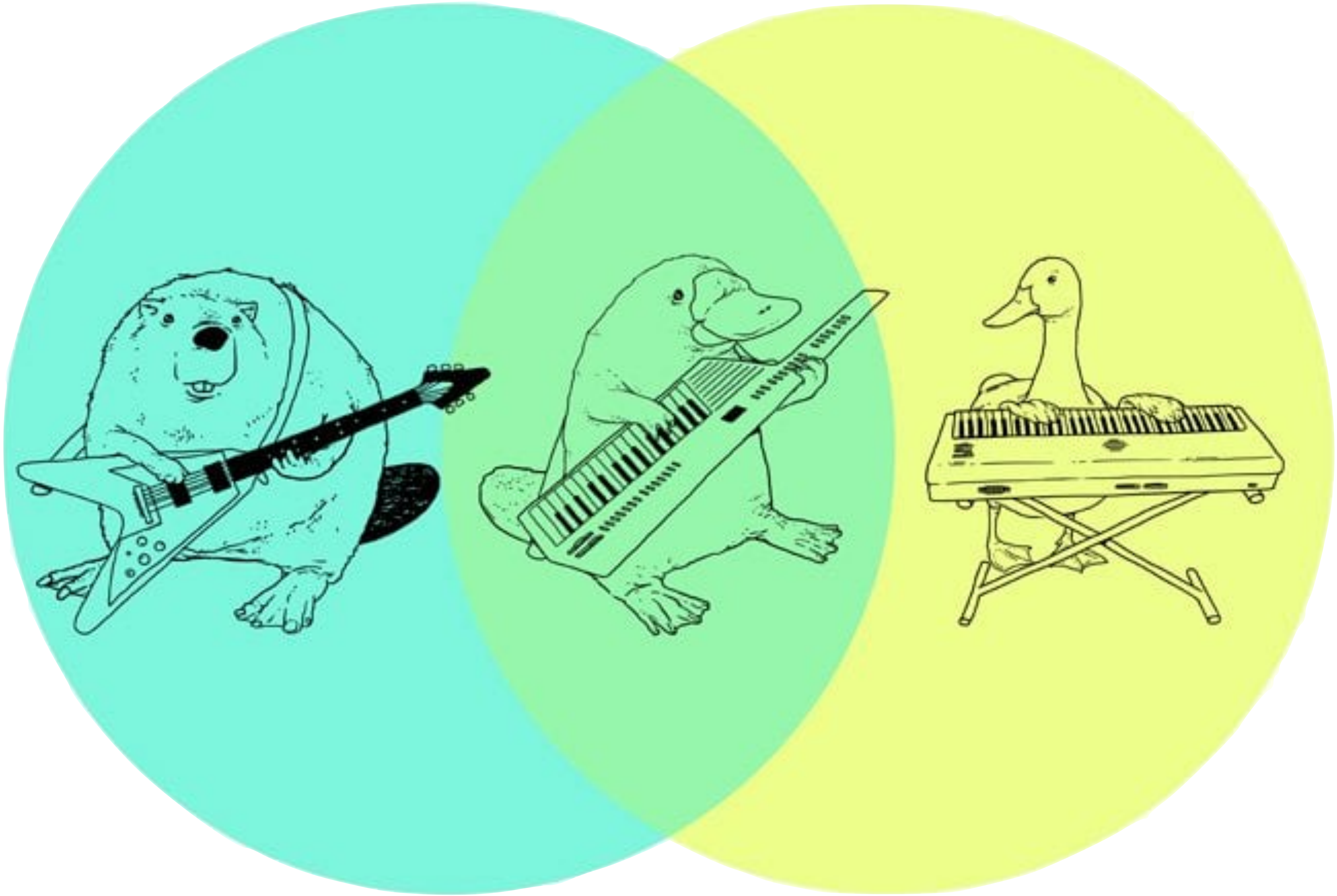
Uli Haisch, MPI Munich
La Thuile 2023, 10.03.23

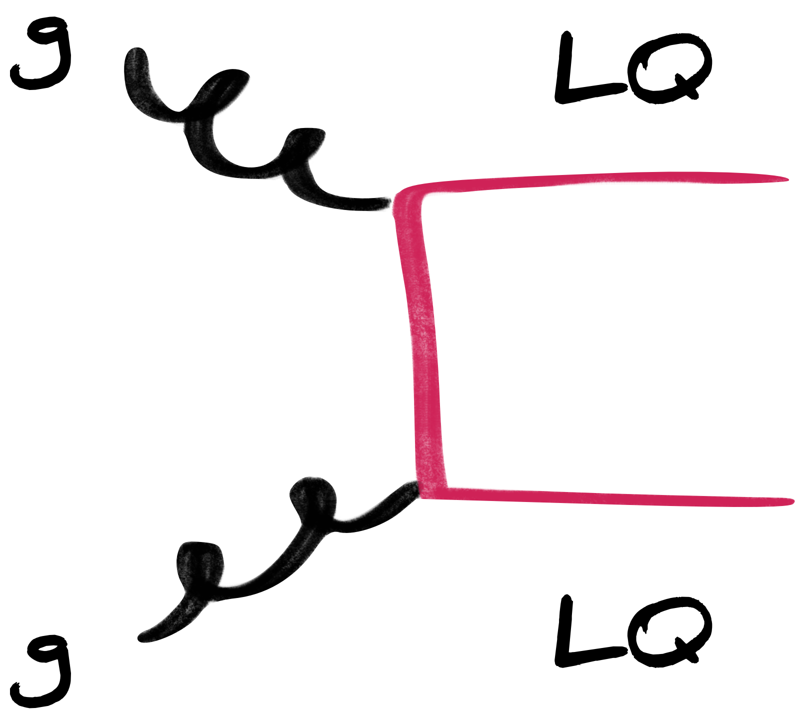
Collider signatures of leptoquarks

What is a leptoquark?

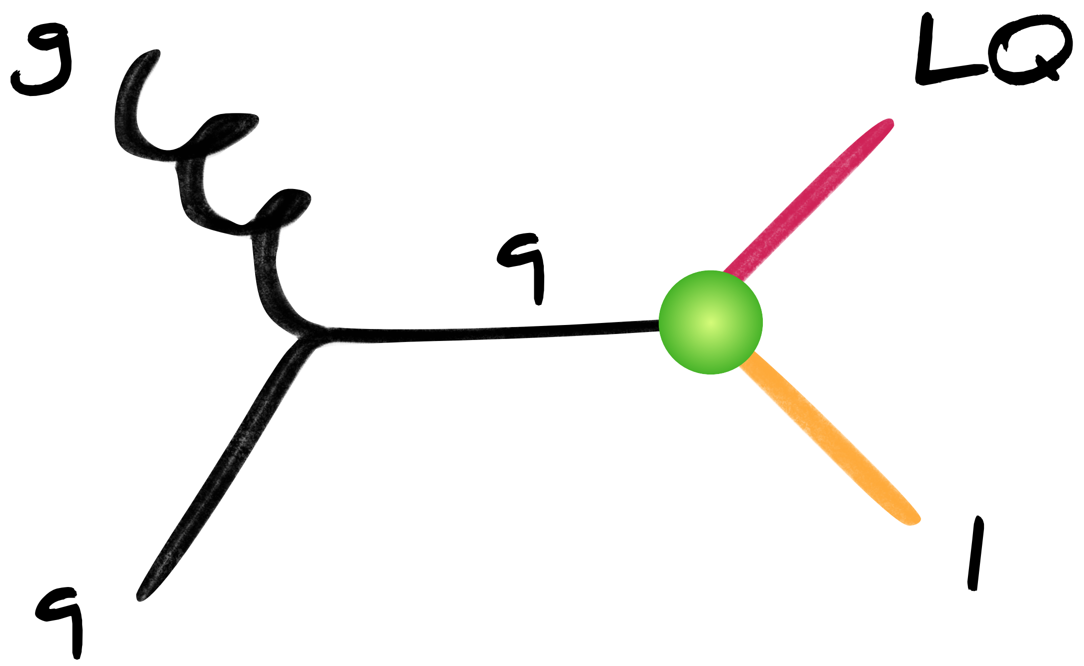


Like a cross between a beaver & a duck is a platypus or a cross between a keyboard & a guitar is a keytar, a cross between a lepton & a quark is a leptoquark (LQ)

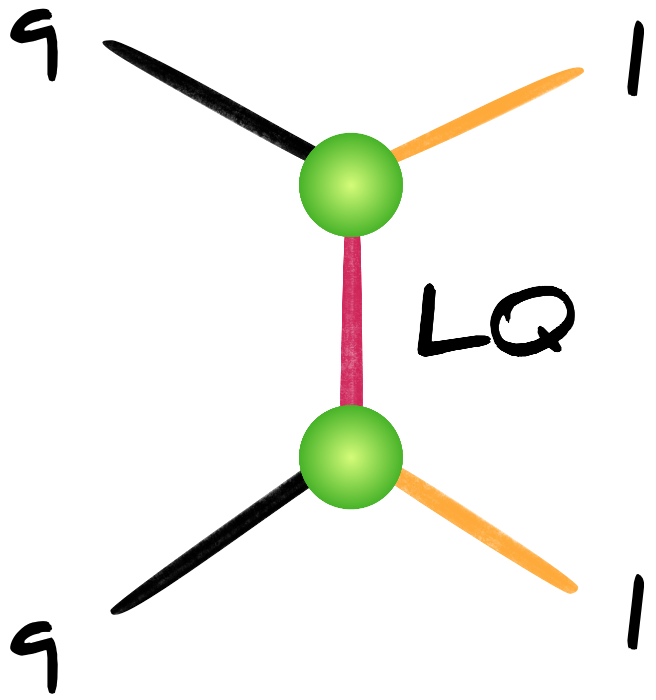
Existing LQ search strategies @ the LHC



pair production (PP)



single production (SP)

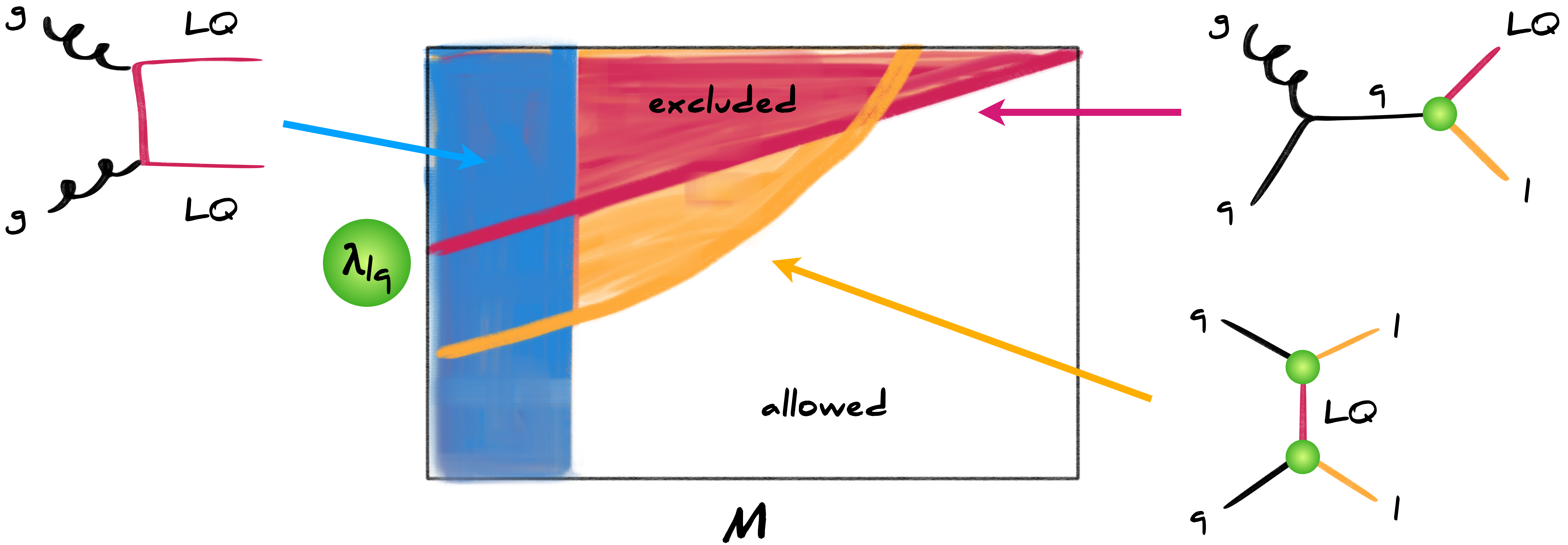


t-channel Drell-Yan (DY)

Since they are coloured, TeV-scale LQs can be produced in pairs @ LHC with fb rates. Also single & t-channel DY production possible but only recently considered by ATLAS & CMS

[full list of ATLAS & CMS results available through their exotics web pages]

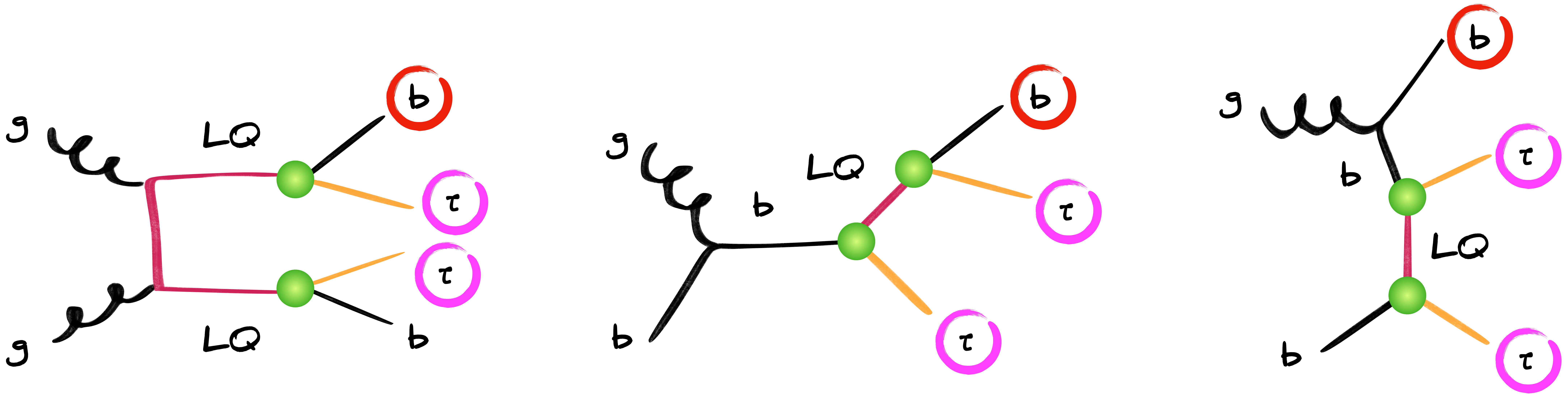
Existing LQ search strategies @ the LHC



Channels complementary because they provide different sensitivities on LQ parameter space

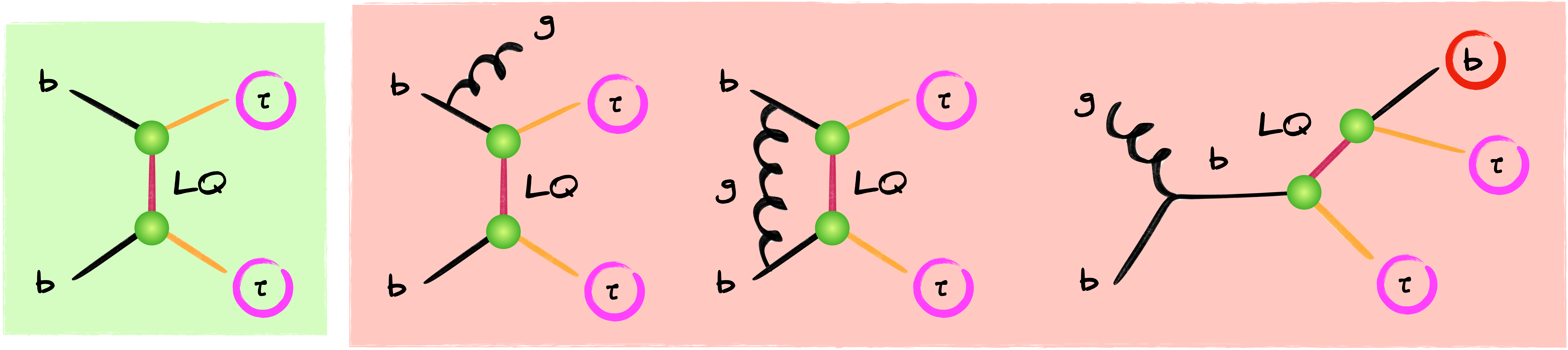
[sketch adopted from Dorsner & Greljo, 1801.07641]

Existing LQ search strategies @ the LHC



LQ production mechanisms studied by ATLAS & CMS lead to complicated multi-particle final states. Depending on experimental selections individual channels lead to overlapping contributions, which calls for a precise modelling of LQ signal at level of hadronic events

Existing LQ search strategies @ the LHC

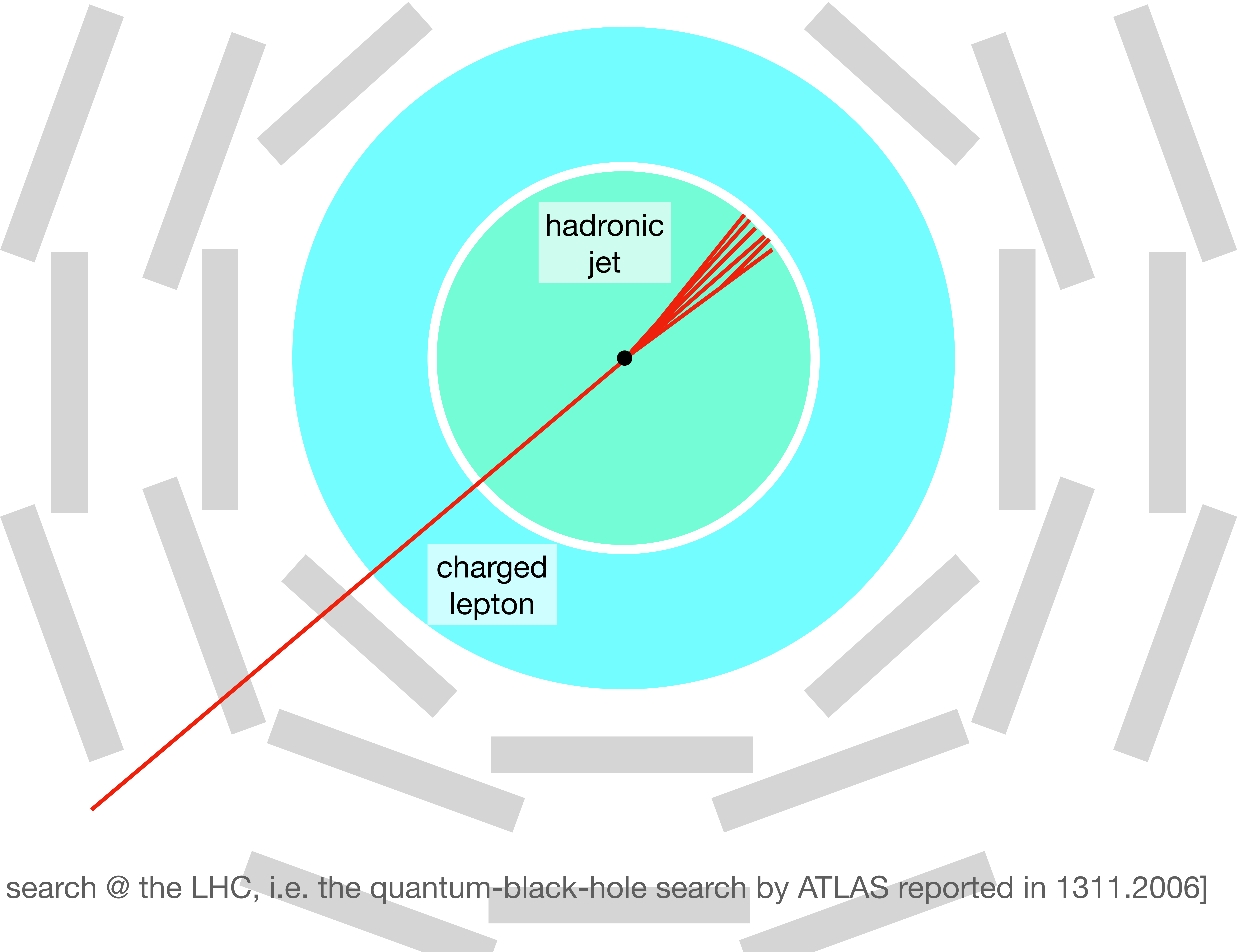


tree level | real NLO | virtual NLO | finite real NLO

QCD effects particularly relevant for final states with b-jets due to small b-quark parton distribution function (PDF). LHC Run II results based on merging & matching but full next-to-leading order plus parton shower (NLO+PS) Monte Carlos now available in some cases

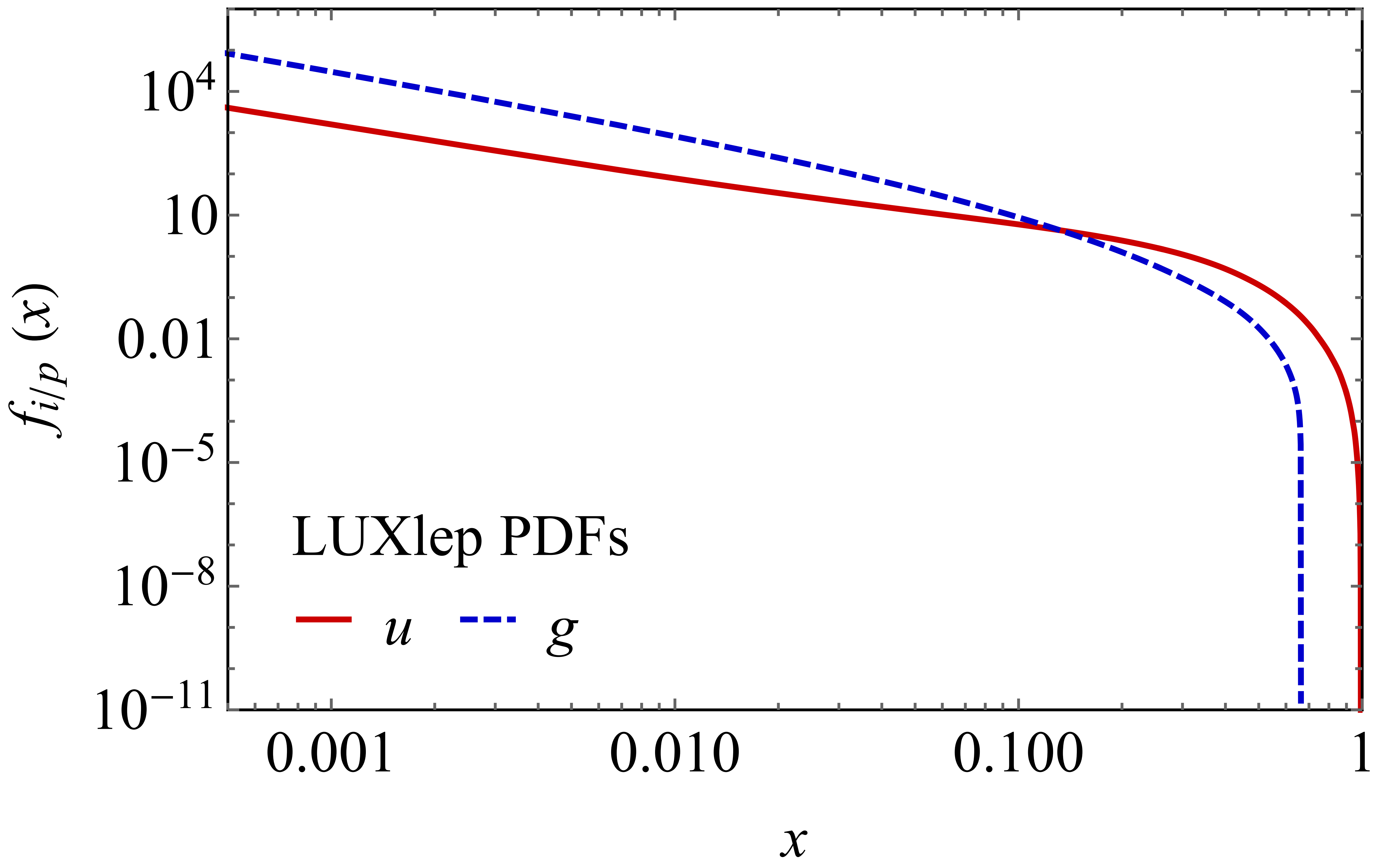
[see for instance NLO+PS POWHEG implementation of pp → l^+l^- based on UH, Schnell & Schulte, 2207.00356; 2209.12780]

Lepton-jet searches are much simpler …

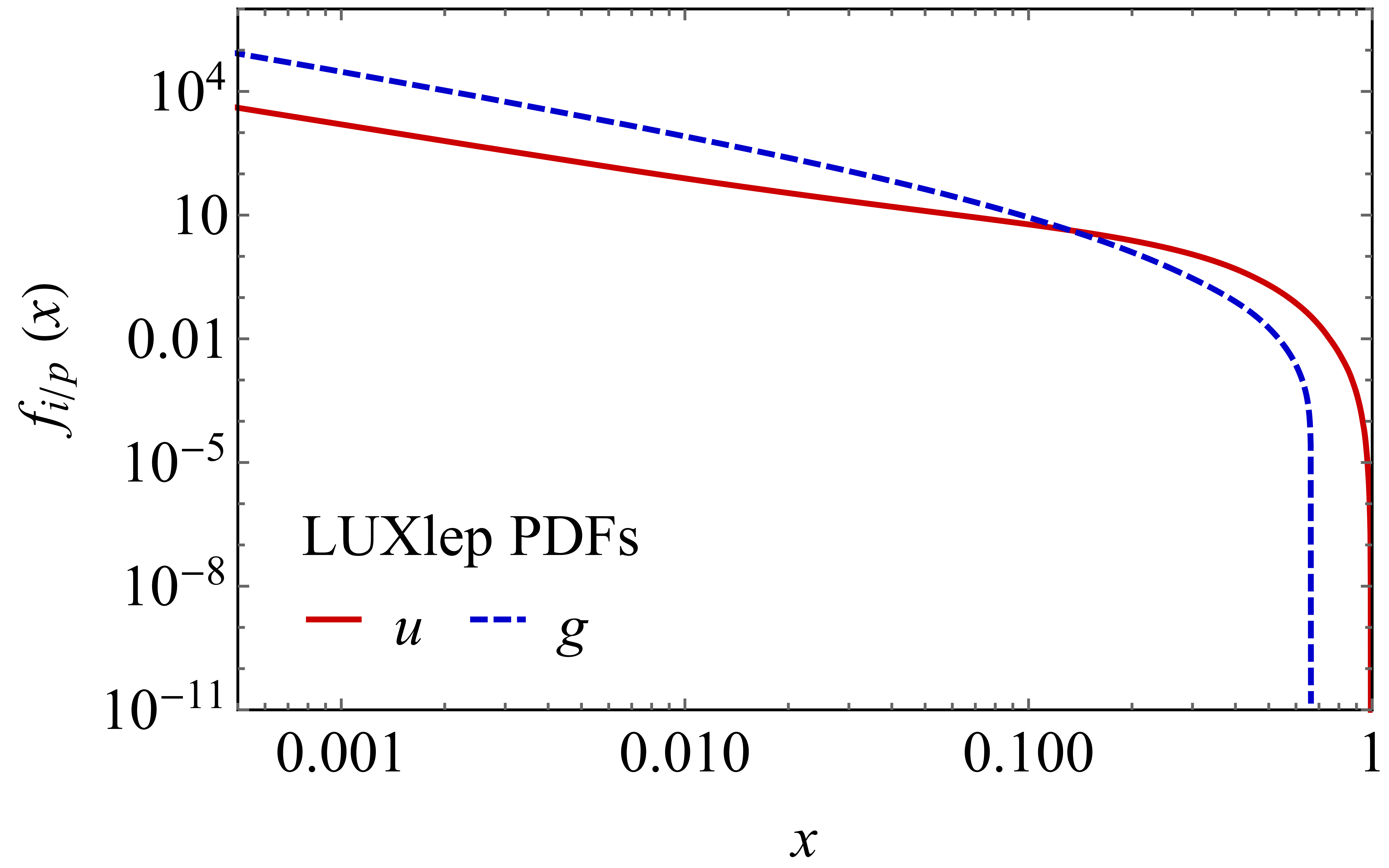


[there is only one such search @ the LHC, i.e. the quantum-black-hole search by ATLAS reported in 1311.2006]

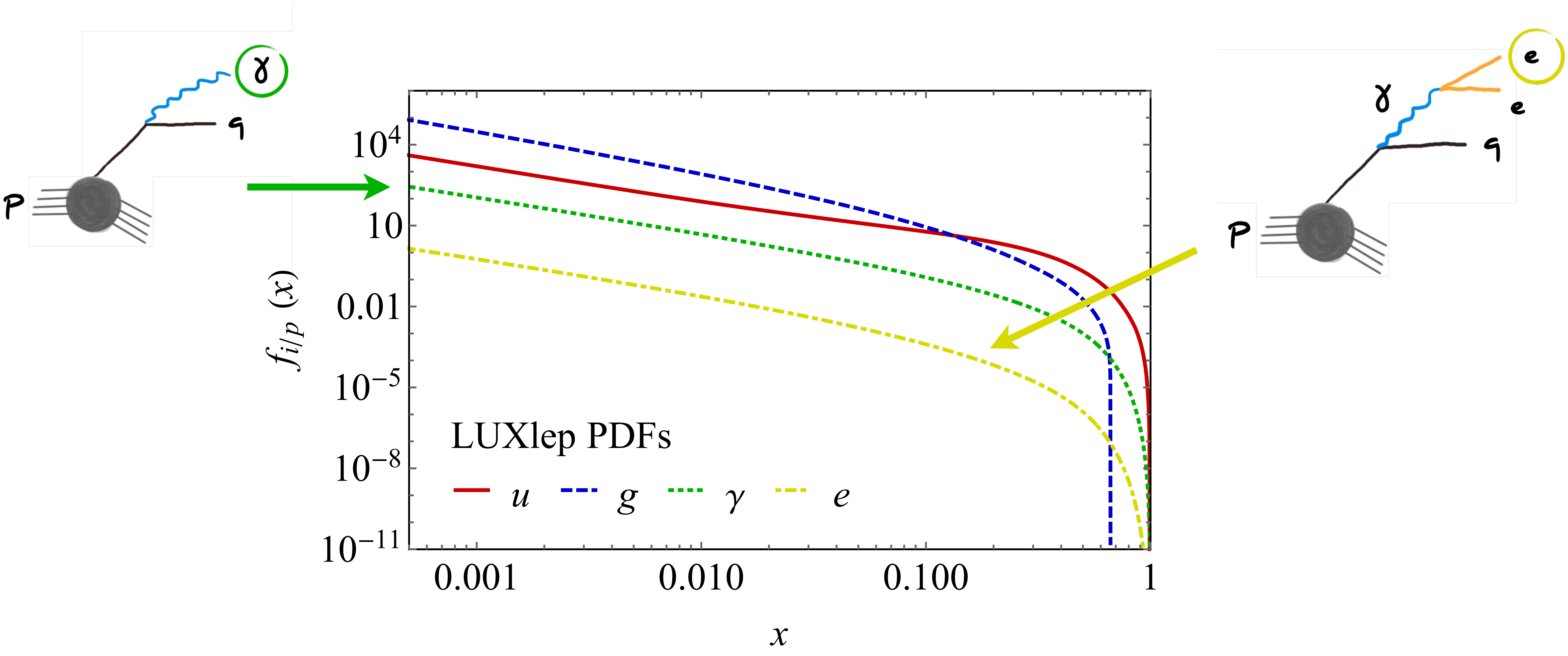
but LHC collides protons …



& protons consist of quarks & gluons

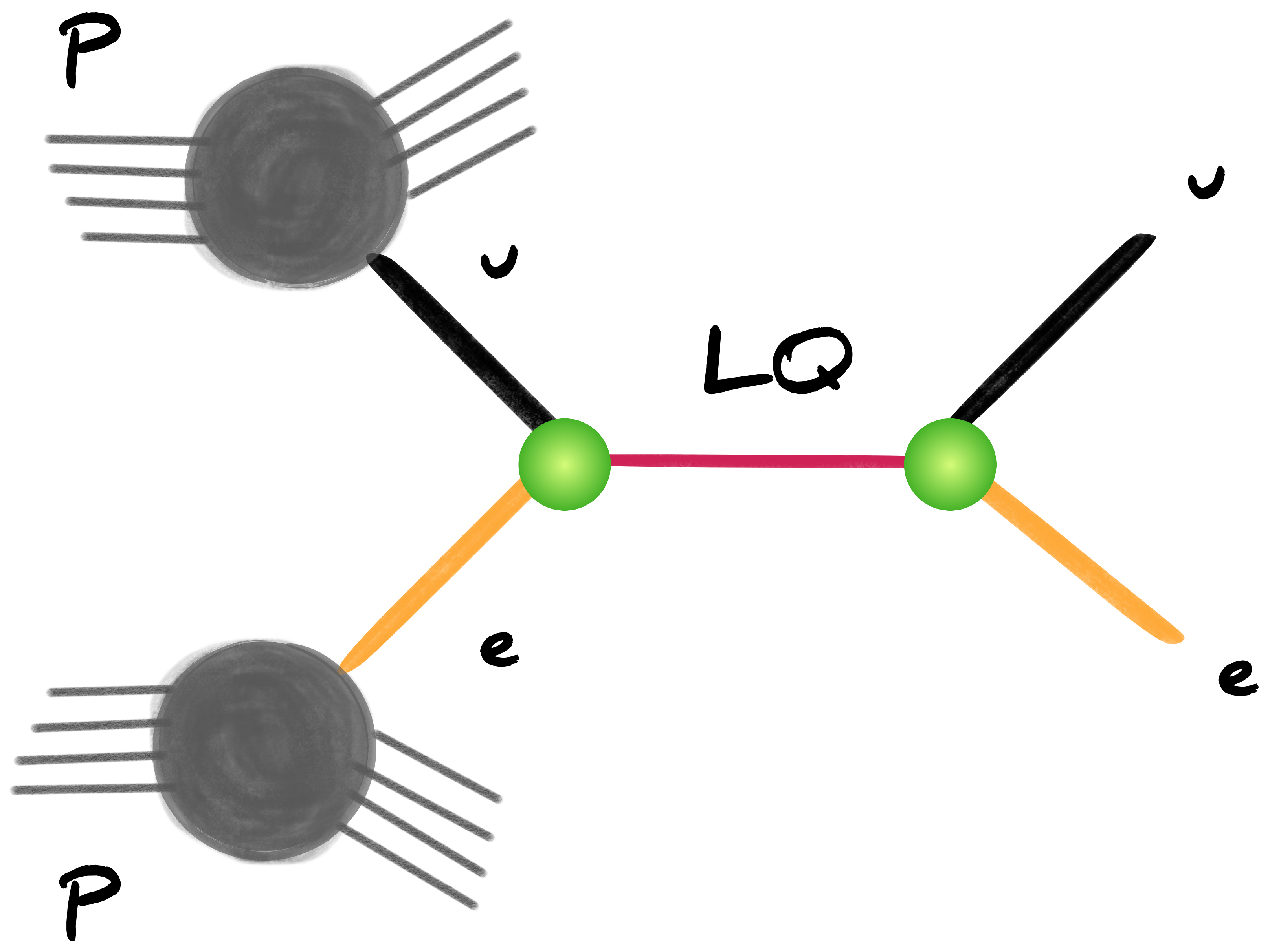


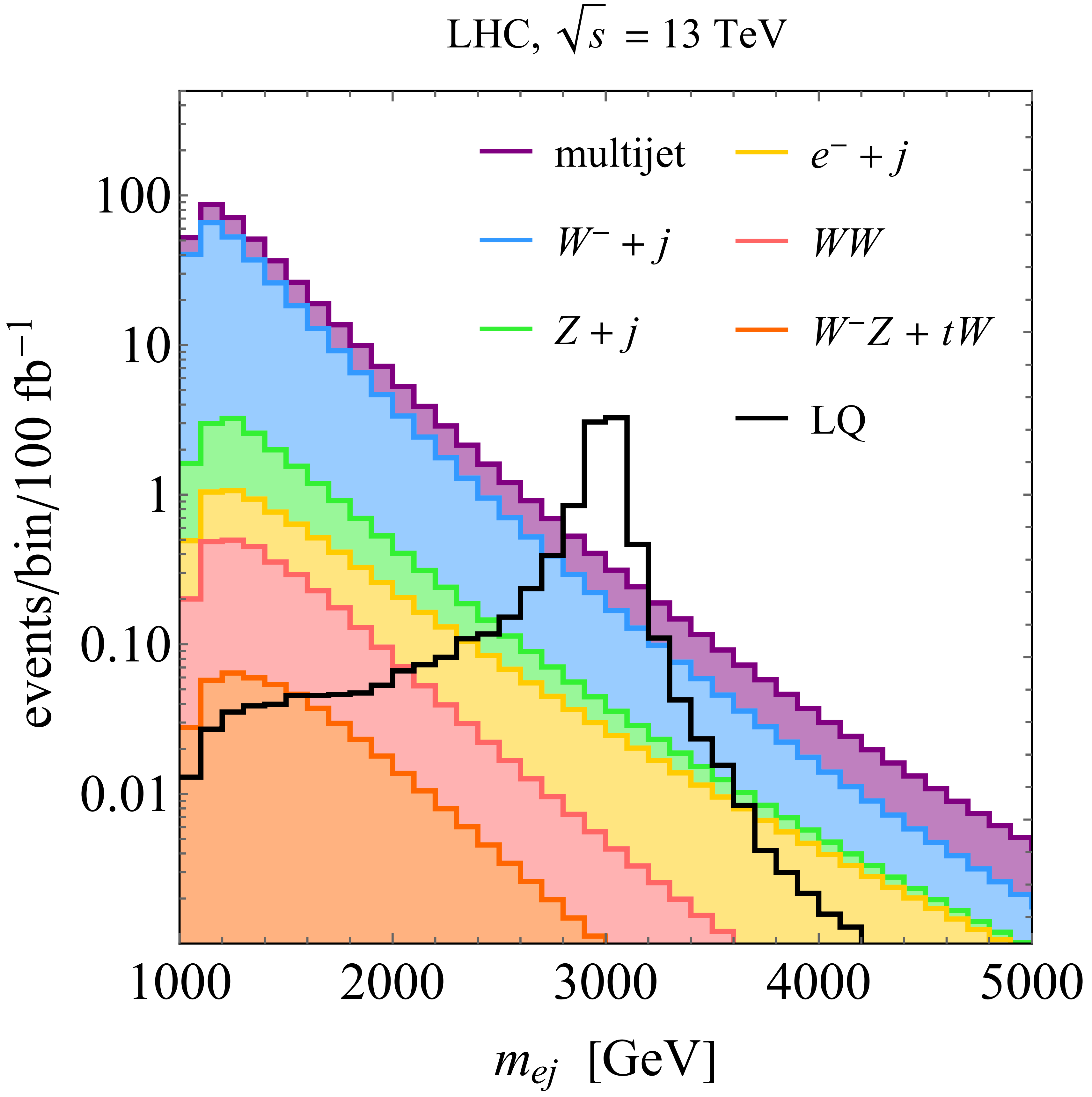
Quantum field theory to the rescue!



[Manohar et al., 1607.04266, 1708.01256; Buonocore et al., 2005.06477]

Resonant LQ production @ LHC

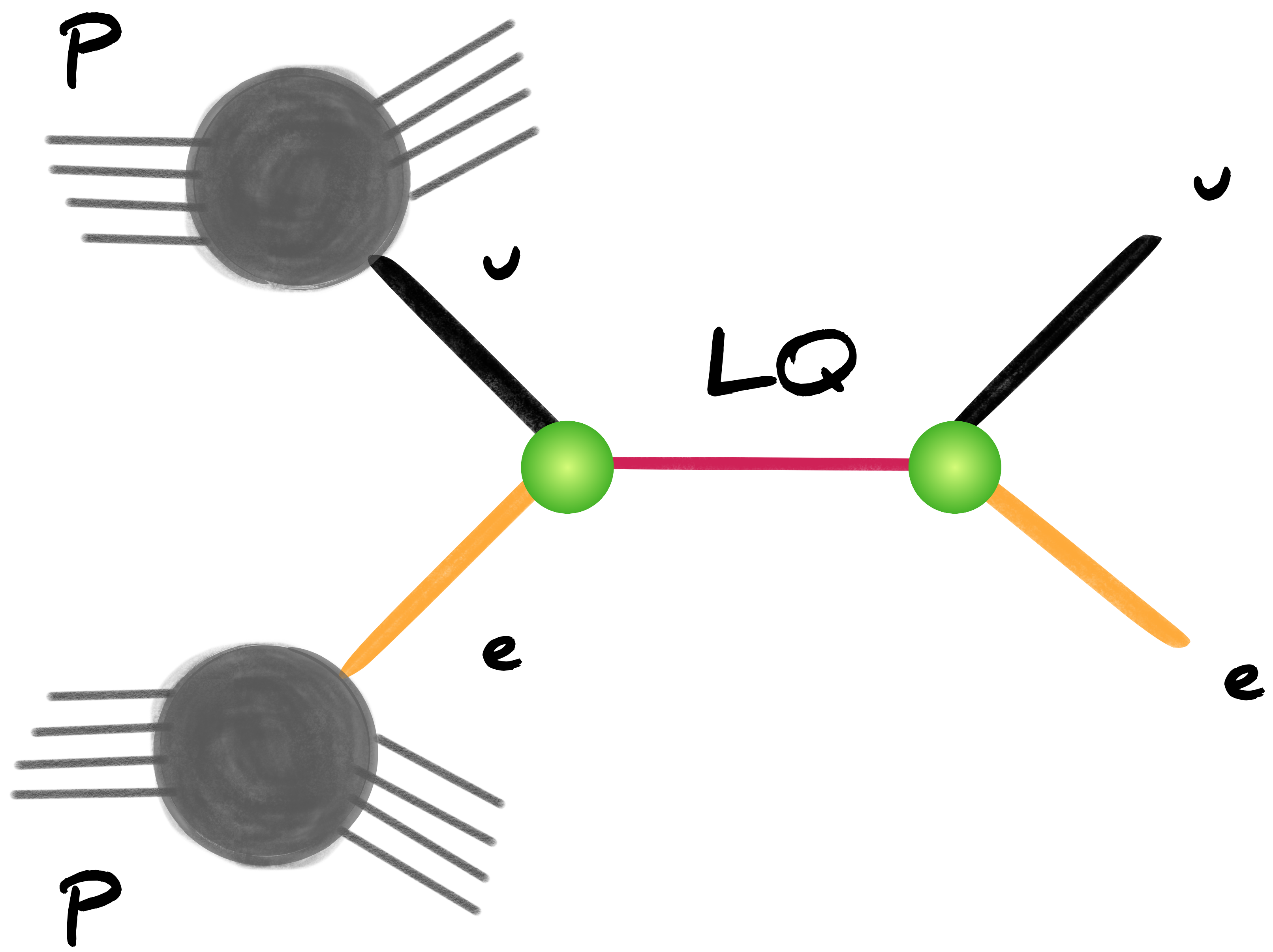


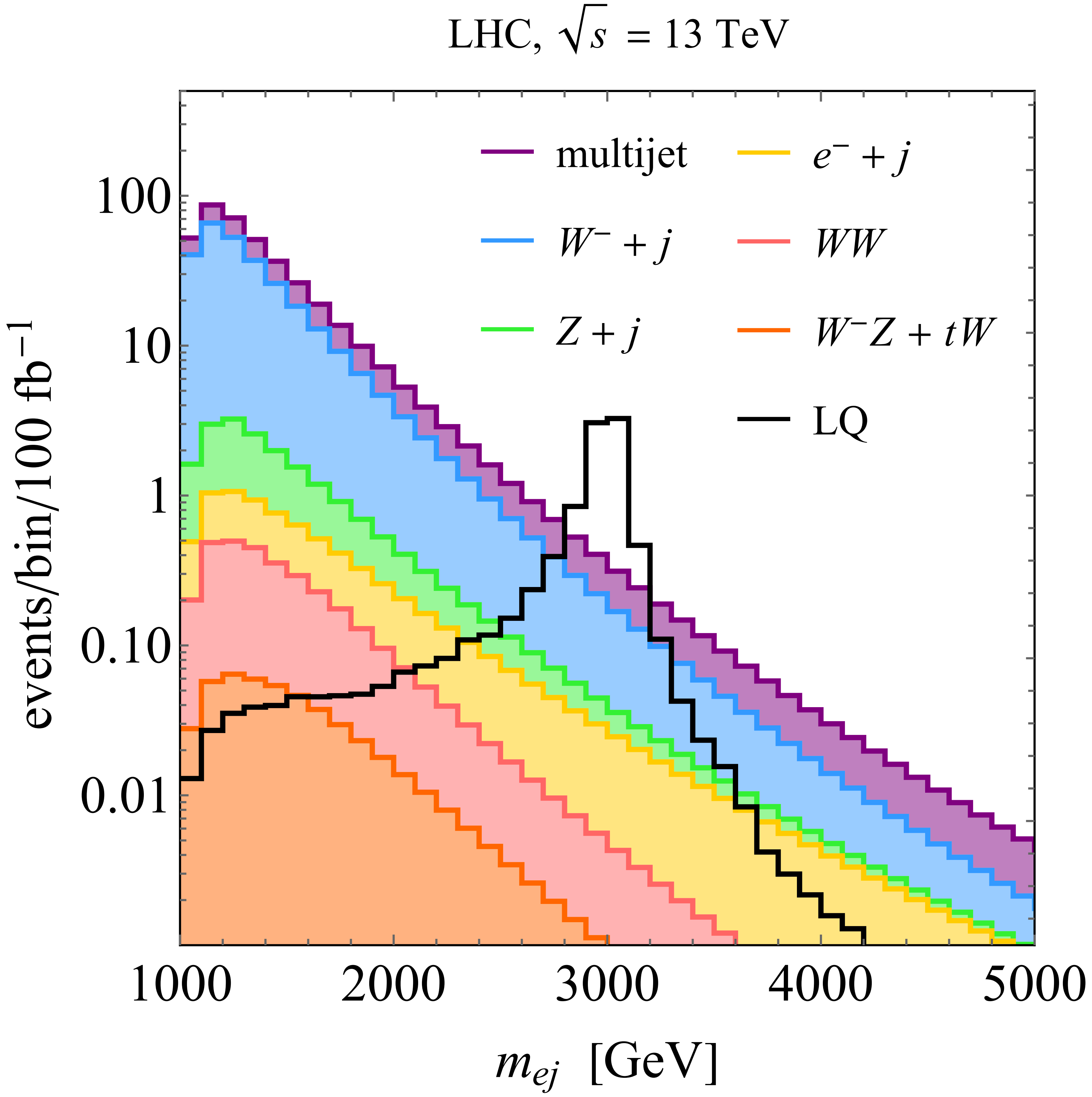


Non-zero lepton PDFs allow for resonant LQ production @ pp machines such as LHC

[search strategy proposed in Buonocore et al., 2005.06475 & refined in Greljo & Selimovic, 2012.02092; Buonocore et al., 2209.02599]

