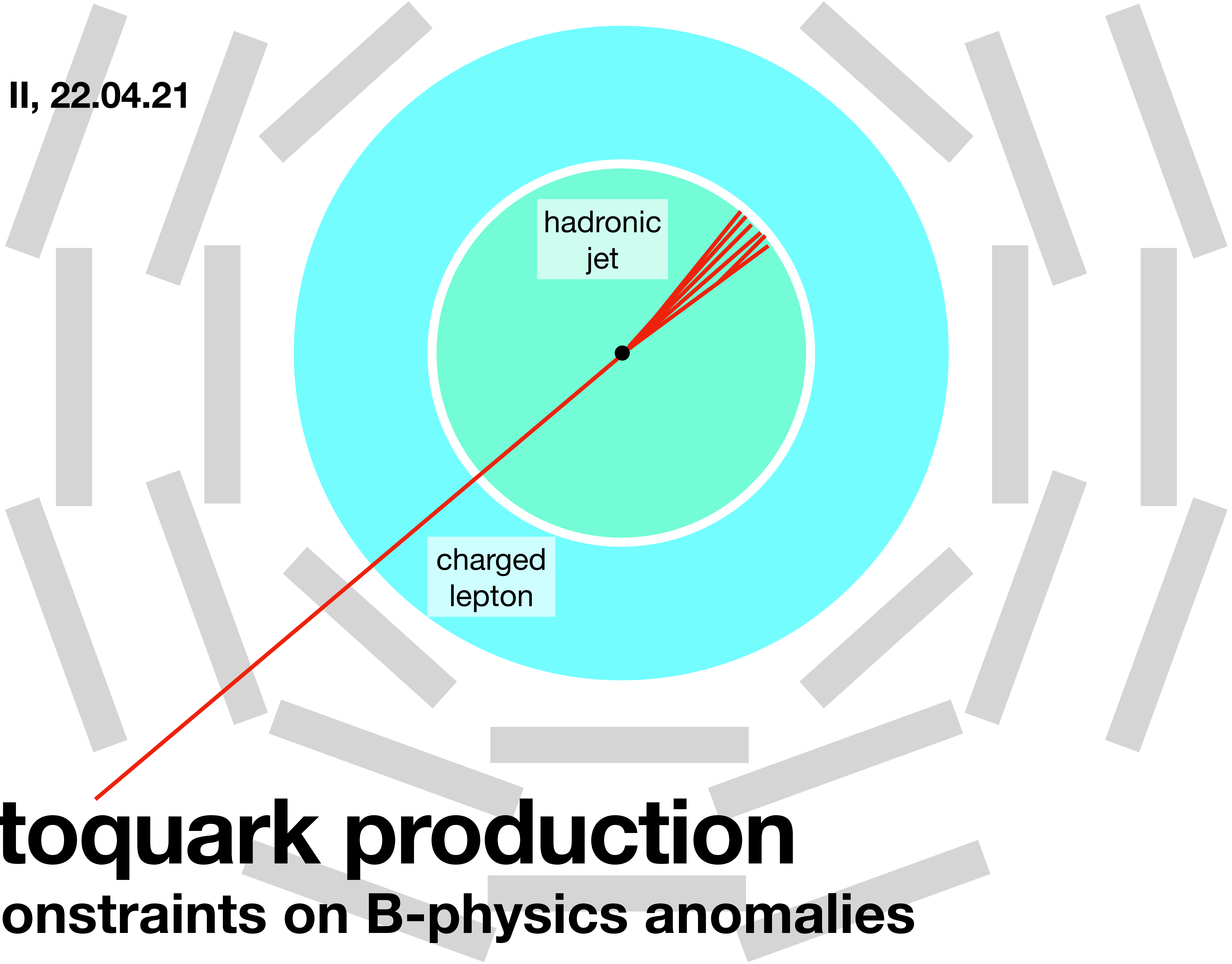
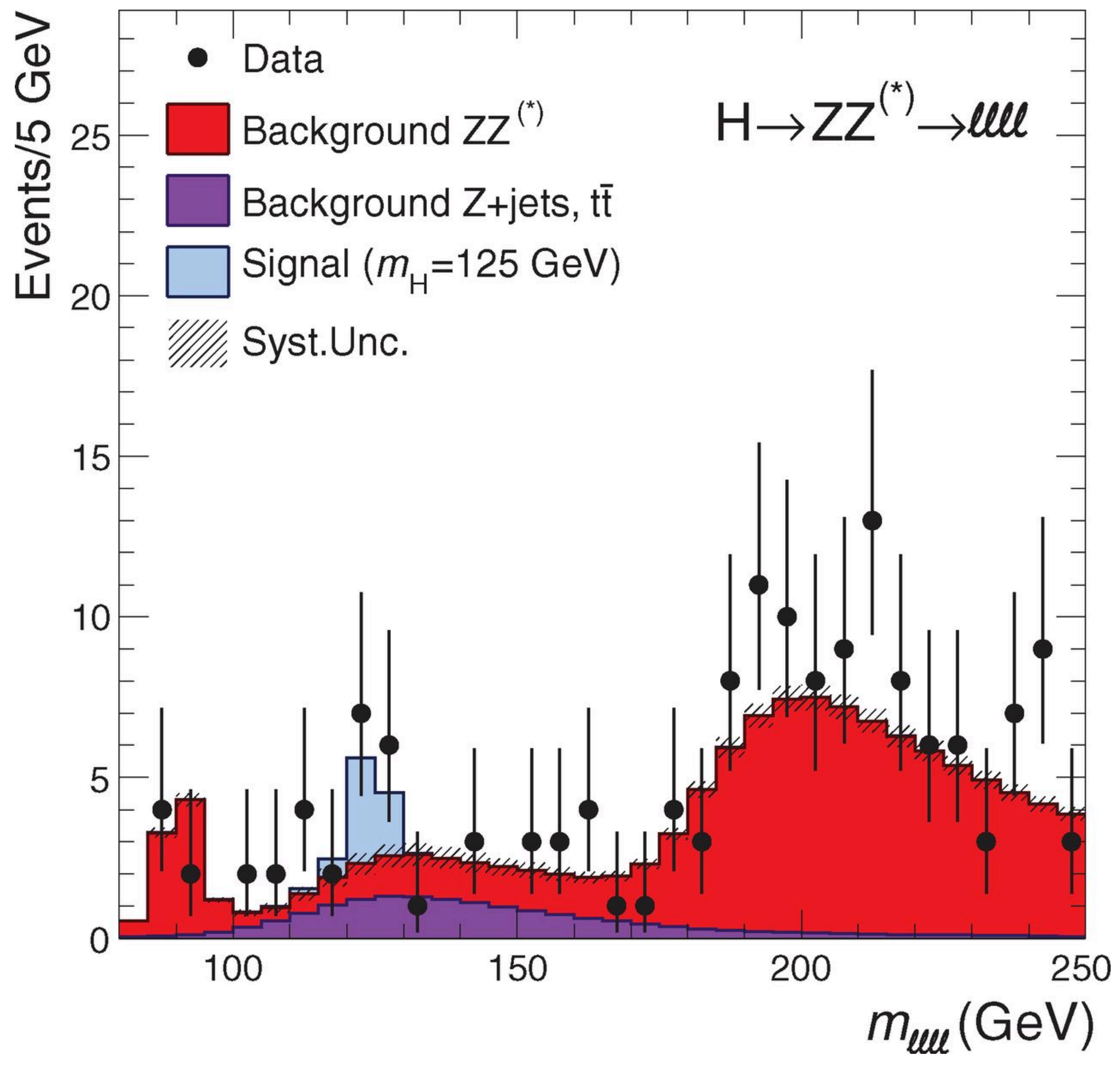
Uli Haisch, MPI Munich
Beyond the Flavour Anomalies II, 22.04.21



Resonant leptoquark production

LHC applications & constraints on B-physics anomalies

5σ: ATLAS Higgs discovery



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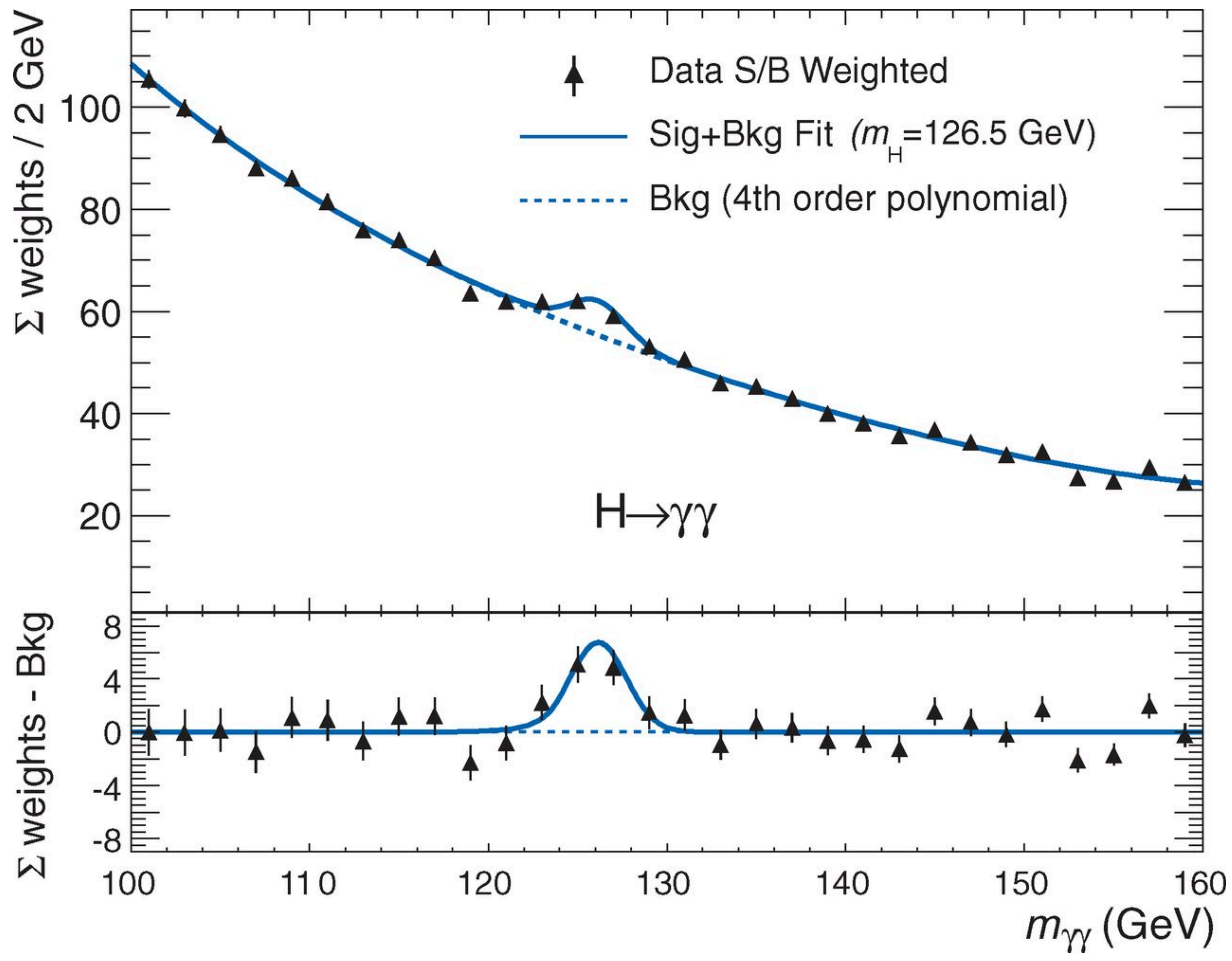
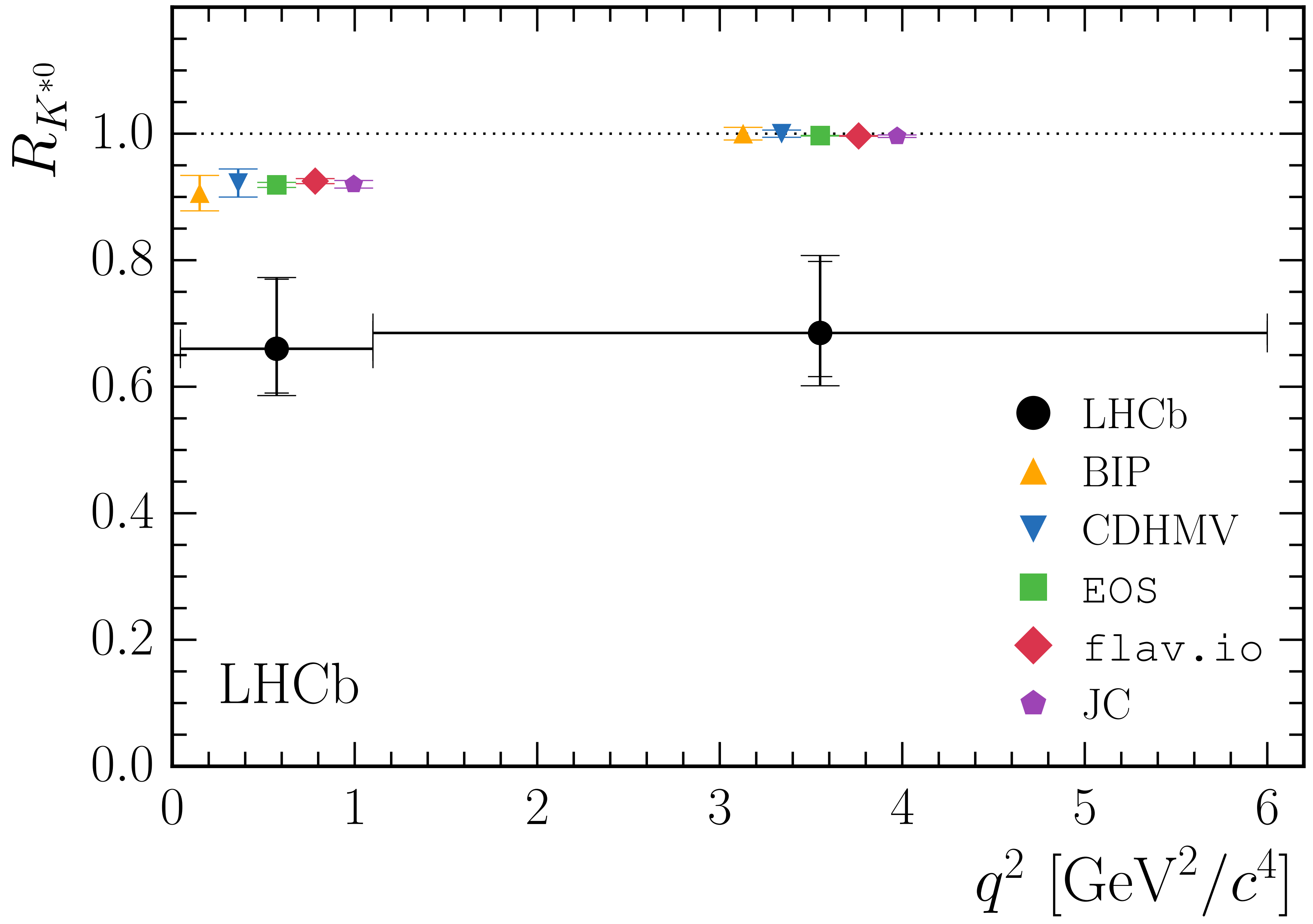


[ATLAS, Science 338 (2012) 1576]

5σ: b → s anomalies



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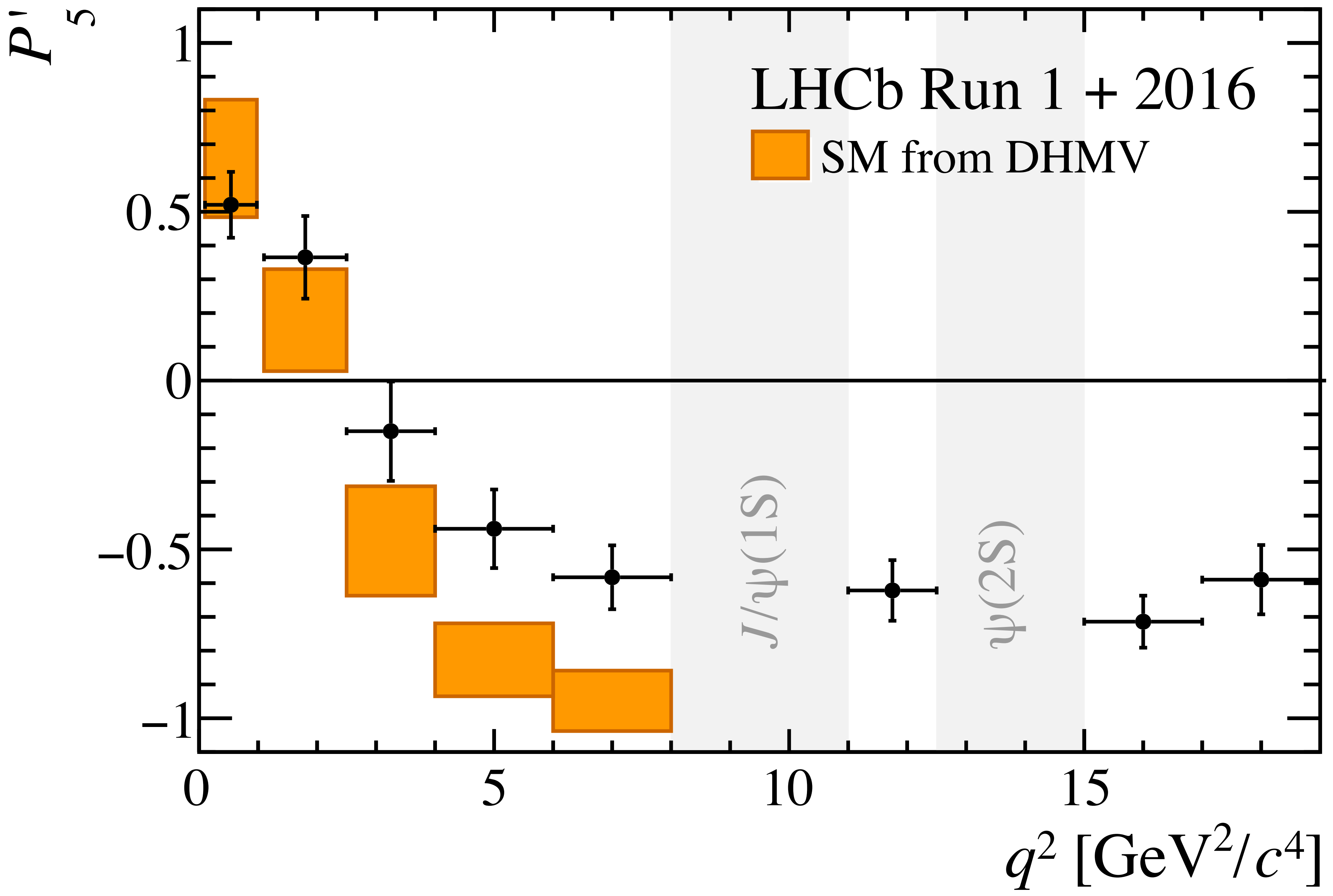
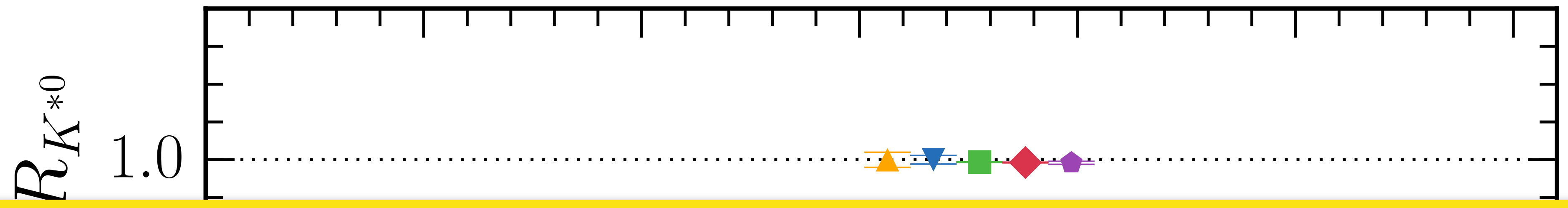
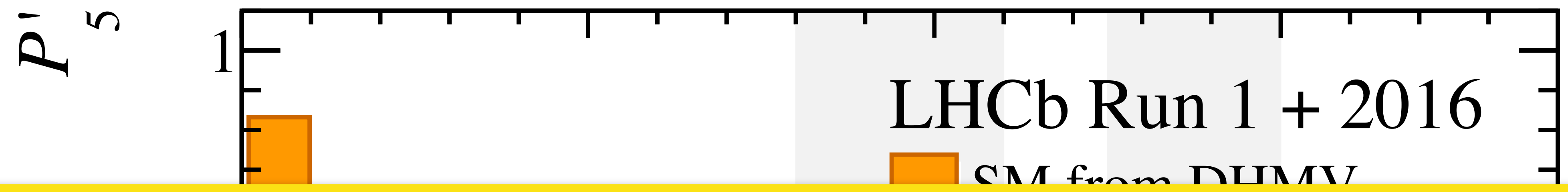


+ order 100 other observables

[LHCb, JHEP 08 (2017), 055; PRL 125 (2020) 011802; …; global fits by many theorists]

5σ: b → s anomalies



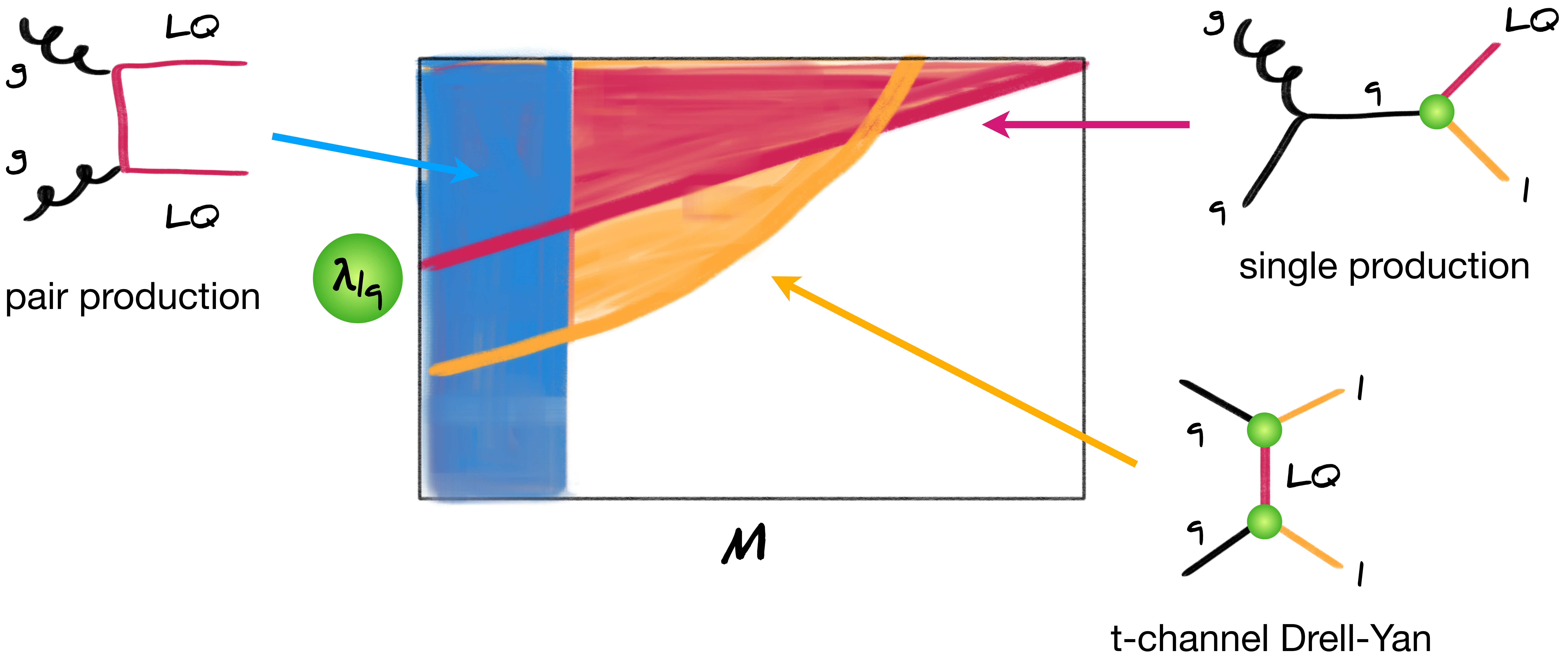


While b → s anomalies may have similar significance than data that led to Higgs discovery, there are at least two important differences. First, Higgs has been discovered by two independent experiments & second Higgs has been detected by observing a resonance in two different final states. Case of flavour anomalies would be significantly stronger IMHO, if ATLAS/CMS would also see hints of them, in best-case scenario by finding a bump in a high-p_T search

