Probing New Lepton Interactions with the ATLAS Experiment

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on behalf of the ATLAS Collaboration

LHC Seminar, 06/07/21

Q: Lepton Interactions

- Known unknowns:
  - Origin of neutrino masses and why they are so small?
    - Just an extra Dirac ν_R with tiny Yukawa couplings or more complex scenarios (e.g. seesaw models and extra heavy leptons)?
  - Origin of magnitude and pattern of Yukawa interactions?
    - Off-diagonal (LFV) or CP-violating terms?
- Hints of something unknown:
  - Growing evidence of lepton flavour universality (LFU) violation in B-meson decays and other anomalies, e.g. $(g-2)_\mu$
- Knowns:
  - SM predictions confirmed by countless experiments at low- and high-energy
    - No evidence of new particles/interactions at the $\lesssim$TeV scale
  - In SM, LFU only broken by Yukawa interactions (lepton-mass effects) and lepton flavour conservation is an accidental symmetry

Q: Lepton Interactions

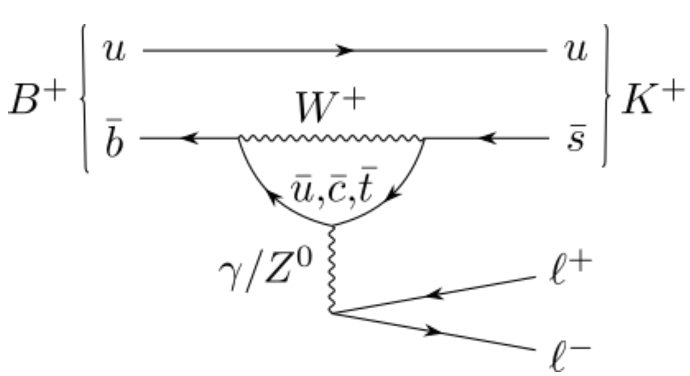
- No clear indication of a common explanation to all open questions within current experimental data, but maybe a pattern is emerging…
- ATLAS has a broad physics program to gather more experimental inputs and probe these anomalies at high energy
- **Outline:**
- Summary* of anomalies and their potential explanations
- Recent ATLAS results on searches for new lepton interactions
  - Search for new phenomena in $e^+e^-/\mu^+\mu^- + 0/1\,b$ final state
  - Search for type-III seesaw heavy leptons
  - Search for 3rd-generation vector or scalar leptoquarks
  - Search for lepton-flavour-violating (LFV) $Z \to \ell\tau$ decays

(*) Selected summary of the anomalies, but there are more. Vast literature on the topic, references here are examples

Anomalies in B decays

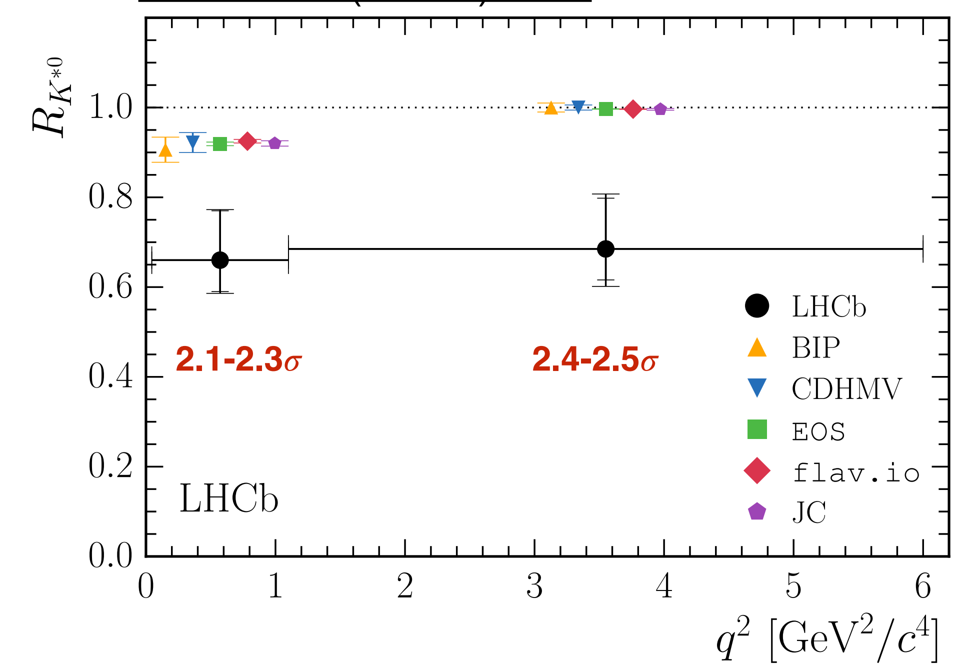
- **Hints of LFU violation** in $b \to s\ell\ell$ transitions (**neutral current**)
- R(K) and R(K*):
  - Ratio of decay branching fractions very clean observable (QCD effects cancel out)
  - R_{SM}=1 (LFU), but new physics can break universality
  - R(K): 3.1σ deficit wrt SM [arXiv:2103.11769]
- $\mathscr{B}(B_s \to \mu\mu)$: 2.1σ deficit wrt SM
- Similar discrepancies in absolute branching fractions and in angular distributions (although less "clean" measurements)

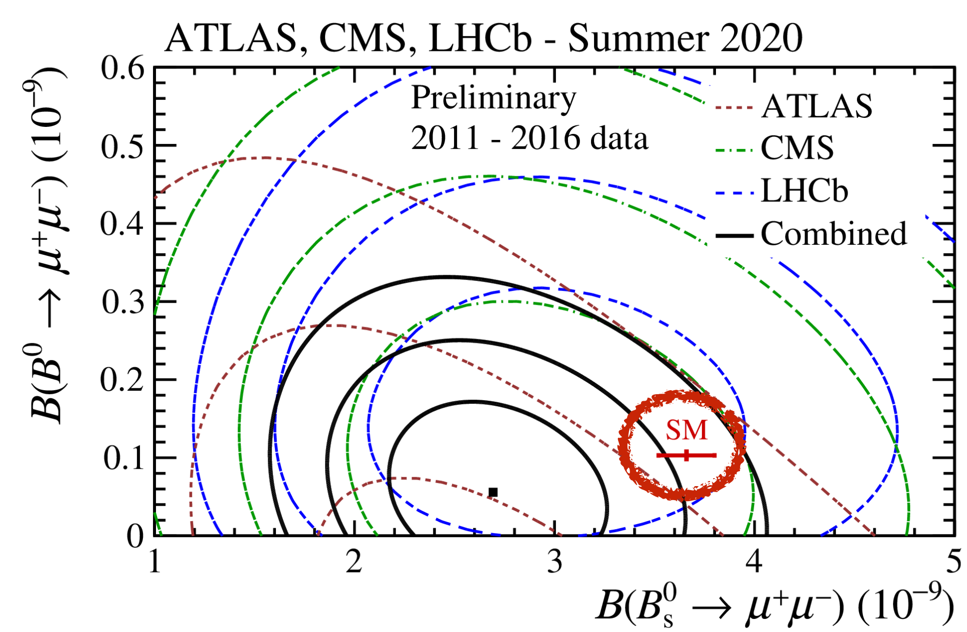
Loop-suppressed
(Non-resonant decay at low-q^2)



