Searching for leptoquarks with the ATLAS detector

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on behalf of the ATLAS Collaboration

14th February 2019

ATLAS EXPERIMENT

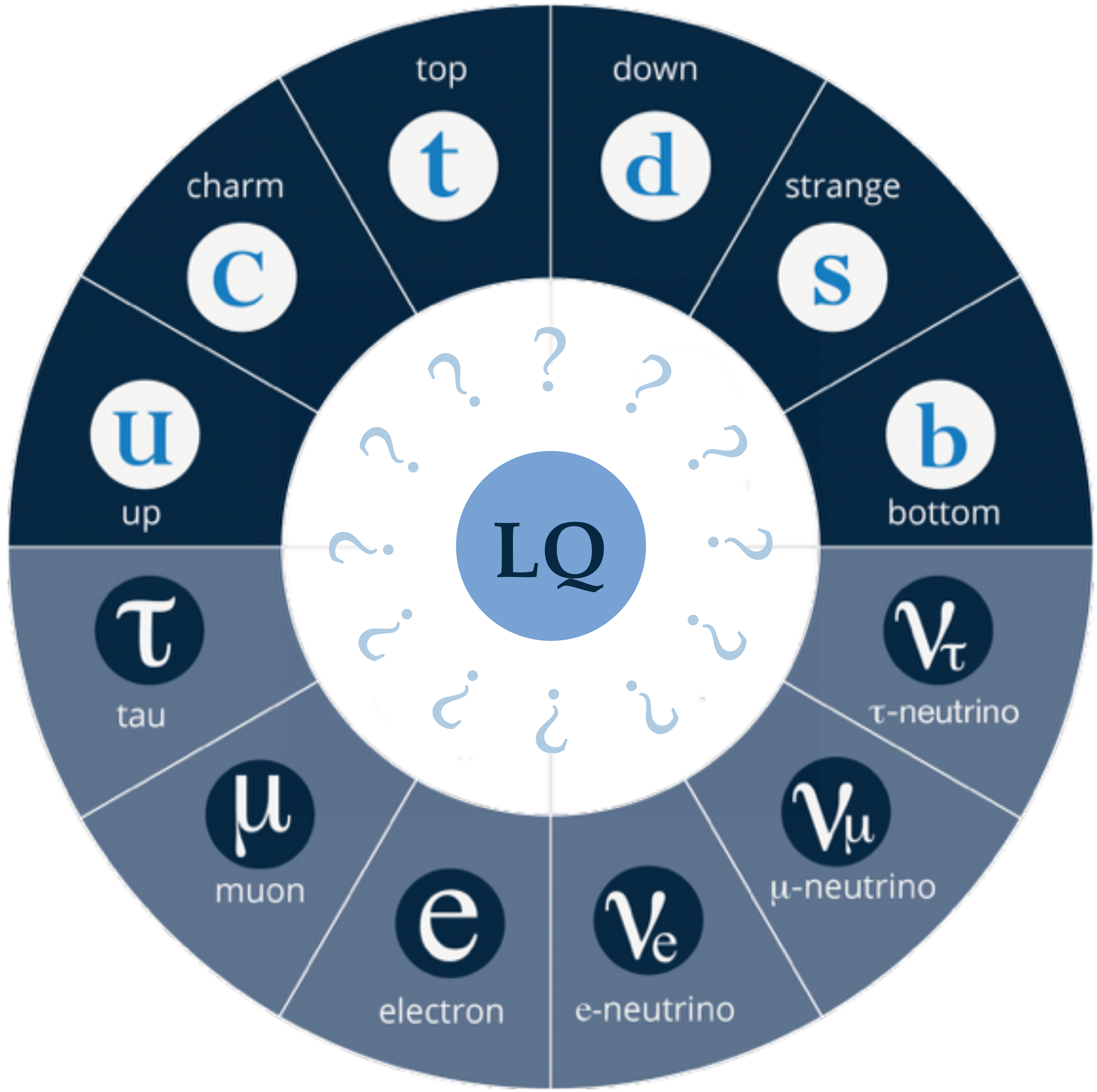
SMU

Leptoquarks

The Standard Model has been very successful, but leaves many questions unanswered…

- Why are there so many similarities between quarks and leptons (mass hierarchy, charge cancellation etc).
- Similarities between quarks and leptons suggest a possible link between the two sectors.

→ Leptoquarks



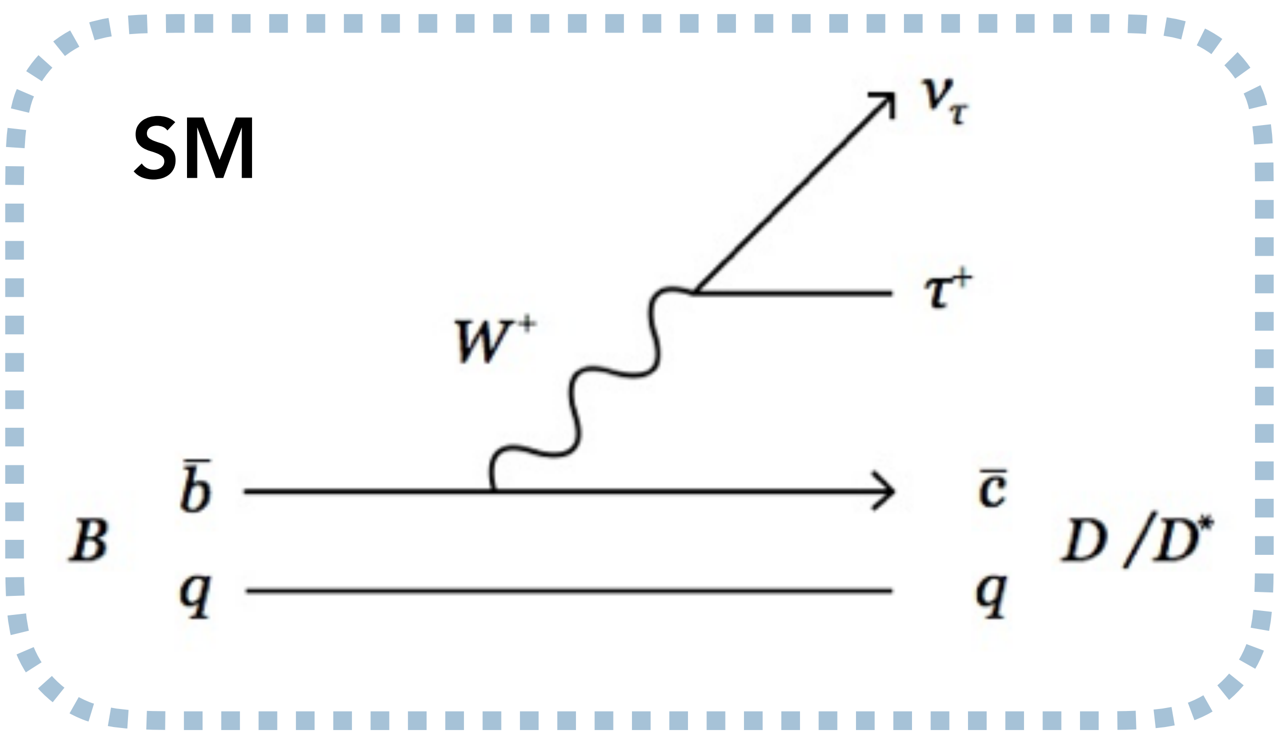
Hints from the flavour sector

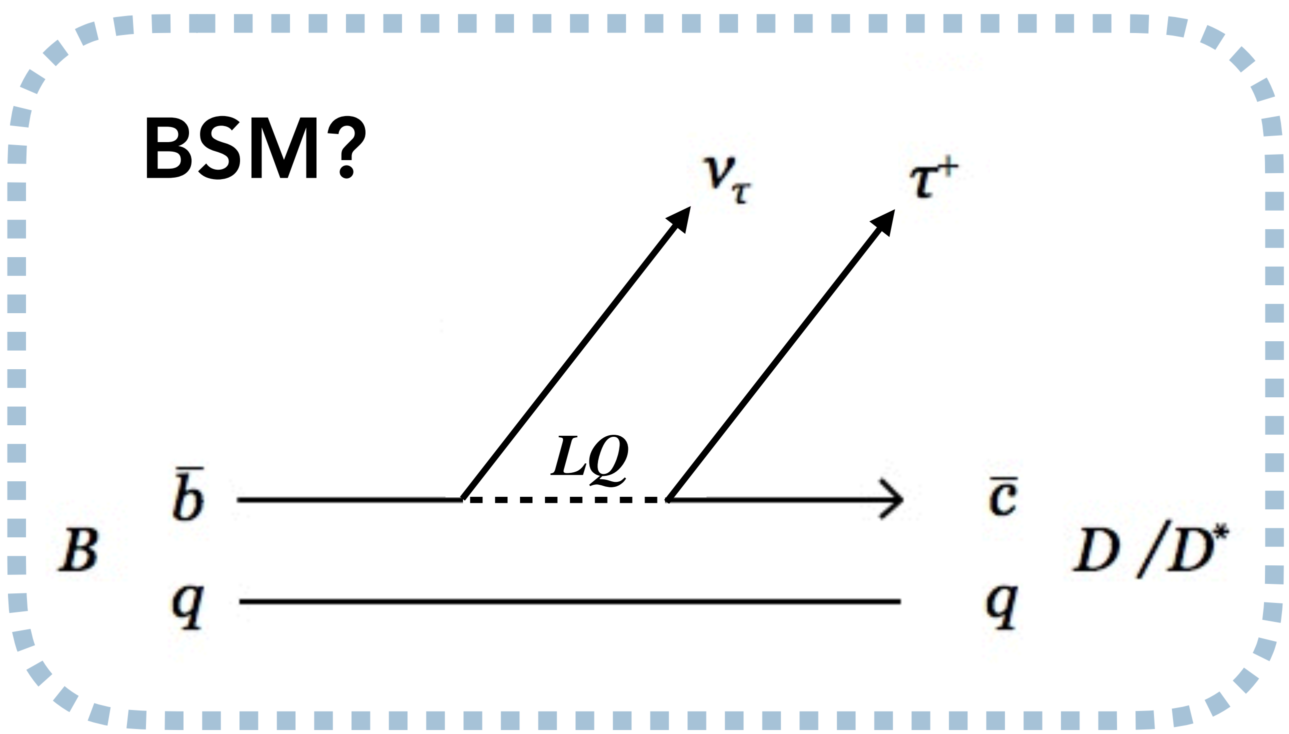
- Experimental data from flavour experiments hint at lepton non-universality.
- R(D),R(D*) combination deviates from SM by ~4σ.
- R(K) and R(K*) ~2-2.5σ from SM.

See talks by Mick Mulder and Jernej Kamenik in Tuesday am session

$$R(D^{(*)}) = \frac{BR(B \to D^{(*)}\tau\nu)}{BR(B \to D^{(*)}\mu\nu)} \qquad R(K^{(*)}) = \frac{BR(B \to K^{(*)}\mu^+\mu^-)}{BR(B \to K^{(*)}e^+e^-)}$$

- First hint of BSM physics? Leptoquarks a leading explanation for anomalies.

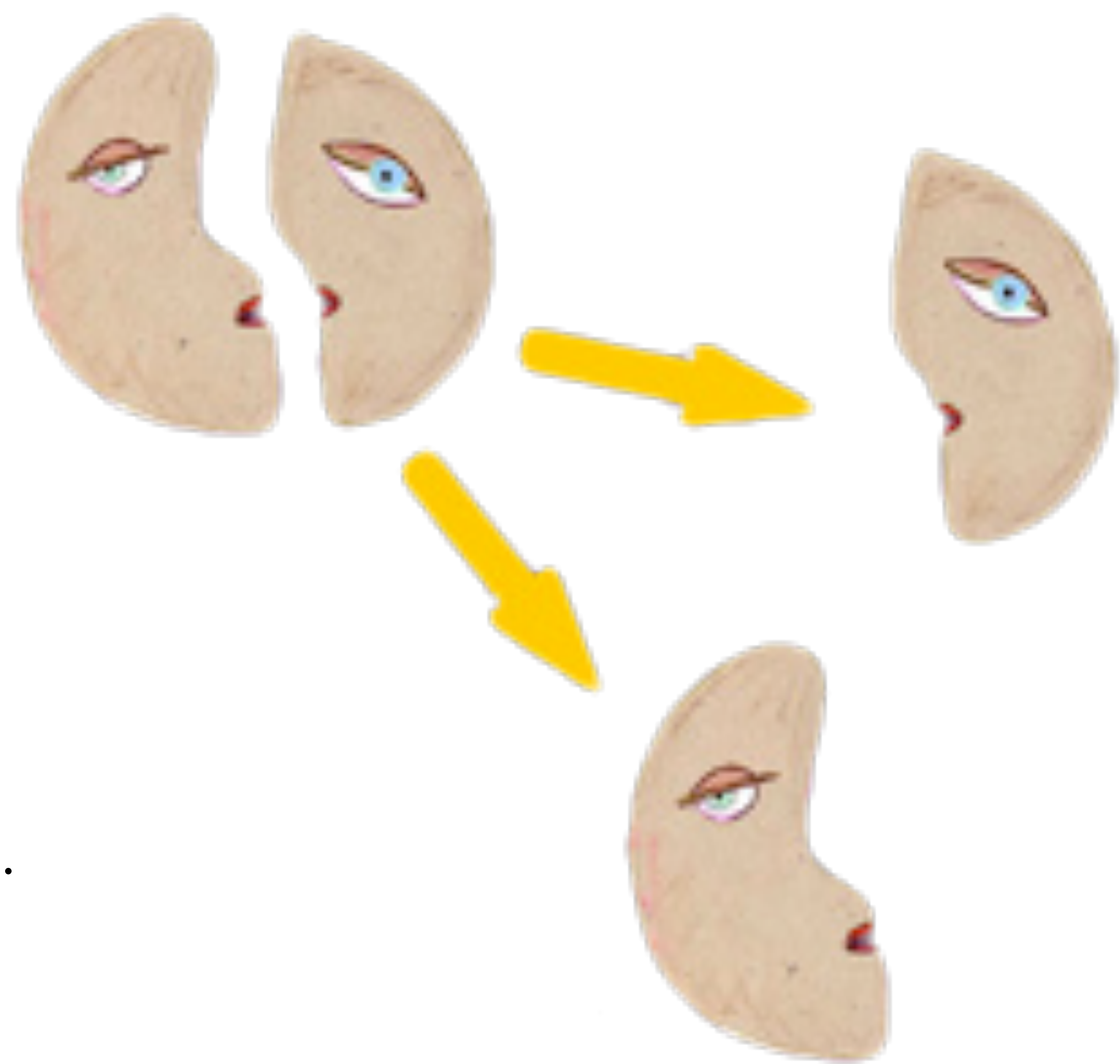




Leptoquarks

- Appear in a wide range of theories, including SU(5) grand unification, superstrings, SU(4) PatiSalam, and compositeness models.

- Minimal Buchmüller-Rückl-Wyler model used as benchmark for ATLAS searches:
  - Leptoquarks couple to quarks and leptons from the same generation.
  - Prohibits flavour-changing neutral currents.
  - Design analyses to also be sensitive to models with cross-generational decays.



- Search for pair-produced scalar leptoquarks.
  - Assume narrow width and prompt decay.

This talk

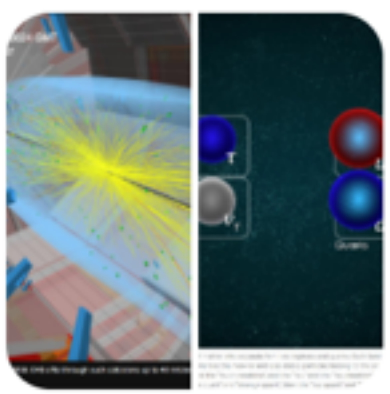
- Searches for 1st and 2nd generation leptoquarks in ATLAS.
  - BONUS: differential cross sections for $\ell\ell$+jj events ($Z\rightarrow ee$, $Z\rightarrow \mu\mu$ and ttbar processes) in search control regions.

- Searches for up- and down-type 3rd generation leptoquarks.

NOT in this talk

Katariina Nykyri @KatariinaNykyri · 20 Sep 2018

leptons and quarks may merge at high energies into #leptoquarks and are proposed in theories attempting to unify the strong, weak and electromagnetic forces. **#kleptoquarks**, on the other hand, are quarks that like to impulsively steal forces carried by other particles 😋 @CERN



CERN @CERN

The hunt for leptoquarks is on

➡️ Full story: cern.ch/go/wS9t

1st & 2nd generation LQ searches

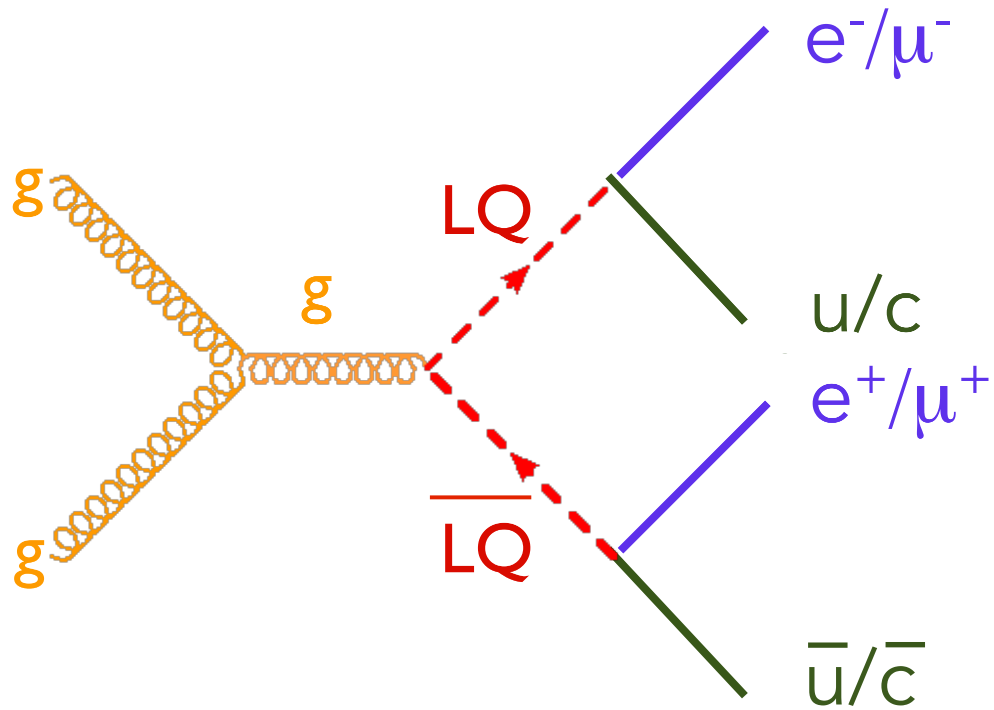
Final state	$\ell\ell jj$	$\ell\nu jj$	$\nu\nu jj$
σ x BR	β^2	$2(1-\beta)\beta$	$(1-\beta)^2$