Resonant LQ production @ LHC

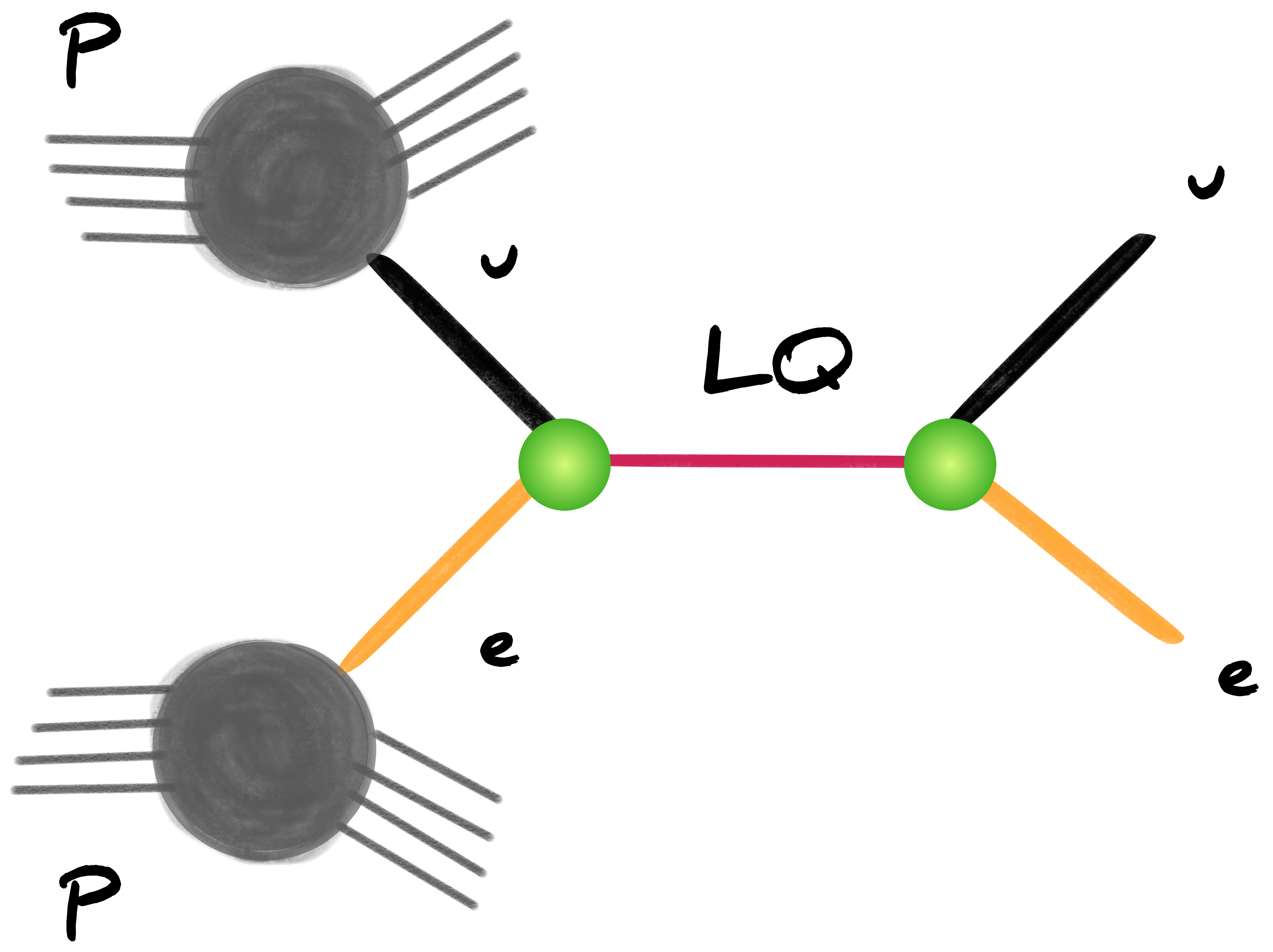


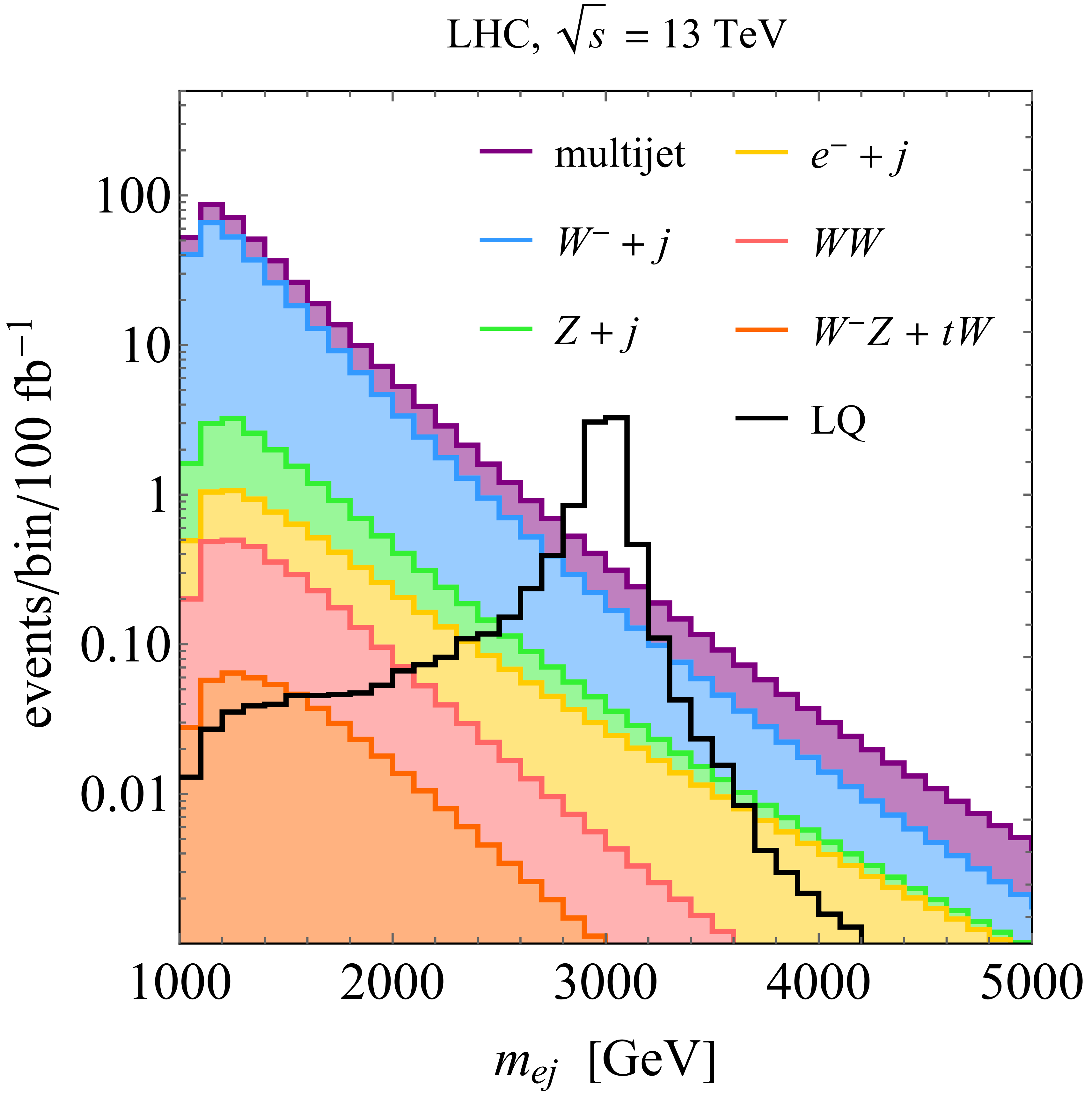


Sum over backgrounds is a steeply falling distribution, while signal exhibits a narrow peak

[search strategy proposed in Buonocore et al., 2005.06475 & refined in Greljo & Selimovic, 2012.02092; Buonocore et al., 2209.02599]

Resonant LQ production @ LHC

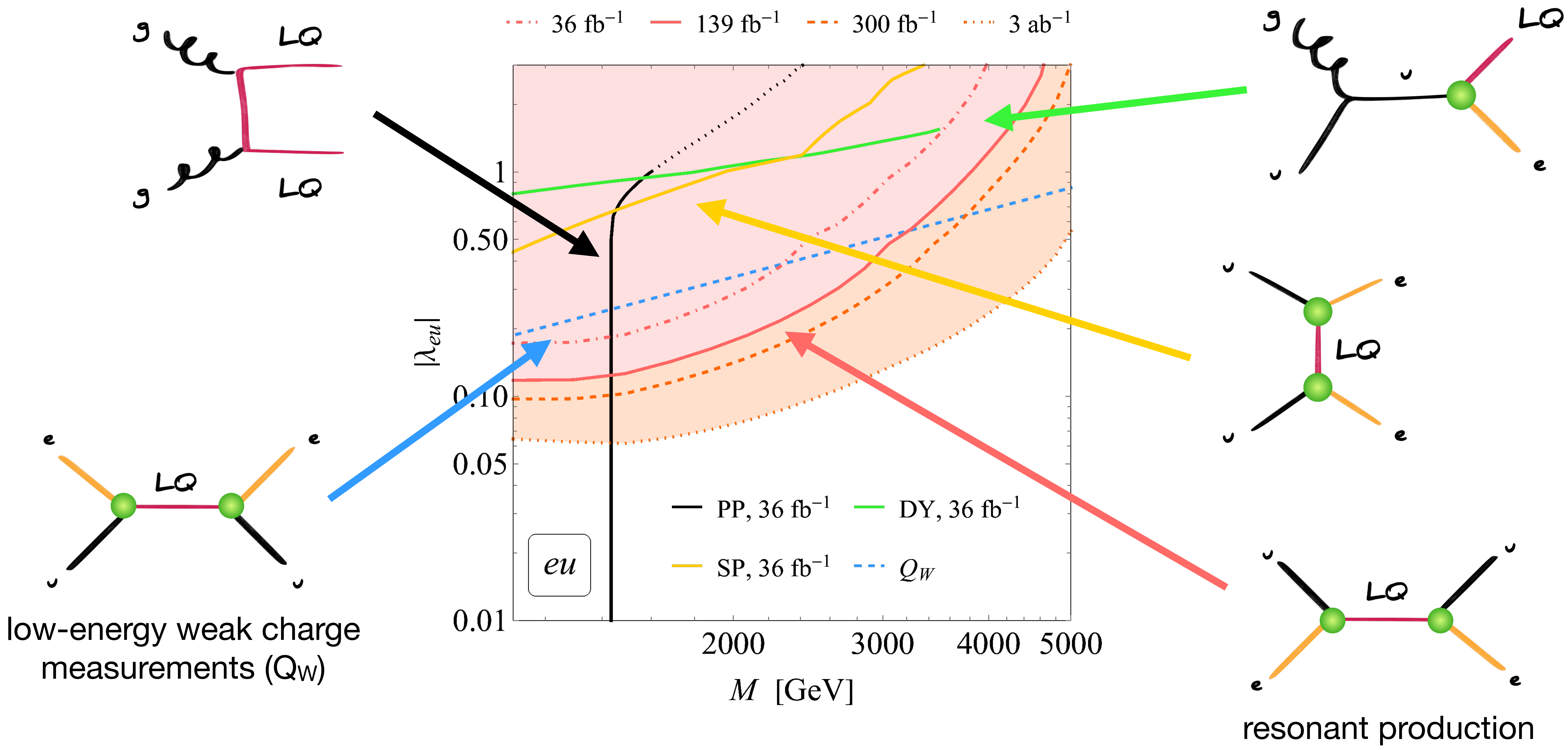




Compared to 1 background event, 9 events per 100 fb^{-1} for LQ of M = 3 TeV & λ_{eu} = 1 @ 13 TeV

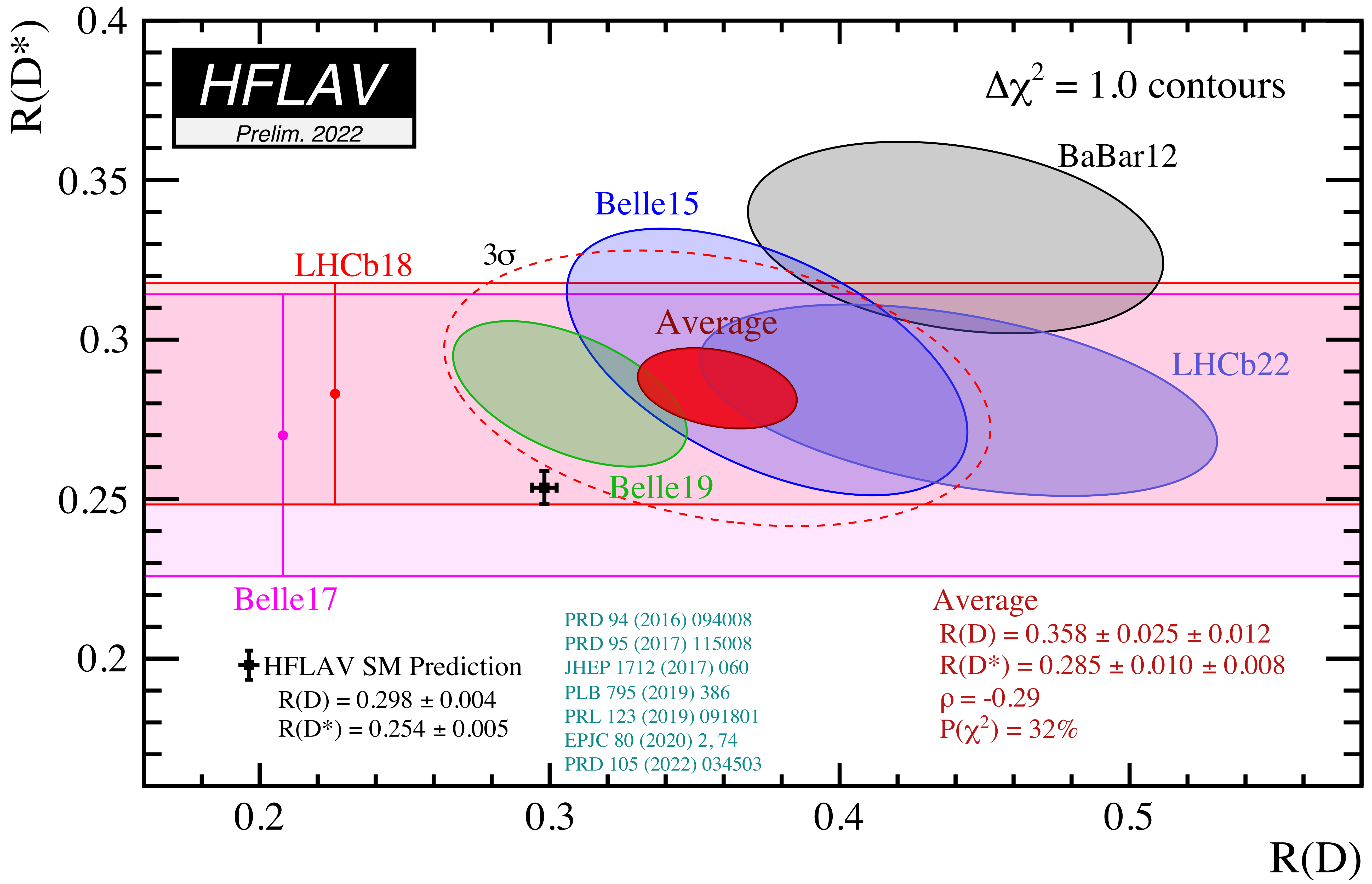
[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

LHC limits on 1st & 2nd generation LQs



[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

Lepton flavour non-universality in b → clν



BaBar, Belle & LHCb measurements of lepton flavour universality ratios $R_{D^{(*)}}$ show a 3σ tension

[https://hflav-eos.web.cern.ch/hflav-eos/semi/fall22/r_dtaunu/rdrds_prel_2022.pdf]

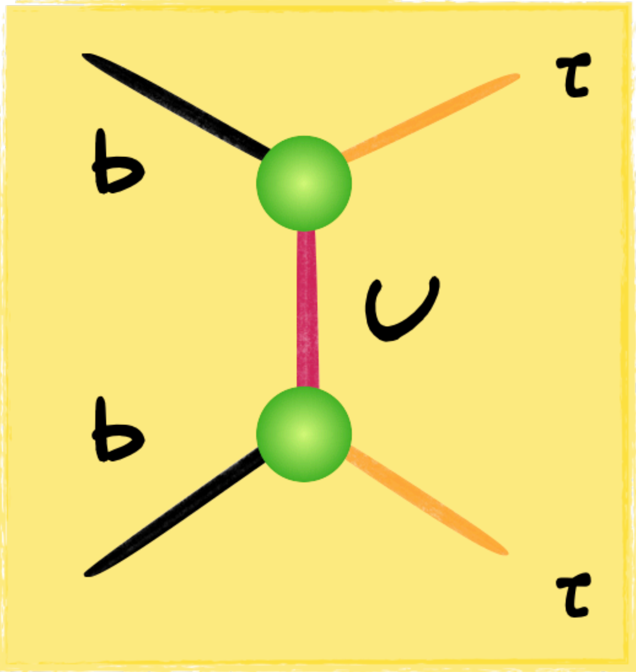
Singlet vector LQ models for B anomalies

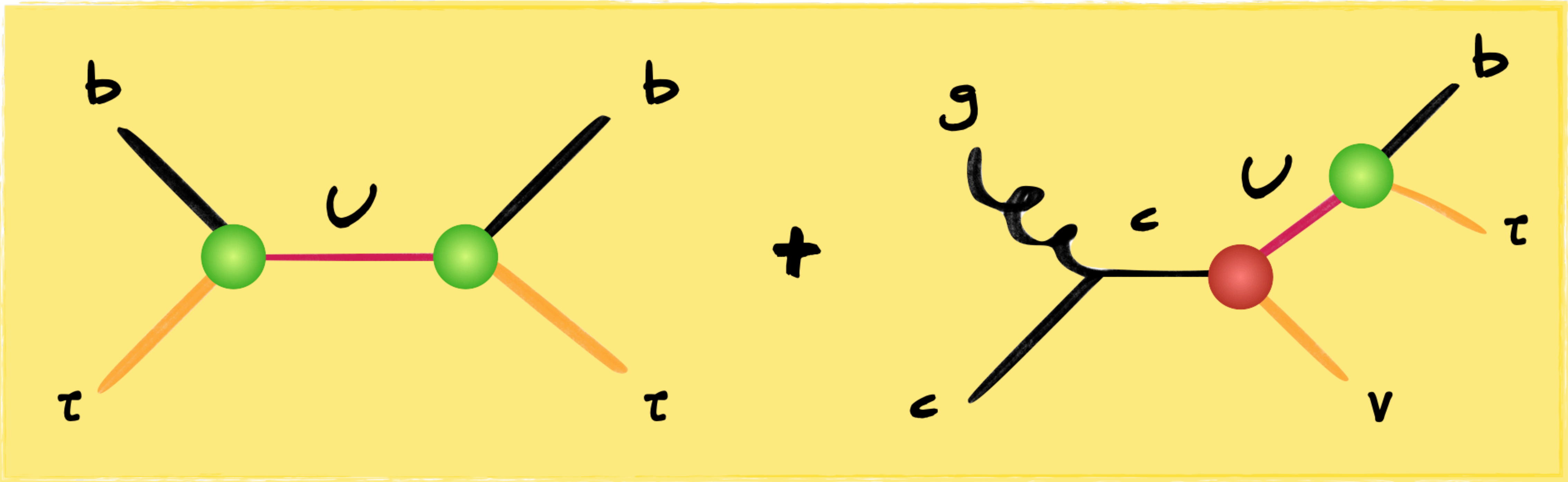
$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} \left[\beta_L^{ij}\, \bar{Q}_L^{i,a} \gamma_\mu L_L^j + \beta_R^{ij}\, \bar{d}_R^{i,a} \gamma_\mu \ell_R^j \right] U^{\mu,a} \; + \text{h.c.}$$

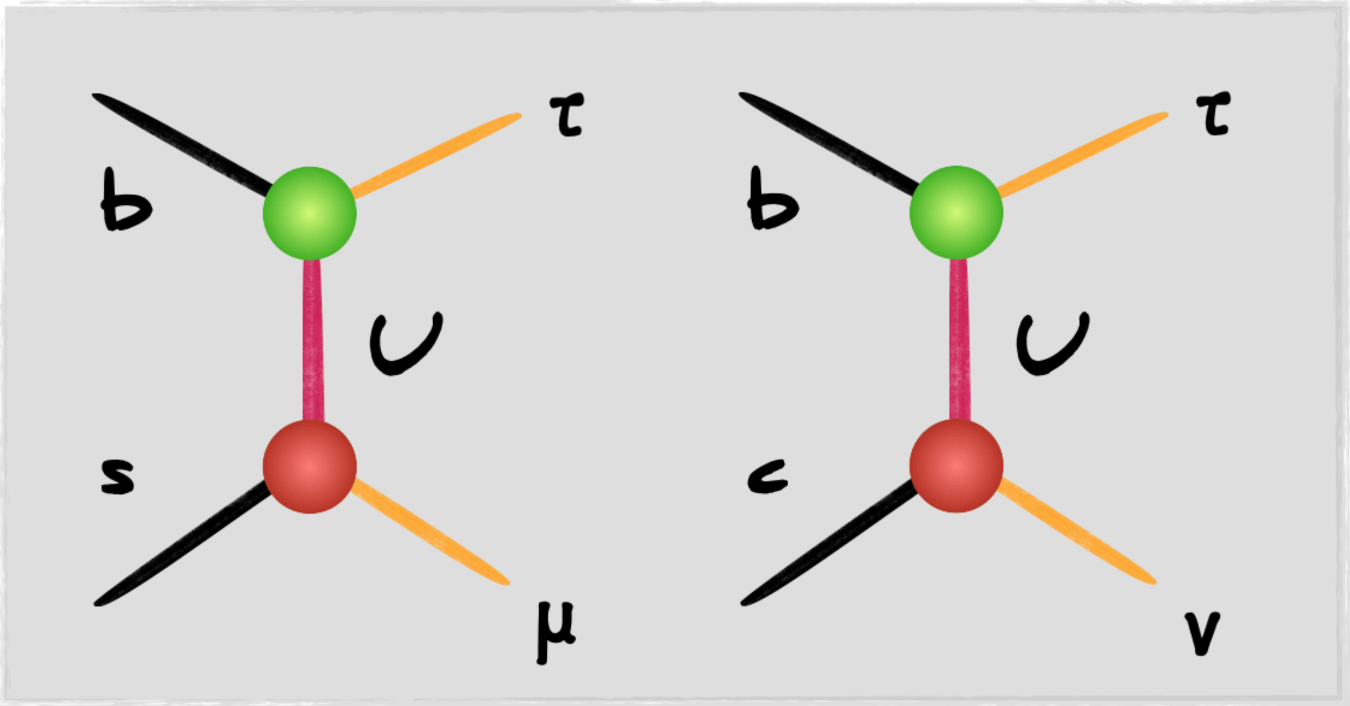
$$|\beta_L^{22}| \lesssim |\beta_L^{32}| \ll |\beta_L^{23}| \lesssim |\beta_L^{33}| = \mathcal{O}(1)$$

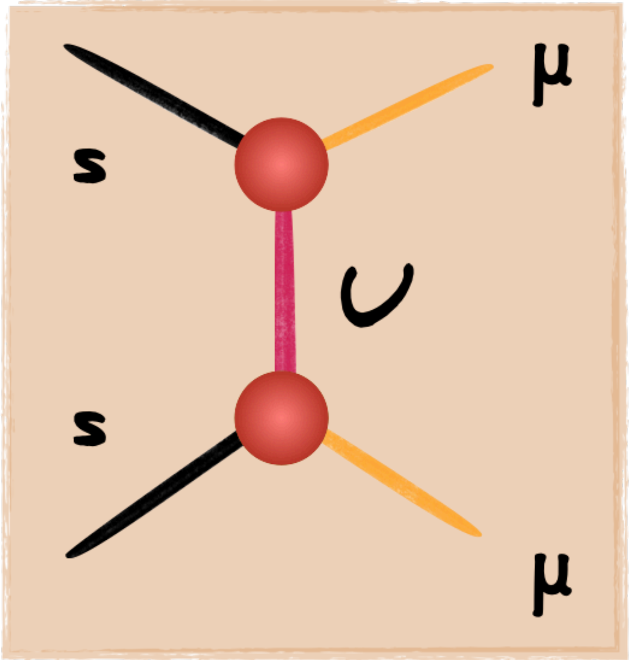
Parameters		Branching ratios			
β_L^{33}	β_L^{23}	$\text{BR}\,(U \to b\tau^+)$	$\text{BR}\,(U \to t\bar{\nu}_\tau)$	$\text{BR}\,(U \to s\tau^+)$	$\text{BR}\,(U \to c\bar{\nu}_\tau)$
1	0	51%	49%	0%	0%
1	1	25%	22%	25%	27%

Possible singlet vector LQ signatures





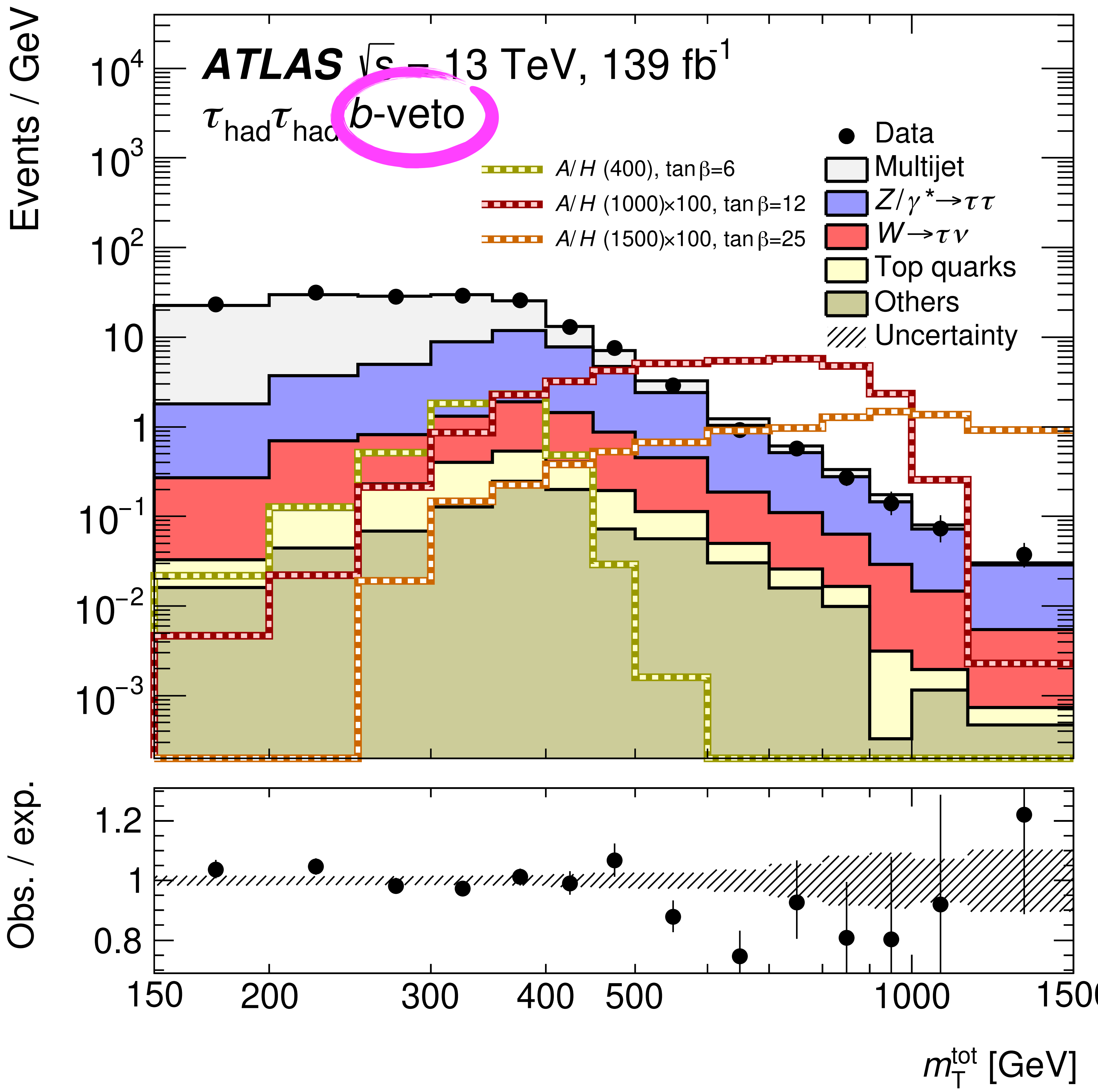


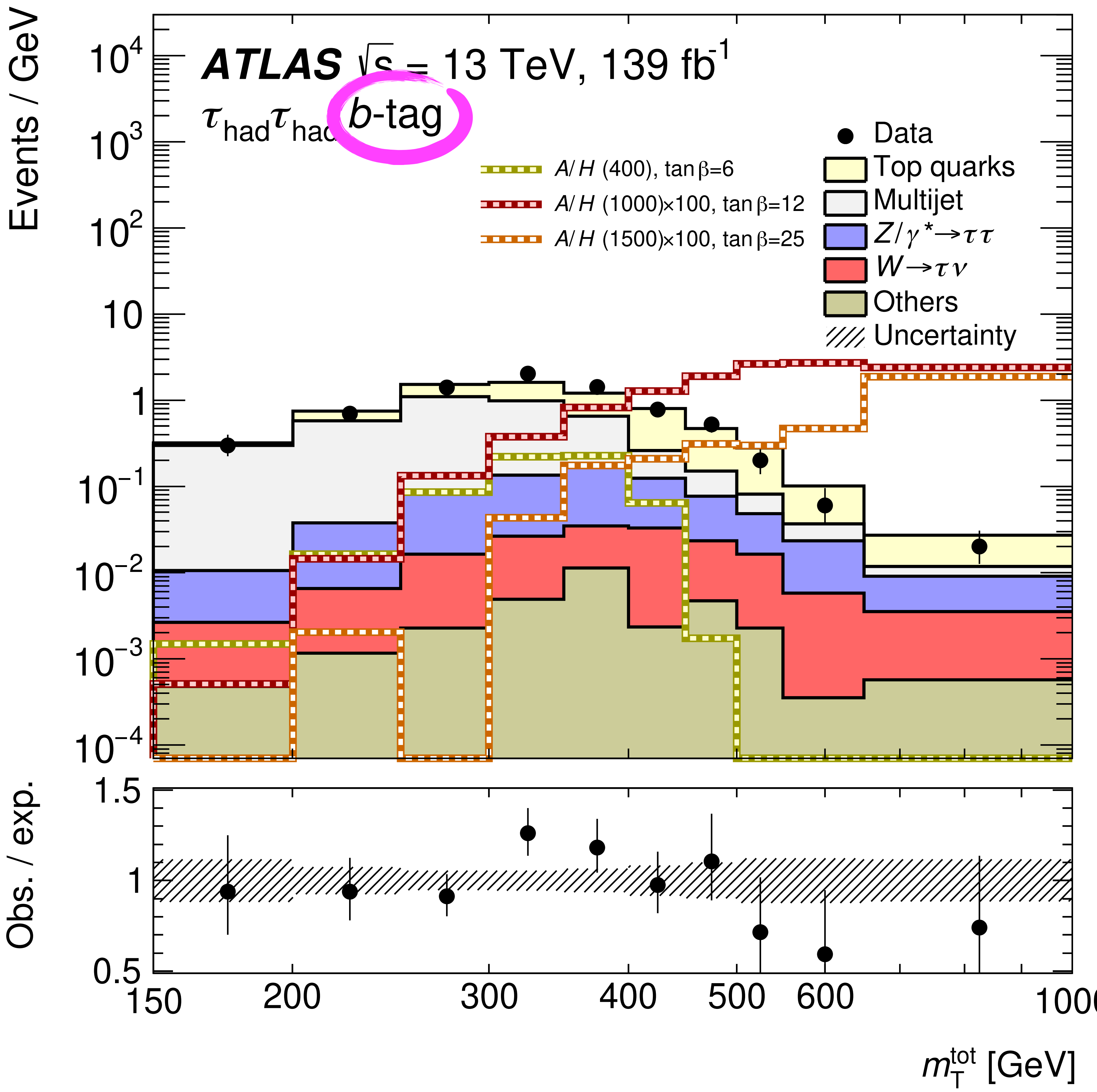


$b \to c l \nu$ anomalies single out $pp \to \tau^+\tau^-$ as most interesting channel. After latest LHCb measurements of $R_{K^{(*)}}$, $pp \to b\tau$, $\tau\mu$, $\tau\nu$ & $\mu^+\mu^-$ production seem less relevant

[singlet vector LQ effects in $pp \to b\tau$, mono-top & mono-jet production have been studied in UH & Polesello, 2012.11474]

Ditau searches @ LHC Run II

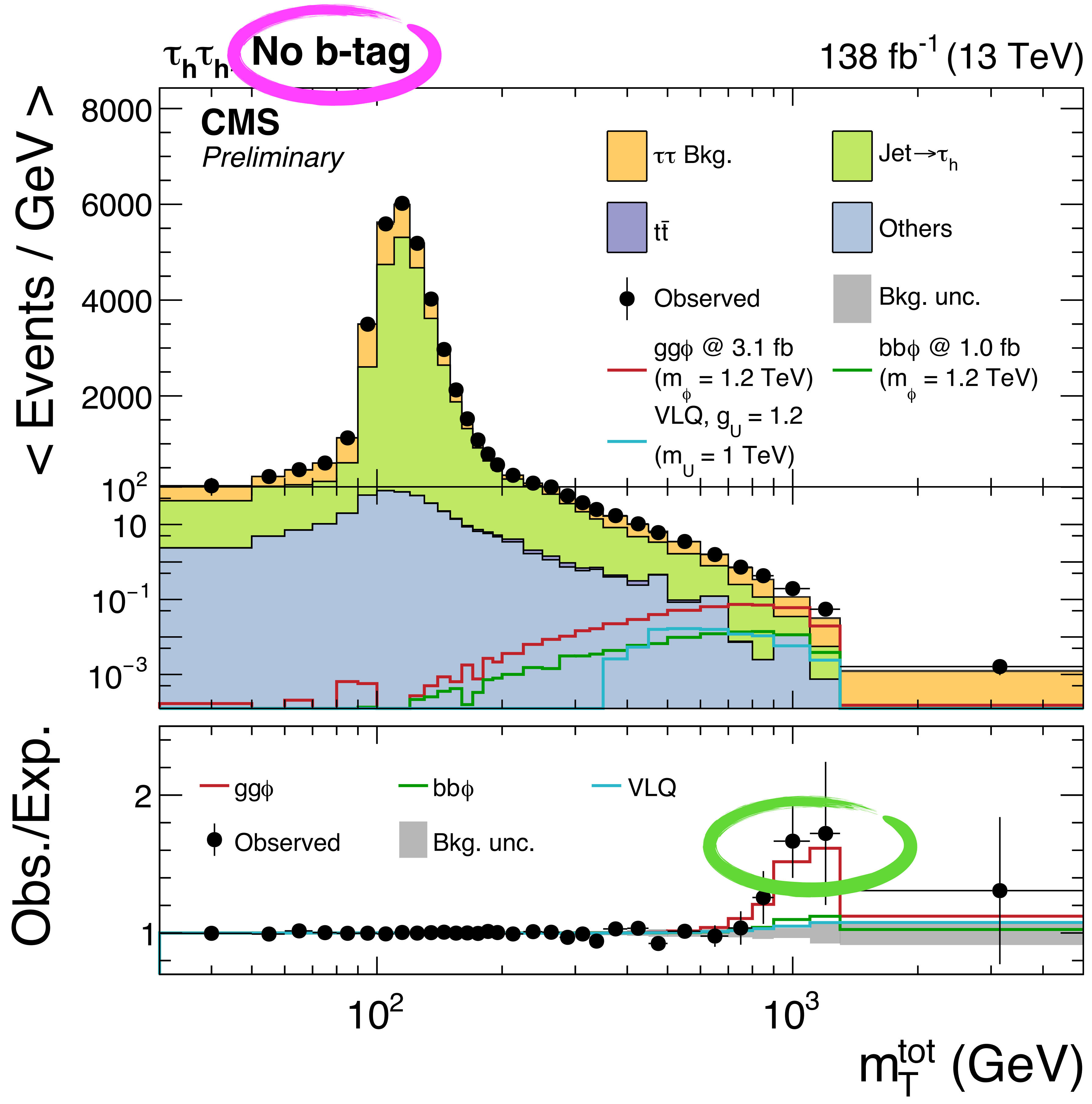


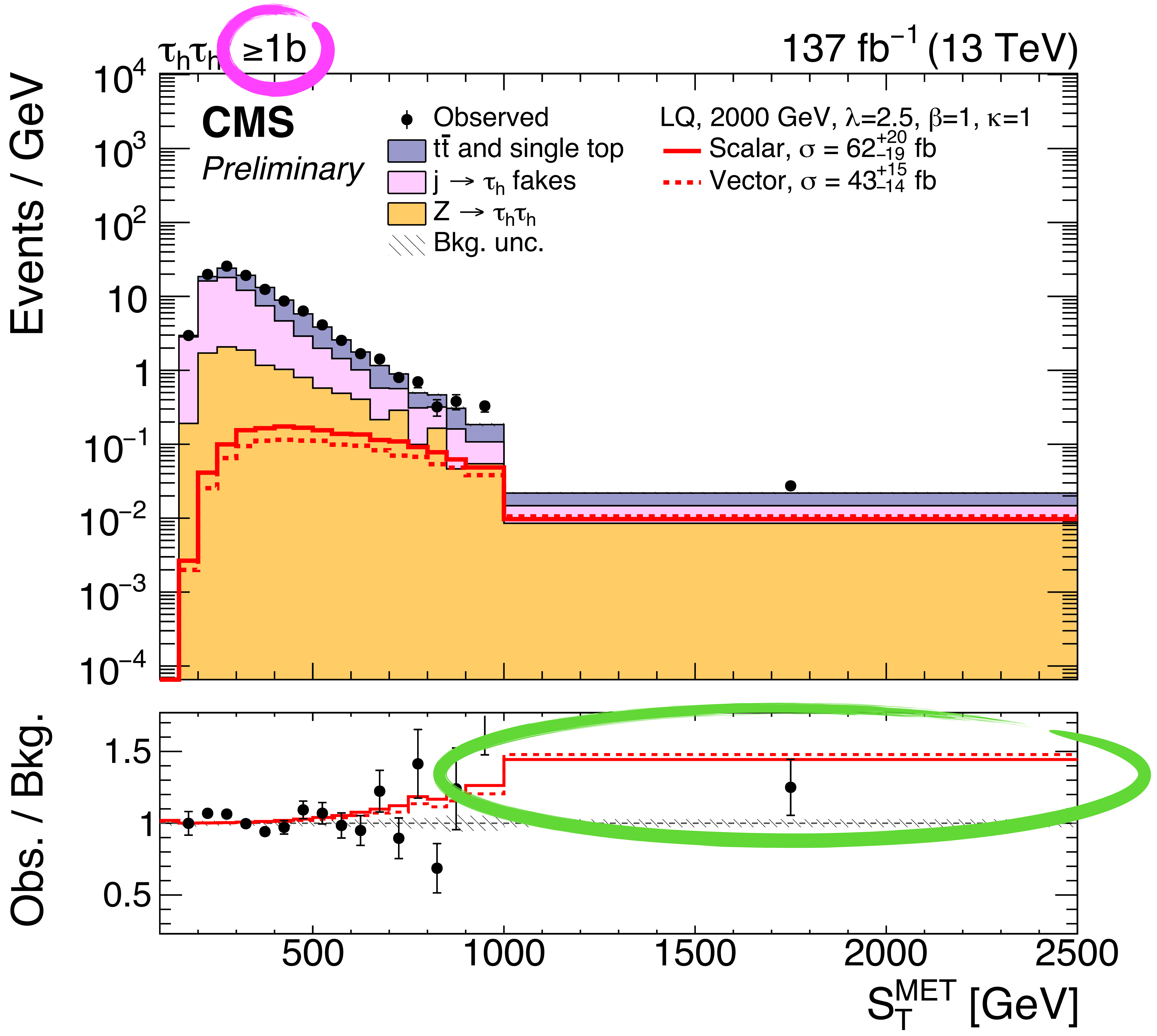


Three different ditau LHC Run II analyses, all considering events without & with an extra b-jet

[ATLAS, 2002.12223; CMS, 2208.02717; CMS PAS EXO-19-016]

Ditau searches @ LHC Run II

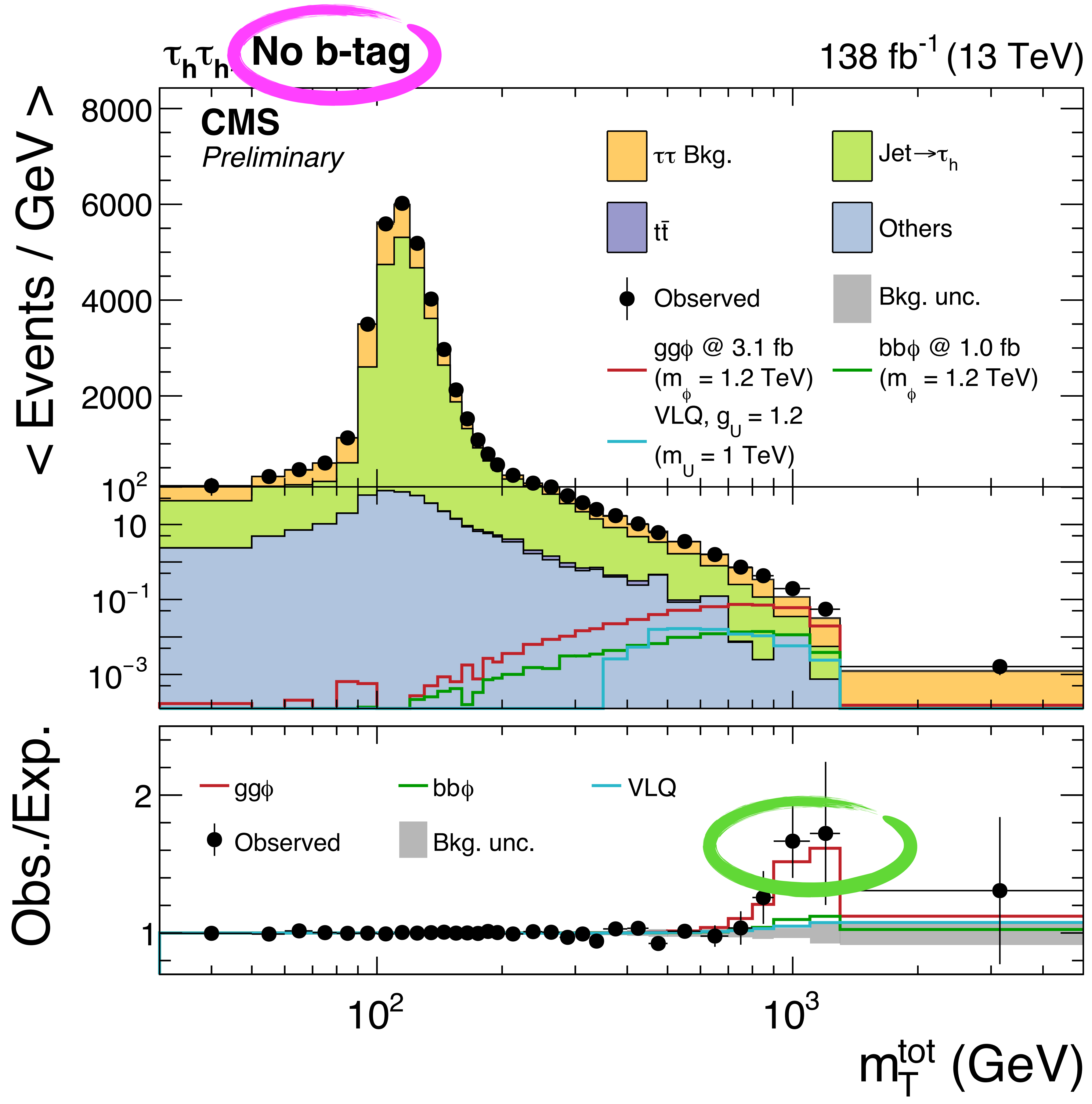


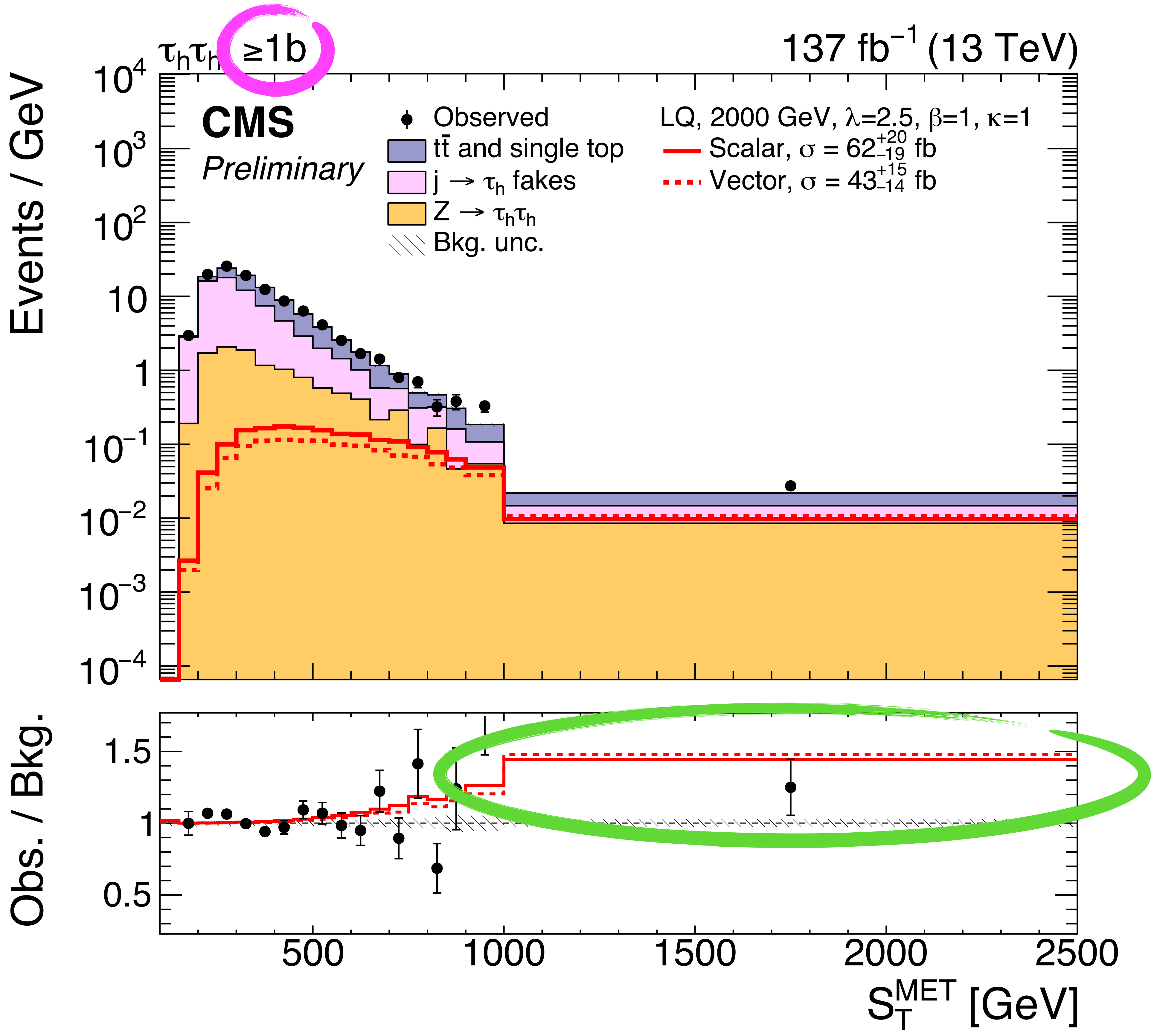


ATLAS data agrees with background predictions but both CMS analyses see a 3σ excess