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

JHEP 08 (2017) 055



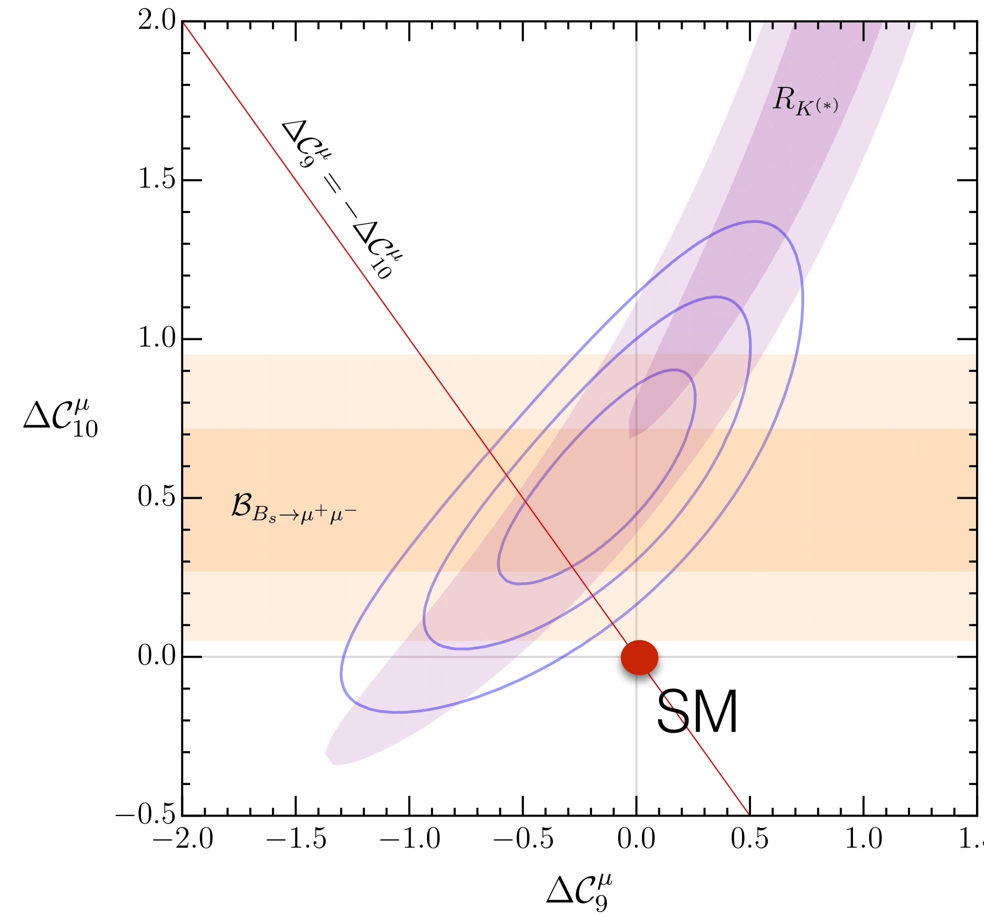


ATLAS-CONF-2020-049

Anomalies in B decays

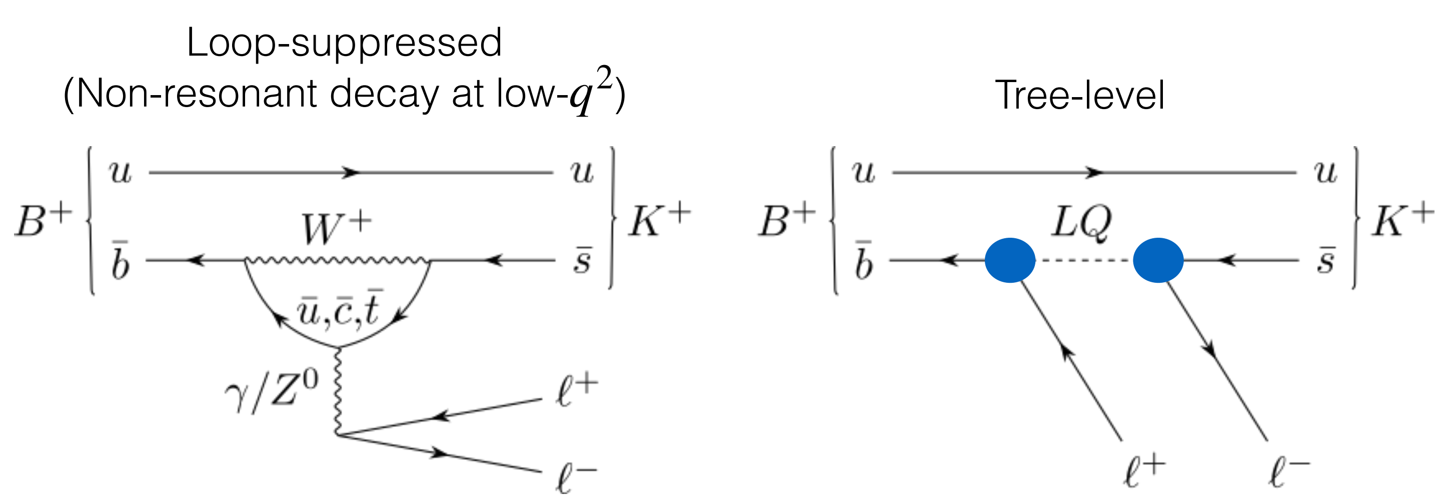
- Model-independent EFT fit of $b \rightarrow s\ell\ell$ data
  - Addition of **left-handed 4-fermion contact interactions** provide better fit to data than SM
  - Considering look-elsewhere effects, interpretation of data with new physics has a significance of 3.9σ [arXiv:2104.05631]
- Resolving this contact interactions in direct searches at the LHC may be challenging as $\Lambda/g^* \approx 30$ TeV [arXiv:1805.11402]
  - Small effect which competes with SM loop process
- TeV-scale **leptoquarks** provide promising UV completion of SM compatible with EFT fit
  - Tree-level $qq\ell\ell$ transition which breaks flavour symmetry

arXiv:2103.16558



$$\mathcal{O}_9^\mu = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\mu)$$

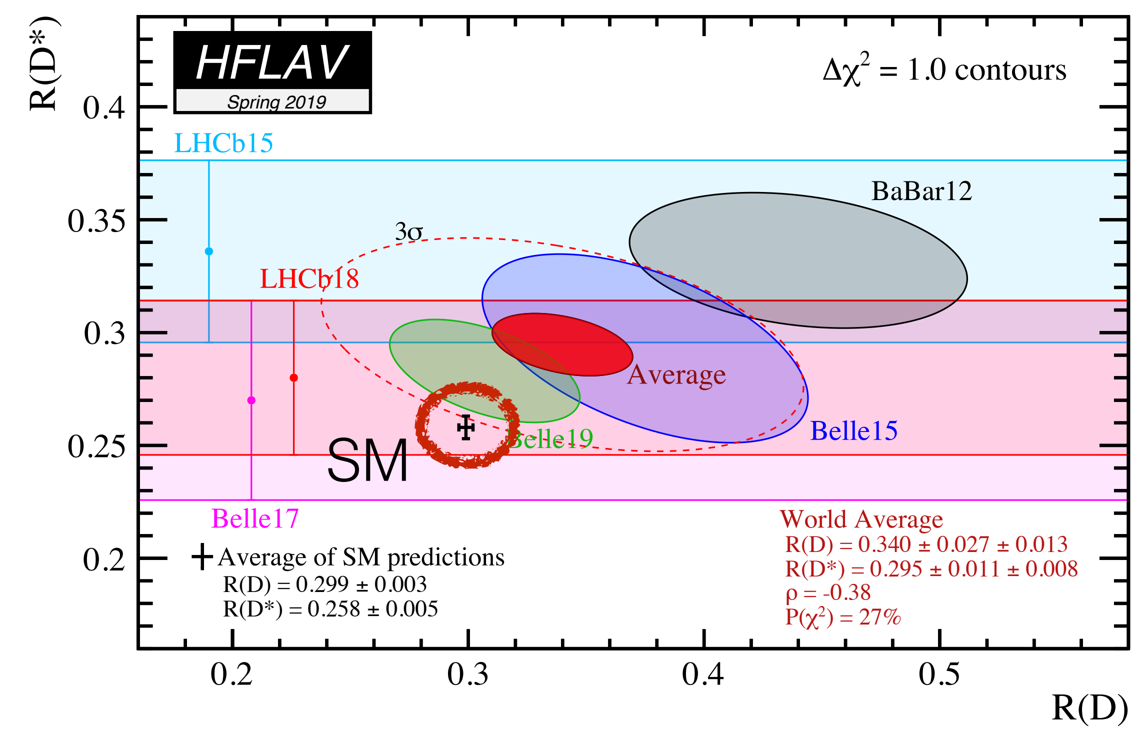
$$\mathcal{O}_{10}^\mu = \frac{\alpha}{4\pi}(\bar{s}_L\gamma_\mu b_L)(\bar{\mu}\gamma^\mu\gamma_5\mu)$$



Anomalies in B decays

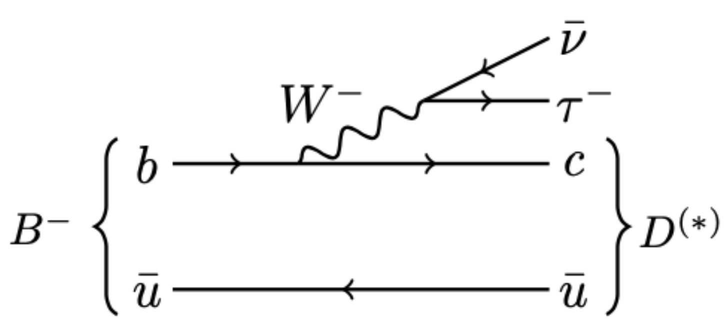
- **Hints of LFU violation** also in **charged current** $b \to c\ell\nu$ transitions
- R(D) and R(D*):
  - Clean SM prediction
  - Combined 3.1σ discrepancy from SM
- EFT fit points to similar operators, but at a lower scale $\Lambda/g^* \approx 2$ TeV
  - Large effect that competes with SM tree-level process
- **Leptoquarks** may explain both B anomalies [arXiv:2103.16558]
  - $\Lambda_{NP} \sim$ few TeV
  - Couplings with flavour structure
  - Tree-level semileptonic transition, but no 4-ℓ or 4-q interactions

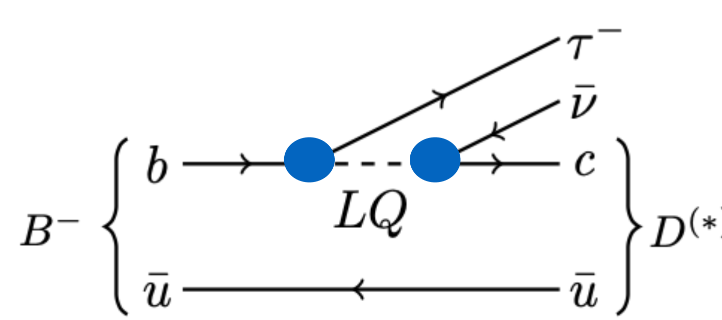
arXiv:/1909.12524



$$R(D^{(*)}) = \frac{\mathscr{B}(B \to D^{(*)}\tau\nu_\tau)}{\mathscr{B}(B \to D^{(*)}\ell\nu_\ell)}$$