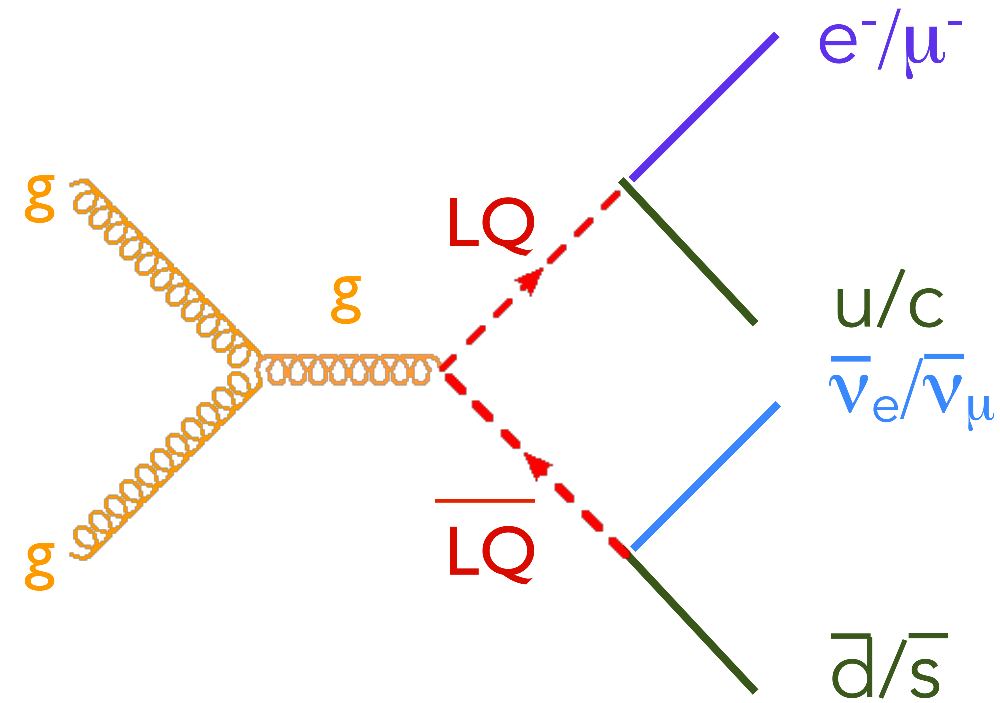
$\ell = e/\mu$

$\beta = BR(LQ \to \ell q)$

Analysis with 36 fb^{-1} data, $\sqrt{s}$ = 13 TeV
arXiv:1902.00377

Submitted to EPJC



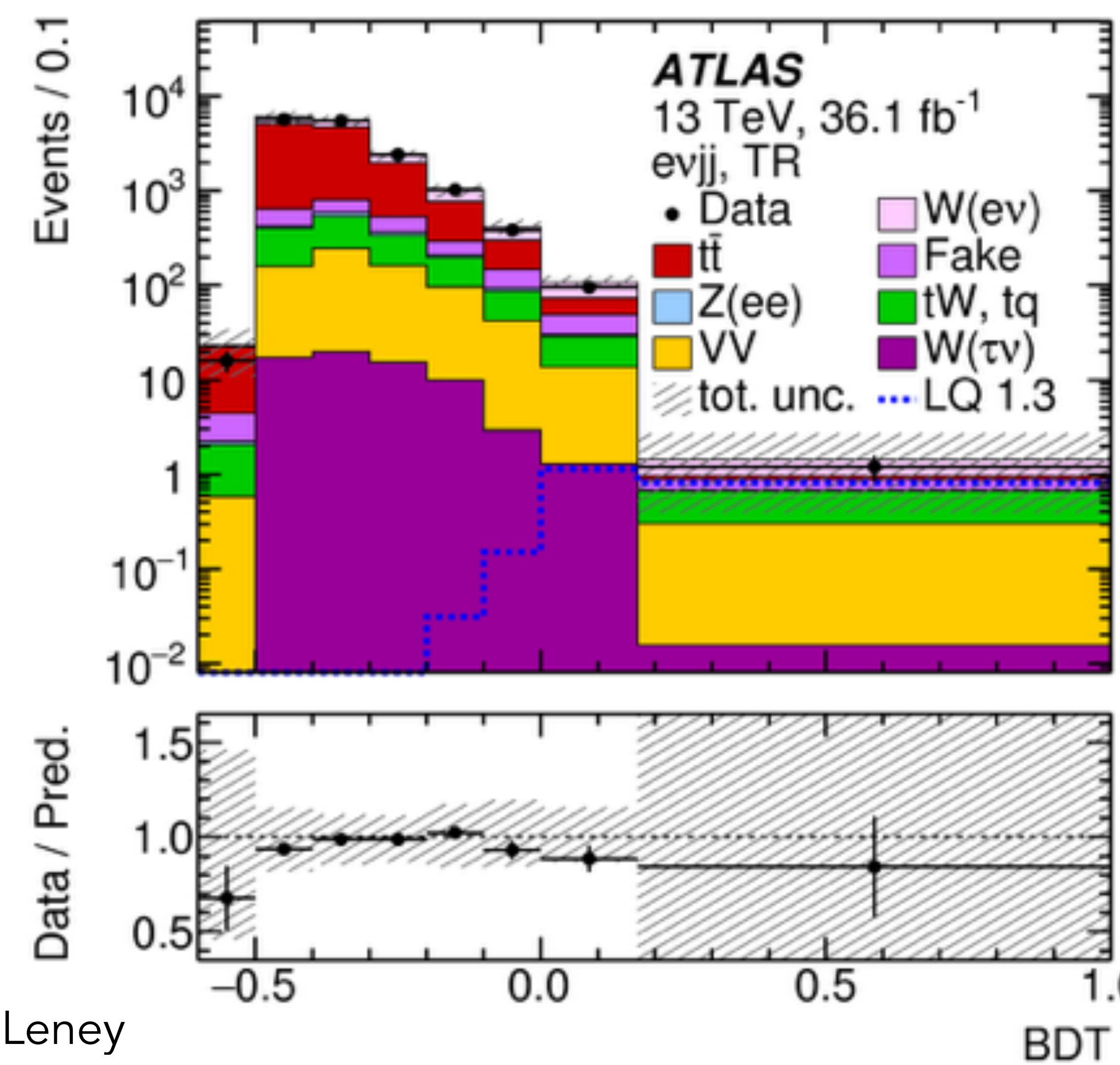


Analysis Strategy

- Use Boosted Decision Trees (BDT) to separate leptoquark signals from backgrounds.

Channel	Input variables
$\ell\ell jj$	$m_{\mathrm{LQ}}^{\mathrm{min}}$, $m_{\ell\ell}$, p_{T}^{j2}, $p_{\mathrm{T}}^{\ell 2}$, $m_{\mathrm{LQ}}^{\mathrm{max}}$
$\ell\nu jj$	m_{LQ}, $m_{\mathrm{LQ}}^{\mathrm{T}}$, m_{T}, $E_{\mathrm{T}}^{\mathrm{miss}}$, p_{T}^{j2}, p_{T}^{ℓ}

- Separate BDTs for each mass point and channel.
- Single bin signal regions defined by cutting on BDT output score to optimise significance.
- $\ell\ell$jj and $\ell\nu$jj signal regions fit simultaneously.

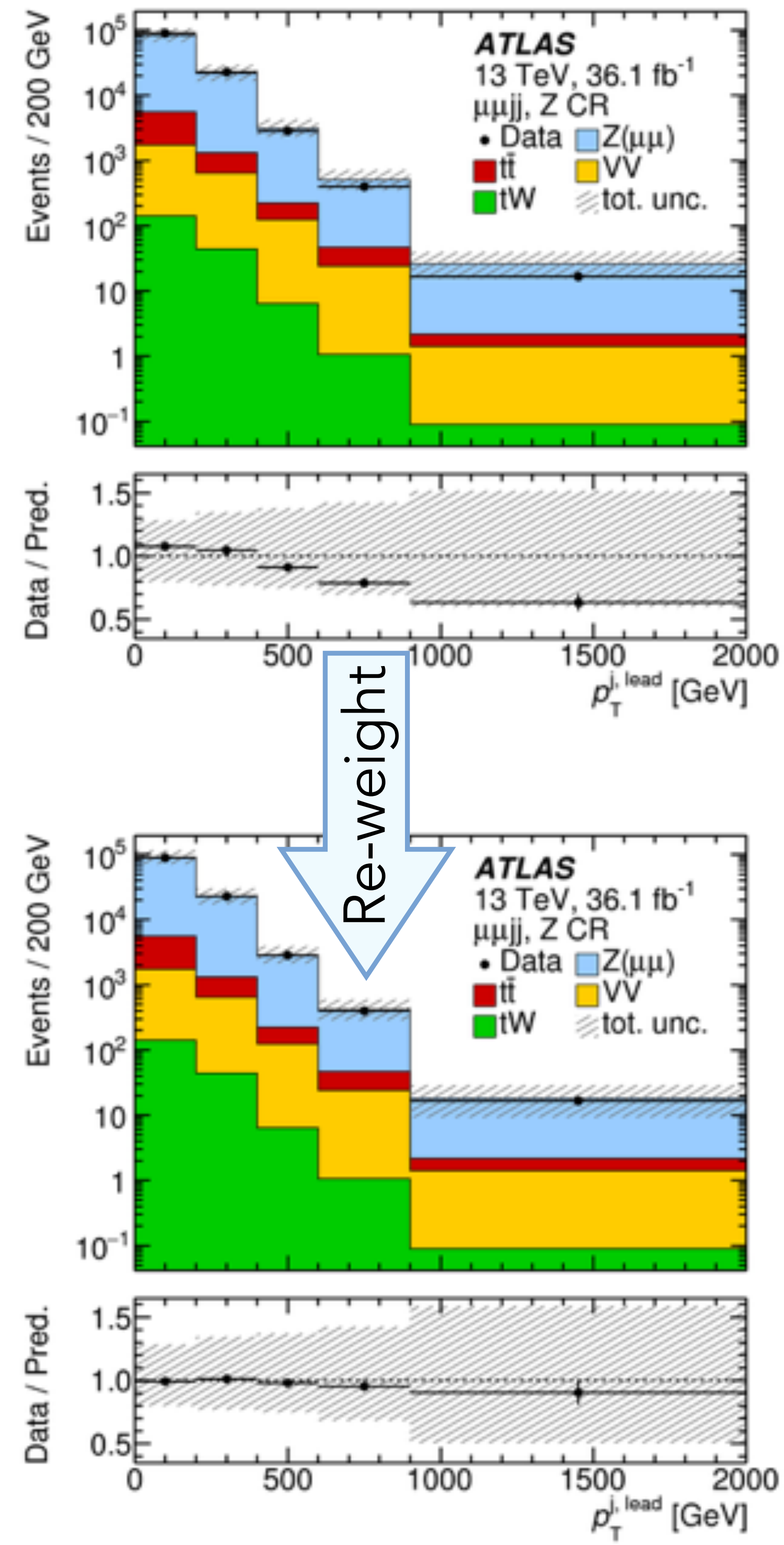


No requirements made on jet flavour → remain agnostic to cross-generational decays.

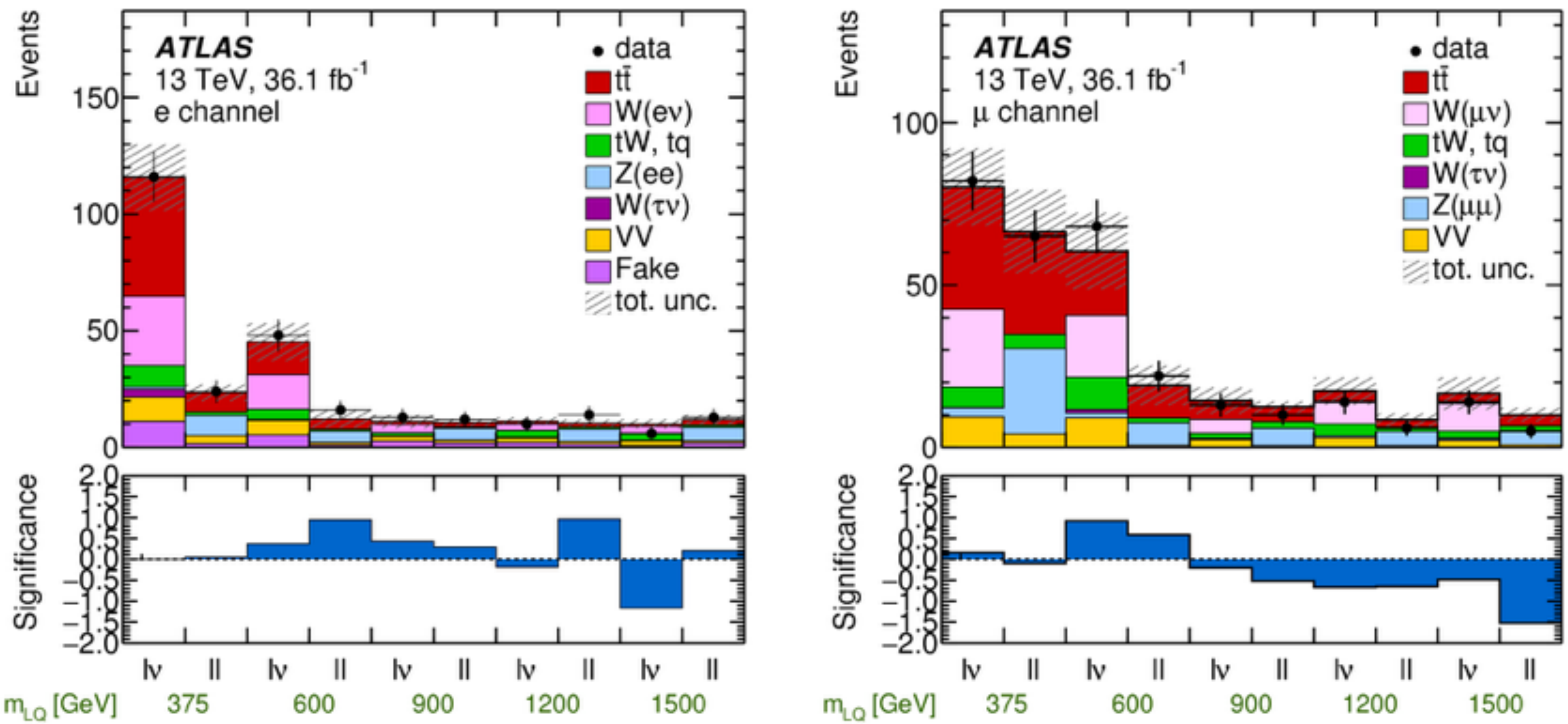
Background Estimation

Background Process	Estimation Method
ttbar	Simultaneous fit to 3 single-bin control regions
W+jets	
Z+jets	
Fake and non-prompt electrons	Matrix method
Others	MC

- Major backgrounds estimated/normalised from data.
- W/Z+jets MC (SHERPA 2.2.1) poorly describes data.
  - Re-weighted using m_{jj}.
  - Modelling of other variables improved.



Results

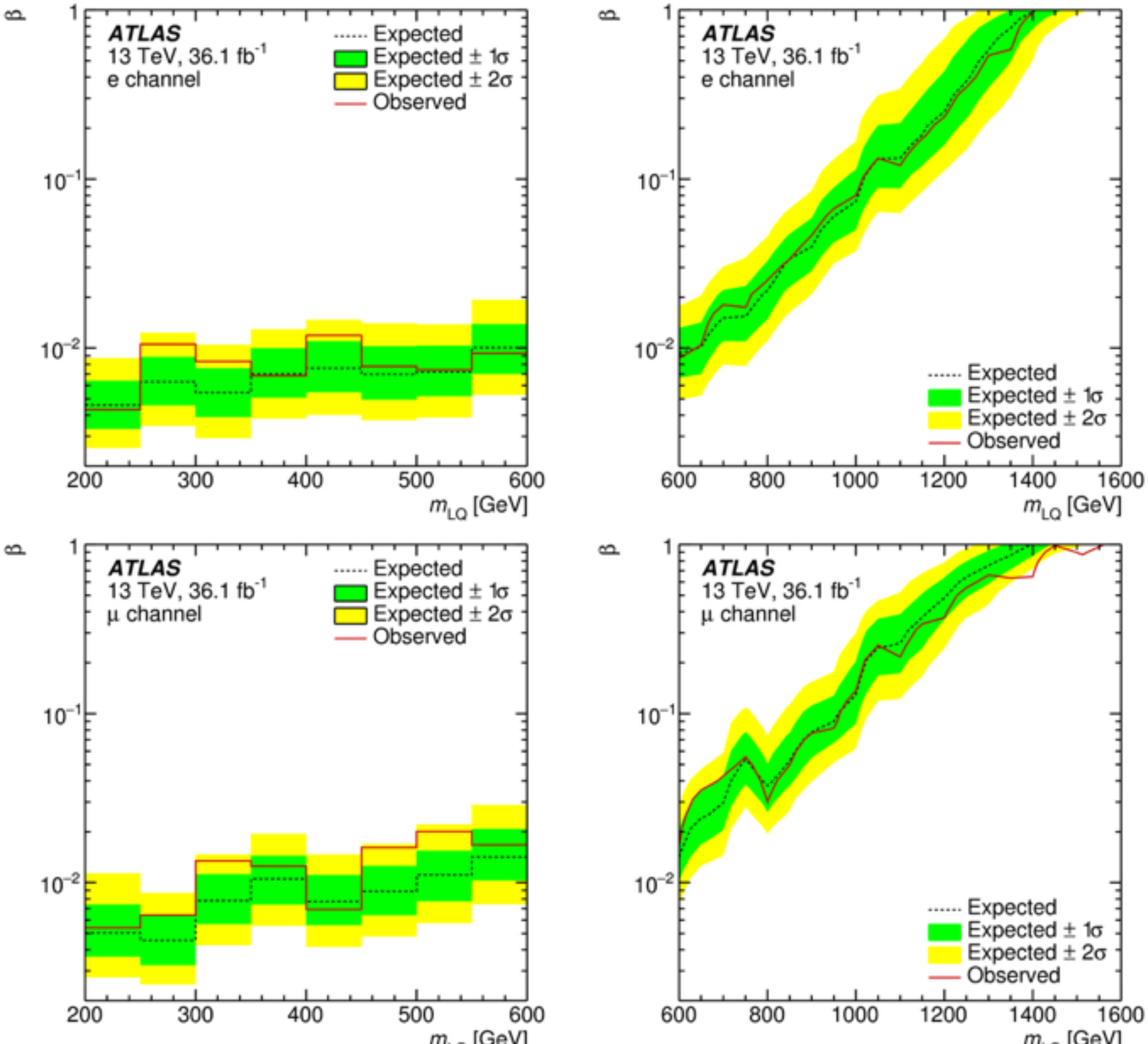


β	m_{LQ1} [GeV]		m_{LQ2} [GeV]	
	Expected	**Observed**	**Expected**	**Observed**
1.0	1400	1400	1400	1560
0.5	1280	1290	1200	1230
0.1	1020	1010	960	960

