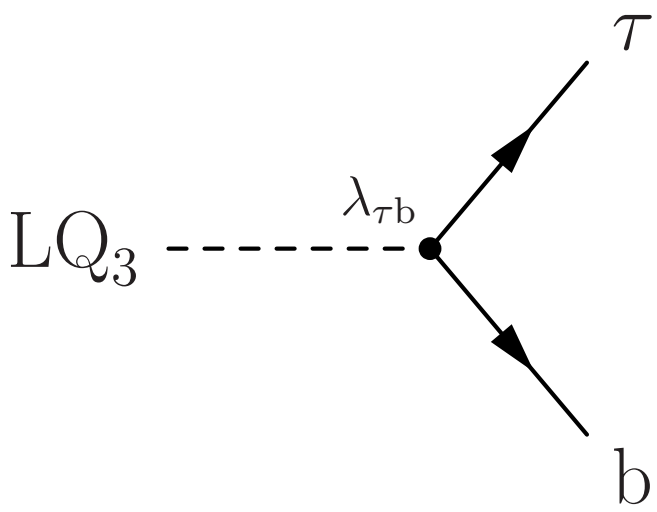
Universität Zürich[UZH]
Physik-Institut



Search for a third-generation leptoquark at CMS

Izaak Neutelings, Yuta Takahashi, Ben Kilminster
izaak.neutelings@uzh.ch

10/10/19

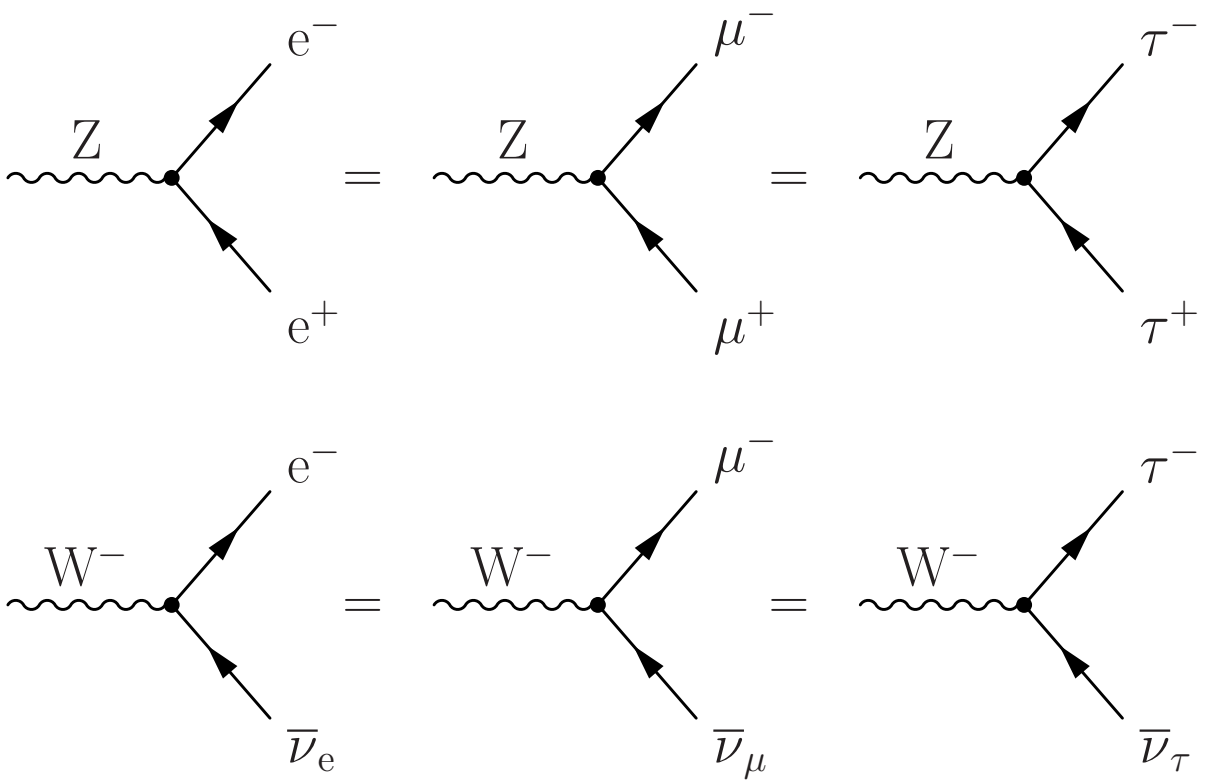
Conserved quantities & symmetries in the SM

quantity	symmetries	electromagnetic	weak	strong
energy	time translation	✔	✔	✔
linear momentum	spatial translation	✔	✔	✔
angular momentum	rotational energy	✔	✔	✔
charge, color, …	gauge transformation	✔	✔	✔
lepton number L		✔	✔	✔
baryon number B		✔	✔	✔
isospin		✔	✘	✘
lepton flavor		✔	✔	✔
quark flavor		✔	✘	✔
parity P		✔	✘	✔
charge conjugation C		✔	✘	✔
time reversal T		✔	✘	✔
CP		✔	✘	✔
CPT		✔	✔	✔

fundamental to QFTs and gauge theories, like the SM

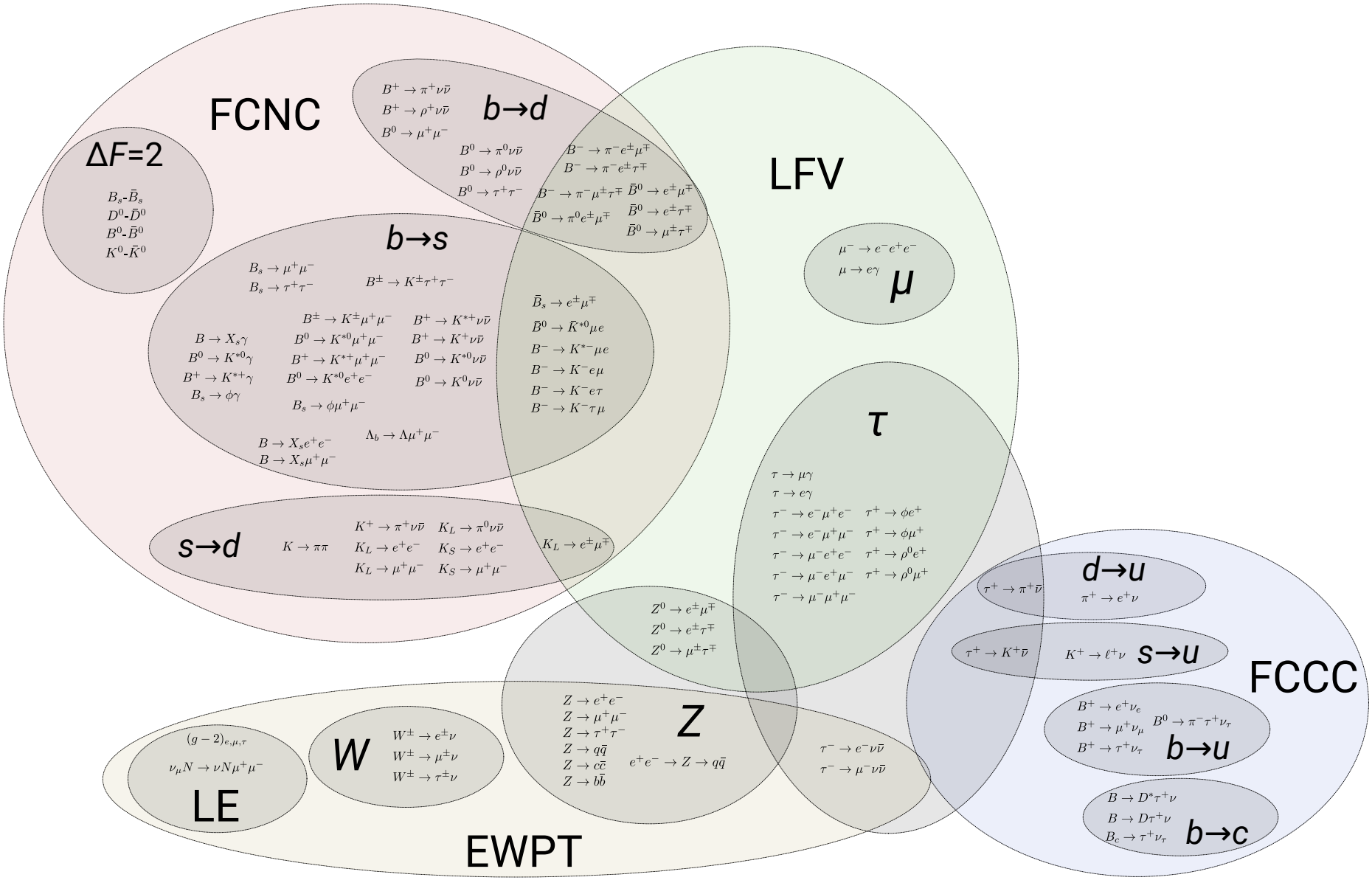
Lepton flavor universality in the SM

assuming $M_Z >> m_\tau, m_\mu, m_e \sim 0$,

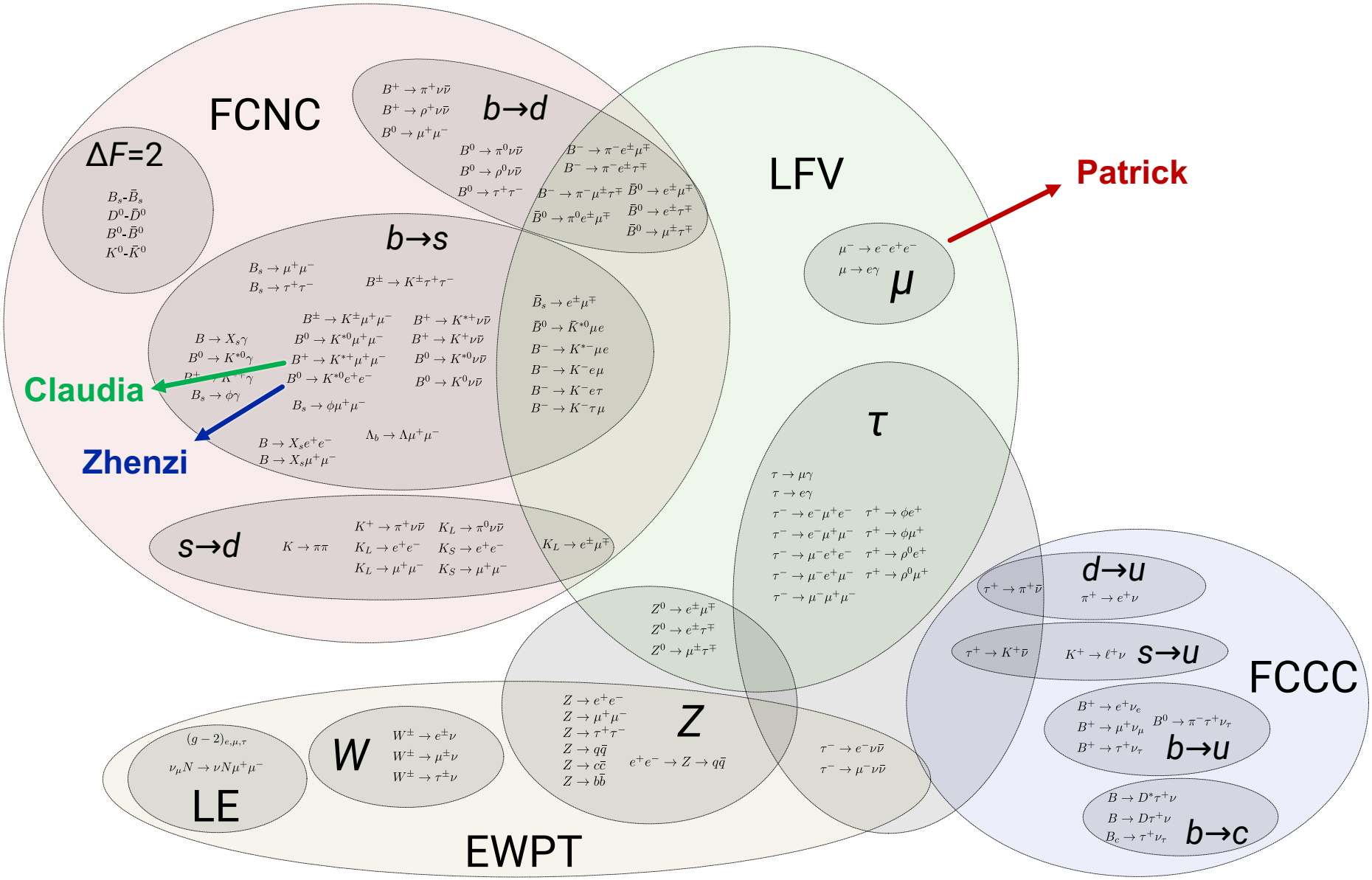


→ but **no fundamental reason why** these couplings should be universal !

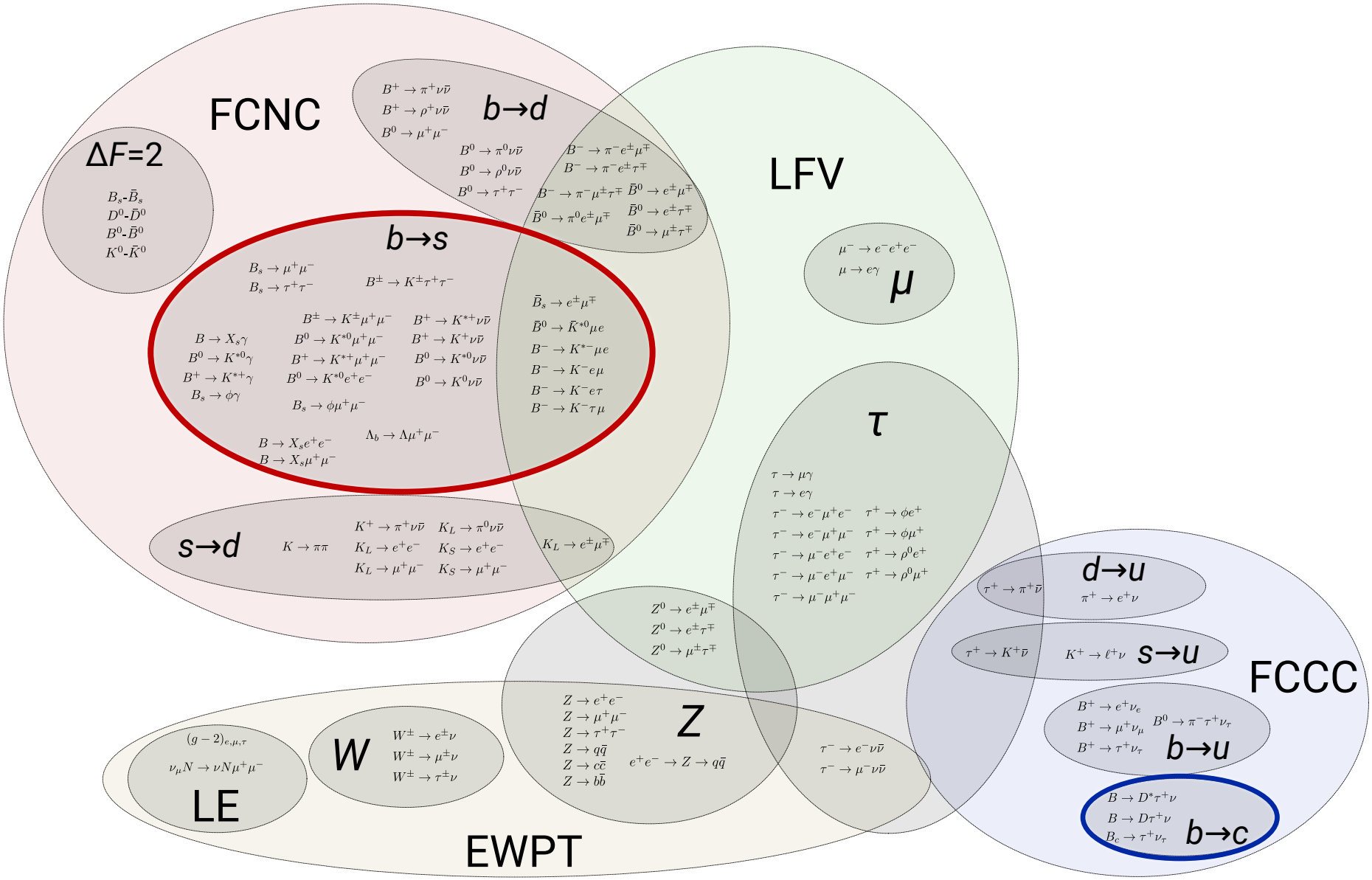
DOES NATURE RESPECT LEPTON FLAVOR UNIVERSALITY ?



Straub [Moriond 2019], Aebischer et al. [arXiv:1810.07698]



Straub [Moriond 2019], Aebischer et al. [arXiv:1810.07698]

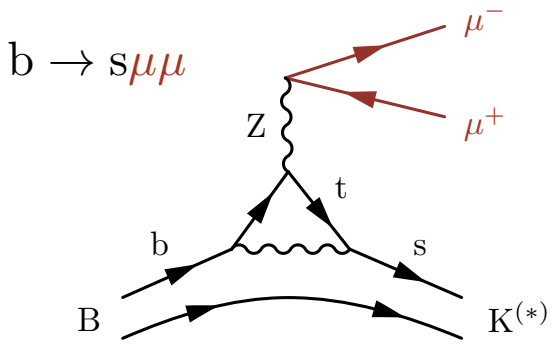


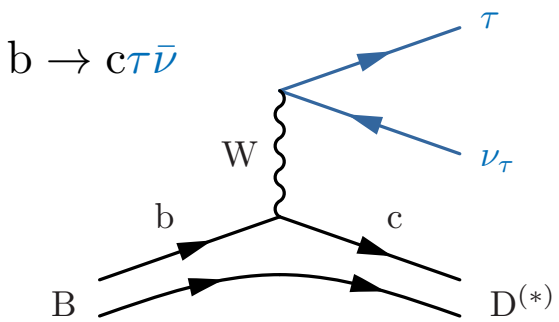
Straub [Moriond 2019], Aebischer et al. [arXiv:1810.07698]

Rare semi-leptonic B decays

$\Gamma(B \to K^{(*)} \mu\mu)$

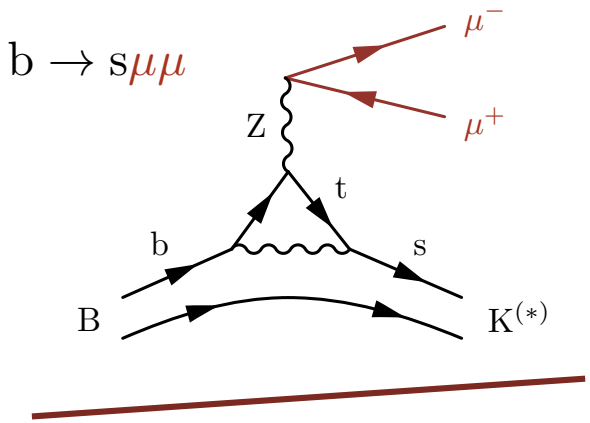
$\Gamma(B \to D^{(*)} \tau\bar{\nu})$

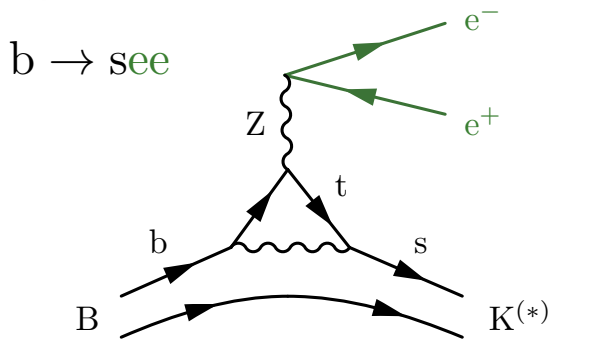


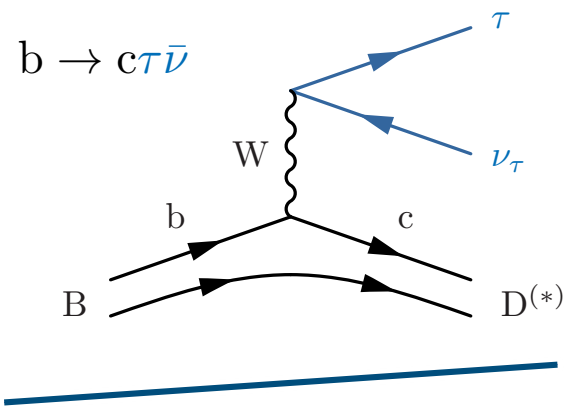


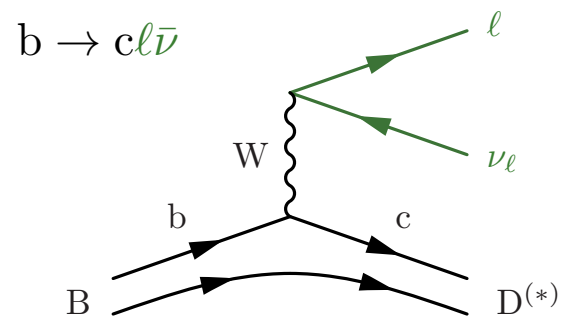
Test lepton flavor universality

$$R_{K^{(*)}} = \frac{\Gamma\left(B \to K^{(*)}\mu\mu\right)}{\Gamma\left(B \to K^{(*)}\mathrm{ee}\right)} \overset{\mathrm{SM}}{\sim} 1 \qquad R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\Gamma\left(B \to D^{(*)}\ell\bar{\nu}\right)} \overset{\mathrm{SM}}{\sim} 0.25$$





