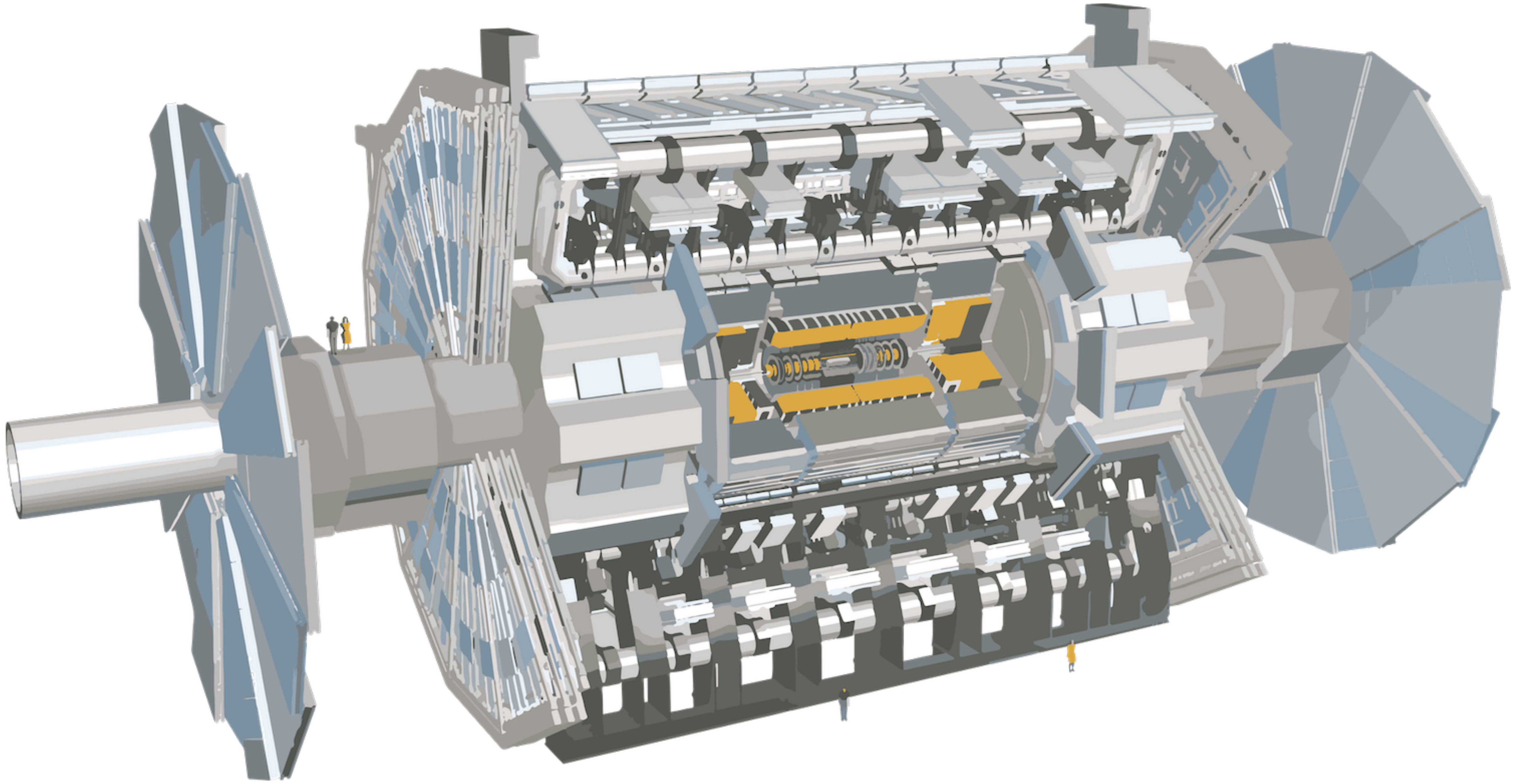
Uli Haisch, MPI Munich
Flavor at the Crossroads 2022, 19.04.22

$R_{D^{(*)}}$

P_5' $R_{K^{(*)}}$

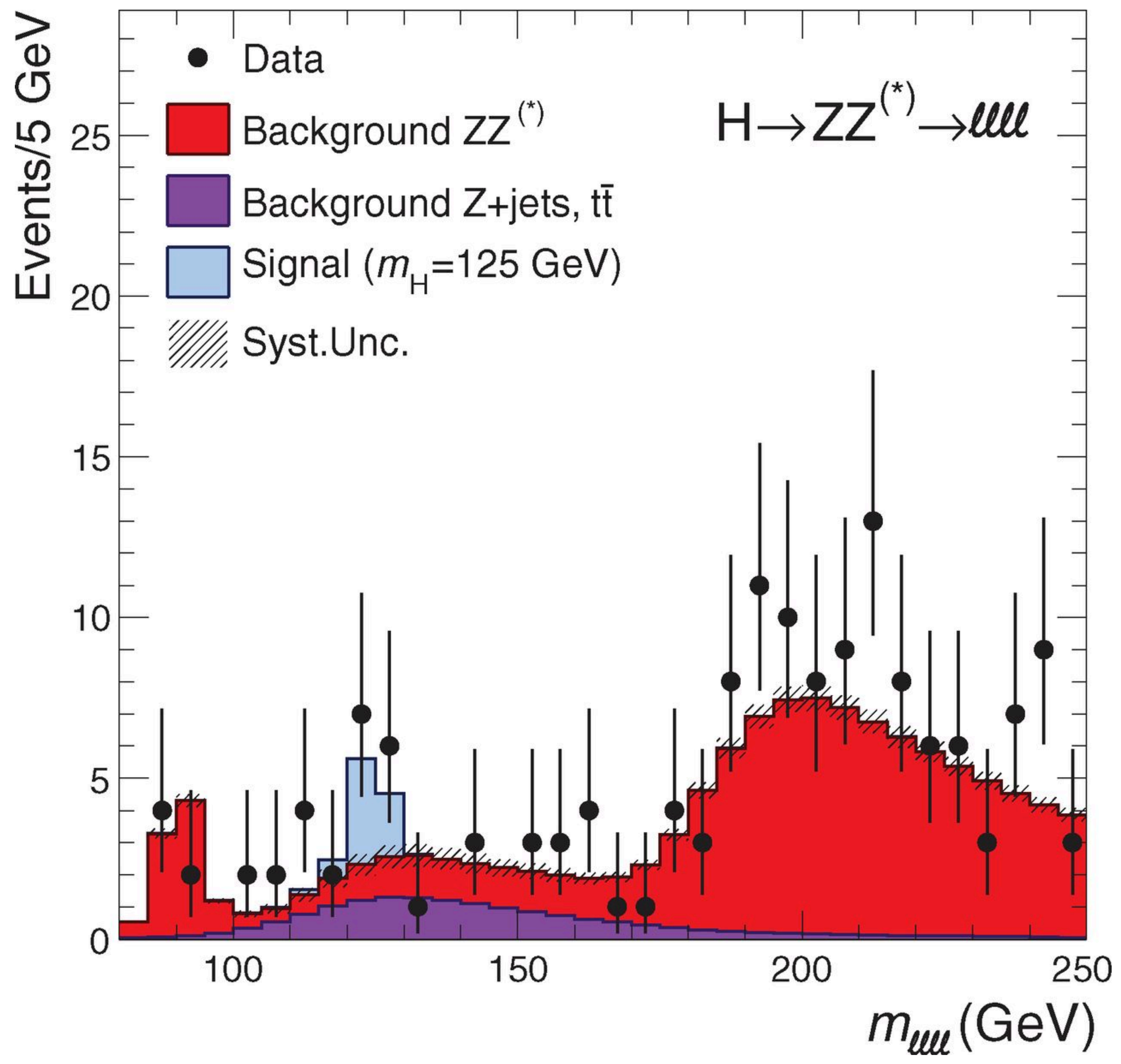
? →



B-physics anomalies

Possible high-p_T implications

Higgs discovery @ LHC



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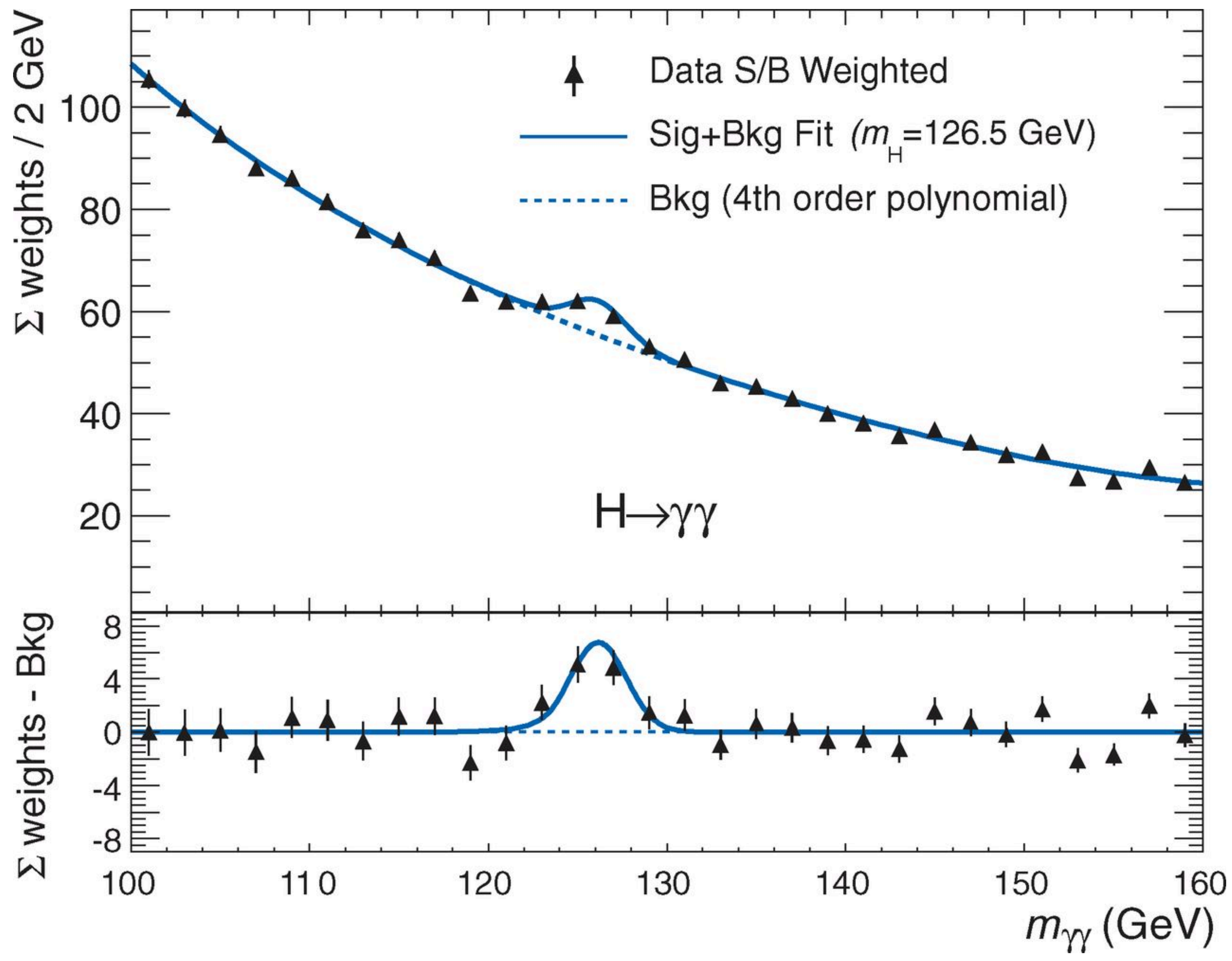
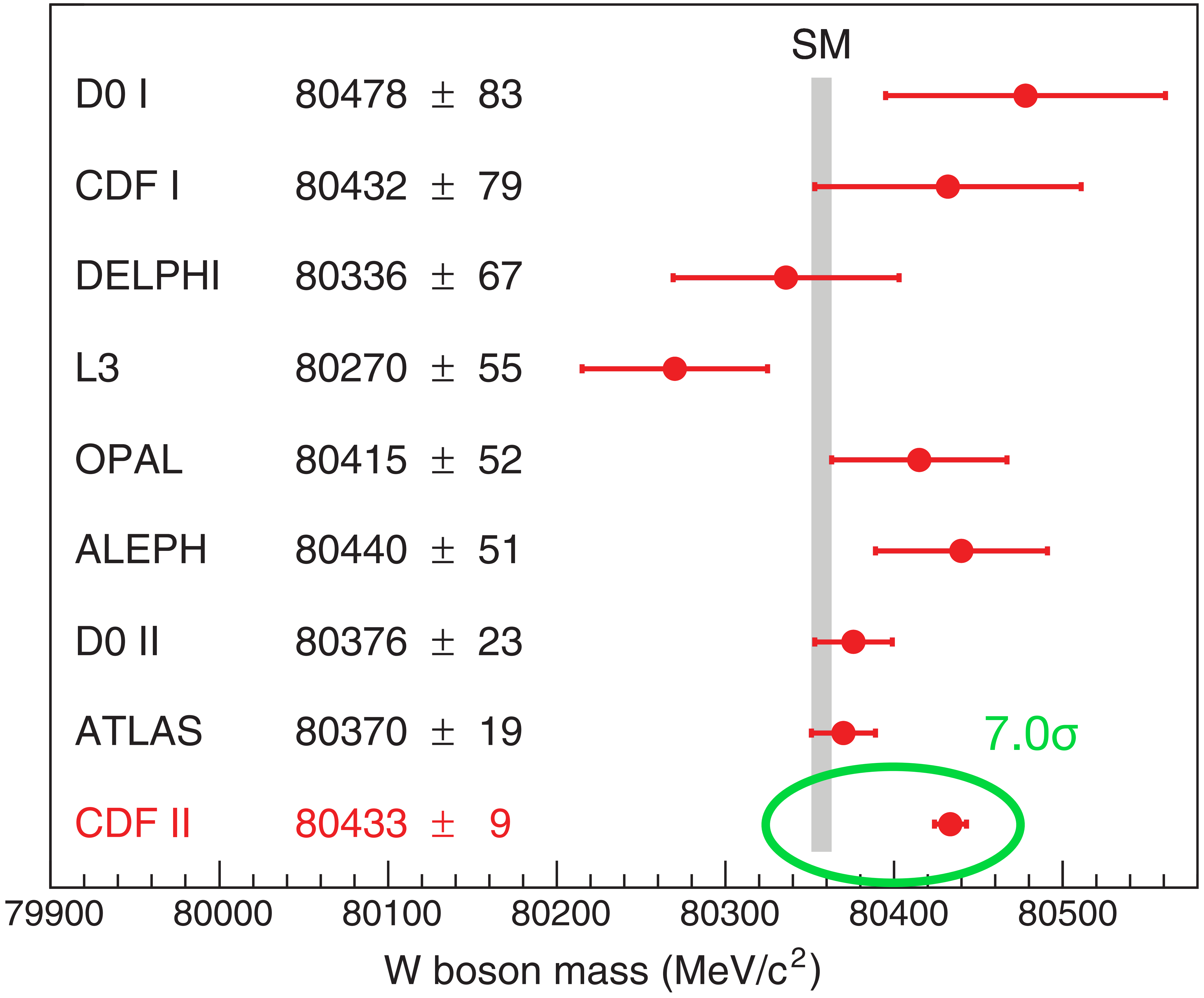


[ATLAS, Science 338 (2012) 1576; similar results & plots by CMS]

M_W measurement by CDF



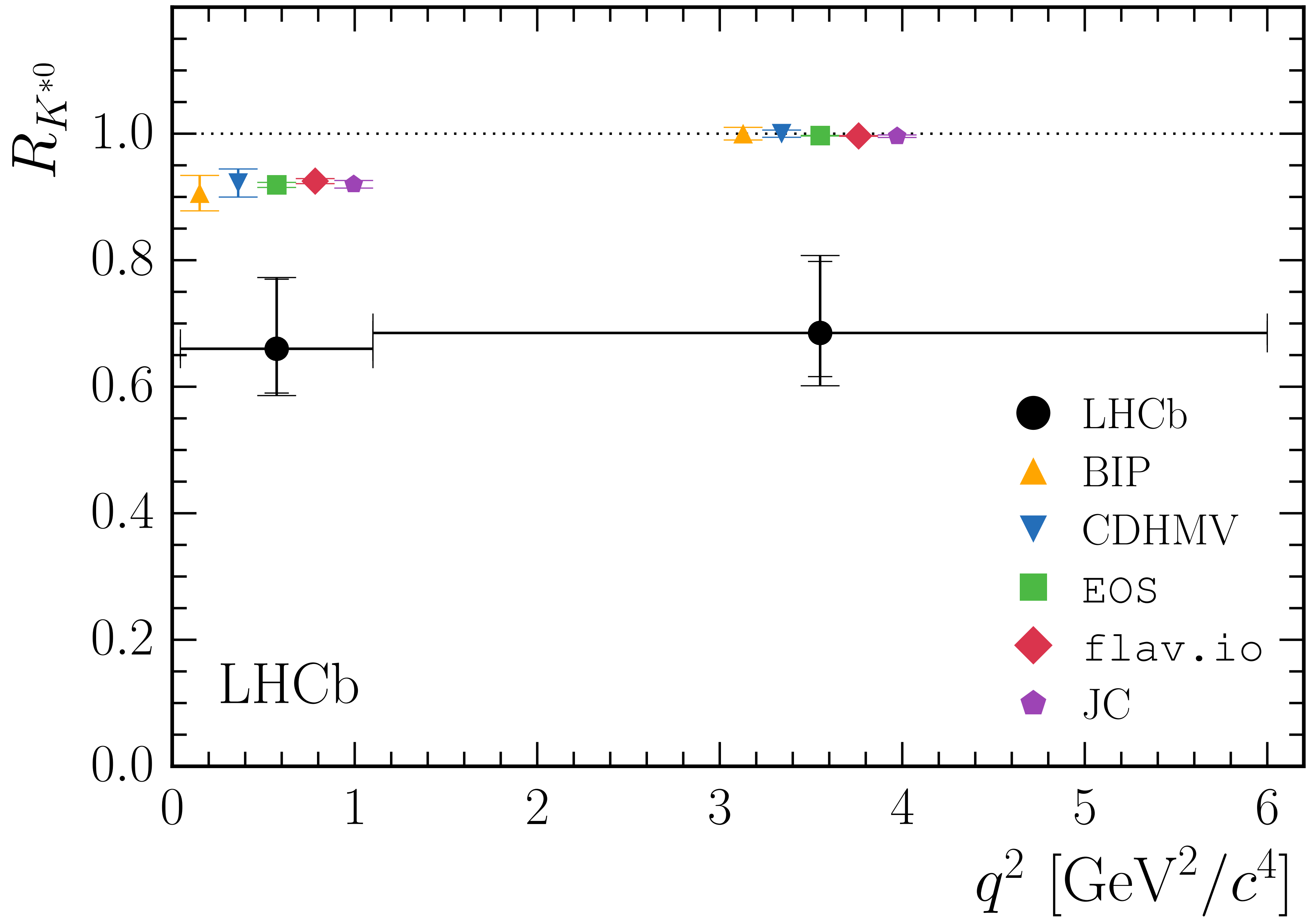
With 4 times more data CDF manages to measure M_W with an uncertainty that is improved by a factor of almost 9. Measurement shows a 7.0σ deviation with Standard Model (SM) value

[CDF, Science 376 (2022) 6589]

Unlike Higgs discovery, CDF extraction of M_W relies (a lot) on theory. Theory good enough to claim O(10 MeV) errors?

[Behring et al., 2103.02671]

Flavor anomalies



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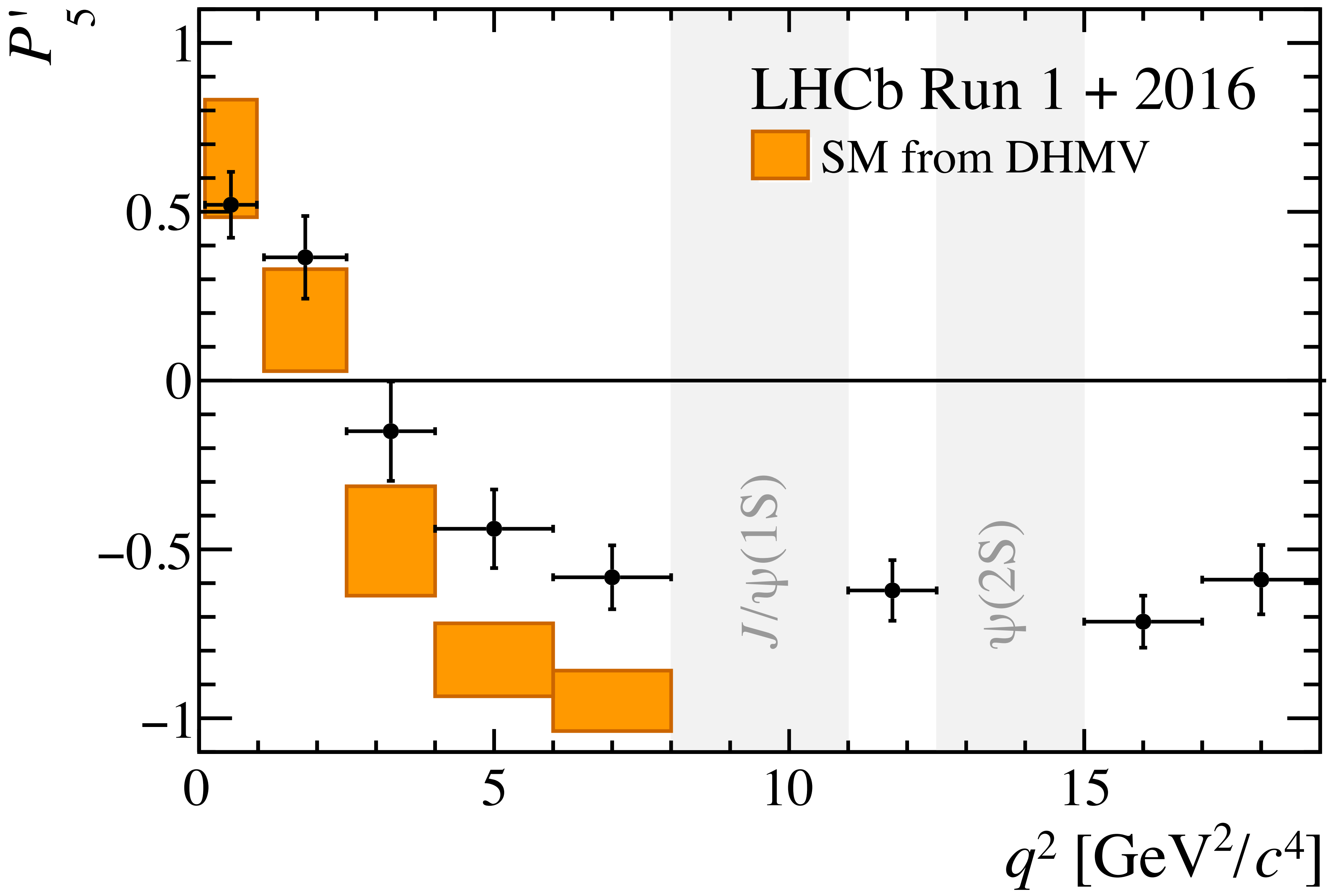
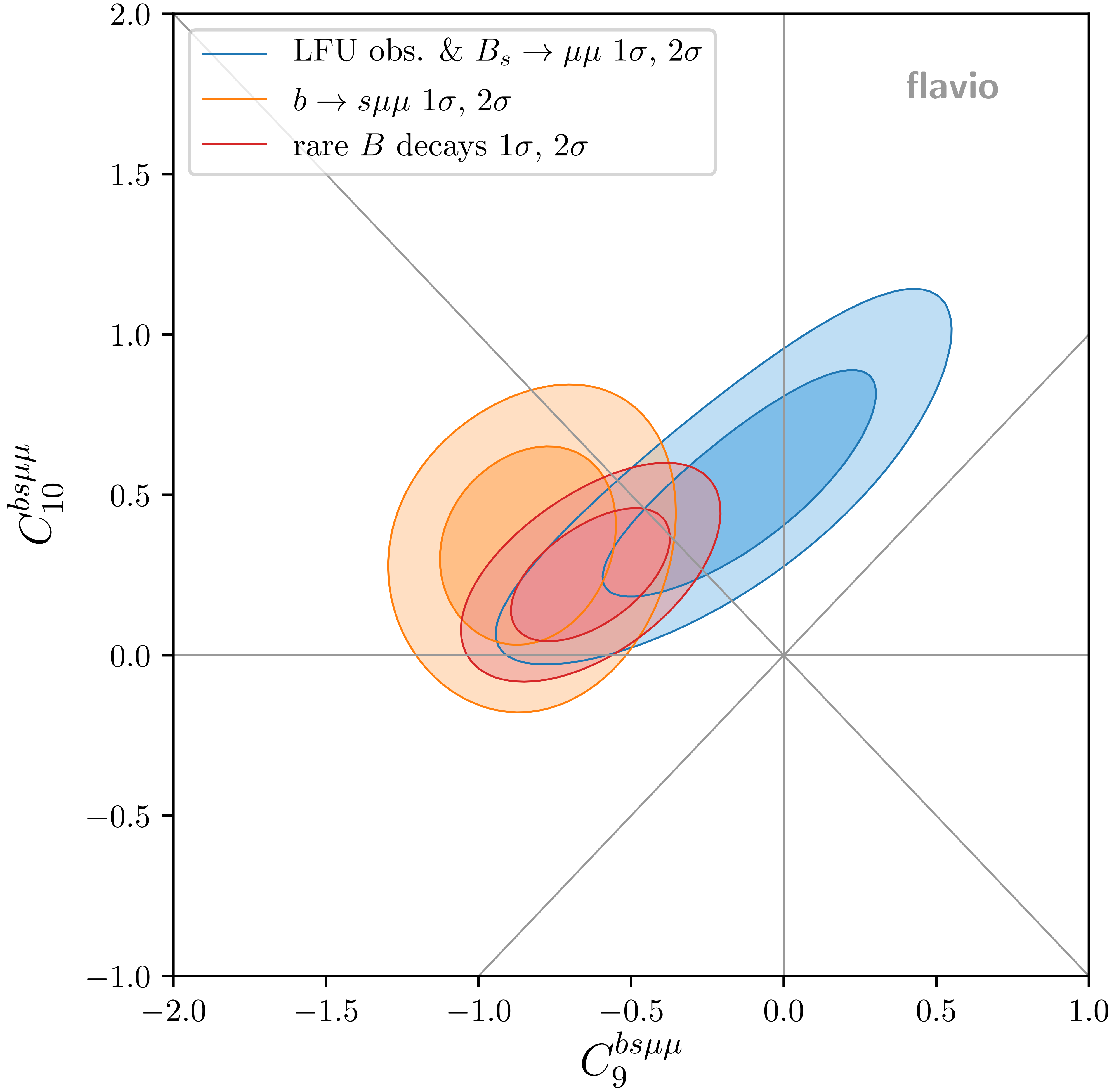


+ order 100 other observables

[LHCb, 1705.05802; 2003.04831; …; global fits by many theorists]

Flavor anomalies

[Altmannshofer & Stangl, 2103.13370]



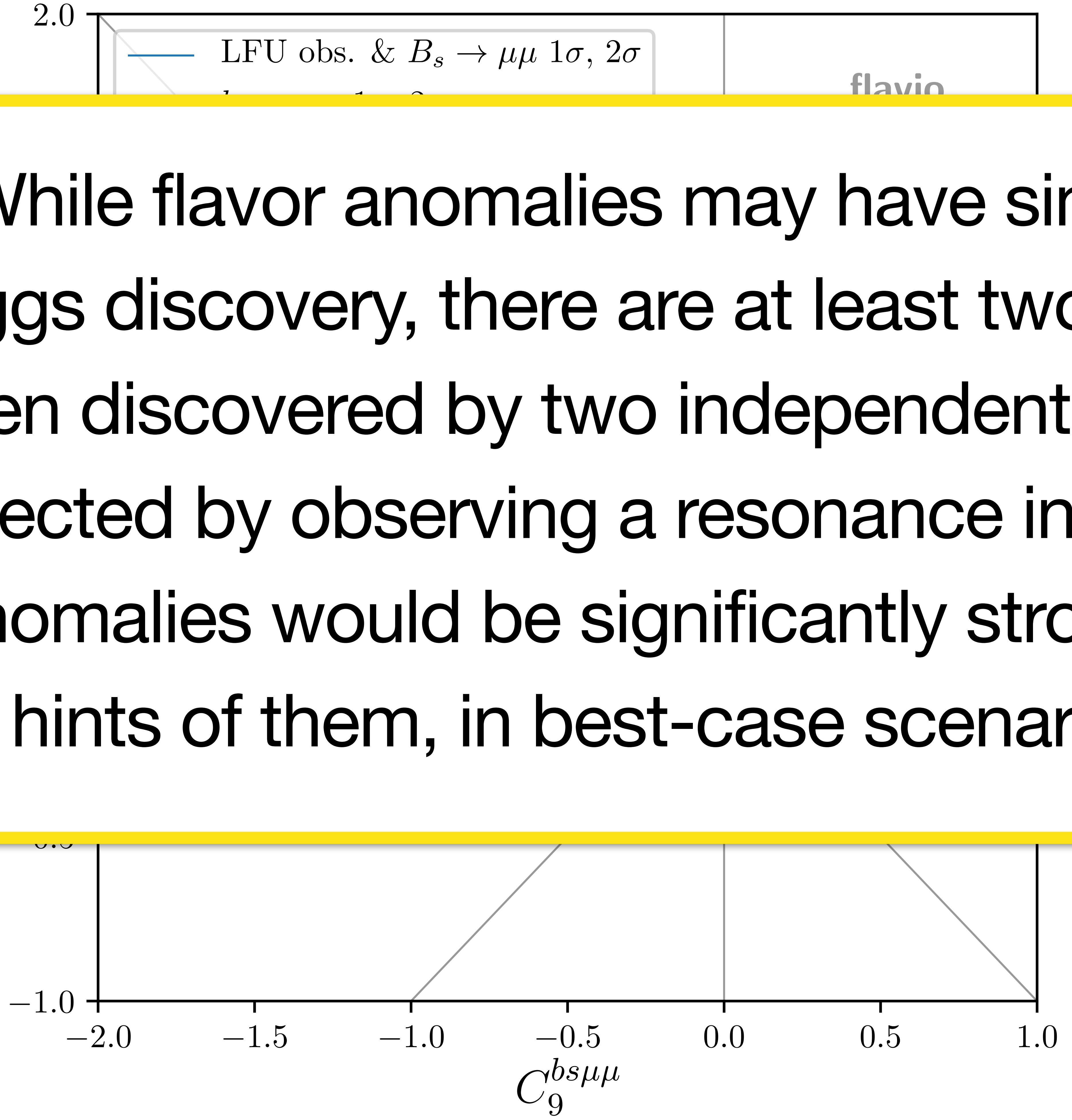
All b → s data coherently point to well-defined non-SM contributions of short-distance origin

Global significance amounts to 3.9σ for any kind of heavy new physics, if only theoretically clean observables are considered

[Lancierini et al., 2104.05631]

Flavor anomalies

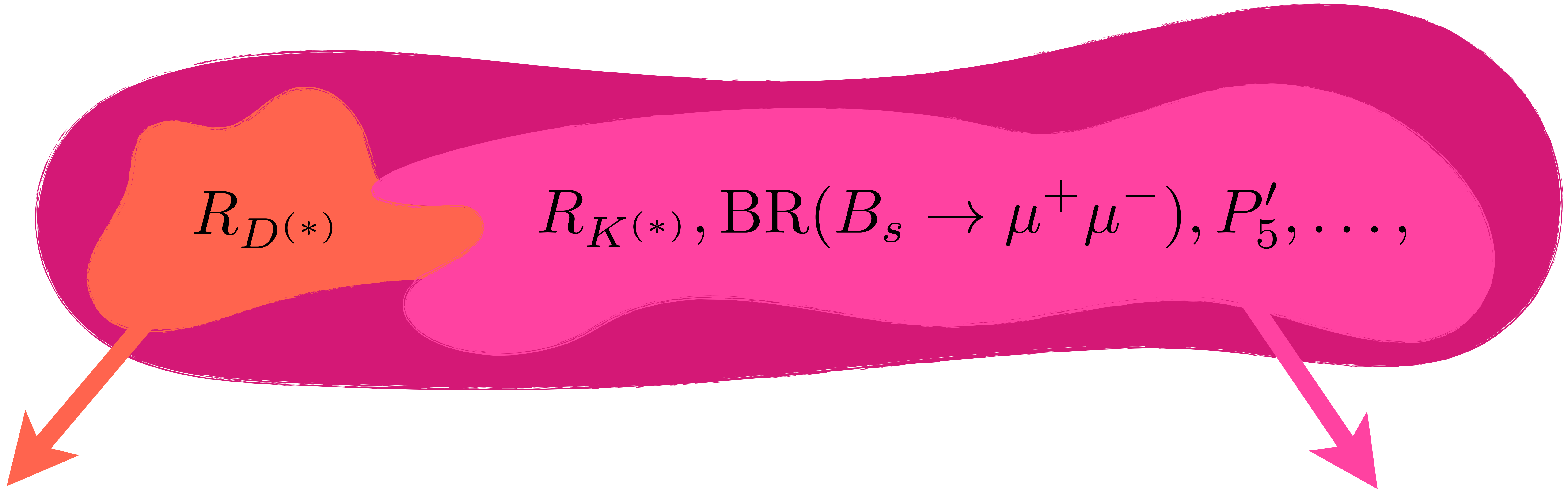
[Altmannshofer & Stangl, 2103.13370]



While flavor 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 flavor 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

[Lancierini et al., 2104.05631]

B anomalies in a nutshell

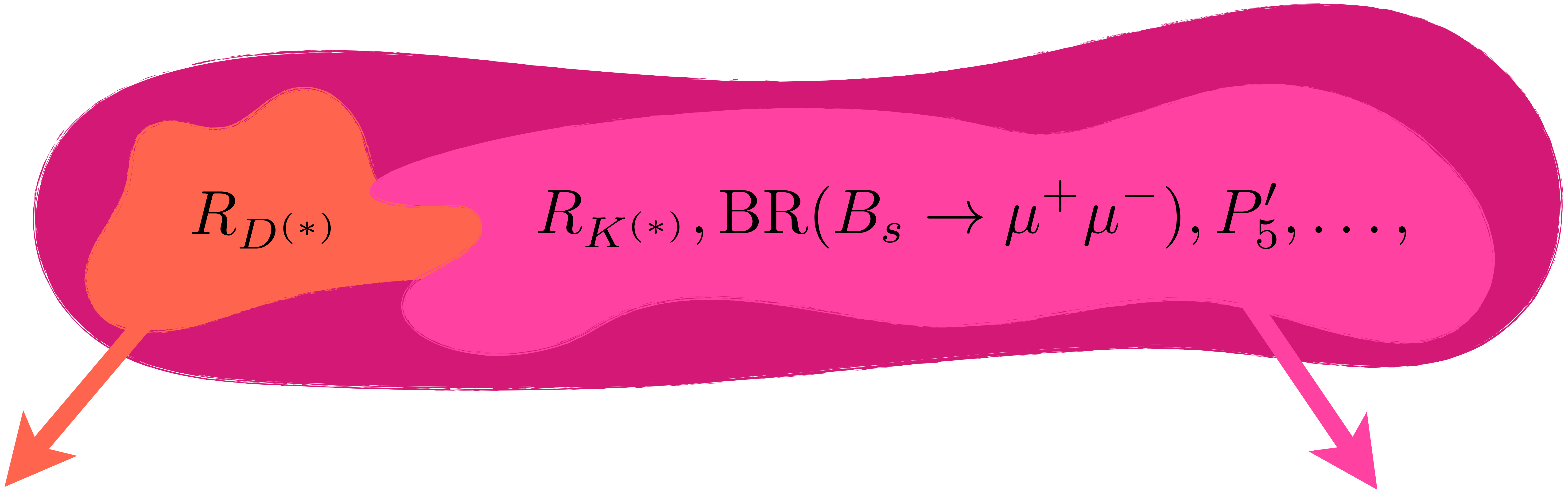


$$\frac{1}{(1.2\,\mathrm{TeV})^2}\,(\bar{c}_L \gamma_\alpha b_L)\,(\bar{\tau}_L \gamma^\alpha \nu_L)$$

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

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

B anomalies in a nutshell



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

Mass/scale suppression of effective operators suggests that explanations of b → c anomalies should lead to high-p_T imprints testable @ LHC, while b → s case looks much less promising

A digression on LFU

Decay	Precision	Channels	Deviation
Z	0.3%	e, μ, τ	—
W	0.8%	e, μ	—
W	3%	τ	2.8σ
μ, τ	0.15%	e, μ	—
π	0.3%	e, μ	—
K	0.4%	e, μ	—
J/ψ	0.65%	e, μ	—
D_s	6%	μ, τ	—

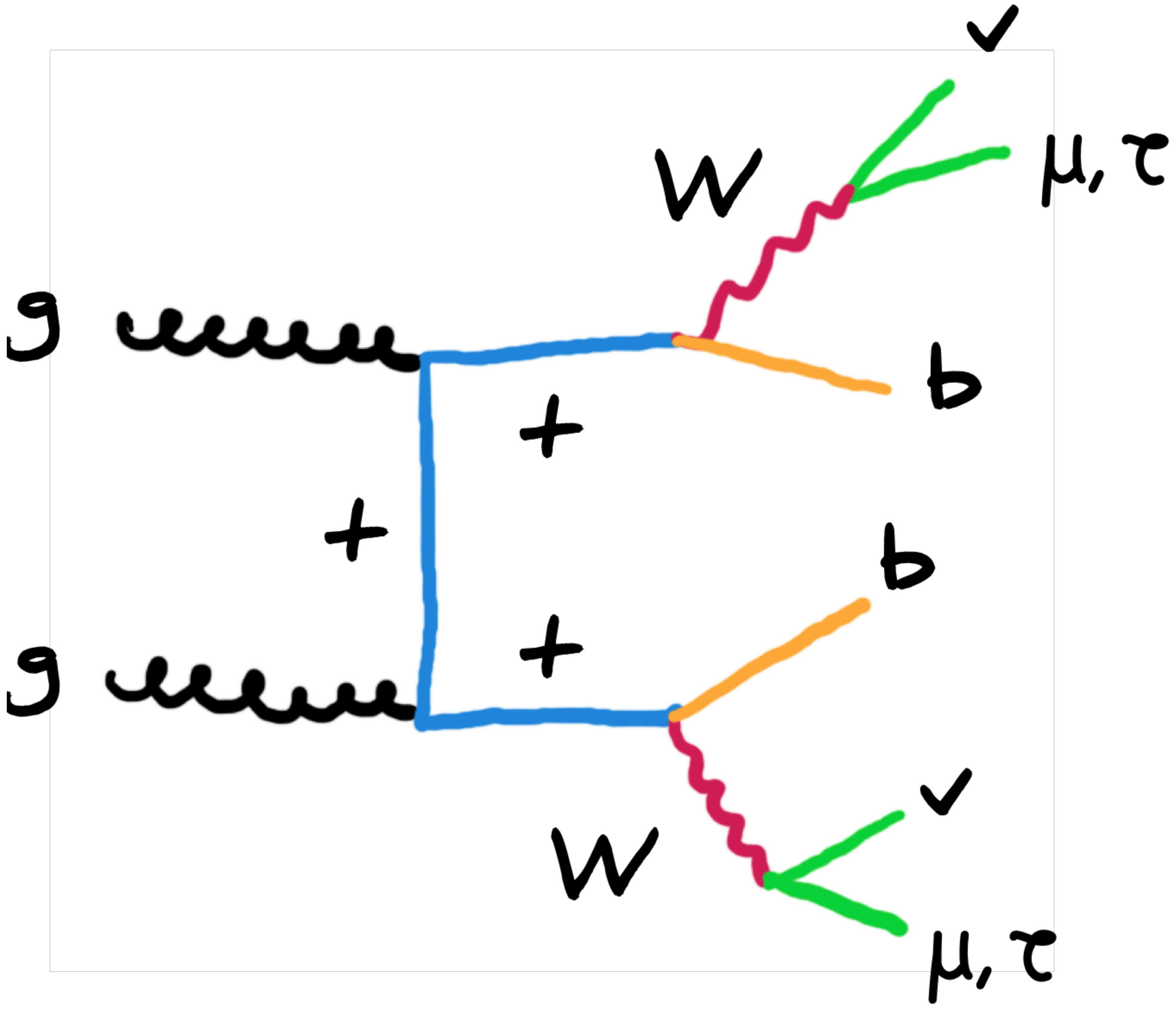
Summer 2011

Before 2012, stringent experimental test of LFU in B-meson decays did not exist

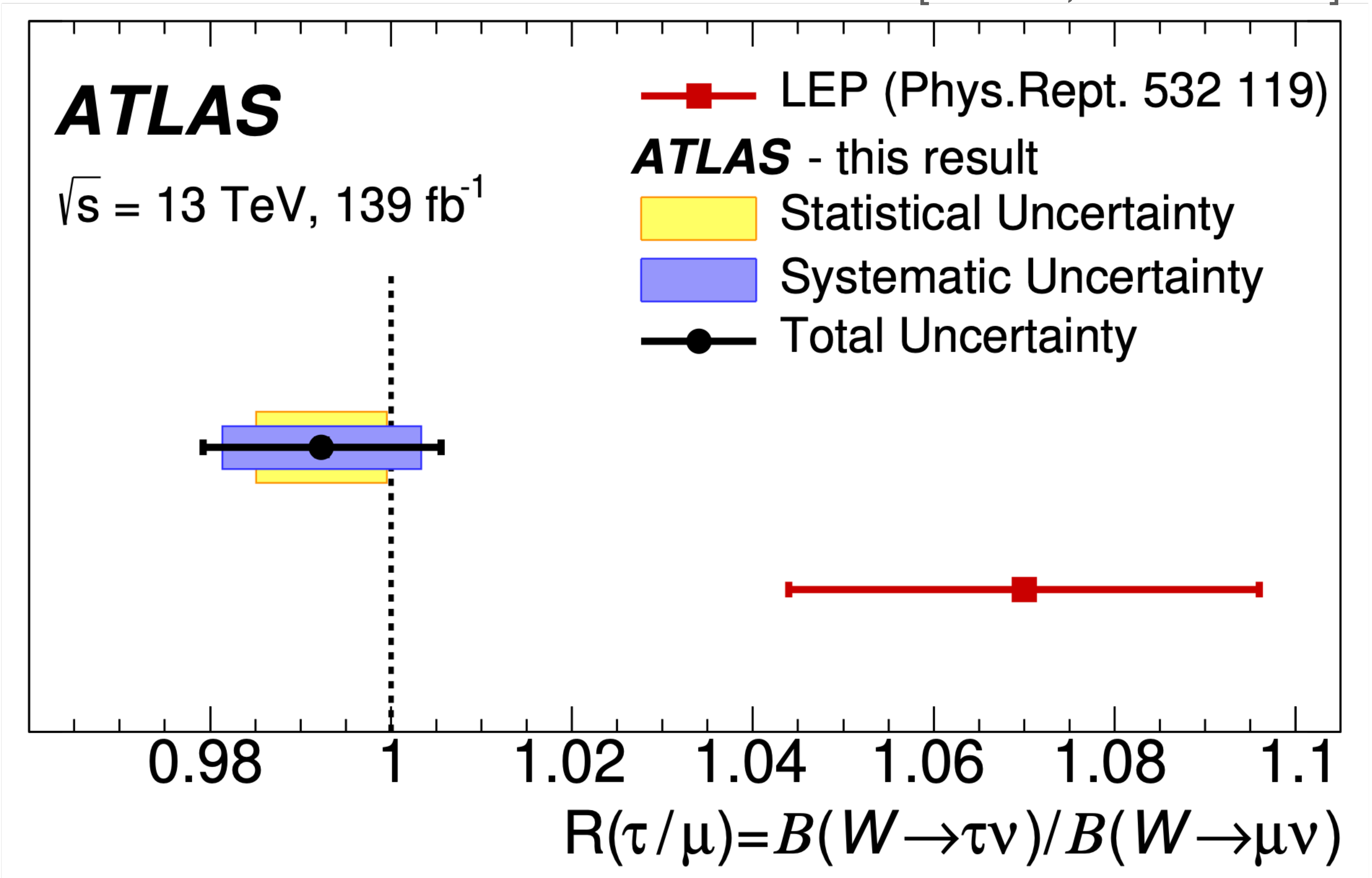
Combined LEP results hint towards LFU violation in W-boson decay with significance of 2.8σ

[LEPEWWG, hep-ex/0511027]

LFU violation in W decays?