Results

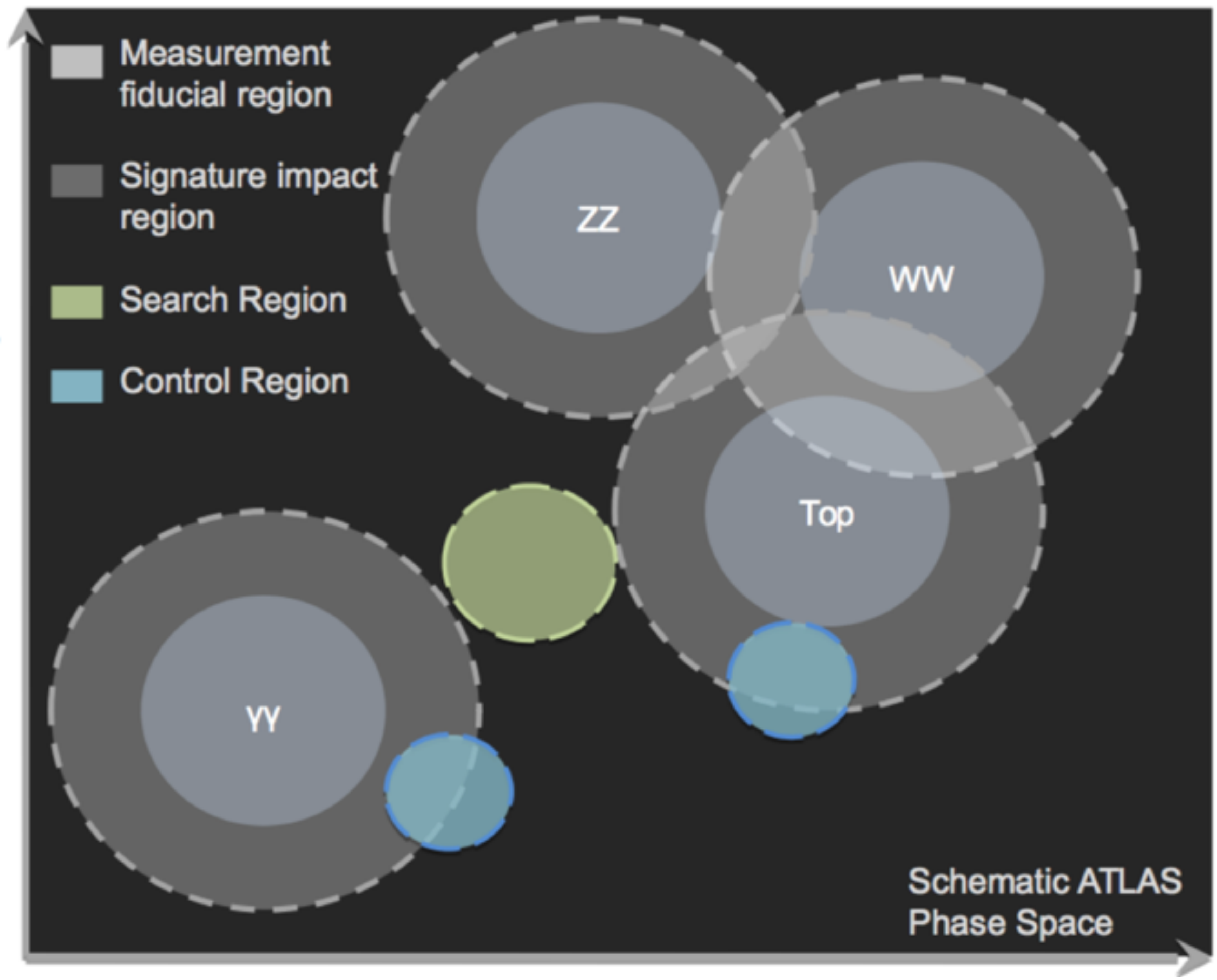
Electron Channel

Muon Channel



Differential-σ Measurements

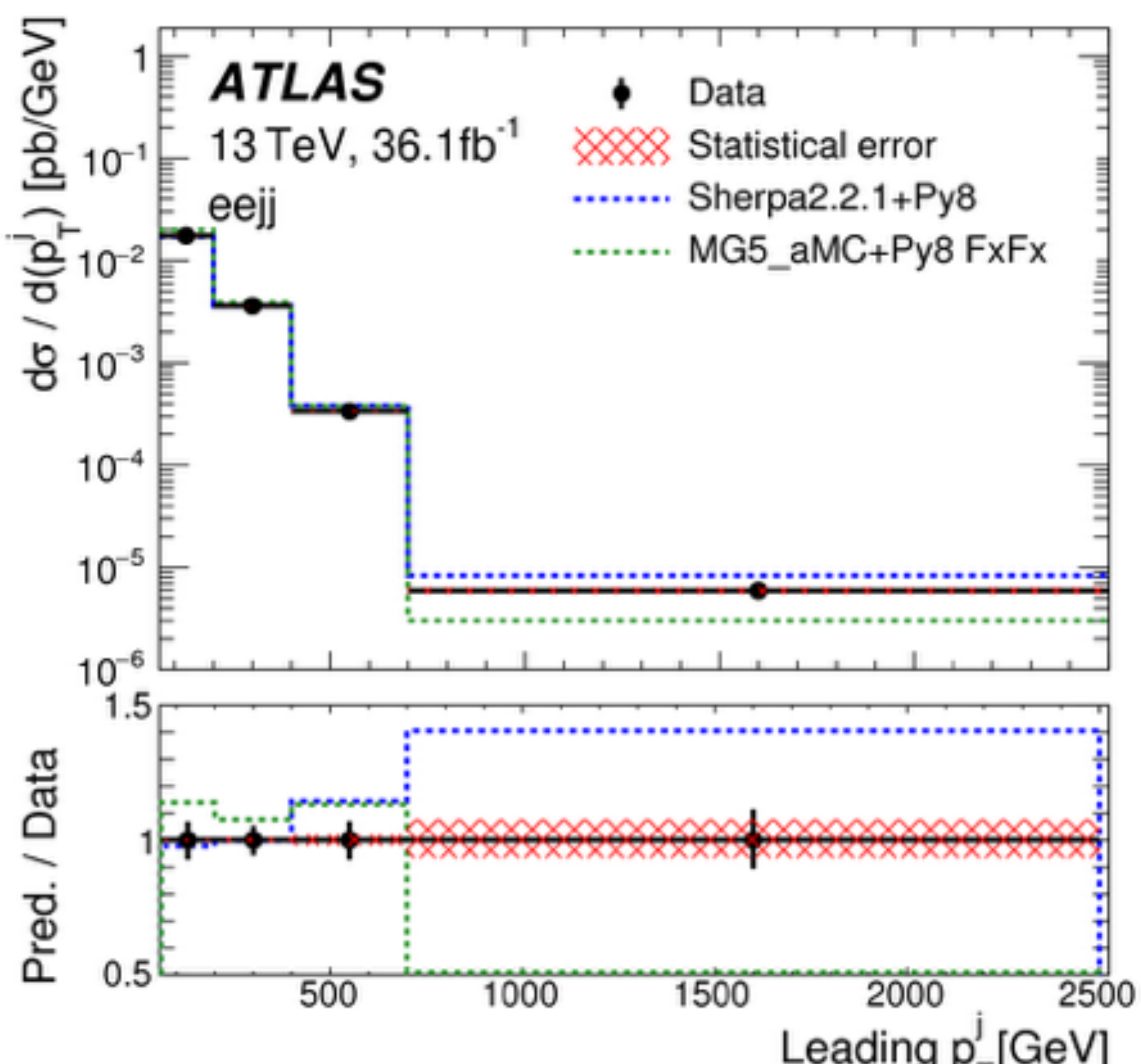
- Particle-level cross-section measurements in LQ search control regions.
- More extreme regions of phase space can provide complementary information (e.g. for tuning generators) to dedicated SM measurements.



Differential-σ Measurements

MR	Dominant process (purity)	Required leptons and jets	$m_{\ell\ell}$ selection	S_T selection
$eejj$	$Z \to ee$ (93%)	$= 2e$; $\geq$ 2jets	$70 < m_{\ell\ell} < 110$ GeV	-
$\mu\mu jj$	$Z \to ee$ (93%)	$= 2\mu$; $\geq$ 2jets	$70 < m_{\ell\ell} < 110$ GeV	-
$e\mu jj$	$t\bar{t} \to e\mu$ (93%)	$= 1\mu, 1e$; $\geq$ 2jets	-	-
Extreme $eejj$	$Z \to ee$ (94%)	$= 2e$; $\geq$ 2jets	$70 < m_{\ell\ell} < 110$ GeV	$S_T > 600$ GeV
Extreme $\mu\mu jj$	$Z \to \mu\mu$ (94%)	$= 2\mu$; $\geq$ 2jets	$70 < m_{\ell\ell} < 110$ GeV	$S_T > 600$ GeV
Extreme $e\mu jj$	$t\bar{t} \to e\mu$ (86%)	$= 1\mu, 1e$; $\geq$ 2jets	-	$S_T > 600$ GeV

- Mis-modelling observed in some variables, e.g. leading jet pT in $Z \to \ell\ell$ + 2 jet processes.
- Full results on HEPData soon!



Differential σ measurements
$p_T(\ell\ell)$
$\Delta\phi(\ell\ell)$
Min $\Delta\phi(\ell j_1)$
Min $\Delta\phi(\ell j_2)$
S_T*
$p_T(j_1)$
$p_T(j_2)$
$\Delta\phi(j_1 j_2)$
$\Delta\eta(j_1 j_2)$
$\lvert p_T(j_1)\rvert + \lvert p_T(j_2)\rvert$
$m(j_1 j_2)$

*S_T = scalar sum of LQ decay products

3rd generation LQ searches

NEW

Allowed decays	
Up-type (Q=2/3)	**Down-type (Q=1/3)**
$LQ_3 \rightarrow b\tau$	$LQ_3 \rightarrow t\tau$
$LQ_3 \rightarrow t\nu$	$LQ_3 \rightarrow b\nu$

Search for pair-produced, third generation scalar leptoquarks
36 fb^{-1} data, $\sqrt{s}$ = 13 TeV
CERN-EP-2019-026

Reinterpretations of SUSY analyses

Stop pair-production (0ℓ + jets + E_T^{miss})
JHEP 12 (2017) 085

Stop pair-production (1ℓ + jets + E_T^{miss})
JHEP 06 (2018) 108

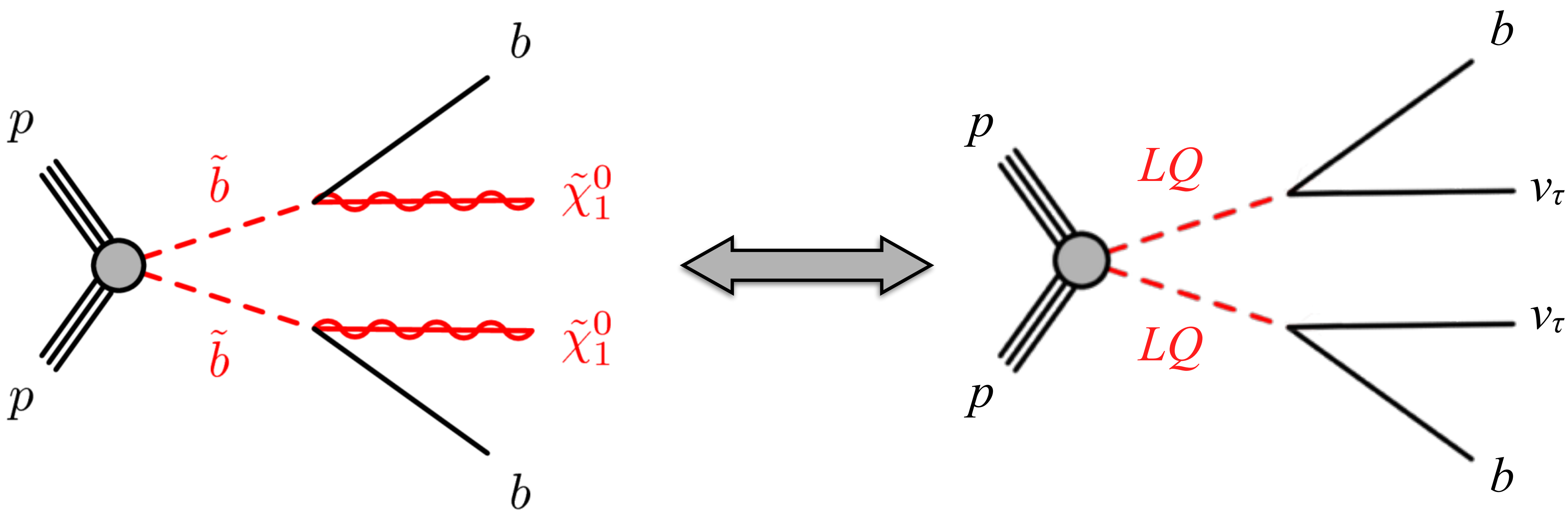
Sbottom pair-production (bb + E_T^{miss})
JHEP 11 (2017) 195

Stop → stau ($\tau\tau$ + b + E_T^{miss})
Phys. Rev. D 98 (2018) 032008

Dedicated search for
$LQ_3LQ_3 \rightarrow b\tau b\tau$

Analysis modelled on $HH \rightarrow bb\tau\tau$
Phys. Rev. Lett. 121 (2018) 191801

SUSY Reinterpretations

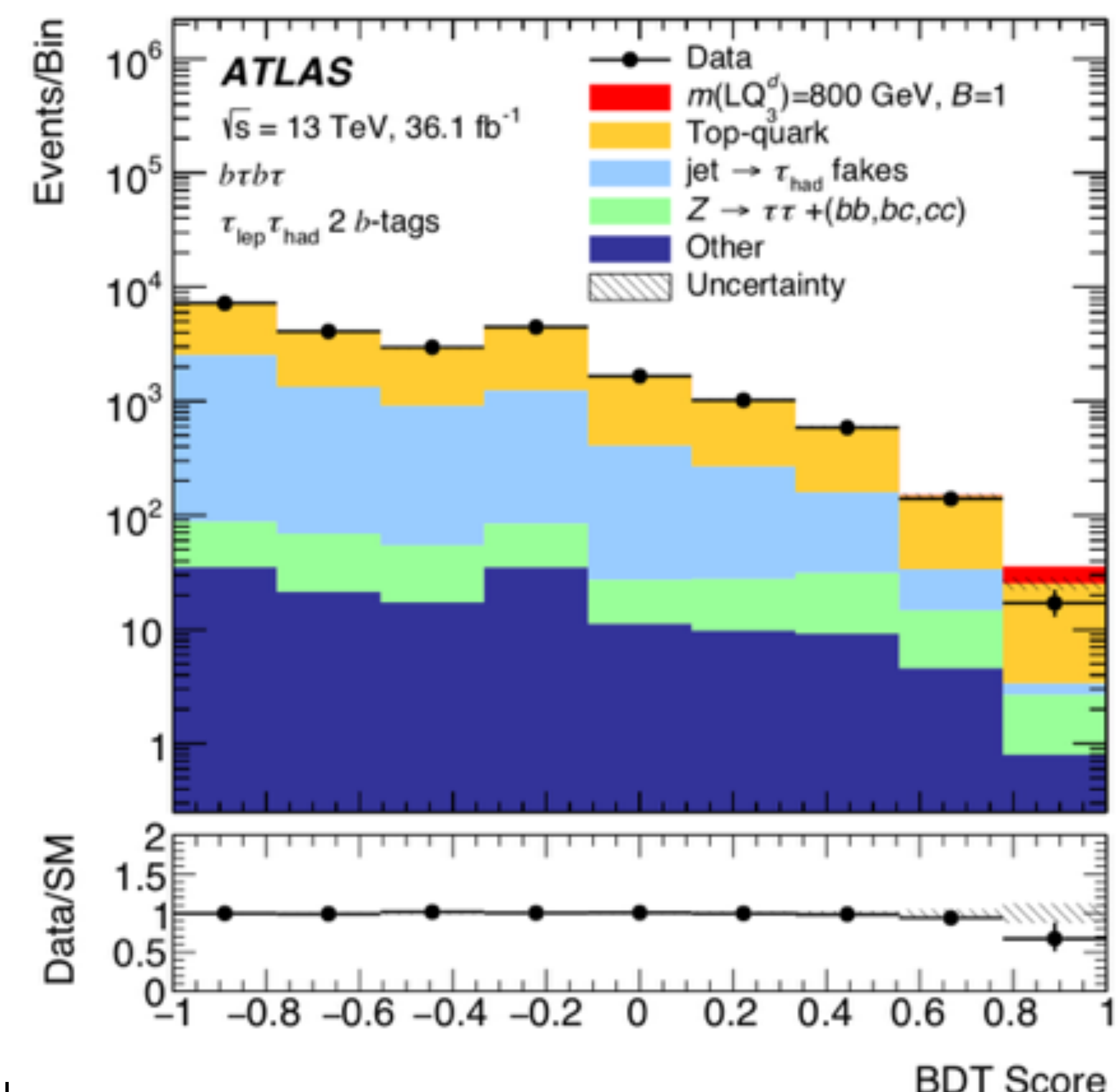


- Squark and LQ pair-production diagrams are very similar.
  - Similar experimental signatures (identical for β=0 scenarios).
- Perform `simple' reinterpretations of SUSY analyses to set limits on LQ production.
  - Signal regions targeting small m_χ values typically most sensitive to LQs.
  - Sensitivity is tested for different β values.