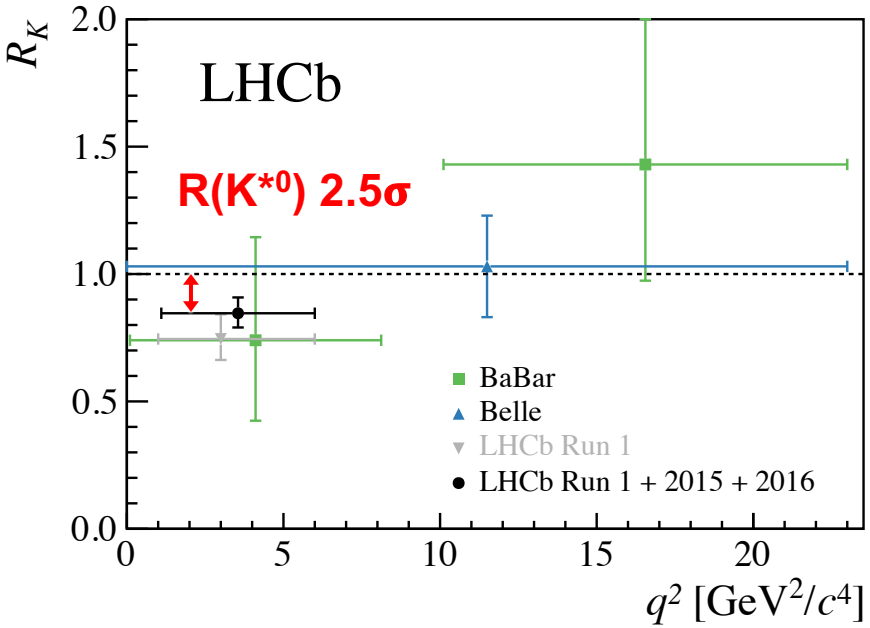


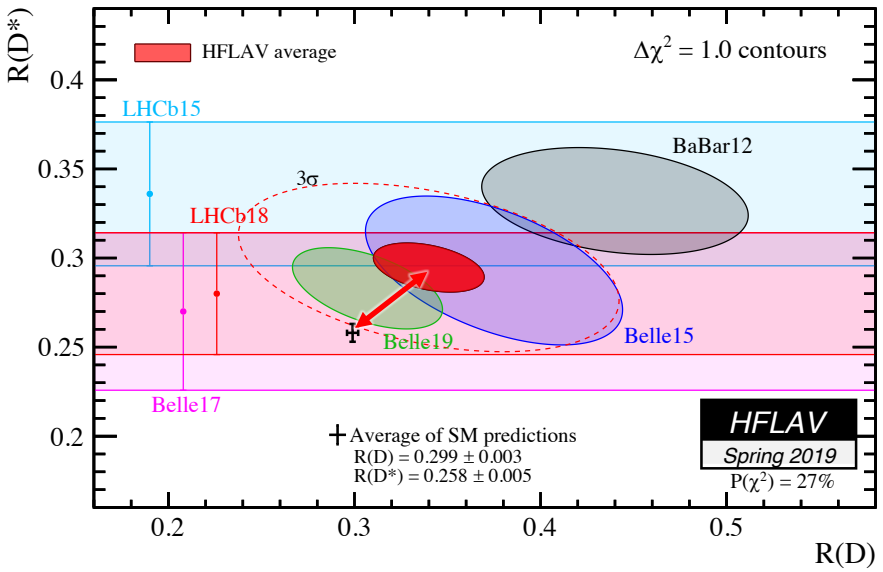


B anomalies at Belle, BaBar, LHCb

$$R_{K^{(*)}} = \frac{\Gamma\left(B \to K^{(*)}\mu\mu\right)}{\Gamma\left(B \to K^{(*)}\mathrm{ee}\right)} \overset{\text{SM}}{<} 1$$

$$R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\Gamma\left(B \to D^{(*)}\ell\bar{\nu}\right)} \overset{\text{SM}}{>} 0.25$$





R(K$^{(*)}$) and angular observables combined ~ 4σ deviation

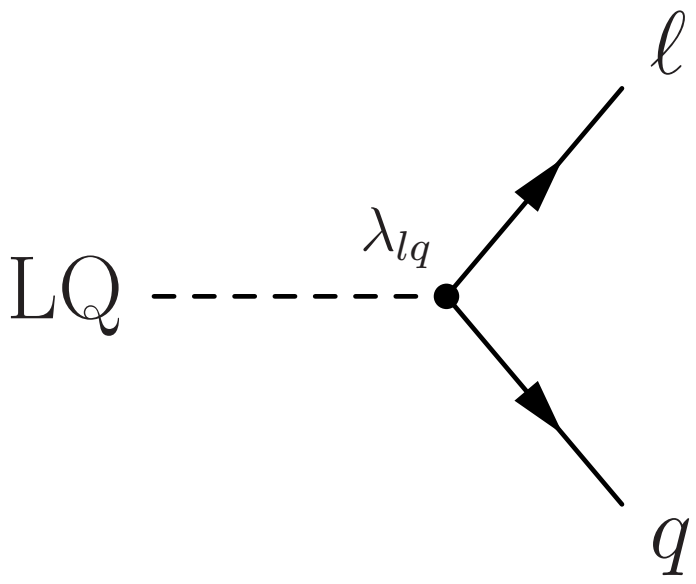
R(D$^{(*)}$) combined 3.1σ deviation

⇒ lepton flavor universality violated ?

⇒ signs of new physics ?

HOW CAN WE EXPLAIN THE ANOMALIES ?

Leptoquarks



- **scalar** or **vector boson**
- **decays into ℓq**

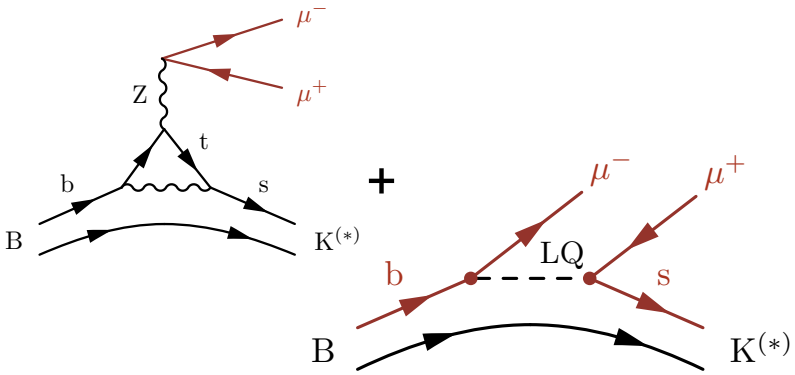
  $\Rightarrow$ carries L, B, color

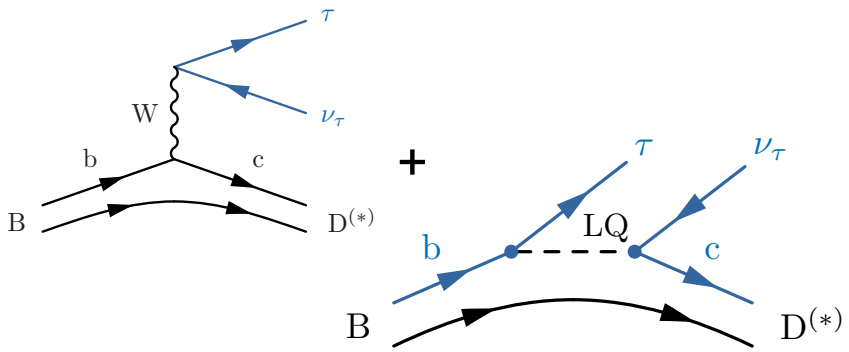
$$\underbrace{\mathrm{LQ}}_{\pm\frac{1}{3},\pm\frac{2}{3},\pm\frac{4}{3},\pm\frac{5}{3}} \rightarrow \underbrace{\ell}_{\pm 1,0} \quad \underbrace{q}_{\mp\frac{1}{2},\pm\frac{2}{3}}$$

- **fractional charge**
- **coupling $\lambda_{\ell q}$**

B anomalies according to LQs

$$R_{K^{(*)}} = \frac{\Gamma\left(B \to K^{(*)}\mu\mu\right)}{\Gamma\left(B \to K^{(*)}\mathrm{ee}\right)} \overset{\text{SM}}{<} 1 \qquad R_{D^{(*)}} = \frac{\Gamma\left(B \to D^{(*)}\tau\bar{\nu}\right)}{\Gamma\left(B \to D^{(*)}\ell\bar{\nu}\right)} \overset{\text{SM}}{>} 0.25$$

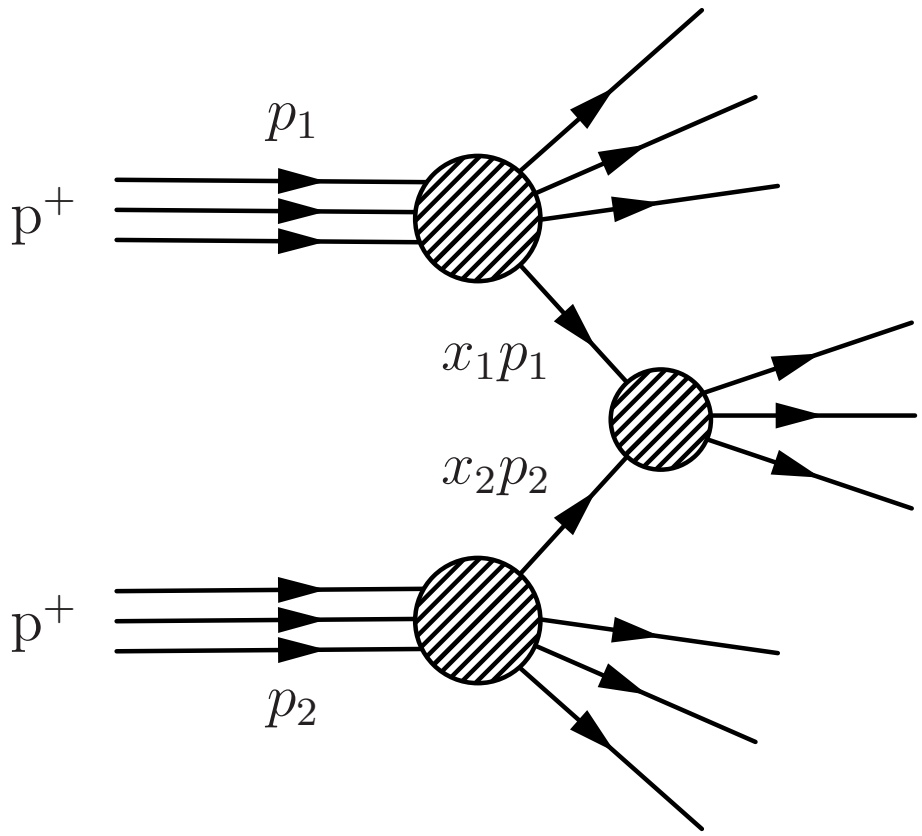




$$\Rightarrow \quad \lambda_{\ell q} \sim \begin{array}{c} \\ \mathrm{d/u'} \\ \mathrm{s/c'} \\ \mathrm{b/t'} \end{array} \begin{array}{c} \begin{array}{ccc} \mathrm{e}/\nu_\mathrm{e} & \mu/\nu_\mu & \tau/\nu_\tau \end{array} \\ \begin{pmatrix} 0 & 0 & -0.02 \\ 0 & +0.02 & 0.13 \\ 0 & -0.13 & 1 \end{pmatrix} \end{array} \qquad \mathrm{LQ} \approx \mathrm{LQ}_3$$

signs for destructive interference with SM in B → K$\mu\mu$ decay

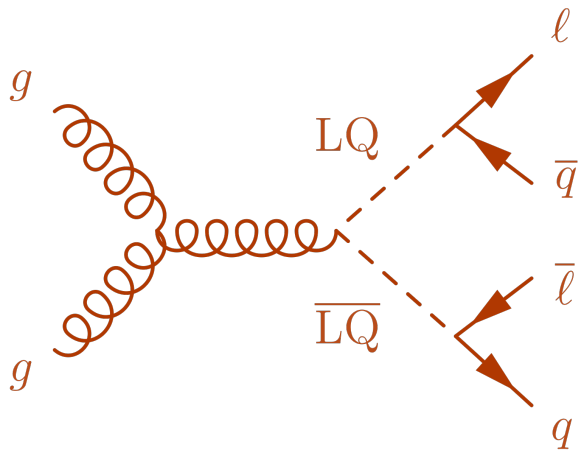
[Isidori group: arXiv:1706.07808, arXiv:1903.11517, Julie's talk]

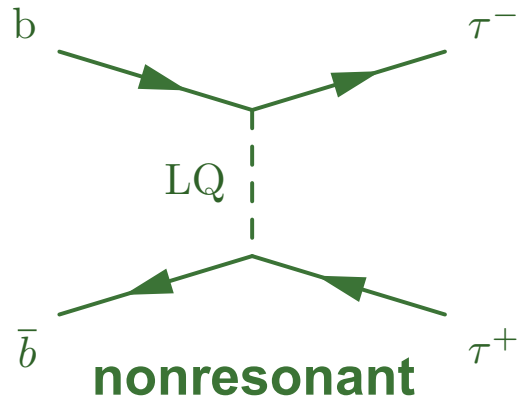


HOW DO WE FIND LQs ?