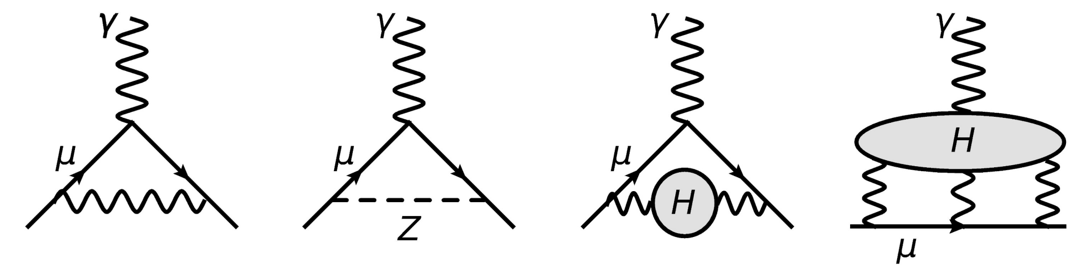
$(\ell = e, \mu)$



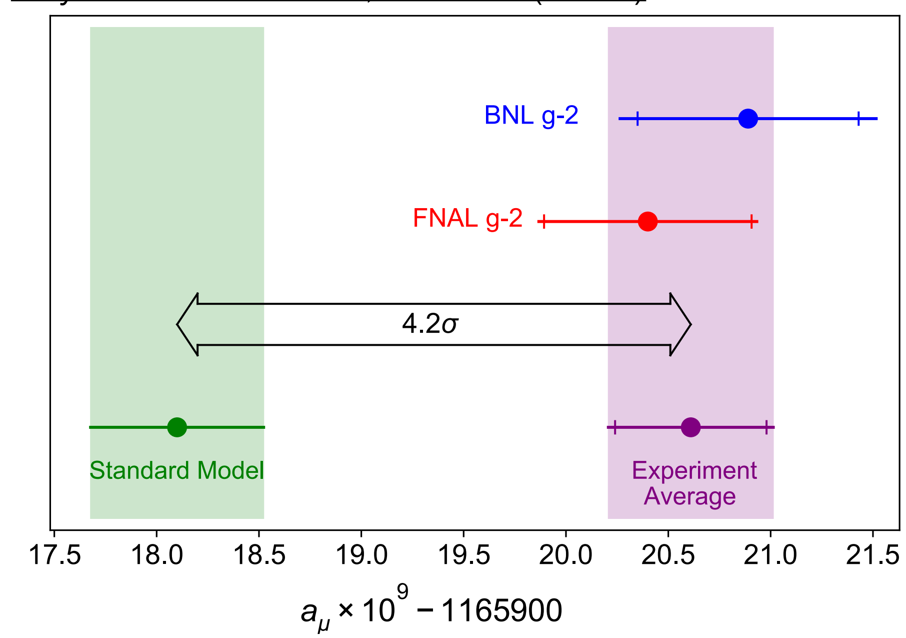


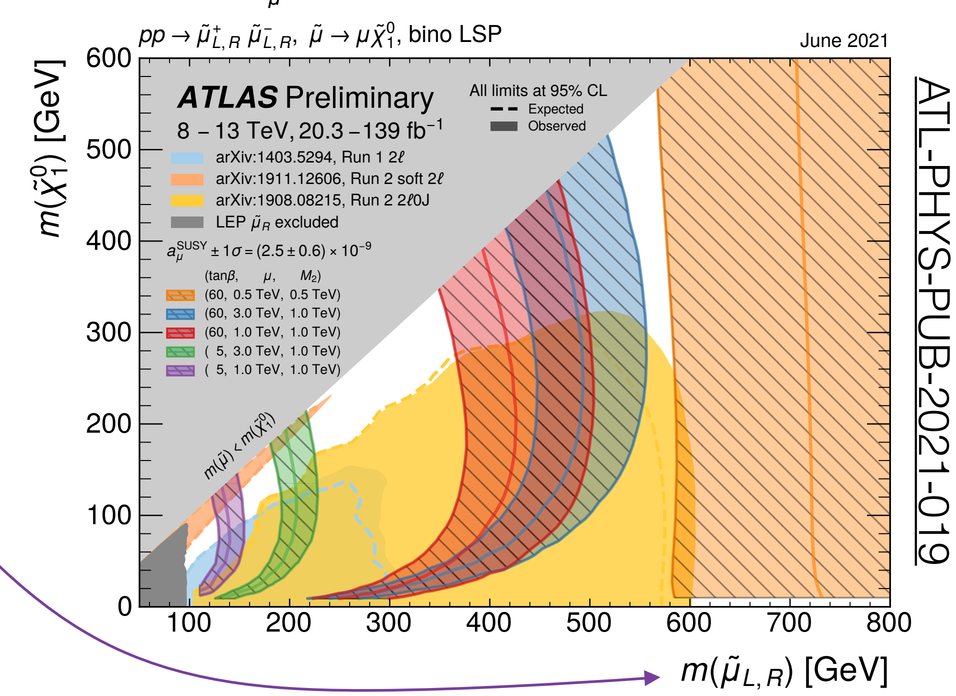
Muon g-2

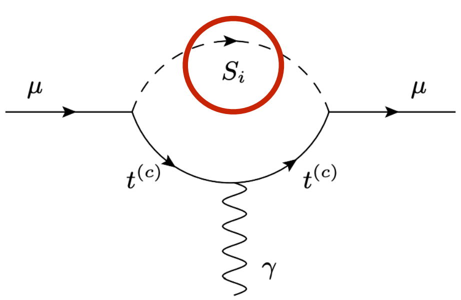
- Chirality-changing observable that vanishes in massless limit and possibly connected to LFU violation
- Theoretical prediction and measurements are very challenging
- Discrepancy may be explained by
  - **LQs** (at least two) [arXiv:2008.02643, arXiv:2104.05730]
  - **Vector-like leptons**, similar in phenomenology to Type-III seesaw heavy lepton multiplets [arXiv:1712.09360, arXiv:2104.03228]
  - SUSY **smuons**, …

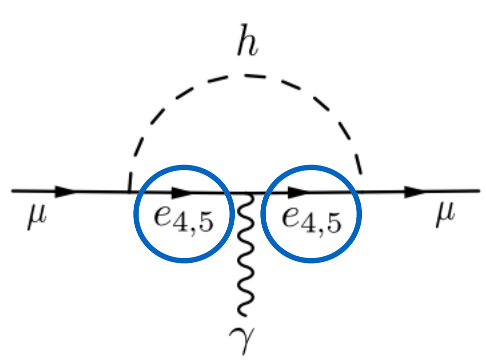


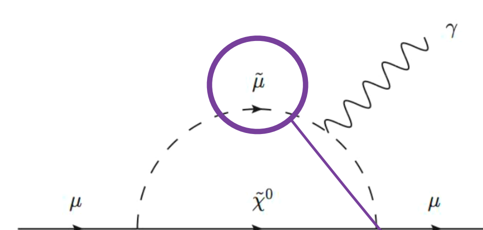
Phys. Rev. Lett. 126, 141801 (2021)





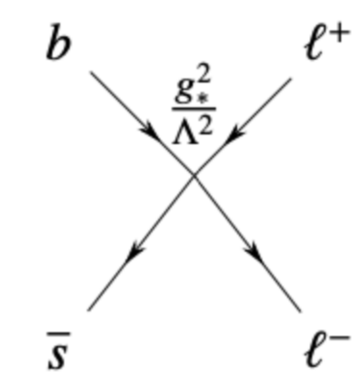


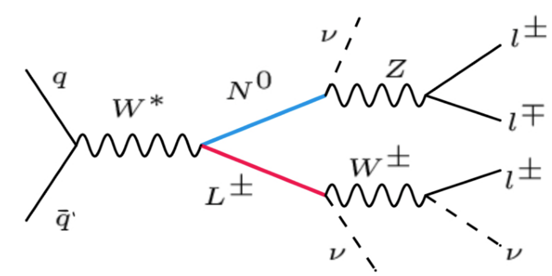


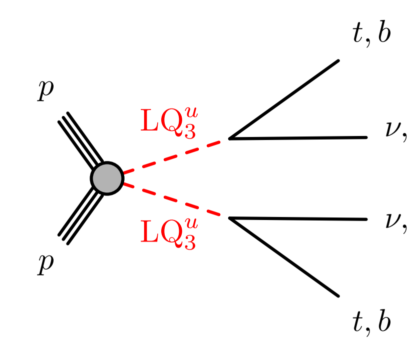


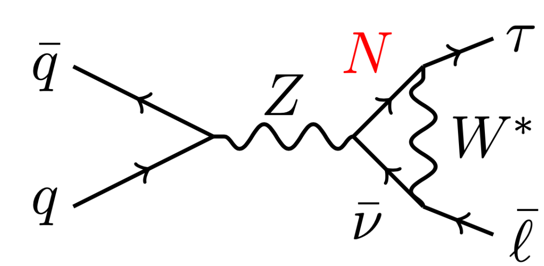
Search Programme

- Anomalies provide additional motivations and guidance, but clearly more experimental inputs are needed to solve the puzzles around lepton interactions
- ATLAS programme of searches and measurements is broad and ambitious, as attested by results presented today
- Search for new phenomena in $e^+e^-/\mu^+\mu^- + 0/1\, b$ events
  - Sensitive to $bs\ell\ell$ **contact interactions** indicated by $b \to s\ell\ell$ anomalies
- Search for new heavy particles
  - **Simplified models of UV-completions of SM**
  - Search for type-III seesaw heavy leptons
    - Similar pheno as Vector-Like Leptons possibly connected to g-2
  - Search for leptoquarks
    - Possibly connected to B anomalies
- Search for LFV $Z \to \ell\tau$ decays
  - **Model-independent test of accidental SM symmetry**





