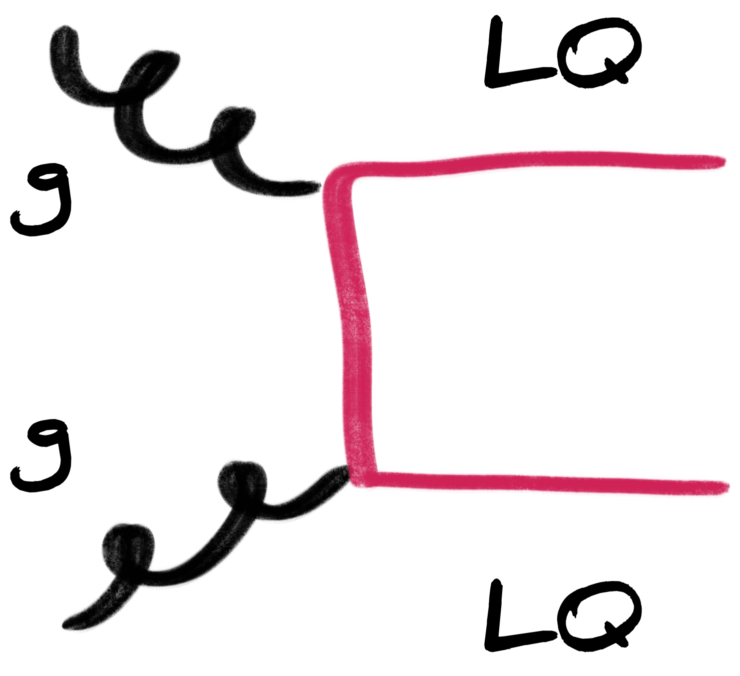
Resonant leptoquark production at hadron colliders

SM/BSM seminar, CERN, 12. June 2020

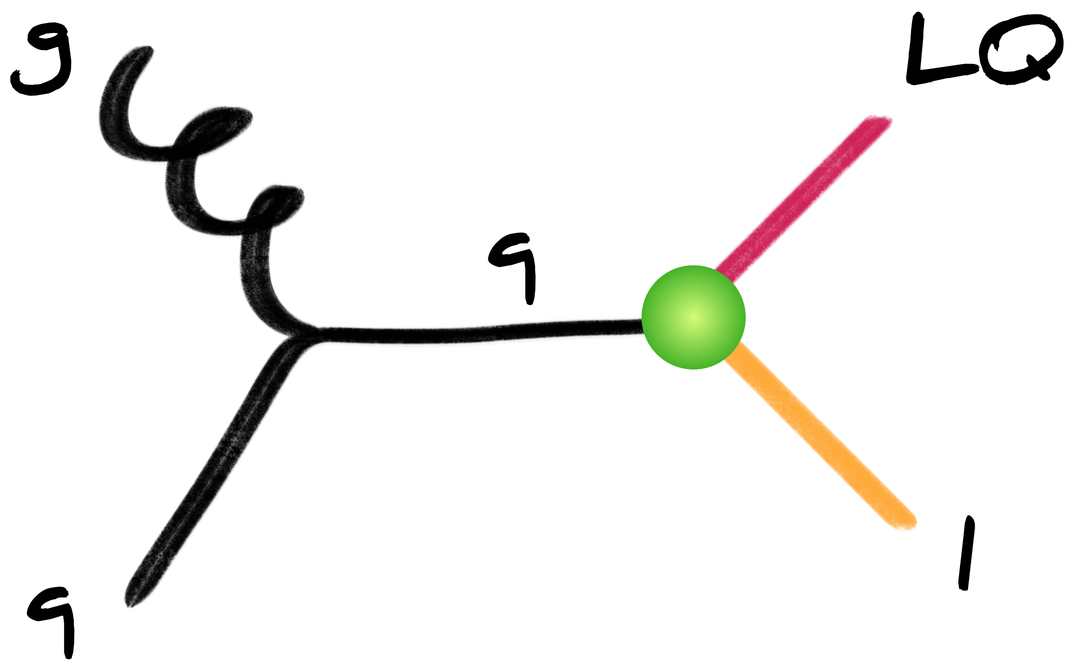
Luca Buonocore, Ulrich Haisch, Paolo Nason, Francesco Tramontano & Giulia Zanderighi, 2005.06475

Leptoquarks (LQs) in a nutshell

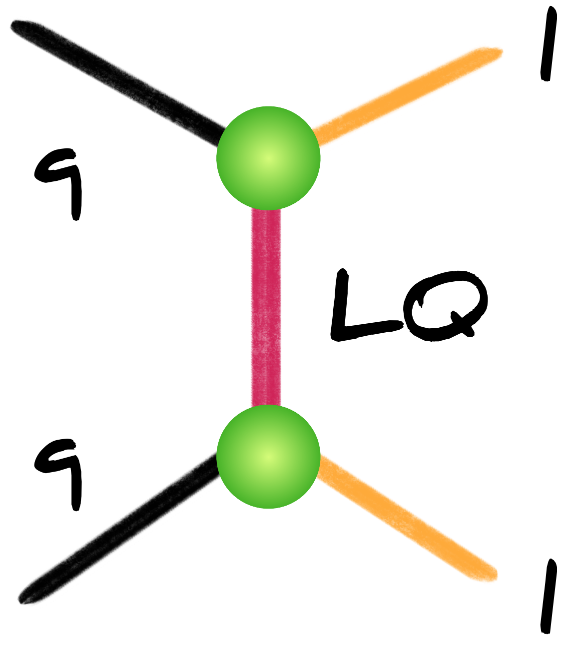
$$\mathcal{L} \supset |D_\mu \mathrm{LQ}|^2 + \lambda_{ql}\, \mathrm{LQ}\,(ql)$$



pair production (PP)



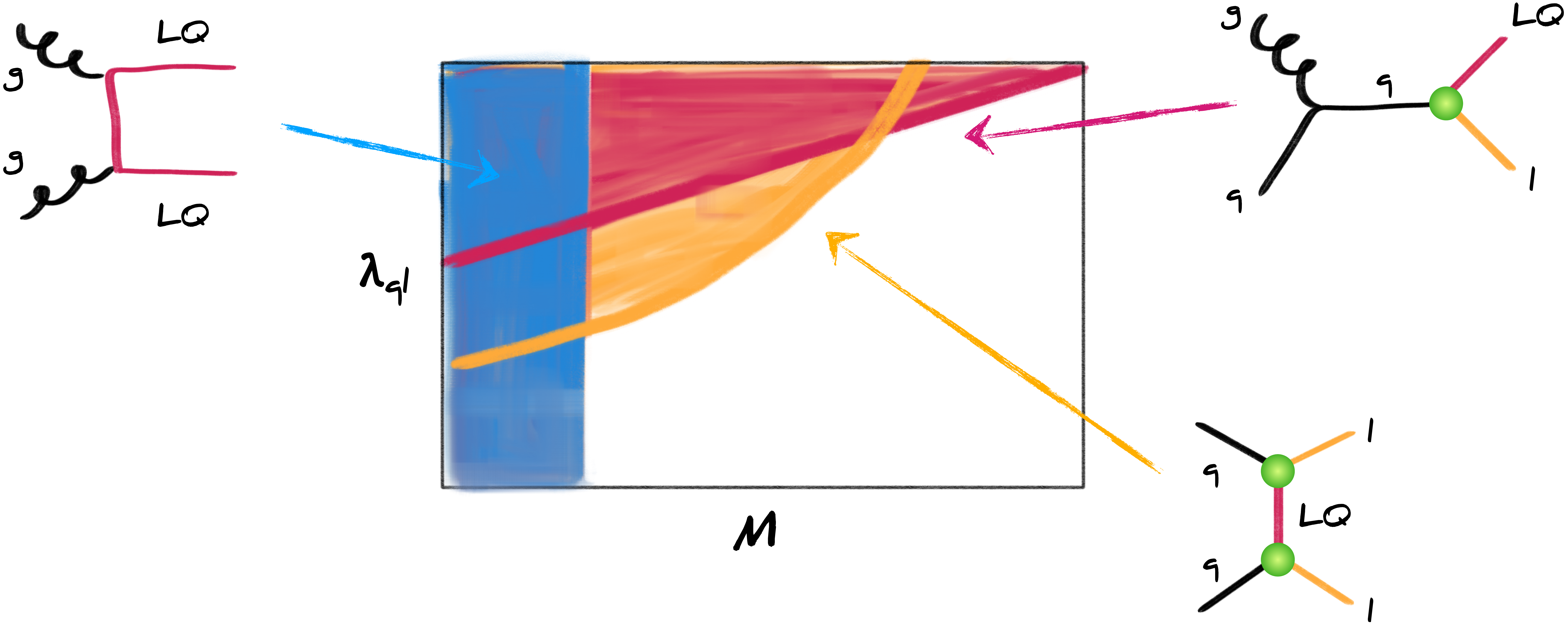
single production (SP)



Drell-Yan (DY) t-channel

for a recent LQ review see Dorsner et al., 1603.04993

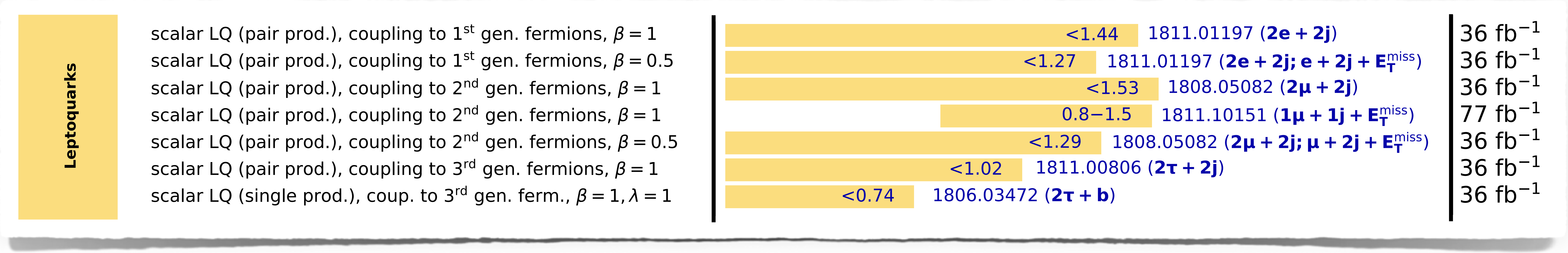
Complementarity of LQ searches



sketch adopted from Dorsner & Greljo, 1801.07641

May 2020 summary of LHC limits

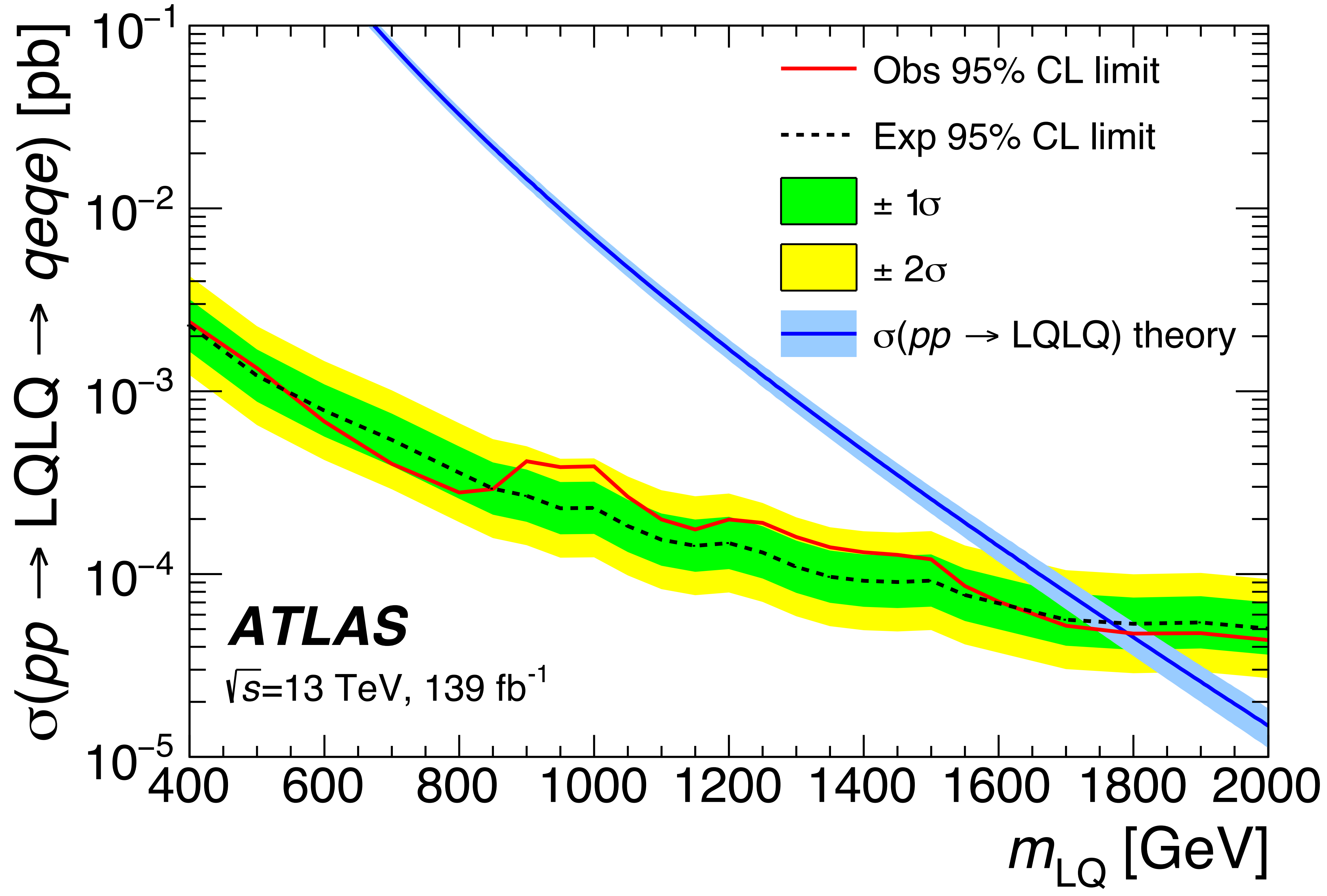
ATLAS Exotics Searches

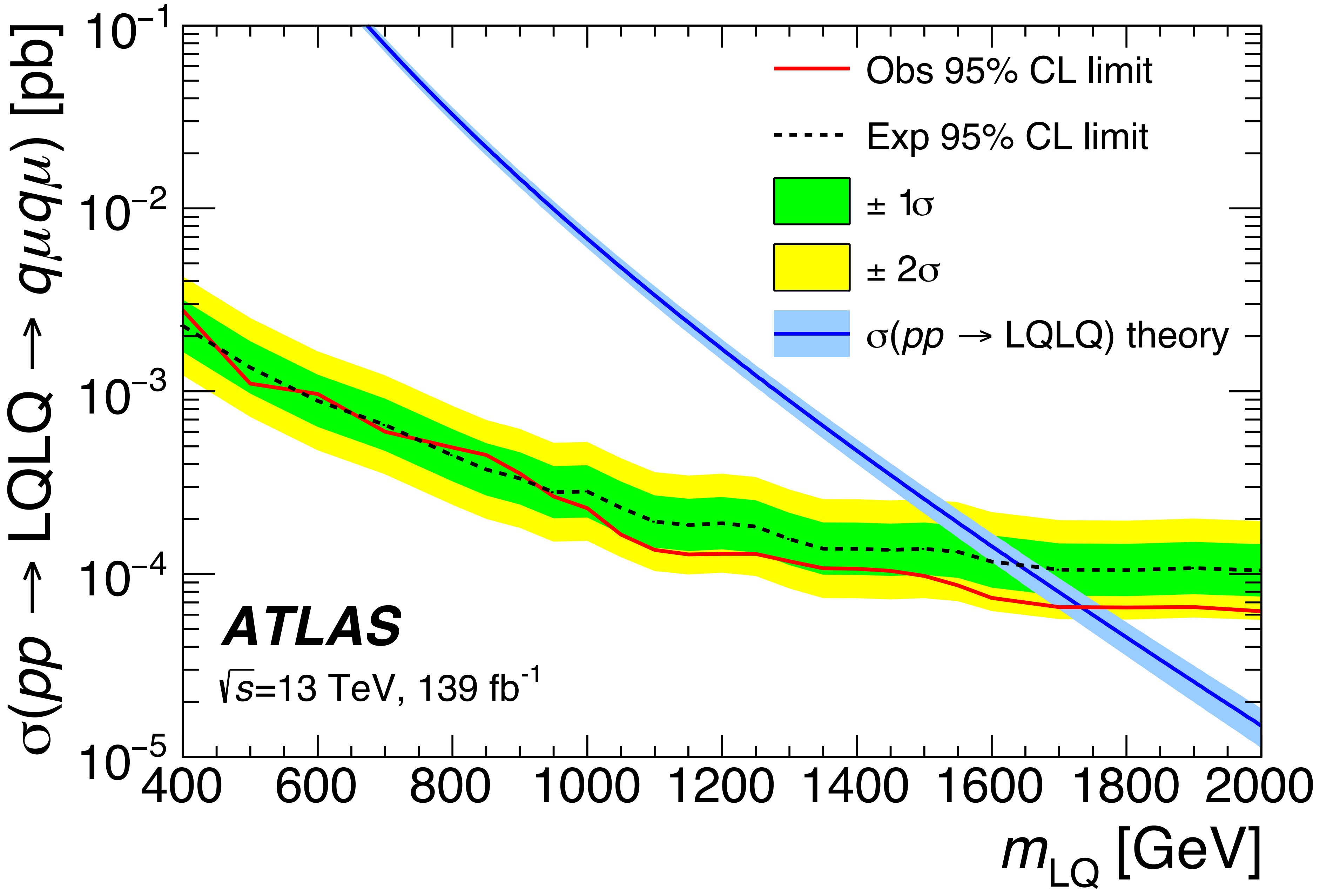


CMS EXO results

Most existing searches have targeted LQ PP. Scalar LQ masses below around 1.5 TeV (1.0 TeV) are excluded for 1st & 2nd (3rd) generation LQs

First full LHC Run II results of ATLAS



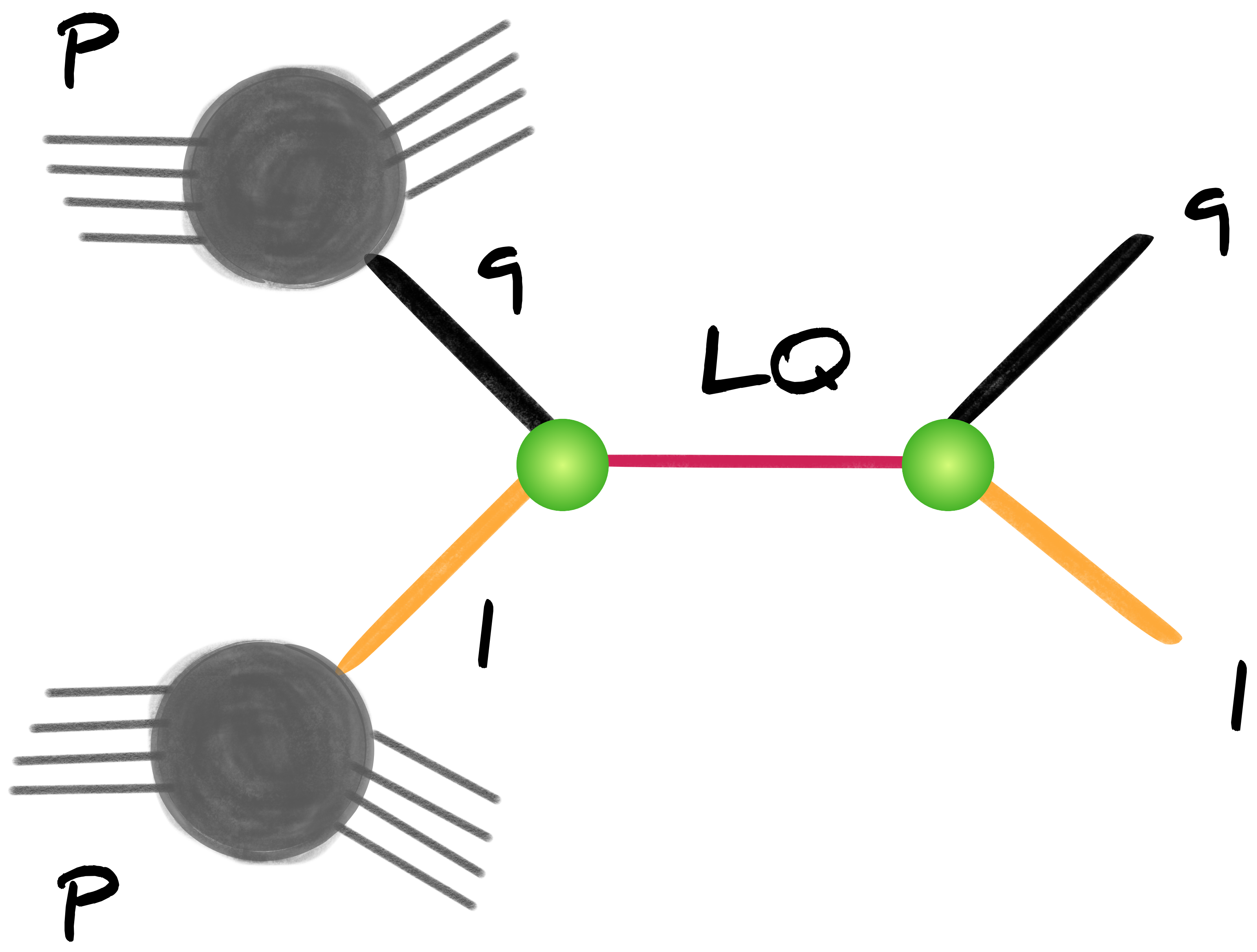


LQs masses below 1.8 TeV (1.7 TeV) are excluded in the electron (muon) channel, assuming a branching ratio into a charged lepton & a quark of 100%