LQ production at CMS

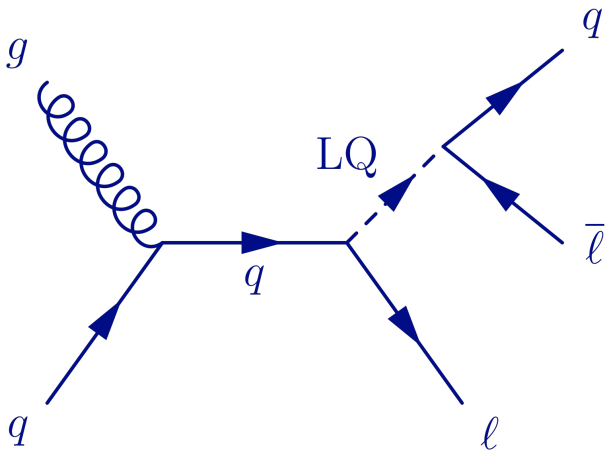
pair

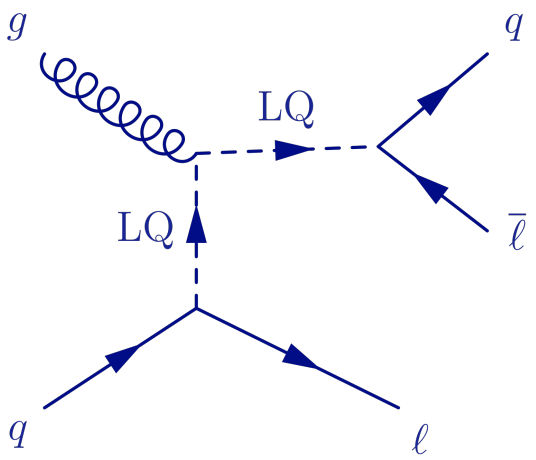




nonresonant

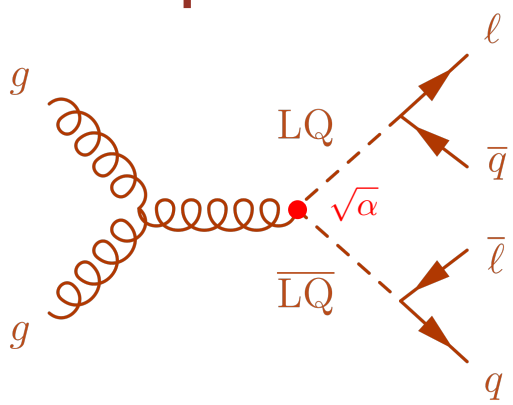
single





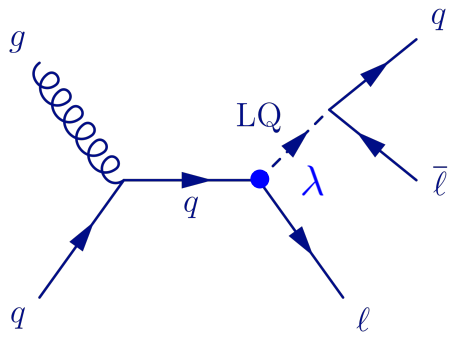
LQ production properties

pair



- large,
- model independent

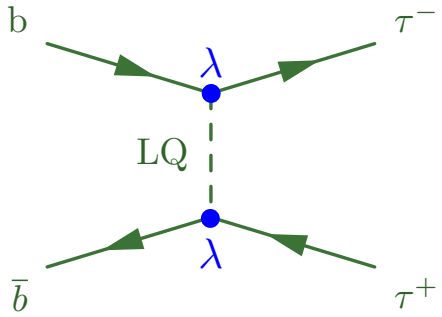
single



$\sigma \propto \lambda^2$

- b-PDF suppression

nonresonant

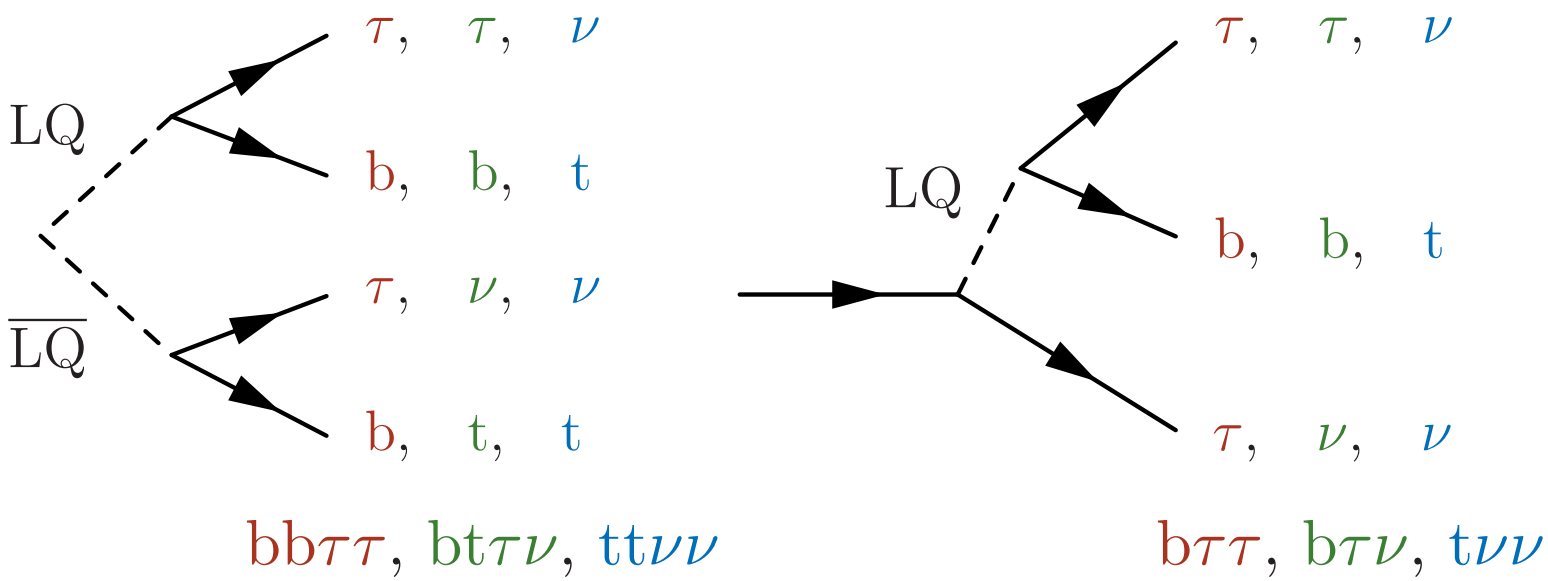


$\sigma \propto \lambda^4$

- PDF suppression ^ 2
- wide resonance

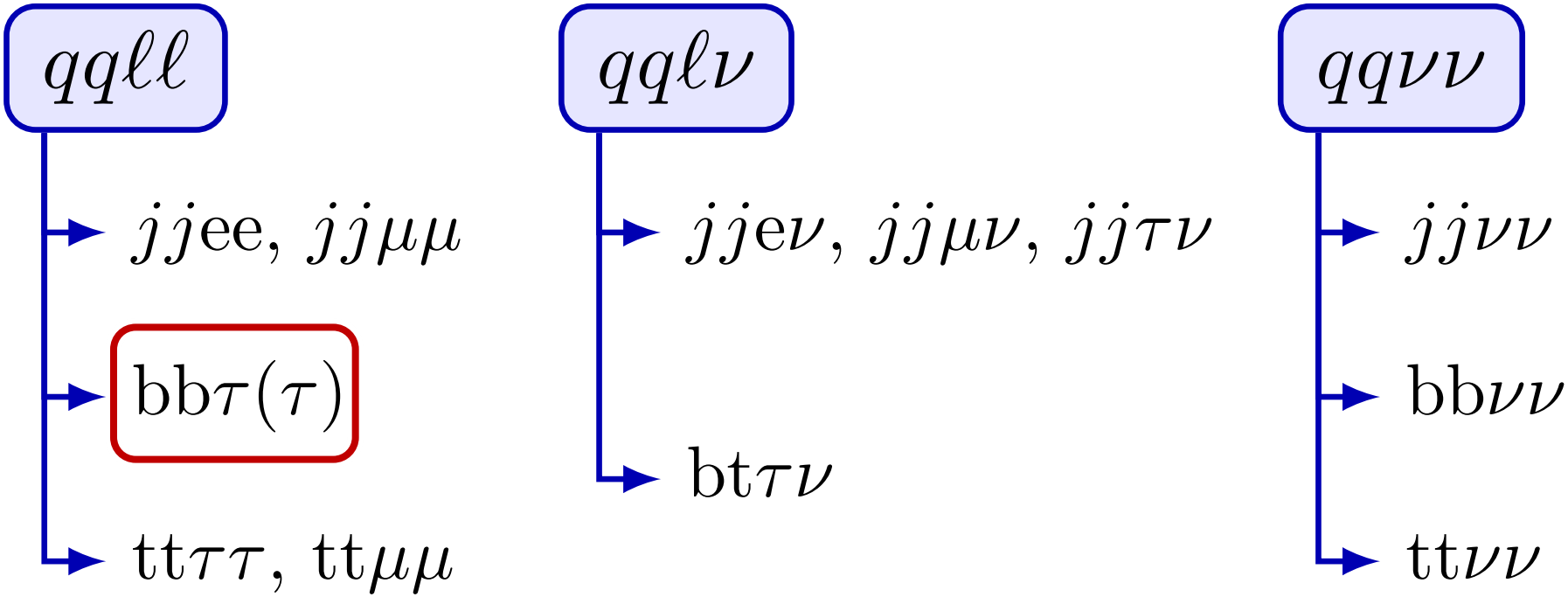
LQ decay signatures at CMS

purely third-generation $LQ_3 \rightarrow b\tau$ or $t\nu$:

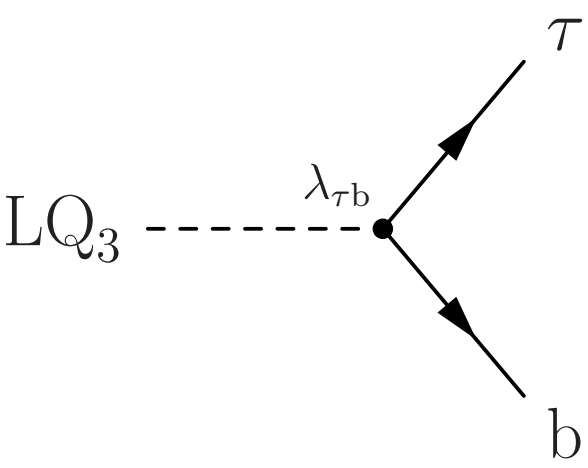


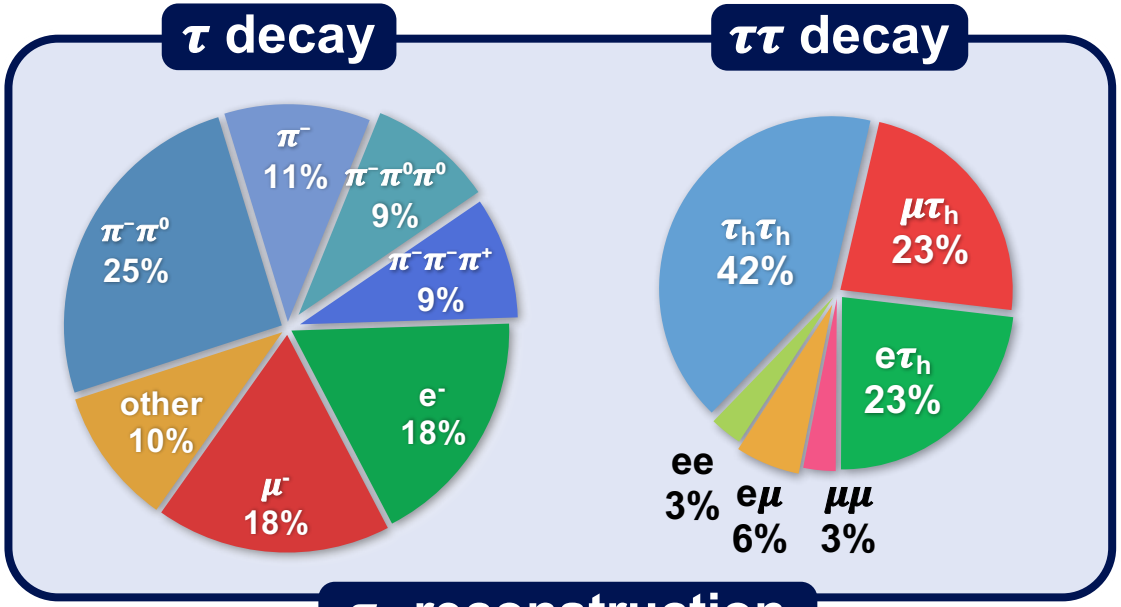
LQ analyses at the LHC

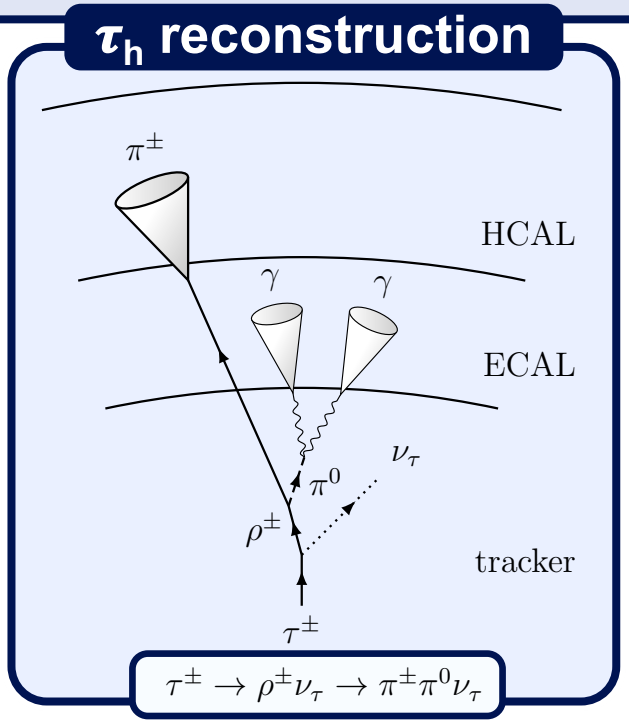
ordered by final state:



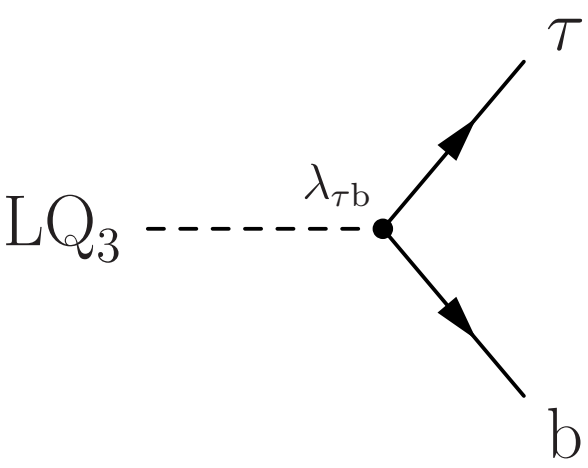
LQ reconstruction

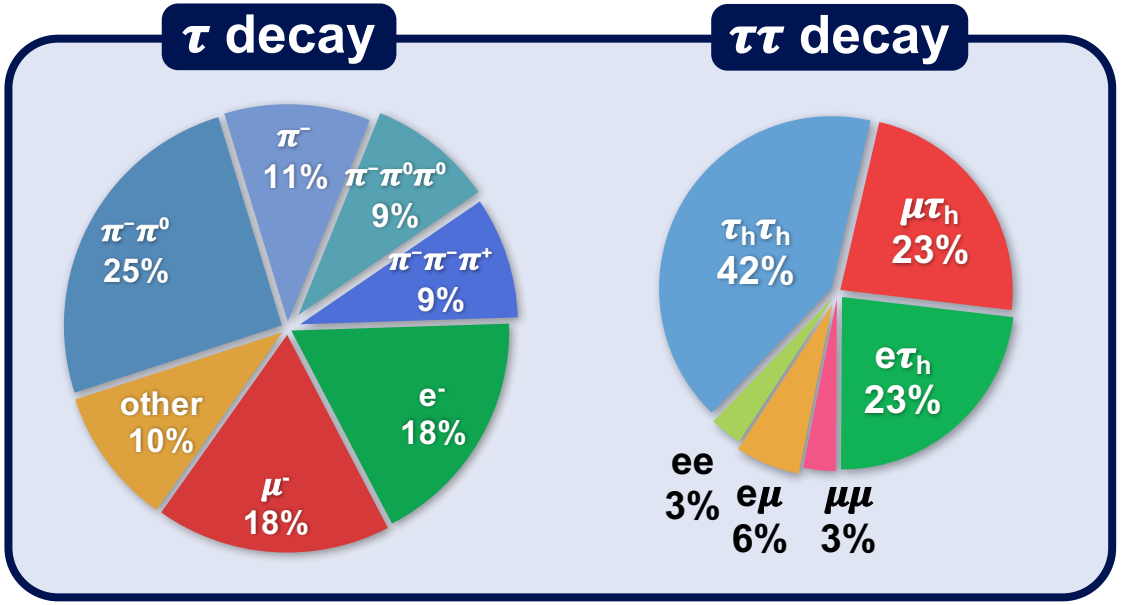


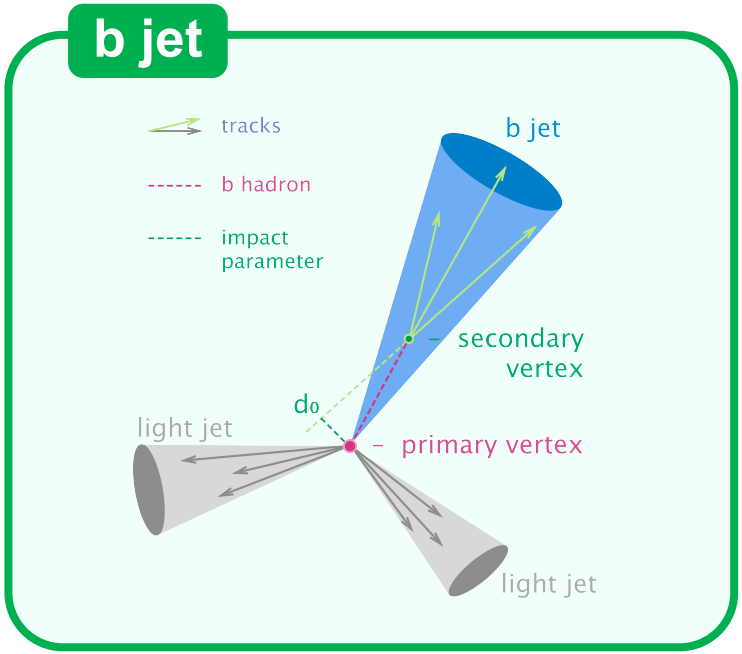




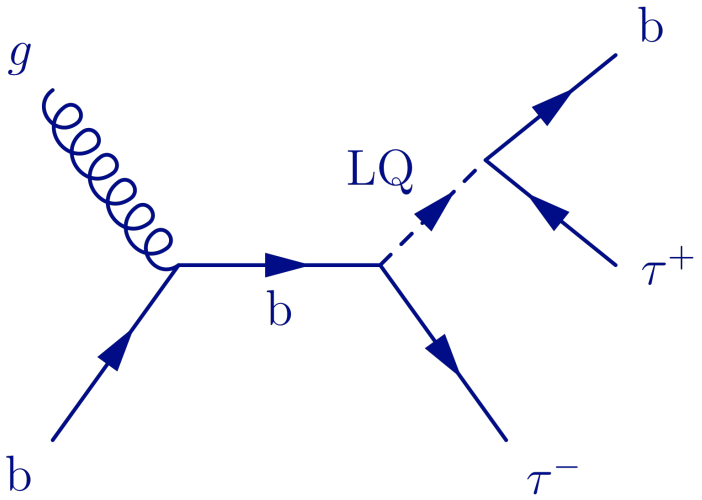
LQ reconstruction

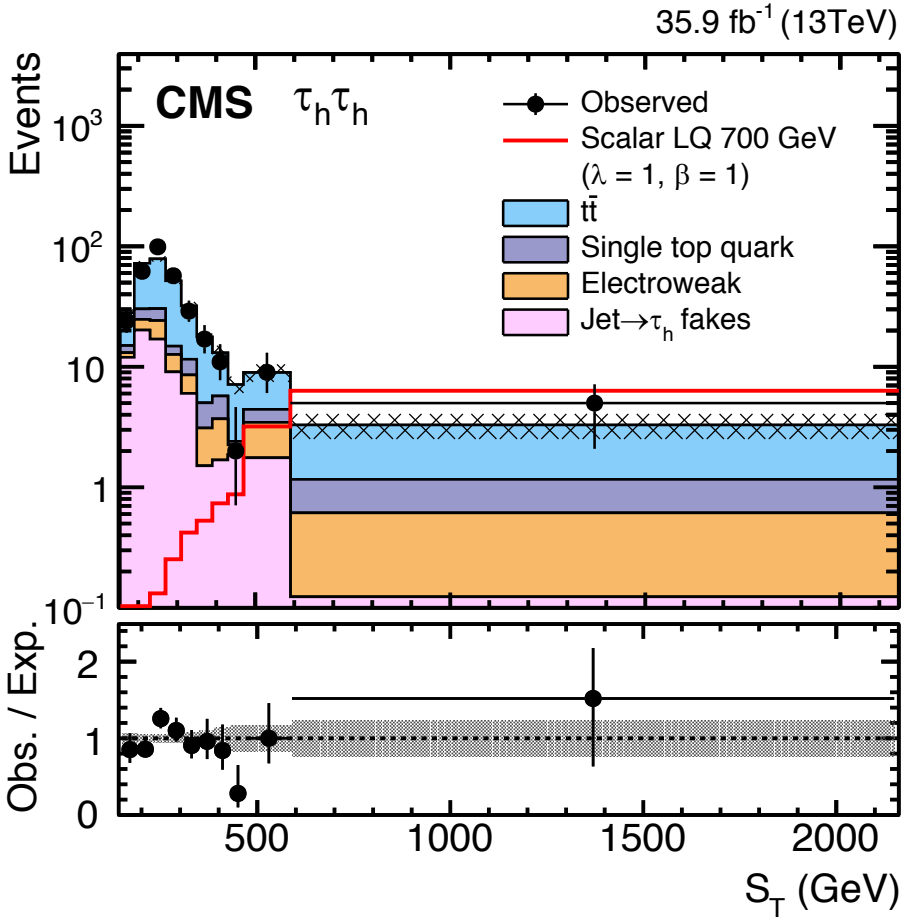






LQ reconstruction



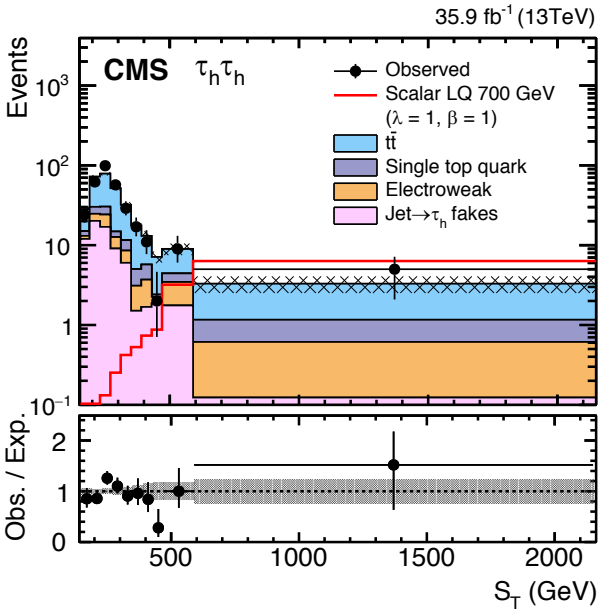


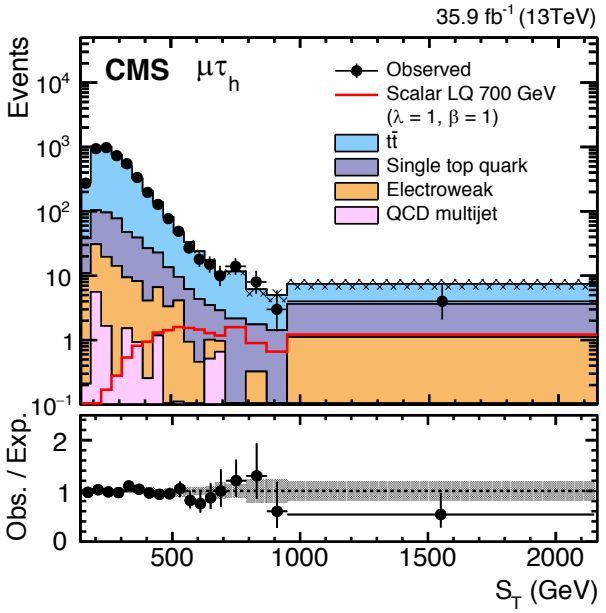
discriminating variable: "scalar sum-p_T"

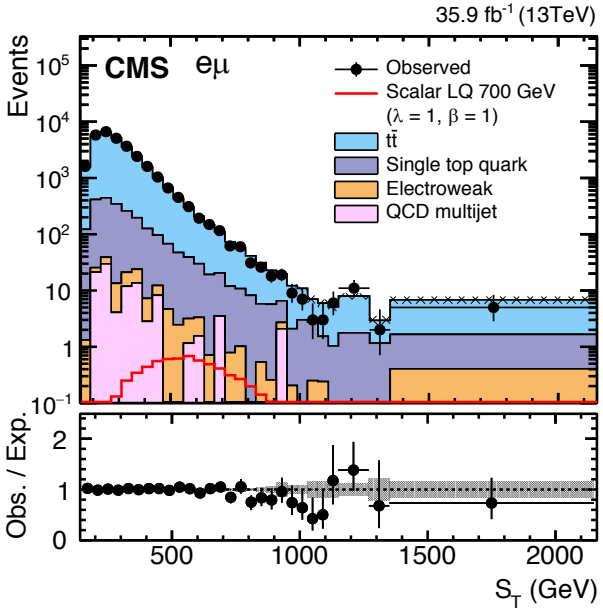
$$S_{\mathrm{T}} = p_{\mathrm{T}}^{\tau^+} + p_{\mathrm{T}}^{\tau^-} + p_{\mathrm{T}}^{j}$$

