Third-family lepton-quark fusion

Resonant U_1 leptoquark production @ LHC

in collaboration with Peter Krack (NIKHEF) & Nudžeim Selimović (INFN Padova)

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Arman Korajac (INFN Pisa)

OUTLINE

- UV model for U_1
- NLO QCD + QED results
- Simulation details & exclusion limits
- Conclusions

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- **UV model for U_1**
- **NLO QCD + QED results**
- **Simulation details & exclusion limits**
- **Conclusions**

4321 for U1

- Passing step in many UV flavor theories
- Decoupling the 3rd gen and the light fermions in the UV, effectively starting out with a U(2)⁵ flavor symmetry
- Motivated by solving the R(D*) anomaly

$$\begin{tikzcd}
{[SU(4)\times SU(2)_L\times SU(2)_R]^{[3]}\times[SU(3)\times SU(2)_L\times U(1)_{B-L}\times U(1)_R]^{[12]}} \arrow[d, "\langle\phi\rangle"] \\
{[SU(4)\times SU(2)_L\times SU(2)_R]^{[3]}\times[SU(3)\times SU(2)_L\times U(1)_Y]^{[12]}} \arrow[d, "\langle\Sigma_L\rangle"', "\langle\Sigma_R\rangle"] \\
{\color{blue}SU(4)^{[3]}\times SU(3)^{[12]}\times SU(2)_L\times U(1)_X} \arrow[d, "\langle\Omega_3\rangle"', "\langle\Omega_1\rangle"] \\
SU(3)_c\times SU(2)_L\times U(1)_Y\,,
\end{tikzcd}$$

[Courtesy of N. Selimović]

[L. Di Luzio, A. Greljo and M. Nardecchia, arXiv: 1708.08450]
[L. Di Luzio, J. Fuentes-Martin, A. Greljo, M. Nardecchia, S. Renner, arXiv: 1808.00942]
[M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv: 1712.01368, 1805.09328]
[H. Georgi, Y. Nakai, arXiv: 1606.05865]
[Fuentes-Martin et al, arXiv: 1910.13474, 2006.16250, 2009.11296]
[D. Guadagnoli, M. Reboud, P. Stangl, arXiv: 2005.10117] …

4321 for U1

- Using the minimal set-up, enough for gauge boson dynamics:

$$\mathcal{L} \supset -\frac{1}{4}H^a_{\mu\nu}H^a_{\mu\nu} + \sum_{i=1,3}(D_\mu\Omega_i)^\dagger(D_\mu\Omega_i) + \sum_{f=L,R^\pm} i\bar{\psi}_f \not{D}\psi_f + V(\Omega_i)$$

$$- Y^{ij}_{\text{light,u}}\bar{q}^i_L \tilde{H} u^j_R - Y^{ij}_{\text{light,d}}\bar{q}^i_L H d^j_R - y^-_{LR}\bar{\psi}_L H \psi^-_R - y^+_{LR}\bar{\psi}_L \tilde{H}\psi^+_R + \text{h.c.}$$

Field	$SU(4)_3$	$SU(3)_{12}$	$SU(2)_L$	$U(1)_X$
ψ_L	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{2}$	0
ψ_R^+	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$1/2$
ψ_R^-	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
q_L^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
ℓ_L^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
u_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
d_R^i	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
e_R^i	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	-1
H	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$
Ω_3	$\bar{\mathbf{4}}$	$\mathbf{3}$	$\mathbf{1}$	$1/6$
Ω_1	$\bar{\mathbf{4}}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$

$i = 1{,}2$

$$\psi_L \equiv (q_L^3 \;\; \ell_L^3)^\intercal$$

$$\psi_R^- \equiv (d_R^3 \;\; e_R^3)^\intercal \qquad \psi_R^+ \equiv (u_R^3 \;\; \nu_R^3)^\intercal$$

4321 for U1

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ψ^-_R	$\mathbf{4}$	$\mathbf{1}$	$\mathbf{1}$	$-1/2$
q^i_L	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{2}$	$1/6$
ℓ^i_L	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
u^i_R	$\mathbf{1}$	$\mathbf{3}$	$\mathbf{1}$	$2/3$
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4321 for U1

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$$\text{SSB} : \mathscr{G}_{4321} \to \mathscr{G}_{\text{SM}}$$

$$G' \sim (\mathbf{8},\mathbf{1},0), \quad \boxed{U_1 \sim (\mathbf{3},\mathbf{1},2/3),} \quad Z' \sim (\mathbf{1},\mathbf{1},0)$$

SM fields

$$G^a_\mu = s_3 H^a_\mu + c_3 C^a_\mu\,, \quad B_\mu = s_1 H^{15}_\mu + c_1 X_\mu$$

Massive gauge bosons

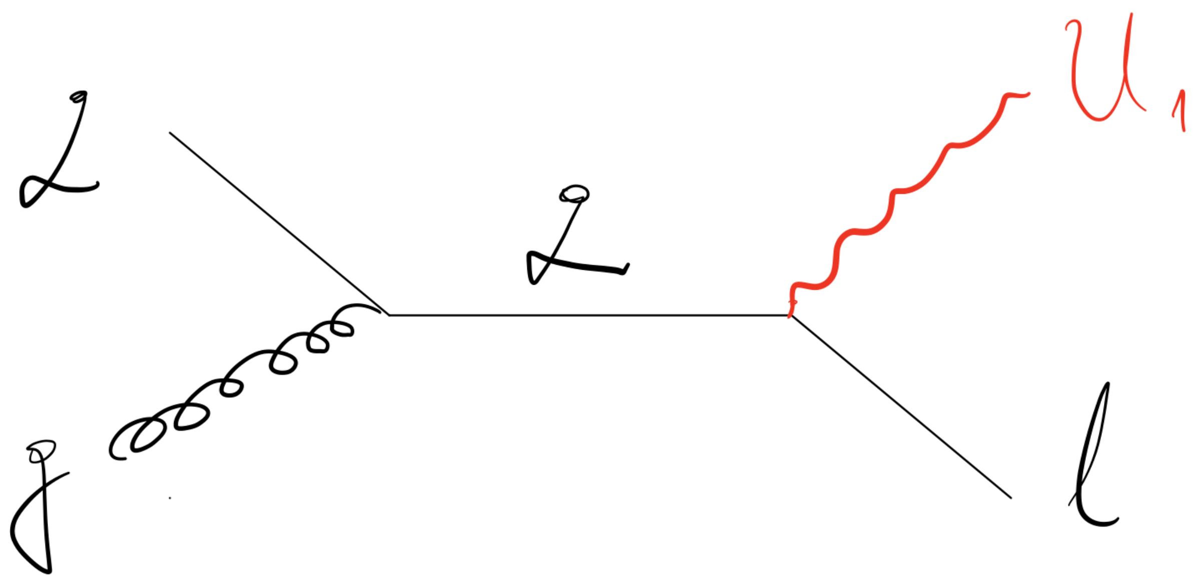
$$G'^a_\mu = c_3 H^a_\mu - s_3 C^a_\mu\,, \quad Z'_\mu = c_1 H^{15}_\mu - s_1 X_\mu$$

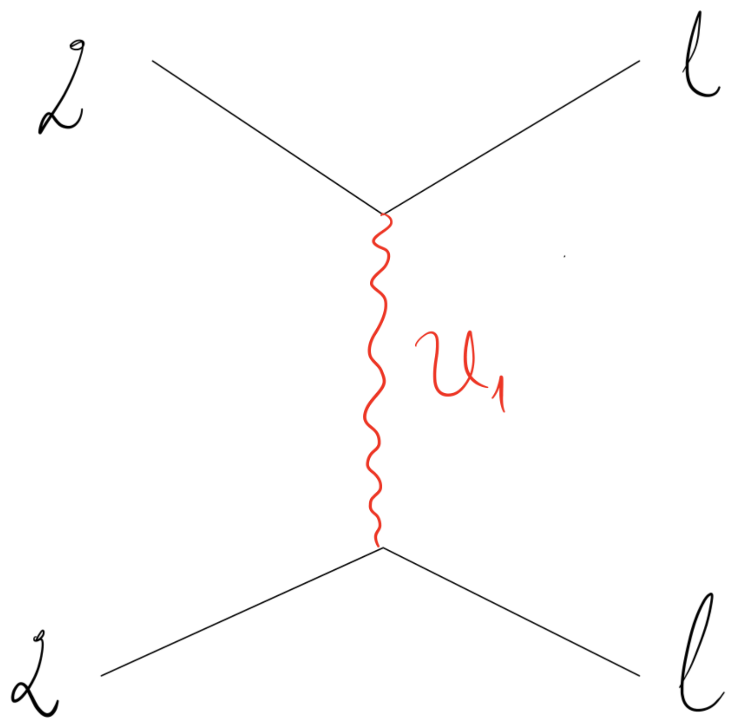
$$U^{1,2,3}_\mu = \frac{1}{\sqrt{2}}(H^{9,11,13}_\mu - iH^{10,12,14}_\mu)$$