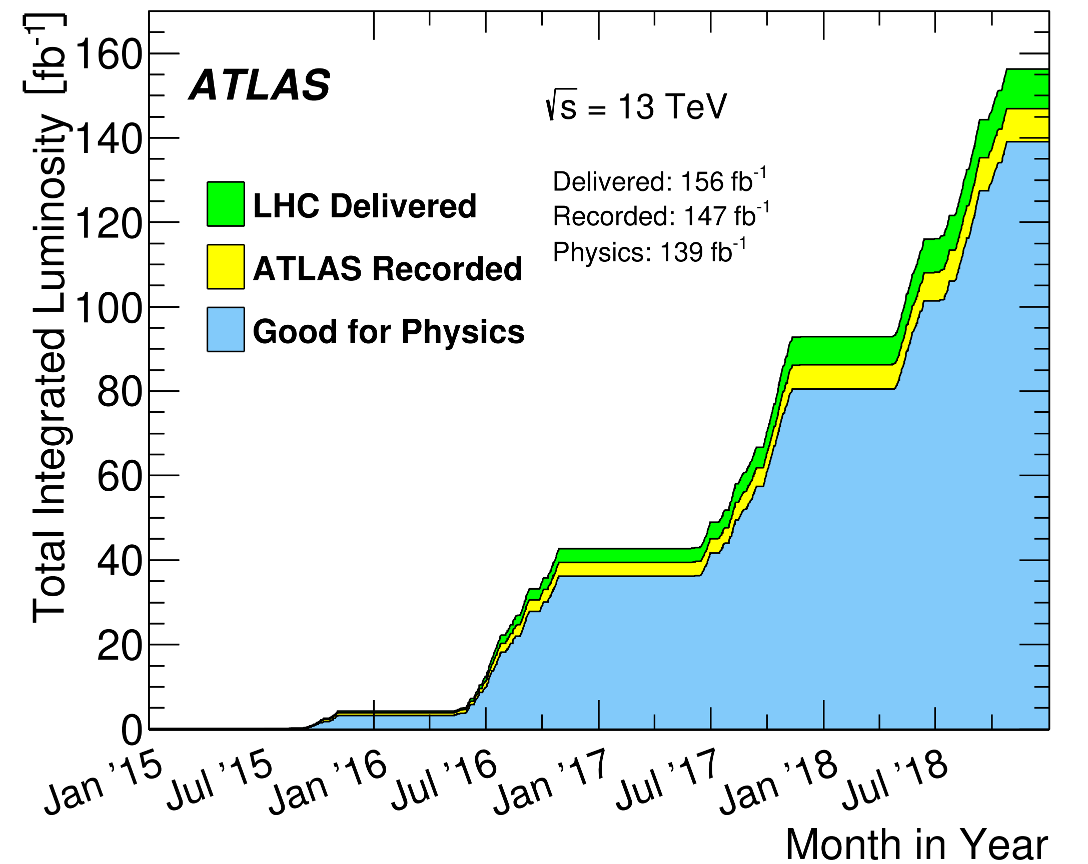




ATLAS Performance

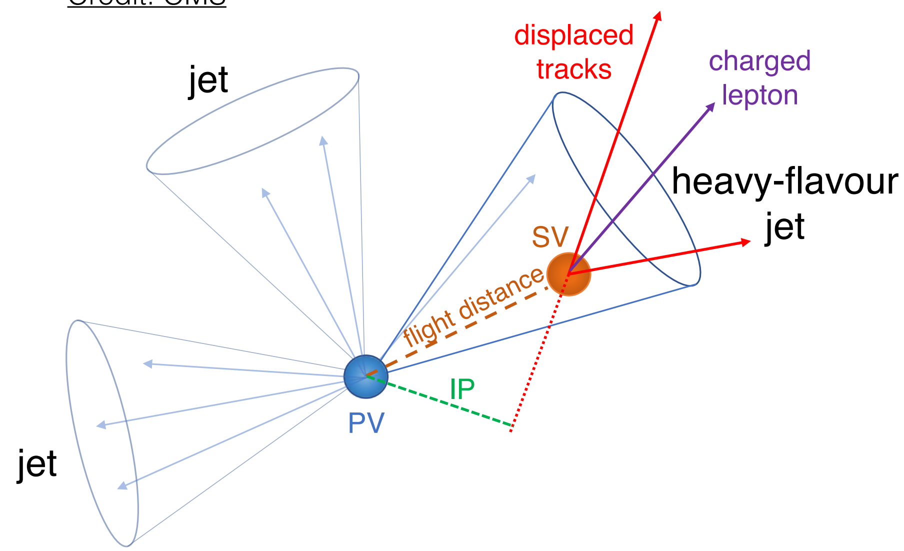
- **Sensitivities of searches driven by size of recorded data set**
- Searches enabled by:
  - Outstanding performance of LHC and ATLAS detector during Run-2 with 139 fb^{-1} of good *pp* data at $\sqrt{s} = 13$ TeV (DQ efficiency of 95.6%)
  - Highly-efficient event/object reconstruction (next slide)

JINST 15 (2020) P04003

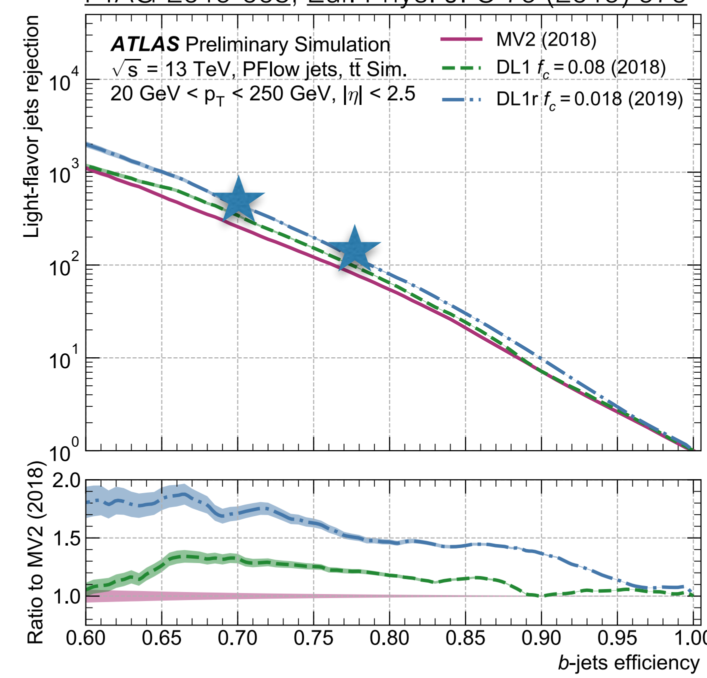


ATLAS Performance

Credit: CMS



FTAG-2019-005, Eur. Phys. J. C 79 (2019) 970



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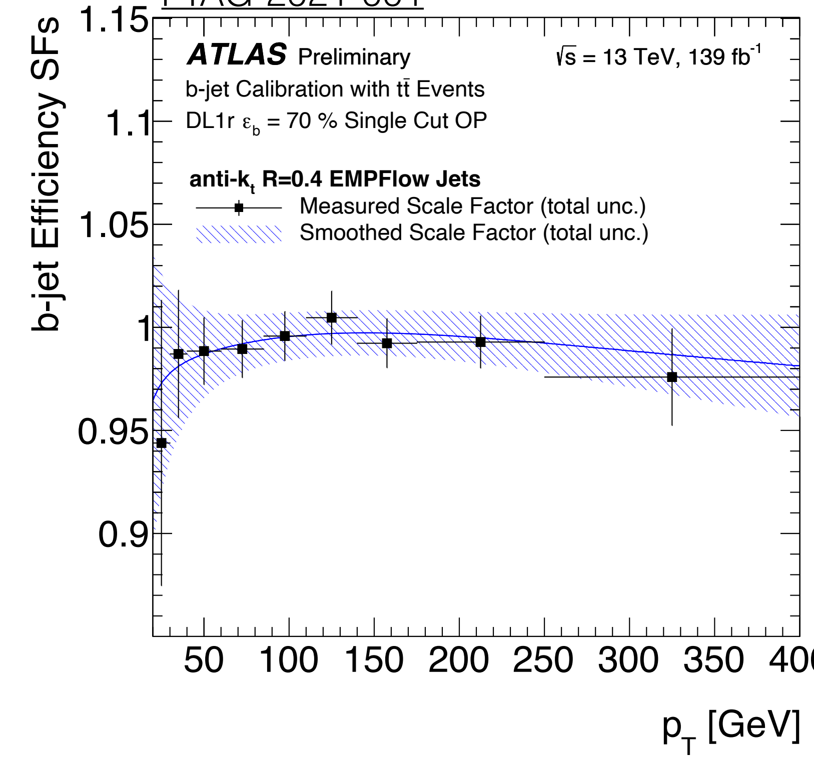
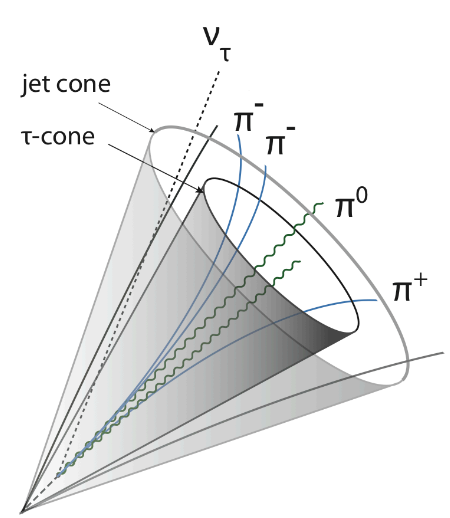


- Extensive use of particle-flow reconstruction and ML identification of hadronic signatures
- ***b*-jet tagging** with multi-class deep neural network with inputs from tracks and vertices inside jet
- **Hadronic τ decay** identified with recurrent neural network based on properties of tracks and clusters



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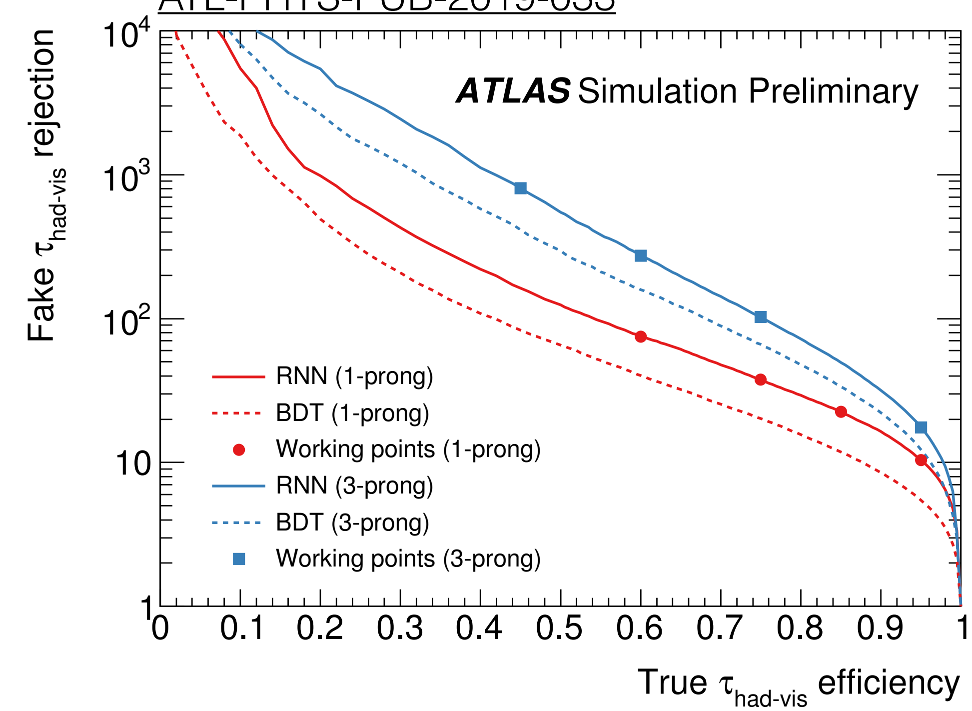
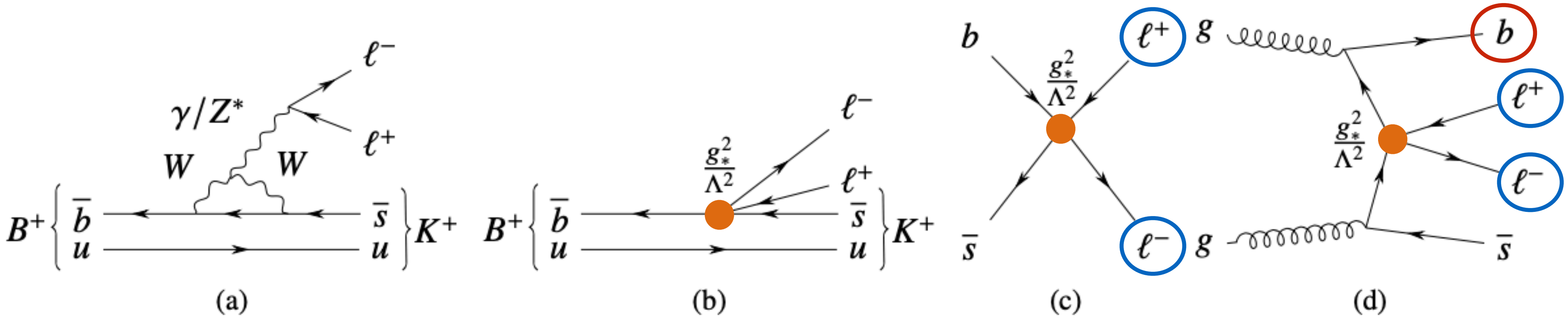
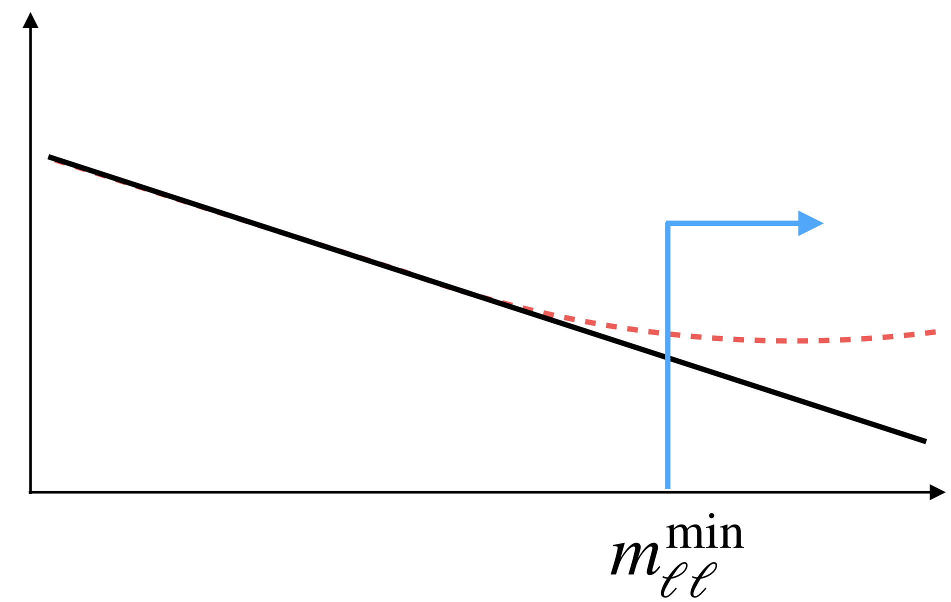


