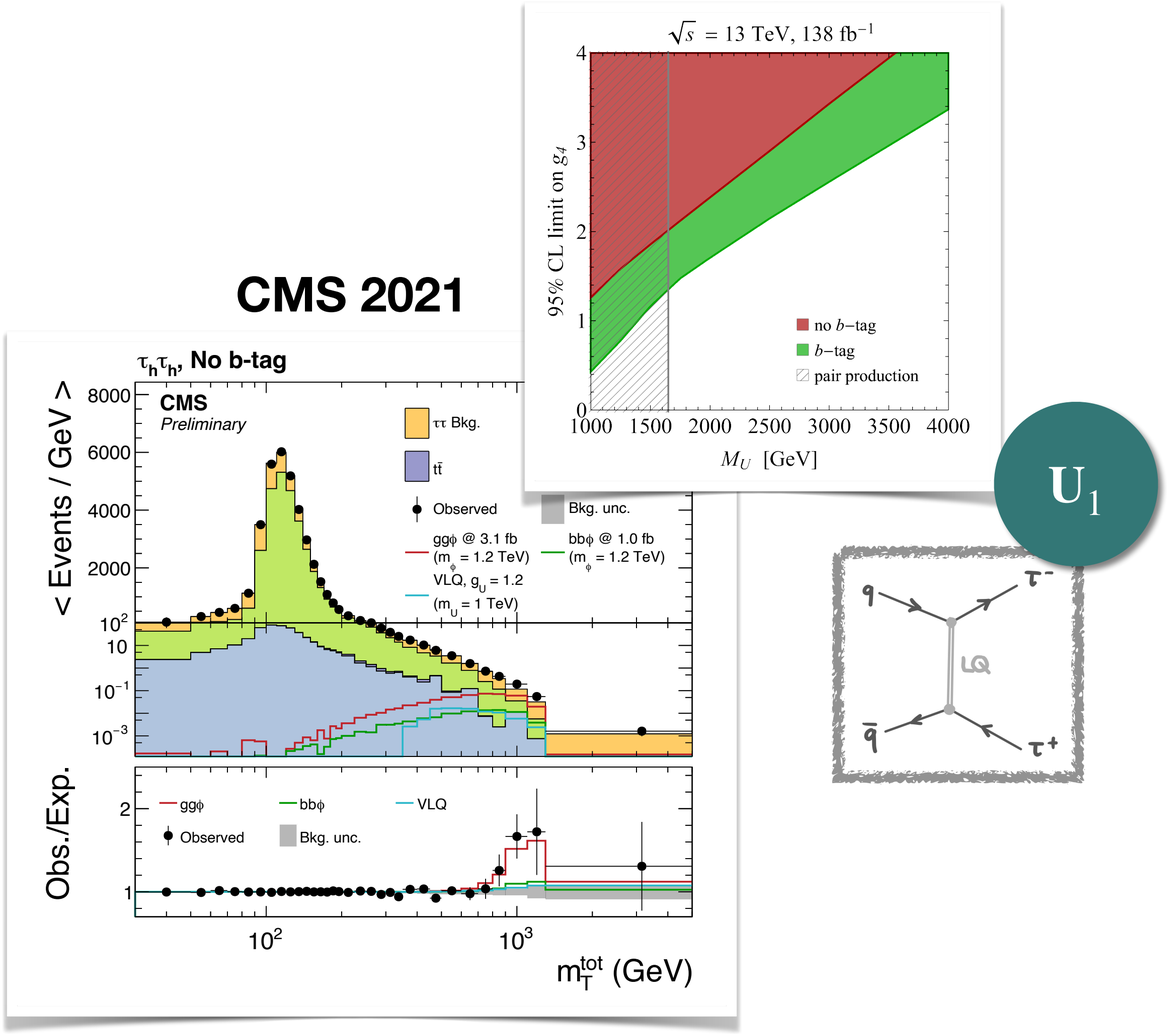
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Technische Universität München

Drell-Yan production of leptoquarks coupling to heavy quark flavours

Luc Schnell

Workshop on Tools for High Precision LHC Simulations
November 4, 2022



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

1. Introduction

1.1 Low-energy anomalies

1.2 UV-complete models

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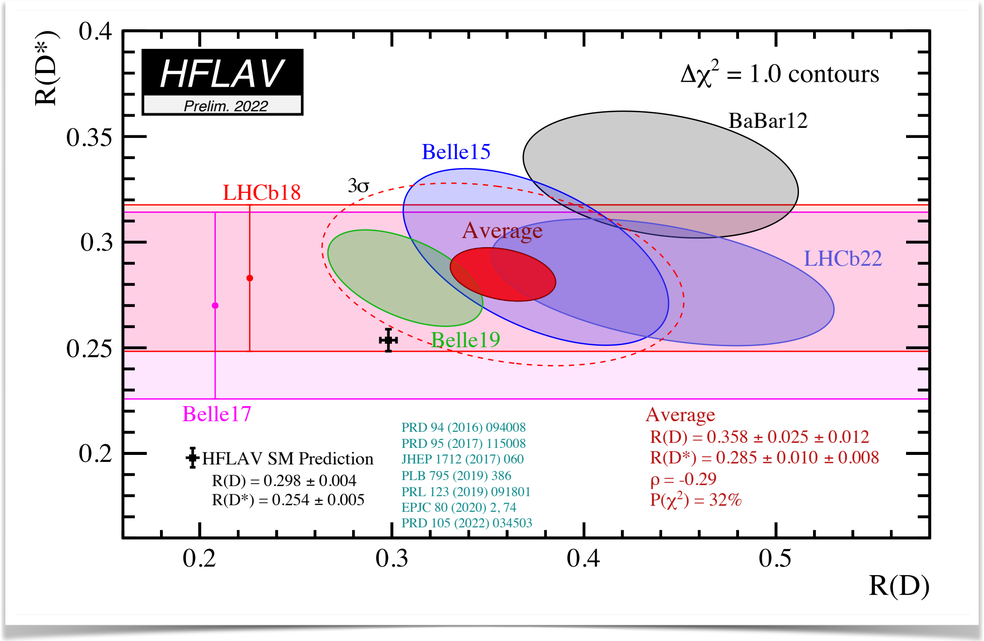

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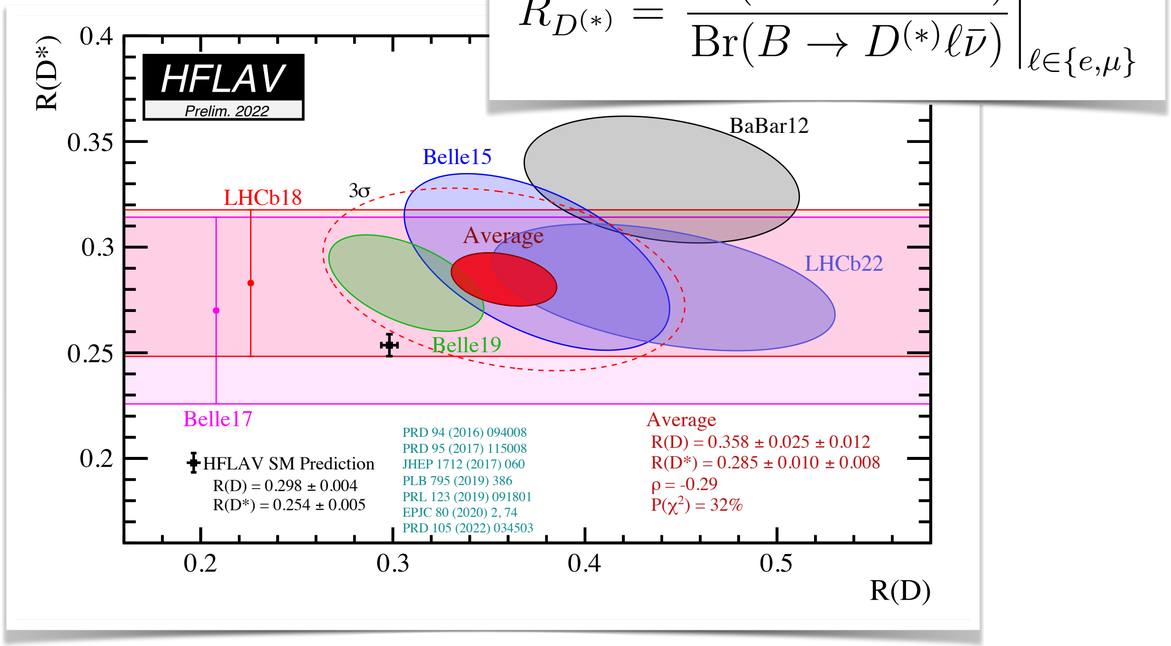

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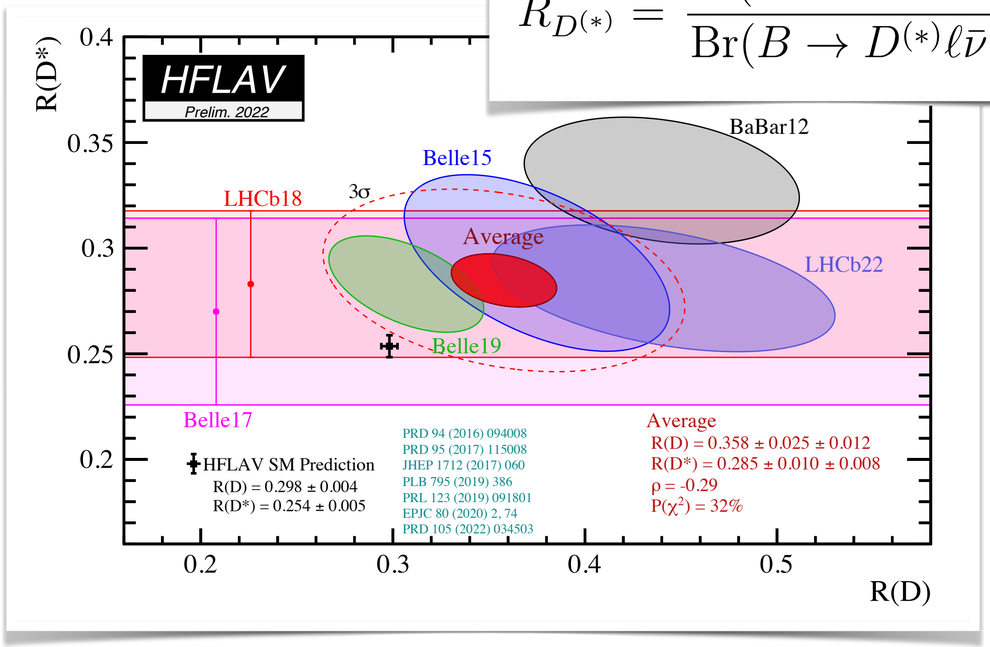

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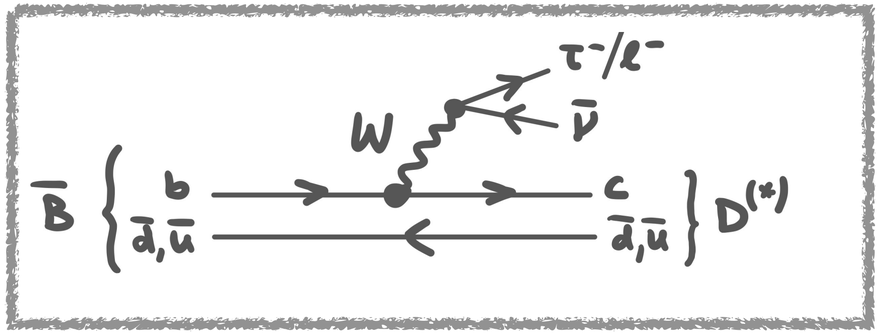

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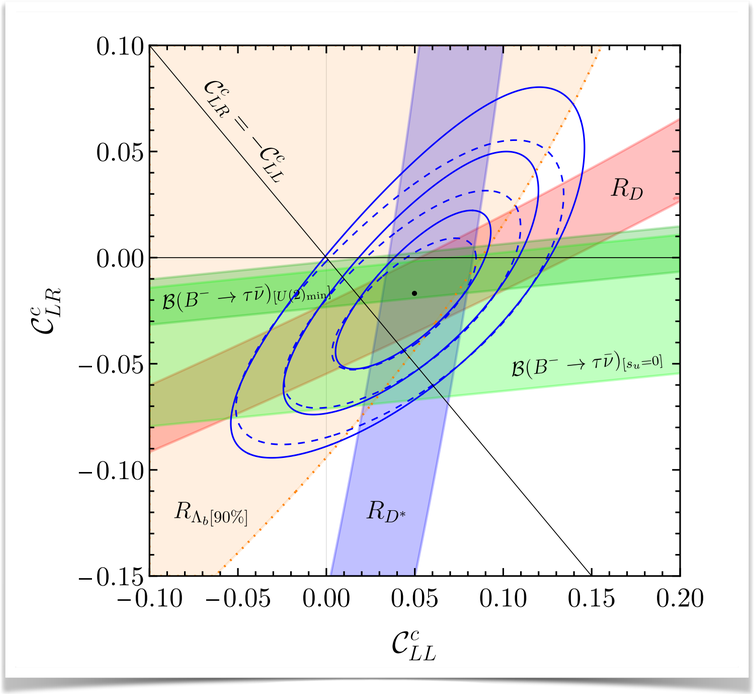

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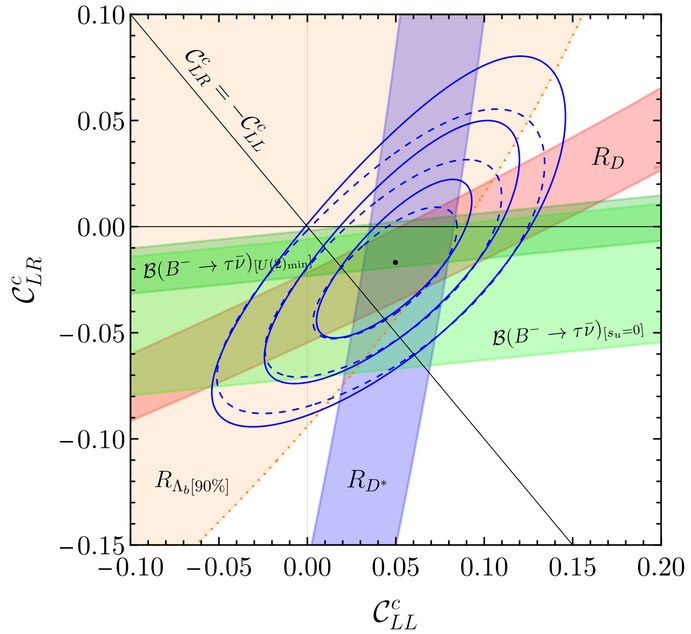

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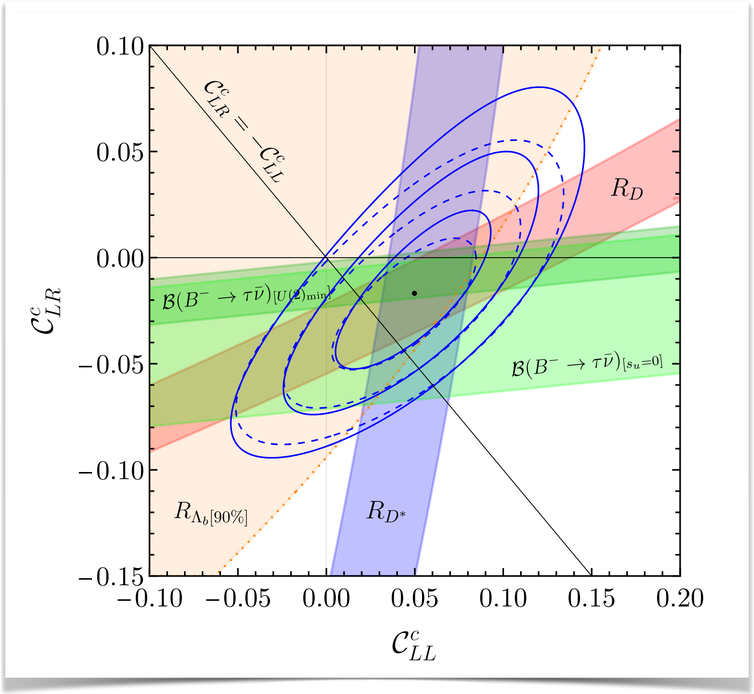

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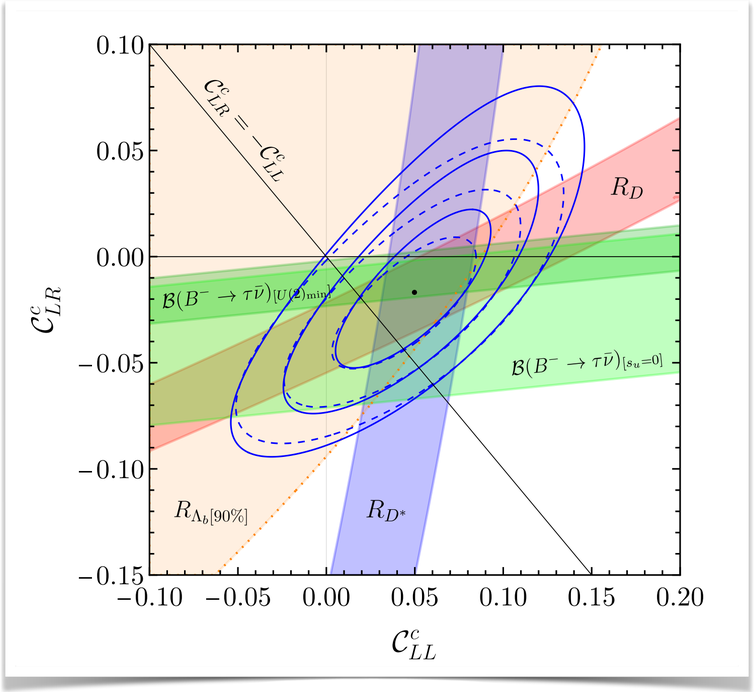

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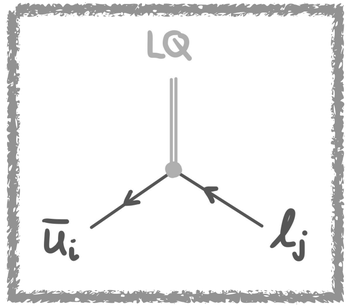

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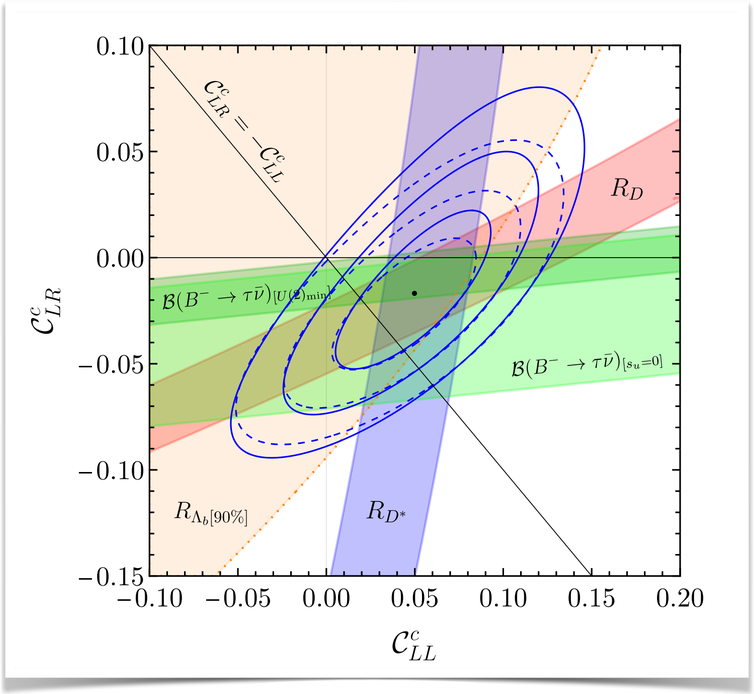

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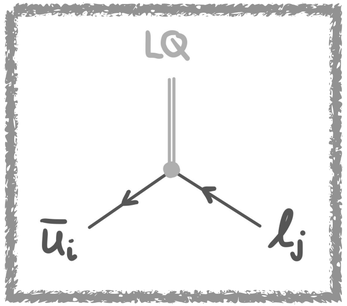

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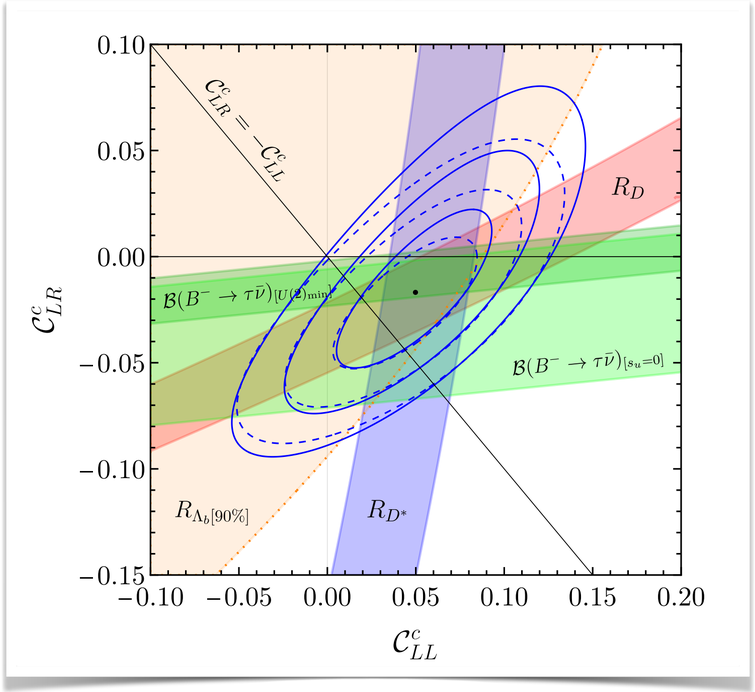

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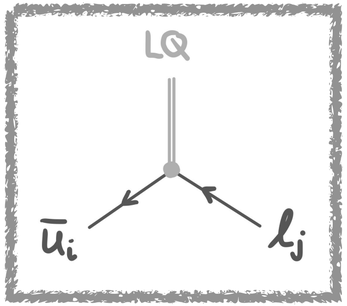

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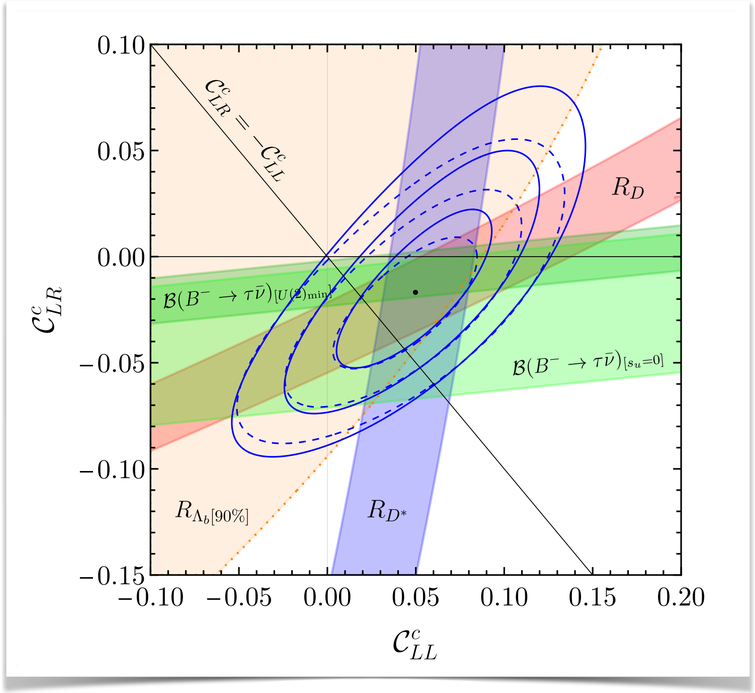

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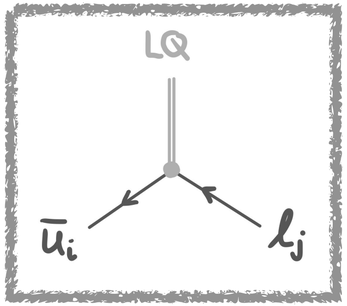

