Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

SFB 1258 Neutrinos Dark Matter Messengers

Technische Universität München

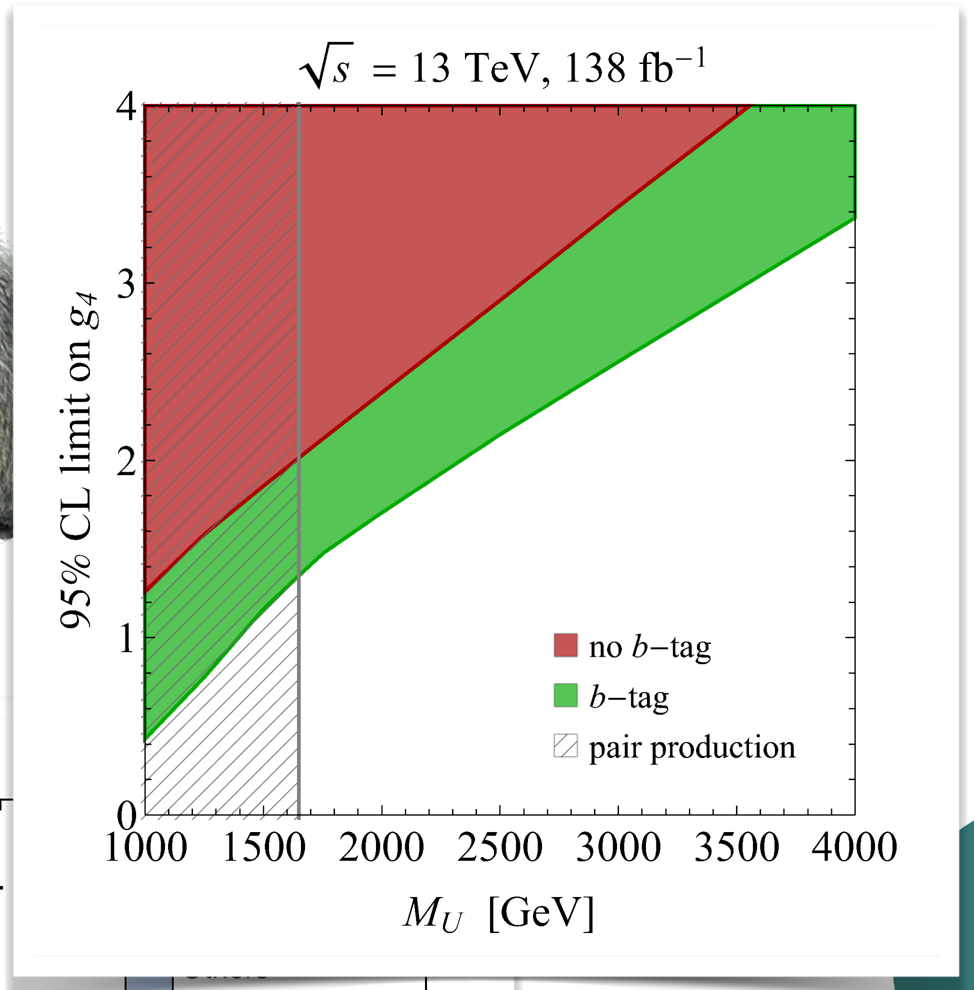
Drell-Yan production in third-generation gauge **vector leptoquark** models at **NLO+PS** in QCD

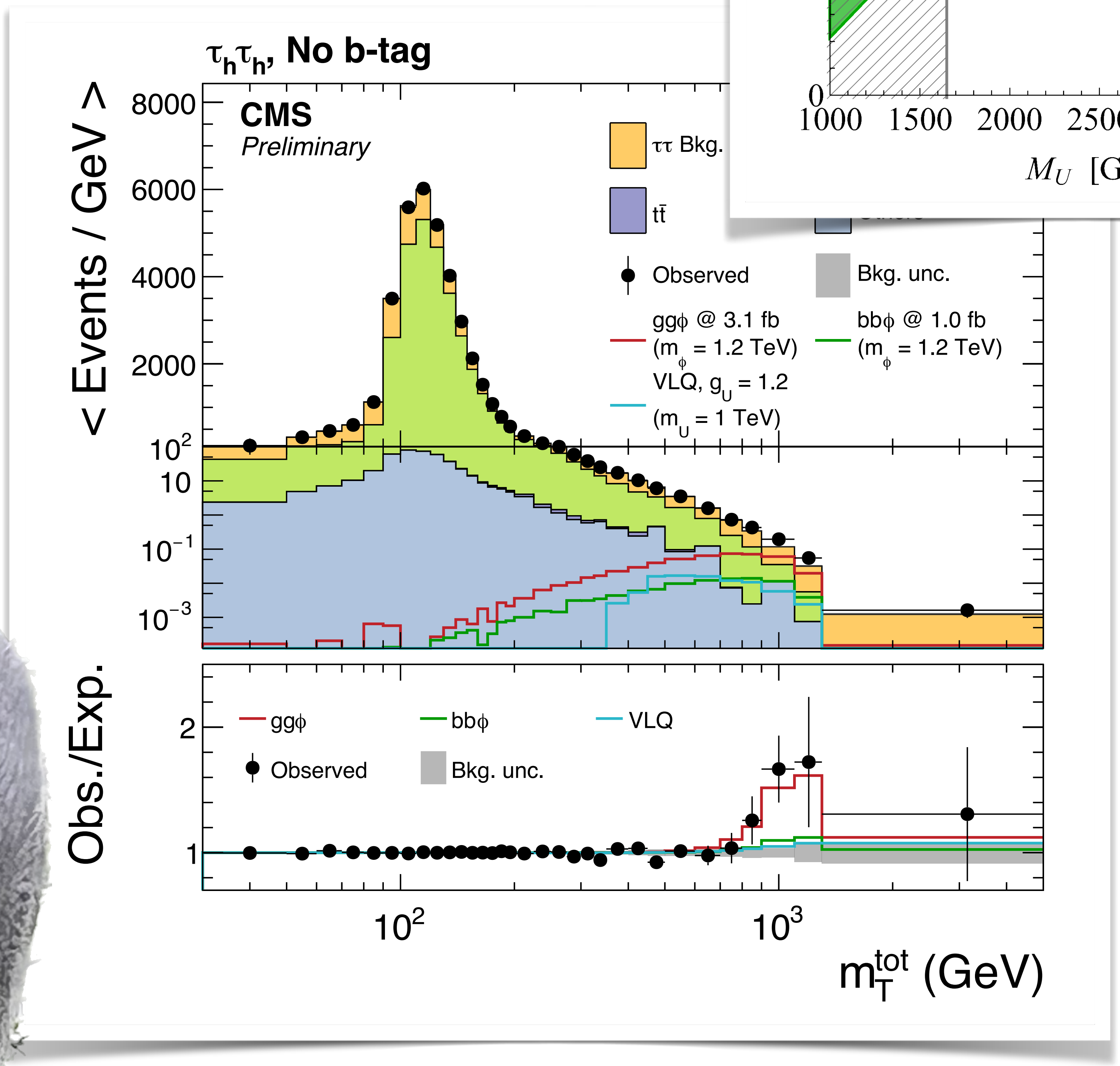
Luc Schnell

Kruger 2022: Discovery Physics at the LHC

December 7, 2022

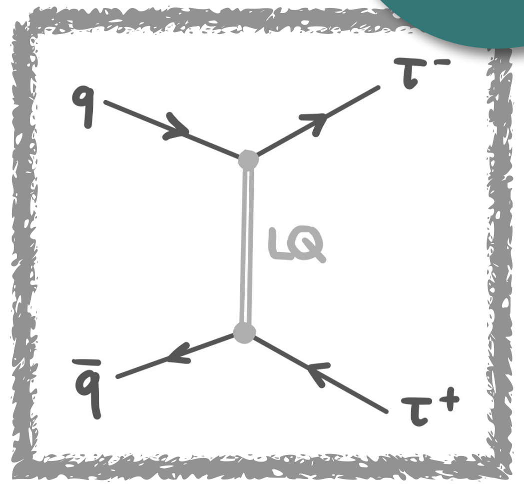
CMS 2021





Source: HIG-21-001-PAS (CMS)

U_1



1. Introduction

1.1 Low-energy anomalies

1.2 UV-complete models

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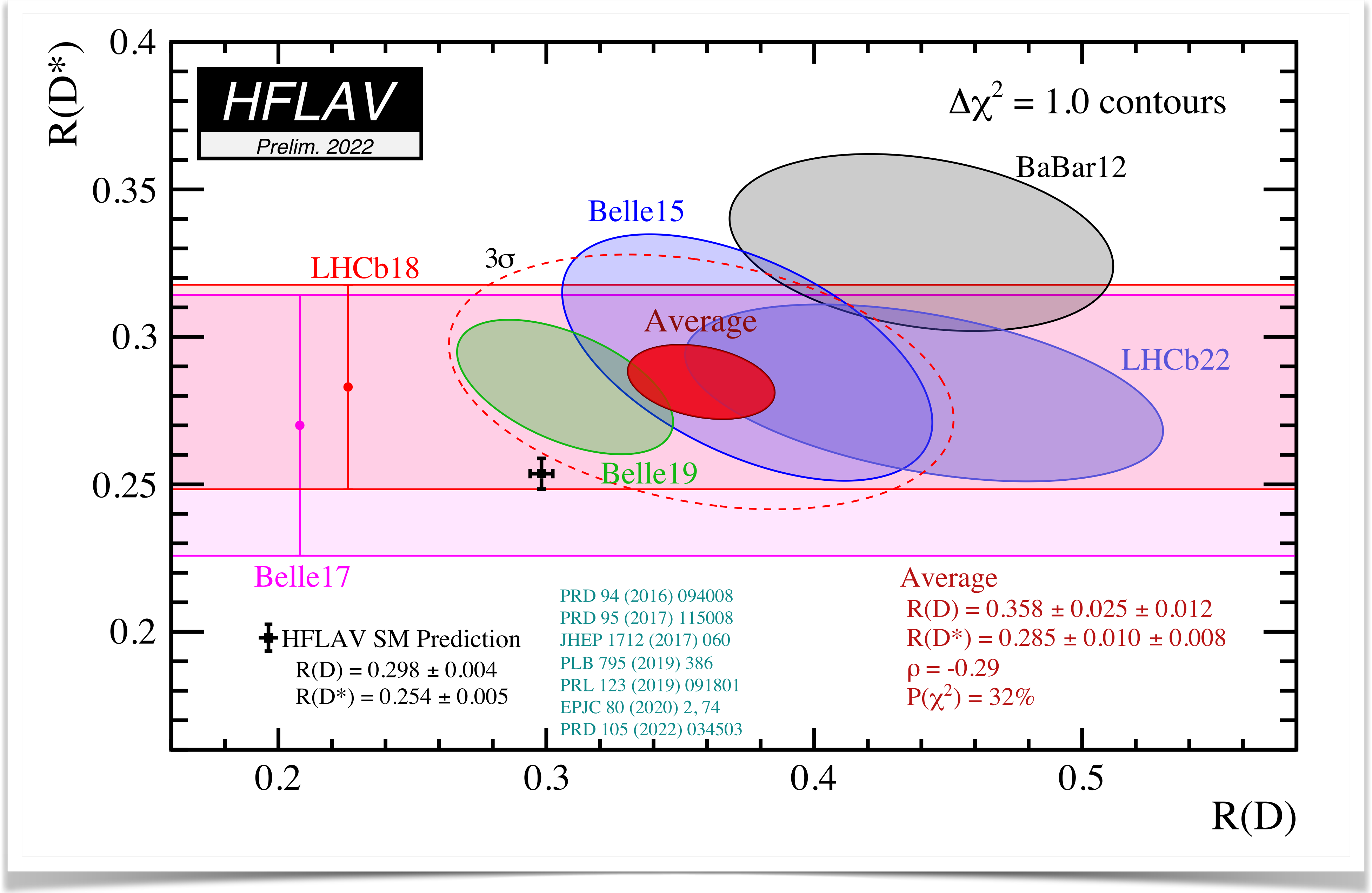

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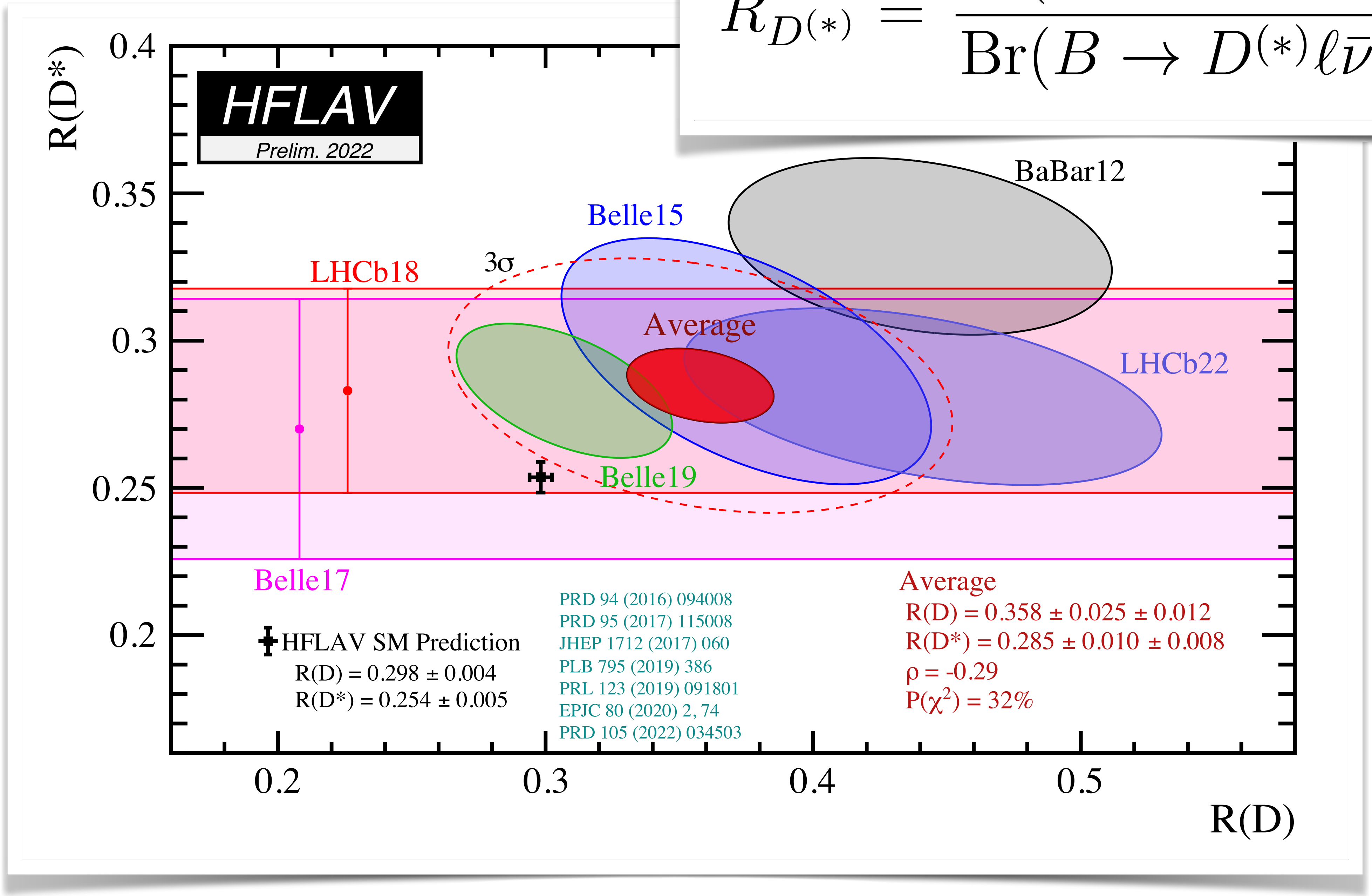

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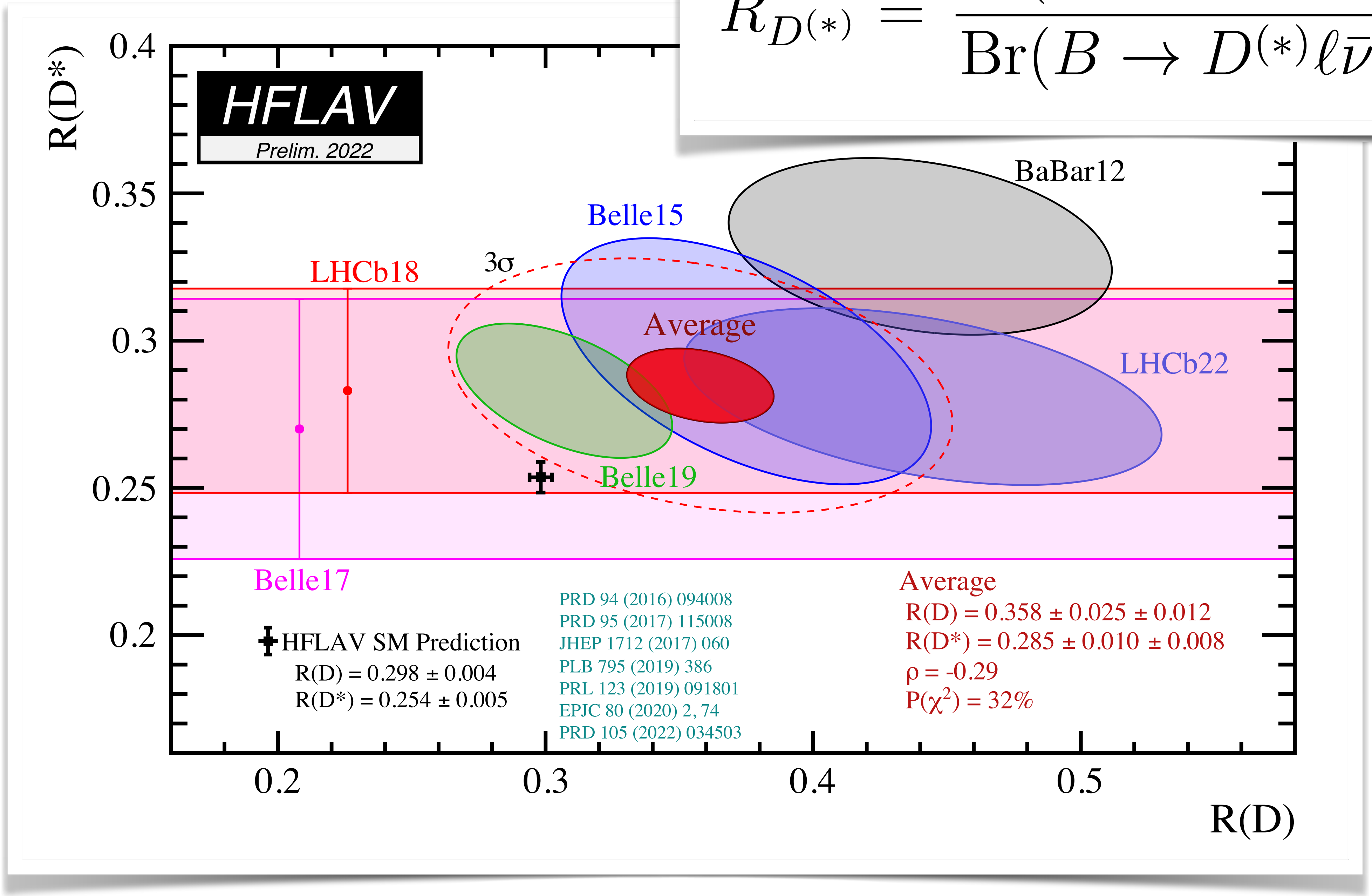

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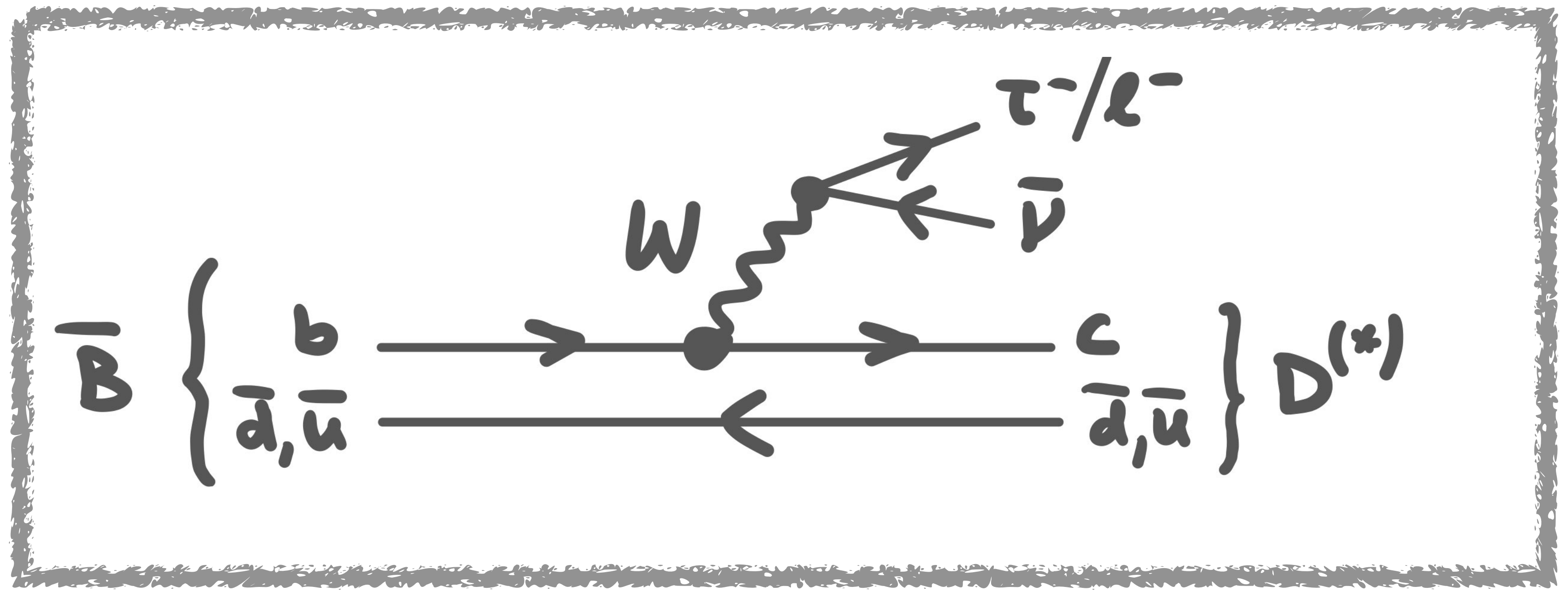

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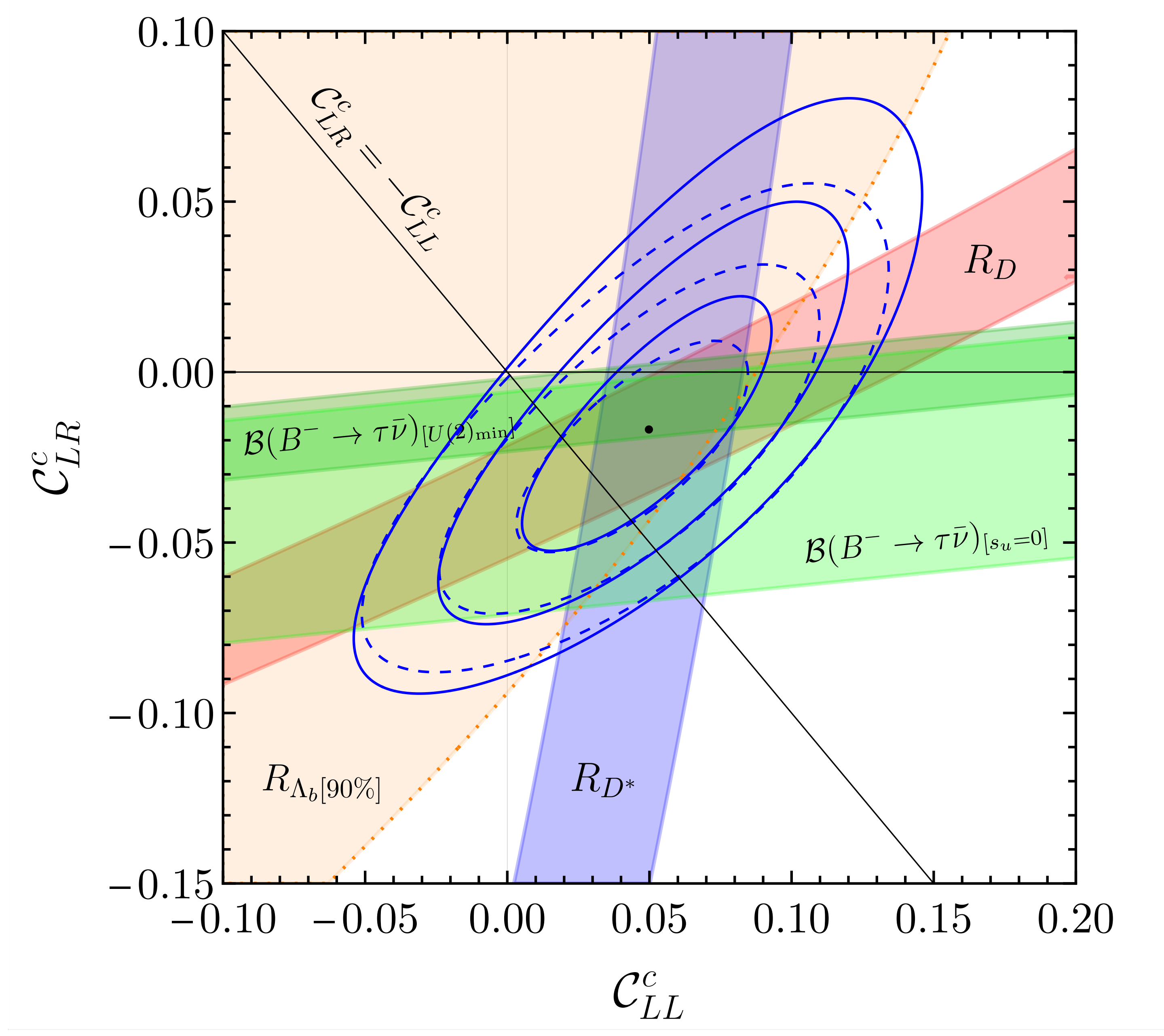

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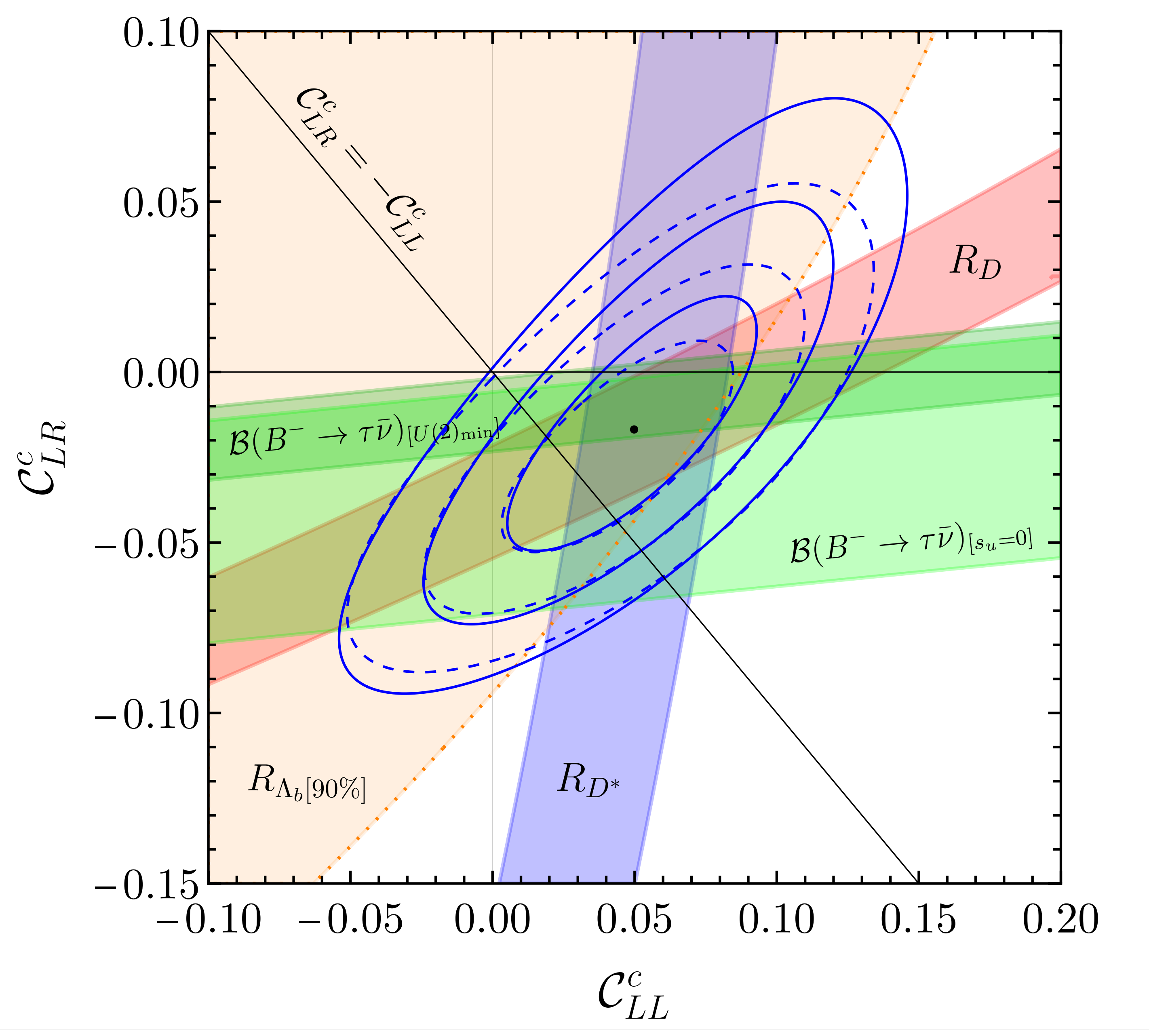

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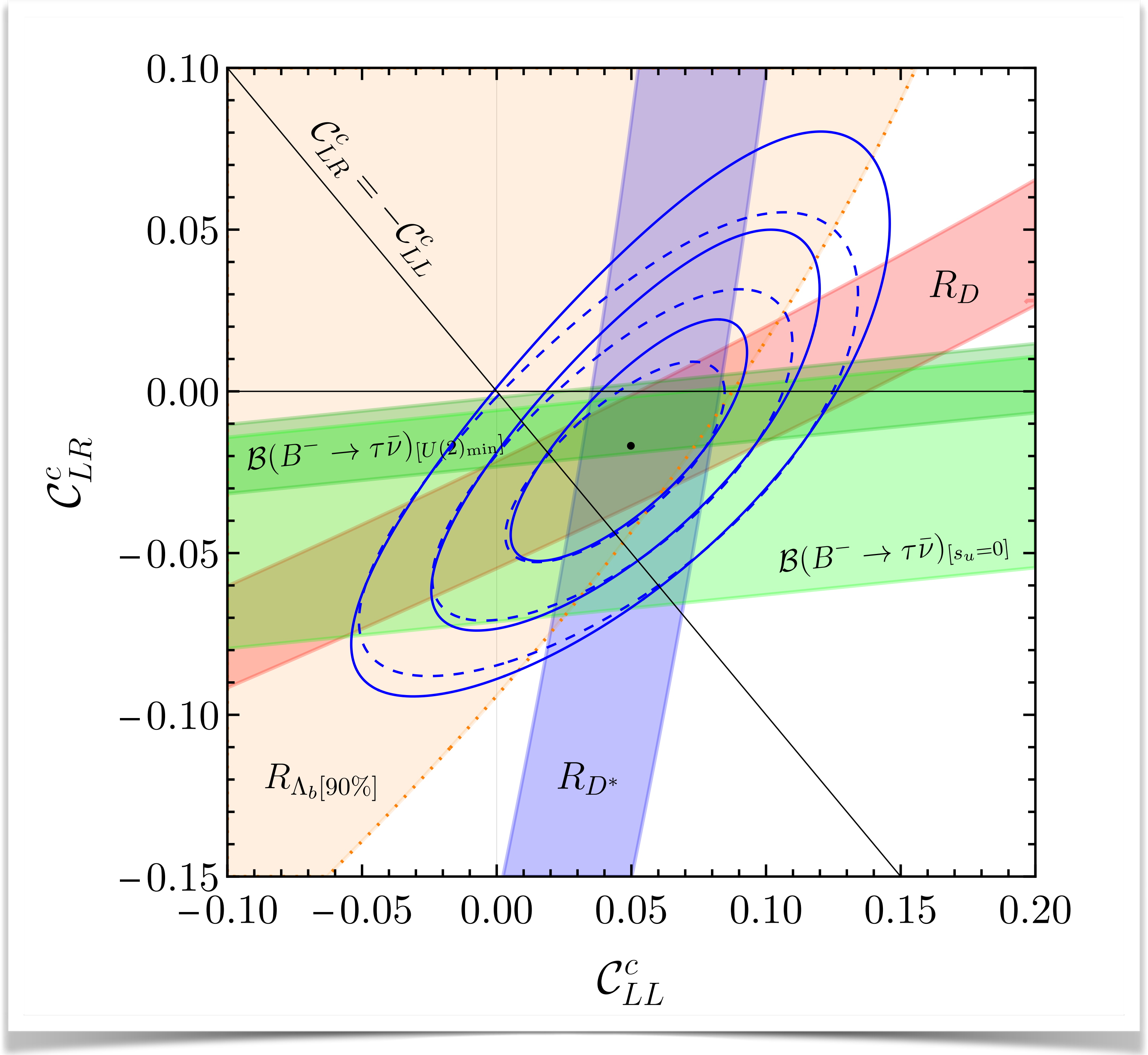

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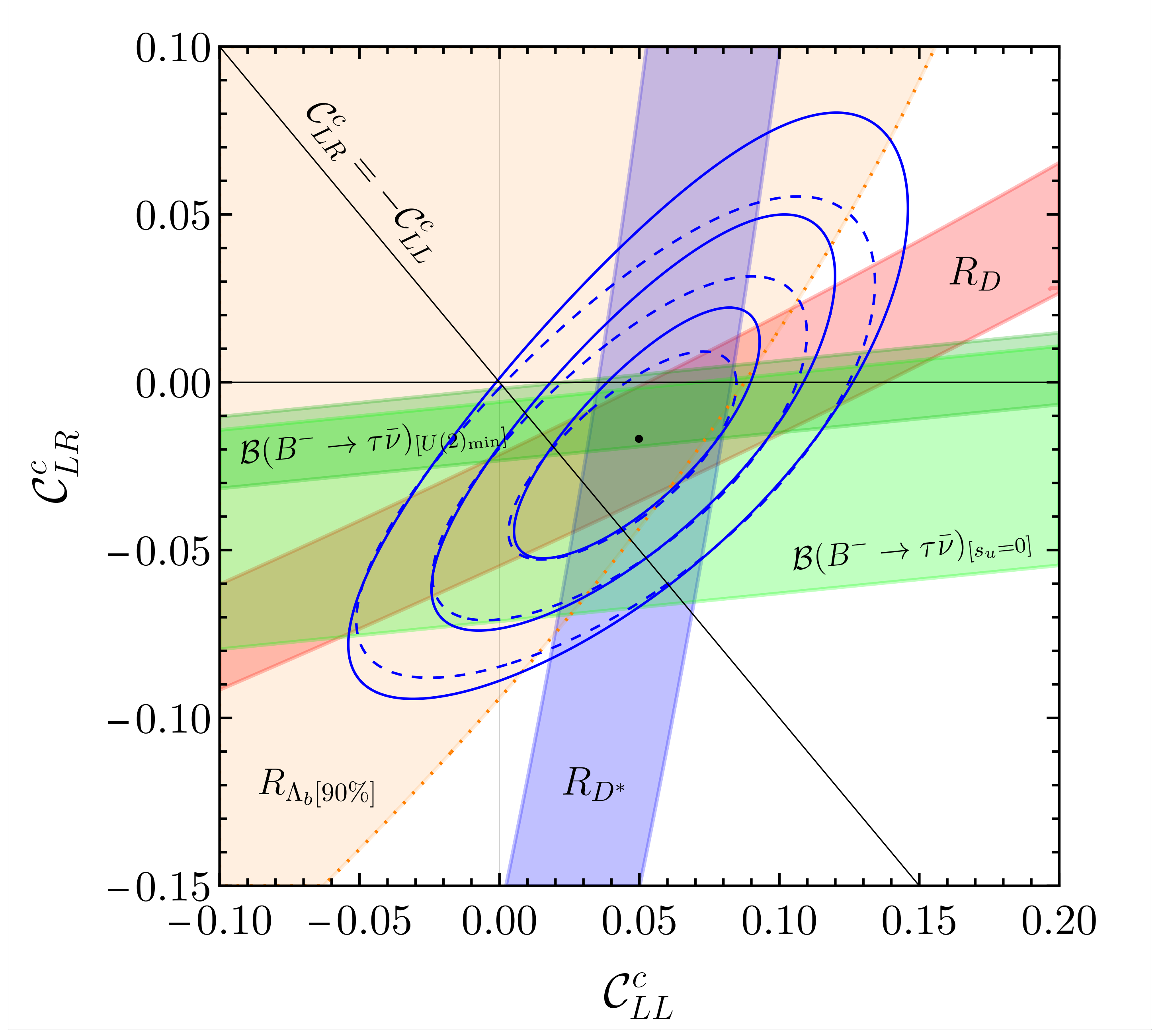

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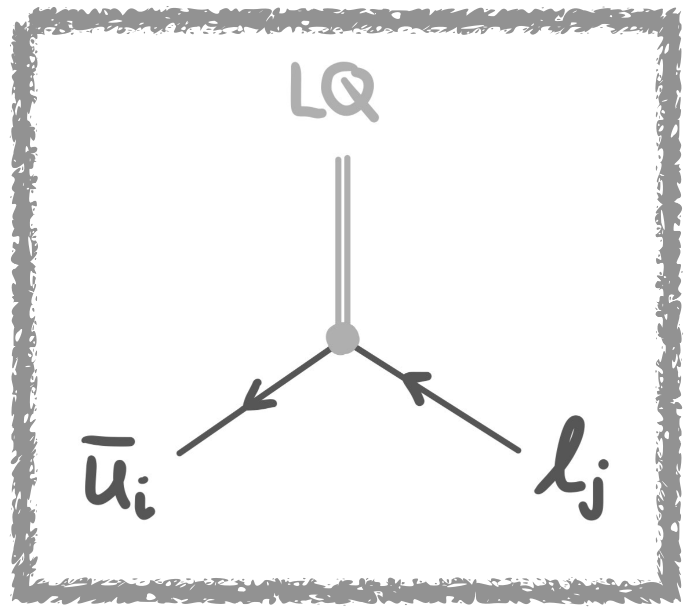

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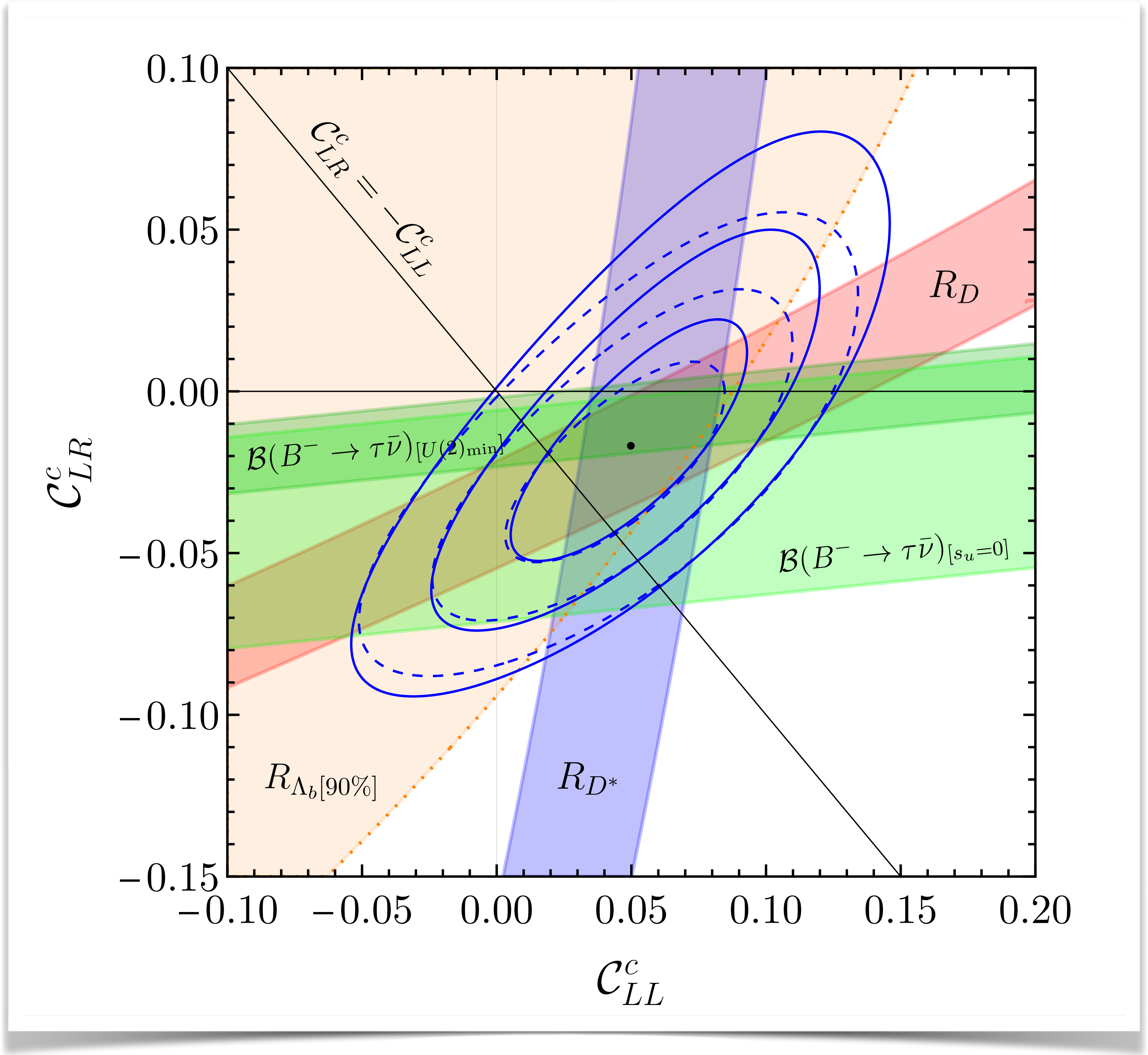

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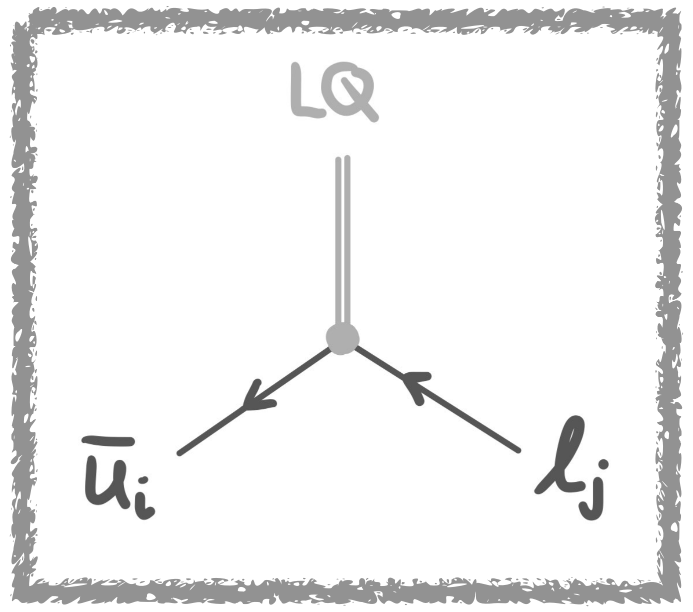

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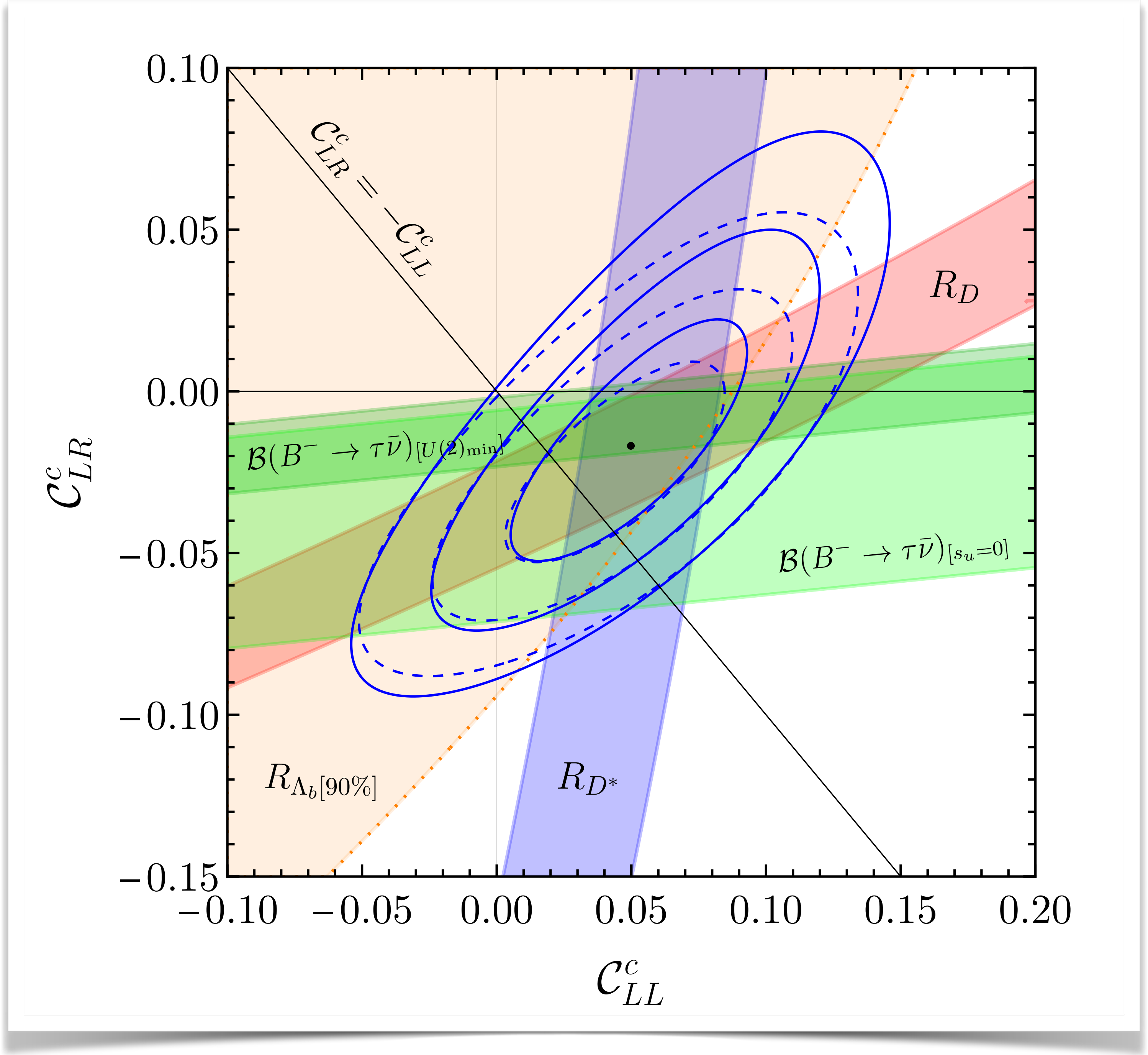