ATLAS, 2006.05872

Main idea of 2005.06475

But as Luca explained before, "a proton is a quark is a photon is a lepton", so LQs can also be produced resonantly in proton-proton collisions. Are the corresponding rates large enough to be measurable at the LHC?



see also Ohnemus et al., hep-ph/9406235

Analysis strategy

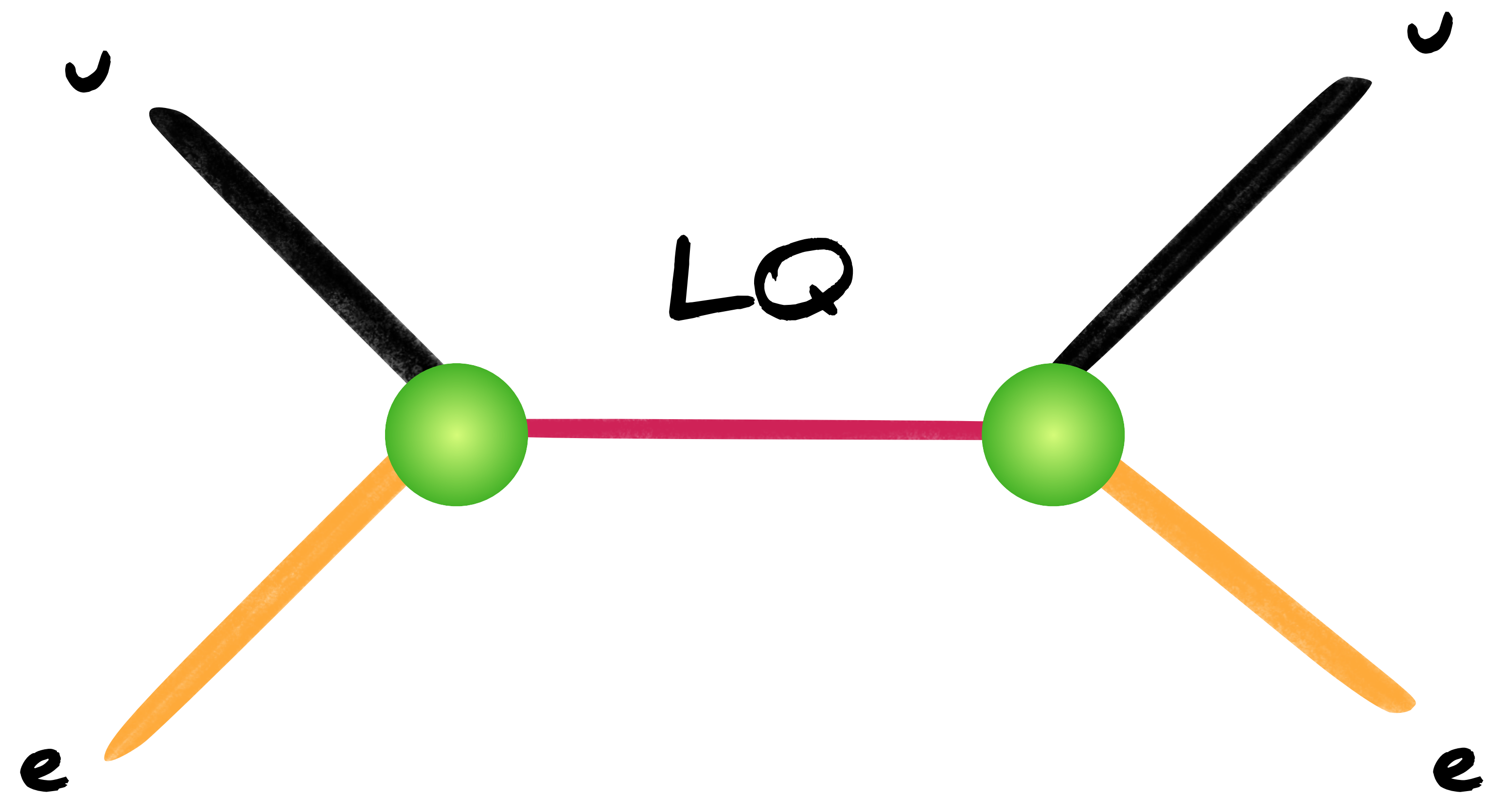
- Target final states with a high transverse momentum (p_T) lepton & a high-p_T jet:

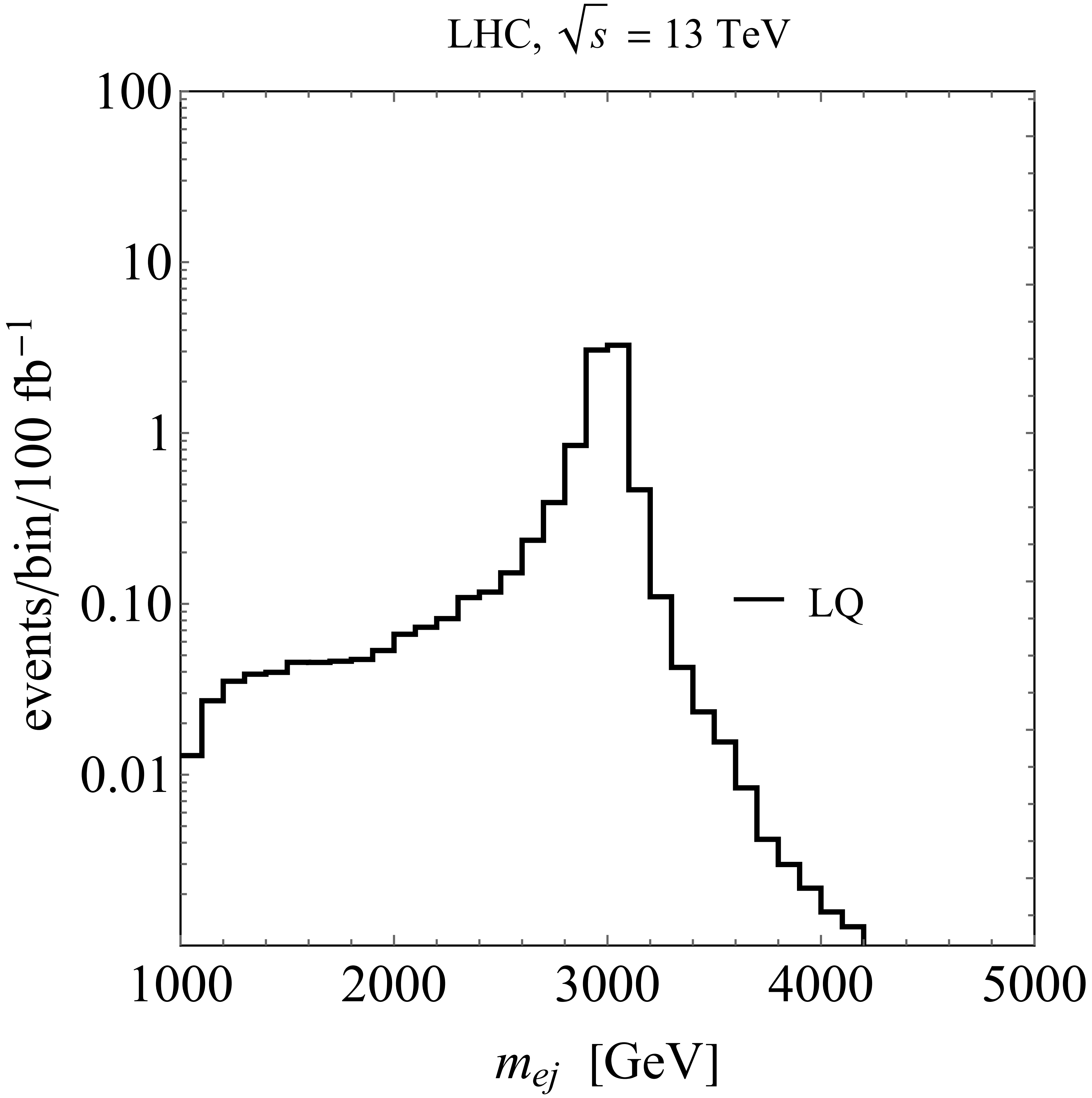
$$|\eta_{l_1}| < 2.5\,, \quad p_{T,l_1} > 500\,\mathrm{GeV}\,, \quad |\eta_{j_1}| < 2.5\,, \quad p_{T,j_1} > 500\,\mathrm{GeV}$$

- To suppress backgrounds, cut on missing energy ($E_{T,\mathrm{miss}}$), veto extra leptons & jets:

$$E_{T,\mathrm{miss}} < 50\,\mathrm{GeV}\,, \quad |\eta_{l_2}| < 2.5\,, \quad p_{T,l_2} > 7\,\mathrm{GeV}\,, \quad |\eta_{j_2}| < 2.5\,, \quad p_{T,j_2} > 30\,\mathrm{GeV}$$

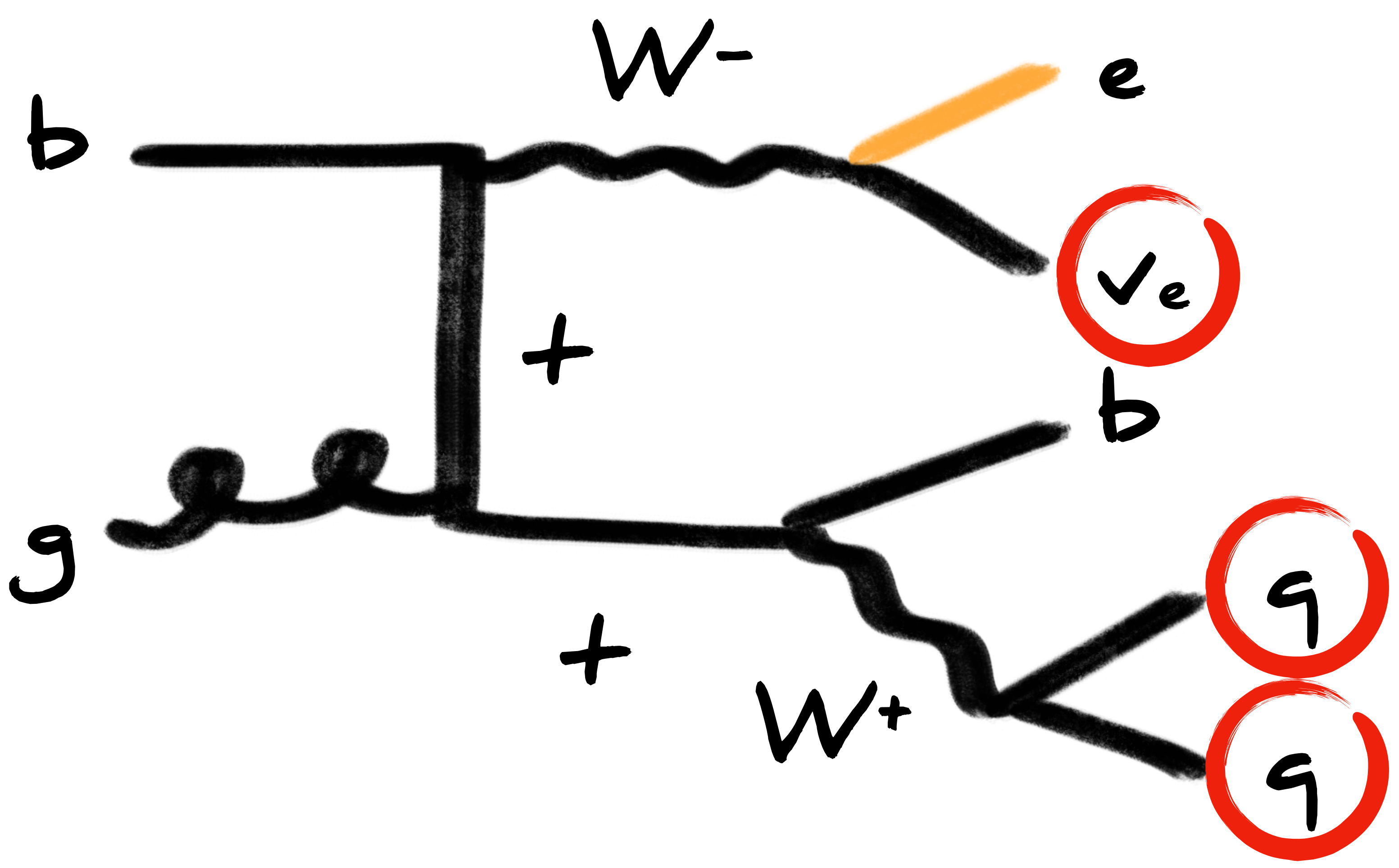
Benchmark signal

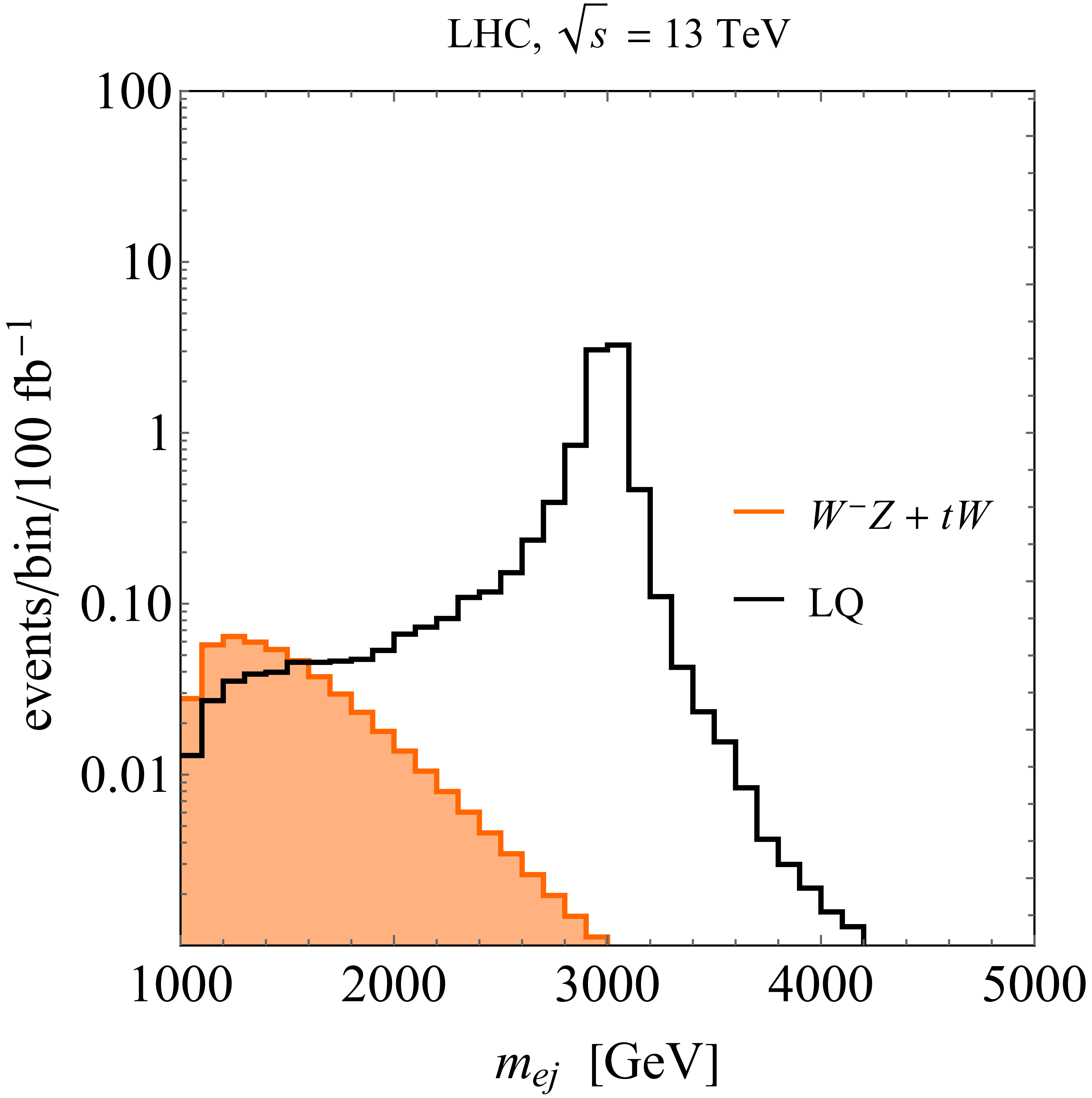




At 13 TeV LHC, 9 events per 100 fb^{-1} for minimal scalar LQ of $M = 3$ TeV & $g_{eu} = 1$

