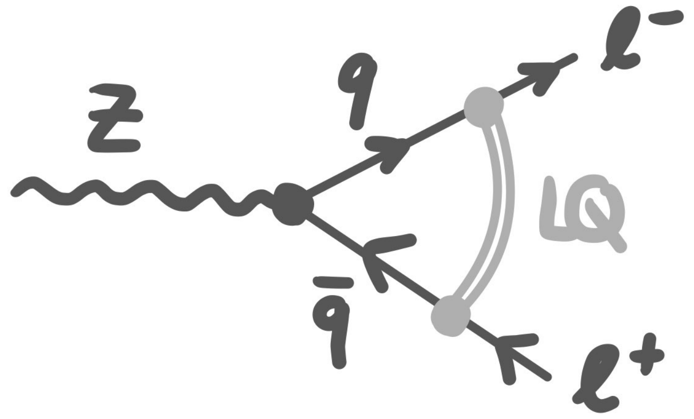
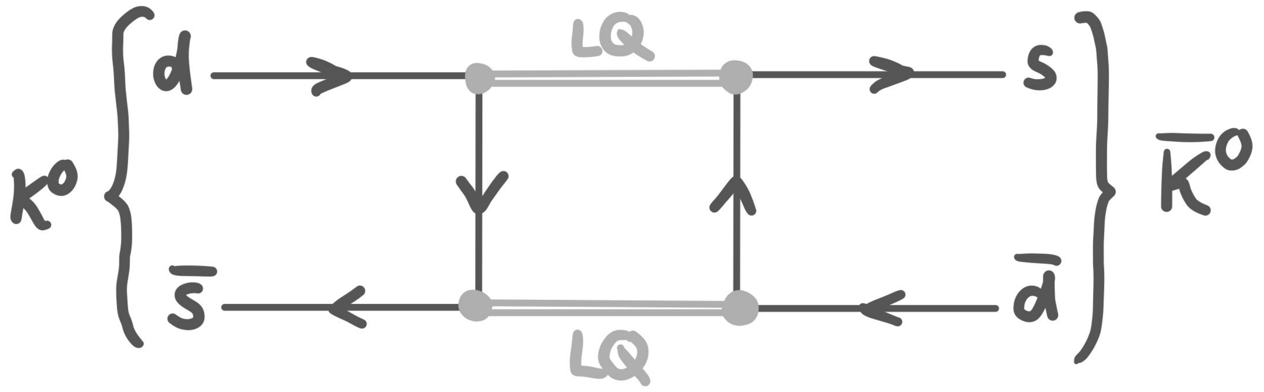
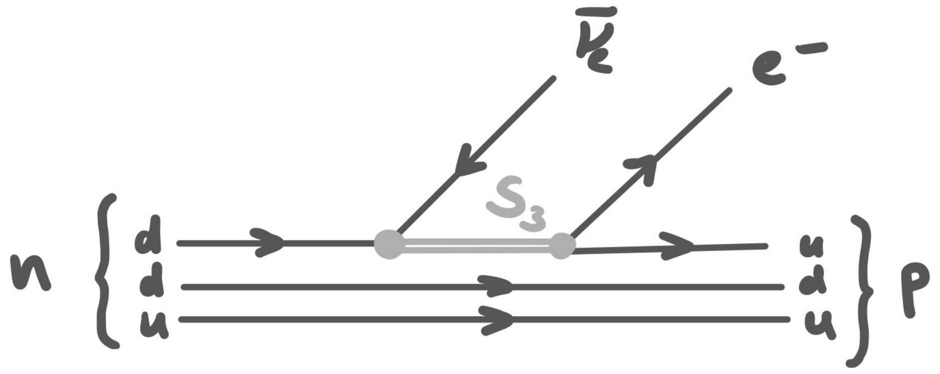
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)
Technische Universität München

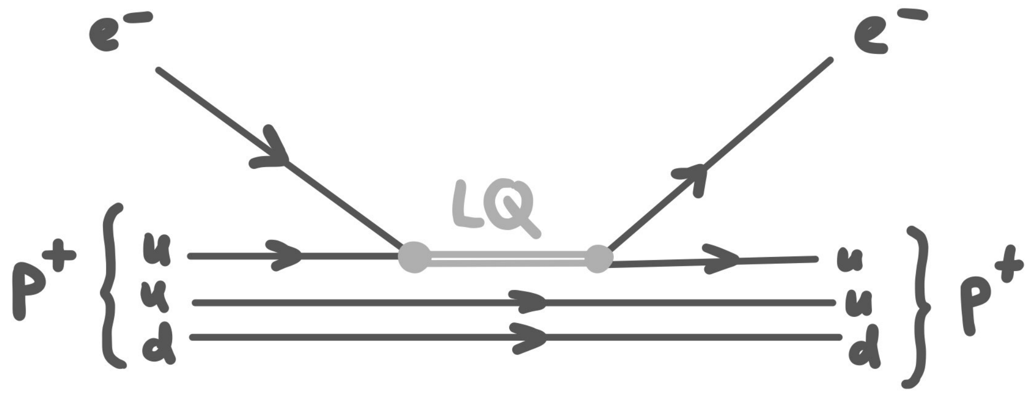
Leptoquark Signatures: from Precision Physics to the LHC

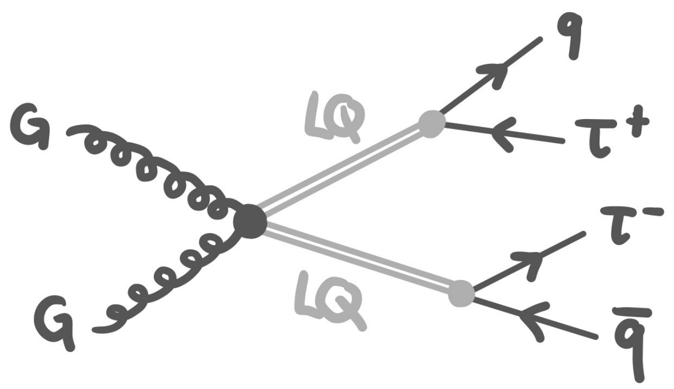
Luc Schnell
Electroweak Precision Physics Workshop
October 25, 2022

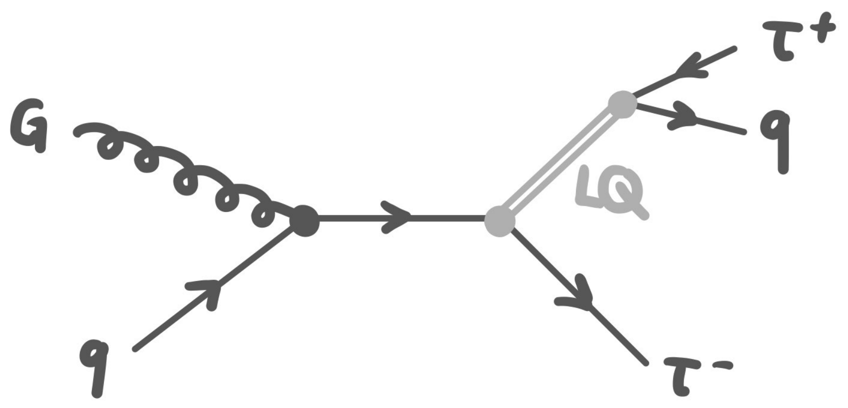


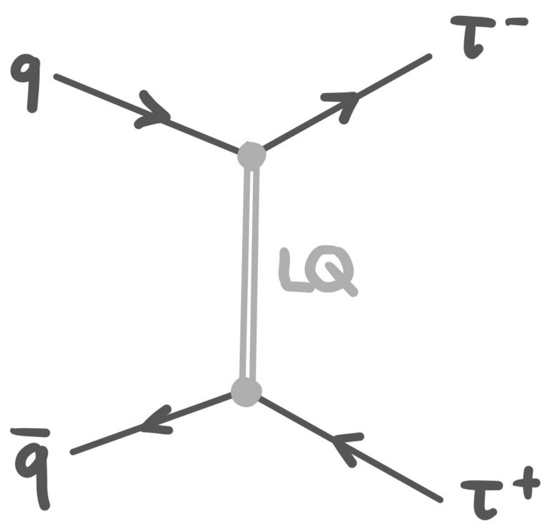


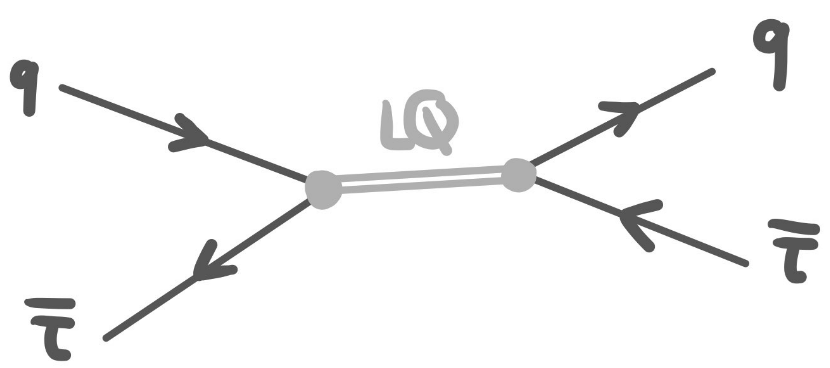












1. Introduction

1.1 Leptoquark representations

1.2 Motivation

1.3 Lagrangian

1.4 UV-complete models

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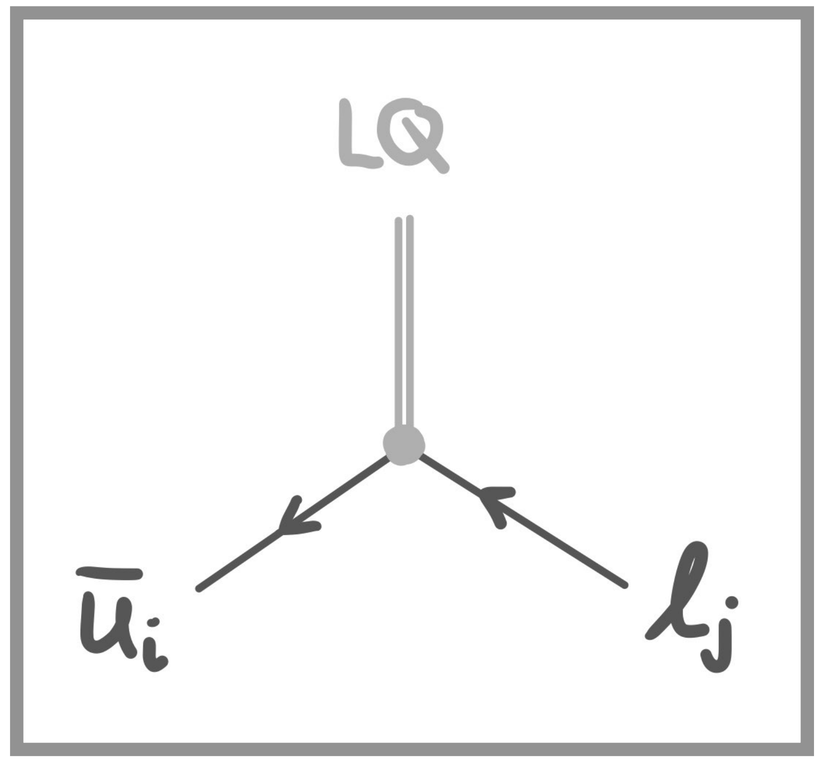

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1.1 Leptoquark representations

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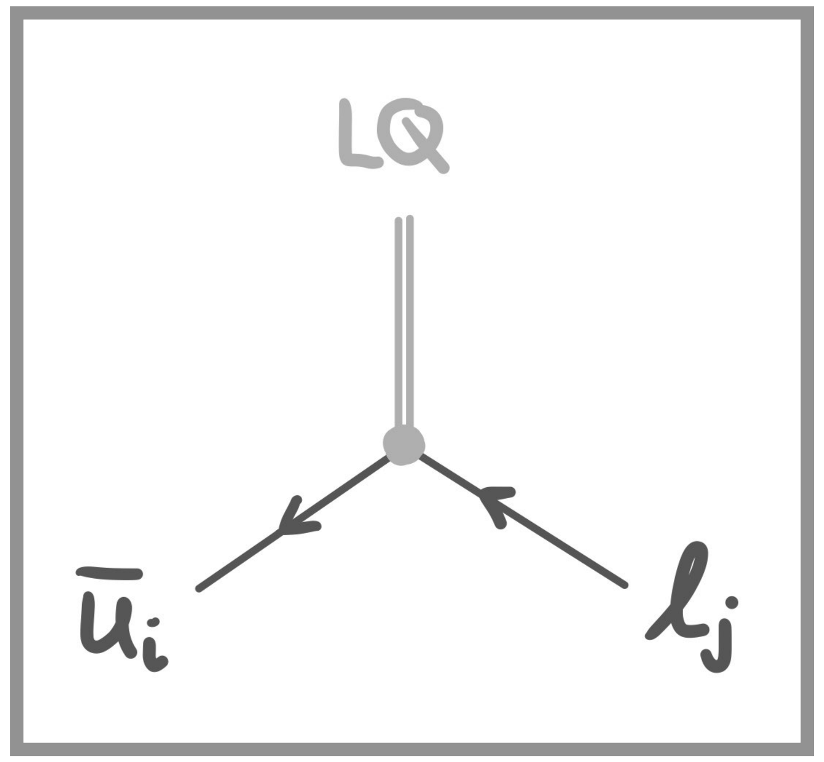
- Ten such representations are possible under $SU(3)_c \times SU(2)_L \times U(1)_Y$, of which five are **scalar** particles and five are **vector** particles.



Field	Φ_1	$\tilde{\Phi}_1$	Φ_2	$\tilde{\Phi}_2$	Φ_3	V_1	$\tilde{V}_1$	V_2	$\tilde{V}_2$	V_3
$SU(3)_c$	3	3	3	3	3	3	3	3	3	3
$SU(2)_L$	1	1	2	2	3	1	1	2	2	3
$U(1)_Y$	$-\frac{2}{3}$	$-\frac{8}{3}$	$\frac{7}{3}$	$\frac{1}{3}$	$-\frac{2}{3}$	$\frac{4}{3}$	$\frac{10}{3}$	$-\frac{5}{3}$	$\frac{1}{3}$	$\frac{4}{3}$

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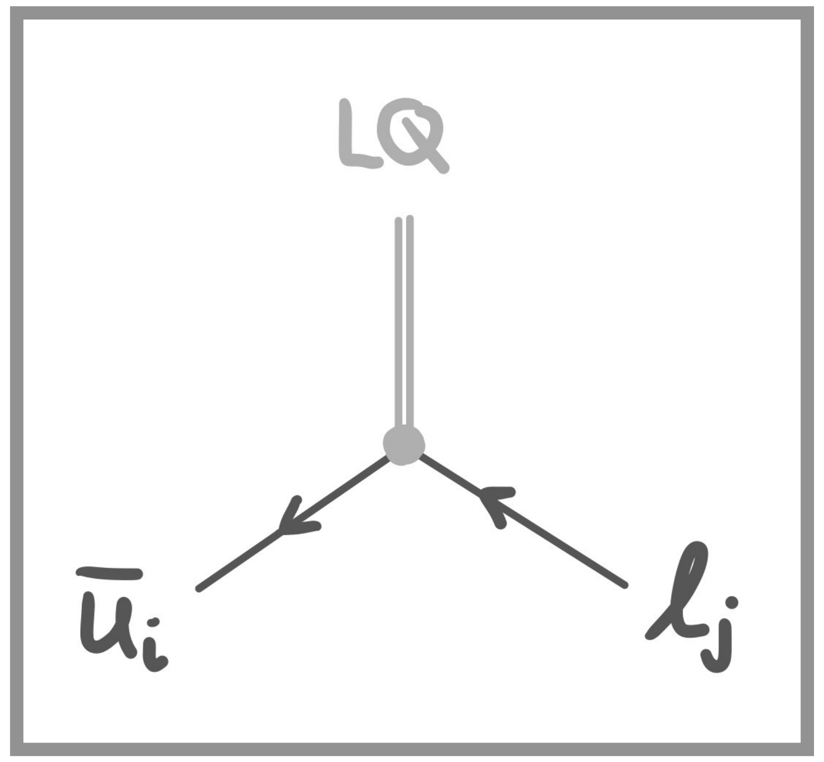

SLQs

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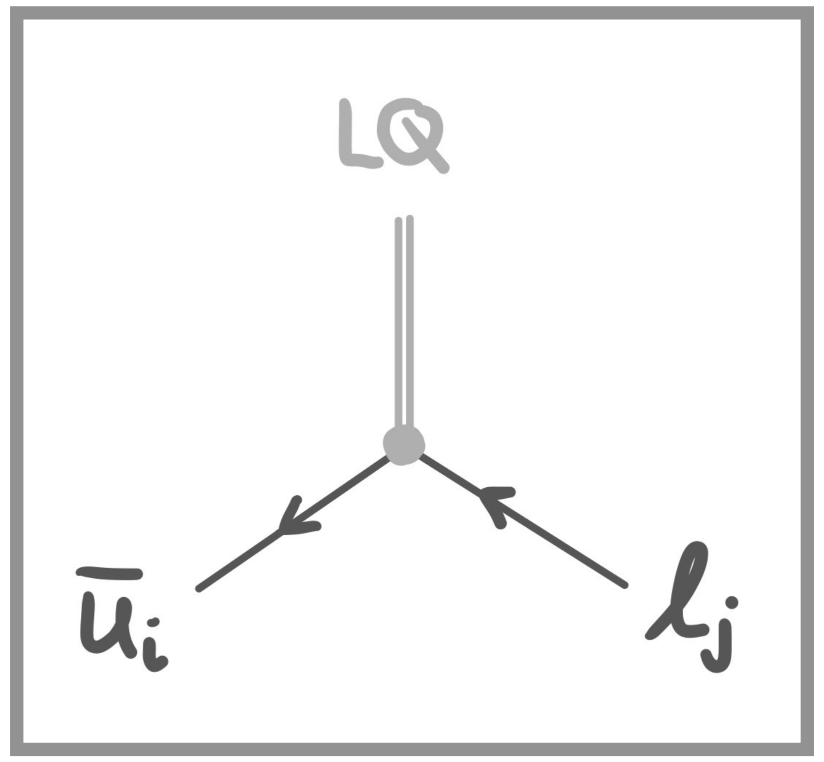

SLQs

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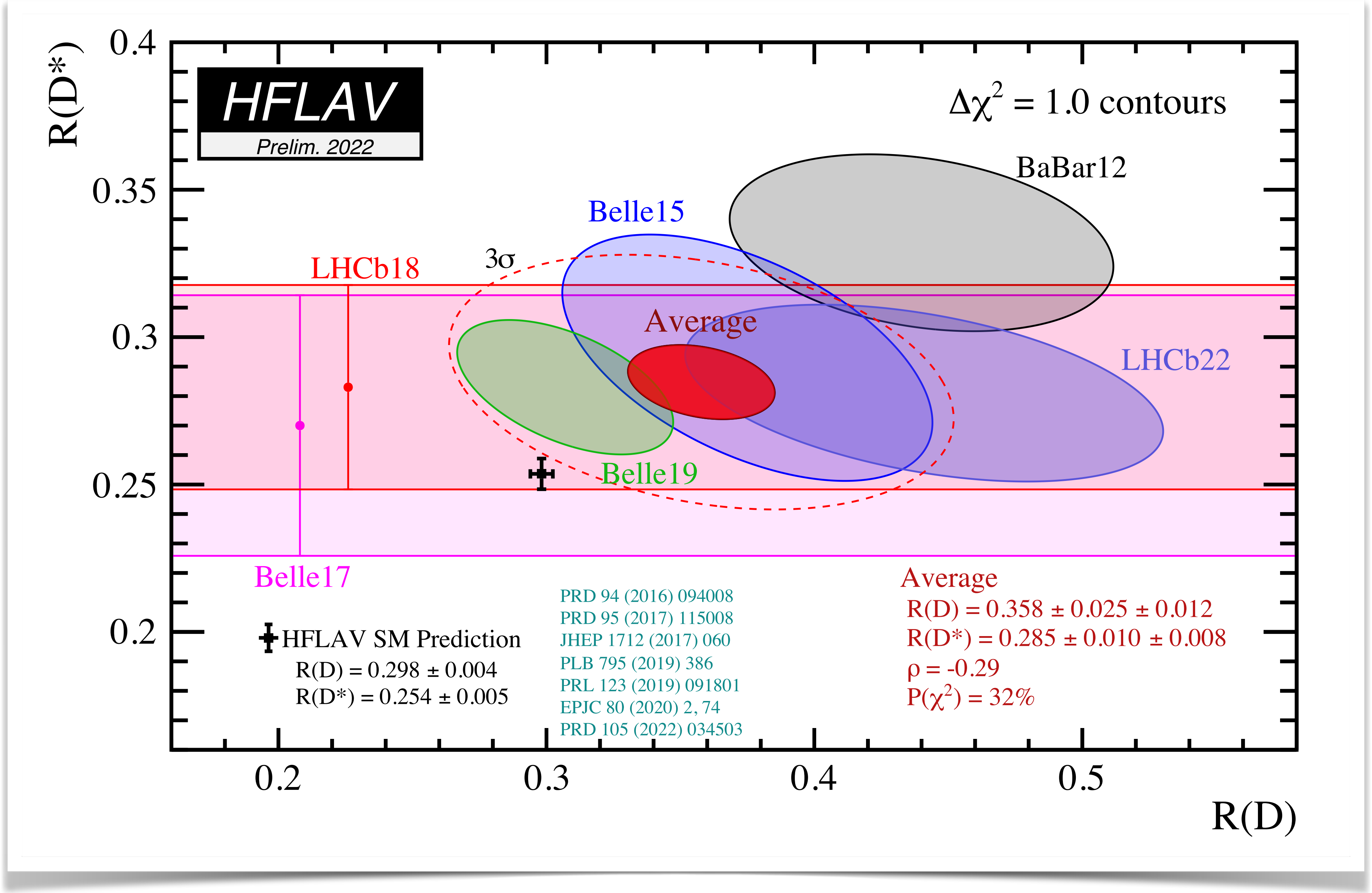

Source: LHCb talk by G.M. Ciezarek

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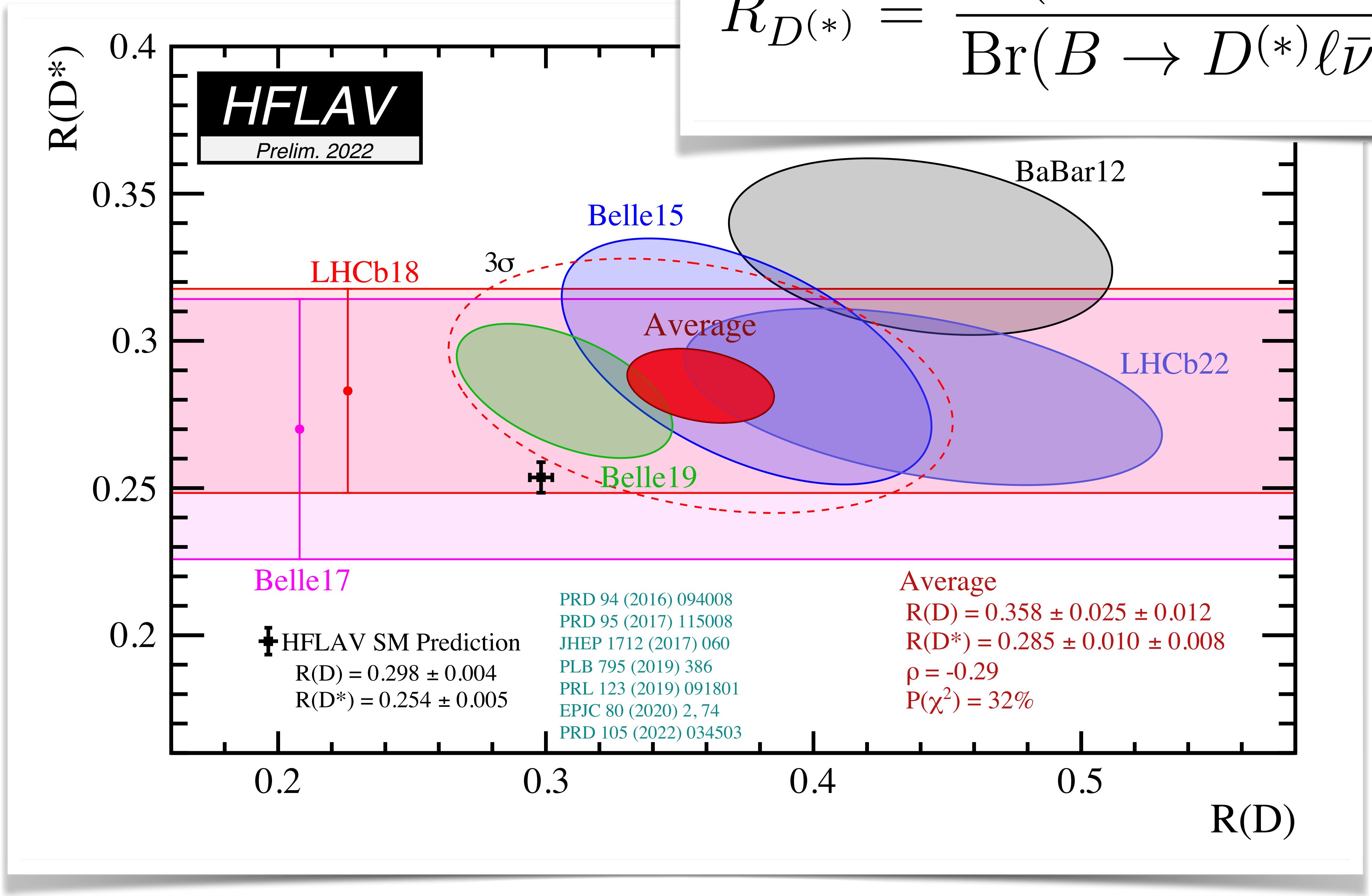

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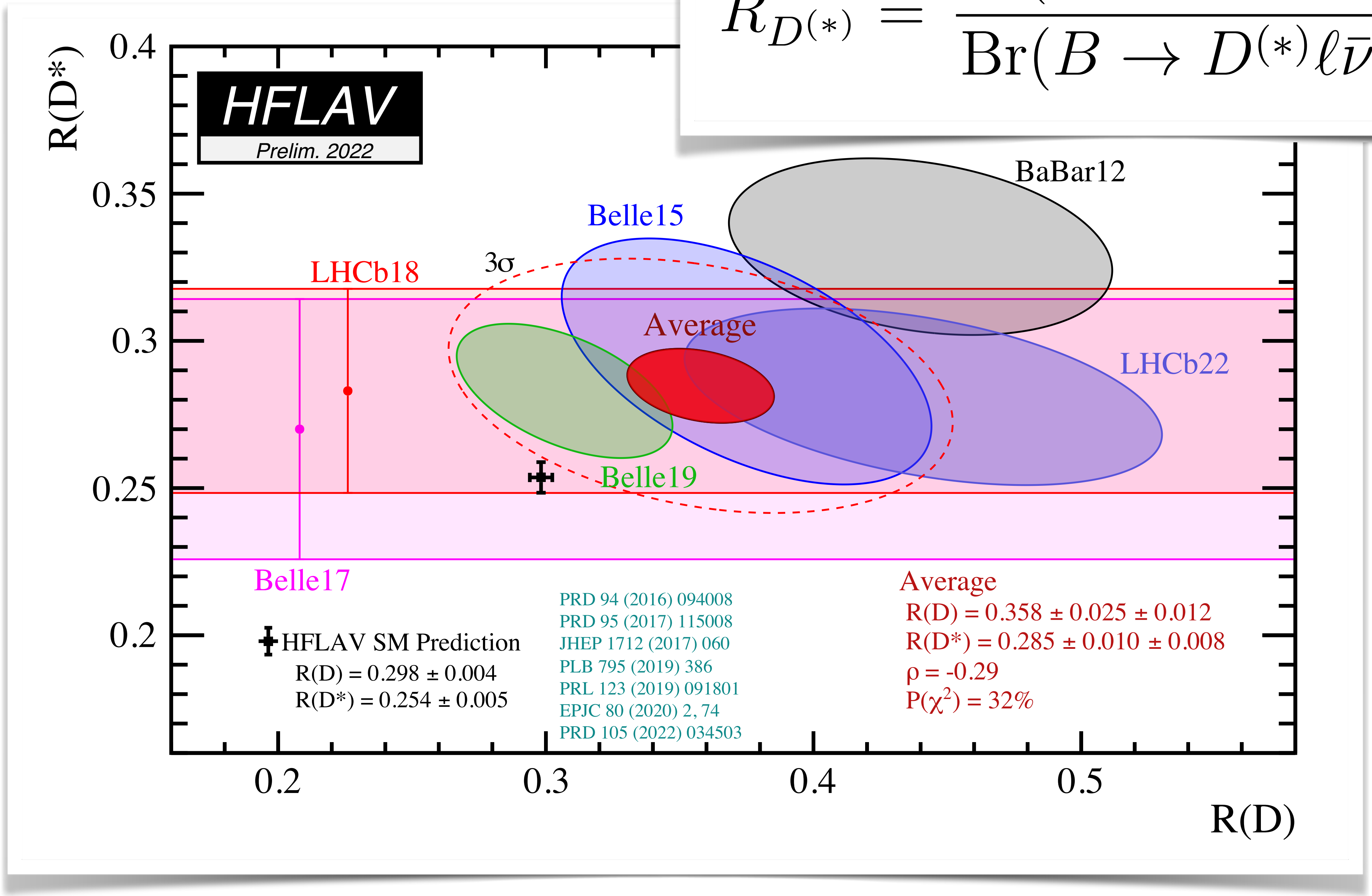

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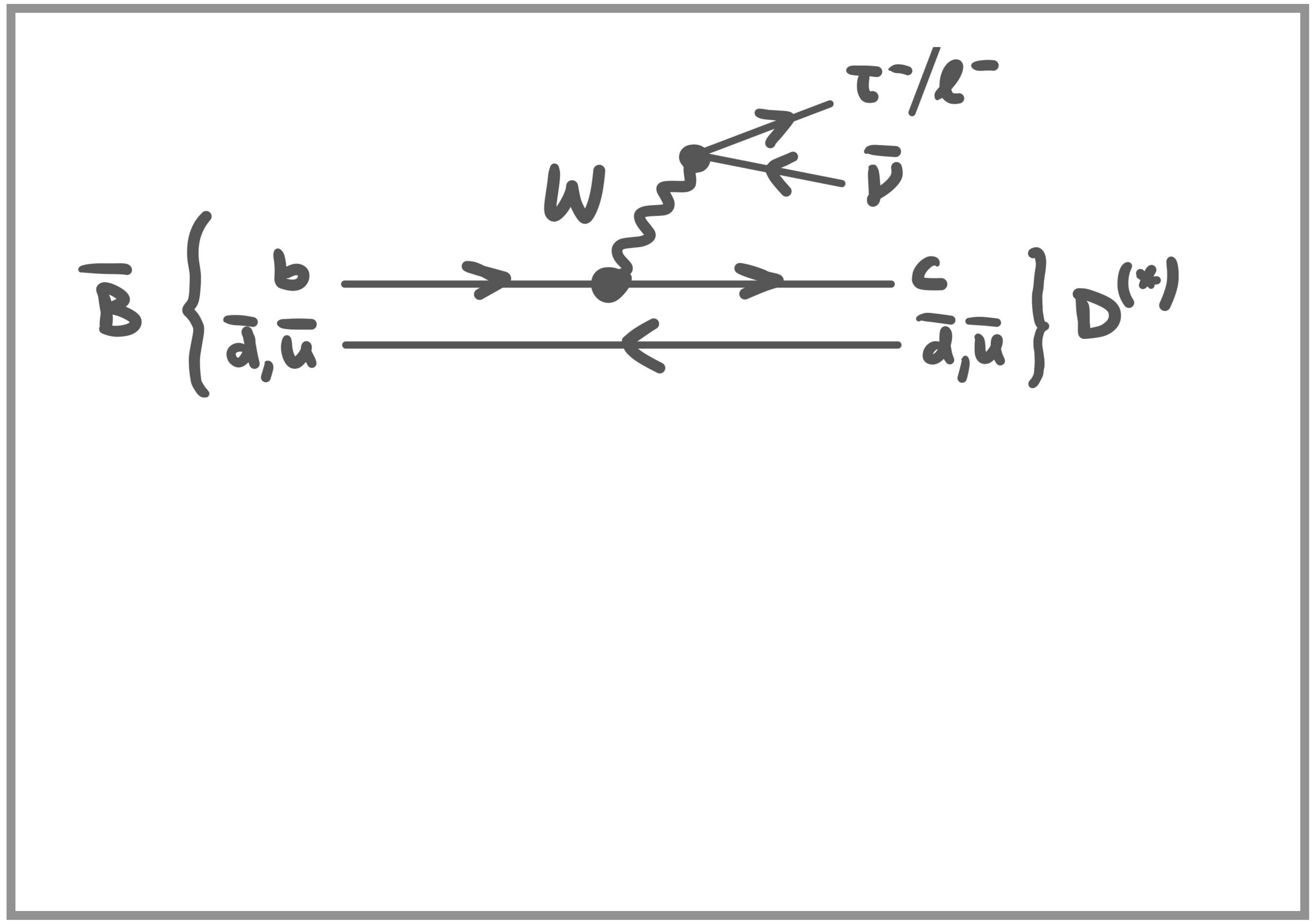

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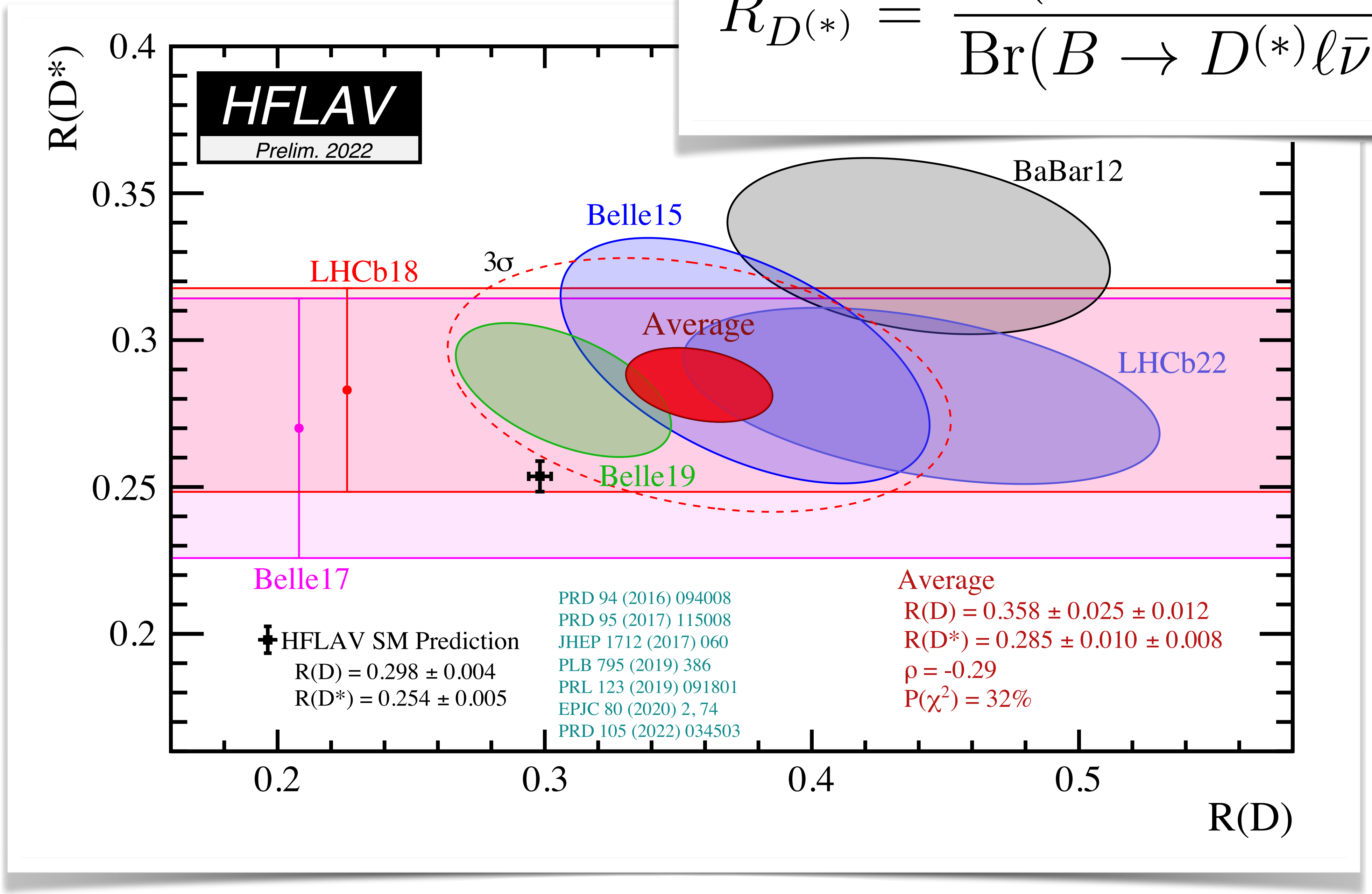

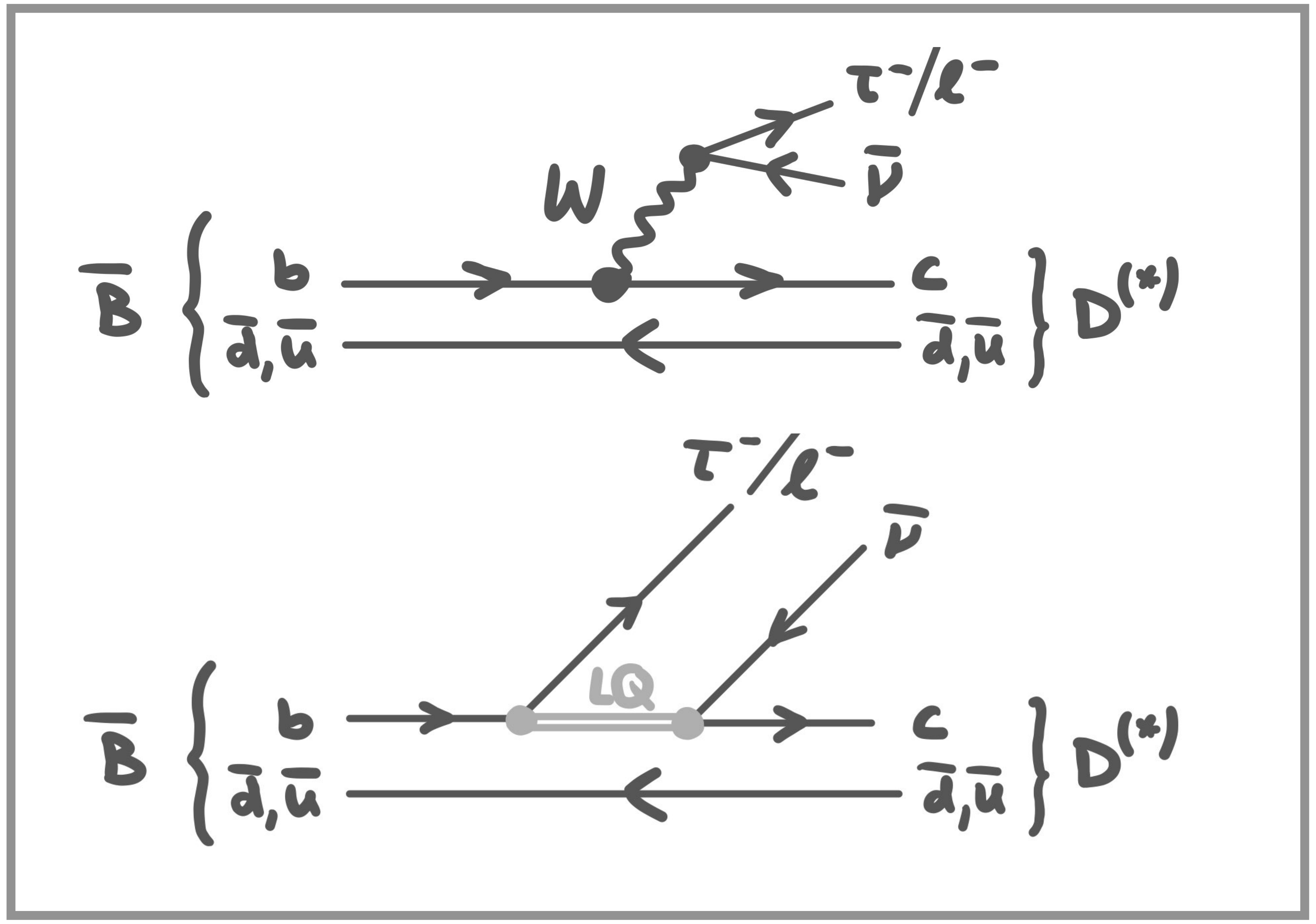

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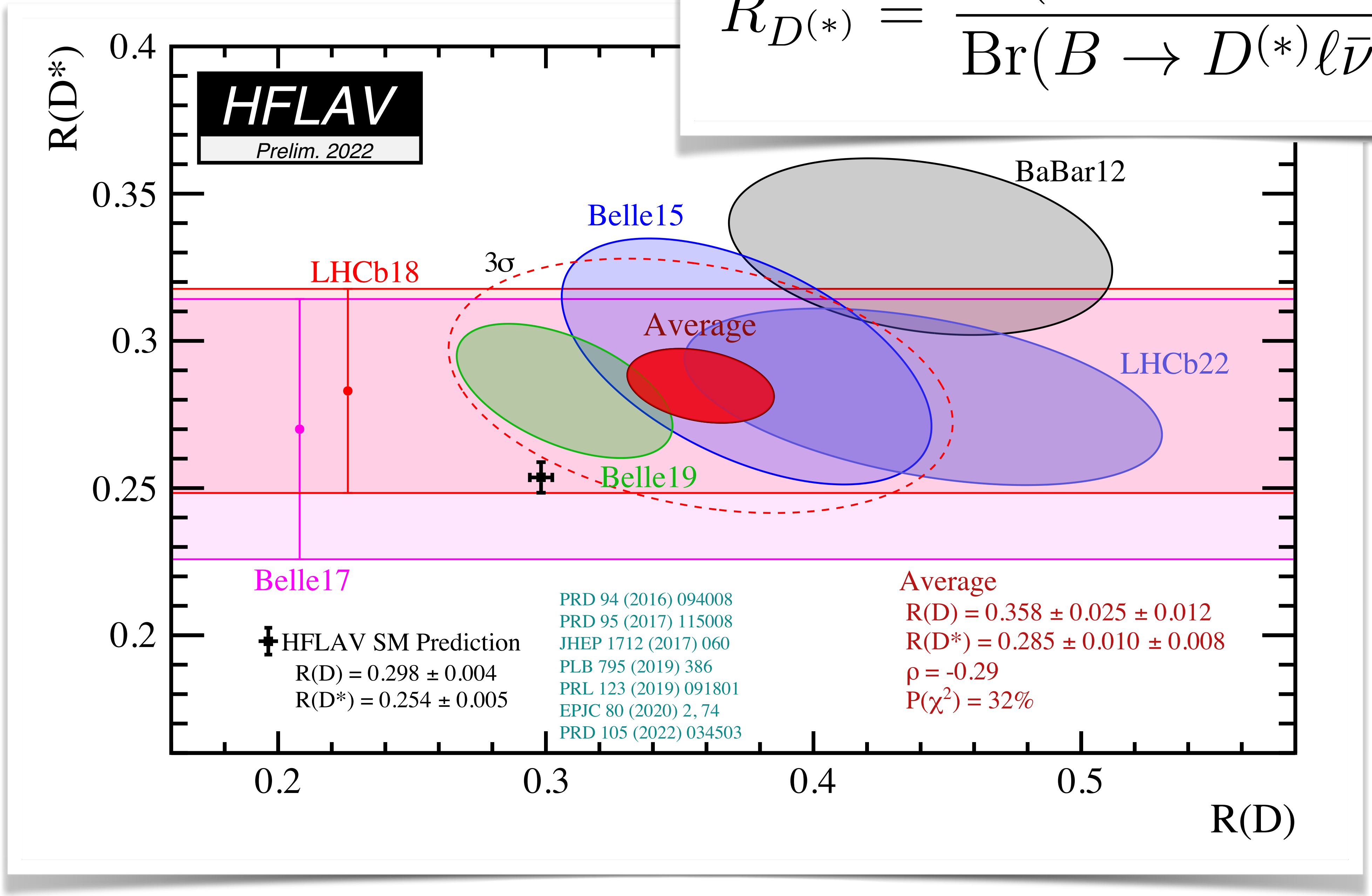

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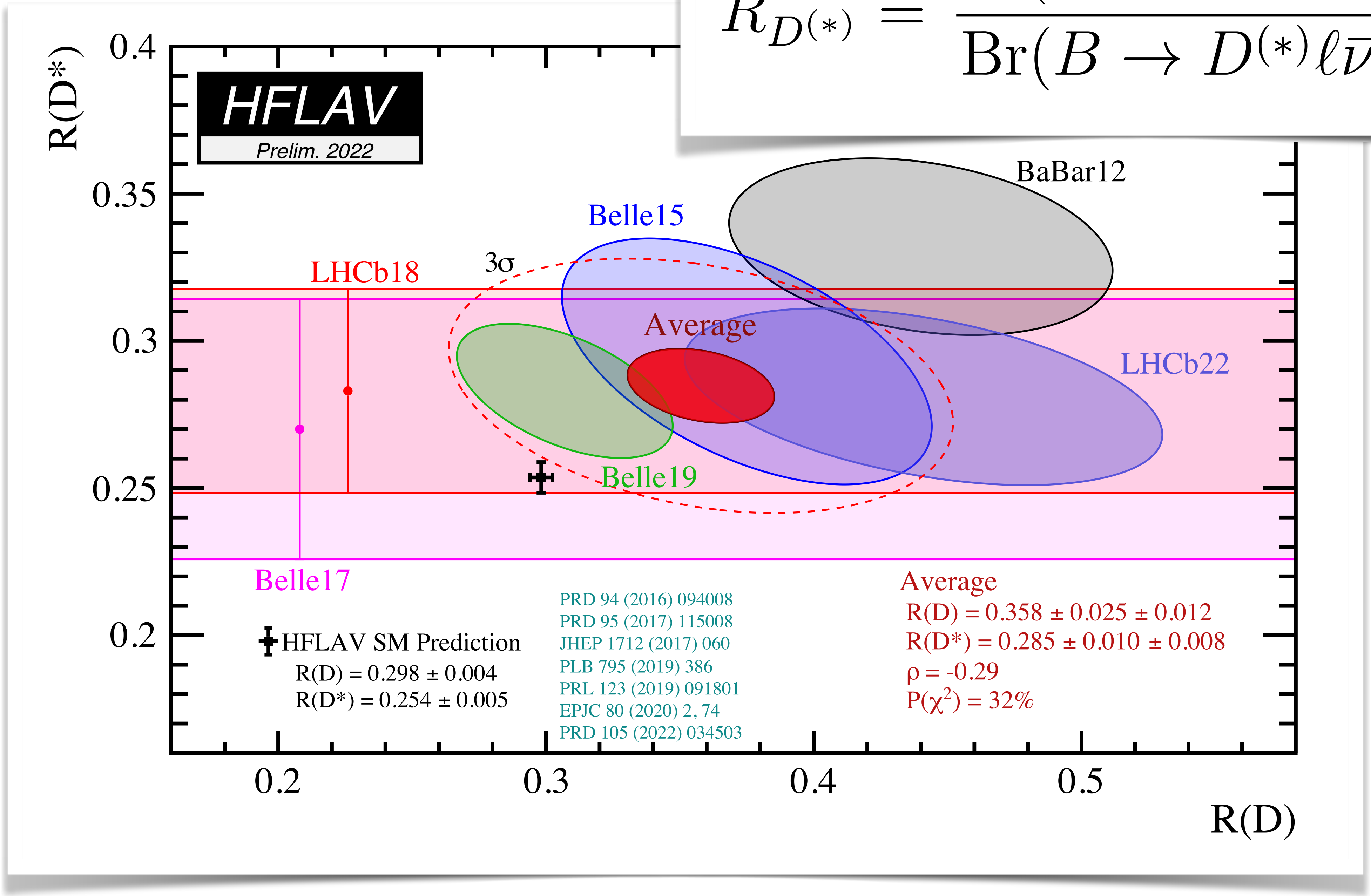

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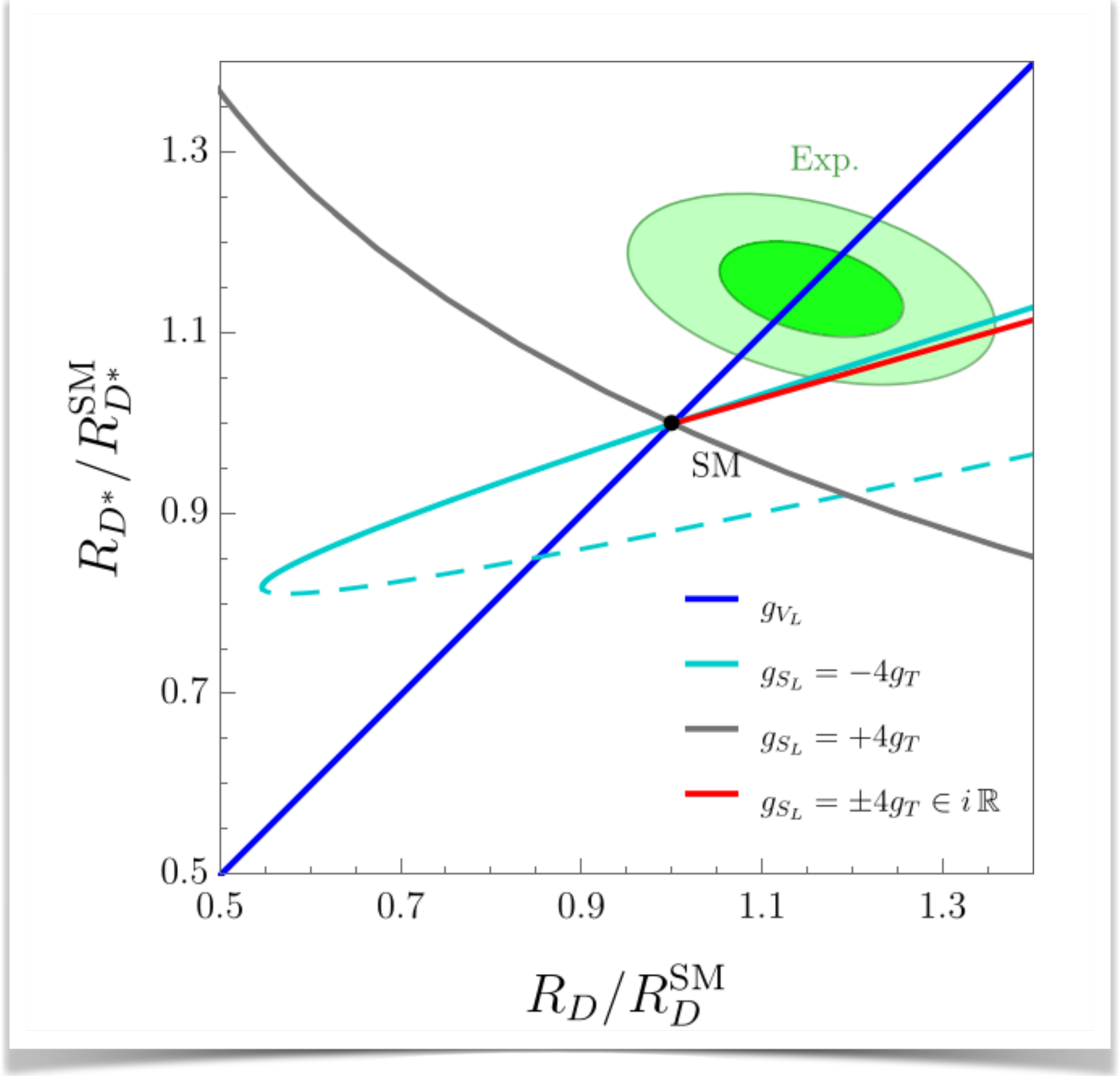

Source: ArXiv:2103.12504 (A. Angelescu, D. Becirevic, D.A. Faroughy, F. Jaffredo, O. Sumensari)

1. Introduction

1.3 Lagrangian

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1.3 Lagrangian

SLQs

$$Y^{RR}_{1,ij}\,\bar{u}'^{c}_i \ell'_j \Phi^\dagger_1 + Y^{LL}_{1,ij}\,\left(\bar{Q}'^{c\intercal}_i i\sigma_2 L'_j\right)\Phi^\dagger_1 + \text{h.c.}$$

- Simplified S_1 couplings.

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$$\mathcal{L}_{2\Phi}=-\sum_{a=1}^{3}\left(m_a^2+Y_a\left(H^{\dagger}H\right)\right)\left(\Phi_a^{\dagger}\Phi_a\right)$$

- One can just introduce a mass term.

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1.3 Lagrangian

$$\mathcal{L}_{2\Phi} = -\sum_{a=1}^{3}\left(\boxed{m_a^2} + Y_a\left(H^\dagger H\right)\right)\left(\Phi_a^\dagger\Phi_a\right)$$

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→ Complete SLQ Lagrangian in **FeynRules**

Source: ArXiv:2105.04844 (A. Crivellin, LS)

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1.3 Lagrangian

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U_1

$$\frac{g_U}{\sqrt{2}} \left[\beta^{ij}_L \,\bar{Q}^{\,i,a} \gamma_\mu L^j + \beta^{ij}_R \,\bar{d}^{\,i,a} \gamma_\mu e^j\right] U^{\mu,a} + \text{h.c.}$$

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→ How can this be turned into a **UV-complete model**?