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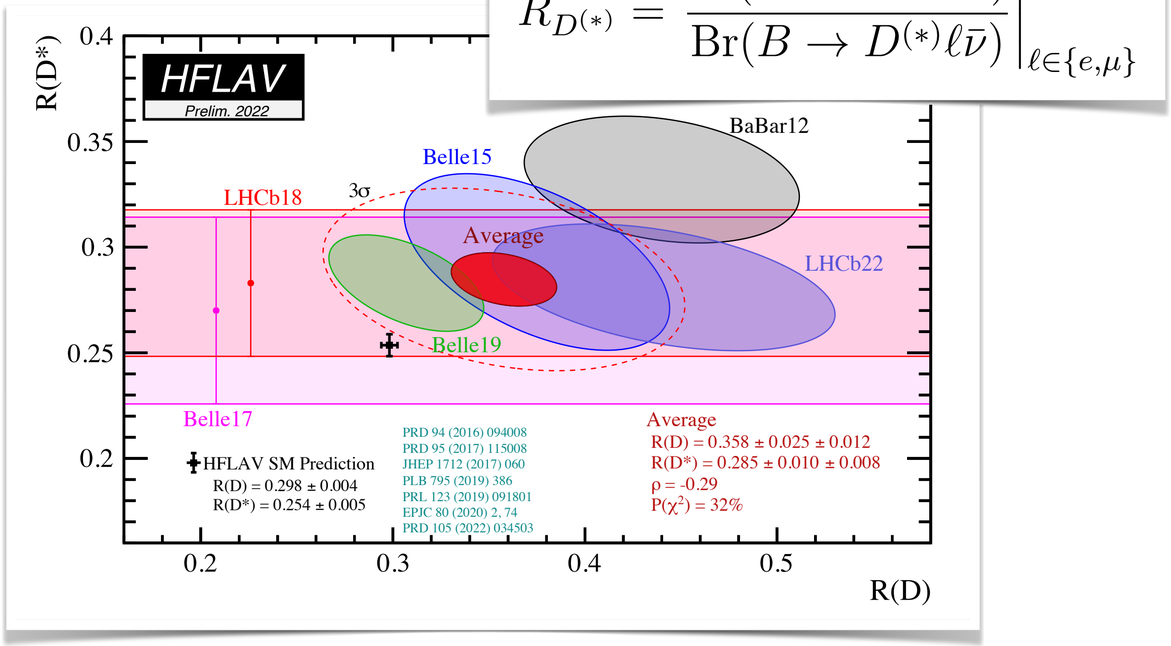

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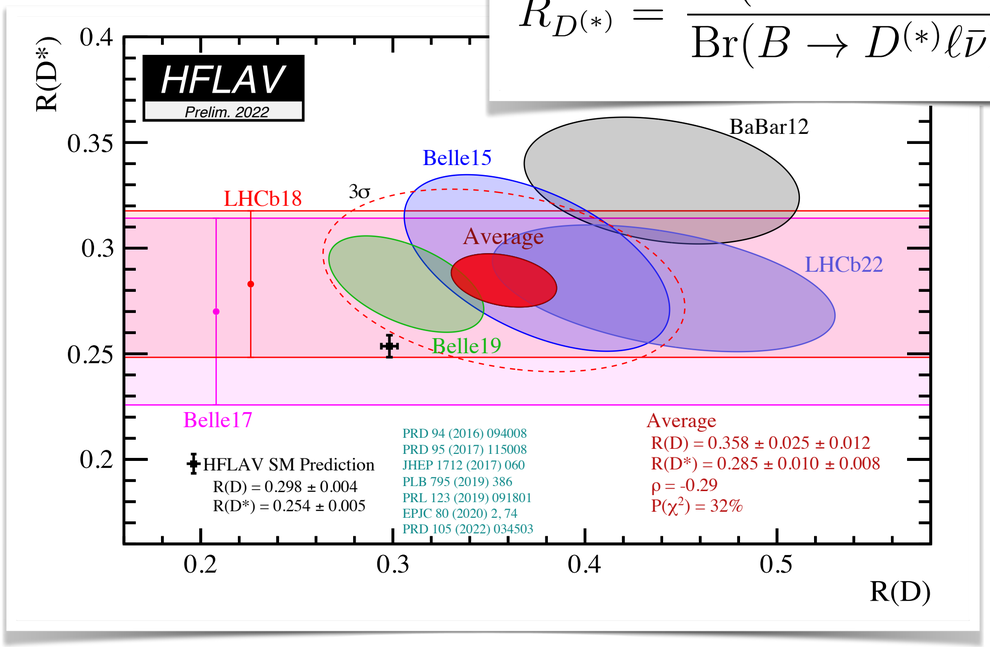

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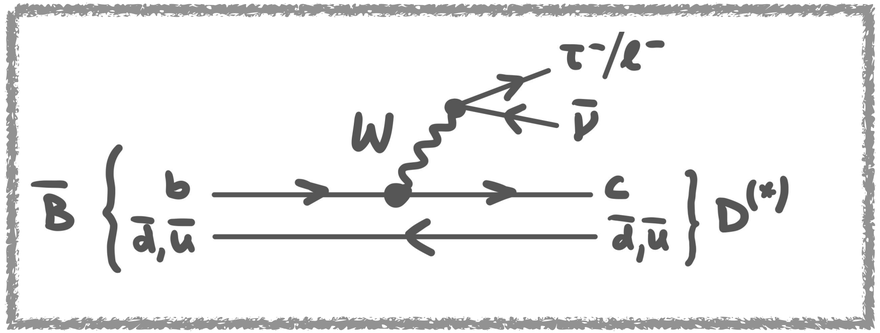

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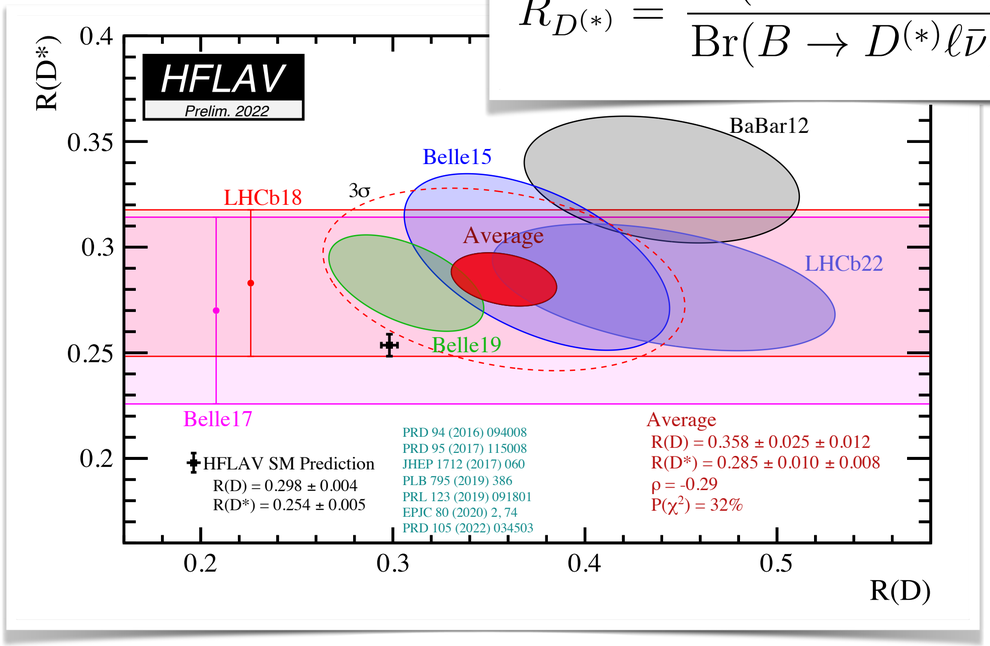

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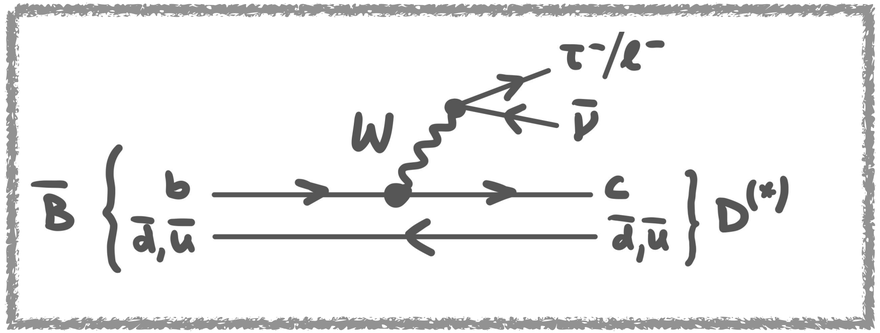

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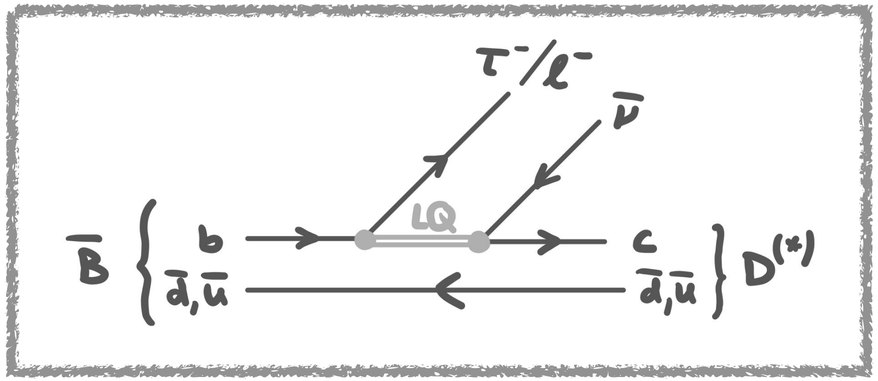

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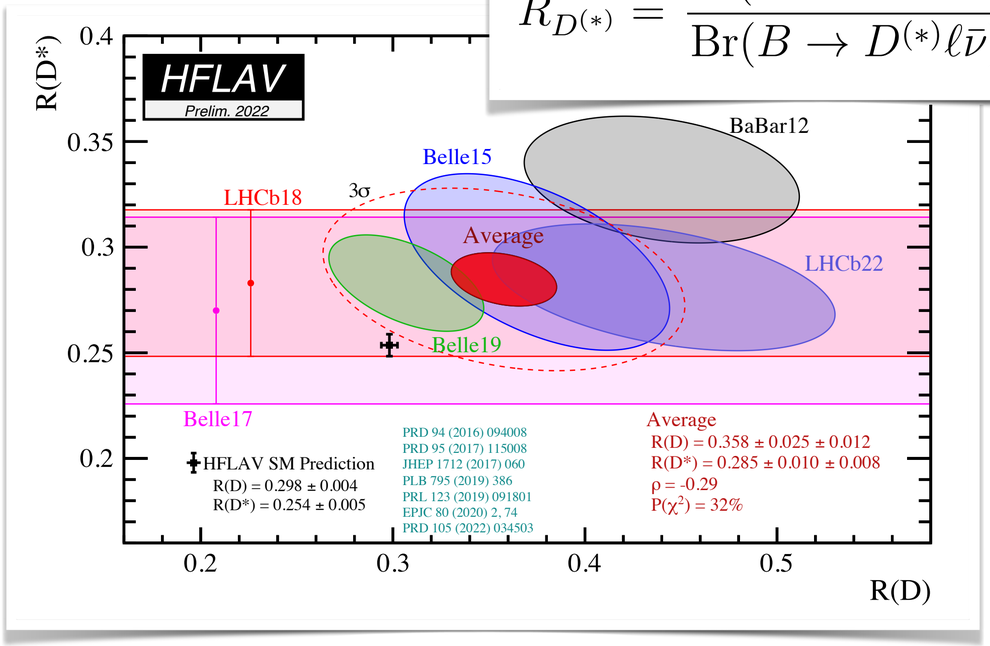

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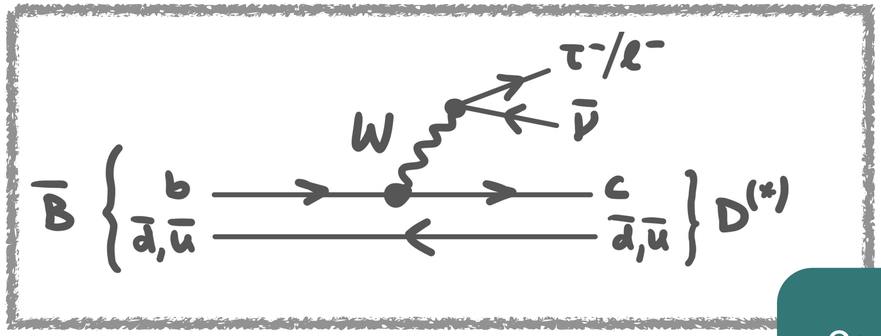

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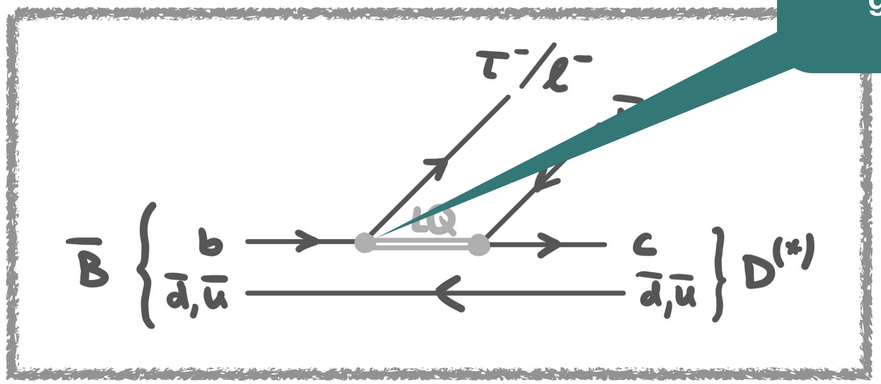

Couplings mainly to third fermion generation.

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$\mathbf{U_1}$

$\mathbf{Z'}$

1. Introduction

1.2 UV-complete gauge models

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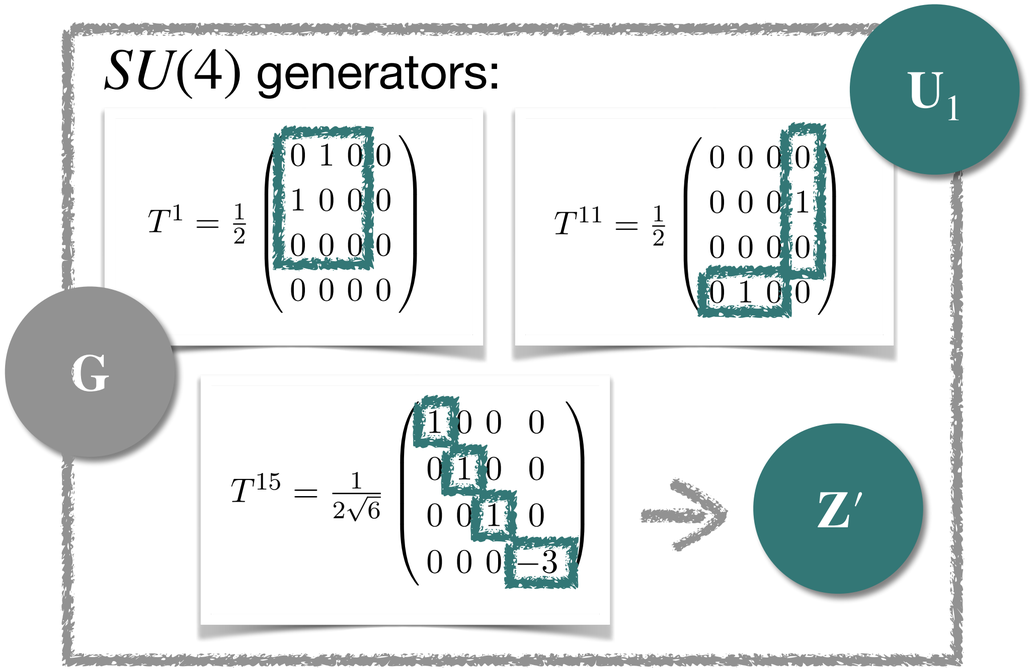

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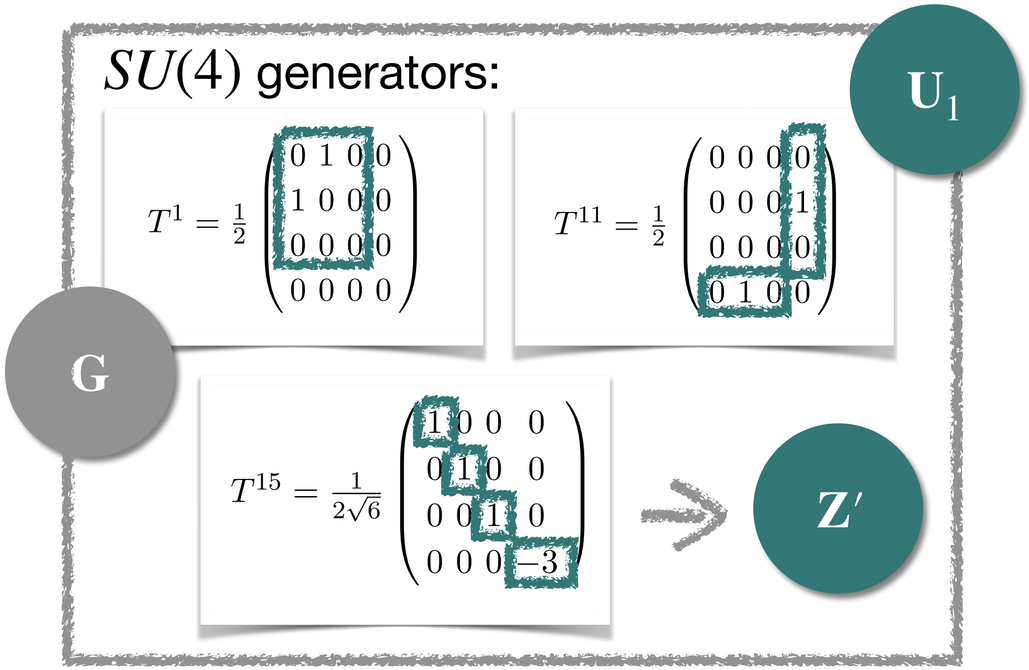

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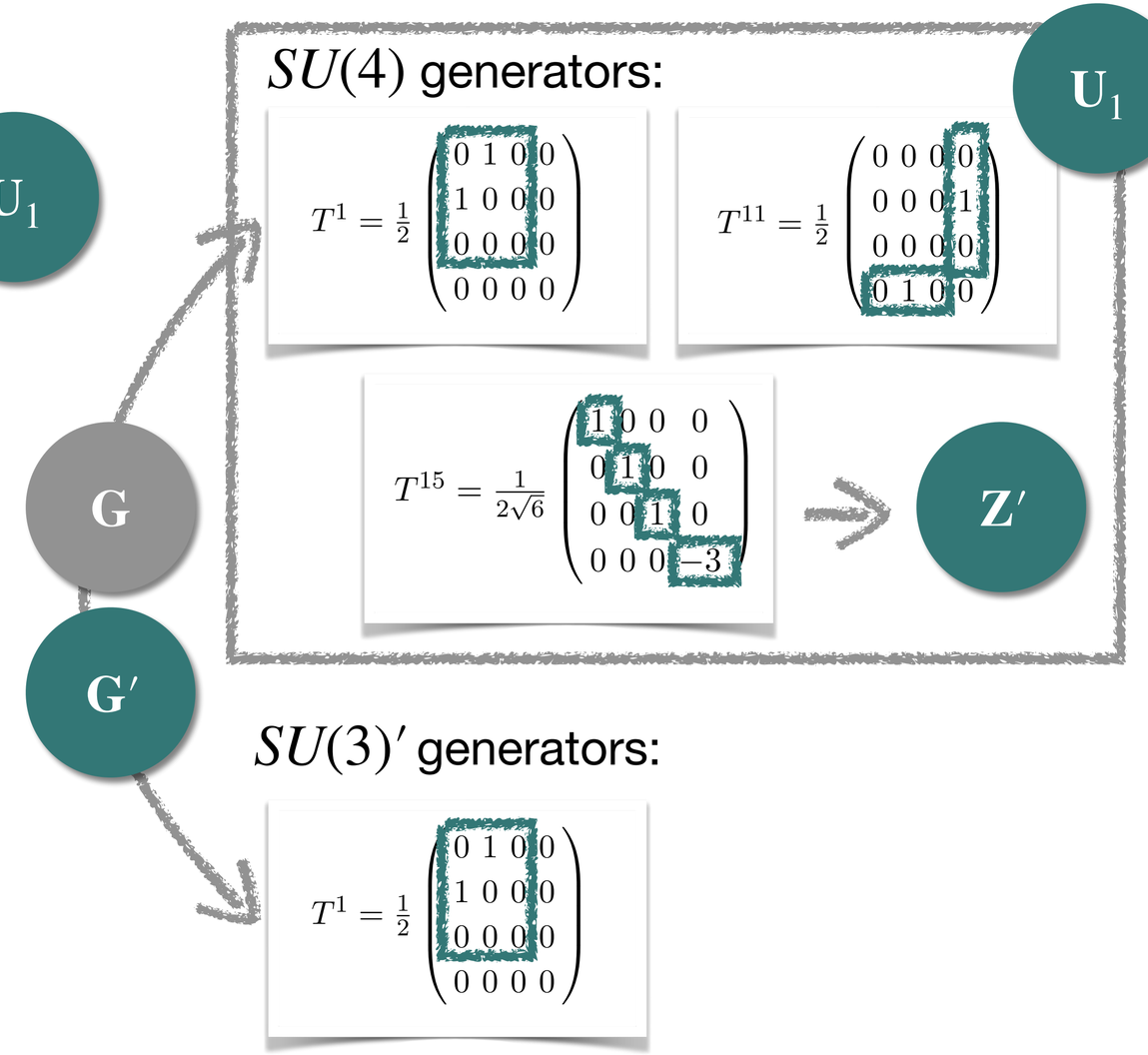

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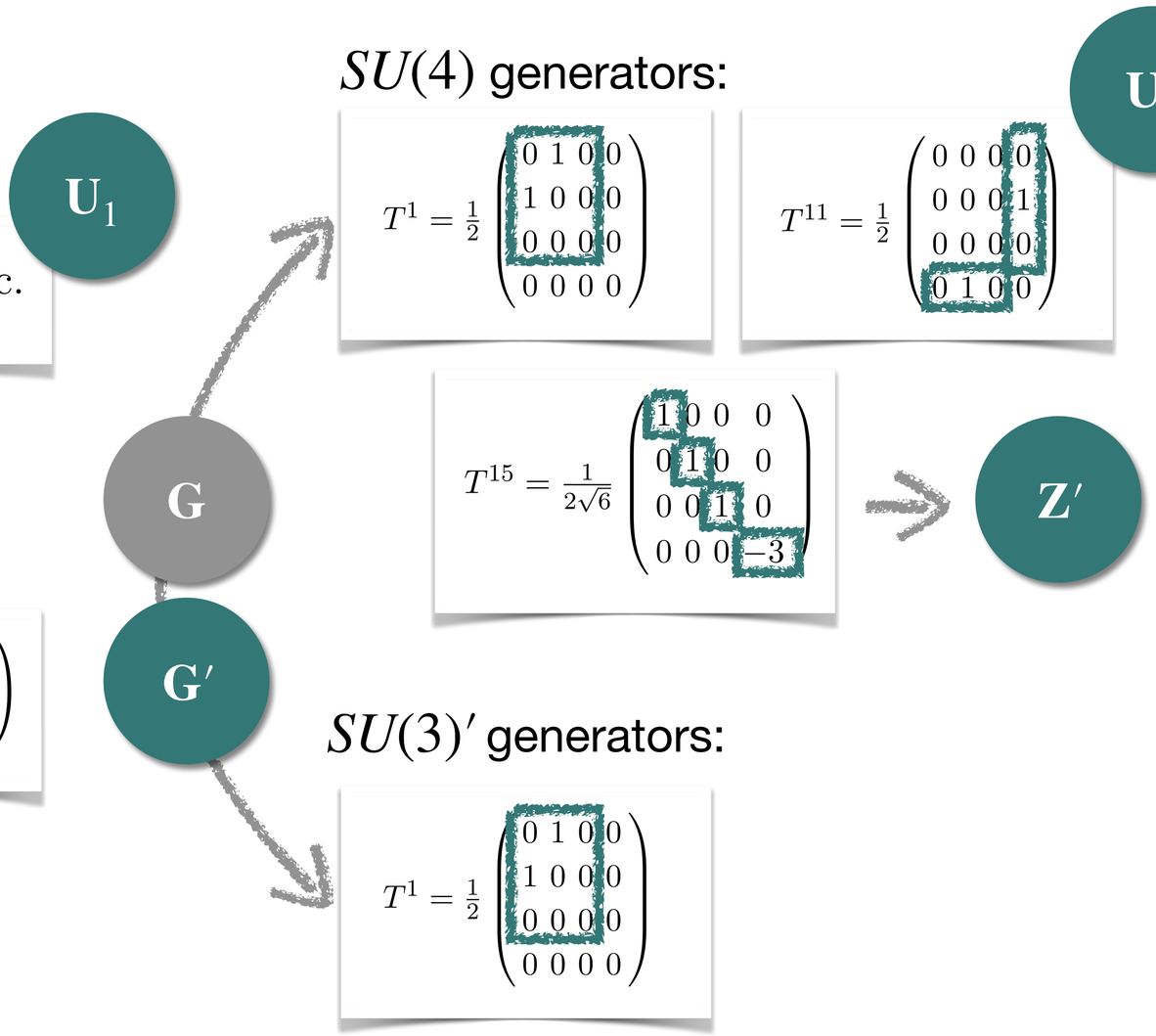