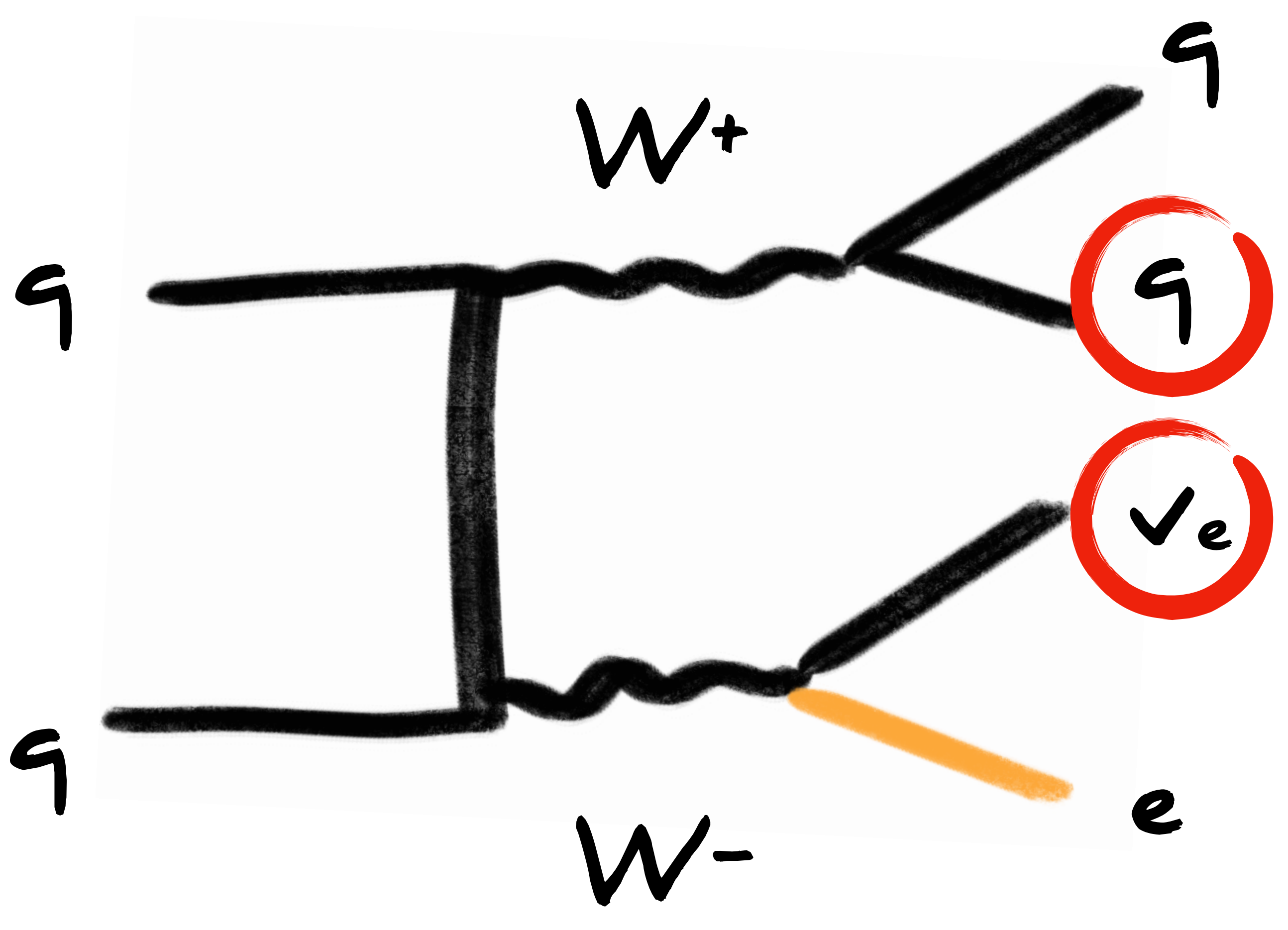
Backgrounds

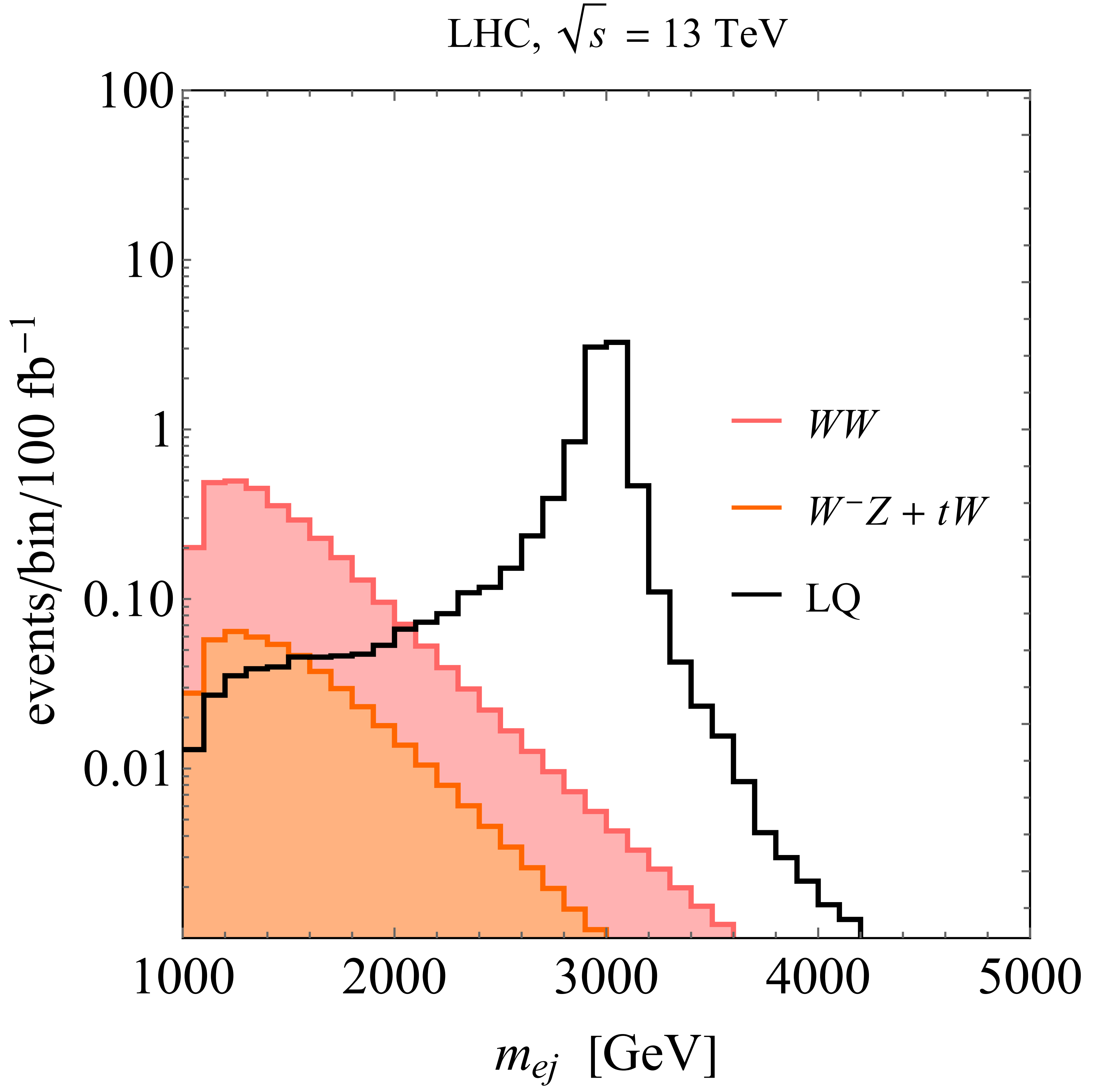




Suppressed by $E_{T,miss}$ requirement & jet veto

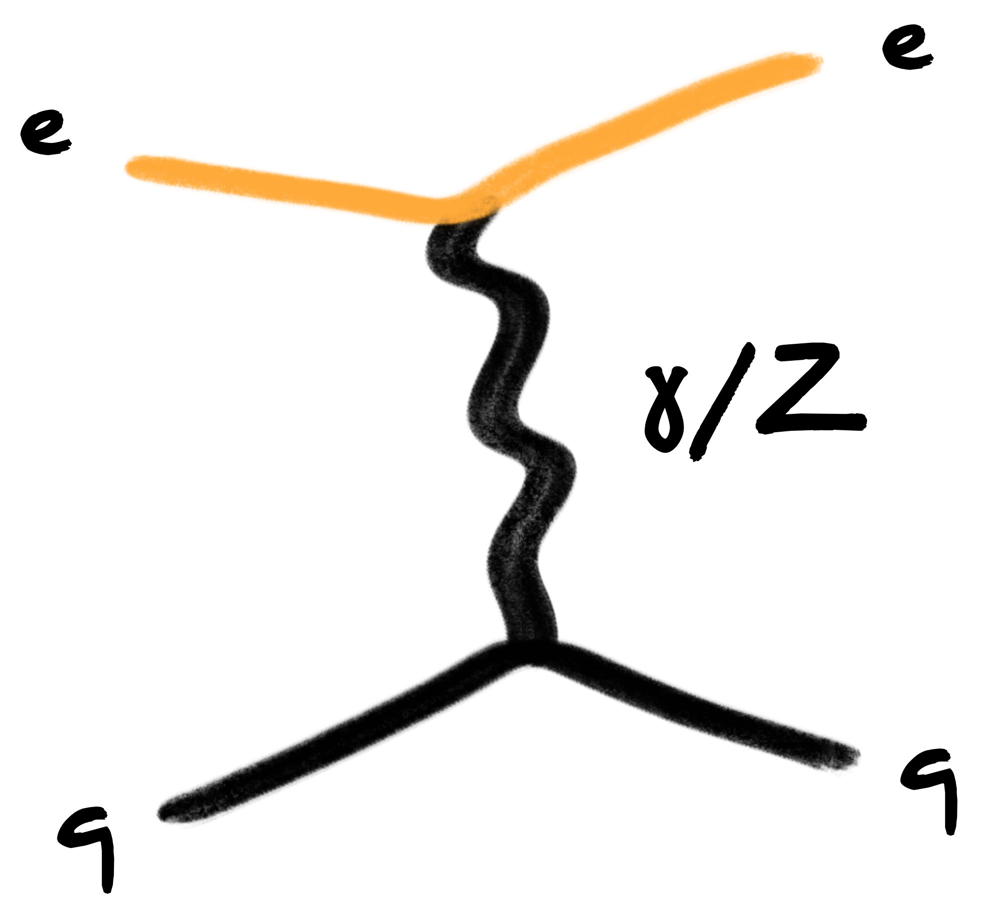
Backgrounds

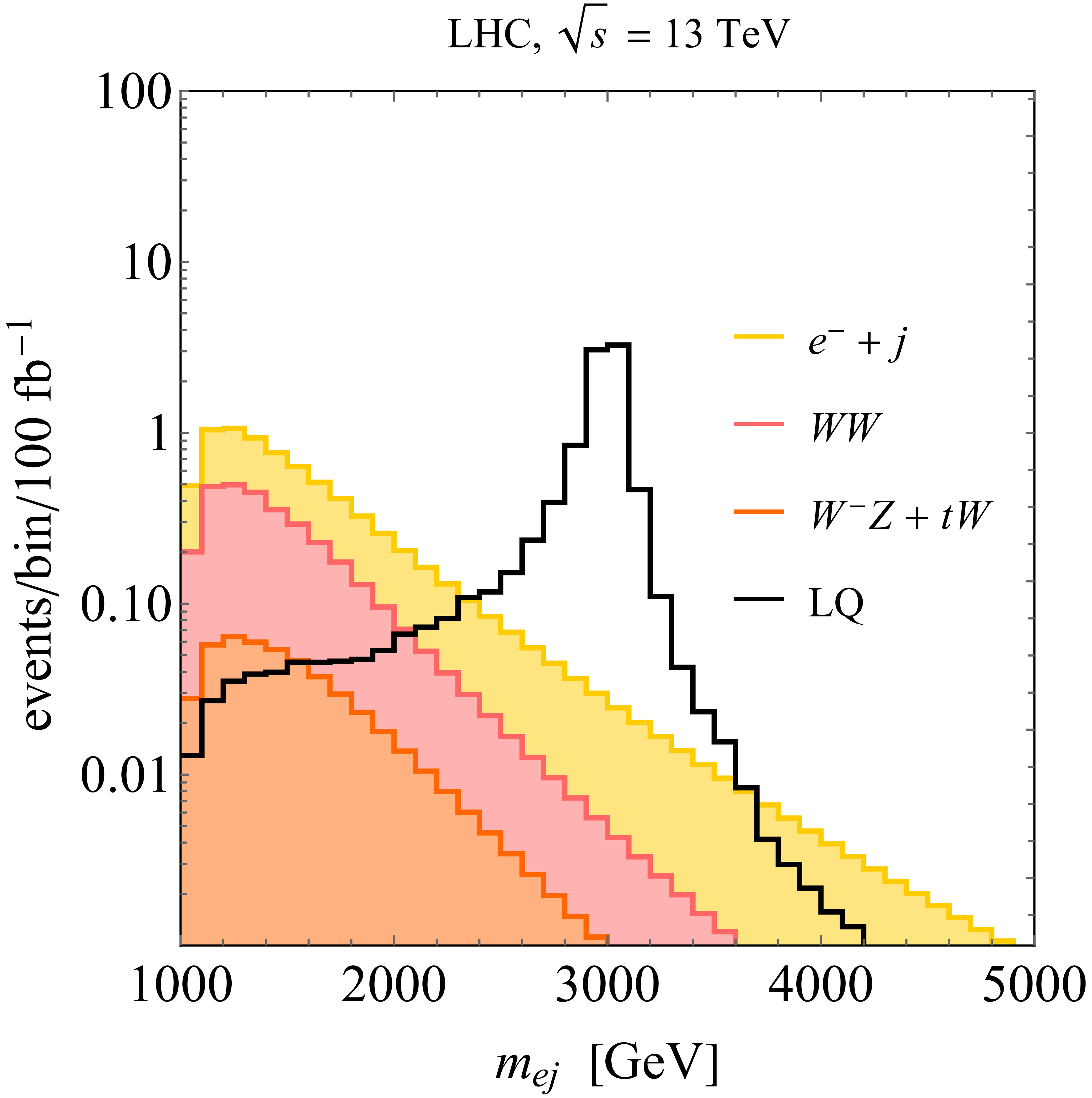




Suppressed by $E_{T,miss}$ requirement & jet veto

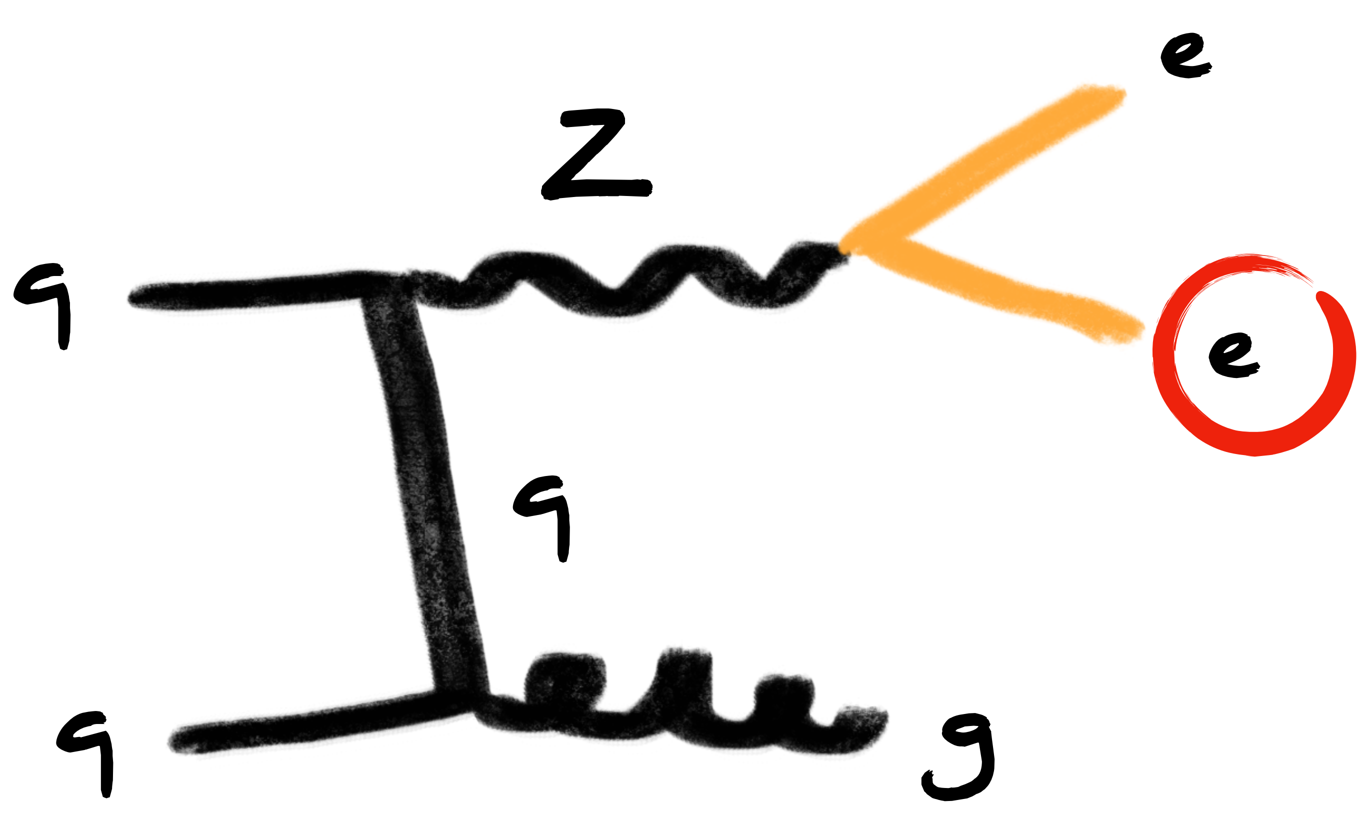
Backgrounds

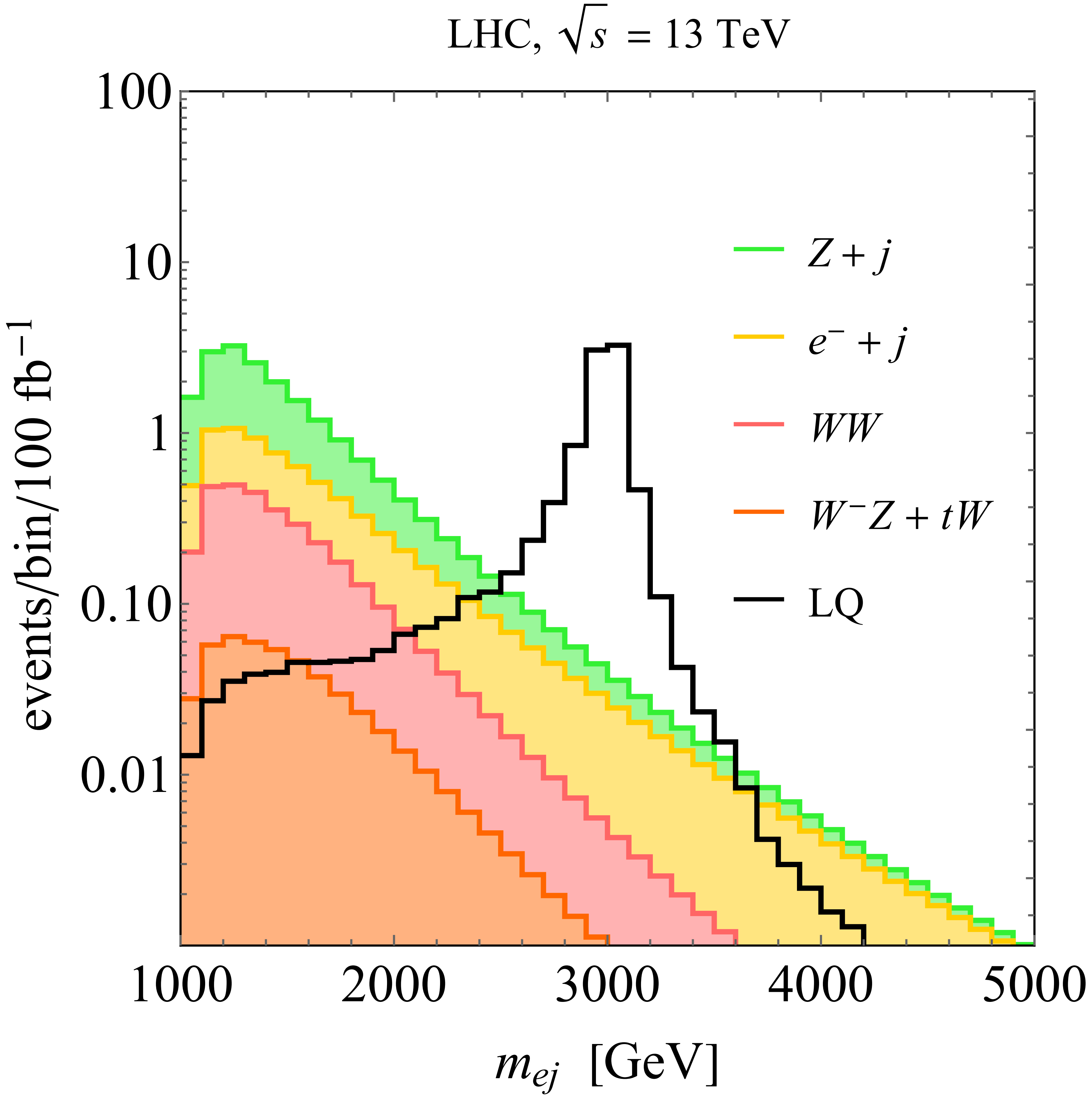




Irreducible background particularly relevant at high invariant lepton-jet mass

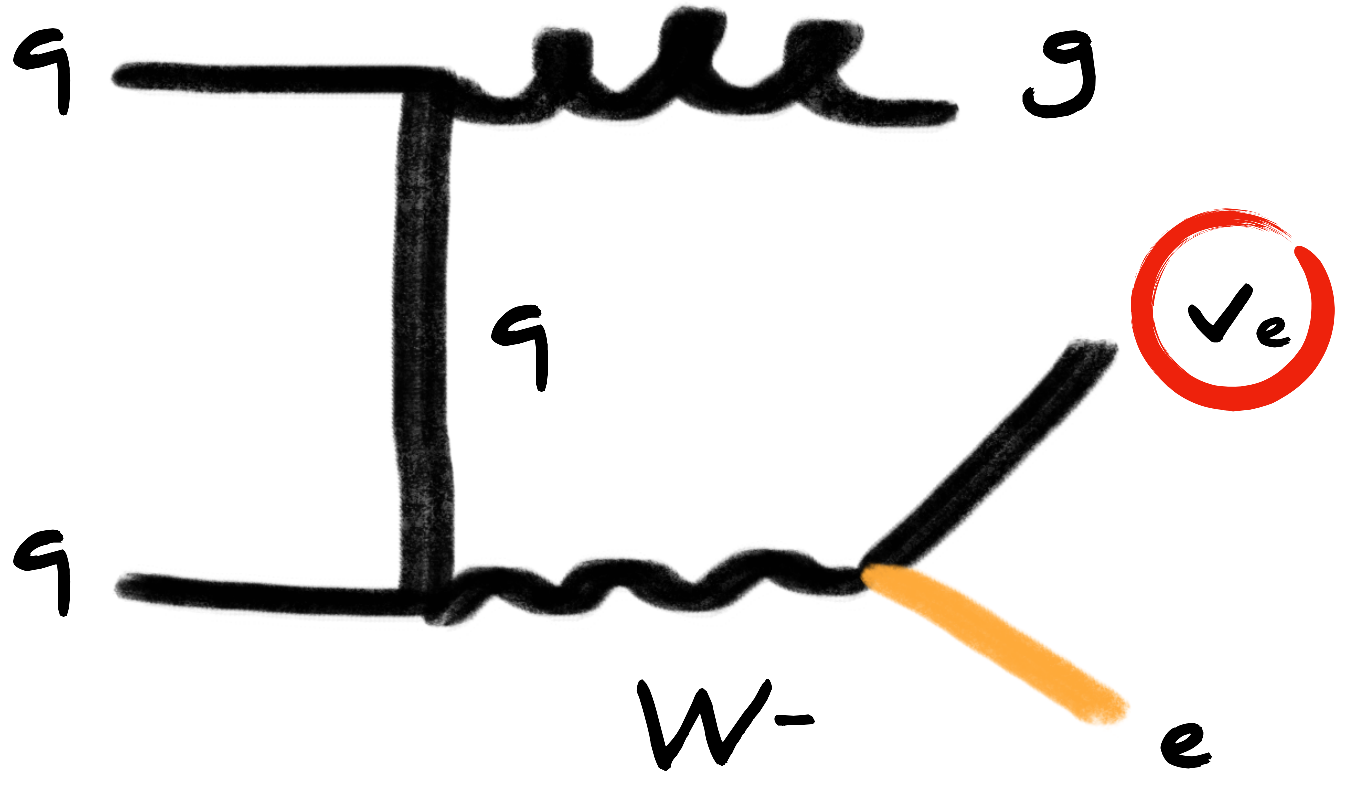