[ATLAS, 2002.12223; CMS, 2208.02717; CMS PAS EXO-19-016]

Ditau searches @ LHC Run II

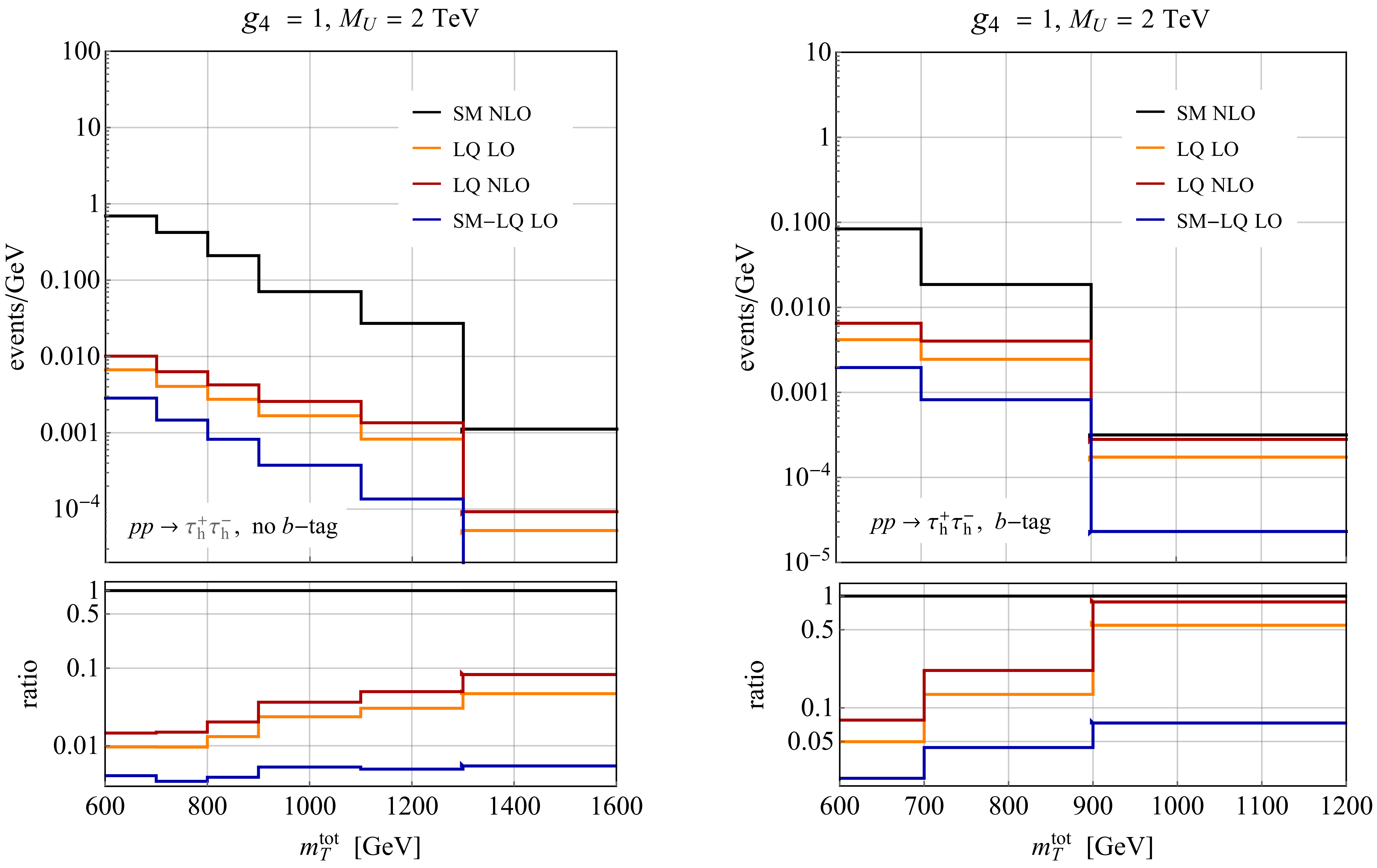




Non-resonant (resonant) excess in b-tag (b-veto) sample fits (does not fit) LQ explanation

[ATLAS, 2002.12223; CMS, 2208.02717; CMS PAS EXO-19-016]

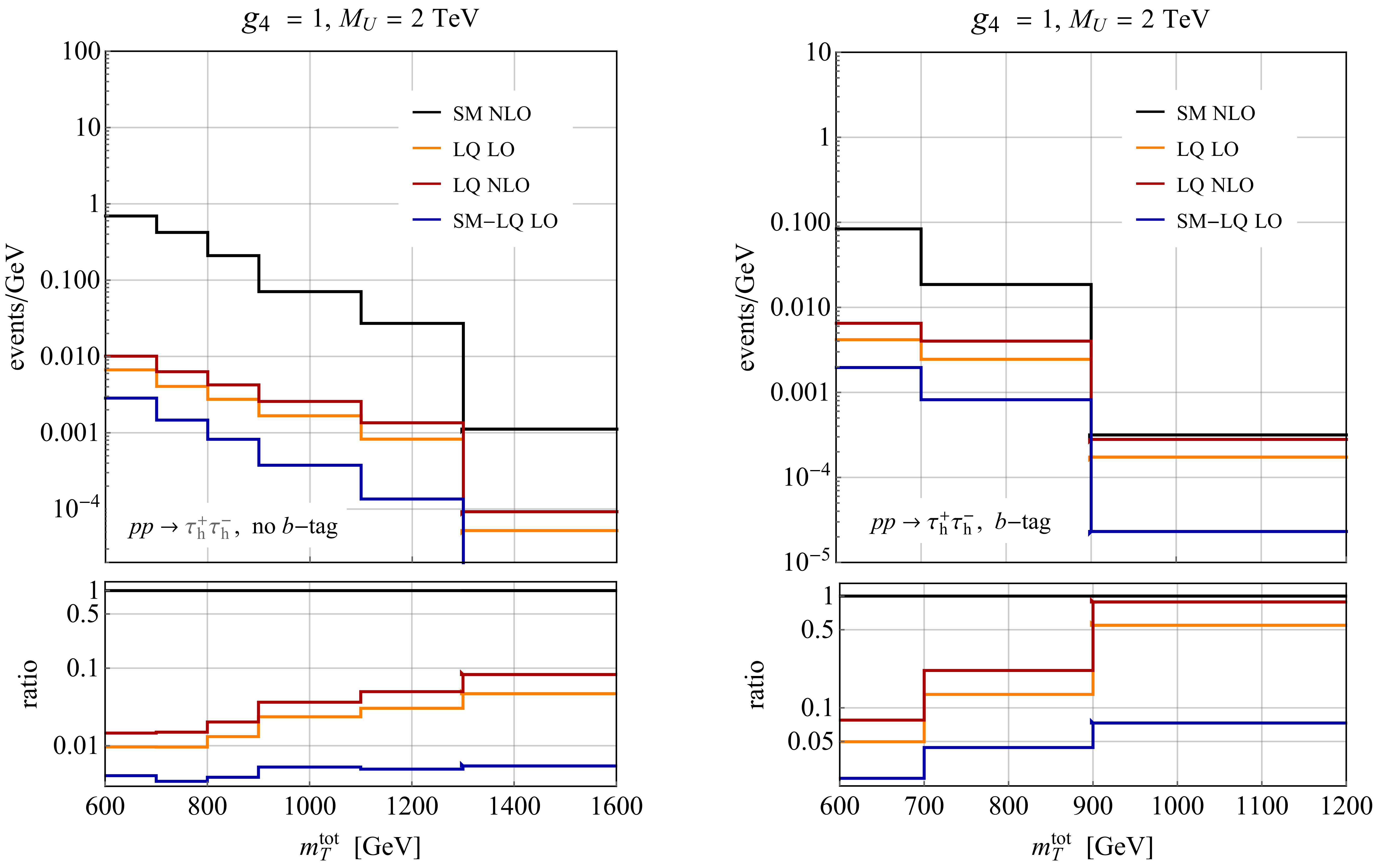
Size of NLO & interference effects



In b-veto (b-tag) sample, LQ corrections amount to 10% (85%) compared to DY background

[UH, Schnell & Schulte, 2209.12780]

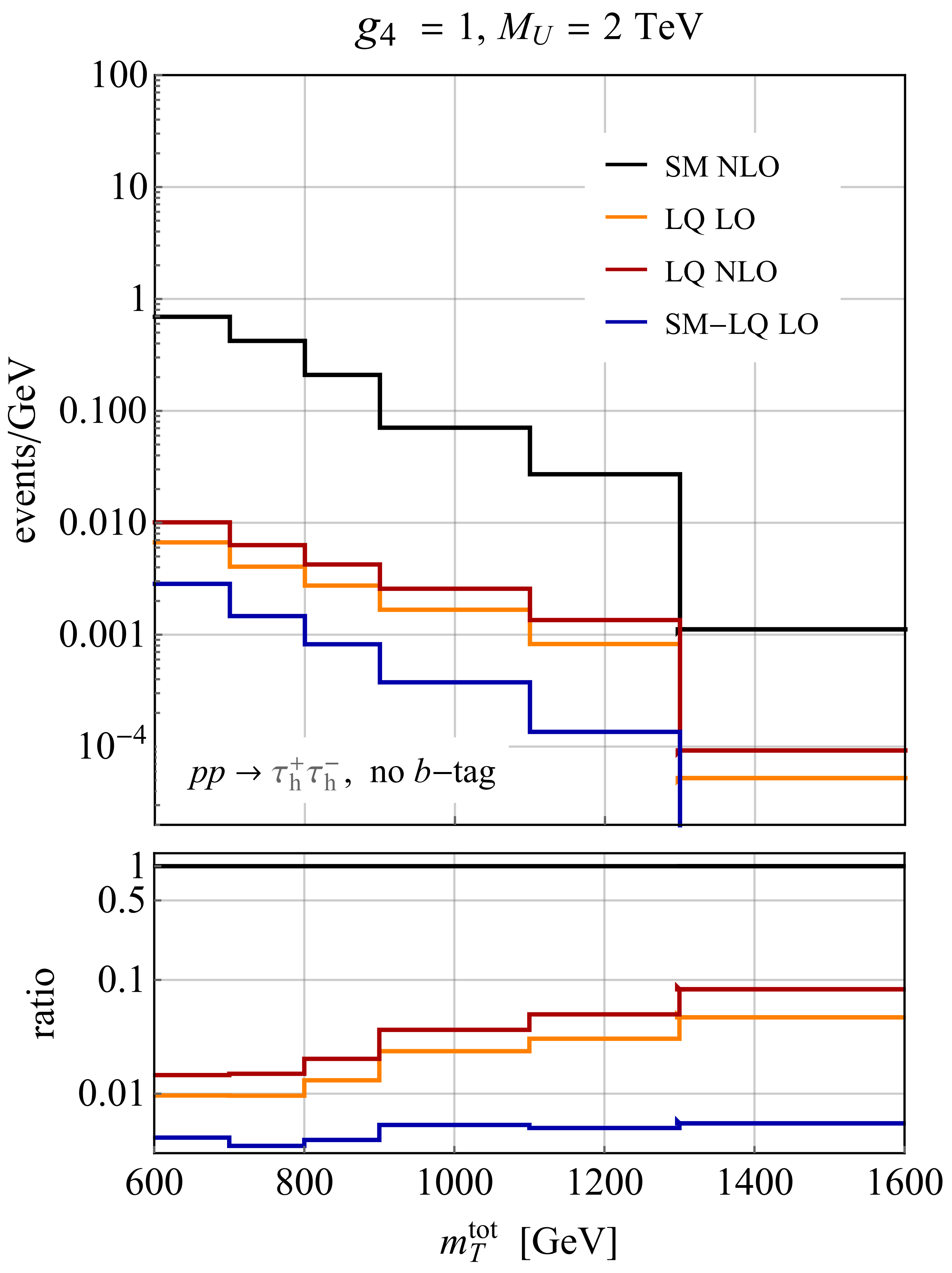
Size of NLO & interference effects

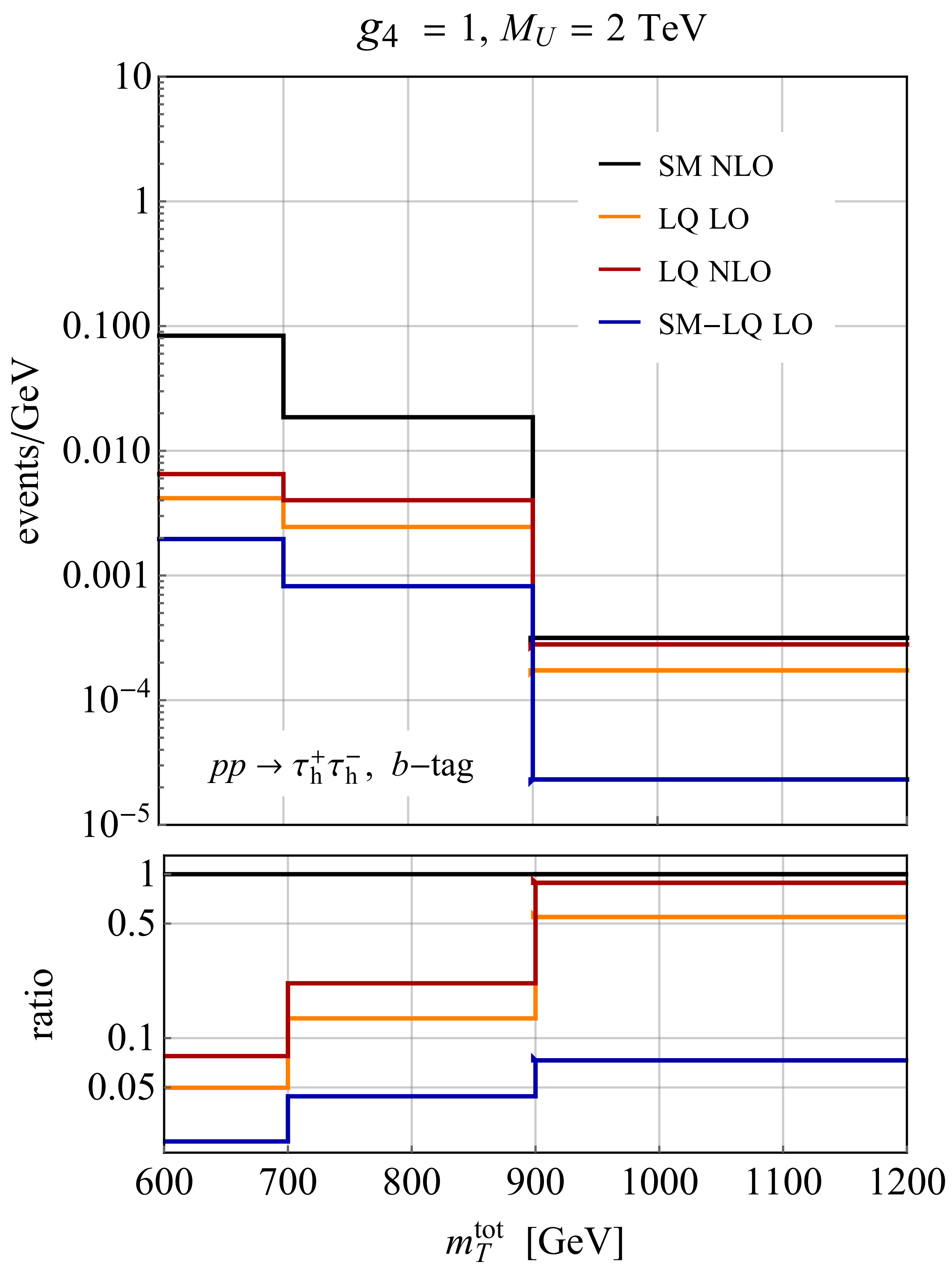


NLO QCD corrections exceed 50% in signal regions & grow in size with transverse mass

[UH, Schnell & Schulte, 2209.12780]

Size of NLO & interference effects

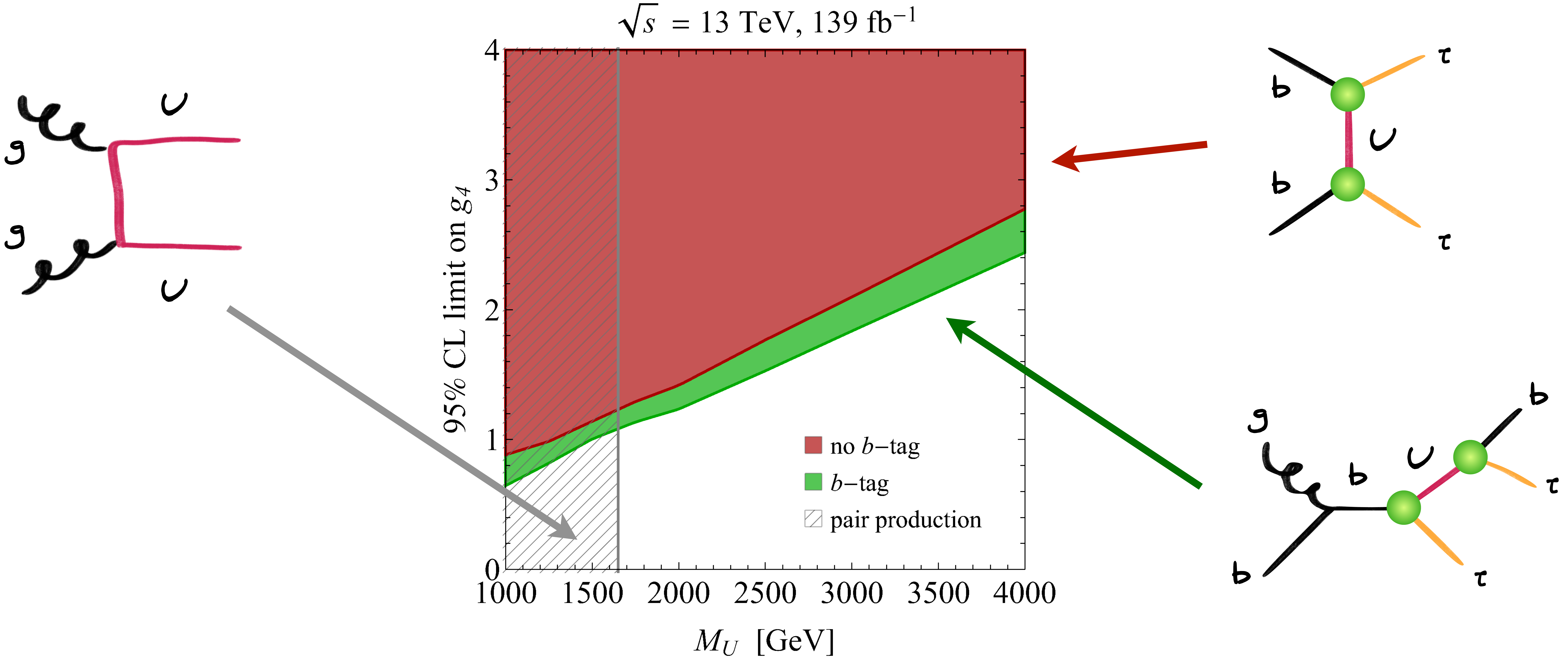




Relative to LQ tree-level contributions interference effects do not exceed level of 10%

[UH, Schnell & Schulte, 2209.12780]

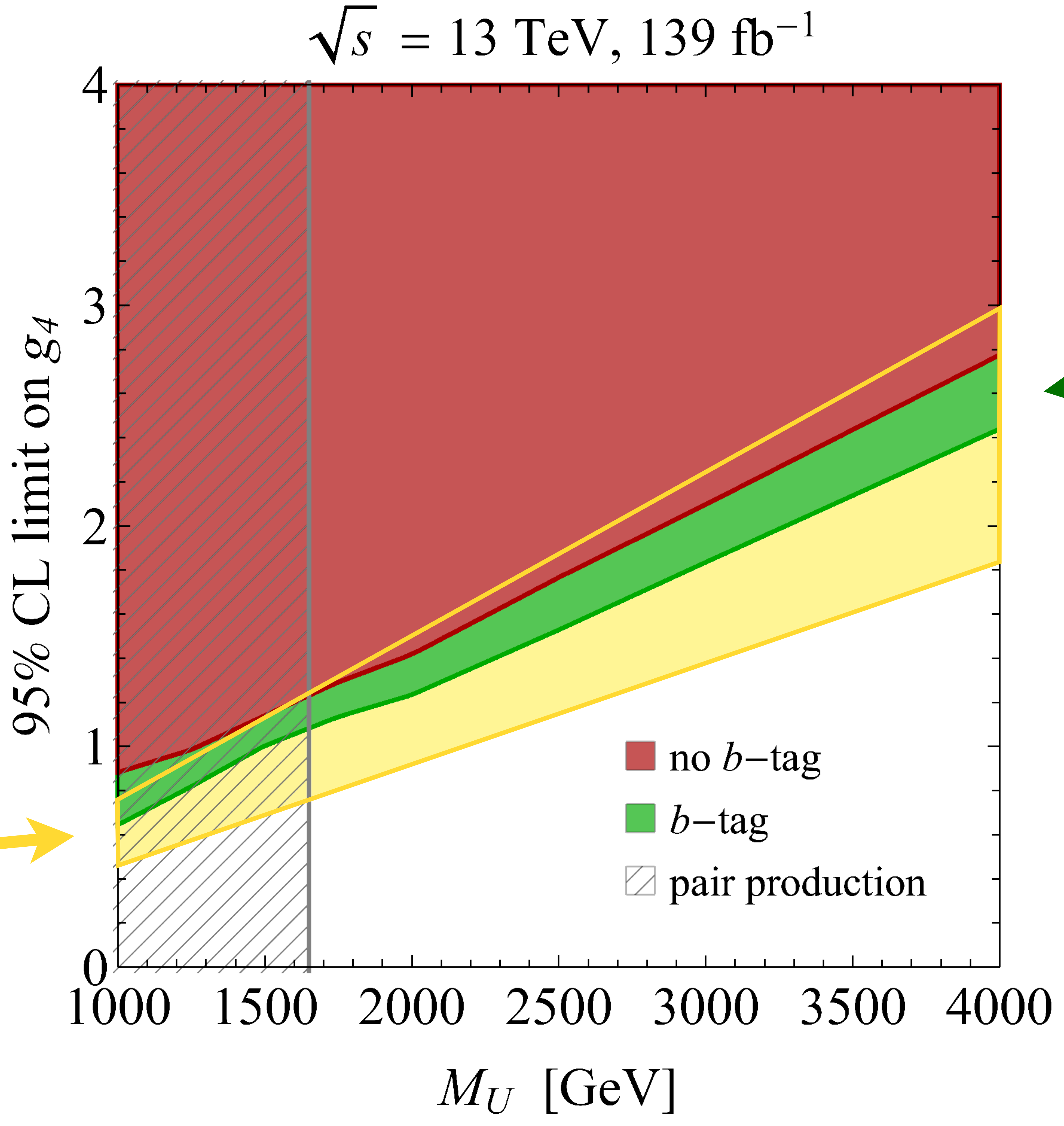
ATLAS ditau limits on singlet vector LQs



[UH, Schnell & Schulte, 2209.12780]

ATLAS ditau limits on singlet vector LQs

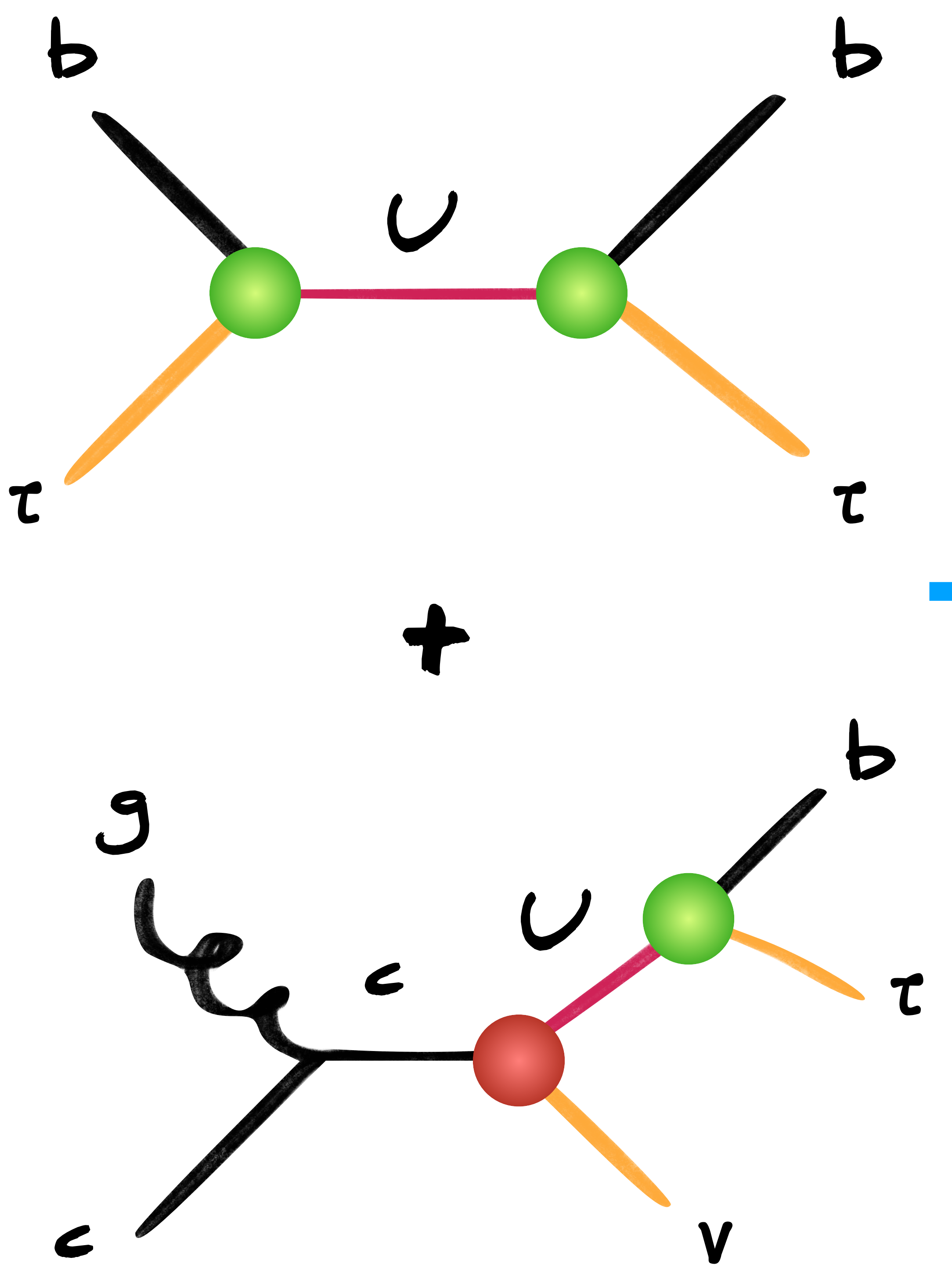
95% CL region favoured by b → c anomalies

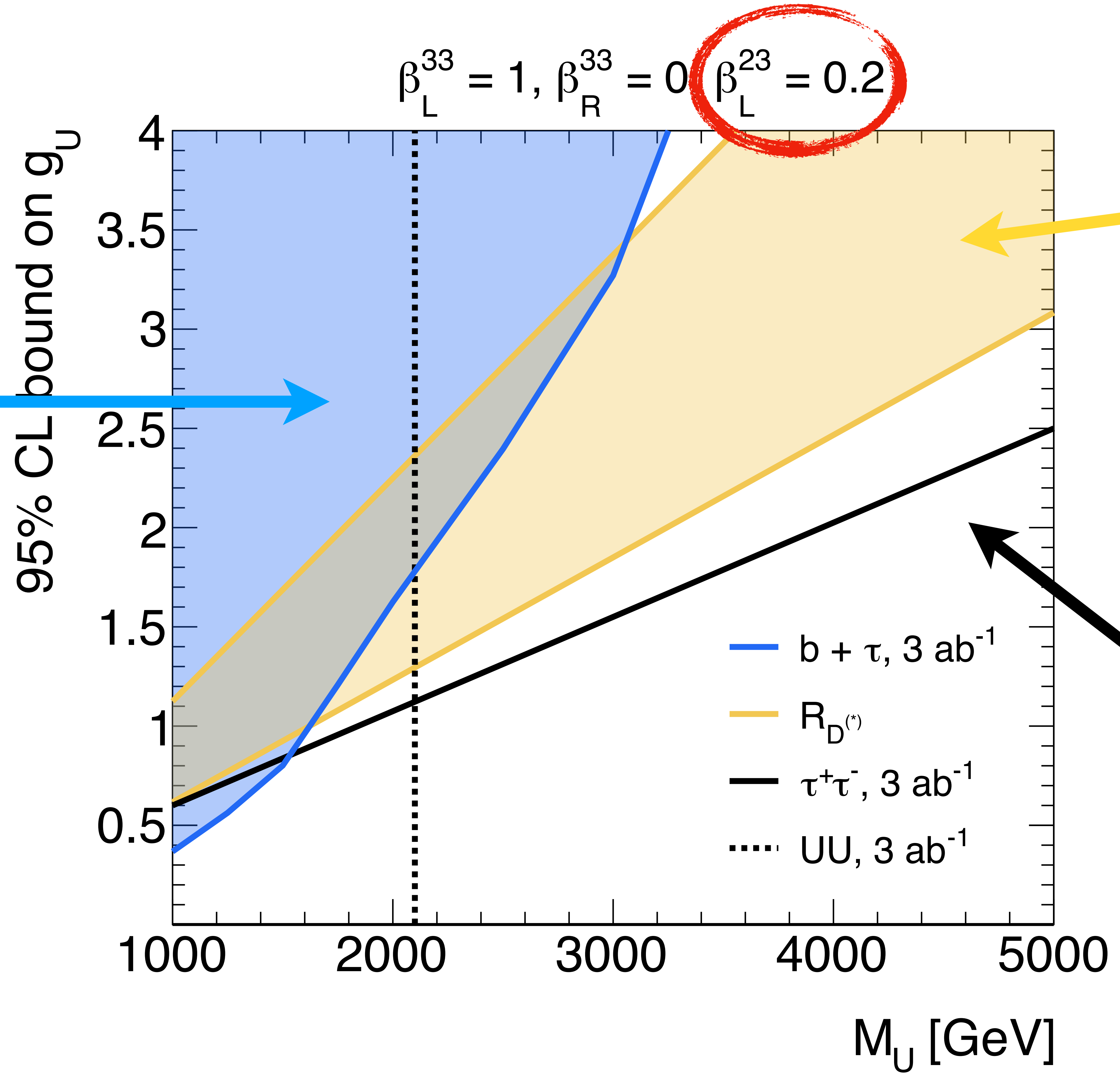


ditau constraints start to test LQ explanations of b → c anomalies — leading limits arise from events with b-jets

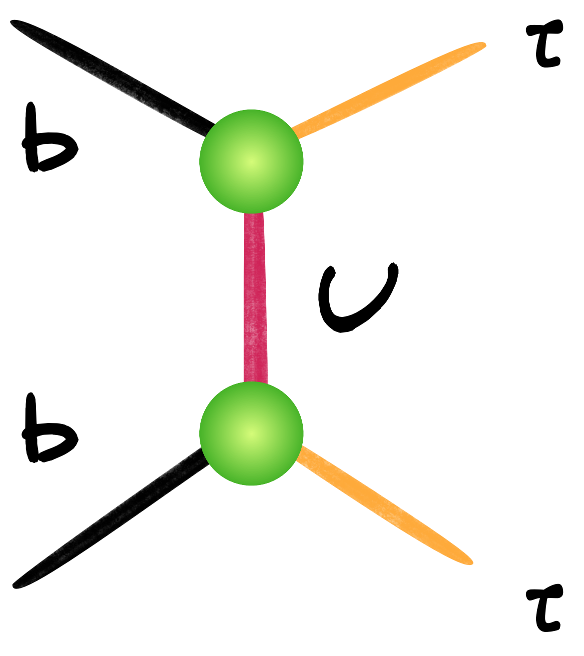
[UH, Schnell & Schulte, 2209.12780]

LHC 3 ab^{-1} projections for singlet vector LQs





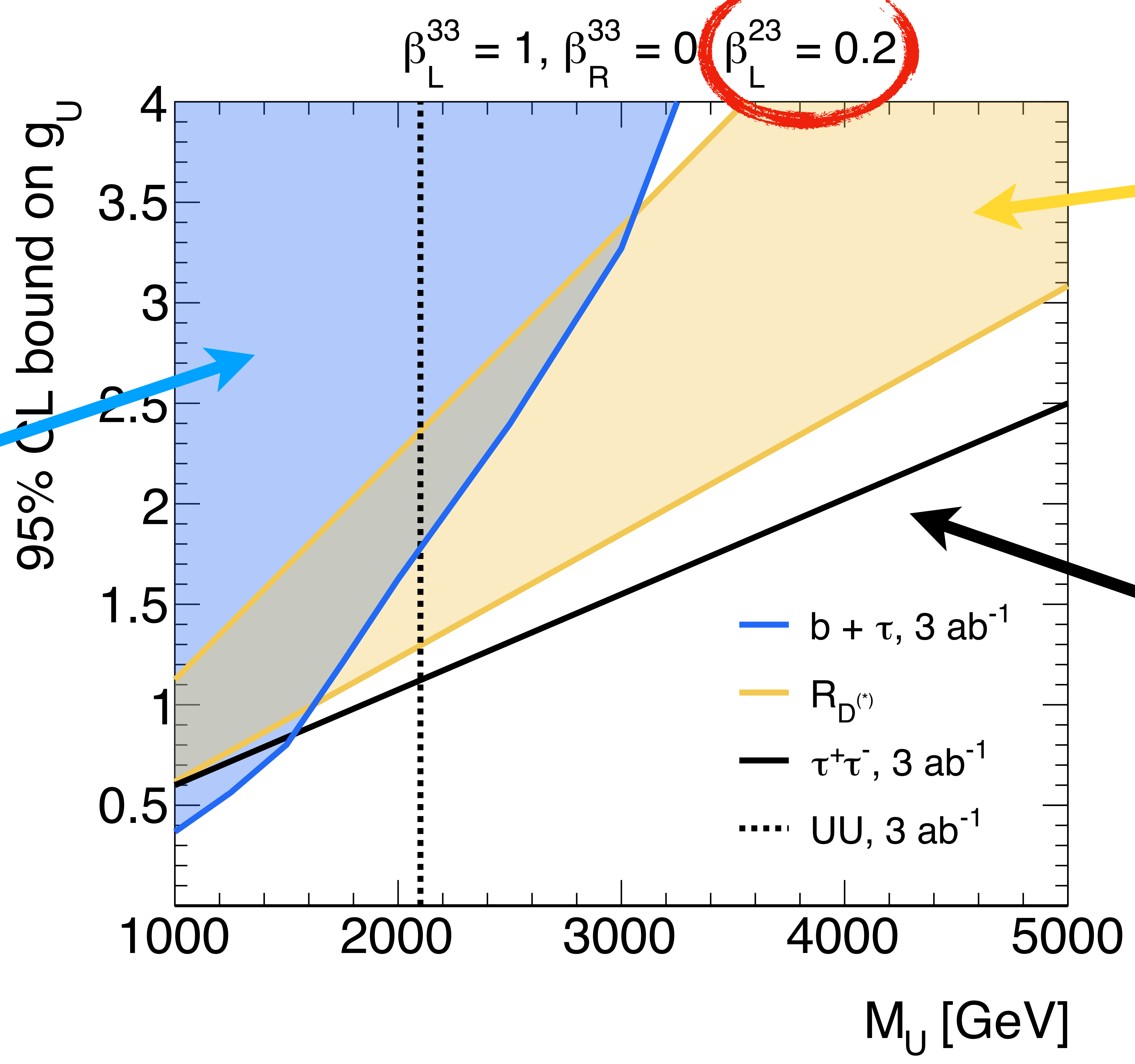
95% CL region favoured by b → c anomalies



[UH & Polesello, 2012.11474; Cornella, Faroughy, Fuentes-Martin, Isidori & Neubert, 2103.16558]

LHC 3 ab^{-1} projections for singlet vector LQs

weaker but complementary information provided by searches for resonant 3rd-generation LQ signatures



95% CL region favoured by b → c anomalies

probably all singlet vector LQ explanations of b → c anomalies can be tested with 3 ab^{-1} of data via ditau searches

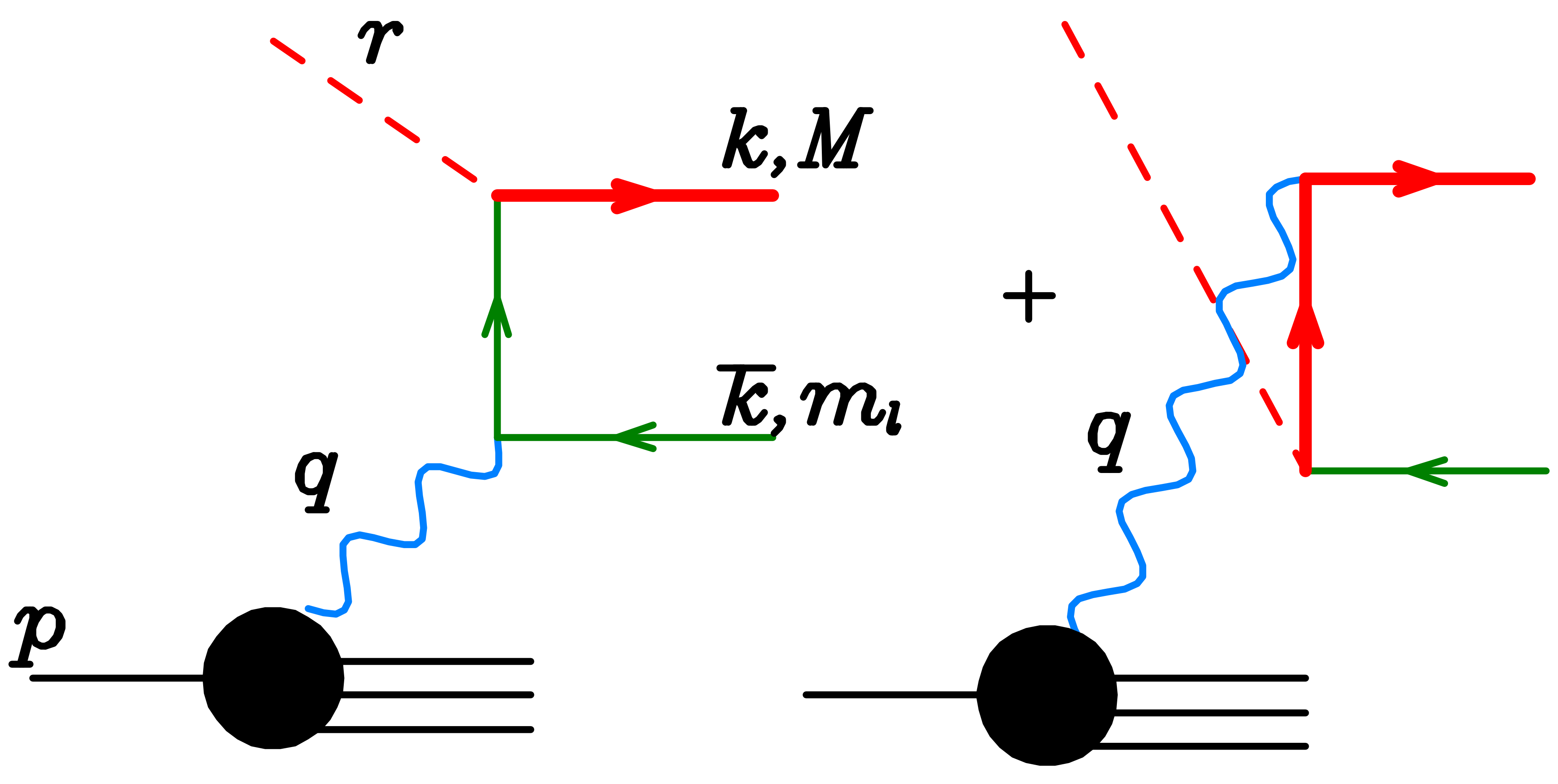
[UH & Polesello, 2012.11474; Cornella, Faroughy, Fuentes-Martin, Isidori & Neubert, 2103.16558]

Conclusions & outlook

- Precision determination of lepton PDFs opens up new ways to test Standard Model (e.g. $l^{\pm}l^{\pm}$ production) & to search for new physics @ the LHC. For instance, resonant LQ production allows to probe so far unexplored parameter space & has discovery potential
- Models of new physics such as singlet vector LQs that explain $b \to cl\nu$ anomalies generically lead to signatures (e.g. $pp \to \tau^+\tau^-$, $b\tau$, $t\bar{t}$ & high-multiplicity final states with τ, b, t & $E_{T,miss}$) testable @ the LHC. High-luminosity LHC needed to cover full theory space

Backup

Computation of lepton PDFs



leptonic tensor

hadronic tensor

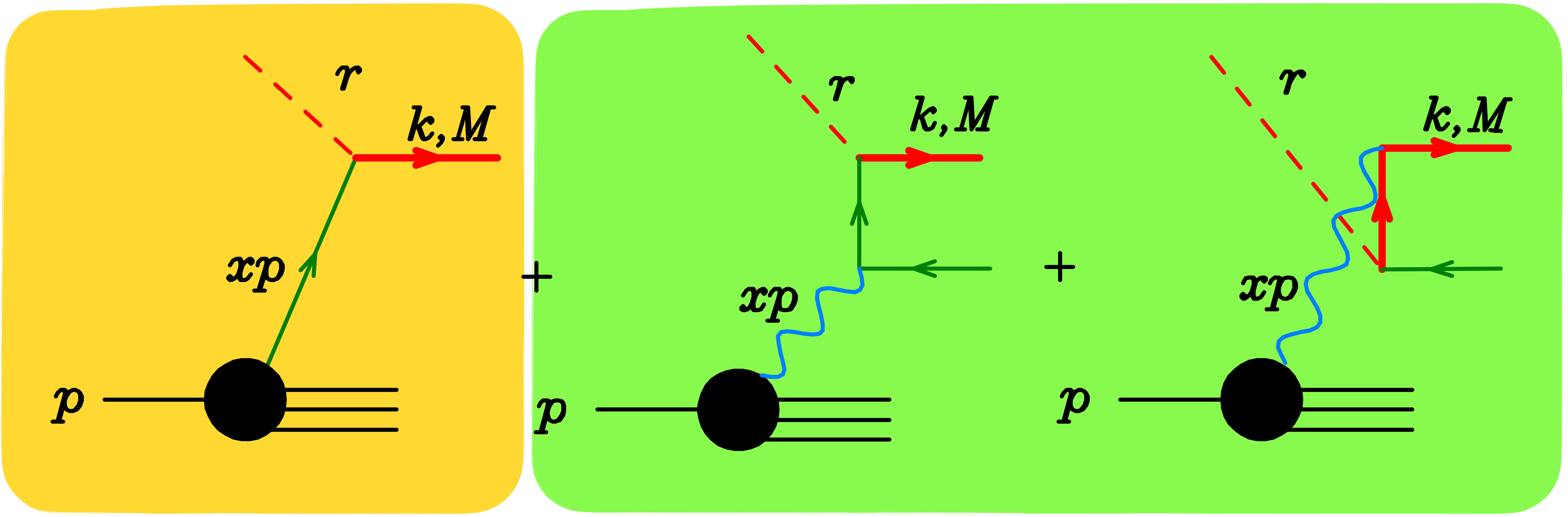
$$\sigma = \frac{1}{4p\cdot r}\int \frac{d^4q}{(2\pi)^4}\frac{1}{Q^4} L^{\mu\nu}(r,q)(4\pi)W_{\mu\nu}(p,q)$$

proton structure functions that can be precisely extracted from low-energy ep scattering data

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

[Buonocore, Nason, Tramontano & Zanderighi, 2005.06477]

