Searches for Leptoquarks with the ATLAS detector

34th Rencontres de Blois

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On behalf of the ATLAS Collaboration

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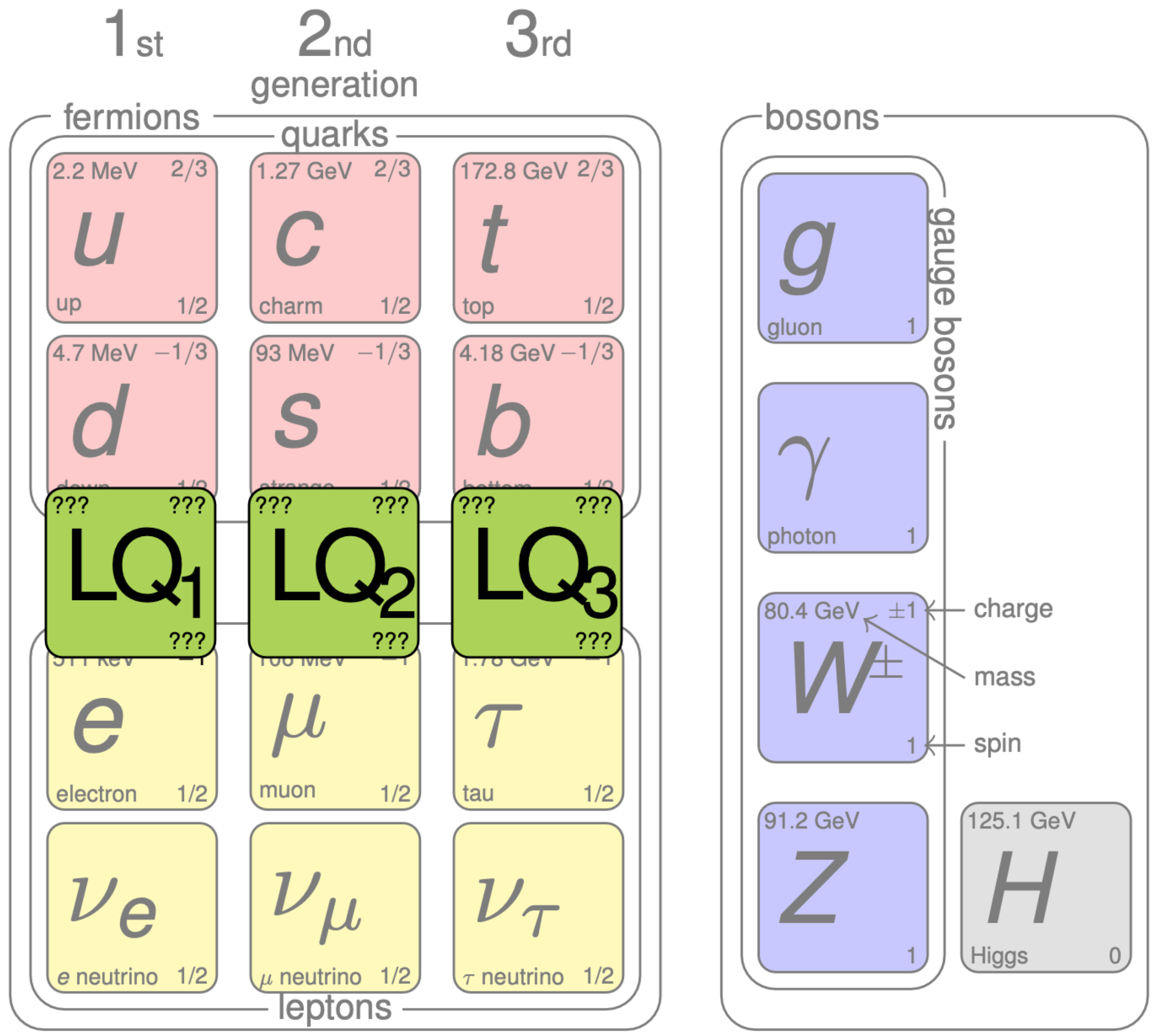
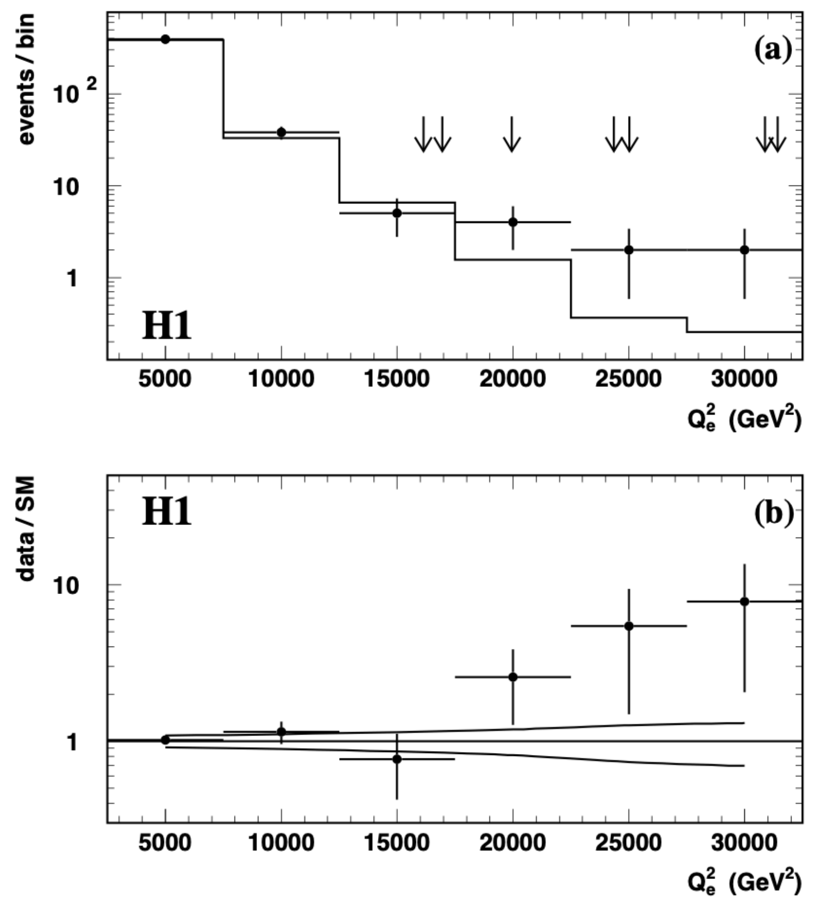
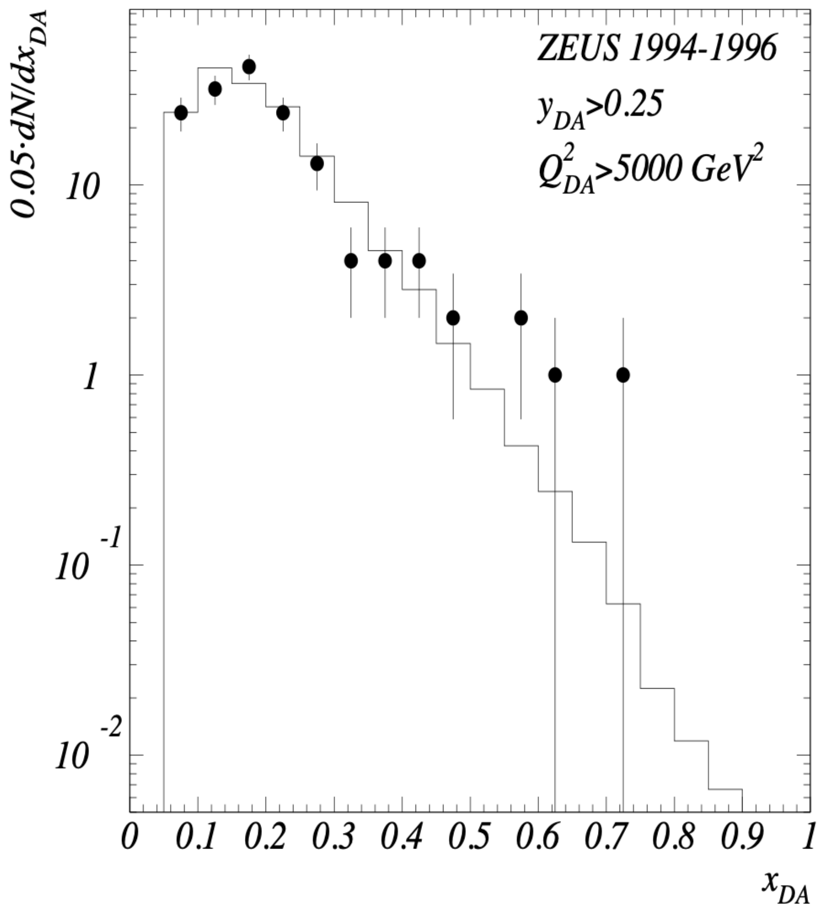
Motivation

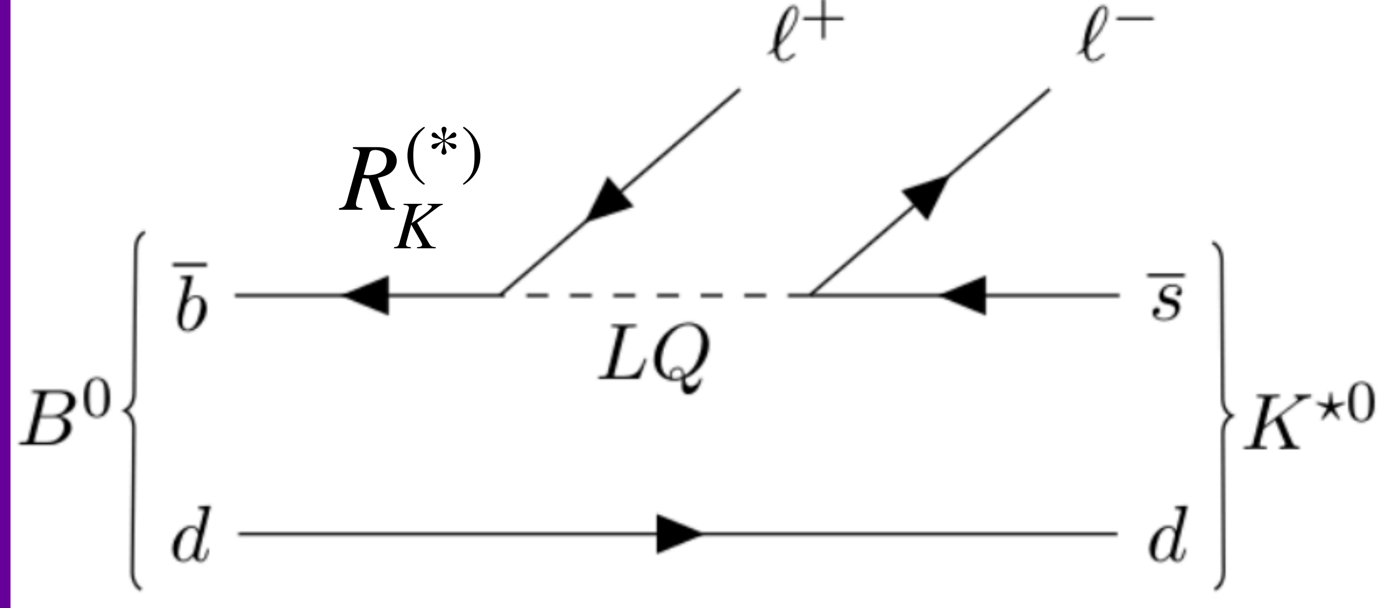
- Leptoquarks (LQs) introduced in BSM theories addressing various problems in the SM
  - $b \to s\ell\ell$, $b \to c\ell\nu$, $(g-2)_\mu$, neutrino masses, …
- Can be scalars or vectors
- Carry colour, electrical charges, baryon & lepton numbers
- Historically, couplings within one generation ("$\mathrm{LQ}_{1/2/3}$") as direct connection between quark and lepton sector
- Allow mixing between generations to explain flavour anomalies ("LQ_{mix}")

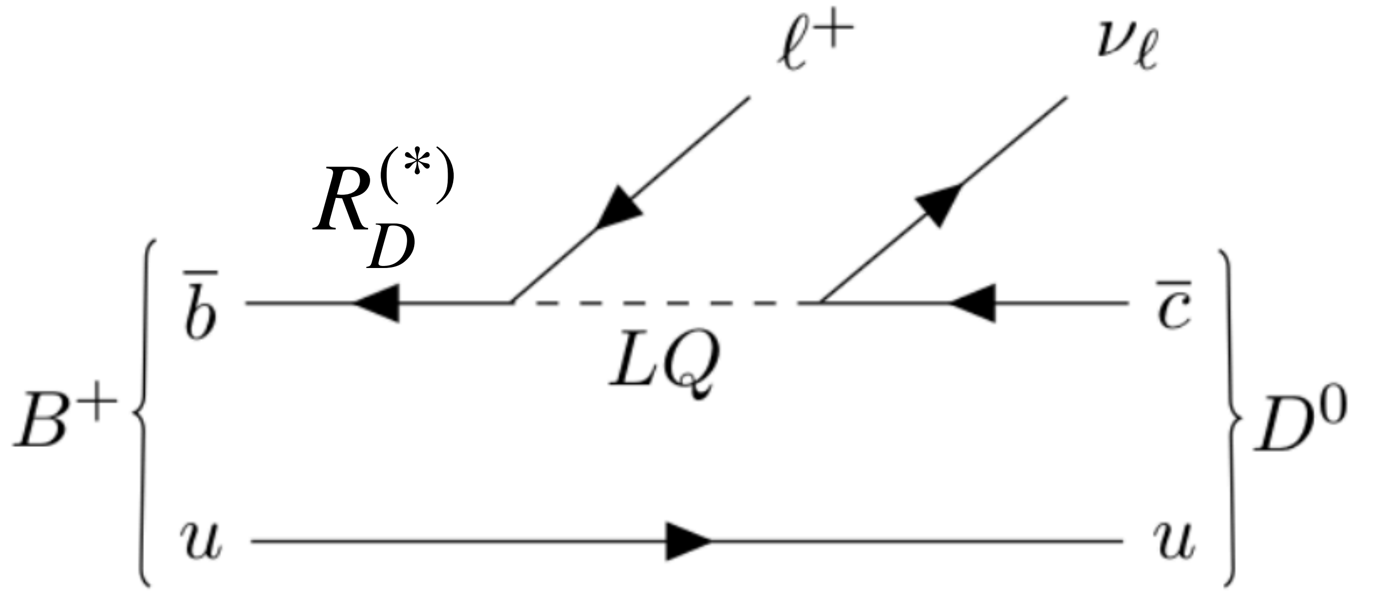


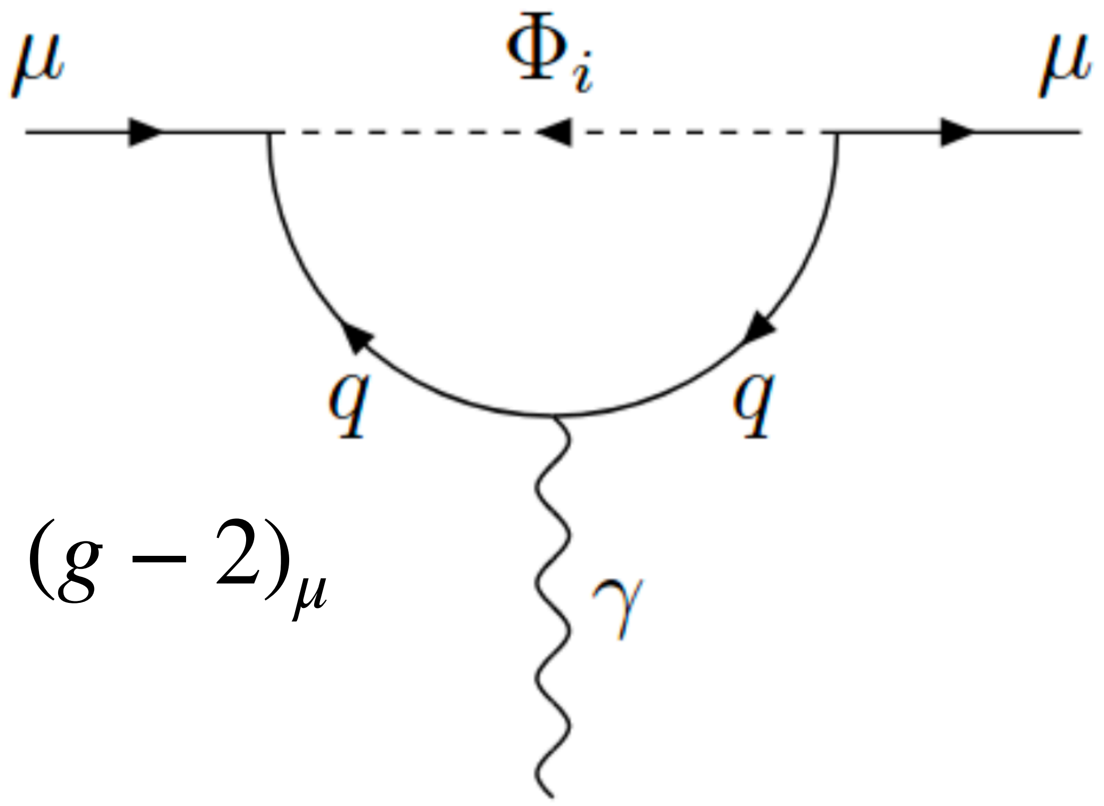




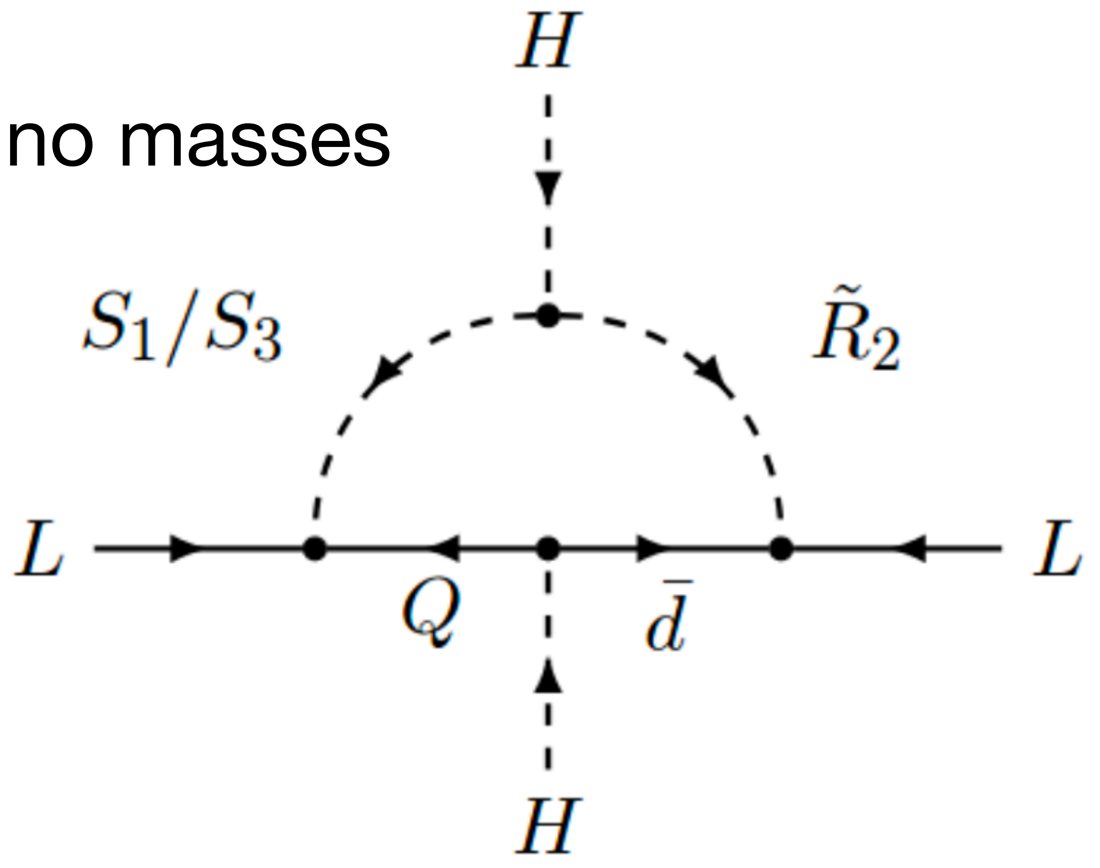
Short-lived excitement in the '90s about apparent excesses at HERA, but alas …







Neutrino masses



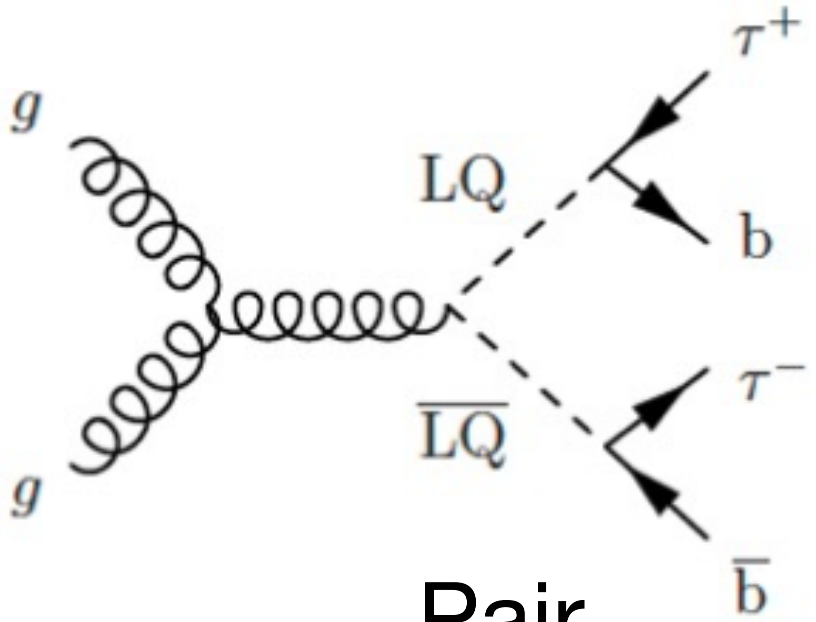
Production and Decay

- LQs produced at the LHC via pair, single, or non-resonant production
- Pair production production cross-section independent of coupling λ
- Single and non-resonant production dominant for large λ at high masses

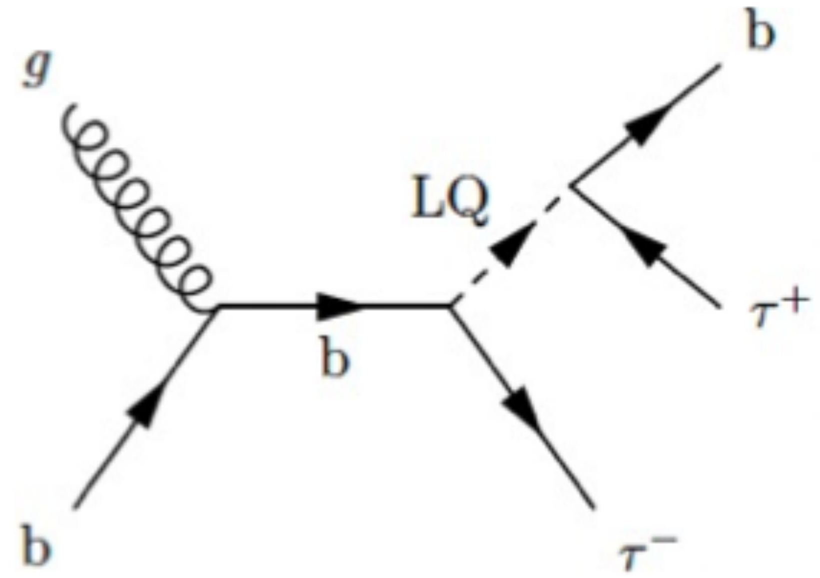
- Vector LQ pair-production cross-sections larger than scalar
- Small differences in kinematics between vector and scalar LQs

- Decays into quarks and charged or uncharged leptons
  - Assume $\mathcal{B}(\mathrm{LQ} \to q_i \ell) = 1 - \mathcal{B}(\mathrm{LQ} \to q_i' \nu)$

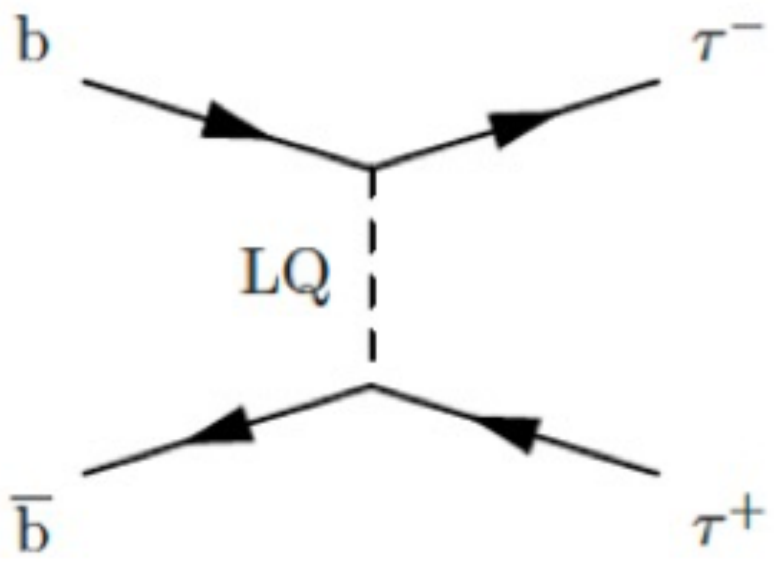
Production Modes



Pair

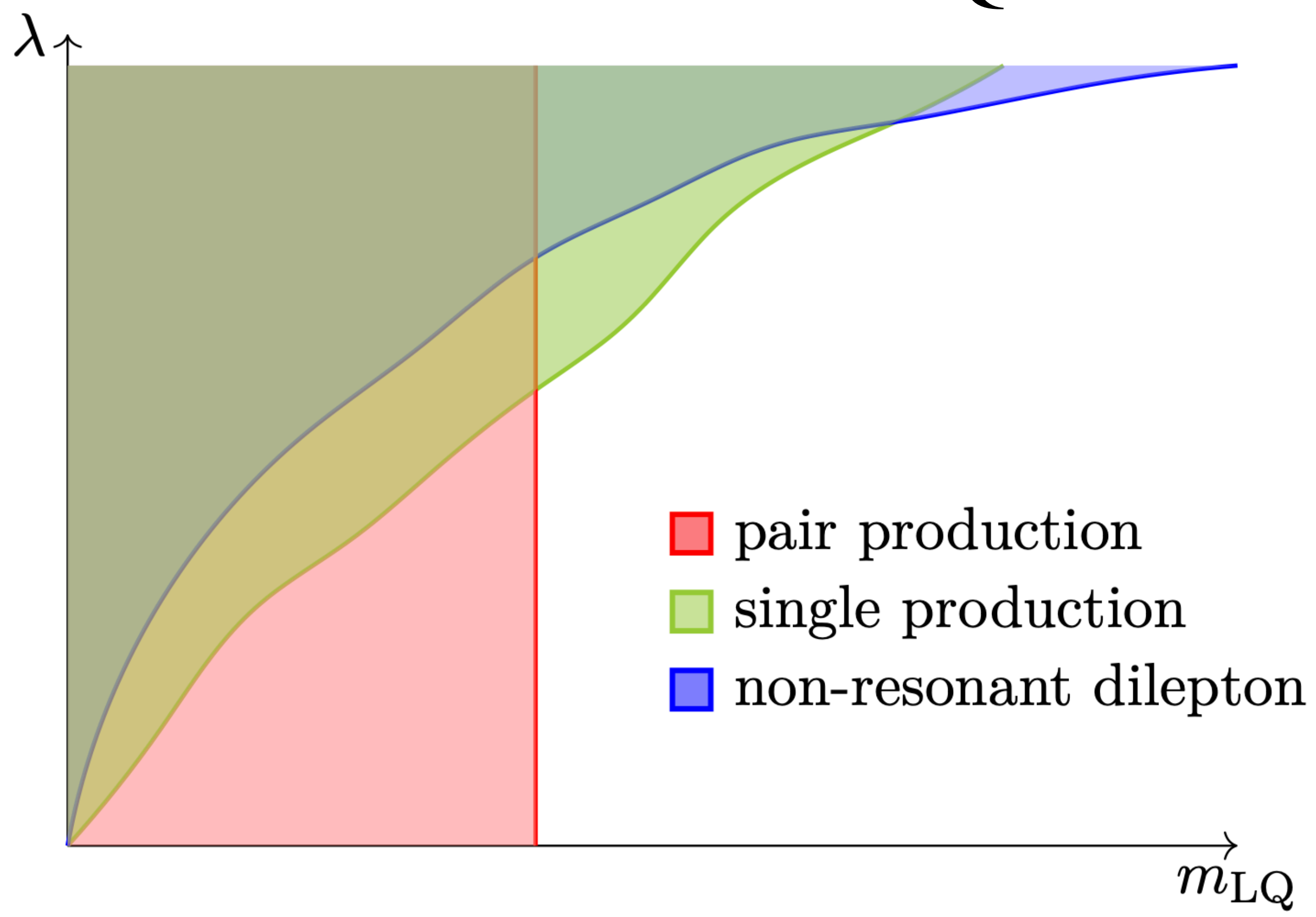


Single (σ~λ^2)

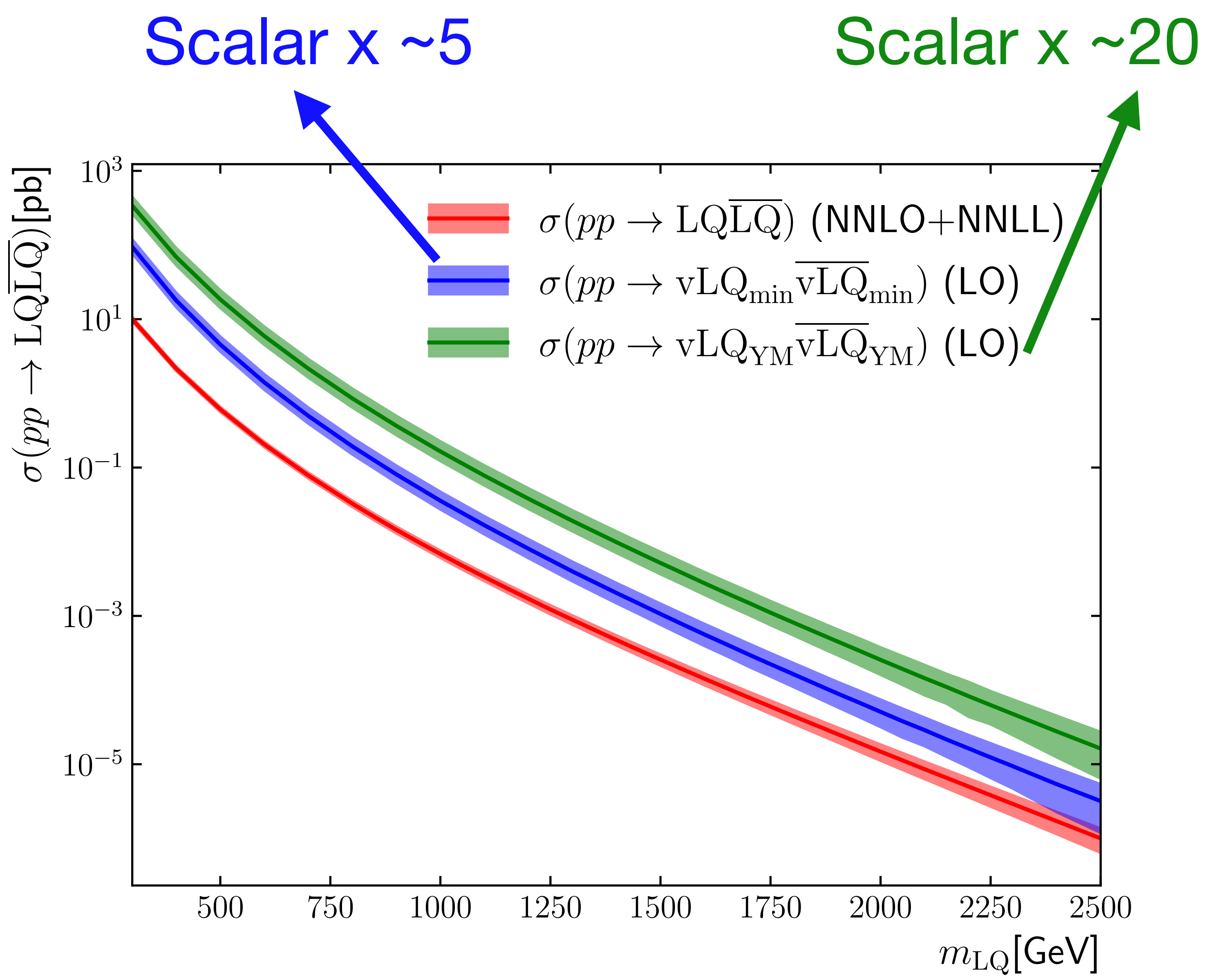


Non-resonant (σ~λ^4)

σ only depends on m_{LQ}



Two coupling scenarios for vector LQs:
- Minimal coupling ($\mathrm{vLQ_{min}}$)
- Yang-Mills coupling ($\mathrm{vLQ_{YM}}$)

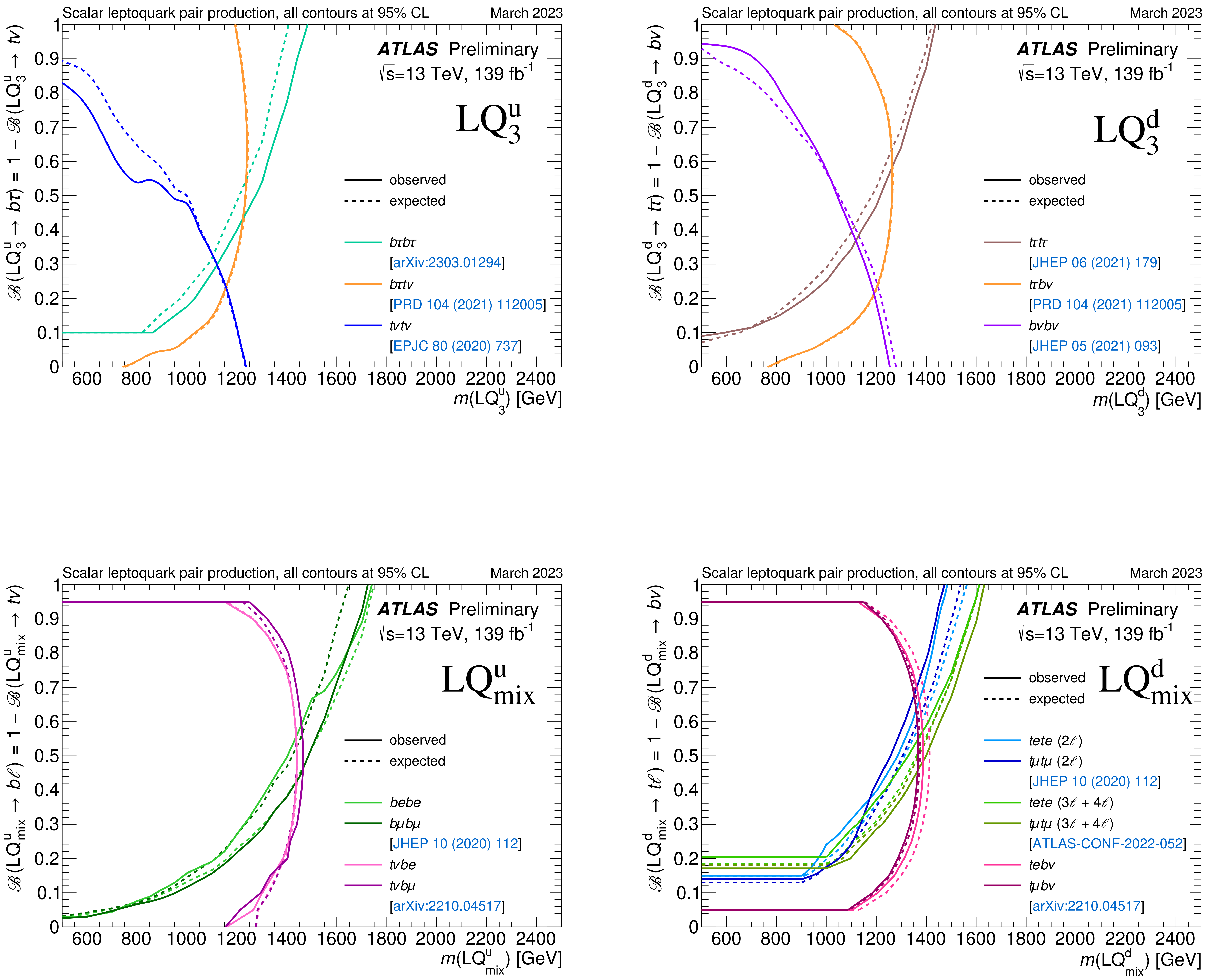


LQ Searches @ ATLAS

- Extensive search programme for pair-produced LQs
  - Wide range of final states
  - Focus on couplings to 3rd gen. quarks

	b	t
$\nu\nu$	JHEP 05 (2021) 093	Eur. Phys. J. C 80 (2020) 737
$\ell\nu$	arXiv:2210.04517 (accepted by JHEP)	
$\ell\ell$	JHEP 10 (2020) 112	Eur. Phys. J. C 81 (2021) 313 (2l) ATLAS-CONF-2022-53 (3l+4l)
$\tau\nu$	Phys. Rev. D 104 (2021) 112005	
$\tau\tau$	EXOT-2021-015	JHEP 06 (2021) 179

  - But also results with couplings to light quarks available
- Growing programme of searches for singly-produced LQs



ATL-PHYS-PUB-2023-006

LQ Searches @ ATLAS

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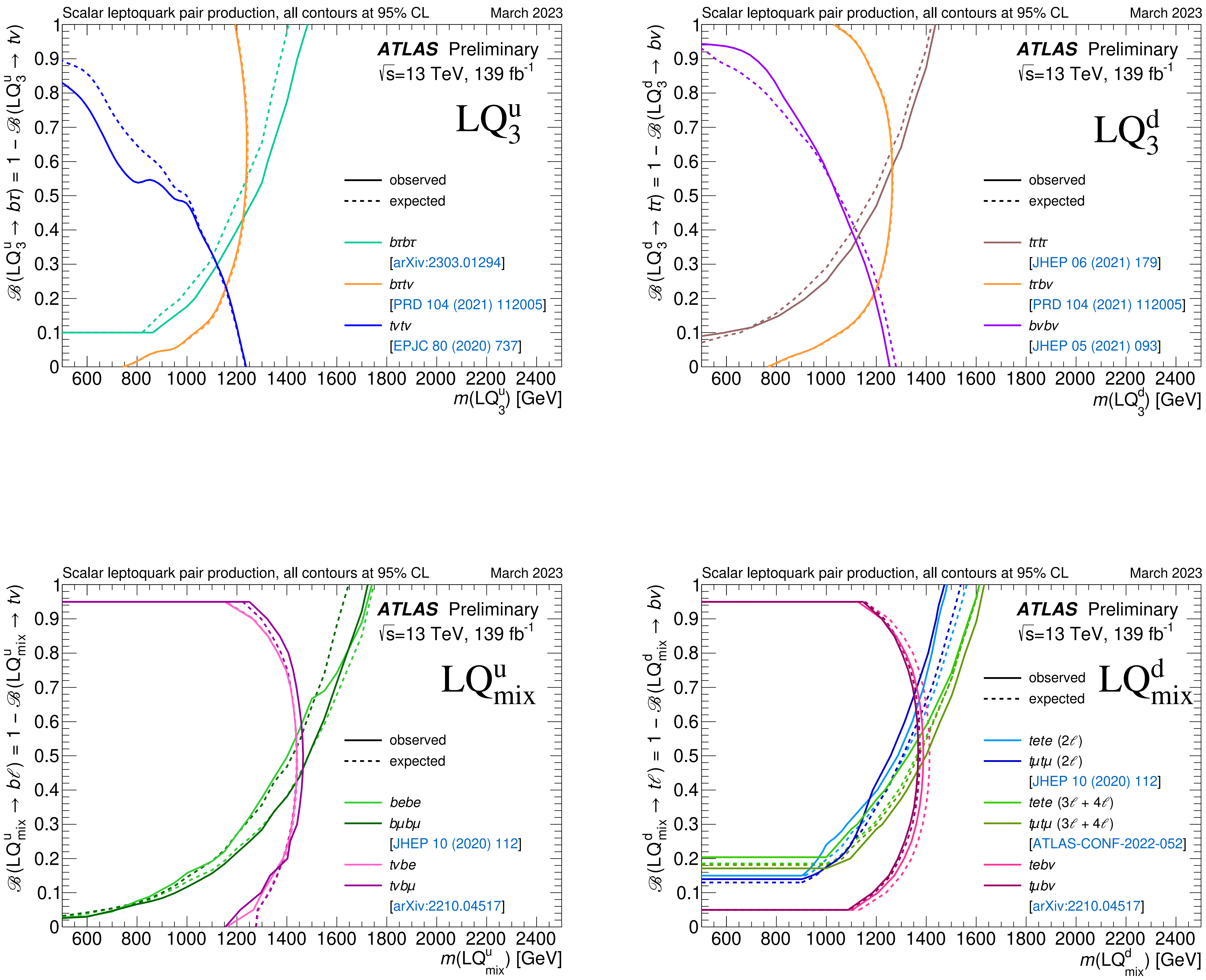
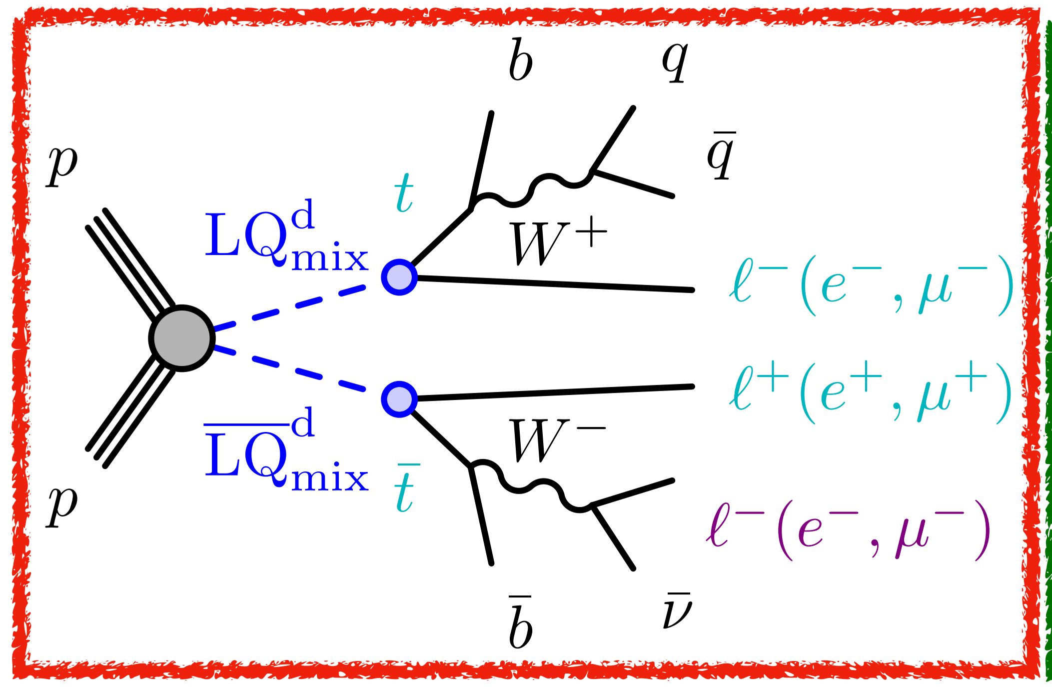
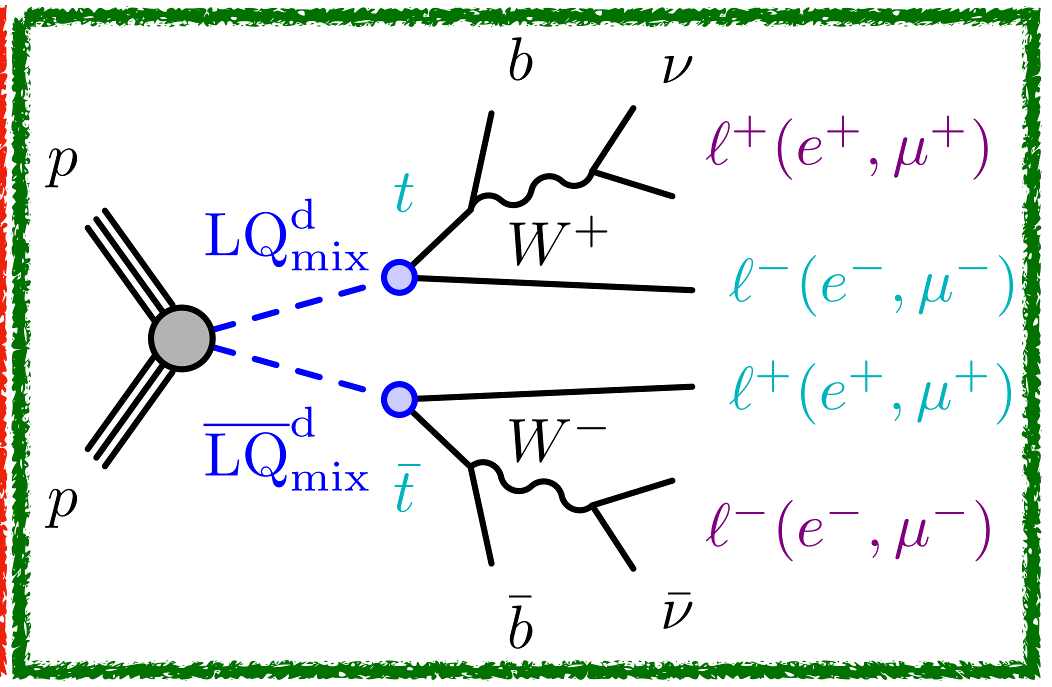


ATL-PHYS-PUB-2023-006

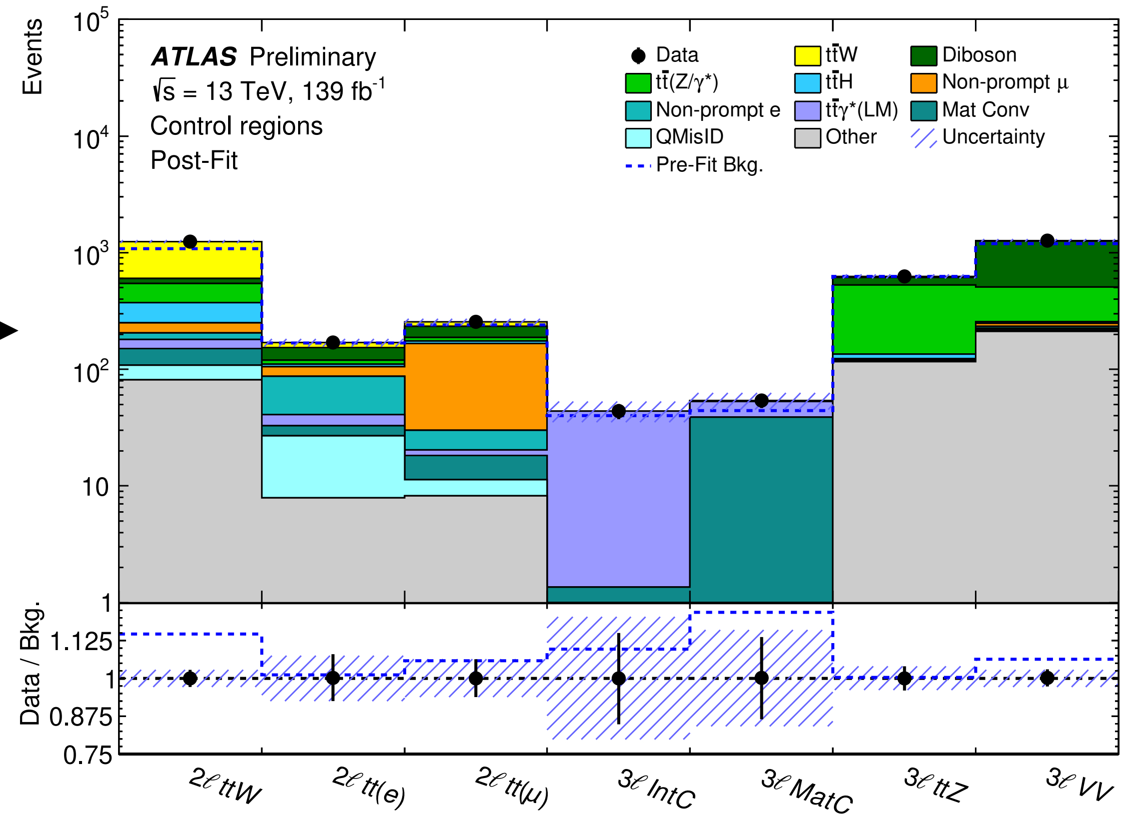
$\mathbf{LQ\,LQ \rightarrow t\ell\, t\ell}$ ($\ell = \mathbf{e}, \mu$) ATLAS-CONF-2022-052