1. Introduction

1.4 UV-complete gauge models

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U_1

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

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1.4 UV-complete gauge models

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1.4 UV-complete gauge models

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  - First idea: **Pati-Salam-type model**

$$G_{\text{NP}}^{\min} = SU(4)\times SU(2)_L \times U(1)_{T_R^3}\ ,$$

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1.4 UV-complete gauge models

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1.4 UV-complete gauge models

$SU(4)$ generators:

U_1

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U$_1$

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$SU(4)$ generators:

$$T^1 = \frac{1}{2}\begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

G

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1.4 UV-complete gauge models

U_1

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U_1

$$T^1 = \frac{1}{2}\begin{pmatrix} 0&1&0&0\\ 1&0&0&0\\ 0&0&0&0\\ 0&0&0&0 \end{pmatrix} \qquad T^{11} = \frac{1}{2}\begin{pmatrix} 0&0&0&0\\ 0&0&0&1\\ 0&0&0&0\\ 0&1&0&0 \end{pmatrix}$$

G

1. Introduction

1.4 UV-complete gauge models

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

U_1

- Gauge models: $$G_{\rm NP}\supset G_{\rm SM}$$
  - First idea: **Pati-Salam-type model**

$$G_{\rm NP}^{\rm min}=SU(4)\times SU(2)_L\times U(1)_{T_R^3}\;,\qquad \psi_L^{\rm SM}=\begin{pmatrix} q_L^\beta \\ \ell_L \end{pmatrix}$$

$SU(4)$ generators:

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$$T^1=\frac{1}{2}\begin{pmatrix}0&1&0&0\\1&0&0&0\\0&0&0&0\\0&0&0&0\end{pmatrix}\qquad T^{11}=\frac{1}{2}\begin{pmatrix}0&0&0&0\\0&0&0&1\\0&0&0&0\\0&1&0&0\end{pmatrix}$$

G

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

1. Introduction

1.4 UV-complete gauge models

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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)

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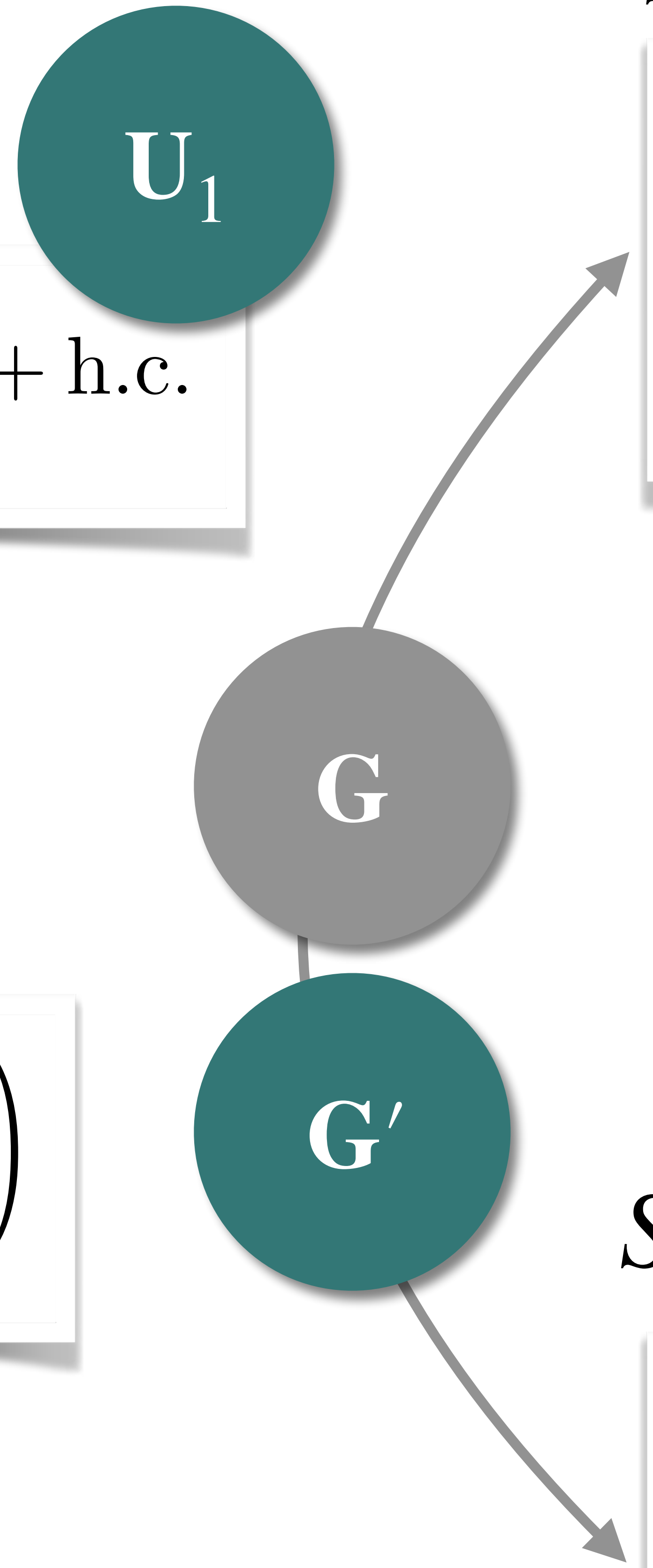

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$\mathbf{G}$

$$g_s = s_3\, g_4 = c_3\, g_3$$

$\mathbf{G'}$

$$(c_3\, g_4)^2 = g_4^2 - g_s^2 .$$

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2. Precision observables

2.1 Search channels

2.2 β-decays / Cabibbo angle anomaly

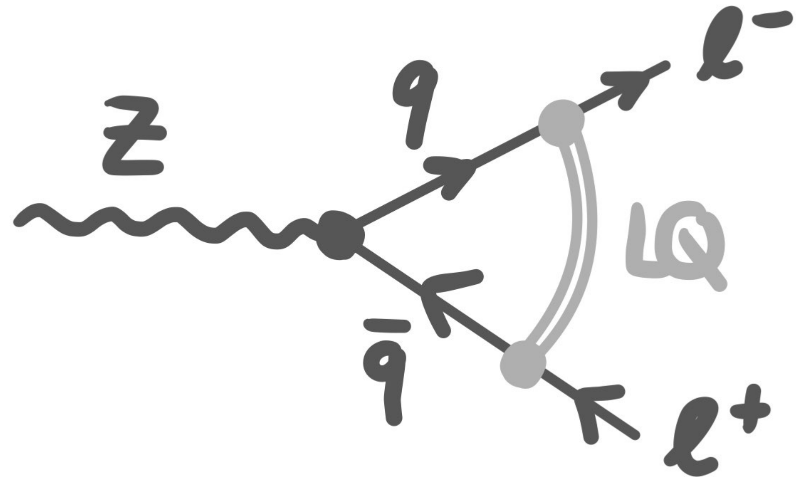
2.3 Parity violation experiments

2. Precision observables

2.1 Search channels

2. Precision observables

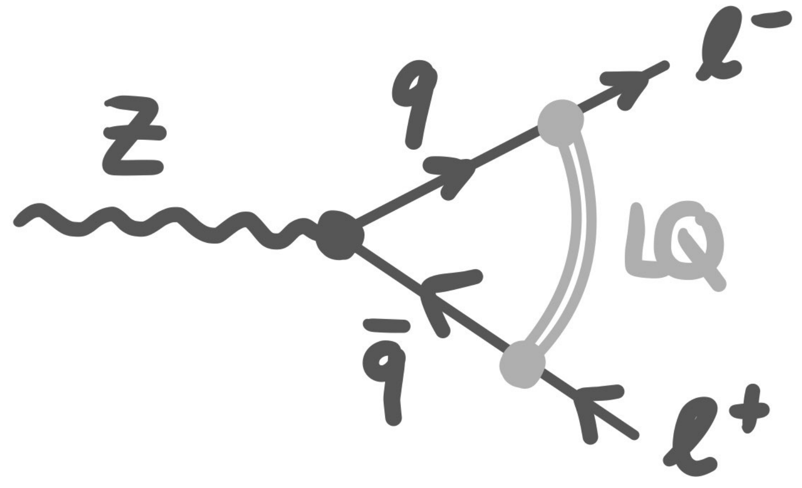
2.1 Search channels



Z-pole measurements

2. Precision observables

2.1 Search channels



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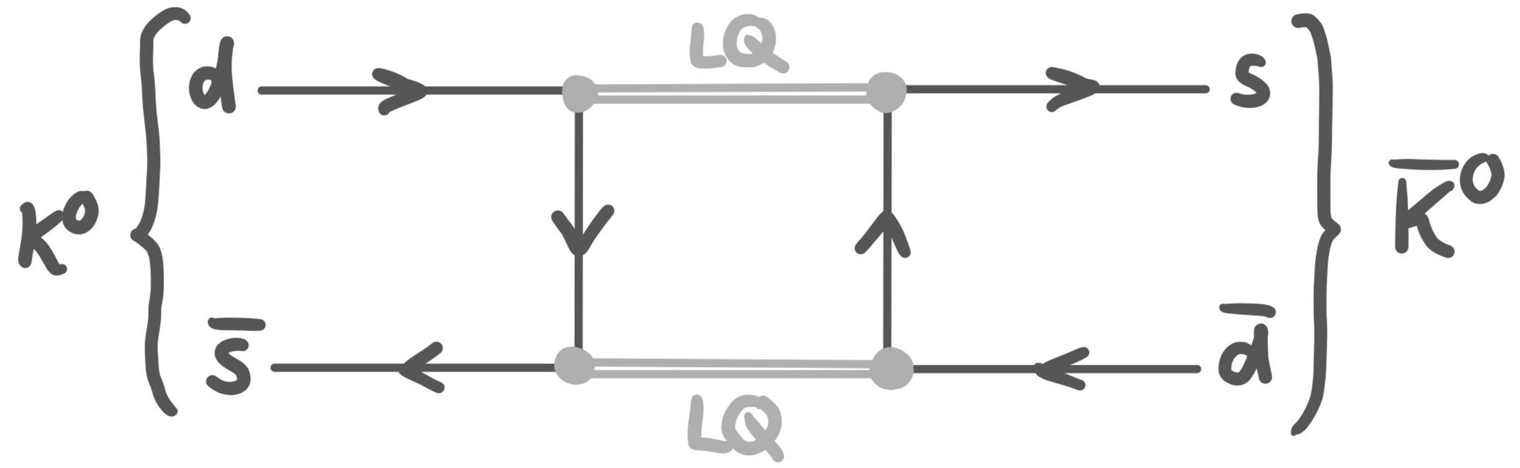

Meson mixing

2. Precision observables

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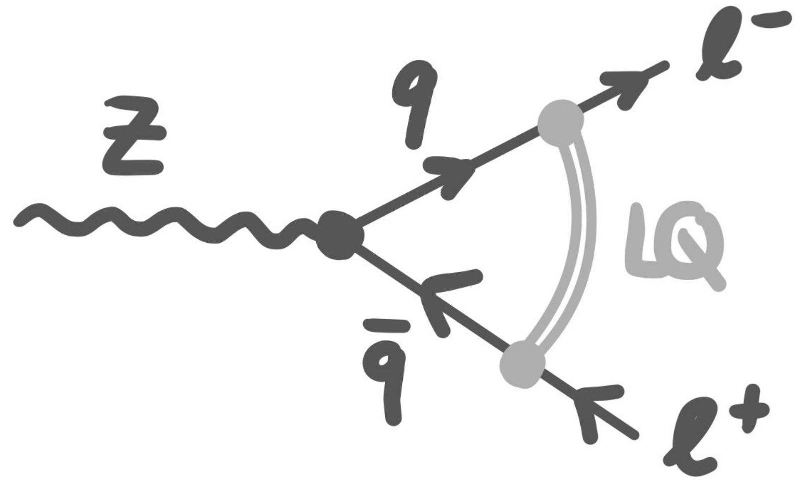

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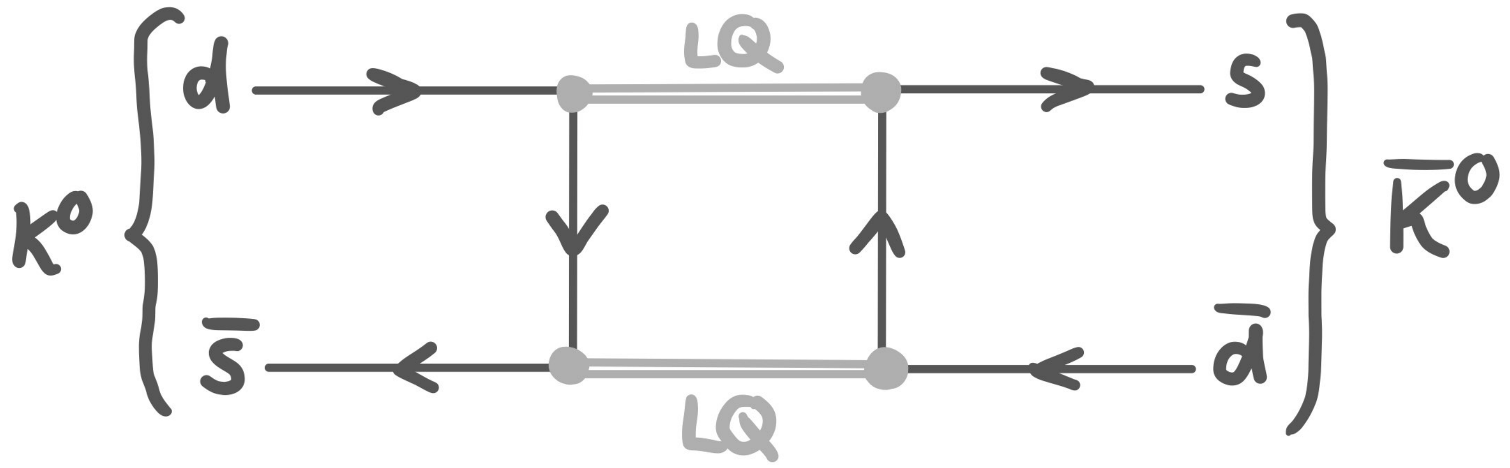

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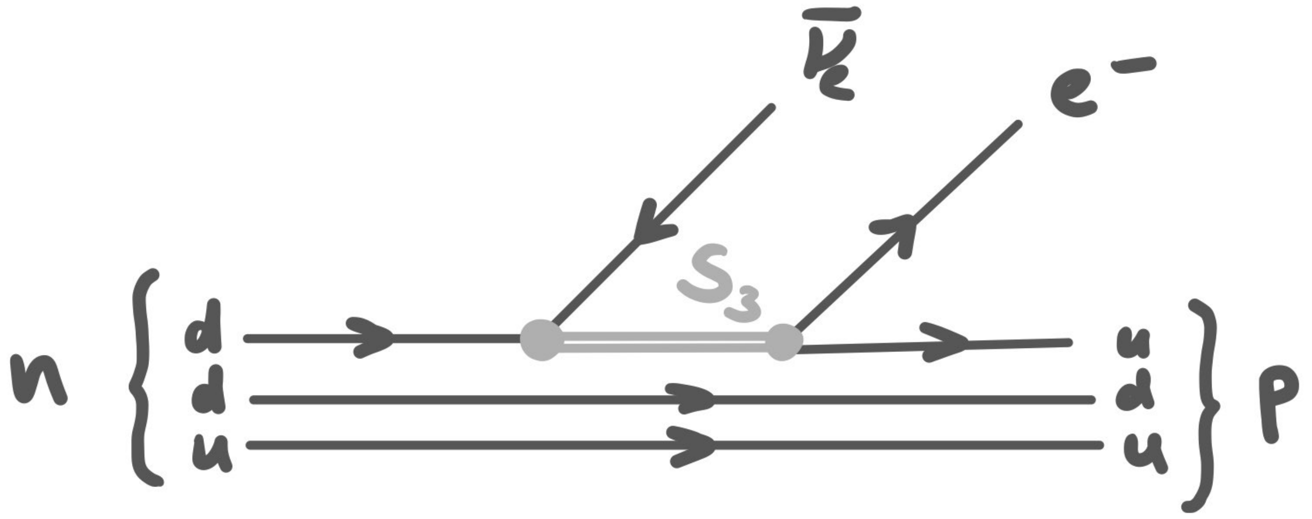

β-decays / Cabibbo angle anomaly

2. Precision observables

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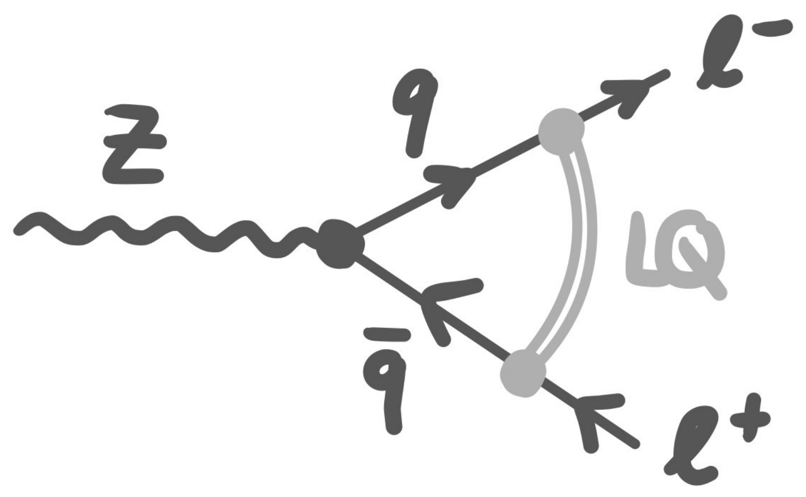

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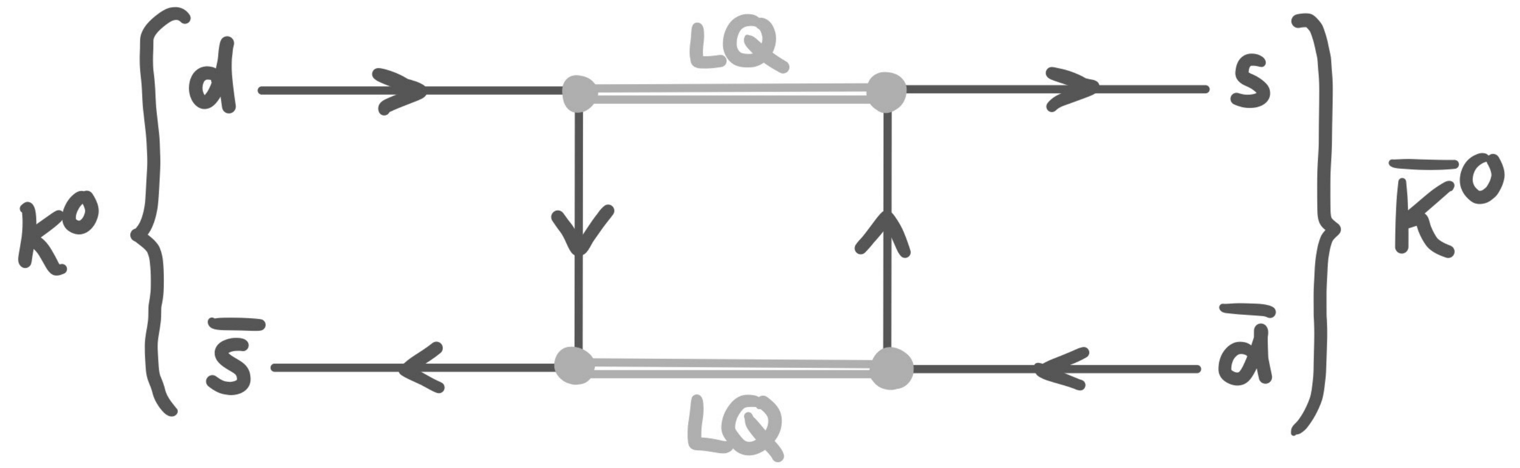

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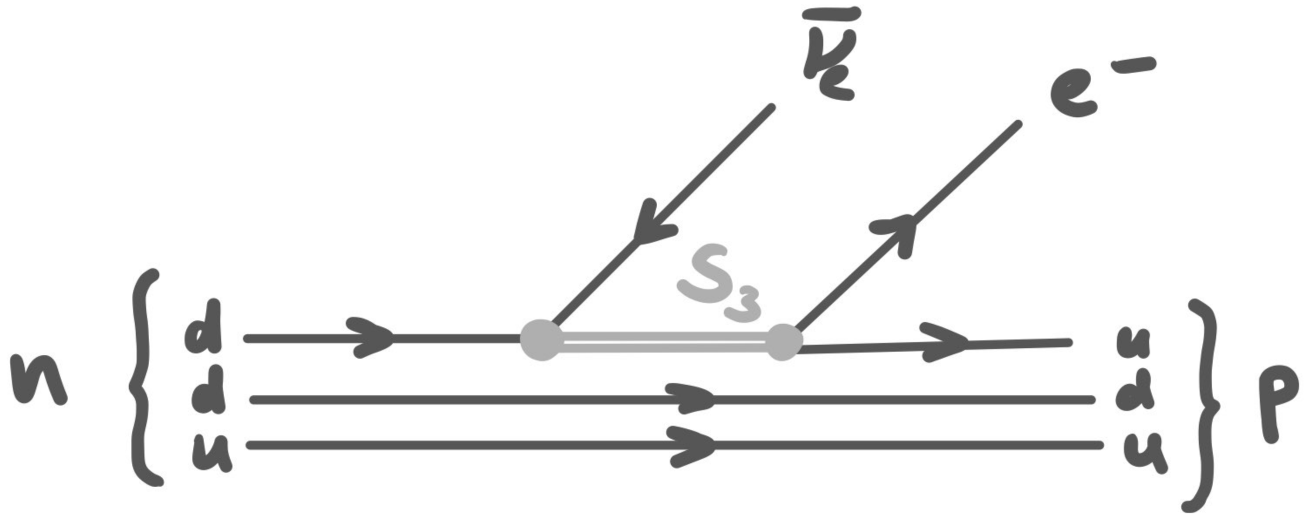

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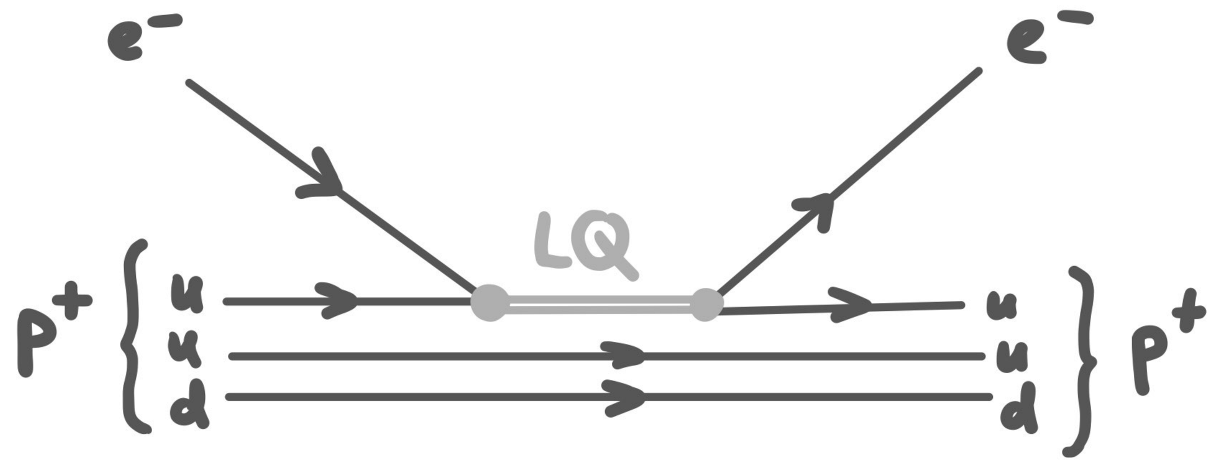

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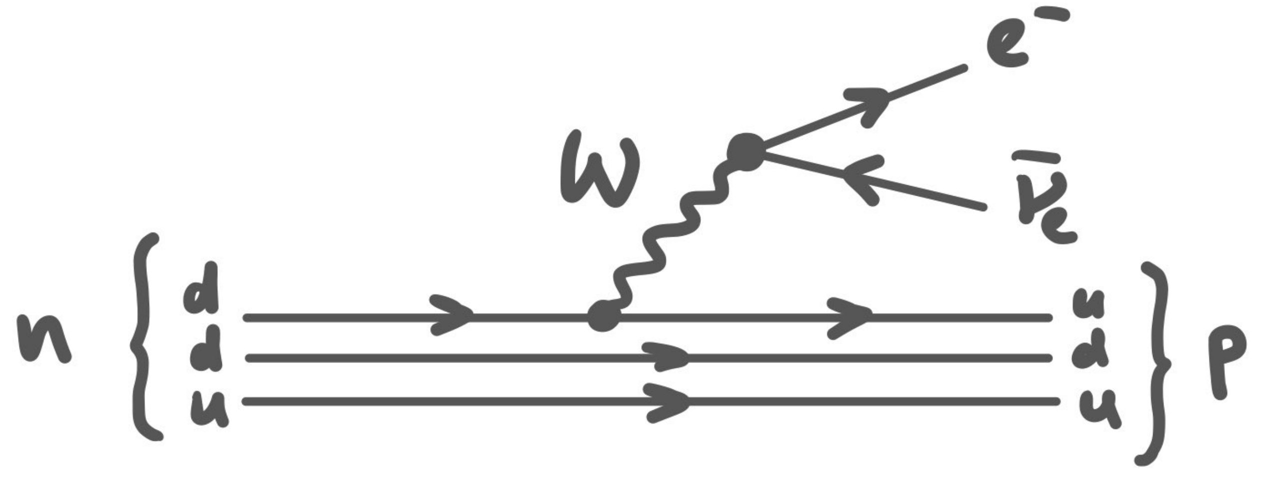
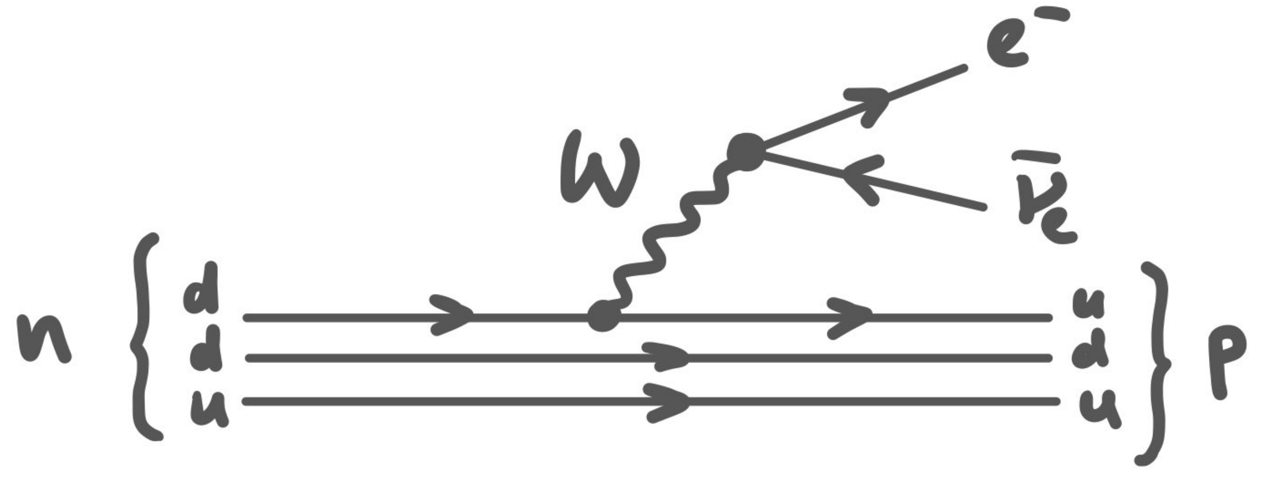


Superallowed β-decays

2. Precision observables

2.2 β-decays / Cabibbo angle anomaly

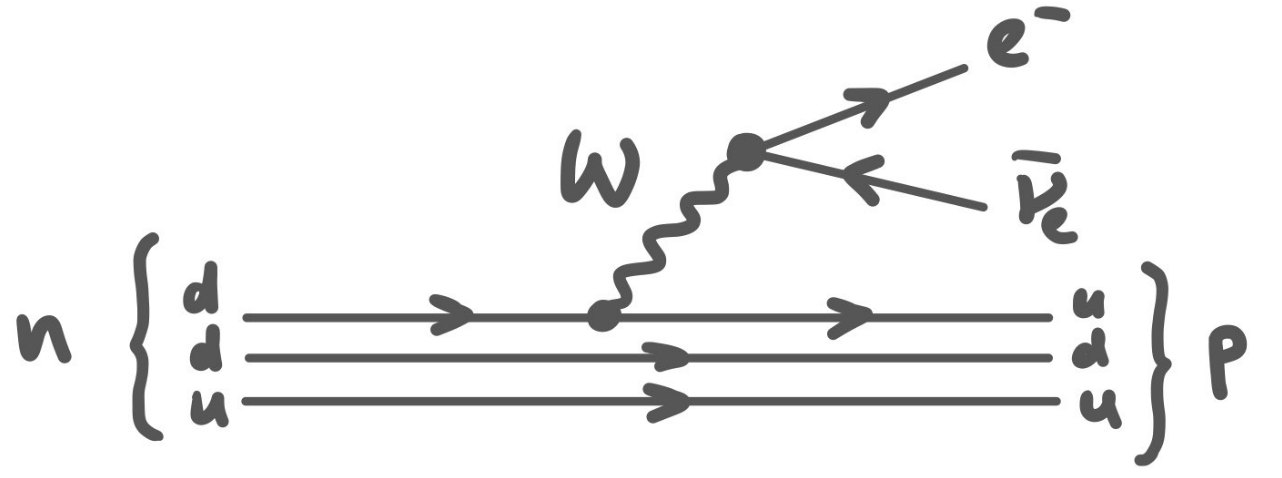


Superallowed β-decays

$$\boxed{V_{ud}^{\beta}}$$

2. Precision observables

2.2 β-decays / Cabibbo angle anomaly



Superallowed β-decays

$\boxed{V_{ud}^{\beta}}$

$$\mathcal{H}_{\text{eff}}^{\ell\nu} = \frac{4G_F}{\sqrt{2}} V_{jk} \hat{C}_{jk}^{e\nu} \left[\bar{u}_j \gamma^\mu P_L d_k\right] \left[\bar{e}\gamma_\mu P_L \nu_e\right] \,,$$

2. Precision observables

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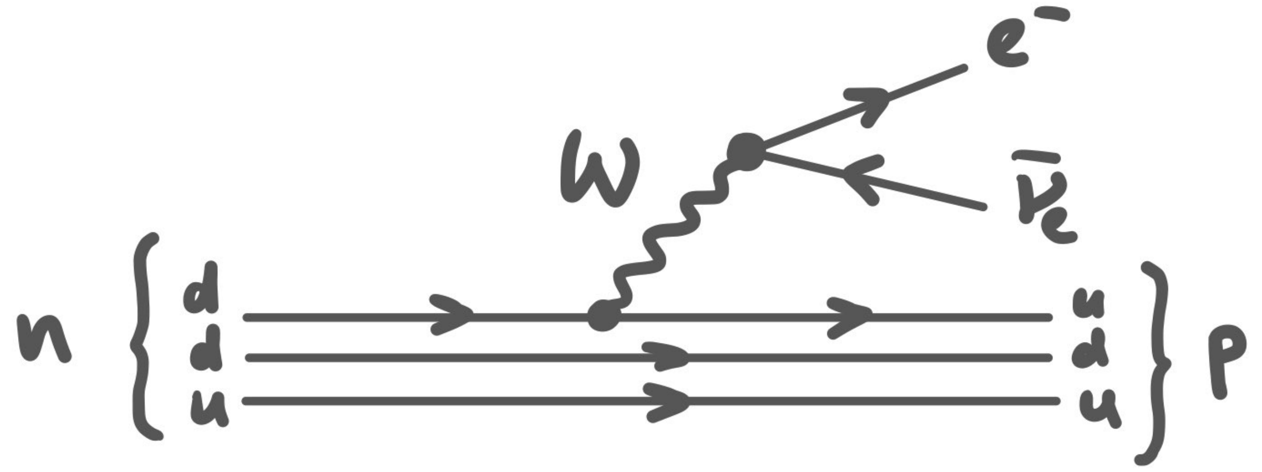

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2. Precision observables

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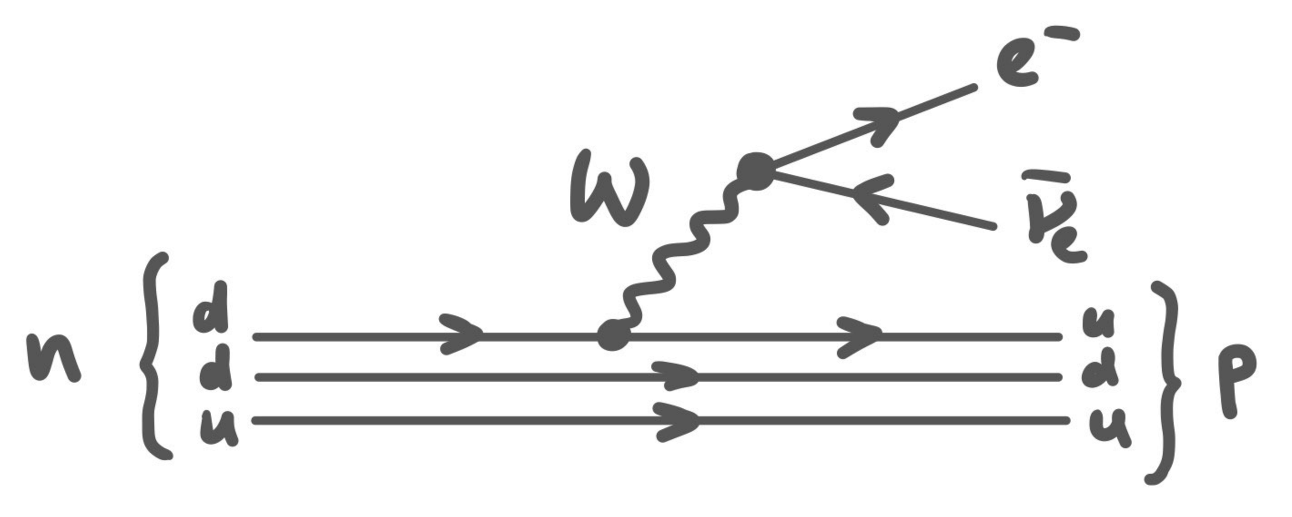
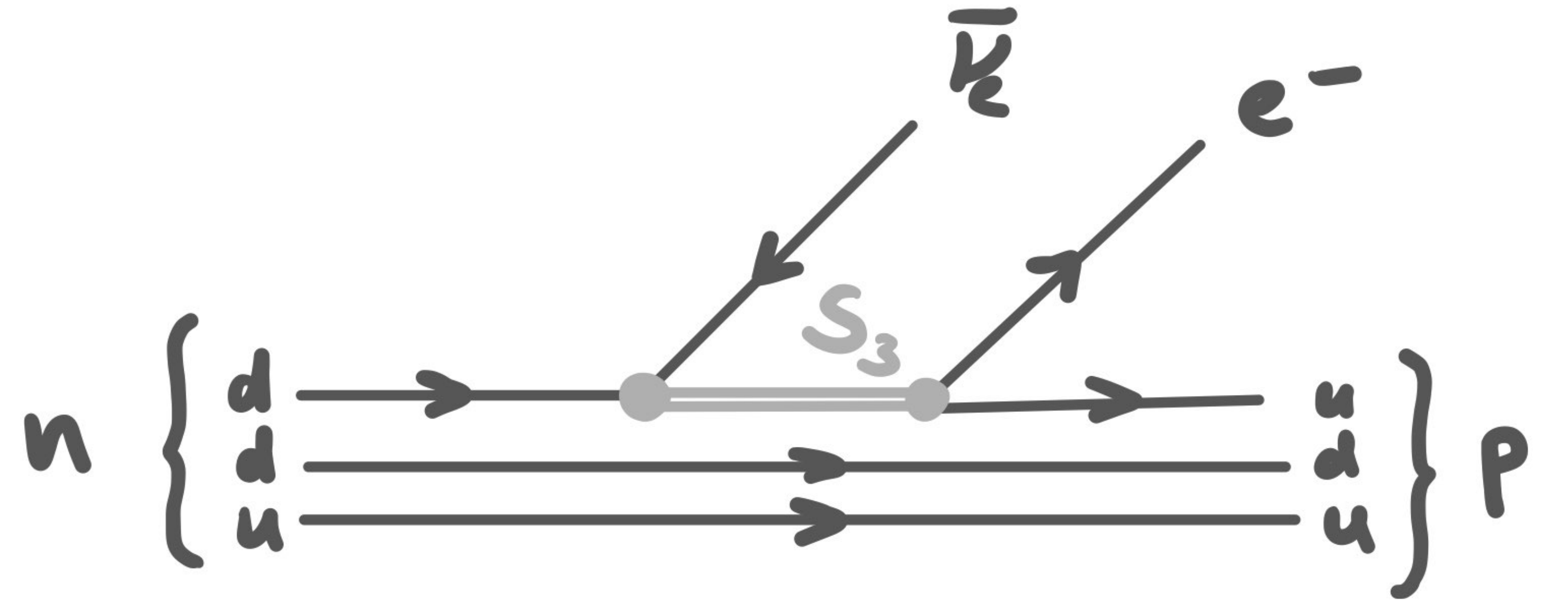


Superallowed β-decays

V_{ud}^{β}



S_3 LO contribution

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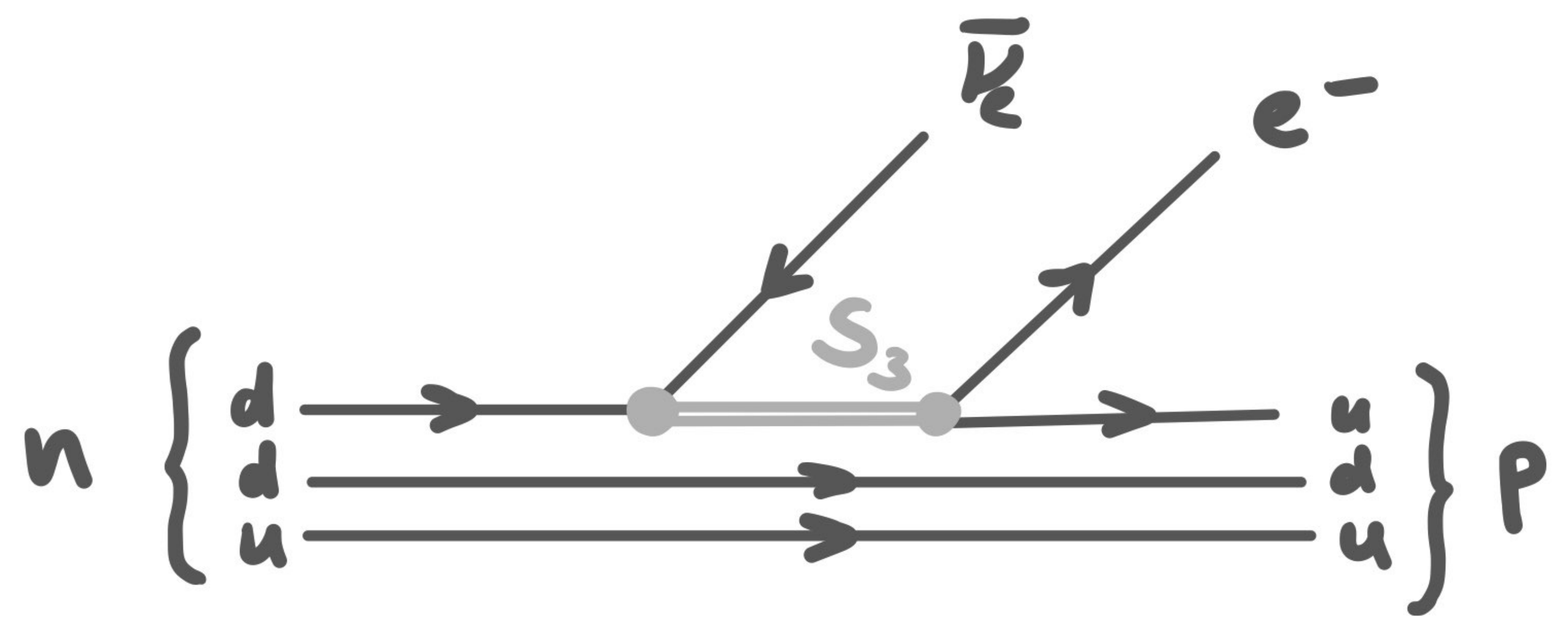
$$C_{11}^{e\nu} = \frac{-1}{\sqrt{2}G_F} \frac{c_\beta c_{\beta-\theta}}{V_{ud}} \boxed{C_{\ell q}^{(3)}} ,$$

SLQs

2. Precision observables

2.2 β-decays / Cabibbo angle anomaly



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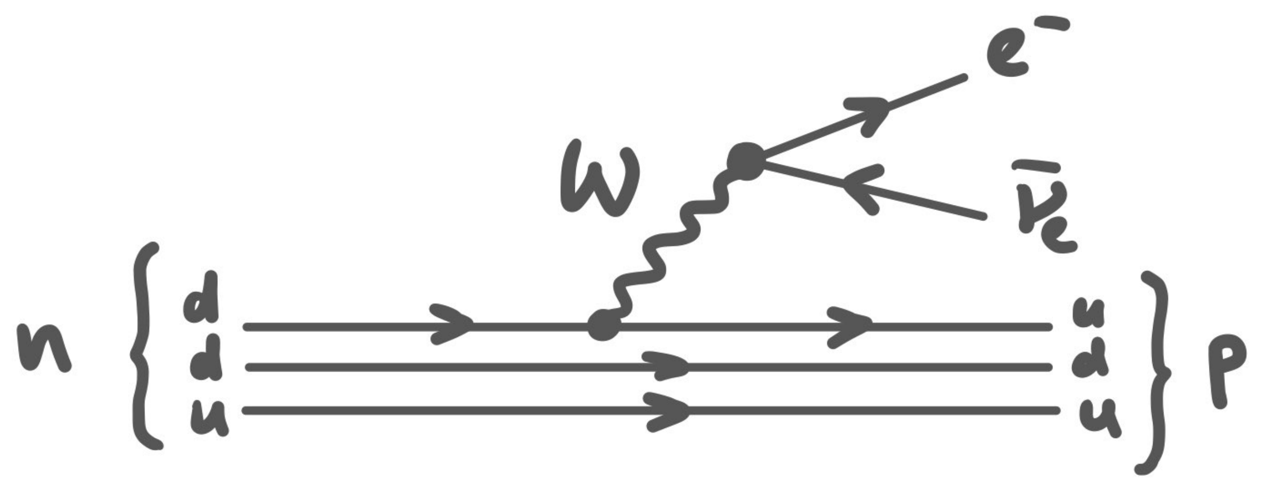

Superallowed β-decays

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$$C_{11}^{e\nu} = \frac{-1}{\sqrt{2}G_F}\frac{c_\beta c_{\beta-\theta}}{V_{ud}}\boxed{C_{\ell q}^{(3)}},$$

$$V_{ud}^{\beta} = V_{ud}^{L}\left(1 + C_{11}^{e\nu_e}\right).$$

$$V_{us}^{\beta} = 0.2281(7)\,,\quad V_{us}^{\beta}|_{\rm NNC} = 0.2280(14)\,,$$

CAA

$$V_{us}^{K_{\mu 3}} = 0.22345(67)\,,\quad V_{us}^{K_{e3}} = 0.22320(61)\,,$$
$$V_{us}^{K_{\mu 2}} = 0.22534(42)\,,\quad V_{us}^{\tau} = 0.2195(19)\,,$$

Source: ArXiv:2101.07811 (A. Crivellin, D. Müller, LS)

2. Precision observables

2.2 β-decays / Cabibbo angle anomaly

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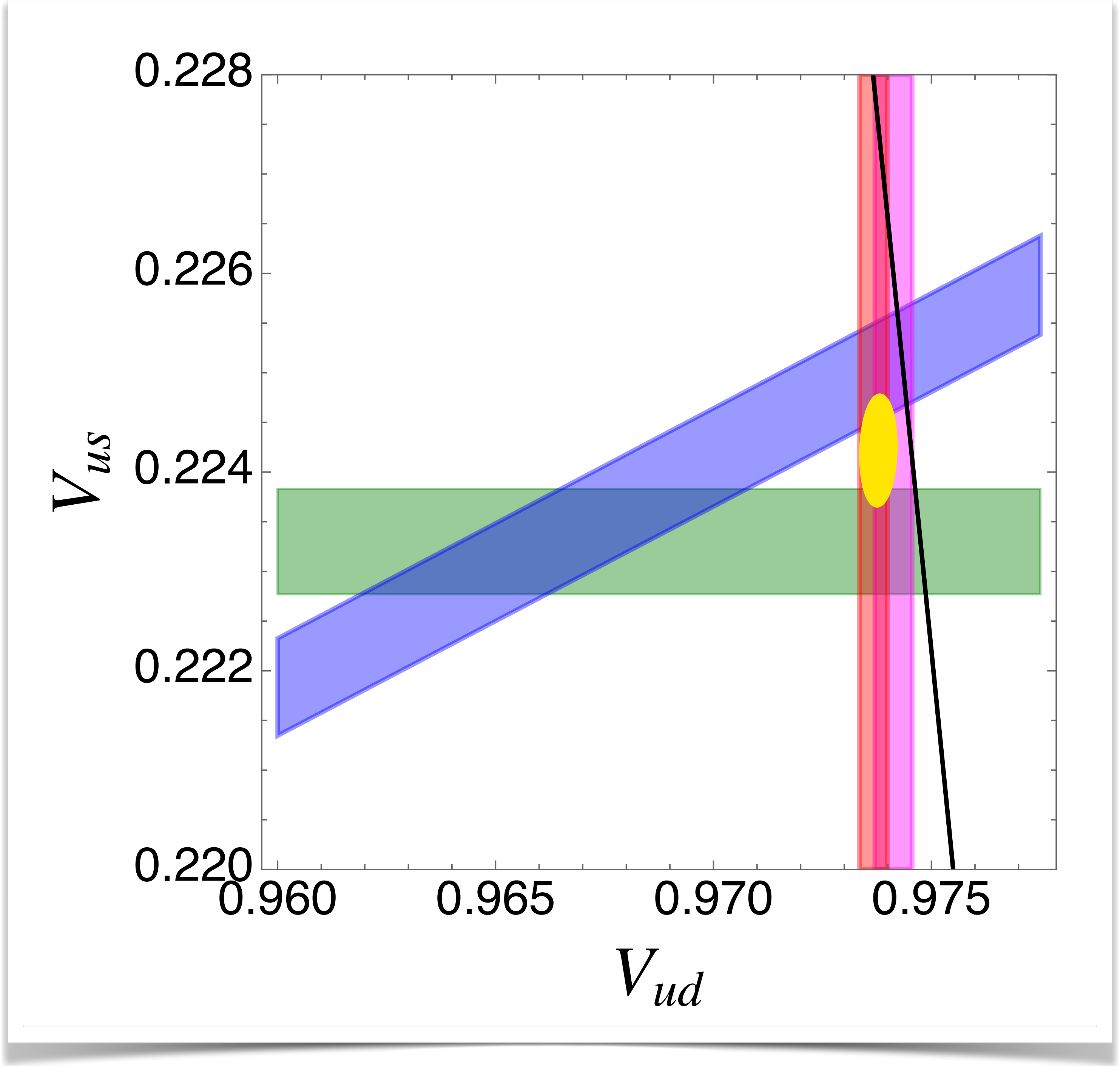

Source: ArXiv:2208.11707 (V. Cirigliano, A. Crivellin, M. Hoferichter, M. Moulson)

SLQs

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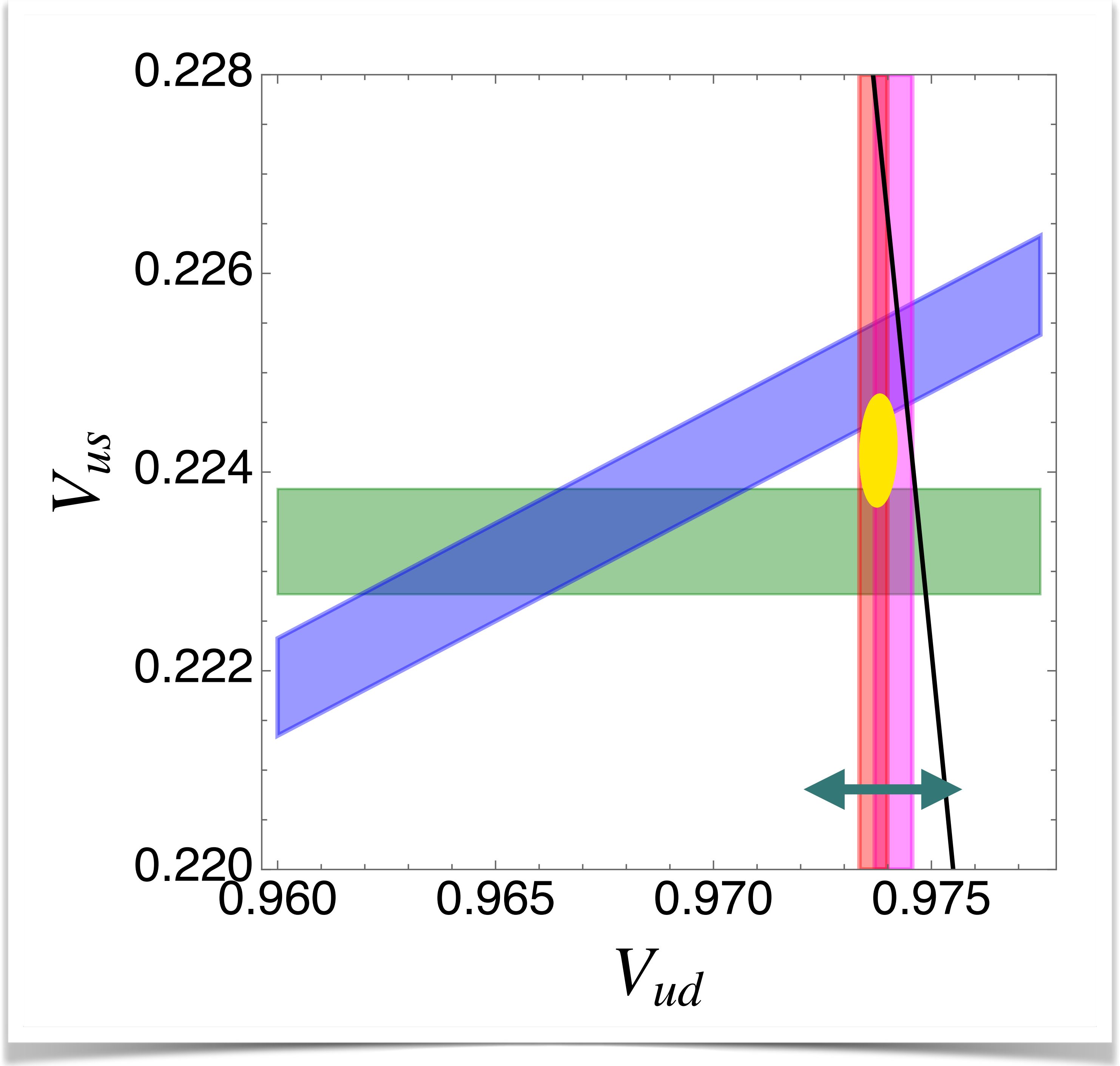

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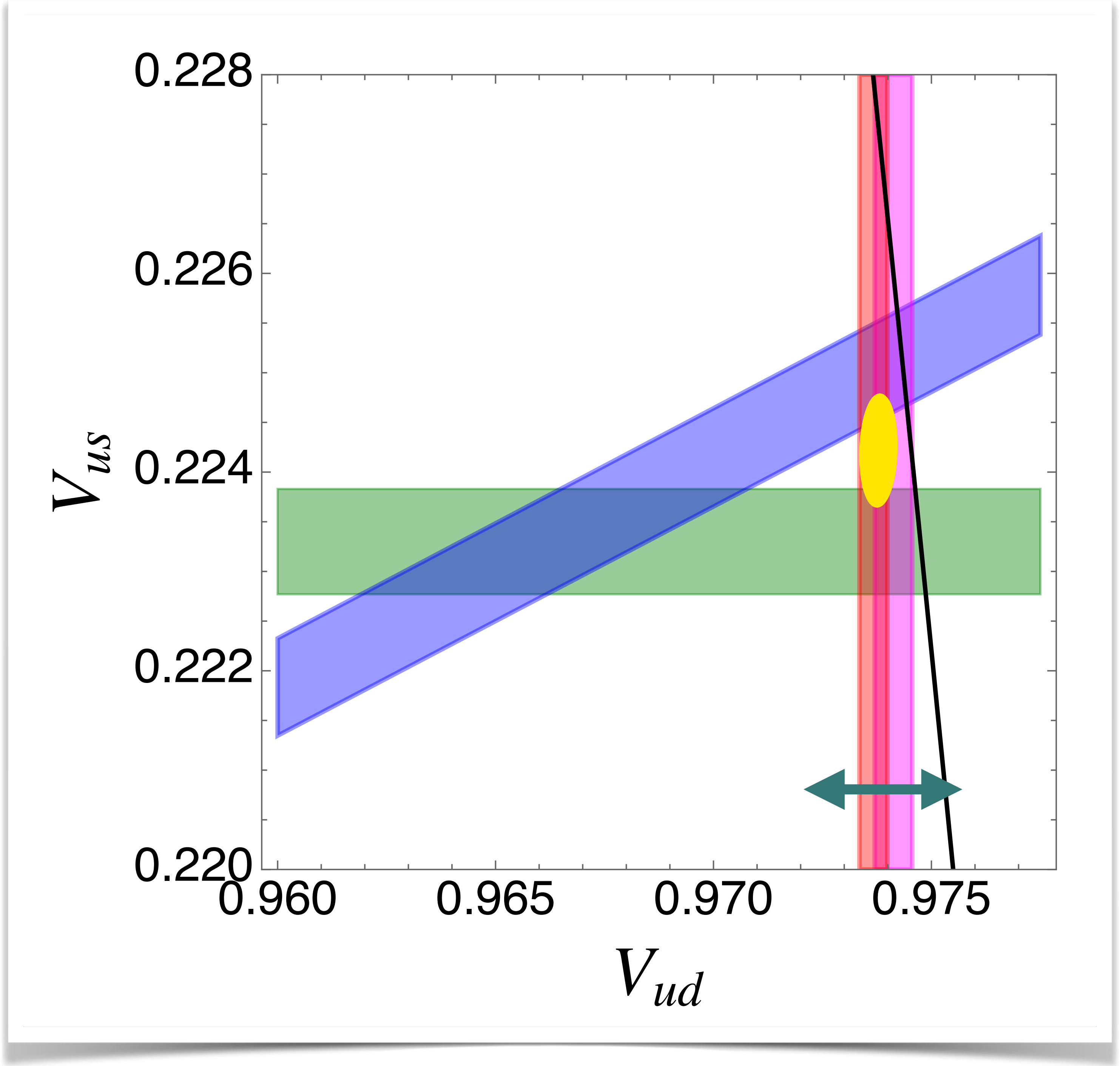
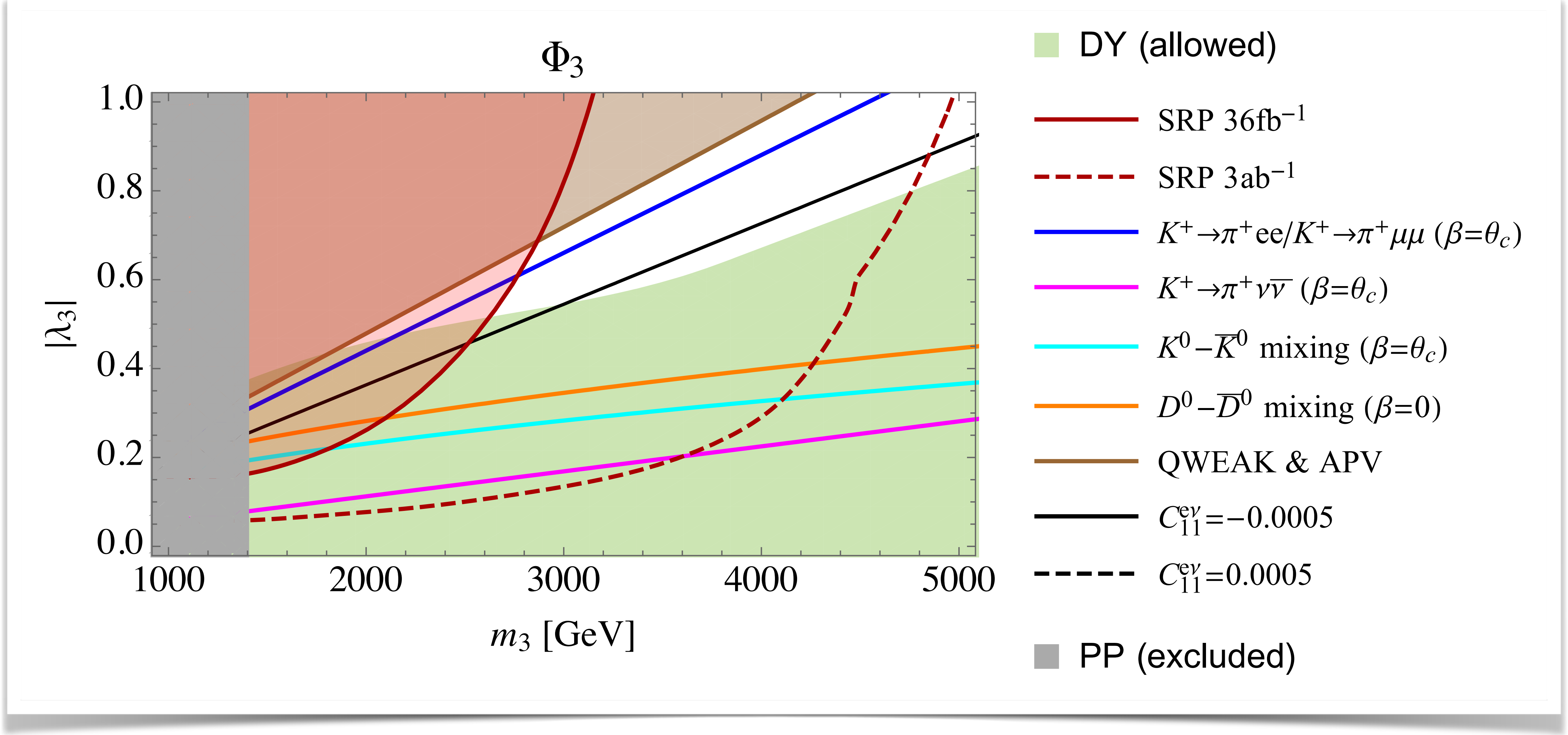
SLQs

2. Precision observables

2.2 β-decays / Cabibbo angle anomaly



Source: ArXiv:2208.11707 (V. Cirigliano, A. Crivellin, M. Hoferichter, M. Moulson)

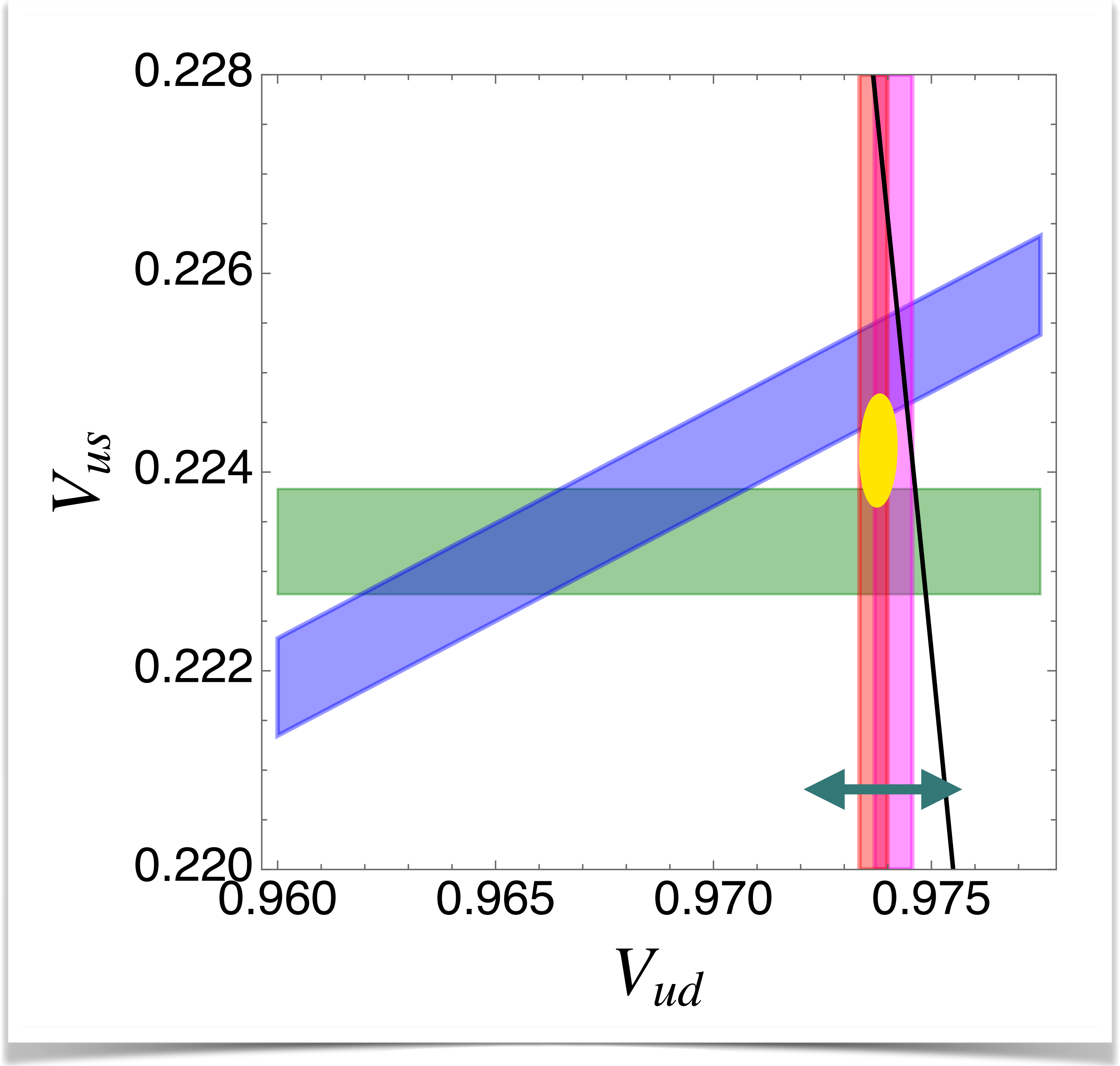


Source: ArXiv:2101.07811 (A. Crivellin, D. Müller, LS)

2. Precision observables

2.2 β-decays / Cabibbo angle anomaly

$C_{11}^{e\nu_e} \approx -0.001$ needed



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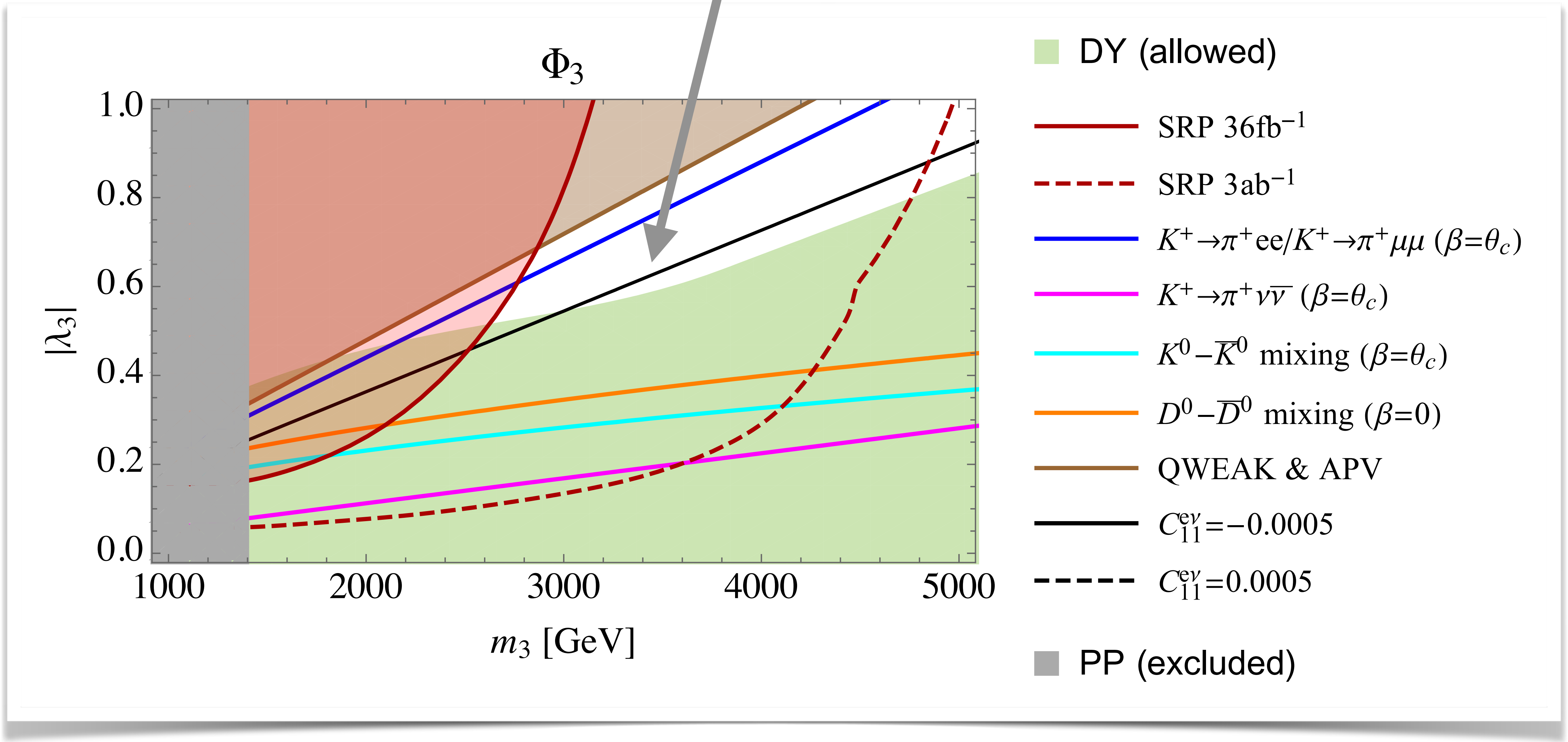

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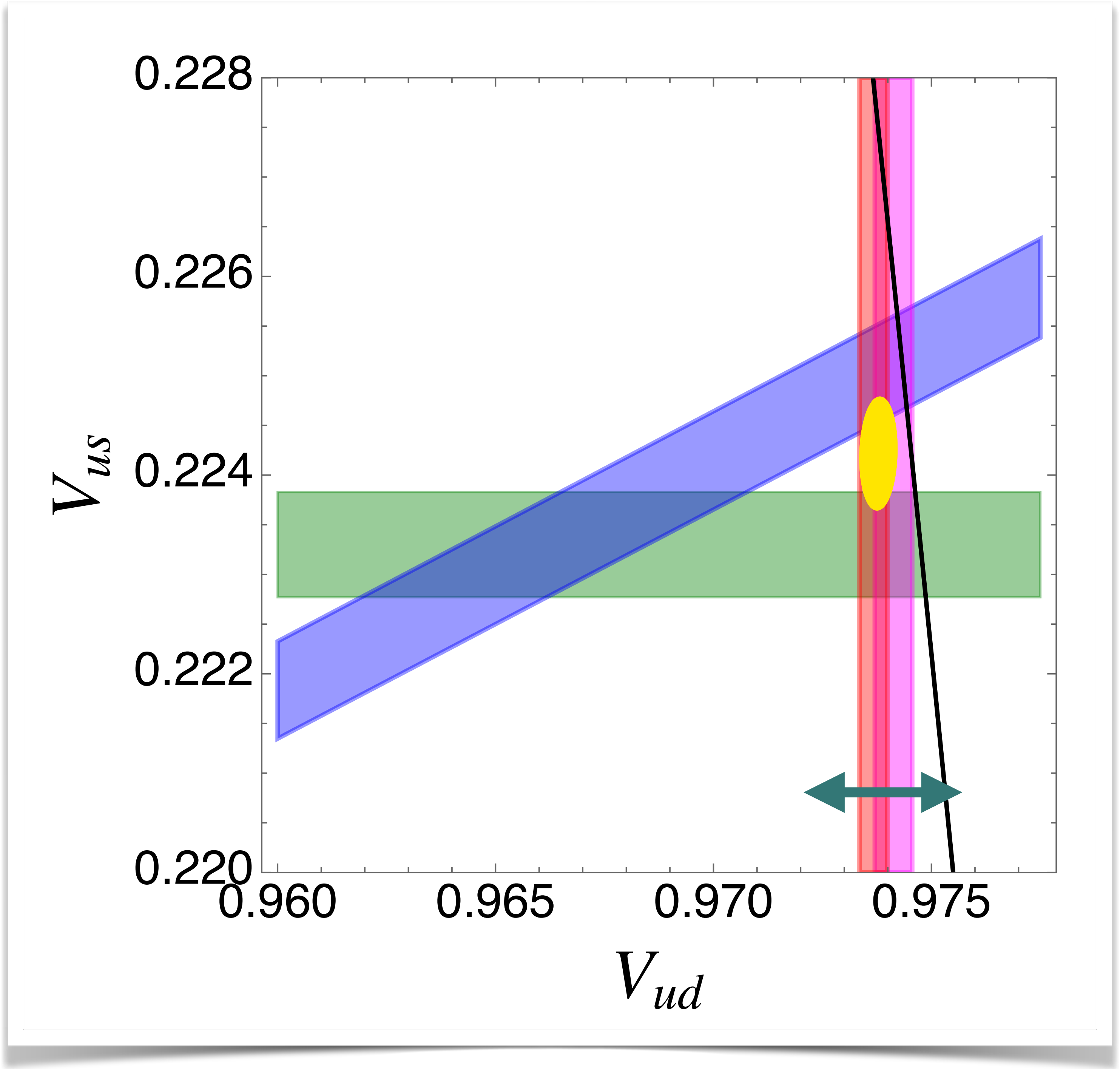

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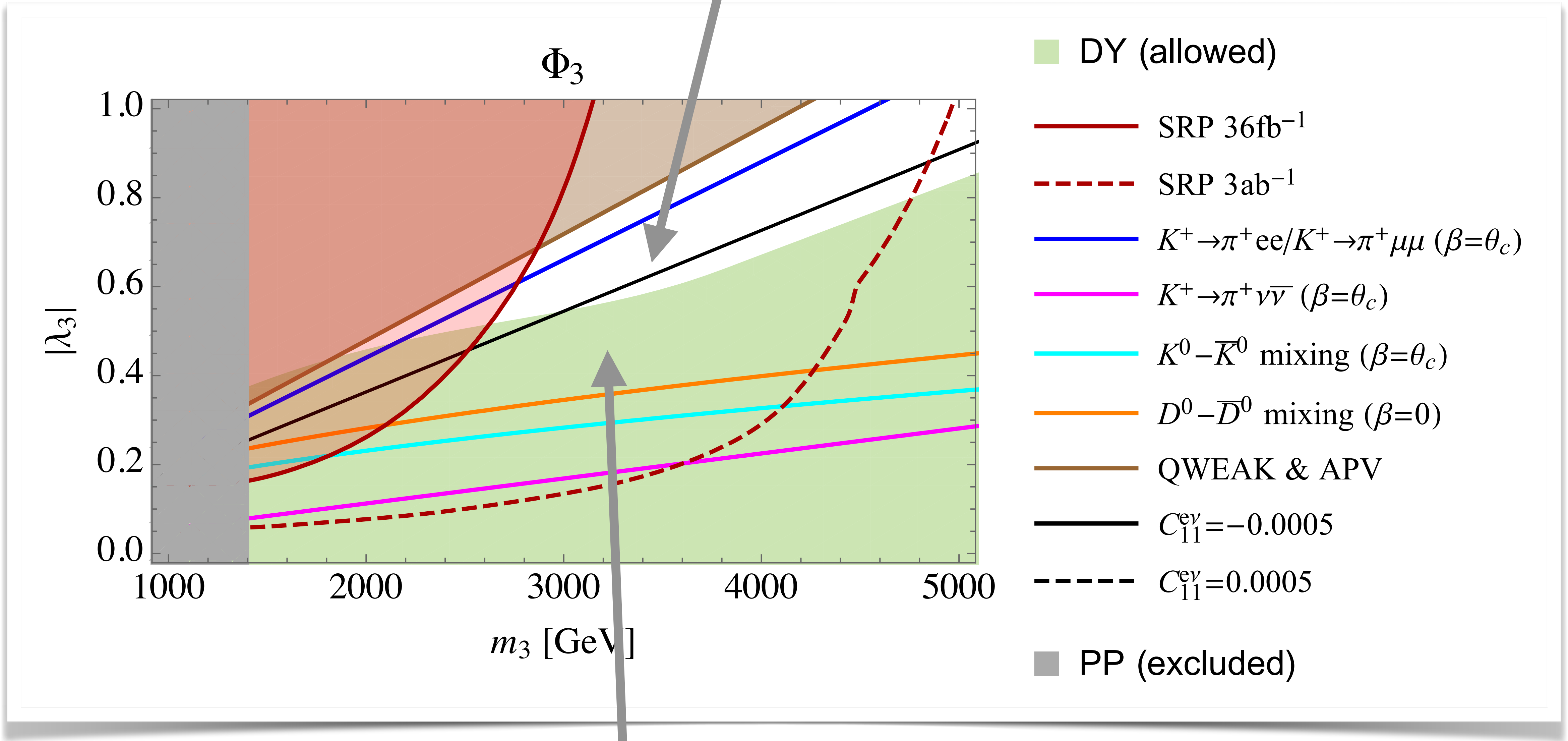

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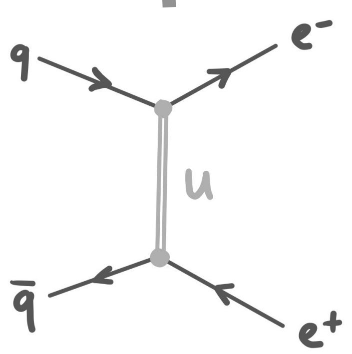

Constraints from **Drell-Yan** spectrum.