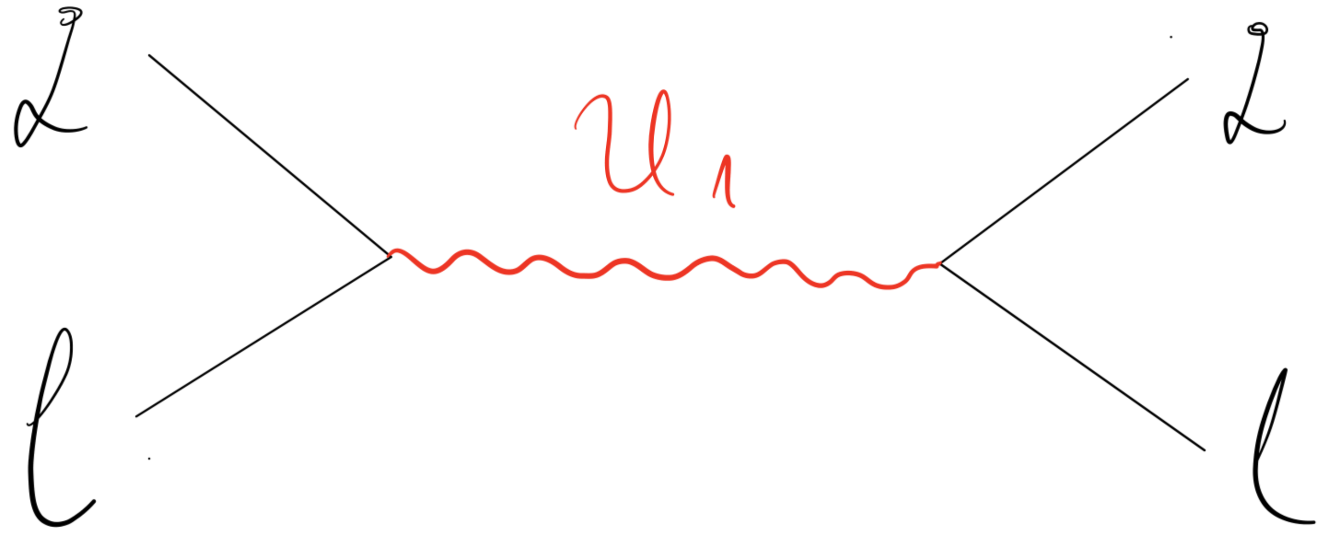
4321 for U1

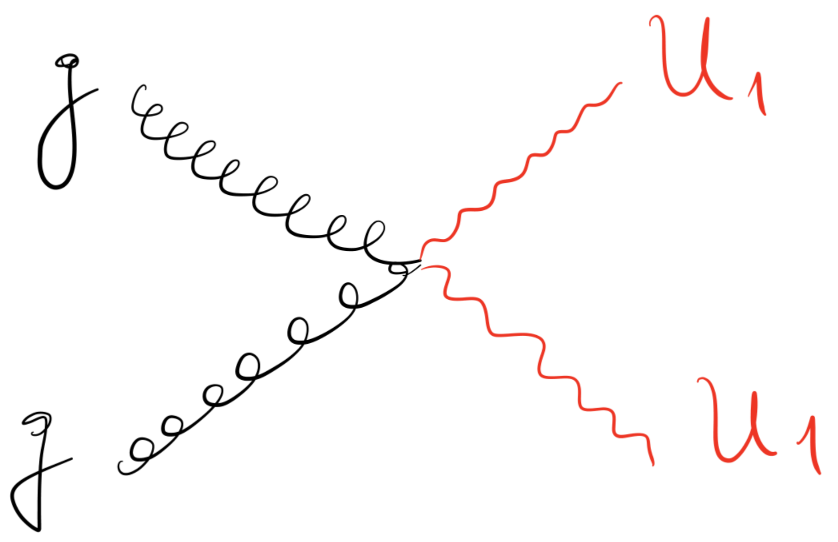
$$\mathcal{L}_{U_1} \supset \frac{g_4}{\sqrt{2}} U_\mu \left(\beta_L^{33}\, \bar{q}_L^3 \gamma^\mu \tau_L + \beta_R^{33}\, \bar{b}_R \gamma^\mu \tau_R + \mathrm{h.c.}\right)$$
$$- i g_s U_\mu^\dagger T^a U_\nu G^{a,\mu\nu} - \frac{2}{3} i e\, U_\mu^\dagger U_\nu F^{\mu\nu}$$

Can be extended to couplings with light-gen fermions; additional fields required









- Signature can be seen through t-channel production, LQ + lepton or double LQ production
- **Goal: Examine the resonant s-channel production for U1**
- Already done, *however*:
  - no lepton PDFs at that moment
  - no experimental results at that time
  - @ LO.

[U. Haisch, G. Polesello, arXiv:2012.11474]

[Buonocore et al, arXiv: 2005.06475]

4321 for U1

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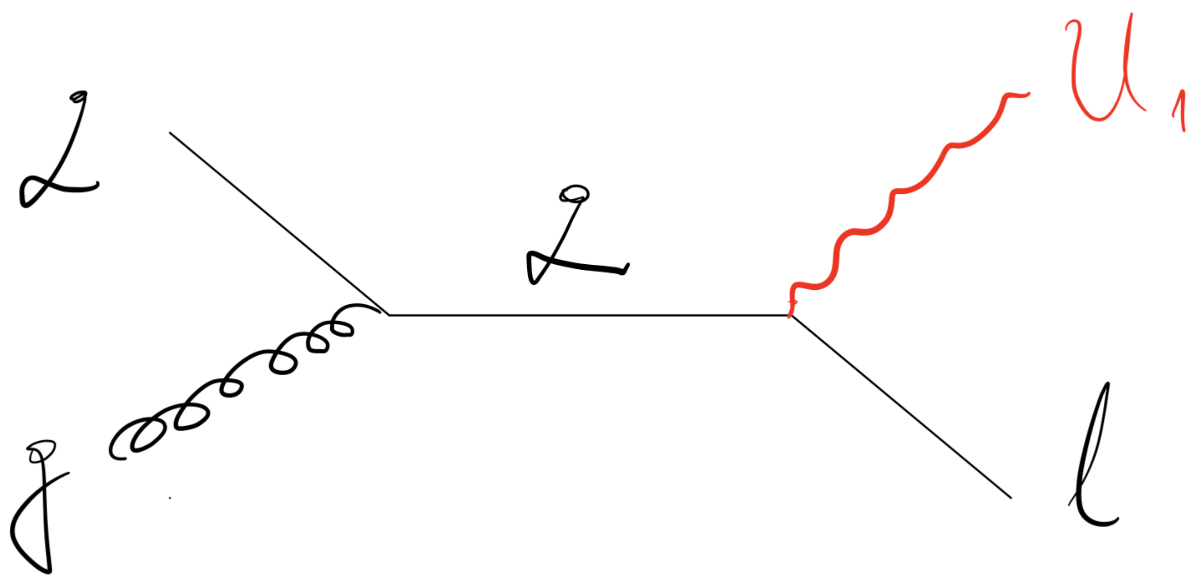