$LQ_3LQ_3 \rightarrow b\tau b\tau$ Search

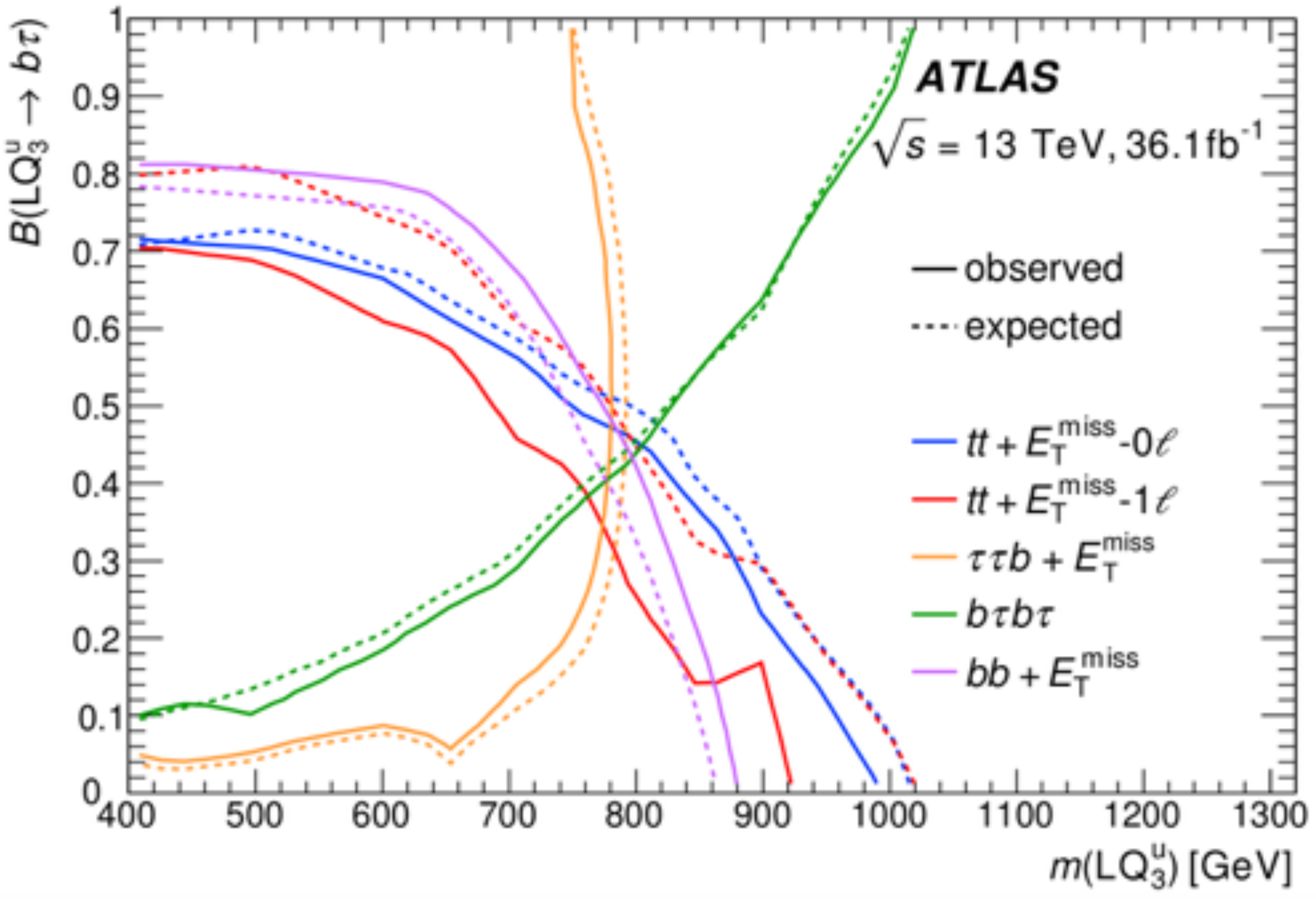
- Consider semi-leptonic and full hadronic decays of the tau pairs.
- Select events compatible with $\ell b+\tau_h b$ and $\tau_h b+\tau_h b$ final states.
  - Also consider signal region with 1 b-tagged jet + 1 other jet.
- Use BDTs to separate signal from backgrounds.
  - Dominant backgrounds (tt, $Z(\rightarrow\tau\tau)$+bb, multijet) estimated using data-driven methods.

BDT Input	$\ell\tau_h$ channel	$\tau_h\tau_h$ channel
	S_T	
	$m(\tau_h, \text{jet})$	$m(\tau_{h1}, \text{jet})$
	$m(\ell, \text{jet})$	-
	$\Delta\phi(\ell,\text{jet})$	$\Delta\phi(\tau_h,\text{jet})$
	E_T^{miss} - ϕ centrality (E_T^{miss} direction relative to vis τ decay products)	
	$p_T(\tau_h)$	$p_T(\tau_{h1})$
	$\Delta\phi(\ell, E_T^{miss})$	-

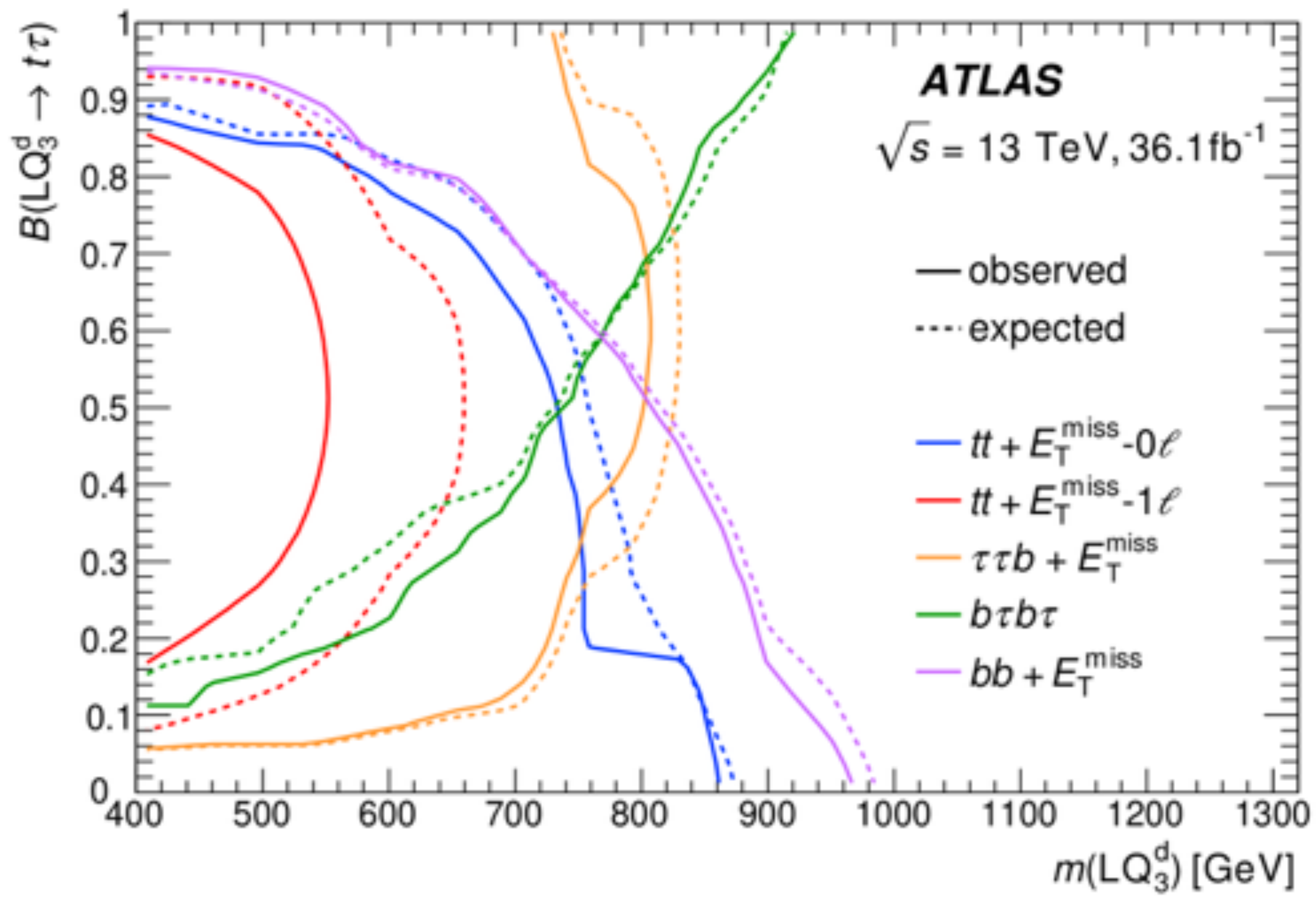


Results

Up-type leptoquarks



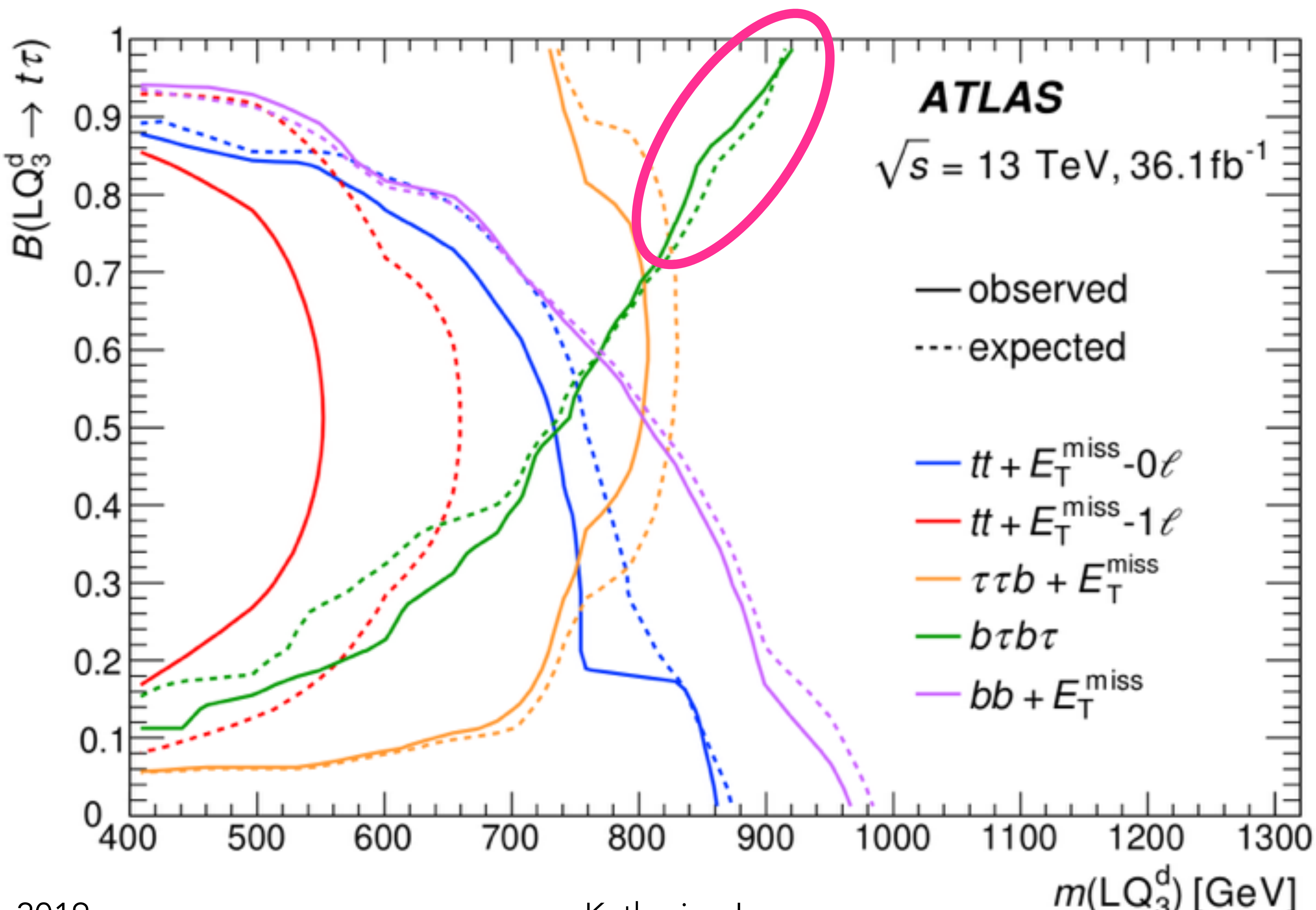
Down-type leptoquarks



- Masses below 800 GeV excluded for both up- and down-type LQs, independently of branching ratio.
- Masses below ~1 TeV excluded for BR(LQ→$\ell^{\pm}$q) = 0,1 extremities.

"Buy-one-get-one-free"

- bτbτ search also sensitive to down-type LQs decaying to tτtτ (where W's from top quark decay hadronically) due to no upper limit on jet multiplicity.
- Comparable sensitivity to CMS (exclude m_{LQ} < 900 GeV).
  - Eur. Phys. J. C 78 (2018) 707).



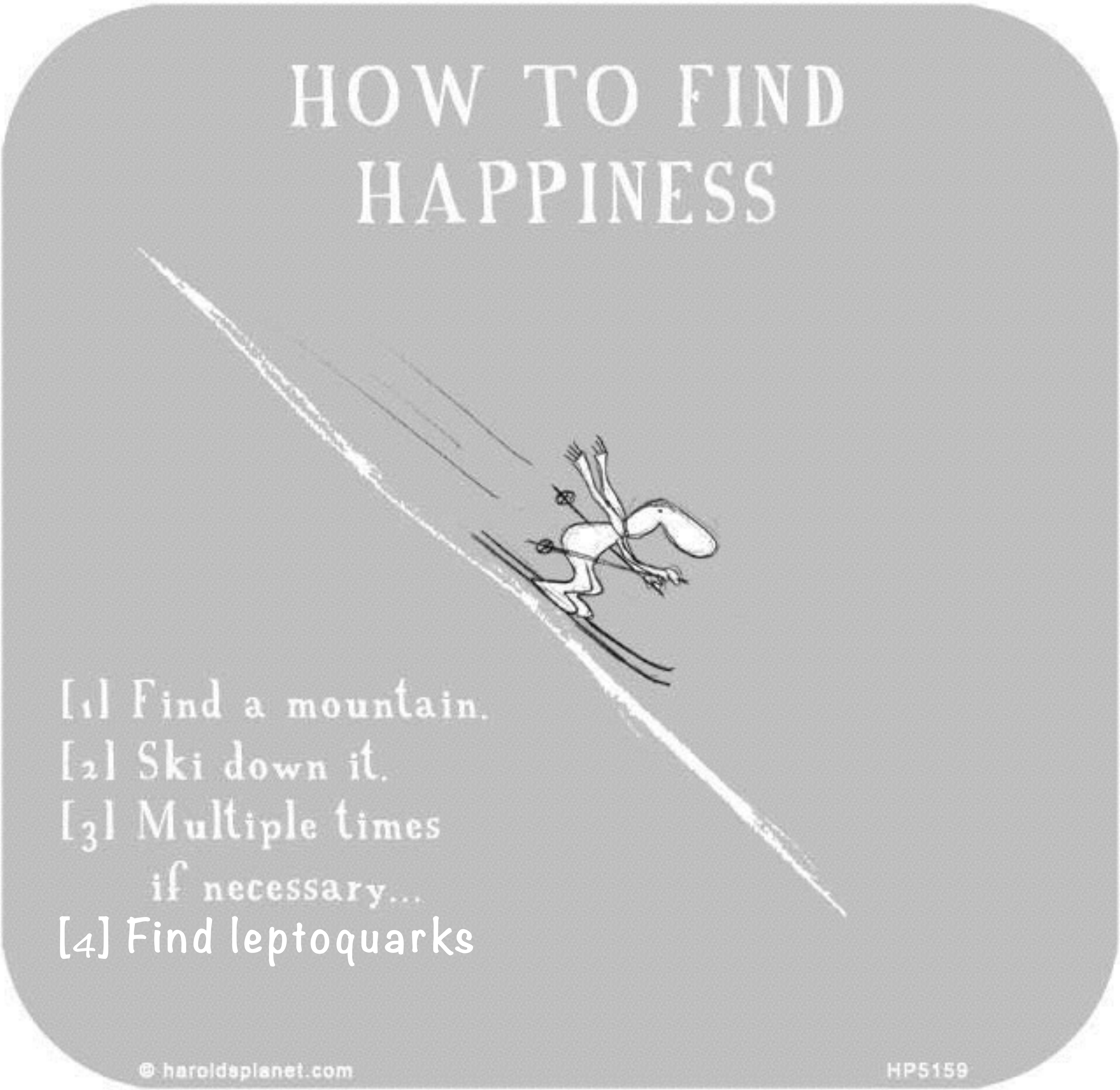
Summary

- Leptoquarks well motivated model for BSM physics.
  - Results from flavour factories has reinvigorated interest recently.

- ATLAS has comprehensive leptoquark search programme.
  - Look for leptoquarks coupling to all three generations.
  - 1st and 2nd generation LQ searches are also sensitive to cross-generational decays, e.g. LQ→μb.
  - 3rd generation LQ results obtained by reinterpretations of SUSY analyses or re-working of analyses with similar final states.

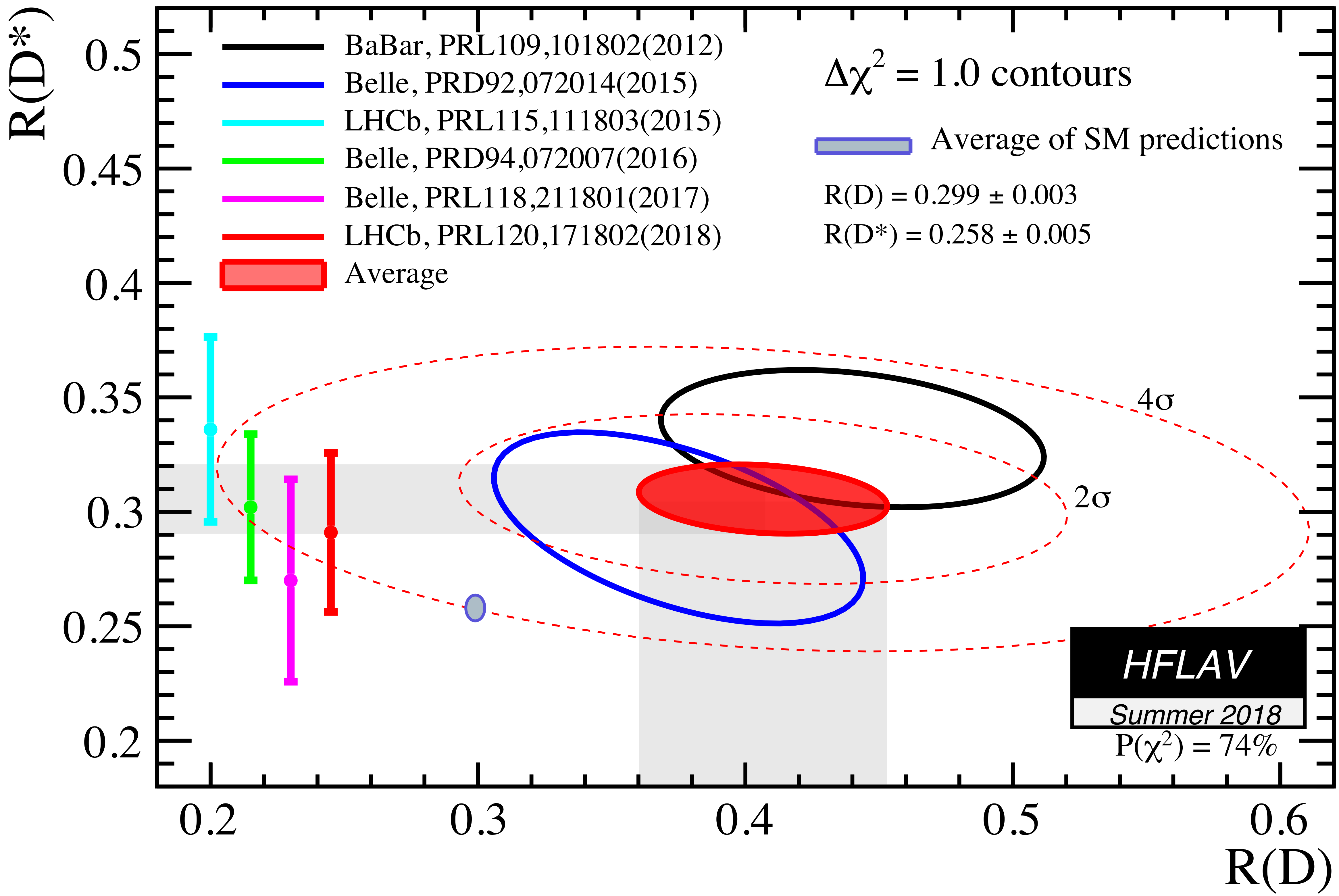
- Differential cross-section measurements in background control regions provided.
  - Complementary information in extreme regions of phase space, compared to typical SM measurements.
  - Use to improve generator tunes.