Search for new phenomena in $e^+e^-/\mu^+\mu^- + 0/1\,b$

Search for new phenomena in $e^+e^-/\mu^+\mu^- + 0/1\, b$

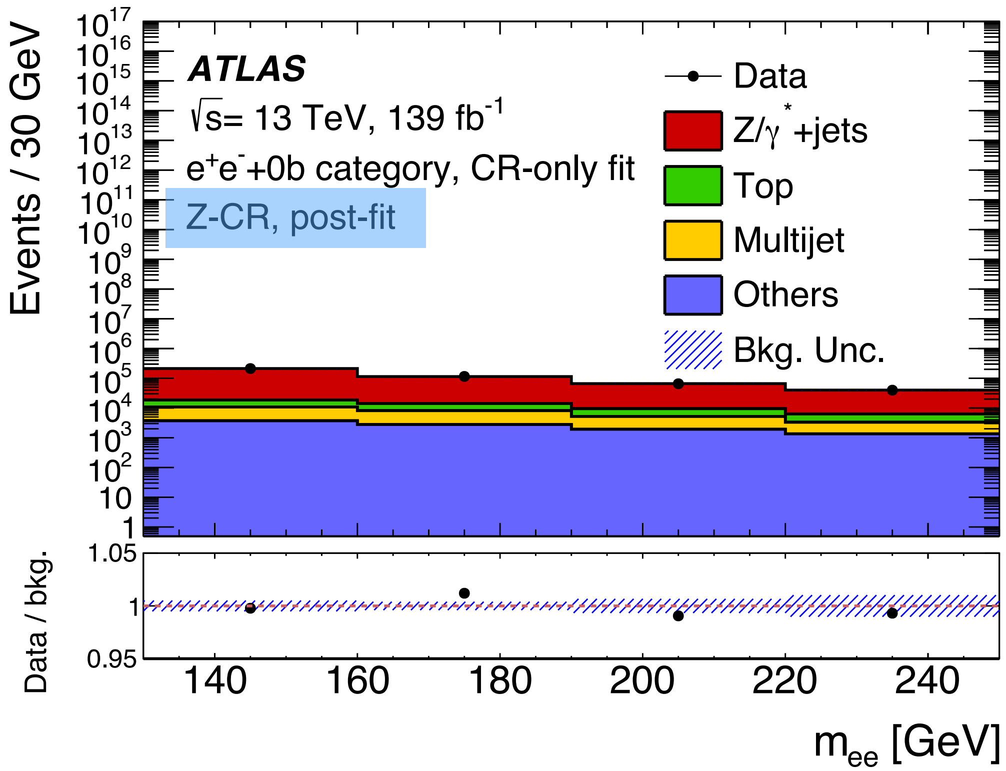


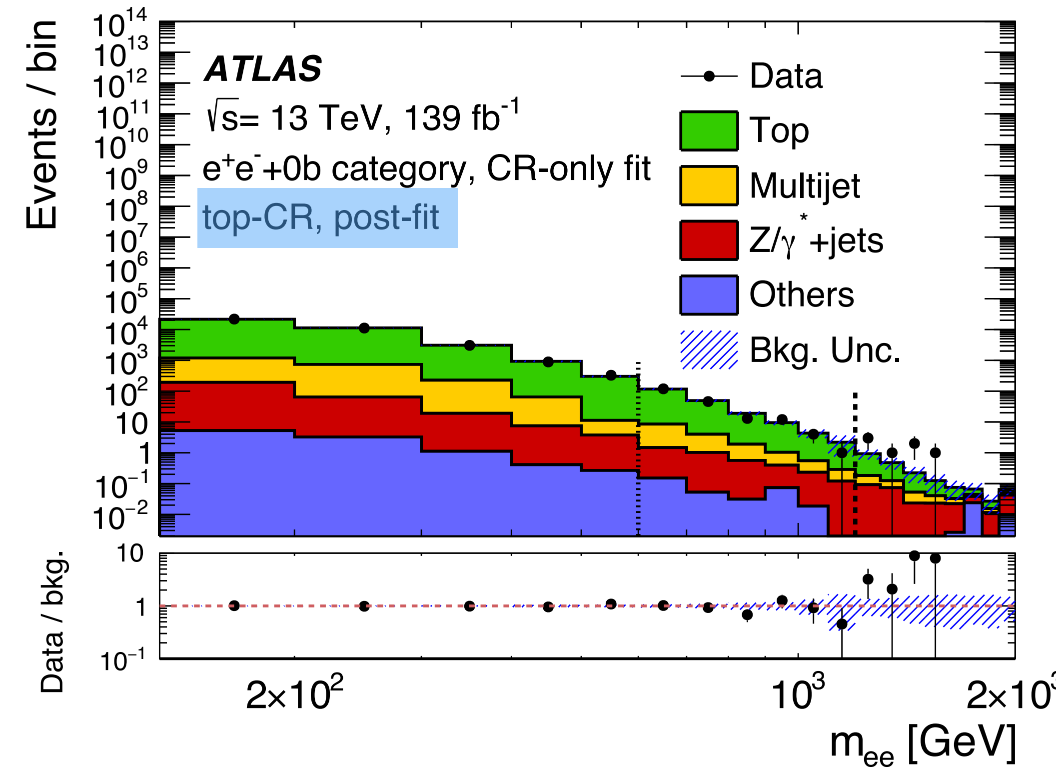
- Analysis is sensitive to a variety of models
- Benchmark model: $bs\ell\ell$ **contact interaction** motivated by B anomalies
- Dominant backgrounds:
  - Off-shell Z/γ^*+jets events
  - Top events ($t\bar{t}, tW, t\bar{t}V$)
- Challenges:
  - **Estimations of background tails**
    - In-situ determination of background normalisations
    - Mitigation of statistical uncertainties with extrapolations
  - **Reconstruction of high-p_T objects**
    - Dedicated "high-pt" muon reconstruction to improve momentum resolution [arXiv:2012.00578]



