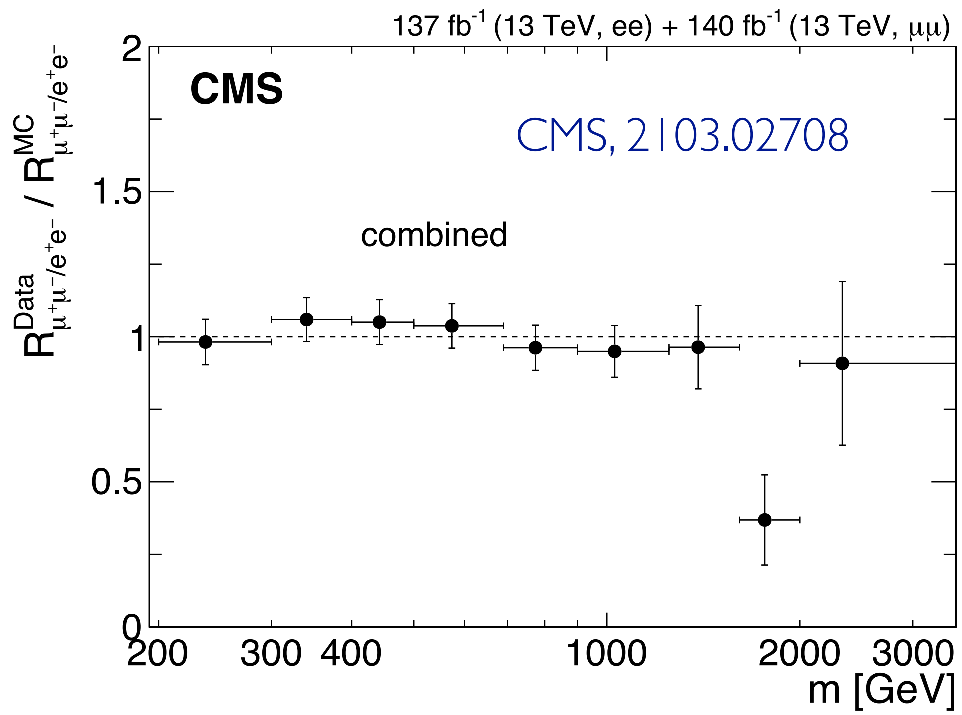
- Smooth distortions expected

[AG, Marzocca]
Eur.Phys.J. C77 (2017) no.8, 548

$$R_{\mu^+\mu^-/e^+e^-} = \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)/dm_{\ell\ell}}{d\sigma(q\bar{q} \to e^+e^-)/dm_{\ell\ell}}$$



- Recent CMS measurement of $R_{\mu/e}$



Cross section enhancements

- Partonic level cross section (charged currents example)

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

- 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.

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?

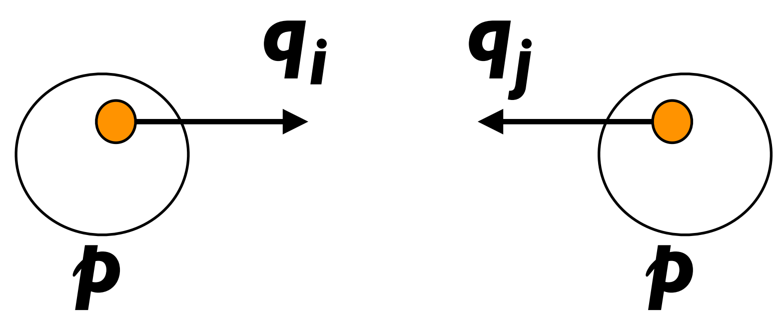
- The uncertainty on the signal prediction from NLO QCD and PDF replicas estimated to be ~ 10 % on the rate in the most sensitive bin. Electroweak corrections at the similar level. $\Delta\epsilon_X/\epsilon_X \approx 0.5\,\Delta\sigma/\sigma$

How well do we know PDFs?

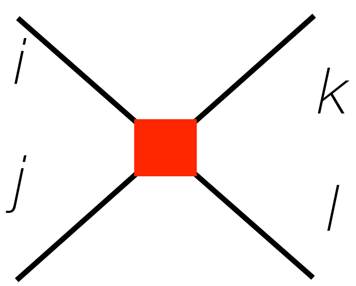
- The PDF determination assumes the SM. The impact of the Drell-Yan data in the global PDF fit is small at the moment. The issue is there in the future.

AG et al, 2104.02723

Previous studies

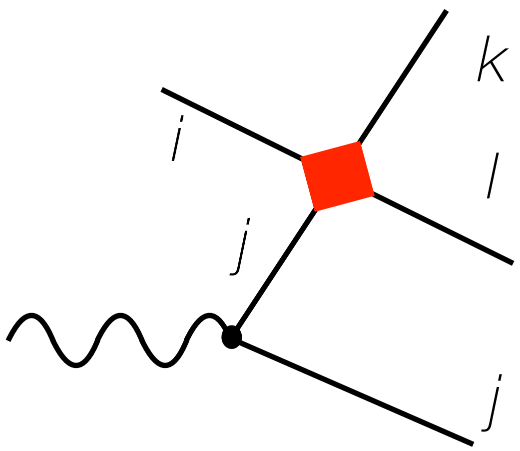


- Plethora of topologies:



2 > 2

Drell-Yan versus eg. *B-physics*, *D-physics*, *LFU*, *LFV*, …
1609.07138, 1704.09015, 1811.07920, 1809.01161, 2002.05684, 2003.12421, …



2 > 3

eg. 1704.06659, 2005.06457, 2008.07541 …

- Many improvements; soft b-jet, angular kinematics, etc.