- Looking forward to seeing what the rest of the Run 2 data holds!

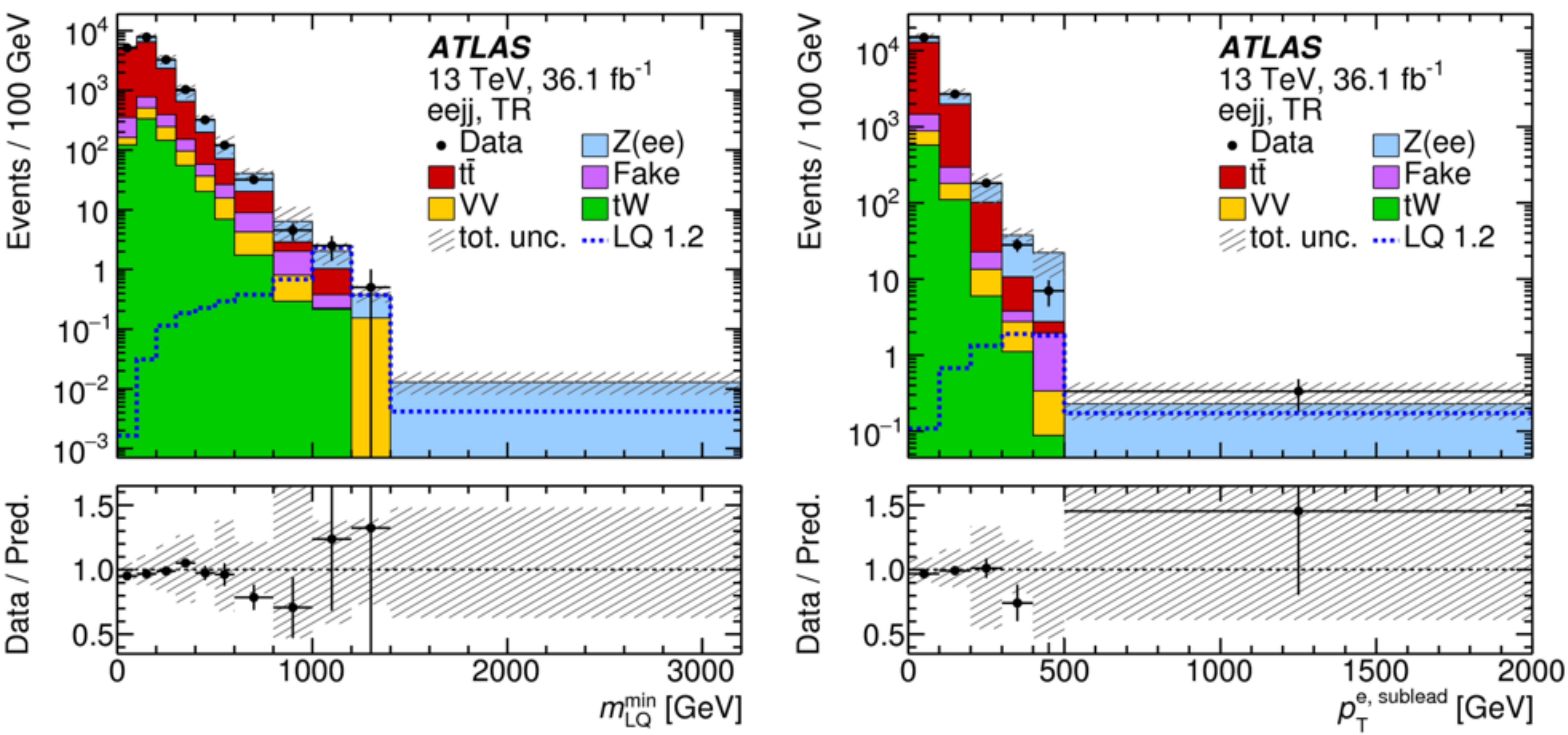

HOW TO FIND HAPPINESS
[1] Find a mountain.
[2] Ski down it.
[3] Multiple times if necessary...
[4] Find leptoquarks
© haroldsplanet.com
HP5159

Back Up

R(D),R(D*) Results

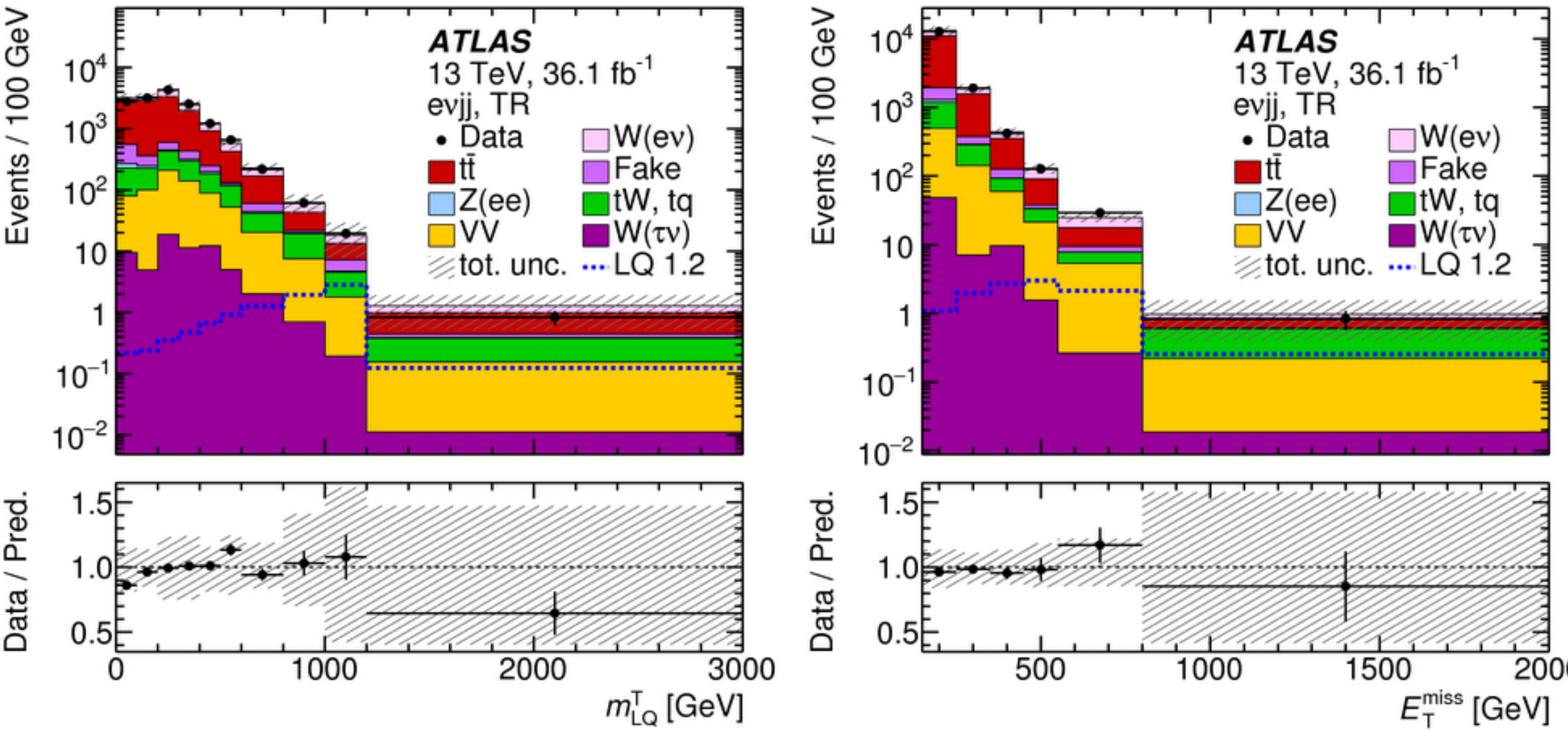


LQ1 (eejj)

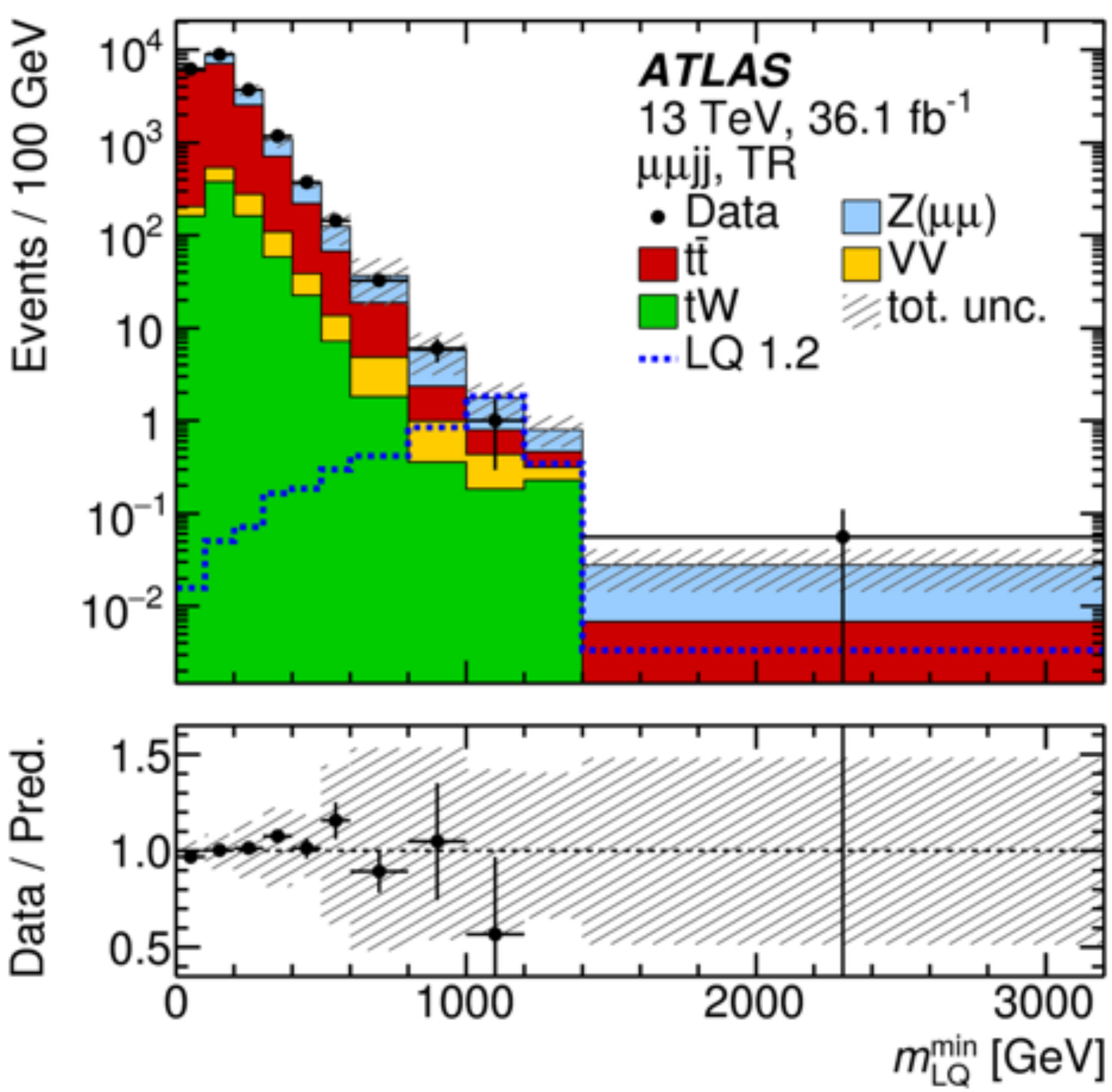


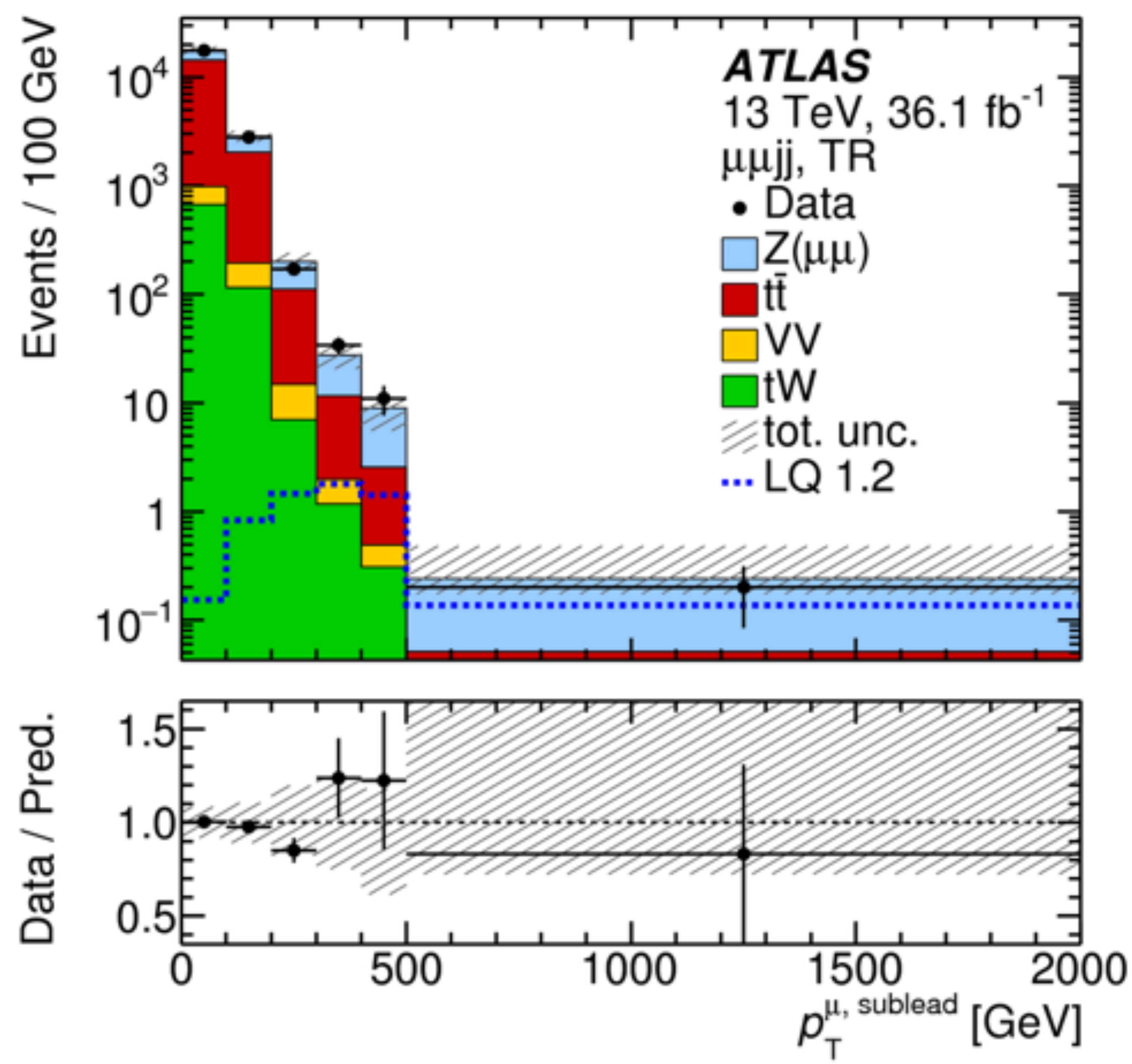
ATLAS
13 TeV, 36.1 fb^{-1}
eejj, TR
Data
$t\bar{t}$
VV
tot. unc.
Z(ee)
Fake
tW
LQ 1.2
Events / 100 GeV
Data / Pred.
m_{LQ}^{min} [GeV]
$p_T^{e, sublead}$ [GeV]

LQ1 (eνjj)

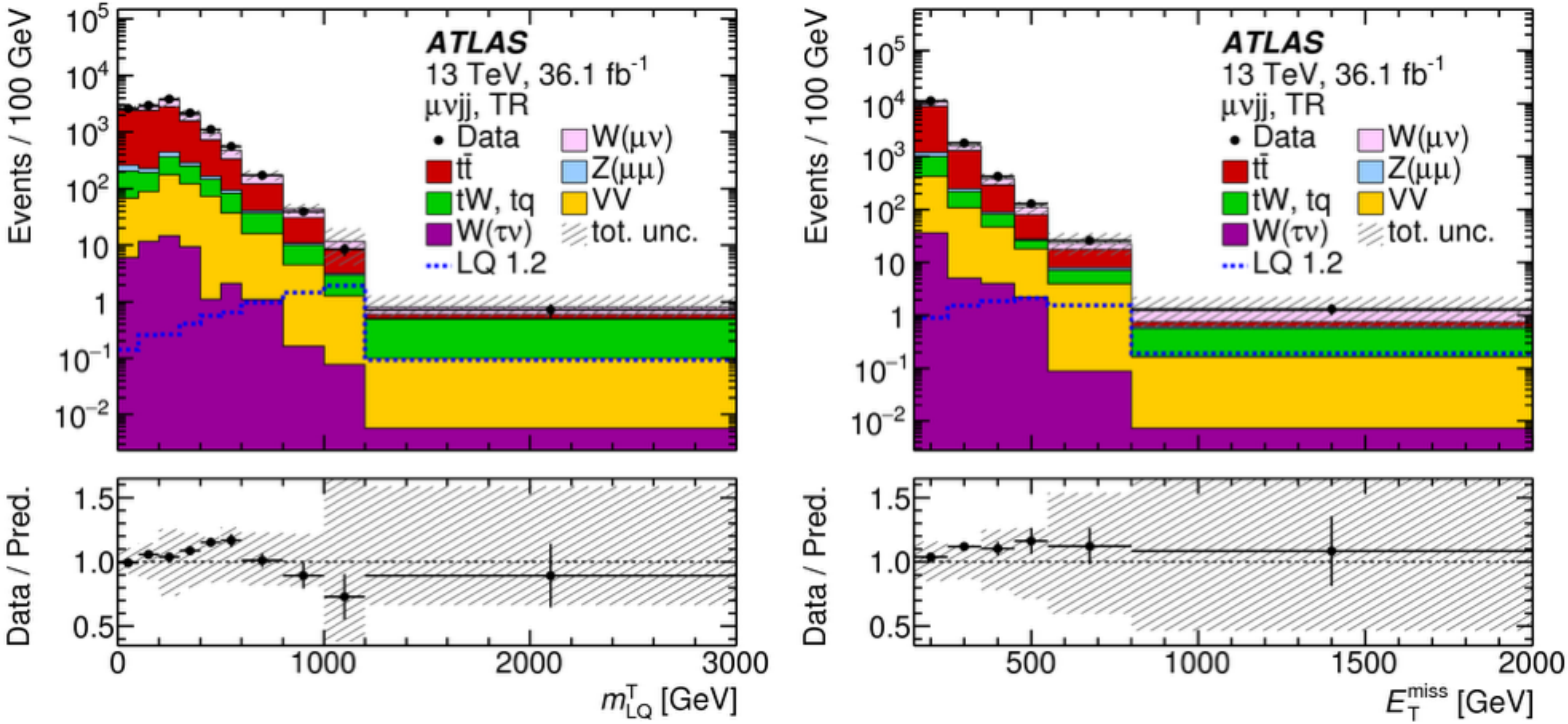

ATLAS
13 TeV, 36.1 fb-1
eνjj, TR
Data
W(eν)
tt̄
Fake
Z(ee)
tW, tq
VV
W(τν)
tot. unc.
LQ 1.2
Events / 100 GeV
Data / Pred.
m^T_LQ [GeV]
E^miss_T [GeV]