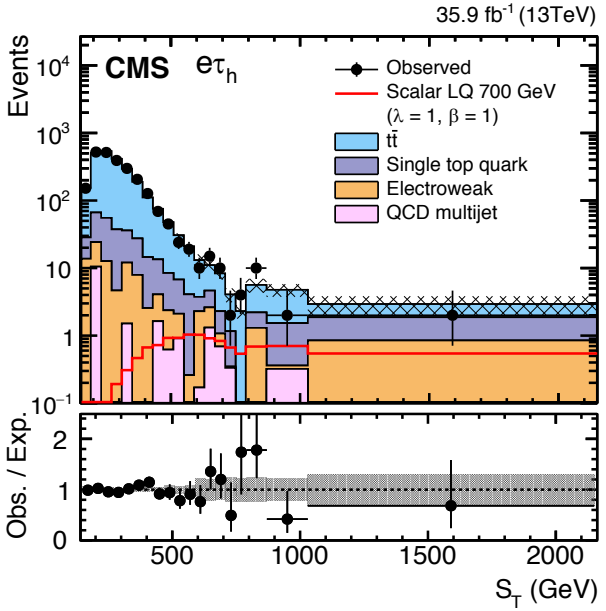
LQ → bτ single production

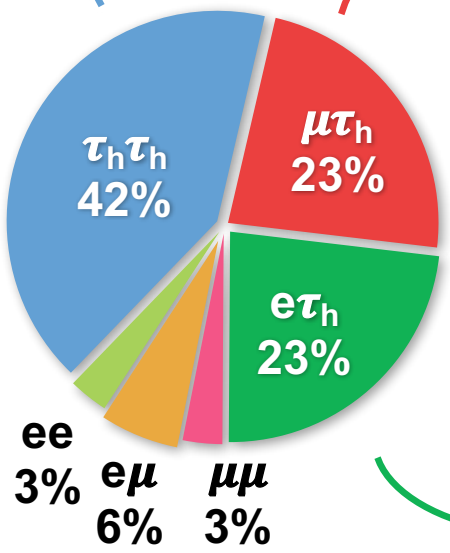
require 1 b jet
+ ττ final states:









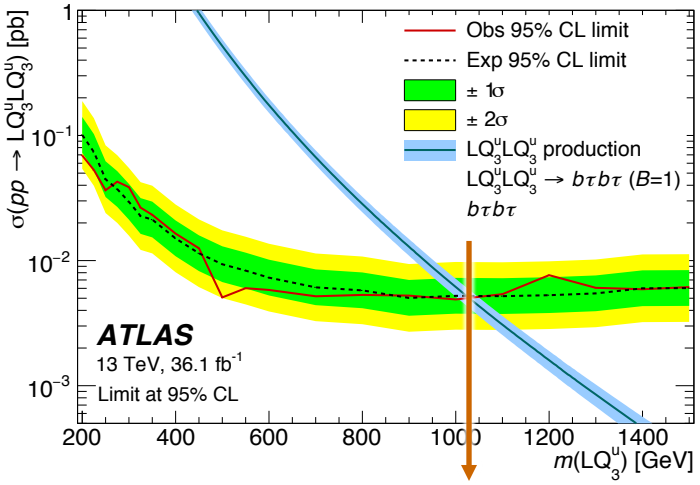


eμ control region to constrain uncertainties

EXO-17-029

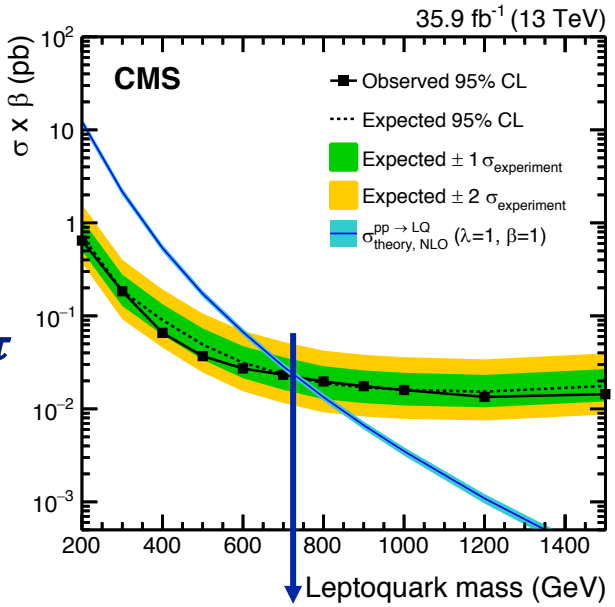
Upper limits on LQ → bτ

pair
LQ LQ → bbττ



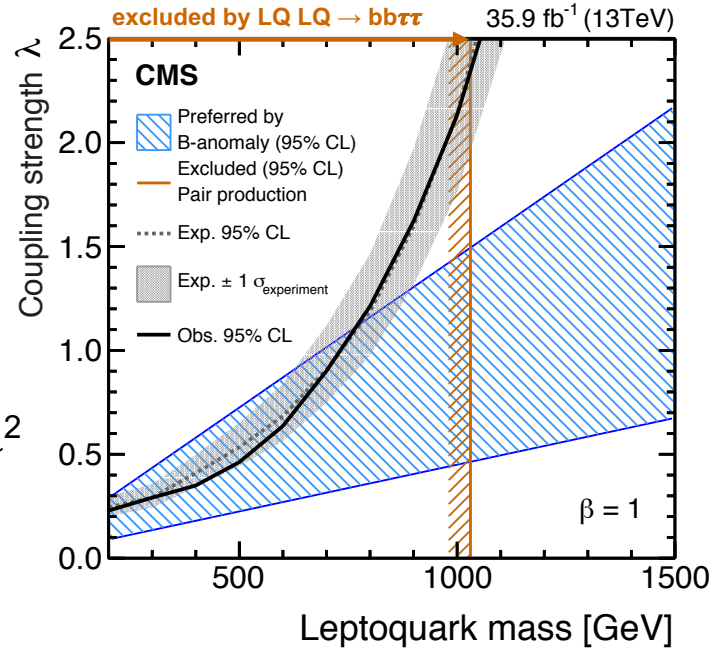
lower limit m_{LQ} ~ 1030 GeV

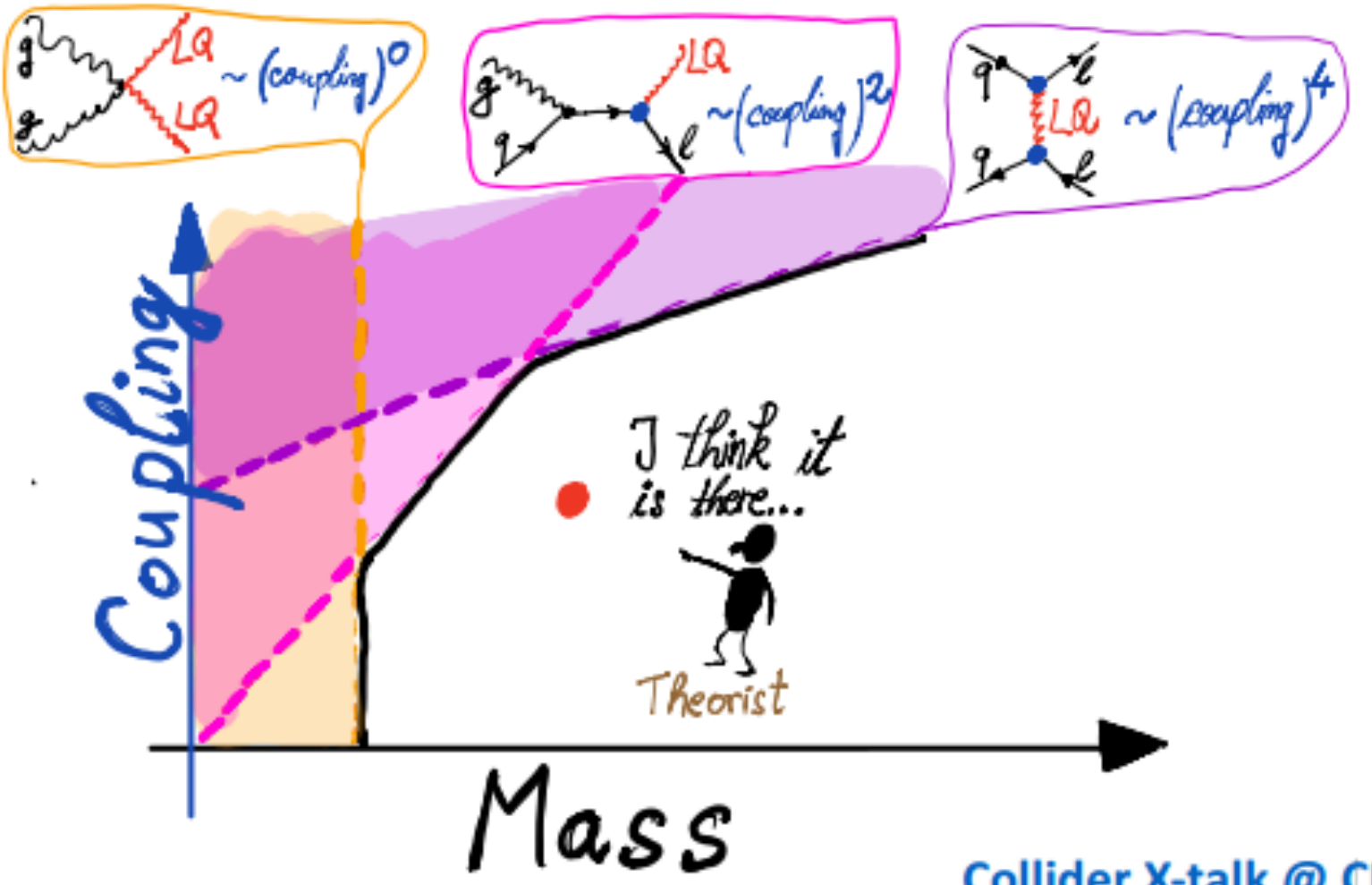
single
LQ τ → bττ



m_{LQ} > 744 GeV

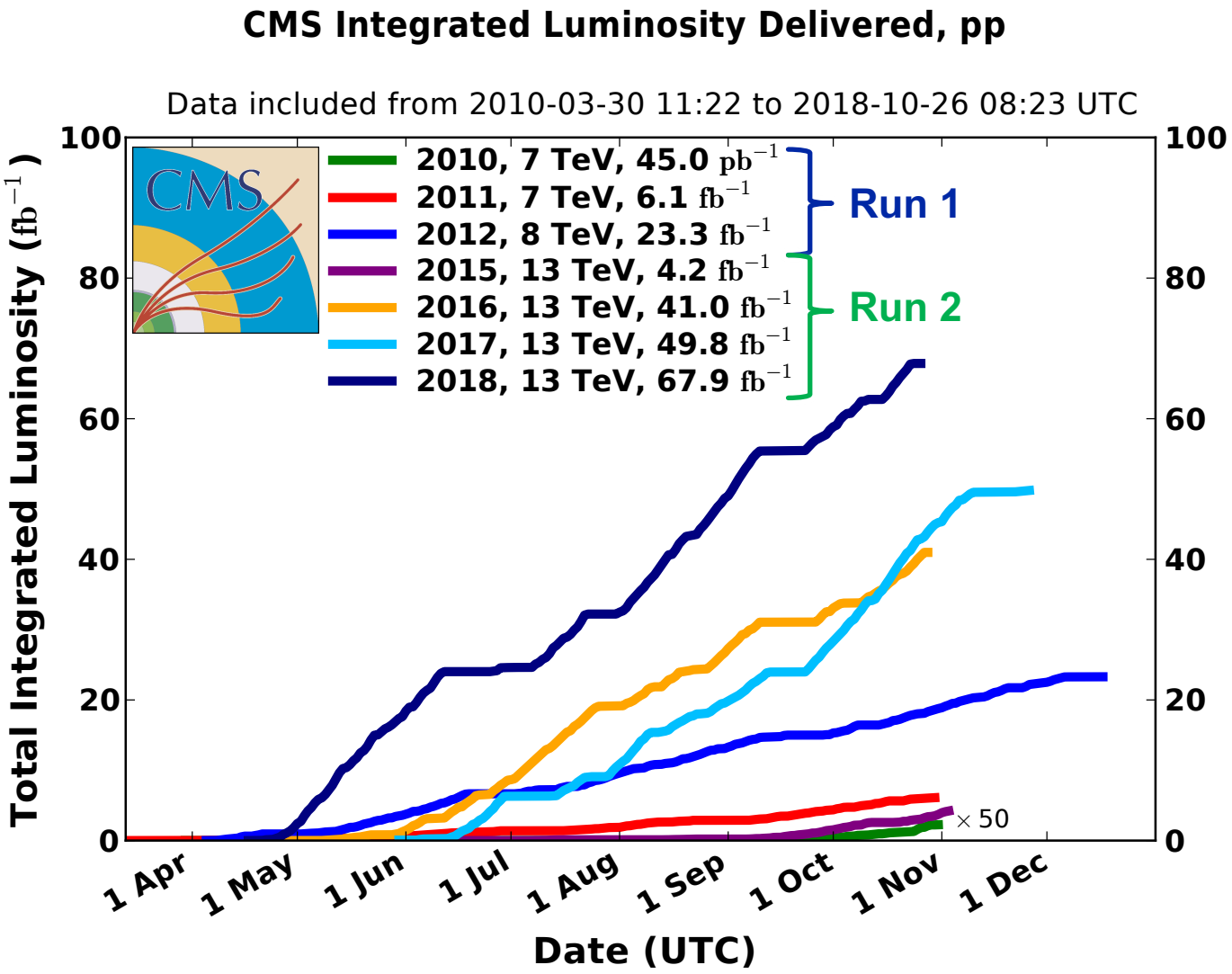
$\sigma(\text{single}) \sim \lambda^2$





[Collider X-talk @ CERN]
(A. Greljo, 29 Nov.)

More data !

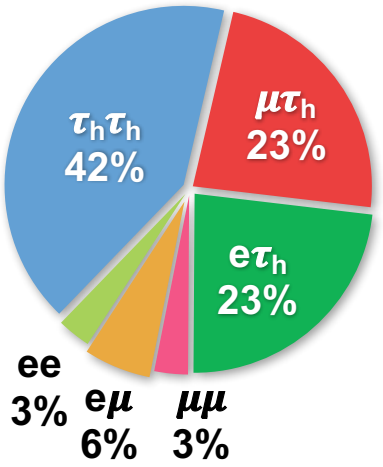

CMS Integrated Luminosity Delivered, pp
Data included from 2010-03-30 11:22 to 2018-10-26 08:23 UTC
Total Integrated Luminosity (fb^{-1})
2010, 7 TeV, 45.0 pb^{-1}
2011, 7 TeV, 6.1 fb^{-1}
2012, 8 TeV, 23.3 fb^{-1}
2015, 13 TeV, 4.2 fb^{-1}
2016, 13 TeV, 41.0 fb^{-1}
2017, 13 TeV, 49.8 fb^{-1}
2018, 13 TeV, 67.9 fb^{-1}
Run 1
Run 2
× 50
0
20
40
60
80
100
1 Apr
1 May
1 Jun
1 Jul
1 Aug
1 Sep
1 Oct
1 Nov
1 Dec
Date (UTC)

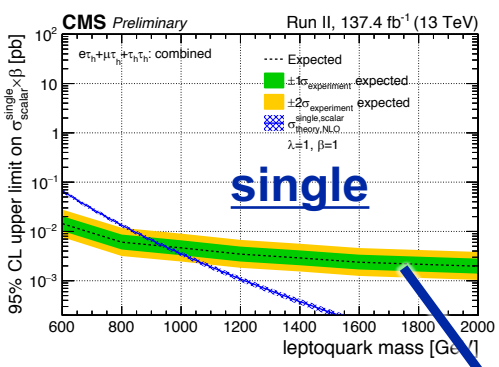
Run-2 legacy LQ → bτ

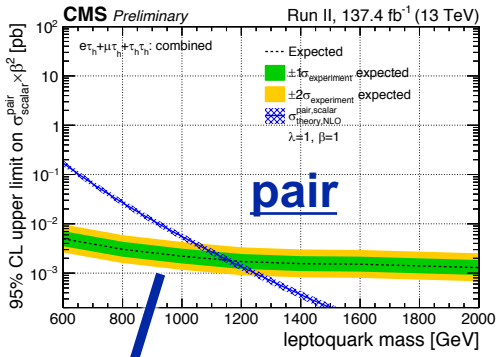
- combine **2016 + 2017 + 2018**
- combine most important **ττ channels**:

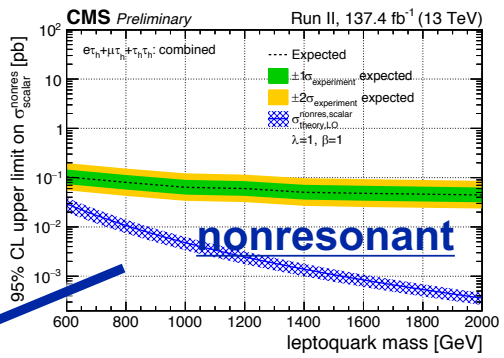
  $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$

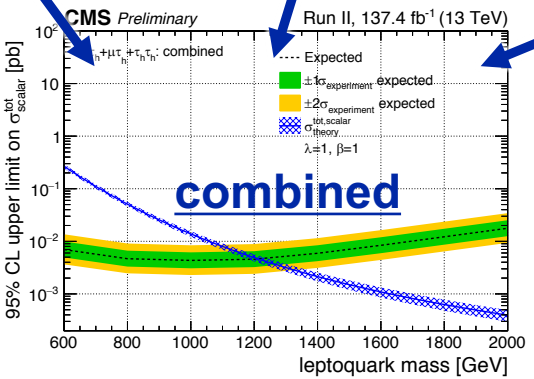
- combine **all three production modes** through several b jet categories
- currently updating DeepTauID for higher efficiency