2. Precision observables

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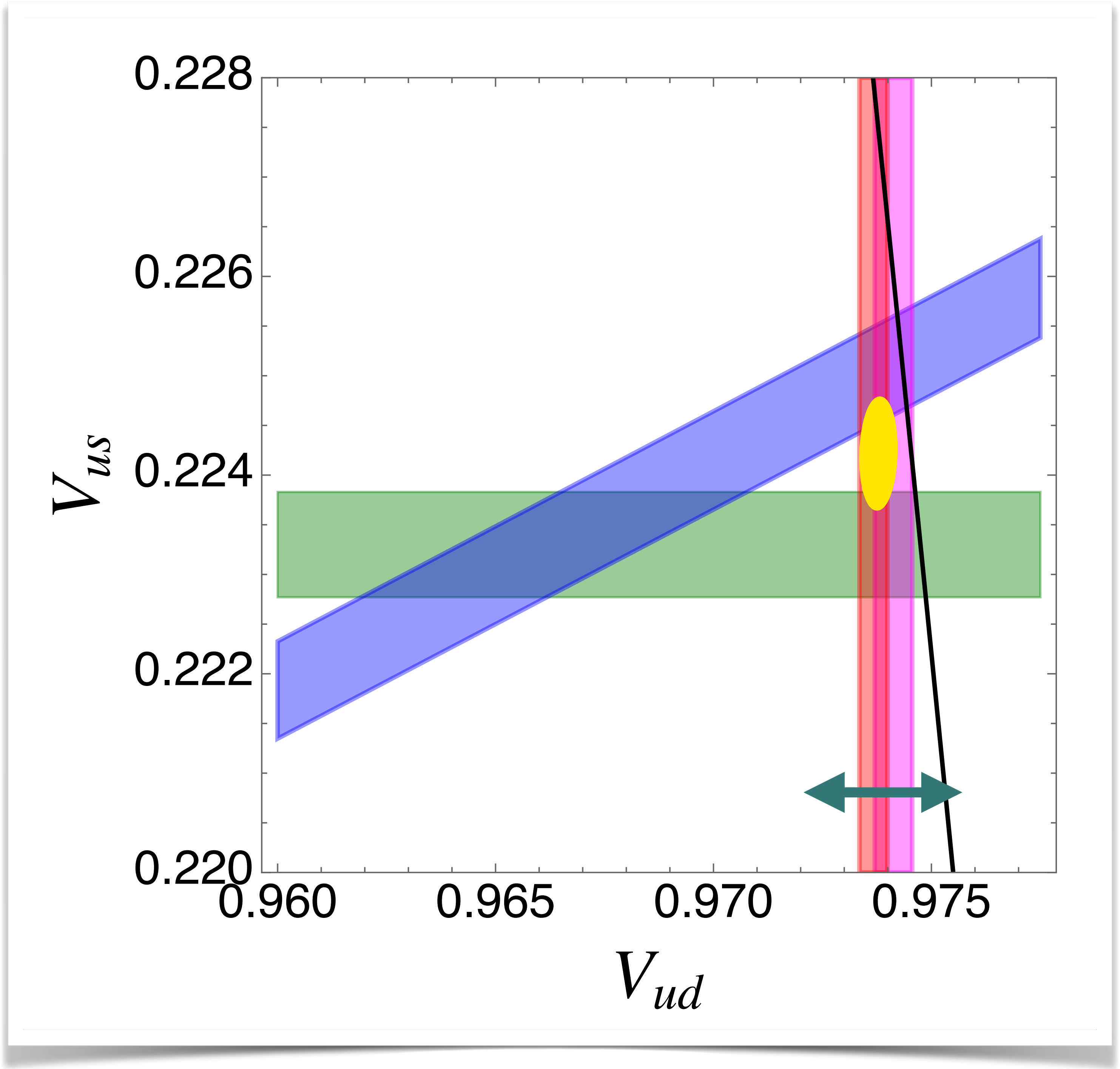

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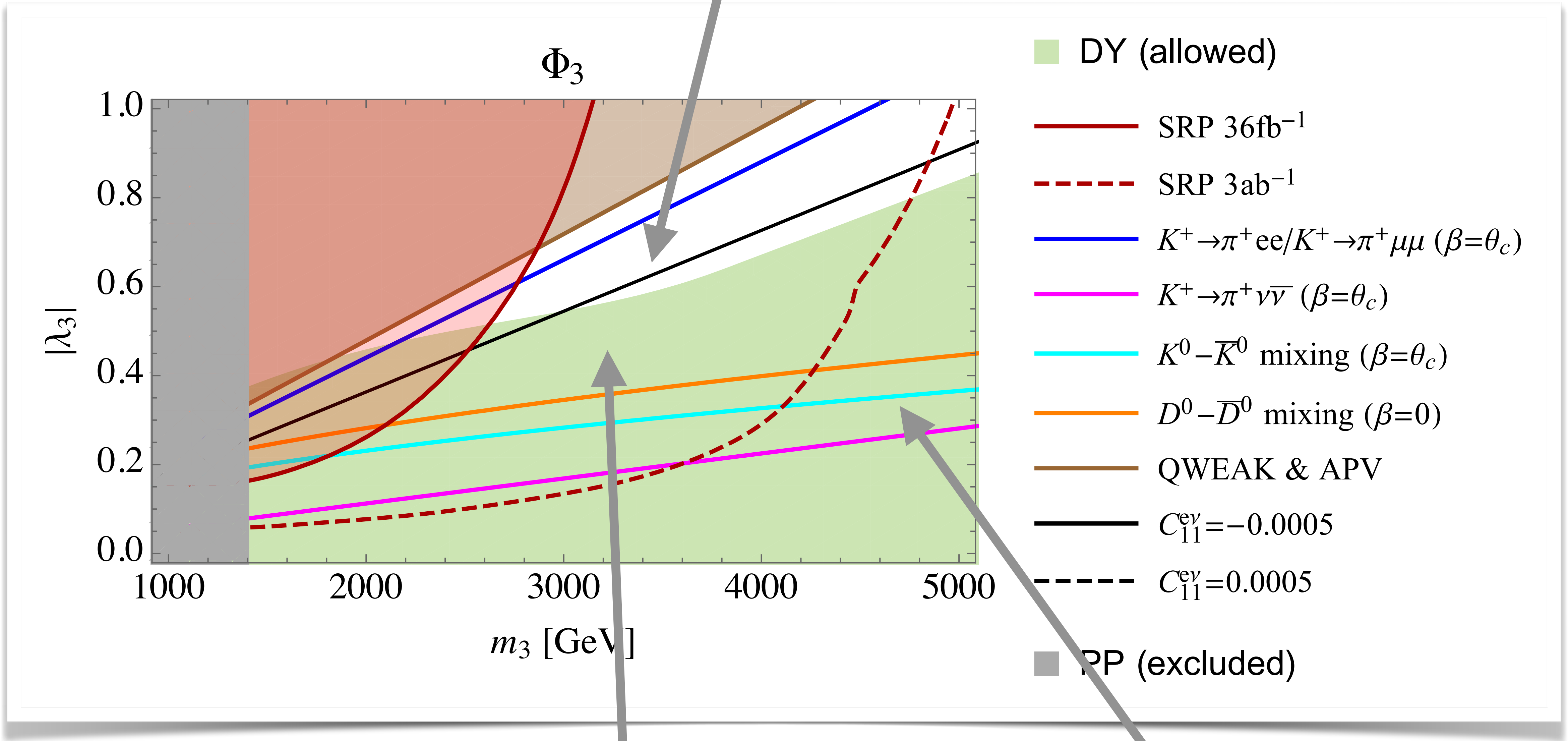

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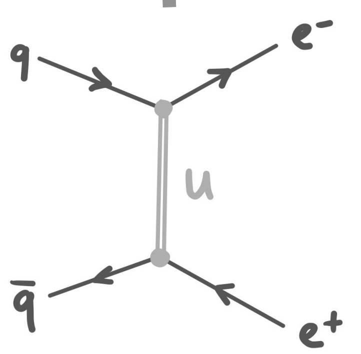

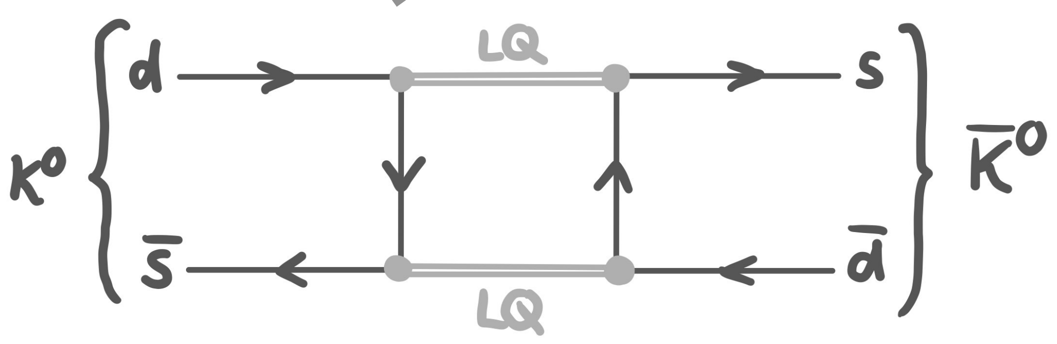

Constraints from **Drell-Yan** spectrum.

Constraints from **meson mixing.**

2. Precision observables

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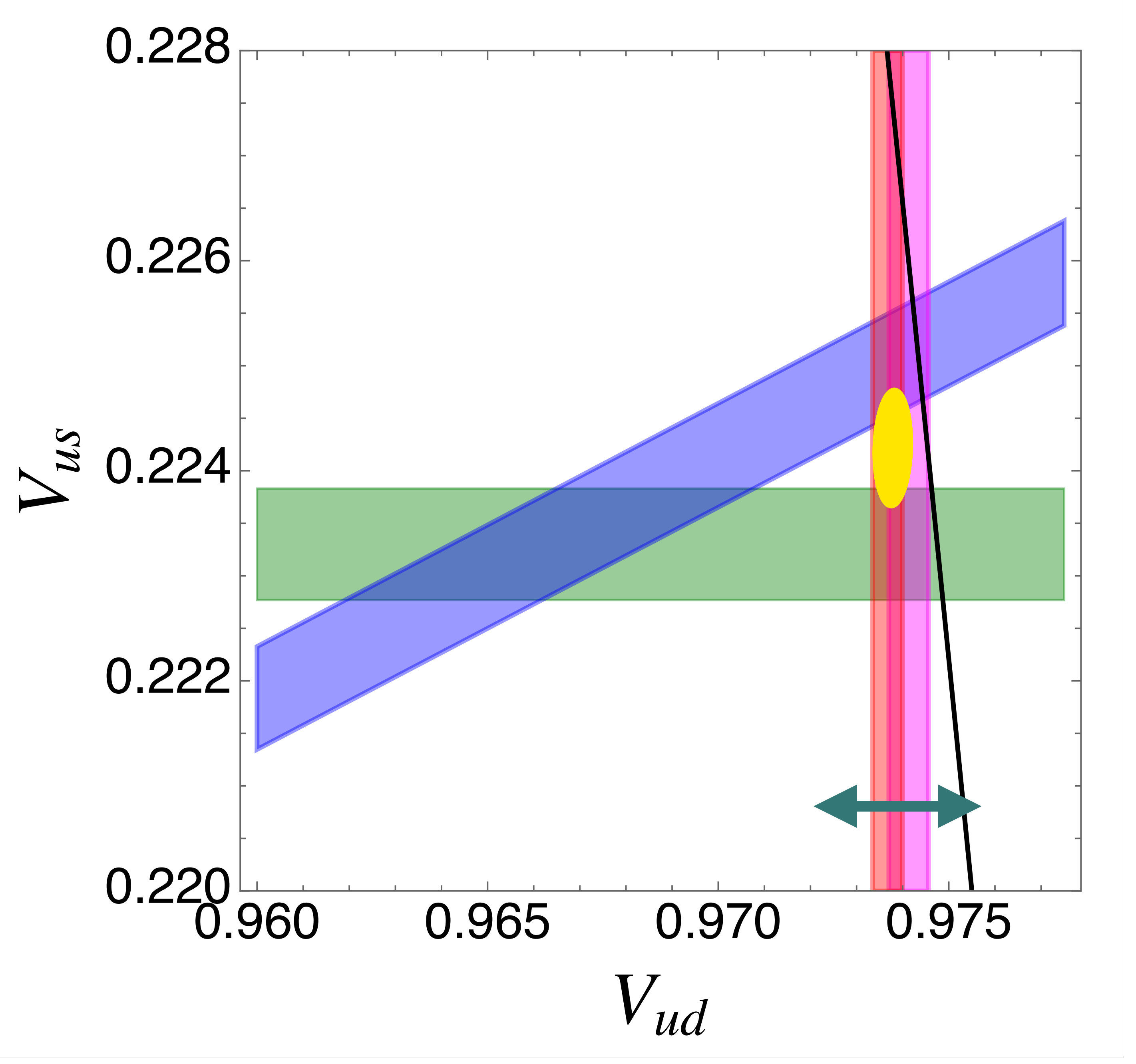
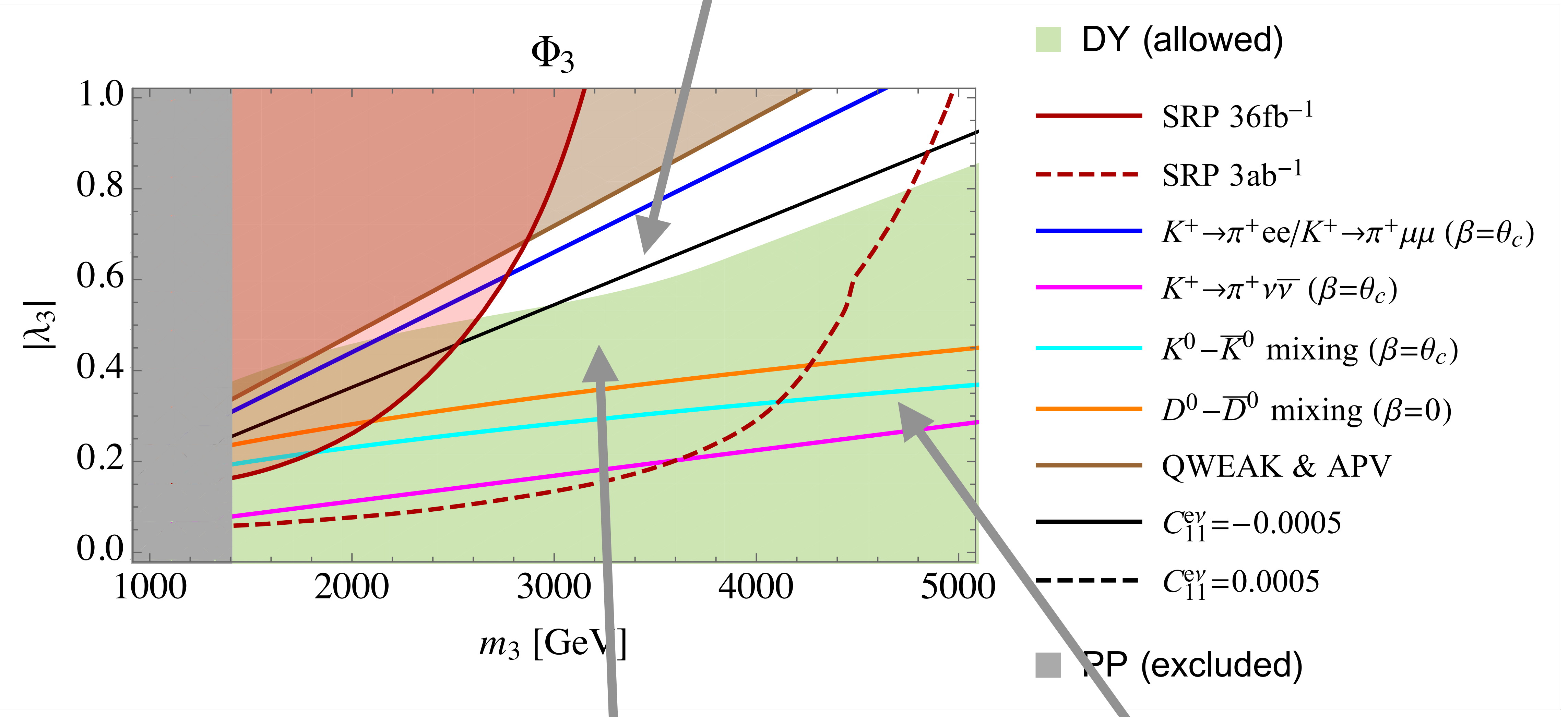


Source: ArXiv:2208.11707 (V. Cirigliano, A. Crivellin, M. Hoferichter, M. Moulson)

→ **excluded!**

$C_{11}^{e\nu_e} \approx -0.001$ needed



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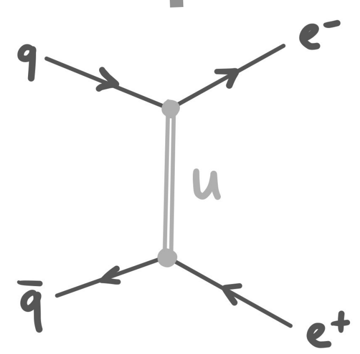
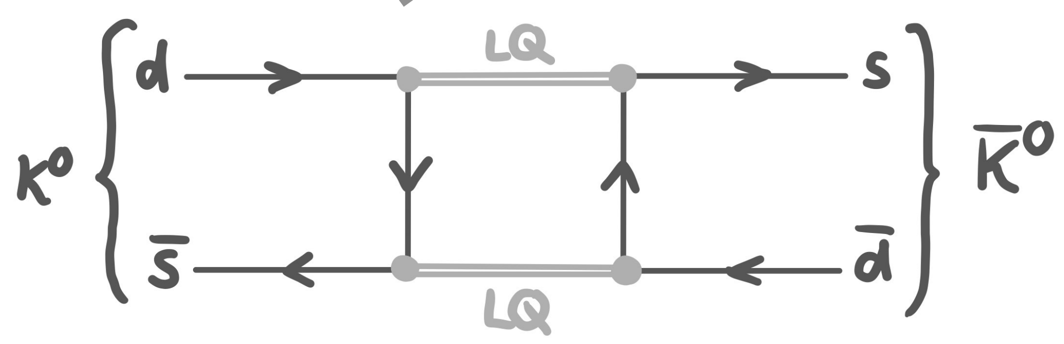


Constraints from **Drell-Yan** spectrum.



Constraints from **meson mixing.**

SLQs

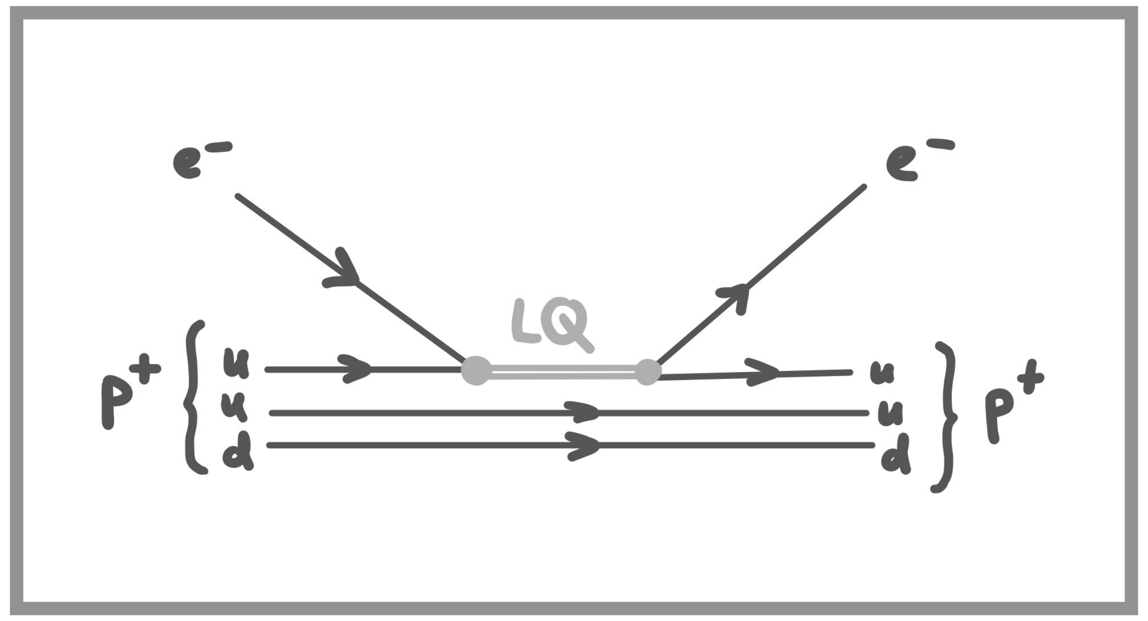
2. Precision observables

2.3 Parity violation experiments

SLQs

2. Precision observables

2.3 Parity violation experiments

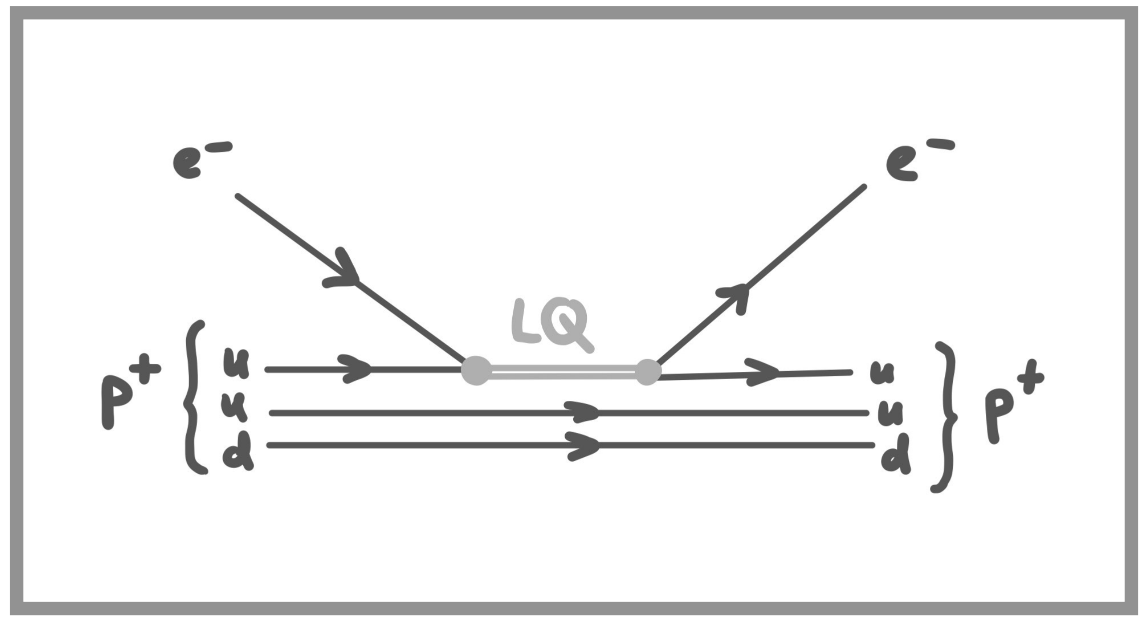


Parity-violating electron scattering (PVES)

SLQs

2. Precision observables

2.3 Parity violation experiments



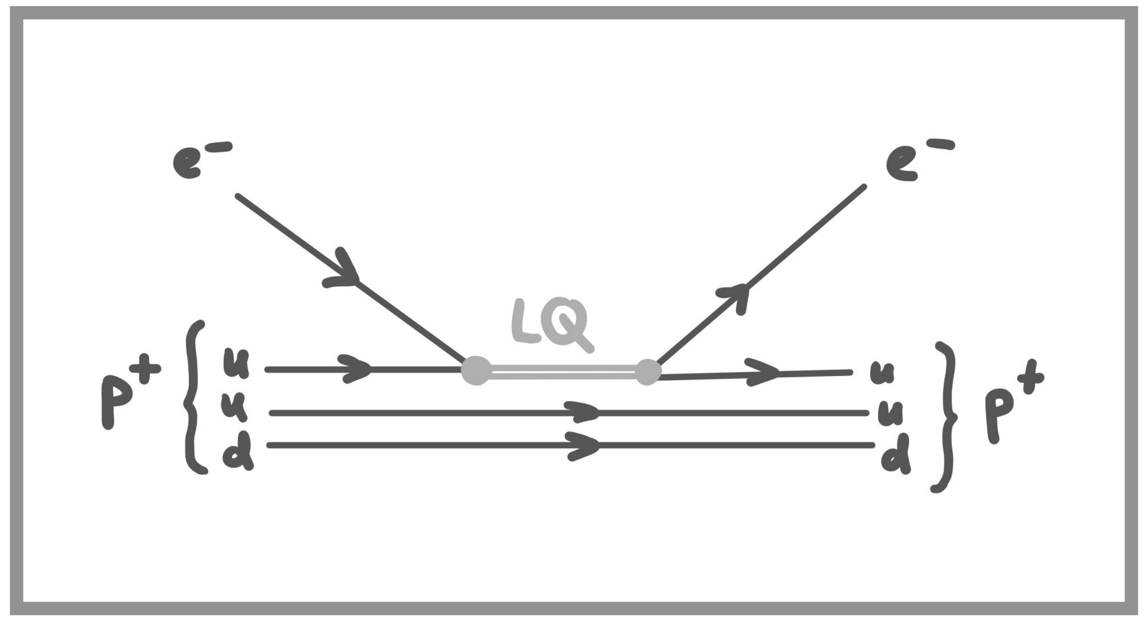
Parity-violating electron scattering (PVES)

- Longitudinally-polarized electron beam incident on an unpolarized proton target.
- PV asymmetry: $$A_e^N = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

SLQs

2. Precision observables

2.3 Parity violation experiments



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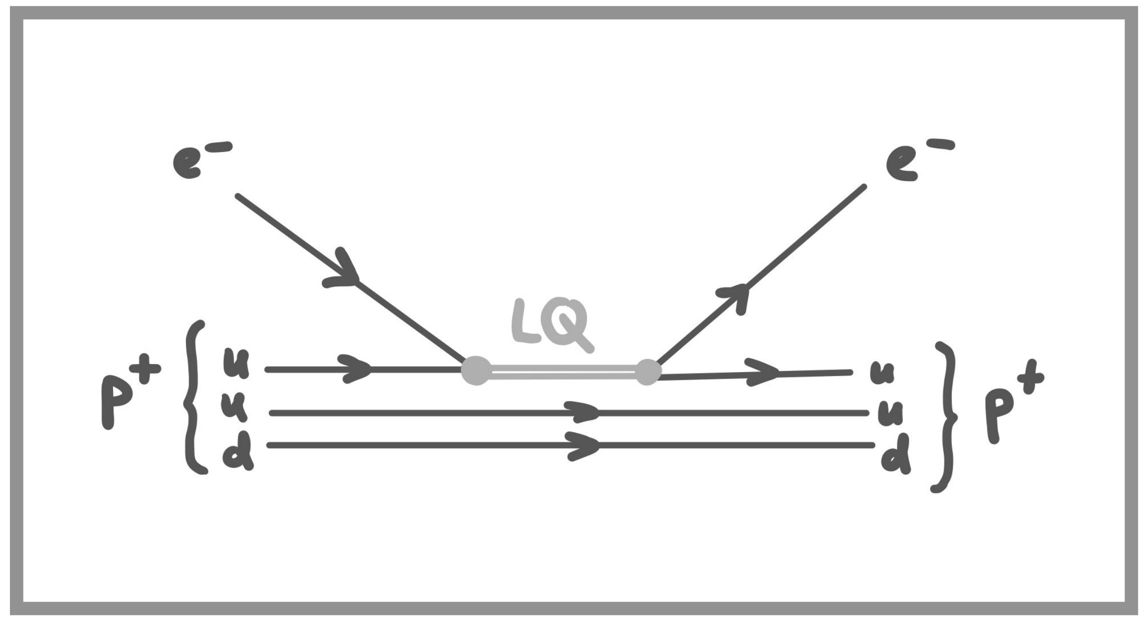
→ **P2** experiment at **MESA** in Mainz

2. Precision observables

2.3 Parity violation experiments



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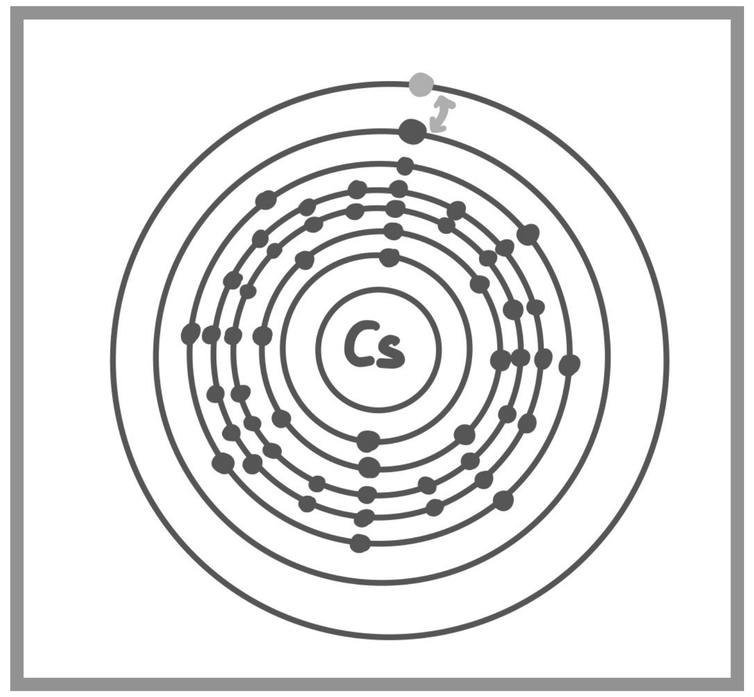

Atomic parity violation experiments

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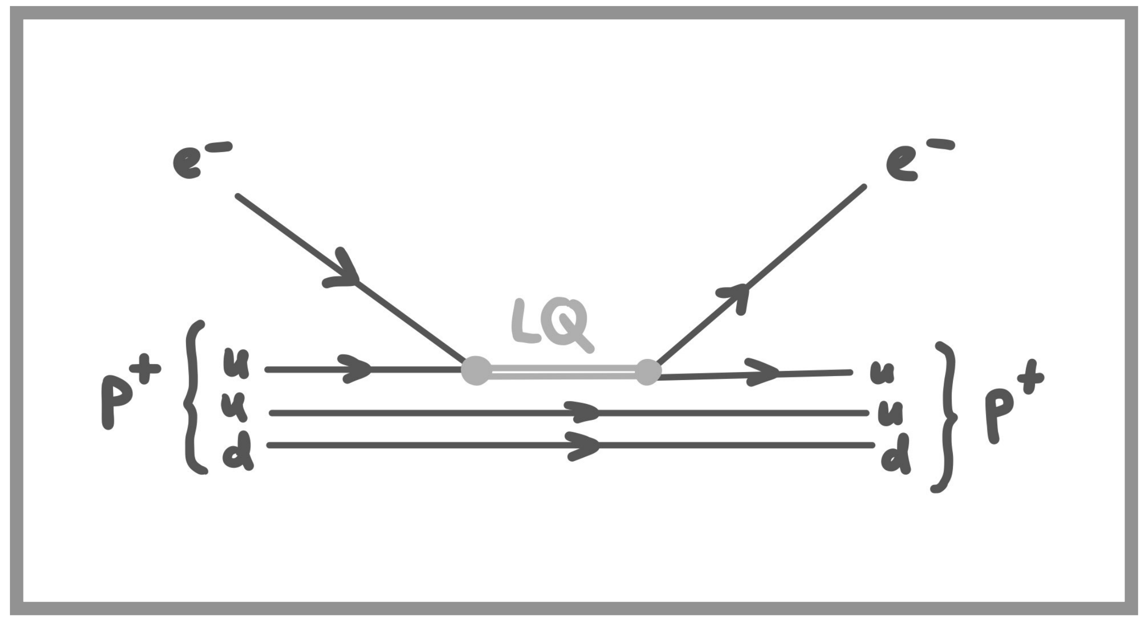
2.3 Parity violation experiments



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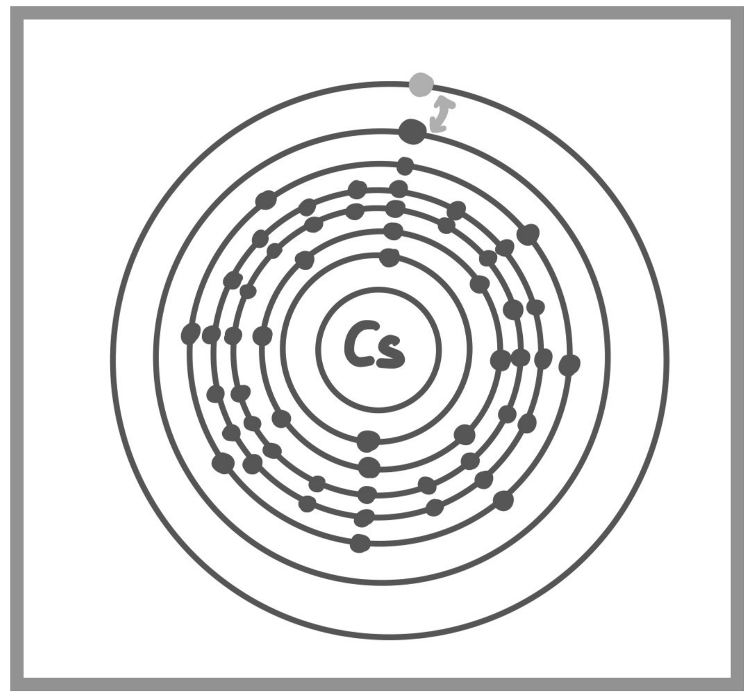
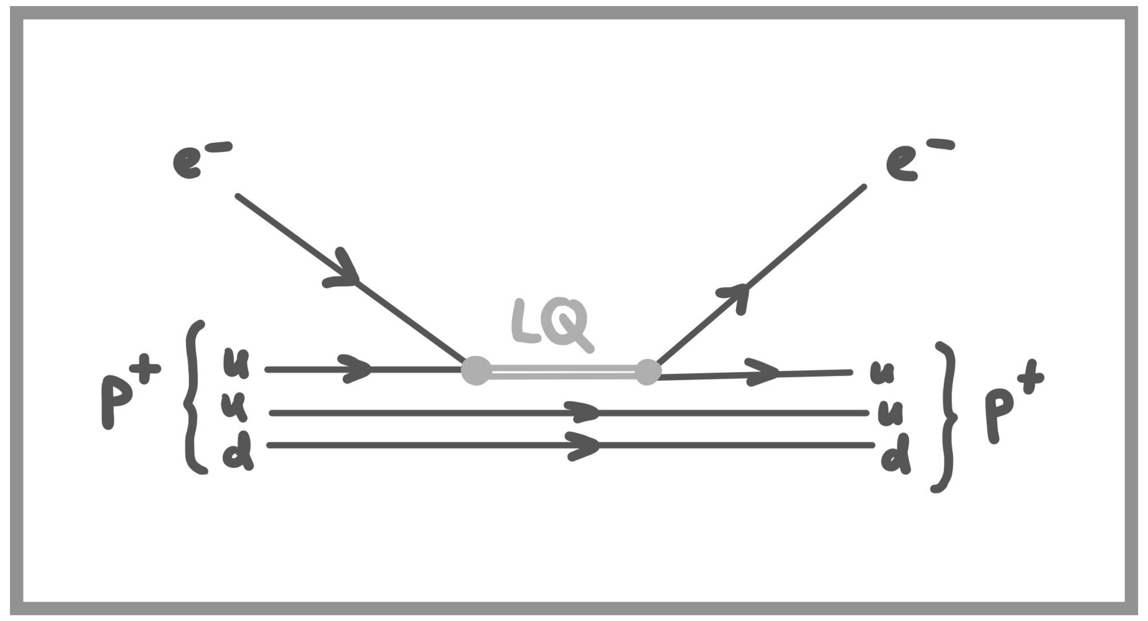


Atomic parity violation experiments

- Stimulated emission in a highly forbidden atomic transition.

2. Precision observables

2.3 Parity violation experiments



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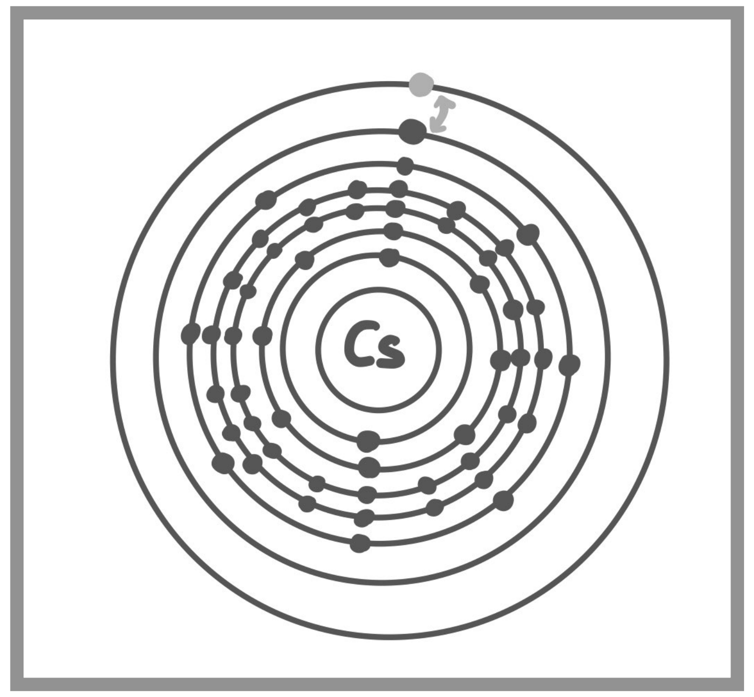

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- Stimulated emission in a highly forbidden atomic transition.
- APV experiment with ^{133}Cs:

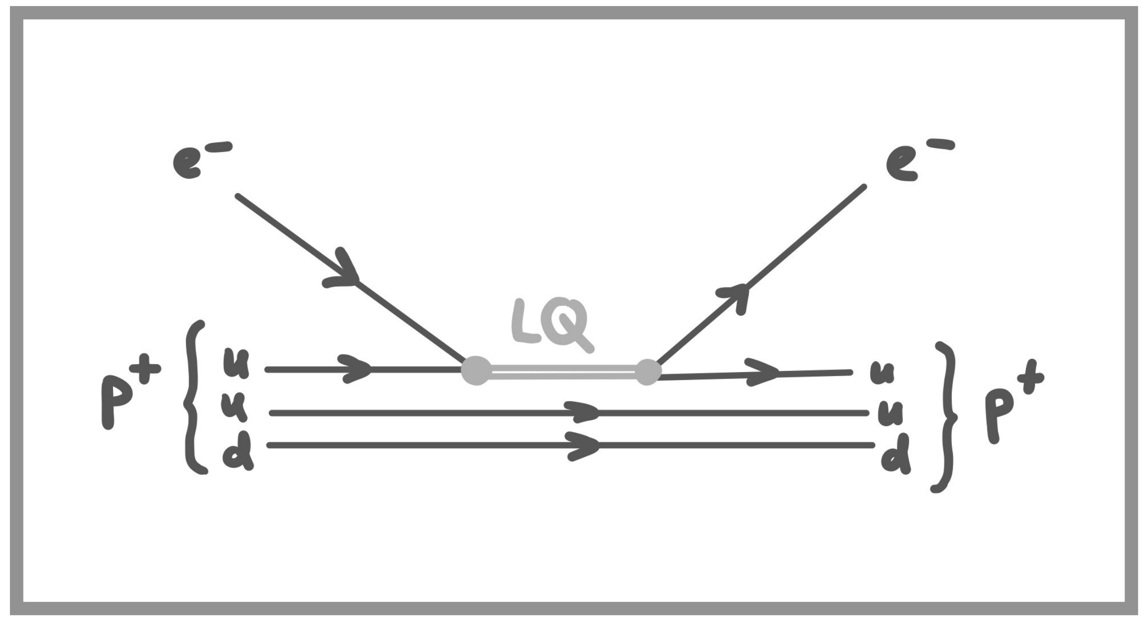
$$6S \rightarrow 7S$$

$$Q_{\mathrm{w}}\left(^{133}\mathrm{Cs}\right) = -72.94(43),$$

→ $\mathbf{Ra}^+$ experiments

2. Precision observables

2.3 Parity violation experiments



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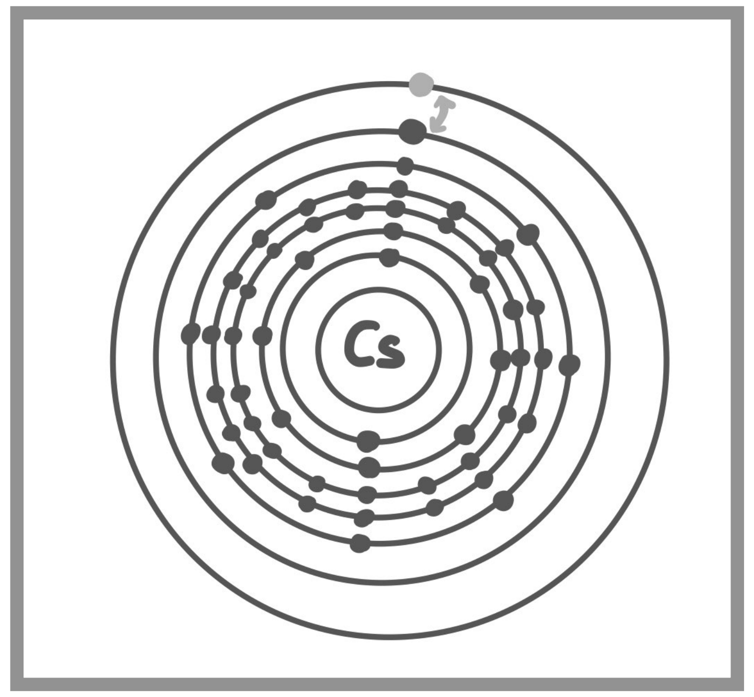

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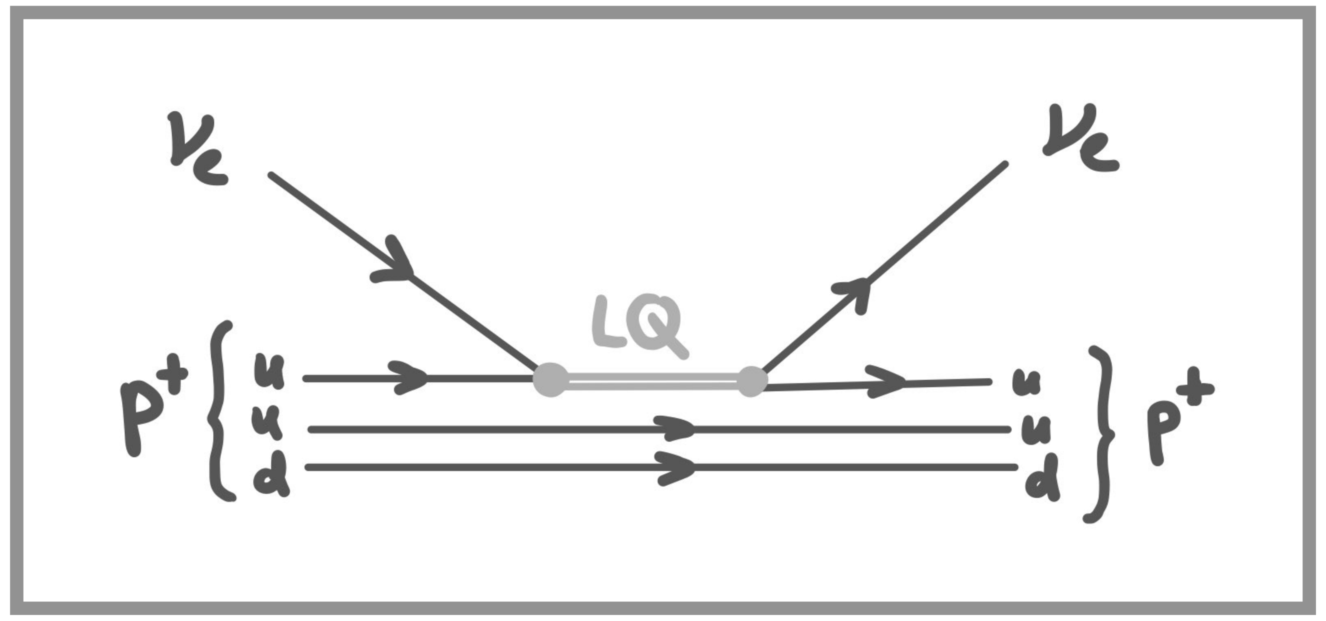
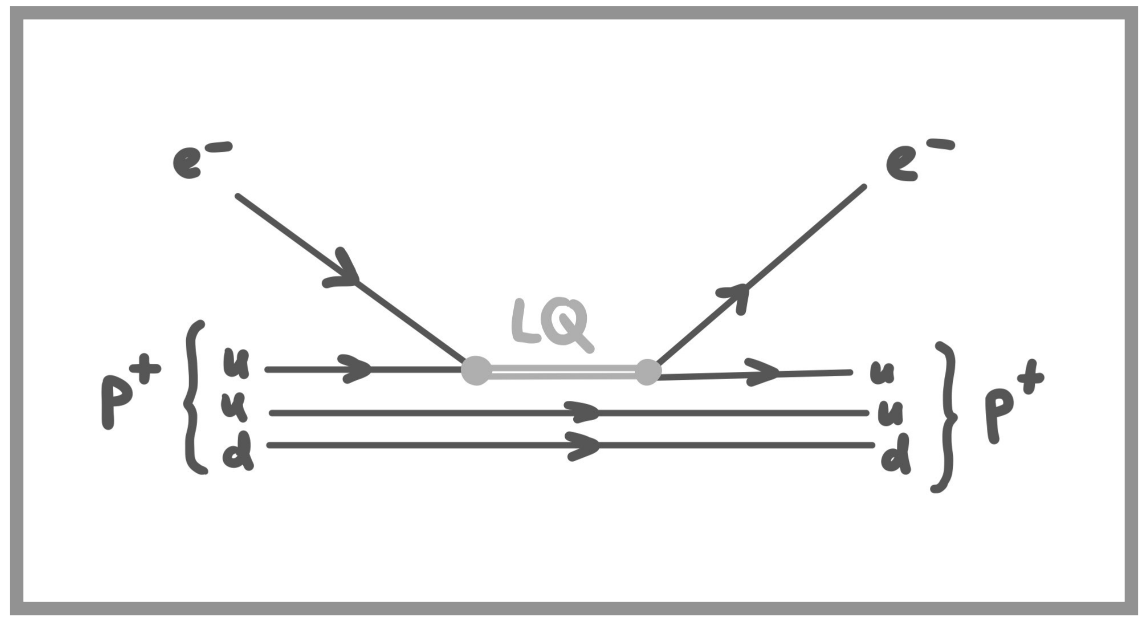


Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

SLQs

2. Precision observables

2.3 Parity violation experiments



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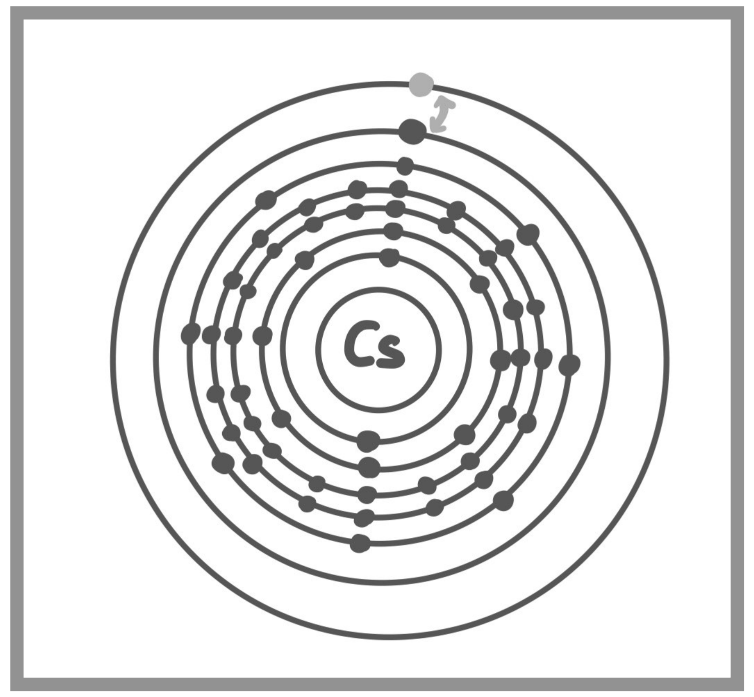

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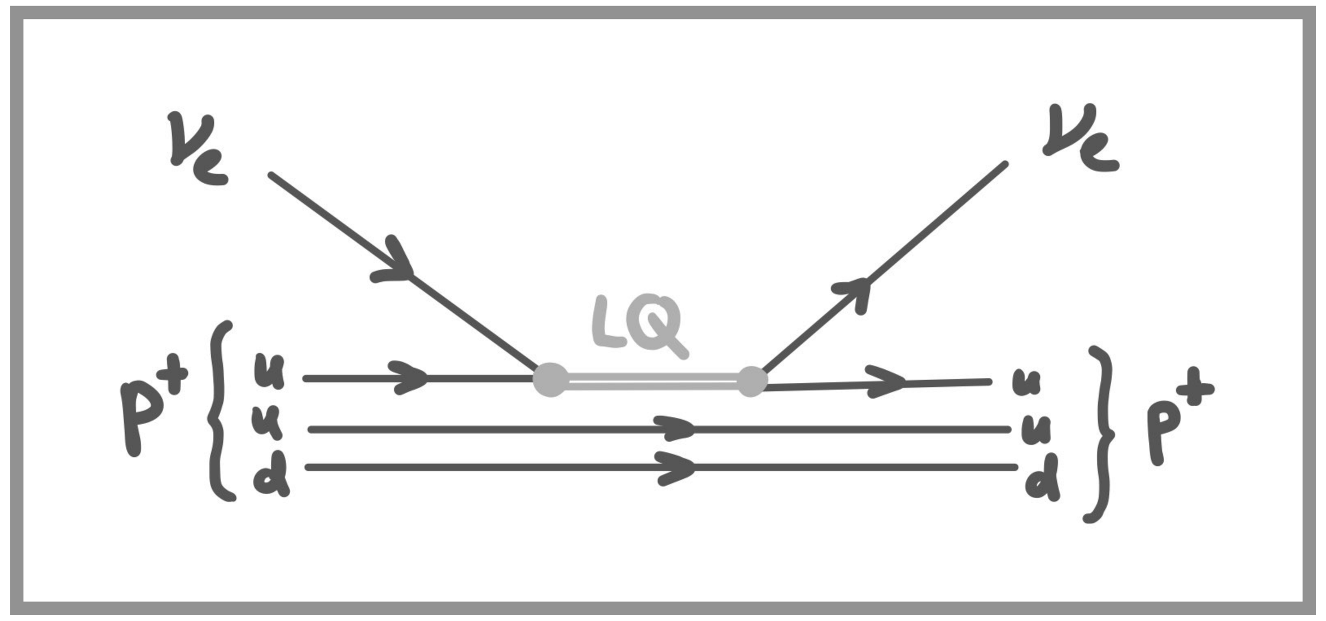
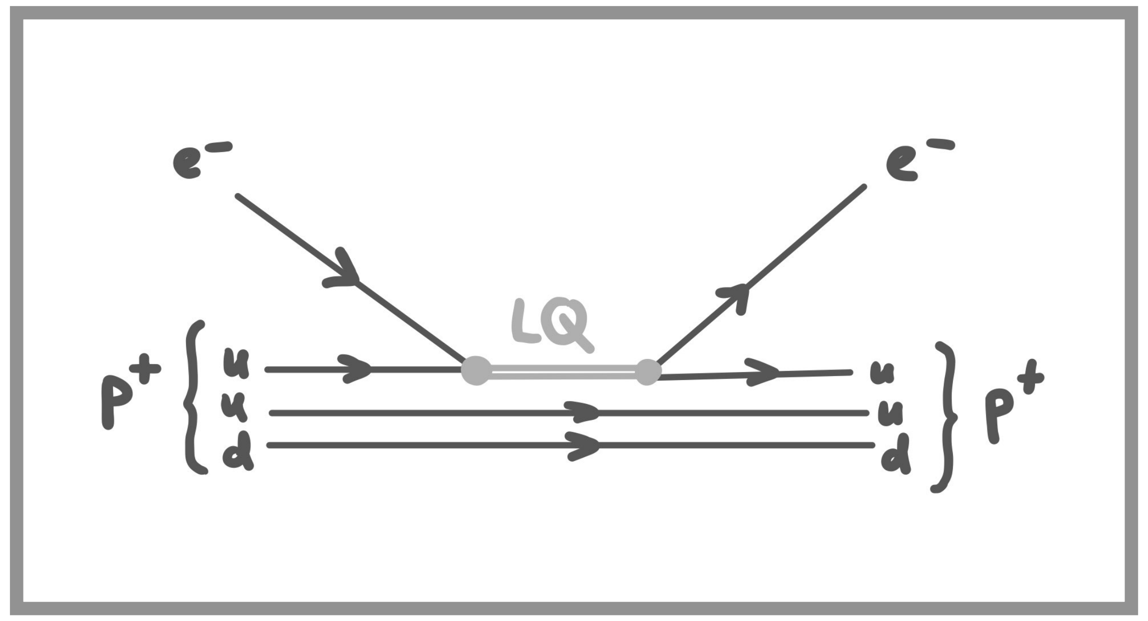


Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

- Neutrino interacts with nucleus via a neutral current, elastic recoil of the nucleus is measured.