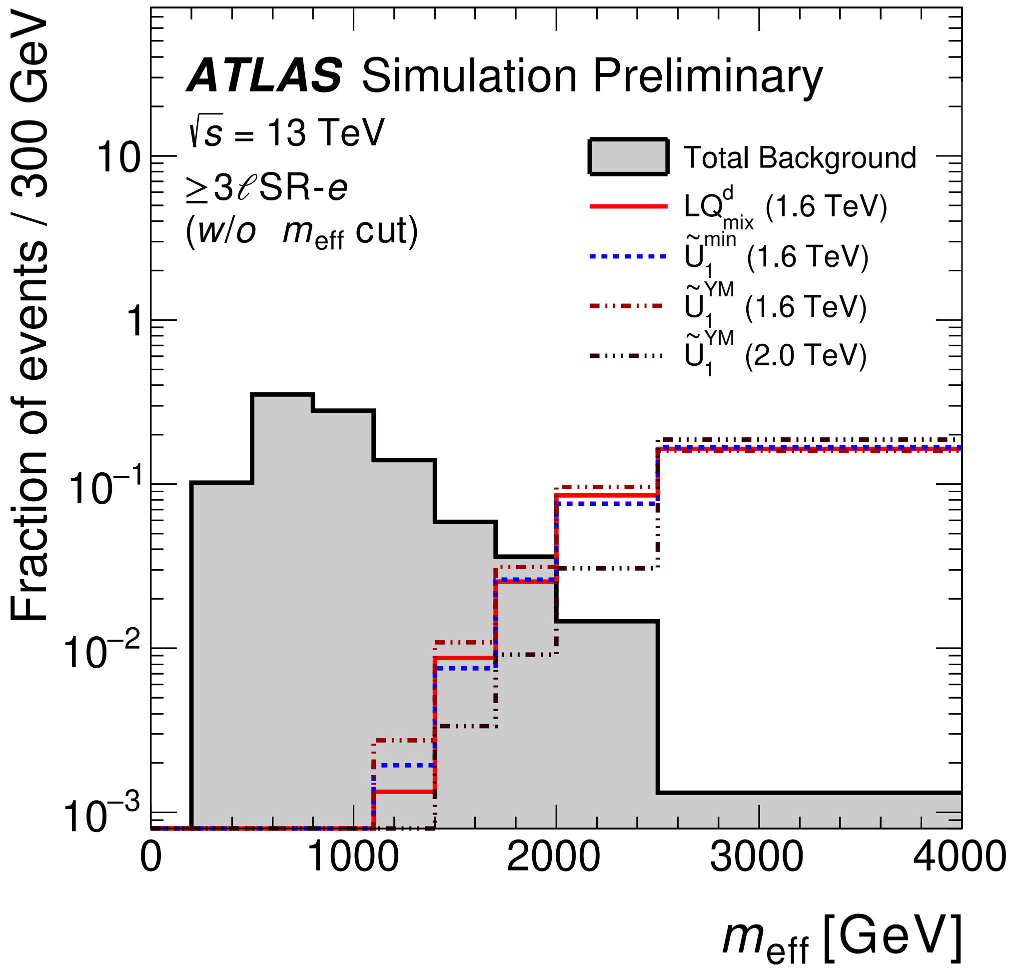




- Target pair-produced LQs with $\mathscr{B}(\mathrm{LQ} \rightarrow t\ell) = 1.0$
- Analysis strategy:
  - 3 or 4 light leptons, ≥2 jets, ≥1 b-jet
  - Two separate signal regions (3ℓ, 4ℓ) each for $tete/t\mu t\mu$ with $\min(m_{\ell\ell}) > 100$ GeV
  - Control and validation regions for main backgrounds (ttW, ttZ/γ^*, diboson) with $\min(m_{\ell\ell}) < 100$ GeV
  - Discriminating variable: $m_{\mathrm{eff}} = \sum_{\ell,\mathrm{jets}} p_{\mathrm{T}} + p_{\mathrm{T}}^{\mathrm{miss}}$

Good post-fit agreement in control regions and signal regions

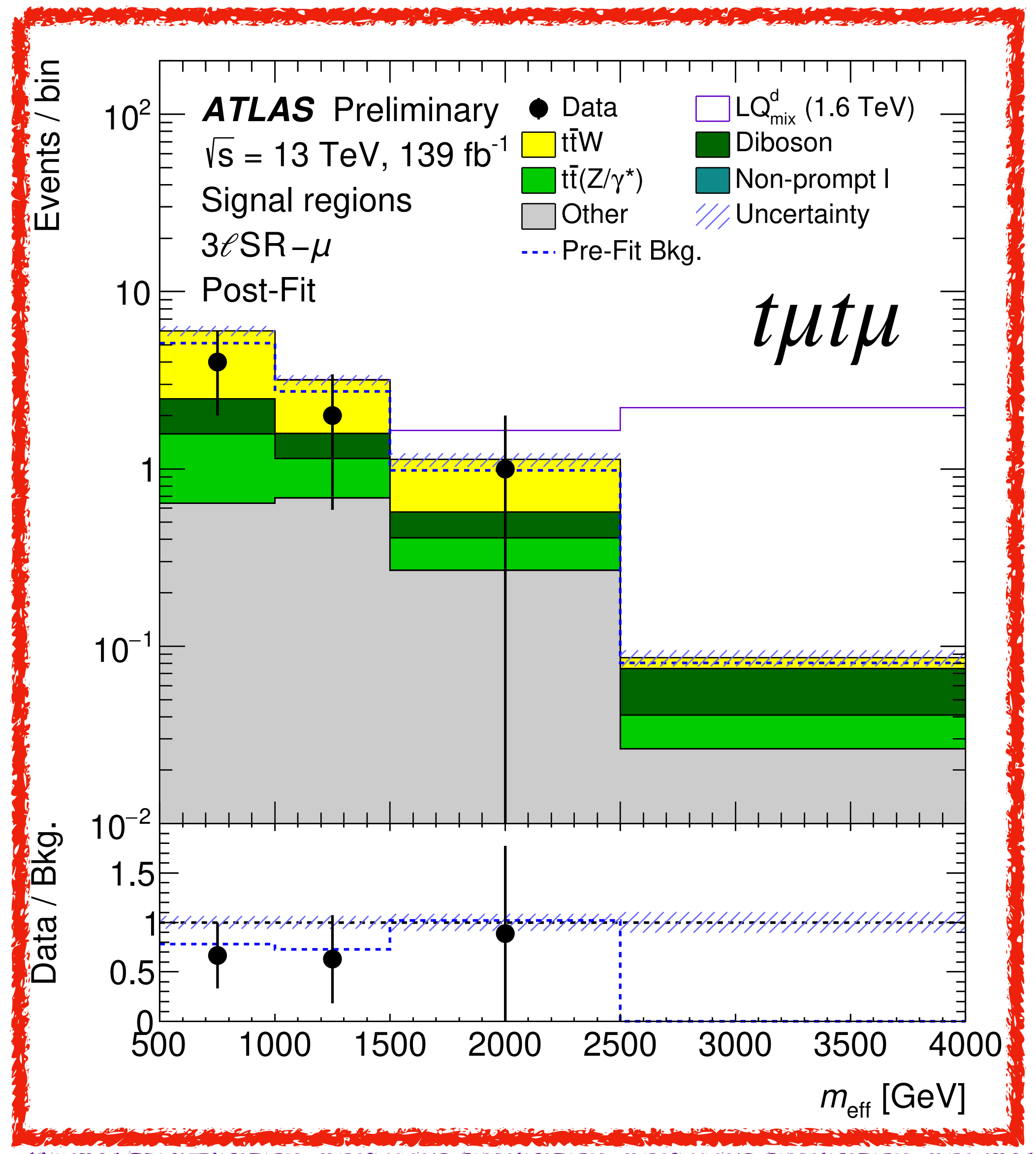


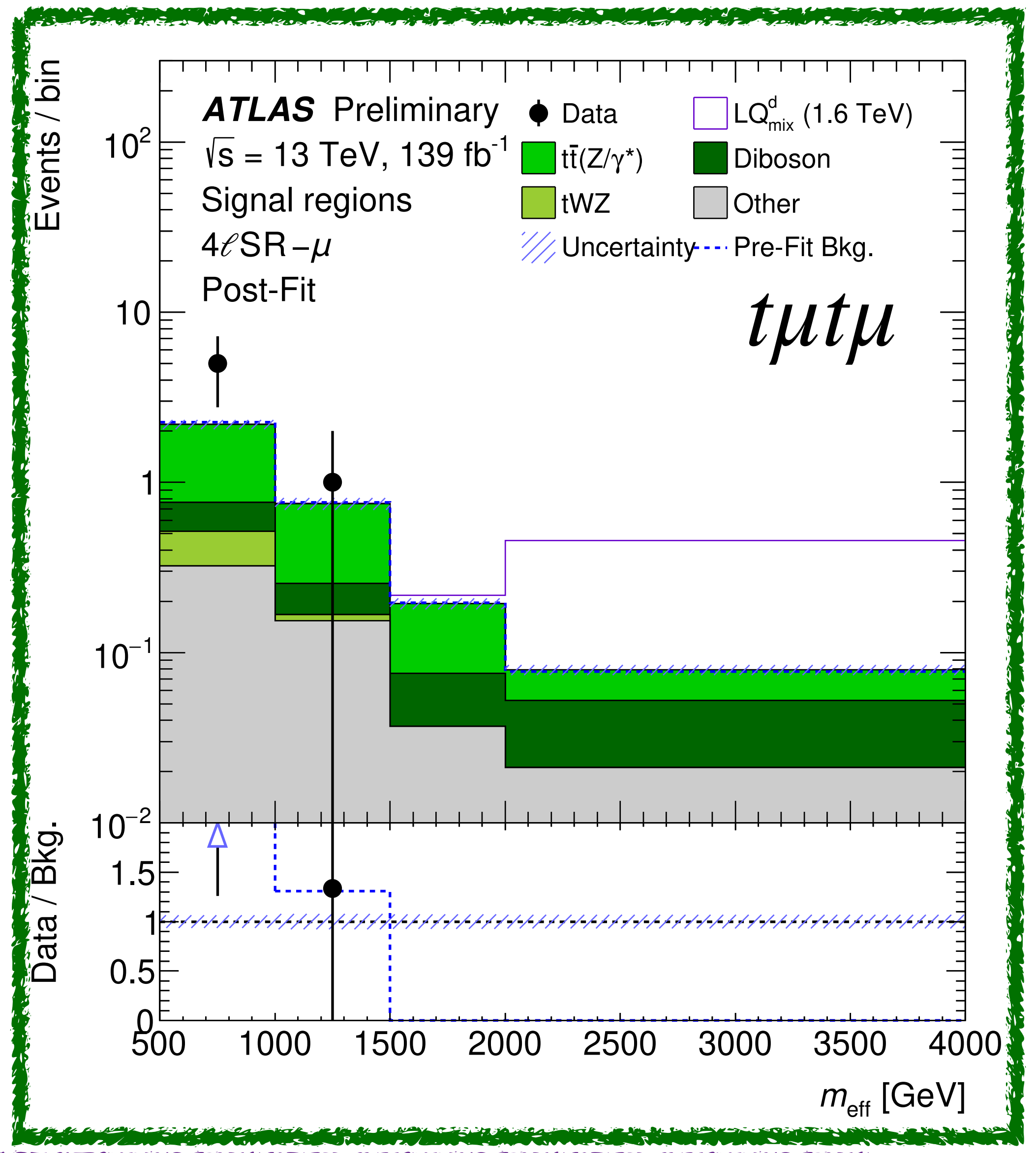


Backgrounds estimated from Monte Carlo (MC), except: electrons with misassigned charge (QMisID)

Data-driven corrections for:

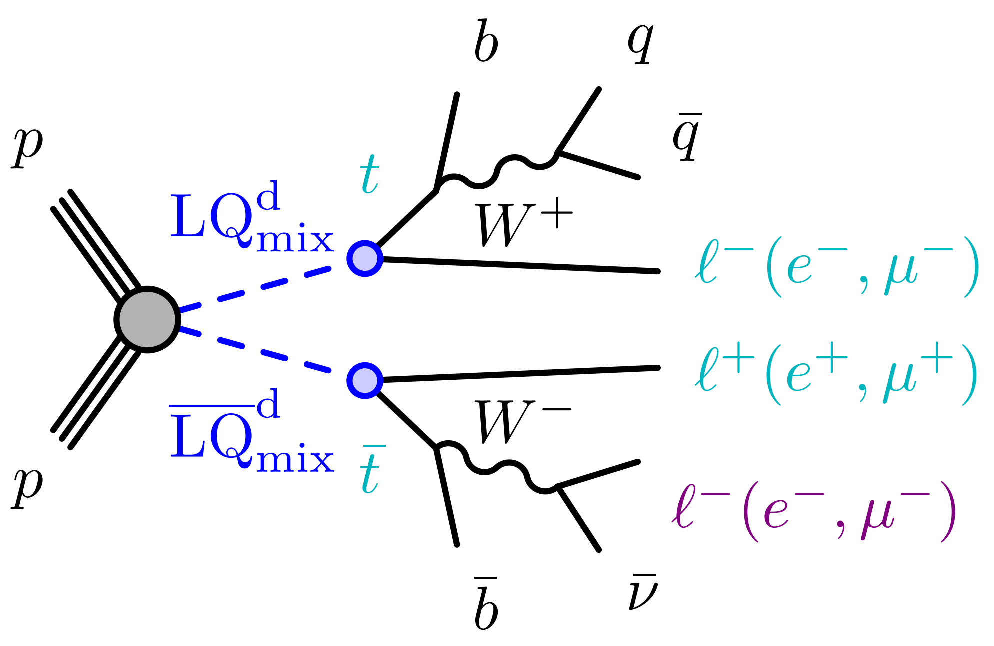
- Diboson as function of jet multiplicity
- Normalisation of $t\bar{t} + \mathrm{HF}$
- Non-prompt-lepton processes as a function of b-jet multiplicity

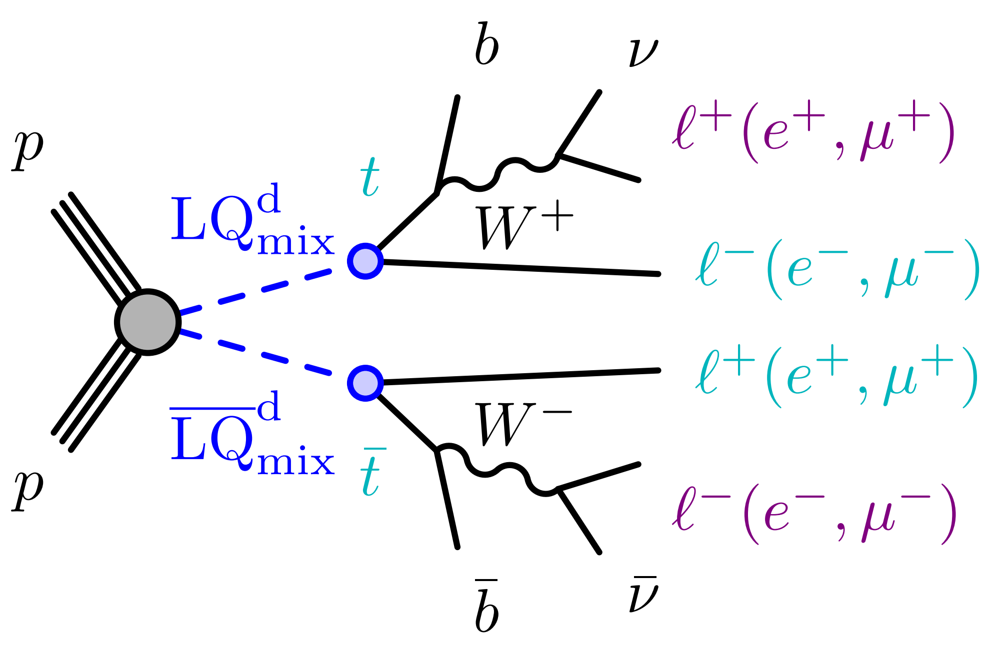




Good agreement between data and SM expectation

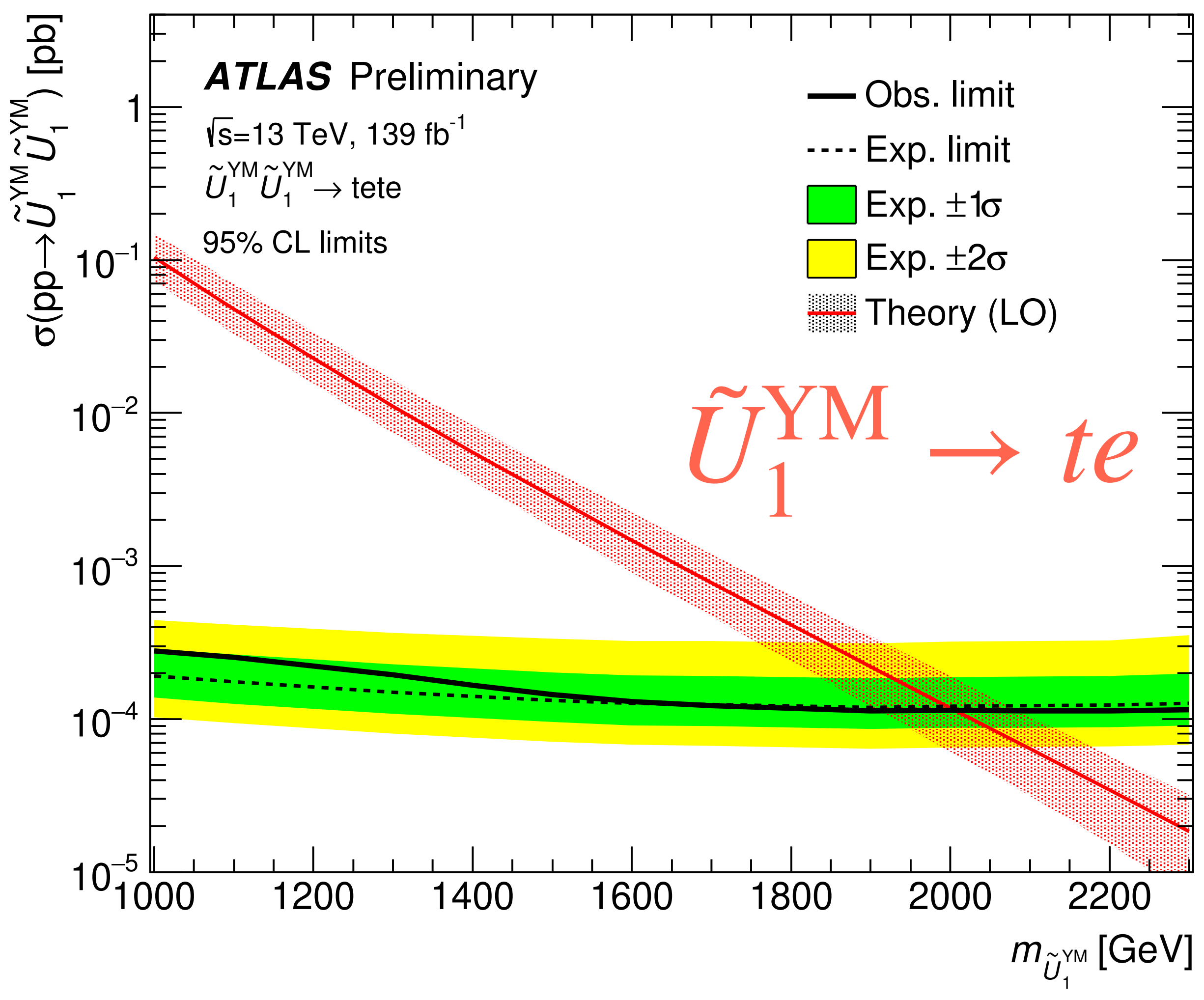
$\mathrm{LQ\,LQ} \to t\ell\, t\ell\ \ (\ell = e, \mu)$ ATLAS-CONF-2022-052

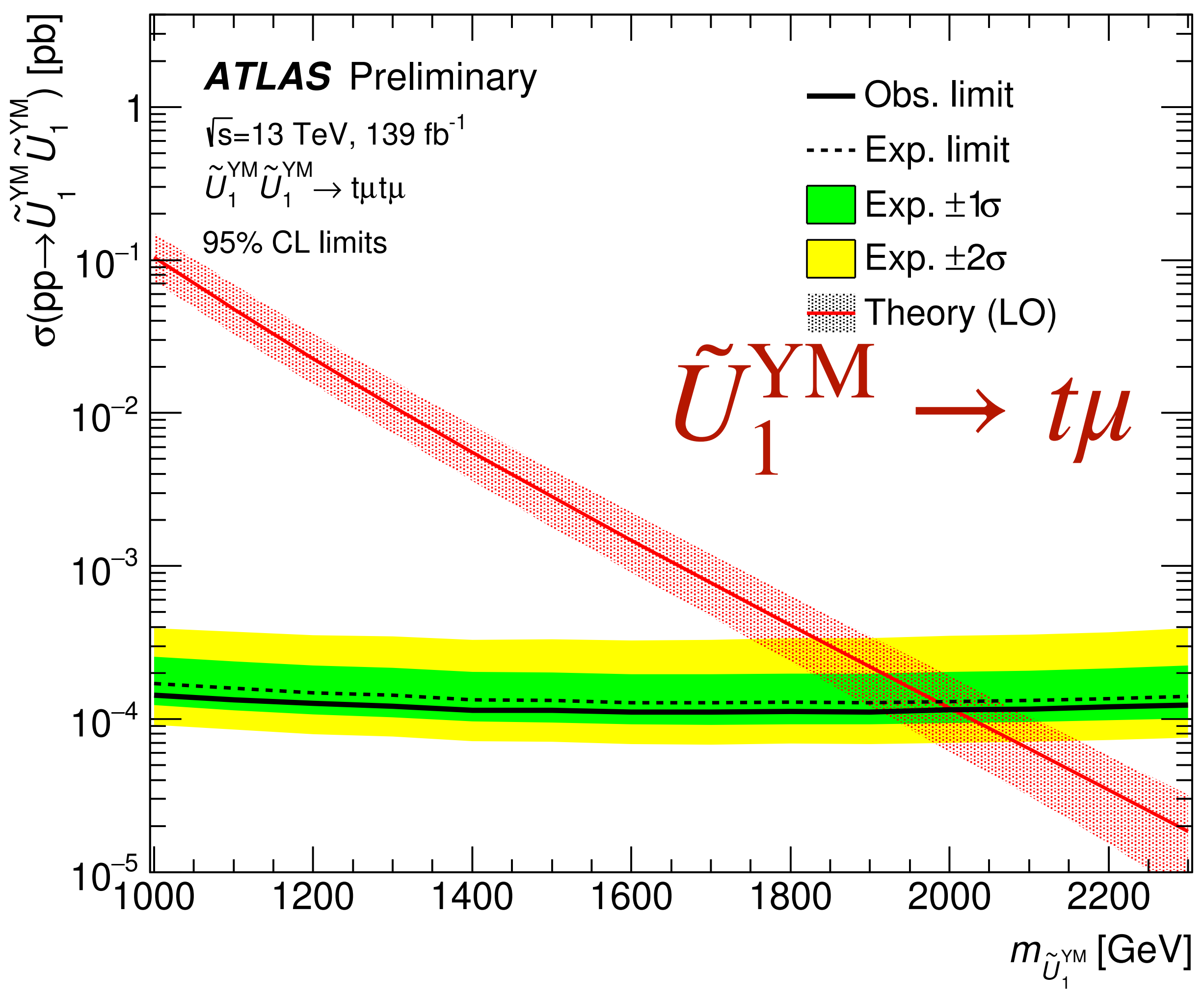


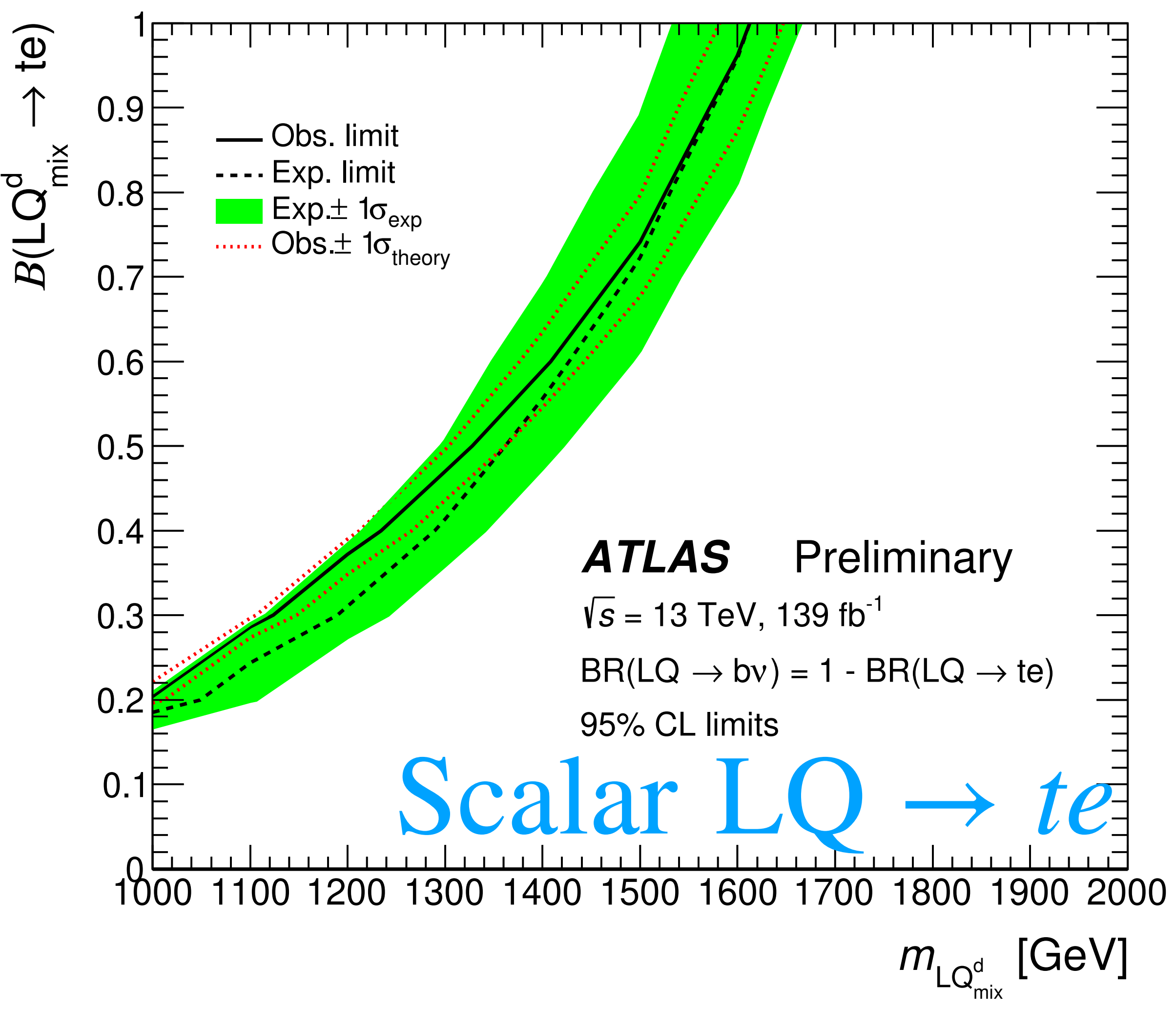


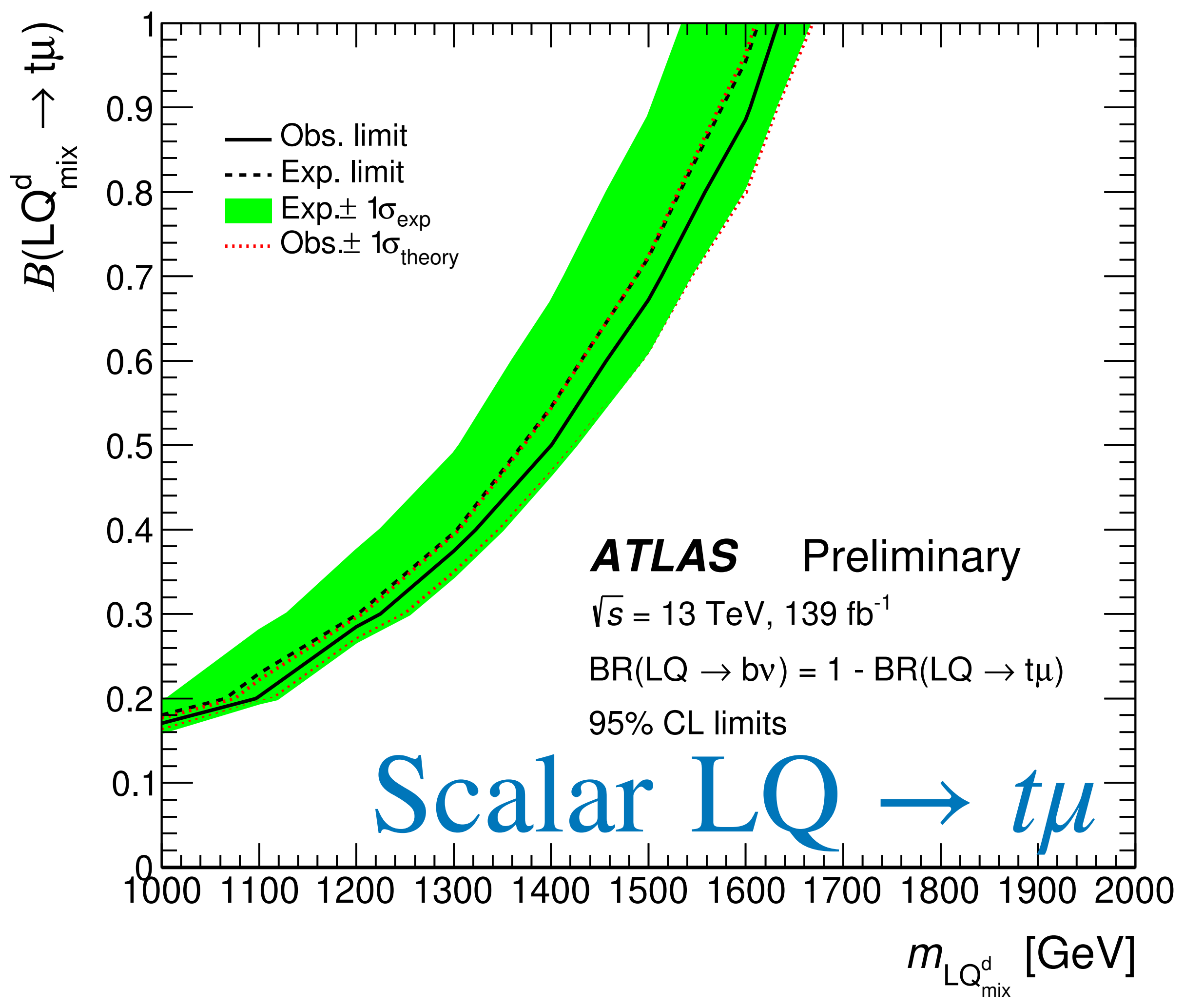
- Observed 95% CL limits at $\mathscr{B}(\mathrm{LQ} \to t\ell) = 1.0$:

	$\mathscr{B}(\mathrm{LQ} \to te) = 1.0$	$\mathscr{B}(\mathrm{LQ} \to t\mu) = 1.0$
$\mathrm{LQ^d_{mix}}$	1.61 TeV	1.64 TeV
$\tilde{U}_1^{\mathrm{min}}$	1.71 TeV	1.73 TeV
$\tilde{U}_1^{\mathrm{YM}}$	2.0 TeV	2.0 TeV

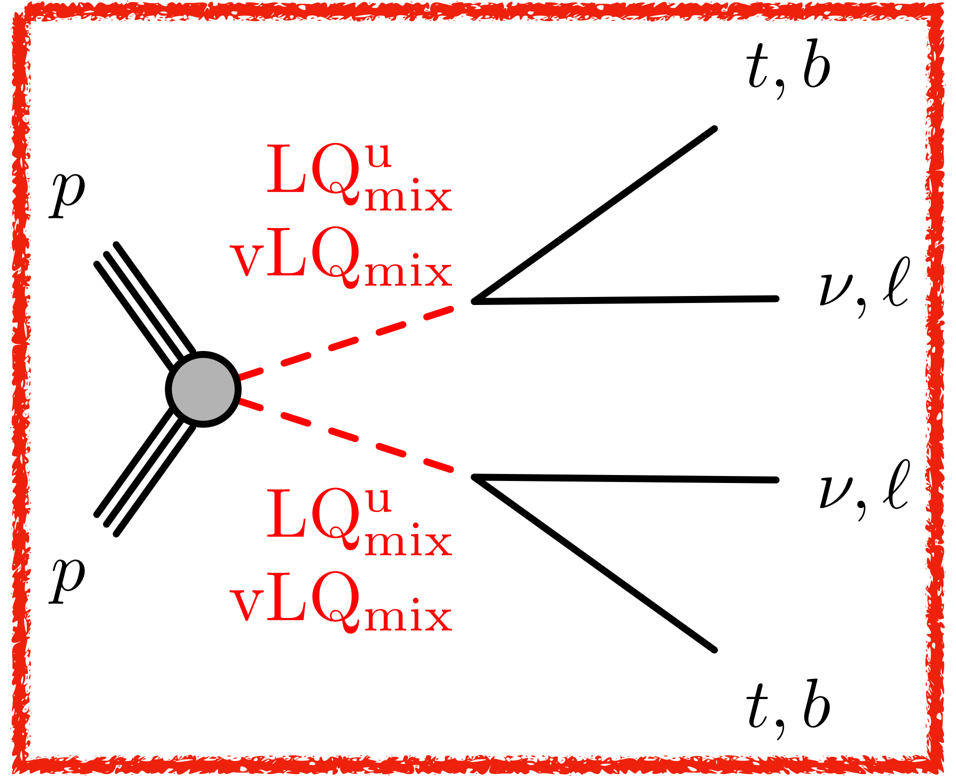


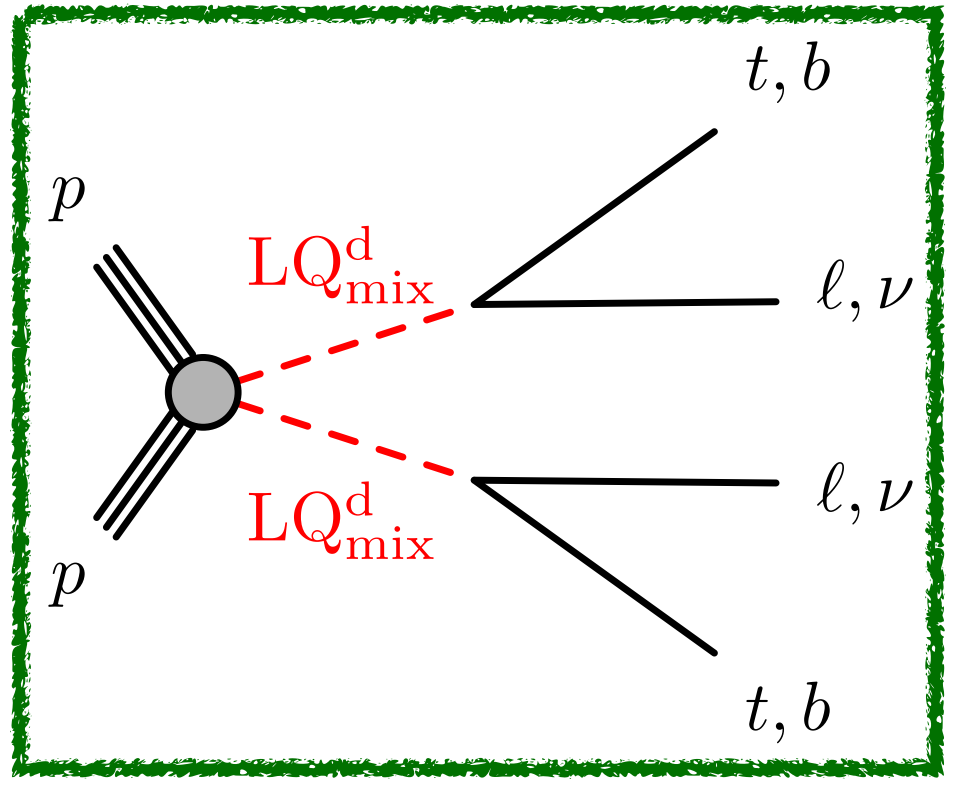






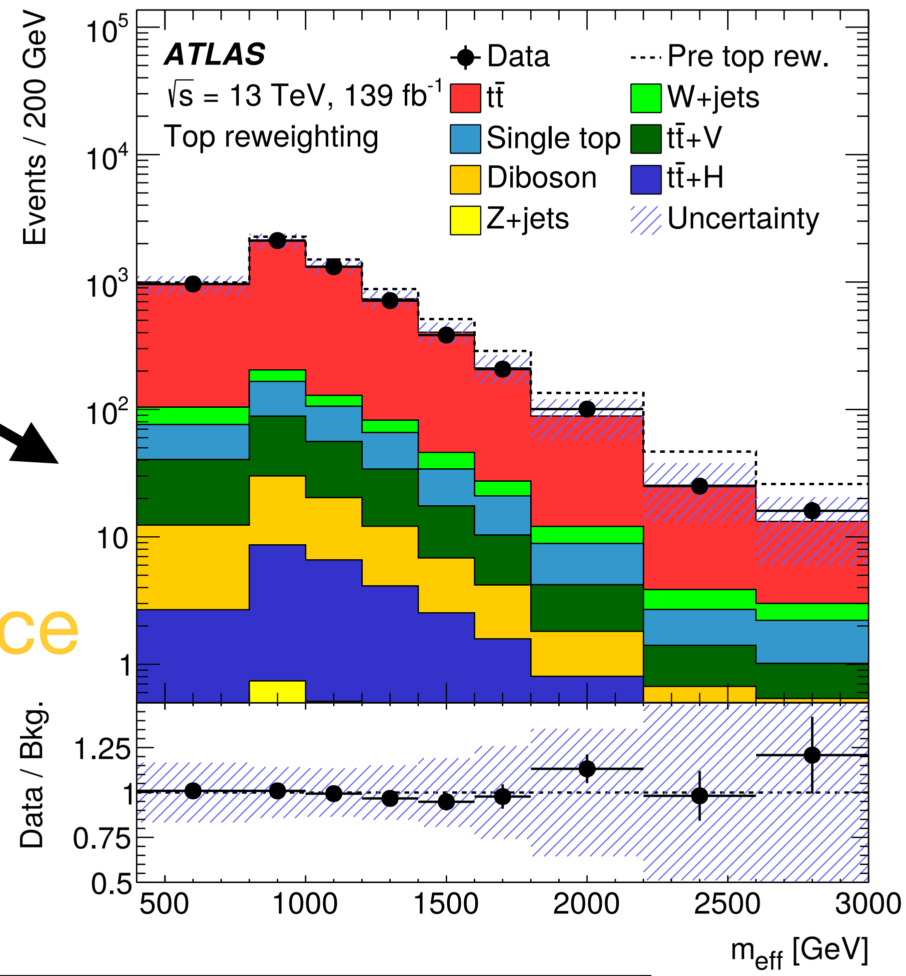
$\mathbf{LQ\,LQ \to t\nu\, b\ell}$ $(\ell = \mathbf{e}, \mu)$ EXOT-2019-12



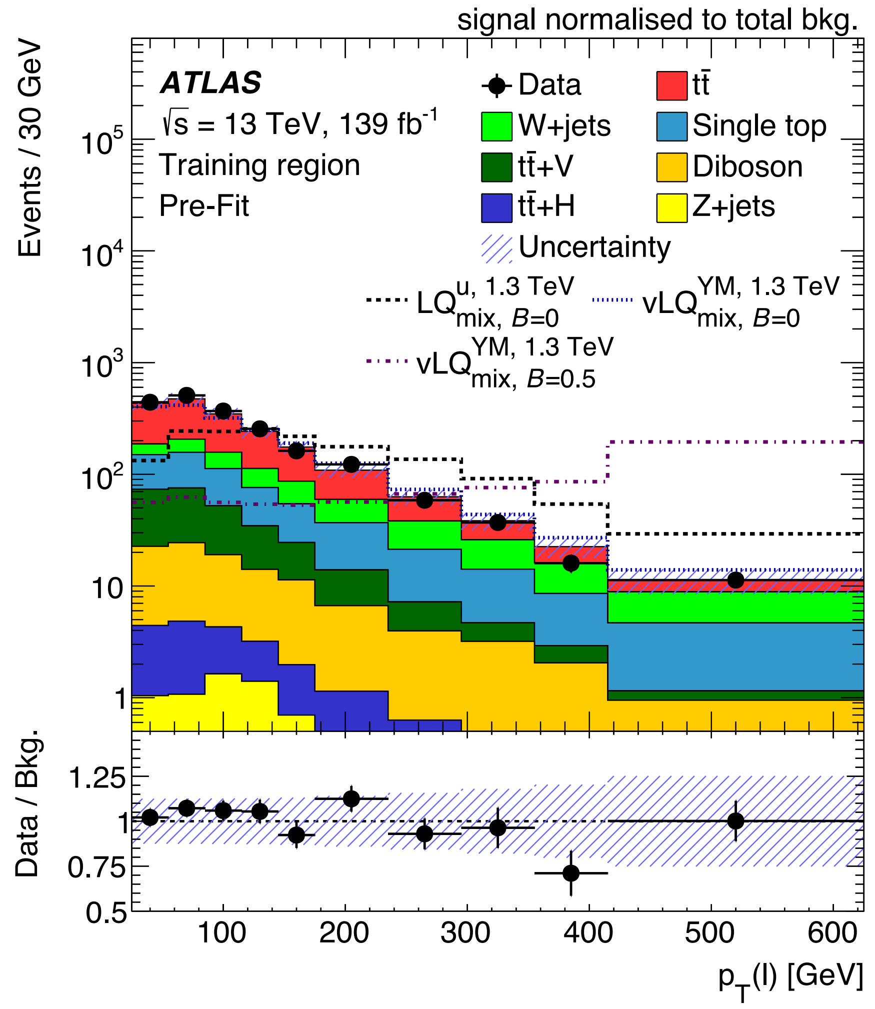


- Target pair-produced up- and down-type LQs with $\mathscr{B}(\mathrm{LQ} \to q_3\ell) = 0.5$
- Analysis strategy:
  - 1 light lepton, ≥2 jets, ≥1 b-jet, $p_{\mathrm{T}}^{\mathrm{miss}} \geq 250\mathrm{GeV}$
  - Train neural networks (NNs) for several signals (scalar/vector, up/down, $\mathscr{B}(\mathrm{LQ}^{\mathrm{u}}_{\mathrm{mix}} \to b\ell)$) in inclusive "training" region
  - NN score as discriminating variable
  - Normalisations of main backgrounds ($t\bar{t}$, single top, W+jets) constrained in dedicated control regions

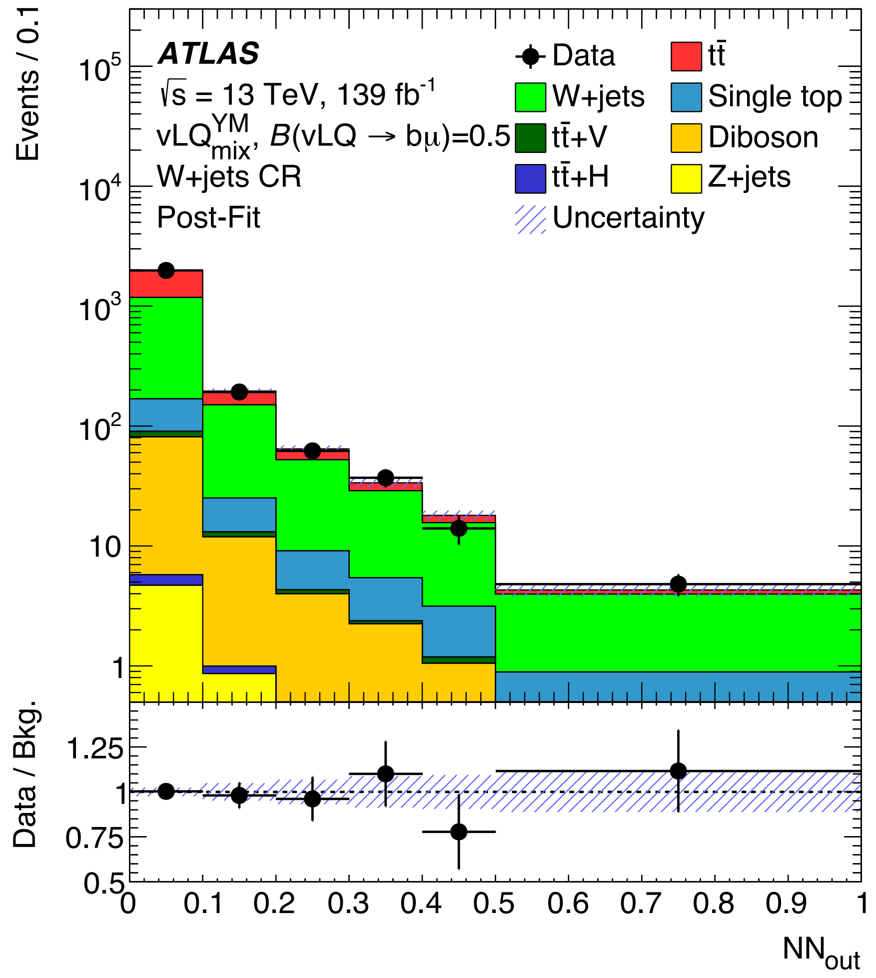
Mismodelling of high-p_{T} top quarks → data-driven correction of $t\bar{t}$ and single top backgrounds