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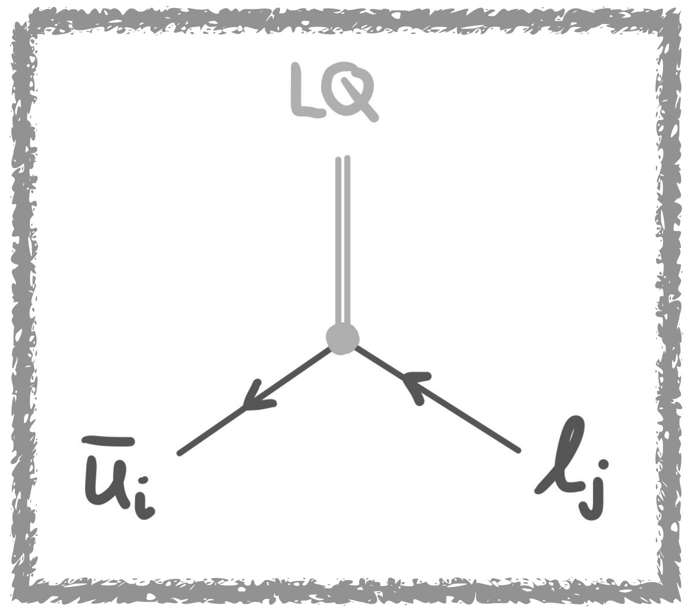

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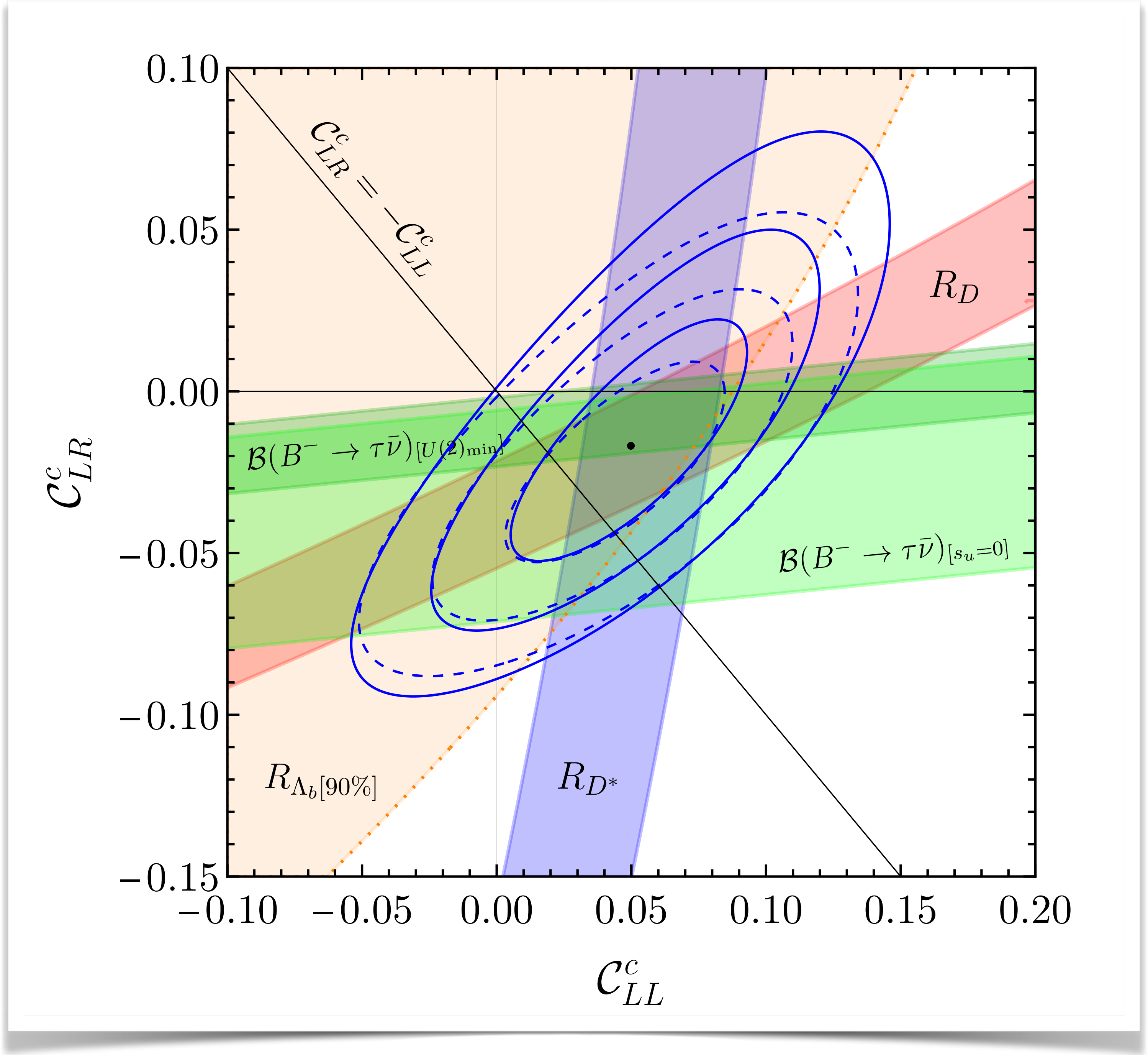

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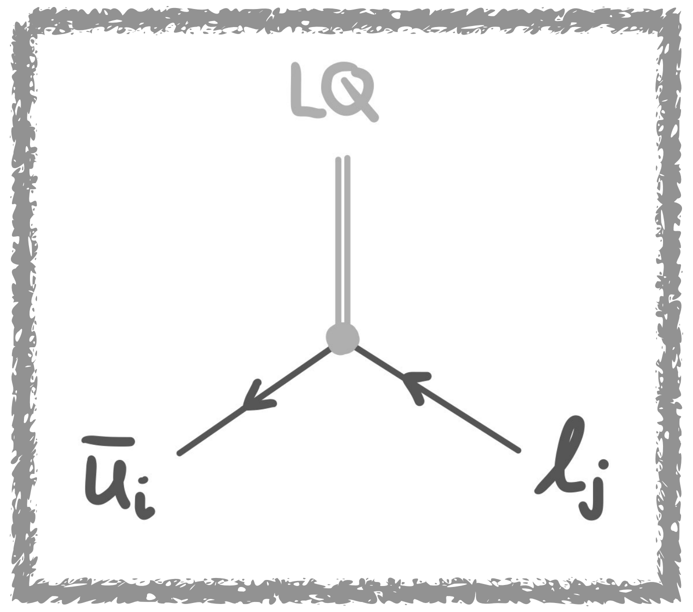

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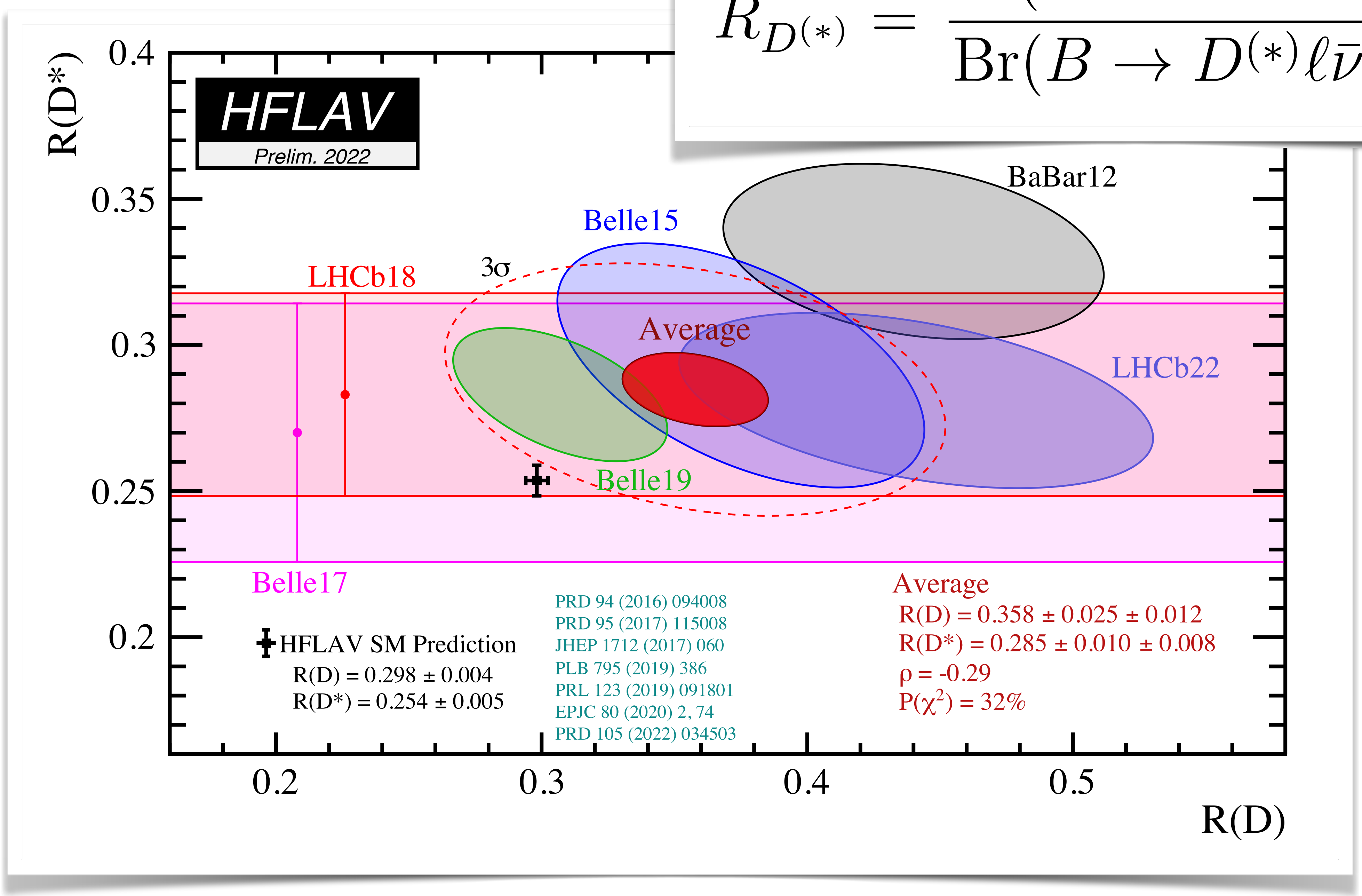

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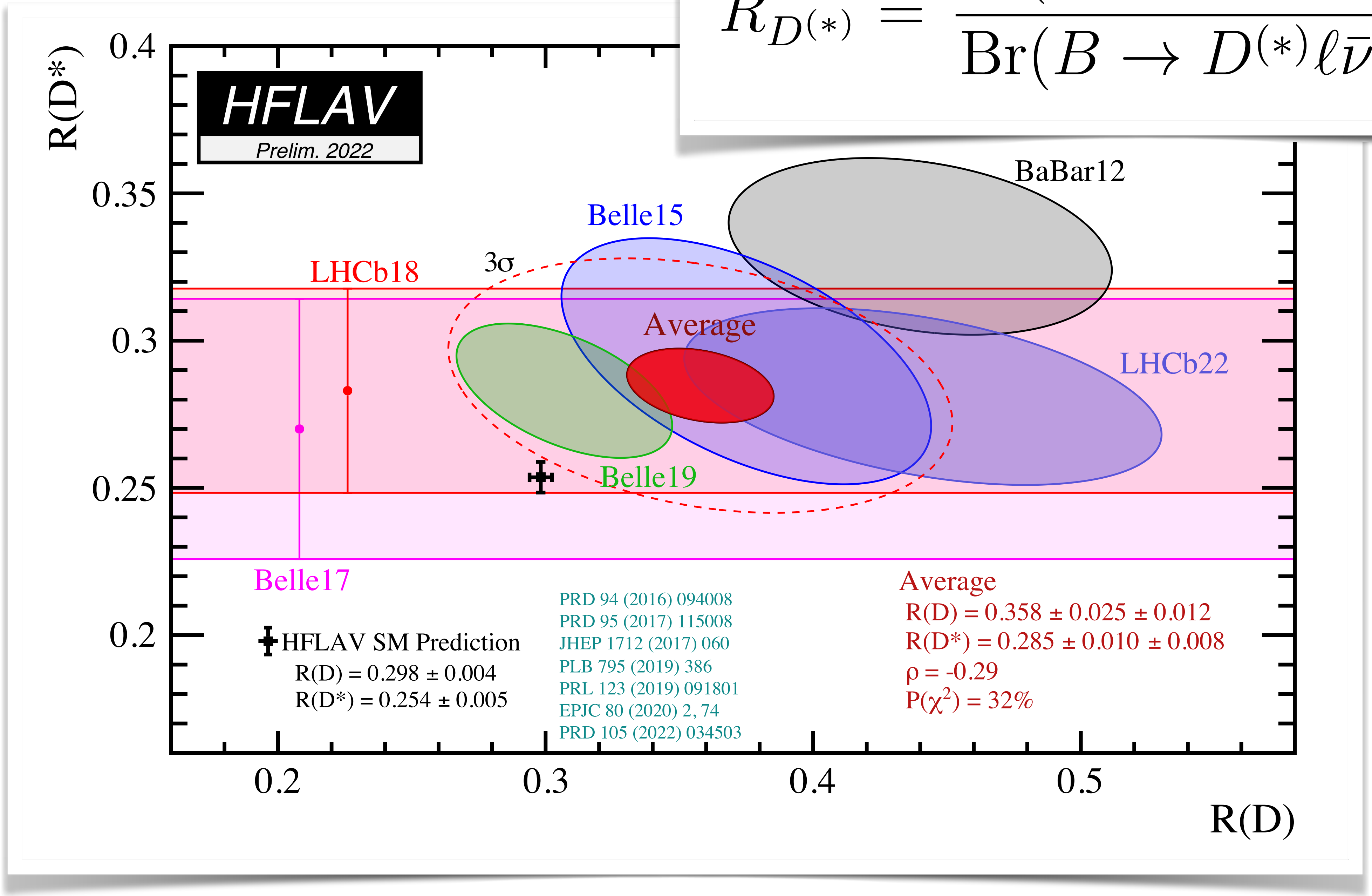

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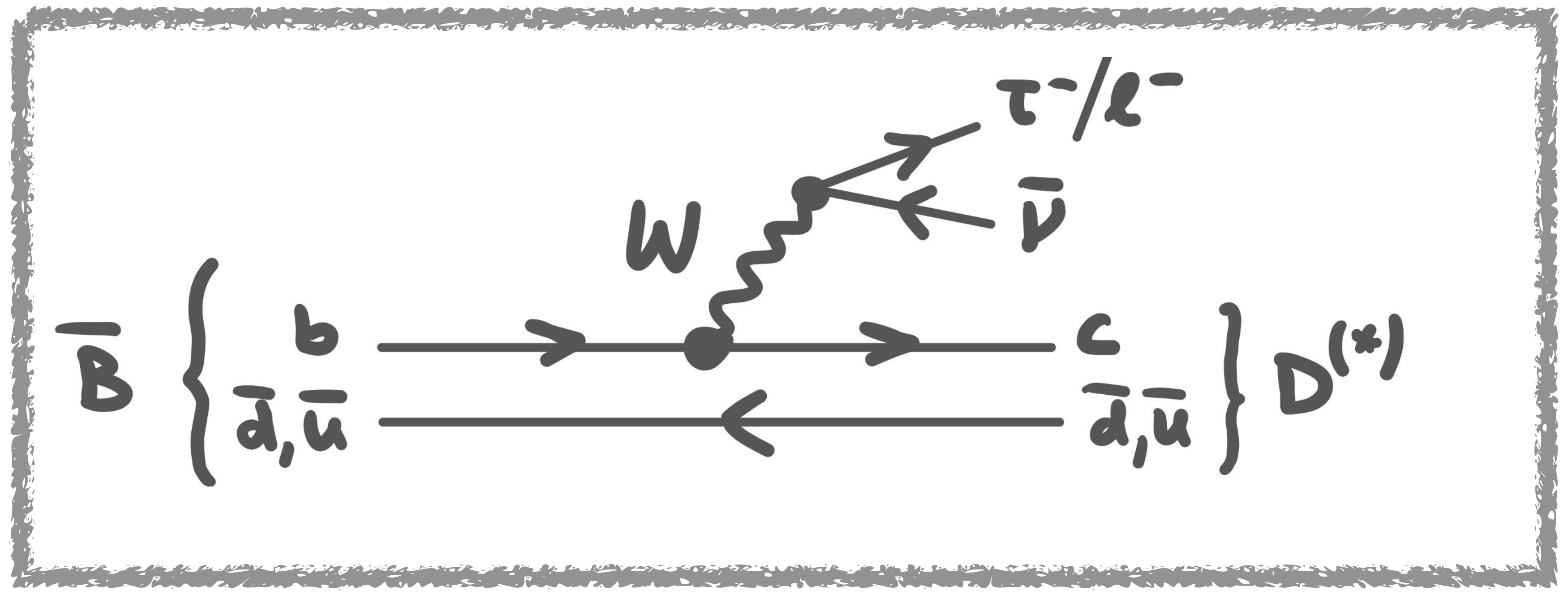

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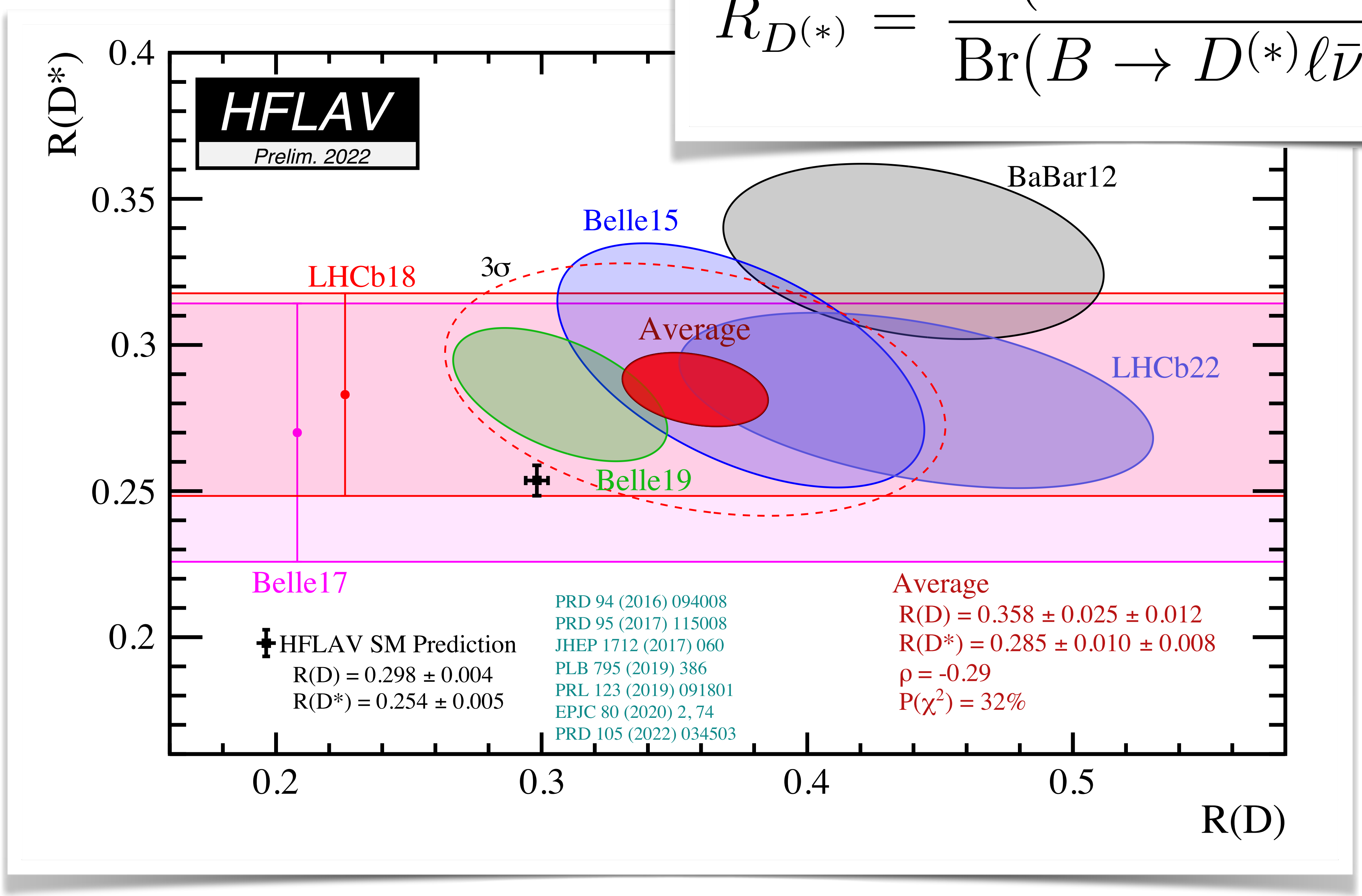

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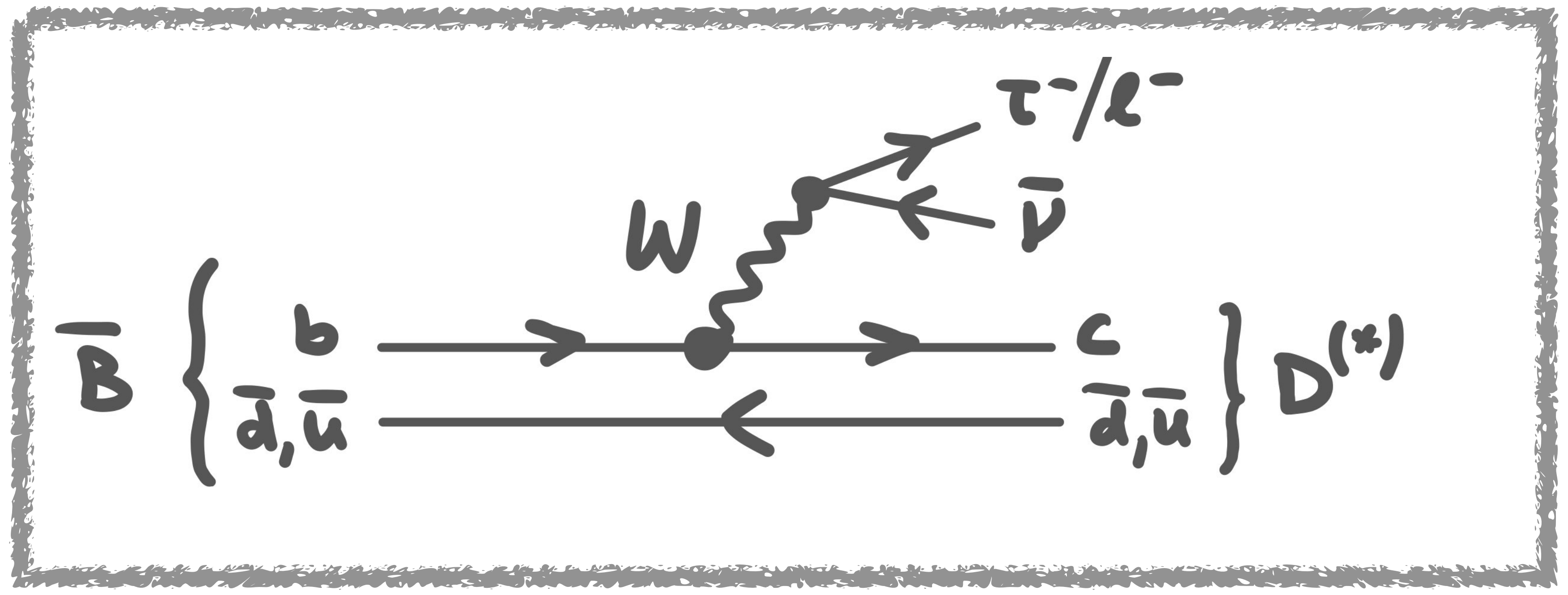

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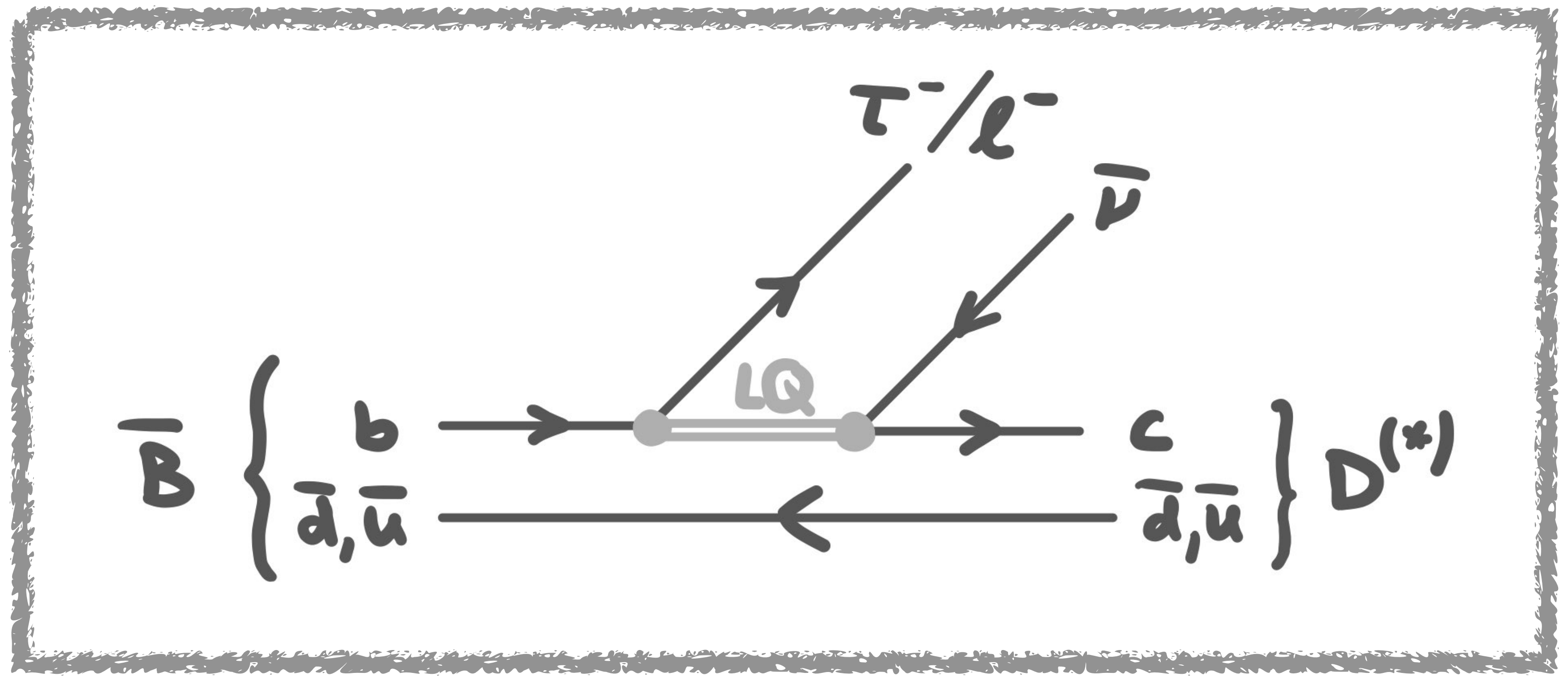

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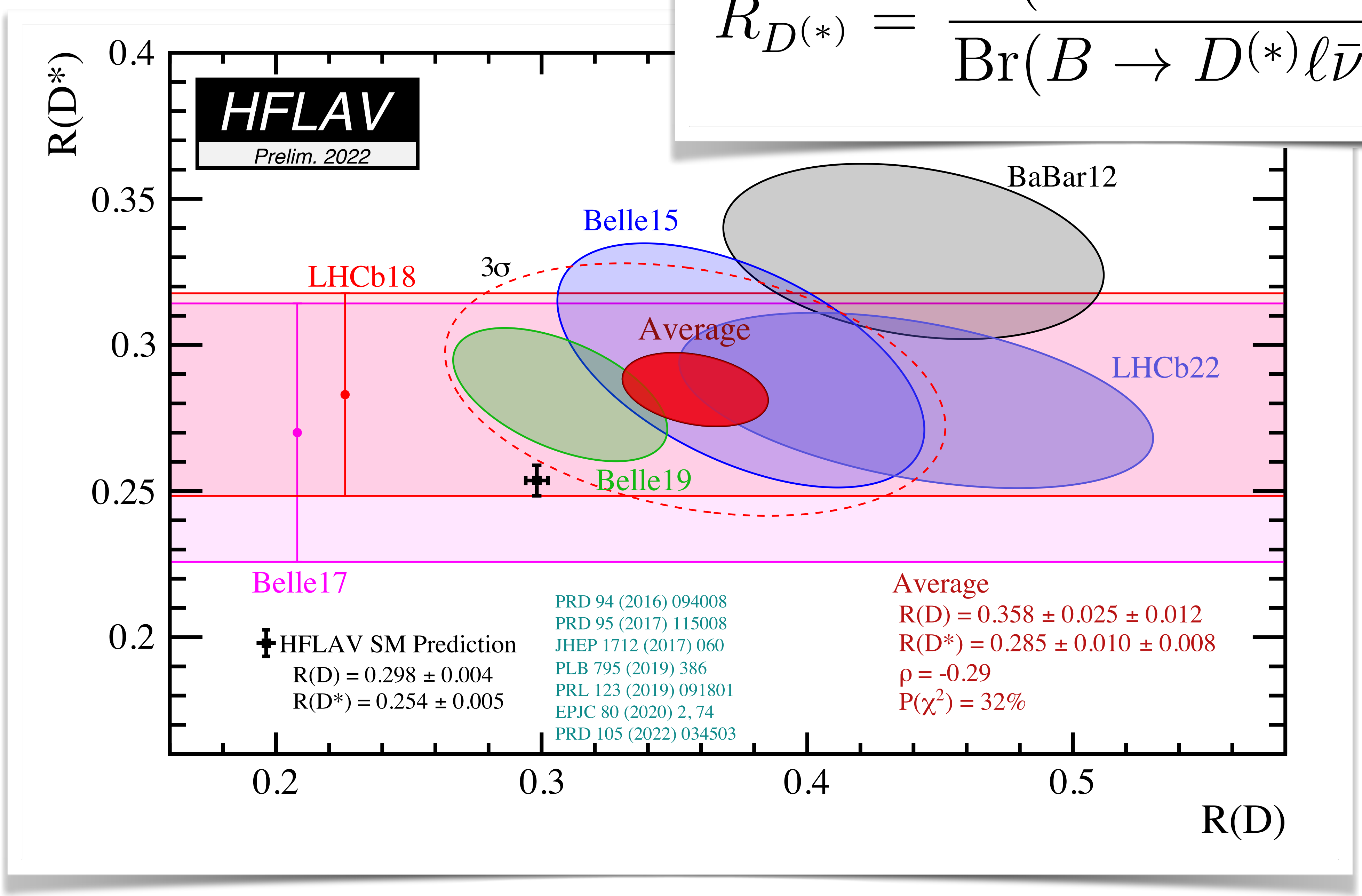

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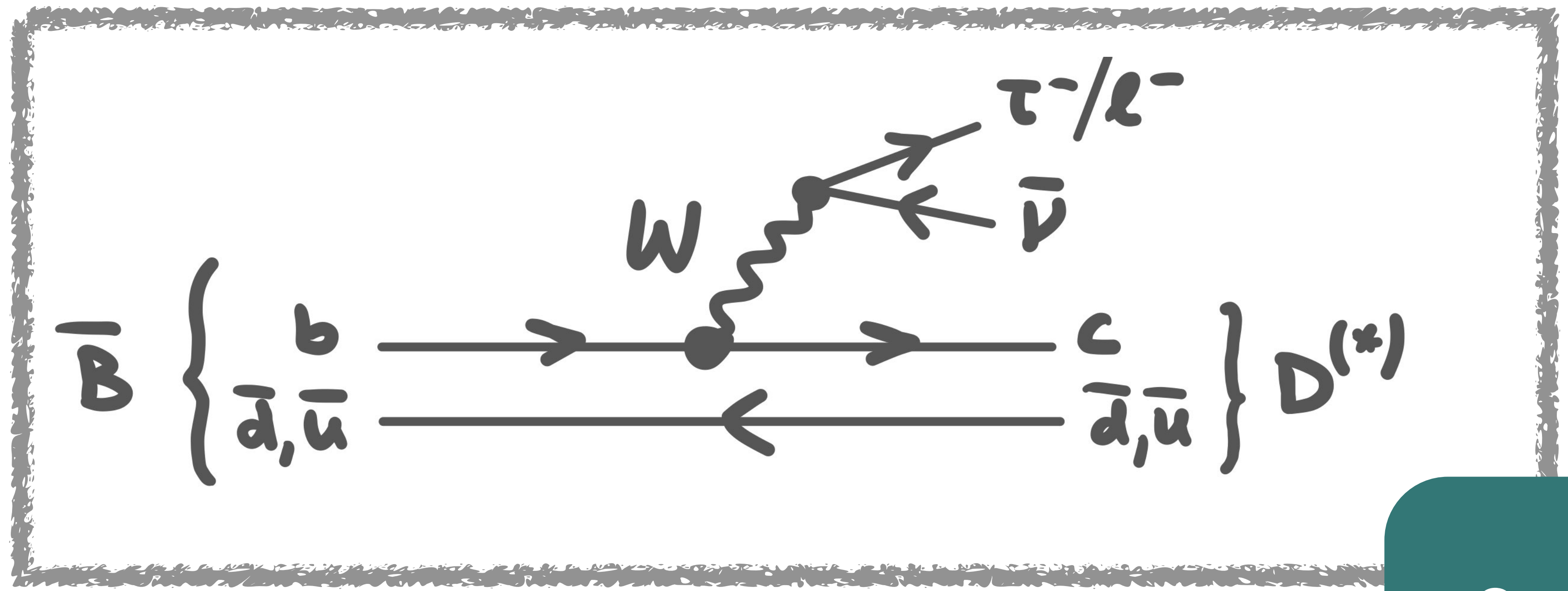

Couplings mainly to third fermion generation.

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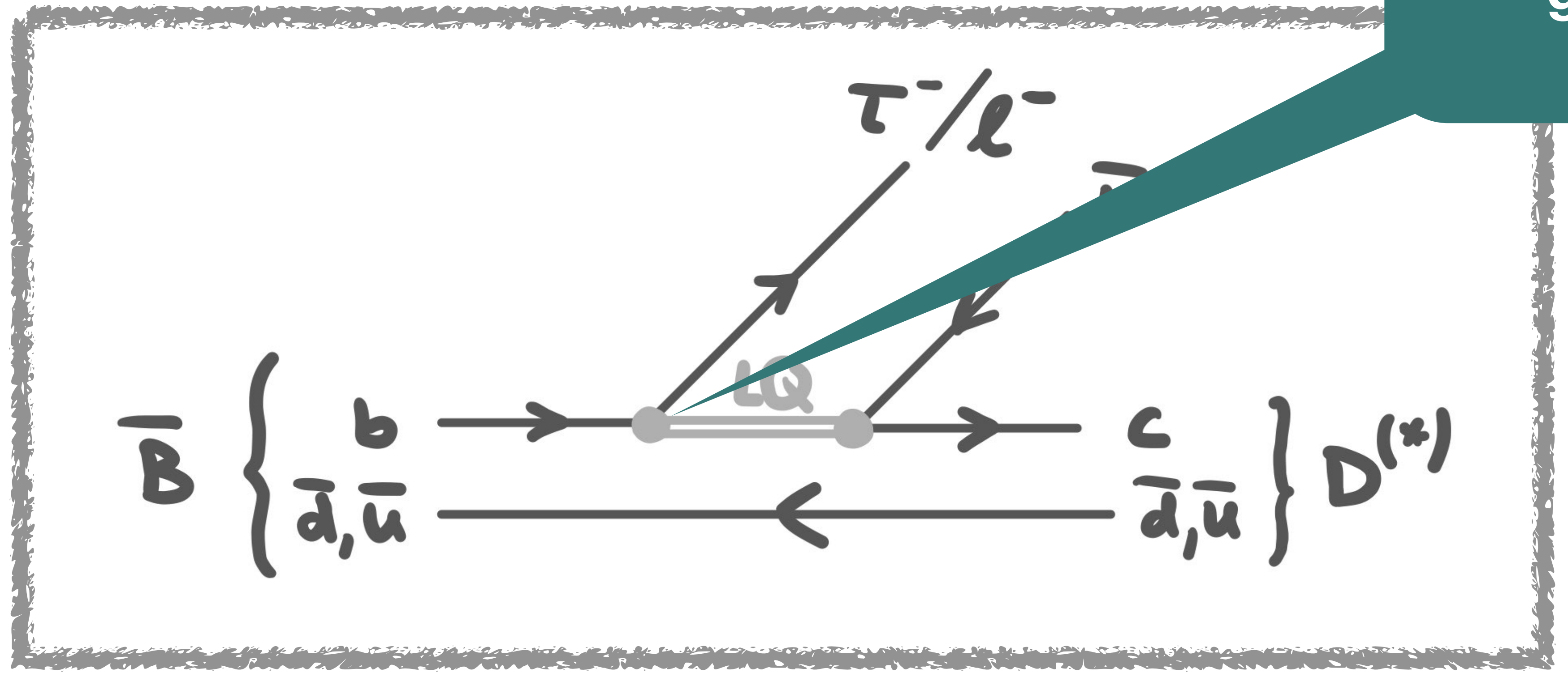

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G

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G

$$T^{15} = \frac{1}{2\sqrt{6}}\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -3 \end{pmatrix} \rightarrow \mathrm{Z}'$$

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$\mathrm{U_1}$

G

$$T^{15} = \frac{1}{2\sqrt{6}}\begin{pmatrix} 1&0&0&0\\ 0&1&0&0\\ 0&0&1&0\\ 0&0&0&-3 \end{pmatrix} \rightarrow Z'$$

Inspired by : ArXiv:1808.00942 (L. Di Luzio, J. Fuentes-Martin, A. Greljo, M. Nardecchia, S. Renner), ArXiv:1901.10480 (M.J. Baker, J. Fuentes-Martin, G. Isidori, M. König)

1. Introduction
1.2 UV-complete gauge models

- **U_1 VLQ:** $$\frac{g_U}{\sqrt{2}}\left[\beta_L^{ij}\,\bar{Q}^{i,a}\gamma_\mu L^j + \beta_R^{ij}\,\bar{d}^{i,a}\gamma_\mu e^j\right]U^{\mu,a} + \text{h.c.}$$

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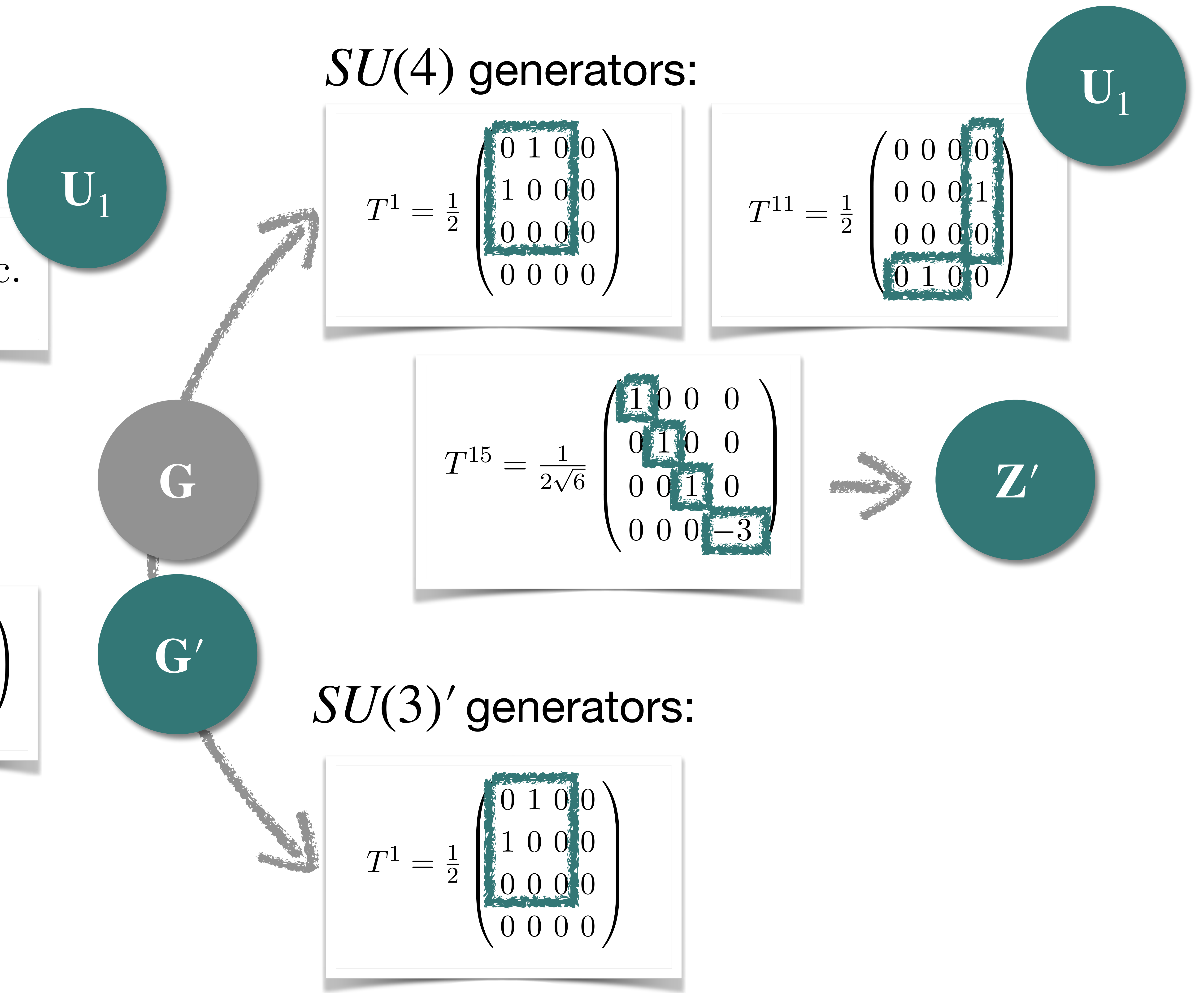

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2. Constraints from the LHC

2.1 Channels

2.2 Drell-Yan production

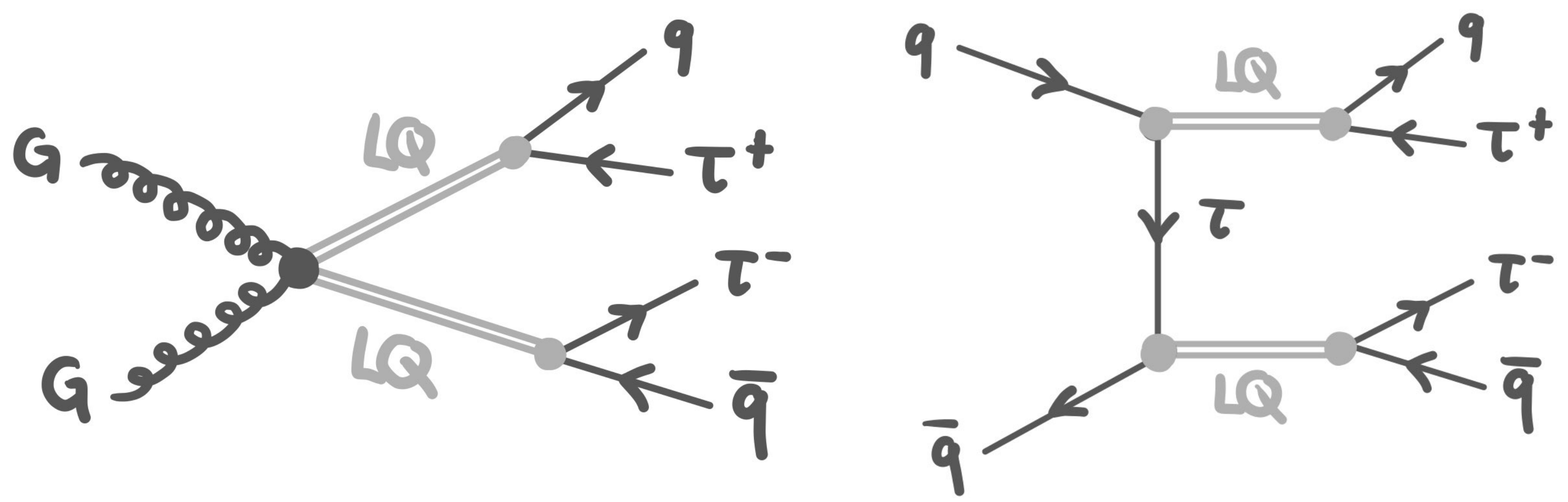
2.3 Single-resonant production

2. Constraints from the LHC

2.1 Channels

2. Constraints from the LHC

2.1 Channels



Pair-production

2. Constraints from the LHC

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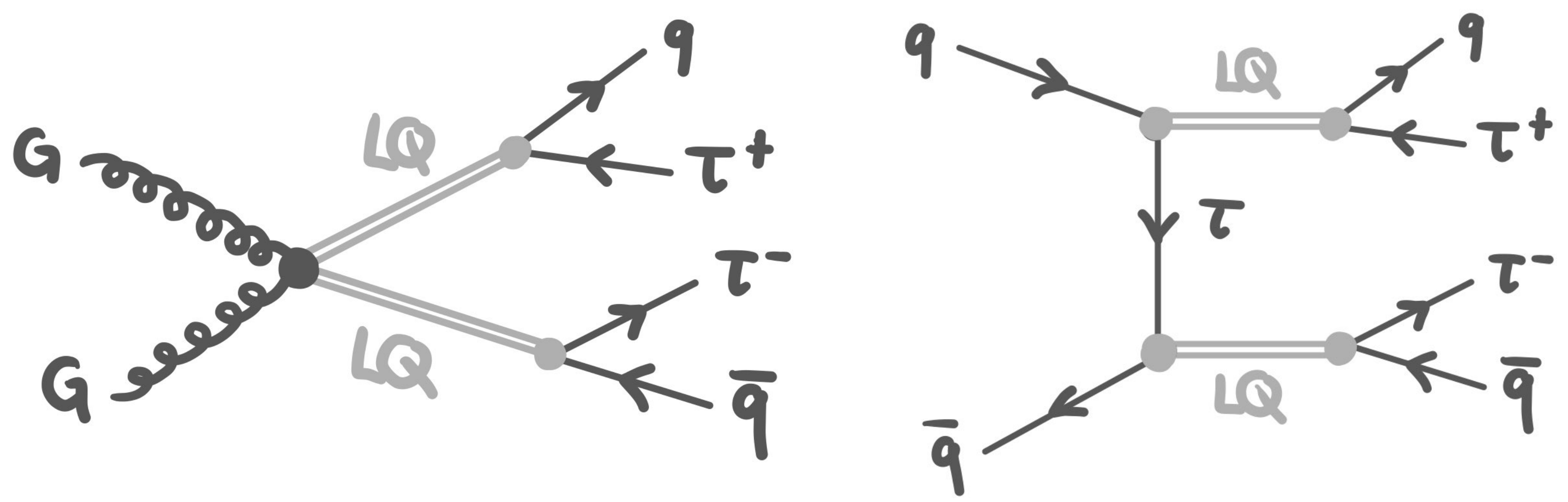

