Searches for leptoquarks

with the ATLAS detector

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on behalf of the ATLAS Collaboration

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(B) SM flavour structure ?

An extensive flavour puzzle…

Fermions: spin 1/2

1a 2a 3a — generation

+ mass

6 quarks

+ 6 anti-quarks

6 leptons

+ 6 anti-leptons

- **Why similar structure of quarks and leptons?**
  - Underlying symmetry connecting both sectors?
  - Many grand unified theories (GUT SU(5), Pati-Salam SU(4), RPV SUSY) predict **leptoquarks (LQ)**, carrying both lepton and baryon number
  - LQ are colour triplet bosons with a fractional electric charge
  - LQ can mediate flavour-changing-neutral-currents and enable violation of lepton flavour universality

Anomalies in B-meson sector

- Hints for lepton flavour universality violation observed in **charged** and **neutral** current processes in B-physics

$$R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)+}\tau\nu)}{\mathcal{B}(B^0 \to D^{(*)+}\ell\nu)}, \quad \ell = \mu, e$$

3.1σ excess in R_D and R_{D^*} combination [1909.12524]

$$R(K^{(*)}) = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

3.1σ excess in R_K [LHCb: 2103.11769]

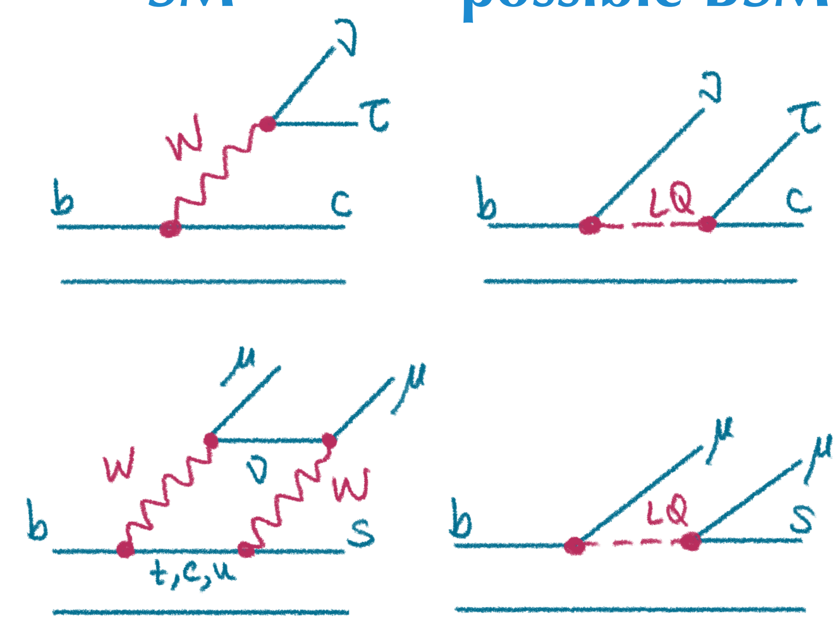
+ tensions in angular observables and BRs

3.9σ global significance of NP in b→sμμ [2104.05631]

- The size of the anomalies suggest a tree-level mediator, such as **leptoquarks (LQ)**

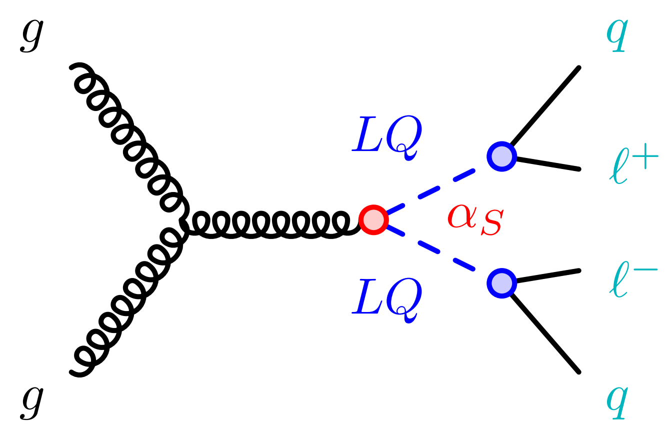
- Two scalar or a single vector **LQ(s)** could explain the LFU anomalies
  - LQ decays into *flavour-diagonal* and *cross-generational* final states

SM **possible BSM?**



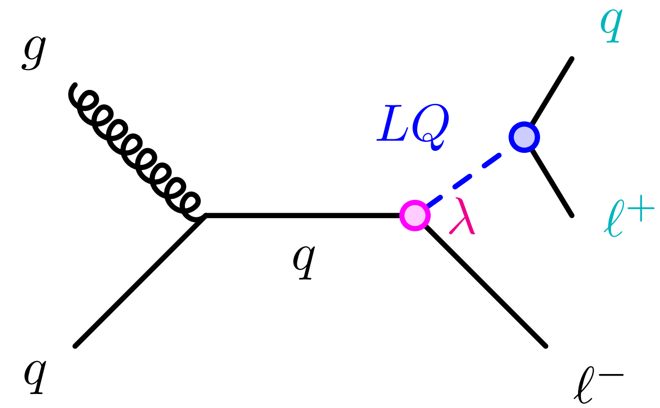
Leptoquark production and decay

Pair production



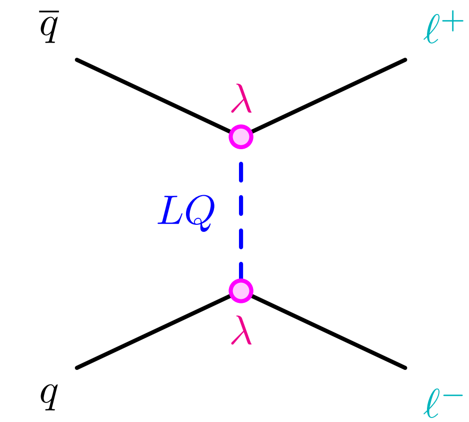
large QCD production
cross section only depends on m_{LQ}
resonant LQs

Single production



cross section ∝ λ^2
sensitive to higher m_{LQ}
for sufficiently high λ

Off-shell production



cross section ∝ λ^4
non-resonant
sensitive to very high m_{LQ}
for sufficiently high λ

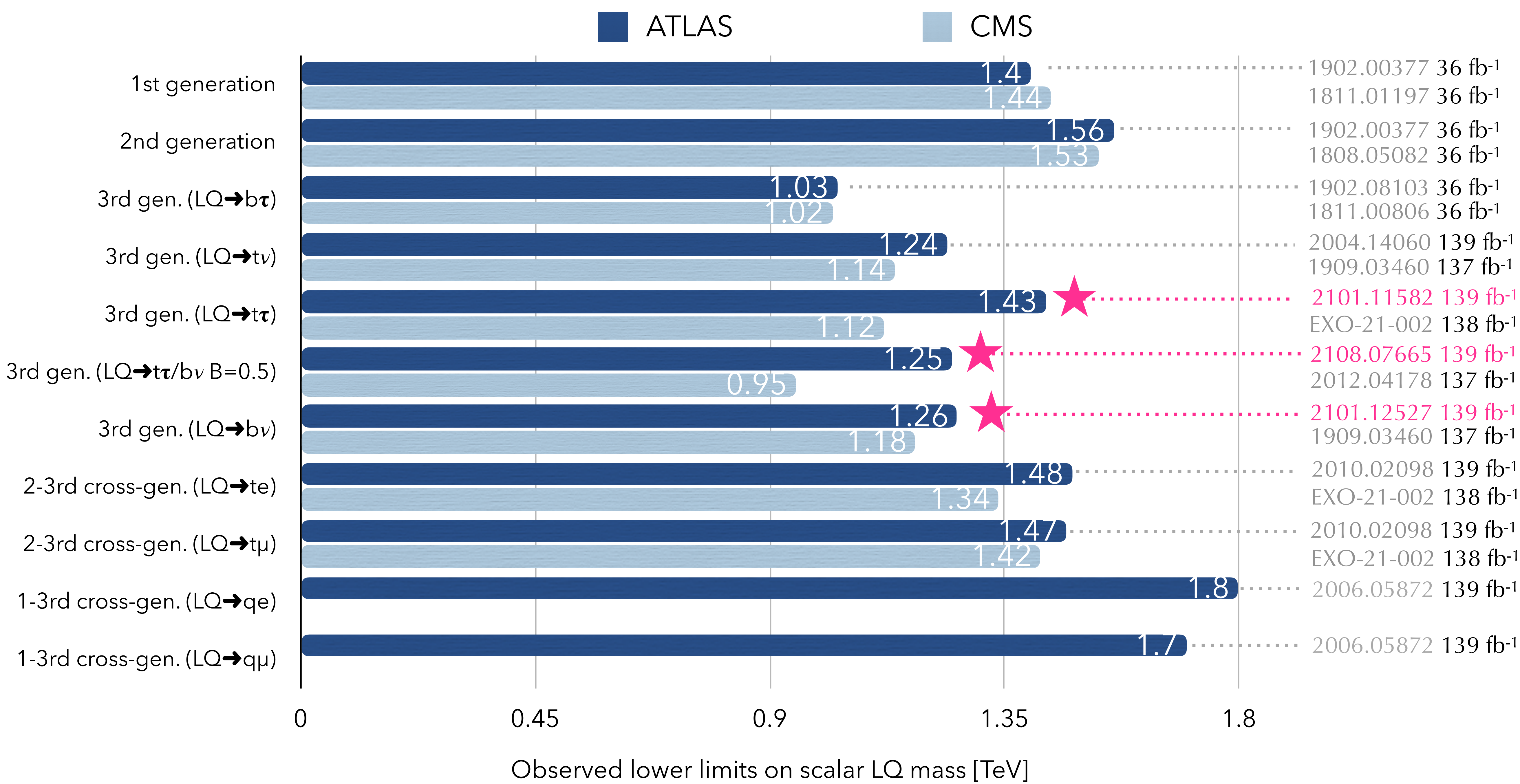
- Couplings determined by the **parameter λ** ○ via Yukawa interaction
- Also **single LQ resonant production**: although PDF for leptons inside the proton minuscule, compensated by resonant enhancement
- Simplified search strategy targeting certain final states from LQ decays at ATLAS
  - **up**- (Q=2/3e) or **down**- (Q=-1/3e) type LQs
- Thorough search for pair production of **scalar LQs**
- Re-interpretations based on **vector LQs** ongoing

LQ decay	B=1	B=0
LQ_{up}	$b\tau$	$t\nu$
LQ_{down}	$t\tau$	$b\nu$

ex.: 3rd generation flavour-diagonal scalar LQ

Scalar LQ state of the art

- Searches for leptoquarks cover a large variety of scenarios
- Here focusing on scalar leptoquark pair production



Latest ATLAS LQ pair production results

- Dedicated and complementary searches targeting **B=0, 0.5** or **1**
- LQ simulation at **NLO QCD** with **`MadGraph5_aMC@NLO + Pythia8`**
- LQ cross-section calculations equivalent to pair-produced top squarks
  - **Approximate NNLO QCD + NNLL** accuracy

<table>
<tr><th></th><th></th><th>u/d/s</th><th>c</th><th>b</th><th>t</th></tr>
<tr><td rowspan="3">B=1</td><td>e</td><td colspan="3" rowspan="2">JHEP 10 (2020) 112
*not covered today</td><td rowspan="2">Eur. Phys. J. C 81 (2021) 313
*not covered today</td></tr>
<tr><td>μ</td></tr>
<tr><td>τ</td><td colspan="2">-</td><td>JHEP 06 (2019) 144 (36 fb^{-1})
*not covered today</td><td>JHEP 06 (2021) 179
$t\tau t\tau$</td></tr>
<tr><td>B=0</td><td>ν</td><td colspan="2">-</td><td>JHEP 05 (2021) 093
$b\nu b\nu$</td><td>Eur. Phys. J. C 80 (2020) 737
*not covered today</td></tr>
<tr><td>B=0.5</td><td>τ/ν</td><td colspan="2">-</td><td colspan="2">2108.07665 [accepted by PRD]
$t\tau b\nu$</td></tr>
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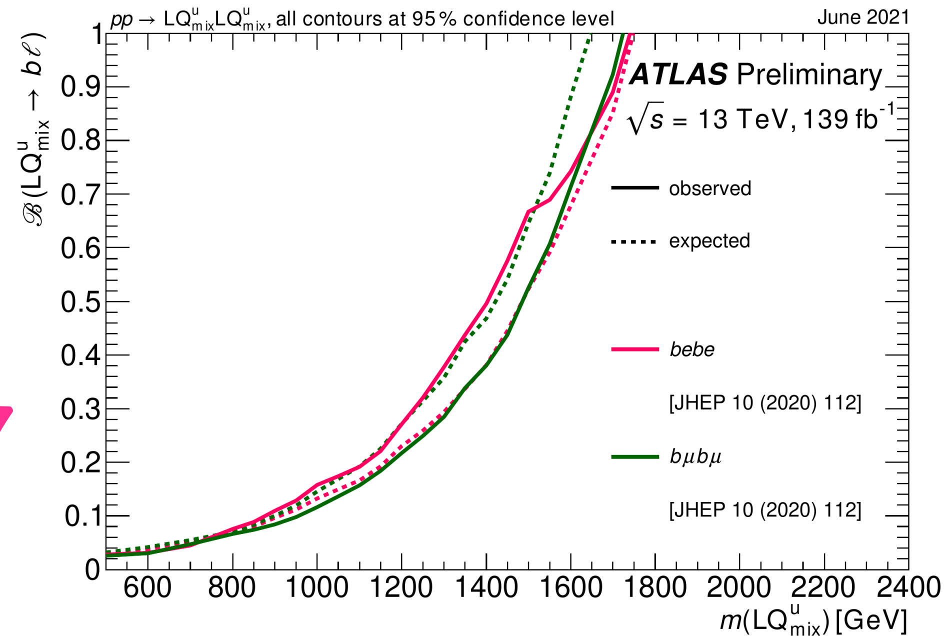
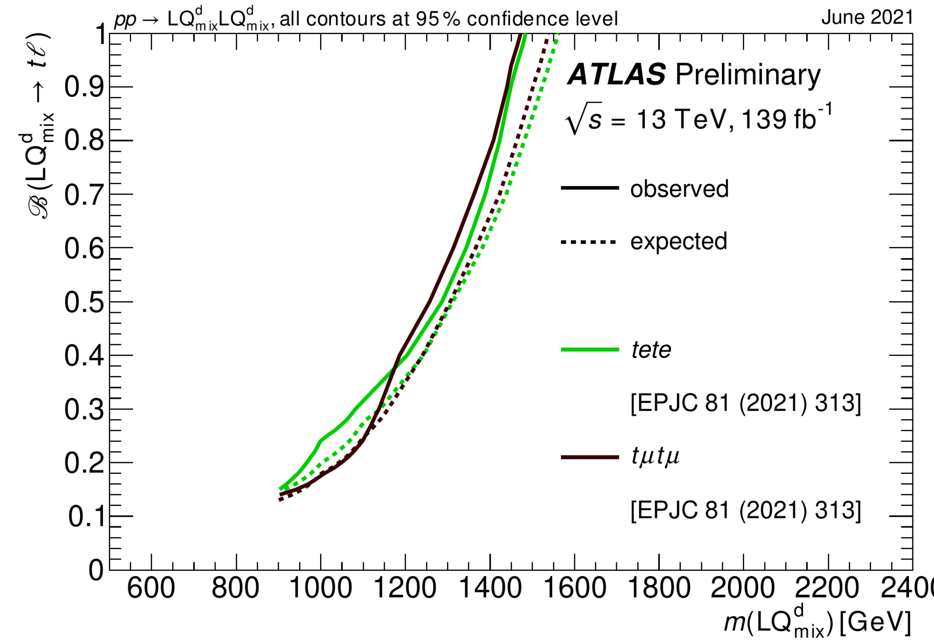
Latest ATLAS LQ pair production results

ATL-PHYS-PUB-2021-017

cross-generational LQ searches



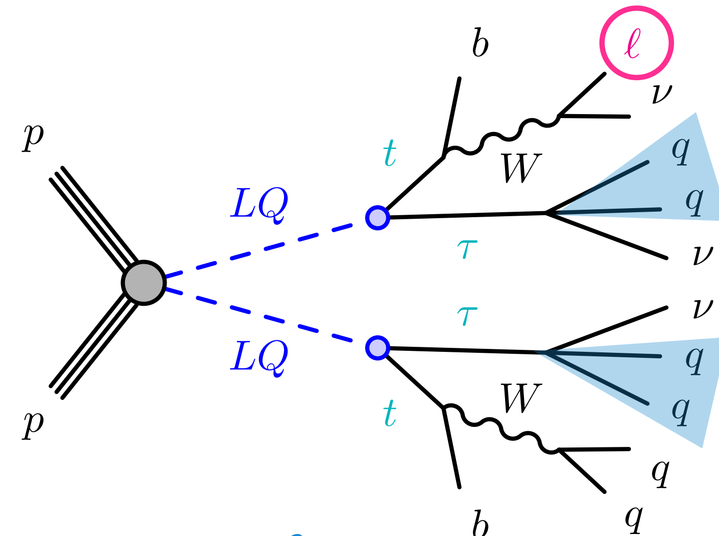


		u/d/s	c	b	t
B=1	e	JHEP 10 (2020) 112 *not covered today			Eur. Phys. J. C 81 (2021) 313 *not covered today
	μ				
	τ	-		JHEP 06 (2019) 144 (36 fb-1) *not covered today	**JHEP 06 (2021) 179** tτtτ
B=0	ν	-		**JHEP 05 (2021) 093** bνbν	Eur. Phys. J. C 80 (2020) 737 *not covered today
B=0.5	τ/ν	-		**2108.07665 [accepted by PRD]** tτbν	

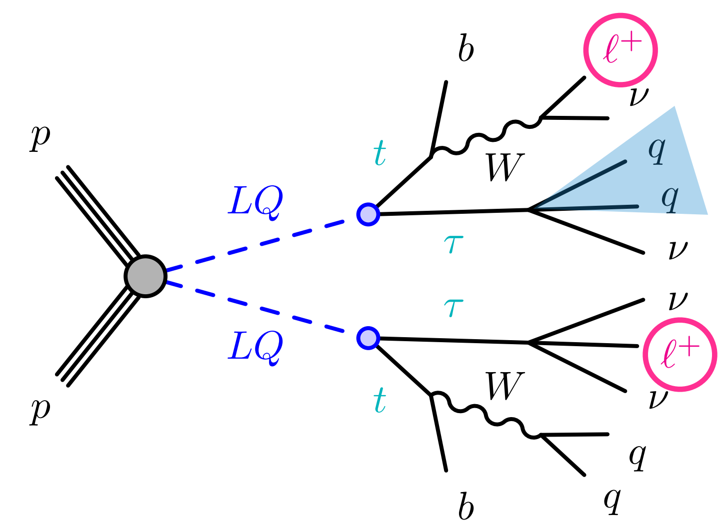
LQLQ → τtτt: analysis strategy

JHEP 06 (2021) 179

- First dedicated ATLAS search
- $1\ell+\geq1\tau_{had}$ or $\geq2\ell$
- ≥2 jets; ≥1 bjet
- Single and dilepton triggers

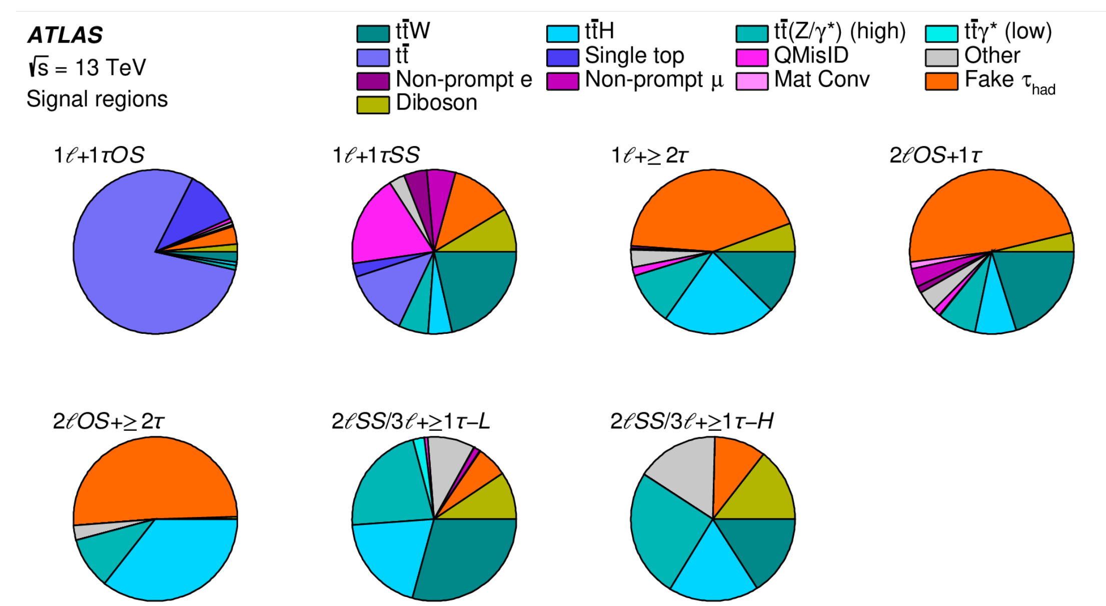


$1\ell+2\tau_{had}$



$2\ell SS+1\tau_{had}$

- Tighter light lepton isolation and identification in **multilepton** (2ℓSS/3ℓ) regions to reduce contribution from non-prompt ℓ background
- Large variety of background contributions in each SR
- **M_{eff}** (=Σ(jet,e,μ,**τ**) p_T + MET) as discriminating variable in SRs