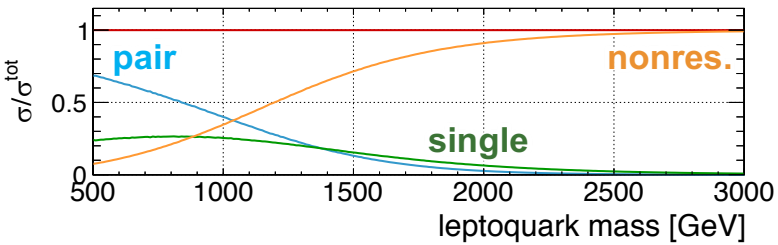






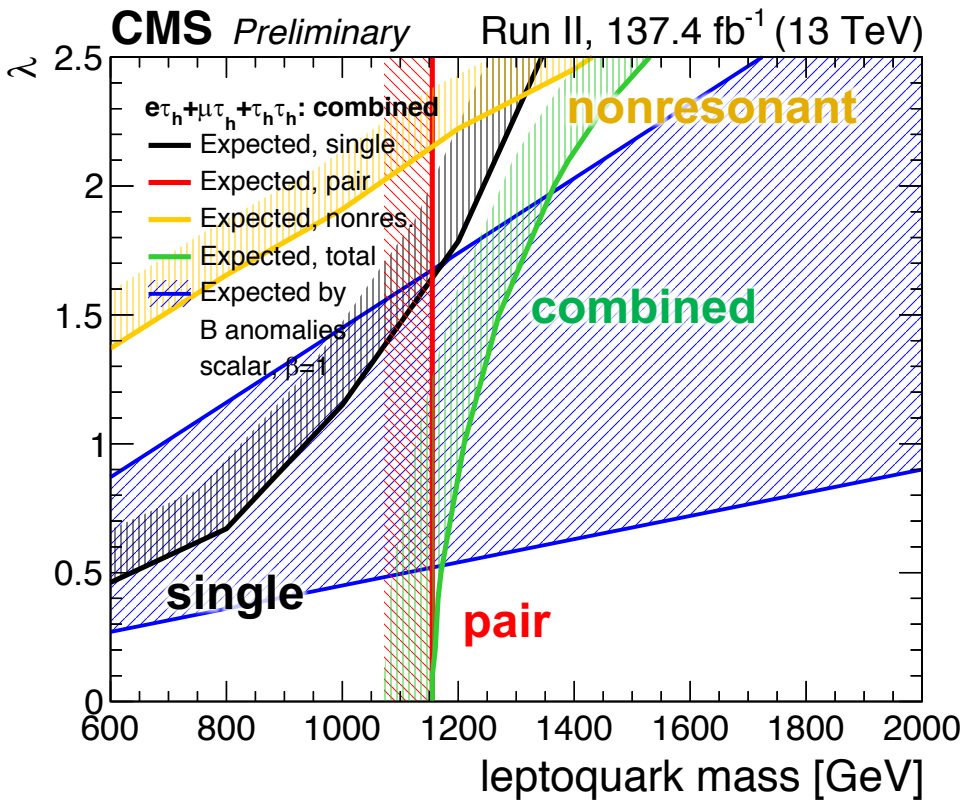




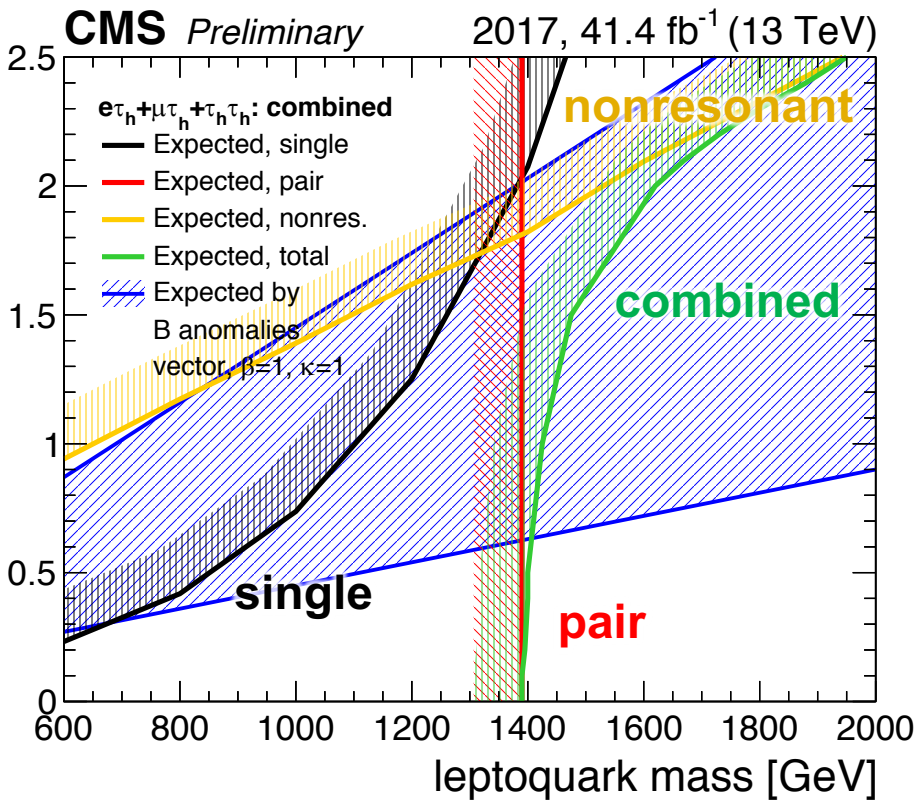


Exclusion in λ vs. m_{LQ} space

scalar – Run 2

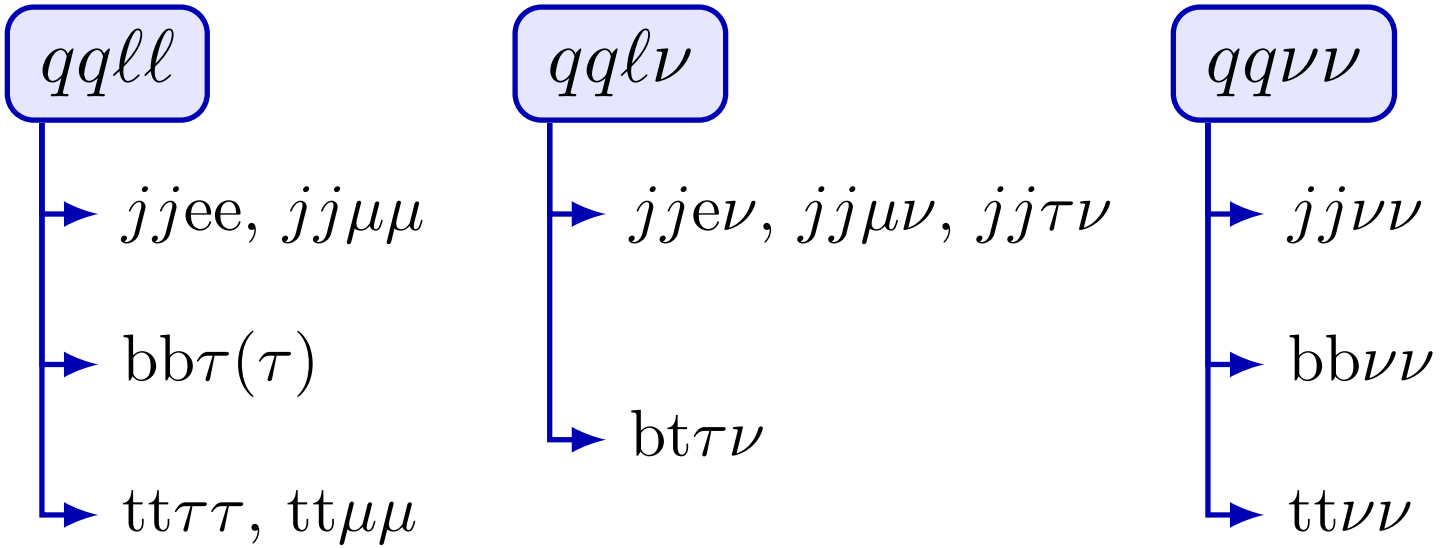


vector – 2017



OTHER SEARCHES ?

Explored couplings

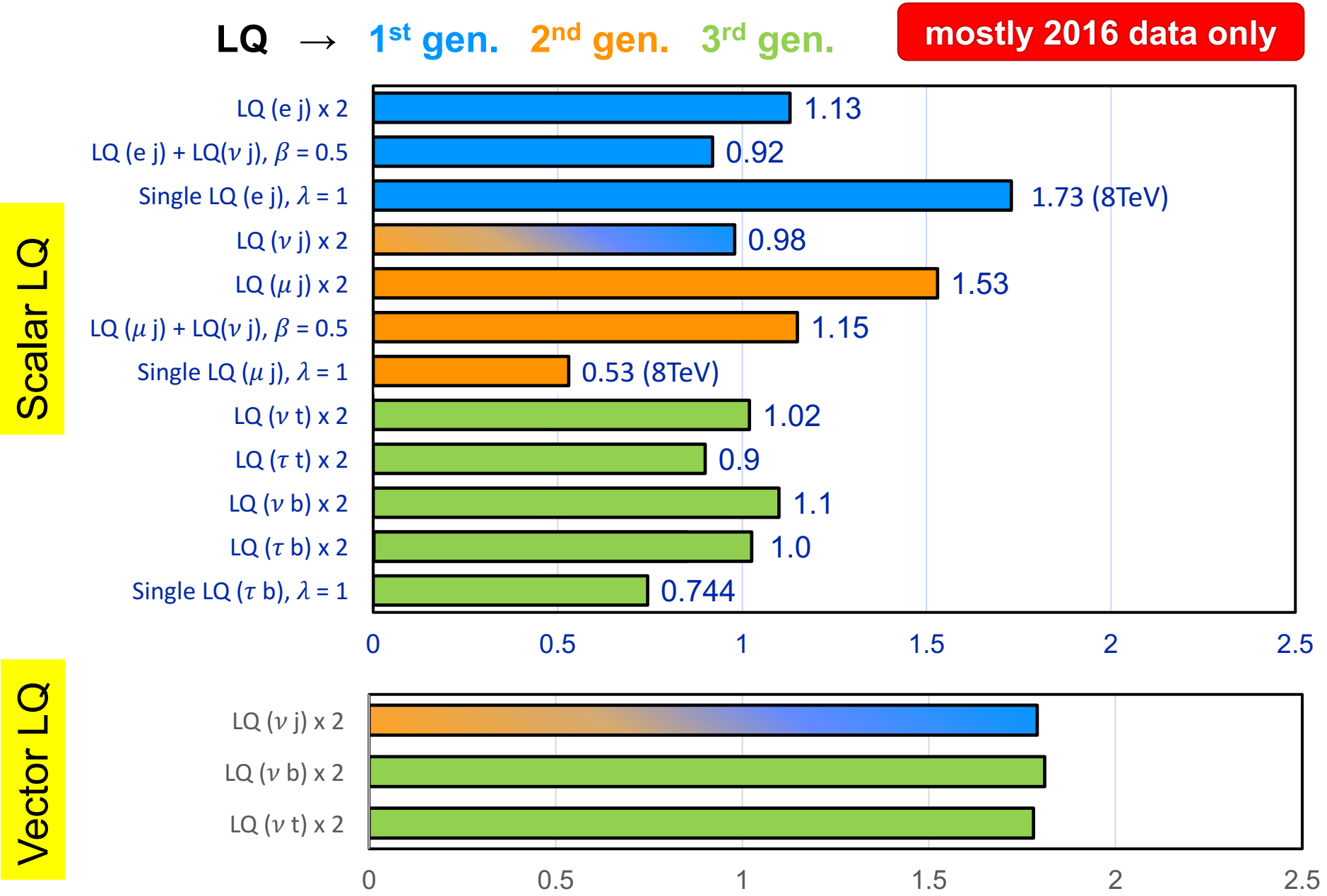


	q	b	t
ν	✓	✓	✓
μ	✓		✓
τ		✓	✓

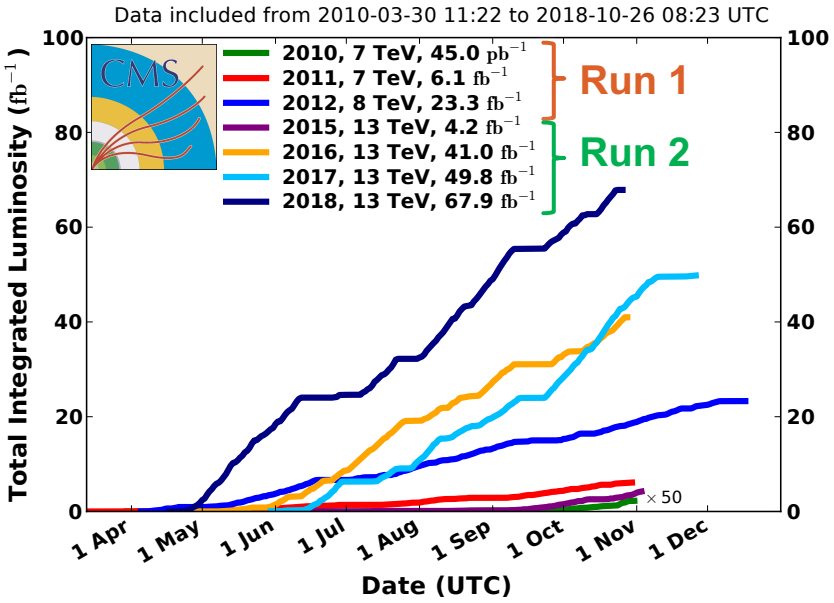
limits available indirectly or in progress

CMS LQ search summary

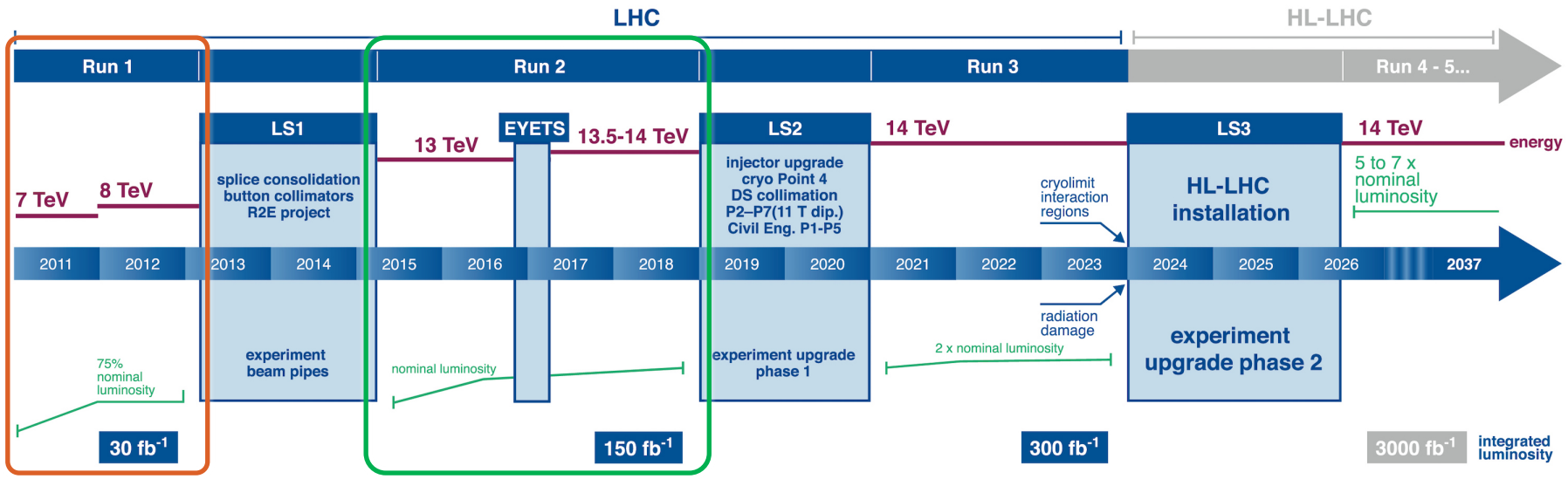
[credit to Yuta]



WHAT’S NEXT ?

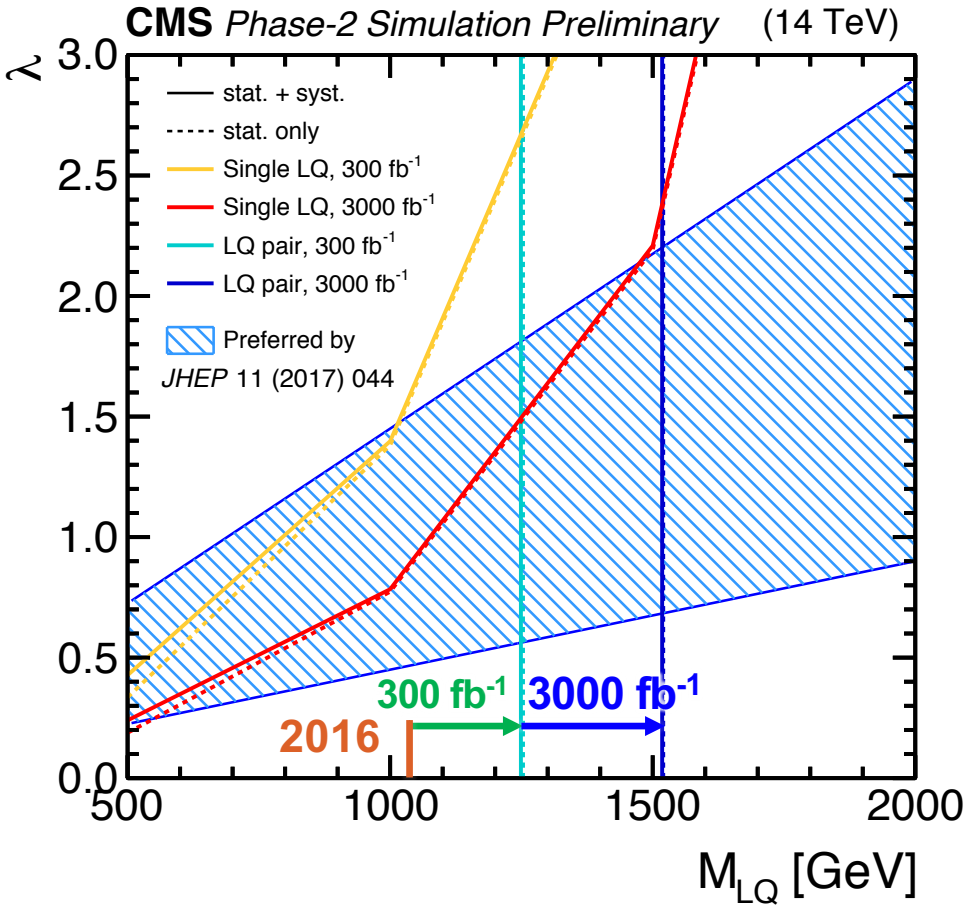


LHC / HL-LHC Plan



HL-LHC LQ → bτ

- limit can be further improved with larger dataset, and higher $\sqrt{s}$
- some searches will have to contend with increased pileup



[CMS-PAS-FTR-18-028 (Pablo & Yuta), CMS-PAS-FTR-18-008]

CONCLUSIONS

Conclusion

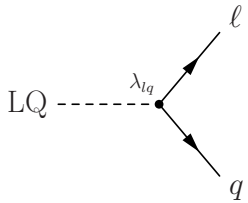
- **third-generational LQs** with $m_{LQ} \sim O(\text{TeV})$ have are **well motivated** by the B anomalies
- many LQ couplings have been probed at the LHC
- so far, **no deviations above the SM** observed with m_{LQ} exclusions in the TeV range
- analyses have been mostly been statistically limited
- looking forward to **new results with full Run-2 data**, and including the nonresonant mode

References

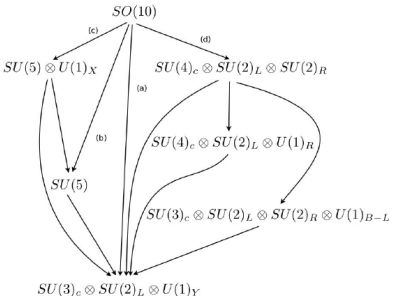
- LHC Seminar talk on LQ_3 by Francesco Romeo
  https://indico.cern.ch/event/719627/
- *The Leptoquark Hunter's Guide: Pair Production*
  https://arxiv.org/abs/1706.05033
- *The Leptoquark Hunter's Guide: Large Coupling* (single + *t*-channel)
  https://arxiv.org/abs/1810.10017
- *B-physics anomalies: a guide to combined explanations*
  https://arxiv.org/abs/1706.07808
- *Revisiting the vector leptoquark explanation of the B-physics anomalies*
  https://arxiv.org/abs/1903.11517
- *Leptoquark toolbox for precision collider studies*
  https://arxiv.org/abs/1801.07641
- SM@LHC 2017 by Arne Reimers
  https://indico.cern.ch/event/760184/

BACK UP

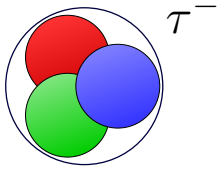
Some general BSM predicting LQs



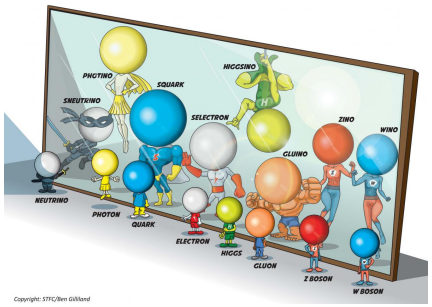
- **Grand Unified Theory**: larger symmetry group from which SM's $SU(3)_C x SU(2)_L x U(1)_Y$ emerges
  → quarks and leptons unified in one fermion multiplet
  ⇒ lepton-quark interaction via new gauge bosons



- **Compositeness**: fermions are composite particles
  ⇒ bound states may decay into a lepton + quark



- **Supersymmetry** with *R*-parity violation:
  ⇒ sparticles may decay into lepton + quark



⇒ new gauge bosons carrying both lepton and baryon number: leptoquarks !