\+ order 100 other observables

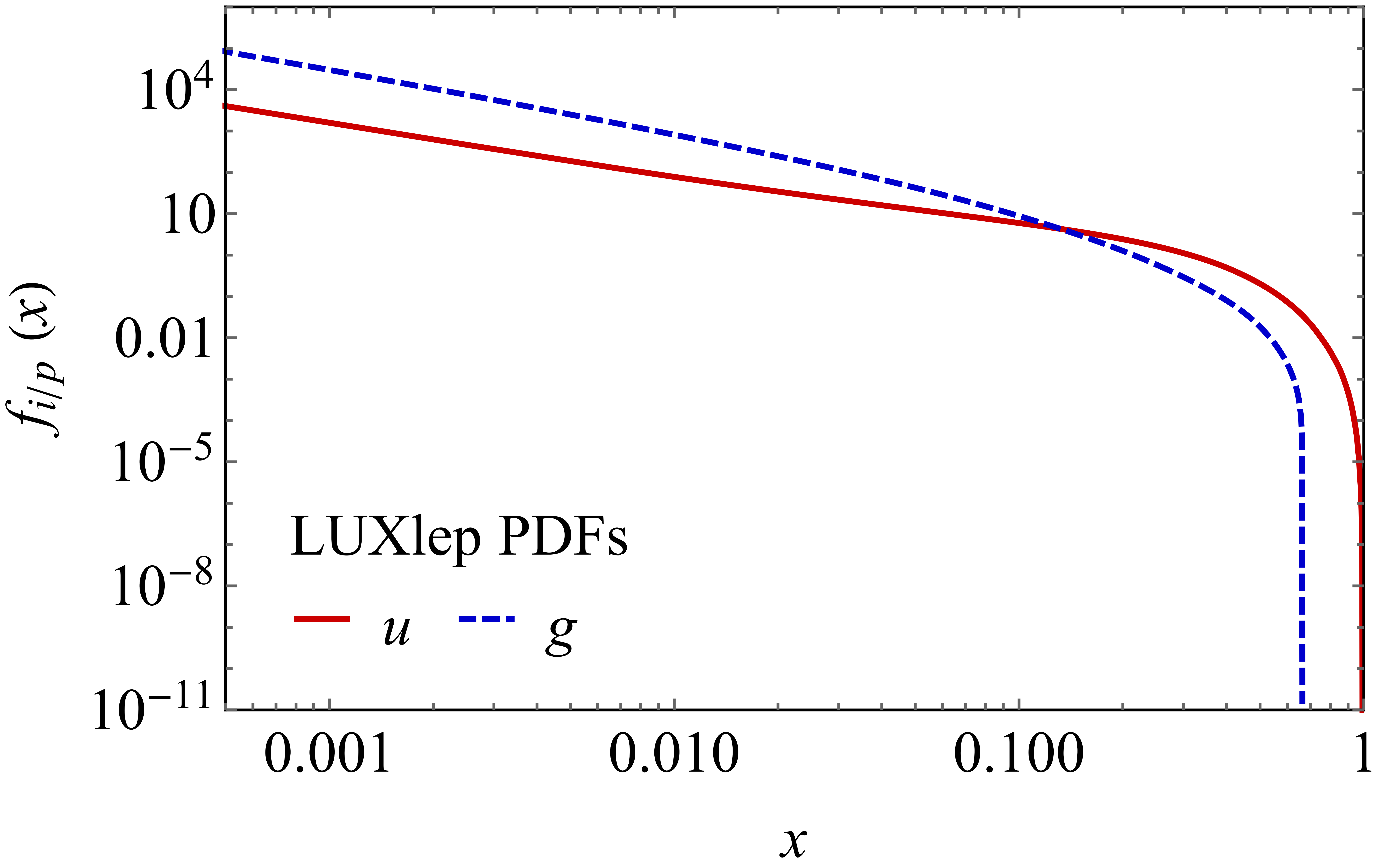
[LHCb, JHEP 08 (2017), 055; PRL 125 (2020) 011802; …; global fits by many theorists]

Leptoquark (LQ) search strategies @ the LHC

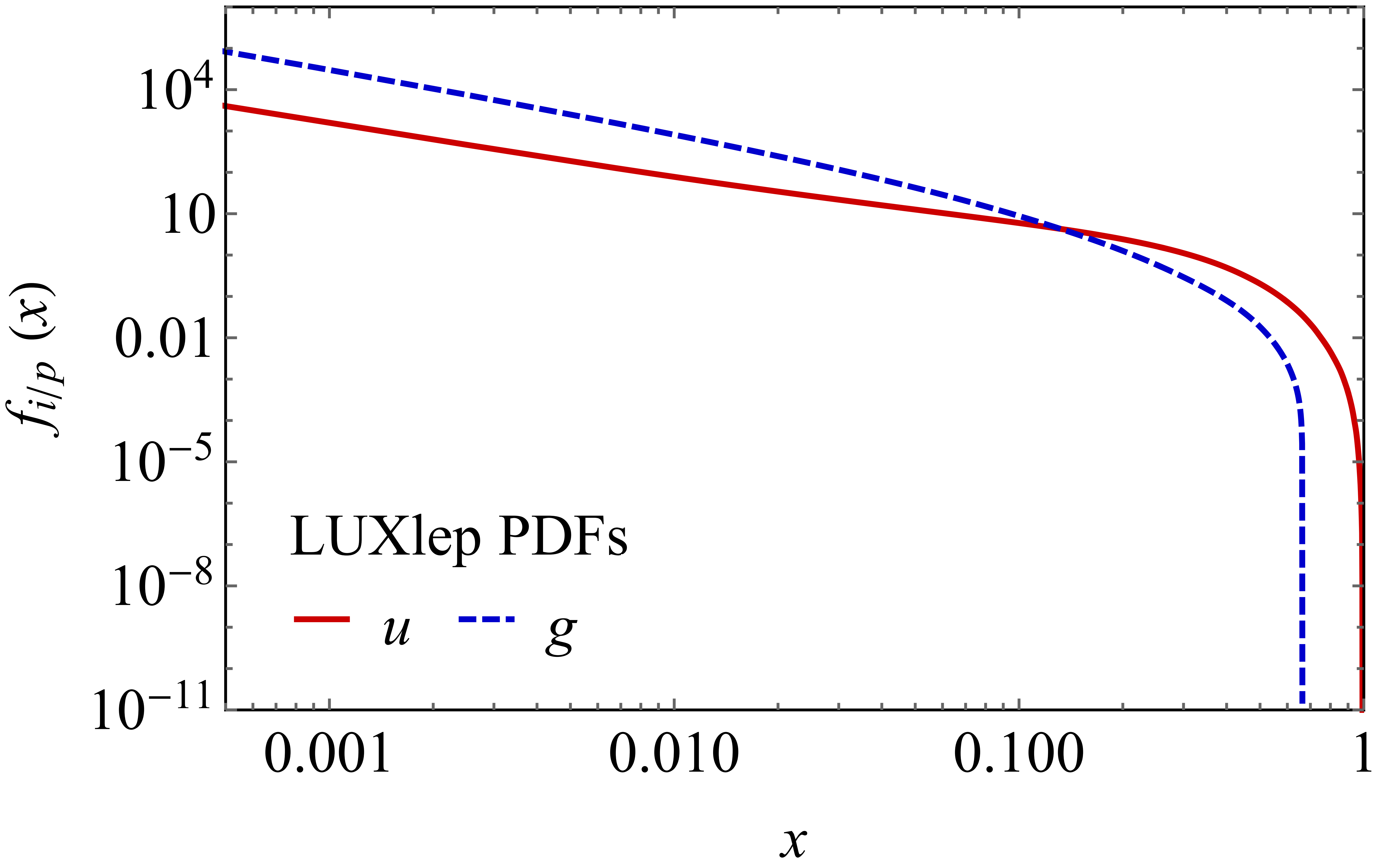


[sketch adopted from Dorsner & Greljo, JHEP 05 (2018) 126]

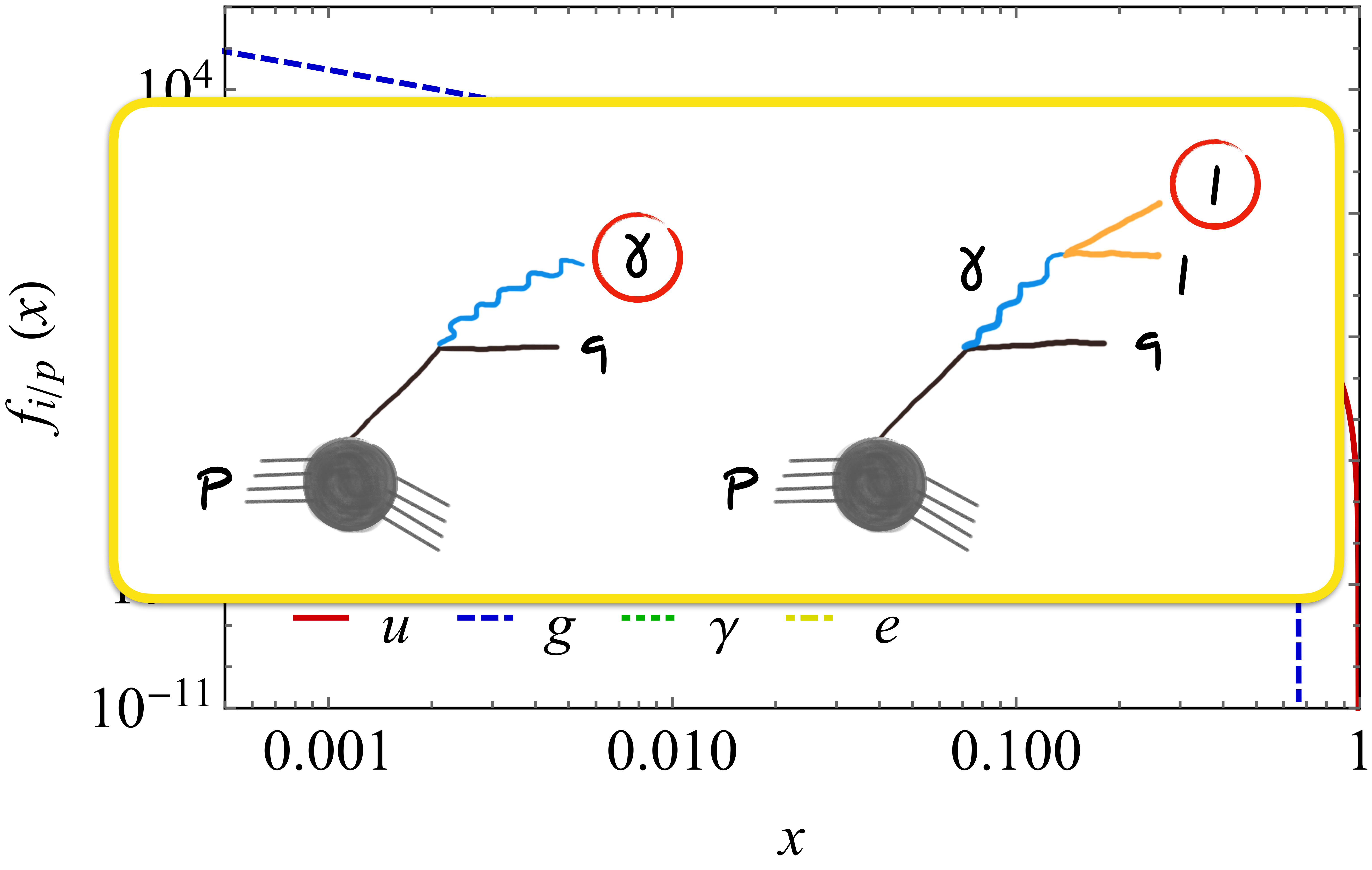
But @ LHC no resonant LQ production …



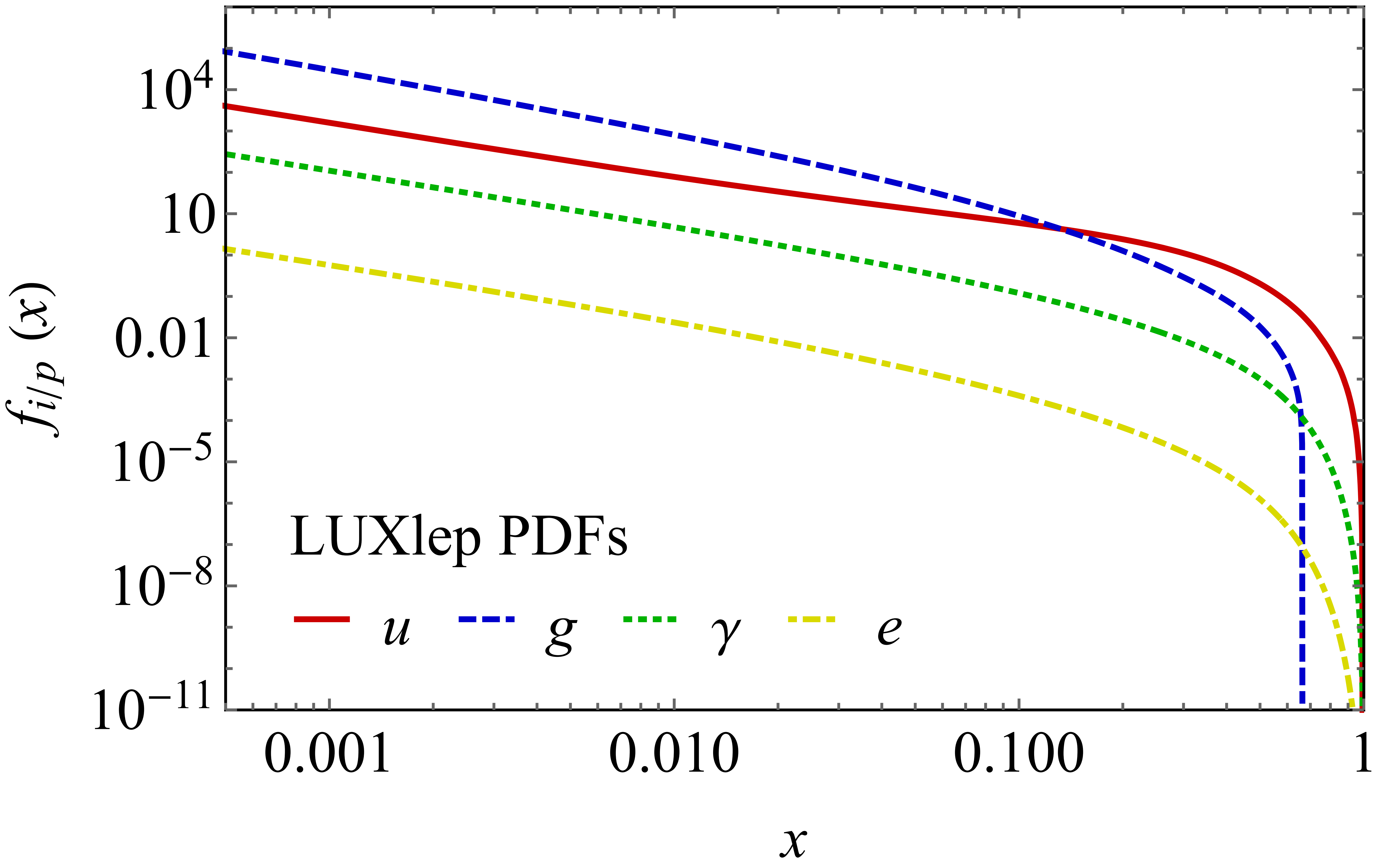
… since a proton consists of quarks & gluons



QFT to the rescue!

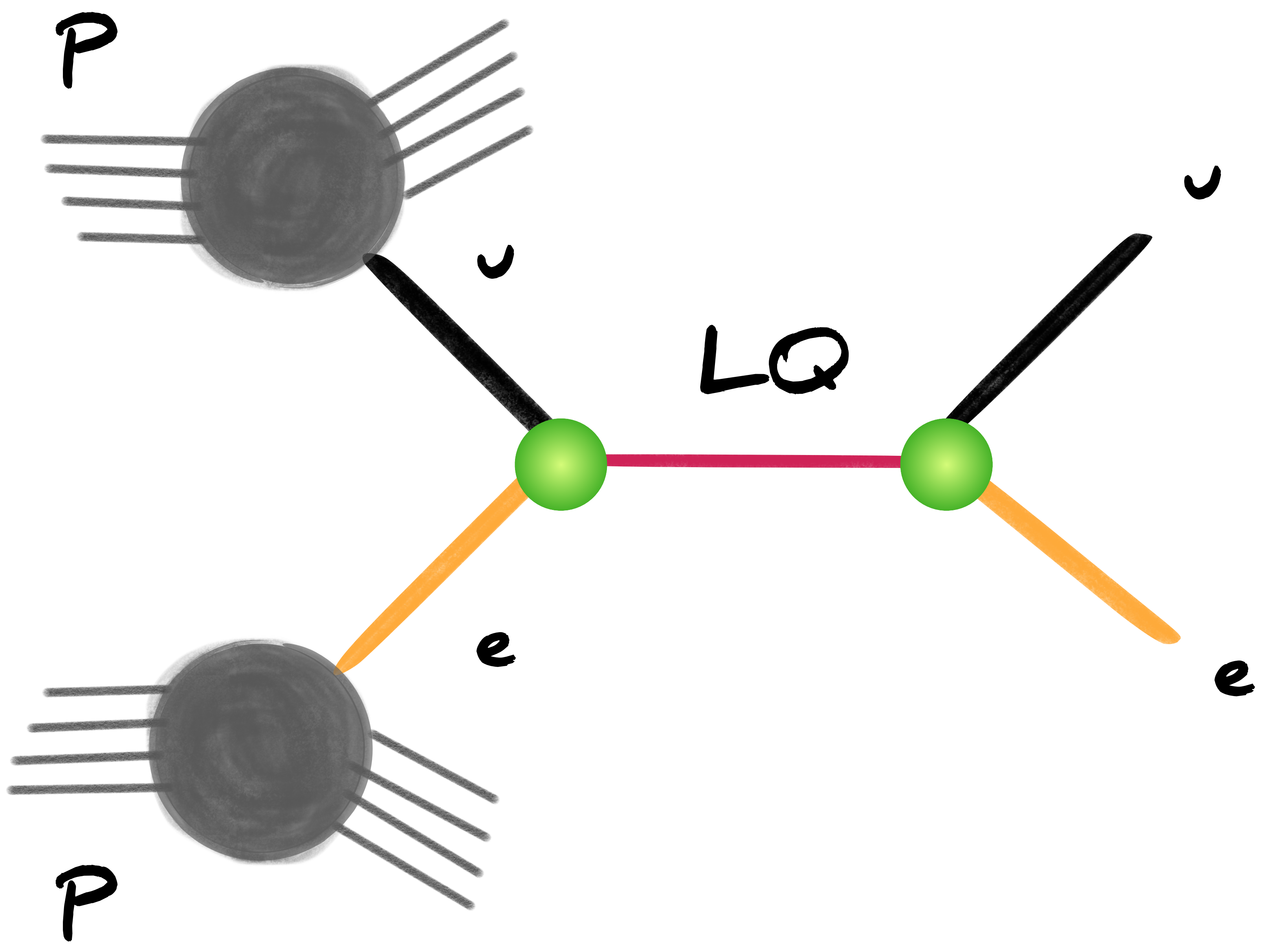


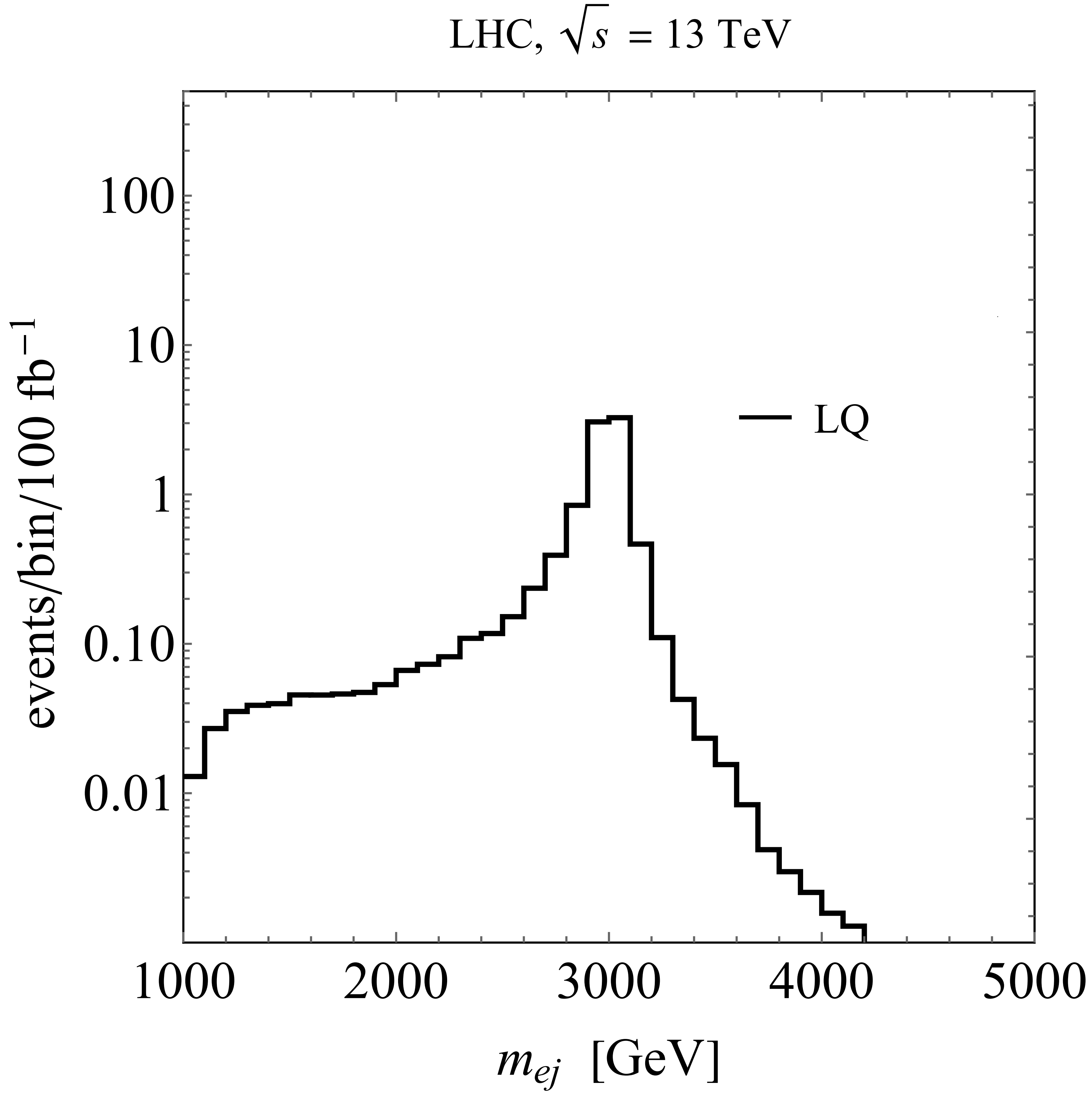
Proton has a little bit of photons & leptons!



[Manohar et al. PRL 117 (2016) 24; JHEP 12 (2017) 046; Buonocore et al., JHEP 08 (2020) 019]

Resonant LQ production @ the LHC

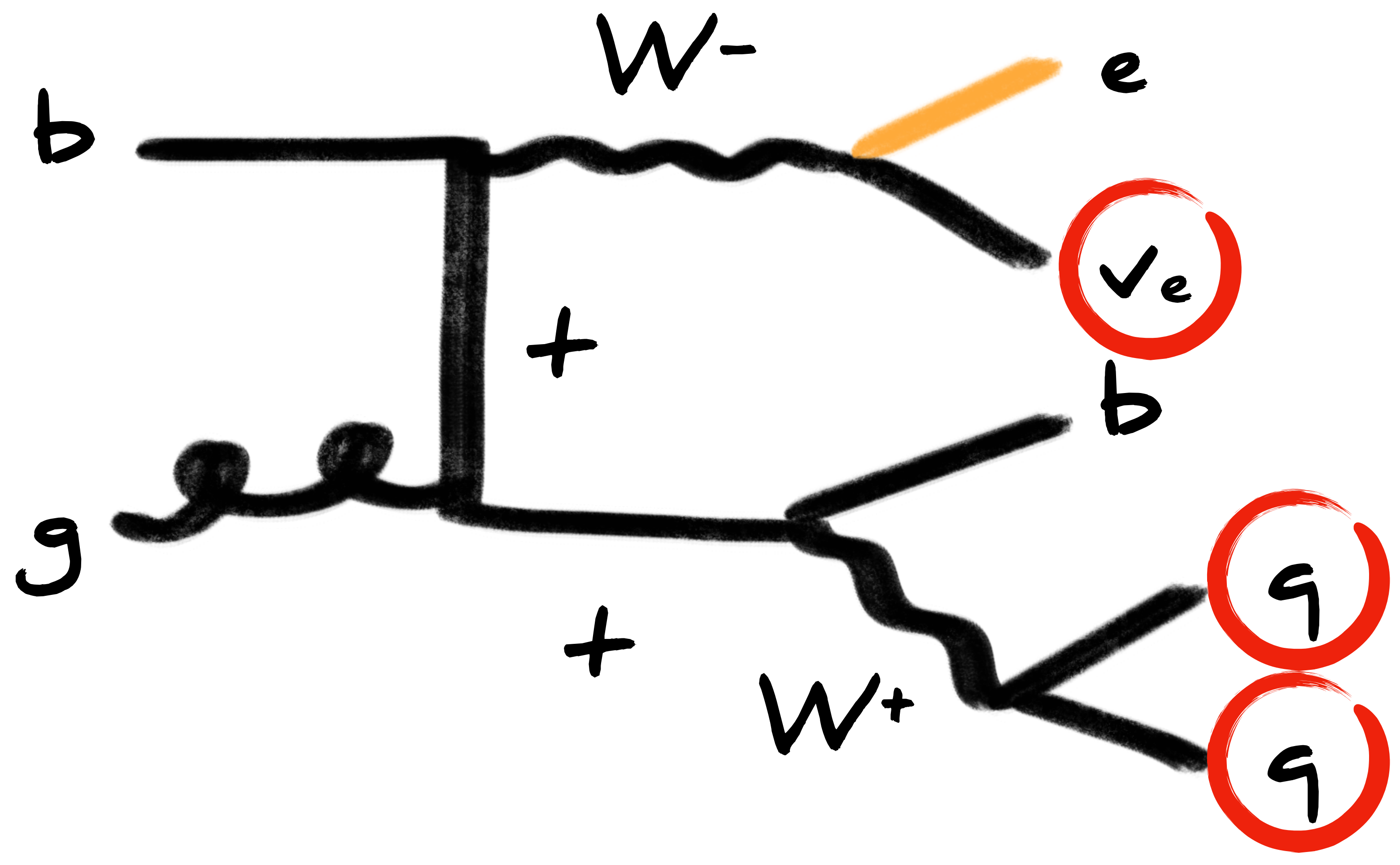


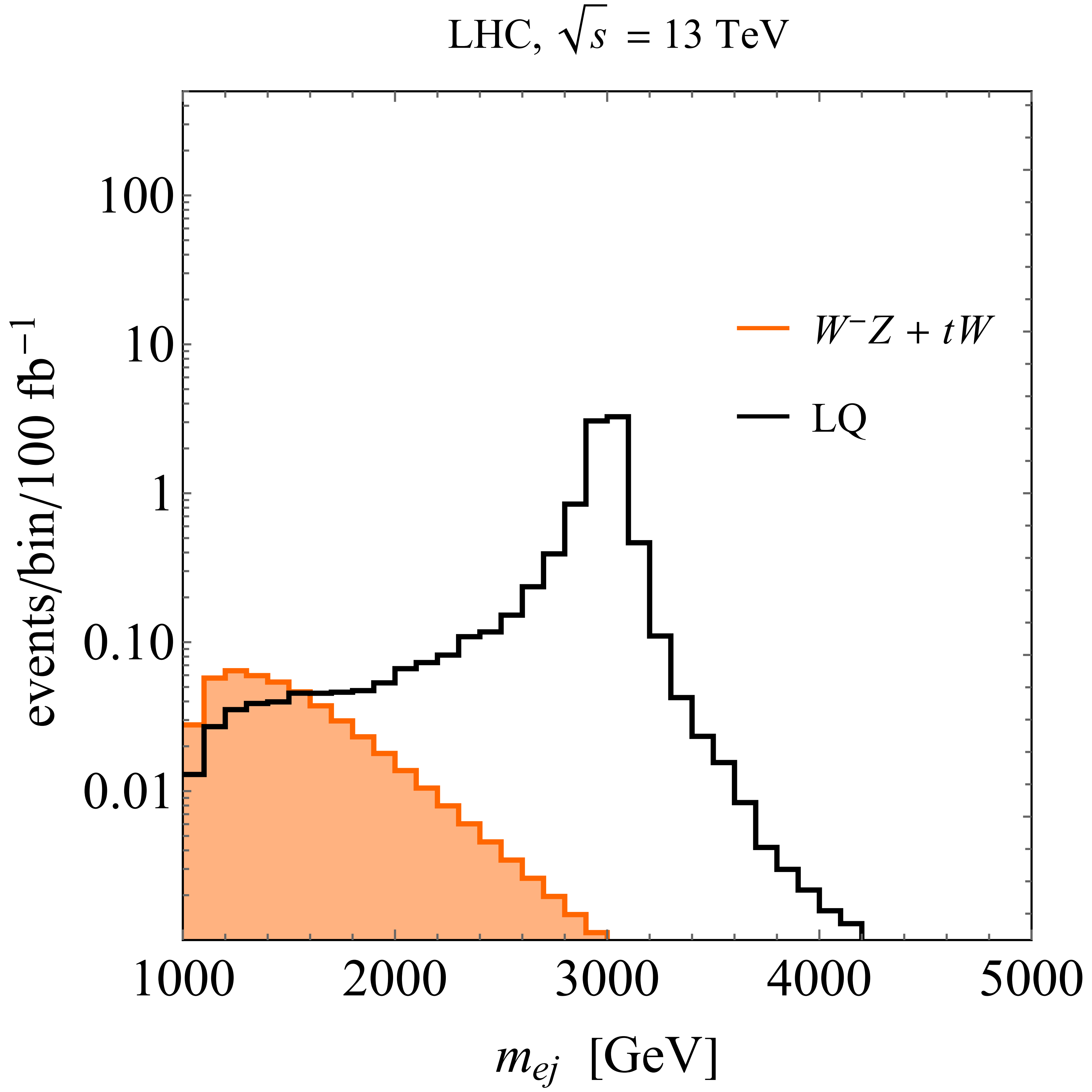


At 13 TeV LHC, 9 events per 100 fb^{-1} for minimal scalar LQ of M = 3 TeV & λ_{eu} = 1