Region	SR	ZCR	TopCR
#bjets	0/1	0/1	2
$m_{\ell\ell}$ [GeV]	>400+n100	130-250	>130

Search for new phenomena in $e^+e^-/\mu^+\mu^- + 0/1\,b$



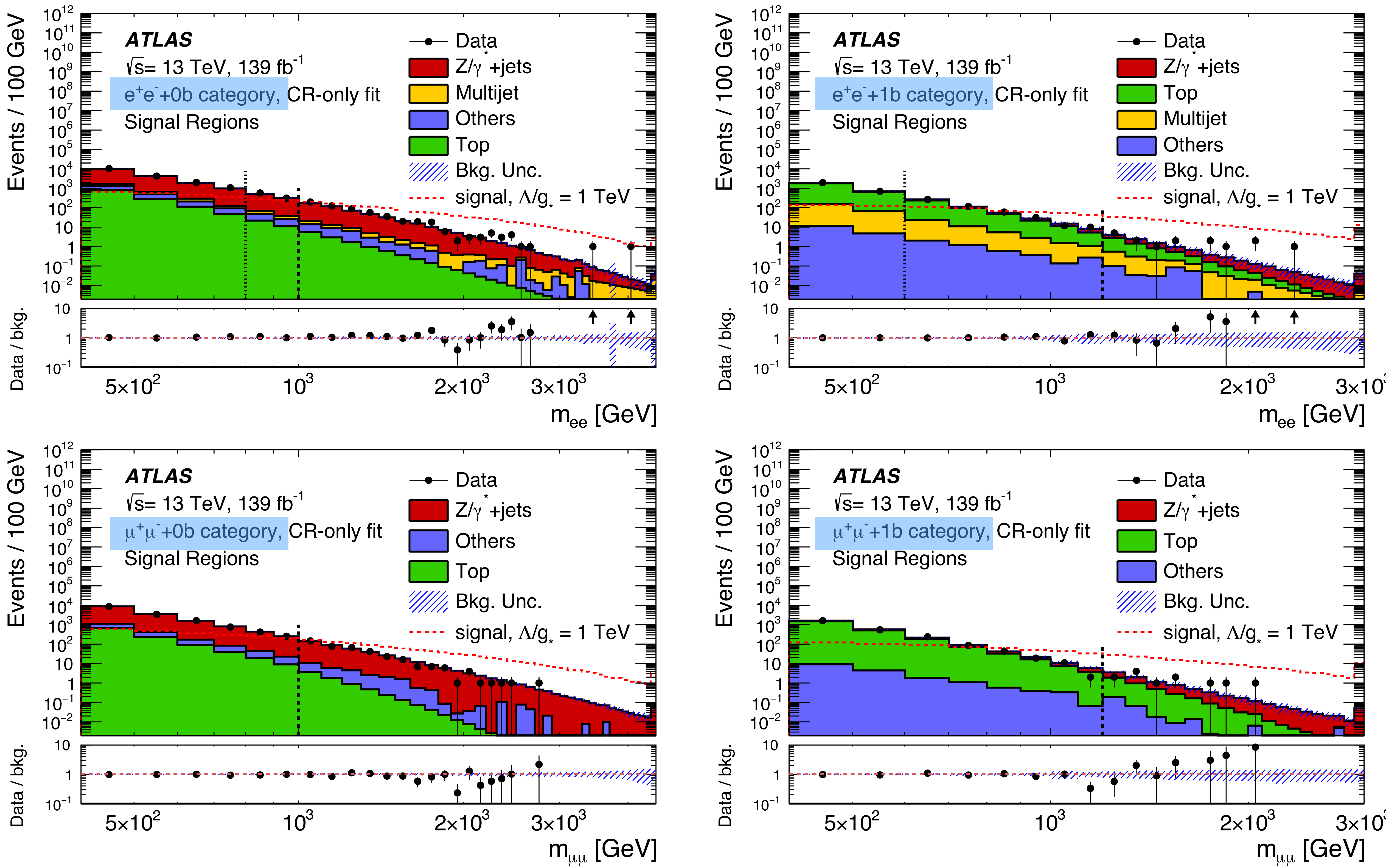


- Z+jets and top events normalised in CRs
- Multijet events in ee channel estimated from data
- Extrapolation of top and multijet events to high-$m_{\ell\ell}$ with parametrised functions

Source	$e^+e^- + 0b$ $(1b)$ [%]		$\mu^+\mu^- + 0b$ $(1b)$ [%]	
	Signal $0b$ $(1b)$	Background $0b$ $(1b)$	Signal $0b$ $(1b)$	Background $0b$ $(1b)$
Luminosity	1.7 (1.7)	1.6 (1.5)	1.7 (1.7)	1.7 (1.7)
Pileup	<0.5 (<0.5)	<0.5 (0.7)	<0.5 (<0.5)	<0.5 (<0.5)
Leptons	8.7 (8.6)	8.6 (6.3)	8.5 (6.5)	9.1 (4.2)
Jets	<0.5 (1.8)	<0.5 (3.4)	<0.5 (1.6)	<0.5 (1.9)
b-tagging	<0.5 (1.4)	<0.5 (2.0)	<0.5 (1.4)	<0.5 (2.2)
Top bkg. extrapolation	-	3.5 (32.0)	-	<0.5 (36.0)
Multijet extrapolation	-	7.5 (15.0)	-	-
Top bkg. modeling	-	<0.5 (<0.5)	-	<0.5 (<0.5)
Z/γ^*+jets bkg. modeling	-	9.4 (4.3)	-	10.0 (5.5)
MC statistics	0.6 (0.8)	1.9 (3.5)	0.7 (1.0)	1.7 (2.4)
Total	8.9 (9.1)	15.0 (37.0)	8.7 (7.1)	14.0 (37.0)

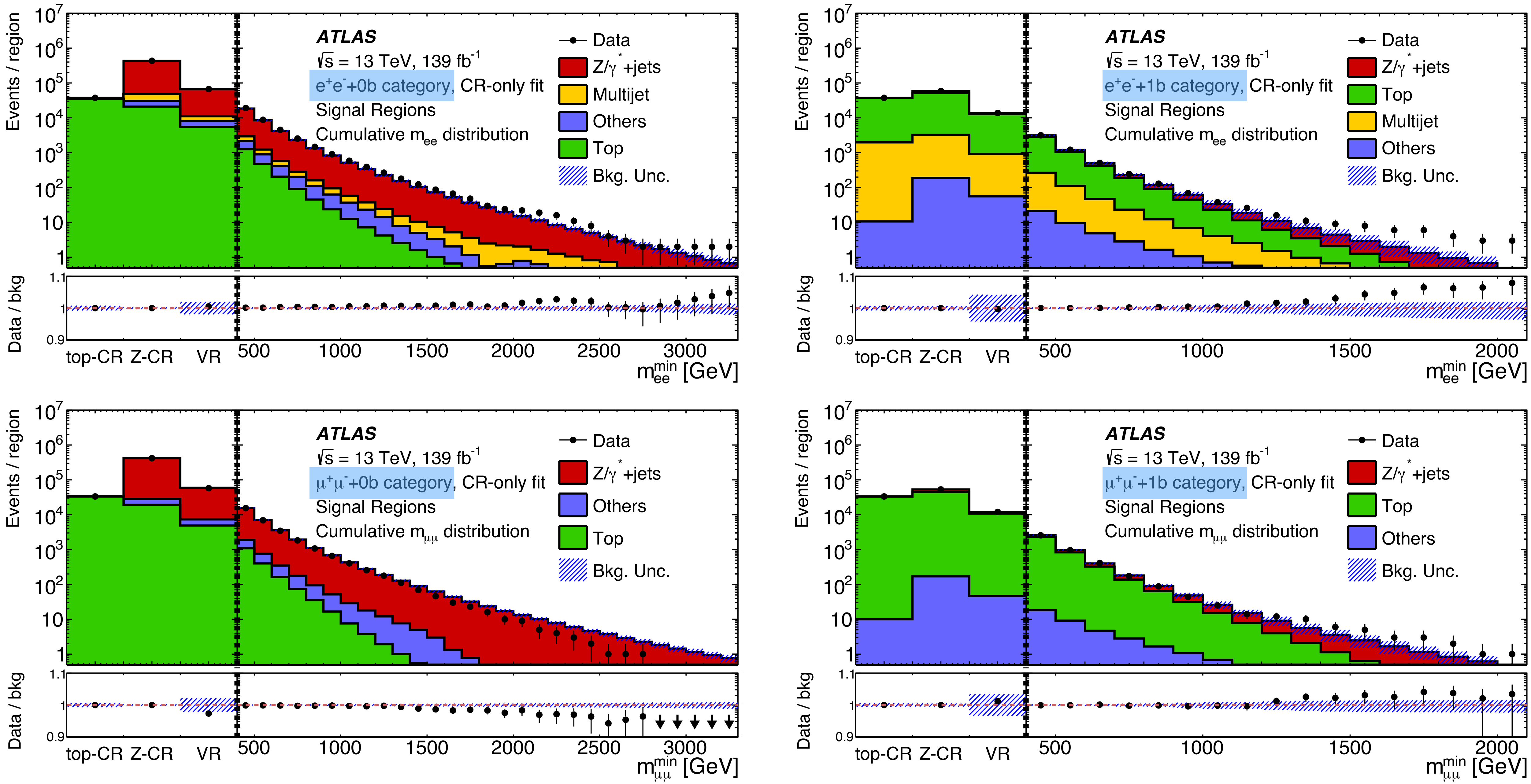
Relative syst uncertainties for $m_{\ell\ell} > 2000(1500)$ GeV for SRs without(with) 1bjet