Backgrounds

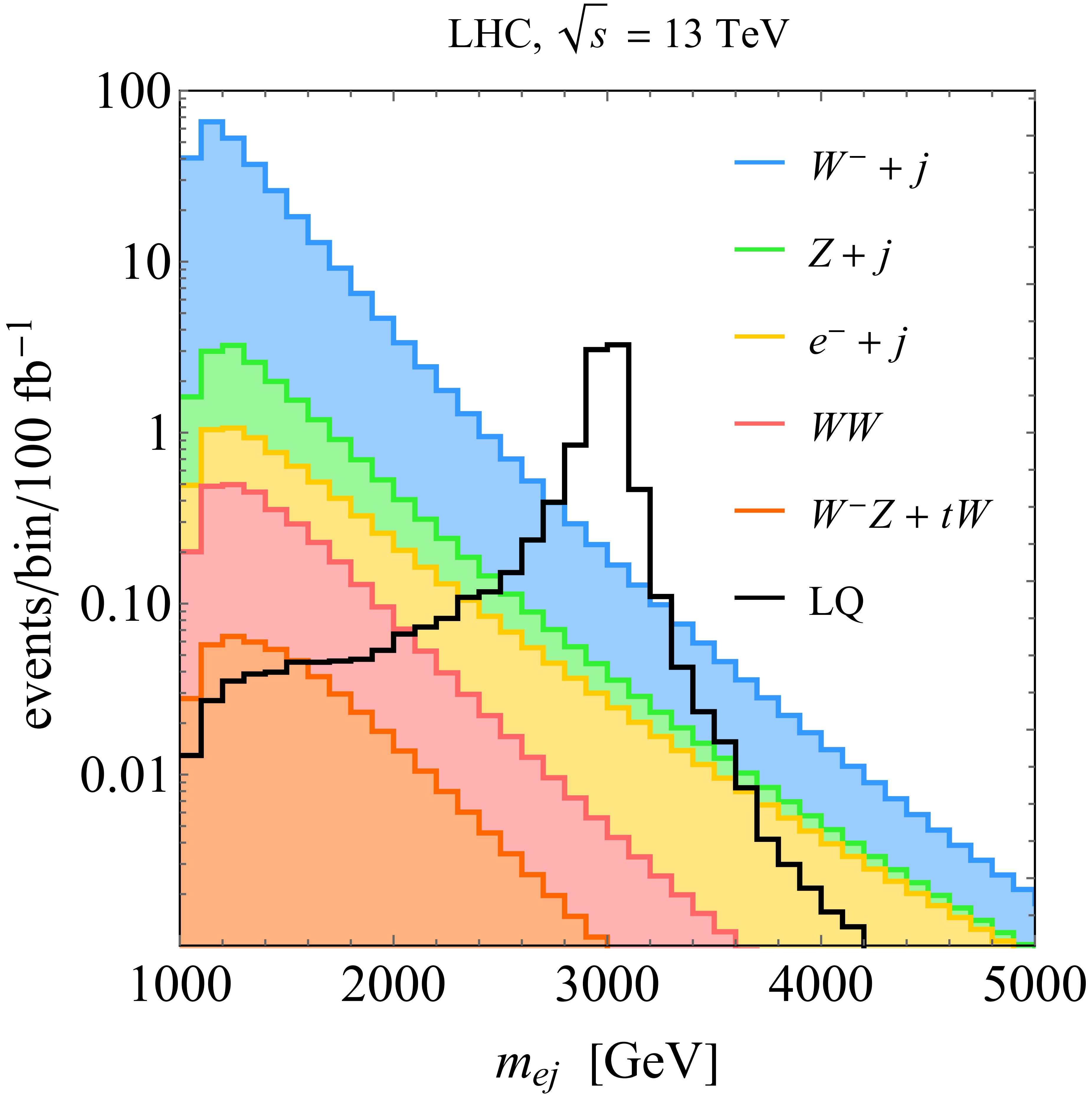




Suppressed by lepton veto

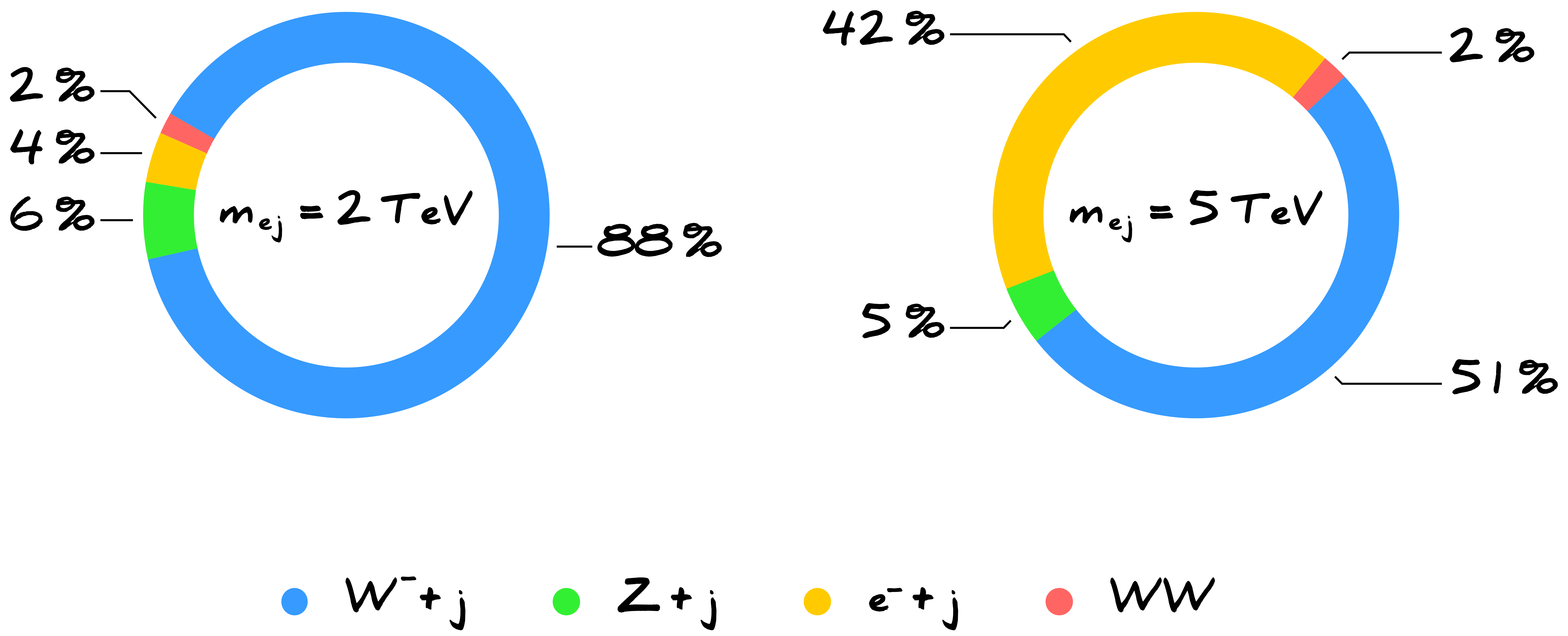
Backgrounds



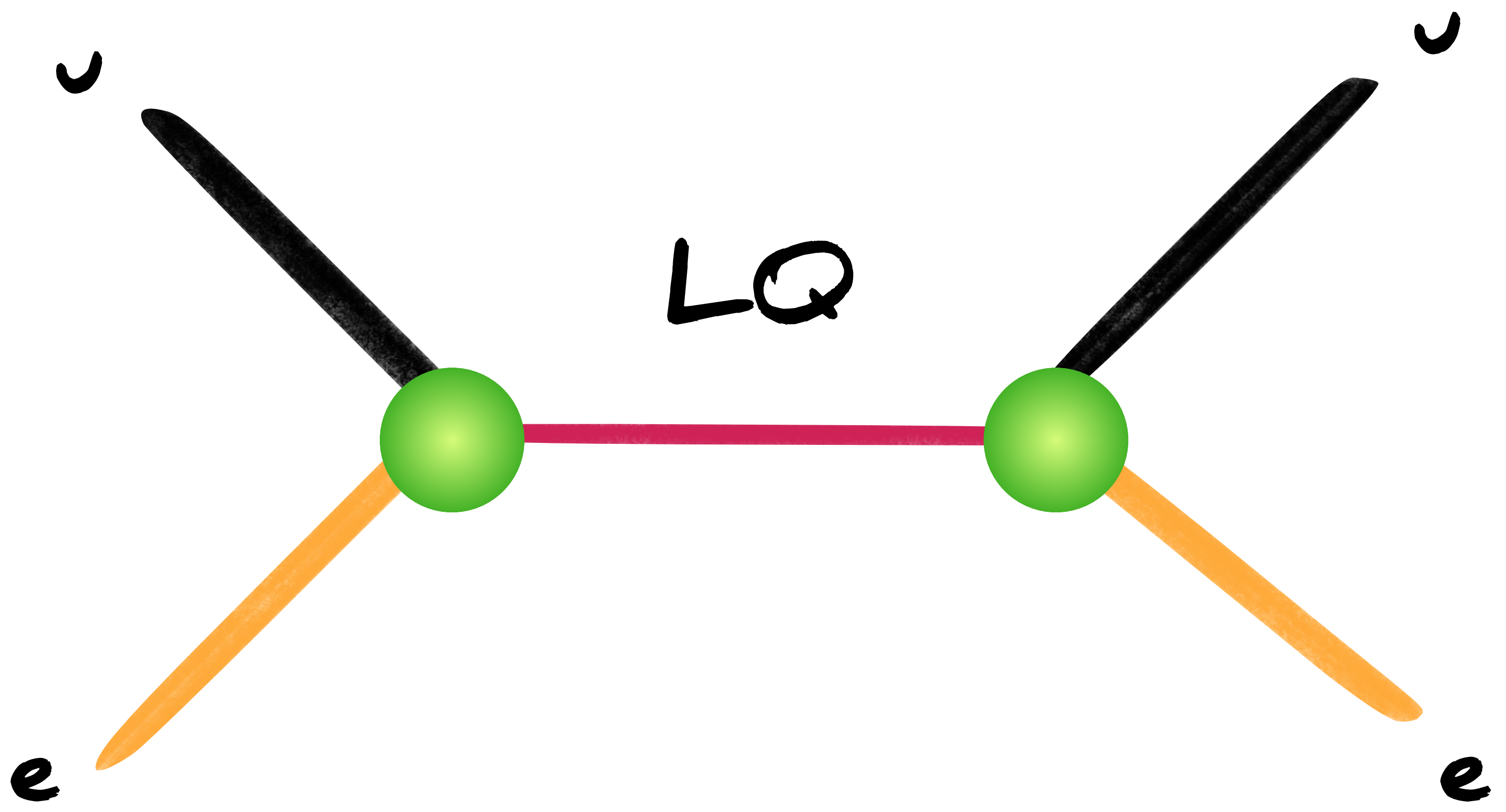


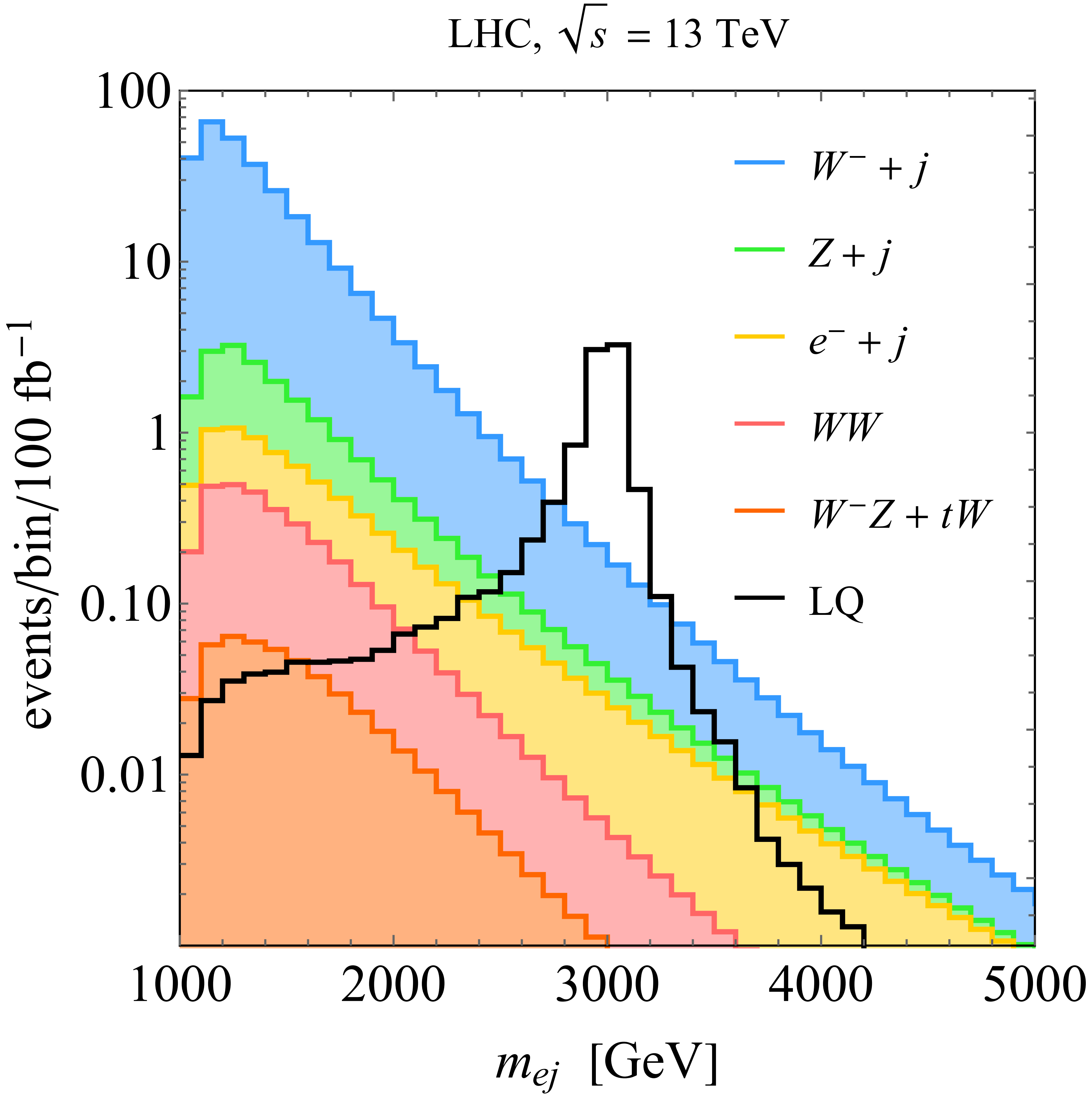
Suppressed by $E_{T,miss}$ requirement

Background decomposition



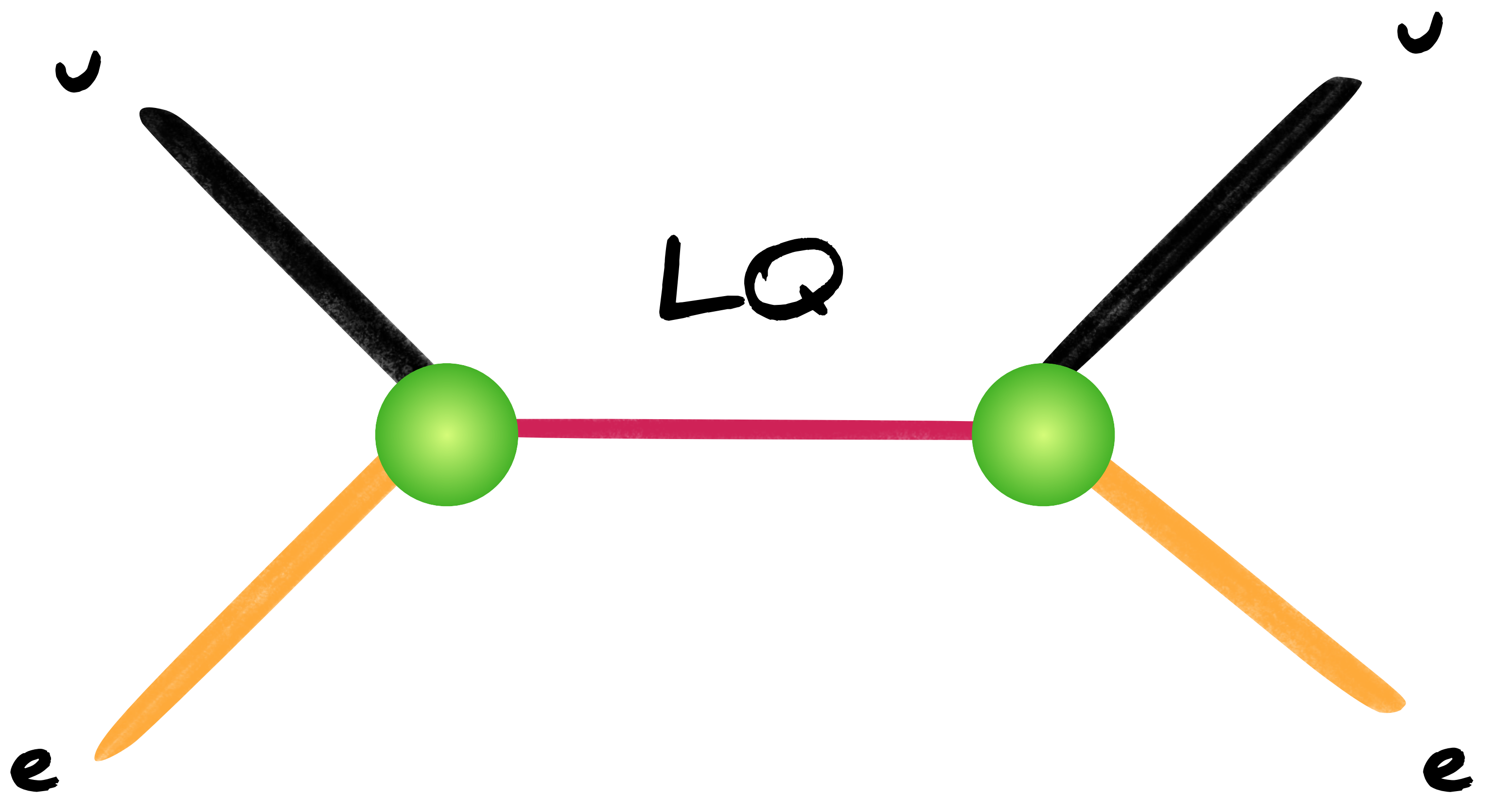
Signal vs. backgrounds

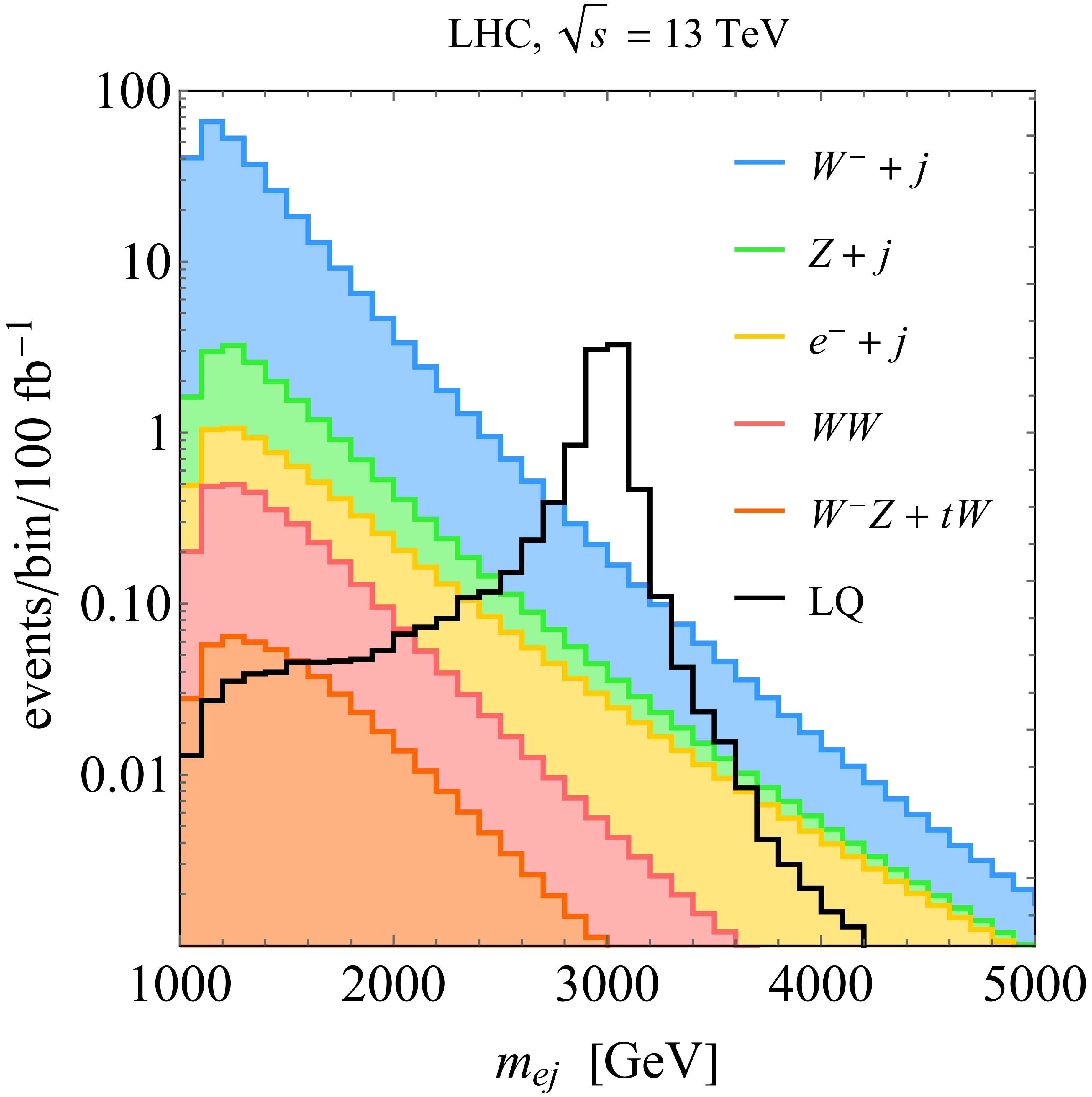




Sum over backgrounds is a steeply falling distribution, while signal exhibits a narrow peak