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

Resonant LQ production @ the LHC

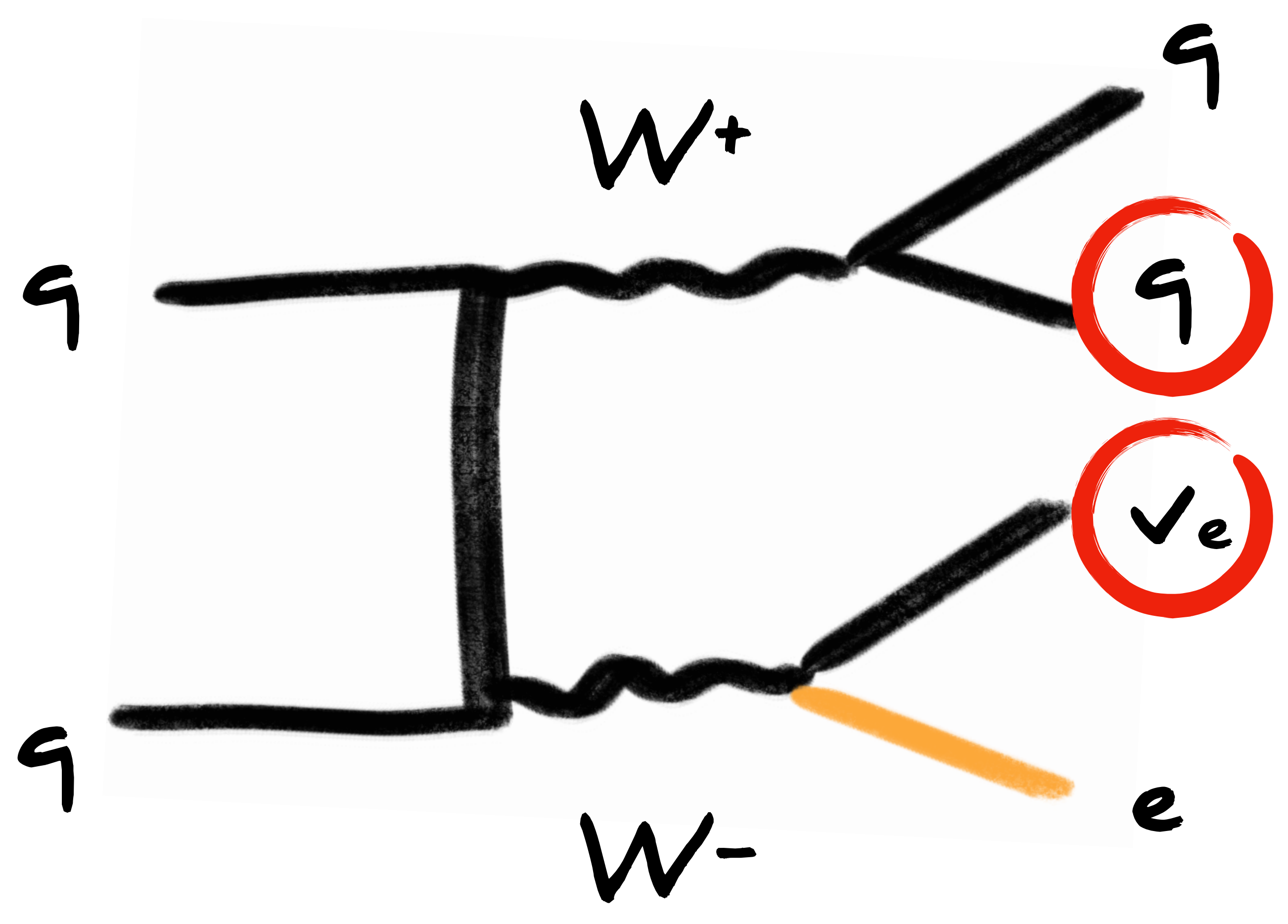


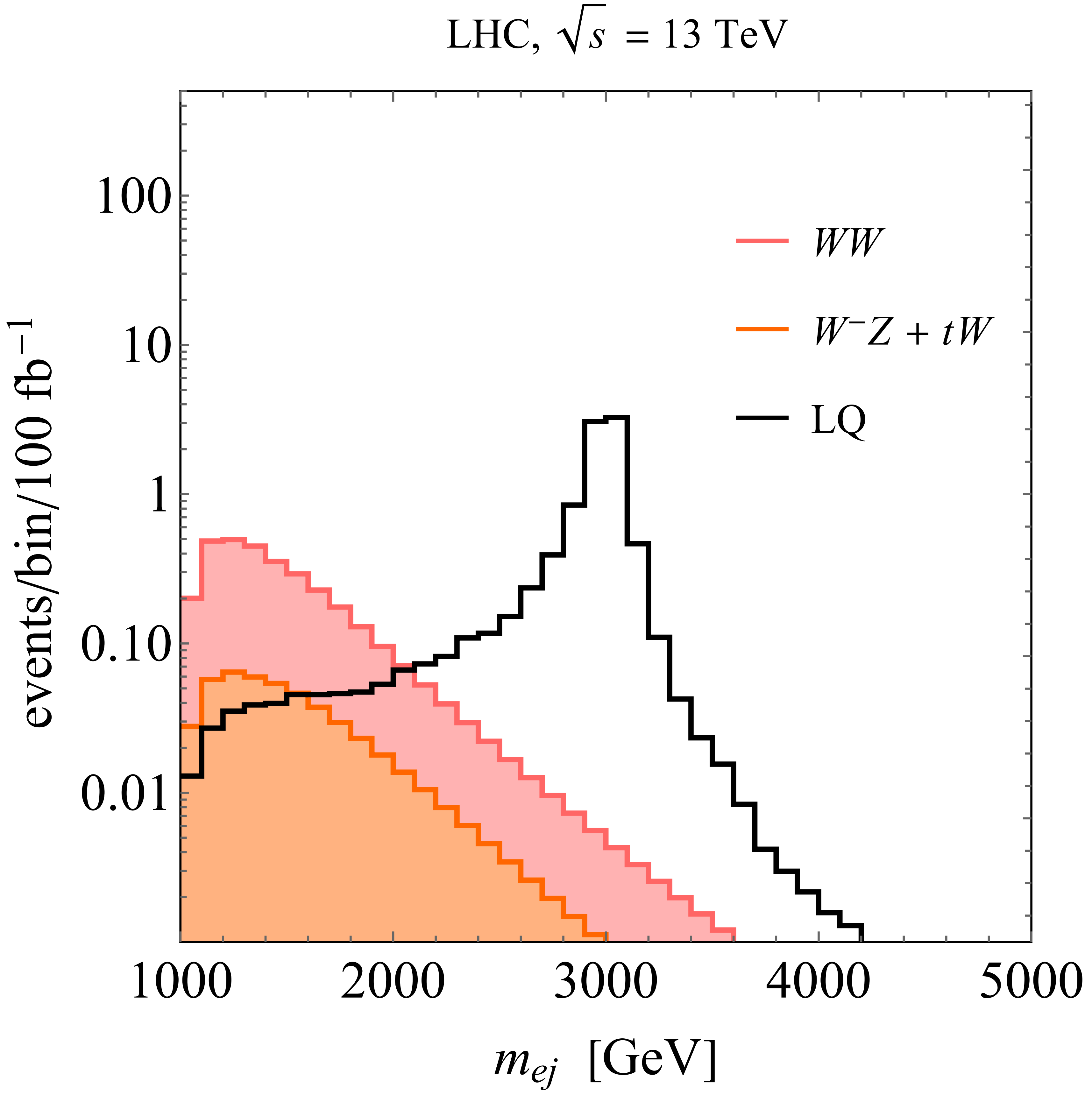


Suppressed by $E_{T,miss}$ requirement & jet veto

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

Resonant LQ production @ the LHC





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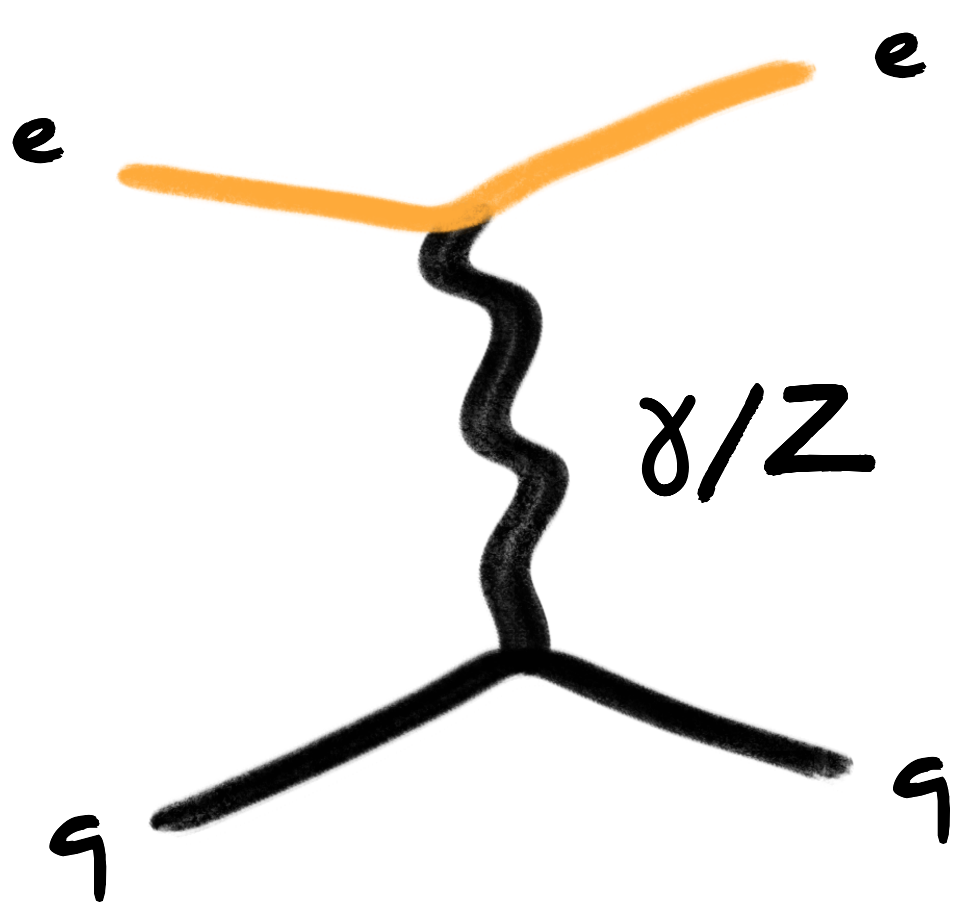
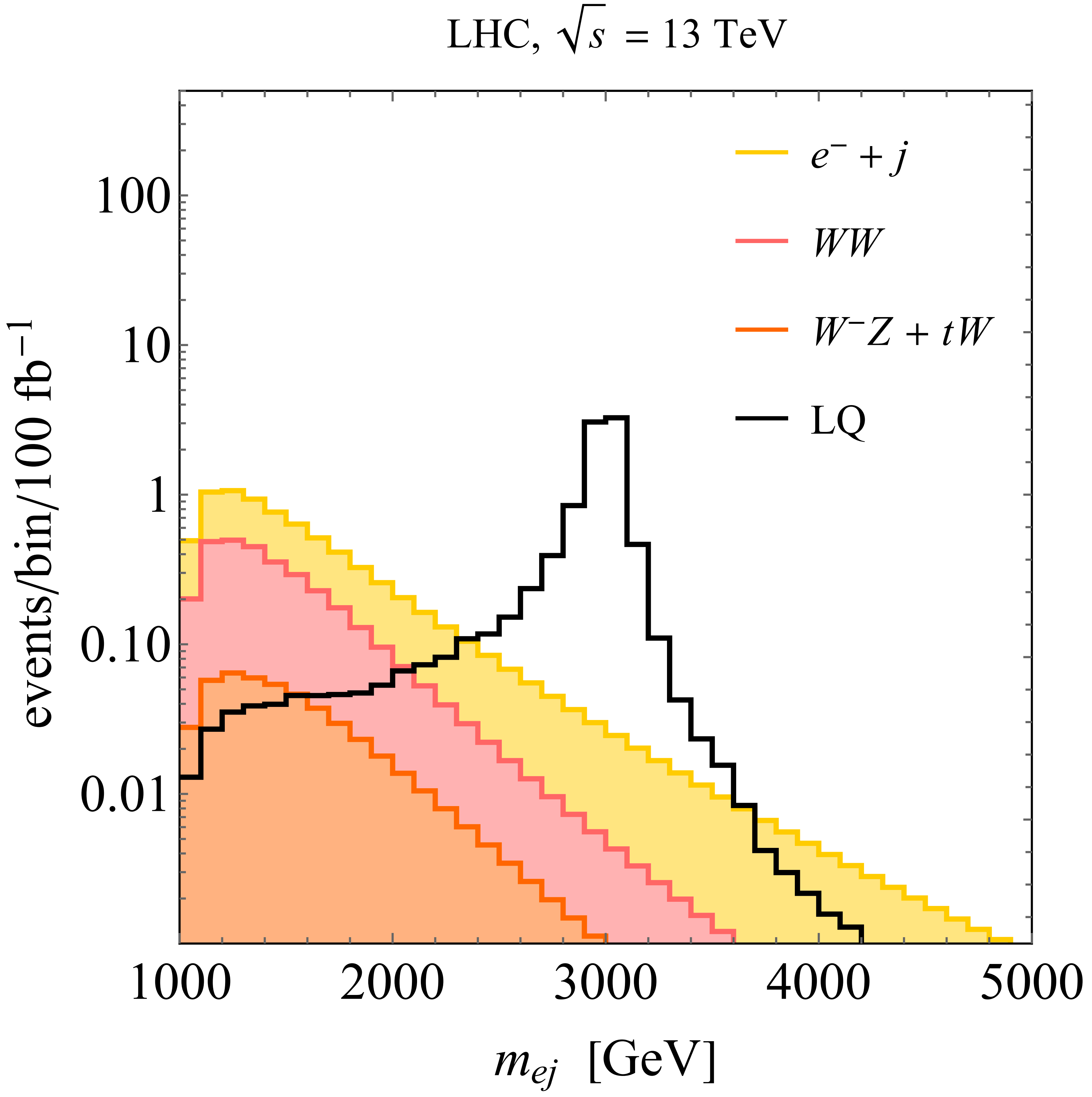
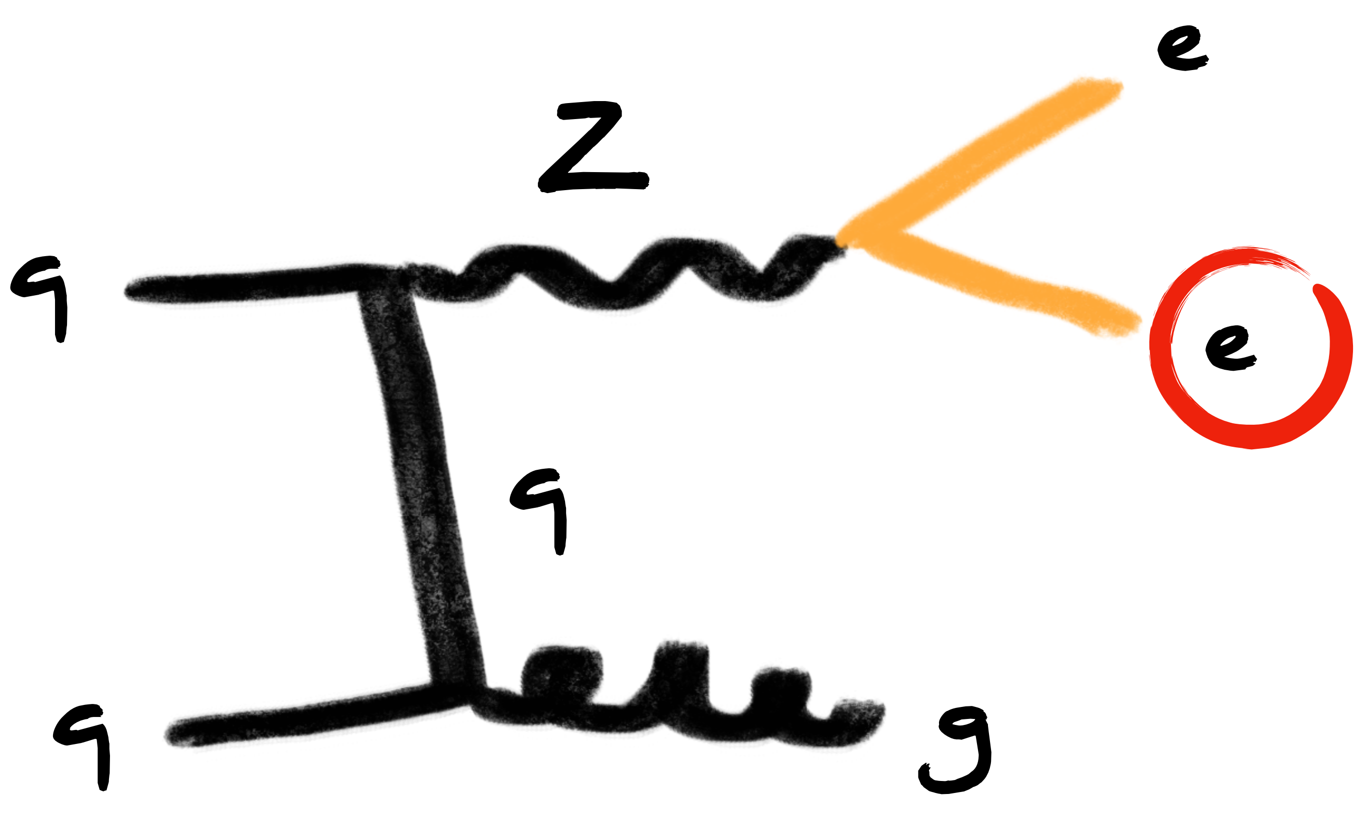




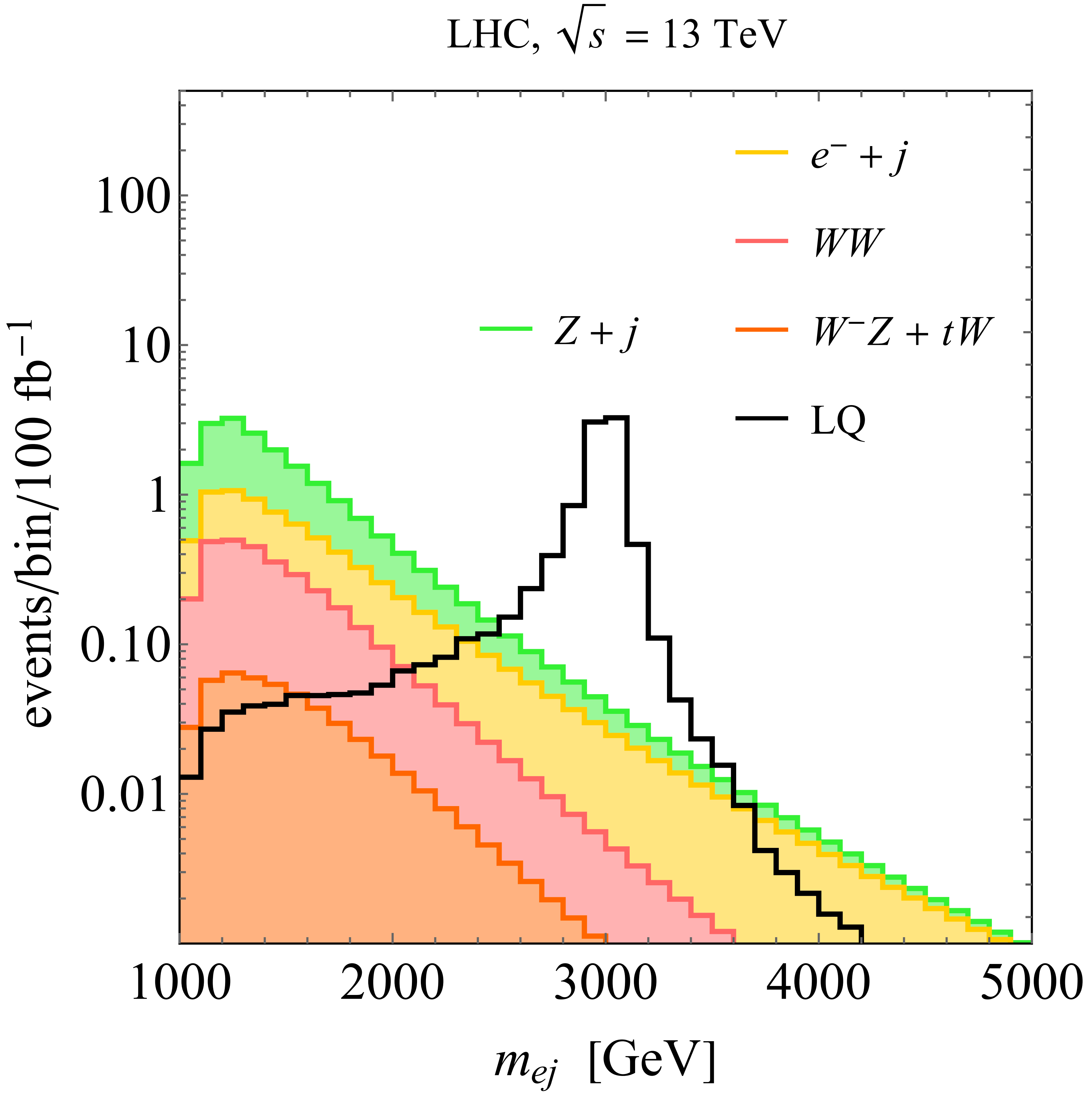
Irreducible background particularly relevant
@ high invariant lepton-jet mass