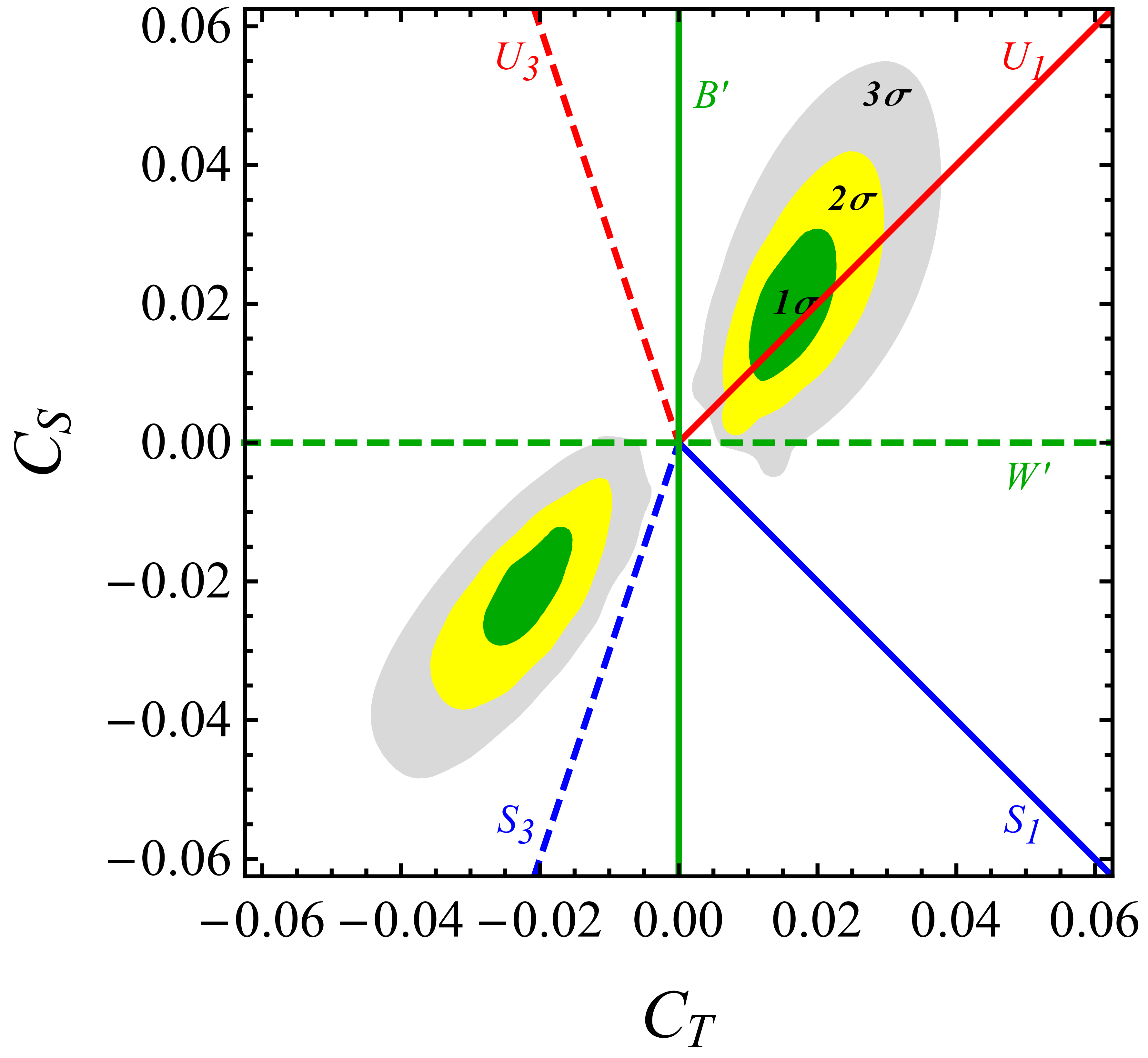
[ATLAS, 2007.14040]



ATLAS LHC Run-II measurement in full agreement with LFU as predicted in SM

Simplified models for B anomalies

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



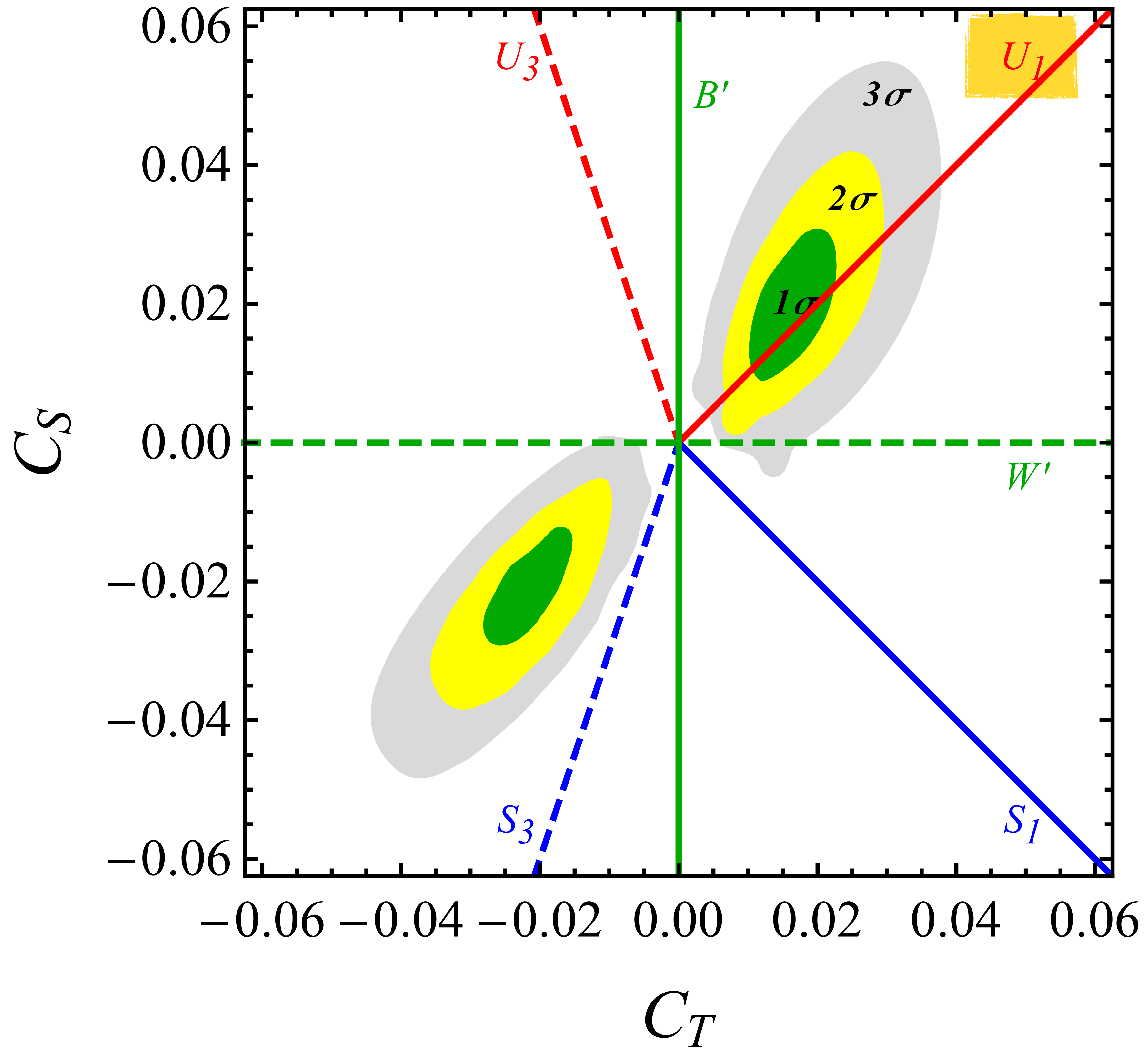
Model	Mediator	$b \to s$	$b \to c$
Colorless vectors	$B' = (1,1,0)$	✓	✗
	$W' = (1,3,0)$	✗	✓
Scalar leptoquarks	$S_1 = (\bar{3},1,1/3)$	✗	✓
	$S_3 = (\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1 = (3,1,2/3)$	✓	✓
	$U_3 = (3,3,2/3)$	✓	✗

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

[see for instance Buttazzo, Greljo, Isidori & Marzocca, 1706.07808]

Simplified models for B anomalies

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

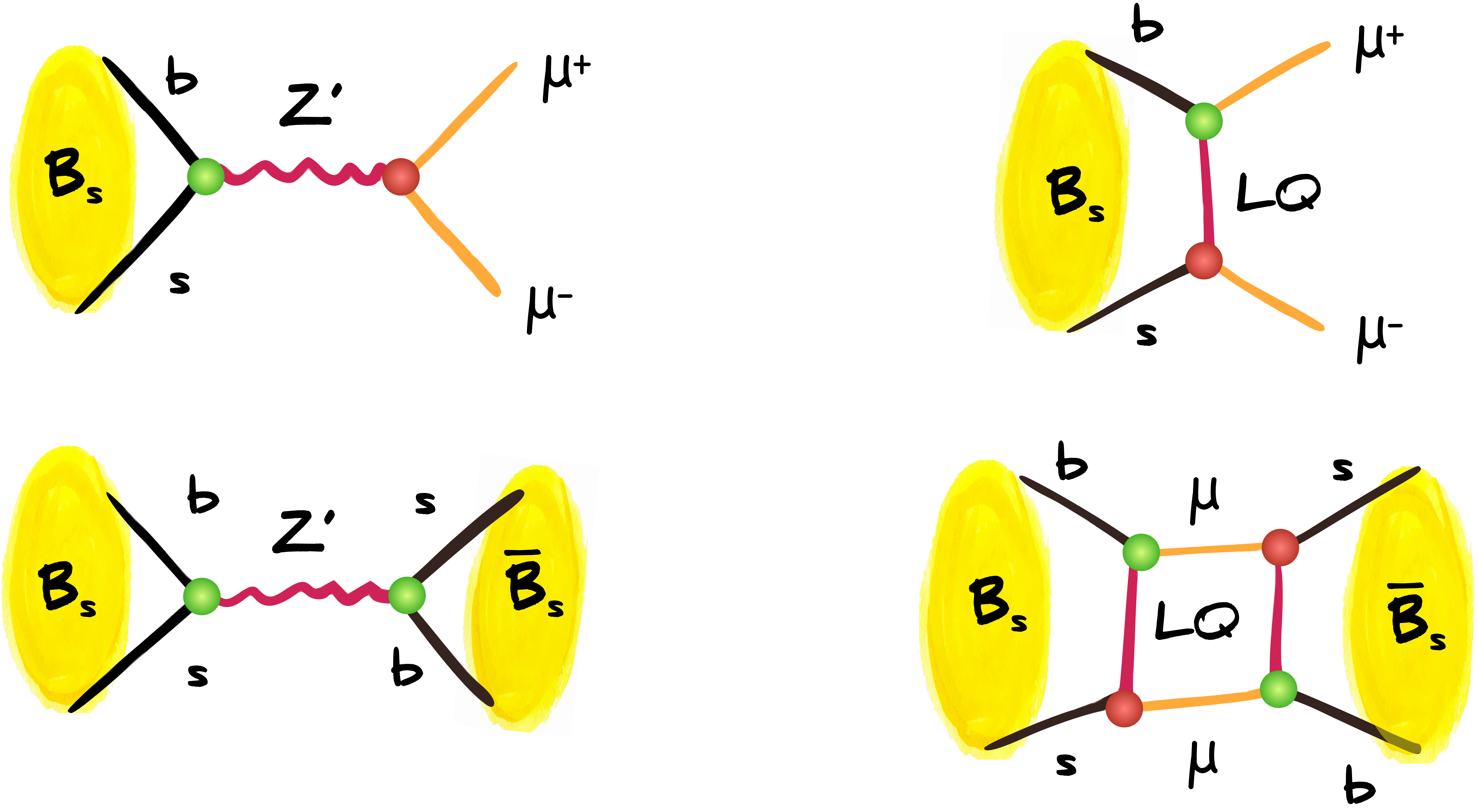


Model	Mediator	$b\to s$	$b\to c$
Colorless vectors	$B'=(1,1,0)$	✓	✗
	$W'=(1,3,0)$	✗	✓
Scalar leptoquarks	$S_1=(\bar{3},1,1/3)$	✗	✓
	$S_3=(\bar{3},3,1/3)$	✓	✗
Vector leptoquarks	$U_1=(3,1,2/3)$	✓	✓
	$U_3=(3,3,2/3)$	✓	✗

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

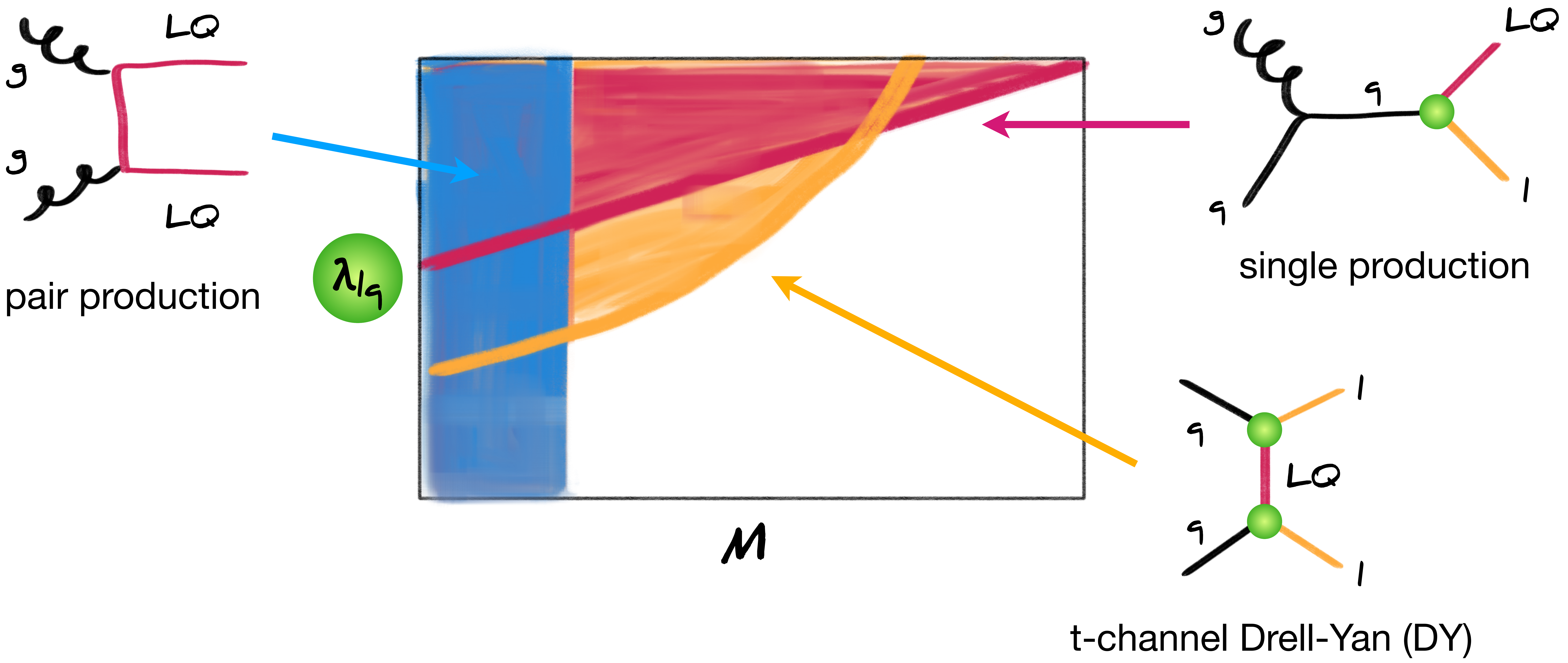
[see for instance Buttazzo, Greljo, Isidori & Marzocca, 1706.07808]

A digression on LQs



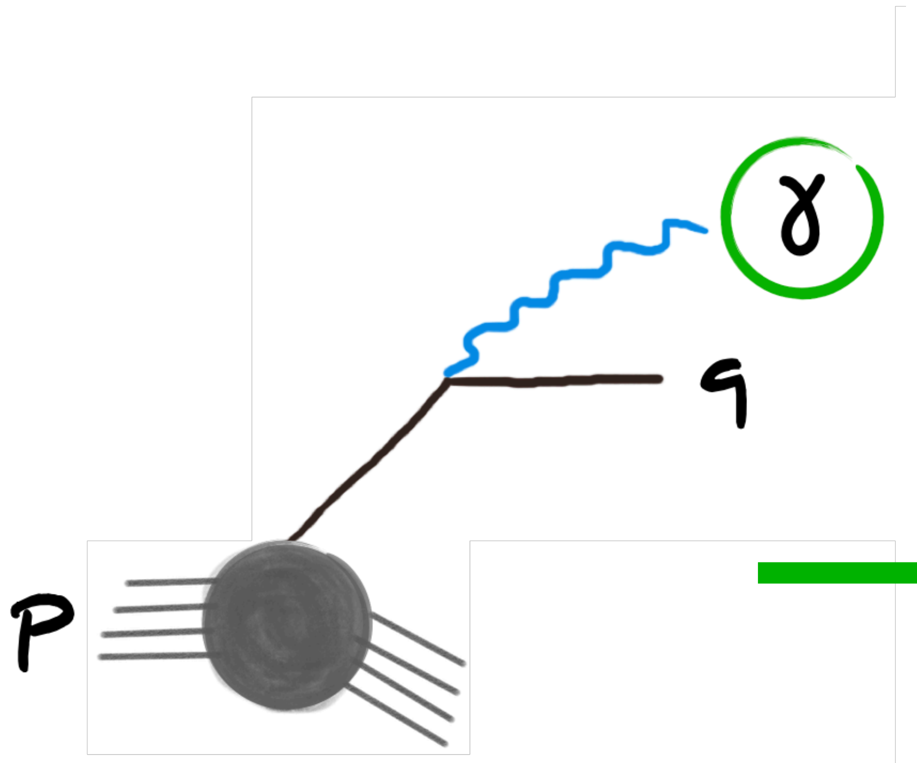
Both scalar & vector LQ have strong advantage with respect to other tree-level mediators that they do not induce tree-level contributions to B-mixing & $\tau \to \mu\nu\nu$

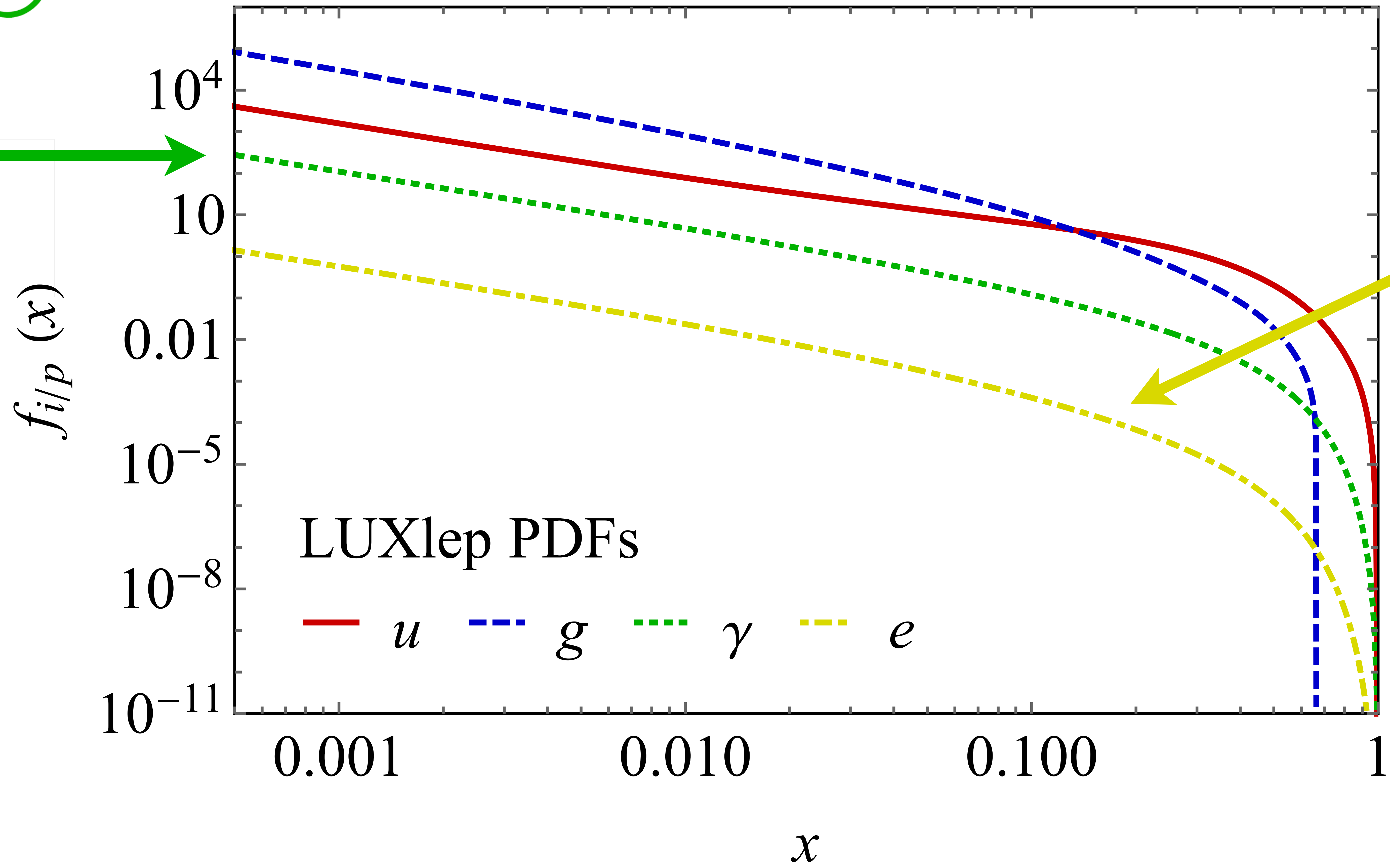
Well-known LQ search strategies @ LHC

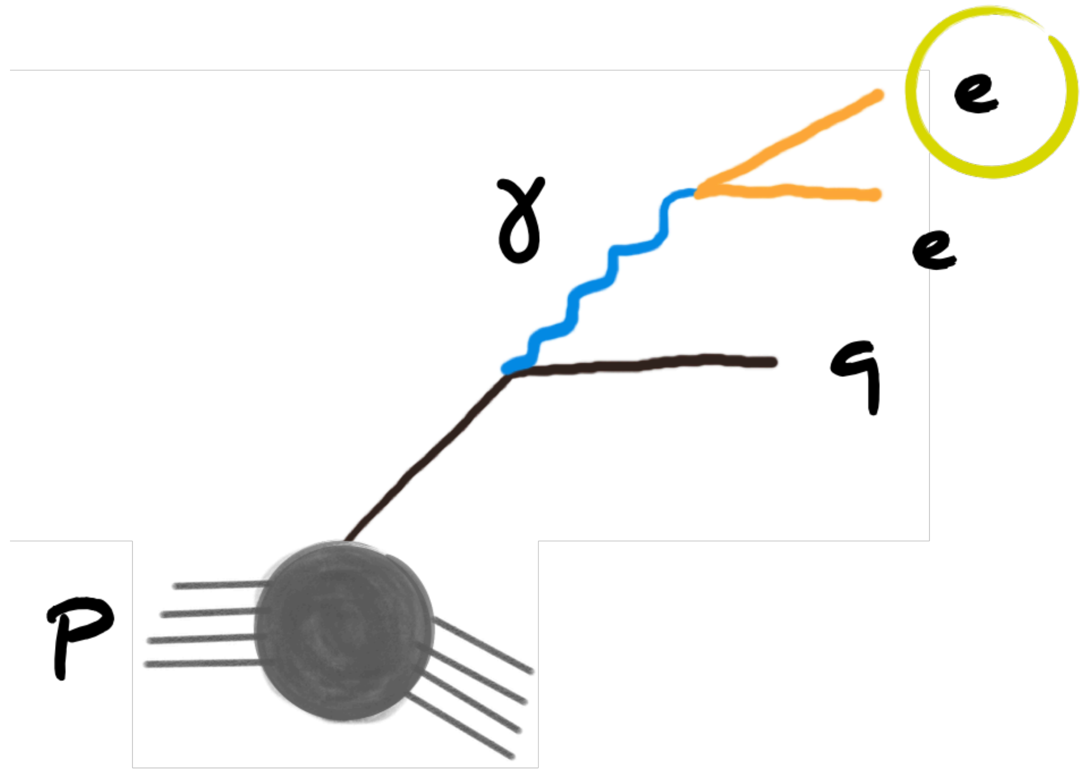


[sketch adopted from Dorsner & Greljo, 1801.07641]

Photon & lepton content of proton

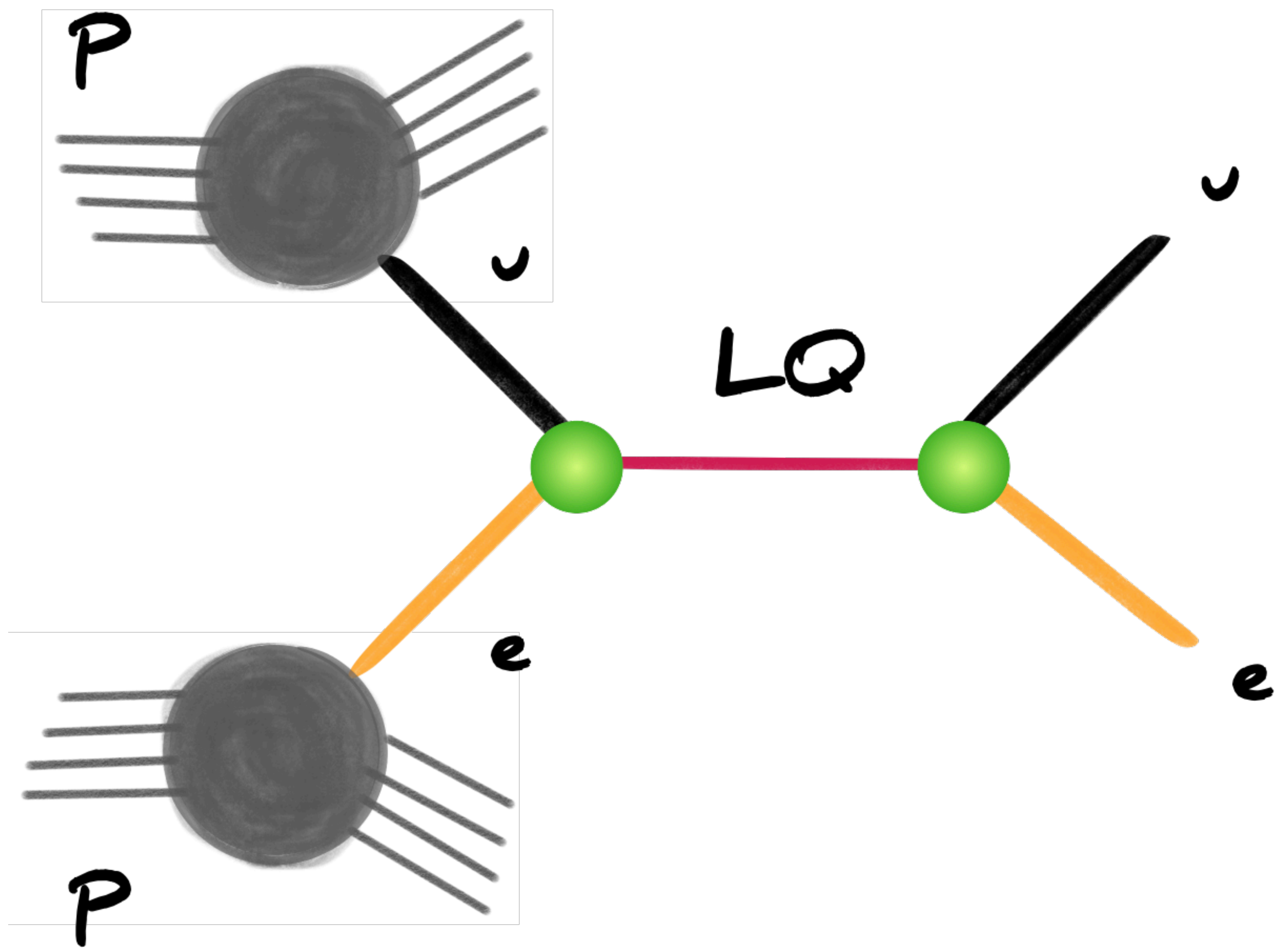


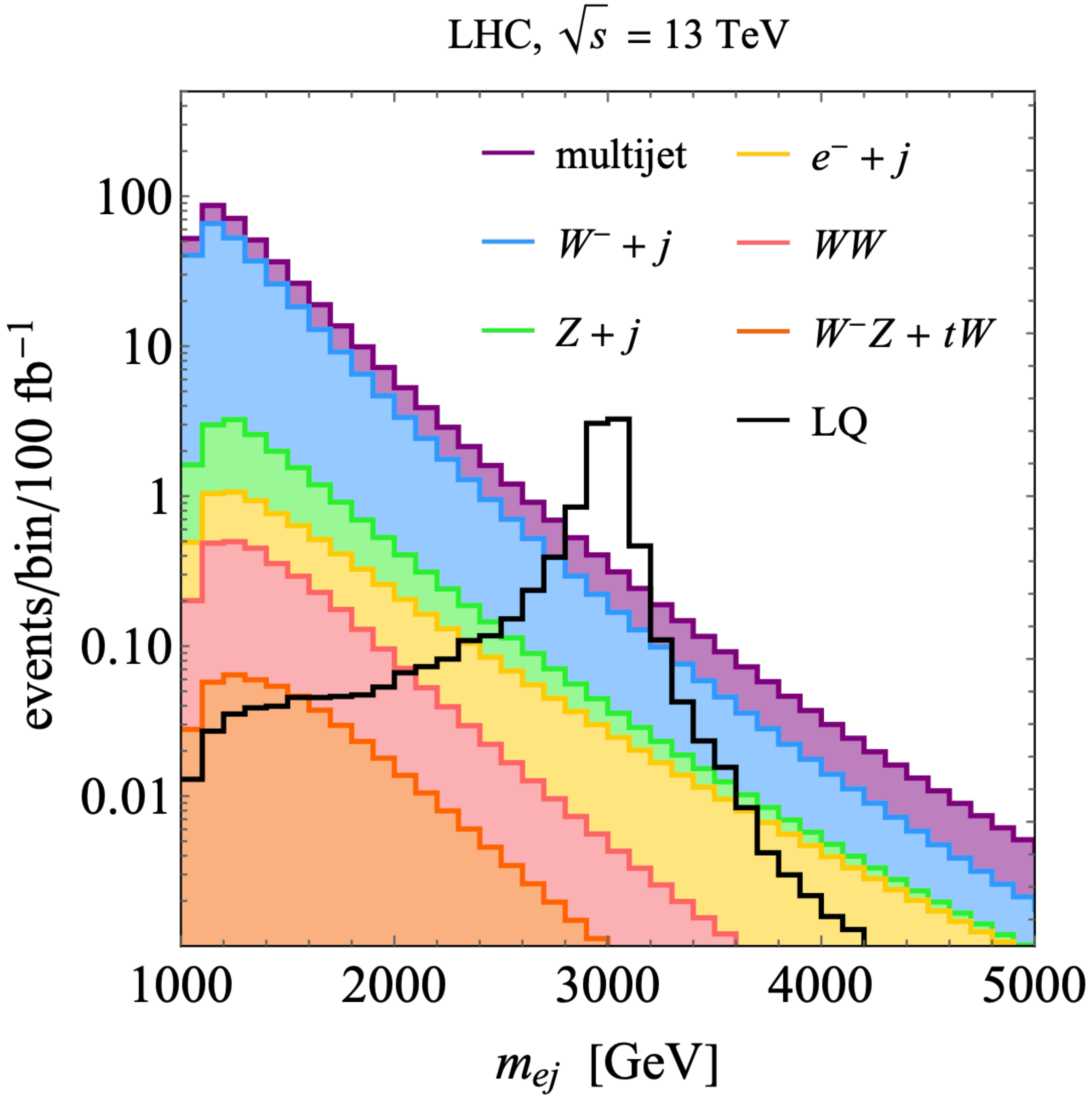




[Manohar et al., 1607.04266, 1708.01256; Buonocore et al., 2005.06477]

Resonant LQ production @ LHC

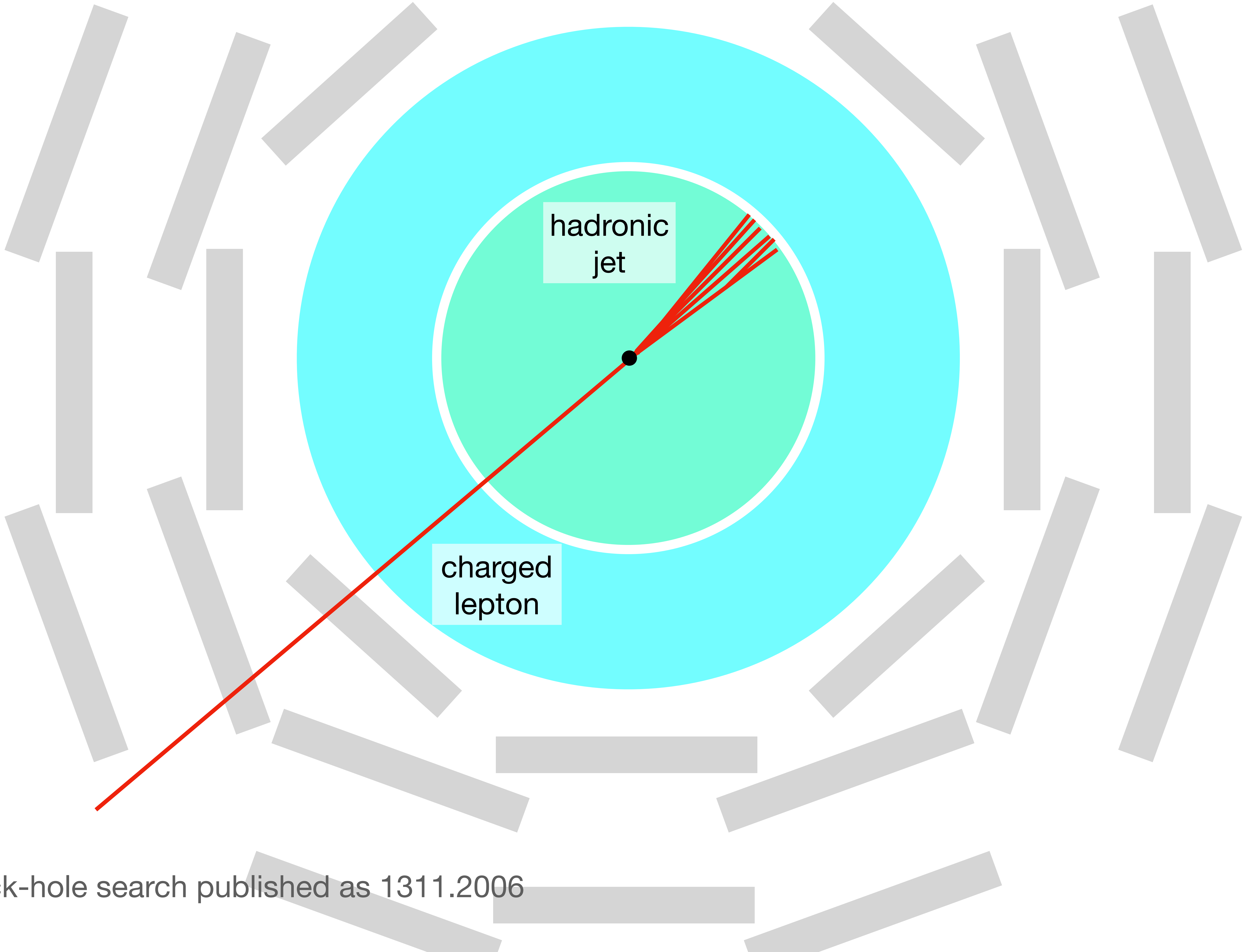




Non-zero lepton parton distribution functions allow for resonant LQ production @ LHC, but single lepton-jet final states are not part of exotics search canon of ATLAS & CMS

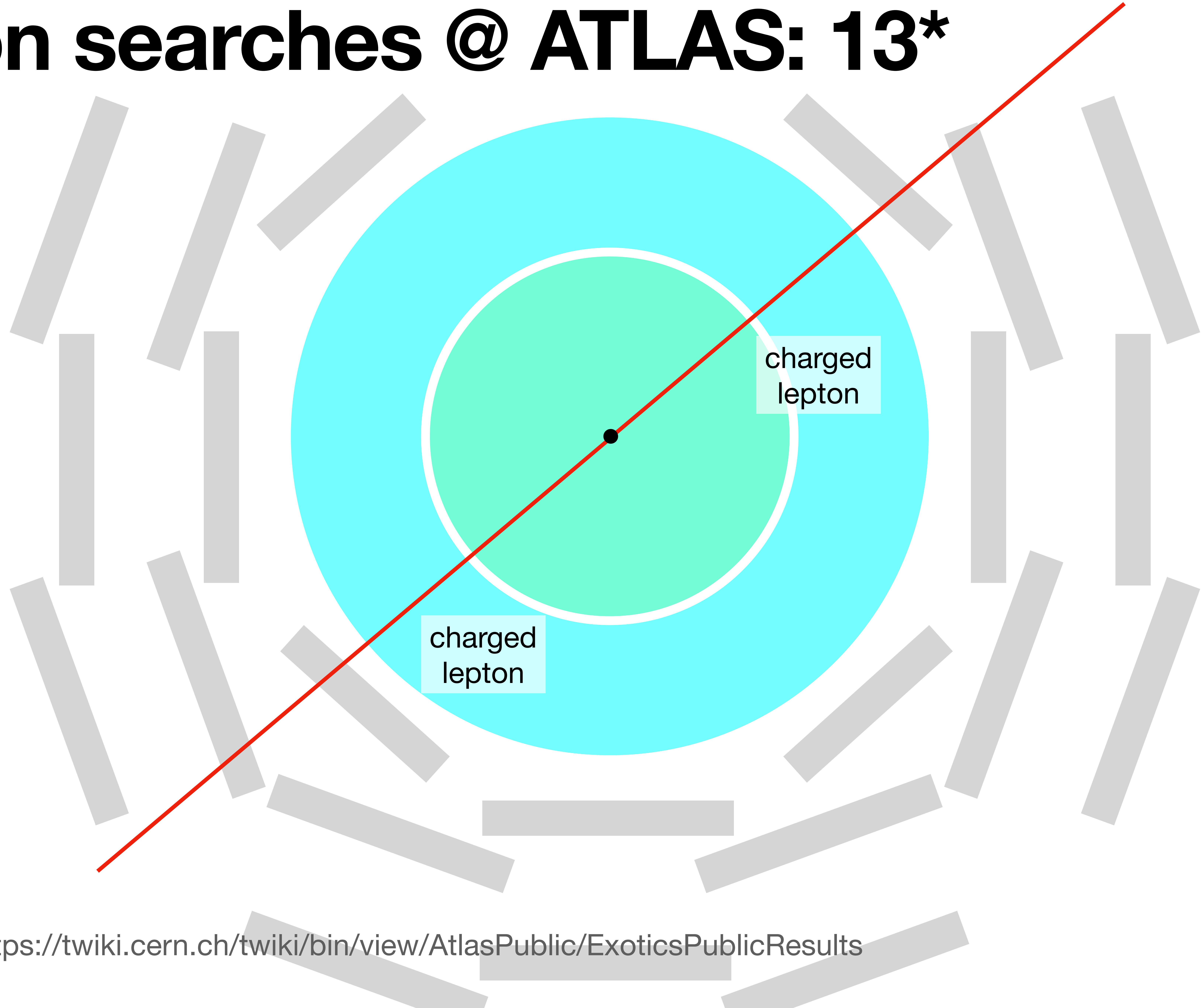
[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475; Greljo & Selimovic, 2012.02092]

Lepton-jet final state searches @ ATLAS: 1*



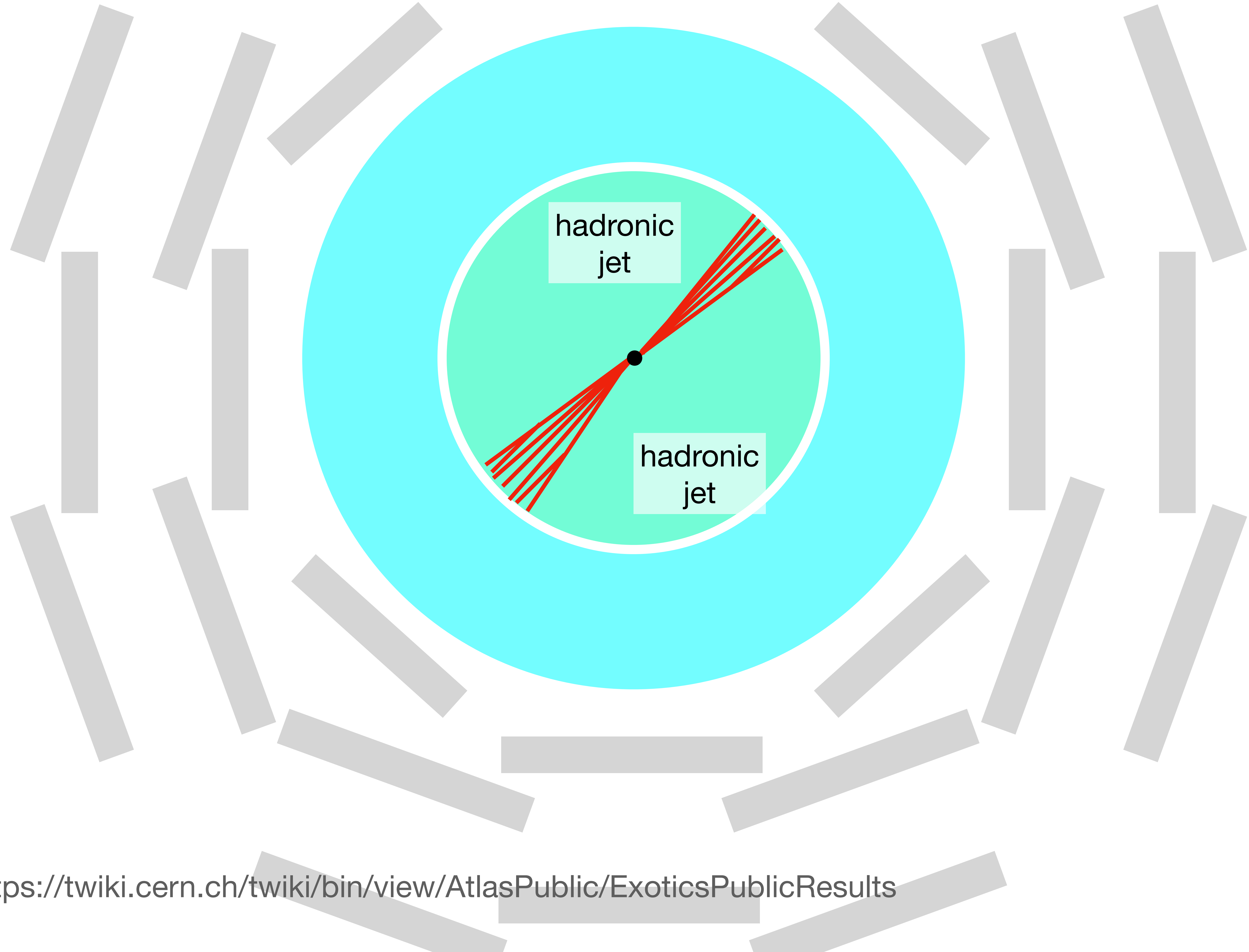
*i.e. the quantum-black-hole search published as 1311.2006

Dilepton searches @ ATLAS: 13*



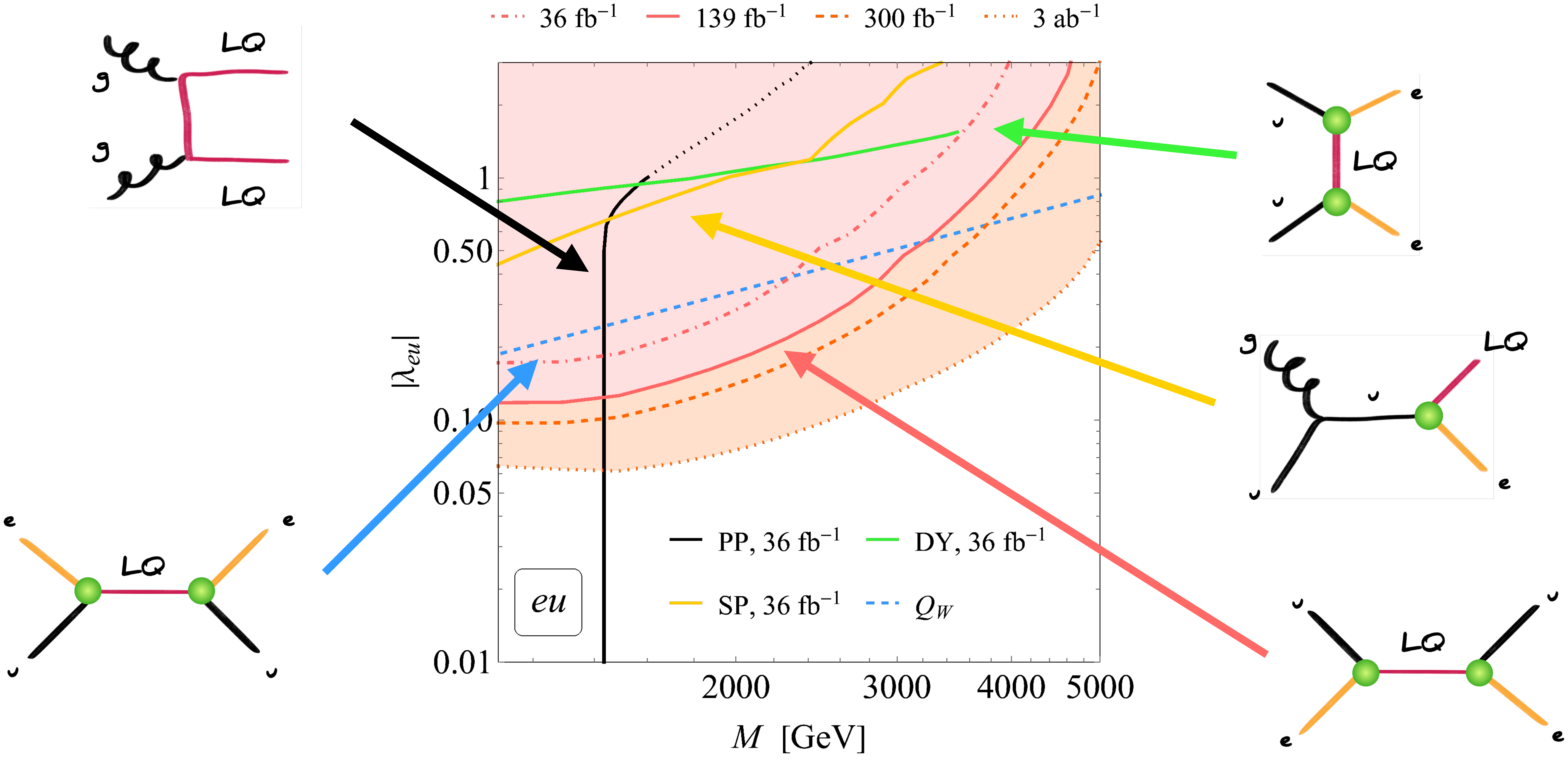
*number based on https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

Dijet searches @ ATLAS: 12*



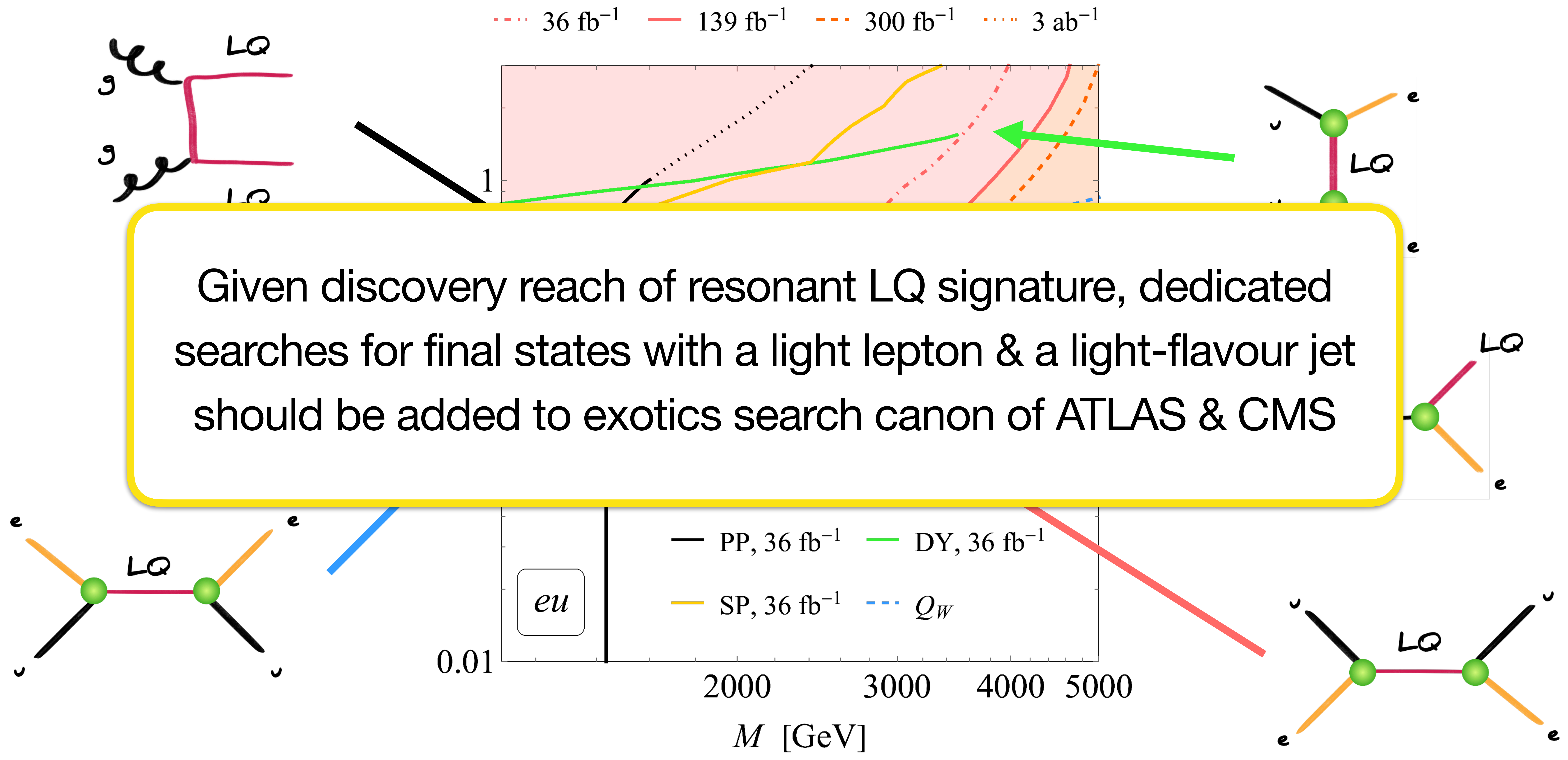
*number based on https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults

LHC limits on 1st & 2nd generation LQs



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

LHC limits on 1st & 2nd generation LQs



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, 2005.06475]

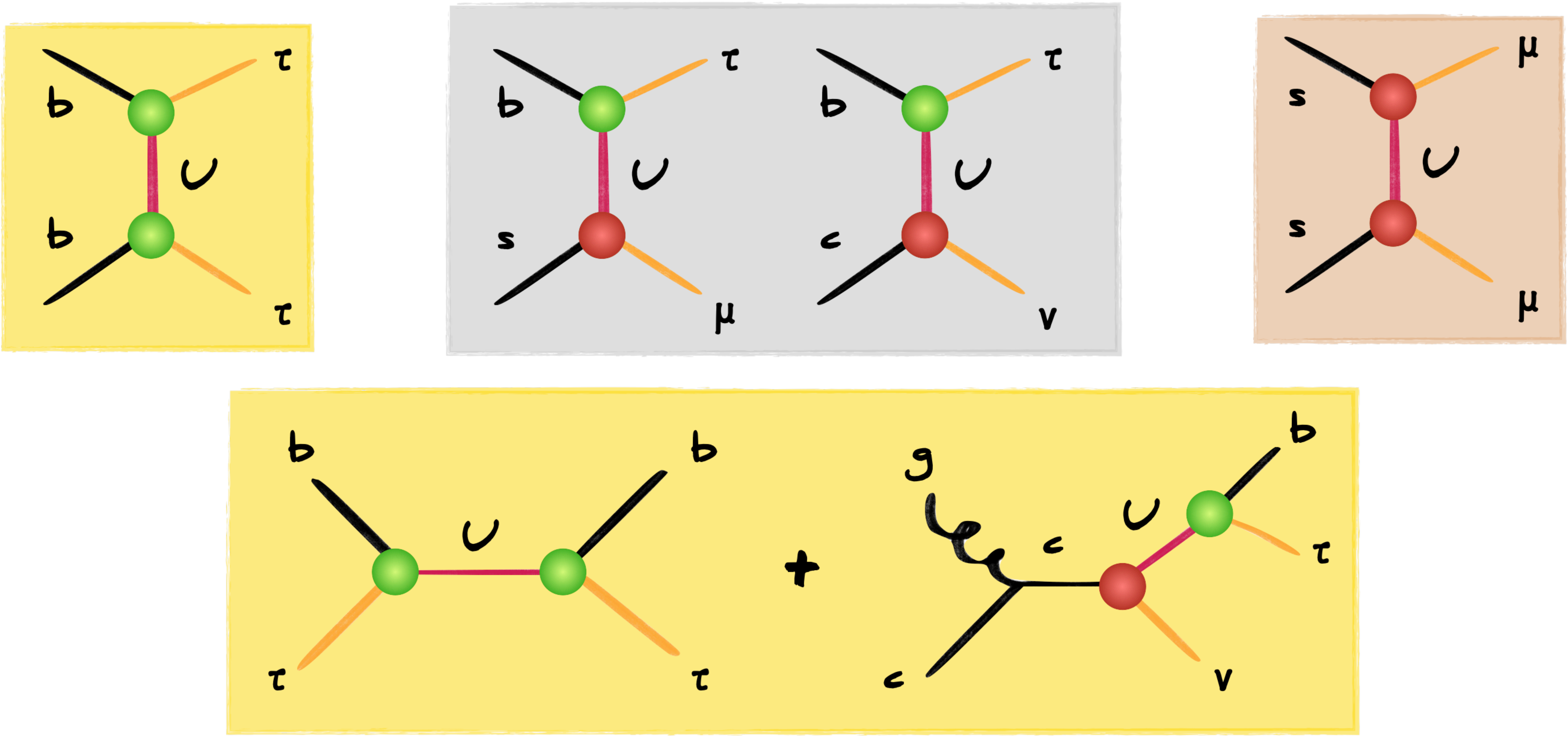
Singlet vector LQ models for B anomalies

