Resonant U_1 leptoquark production @ LHC

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

Eur. Phys. J. C 84, 304 (2024)
arXiv: 2311.13635

Val di Luce, 2024

Arman Korajac (INFN Pisa)

Resonant U_1 leptoquark production @ LHC

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

Eur. Phys. J. C 84, 304 (2024)
arXiv: 2311.13635

Val di Luce, 2024

Arman Coraiazz (INFN Pisa)

OUTLINE

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

OUTLINE

- 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

$$[SU(4) \times SU(2)_L \times SU(2)_R]^{[3]} \times [SU(3) \times SU(2)_L \times U(1)_{B-L} \times U(1)_R]^{[12]}$$

$$\downarrow \langle \phi \rangle$$

$$[SU(4) \times SU(2)_L \times SU(2)_R]^{[3]} \times [SU(3) \times SU(2)_L \times U(1)_Y]^{[12]}$$

$$\langle \Sigma_L \rangle \downarrow \langle \Sigma_R \rangle$$

$$SU(4)^{[3]} \times SU(3)^{[12]} \times SU(2)_L \times U(1)_X$$

$$\langle \Omega_3 \rangle \downarrow \langle \Omega_1 \rangle$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y \,,$$

[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	**4**	**1**	**2**	0
ψ_R^+	**4**	**1**	**1**	1/2
ψ_R^-	**4**	**1**	**1**	−1/2
q_L^i	**1**	**3**	**2**	1/6
ℓ_L^i	**1**	**1**	**2**	−1/2
u_R^i	**1**	**3**	**1**	2/3
d_R^i	**1**	**3**	**1**	−1/3
e_R^i	**1**	**1**	**1**	−1
H	**1**	**1**	**2**	1/2
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	1/6
Ω_1	$\bar{\mathbf{4}}$	**1**	**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

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

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

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

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

$i = 1,2$

$$\psi_L \equiv (q^3_L \;\; \ell^3_L)^\intercal$$

$$\psi^-_R \equiv (d^3_R \;\; e^3_R)^\intercal \qquad \psi^+_R \equiv (u^3_R \;\; \nu^3_R)^\intercal$$

4321 for U1

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

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

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

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

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

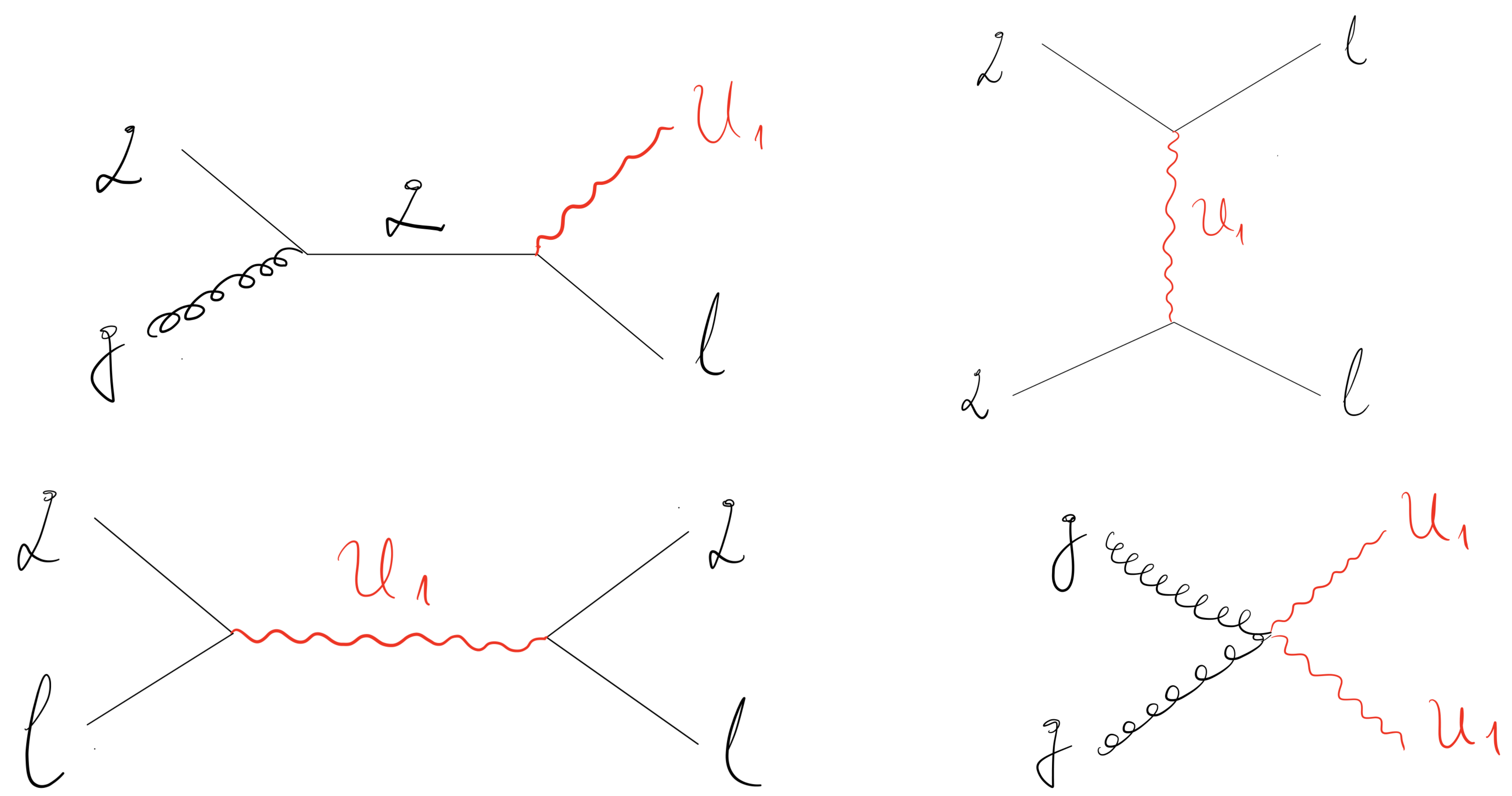
$$G'^a_\mu = c_3 H^a_\mu - s_3 C^a_\mu\,, \quad Z'_\mu = c_1 H^{15}_\mu - s_1 X_\mu$$

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

4321 for U1

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

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.

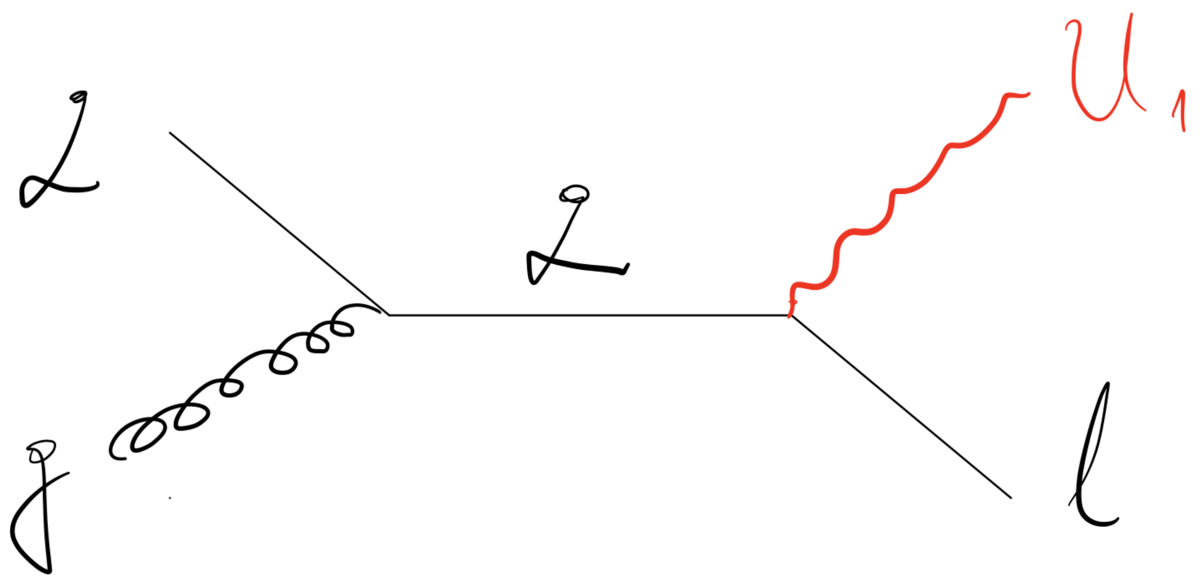
[U. Haisch, G. Polesello, arXiv:2012.11474]

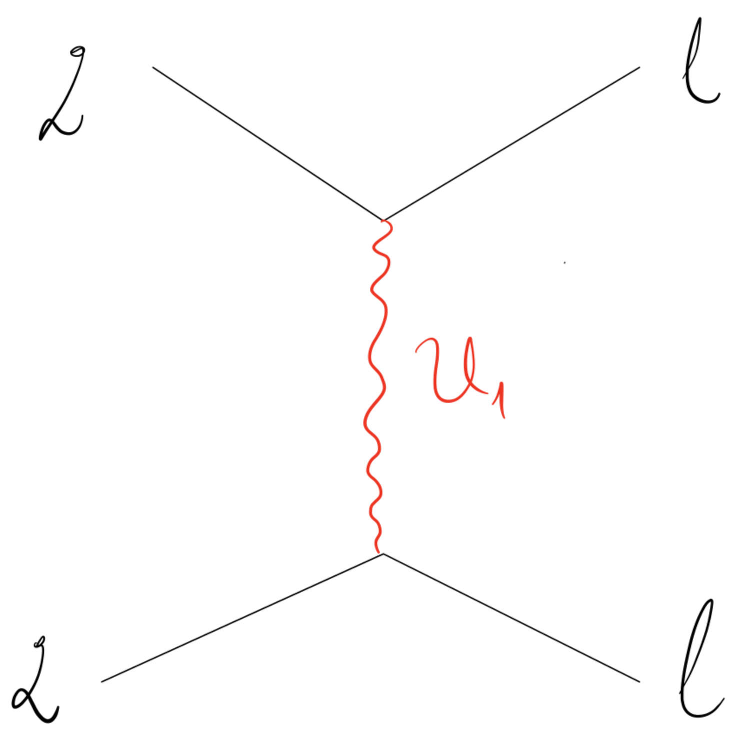
[Buonocore et al, arXiv: 2005.06475]