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

Resonant LQ production @ the LHC

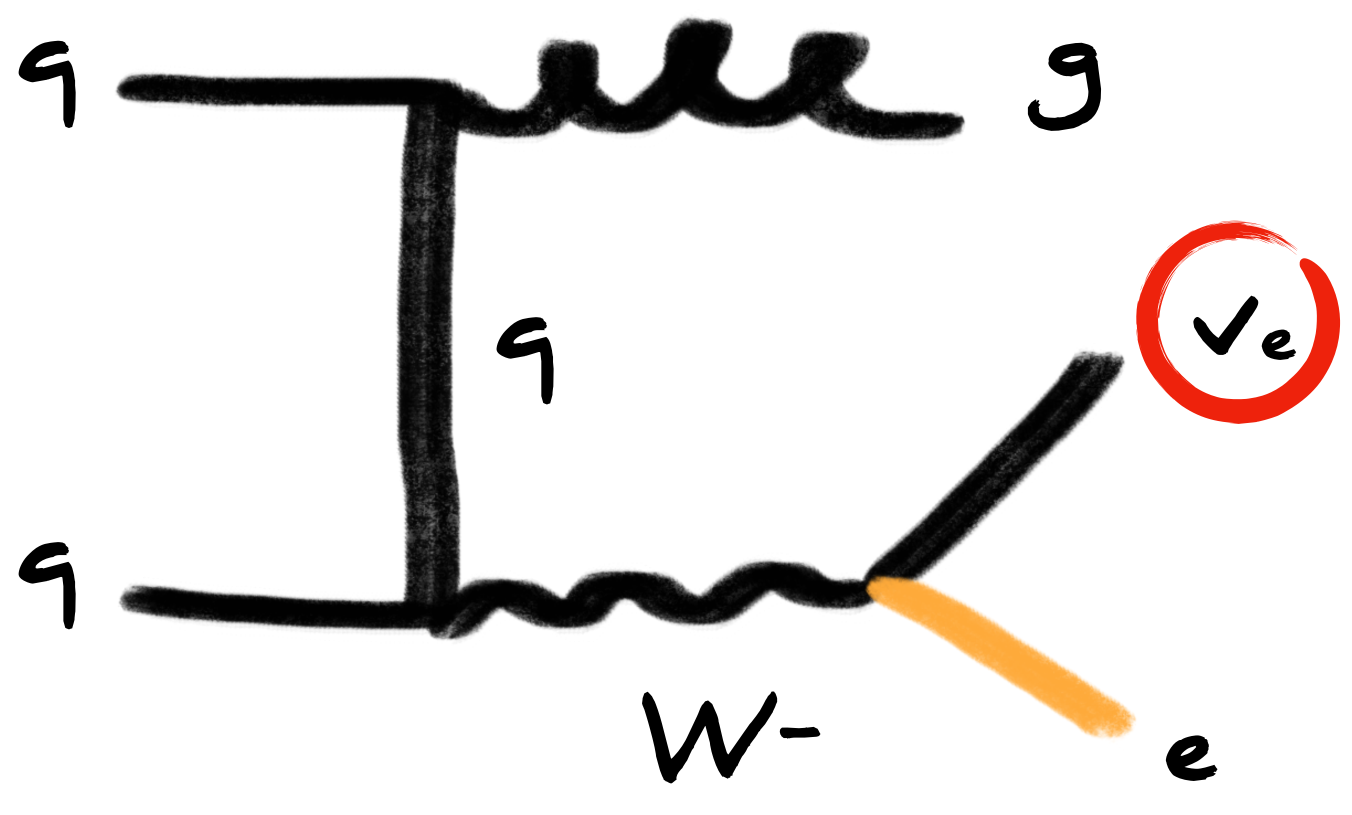


Suppressed by lepton veto

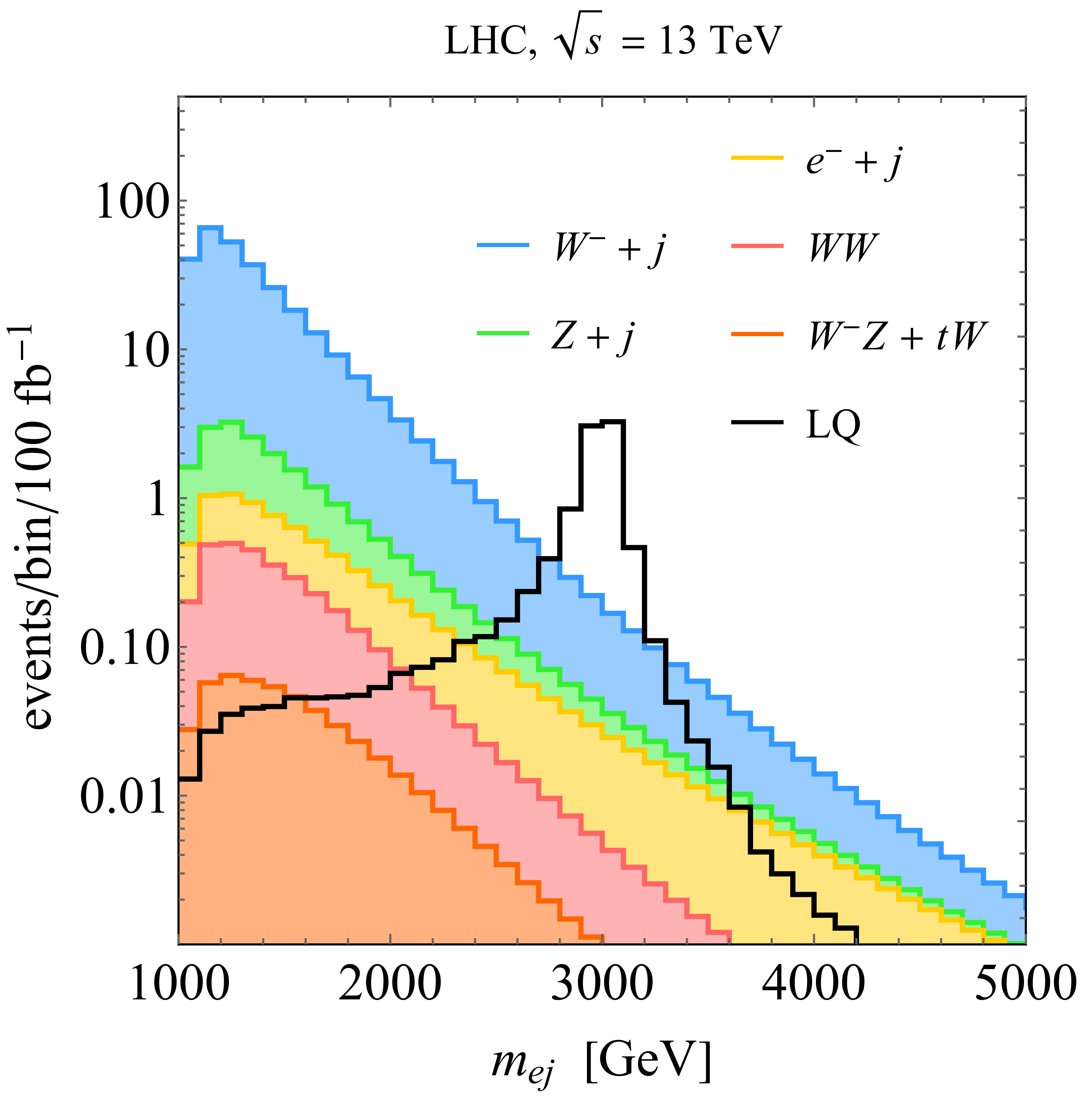


[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

Resonant LQ production @ the LHC

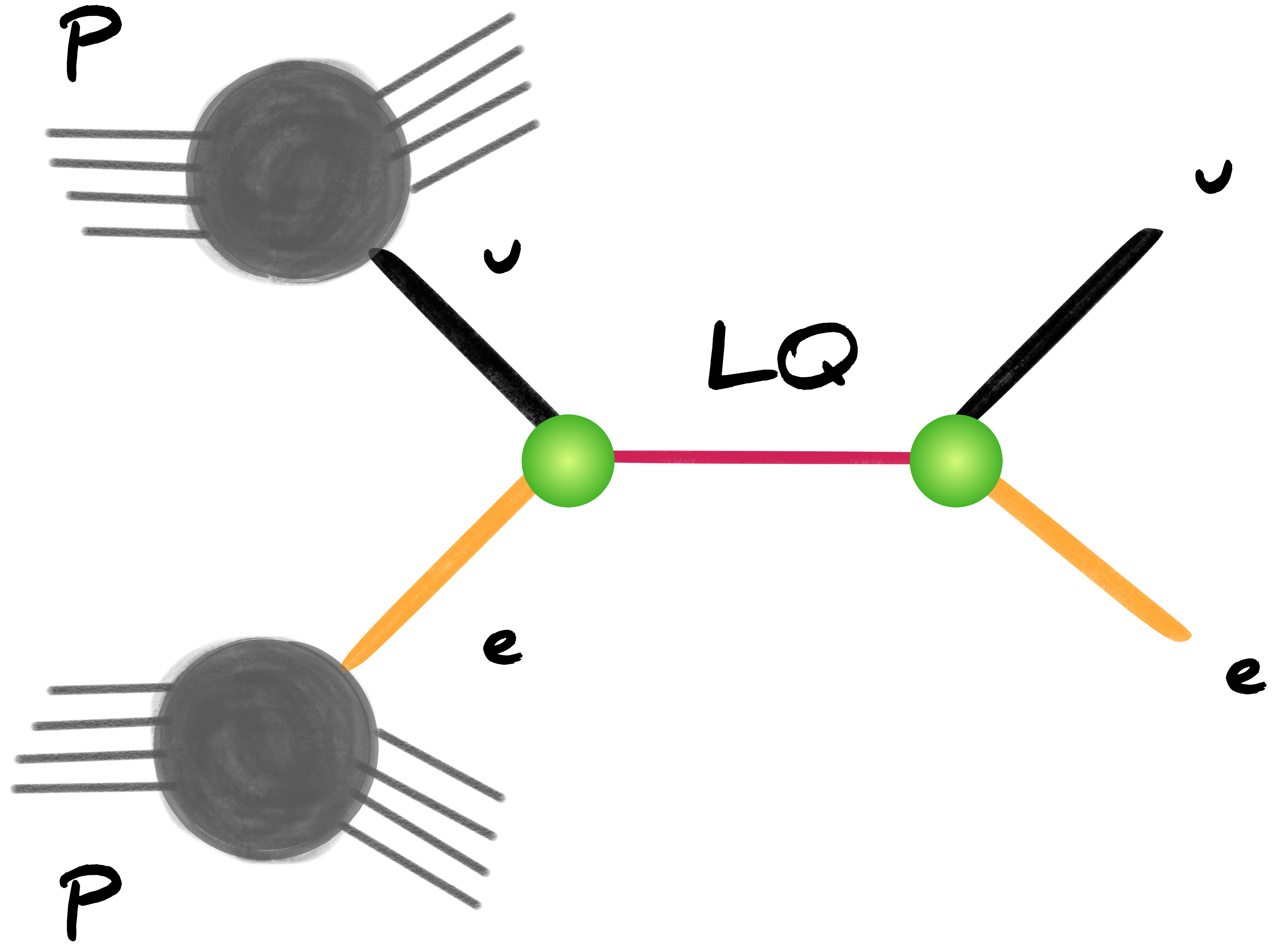


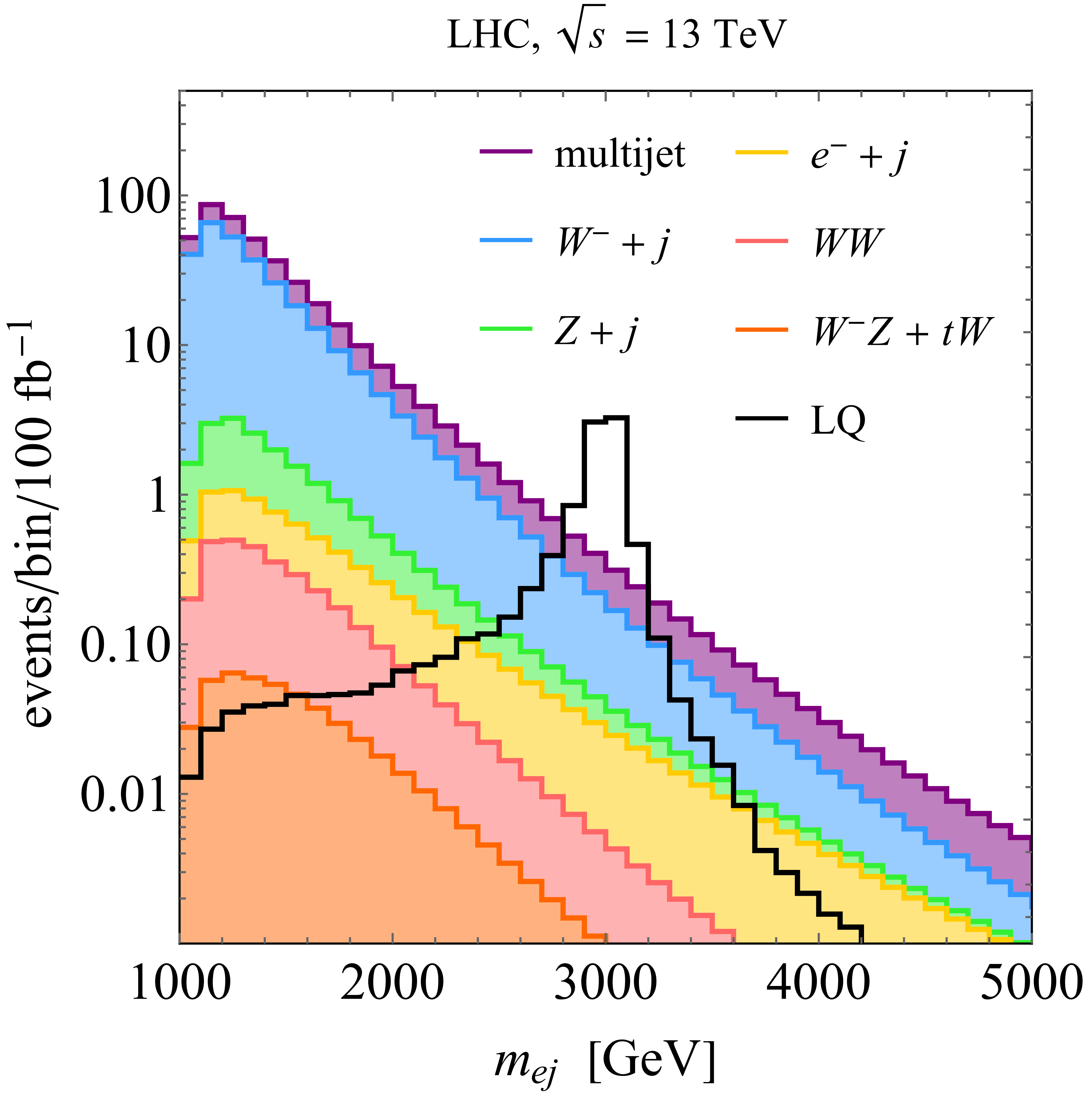
Suppressed by $E_{T,miss}$ requirement



[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

Resonant LQ production @ the LHC

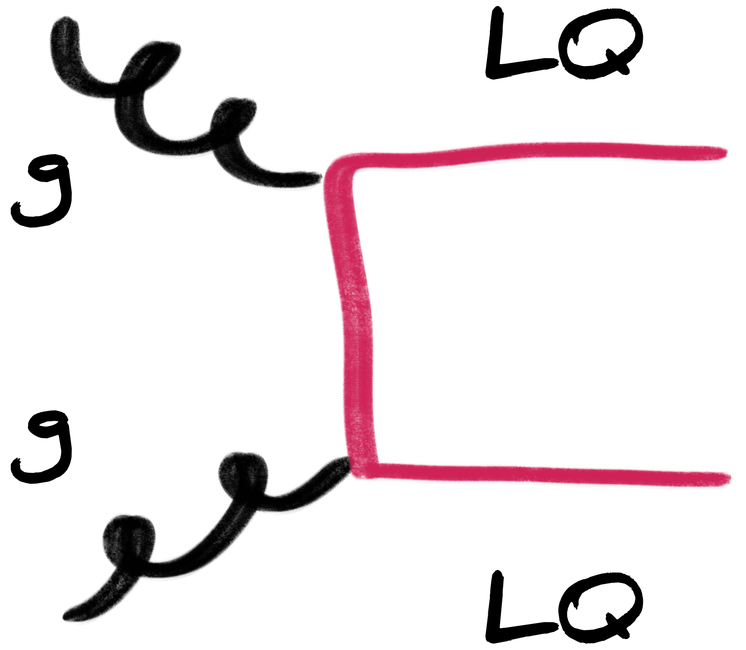




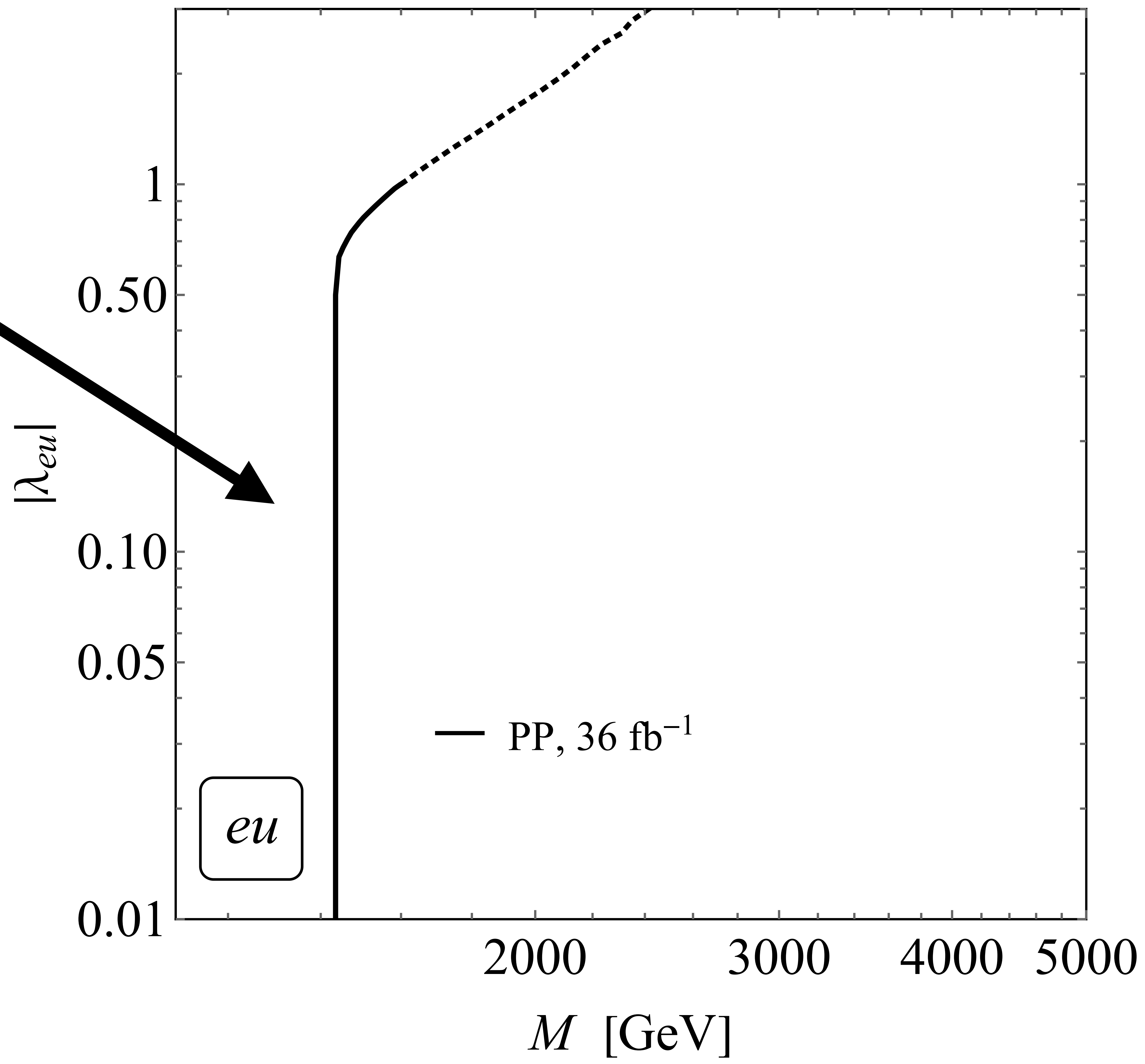
Sum over backgrounds is a steeply falling distribution, while signal exhibits a narrow peak

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs

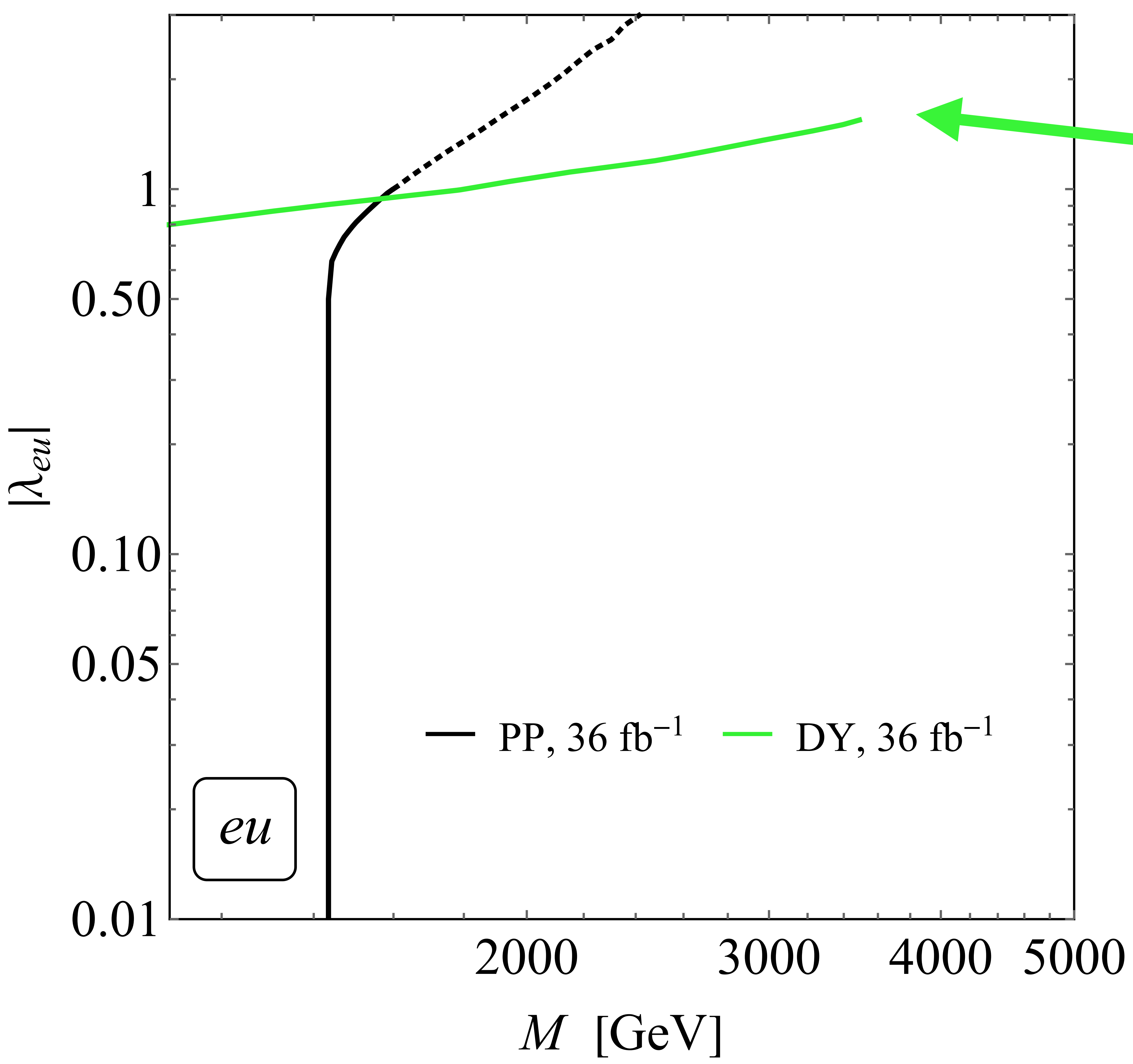


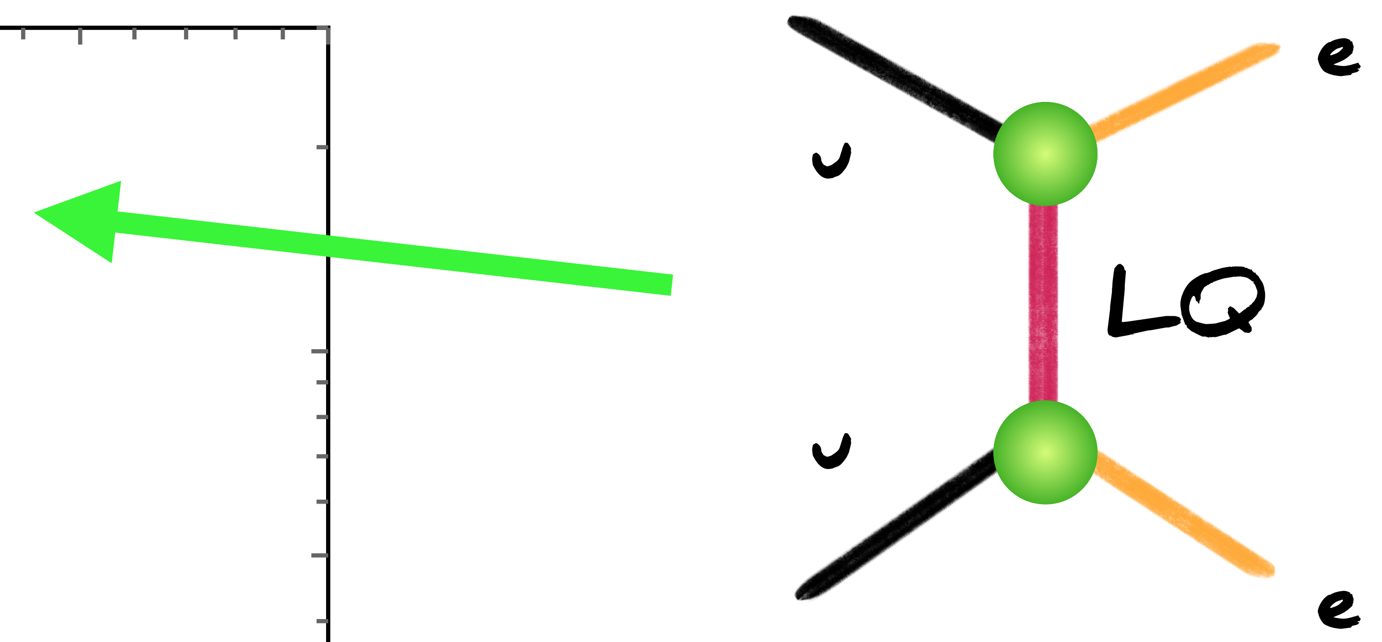
LQ pair production (PP)