LQ2 (μμjj)


ATLAS
13 TeV, 36.1 fb-1
μμjj, TR
Data
tt̄
tW
LQ 1.2
Z(μμ)
VV
tot. unc.
Events / 100 GeV
Data / Pred.
m_{LQ}^{min} [GeV]


ATLAS
13 TeV, 36.1 fb-1
μμjj, TR
Data
Z(μμ)
tt̄
VV
tW
tot. unc.
LQ 1.2
Events / 100 GeV
Data / Pred.
$p_T^{\mu, sublead}$ [GeV]

LQ2 (μνjj)



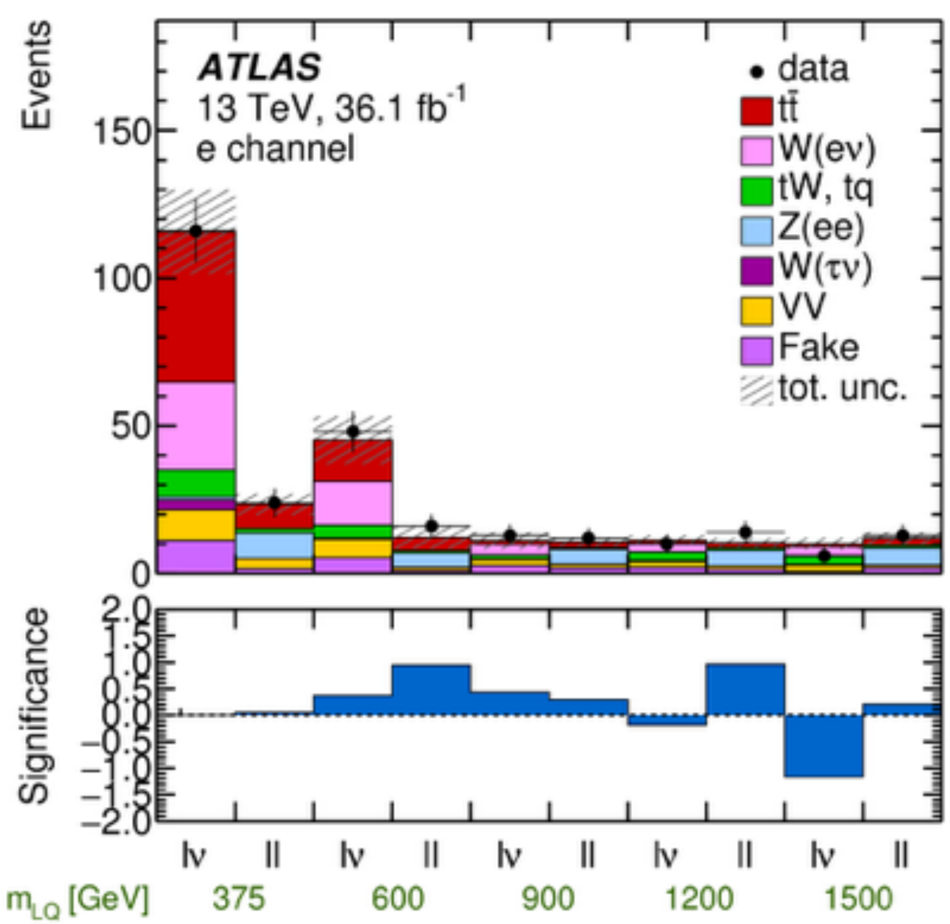
ATLAS
13 TeV, 36.1 fb^{-1}
μνjj, TR
Data
$t\bar{t}$
tW, tq
W(τν)
LQ 1.2
W(μν)
Z(μμ)
VV
tot. unc.
Events / 100 GeV
Data / Pred.
m_{LQ}^{T} [GeV]
E_{T}^{miss} [GeV]

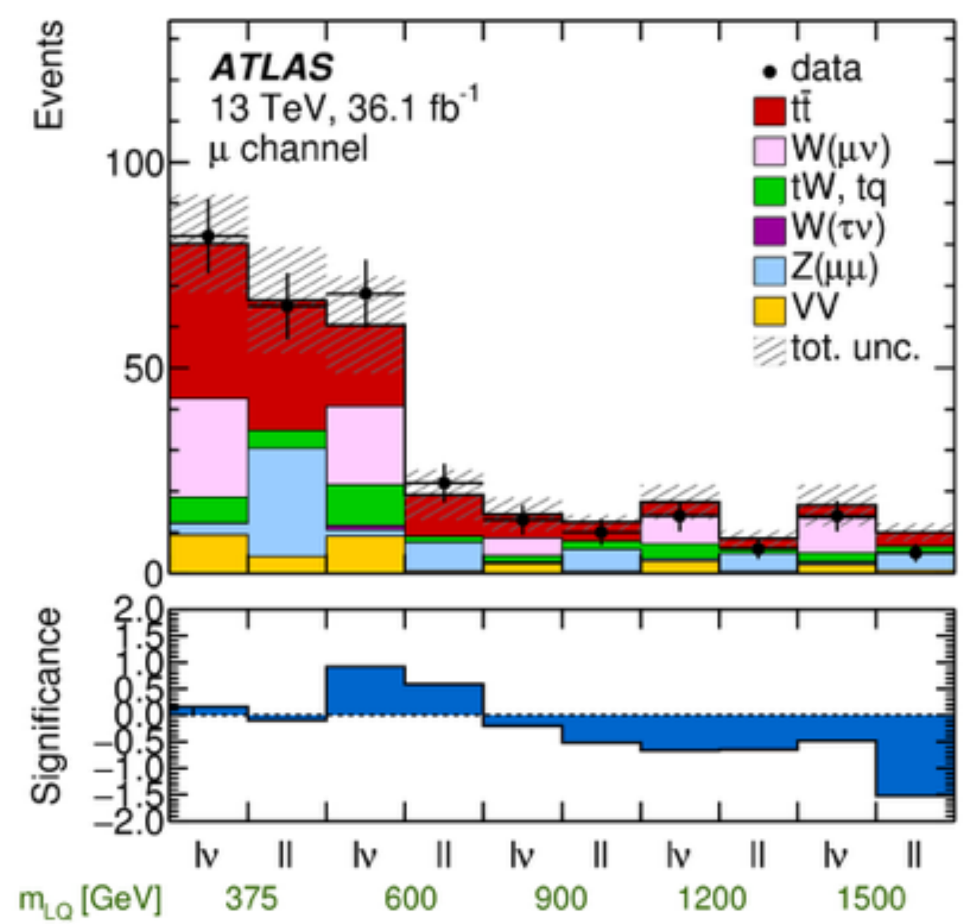
LQ1,2 Background Estimation

<table>
<tr><td>Common selections</td><td colspan="3">≥ 2 jets, $p_{\mathrm{T}} > 60$ GeV, $|\eta| < 2.5$
$|\eta_{muon}| < 2.5$, $|\eta_{elec}| < 2.47$</td></tr>
<tr><td></td><td>$\ell\ell jj$</td><td colspan="2">$\ell\nu jj$</td></tr>
<tr><td></td><td>$E_T^{\ell} > 40\,\mathrm{GeV}$</td><td colspan="2">$E_T^{\ell} > 65\,\mathrm{GeV}$</td></tr>
<tr><td>Z CR</td><td>$70 < m_{\ell\ell} < 110\,\mathrm{GeV}$</td><td colspan="2">-</td></tr>
<tr><td>W CR</td><td>-</td><td rowspan="2">$40 < m_{\mathrm{T}} < 130$ GeV
$E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV
$S > 4$</td><td>0 b-jets</td></tr>
<tr><td>$t\bar{t}$ CR</td><td>-</td><td>≥ 2 b-jets</td></tr>
</table>

Analysis Strategy

- Separate BDTs for each mass point and channel.
- Cut on BDT output score to define single bin signal regions.
  - Low mass region (m_{LQ} < 600 GeV): mass resolution < intervals between mass points → limits obtained by training on neighbouring mass points.
  - High mass region (m_{LQ} > 600 GeV): mass resolution > intervals between mass points → limits interpolated.
- $\ell\ell$jj and $\ell\nu$jj signal regions fitted simultaneously.

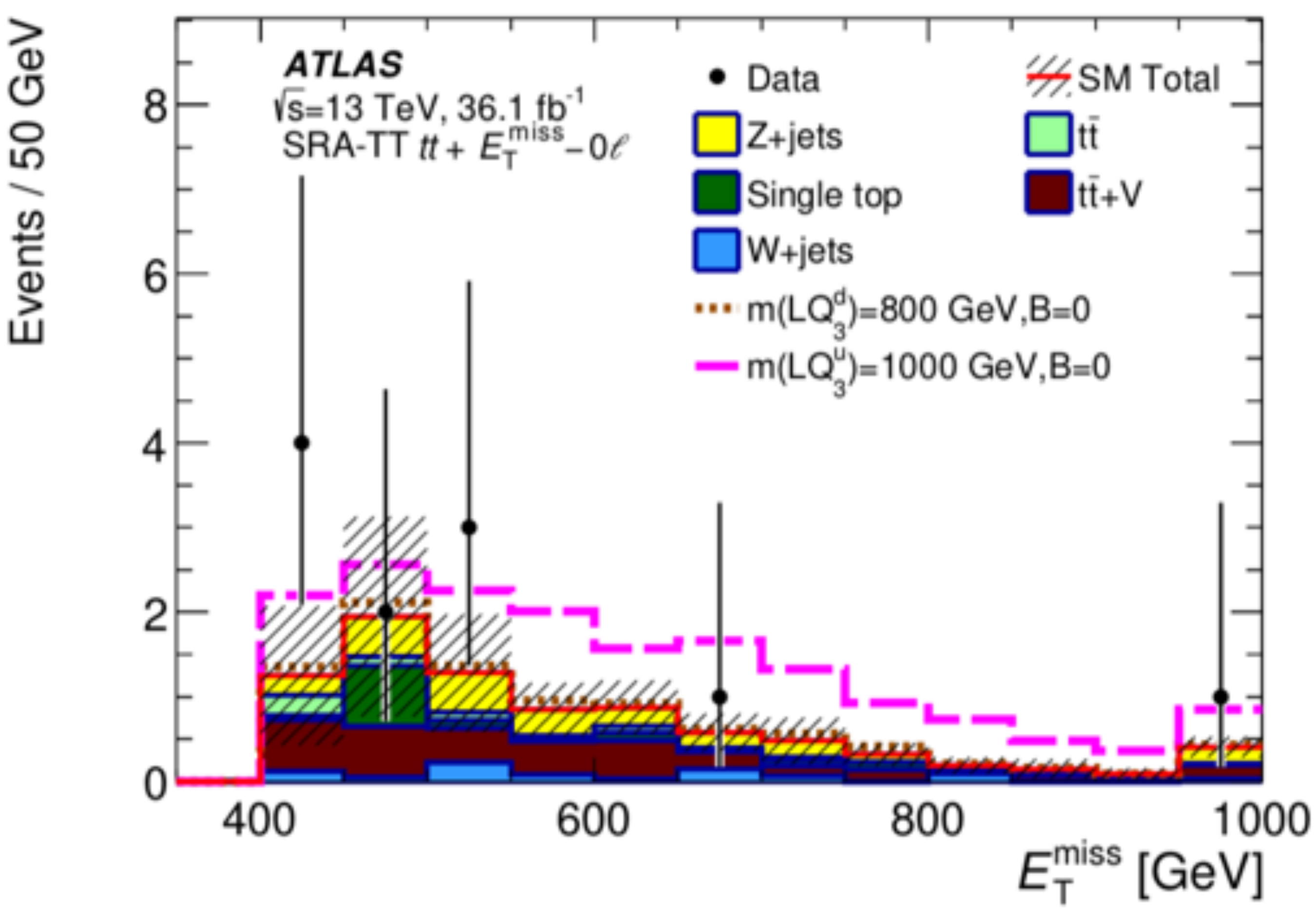


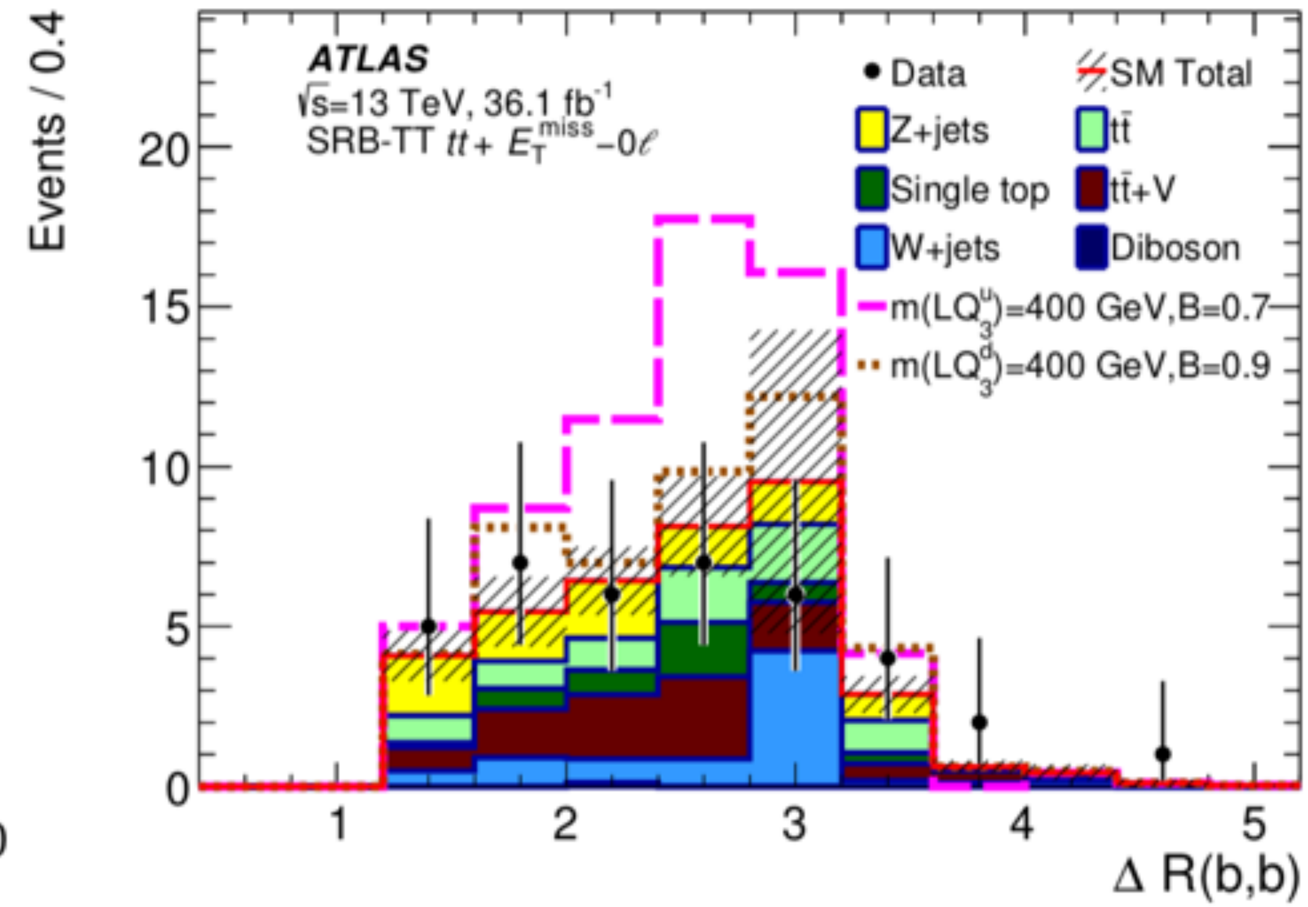


LQ3 decays

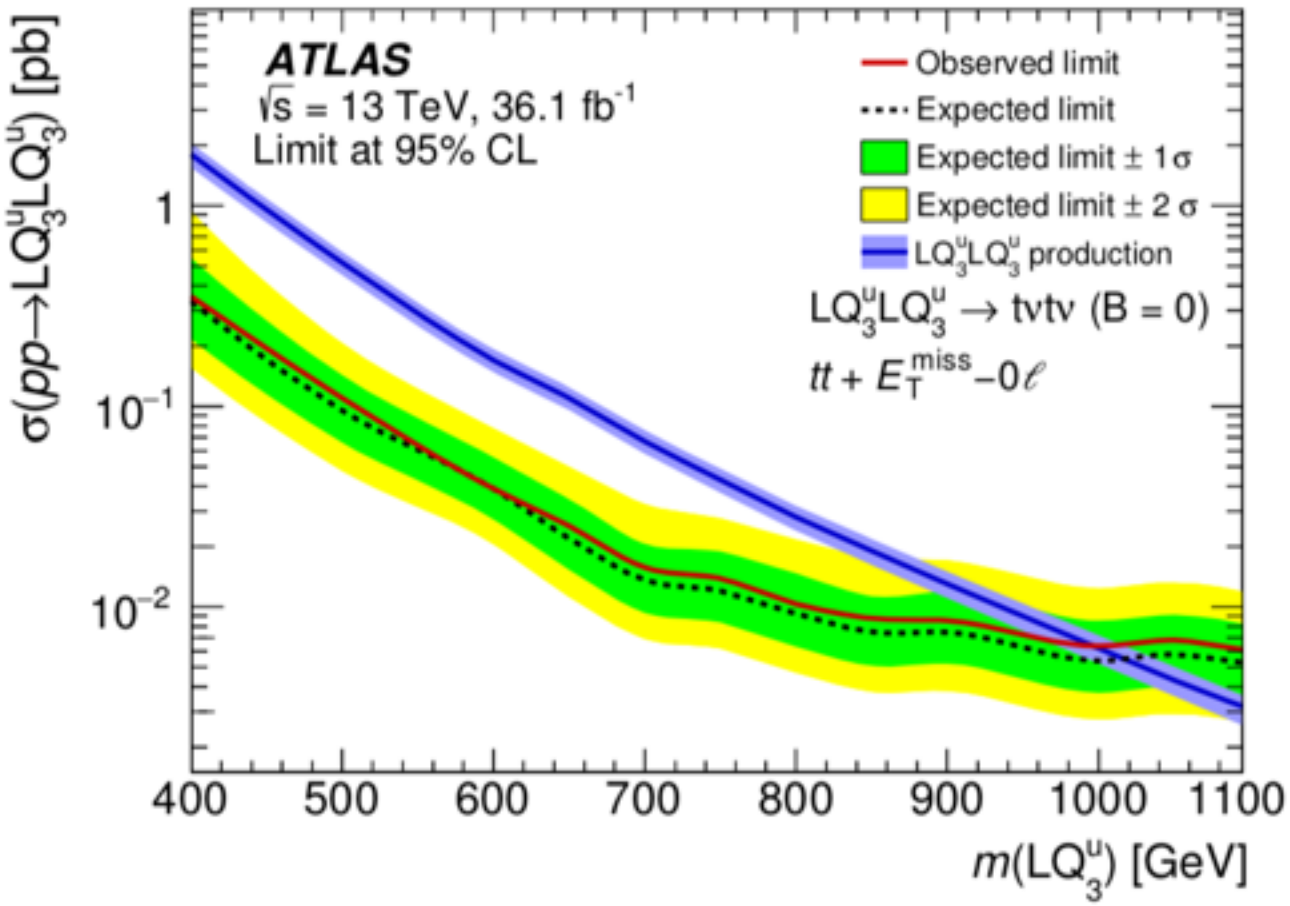
Decay Mode	Allowed Charge(s)	Type
$t\nu$	2/3	Up
$b\tau$	2/3, 4/3	Up
$b\nu$	1/3	Down
$t\tau$	1/3, 5/3	Down