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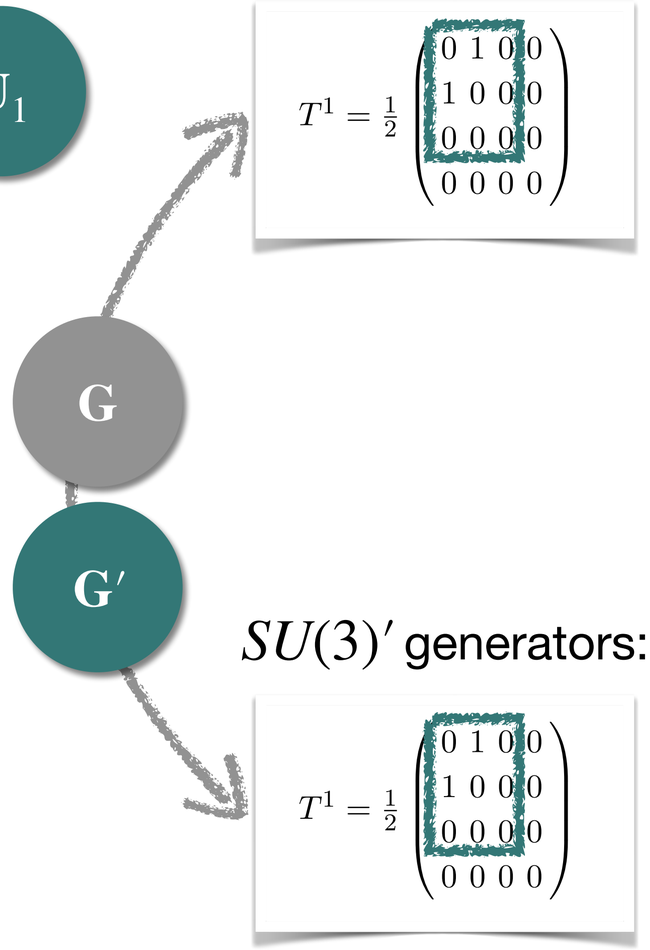

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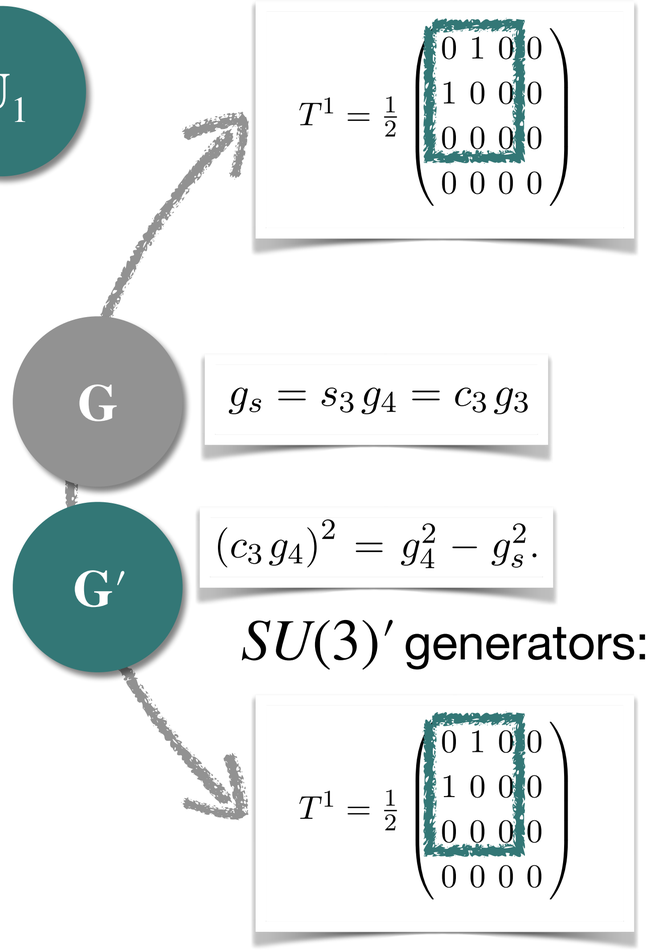

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2. Constraints from the LHC

2.1 Channels

2.2 Drell-Yan production

2.3 Single-resonant production

2. Constraints from the LHC

2.1 Channels

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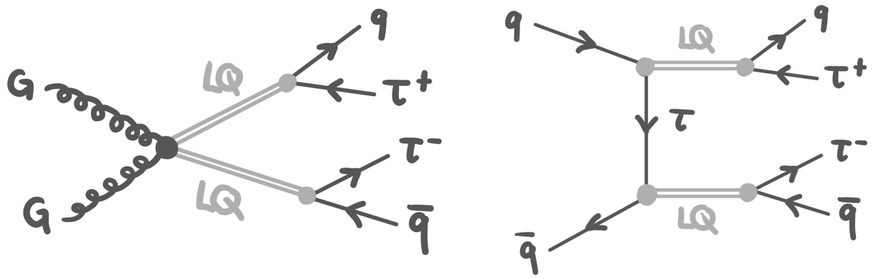

Pair-production

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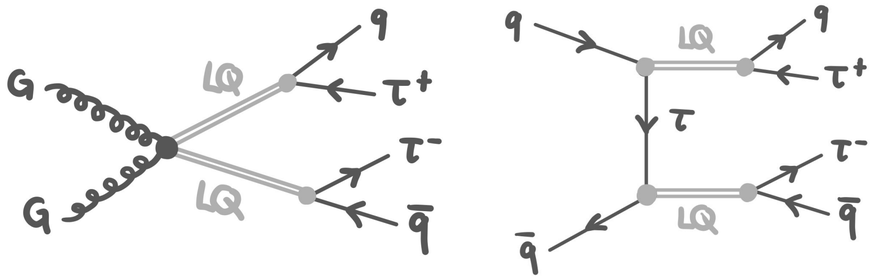

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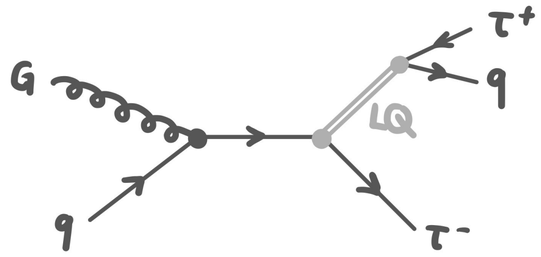

Single production

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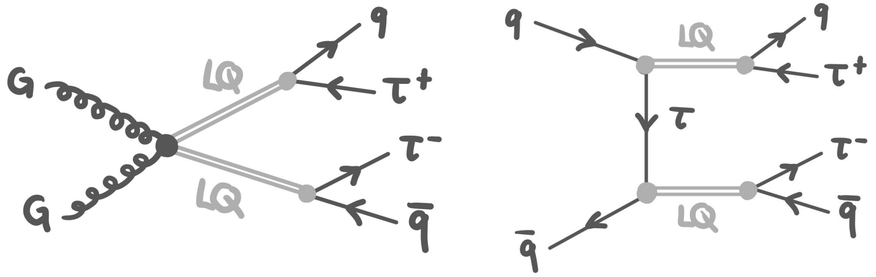

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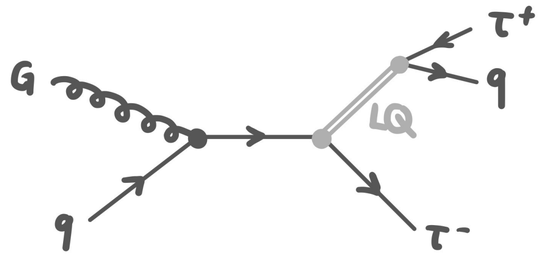

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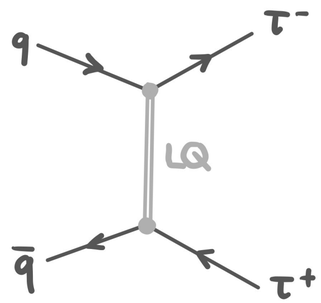

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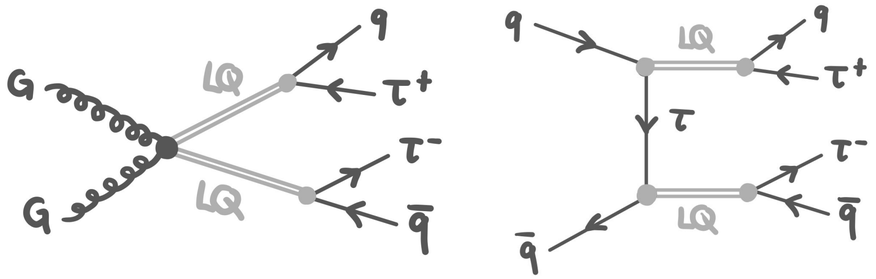

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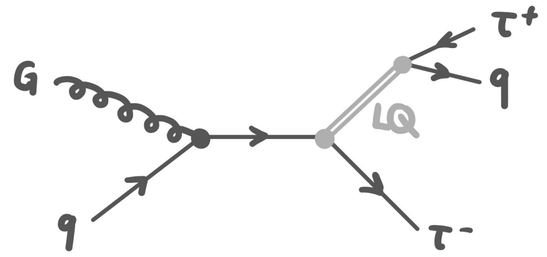

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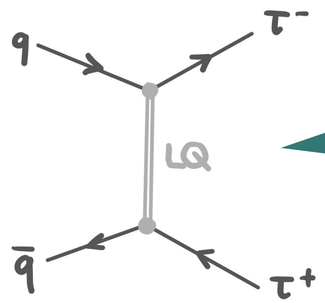

Non-resonant signatures in the tails

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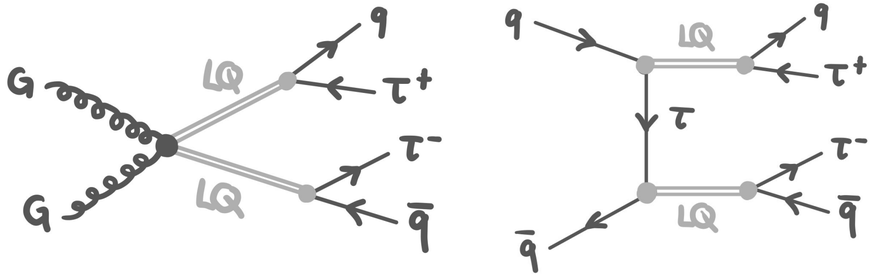

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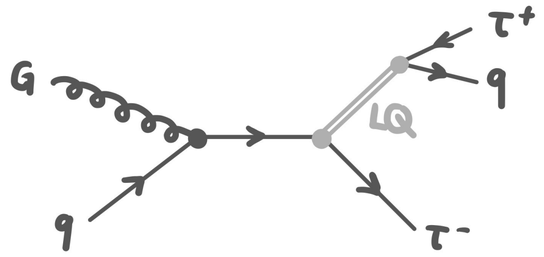

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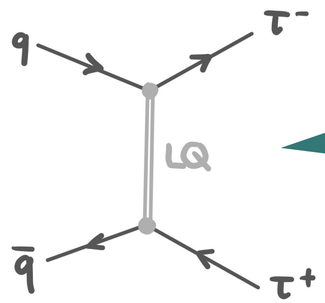

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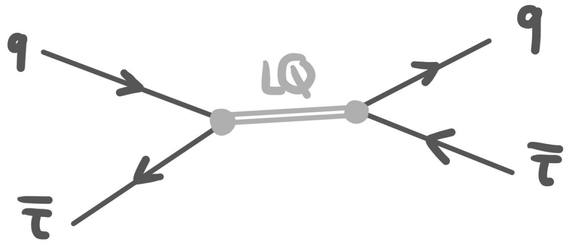

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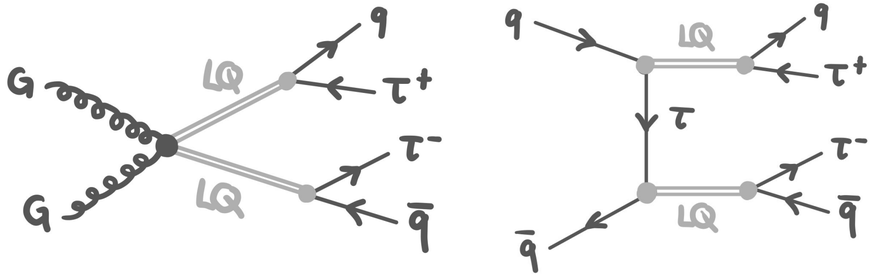

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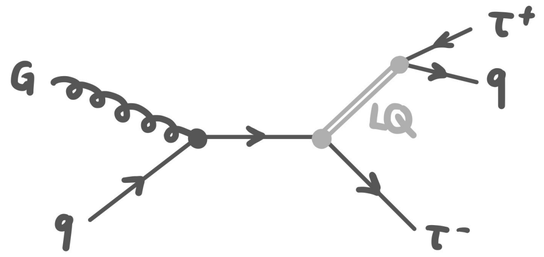

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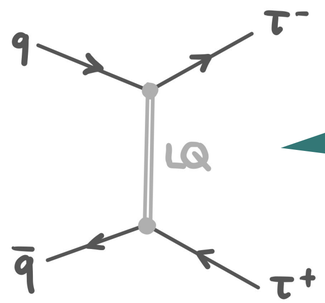

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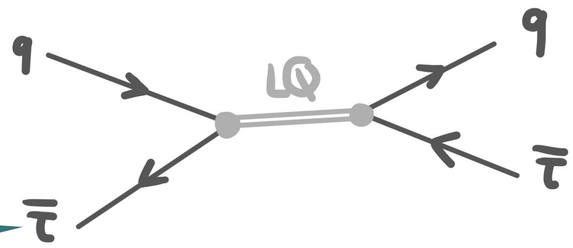

Lepton PDF of the proton

Single-resonant production

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2.2 Drell-Yan production: Overview

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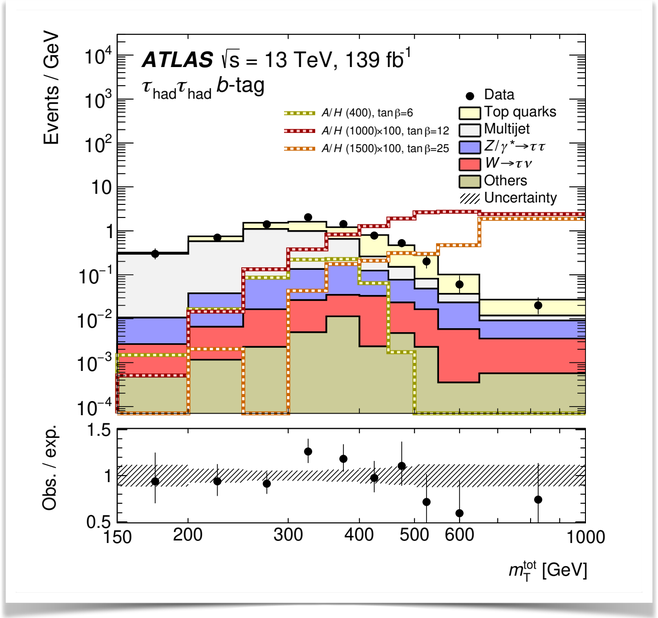
ATLAS 2020



Source: ArXiv:2002.12223 (ATLAS)

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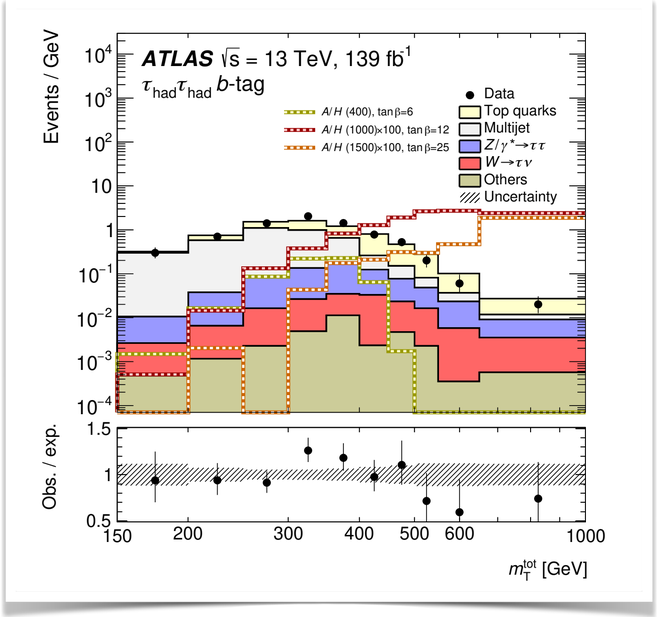

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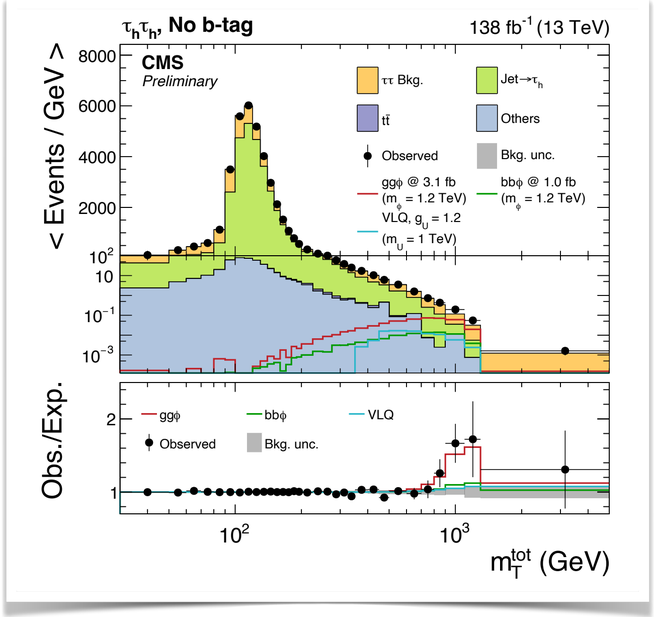
CMS 2021



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

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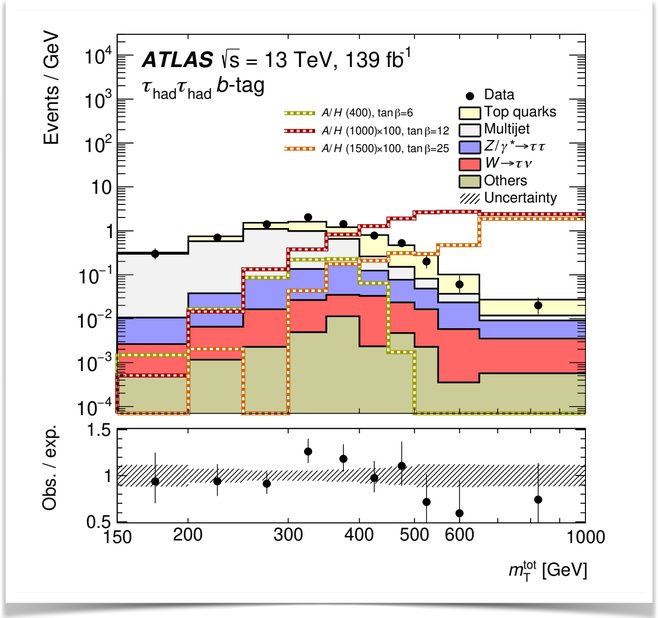

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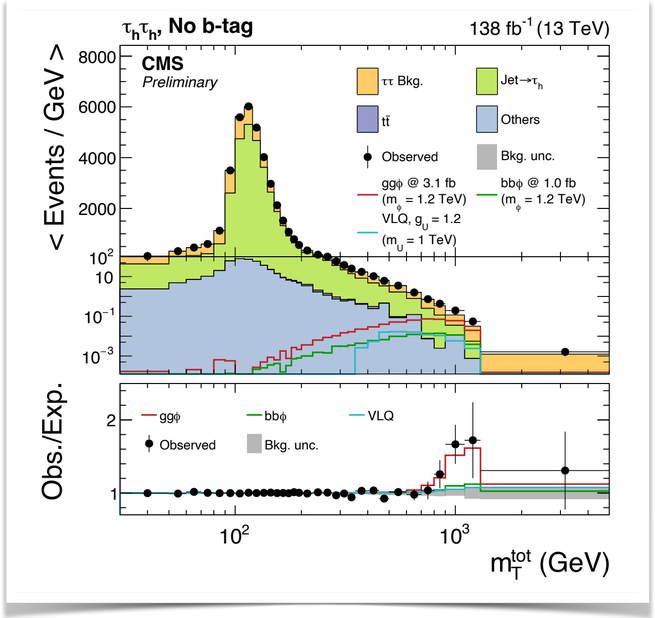

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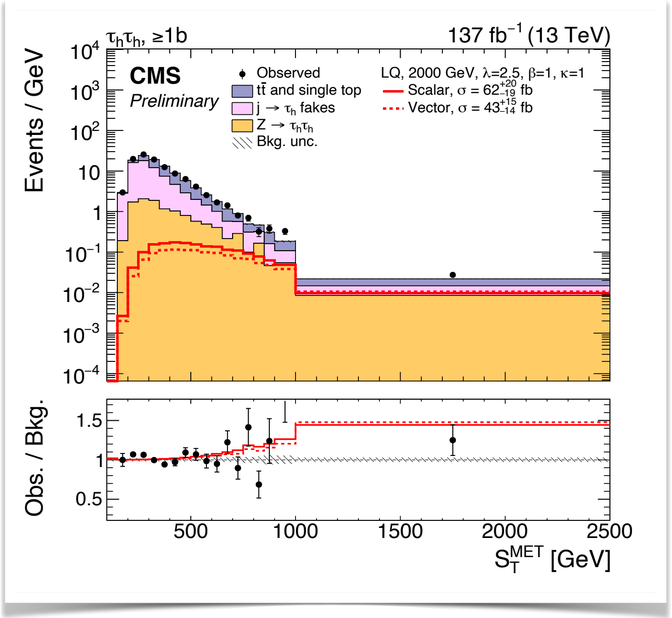
CMS 2022



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

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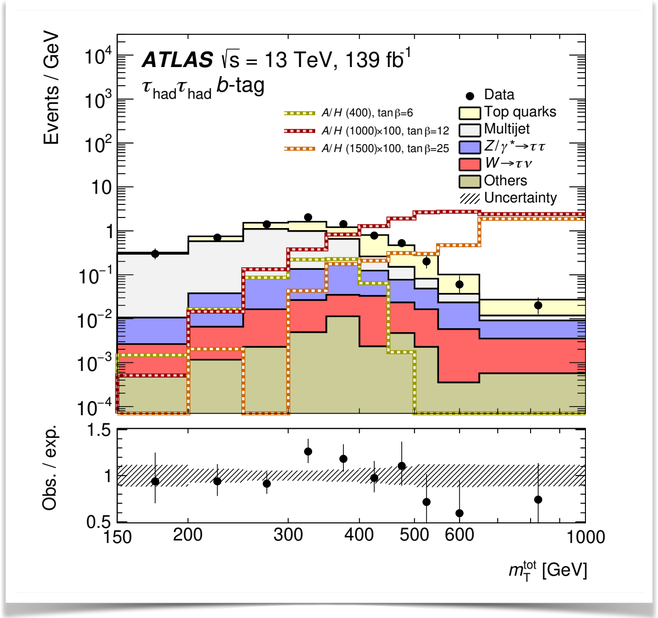

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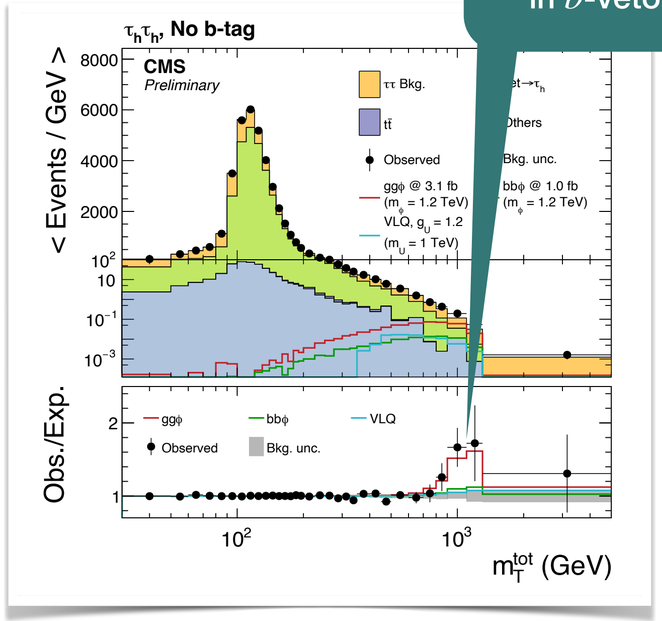
CMS 2021

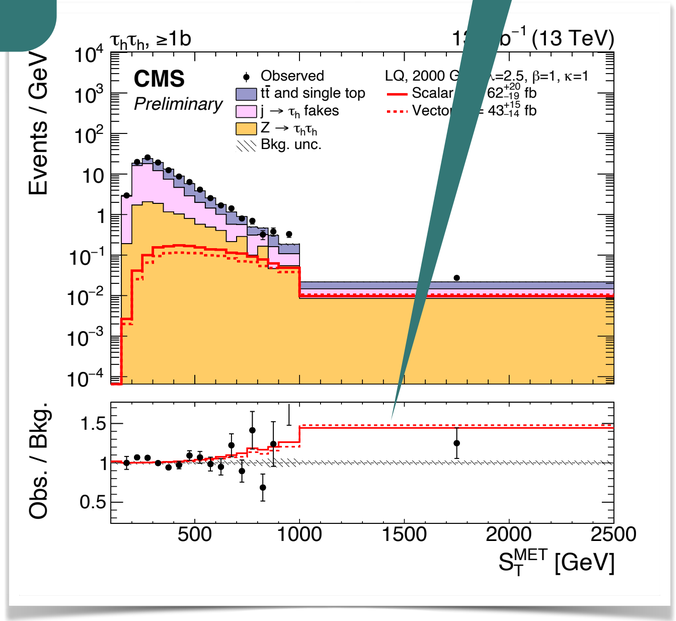
Resonant 3σ excess in b-veto (???)