CR	1ℓ+≥1τ	*eμOS+0τ	**2ℓOS+≥1τ	2ℓSS+0τ	3ℓ+0τ
SR	1ℓ+≥1τ	2ℓOS+≥1τ		2ℓSS/3ℓ+≥1τ	

Number of e/μ

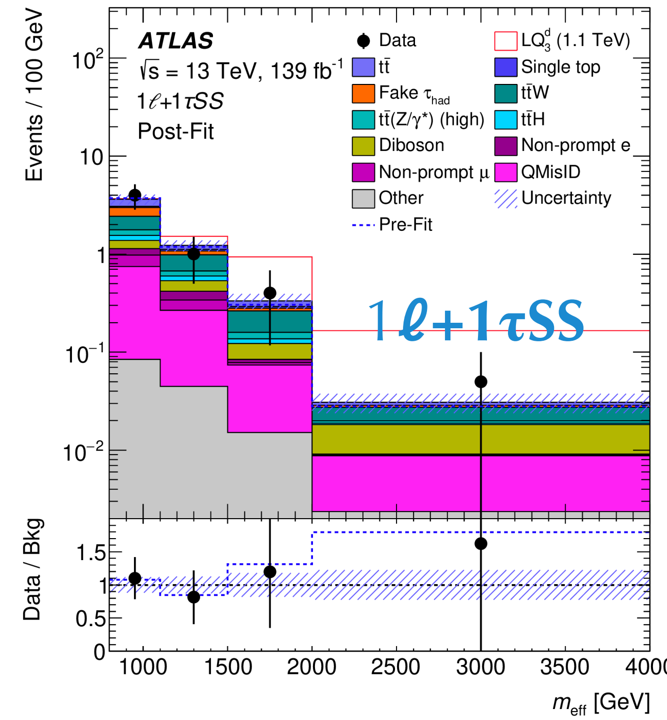
* used for tt̄ correction

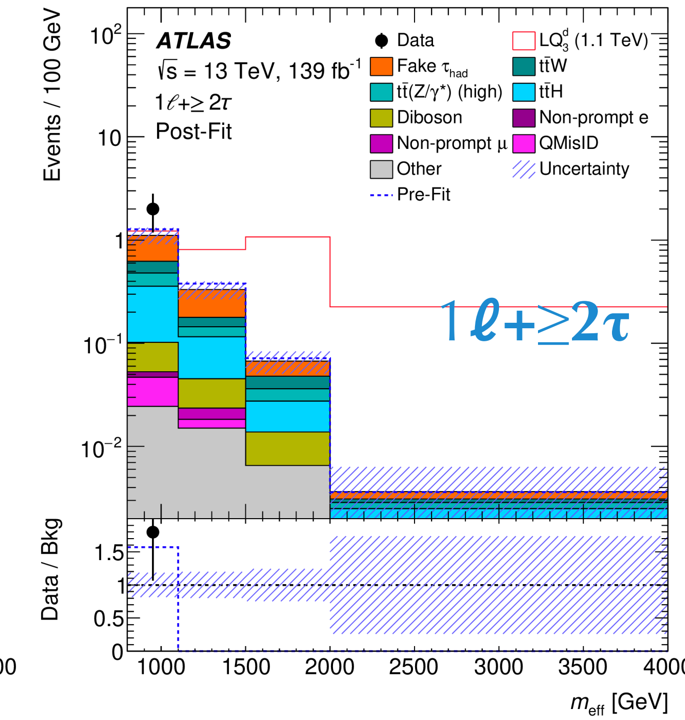
** used for fake τ_{had} correction

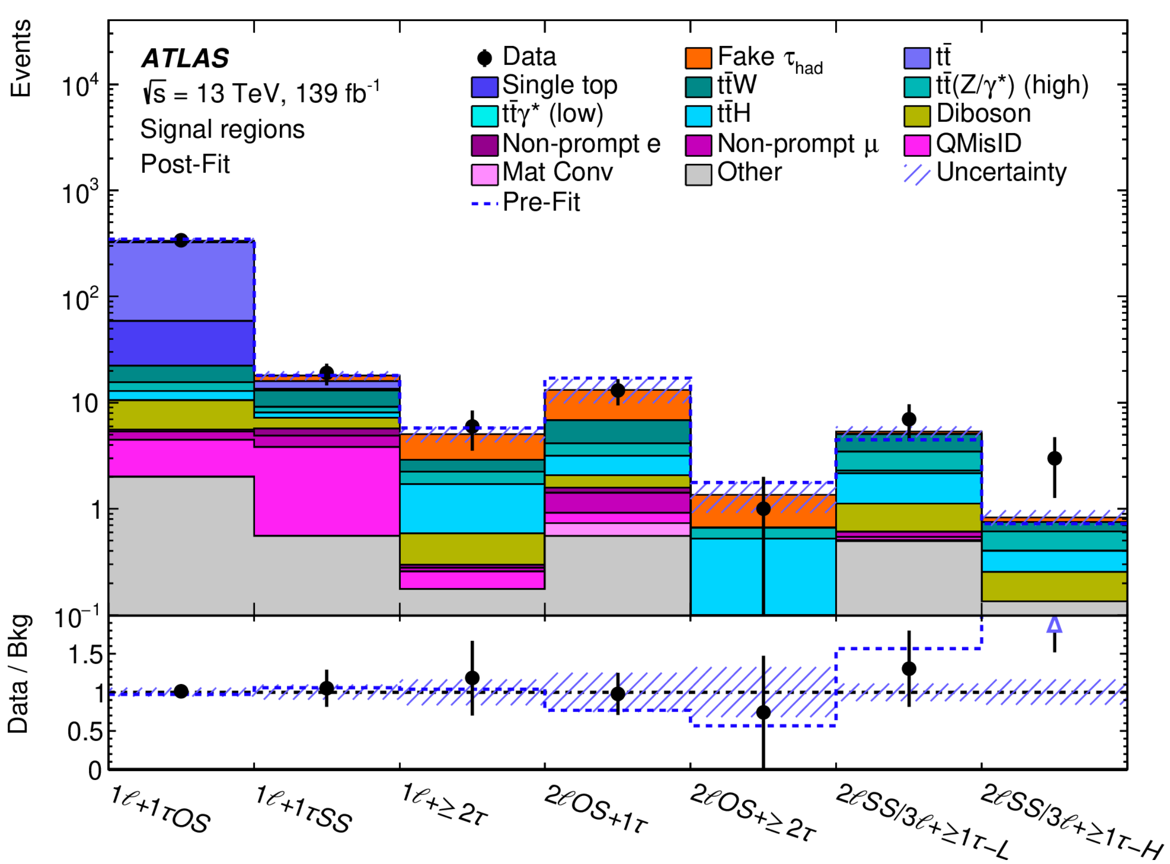
LQLQ → tτtτ: results

JHEP 06 (2021) 179

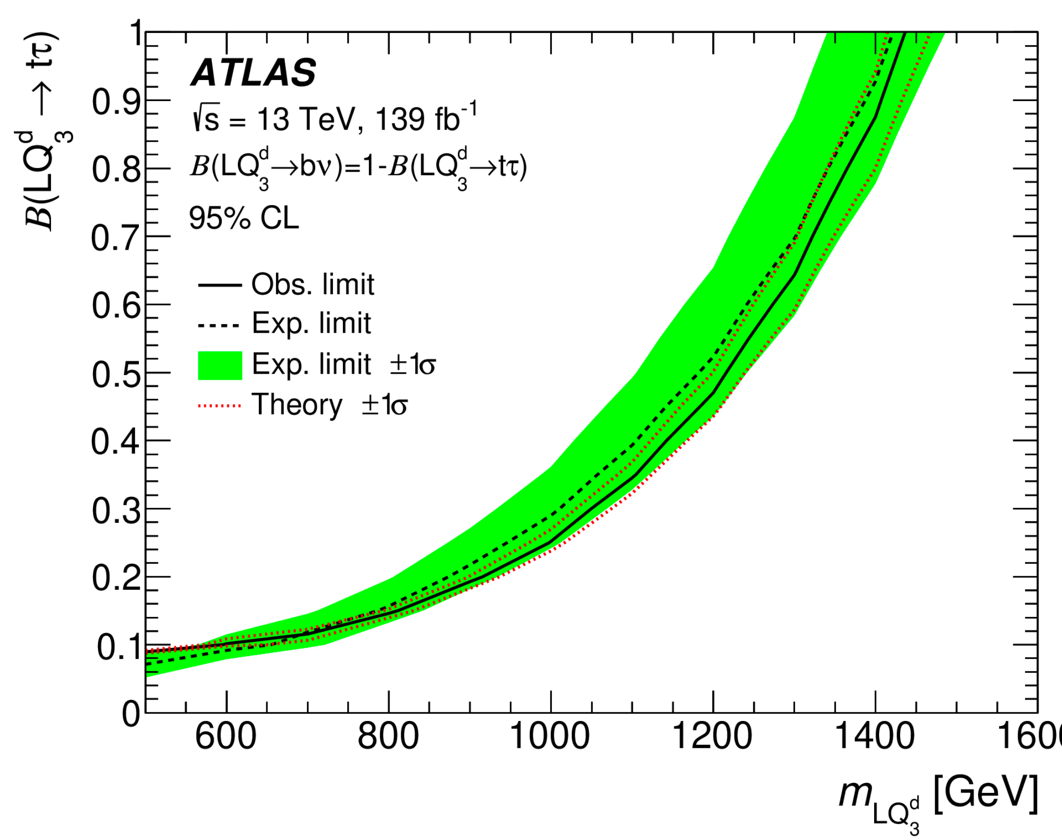
- Simultaneous fit of 7 SRs and 15 CRs
- Main systematic uncertainties from:
  - τ identification and energy scale calibration, $t\bar{t}$ modelling
- Sensitivity dominated by 1ℓ+≥1τ channel
- Statistically-limited search at high masses
- No significant excess over the SM background observed







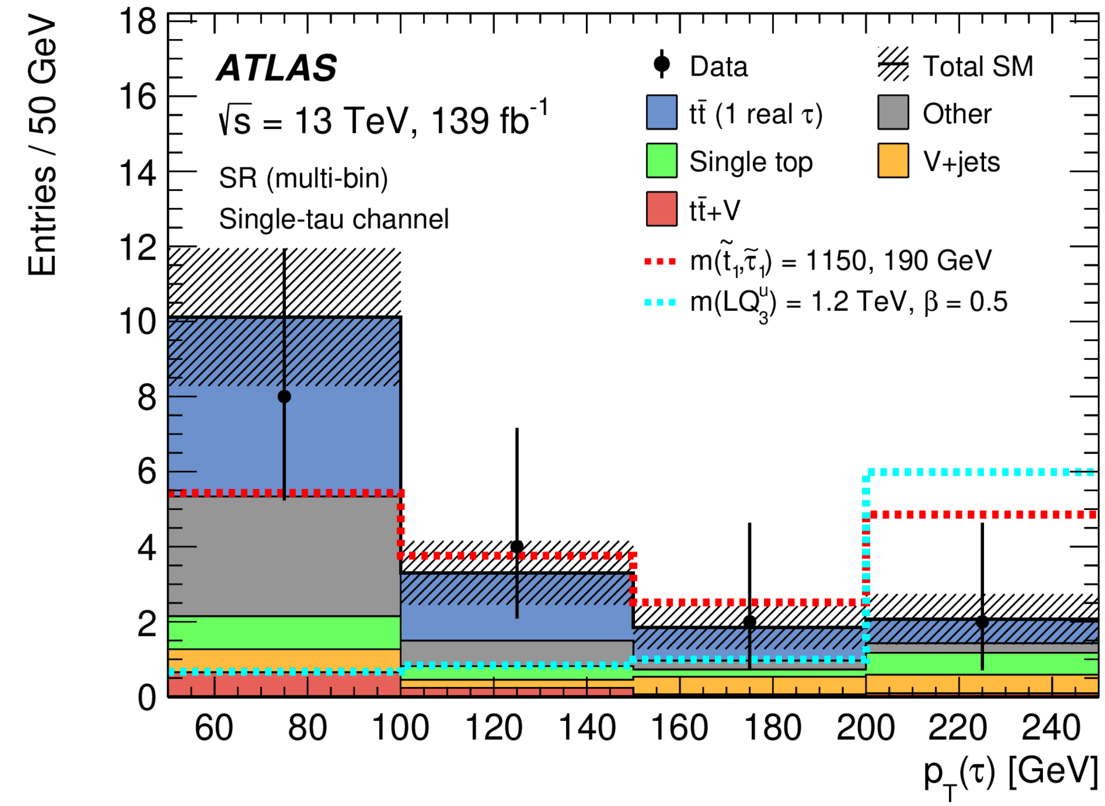
m_{LQ} < 1.43 TeV (1.22 TeV) excluded for B=1 (B=0.5)



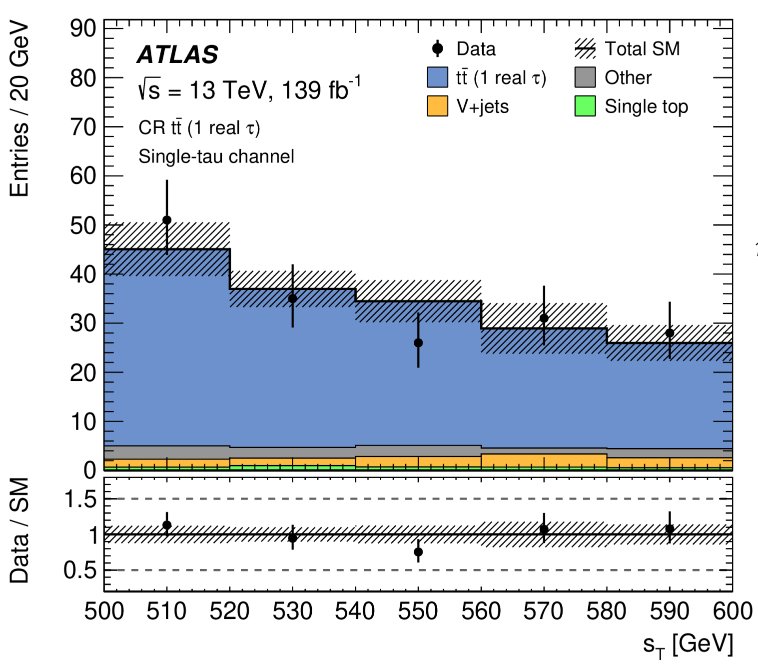
LQLQ → tτbν / tνbτ: analysis strategy

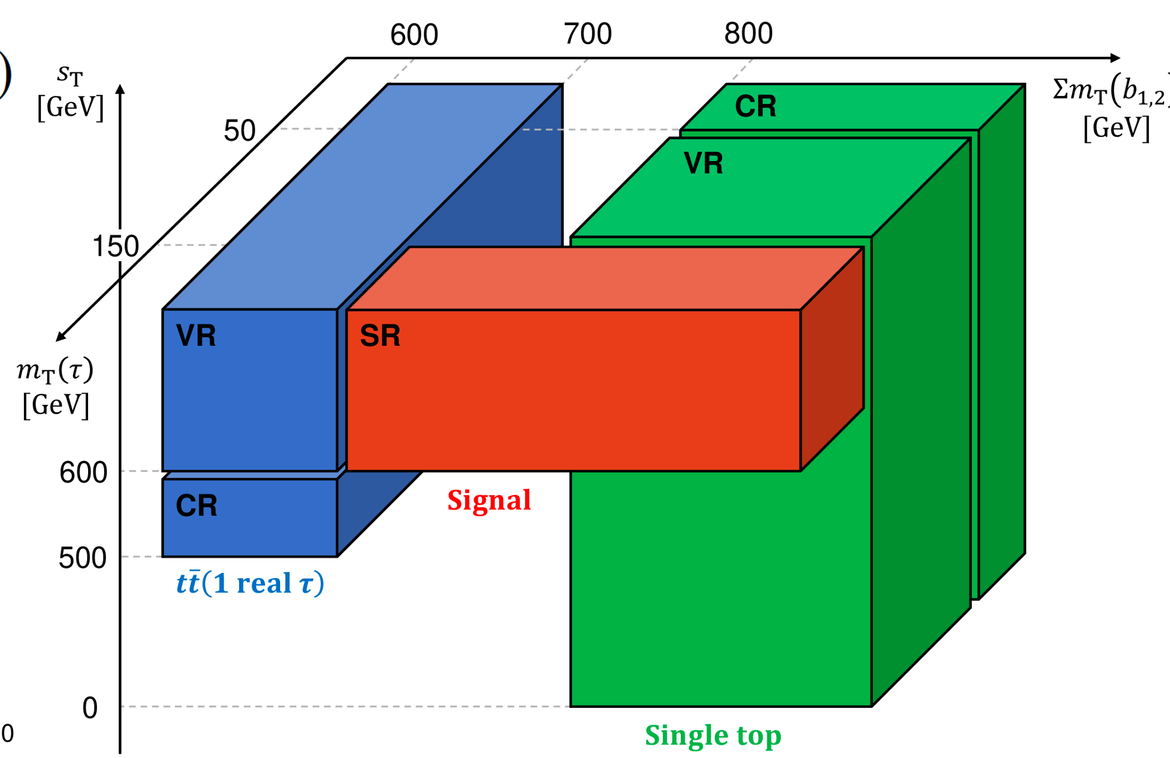
2108.07665 [accepted by PRD]

- MET trigger and offline MET > 280 GeV
- 1τ_{had}, no light leptons, ≥2 bjets
- Dedicated CRs and VRs for main backgrounds: $t\bar{t}$ (1 real τ) and single top
  - Large impact of single top vs $t\bar{t}$ interference modelling in measured single top normalisation correction

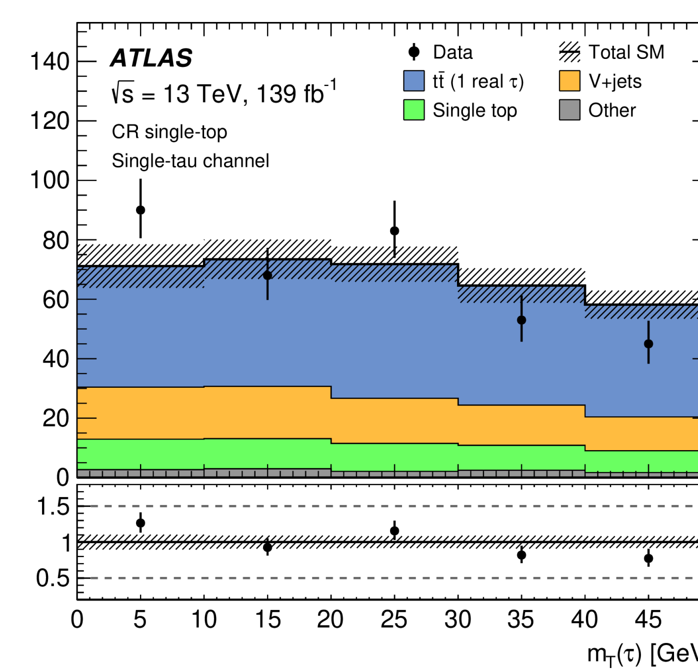


$$s_T = p_T(\tau) + p_T(\text{jet}_1) + p_T(\text{jet}_2)$$





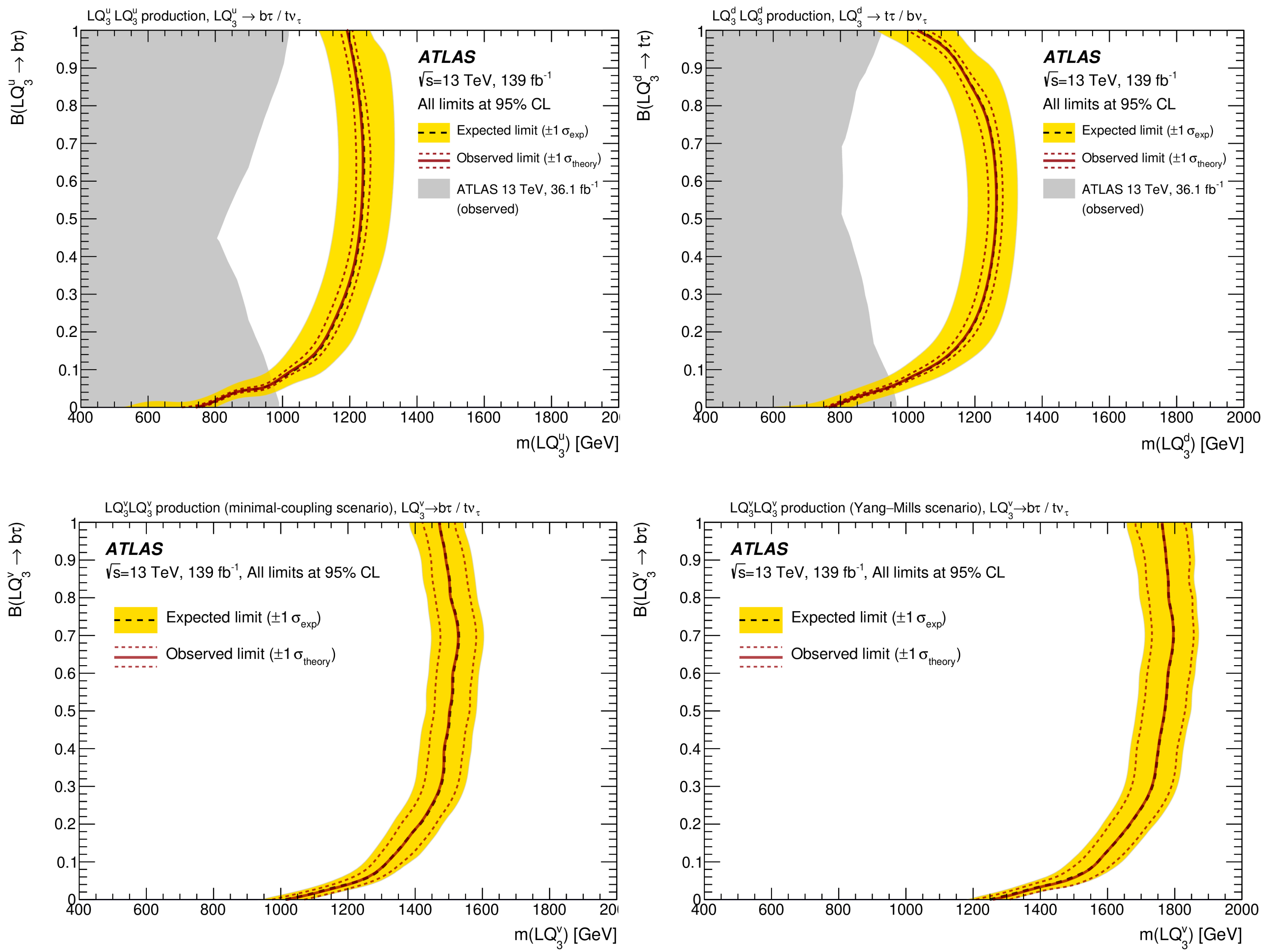
$$m_T(A) \equiv m_T(\mathbf{p}_T^A, \mathbf{E}_T^{\text{miss}})$$



LQLQ → $t\tau b\nu$ / $t\nu b\tau$: results

2108.07665 [accepted by PRD]

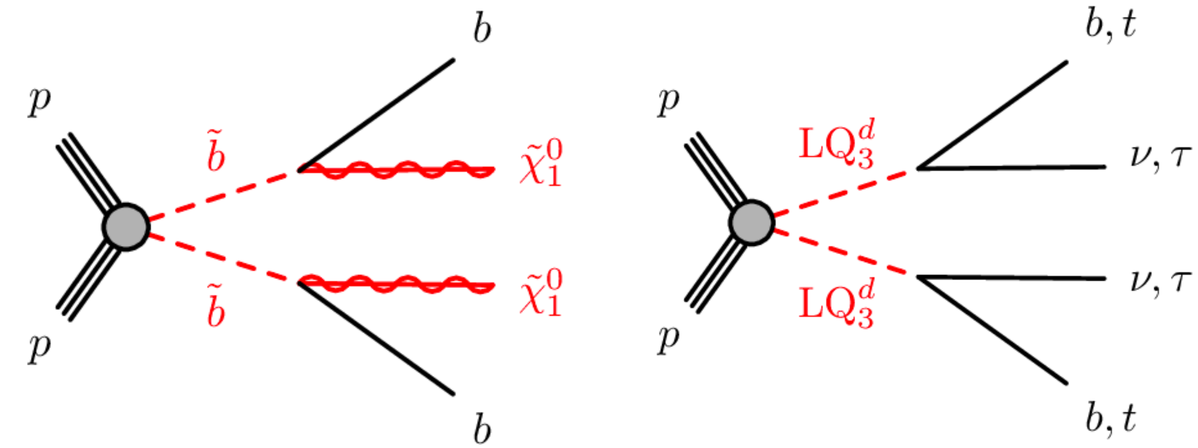
- Strongest limits on pair-produced 3rd-generation scalar LQs for B=0.5 ($t\tau/b\nu$)
- First interpretation for vector LQs in ATLAS!