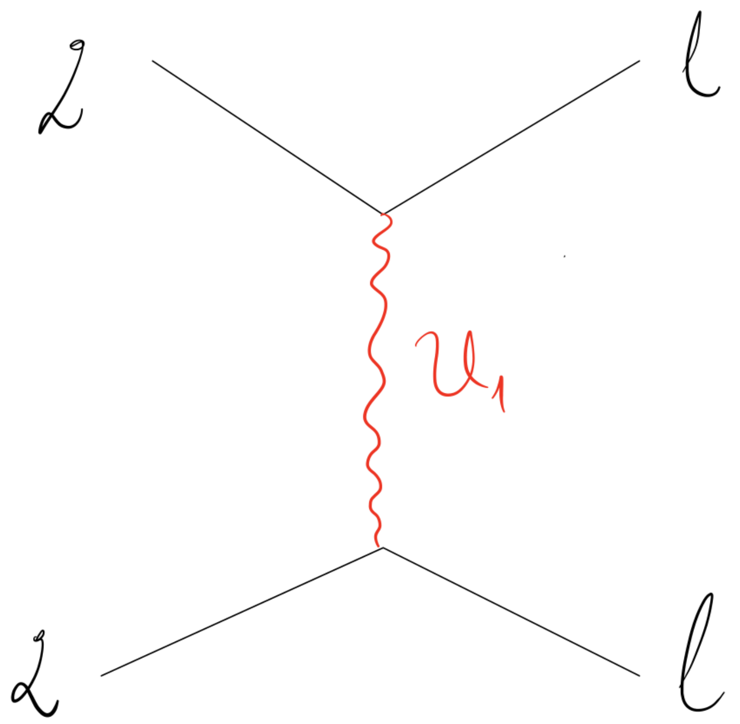

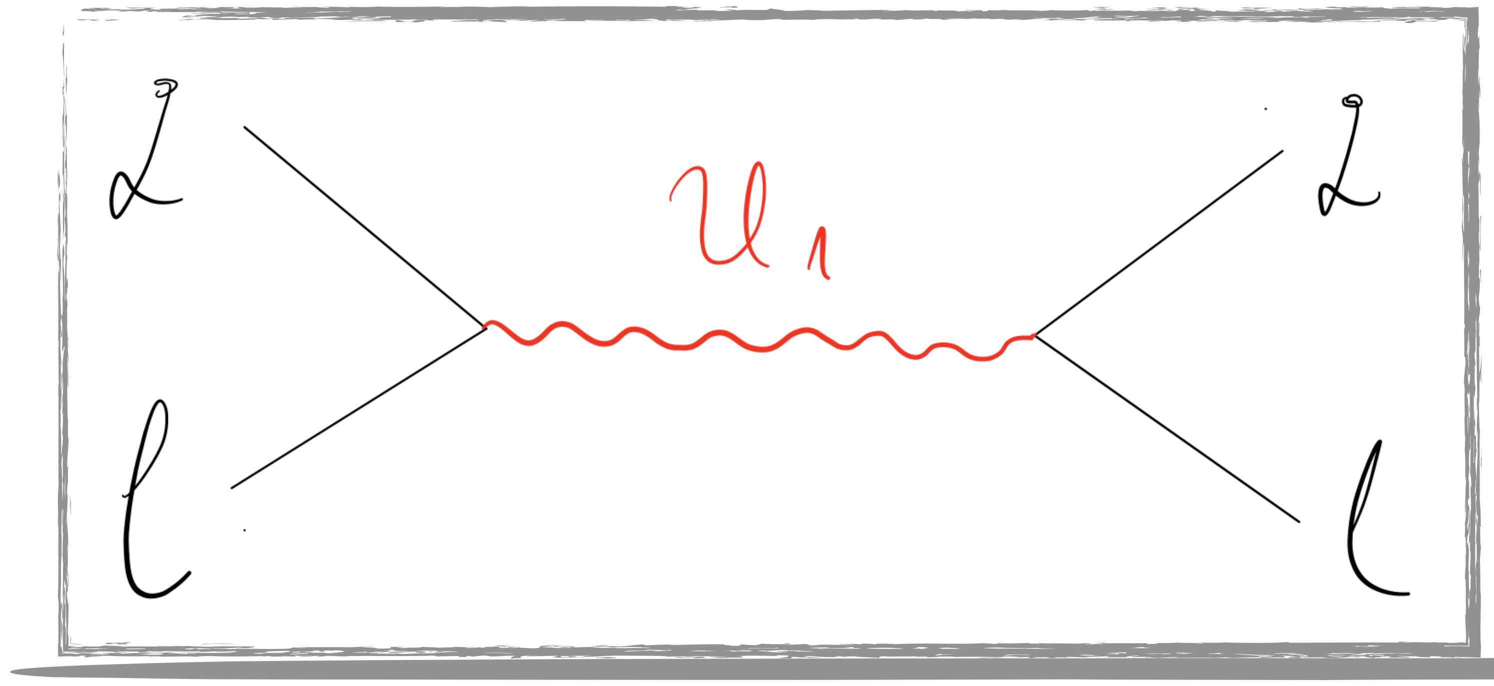

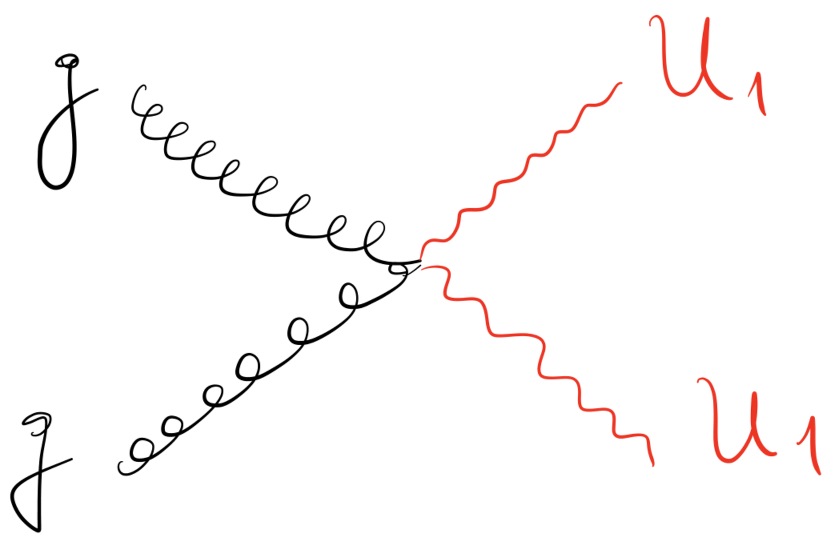

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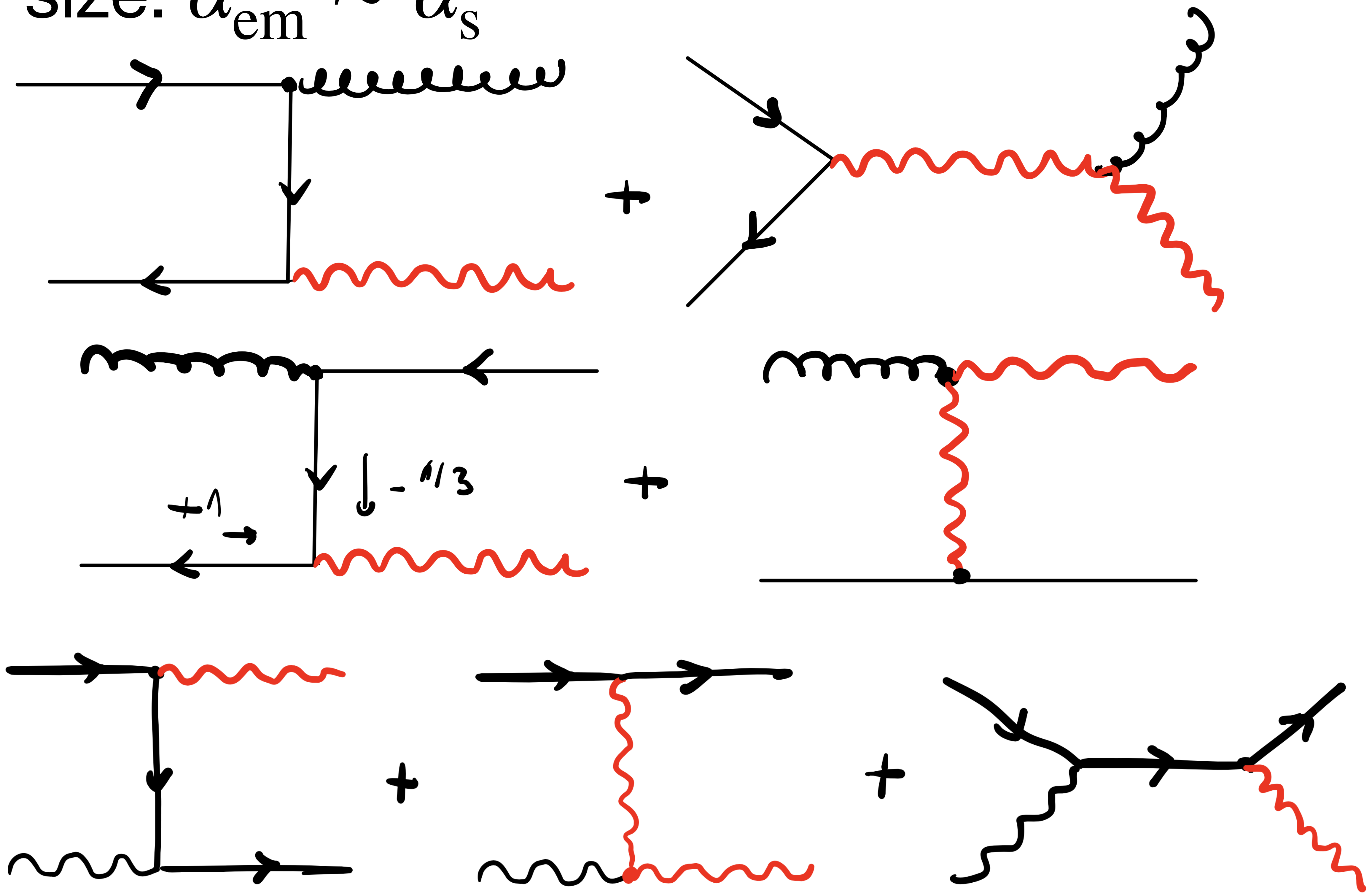
NLO QCD + QED results