2. Precision observables

2.3 Parity violation experiments



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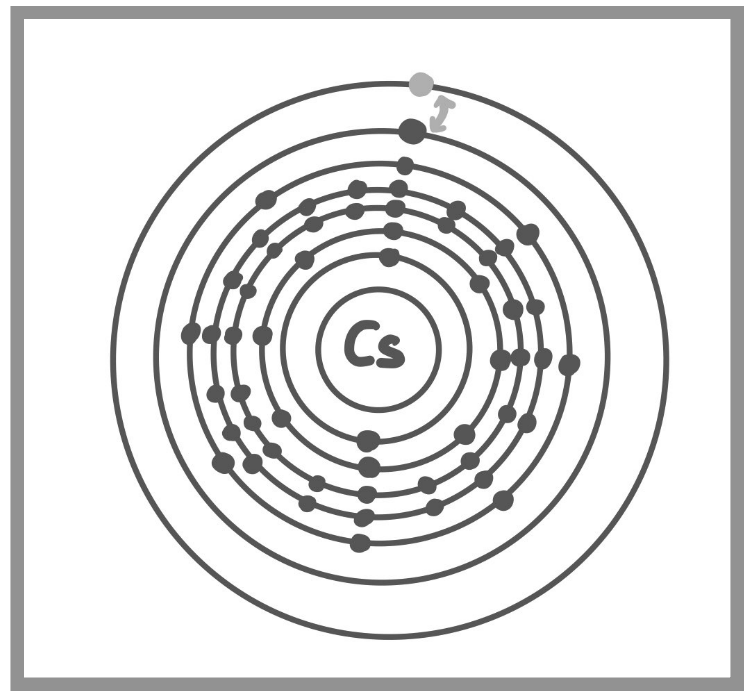

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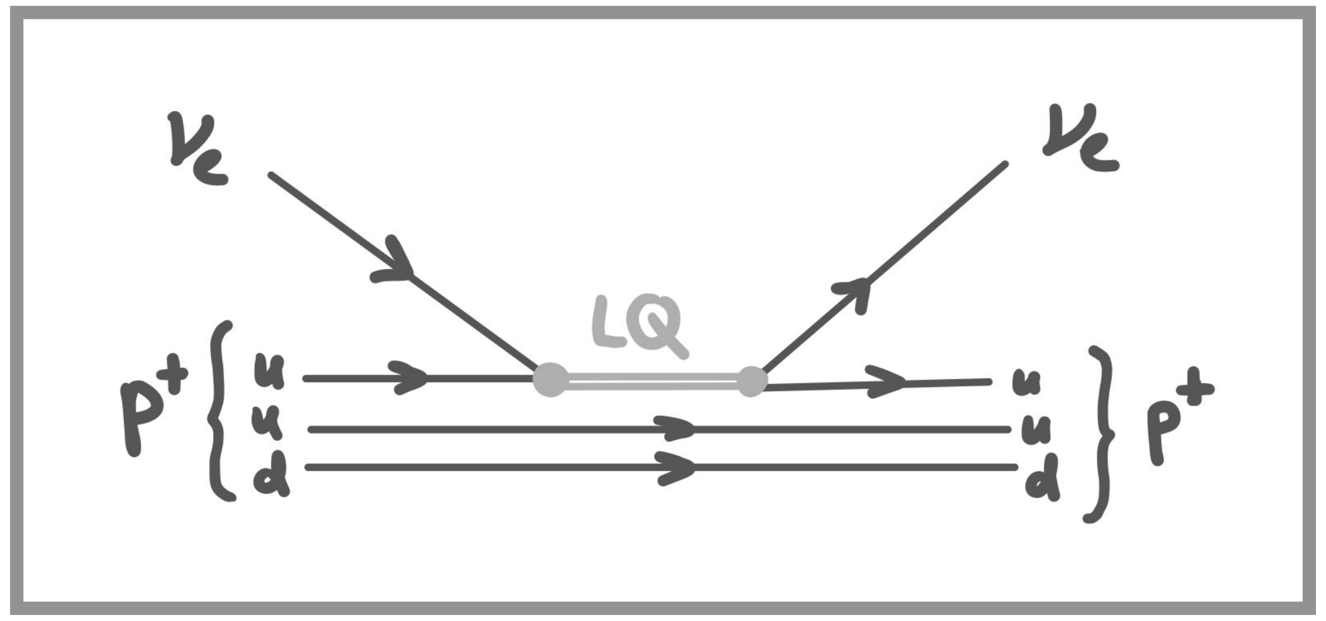

Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

- Neutrino interacts with nucleus via a neutral current, elastic recoil of the nucleus is measured.
- NP constraints from **COHERENT (CsI and Ar targets)** not yet competitive.
- $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

2. Precision observables

2.3 Parity violation experiments

SLQs

2. Precision observables

2.3 Parity violation experiments

$$\mathcal{L}_{\text{eff}}^{ee} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d,s} \Big(C_{1q}^{e} \left[\bar{q}\gamma^{\mu} q\right] \left[\bar{e}\gamma_{\mu}\gamma_5 e\right] + C_{2q}^{e} \left[\bar{q}\gamma^{\mu}\gamma_5 q\right] \left[\bar{e}\gamma_{\mu} e\right] \Big),$$

$$C_{1u}^{e,\text{NP}} = \frac{\sqrt{2}}{4G_F} \Big(C_{\ell q}^{(3)} - C_{\ell q}^{(1)} + C_{eu} + C_{qe} - C_{\ell u} - |V_{ud}|^2 \Big(C_{\phi q}^{(3)} - C_{\phi q}^{(1)} \Big) + C_{\phi u} \Big),$$

SLQs

2. Precision observables

2.3 Parity violation experiments

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$$Q_{\rm w}^p = -2(2C_{1u}^e + C_{1d}^e + 0.00005)\left(1 - \frac{\alpha}{2\pi}\right) = 0.0710(4).$$

$$Q_{\rm w}(^{133}{\rm Cs}) = -2\Big[Z\big(2C_{1u}^e + C_{1d}^e + 0.00005\big) + N\big(C_{1u}^e + 2C_{1d}^e + 0.00006\big)\Big]\left(1 - \frac{\alpha}{2\pi}\right)$$

SLQs

2. Precision observables

2.3 Parity violation experiments

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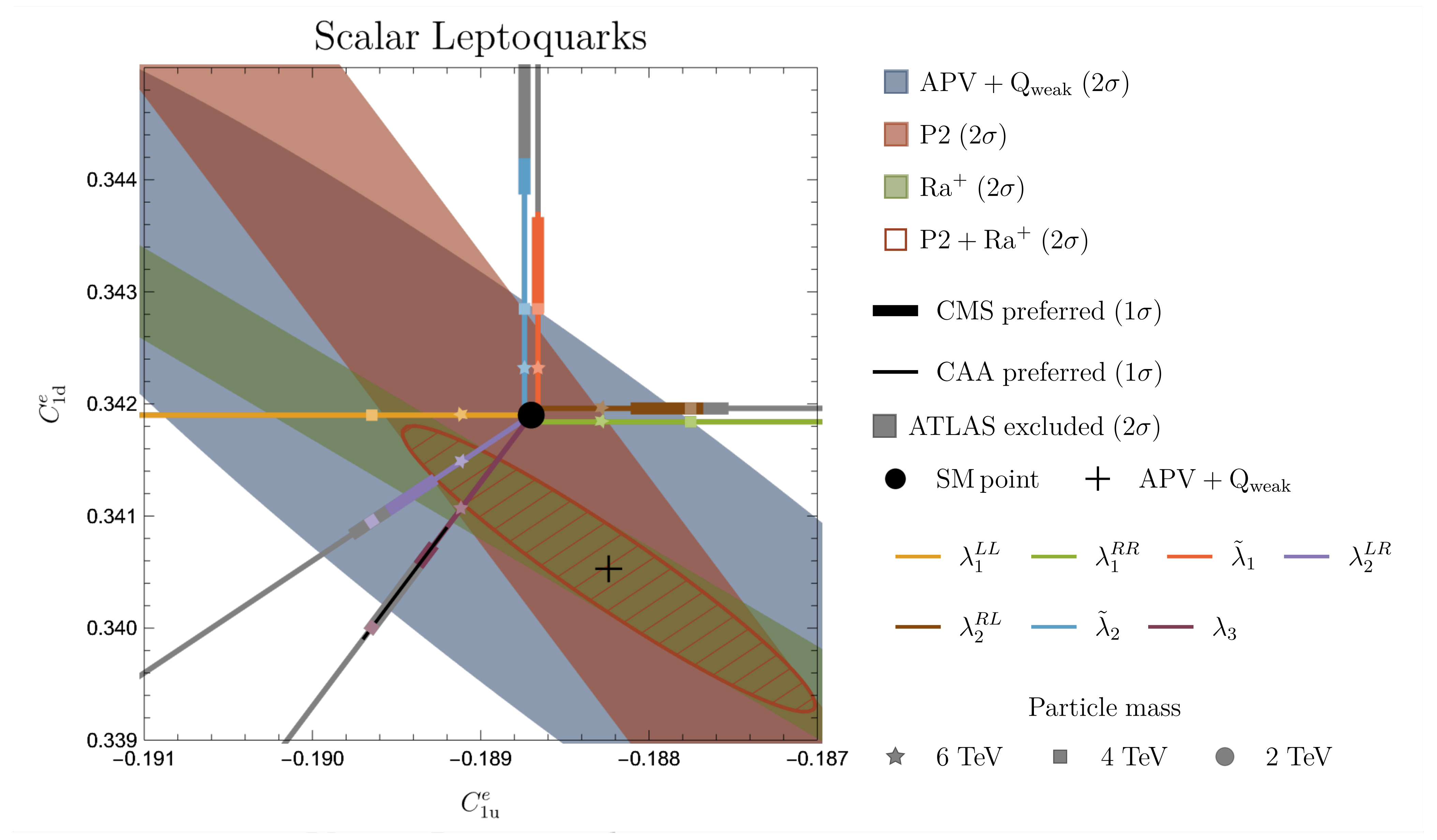

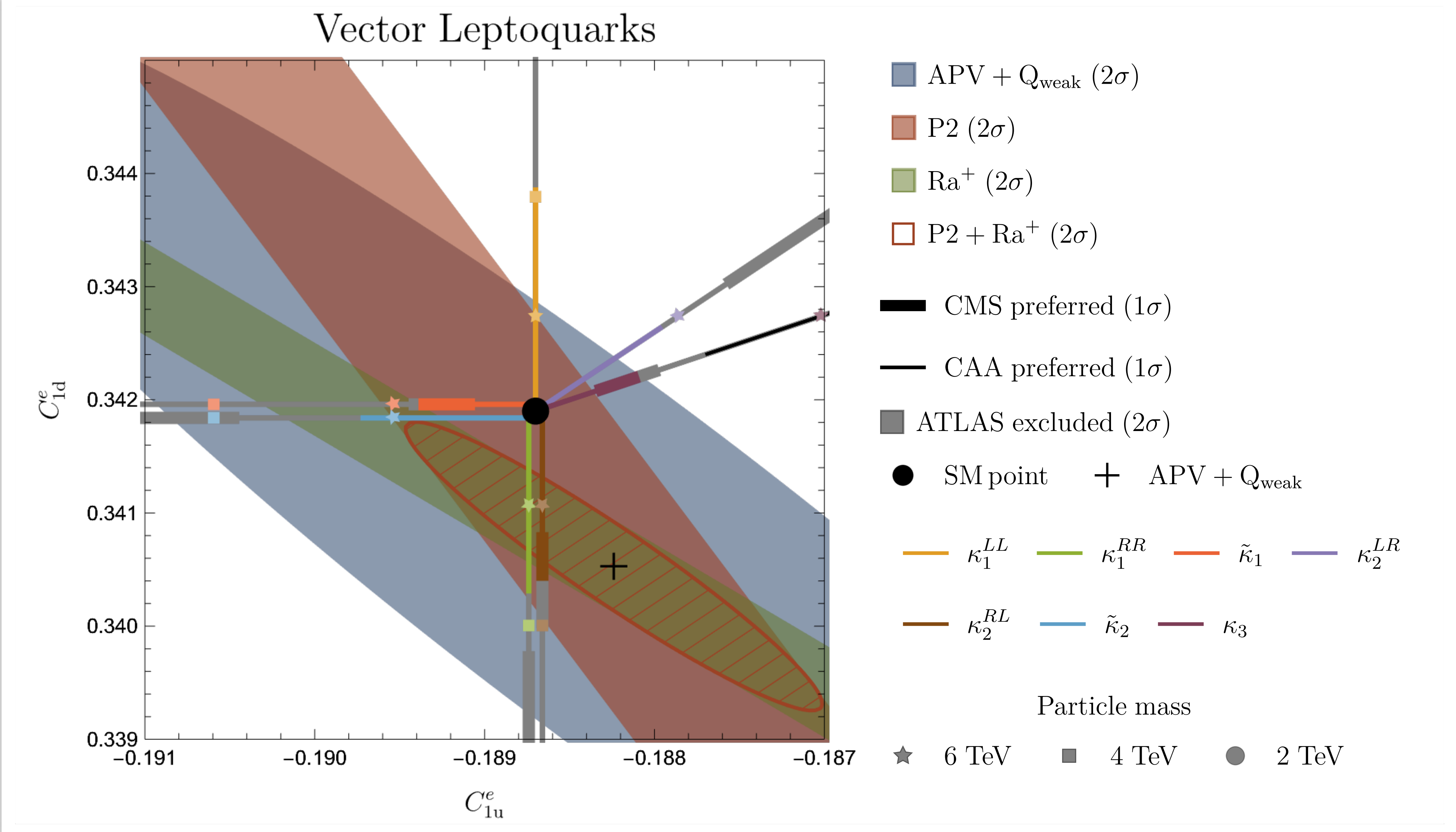

Source: ArXiv:2107.13569 (A. Crivellin, M. Hoferichter, M. Kirk, C.A. Manzari, LS)

3. High-energy searches at the LHC

3.1 Search channels

3.2 Drell-Yan production

3.3 Single-resonant production

3. High-energy searches at the LHC

3.1 Search channels

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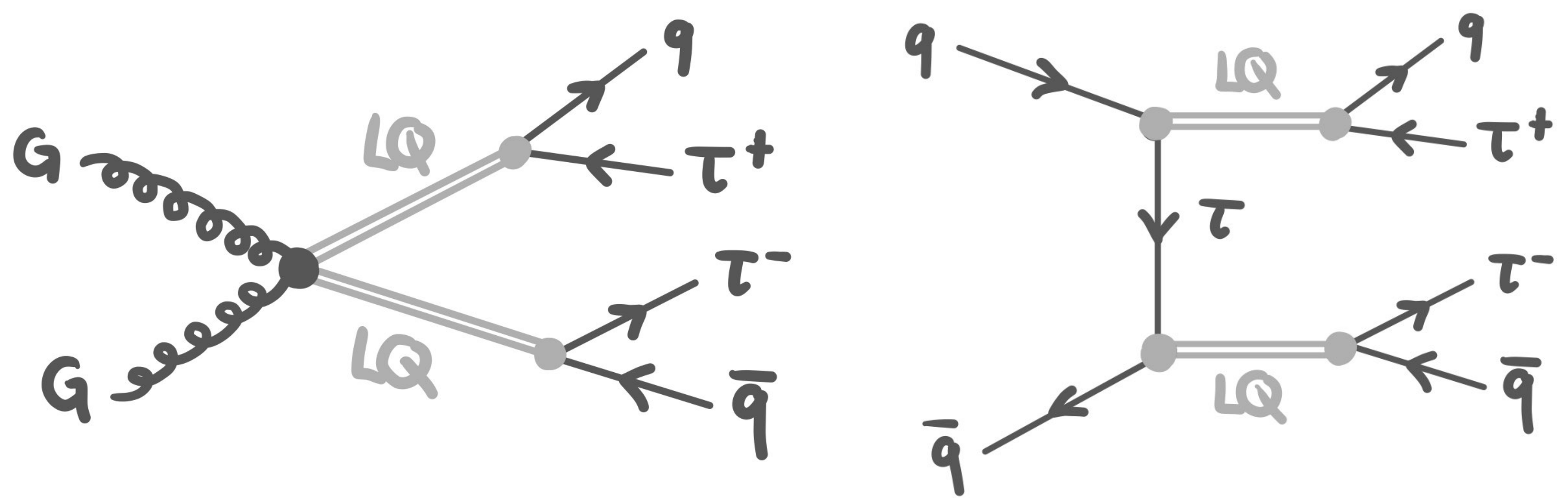

Pair-production

3. High-energy searches at the LHC

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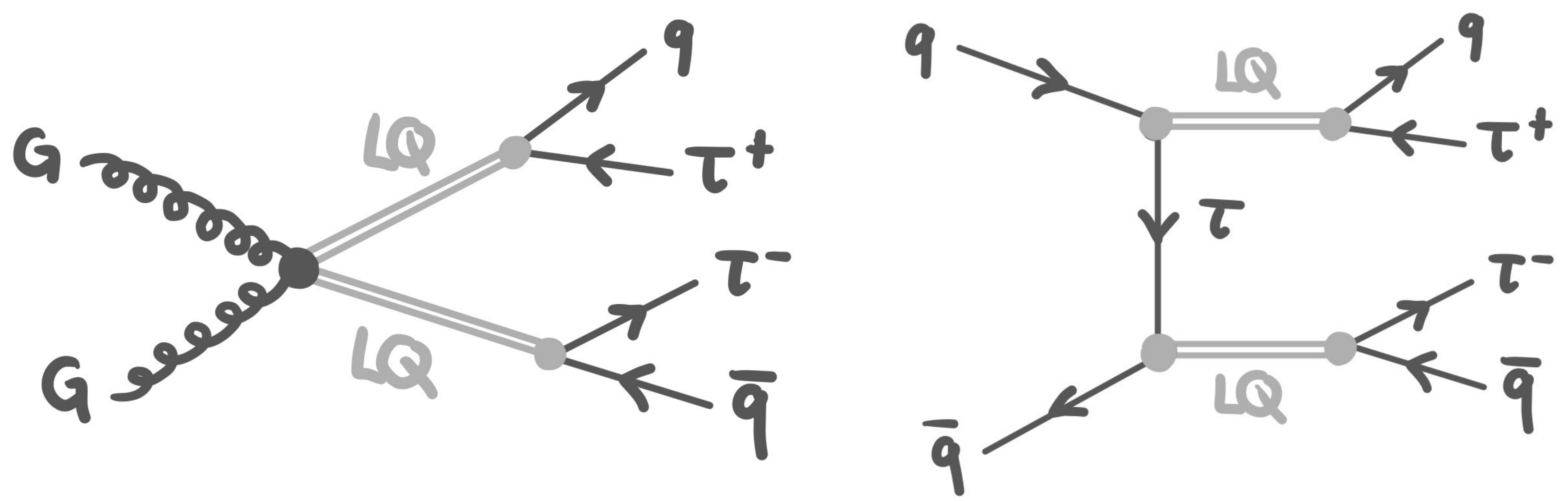
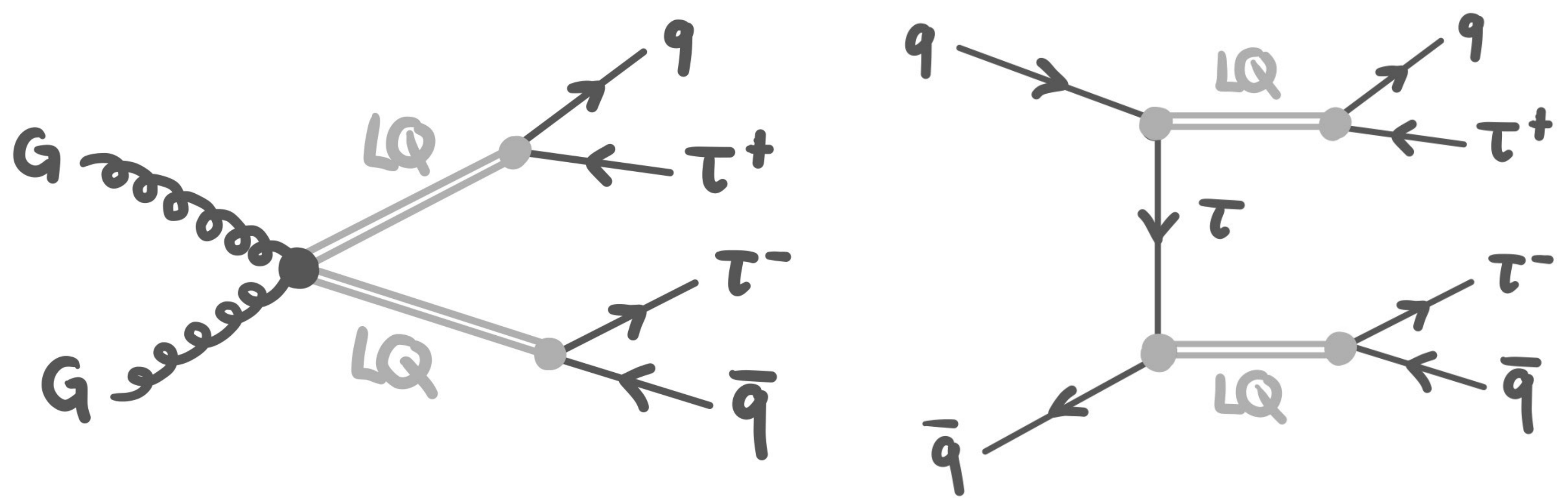


Pair-production

Dependent on Yukawa couplings

3. High-energy searches at the LHC

3.1 Search channels



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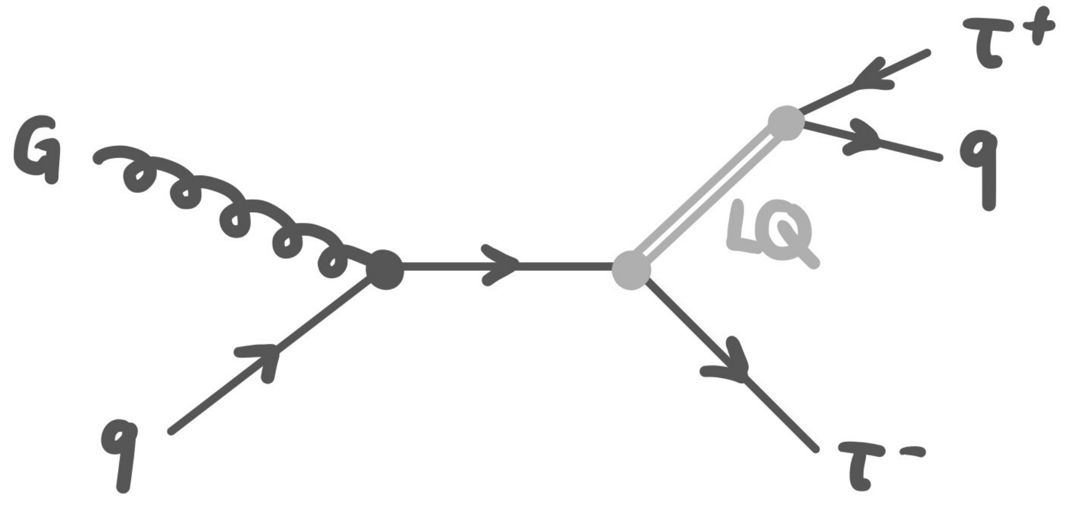
Pair-production



Single production

3. High-energy searches at the LHC

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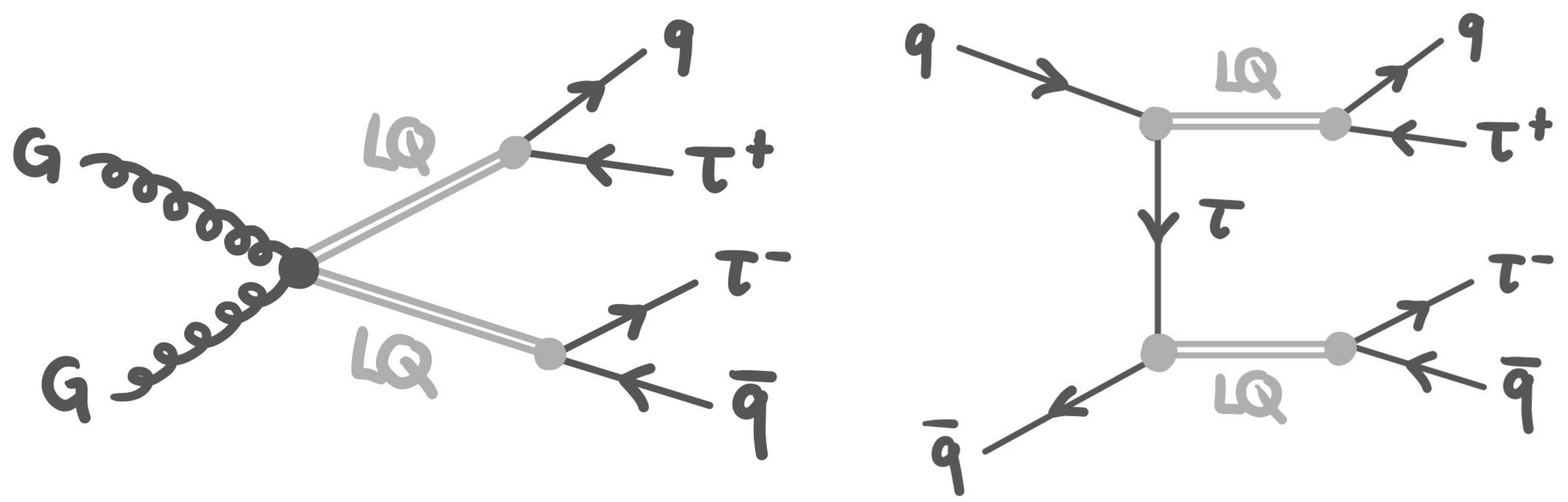

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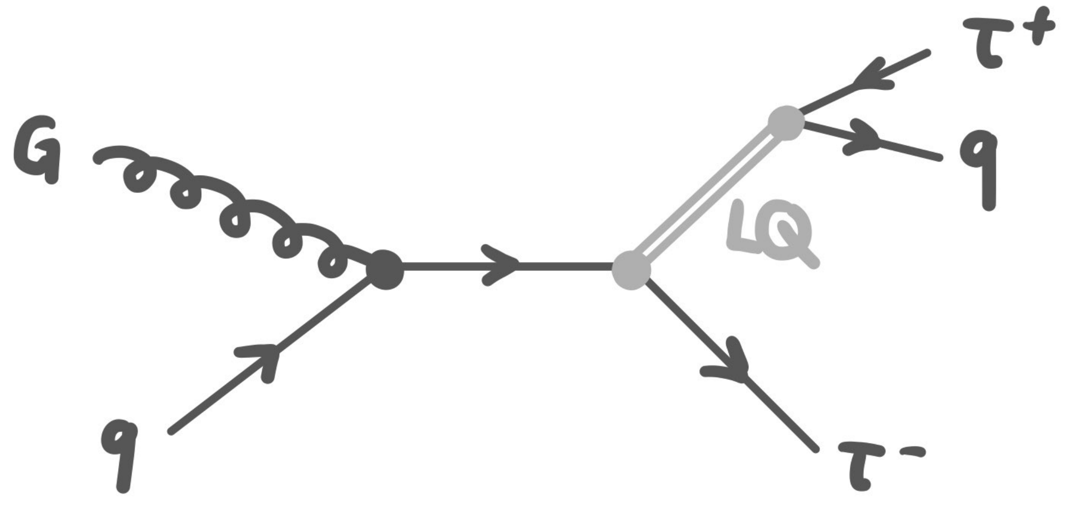

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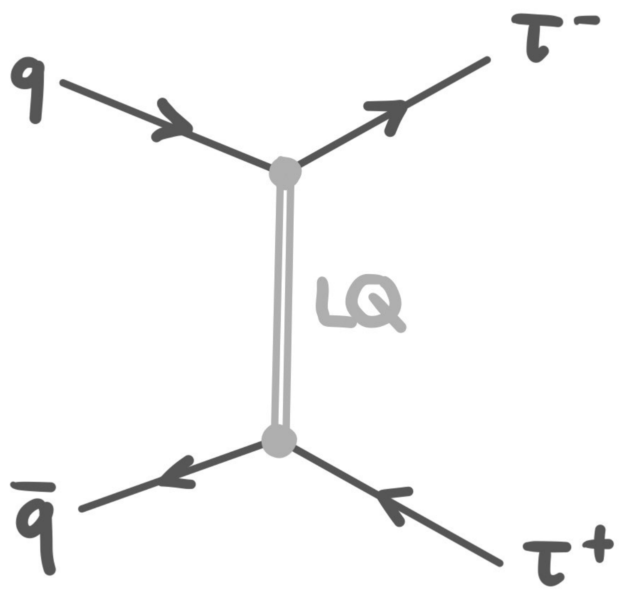

Drell-Yan production

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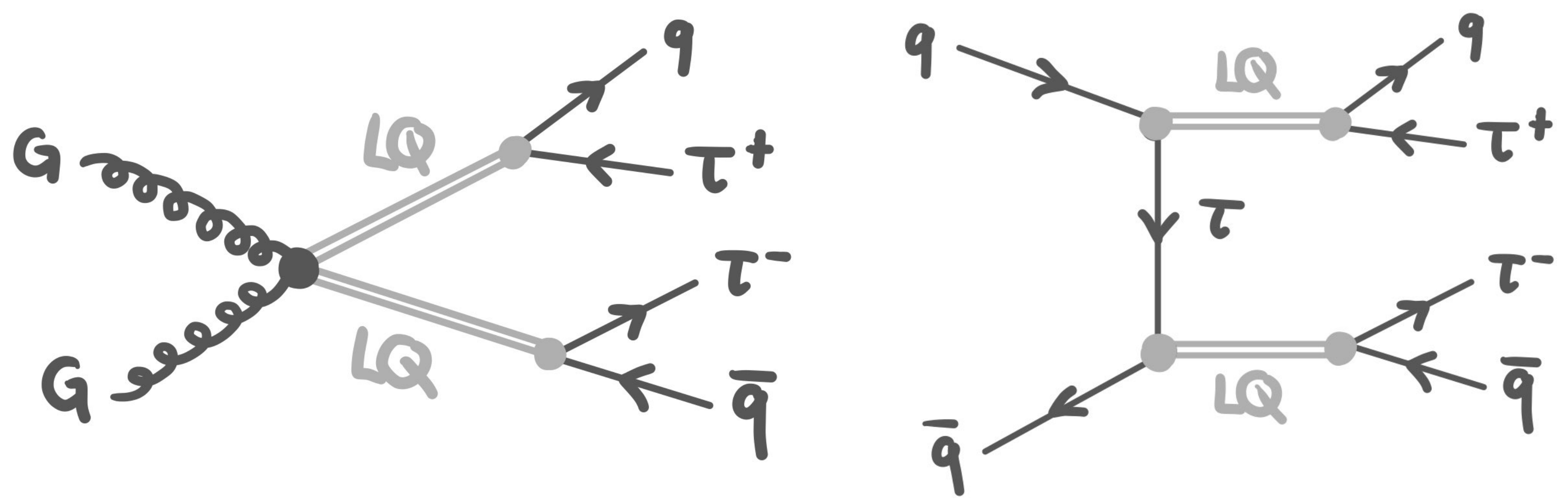

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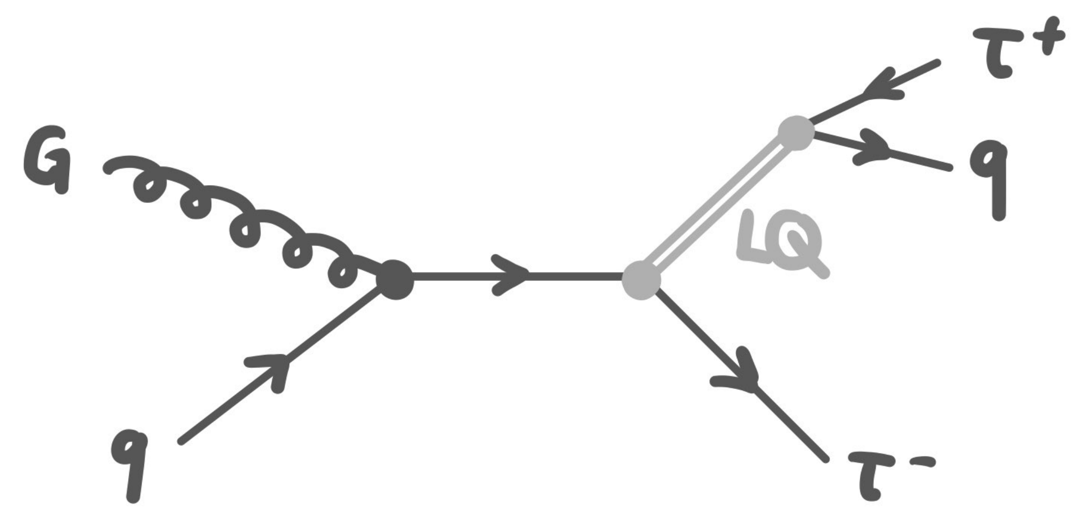

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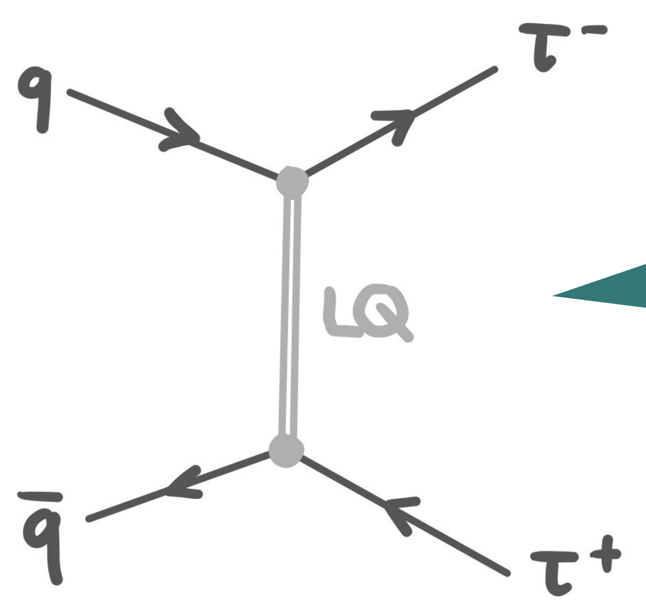

Non-resonant signatures in the tails

Drell-Yan production

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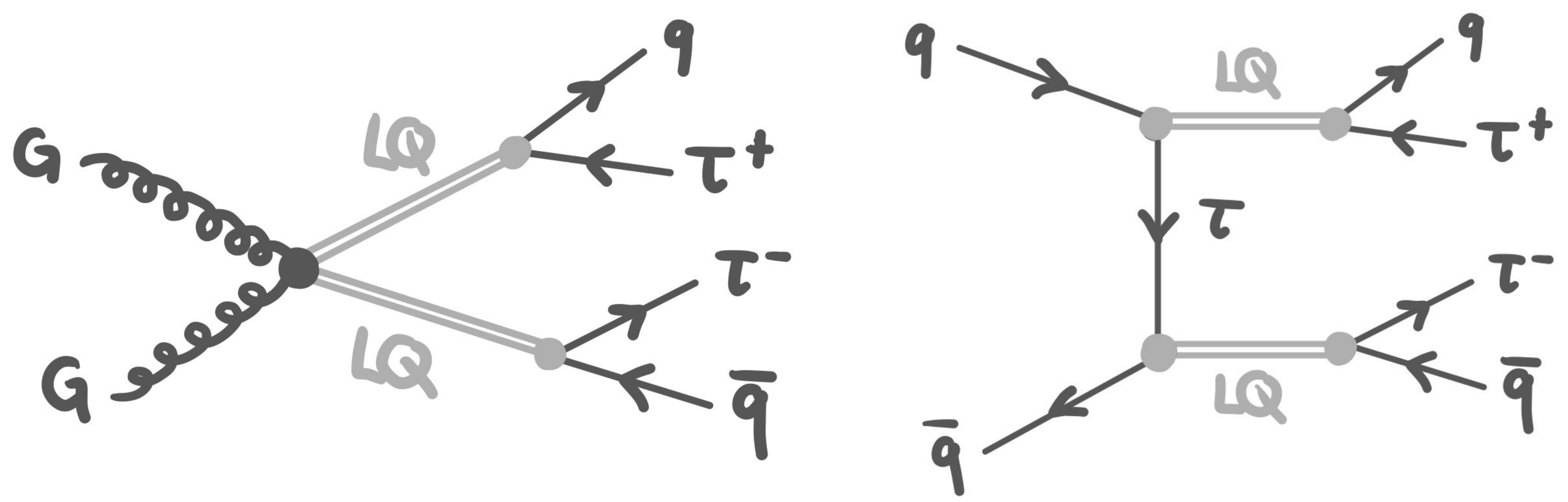
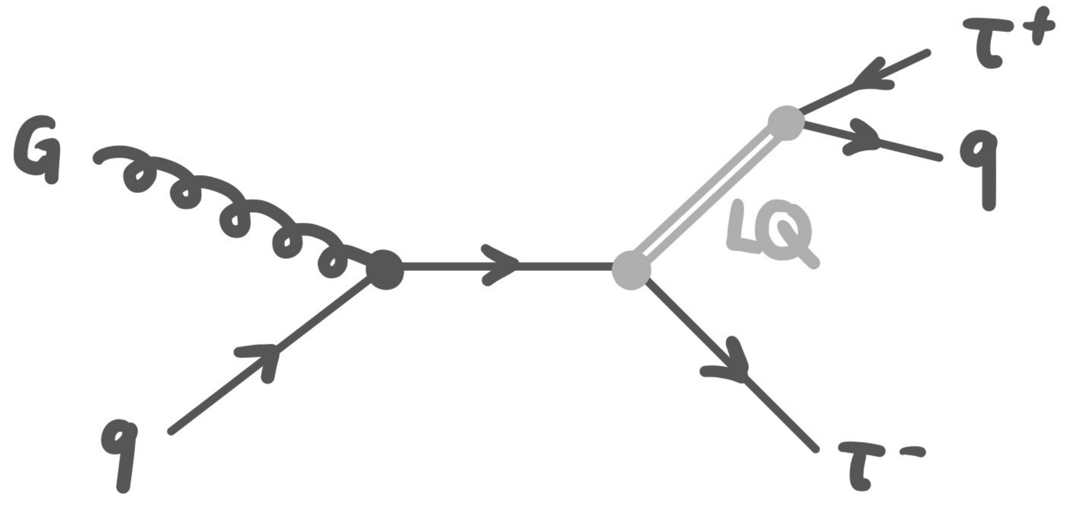
3.1 Search channels

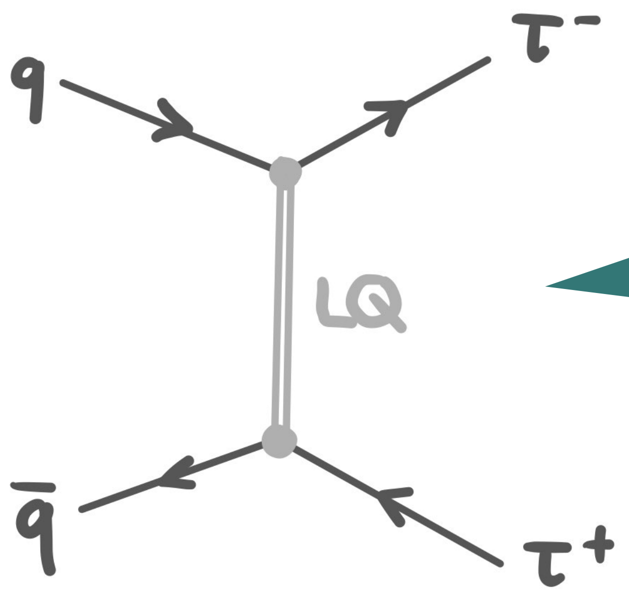


Dependent on Yukawa couplings

Pair-production

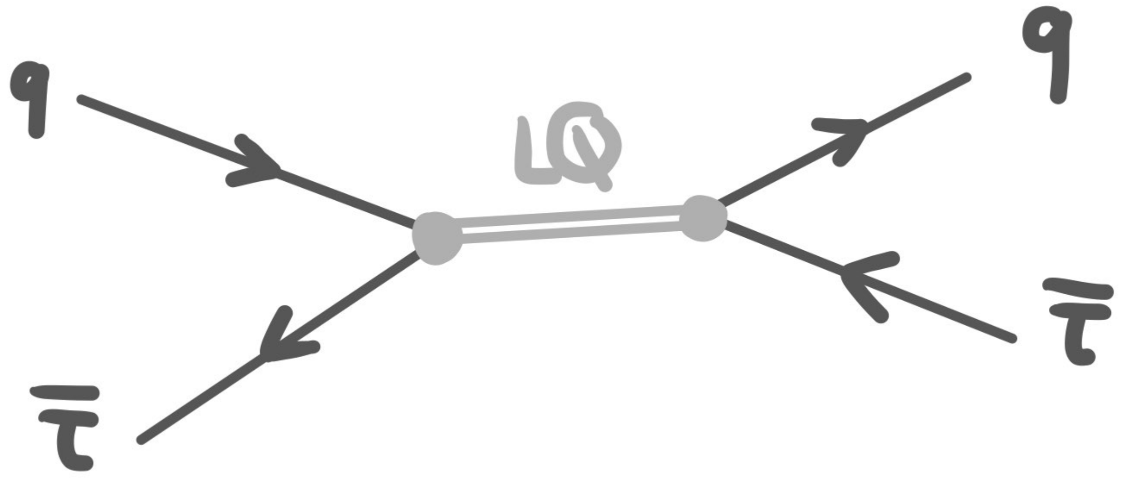


Single production



Non-resonant signatures in the tails

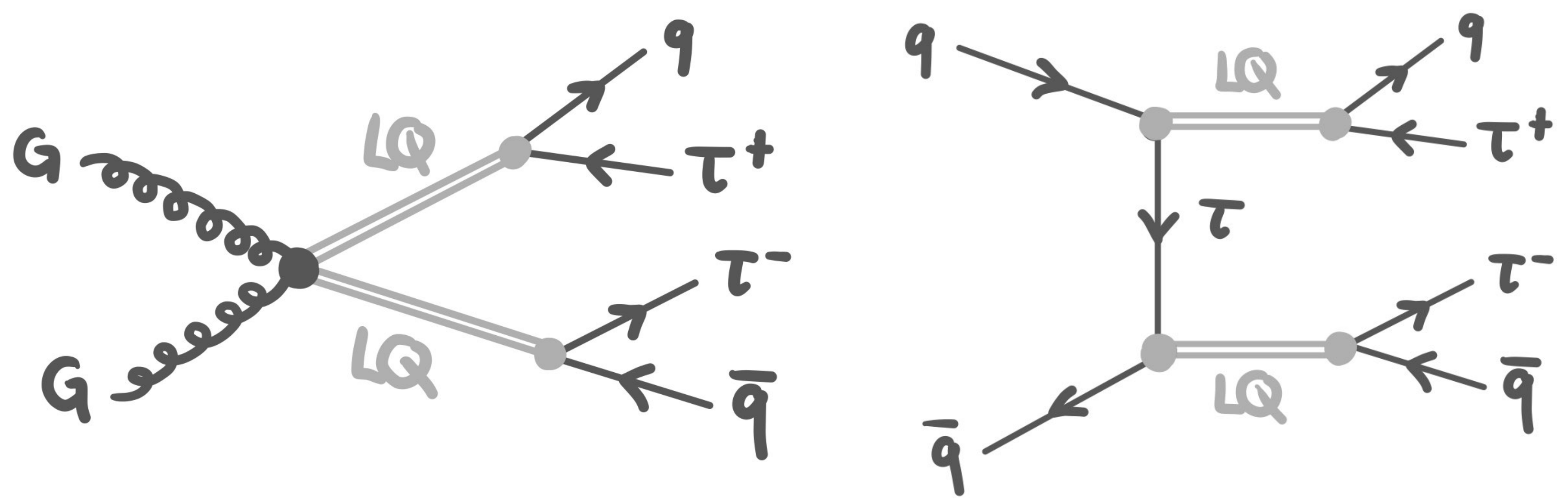
Drell-Yan production



Single-resonant production

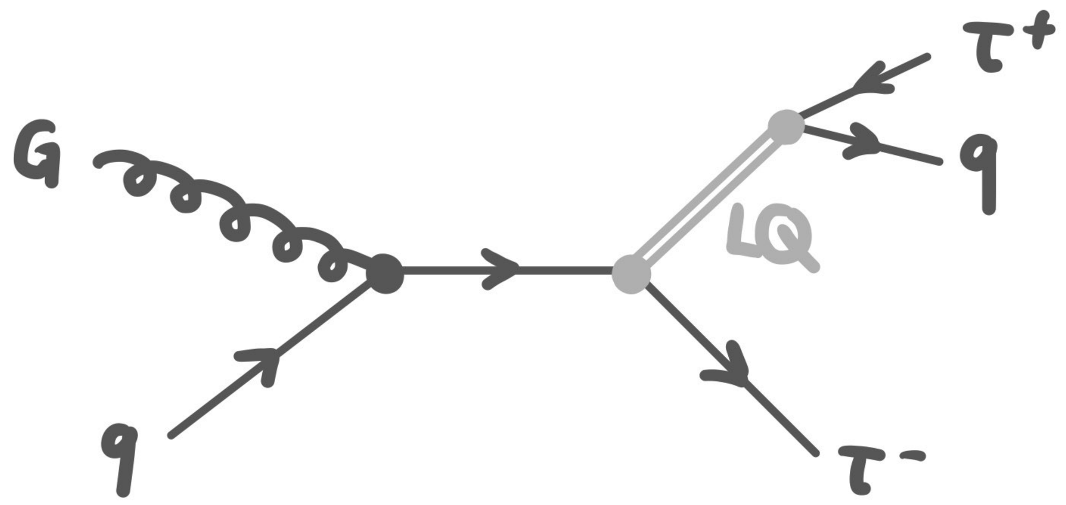
3. High-energy searches at the LHC

3.1 Search channels

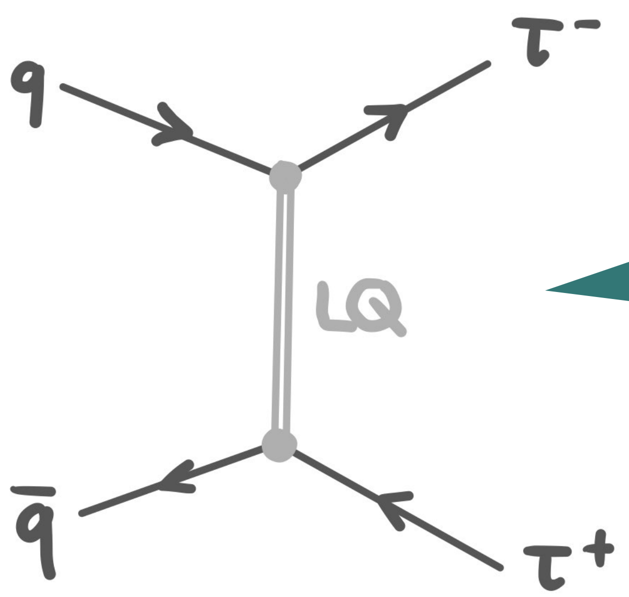


Pair-production

Dependent on Yukawa couplings



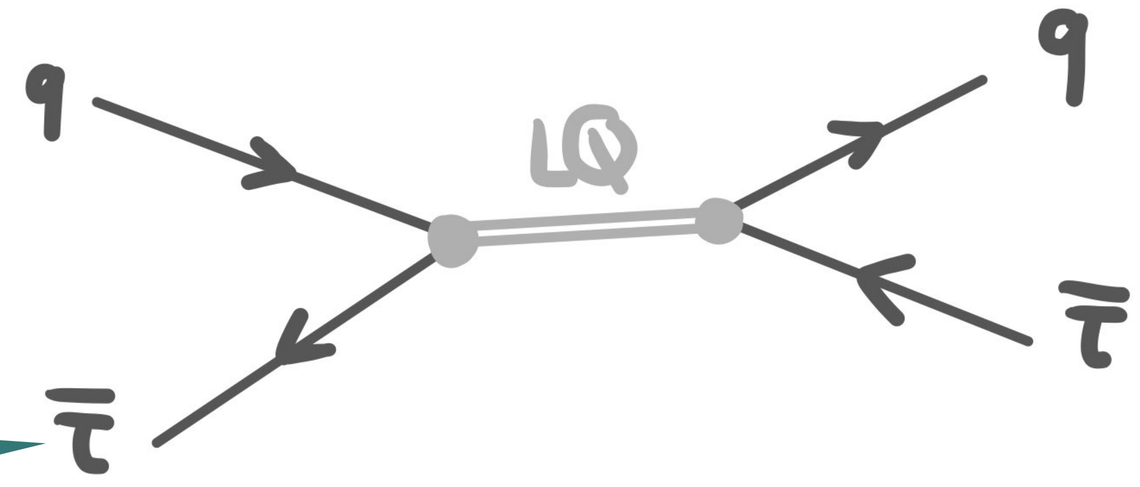
Single production



Non-resonant signatures in the tails

Drell-Yan production

Lepton PDF of the proton



Single-resonant production

U_1

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): Overview

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): Overview

- CMS and ATLAS are searching for U_1 signatures in the **Drell-Yan spectrum**.

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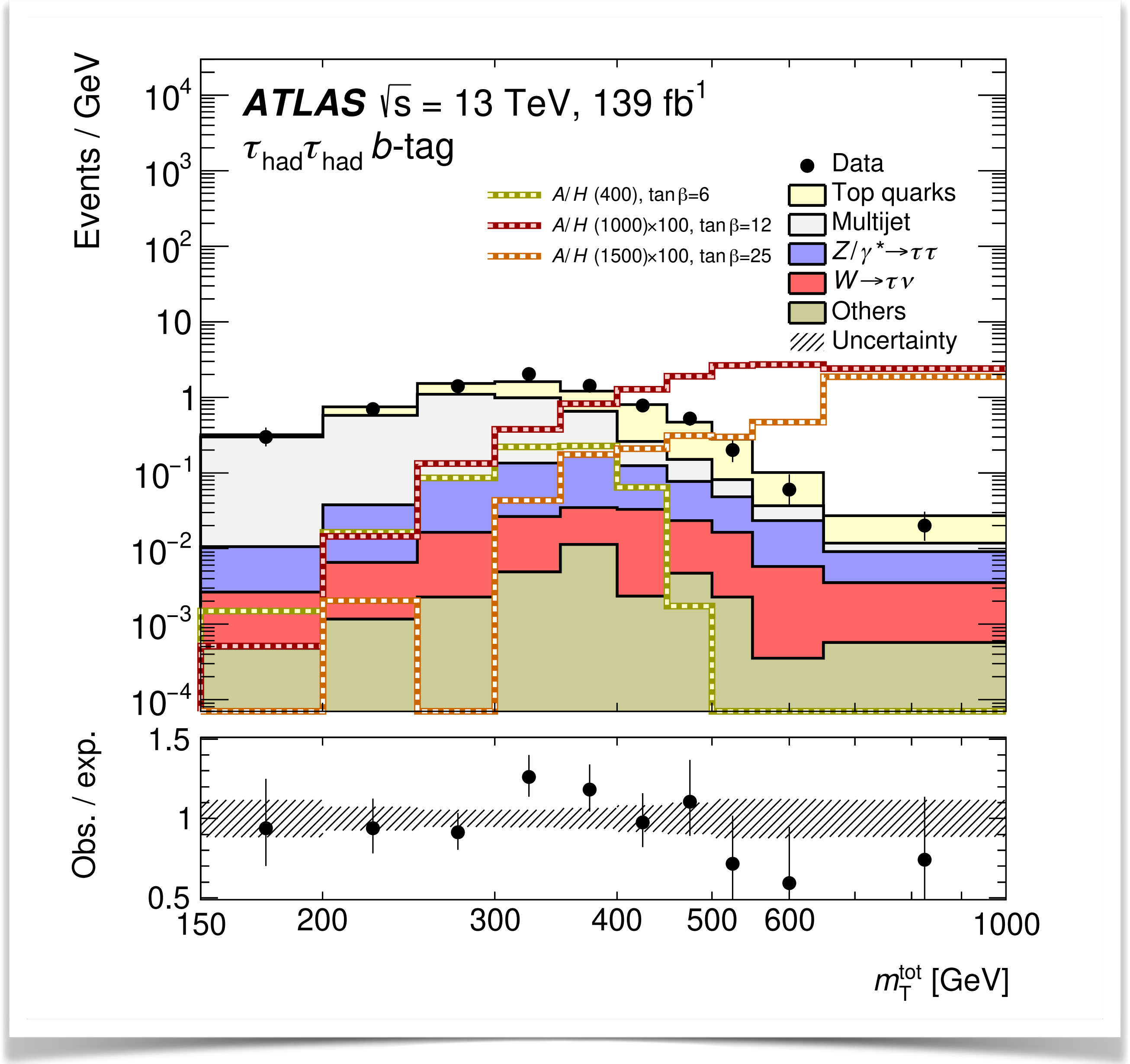
ATLAS 2020



Source: ArXiv:2002.12223 (ATLAS)

U_1

3. High-energy searches at the LHC

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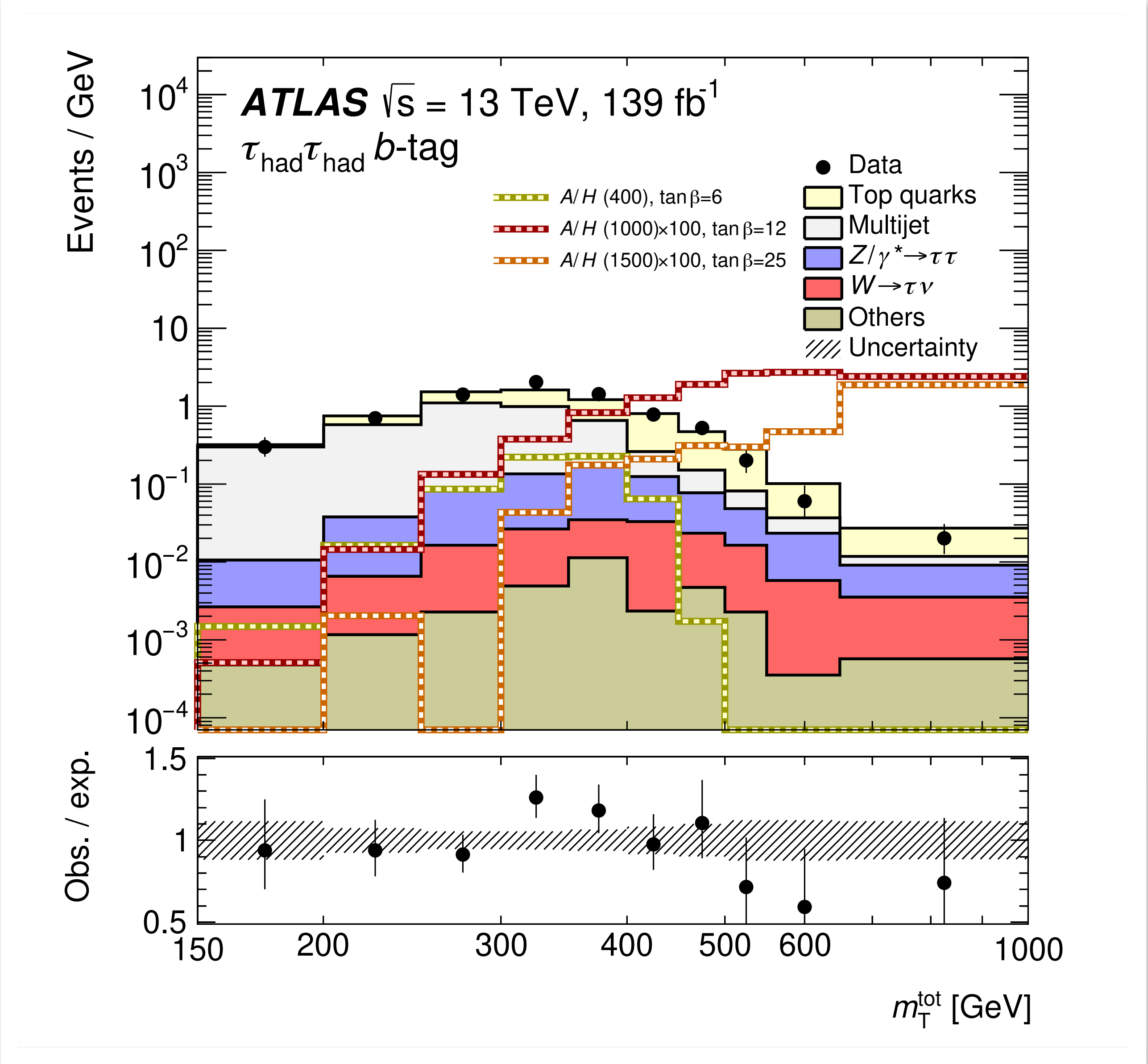

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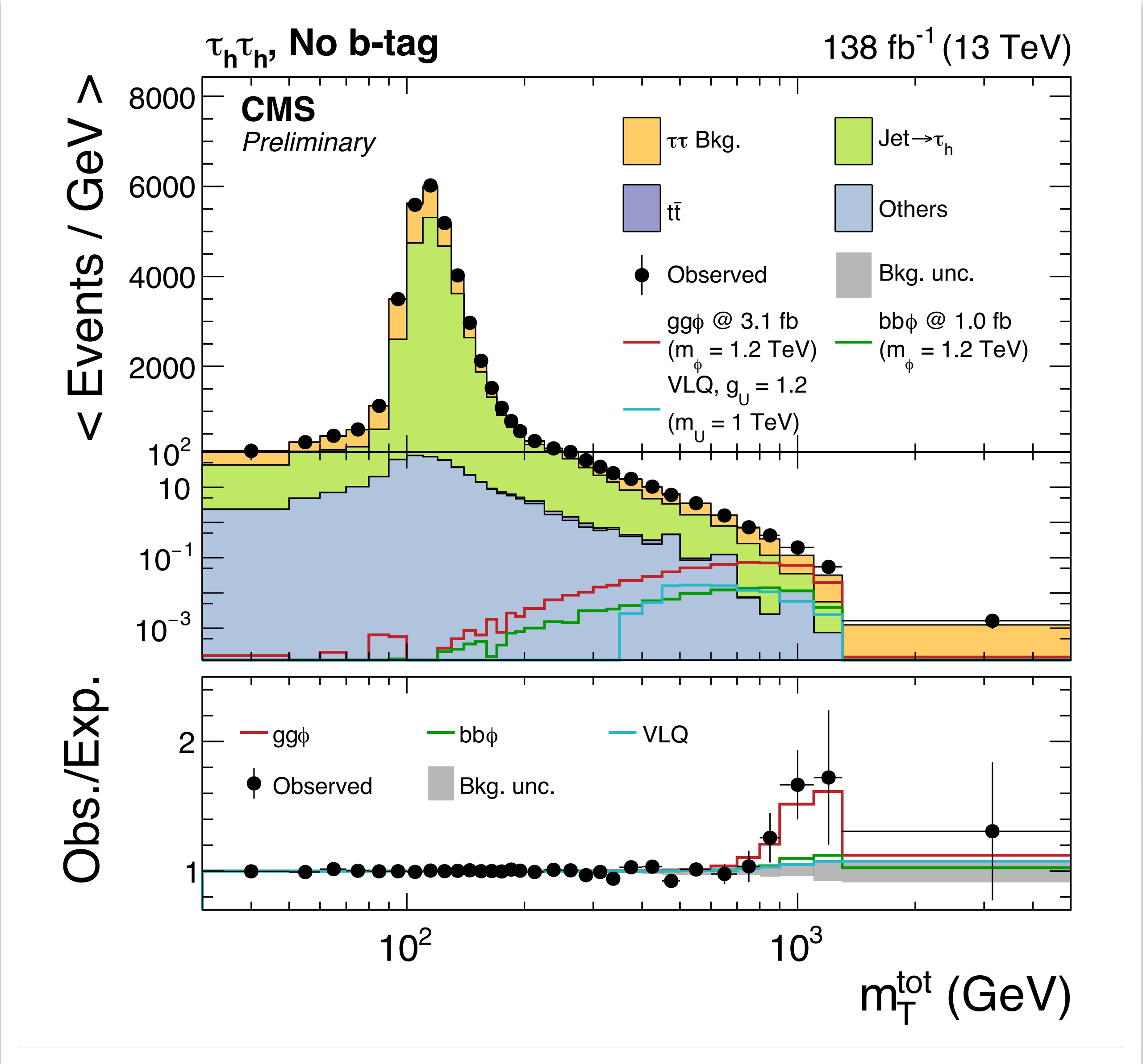
CMS 2021



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

U_1

3. High-energy searches at the LHC

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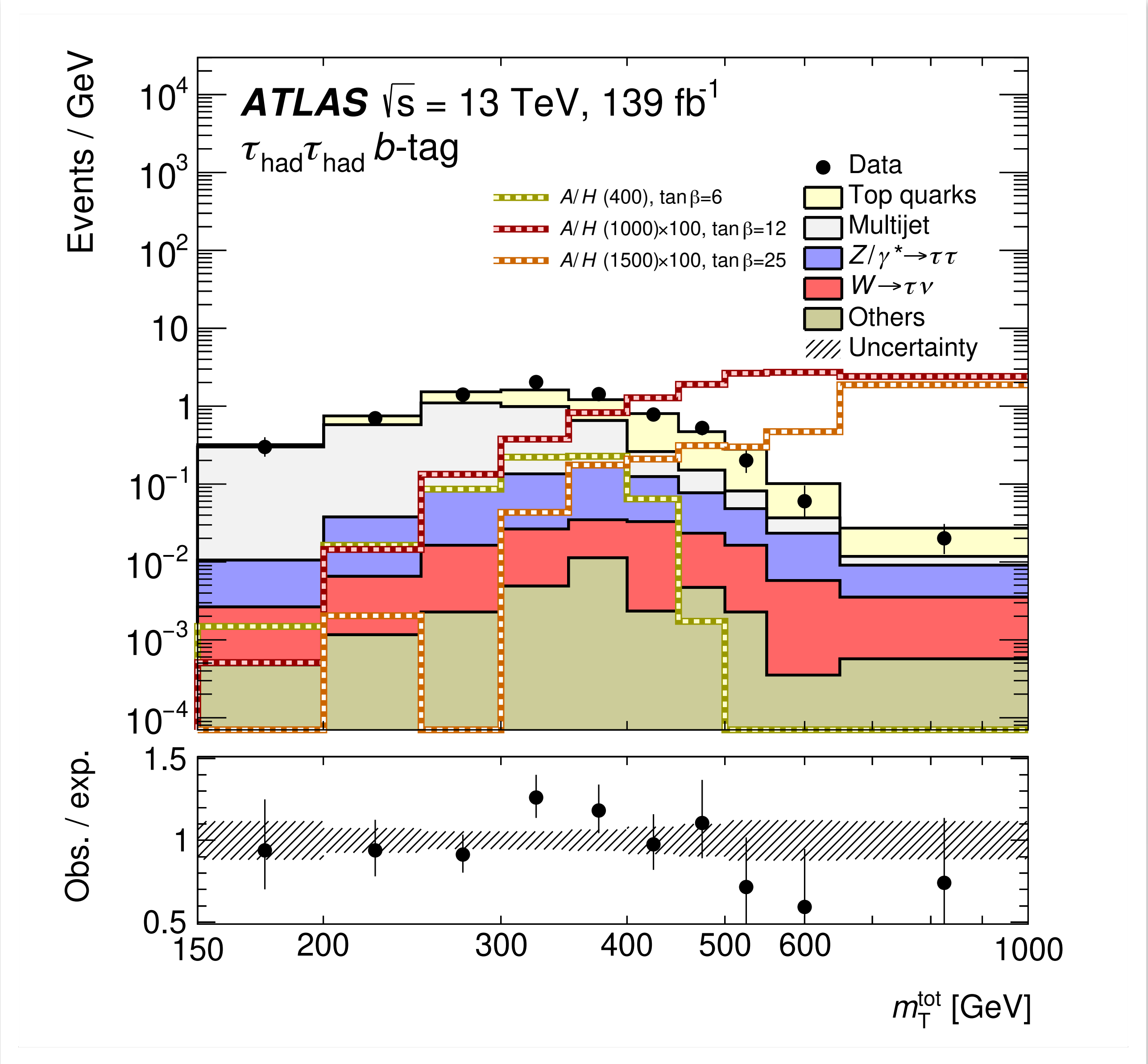

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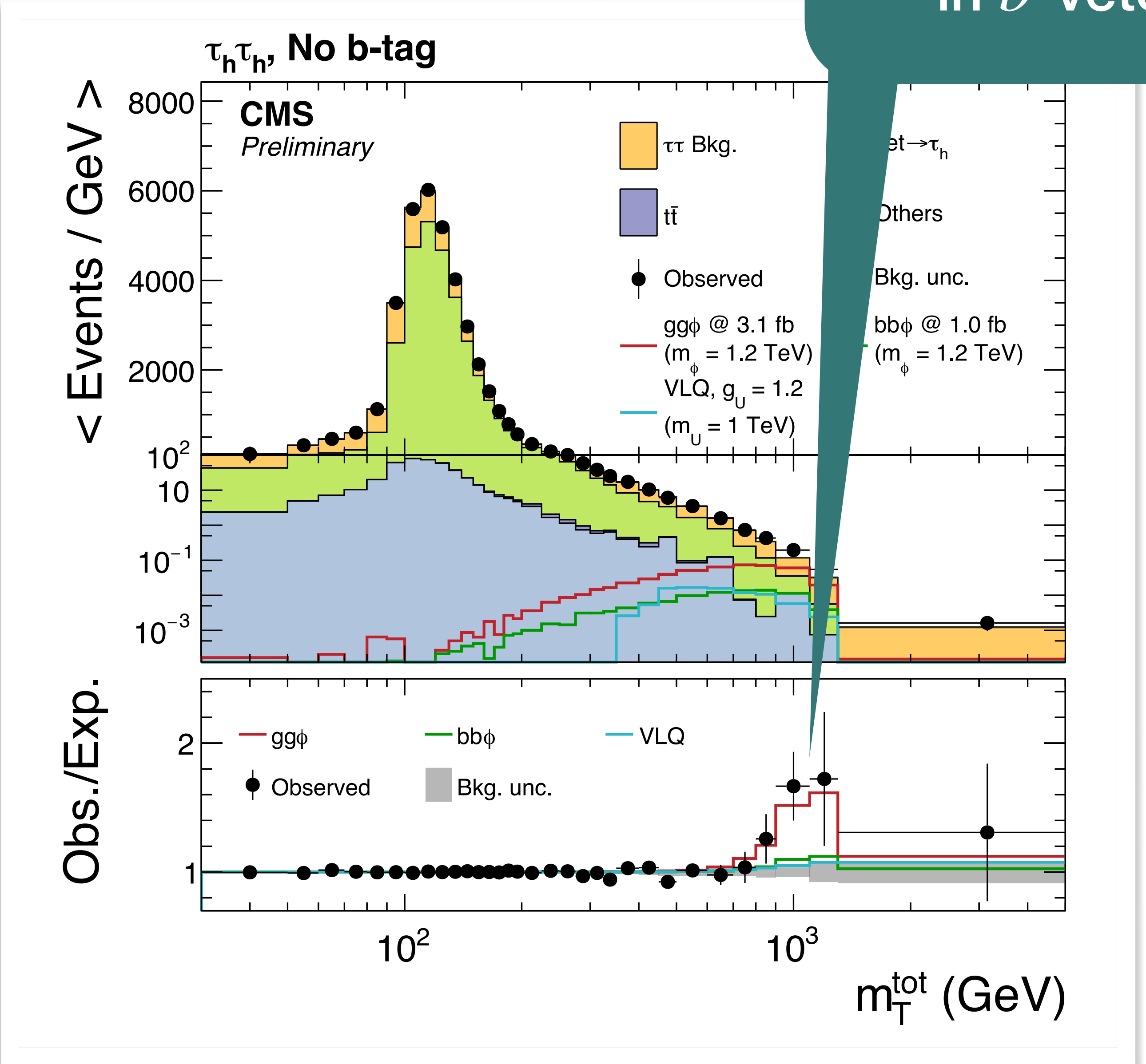
CMS 2021