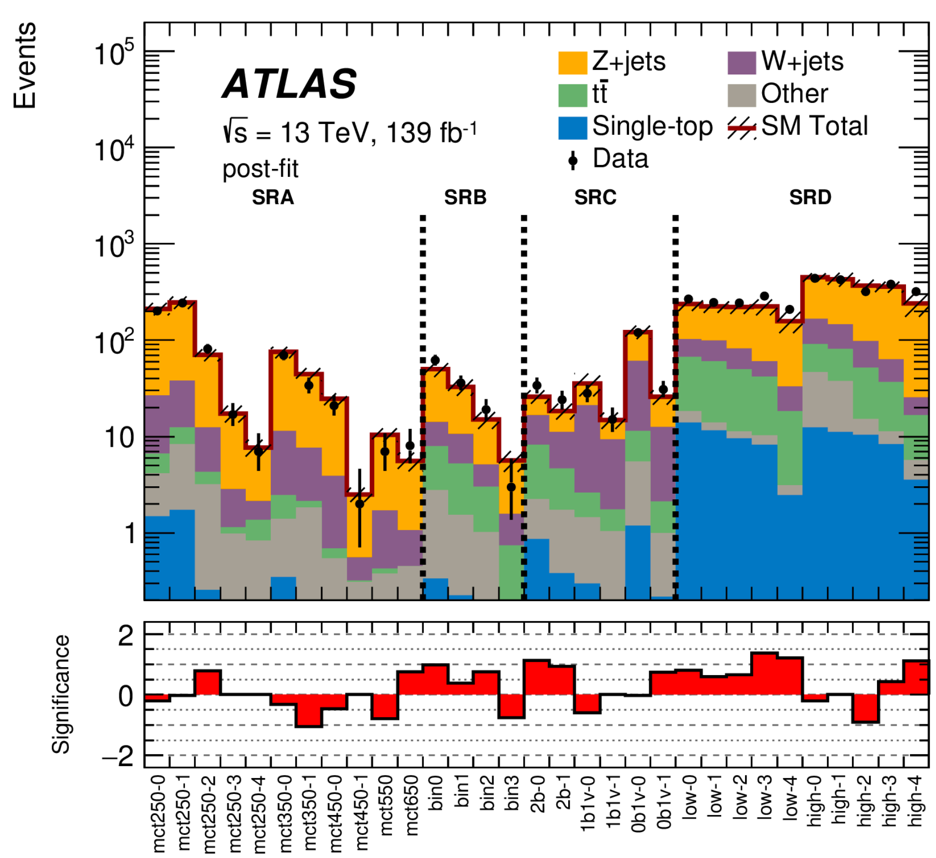
LQLQ → bνbν

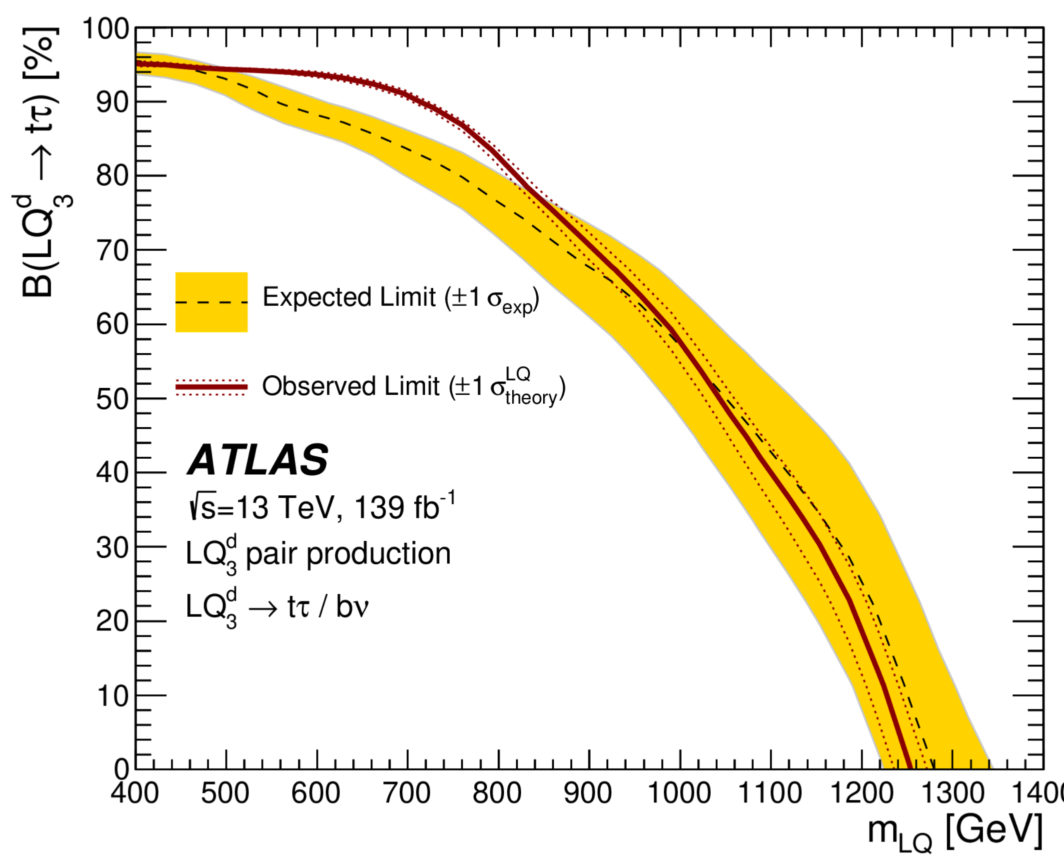
JHEP 05 (2021) 093

- Reinterpretation from search for pair-produced $\tilde{b}\tilde{b}$ decaying into a b-quark and a stable neutralino (0ℓ)
- SRA: optimised for large $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0)$
- SRB: optimised for 50 < $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0)$ < 200 GeV
- SRC: optimised for $\Delta m(\tilde{b}_1, \tilde{\chi}_1^0)$ < 50 GeV
- Take best limits from SRA+SRB or SRC for leptoquark interpretation



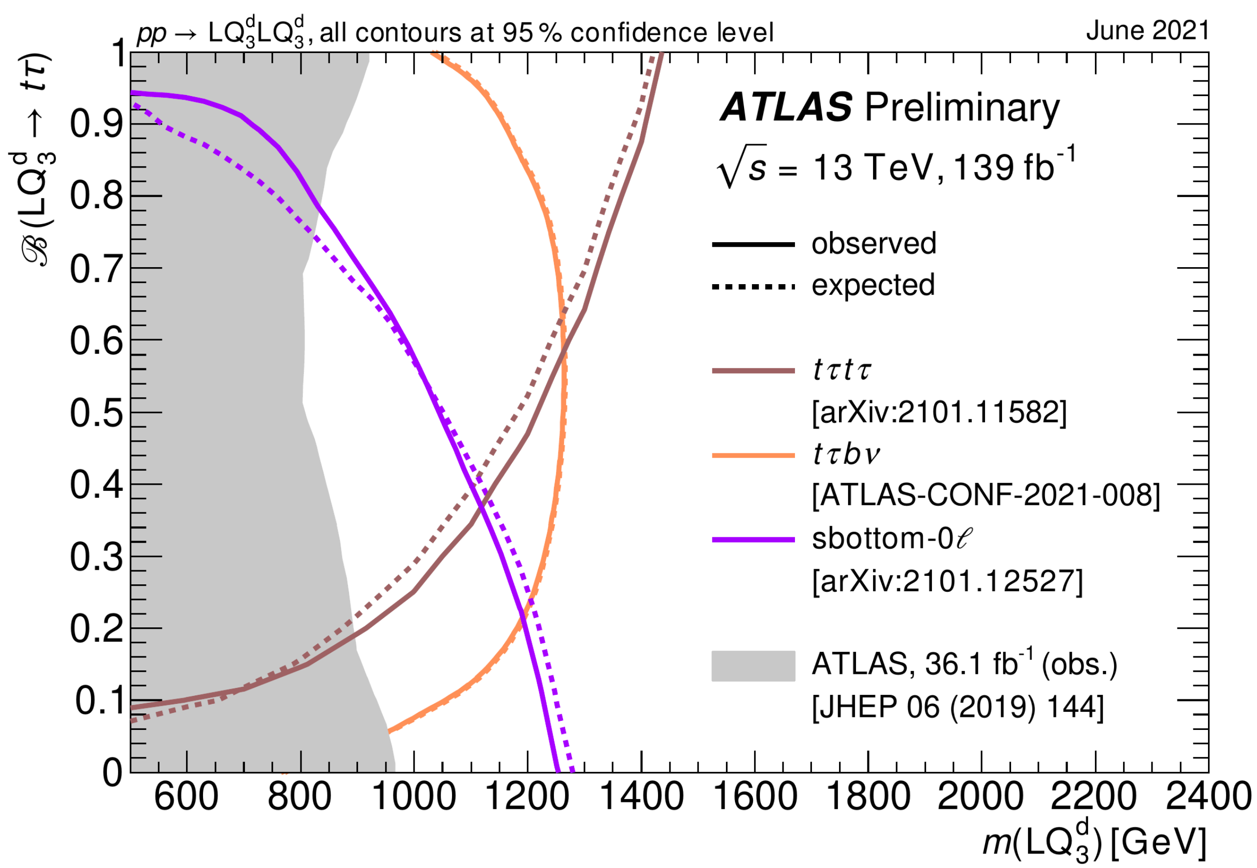
m_{LQ} < 1.26 TeV (0.4 TeV) excluded for B=0 (B=0.95)

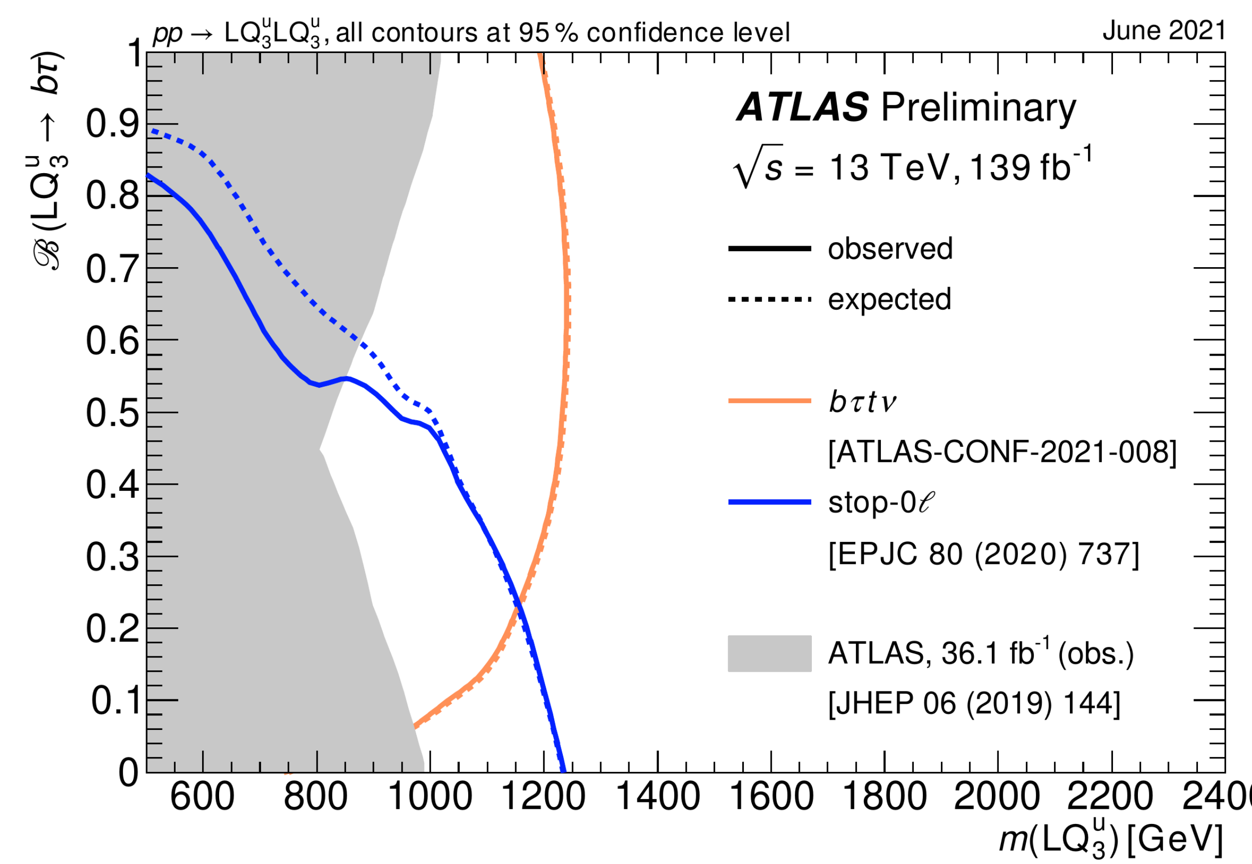




Towards combination

- Overlaying the LQ_3^d limits from t**τ**t**τ**, t**τ**bν and bνbν results and LQ_3^u limits from b**τ**tν and tνtν results
  - LQ_3^d : covering the full phase space with 3 complementary analyses
  - Next step: **COMBINATION!**





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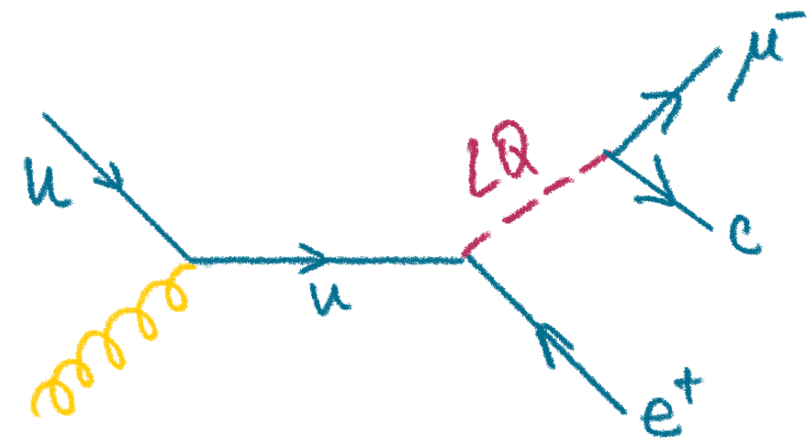
Single LQ production

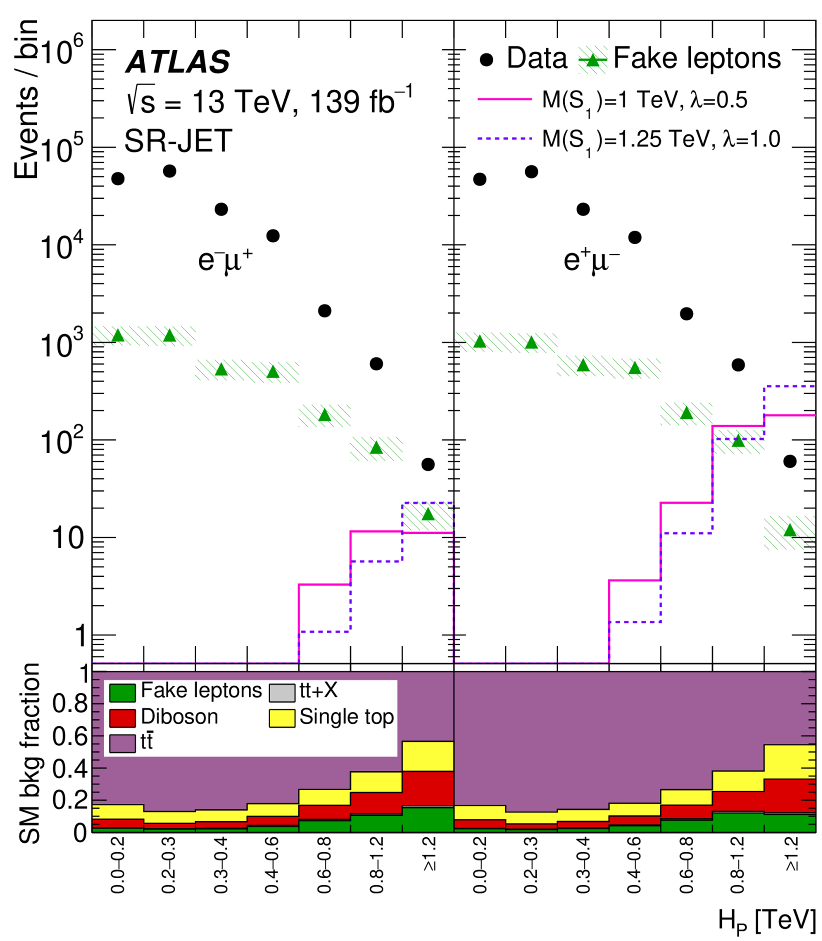
arXiv:2112.08090

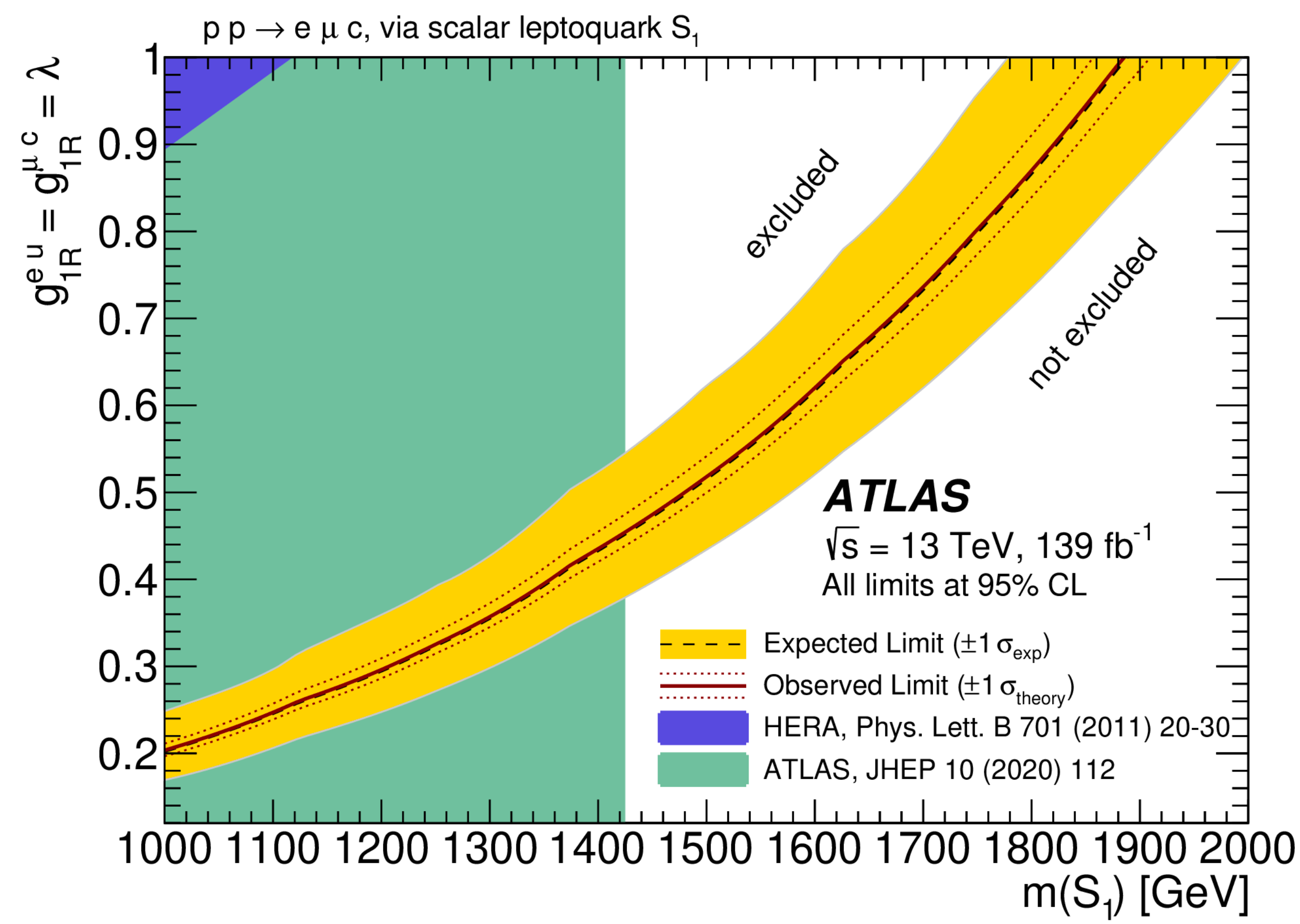
- First ATLAS single LQ production limits last Summer!
  - Assume LQ couples to eu and μc
  - LQ couplings of $g^{eu}_{1R} = g^{\mu c}_{1R} > 0.46$ newly excluded for $m_{LQ} > 1420$ GeV up to $g^{eu}_{1R} = g^{\mu c}_{1R} = 1$ for $m_{LQ} = 1880$ GeV

expect more singly-produced LQ in $e^+\mu^-$ than $e^-\mu^+$



$$H_P \equiv |\vec{p}_T^{\,e}| + |\vec{p}_T^{\,\mu}| + |\vec{p}_T^{\,j_1}|$$

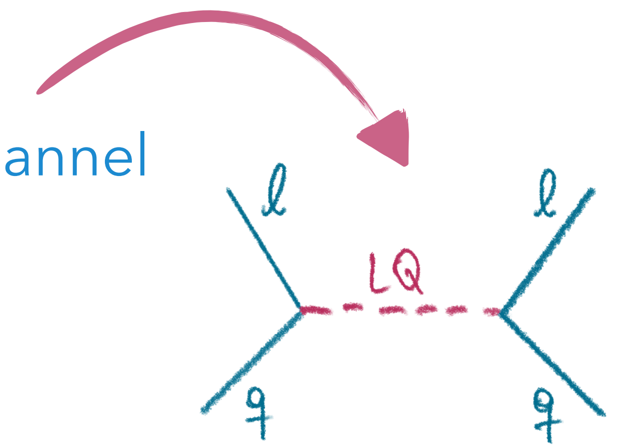




Conclusions

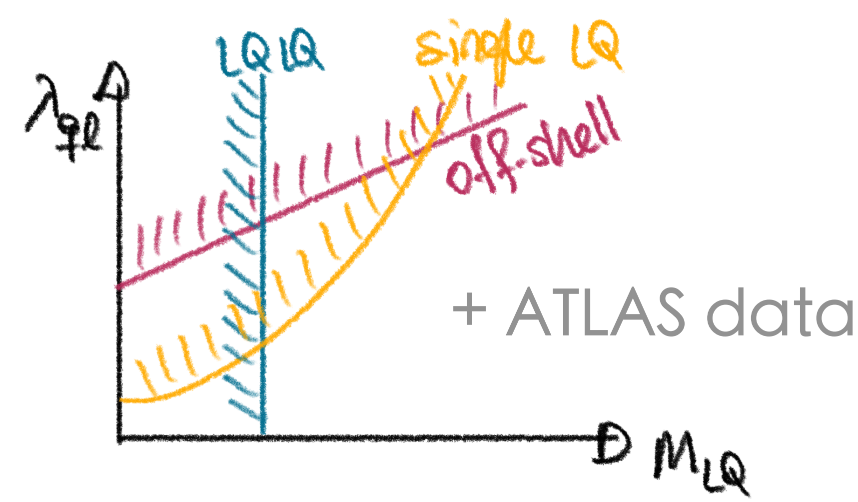
- Latest findings from searches for leptoquarks with the ATLAS experiment
- Stringent limits set on scalar leptoquarks with flavour-diagonal and cross-generational couplings

- **Just the start!**
  - Many more scenarios to be covered (vector LQ, single LQ, s-channel and off-shell production)
  - Object improvements to be further exploited
  - All these searches are statistically limited → LHC expected to further improve sensitivity with increasing luminosity!