QED coupling size: $\alpha_{\mathrm{em}} \sim \alpha_s^2$

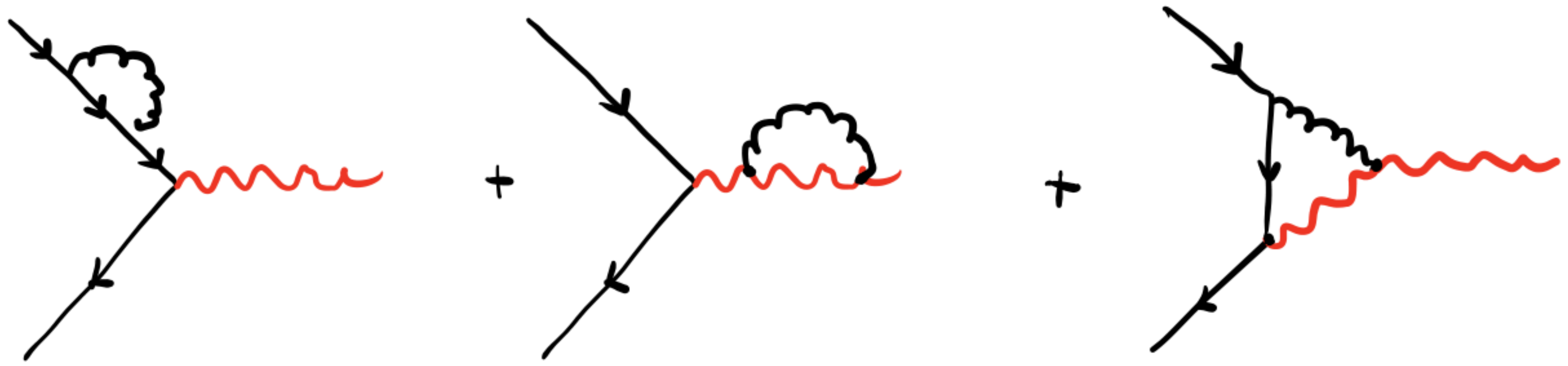
$q + \ell \to g + U_1$

$g + \ell \to q + U_1$

$\gamma + q \to \ell + U_1$



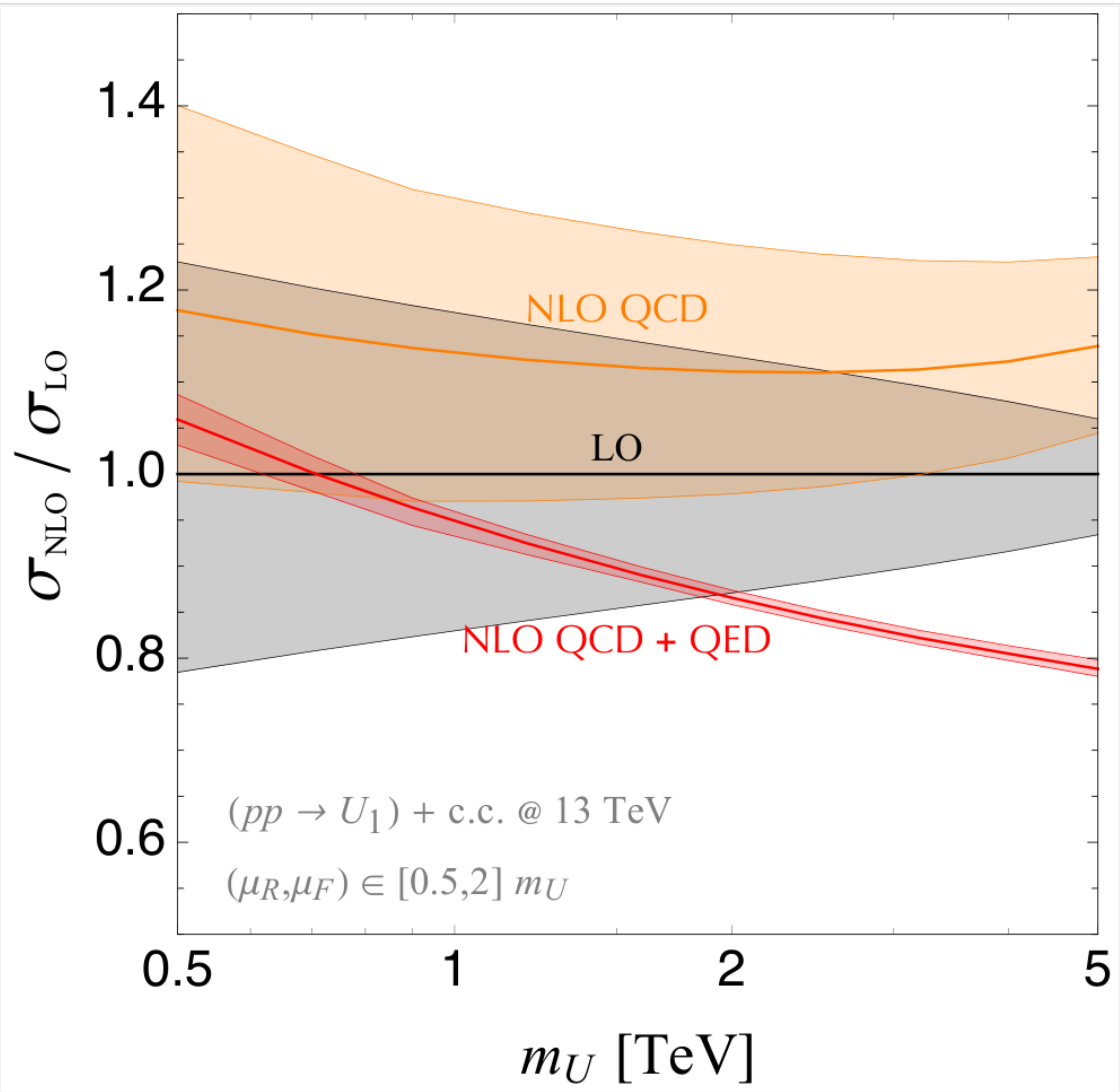
Virtual



[Buonocore et al, arXiv: 2005.06475]