[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs

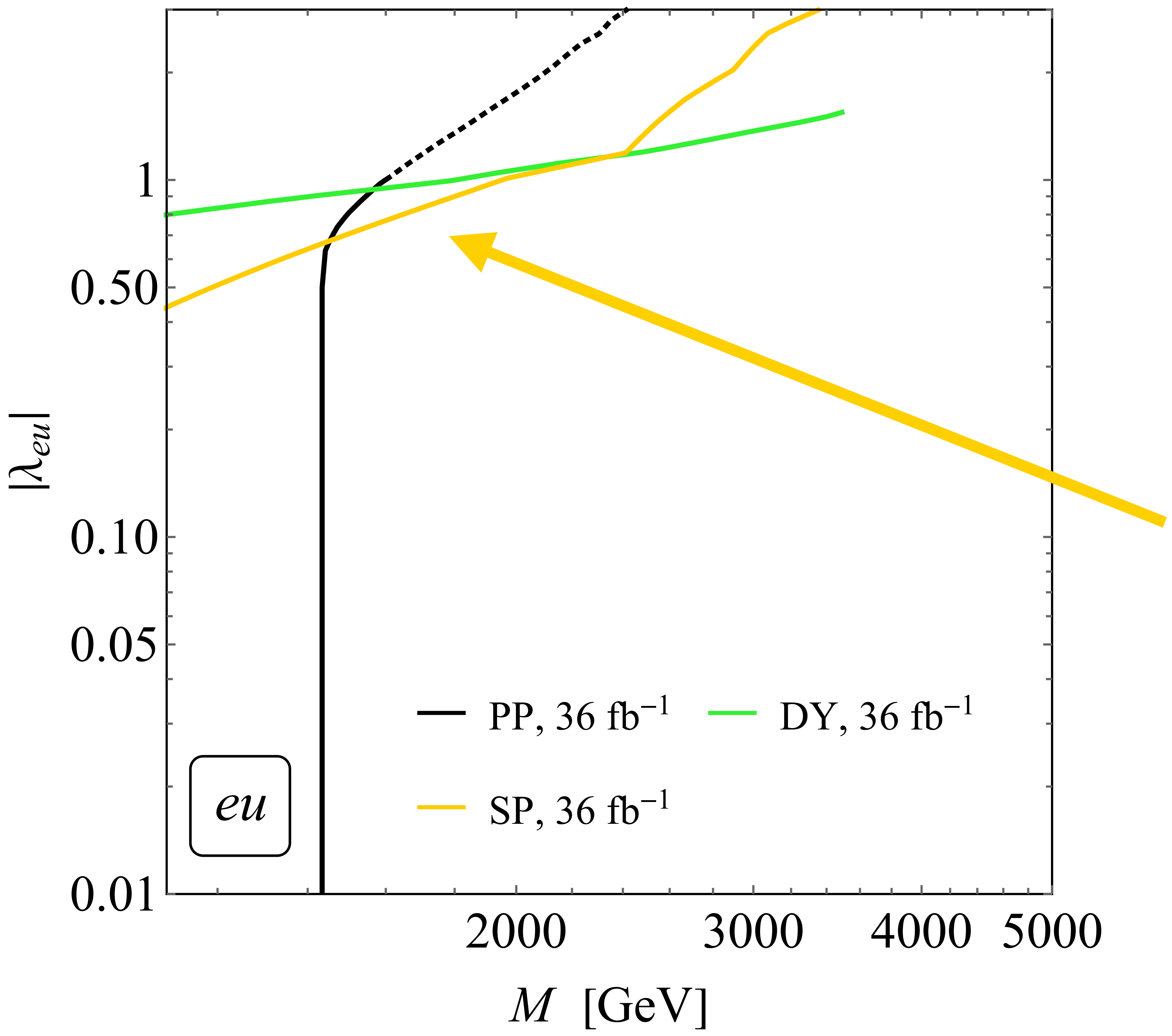


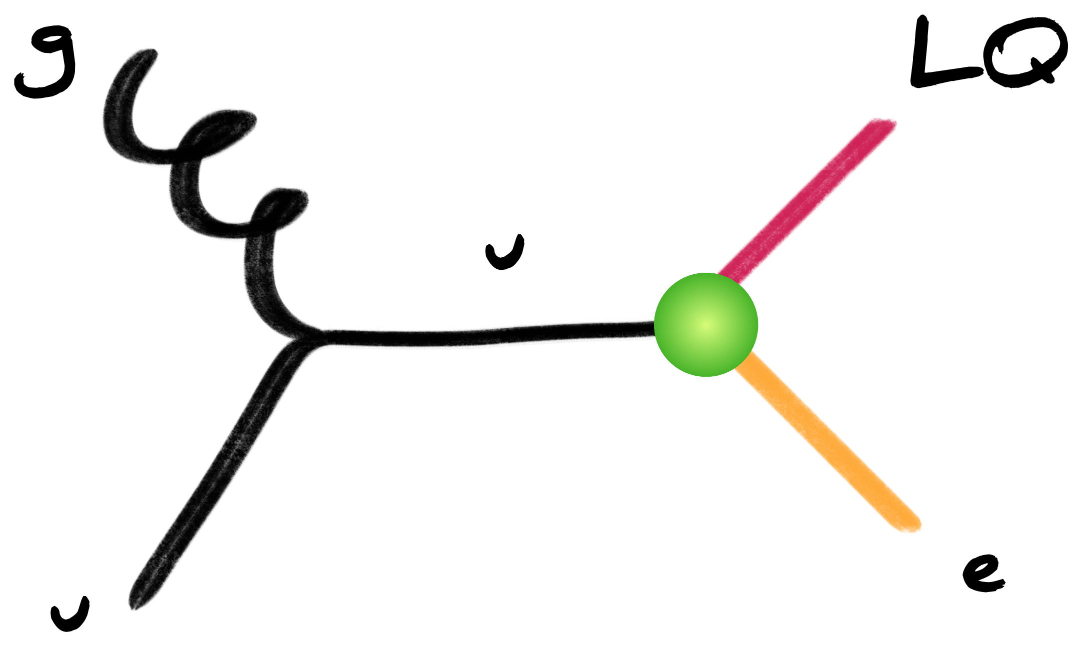


t-channel Drell-Yan (DY)

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs

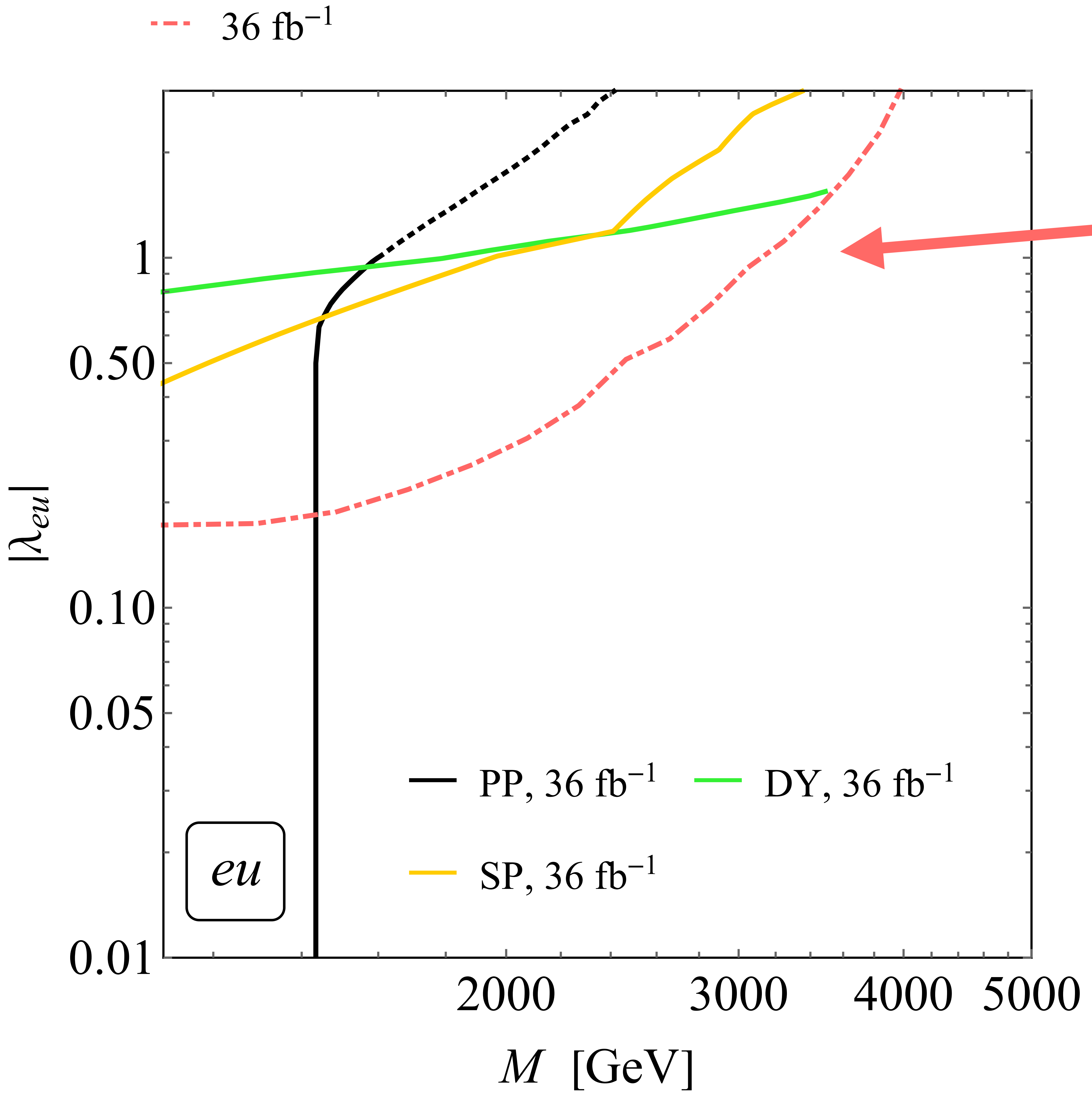


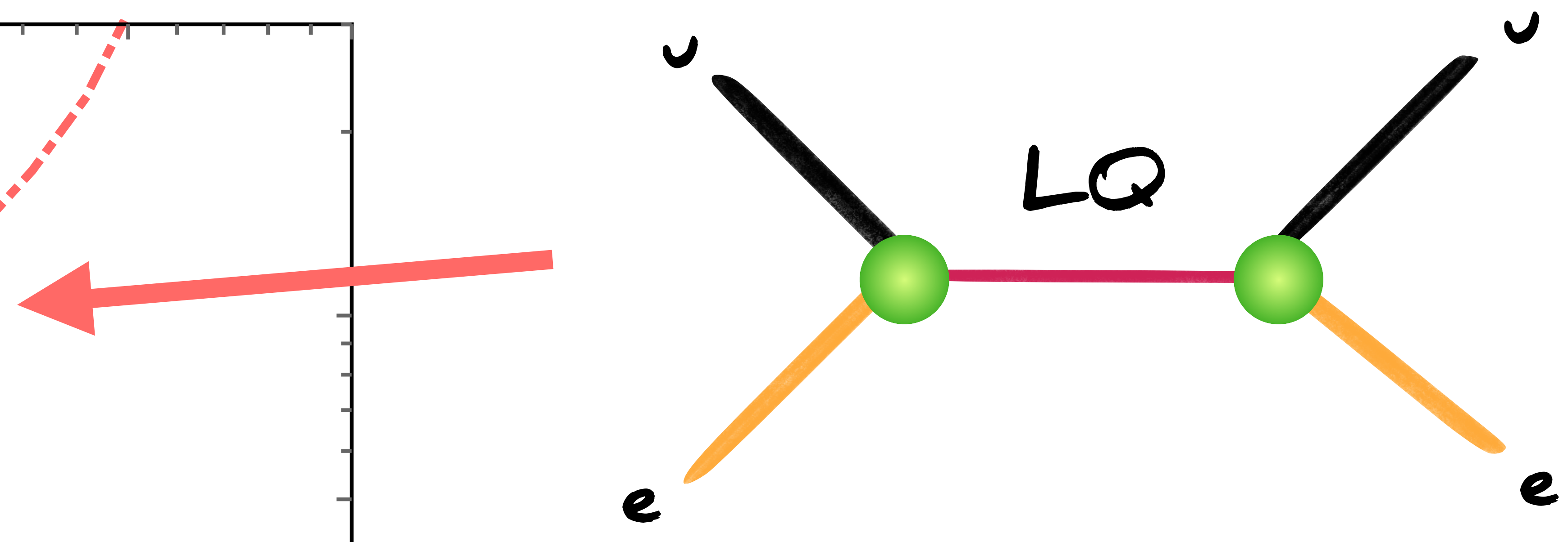


single LQ production (SP)