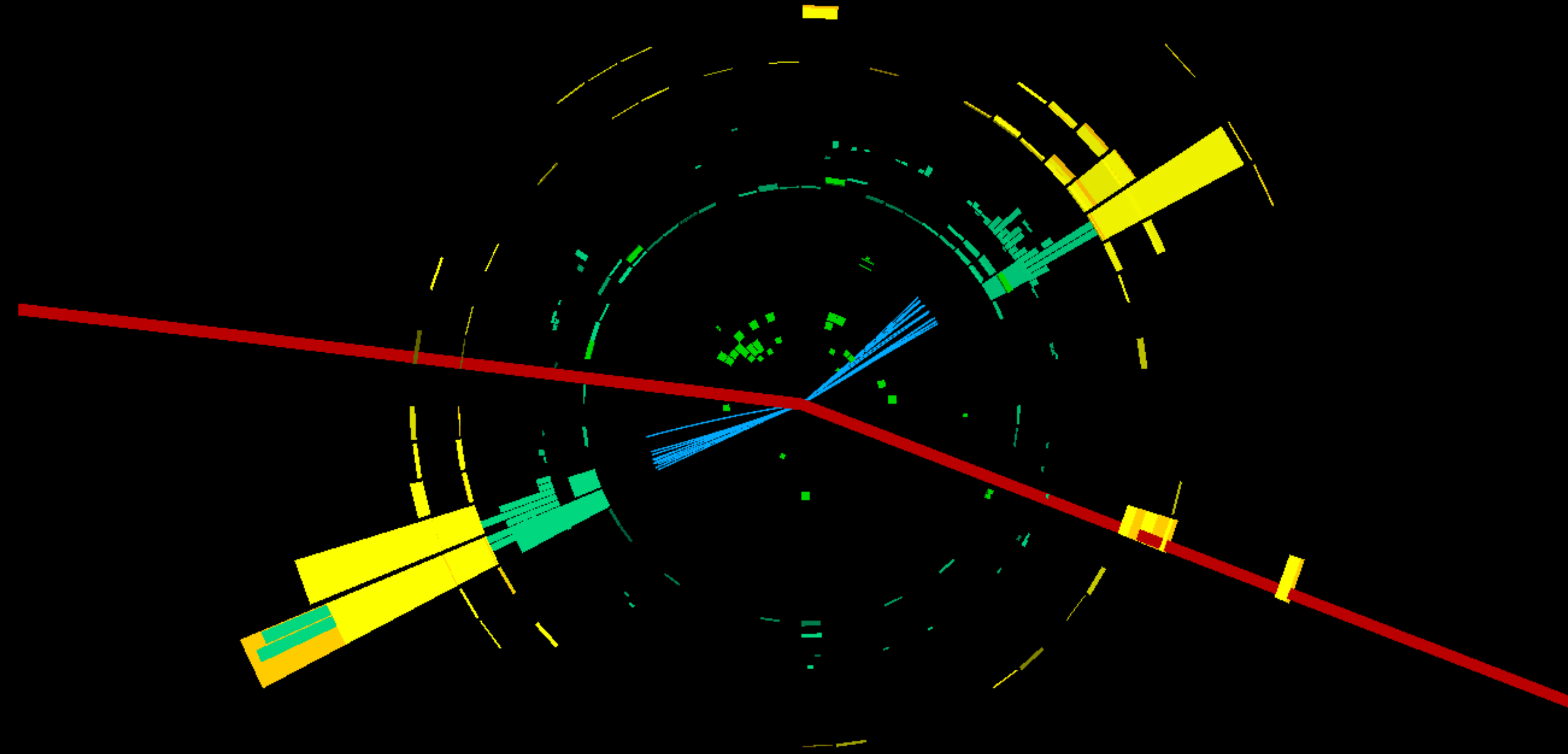
<u>Final goal:</u> explore the full phase-space

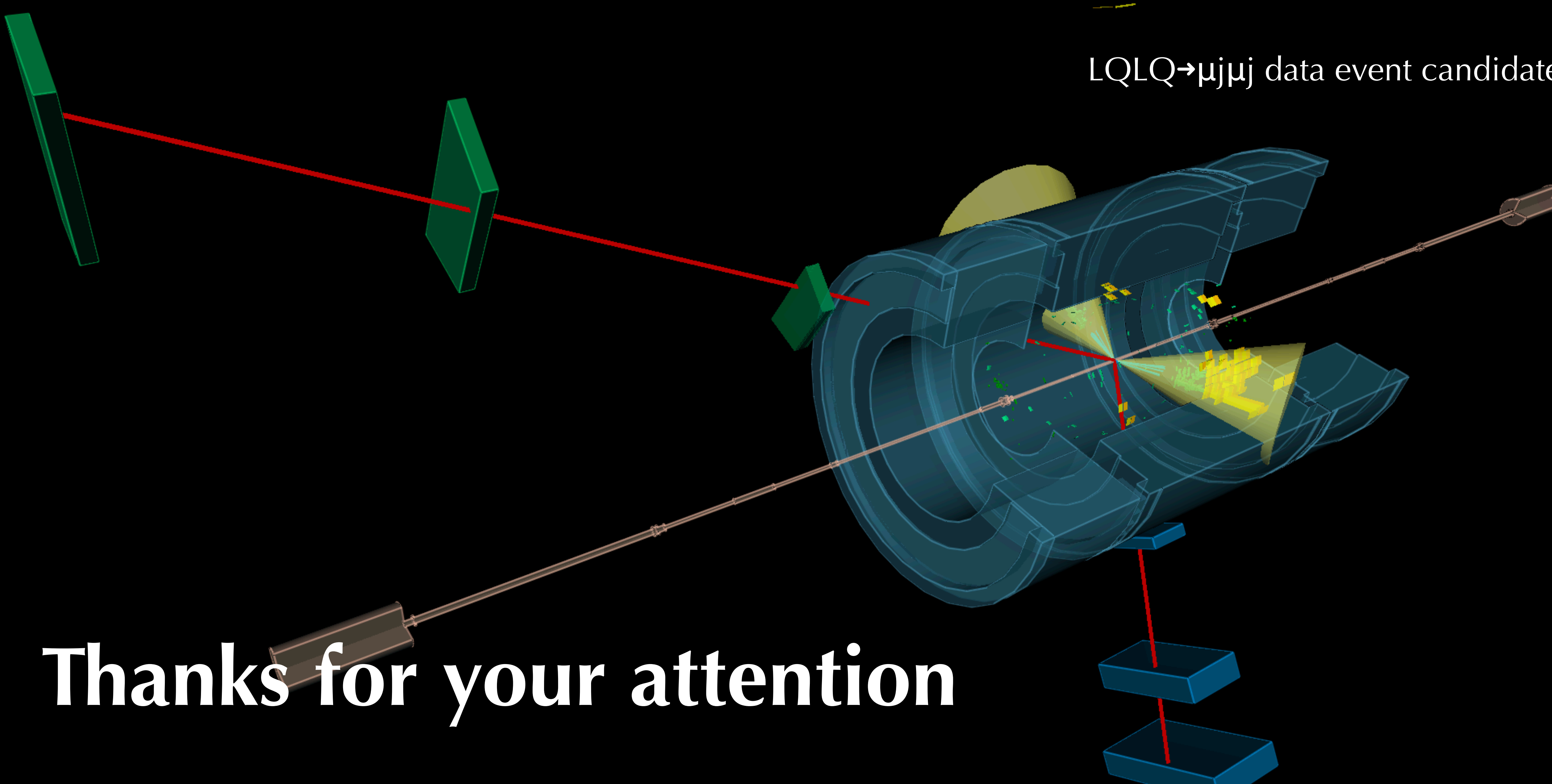
… and discover new physics!



ATLAS EXPERIMENT

Run: 280231
Event: 912117525
2015-09-24 09:18:55 CEST



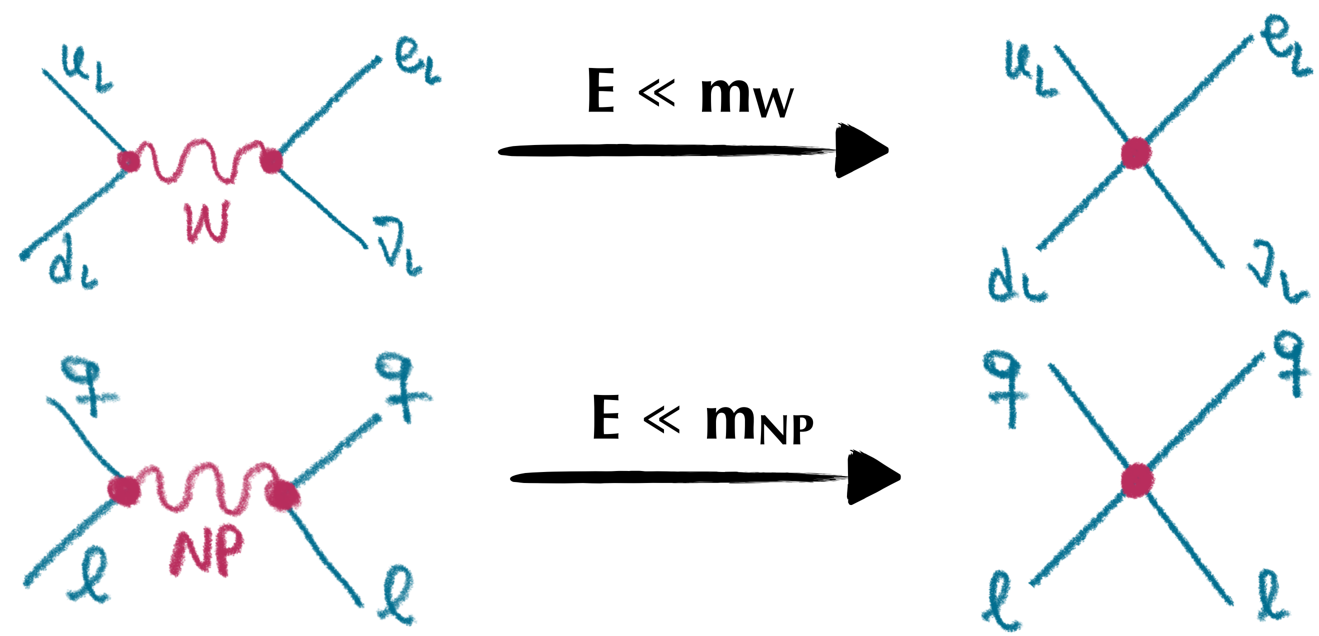


LQLQ→$\mu j \mu j$ data event candidate

Thanks for your attention

If BSM... how to explain it?

- **EFT analysis**
  - Interpret data based on effective Lagrangian
    - Fermi theory [$E \ll m_W$]
    - SMEFT [$E \ll m_{NP}$]



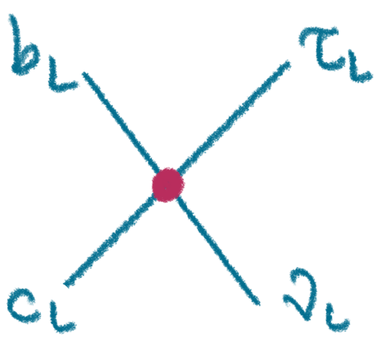
- **Simplified model**
  - Which mediator could explain these tensions?
  - UV completion models including new mediator ➜ extra new particles

EFT analysis (I)

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_i C_i \mathcal{O}_i$$

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i O_i$$

$$O_9^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu)$$
$$O_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$



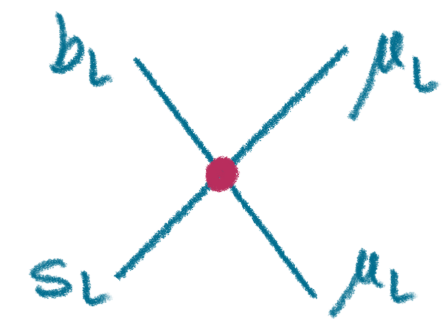
$$\sim \frac{1}{(3\ \text{TeV})^2}$$

$$3_q \to 2_q 3_\ell 3_\ell$$

$\gg$

$$\sim \frac{1}{(40\ \text{TeV})^2}$$

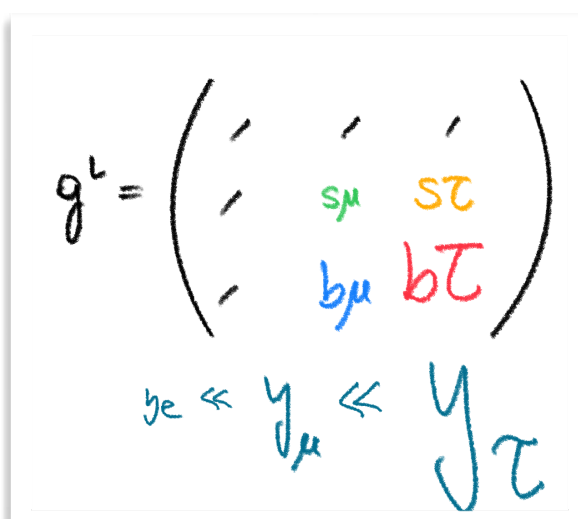
$$3_q \to 2_q 2_\ell 2_\ell$$



- Taken together, they point out to a well-defined structure of NP coupled mainly to **3rd generation**, with a flavour structure connected to that appearing in the **SM Yukawa couplings**

$$\sim \frac{1}{(1\ \text{TeV})^2} |V_q|$$

[1909.02519]



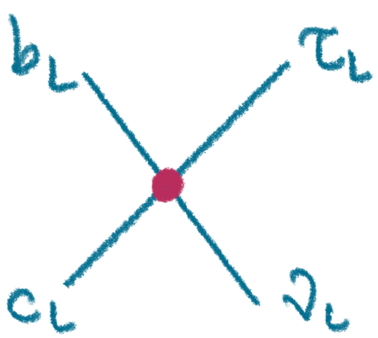
$$\sim \frac{1}{(1\ \text{TeV})^2} |V_q|\,|V_\ell|^2$$

Food-for-thought: connection to the hierarchy problem?

EFT analysis (II)

- **EFT analysis**

$$\mathscr{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{cb} \sum_i C_i \mathcal{O}_i$$



$$\sim \frac{1}{(3\ \text{TeV})^2}$$

$$3_q \to 2_q 3_\ell 3_\ell$$

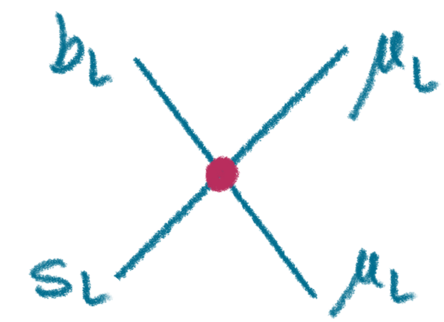
$\gg$

$$\mathscr{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_i C_i O_i$$

$$O_9^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \mu)$$
$$O_{10}^\mu = (\bar{s}_L \gamma_\mu b_L)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

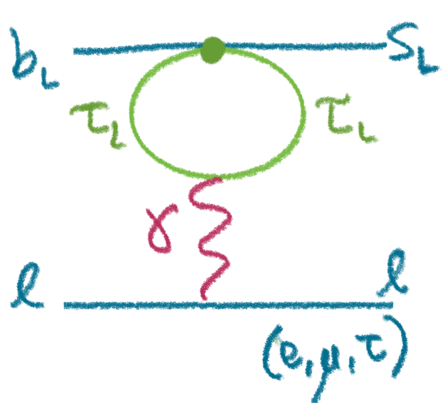
$$\sim \frac{1}{(40\ \text{TeV})^2}$$

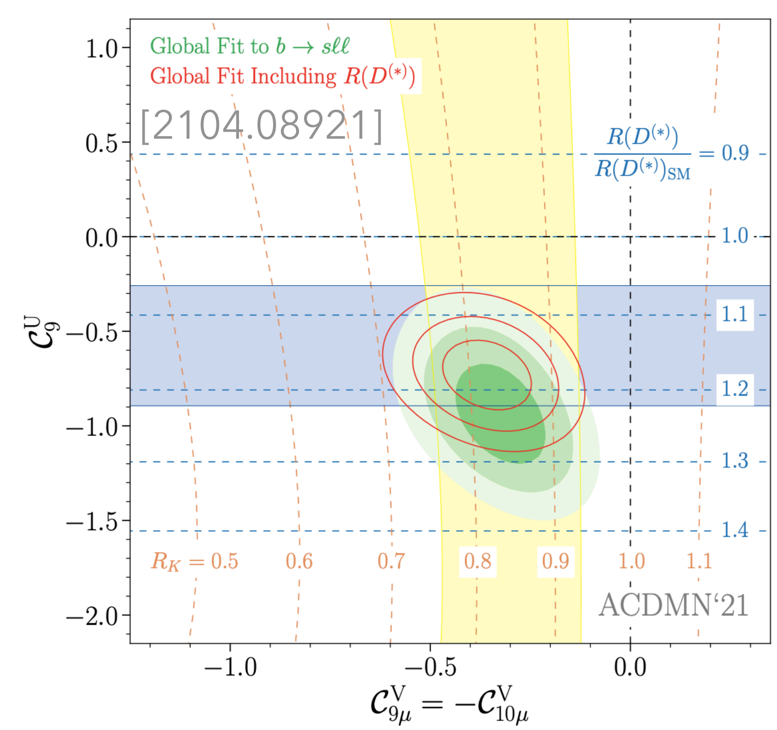
$$3_q \to 2_q 2_\ell 2_\ell$$



- Taken together, they point out to a well-defined structure of NP coupled mainly to **3rd generation**, with a flavour structure connected to that appearing in the **SM Yukawa couplings**

Positive feedback between anomalies!
Improved fit to b➔sℓℓ

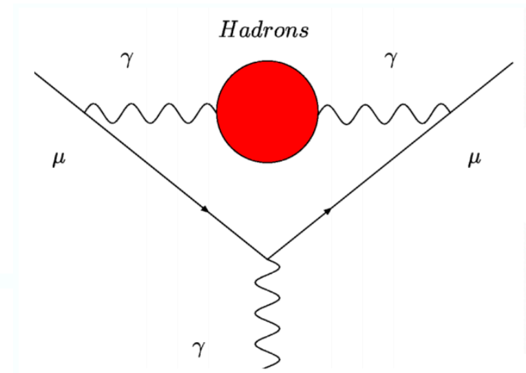


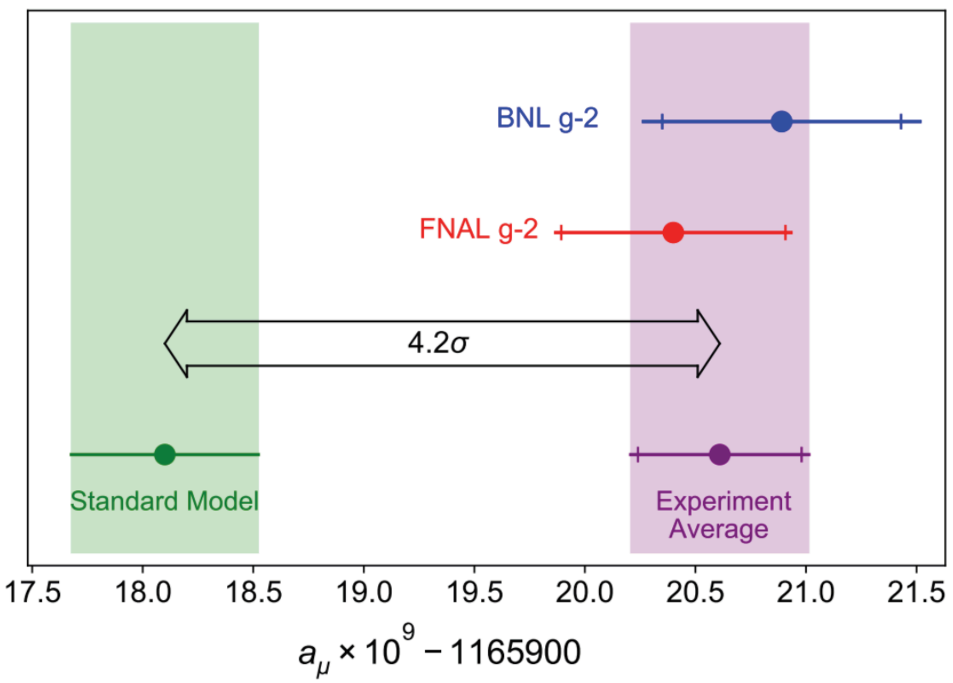


Additionally… muon g-2

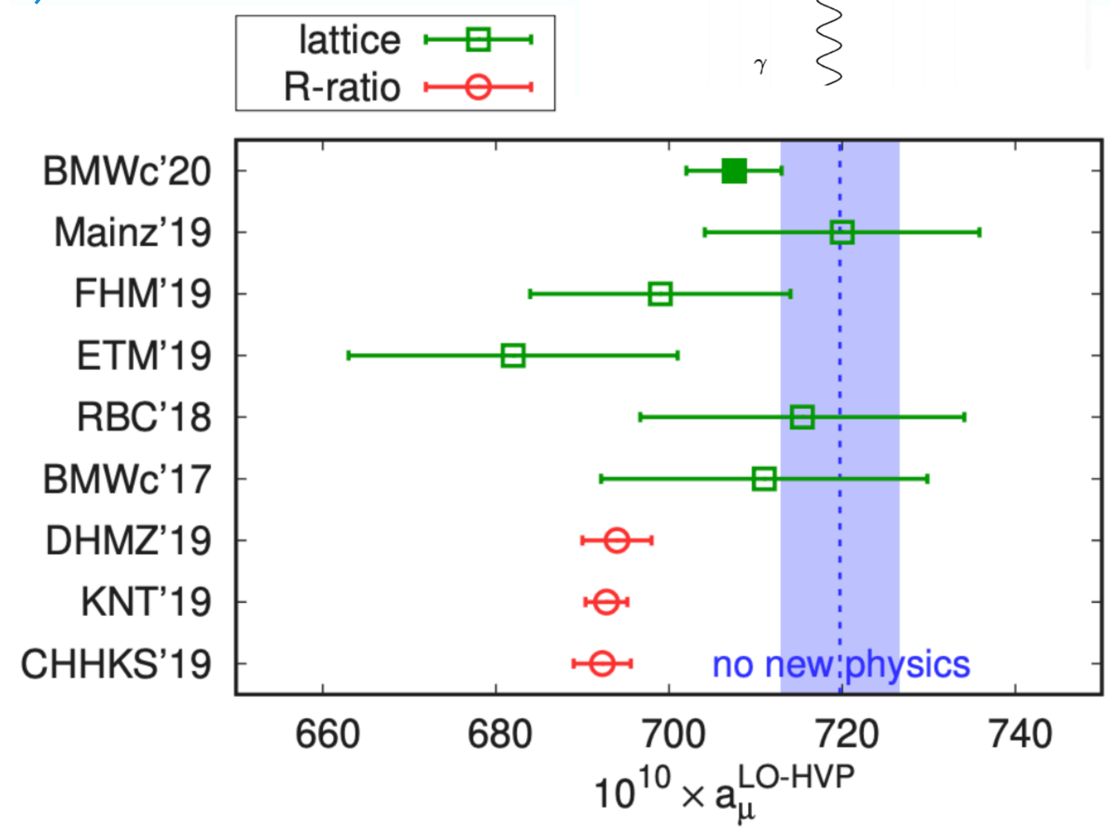
- Recent confirmation by Fermilab of the Brookhaven experimental result
    - Strong evidence of new physics: **4.2σ** (Fermilab + Brookhaven combo) *if using as benchmark the data-driven (R-ratio) SM calculation*