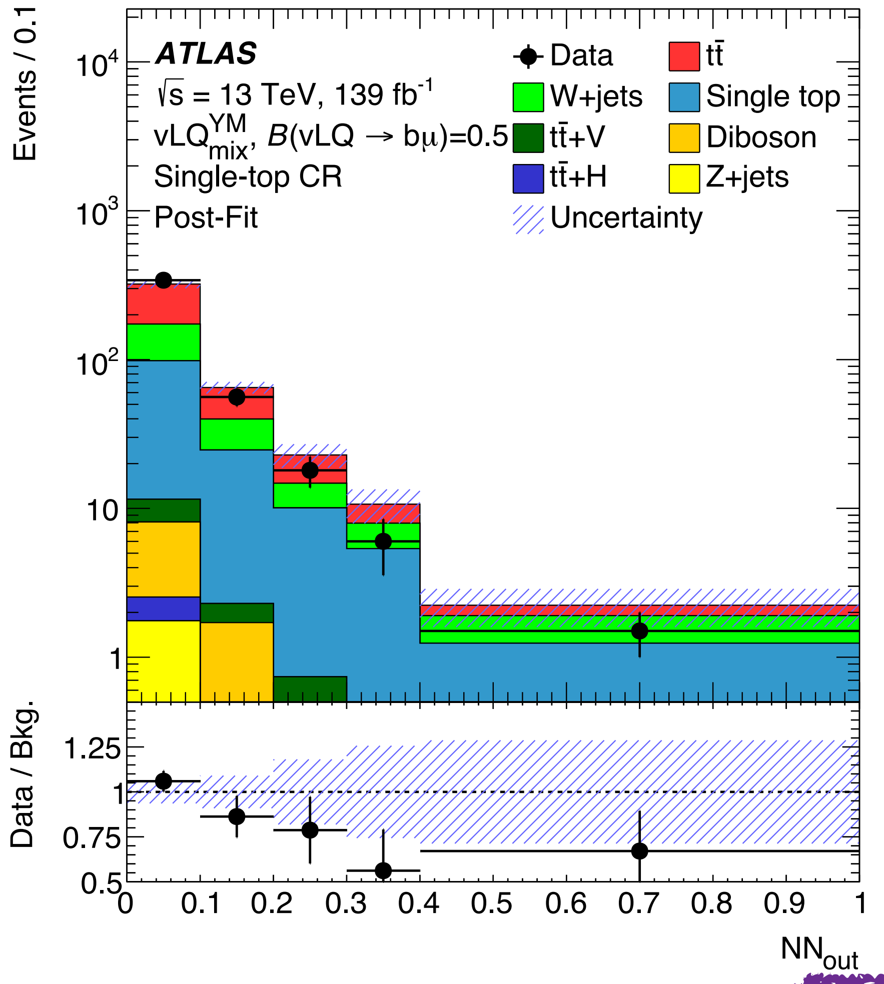


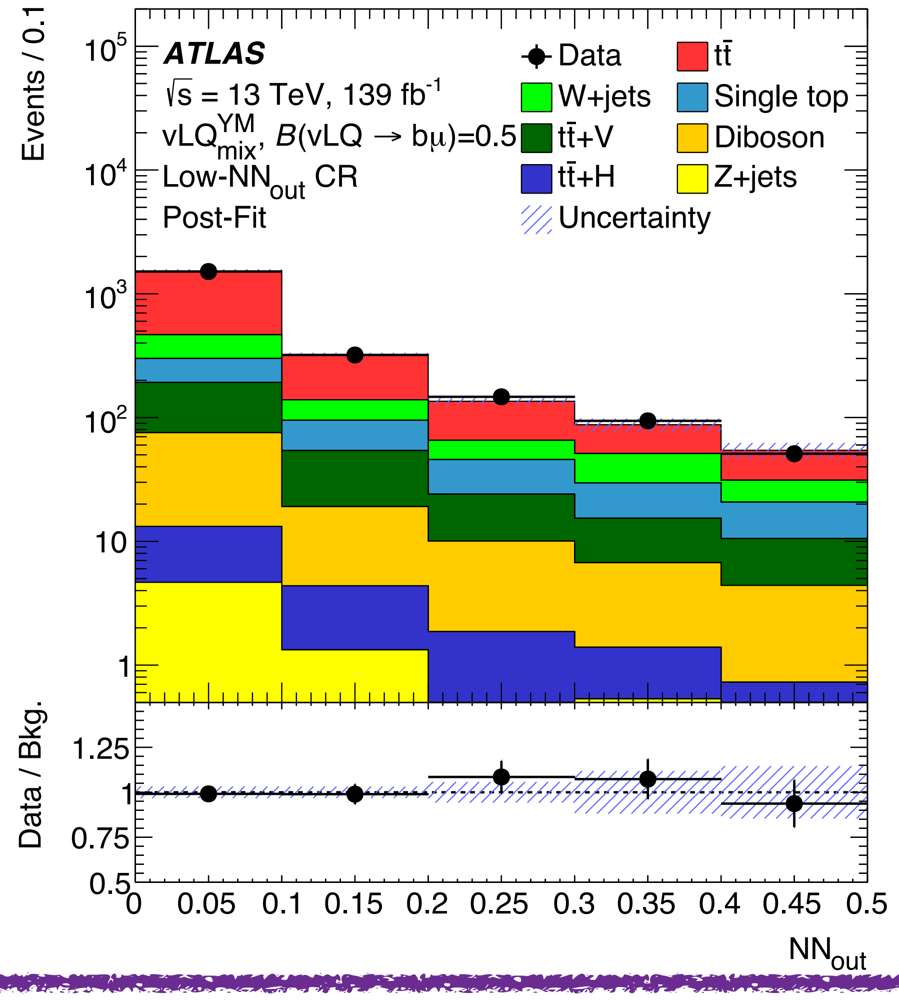
Post-fit disagreements due to known modelling issue of $t\bar{t} - tWb$ interference

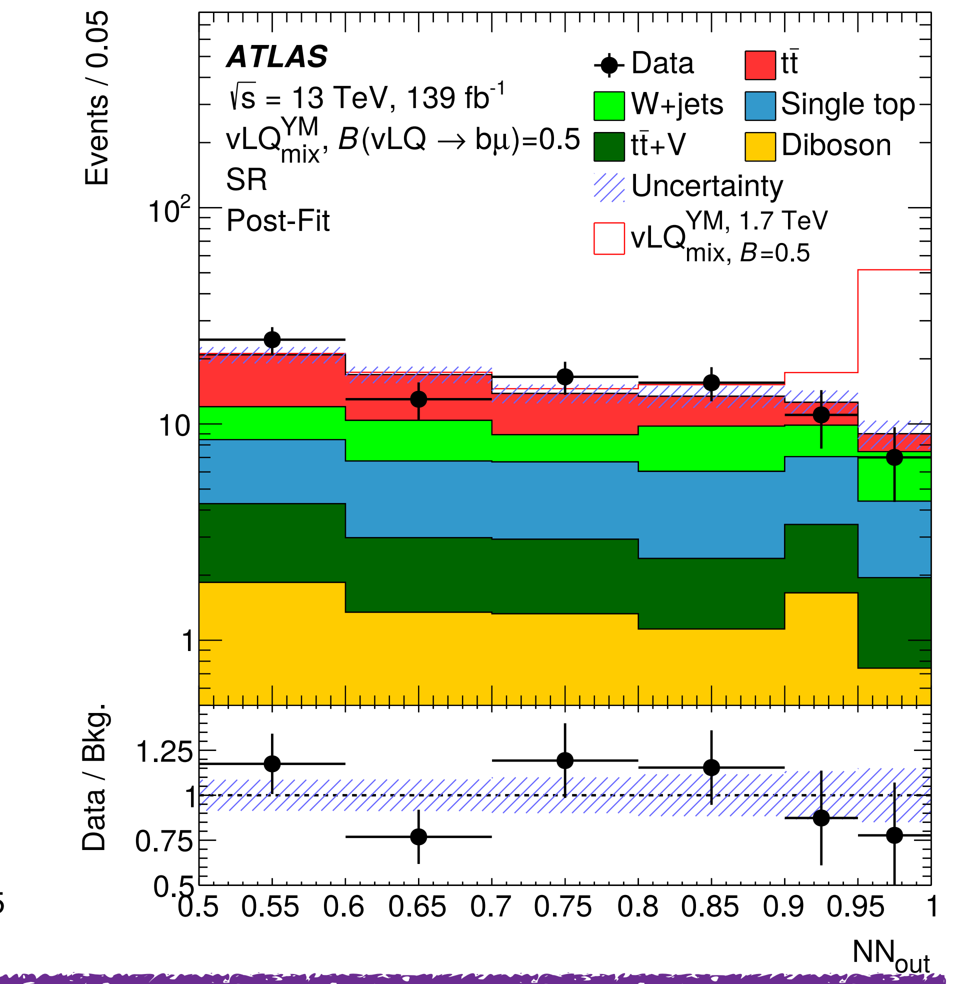


Set of ~15 input variables for NN, depending on signal hypothesis



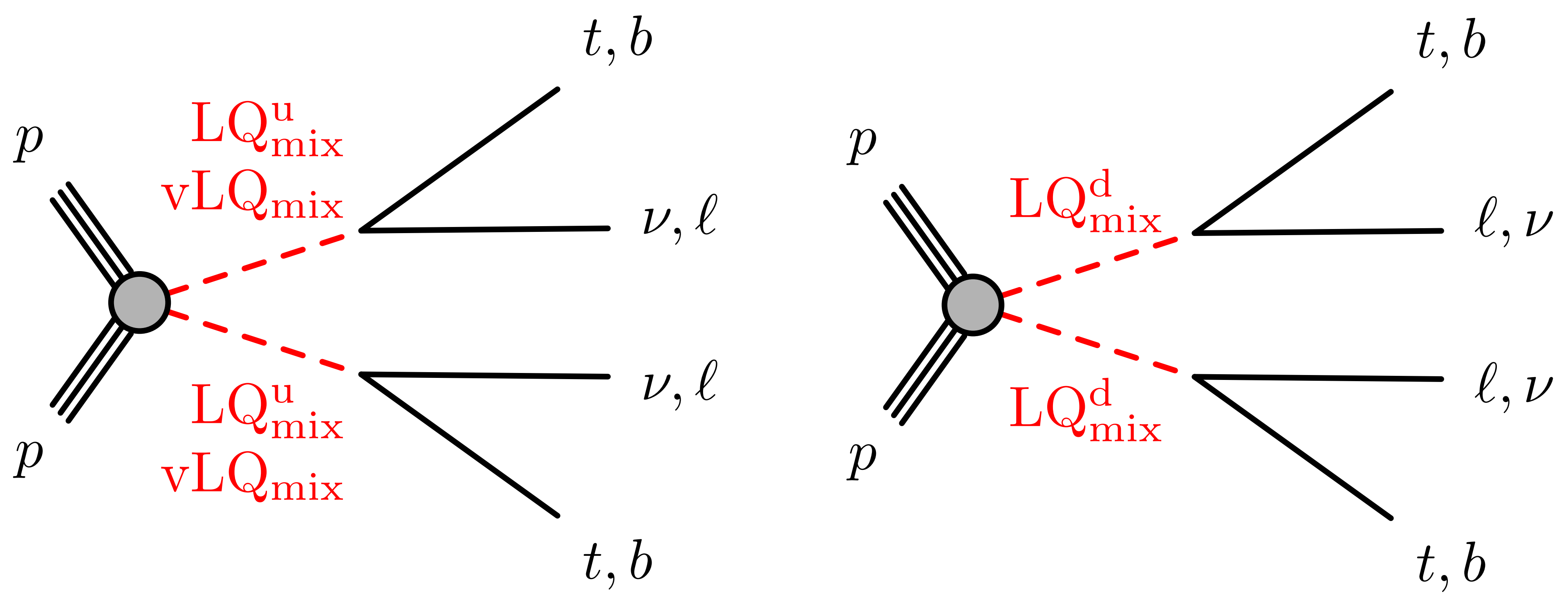






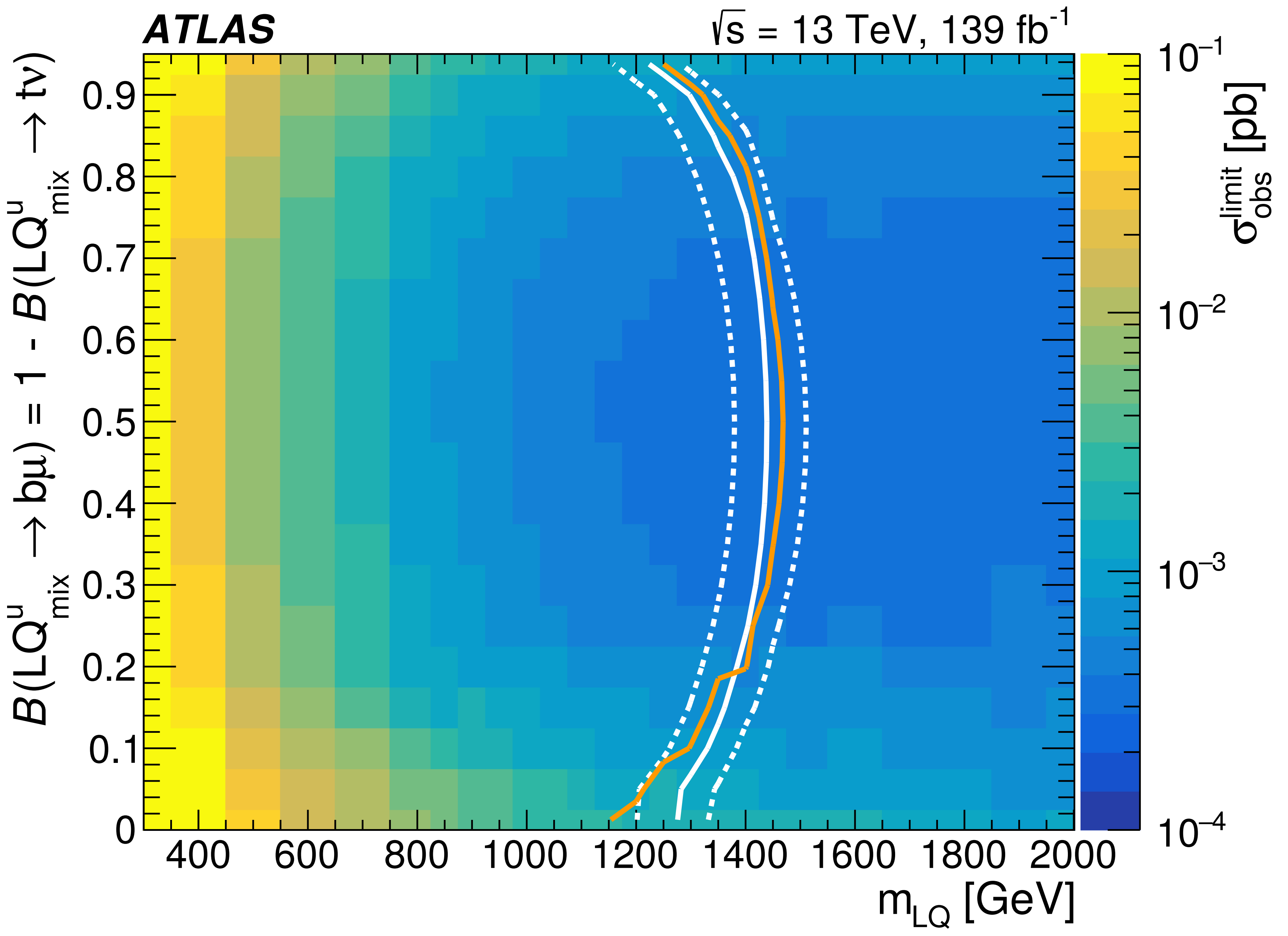
Good agreement between data and SM expectation

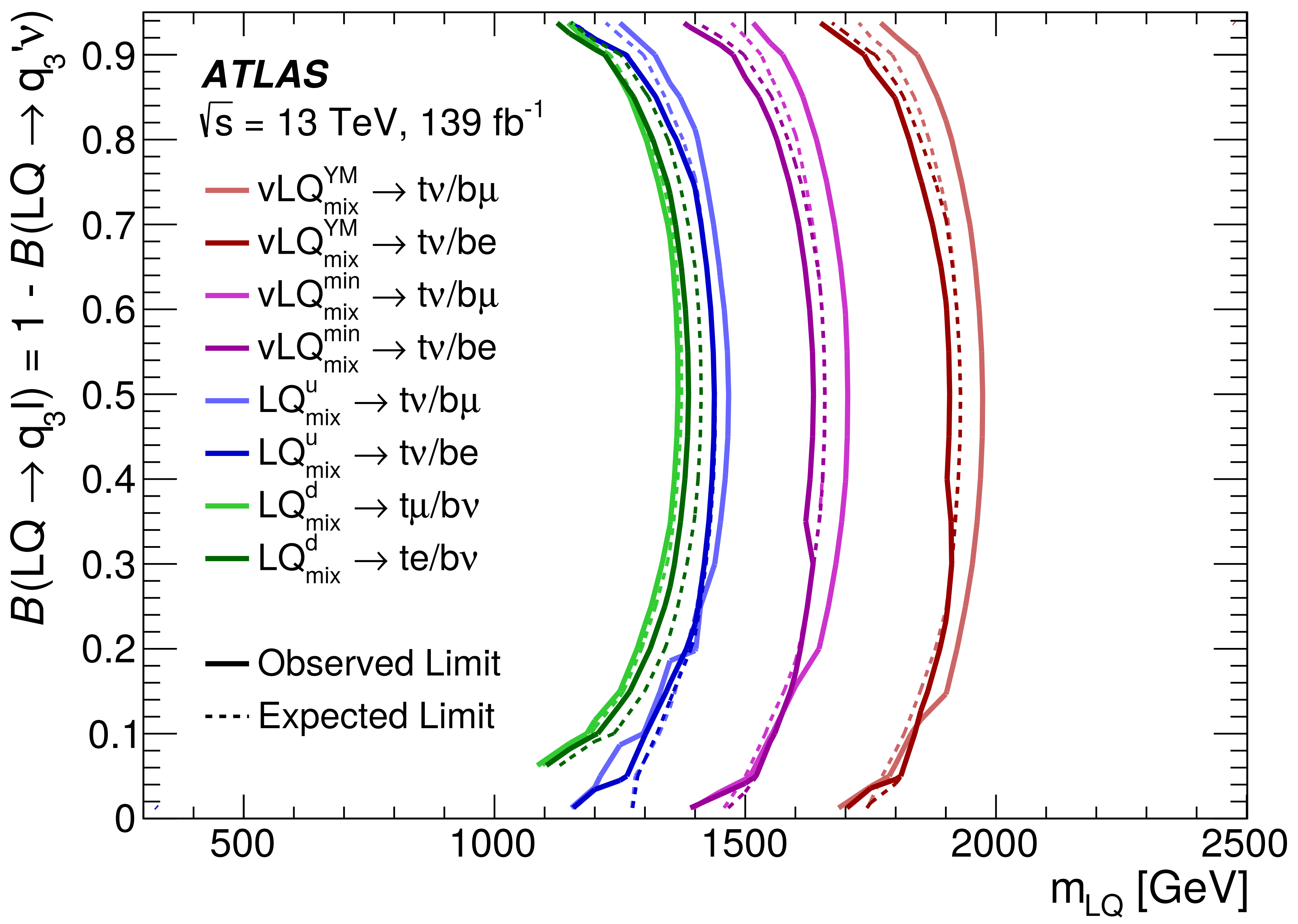
$\mathrm{LQ\,LQ} \to t\nu\, b\ell\ \ (\ell = e, \mu)$ EXOT-2019-12



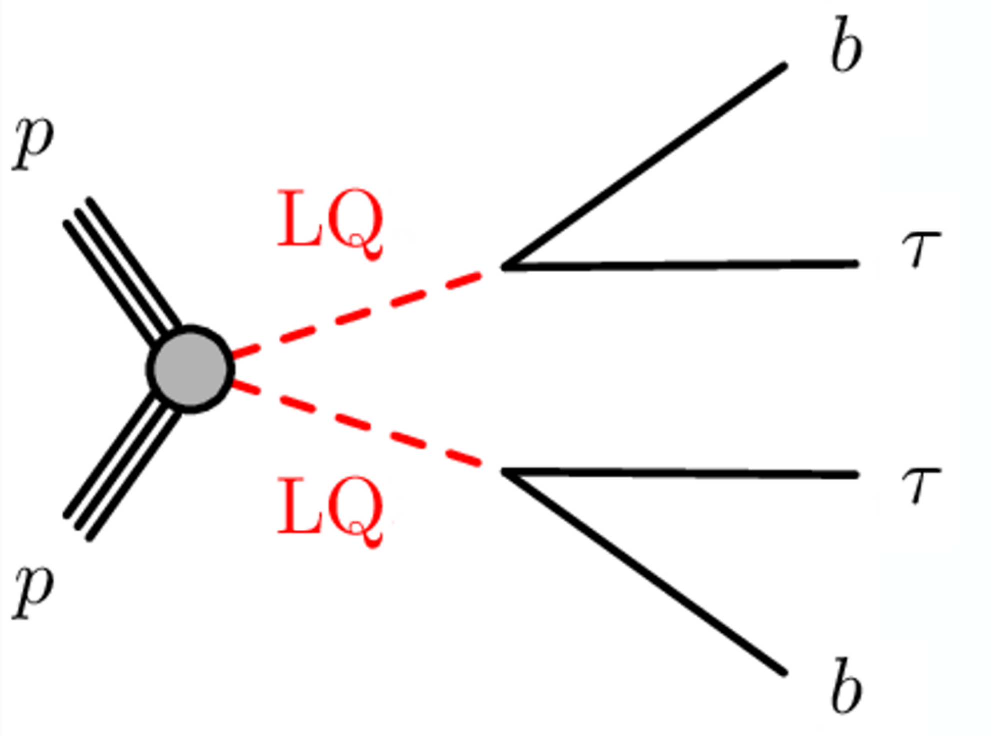
- Observed 95% CL limits at $\mathscr{B}(\mathrm{LQ} \to q_3\ell) = 0.5$:

	$\mathscr{B}(\mathrm{LQ} \to q_3 e) = 0.5$	$\mathscr{B}(\mathrm{LQ} \to q_3 \mu) = 0.5$
LQ^{u}_{mix}	1.44 TeV	1.46 TeV
LQ^{d}_{mix}	1.39 TeV	1.37 TeV
U_1^{min}	1.62 TeV	1.71 TeV
U_1^{YM}	1.90 TeV	1.98 TeV





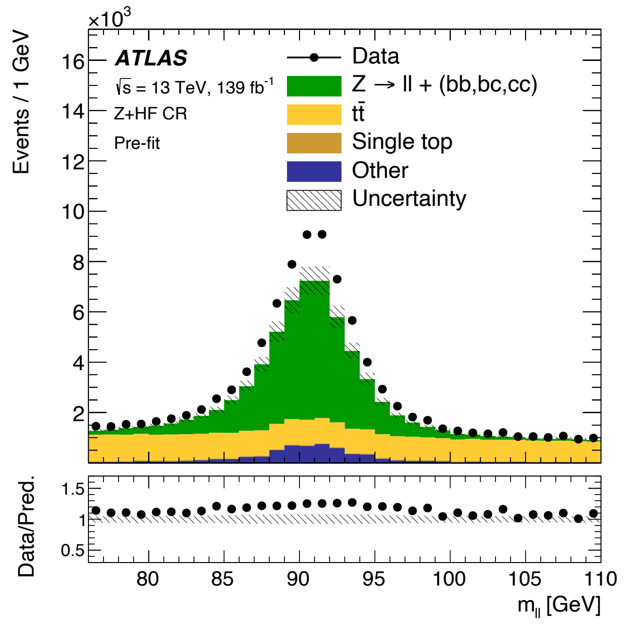
LQ LQ → bτ bτ EXOT-2021-15



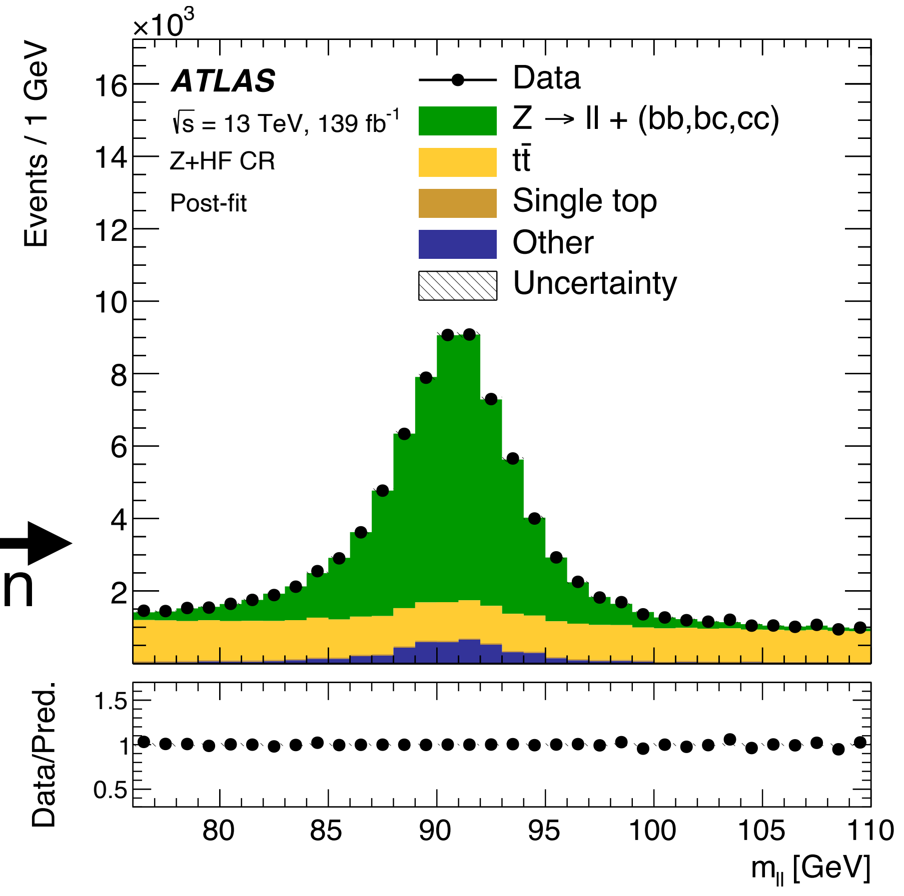
- Target pair-produced up-type LQs with $\mathscr{B}(\mathrm{LQ} \rightarrow b\tau) = 1.0$
- Analysis strategy:
  - Two channels: $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$, $\tau_{\mathrm{had}}\tau_{\ell}\ (\ell = e, \mu)$
  - ≥2 jets, ≥1 b-jet
  - Train parametric NN (PNN) in each channel, use PNN scores as discriminating variable
  - Main backgrounds: top, Z+HF, τ_{had} fakes

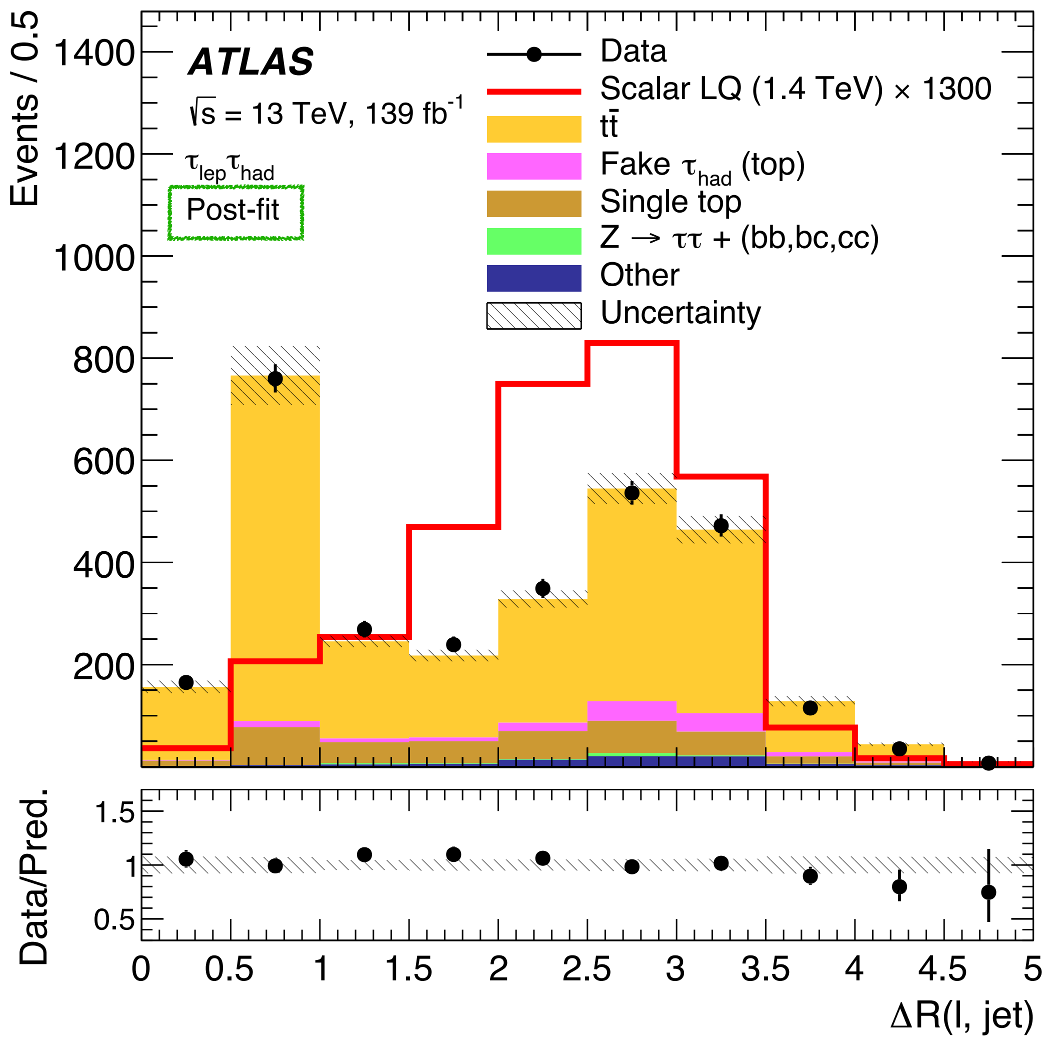
Backgrounds estimated from MC, except data-driven approach for multi-jet in $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$

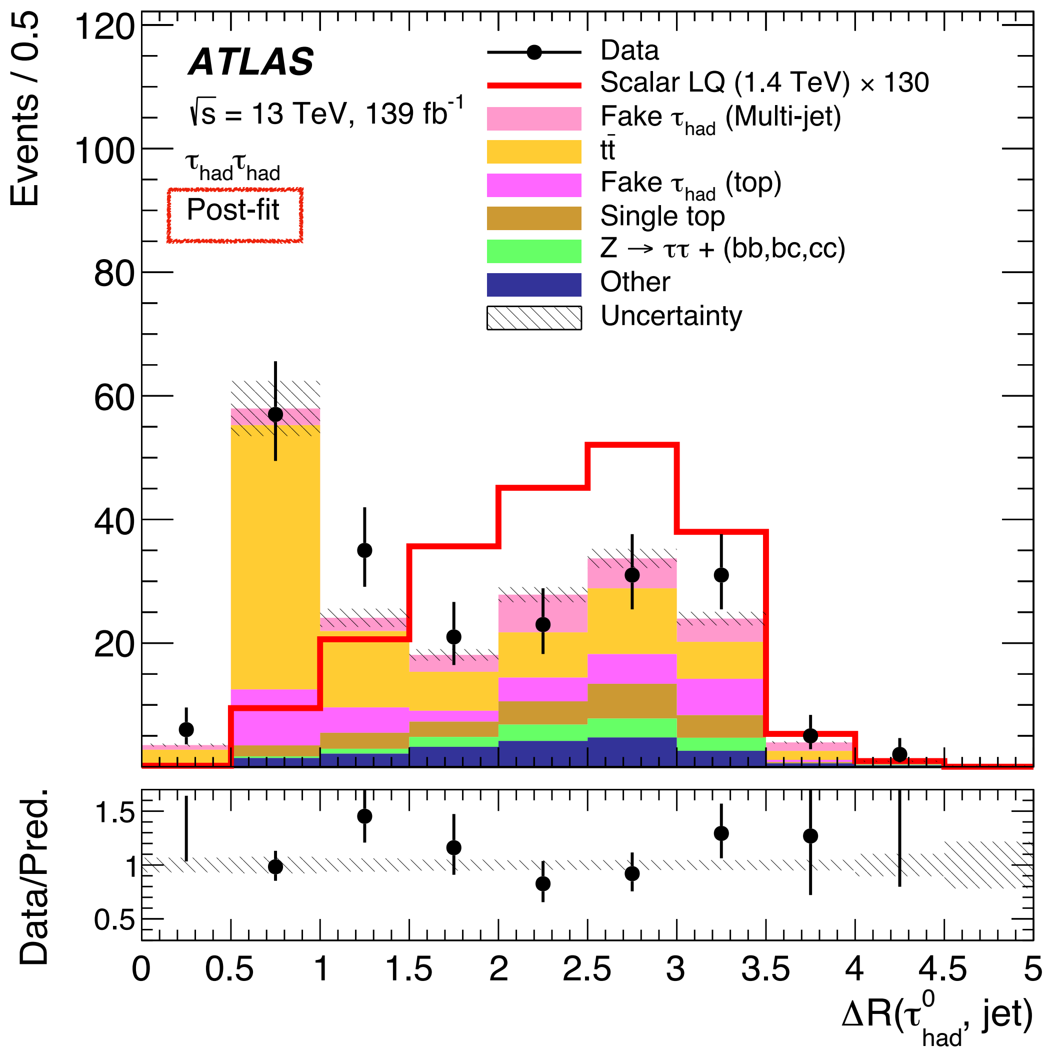
Additional data-driven corrections derived in dedicated control regions for top, Z+HF background processes



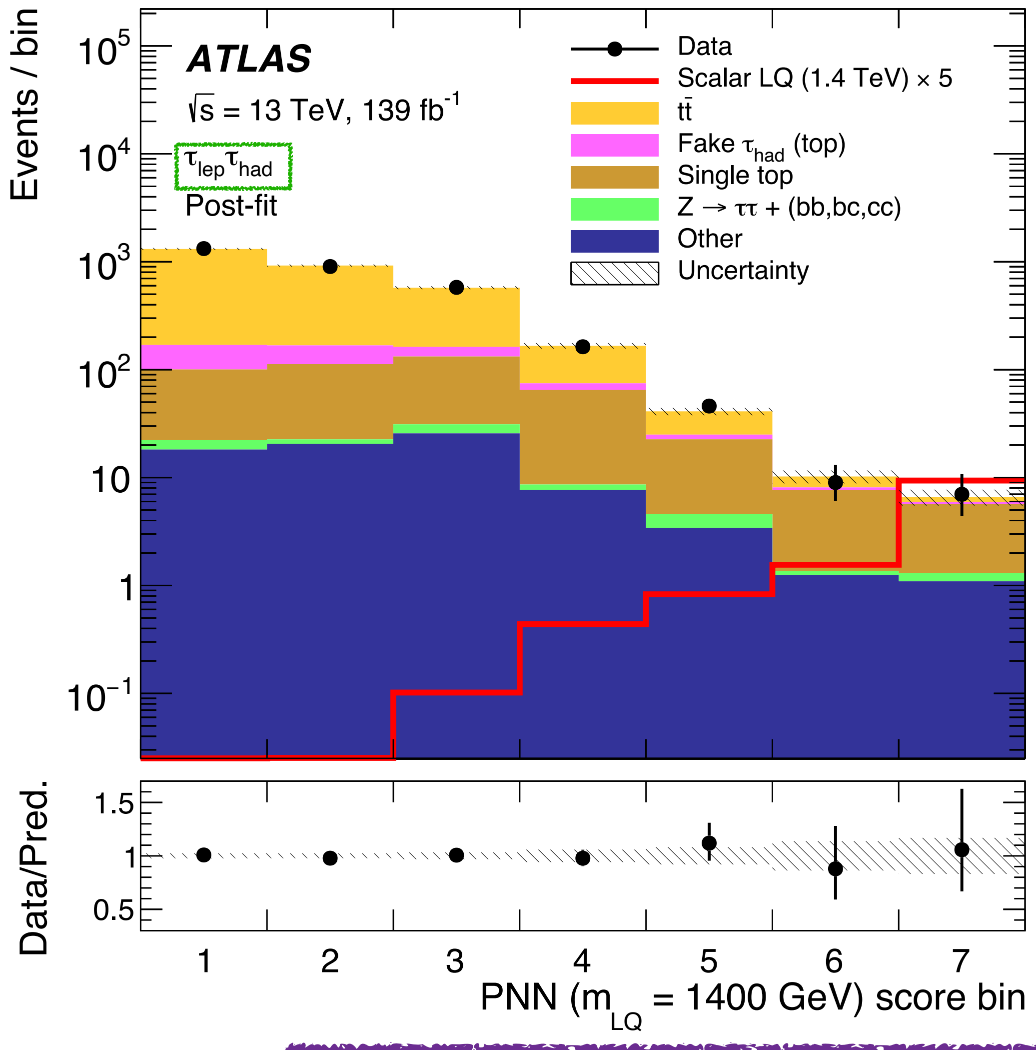
Z+HF normalisation from fit in control region

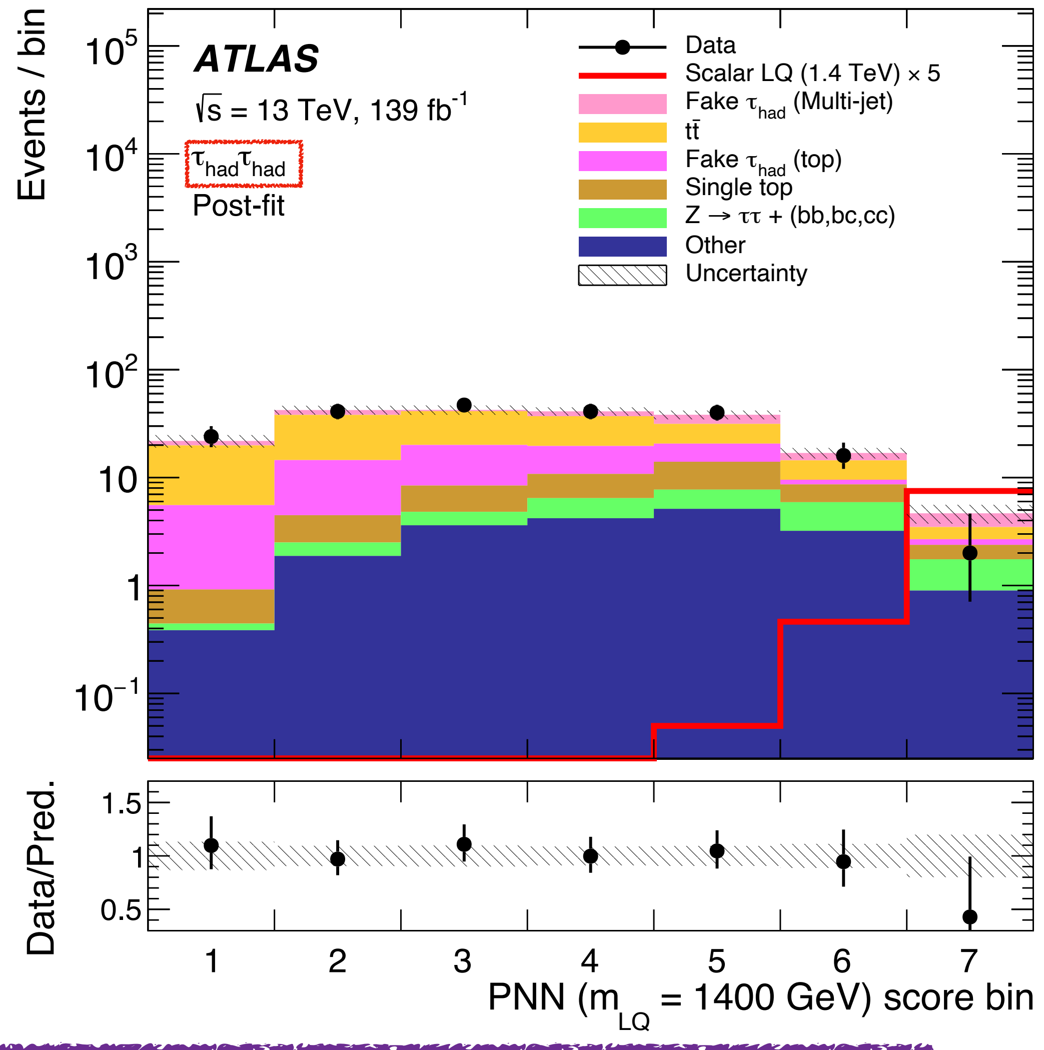






Set of 6-7 variables as input for PNNs





Good agreement between data and SM expectation

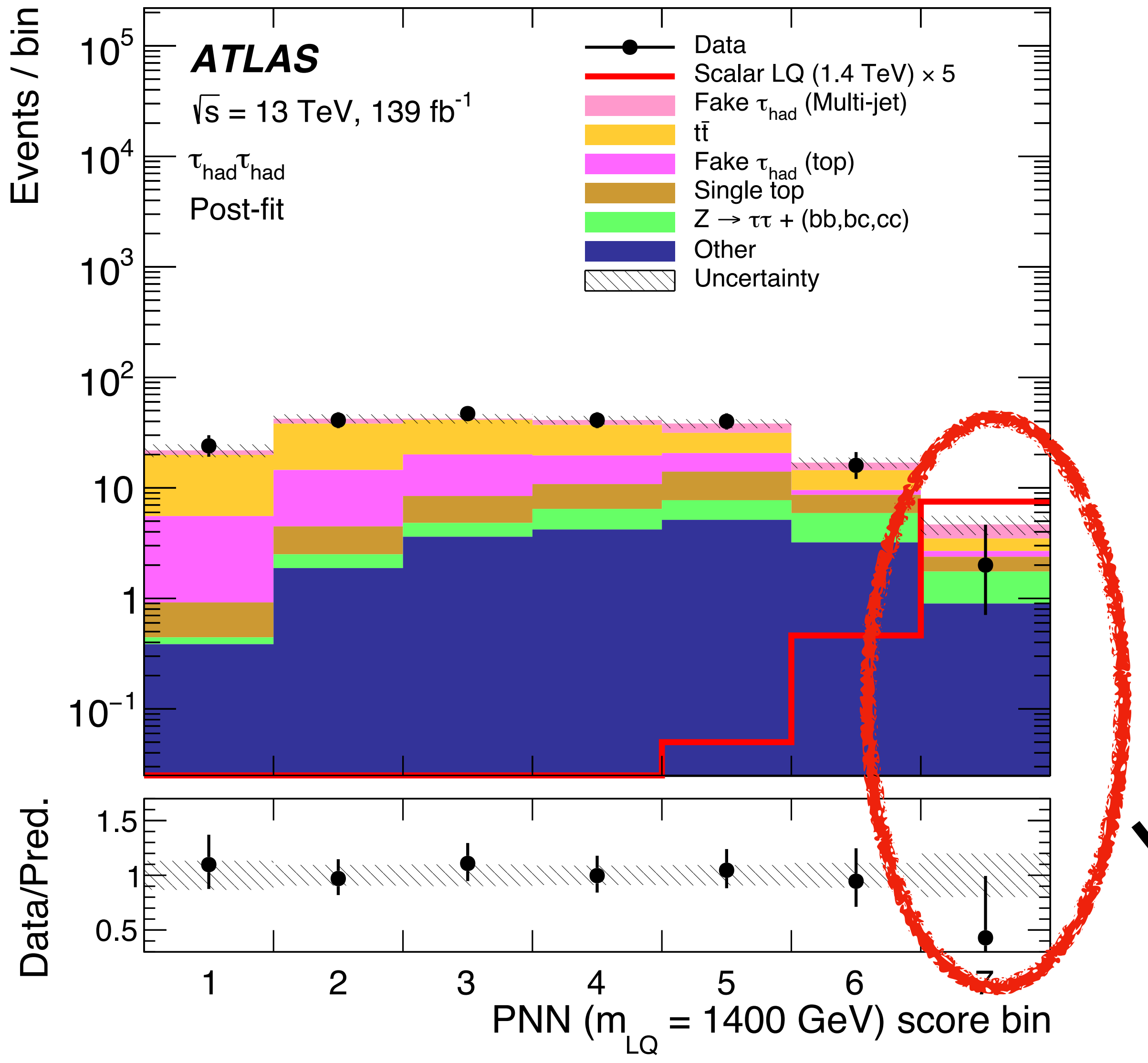
LQ LQ → bτ bτ EXOT-2021-15

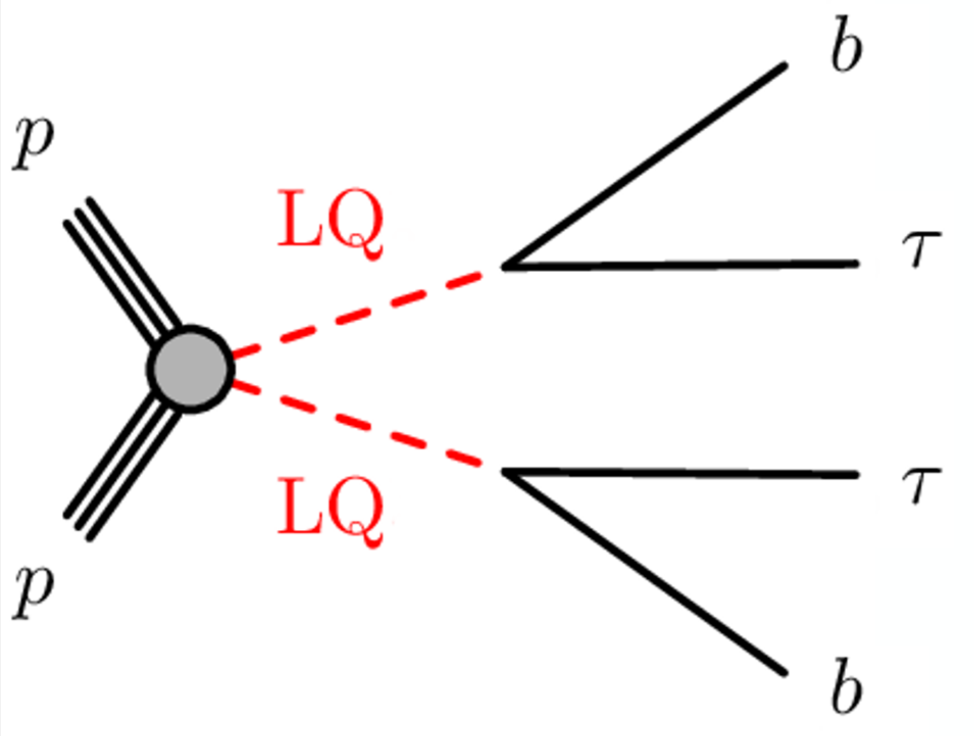
- Observed 95% CL limits at $\mathscr{B}(\mathrm{LQ} \to t\ell) = 1.0$:

	$\mathscr{B}(\mathrm{LQ} \to b\tau) = 1.0$
$\mathrm{LQ}_3^{\mathrm{u}}$	1.49 TeV
U_1^{min}	1.69 TeV
U_1^{YM}	1.96 TeV

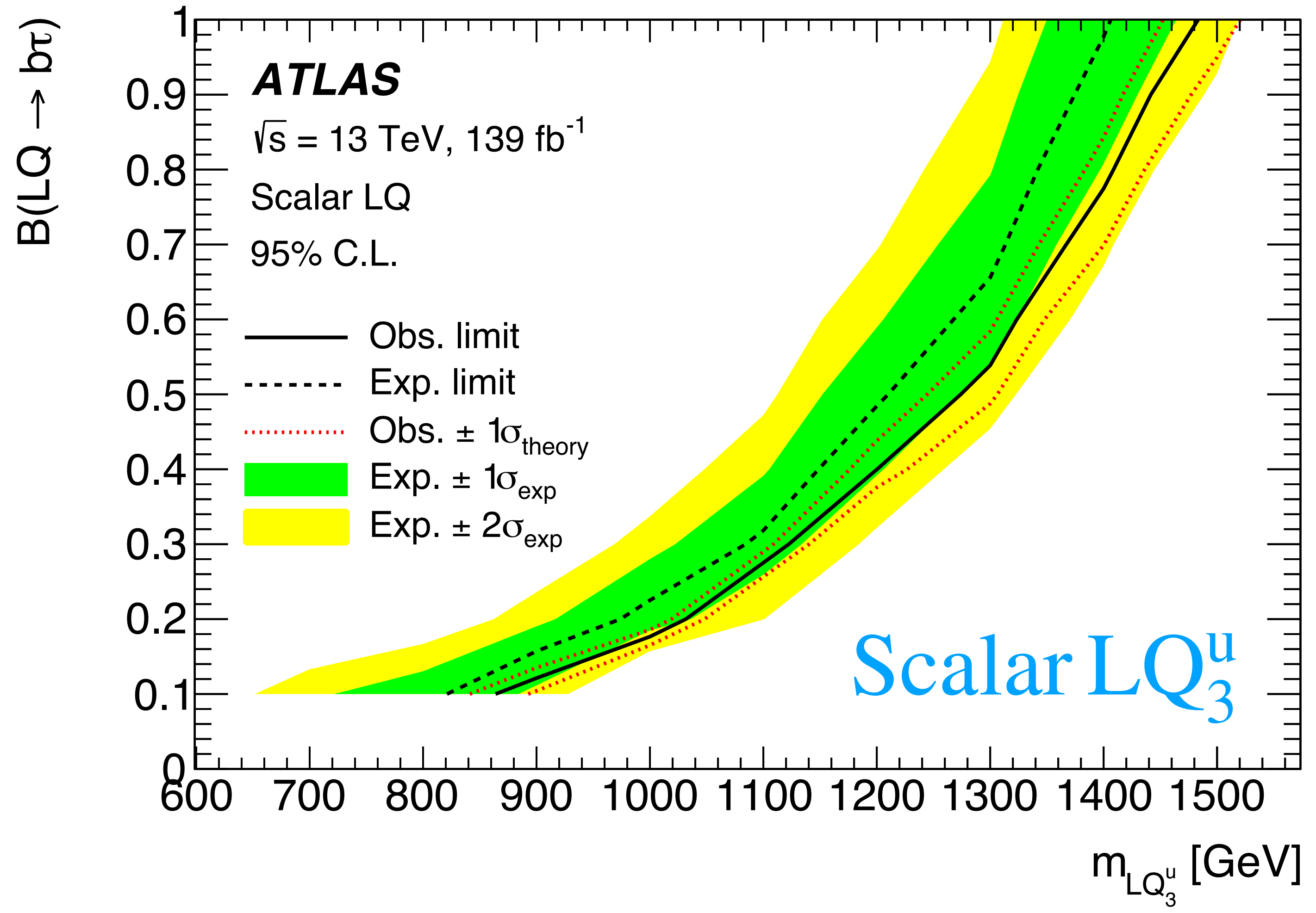
Better sensitivity wrt to partial Run-2 ATLAS analysis due to improvements in: JHEP 06 (2019) 144