Computation of lepton PDFs



lepton PDF

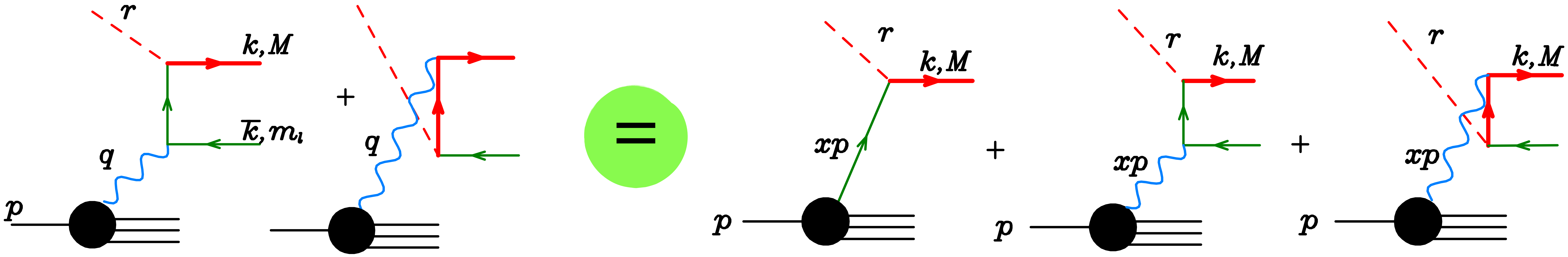
photon PDF

$$\frac{\sigma}{\sigma_B} = \int \mathrm{d}x\, f_\ell(x, \mu_F^2)\delta(Sx - M^2) + \frac{\alpha}{2\pi}\frac{1}{M^2}\int_{\frac{M^2}{S}}^{1} \mathrm{d}x\, f_\gamma(x, \mu_F^2)$$

$$\times \left\{ z_\ell P_{\ell\gamma}(z_\ell) \left[\log\frac{M^2}{\mu_F^2} + \log\frac{(1-z_\ell)^2}{z_\ell^2} \right] + 4z_\ell^2(1-z_\ell) \right\},$$

[Buonocore, Nason, Tramontano & Zanderighi, 2005.06477]

Computation of lepton PDFs



lepton PDF

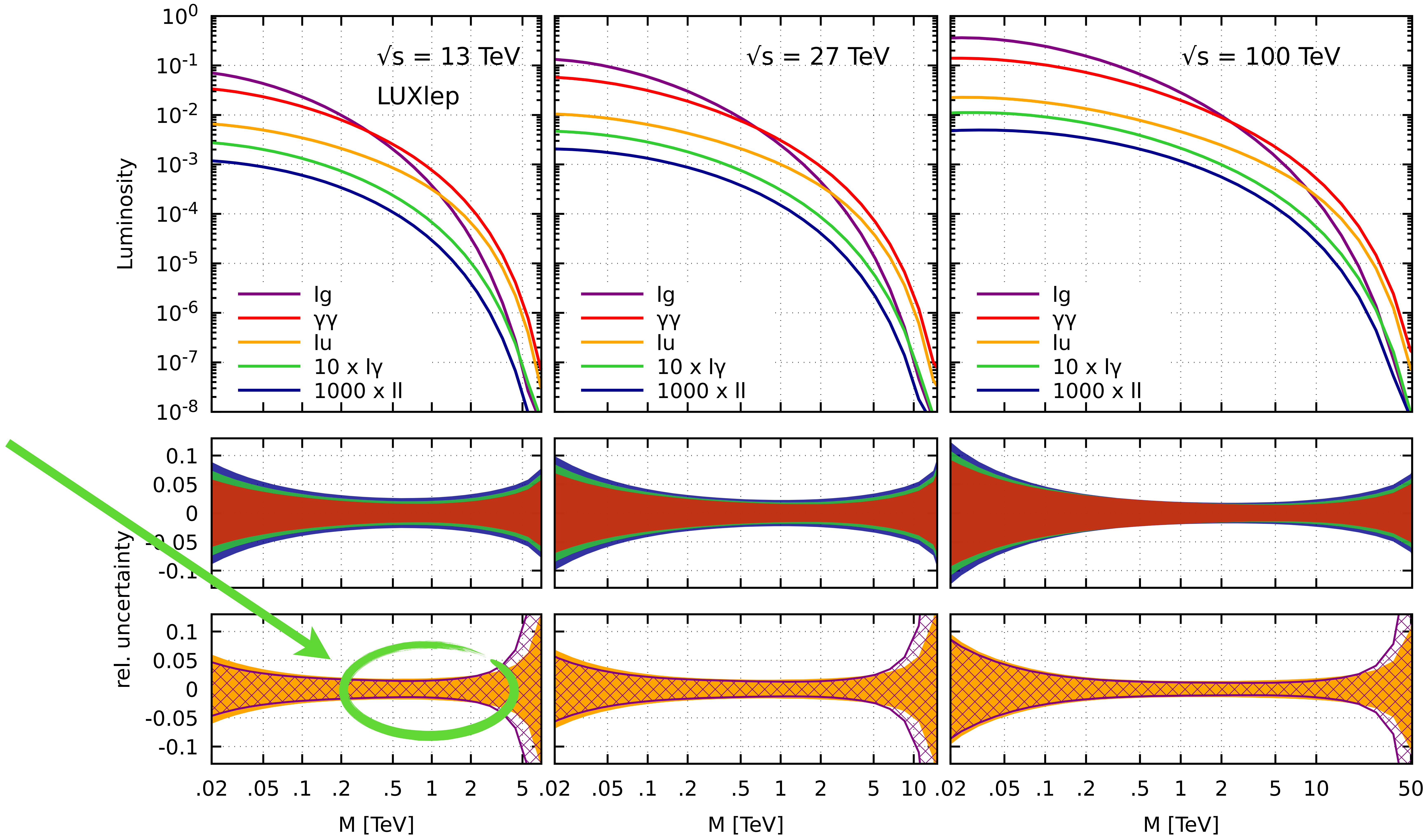
$$x_\ell f_\ell(x_\ell, \mu_F^2) =$$

convolution involving photon PDF & γ → l^+l^- splitting function +
convolution involving proton structure functions & splitting functions

[Buonocore, Nason, Tramontano & Zanderighi, 2005.06477]

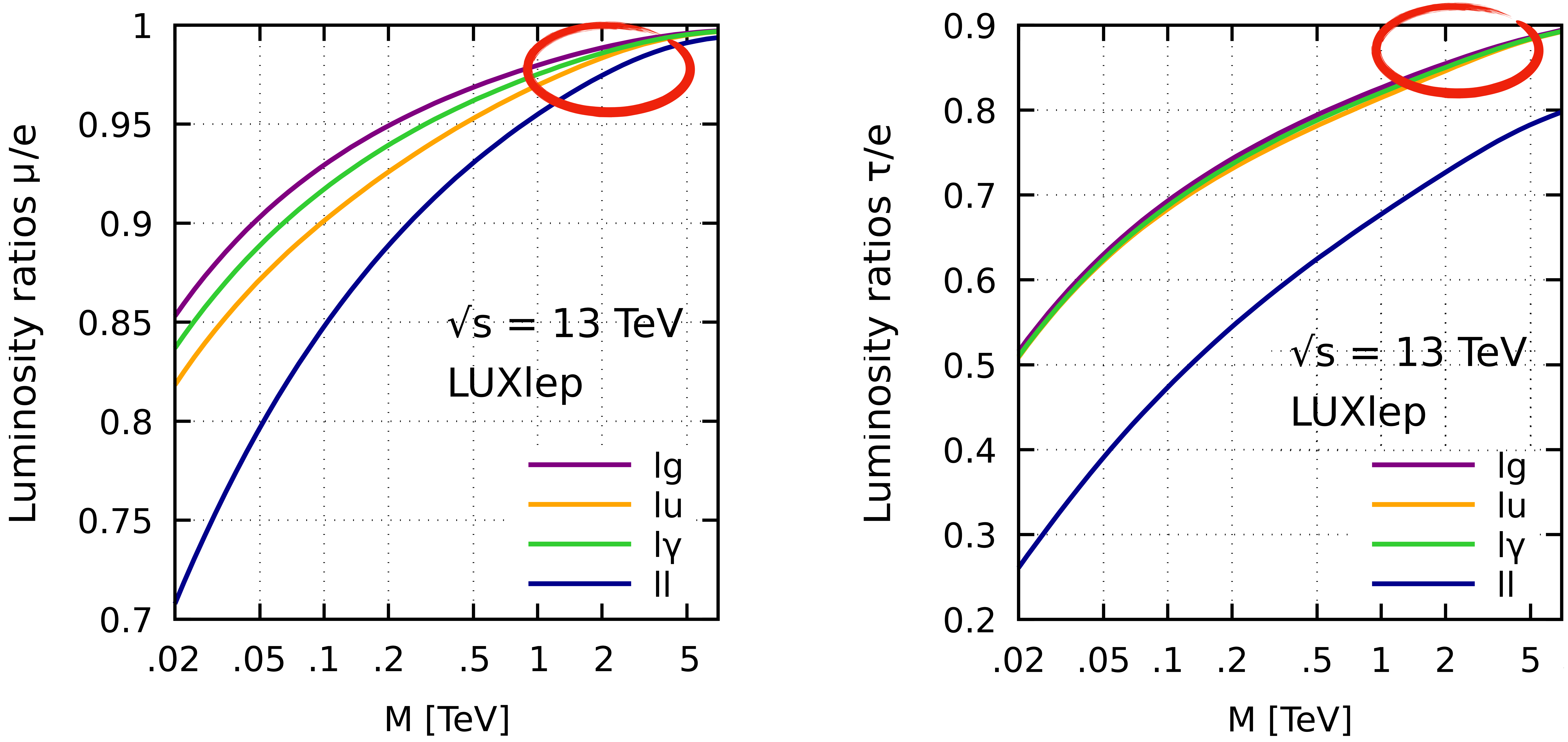
Luminosities @ LHC & beyond

uncertainties below 5% for a wide range of invariant masses



[Buonocore, Nason, Tramontano & Zanderighi, 2005.06477]

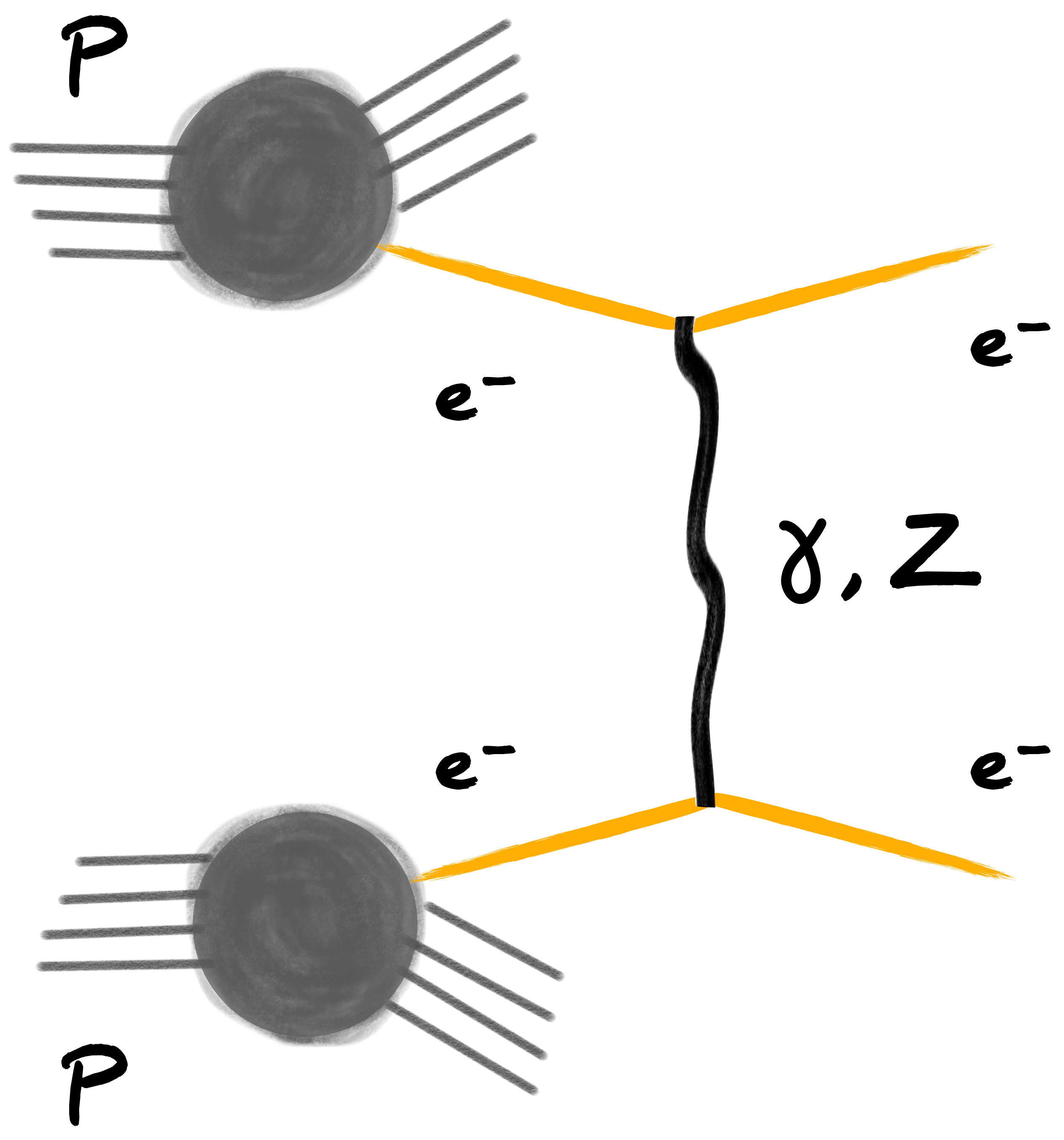
Luminosities ratios



For TeV-scale resonances, μ/e (τ/e) luminosity ratio above 95% (around 85%)

[Buonocore, Nason, Tramontano & Zanderighi, 2005.06477]

Same sign lepton-pair production @ LHC



Signal events after cuts:

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

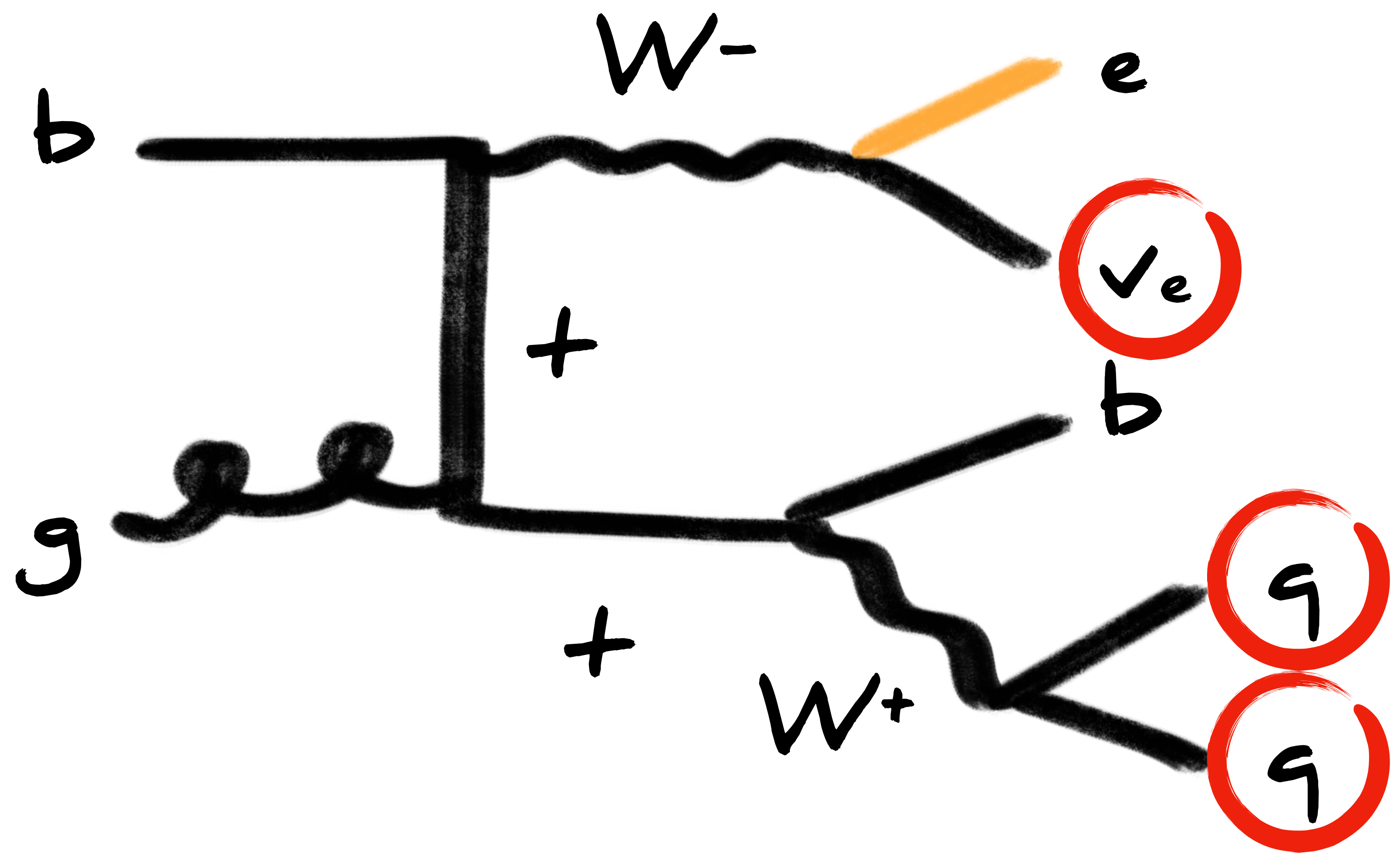
$N_{HL\text{-}LHC}(\mu^-\mu^-) \simeq 550$,

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

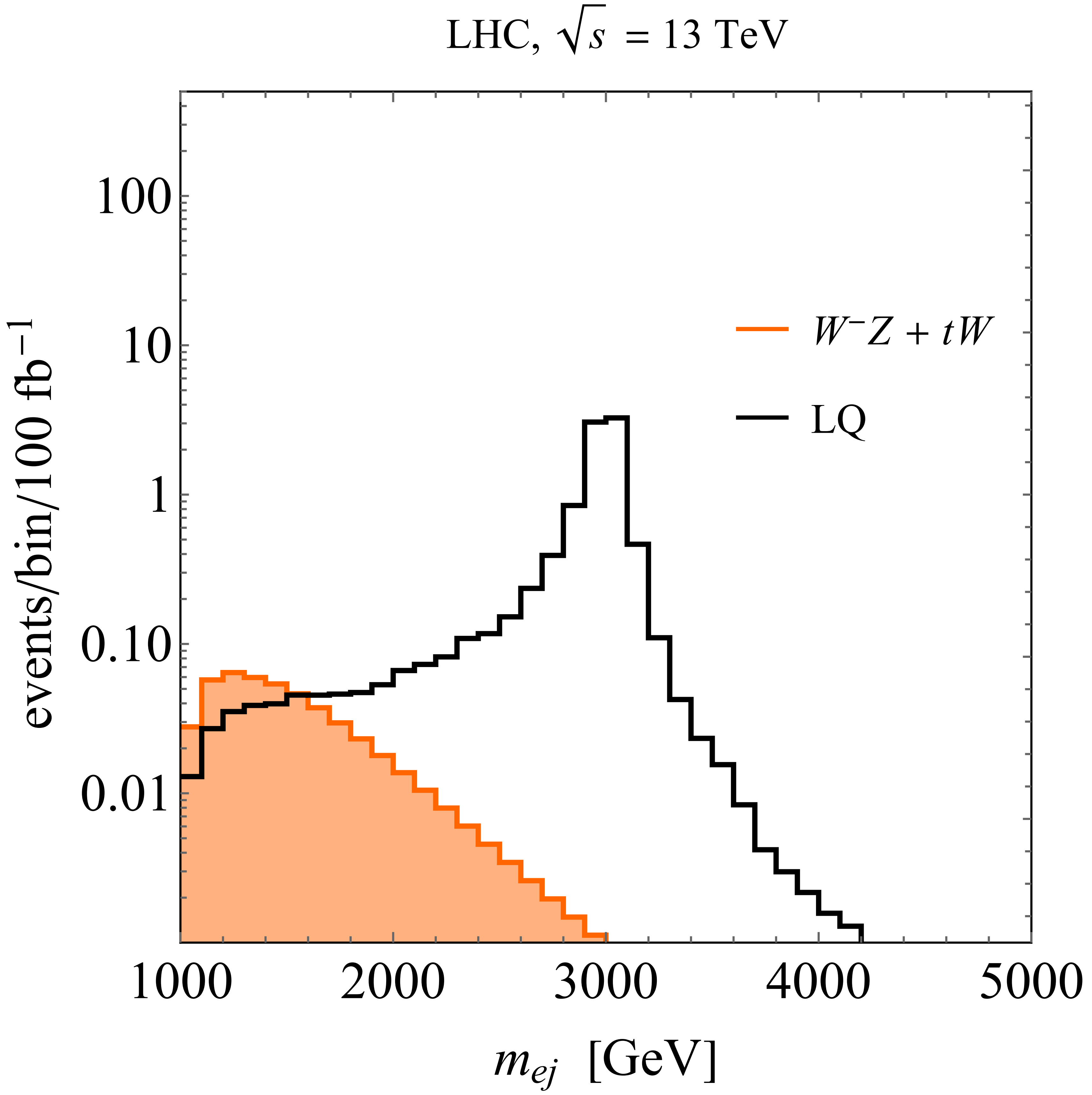
Dominant SM background from W^-W^- production after same cuts close to 0

[Buonocore, Nason, Tramontano & Zanderighi, 2005.06477]

Resonant LQ production @ the LHC

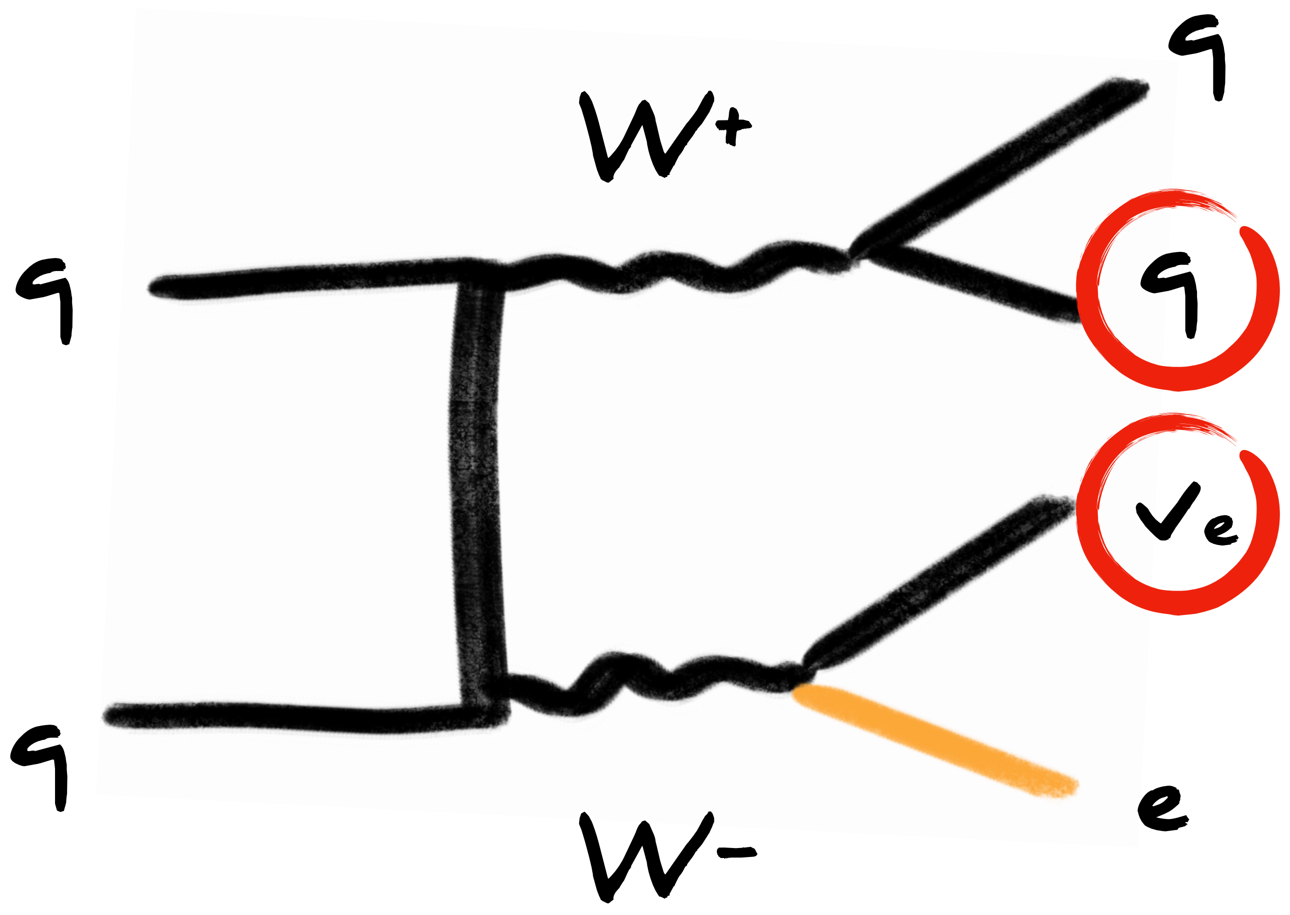


suppressed by $E_{T,miss}$ requirement & jet veto



[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

Resonant LQ production @ the LHC



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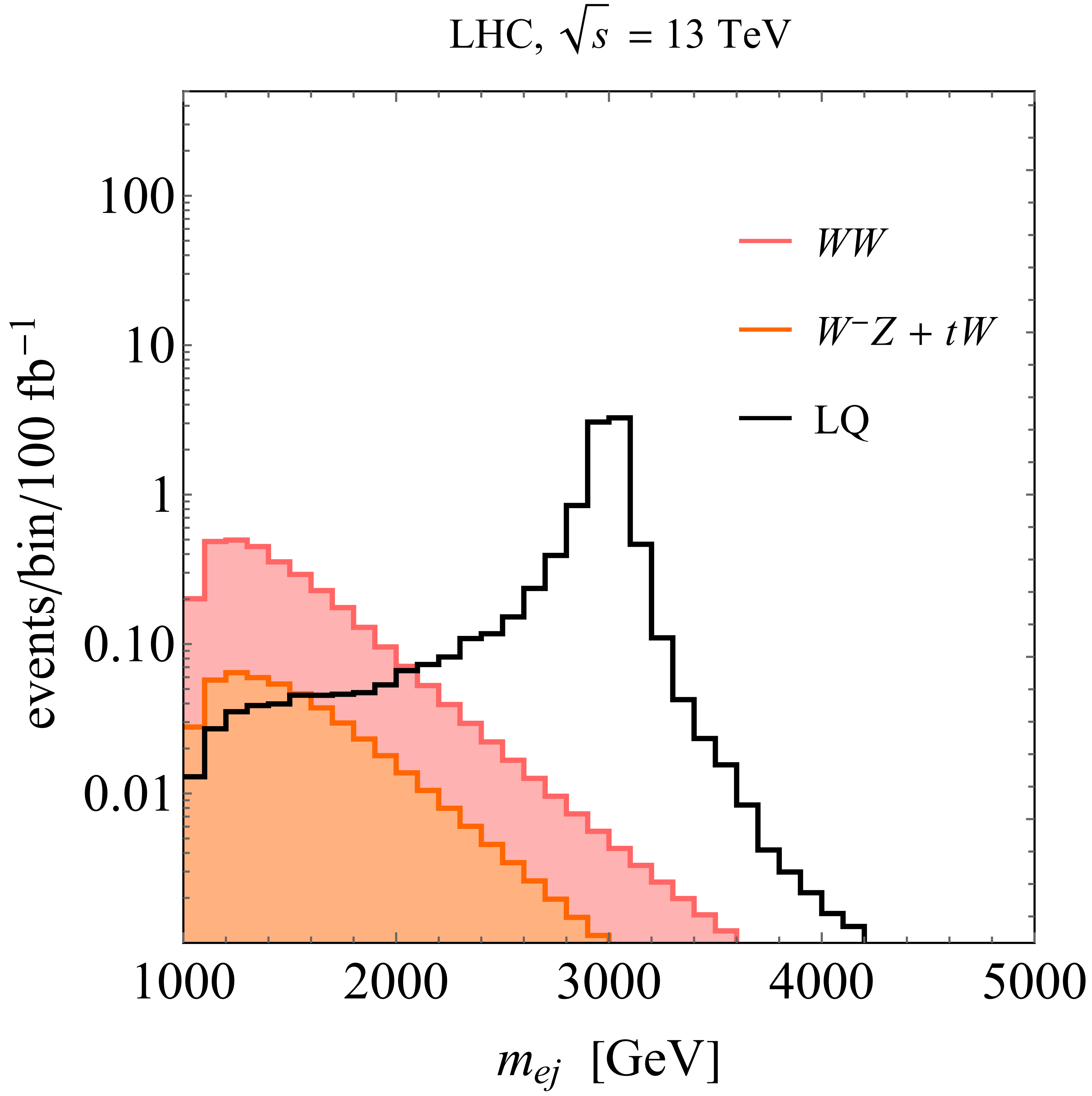

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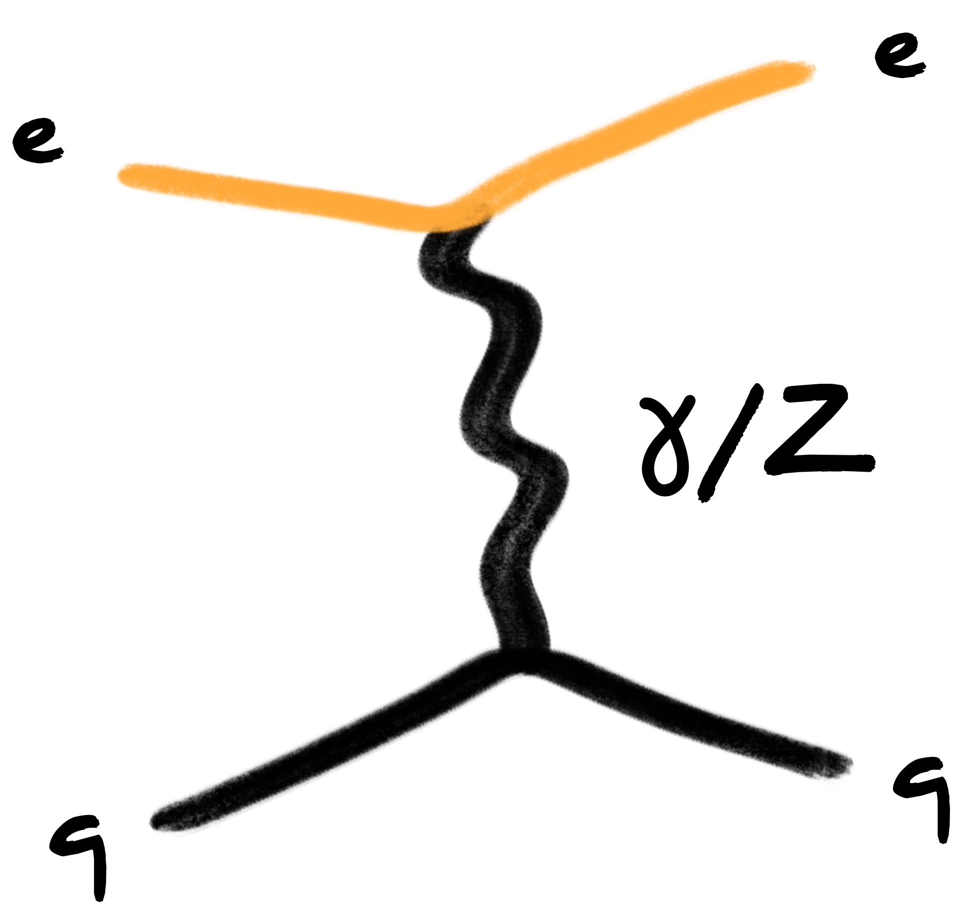
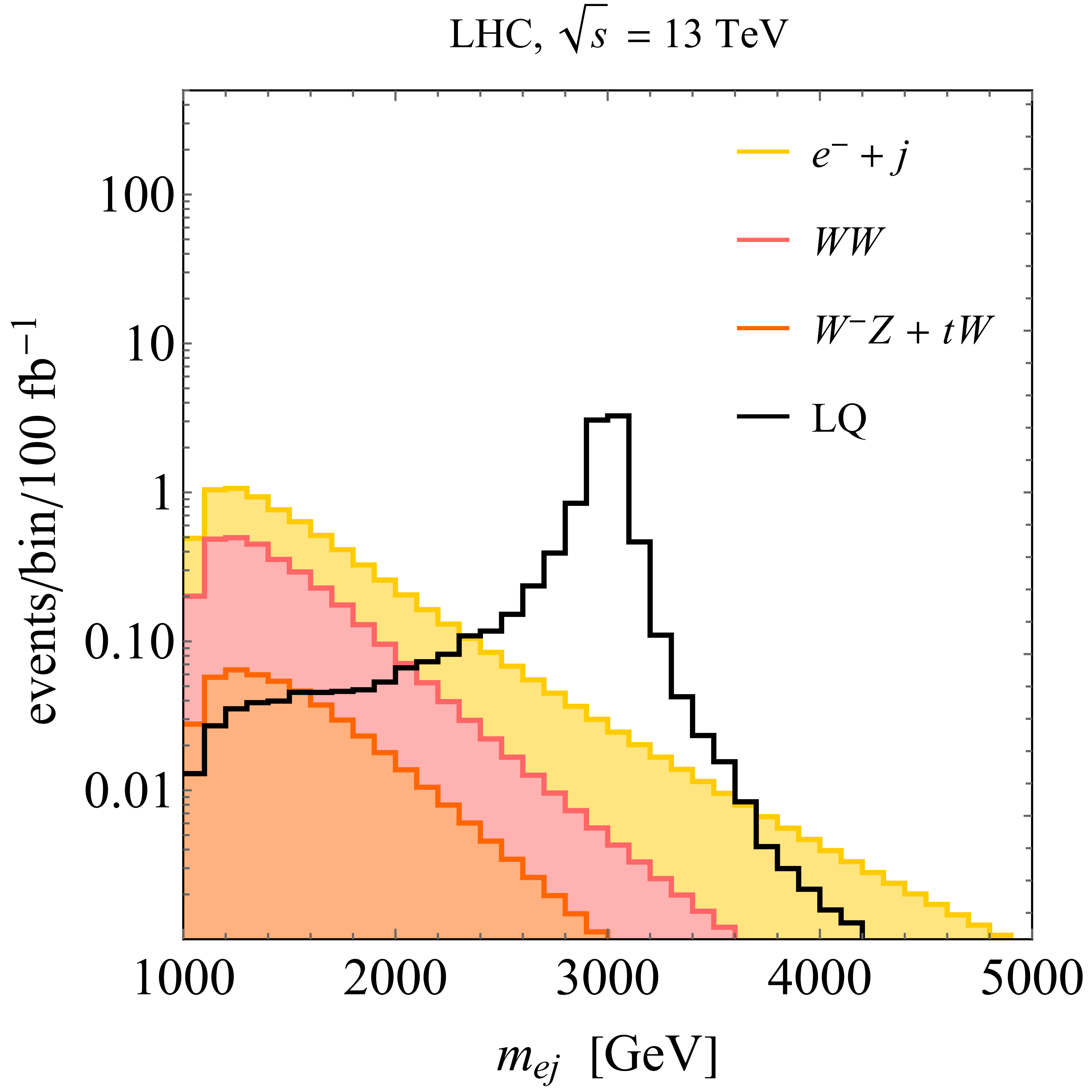
Resonant LQ production @ the LHC

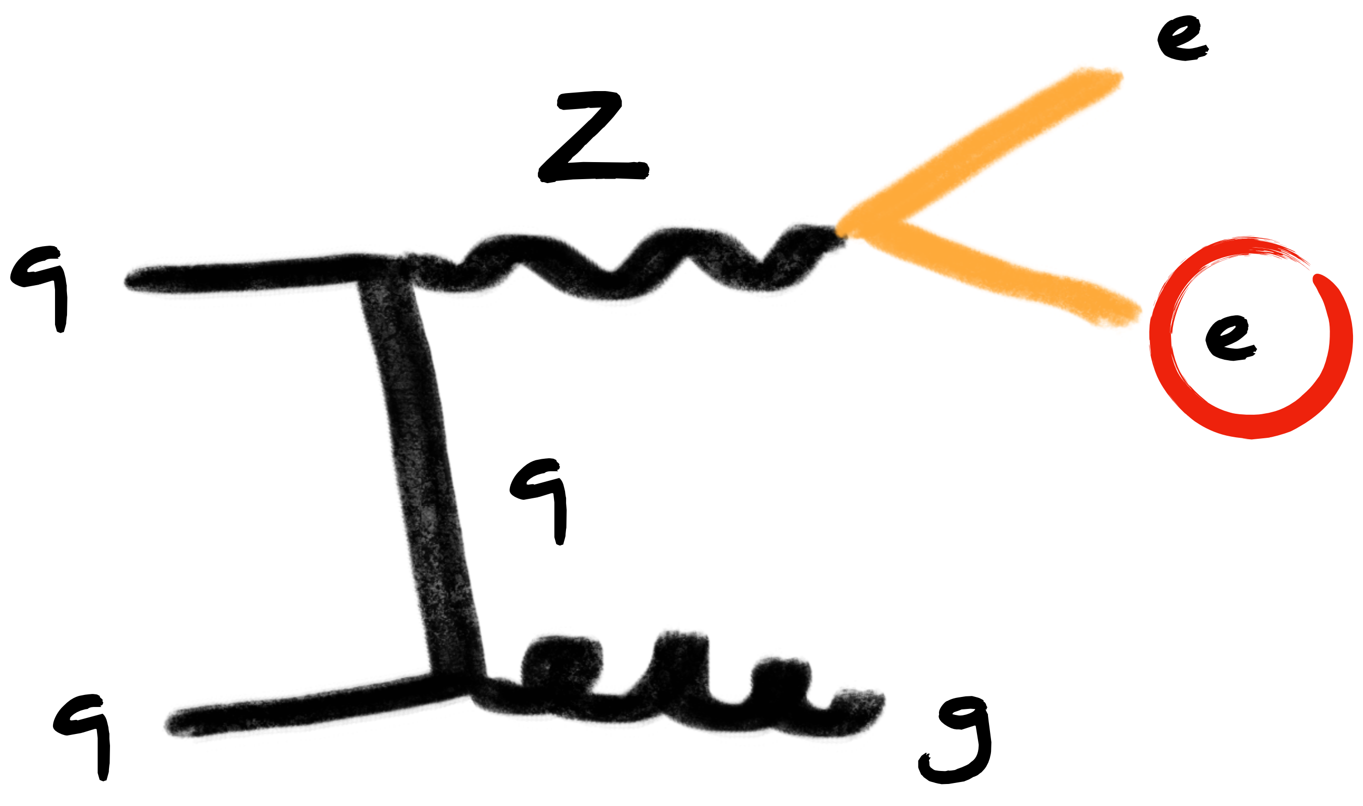




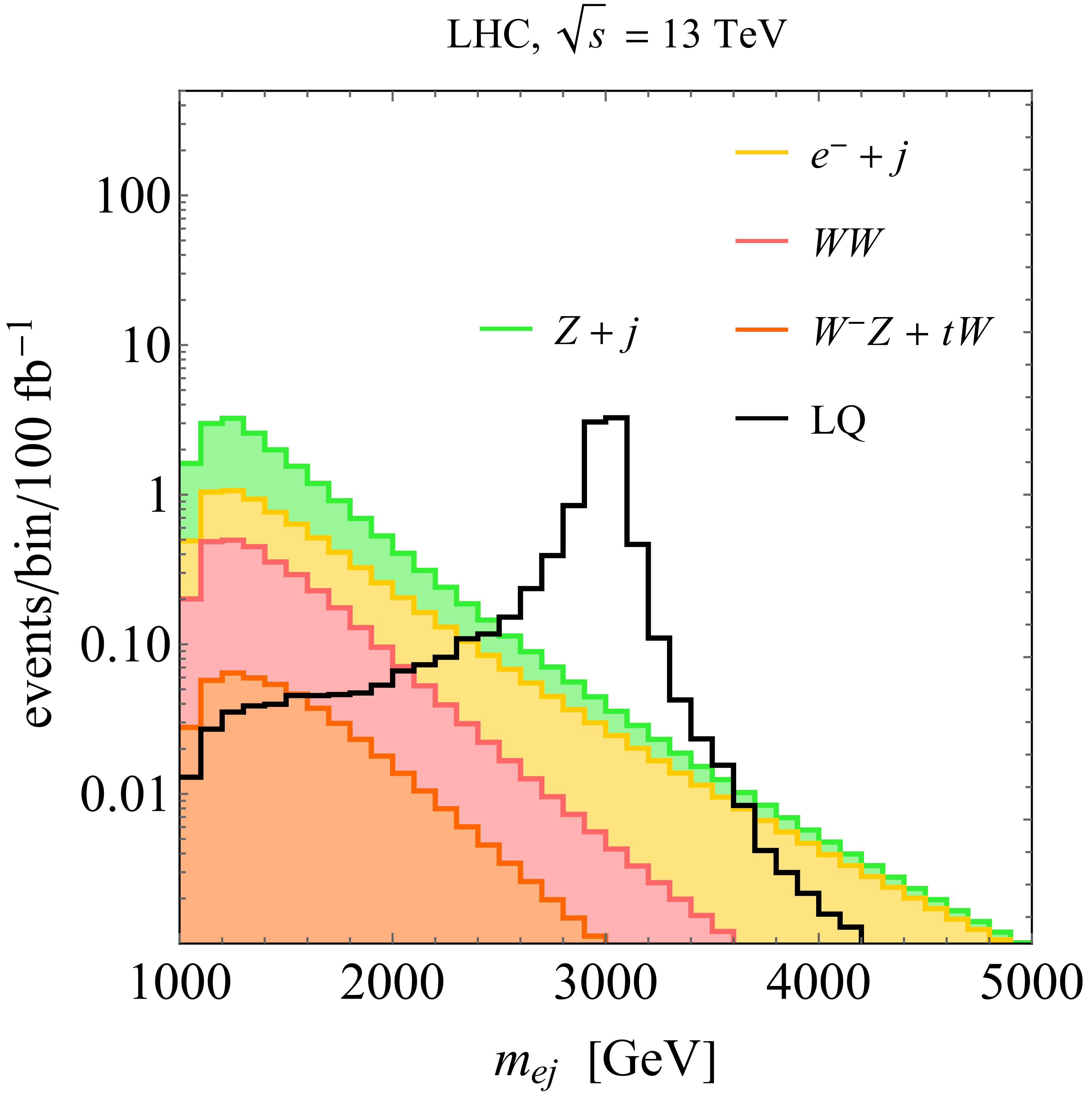
irreducible background particularly relevant
@ high invariant lepton-jet mass