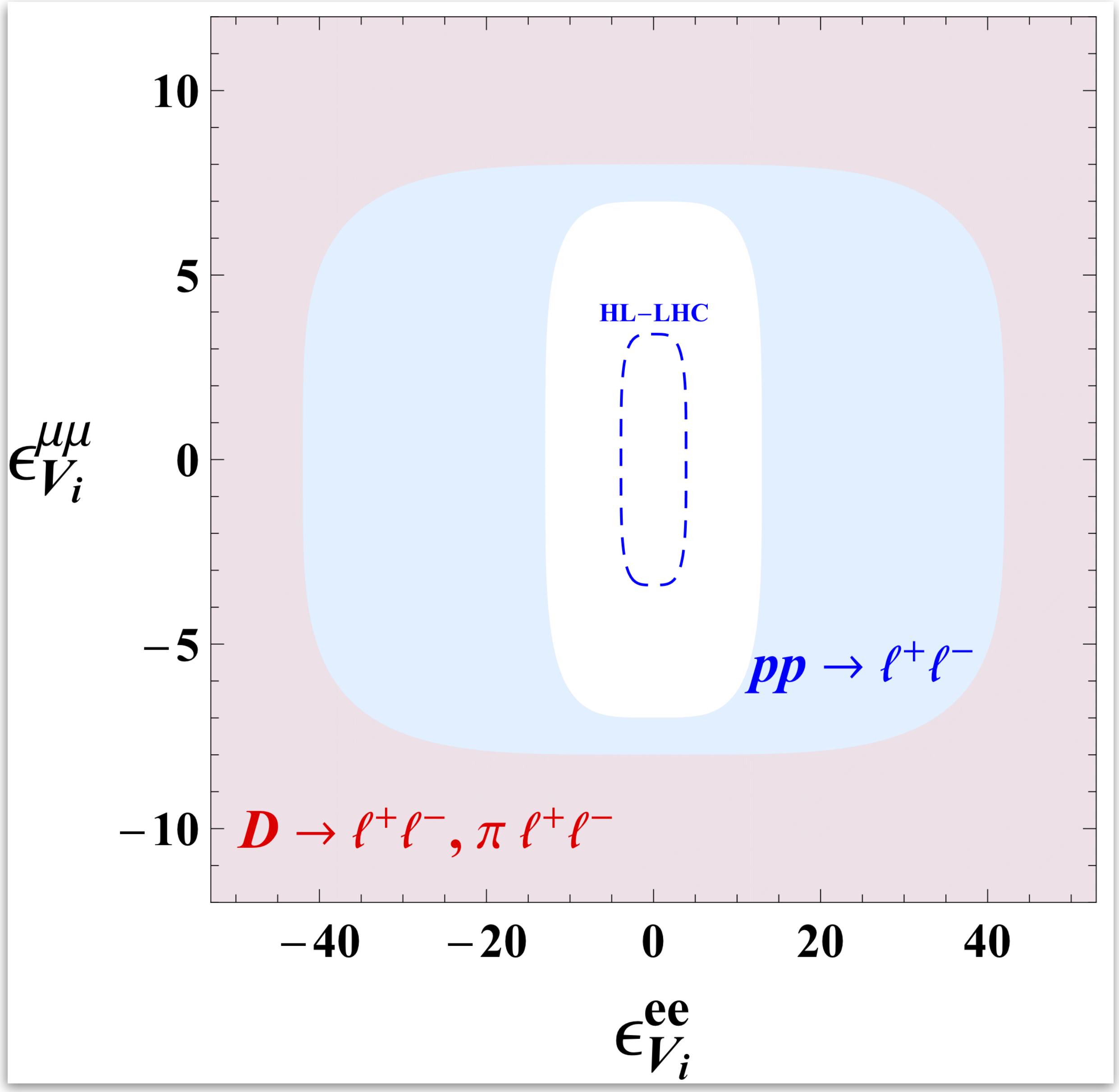
It is a vivid field of research…

Rare charm FCNC

Example

- Tiny SM decay rates:
  short-distance contribution negligible, efficient GIM suppression, long-distance dominated
  $BR(D^0 \to \mu^+\mu^-) \sim \mathcal{O}(10^{-13})$
- Already strong experimental upper limits
  $BR(D^0 \to \mu^+\mu^-) \lesssim 6 \times 10^{-9}$ LHCb
- Practically null test of the SM sensitive to New Physics eg. 1909.11108