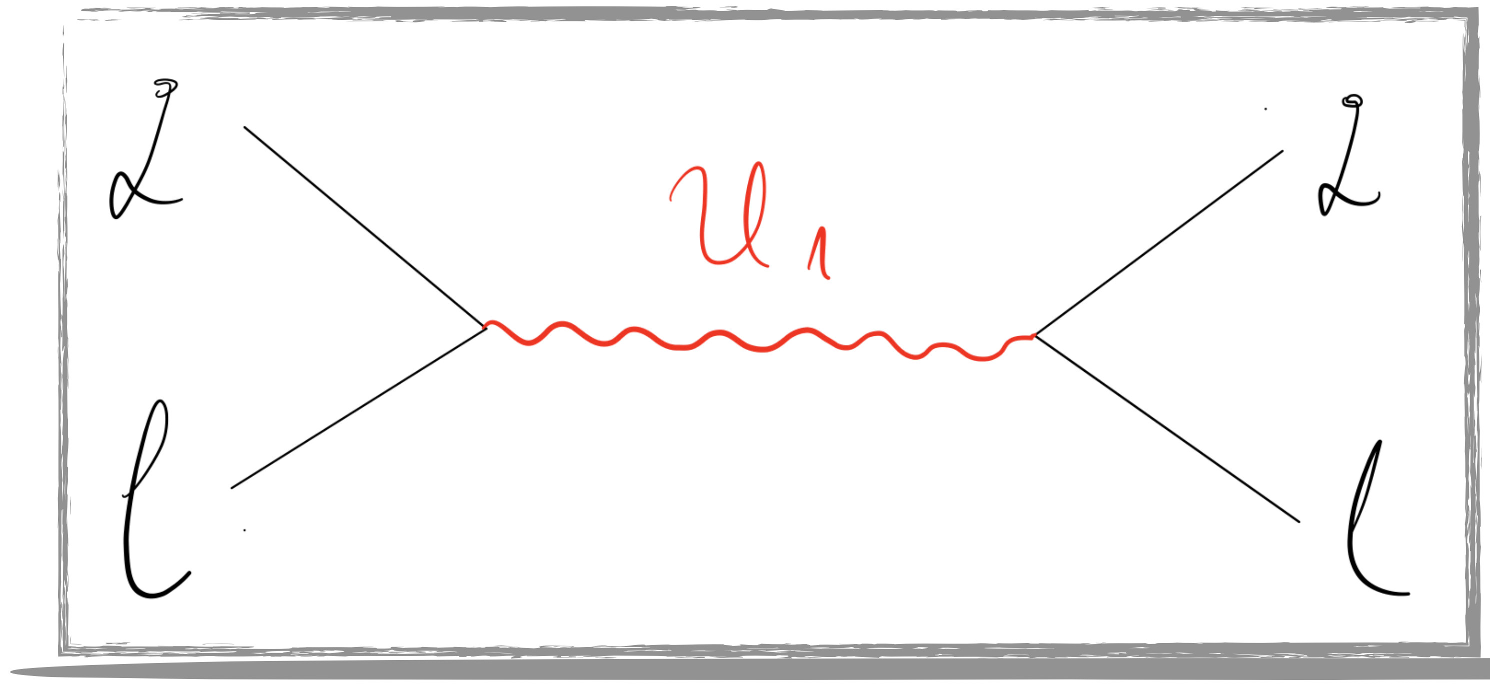
4321 for U1

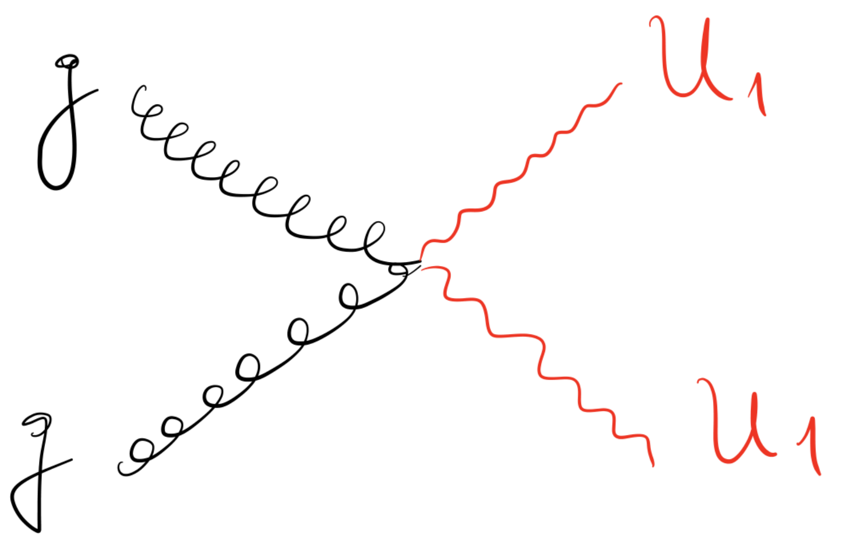
$$\mathcal{L}_{U_1} \supset \frac{g_4}{\sqrt{2}} U_\mu \left(\beta_L^{33}\, \bar{q}_L^3 \gamma^\mu \tau_L + \beta_R^{33}\, \bar{b}_R \gamma^\mu \tau_R + \text{h.c.}\right)$$
$$- i g_s U_\mu^\dagger T^a U_\nu G^{a,\mu\nu} - \frac{2}{3} ie\, U_\mu^\dagger U_\nu F^{\mu\nu}$$

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]

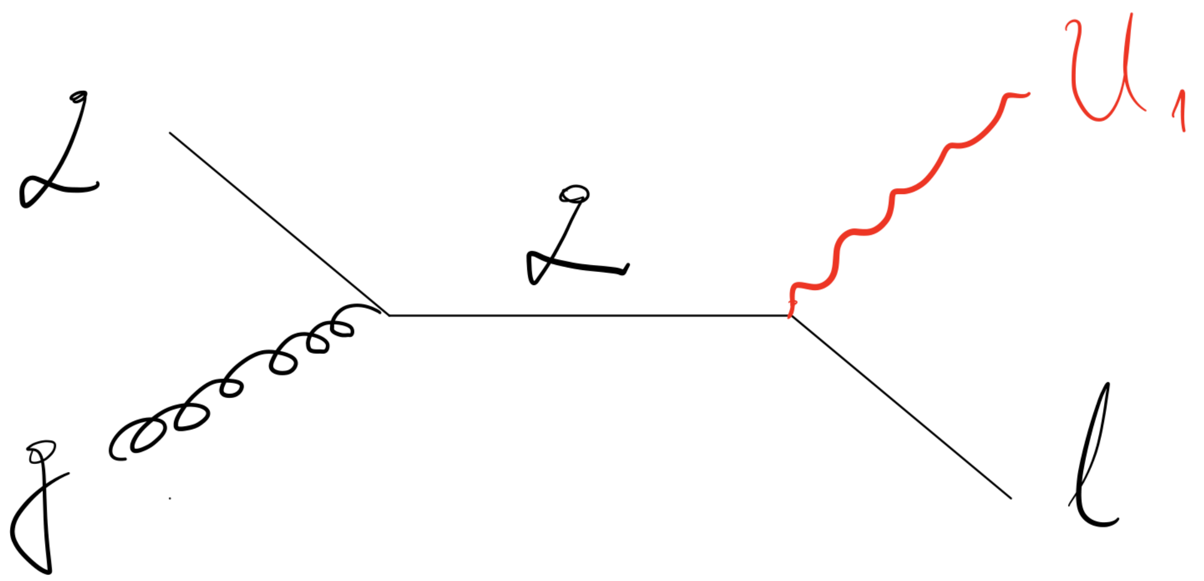
[Buonocore et al, arXiv: 2005.06475]

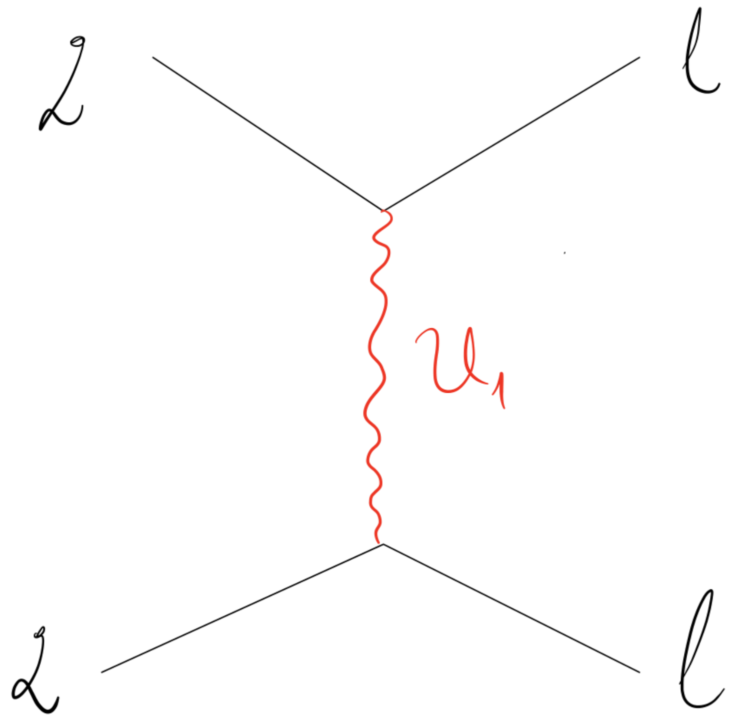
4321 for U1

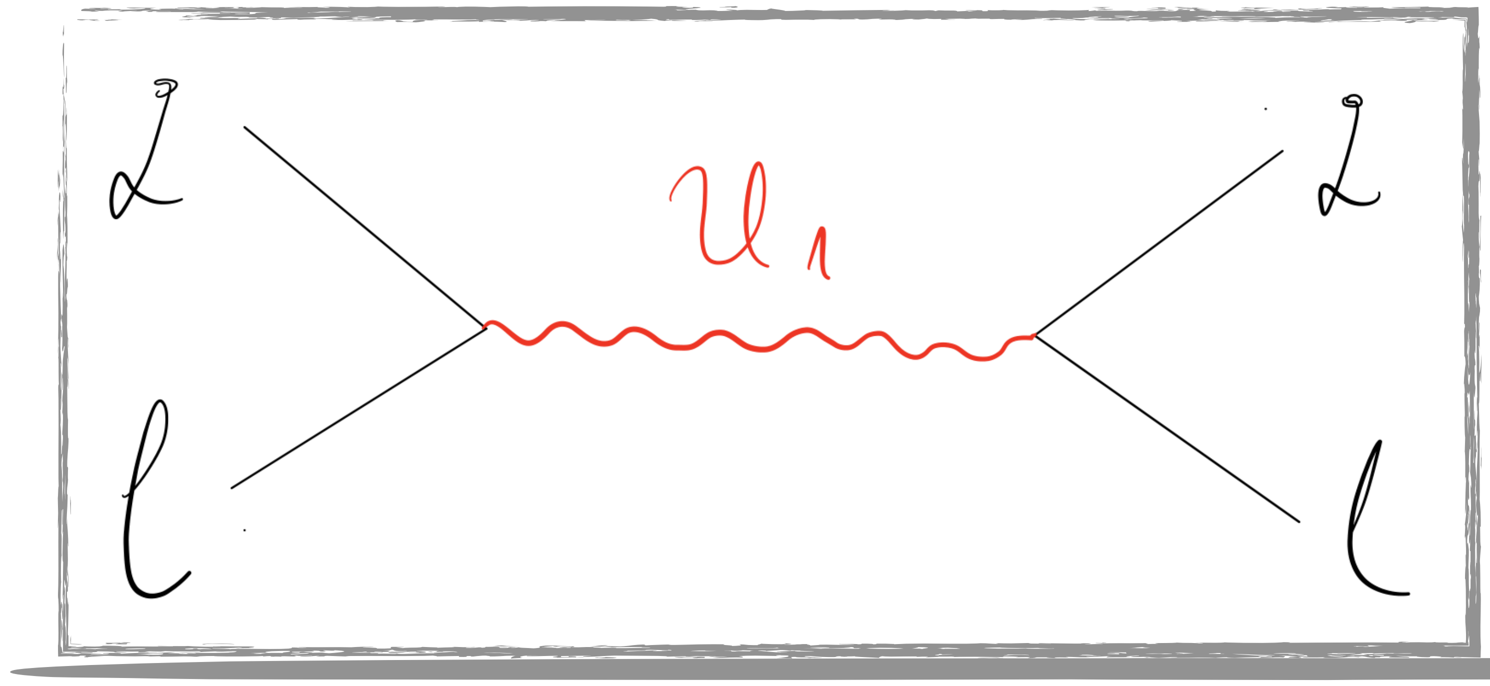
$$\mathcal{L}_{U_1} \supset \frac{g_4}{\sqrt{2}} U_\mu \left(\beta_L^{33}\, \bar{q}_L^3 \gamma^\mu \tau_L + \beta_R^{33}\, \bar{b}_R \gamma^\mu \tau_R + \text{h.c.}\right)$$