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs

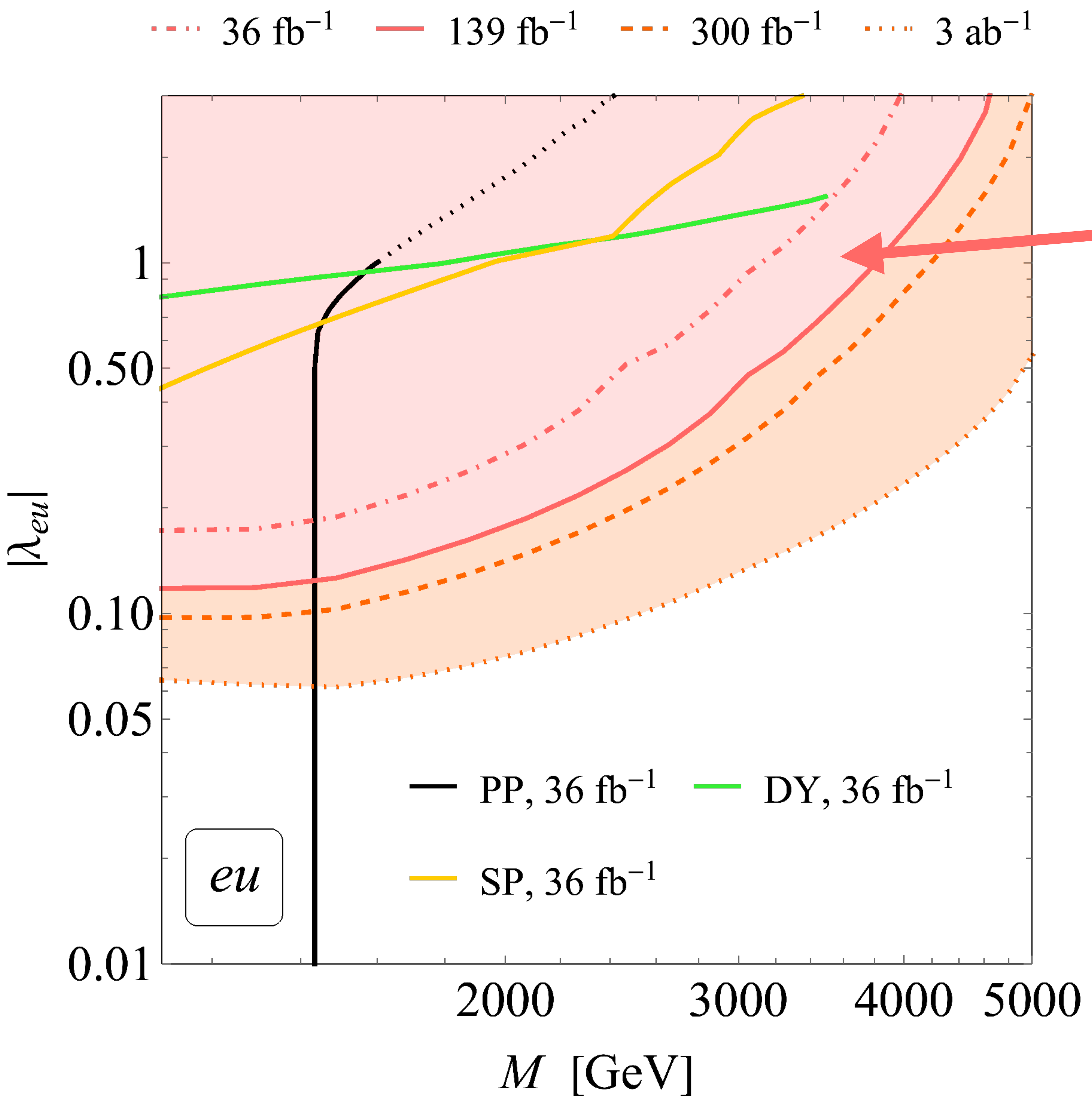


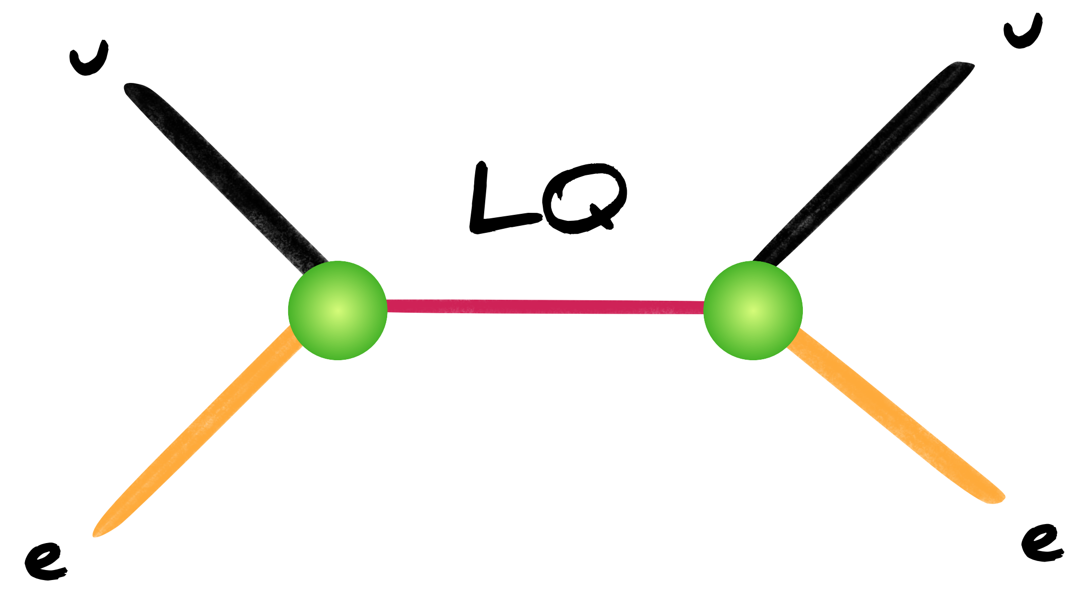


resonant LQ production

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs

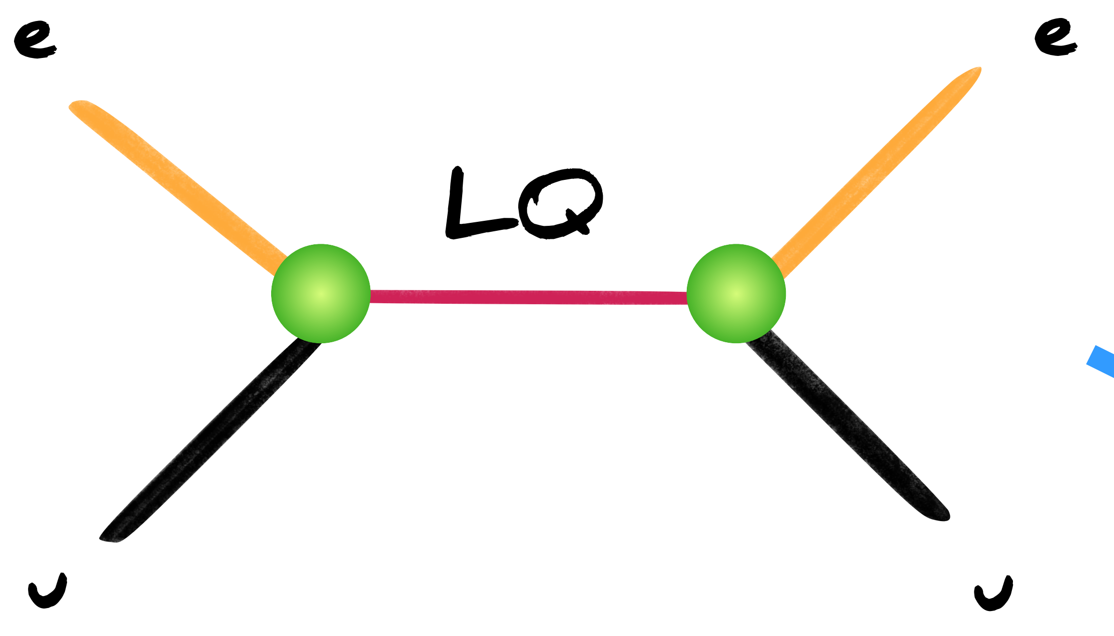




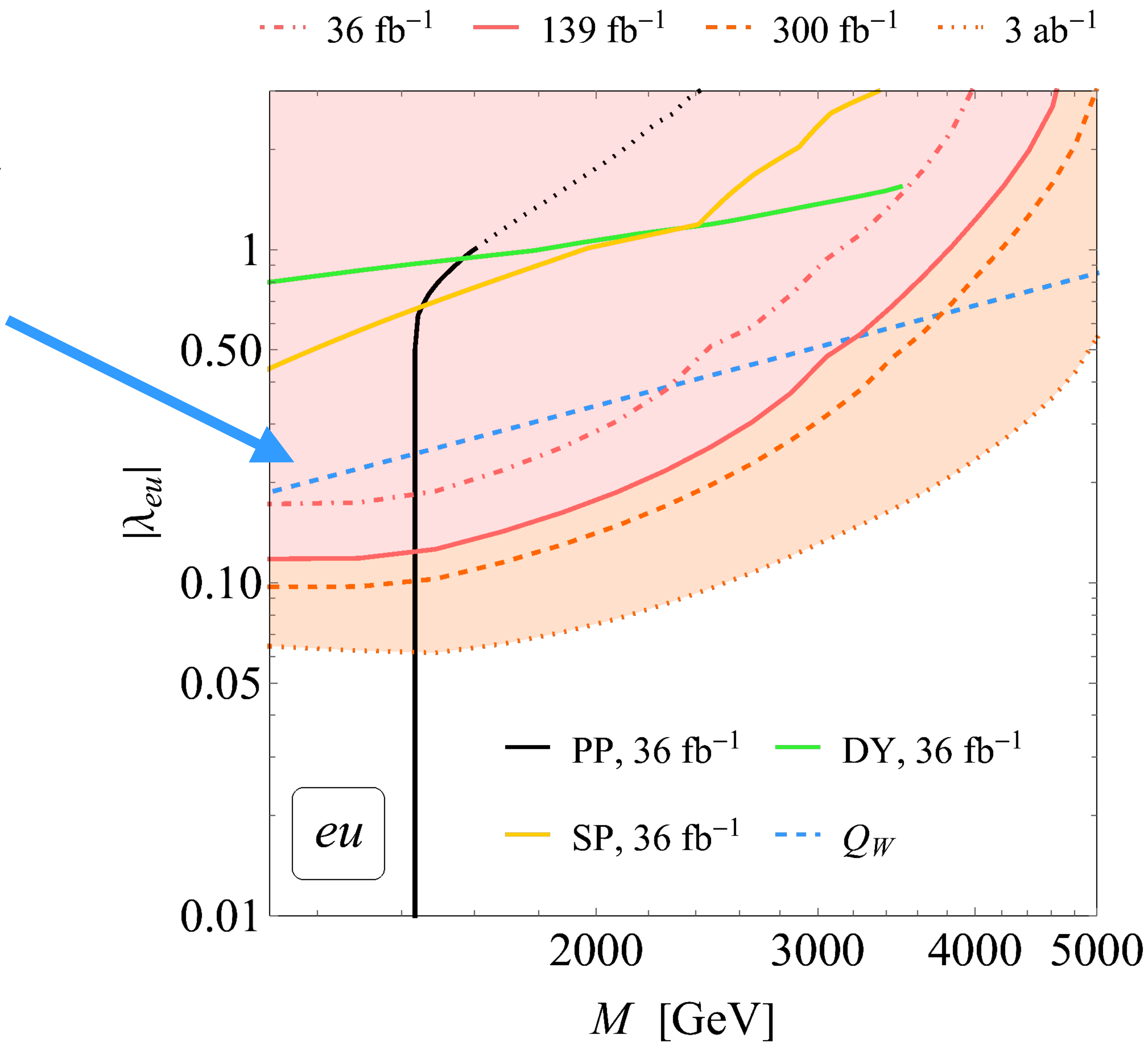
resonant LQ production

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs

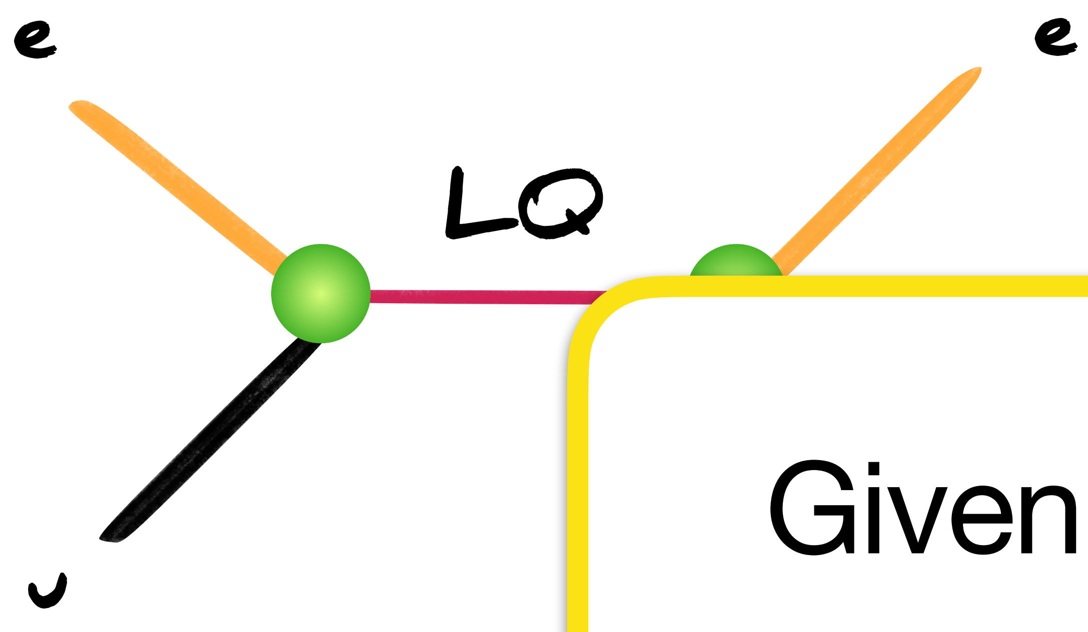


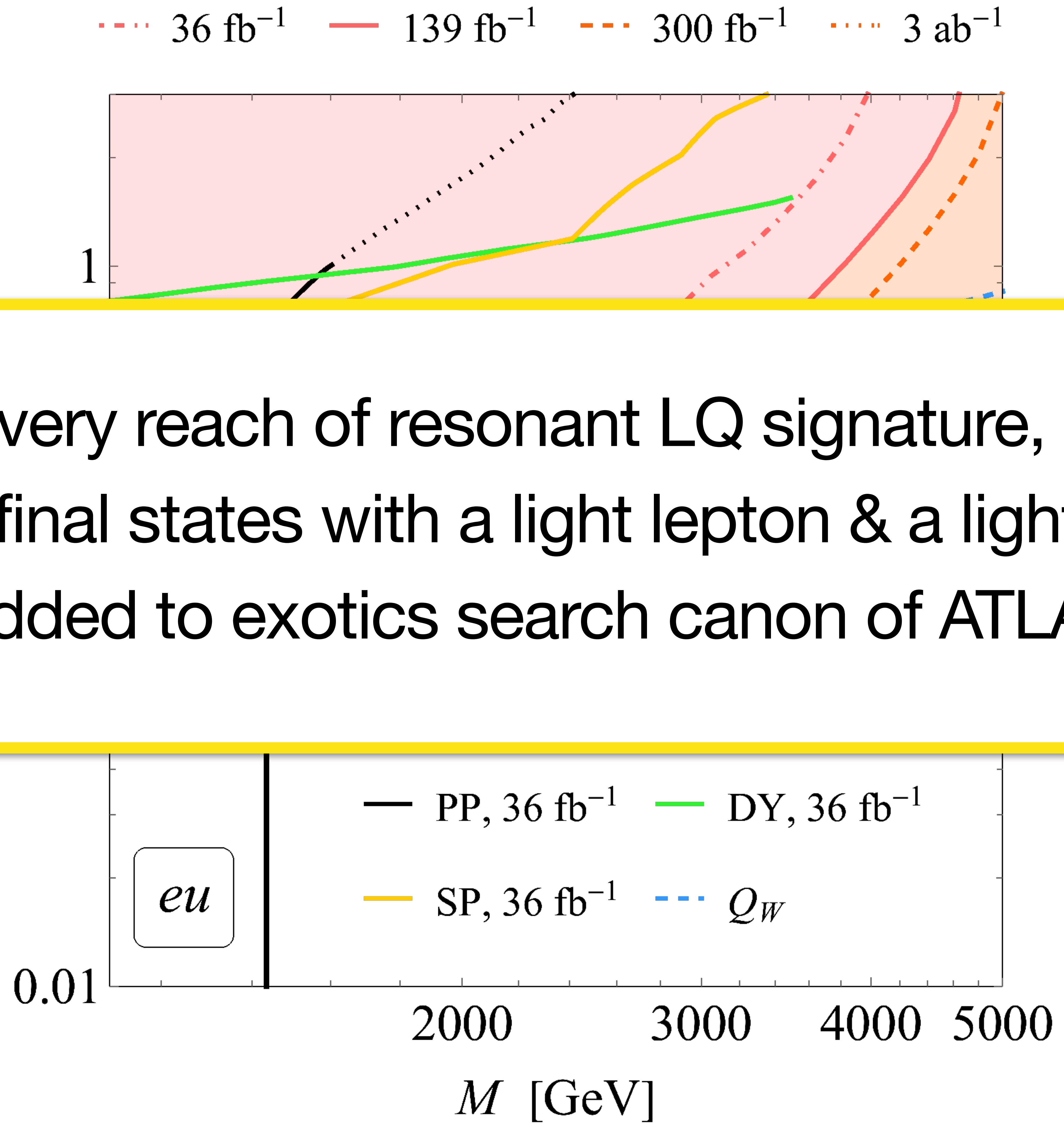
weak charge measurements (Q_W)



[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

LHC limits on 1st & 2nd generation LQs





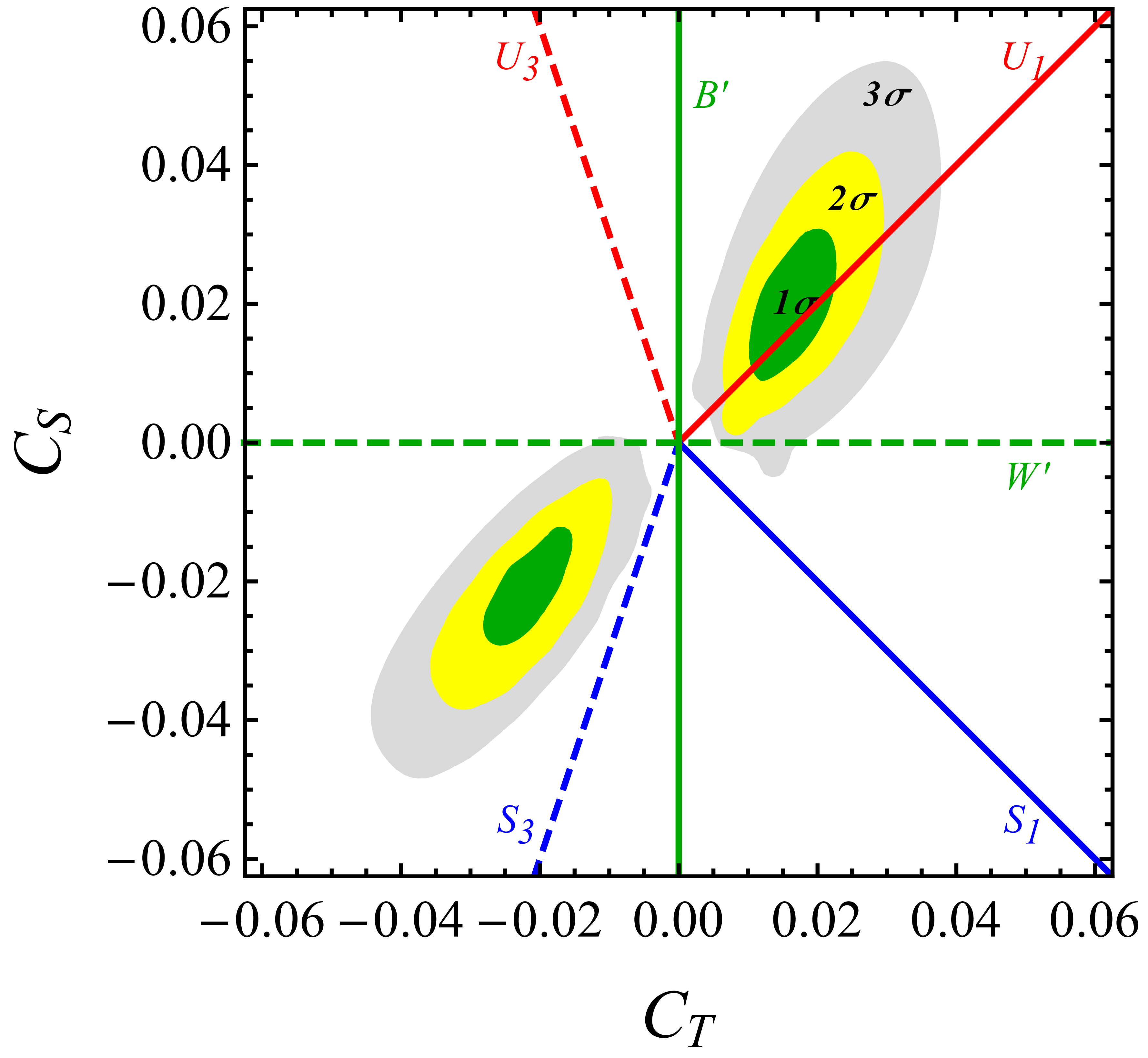
weak c
measurem

Given discovery reach of resonant LQ signature, dedicated searches for final states with a light lepton & a light-flavour jet should be added to exotics search canon of ATLAS & CMS

[Buonocore, UH, Nason, Tramontano & Zanderighi, PRL 125 (2020) 23]

Simplified models for B anomalies

$$\lambda^q_{ij}\lambda^l_{\alpha\beta}\left(C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L)+C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right)$$



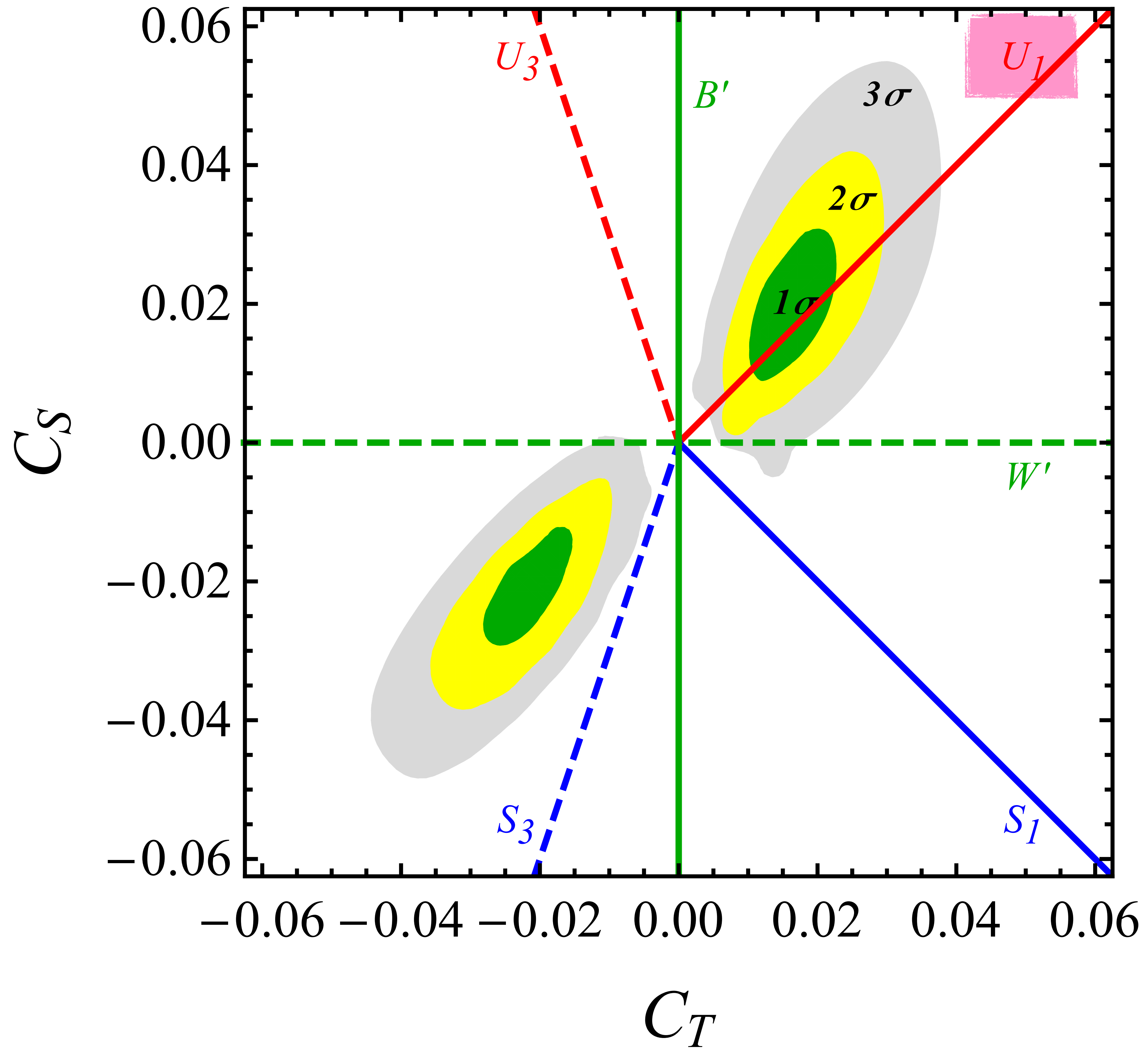
Model	Mediator	$b\to s$	$b\to c$
Colorless vectors	$B'=(1,1,0)$	✓	✗
	$W'=(1,3,0)$	✗	✓
Scalar leptoquarks	$S_1=(\bar{3},1,1/3)$	✗	✓
	$S_3=(\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1=(3,1,2/3)$	✓	✓
	$U_3=(3,3,2/3)$	✓	✗

b → s (b → c) anomalies alone can be accommodated by several simple single-mediator models

[see for instance Buttazzo, Greljo, Isidori & Marzocca, JHEP 11 (2017) 044]

Simplified models for B anomalies

$$\lambda^q_{ij}\lambda^l_{\alpha\beta}\left(C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right)$$



Model	Mediator	$b \to s$	$b \to c$
Colorless vectors	$B' = (1,1,0)$	✓	✗
	$W' = (1,3,0)$	✗	✓
Scalar leptoquarks	$S_1 = (\bar{3},1,1/3)$	✗	✓
	$S_3 = (\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

U_1 singlet vector LQ is the only single-mediator model that can explain both sets of anomalies

[see for instance Buttazzo, Greljo, Isidori & Marzocca, JHEP 11 (2017) 044]

Singlet vector LQ models for B anomalies

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} \left[\beta_L^{ij}\, \bar{Q}_L^{i,a} \gamma_\mu L_L^j + \beta_R^{ij}\, \bar{d}_R^{i,a} \gamma_\mu \ell_R^j \right] U^{\mu,a} + \text{h.c.}\,, \qquad |\beta_L^{22}| \lesssim |\beta_L^{32}| \ll |\beta_L^{23}| \lesssim |\beta_L^{33}| = \mathcal{O}(1)$$

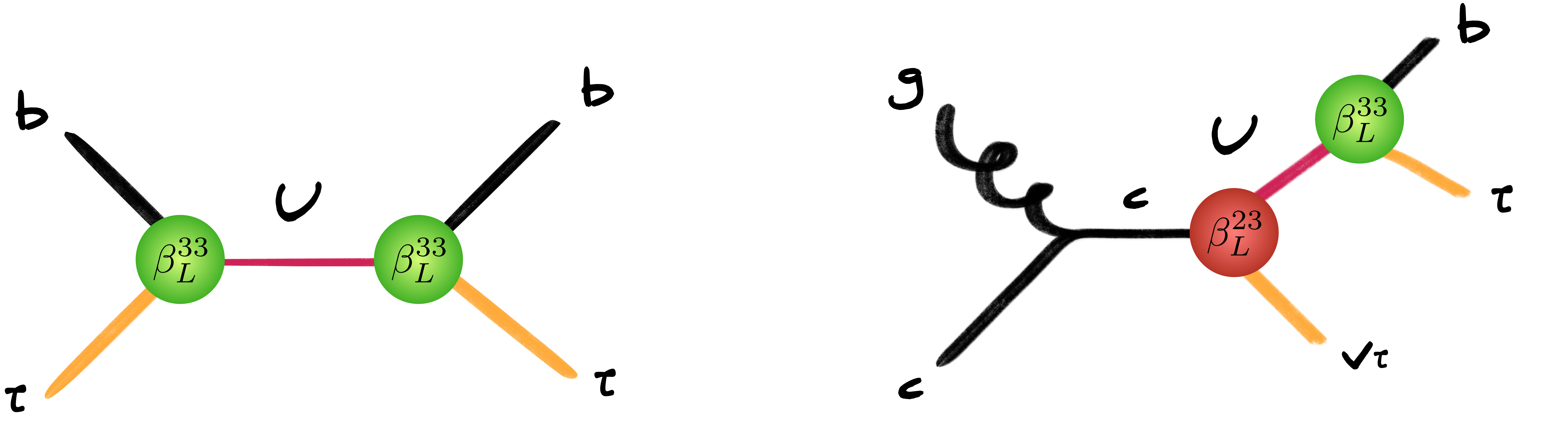
Parameters		Branching ratios			
β_L^{33}	β_L^{23}	$\text{BR}(U \to b\tau^+)$	$\text{BR}(U \to t\bar{\nu}_\tau)$	$\text{BR}(U \to s\tau^+)$	$\text{BR}(U \to c\bar{\nu}_\tau)$
1	0	51%	49%	0%	0%
1	1	25%	22%	25%	27%

b + τ signature

mono-top signature

mono-jet signature

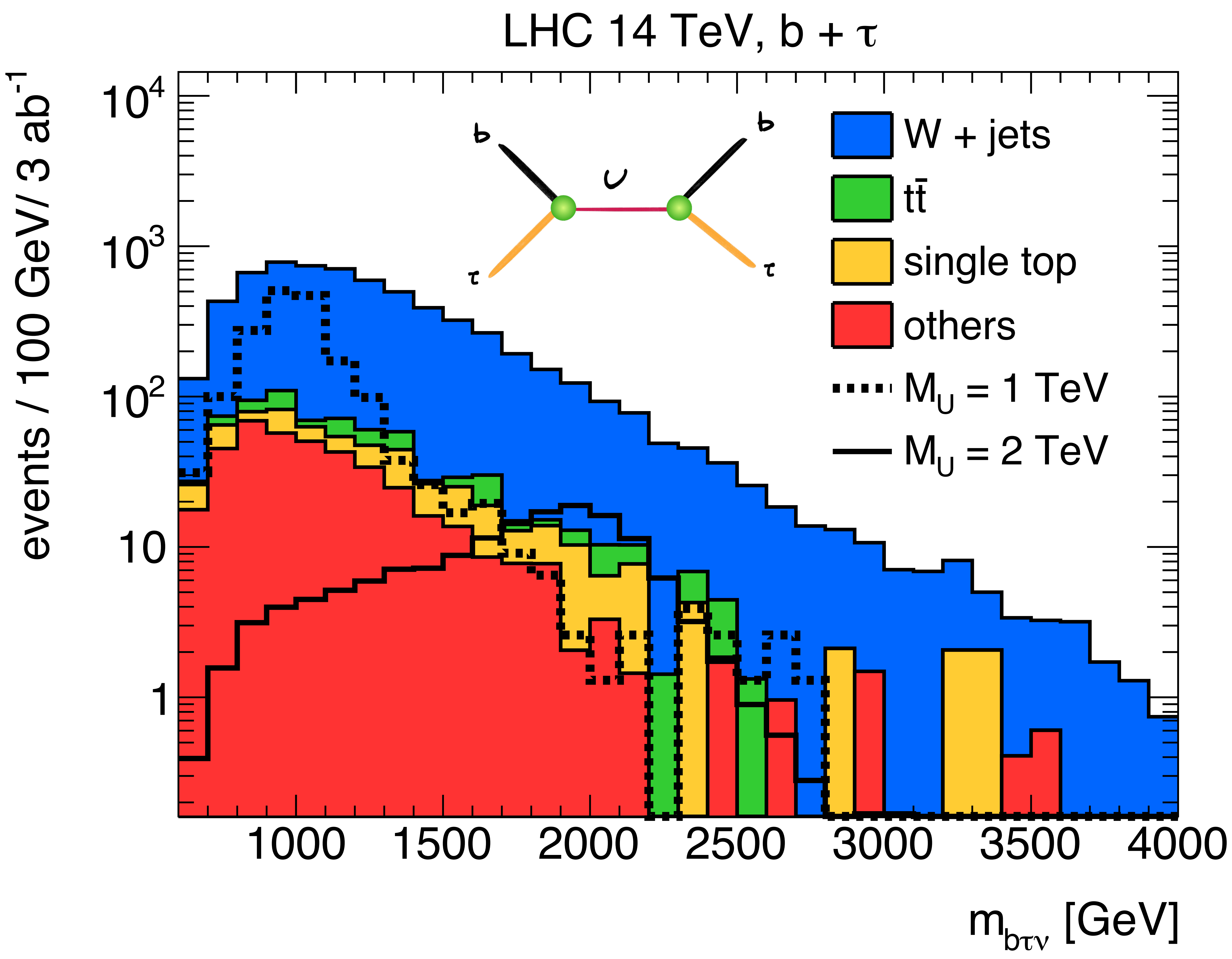
LQ contributions to b + τ signature

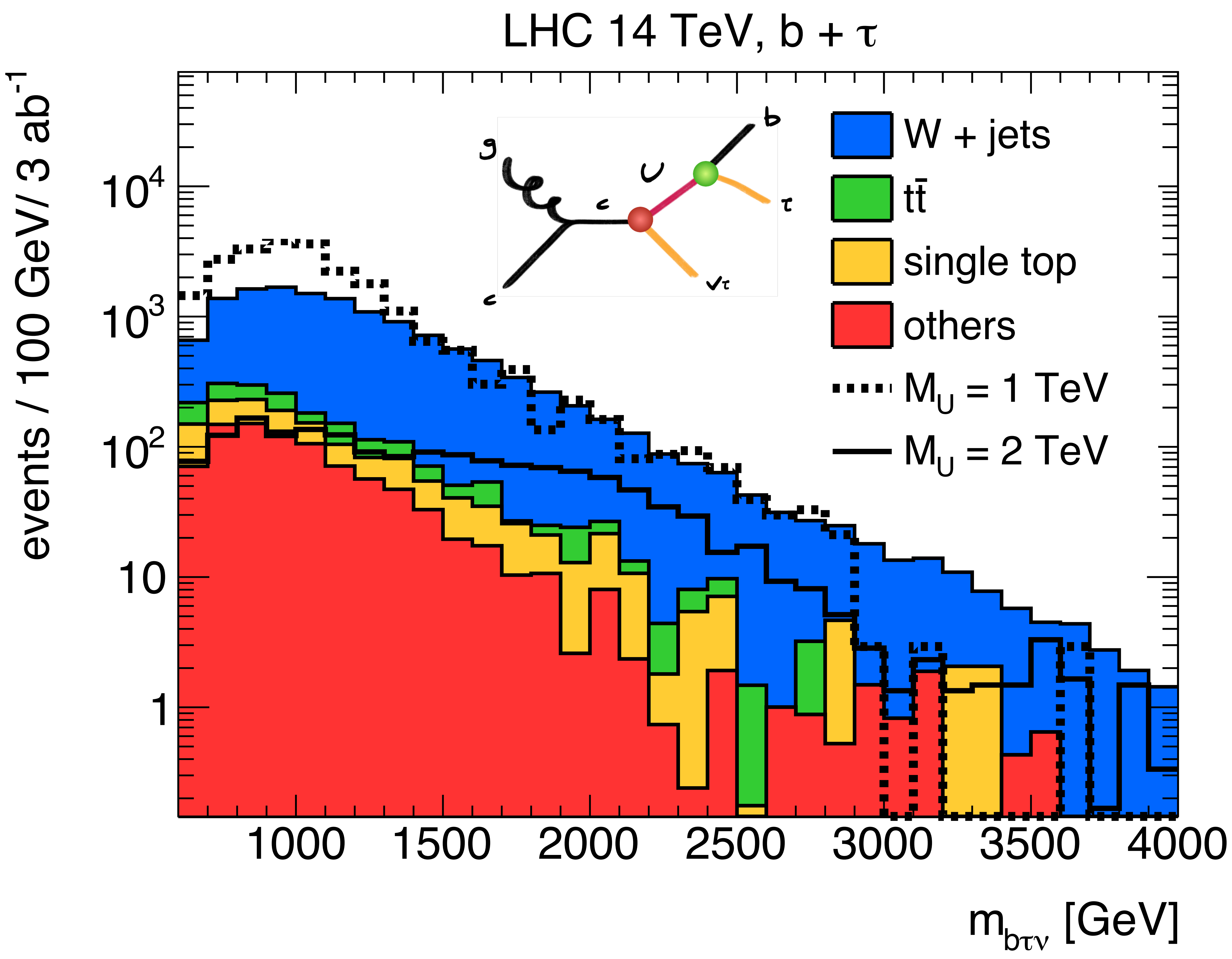


For $\beta_L^{23} = 0$, b + τ signal arises only from 2 → 2 process, while for $\beta_L^{23} \neq 0$ also 2 → 3 scattering is relevant. Since two topologies lead to final states with very different kinematic features, it is essential to develop two separate search strategies for them

[UH & Polesello, 2012.11474]