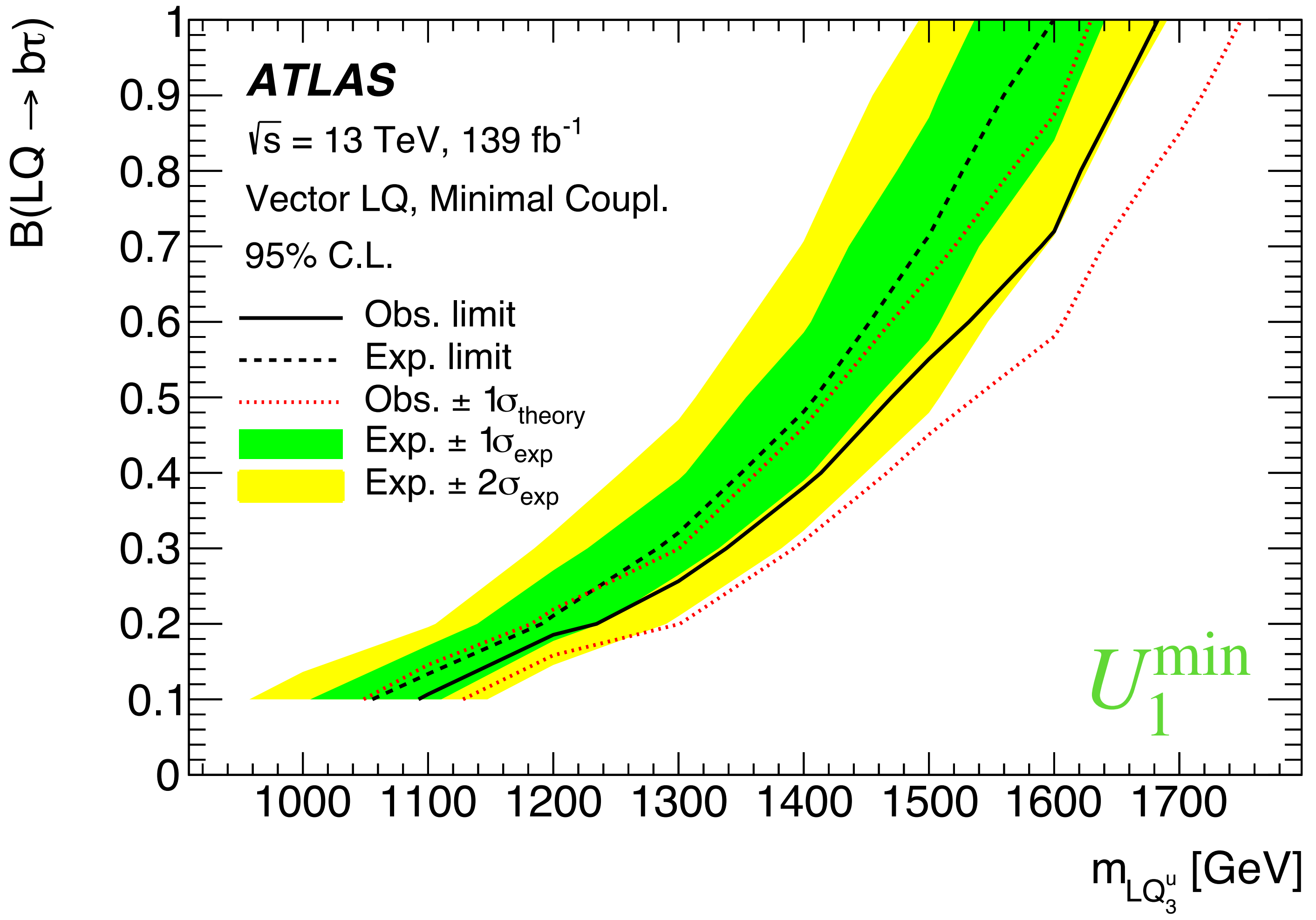
- τ identification
- b-jet identification
- MVA for signal/background separation
- Jet reconstruction

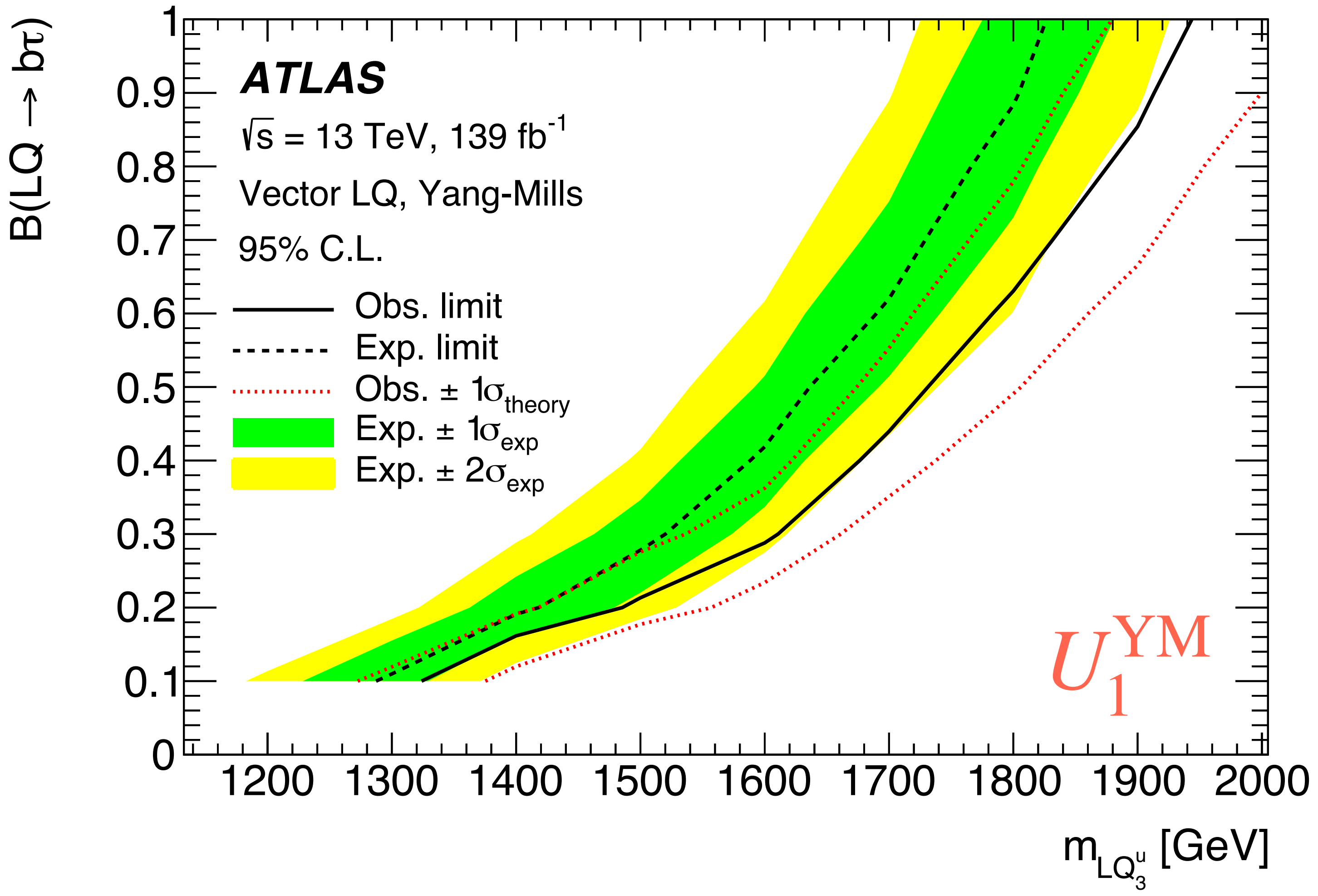




Better observed limits than expected due to downwards fluctuation in data in last bin of PNN score

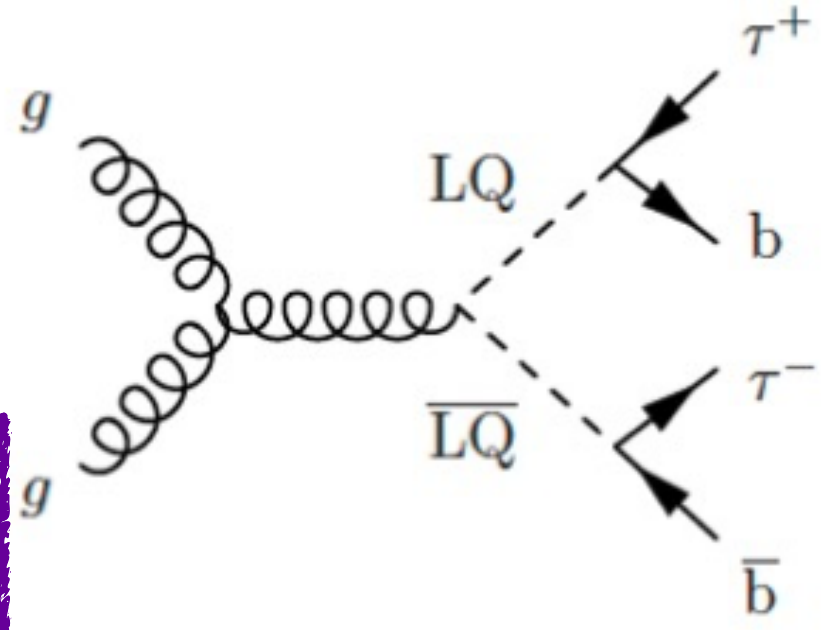


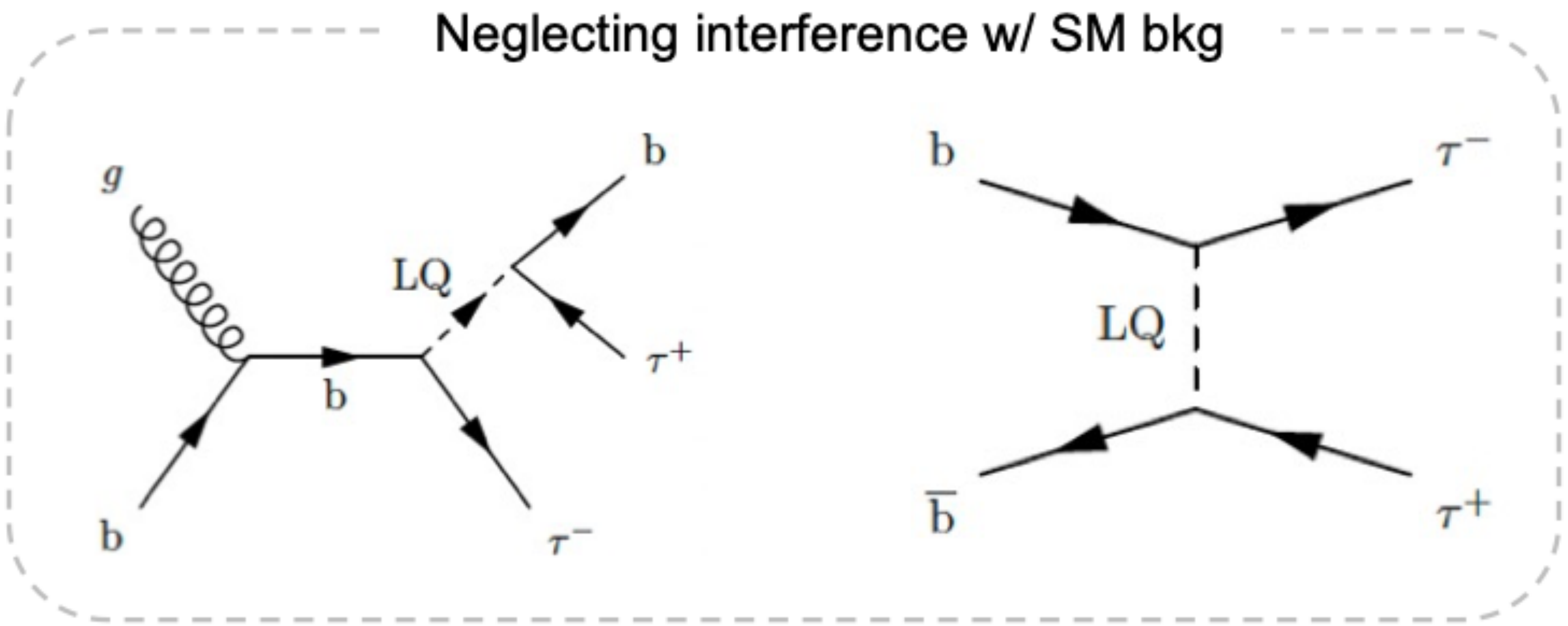




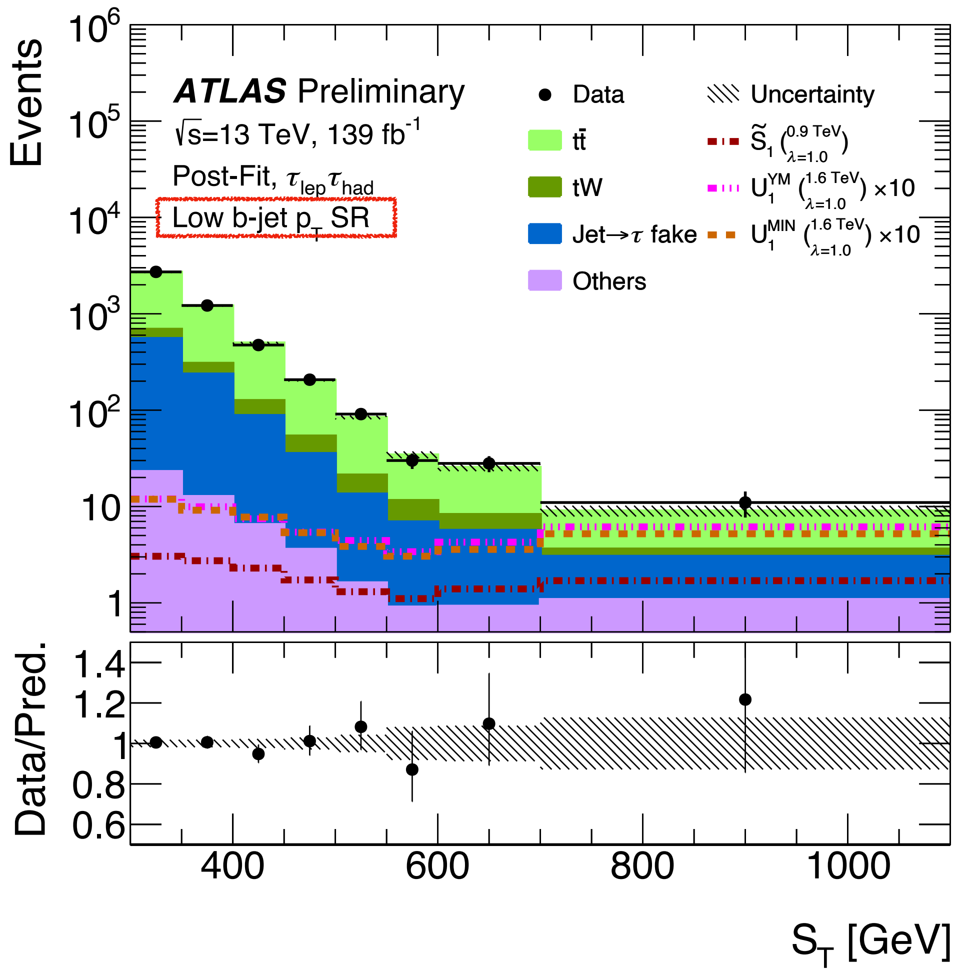
LQ → $b\tau$ EXOT-2022-39
(all production modes)

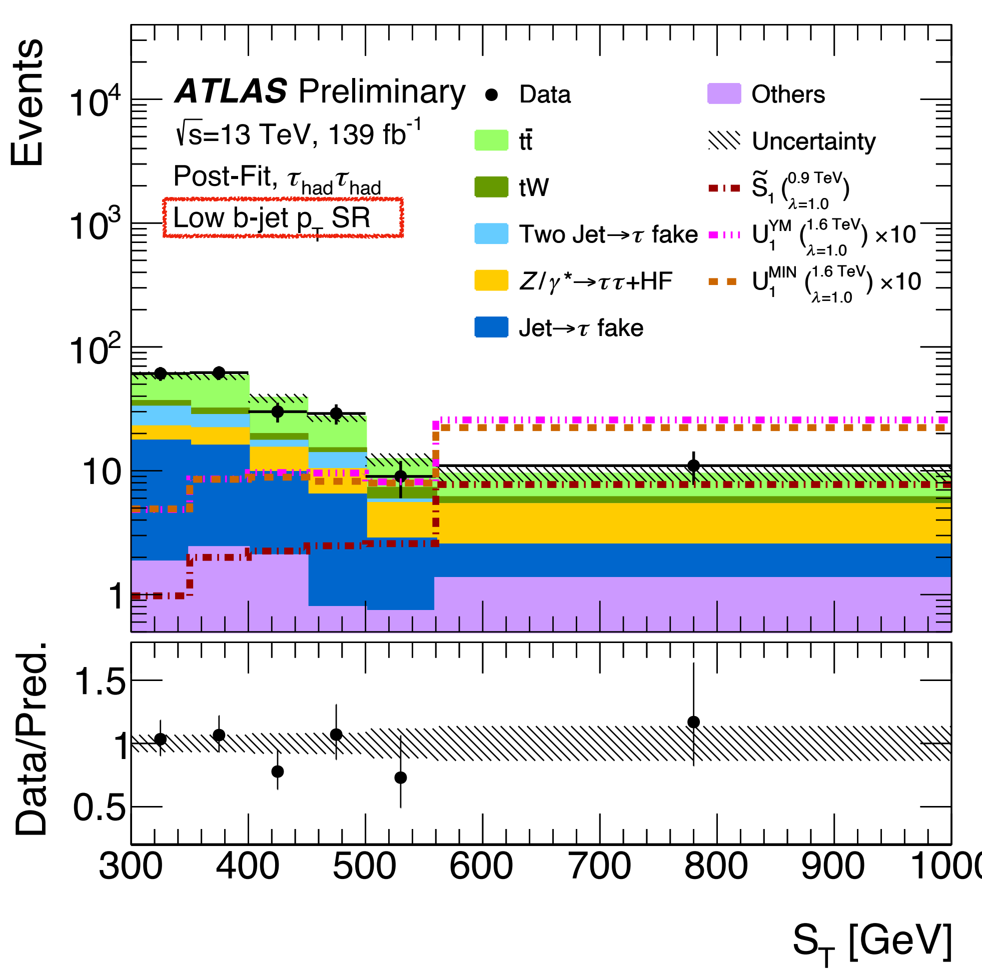
- Target up-type LQs with $\mathscr{B}(\mathrm{LQ} \to b\tau) = 1.0$
- Analysis strategy:
  - Two channels: $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$, $\tau_{\mathrm{had}}\tau_{\ell}$ $(\ell = e, \mu)$
  - ≥1 jet, ≥1 b-jet
  - Split signal regions by b-jet p_{T}:
    - High b-jet p_{T} SR: $p_{\mathrm{T}}^{b_1} > 200\mathrm{GeV}$
    - Low b-jet p_{T} SR: $25\mathrm{GeV} < p_{\mathrm{T}}^{b_1} < 200\mathrm{GeV}$
  - Discriminating variable $S_T = p_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + p_{\mathrm{T}}^{\mathrm{miss}}$
  - Main backgrounds: top, τ_{had} fakes, Z+jets

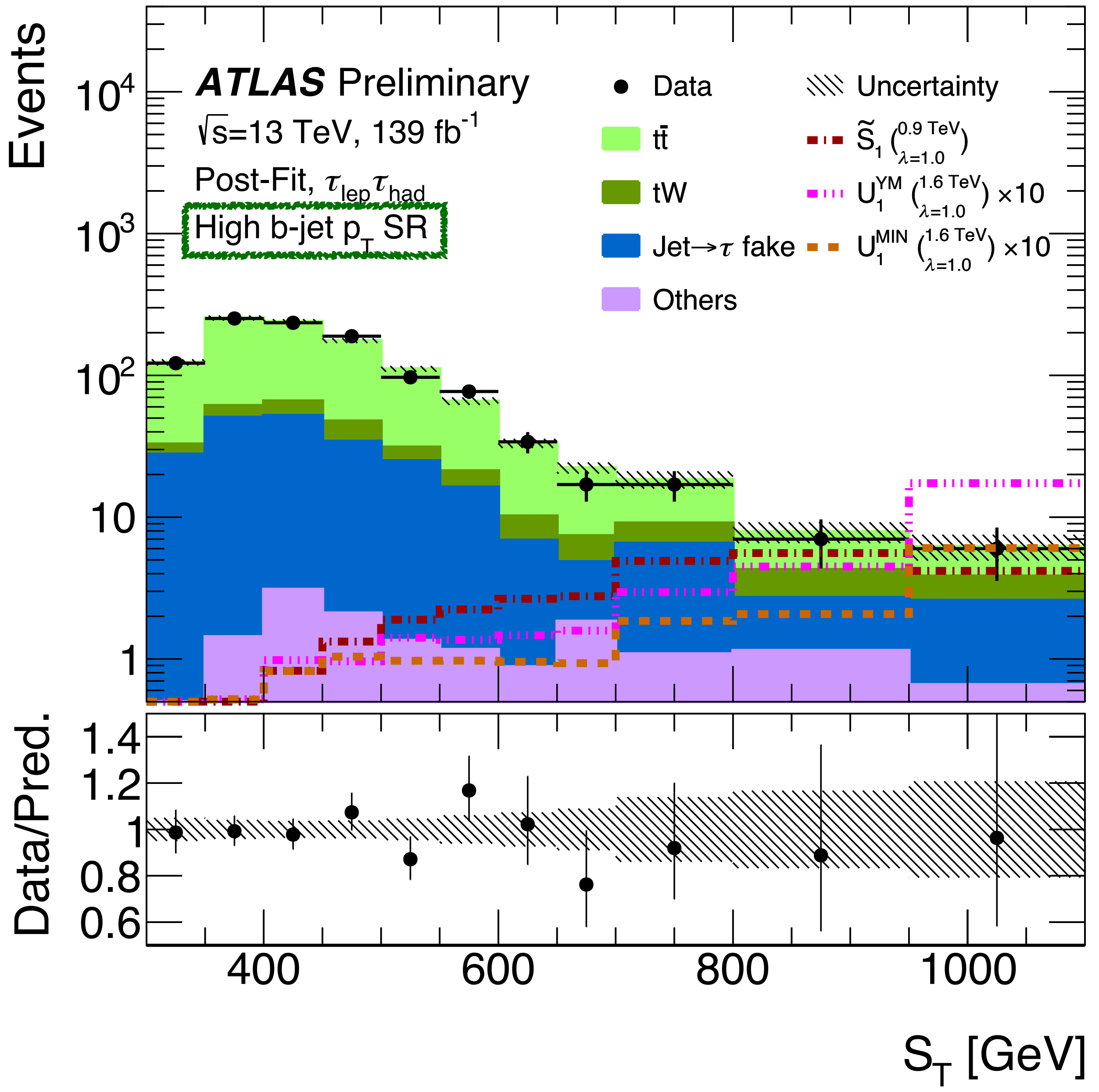


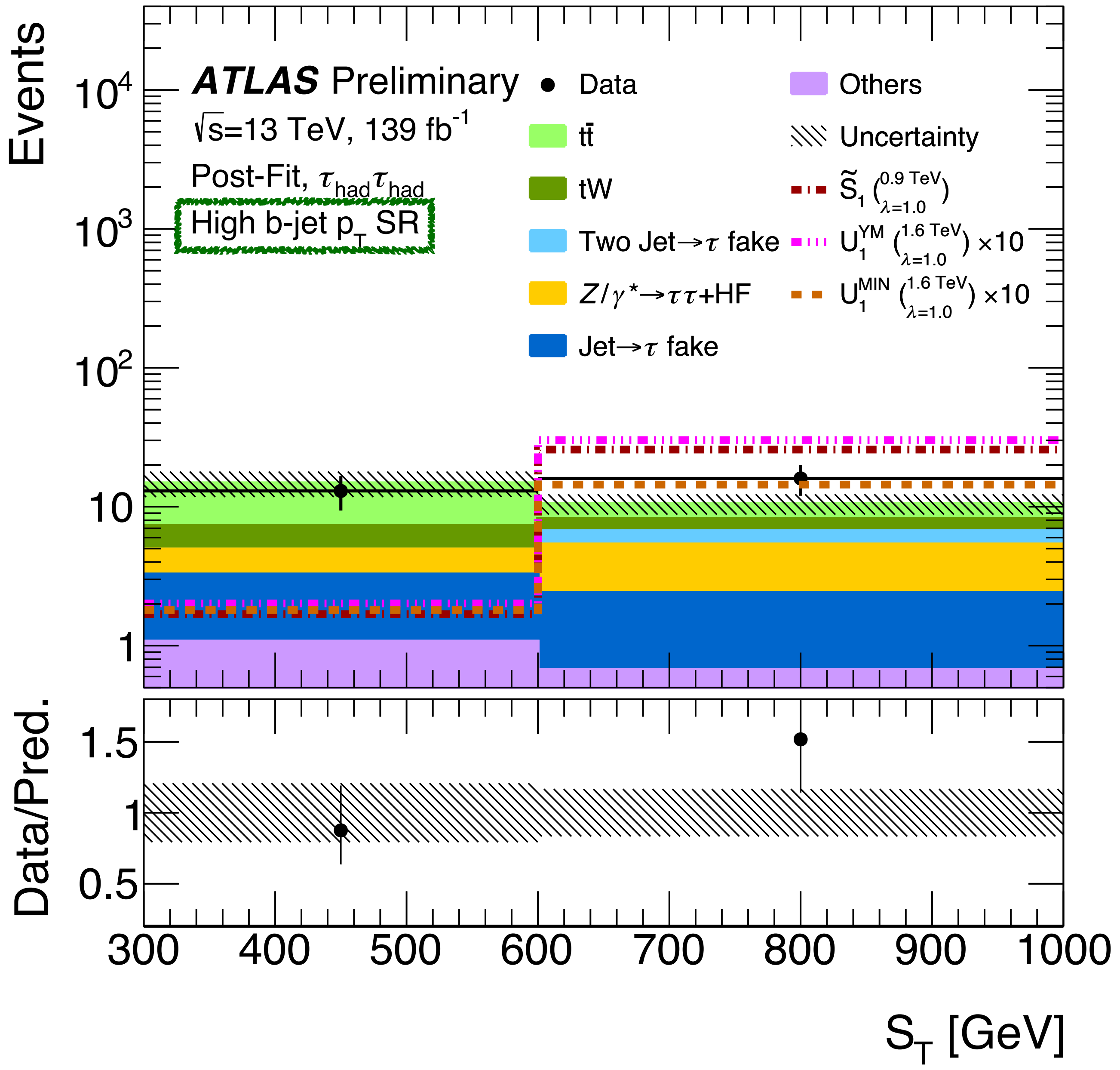


- Neglect interference between non-resonant LQ production and SM background processes
- But potentially non-negligible effects in low b-jet p_{T} SR
  → derive limits on LQ production from high b-jet p_{T} SR only





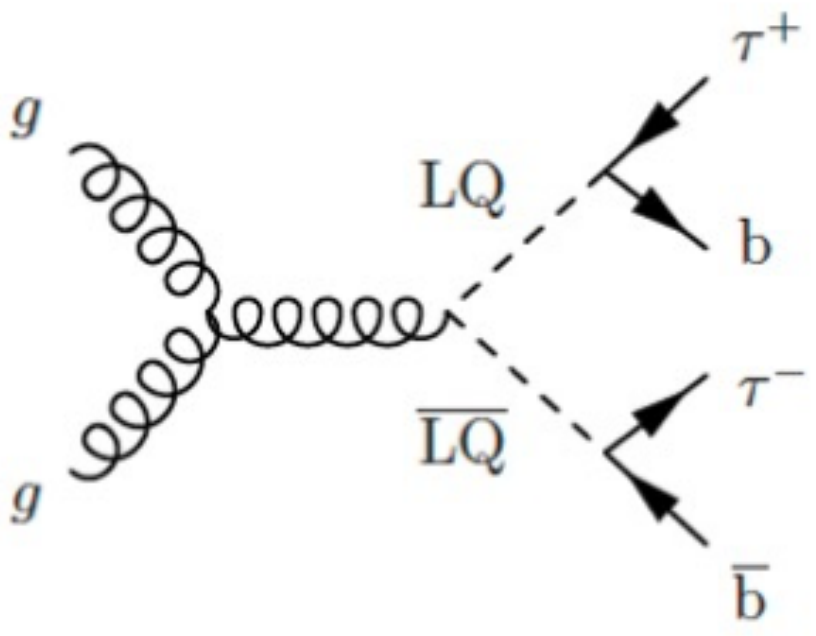




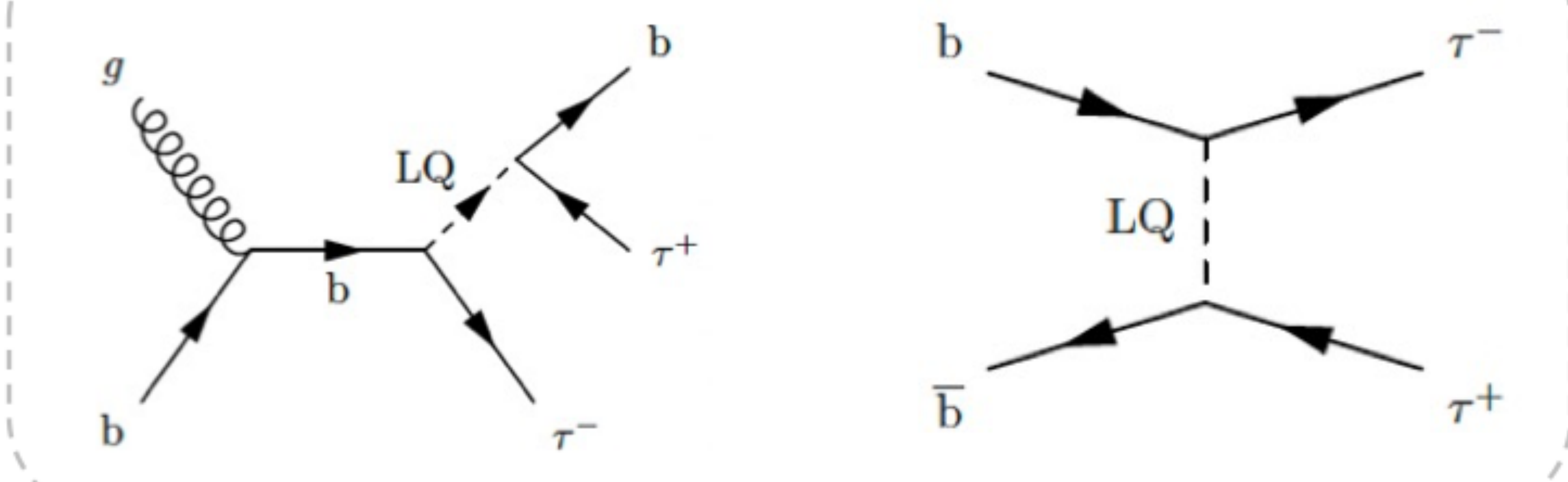
Good agreement between data and SM expectation

$LQ \rightarrow b\tau$ EXOT-2022-39
(all production modes)

- Set limits on cross-section as function of coupling λ
- Combined limits significantly improved wrt to individual production modes for intermediate λ

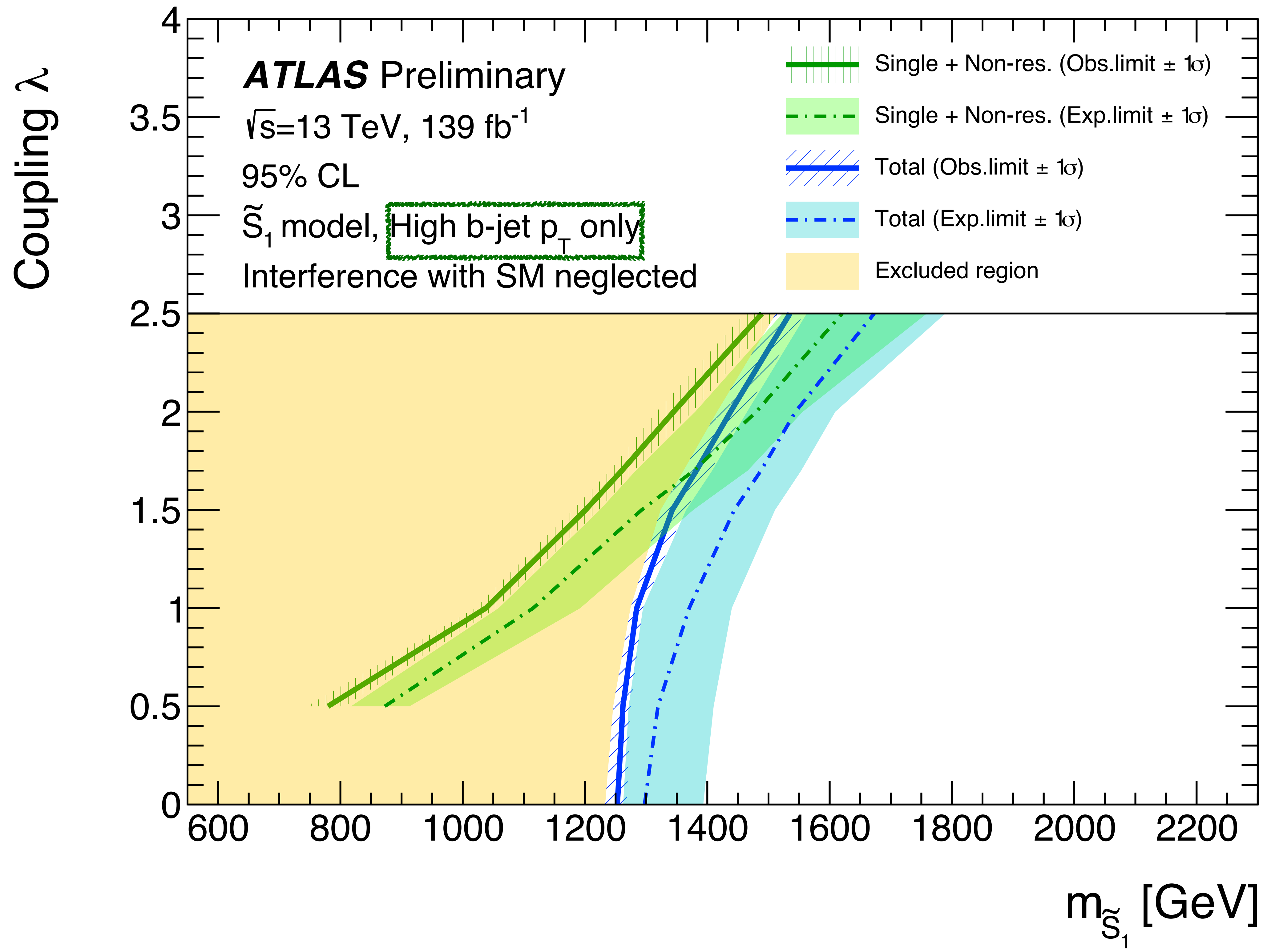


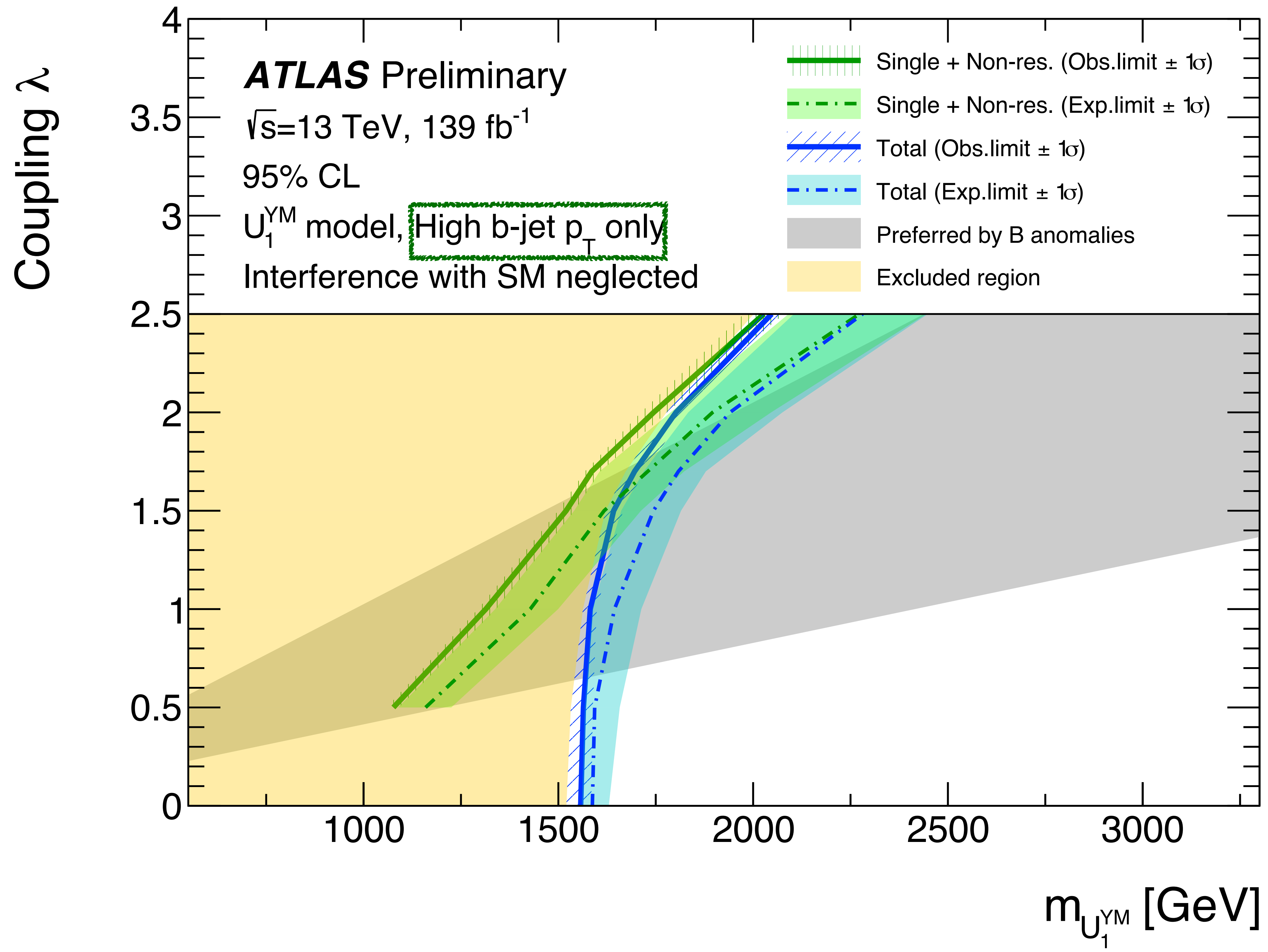
Neglecting interference w/ SM bkg



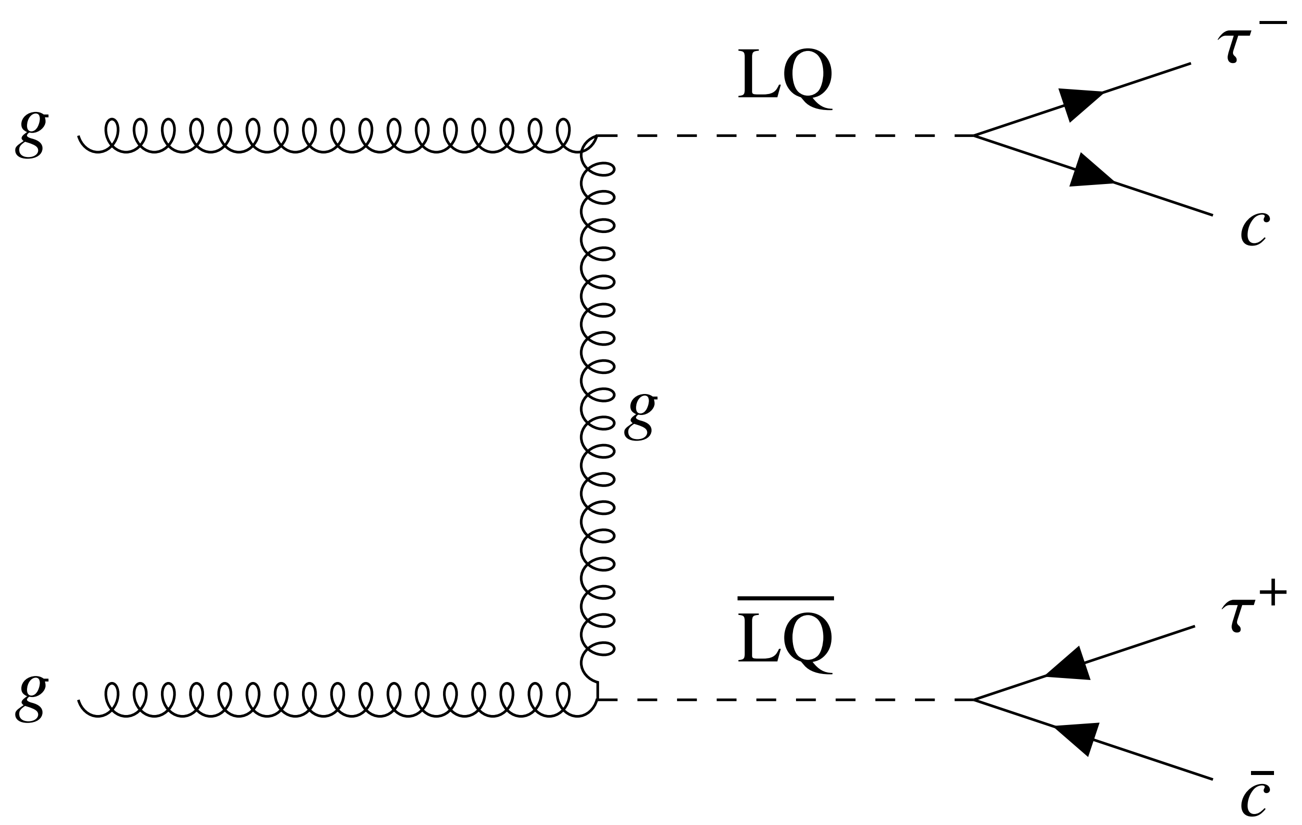
Observed 95% CL limits for $\lambda = 2.5$:

- LQ_3^u $\left(\mathscr{B}(LQ \rightarrow b\tau) = 1.0\right)$: 1.53 TeV
- U_1^{YM} $\left(\mathscr{B}(LQ \rightarrow b\tau) = 0.5\right)$: 2.09 TeV



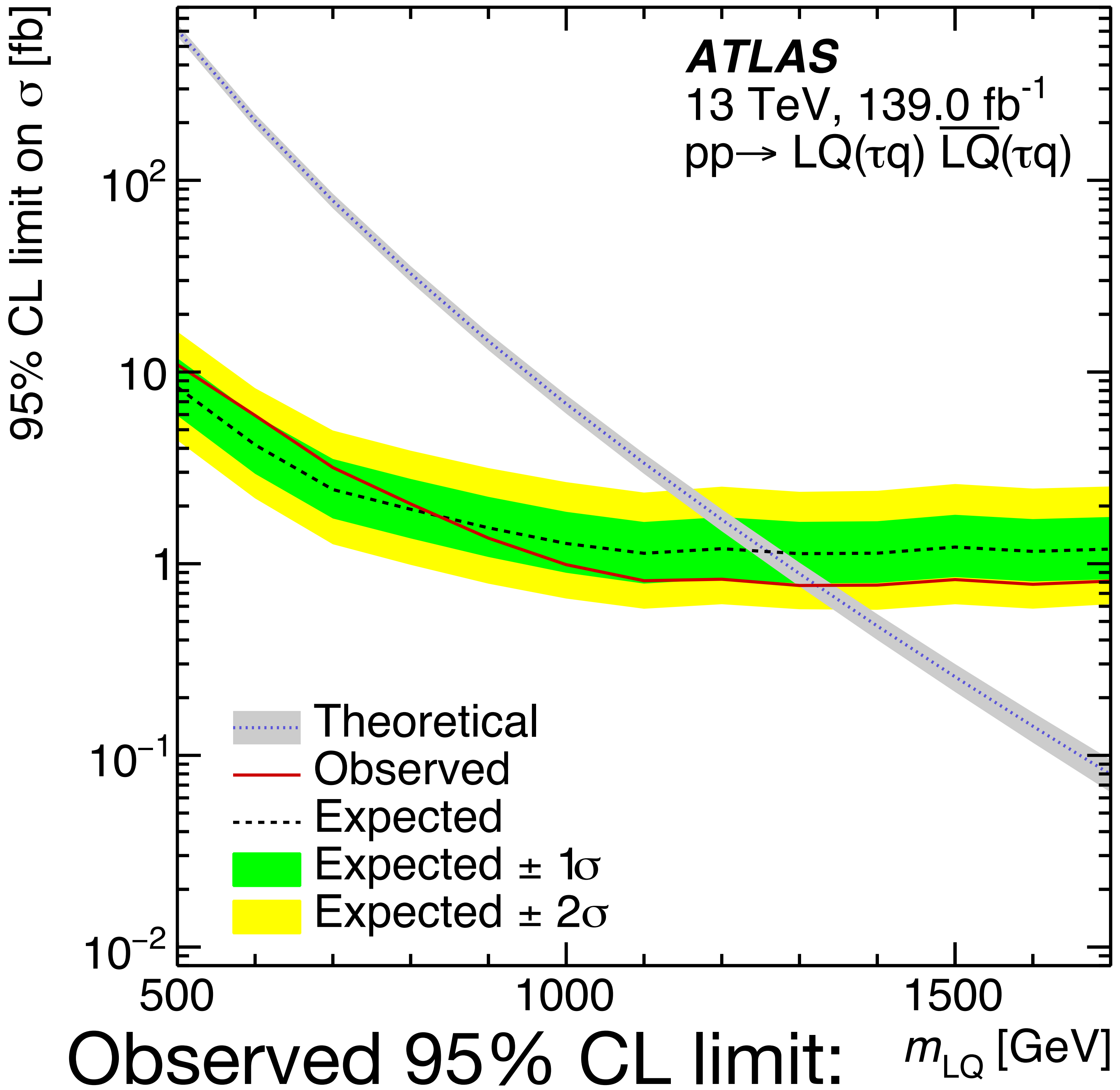


LQ LQ → qτ qτ (q = u, d, c, s) EXOT-2020-18

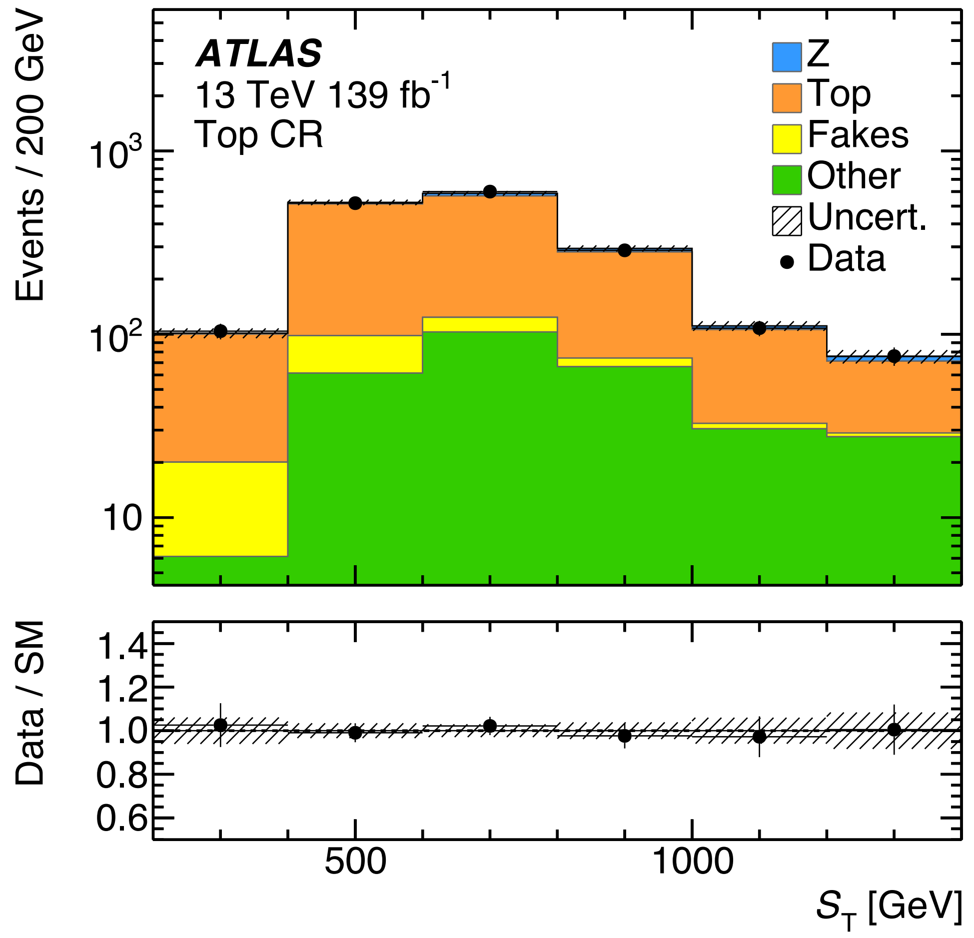


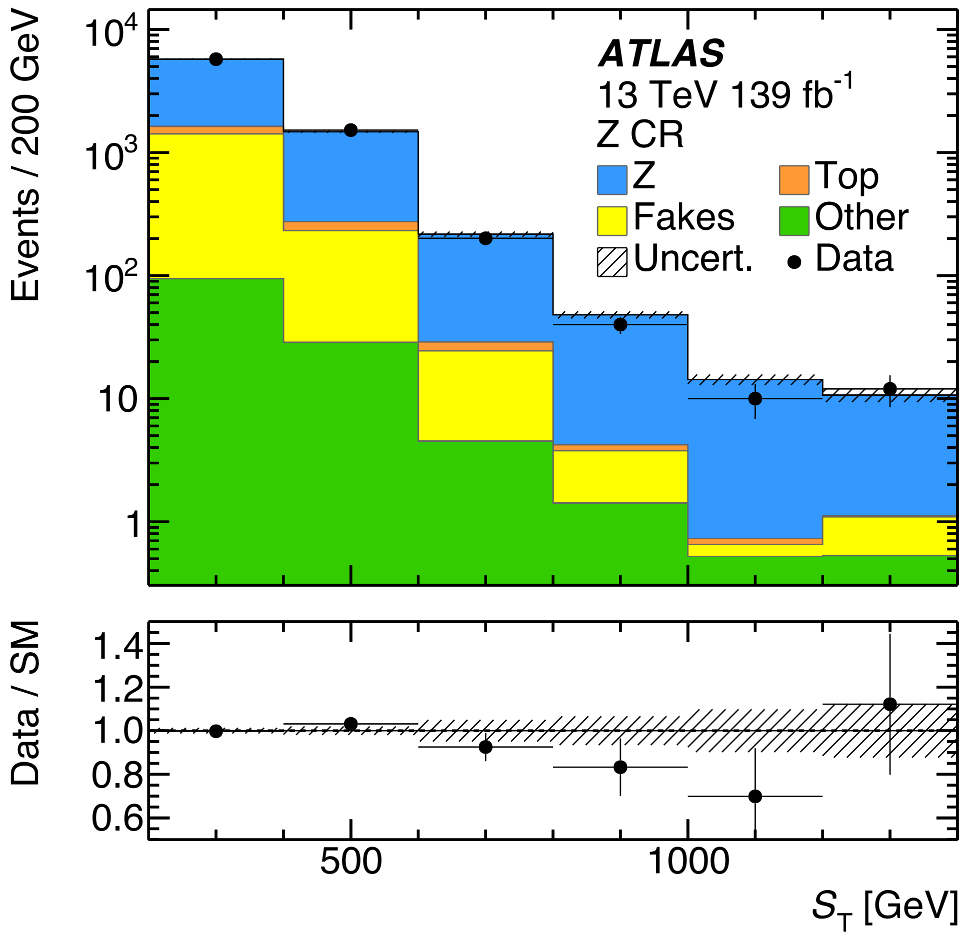
- Target excited τ-leptons and pair-produced LQs with $\mathcal{B}(\mathrm{LQ} \to q\tau) = 1.0\ (q = u, d, c, s)$
- Analysis strategy:
  - 2 OS τ_{had}, ≥ 2 jets
  - Collinear approximation to decompose $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ in transverse plane along $\tau_{1,2}$
  - Normalisation of main background processes constrained in dedicated CRs
  - Fake τ_{had} background estimated using data-driven fake factor method
  - Final discriminant: $S_{\mathrm{T}} = p_{\mathrm{T}}^{\tau_1} + p_{\mathrm{T}}^{\tau_2} + p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}$