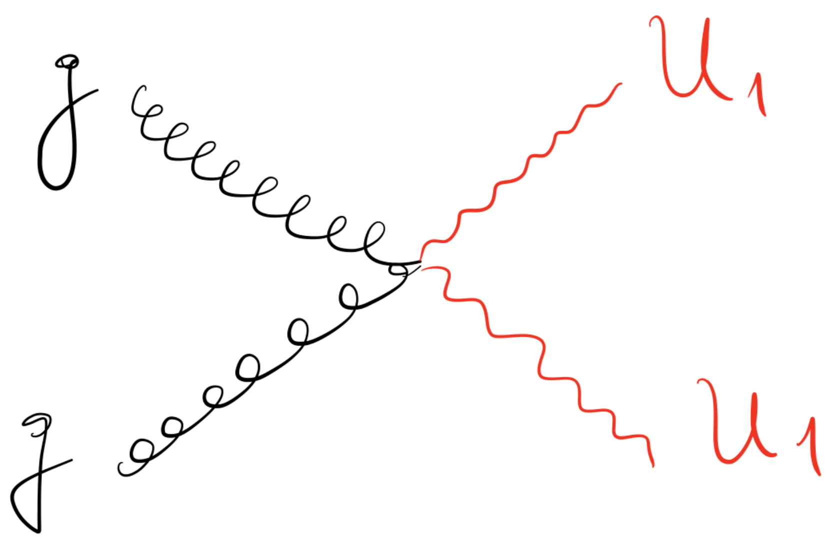
$$- i g_s U_\mu^\dagger T^a U_\nu G^{a,\mu\nu} - \frac{2}{3} i e\, U_\mu^\dagger U_\nu F^{\mu\nu}$$

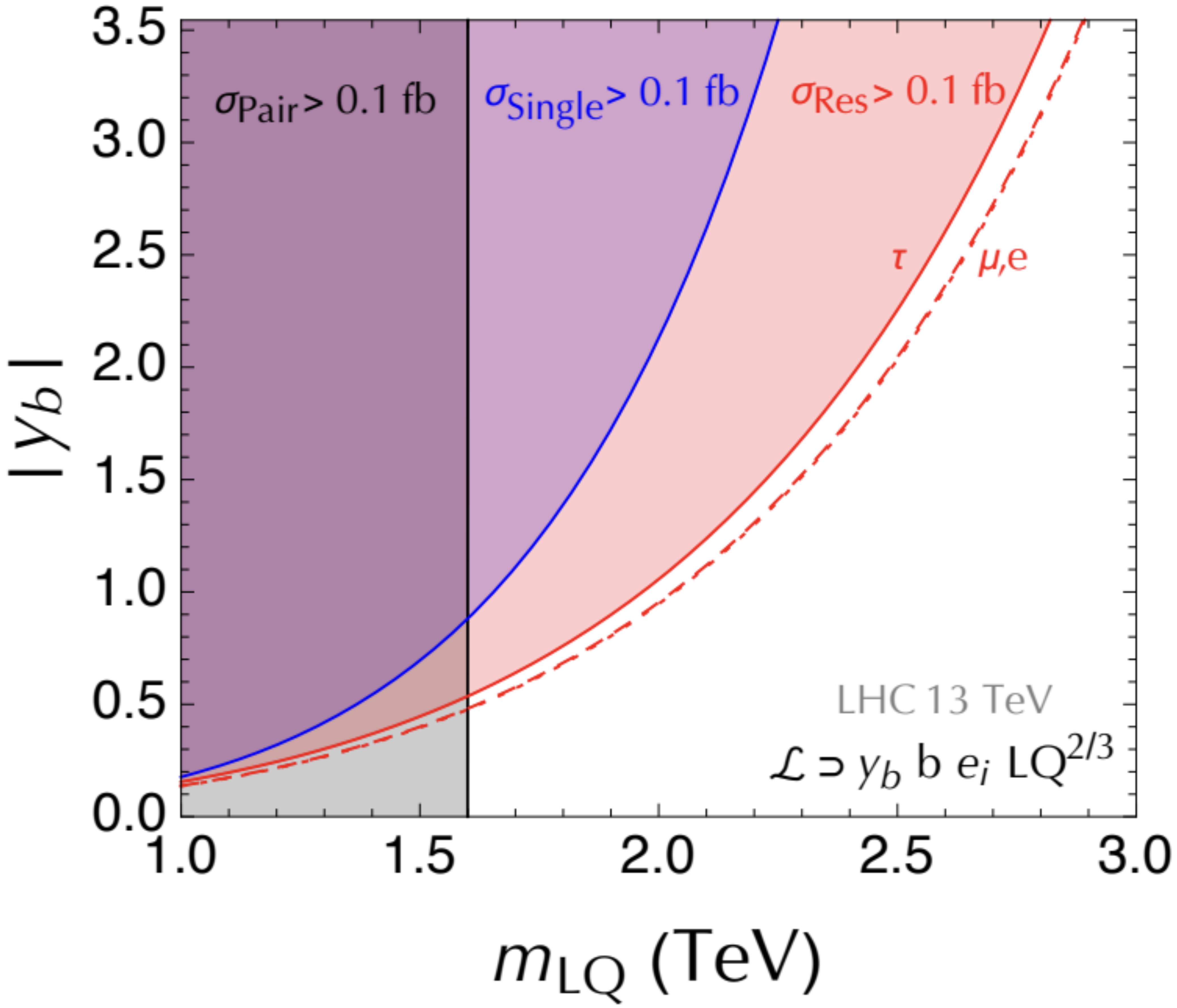
Can be extended to couplings with light-gen fermions; additional fields required











A. Greljo and N. Selimović, 2012.02092

OUTLINE

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

NLO QCD + QED results - Power counting

[Manohar, Nason, Salam, Zanderighi, arXiv: 1607.04266]

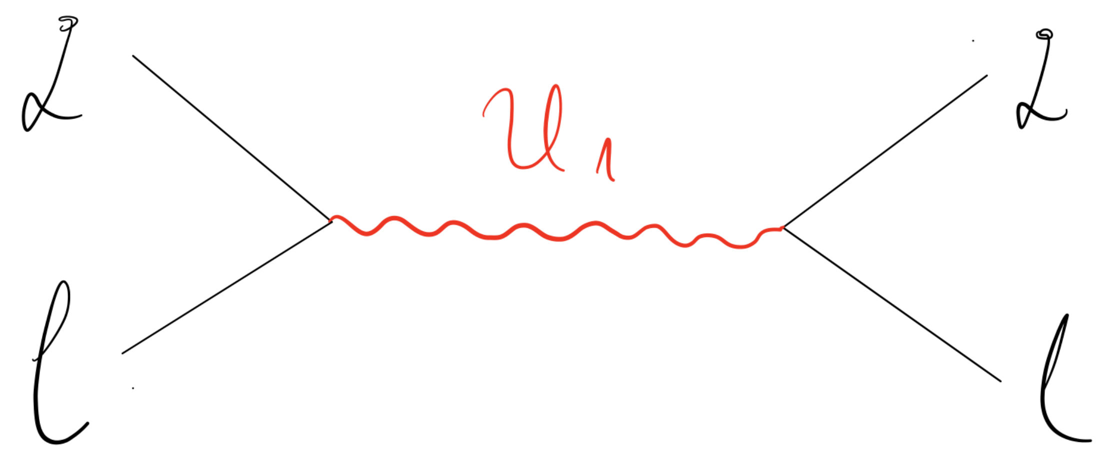
[A. Greljo and N. Selimović, arXiv: 2012.02092]