SM prediction dominated by QED, but SM error dominated by QCD



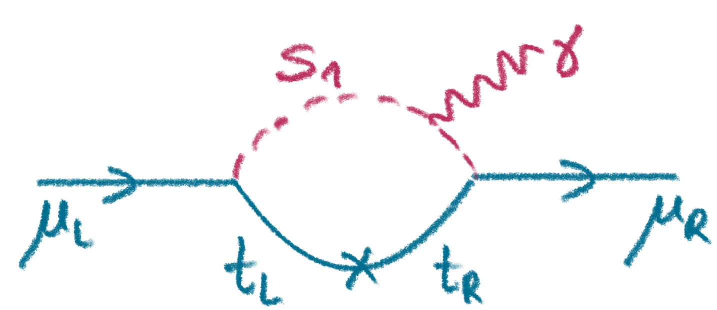


[Muon g-2 collaboration, 2104.03281]



[Borsanyi et al., 2002.12347]

- If the S_1 coupling to RH fermions is allowed, also a solution to $(g-2)_\mu$ is possible

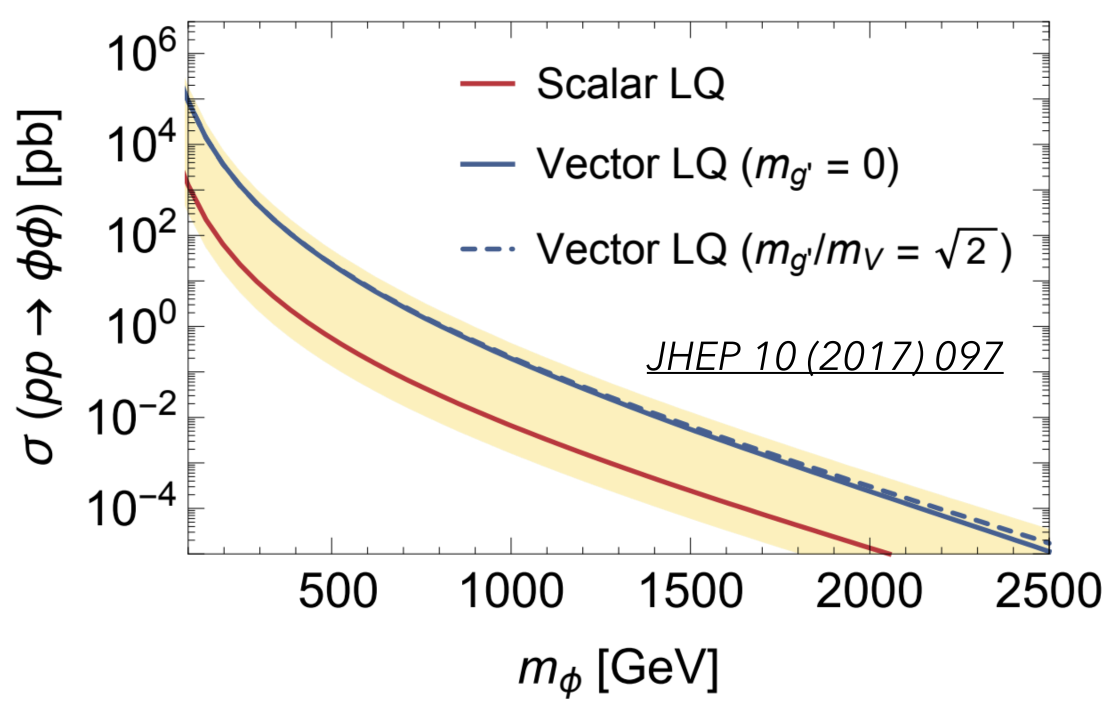


ATLAS LQ search strategy

- Simplified search strategy targeting certain final states from LQ decays
  - Extended Buchmüller, Rückl, Wyler (BRW) model [Phys. Lett. B 191 (1987) 442]
  - **up**- (Q=2/3e) or **down**- (Q=-1/3e) type LQs
- Searches for pair production of **scalar LQs ($LQ_{up/down}$)**
  - More model independent than vector LQ
  - Can be a pseudo-Nambu Goldstone boson (where the Higgs boson would also be included as a pNGB)
- Re-interpretations based on **vector LQs (LQ_V)** ongoing
  - Same charge and decay mode as LQ_{up}
  - **Minimal-coupling (MC):** LQ couples to SM gauge bosons through covariant derivative
  - **Yang-Mills (YM):** LQ is massive gauge boson with additional couplings to SM gauge bosons
- Comparison of cross-sections (3rd generation):
  - $\sigma_{YM}(LQ_V)$ ~ 5$\sigma_{MC}(LQ_V)$ ~ 20$\sigma(LQ_{up/down})$ for m(LQ)=1.5 TeV

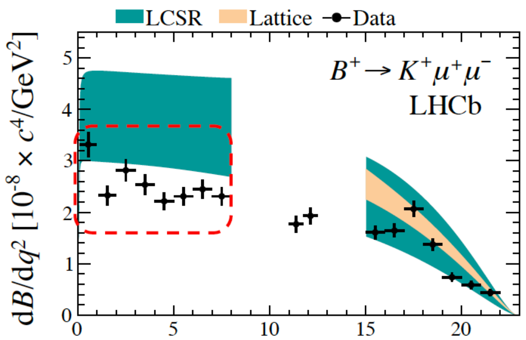
ex.: 3rd generation flavour-diagonal scalar LQ

LQ decay	B=1	B=0
LQ_{up}	$b\tau$	$t\nu$
LQ_{down}	$t\tau$	$b\nu$

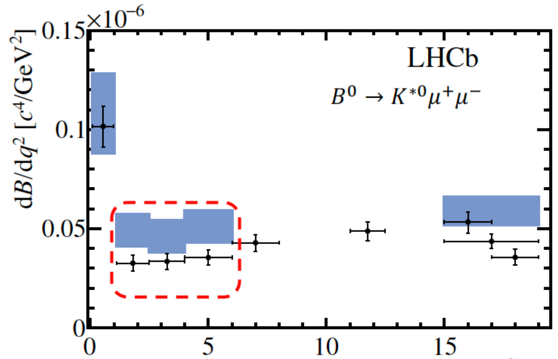


Other b→s μ⁺μ⁻ probes

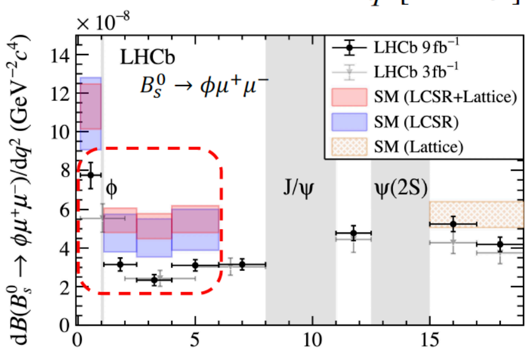
- **Branching fractions of $b \to s\mu^+\mu^-$ decays**



JHEP 1406 (2014) 133



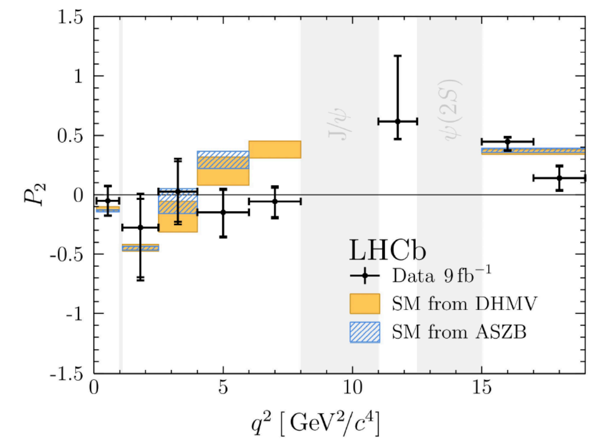
JHEP 04 (2017) 142

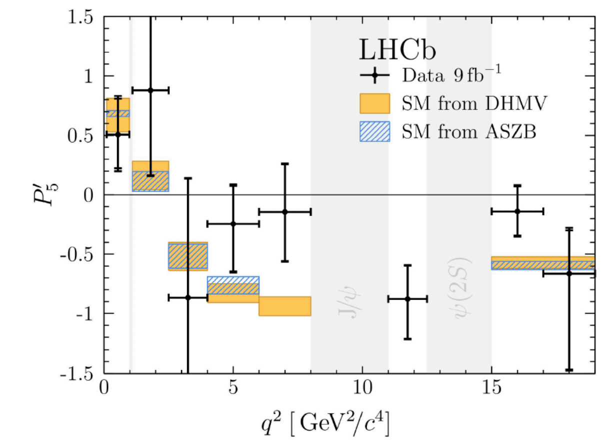


Phys. Rev. Lett. 127 (2021) 15

- Multiple measurements are below SM predictions at low dilepton mass squared (q^2)
- SM predictions suffer from large hadronic uncertainties

- **Angular analyses:** $B^+ \to K^{*+}\mu^+\mu^-$



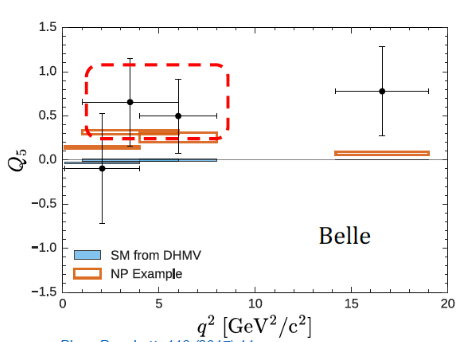


- Combined tension with SM at **3.1 sigma** when floating $Re(C_9)$

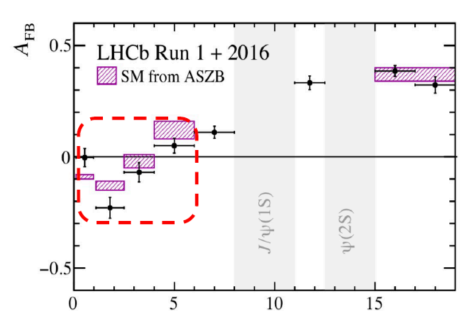
Phys. Rev. Lett. 126 (2021) 161802

Harry Cliff, LHC seminar

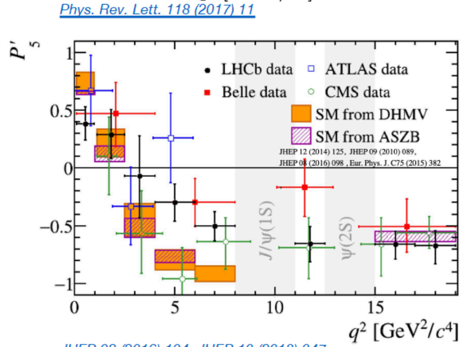
- **Angular analyses:** $B^0 \to K^{*0}\mu^+\mu^-$



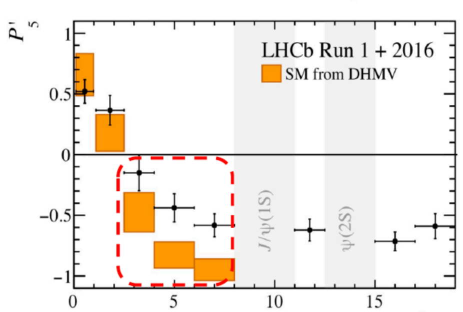
Phys. Rev. Lett. 118 (2017) 11



Phys. Rev. Lett. 125 (2020) 1



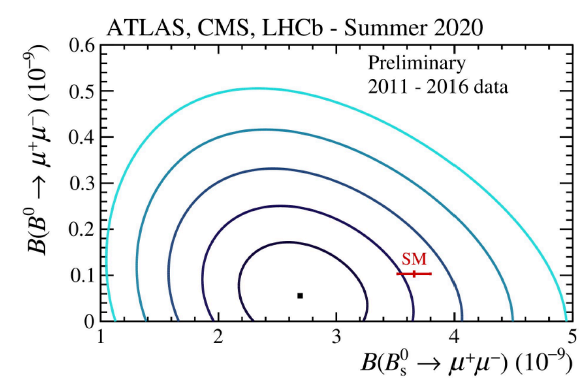
JHEP 02 (2016) 104, JHEP 10 (2018) 047, Phys. Lett. B 781 (2018) 517, Phys. Rev. Lett. 118 (2017) 11



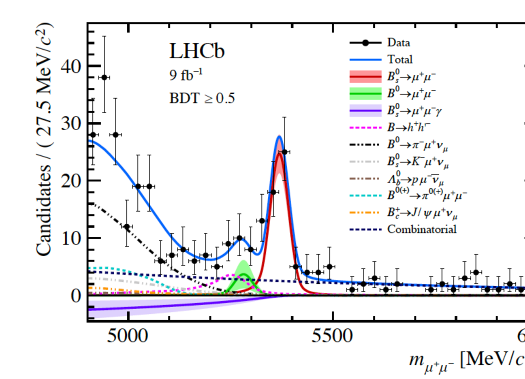
Phys. Rev. Lett. 125 (2020) 1

- Large number of observables offering complementary information on NP
- SM uncertainties smaller than for BFs
- Combined tension between latest LHCb analysis and SM at **3.3 sigma** when floating $Re(C_9)$
- Extent of hadronic contributions still matter of debate

- **Branching fraction of $B^0_{(s)} \to \mu^+\mu^-$ decays**



ATLAS-CONF-2020-049



arXiv:2108.09284

Cross-sections LQ pair vs s-channel

LQ pair production

LQ mass GeV	σ_{LO} [pb]	$\sigma_{NNLO+NNLL}$ [pb]	Uncertainties %	K-factor
500	4.19E-01	6.09E-01	7.53	1.24
600	1.66E-01	2.05E-01	8.12	1.23
700	6.33E-01	7.83E-02	8.80	1.24
800	2.63E-02	3.26E-02	9.53	1.24
850	1.74E-02	2.16E-02	9.93	1.24
900	1.16E-02	1.45E-02	10.33	1.25
950	7.96E-03	9.91E-03	10.76	1.24
1000	5.46E-03	6.83E-03	11.20	1.25
1050	3.79E-03	4.76E-03	11.65	1.26
1100	2.66E-03	3.35E-03	12.12	1.26
1150	1.88E-03	2.38E-03	12.62	1.27
1200	1.35E-03	1.70E-03	13.13	1.26
1250	9.67E-04	1.22E-03	13.66	1.26
1300	6.99E-04	8.87E-04	14.21	1.27
1350	5.06E-04	6.46E-04	14.78	1.28
1400	3.69E-04	4.73E-04	15.37	1.28
1450	2.70E-04	3.48E-04	15.99	1.29
1500	2.01E-04	2.57E-04	16.63	1.28
1550	1.47E-04	1.91E-04	17.28	1.30
1600	1.10E-04	1.42E-04	17.96	1.29

[1607.07741]

resonant s-channel production

m_{LQ} [TeV]	Partons	$\sigma_{S^{1/3}}$ [pb]	$\sigma_{S^{5/3}}$ [pb]
0.9	$u + e$	$(1.45 \times 10^{-1})^{+3.1\%}_{-3.7\%} \pm 1.8\%$	$(1.58 \times 10^{-1})^{+2.9\%}_{-3.4\%} \pm 1.8\%$
	$u + \mu$	$(1.39 \times 10^{-1})^{+3.1\%}_{-3.8\%} \pm 1.9\%$	$(1.52 \times 10^{-1})^{+2.9\%}_{-3.5\%} \pm 1.8\%$
	$u + \tau$	$(1.11 \times 10^{-1})^{+3.6\%}_{-4.0\%} \pm 2.0\%$	$(1.23 \times 10^{-1})^{+3.4\%}_{-3.6\%} \pm 2.0\%$
	$c + e$	$(1.32 \times 10^{-2})^{+4.2\%}_{-5.1\%} \pm 12.1\%$	$(1.44 \times 10^{-2})^{+3.9\%}_{-4.7\%} \pm 12.2\%$
	$c + \mu$	$(1.29 \times 10^{-2})^{+4.3\%}_{-5.2\%} \pm 12.0\%$	$(1.40 \times 10^{-2})^{+3.9\%}_{-4.8\%} \pm 12.0\%$
	$c + \tau$	$(1.01 \times 10^{-2})^{+4.6\%}_{-5.5\%} \pm 12.2\%$	$(1.12 \times 10^{-2})^{+4.1\%}_{-5.0\%} \pm 12.2\%$
1.6	$u + e$	$(1.40 \times 10^{-2})^{+2.8\%}_{-3.3\%} \pm 2.0\%$	$(1.49 \times 10^{-2})^{+2.7\%}_{-3.1\%} \pm 2.0\%$
	$u + \mu$	$(1.36 \times 10^{-2})^{+2.9\%}_{-3.4\%} \pm 2.0\%$	$(1.46 \times 10^{-2})^{+2.7\%}_{-3.1\%} \pm 2.0\%$
	$u + \tau$	$(1.11 \times 10^{-2})^{+3.3\%}_{-3.5\%} \pm 2.2\%$	$(1.20 \times 10^{-2})^{+2.9\%}_{-3.2\%} \pm 2.2\%$
	$c + e$	$(7.31 \times 10^{-4})^{+3.8\%}_{-4.4\%} \pm 24.2\%$	$(7.80 \times 10^{-4})^{+3.6\%}_{-4.1\%} \pm 24.3\%$
	$c + \mu$	$(7.16 \times 10^{-4})^{+3.8\%}_{-4.4\%} \pm 24.0\%$	$(7.65 \times 10^{-4})^{+3.6\%}_{-4.1\%} \pm 24.1\%$
	$c + \tau$	$(5.78 \times 10^{-4})^{+4.1\%}_{-4.7\%} \pm 24.2\%$	$(6.28 \times 10^{-4})^{+3.8\%}_{-4.3\%} \pm 24.3\%$
2.5	$u + e$	$(1.53 \times 10^{-3})^{+2.6\%}_{-3.0\%} \pm 2.4\%$	$(1.61 \times 10^{-3})^{+2.5\%}_{-2.8\%} \pm 2.4\%$
	$u + \mu$	$(1.50 \times 10^{-3})^{+2.6\%}_{-3.0\%} \pm 2.4\%$	$(1.59 \times 10^{-3})^{+2.5\%}_{-2.9\%} \pm 2.4\%$
	$u + \tau$	$(1.25 \times 10^{-3})^{+2.9\%}_{-3.2\%} \pm 2.5\%$	$(1.33 \times 10^{-3})^{+2.6\%}_{-3.0\%} \pm 2.5\%$
	$c + e$	$(5.52 \times 10^{-5})^{+3.3\%}_{-3.8\%} \pm 41.9\%$	$(5.83 \times 10^{-5})^{+3.1\%}_{-3.6\%} \pm 42.1\%$
	$c + \mu$	$(5.43 \times 10^{-5})^{+3.3\%}_{-3.8\%} \pm 41.8\%$	$(5.74 \times 10^{-5})^{+3.2\%}_{-3.6\%} \pm 41.9\%$
	$c + \tau$	$(4.48 \times 10^{-5})^{+3.5\%}_{-4.0\%} \pm 42.0\%$	$(4.79 \times 10^{-5})^{+3.3\%}_{-3.8\%} \pm 42.1\%$
4.0	$u + e$	$(7.21 \times 10^{-5})^{+2.3\%}_{-2.6\%} \pm 3.1\%$	$(7.49 \times 10^{-5})^{+2.2\%}_{-2.5\%} \pm 3.0\%$
	$u + \mu$	$(7.14 \times 10^{-5})^{+2.3\%}_{-2.6\%} \pm 3.1\%$	$(7.42 \times 10^{-5})^{+2.2\%}_{-2.5\%} \pm 3.1\%$
	$u + \tau$	$(6.02 \times 10^{-5})^{+2.4\%}_{-2.7\%} \pm 3.2\%$	$(6.30 \times 10^{-5})^{+2.3\%}_{-2.6\%} \pm 3.2\%$
	$c + e$	$(2.35 \times 10^{-6})^{+2.6\%}_{-3.0\%} \pm 63.0\%$	$(2.45 \times 10^{-6})^{+2.6\%}_{-2.9\%} \pm 63.1\%$
	$c + \mu$	$(2.33 \times 10^{-6})^{+2.7\%}_{-3.0\%} \pm 62.9\%$	$(2.42 \times 10^{-6})^{+2.6\%}_{-2.9\%} \pm 63.1\%$
	$c + \tau$	$(1.96 \times 10^{-6})^{+2.8\%}_{-3.1\%} \pm 63.1\%$	$(2.05 \times 10^{-6})^{+2.7\%}_{-3.0\%} \pm 63.2\%$

Table 1. Inclusive cross sections in **pb** for the resonant leptoquark production from up-type quarks, $pp \to$ LQ + charge-conjugated process, as a function of the leptoquark mass m_{LQ} at $\sqrt{s} = 13$ TeV. The cross section $\sigma_{S^{1/3}}$ ($\sigma_{S^{5/3}}$) corresponds to the resonant production of scalar LQ with absolute electric charge 1/3 (5/3) when the associated Yukawa coupling strength is set to one, $y_{q\ell} = 1$. The second column denotes which quark-lepton pair couples to the corresponding leptoquark. First (second) uncertainty is due to the renormalisation and factorisation scale variations (PDF replicas), and is given in per cent units. See Section 3 for details.