[Fuentes-Martin, AG, Martin-Camalich, Ruiz-Alvarez]
JHEP 11 (2020) 080

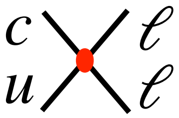


- Take NP solely affecting charm

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

- Calculate

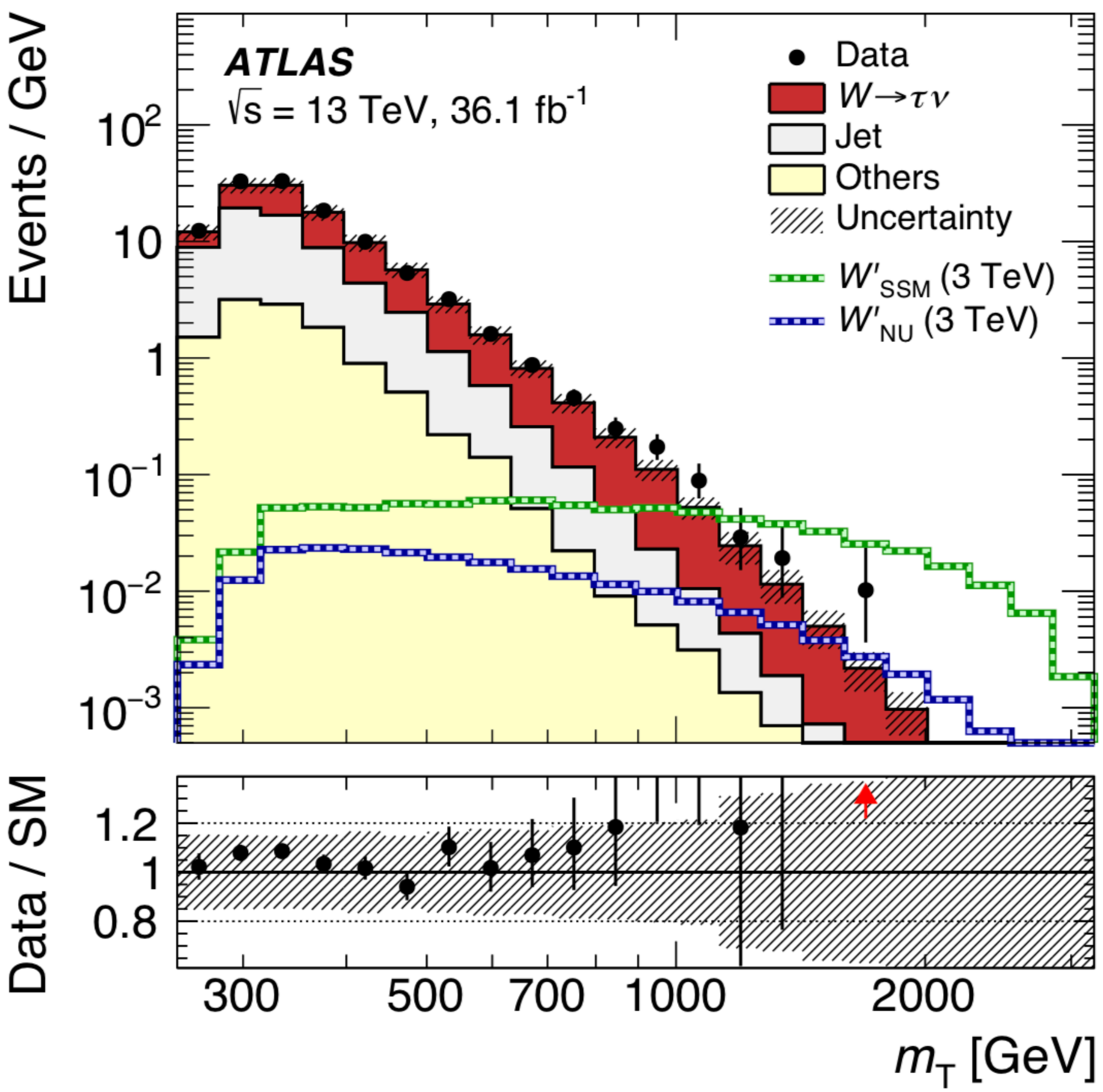
c u > l+ l- Drell-Yan

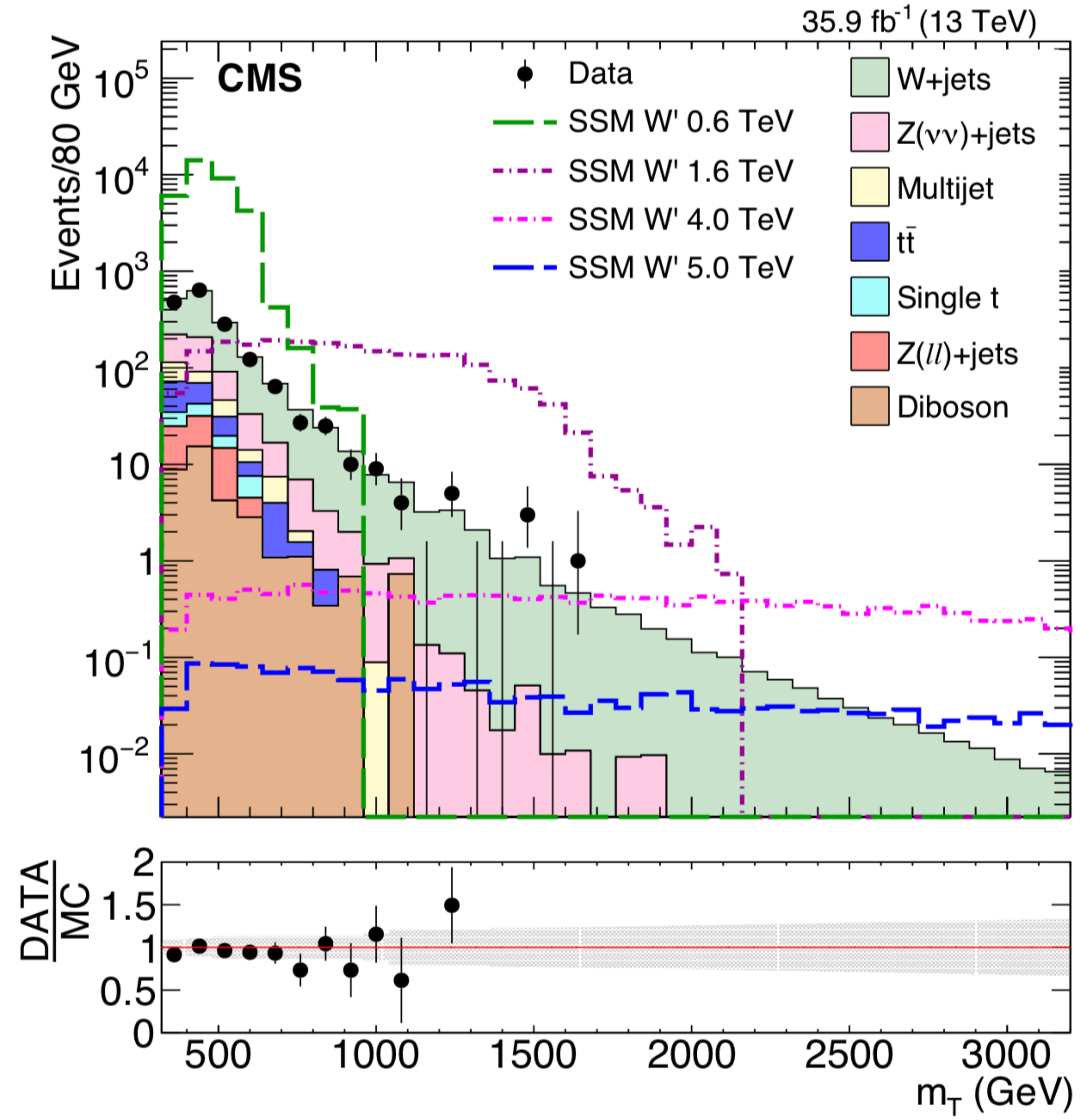


(*) c u > tau+ tau- uniquely probed at high-p_T

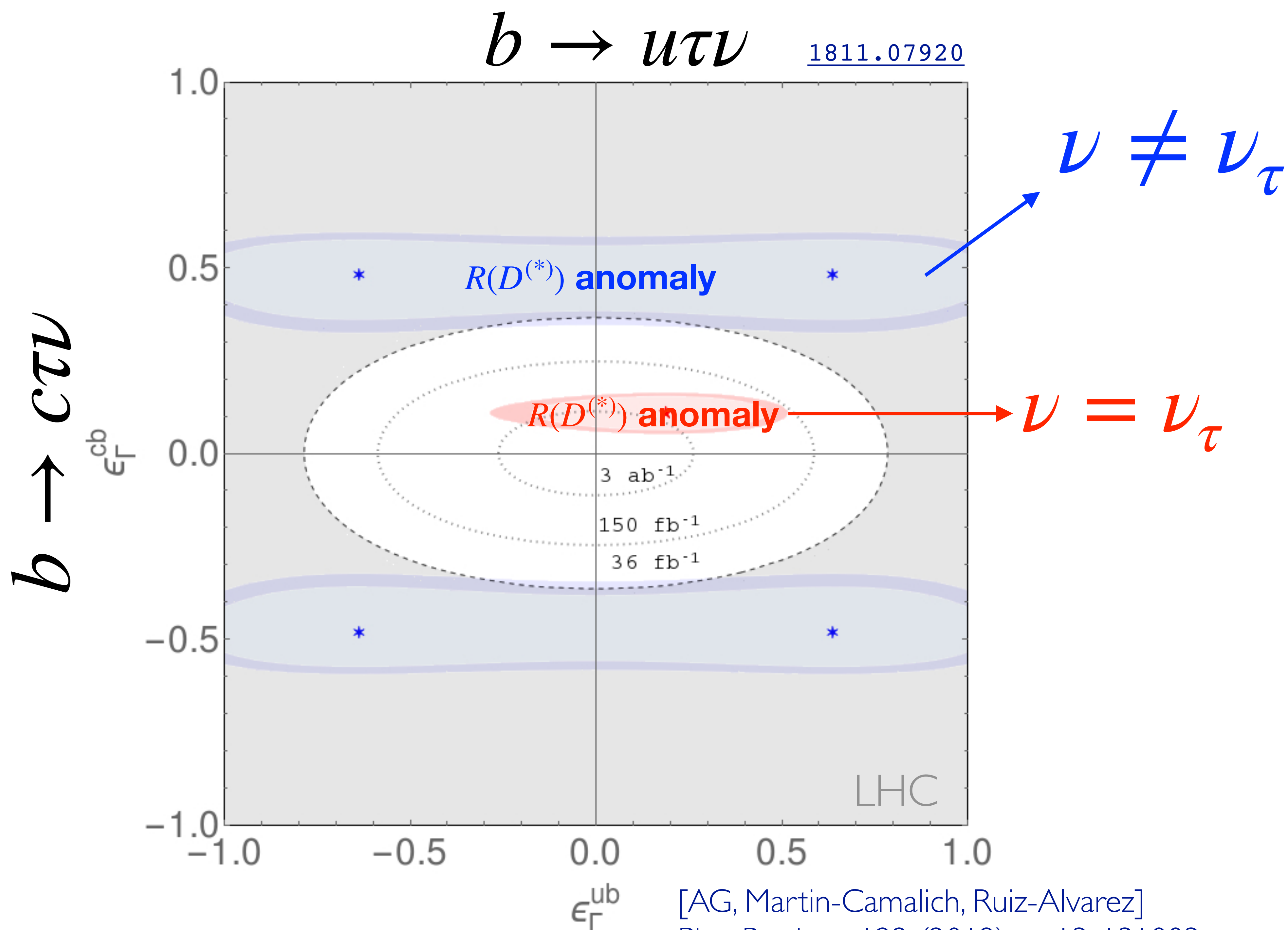
Recast of the existing searches