Resonant excess in b-veto



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

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): Overview

U_1

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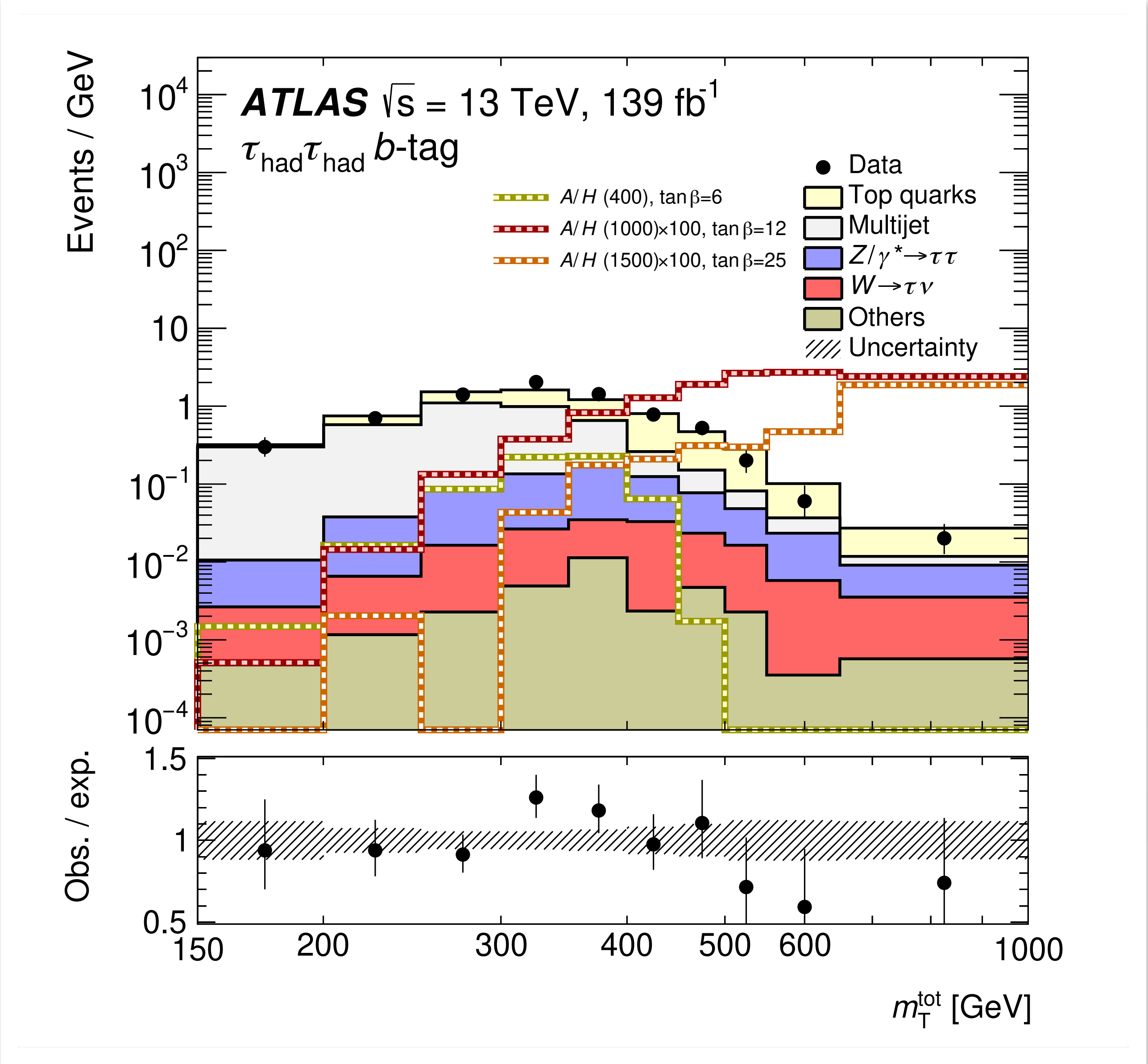
ATLAS 2020



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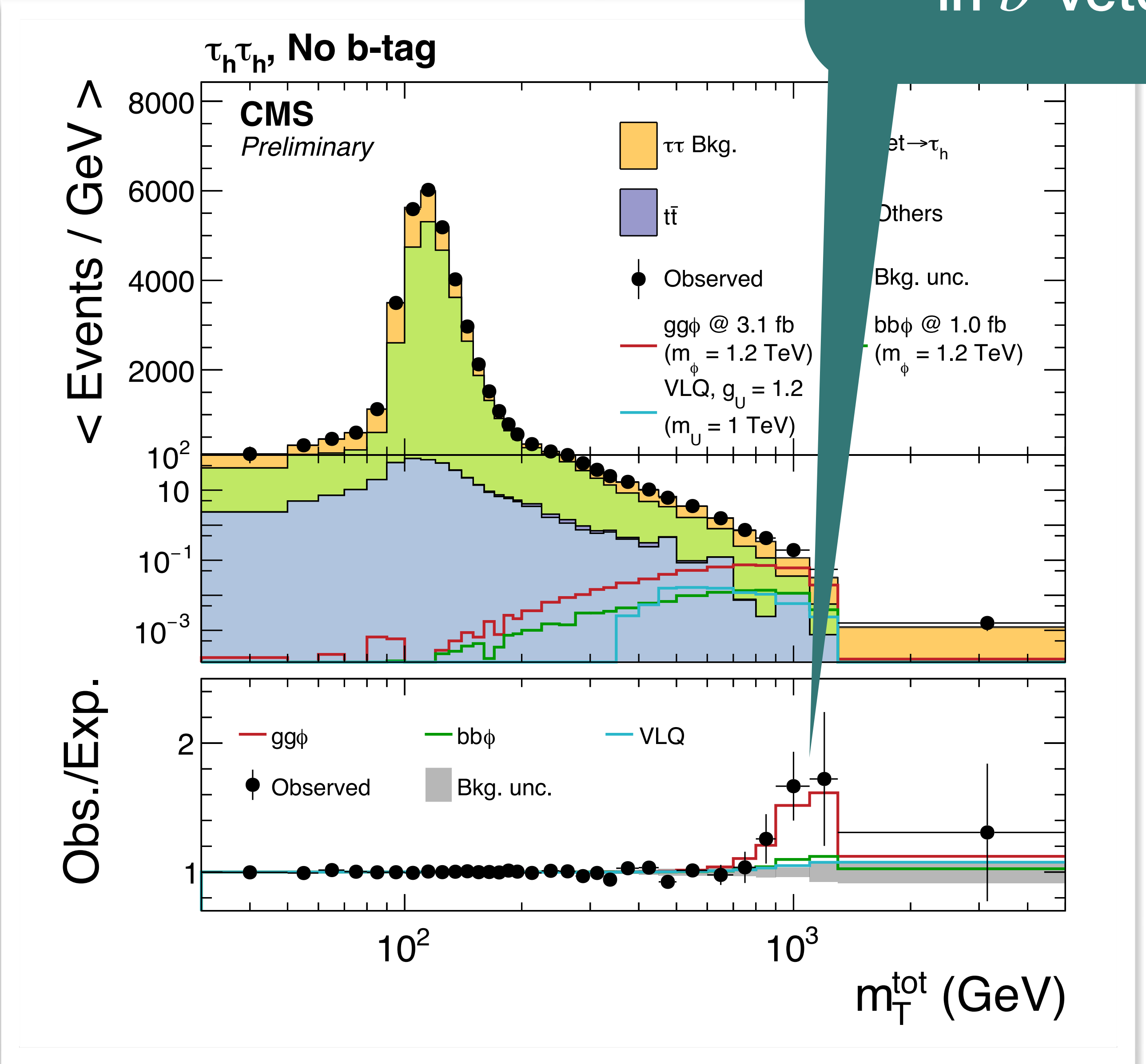
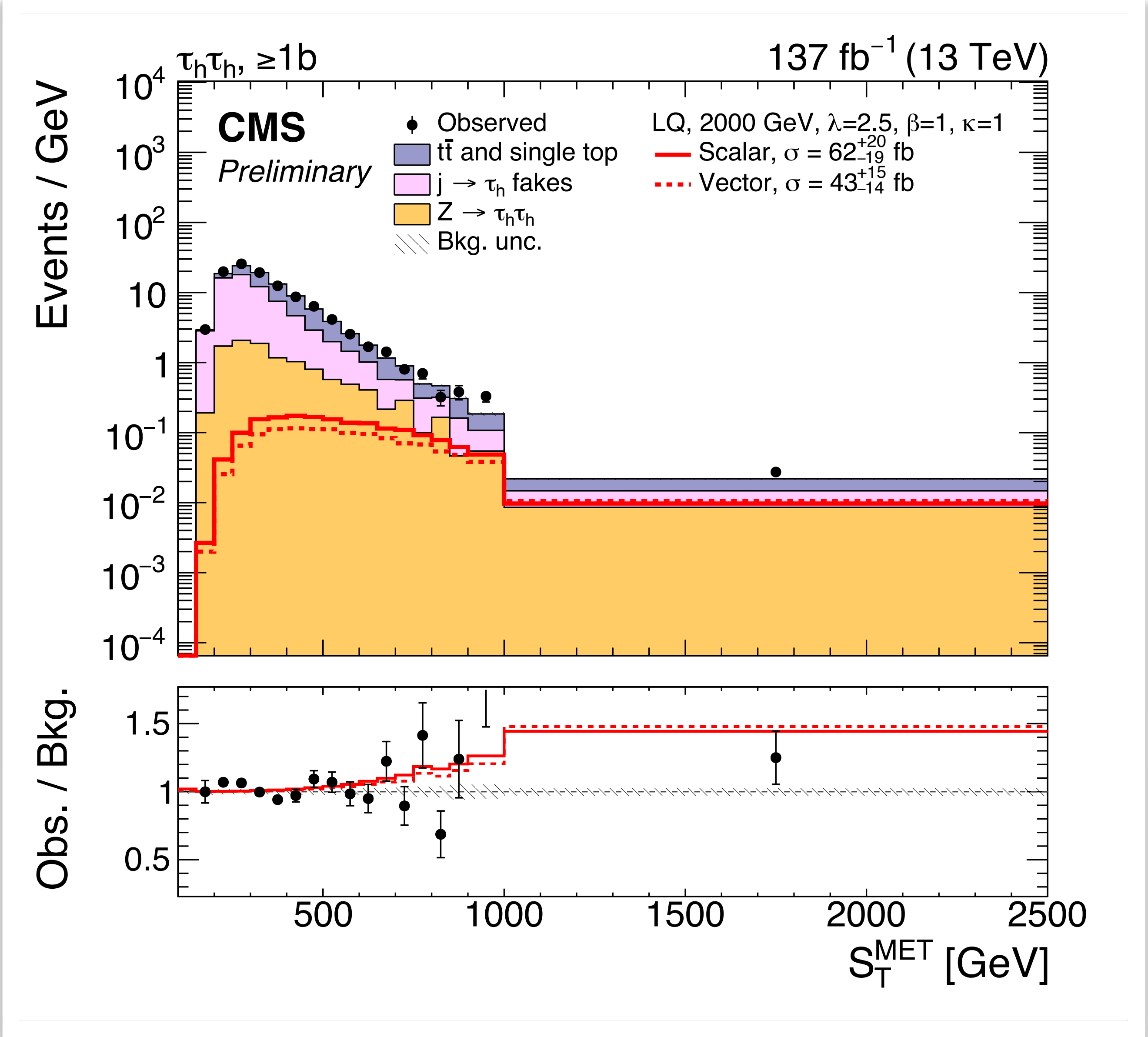


Source: HIG-21-001-PAS (CMS)

CMS 2022



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

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): Overview

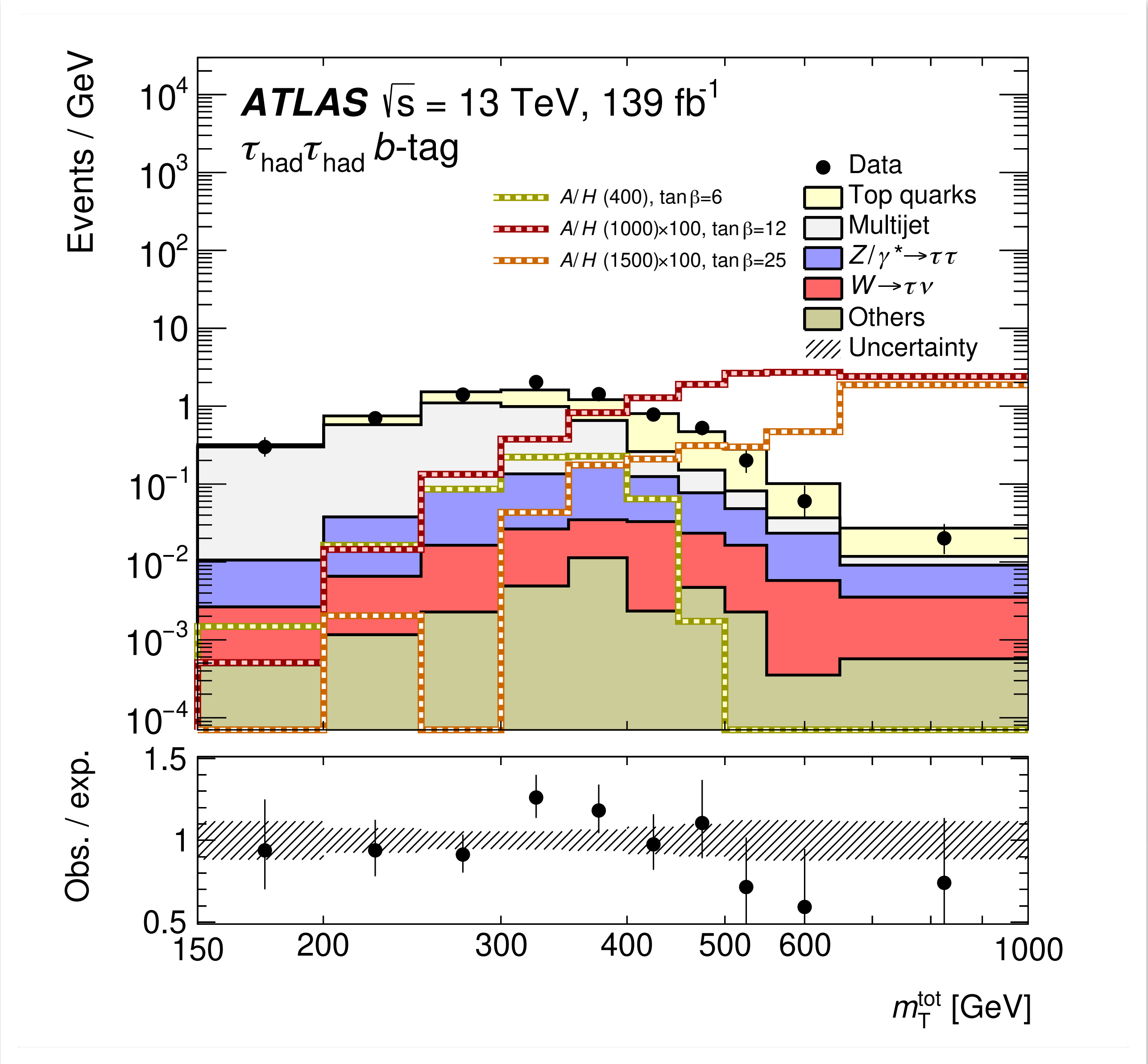
U_1

- CMS and ATLAS are searching for U_1 signatures in the **Drell-Yan spectrum**.

Resonant excess in b-veto

Non-resonant excess in b-tag

ATLAS 2020



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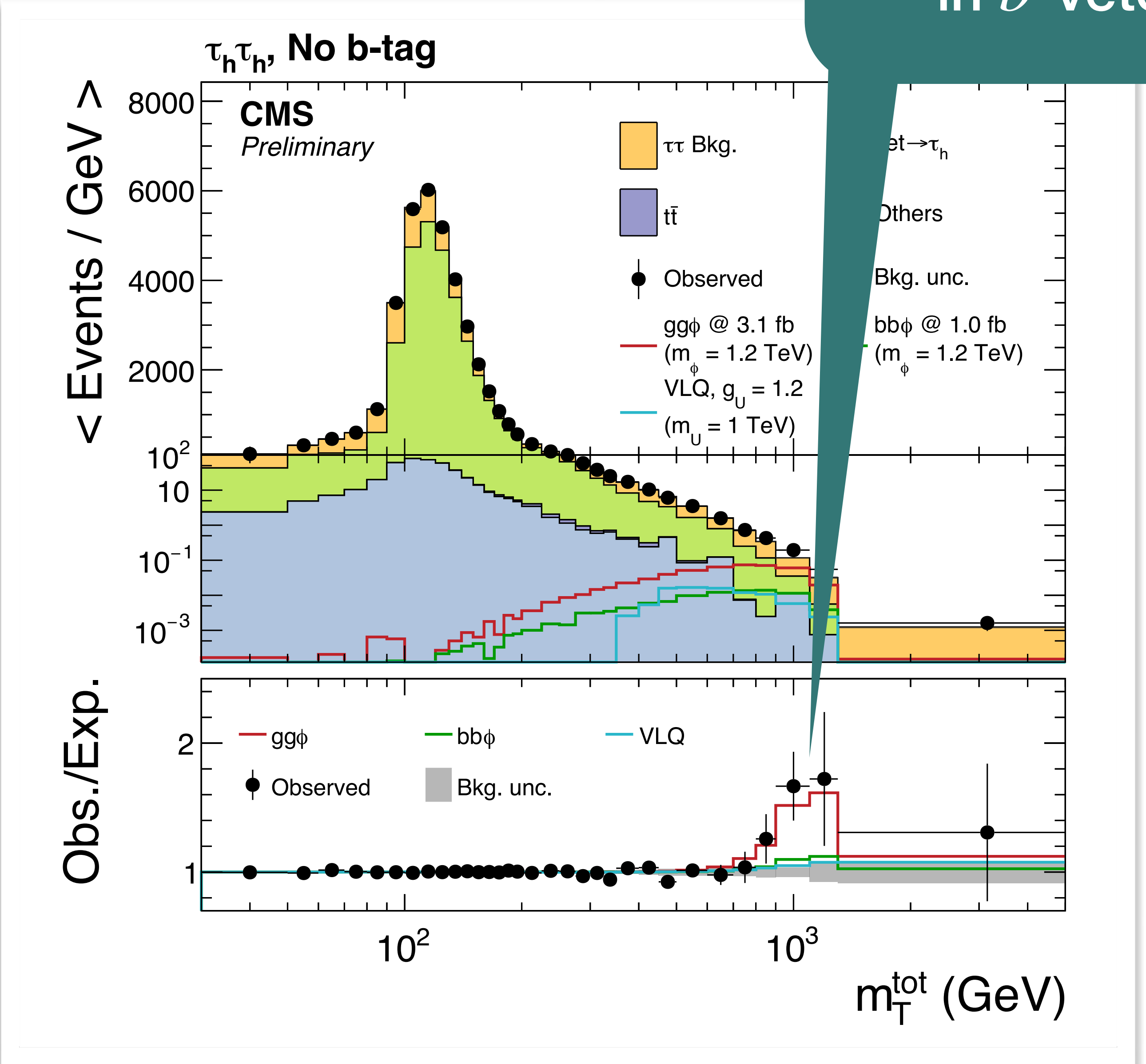
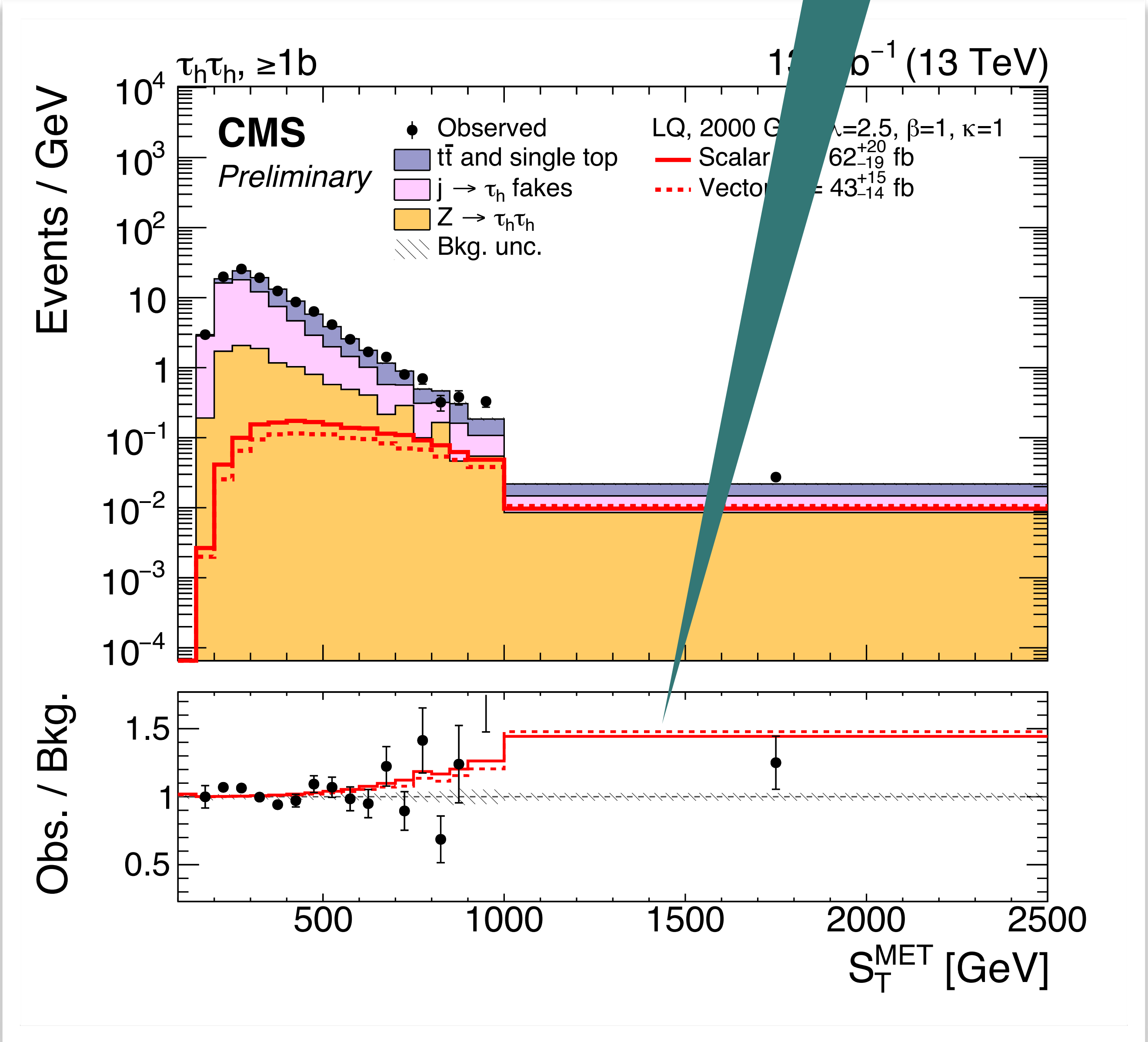
CMS 2021



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

CMS 2022



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

3. High-energy searches at the LHC

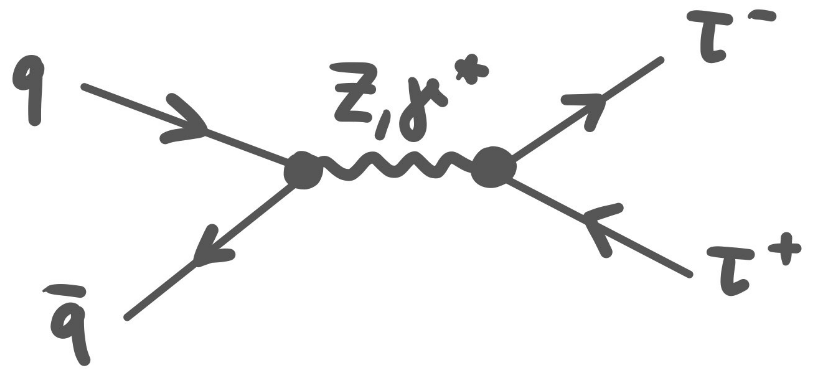
3.2 Drell-Yan production (DY): Going beyond the LQ LO

U_1

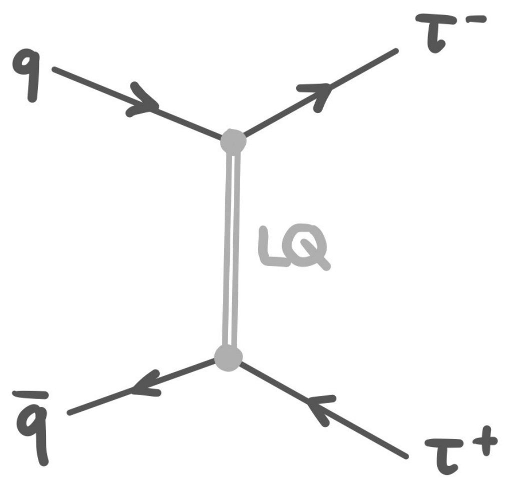
U_1

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): Going beyond the LQ LO



SM LO



LQ LO

3. High-energy searches at the LHC

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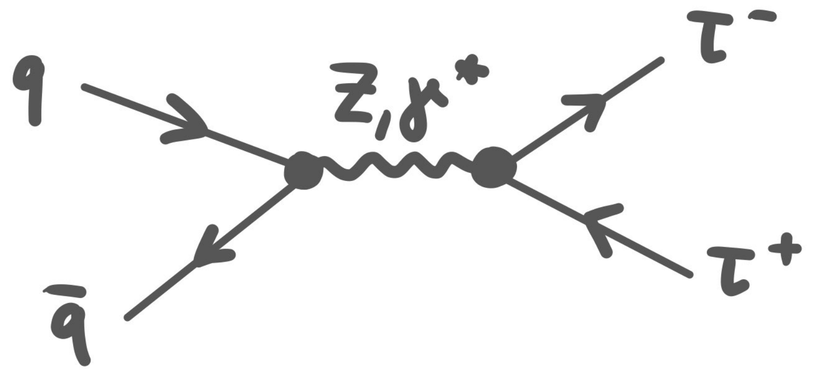
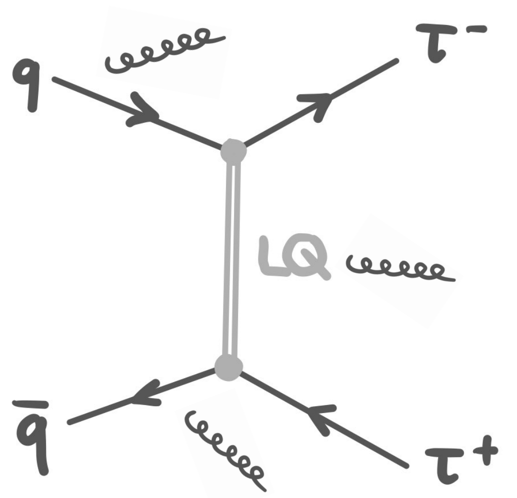


SM LO



LQ LO

U$_1$

3. High-energy searches at the LHC

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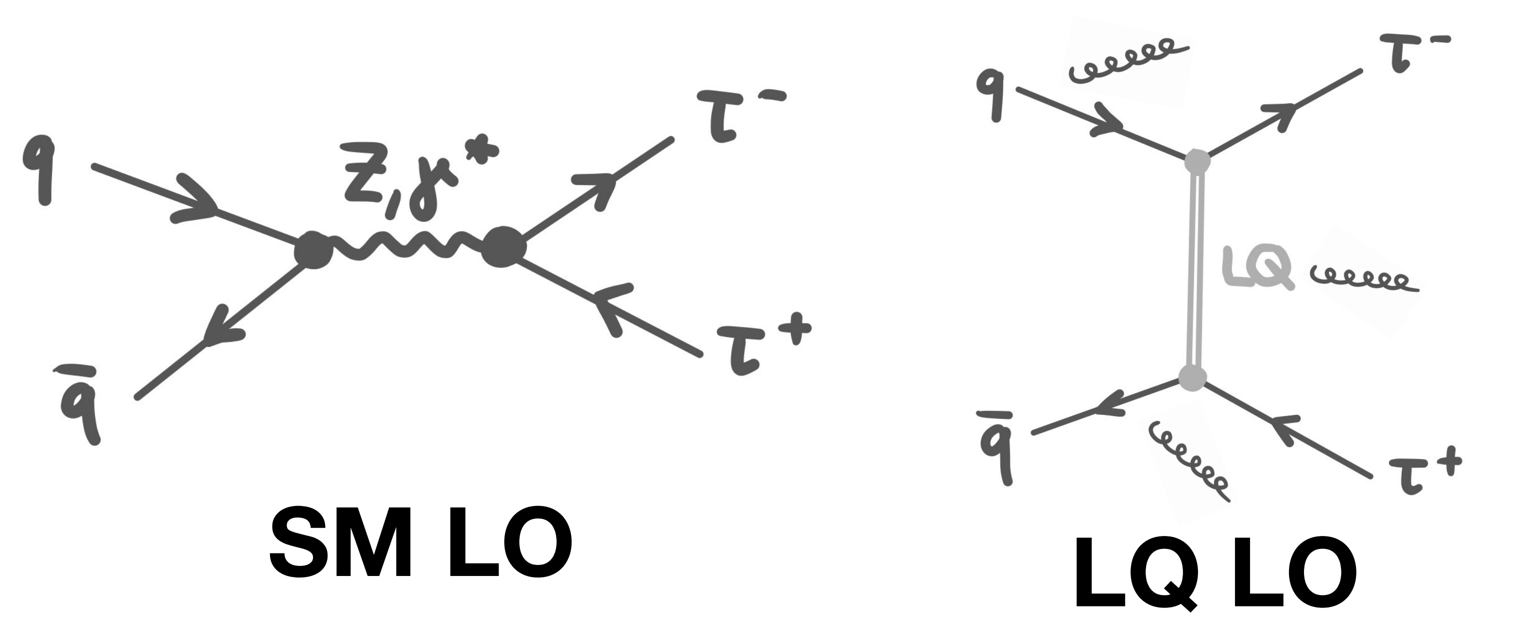
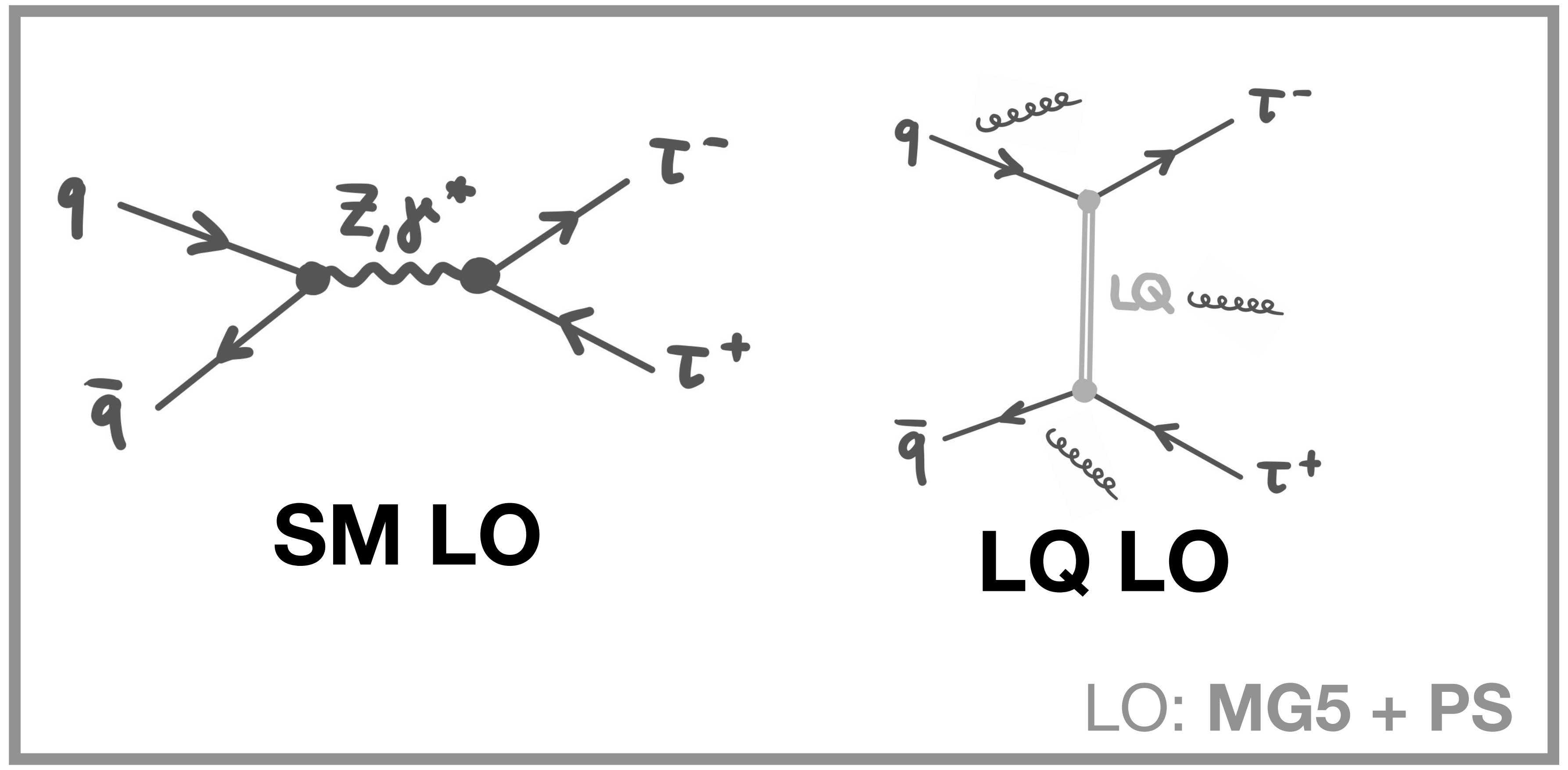


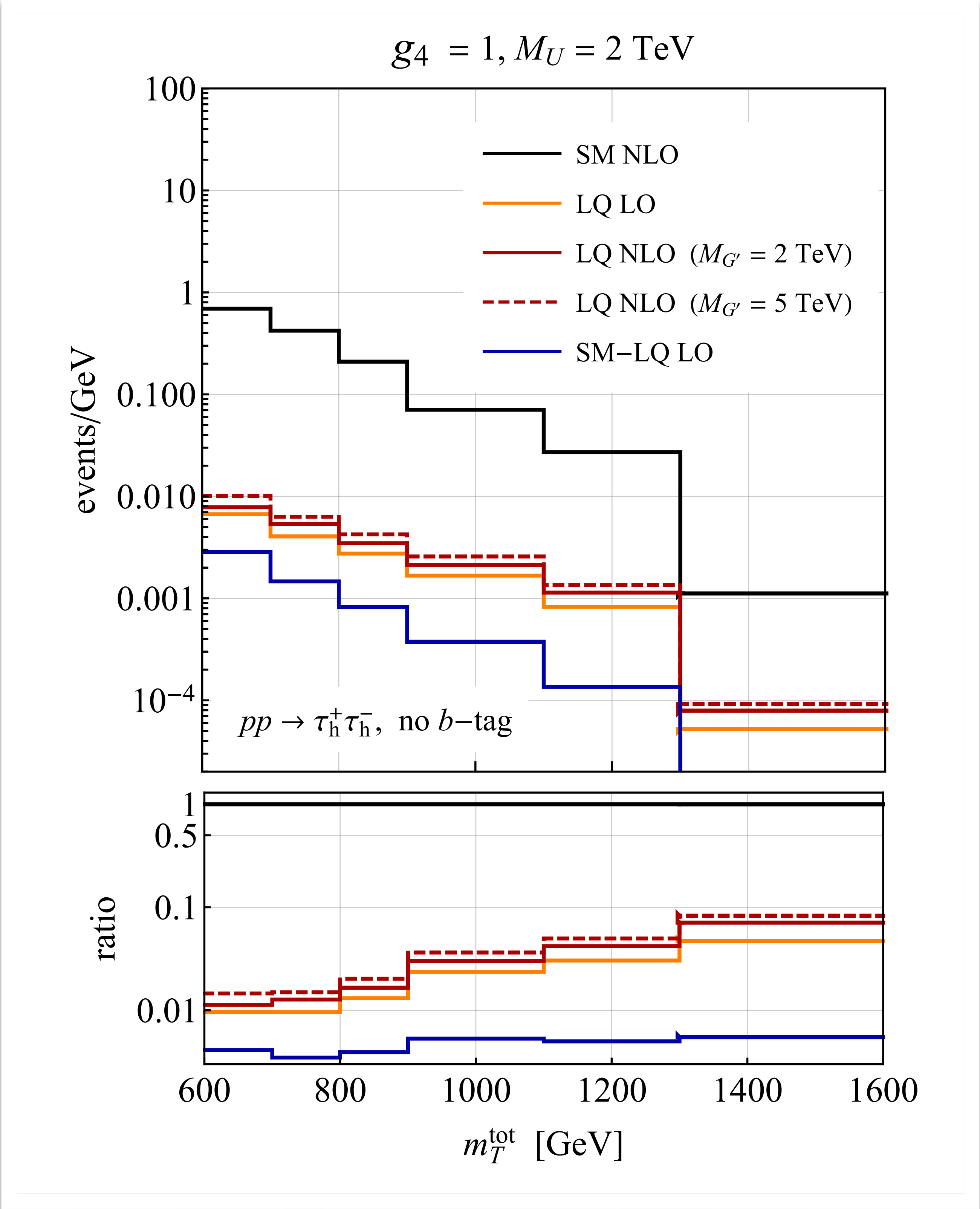
LO: **MG5 + PS**

U1

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): Going beyond the LQ LO



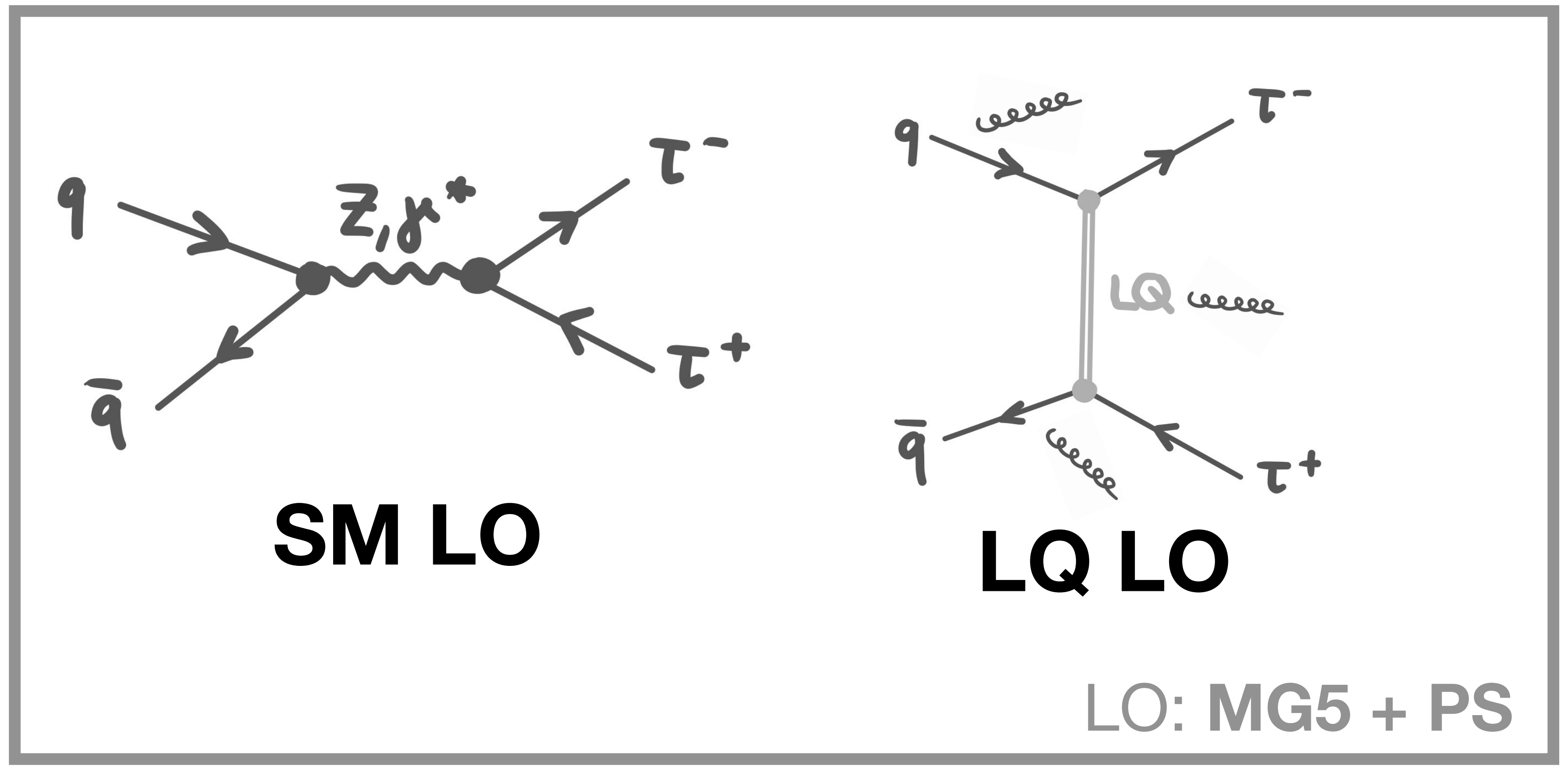


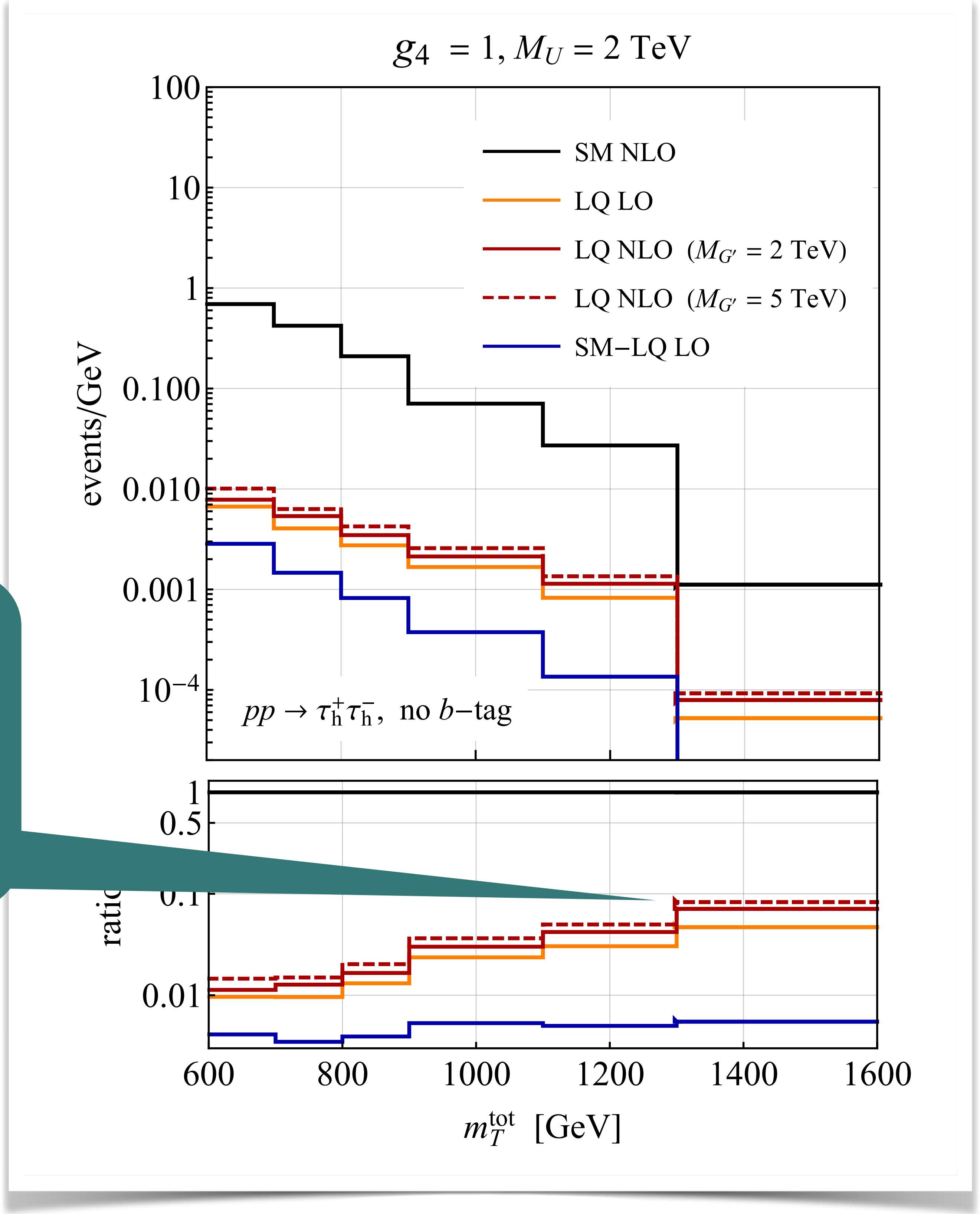
Source: ArXiv:2209.12780
(U. Haisch, LS, S. Schulte)

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): Going beyond the LQ LO

U$_1$





One can win over SM background in the tails

Source: ArXiv:2209.12780
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U_1

3. High-energy searches at the LHC

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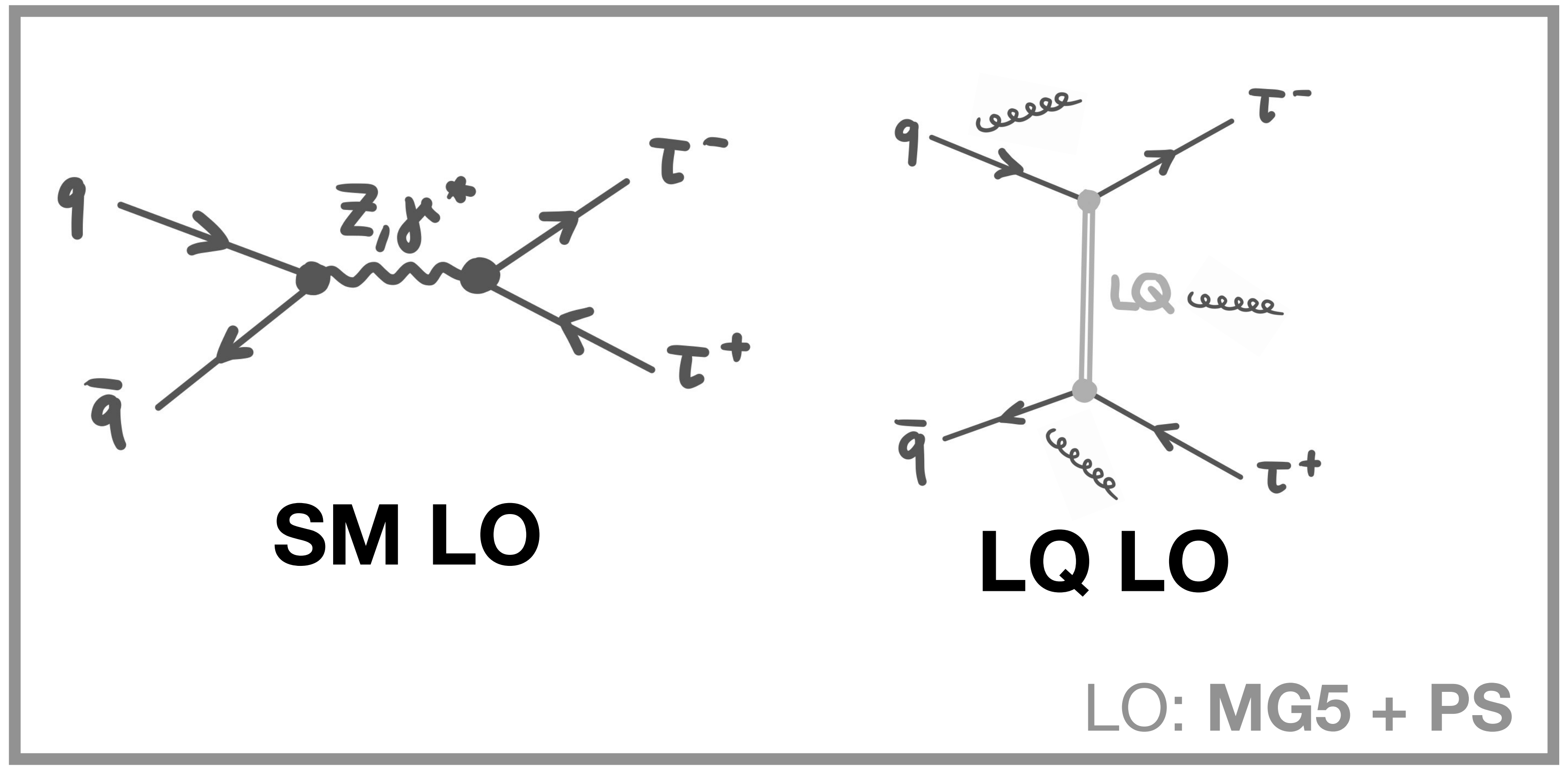
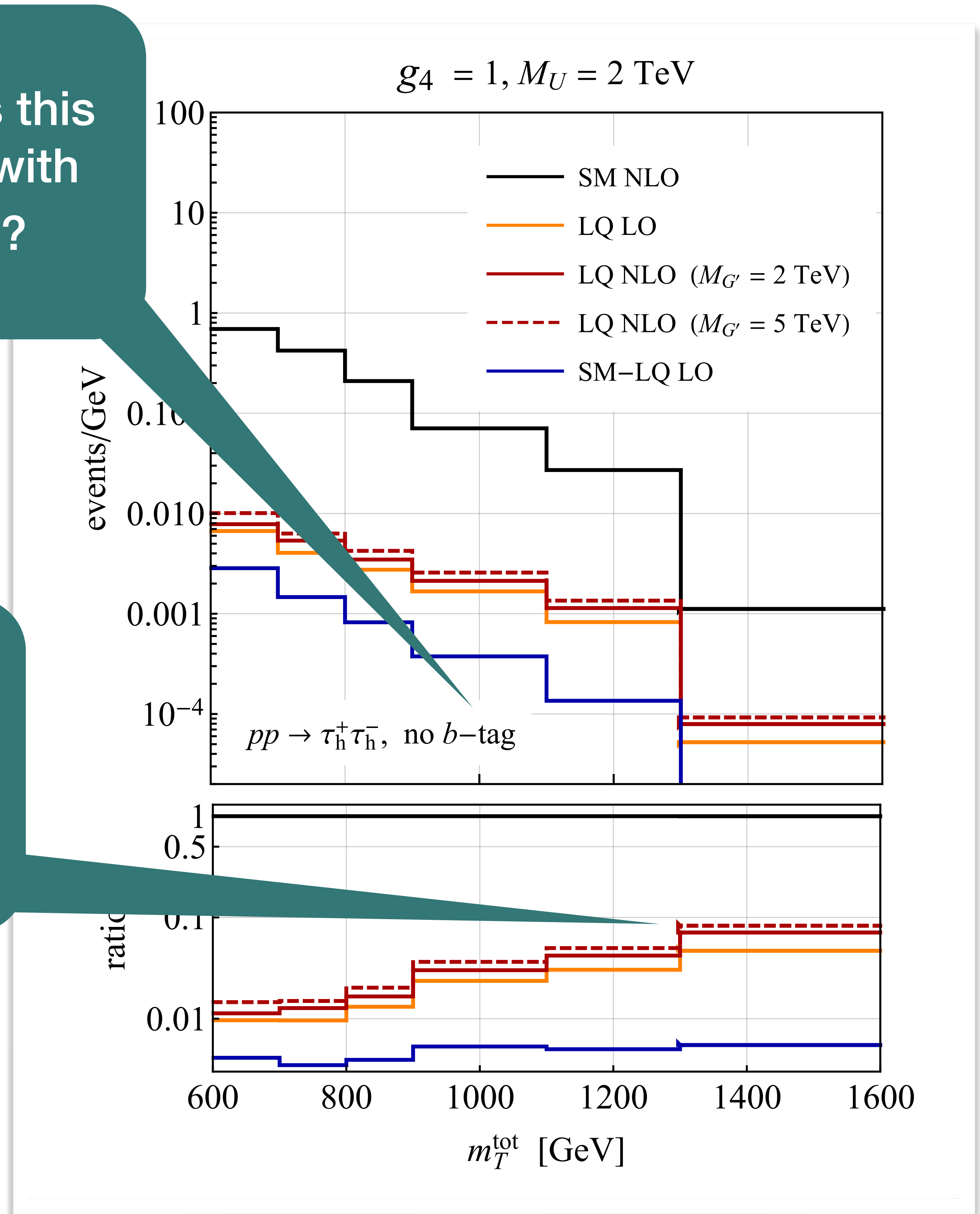


How does this improve with **b-tags?**



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U_1

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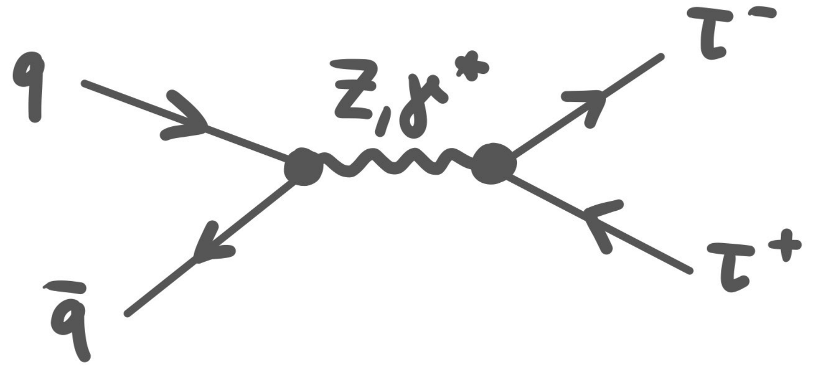
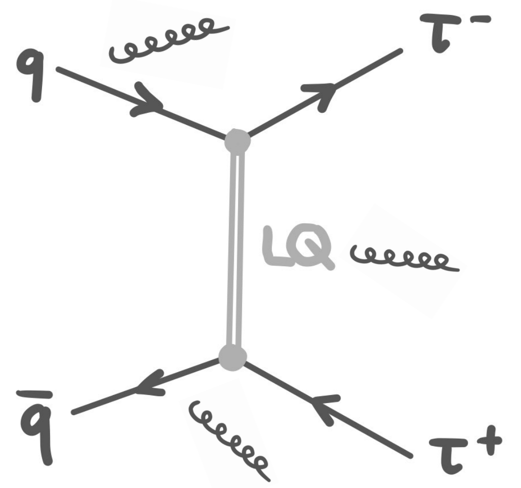
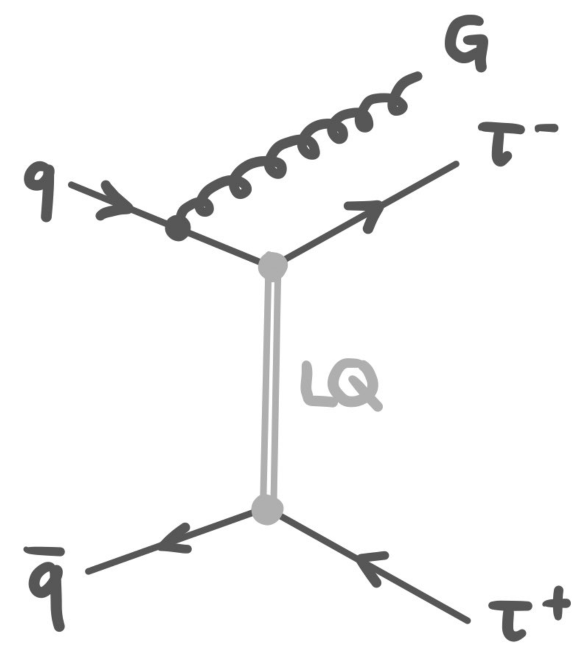


SM LO

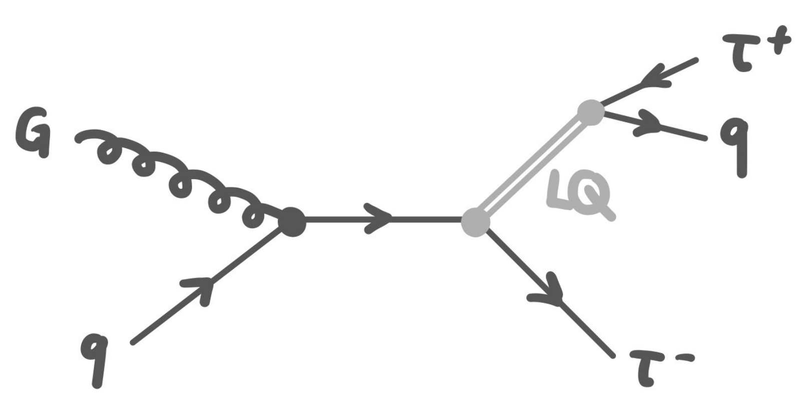


LQ LO

LO: **MG5 + PS**



LQ NLO real (non-res.)



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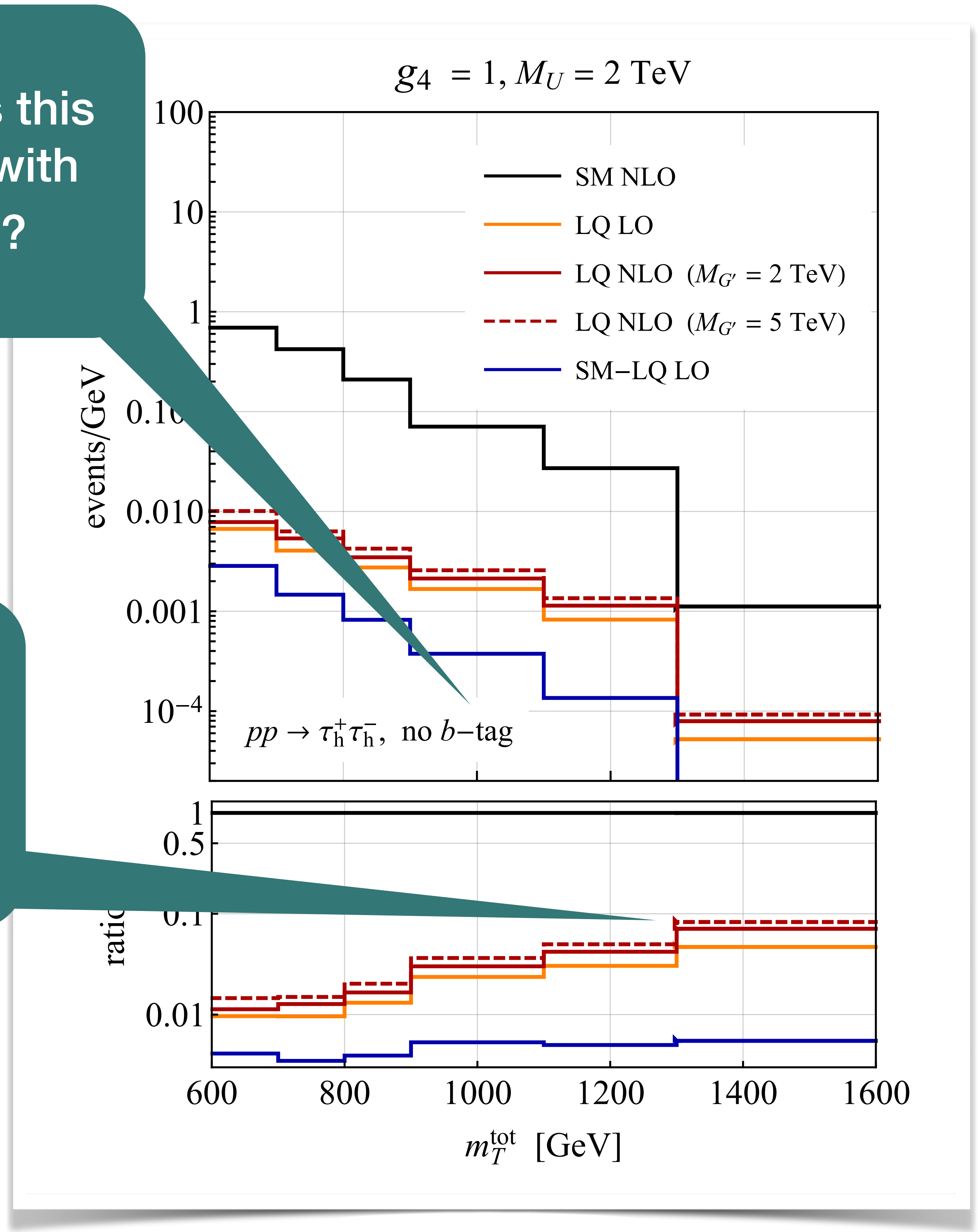

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3. High-energy searches at the LHC

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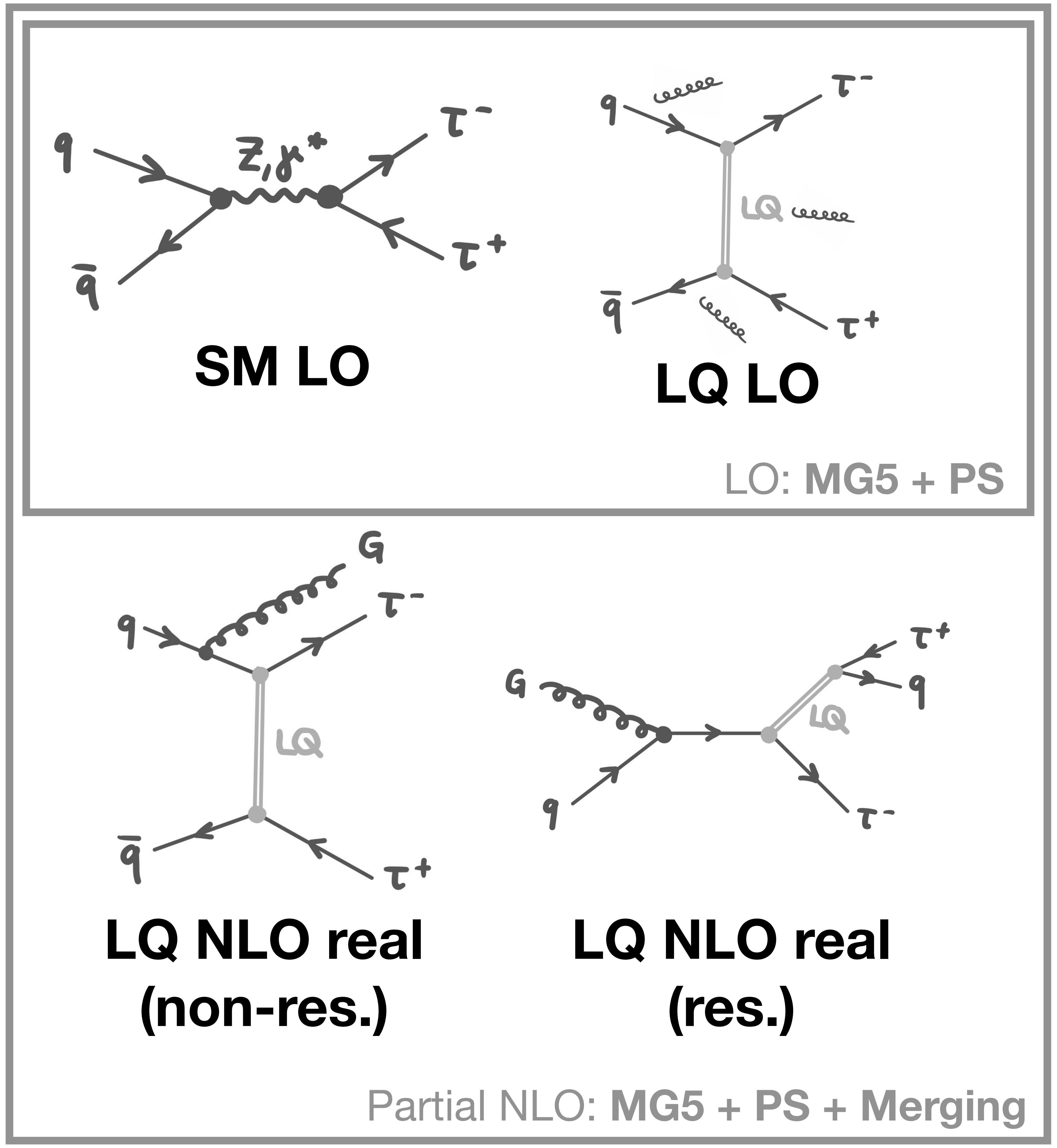

U$_1$

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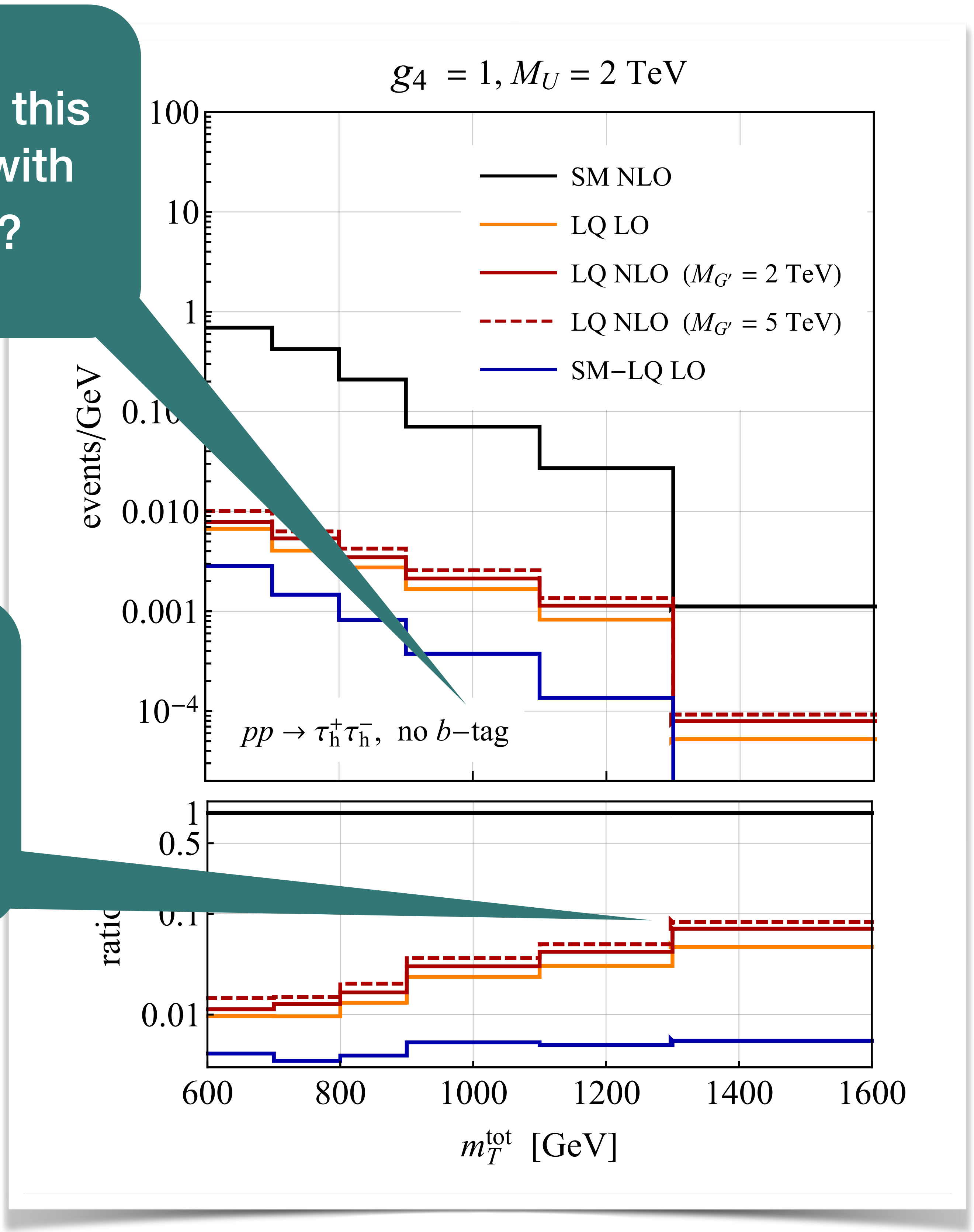

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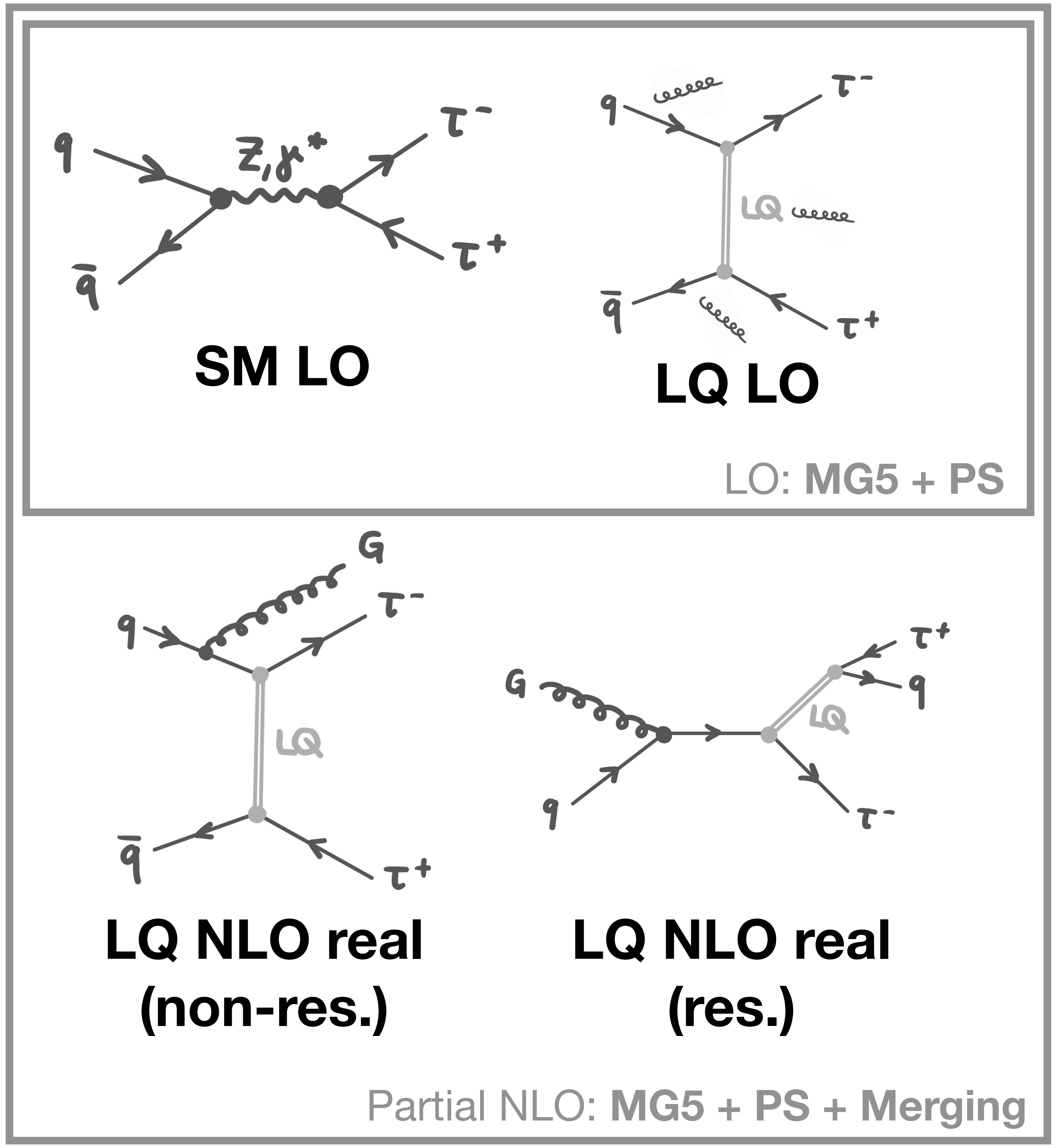
U_1



How does this improve with b-tags?