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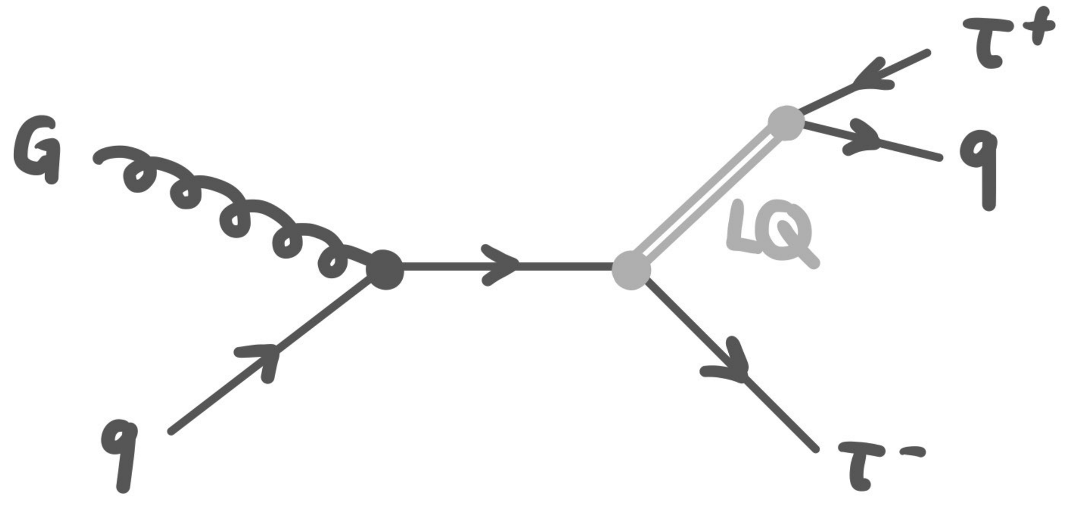

Single production

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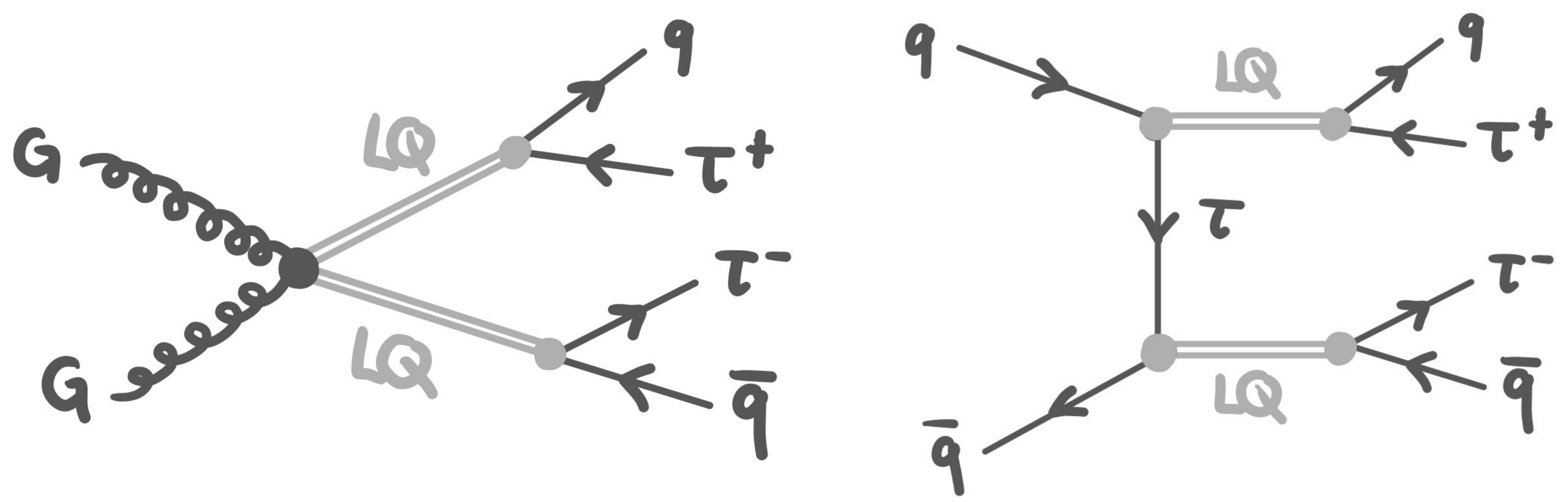

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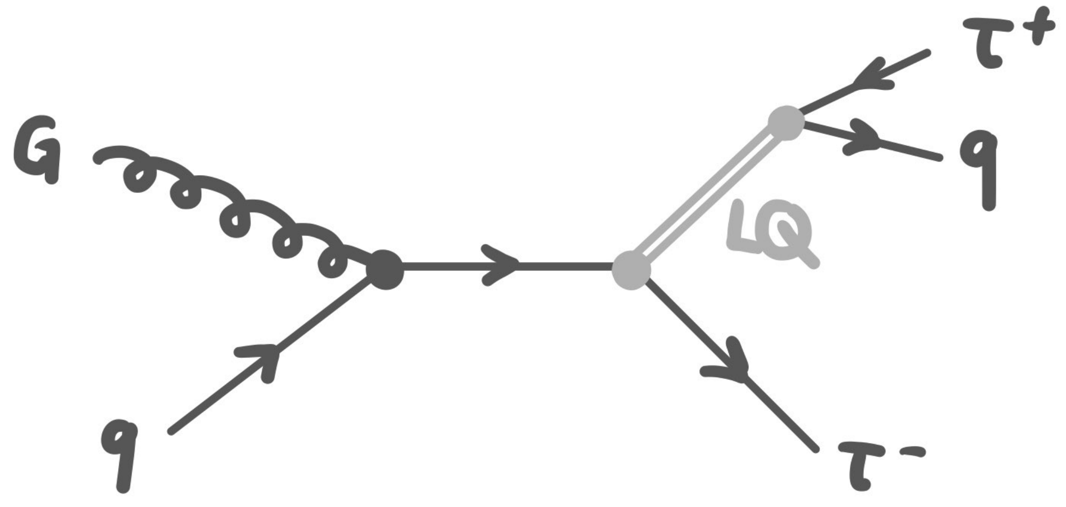
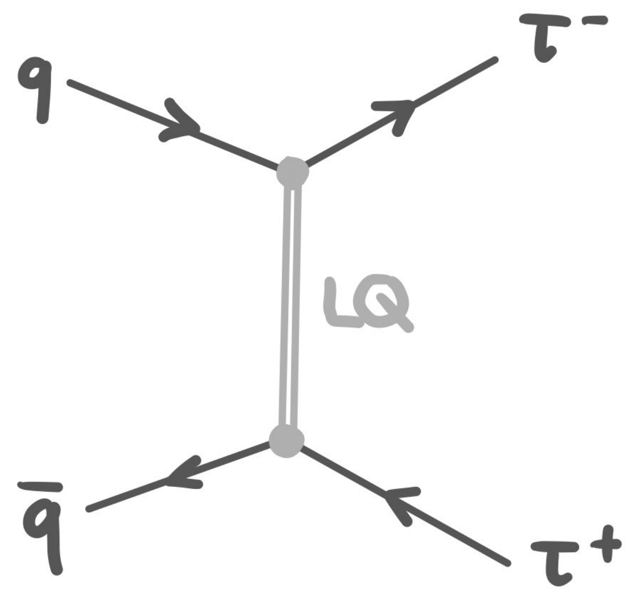


Single production



Drell-Yan production

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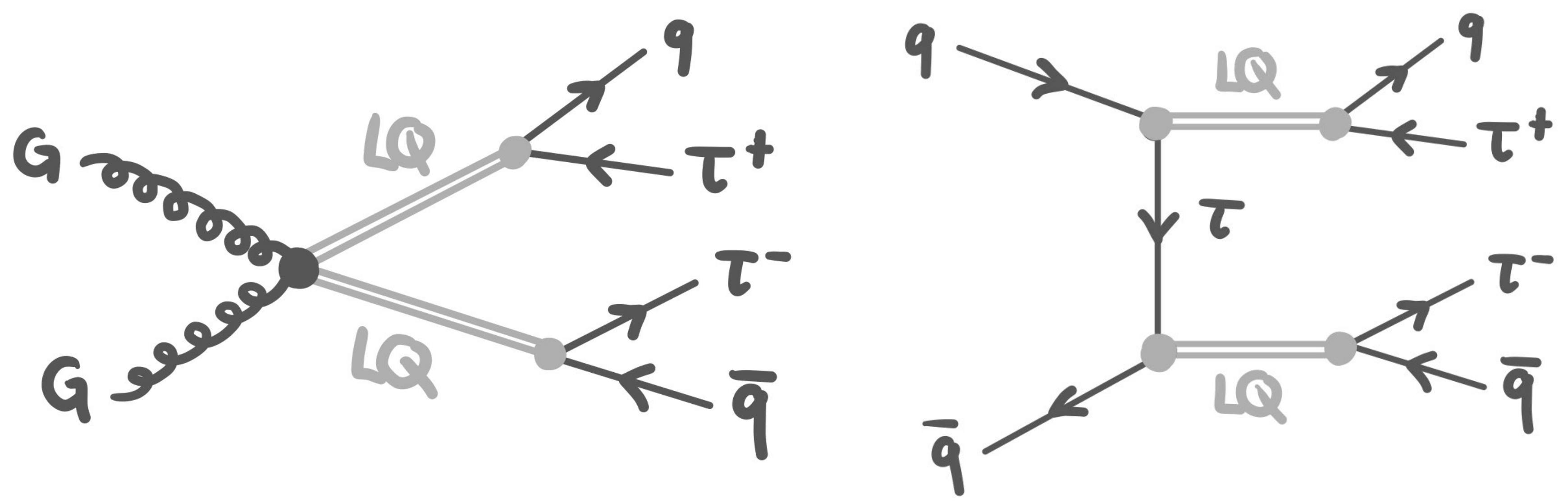

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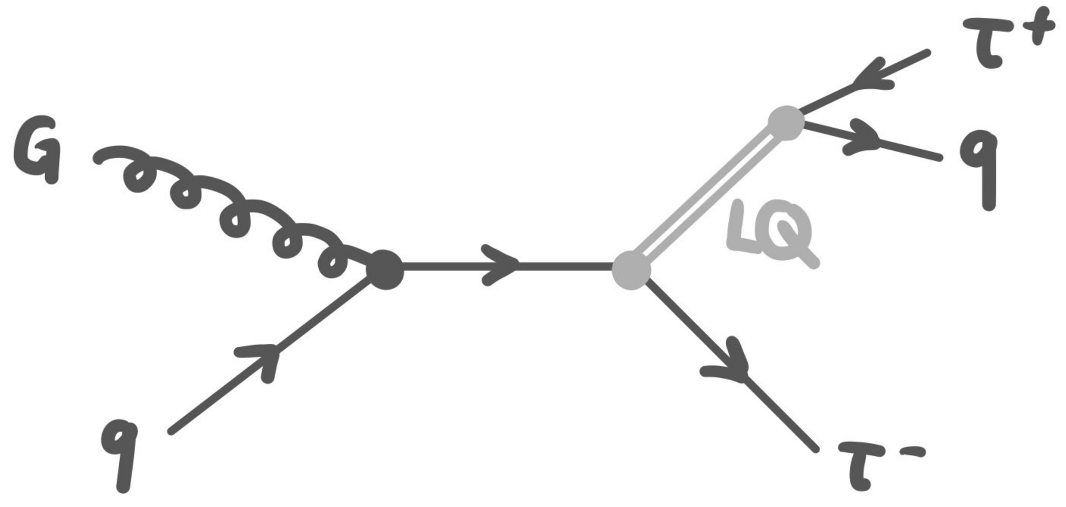

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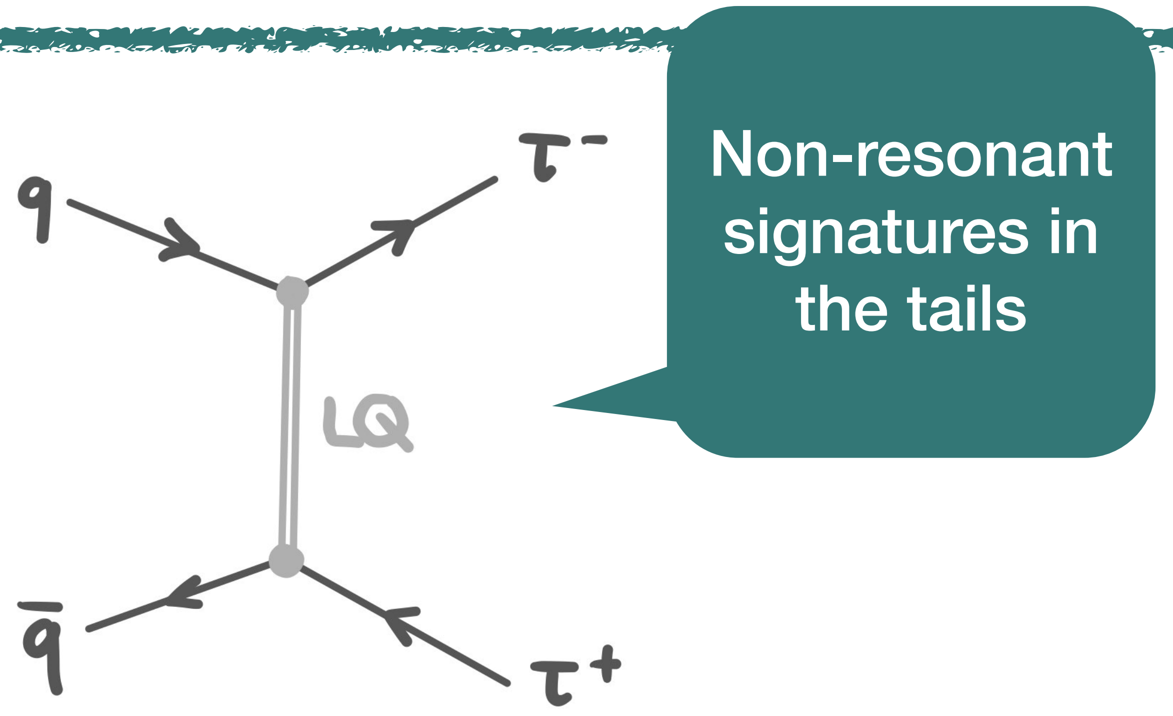

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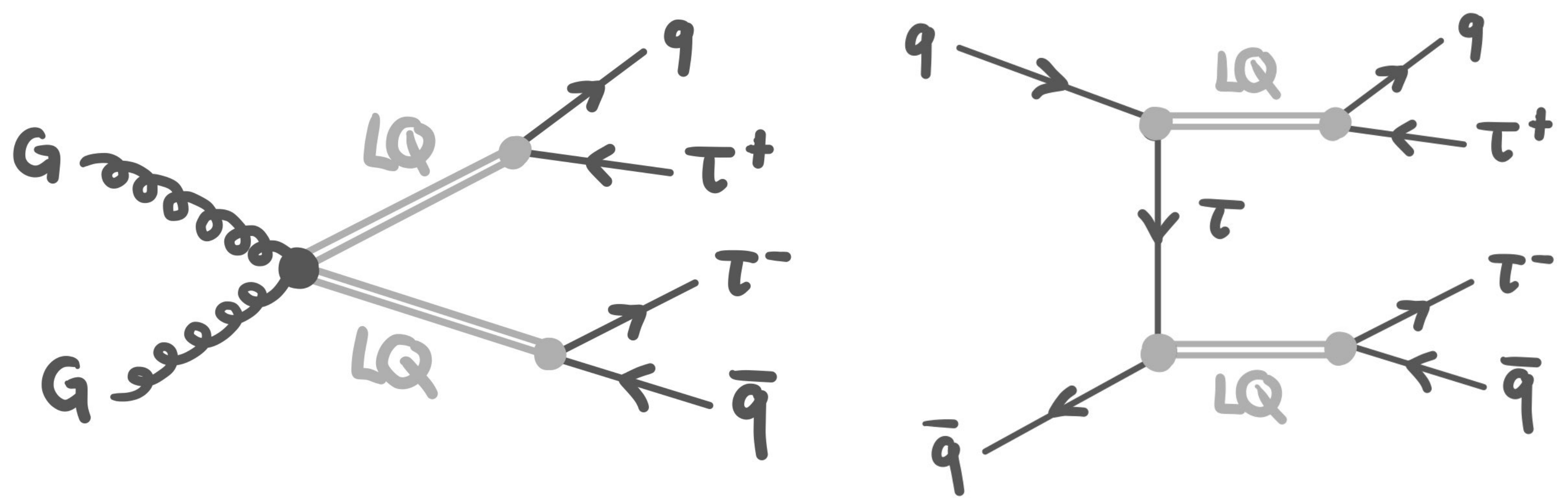
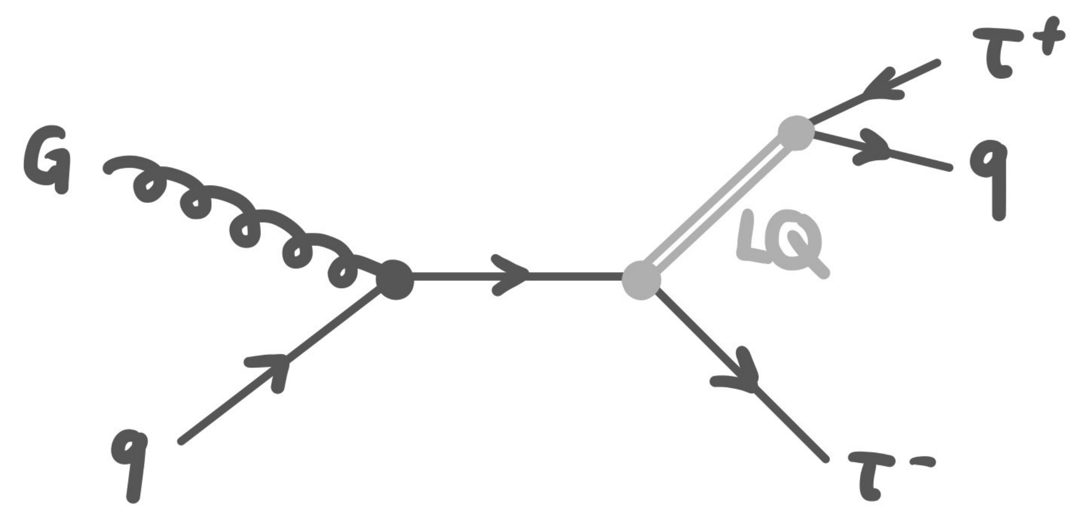


Pair-production



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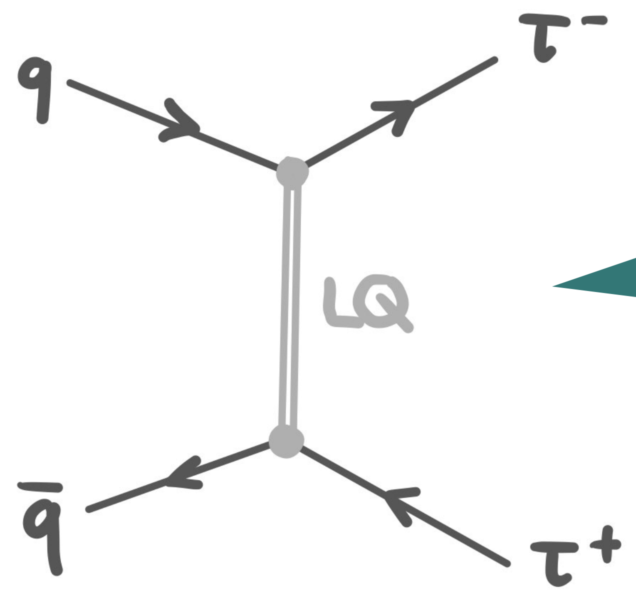
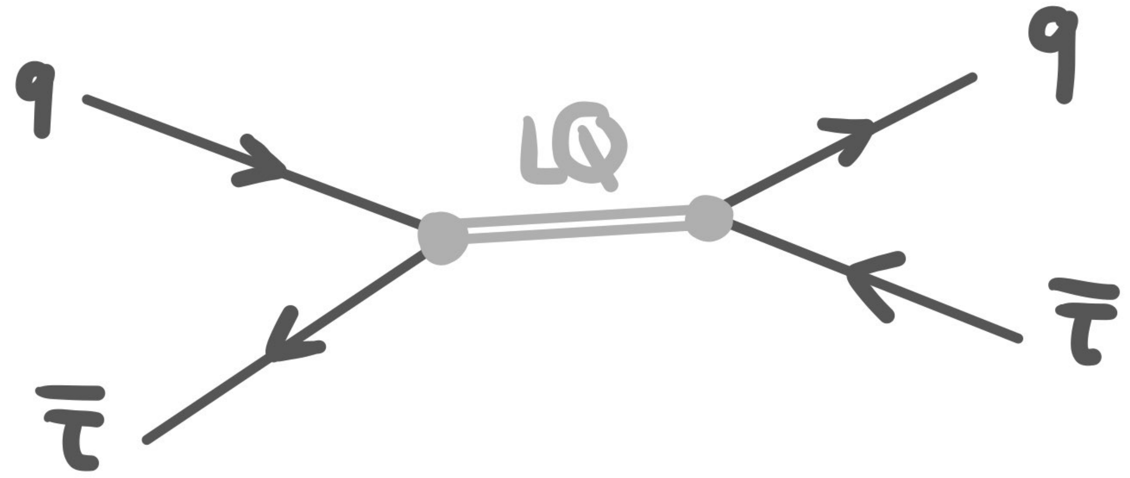


Non-resonant signatures in the tails

Drell-Yan production



Single-resonant production

2. Constraints from the LHC

2.2 Drell-Yan production: Overview

2. Constraints from the LHC

2.2 Drell-Yan production: Overview

- **Drell-Yan: clean** and **well-reconstructable** experimental signature with excellent detection efficiency.
- A pillar of the research programme at LHC.

2. Constraints from the LHC

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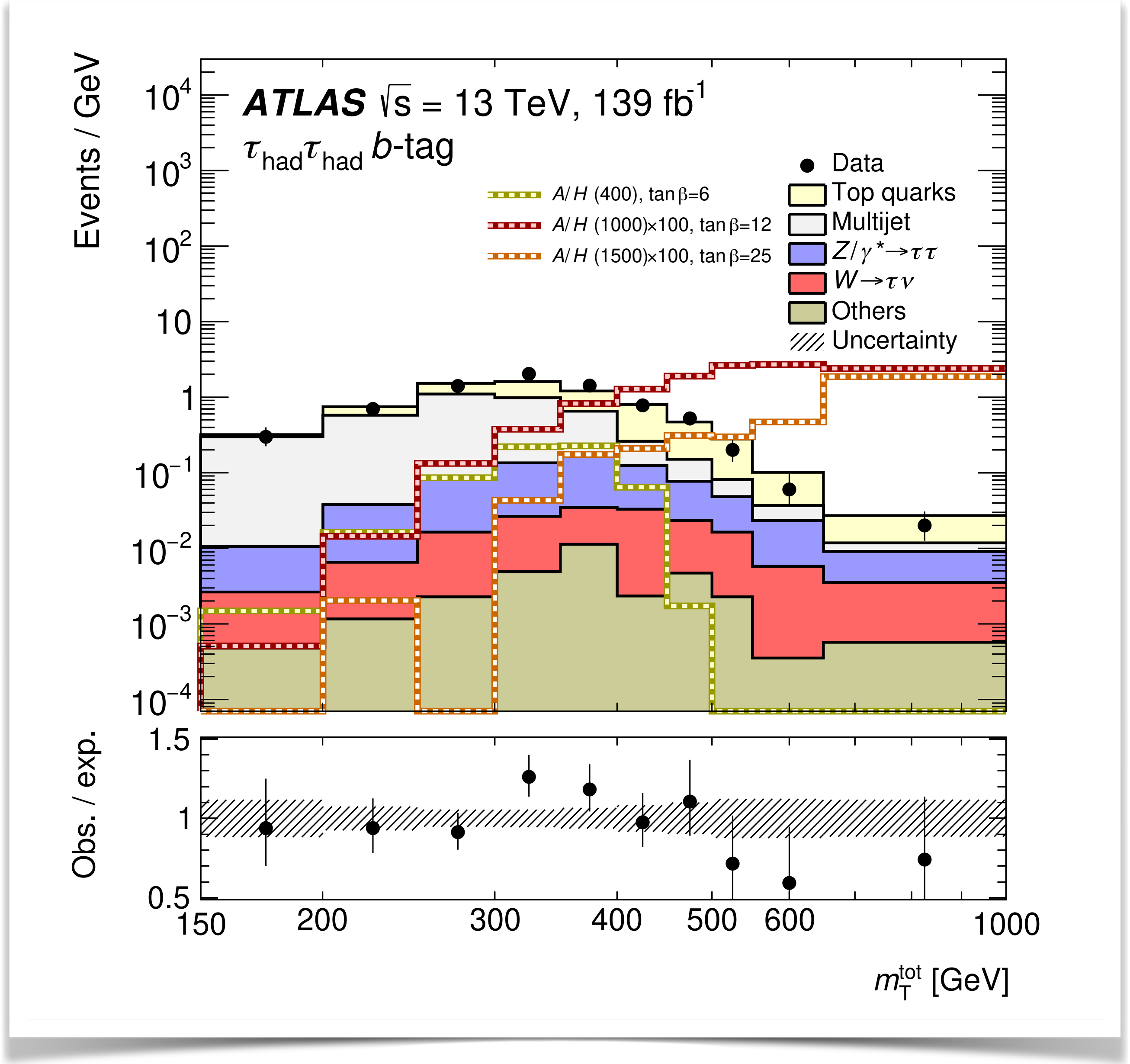
ATLAS 2020



Source: ArXiv:2002.12223 (ATLAS)

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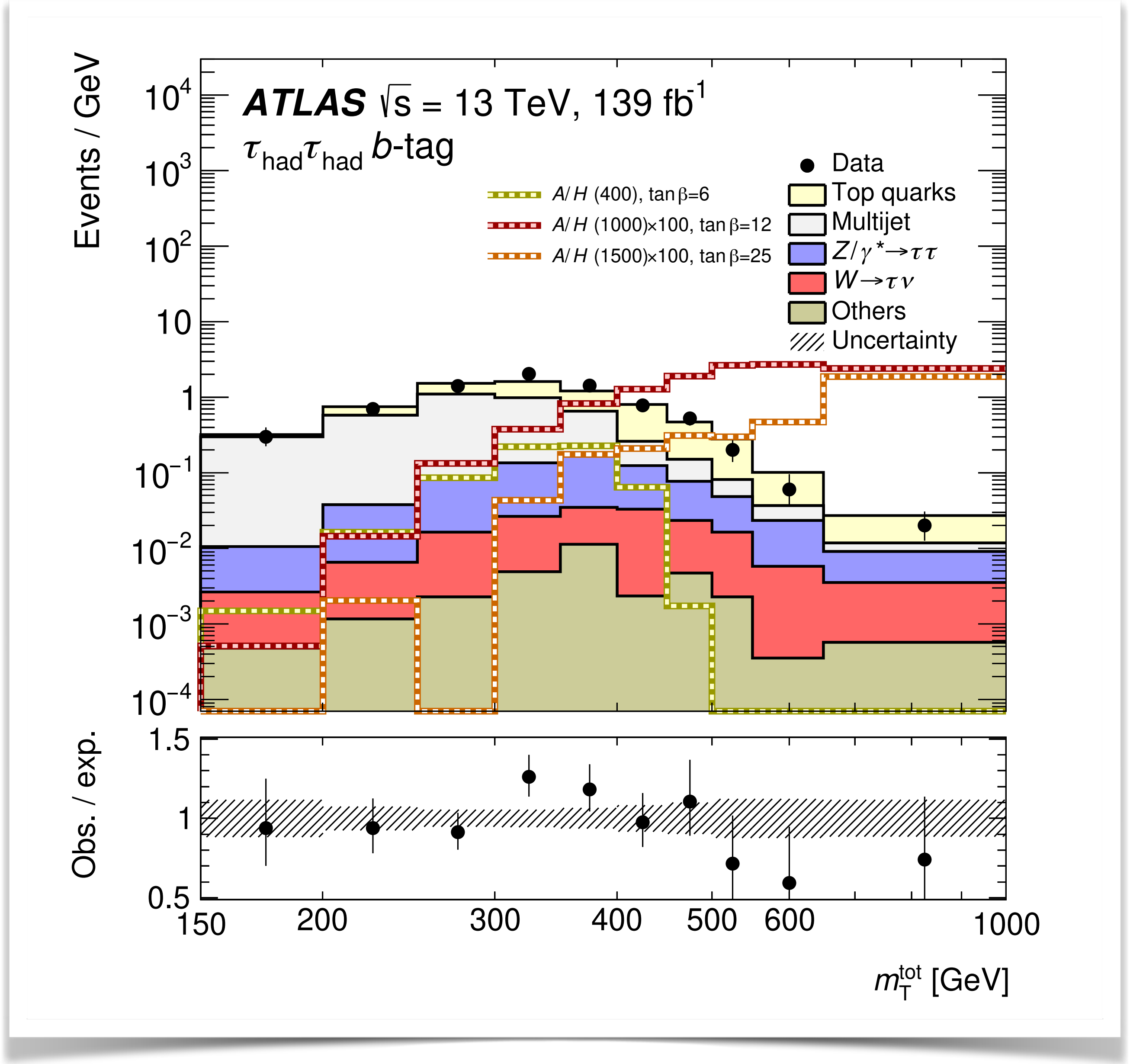

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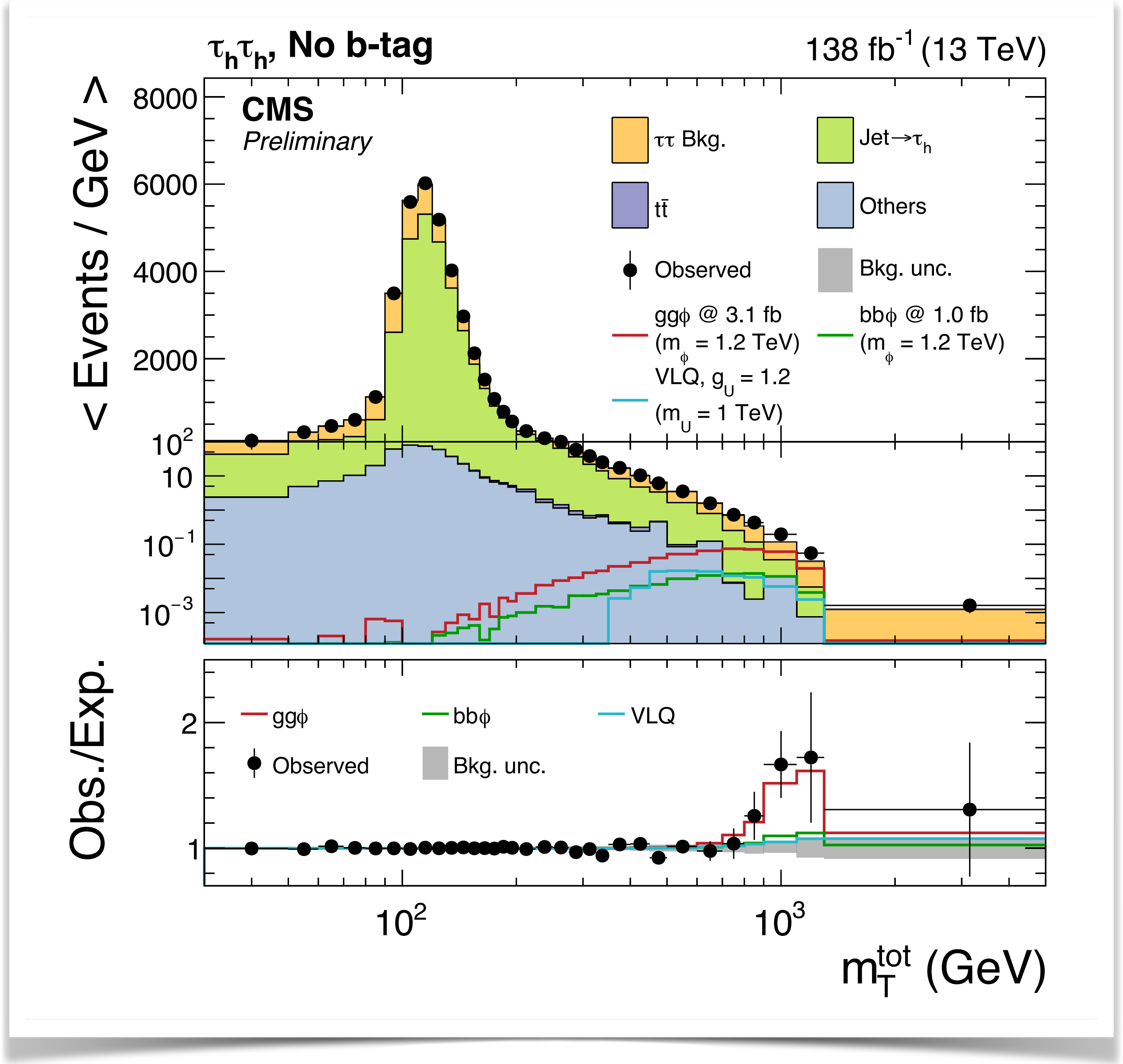
CMS 2021



Source: HIG-21-001-PAS (CMS)

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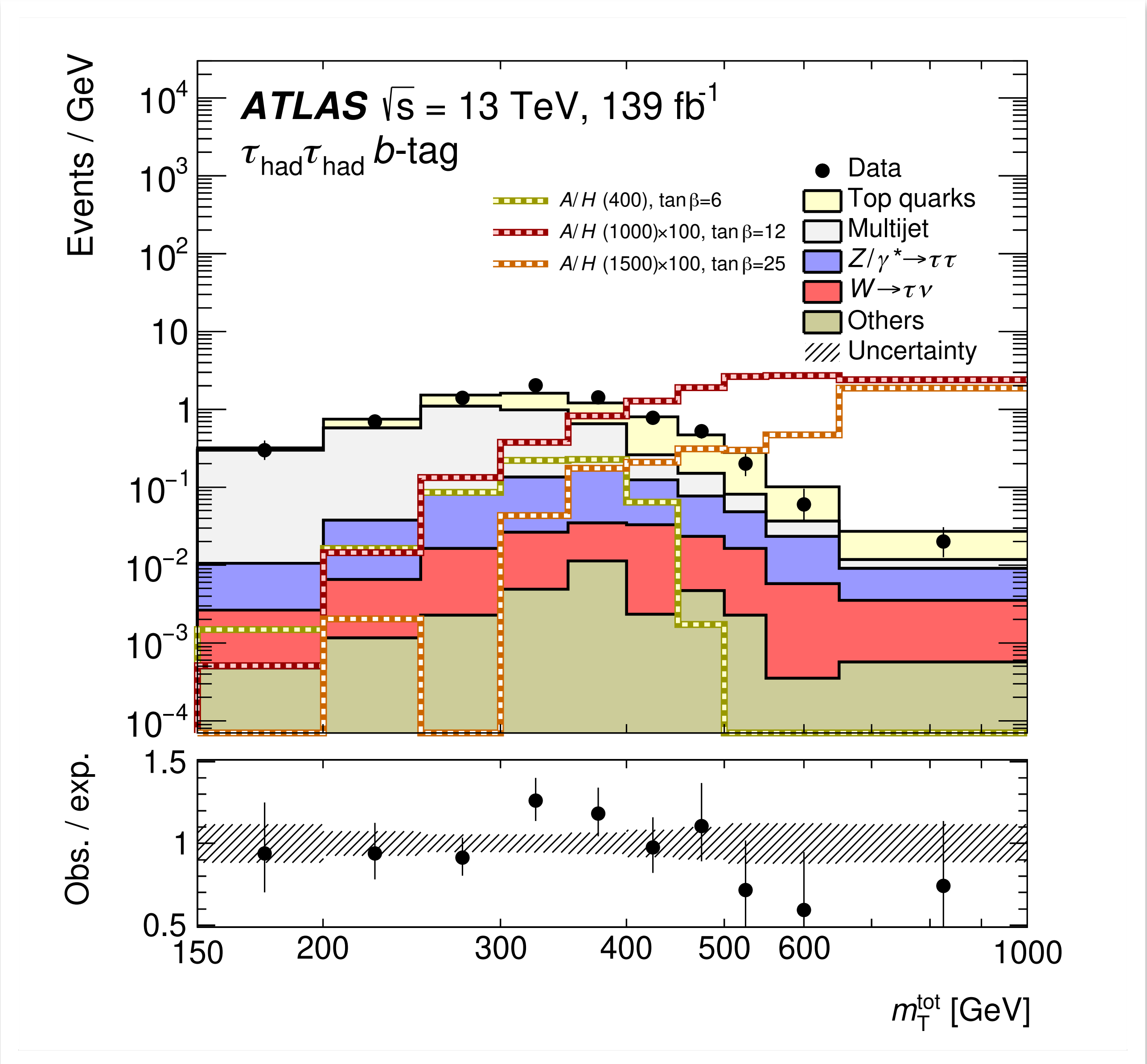

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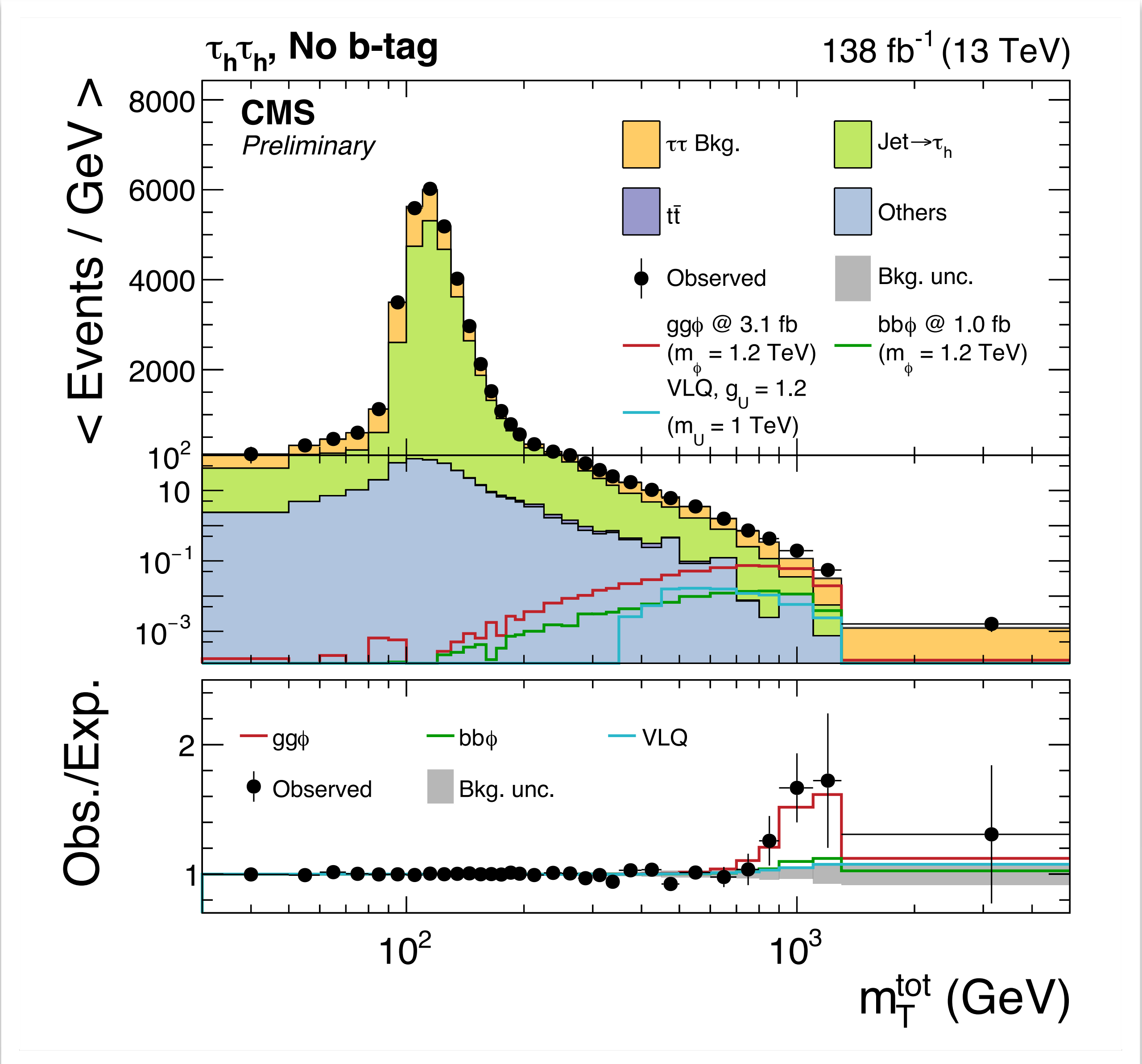
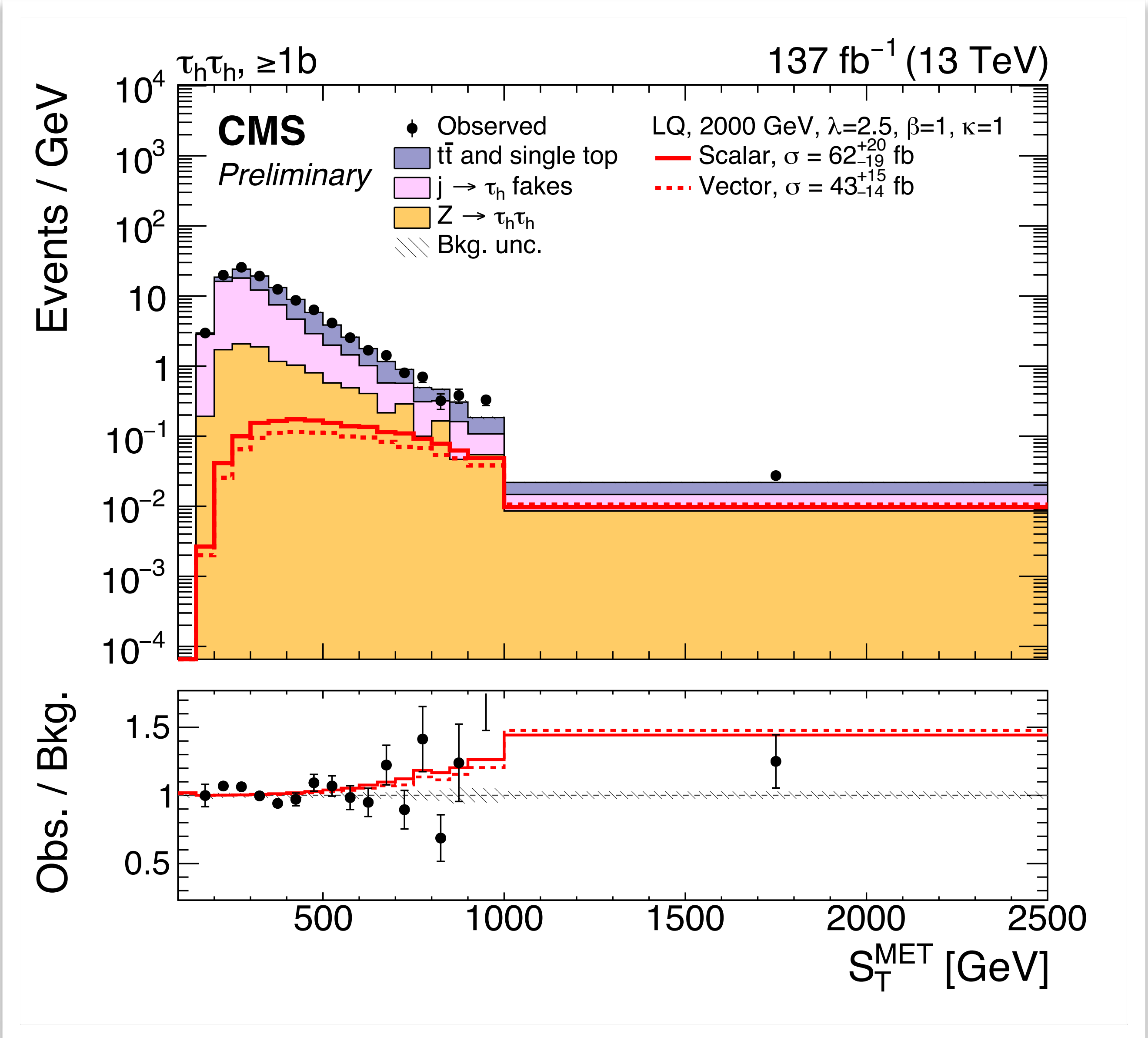


Source: HIG-21-001-PAS (CMS)

CMS 2022



Source: EXO-19-016-PAS (CMS)