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

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

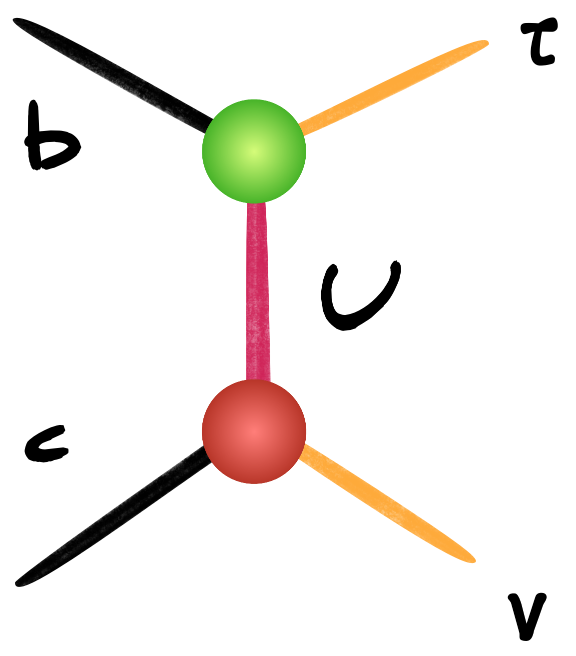
Parameters		Branching ratios			
β_L^{33}	β_L^{23}	$\mathrm{BR}\,(U \to b\tau^+)$	$\mathrm{BR}\,(U \to t\bar{\nu}_\tau)$	$\mathrm{BR}\,(U \to s\tau^+)$	$\mathrm{BR}\,(U \to c\bar{\nu}_\tau)$
1	0	51%	49%	0%	0%
1	1	25%	22%	25%	27%

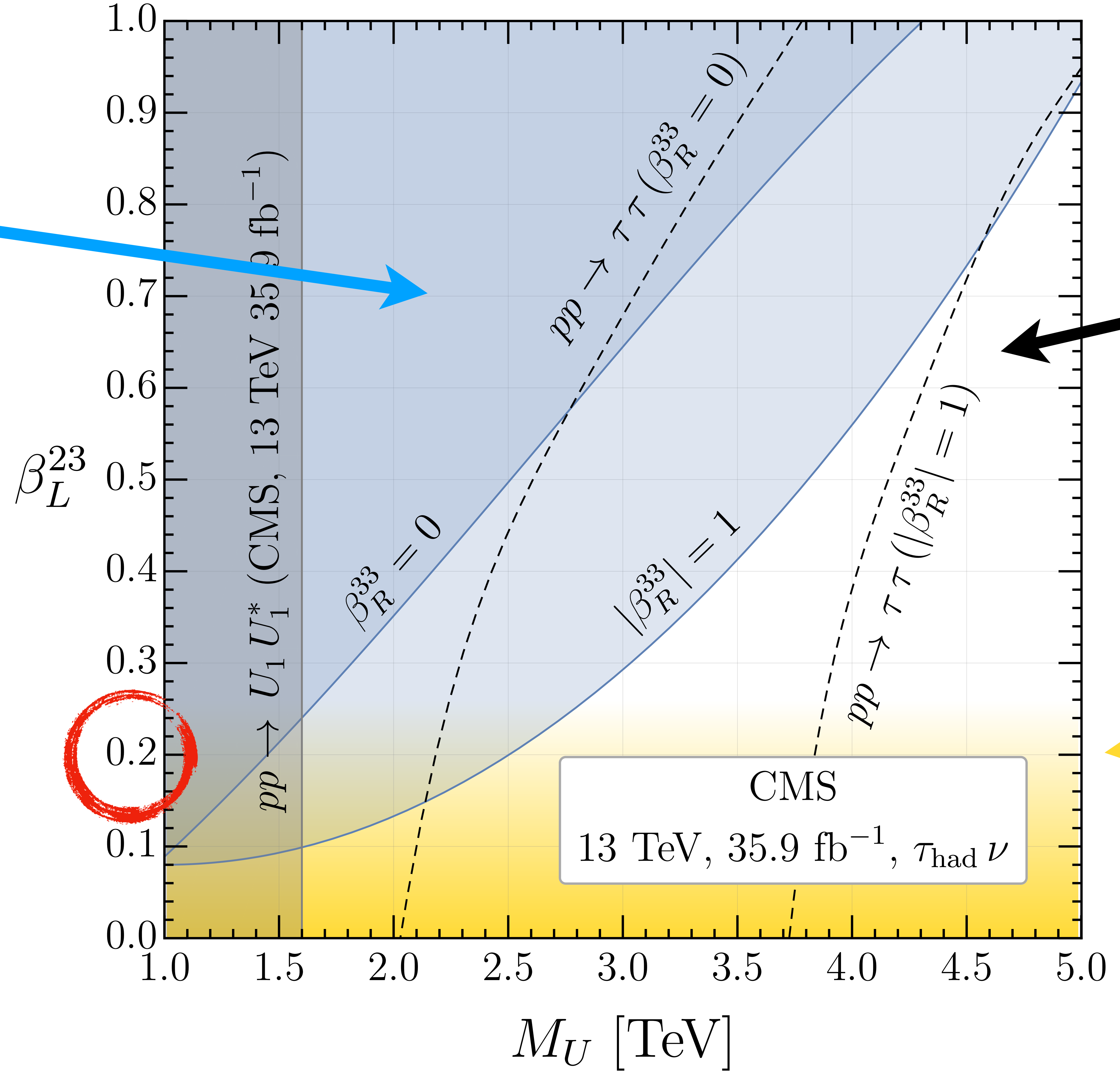
Possible singlet vector LQ signatures

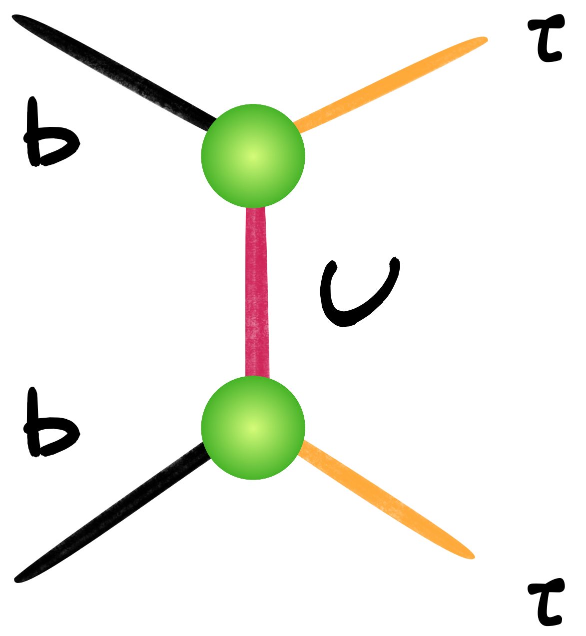


Flavor structure as suggested by $b \to c$ anomalies singles out $pp \to \tau^+\tau^-$, $b\tau$ as most interesting channels — $pp \to \tau\mu$, $\tau\nu$, $\mu^+\mu^-$, $t\nu$, $c\nu$ may be important as well in case of discovery or if $b \to c$ anomalies disappear

LHC bounds: pp → ττ vs. pp → τν



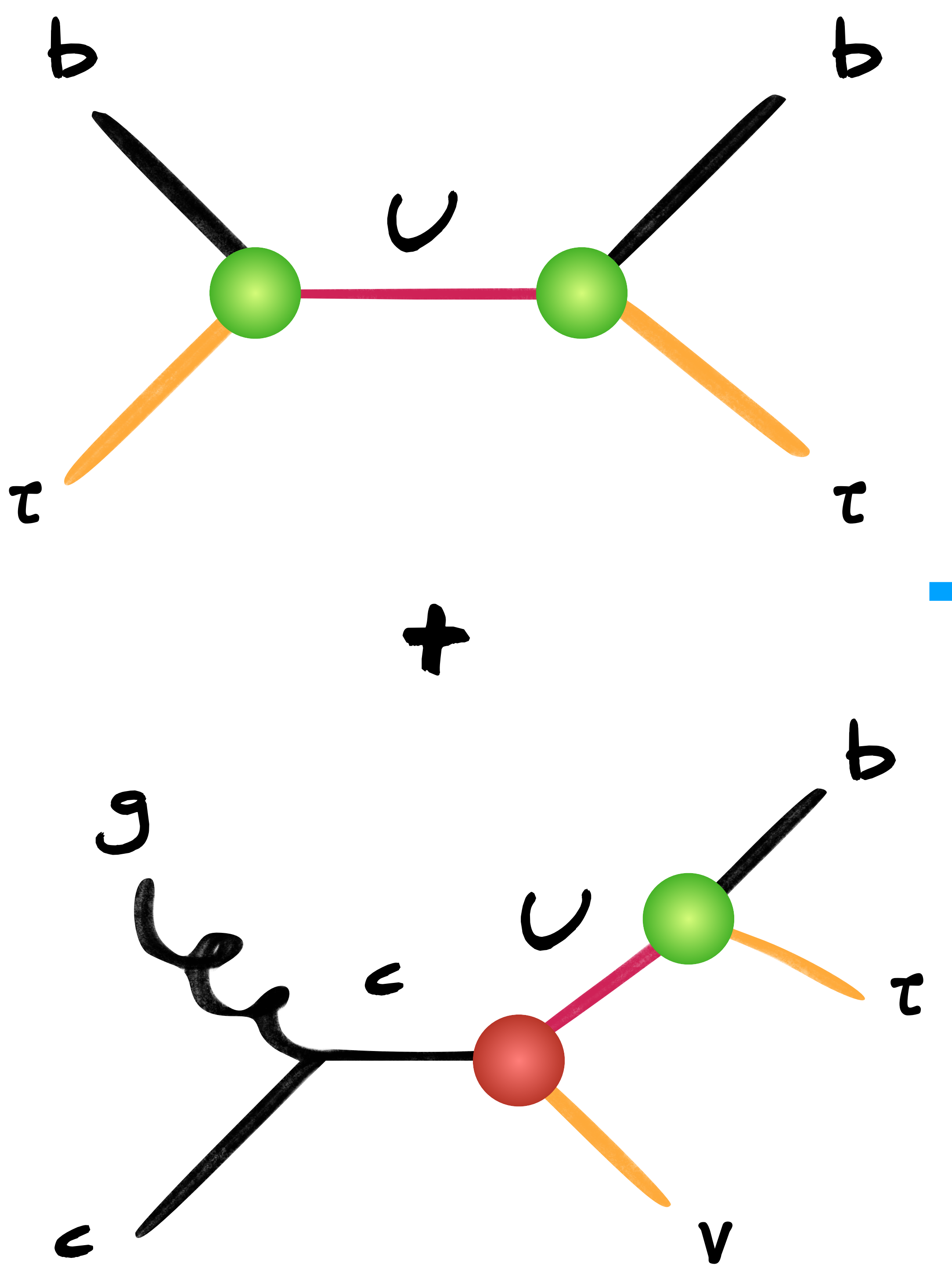


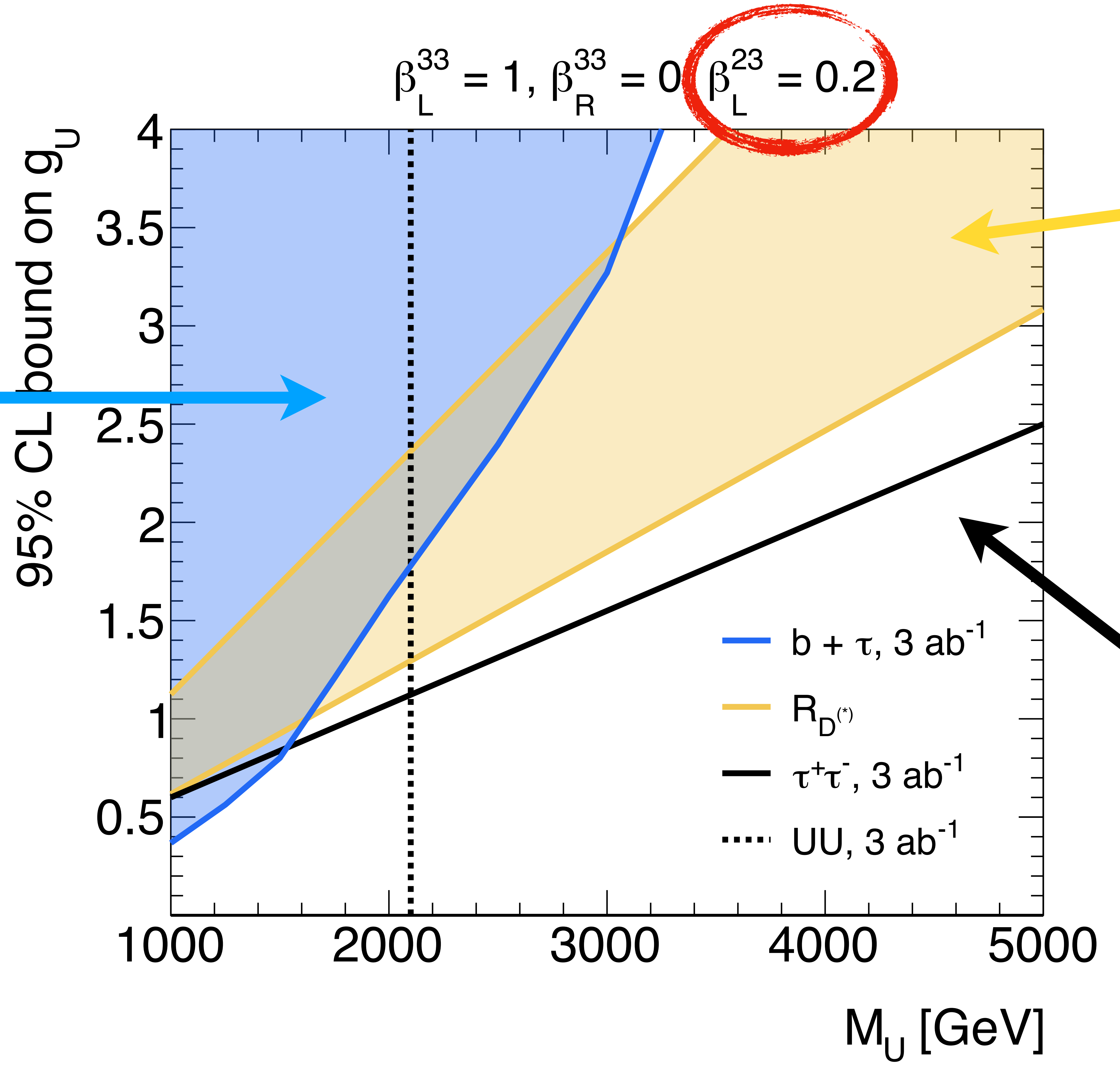


parameter space of singlet vector LQ with natural flavor structure

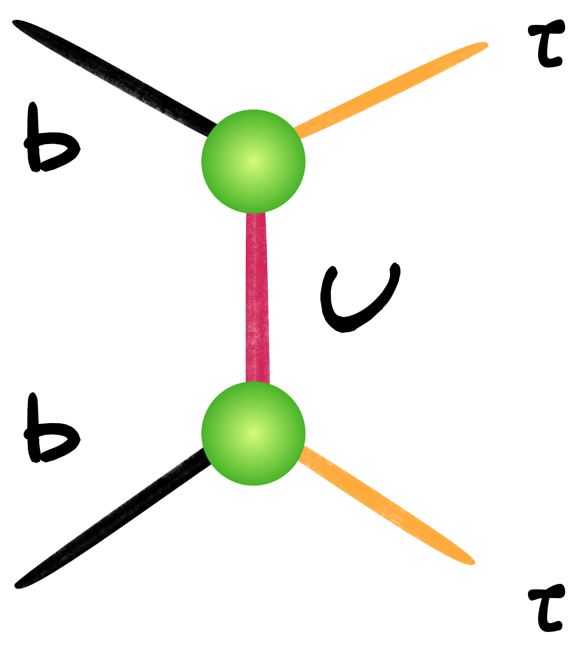
[Baker et al., 1901.10480; ATLAS, 1709.07242; CMS, 1807.11421]

LHC prospects of LQ search strategies



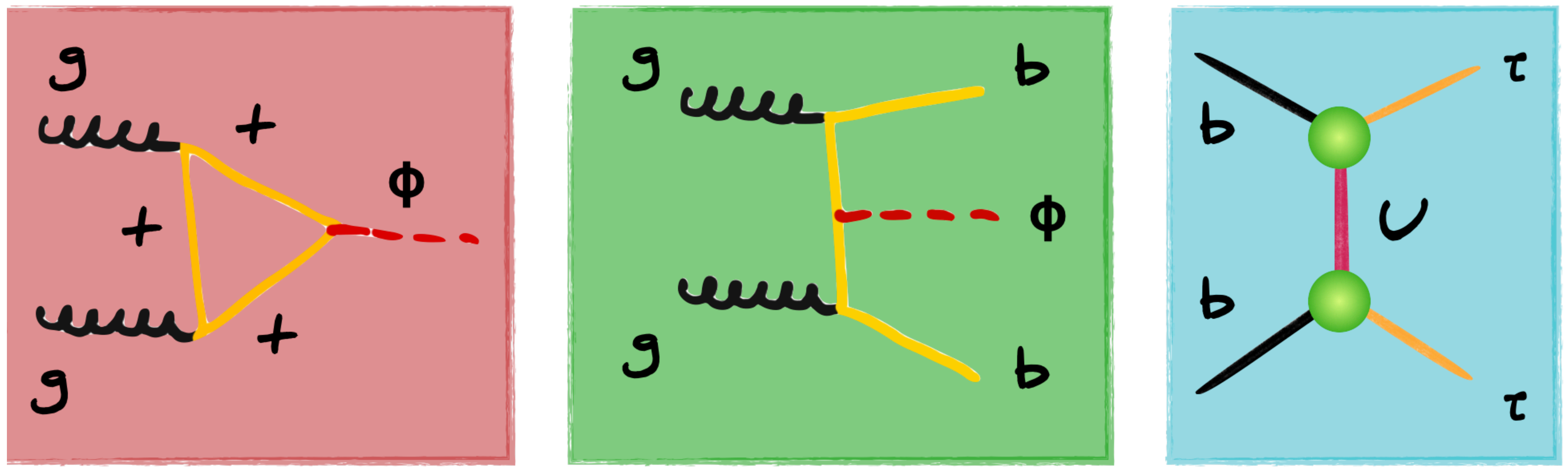


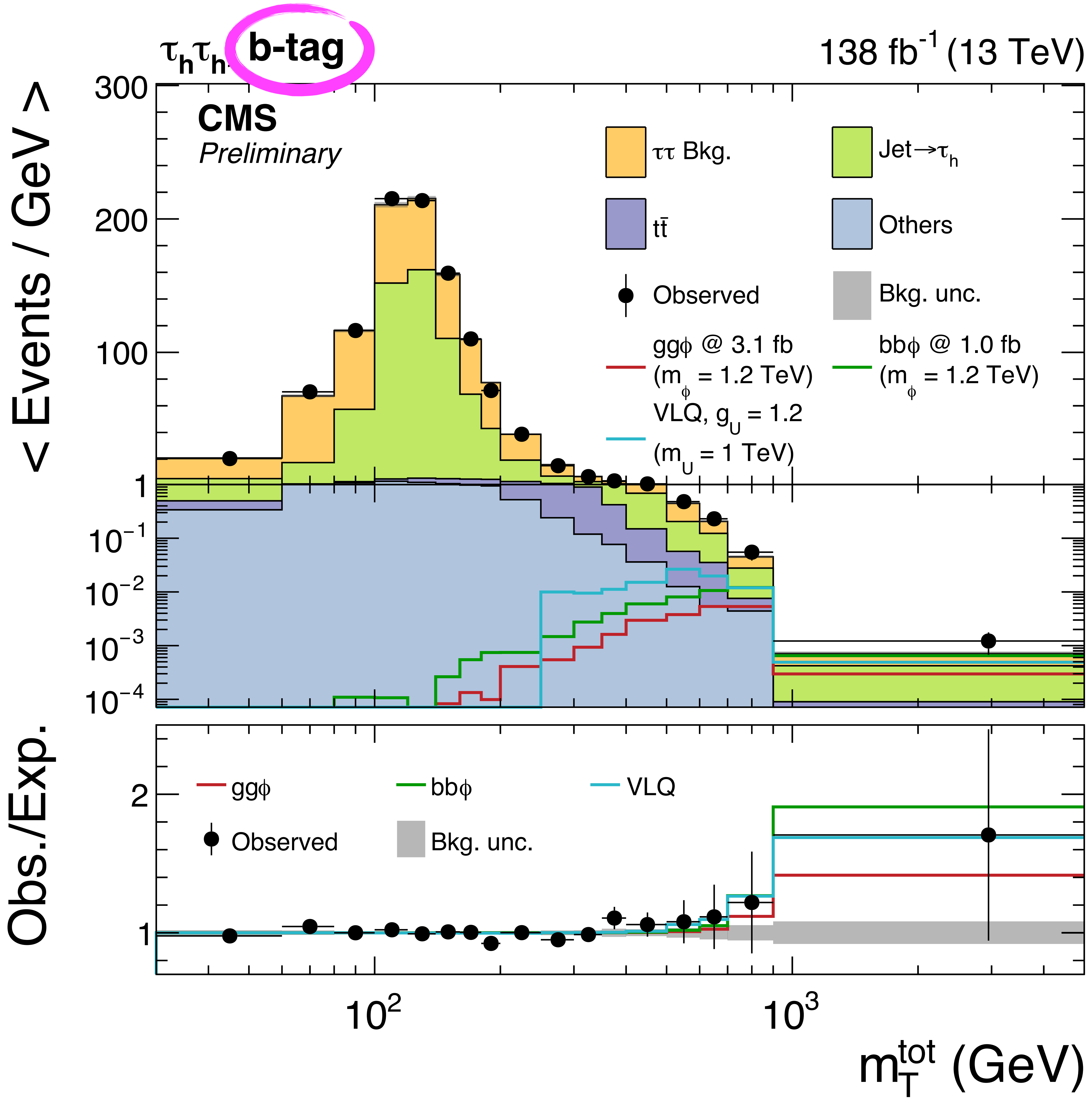
95% CL region favoured by b → c anomalies



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

News flash: CMS ditau search

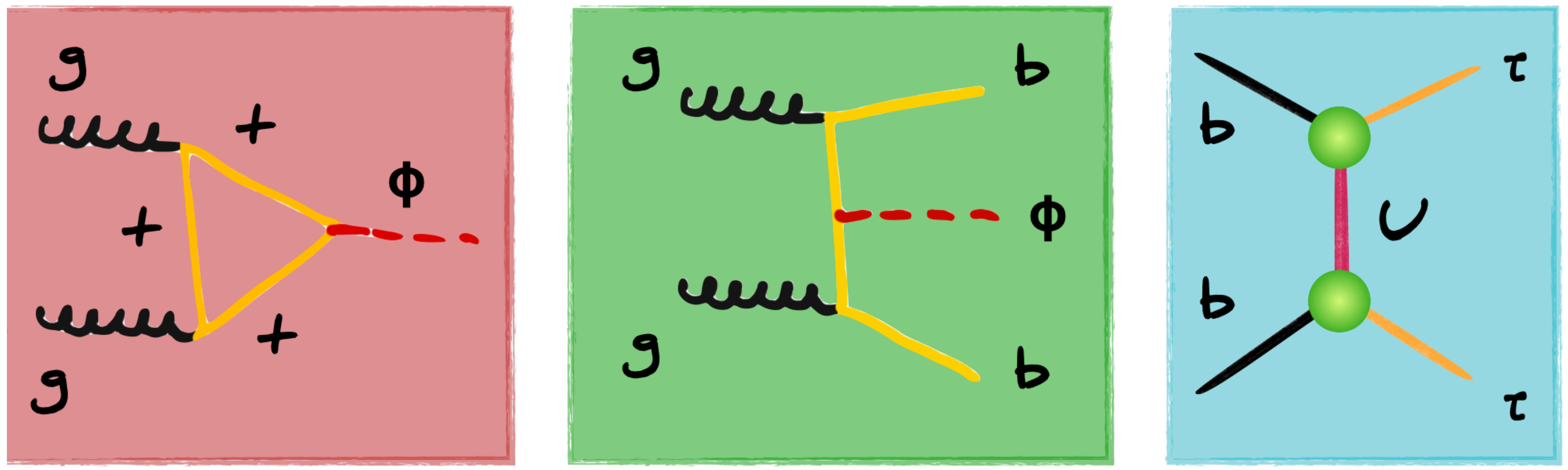


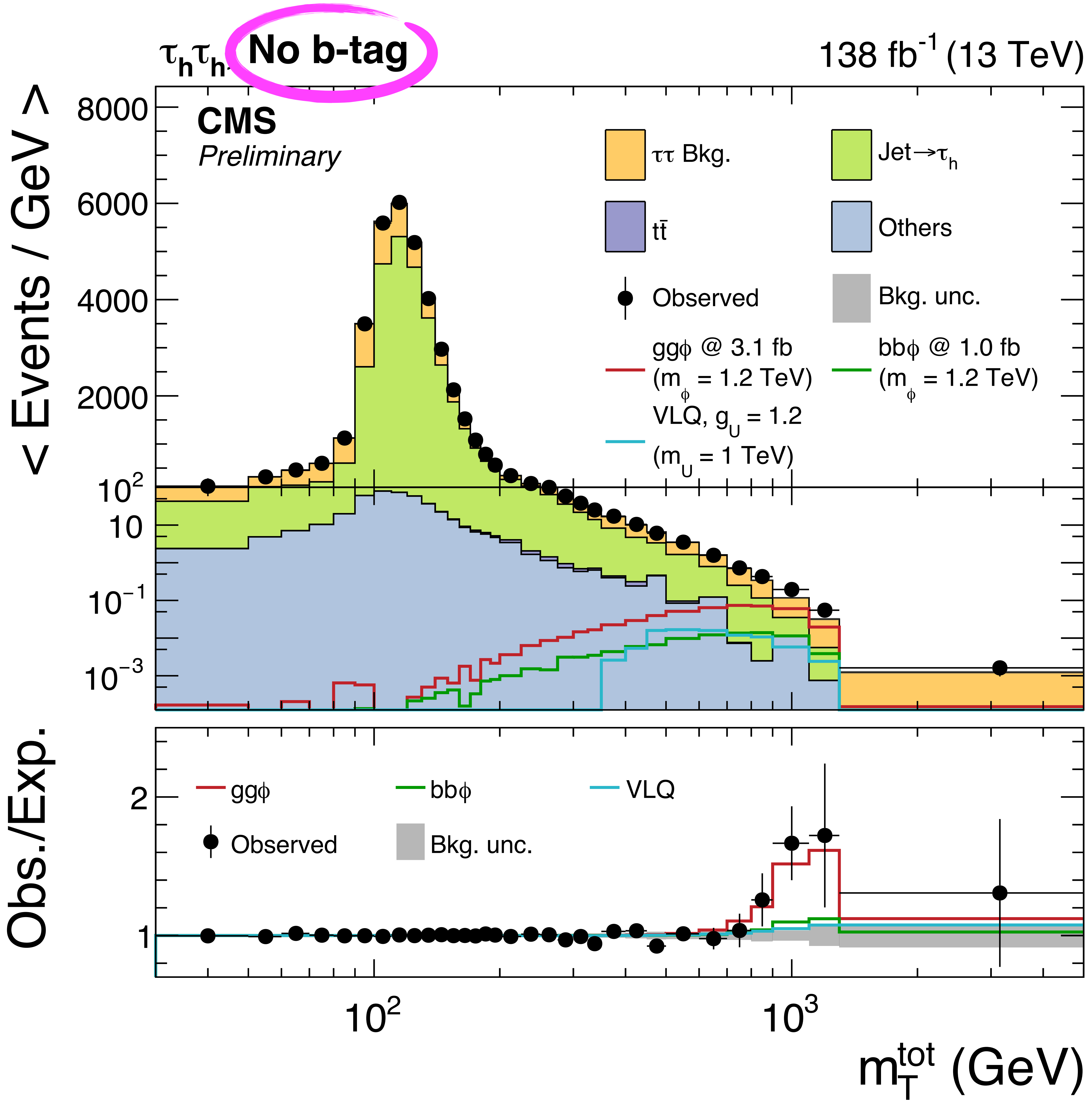


CMS studies three signal hypotheses, i.e. scalar production in gluon-fusion & in association with bottom quarks & t-channel exchange of a vector LQ. Both events with & without a b-tagged jet are considered

[CMS PAS HIG-21-001]

News flash: CMS ditau search

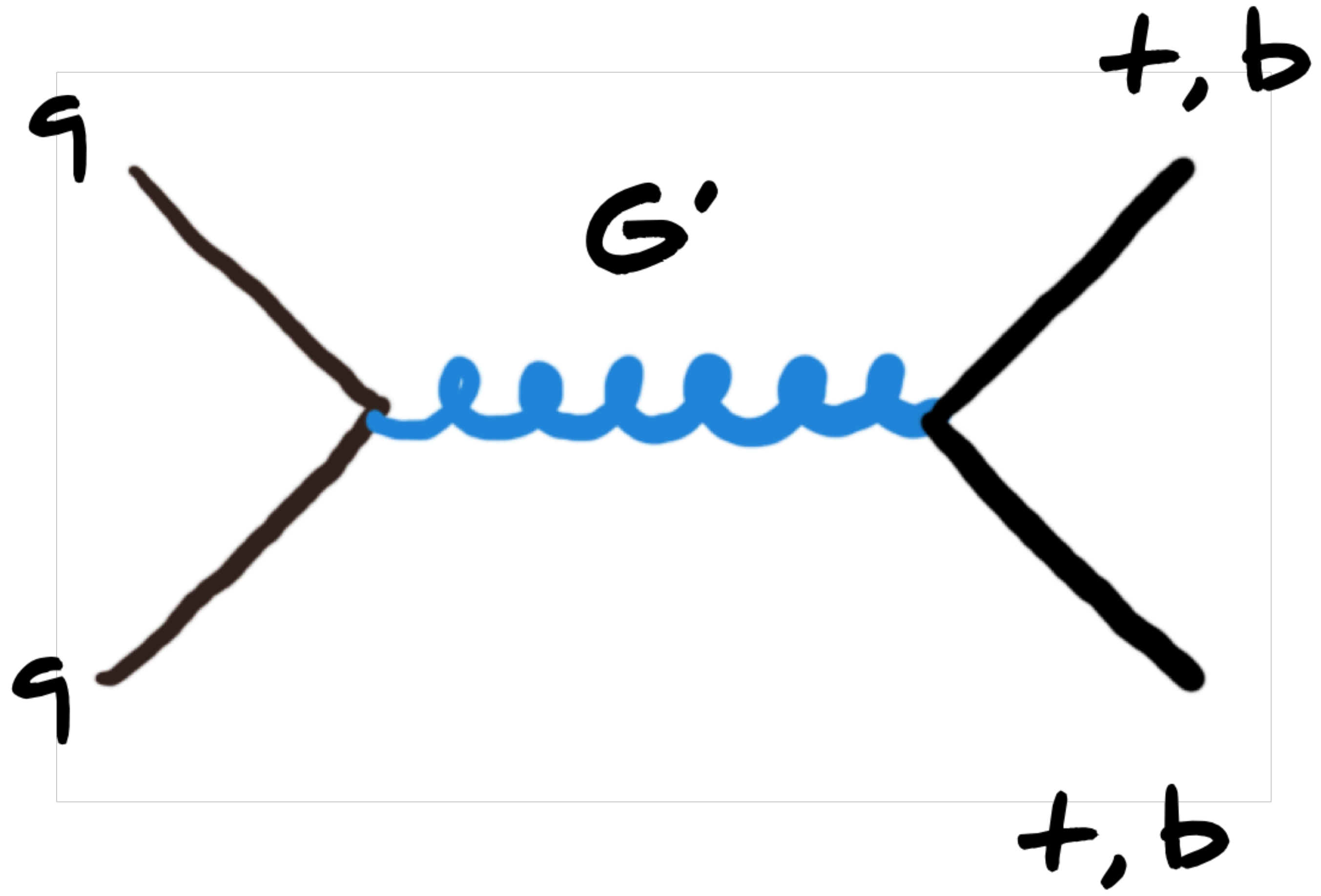


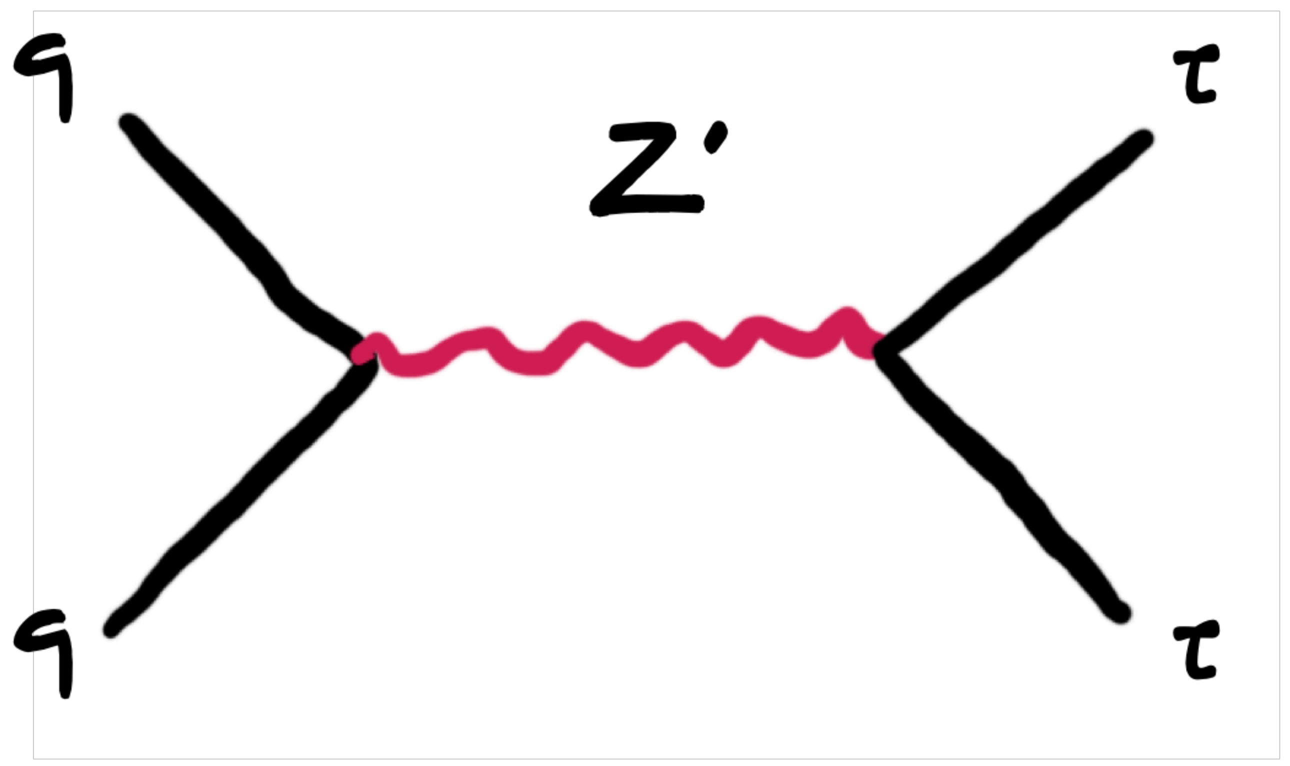


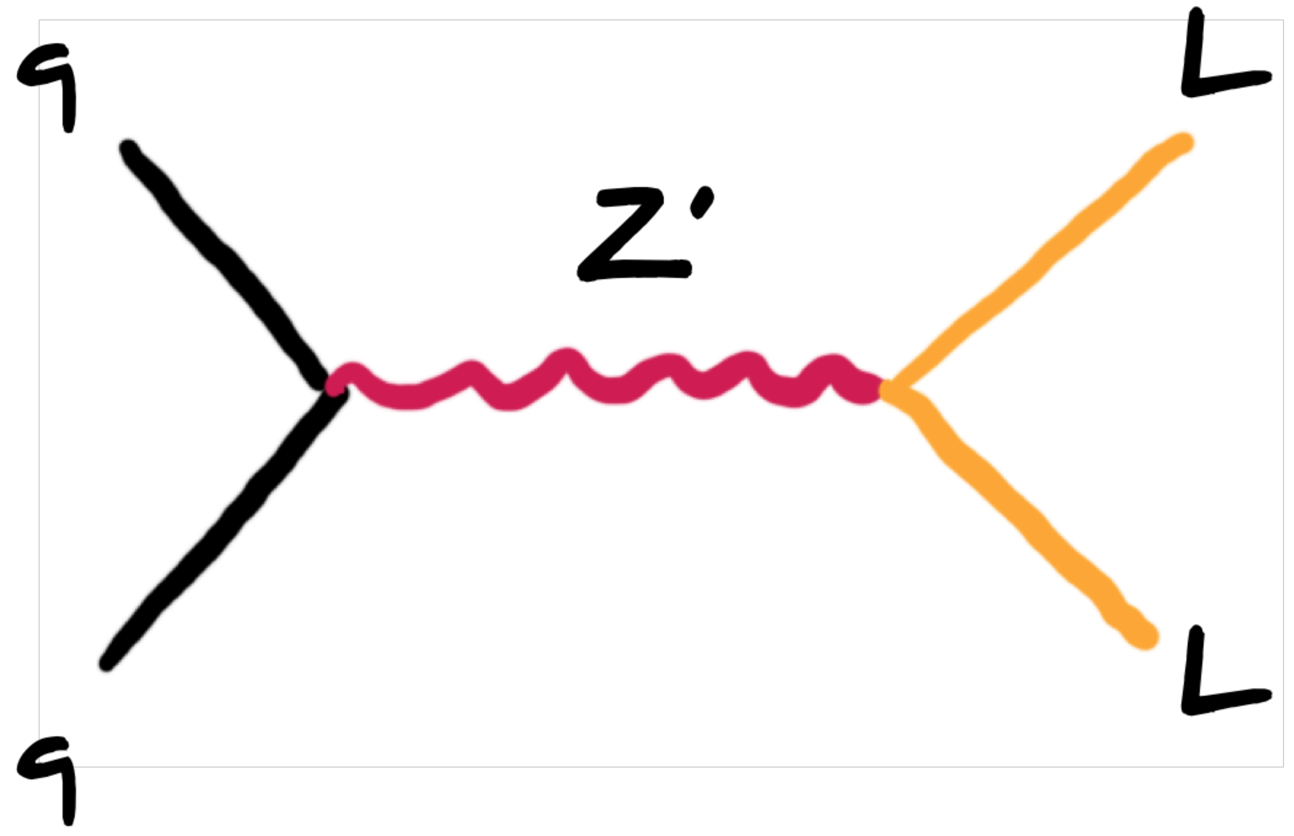
Scalar production in gluon-fusion seems to best describe slight excess of events at large transverse mass. LQ explanations IMHO problematic because they necessarily lead to non-negligible b-jet activity

[CMS PAS HIG-21-001]

Beyond simplified LQ models



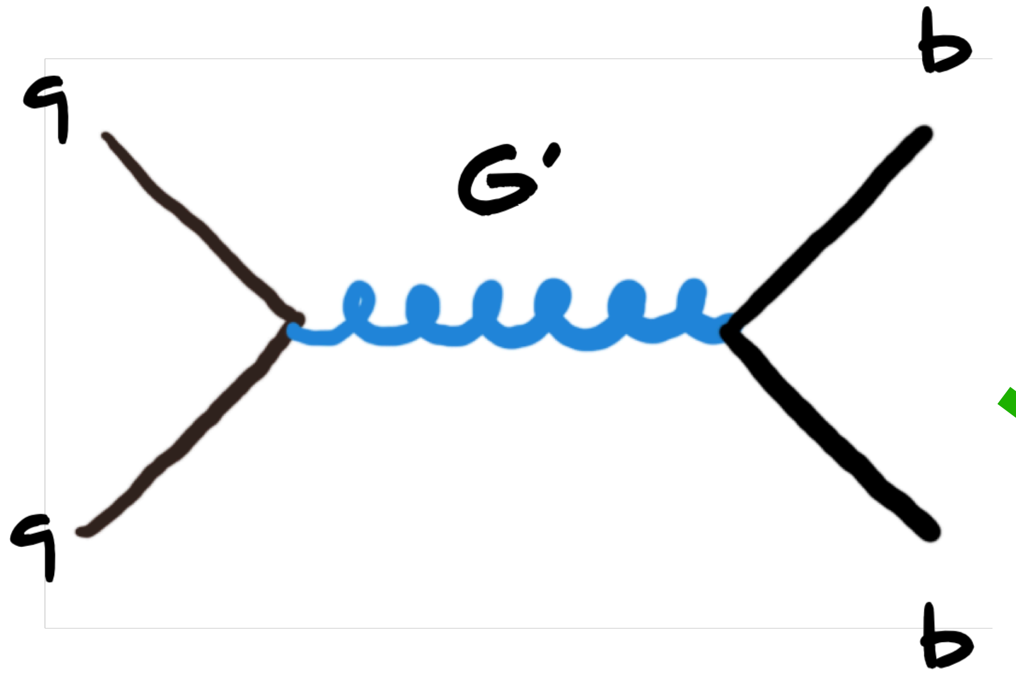


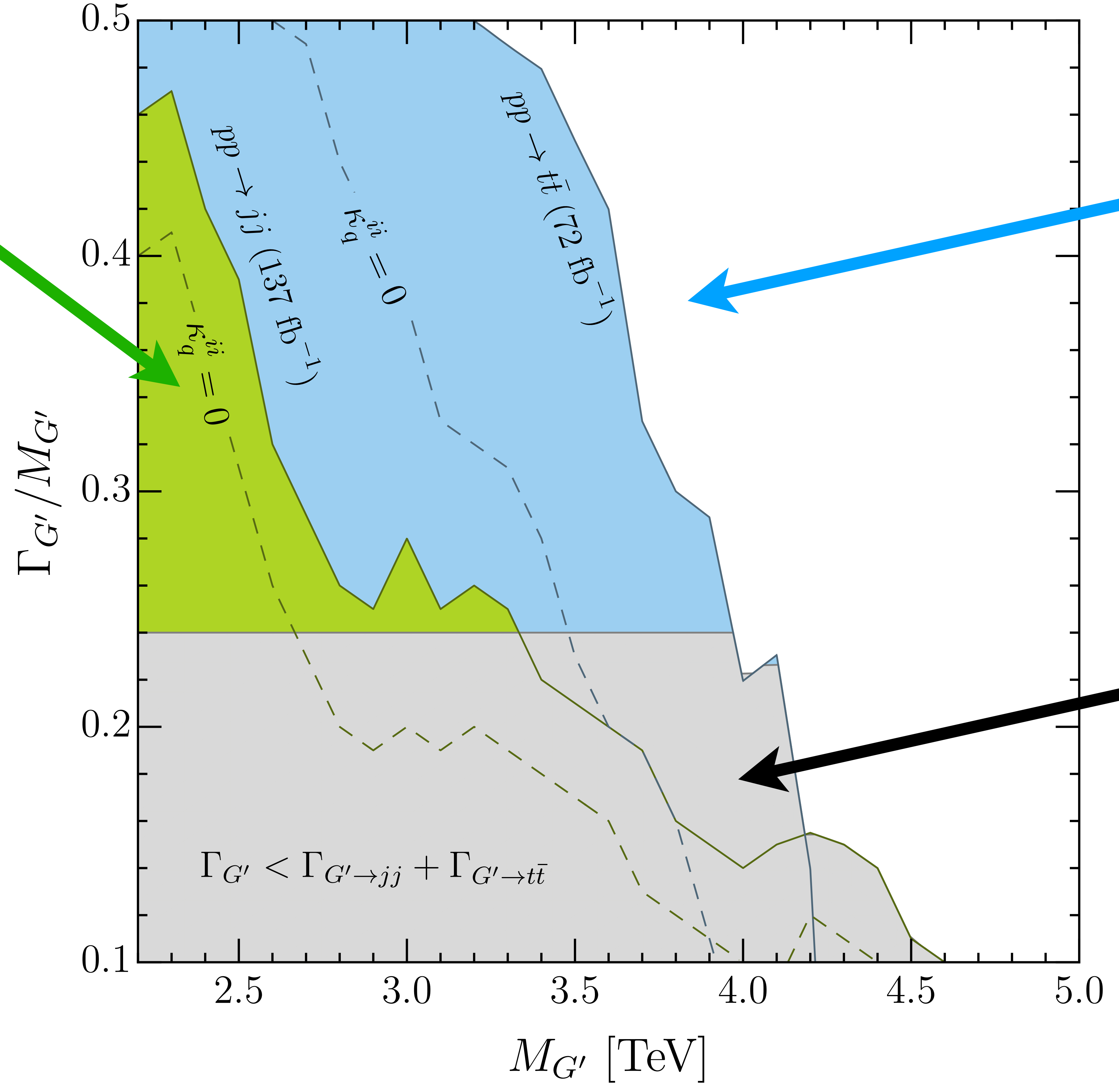


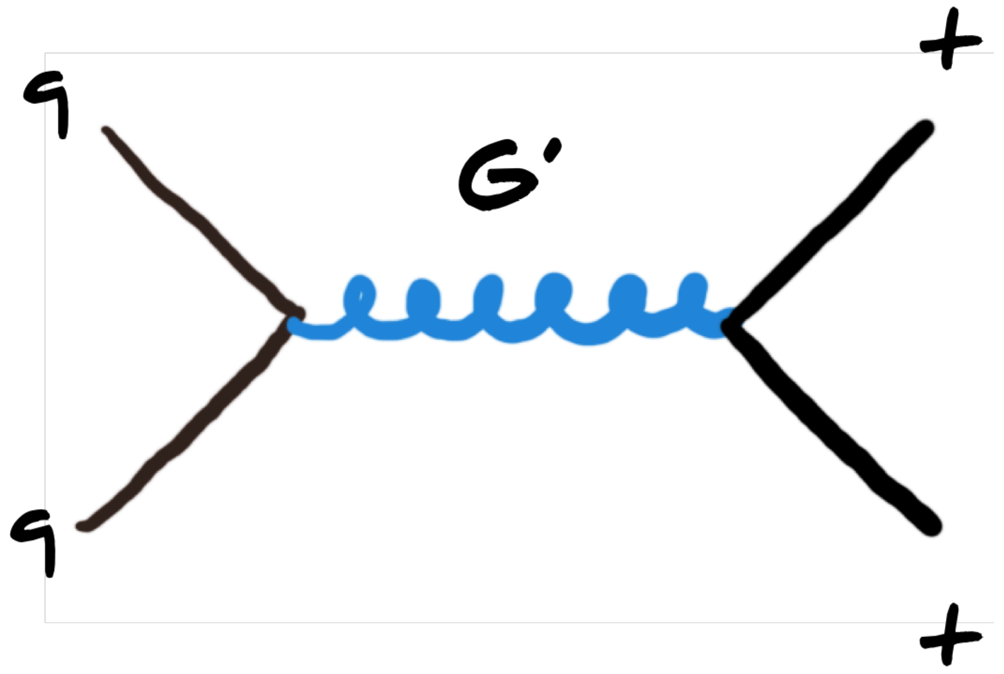
Ultraviolet complete LQ models typically contain new degrees of freedom besides LQ such as a heavy gluon G′, a Z′, vector-like leptons L, additional Higgses, etc.