More accurate NP predictions for the tails

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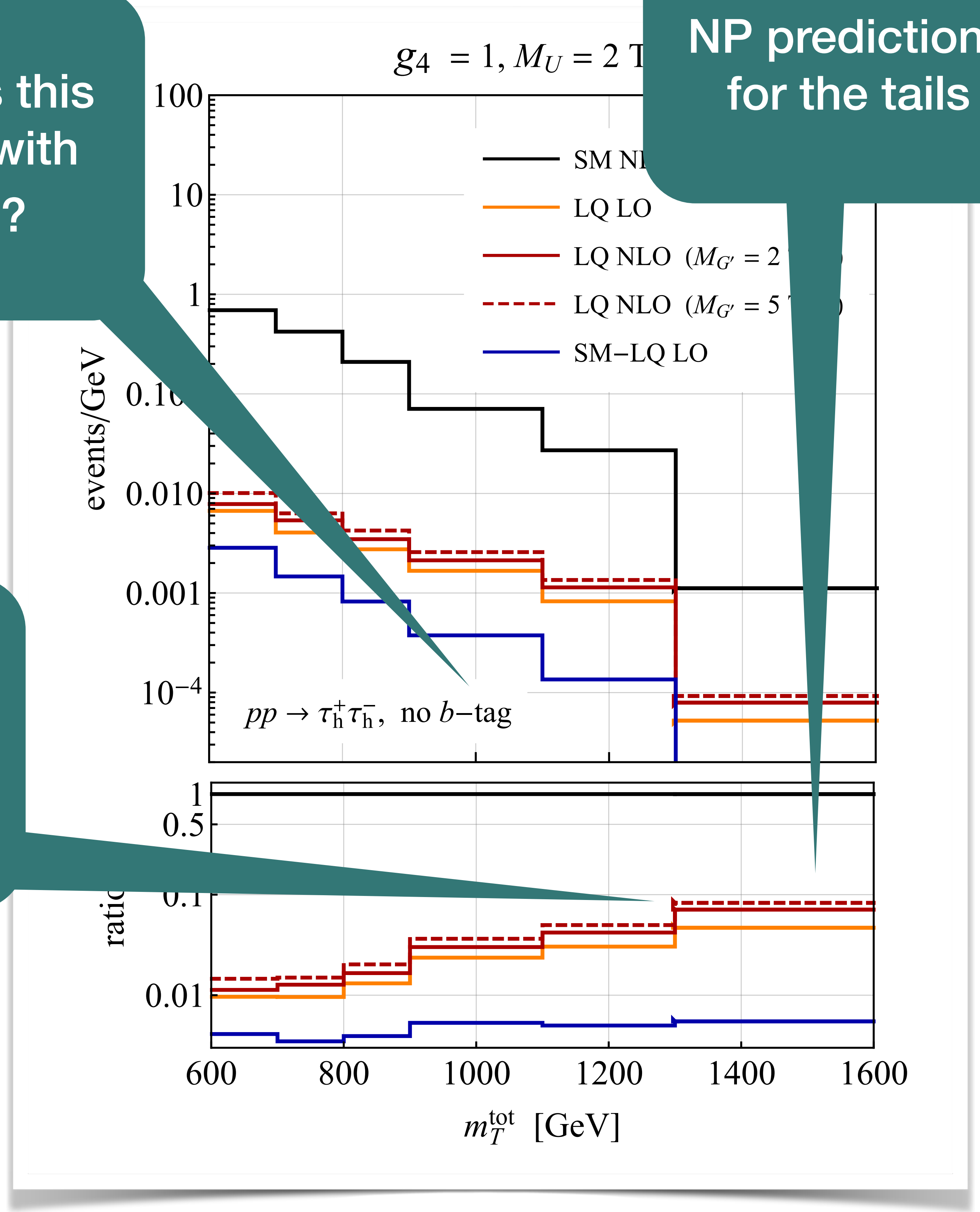

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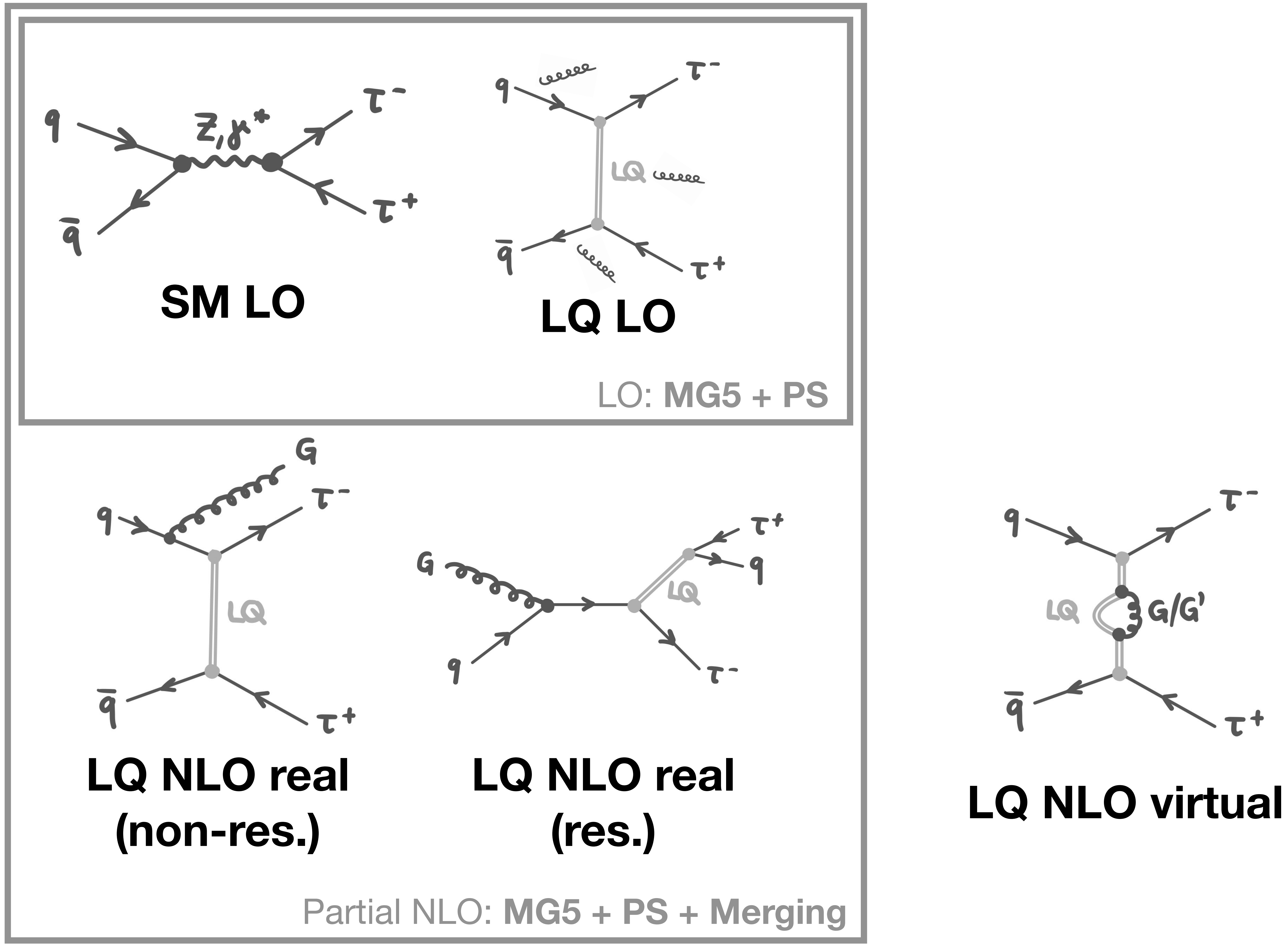
U_1



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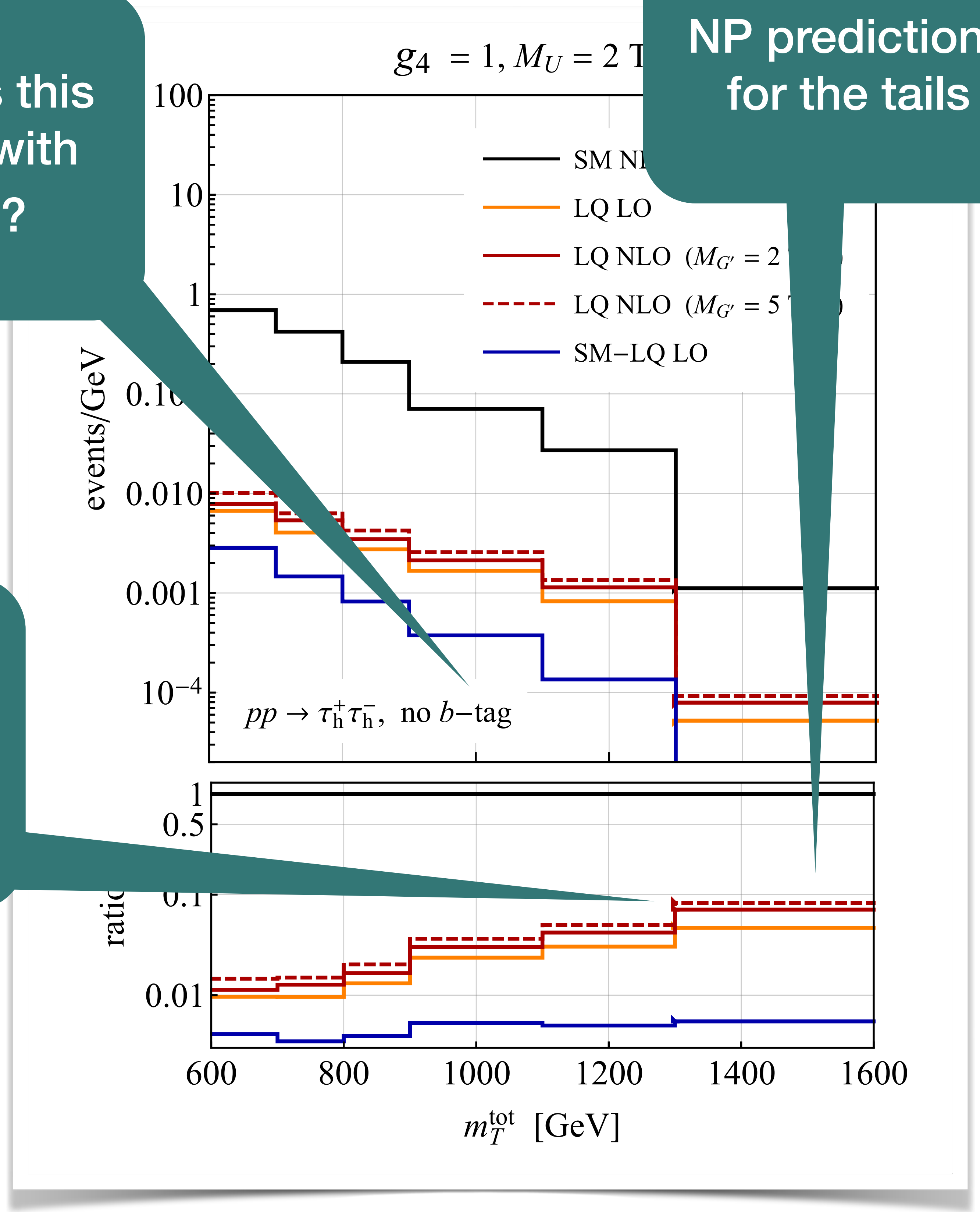

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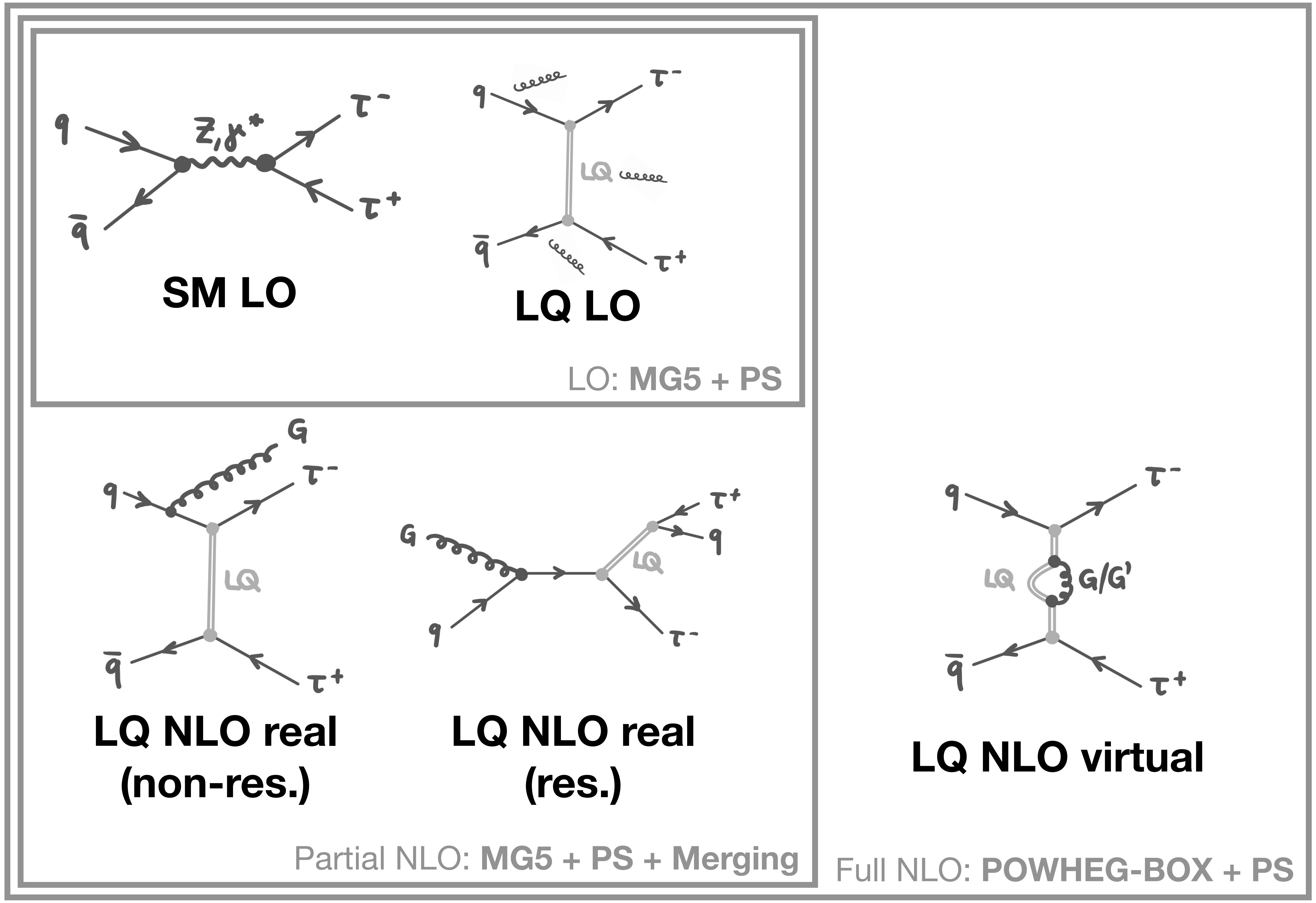

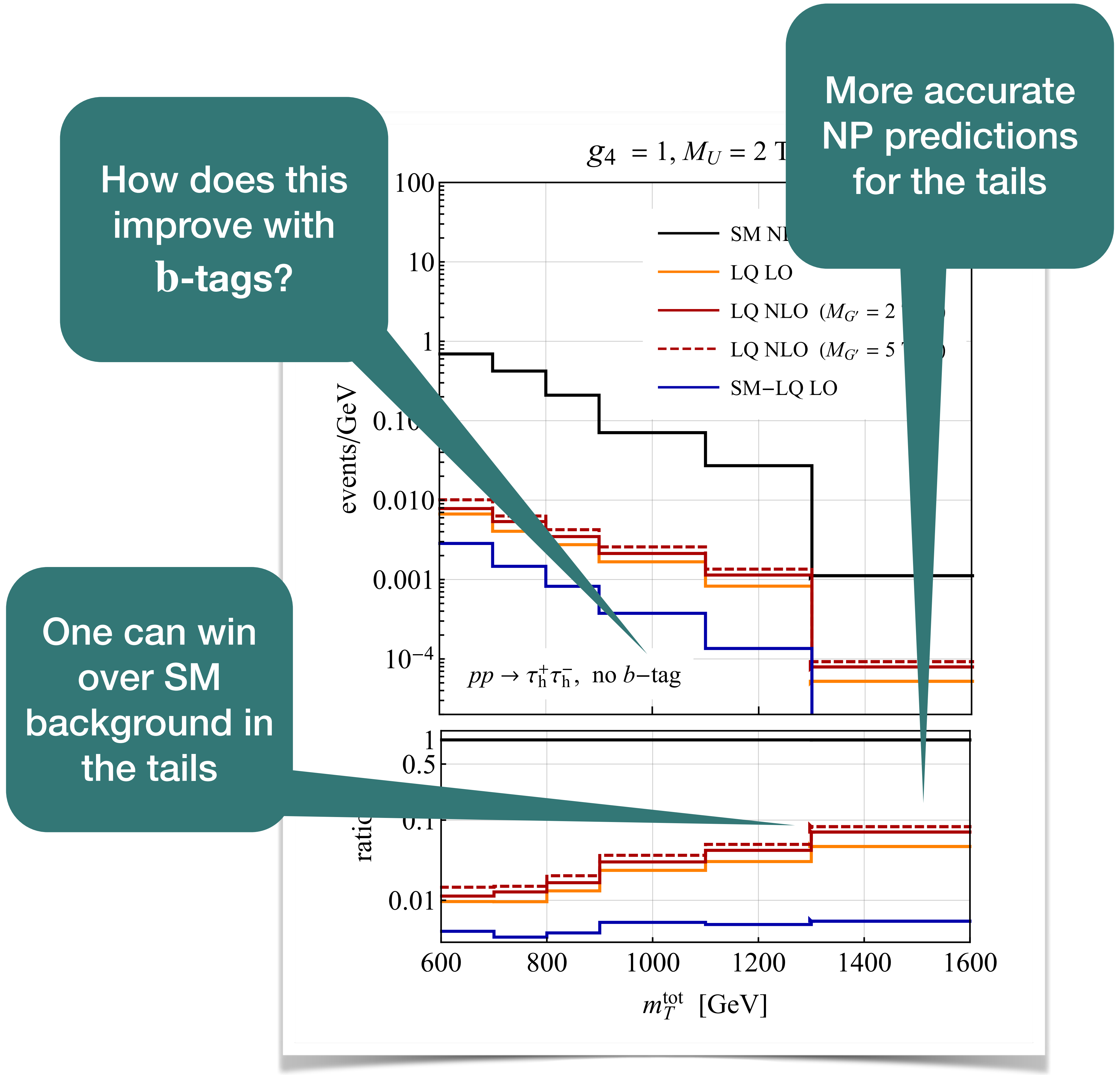

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3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): POWHEG-BOX implementation

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): POWHEG-BOX implementation

Input parameters

powheg.input
PhysPars.h
init_couplings.f

Flavour structure and phase space

Born_phsp.f
init_processes.f

Matrix elements

Born.f
real.f
virtual.f

3. High-energy searches at the LHC

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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'.

U_1

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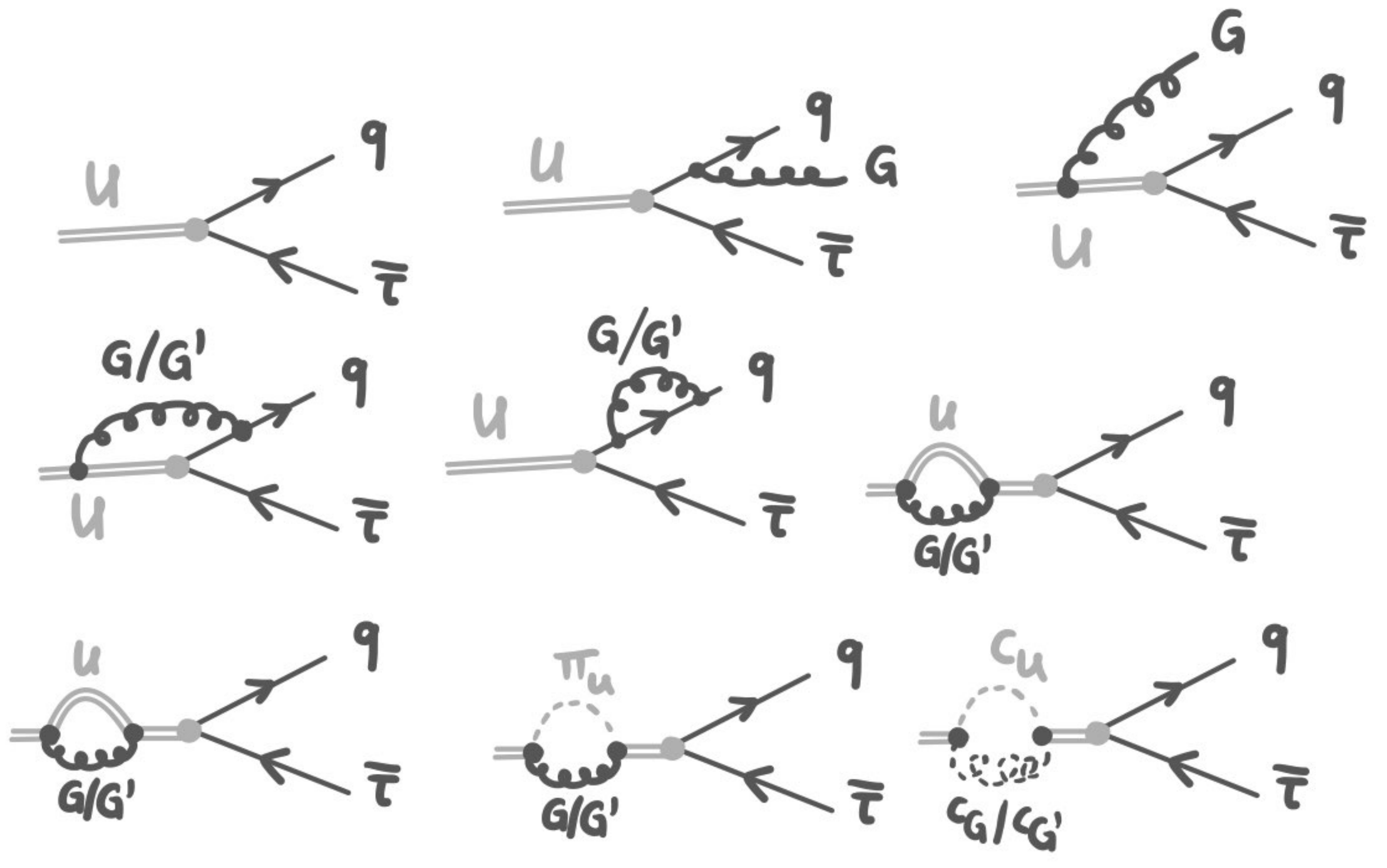
`MGp`	10000	**(Real)** Mass (in GeV) of the coloron G'.

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

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

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

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



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

U_1

3. High-energy searches at the LHC

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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

U_1

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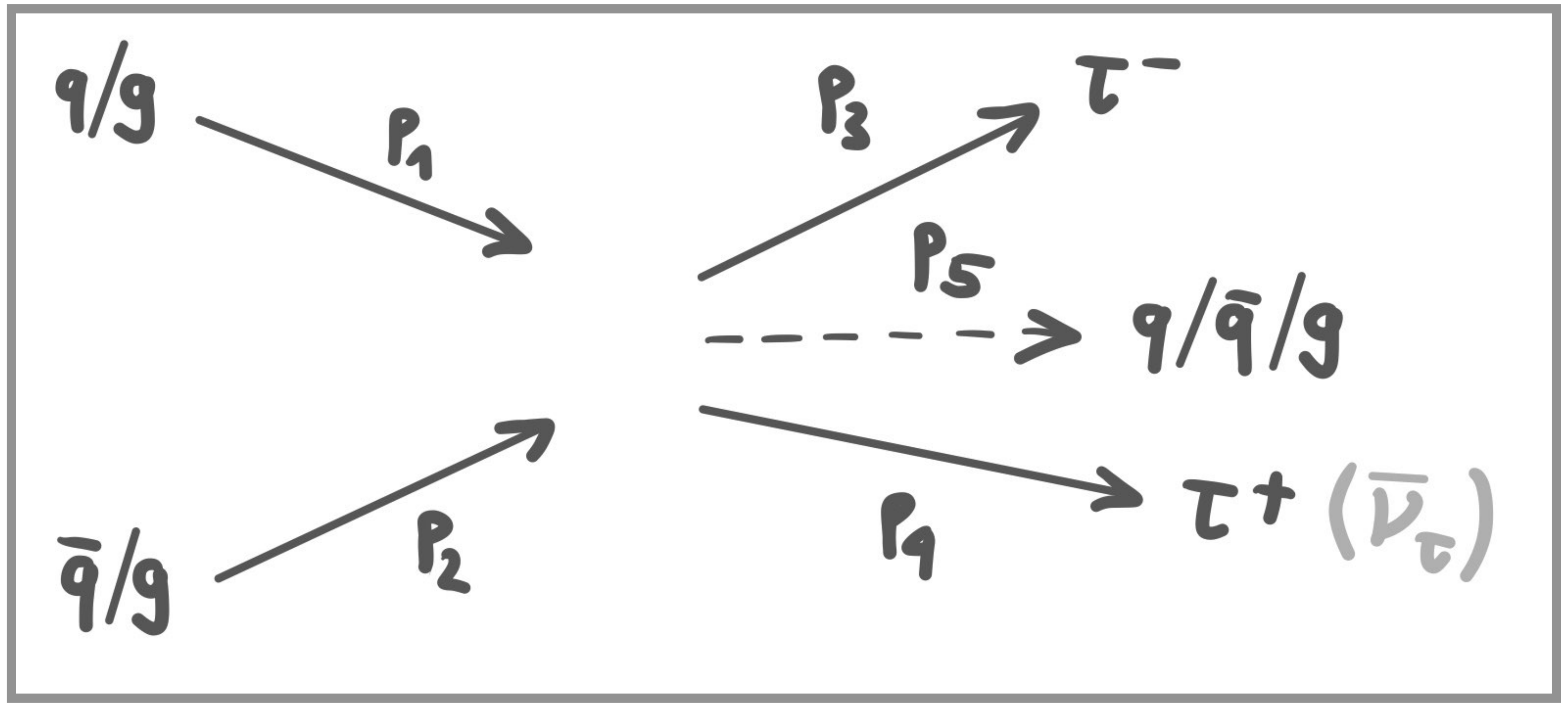
Input parameters	Flavour structure and phase space	Matrix elements
powheg.input PhysPars.h init_couplings.f	Born_phsp.f init_processes.f	Born.f real.f virtual.f

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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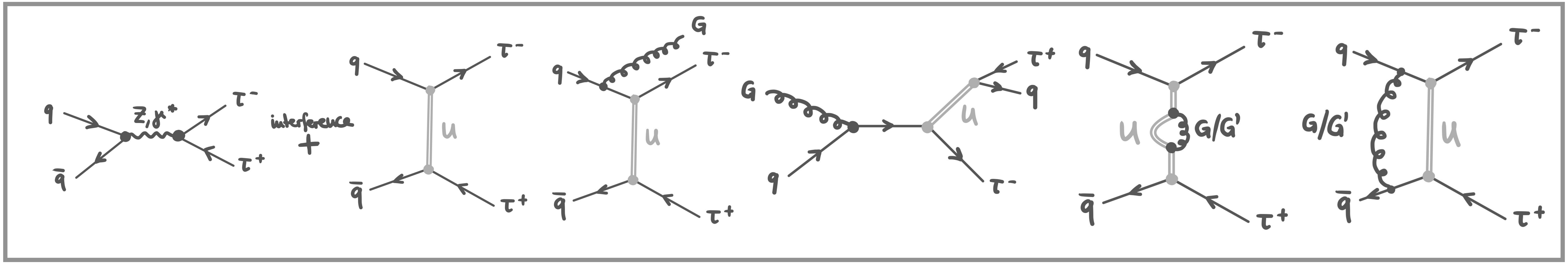

- Calculation with **PackageX**, cross-checked with **FormCalc**, numerical evaluation with **LoopTools.**
- **UV divergences cancel** between the G and G' contributions, IR divergences handled with **dimensional regularisation**.

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): POWHEG-BOX implementation

U_1

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): POWHEG-BOX implementation

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): POWHEG-BOX implementation

U_1

```
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.
c ==============================================

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)
```