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

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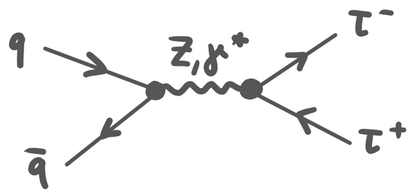
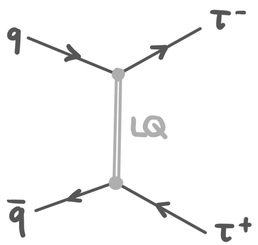


SM LO



LQ LO

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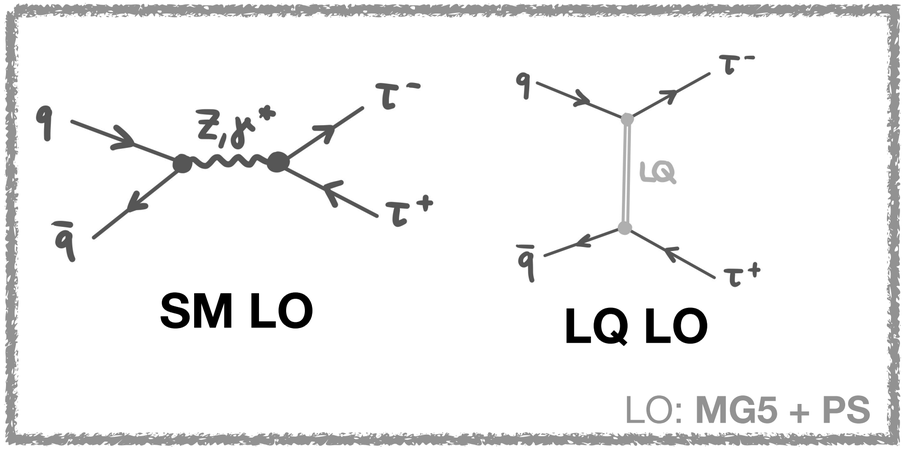

LO: **MG5 + PS**

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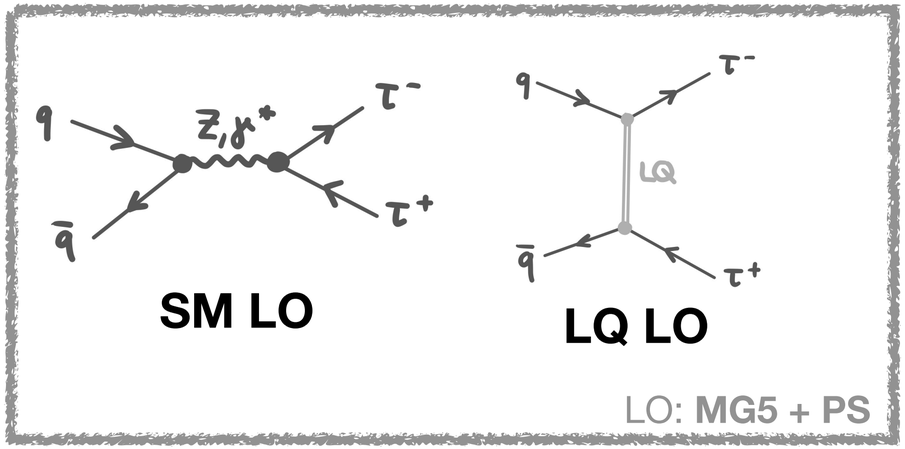

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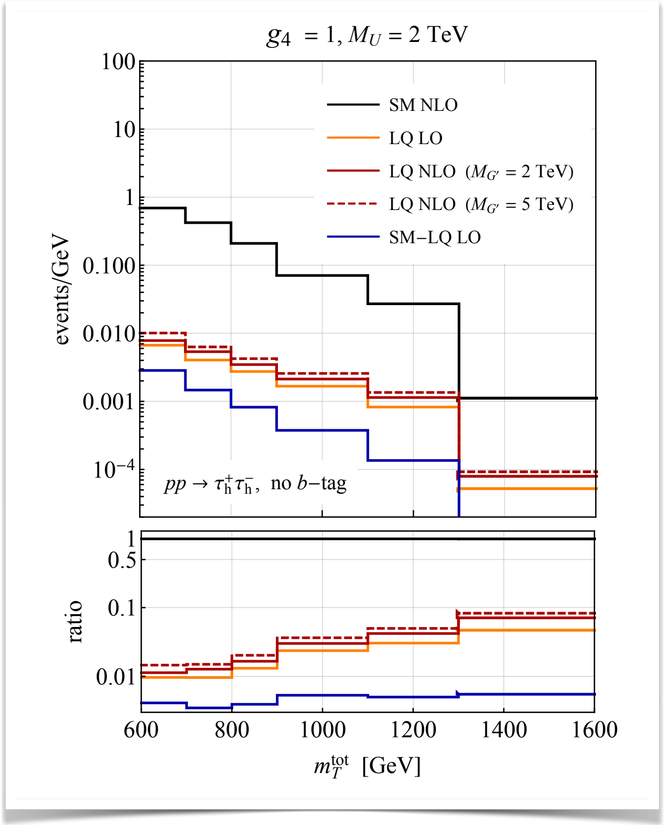

Source: ArXiv:2209.12780
(U. Haisch, LS, S. Schulte)

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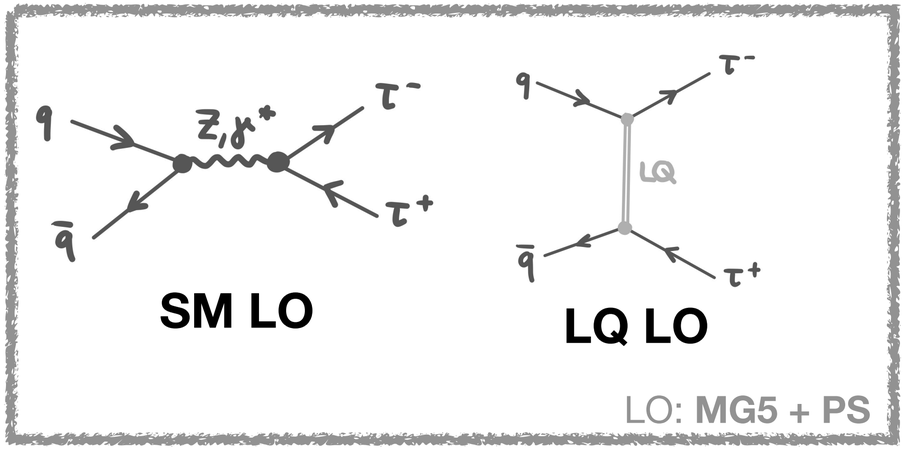

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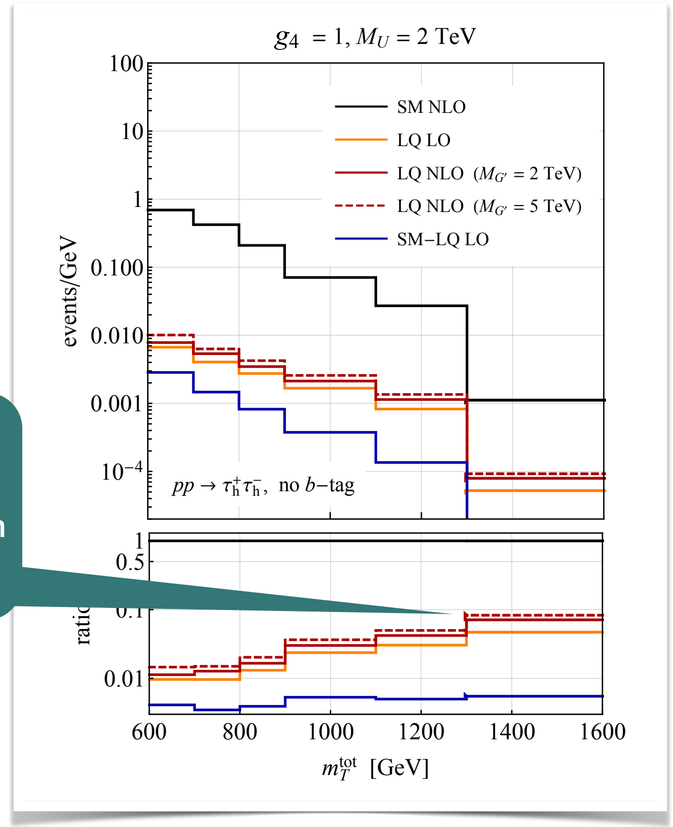

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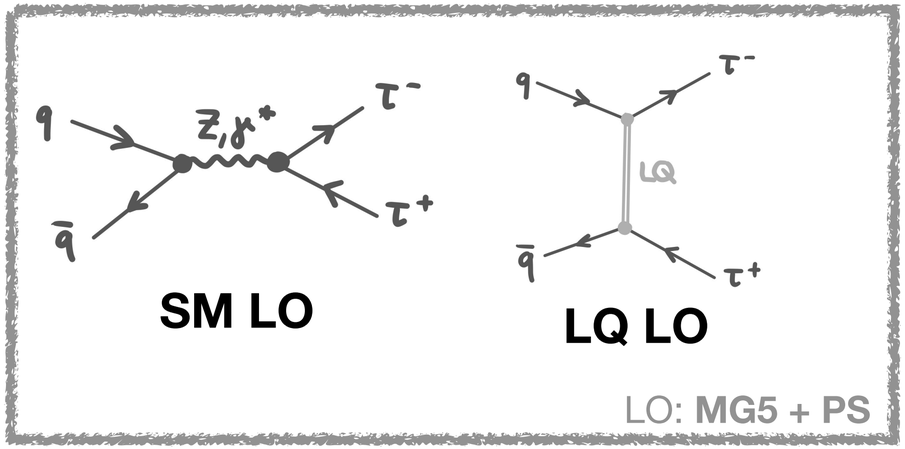

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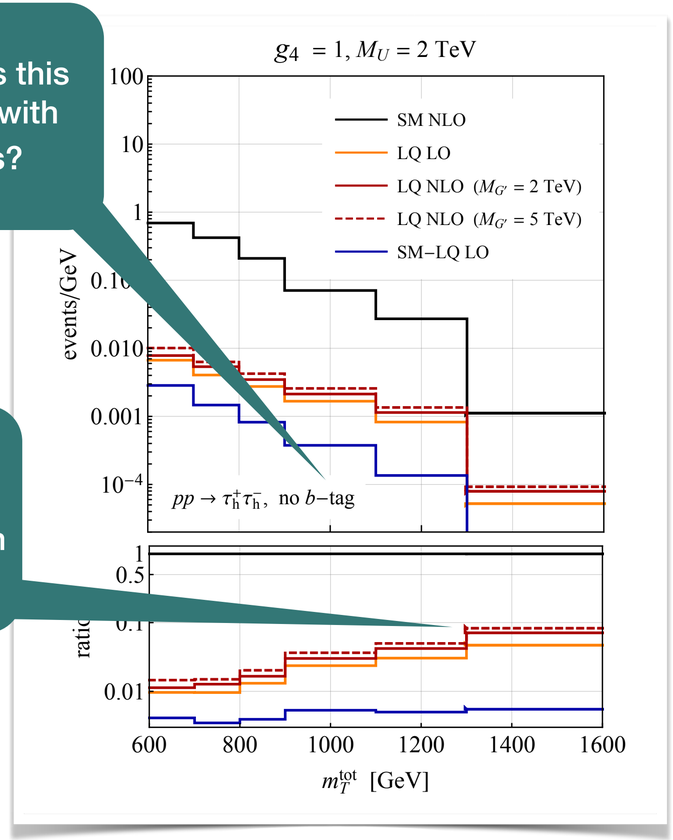

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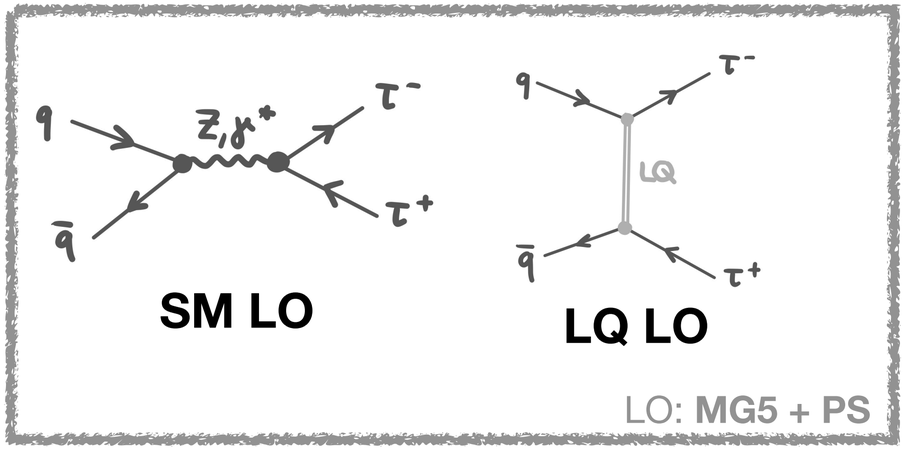
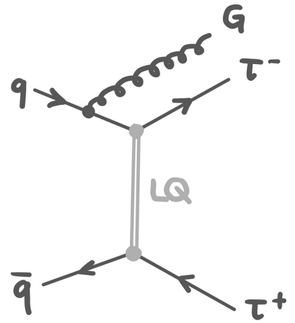
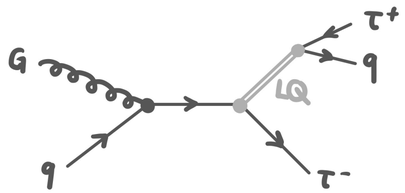




LQ NLO real (non-res.)



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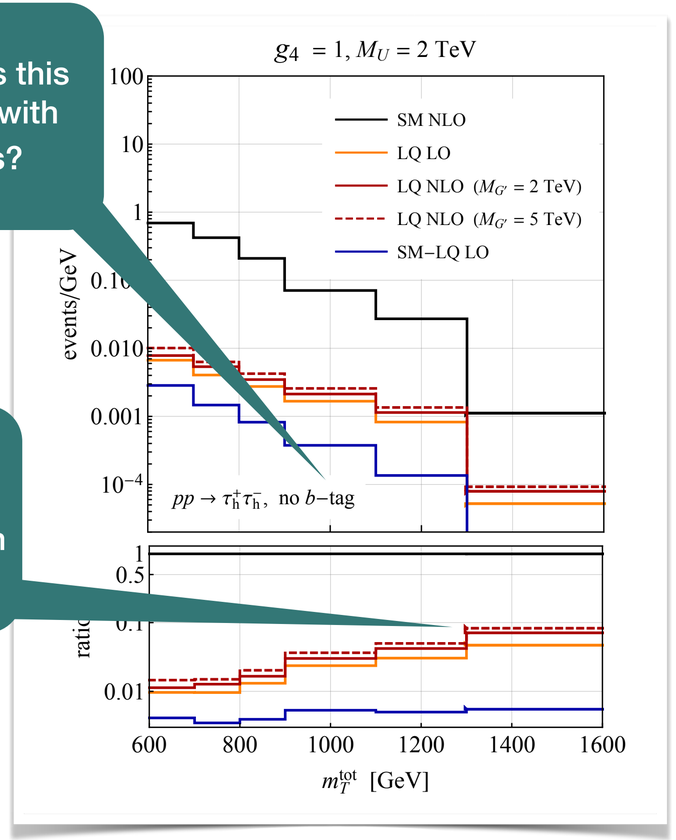

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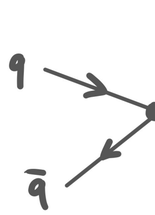

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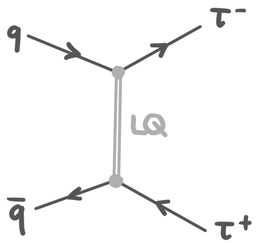

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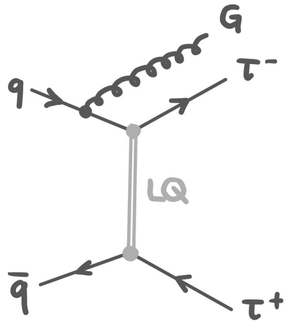
LO: **MG5 + PS**



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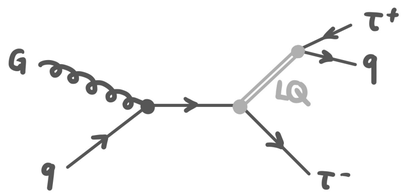

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Partial NLO: **MG5 + PS + Merging**

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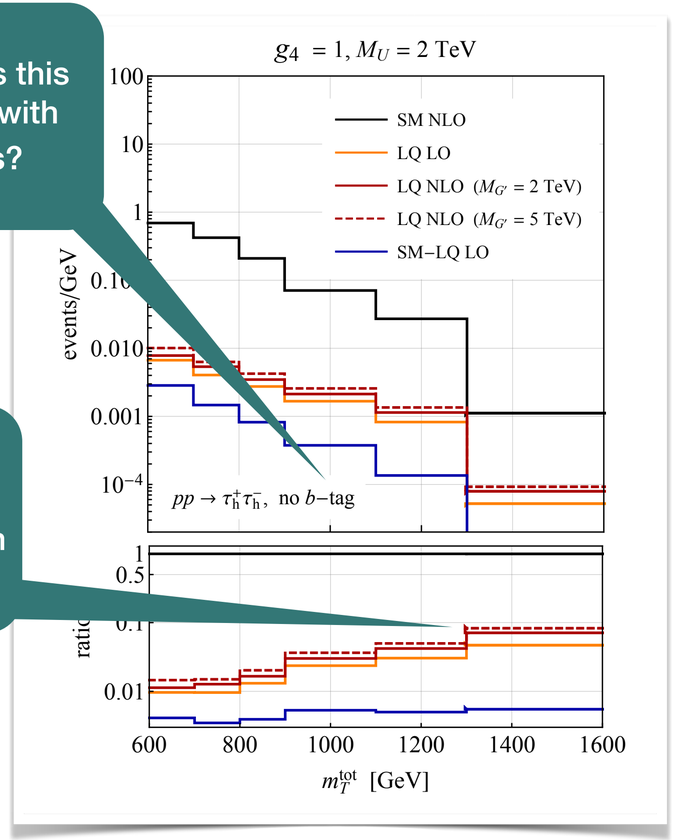

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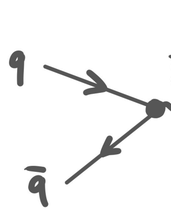

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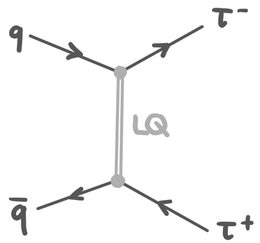

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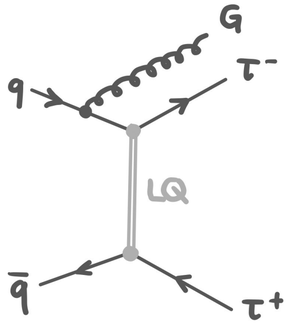

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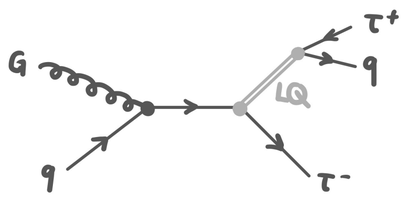

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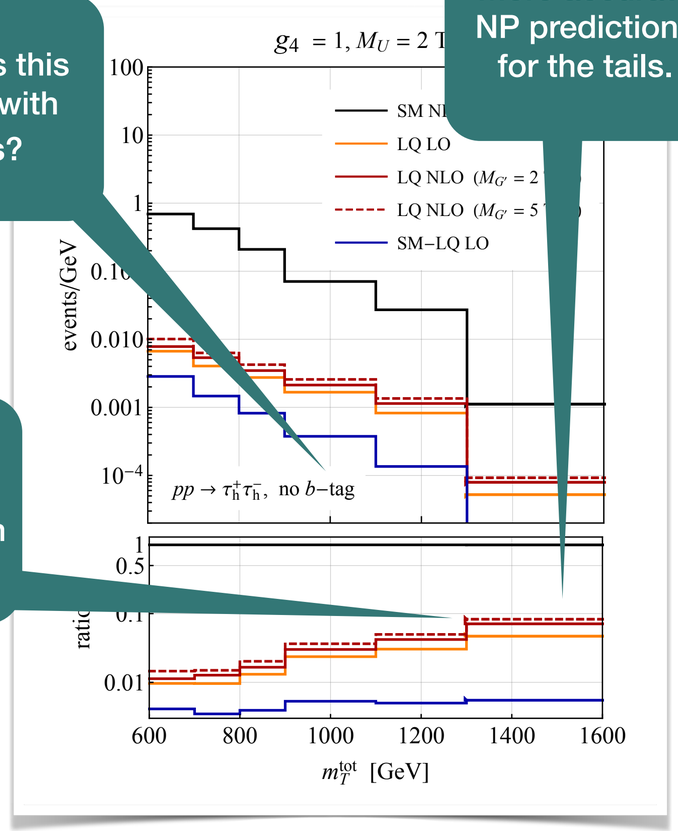

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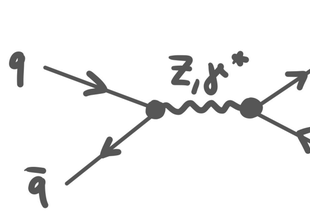