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

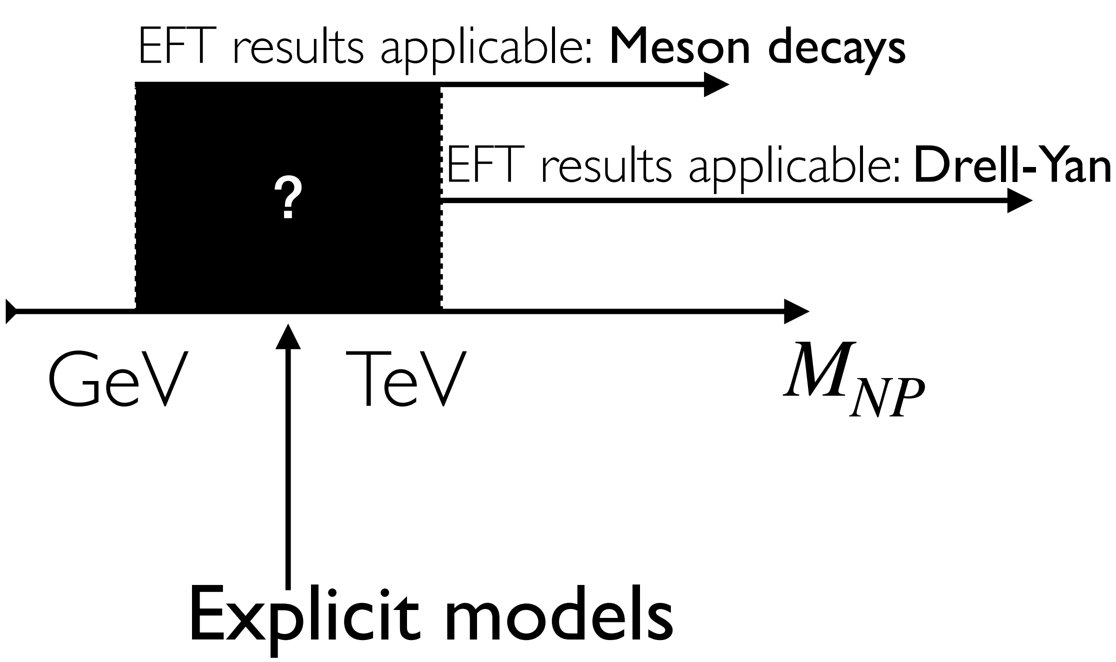


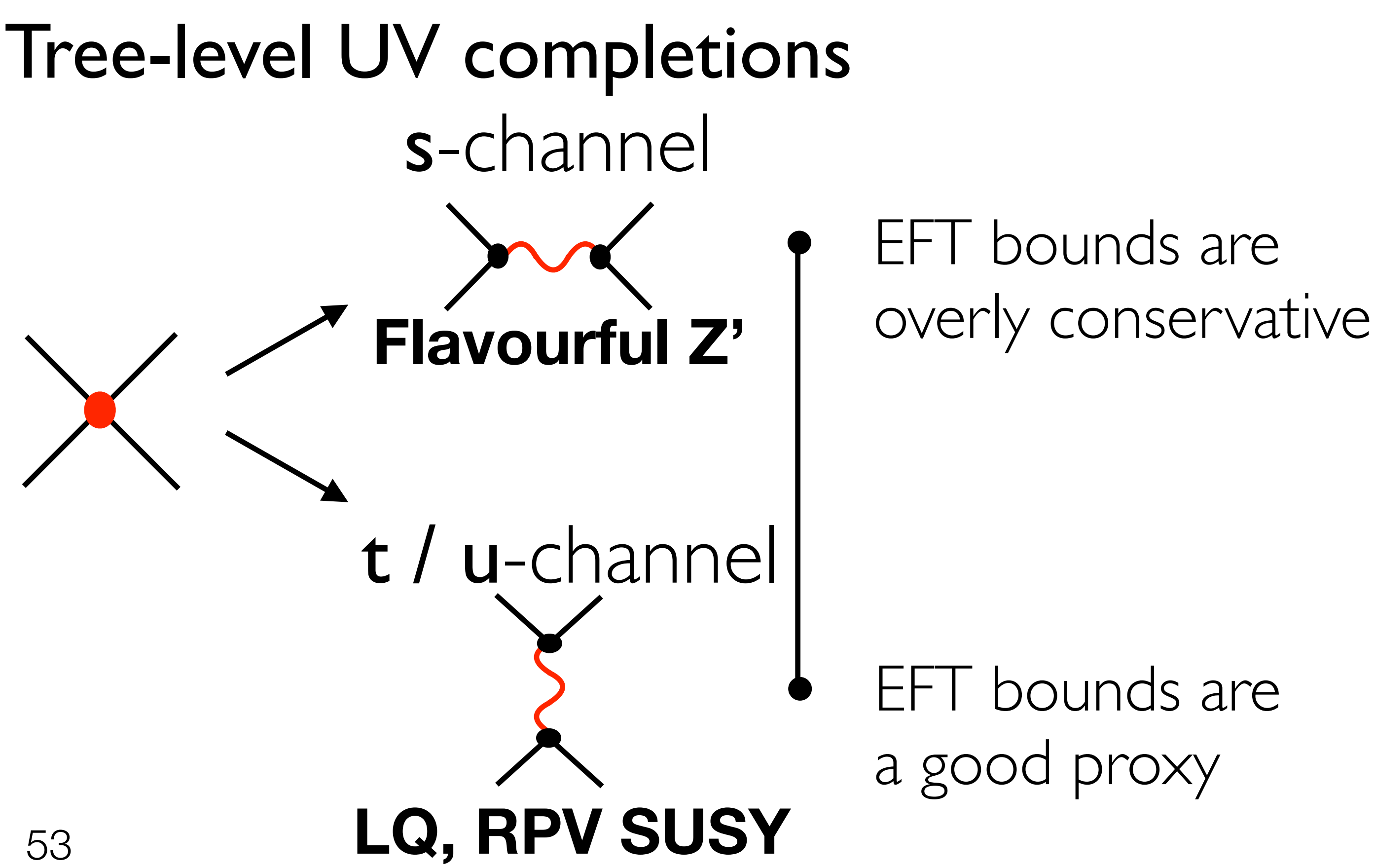
[AG, Martin-Camalich, Ruiz-Alvarez]
Phys.Rev.Lett. 122 (2019) no.13, 131803