New states cannot be arbitrarily heavy in models that address $b \to c$ anomalies

Bounds on G′ motivated by b → c anomalies



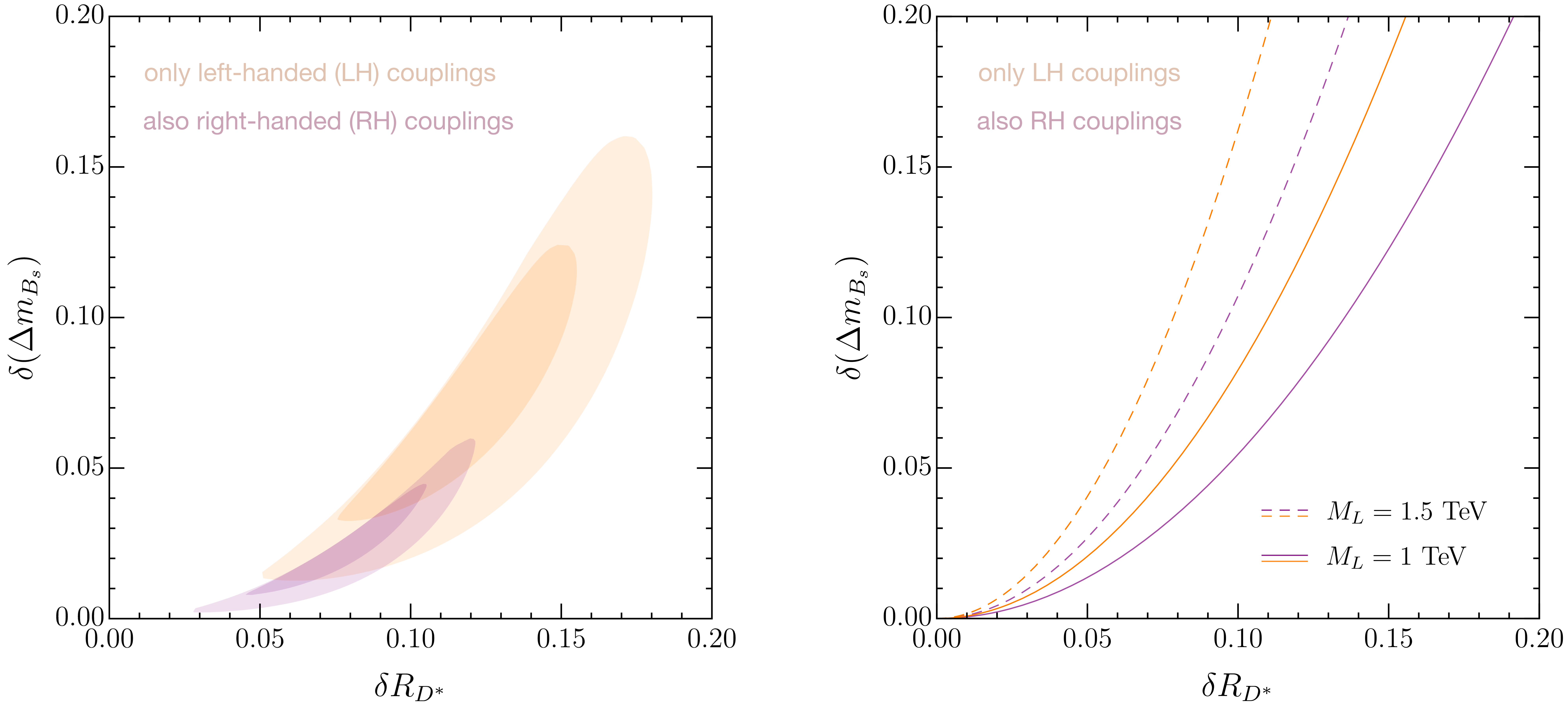




parameter region
where G′ decays
only to SM quarks

[Cornella et al., 2103.16558; CMS, 1911.03947; ATLAS, 1801.02052; CMS-PAS-TOP-18-013]

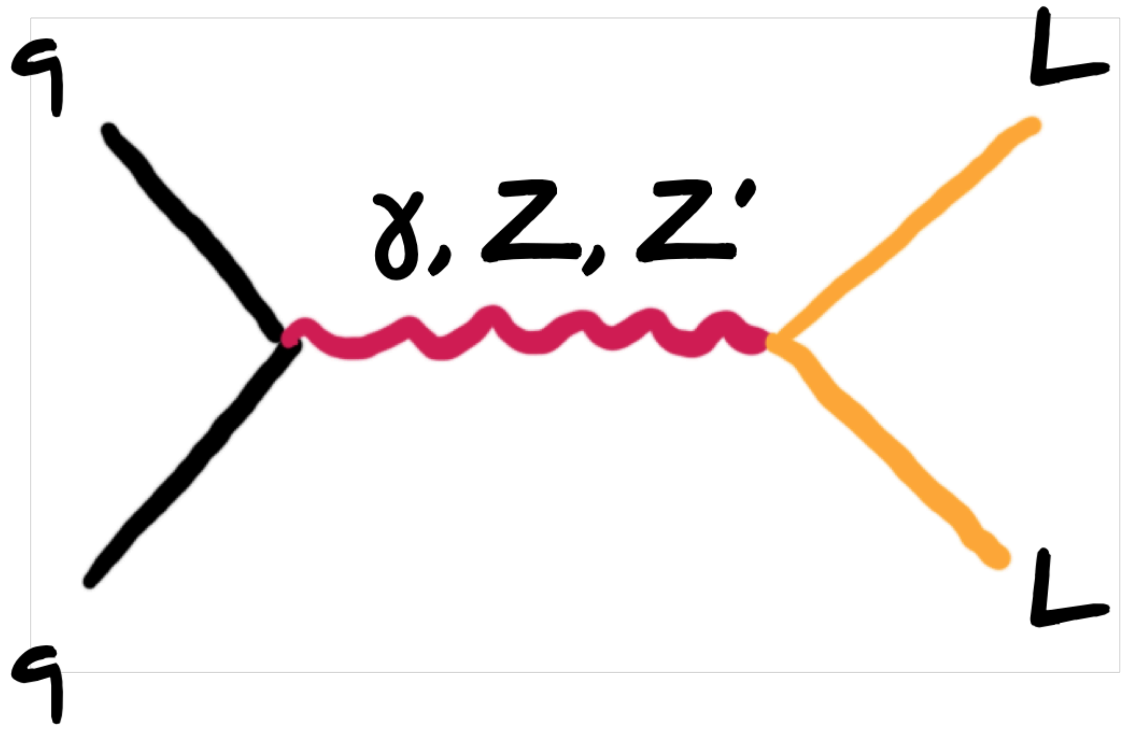
Vector-like leptons in singlet vector LQ model

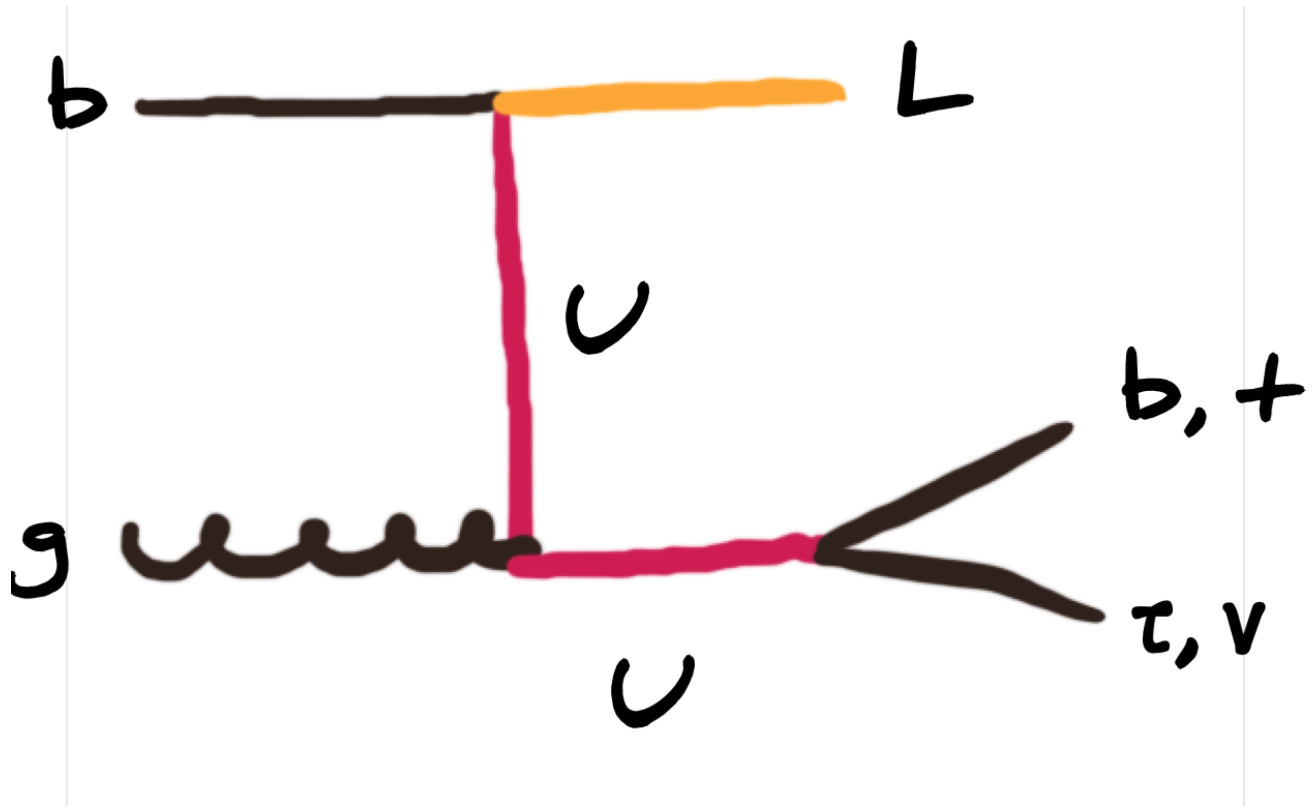


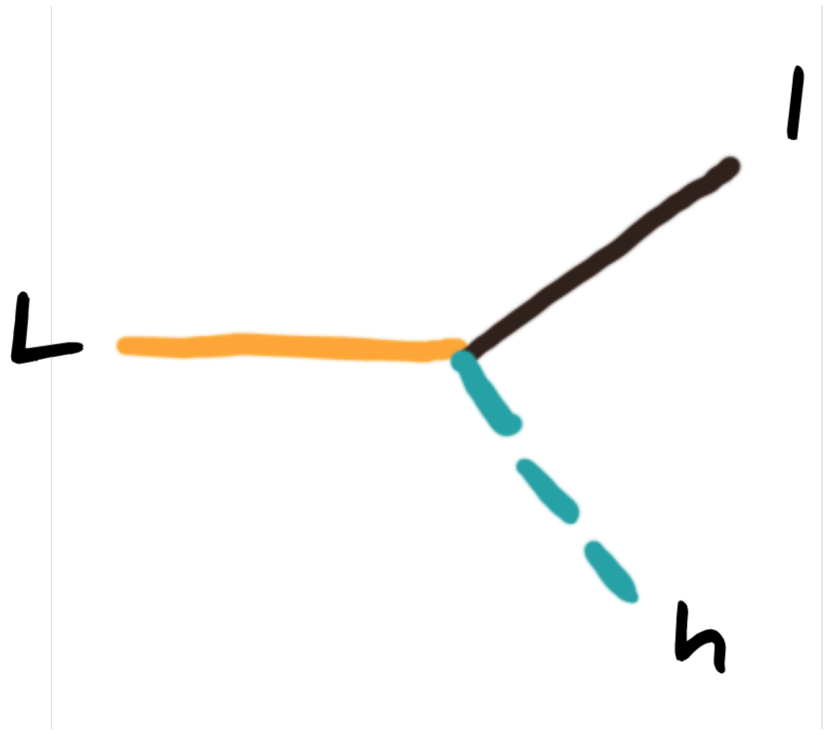
Additional vector-like leptons need to be light to reduce LQ contribution to B_s mixing

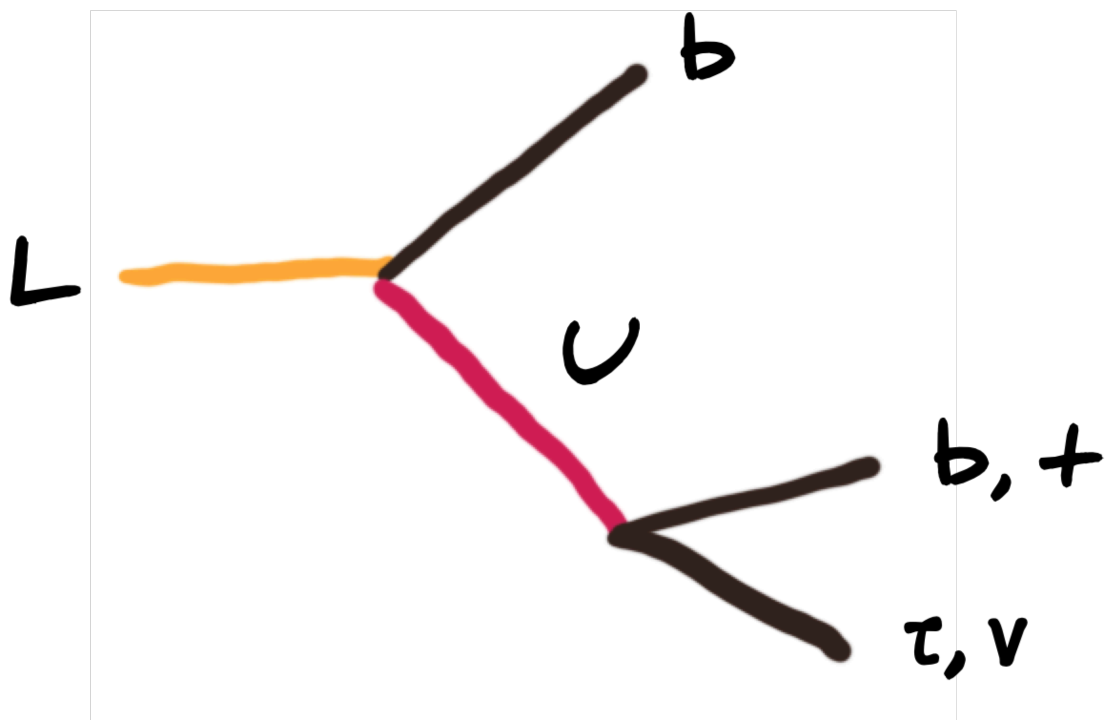
[Cornella, Fuentes-Martin, Faroughi, Isidori & Neubert, 2103.16558]

LHC searches for vector-like leptons





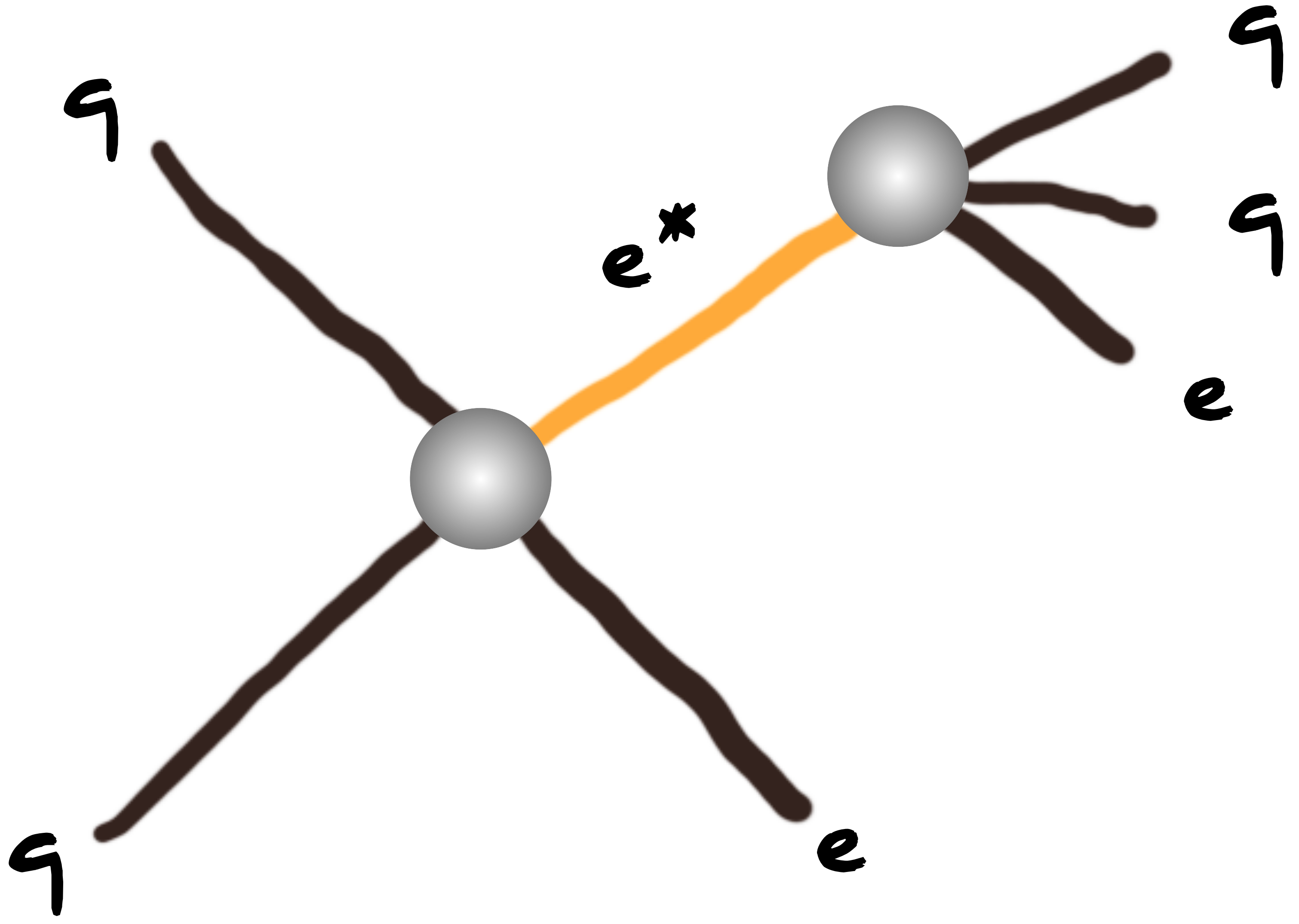


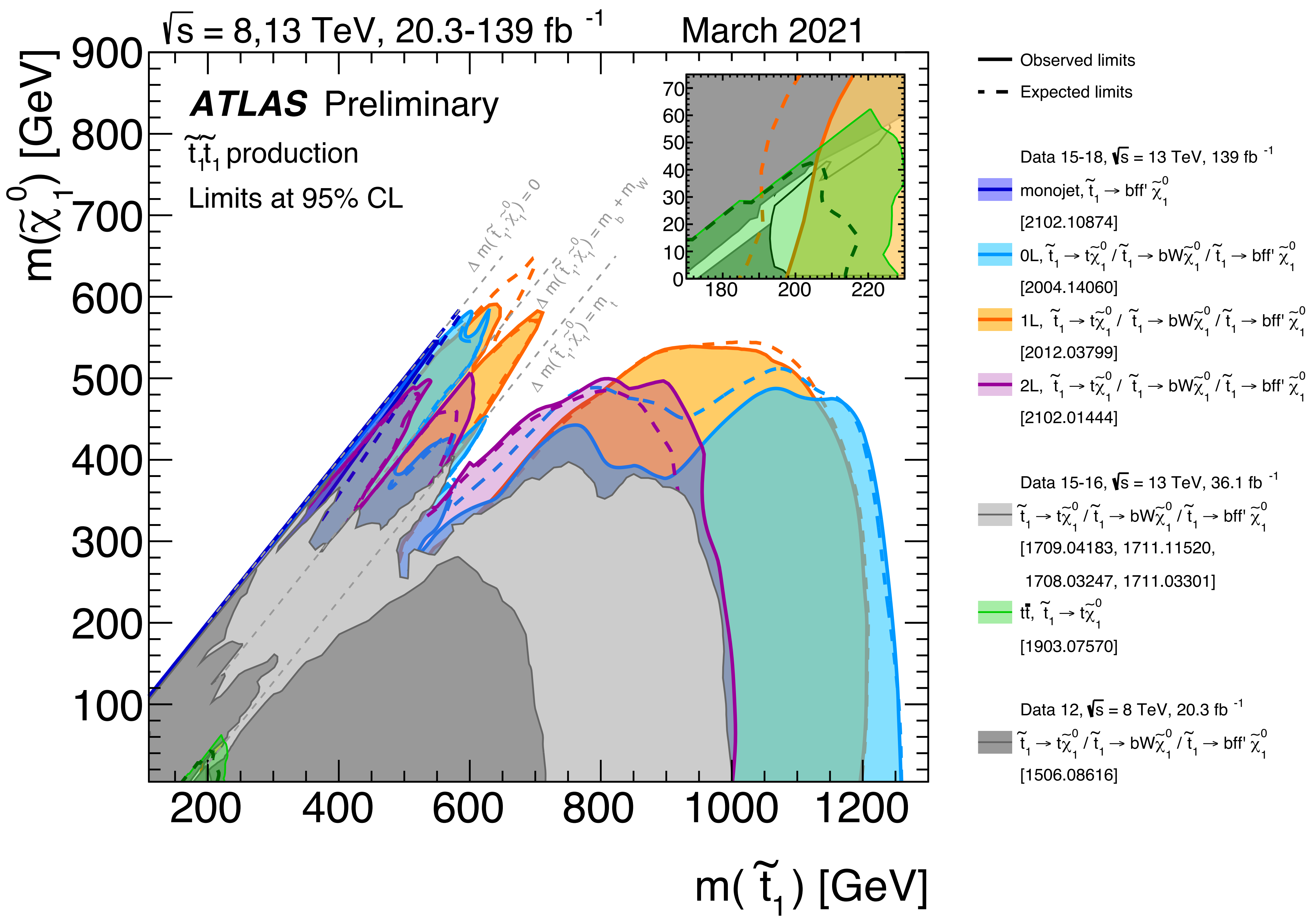


Vector-like lepton production in context of LQ models addressing b → c anomalies is expected to lead to high-multiplicity final states with τ, b, t & $E_{T,miss}$

[see for instance Di Luzio et al., 1808.0094; Cornella et al., 2103.16558]

LHC searches for vector-like leptons

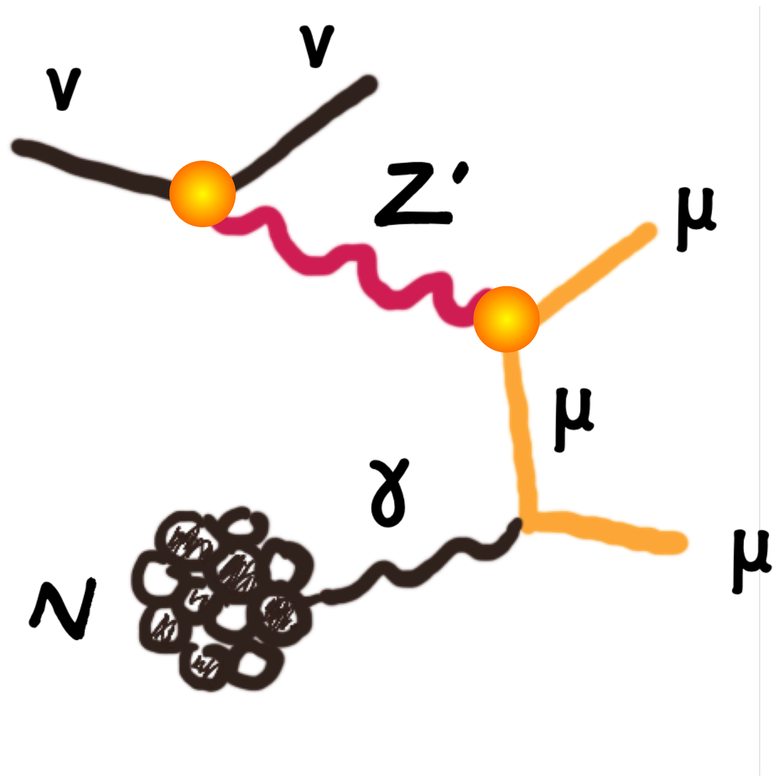




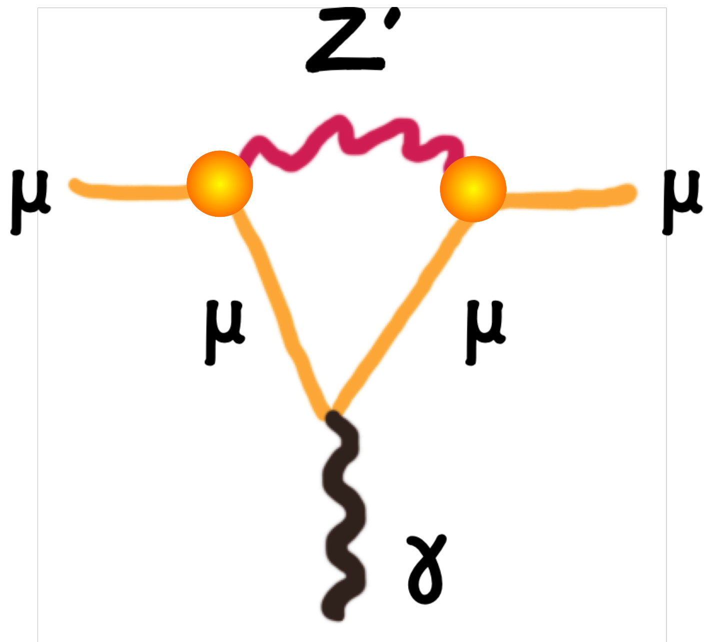
Existing searches for excited leptons l* focus on single production & 1st, 2nd generation fermions. Stop searches can be reinterpreted to set limit of $M_L \gtrsim 800$ GeV. Dedicated analysis for vector-like leptons appearing in singlet vector LQ model do not exist

[Di Luzio et al., 1808.0094; ATLAS, 1810.05573; CMS, 2001.04521]

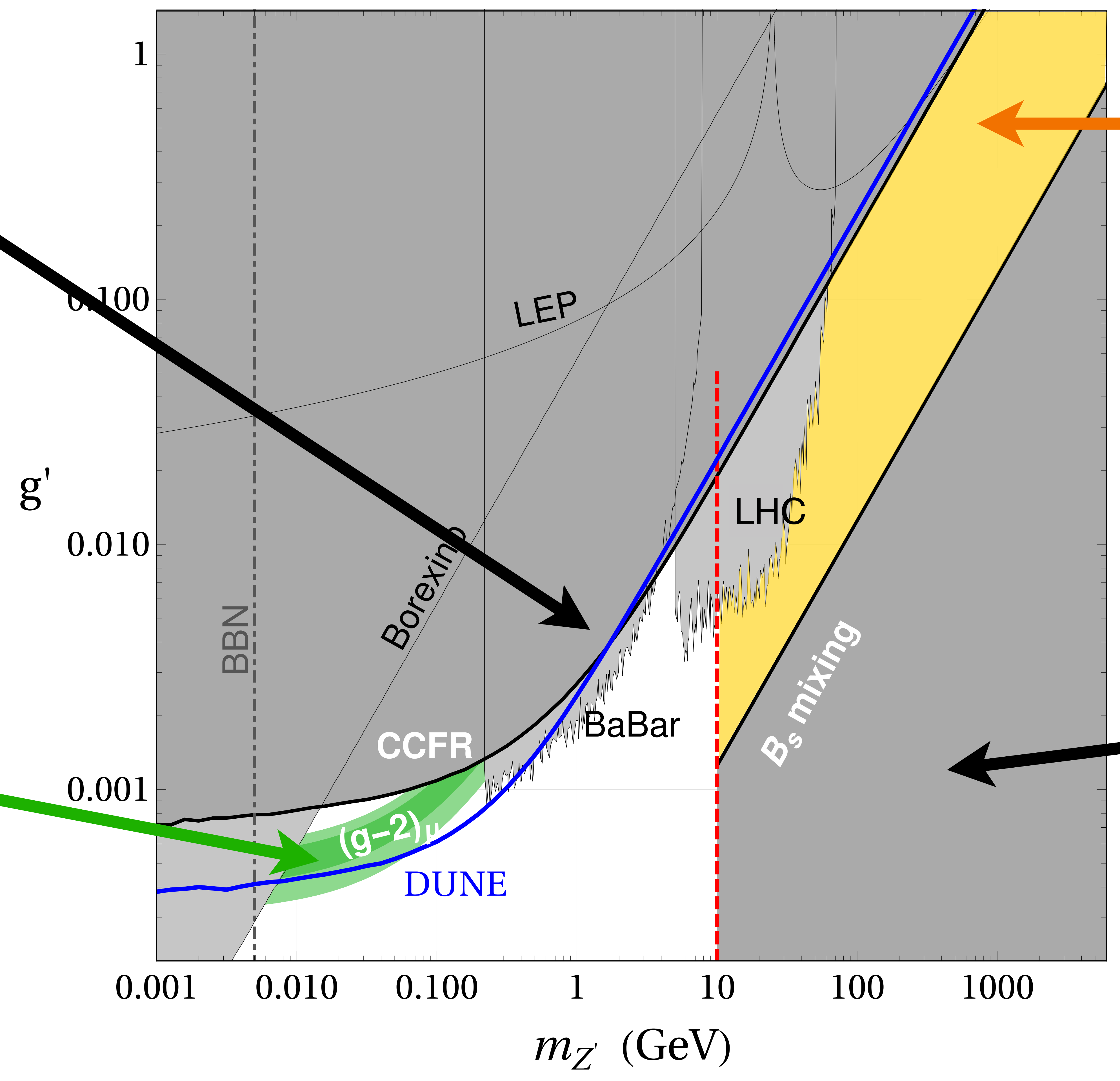
Z′ for b → s anomalies: L_μ-L_τ models

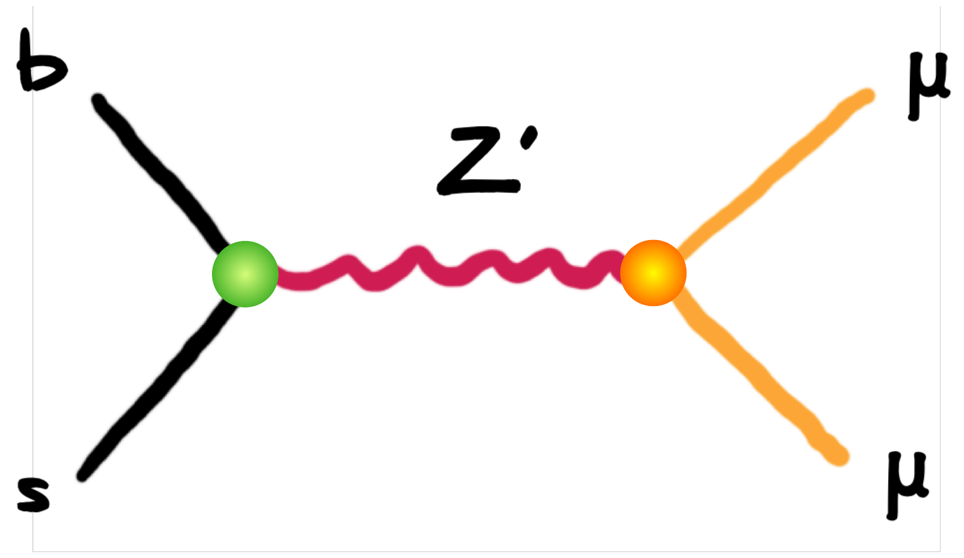


excluded by neutrino trident production

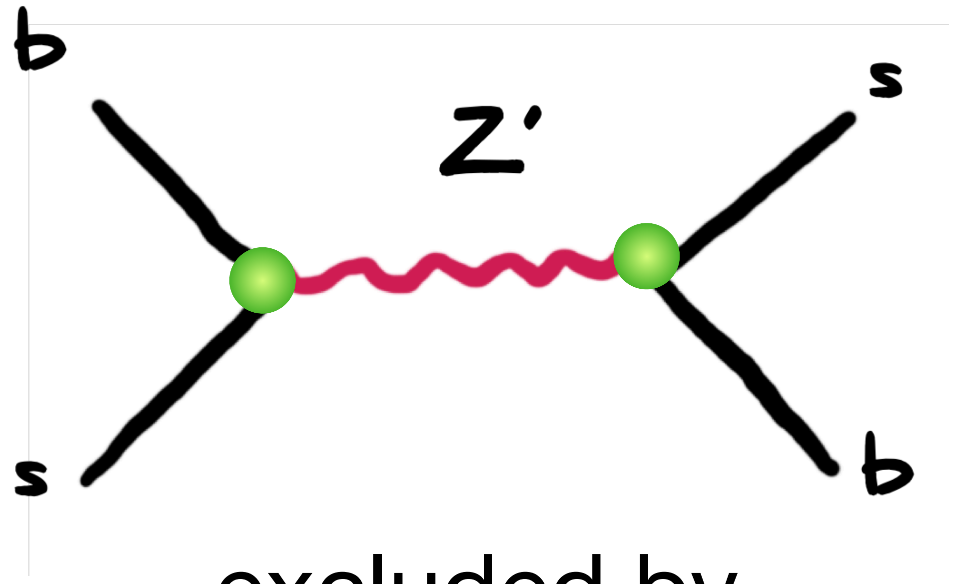


$(g\text{-}2)_\mu$ explained





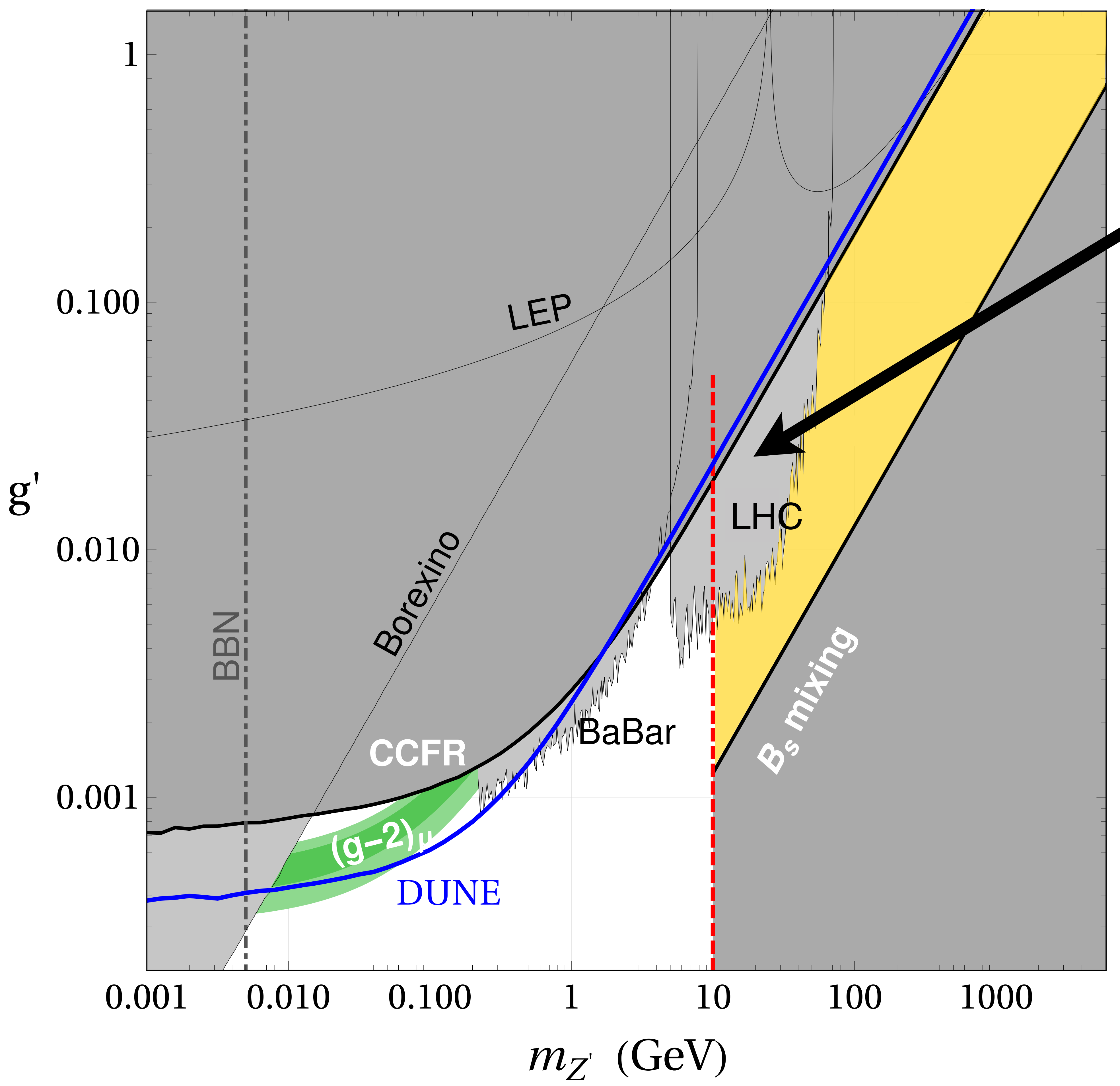
b → s anomalies explained

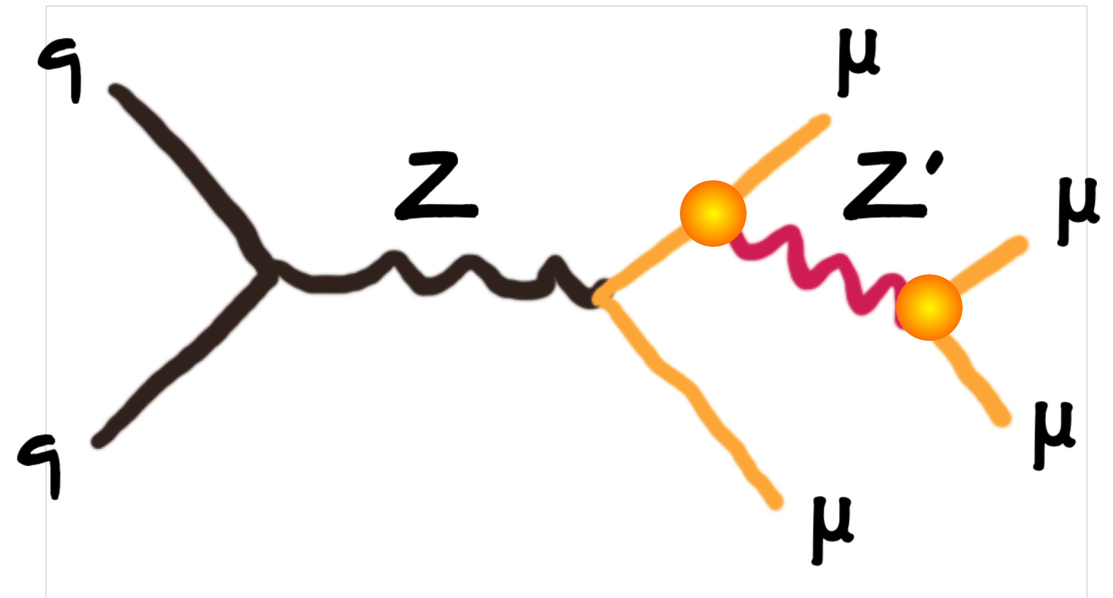


excluded by B_s mixing

[see for instance Altmannshofer et al., 1403.1269, 1508.07009 & 1902.06765]

Z′ for b → s anomalies: L_μ-L_τ models



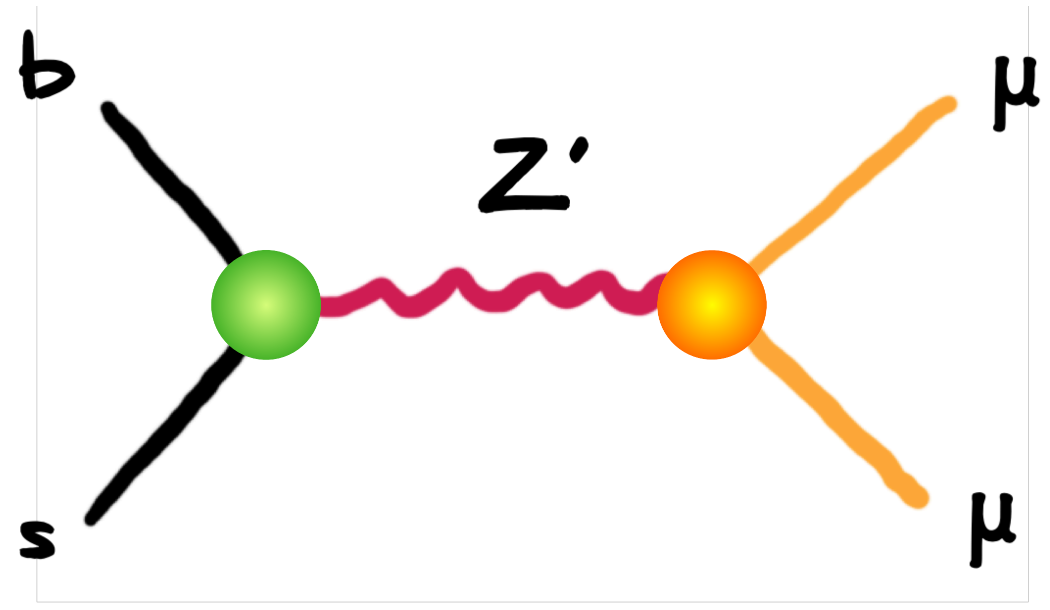


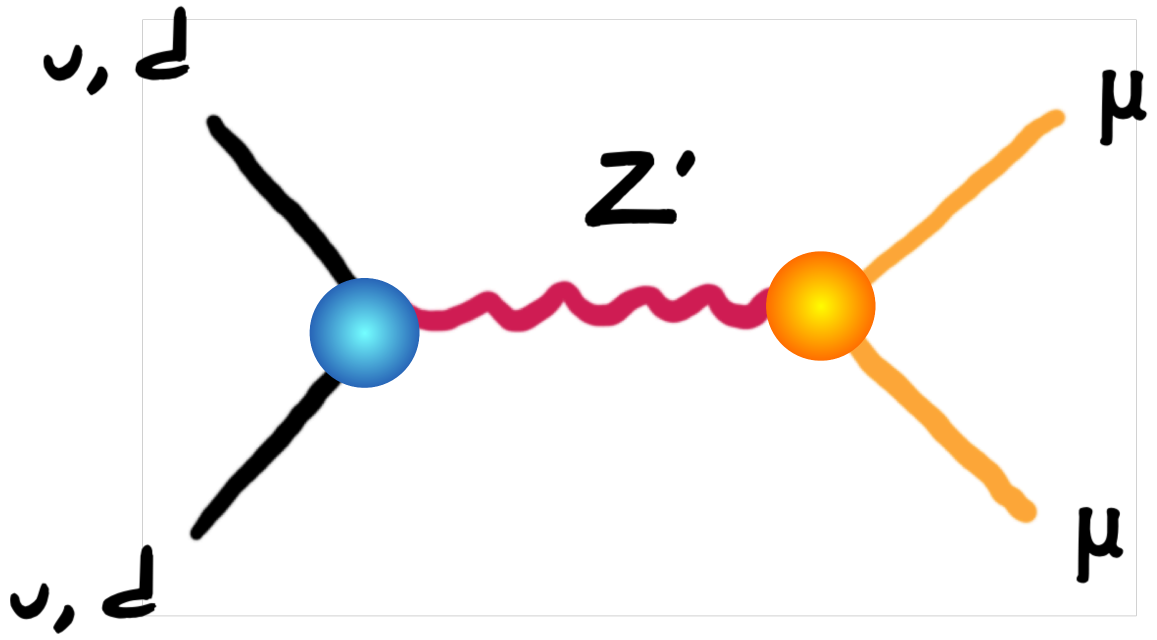
excluded by LHC searches for pp → 4μ

[CMS, 1808.03684]

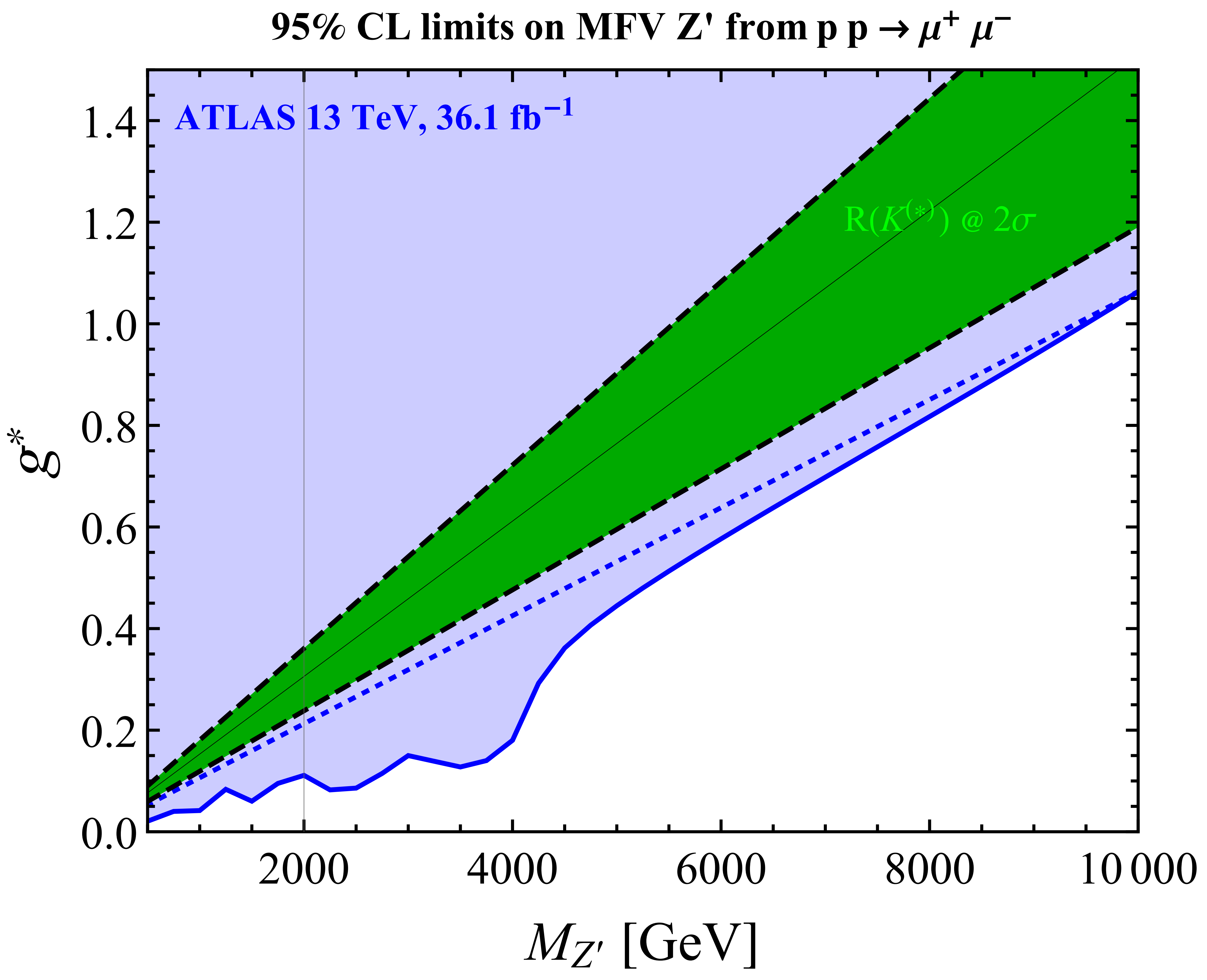
[see for instance Altmannshofer et al., 1403.1269, 1508.07009 & 1902.06765]

Dilepton searches in L_μ-L_τ models





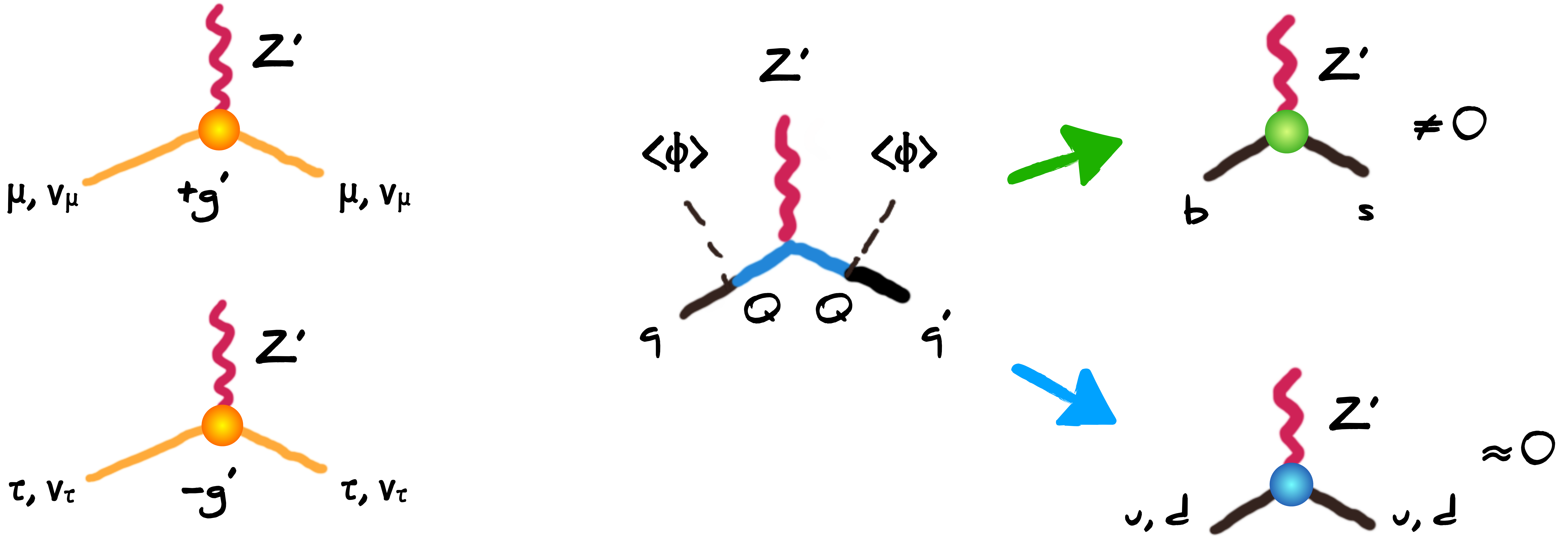
$$= |V_{ts}|\, g^* \simeq 0.04\, g^* \qquad = g^*$$