Signal vs. backgrounds





For 36 fb^{-1} of 13 TeV LHC data, benchmark disfavoured with a significance of 2σ

Comments on simulation of signal

- Since PYTHIA currently[†] cannot handle incoming leptonic partons, initial-state leptons have been replaced by photons to shower events. Our simulation does thus not include leptons but quarks from photon splitting in the parton (PS) shower backward evolution

- In consequence, the jet- & lepton-veto induce a mismodelling of the signal strength. By studying the process $q\gamma \to LQ\, l \to q\, l\, l$, we estimate this effect to be of $O(10\%)$ & therefore to only mildly affect the derived LQ limits

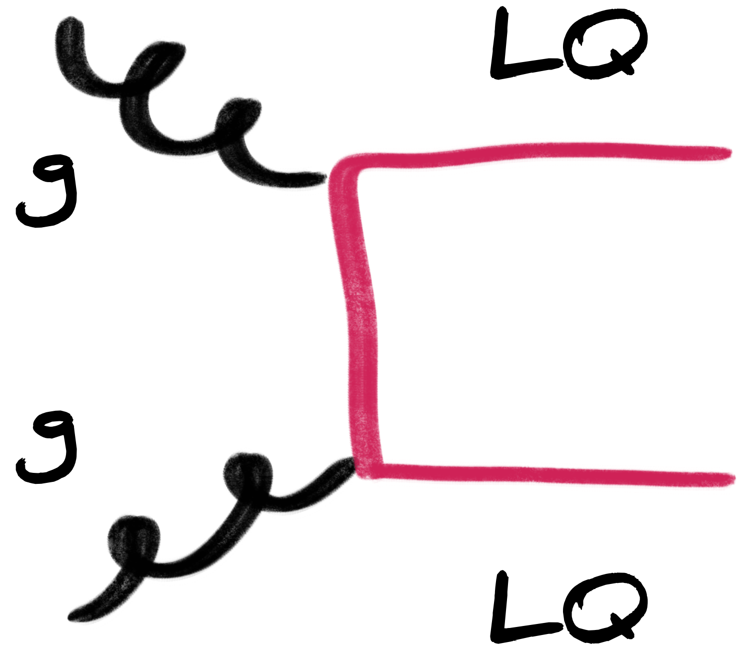
- The above PS issue needs to be resolved before next-to-leading order corrections for the signal can be correctly included

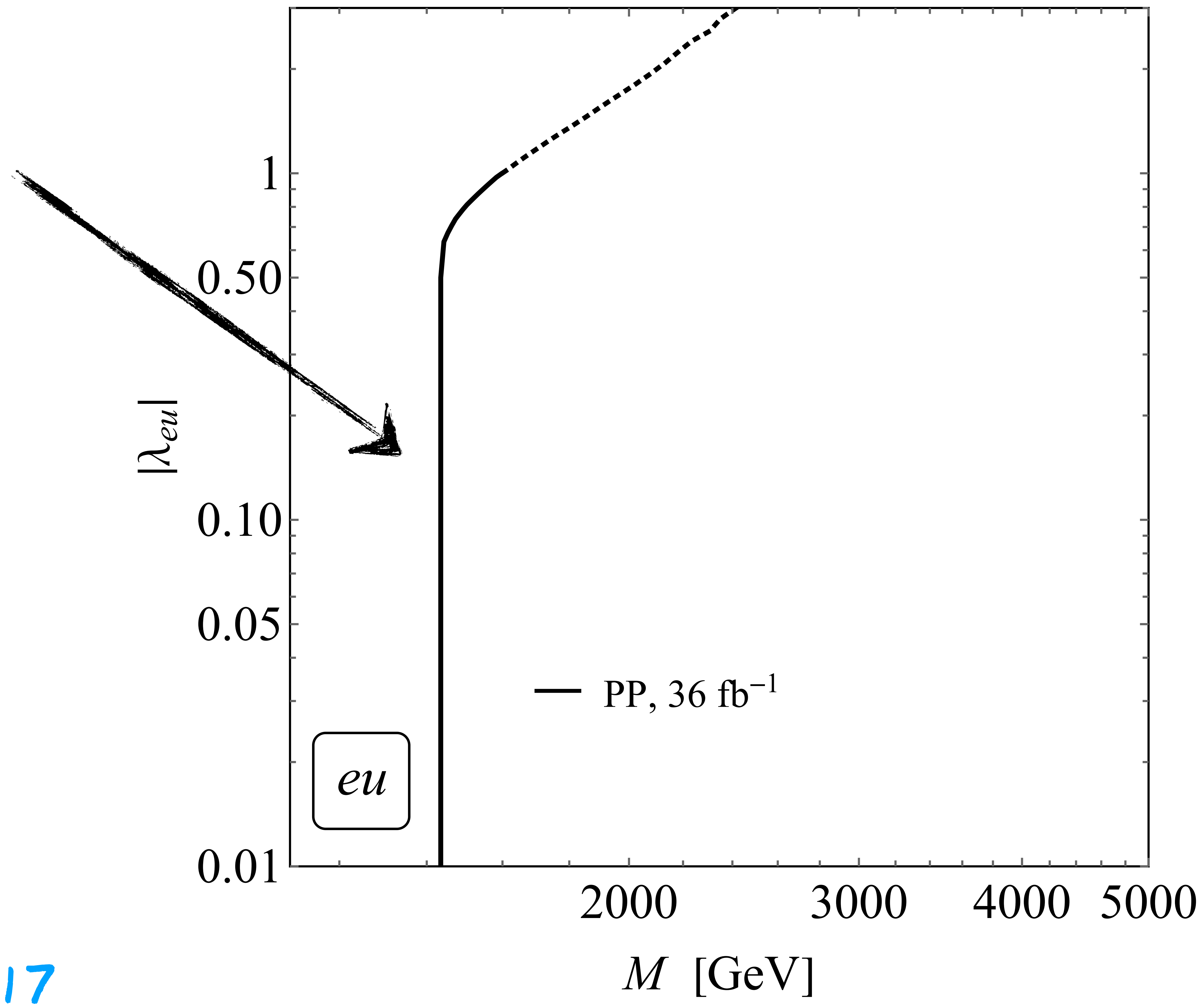
† In the meantime, Peter Richardson implemented initial-state leptons into HERWIG. Now undergoing testing ...

Comments on backgrounds & analysis

- The impact of multijet backgrounds is incorporated in our analysis by employing the post-fit systematic uncertainties of the ATLAS $l + E_{T,miss}$ search 1906.05609. Doubling the quoted errors we find uncertainties of 3%, 30% & 250% (3%, 24% & 50%) for m_{ej} ($m_{\mu j}$) values of 1 TeV, 3 TeV & 5 TeV
- The resolution of the invariant lepton-jet mass is estimated by combining the information on the dilepton & dijet mass resolutions given in 1903.06248 & 1910.08447. We find that the mass resolution amounts to 2.2% (4.3%) at 1 TeV & 1.5% (11%) at 5 TeV in the electron (muon) case
- Derived limits IMHO conservative, as ATLAS & CMS could probably improve analysis