See Elise's talk later in this session

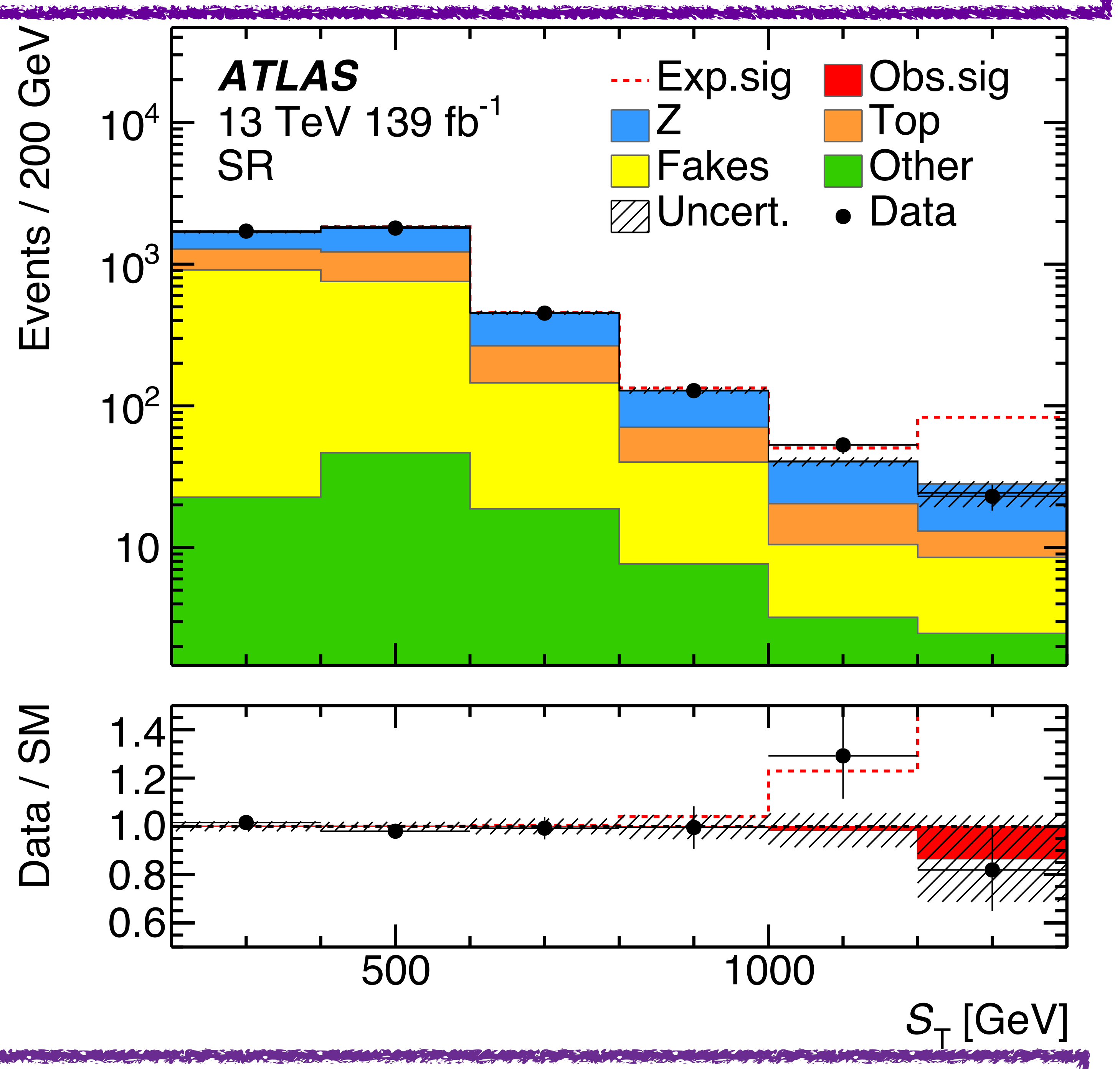


Observed 95% CL limit: 1.3 TeV





dedicated control and validation regions for Z+jets, top, fake τ's



Good agreement between data and SM expectation

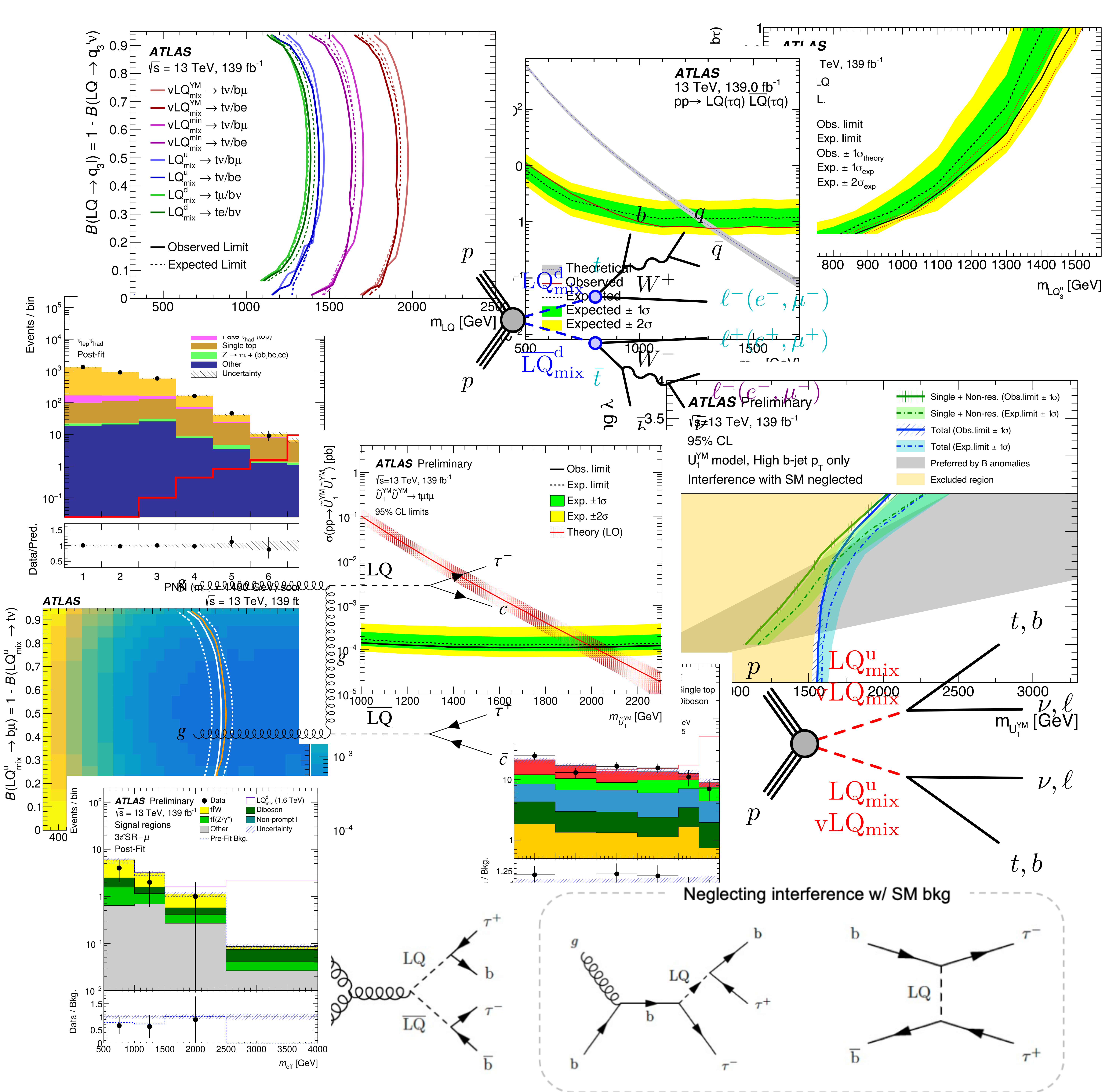
Signal region does not rely on charm-tagging → results valid for all LQs decaying into τ leptons and light quarks

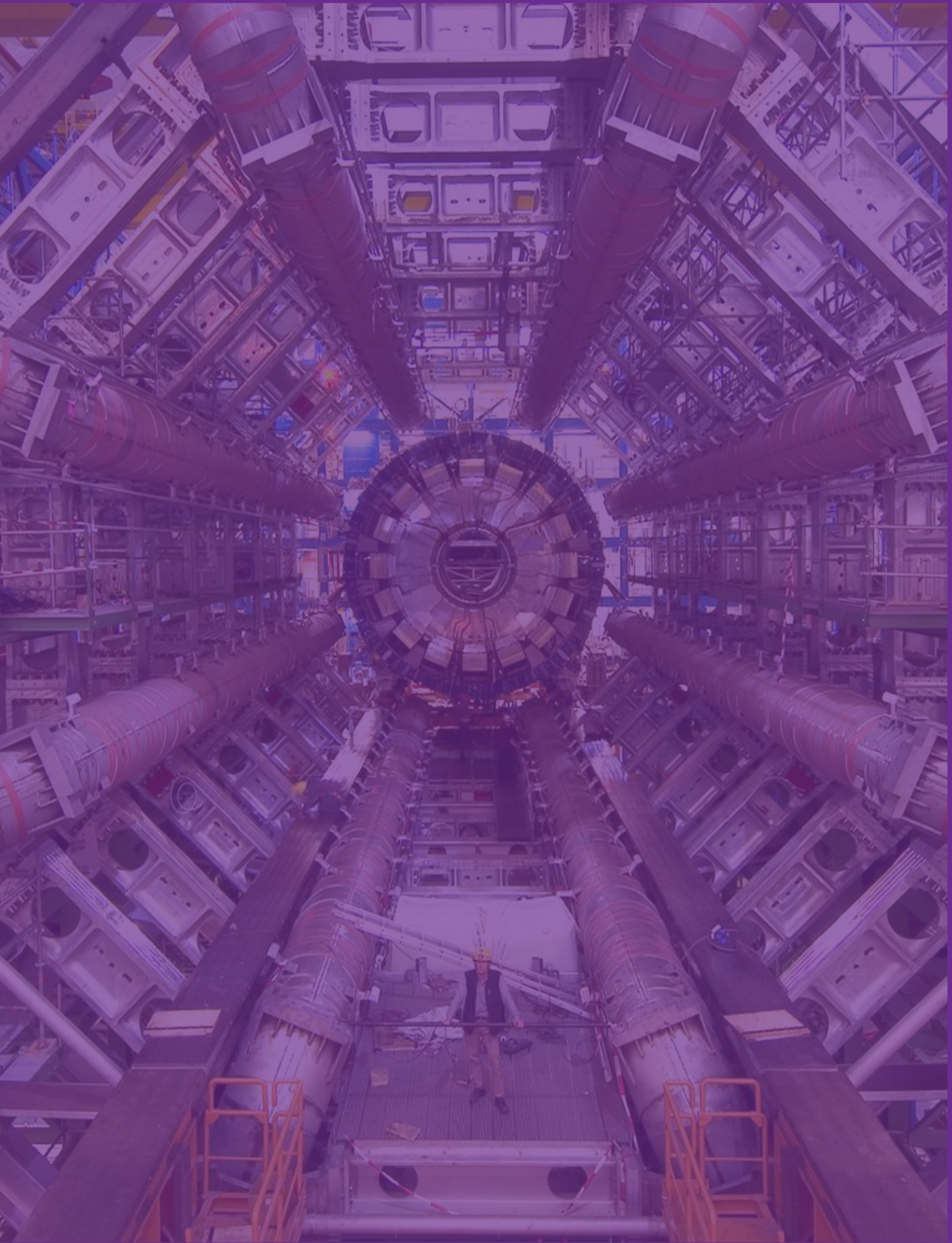
Conclusions

- Extensive search programme for leptoquarks at ATLAS during Run-2
- Covering wide range of potential final states
- Lower mass limits reaching 2 TeV and beyond, depending on model

- Looking forward to further sensitivity improvements in Run-3

- Thank you -





Backup

Leptoquark models

U_1

$$\mathcal{L}_{\rm NP} = -\frac{1}{2}U^{a\,\dagger}_{1\,\mu\nu}U_1^{\mu\nu,\,a} + m^2_{\rm LQ}U^{a\,\dagger}_{1\,\mu}U_1^{\mu,\,a} - ig_s(1-\kappa)U^{a\,\dagger}_{1\,\mu}T^b U_{1\,\nu}G^{\mu\nu,\,b} + \mathcal{L}_{U_1,\gamma/Z} + + (U_1^{\mu,\,a}J^a_\mu + \text{h.c.})$$

$$J^a_\mu = \frac{g_U}{\sqrt{2}}\left(\beta_L^{ij}\bar{Q}_L^{i,a}\gamma_\mu L_L^j + \beta_R^{ij}\bar{d}_R^{i,a}\gamma_\mu \ell_R^j\right) = \frac{g_U}{\sqrt{2}}\left(t^a_L\gamma_\mu\nu_\tau + b^a_L\gamma_\mu\tau_L\right) \quad \text{for} \quad \beta^{ij}_\lambda = \delta_{i3}\delta_{j3}\delta_{\lambda L}$$

Strength of coupling to gluons fusion depends on κ

$\tilde{U}_1$

$$\mathcal{L}_{\rm NP} = -\frac{1}{2}\tilde{U}^{a\,\dagger}_{1\,\mu\nu}\tilde{U}_1^{\mu\nu,\,a} + m^2_{\rm LQ}\tilde{U}^{a\,\dagger}_{1\,\mu}\tilde{U}_1^{\mu,\,a} - ig_s(1+\kappa_t)\tilde{U}^{a\,\dagger}_{1\,\mu}T^b\tilde{U}_{1\,\nu}G^{\mu\nu,\,b} - ig'_s(1+\kappa_s)\tilde{U}^{a\,\dagger}_{1\,\mu}T^b\tilde{U}_{1\,\nu}G'^{\mu\nu,\,b} + (\tilde{U}_1^{\mu,\,a}J^a_\mu + \text{h.c.})$$

$$J^a_\mu = y_U^{\ell q}\left(\bar{u}_R^{i,a}\gamma_\mu\ell_R^j\right)$$

Additional couplings to heavy gluons

Scalar

$$\mathcal{L}_{\rm NP} = (D_\mu\Phi)^\dagger(D^\mu\Phi) - m^2_{\rm LQ}\Phi^\dagger\Phi + \mathcal{L}^{\rm up/down}_{\ell q\Phi}$$

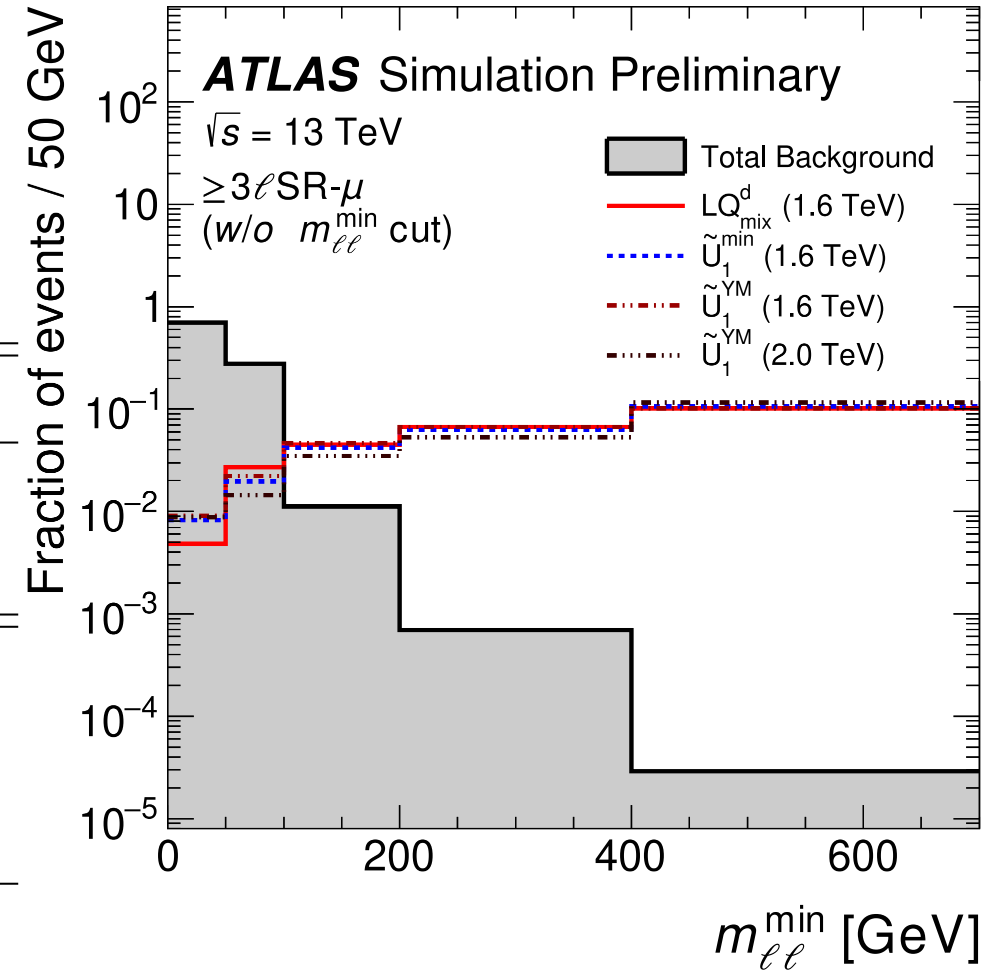
$$\mathcal{L}^{\rm up}_{\ell q\Phi} = \lambda\sqrt{\beta^{ij}}\bar{d}^i_R\ell^j_L\Phi + \lambda\sqrt{1-\beta^{ij}}\bar{u}^i_R\nu^j\Phi + \text{h.c.}$$

$$\mathcal{L}^{\rm down}_{\ell q\Phi} = \lambda\sqrt{\beta^{ij}}\bar{u}^i_R\ell^j_L\Phi + \lambda\sqrt{1-\beta^{ij}}\bar{d}^i_R\nu^j\Phi + \text{h.c.}$$

Symbol	Spin	F	$\lvert q\rvert$
S_1	0	-2	1/3
$\widetilde{S}_1$	0	-2	1/3
S_3	0	-2	4/3, 1/3, 2/3
R_2	0	0	5/3, 2/3
$\widetilde{R}_2$	0	0	2/3, 1/3
U_1	1	0	2/3
$\widetilde{U}_1$	1	0	5/3
U_3	1	0	5/3, 2/3, 1/3
V_2	1	-2	4/3, 1/3
$\widetilde{V}_2$	1	-2	4/3, 1/3

$LQ\,LQ \rightarrow t\ell\, t\ell \;\; (\ell = e, \mu)$ ATLAS-CONF-2022-052

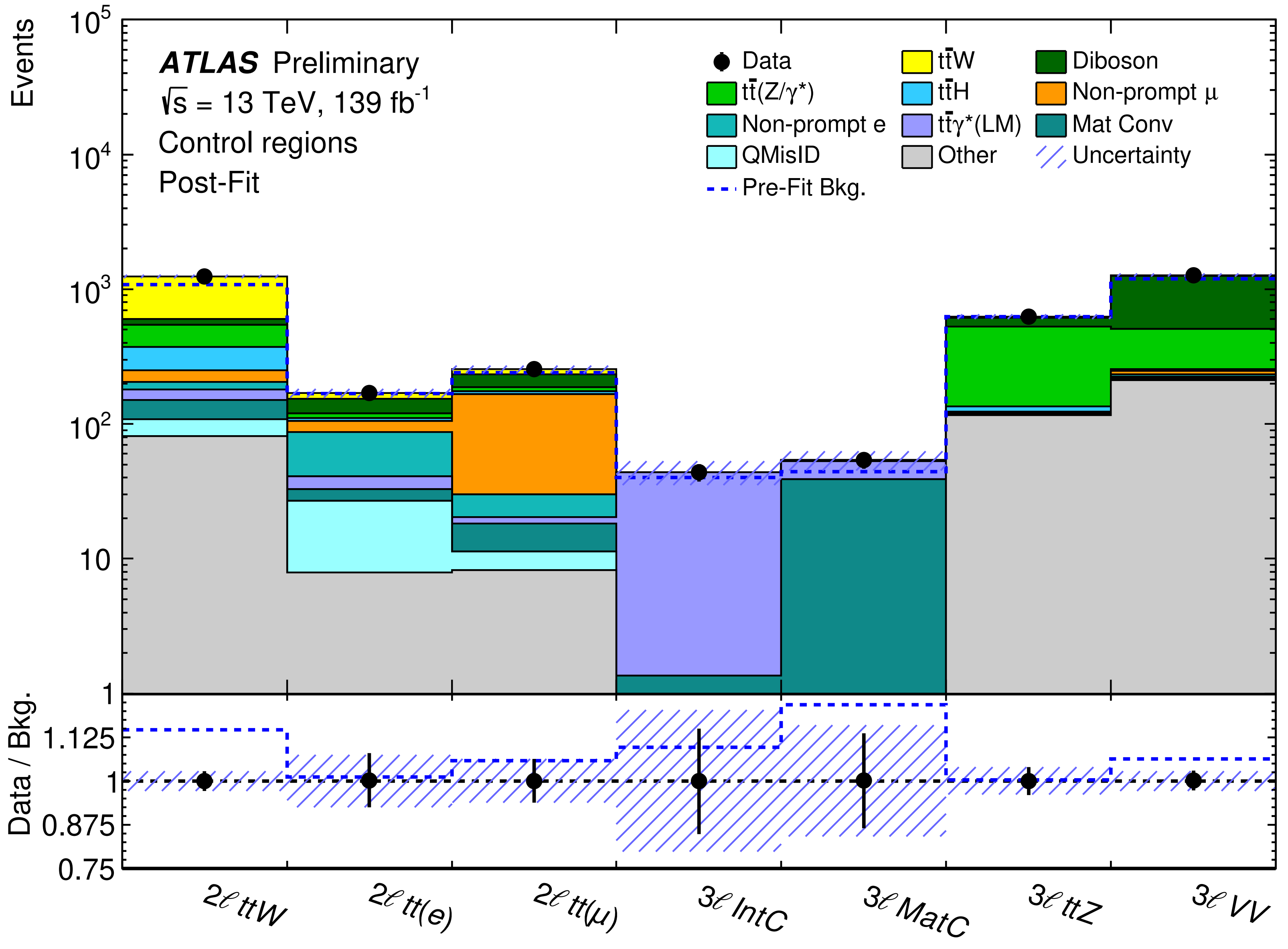
$m_{\ell\ell}^{\min}$: minimum of all combinations of dilepton invariant mass

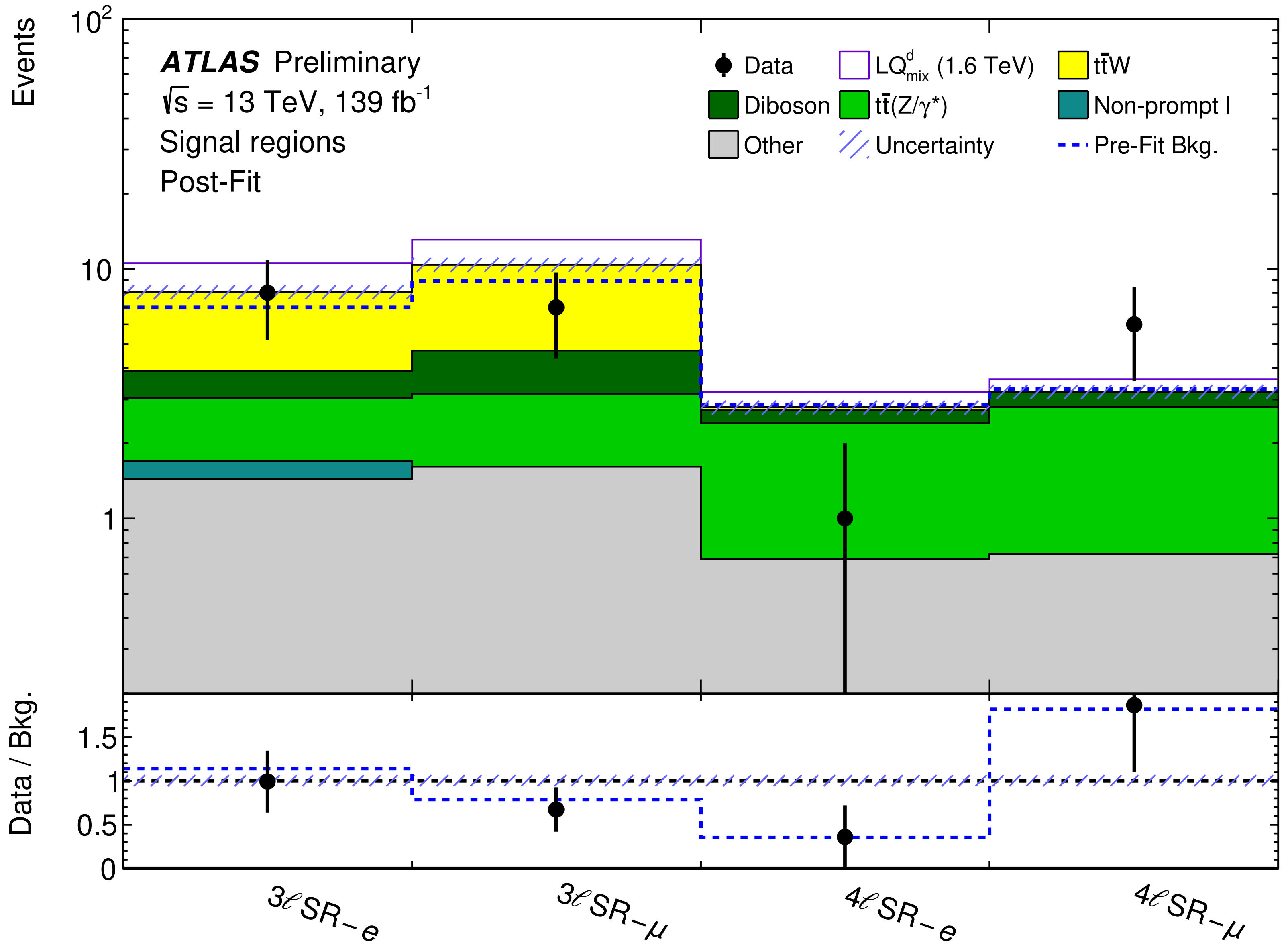


	3ℓ						
	CR				VR	SR	
	3ℓVV	3ℓttZ	3ℓIntC	3ℓMatC	3ℓVR	3ℓSR-e	3ℓSR-μ
e/μ selection	M (SS pair), L other						
e/μ combination	$3e$ / $2e1\mu$ / $2\mu1e$ / 3μ					$3e$ / $2e1\mu$	3μ / $2\mu1e$
Total charge	±1		–		±1		
e internal conversion veto	Yes		Inverted (ℓ_1 or ℓ_2)	Yes (ℓ_1 and ℓ_2)	Yes		
e material conversion veto	Yes		Yes (ℓ_1 and ℓ_2)	Inverted (ℓ_1 or ℓ_2)	Yes		
Number of jets	≥ 2		≥ 0		≥ 2		
Number of b-jets	1	≥ 2	0		≥ 1		
p_T^{ℓ} [GeV]	> 20 (SS pair), > 10 other				> 20		
$m_{\ell^+\ell^-}^{OS-SF}$ [GeV]	> 12						
$\lvert m_{\ell^+\ell^-}^{OS-SF} - m_Z \rvert$ [GeV]	< 10		> 10		> 10		
$\lvert m_{\ell\ell\ell} - m_Z \rvert$ [GeV]	–		< 10		–		
$m_{\ell\ell}^{\min}$ [GeV]	–				< 200	≥ 200	
m_{eff} [GeV]	–				–	≥ 500	

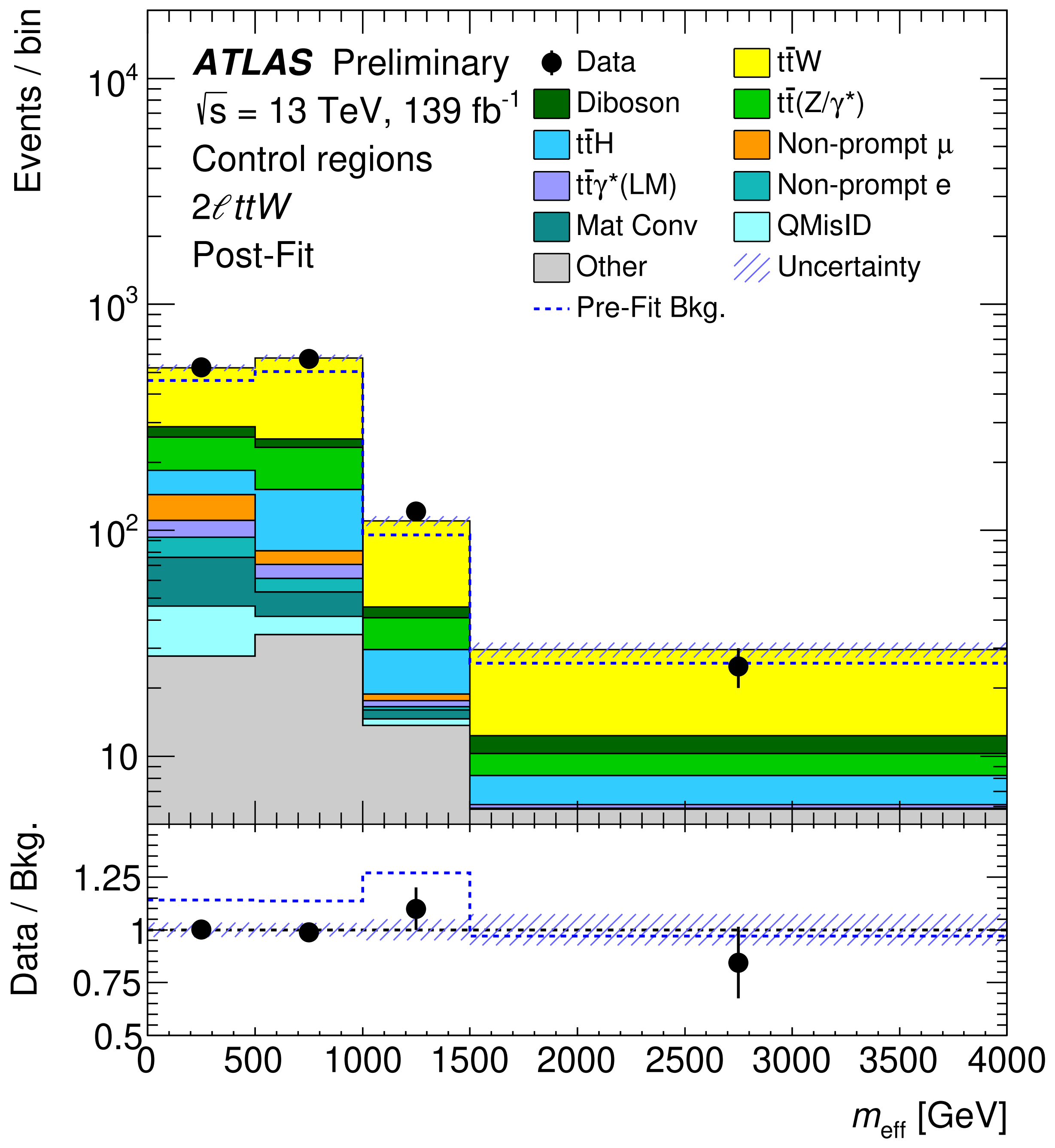
	4ℓ		
	VR	SR	
	4ℓVR	4ℓSR-e	4ℓSR-μ
e/μ selection	L		
e/μ combination	$4e$ / $3e1\mu$ / $2e2\mu$ / $3\mu1e$ / 4μ	$4e$ / $3e1\mu$ / $2e2\mu$ (lead e)	4μ / $3\mu1e$ / $2\mu2e$ (lead μ)
Total charge	0		
Number of jets	≥ 2		
Number of b-jets	≥ 1		
p_T^{ℓ} [GeV]	> 10		
$m_{\ell^+\ell^-}^{OS-SF}$ [GeV]	> 12		
$\lvert m_{\ell^+\ell^-}^{OS-SF} - m_Z \rvert$ [GeV]	> 10		
$m_{\ell\ell}^{\min}$ [GeV]	< 100	≥ 100	
m_{eff} [GeV]	–	≥ 500	

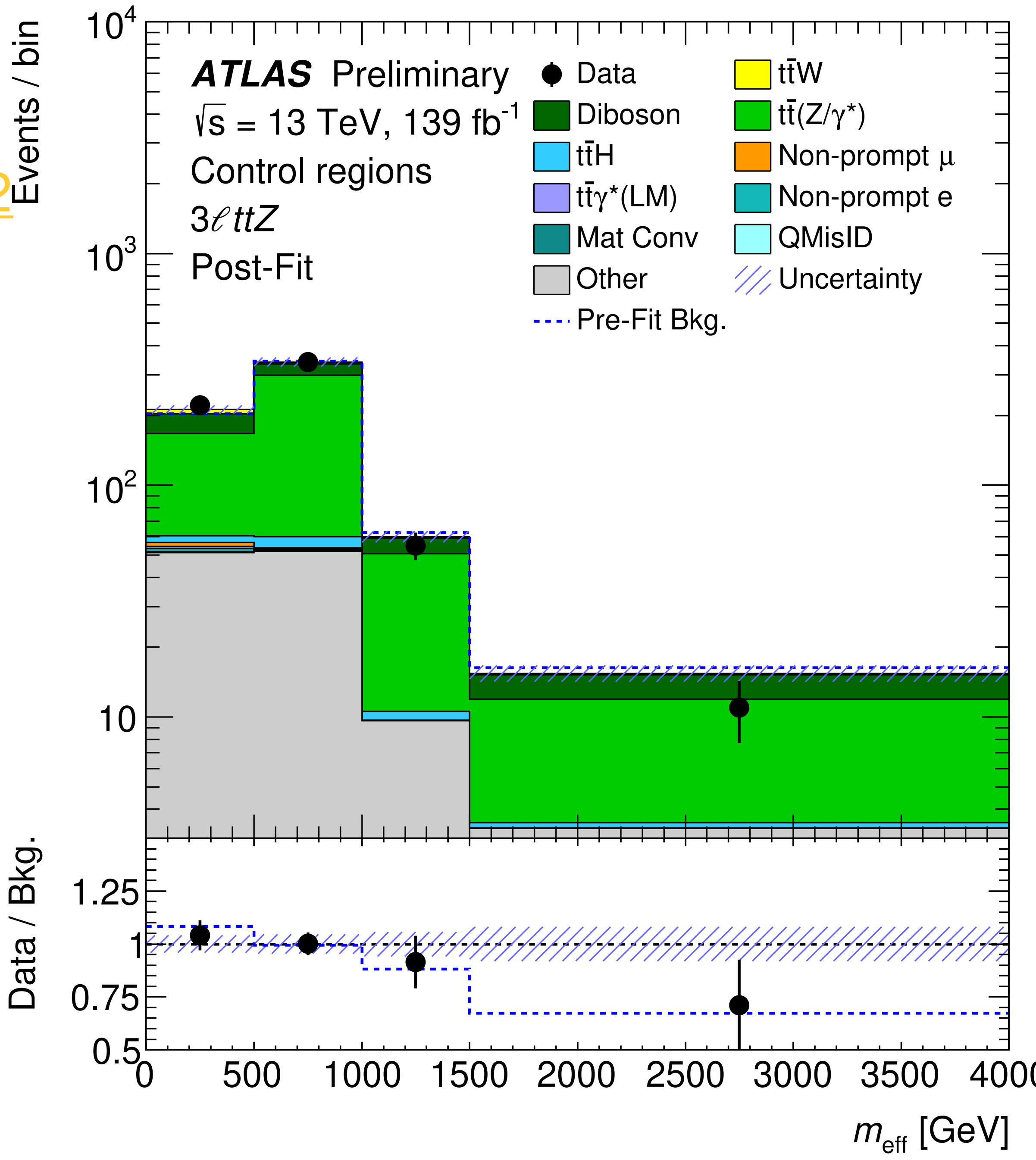
2ℓSS CRs for $t\bar{t}W$ and non-prompt backgrounds:
- at least two jets
- at least one b-jet

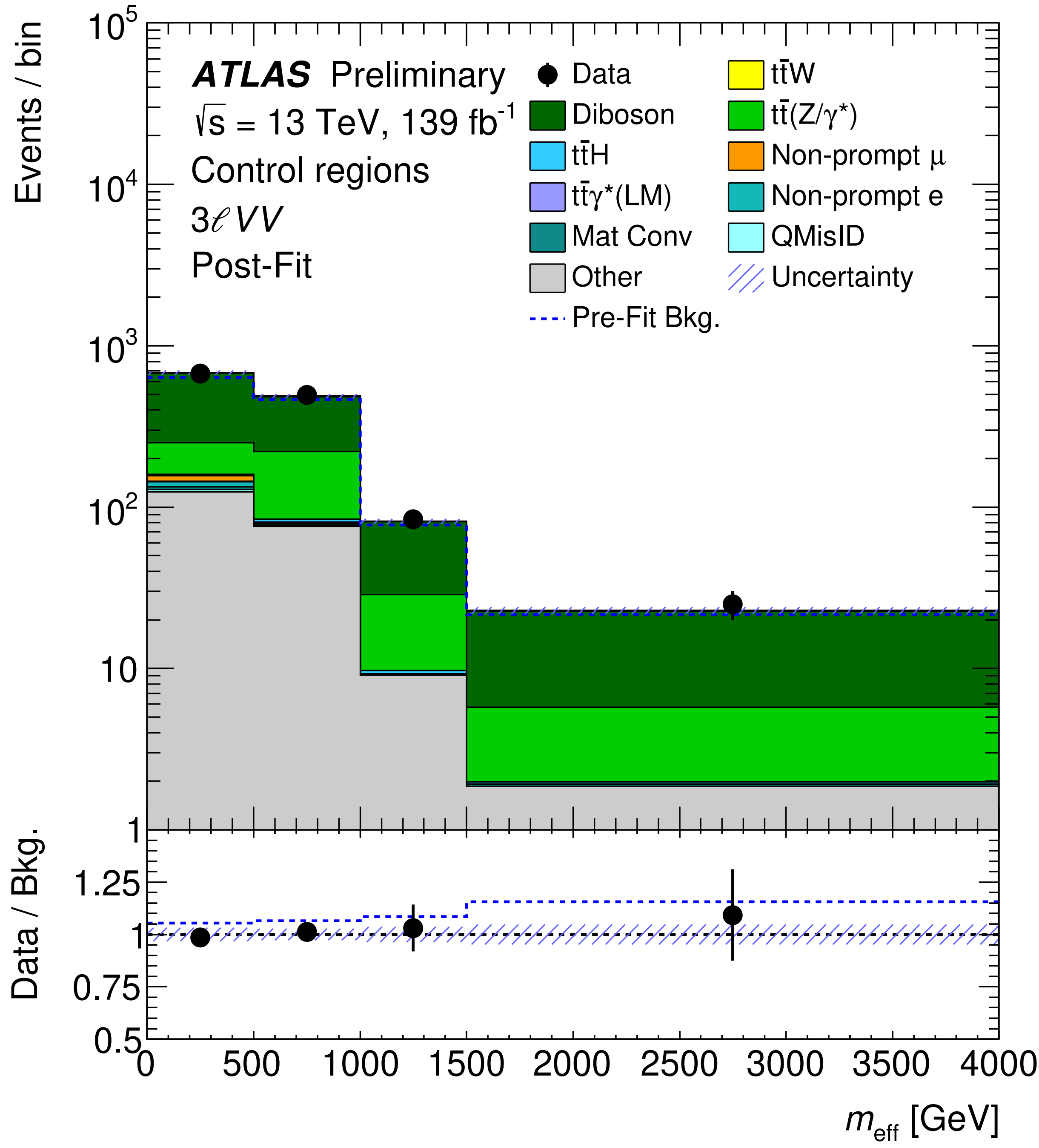


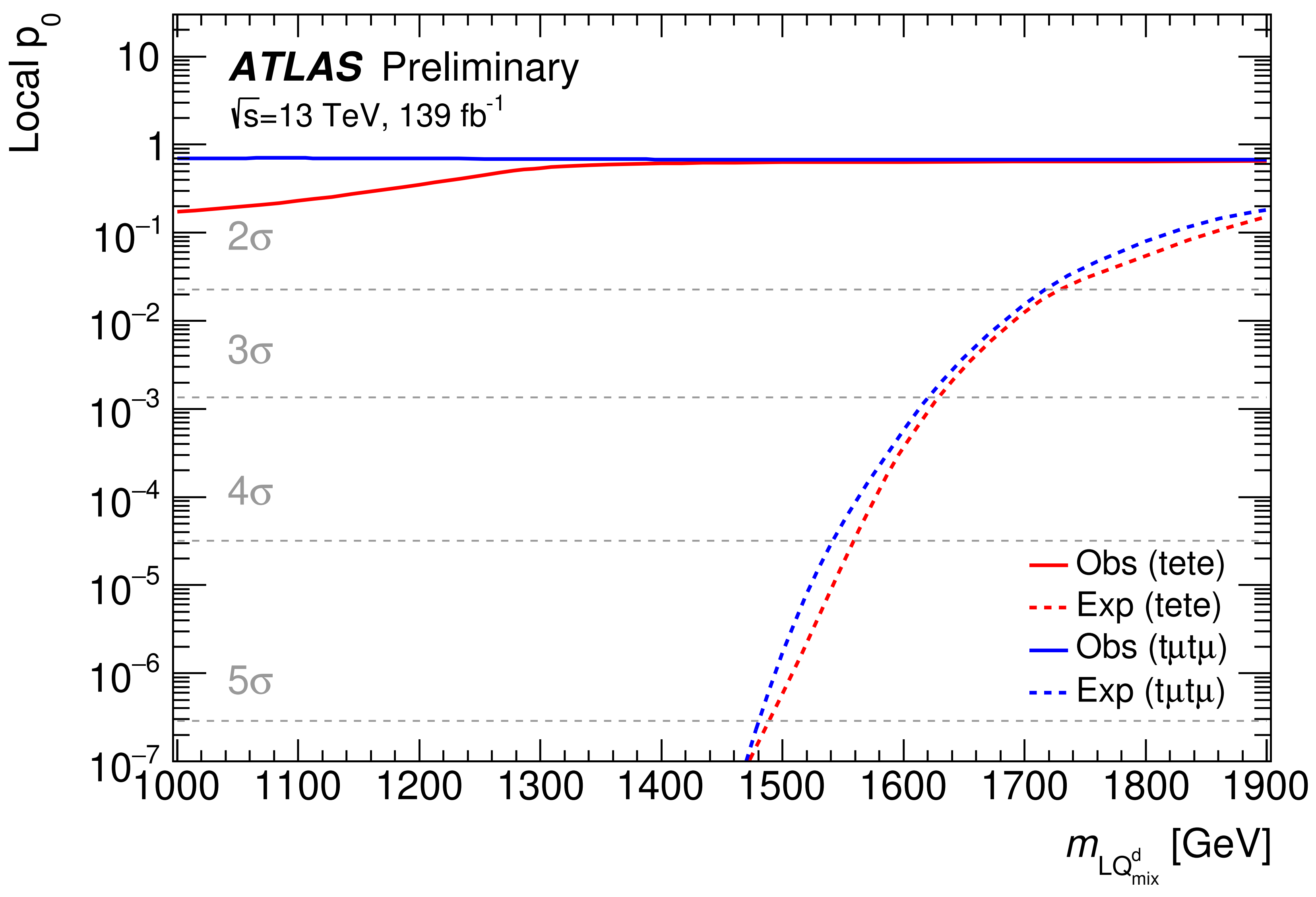


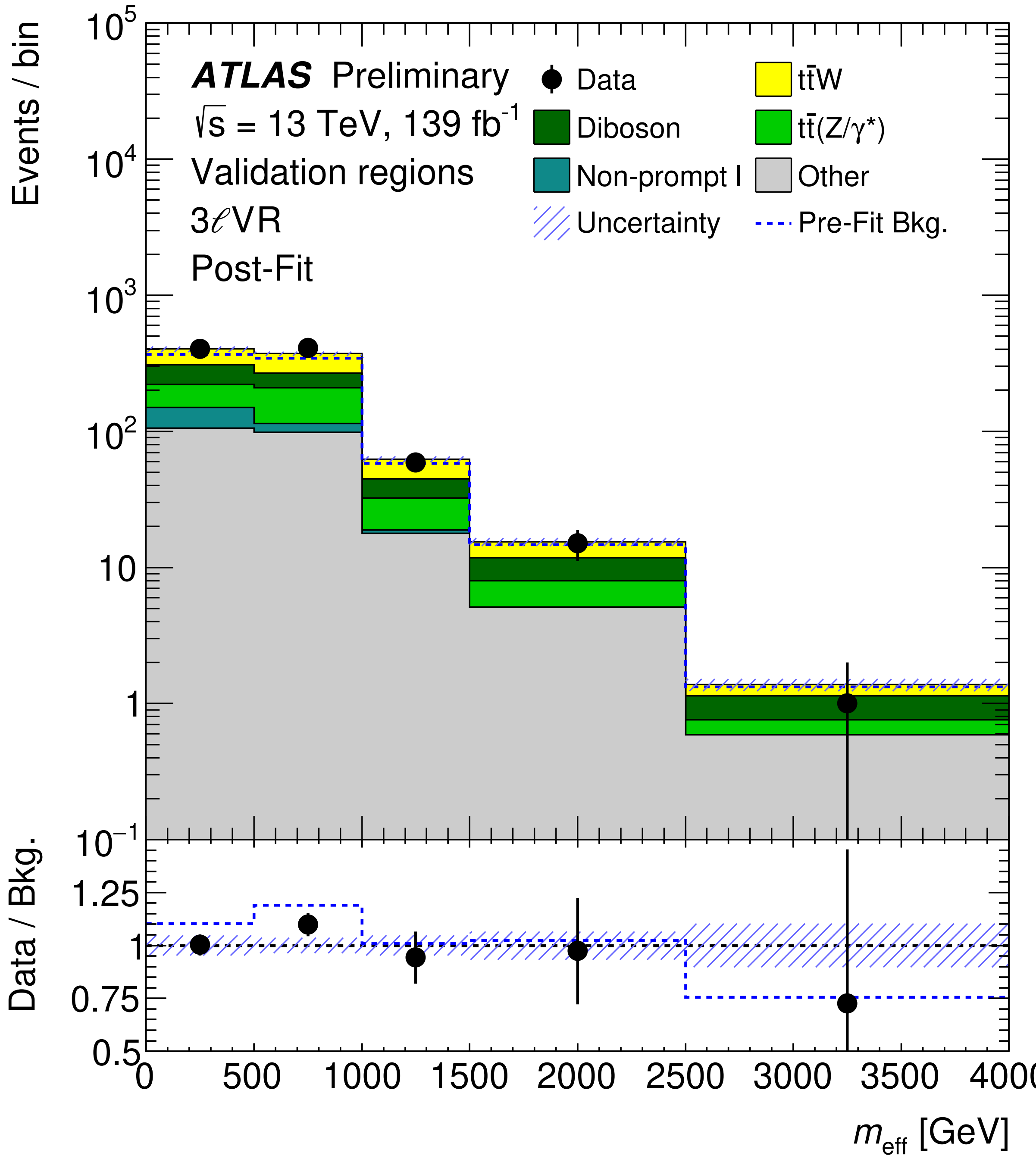
$LQ\,LQ \rightarrow t\ell\, t\ell \;\; (\ell = e, \mu)$ ATLAS-CONF-2022-052