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

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

Λ - hadronic scale

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



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

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

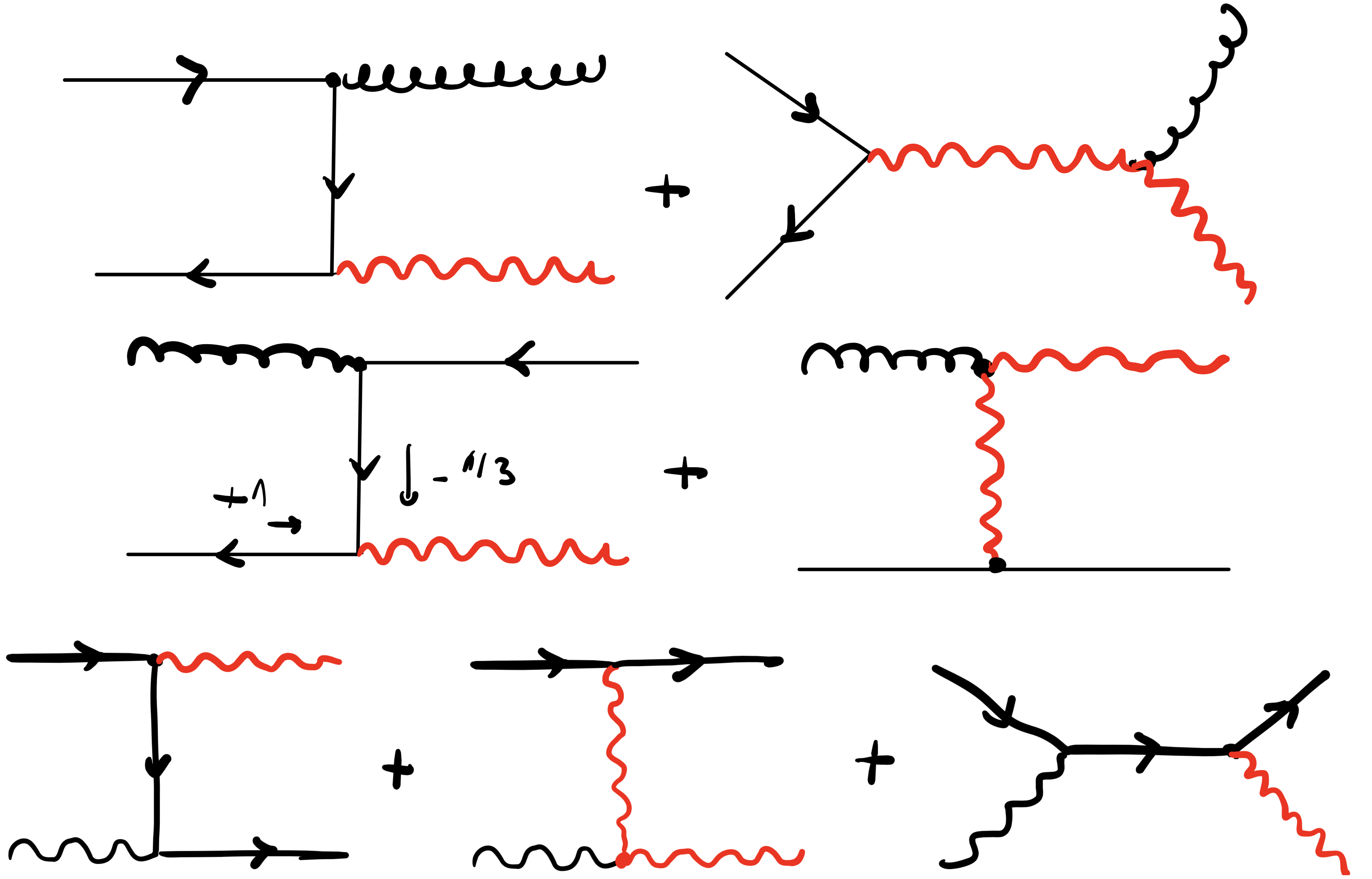
$$\sigma_{q\gamma}(s) \sim \int (f_q \otimes f_\gamma)\, \hat{\sigma}_{q\gamma} \sim 1 \times \alpha_{\rm s} \times \alpha_{\rm em} \sim \alpha_{\rm s}^3$$

NLO QCD + QED results

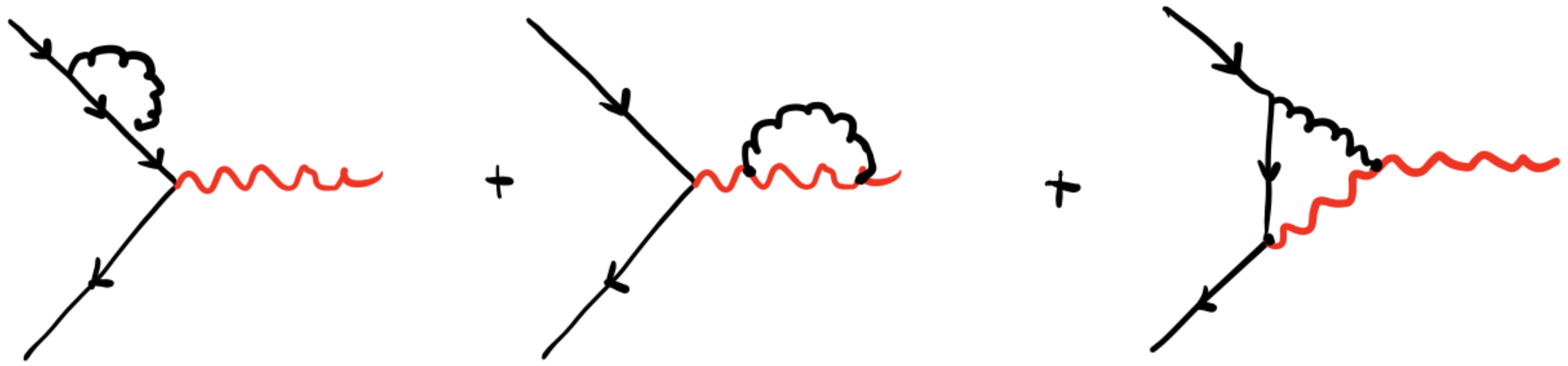
$q + \ell \to g + U_1$

$g + \ell \to q + U_1$

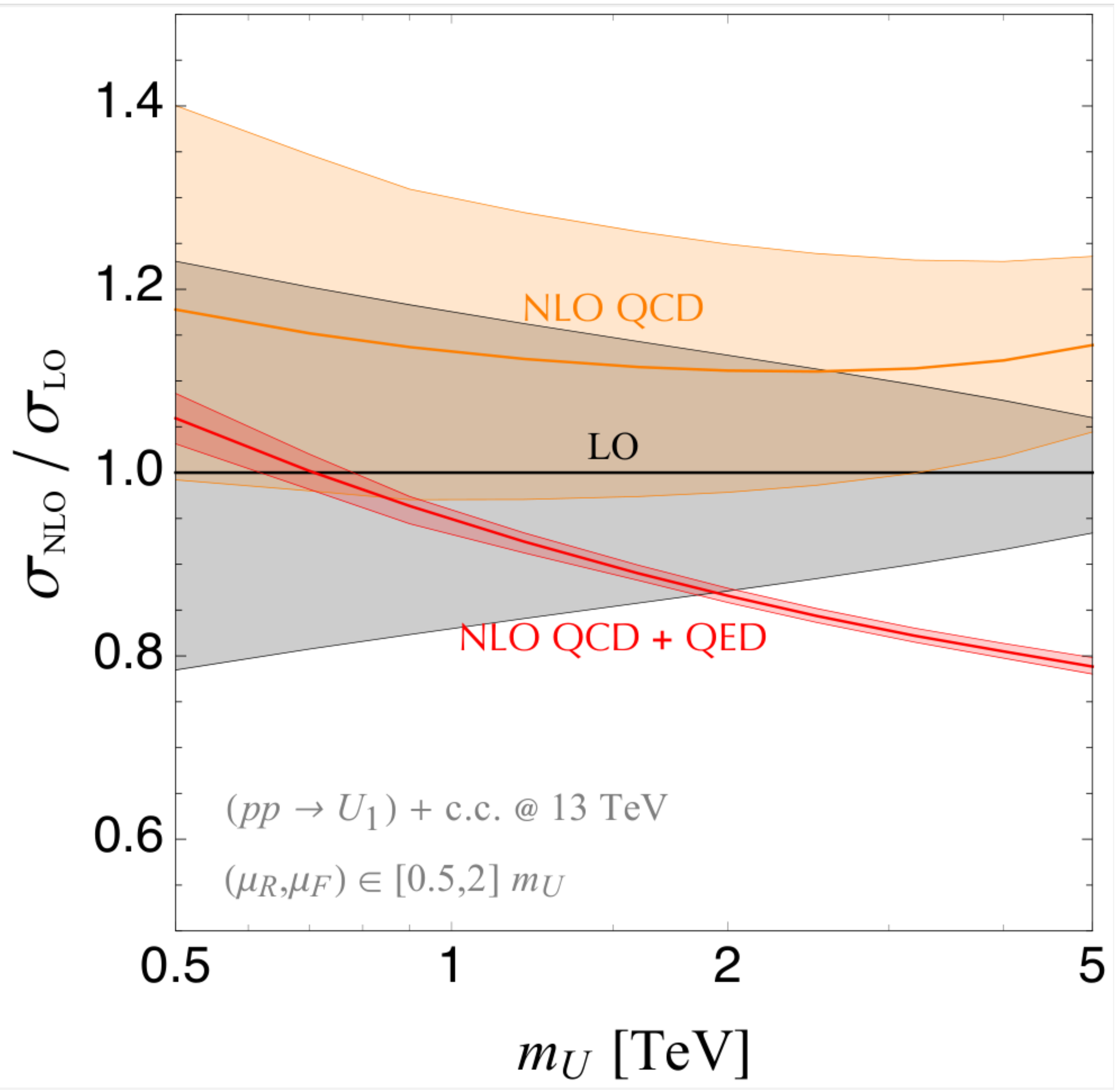
$\gamma + q \to \ell + U_1$



Virtual



K-factor



g_4, LQ propagator - OS ren. scheme

Kunszt, Stirling, Z.Phys.C 75, 453-463 (1997)

[Buonocore et al, arXiv: 2005.06475]