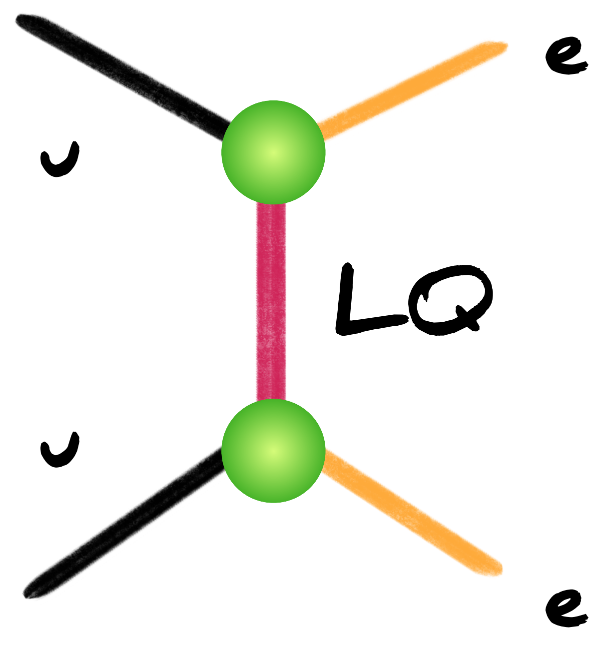
Summary of 95% CL limits: eu case

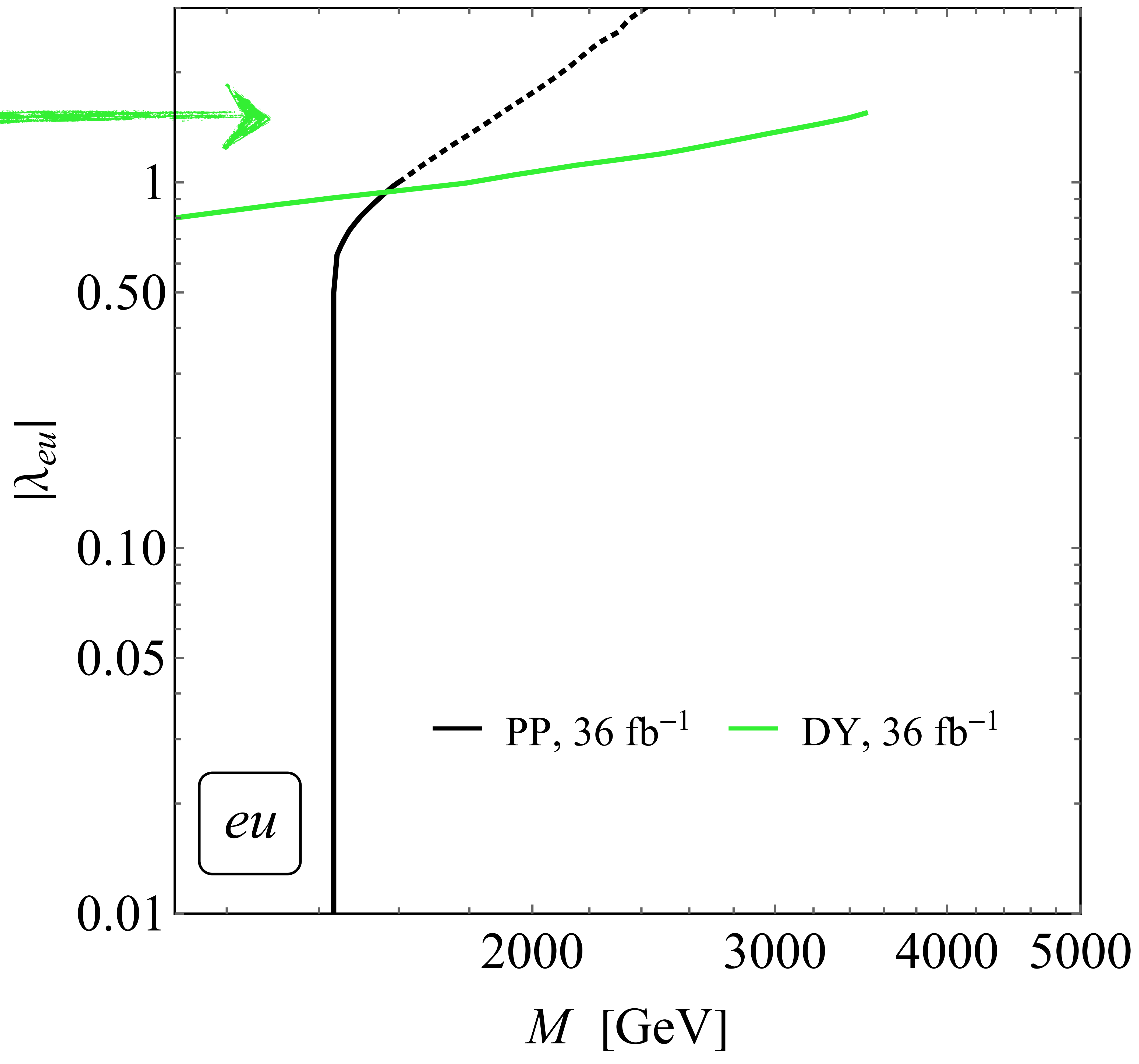




PP limit from Schmaltz & Zhong, 1810.10017

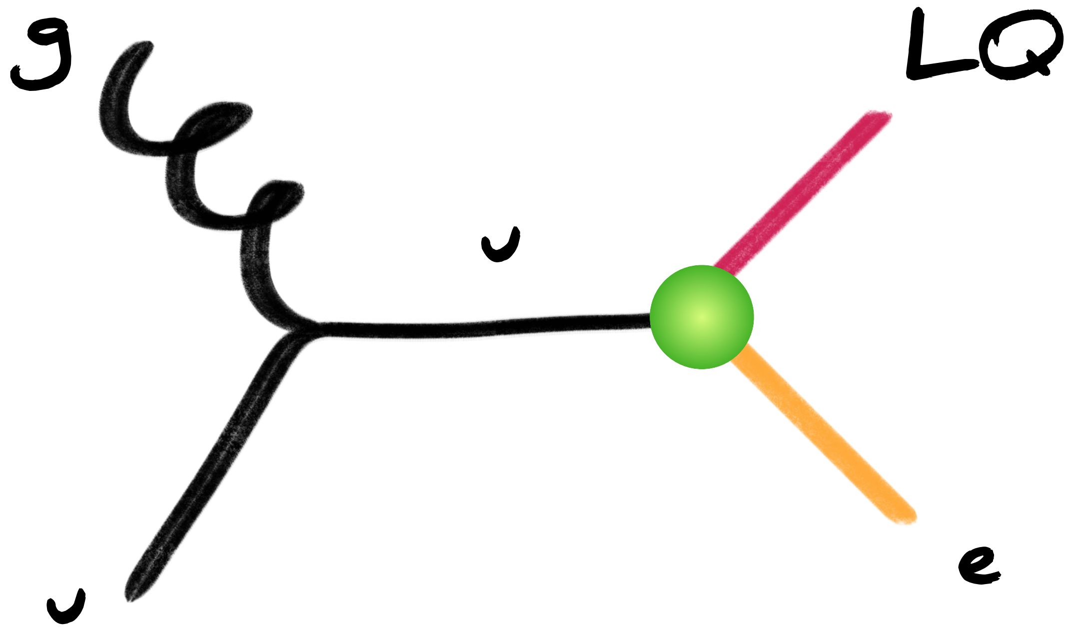
Summary of 95% CL limits: eu case

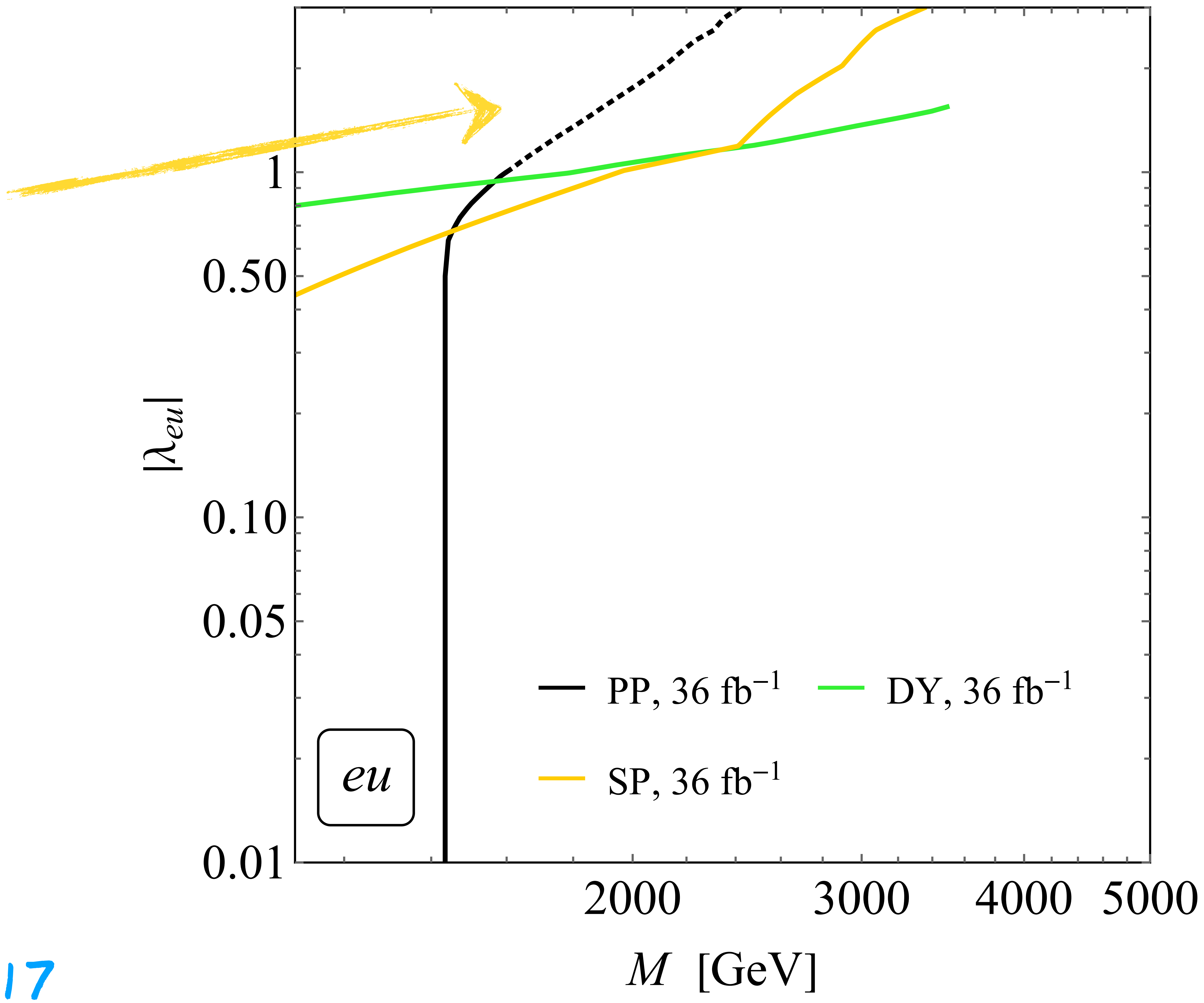




DY limit from Schmaltz & Zhong, 1810.10017

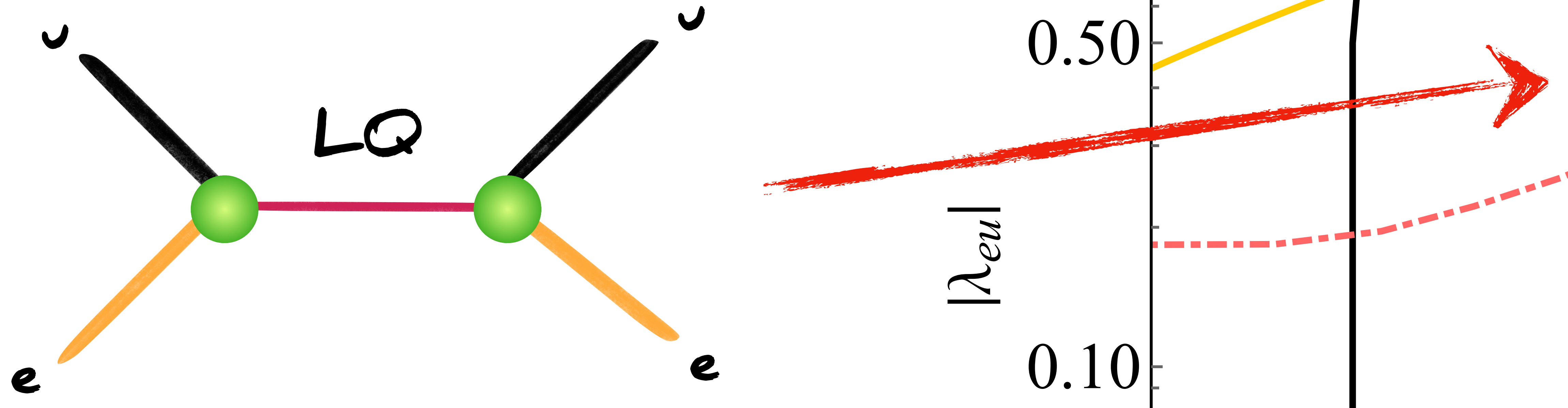
Summary of 95% CL limits: eu case

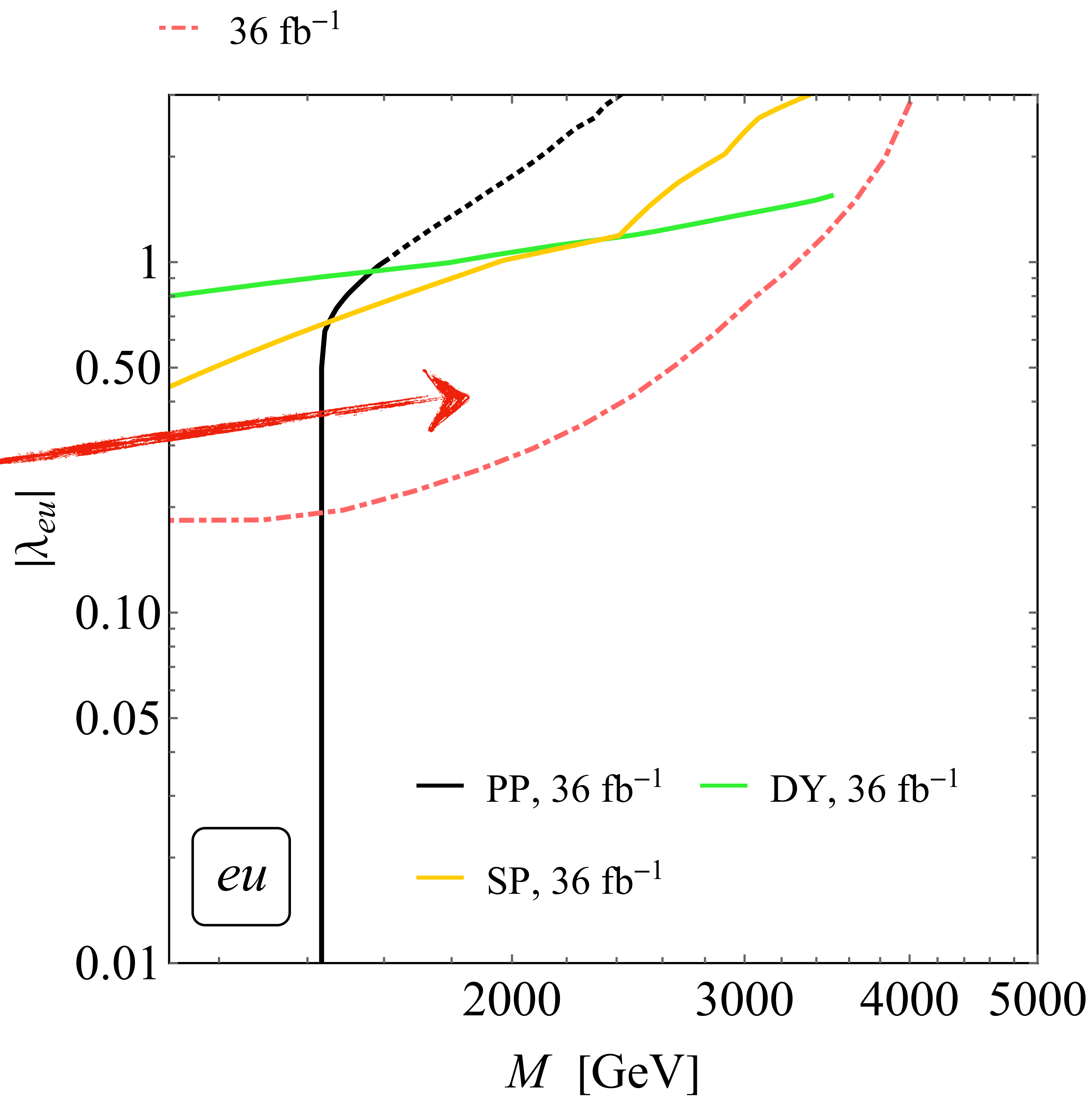




SP limit from Schmaltz & Zhong, 1810.10017

Summary of 95% CL limits: eu case





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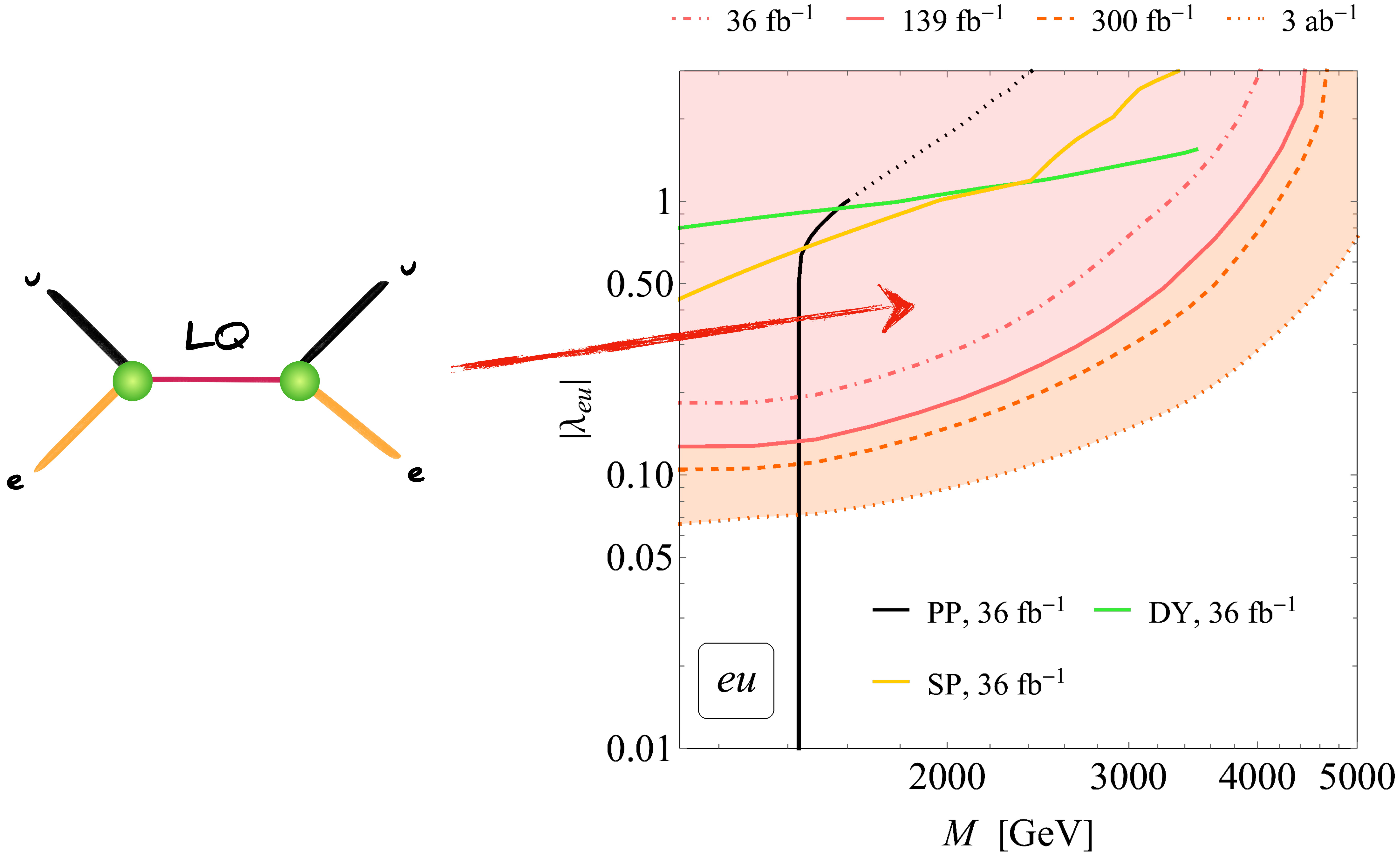
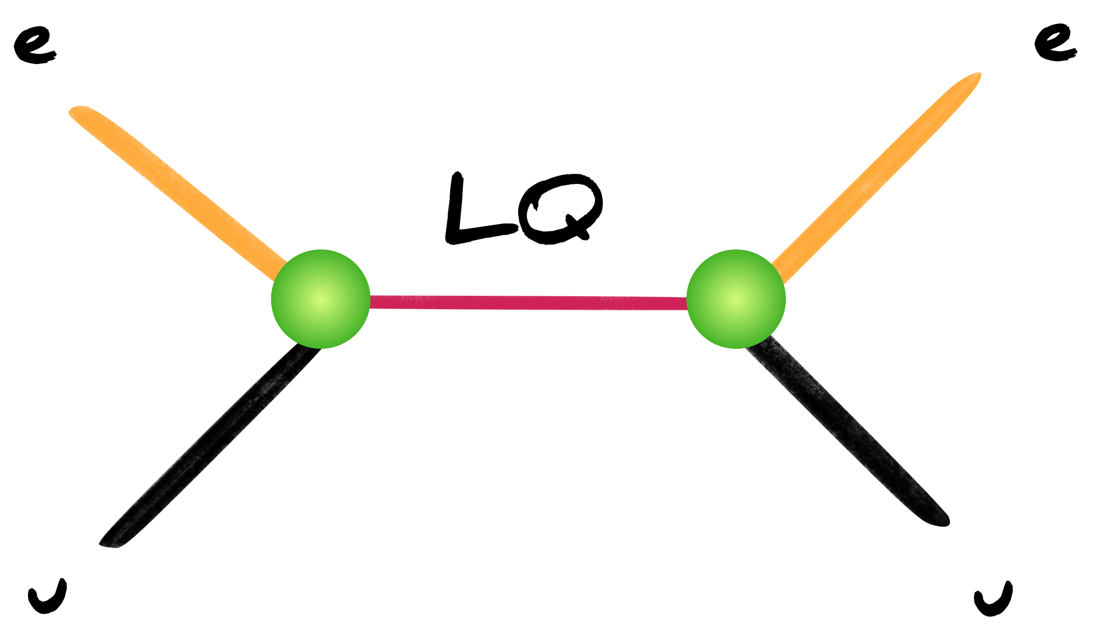
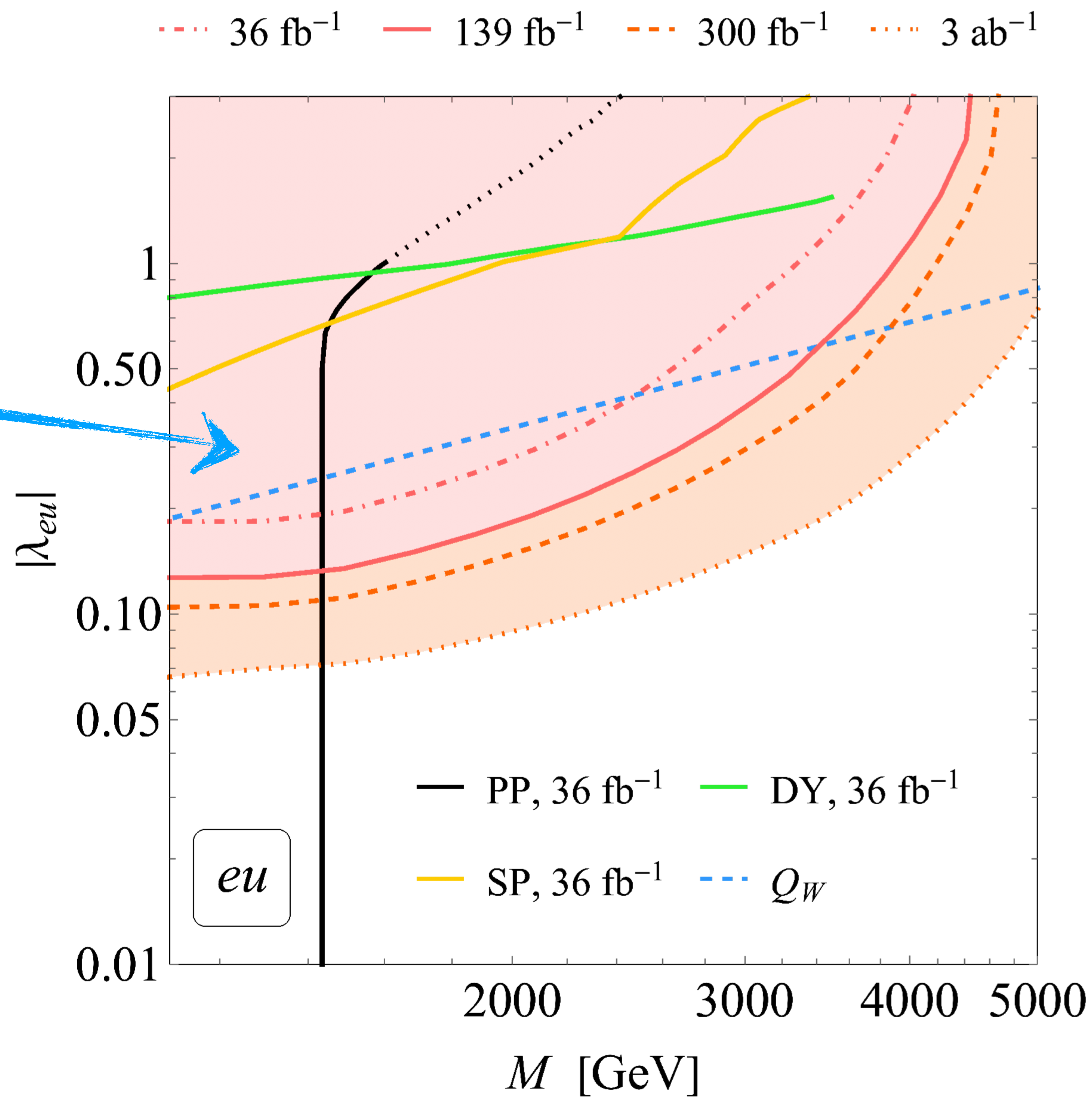


Summary of 95% CL limits: eu case



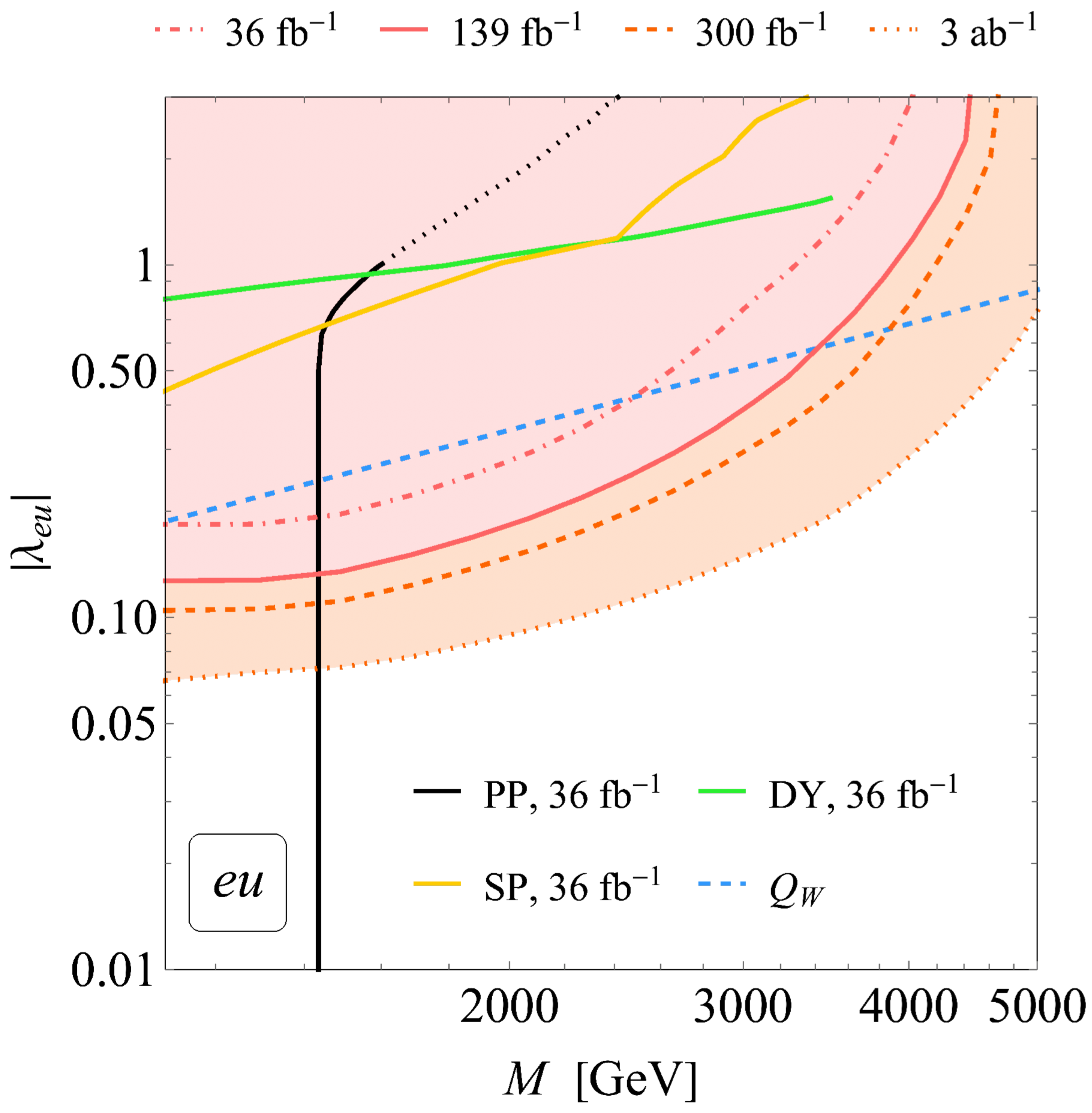
weak charge measurements (Q_W) from parity-violating electron scattering & atomic parity violation



Q_W limit from Schmaltz & Zhong, 1810.10017

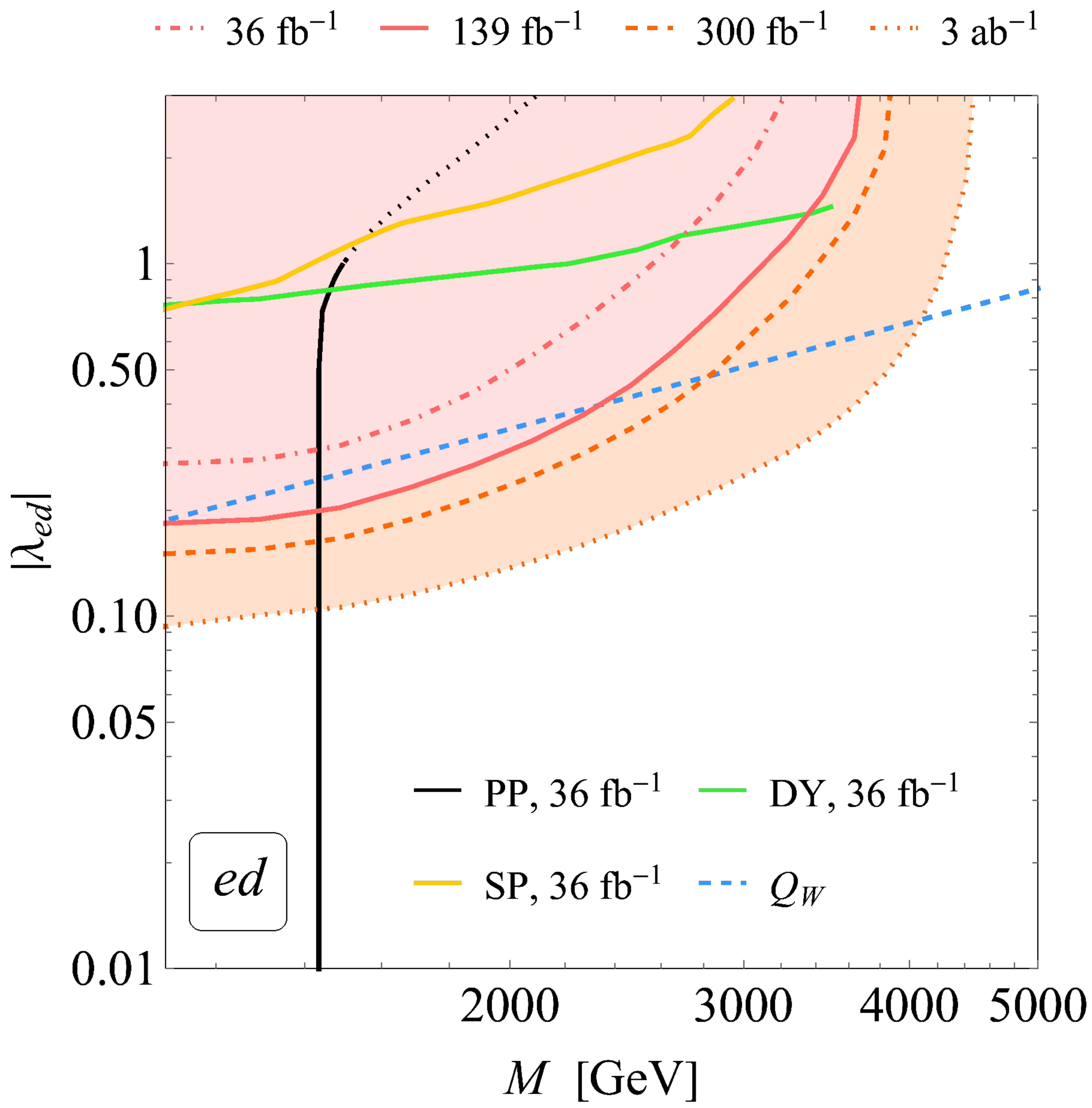
Summary of 95% CL limits: eu case

In eu case our hypothetical 139 fb^{-1} bounds are more stringent than the constraints from Q_W measurements for LQ masses below around 3.4 TeV. At high-luminosity LHC the corresponding limits can be improved to 5.2 TeV