[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

Resonant LQ production @ the LHC

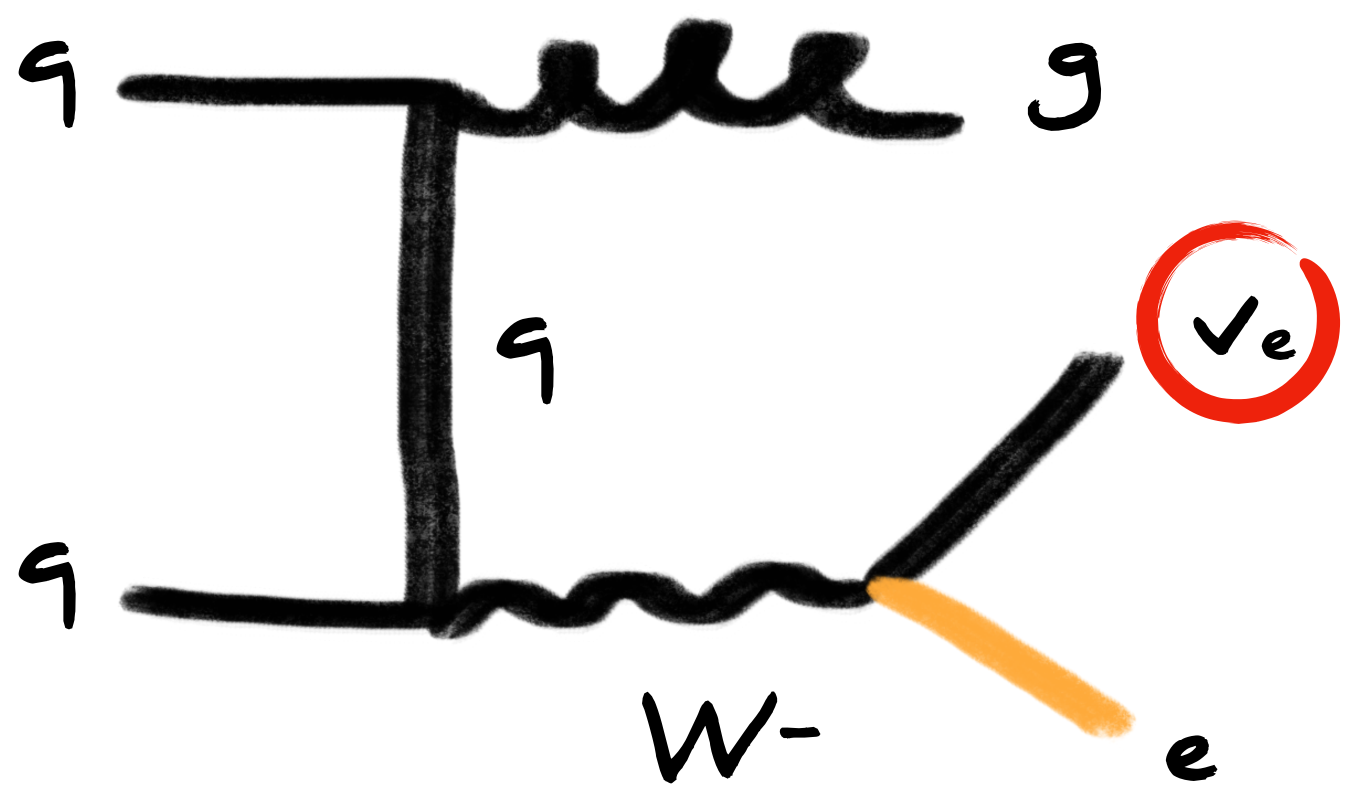


suppressed by lepton veto

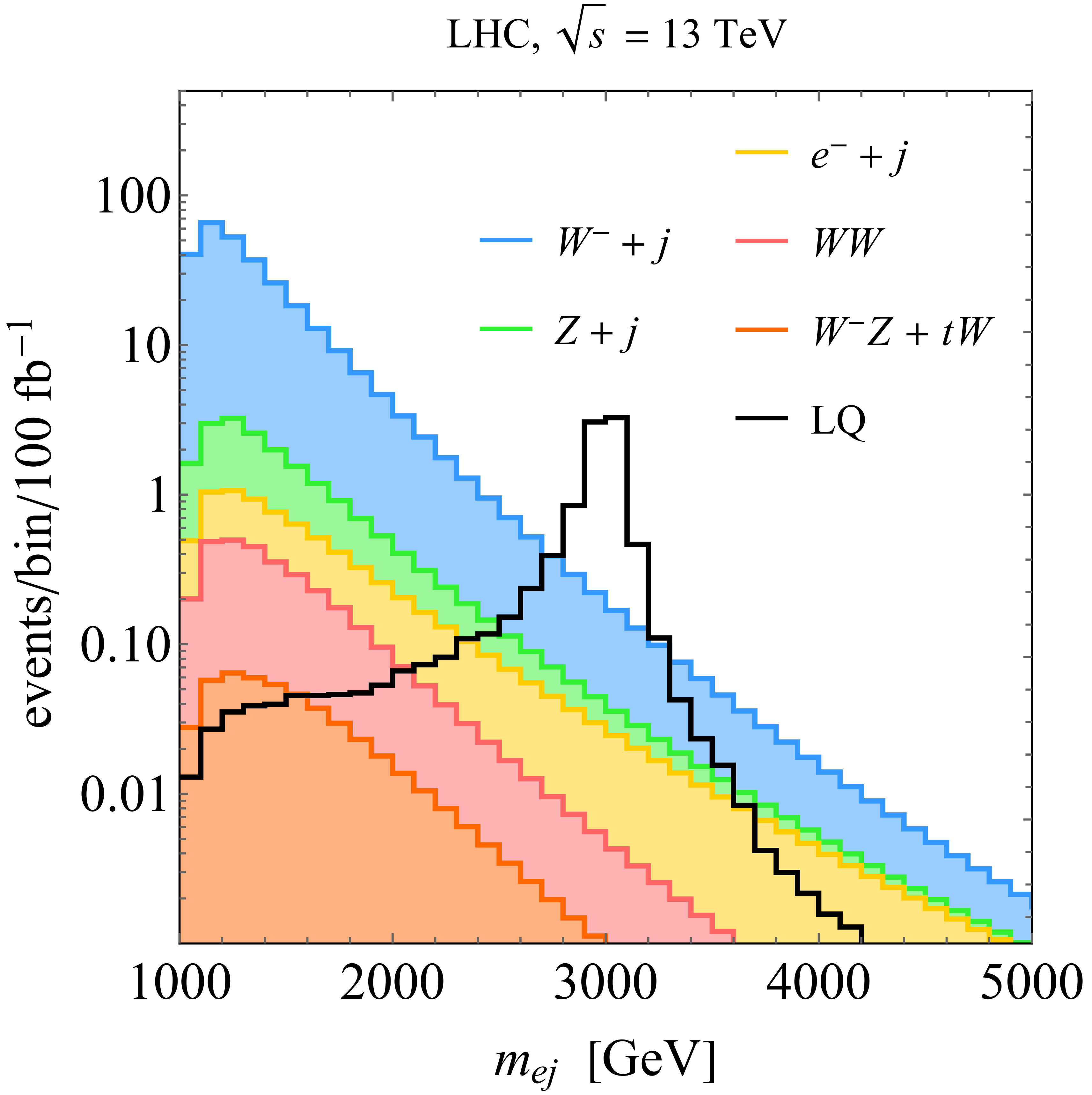


[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

Resonant LQ production @ the LHC

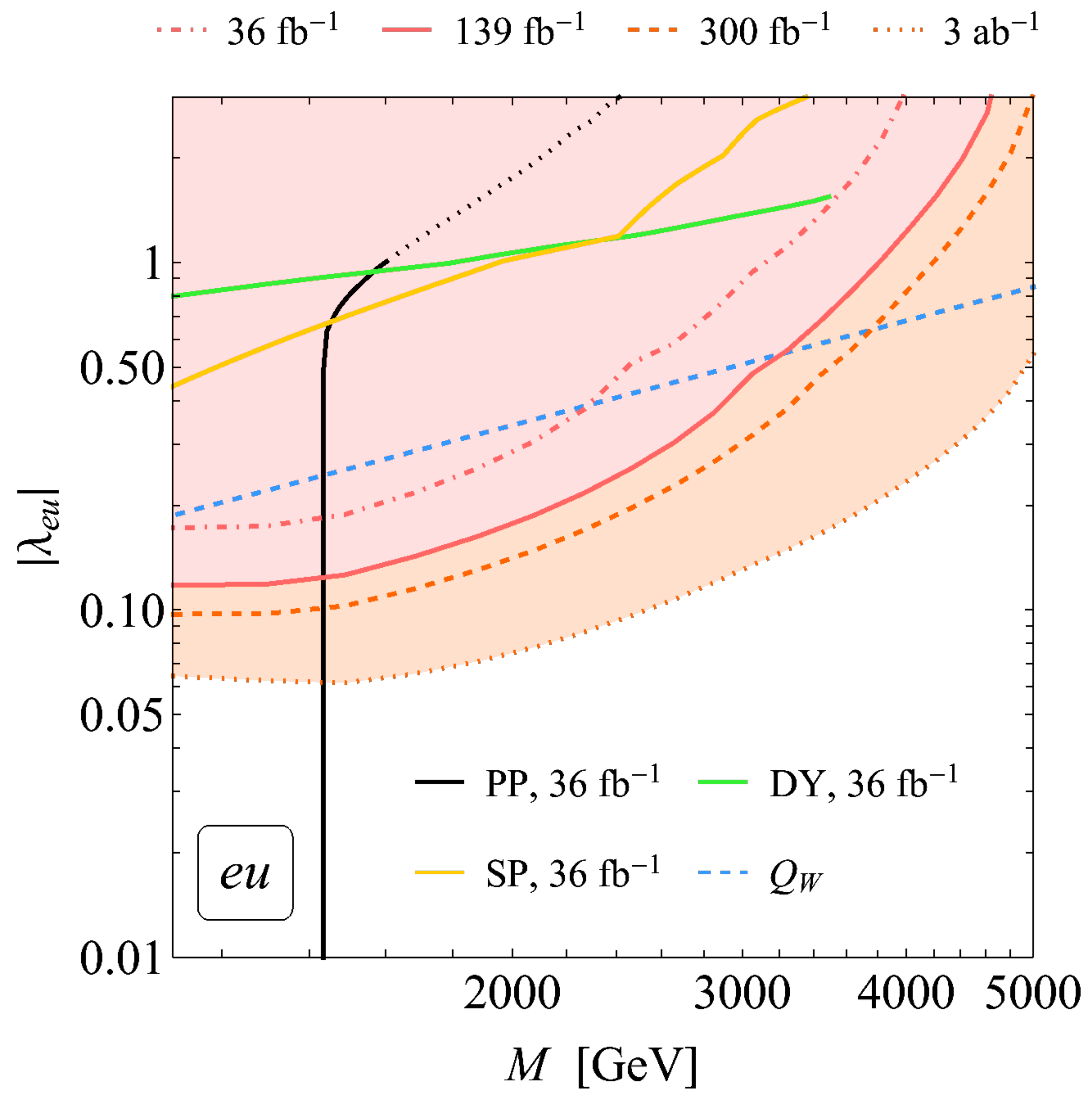


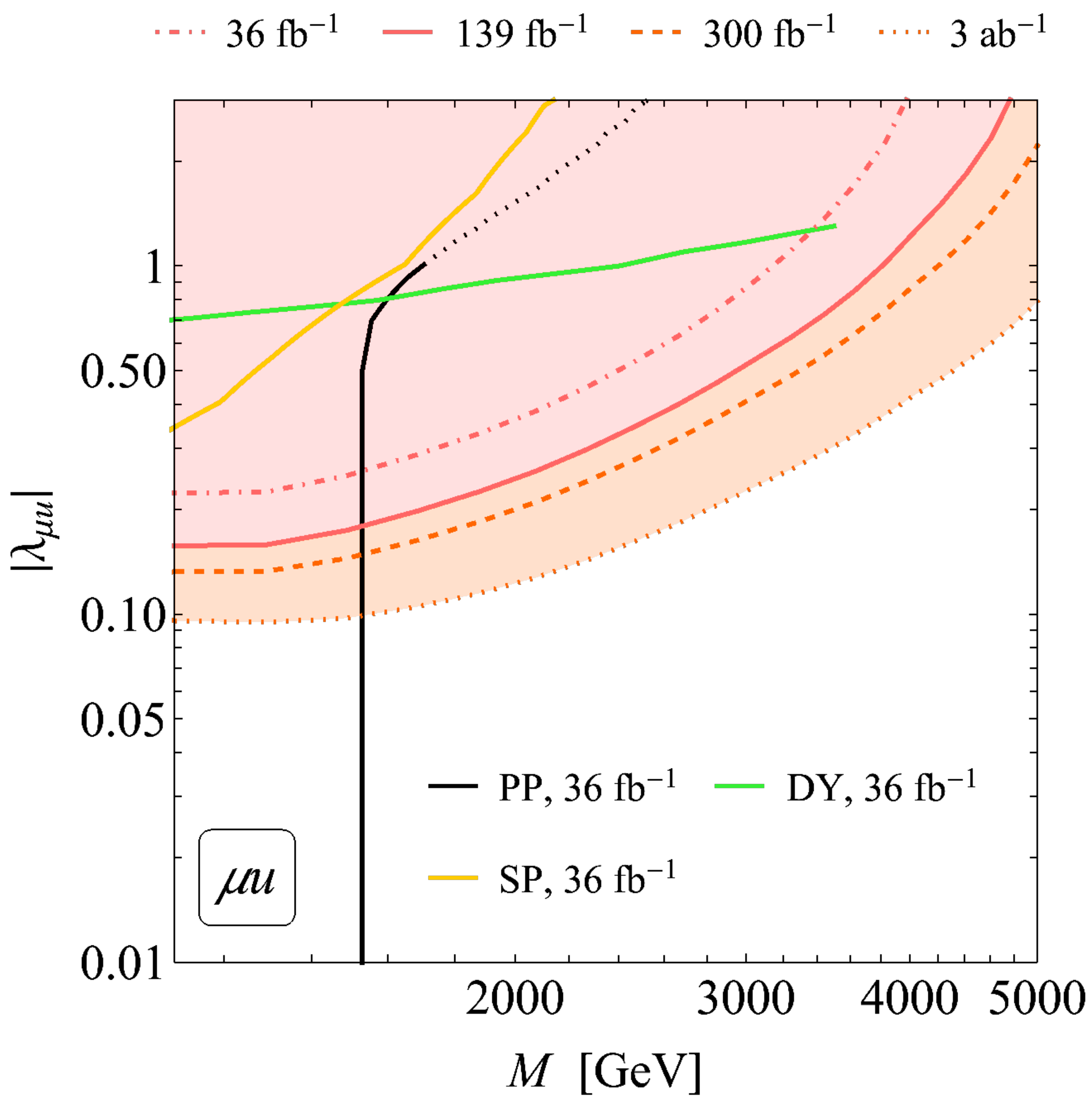
suppressed by $E_{T,miss}$ requirement



[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

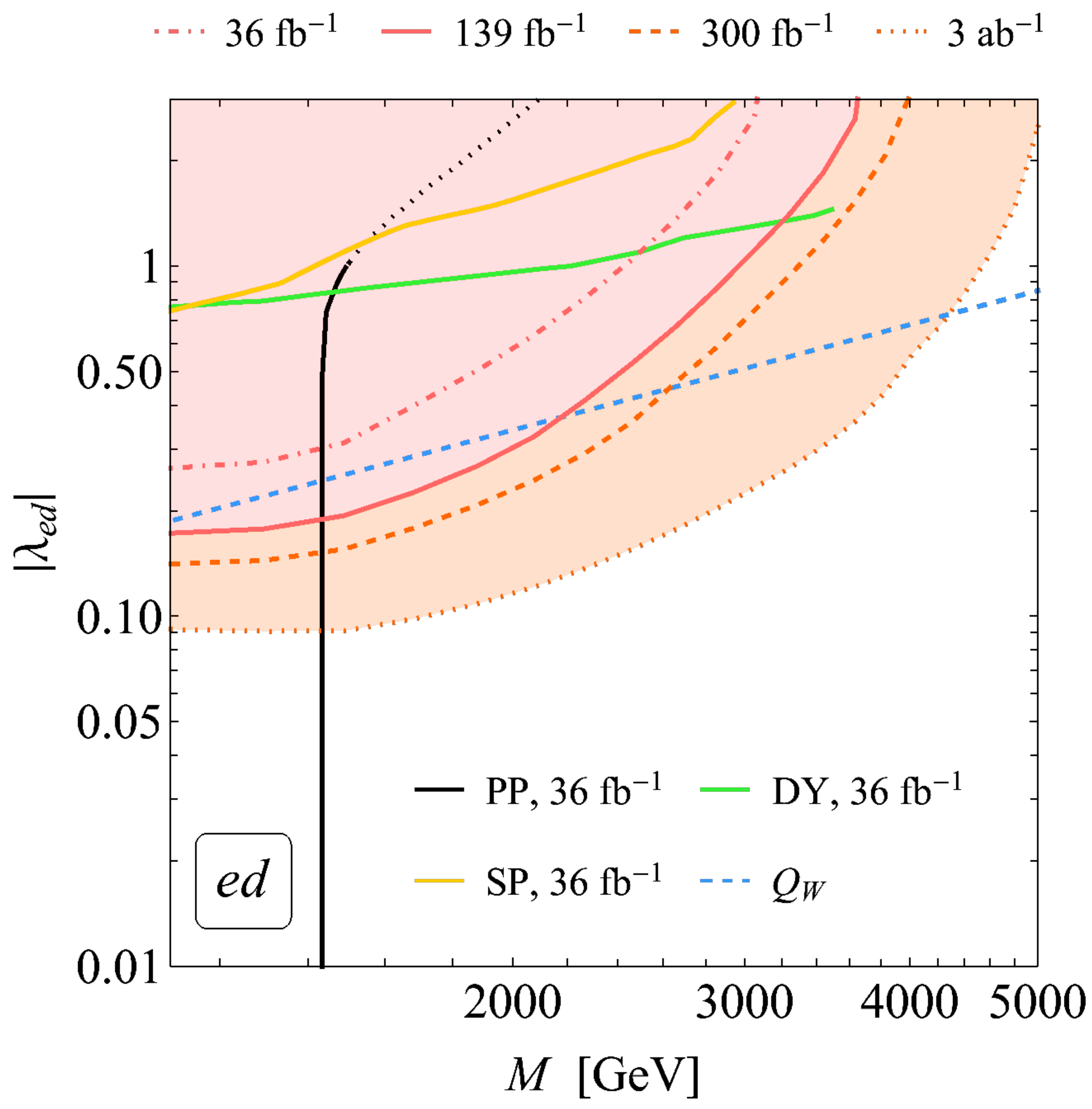
LHC limits on 1st & 2nd generation LQs

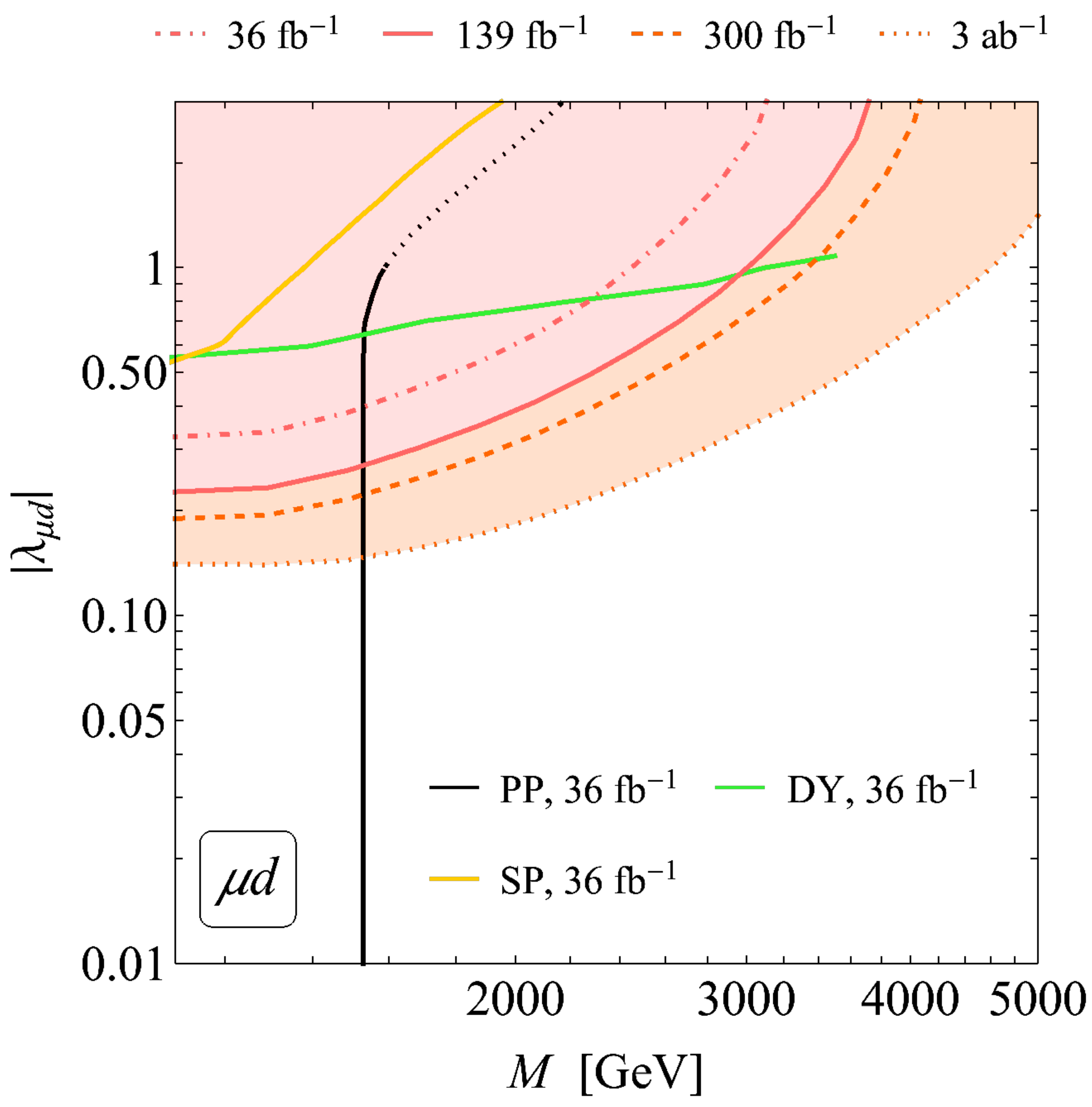




[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

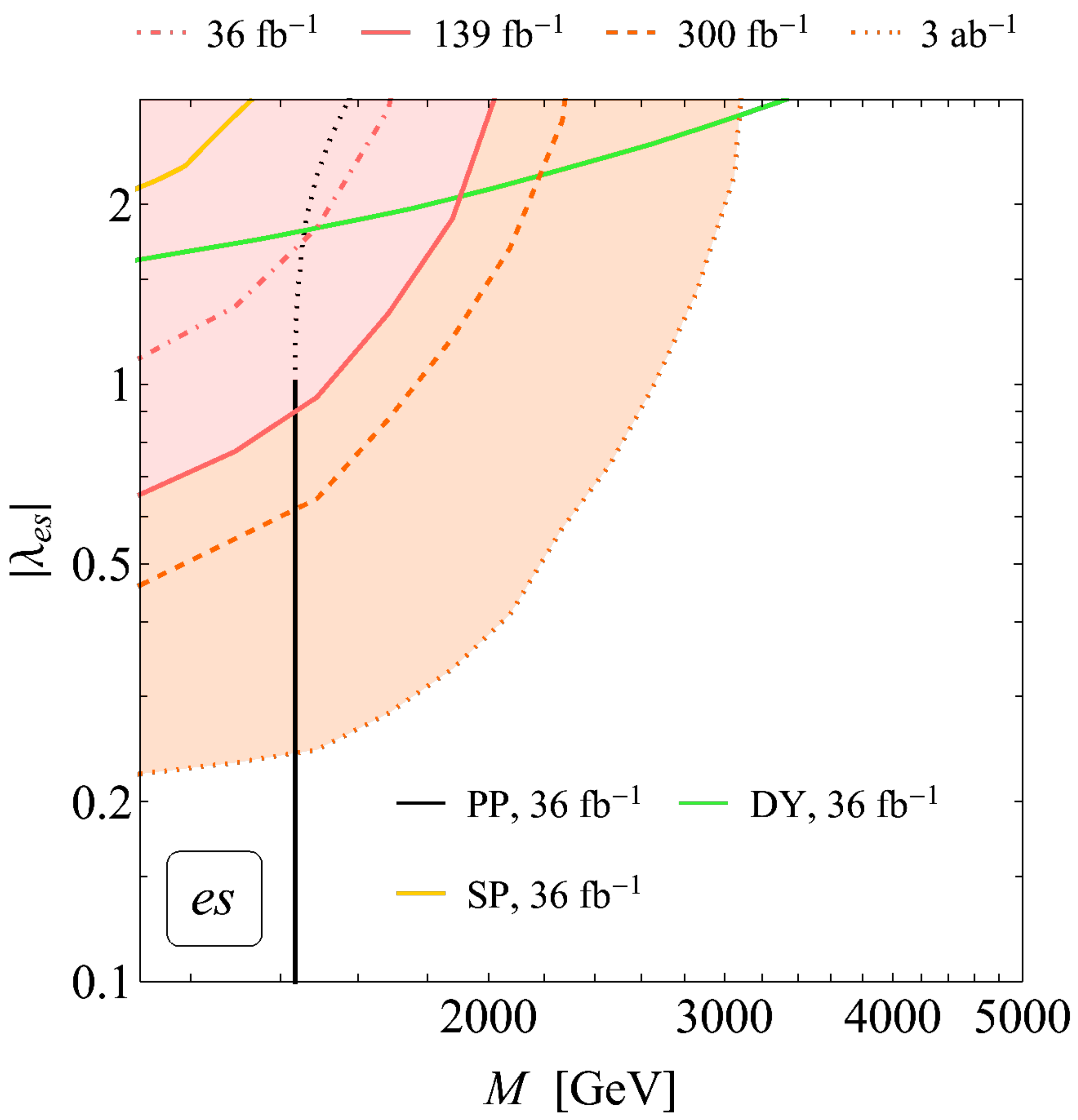
LHC limits on 1st & 2nd generation LQs

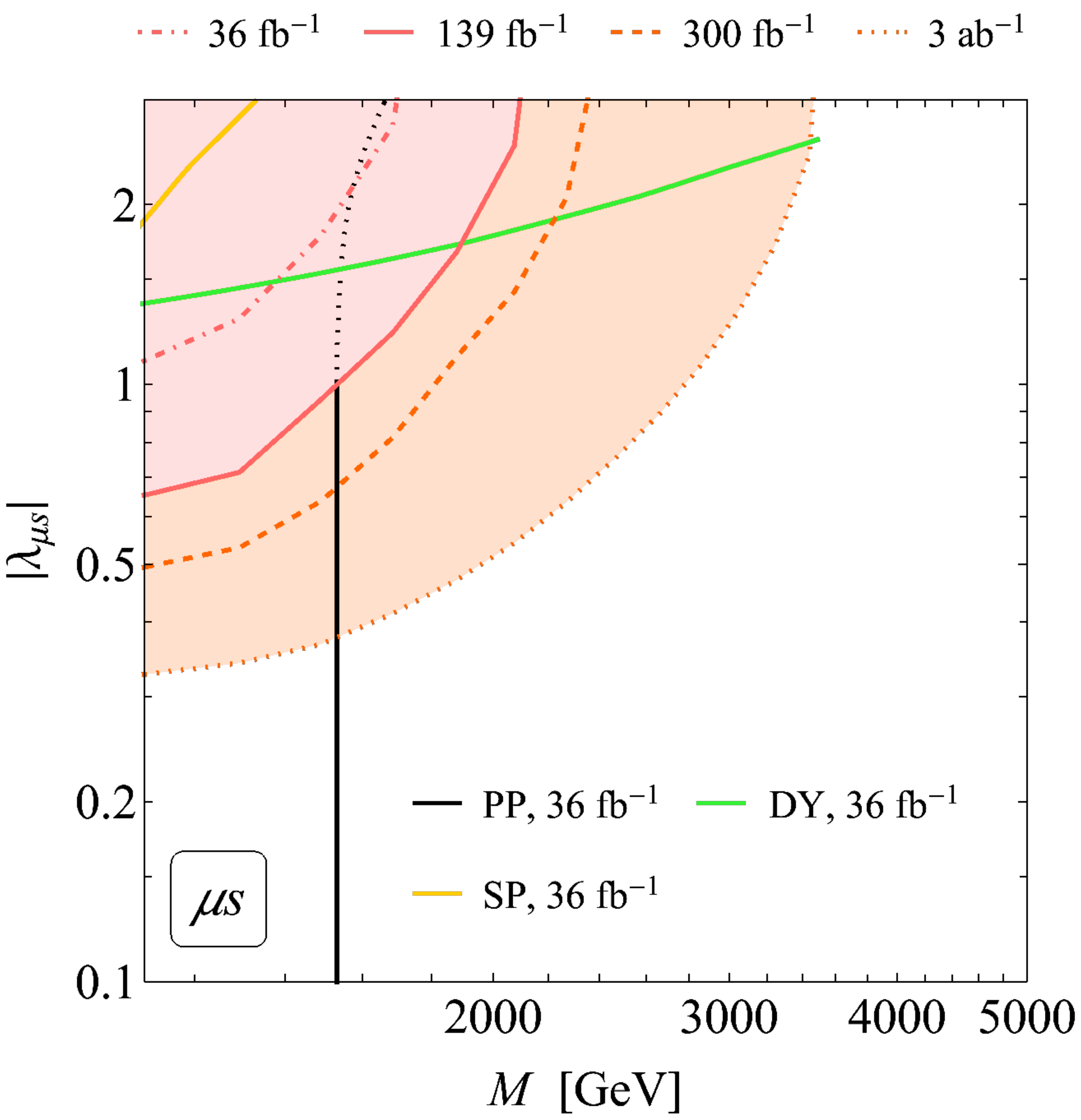




[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

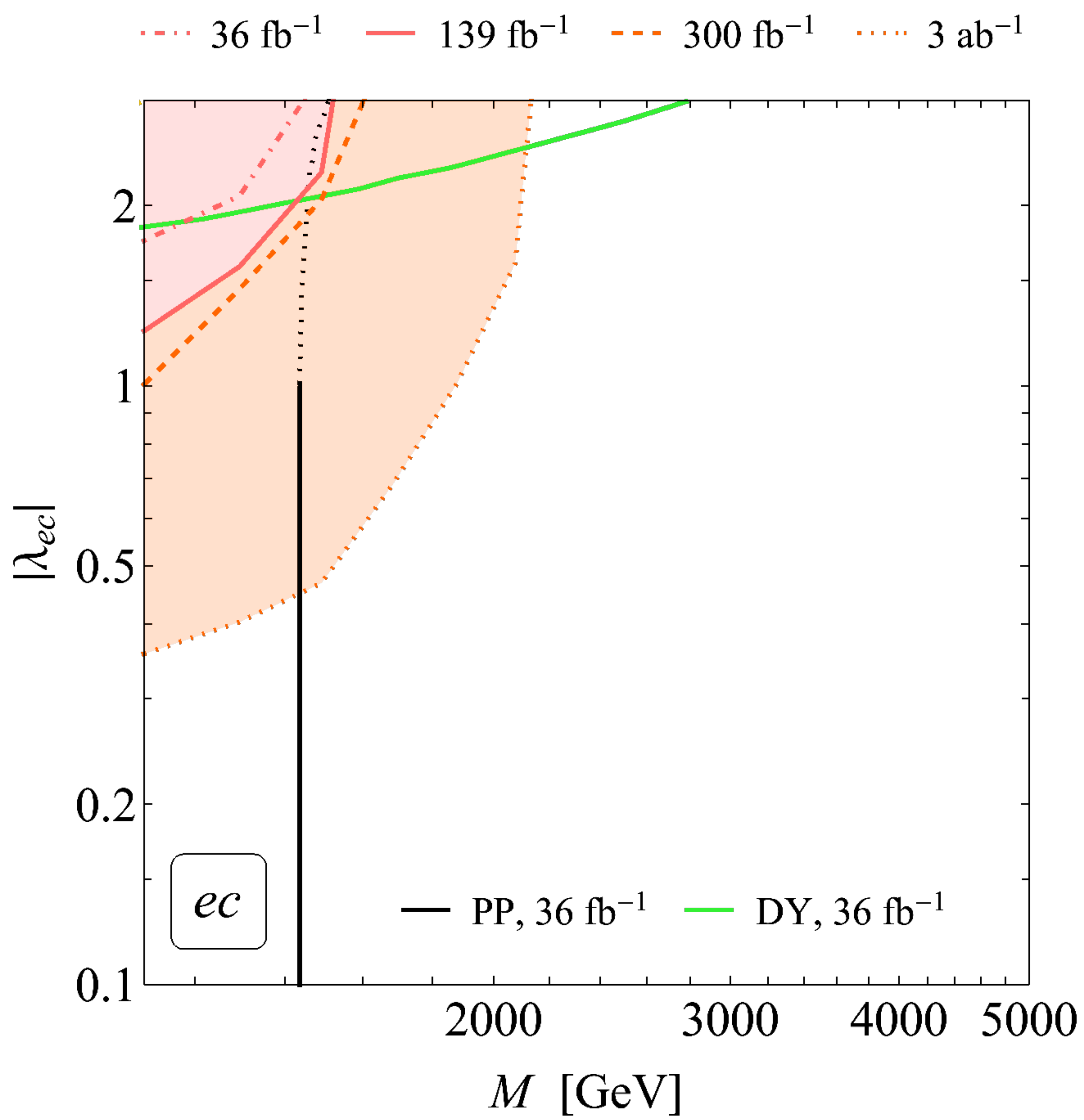
LHC limits on 1st & 2nd generation LQs

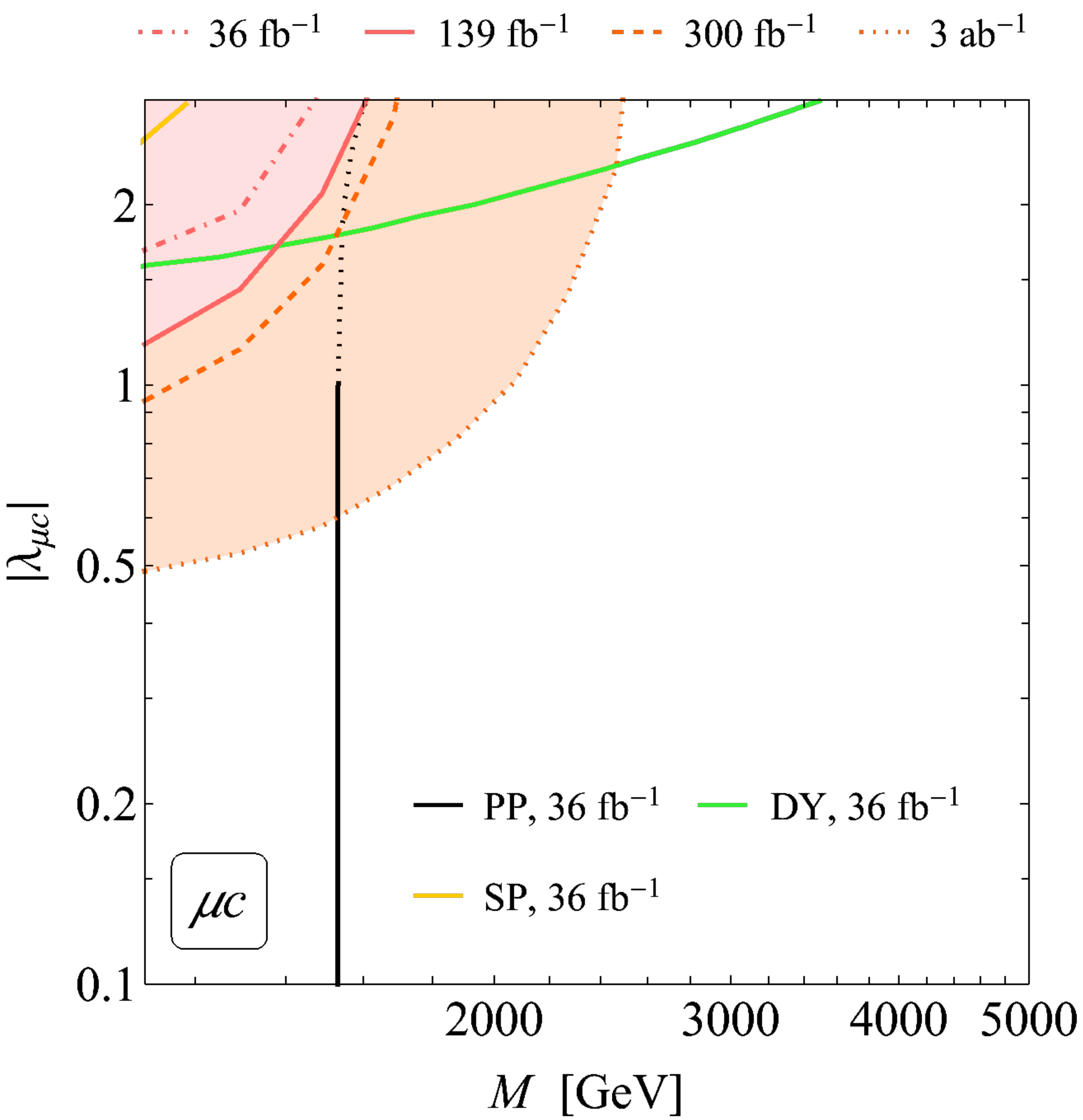




[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

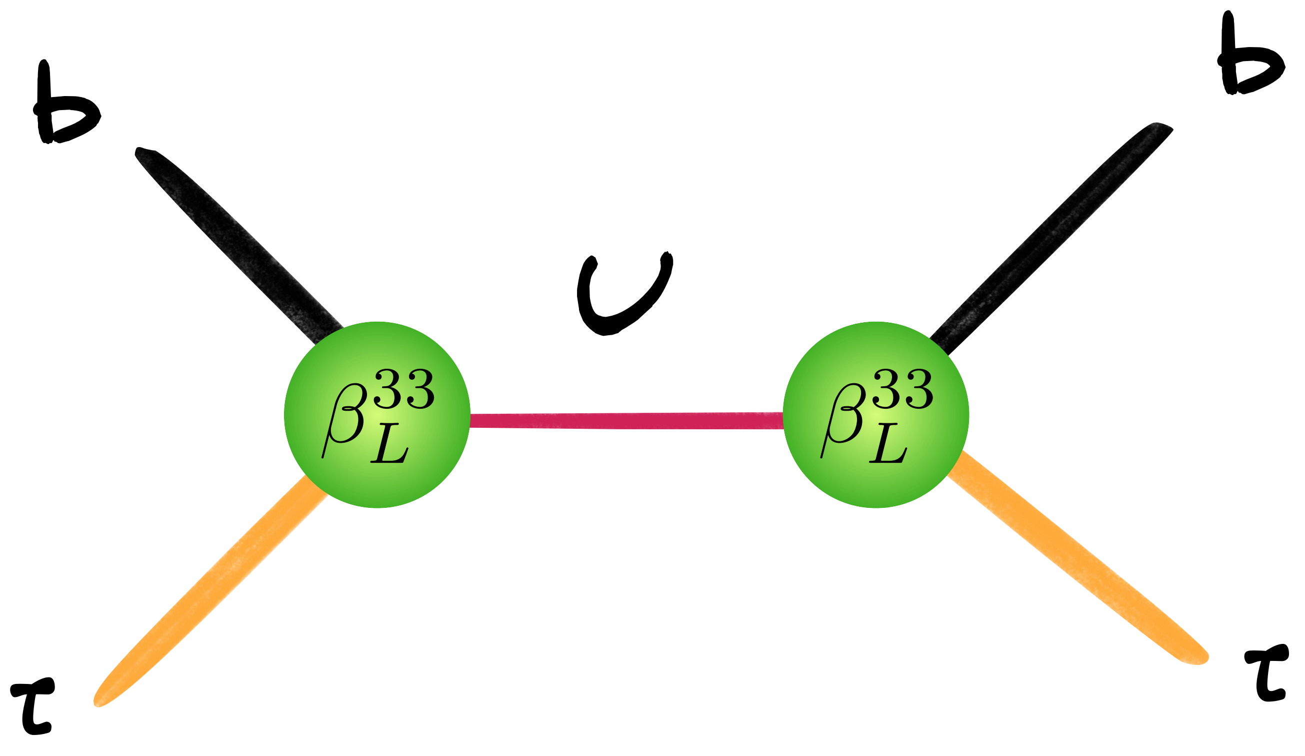
LHC limits on 1st & 2nd generation LQs

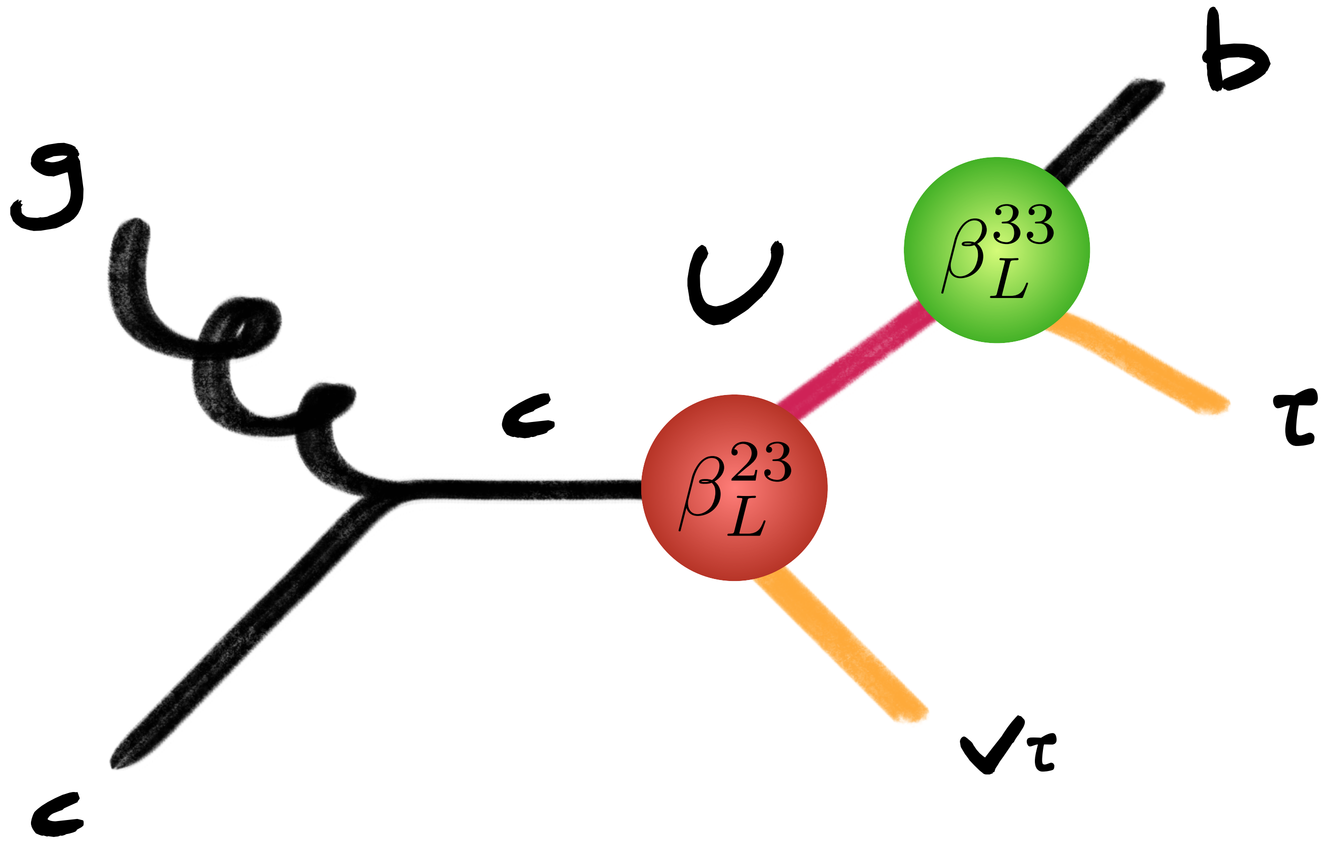




[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

LQ contributions to pp → bτ signature

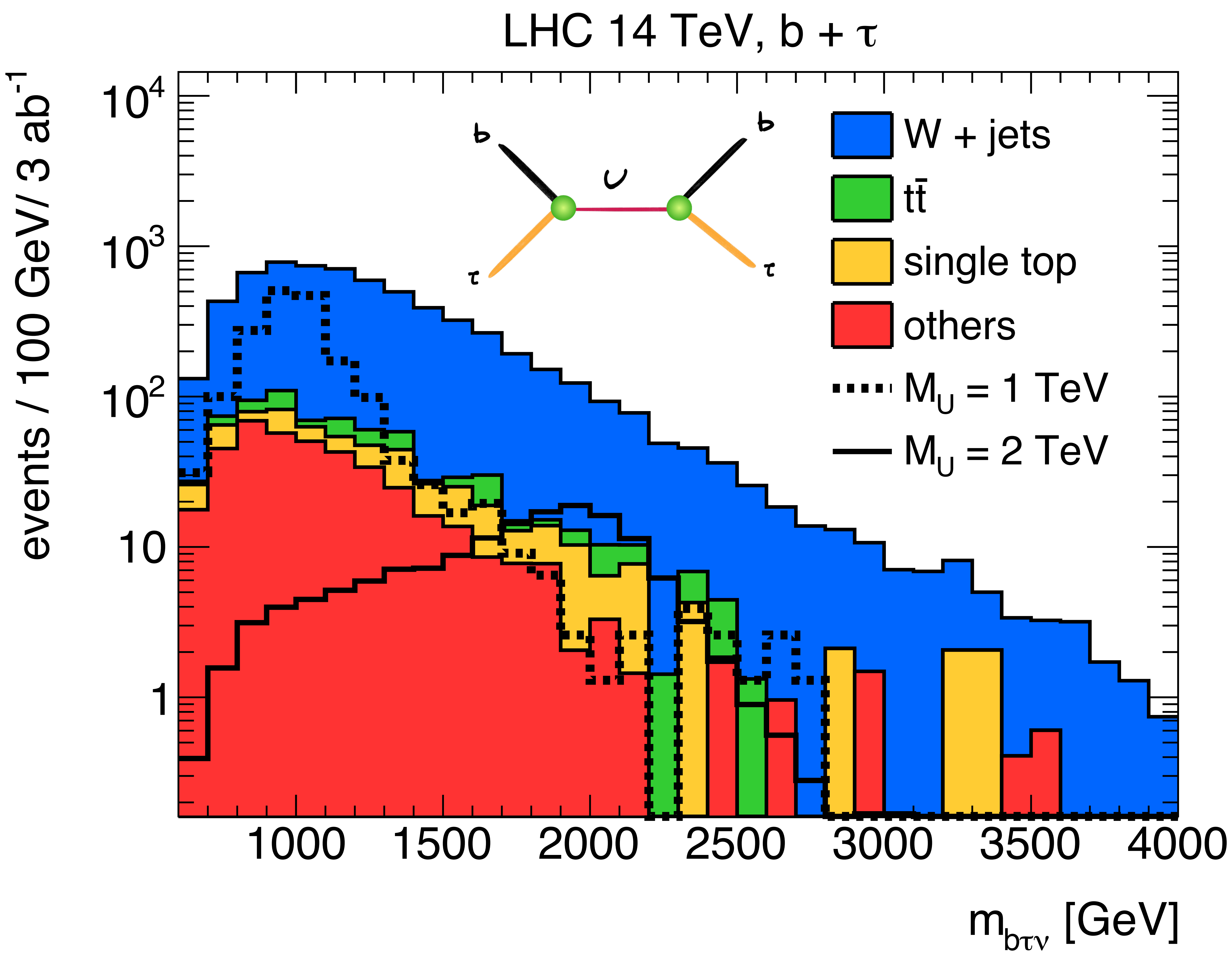


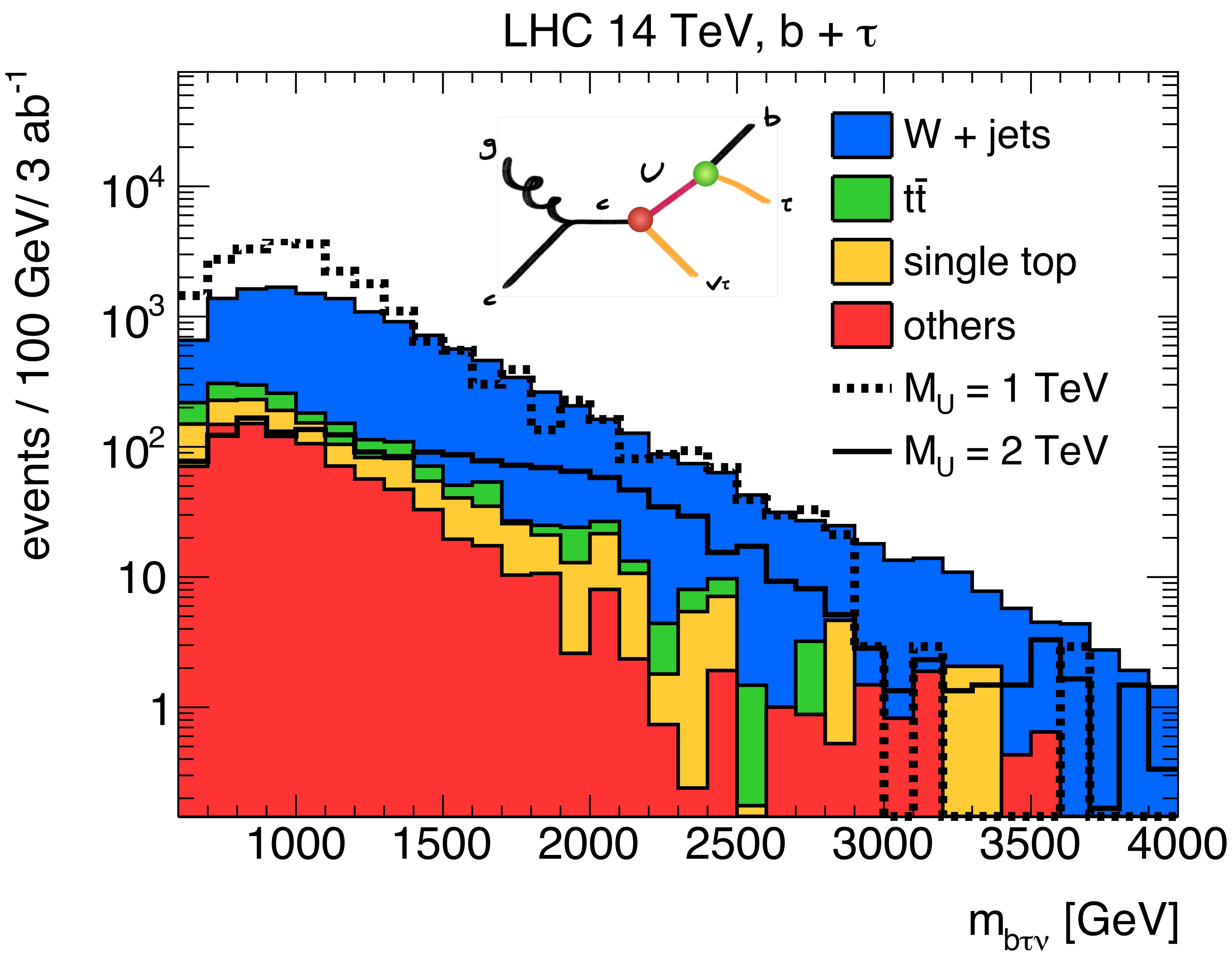


For $\beta_L^{23} = 0$, bτ signal arises only from 2 → 2 process, while for $\beta_L^{23} \neq 0$ also 2 → 3 scattering is relevant. Since two topologies lead to final states with very different kinematic features, it is essential to develop two separate search strategies for them