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

OUTLINE

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

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**

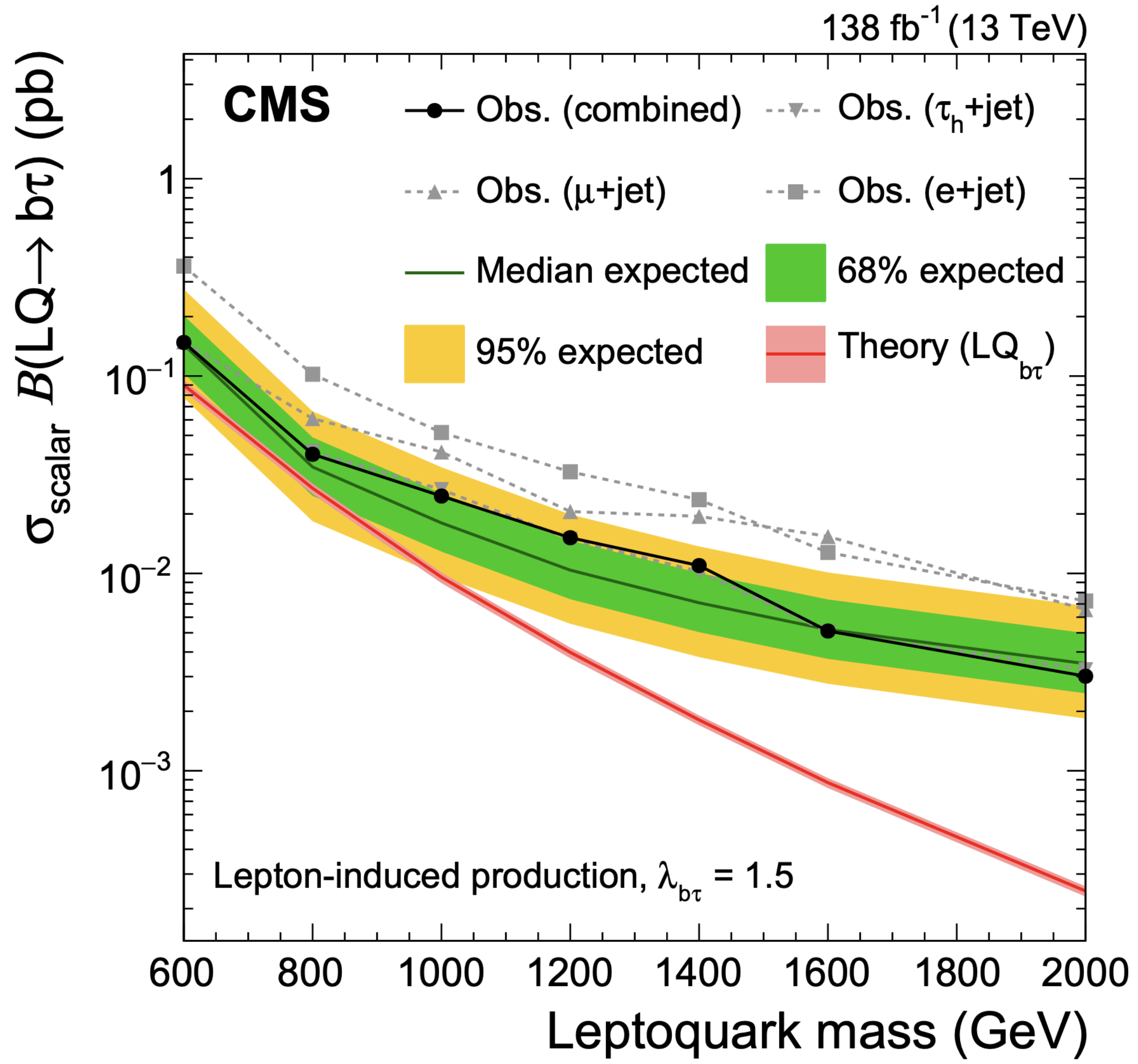
- Jet clustering - FastJet

- 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]

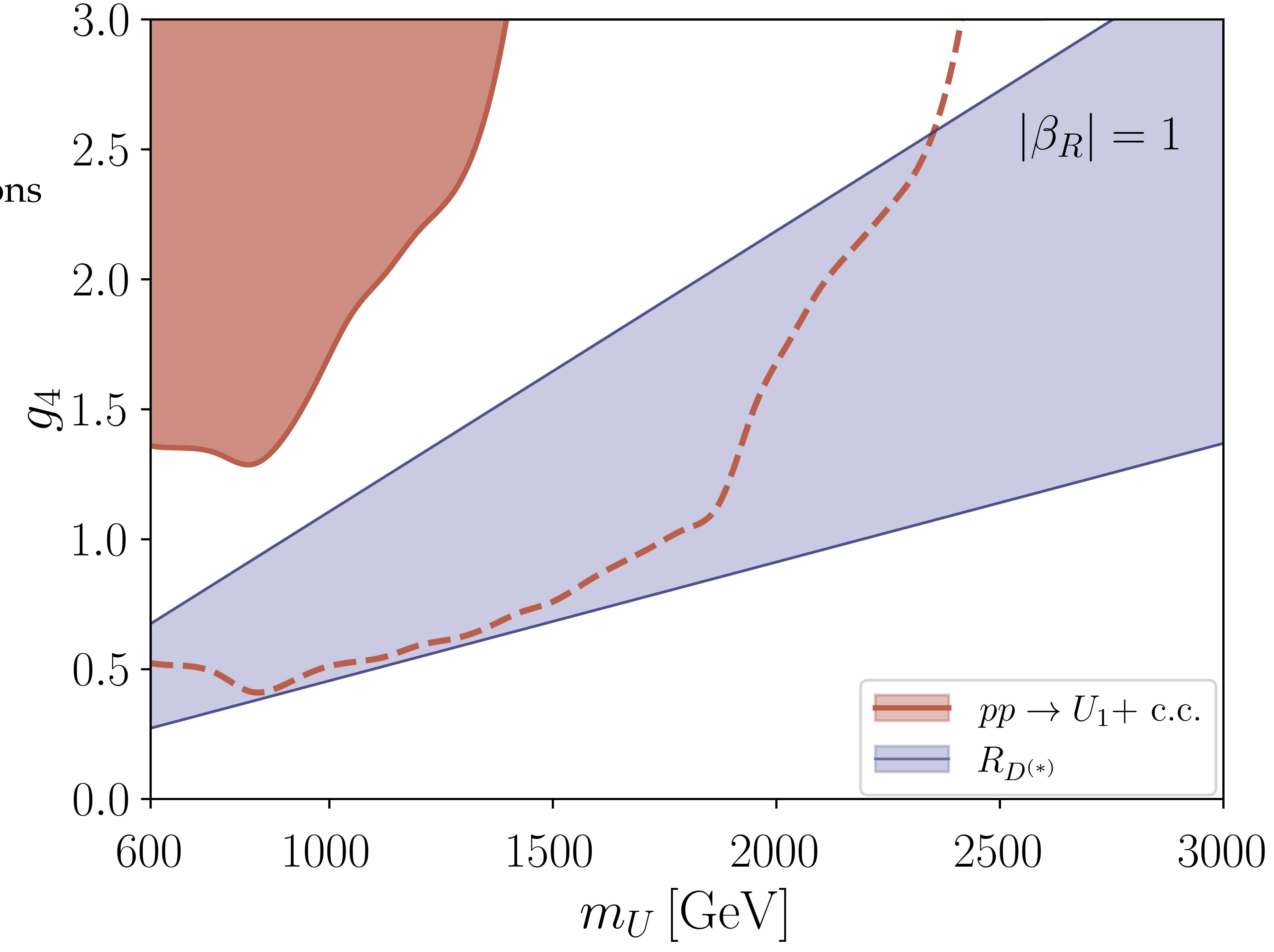


- Data for Brazilian bands (for different couplings) available on HEPData http://dx.doi.org/10.17182/hepdata.141335

- Input our signal, check when exclusion bounds are saturated

Simulation details & exclusion limits

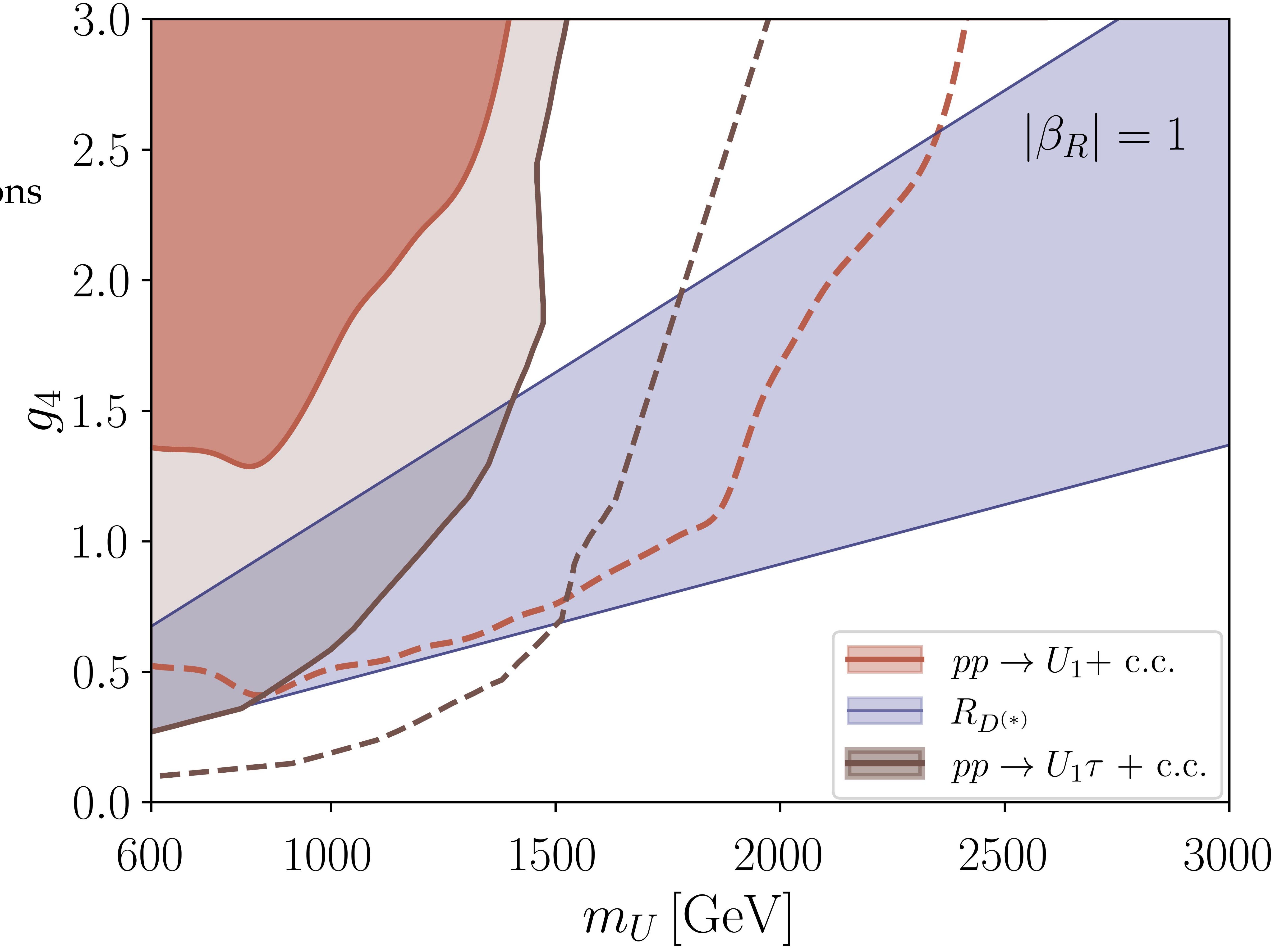
Solid lines - present limits
Dashed lines - HL-LHC projections



[ATLAS, arXiv: 2305.15962]