[2012.02092]

Leptoquarks and quantum numbers

Table 116.1: Possible leptoquarks and their quantum numbers. *(PDG 2019)*

Spin	$3B+L$	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	Allowed coupling	
0	-2	$\bar{3}$	1	1/3	$\bar{q}^c_L \ell_L$ or $\bar{u}^c_R e_R$	S_1
0	-2	$\bar{3}$	1	4/3	$\bar{d}^c_R e_R$	$\tilde{S}_1$
0	-2	$\bar{3}$	3	1/3	$\bar{q}^c_L \ell_L$	S_3
1	-2	$\bar{3}$	2	5/6	$\bar{q}^c_L \gamma^\mu e_R$ or $\bar{d}^c_R \gamma^\mu \ell_L$	V_2
1	-2	$\bar{3}$	2	$-1/6$	$\bar{u}^c_R \gamma^\mu \ell_L$	$\tilde{V}_2$
0	0	3	2	7/6	$\bar{q}_L e_R$ or $\bar{u}_R \ell_L$	R_2
0	0	3	2	1/6	$\bar{d}_R \ell_L$	$\tilde{R}_2$
1	0	3	1	2/3	$\bar{q}_L \gamma^\mu \ell_L$ or $\bar{d}_R \gamma^\mu e_R$	U_1
1	0	3	1	5/3	$\bar{u}_R \gamma^\mu e_R$	$\tilde{U}_1$
1	0	3	3	2/3	$\bar{q}_L \gamma^\mu \ell_L$	U_3

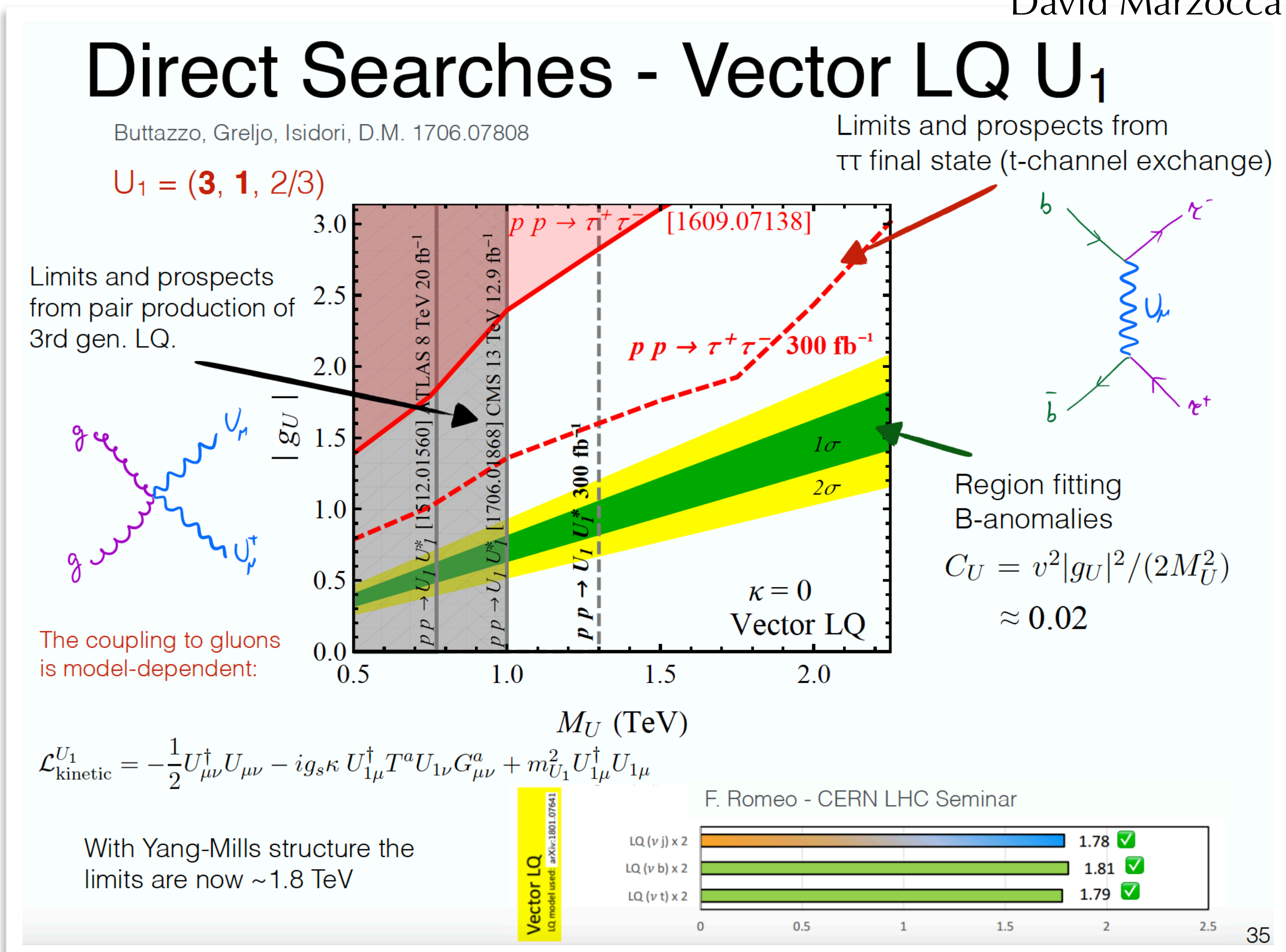
Types of LQs according to Buchmüller, Rückl, Wyler (BRW) model

LQ simulation & uncertainties

- Simulation at **NLO QCD** with **`MadGraph5_aMC@NLO + Pythia8`**
  - ME-PS matching done with CKKW-L prescription with matching scale = 1/4 * m_{LQ}
  - Narrow-decay-width approximation: 0.2% of m_{LQ} (on-shell production dominates)
- Samples with LQ mass between **[400-2000] GeV**
  - 50 GeV mass intervals within [800-1600] GeV, 100 GeV otherwise
  - additional dedicated β=1 samples
- **Signal cross-section calculations** equivalent to **pair-produced top squarks** (both massive, coloured, scalar particles with the same production modes)
  - **Approximate NNLO QCD + NNLL** accuracy
  - For LQ masses [400-2000] GeV, the cross-sections are [2.1 pb - 0.02 fb]
  - Renormalisation and factorisation scale uncertainties: 7-22% for LQ masses [400-2000] GeV
- **Acceptance and efficiency uncertainties**
  - Modelling of initial- and final-state radiation
  - Renormalisation and factorisation scale variations
  - PDF uncertainties

Vector LQs

David Marzocca



$$\mathcal{L}^{U_1}_{\text{kinetic}} = -\frac{1}{2}U^{\dagger}_{\mu\nu}U_{\mu\nu} - ig_s\kappa\, U^{\dagger}_{1\mu}T^a U_{1\nu}G^a_{\mu\nu} + m^2_{U_1}U^{\dagger}_{1\mu}U_{1\mu}$$

[1512.01560]

$$\mathcal{L}_U = -\frac{1}{2}U^{\dagger}_{\mu\nu}U^{\mu\nu} + M_U^2 U^{\dagger}_{\mu}U_{\mu} + \mathcal{L}_{an} \quad (4.1)$$

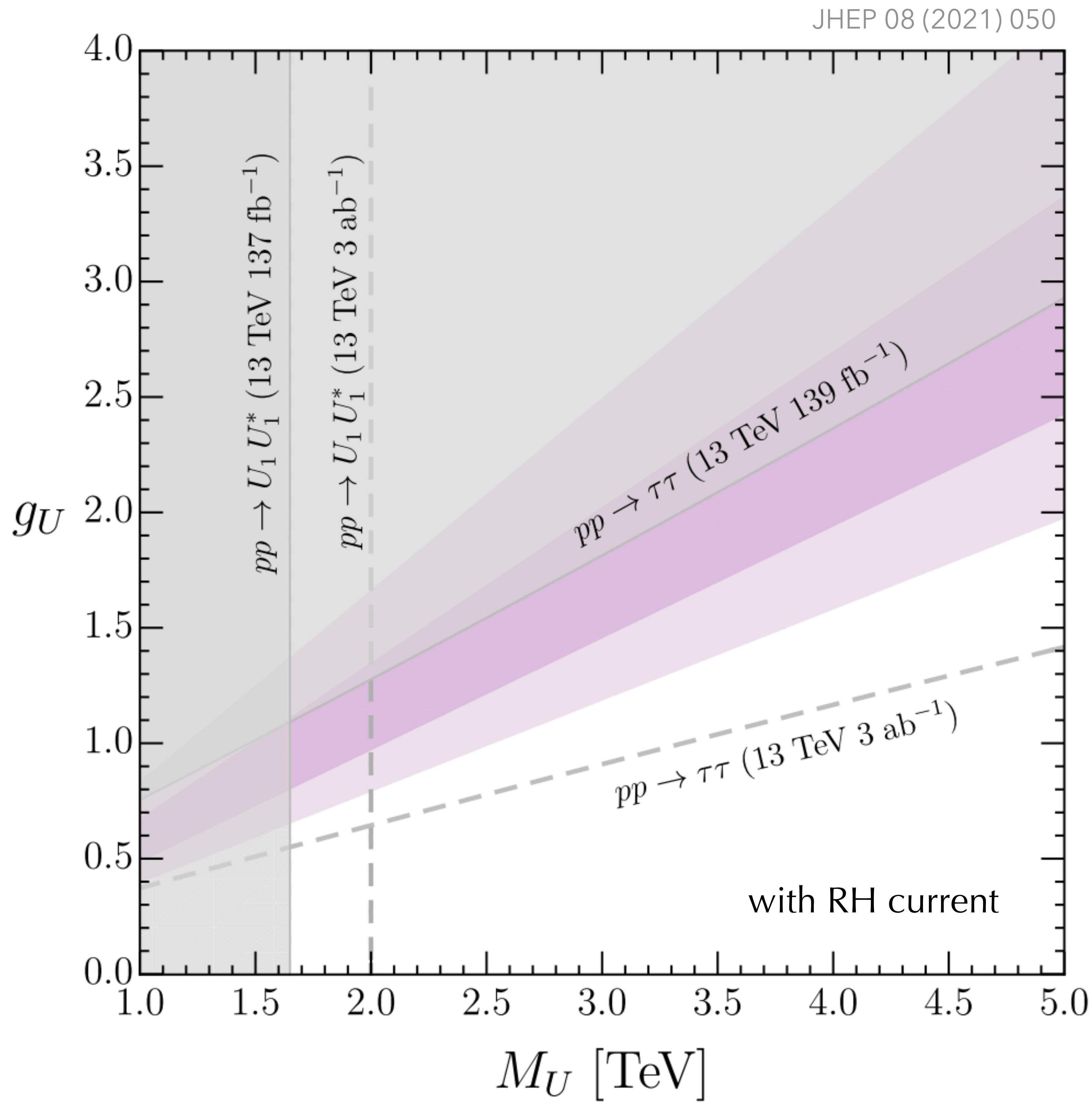
where

$$U_{\mu\nu} = D_\nu U_\mu - D_\nu U_\mu \qquad D_\mu \equiv \partial_\mu - ig_s\frac{\lambda^a}{2}G^a_\mu - ig'\frac{2}{3}B_\mu, \quad (4.2)$$

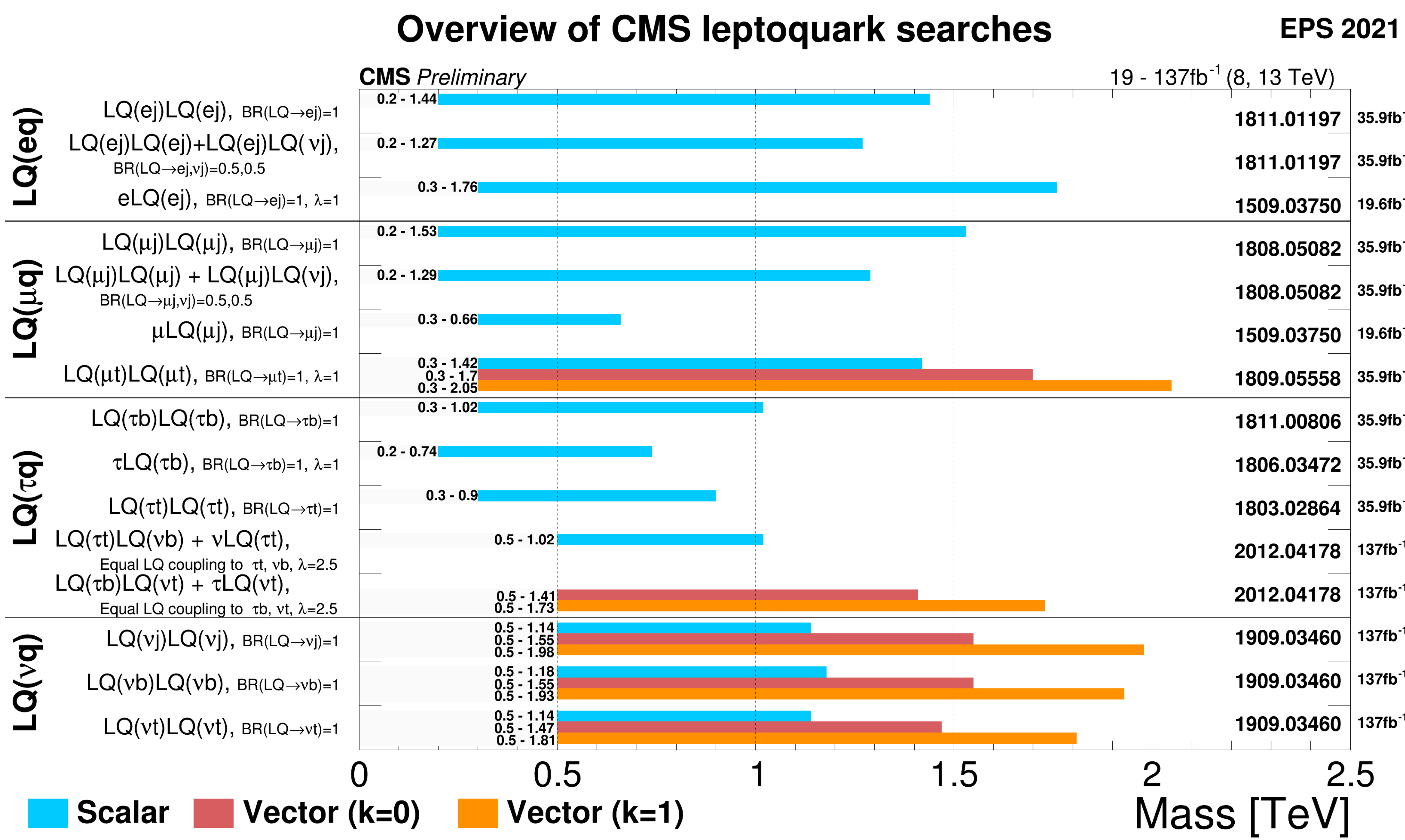
and

$$\mathcal{L}_{an} = -ig_s k_s(U^{\dagger}_\mu\frac{\lambda^a}{2}U_\nu)G^{\mu\nu^a} - ig'\frac{2}{3}k_Y U^{\dagger}_\mu U_\nu B^{\mu\nu} \quad (4.3)$$

LQ bounds and B-anomalies



CMS summary LQ



https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryPlotsEXO13TeV

LQLQ → $b\nu b\nu$

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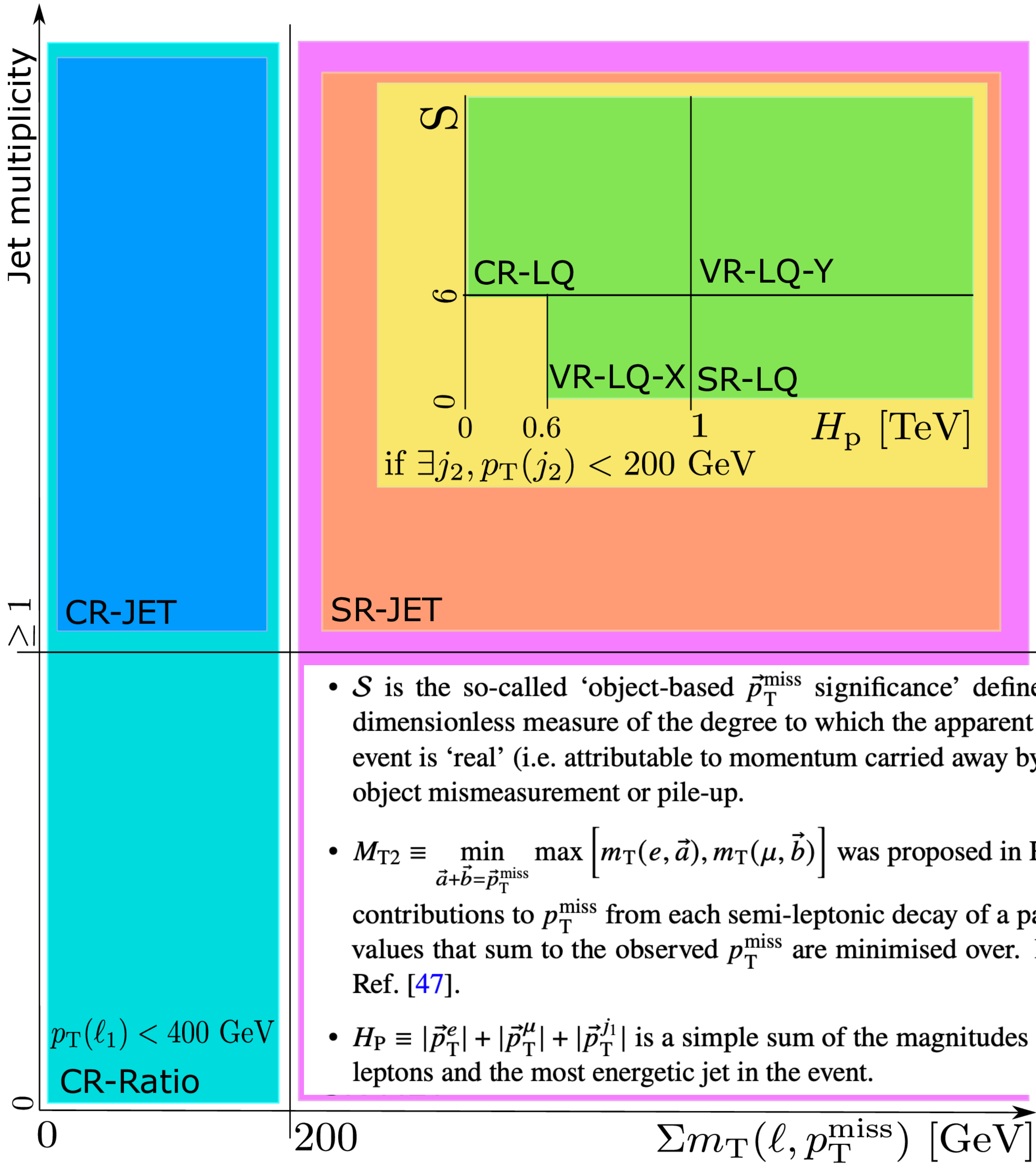
Variable		SRA	CRzA	$\mathrm{VR}^{m_{\mathrm{CT}}}_{\mathrm{A1}}$	$\mathrm{VR}^{m_{bb}}_{\mathrm{A1}}$	$\mathrm{VR}^{m_{\mathrm{CT}}}_{\mathrm{A2}}$	$\mathrm{VR}^{m_{bb}}_{\mathrm{A2}}$
Number of baseline leptons		0	2	0			
Number of high-purity leptons		–	2 SFOS	–			
$p_{\mathrm{T}}(\ell_1)$	[GeV]	–	> 27	–			
$p_{\mathrm{T}}(\ell_2)$	[GeV]	–	> 20	–			
$m_{\mathrm{T}}(\ell, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	[GeV]	–	> 20	–			
$m_{\ell\ell}$	[GeV]	–	[81, 101]	–			
Number of jets		$\in [2, 4]$					
Number of b-tagged jets		2					
j_1 and j_2 b-tagged		✓					
$p_{\mathrm{T}}(j_1)$	[GeV]	> 150					
$p_{\mathrm{T}}(j_2)$	[GeV]	> 50					
$p_{\mathrm{T}}(j_4)$	[GeV]	< 50					
$\min[\Delta\phi(\mathrm{jet}_{1-4}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})]$	[rad]	> 0.4					
$E_{\mathrm{T}}^{\mathrm{miss}}$	[GeV]	> 250	< 100	> 250			
$\tilde{E}_{\mathrm{T}}^{\mathrm{miss}}$	[GeV]	–	> 250	–			
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$		> 0.25	–	–			
$\tilde{E}_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$		–	> 0.25	–			
m_{bb}	[GeV]	> 200		< 200	> 200	< 200	> 200
m_{CT}	[GeV]	> 250		> 250	[150, 250]	> 250	[150, 250]
m_{eff}	[GeV]	> 500		[500, 1500]		> 1500	

Variable		SRB	CRzB	VRzB
Number of baseline leptons		0	2	
Number of high-purity leptons		–	2 SFOS	
$p_{\mathrm{T}}(\ell_1)$	[GeV]	–	> 27	
$p_{\mathrm{T}}(\ell_2)$	[GeV]	–	> 20	
$m_{\ell\ell}$	[GeV]	–	[76, 106]	
$m_{\mathrm{T}}(\ell, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})$	[GeV]	–	> 20	
Number of jets		$\in [2, 4]$		
Number of b-tagged jets		2		
$p_{\mathrm{T}}(j_1)$	[GeV]	> 100		
$p_{\mathrm{T}}(j_2)$	[GeV]	> 50		
$\min[\Delta\phi(\mathrm{jet}_{1-4}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}})]$	[rad]	> 0.4		
j_1 not b-tagged		–	✓	–
$E_{\mathrm{T}}^{\mathrm{miss}}$	[GeV]	> 250	< 100	
$\tilde{E}_{\mathrm{T}}^{\mathrm{miss}}$	[GeV]	–	> 250	
m_{CT}	[GeV]	< 250		
w_{XGB}		> 0.85	[0.3, 0.63]	> 0.63

Variable		SRC-2b	SRC-1b1v	SRC-0b1v	VRC-2b	VRC-1b1v	VRC-0b1v
Number of jets		$\in [2, 5]$					
j_1 not b-tagged		✓					
Number of baseline leptons		0					
Number of b-tagged jets		≥ 2	1	0	≥ 2	1	0
N_{vtx}		≥ 0	≥ 1	≥ 1	≥ 0	≥ 1	≥ 1
m_{vtx}	[GeV]	–	> 0.6	> 1.5	–	> 0.6	> 1.5
$p_{\mathrm{T}}^{\mathrm{vtx}}$	[GeV]	–	> 3	> 5	–	> 3	> 5
$p_{\mathrm{T}}(j_1)$	[GeV]	> 500	> 400	> 400	< 500	> 400	> 400
$E_{\mathrm{T}}^{\mathrm{miss}}$	[GeV]	> 500	> 400	> 400	< 500	> 400	> 400
$H_{\mathrm{T};3}$	[GeV]	–	< 80	< 80	–	< 80	< 80
$\mathcal{A}$		> 0.80	> 0.86	–	[0.8, 0.9]	> 0.86	-
m_{jj}	[GeV]	> 250	> 250	–	[150, 250]	> 250	-
$\Delta\phi(j_1, b_1)$	[rad]	–	> 2.2	–	–	< 2.2	–
$\Delta\phi(j_1, \mathrm{vtx})$	[rad]	–	–	> 2.2	–	–	< 2.2
$\lvert\eta_{\mathrm{vtx}}\rvert$		–	< 1.2	< 1.2	–	> 1.2	> 1.2

Single LQ production

arXiv:2112.08090



- $\mathcal{S}$ is the so-called 'object-based $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ significance' defined in Eq. (15) of Ref. [46]. It is a dimensionless measure of the degree to which the apparent missing transverse momentum in the event is 'real' (i.e. attributable to momentum carried away by invisible particles) rather than due to object mismeasurement or pile-up.
- $M_{\mathrm{T2}} \equiv \min_{\vec{a}+\vec{b}=\vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \max \left[m_{\mathrm{T}}(e, \vec{a}), m_{\mathrm{T}}(\mu, \vec{b}) \right]$ was proposed in Ref. [45], where $\vec{a}$ and $\vec{b}$ represent the contributions to $p_{\mathrm{T}}^{\mathrm{miss}}$ from each semi-leptonic decay of a pair-produced particle, and all possible values that sum to the observed $p_{\mathrm{T}}^{\mathrm{miss}}$ are minimised over. It is evaluated using the algorithm of Ref. [47].
- $H_{\mathrm{P}} \equiv |\vec{p}_{\mathrm{T}}^{\,e}| + |\vec{p}_{\mathrm{T}}^{\,\mu}| + |\vec{p}_{\mathrm{T}}^{\,j_1}|$ is a simple sum of the magnitudes of the transverse momenta of the two leptons and the most energetic jet in the event.