LQ decay signatures at CMS

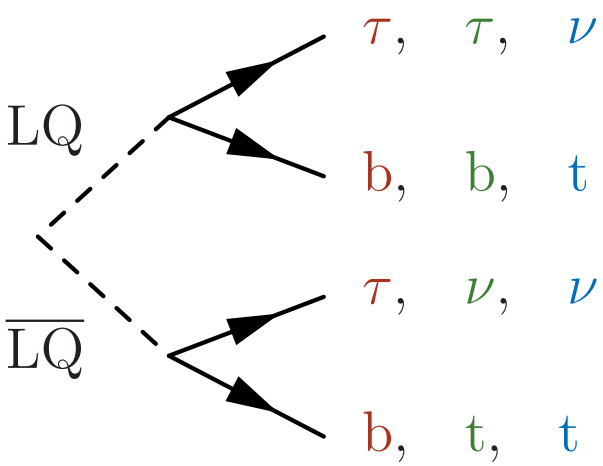
analyses often use a **parameter β**:

$$\mathcal{B}\left(\mathrm{LQ} \to q\ell\right) = \beta$$
$$\mathcal{B}\left(\mathrm{LQ} \to q'\nu\right) = 1 - \beta$$

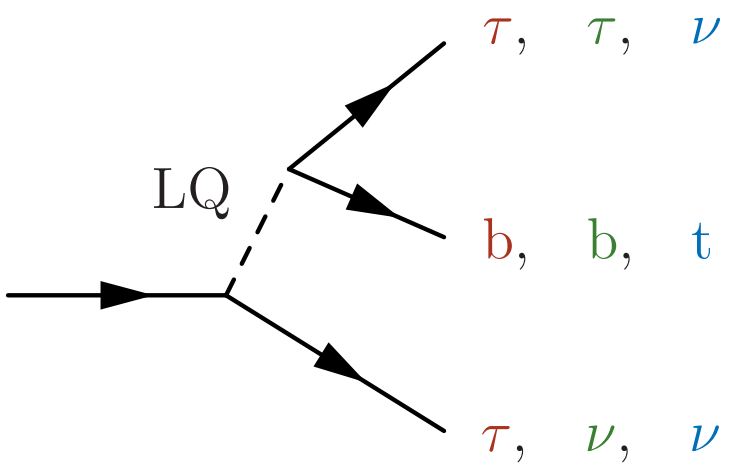
typical benchmarks β = 0, 0.5, 1

e.g. **purely third-generation LQ_3**:

$$\mathcal{B}\left(\mathrm{LQ}_3 \to \mathrm{b}\tau\right) = \beta$$
$$\mathcal{B}\left(\mathrm{LQ}_3 \to \mathrm{t}\nu_\tau\right) = 1 - \beta$$

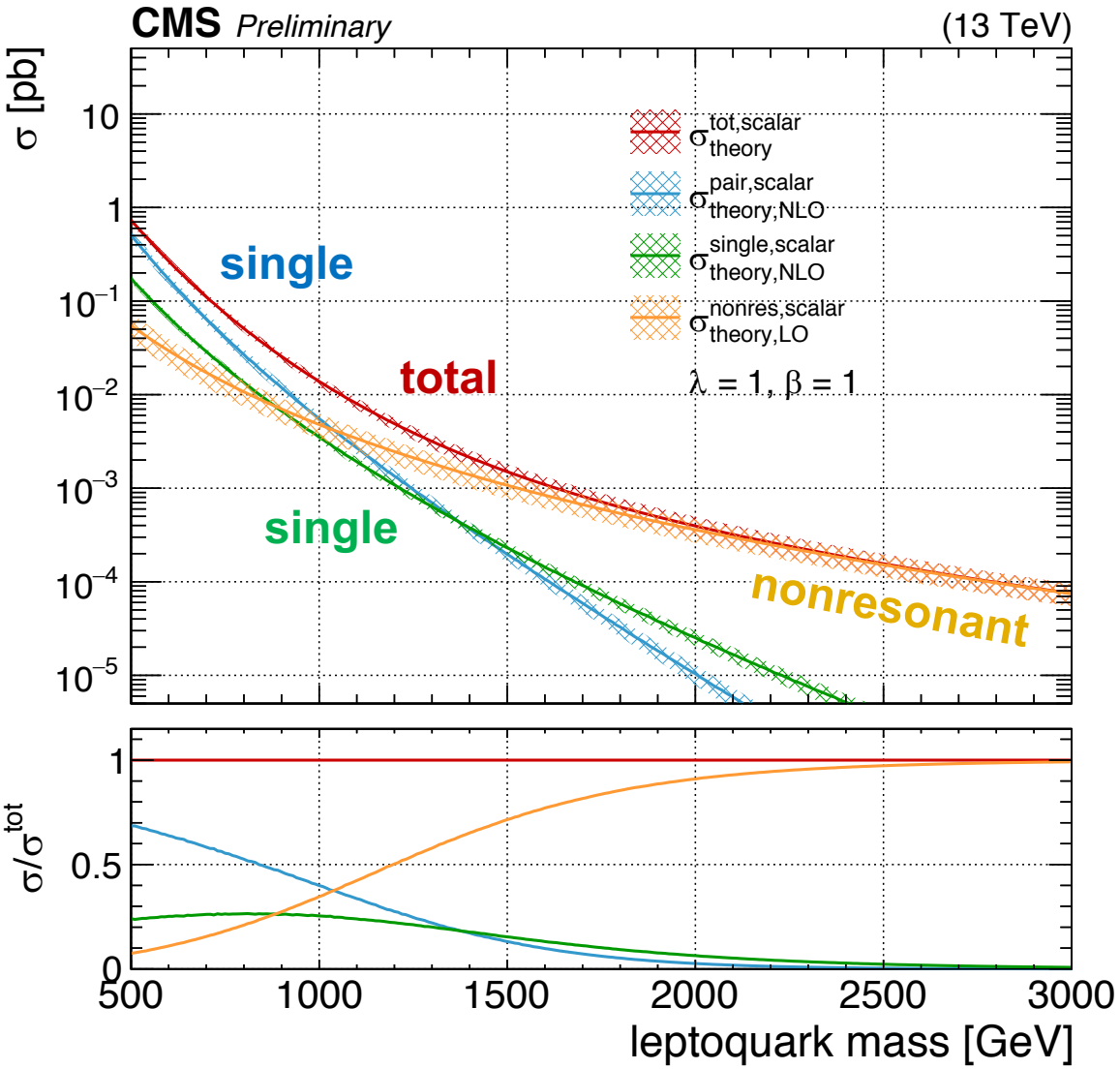


$\mathrm{bb}\tau\tau$, $\mathrm{bt}\tau\nu$, $\mathrm{tt}\nu\nu$



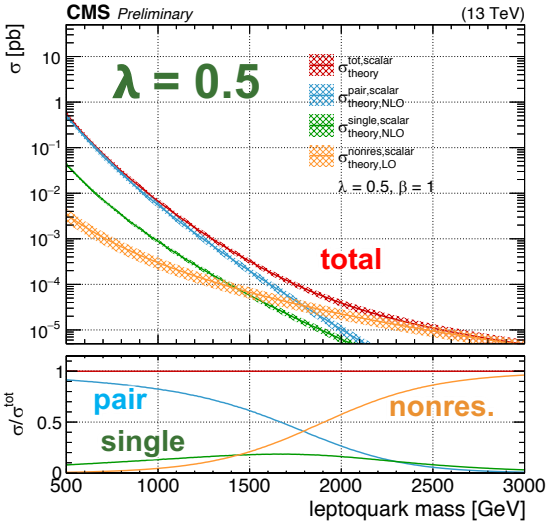
$\mathrm{b}\tau\tau$, $\mathrm{b}\tau\nu$, $\mathrm{t}\nu\nu$

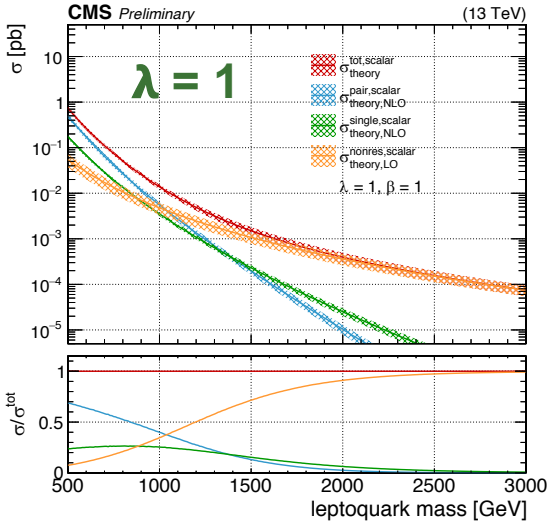
LQ → bτ production cross sections

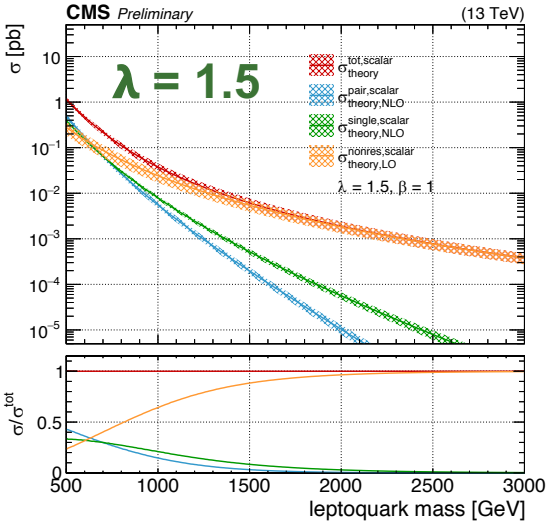


$$\sigma^{\mathrm{tot}}(\lambda) = \lambda^2 \sigma^{\mathrm{single}}_{\lambda=1} + \sigma^{\mathrm{pair}}_{\lambda=1} + \lambda^4 \sigma^{\mathrm{nonres}}_{\lambda=1}$$

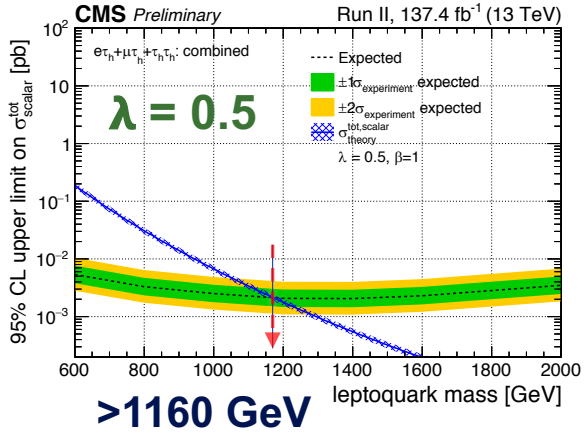
Obtaining exclusion in λ vs. m_{LQ} space

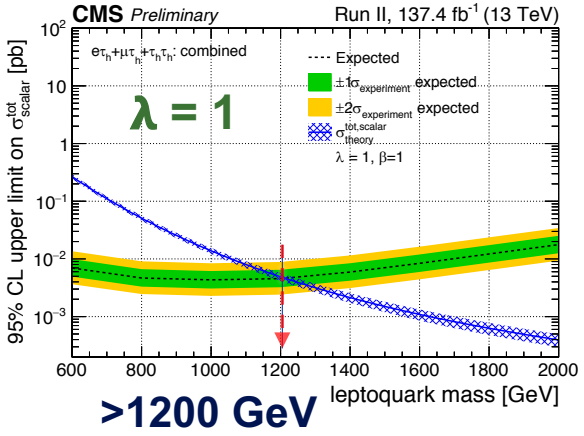


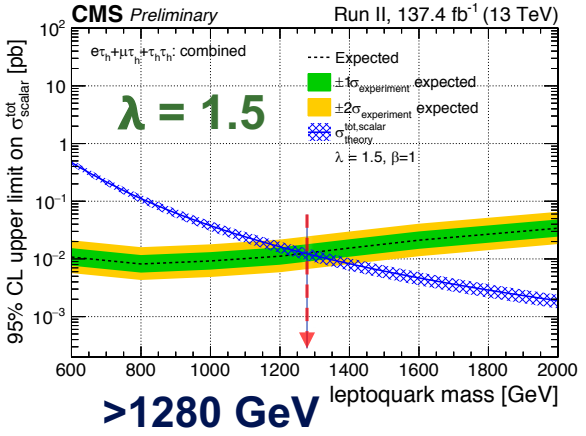




$$\sigma^{\mathrm{tot}}(\lambda) = \lambda^2 \sigma^{\mathrm{single}}_{\lambda=1} + \sigma^{\mathrm{pair}}_{\lambda=1} + \lambda^4 \sigma^{\mathrm{nonres}}_{\lambda=1}$$







RUN-2 LEGACY LQ → b$\tau\tau$

Summary of signal selections

baseline $\ell\tau_h$ and $\tau_h\tau_h$ selections

ℓ/τ_h p_T > 50 GeV

loose DeepCSV

orthogonal:
no jets with p_T > 50 GeV

≥1 **jet** p_T > 50 GeV, ≥1 **b tag**, m_{vis} > 100 GeV

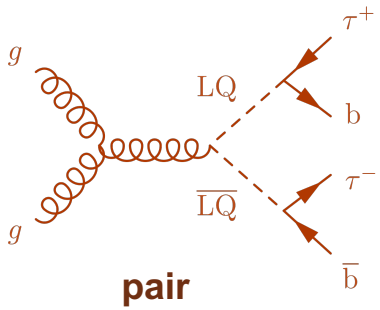
$|\eta_1 + \eta_2| < 2.2$, $\Delta\eta_{\ell\ell} < 3$

discriminating variable:

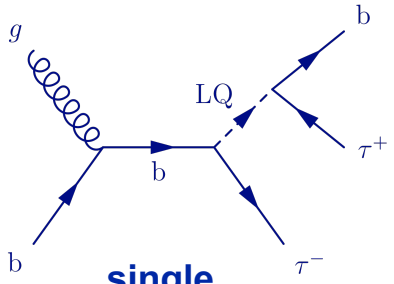
$S_T = p_T^1 + p_T^2 + p_T^j$

discriminating variable:

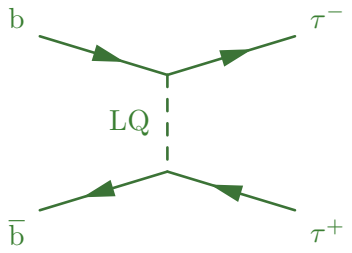
$\chi = e^{2\Delta\eta}$ in m_{vis} bins