Updated by JMC for Portoroz 2019

EFT validity

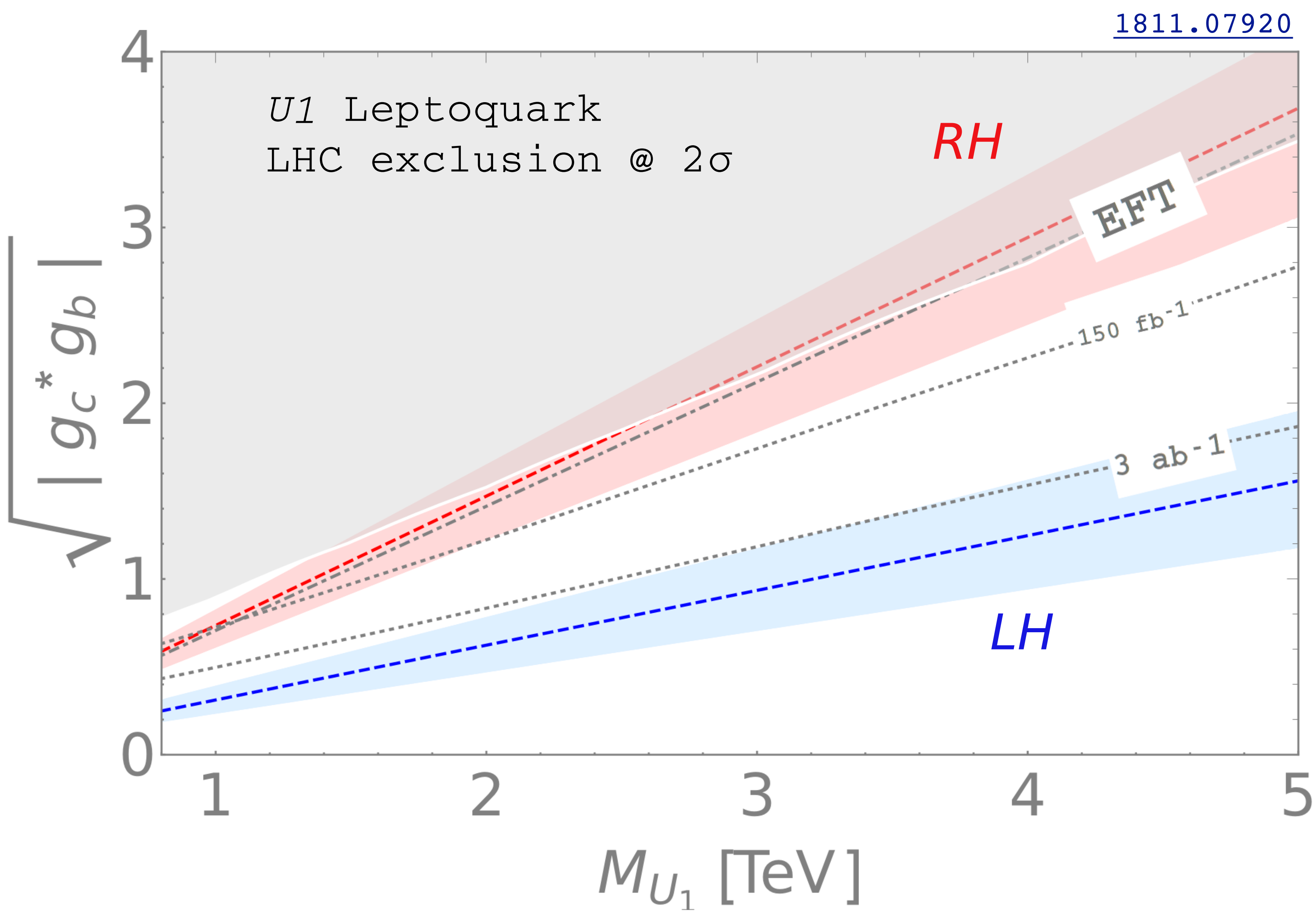
- This EFT exercise is useful even if the EFT validity is not guaranteed.
- If, in the EFT, the high-p_T provides stronger limits, better carefully check the collider pheno of the model.