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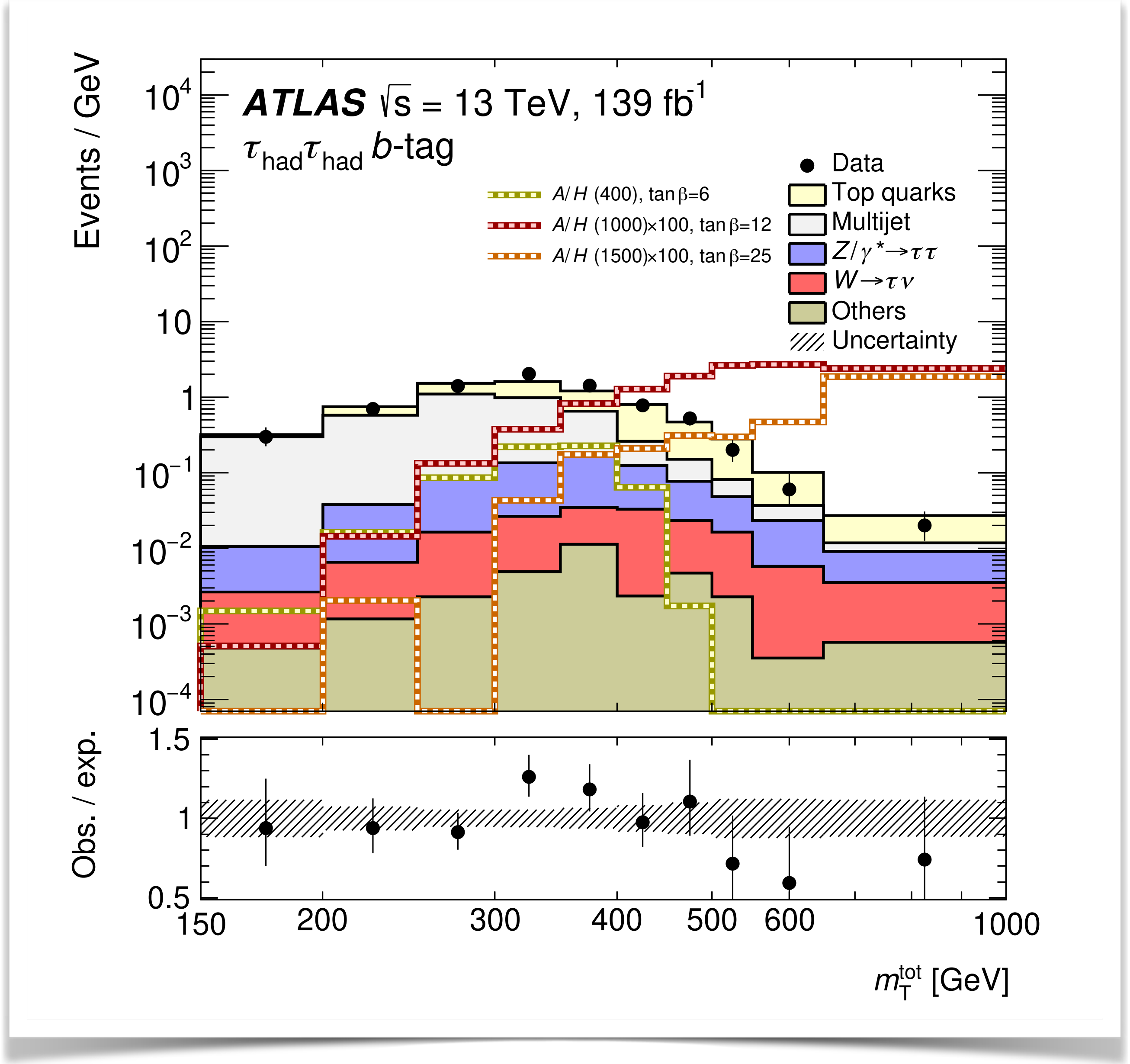
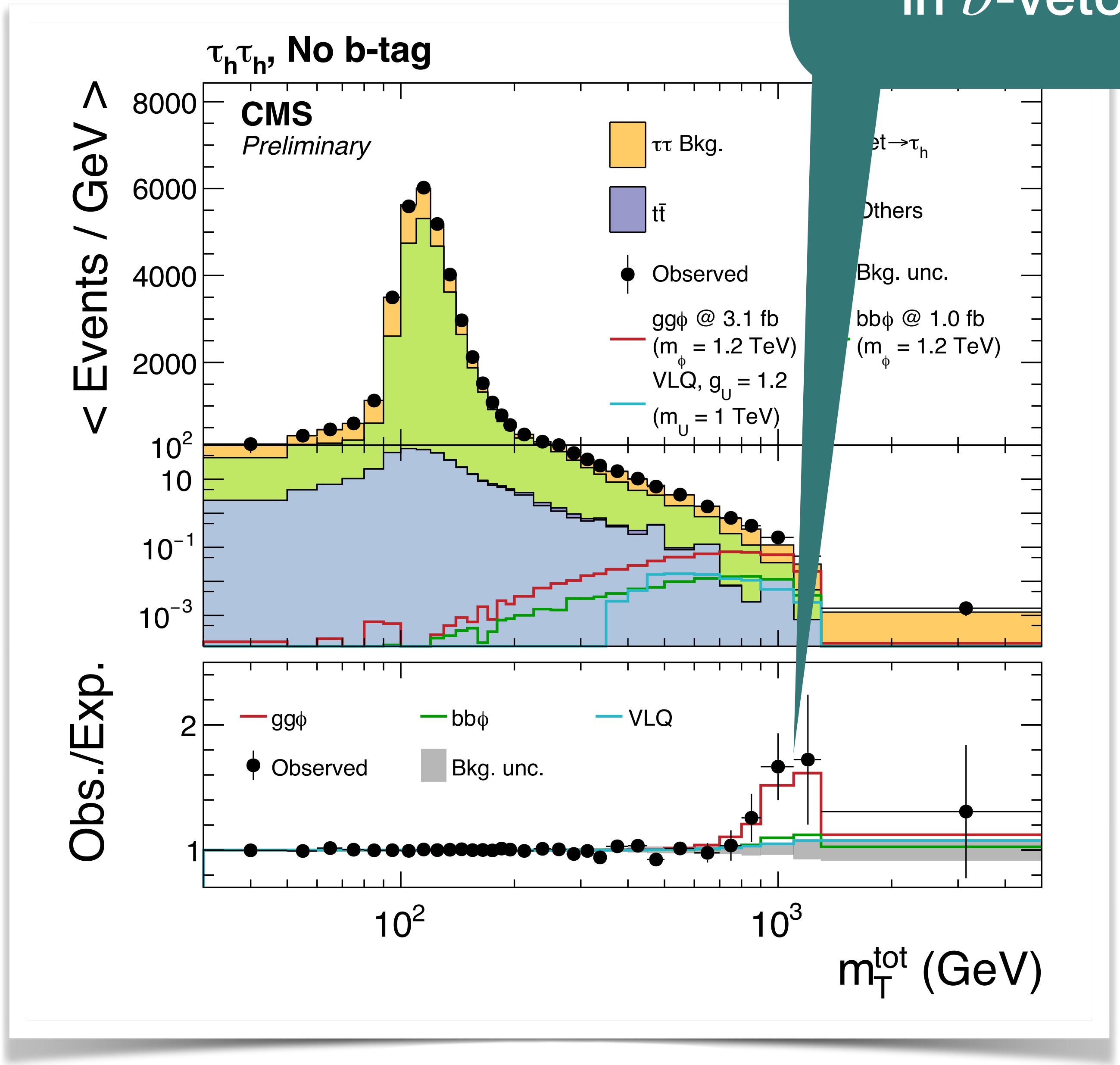


Source: ArXiv:2002.12223 (ATLAS)

CMS 2021

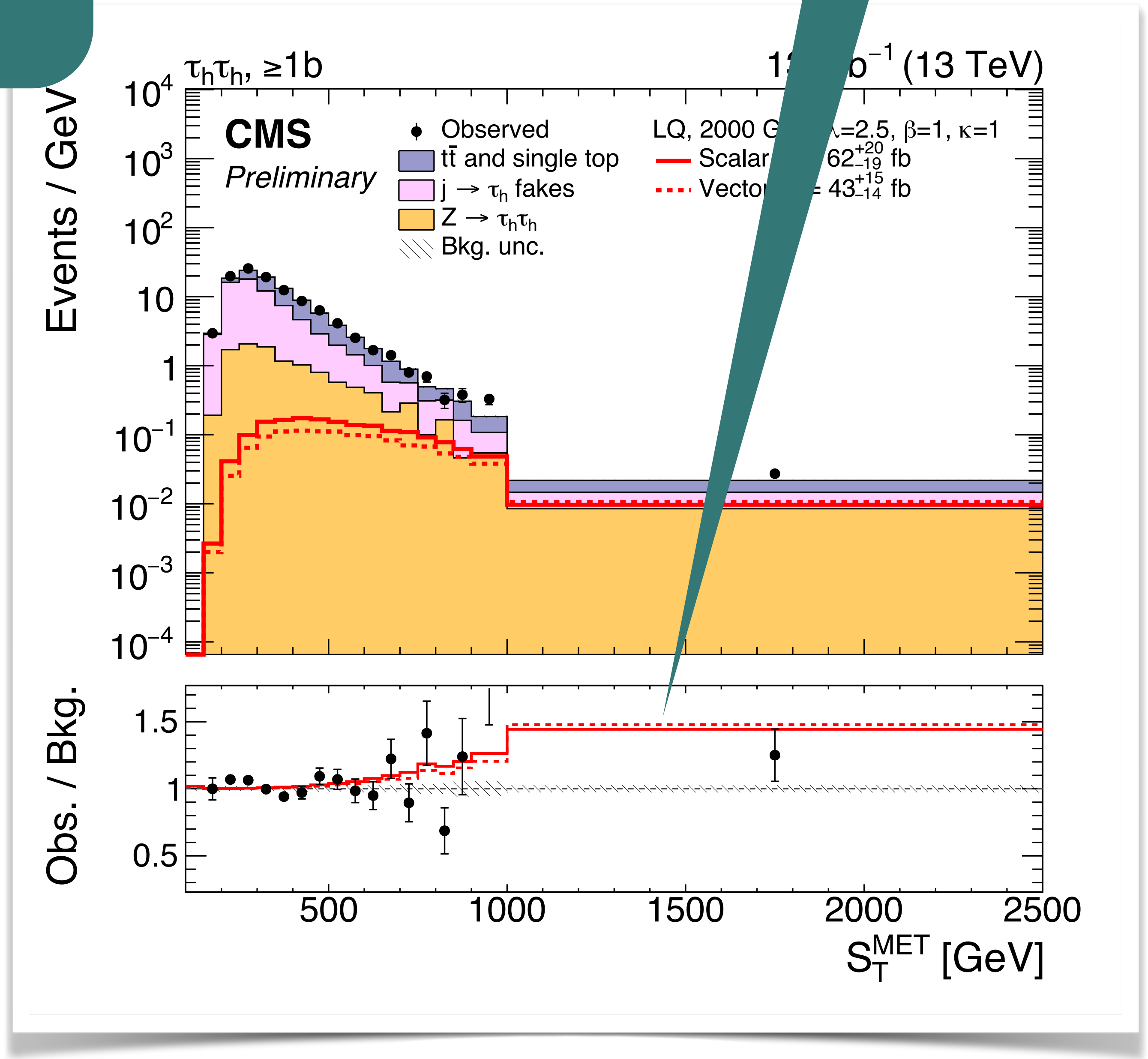
Resonant 3σ excess in b-veto (???)



Source: HIG-21-001-PAS (CMS)

CMS 2022

Non-resonant 3σ excess in b-tag (???)



Source: EXO-19-016-PAS (CMS)

2. Constraints from the LHC

2.2 Drell-Yan production: Going beyond the LQ LO

2. Constraints from the LHC

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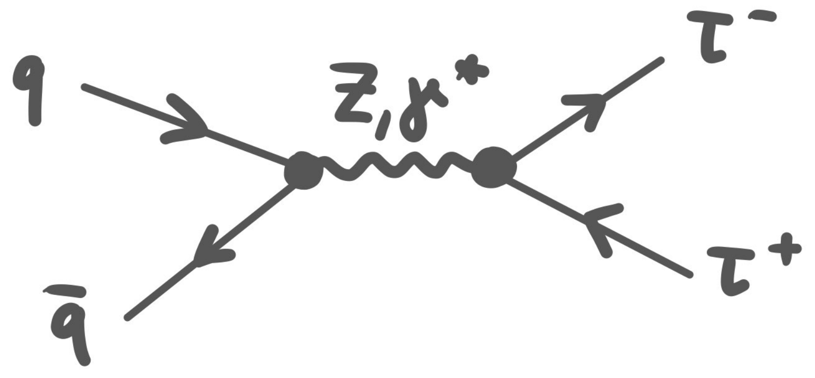
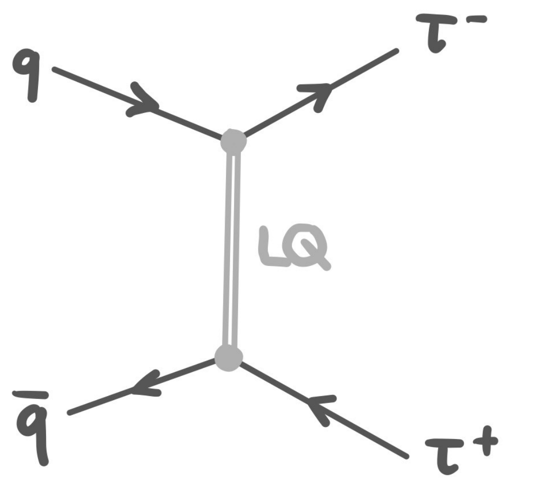


SM LO



LQ LO

2. Constraints from the LHC

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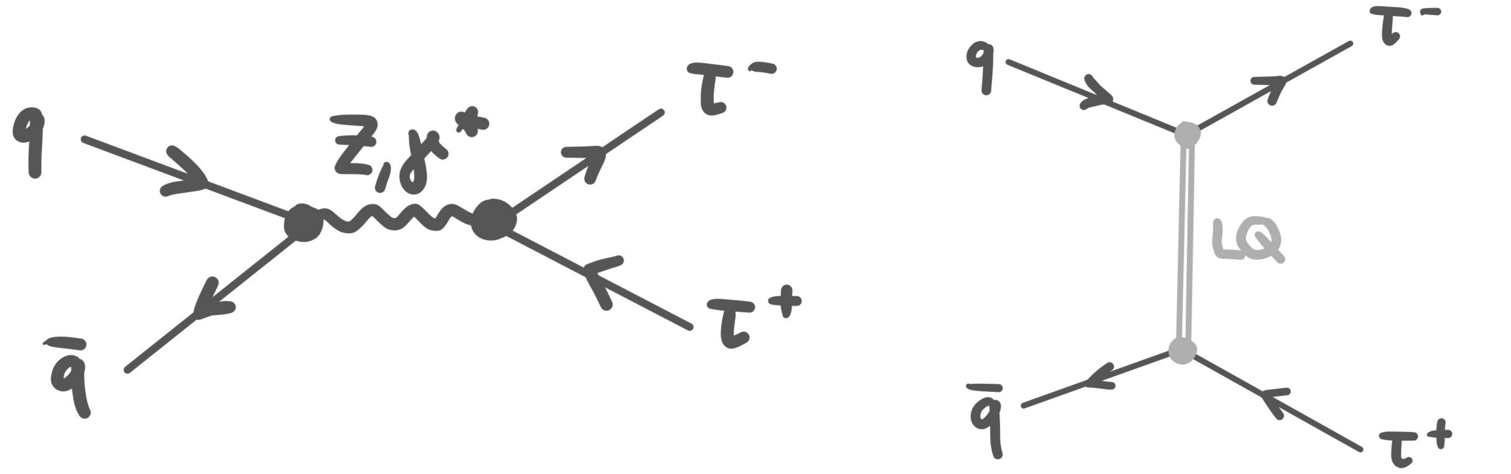

SM LO

LQ LO

LO: **MG5 + PS**

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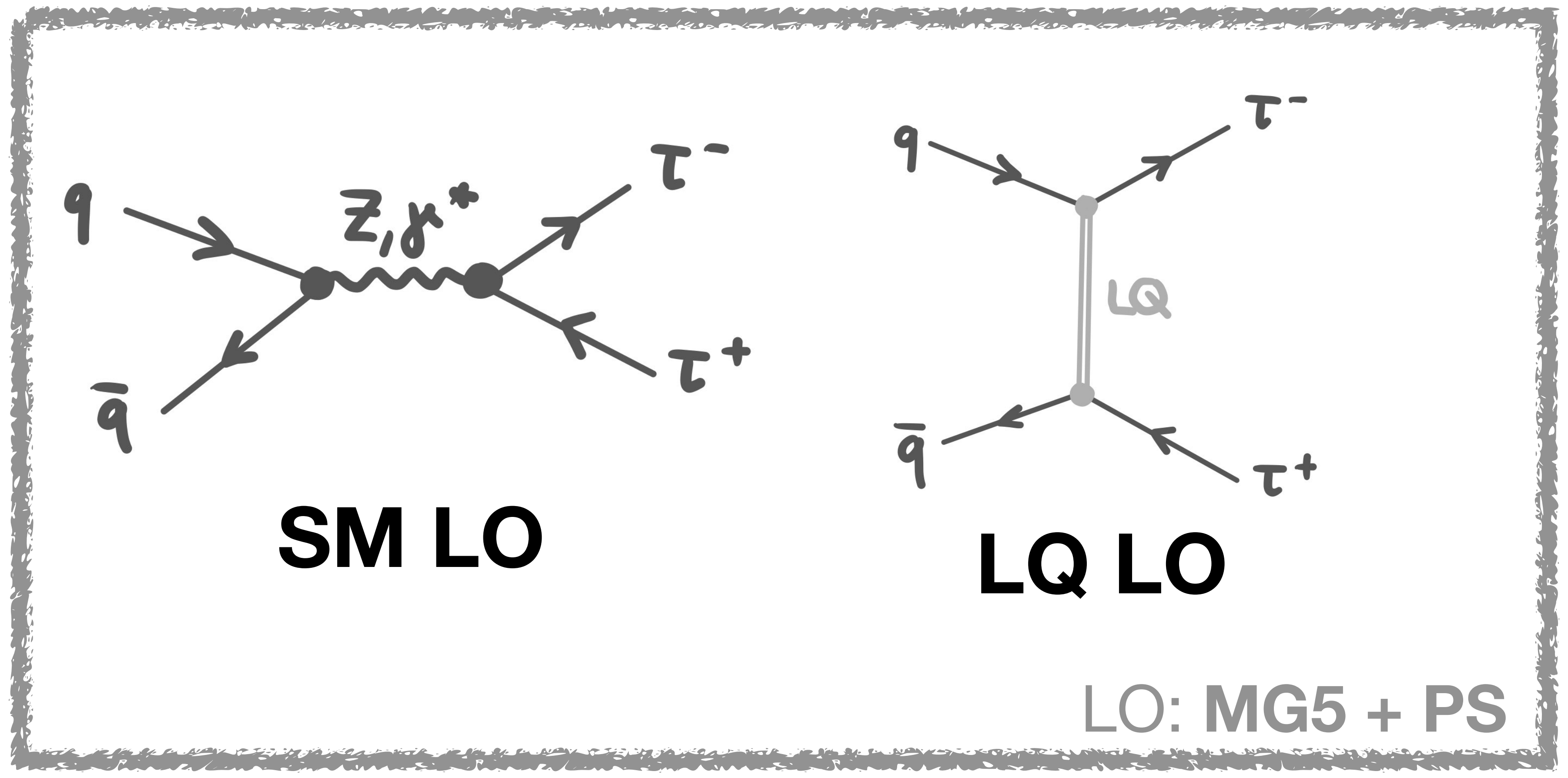

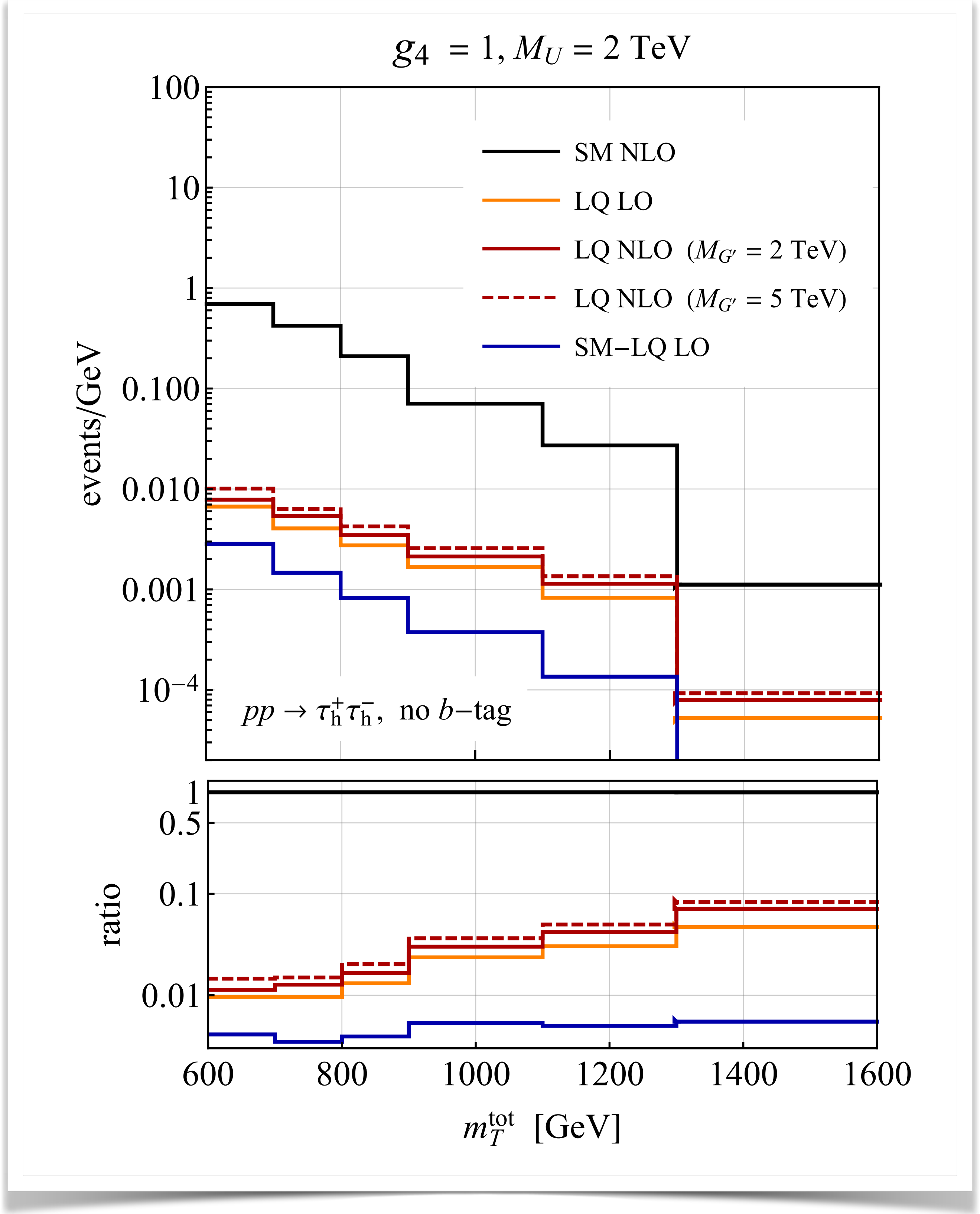

Source: ArXiv:2209.12780
(U. Haisch, LS, S. Schulte)

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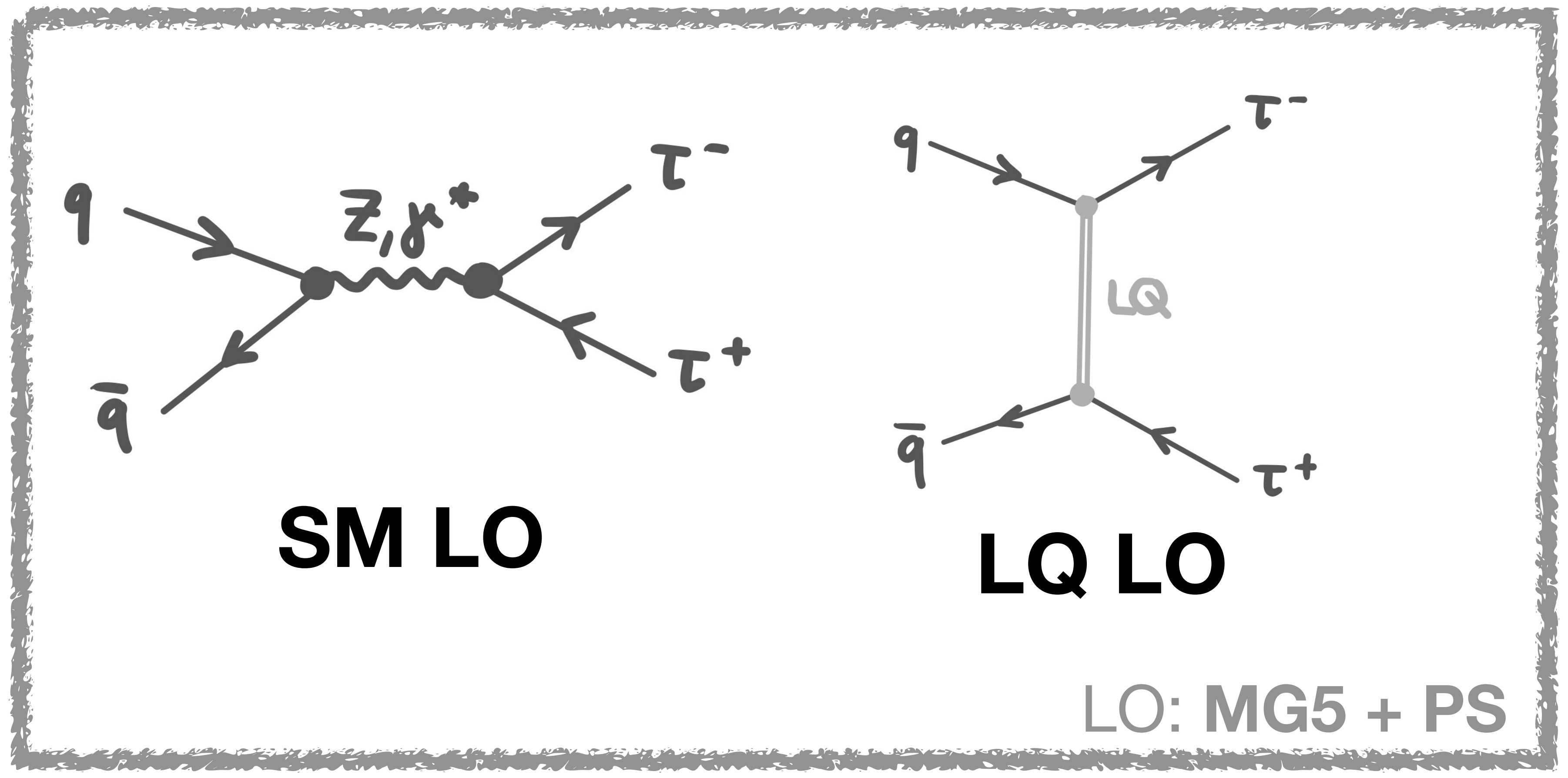

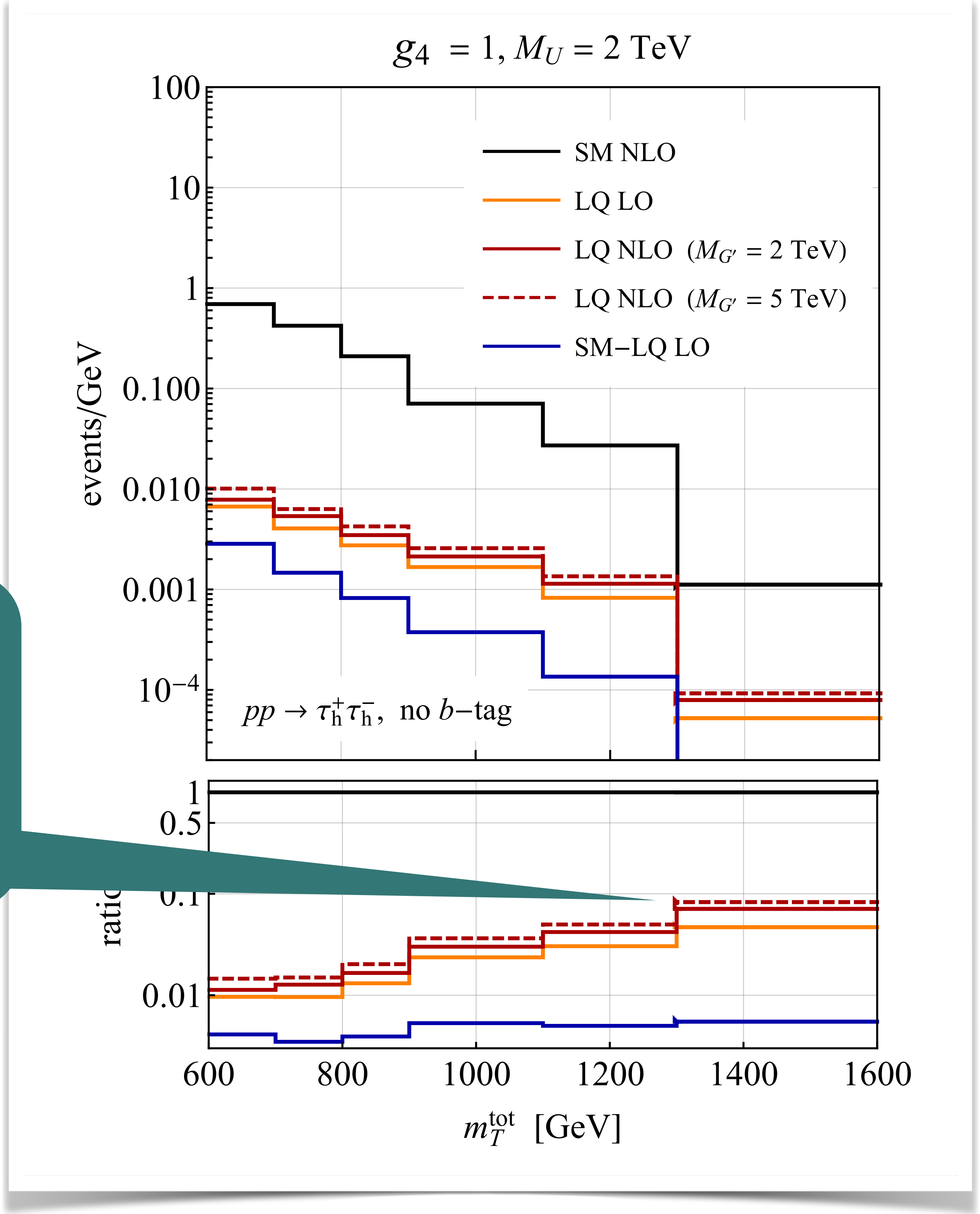

One can win over SM background in the tails.

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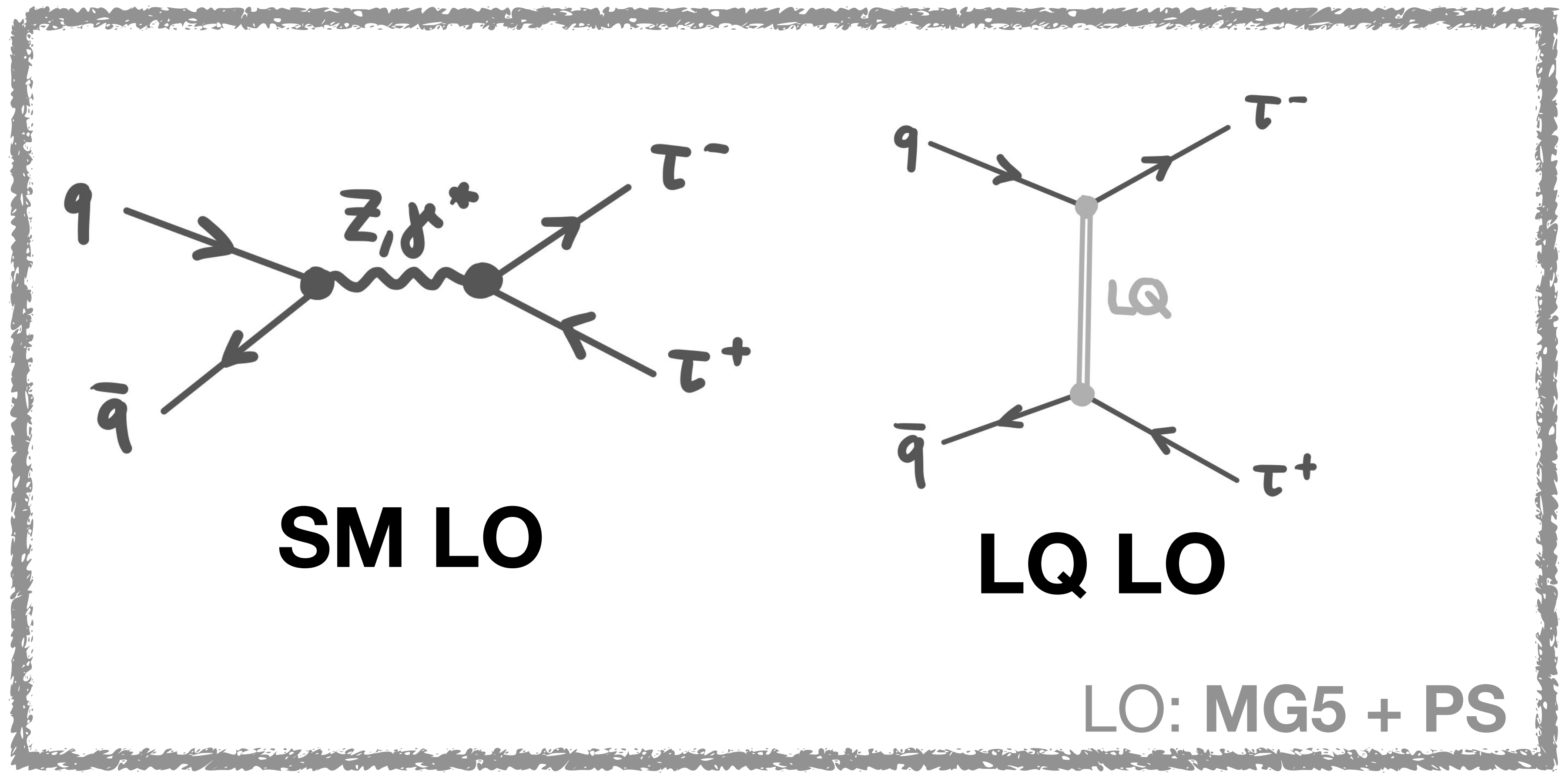

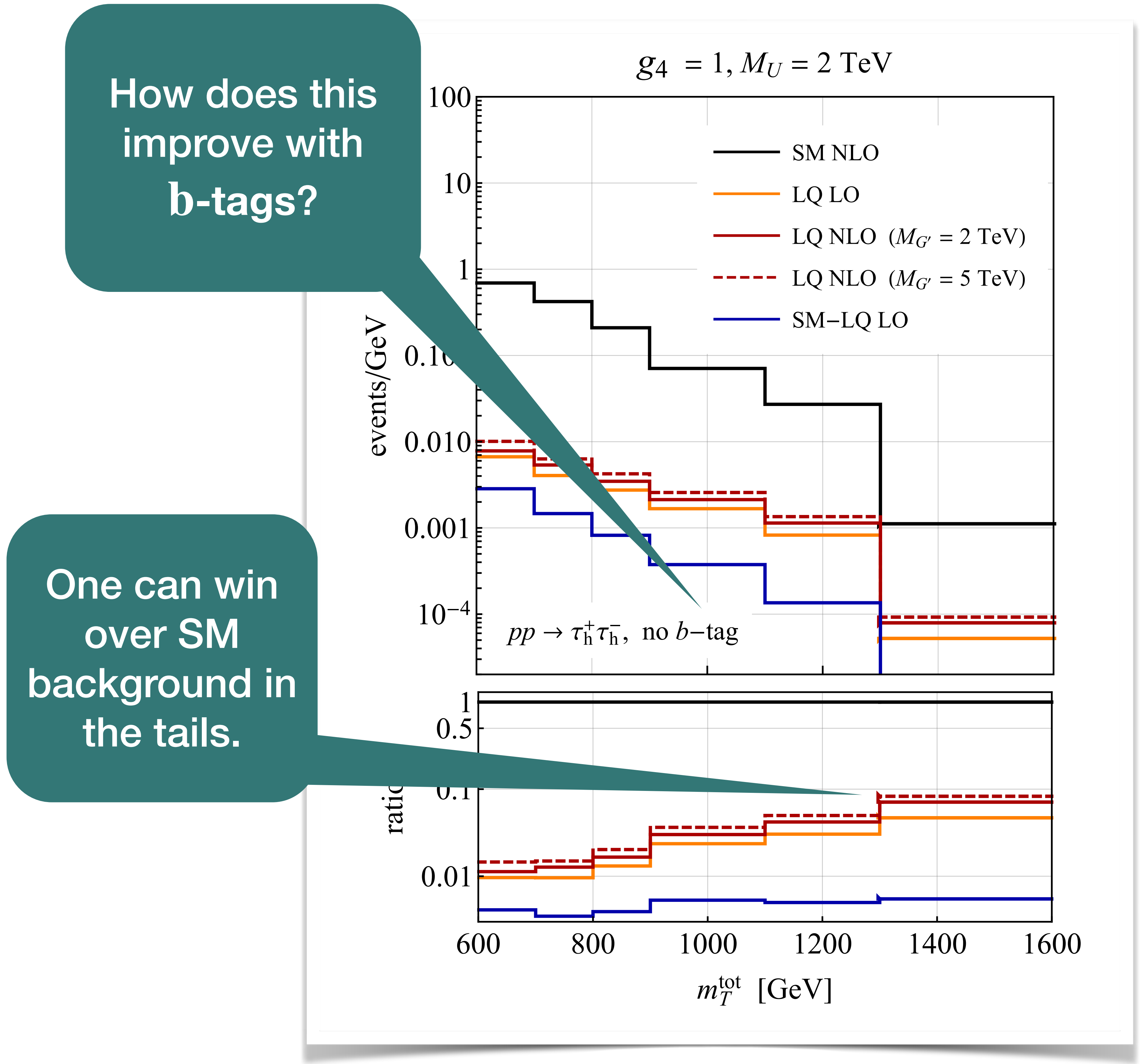

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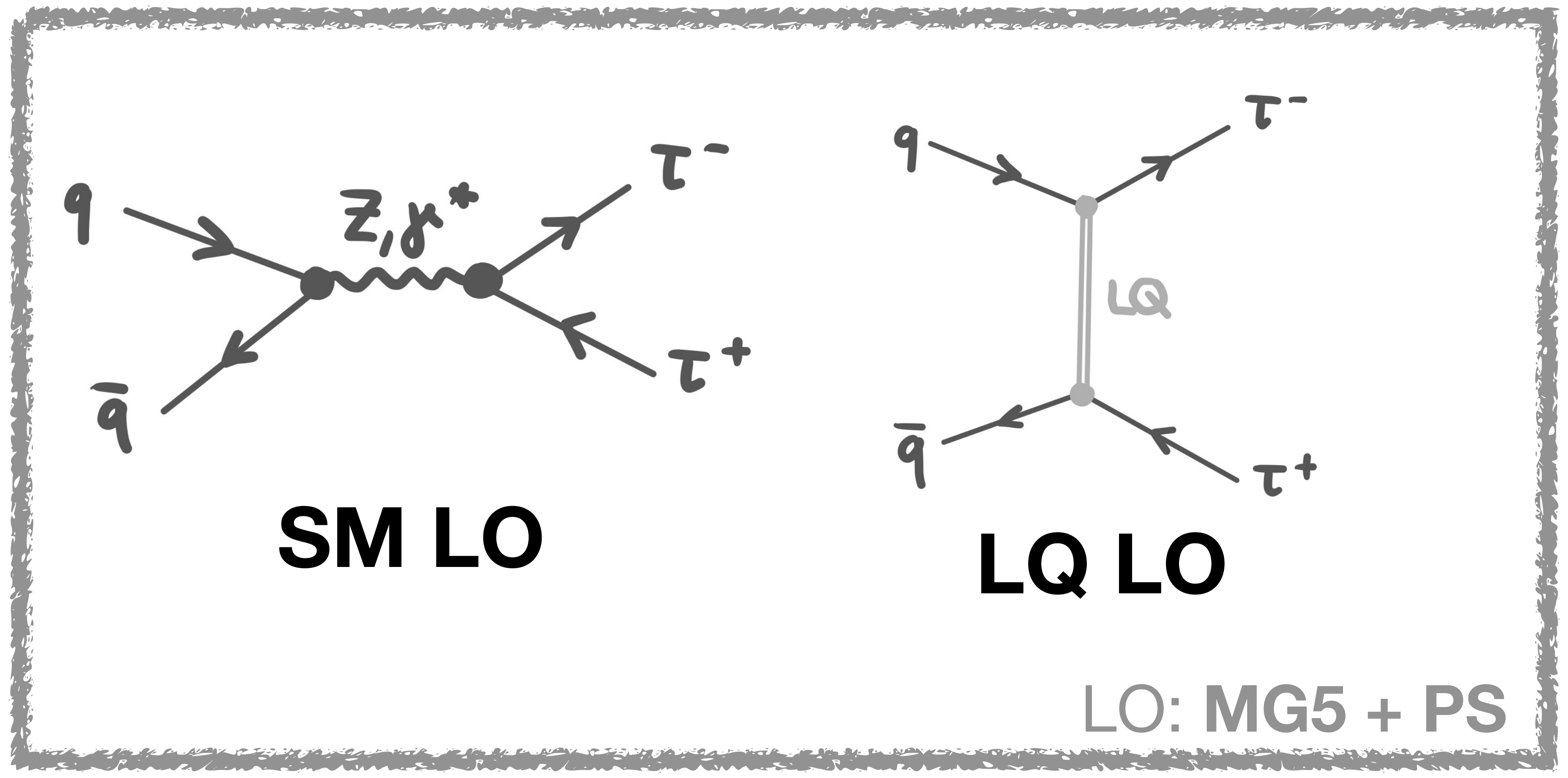
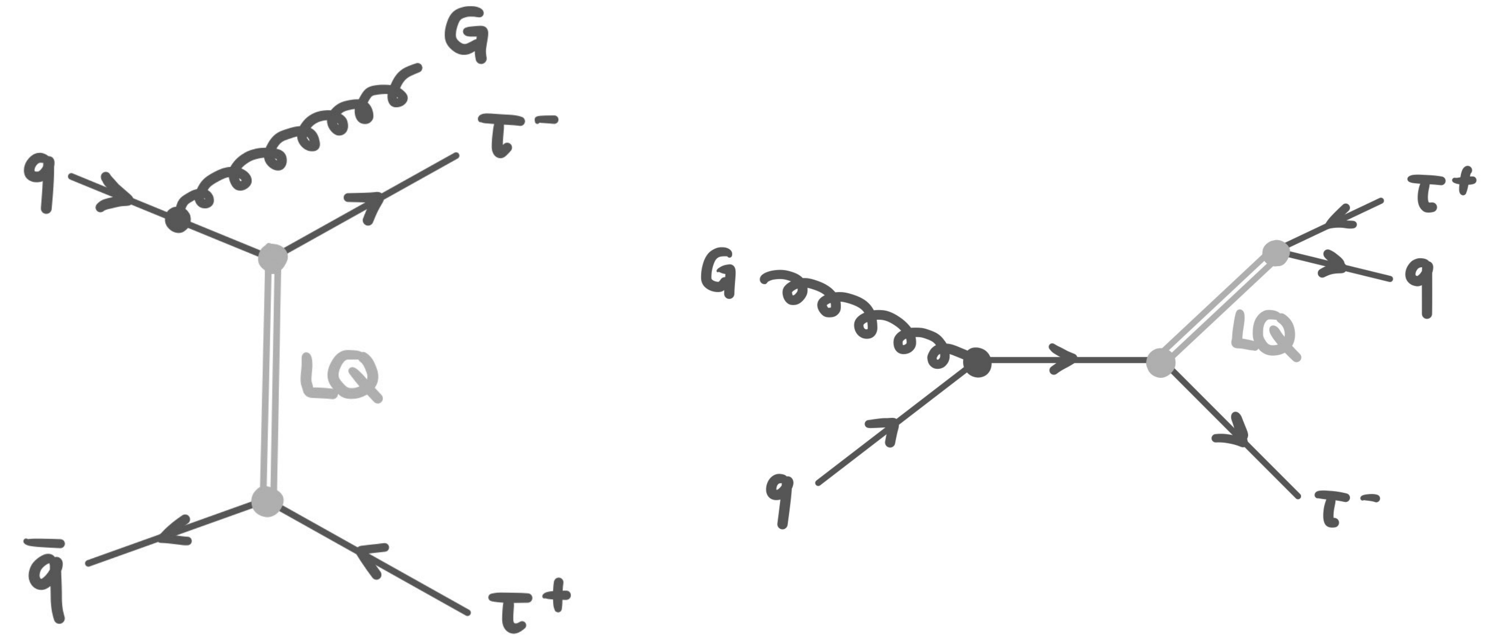


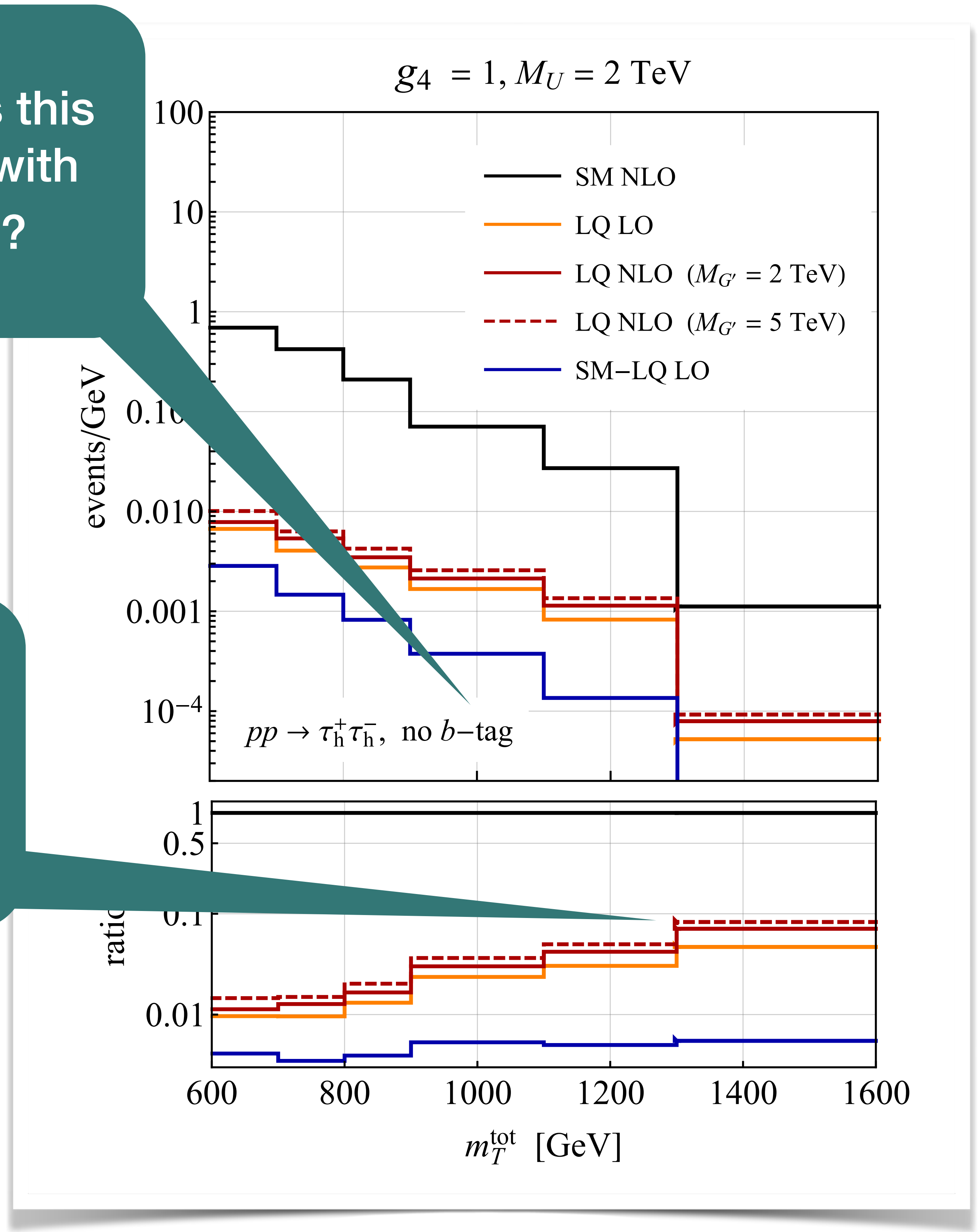


LQ NLO real (non-res.)

LQ NLO real (res.)

How does this improve with b-tags?

One can win over SM background in the tails.