[A. Greljo and N. Selimović, arXiv: 2012.02092]

K-factor



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Simulation details & exclusion limits

- With the matrix elements squared and the finite renormalization piece, build a POWHEG-BOX event generator

  [Frixione et al, arXiv: 0707.3088]

  [Buonocore et al, arXiv: 2209.02599]

- HERWIG has implemented lepton showering algorithm, contrary to Pythia - correction ~30% on the cross-section

- Using the NNPDF3.1 LUXlep PDF set - **with lepton PDFs included**

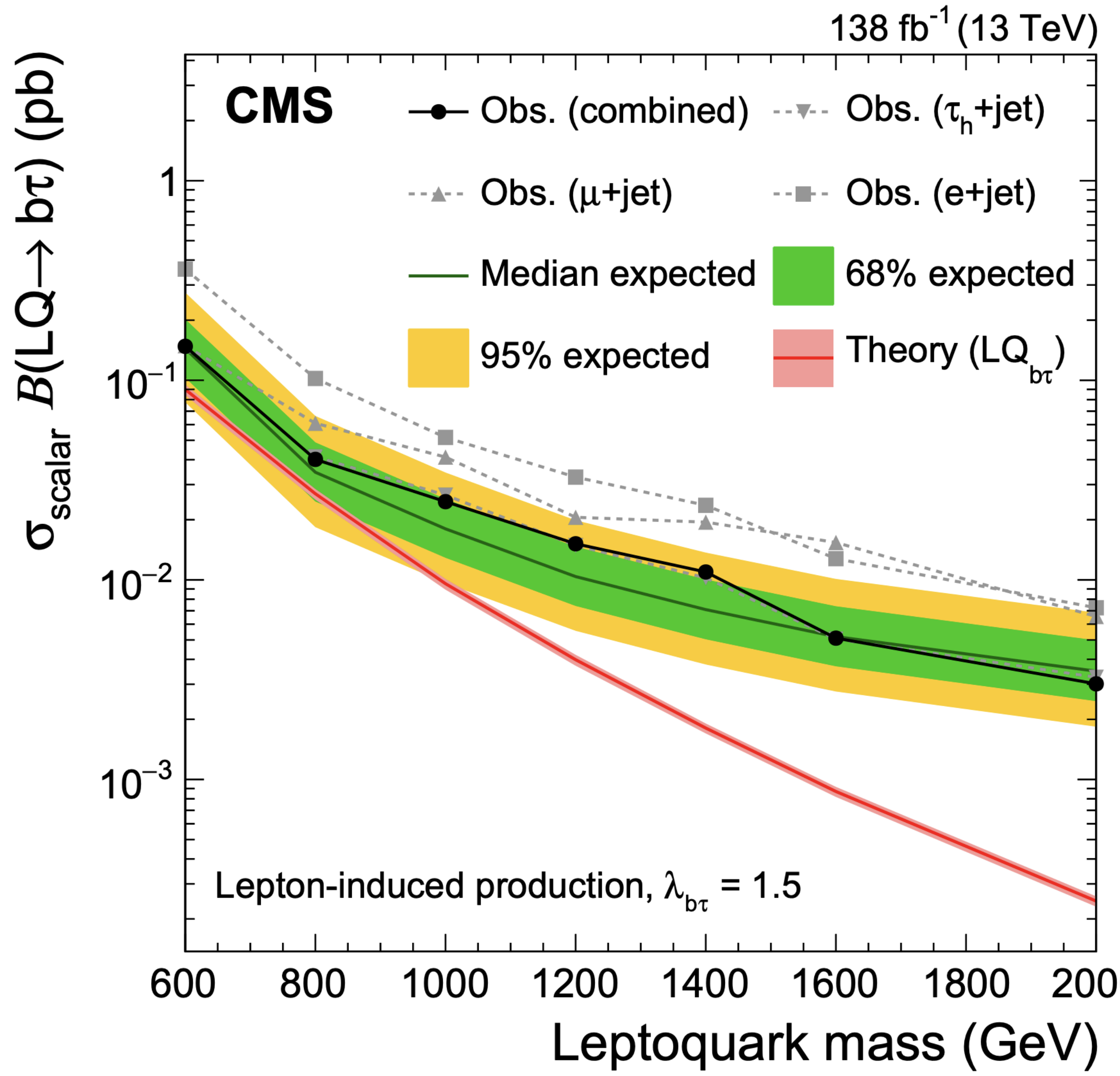
- Jet clustering - FastJet

- Detector effects, tagging and reconstruction - Delphes or own POWHEG algorithm

- https://github.com/peterkrack/3rd-Lepton-Quark-Fusion

- **First experimental search on resonant scalar LQ production, targeting the bτ final state**

  [CMS Collaboration, arXiv: 2308.06143]

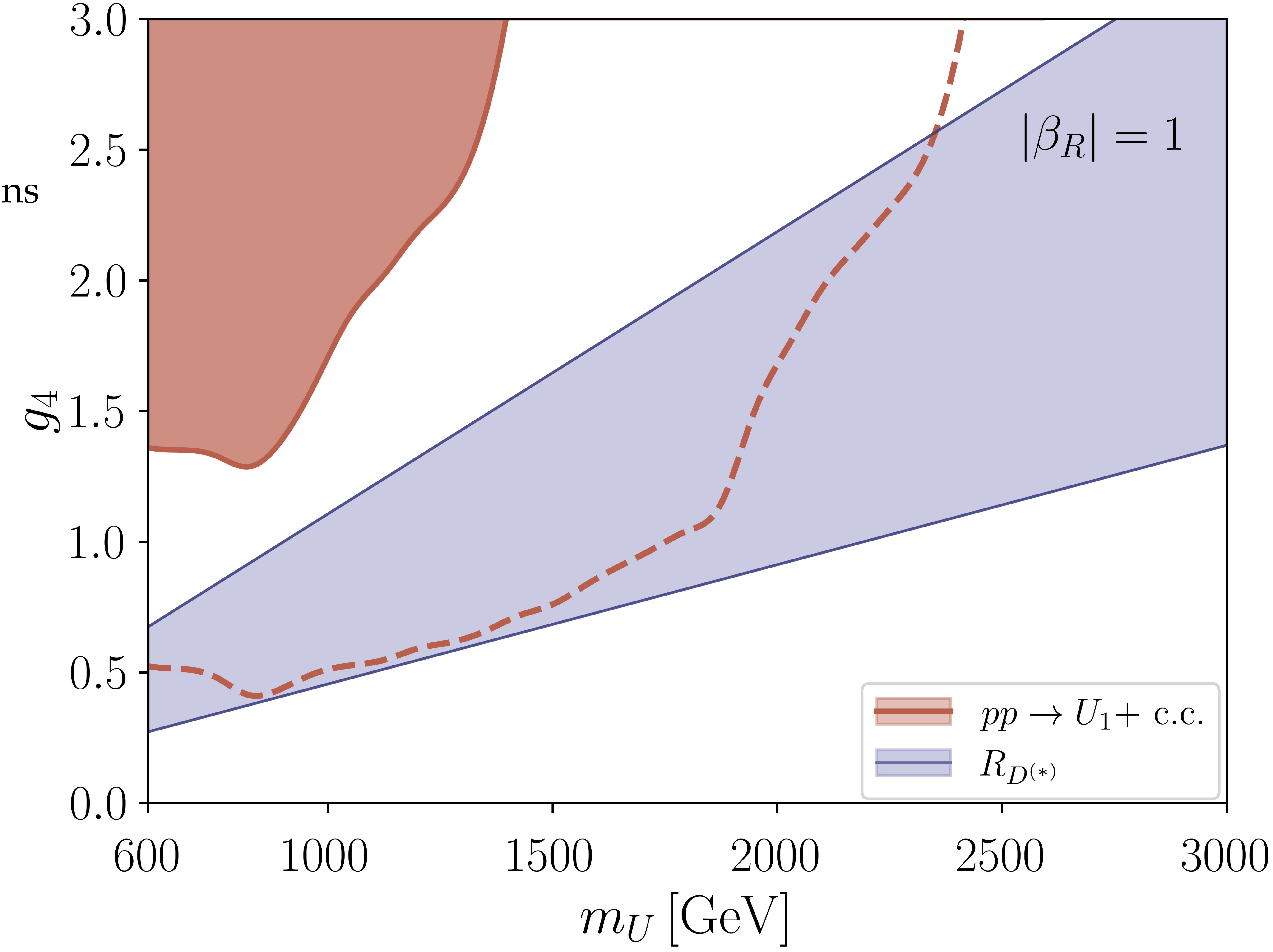


- Data for Brazilian bands (for different couplings) available on HEPData http://dx.doi.org/10.17182/hepdata.141335