Search for new phenomena in $e^+e^-/\mu^+\mu^- + 0/1\,b$



Search for new phenomena in $e^+e^-/\mu^+\mu^- + 0/1\,b$

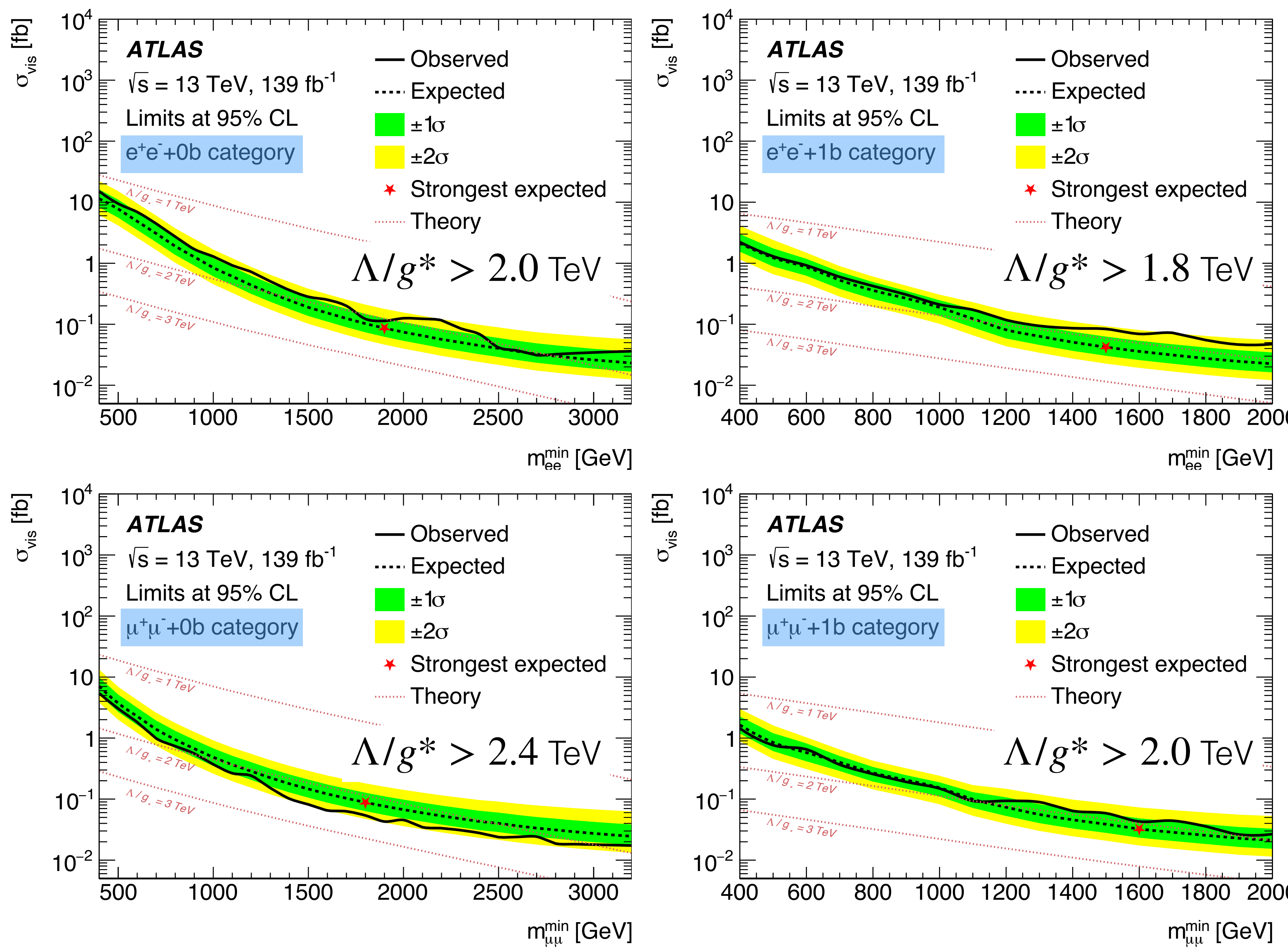
Cumulative distributions

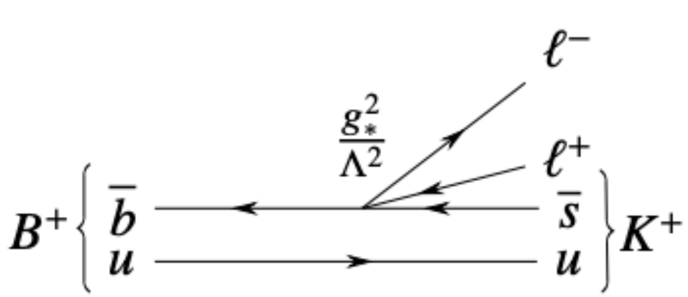


Largest deviation in $ee + 1b$ events at $m_{ee} > 1700$ GeV with local (global) significance of $2.6\,(1.5)\,\sigma$

Search for new phenomena in $e^+e^-/\mu^+\mu^- + 0/1\,b$

- Model independent upper limits on $\sigma_{\text{vis}} = \sigma\epsilon A$ as a function of minimum selection $m_{\ell\ell}$
- Lower limits on Λ/g^* at about 2 TeV for $bs\ell\ell$ benchmark model
  - Far from the scale indicated by B anomalies at ~30 TeV
- Search sensitive also to other contact interactions, like $tq\ell\ell$ that can only be probed at high energy

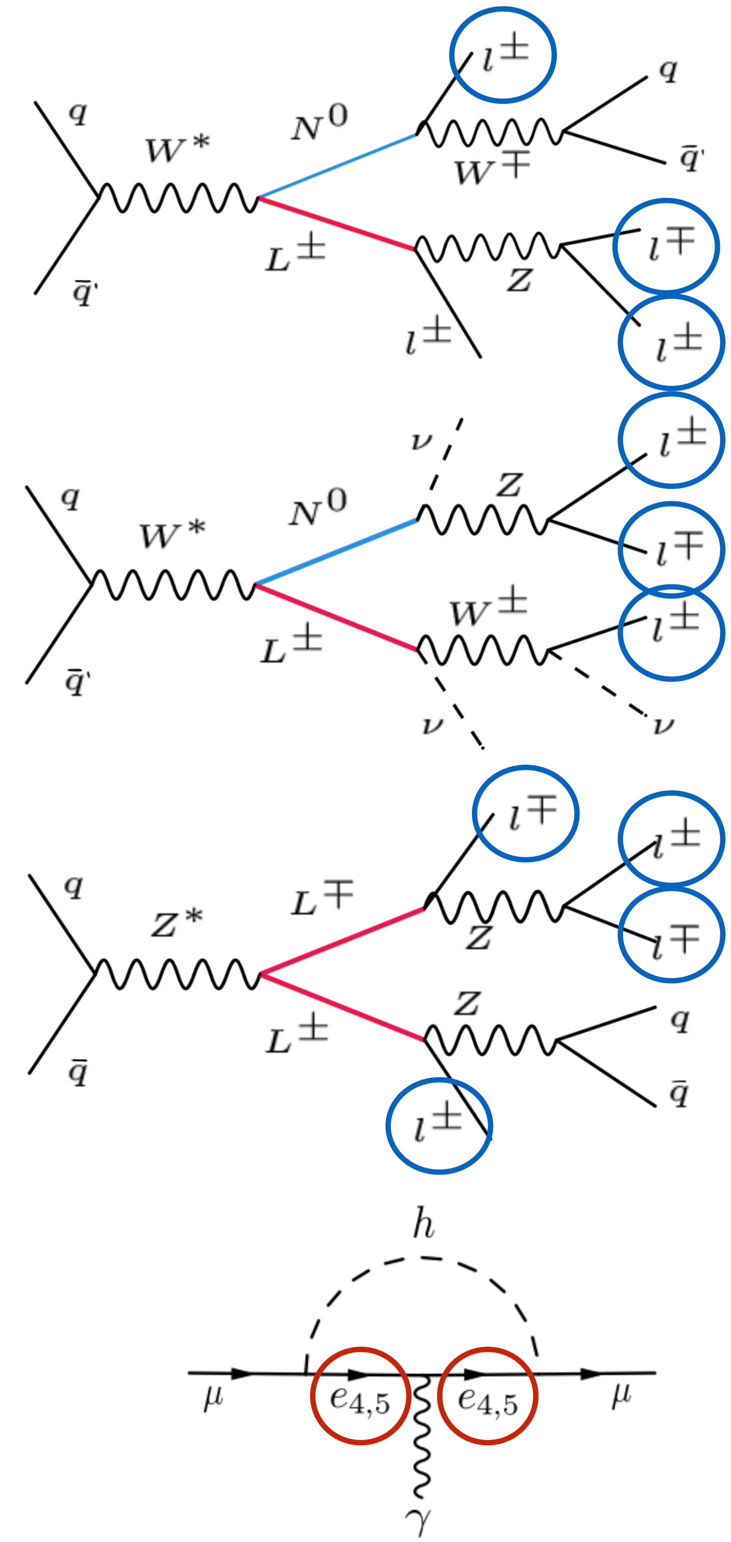




Search for Heavy Leptons

Search for Heavy Leptons

- Search for heavy leptons in events with 3/4 leptons
- Benchmark model:
  - **Type-III seesaw model** which provides a heavy Majorana neutrino that could explain small neutrino mass
  - Extra fermionic $SU(2)_L$ triplet coupled to W,Z,H bosons
  - Heavy leptons $(N^0, L^\pm)$ degenerate in mass and produced in pairs with cross section dependent on heavy lepton mass
  - $\mathscr{B}_e = \mathscr{B}_\mu = \mathscr{B}_\tau = 1/3$ and $2\mathscr{B}_H \simeq 2\mathscr{B}_Z \simeq \mathscr{B}_W \simeq 1/2$
- Phenomenology similar to other models with heavy leptons, like **Vector-Like Lepton** triplets that could be linked to g-2 anomaly
- Dominant backgrounds: WZ, ZZ (diboson), "rare top" production ($t\bar{t}V, t\bar{t}H, tWZ$) and fake non-prompt leptons (FNP)



Search for Heavy Leptons

3ℓ Events:

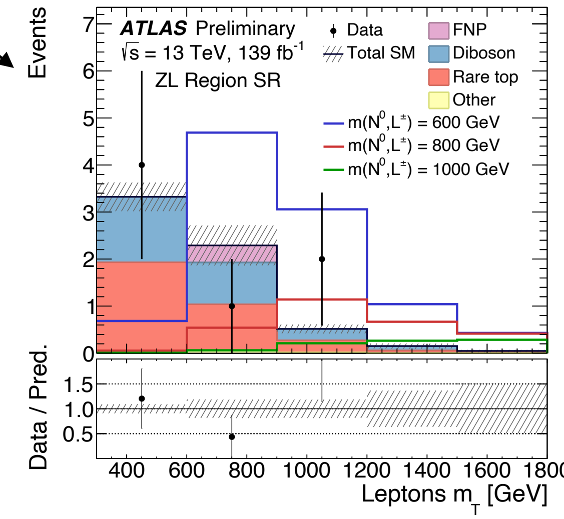
Table 2: Summary of the selection criteria used to define relevant regions in the three-lepton analysis.

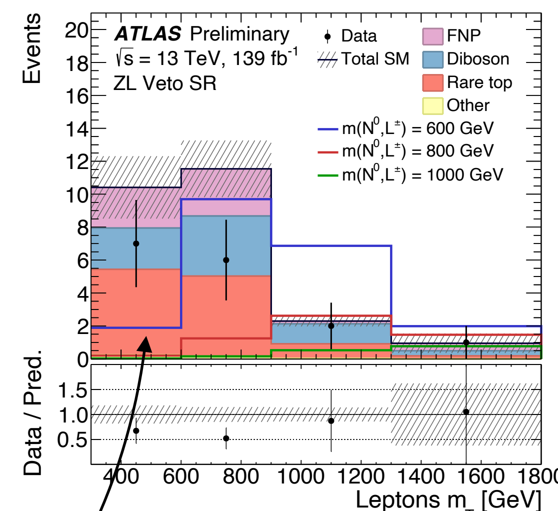
		ZL				**ZLveto**	**JNLow**	
	Fake-VR	CR	DB-VR	RT-VR	SR	SR	VR	SR
	$p_T(l_1) > 40$ GeV $p_T(l_2) > 40$ GeV $p_T(l_3) > 15$ GeV							
$S(E_T^{miss})$	< 5	≥ 5						
$N(jet)$		≥ 2				≥ 2	≤ 1	
$N(bjet)$		-	0	≥ 1	-			
$m_{ll}(OSSF)$ [GeV]		$80 - 100$				≥ 115	≥ 80	
$H_T + E_T^{miss}$ [GeV]						≥ 600		
m_{lll} [GeV]		-	≥ 300			≥ 300		
m_{jj} [GeV]						< 300		
$H_T(SS)$ [GeV]						≥ 300		
$H_T(lll)$ [GeV]							≥ 230	
$m_T(l_1)$ [GeV]			≥ 200				< 240	≥ 240
$m_T(l_2)$ [GeV]		< 200	≥ 200				≥ 150	
$\Delta R(l_1, l_2)$			< 1.2		$1.2 - 3.5$		≥ 1.3	