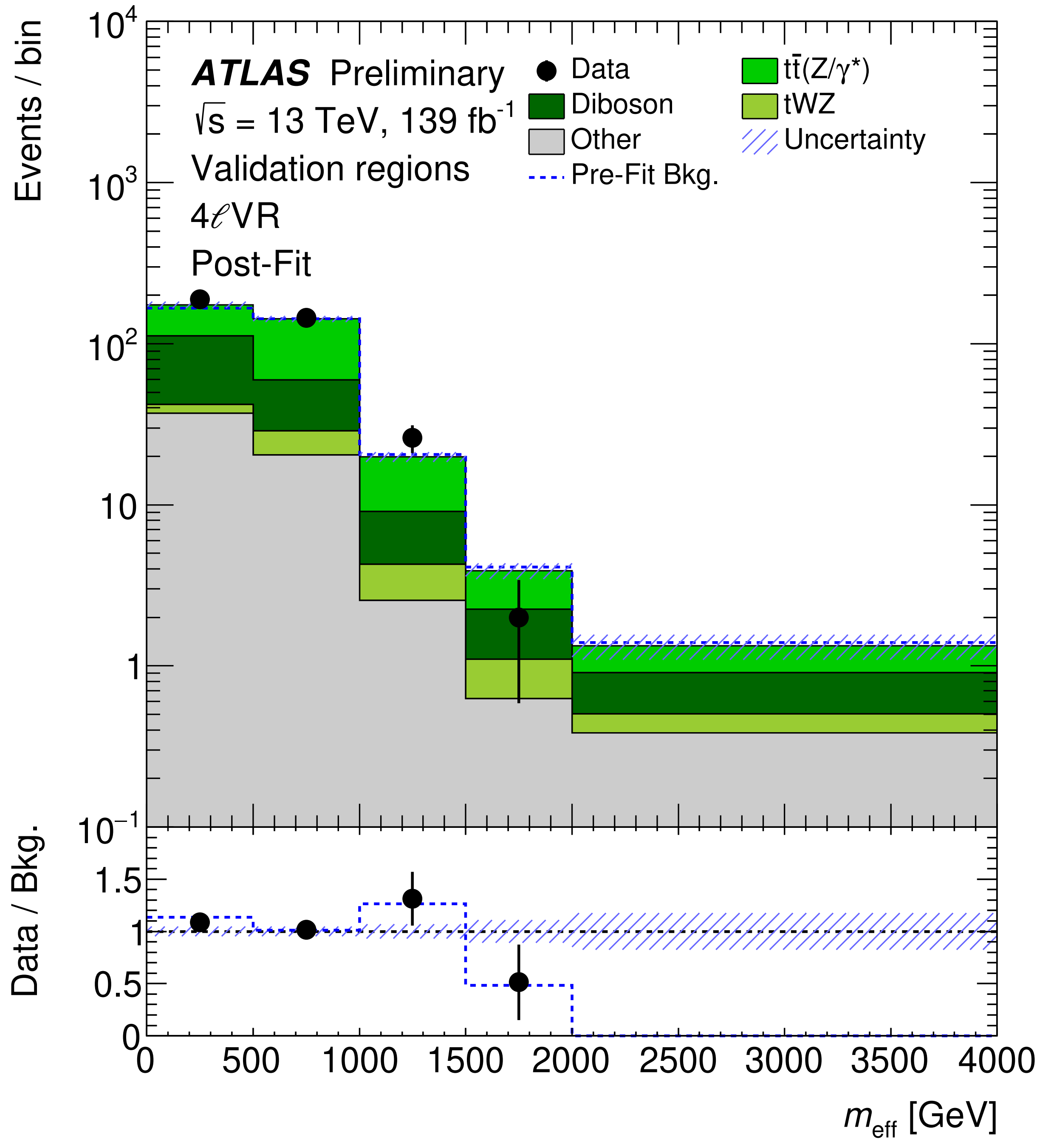








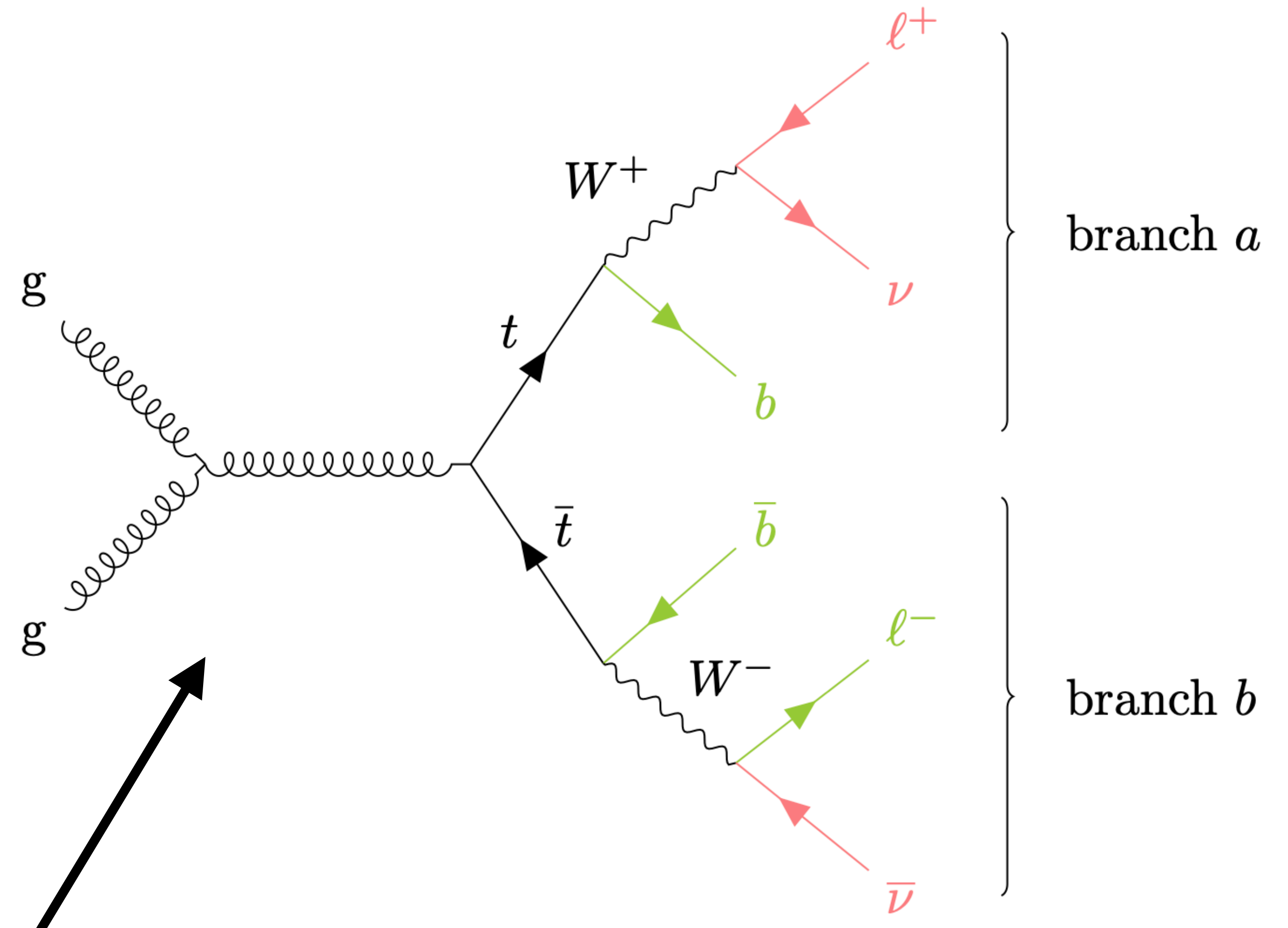




$\mathrm{LQ}\,\overline{\mathrm{LQ}} \rightarrow t\nu\, b\ell\ \ (\ell = e, \mu)$ EXOT-2019-12

Preselection			
E_T^{miss} triggers exactly one signal lepton veto on additional baseline leptons $E_T^{miss} > 250$ GeV ≥ 4 small-R jets $m_T(\ell, E_T^{miss}) > 30$ GeV $\Delta\phi(E_T^{miss}, j_{1,2}) > 0.4$			
Top reweighting region	W+jets CR	Single-top CR	Training region
$n_b \geq 1$	$n_b = 1$	$n_b = 2$	$n_b \geq 1$
$m_T(\ell, E_T^{miss}) \geq 120$ GeV	50 GeV $\leq m_T(\ell, E_T^{miss}) < 120$ GeV	$m_T(\ell, E_T^{miss}) < 120$ GeV	$m_T(\ell, E_T^{miss}) \geq 120$ GeV
$am_{T2} < 200$ GeV	$am_{T2} > 200$ GeV	$am_{T2} > 200$ GeV	$am_{T2} > 200$ GeV
-	t_{had} candidate veto	large-R jet veto	-
-	lepton charge = $+1e$	-	-
-	-	$\Delta R(b_1, b_2) > 1.2$	-

$$amt_2 = \min_{\vec{p}_T(\nu_b)+\vec{p}_T(W_a)=\vec{E}_T^{miss}} \left(\max(m_{T,a}, m_{T,b})\right)$$



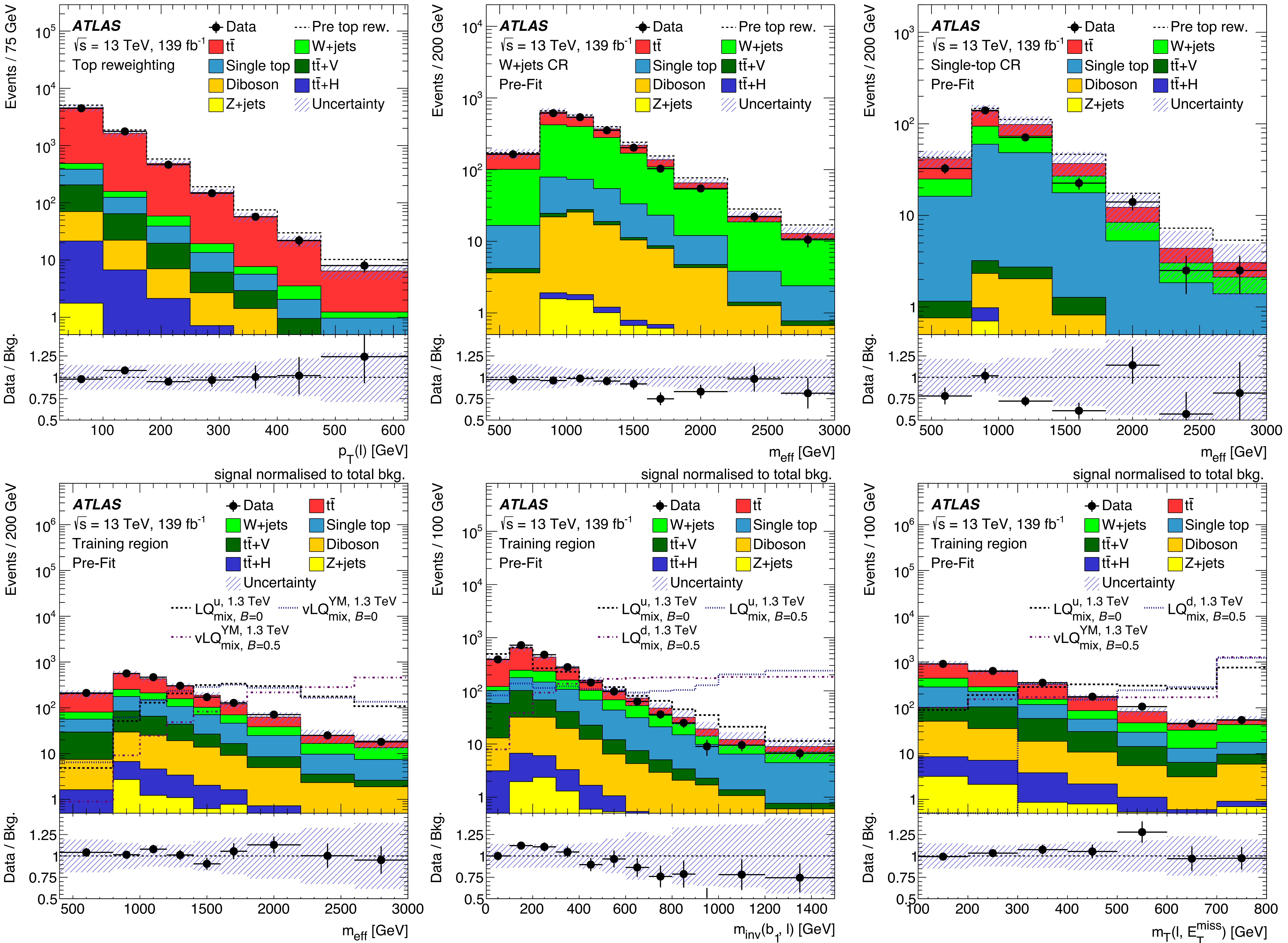
$$S = \frac{E_T^{miss}}{\sqrt{\sigma_L^2(1-\rho_{LT}^2)}}$$

Variance in parallel to measured $\vec{E}_T^{miss}$

Correlation factor between momentum measurements in parallel and perpendicularly to measured $\vec{E}_T^{miss}$

Variable	Description
$m_T(\ell, E_T^{miss})$	transverse mass of lepton and E_T^{miss}
m_{eff}	scalar sum of the transverse momenta of leptons, jets, and E_T^{miss}
Lepton flavour	flavour of the signal lepton
$p_T(\ell)$	transverse momentum of the lepton
$m_{inv}(b_1, \ell)$	invariant mass of the leading-p_T b-jet and the lepton
n_{large}	reclustered large-R jet multiplicity
am_{T2}	asymmetric transverse mass
E_T^{miss} significance	measure for assessing the compatibility of the observed E_T^{miss} with zero, taking resolutions into account
$m_T(b_1, E_T^{miss})$	transverse mass of leading-p_T b-jet and E_T^{miss}
$p_T(t_{had})$	transverse momentum of t_{had}
$\Delta\phi(E_T^{miss}, b_2)$	azimuthal angle separation between E_T^{miss} and subleading-p_T b-jet
$m_{inv}(b_2, \ell)$	invariant mass of subleading-p_T b-jet and lepton
$\Delta\phi(E_T^{miss}, b_1)$	azimuthal angle separation between E_T^{miss} and leading-p_T b-jet
$\Delta\phi(t_{had}, \ell)$	azimuthal angle separation between t_{had} and lepton
$p_T(b_1)$	transverse momentum of leading-p_T b-jet

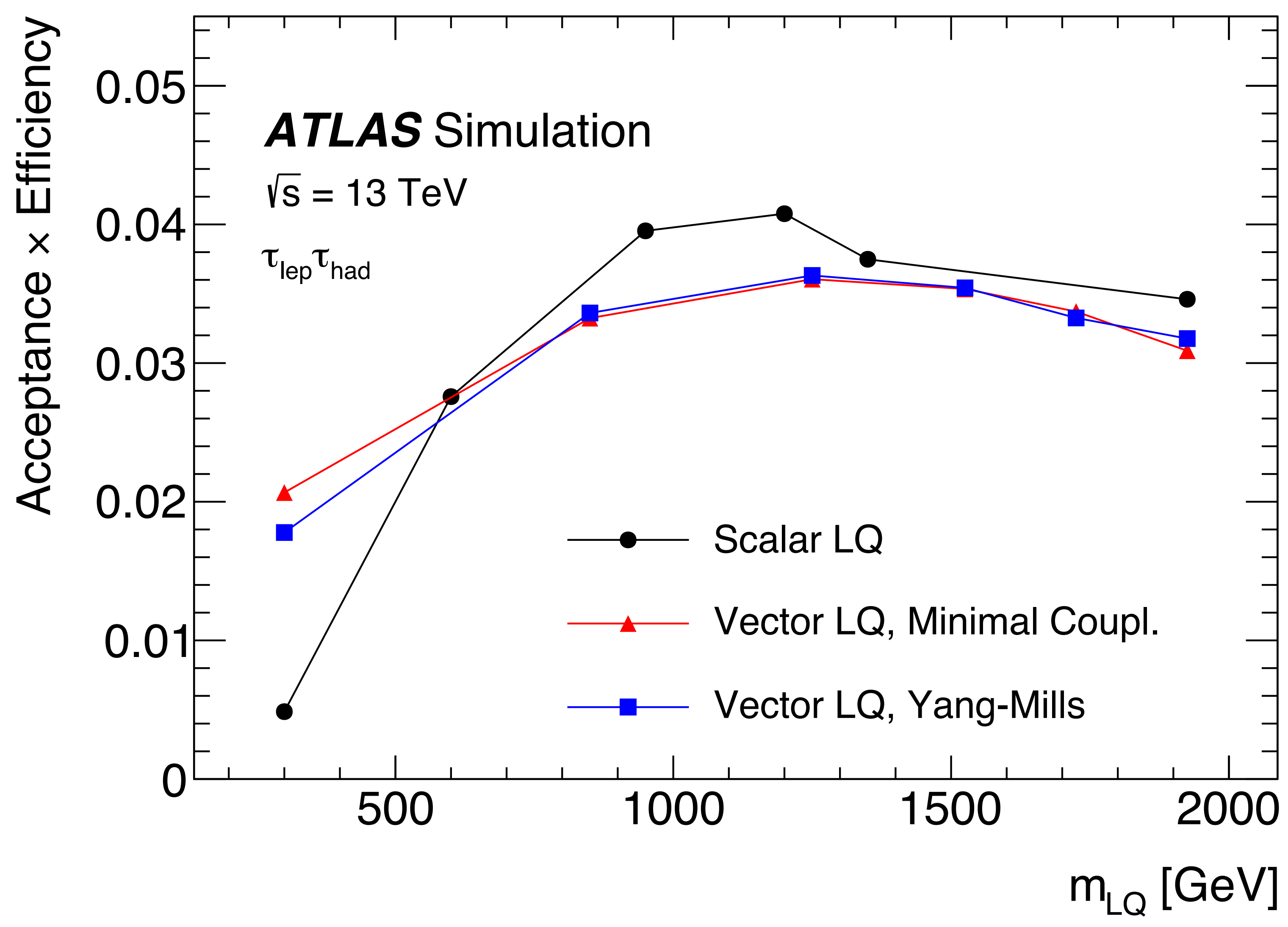
LQ LQ → $t\nu\, b\ell$ ($\ell = e, \mu$) EXOT-2019-12

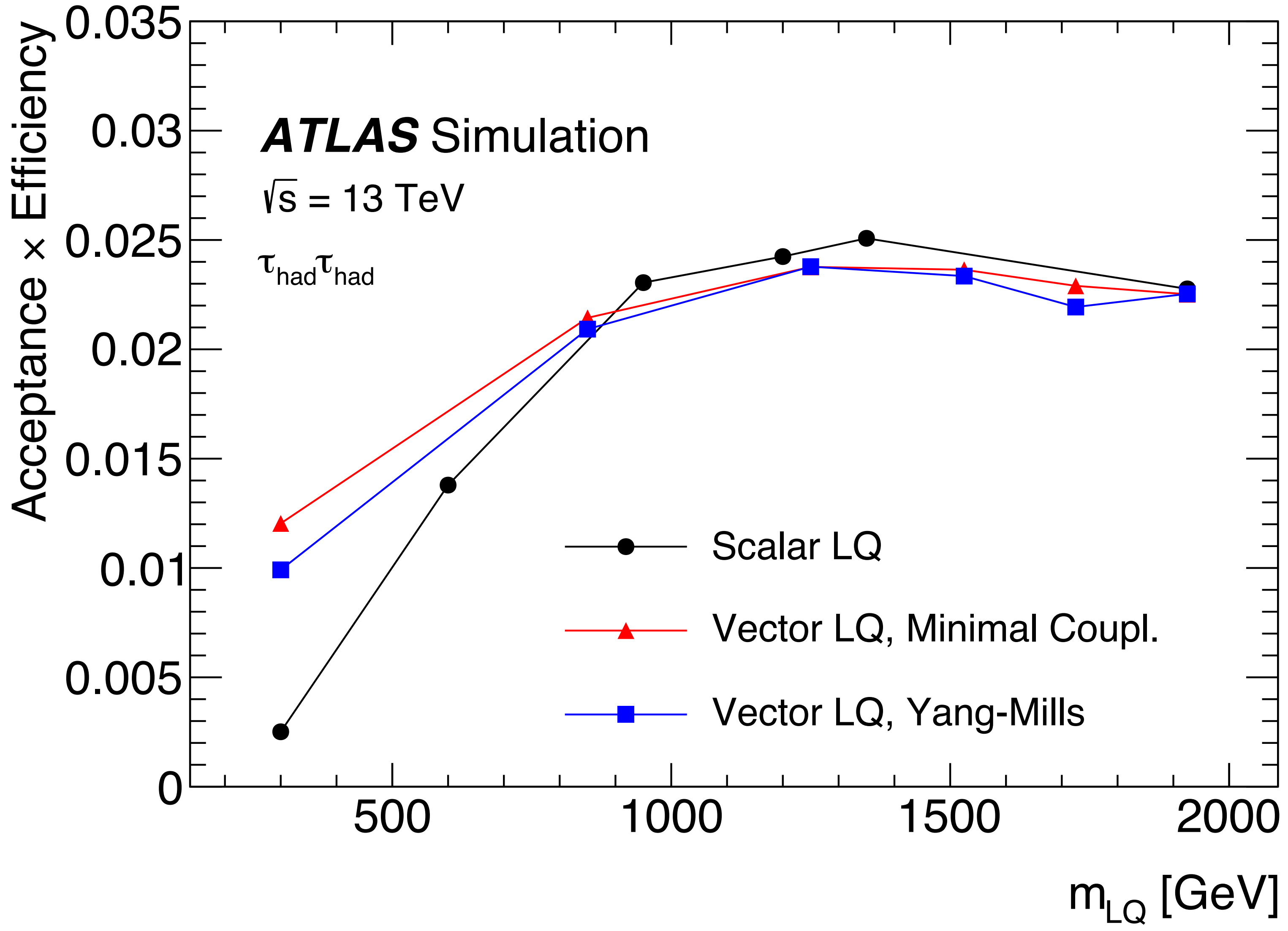


Top reweighing improves modelling in different observables and kinematic regions of phase space

Different observables provide discrimination power between the different signal and background processes

LQ LQ → bτ bτ EXOT-2021-15



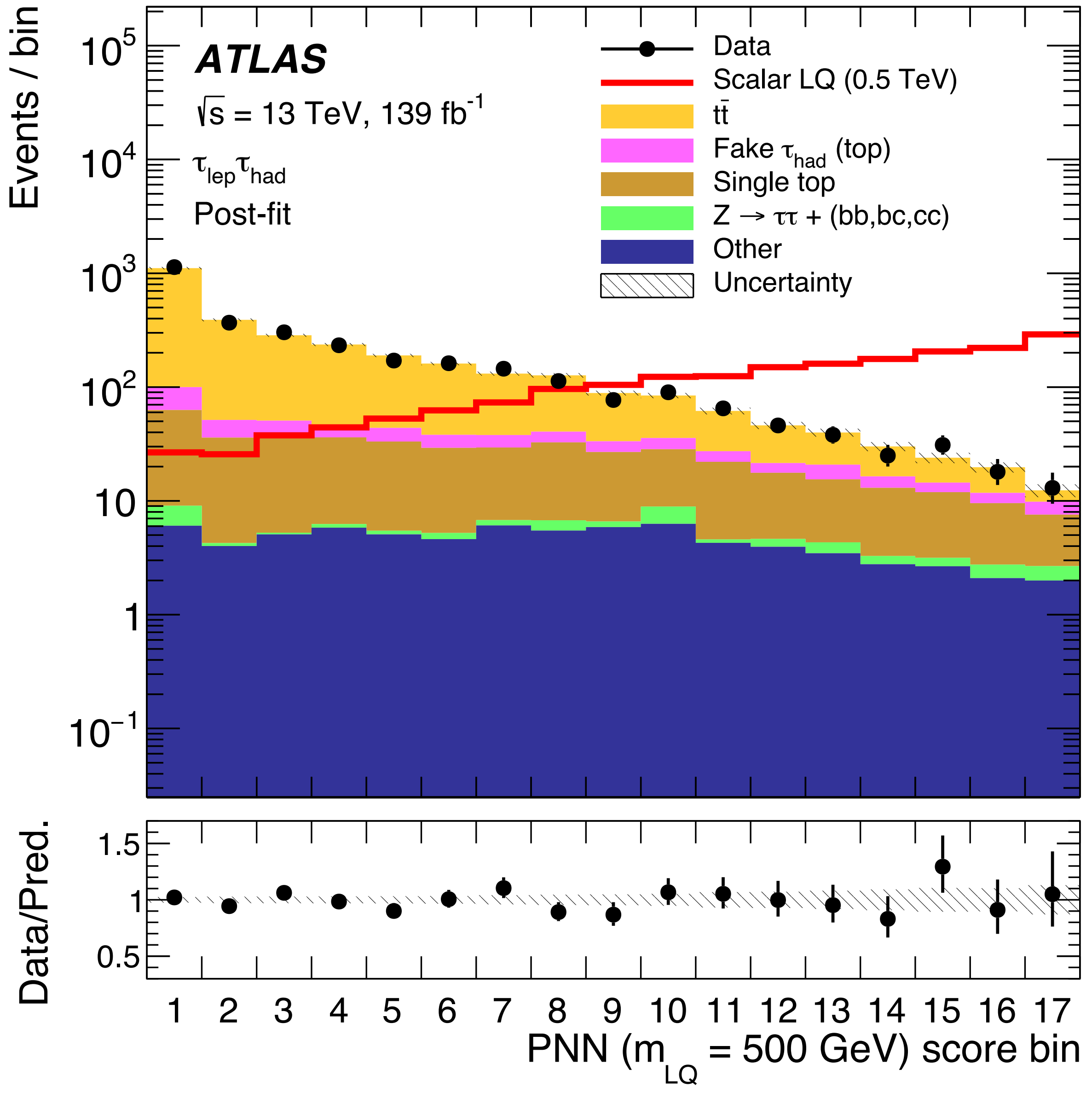


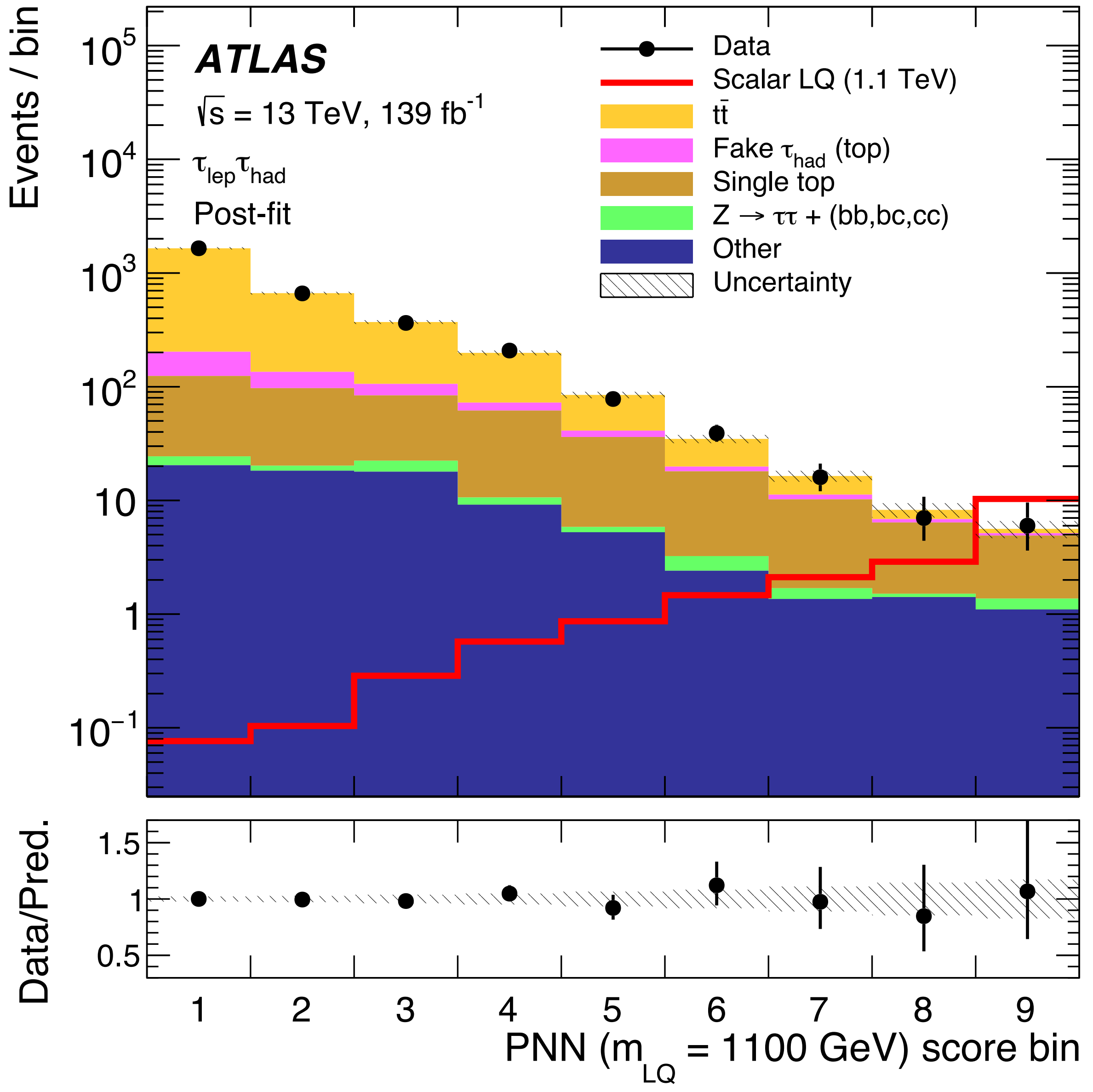
	$\tau_{lep}\tau_{had}$ channel	$\tau_{had}\tau_{had}$ channel
e/μ selection	= 1 'signal' e or μ $p_T^e > 25, 27$ GeV $p_T^\mu > 21, 27$ GeV	No 'veto' e or μ
$\tau_{had\text{-}vis}$ selection	= 1 $\tau_{had\text{-}vis}$ $p_T^\tau > 100$ GeV	= 2 $\tau_{had\text{-}vis}$ $p_T^\tau > 100, 140, 180$ (20) GeV
Jet selection	≥ 2 jets $p_T^{jet} > 45$ (20) GeV 1 or 2 b-jets	
Additional selection	Opposite charge e, μ, τ_{had} and τ_{had} $m_{\tau\tau}^{MMC} \notin 40 - 150$ GeV $E_T^{miss} > 100$ GeV $s_T > 600$ GeV	

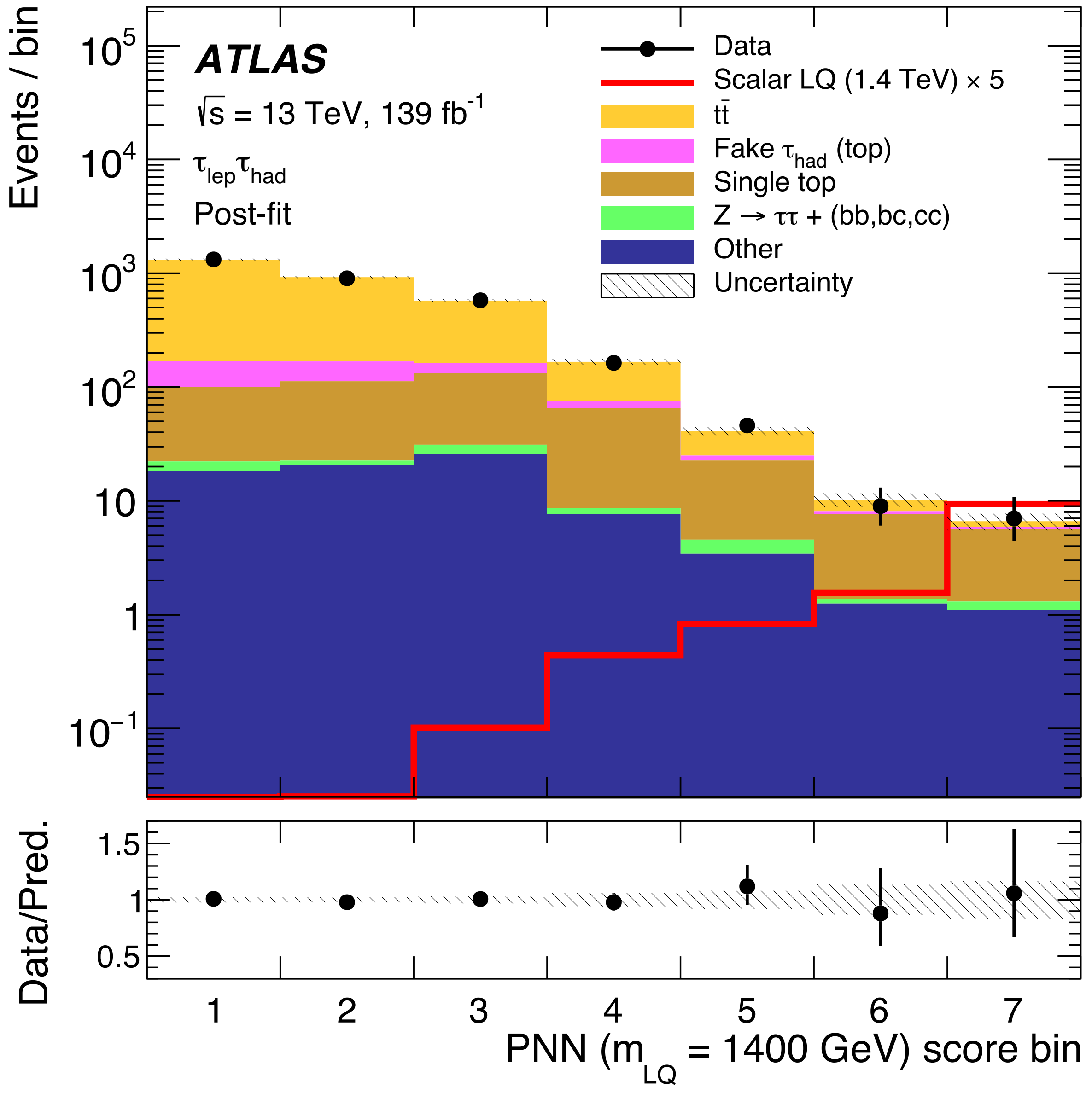
Invariant mass of the two τ leptons, $m_{\tau\tau}^{MMC}$, calculated from decay products by minimising likelihood function, taking expected decay kinematics into account (c.f. Nucl. Instrum. Meth. A 654 (2011) 481)

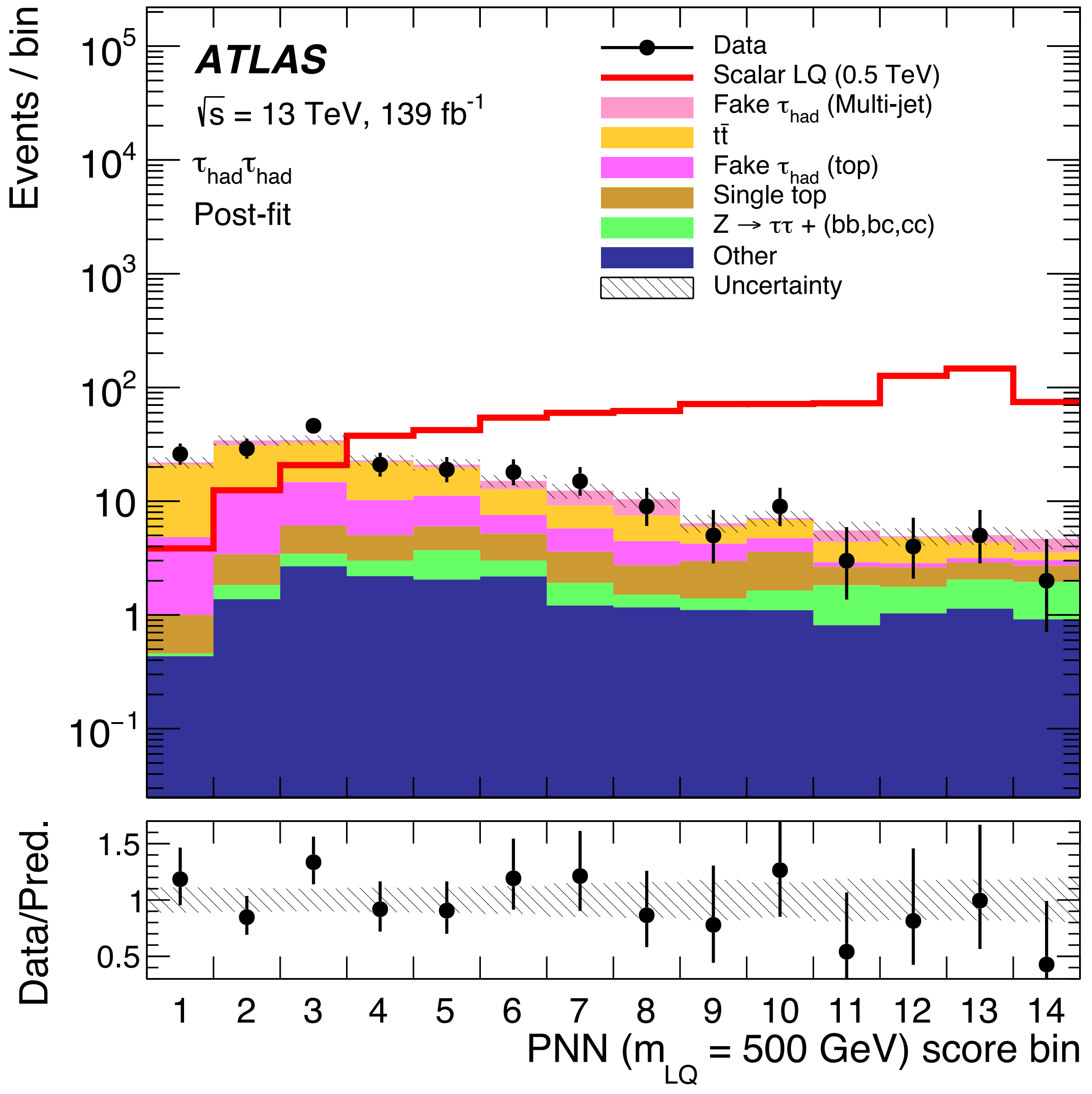
Variable	$\tau_{lep}\tau_{had}$ channel	$\tau_{had}\tau_{had}$ channel
$\tau_{had\text{-}vis}$ p_T^0	✓	✓
s_T	✓	✓
N_{b-jets}	✓	✓
$m(\tau, \text{jet})_{0,1}$		✓
$m(\ell, \text{jet}), m(\tau_{had}, \text{jet})$	✓	
$\Delta R(\tau, \text{jet})$	✓	✓
$\Delta\phi(\ell, E_T^{miss})$	✓	
E_T^{miss} ϕ centrality	✓	✓