[UH & Polesello, 2012.11474]

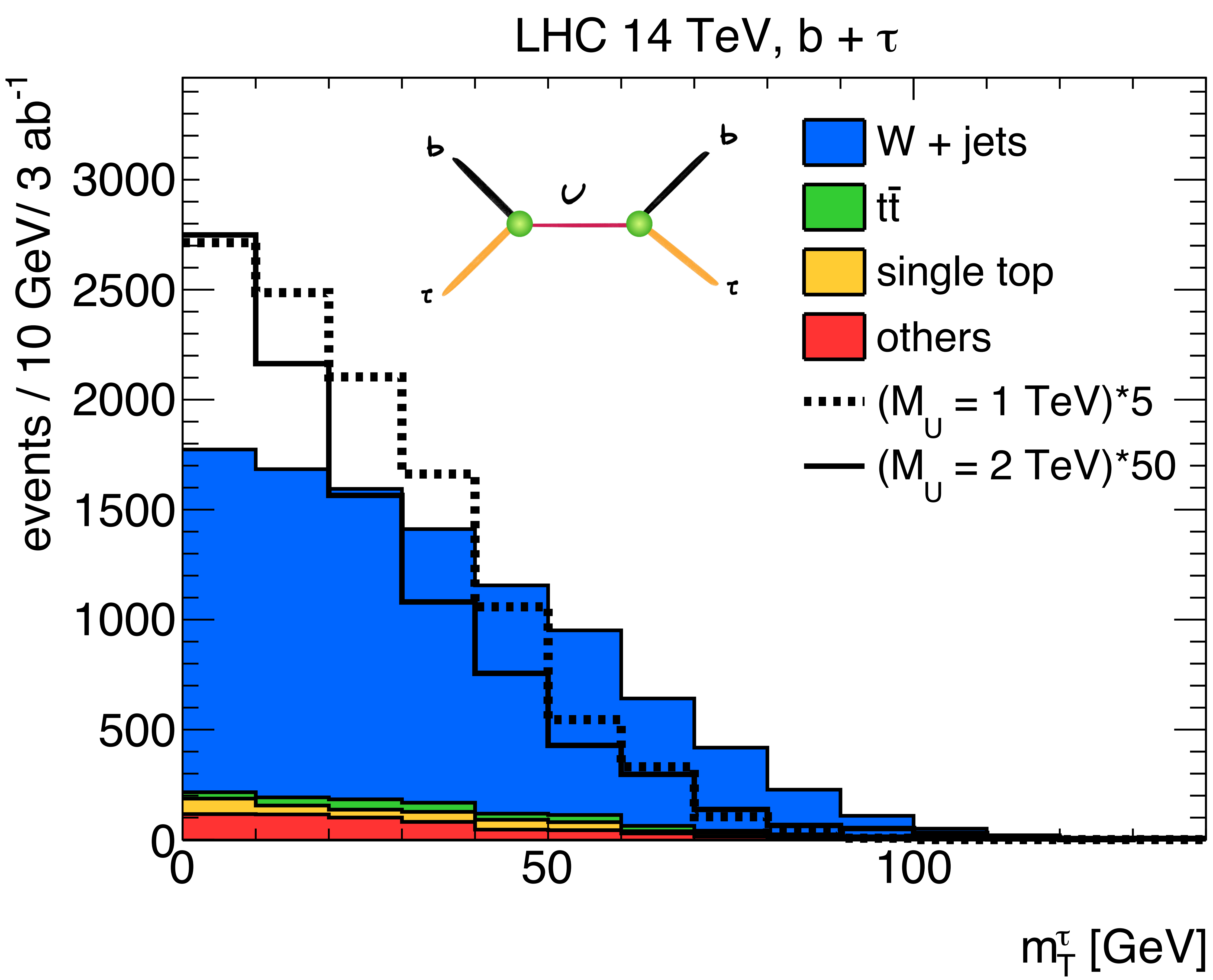
Kinematic distributions of pp → bτ signal

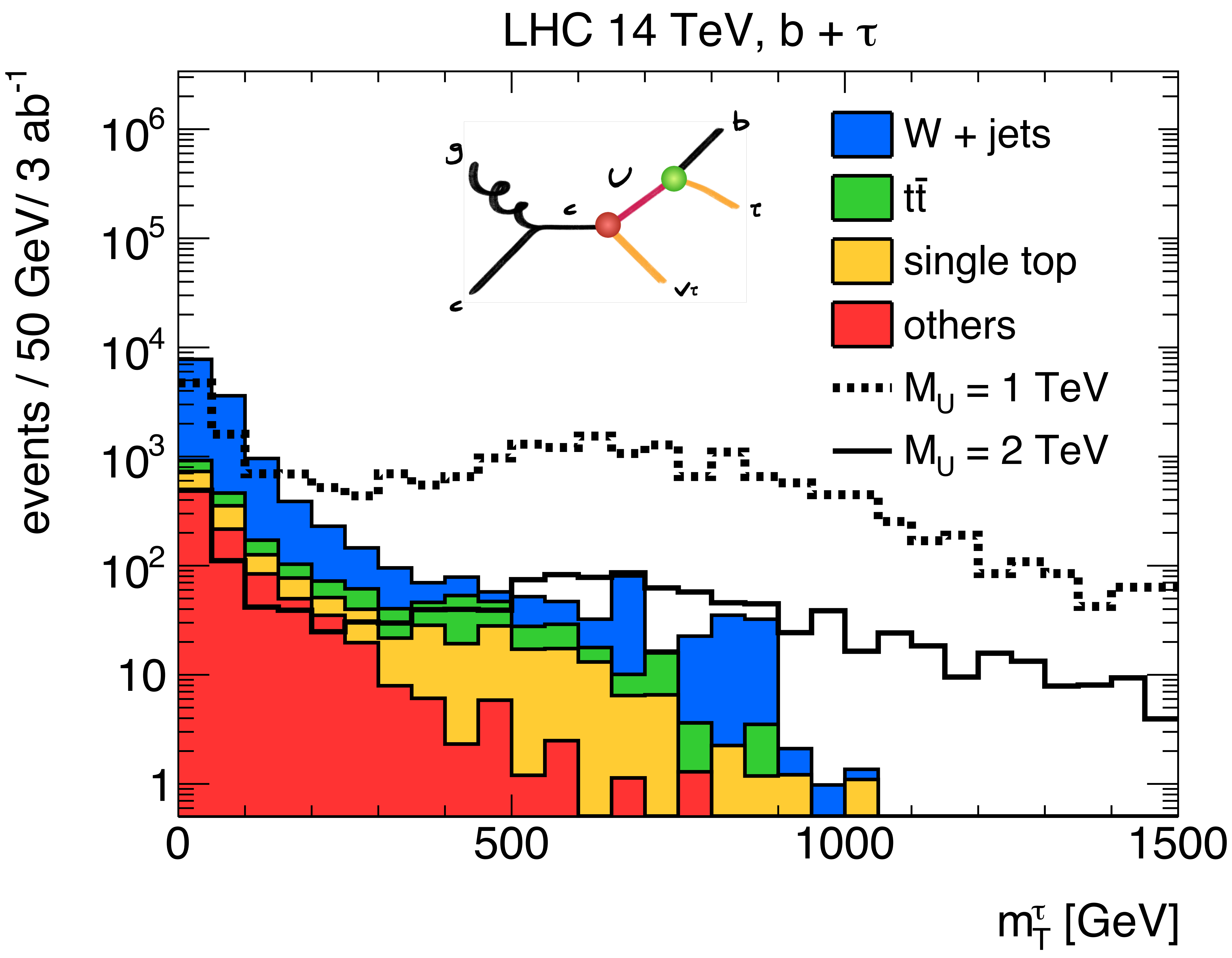




[UH & Polesello, 2012.11474]

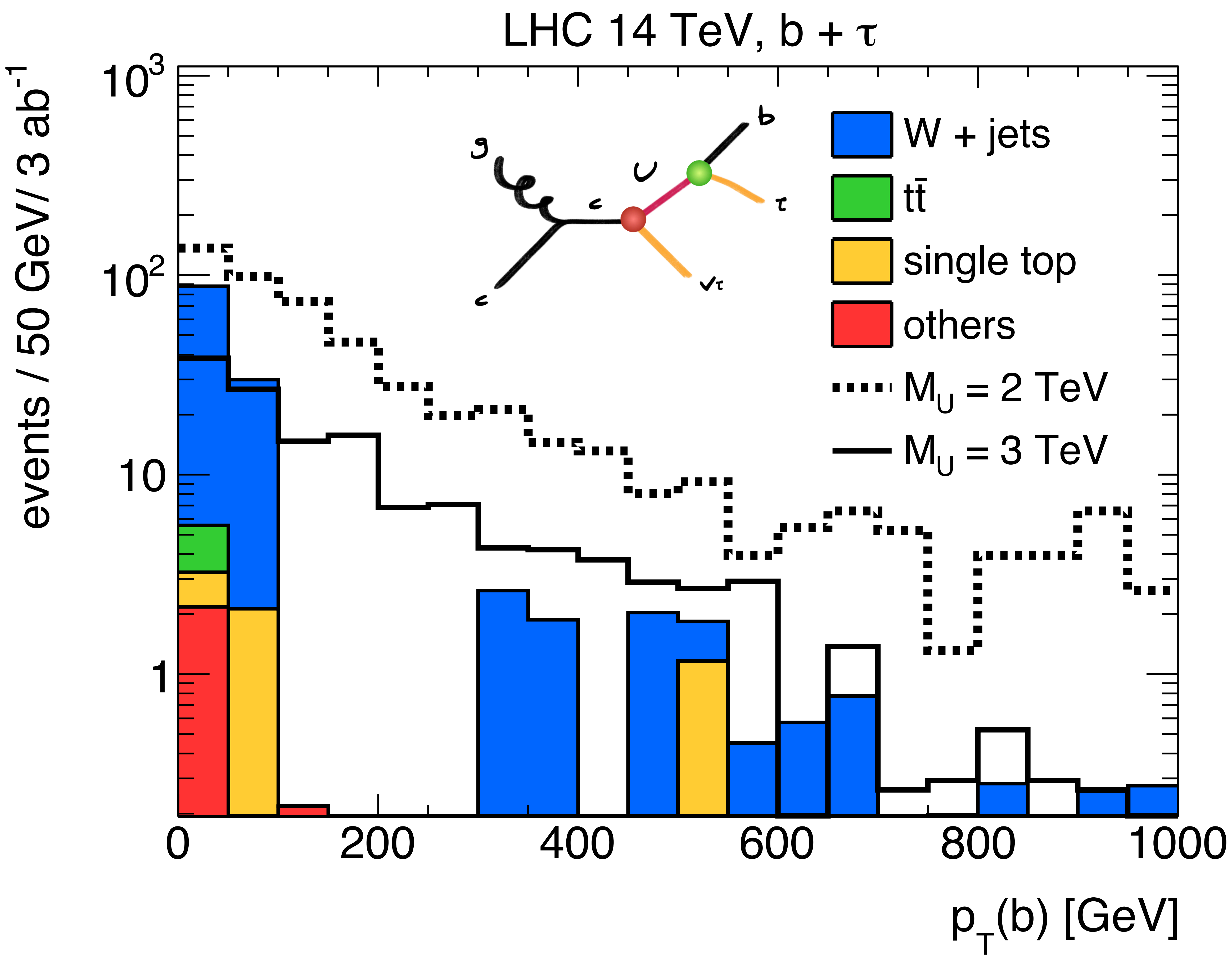
Kinematic distributions of pp → bτ signal

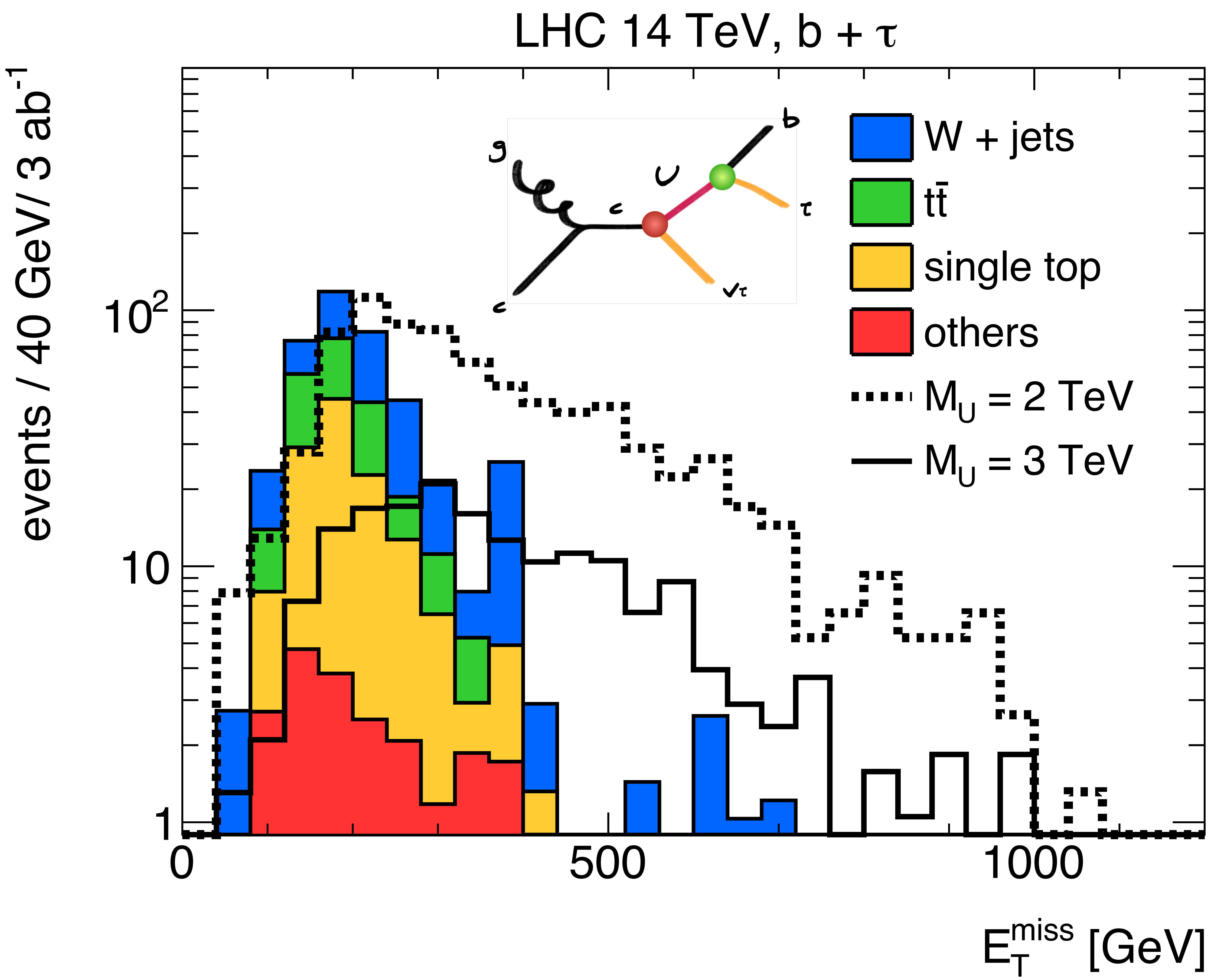




[UH & Polesello, 2012.11474]

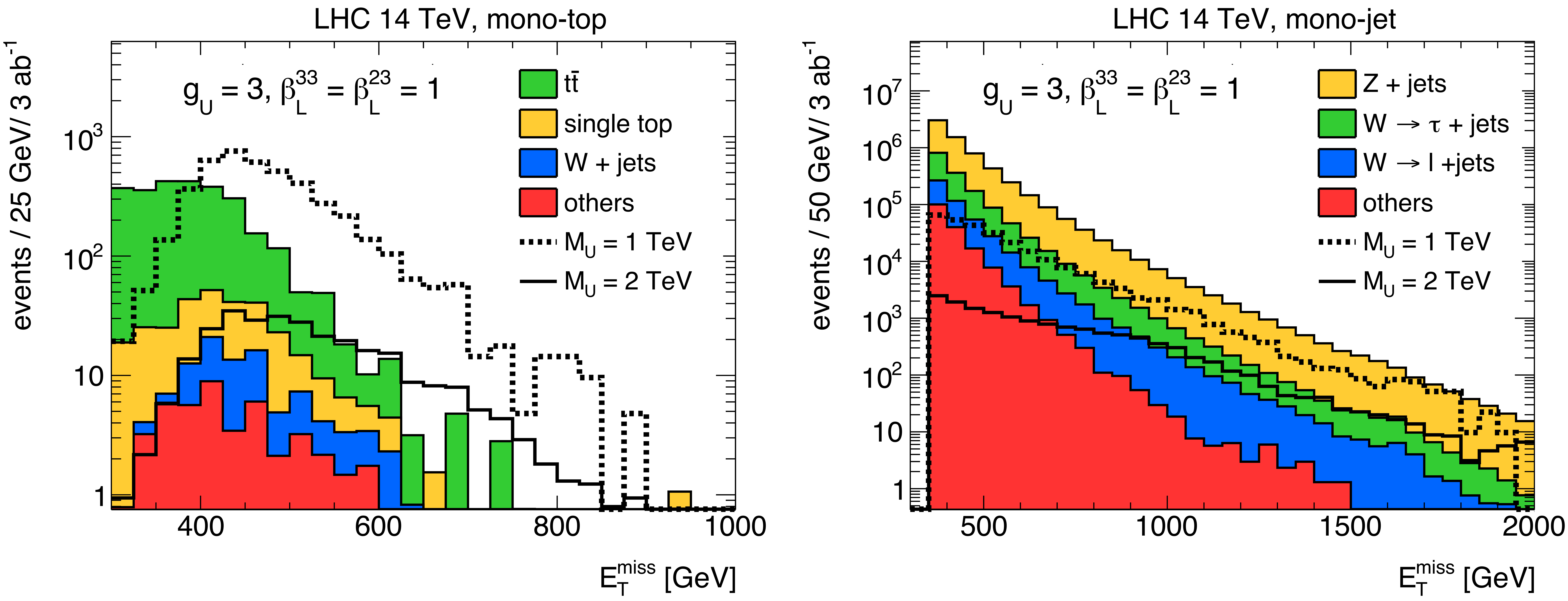
Kinematic distributions of pp → bτ signal





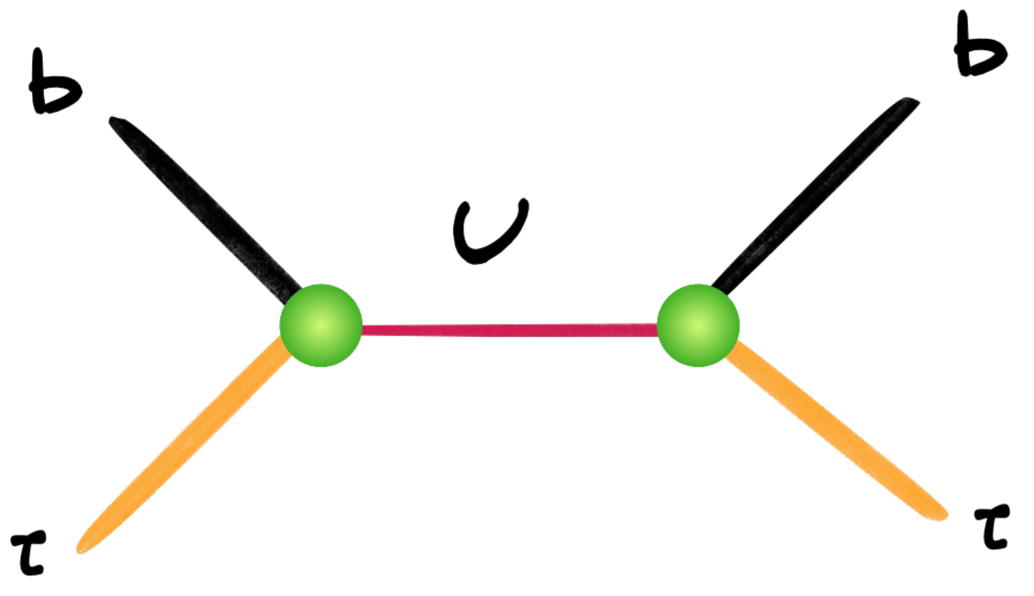
[UH & Polesello, 2012.11474]

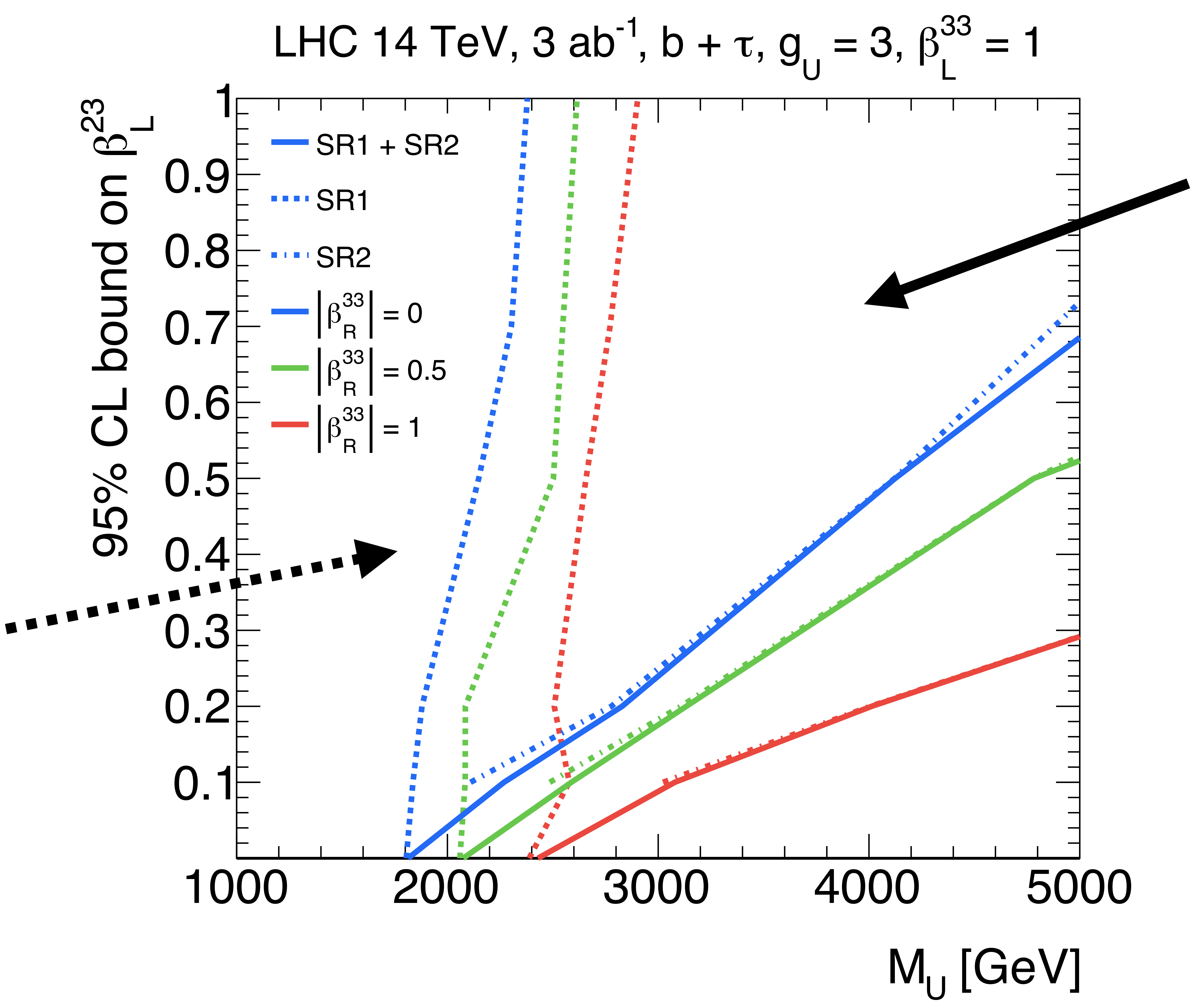
Mono-top & mono-jet distributions

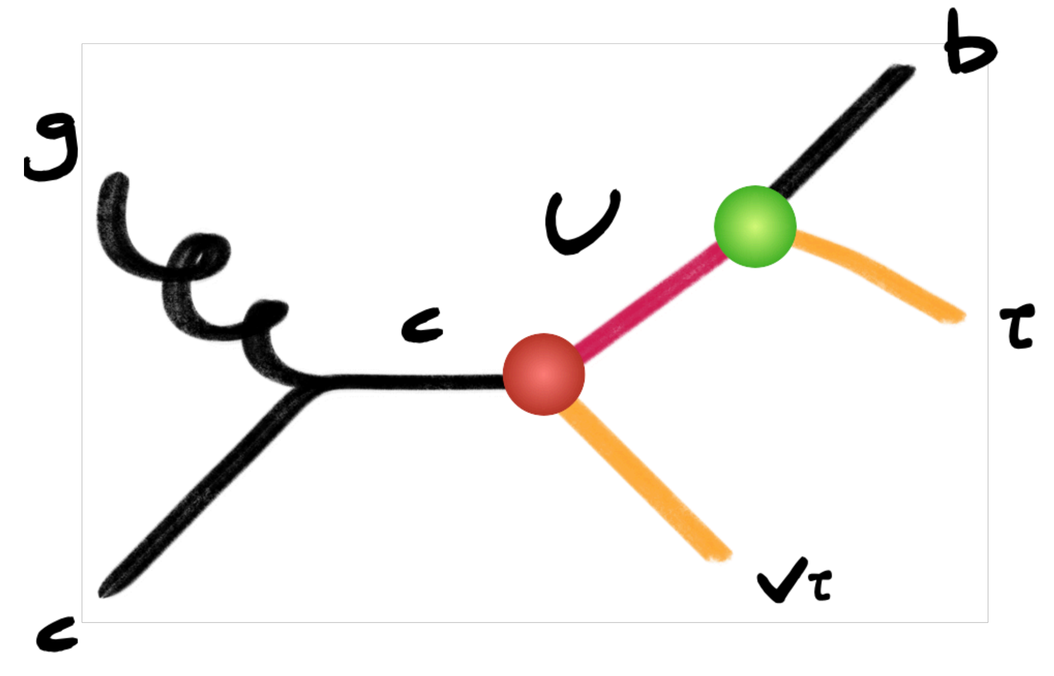


[UH & Polesello, 2012.11474]

pp → bτ constraints from 2 → 2 & 2 → 3 signal

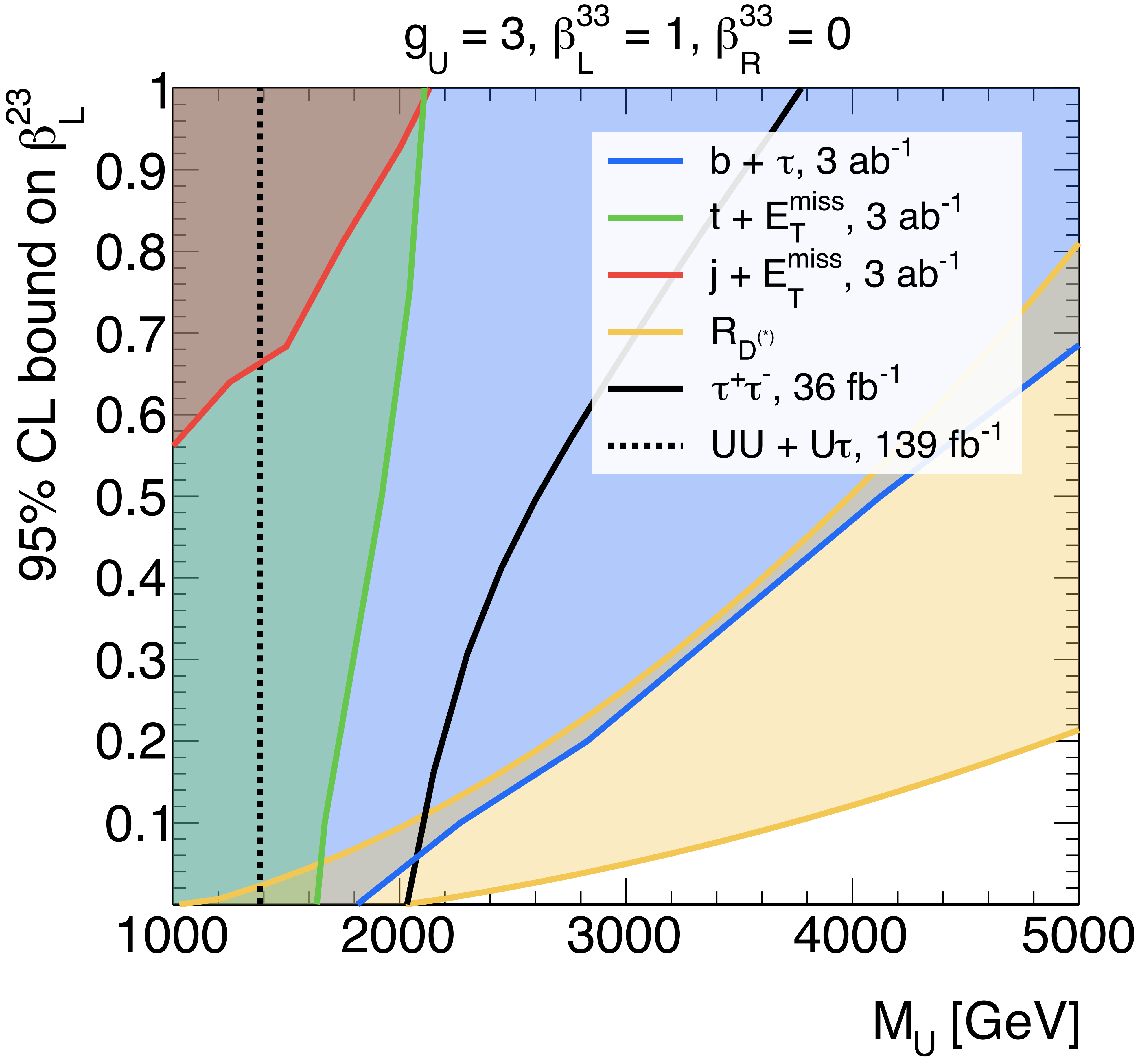


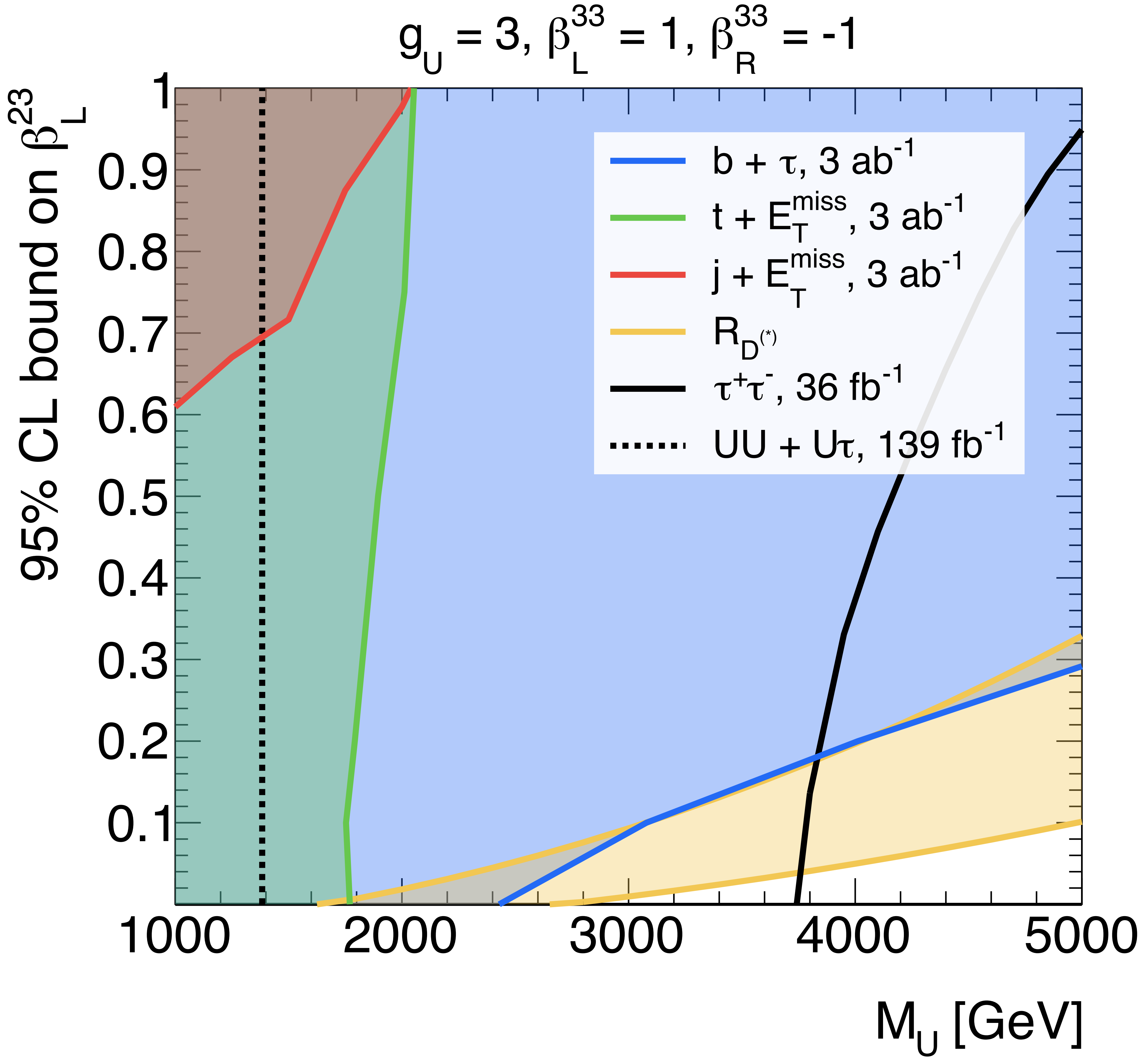




[UH & Polesello, 2012.11474]

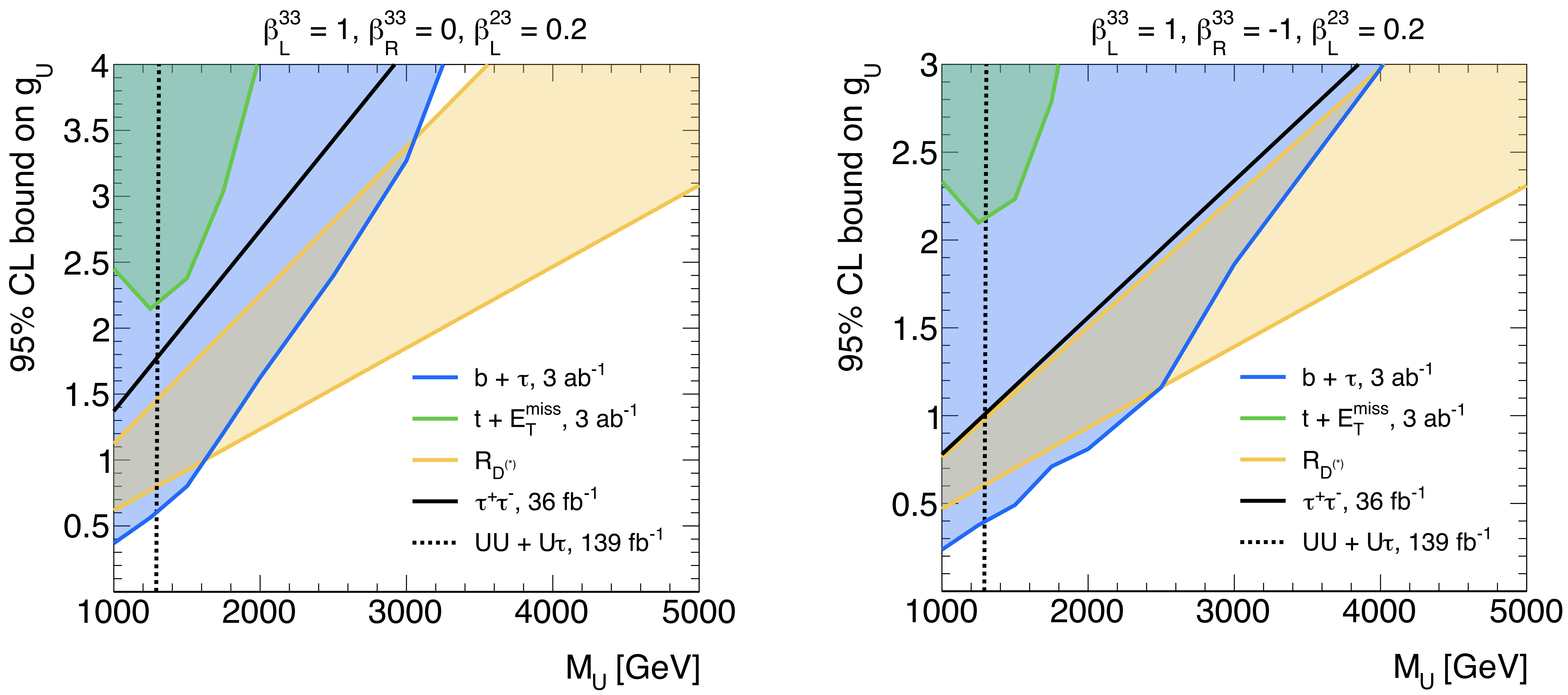
Constraints from bτ, mono-top & mono-jet





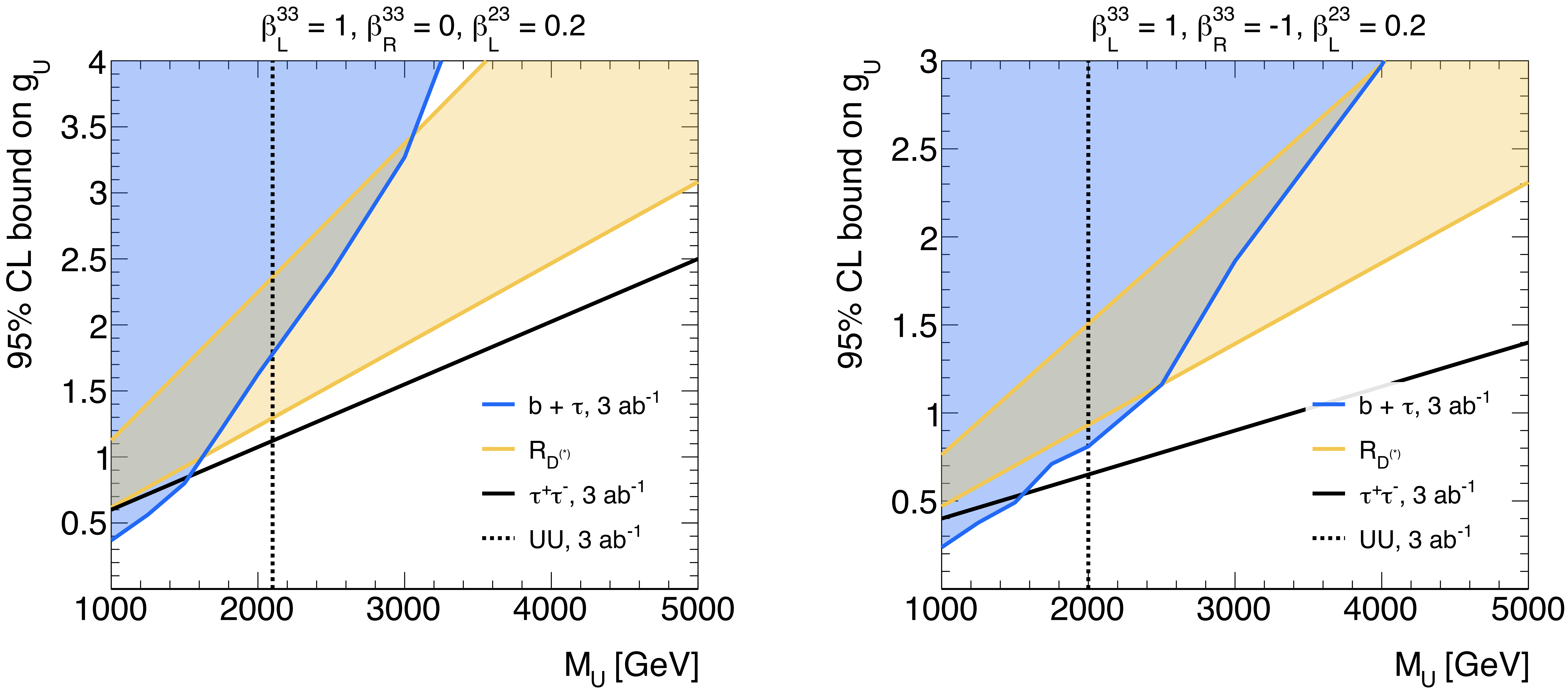
[UH & Polesello, 2012.11474]

Constraints from bτ, mono-top & mono-jet



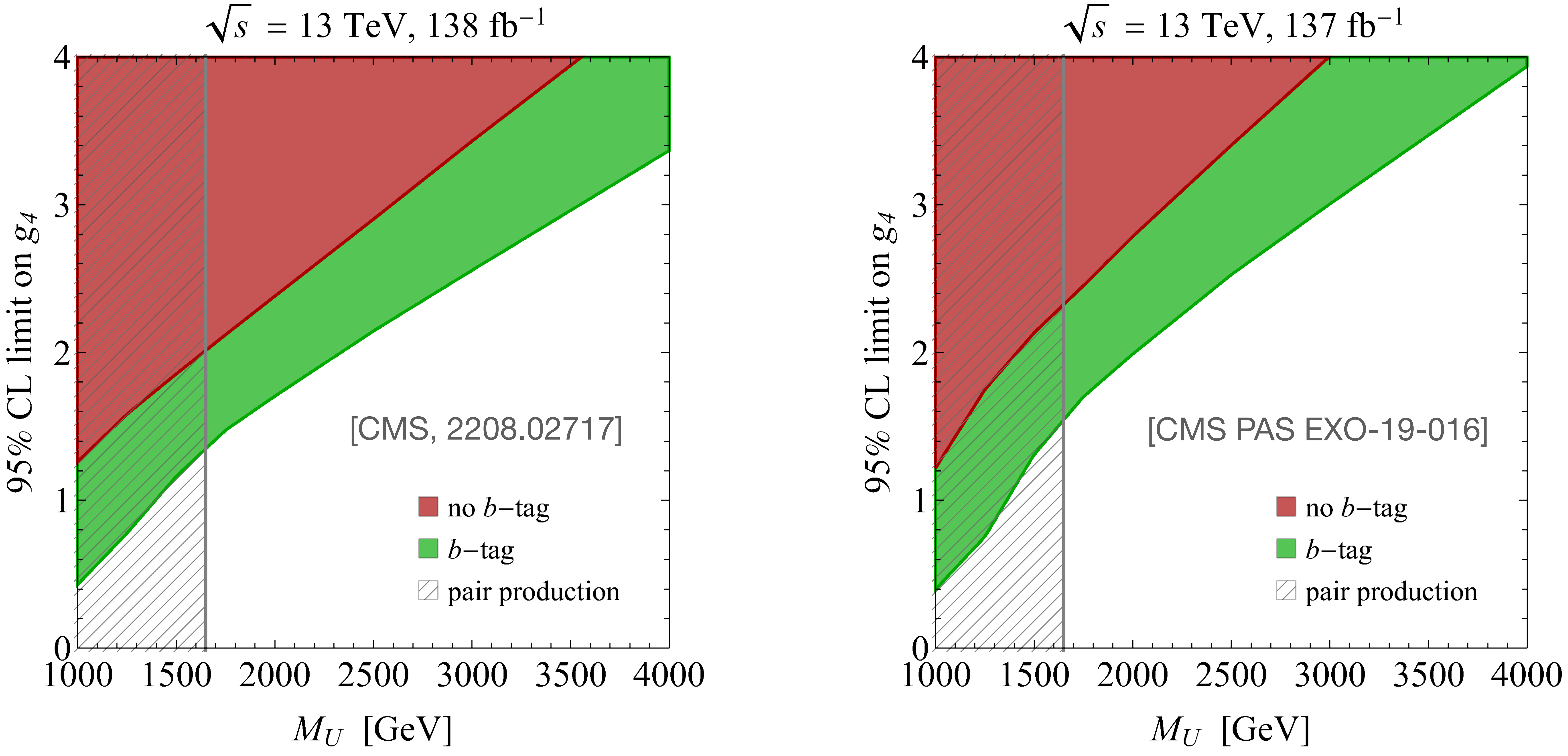
[UH & Polesello, 2012.11474]