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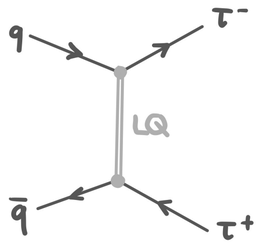

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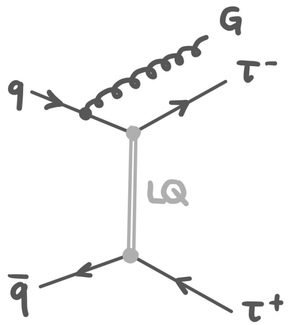

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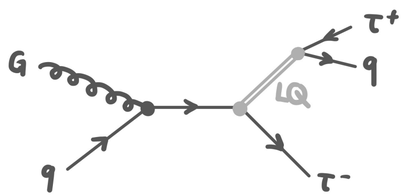

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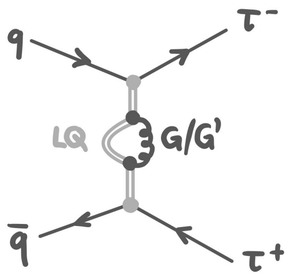

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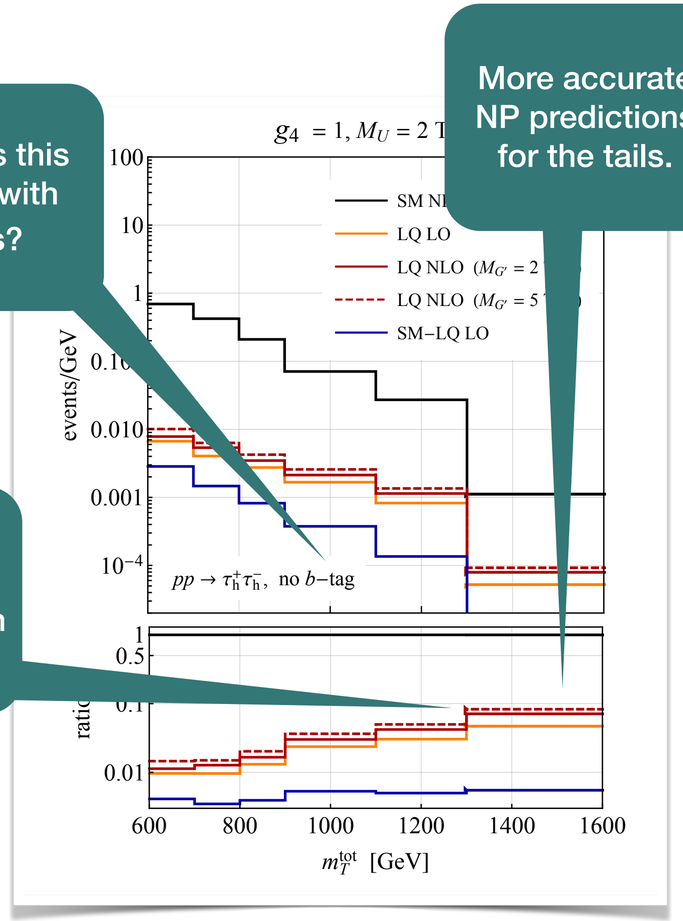

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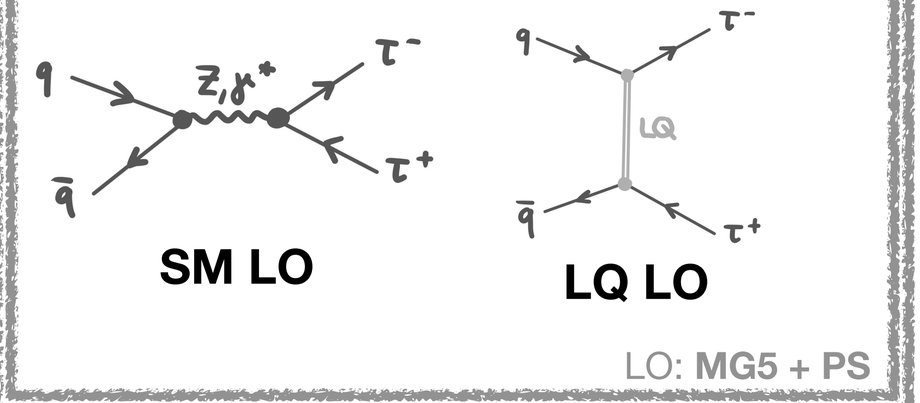

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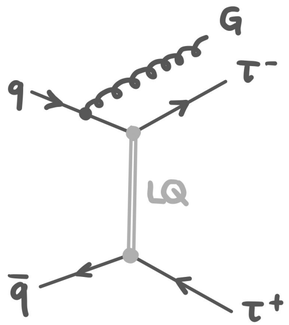

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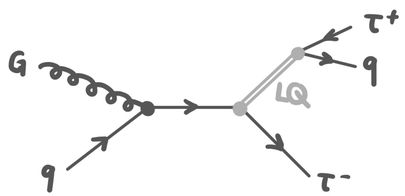

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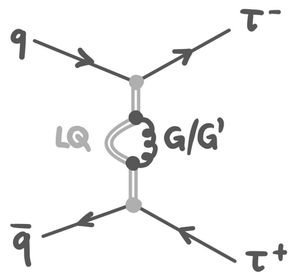

LQ NLO virtual

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

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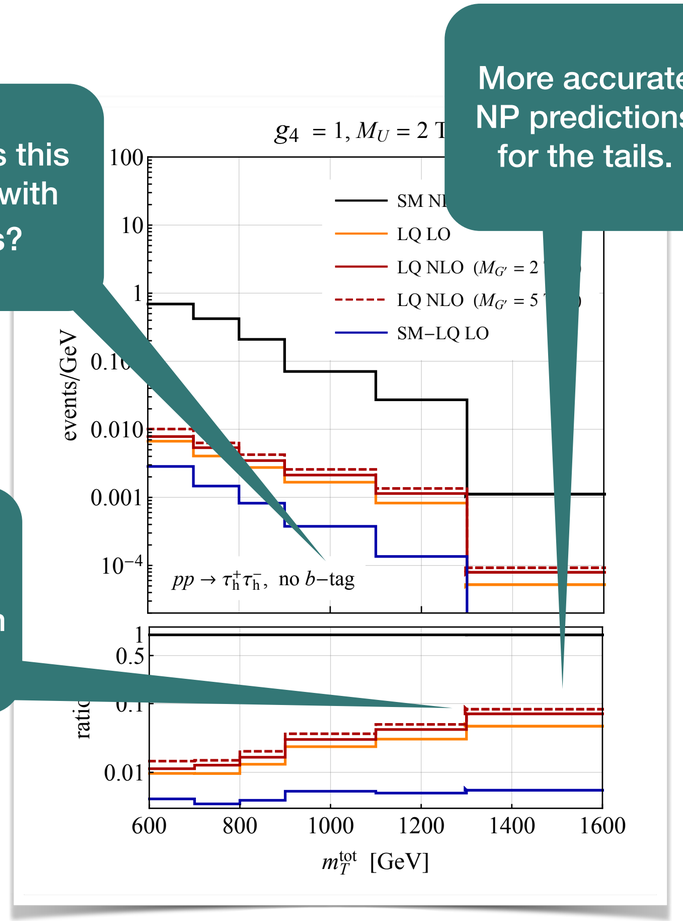

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2. Constraints from the LHC

2.2 Drell-Yan production: POWHEG-BOX implementation

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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

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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 $b_L\tau_L$).
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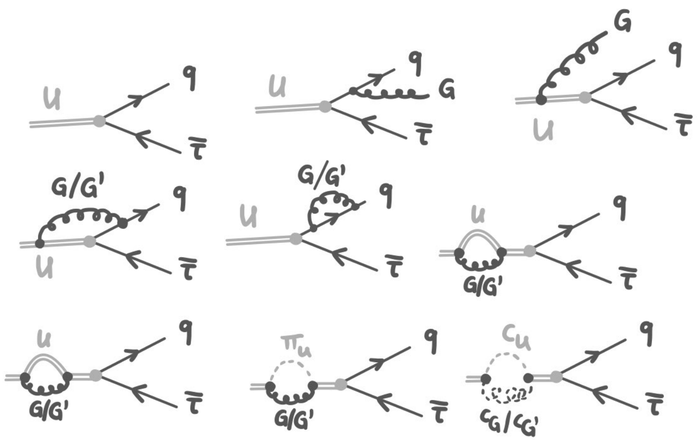
NLO width (PackageX, cross-checked with **FormCalc):**

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

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

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



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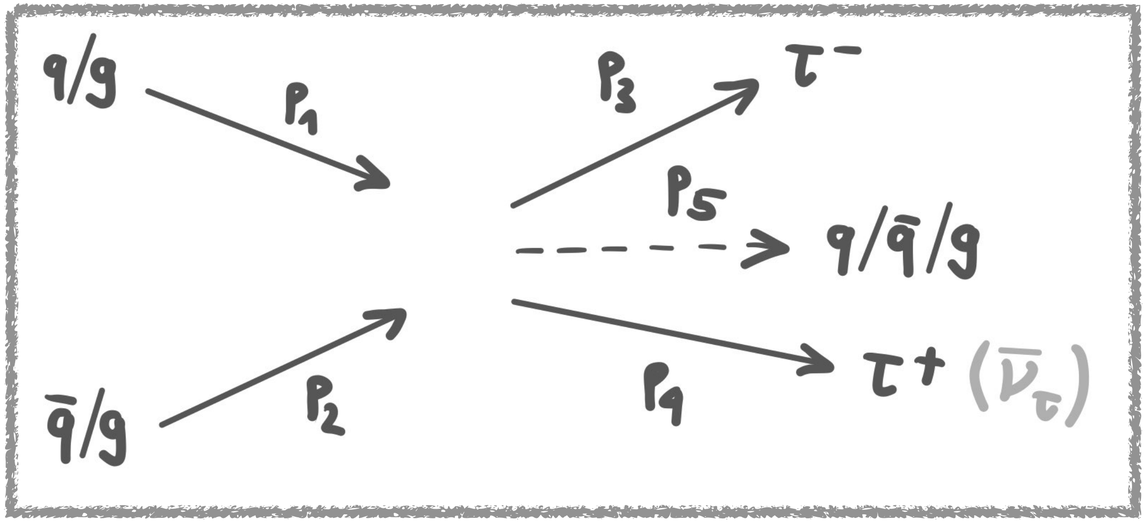
Kinematics the same as in the SM:

- 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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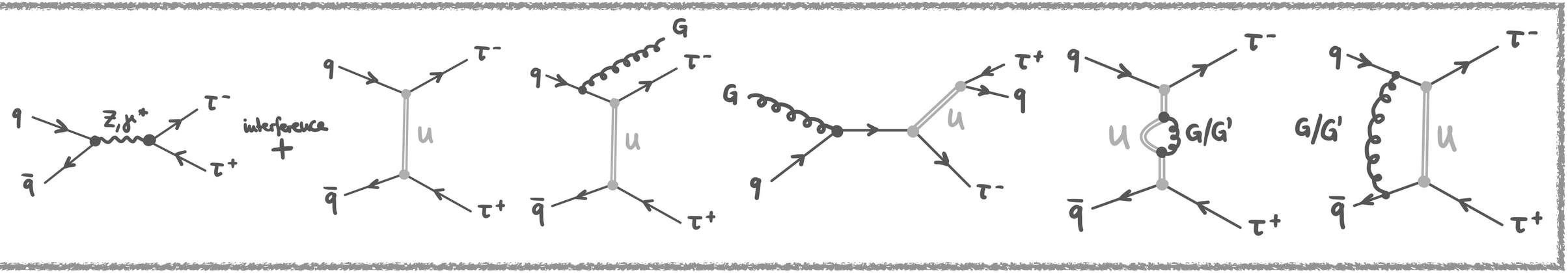

- Calculation with **PackageX**, cross-checked with **FormCalc**, numerical evaluation with **LoopTools.**
- **UV divergences cancel** between the G and G' contributions, IR divergences handled with **dimensional regularisation**.

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

2. Constraints from the LHC

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Inclusive $\mathbf{m}_{\tau\tau}$ spectra:

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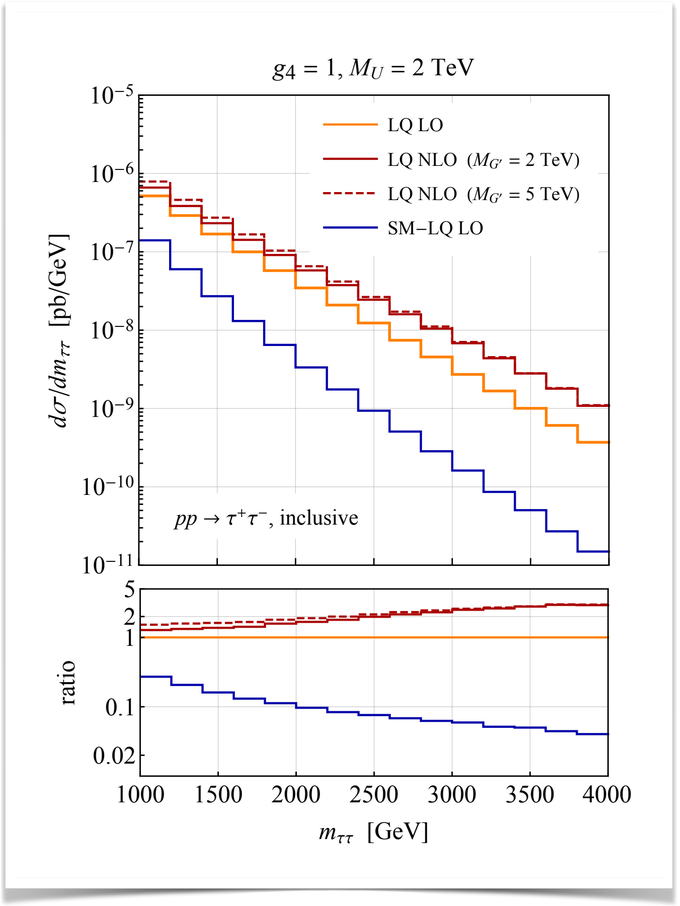

Source: ArXiv:2209.12780 (U. Haisch, LS, S. Schulte)

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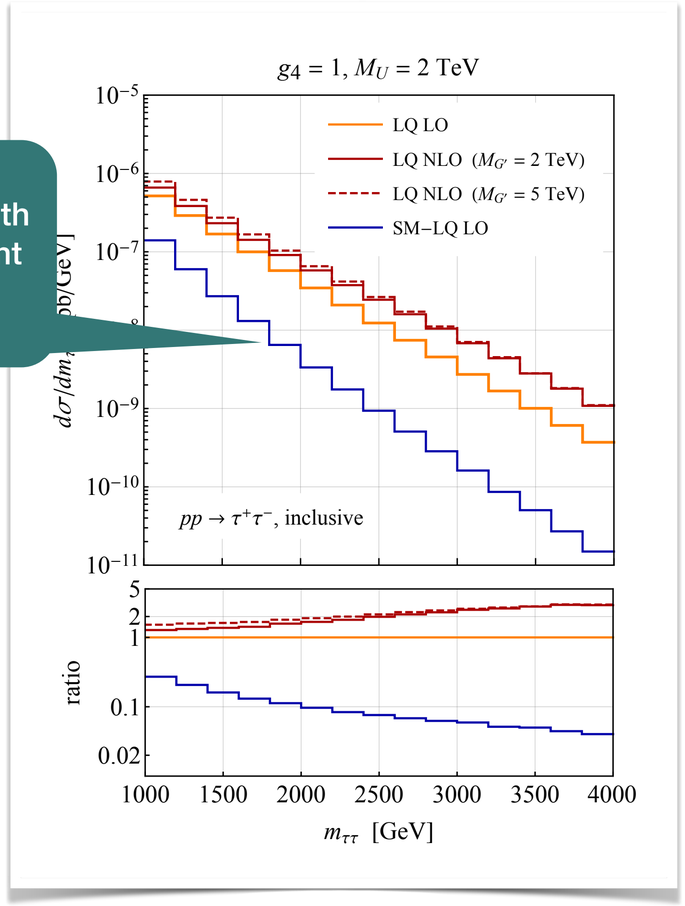
Inclusive $m_{\tau\tau}$ spectra:

Interference with SM not relevant in the tails.



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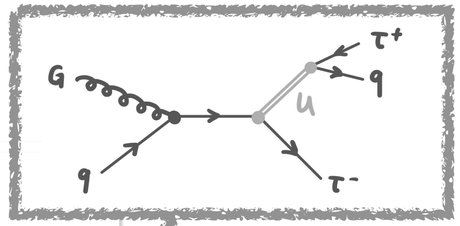

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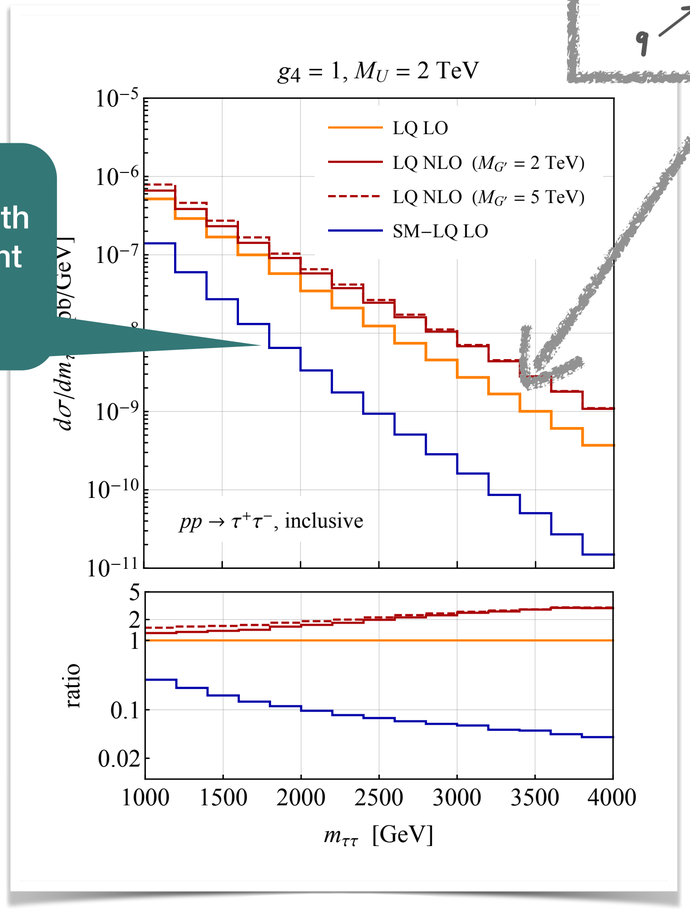

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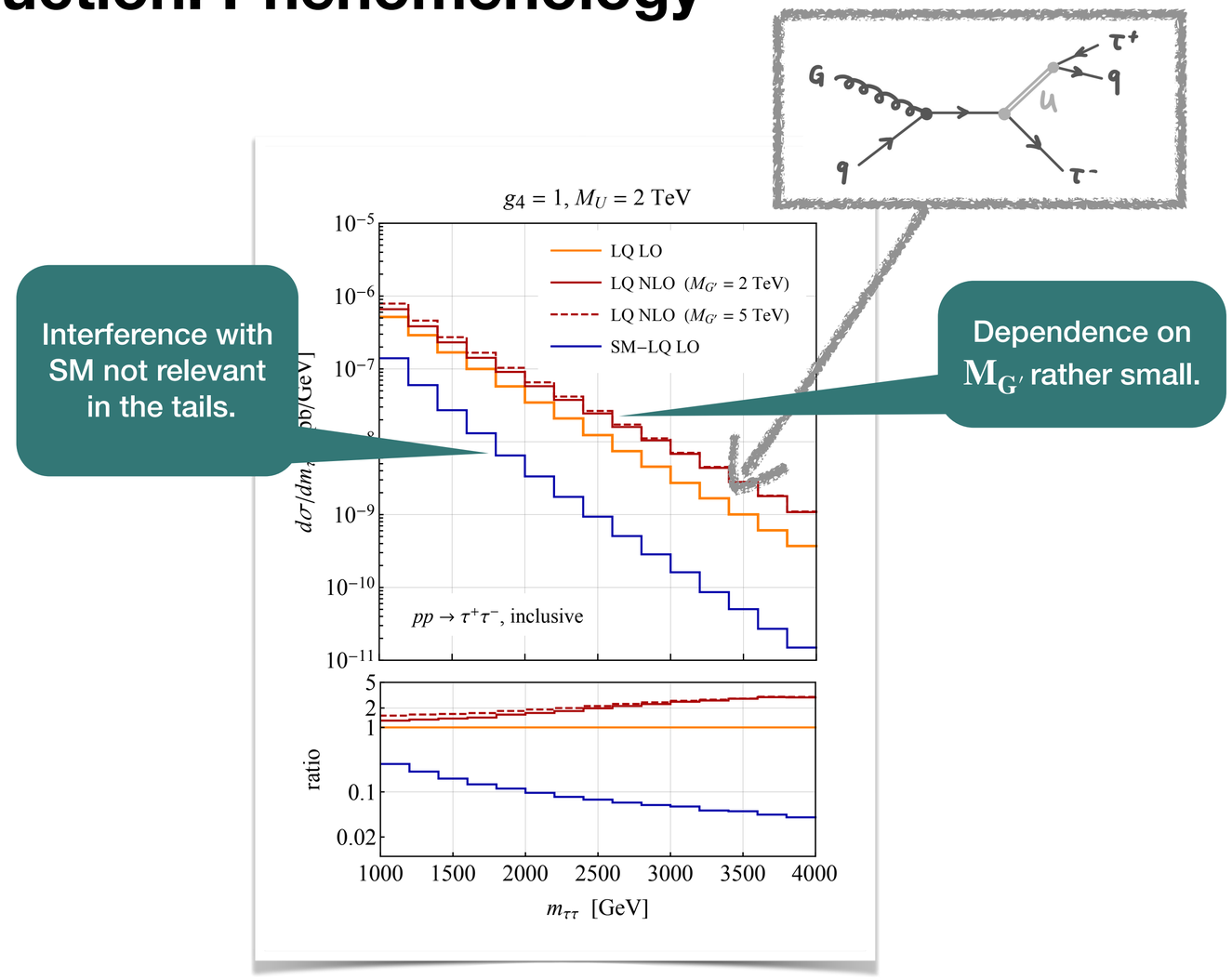
2.2 Drell-Yan production: Phenomenology

Inclusive $\mathbf{m}_{\tau\tau}$ spectra:



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

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

$\mathfrak{b}$-tag/$\mathfrak{b}$-veto:

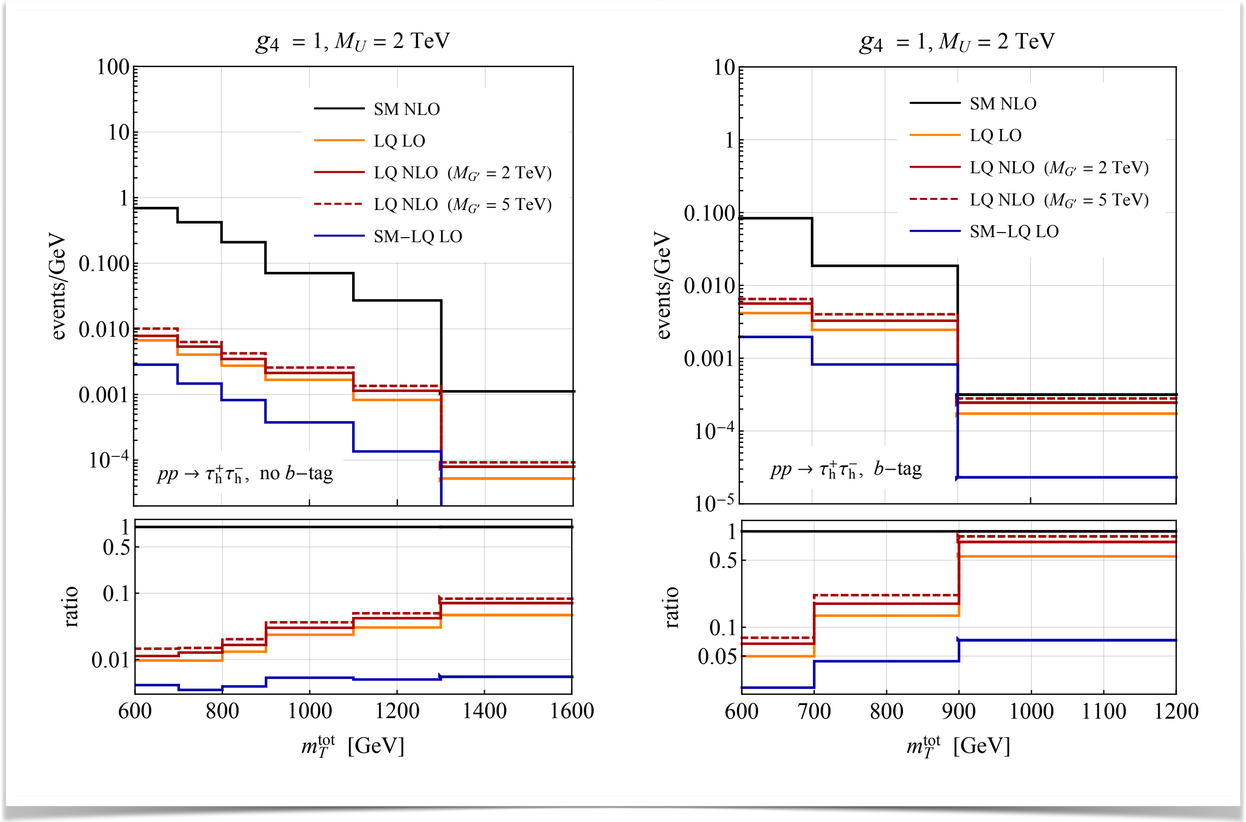
- Full NLO+PS analysis, LHC cuts modelled in **MadAnalysis5** (normal + expert mode).