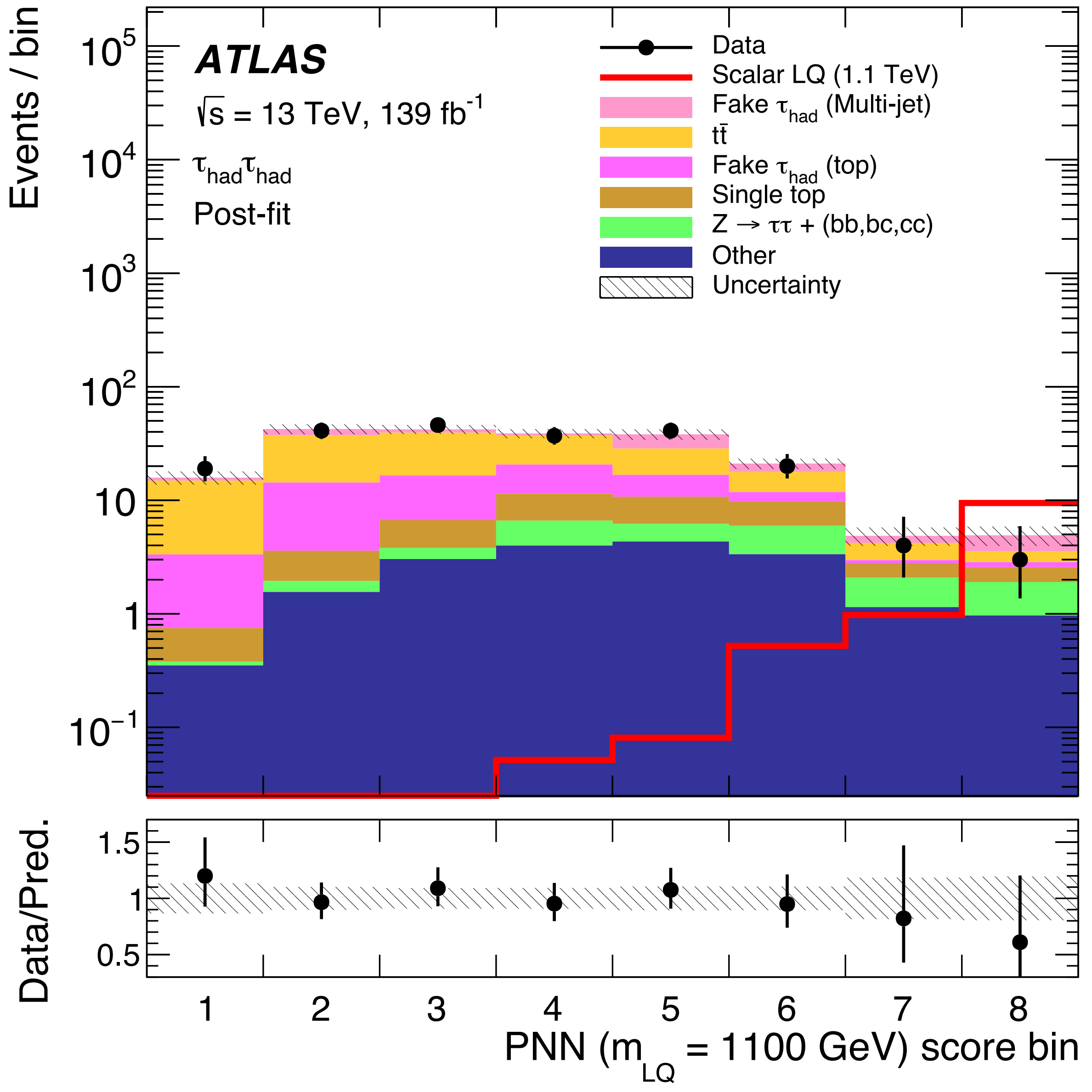
LQ LQ → bτ bτ EXOT-2021-15

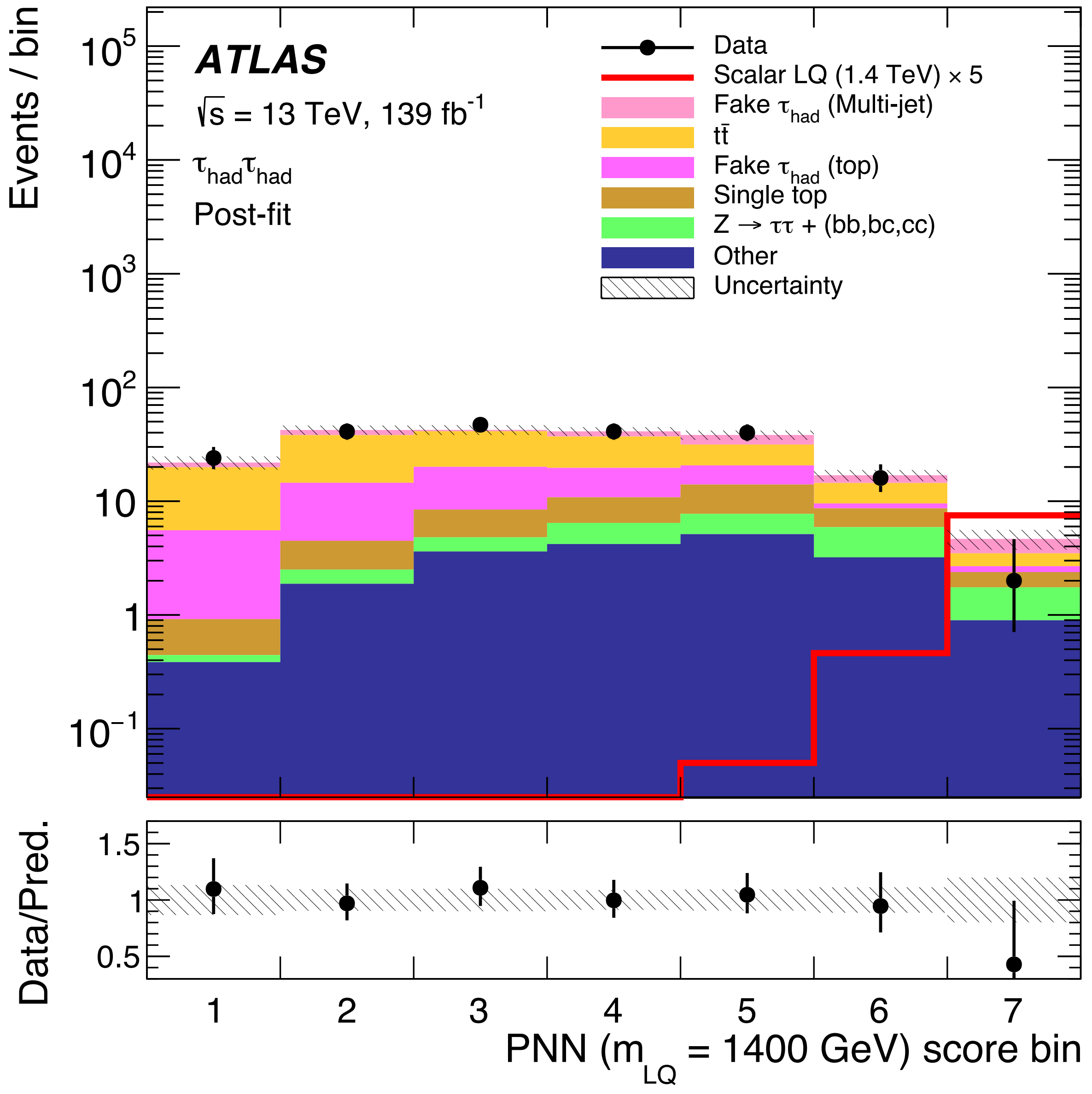






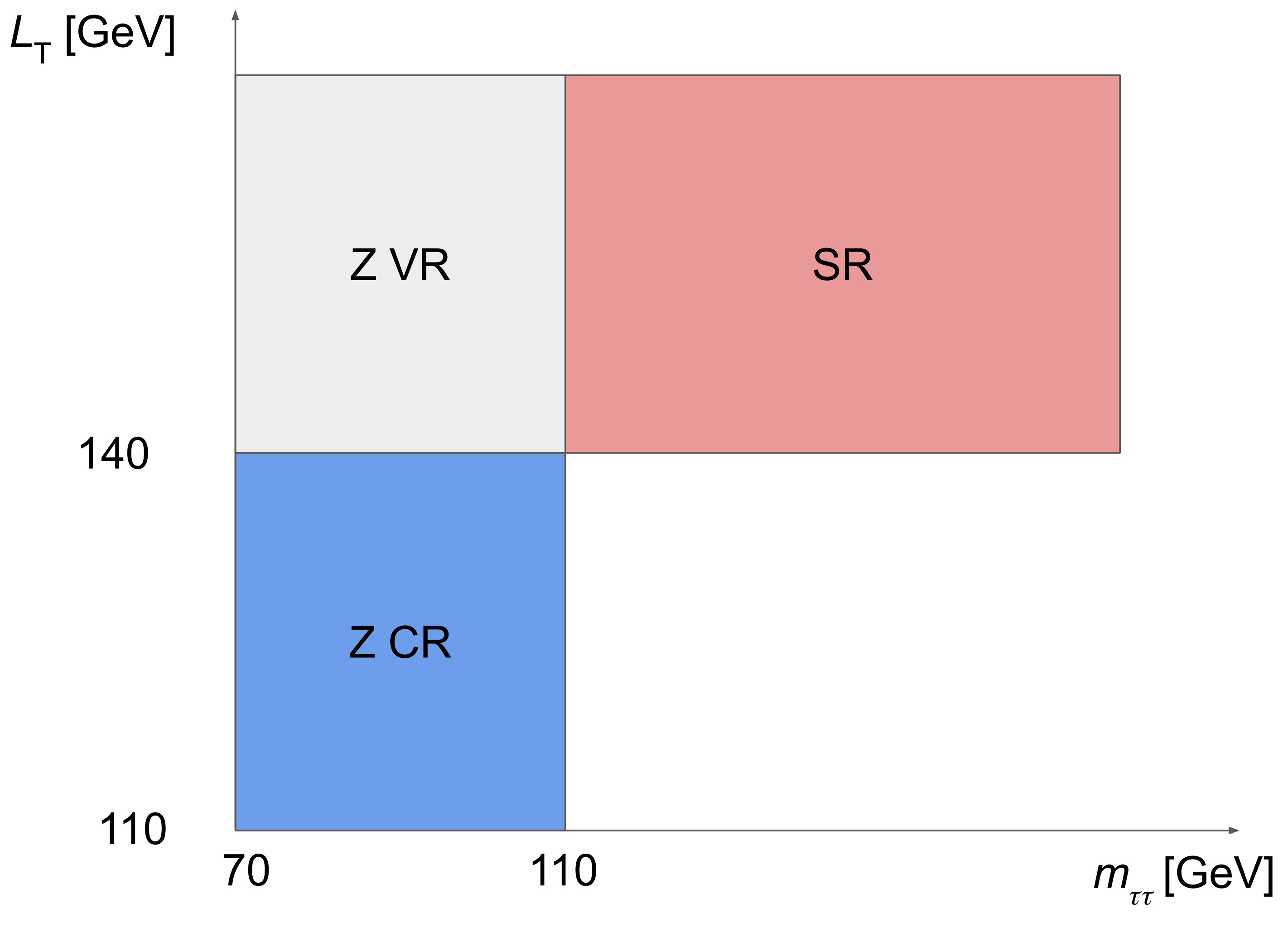




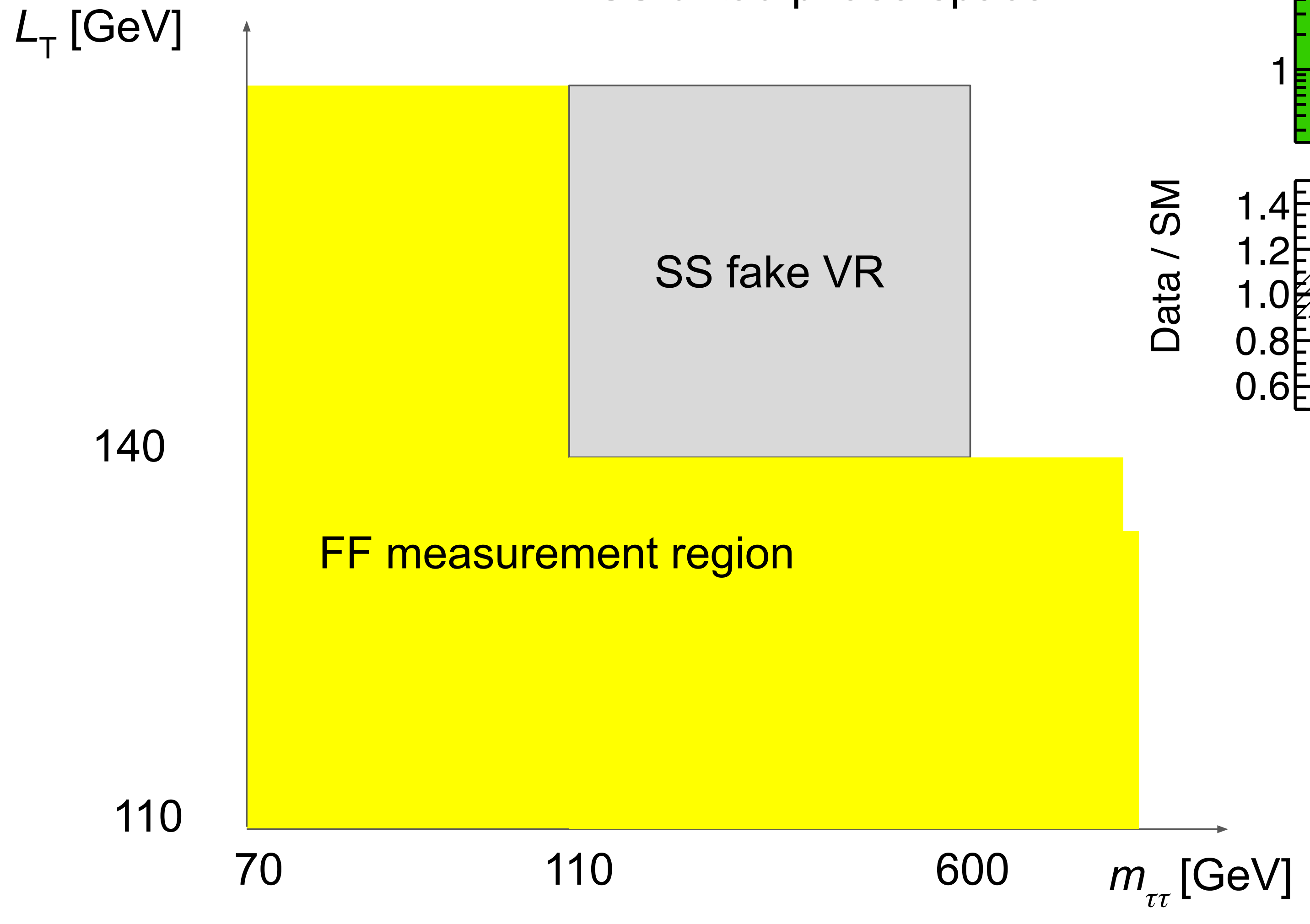


$LQ\,LQ \rightarrow q\tau\, q\tau$ ($q = u, d, c, s$) EXOT-2020-18

Di-tau phase-space

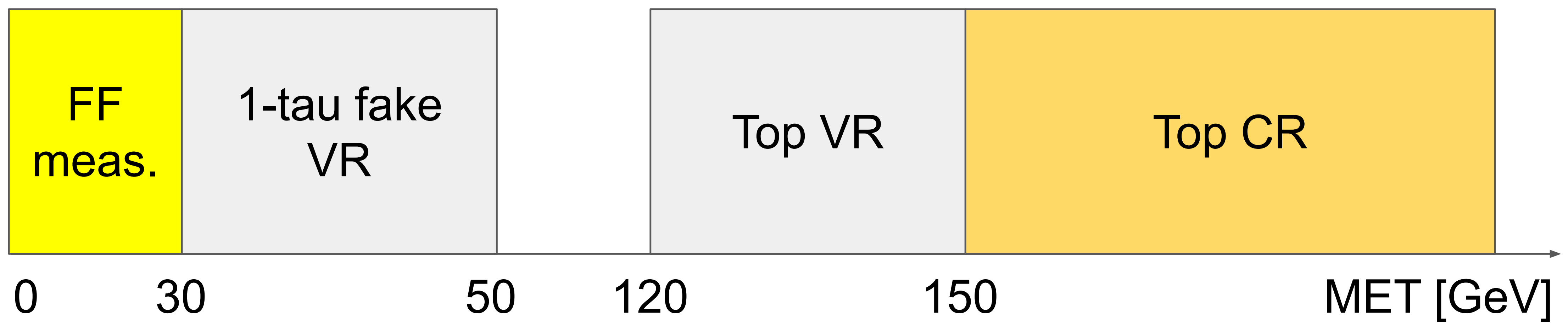


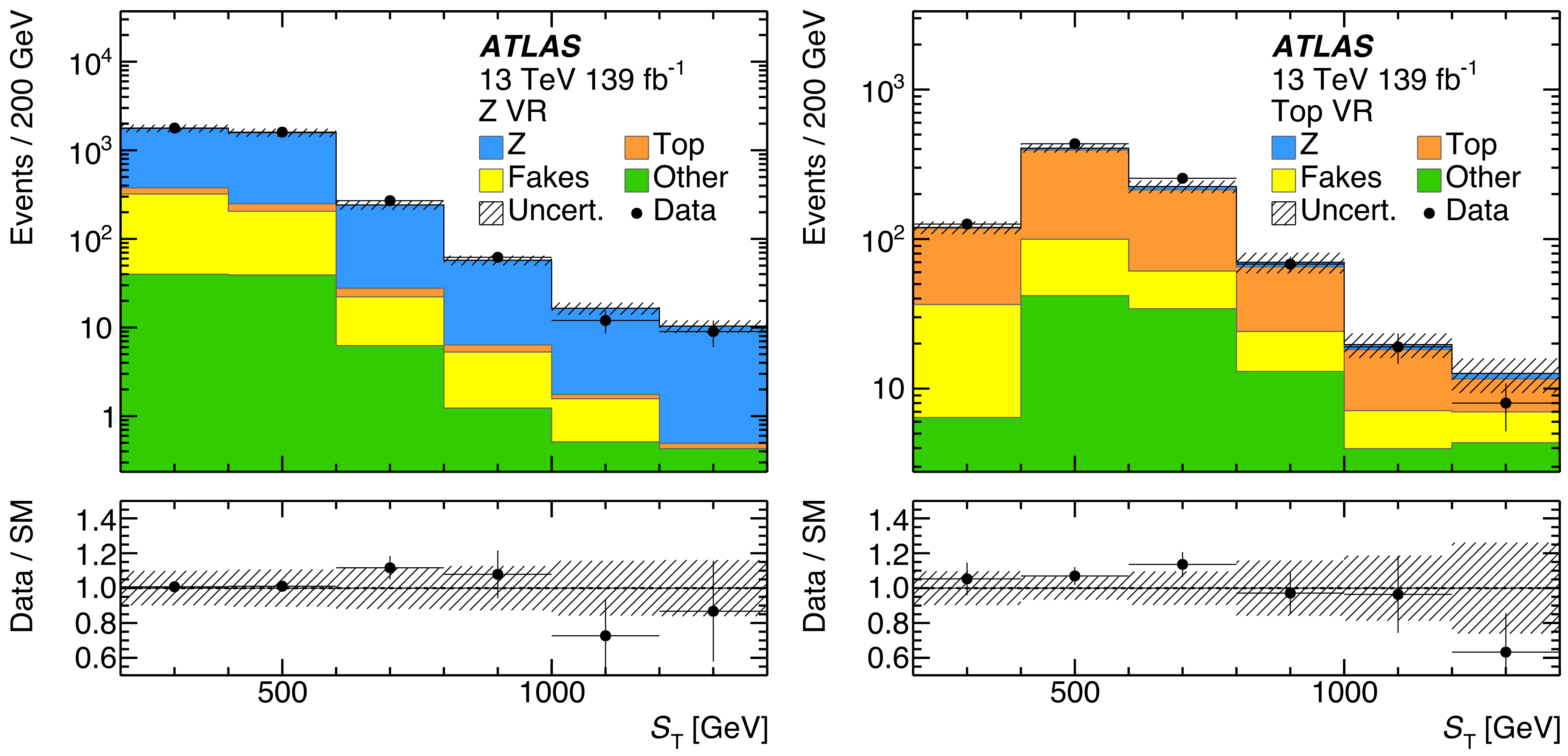
SS di-tau phase-space



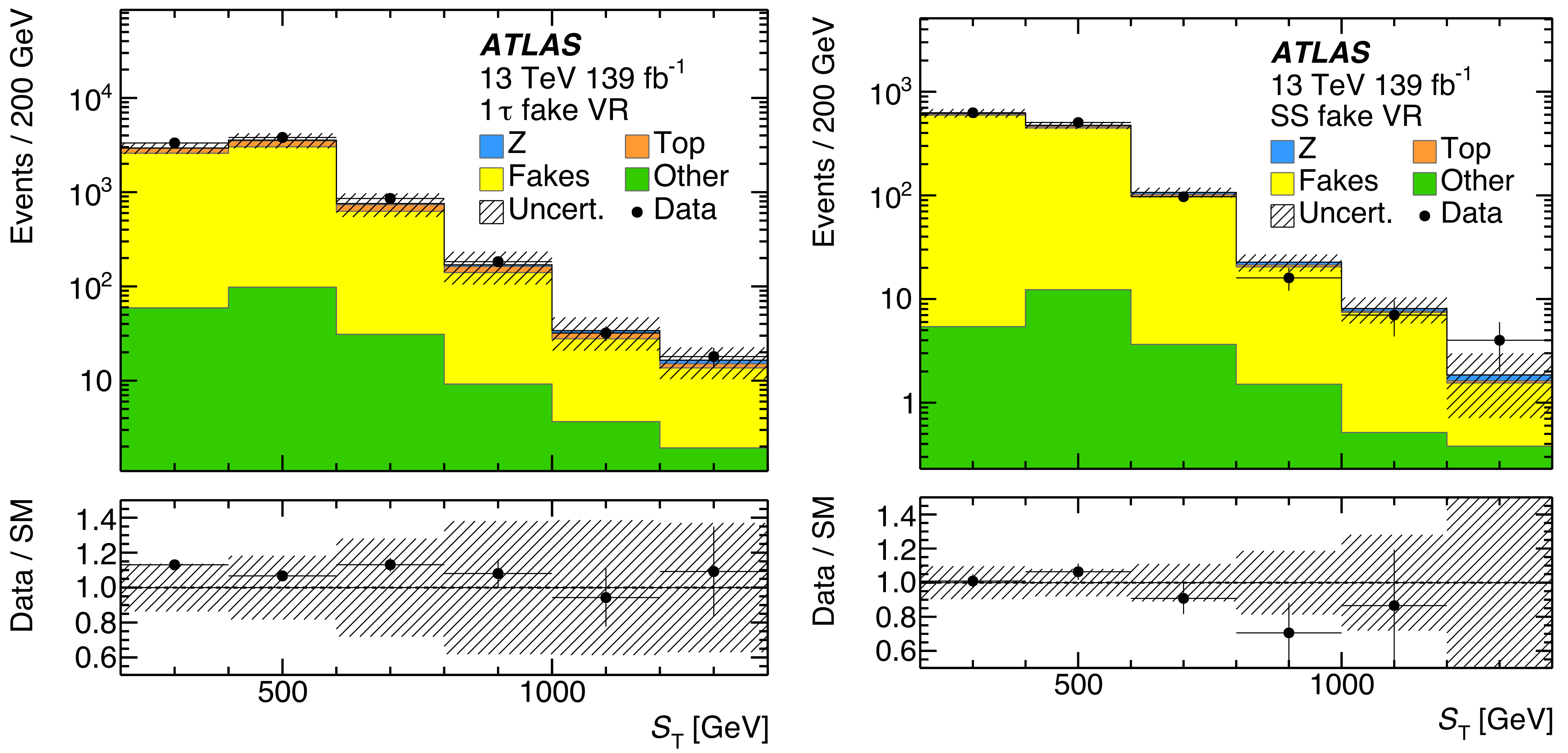
$$L_T = p_T^{\tau_1} + p_T^{\tau_2}$$

Single-tau + 2b phase-space



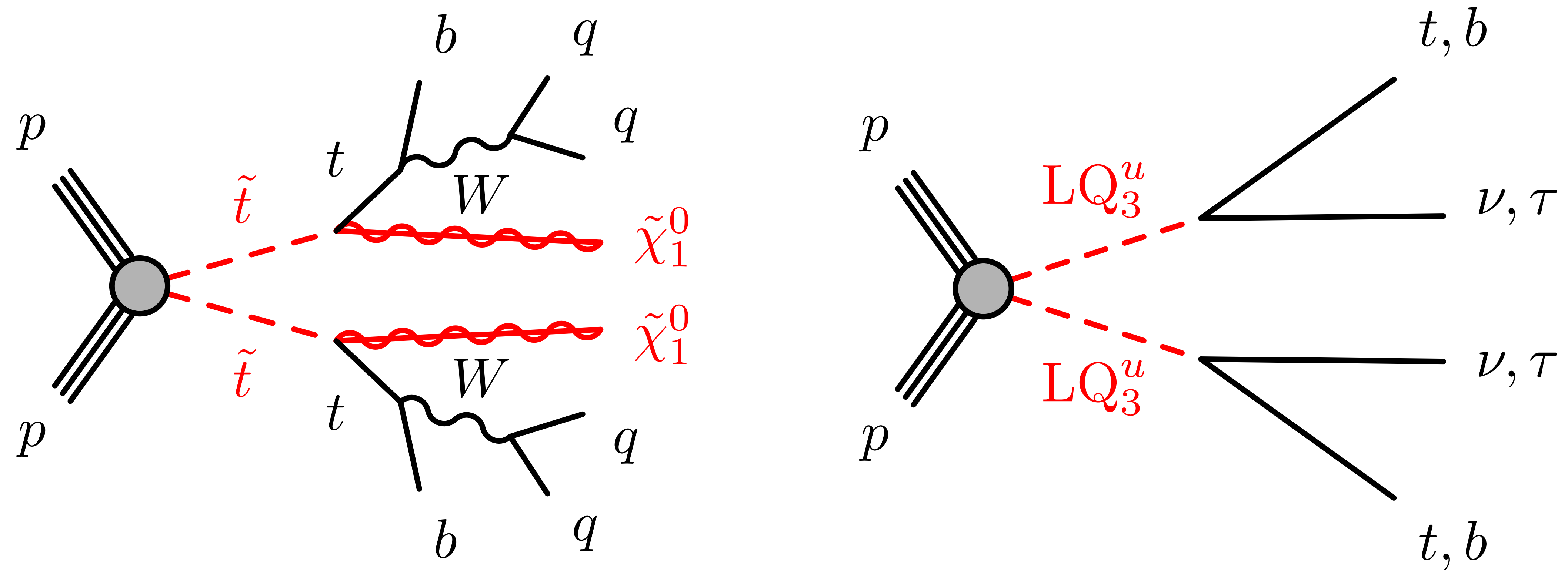


Good agreement also in VRs

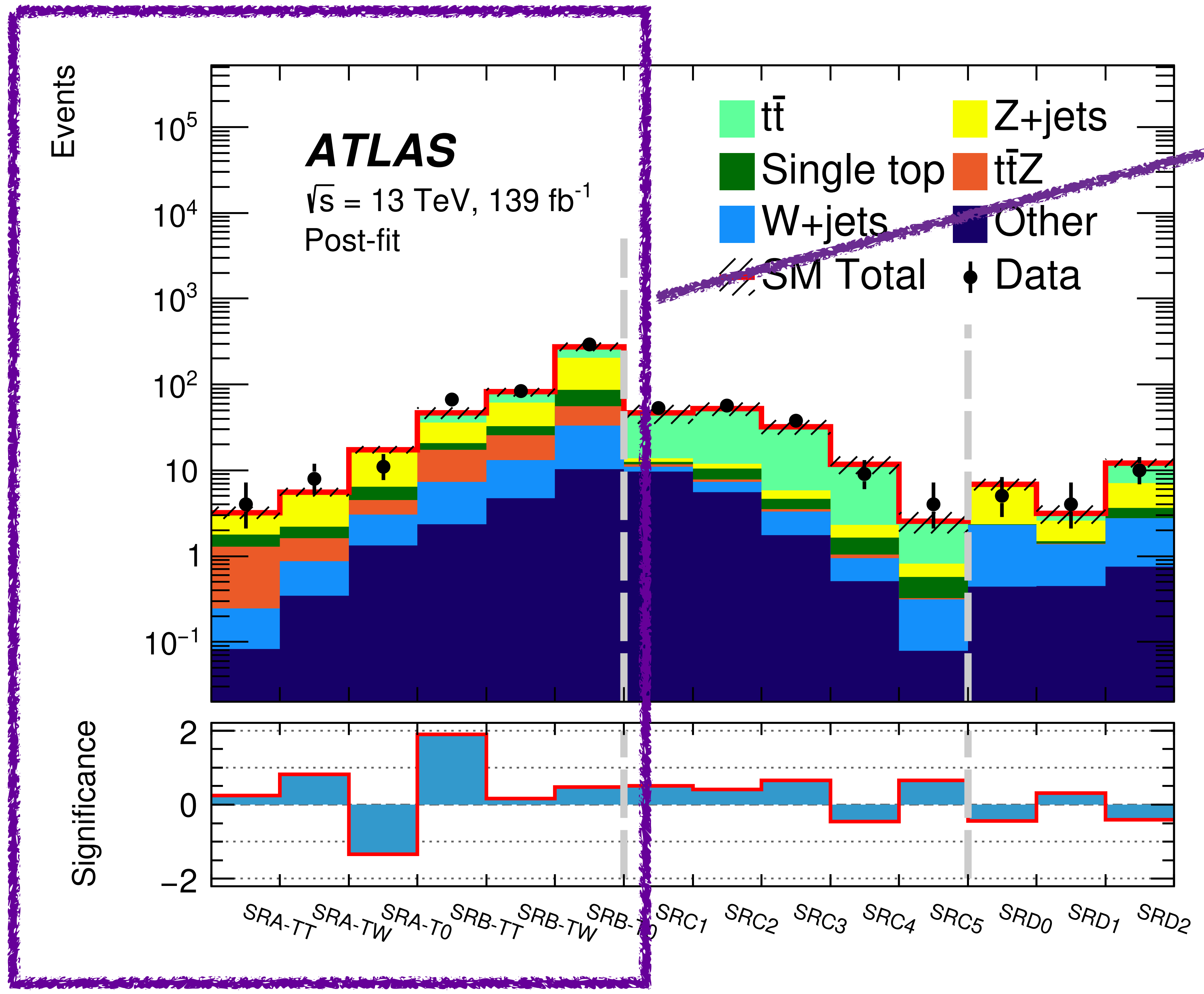


LQ LQ → tν tν EXOT-2018-12

- Target pair-produced top squarks and up-type LQs with $\mathscr{B}(\mathrm{LQ} \to t\nu) = 1.0$
- Analysis strategy:
  - 0 leptons, ≥ 4 jets, ≥ 2 b-jets, $p_{\mathrm{T}}^{\mathrm{miss}} \geq 250$ GeV
  - Optimise SRs for different parameters of stop-quark decays



LQs have same signature as heavy top squarks decaying into massless neutrinalinos



Relevant for LQ re-interpretation

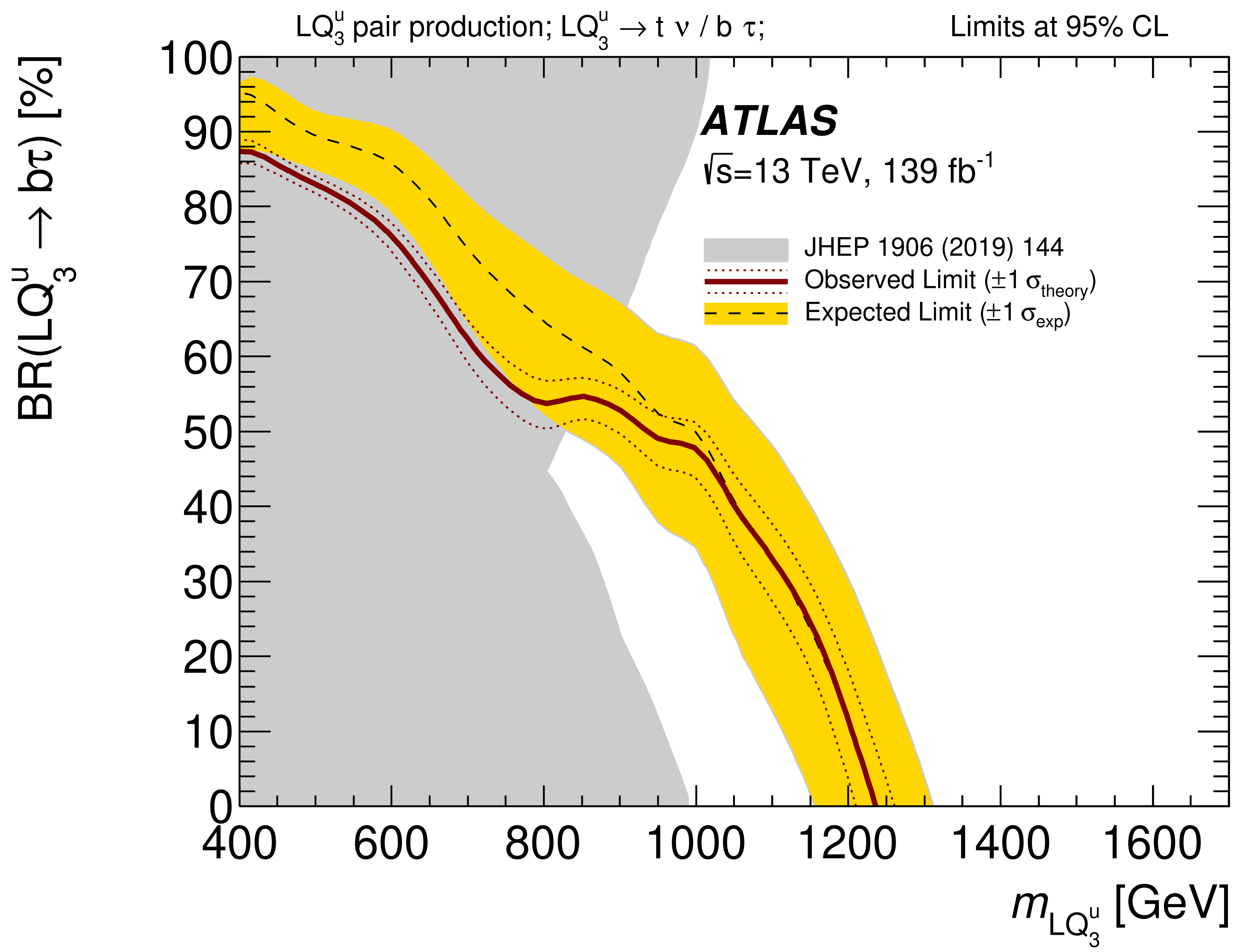
SRA: optimised for

$m_{\tilde{t}} = 1300\,\mathrm{GeV}, m_{\tilde{\chi}_1^0} = 1\,\mathrm{GeV}$

SRB: optimised for

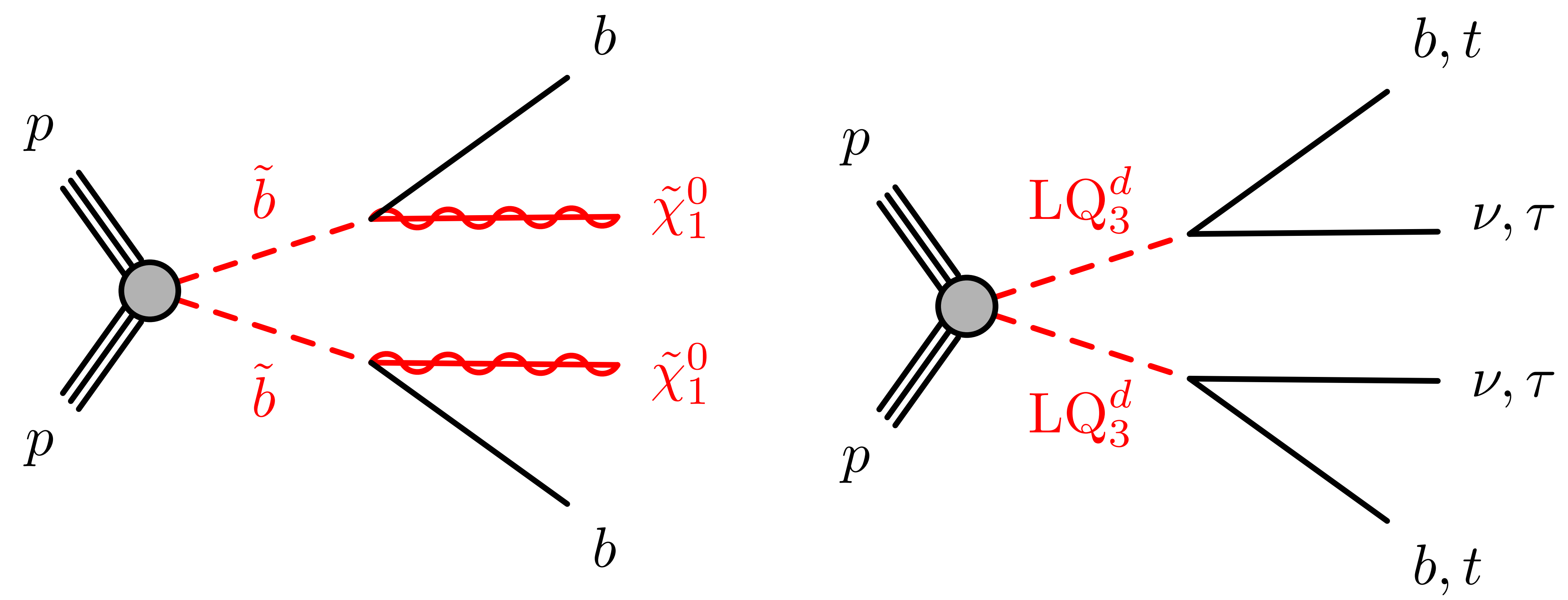
$m_{\tilde{t}} = 700\,\mathrm{GeV}, m_{\tilde{\chi}_1^0} = 400\,\mathrm{GeV}$

SRs split by large-R jet multiplicities into TT, TW, T0

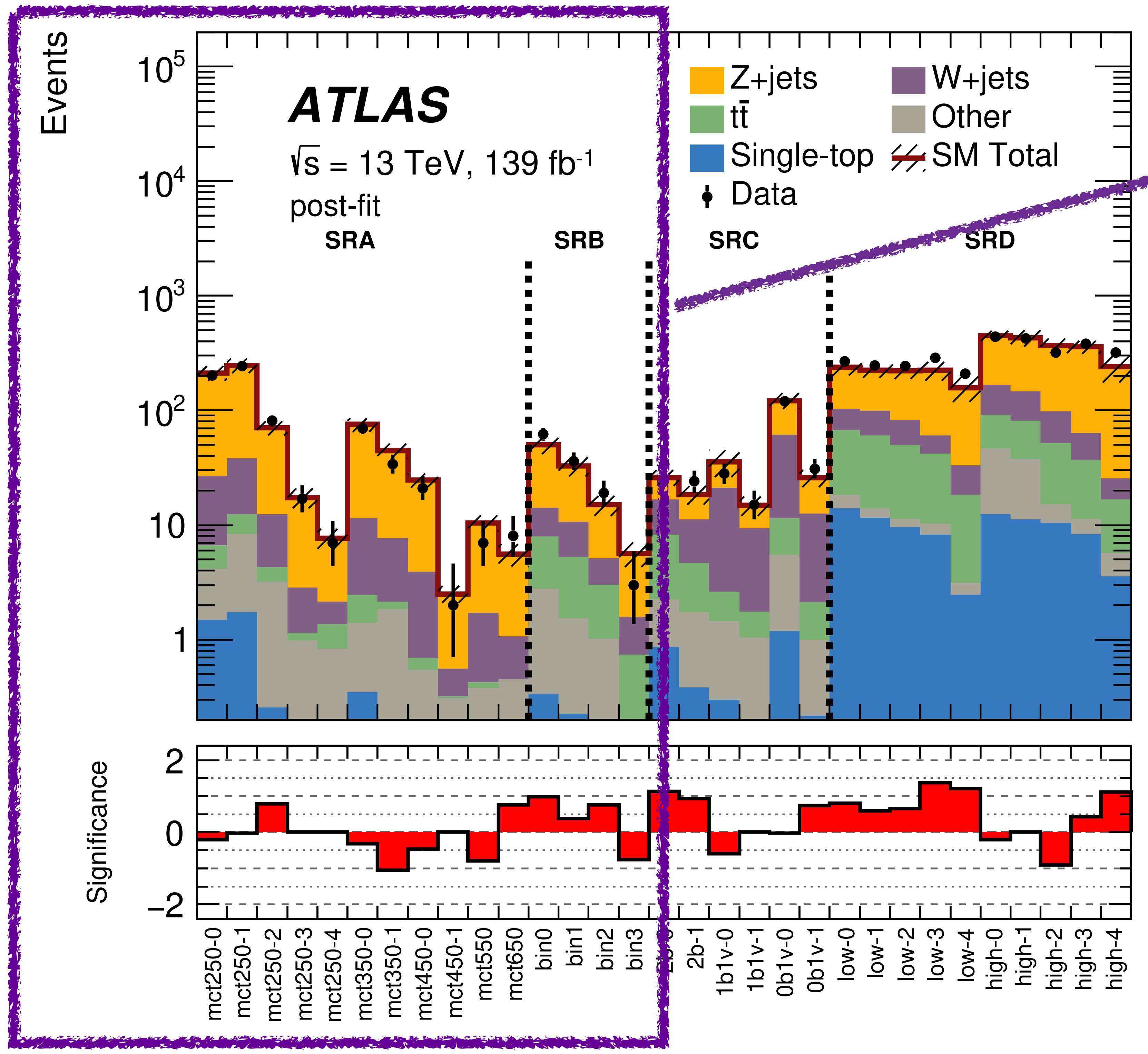


LQ LQ → $b\nu$ $b\nu$ EXOT-2018-34

- Target pair-produced bottom squarks and down-type LQs with $\mathcal{B}(\mathrm{LQ} \rightarrow b\nu) = 1.0$
- Analysis strategy:
  - 0 leptons, 2-4 jets, 2 b-jets, $p_{\mathrm{T}}^{\mathrm{miss}} \geq 250$ GeV
  - Optimise SRs for different parameters of sbottom-quark decays



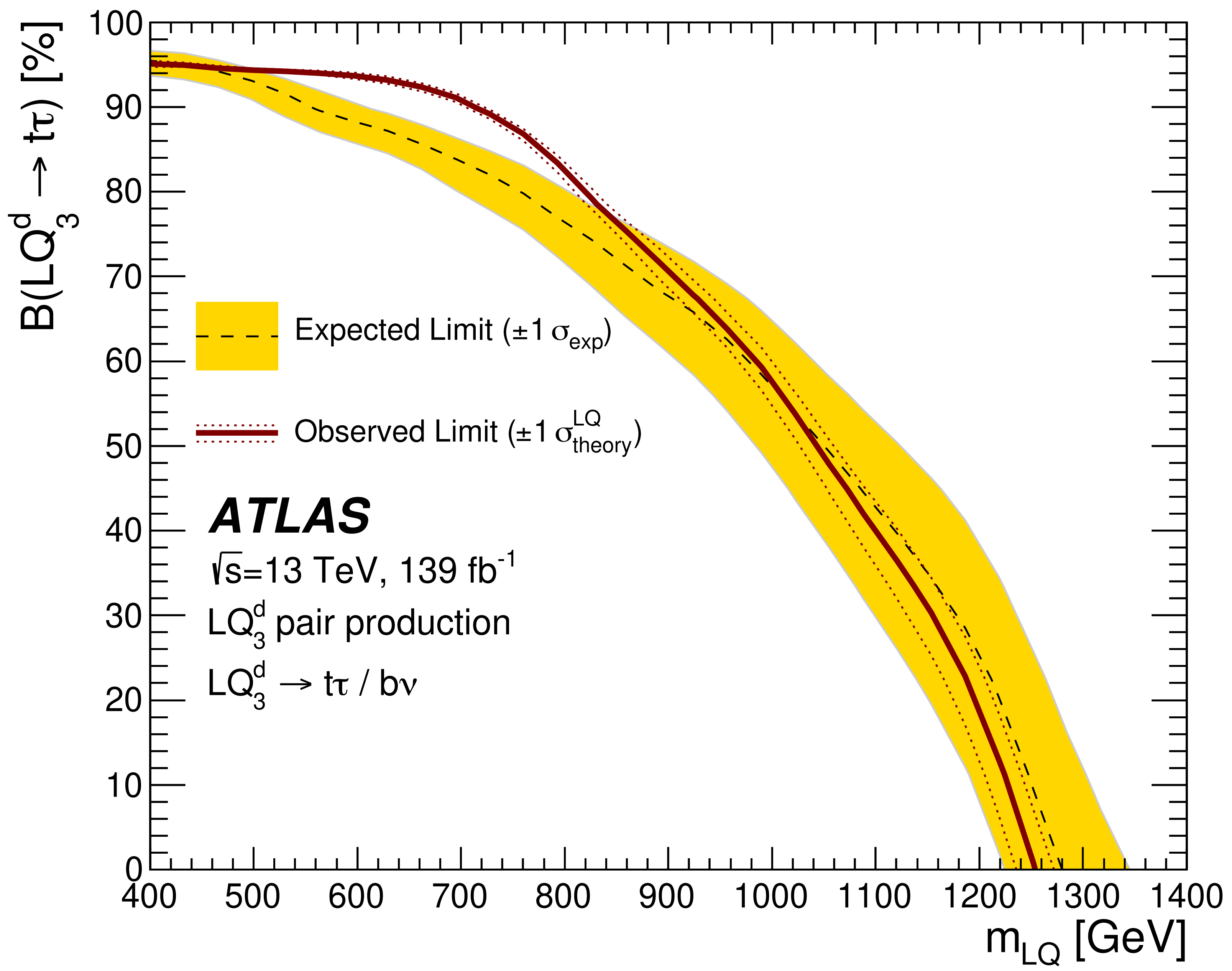
LQs have same signature as heavy bottom squarks decaying into massless neutralinos



Relevant for LQ re-interpretation

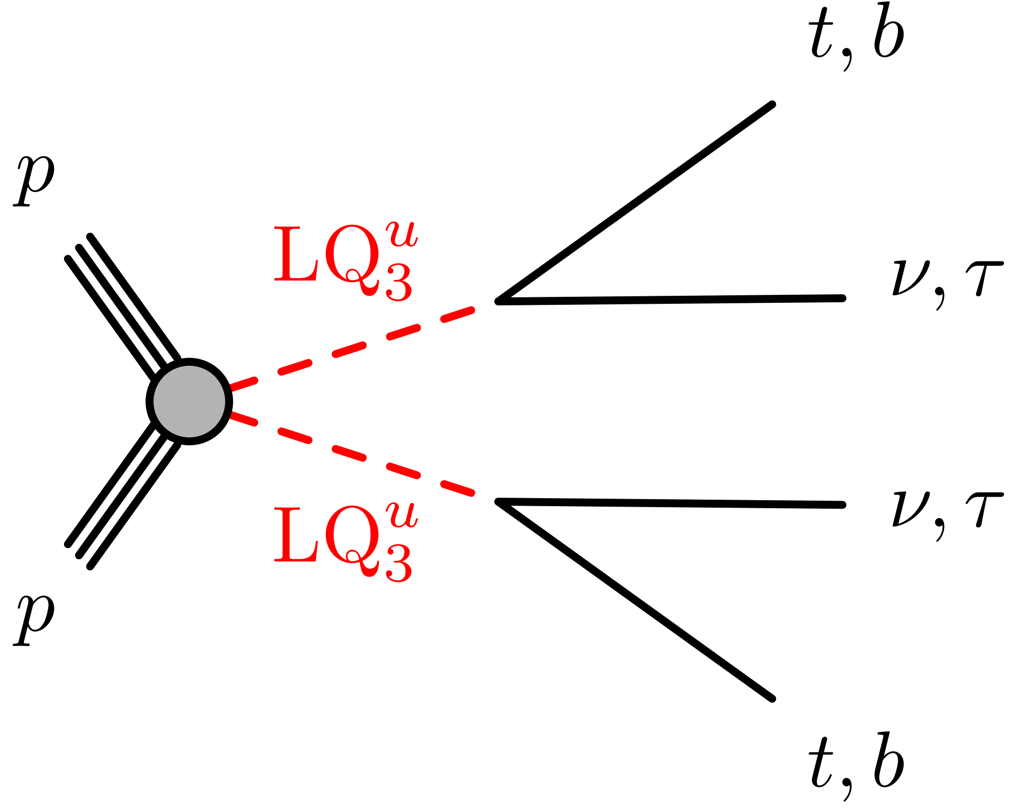
SRA: optimised for large mass differences between $\tilde{b}$ and $\tilde{\chi}_1^0$, binned in m_{CT} and m_{eff}

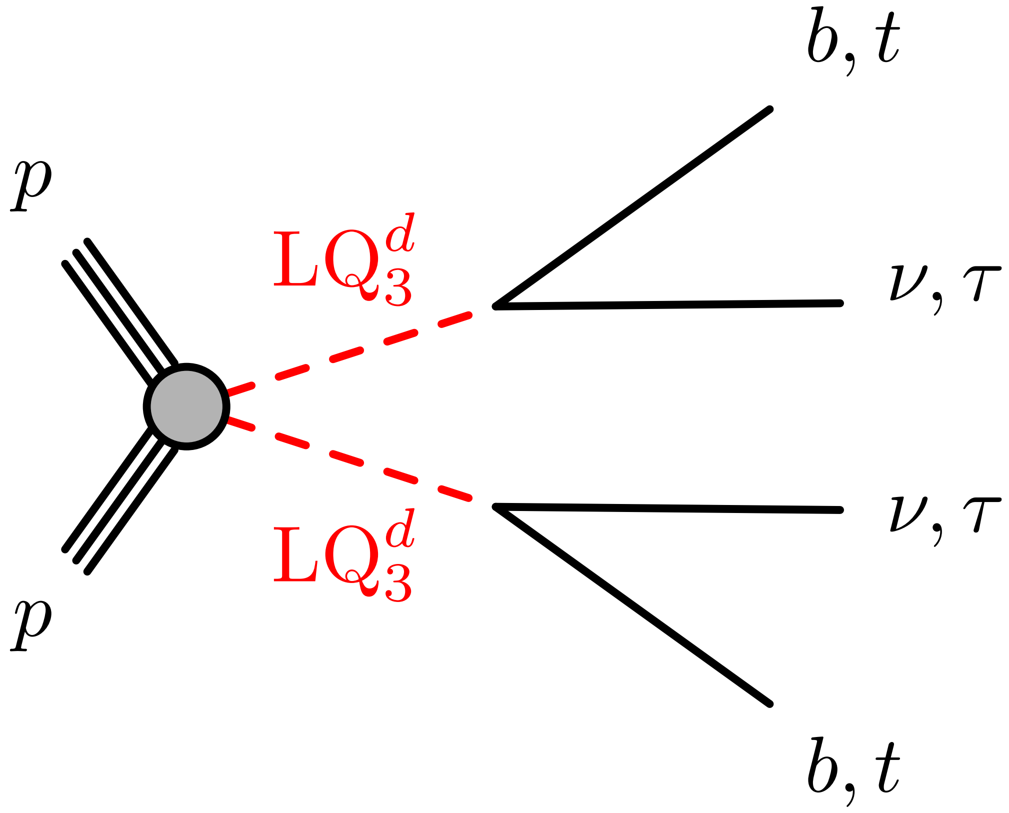
SRB: optimised for intermediate mass differences between $\tilde{b}$ and $\tilde{\chi}_1^0$, binned in BDT score for improved separation



LQ LQ → $t\nu$ $b\tau$ EXOT-2019-18

- Target pair-produced top squarks and LQs with $\mathcal{B}(\mathrm{LQ} \to q_3\tau) = 0.5$
- Analysis strategy:
  - ≥ 1 τ_{had}, ≥ 1 b-jets, $p_{\mathrm{T}}^{\mathrm{miss}} \geq 250$ GeV
  - Split into single-tau and di-tau channels
  - Main background processes ($t\bar{t}$, tW) constrained in dedicated CRs