Z′ couplings that follow minimal flavor violating (MFV) pattern excluded by dilepton searches

[Greljo & Marzocca, 1704.09015; ATLAS, 1707.02424]

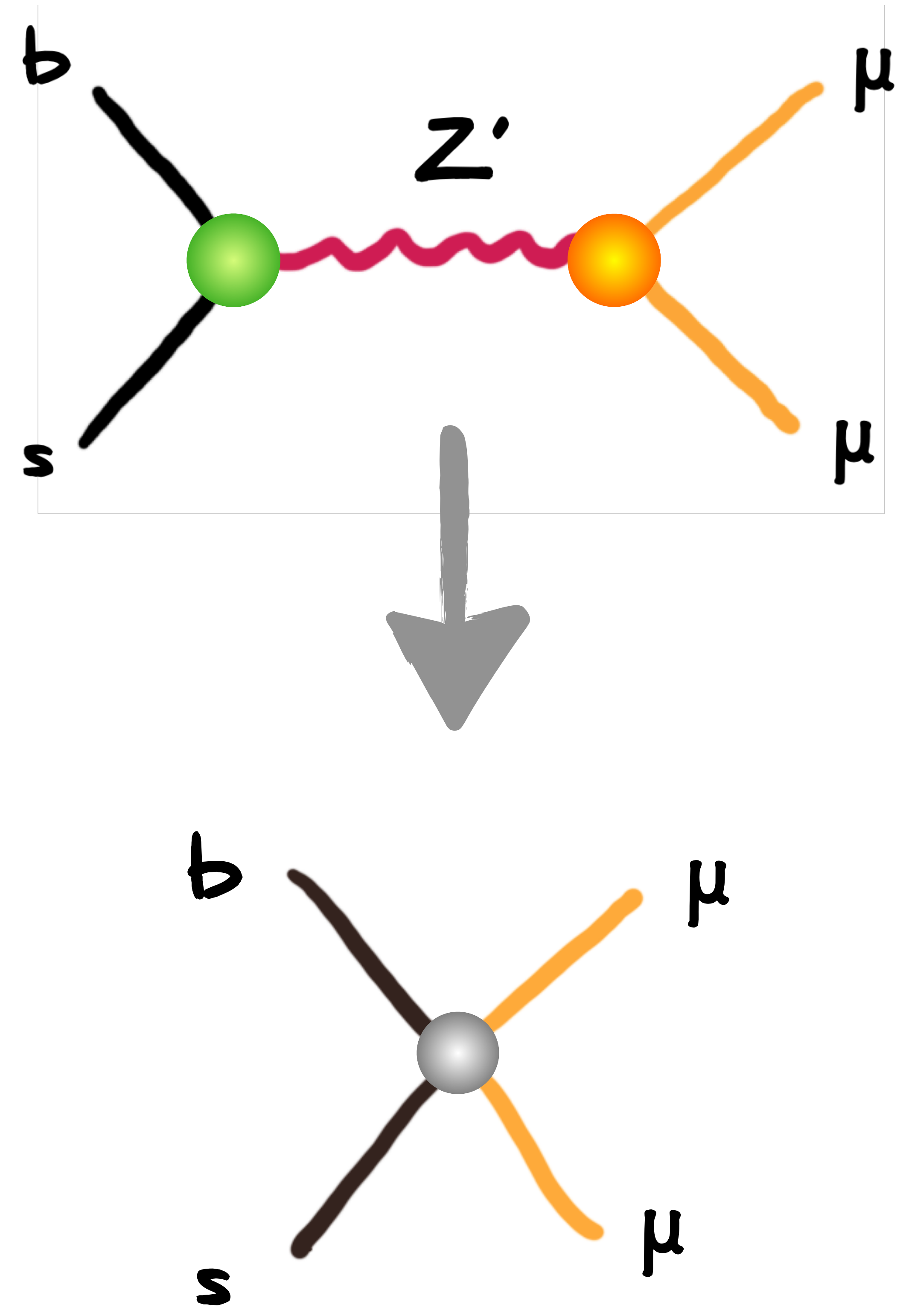
Dilepton searches in L_μ-L_τ models

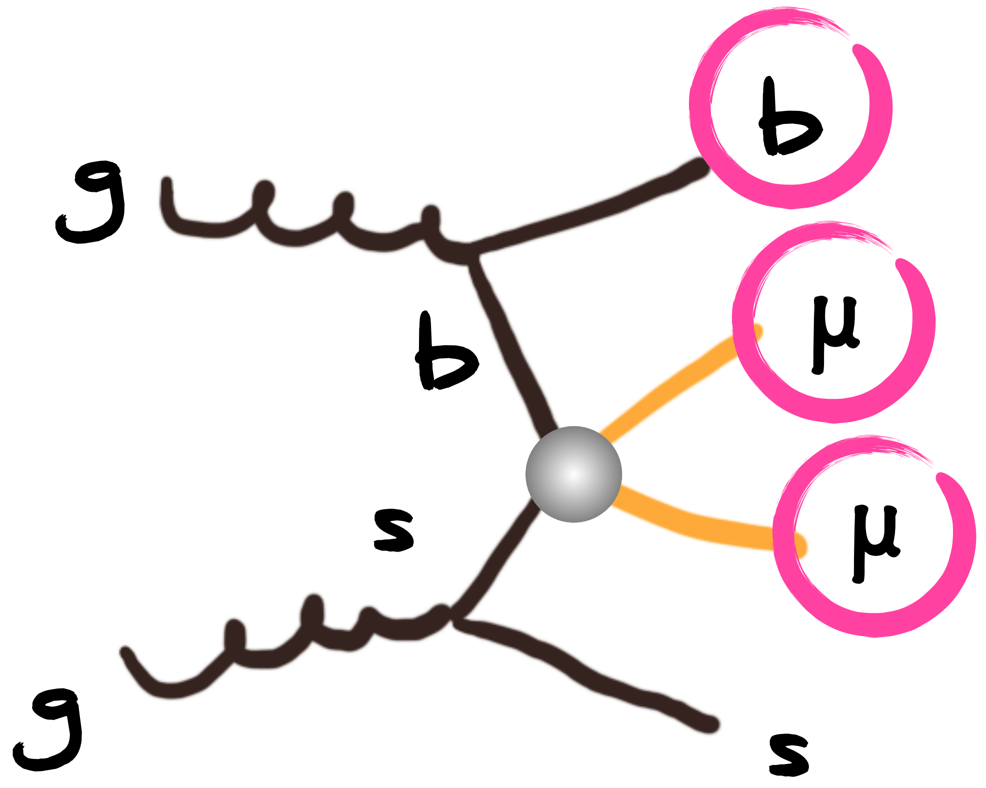


Gauging L_μ-L_τ gives gives Z′ with vectorial couplings to μ, τ & corresponding ν. Introduce vector-like quarks Q to generate bsZ′ coupling & suppress Z′ couplings to light quarks

[see for instance Altmannshofer et al., 1403.1269, 1508.07009 & 1902.06765]

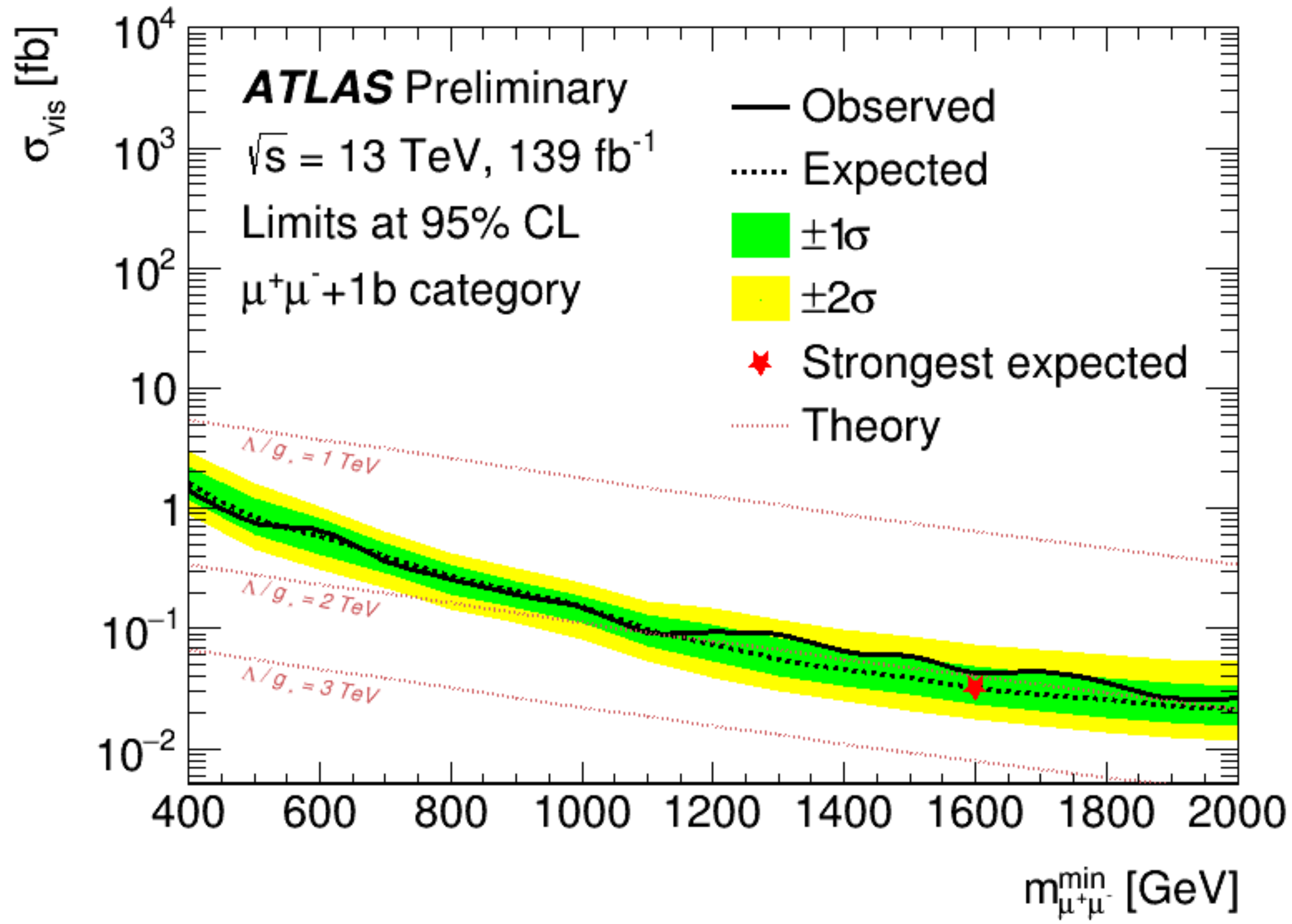
Searches for bsμμ contact interactions





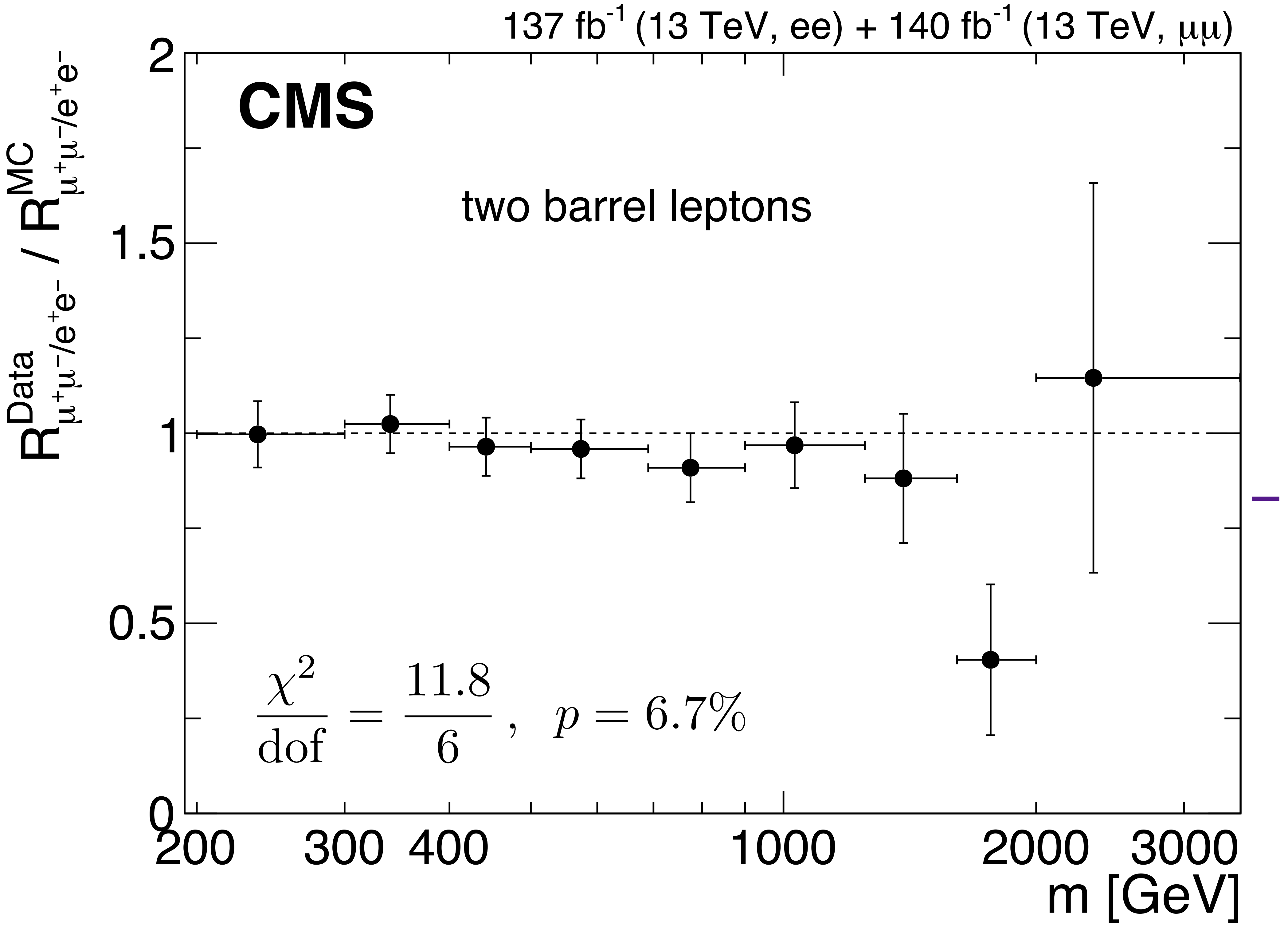
$$\bullet = \frac{g_*^2}{\Lambda^2}$$

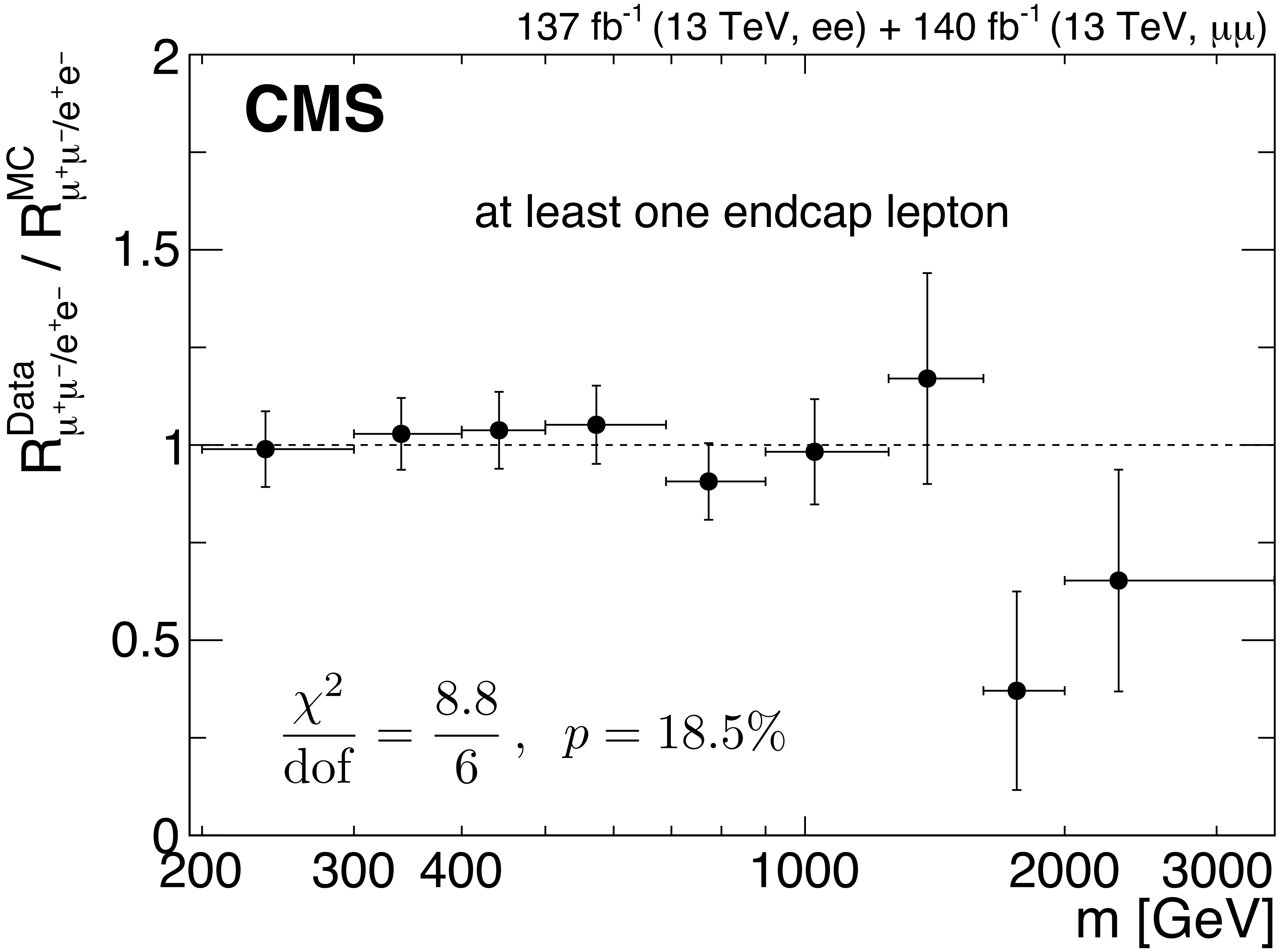
[ATLAS-CONF-2021-012]



First search for bsμμ 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

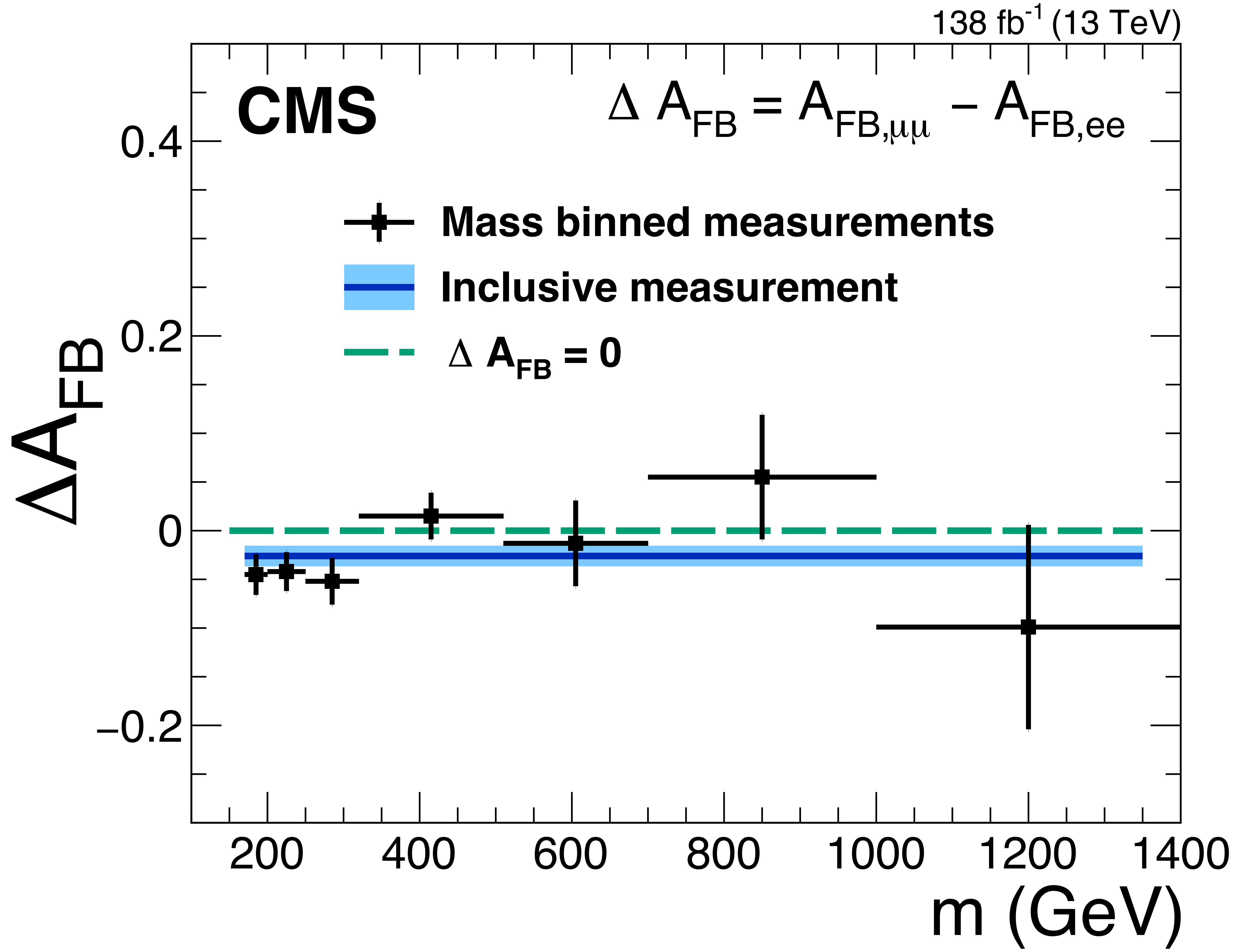




CMS observes good agreement with LFU up to masses of 1.5 TeV, but above 1.8 TeV there is slight excess in dielectron channel. Interesting but still inconclusive IMHO

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

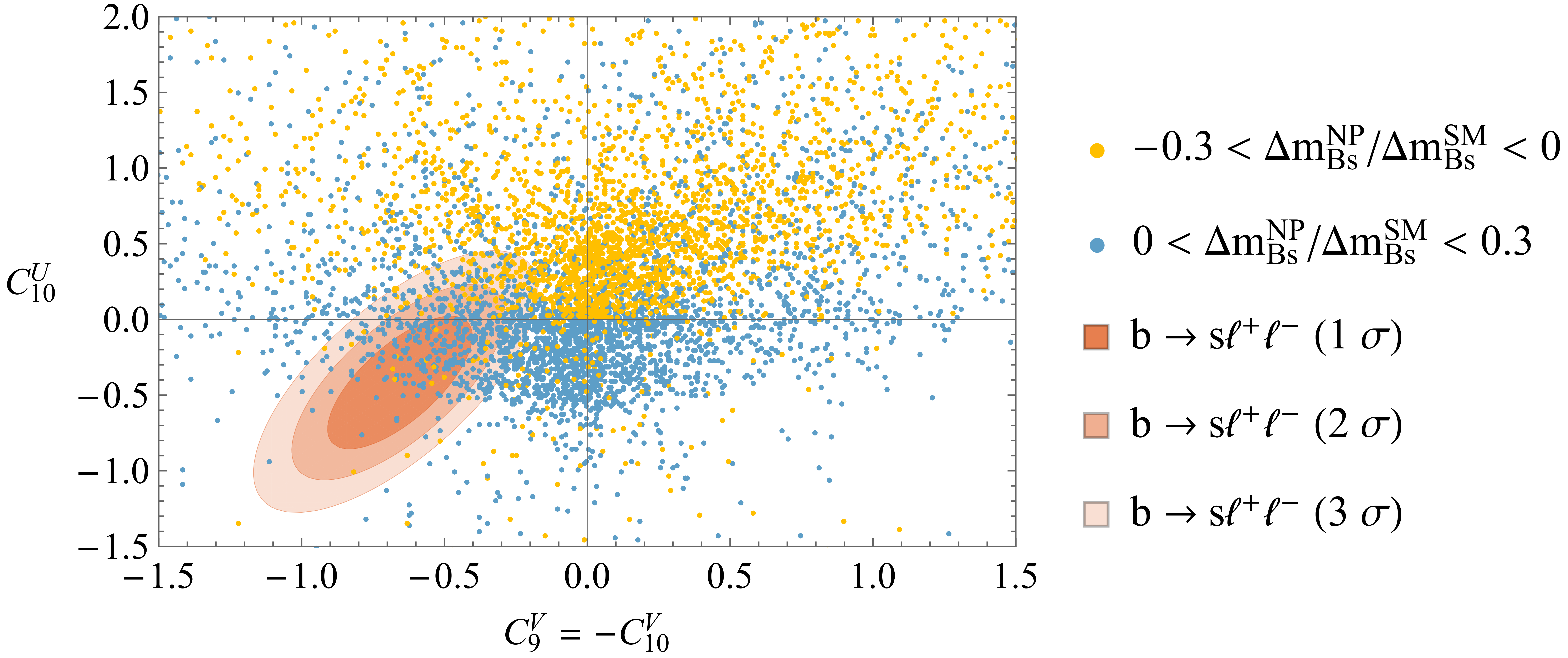
Testing LFU with dilepton events @ LHC



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]

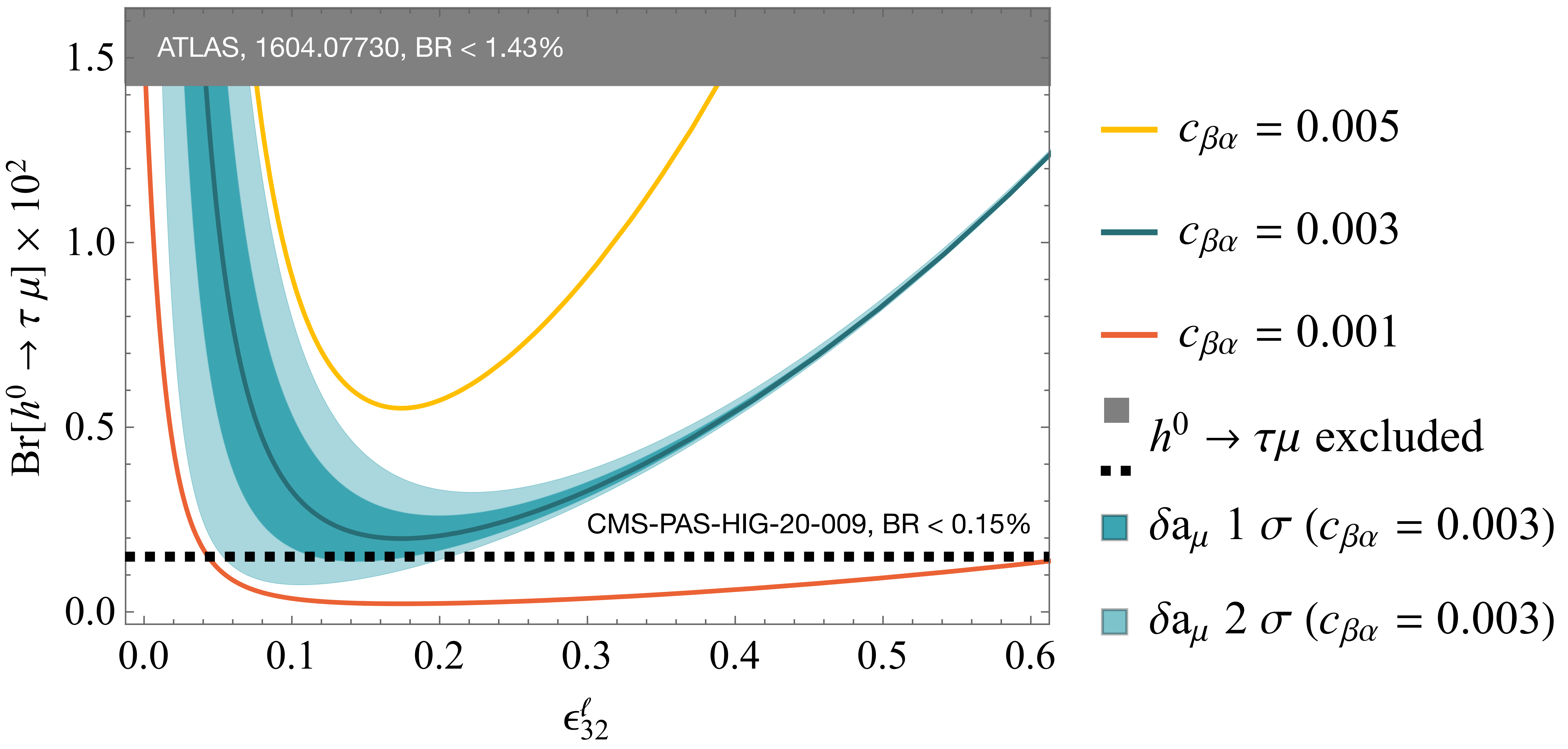
Flavorful 2HDM with right-handed neutrinos



Box diagrams with a charged Higgs boson & a right-handed neutrino are able to generate LFU violating effects needed to explain b → s anomalies

[Crivellin, Müller & Wiegand, 1903.10440]

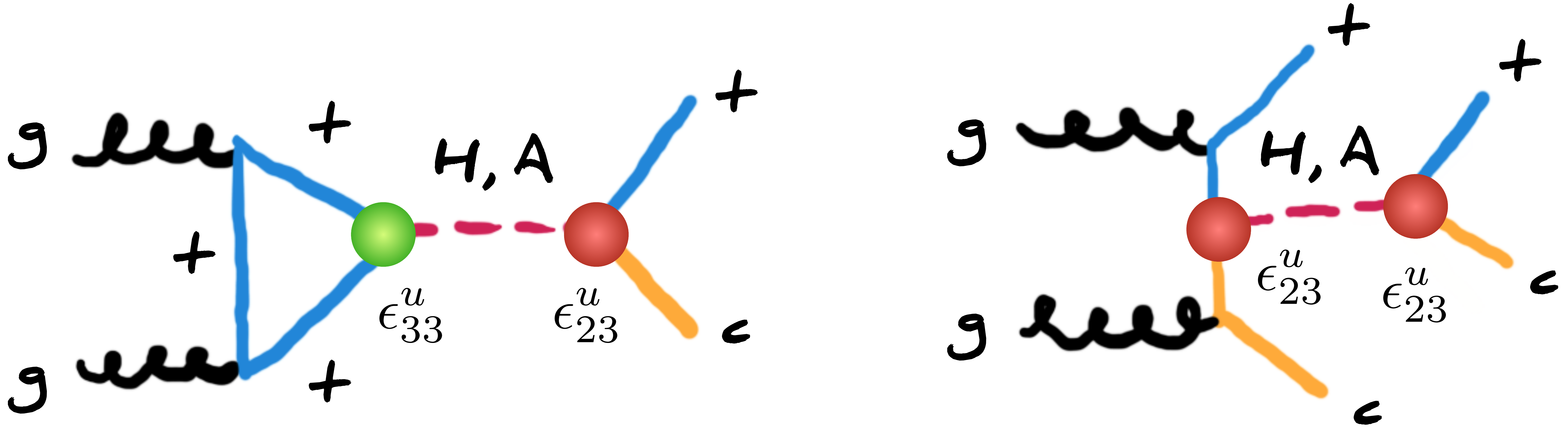
Flavorful 2HDM with right-handed neutrinos



In 2016 explanation of muon anomalous magnetic moment possible without violating h → τμ bound if Higgs sector close to alignment. Now possibility even stronger constrained

[Crivellin, Müller & Wiegand, 1903.10440]

Flavorful 2HDM with right-handed neutrinos



LHC phenomenology of model not worked out, but exotic decays such as H, A → tc (τμ) & $H^{\pm}$ → cb generically expected & wait for interest of community. Challenging searches but may reveal first direct evidence of beyond SM physics & unravel origin of flavor

[see Gori, Grojean, Juste & Paul, 1710.03752 for a related discussion]

Conclusions & outlook

- Beyond SM models that explain all B-physics 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 @ LHC. If $b \to c$ anomalies persist, IMHO likely that LHC sees something
- BSM models that explain only $b \to s$ anomalies can be easily hidden from leaving imprint on high-p_T LHC physics. Still, searches for $bs\mu\mu$ contact interactions, LFU violation in dilepton production, etc. may shed light on origin of anomalies
- Signals in Higgs & diboson physics connected to B-physics anomalies possible (e.g. $h \to \tau\mu$ & exotics decays of heavy Higgses) but model dependent

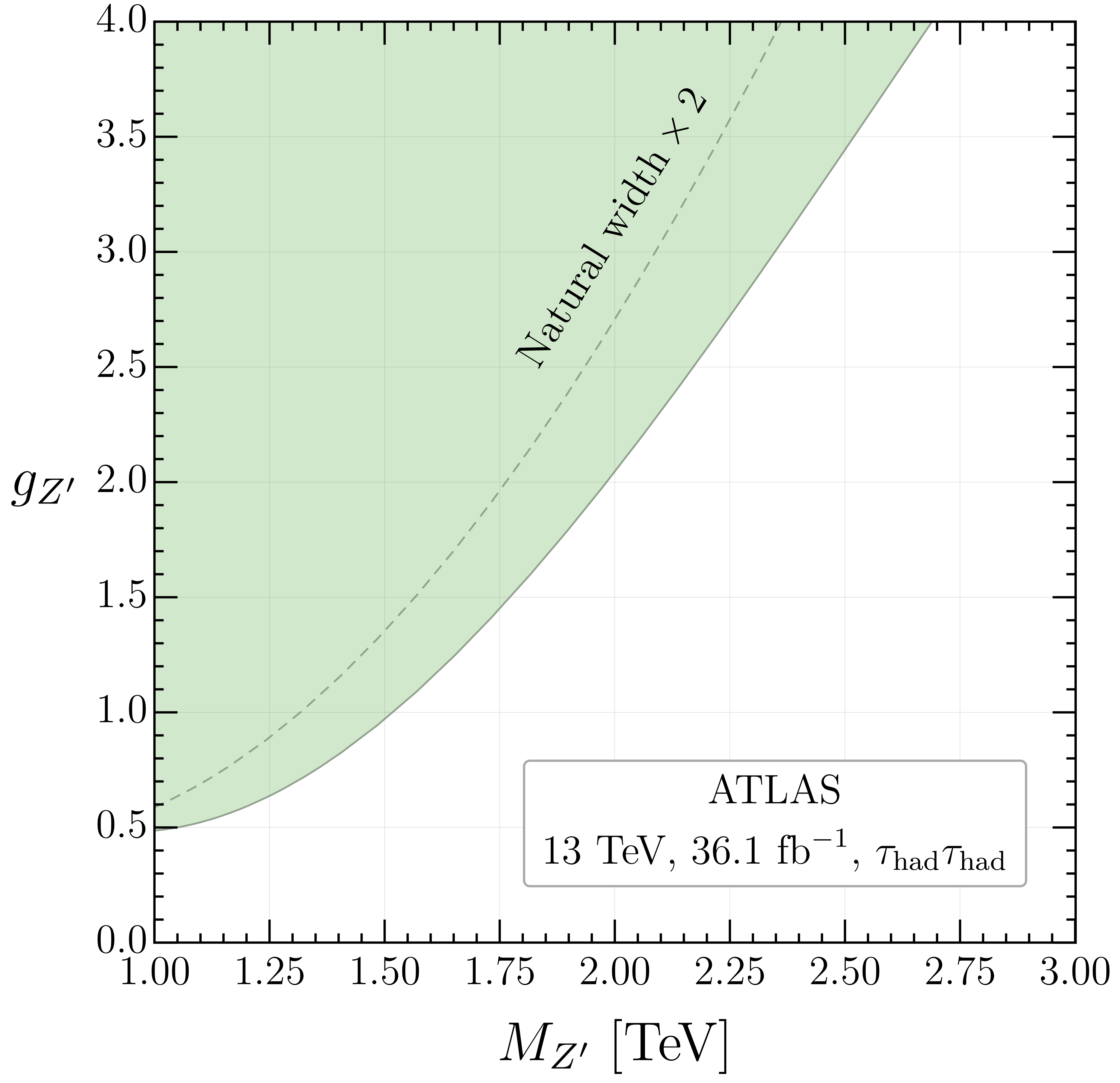
Backup

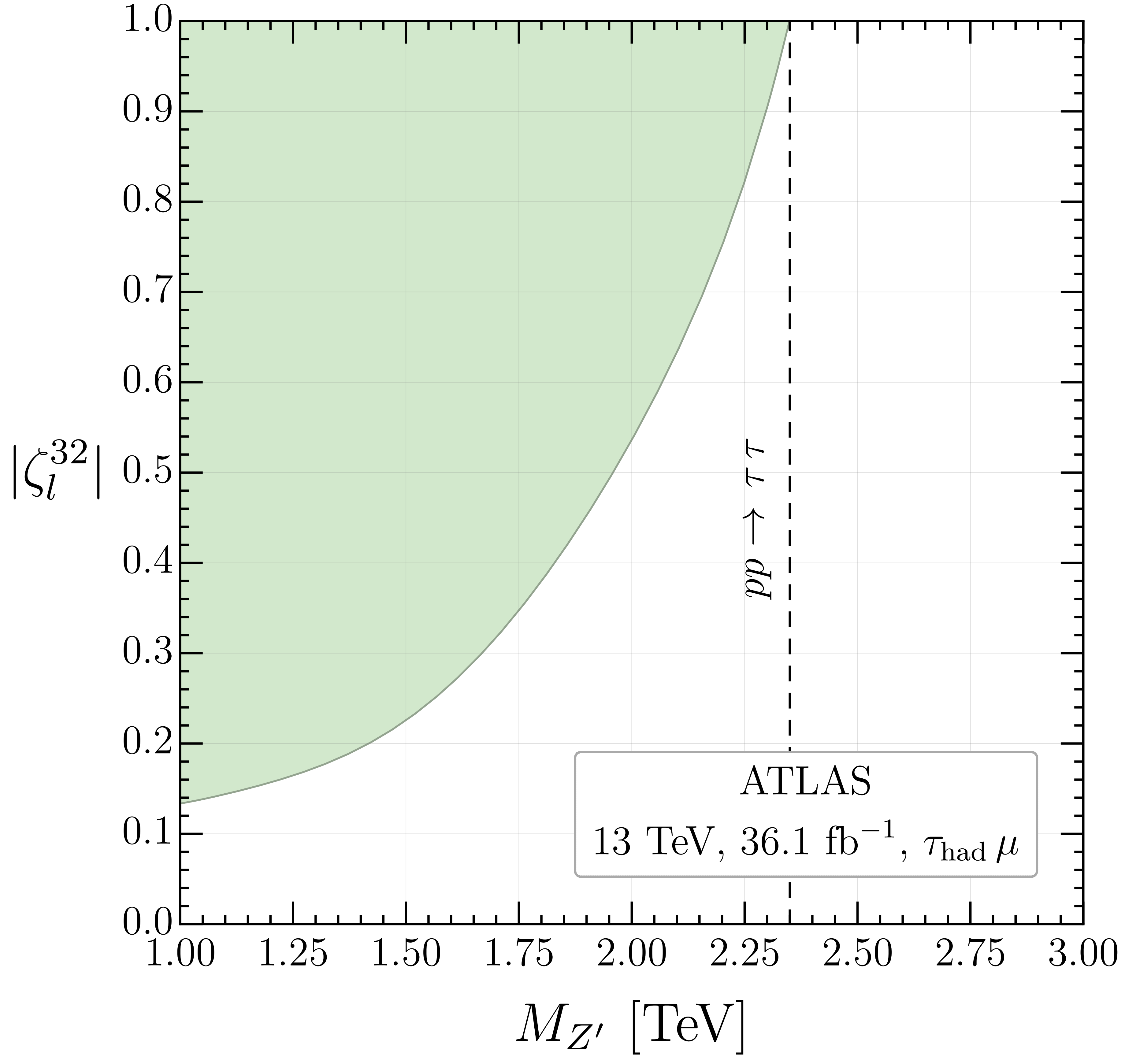
M_W measurement by CDF

Distribution	*W* boson mass (MeV)	χ^2/dof
$m_T(e, \nu)$	$80{,}429.1 \pm 10.3_{stat} \pm 8.5_{syst}$	39/48
$p_T^{\ell}(e)$	$80{,}411.4 \pm 10.7_{stat} \pm 11.8_{syst}$	83/62
$p_T^{\nu}(e)$	$80{,}426.3 \pm 14.5_{stat} \pm 11.7_{syst}$	69/62
$m_T(\mu, \nu)$	$80{,}446.1 \pm 9.2_{stat} \pm 7.3_{syst}$	50/48
$p_T^{\ell}(\mu)$	$80{,}428.2 \pm 9.6_{stat} \pm 10.3_{syst}$	82/62
$p_T^{\nu}(\mu)$	$80{,}428.9 \pm 13.1_{stat} \pm 10.9_{syst}$	63/62
Combination	$80{,}433.5 \pm 6.4_{stat} \pm 6.9_{syst}$	7.4/5

[CDF, Science 376 (2022) 6589]

Z′ bounds in singlet vector LQ model

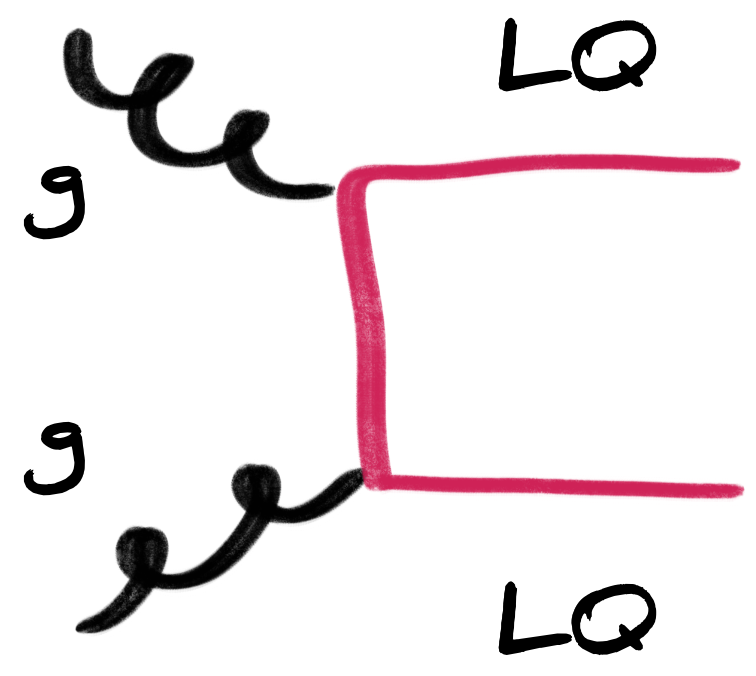


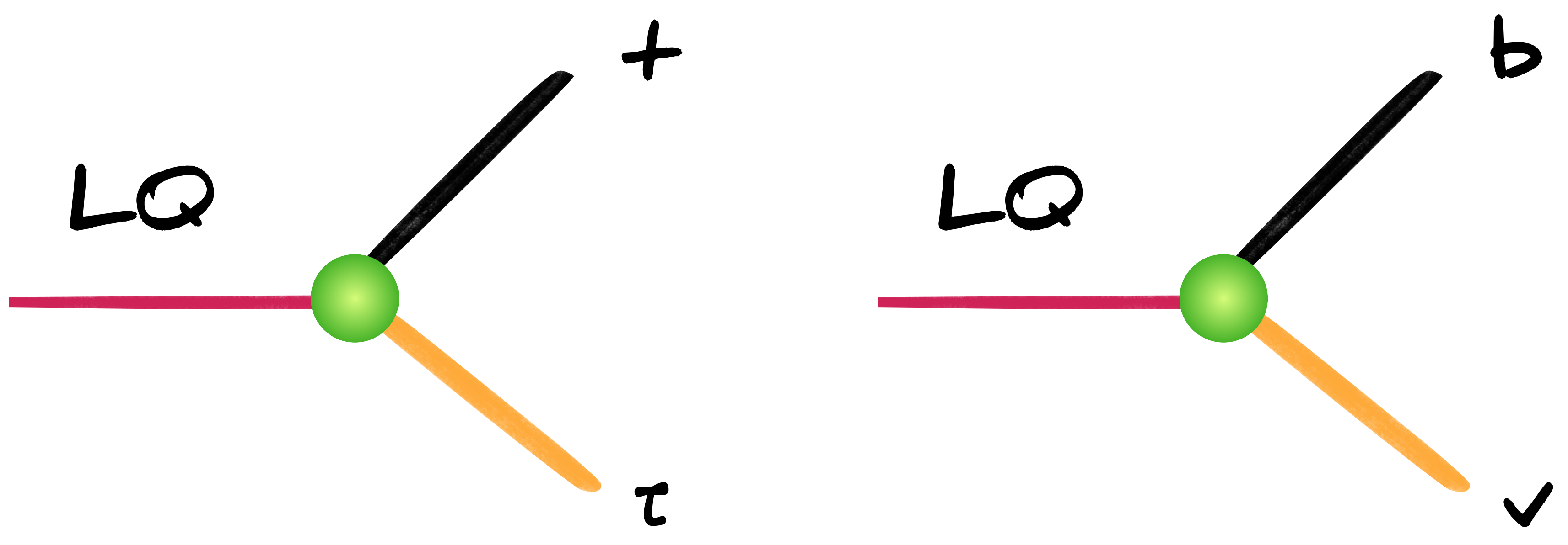


Z′ searches in general not competitive with limits obtained from LQ or G′ searches

[Baker et al., 1901.10480; ATLAS, 1709.07242; CMS, 1807.11421]