EFT validity

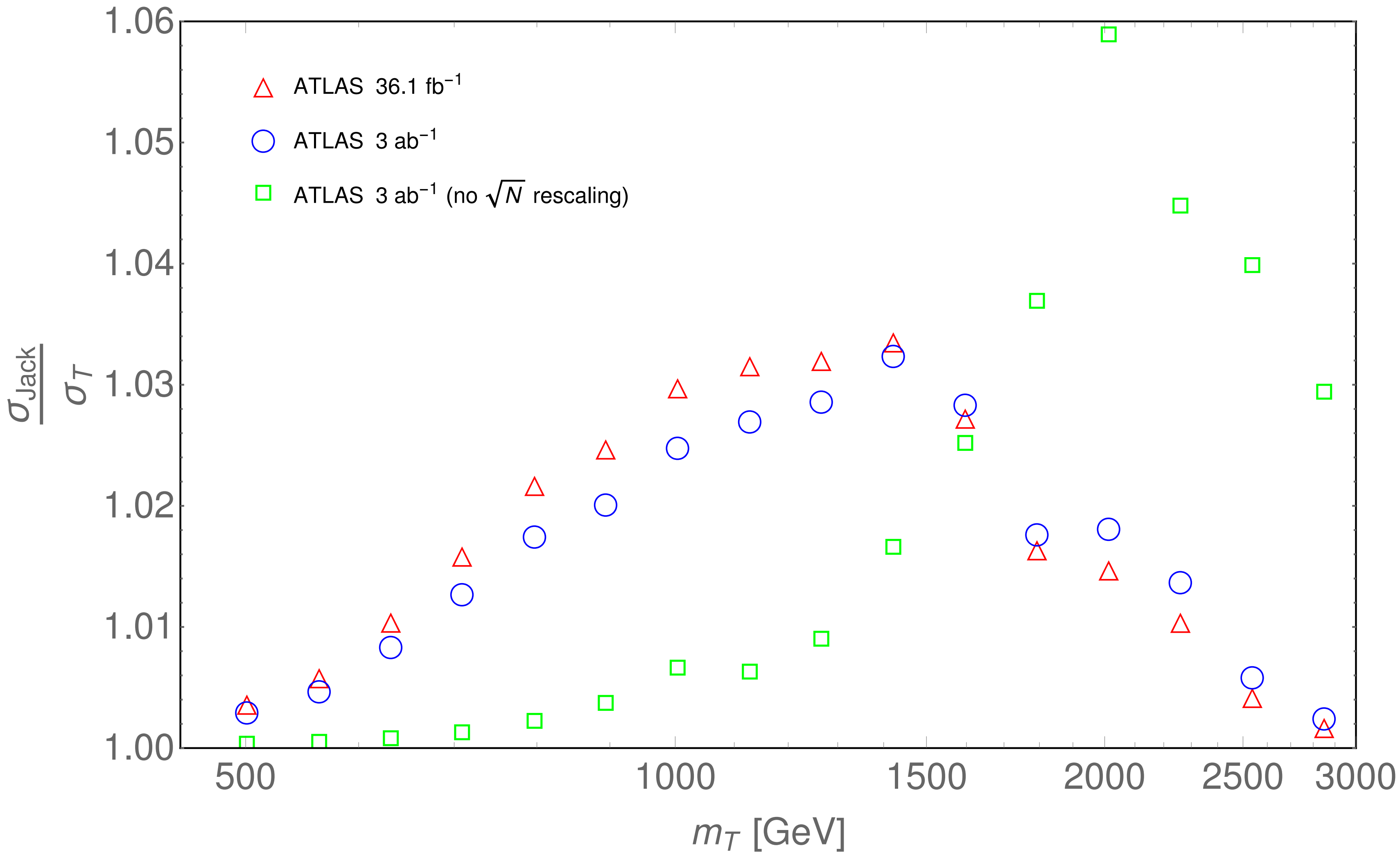
- Explicit model example



EFT validity

- The most sensitive bin analysis

1811.07920



Back-of-the-envelope

- Five quark flavors accessible in the incoming proton PDFs

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

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

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

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

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

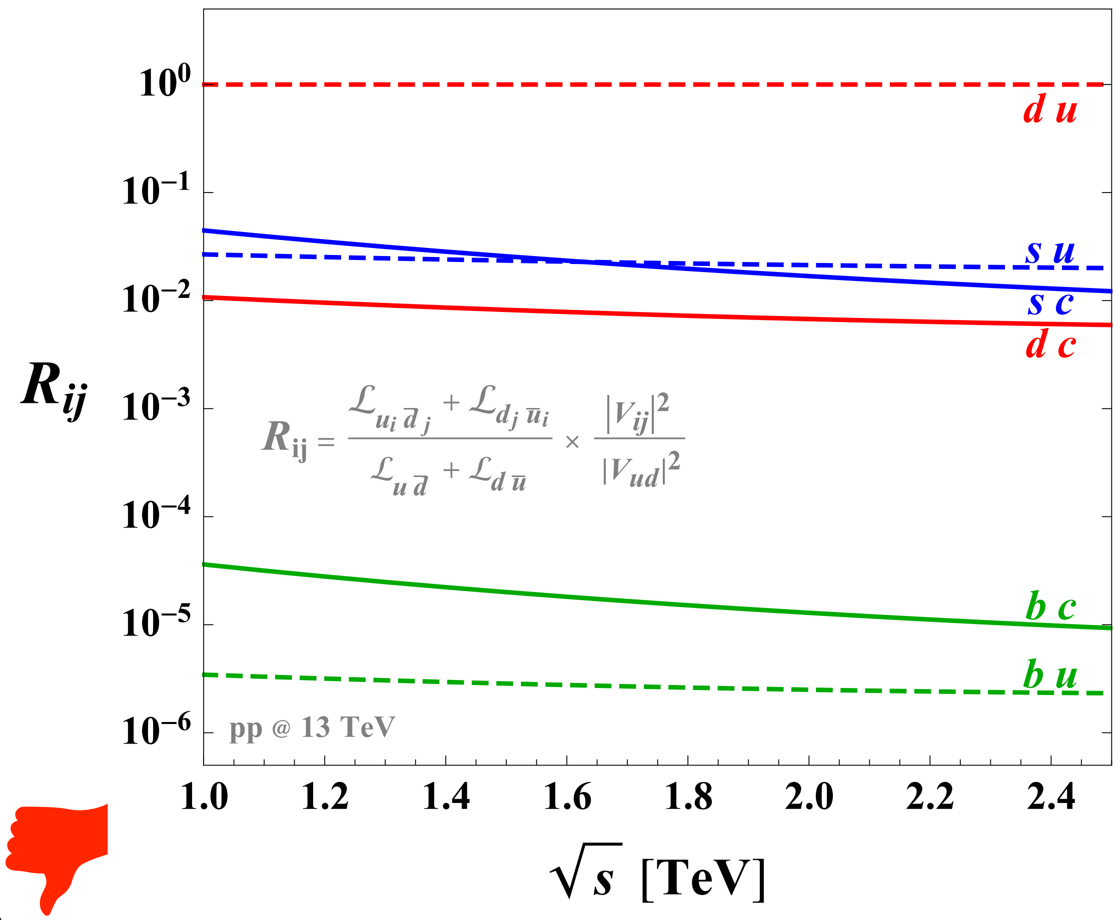
e.g. $\rightarrow$ $\epsilon_L^{cs} \lesssim \mathcal{O}(0.01)$