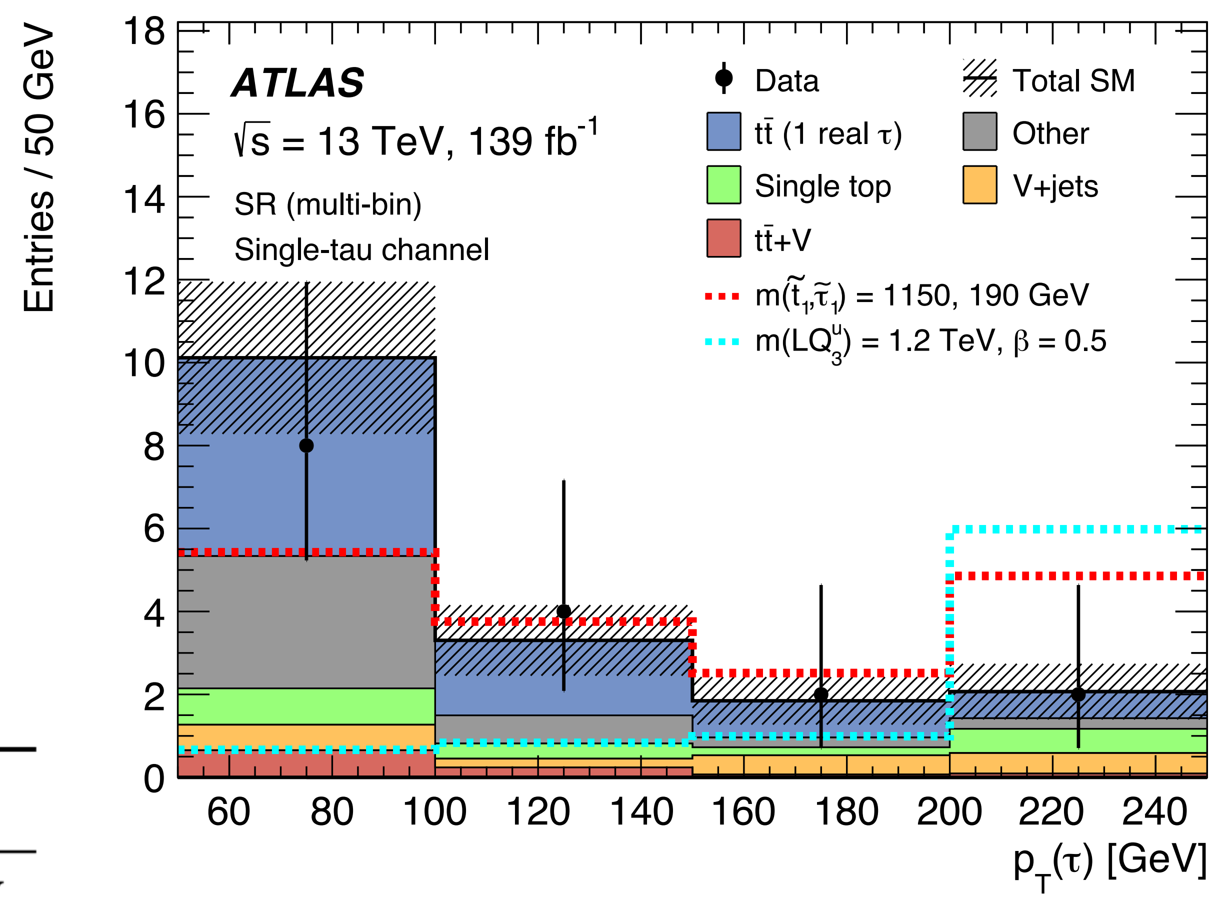


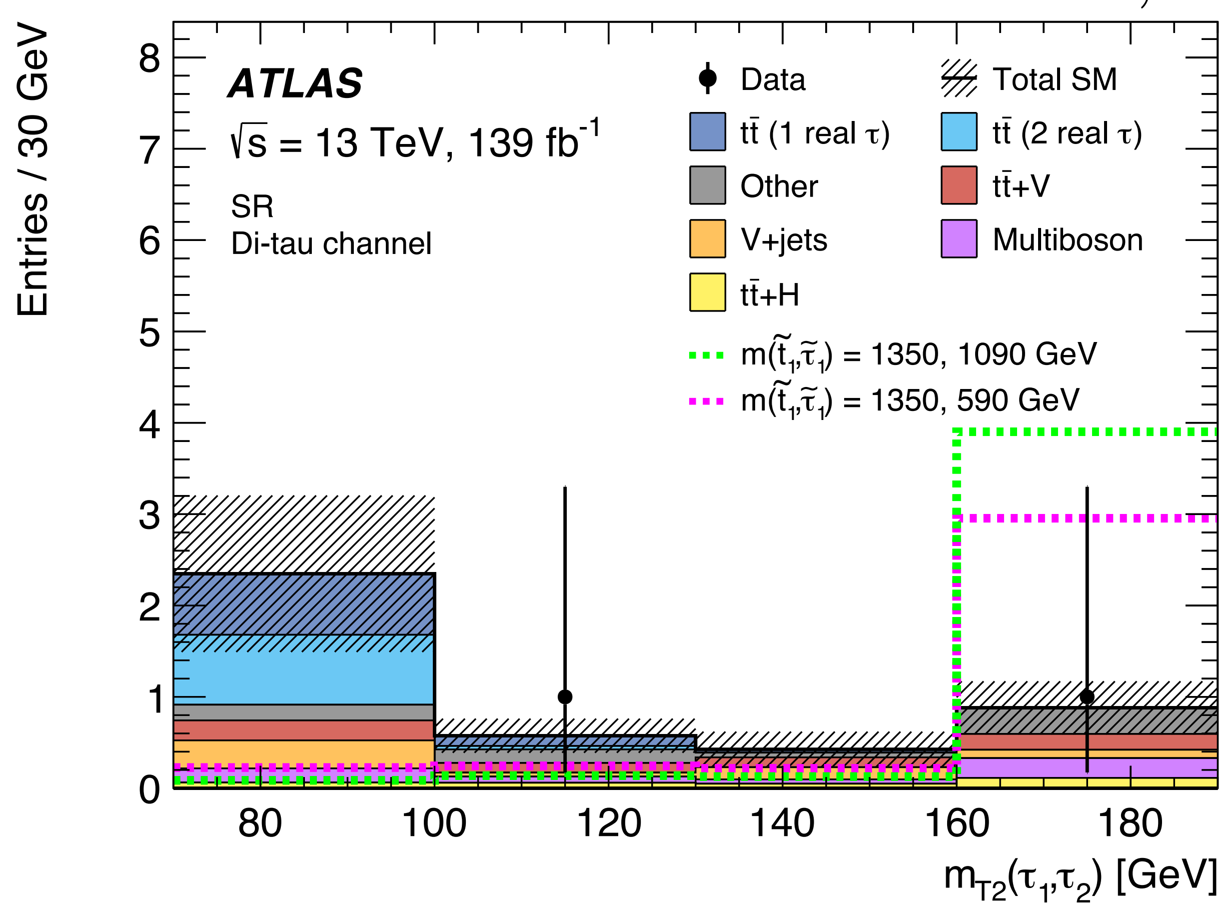
2τ channel

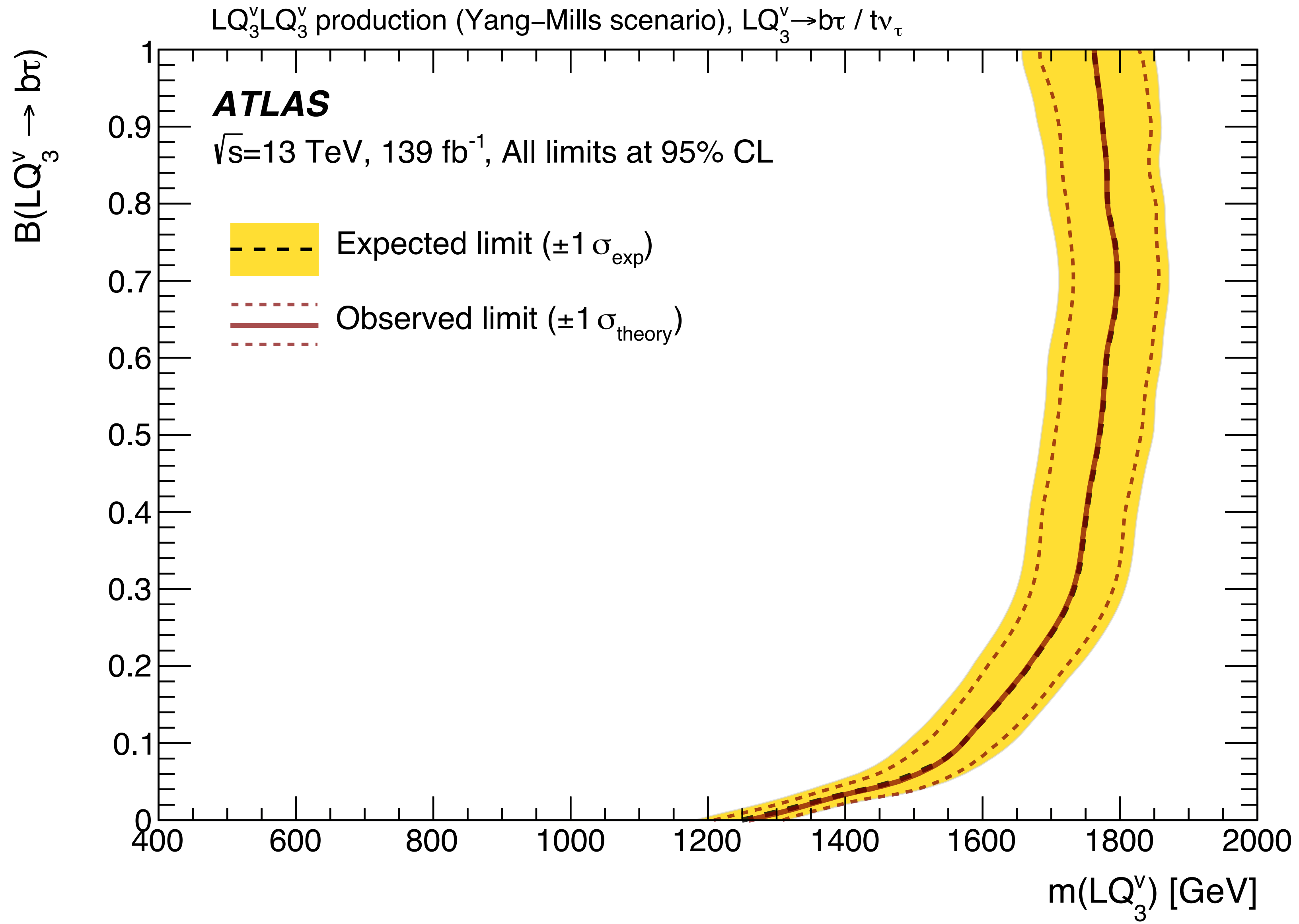
Variable	CR $t\bar{t}$ (2 real τ)	CR $t\bar{t}$ (1 real τ)	VR $t\bar{t}$ (2 real τ)	VR $t\bar{t}$ (1 real τ)	SR
$E_{\mathrm{T}}^{\mathrm{miss}}$	—	—	—	—	>280 GeV
$OS(\tau_1,\tau_2)$	1	—	1	—	1
$m_{\mathrm{T2}}(\tau_1,\tau_2)$	<35 GeV	<35 GeV	$[35,70]$ GeV	$[35,70]$ GeV	>70 GeV
$m_{\mathrm{vis}}(\tau_1,\tau_2)$	>50 GeV	>50 GeV	—	—	—
$m_{\mathrm{T}}(\tau_1)$	>50 GeV	<50 GeV	>70 GeV	<70 GeV	—

1τ channel

Variable	CR $t\bar{t}$ (1 real τ)	CR single top	VR $t\bar{t}$ (1 real τ)	VR single top	SR
$E_{\mathrm{T}}^{\mathrm{miss}}$	>280 GeV	>280 GeV	>280 GeV	>280 GeV	>280 GeV
s_{T}	$[500,600]$ GeV	—	>600 GeV	—	$>800(600)$ GeV
$\sum m_{\mathrm{T}}(b_{1,2})$	$[600,700]$ GeV	>800 GeV	$[600,700]$ GeV	>800 GeV	>700 GeV
$m_{\mathrm{T}}(\tau)$	—	<50 GeV	—	$[50,150]$ GeV	$>300(150)$ GeV
$p_{\mathrm{T}}(\tau)$	—	>80 GeV	—	>80 GeV	— (binned)

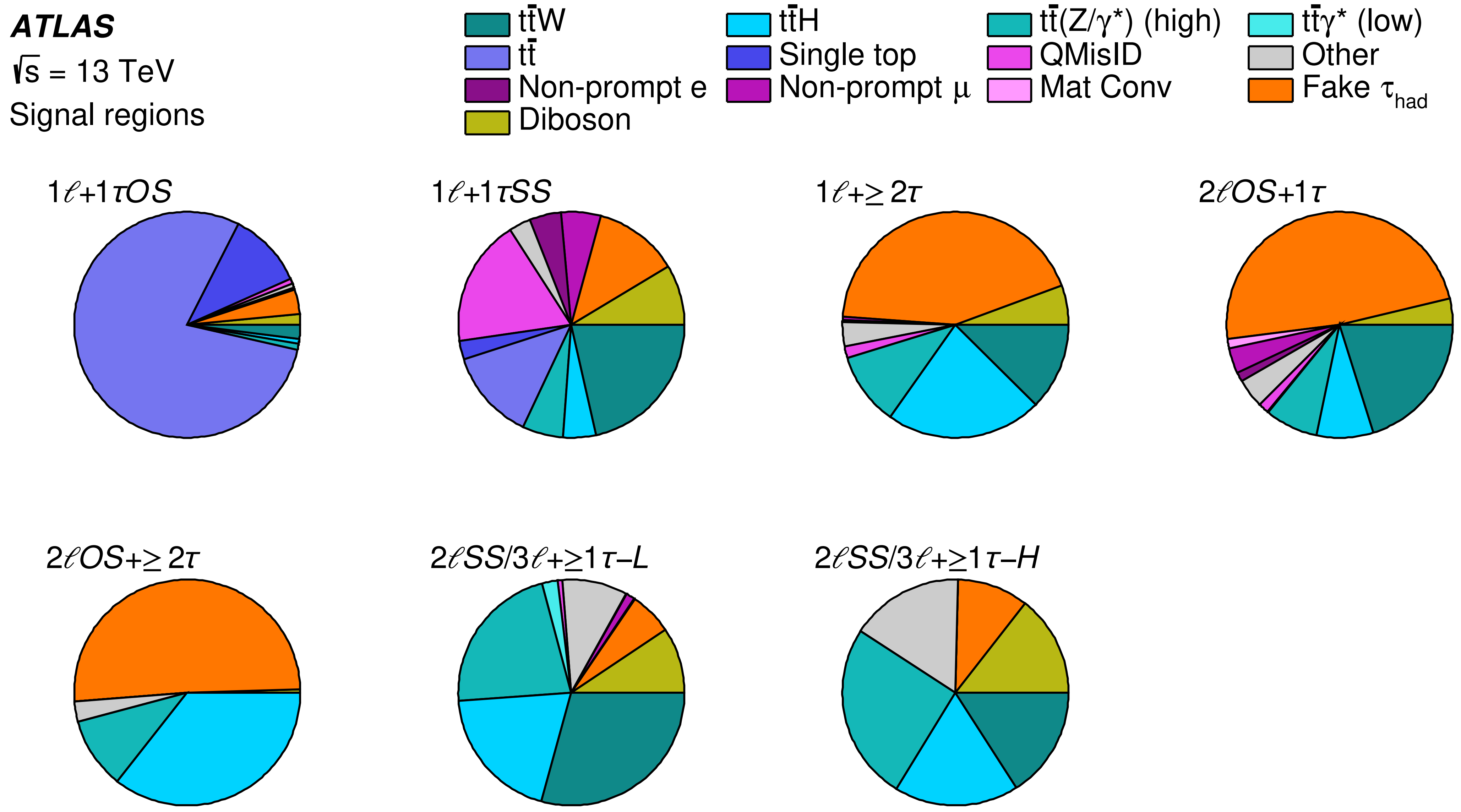


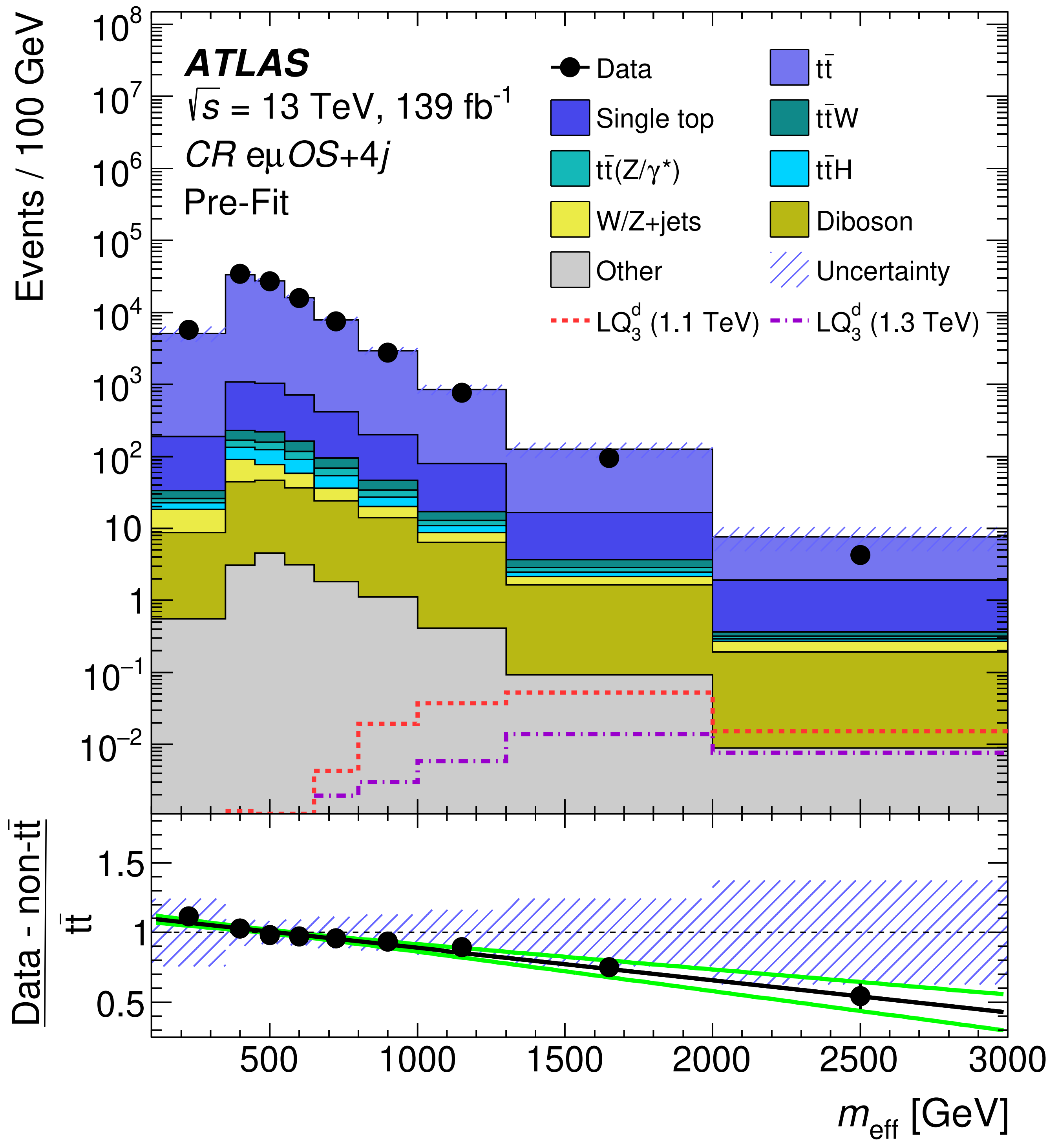


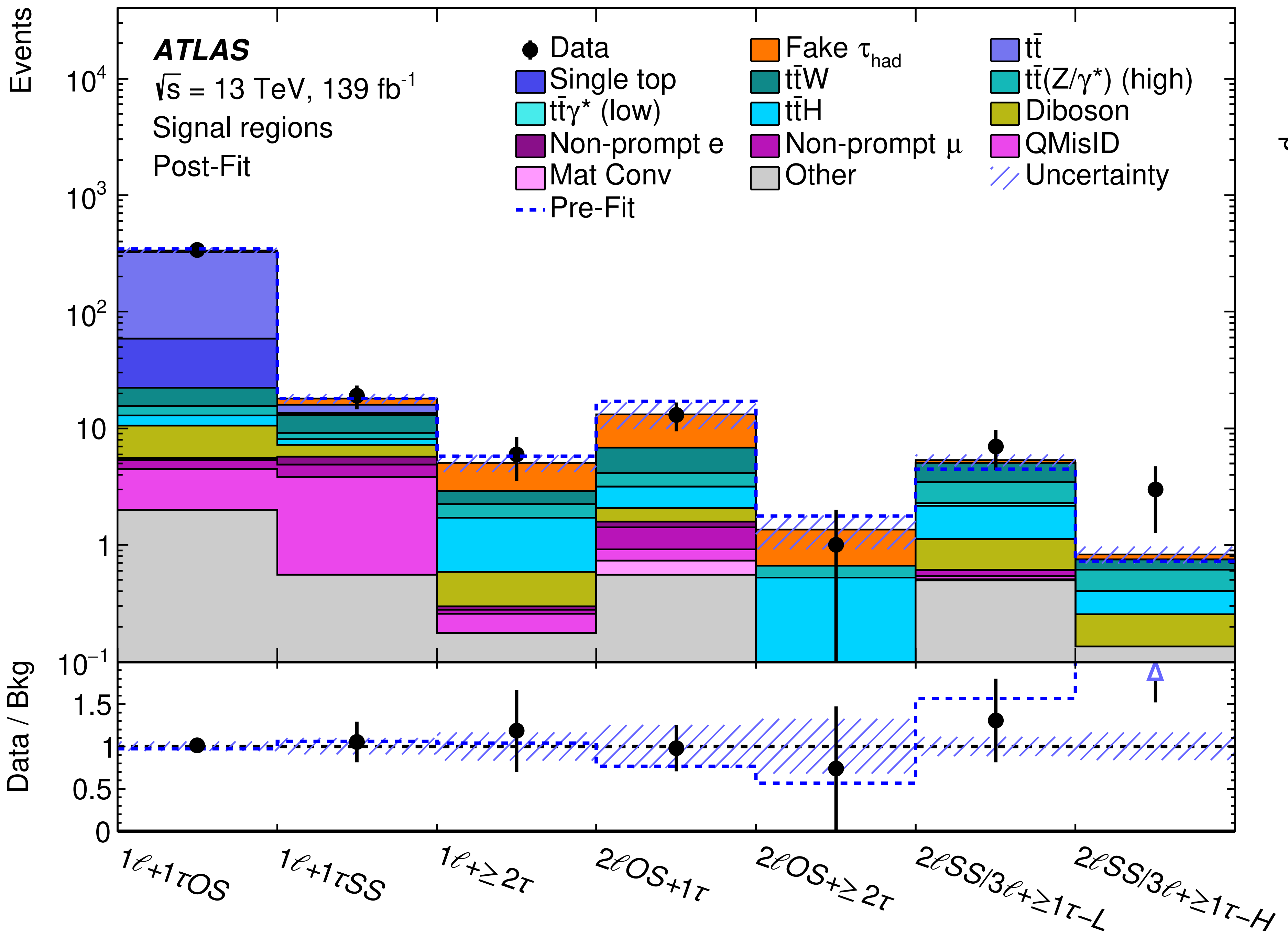


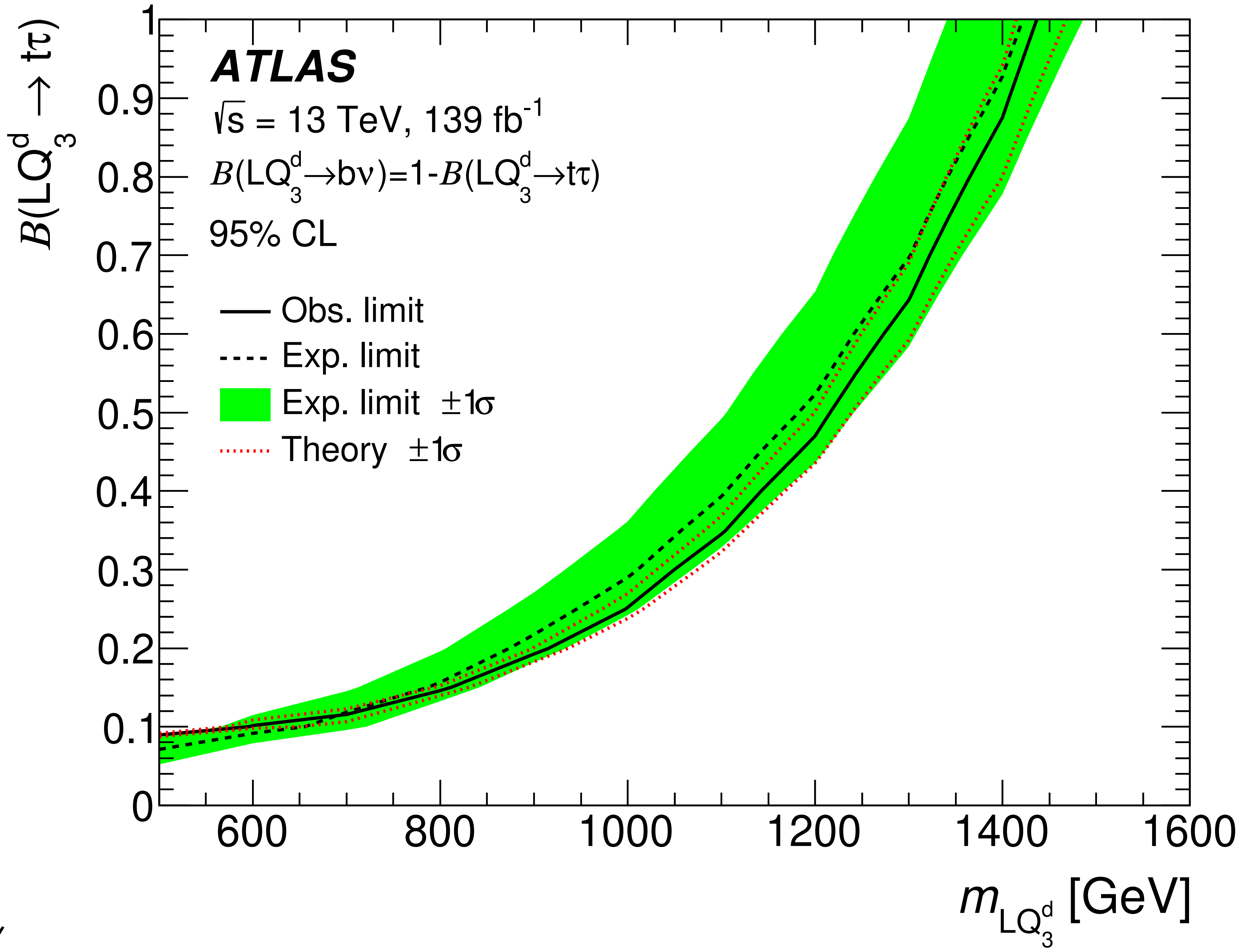
LQ LQ → $t\tau\, t\tau$ EXOT-2019-15

- Target down-type LQs with $\mathscr{B}(\mathrm{LQ} \to t\tau) = 1.0$
- Analysis strategy:
  - 1-3 ℓ, $\geq 0\tau_{\mathrm{had}}$
  - Kinematic reweighing necessary due to known mismodelling at high top-p_{T}





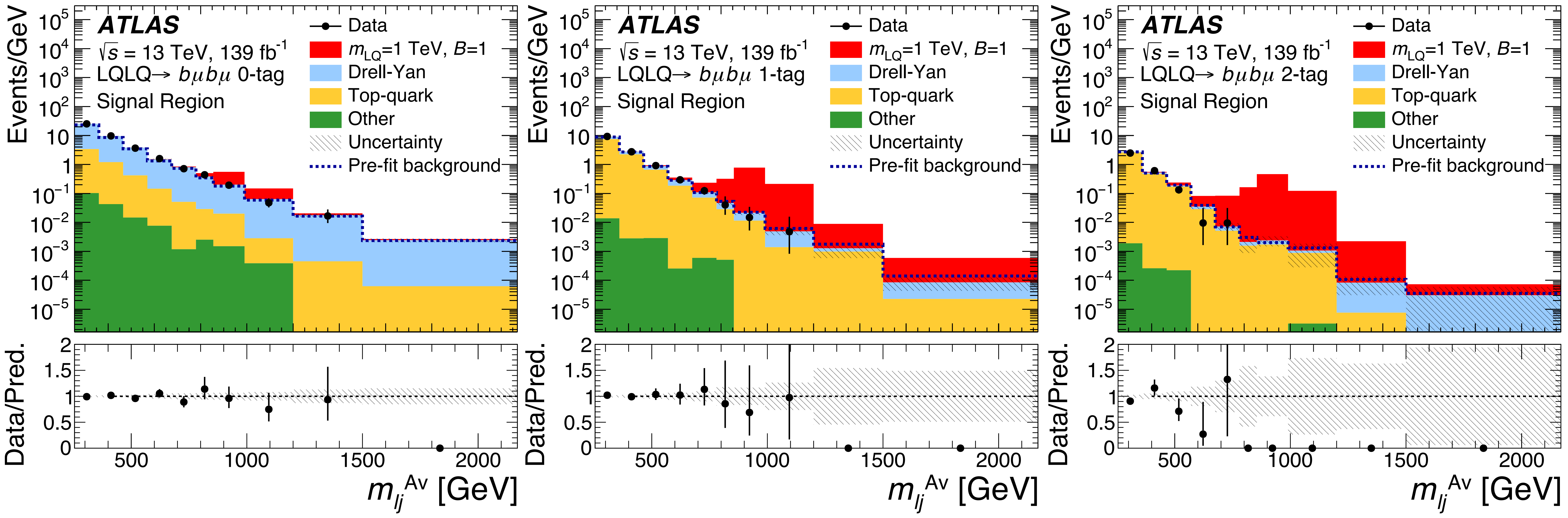




LQ LQ → $q\ell\, q\ell$ (q = u, d, c, s, b) EXOT-2019-13

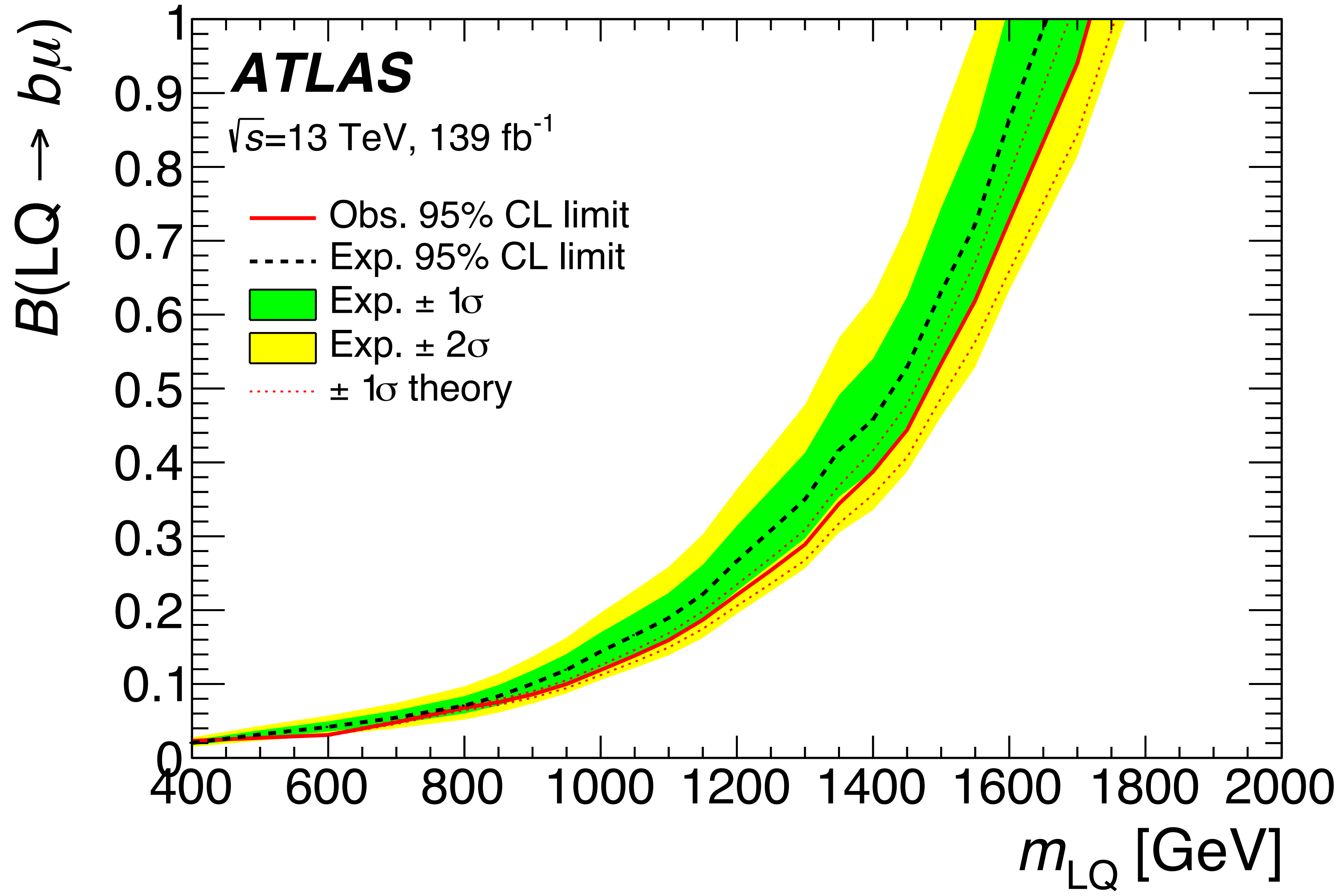
- Target up-type and down-type LQs with $\mathcal{B}(\mathrm{LQ} \to q\ell) = 1.0$
- Analysis strategy:
  - 2 OS ℓ, ≥ 2 jets
  - Normalisation of main backgrounds constrained in top CR and sideband (SB) region
  - Employ c- and b-tagging techniques to target different generations of quarks

Preselection		
2 opposite charge leptons (e, μ)		
2 or more jets		
$p_T^e > 27$ GeV, $\lvert\eta_e\rvert < 2.47$; $p_T^\mu > 27$ GeV, $\lvert\eta_\mu\rvert < 2.7$		
$p_T^j > 45$ GeV, $\lvert\eta_j\rvert < 2.5$		
$p_T^{\ell\ell} > 75$ GeV		
$E_T^{\mathrm{miss}}/\sqrt{H_T} < 3.5\ \mathrm{GeV}^{1/2}$		
$m_{\ell\ell} > 130$ GeV		
SB	SR	Top CR
ee or $\mu\mu$		$e\mu$
$0.2 < m^{\mathrm{asym}} < 0.4$	$m^{\mathrm{asym}} < 0.2$	



Signal regions divided by number of c/b-tags

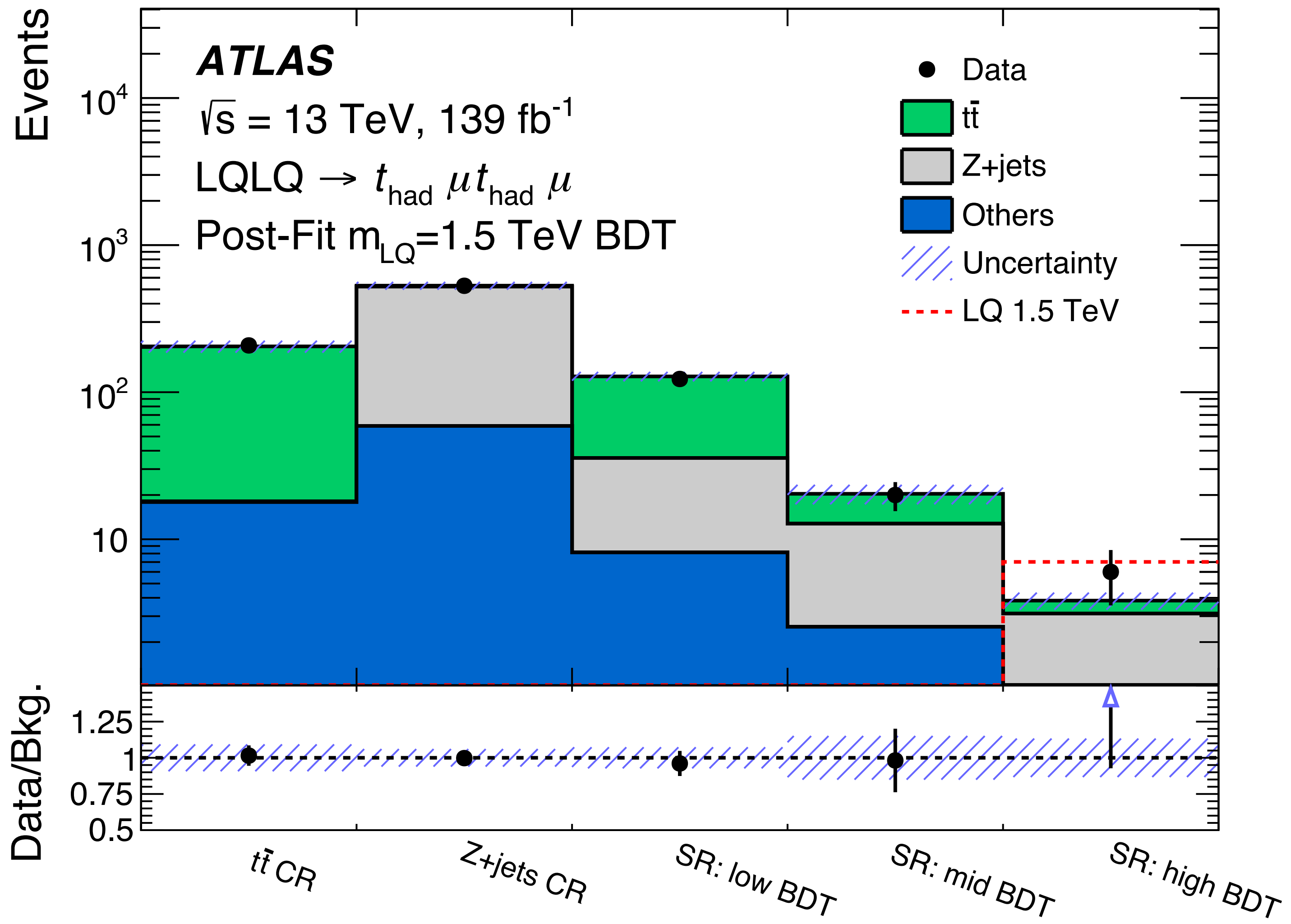
$$m^{\mathrm{asym}} = \frac{m_{\ell j}^{\max} - m_{\ell j}^{\min}}{m_{\ell j}^{\max} + m_{\ell j}^{\min}} < 0.4,$$

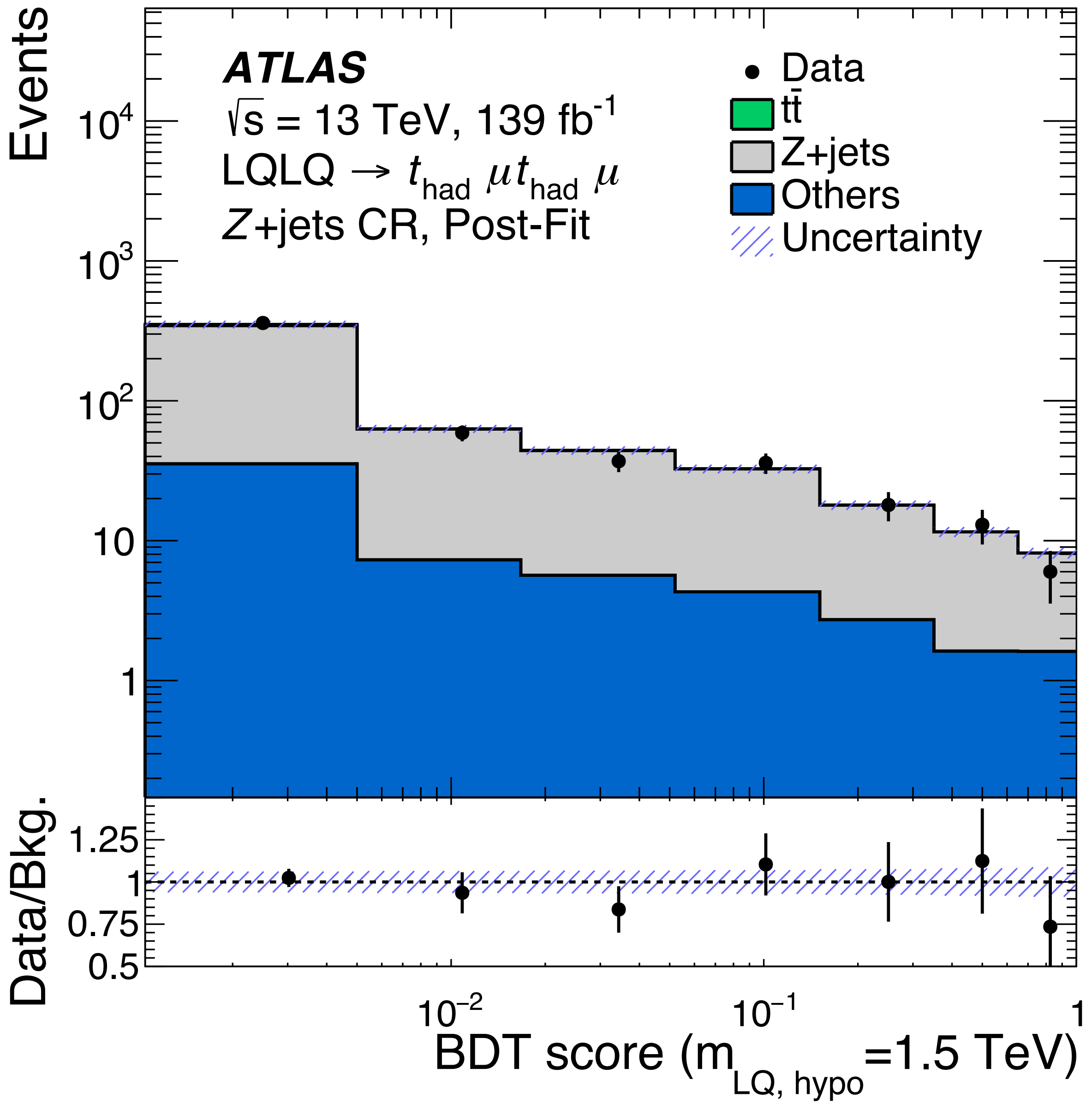


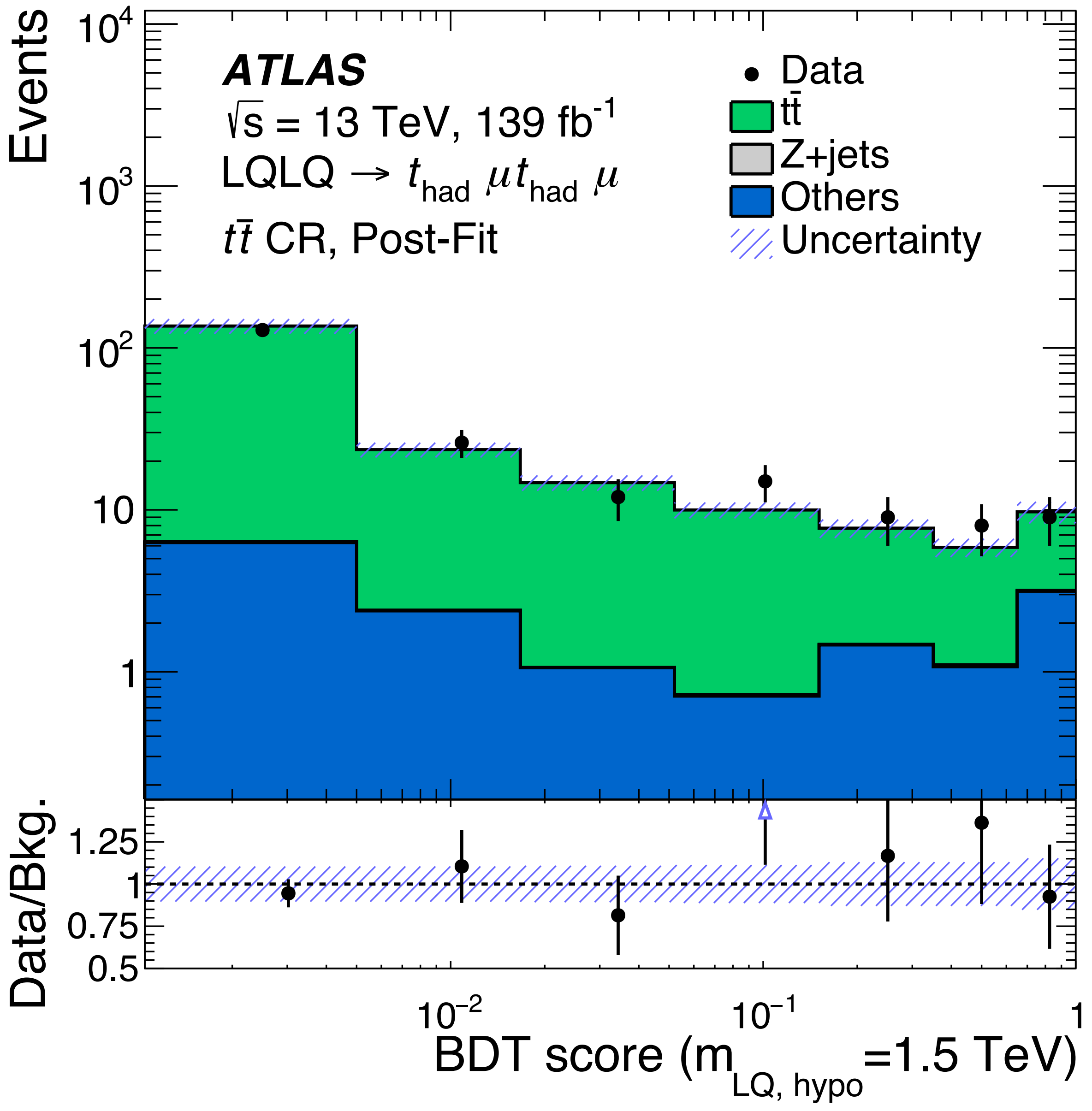
LQ LQ → $t\ell$ $t\ell$ EXOT-2019-19

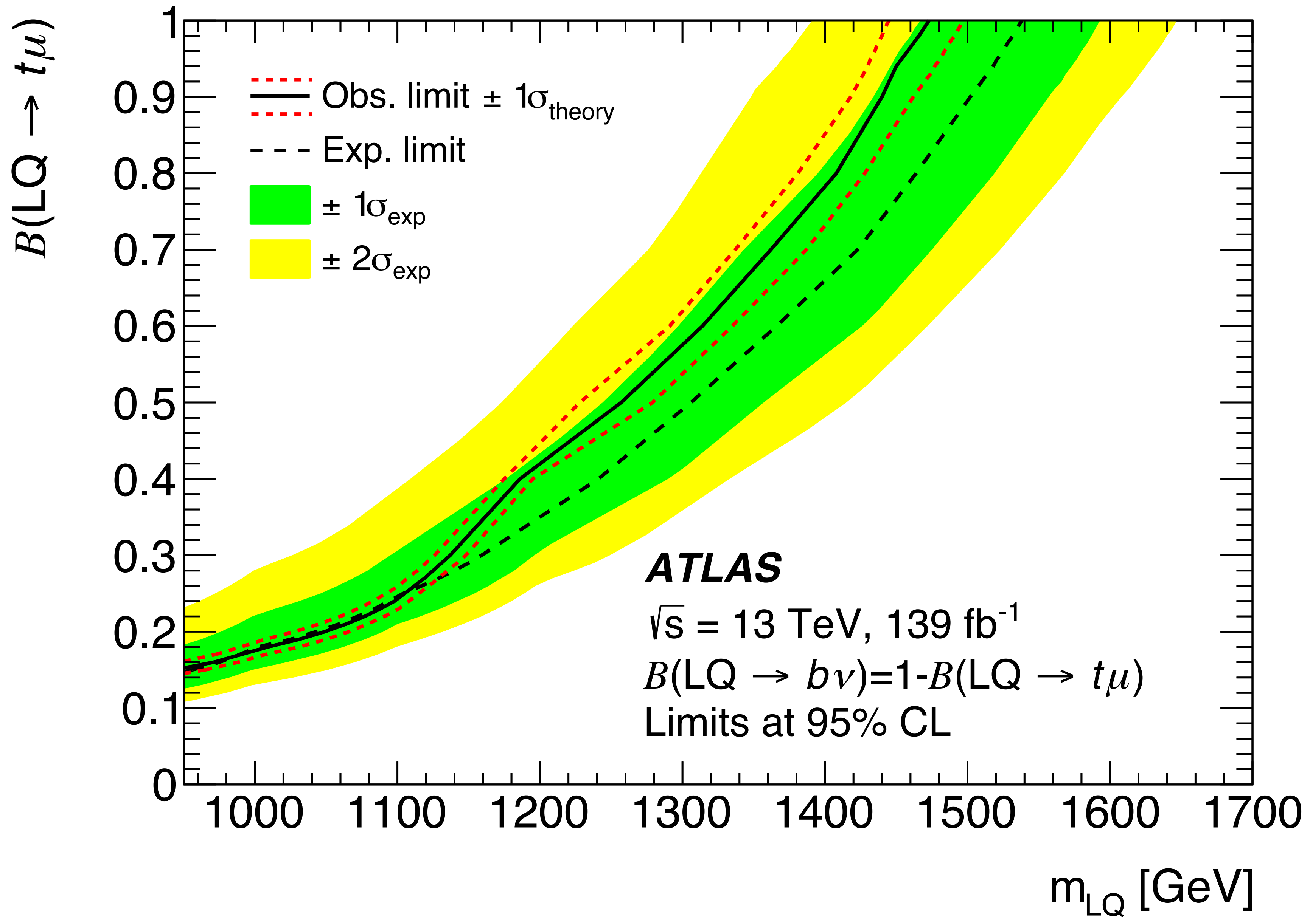
- Target down-type LQs with $\mathcal{B}(\mathrm{LQ} \rightarrow t\ell) = 1.0$
- Analysis strategy:
  - 2 OS ℓ, ≥ 2 large-R jets
  - Resolve kinematic and combinatoric ambiguities with recursive jigsaw algorithm for signal and dominating background processes ($t\bar{t}$)
  - BDT trained on signal, $t\bar{t}$, Z+jets to improve signal-background separation

	$t\bar{t}$ CR	Z + jets CR	SR
Leptons	$p_{\mathrm{T}}^{\ell} > 100$ GeV, $\lvert\eta_e\rvert < 2.47$, $\lvert\eta_\mu\rvert < 2.5$ $N_\ell = 2$; opposite-sign		
Large-R jets	$p_{\mathrm{T}}^{\mathrm{J}} > 200$ GeV, $\lvert\eta_{\mathrm{J}}\rvert < 2.0$, $m_{\mathrm{J}} > 50$ GeV $N_{\mathrm{J}} \geq 2$		
Dilepton invariant mass	$m_{\ell\ell} > 120$ GeV	70 GeV $< m_{\ell\ell} <$ 110 GeV	$m_{\ell\ell} > 120$ GeV
Lepton flavour	$e\mu$	ee or $\mu\mu$	









Background normalisation constrained in dedicated CRs