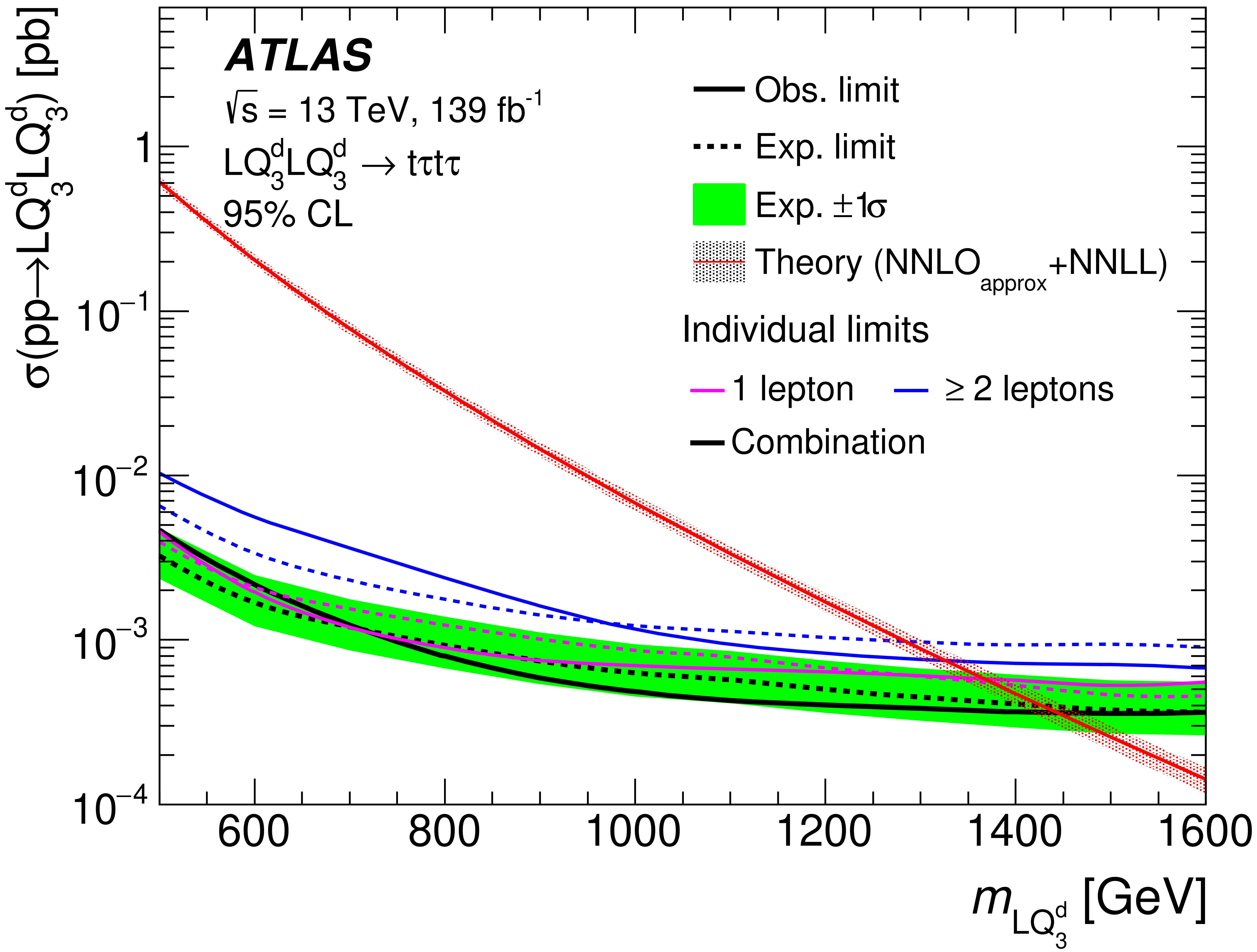
LQ search triggered by B anomalies



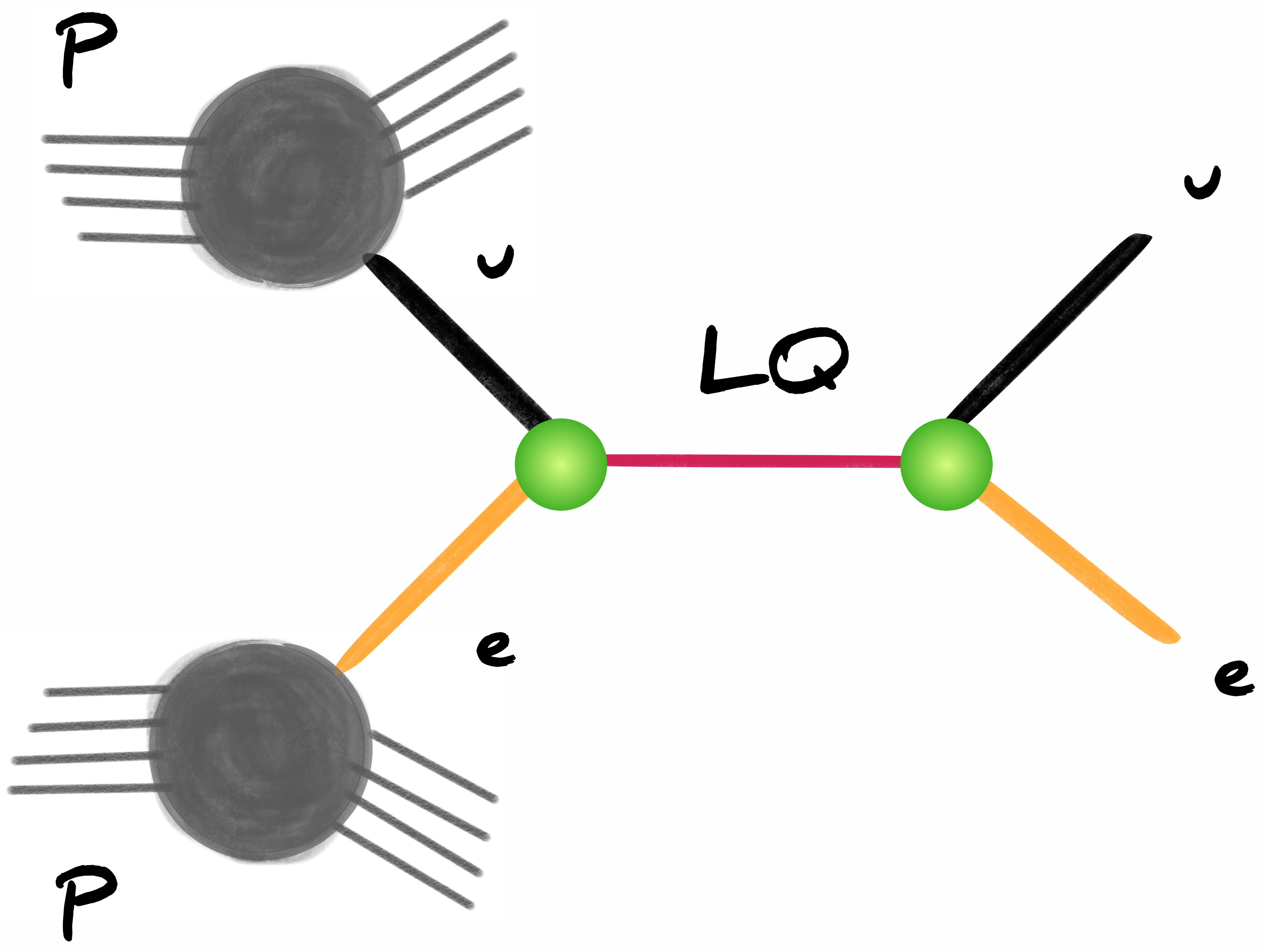


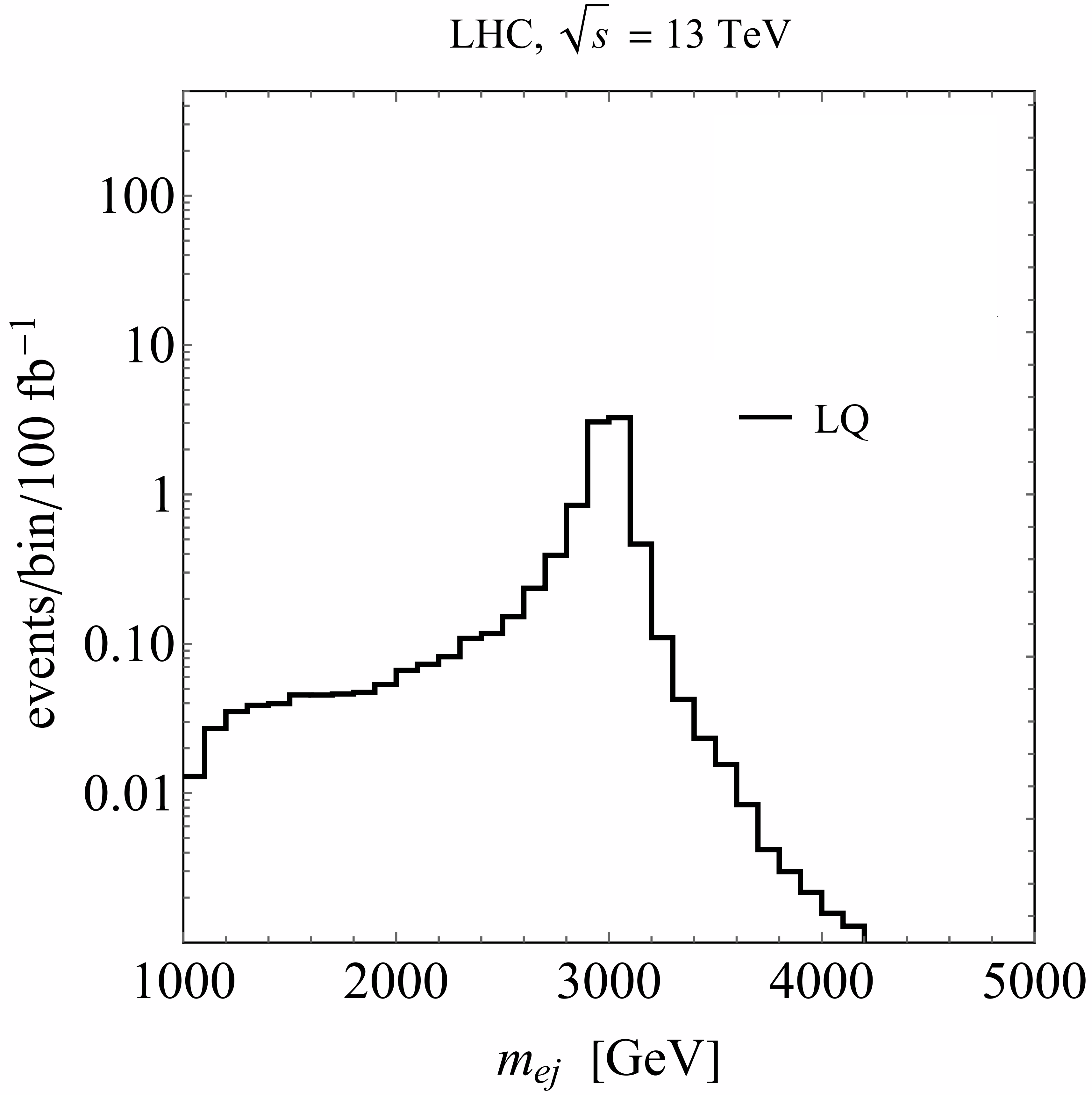
[Bauer & Neubert, 1511.01900]

[ATLAS, 2101.11582]



Resonant LQ production @ the LHC

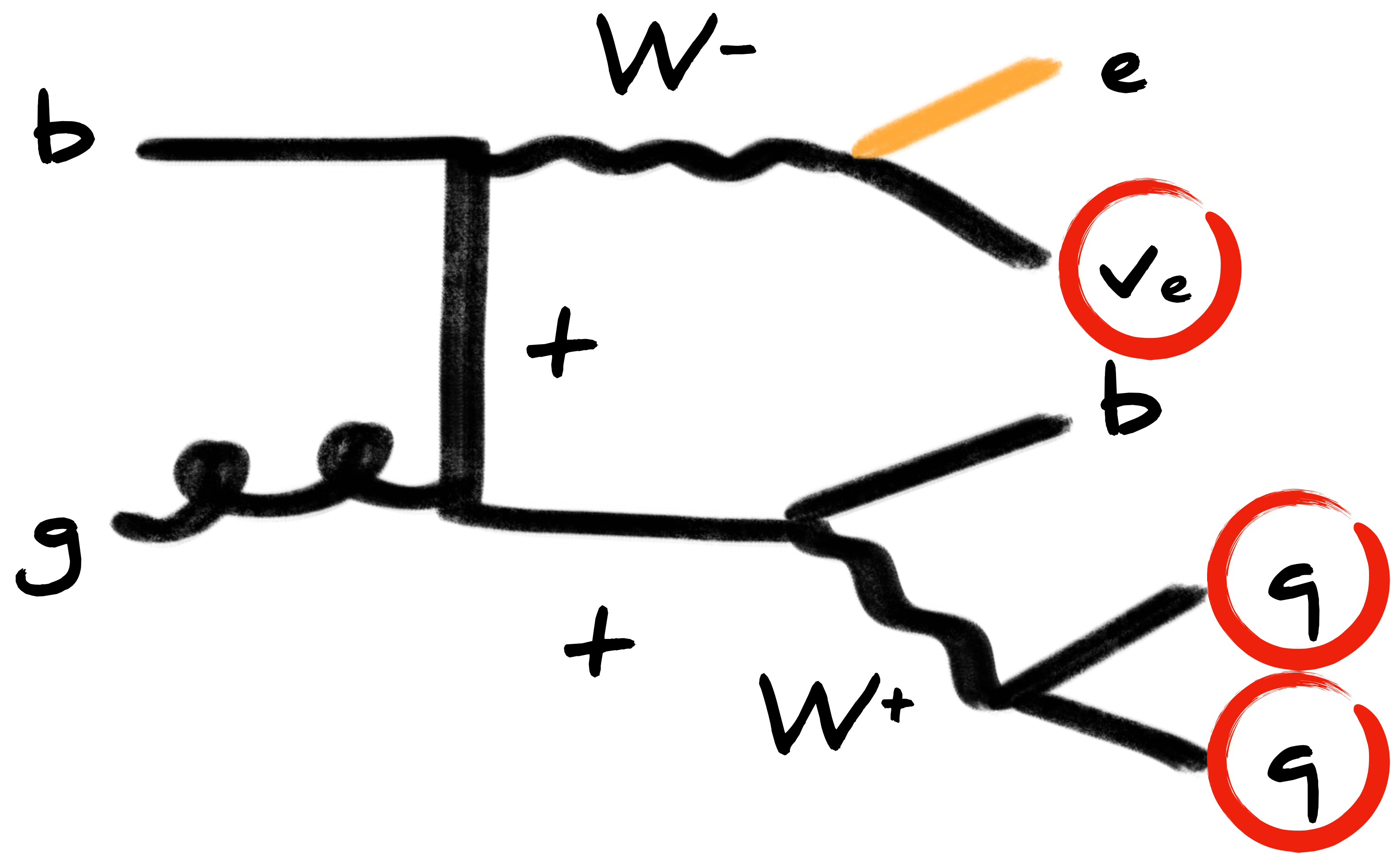


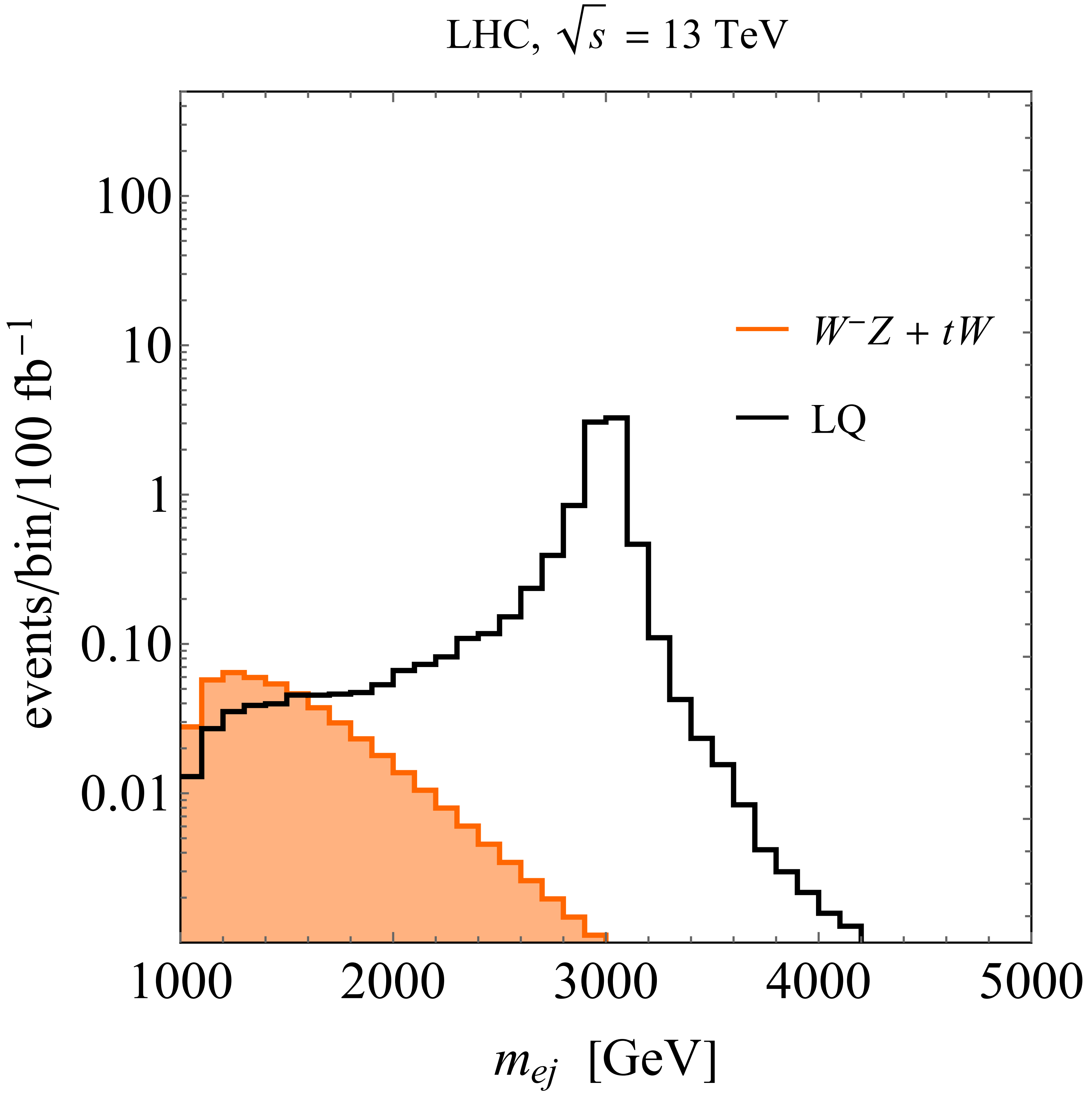


At 13 TeV LHC, 9 events per 100 fb^{-1} for minimal scalar LQ of M = 3 TeV & λ_{eu} = 1

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

Resonant LQ production @ the LHC

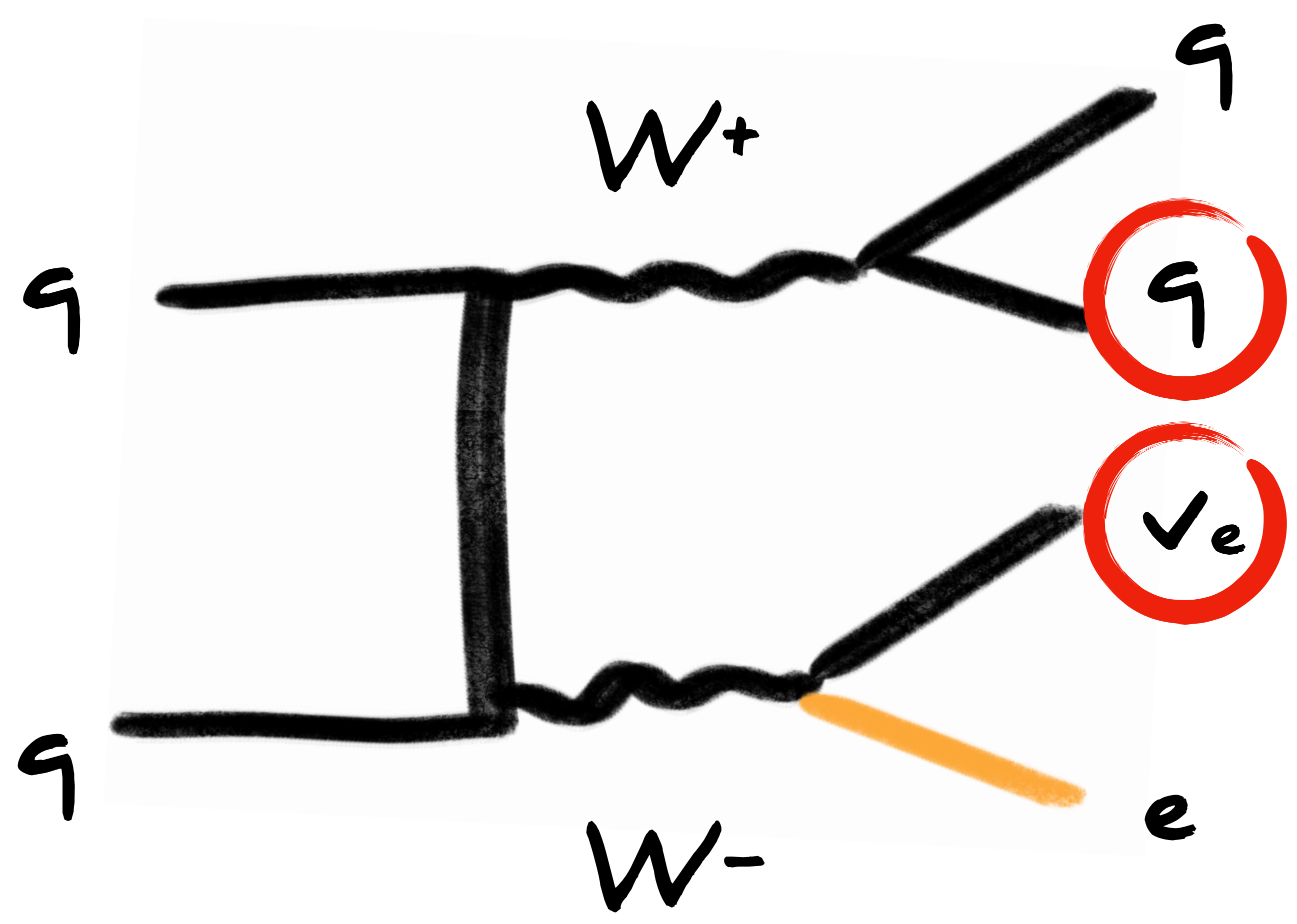




Suppressed by $E_{T,miss}$ requirement & jet veto

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

Resonant LQ production @ the LHC



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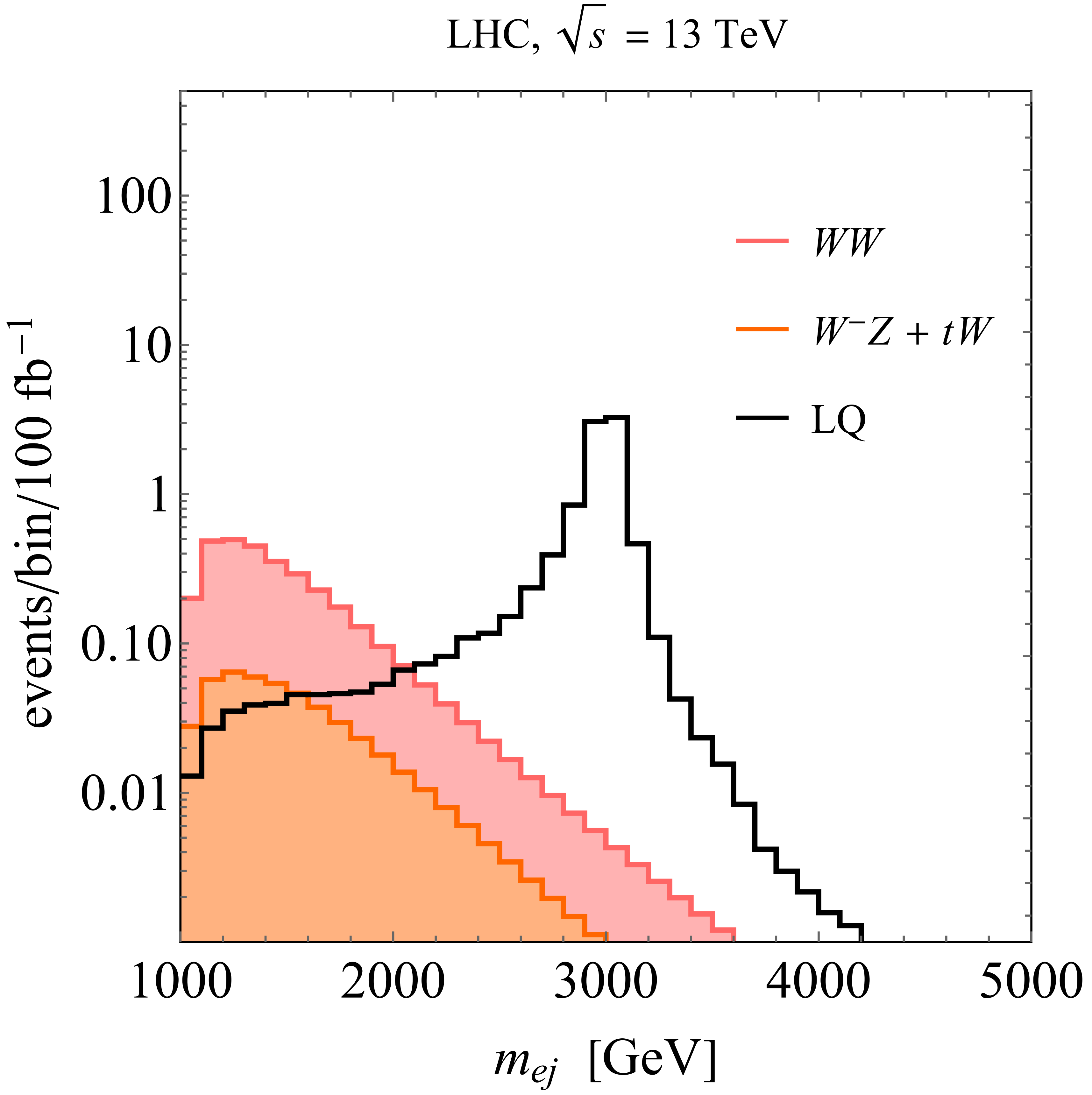
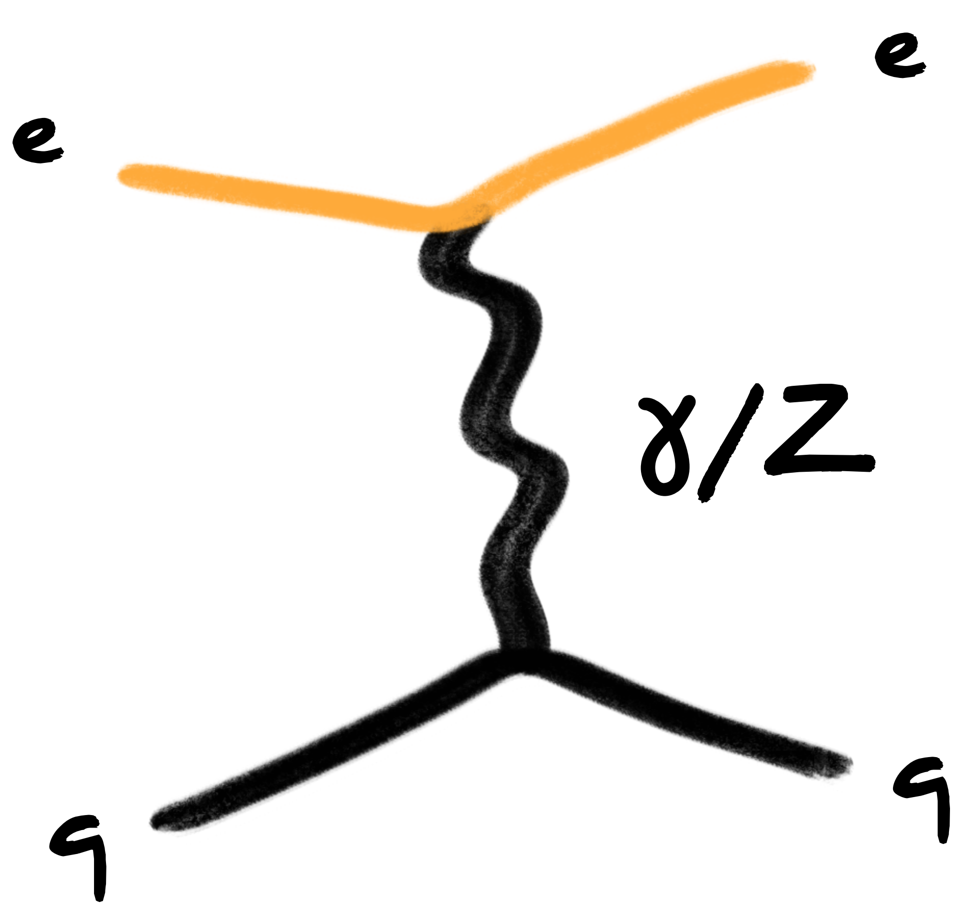
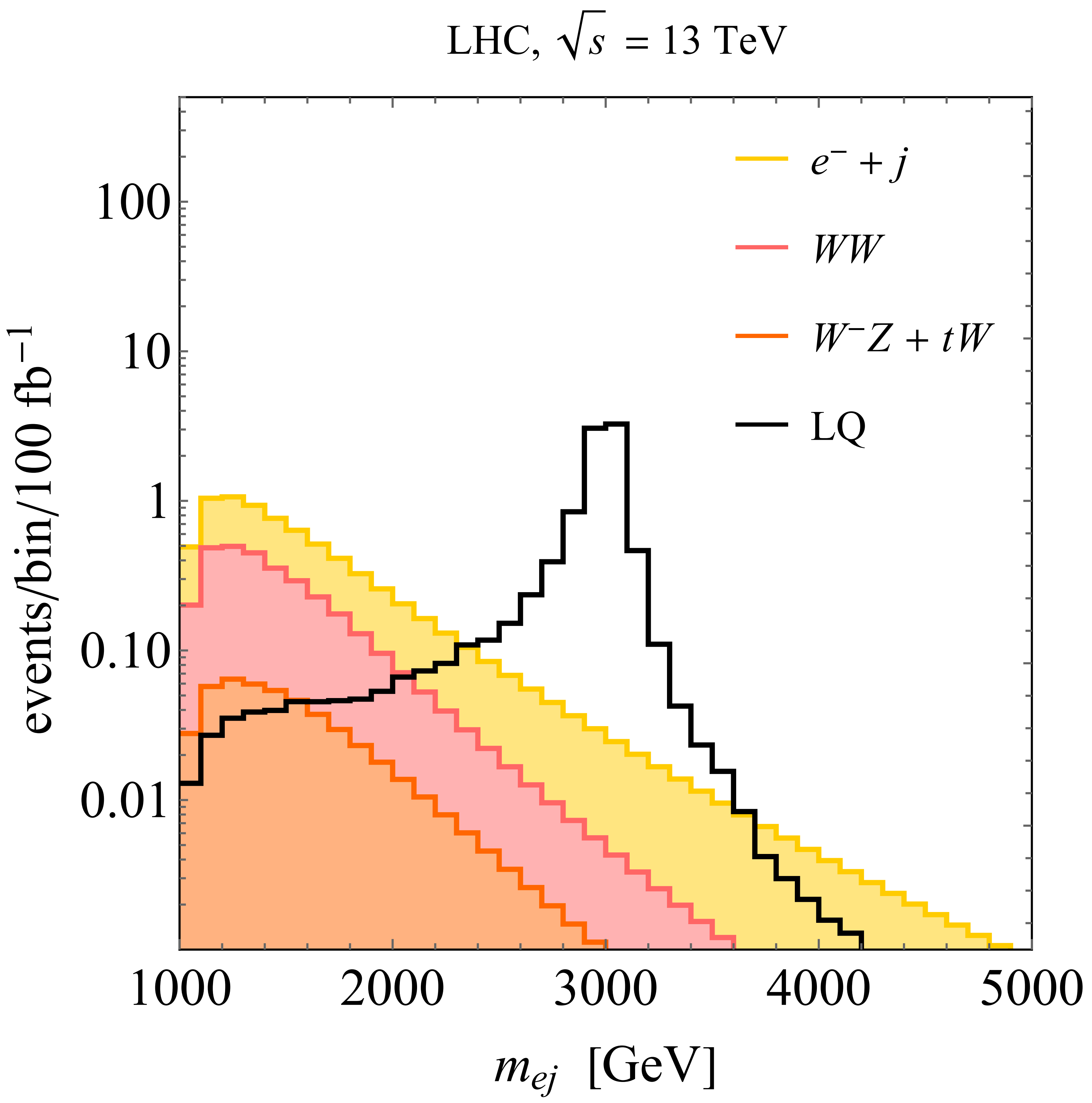


[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

Resonant LQ production @ the LHC

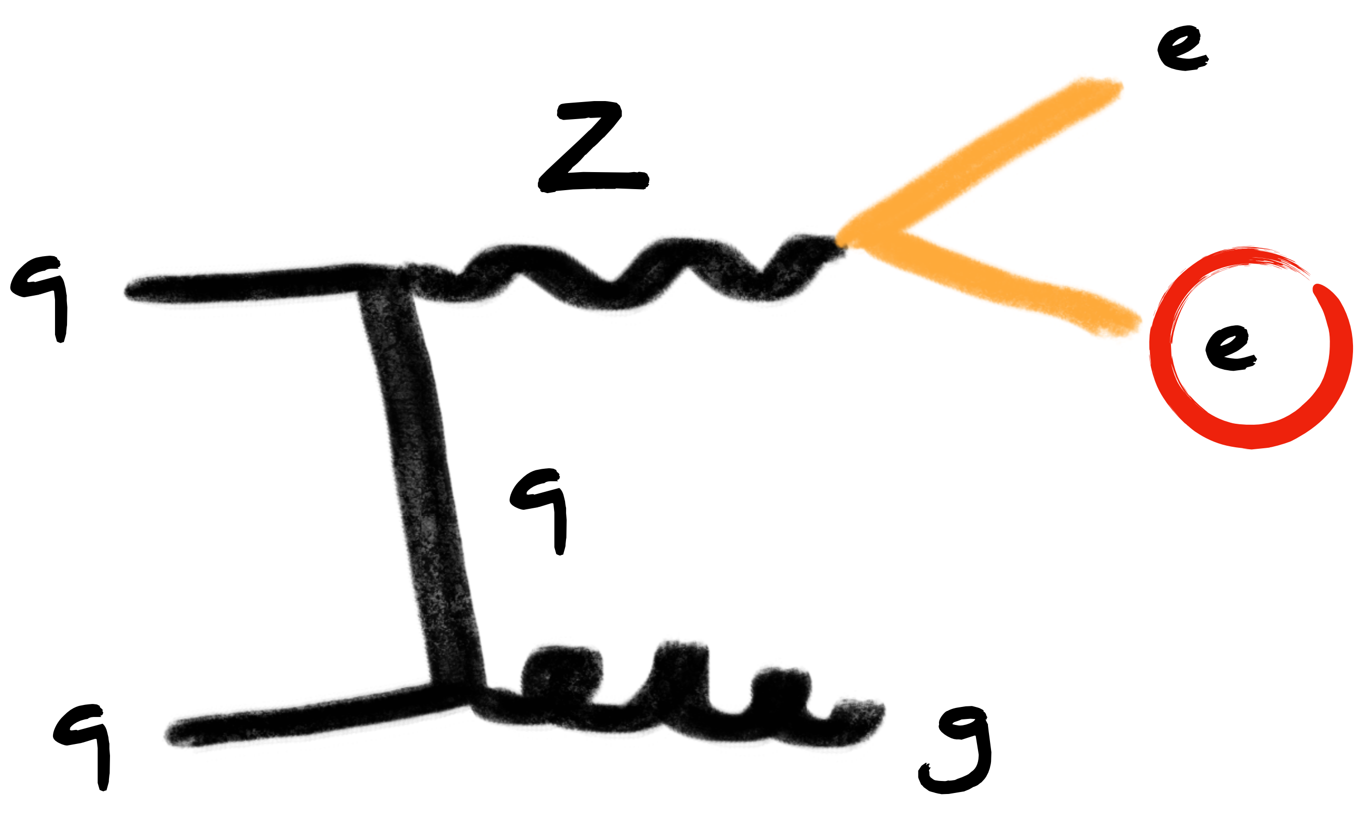




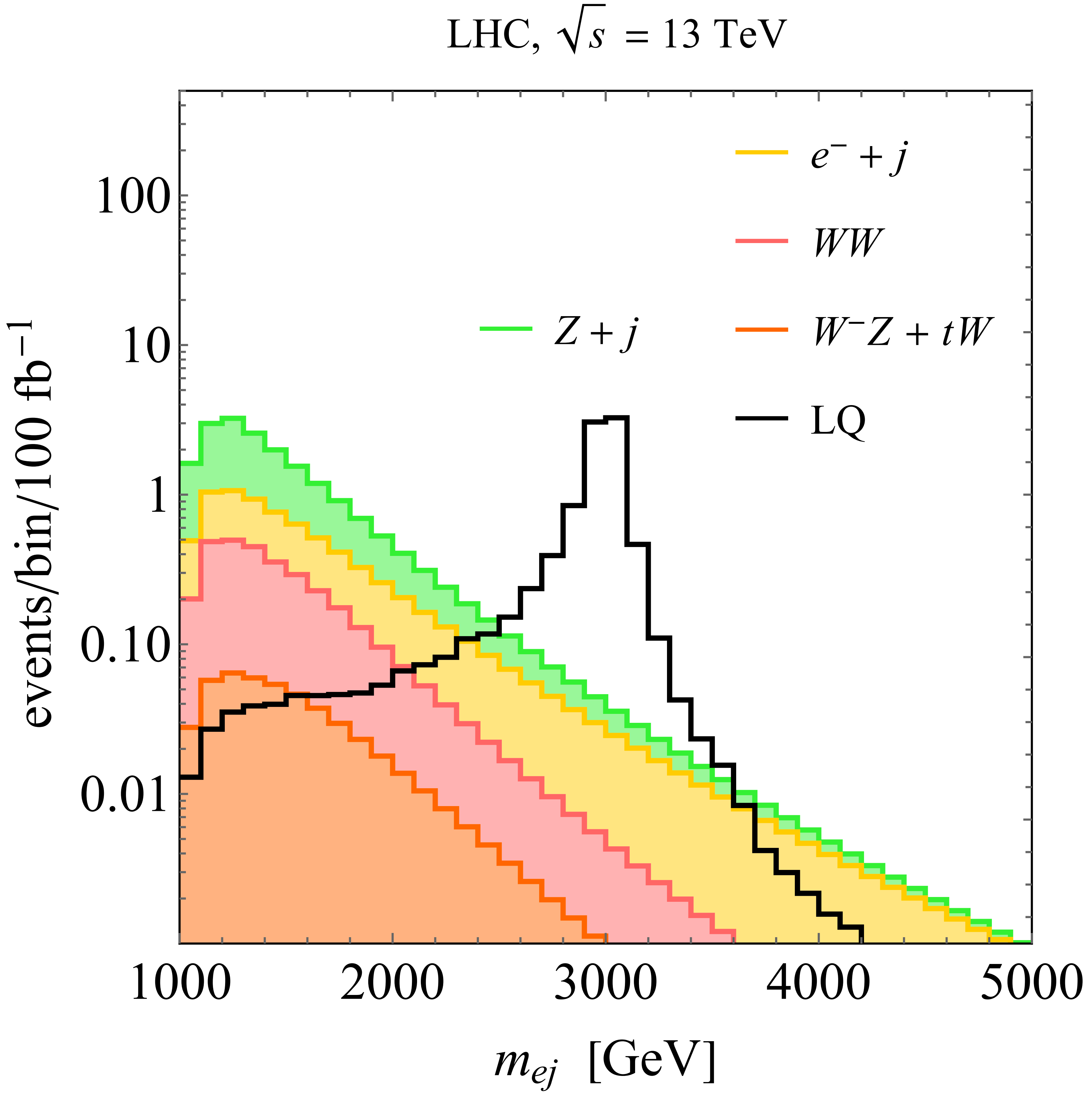
Irreducible background particularly relevant
@ high invariant lepton-jet mass

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

Resonant LQ production @ the LHC

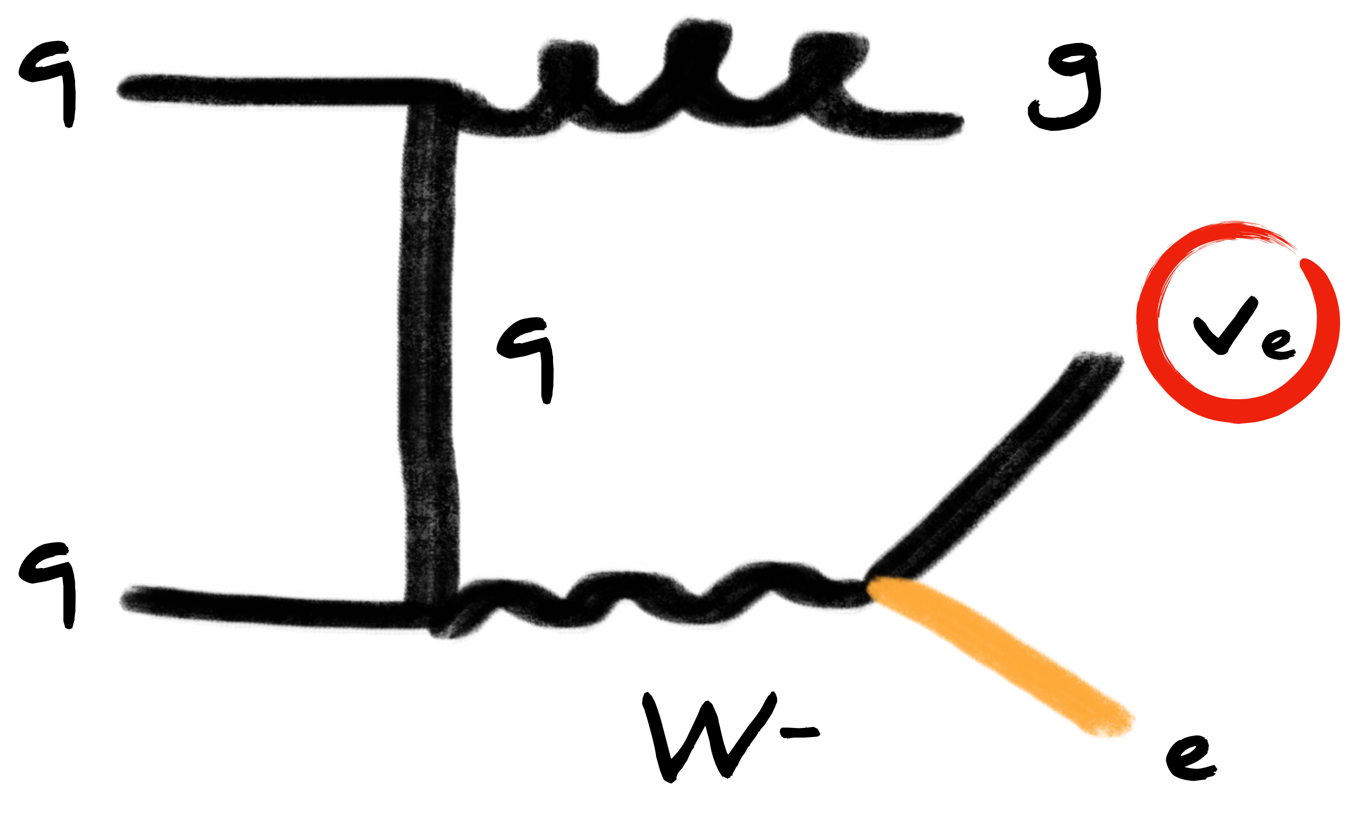


Suppressed by lepton veto

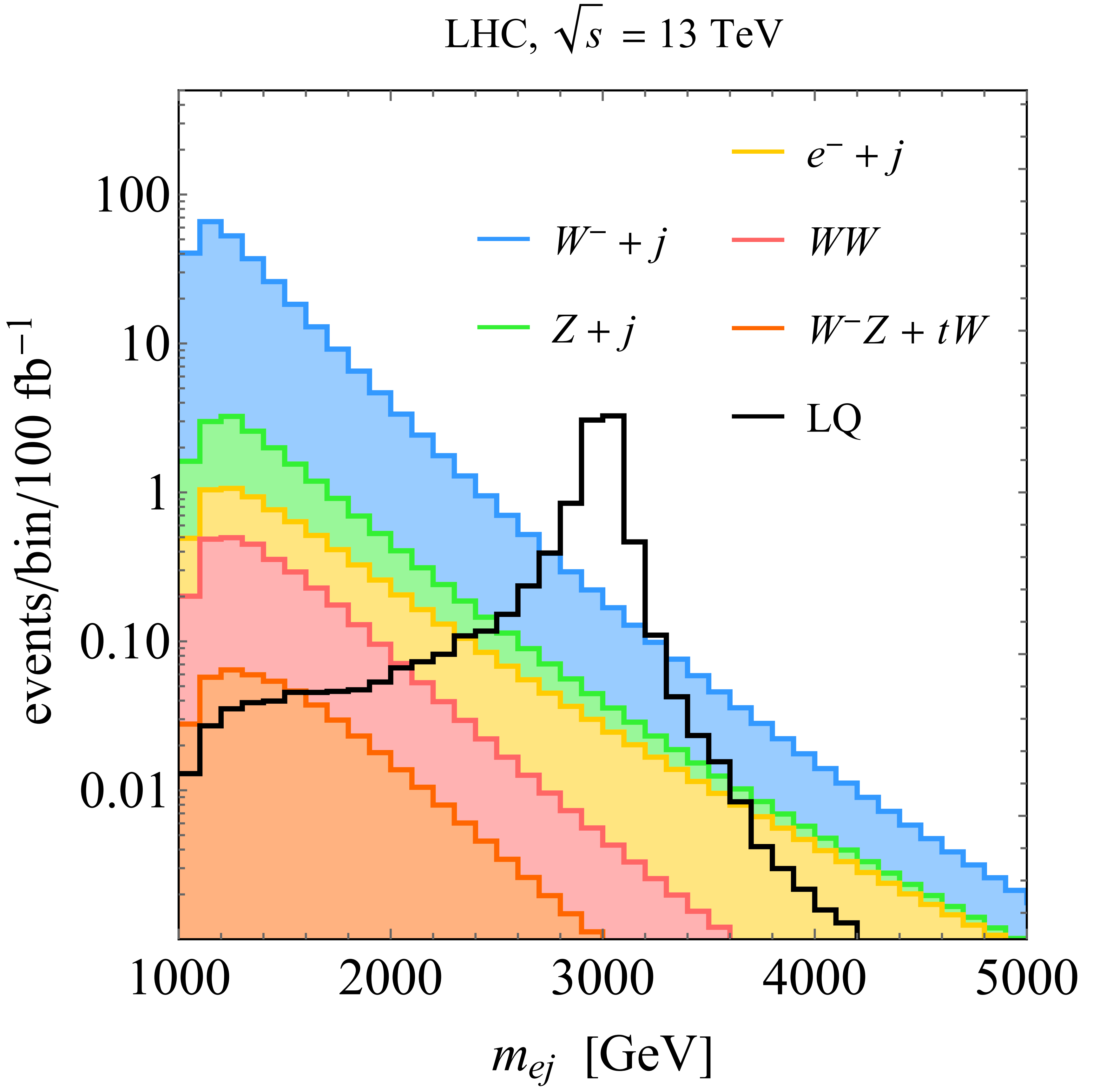


[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475]