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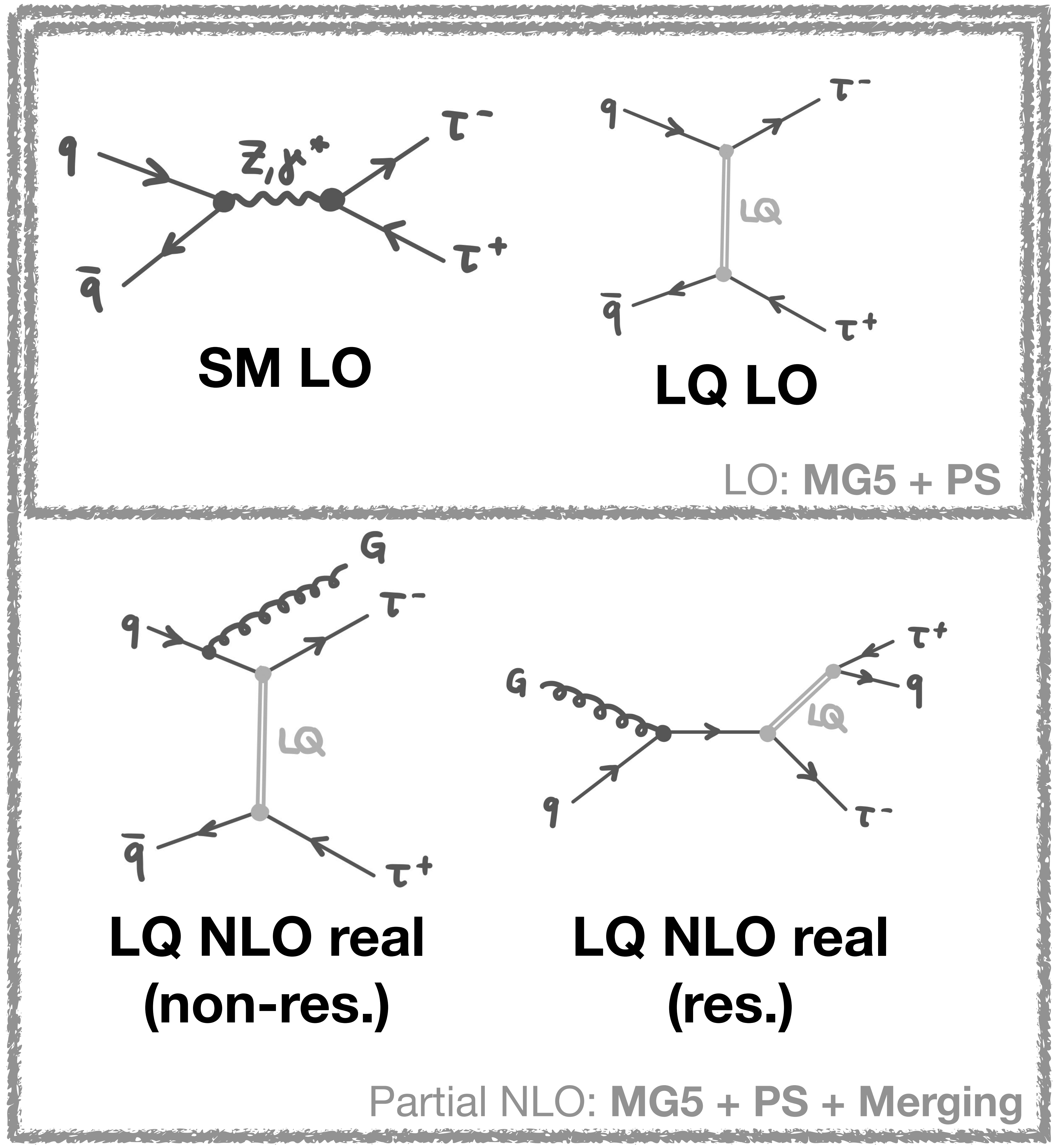

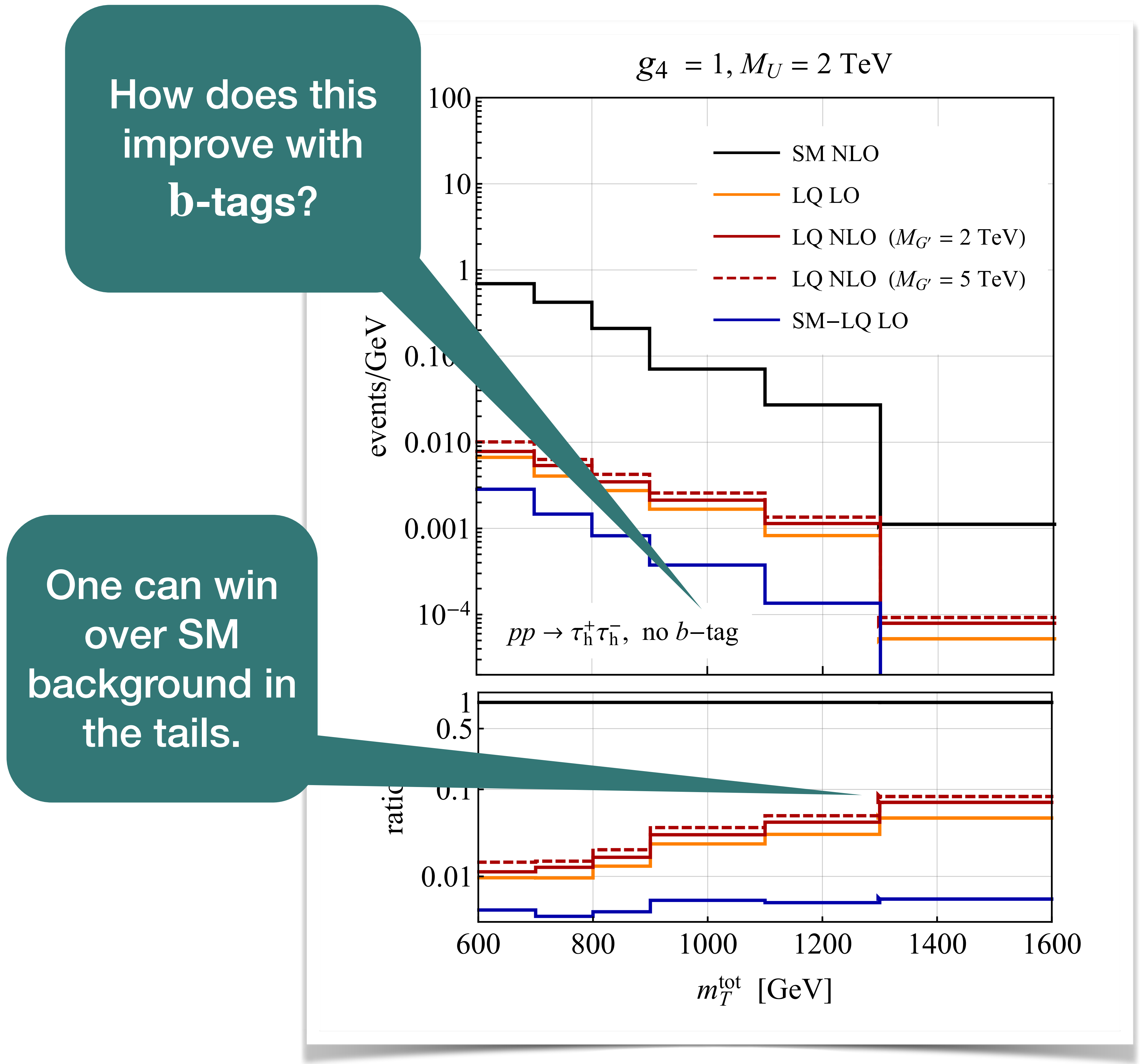

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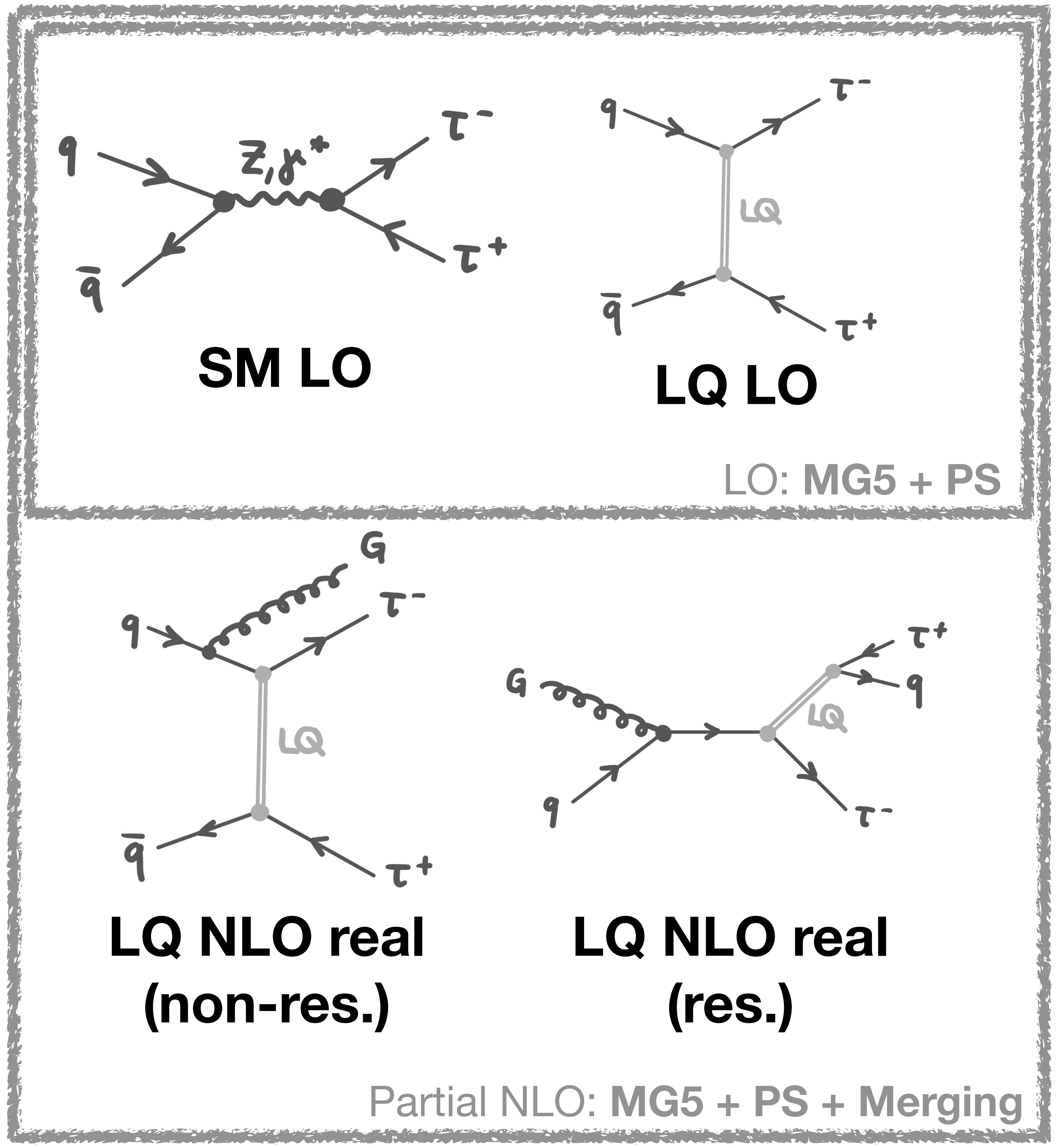
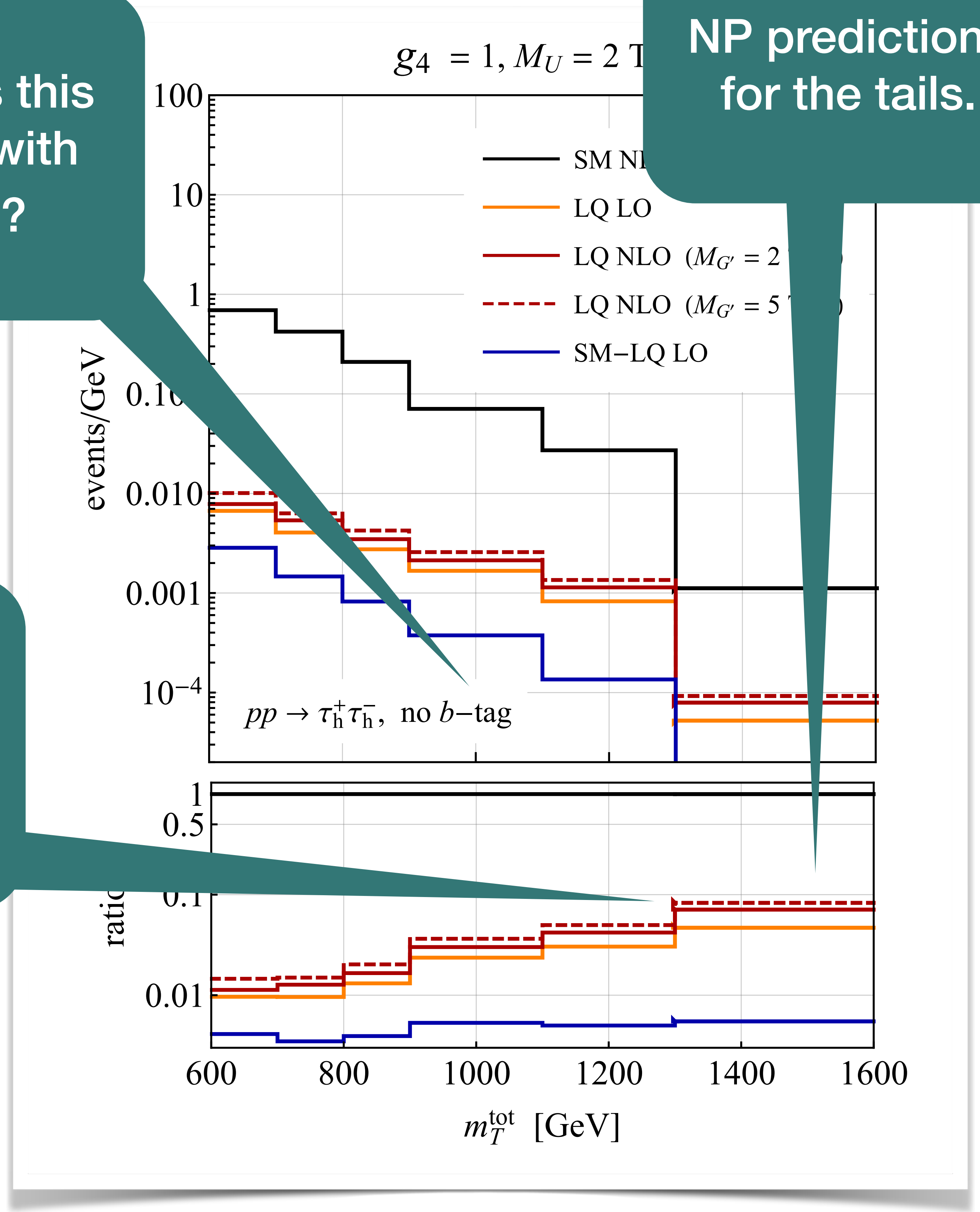


How does this improve with b-tags?

More accurate NP predictions for the tails.

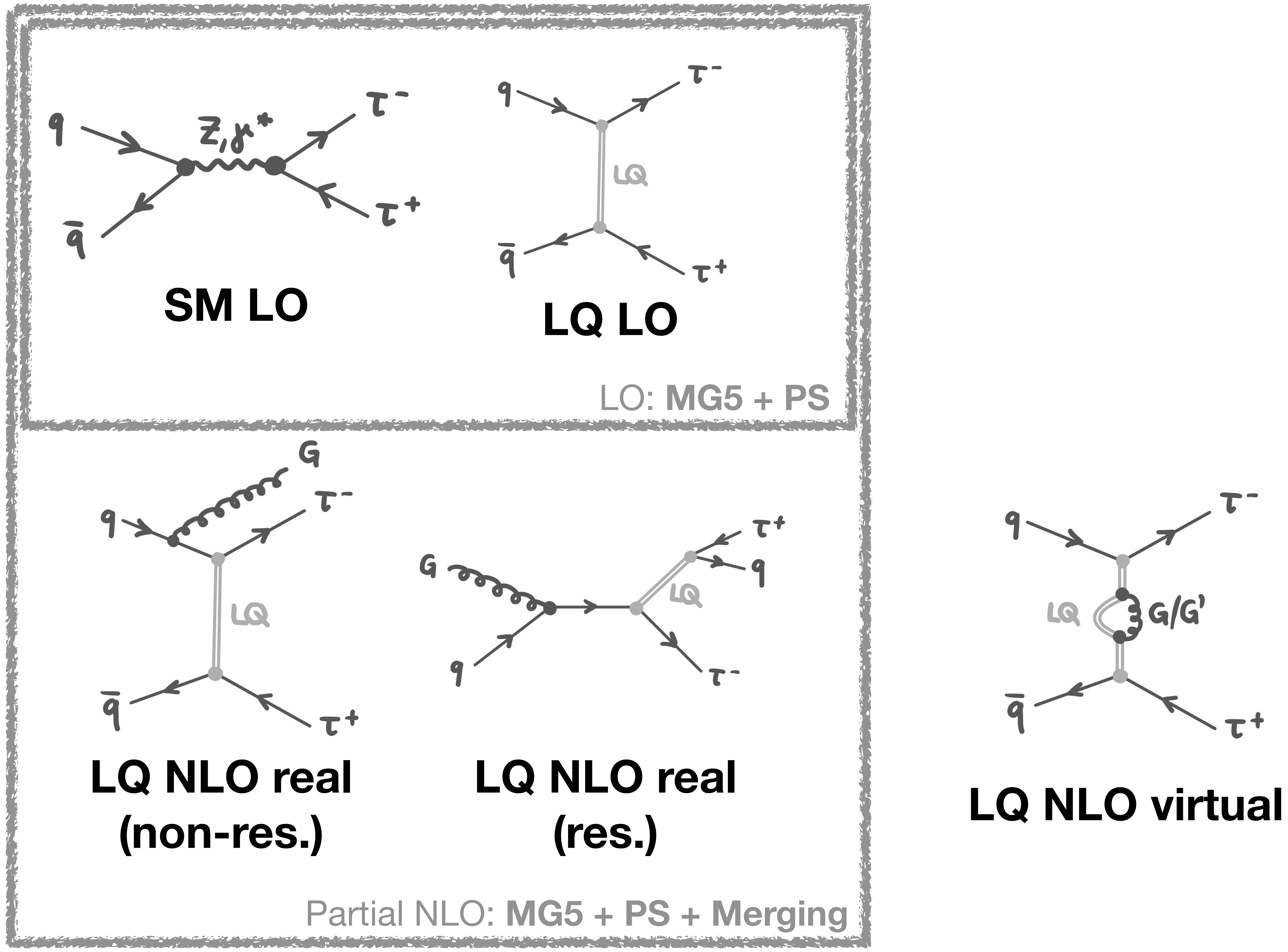
One can win over SM background in the tails.



Source: ArXiv:2209.12780
(U. Haisch, LS, S. Schulte)

2. Constraints from the LHC

2.2 Drell-Yan production: Going beyond the LQ LO



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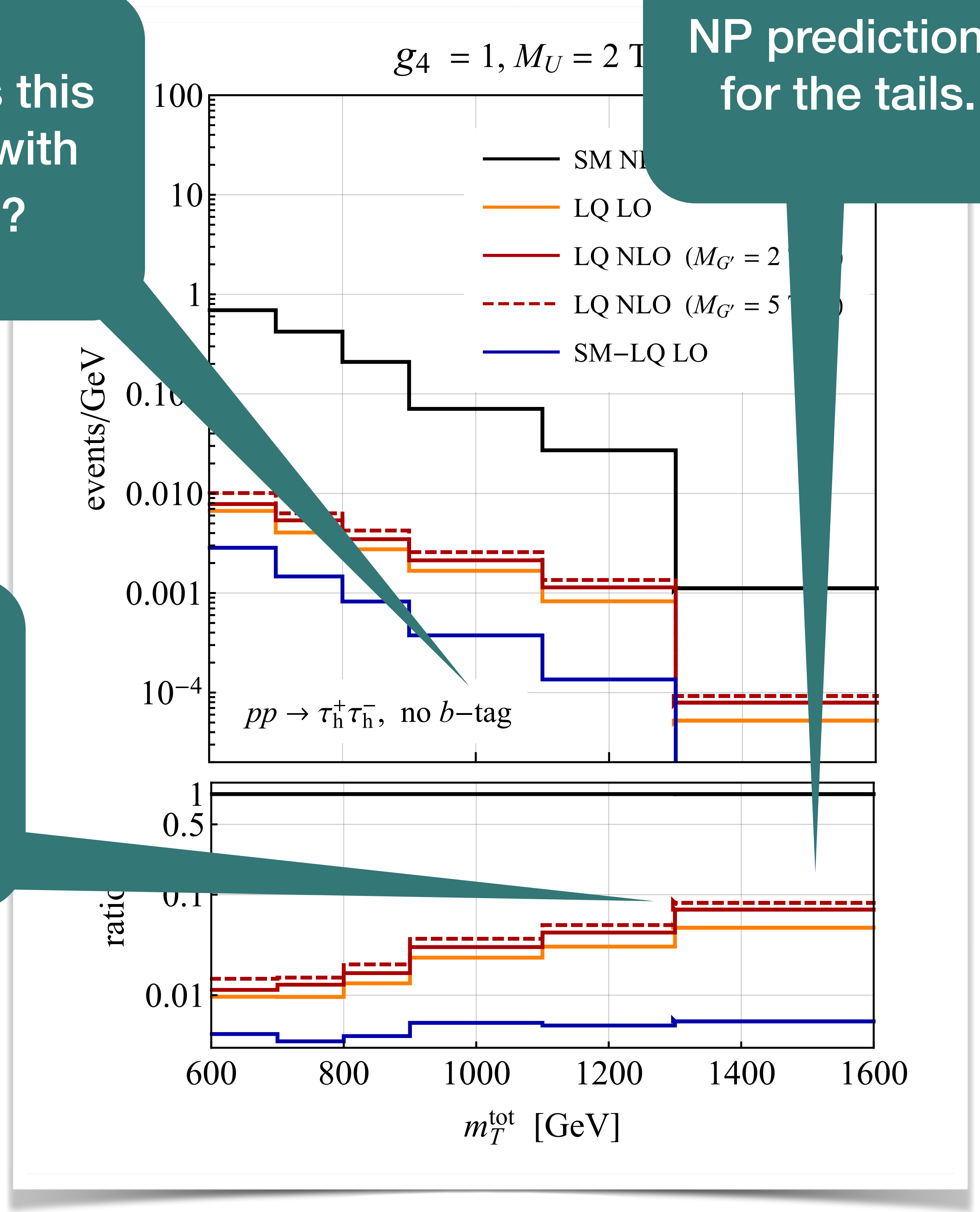

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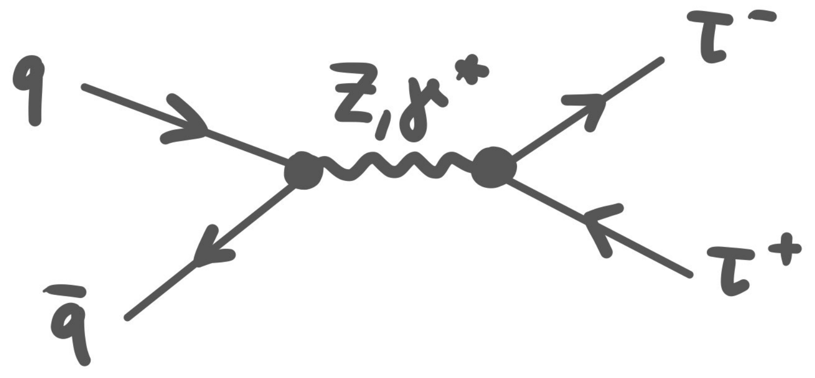
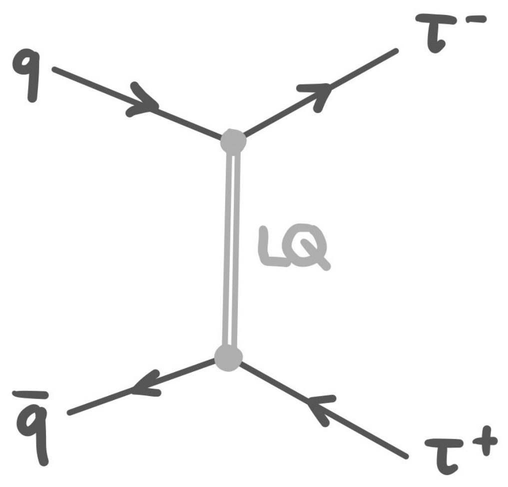
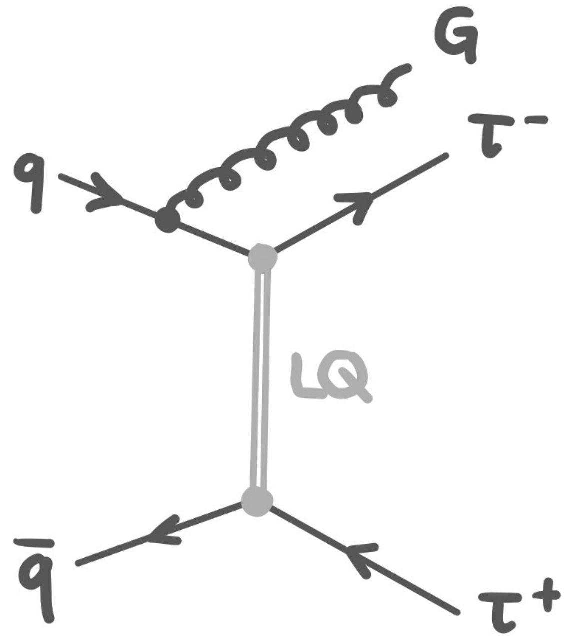


SM LO

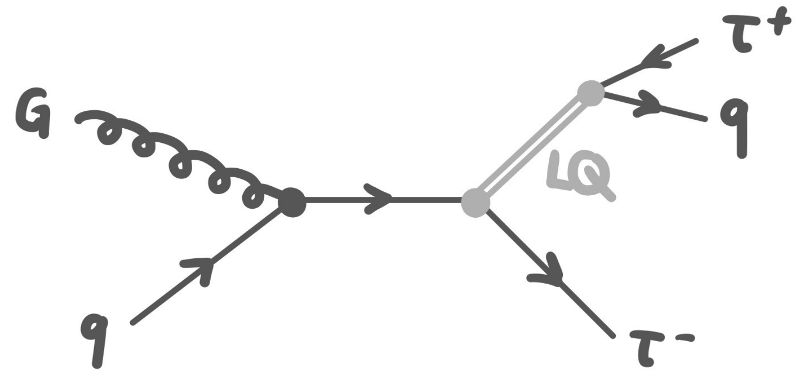


LQ LO

LO: **MG5 + PS**

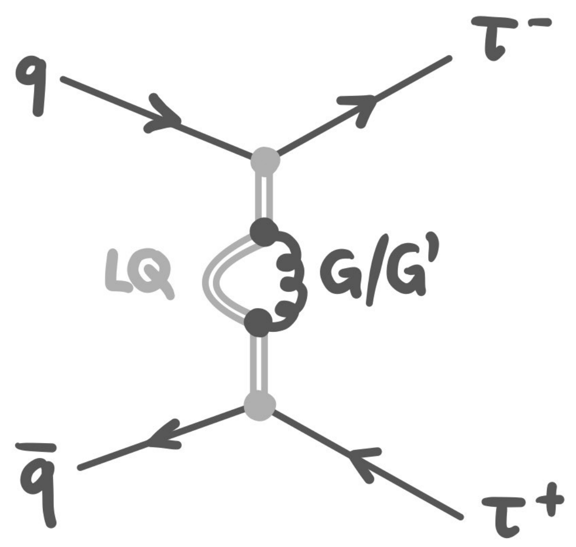


LQ NLO real (non-res.)



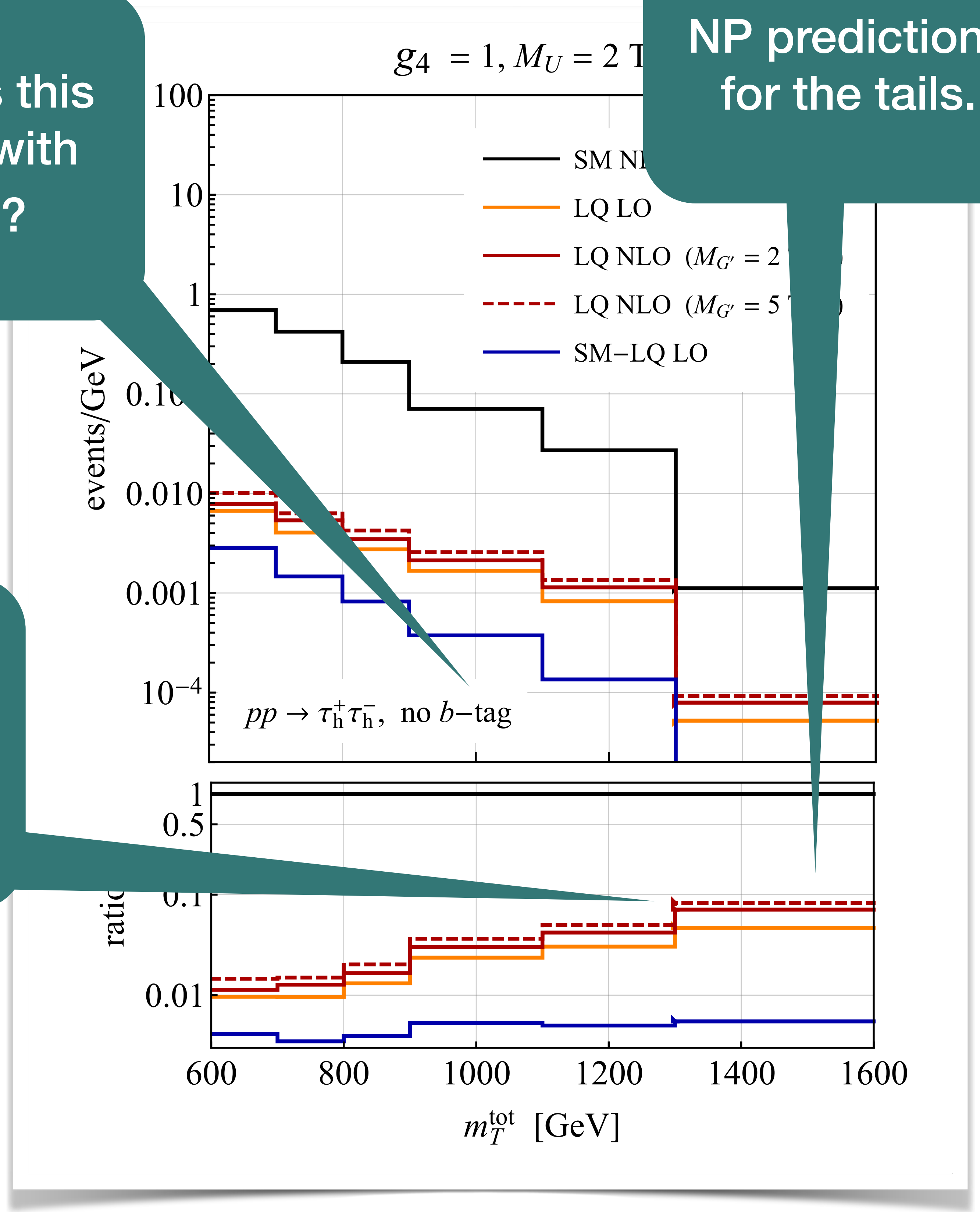
LQ NLO real (res.)

Partial NLO: **MG5 + PS + Merging**



LQ NLO virtual

Full NLO: **POWHEG-BOX + PS**



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2. Constraints from the LHC

2.2 Drell-Yan production: POWHEG-BOX implementation

2. Constraints from the LHC

2.2 Drell-Yan production: POWHEG-BOX implementation

Input parameters	Flavour structure and phase space	Matrix elements
powheg.input PhysPars.h init_couplings.f	Born_phsp.f init_processes.f	Born.f real.f virtual.f

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Matrix elements

Born.f
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Input parameters:

g4	0	**(Real)** Overall coupling-strength of the $SU(4)$ gauge group. This sets the overall coupling strength of U to fermions.
betaL3x3	1	**(Real)** Relative strength of U to left-handed fermions of the third generation ($t_L \nu_\tau$ and $b_L \tau_L$).
betaR3x3	1	**(Real)** Relative strength of U to right-handed fermions of the third generation ($b_R \tau_R$).
MU1	10000	**(Real)** Mass (in GeV) of U.
MGp	10000	**(Real)** Mass (in GeV) of the coloron G'.

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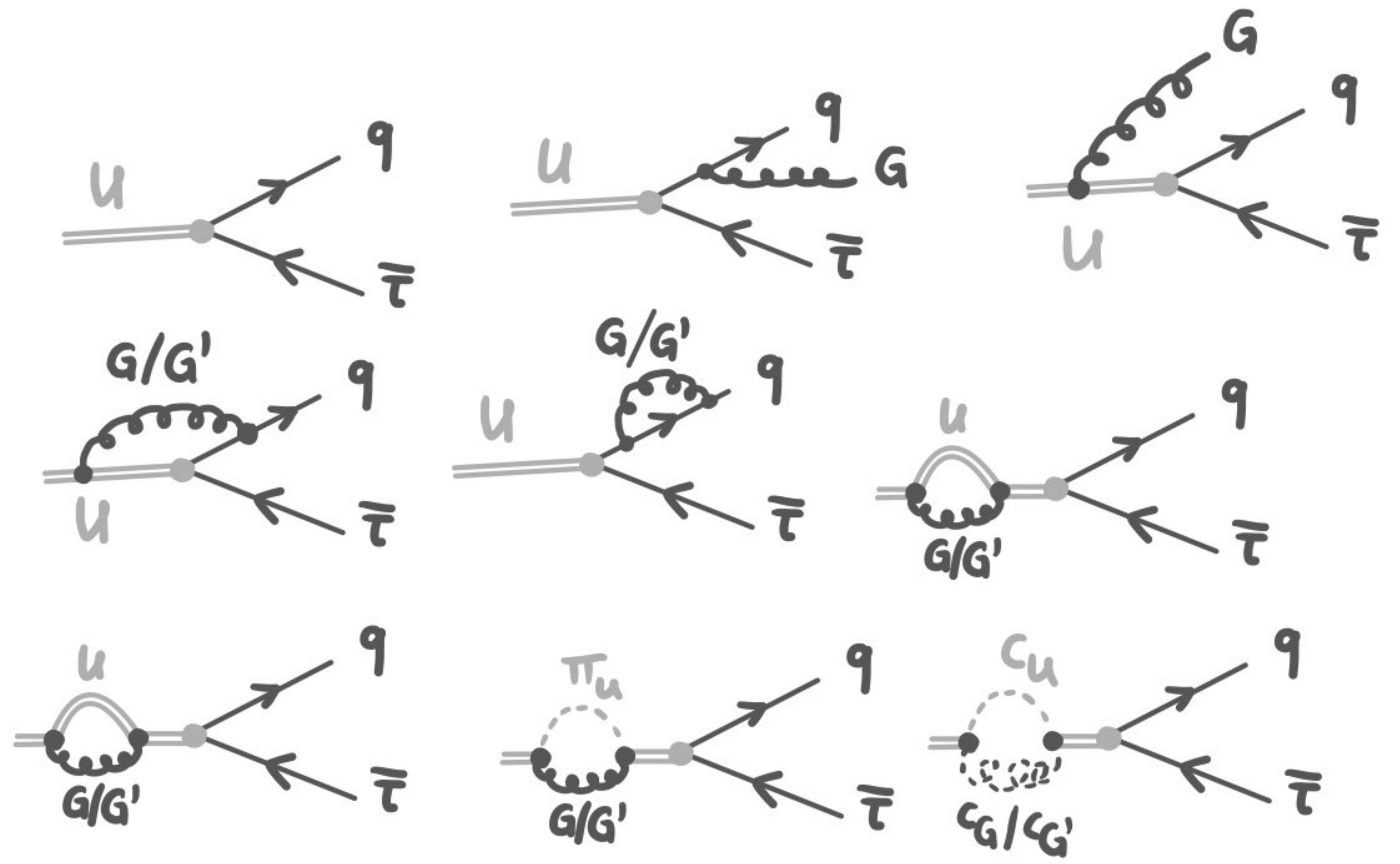
NLO width (PackageX, cross-checked with **FormCalc):**

$$\Gamma\left(U \to b\tau\right) = \frac{g_4^2 M_U}{24\pi}\left(1+\Delta\right) ,$$

$$\Delta = \frac{\alpha_s}{4\pi}\, f\left(x_{G'/U}\right) ,$$

$$f(1) = 76/3 - 32\pi/(3\sqrt{3}),$$



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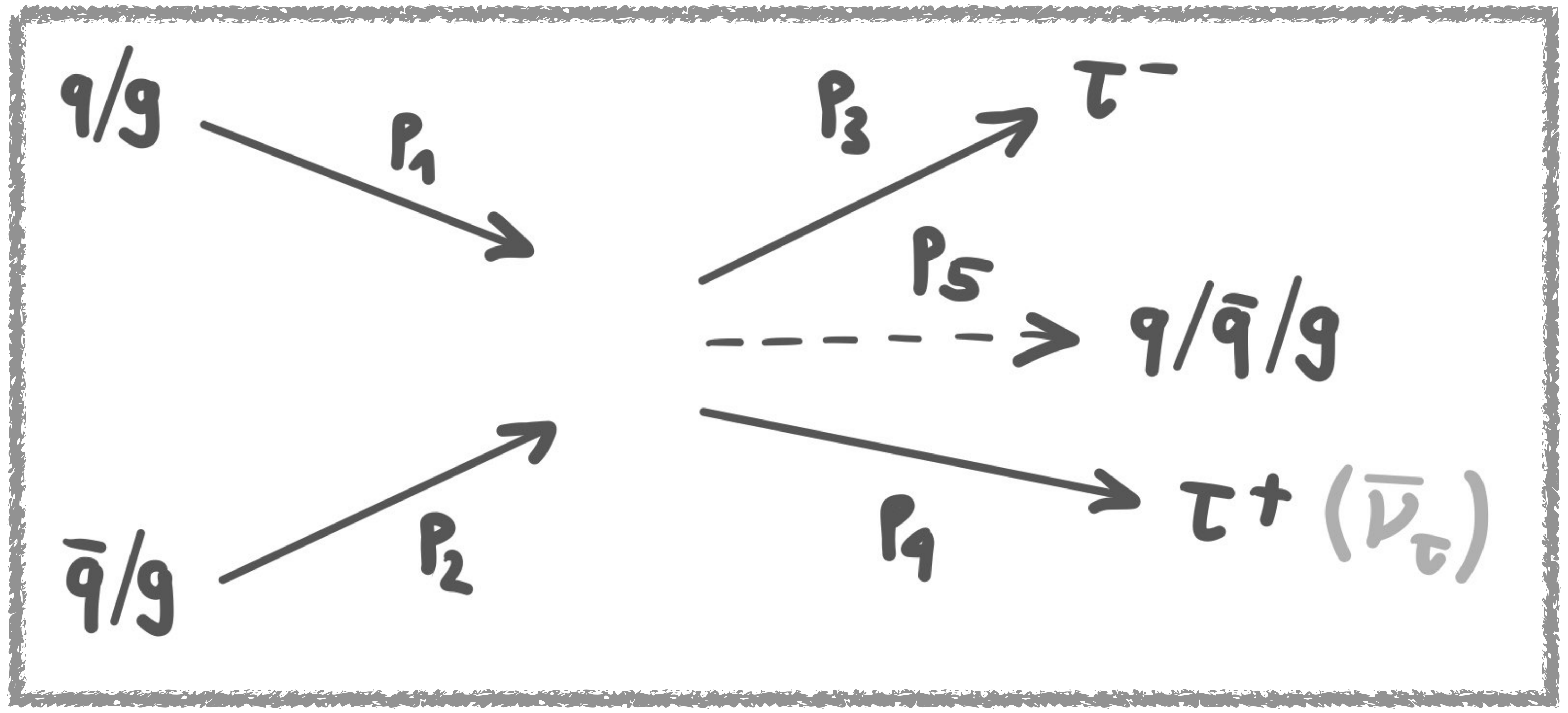
Kinematics the same as in the SM:

- We focussed on $pp \to \tau^+\tau^- + X$.
- There are ideas to extend this to $pp \to \tau\nu_\tau + X$.



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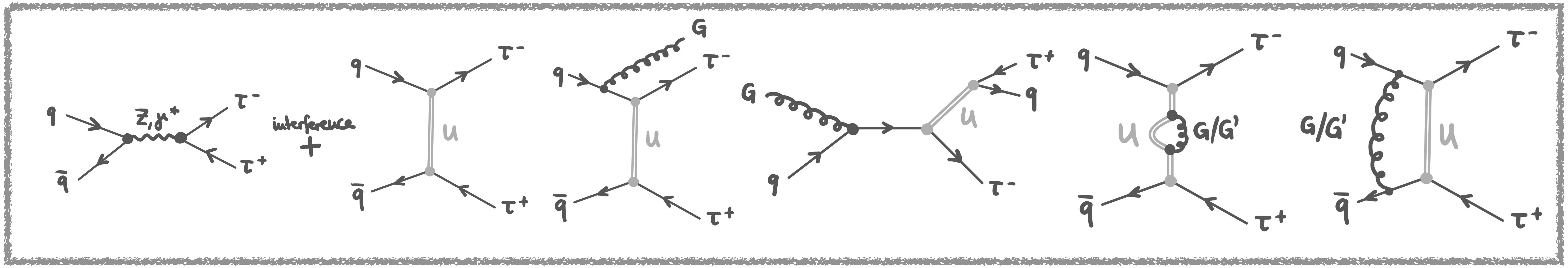

- Calculation with **PackageX**, cross-checked with **FormCalc**, numerical evaluation with **LoopTools.**
- **UV divergences cancel** between the G and G' contributions, IR divergences handled with **dimensional regularisation**.