Energy enhancement

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

PDF and CKM suppression

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



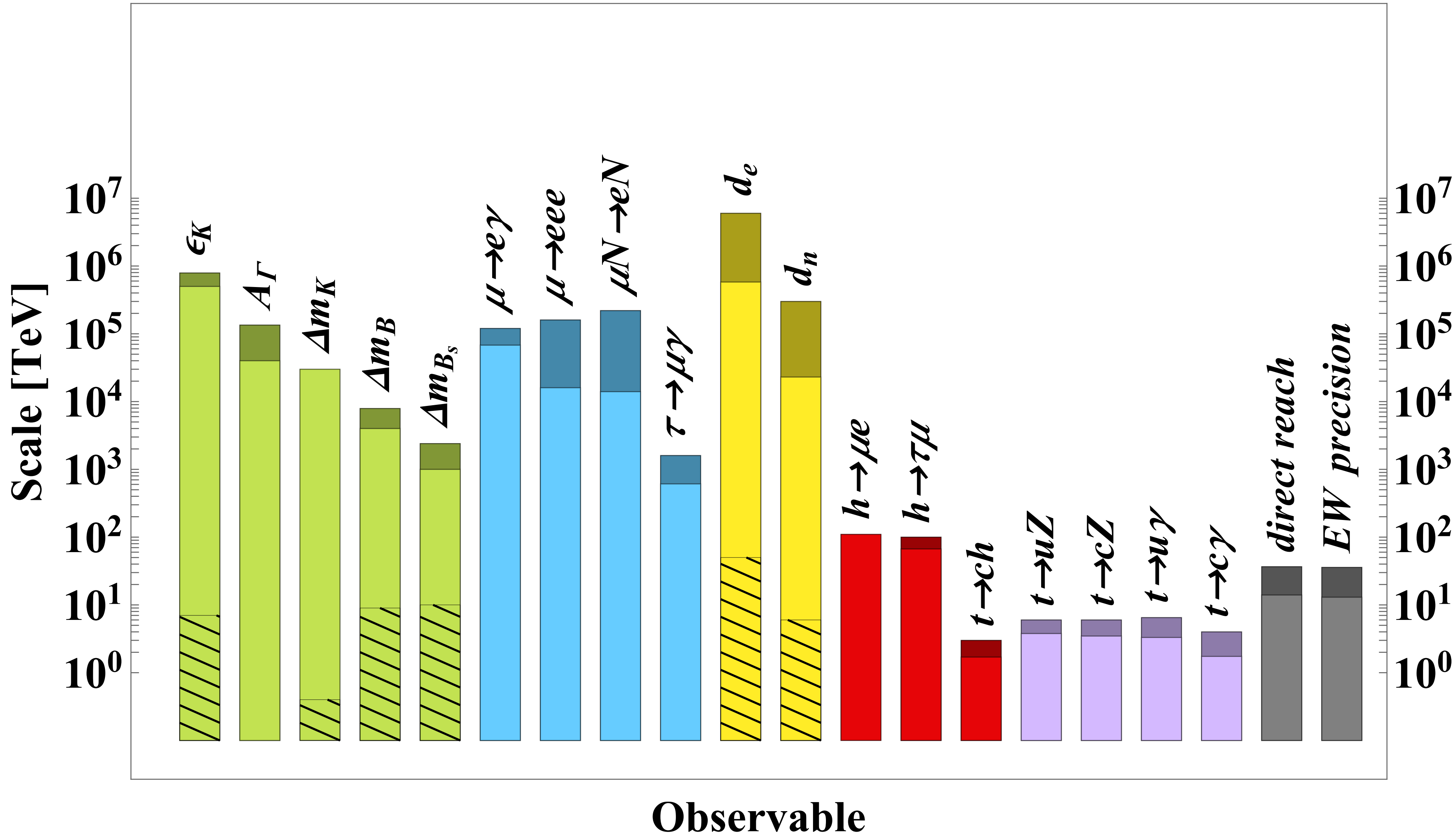


Fig. 5.1: Reach in new physics scale of present and future facilities, from generic dimension six operators. Colour coding of observables is: green for mesons, blue for leptons, yellow for EDMs, red for Higgs flavoured couplings and purple for the top quark. The grey columns illustrate the reach of direct flavour-blind searches and EW precision measurements. The operator coefficients are taken to be either ~ 1 (plain coloured columns) or suppressed by MFV factors (hatch filled surfaces). Light (dark) colours correspond to present data (mid-term prospects, including HL-LHC, Belle II, MEG II, Mu3e, Mu2e, COMET, ACME, PIK and SNS).