Resonant LQ production @ the LHC

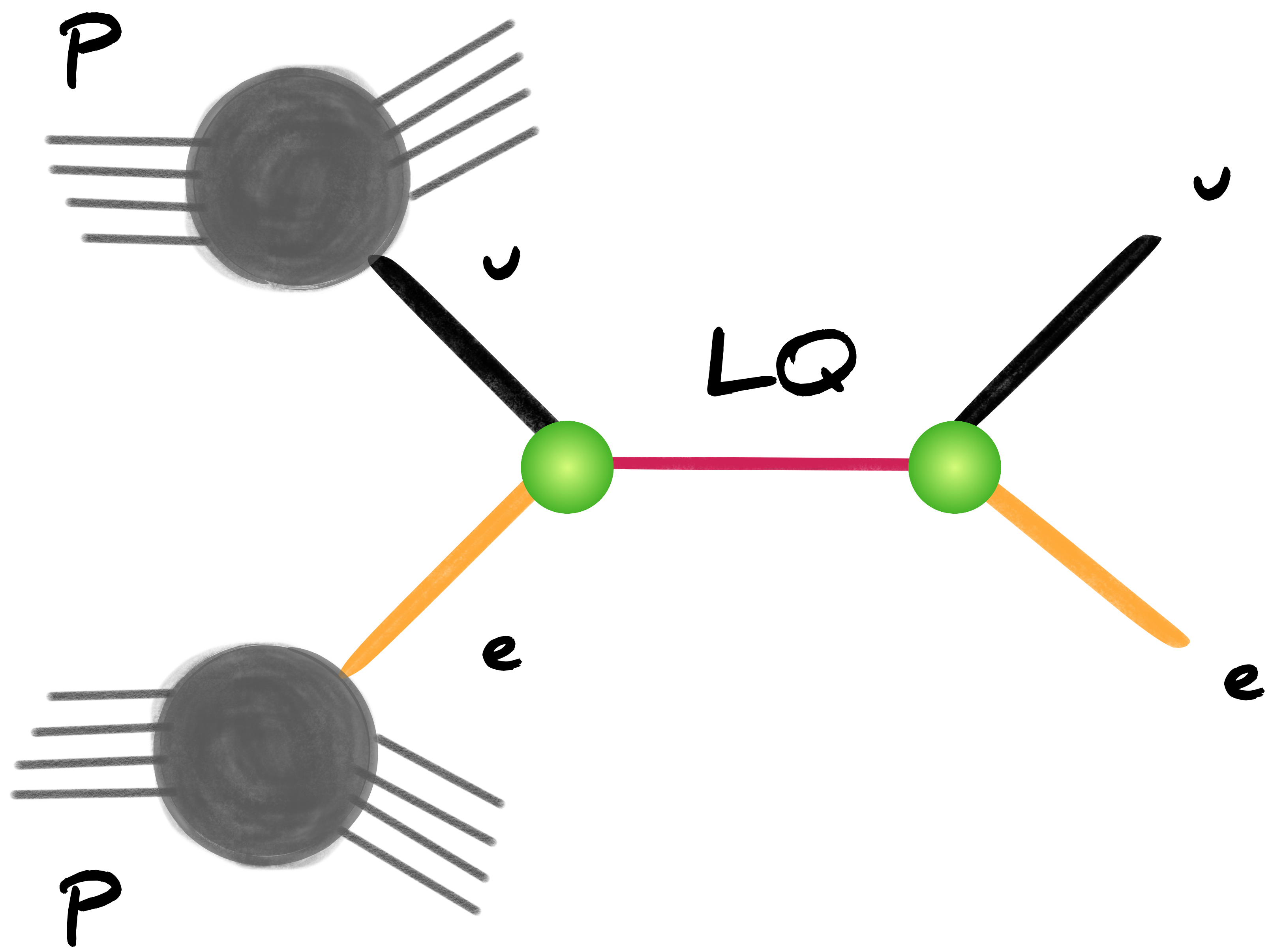


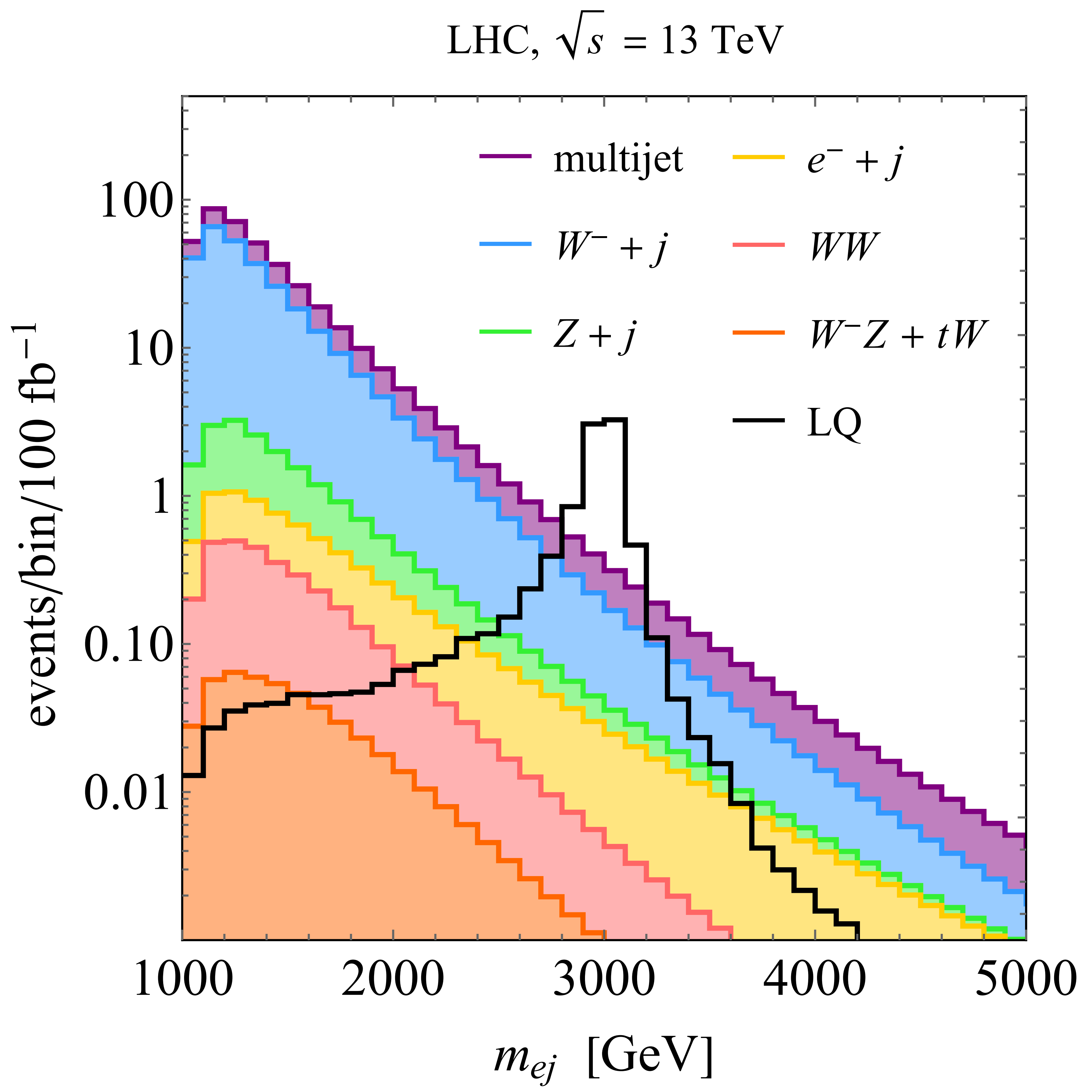
Suppressed by $E_{T,miss}$ requirement



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

Resonant LQ production @ the LHC

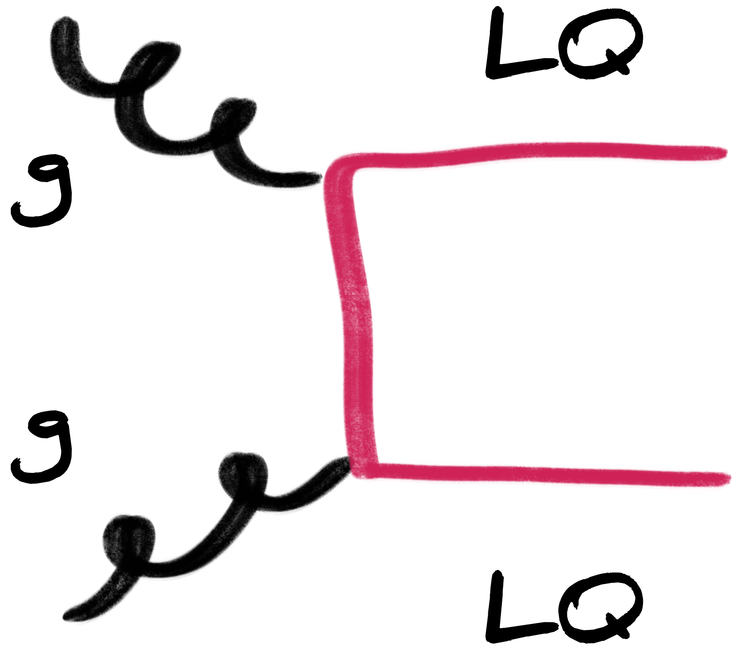




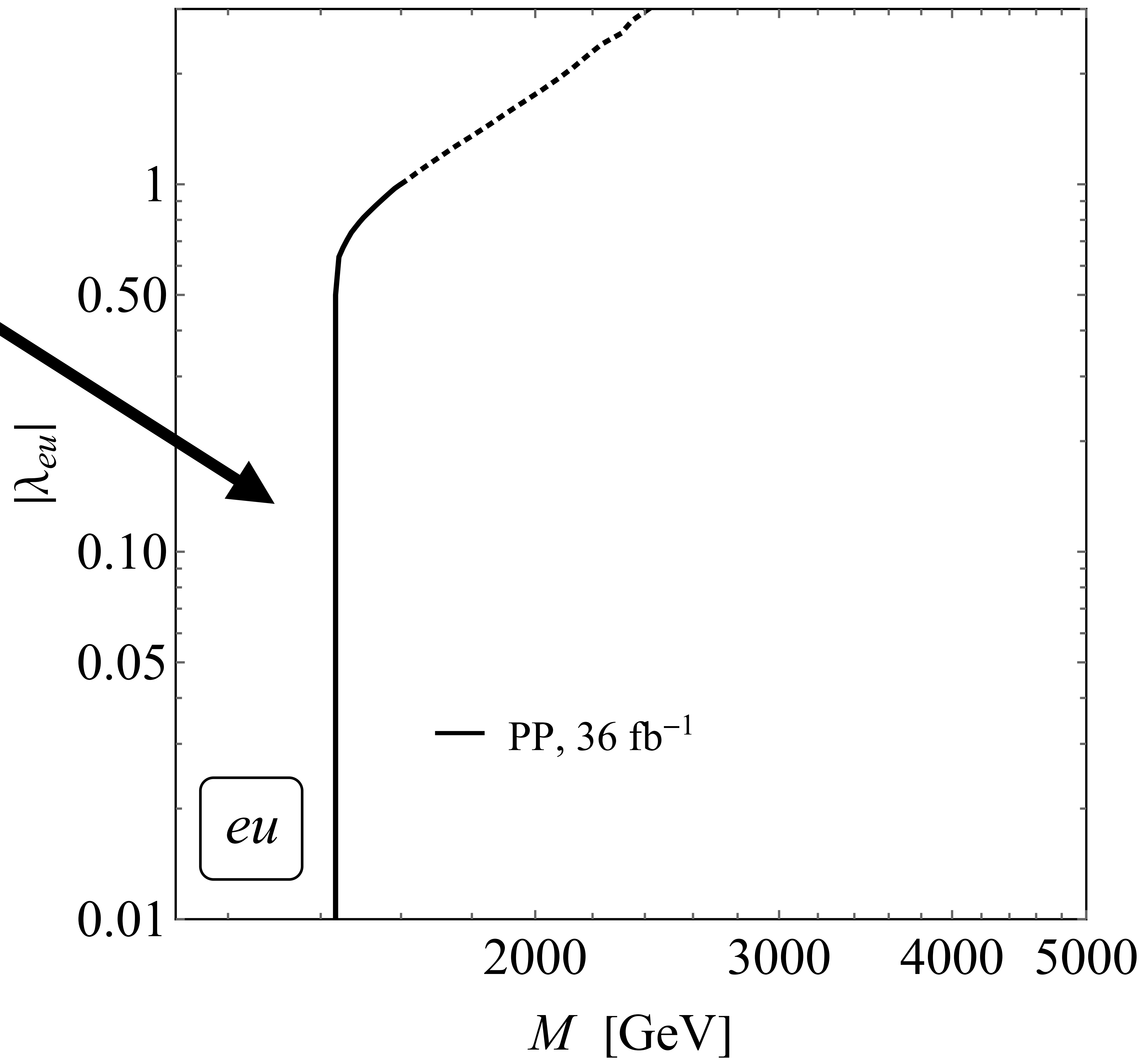
Sum over backgrounds is a steeply falling distribution, while signal exhibits a narrow peak

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

LHC limits on 1st & 2nd generation LQs

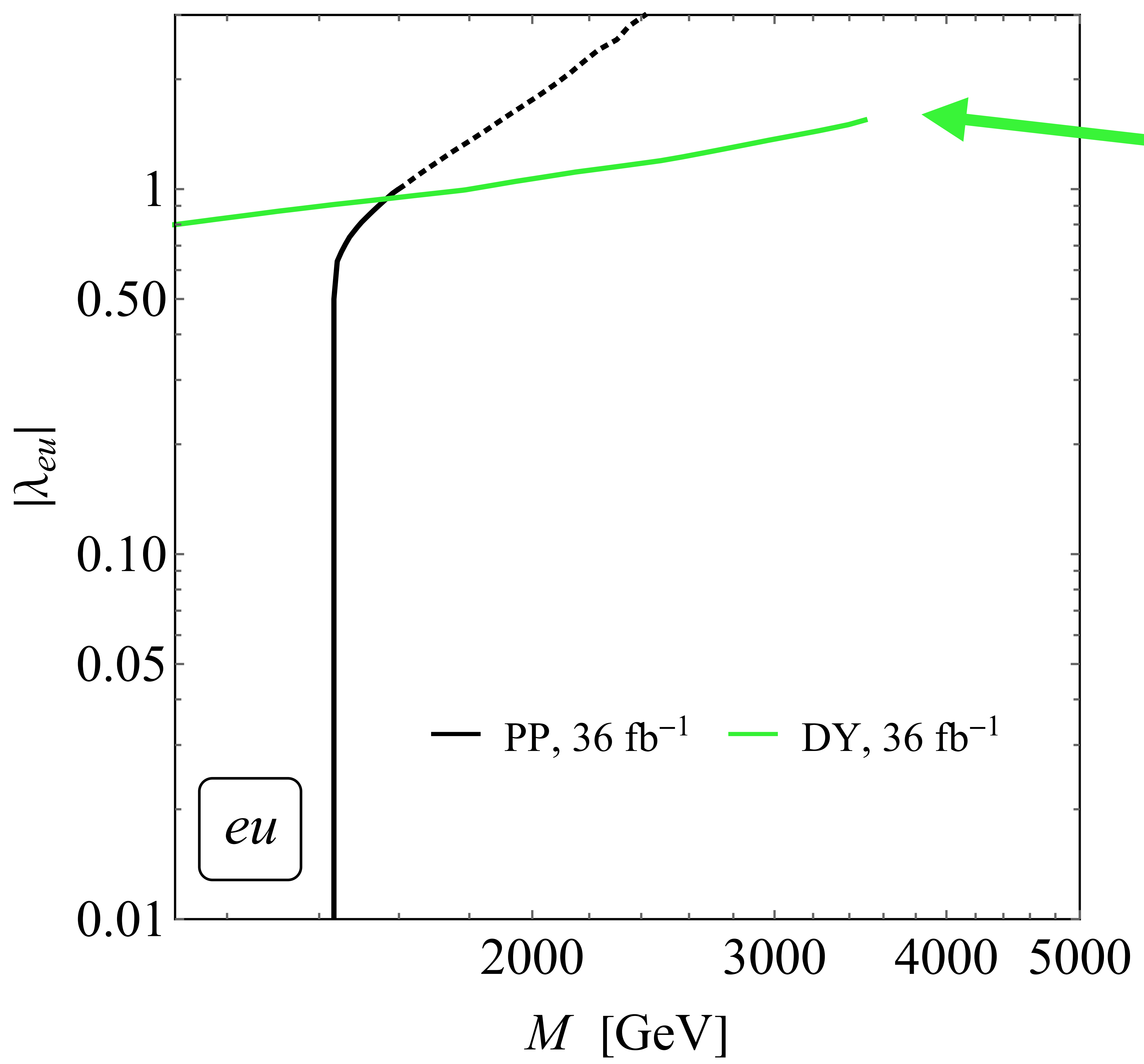


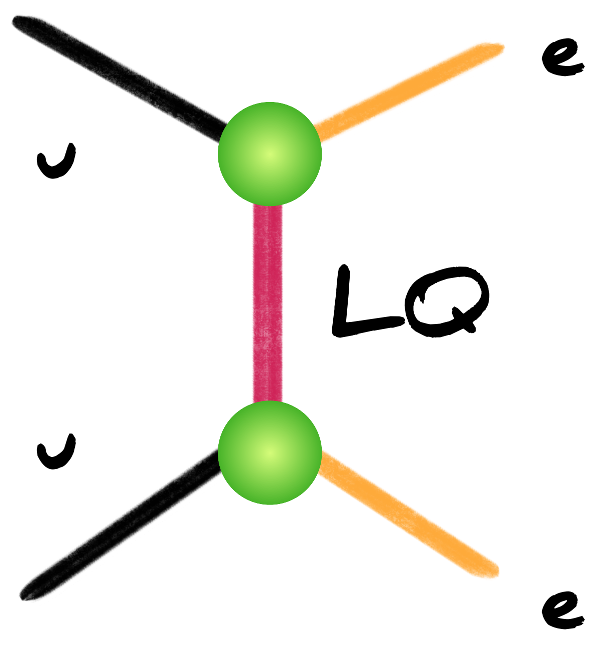
LQ pair production (PP)



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

LHC limits on 1st & 2nd generation LQs

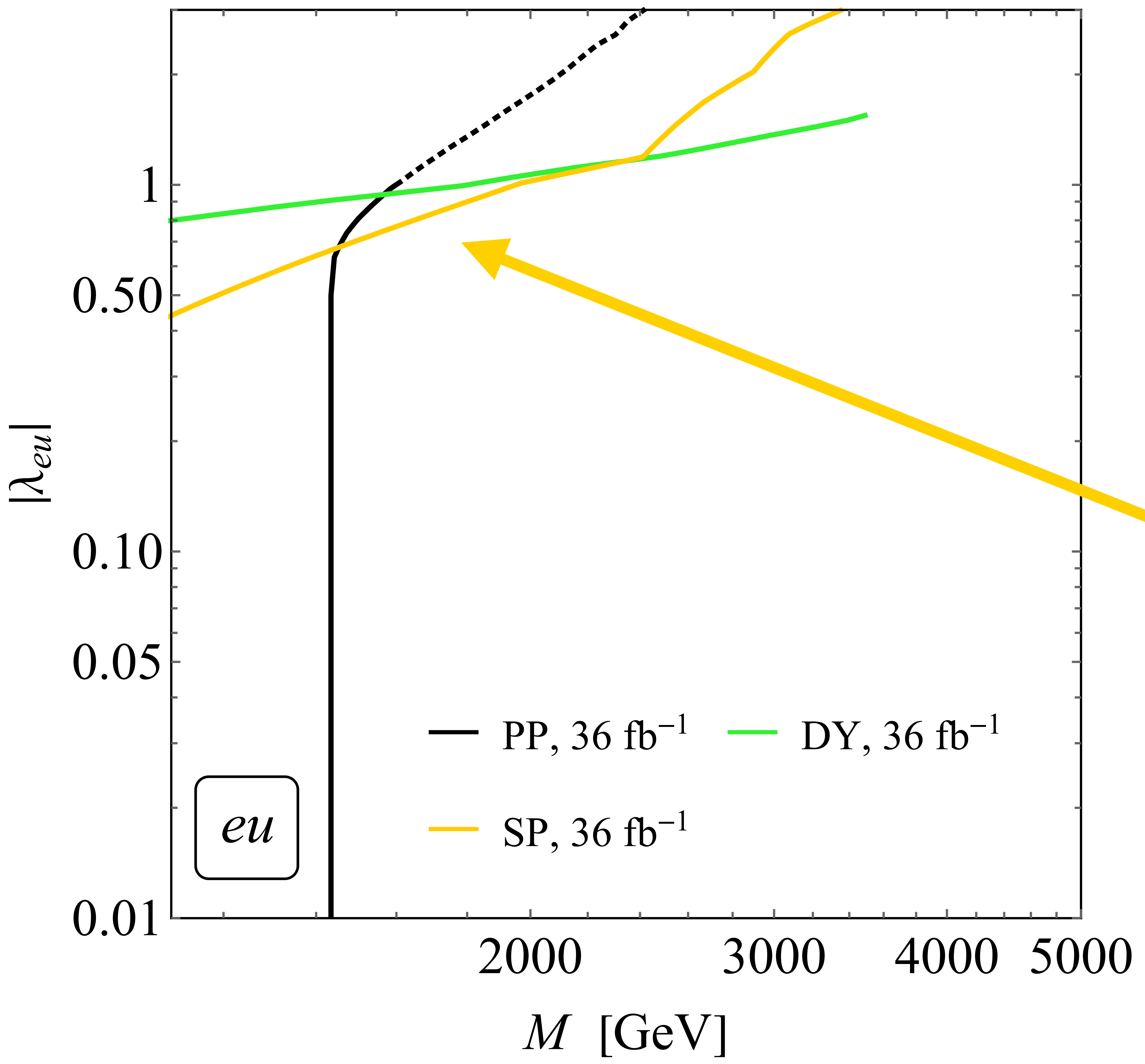


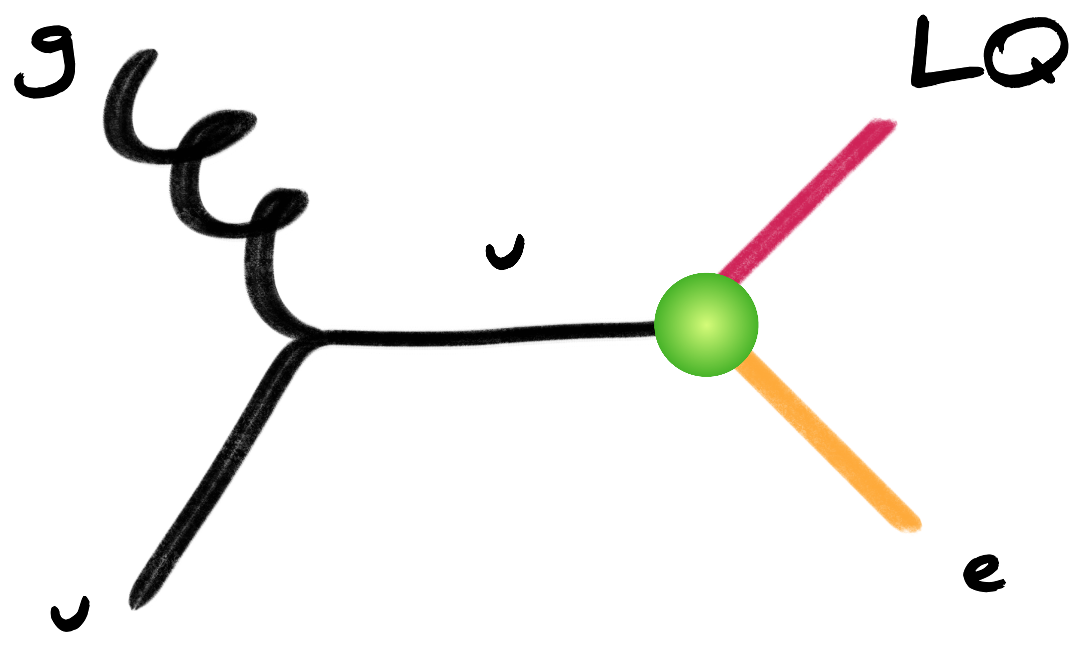


t-channel Drell-Yan (DY)

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

LHC limits on 1st & 2nd generation LQs

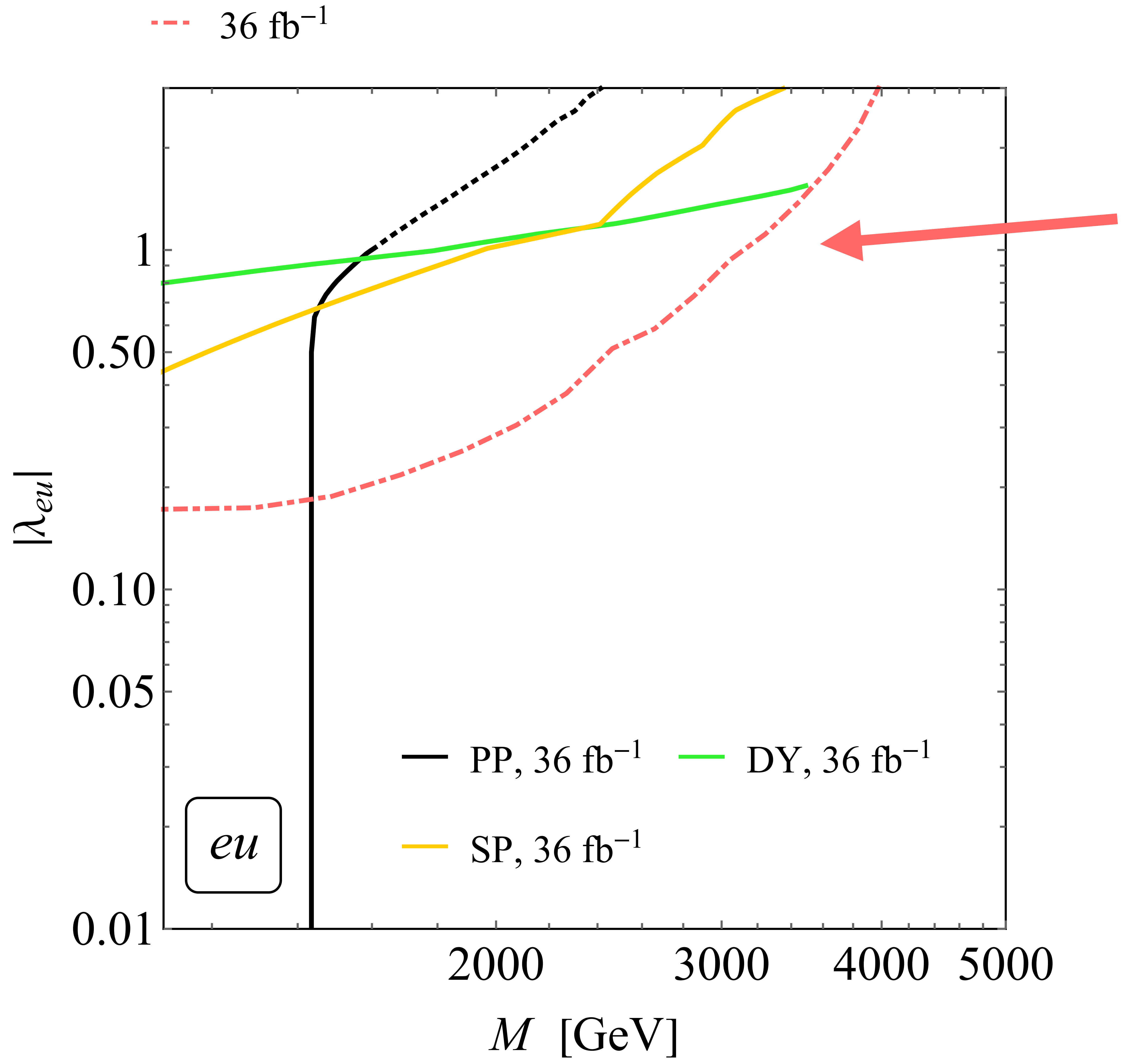


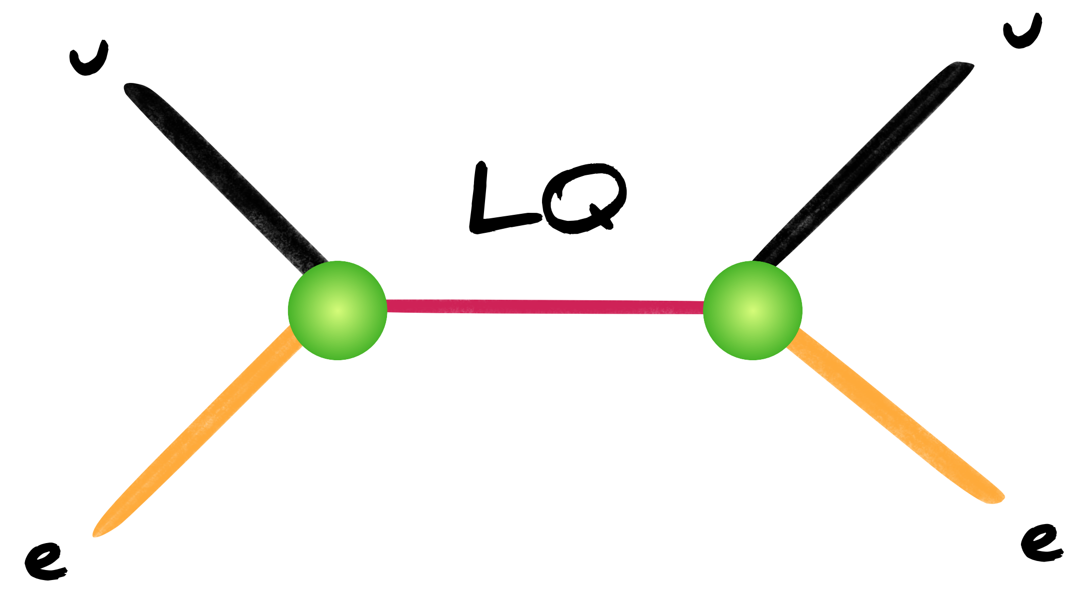


single LQ production (SP)

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

LHC limits on 1st & 2nd generation LQs

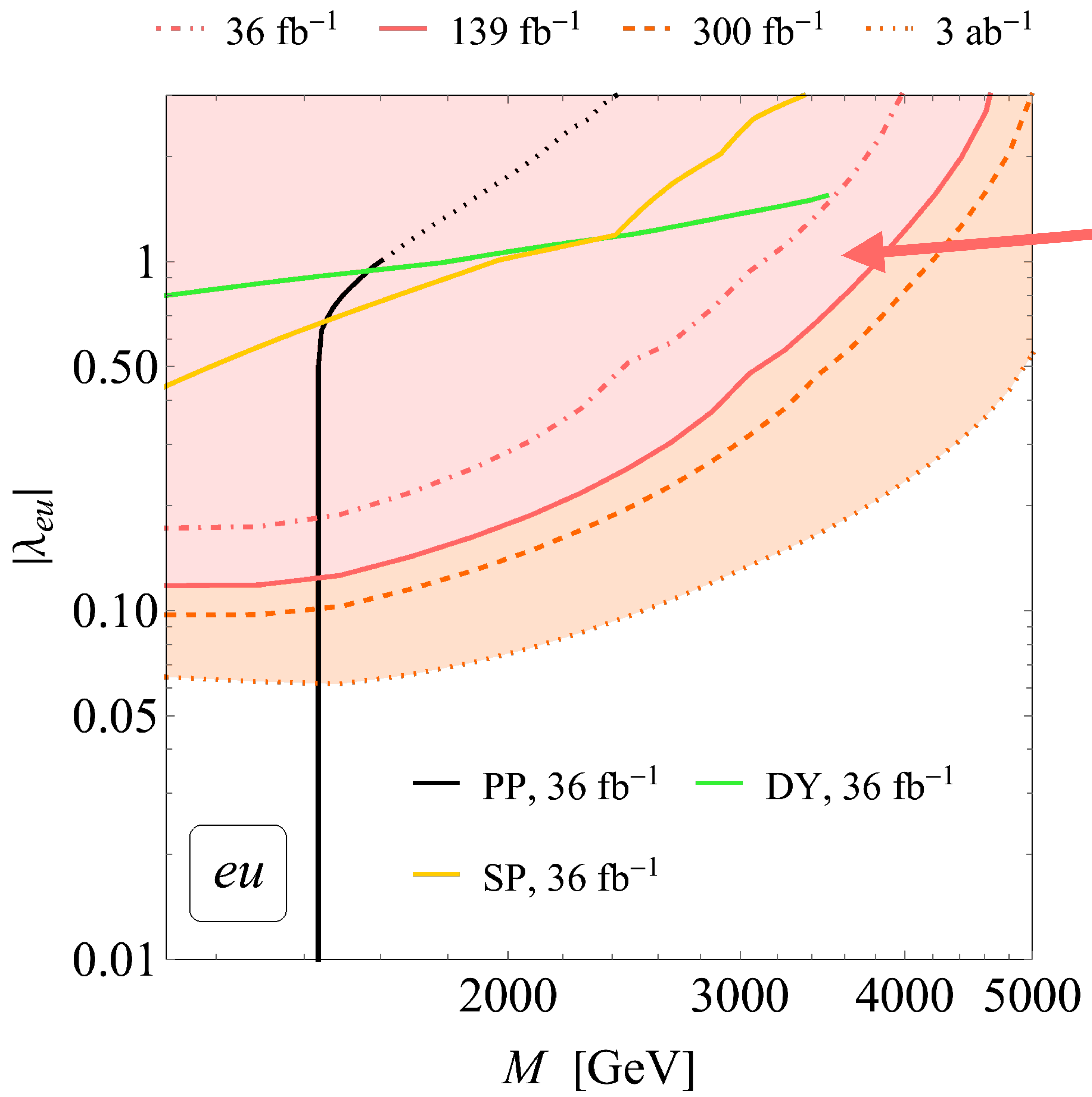


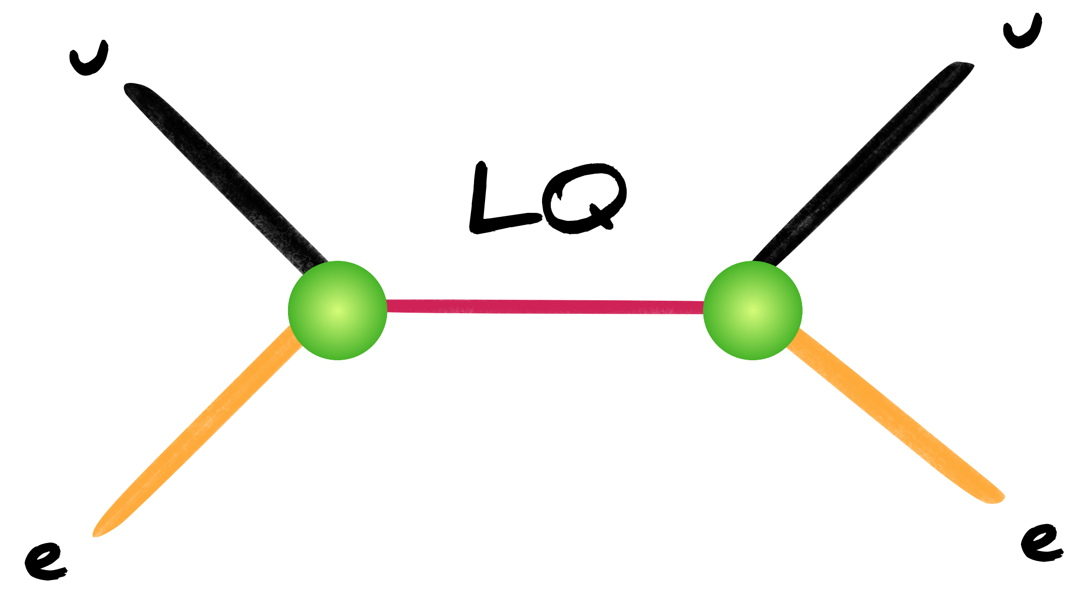


resonant LQ production

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

LHC limits on 1st & 2nd generation LQs

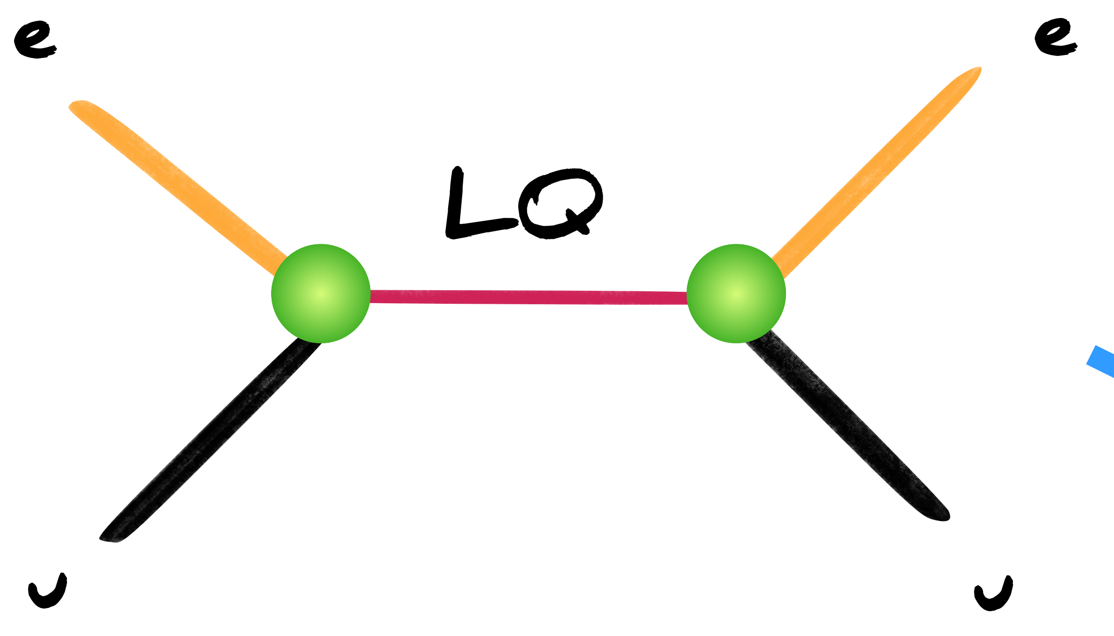




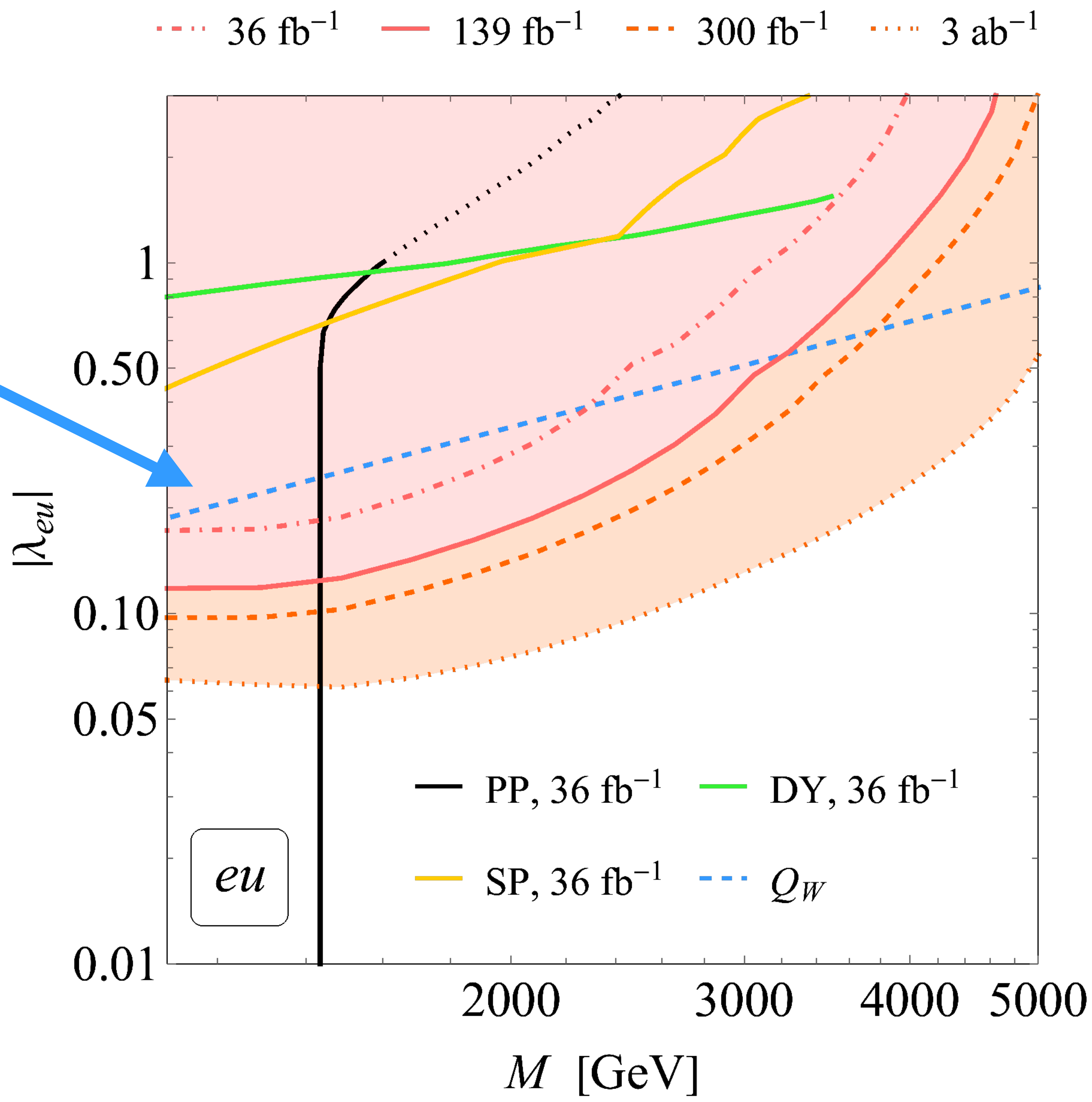
resonant LQ production

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

LHC limits on 1st & 2nd generation LQs

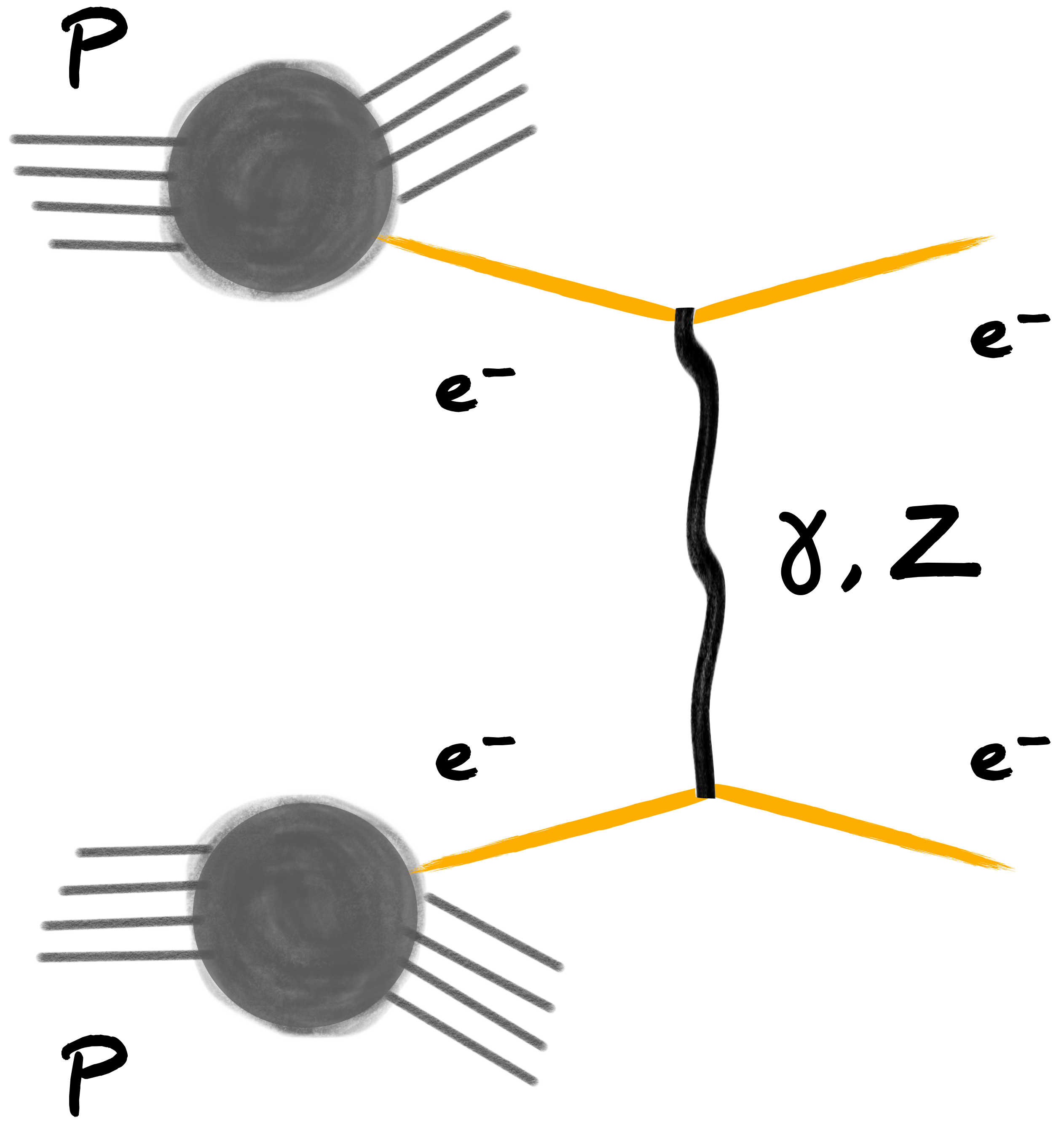


weak charge measurements (Q_W)



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

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

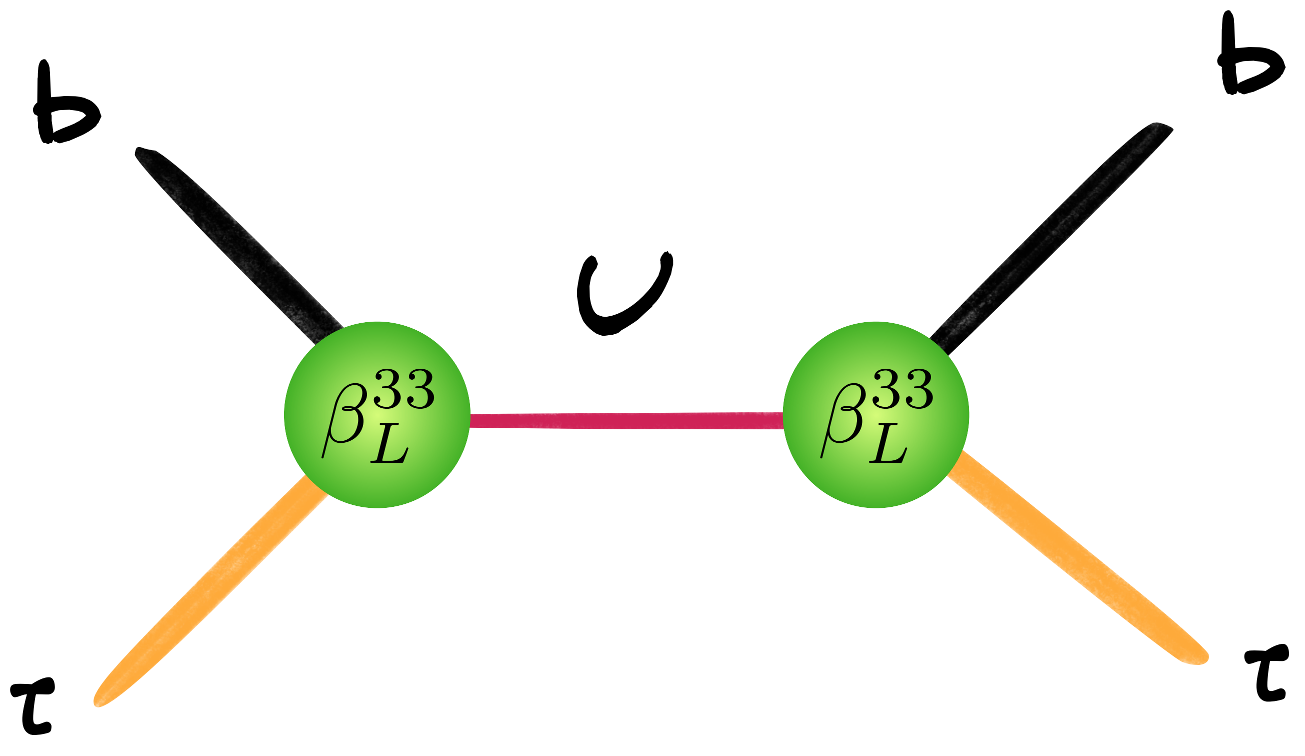
[Buonocore, Nason, Tramontano & Zanderighi, JHEP 08 (2020) 019; ATLAS analysis ongoing]

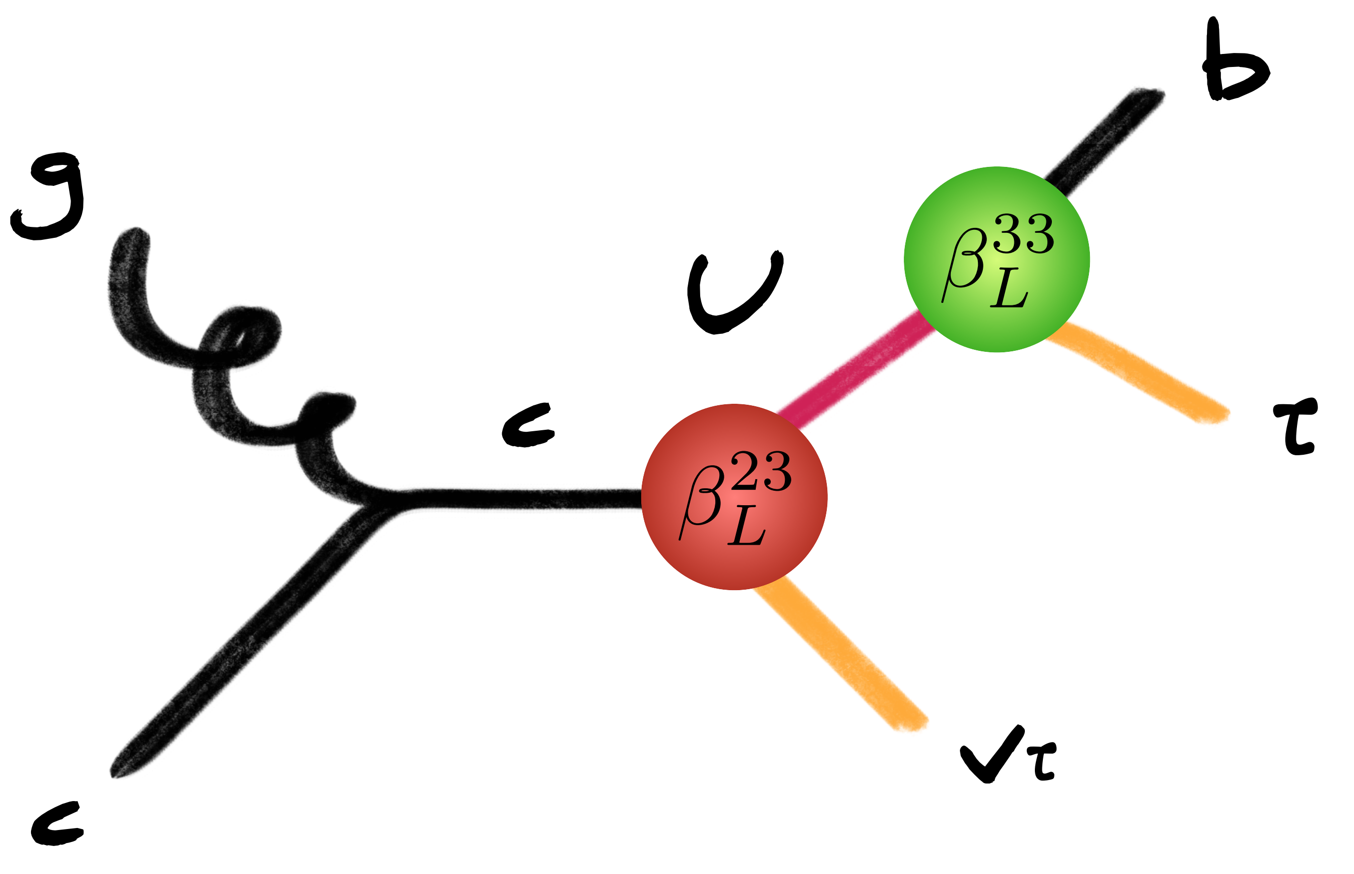
Simulation of 1st & 2nd resonant LQ signals

- 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 parton shower (PS) backward evolution
- As a result, jet- & lepton-veto induce a mismodelling of signal strength. By studying process $q\gamma \to \mathrm{LQ}\, l \to q l^+ l^-$, 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 next-to-leading order (NLO) QCD & QED corrections for LQ signal can be correctly included in differential fashion