Prospects of LQ search strategies



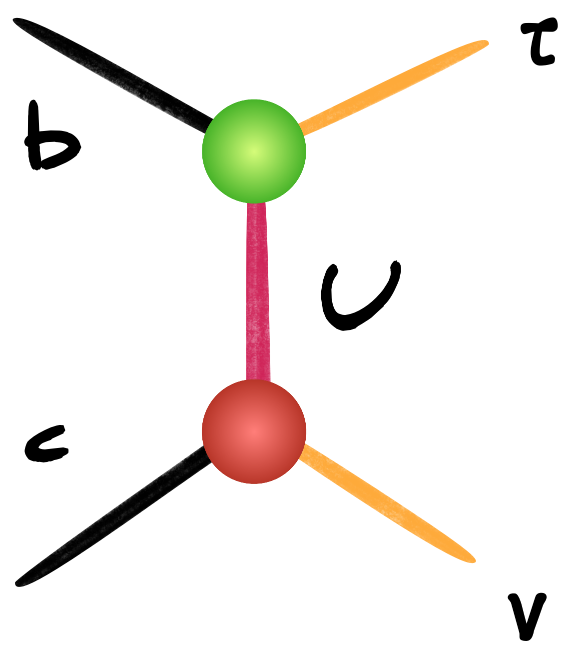
[UH & Polesello, 2012.11474; Cornella, Faroughy, Fuentes-Martin, Isidori & Neubert, 2103.16558]

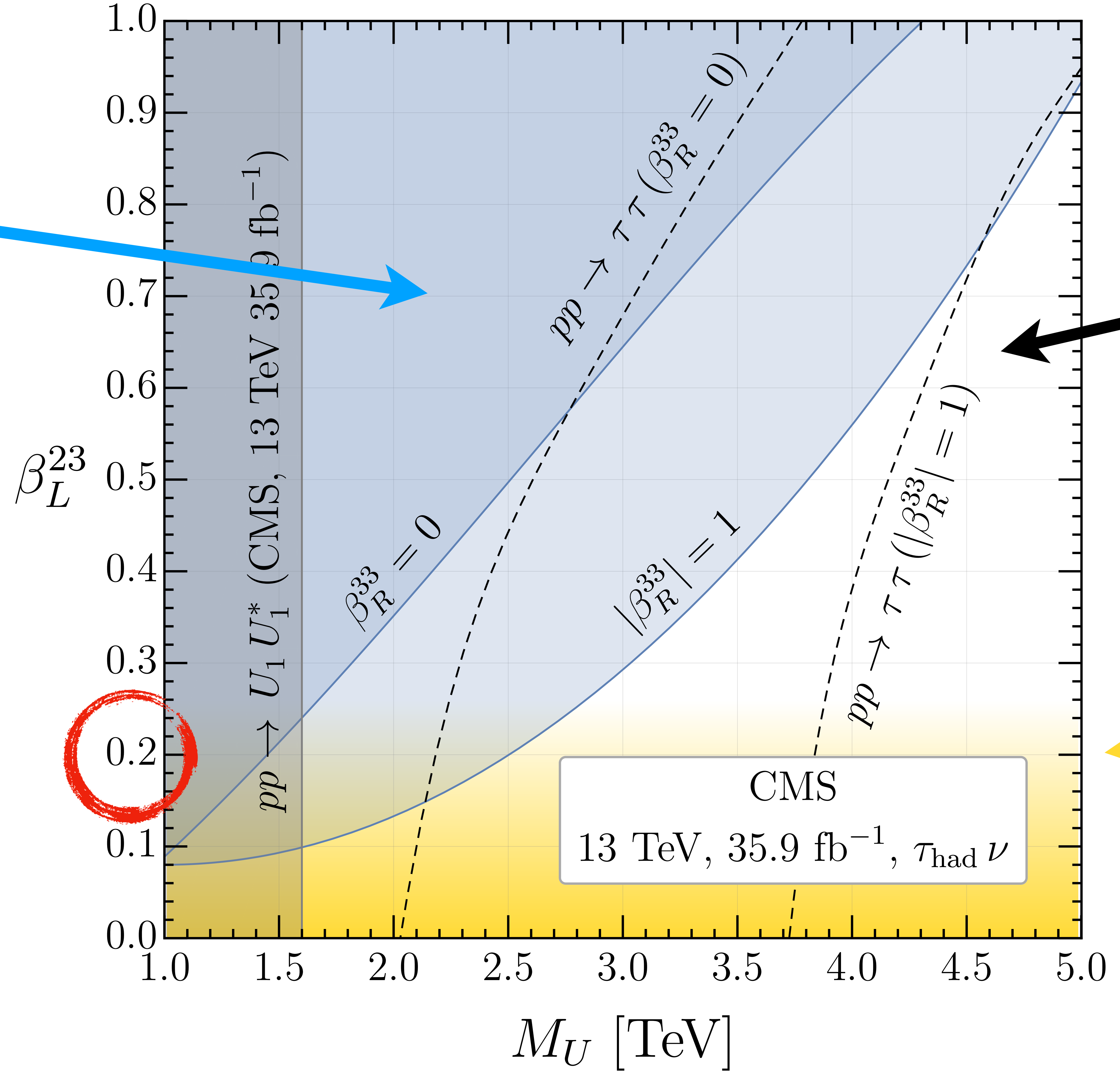
Ditau limits on singlet vector LQs from CMS

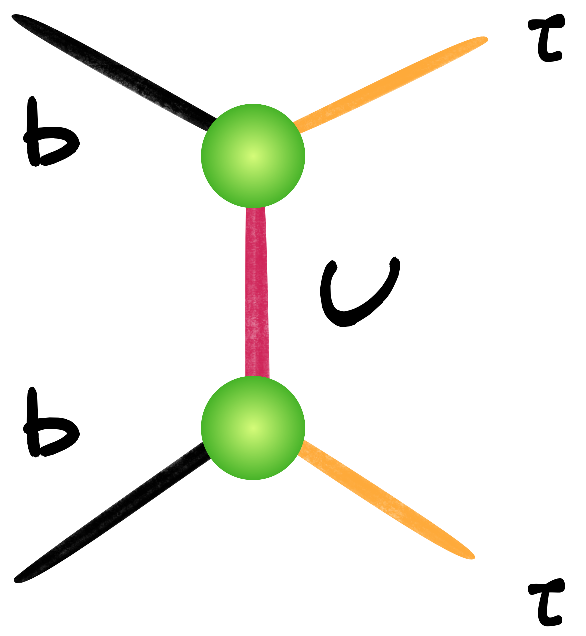


[NLO+PS accurate results for t-channel ditau production in LQ models obtained in UH, Schnell & Schulte, 2207.00356; 2209.12780]

LHC bounds: pp → ττ vs. pp → τν





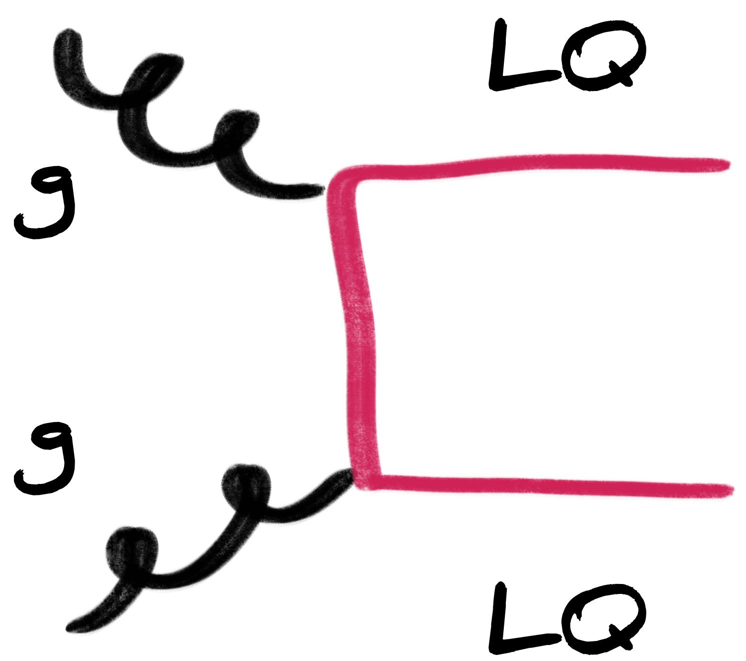


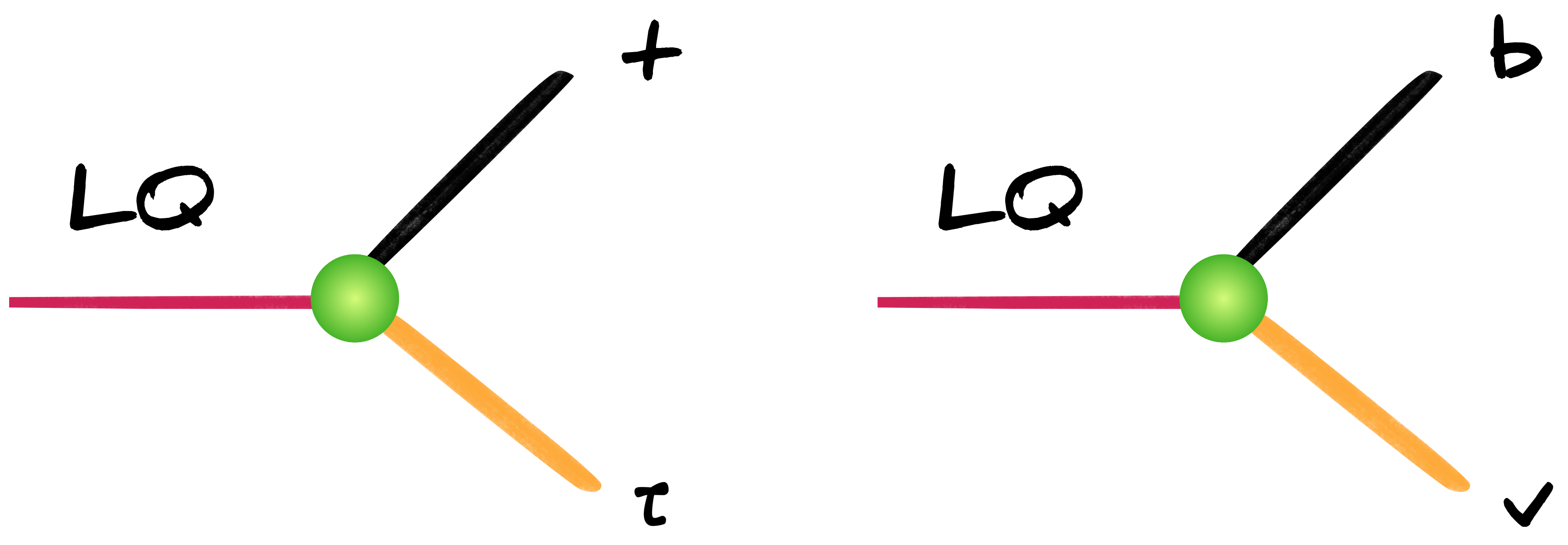
parameter space of singlet vector LQ with natural flavour structure

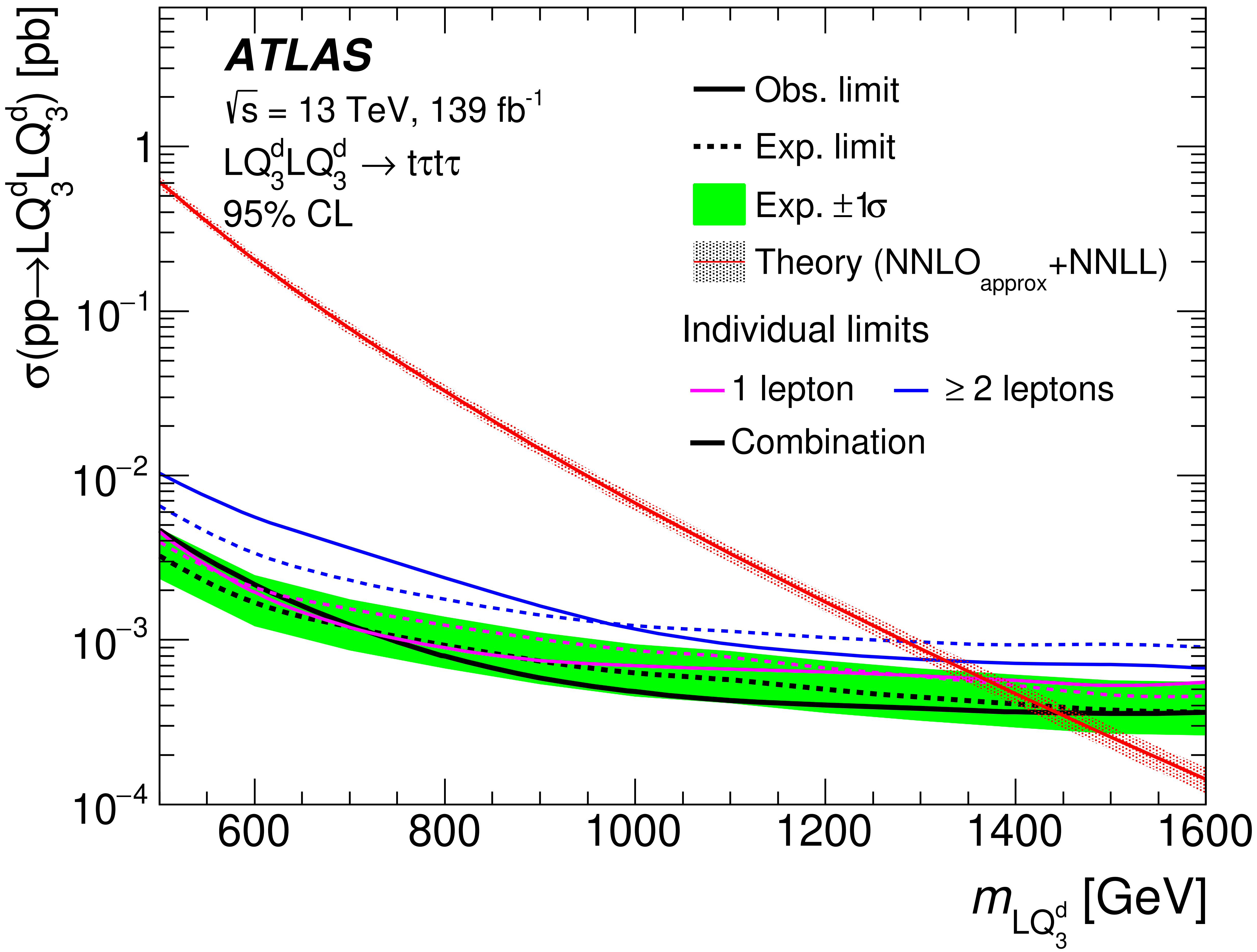
[Baker, Fuentes-Martin, Isidori & König, 1901.10480]

Another LQ search triggered by B anomalies

[ATLAS, 2101.11582]



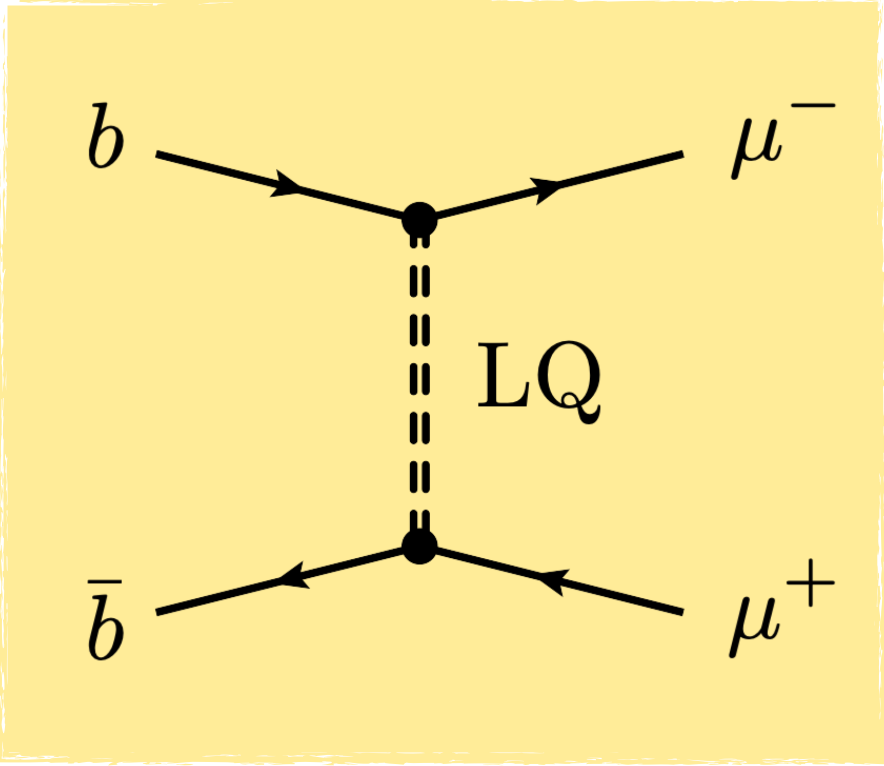




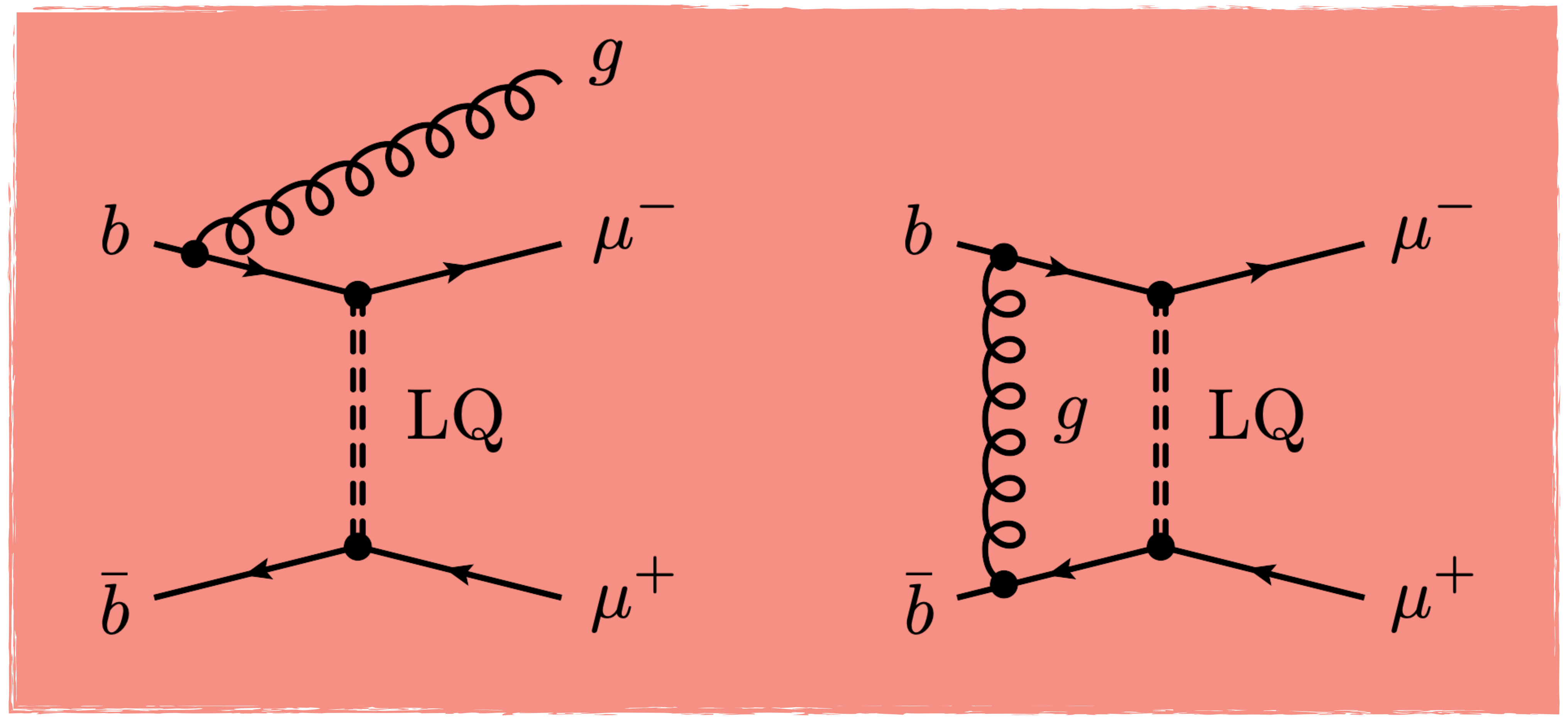
[Bauer & Neubert, 1511.01900]

NLO+PS calculation for scalar LQs

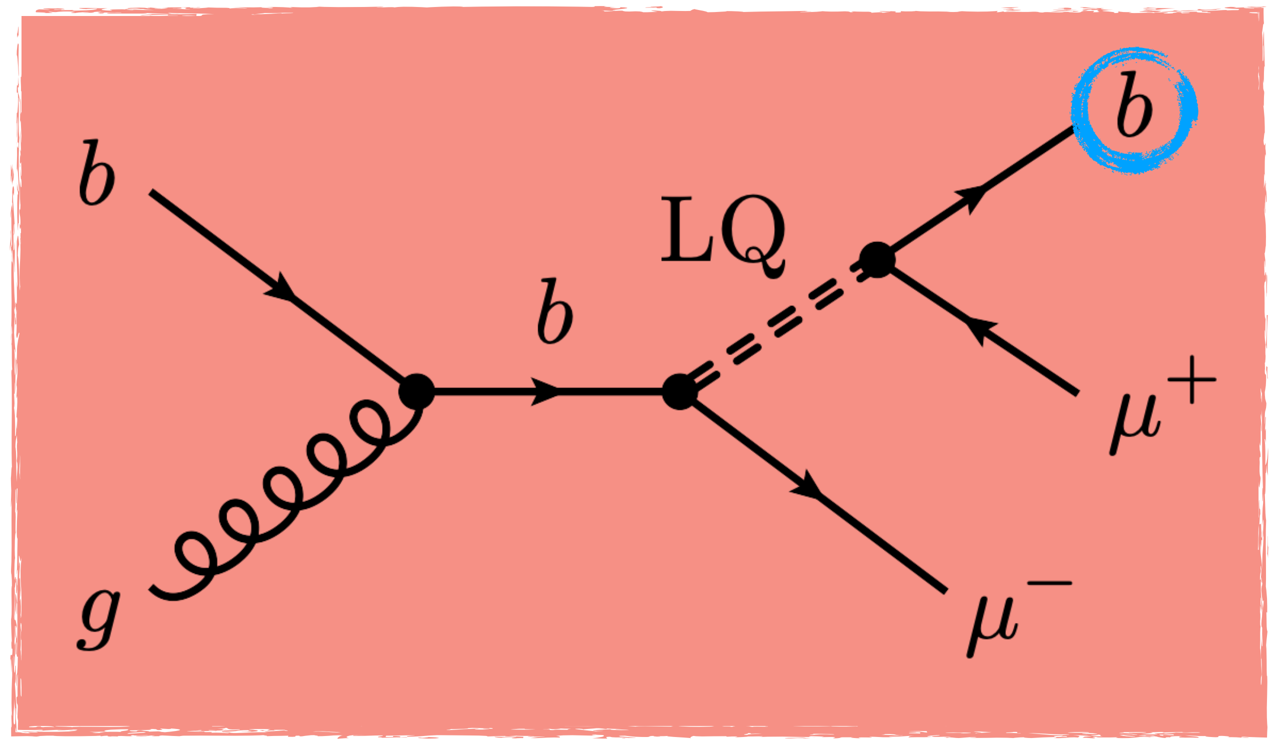
tree-level contribution

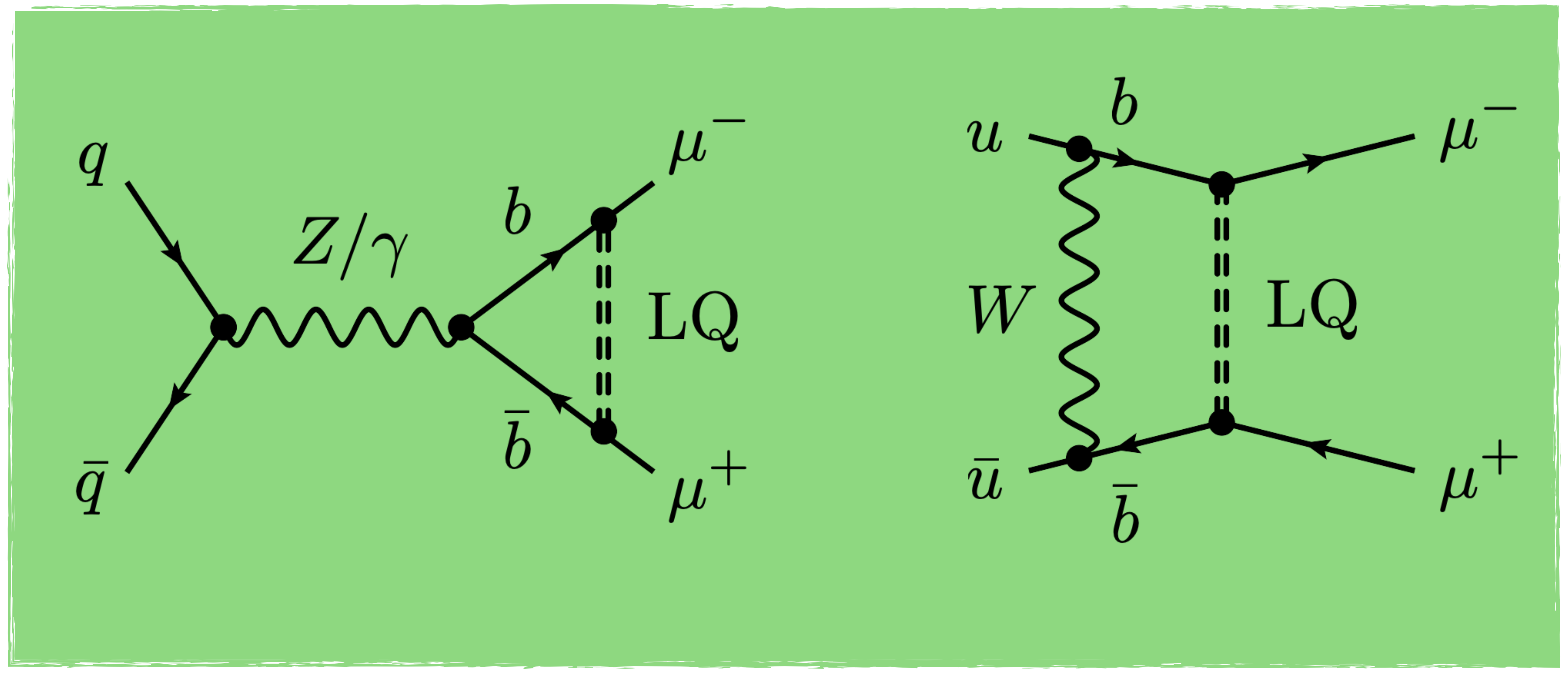


real & virtual correction to Born level



infrared finite QCD correction

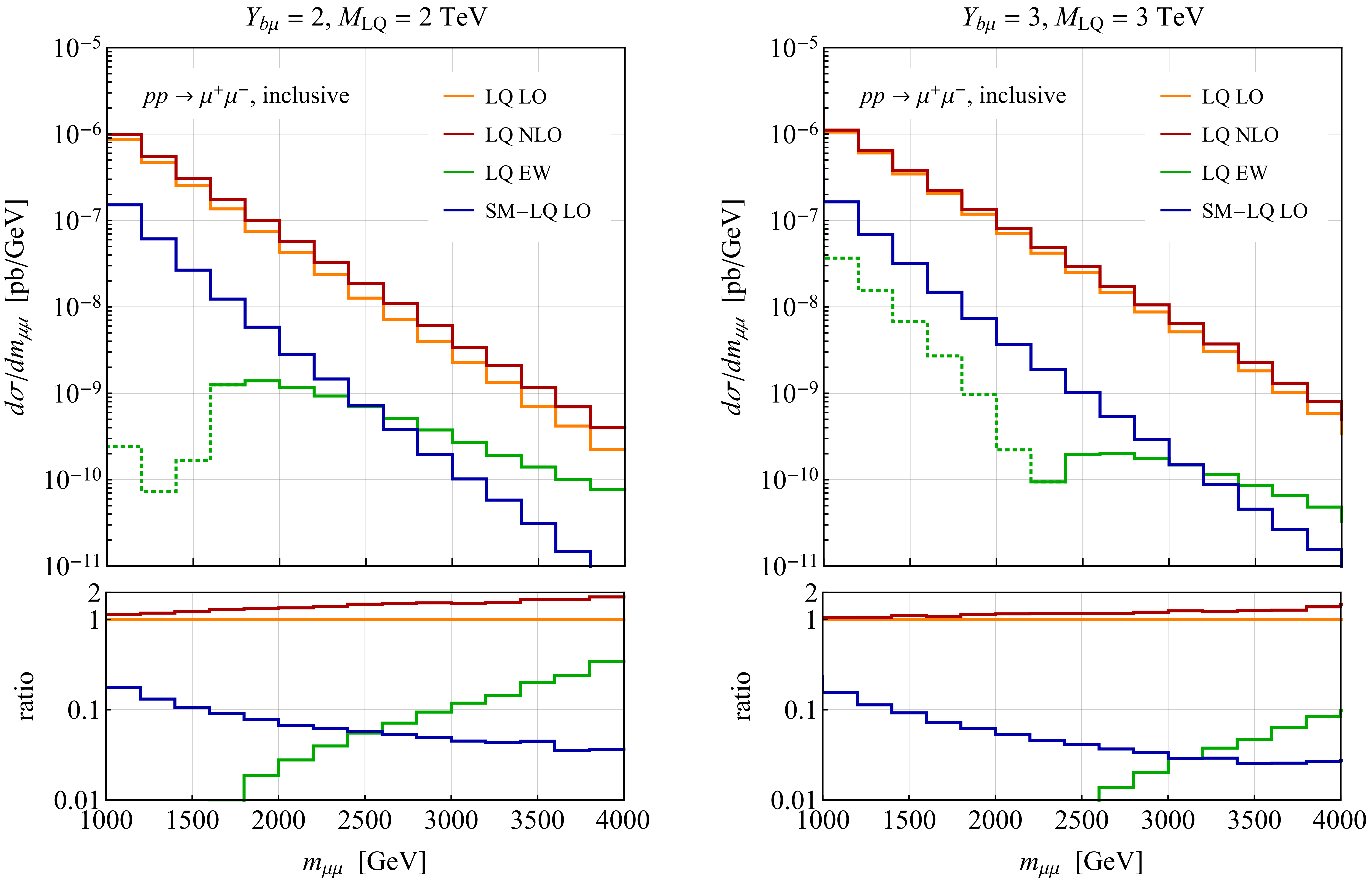




electroweak corrections

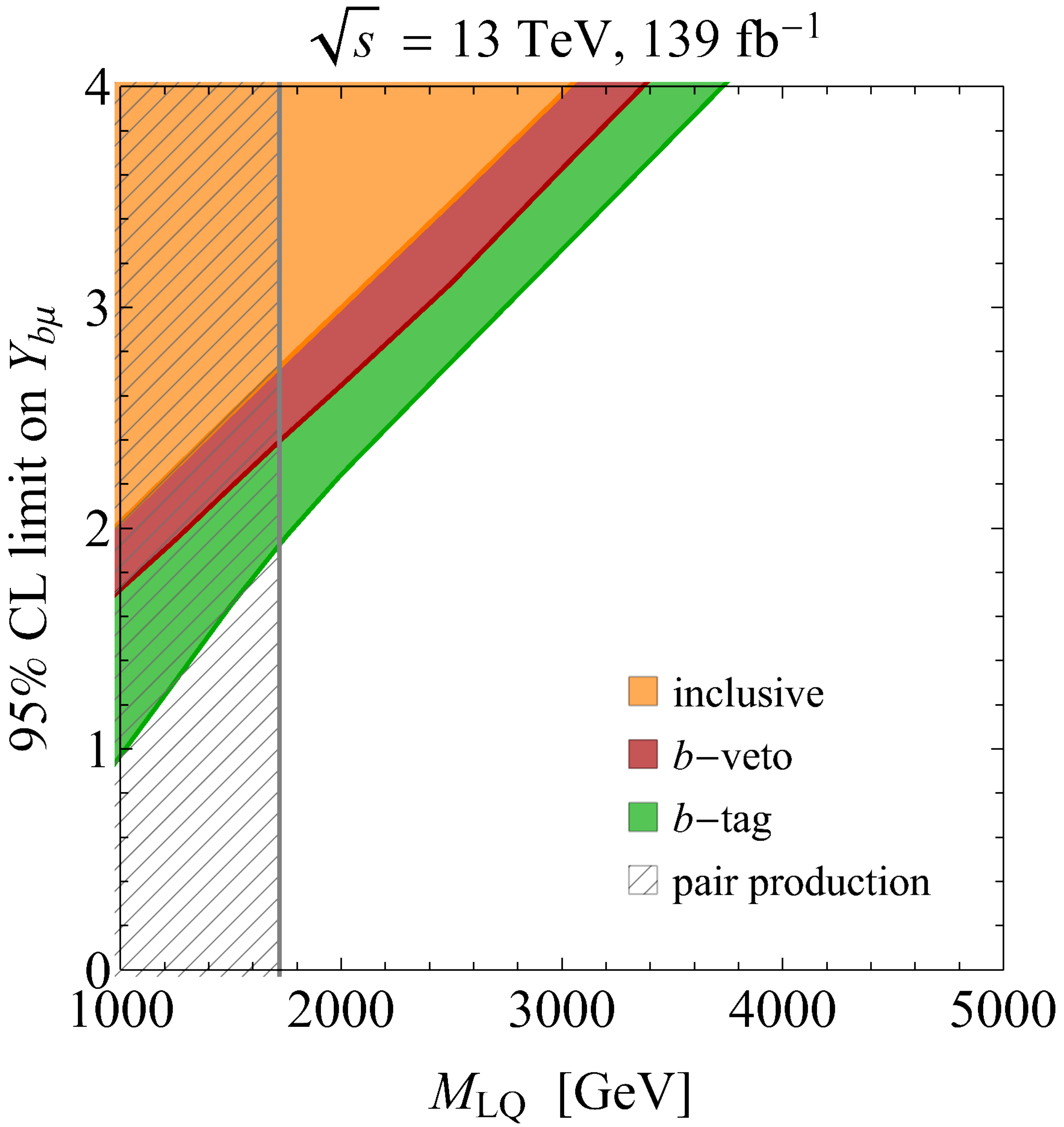
[UH, Schnell & Schulte, 2207.00356]

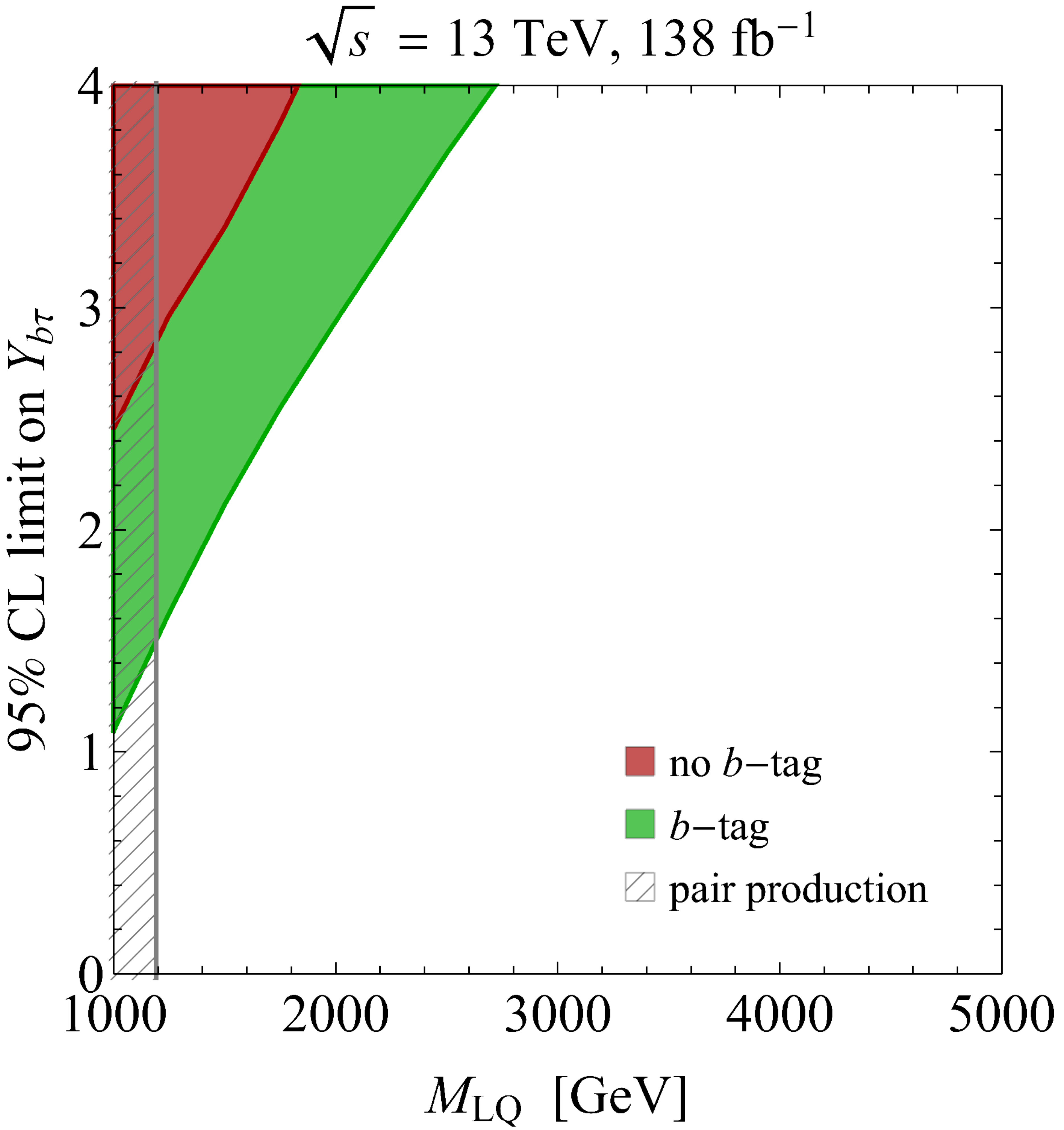
Size of NLO, EW & interference effects



[UH, Schnell & Schulte, 2207.00356]

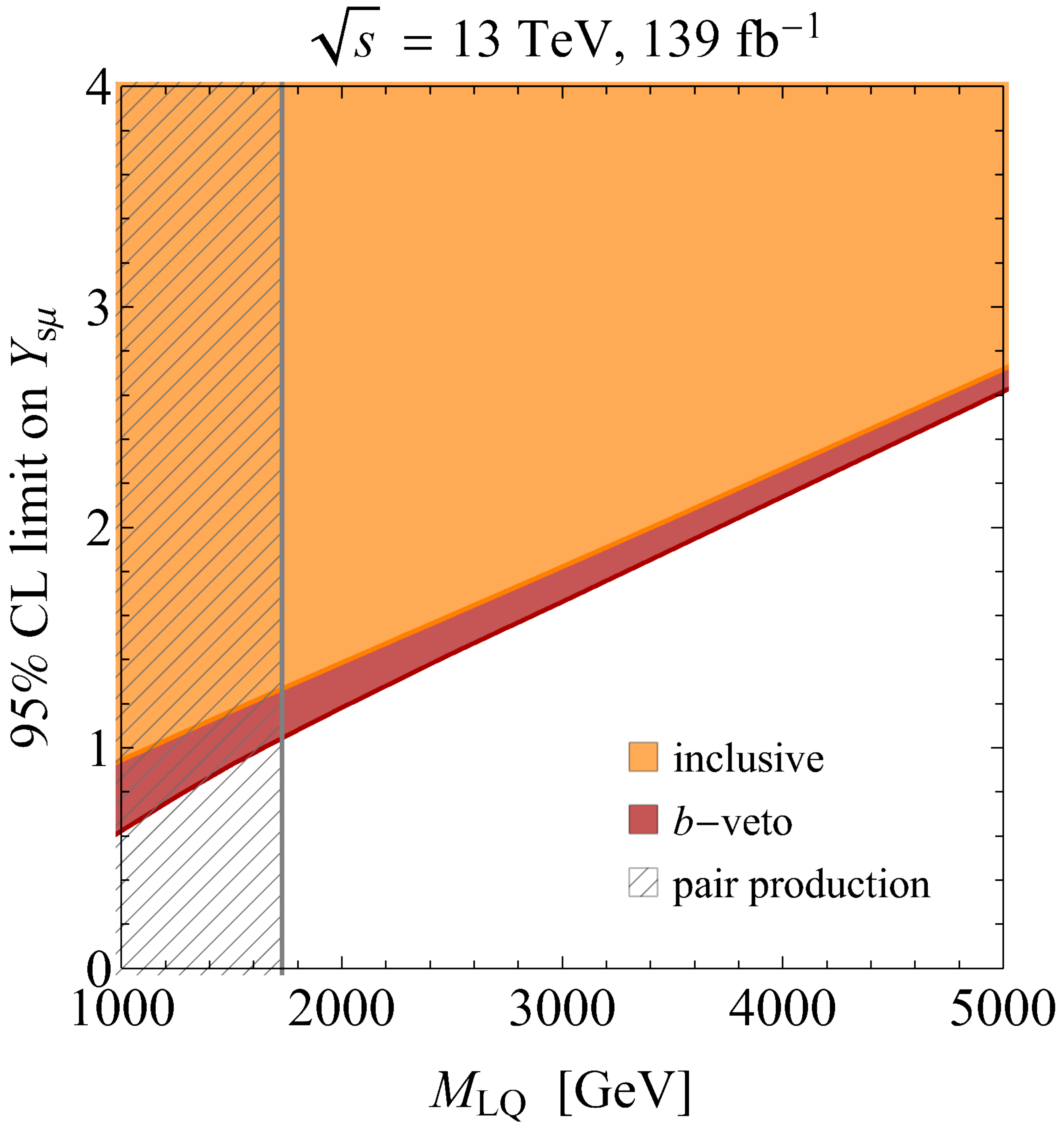
Dimuon constraints on scalar LQs

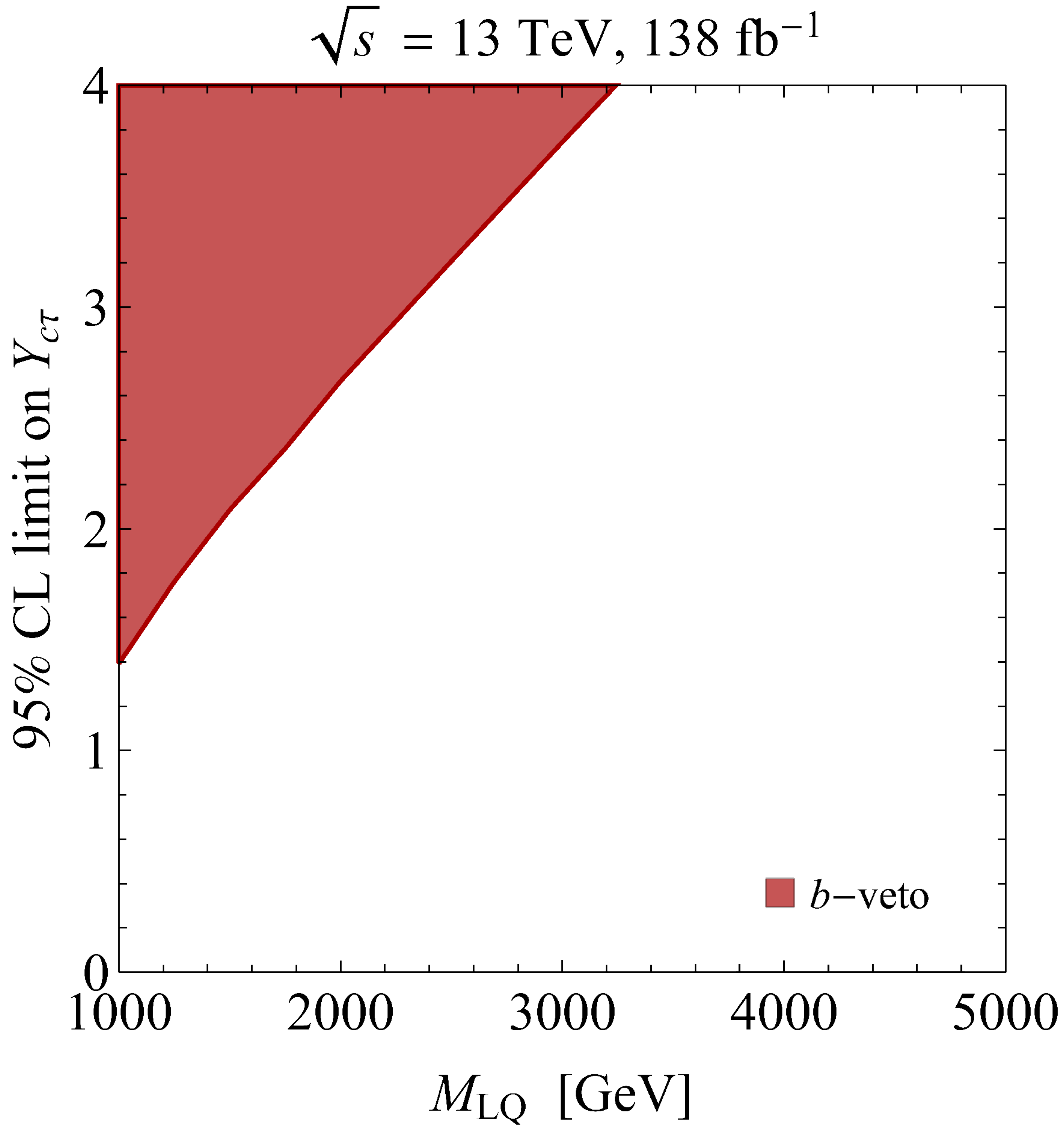




[UH, Schnell & Schulte, 2207.00356]