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

b-tag/b-veto:

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



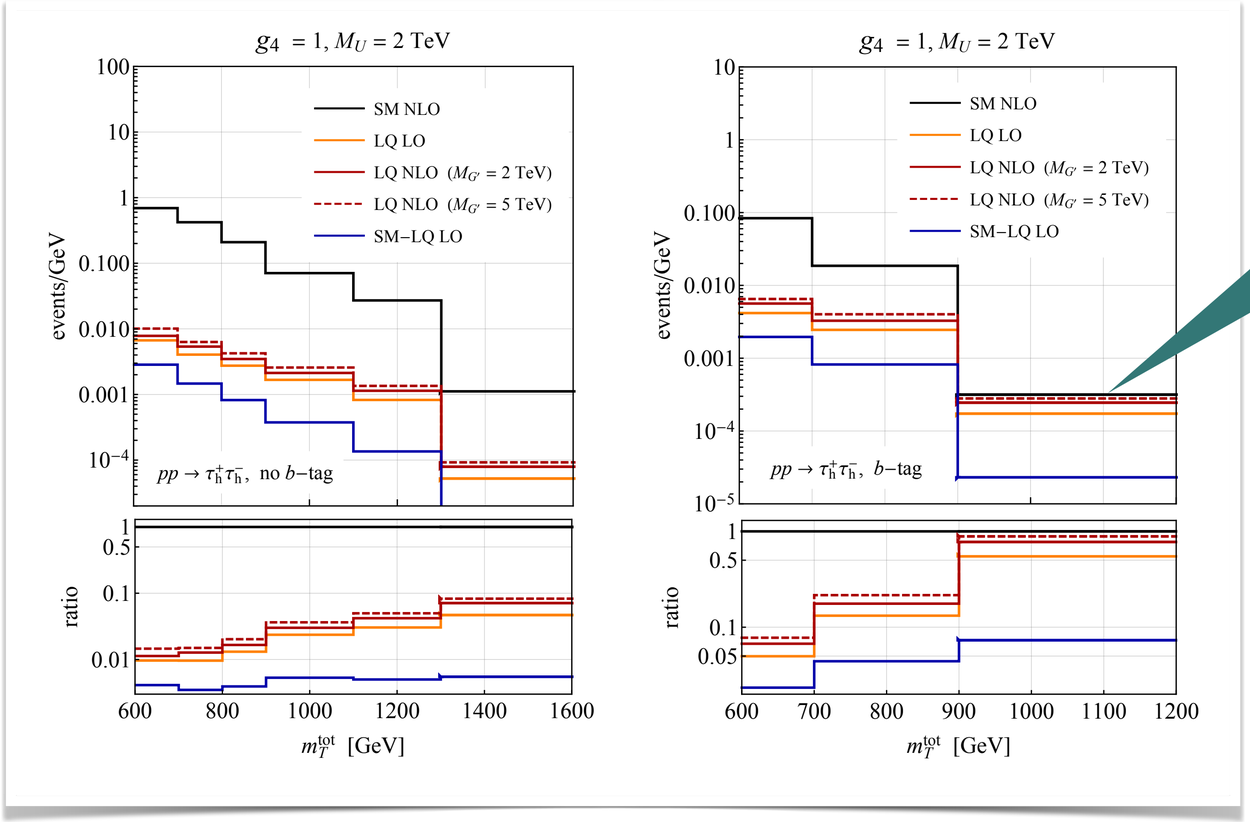
Source: ArXiv:2209.12780 (U. Haisch, LS, S. Schulte)

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

b-tag/b-veto:

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



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

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

2. Constraints from the LHC

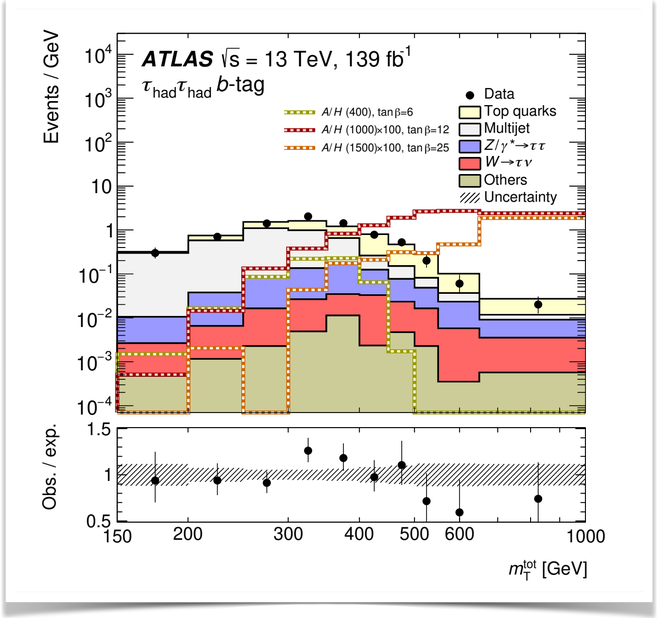
2.2 Drell-Yan production: Phenomenology

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

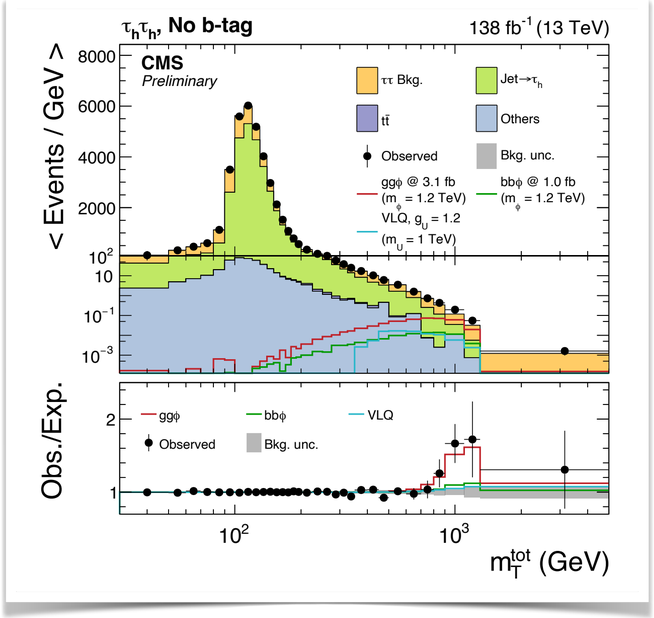
Exclusion limits:

ATLAS 2020



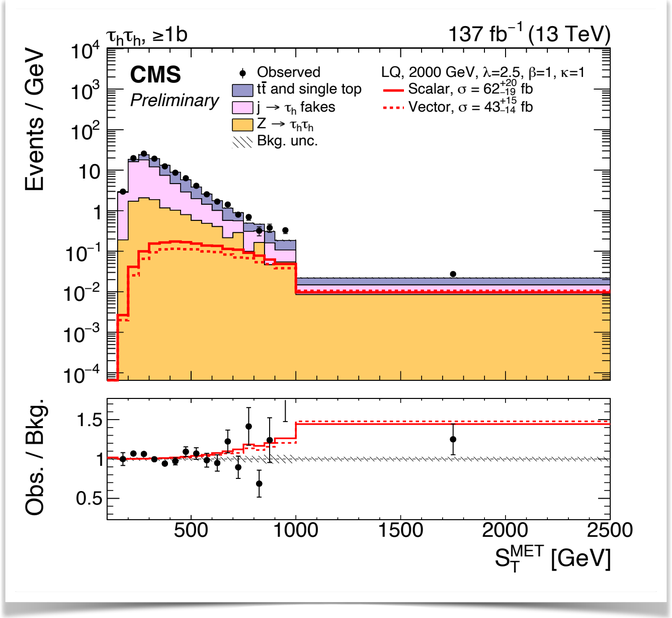
Source: ArXiv:2002.12223 (ATLAS)

CMS 2021



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

CMS 2022



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

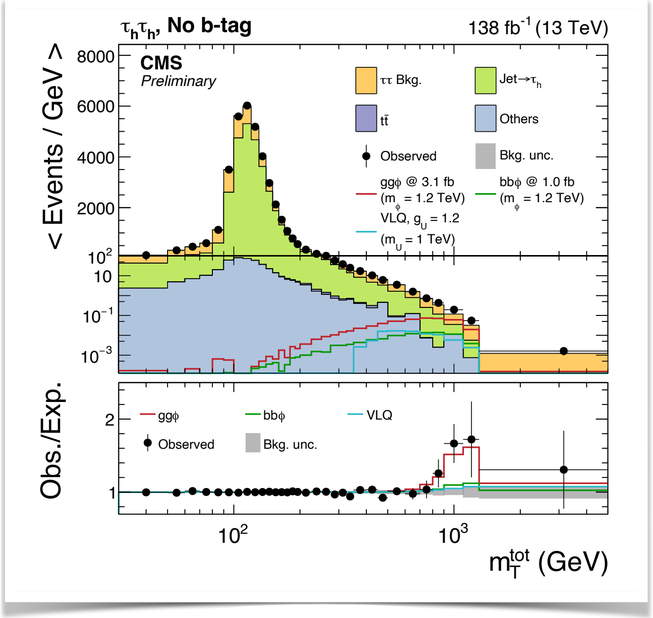
2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

Exclusion limits:

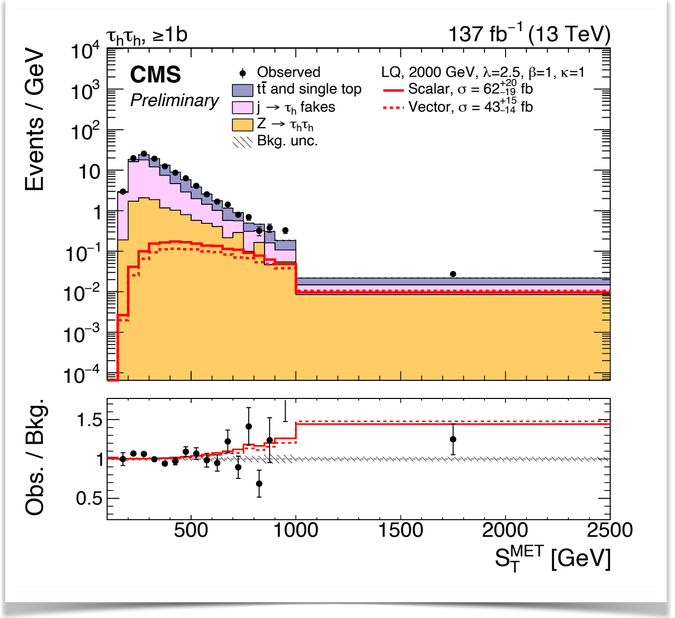
ATLAS 2020

CMS 2021



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

CMS 2022



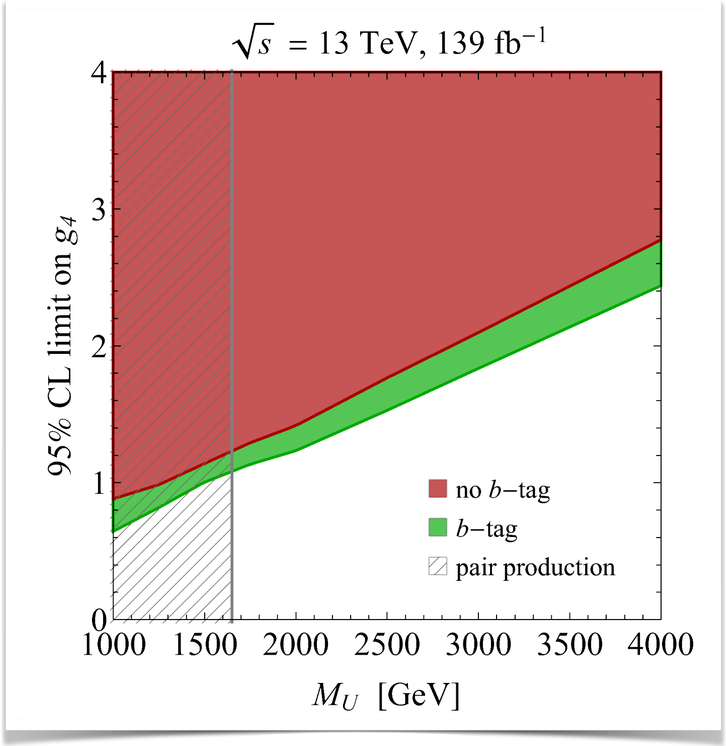
Source: EXO-19-016-PAS (CMS)

2. Constraints from the LHC

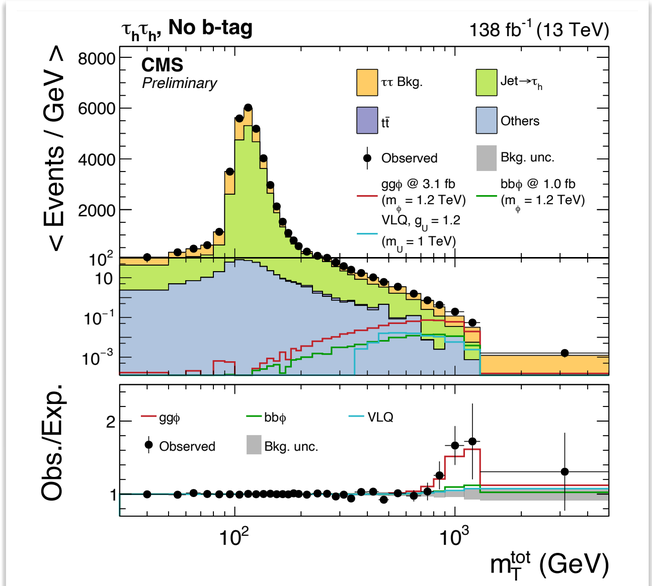
2.2 Drell-Yan production: Phenomenology

Exclusion limits:

ATLAS 2020

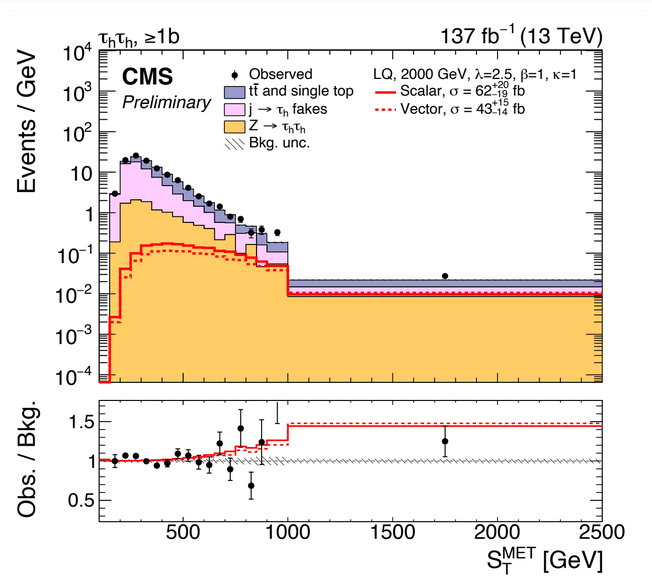


CMS 2021



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

CMS 2022



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

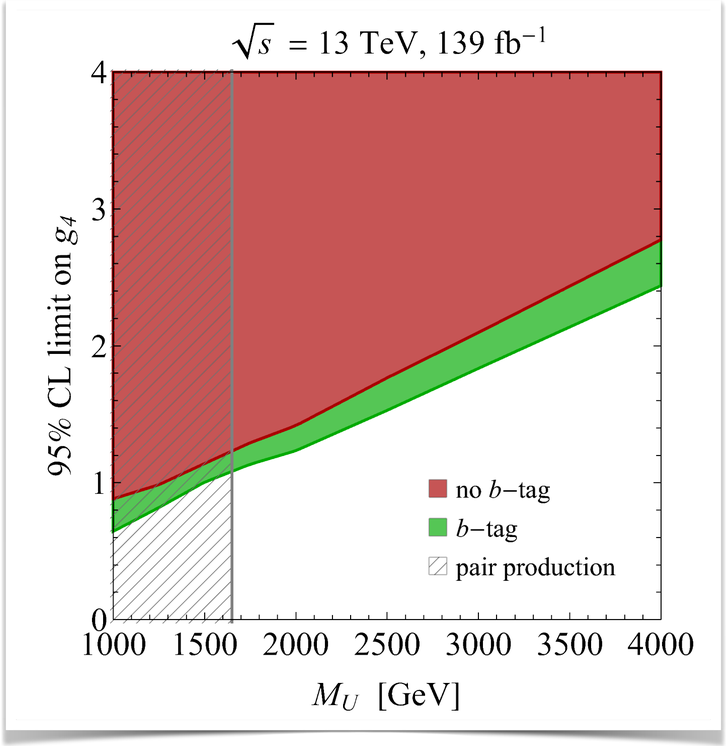
Source: ArXiv:2209.12780 (U. Haisch, LS, S. Schulte)

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

Exclusion limits:

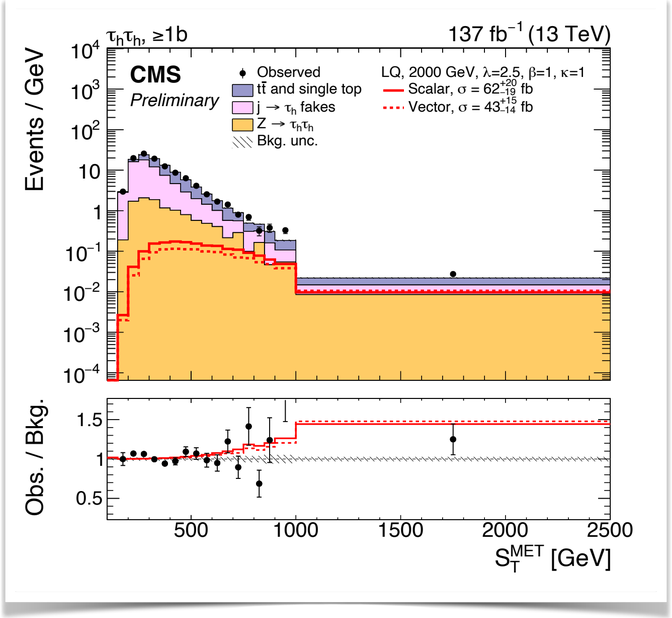
ATLAS 2020



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

CMS 2021

CMS 2022



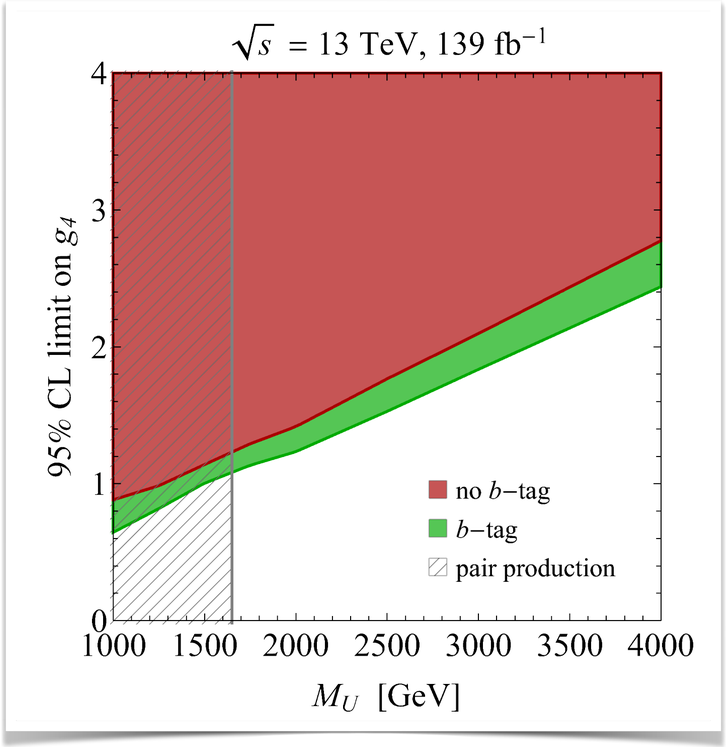
Source: EXO-19-016-PAS (CMS)

2. Constraints from the LHC

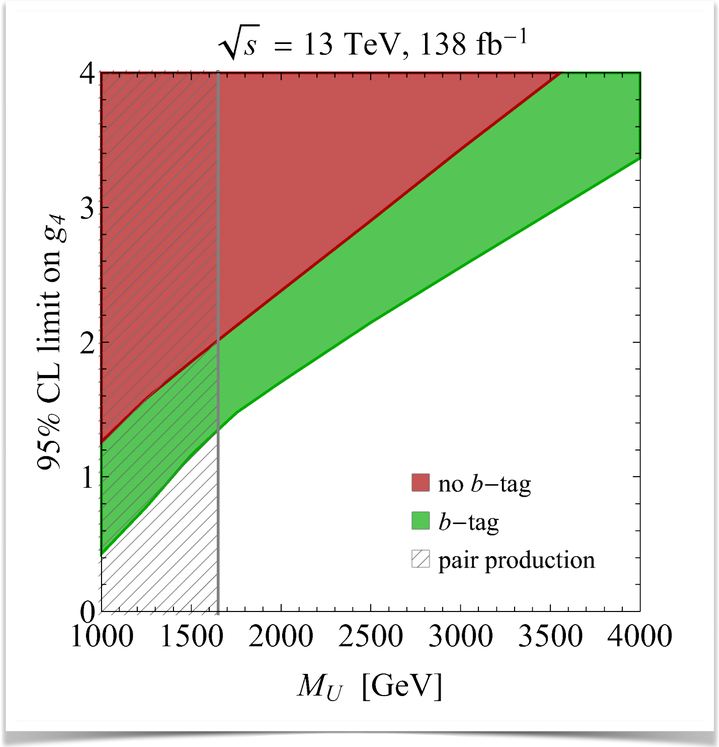
2.2 Drell-Yan production: Phenomenology

Exclusion limits:

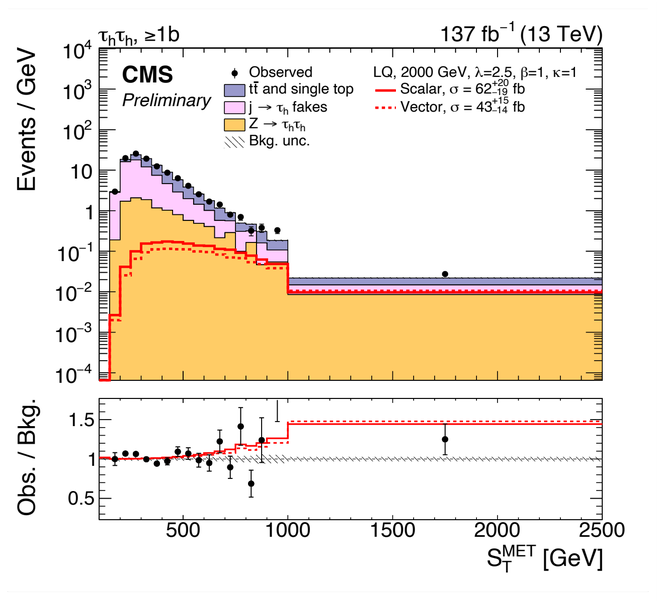
ATLAS 2020



CMS 2021



CMS 2022



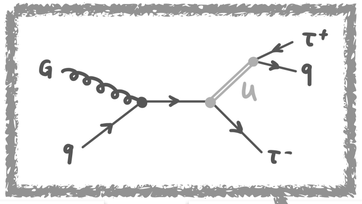
Source: EXO-19-016-PAS (CMS)