- Input our signal, check when exclusion bounds are saturated

Simulation details & exclusion limits

Solid lines - present limits
Dashed lines - HL-LHC projections



[ATLAS, arXiv: 2305.15962]

Simulation details & exclusion limits

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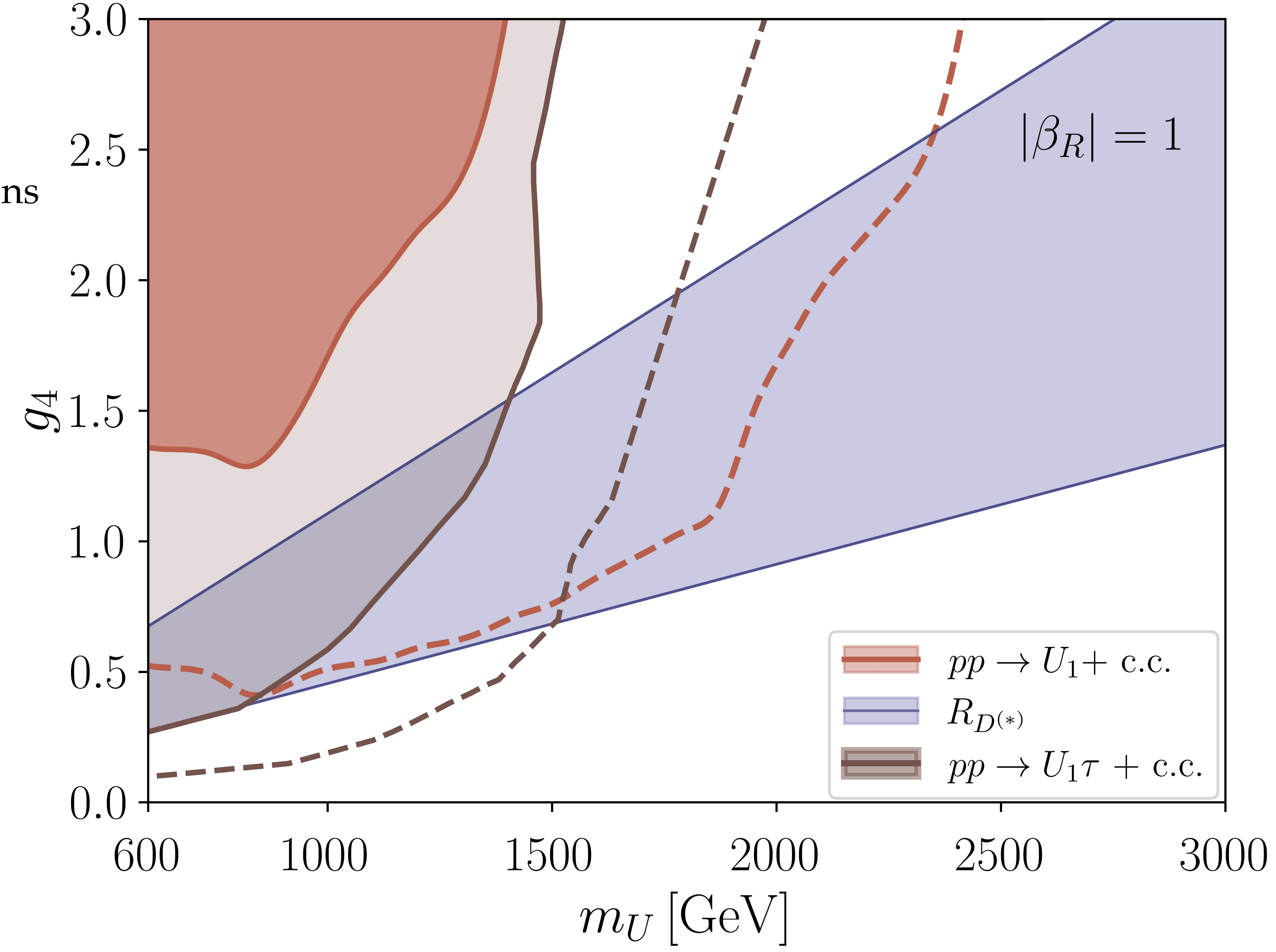

[ATLAS, arXiv: 2305.15962]

[CMS, arXiv: 2012.04178]

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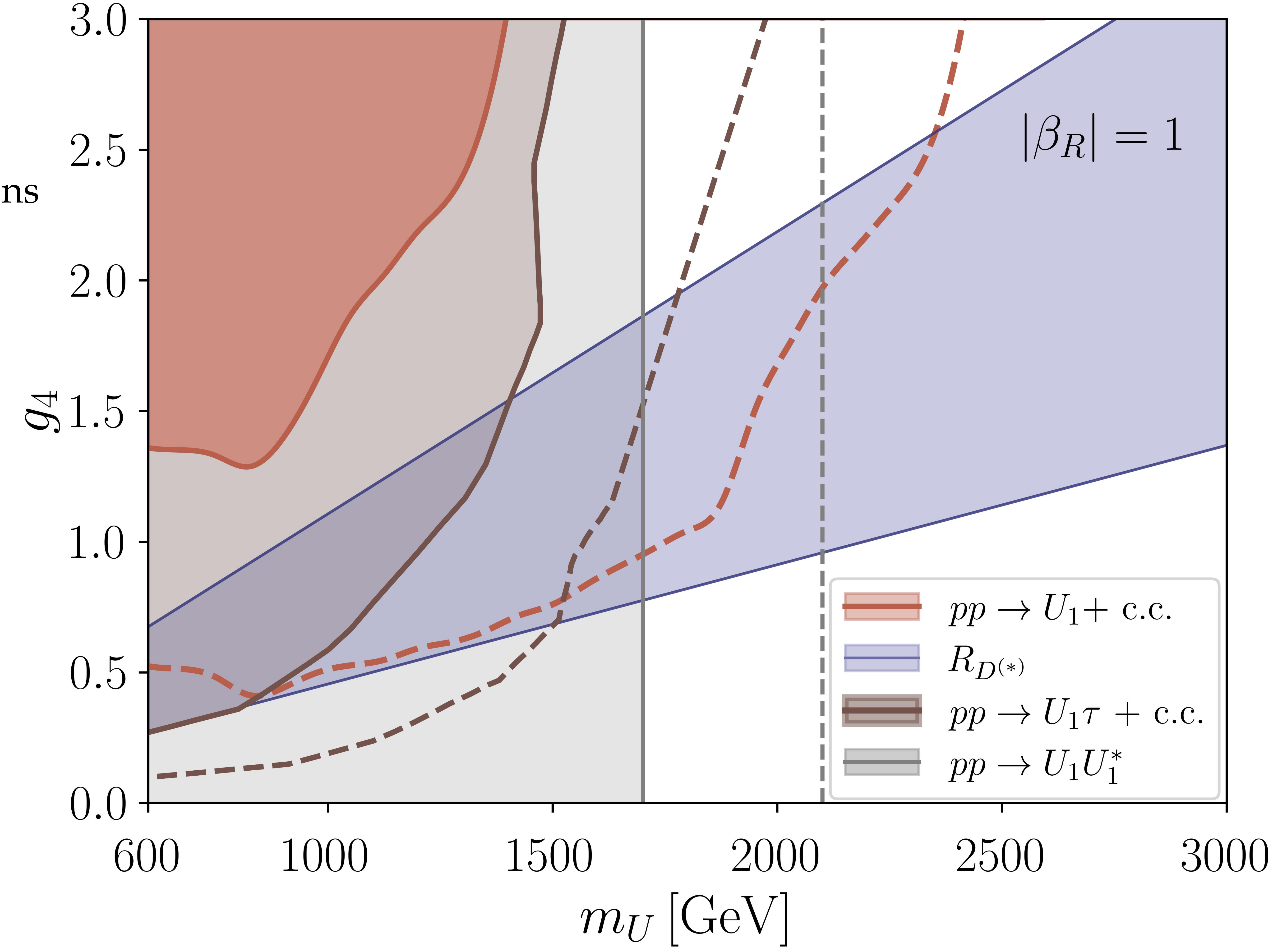