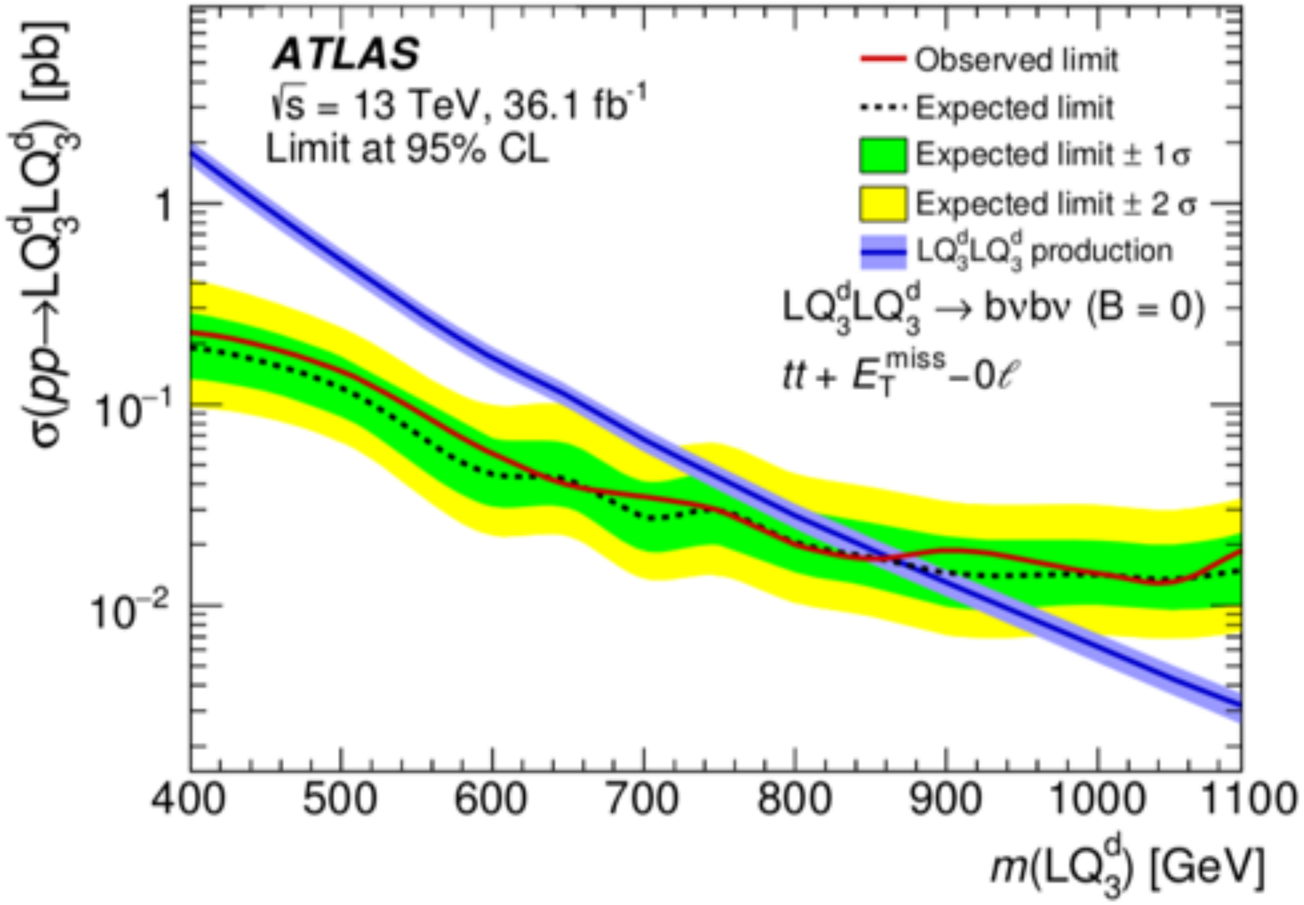
Stop (0ℓ) → LQ3 reinterpretation





Stop (0ℓ) → LQ3 reinterpretation





Stop (1ℓ) → LQ3 reinterpretation

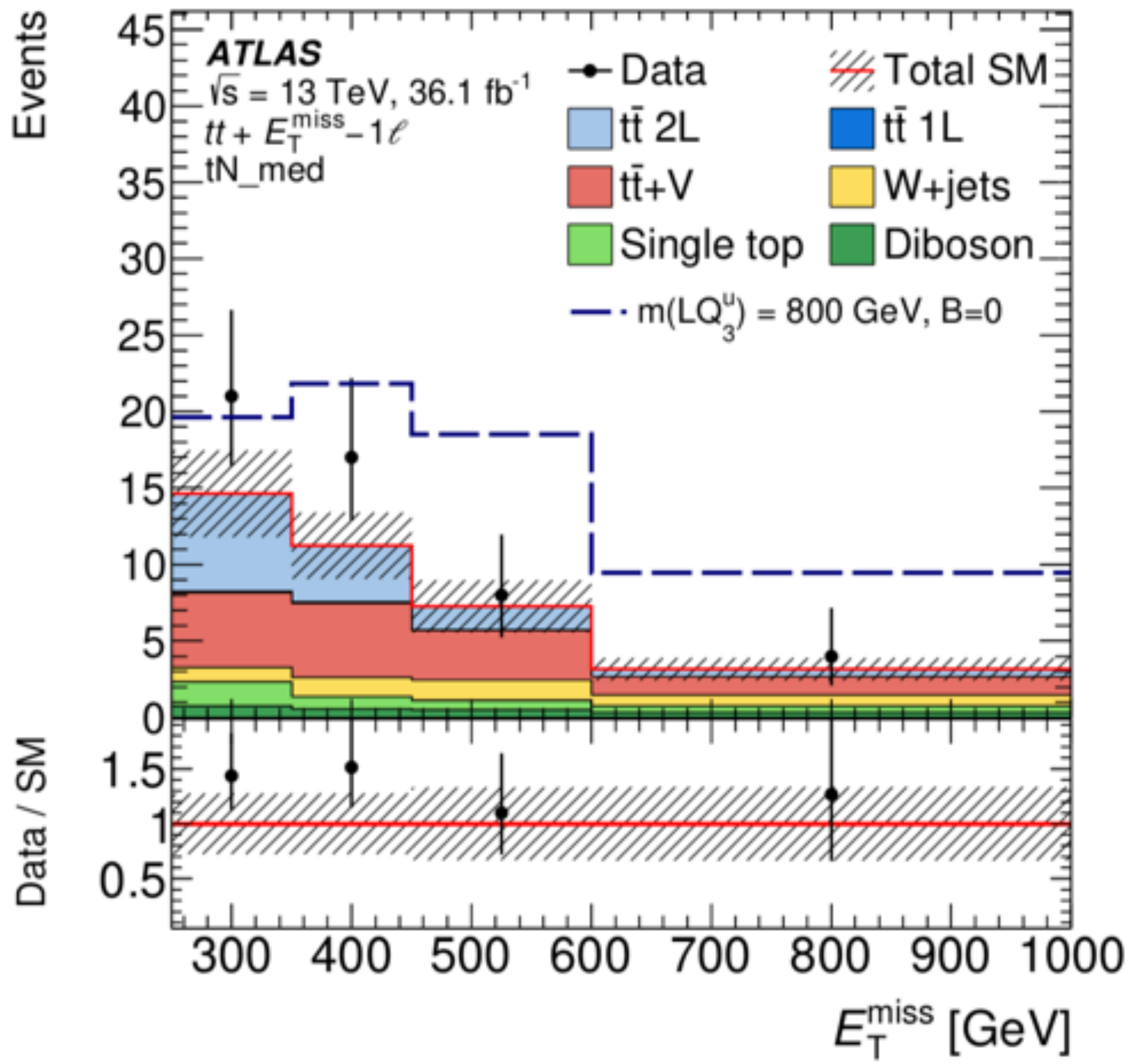
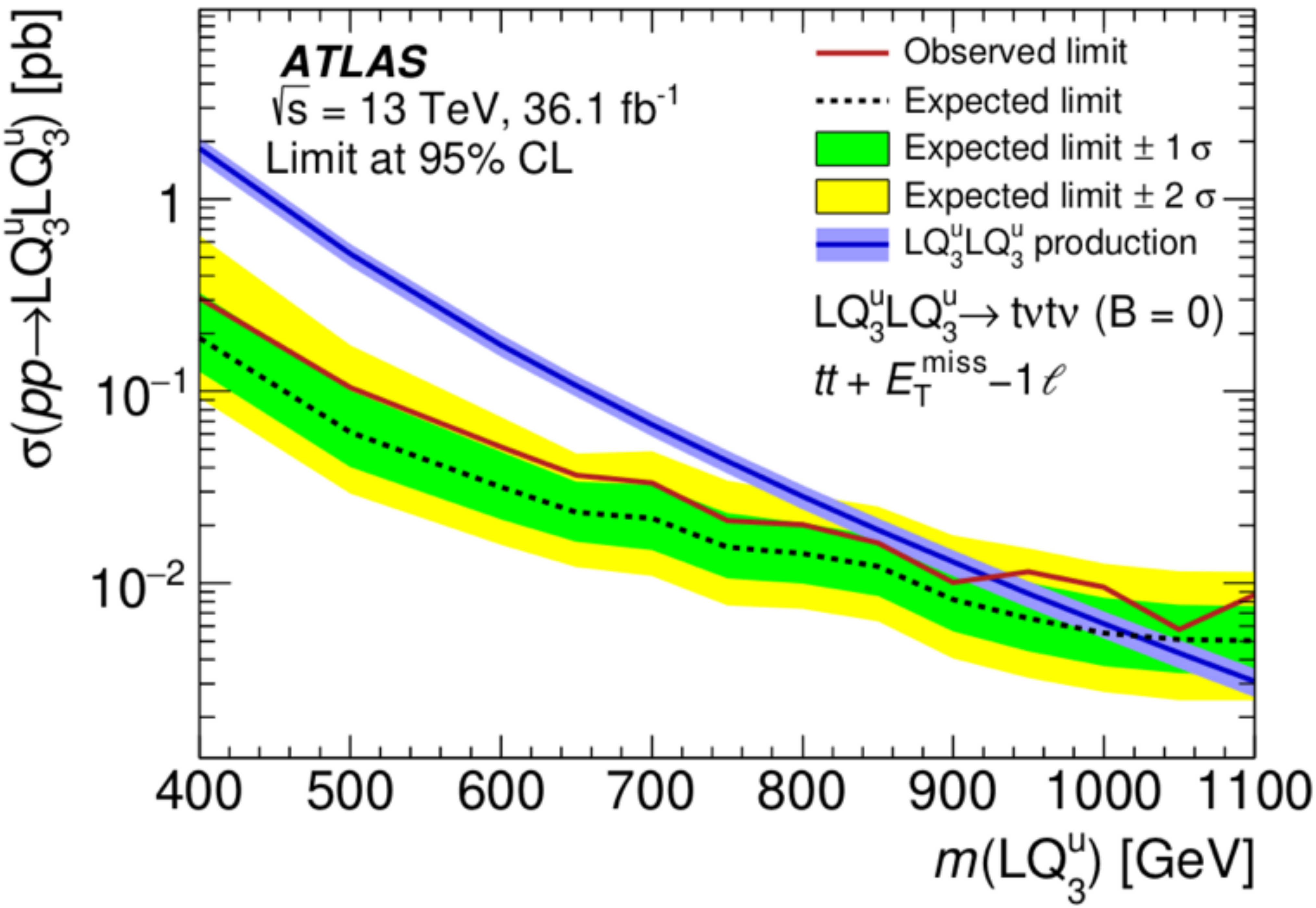


Figure 9: Observed and expected $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions are shown in the tN_med signal region, as is their ratio. The error band includes statistical and systematic uncertainties. The expected SM backgrounds are normalized to the values determined in the fit. The expected number of signal events for an up-type LQ with $m_{\mathrm{LQ}} = 800$ GeV and $B = 0$ is added on top of the SM prediction. The last bin contains the overflow events.

Stop (1ℓ) → LQ3 reinterpretation



Sbottom → LQ3 reinterpretation

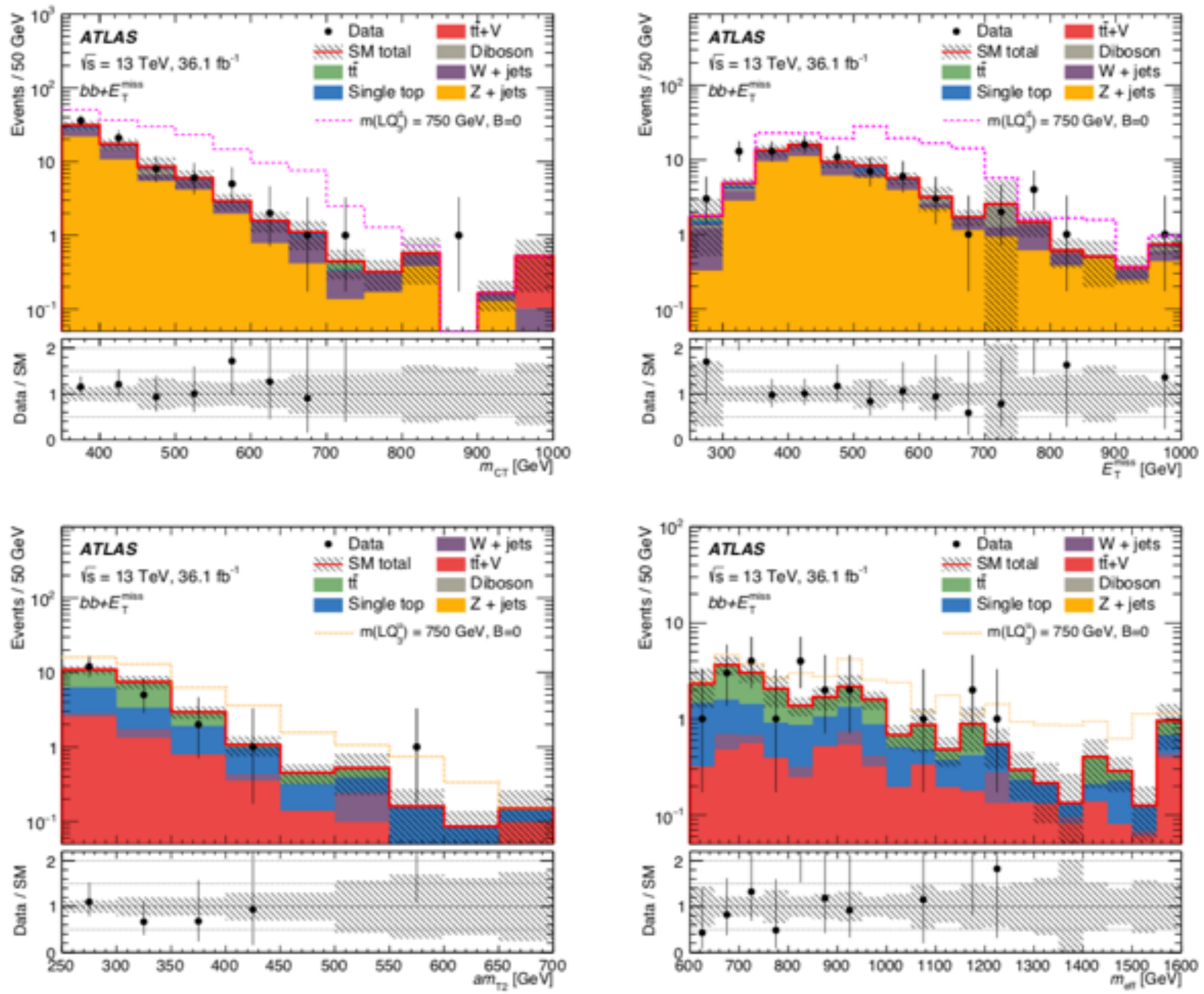


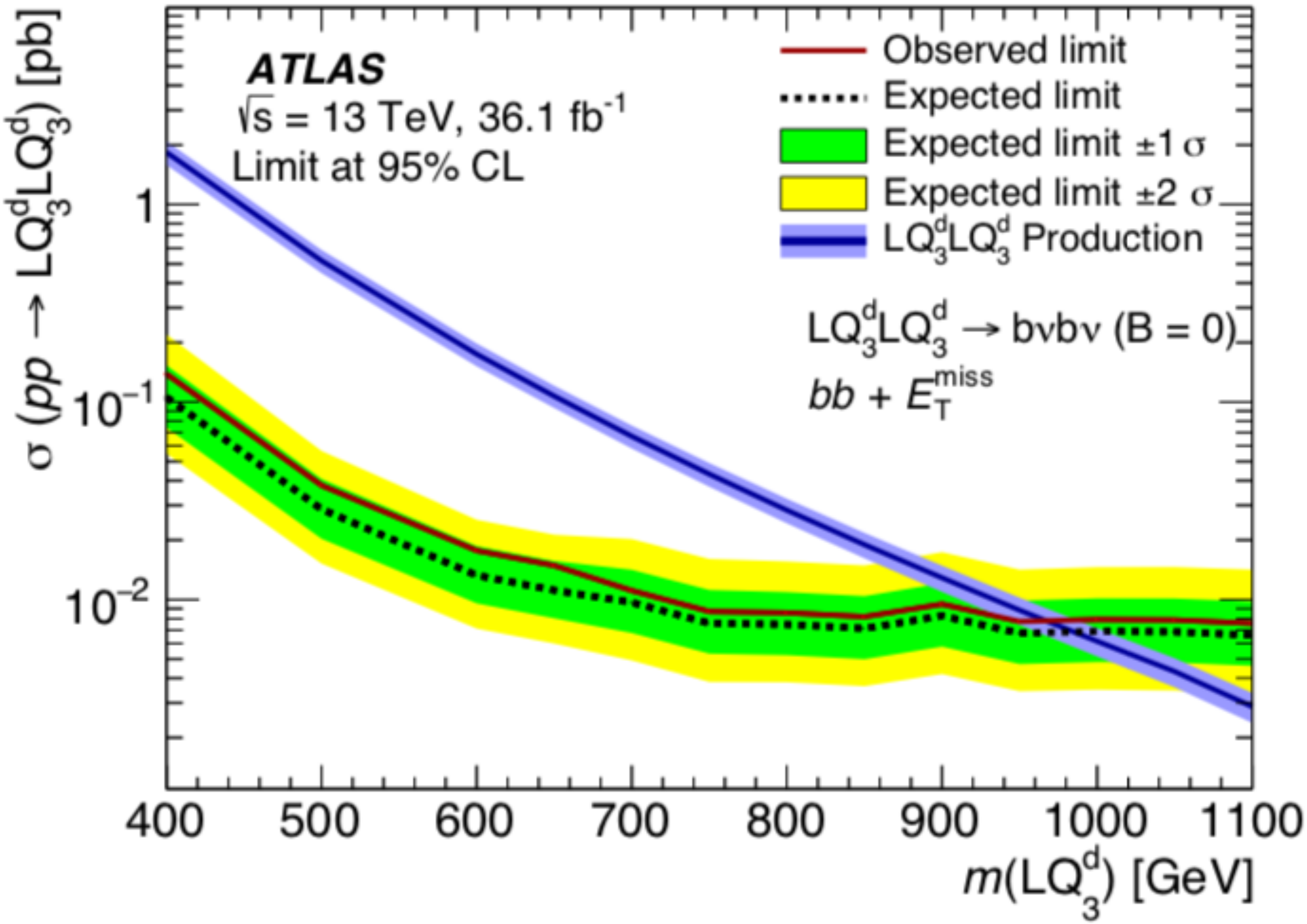
Figure 15: Distributions for key kinematic variables in the zero- and one-lepton SR selections for the contransverse mass, m_{CT} [48] and $E_{\mathrm{T}}^{\mathrm{miss}}$ in the zero-lepton SR (top) and am_{T2} [42] and m_{eff} in the one-lepton SRs (bottom). Two example LQ signal samples are added on top of the SM background, $\mathrm{LQ}_3^{\mathrm{d}}$ (dashed lines top plots) and $\mathrm{LQ}_3^{\mathrm{u}}$ (dashed lines bottom plots). The assumed $B(\mathrm{LQ} \to q\tau)$ for both signal samples is zero, and m_{LQ} is 750 GeV. The expected SM backgrounds are normalized to the values determined in the fit. The last bin contains the overflow events.