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

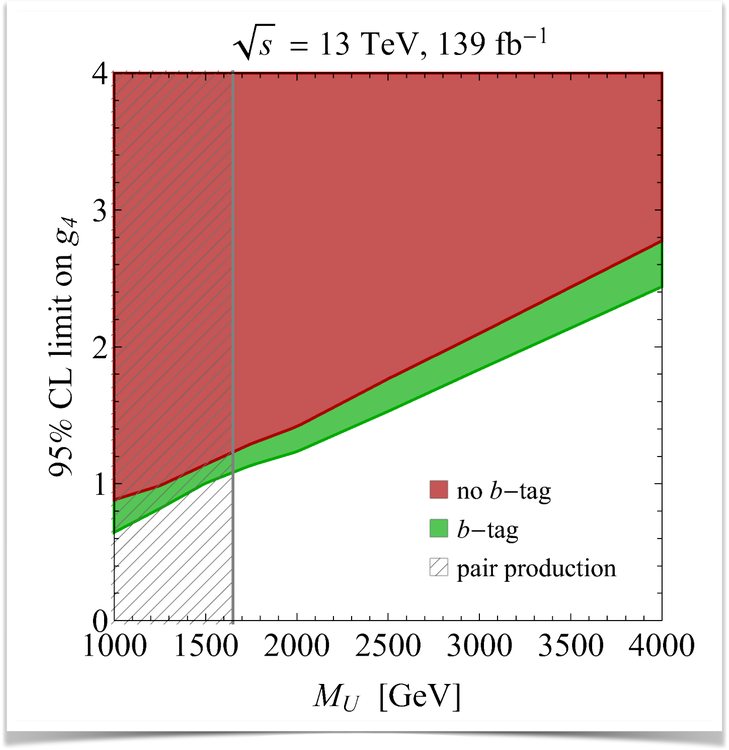
2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

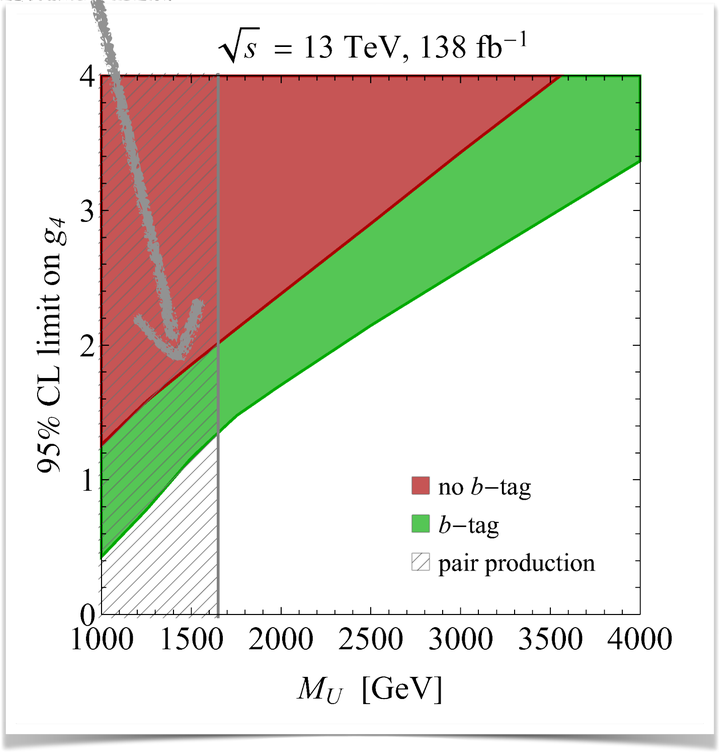
Exclusion limits:



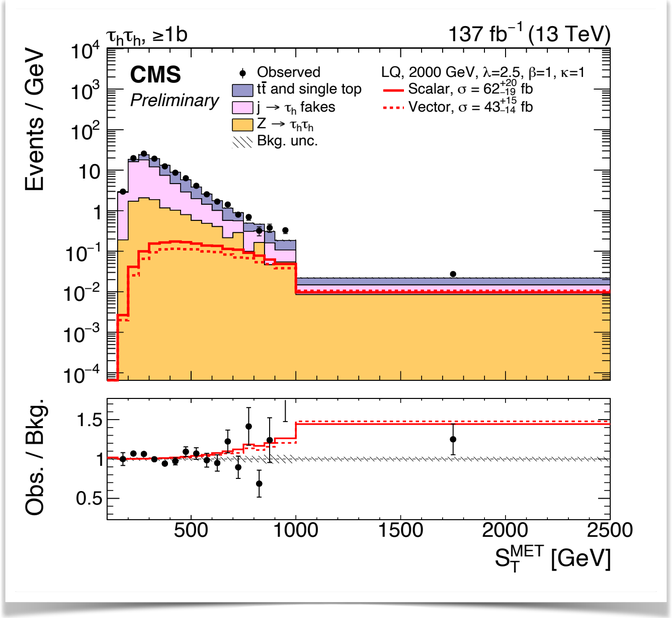
ATLAS 2020



CMS 2021



CMS 2022



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2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

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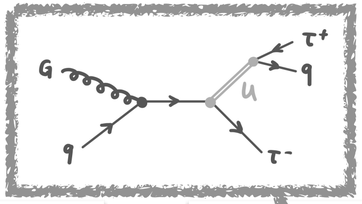
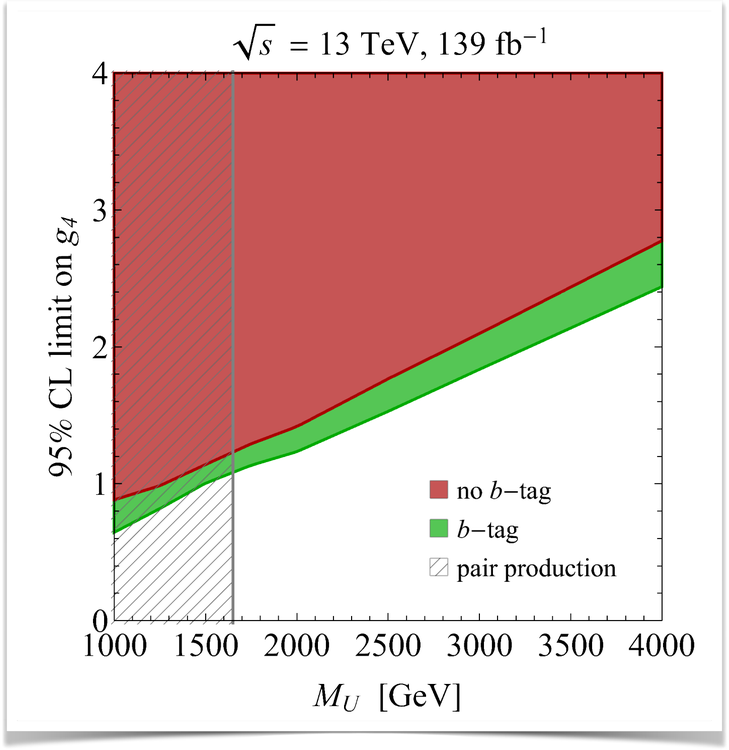
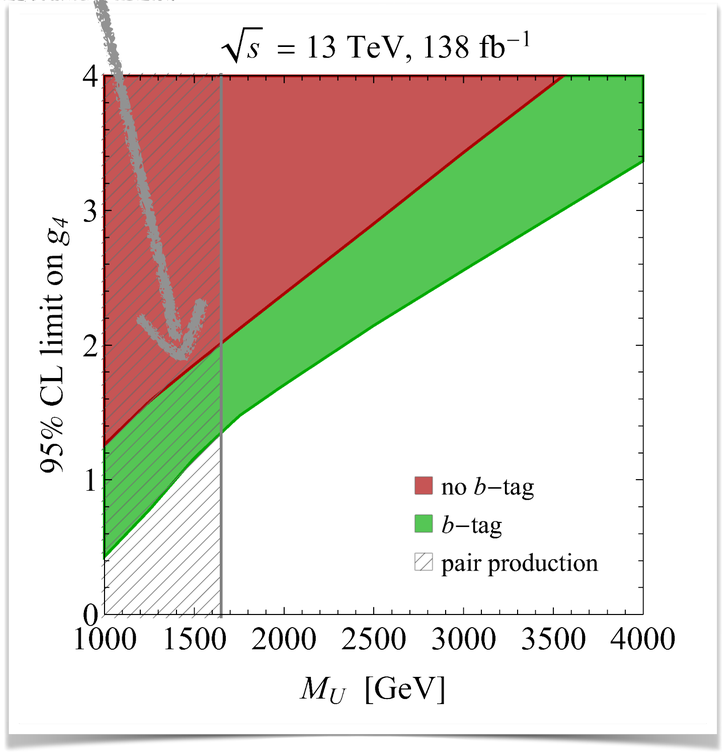


ATLAS 2020



CMS 2021



CMS 2022

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2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

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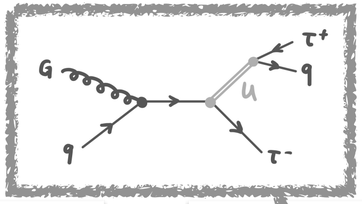
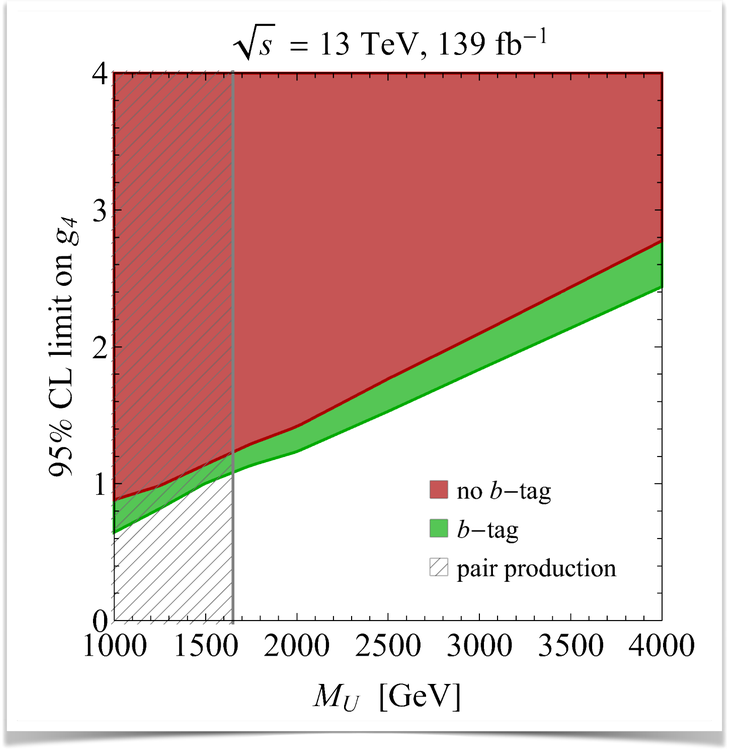
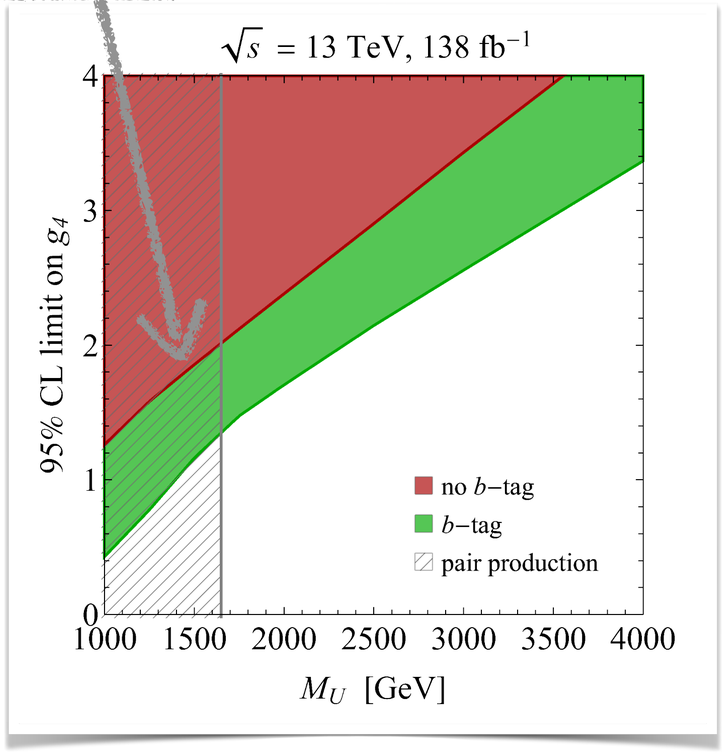


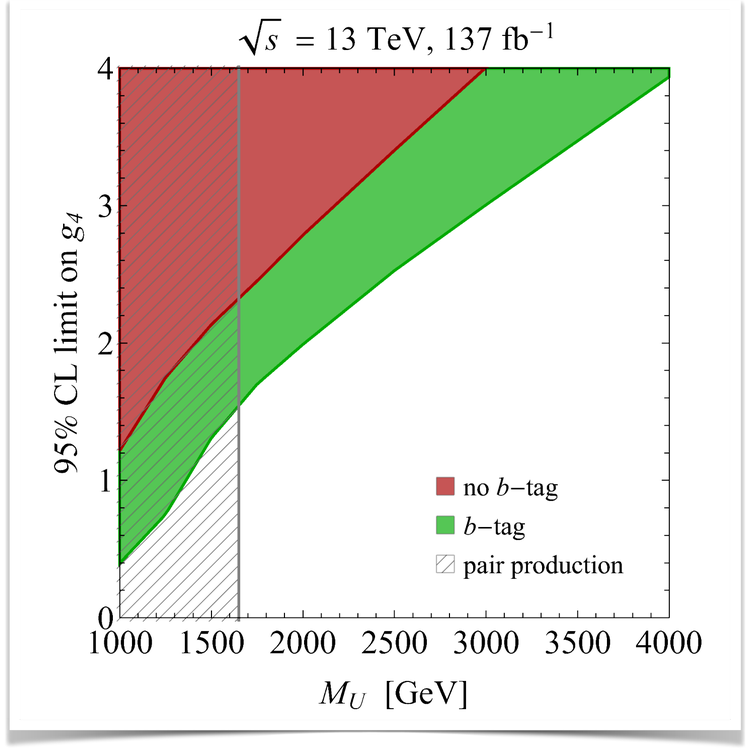
ATLAS 2020



CMS 2021



CMS 2022



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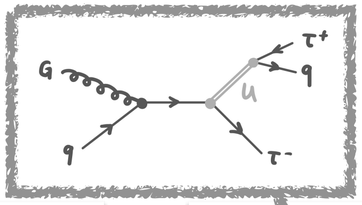
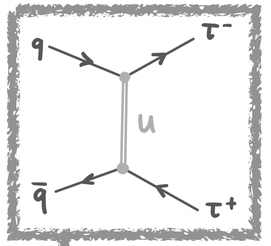
2. Constraints from the LHC

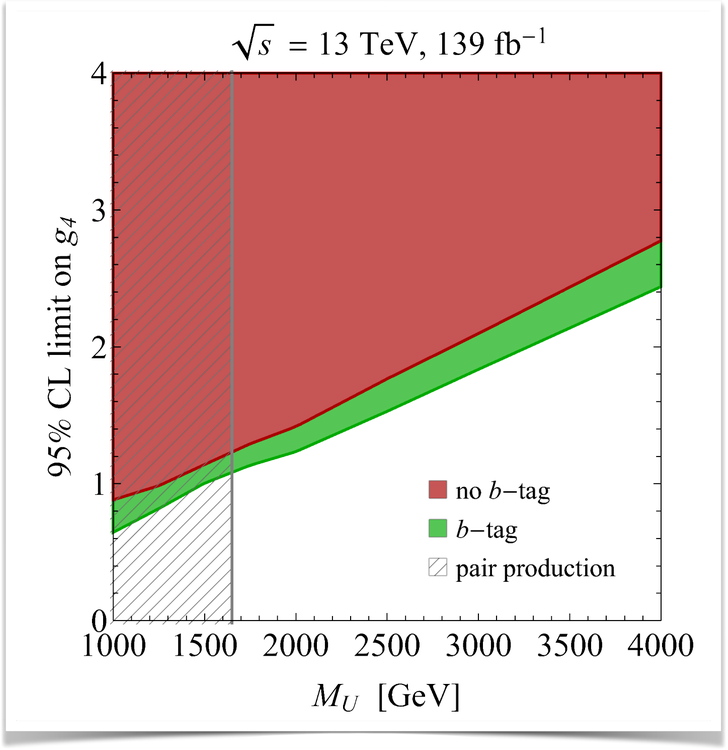
2.2 Drell-Yan production: Phenomenology

Exclusion limits:





ATLAS 2020



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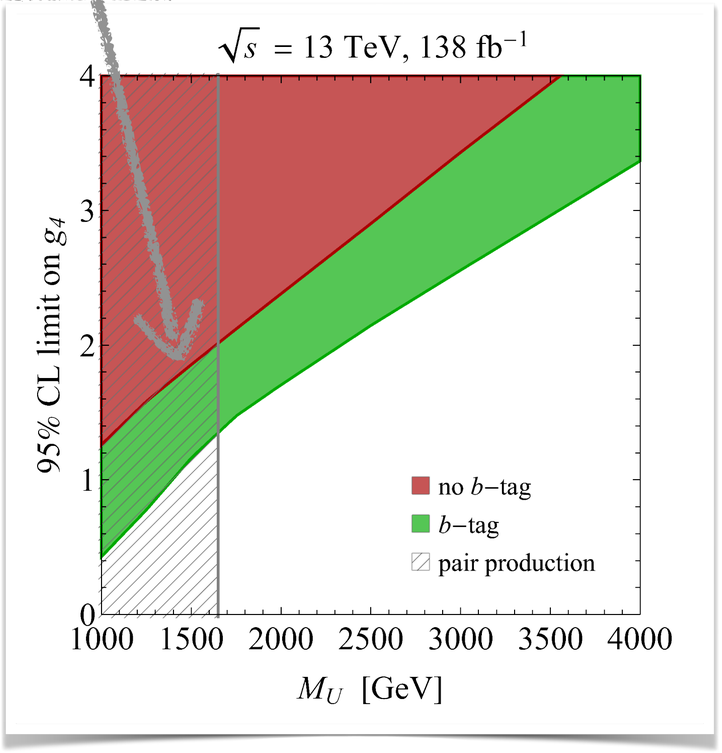
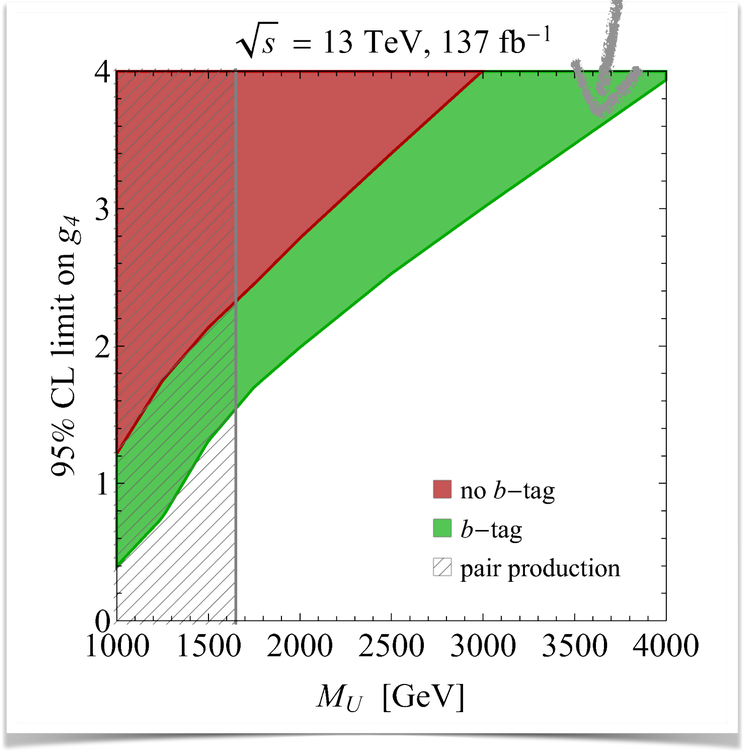


CMS 2022



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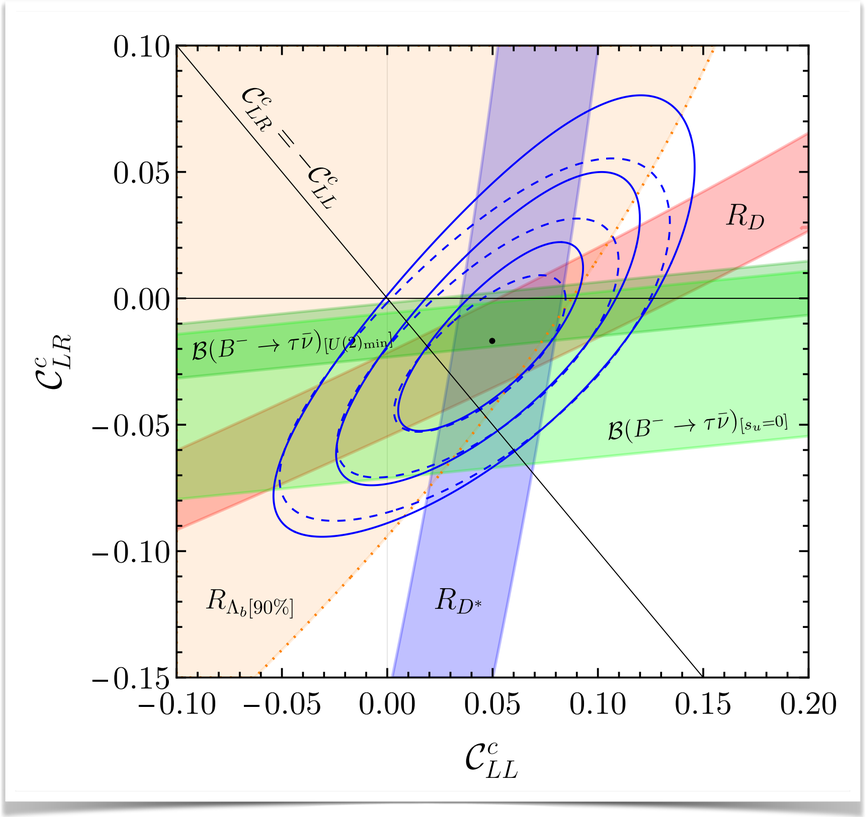
2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

Low-energy fit:

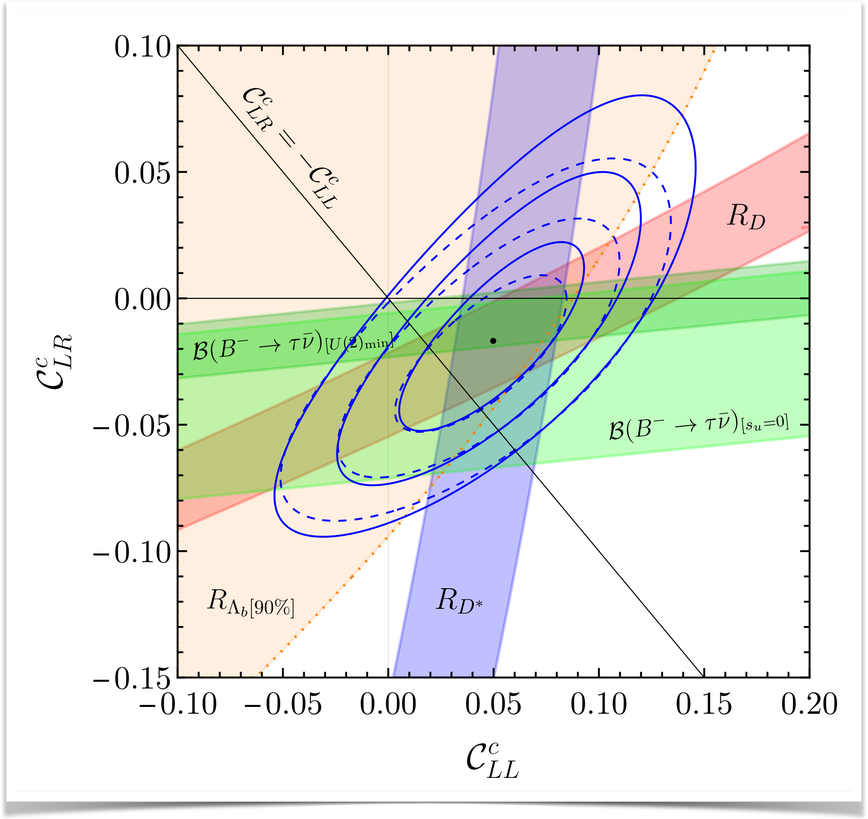


Source: ArXiv:2210.13422 (J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, F. Wilsch)