pair

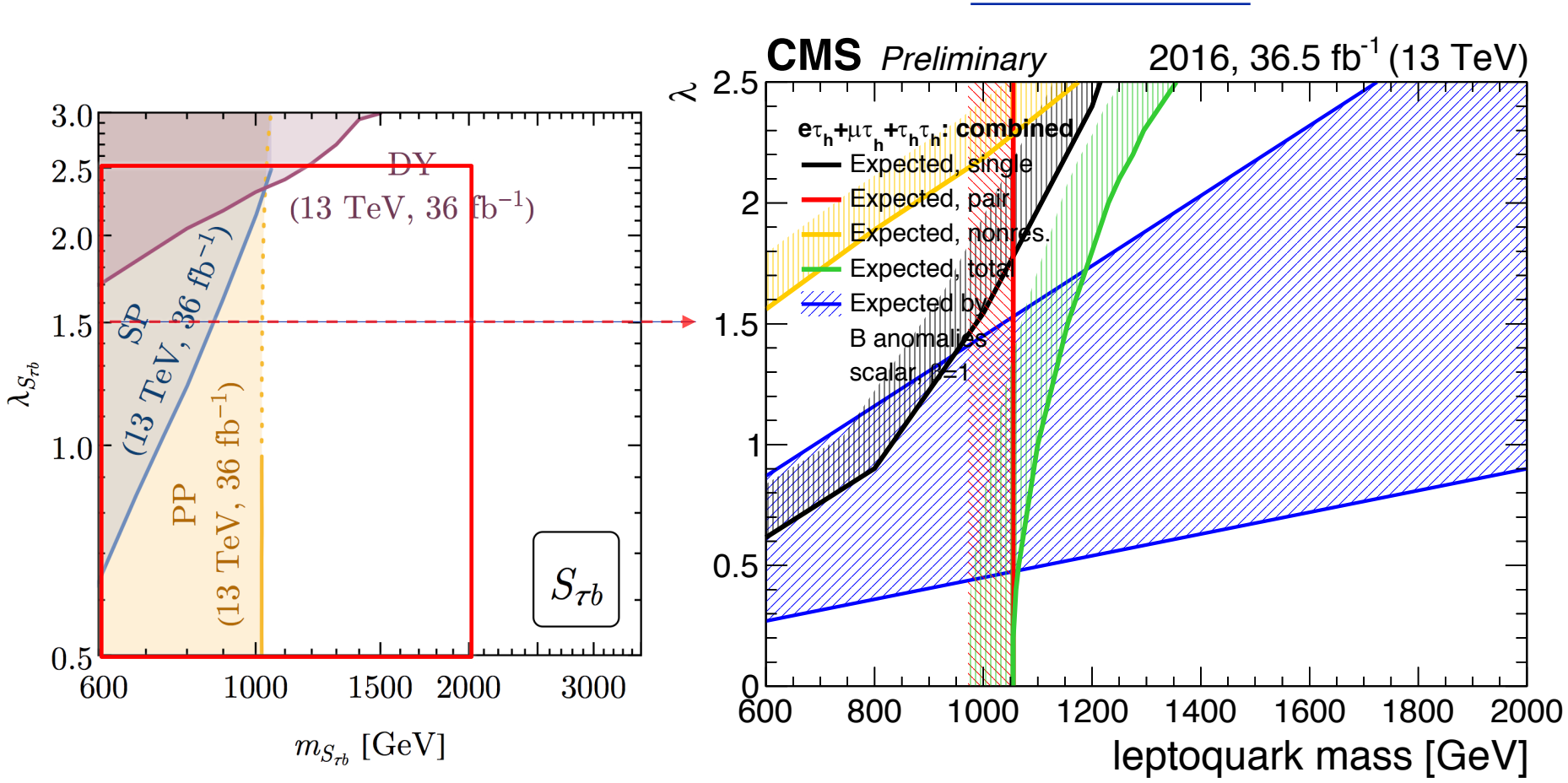


single

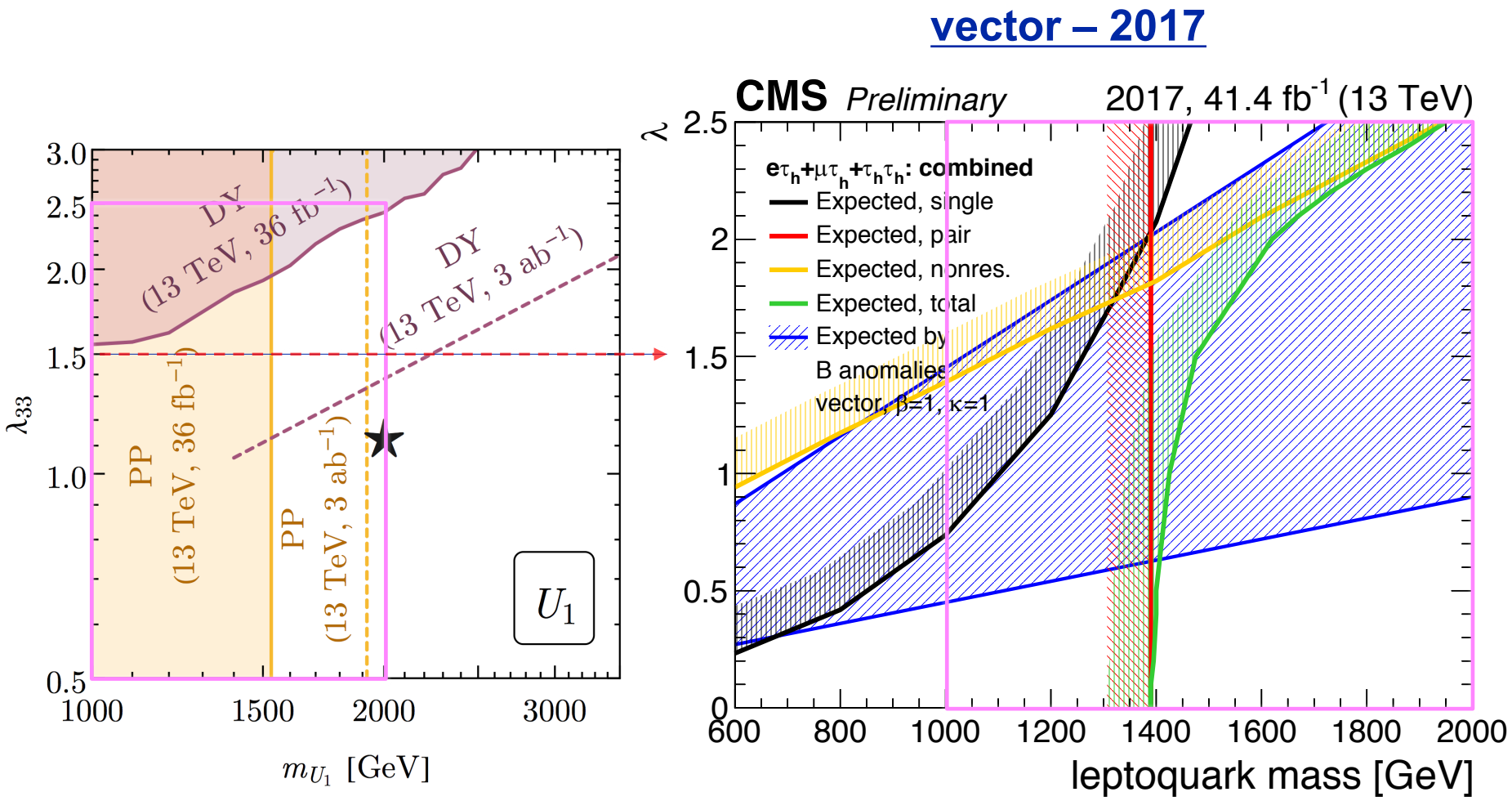


nonresonant

Exclusion in λ vs. m_{LQ} space

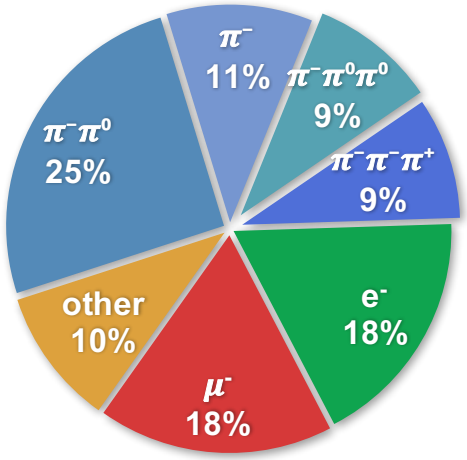


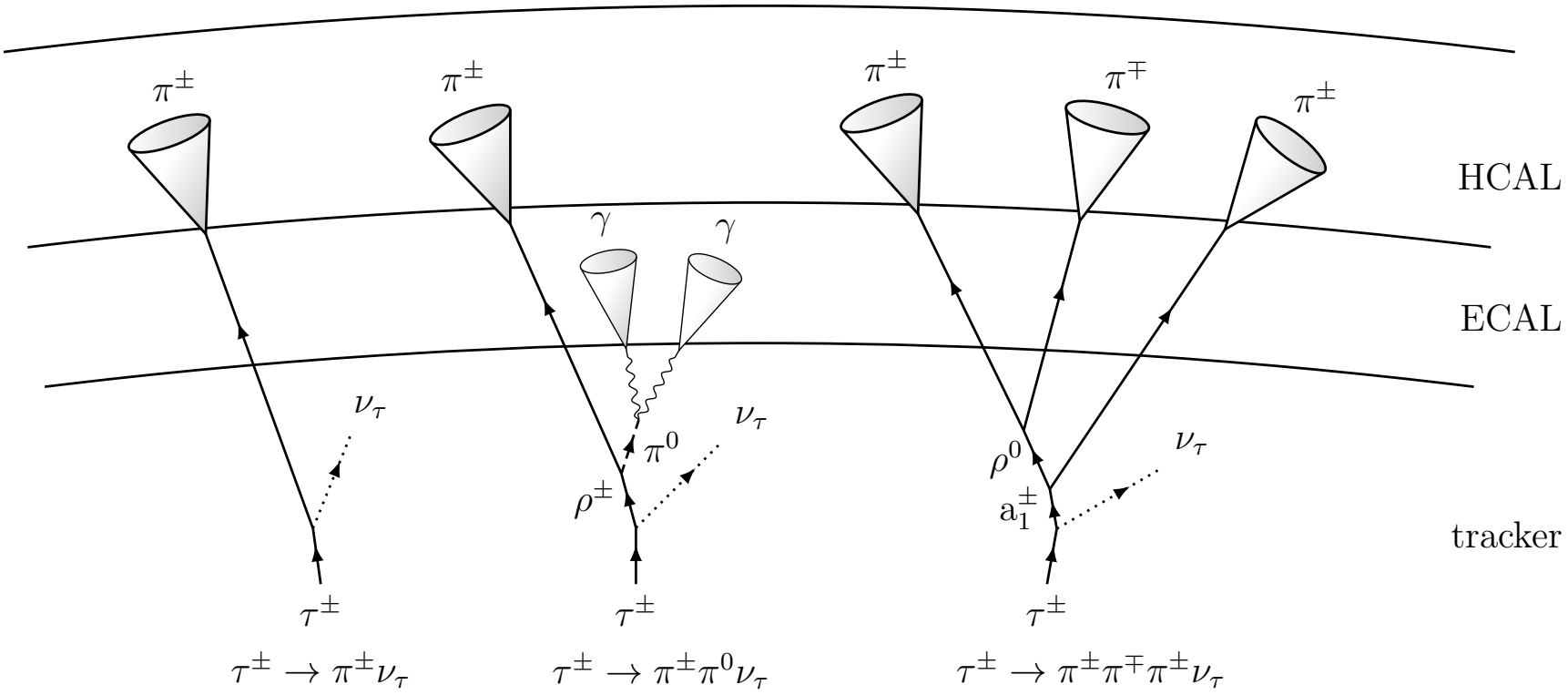
Exclusion in λ vs. m_{LQ} space



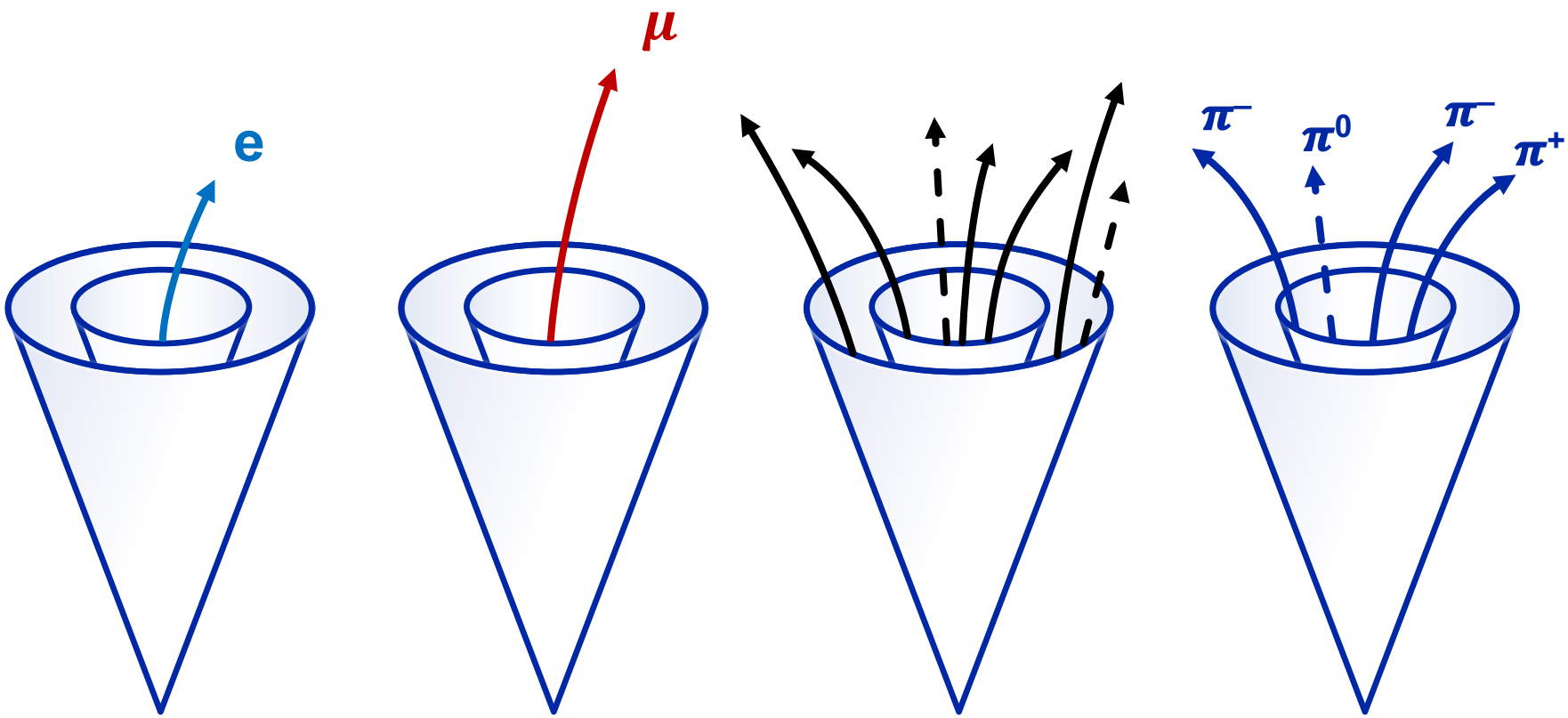
OBJECT RECONSTRUCTION

τ_h reconstruction





τ_h background



$e \rightarrow \tau_h$ fake

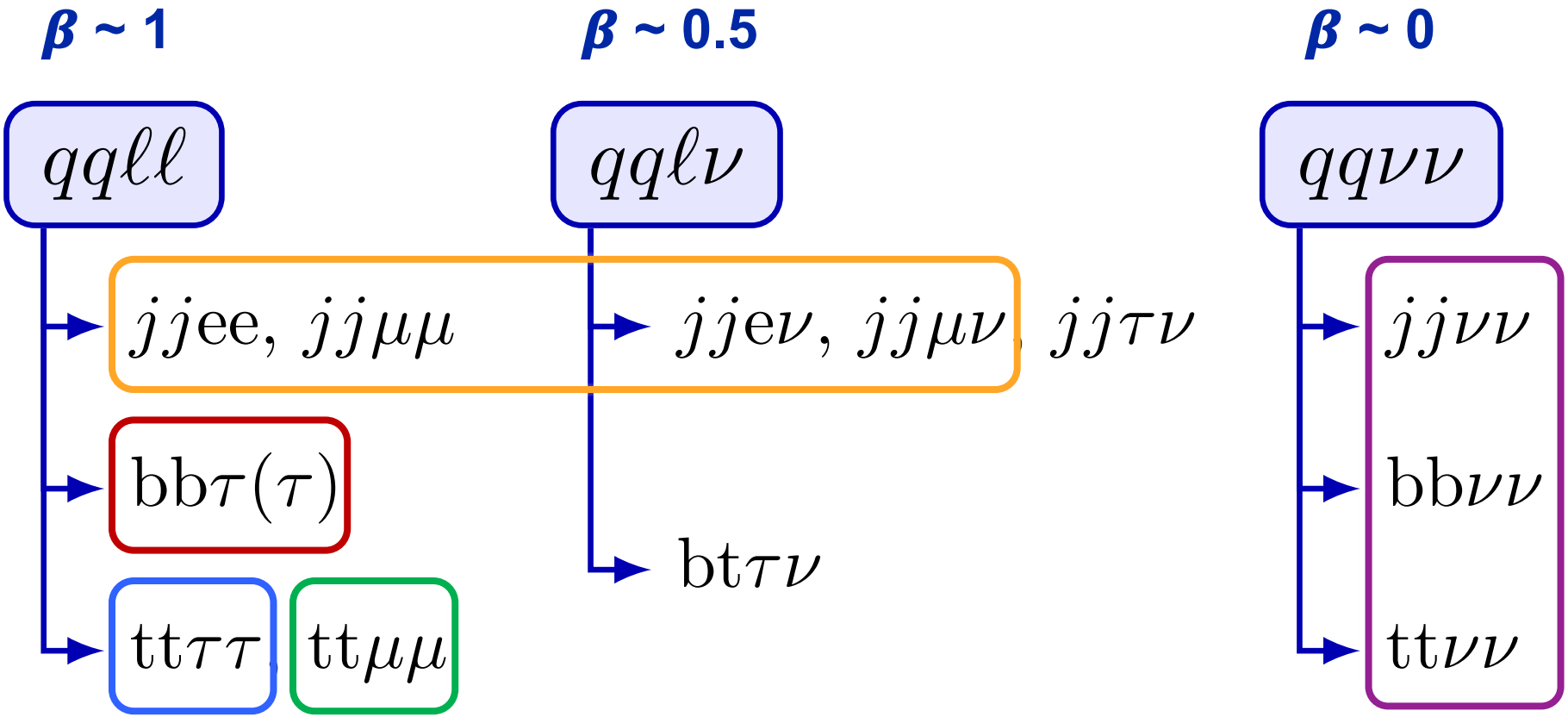
$\mu \rightarrow \tau_h$ fake

$j \rightarrow \tau_h$ fake

real τ_h

LQ SEARCHES AT THE LHC

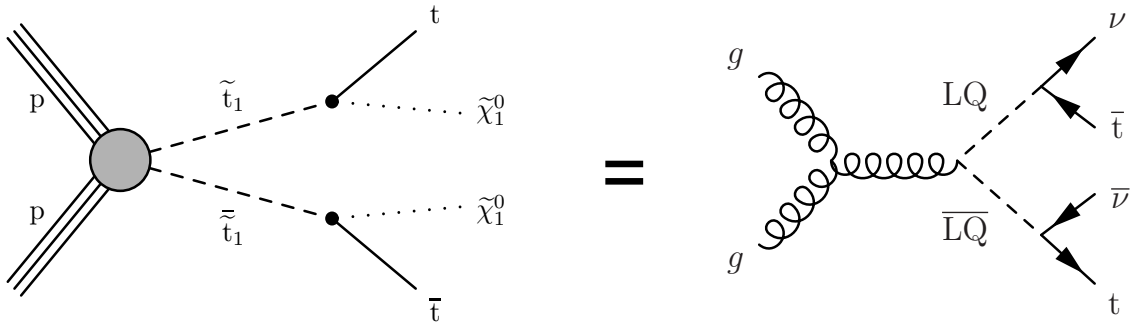
LQ analyses at the LHC



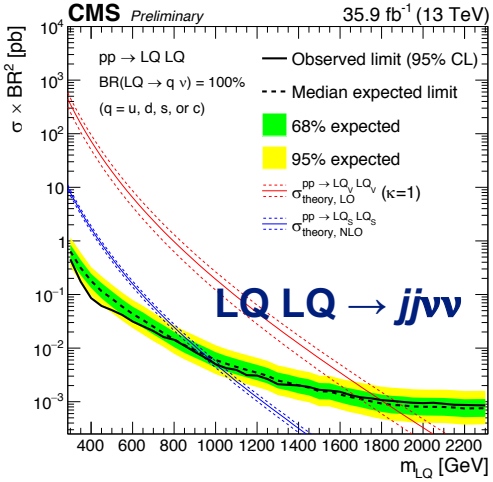
LQ LQ → *jjνν*, bb*νν*, tt*νν*

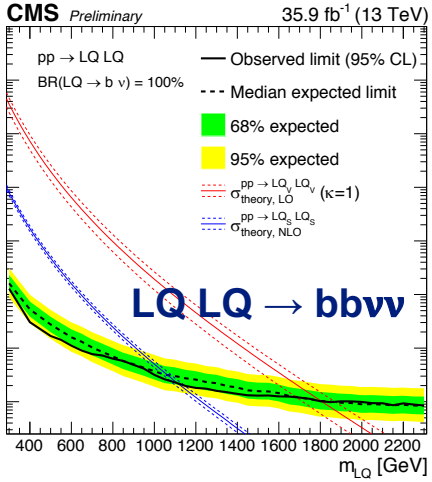
$\beta = 0$

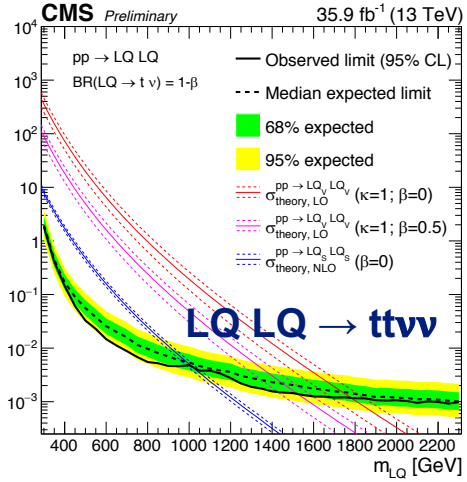
existing SUSY searches with **jets + MET** can be reinterpreted:



identical to scalar LQ with $m_\chi = 0$







LQ excluded up to

	scalar	vector
jjνν	980	1790
bb*νν*	**1100**	**1810**
tt*νν*	1020	1780

sensitive to all LQ generations

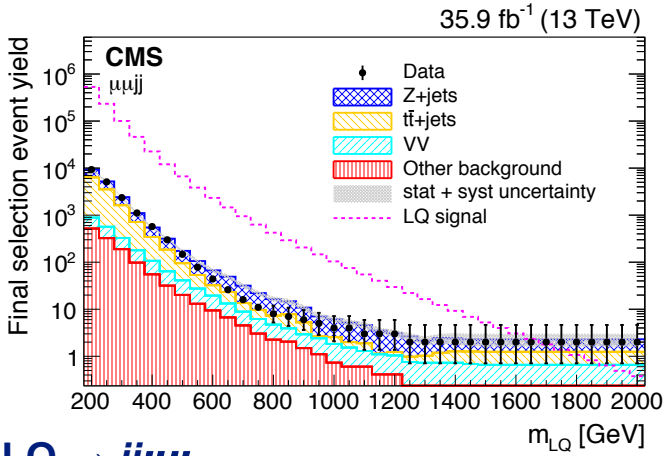
[CMS, arXiv:1805.10228], [ATLAS, arXiv:1902.08103]

LQ LQ → *jjℓℓ, jjℓν*, with ℓ = e or *μ*

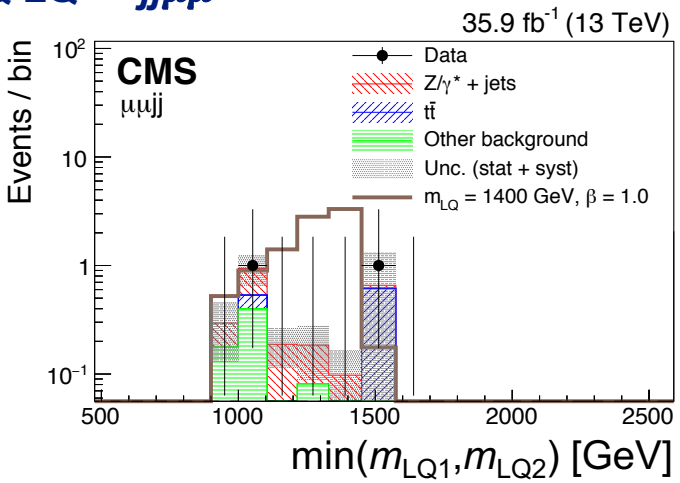
β = 1, 0.5

target 2 jets with either 2 leptons or 1 with MET

CMS reconstructs each LQ, and cuts-and-counts

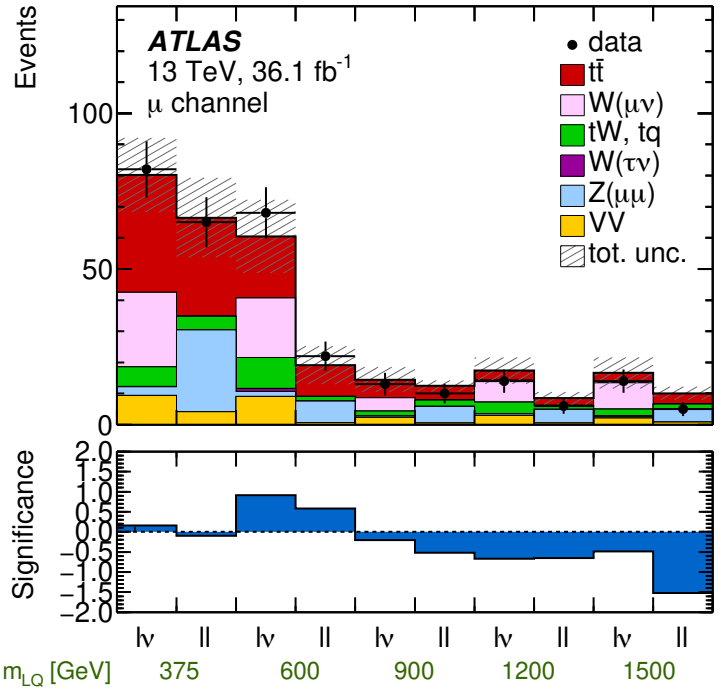


LQ LQ → *jjμμ*



ATLAS uses several inputs to BDT:

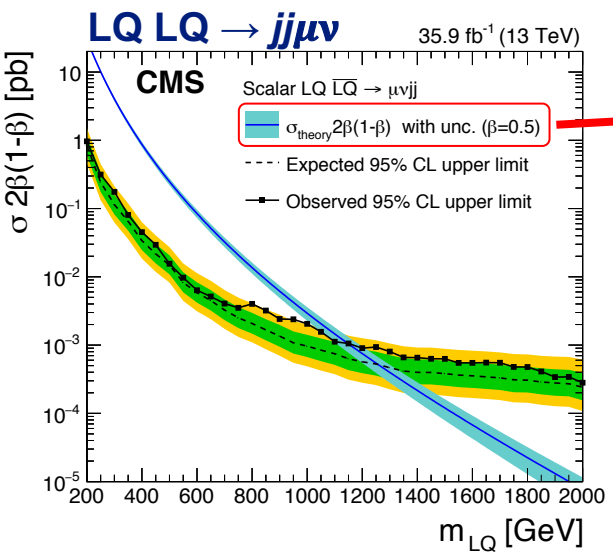
LQ LQ → *jjμν, jjμμ*

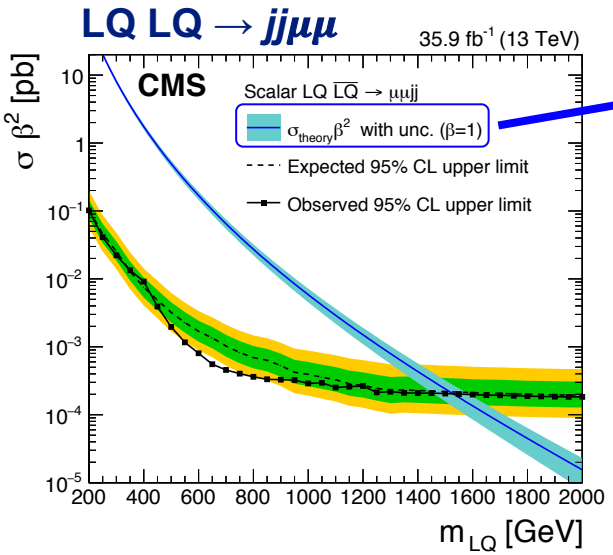


[CMS, arXiv:1811.01197 (e) & arXiv:1808.05082 (μ)], [ATLAS, arXiv:1902.00377]

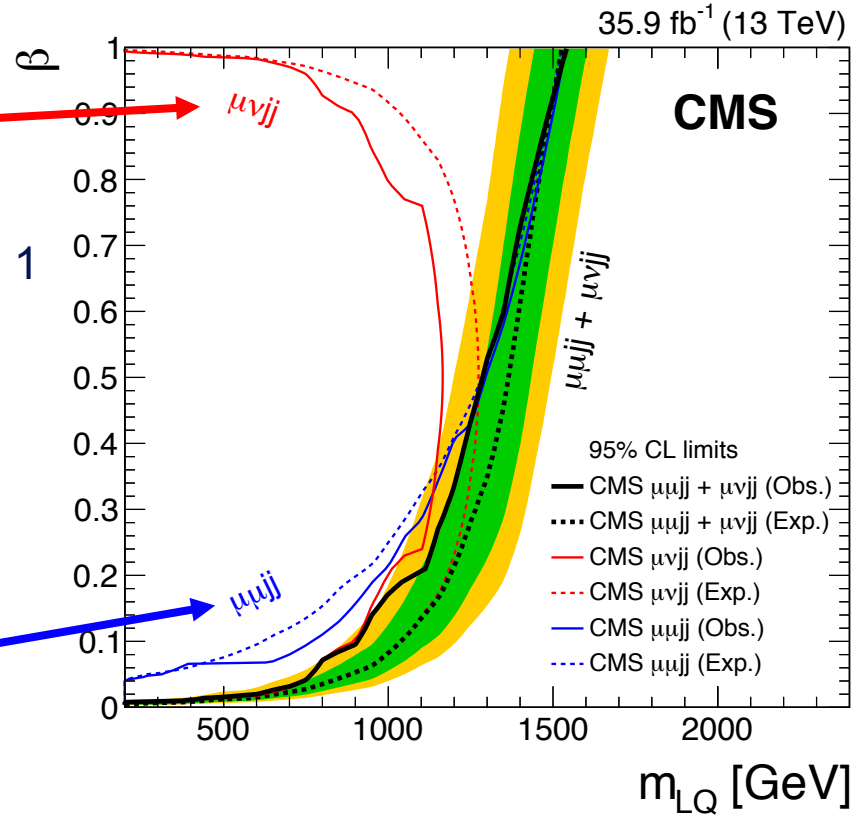
LQ LQ → *jjℓℓ*, *jjℓν*, with ℓ = e or *μ*

β = 1, 0.5





vary β from 0 to 1



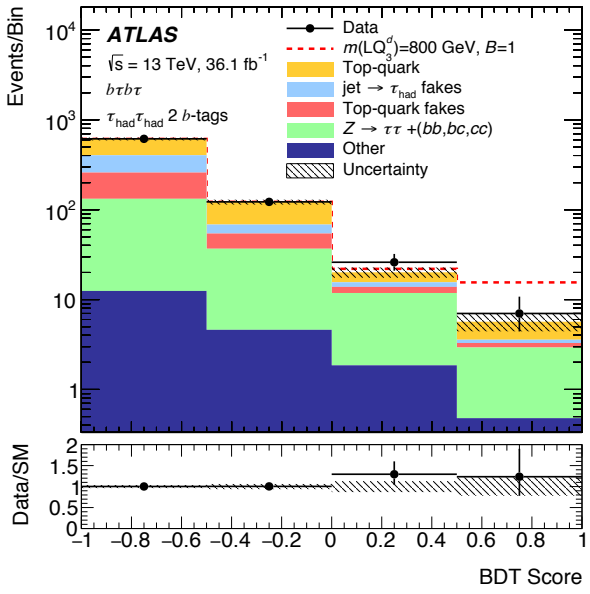
	β = 1 (*jjℓℓ*)		β = 0.5 (*jjℓν*)	
	CMS	ATLAS	CMS	ATLAS
LQ_1 (ℓ = e)	**1435**	1400	1270	**1290**
LQ_2 (ℓ = μ)	1530	**1560**	**1285**	1230

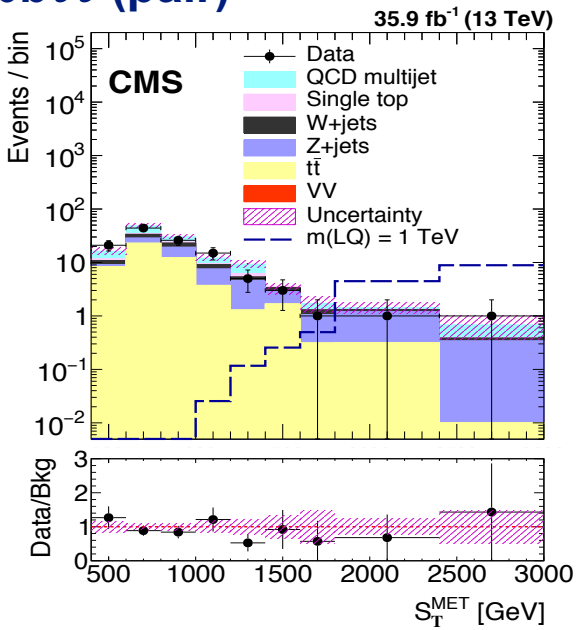
[CMS, arXiv:1811.01197 (e) & arXiv:1808.05082 (μ)]
[ATLAS, arXiv:1902.00377]

LQ LQ → bb$\tau\tau$, LQ τ → b$\tau\tau$

$\beta = 1$

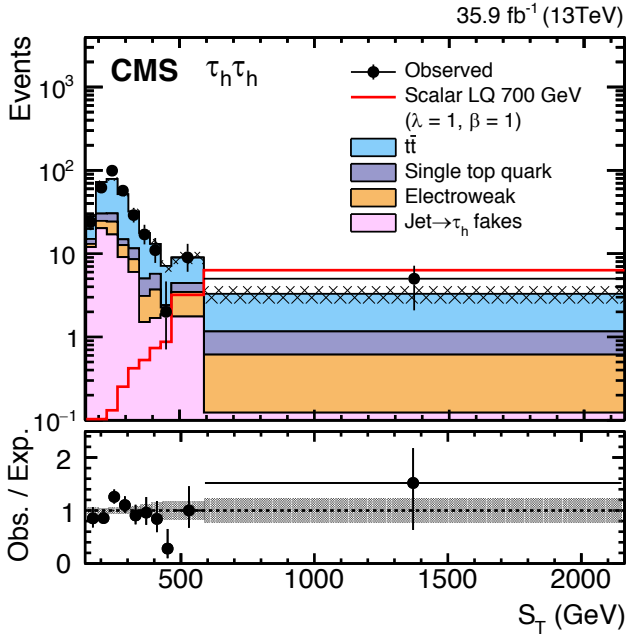
LQ LQ → bb$\tau\tau$ (pair)





- categories in # b tags
- inputs to BDT

LQ τ → b$\tau\tau$ (single)

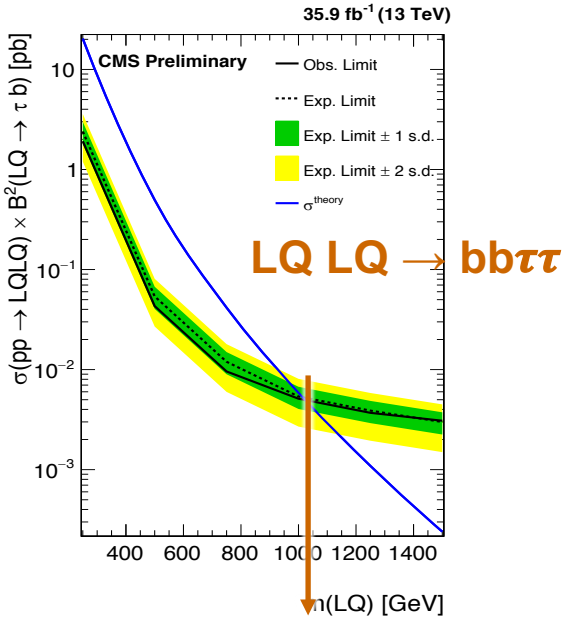


- single category
- fit on S_T = scalar sum p_T
- data-driven methods for fake τ_h

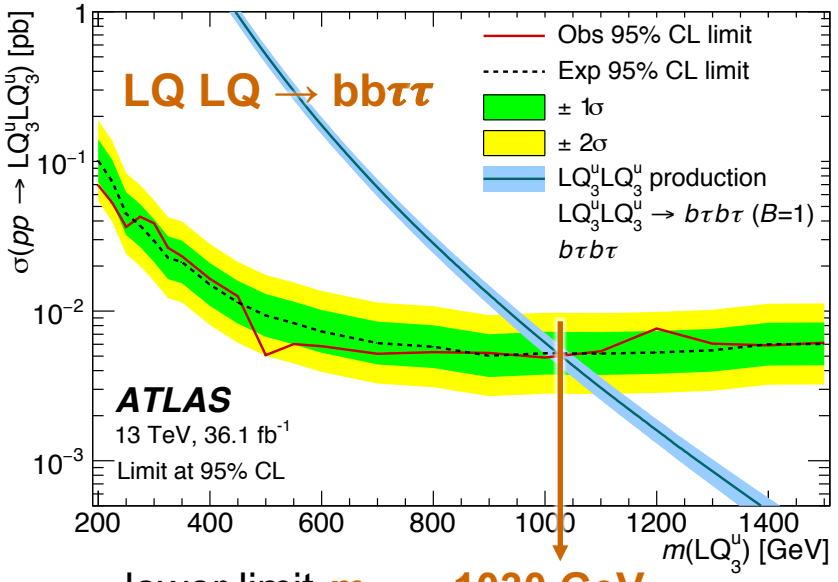
[CMS, arXiv:1811.00806 (pair) & arXiv:1806.03472 (single)], [ATLAS arXiv:1902.08103]

LQ LQ → bbττ, LQ τ → bττ limits

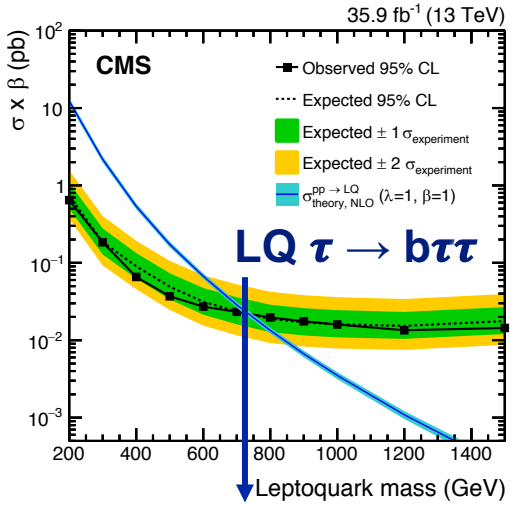
$\beta = 1$



lower limit m_{LQ} ~ 1020 GeV



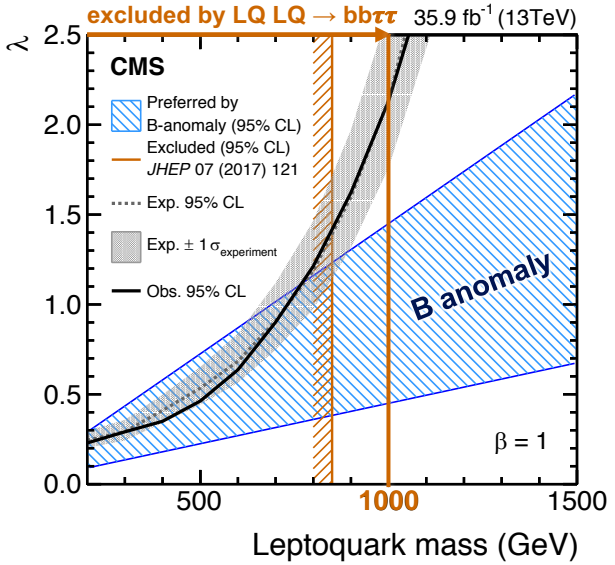
lower limit m_{LQ} ~ 1030 GeV



m_{LQ} > 744 GeV

$\sigma(\text{single}) \sim \lambda^2$

$\Rightarrow$ limit in (λ, m_{LQ})-plane



LQ LQ → ttττ

CMS

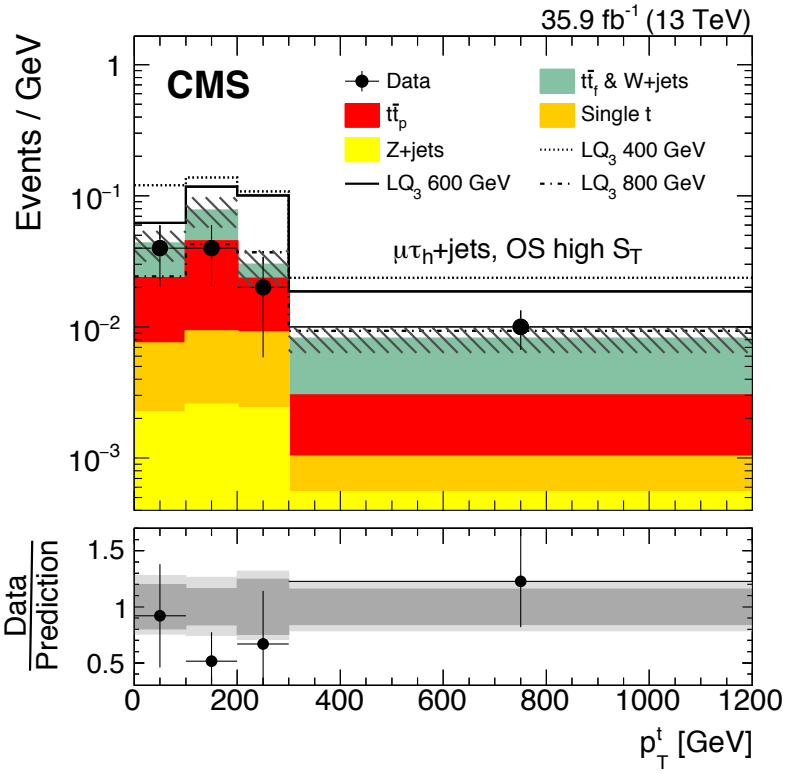
- focus on $1\ell + 1\tau_h$ + jets
- define low and high S_T region
- fit on top p_T

$\Rightarrow m_{LQ} < 900$ GeV

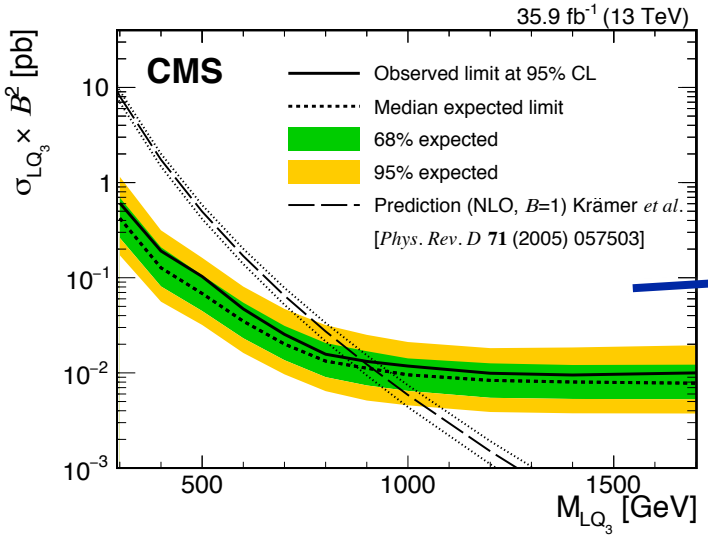
ATLAS

- recast bbττ search

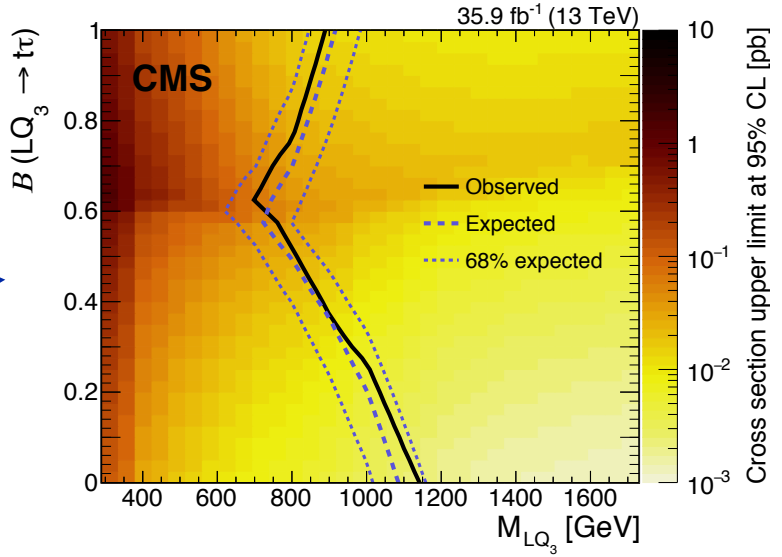
$\Rightarrow m_{LQ} < 930$ GeV



$\beta = 1$



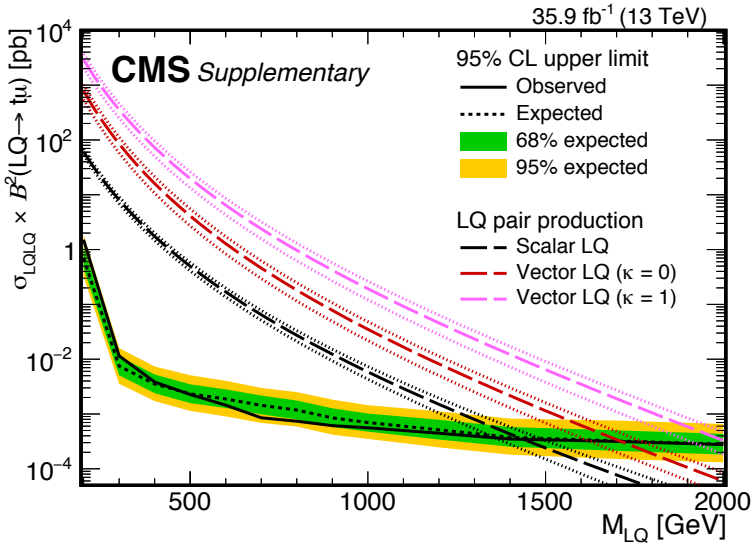
vary β from 0 to 1



[CMS, arXiv:1803.02864], [ATLAS arXiv:1902.08103]

LQ LQ → tt$\mu\mu$

- 2μ + jets
  ⇒ high efficiency
- also combined with
  LQ LQ → bb$\nu\nu$
  LQ LQ → tt$\tau\tau$
- m_{LQ} < 1420 GeV for β = 1
  m_{LQ} < 980 GeV for *any* β



[arXiv:1809.05558]

β = 1