2. Constraints from the LHC

2.2 Drell-Yan production: POWHEG-BOX implementation

2. Constraints from the LHC

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2.2 Drell-Yan production: POWHEG-BOX implementation

```fortran
c LS: We express the virtual corrections below using the Mandelstam variables
          S = 2d0 * dotp(p(0:3,1),p(0:3,2))
          T = -2d0 * dotp(p(0:3,3),p(0:3,1))
          U = -2d0 * dotp(p(0:3,2),p(0:3,3))

c LS: Ratio between the coloron and U1 mass squared
          x = ph_MGp**2/ph_MU1**2

c ==============================================
c Factorizeable virtual corrections
c
c
c LS: These include the one-particle reducible
c     diagrams. The other contributions
c     (box diagrams) are implemented below.
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c ---------------------------------------------------------------------------
c LS: b-quark field strength renormalization
c ---------------------------------------------------------------------------
c LS: This agrees with the result in ArXiv:2006.16250
c UH 15/9/22: Checked!

          deltaZb = 4/3*(Log(dcmplx(st_muren2/ph_MU1**2))
     #- Log(dcmplx(x)) - 0.5d0)
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Fortran code

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- It can be used to **generate events** (.lhe and .hepmc) for dedicated MC studies.
- We have also implemented the contributions from **SLQs**, this is available on **GitLab** and the **POWHEG-BOX** website, too.

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

2. Constraints from the LHC

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Inclusive $m_{\tau\tau}$ spectra:

2. Constraints from the LHC

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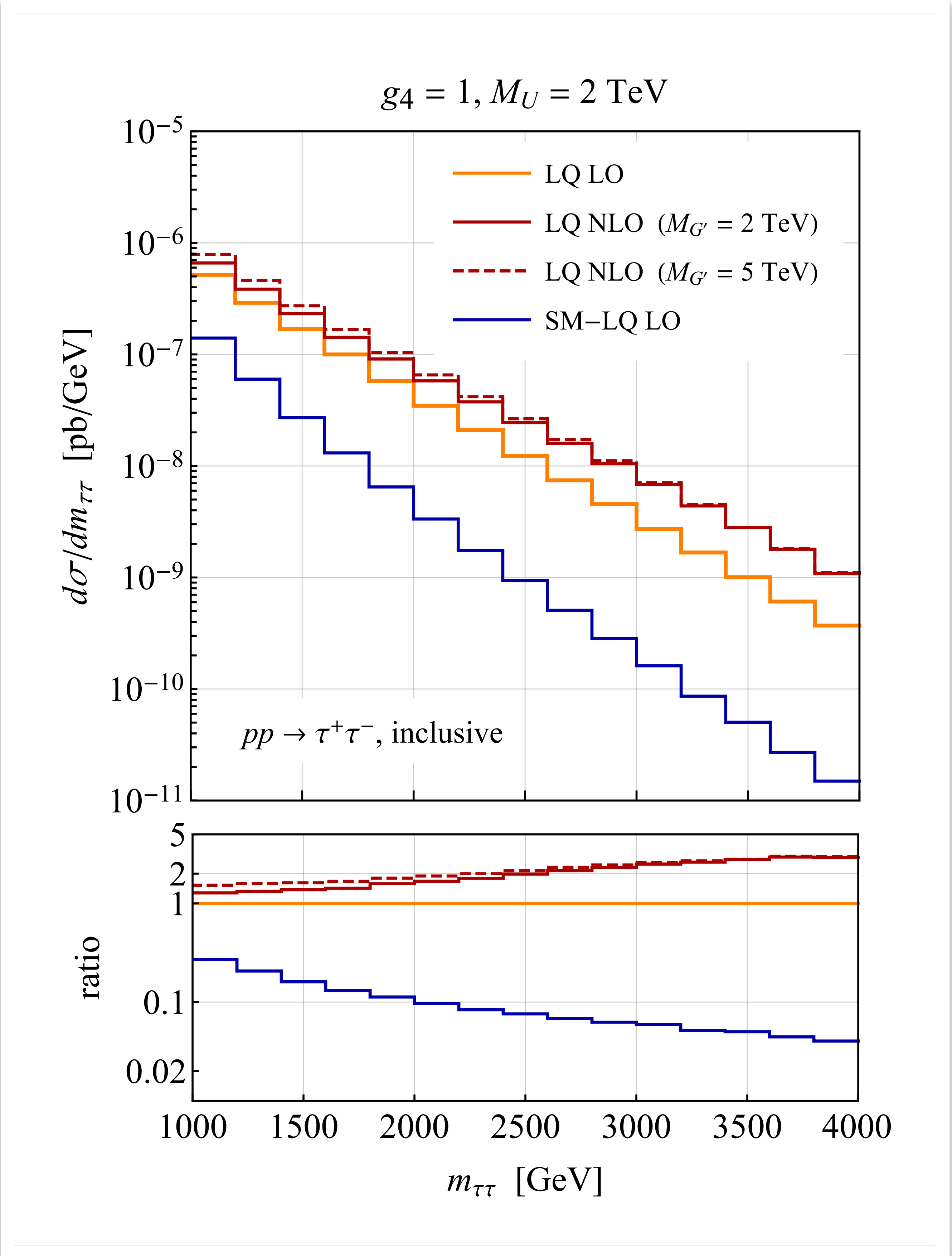

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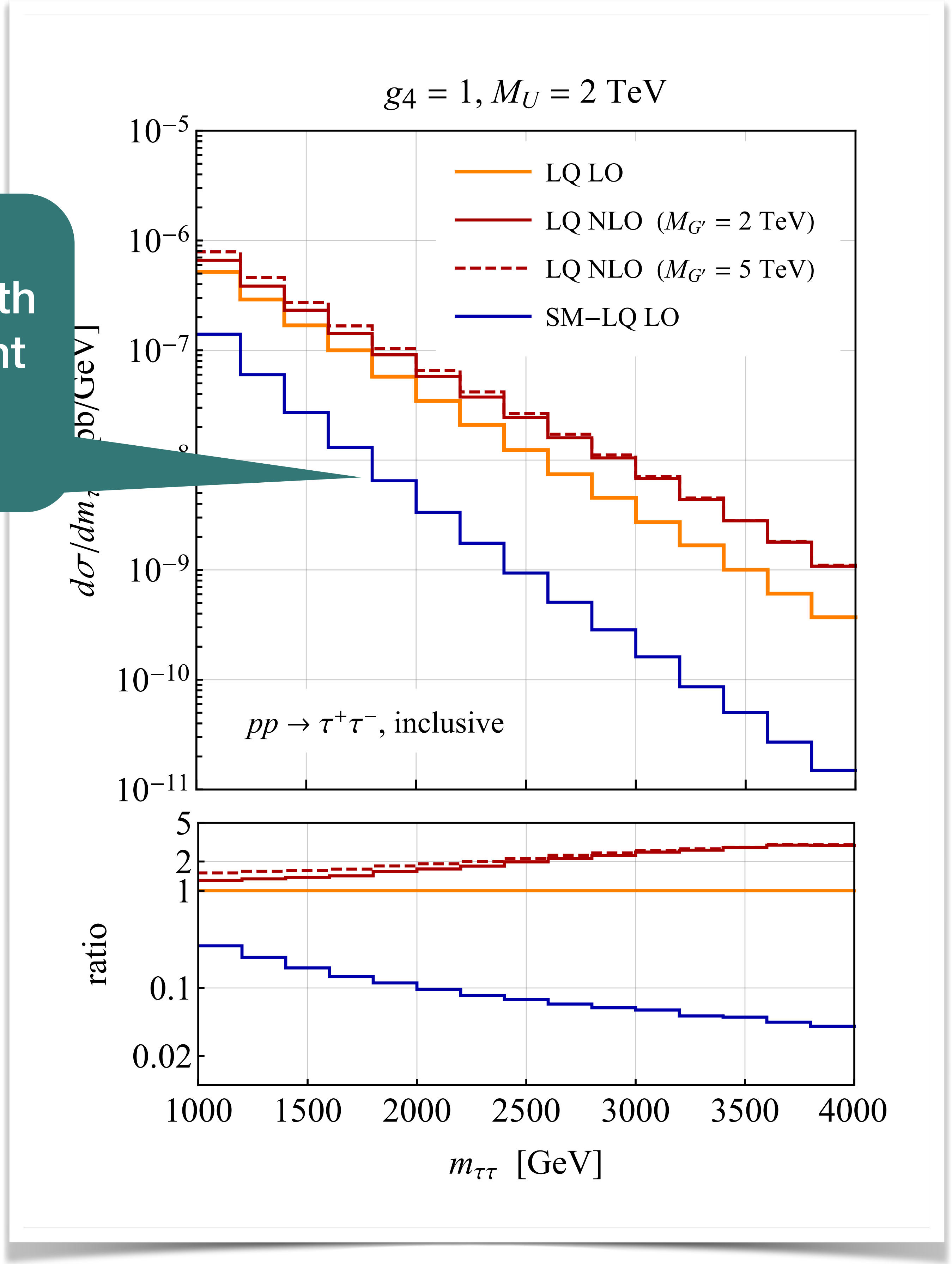

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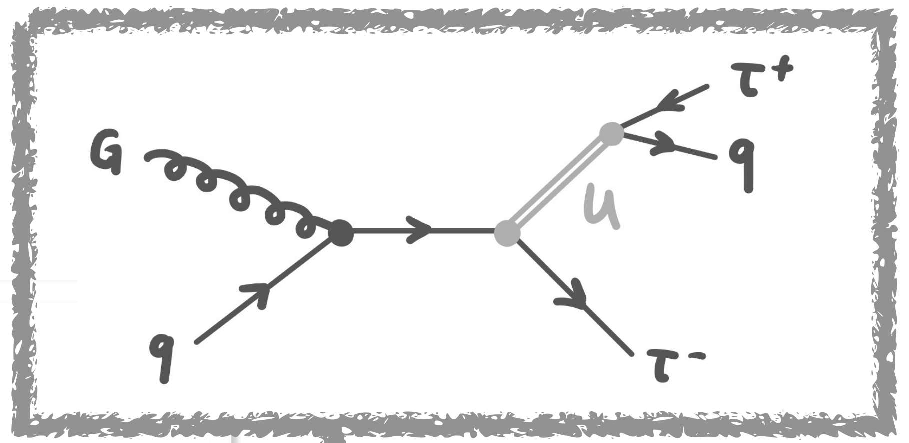

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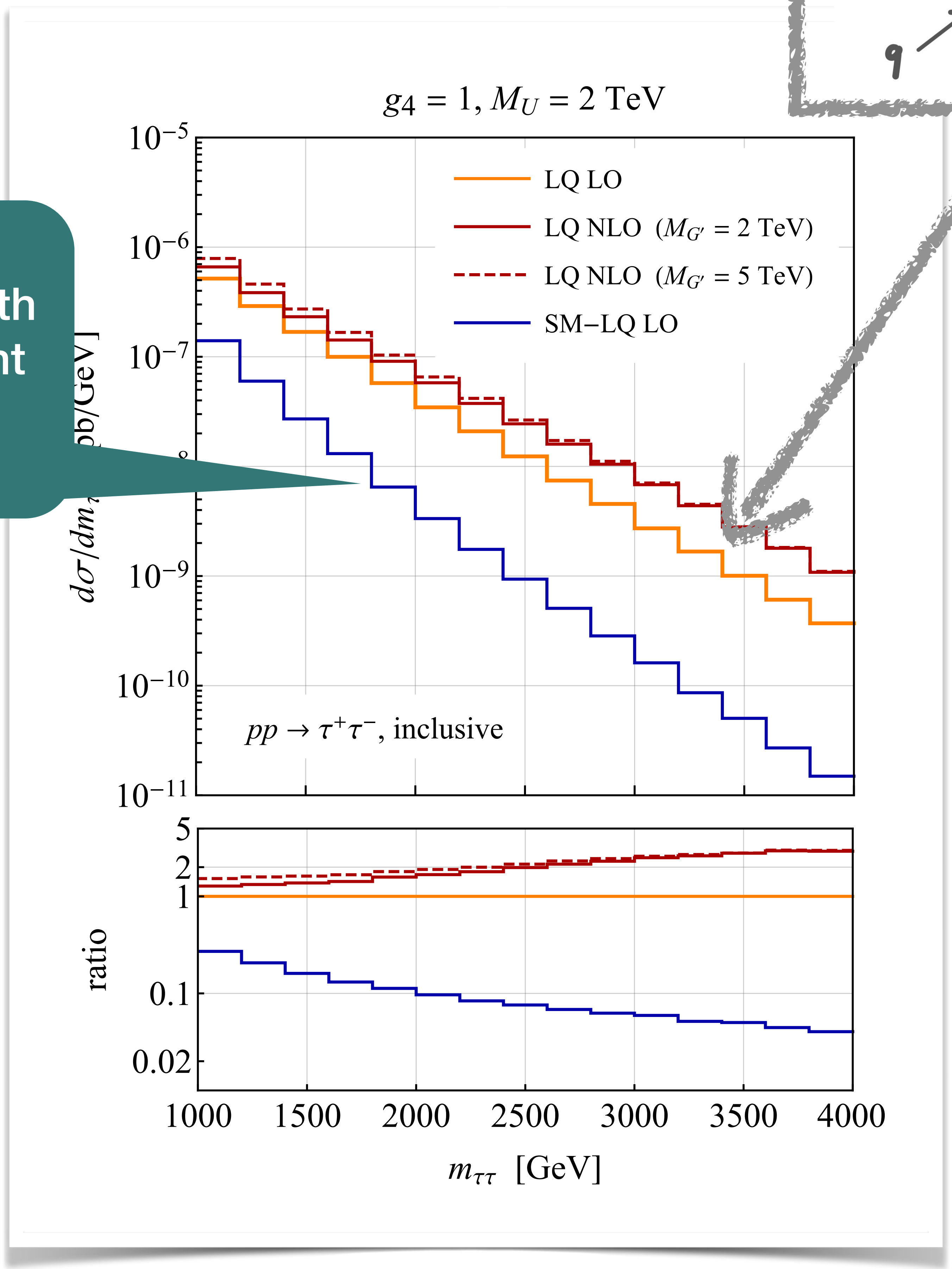

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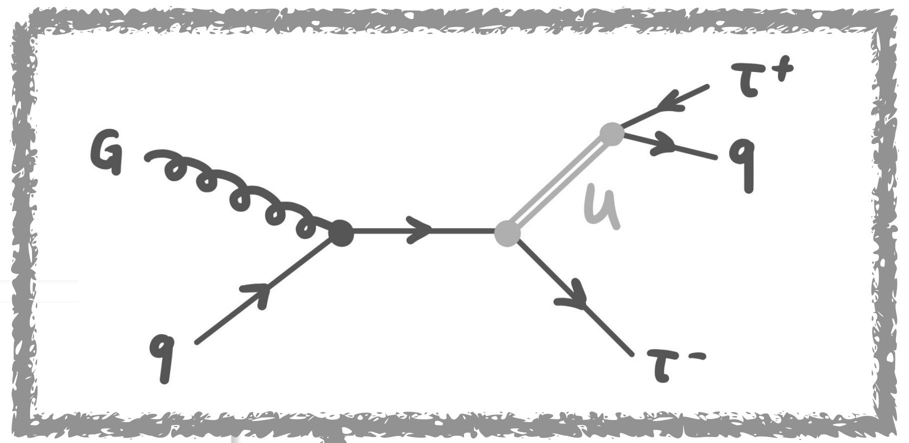