Simulation details & exclusion limits

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

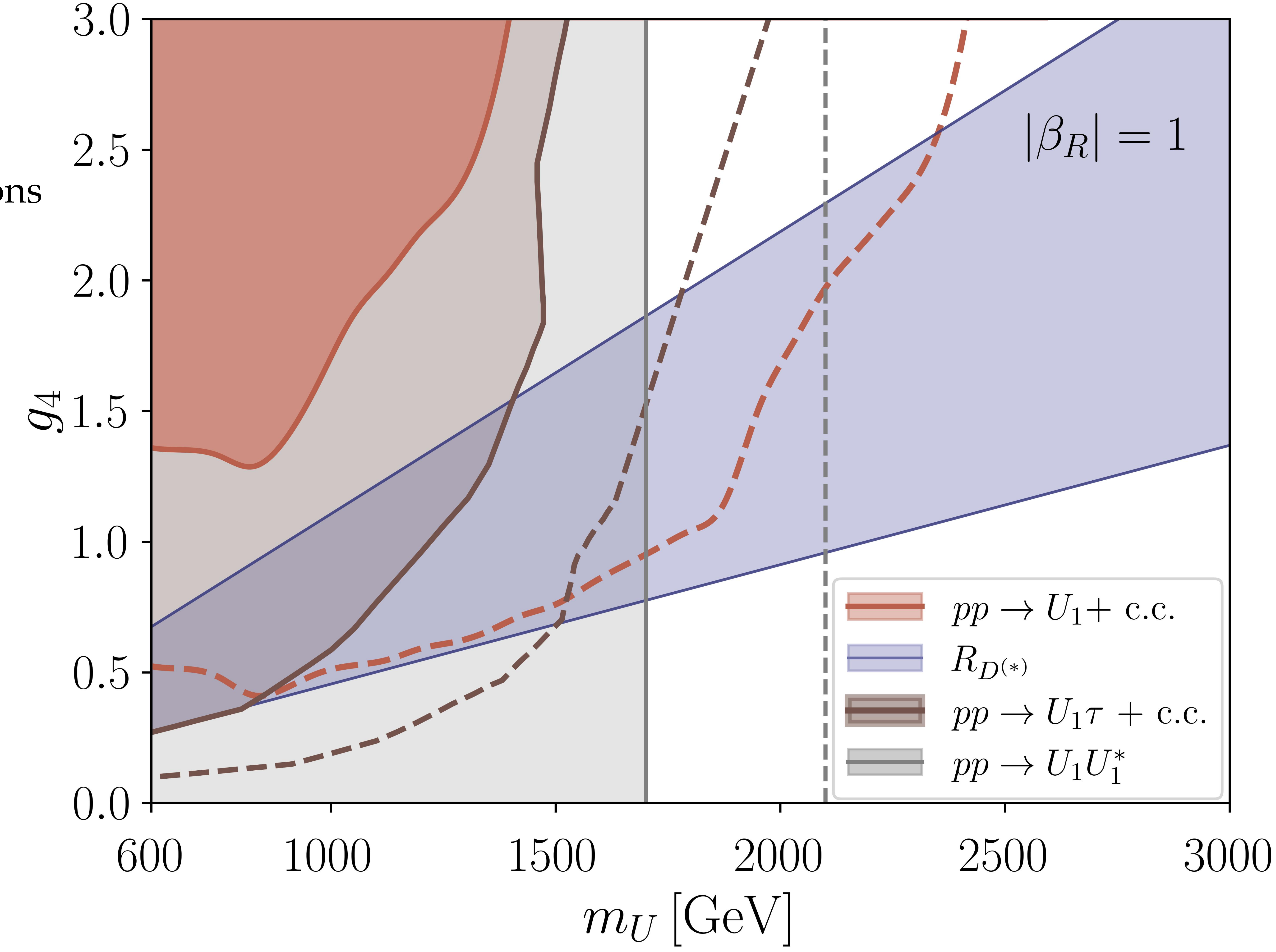


[ATLAS, arXiv: 2305.15962]

[CMS, arXiv: 2012.04178]

Simulation details & exclusion limits

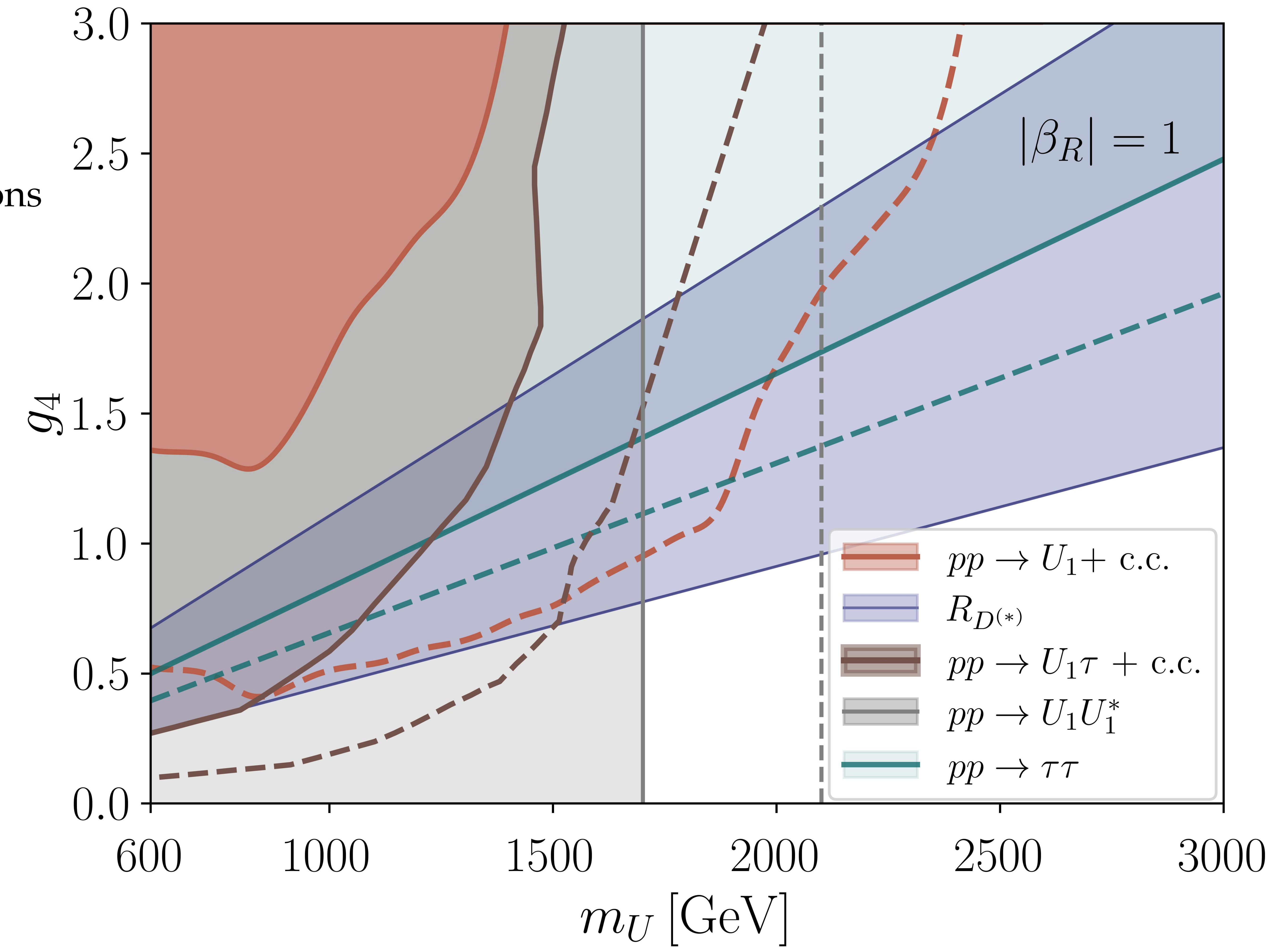
Solid lines - present limits
Dashed lines - HL-LHC projections



[ATLAS, arXiv: 2305.15962]
[CMS, arXiv: 2012.04178]
[Baker et al, arXiv: 2012.11474]