Search for

LQ LQ → $t\tau t\tau$

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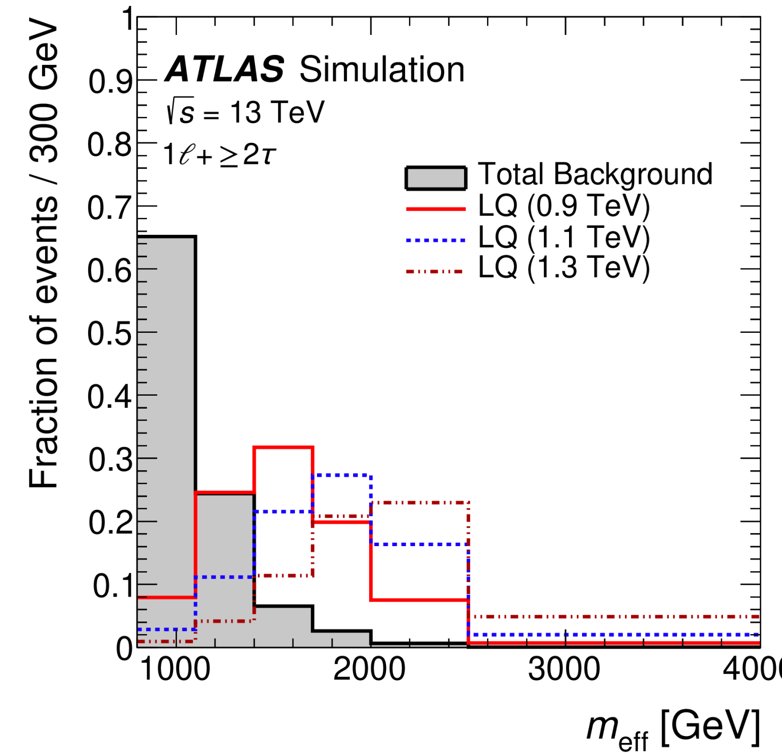
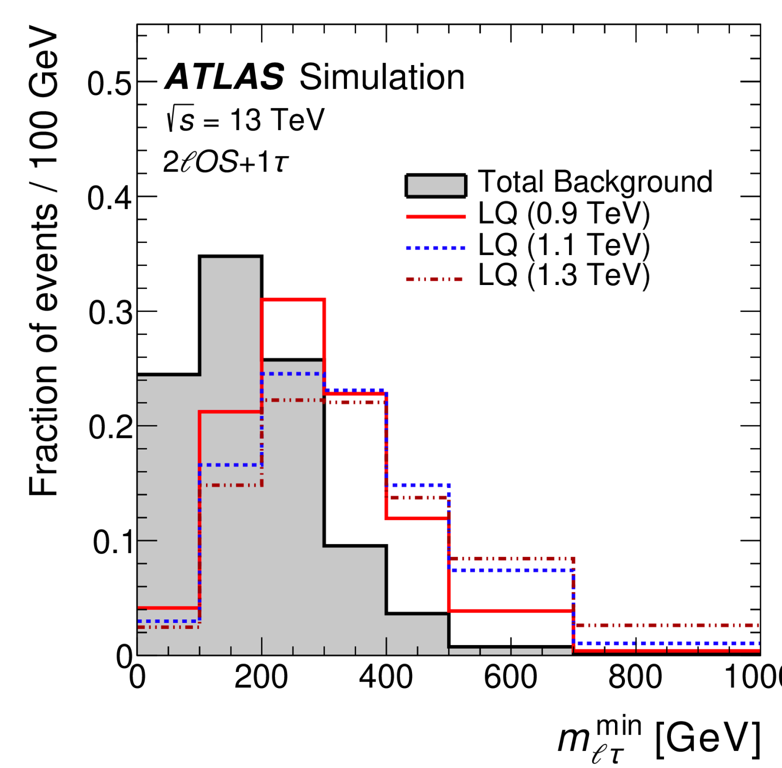
ATLAS EXPERIMENT

Signal regions

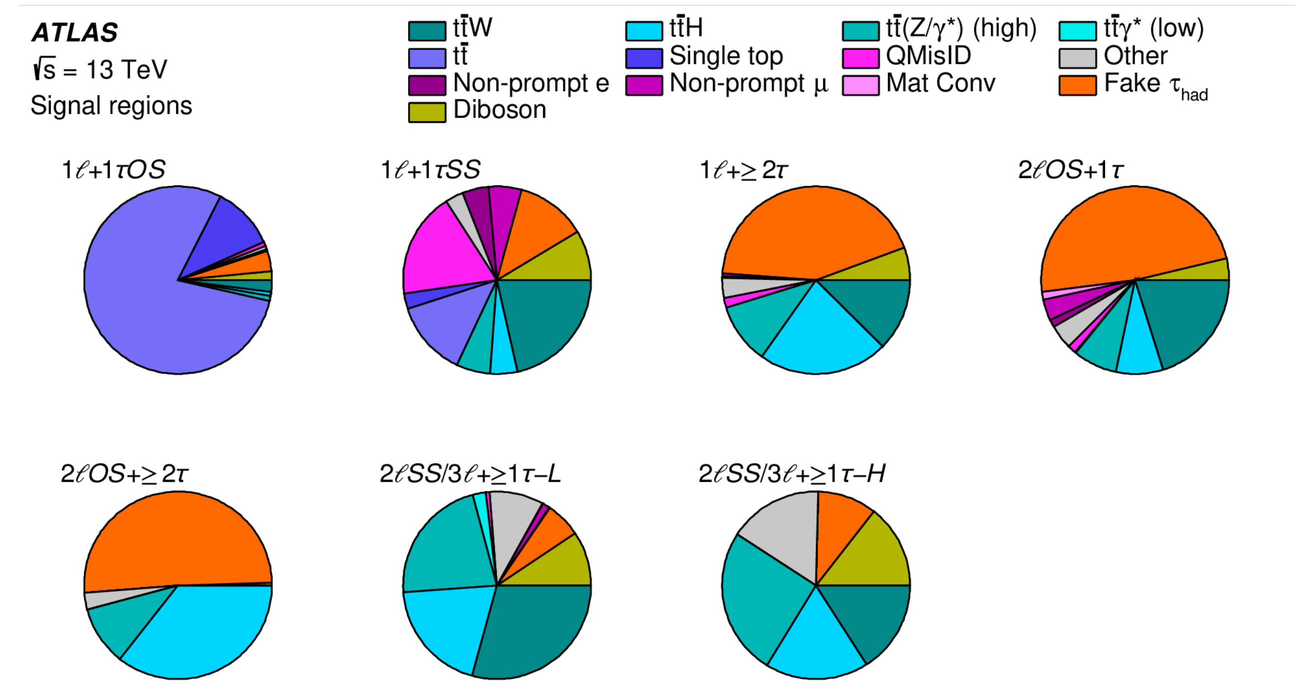
- **$1\ell+\geq 1\tau$ channel**
  - Split into: $1\ell+1\tau$OS, $1\ell+1\tau$SS, $1\ell+\geq 2\tau$
  - Signal regions with additional cuts on p_T^{τ}, E_T^{miss}, $m_{\ell\tau}$, m_{eff}, $m_T(\ell, E_T^{miss})$ and $m_{\tau\tau}$
  - Dominant background: $t\bar{t}$ with real ($1\ell+1\tau$OS) or fake ($1\ell+1\tau$SS, $1\ell+\geq 2\tau$) τ and/or ℓ
- **2ℓOS$+\geq 1\tau$ channel**
  - Split into: 2ℓOS$+1\tau$, 2ℓOS$+\geq 2\tau$
  - Signal regions with additional cuts on p_T^{τ}, $m_{\ell\tau}^{min}$, $m_{\tau\tau}$, $m_{\ell\ell}$
  - Dominant background: $t\bar{t}$ with fake τ and/or ℓ, $t\bar{t}W$, $t\bar{t}Z/\gamma^*$, $t\bar{t}H$
- **2ℓSS$/3\ell+\geq 1\tau$ channel**
  - Split into: SR-H ($p_{T,1}^{\tau} \geq 225$ GeV), SR-L ($125 \leq p_{T,1}^{\tau} < 225$ GeV)
  - Dominant background: $t\bar{t}W$, $t\bar{t}Z/\gamma^*$, $t\bar{t}H$, VV
- Acceptance x efficiency = 10% in the combination of all SRs



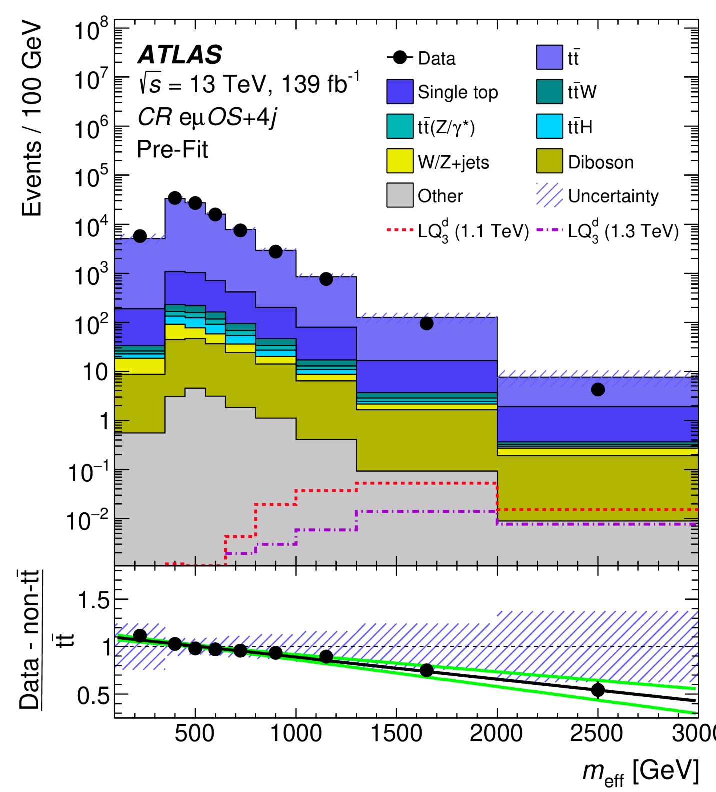


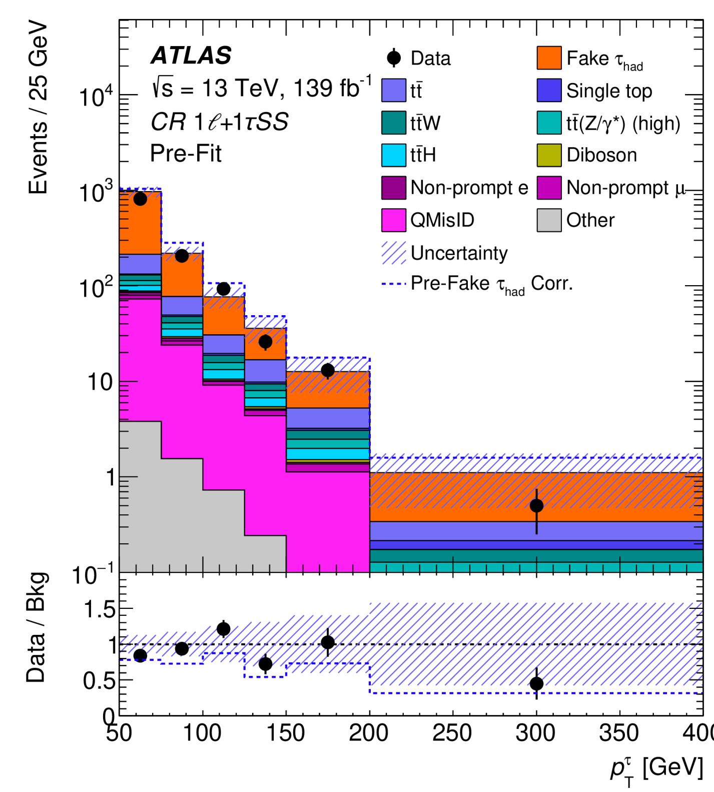
Background estimation (I)

- Large variety of background contributions in each SR
- All backgrounds from MC simulation, data-driven corrections applied for some of them



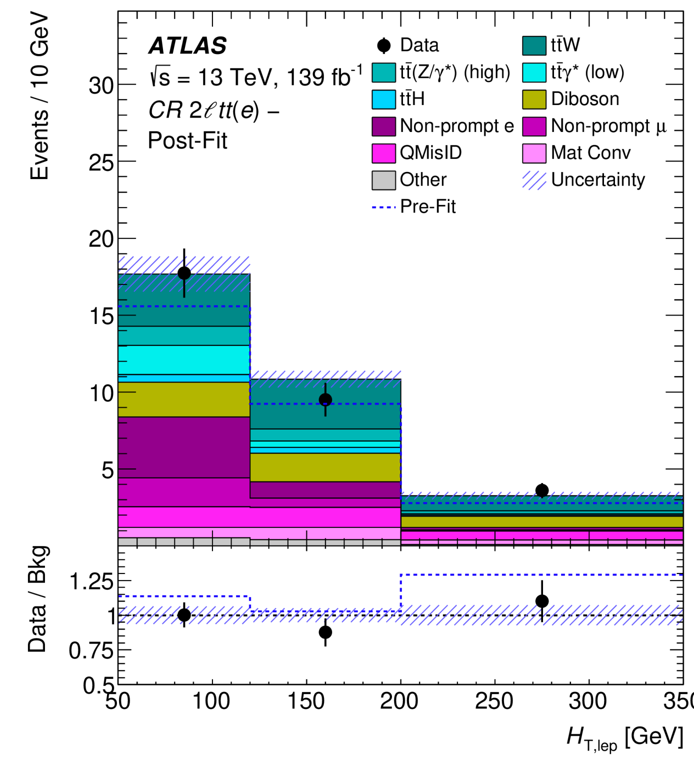
- **tt̄**: background contributes with **real** or **fake ℓ/τ**
  - **N_{jets} and m_{eff} correction**: derived in OSeμ+0τ for tt̄+Wt
  - Systematic variation: correction derived in 1ℓ+1τ channel
- **Fake τ correction**: derived in OSeμ+≥1τ with m_{eff} < 1000 GeV
  - Parametrised in p_T^τ, and number of associated tracks (1 or 3 prongs)
  - Systematic variation: estimate from Z+jets CR OSee/μμ+≥1τ

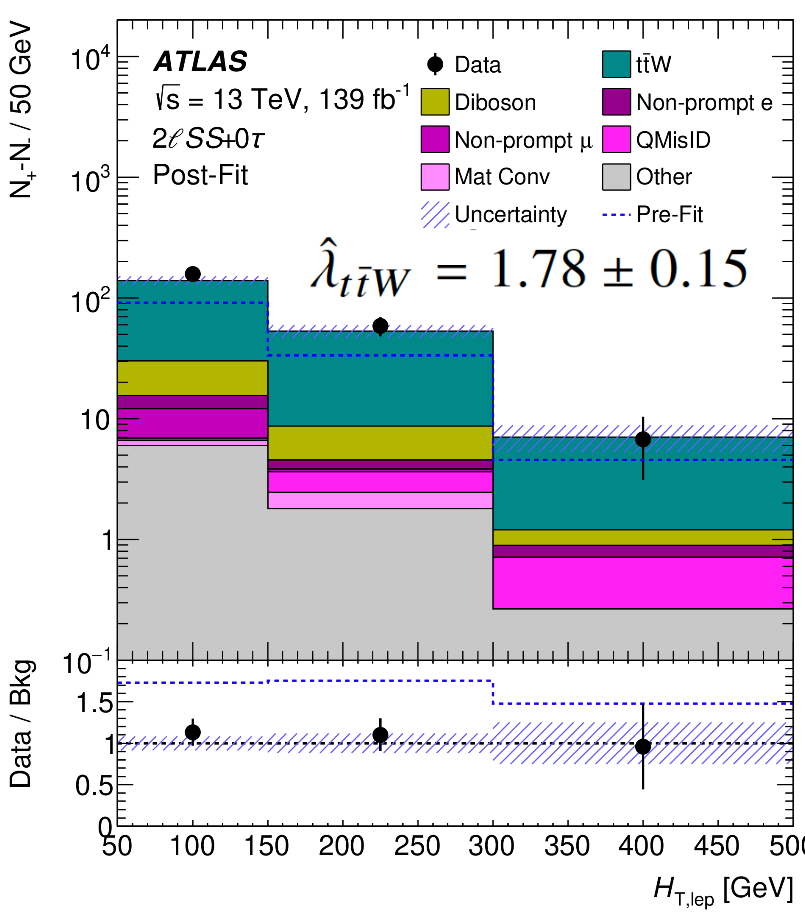


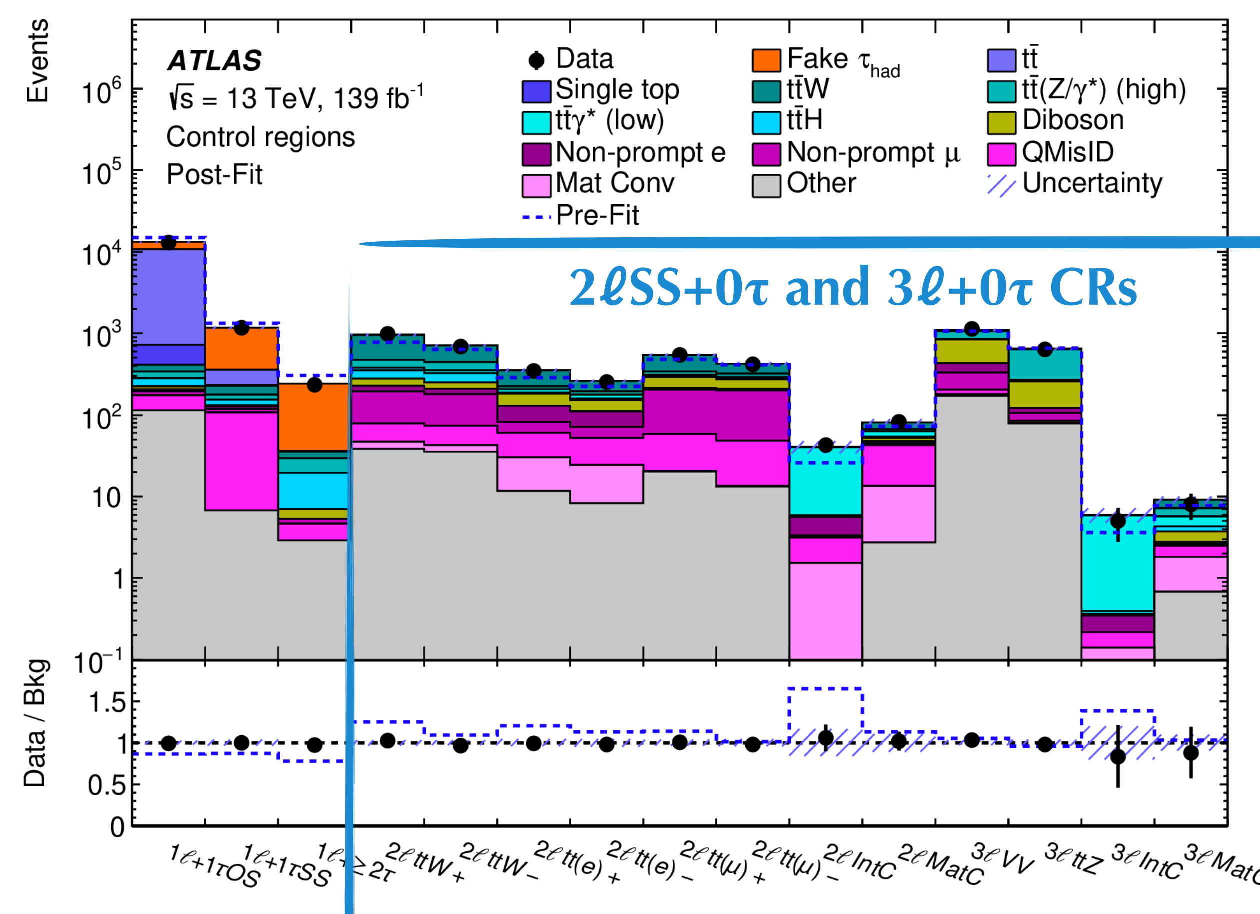


Background estimation (II)

- Corrections derived **simultaneously** in final fit
  - 3 normalisation factors (λ) for **fake ℓ correction** (non-prompt HF electrons and muons, and material conversions + misidentified-charge electrons)
  - 2 λ for **$t\bar{t}W$** and internal conversions ($\gamma^* \to \ell\ell$ with $m_{\ell\ell} < 1$ GeV)
- Possible thanks to the **dedicated CRs in 2ℓSS+0τ and 3ℓ+0τ**
  - H_T^{lep} fitted in non-prompt HF ℓ and $t\bar{t}W$, $t\bar{t}Z$, and VV CRs
  - Event yields used in material and internal conversions CRs







LQ LQ → tτtτ (I)

	$1\ell+1\tau$OS CR	VR	SR	$1\ell+1\tau$SS CR	VR	SR	$1\ell+\geq2\tau$ CR	VR	SR
e/μ selection		T			T			T	
$N_{\tau_{had}}$		1			1			≥ 2	
τ_{had} ID		Medium			Medium			Loose	
$\ell\tau_{had}$ charge		OS			SS			—	
$p_{T,1}^{\tau}$ [GeV]	≥ 50	$50-150$	≥ 150	≥ 50	$50-150$	≥ 150	≥ 50	$50-100$	≥ 100
$p_{T,2}^{\tau}$ [GeV]		—			—		≥ 25	$25-50$	≥ 50
N_{jets}		≥ 4			≥ 3			≥ 2	
$N_{b\text{-}jets}$	≥ 2	≥ 1		≥ 2	≥ 1		≥ 2	≥ 1	
E_T^{miss} [GeV]	—	≥ 80		—	—	≥ 50		—	
$m_{\ell\tau}$ [GeV]	—	≥ 200		—	—	≥ 200		—	
m_{eff} [GeV]	< 800	≥ 800		< 800	≥ 800		< 800	≥ 800	
$m_T(\ell, E_T^{miss})$ [GeV]		—		—	—	≥ 100		—	
$m_{\tau\tau}$ [GeV]		—			—		—	≥ 100	

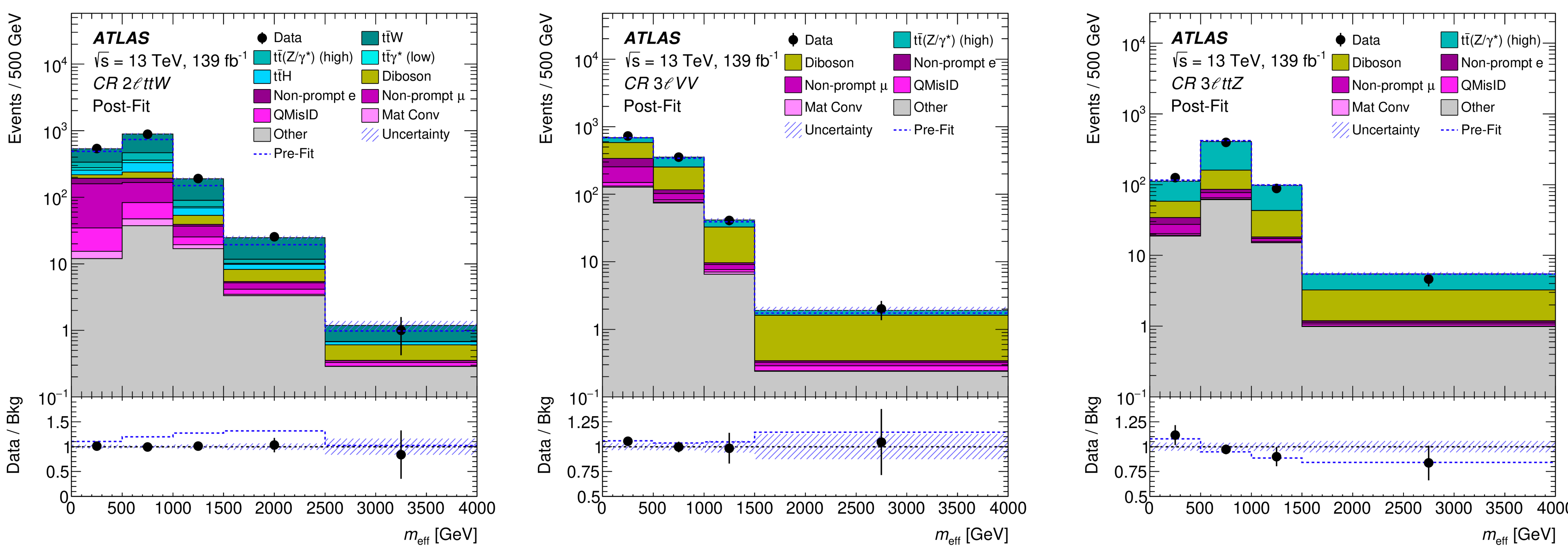
	2ℓOS+1τ CR^Z	CR$^{t\bar{t}}$	VR	SR	2ℓOS+$\geq2\tau$ VR	SR
e/μ selection		T			T	
e/μ combinations	$ee/\mu\mu$	$e\mu$	$ee/\mu\mu$	$ee/\mu\mu/e\mu$	$ee/\mu\mu/e\mu$	
$N_{\tau_{had}}$		1			≥ 2	
τ_{had} ID	Loose/Medium		Medium		Loose	
$p_{T,1}^{\tau}$ [GeV]	≥ 25	≥ 25	25–150	≥ 150	≥ 25	≥ 75
$m_{\ell\tau}^{min}$ [GeV]	—	—	< 100	≥ 100	—	≥ 50
$m_{\tau\tau}$ [GeV]			—		<100	≥ 100
m_{eff} [GeV]	—	< 1000	—	—	—	—
Z veto	Inverted	Yes	Yes	Yes	Yes	
$m_{\ell\ell}$ [GeV]		> 12			> 12	