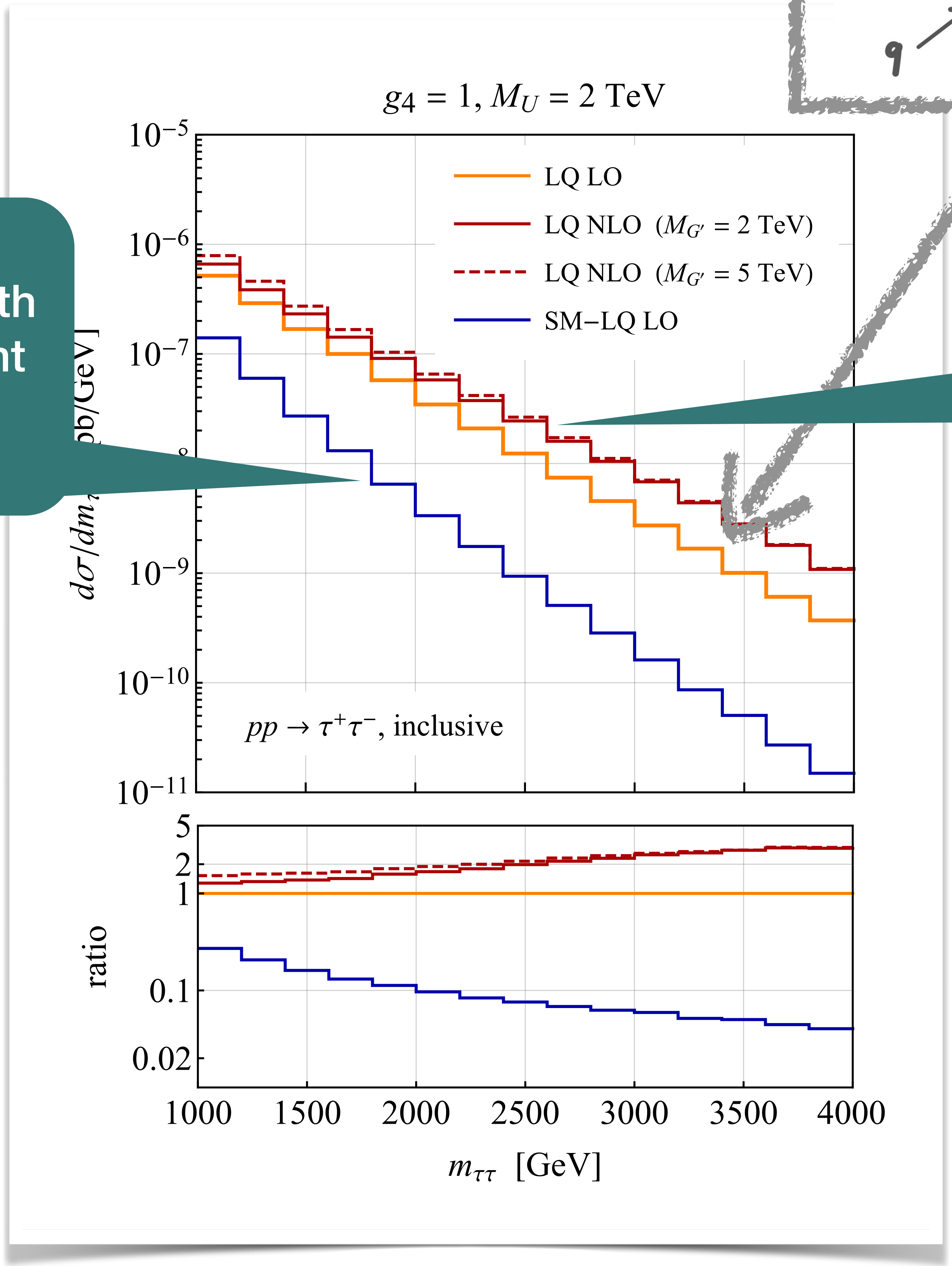


Dependence on $M_{G'}$ rather small.

Interference with SM not relevant in the tails.



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b-tag/b-veto:

- Full NLO+PS analysis, LHC cuts modelled in **MadAnalysis5** (normal + expert mode).

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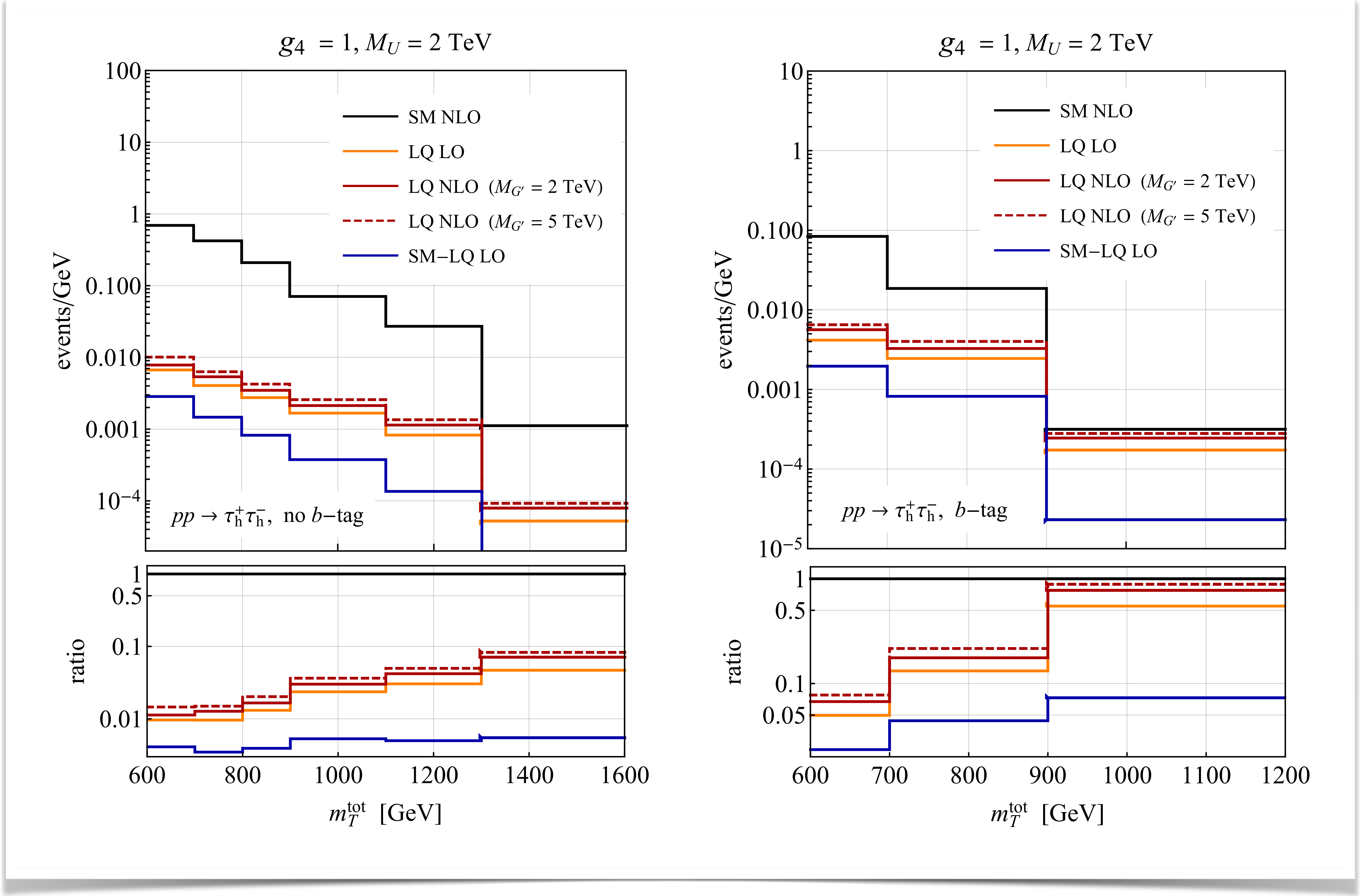

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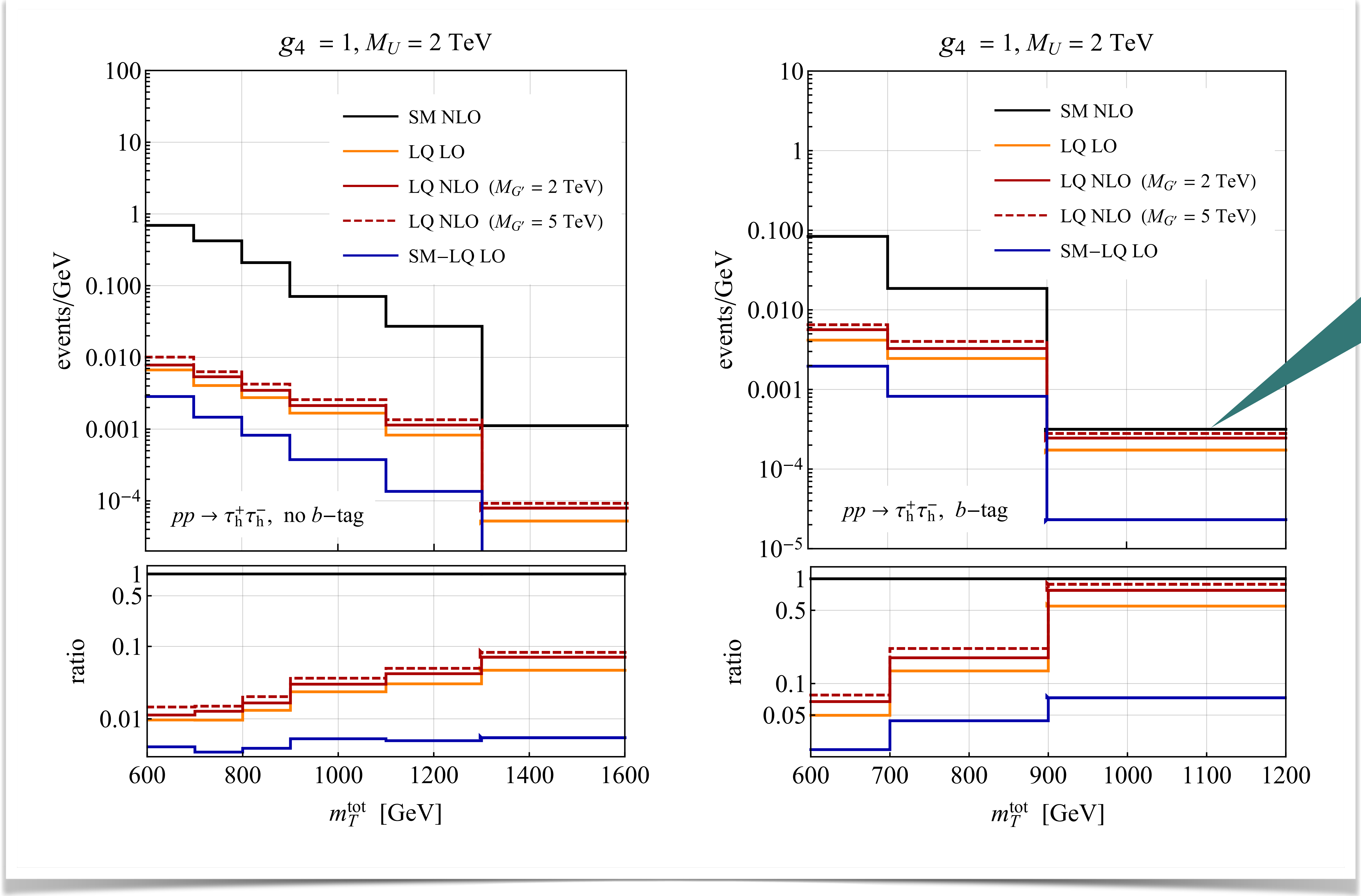

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Signal-to-background ratio is enhanced with **b-tags.**

2. Constraints from the LHC

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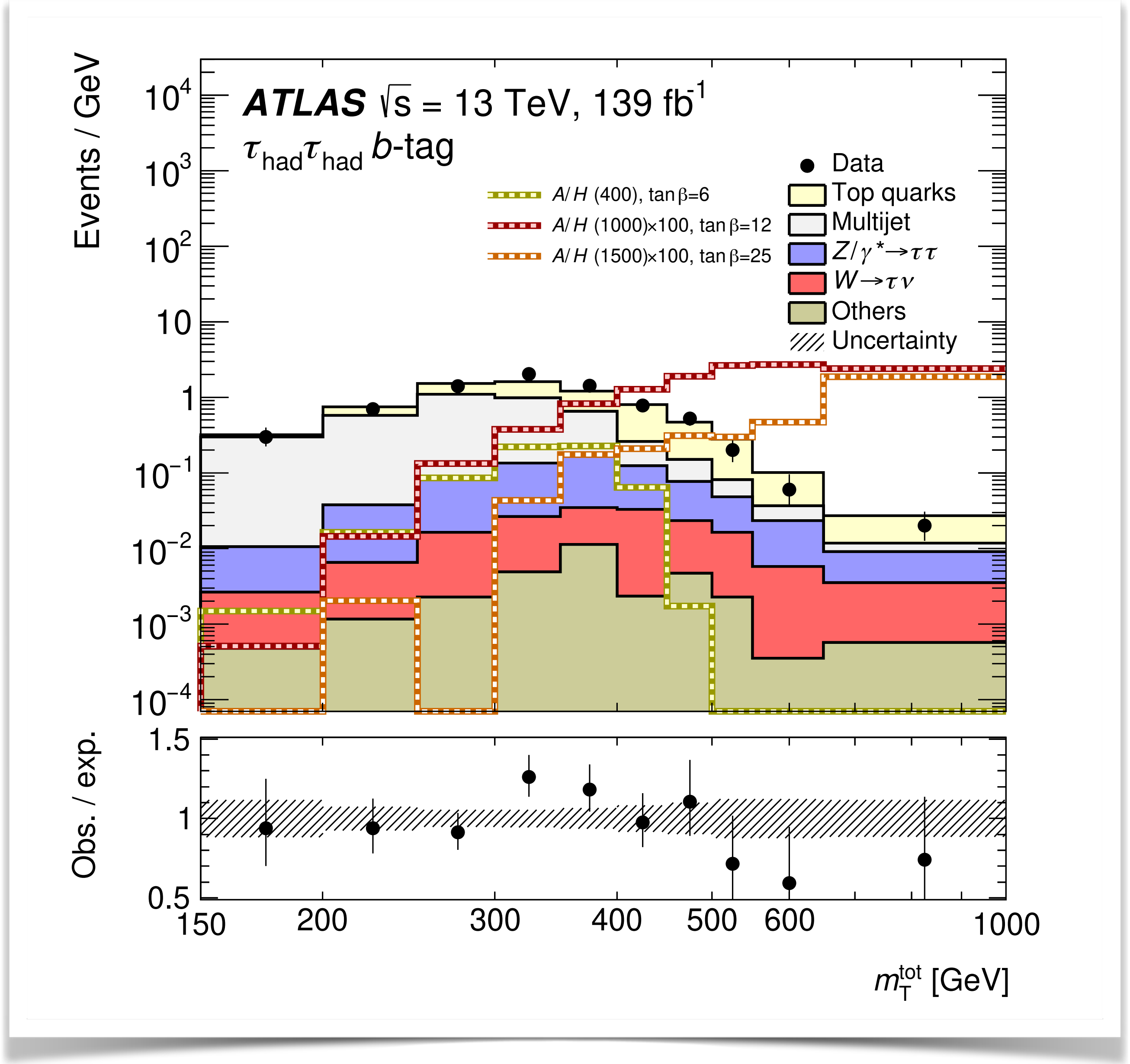
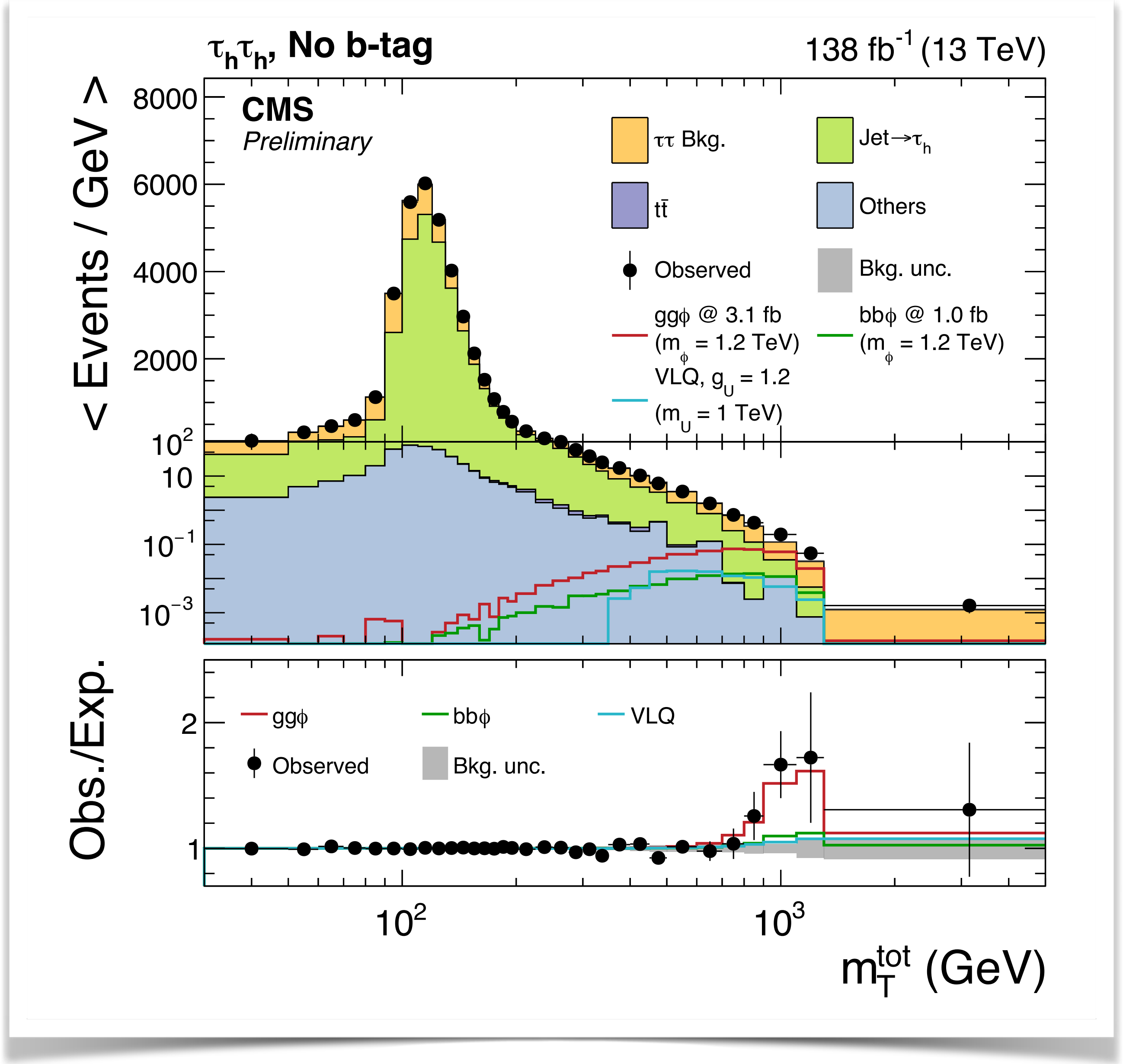
Exclusion limits:

ATLAS 2020



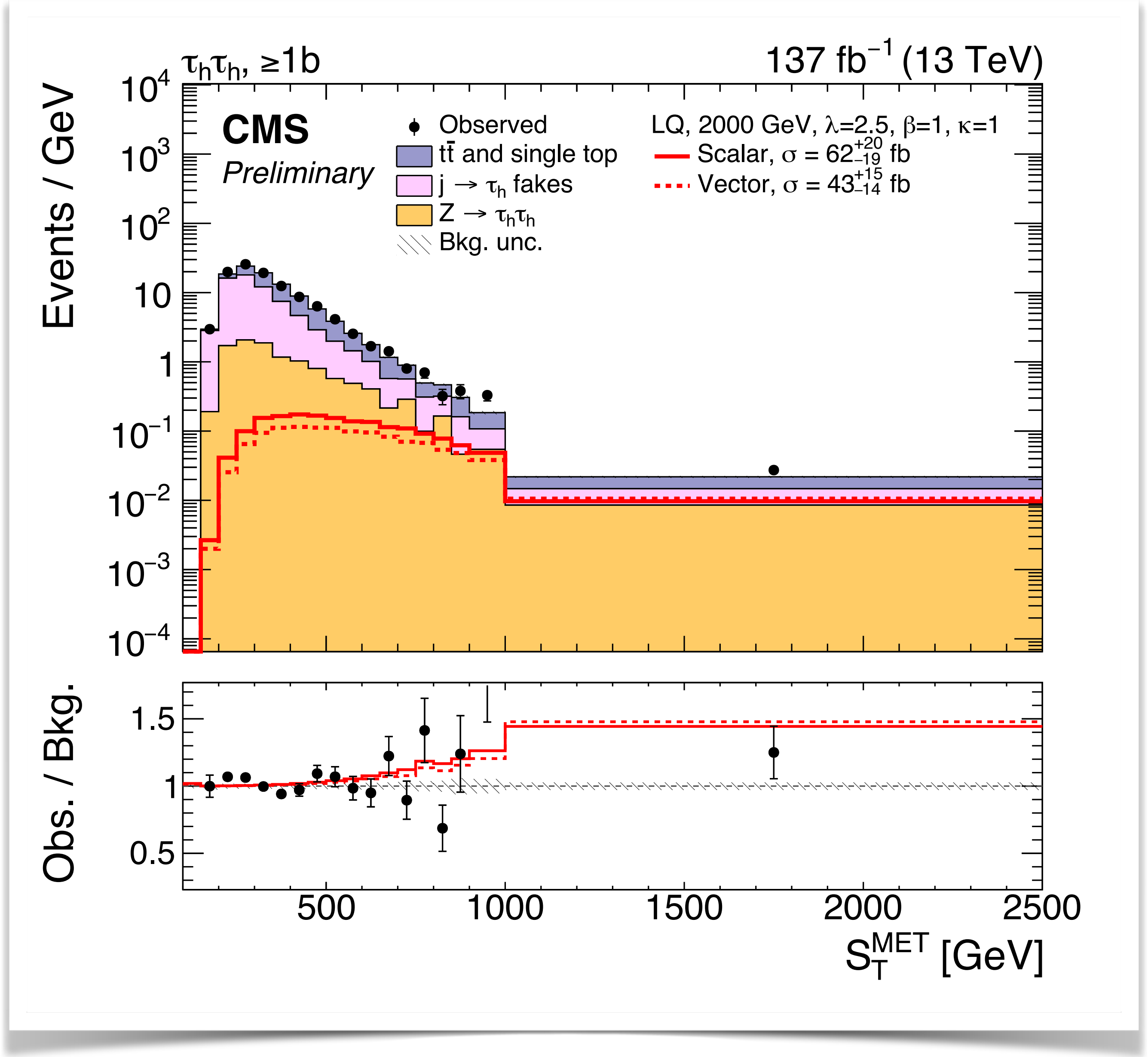
Source: ArXiv:2002.12223 (ATLAS)

CMS 2021



Source: HIG-21-001-PAS (CMS)

CMS 2022



Source: EXO-19-016-PAS (CMS)

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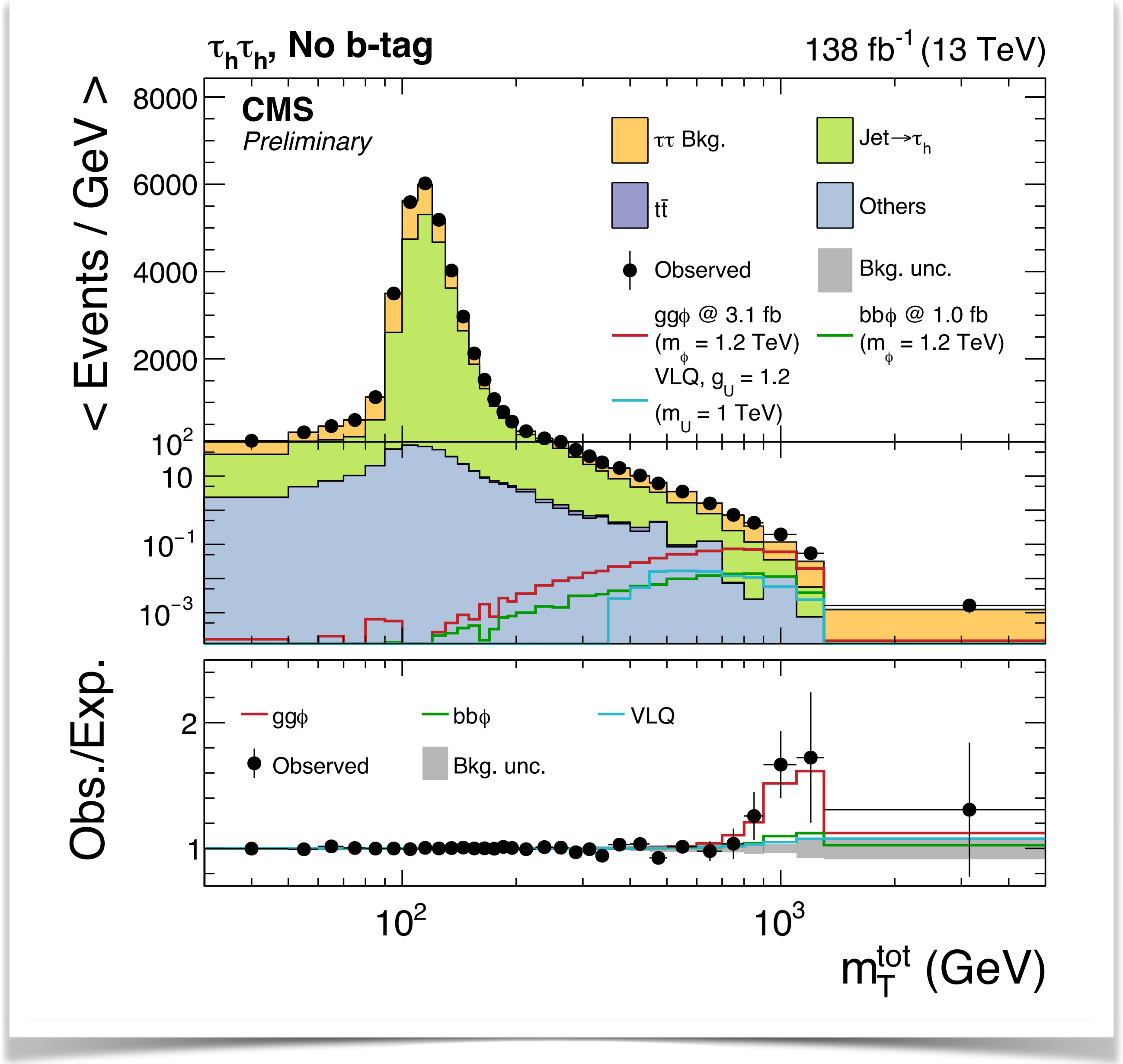
ATLAS 2020

CMS 2021



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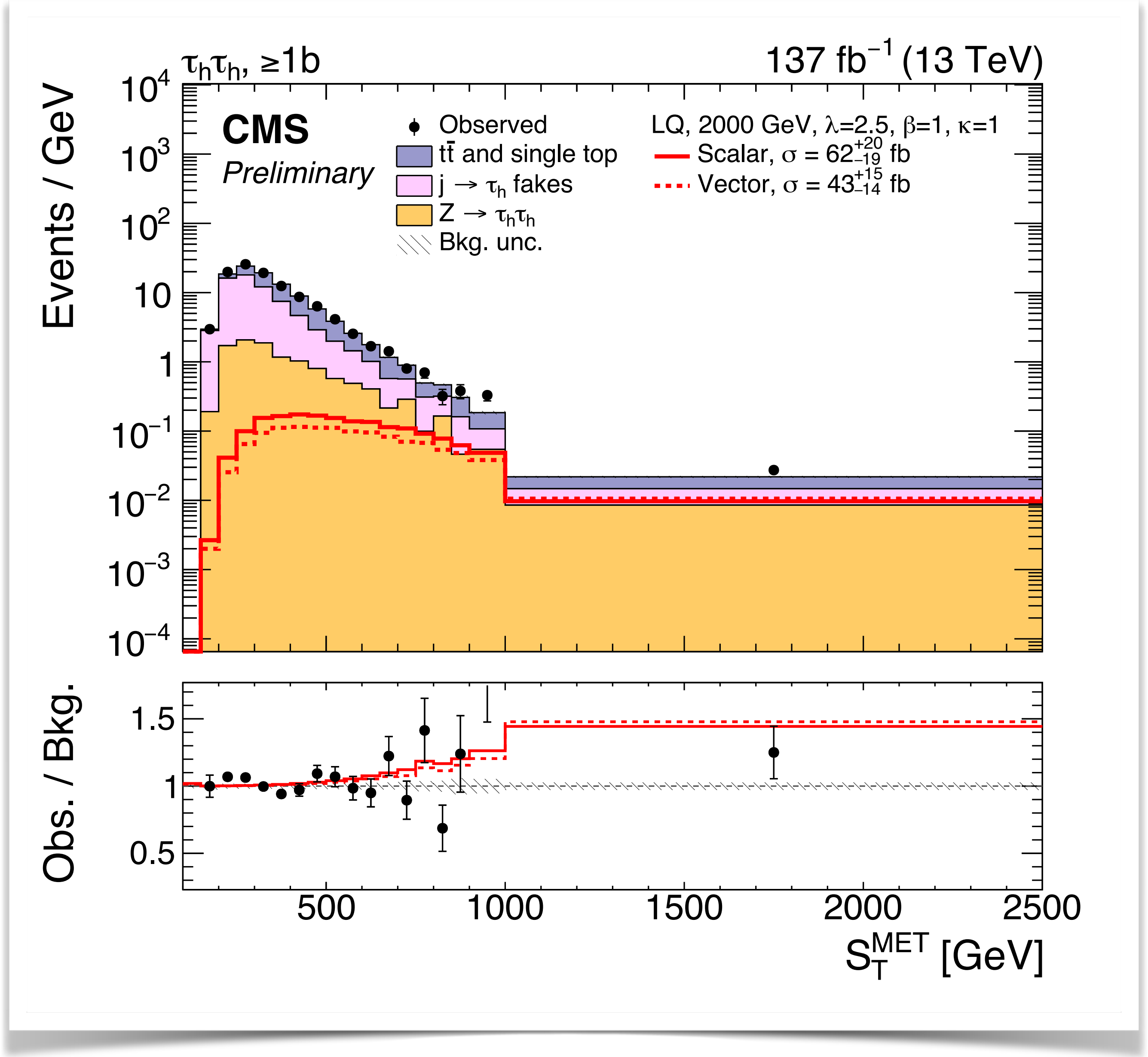

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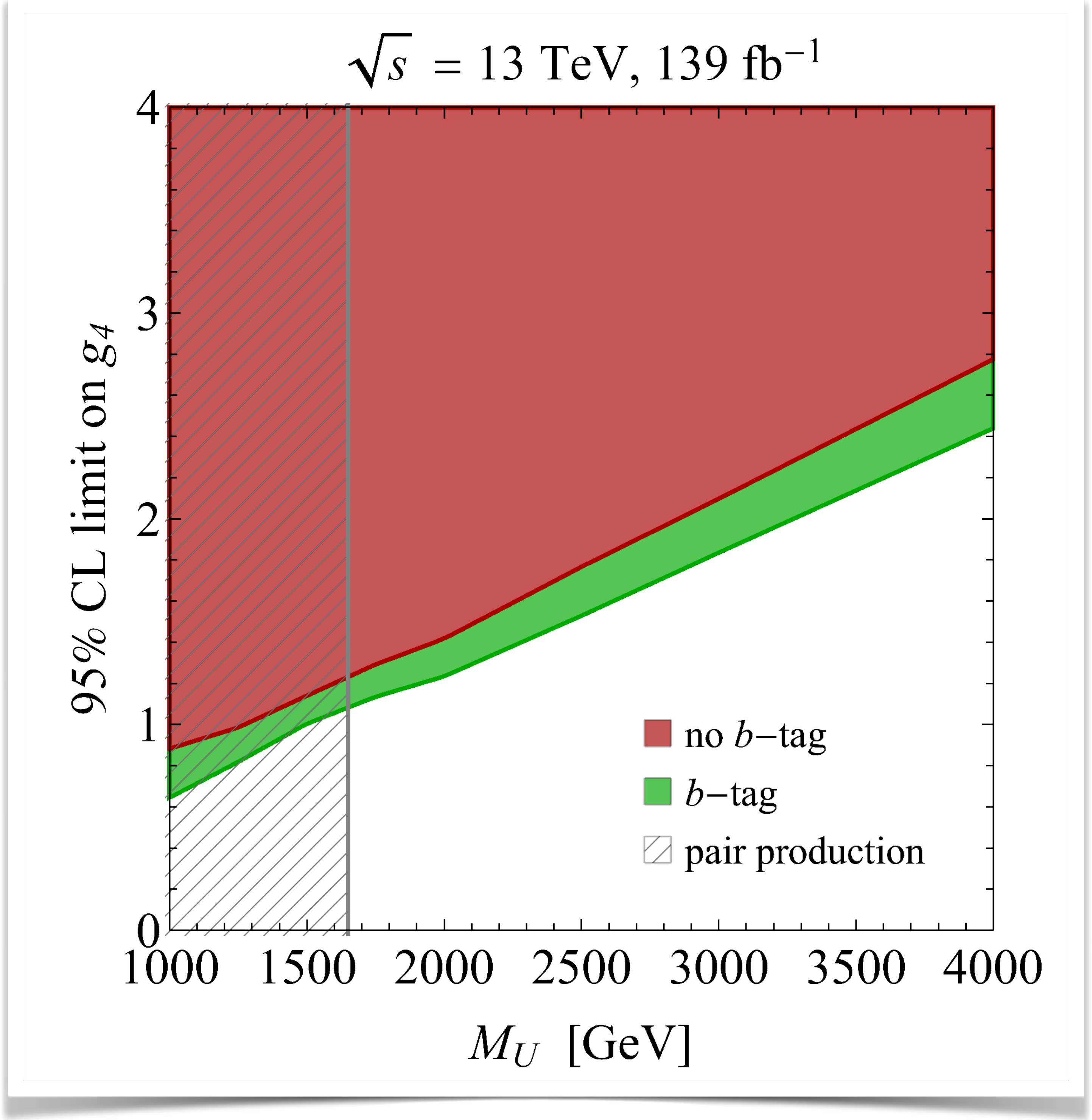

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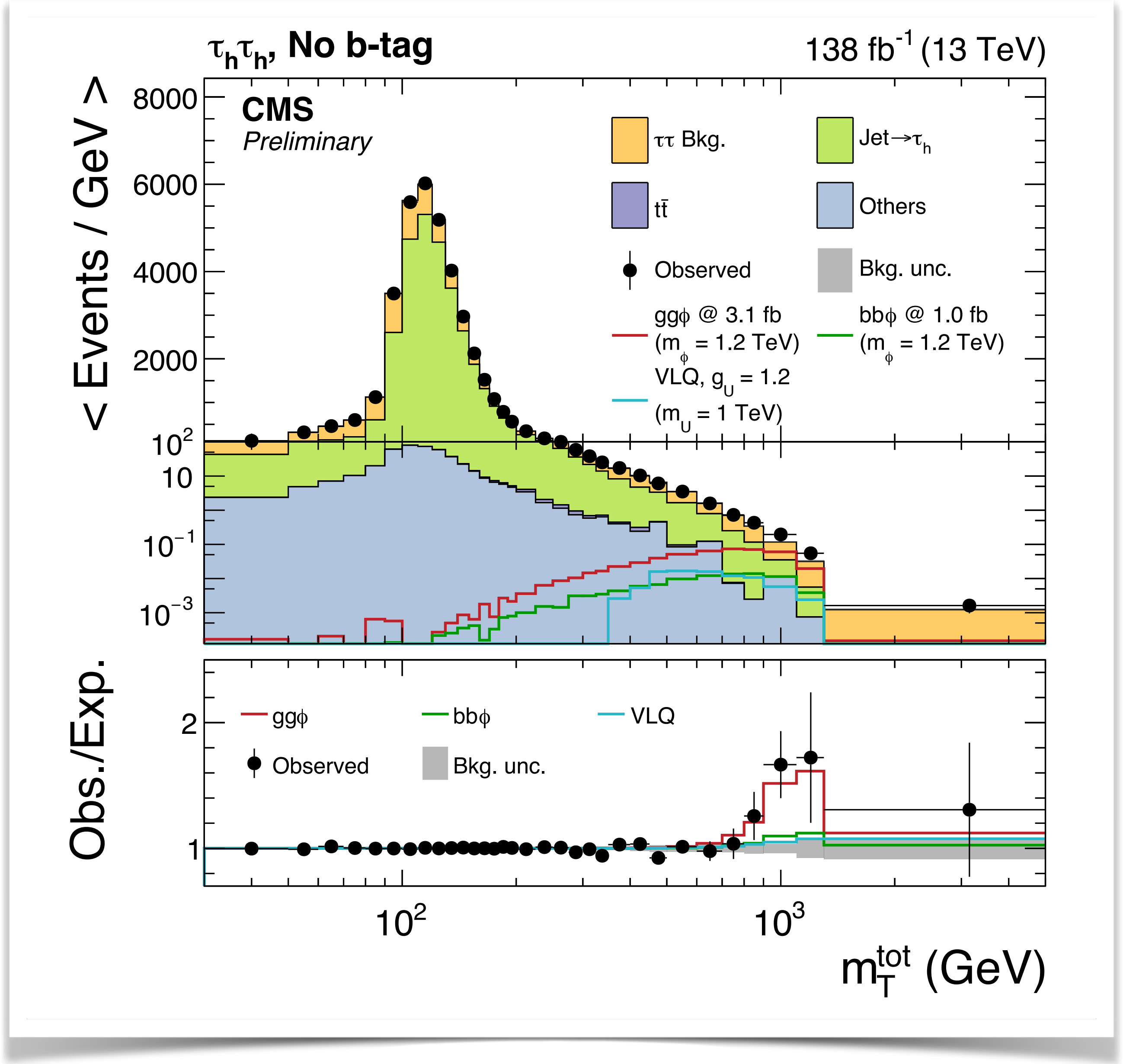

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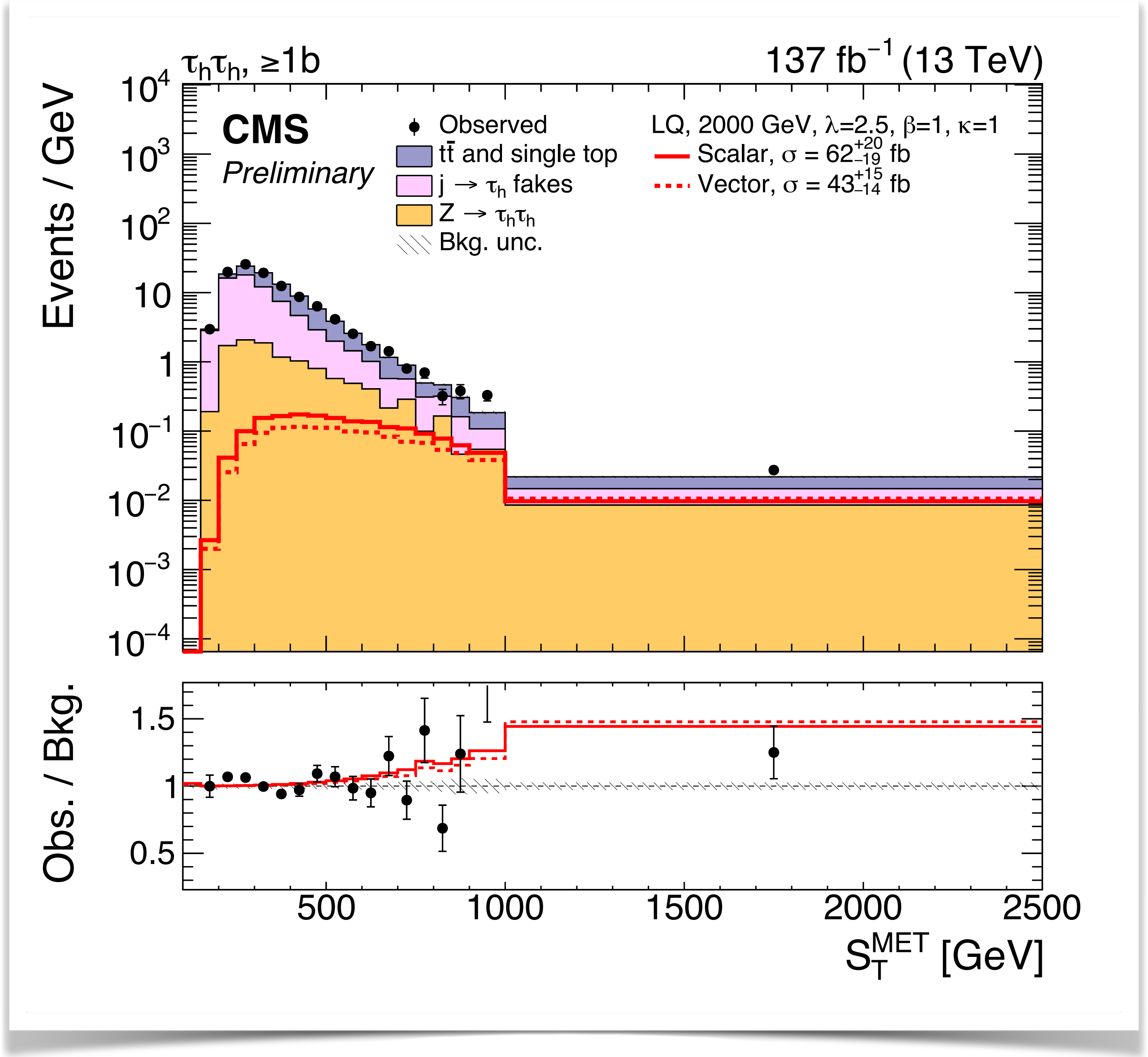

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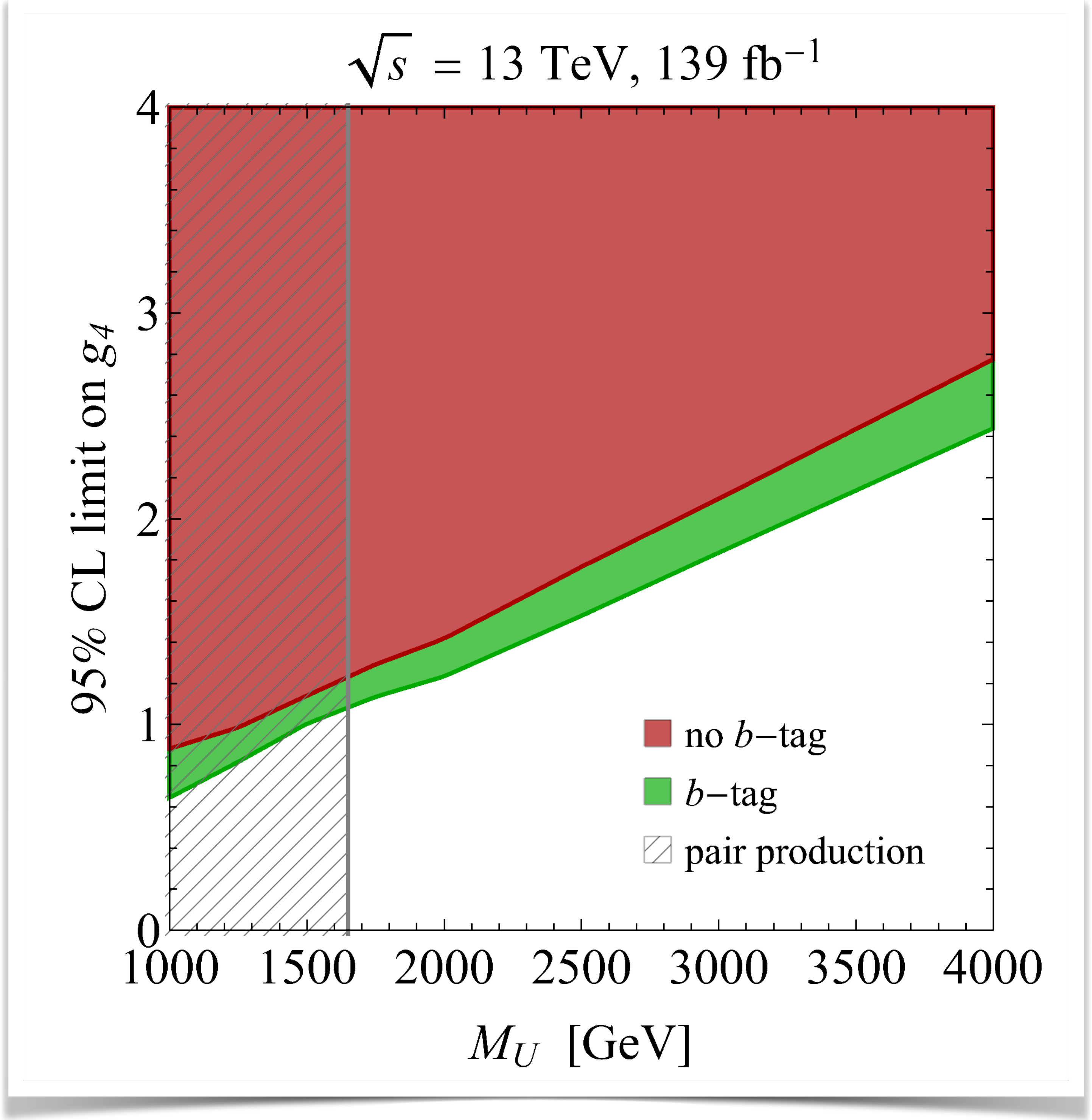

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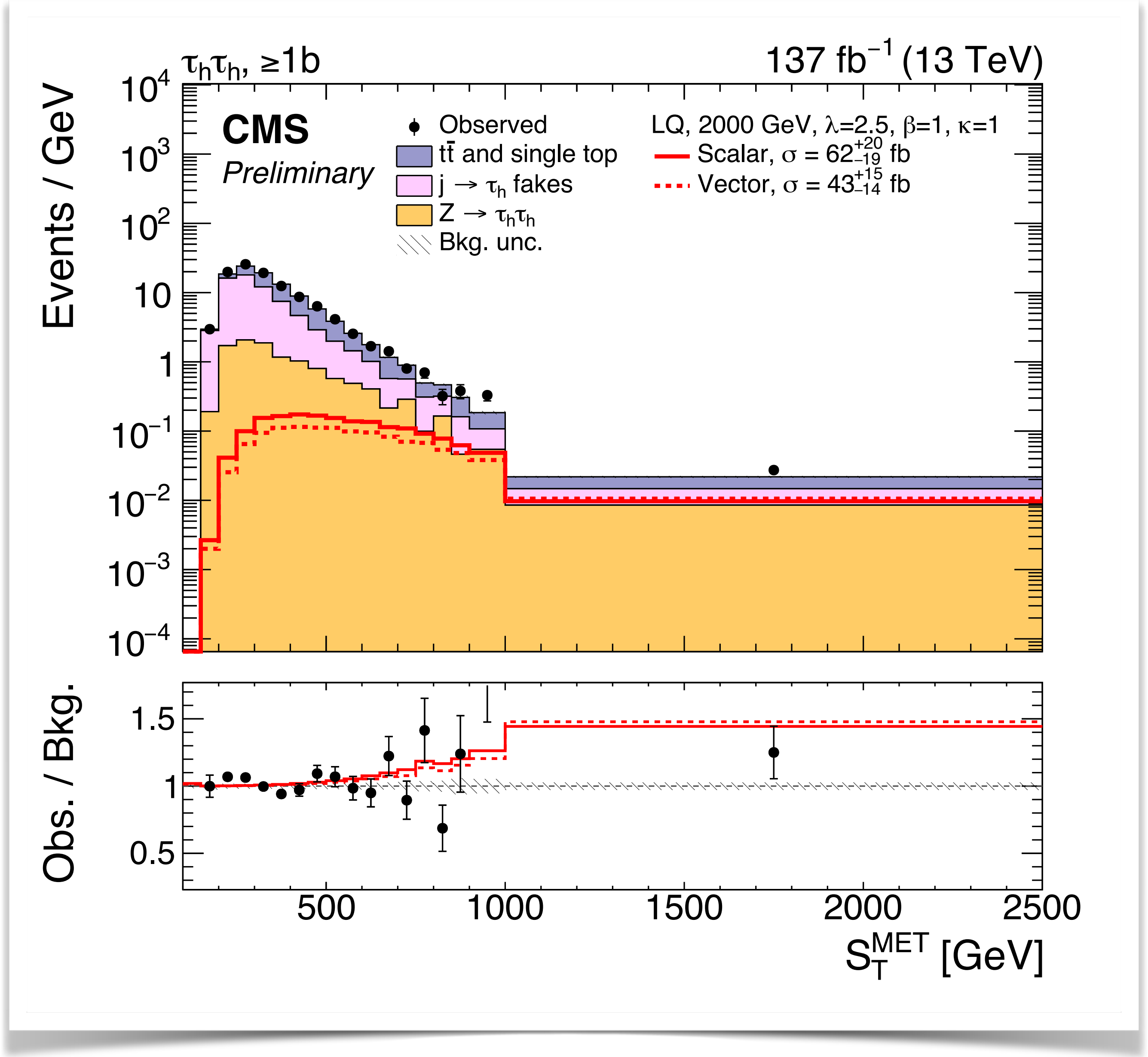

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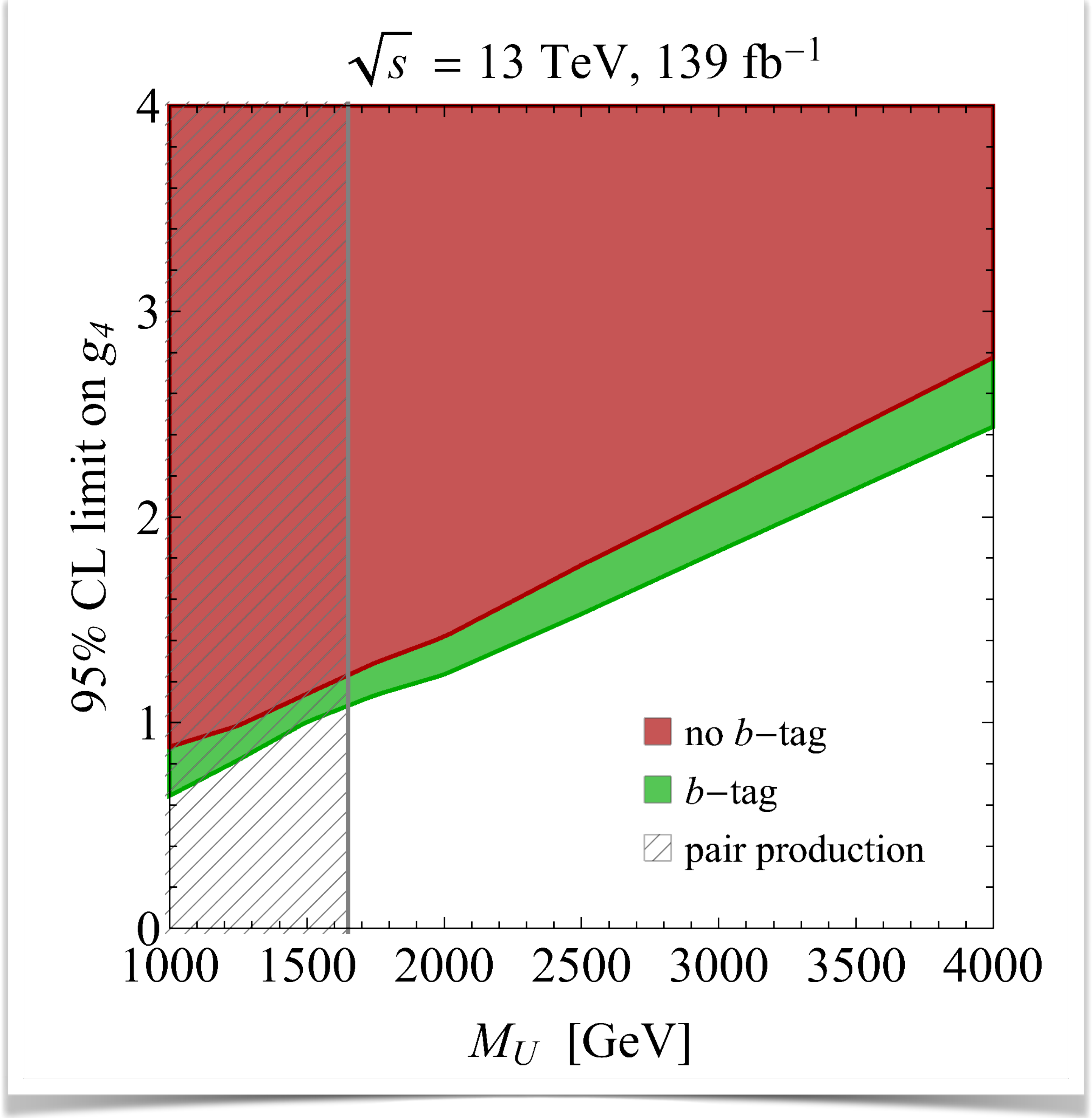

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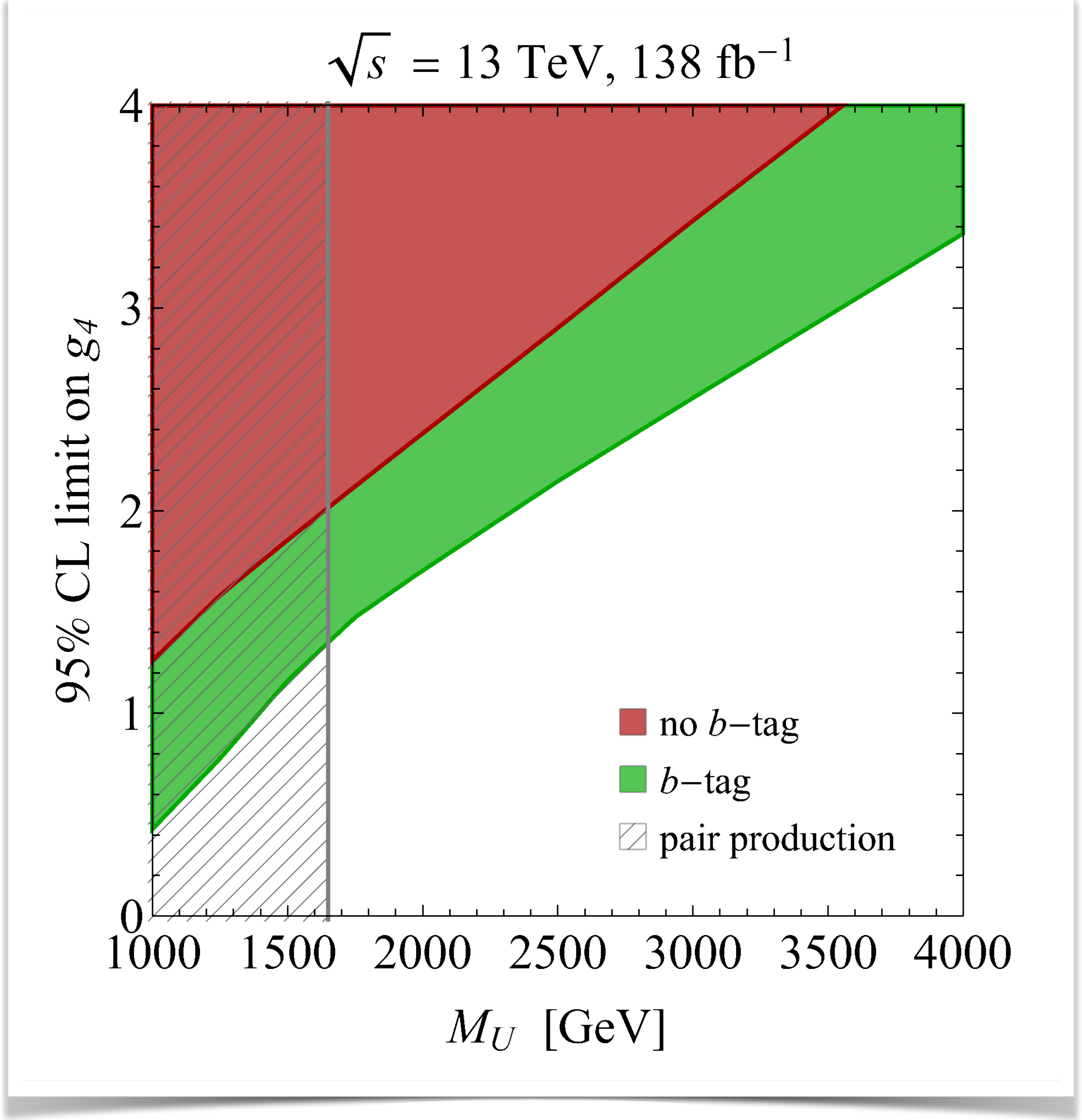

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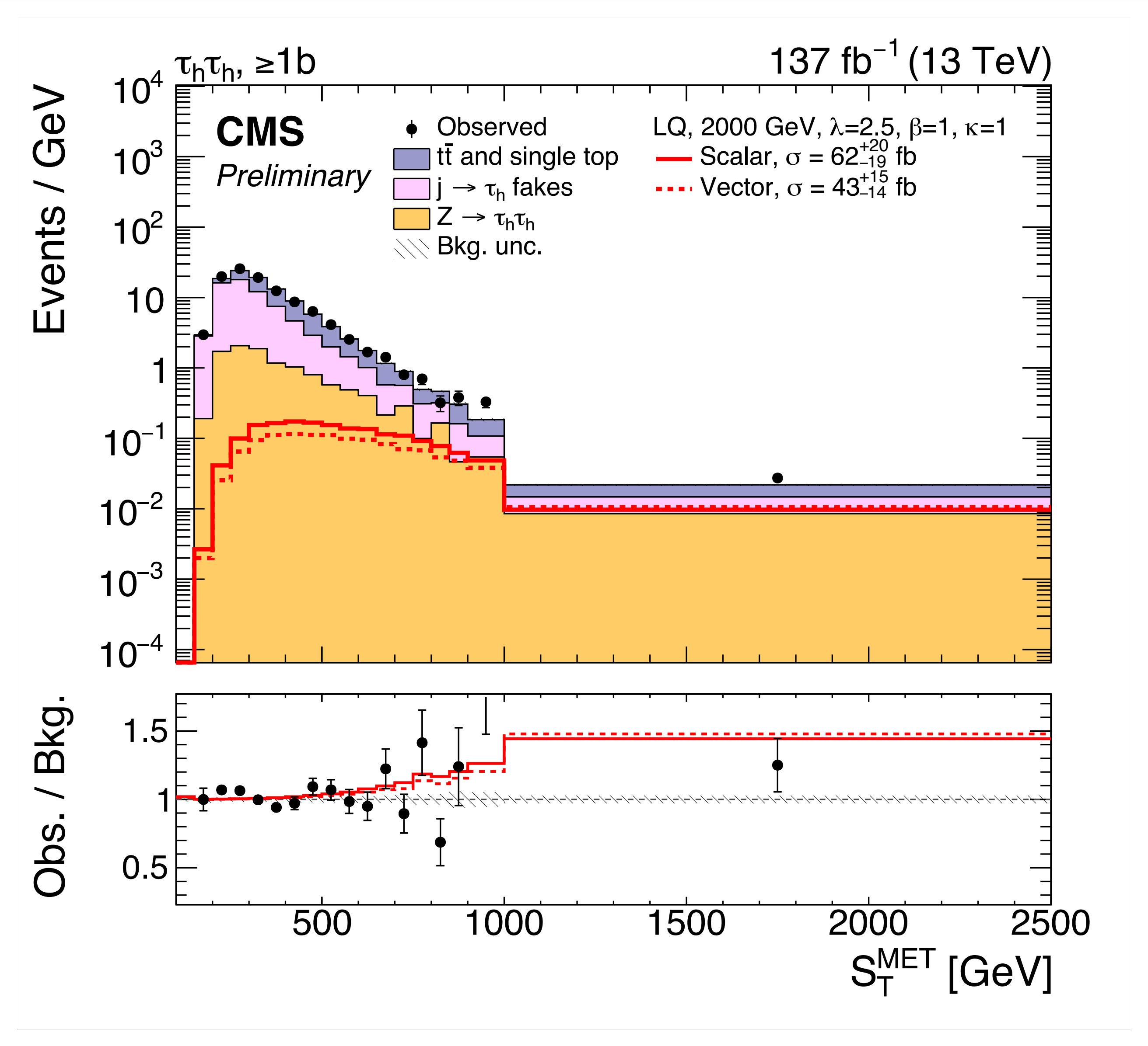

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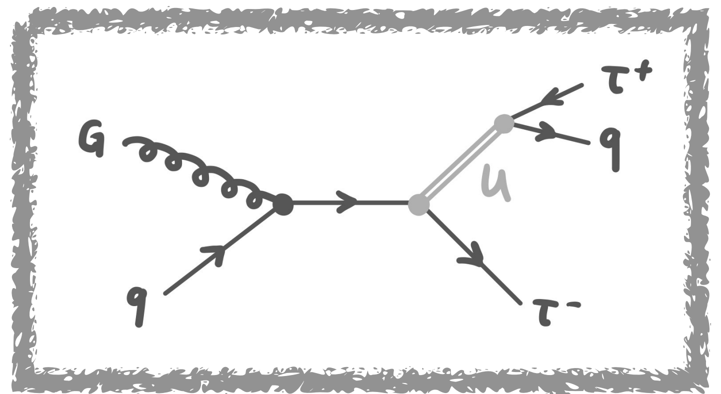

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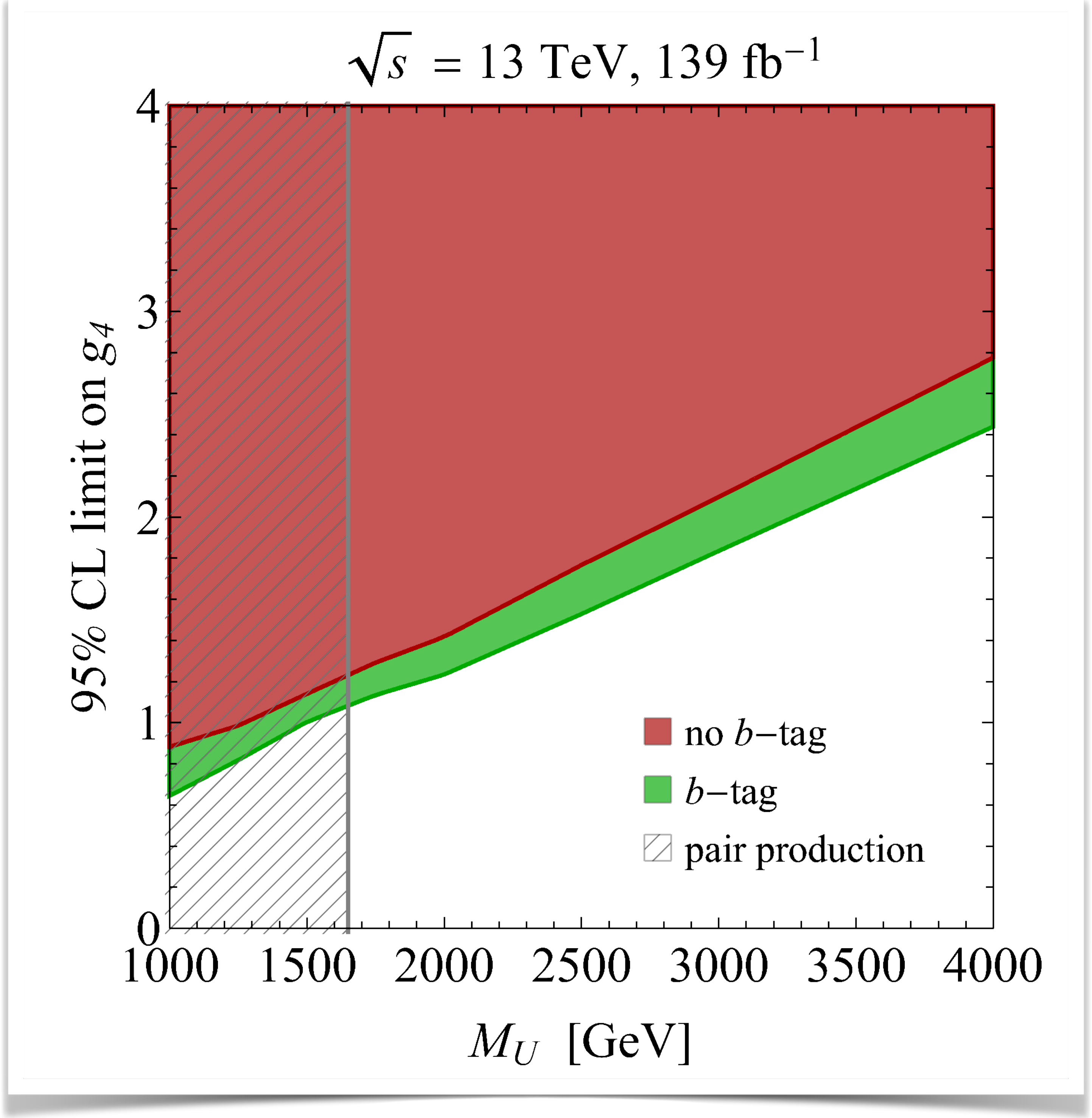

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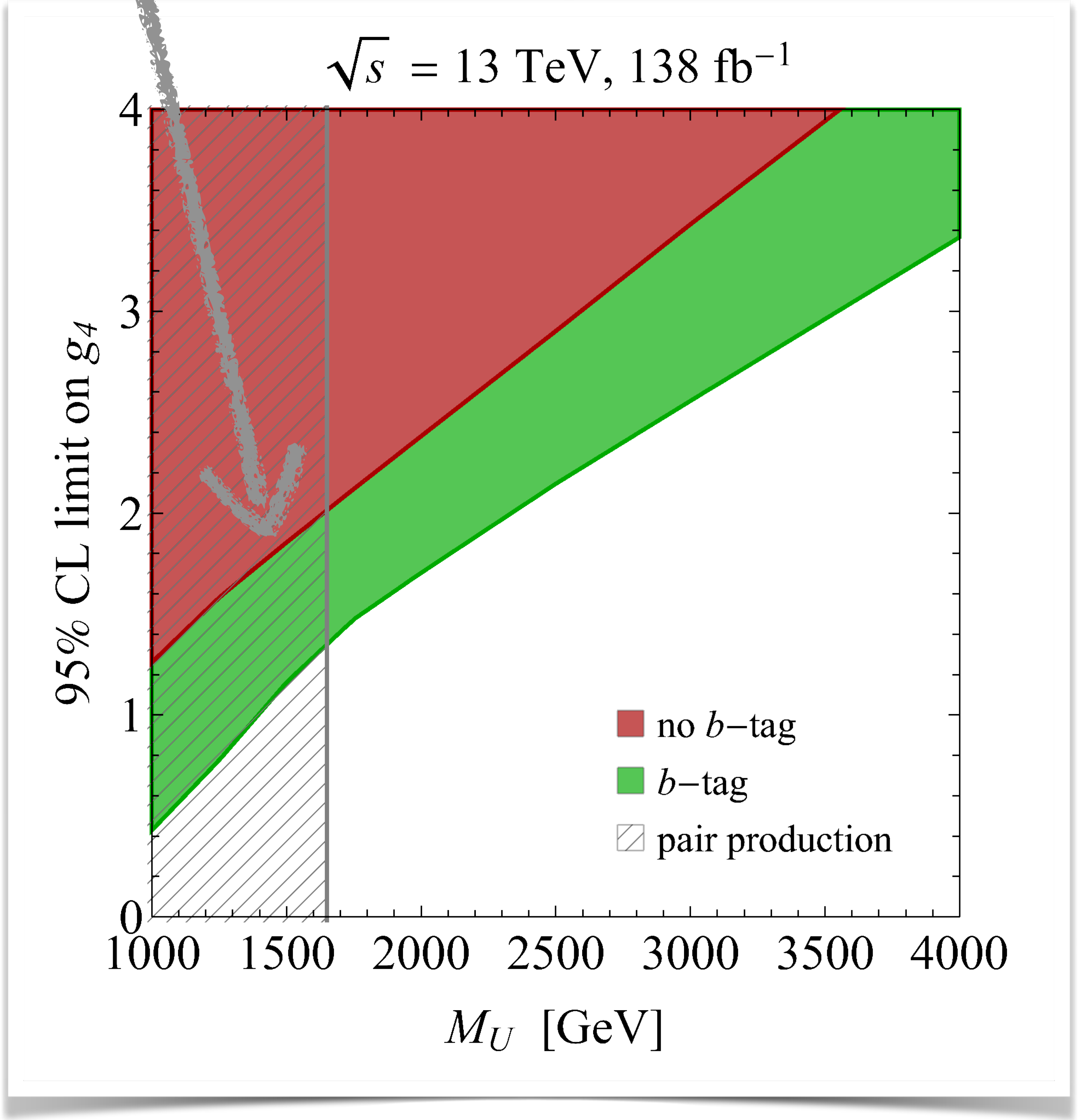