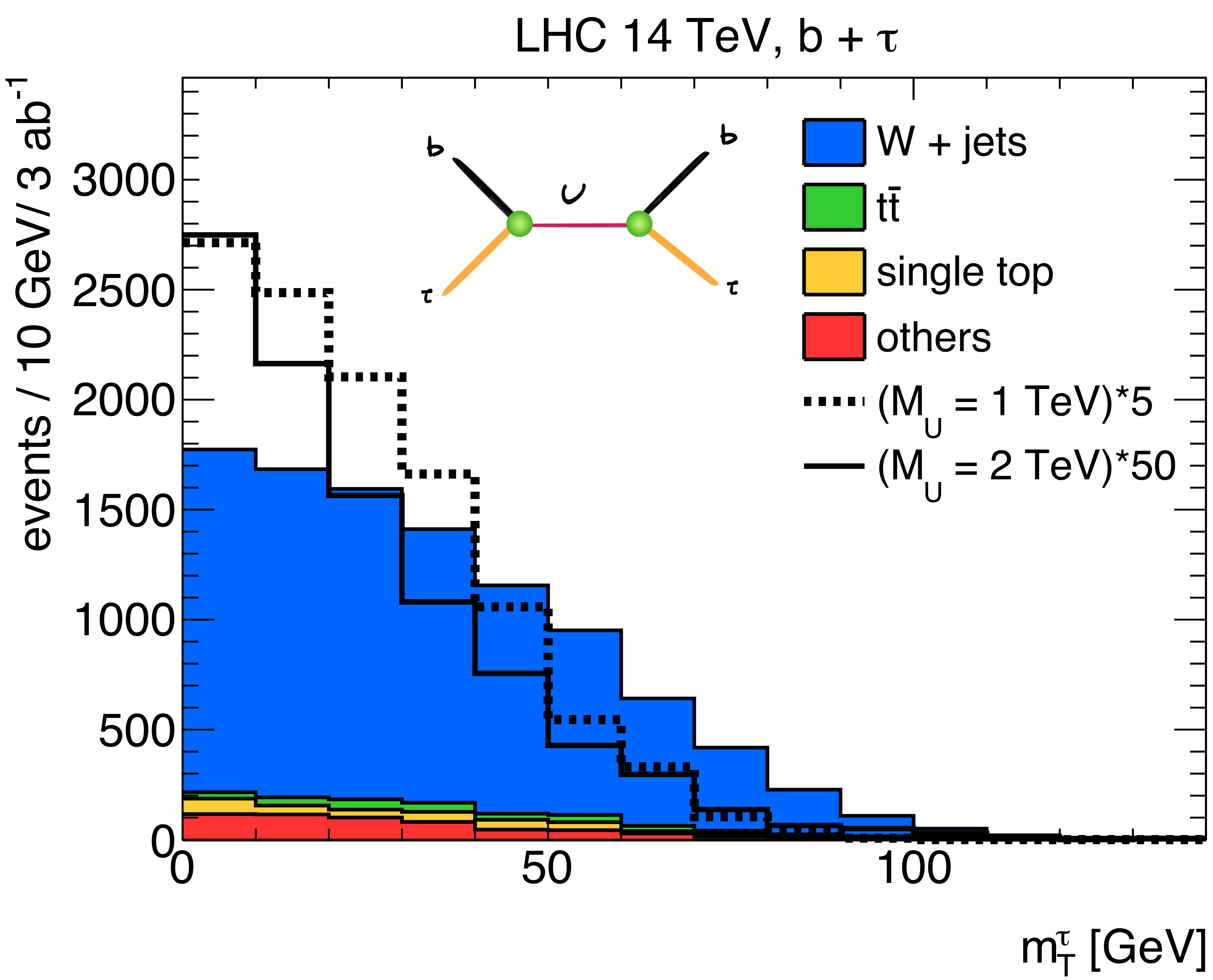
Kinematic distributions of b + τ signal

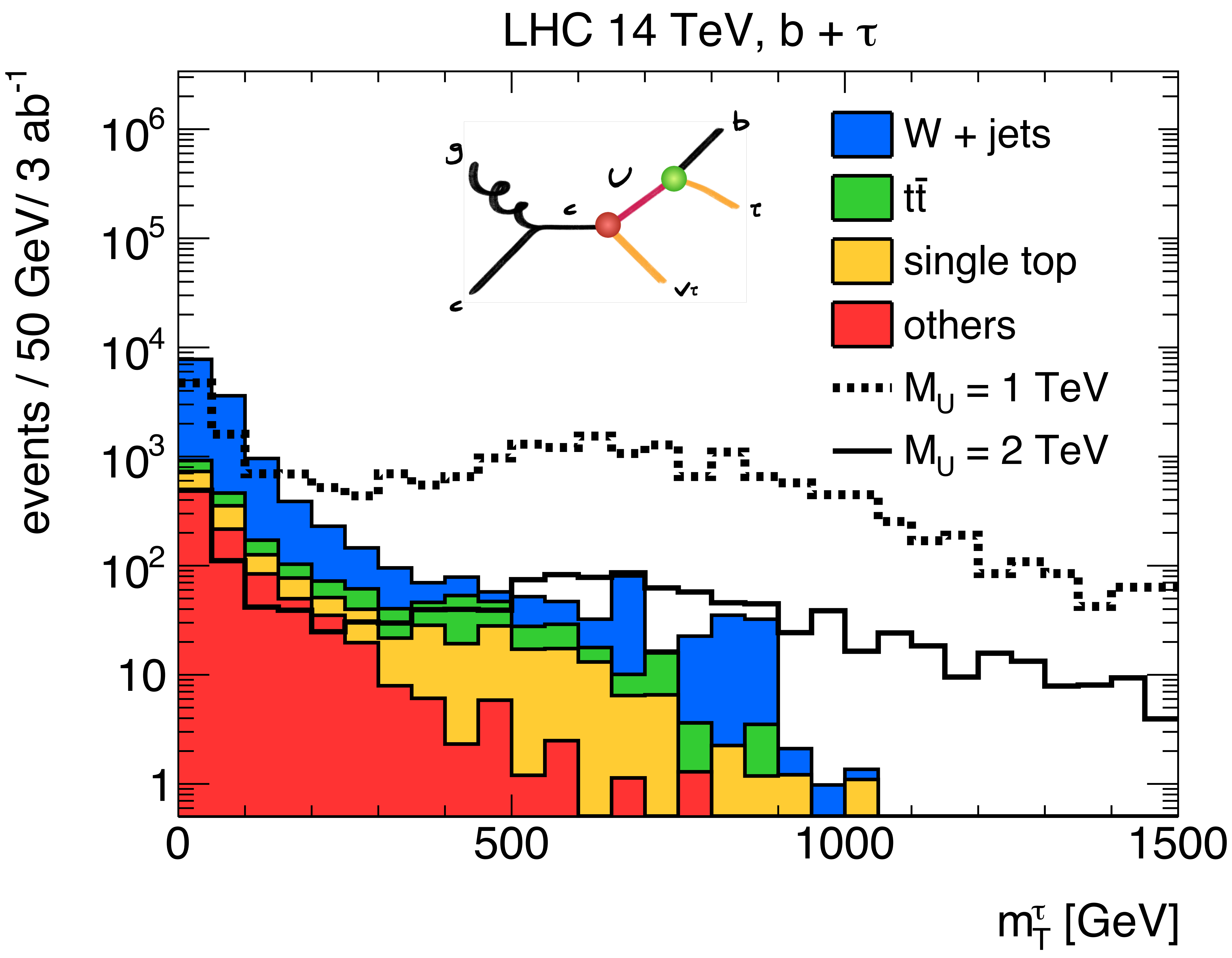




[UH & Polesello, 2012.11474]

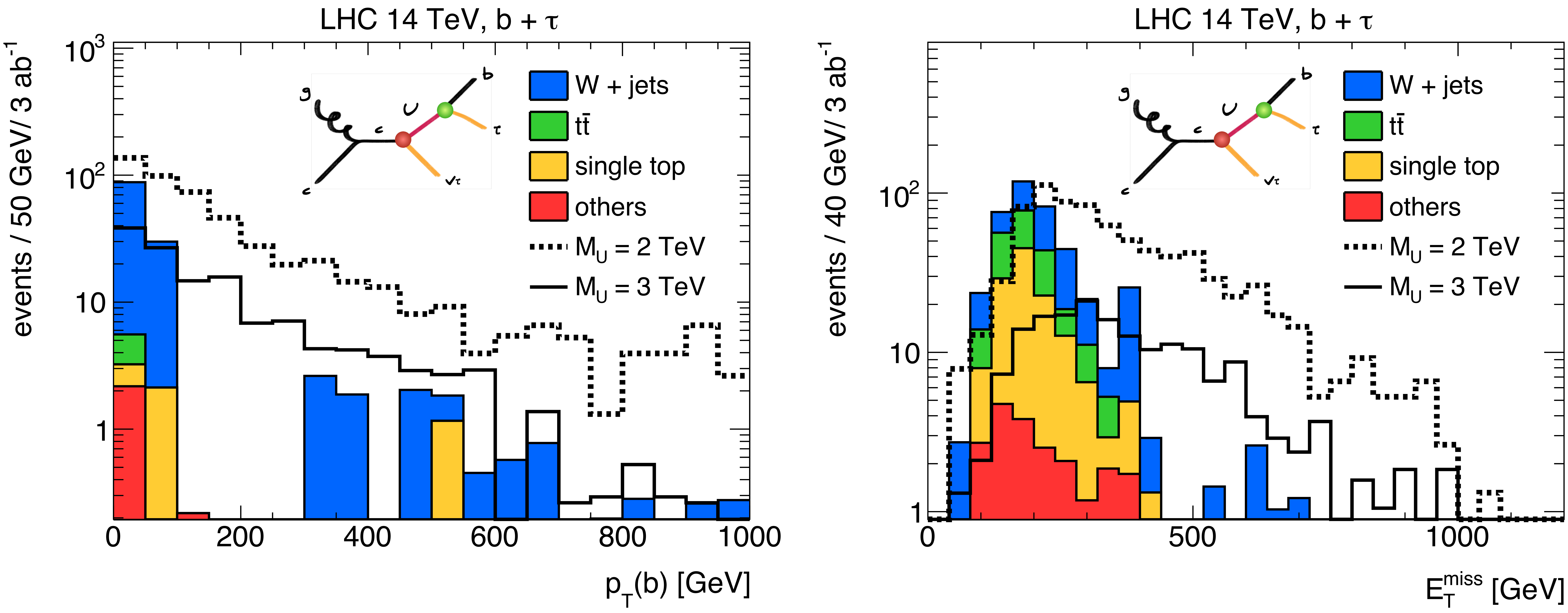
Kinematic distributions of b + τ signal





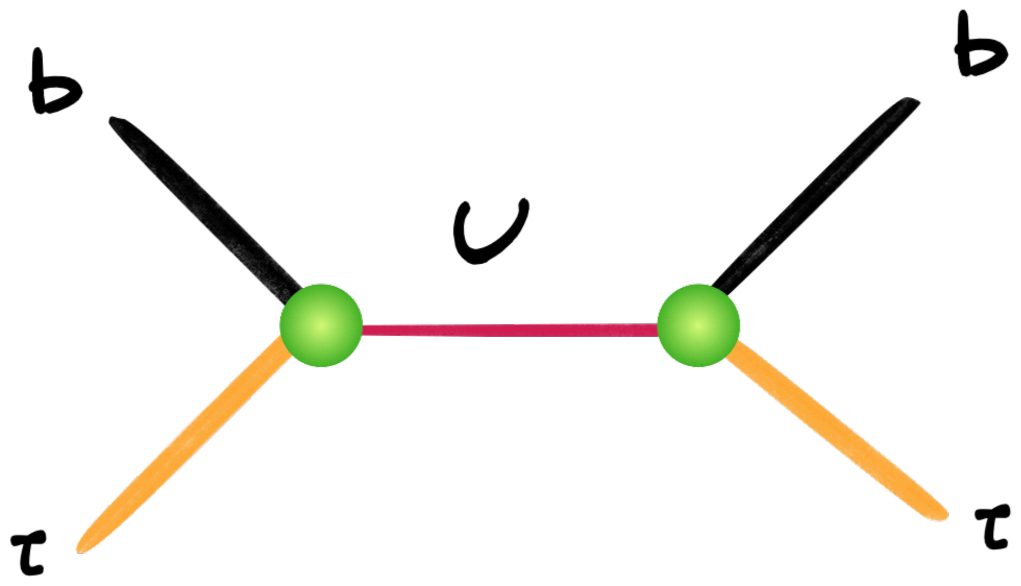
[UH & Polesello, 2012.11474]

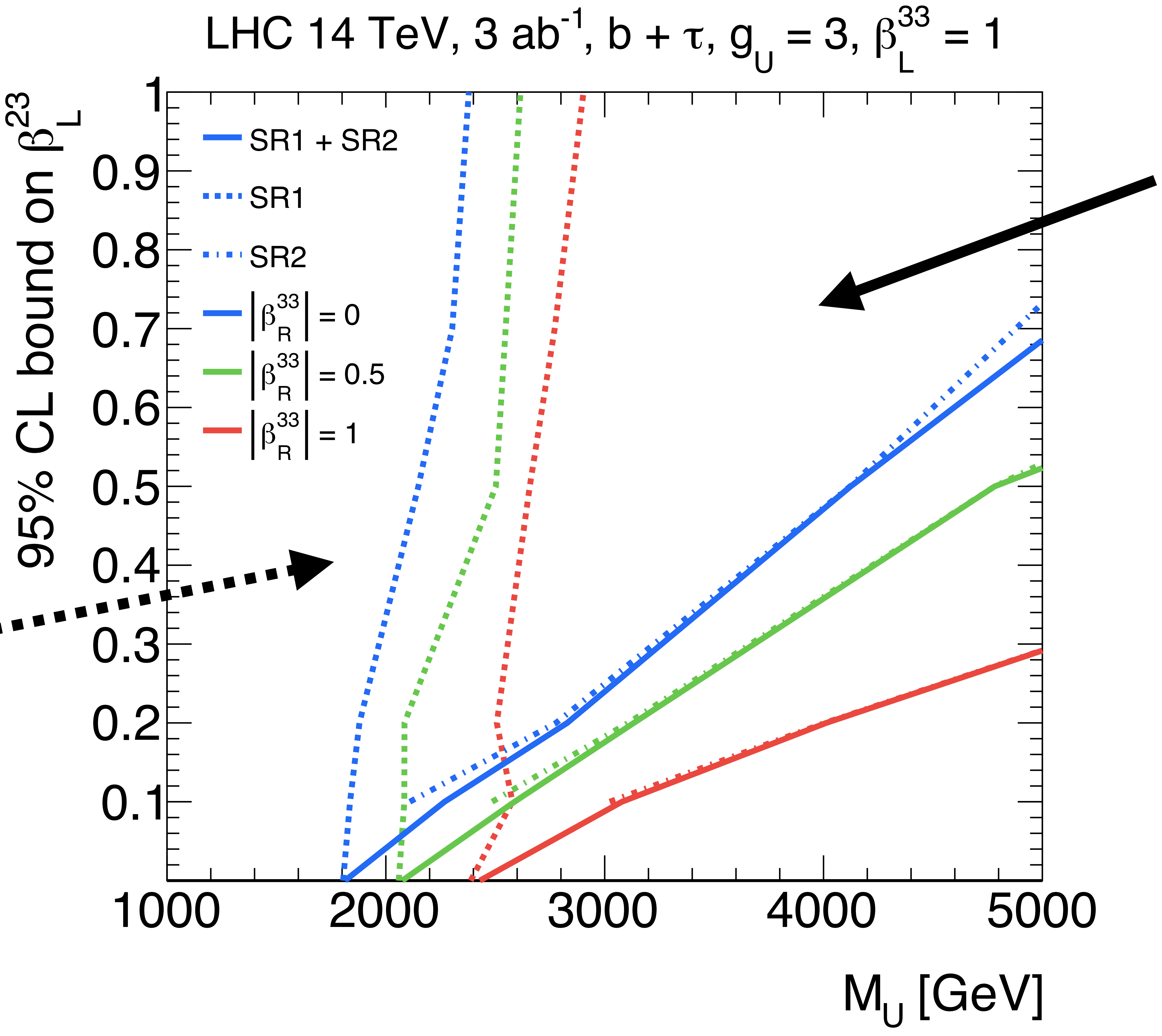
Kinematic distributions of b + τ signal

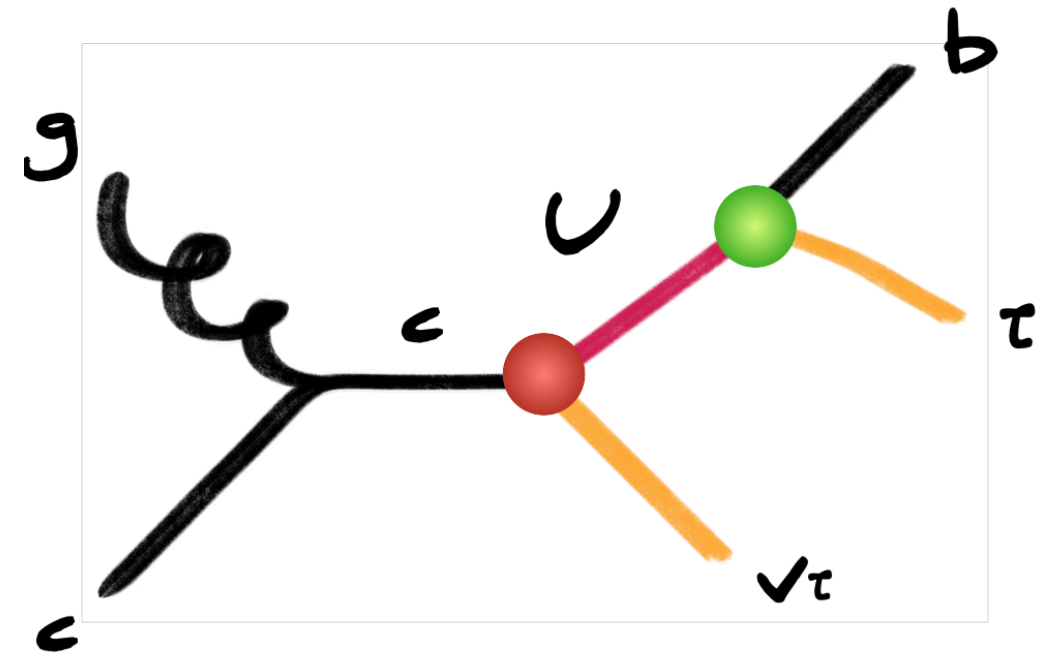


[UH & Polesello, 2012.11474]

b + τ constraints from 2 → 2 & 2 → 3 signal

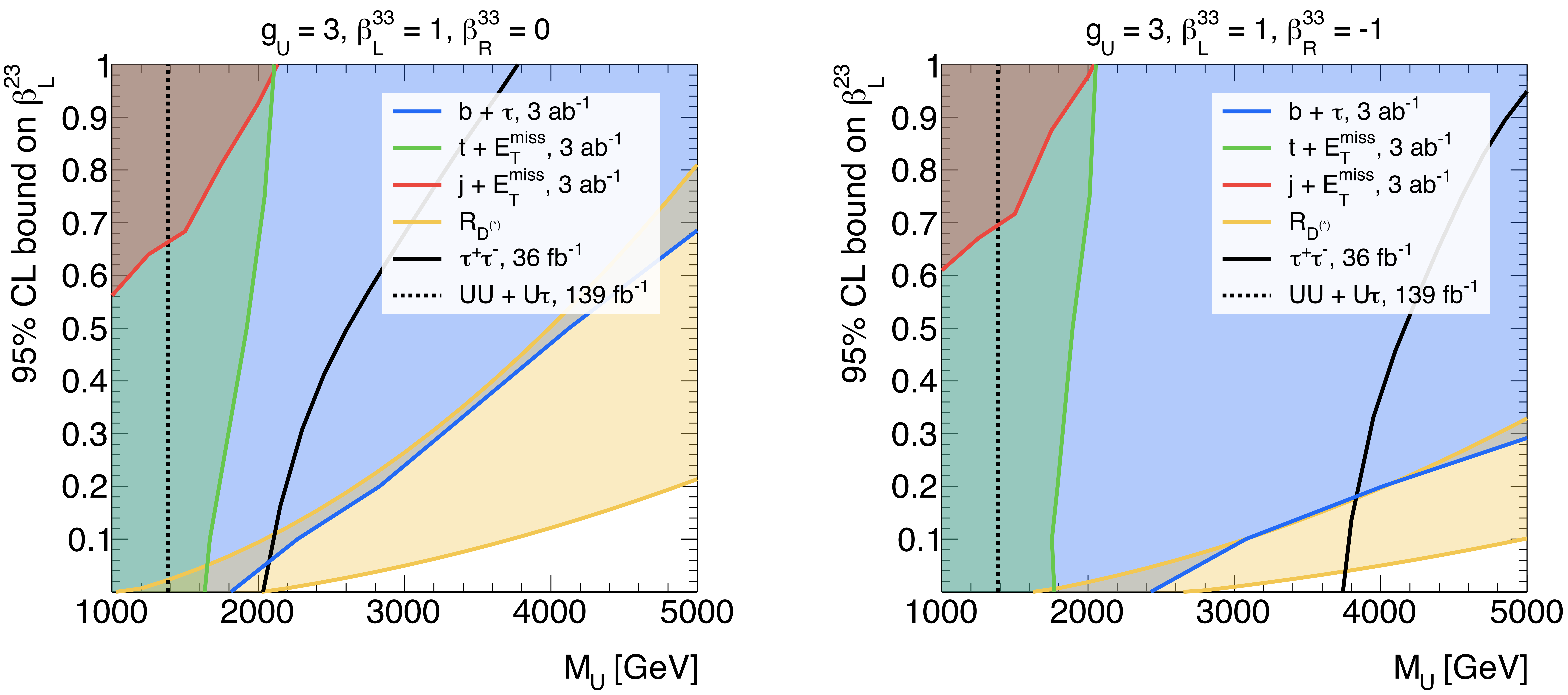






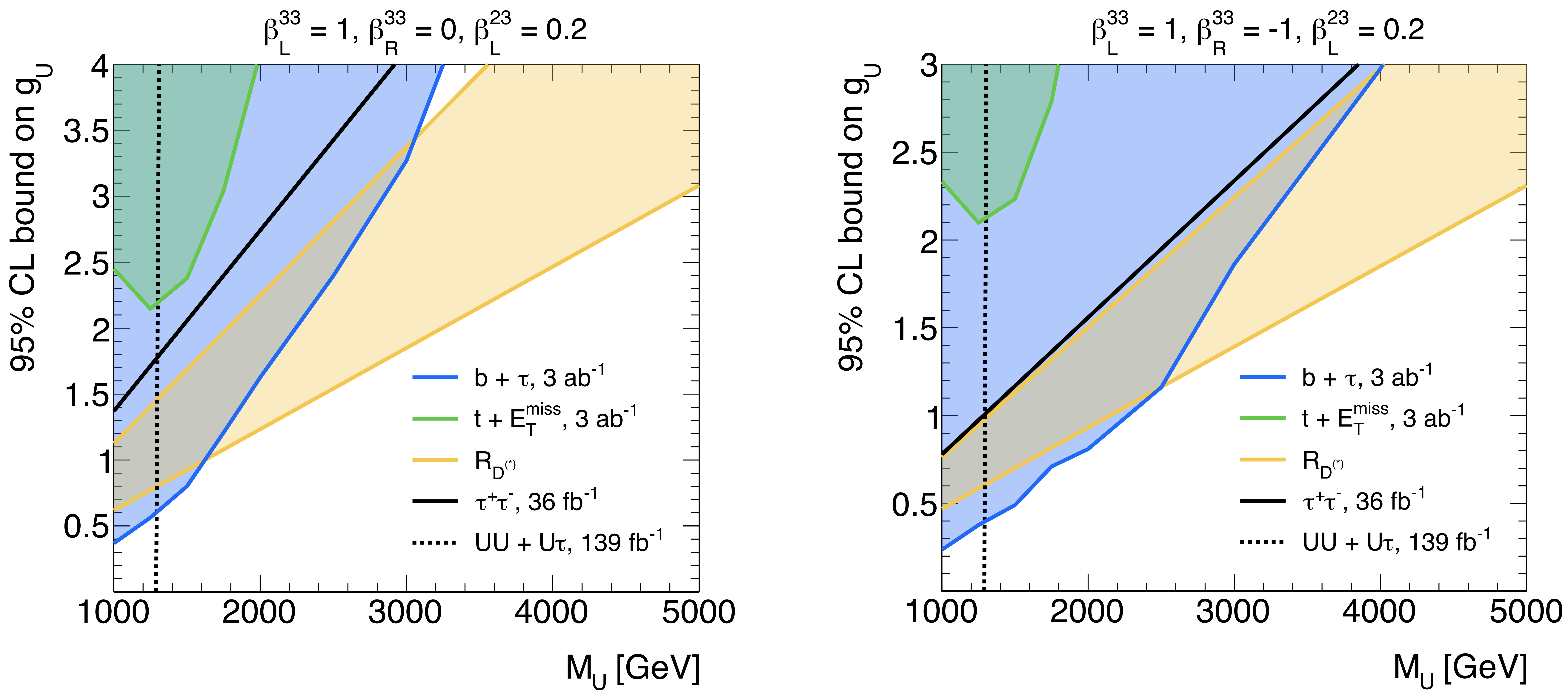
[UH & Polesello, 2012.11474]

Constraints from new LQ search strategies



[UH & Polesello, 2012.11474]

Constraints from new LQ search strategies



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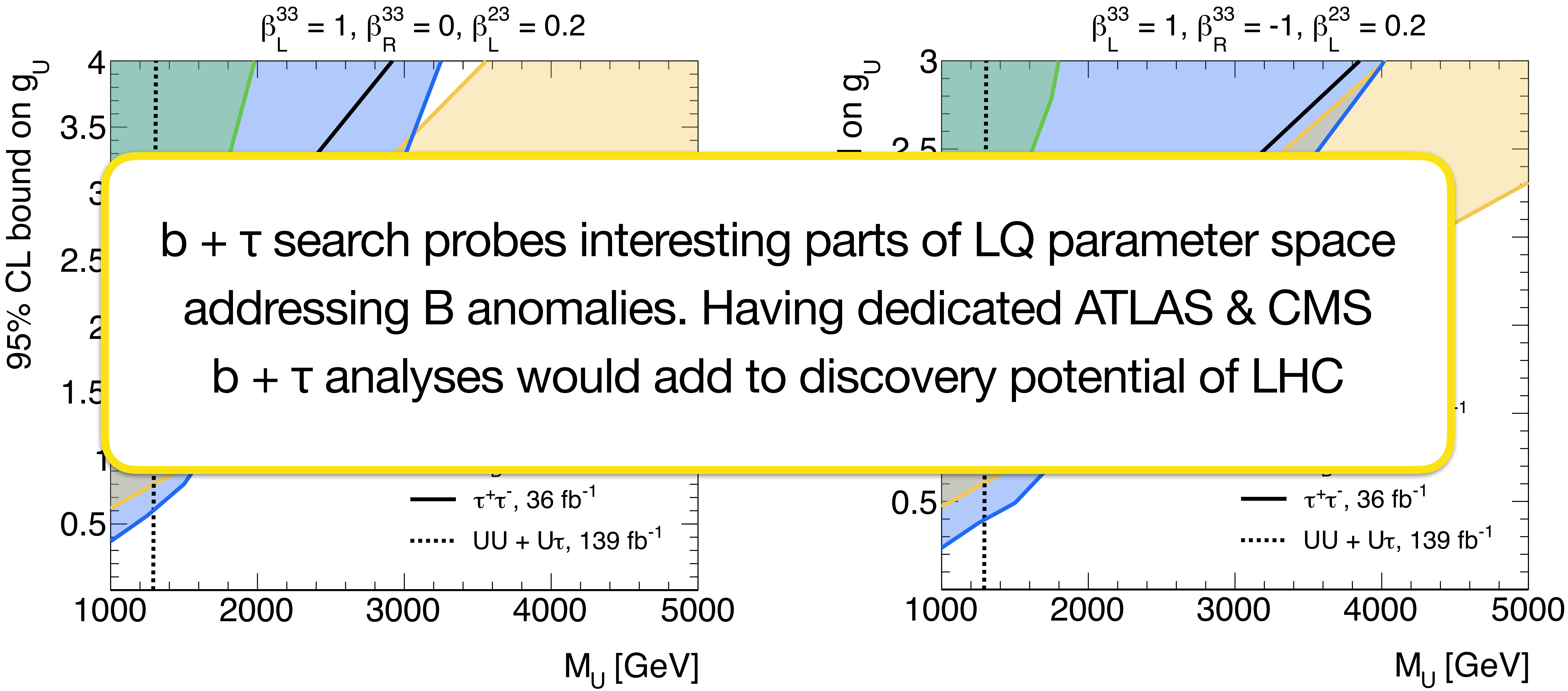
Constraints from new LQ search strategies



b + τ search probes interesting parts of LQ parameter space addressing B anomalies. Having dedicated ATLAS & CMS b + τ analyses would add to discovery potential of LHC