Simulation details & exclusion limits

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

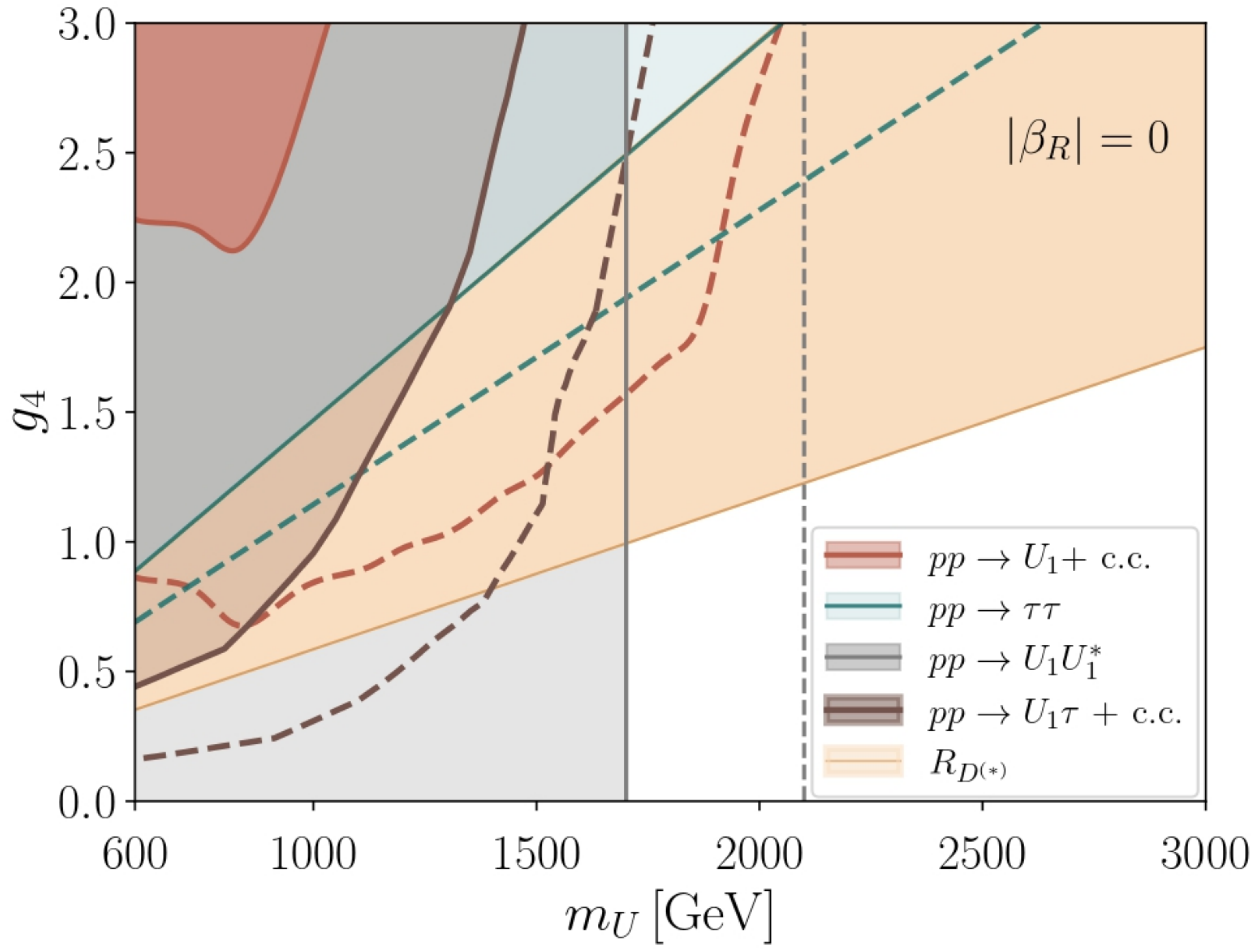


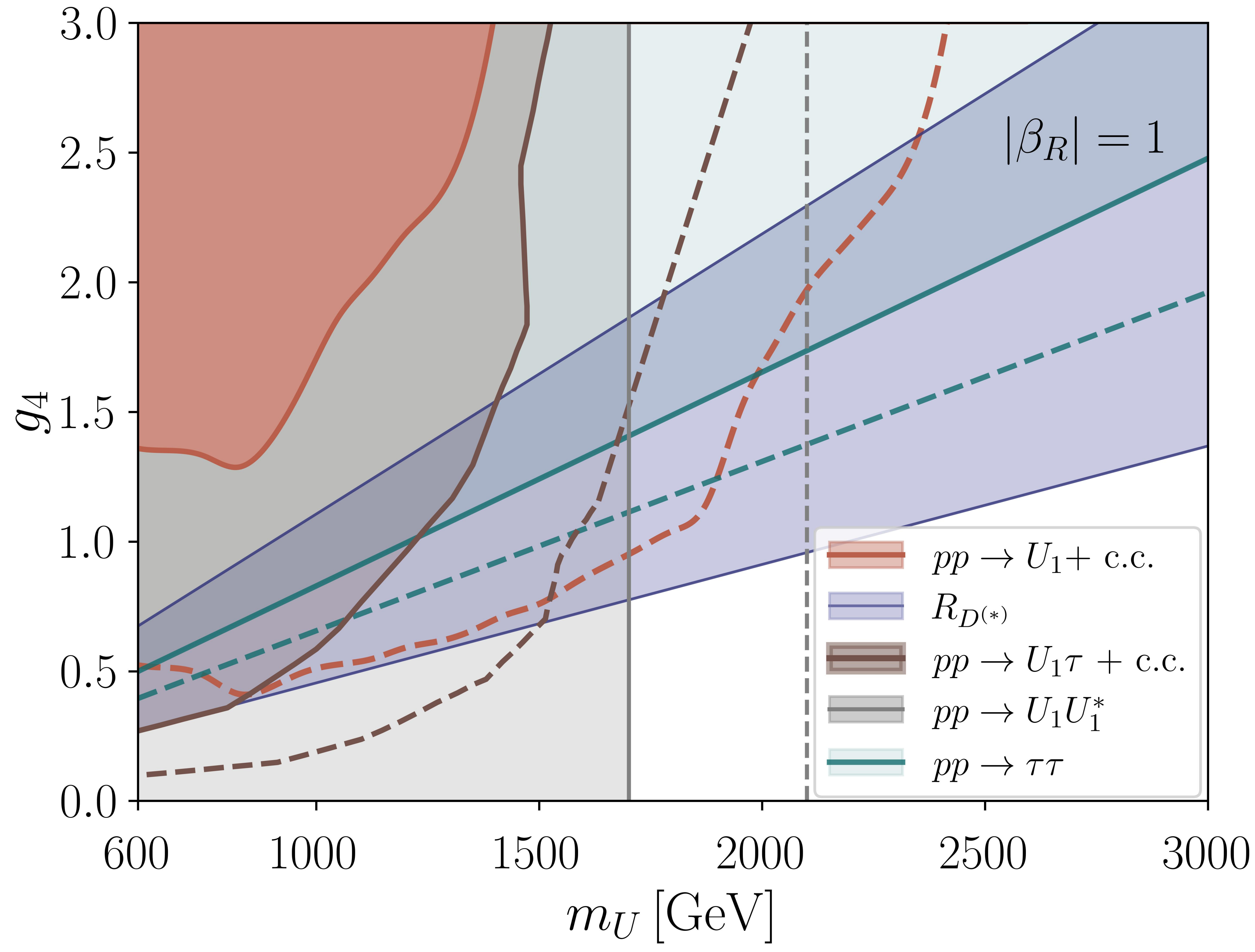
[ATLAS, arXiv: 2305.15962]

[CMS, arXiv: 2012.04178]

[Baker et al, arXiv: 2012.11474]

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)

OUTLINE

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

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

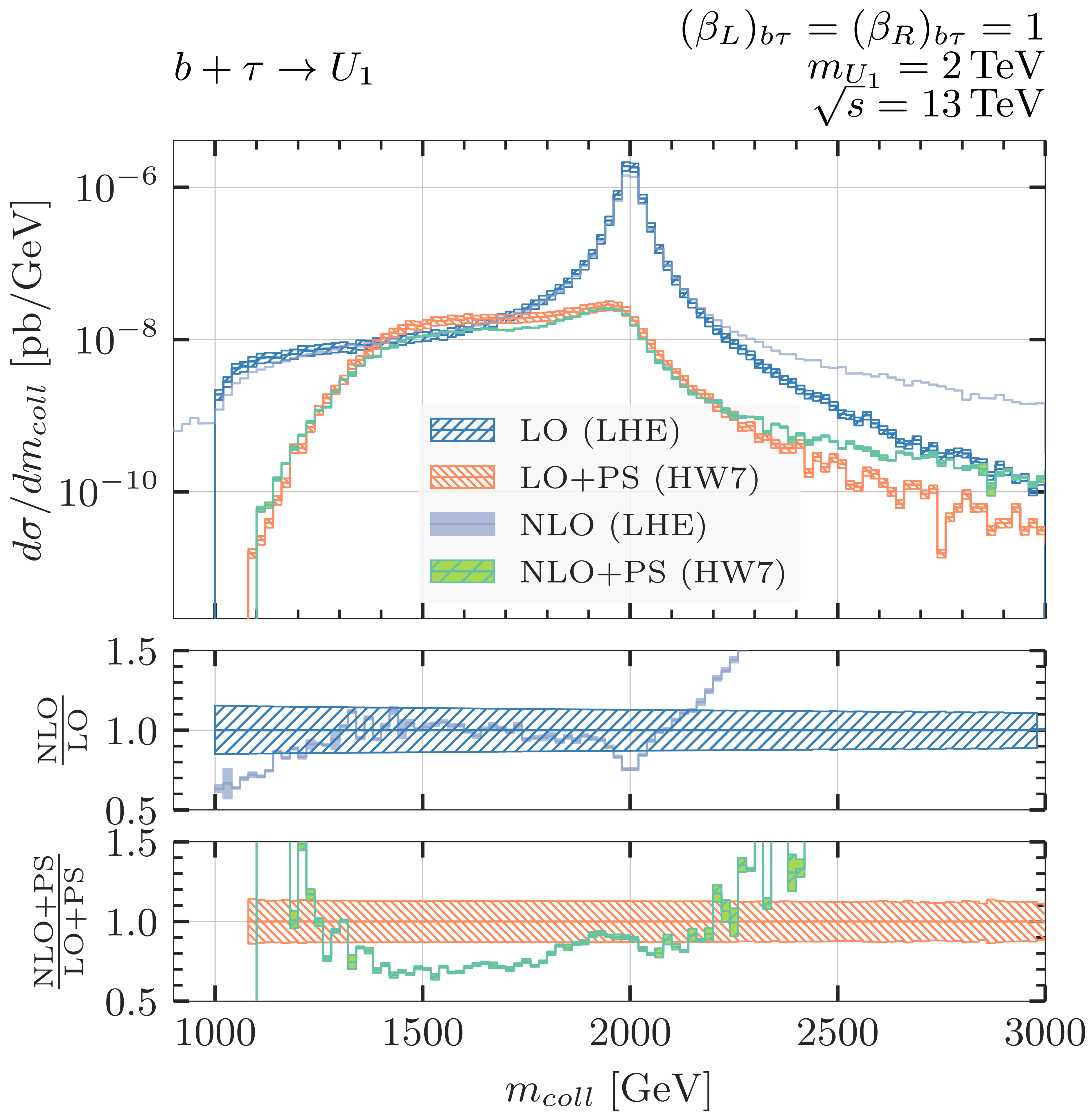
MadGraph/POWHEG/Herwig compatibility - arXiv: 2108.10261 simulate!

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:

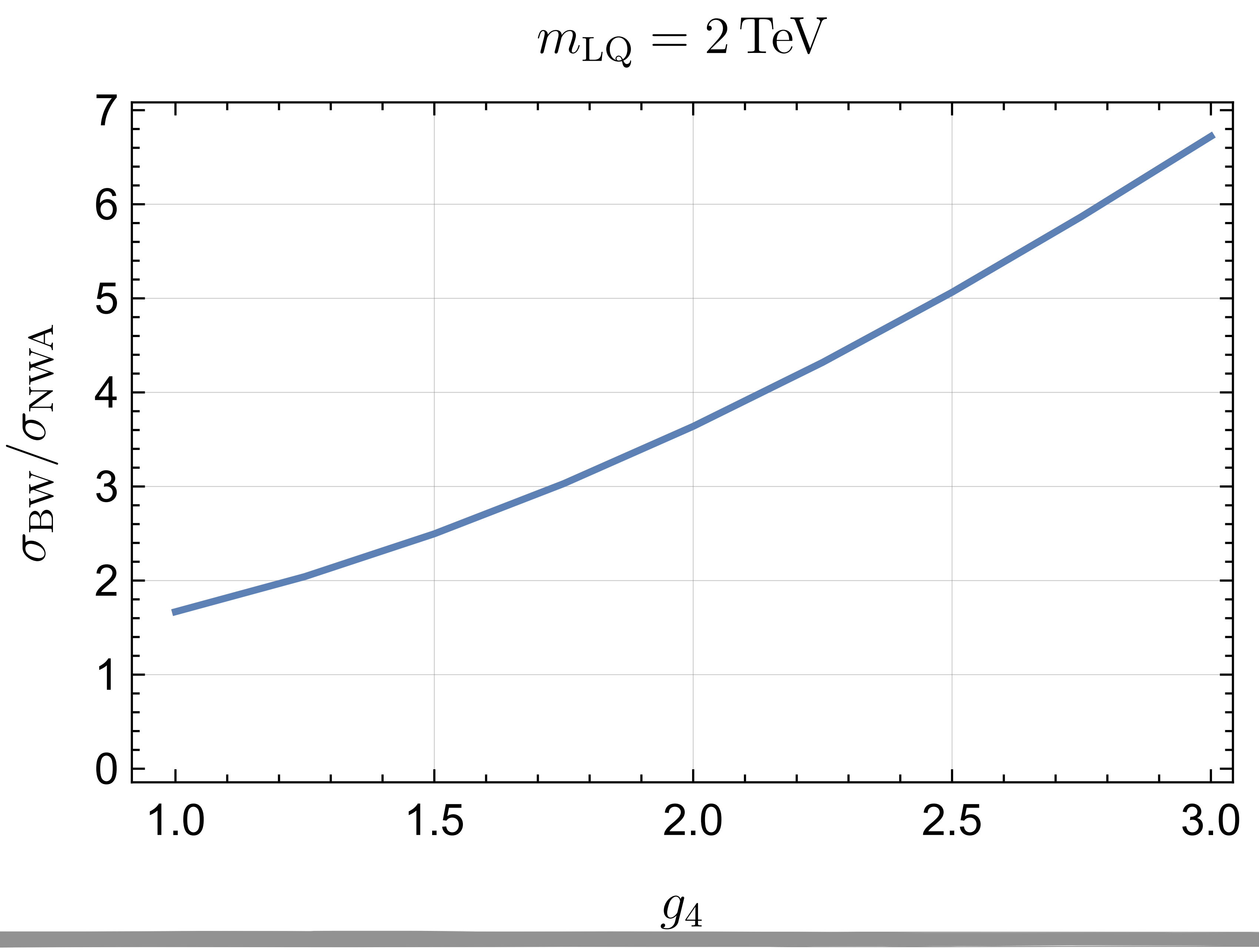
Variable	τ_h + jet	e + jet	μ + jet
p_T^ℓ(GeV)	>200	>100	>100
$\lvert\eta^\ell\rvert$	<2.1	<2.1	<2.1
p_T^{jet}(GeV)	>300	>200	>200
$\lvert\eta^{jet}\rvert$	<2.4	<2.4	<2.4
p_T^{miss}(GeV)	>100	>150	>150
$p_T(\vec{\ell} + \vec{p}_T^{miss})$(GeV)	>100	>100	>100
$\lvert\Delta\phi(\ell, \vec{p}_T^{miss})\rvert$ (radians)	<0.3	<0.2	<0.2
$\Delta R(\ell, jet)$	>0.5	>0.5	>0.5