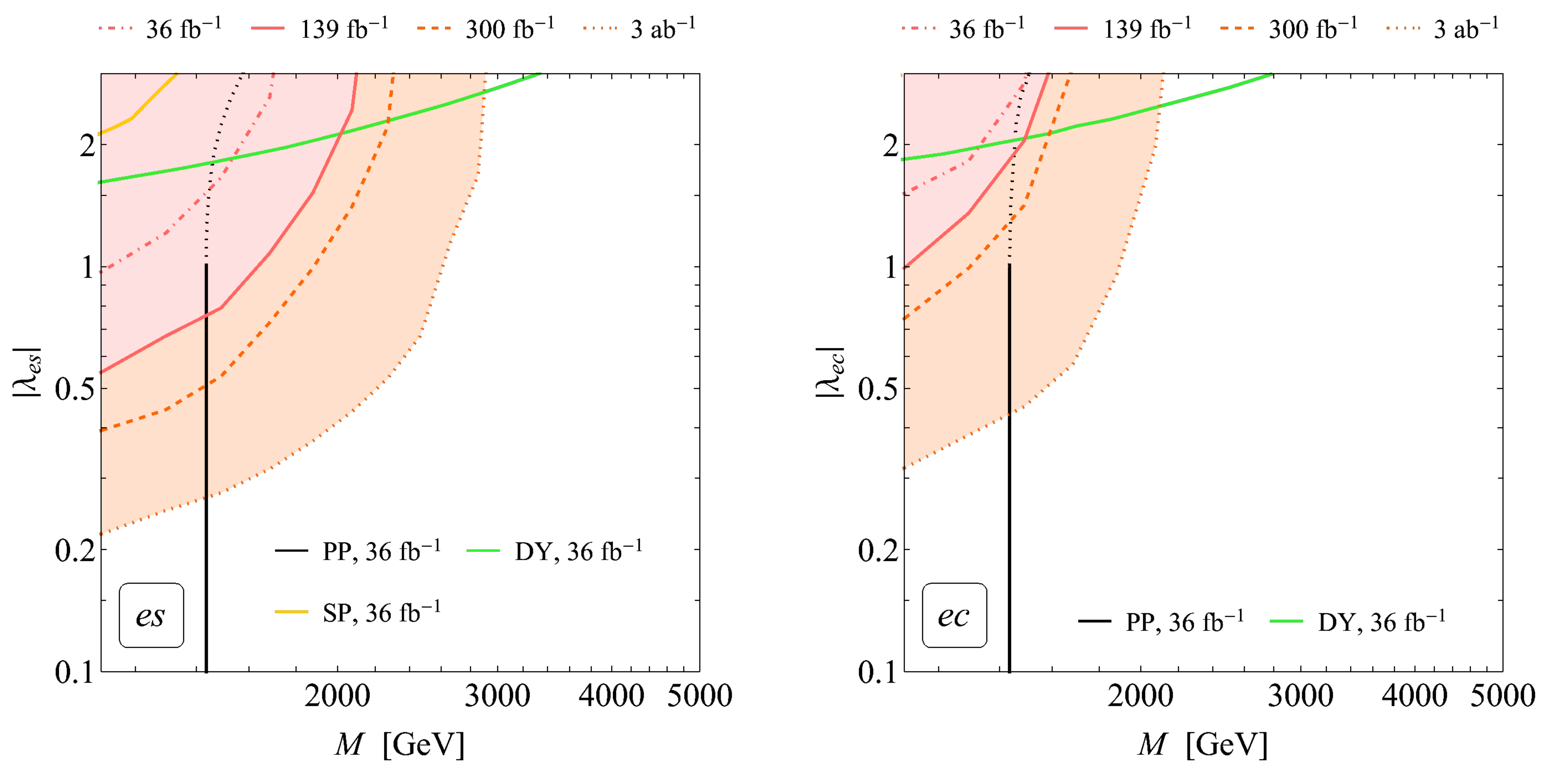


Summary of 95% CL limits: ed case

Slightly weaker limits in ed case due to smaller d luminosity. Nevertheless our bounds are still superior to Q_W measurements for scalar LQ masses below roughly 2.3 TeV (4.1 TeV) assuming 139 fb^{-1} (3 ab^{-1}) of data

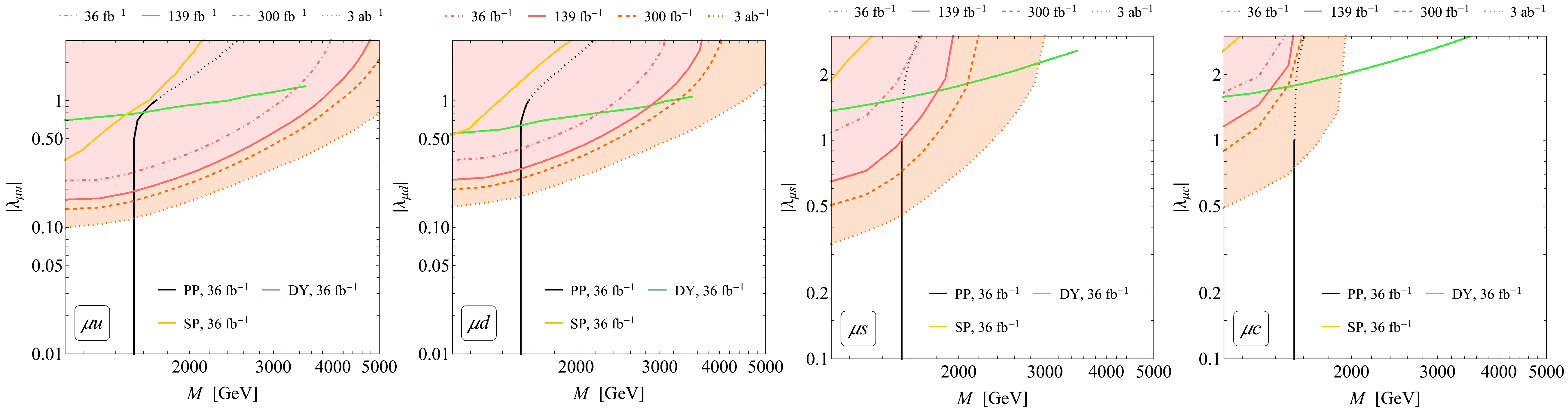


Summary of 95% CL limits: other e cases



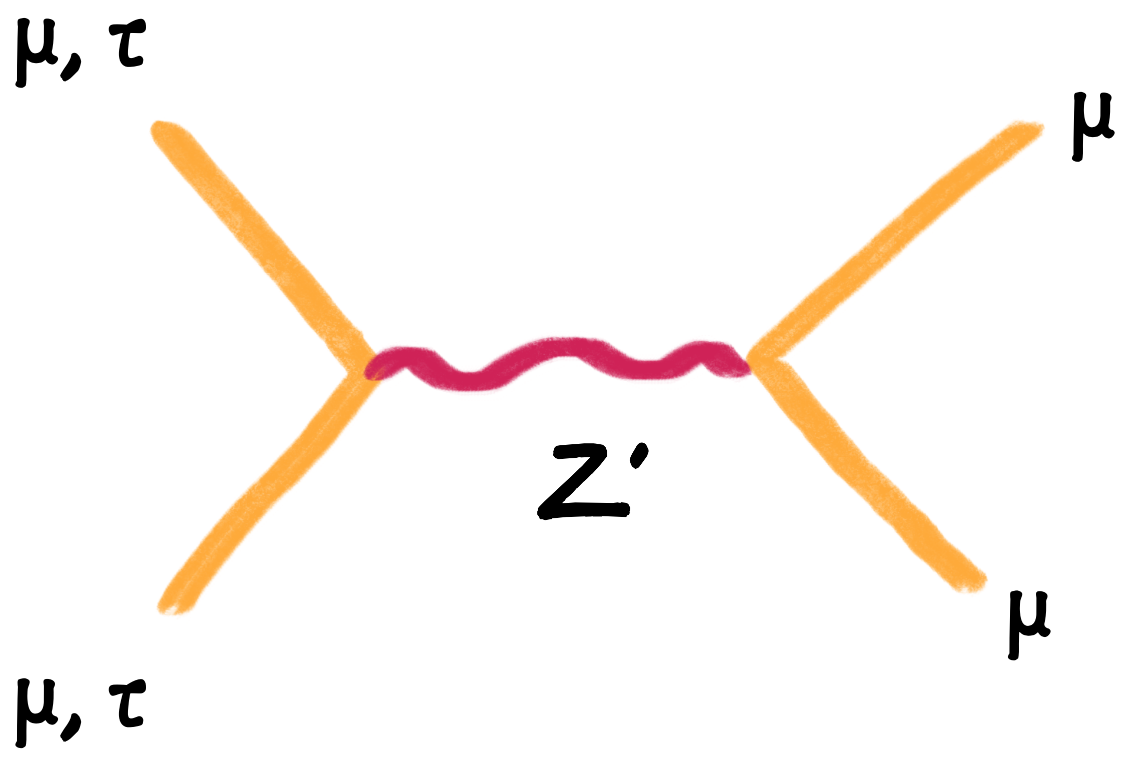
Notable weaker constraints in s & c case due to smaller parton distribution functions (PDFs)

Summary of 95% CL limits: μ cases

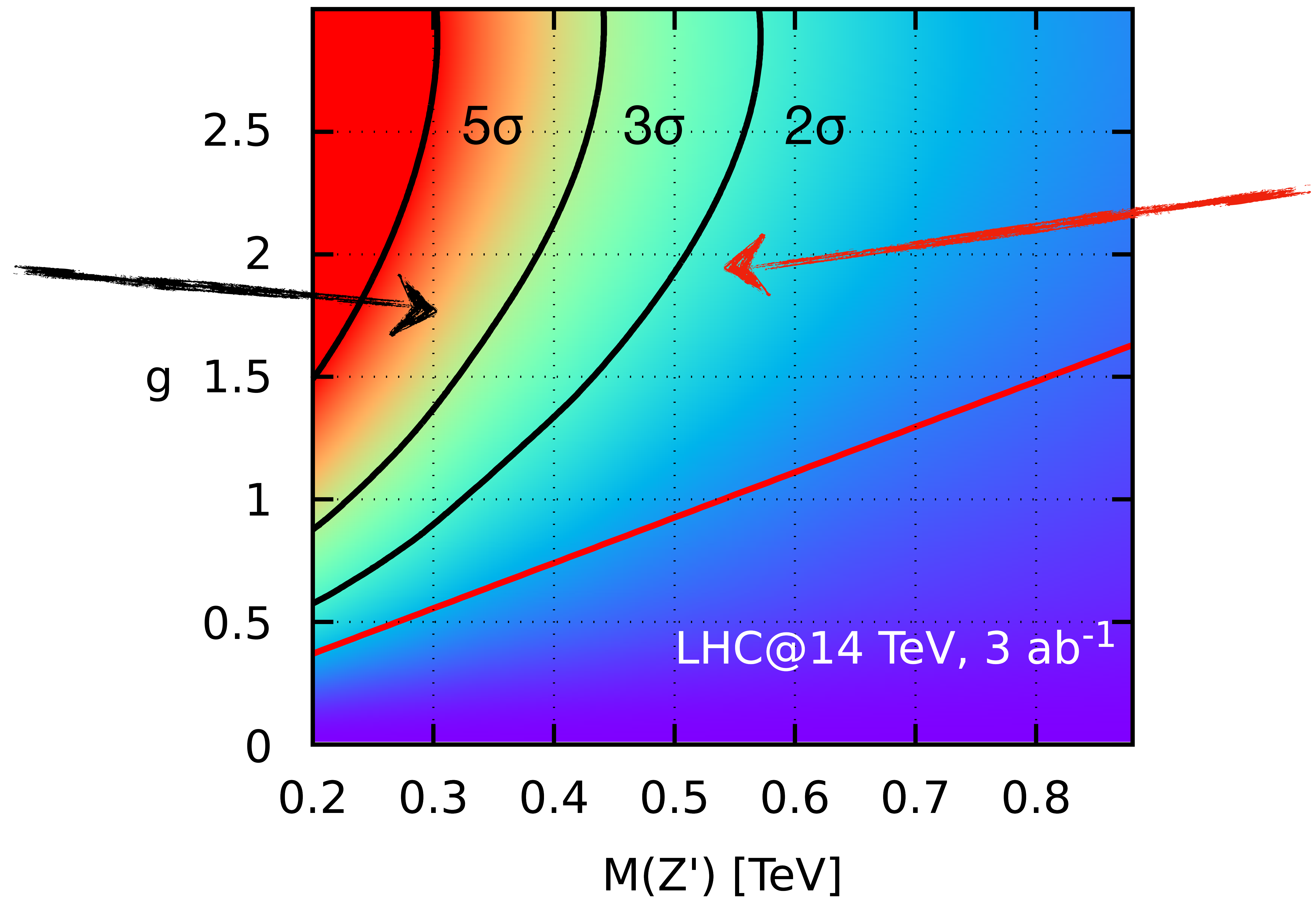


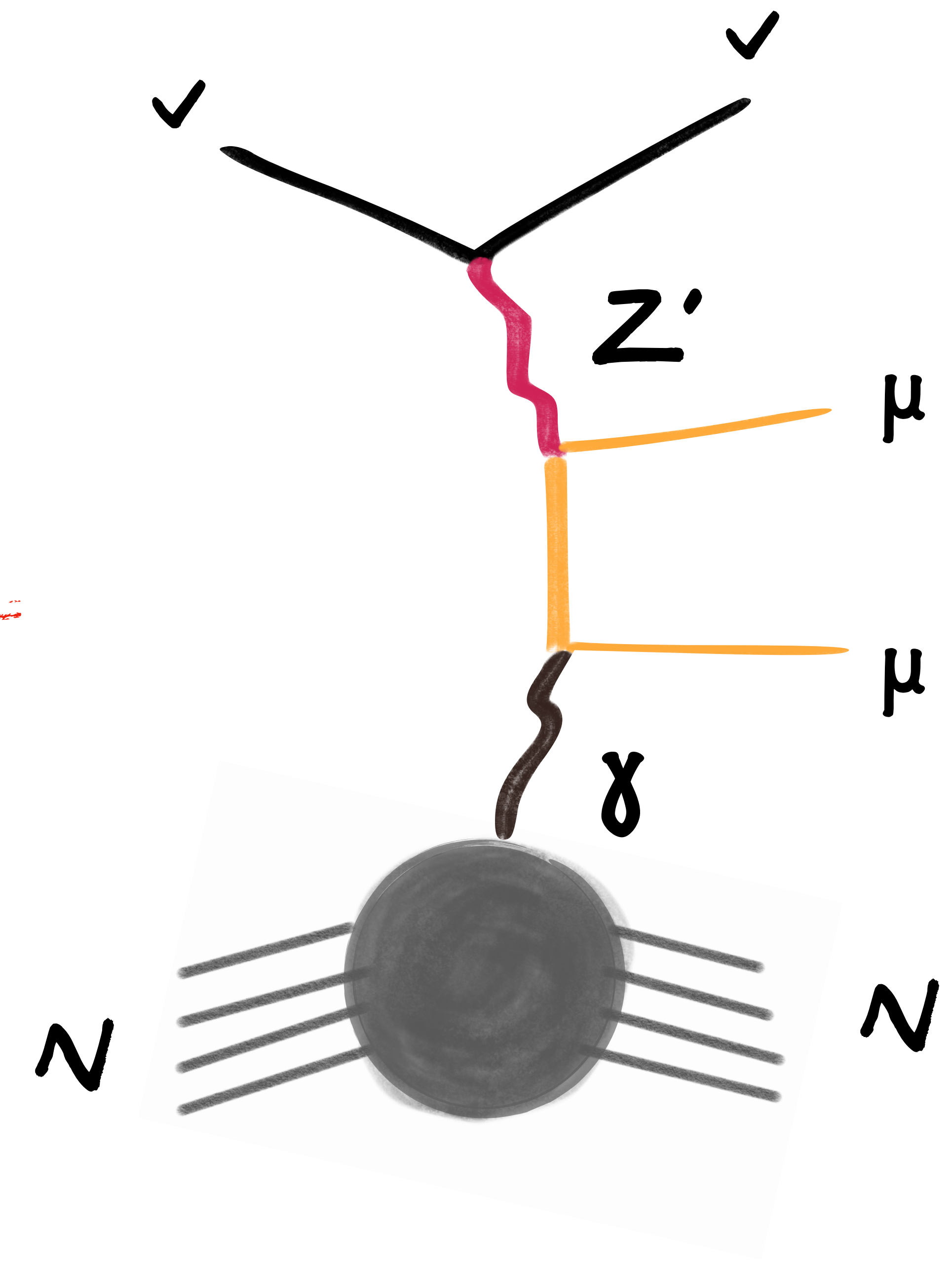
Constraints on μq & eq couplings similar. Weaker μq limits at low LQ mass due to lower muon detection efficiencies, but stronger bounds at high LQ mass given lower multijet background

L_μ-L_τ Z' bosons



Buonocore et al., 2005.06477

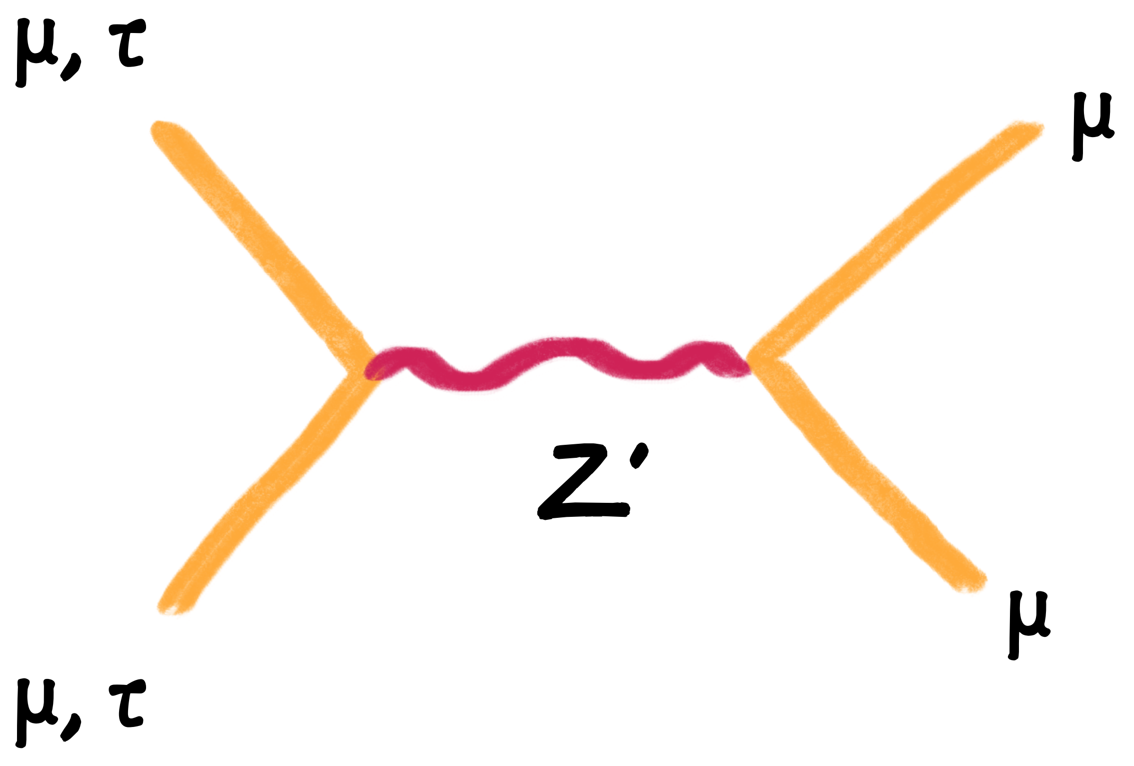




neutrino trident production

Direct LHC limits weaker than indirect constraints from neutrino trident production