Fortran code

3. High-energy searches at the LHC

3.2 Drell-Yan production (DY): POWHEG-BOX implementation

```
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.
c ==============================================

c ----------------------------------------------------------------------------
c LS: b-quark field strength renormalization
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c LS: This agrees with the result in ArXiv:2006.16250
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- Our $\mathbf{U_1}$ code is available on **GitLab** (https://gitlab.com/lucschnell/Drell-Yan-LQ-NLO) and soon on the **POWHEG-BOX website**.

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- It can be used to **generate events** (.lhe and .hepmc) for dedicated MC studies.

$\mathbf{U_1}$

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Fortran code

- Our $\mathbf{U_1}$ code is available on **GitLab** (https://gitlab.com/lucschnell/Drell-Yan-LQ-NLO) and soon on the **POWHEG-BOX website**.
- 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.

3. High-energy searches at the LHC

3.3 Drell-Yan production (DY): Phenomenology

U_1

3. High-energy searches at the LHC

3.3 Drell-Yan production (DY): Phenomenology

U_1

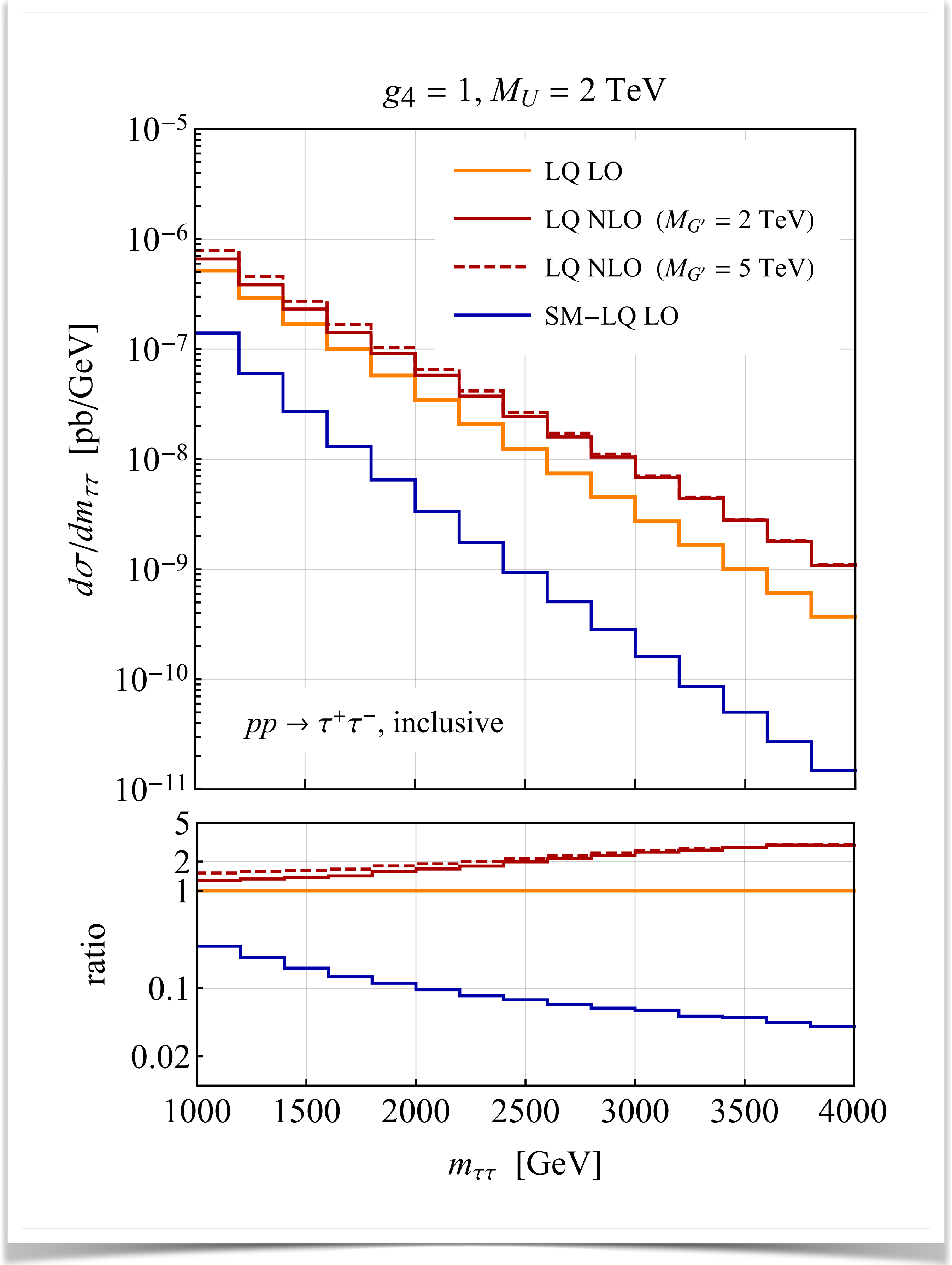
Inclusive $m_{\tau\tau}$ spectra:

3. High-energy searches at the LHC

3.3 Drell-Yan production (DY): Phenomenology

U_1

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



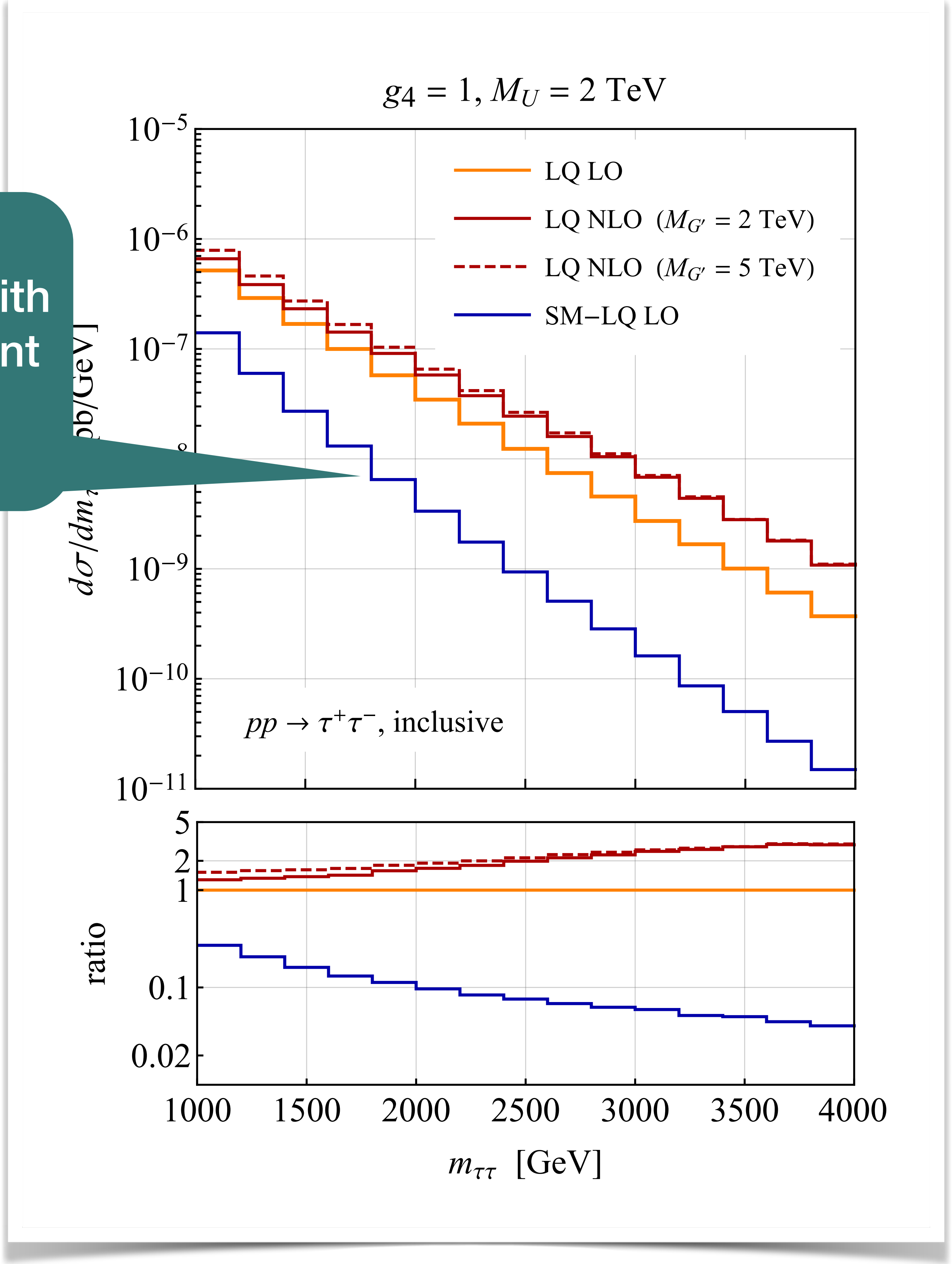
Source: ArXiv:2209.12780 (U. Haisch, LS, S. Schulte)

3. High-energy searches at the LHC

3.3 Drell-Yan production (DY): Phenomenology

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

Interference with SM not relevant in the tails.



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U_1

3. High-energy searches at the LHC

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U_1

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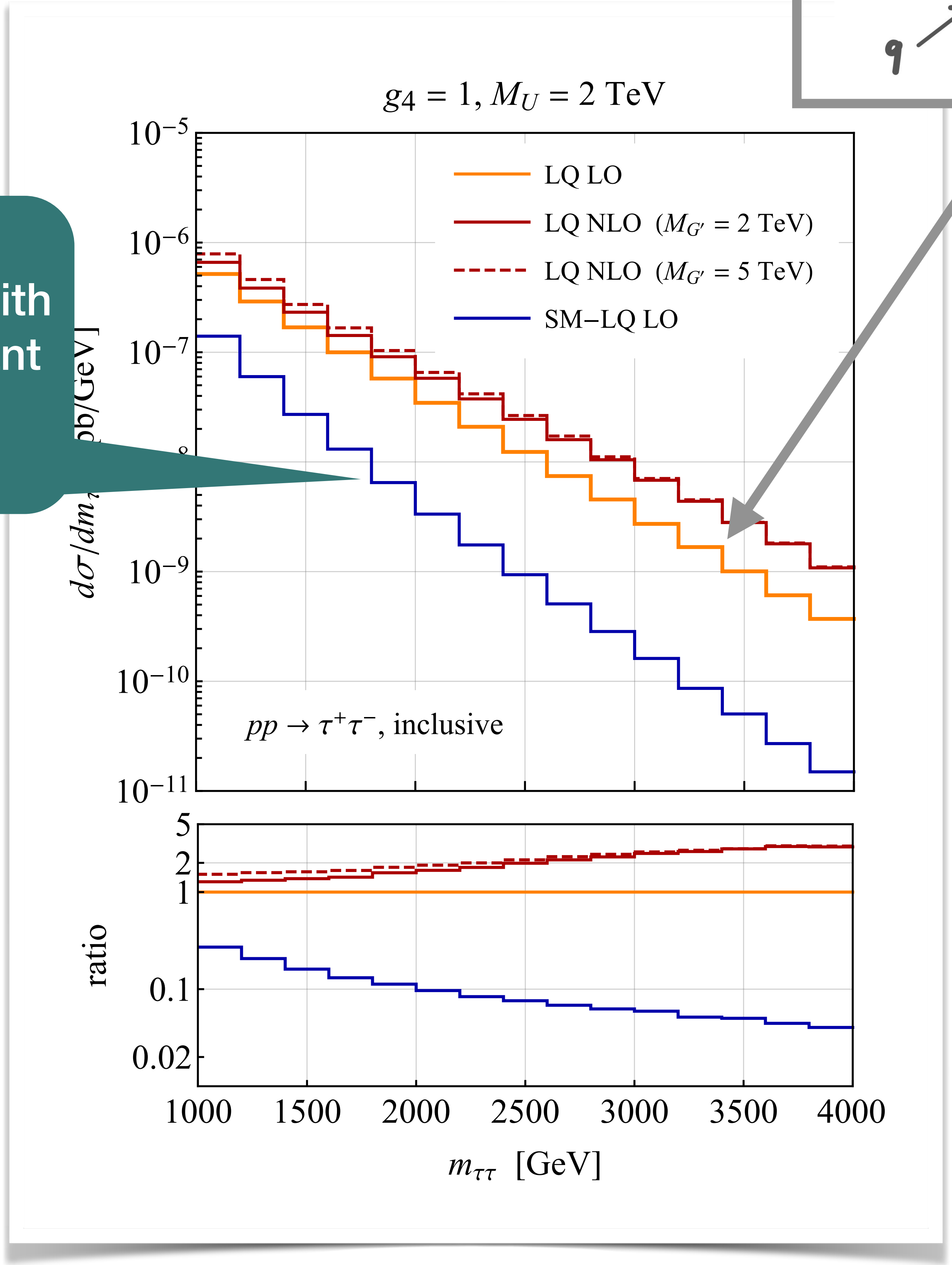

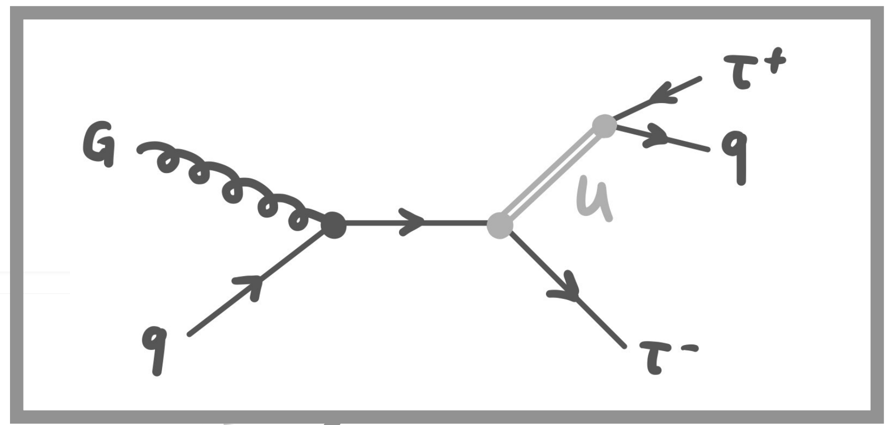

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U_1

3. High-energy searches at the LHC

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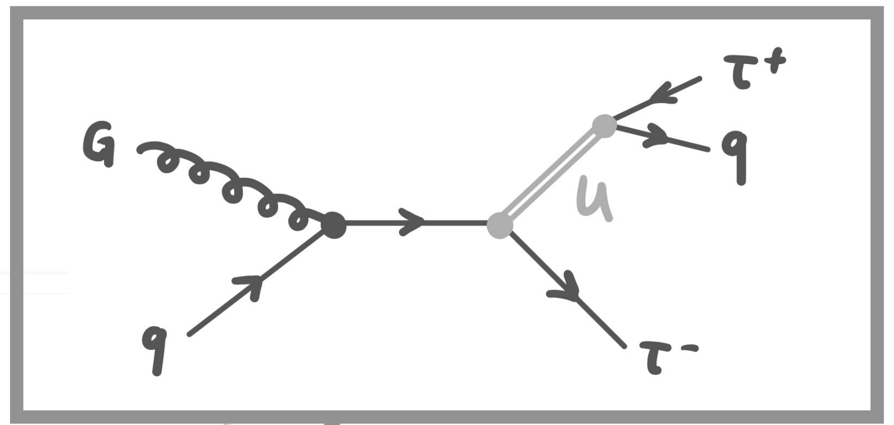
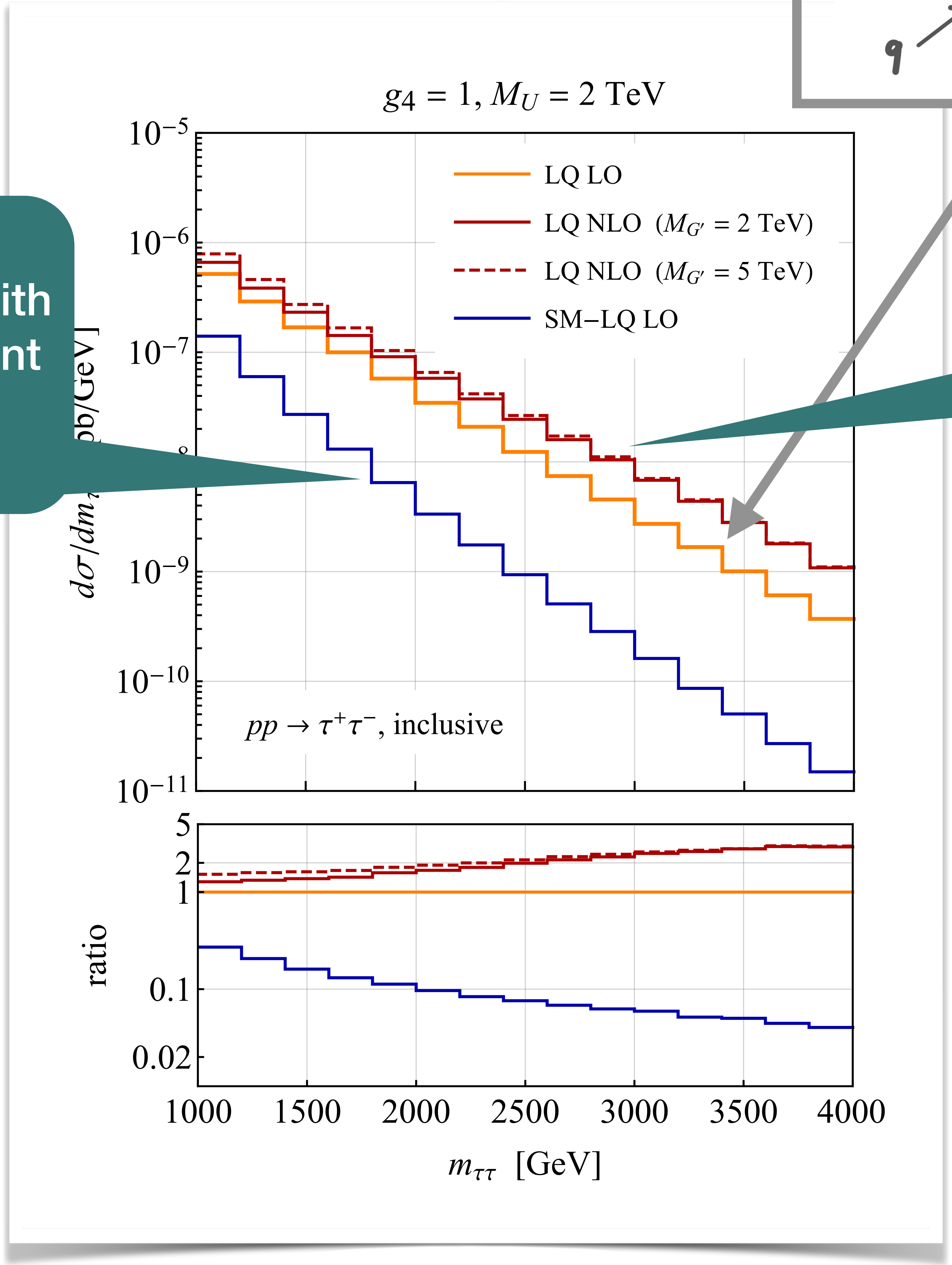


Interference with SM not relevant in the tails.

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



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3. High-energy searches at the LHC

3.3 Drell-Yan production (DY): Phenomenology

U_1

3. High-energy searches at the LHC

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b-tag/b-veto:

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

3. High-energy searches at the LHC

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U$_1$

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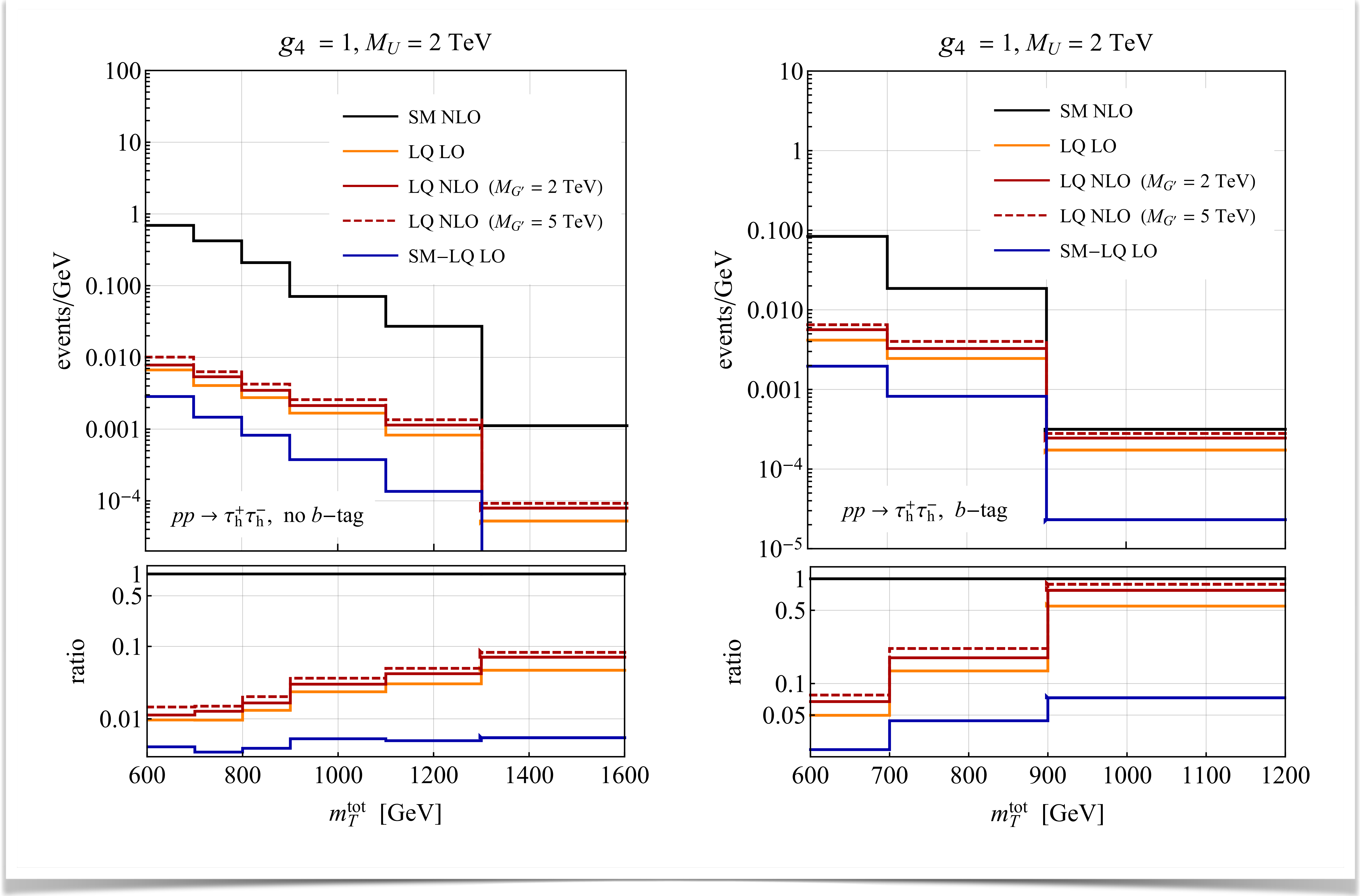

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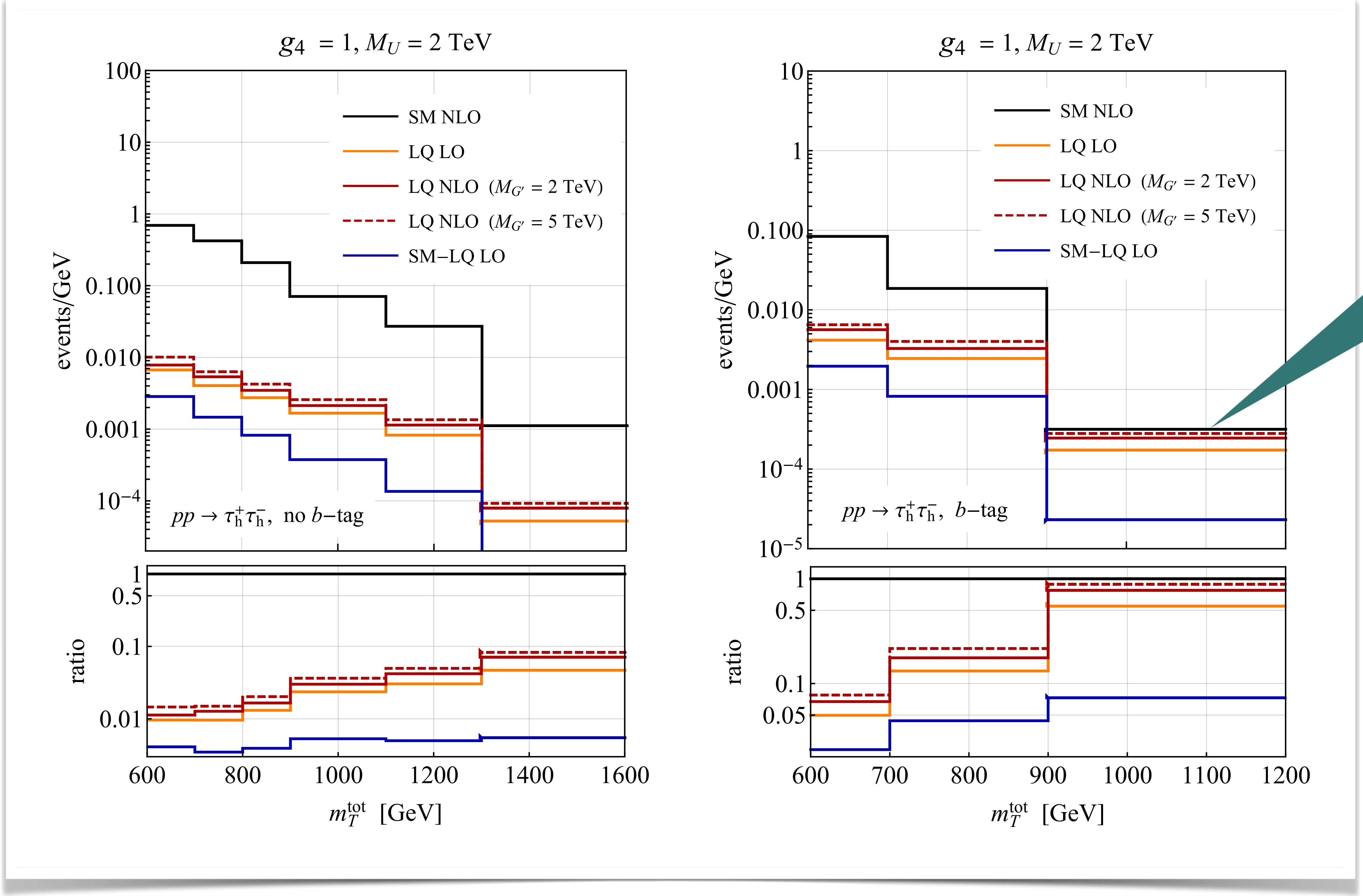

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Signal-to-background ratio is greatly enhanced with b-tags

3. High-energy searches at the LHC

3.3 Drell-Yan production (DY): Phenomenology

U_1

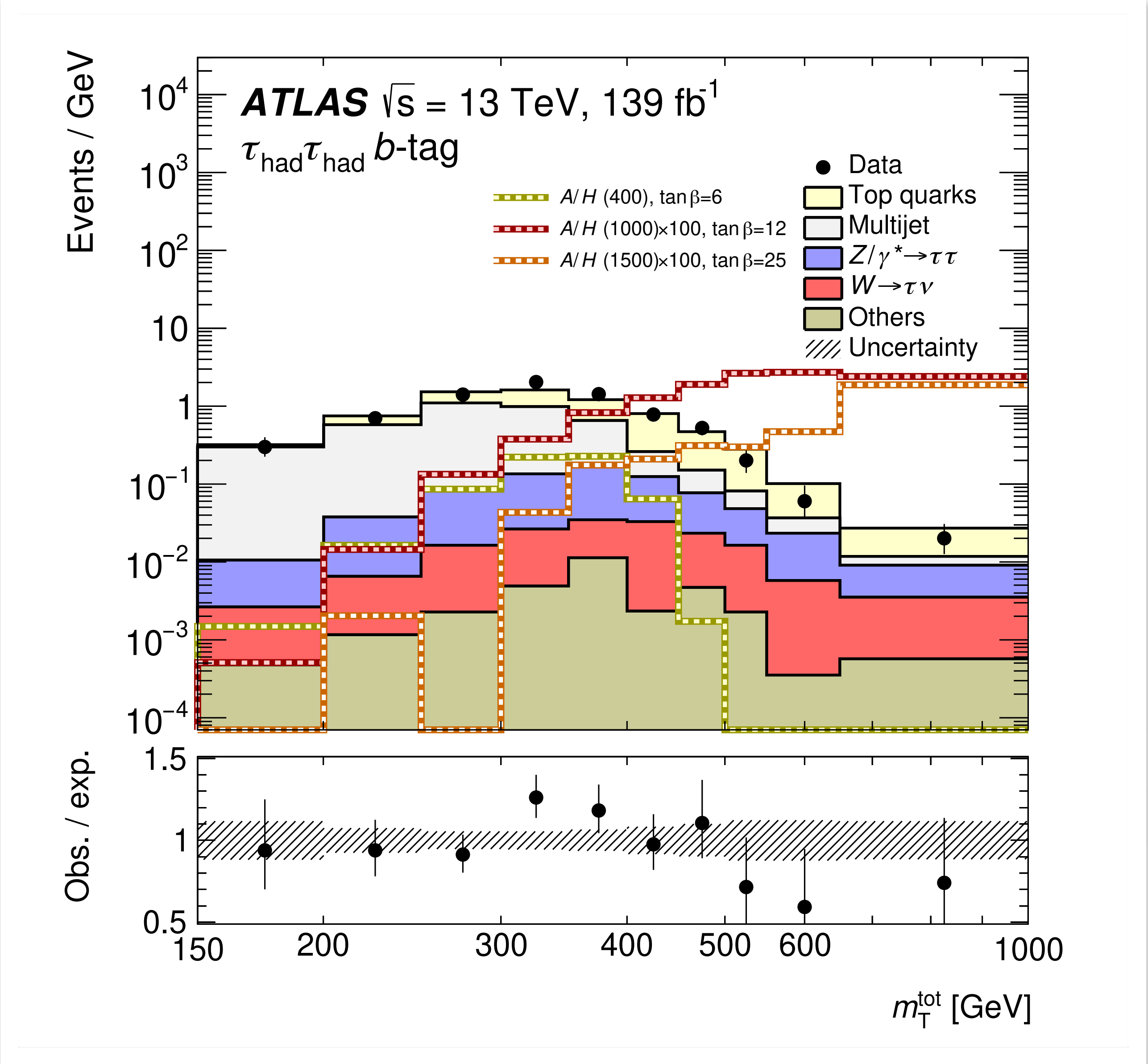
U_1

3. High-energy searches at the LHC

3.3 Drell-Yan production (DY): Phenomenology

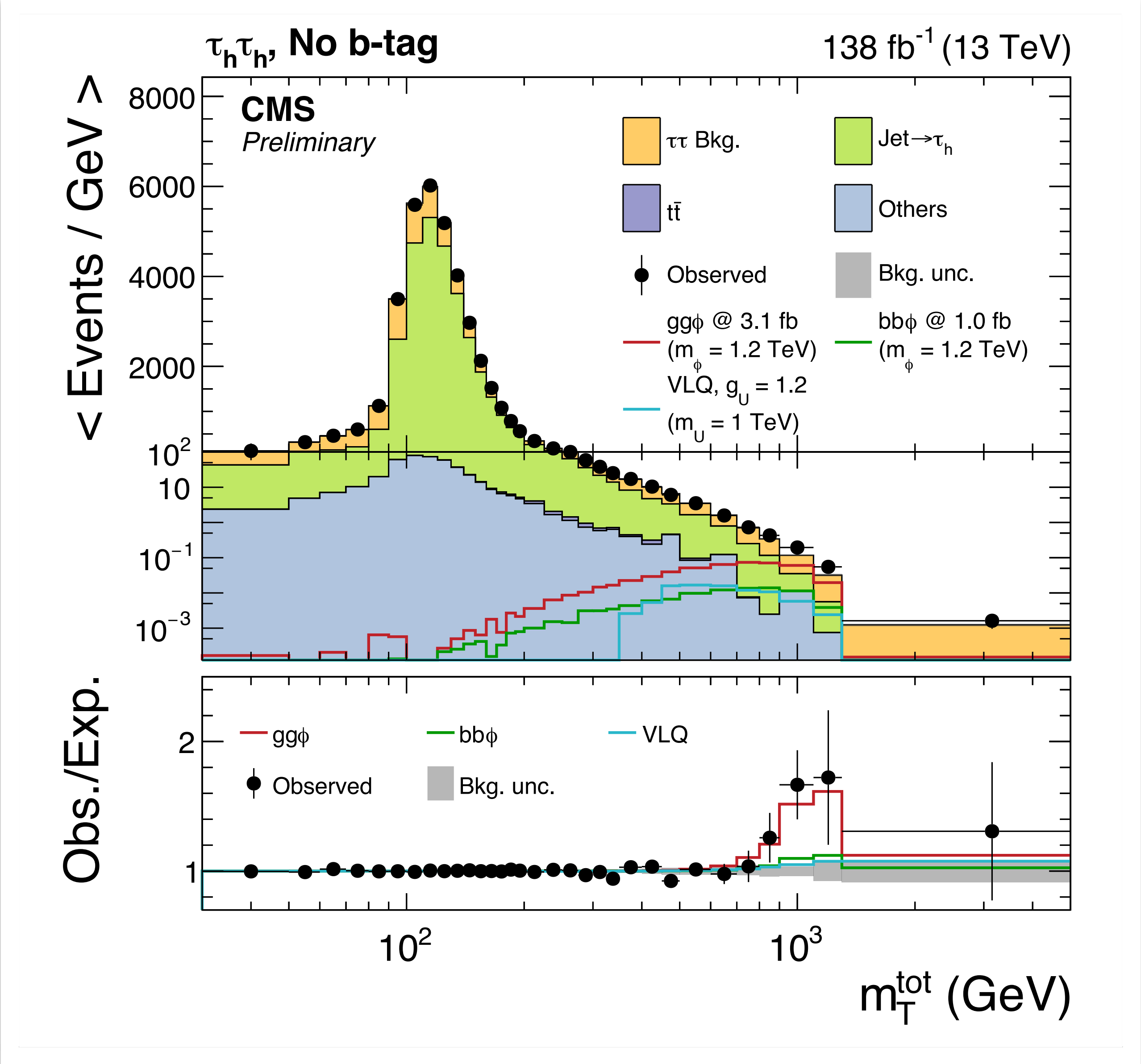
Exclusion limits:

ATLAS 2020



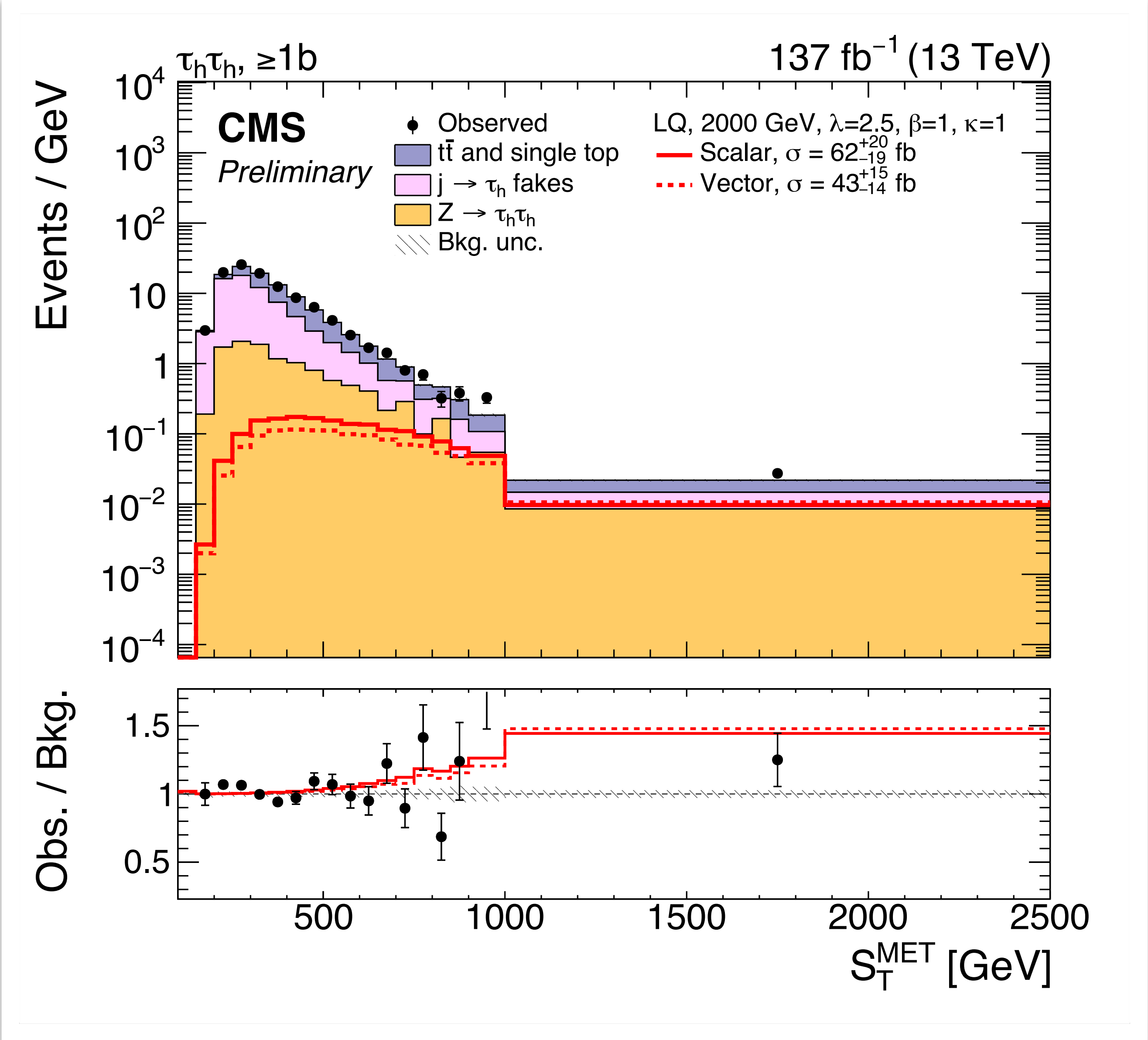
Source: ArXiv:2002.12223 (ATLAS)

CMS 2021



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

CMS 2022



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

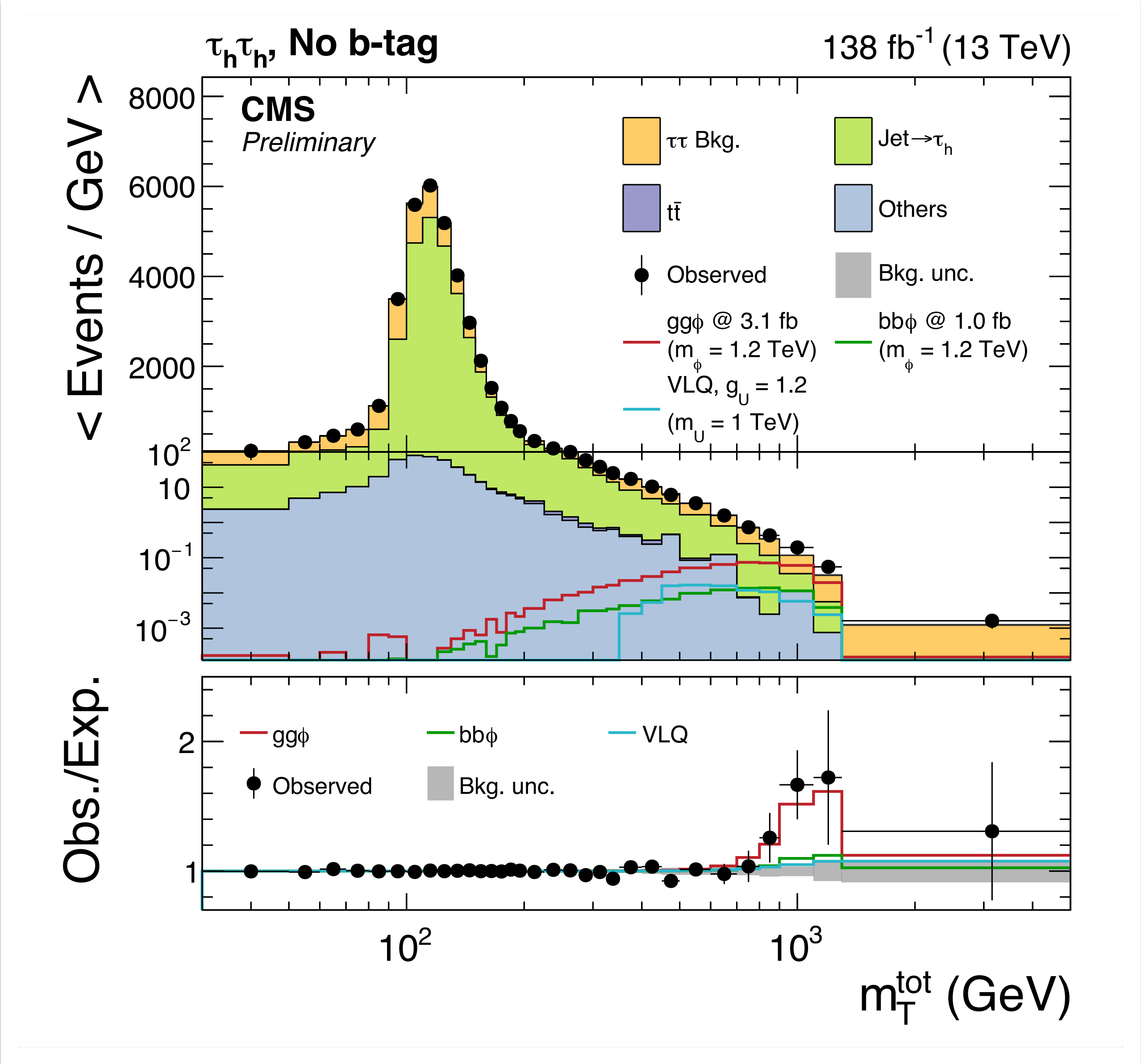
U_1

3. High-energy searches at the LHC

3.3 Drell-Yan production (DY): Phenomenology

Exclusion limits:

ATLAS 2020 **CMS 2021** **CMS 2022**



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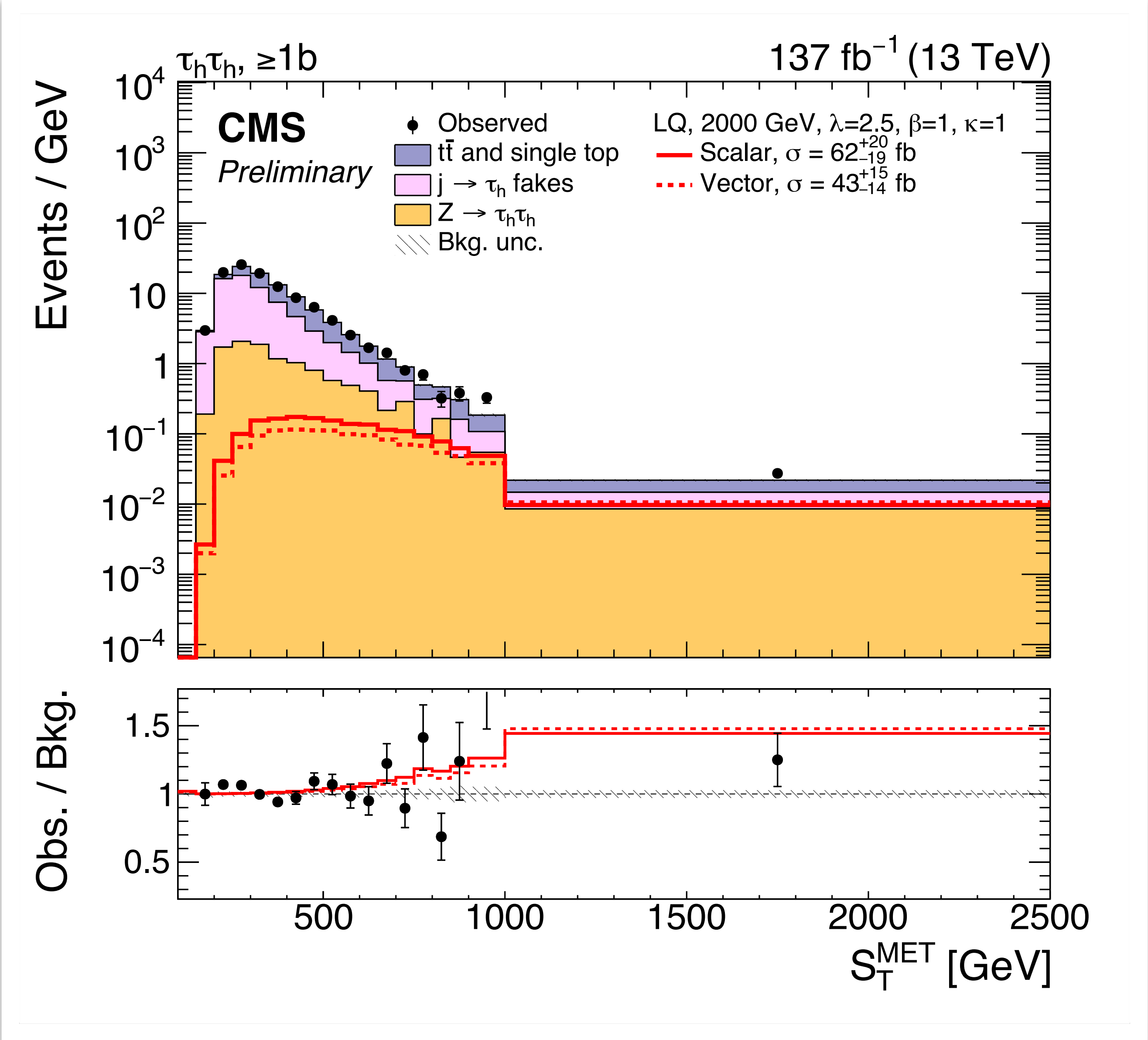

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U$_1$

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3.3 Drell-Yan production (DY): Phenomenology

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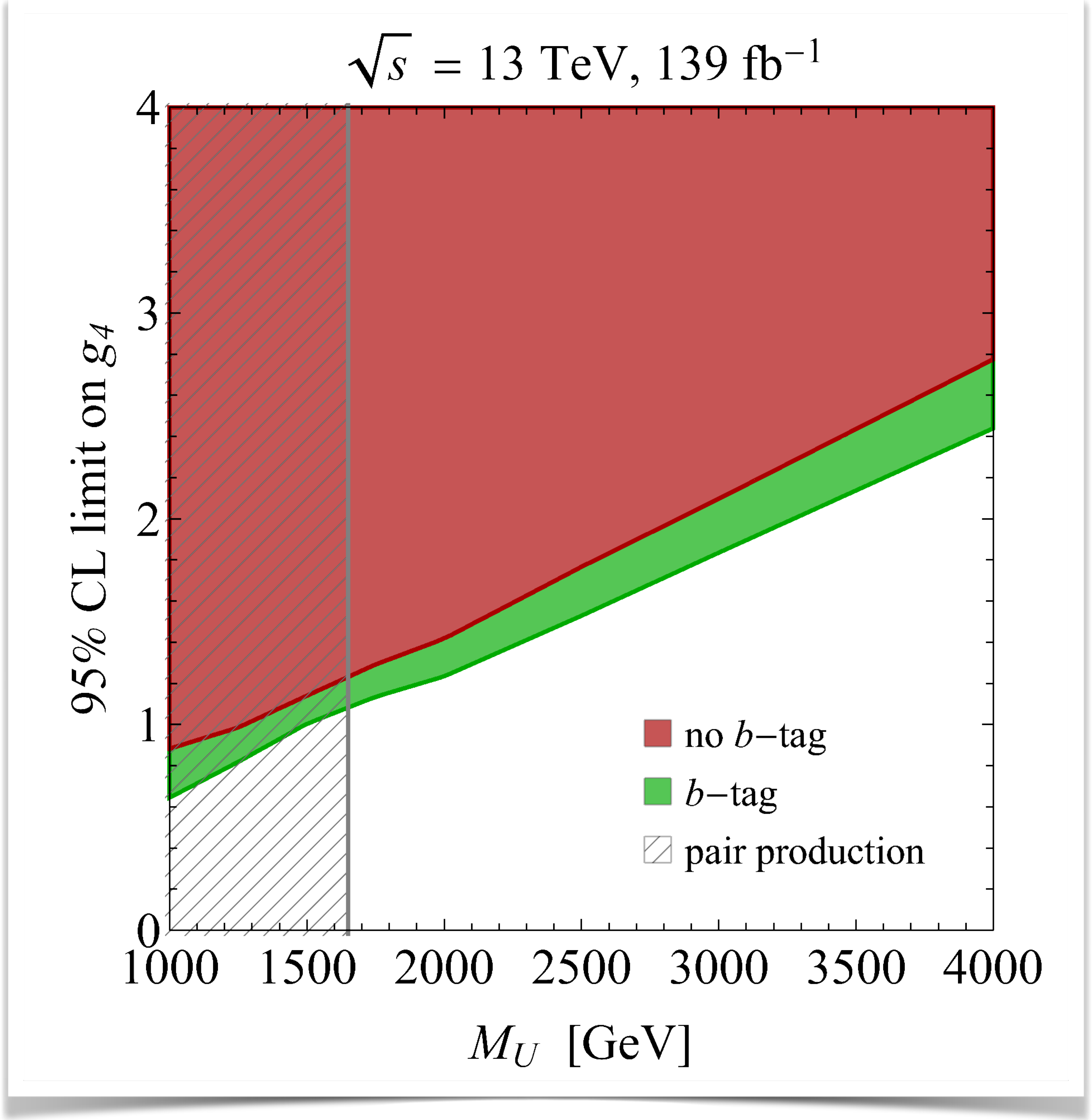
ATLAS 2020