[very recent progress towards NLO PS by Richardson, unpublished; Greljo & Selimovic, 2012.02092]

LQ contributions to b + τ signature

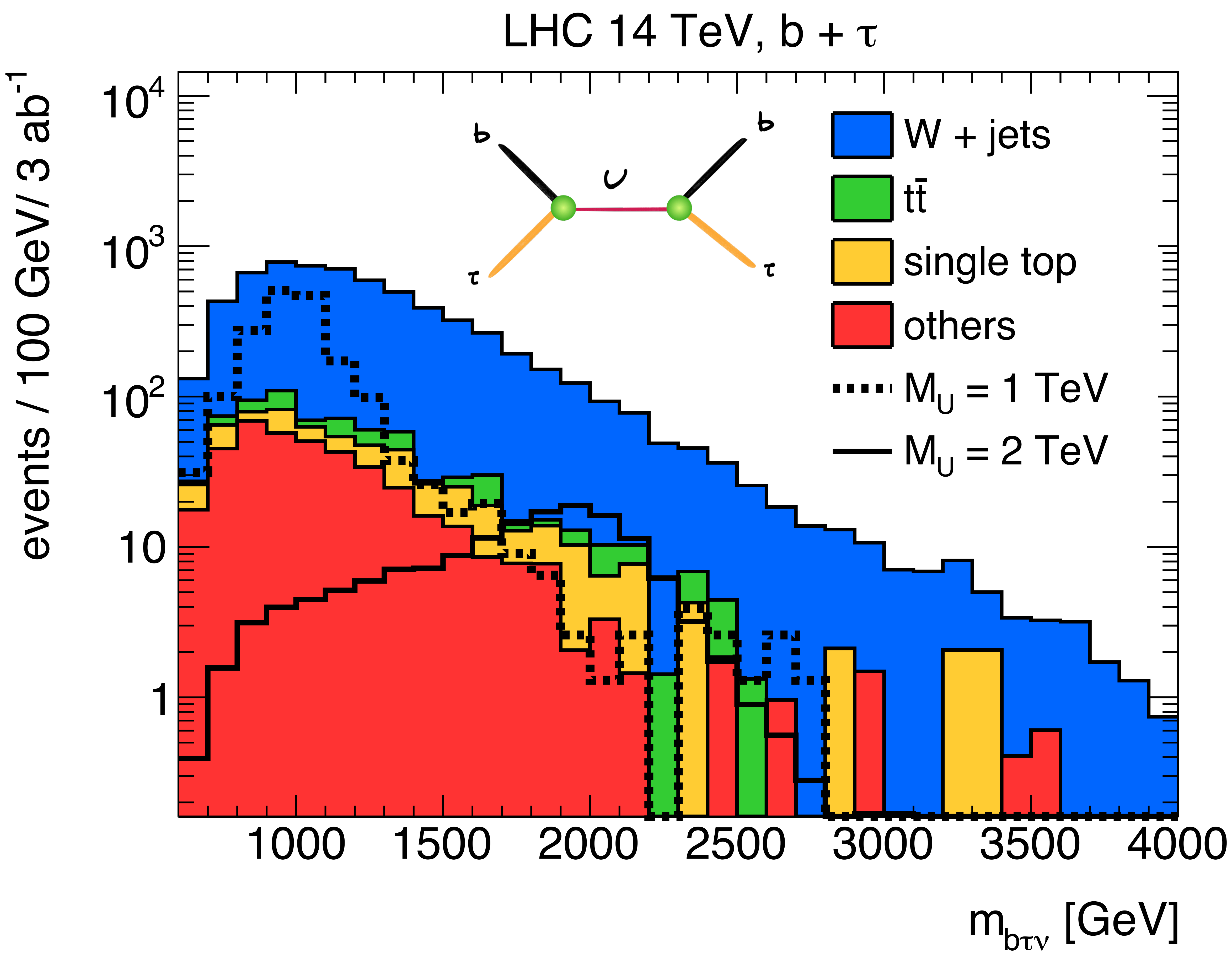


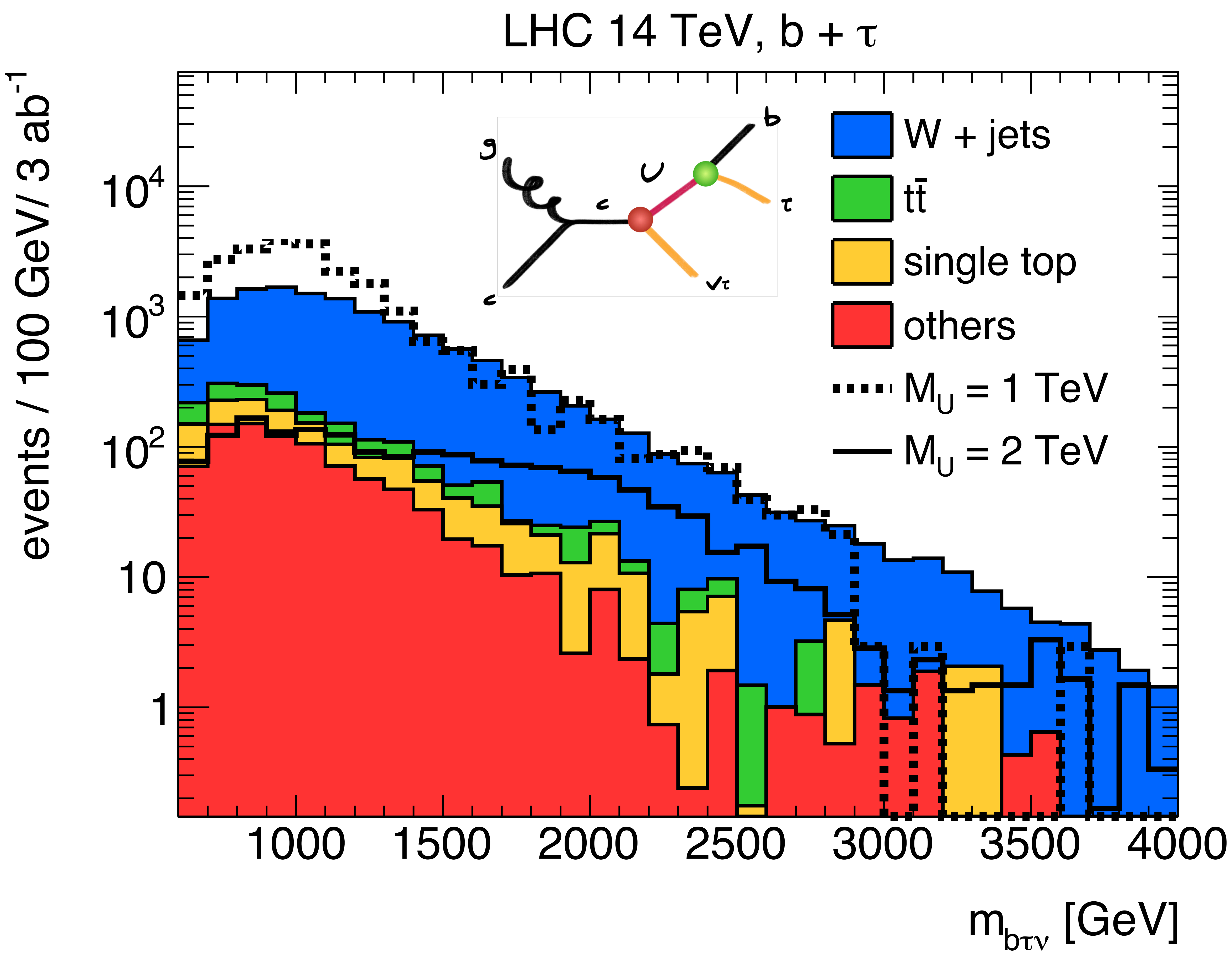


For $\beta_L^{23} = 0$, b + τ signal arises only from 2 → 2 process, while for $\beta_L^{23} \neq 0$ also 2 → 3 scattering is relevant. Since two topologies lead to final states with very different kinematic features, it is essential to develop two separate search strategies for them

[UH & Polesello, 2012.11474]

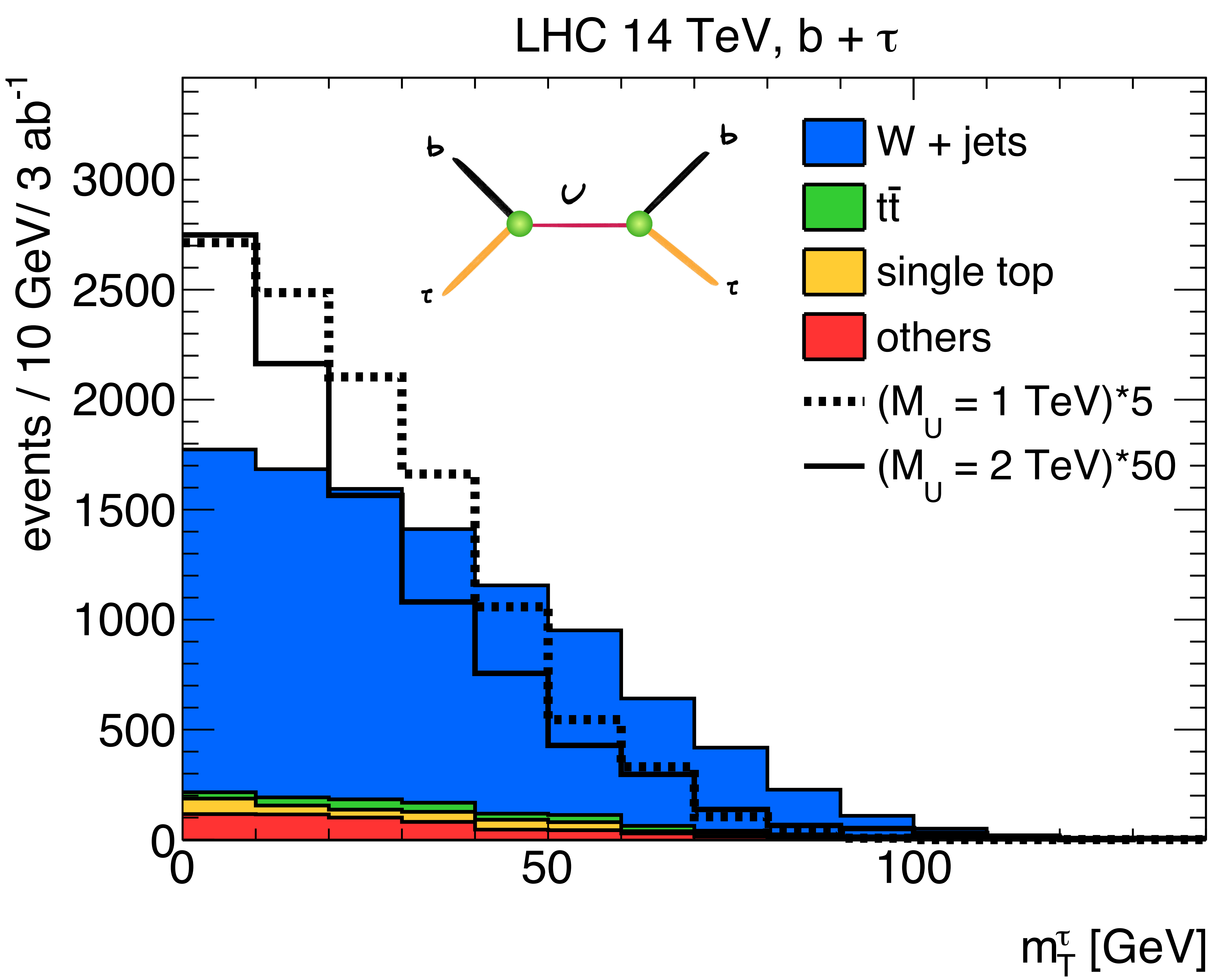
Kinematic distributions of b + τ signal

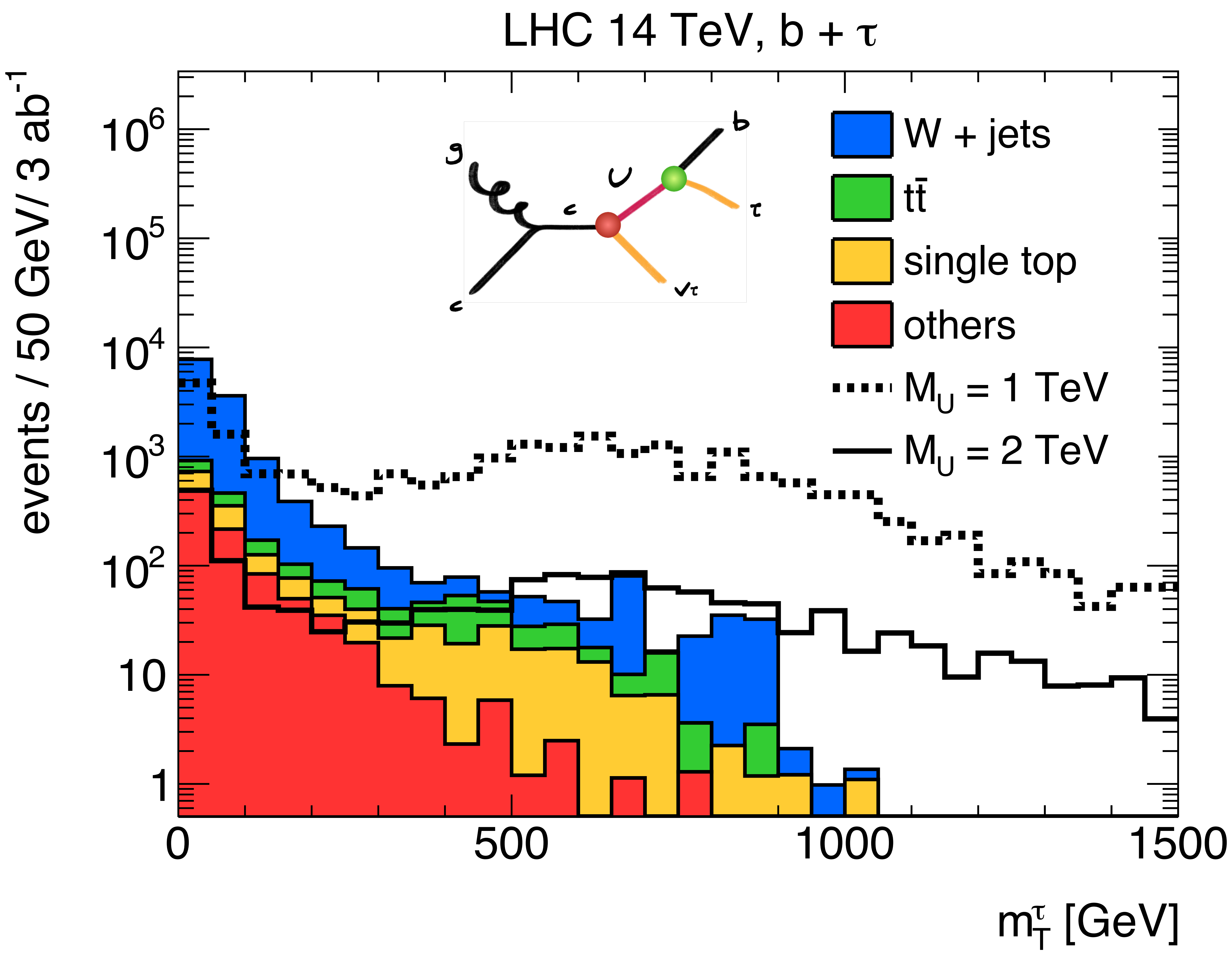




[UH & Polesello, 2012.11474]

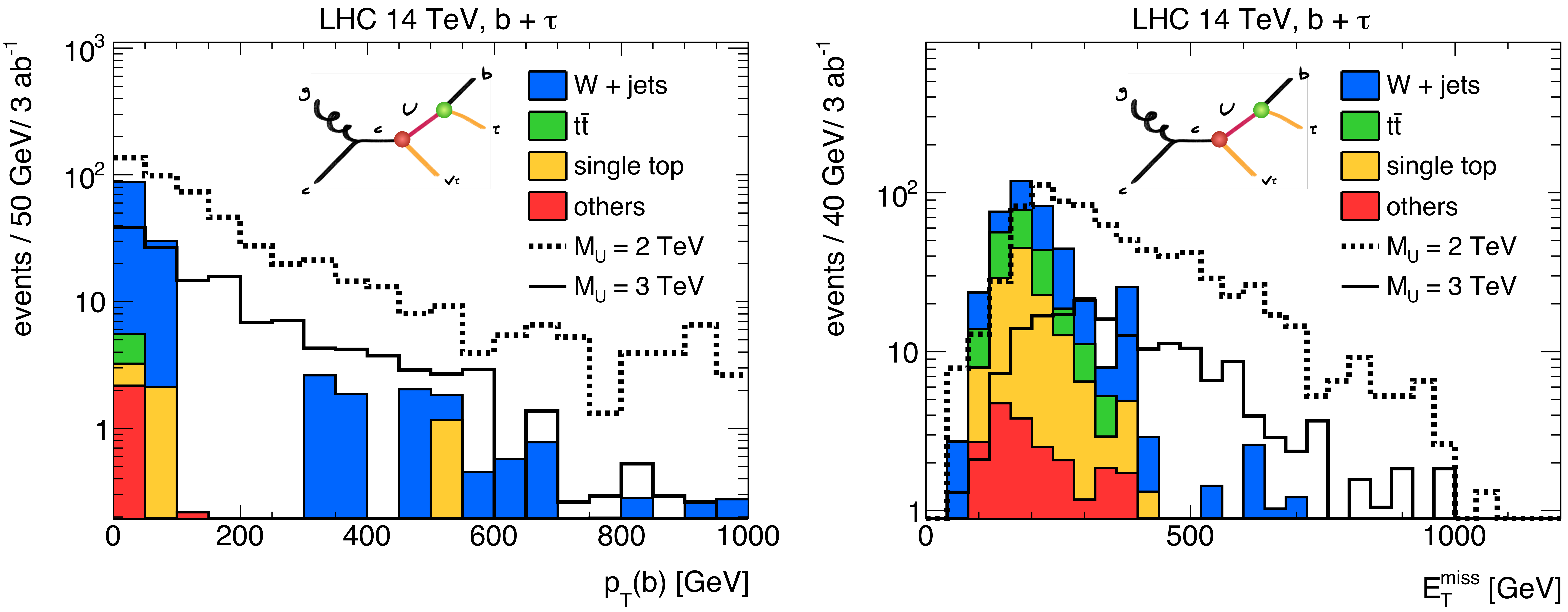
Kinematic distributions of b + τ signal





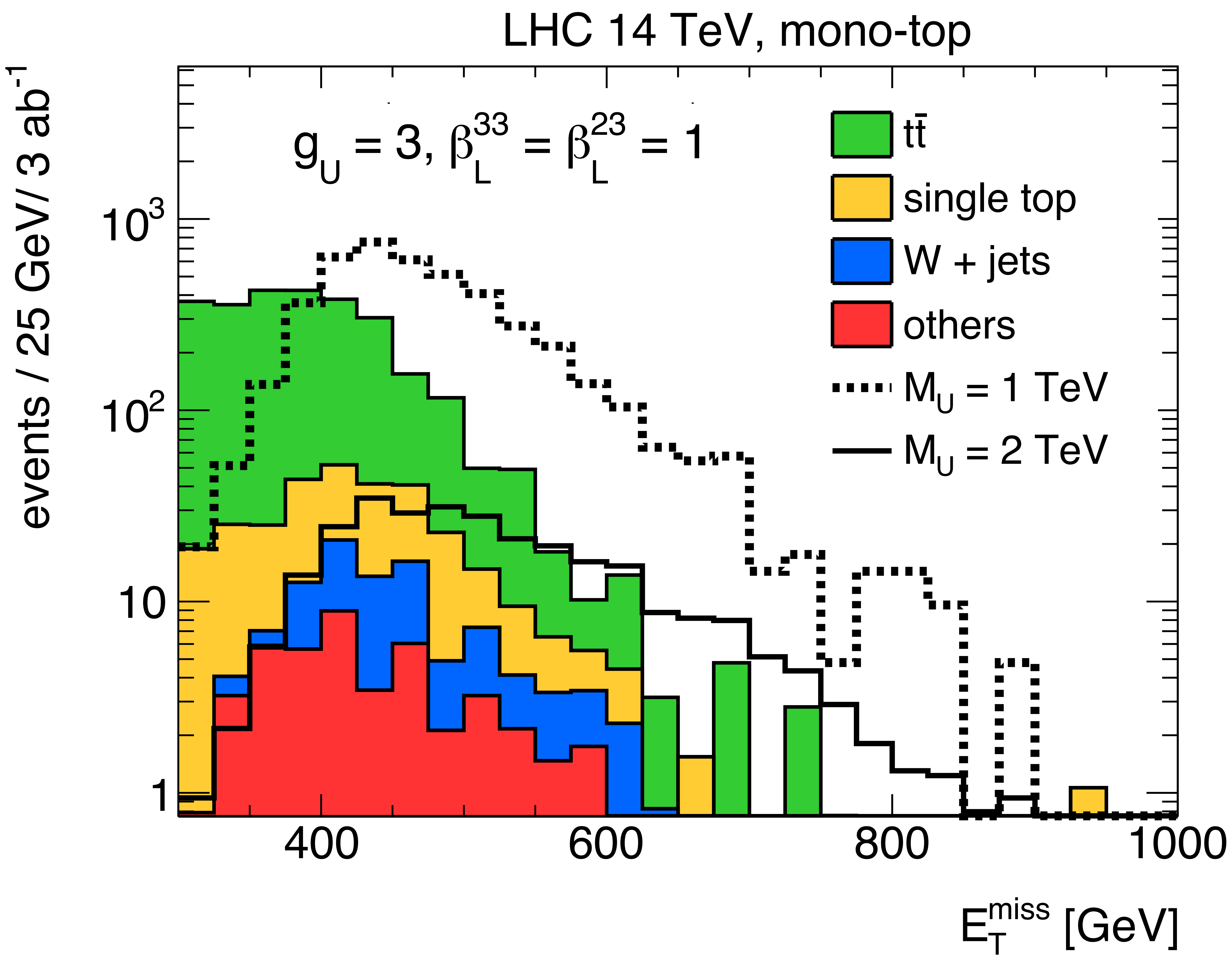
[UH & Polesello, 2012.11474]

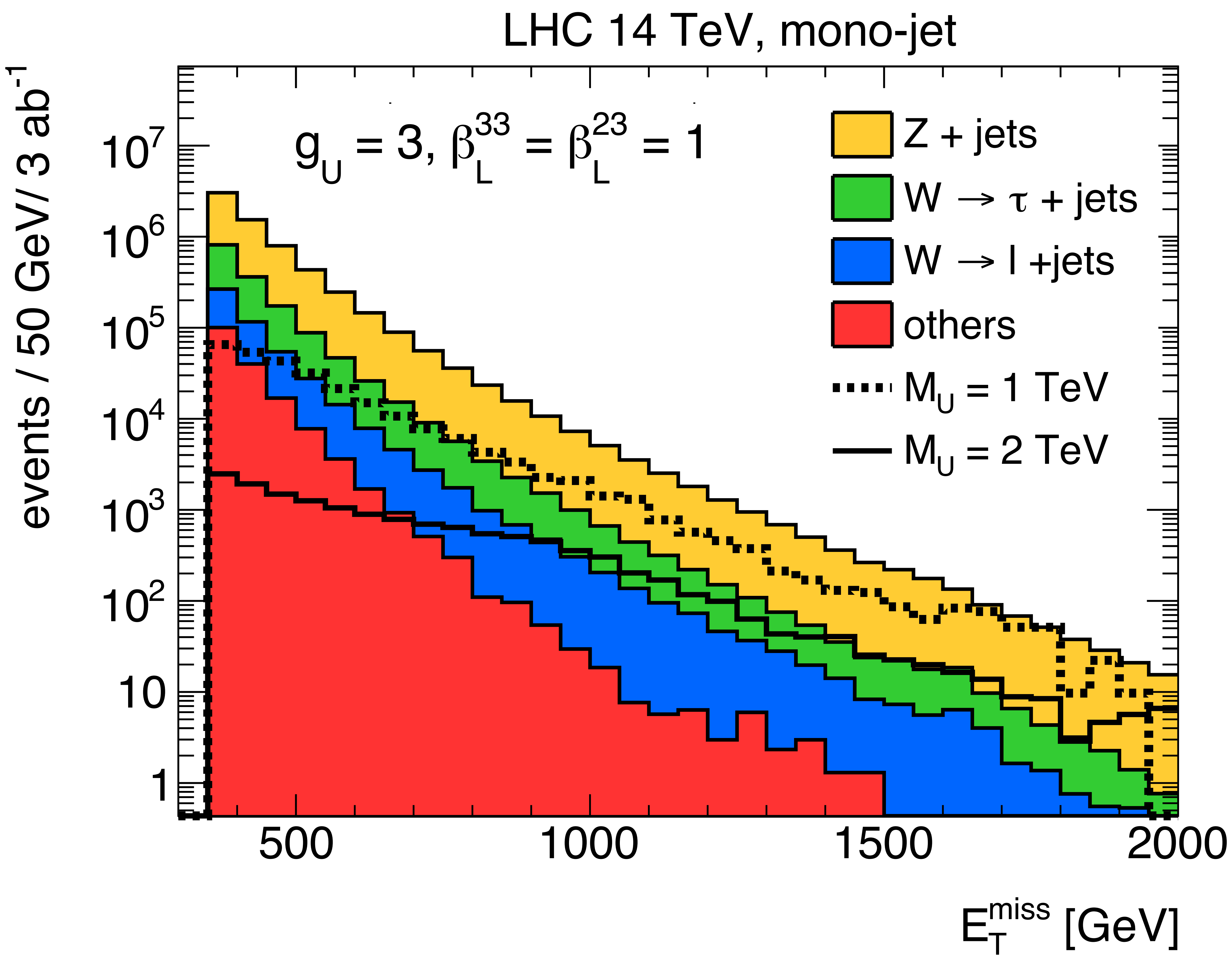
Kinematic distributions of b + τ signal



[UH & Polesello, 2012.11474]

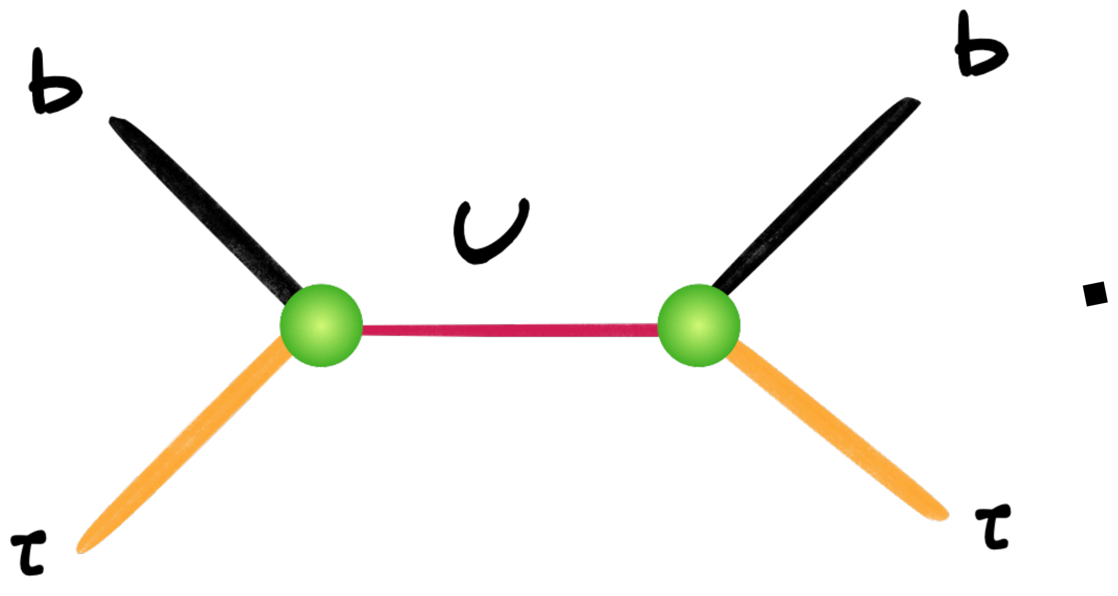
Mono-top & mono-jet distributions

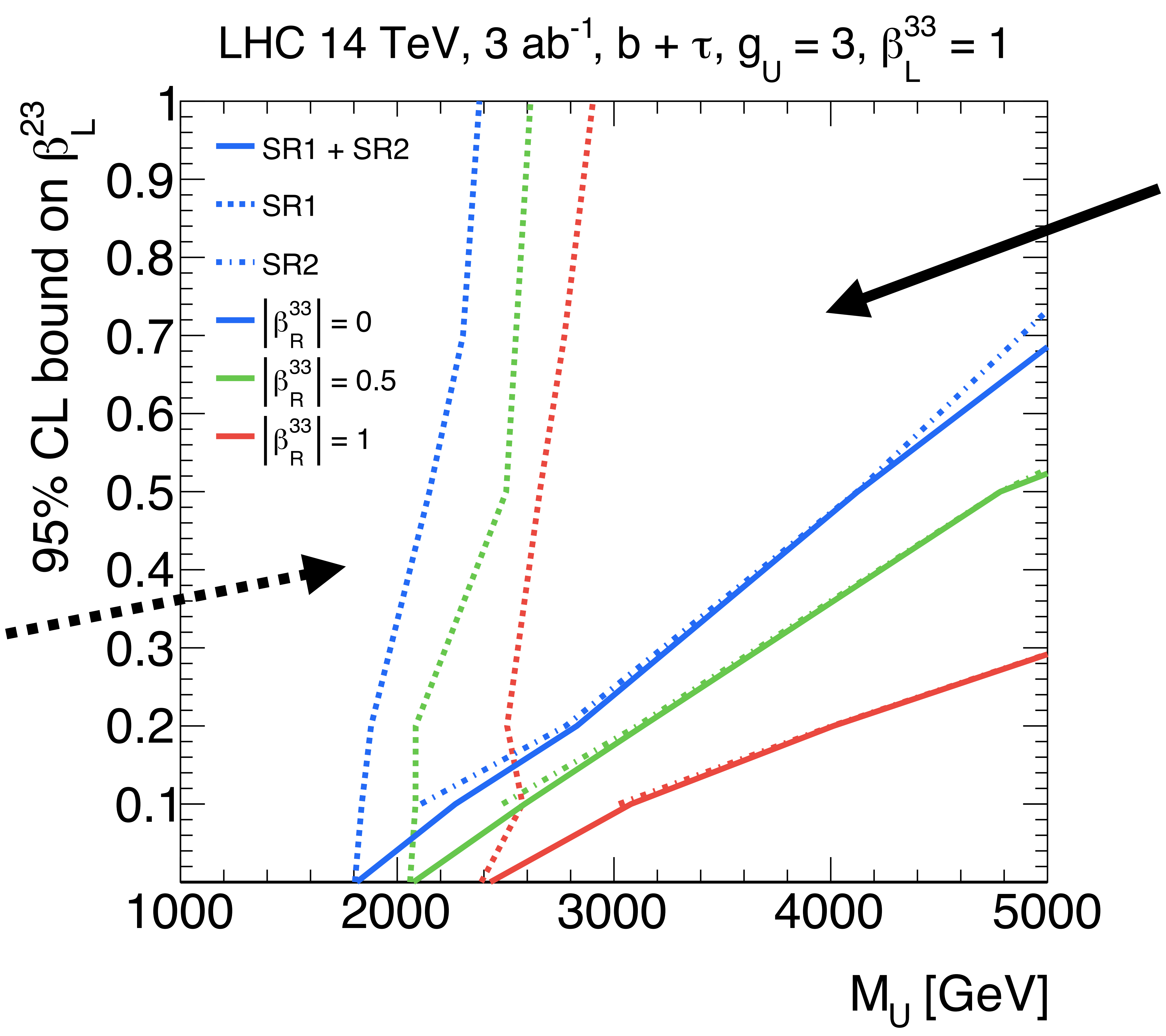


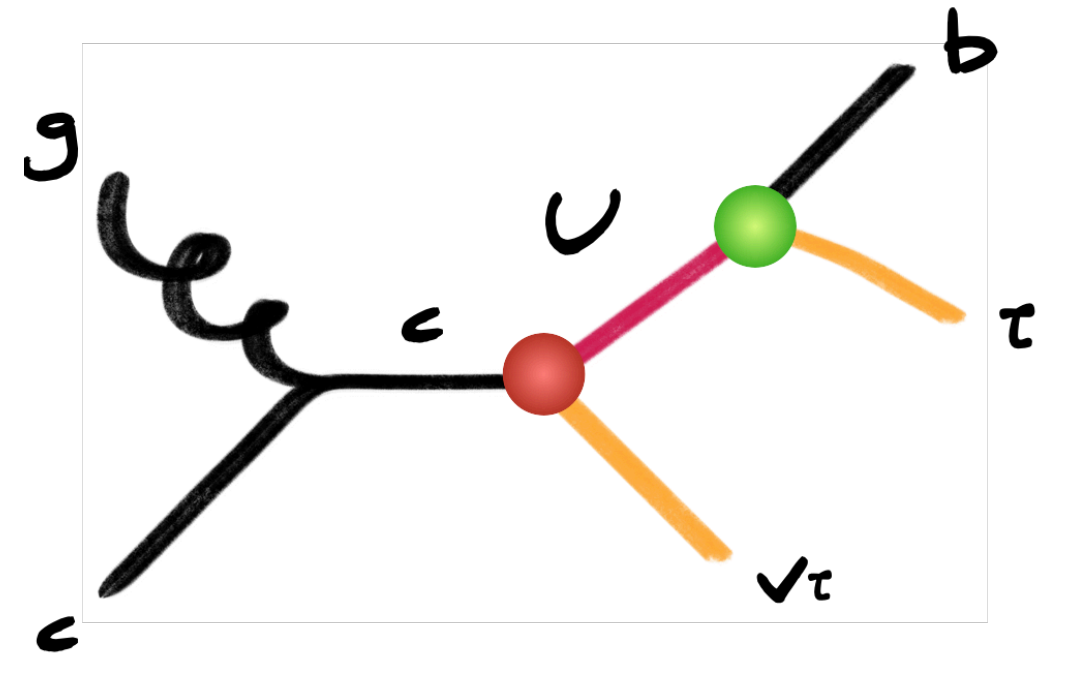


[UH & Polesello, 2012.11474]

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

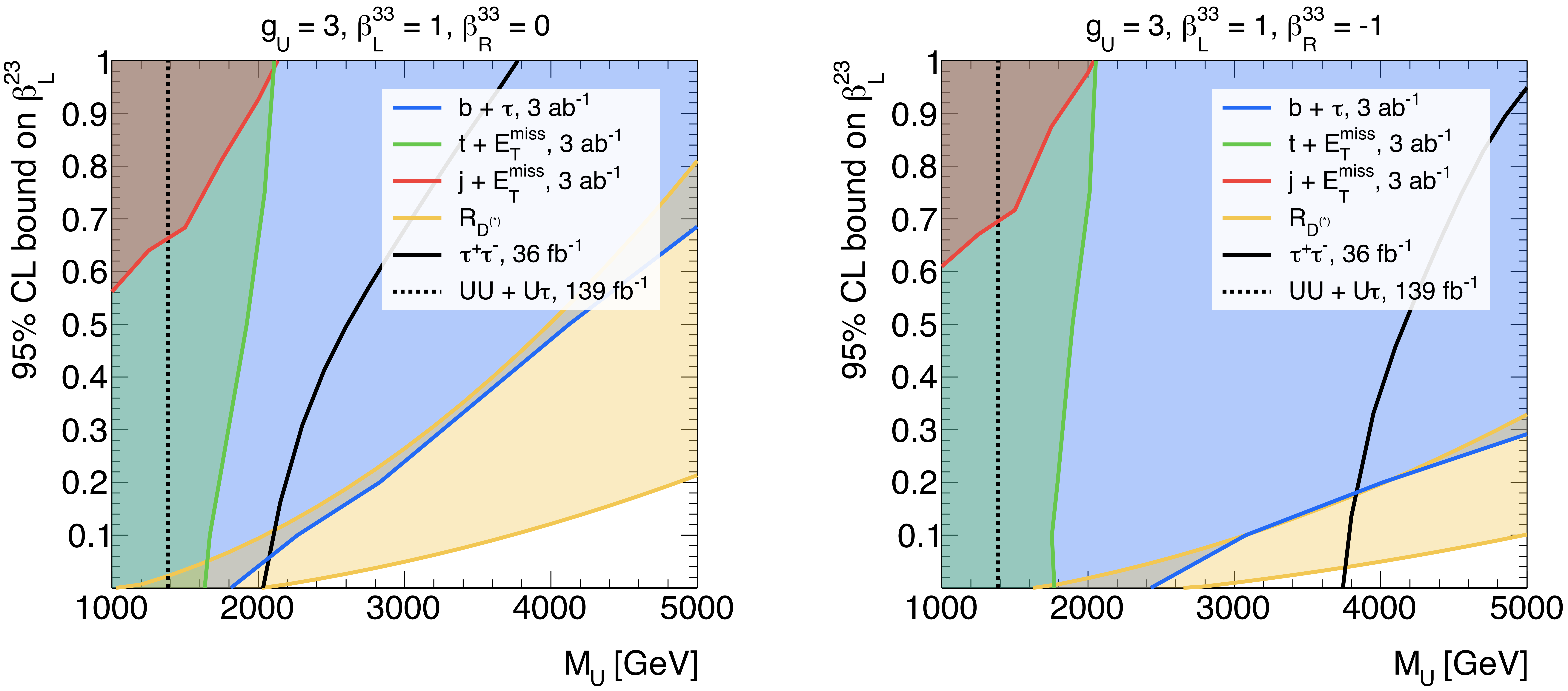






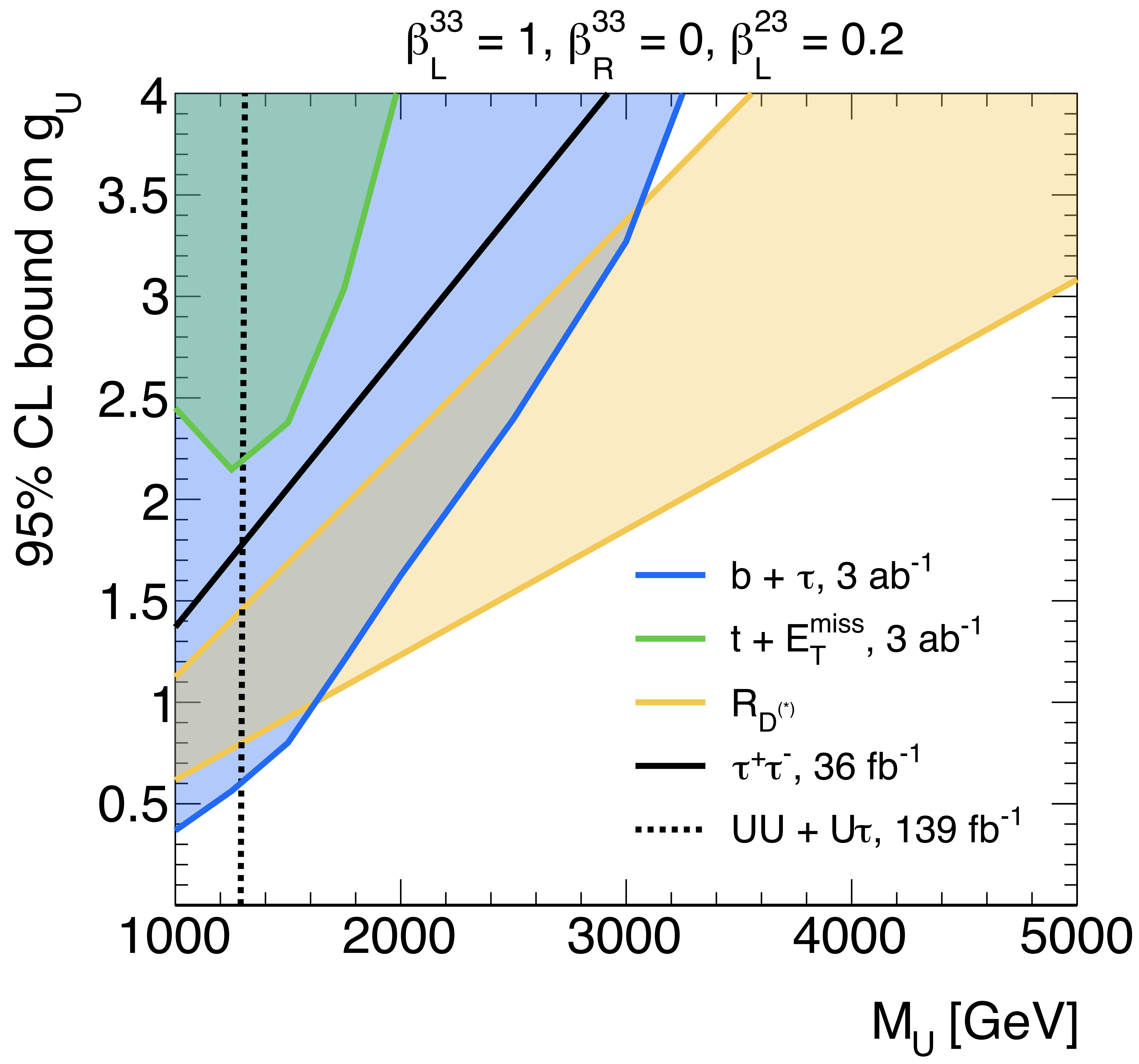
[UH & Polesello, 2012.11474]

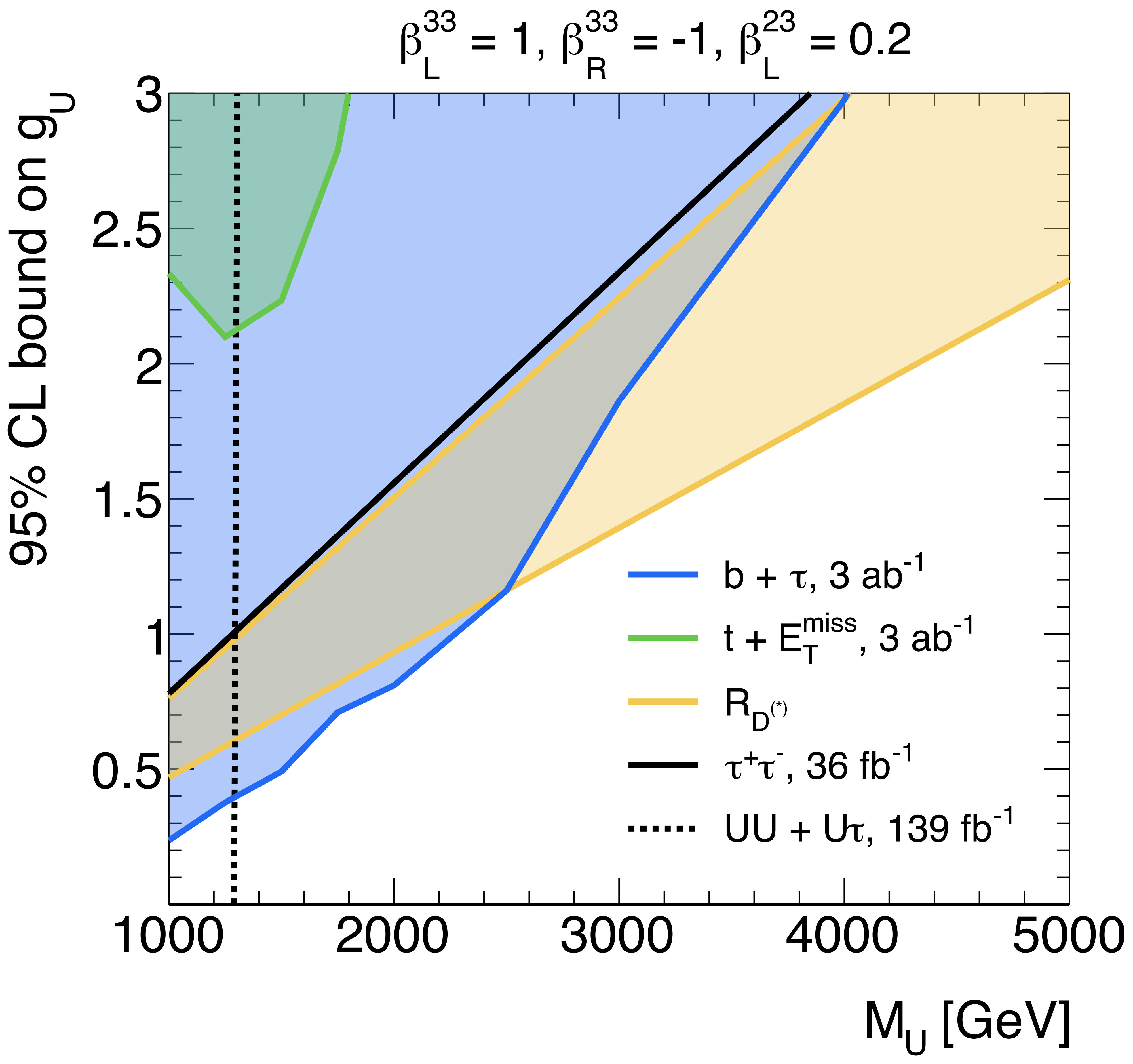
Constraints from new LQ search strategies



[UH & Polesello, 2012.11474]

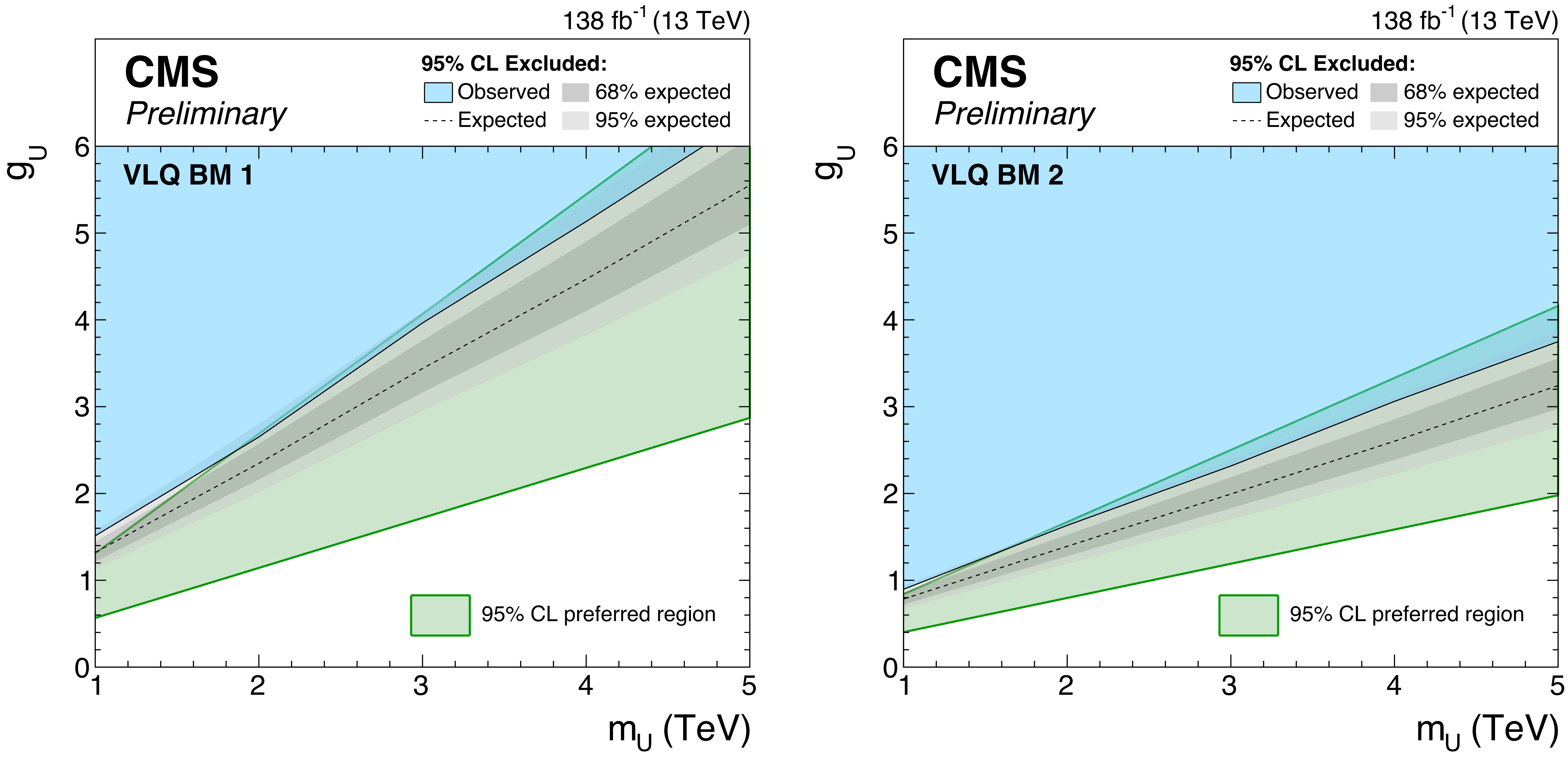
Constraints from new LQ search strategies





[UH & Polesello, 2012.11474]

Constraints from new CMS ditau search



[CMS PAS HIG-21-001]