L_μ-L_τ Z' bosons



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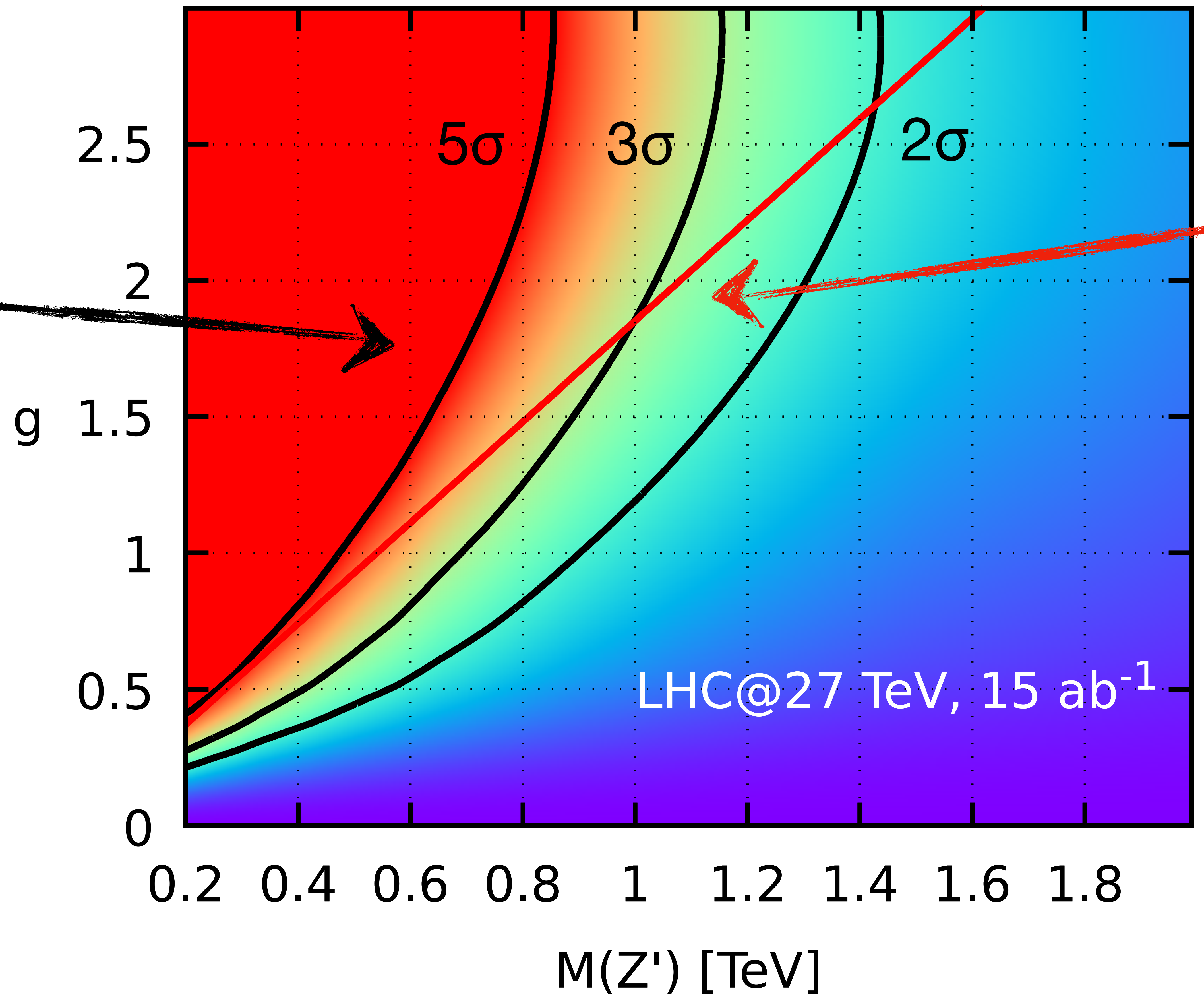
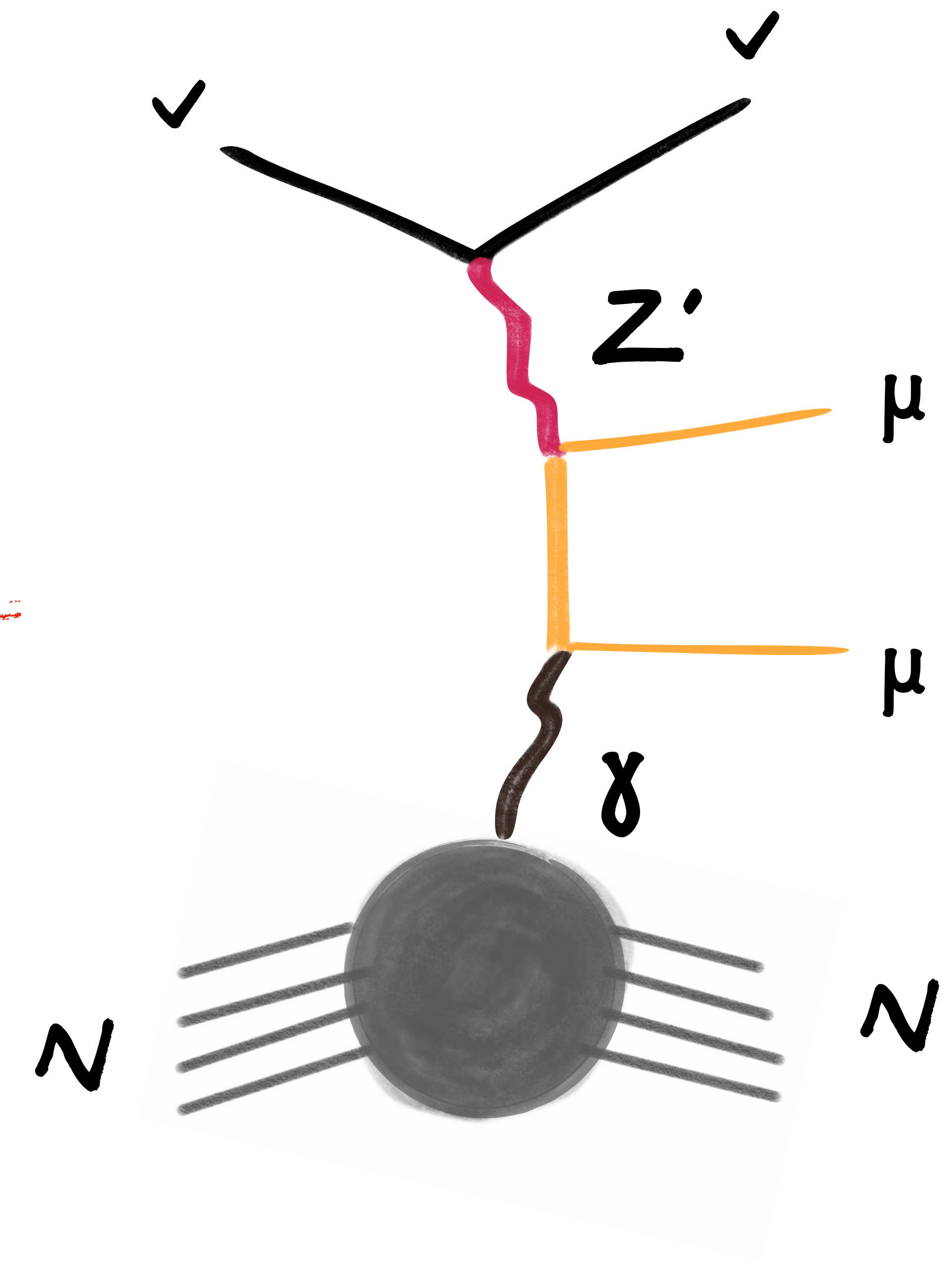


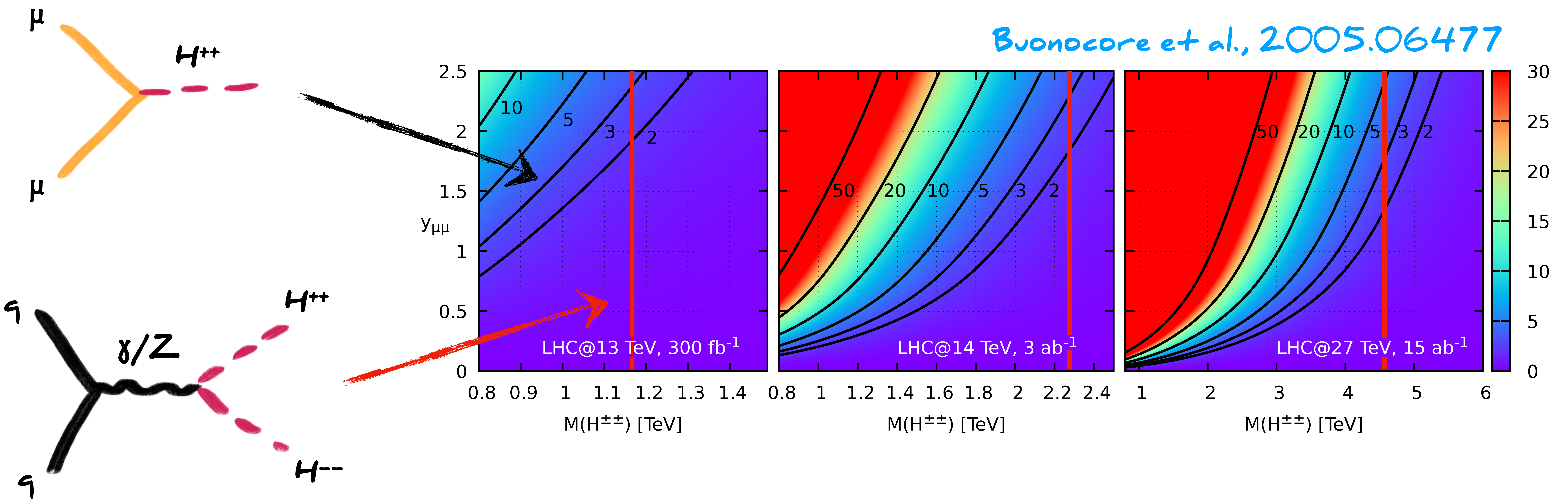


neutrino trident production

Need LHC energy upgrade to make direct & indirect bounds comparable in strength

Doubly-charged Higgses

Buonocore et al., 2005.06477



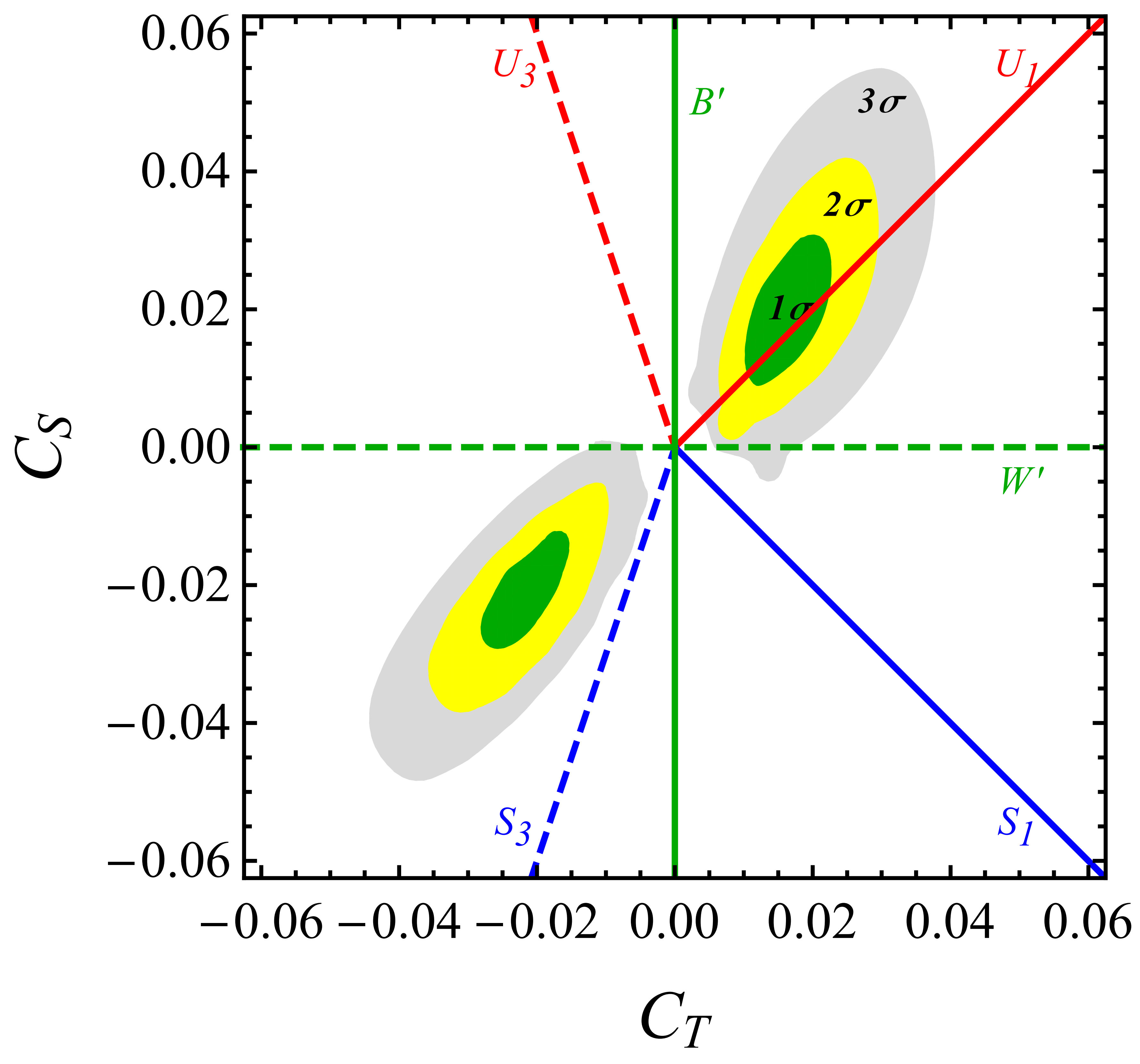
For sufficiently large Yukawa couplings $y_{\mu\mu}$ s-channel production of a doubly-charged Higgs may have a mass reach comparable to analyses relying upon PP

Conclusions & outlook

- Resonant LQ production induced by lepton PDFs provides sensitive direct probes of 1st- & 2nd -generation scalar LQs at the LHC
- In view of the simplicity of the proposed LQ signature & its discovery reach, ATLAS & CMS should perform dedicated resonance searches in lepton-jet final states at future LHC runs
- After some modifications our general search strategy can also be applied to other new-physics searches: leptophilic Z' bosons, doubly-charged Higgses, vector LQs explaining B anomalies, ...

Simplified models for B anomalies

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



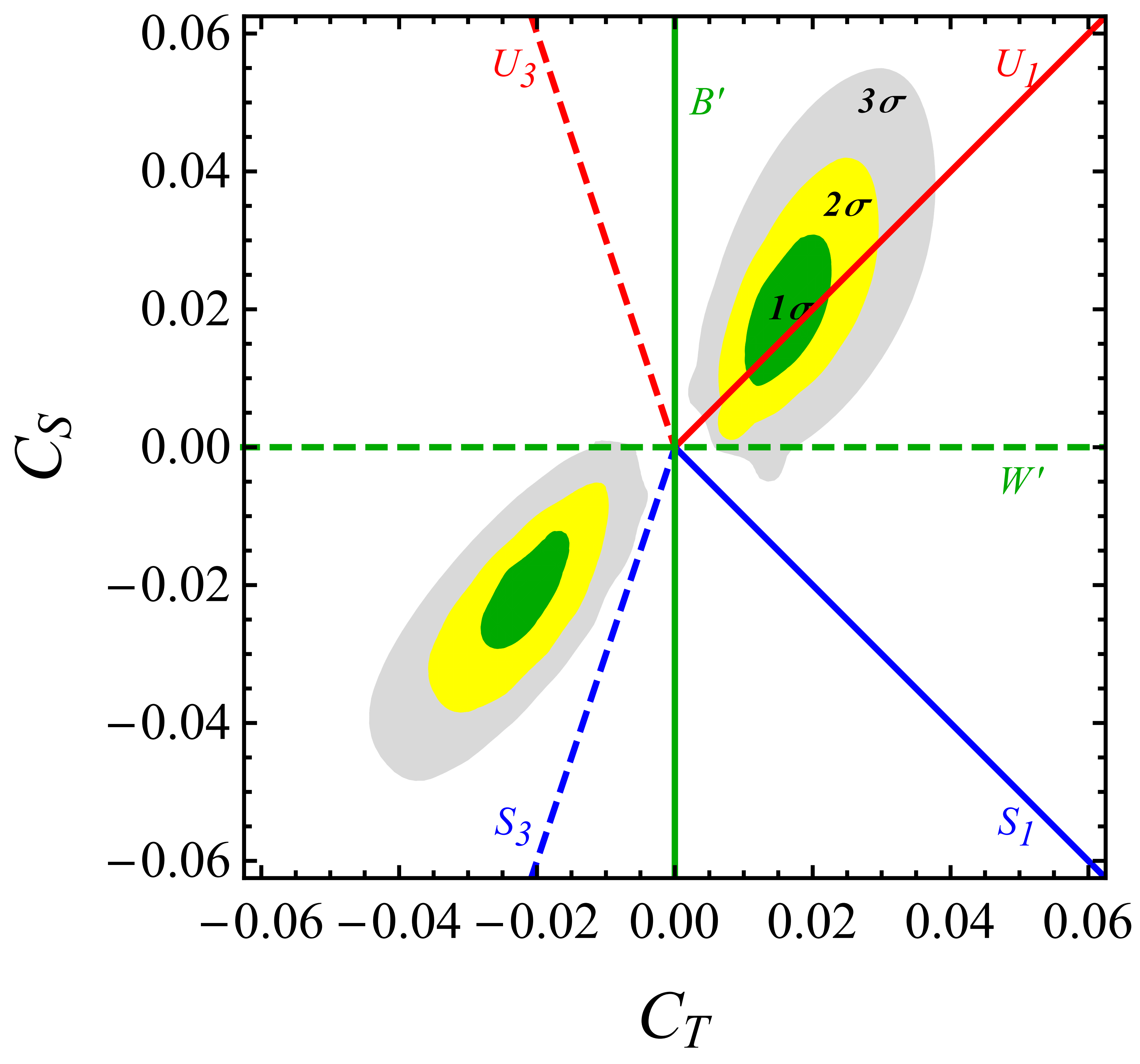
Model	Mediator	$b \to s$	$b \to c$
Colorless vectors	$B' = (1,1,0)$	✓	✗
	$W' = (1,3,0)$	✗	✓
Scalar leptoquarks	$S_1 = (\bar{3},1,1/3)$	✗	✓
	$S_3 = (\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

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

see for instance Buttazzo et al., 1706.07808

Simplified models for B anomalies

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



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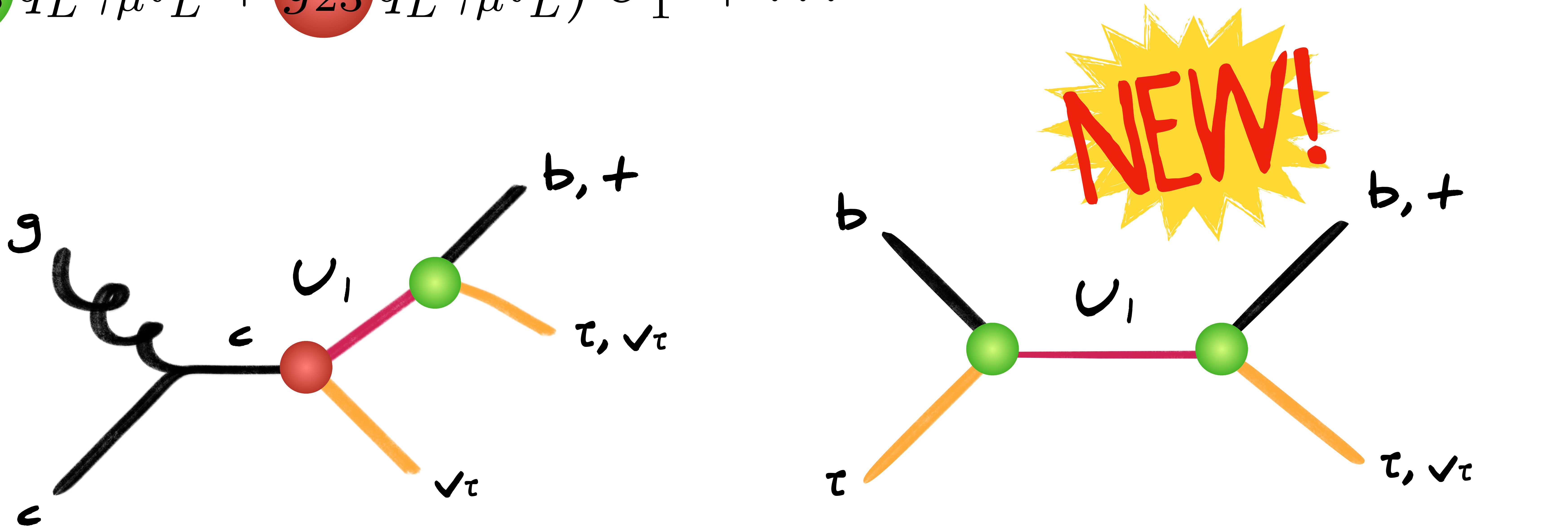
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

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

see for instance Buttazzo et al., 1706.07808

New resonant U_1 search channels

$$\mathcal{L} \supset \left(g_{33}\, \bar{q}_L^3 \gamma_\mu l_L^3 + g_{23}\, \bar{q}_L^2 \gamma_\mu l_L^3 \right) U_1^\mu + \ldots$$



Lepton-initiated scatterings allow for new resonant U_1 contributions to $b\tau$, mono-top & mono-jet production. This feature has not been explored yet