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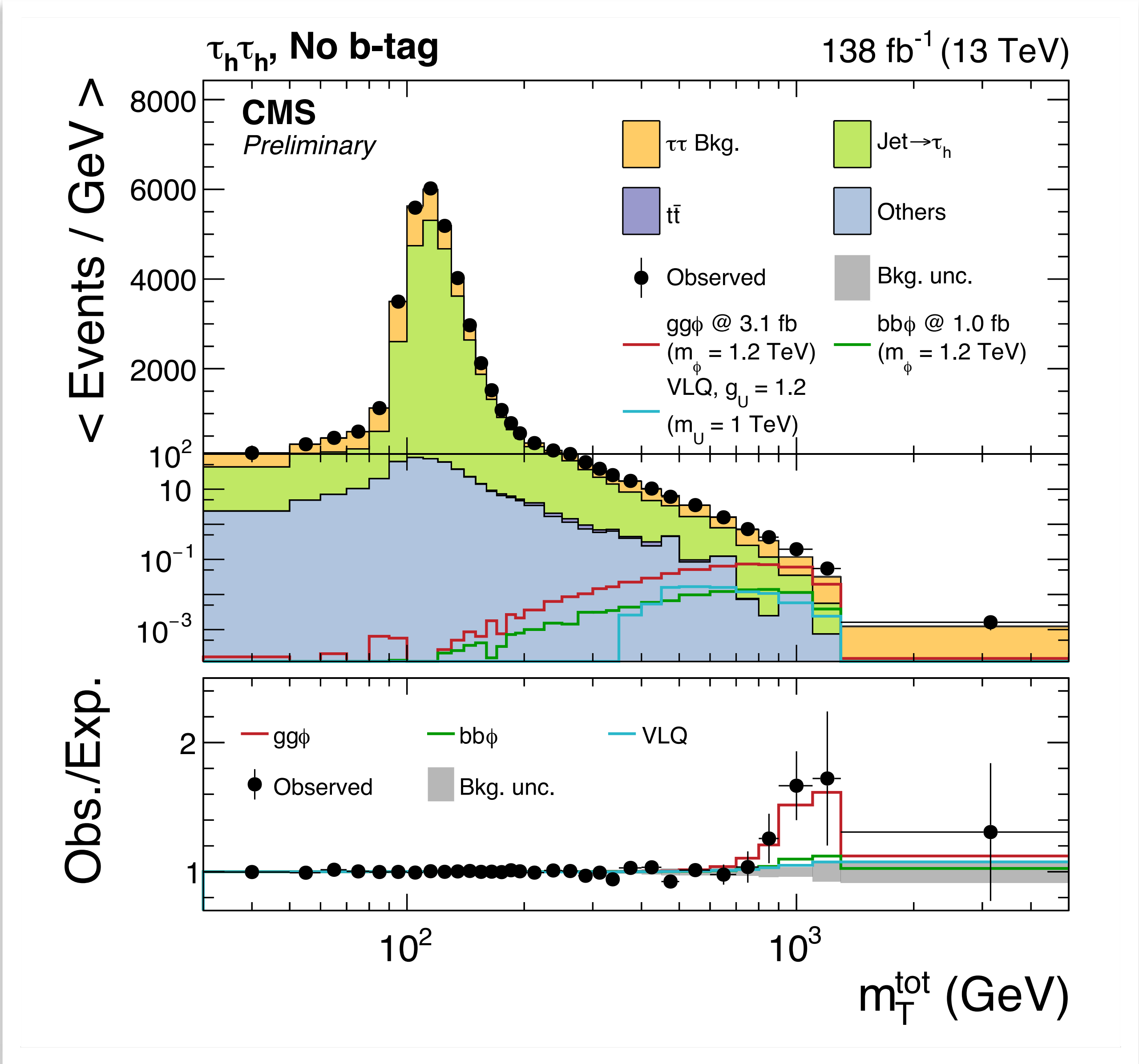

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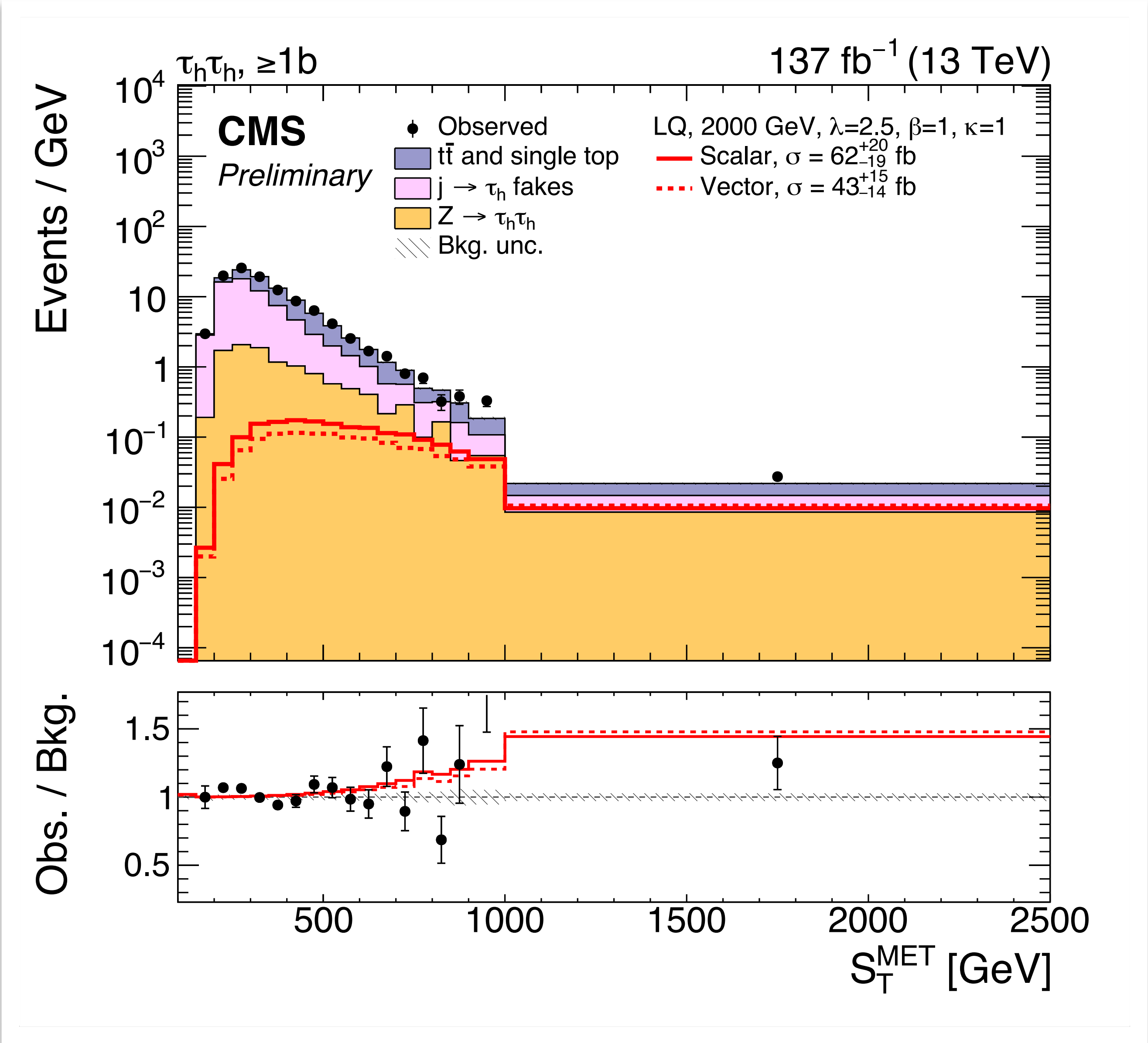
CMS 2022



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U$_1$

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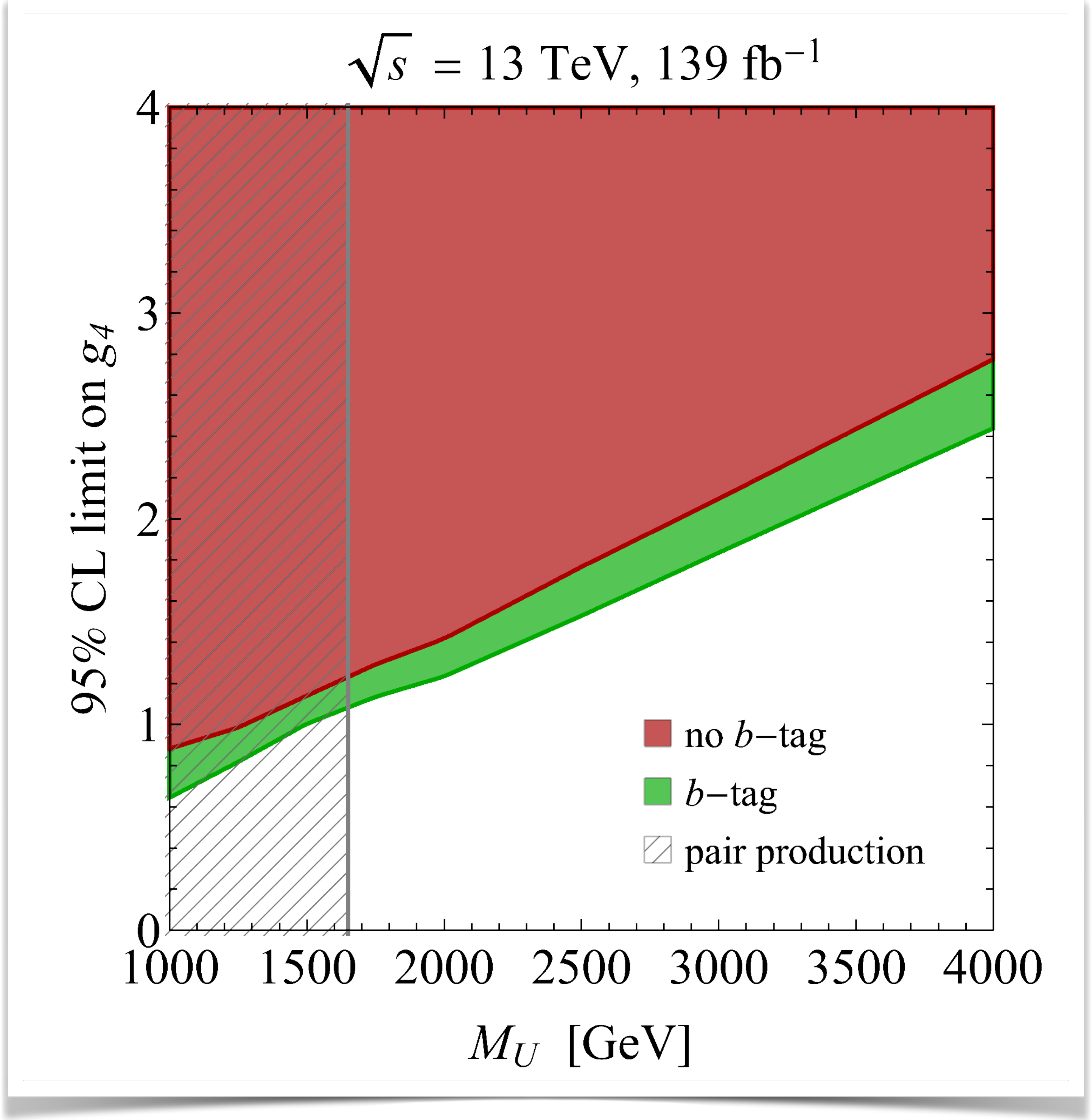

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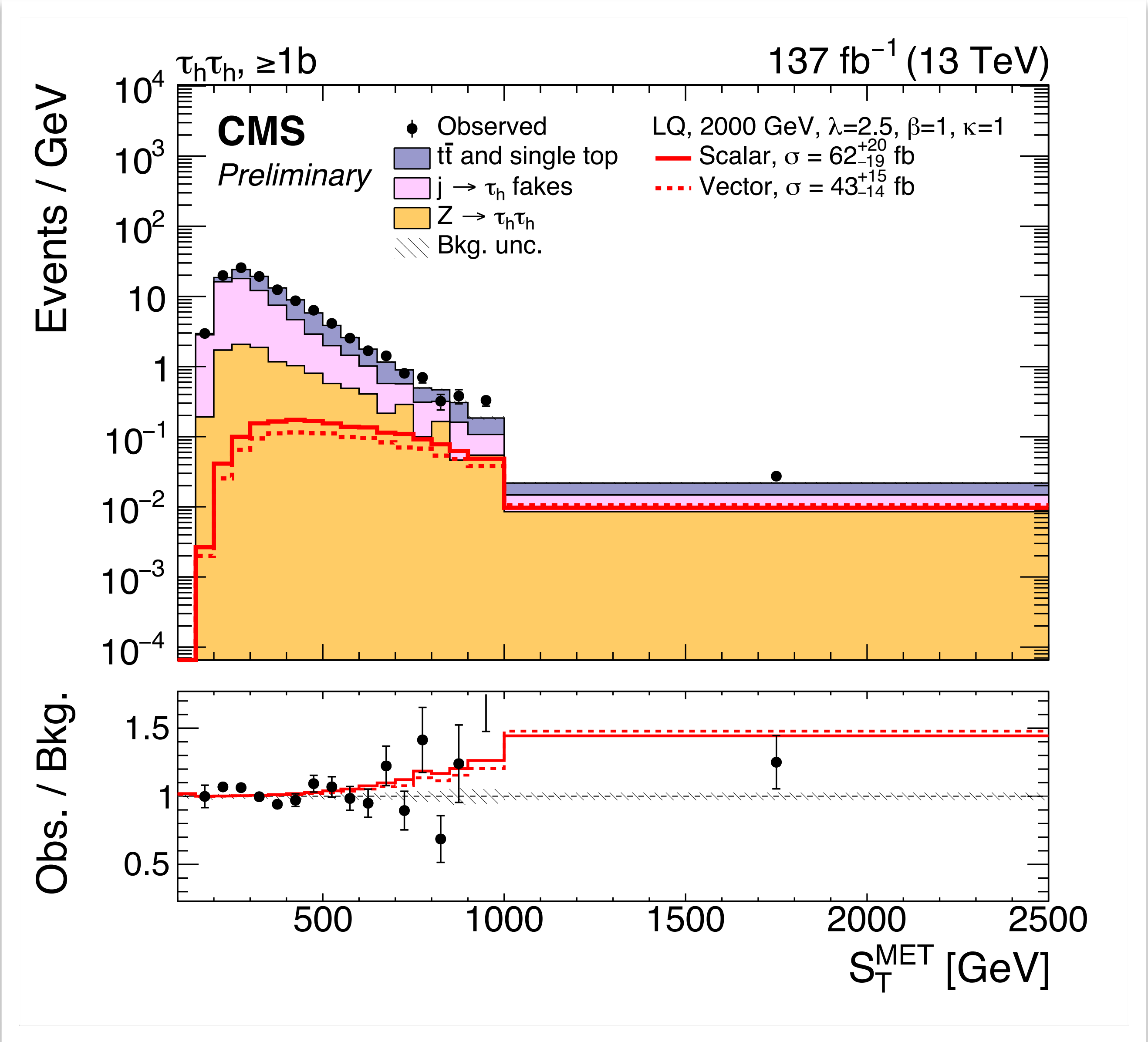

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U$_1$

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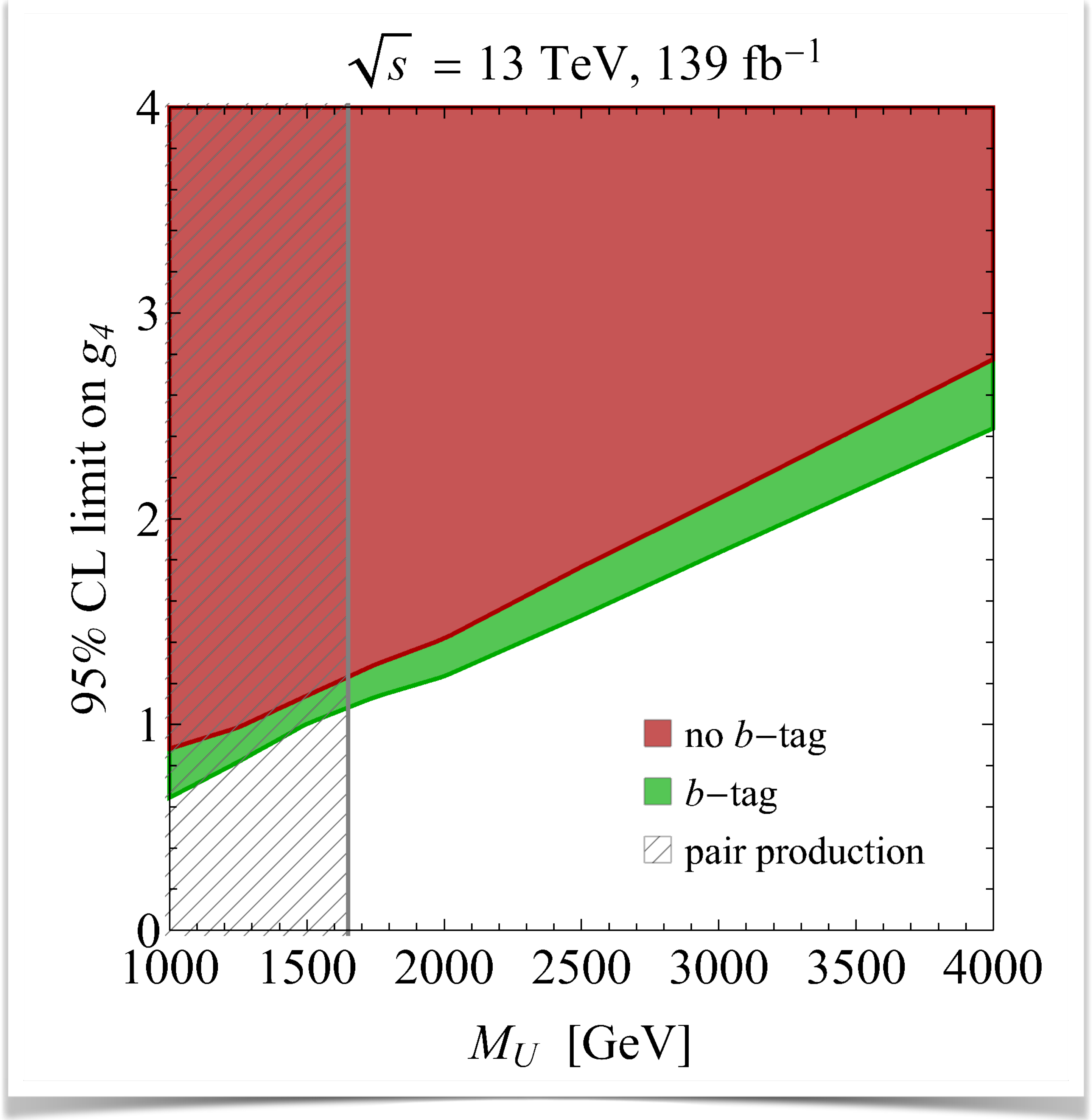

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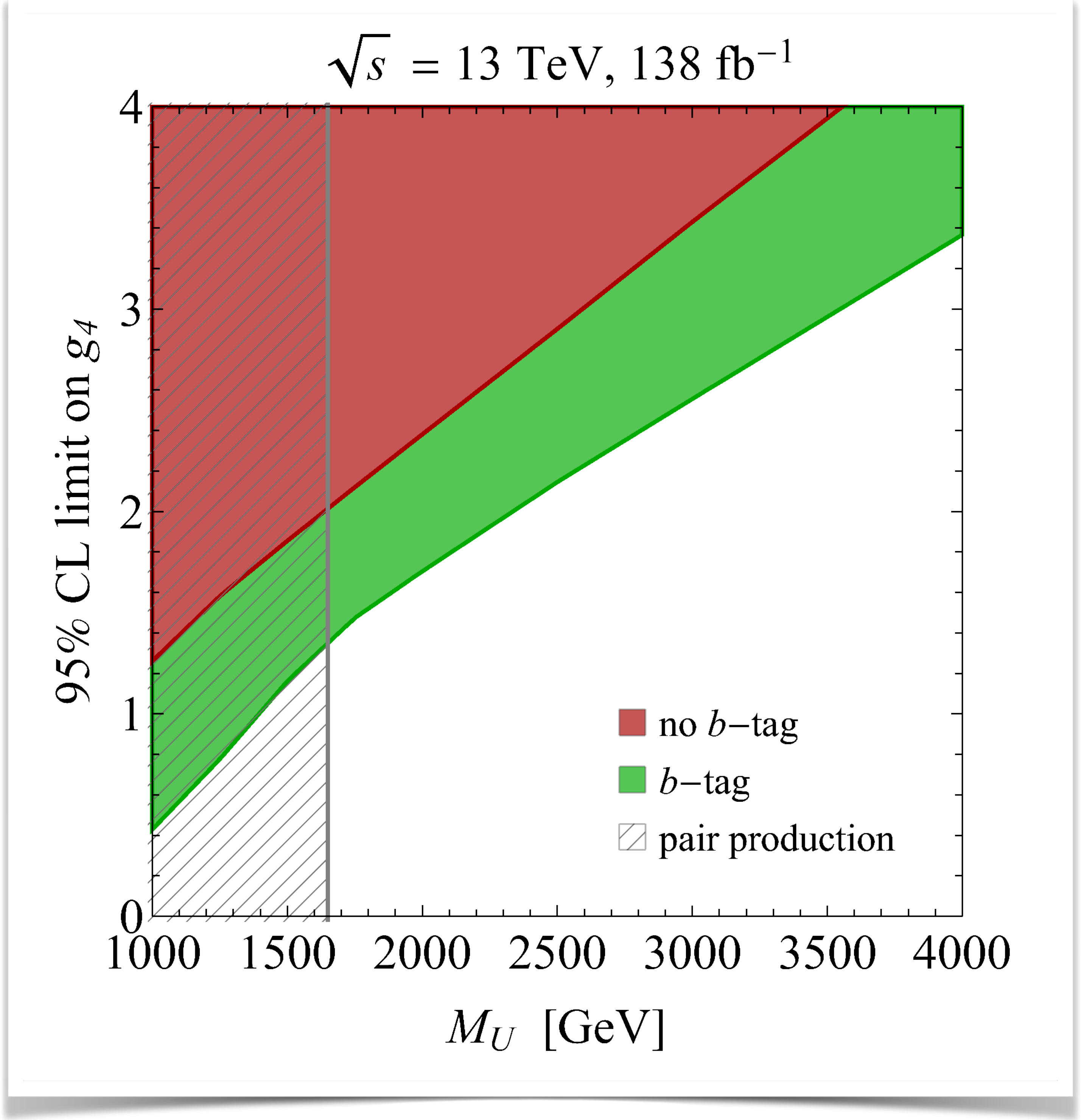
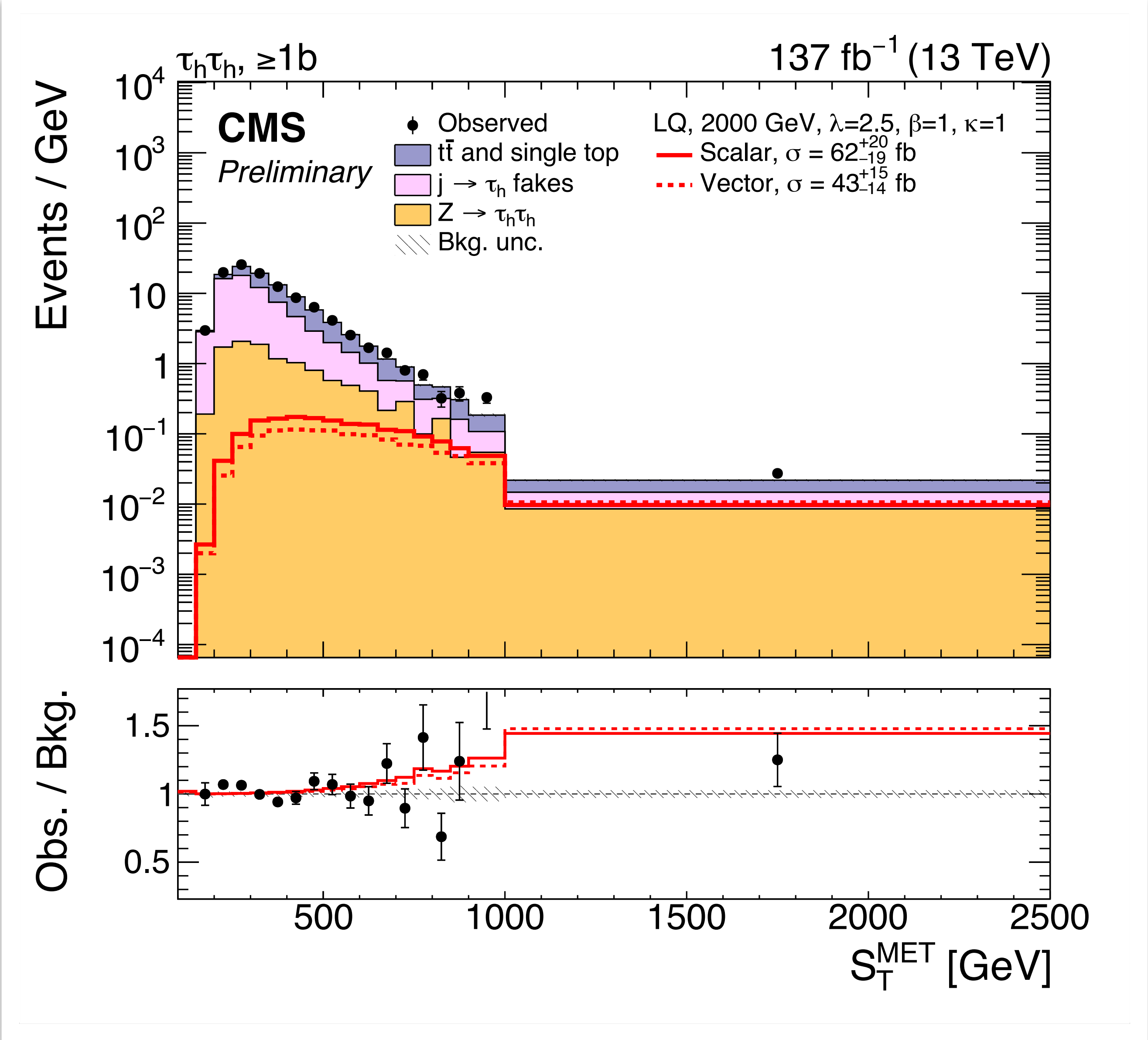


CMS 2022



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U_1

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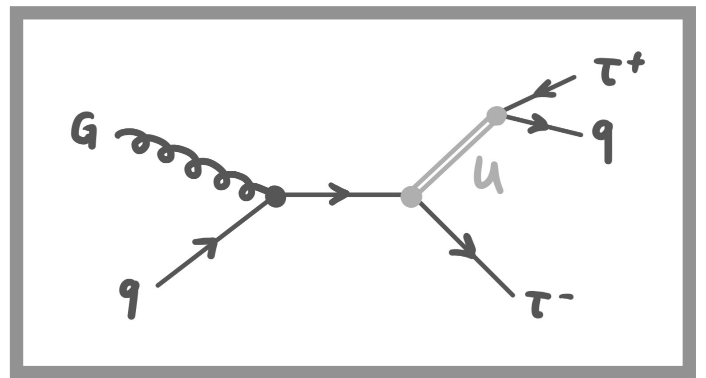
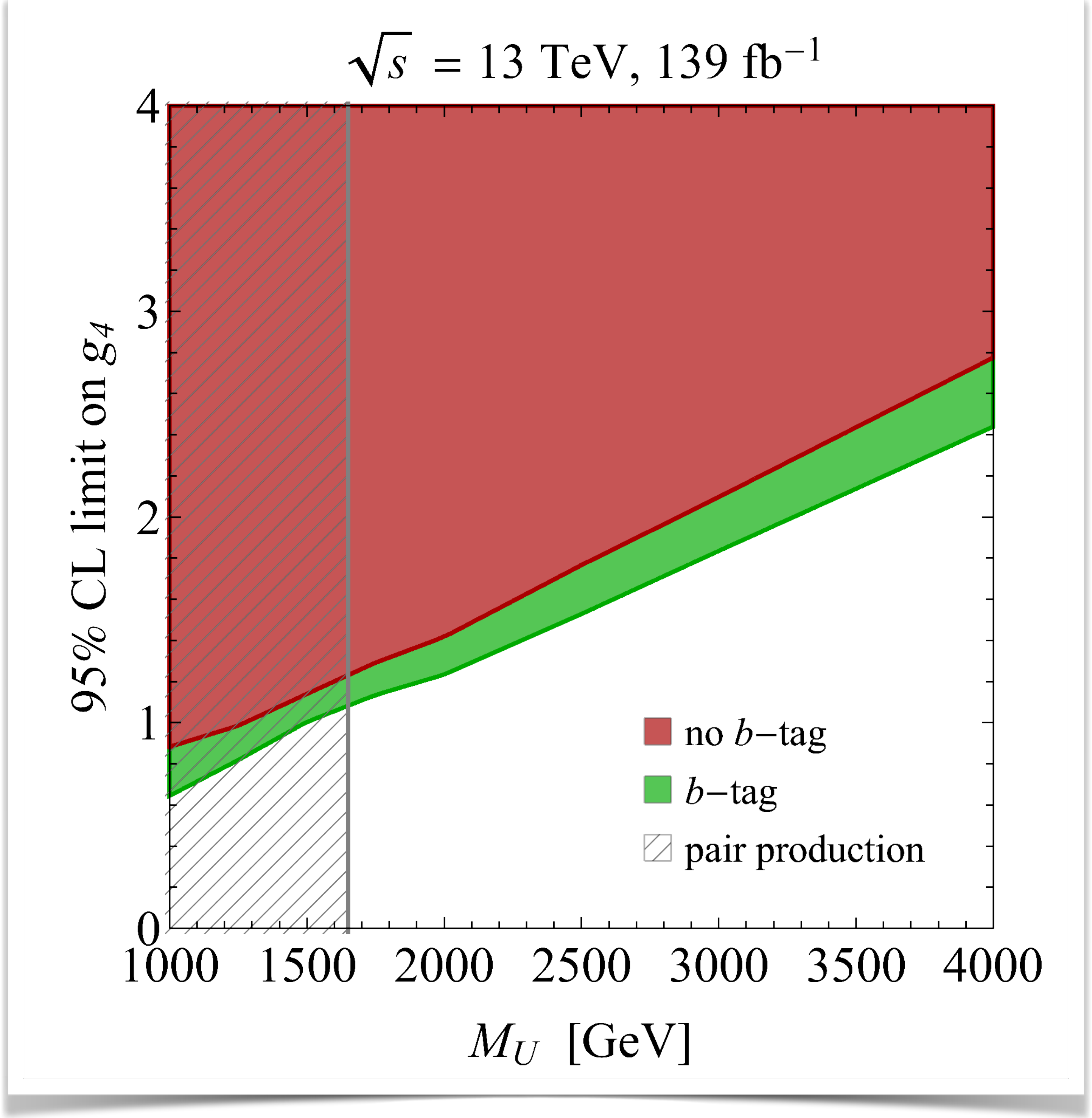
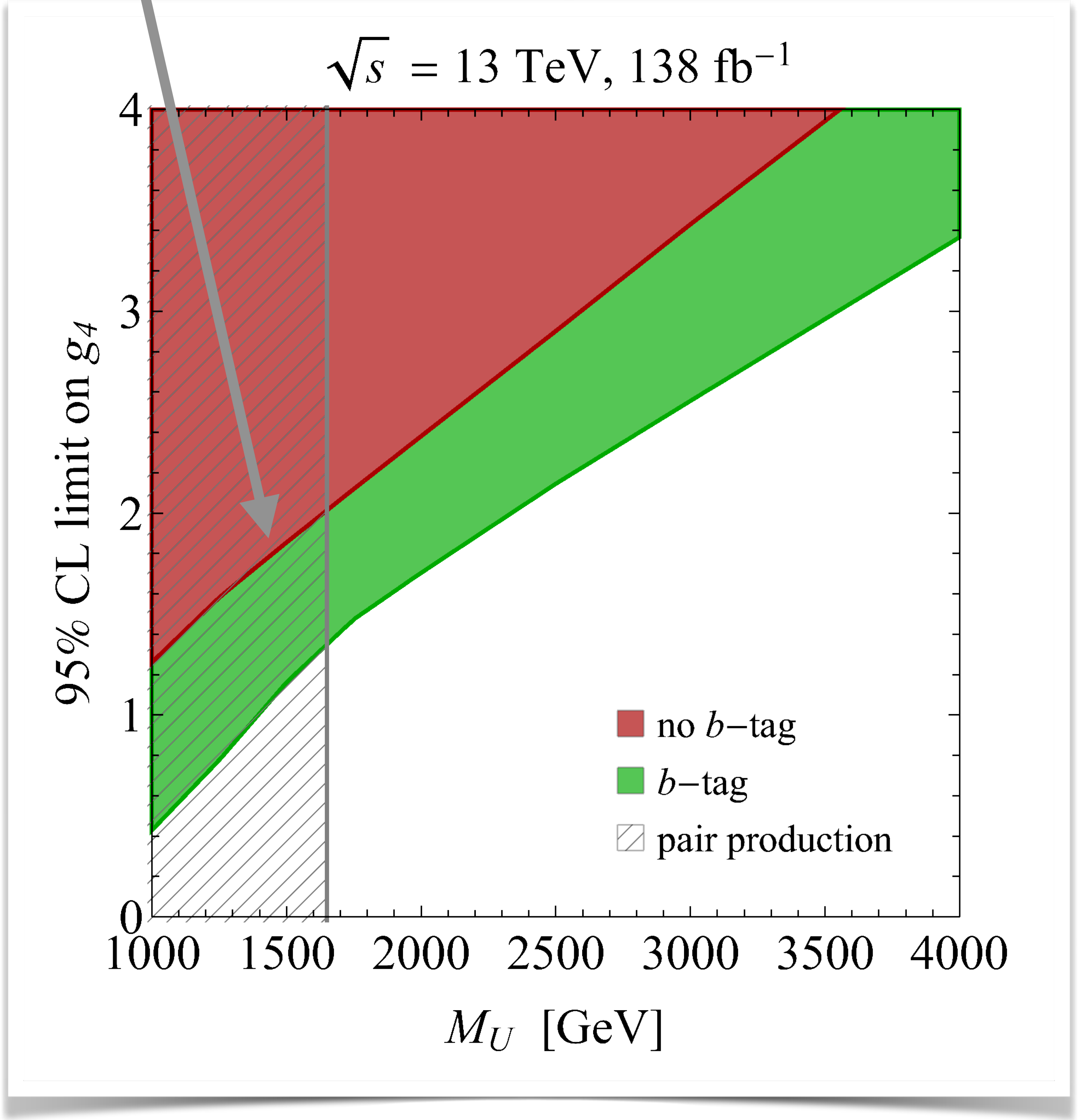


ATLAS 2020



CMS 2021



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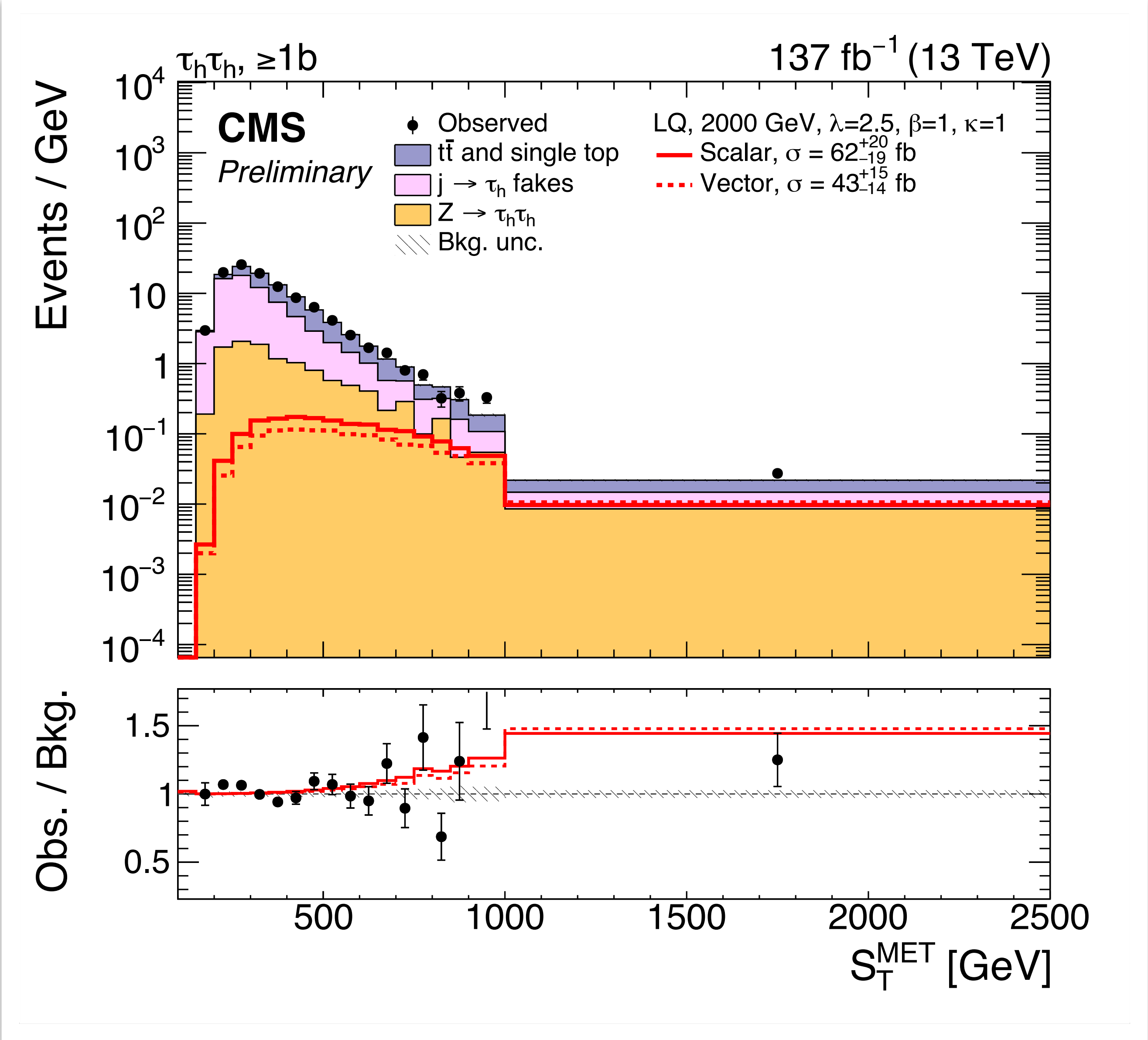

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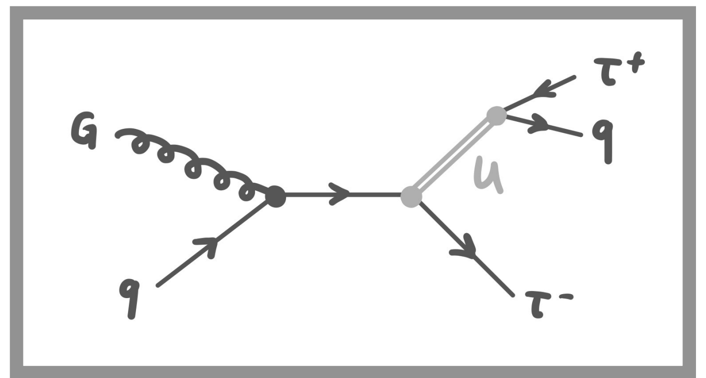

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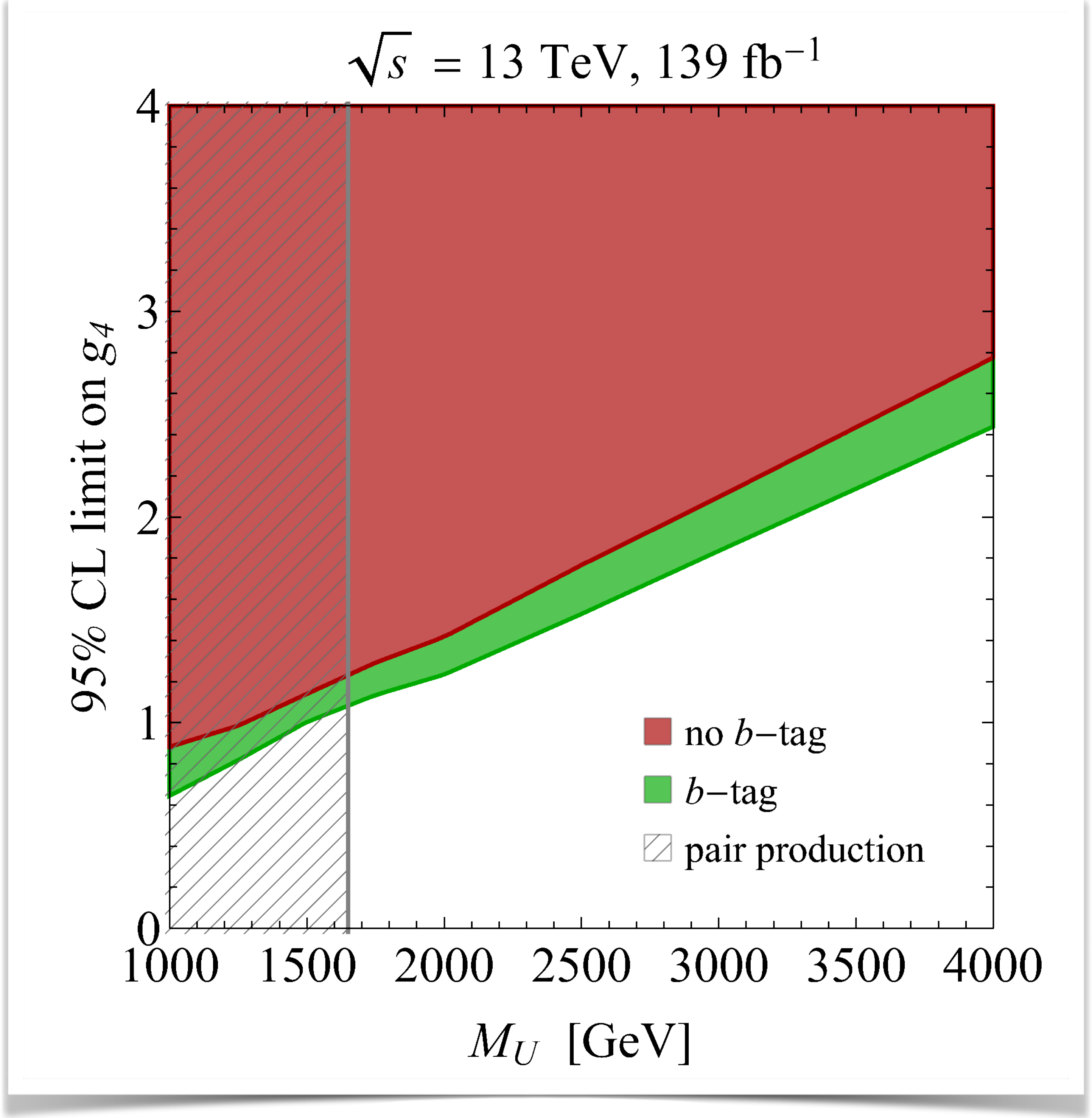

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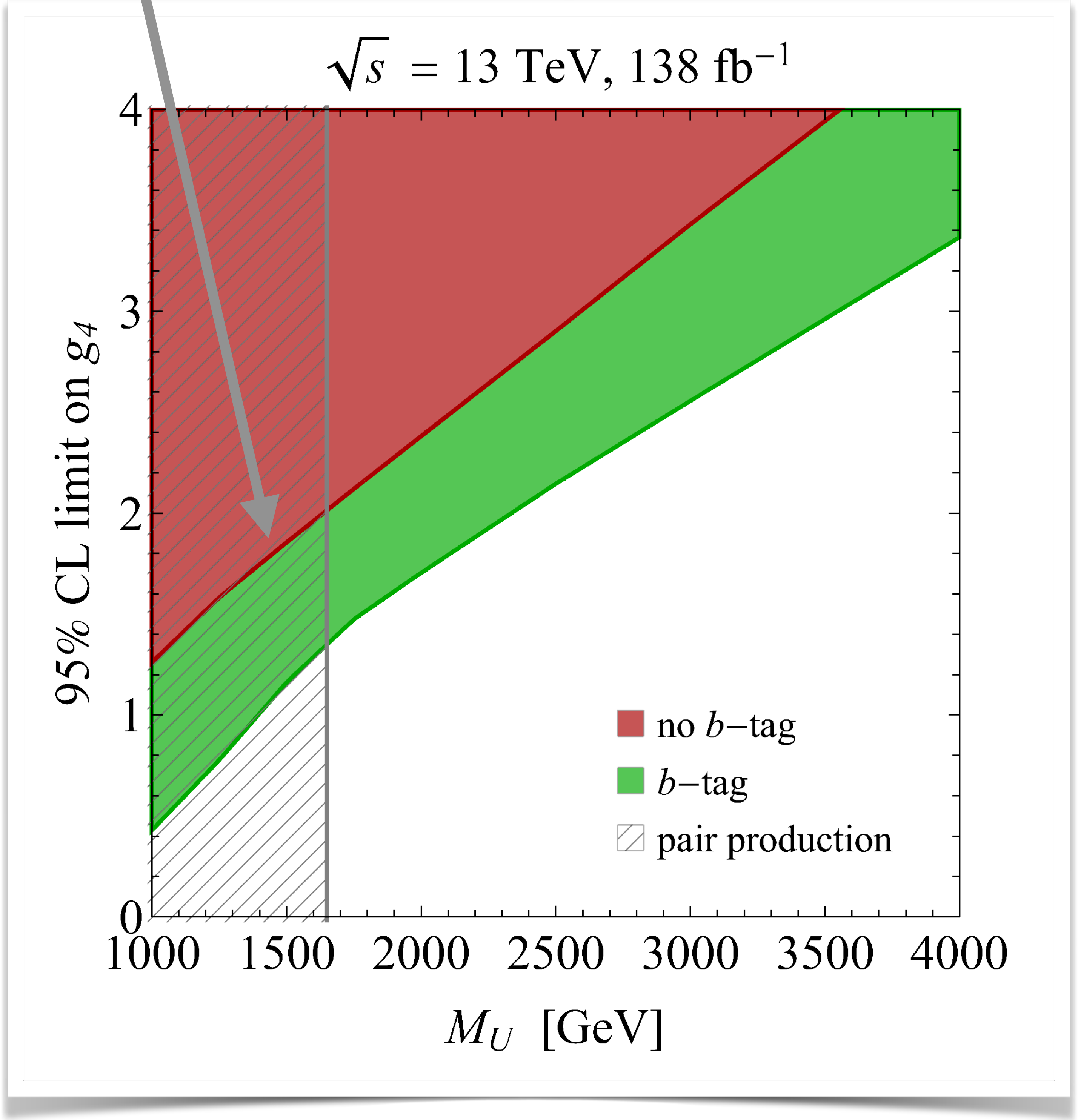

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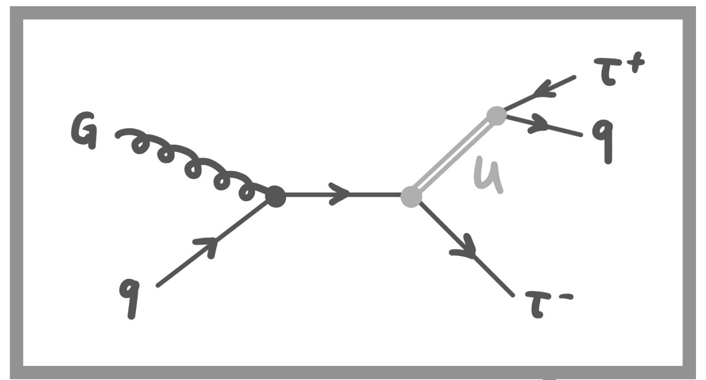

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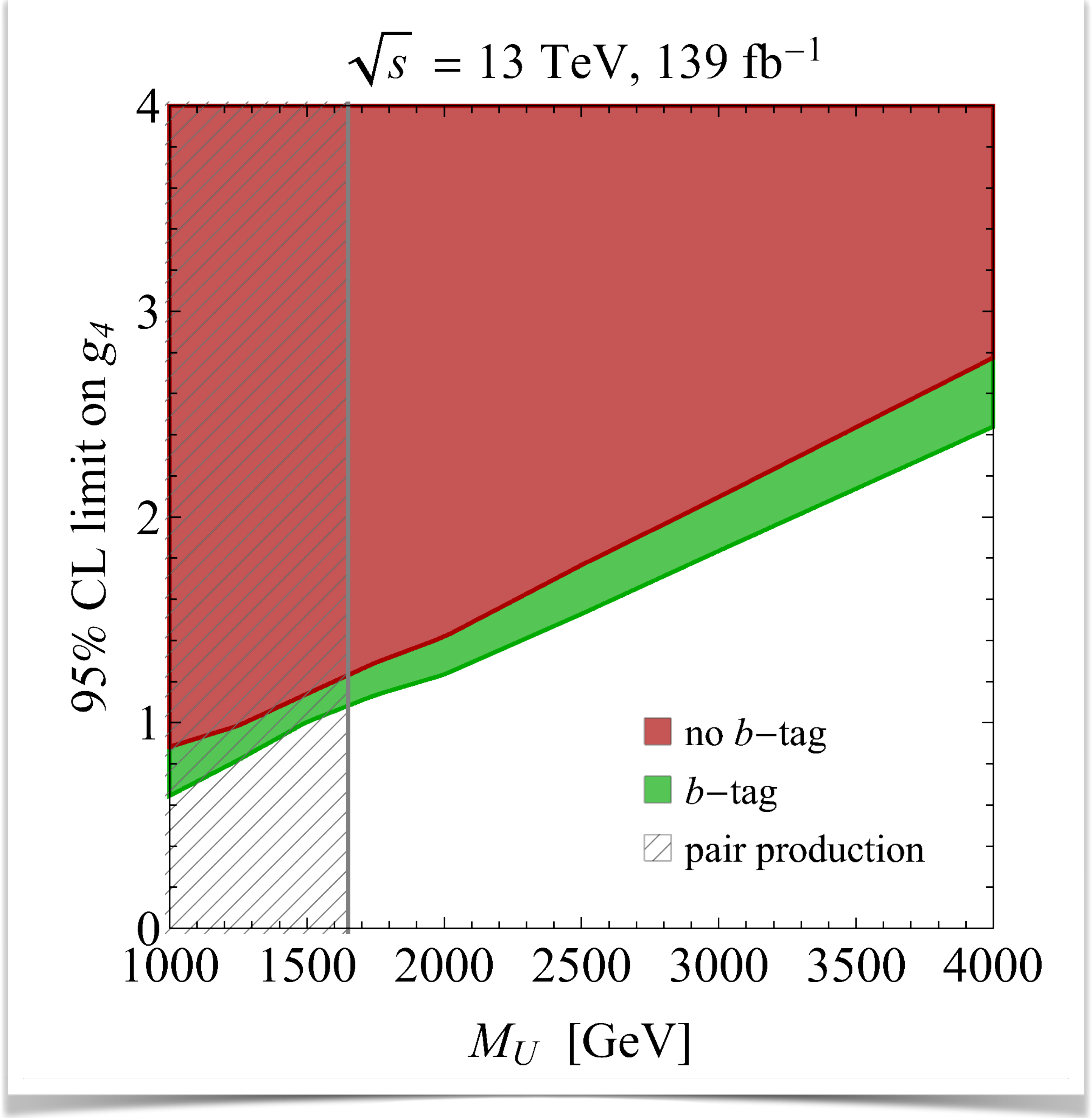

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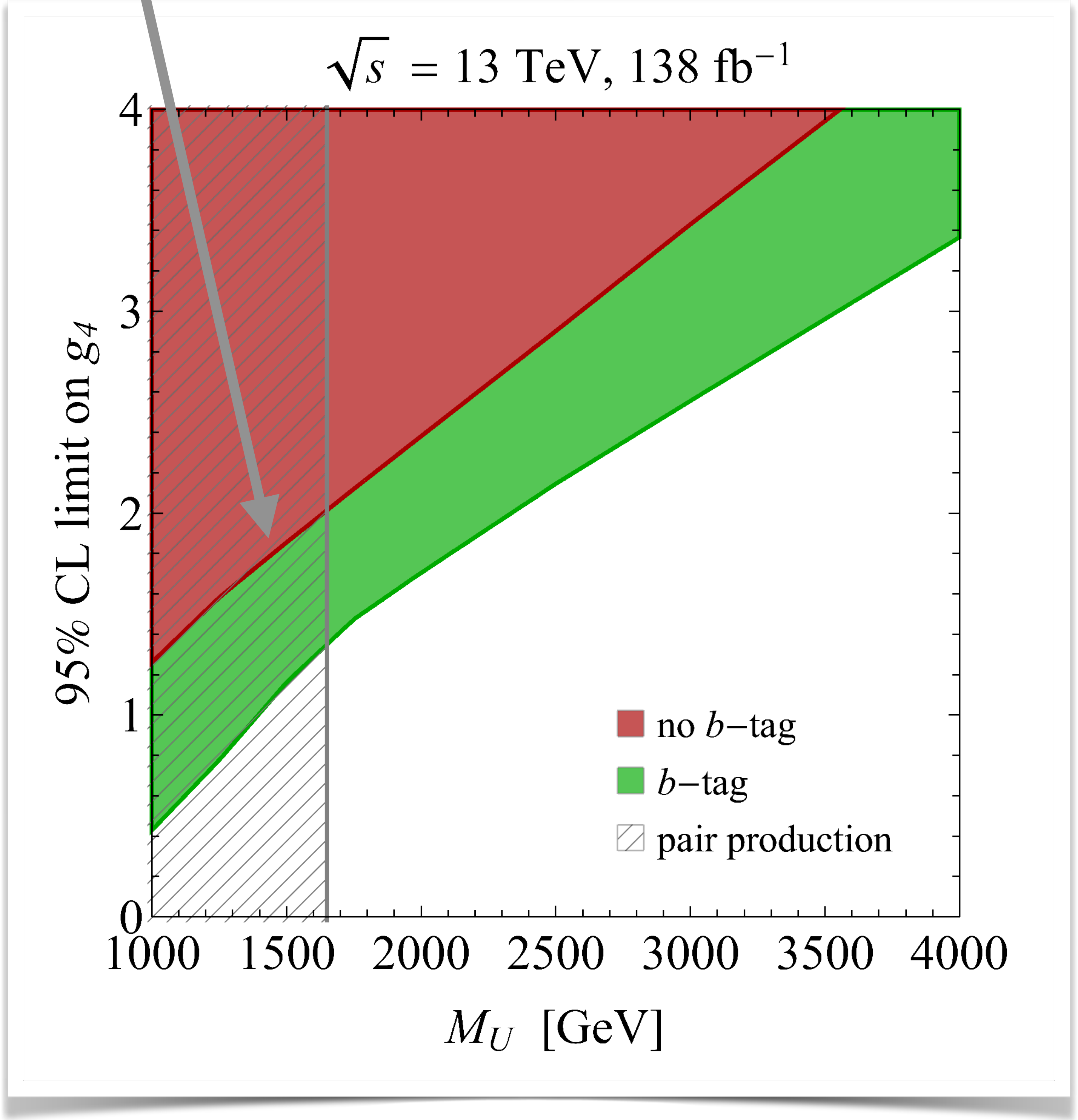

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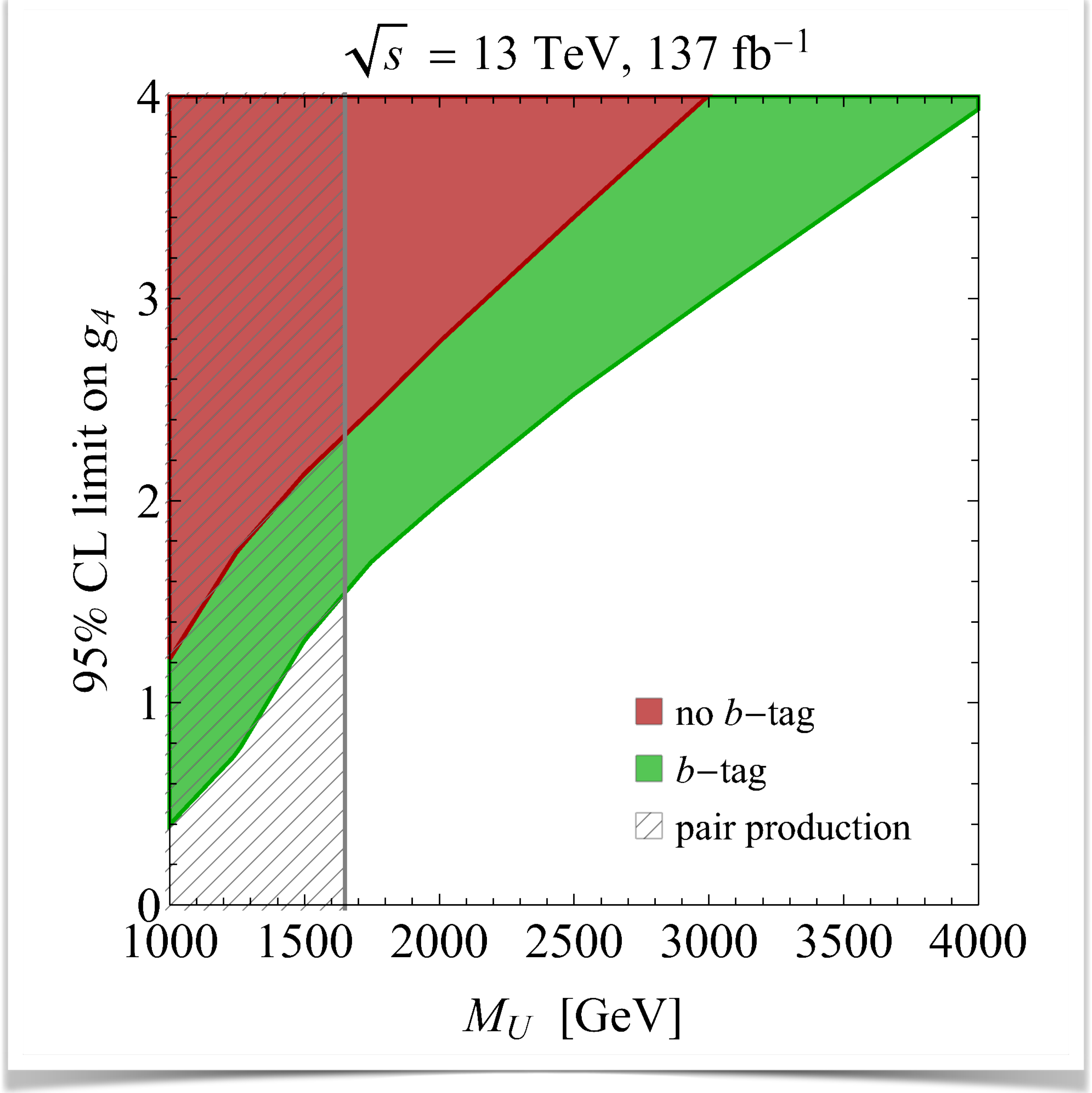

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U_1

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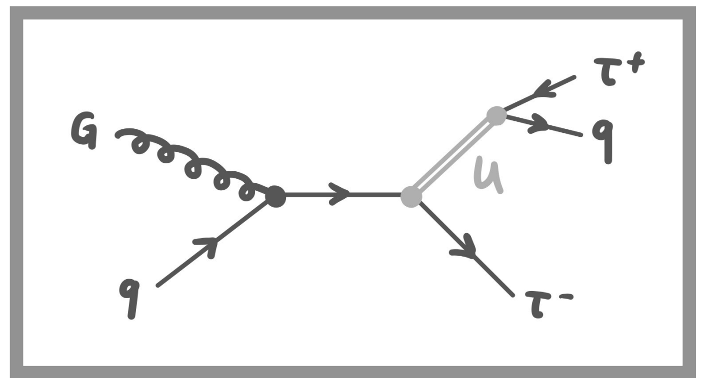

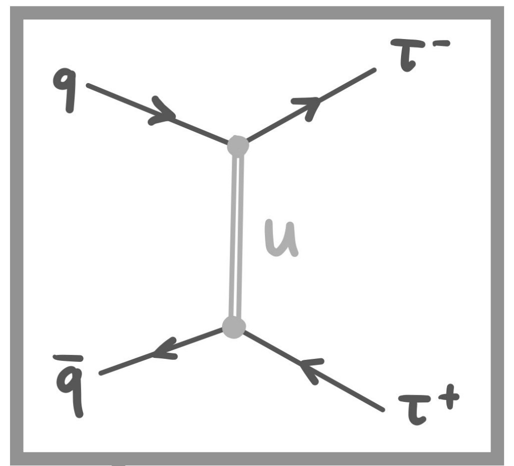

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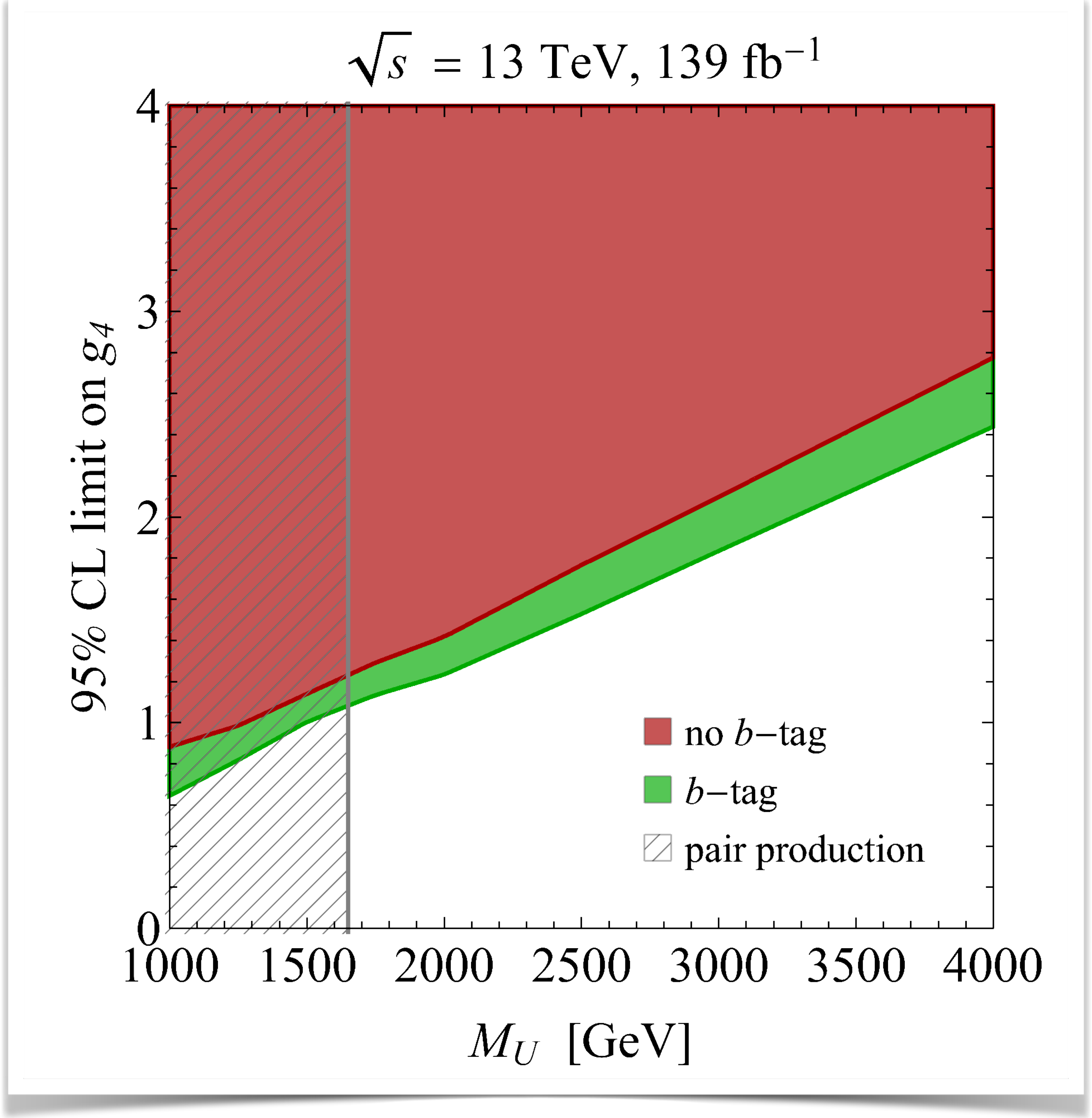

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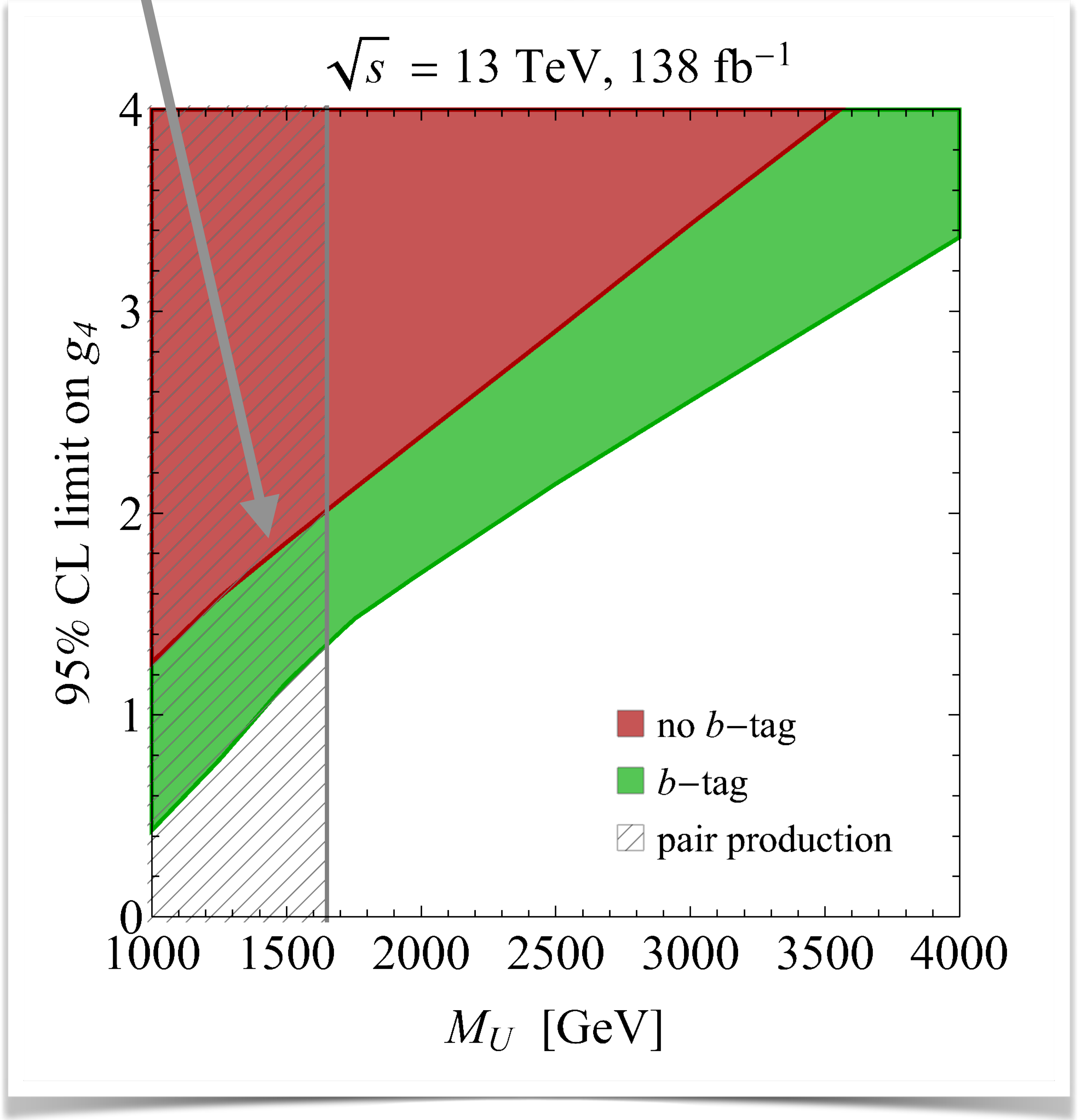
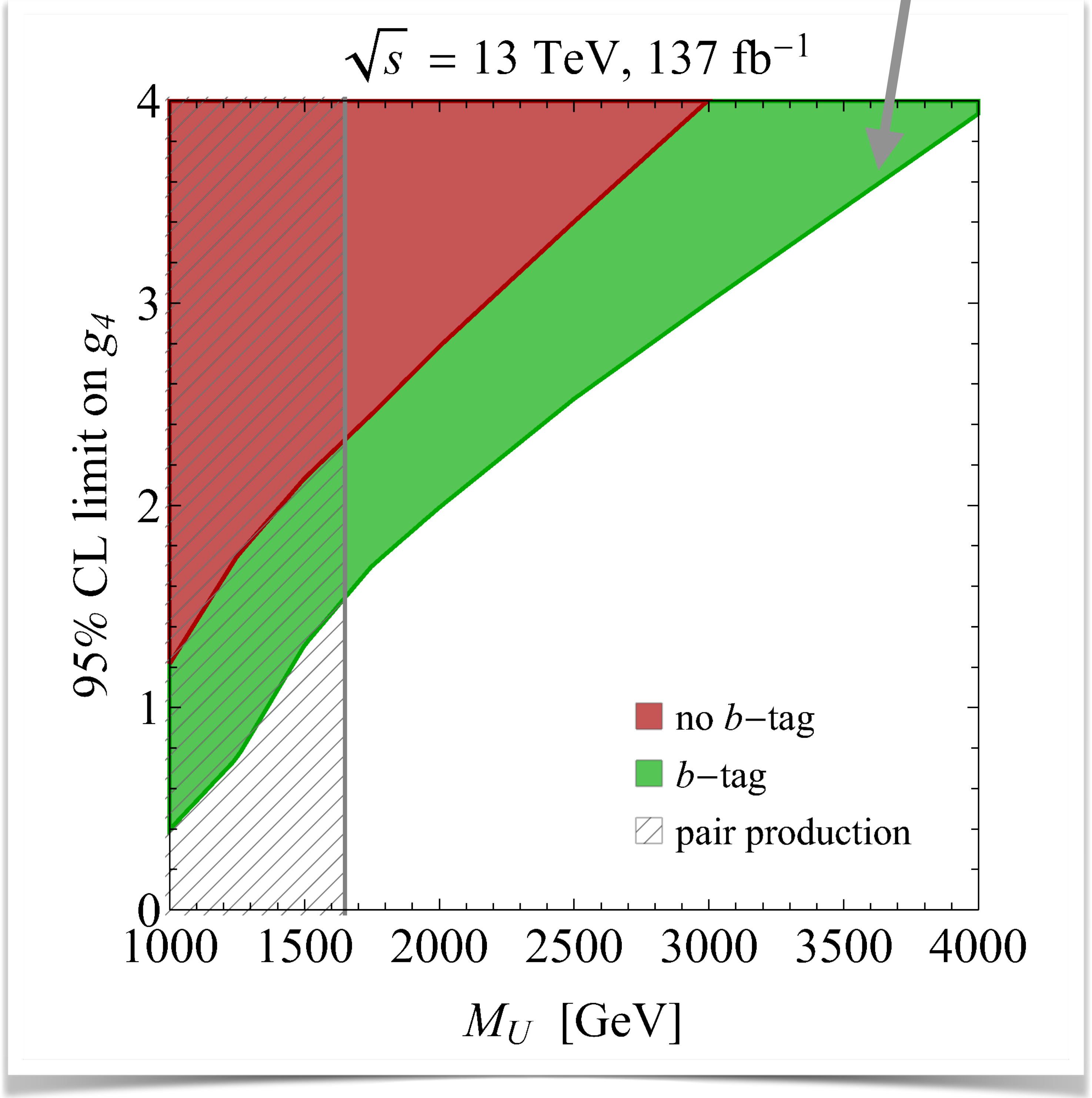


CMS 2022



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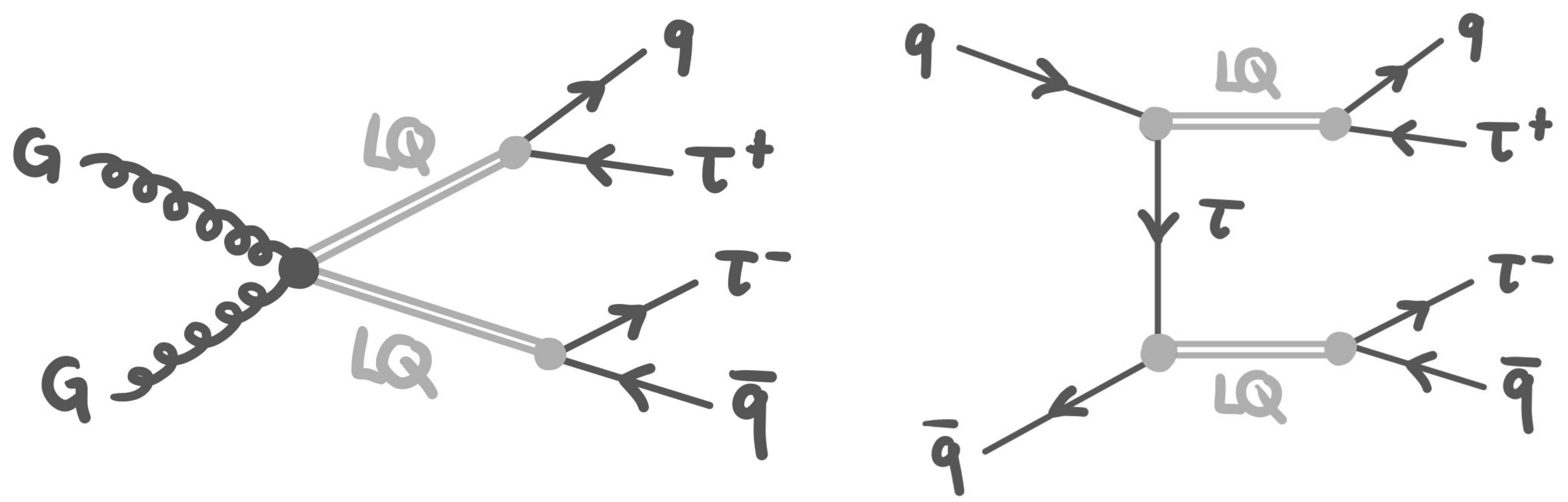
3. High-energy searches at the LHC

3.3 Single-resonant production

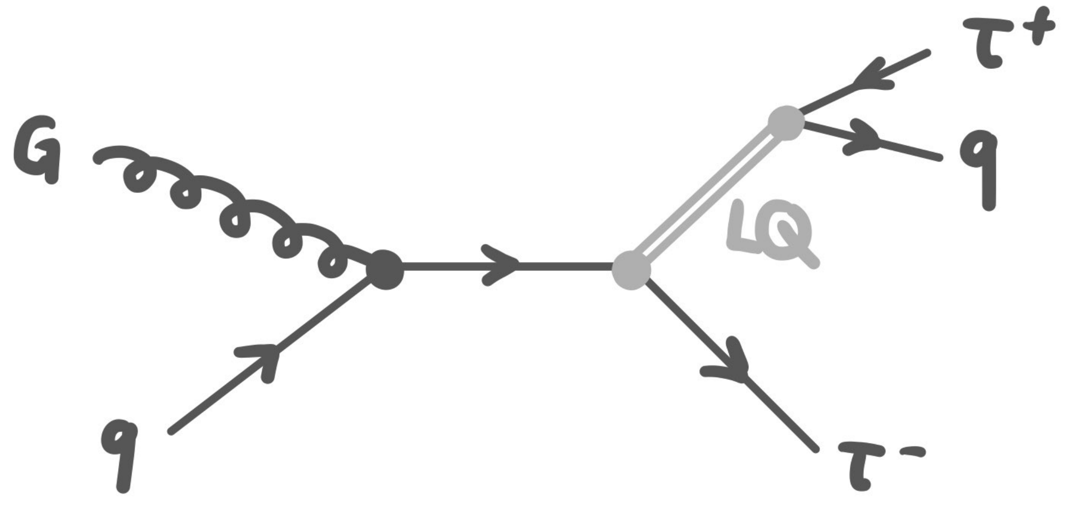
3. High-energy searches at the LHC

3.3 Single-resonant production

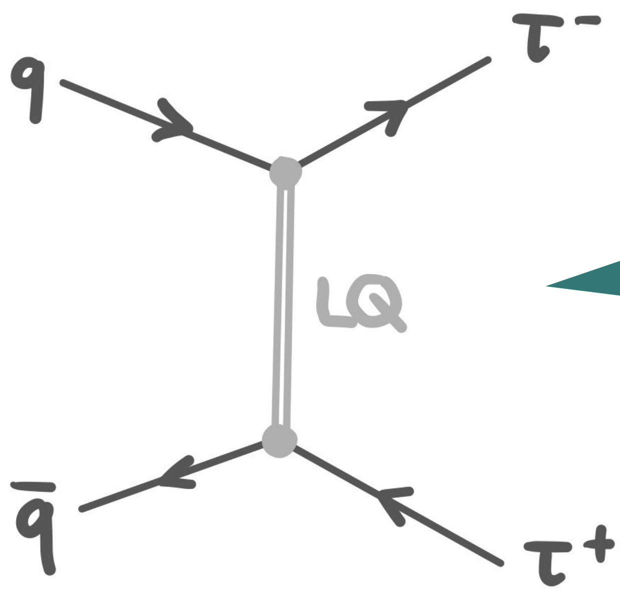
Dependent on Yukawa couplings



Pair-production



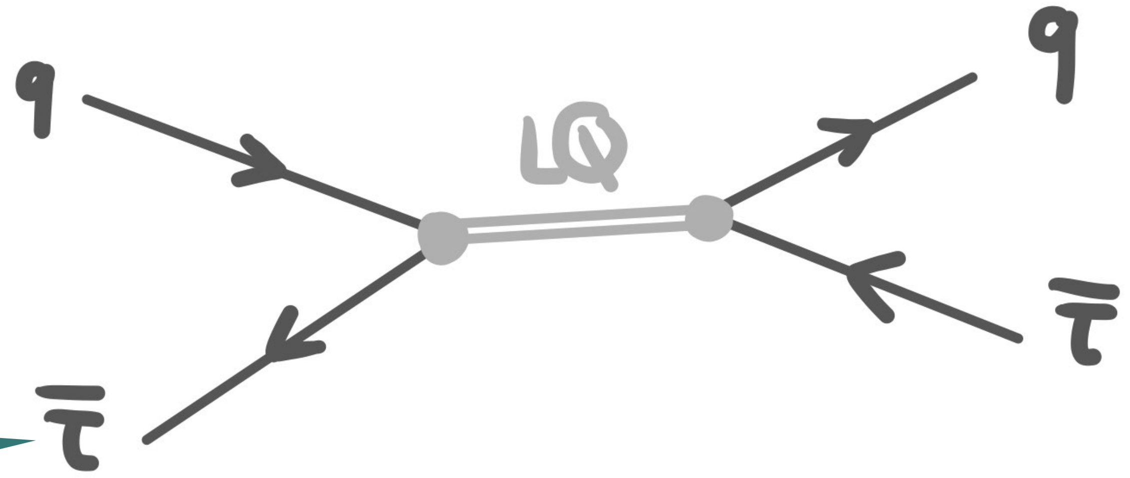
Single production



Non-resonant signatures in the tails

Drell-Yan production

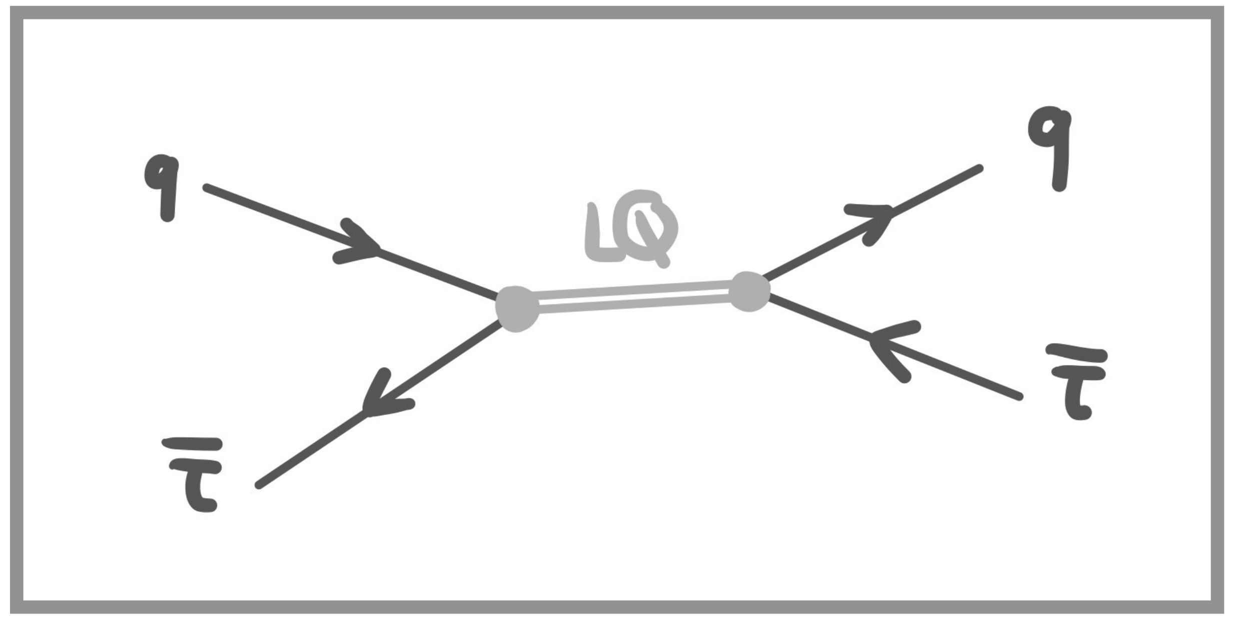
Lepton PDF of the proton



Single-resonant production

3. High-energy searches at the LHC

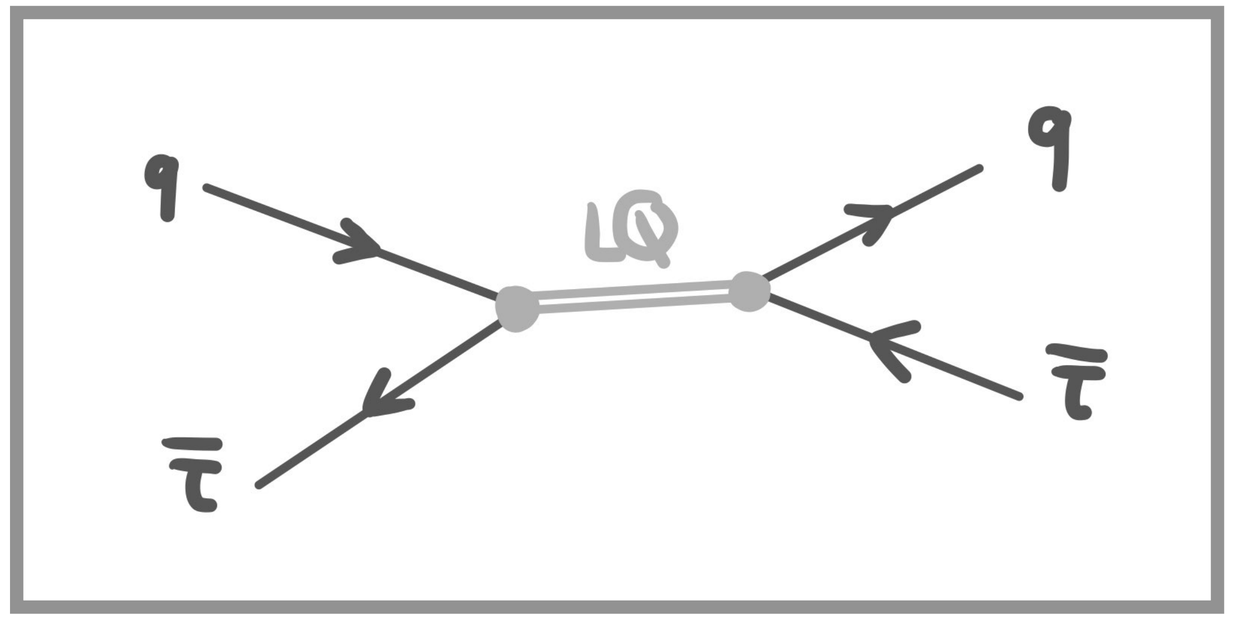
3.3 Single-resonant production

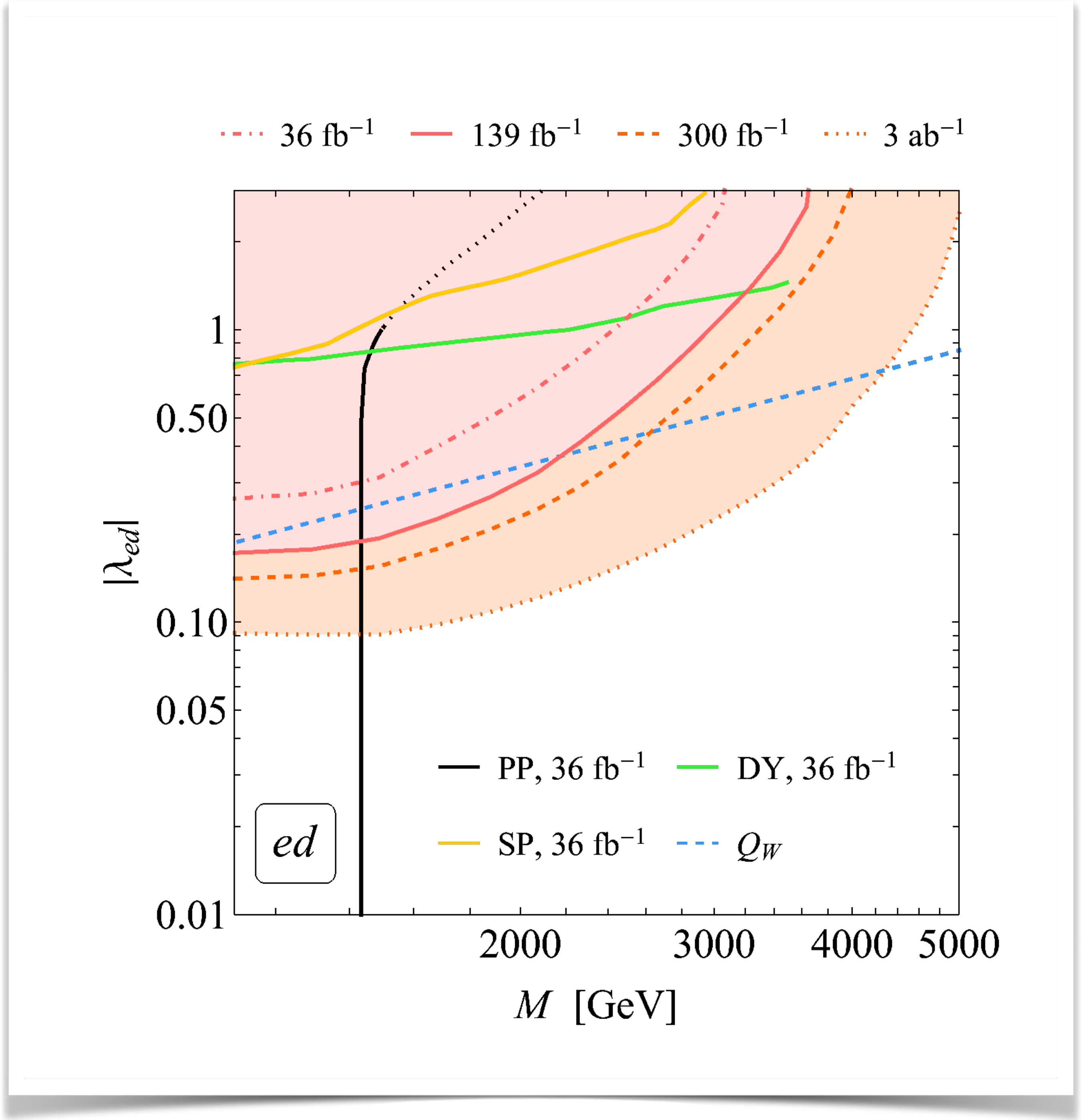


3. High-energy searches at the LHC

3.3 Single-resonant production

- Provides **complementary constraints** if the LQ mass is not too high.



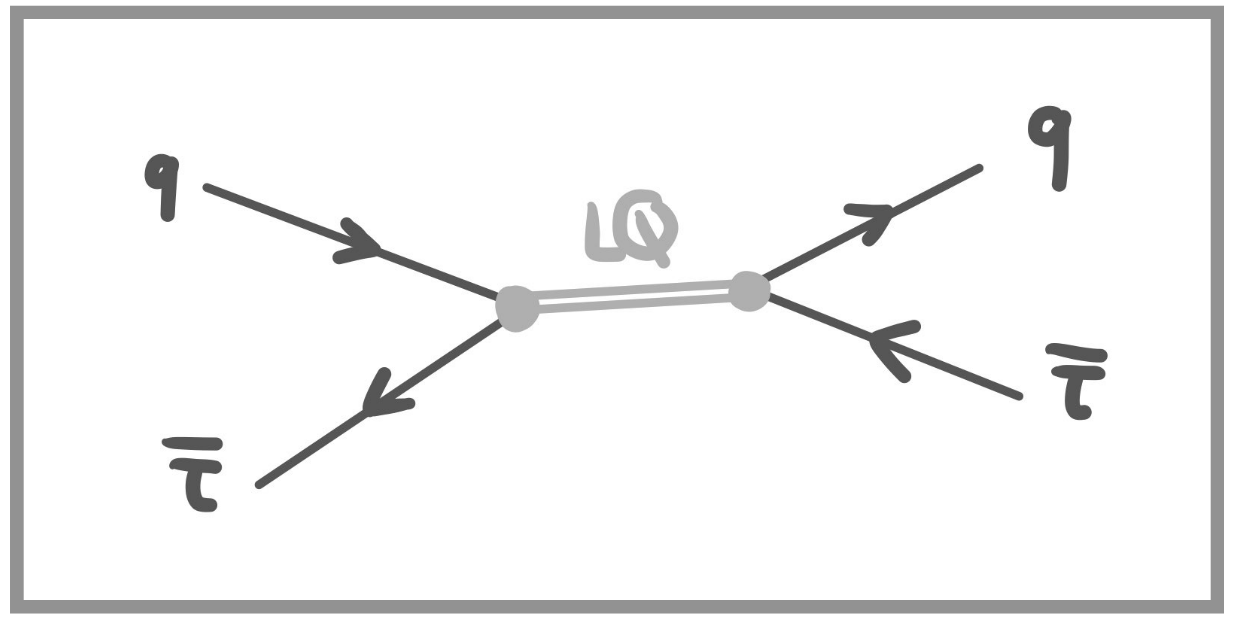


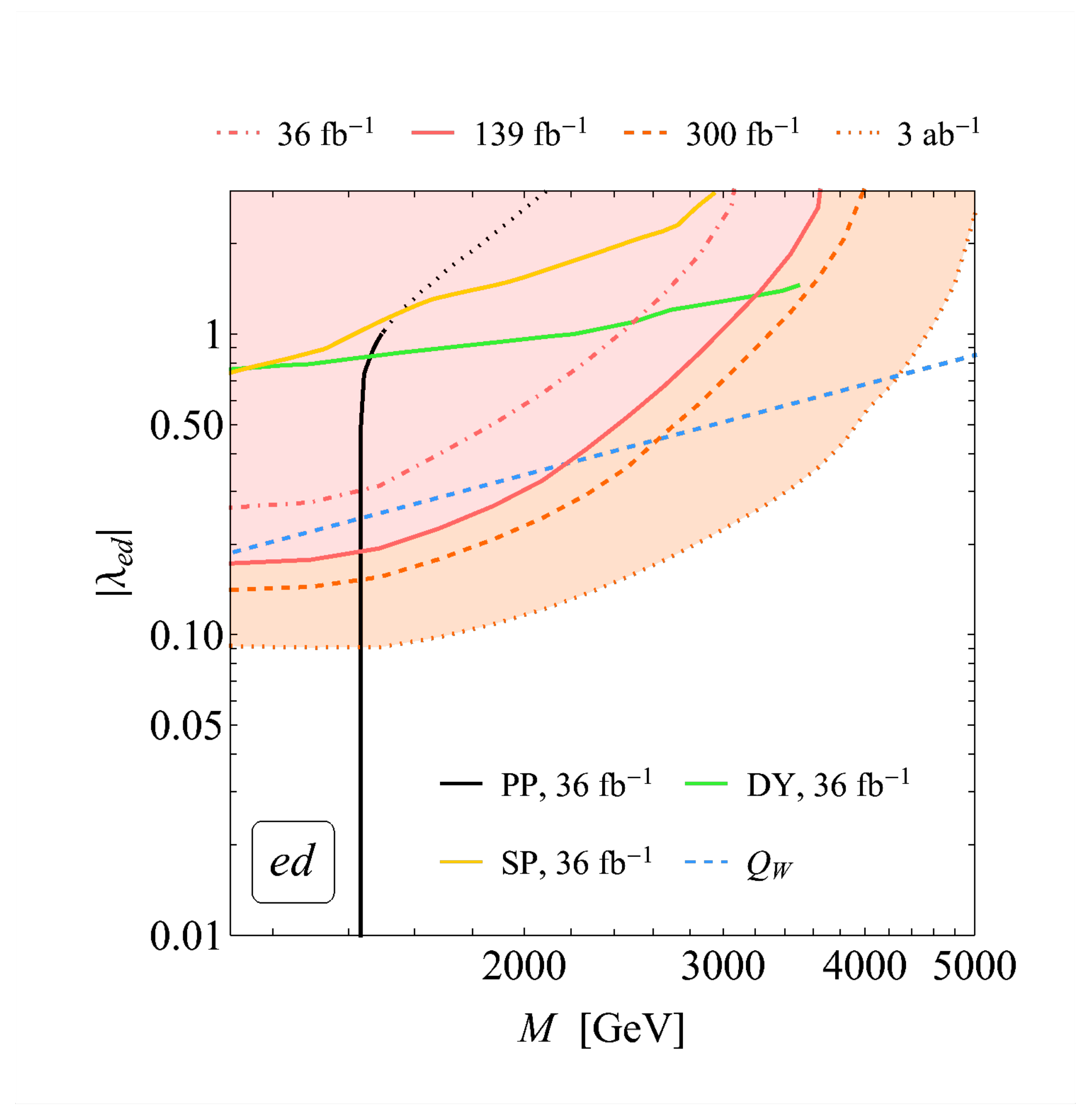
Source: ArXiv:2005.06475 (L. Buonocore, U. Haisch, P. Nason, F. Tramontano, G. Zanderighi)

3. High-energy searches at the LHC

3.3 Single-resonant production

- Provides **complementary constraints** if the LQ mass is not too high.
- Has very recently also been implemented at **NLO+PS** in **POWHEG-BOX**.





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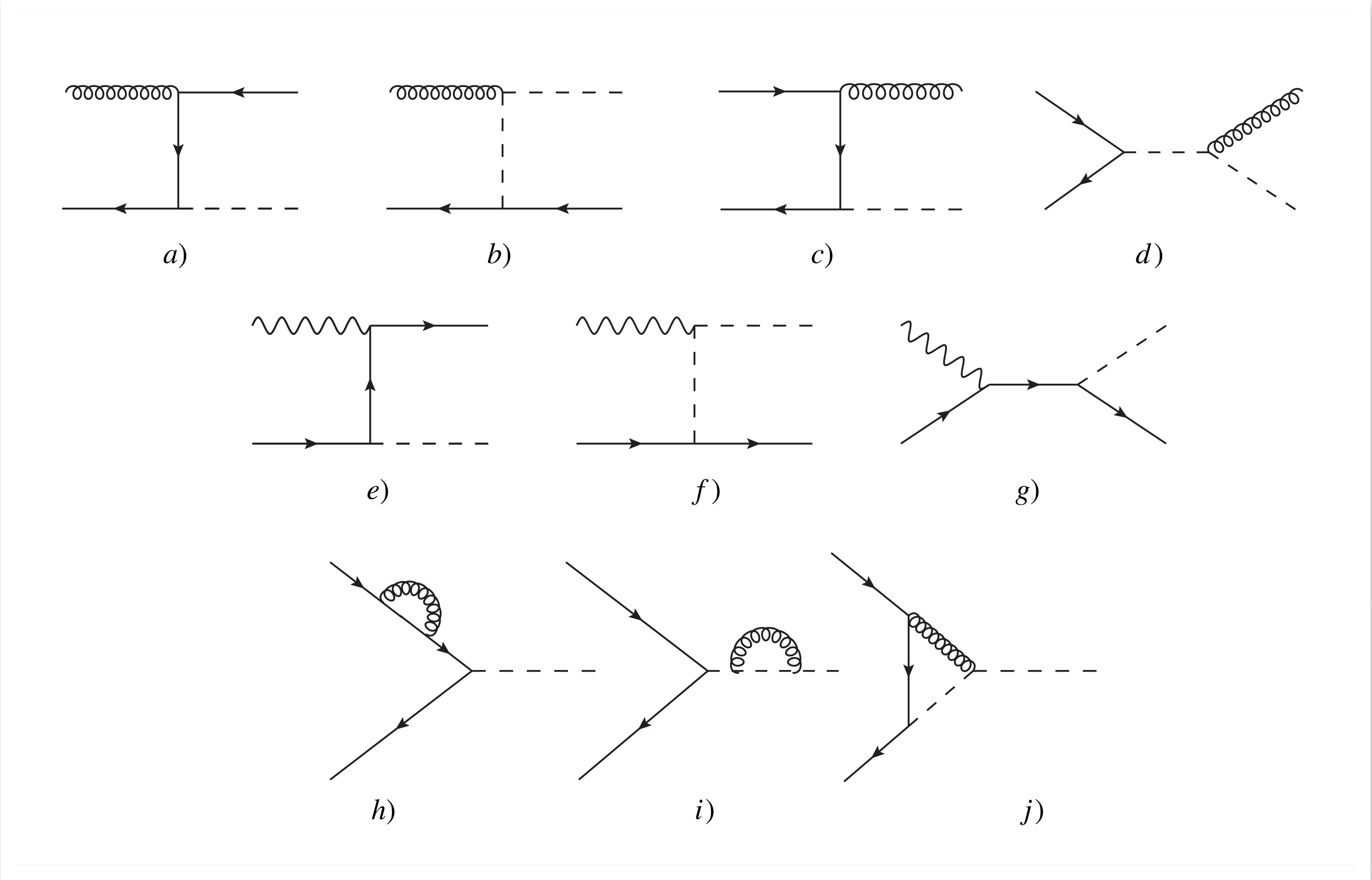
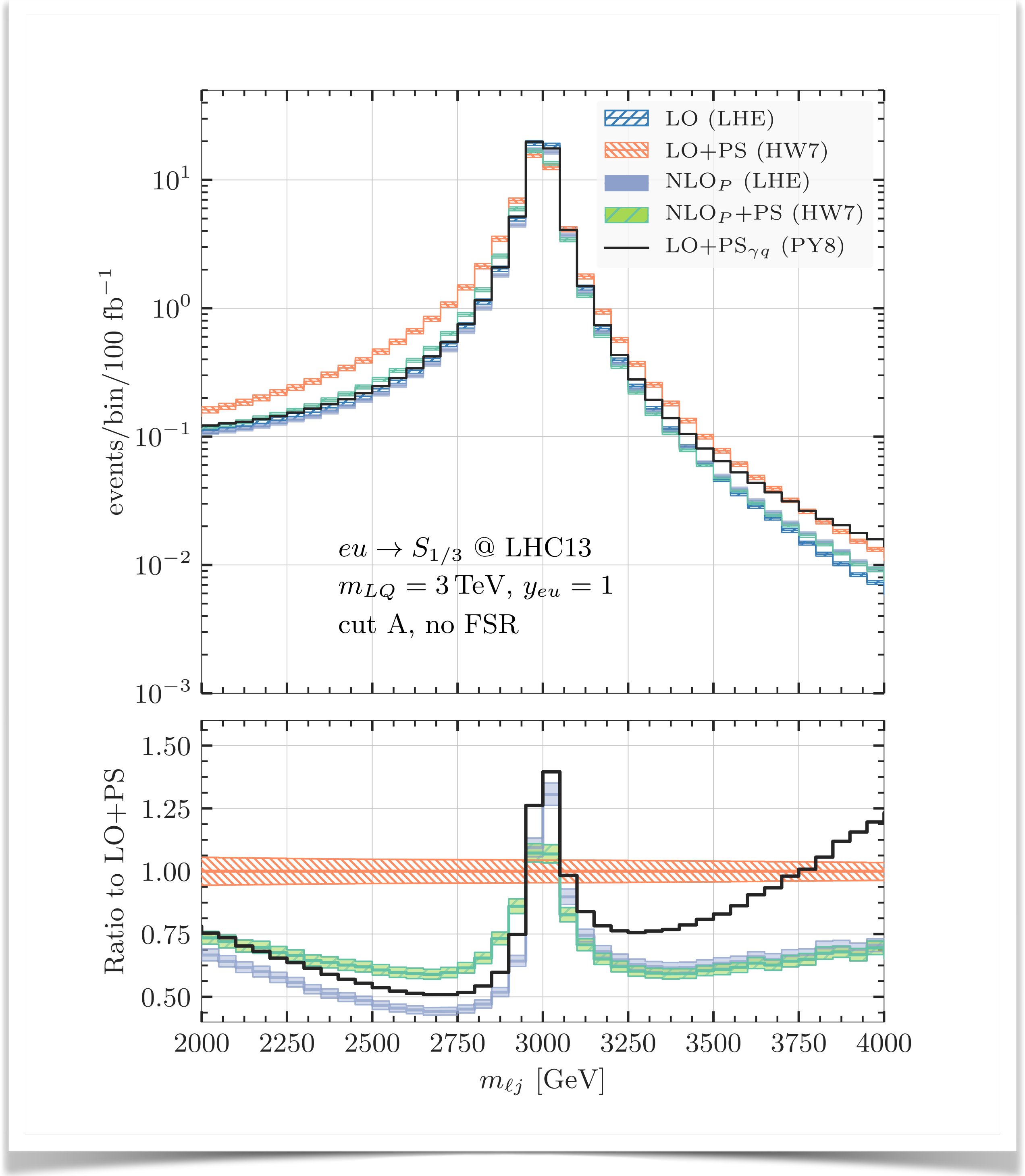


Source: ArXiv:2209.02599 (L. Buonocore, A. Greljo, P. Krack, P. Nason, N. Selimovic, F. Tramontano, G. Zanderighi)



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- **LQ effects in high-energy searches are implemented in POWHEG-BOX at full NLO+PS.**
  - **SLQ** effects in Drell-Yan spectrum.
  - $\mathbf{U_1}$ **from 4321** effects in Drell-Yan spectrum.
    - Interesting interplay between non-resonant/resonant contributions, b-veto/b-tag
  - Single-resonant **SLQ** effects in lepton + jet.

Thank you for your attention!