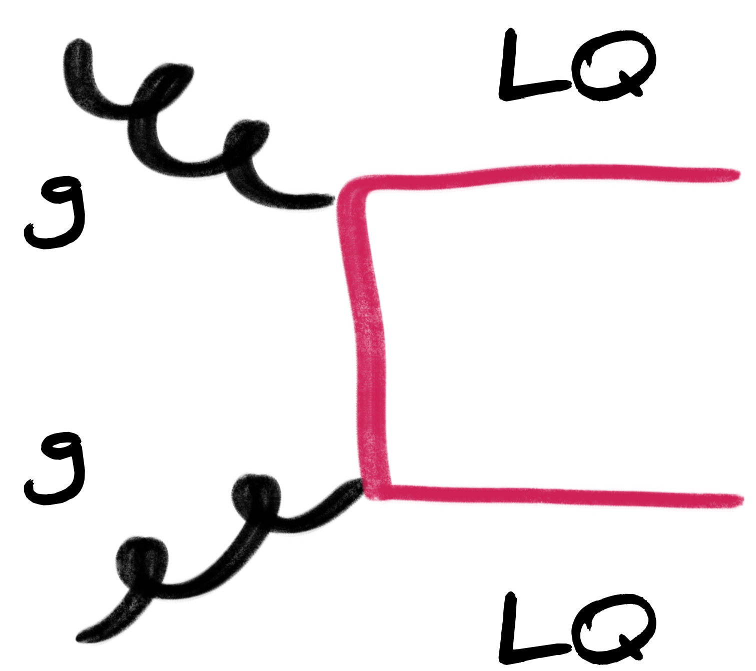
[UH & Polesello, 2012.11474]

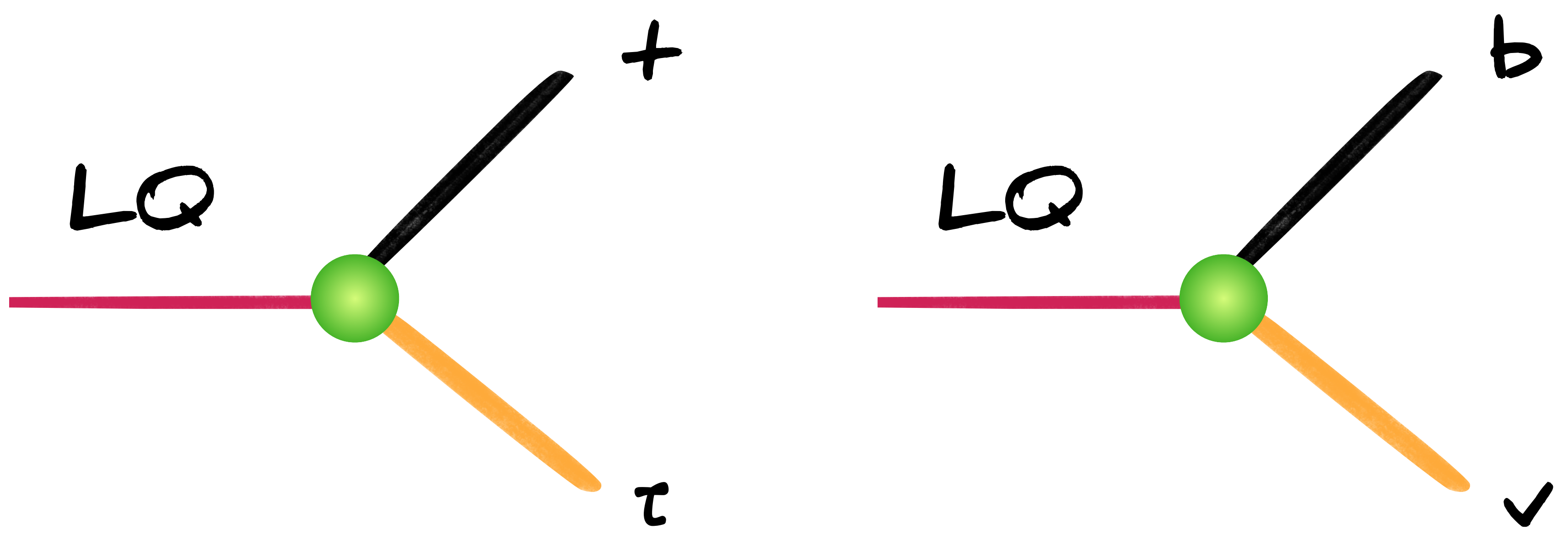
Summary

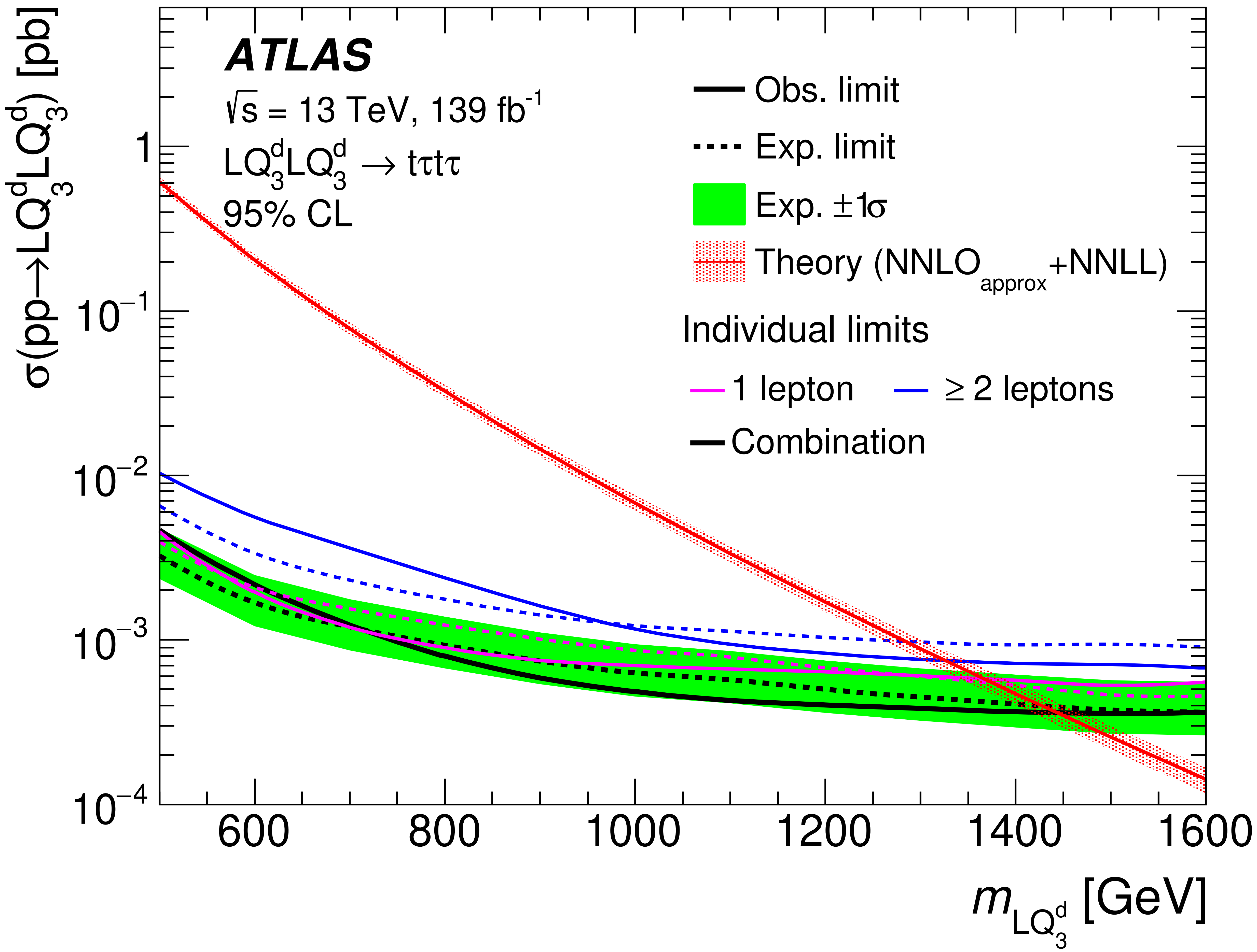
- Precision determination of lepton PDFs opens up new ways to test SM (e.g. $l^{\pm}l^{\pm}$ production) & to search for new physics @ the LHC
- Resonant LQ production allows to probe so far unexplored parameter space & has discovery potential
- Further theoretical developments needed to achieve next-to-leading order (NLO) plus parton shower (PS) accuracy for fiducial LQ cross sections

[very recent progress towards NLO PS by Richardson, unpublished; Greljo & Selimovic, JHEP 03 (2021) 279]

LQ searches triggered by B anomalies

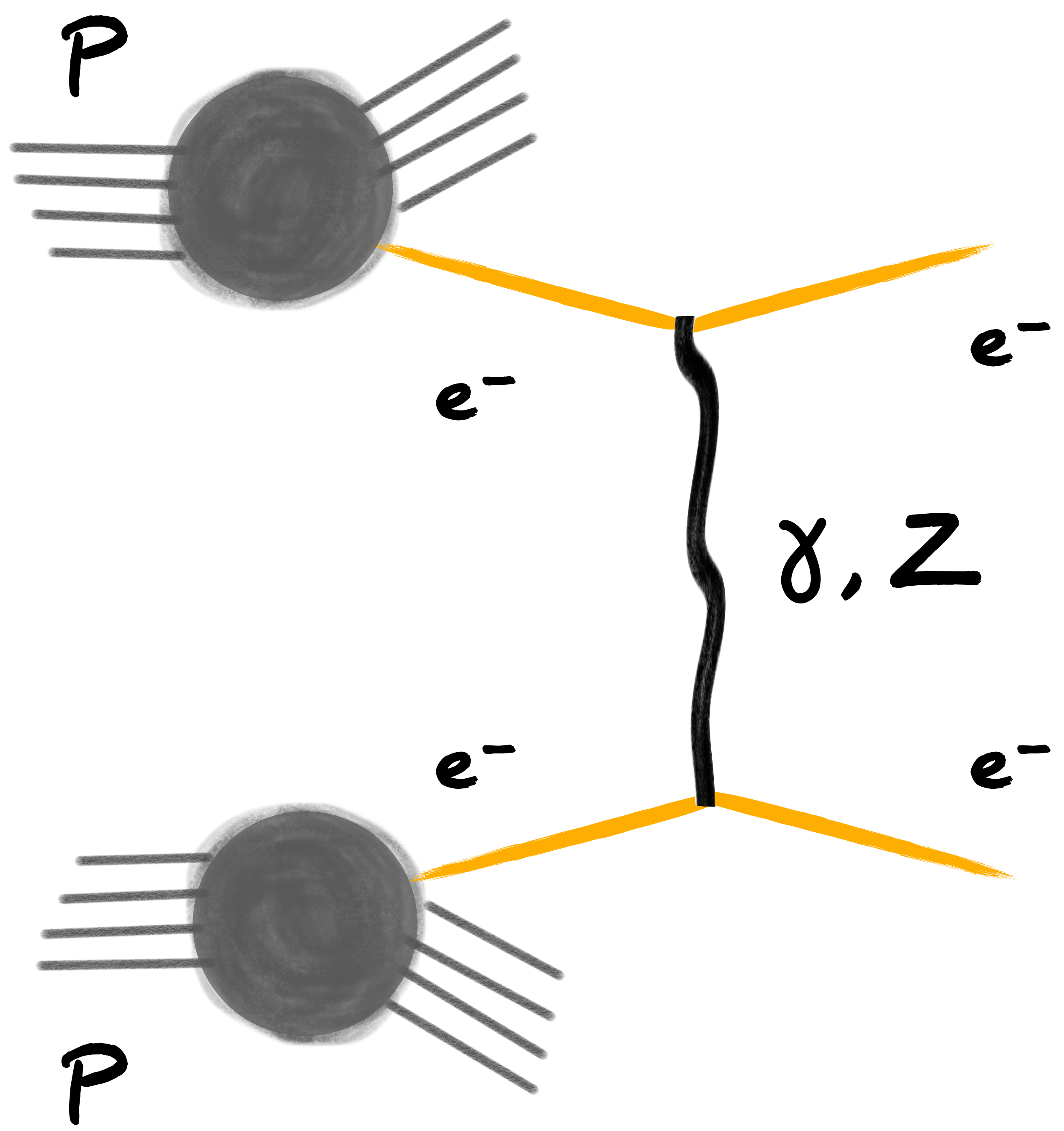






[Bauer & Neubert, PRL 116 (2016) 141802; ATLAS, arXiv:2101.11582]

Same sign lepton-pair production @ LHC



Signal events after cuts:

$N_{HL-LHC}(e^-e^-) \simeq 700$,

$N_{HL-LHC}(\mu^-\mu^-) \simeq 550$,

$N_{HL-LHC}(\tau^-\tau^-) \simeq 250$

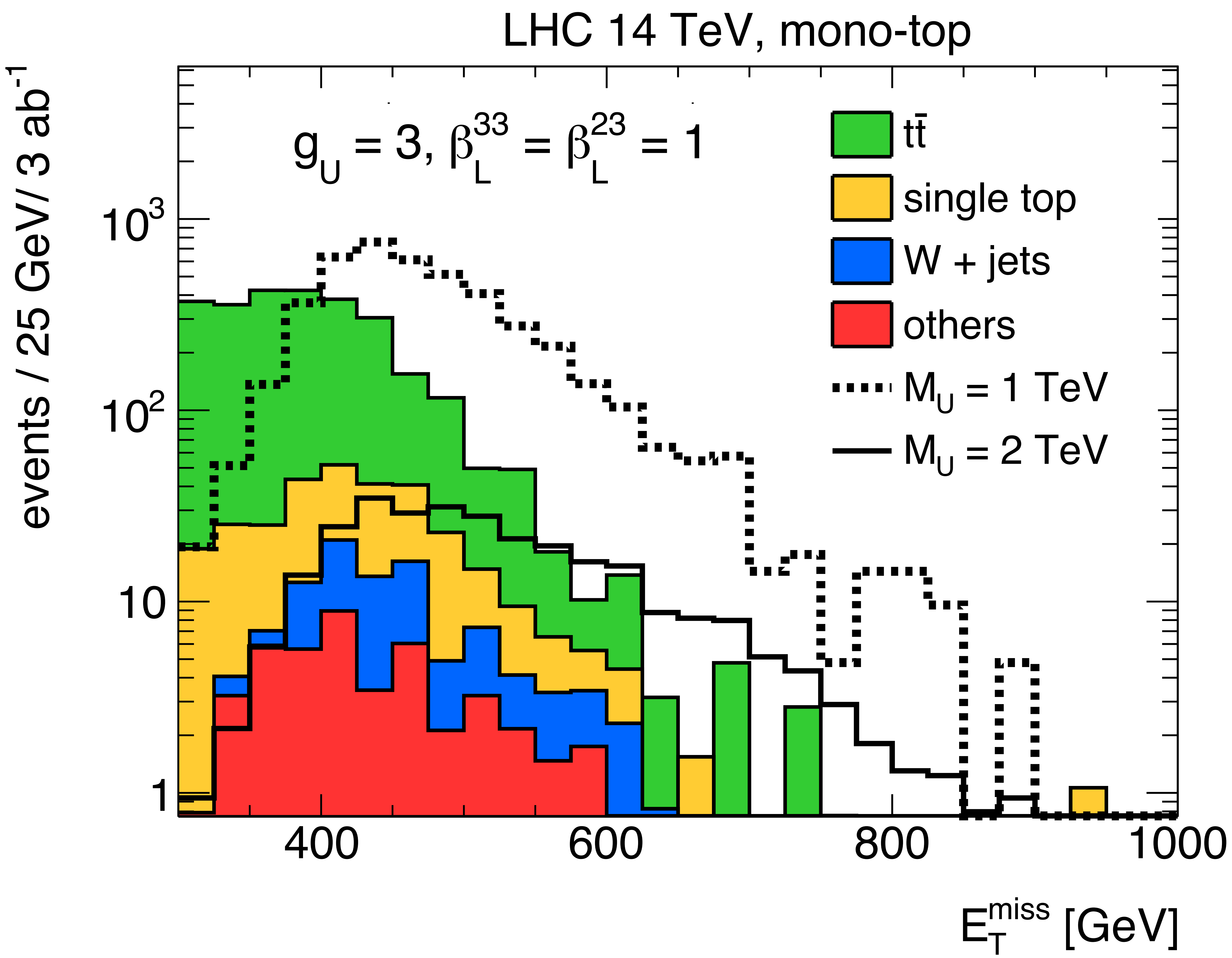
Dominant SM background from W^-W^- production after same cuts close to 0

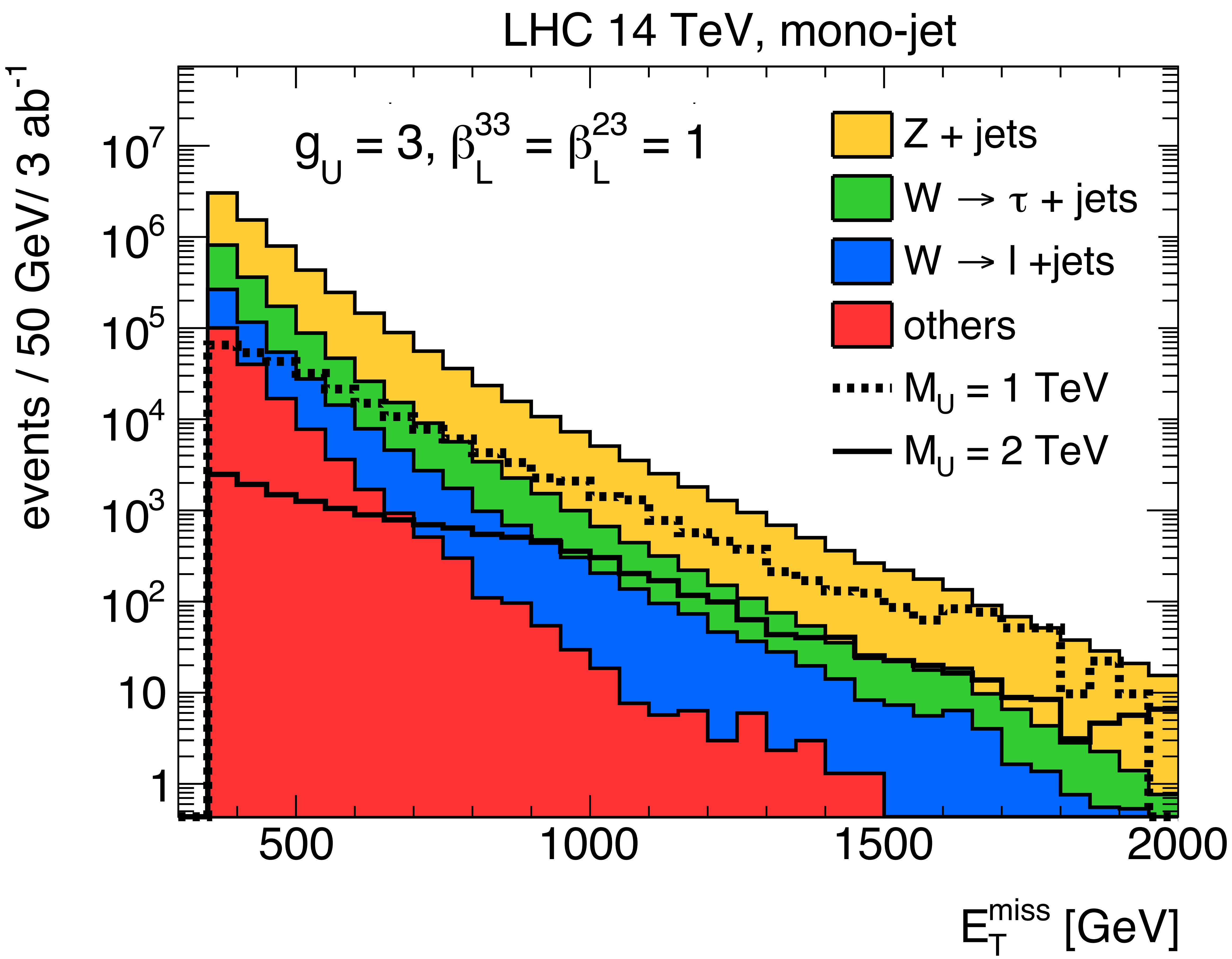
[Buonocore, Nason, Tramontano & Zanderighi, JHEP 08 (2020) 019; ATLAS analysis ongoing]

Simulation of 1st & 2nd resonant LQ signals

- Since PYTHIA currently cannot handle incoming leptonic partons, initial-state leptons have been replaced by photons to shower events. Our simulations do thus not include leptons but quarks from photon splitting in PS backward evolution
- As a result, jet- & lepton-veto induce a mismodelling of signal strength. By studying process $q\gamma \to LQ\, l \to q l^+ l^-$, we estimate this effect to be of O(10%) & therefore to only mildly affect derived LQ limits
- Above PS issue needs to be resolved before NLO QCD & QED corrections for LQ signal can be correctly included in differential fashion

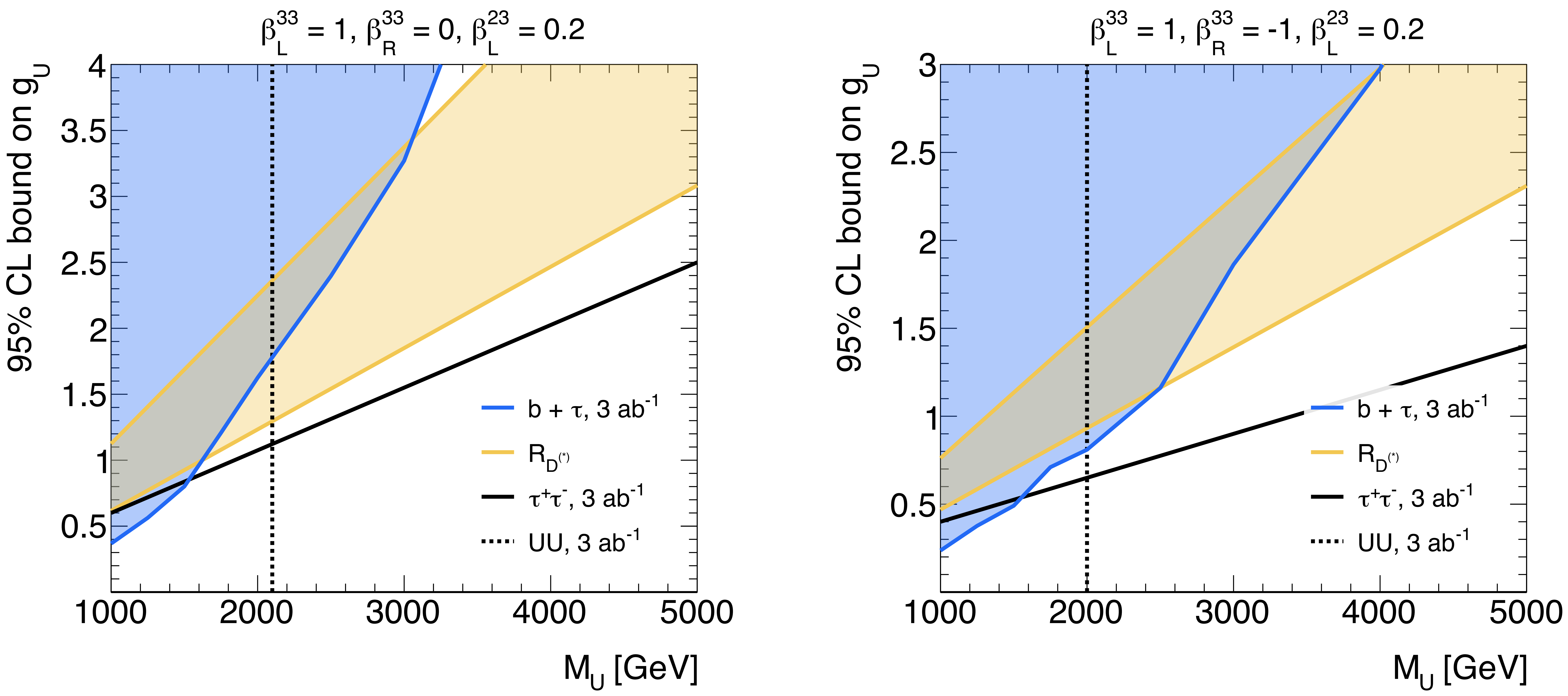
Mono-top & mono-jet distributions





[UH & Polesello, 2012.11474]

Prospects of LQ search strategies



[UH & Polesello, 2012.11474; Cornella et al., 2103.16558]