[ATLAS, arXiv: 2305.15962]

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[Baker et al, arXiv: 2012.11474]

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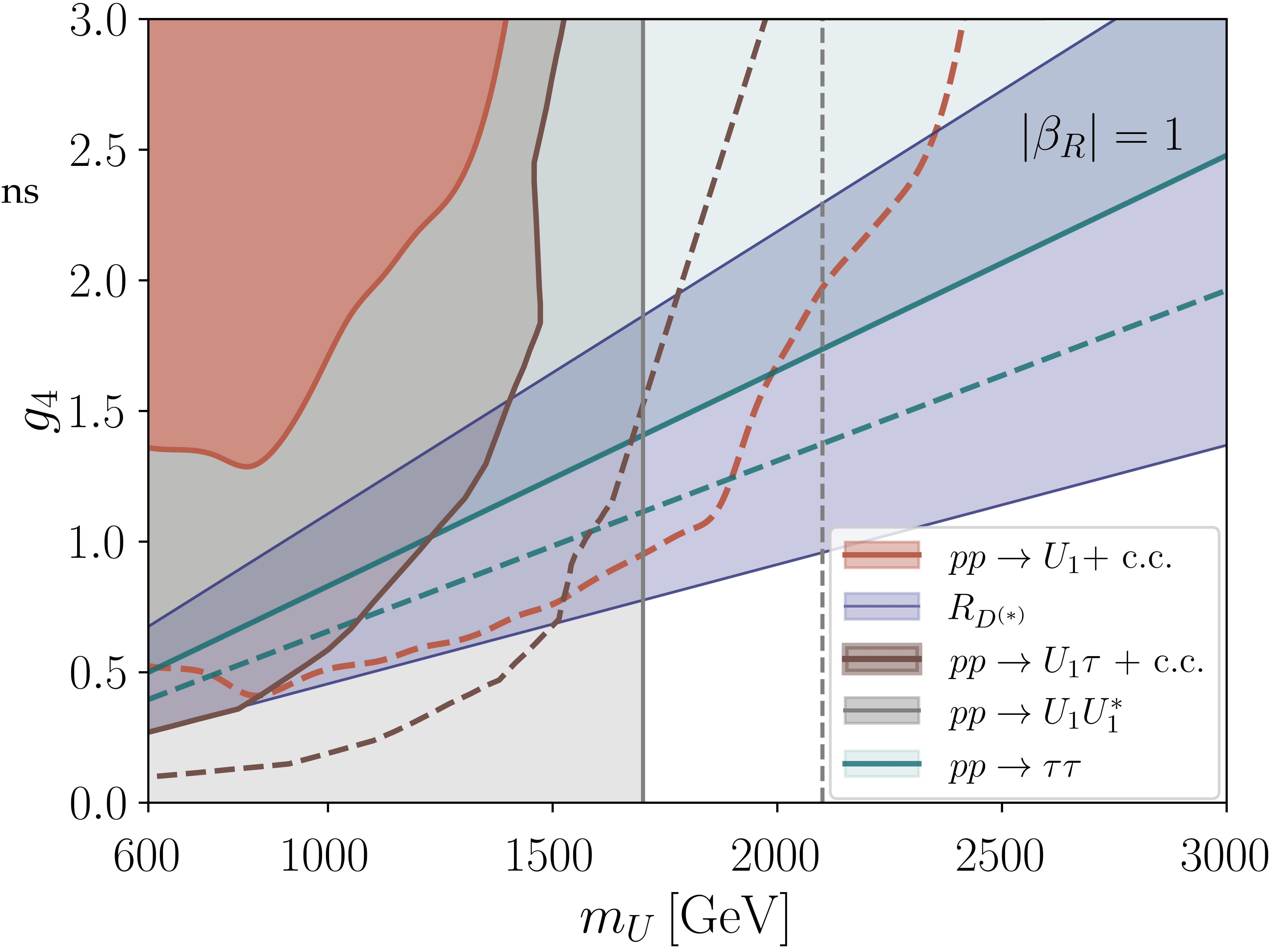

[ATLAS, arXiv: 2305.15962]

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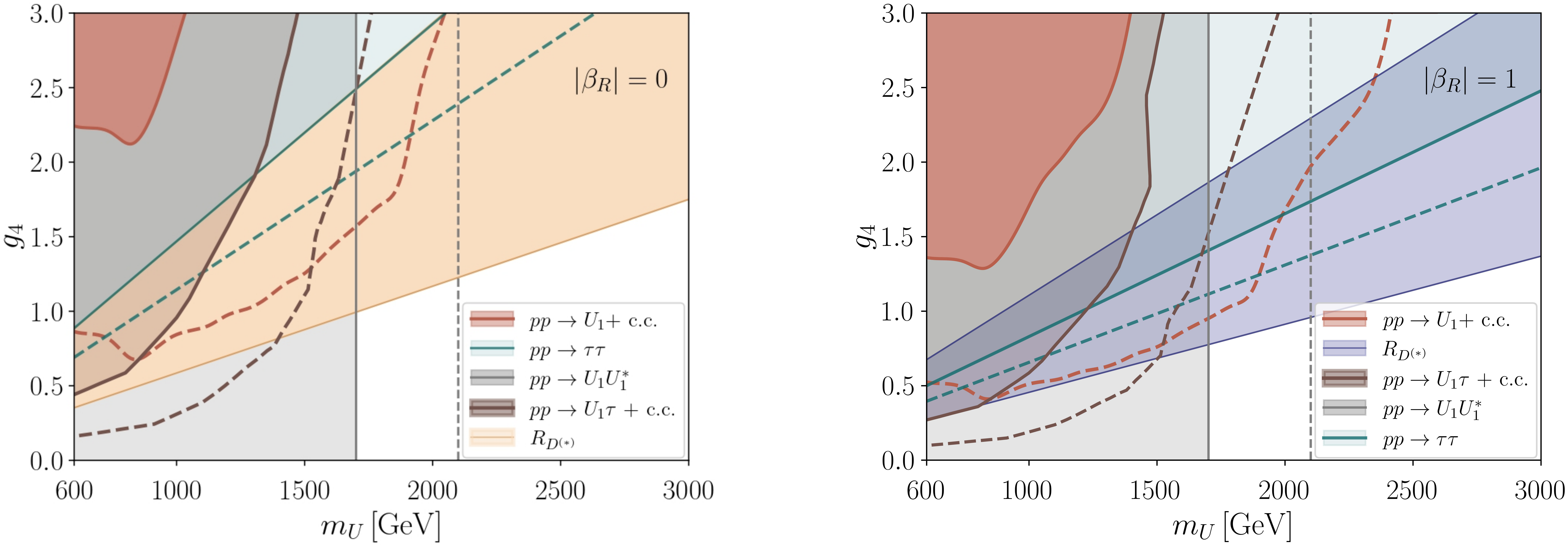
Simulation details & exclusion limits



- Current bounds not competitive with other production mechanisms, mainly due to the lepton PDF suppresion
- BUT: The enhancement of the COM energy very beneficial for the resonant production
- A discovery channel (opposed to t-channel limits)