Dimuon constraints on scalar LQs

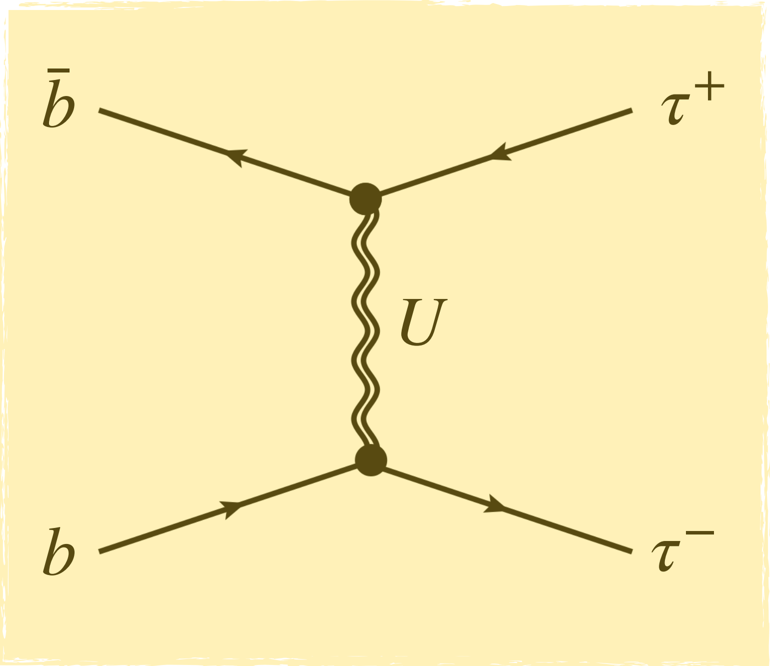


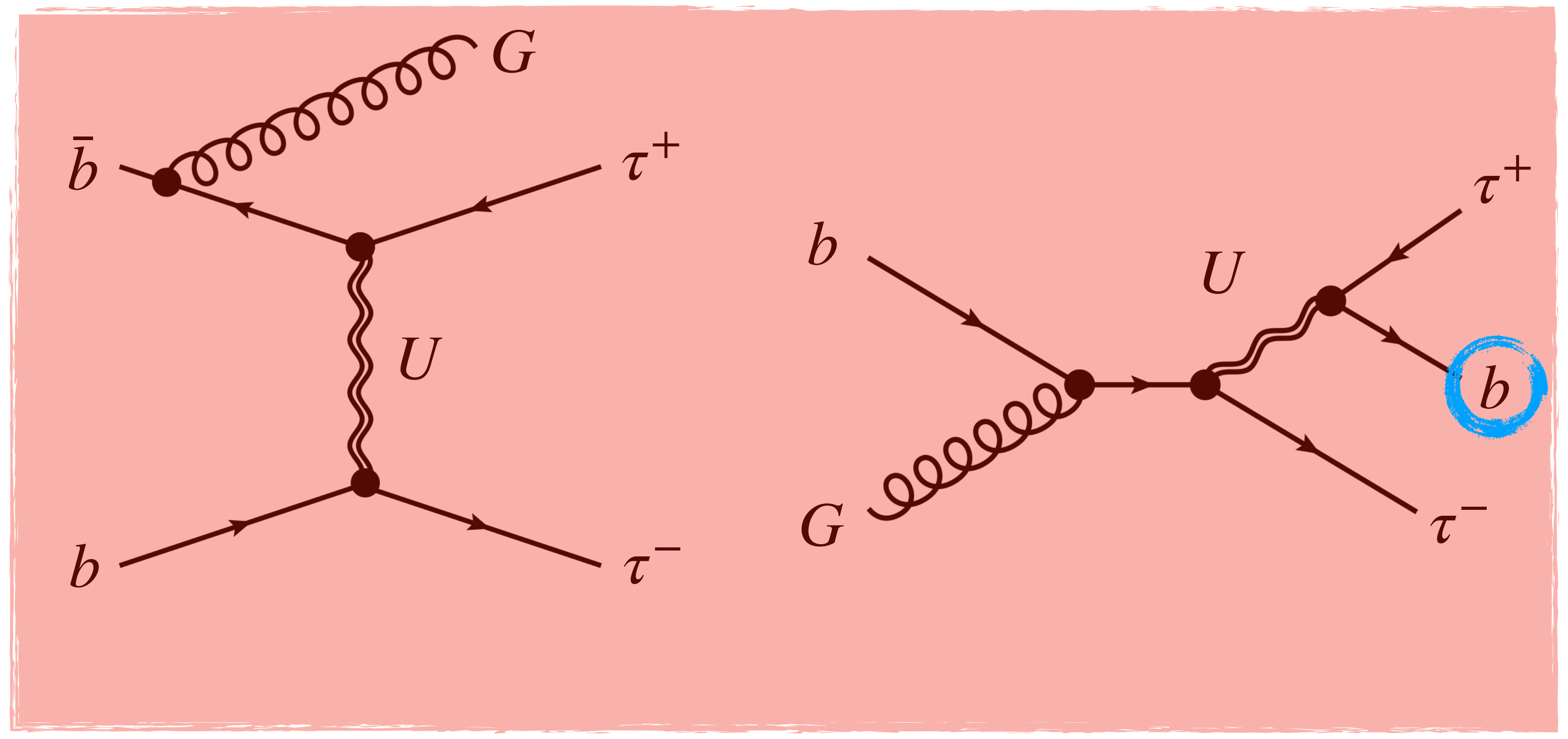


[UH, Schnell & Schulte, 2207.00356]

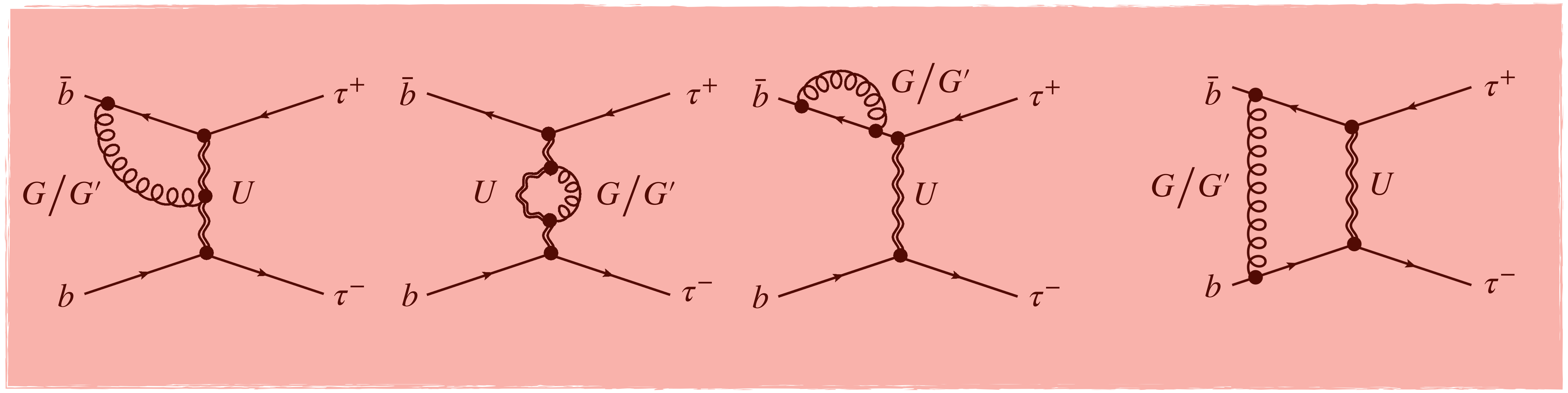
NLO+PS calculation for singlet vector LQs

tree-level contribution





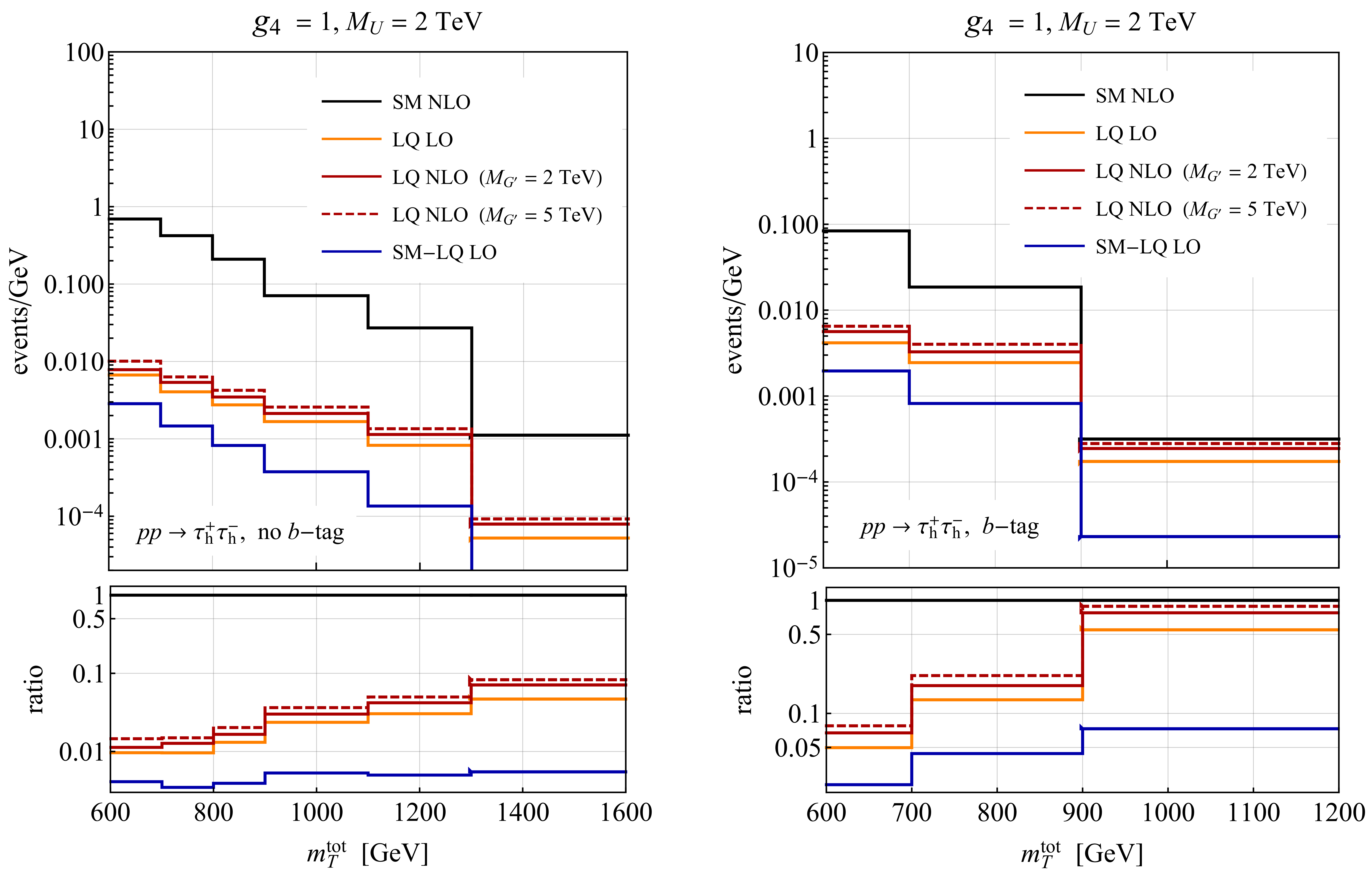
real QCD corrections



virtual QCD effects involving gluon (G) & coloron (G′)

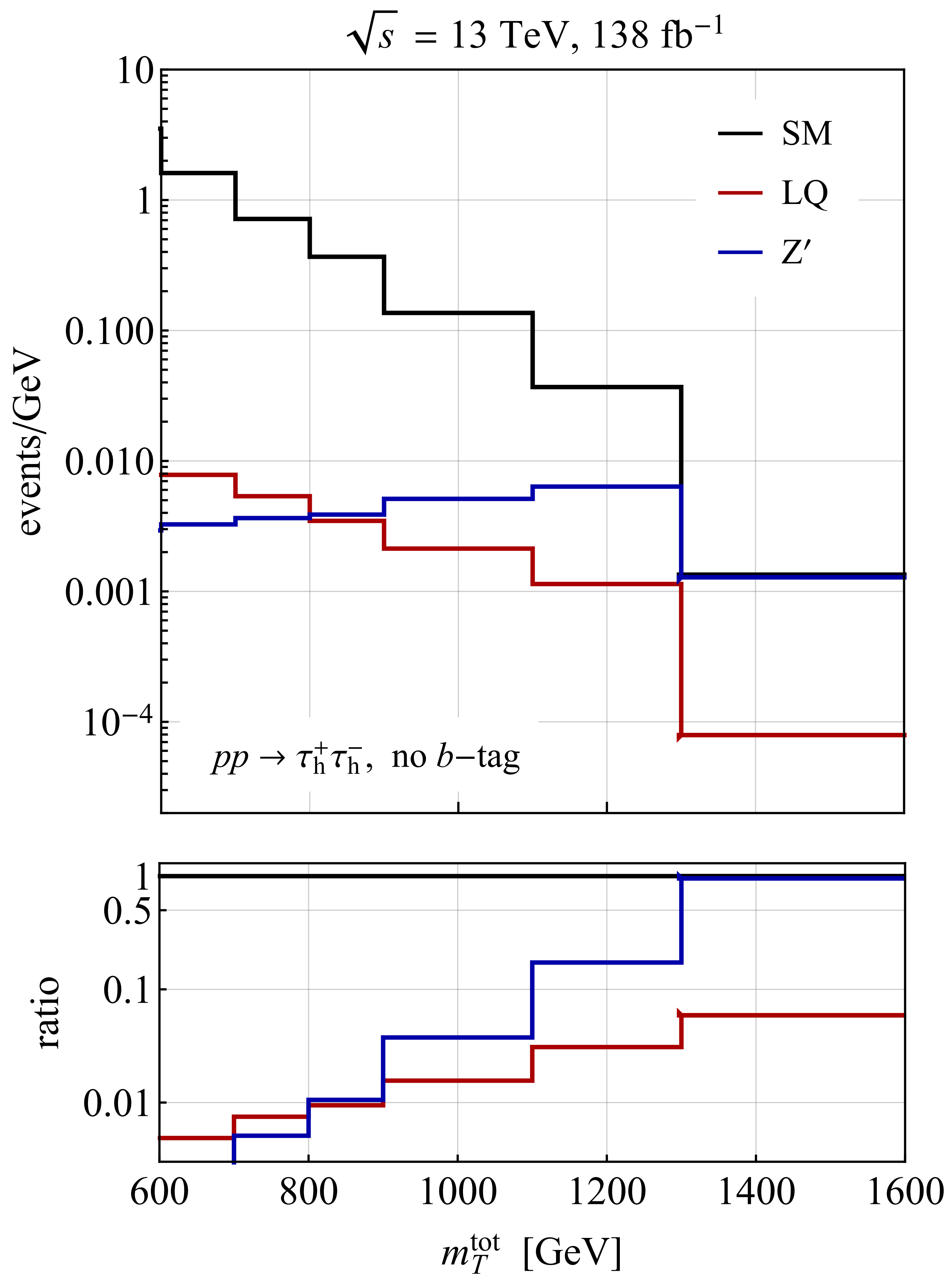
[UH, Schnell & Schulte, 2209.12780]

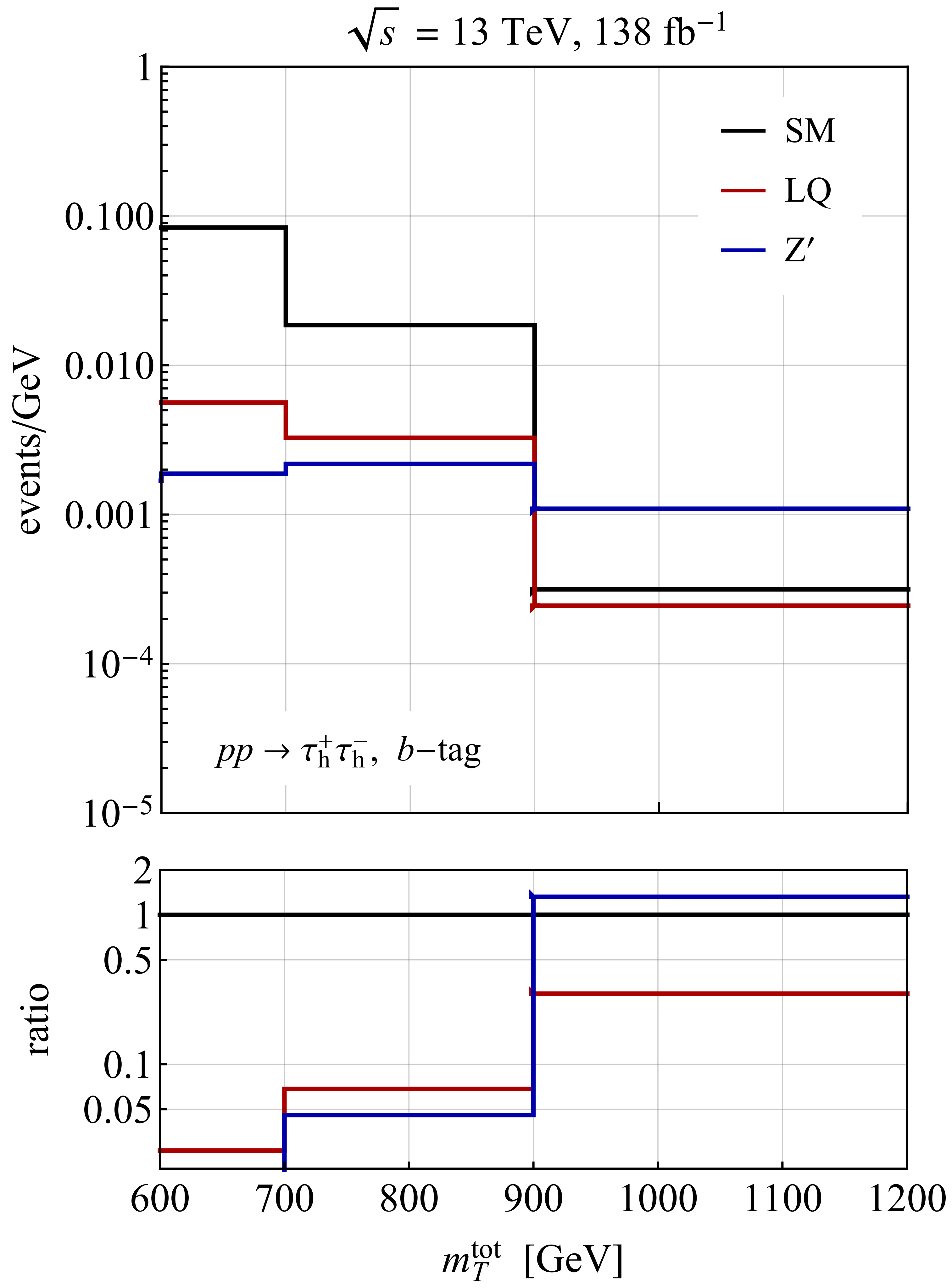
Size of NLO & interference effects



[UH, Schnell & Schulte, 2209.12780]

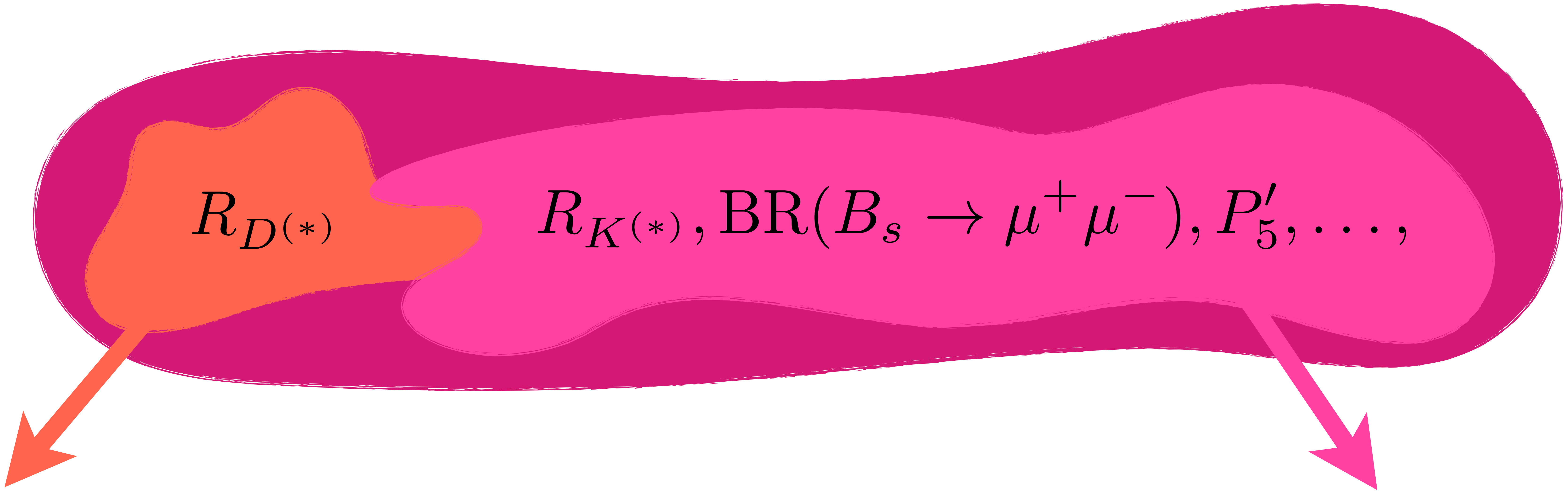
Z′ contributions in 4-3-2-1 model





[UH, Schnell & Schulte, 2209.12780]

B anomalies in a nutshell

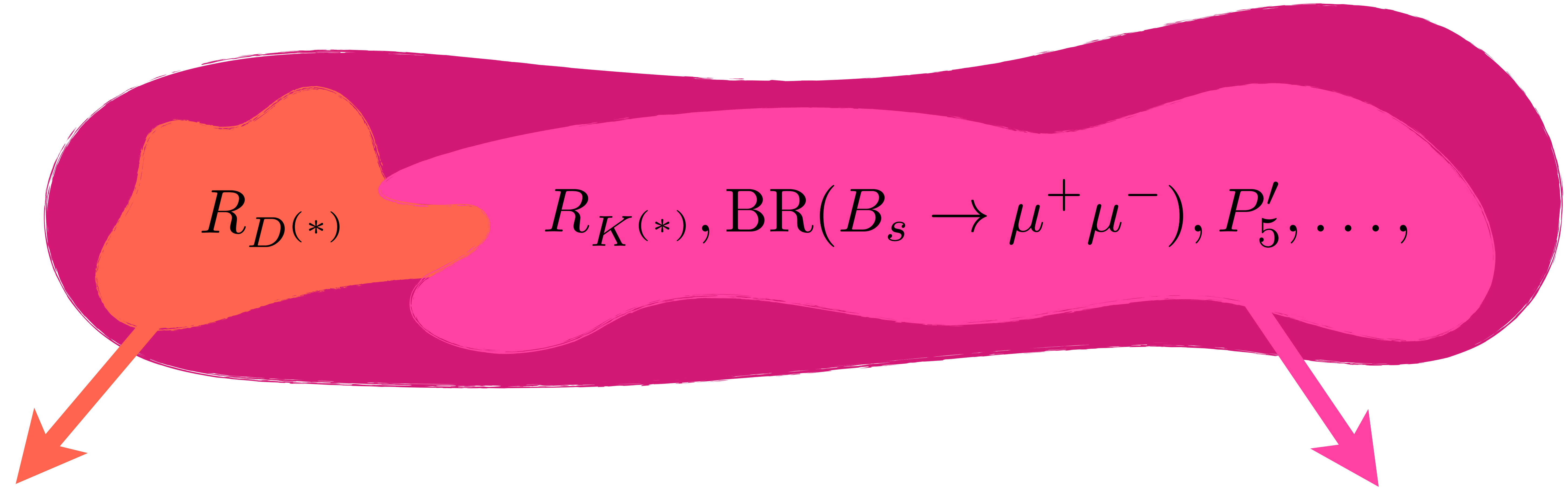


$$\frac{1}{(1.2\,\mathrm{TeV})^2}\,(\bar{c}_L \gamma_\alpha b_L)\,(\bar{\tau}_L \gamma^\alpha \nu_L)$$

$$\frac{1}{(35\,\mathrm{TeV})^2}\,(\bar{s}_L \gamma_\alpha b_L)\,\big(\bar{\mu}_{(L)} \gamma^\alpha \mu_{(L)}\big)$$

Both sets of B anomalies challenge(d) assumption of lepton flavour universality (LFU), which is usually taken for granted in high-energy physics

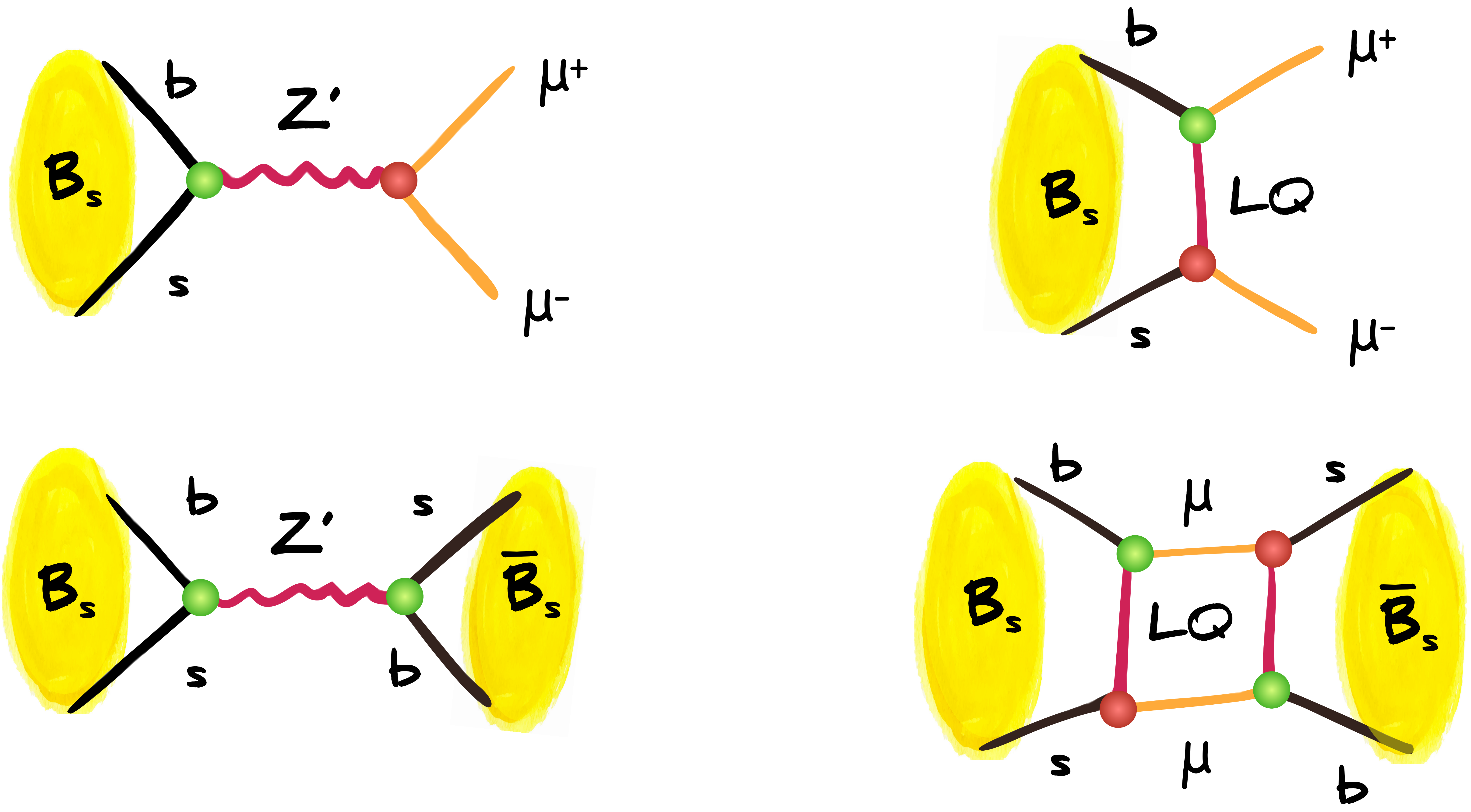
B anomalies in a nutshell



$$\frac{1}{(1.2\,\mathrm{TeV})^2}\,(\bar{c}_L\gamma_\alpha b_L)\,(\bar{\tau}_L\gamma^\alpha\nu_L) \qquad \frac{1}{(35\,\mathrm{TeV})^2}\,(\bar{s}_L\gamma_\alpha b_L)\,\big(\bar{\mu}_{(L)}\gamma^\alpha\mu_{(L)}\big)$$

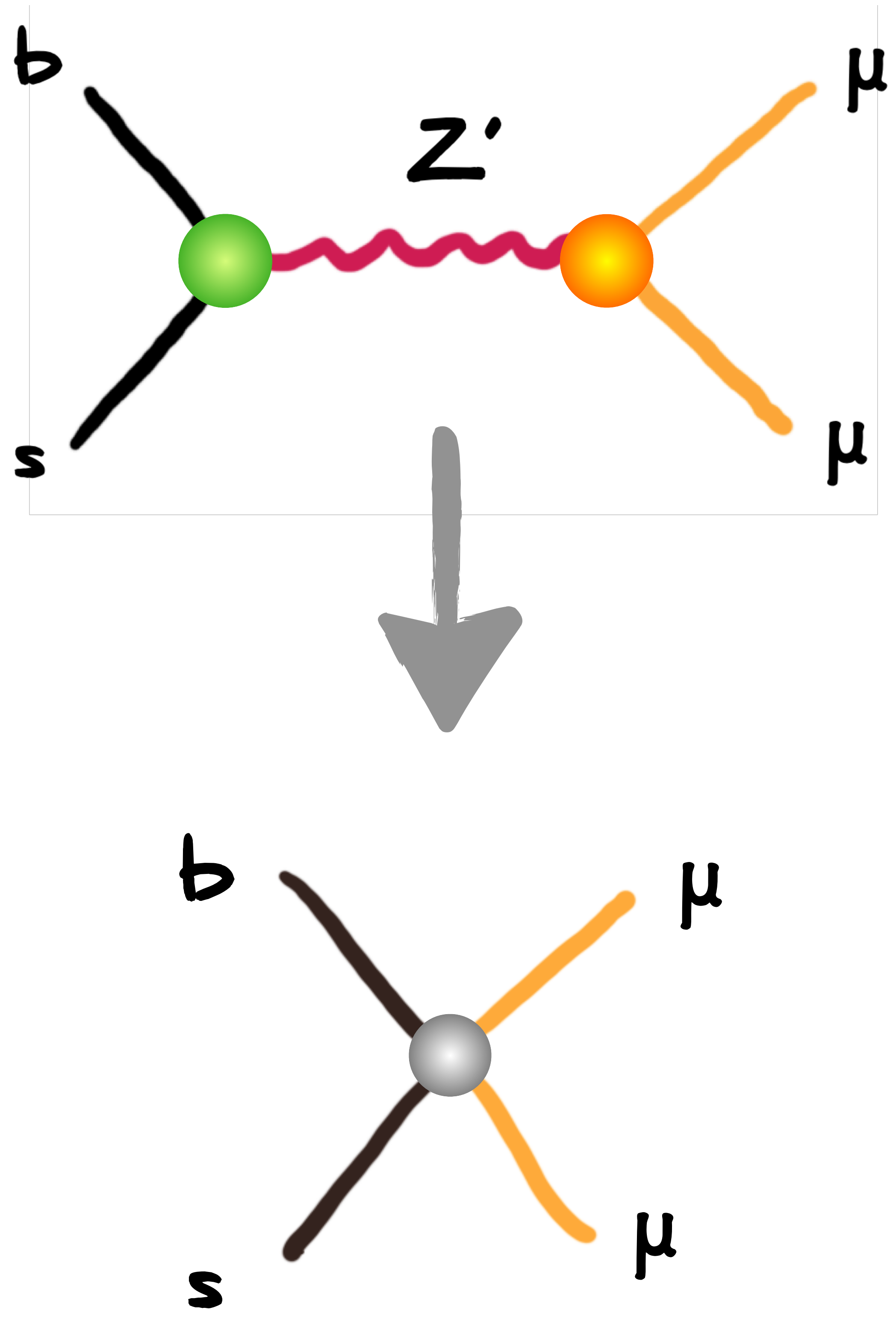
Suppression of operators suggests that explanations of b → c anomalies should lead to testable high-p_T signals, while b → s case looks grim

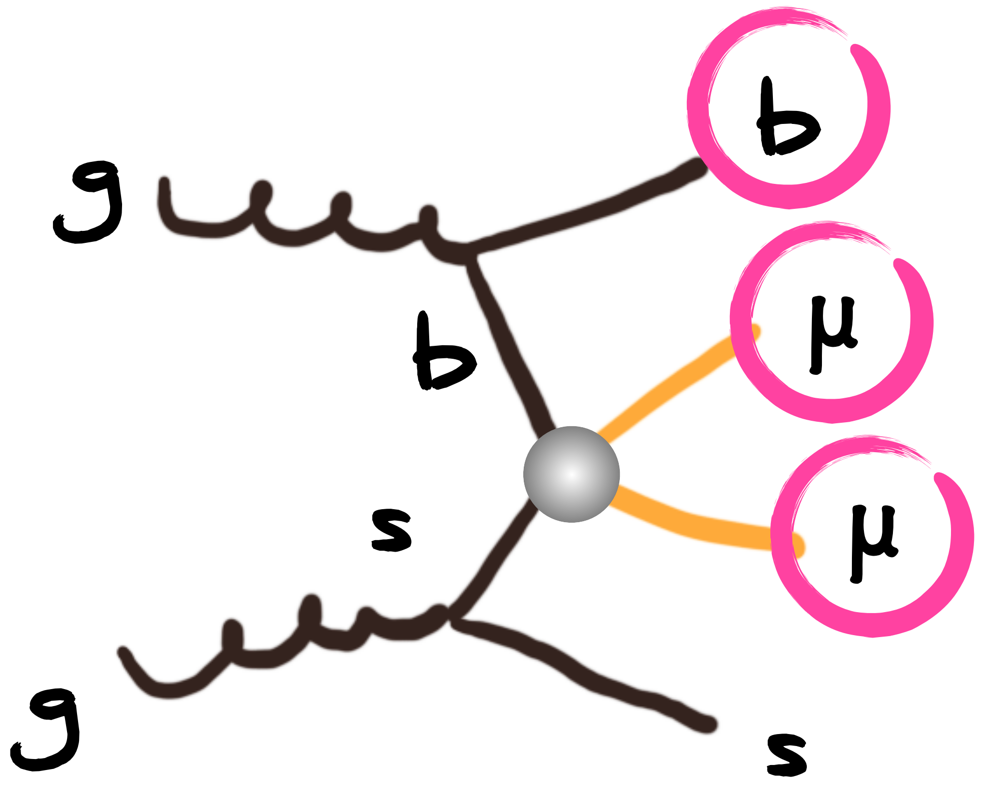
A digression on LQs

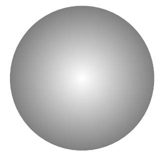


Both scalar & vector LQ have important advantage with respect to other tree-level mediators that they do not induce tree-level contributions to B mixing & $\tau \to \mu\nu\nu$

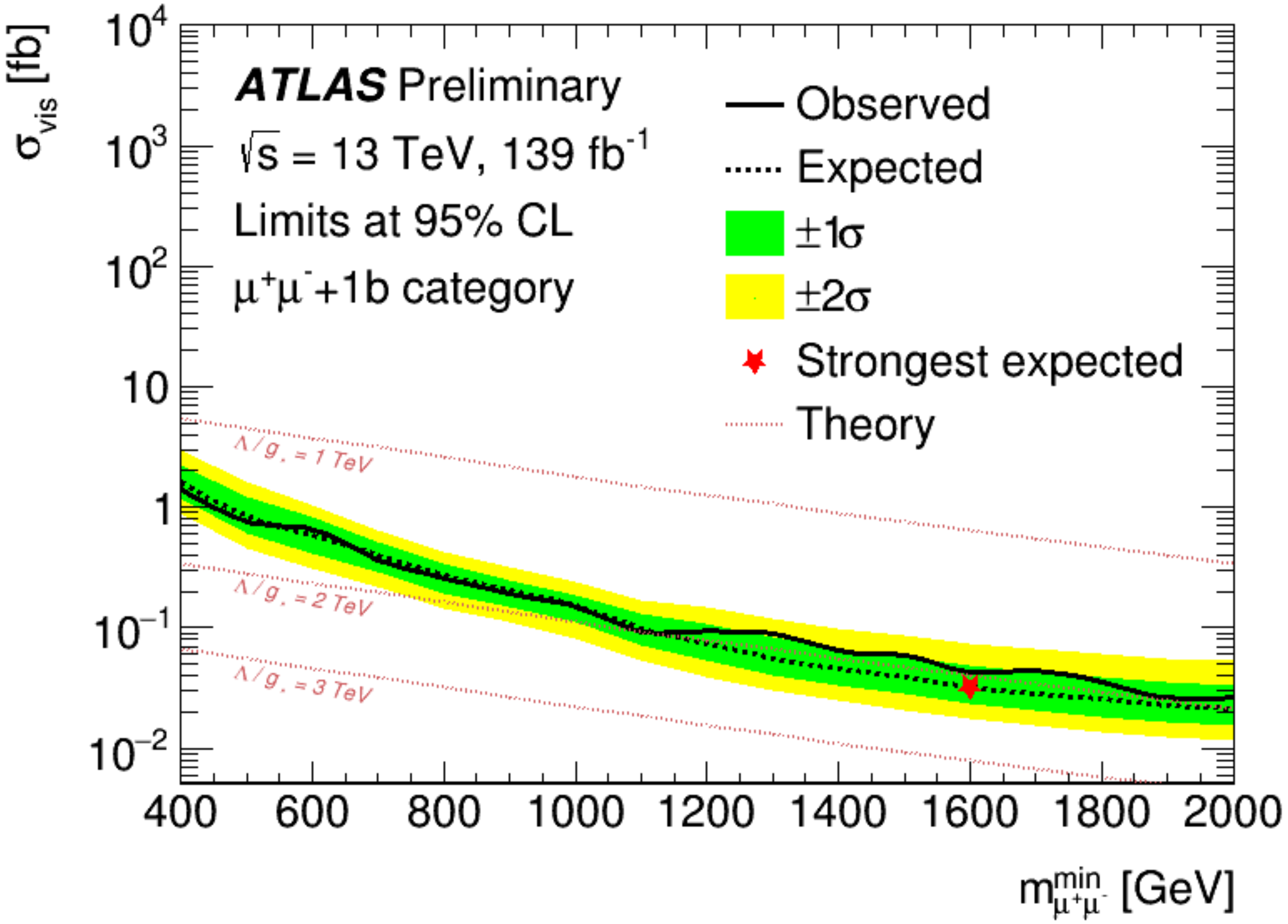
Searches for bsμ⁺μ⁻ contact interactions





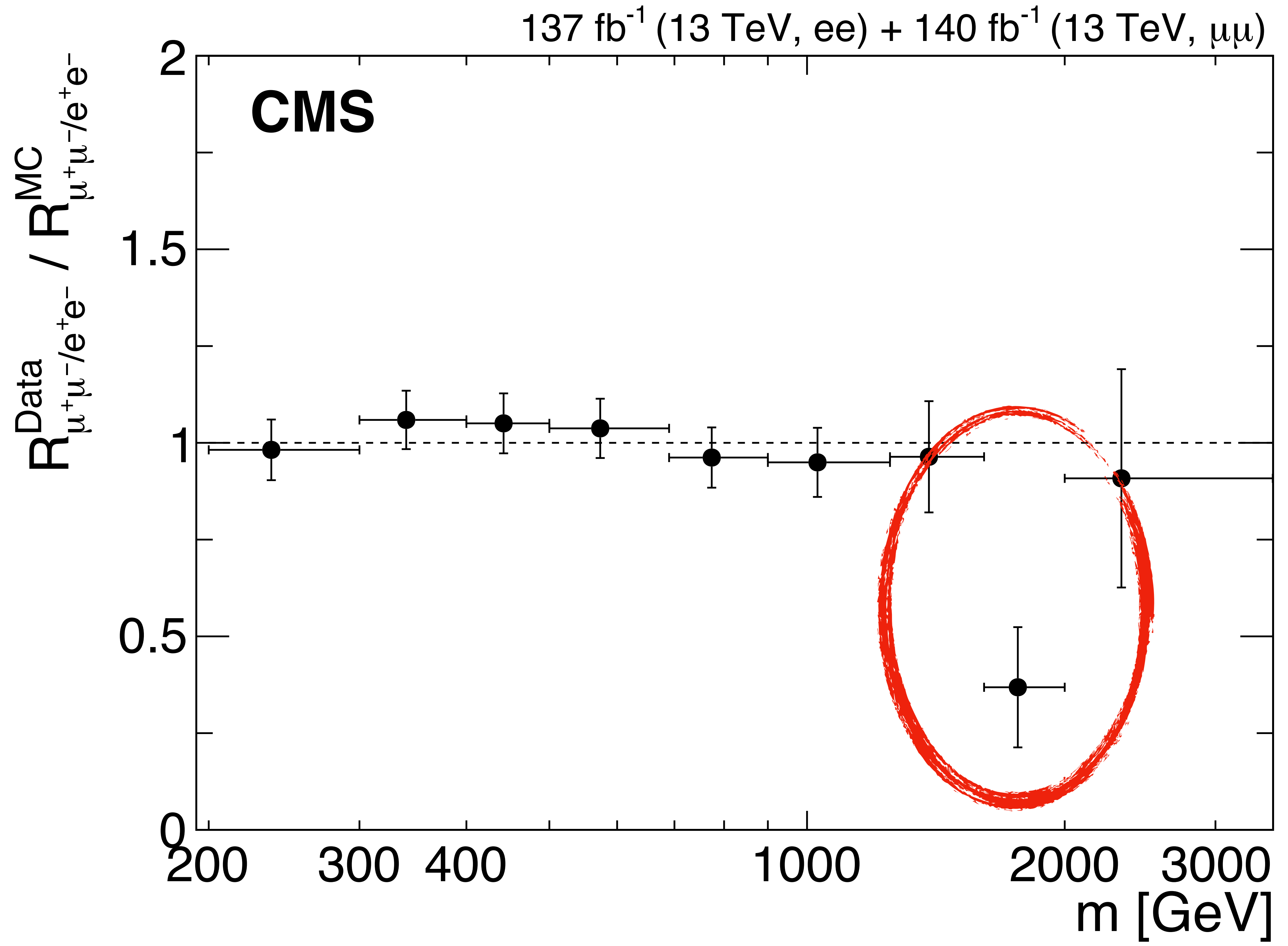
 $= \dfrac{g_*^2}{\Lambda^2}$

[ATLAS-CONF-2021-012]



First search for bs $\mu^+\mu^-$ four-Fermi operator by ATLAS, but bounds on suppression scale are a factor of O(20) below sensitivity needed to test b → s anomalies model independently

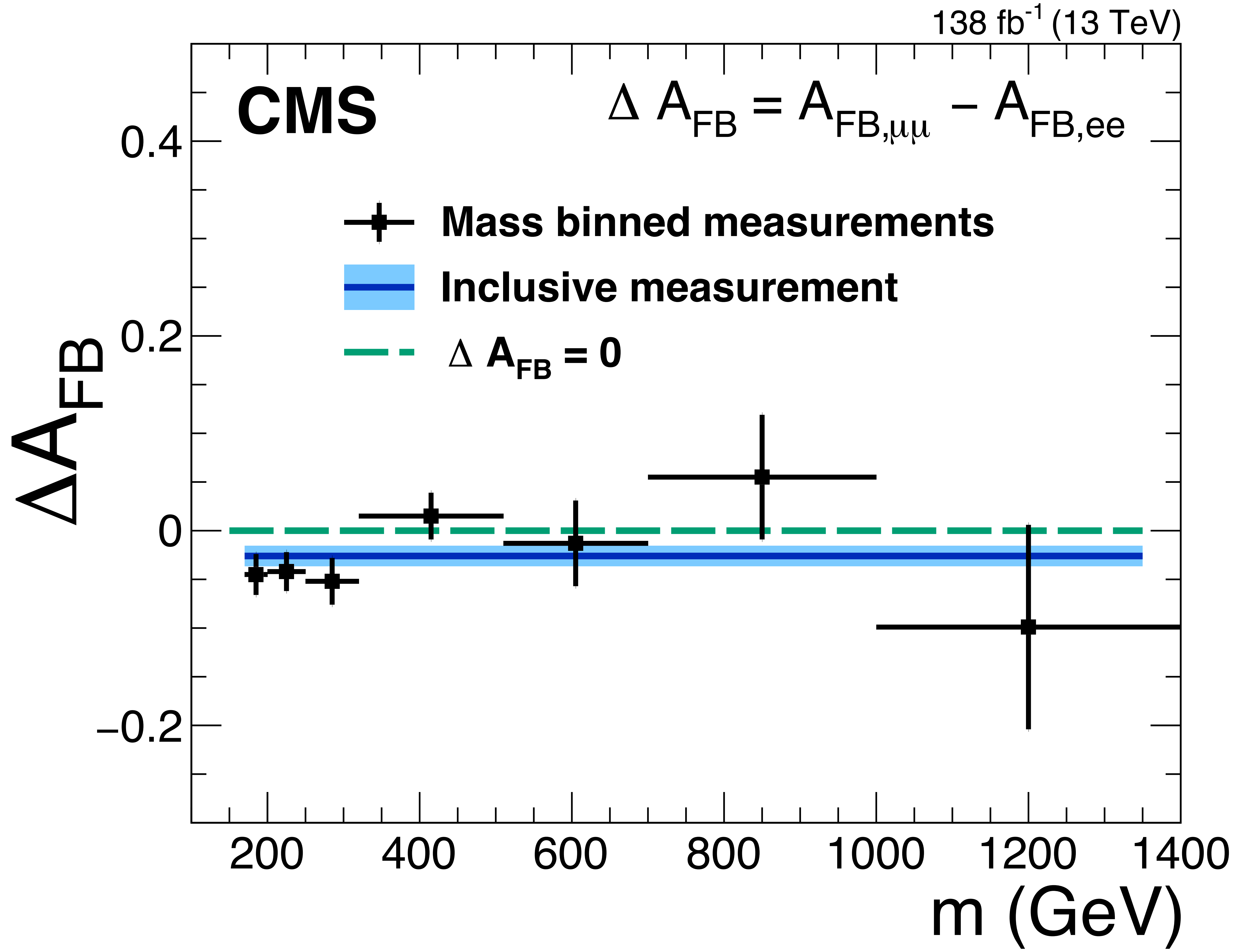
Testing LFU with dilepton events @ LHC



CMS observes good agreement with LFU up to masses of 1.5 TeV, but above 1.8 TeV there is slight excess in dielectron channel leading to a deviation of LFU ratio from 1

[CMS, 2103.02708 & for interpretations see for instance Crivellin et al., 2103.12003, 2104.06417]

Testing LFU with dilepton events @ LHC



CMS recently also measured difference between dimuon & dielectron forward-backward asymmetry (A_{FB}). Result is found to agree with zero within 2.4σ. Like rate measurement, also A_{FB} results show a slight dielectron excess

[CMS, 2202.12327]