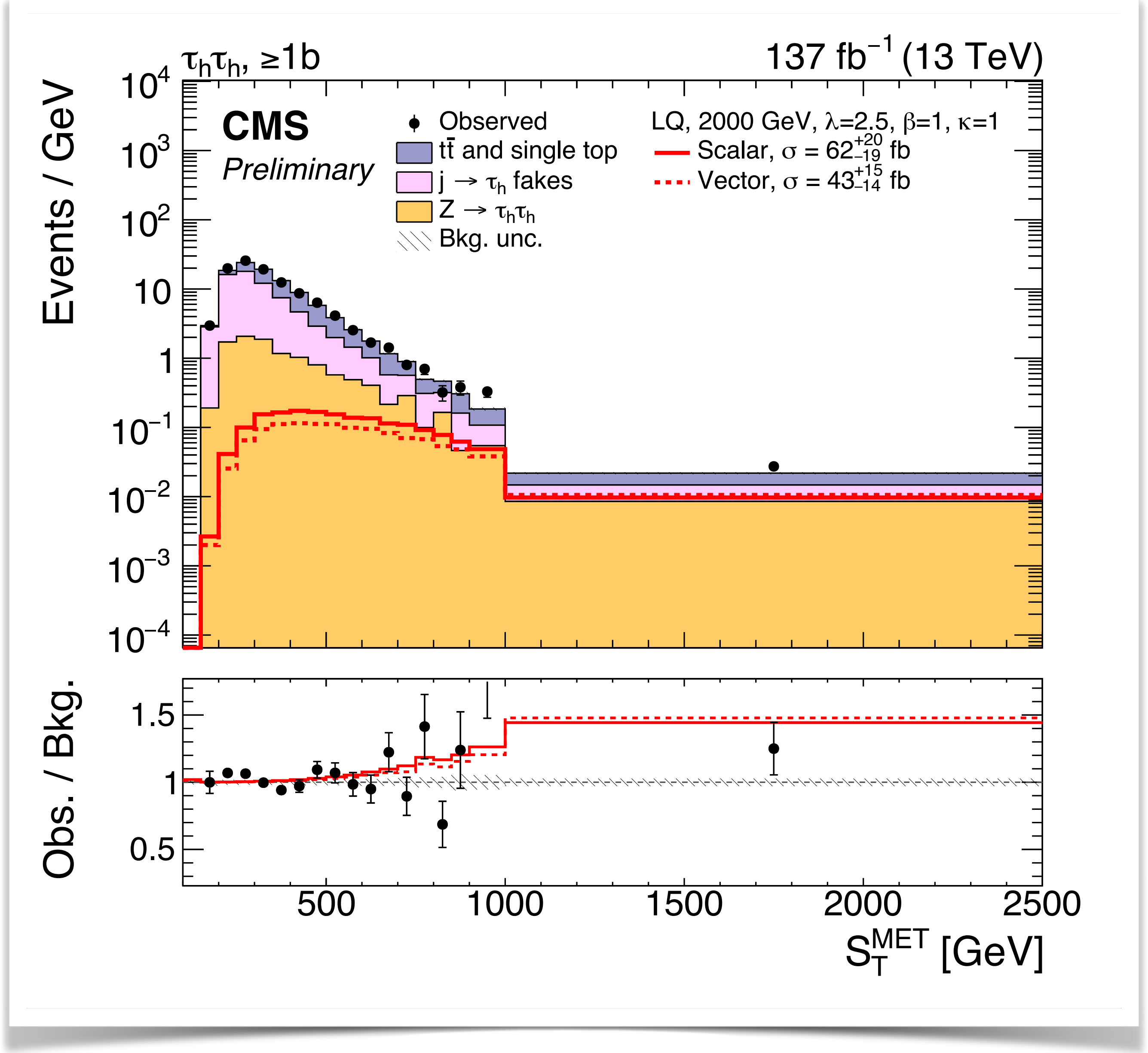


CMS 2022



Source: EXO-19-016-PAS (CMS)

Source: ArXiv:2209.12780 (U. Haisch, LS, S. Schulte)

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

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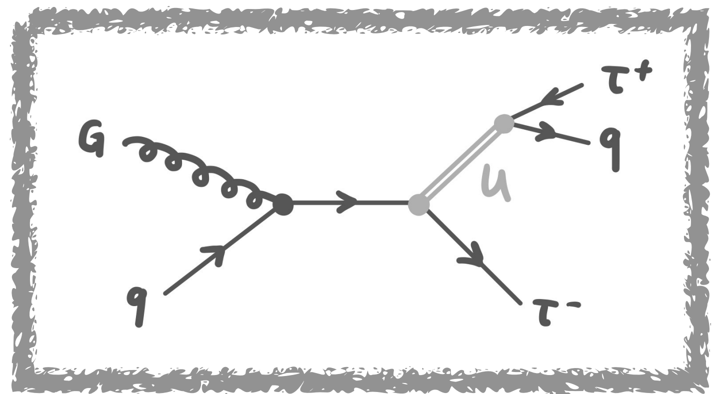
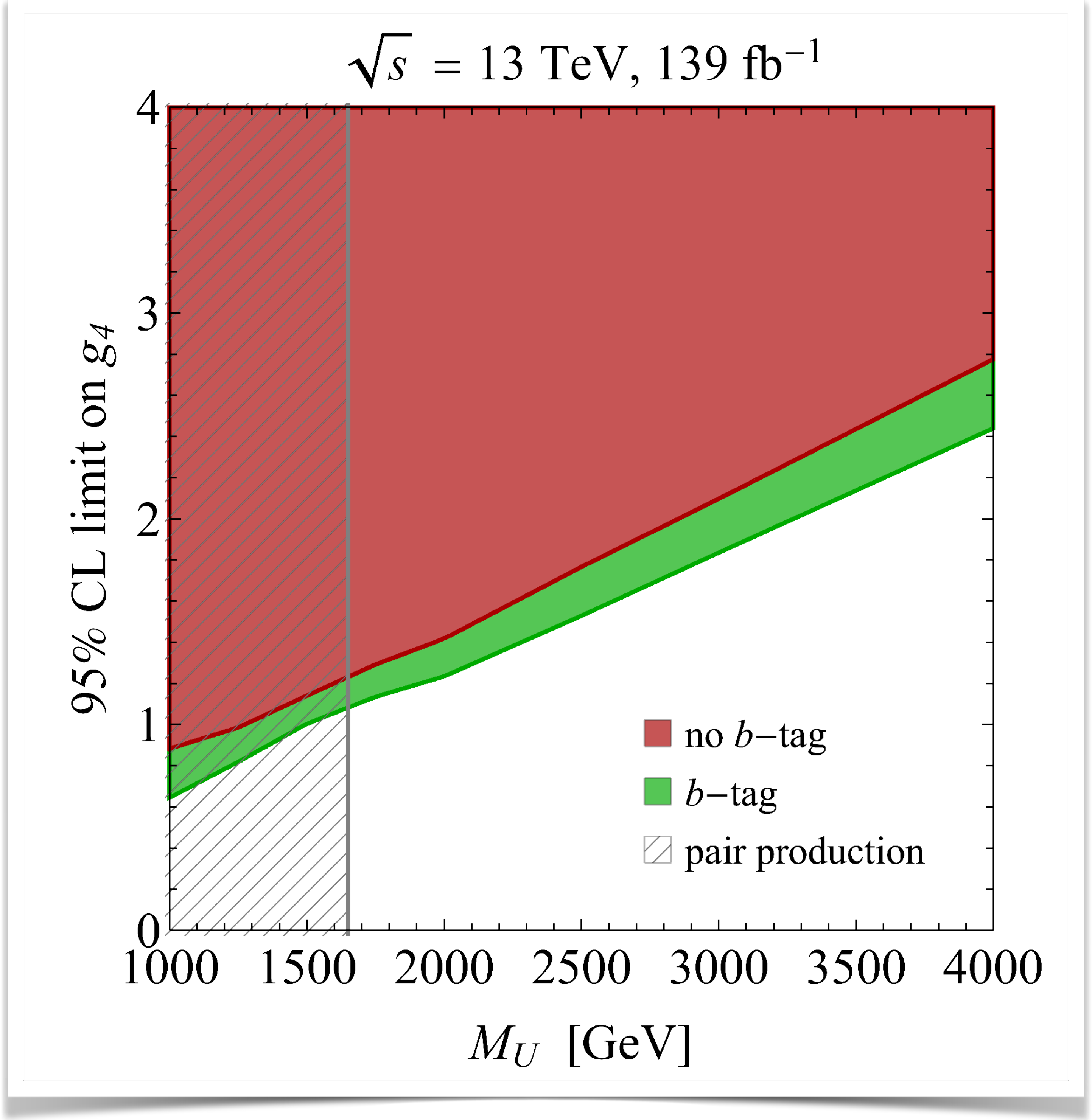
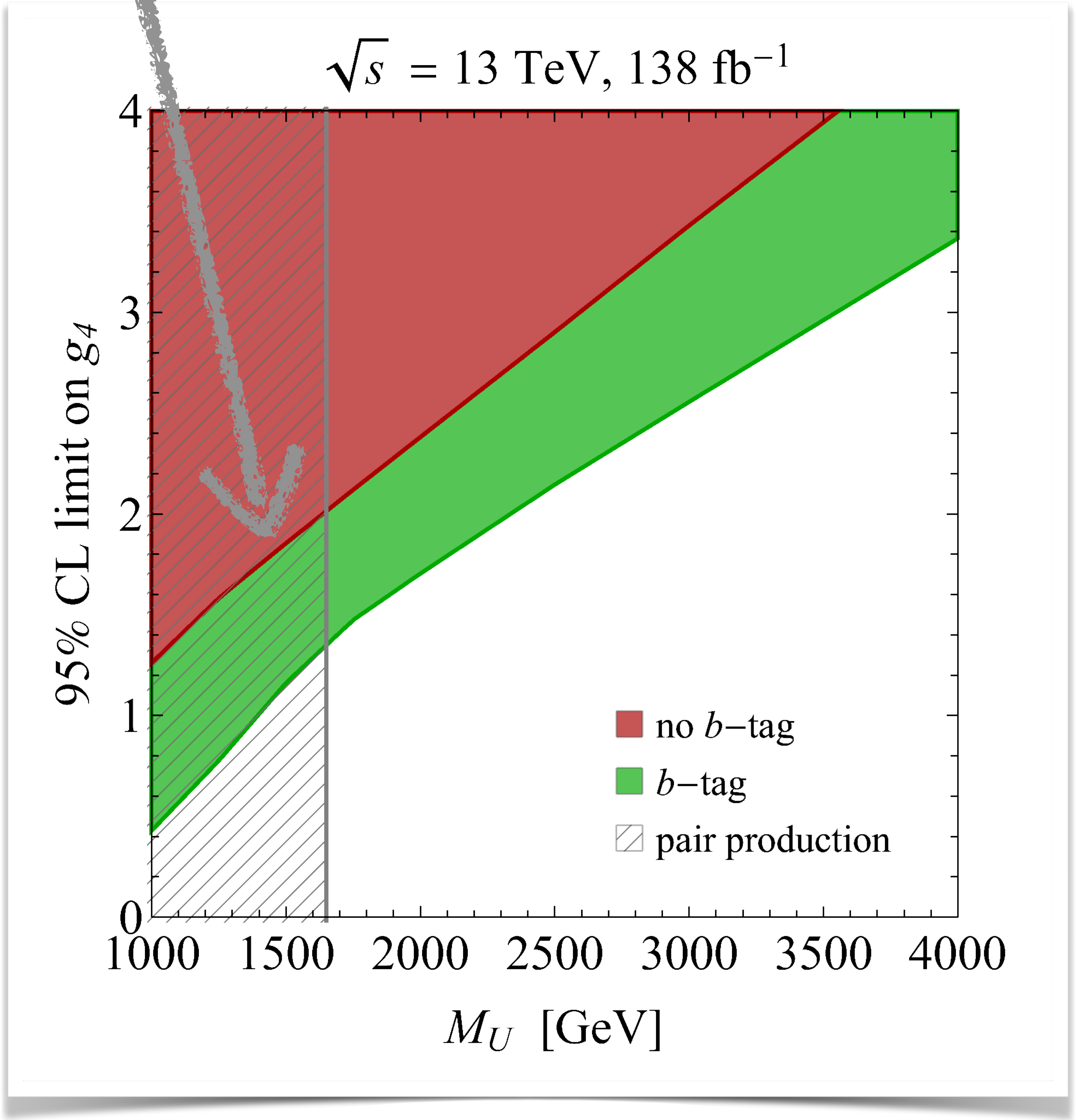


ATLAS 2020



CMS 2021



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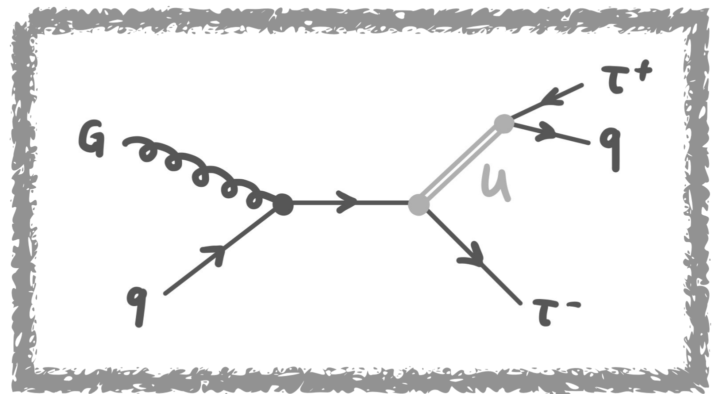

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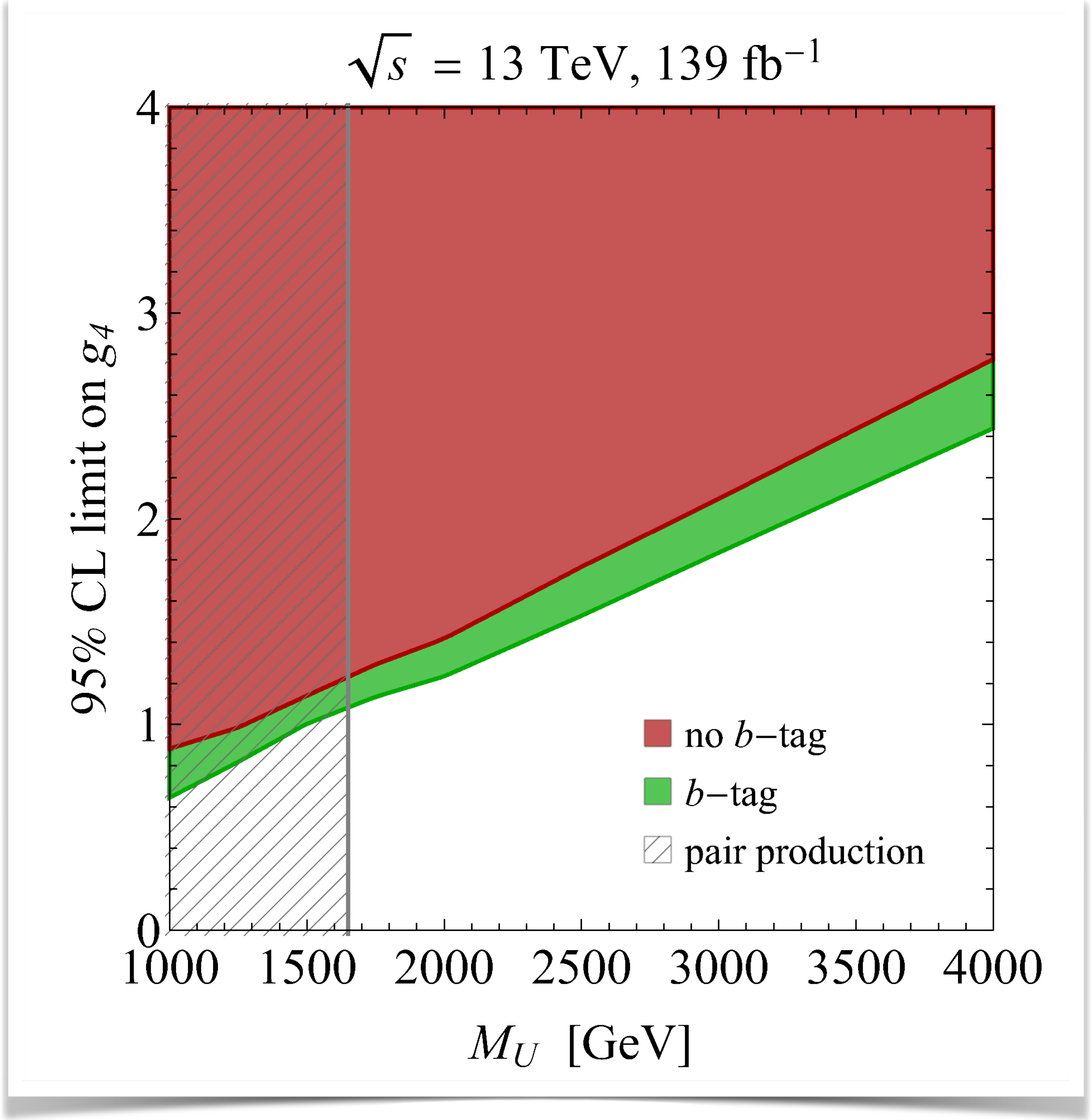

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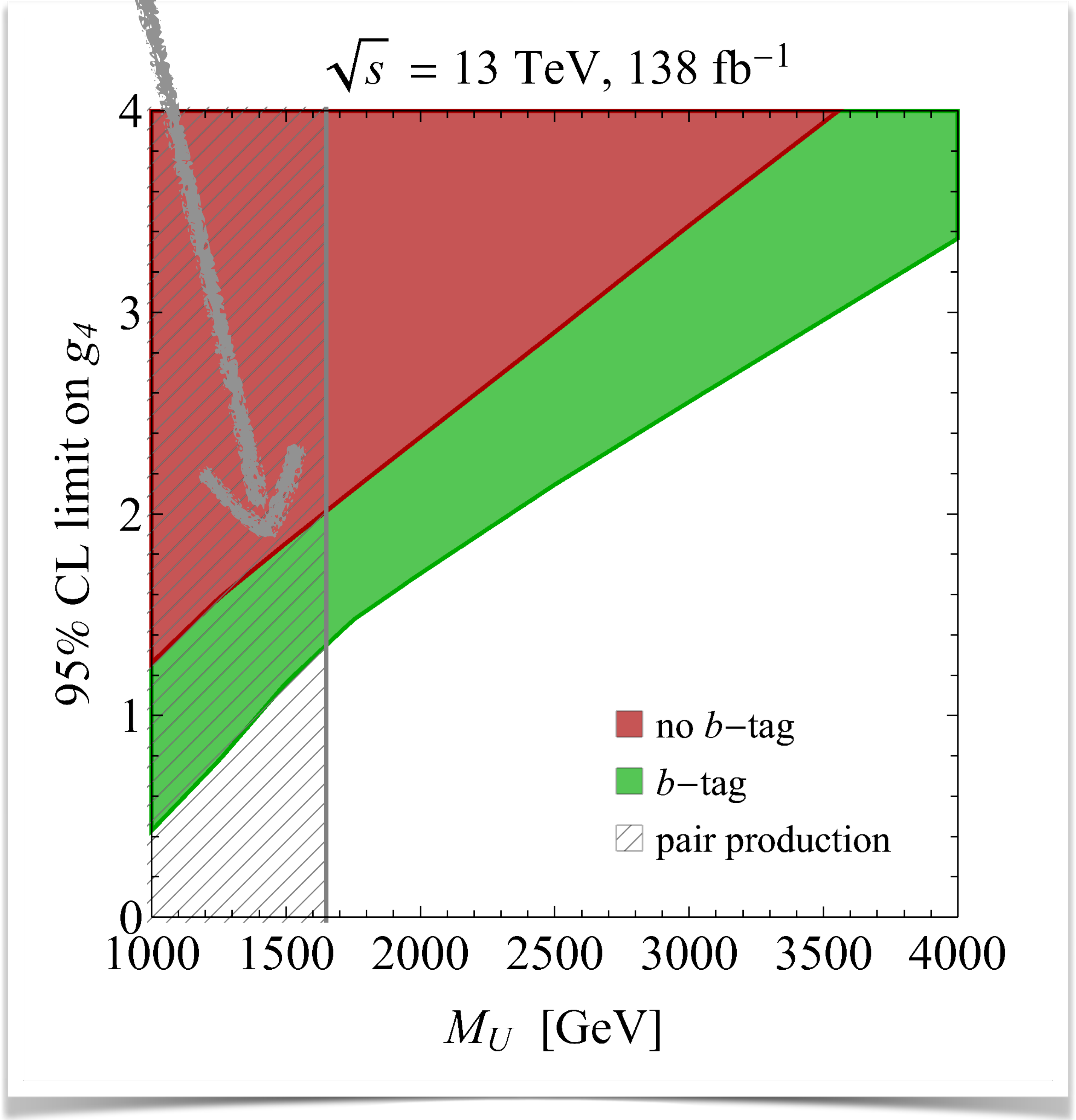

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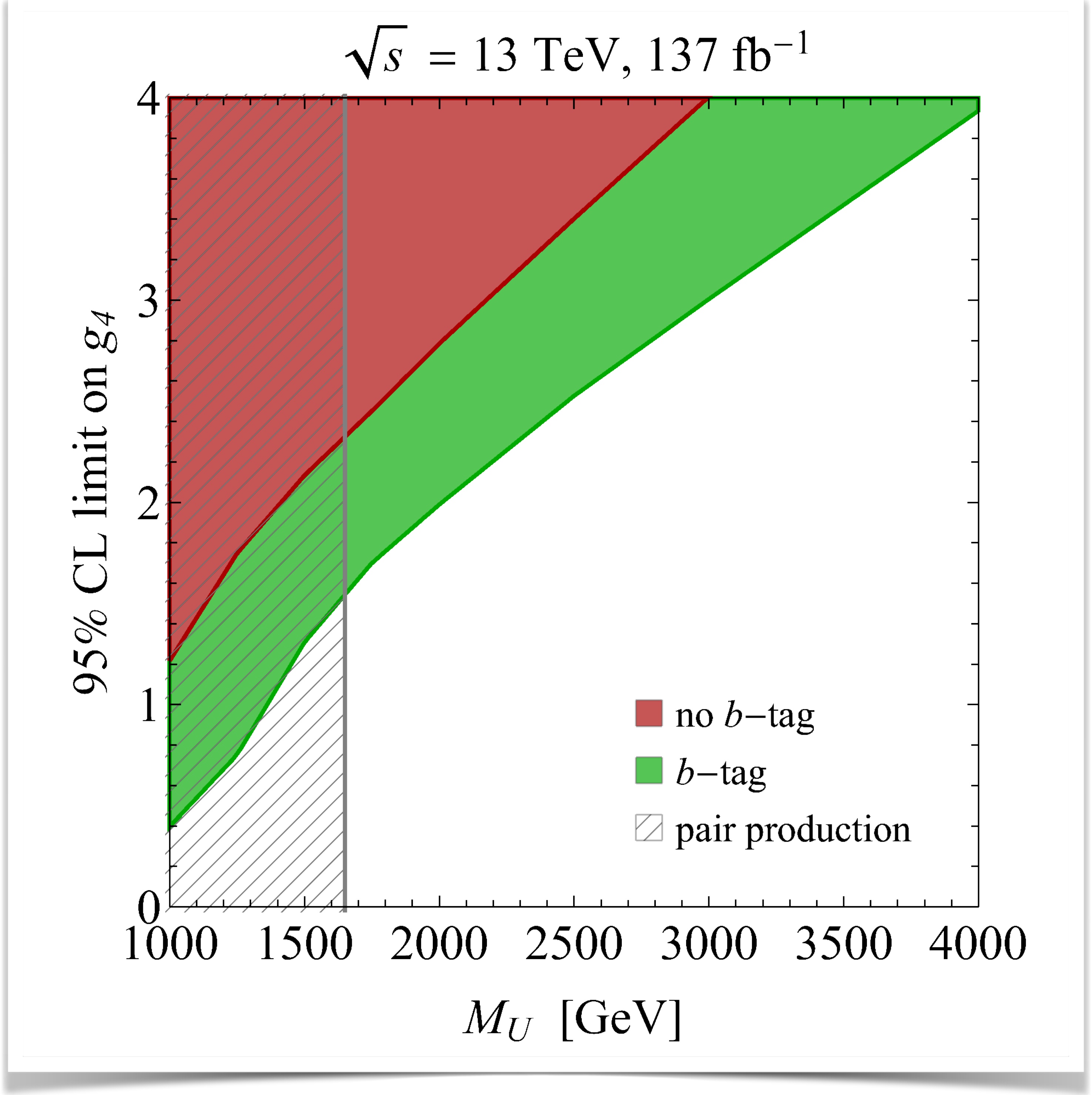

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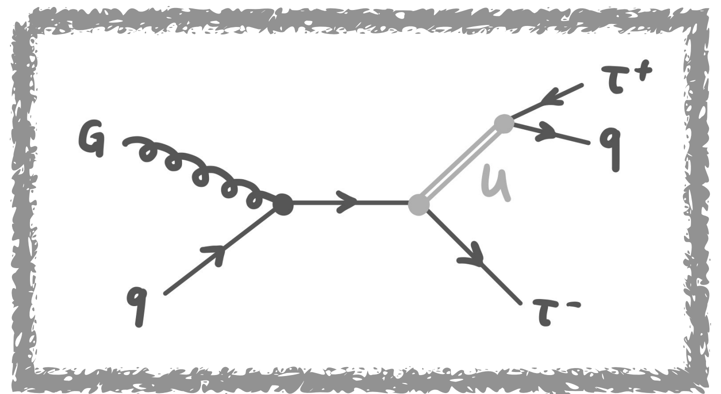

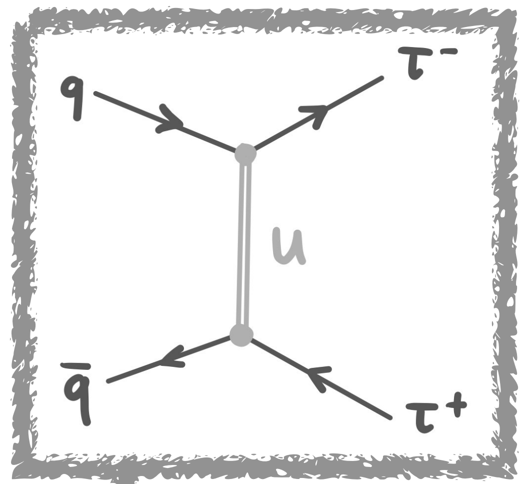

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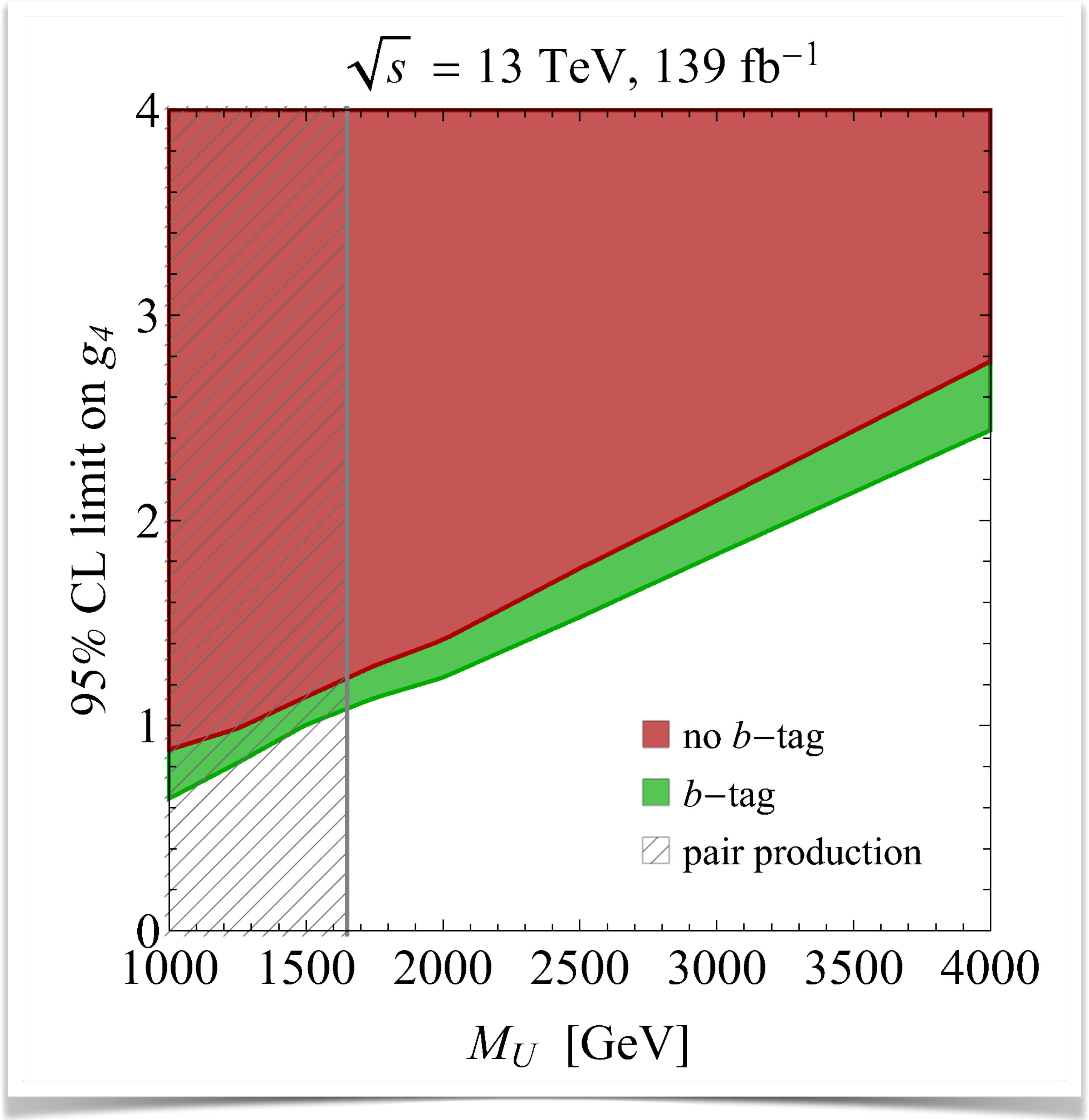

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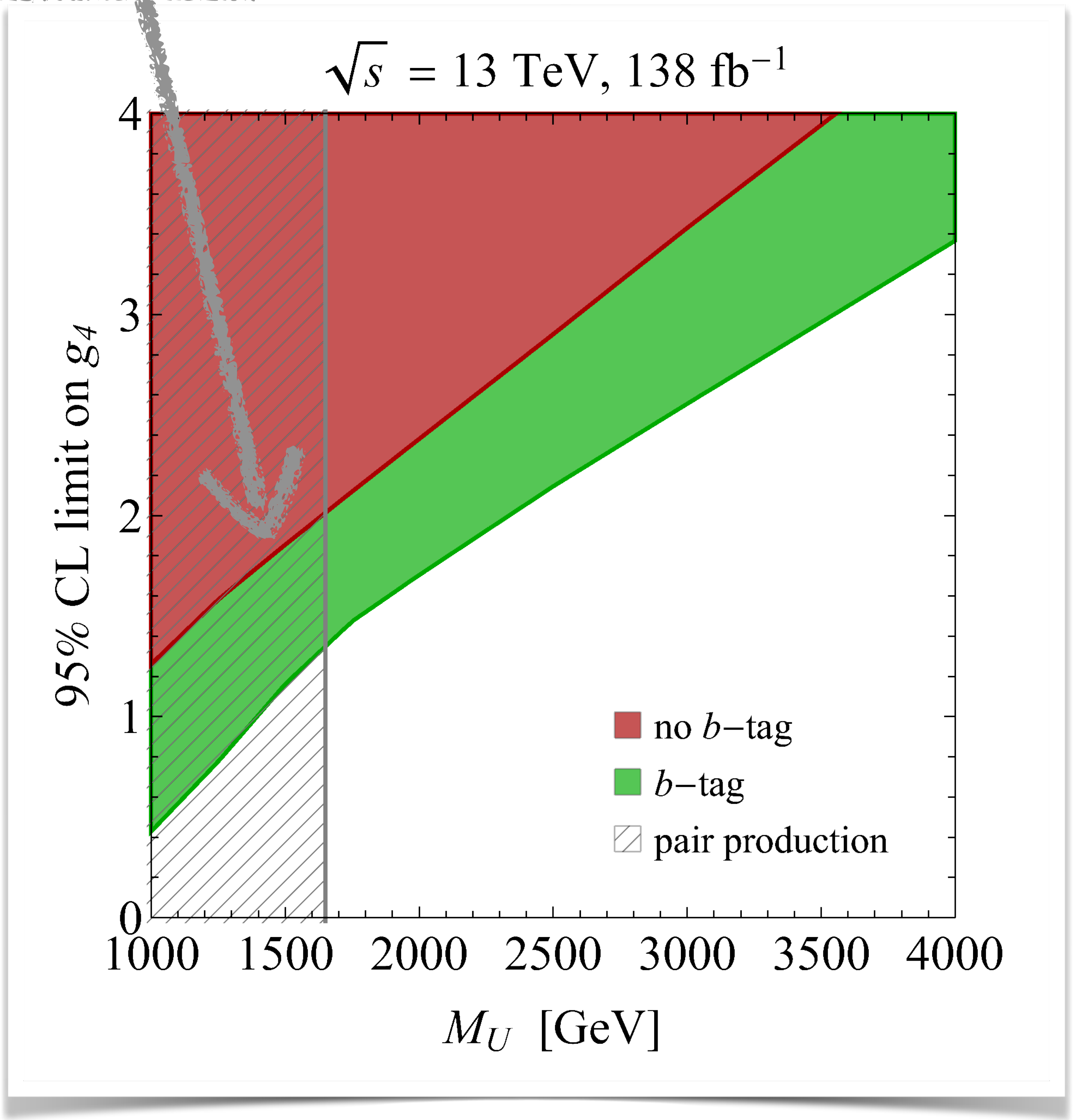

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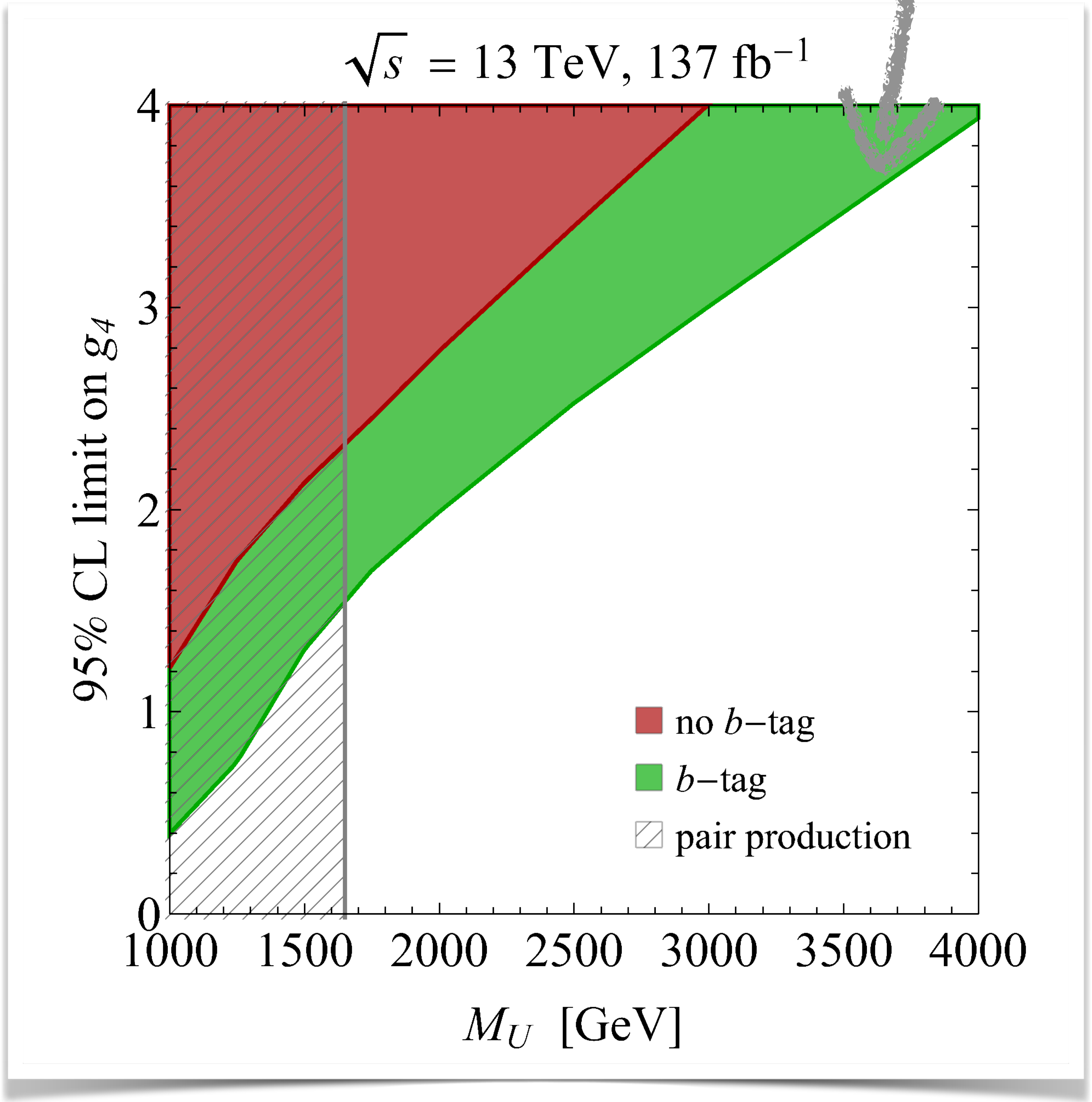

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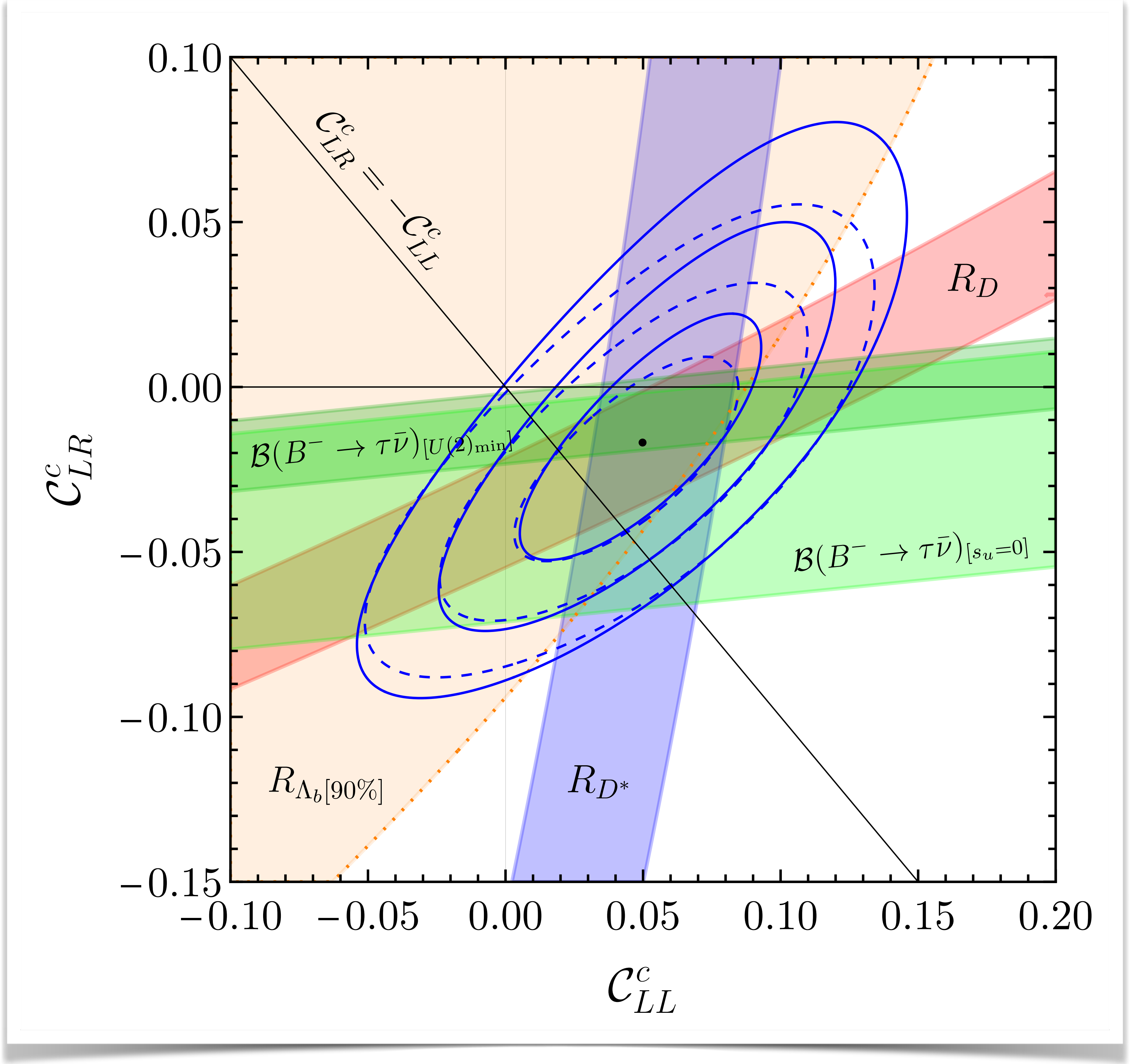

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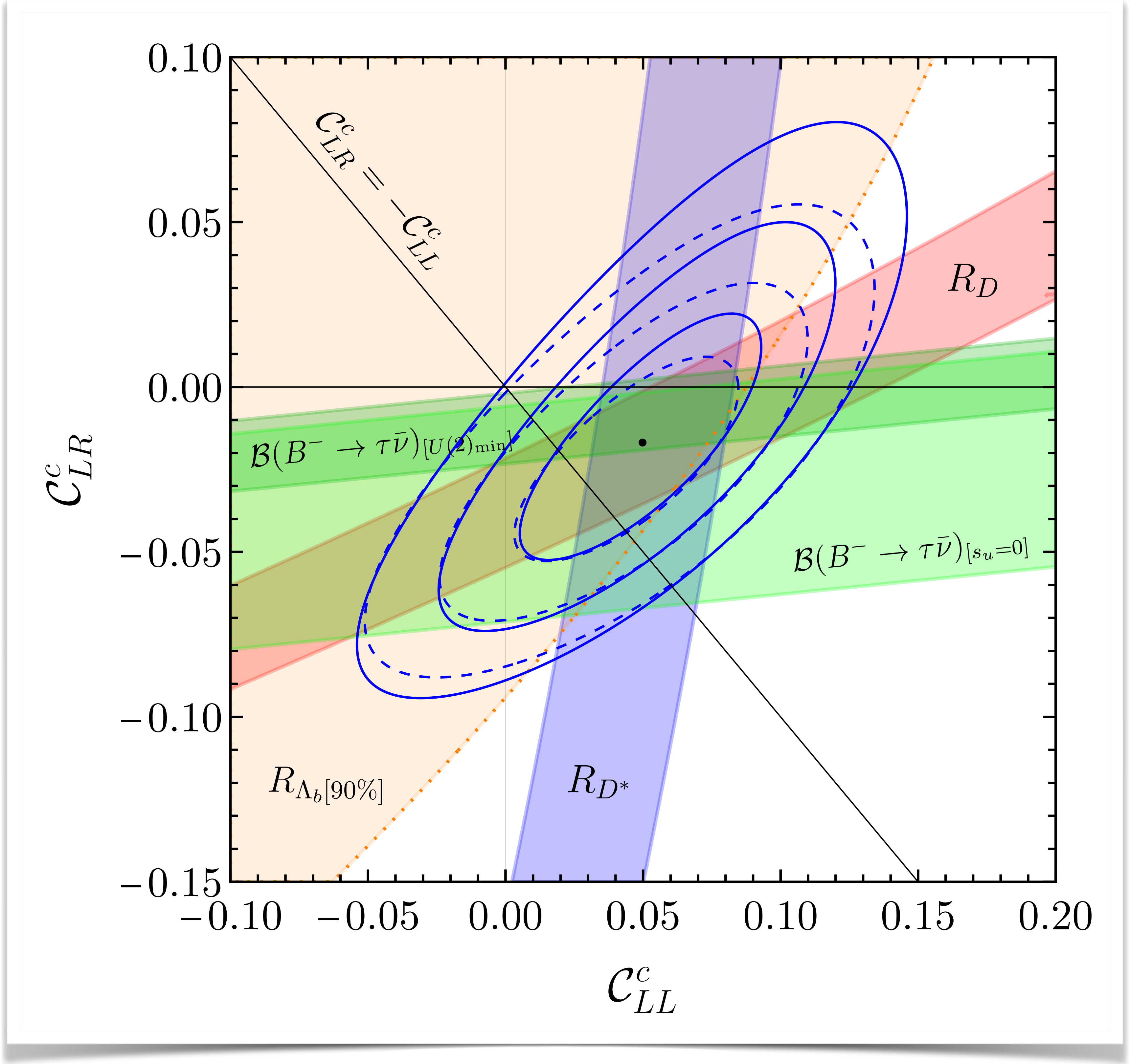

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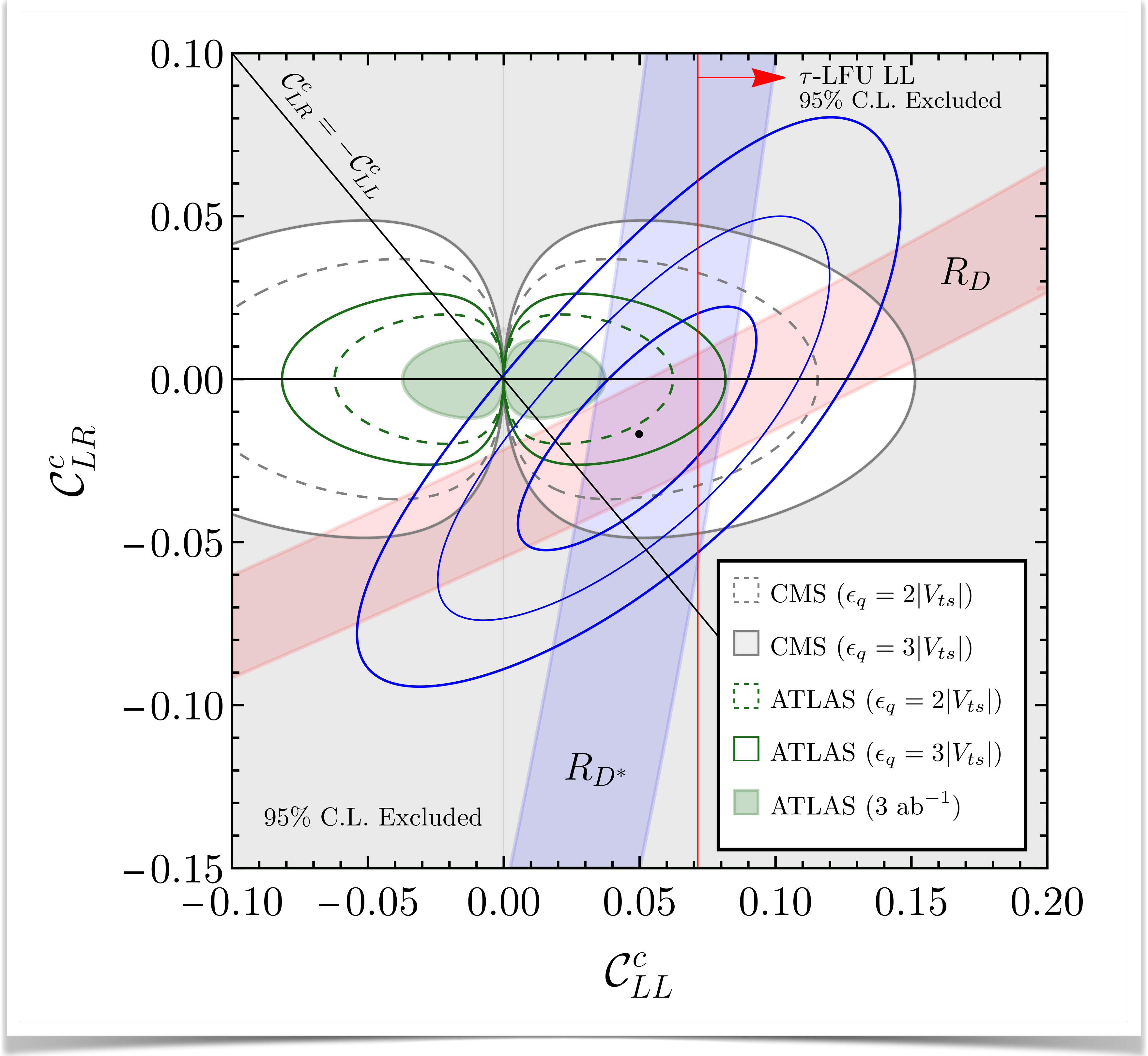

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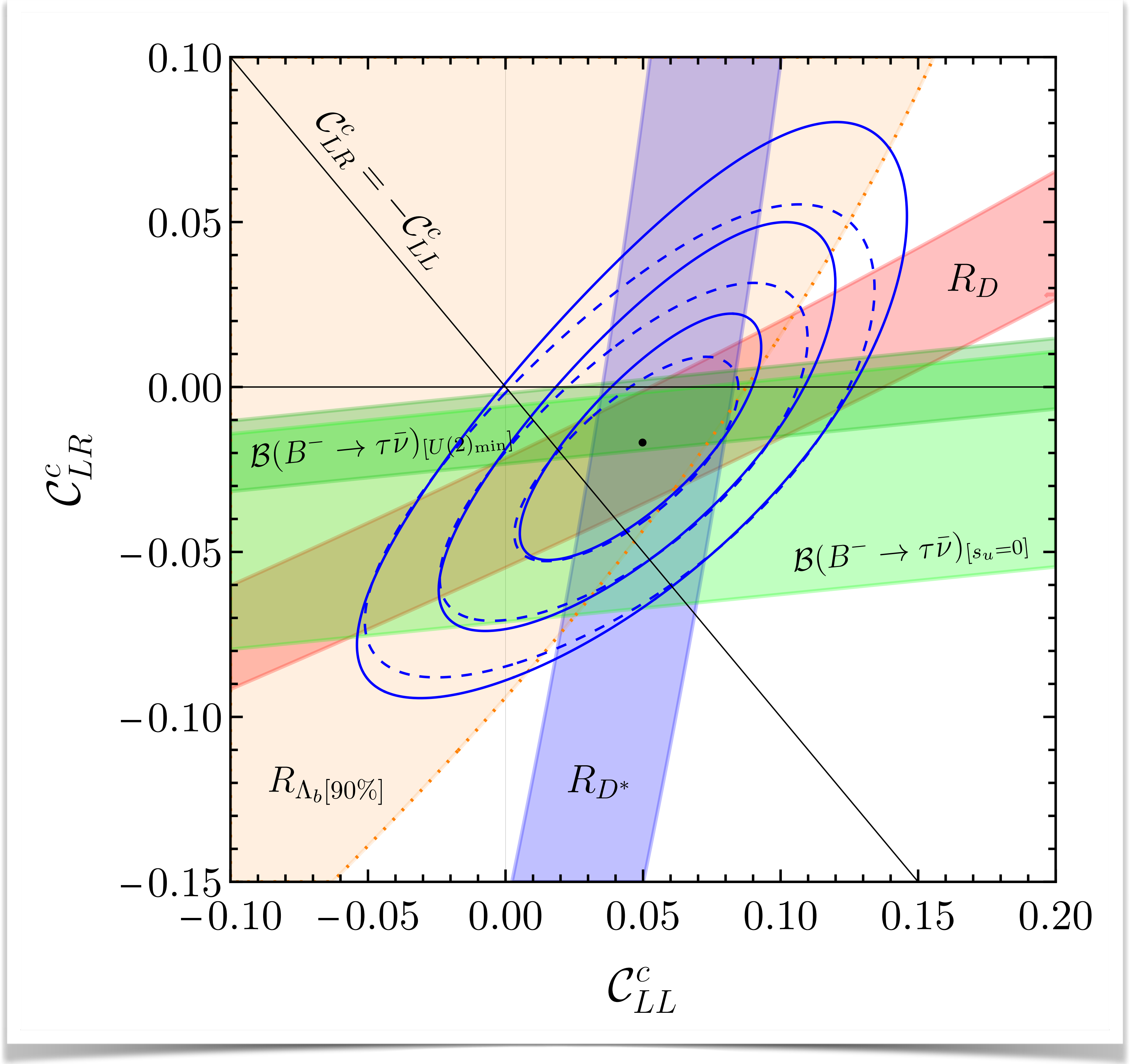

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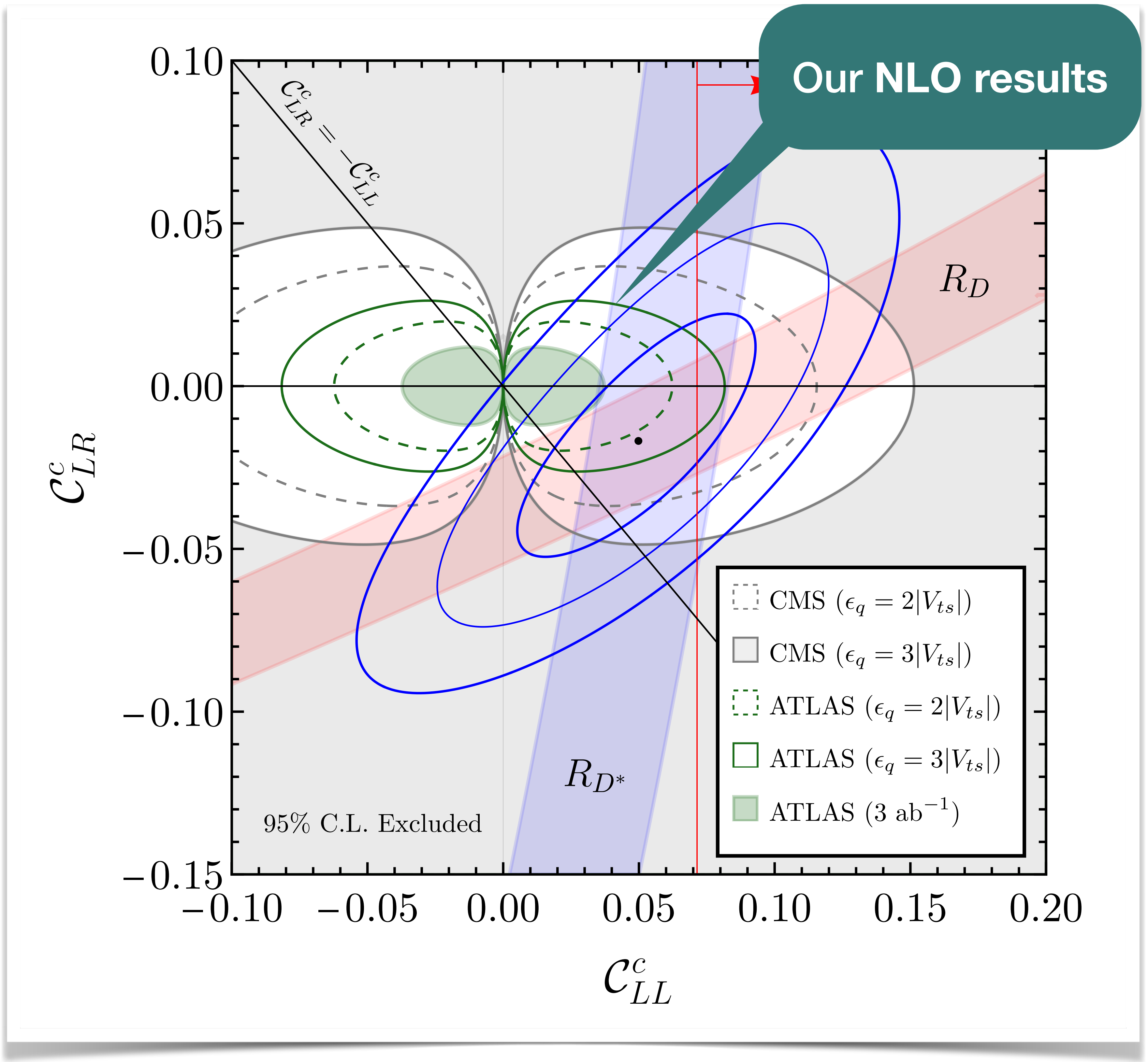

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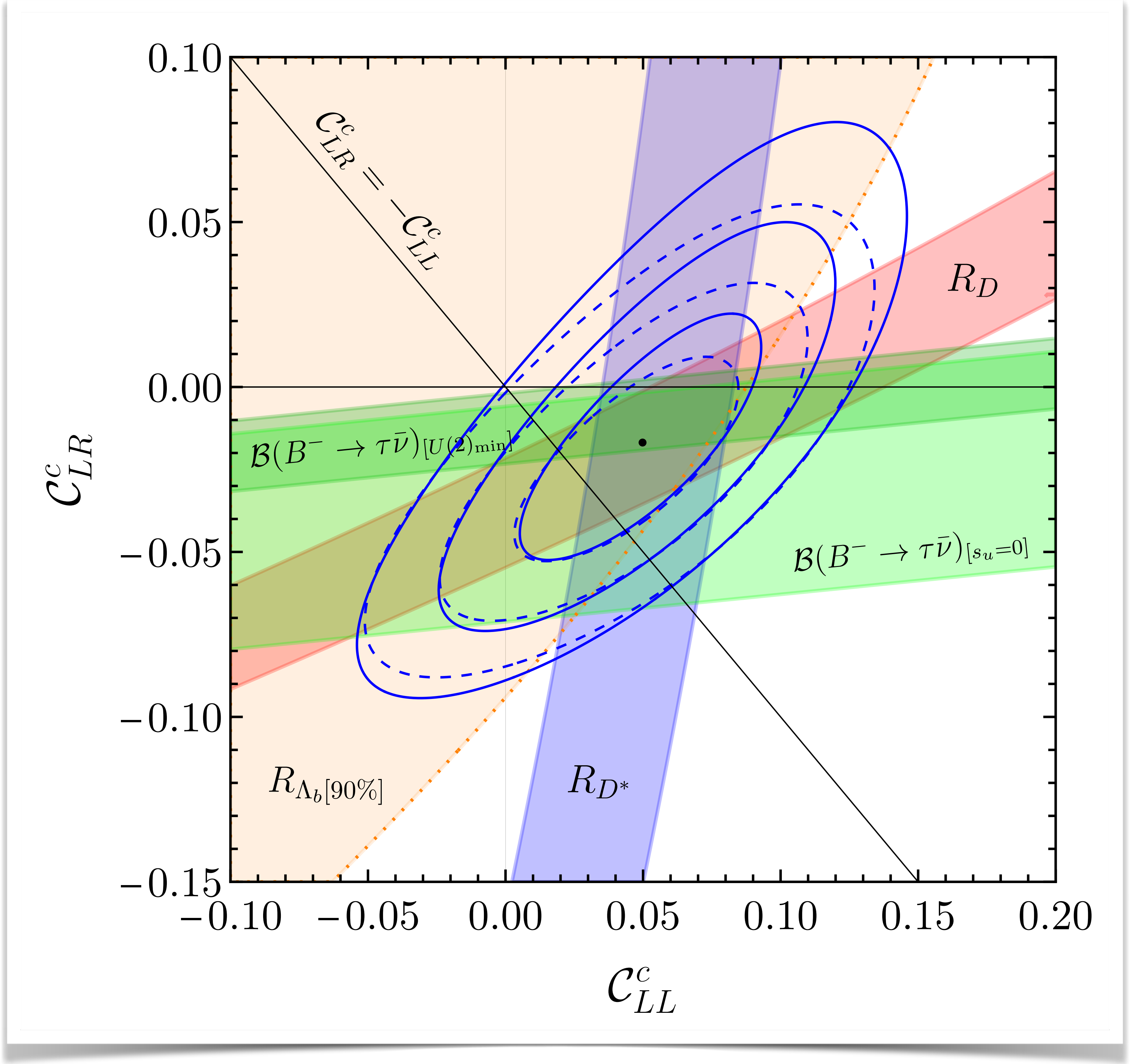

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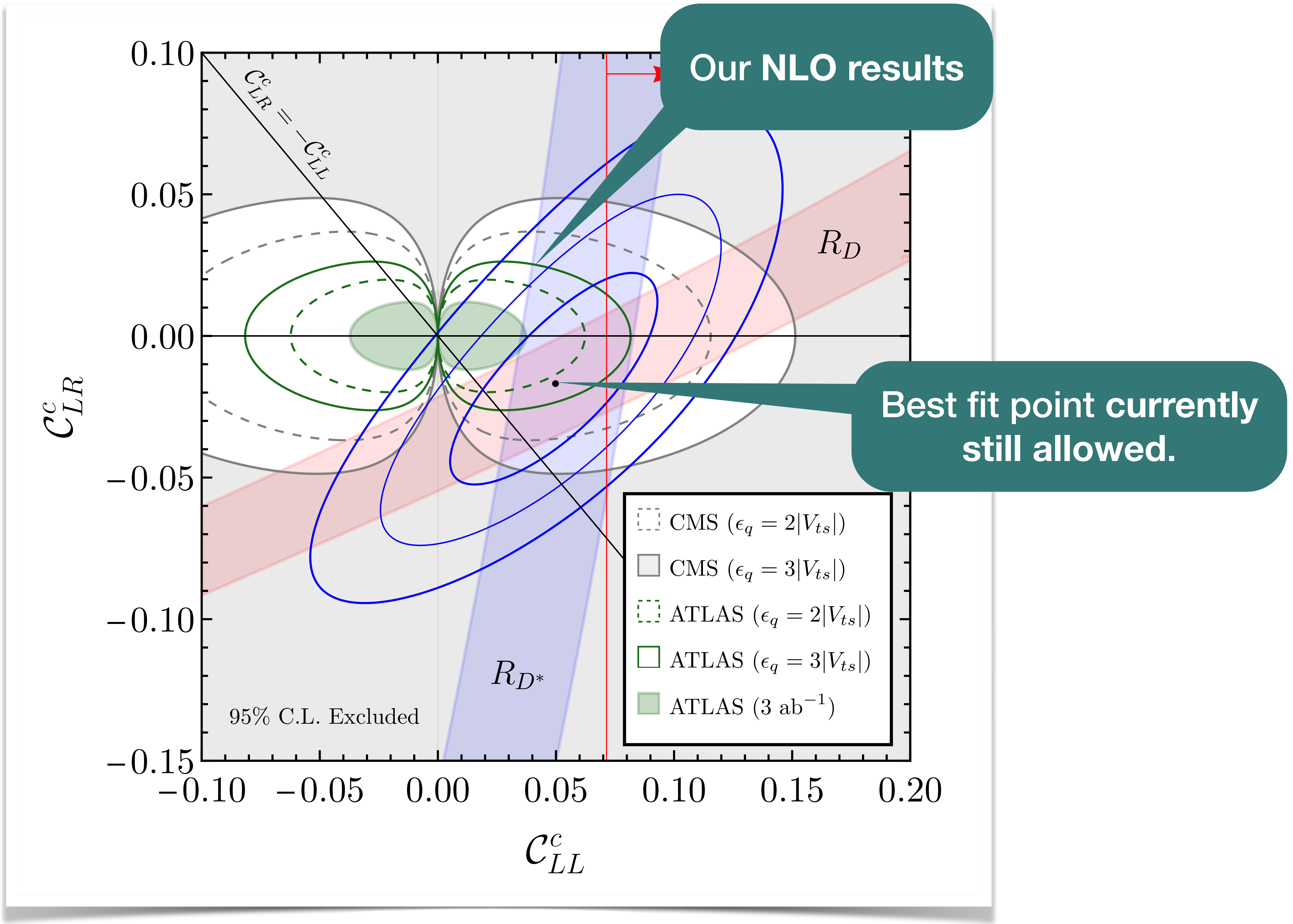

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- **We implemented the $\mathbf{U_1}$ effects in $pp \to \tau^-\tau^+$ at NLO QCD in POWHEG-BOX-V2.**

  - **High-luminosity LHC** will be able to probe the relevant parameter space.

Thank you for your attention!