[CMS Collaboration, arXiv: 2308.06143]

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

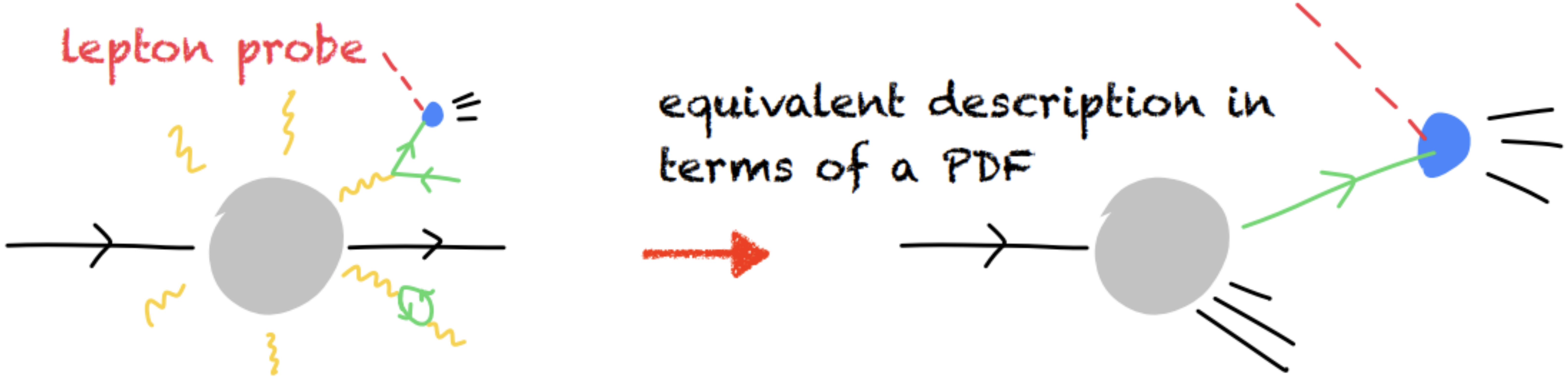
Finite-width effects

- The narrow-width approximation (NWA) can have an $\mathcal{O}(1)$ relative error compared to full Breit-Wigner result for $m_{\mathrm{LQ}} \gtrsim 2\,\mathrm{TeV}$ 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)



Lepton PDFs

Two equivalent descriptions of probing the proton through DIS:

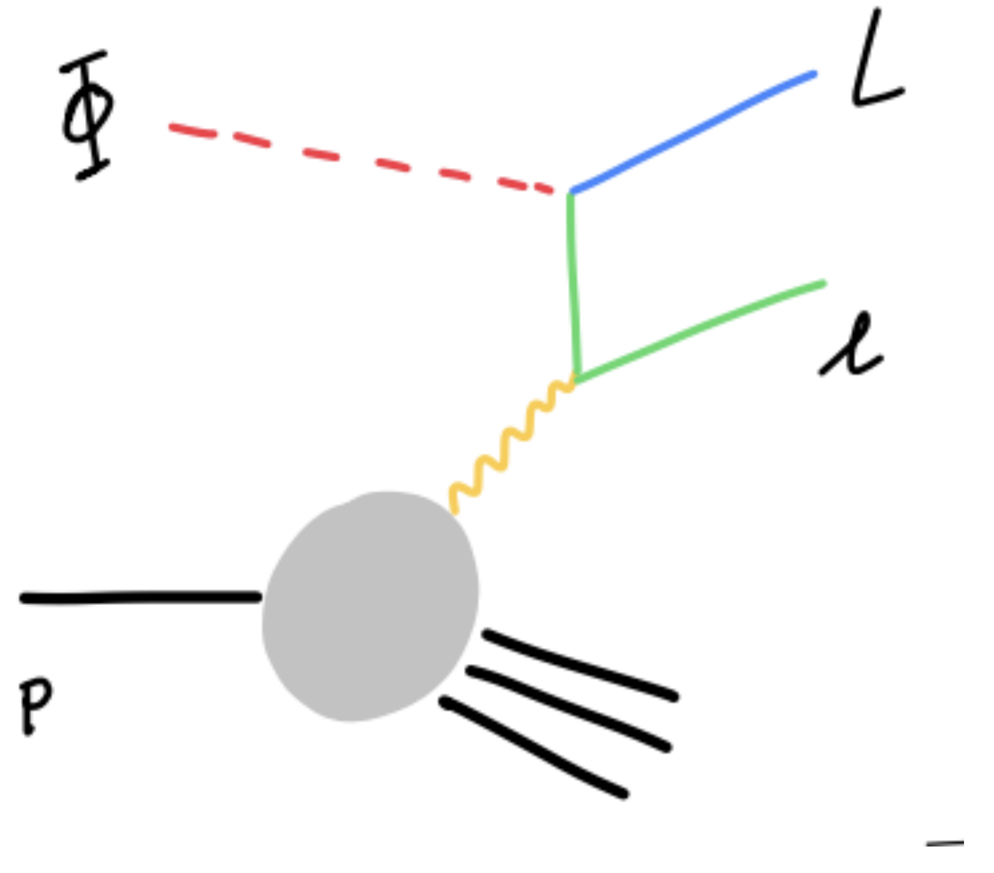


Equate the results of these two methods!

H. Anlauf et al , Comput. Phys. Commun. 70, 97 (1992)
Manohar et al https://arxiv.org/pdf/1607.04266

Lepton PDFs

Method 1 (DIS-style):



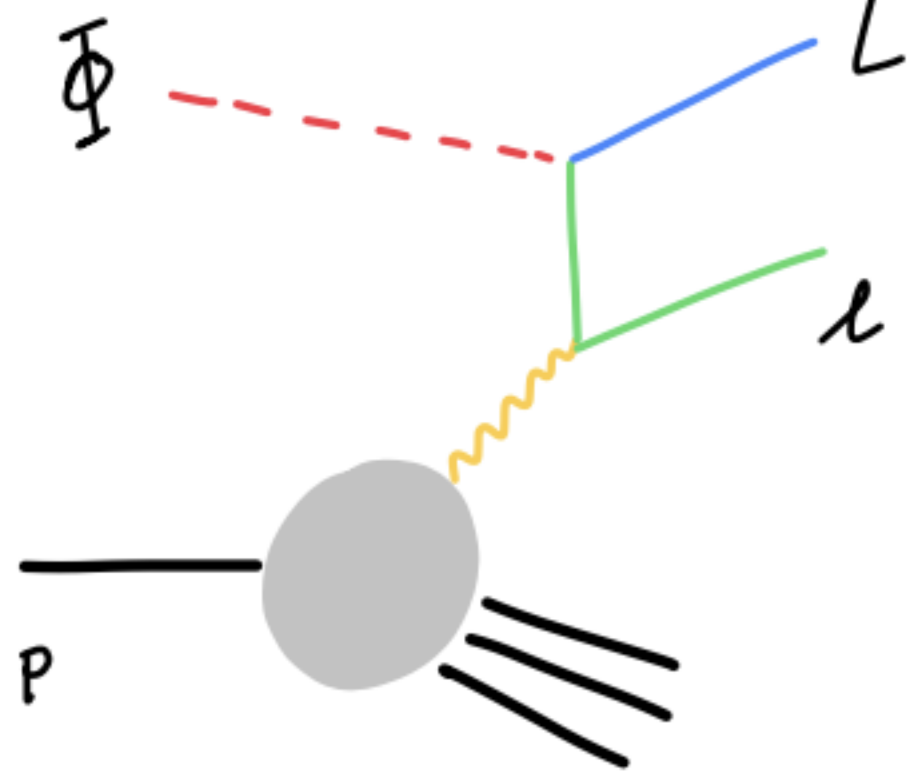
$$\sigma = \frac{1}{4p\cdot r}\int \frac{d^4q}{(2\pi)^4}\frac{1}{Q^4}L^{\mu\nu}(r,q)(4\pi)W_{\mu\nu}(p,q)$$

$$W_{\mu\nu}(p,q) = F_1\left(-g_{\mu\nu}+\frac{q_\mu q_\nu}{q^2}\right)+\frac{F_2}{p\cdot q}\left(p_\mu-\frac{p\cdot q\, q_\mu}{q^2}\right)\left(p_\nu-\frac{p\cdot q\, q_\nu}{q^2}\right)$$

$F_1(x_{bj}, Q^2), F_2(x_{bj}, Q^2)$ **are the proton structure functions**

Lepton PDFs

Method 2 (proton PDF):



LO

$$\frac{\sigma}{\sigma_B} = \int dx f_\ell(x, \mu_F^2)\delta(Sx - M^2)$$

$$+\frac{\alpha}{2\pi}\frac{1}{M^2}\int_{\frac{M^2}{S}}^1 dx f_\gamma(x, \mu_F^2)\left\{ z_\ell P_{l\gamma}(z_\ell)\left[\log\frac{M^2}{\mu_F^2} + \log\frac{(1-z_\ell)^2}{z_\ell^2}\right] + 4z_\ell^2(1-z_\ell)\right\}$$

NLO

$$z_\ell = \frac{M^2}{xS}$$