Sbottom → LQ3 reinterpretation

Table 7: Number of observed events and background-only fit results in the SRs. The uncertainties contain both the statistical and systematic uncertainties. Two example LQ signal samples are also shown for comparison, with various assumptions about $B(\mathrm{LQ} \to q\tau)$.

SR selection	b0L_SRA350	b0L_SRA450	b0L_SRA550	b1L_SRA600	b1L_SRA750
Observed events	81	24	10	21	13
Fitted bkg events	70.1 ± 13.0	21.4 ± 4.5	7.2 ± 1.5	23.0 ± 5.4	14.4 ± 3.6
$m_{\mathrm{LQ}} = 750$ GeV					
$B(\mathrm{LQ}_3^{\mathrm{d}} \to t\tau) = 1.0$	< 0.1	< 0.1	< 0.1	0.4 ± 0.2	0.4 ± 0.2
$B(\mathrm{LQ}_3^{\mathrm{d}} \to t\tau) = 0.5$	28.4 ± 1.7	18.1 ± 1.5	7.6 ± 0.9	5.1 ± 0.8	5.0 ± 0.9
$B(\mathrm{LQ}_3^{\mathrm{d}} \to t\tau) = 0.0$	107.1 ± 6.7	68.3 ± 5.8	29.6 ± 3.7	0.3 ± 0.2	0.3 ± 0.2
$B(\mathrm{LQ}_3^{\mathrm{u}} \to b\tau) = 1.0$	1.3 ± 0.6	0.8 ± 0.5	0.2 ± 0.2	0.6 ± 0.4	0.6 ± 0.3
$B(\mathrm{LQ}_3^{\mathrm{u}} \to b\tau) = 0.5$	2.4 ± 0.4	1.5 ± 0.3	0.3 ± 0.1	10.2 ± 1.1	9.6 ± 0.1
$B(\mathrm{LQ}_3^{\mathrm{u}} \to b\tau) = 0.0$	2.6 ± 1.0	1.7 ± 0.6	0.4 ± 0.3	16.7 ± 3.3	14.7 ± 0.3

Sbottom → LQ3 reinterpretation



Stop(stau) → LQ3 reinterpretation

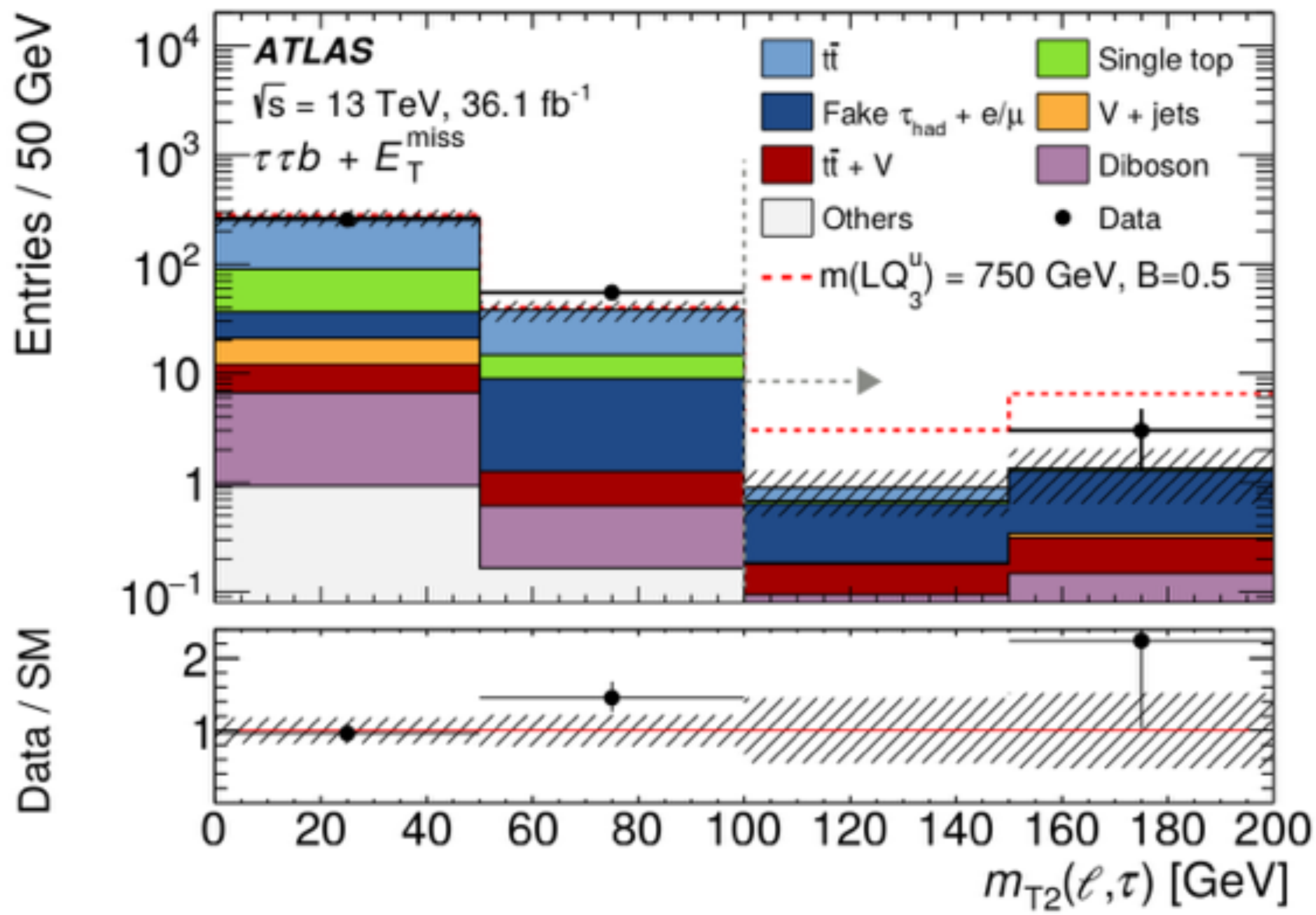
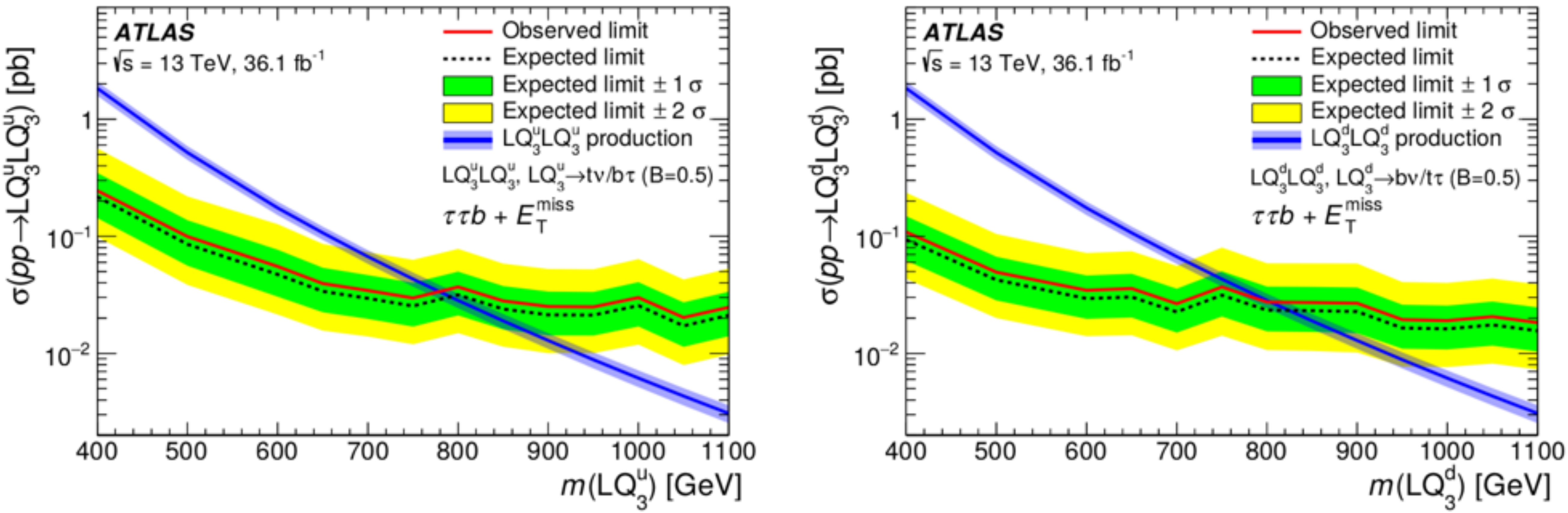
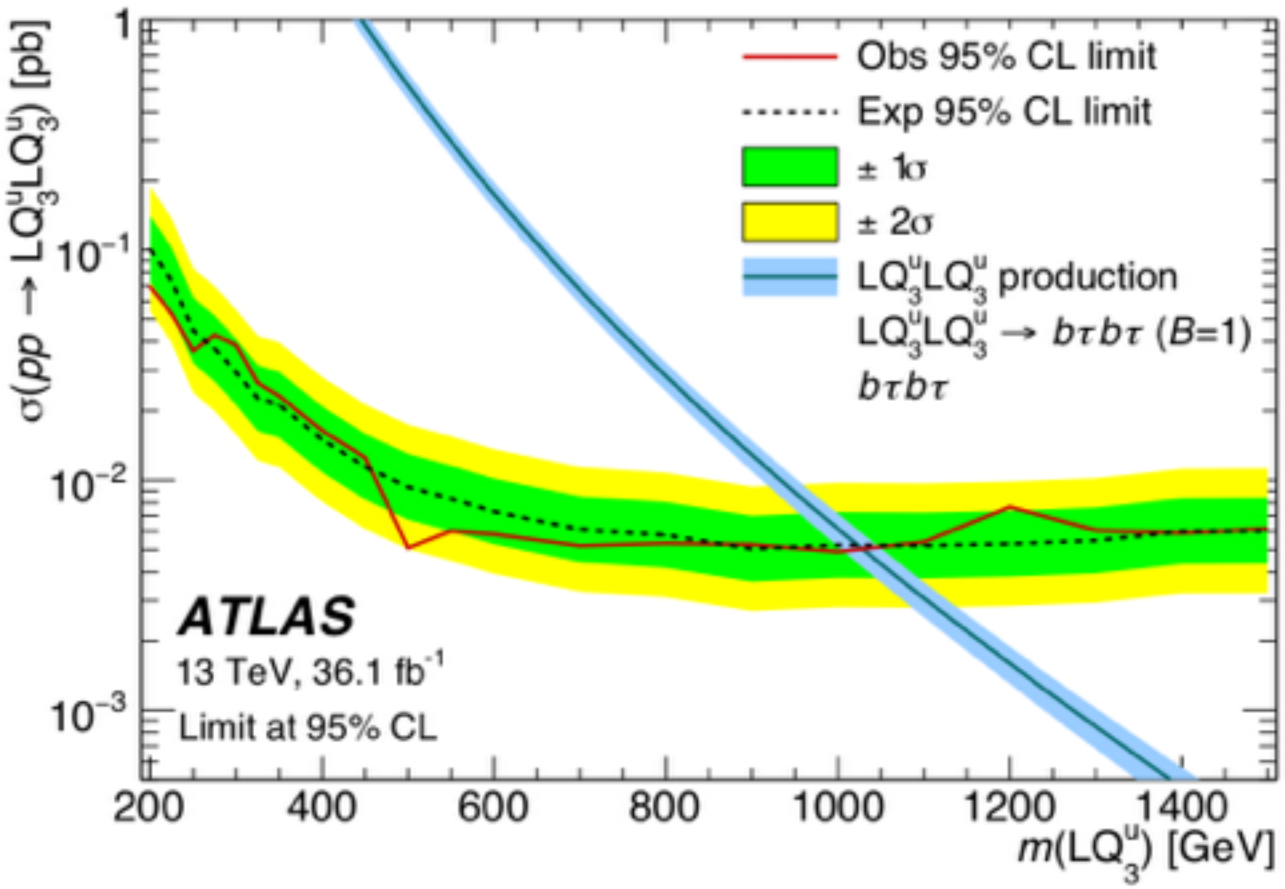


Figure 13: Distribution of the stransverse mass $m_{T2}(\ell, \tau_{had})$ [45–47] in the signal region of the $\tau_\ell \tau_{had}$ channel before applying the selection requirement on $m_{T2}(\ell, \tau_{had})$, which is indicated by the dashed vertical line and arrow. The stacked histograms show the various SM background contributions, which are normalized to the values determined in the fit. The hatched band indicates the total statistical and systematic uncertainty in the SM background. The error bars on the black data points represent the statistical uncertainty in the data yields. The dashed histogram shows the expected additional yields from a leptoquark signal model LQ_3^u with $m_{LQ} = 750$ GeV and $B = 0.5$ added on top of the SM prediction. The rightmost bin includes the overflow.

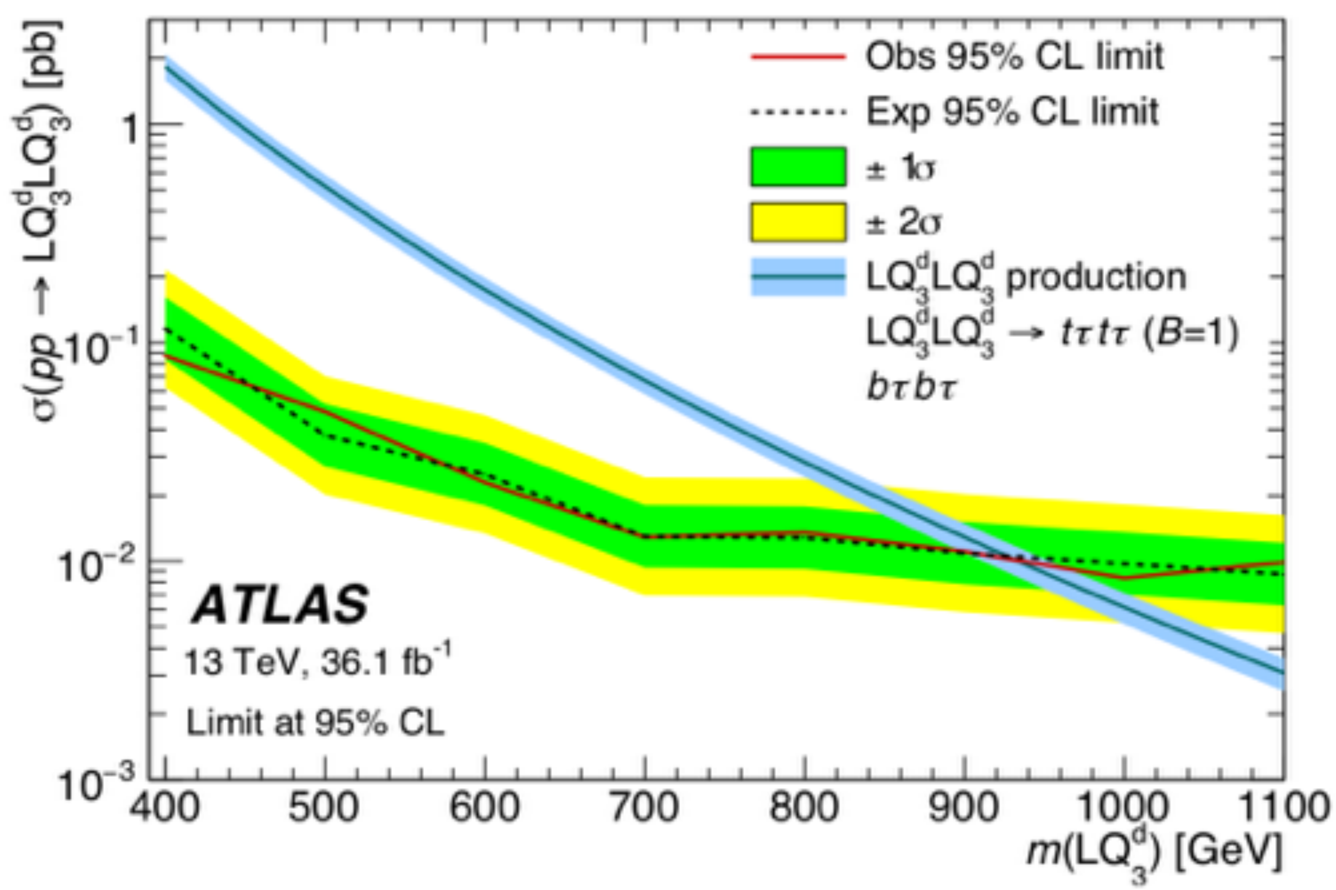
Stop(stau) → LQ3 reinterpretation



LQ3LQ3→bτbτ



Obs 95% CL limit
Exp 95% CL limit
± 1σ
± 2σ
LQ3uLQ3u production
LQ3uLQ3u → bτbτ (B=1)
bτbτ
ATLAS
13 TeV, 36.1 fb-1
Limit at 95% CL
σ(pp → LQ3uLQ3u) [pb]
m(LQ3u) [GeV]



Obs 95% CL limit
Exp 95% CL limit
± 1σ
± 2σ
LQ3dLQ3d production
LQ3dLQ3d → tτtτ (B=1)
bτbτ
ATLAS
13 TeV, 36.1 fb-1
Limit at 95% CL
σ(pp → LQ3dLQ3d) [pb]
m(LQ3d) [GeV]