	2ℓSS/3ℓ+$\geq1\tau$ VR	SR-L	SR-H
e/μ selection		T* (2ℓSS) T*/T (3ℓ)	
$N_{\tau_{had}}$		≥ 1	
τ_{had} ID		Loose	
$p_{T,1}^{\tau}$ [GeV]	25–125	125–225	≥ 225
Z veto		Yes	
$m_{\ell\ell}$ [GeV]		> 12	

LQ LQ → tτtτ (II)

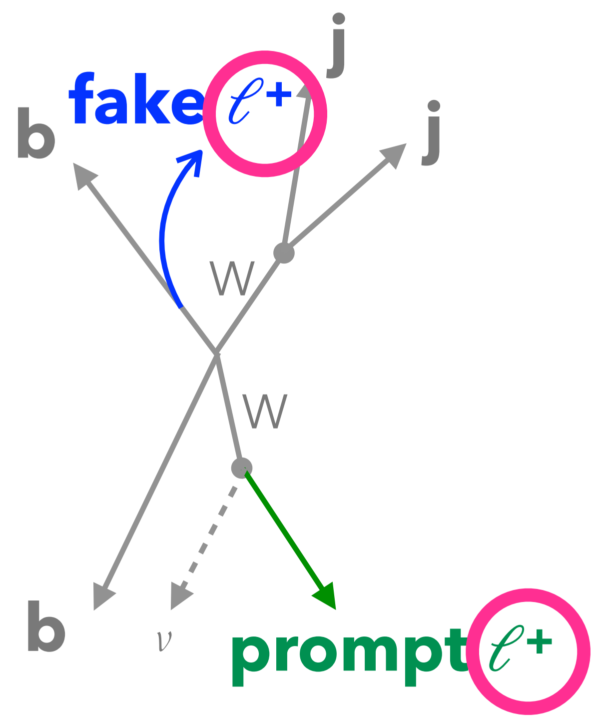
	2ℓSS+0τ				
	$2\ell tt(e)\pm$	$2\ell tt(\mu)\pm$	$2\ell ttW\pm$	2ℓIntC	2ℓMatC
e/μ selection			T*		
e/μ combination	$ee/\mu e$	$\mu\mu/e\mu$	$ee/\mu\mu/e\mu/\mu e$	$ee/e\mu/\mu e$	$ee/e\mu/\mu e$
Electron internal conversion veto	Yes	Yes	Yes	Inverted	Yes
Electron material conversion veto	Yes	Yes	Yes	Yes	Inverted
N_{jets}	2–3	2–3	≥ 4	≥ 2	≥ 2
Z veto			Yes		
m_{ee} [GeV]			≥ 12		

	3ℓ+0τ			
	$3\ell VV$	$3\ell ttZ$	3ℓIntC	3ℓMatC
e/μ selection	T	T	T(ℓ_0), T*(ℓ_1 and ℓ_2)	T(ℓ_0), T*(ℓ_1 and ℓ_2)
Electron internal conversion veto	Yes	Yes	Inverted(ℓ_1 or ℓ_2)	Yes(ℓ_1 or ℓ_2)
Electron material conversion veto	Yes	Yes	Yes(ℓ_1 and ℓ_2)	Inverted(ℓ_1 or ℓ_2)
N_{jets}	2–3	≥ 4	≥ 2	≥ 2
Z veto	Inverted	Inverted	Yes	Yes
$m_{\ell\ell}$ [GeV]			≥ 12	

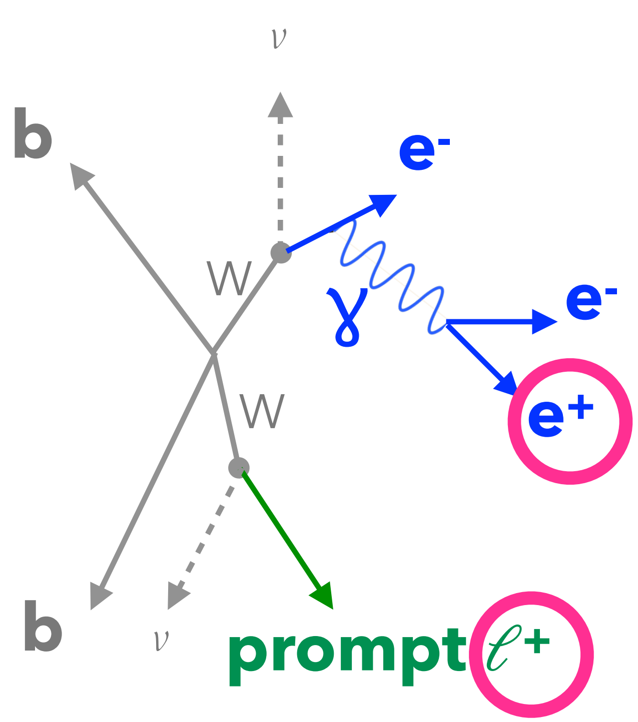


Multilepton channel

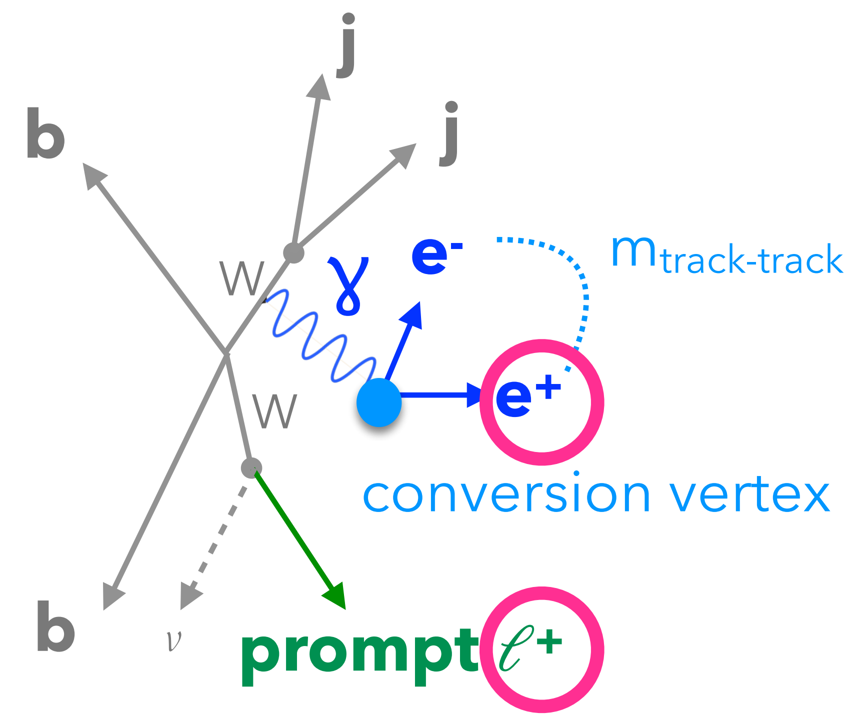
- **multivariate lepton isolation** to reject non-prompt leptons based on:
  - lepton and overlapping track jets properties
  - lepton track/ calorimeter isolation variables



- multivariate lepton identification to **reject misidentified charge electrons**



- The resulting electron candidates are further split into three classes: "Material Conversion," "Internal Conversion," and "Very Tight."



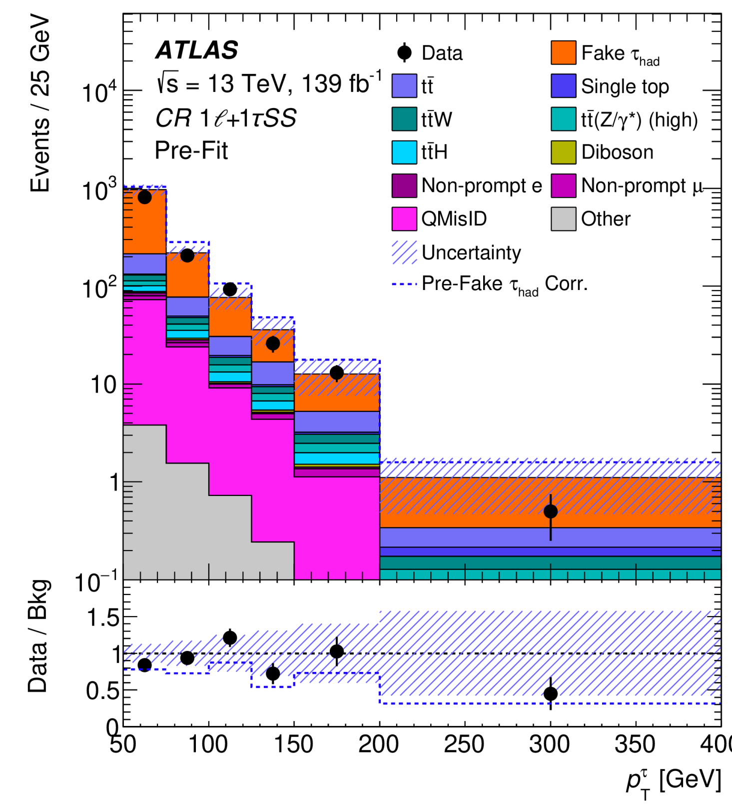
electron CO selection	CO radius	$m_{track-track}$
(1) material CO	> 20 mm	< 100 MeV (wrt. CV)
(2) internal CO	not (1)	< 100 MeV (wrt. PV)
(3) very tight	not (1) and not (2)	

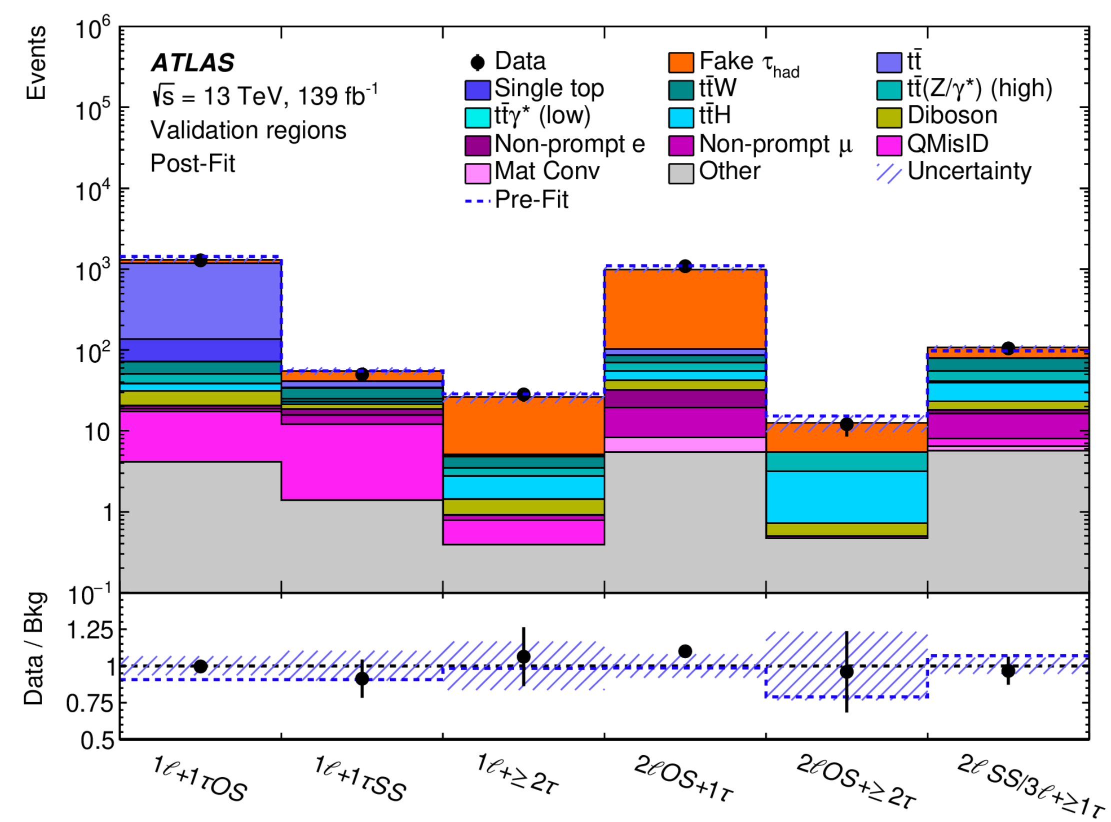
(beam pipe @ 24 mm)

Systematic uncertainties τττ

- **$t\bar{t}$**
  - Similar modelling uncertainties as in tℓtℓ analysis
  - **N_{jets} and m_{eff} correction**: slight difference in slope when derived in the 1ℓ+1**τ** channel
- **Fake τ correction**: alternative estimate from Z+jets CR OSee/μμ+≥1**τ** with $|m_{\ell\ell} - m_Z| < 10$ GeV
- **Fake ℓ correction:** relaxing lepton criteria to enrich samples in different types of fake
- **Internal and material conversions**: 25% extrapolation uncertainty derived in Z→μμɣ*(→ee) VR
- **$t\bar{t}W$, $t\bar{t}Z/\gamma^*$, $t\bar{t}H$**: modelling uncertainties from comparing to alternative generators

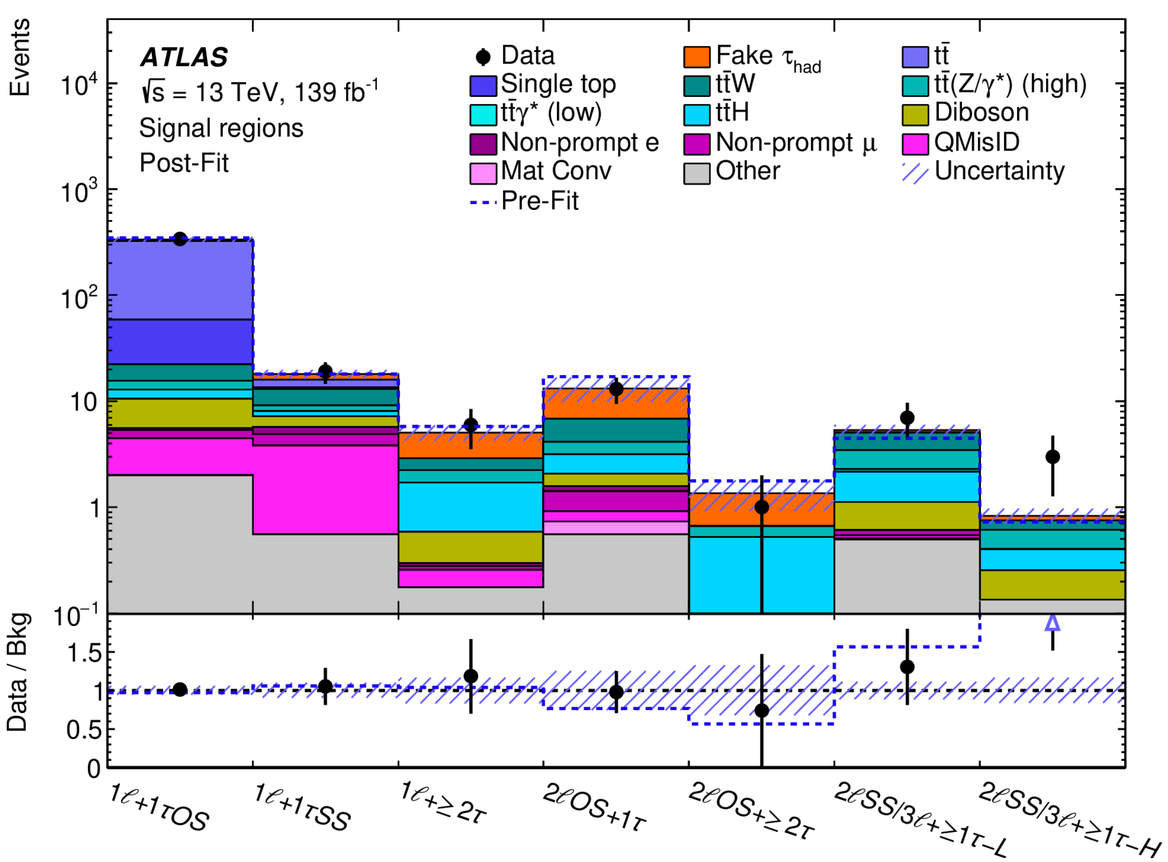
Nevertheless, the analysis is statistically-limited



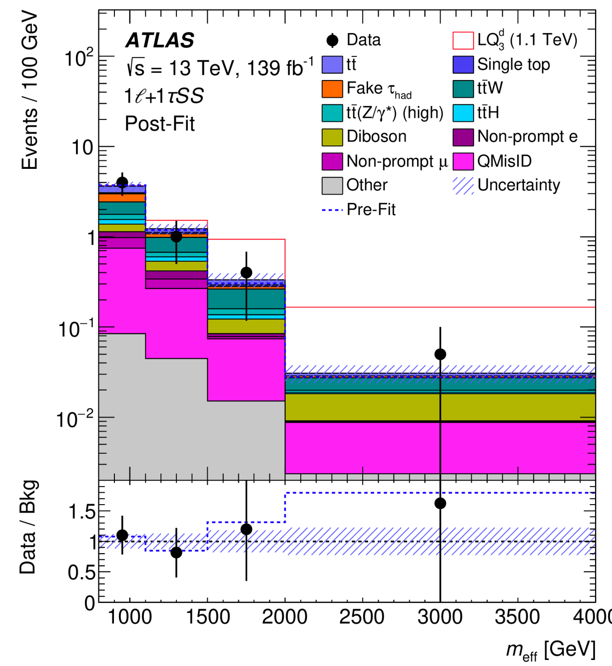


Results (I)

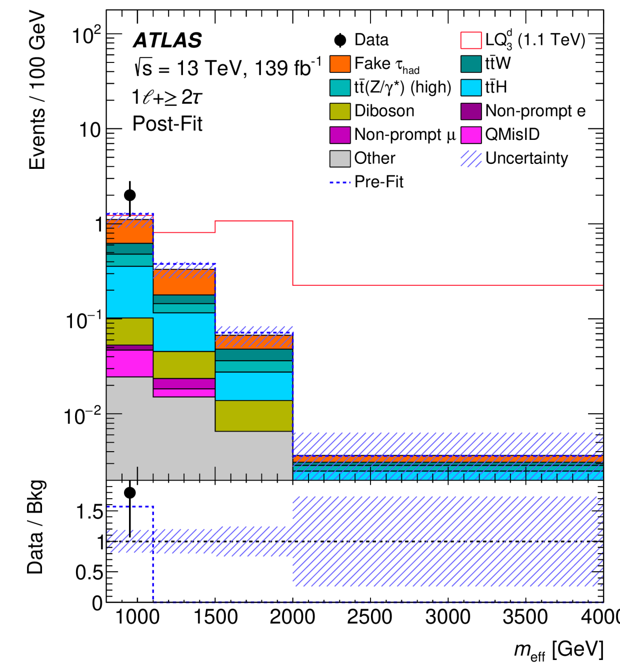
- Simultaneous fit of 7 SRs and 15 CRs
- Main systematic uncertainties from:
  - τ identification and energy scale calibration, $t\bar{t}$ modelling
- Sensitivity dominated by $1\ell+\geq1\tau$ channel
- Statistically-limited search at high masses
- No significant excess over the SM background observed



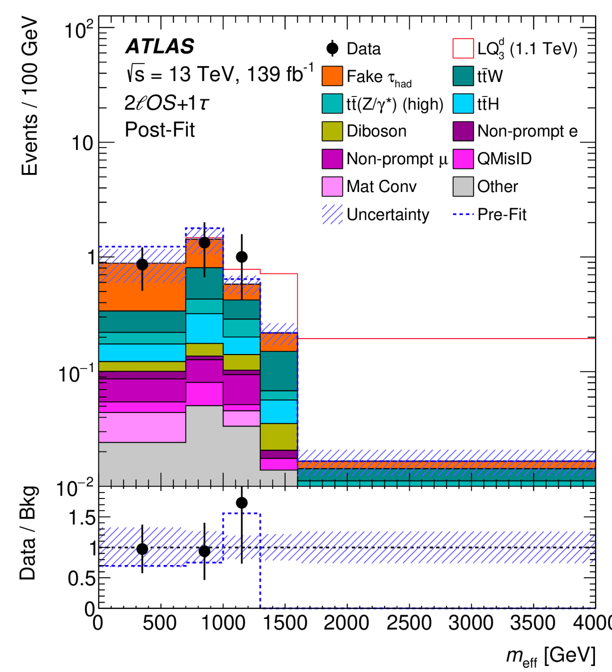
$1\ell+1\tau SS$



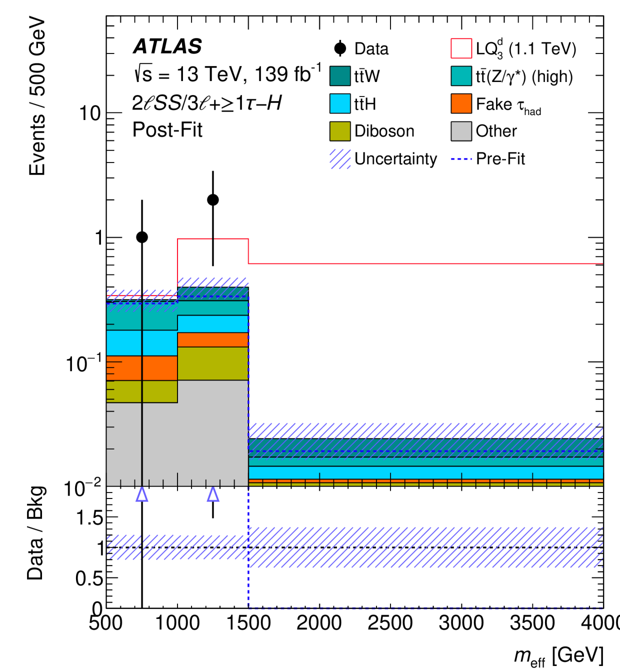
$1\ell+\geq2\tau$



$2\ell OS+1\tau$



$2\ell SS/3\ell+\geq1\tau$



Results (II)

- Upper limits set on the LQ pair production cross-section at 95% CL
  - m_{LQ} < 1.43 TeV (1.22 TeV) excluded for B=1 (B=0.5)