2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

Low-energy fit:



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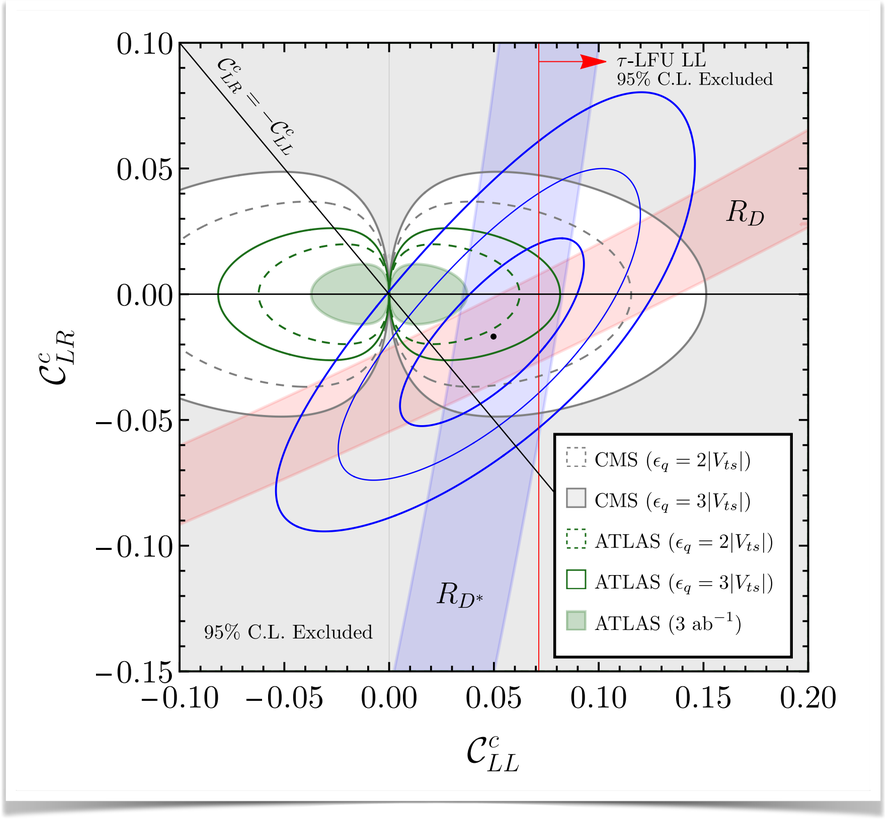
High-energy constraints:



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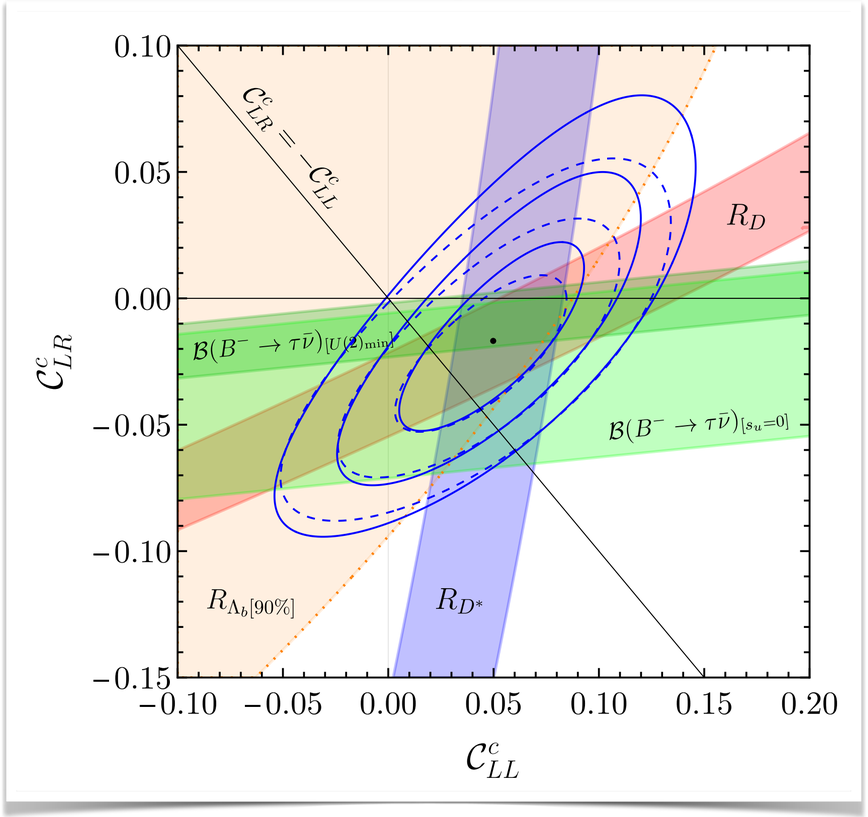
2. Constraints from the LHC

2.2 Drell-Yan production: Phenomenology

Low-energy fit:



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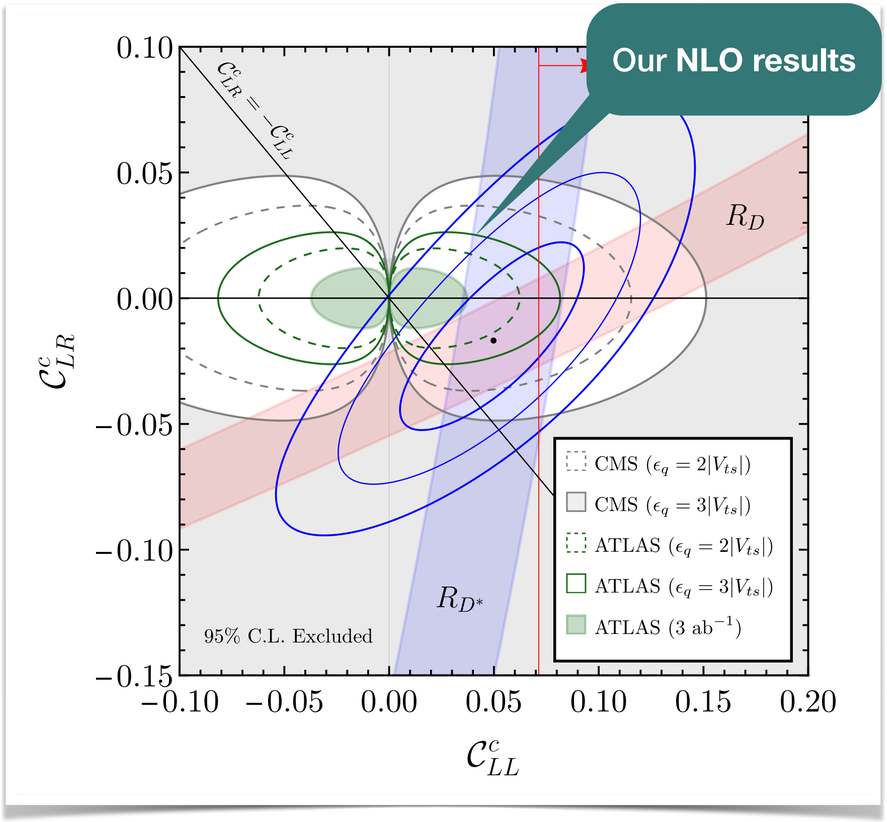
High-energy constraints:



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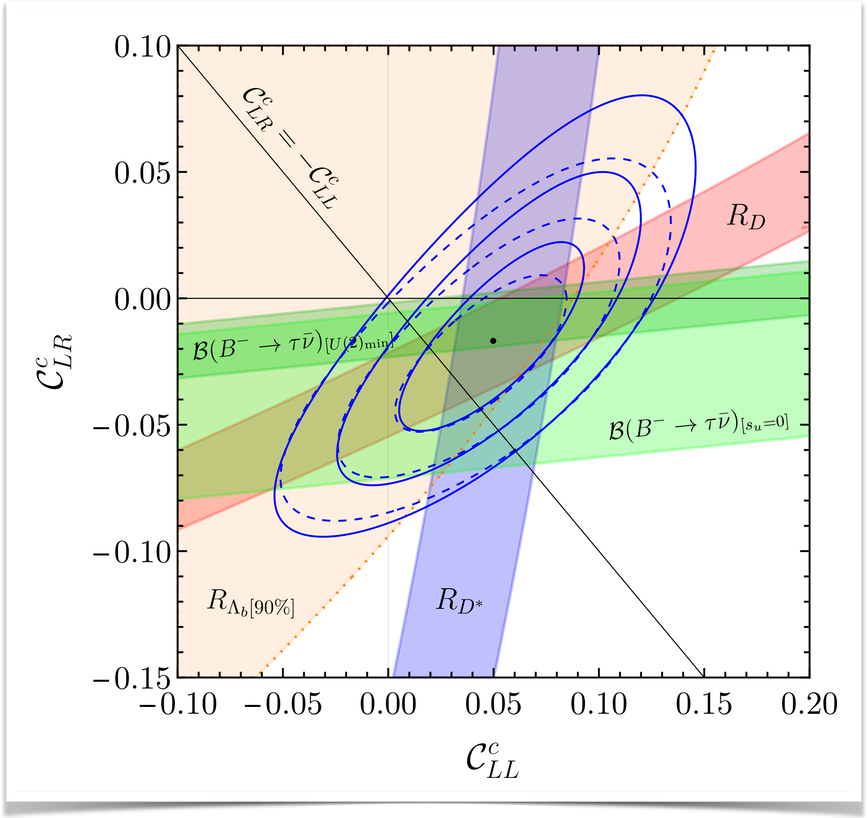
2. Constraints from the LHC

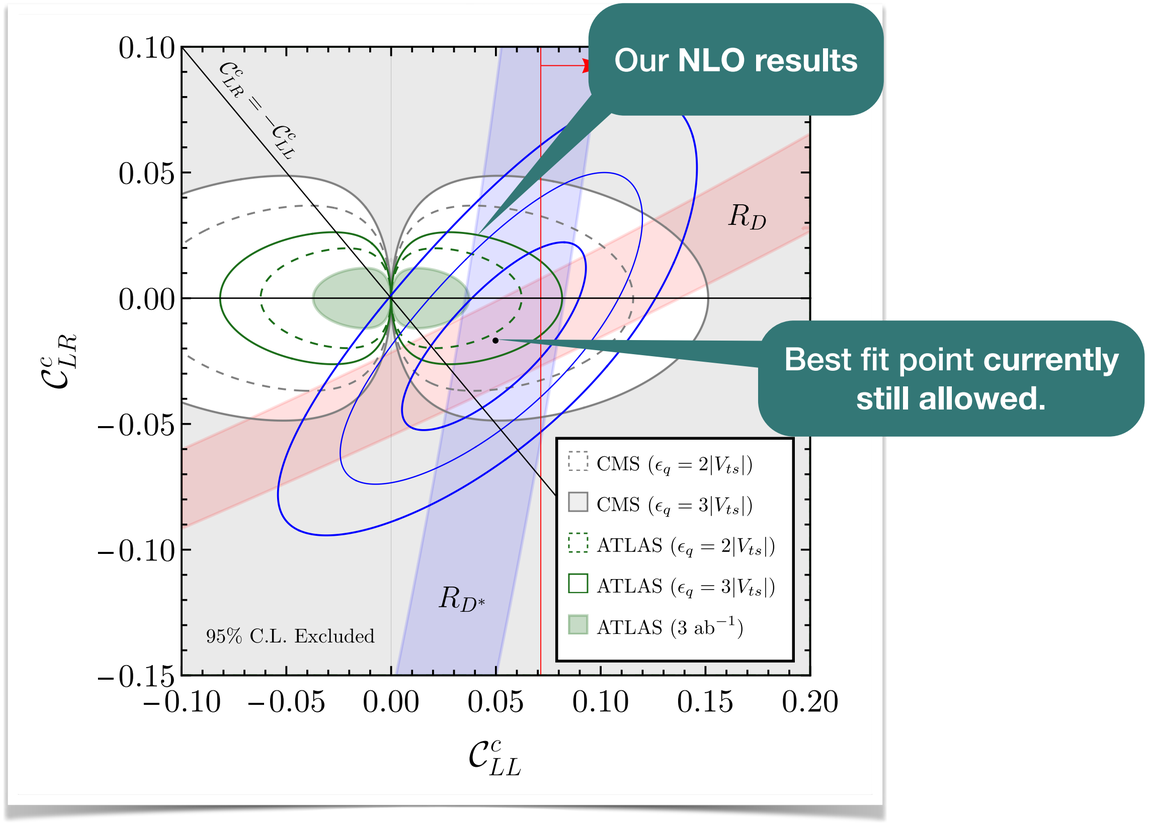
2.2 Drell-Yan production: Phenomenology

Low-energy fit:



Source: ArXiv:2210.13422 (J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, F. Wilsch)

High-energy constraints:



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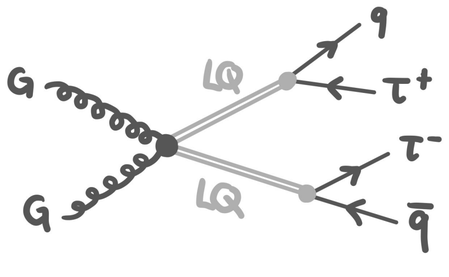
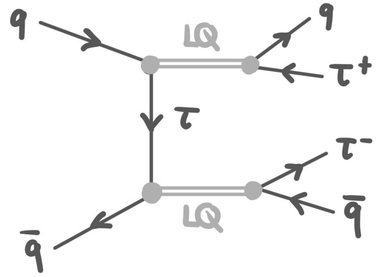
2. Constraints from the LHC

2.3 Single-resonant production

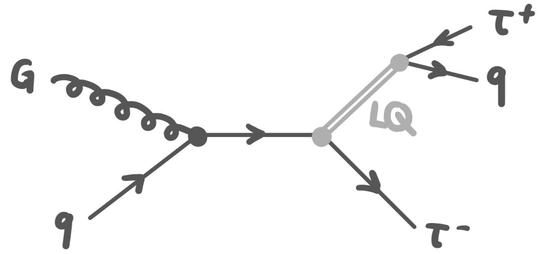
2. Constraints from the LHC

2.3 Single-resonant production

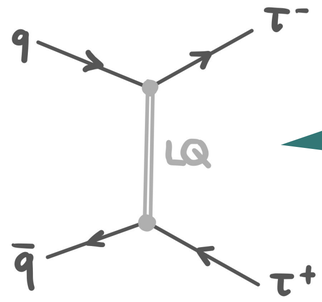




Pair-production

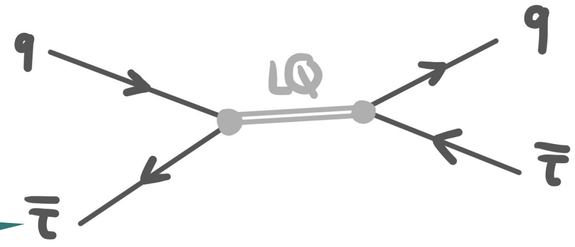


Single production



Drell-Yan production

Non-resonant signatures in the tails

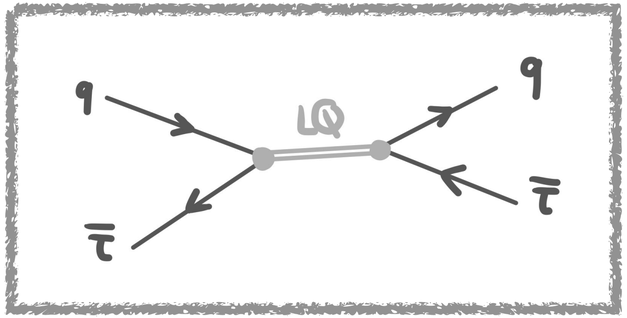


Single-resonant production

Lepton PDF of the proton

2. Constraints from the LHC

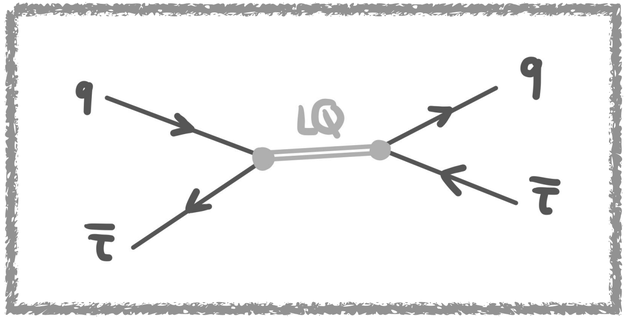
2.3 Single-resonant production

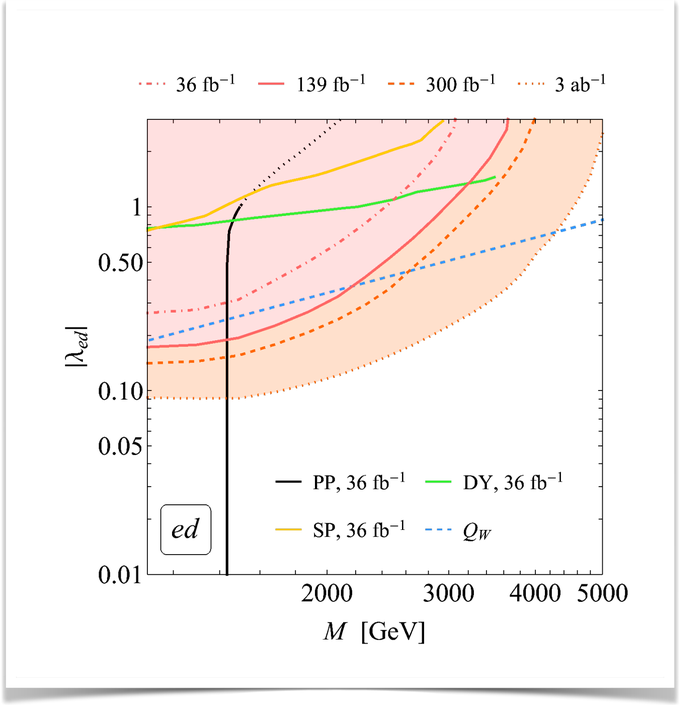


2. Constraints from the LHC

2.3 Single-resonant production

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



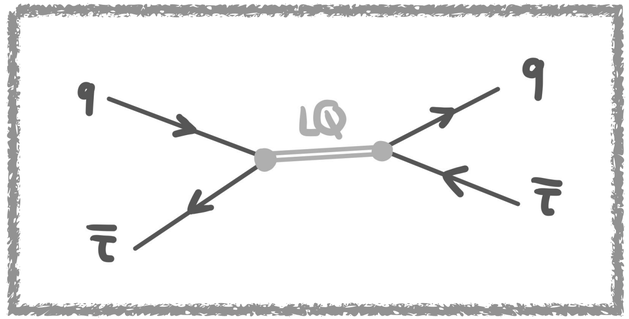


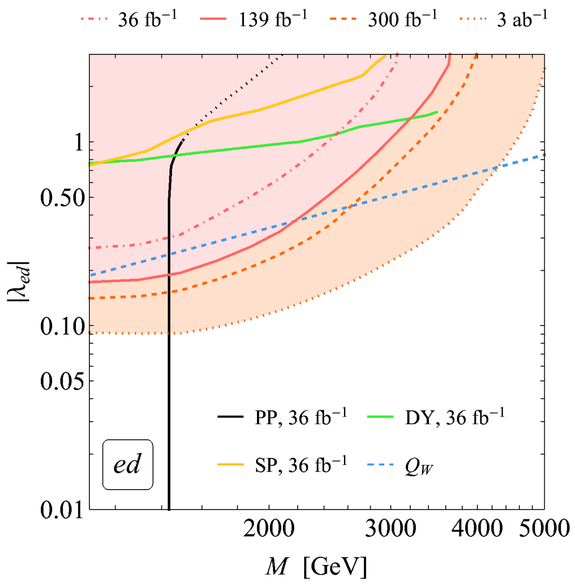
Source: ArXiv:2005.06475 (L. Buonocore, U. Haisch, P. Nason, F. Tramontano, G. Zanderighi)

2. Constraints from the LHC

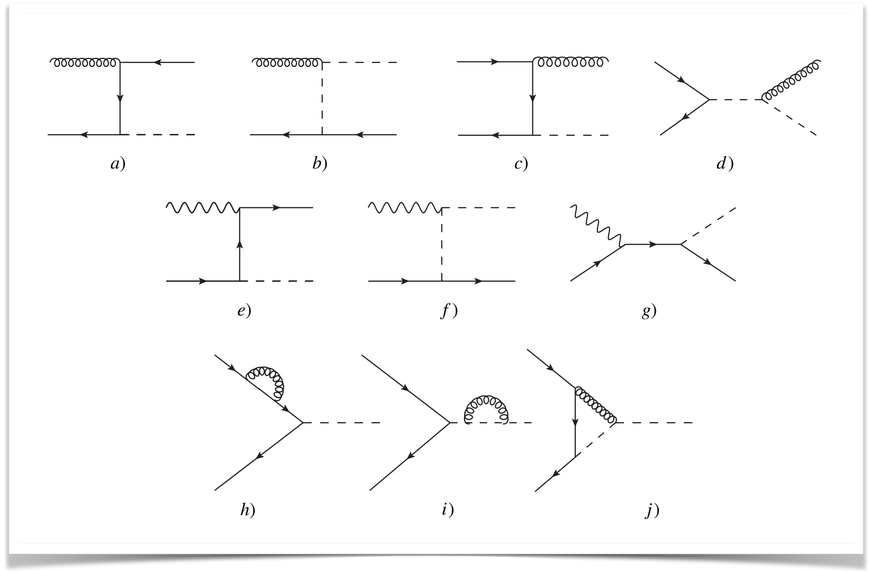
2.3 Single-resonant production

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

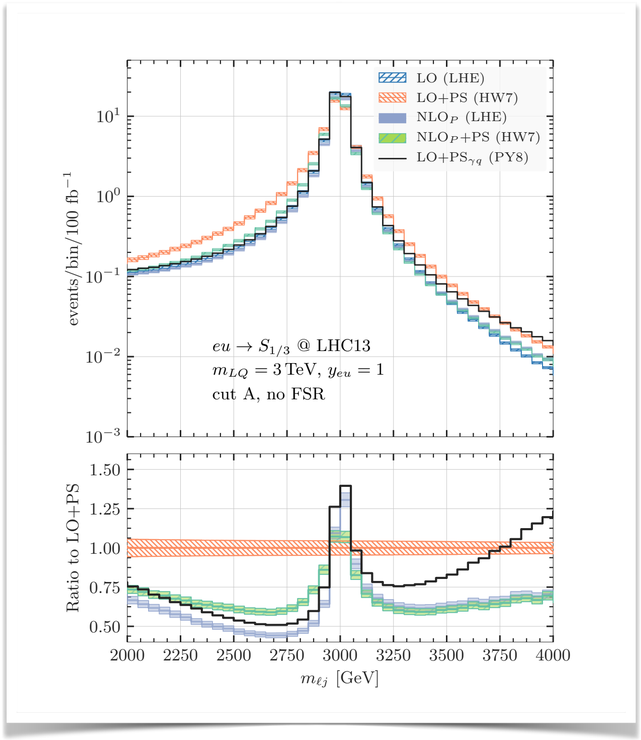




Source: ArXiv:2005.06475 (L. Buonocore, U. Haisch, P. Nason, F. Tramontano, G. Zanderighi)



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



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