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Conclusions

- **Utilized the first resonant LQ search at LHC**
- **Phenomenology of lepton-initiated production mechanism is well-understood, simulationwise it is controllable**
- **Tools for simulations steadily improving, there are more products on the market (for hadronic and lepton colliders)**

Resonant scalar LQ production @ LHC in POWHEG-BOX - Buonocore et al; arXiv: 2209.02599

LePDF - PDFs for lepton colliders (e^+e^-, $\mu^+\mu^-$) - Garosi et al; arXiv: 2303.16964

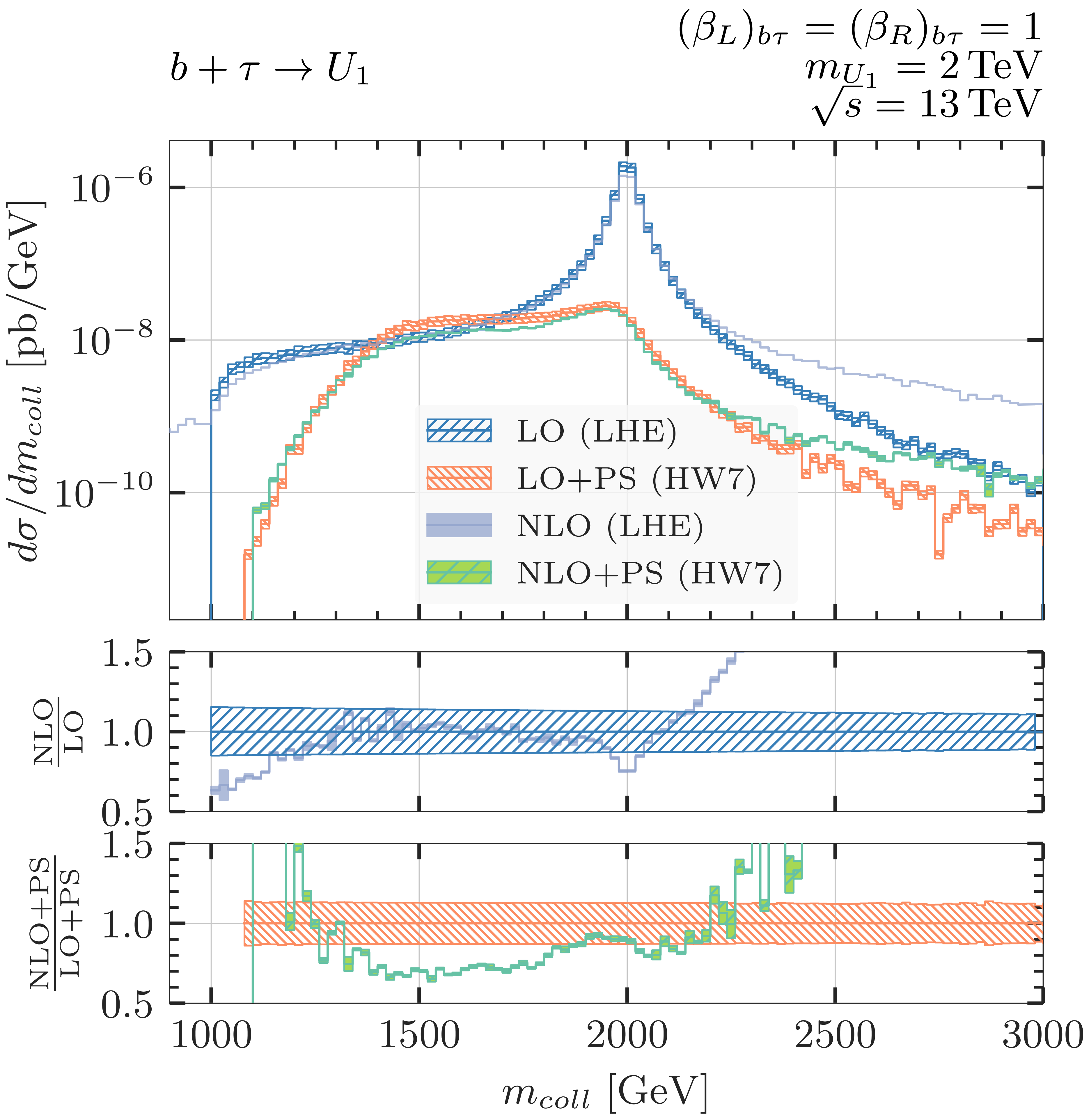
MadGraph/POWHEG/Herwig compatibility - arXiv: 2108.10261 simulate!

Shut up and ~~calculate~~

Thank you!

Backup

Simulation details - Reconstruction



- Taking into account the decay of τ in HERWIG

- Implementation of the CMS cuts in the post-processing:

Variable	$\tau_{\text{h}} + \text{jet}$	$\text{e} + \text{jet}$	$\mu + \text{jet}$
p_{T}^{ℓ}(GeV)	>200	>100	>100
$\lvert\eta^{\ell}\rvert$	<2.1	<2.1	<2.1
$p_{\text{T}}^{\text{jet}}$(GeV)	>300	>200	>200
$\lvert\eta^{\text{jet}}\rvert$	<2.4	<2.4	<2.4
$p_{\text{T}}^{\text{miss}}$(GeV)	>100	>150	>150
$p_{\text{T}}(\vec{\ell} + \vec{p}_{\text{T}}^{\text{miss}})$(GeV)	>100	>100	>100
$\lvert\Delta\phi(\ell, \vec{p}_{\text{T}}^{\text{miss}})\rvert$ (radians)	<0.3	<0.2	<0.2
$\Delta R(\ell, \text{jet})$	>0.5	>0.5	>0.5

[CMS Collaboration, arXiv: 2308.06143]

- Using the quantity $m_{\text{coll}} = m_{\text{vis}}\sqrt{1 + p_T^{\text{invis}}/p_T^{\text{vis}}}$ to reconstruct the peak

NLO QCD + QED results

- The QCD and QED corrections are of the same order:

[A. Greljo and N. Selimović, arXiv: 2012.02092]

$$f_q \sim f_g \sim \mathcal{O}(\sum_n (\alpha_s L)^n) \sim \mathcal{O}(1) \qquad \alpha_s \sim 1/L \qquad L = \log(\mu_F^2/\Lambda^2)$$

Λ - hadronic scale

- QED coupling size: $\alpha_{\mathrm{em}} \sim \alpha_{\mathrm{s}}^2$
  - γ - PDF, 1st order QED effect: $f_\gamma \sim \mathcal{O}(\alpha_{\mathrm{em}} L) \sim \mathcal{O}(\alpha_s)$
  - ℓ - PDF, 2nd order QED effect: $f_\ell \sim \mathcal{O}((\alpha_{\mathrm{em}} L)^2) \sim \mathcal{O}(\alpha_s^2)$

- Including real corrections:
  - $q + \ell \to g + U_1$
  - $g + \ell \to q + U_1$
  - $\gamma + q \to \ell + U_1$

$$\sigma_{q\ell}(s) \sim \int (f_q \otimes f_\ell)\ \hat{\sigma}_{q\ell} \sim 1 \times \alpha_{\mathrm{s}}^2 \times \alpha_{\mathrm{s}} \sim \alpha_{\mathrm{s}}^3$$

$$\sigma_{q\gamma}(s) \sim \int (f_q \otimes f_\gamma)\ \hat{\sigma}_{q\gamma} \sim 1 \times \alpha_{\mathrm{s}} \times \alpha_{\mathrm{em}} \sim \alpha_{\mathrm{s}}^3$$

Finite-width effects

- The narrow-width approximation (NWA) can have an $\mathcal{O}(1)$ relative error compared to full Breit-Wigner result for $m_{\rm LQ} \gtrsim 2\,\mathrm{TeV}$ and $g_4 \gtrsim 1.5$!
- The Breit-Wigner prescription for the propagator can be turned on by setting the flag BWgen $= 1$.
- For larger values of coupling, the convolutional area between the PDFs and the Breit-Wigner is also larger, hence we are more sensitive to the low-x region of the PDFs (enhanced by orders of magnitude compared to the values of the PDF at the mass pole)