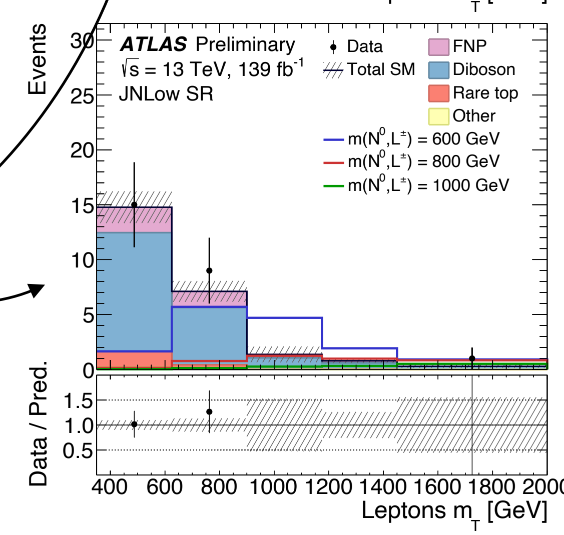
$$m_T(i) = \sqrt{2p_T(i)E_T^{miss}(1 - \cos\Delta\phi(i, E_T^{miss}))}$$

$$H_T = \Sigma_i p_T(i)$$

$$m_T = |\Sigma_i^{3\ell}\overrightarrow{p}_{T,i} + \overrightarrow{p}_T^{miss}|$$





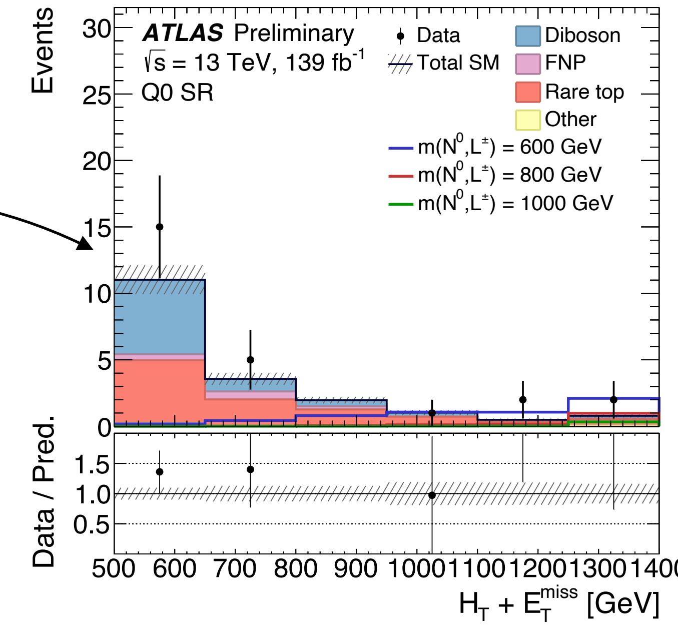


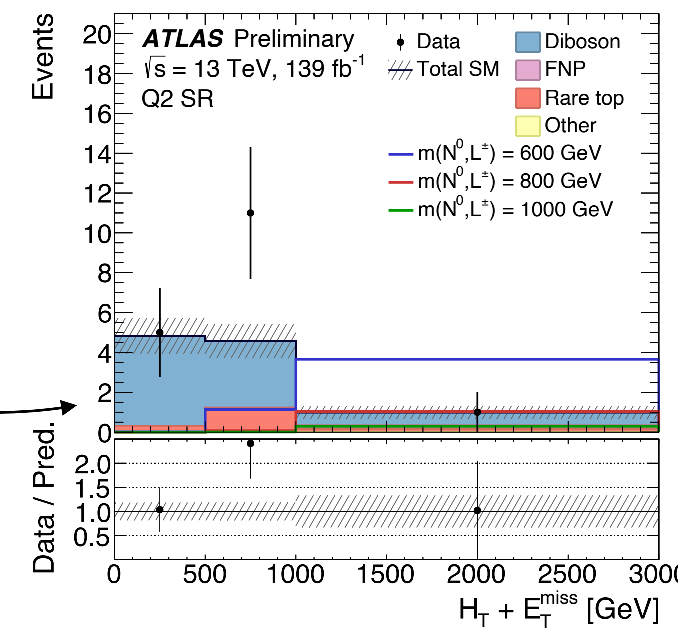
Search for Heavy Leptons

4ℓ Events:

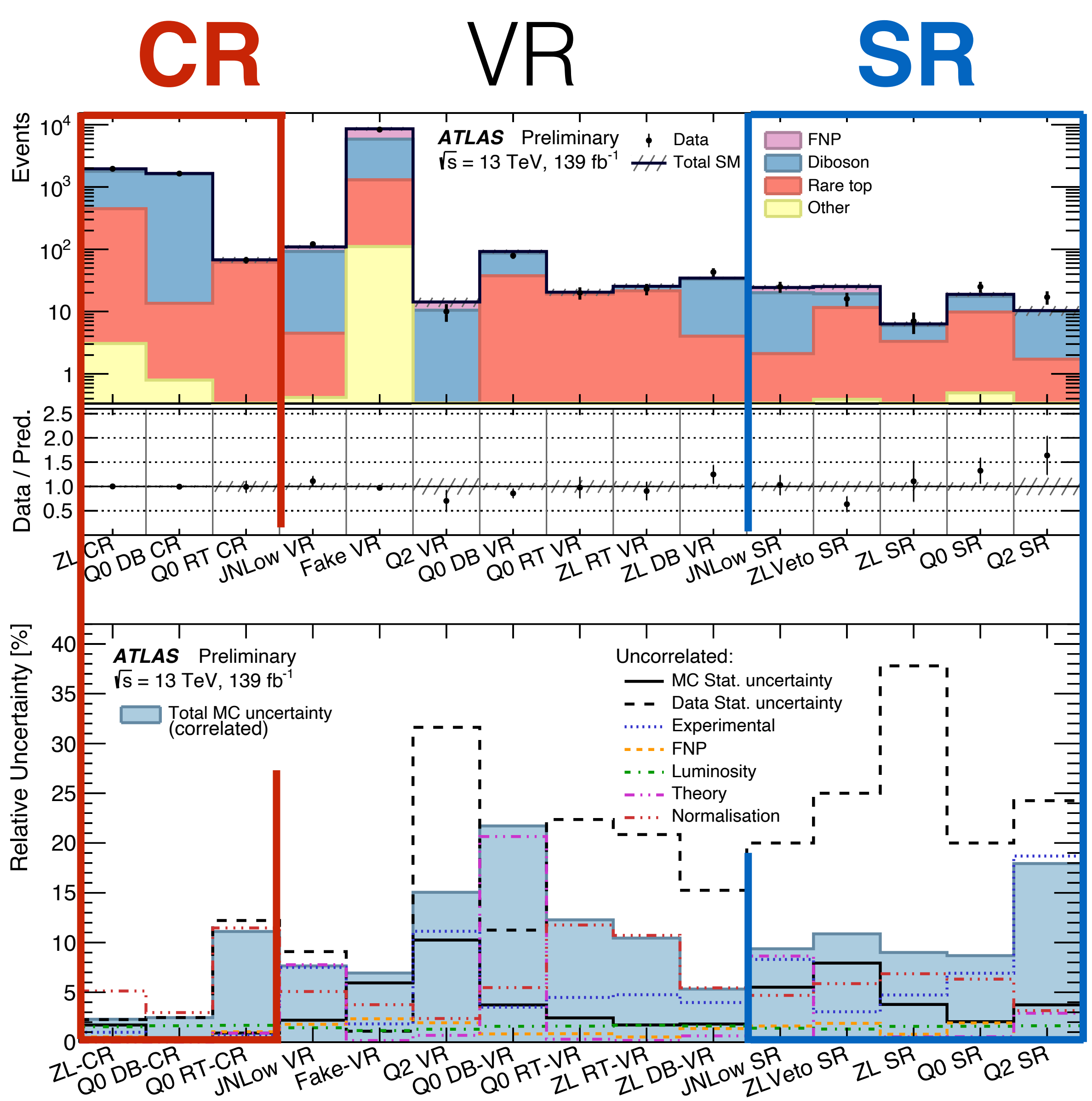
Table 3: Summary of the selection criteria used to define relevant regions in the four-lepton analysis. N_Z is the number of leptonically reconstructed Z, using opposite sign same flavour leptons.

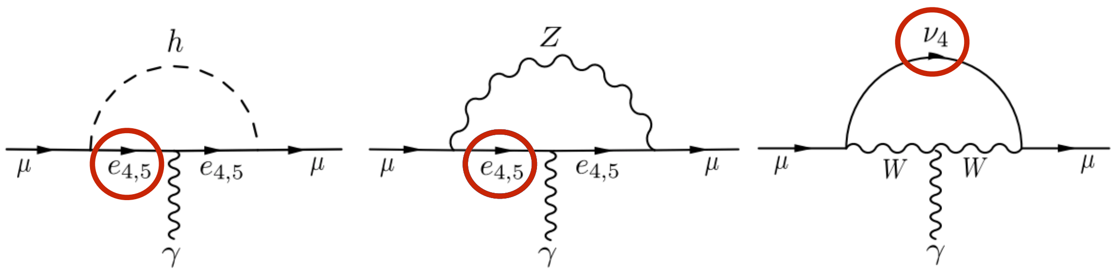
	Q0					Q2	
	DB-VR	RT-VR	DB-CR	RT-CR	SR	VR	SR
$\lvert \sum q_\ell \rvert$	0					2	
$N_{b\text{-jet}}$	1	1	0	≥ 2	0		
m_{llll} [GeV]	$170 - 300$	$300 - 500$	$170 - 300$	< 500	≥ 300	< 200	≥ 300
						OR	
$H_T + E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]		≥ 400			≥ 300	< 300	≥ 300
N_Z					≤ 1		
$\mathcal{S}(E_{\mathrm{T}}^{\mathrm{miss}})$		≥ 5			≥ 5		



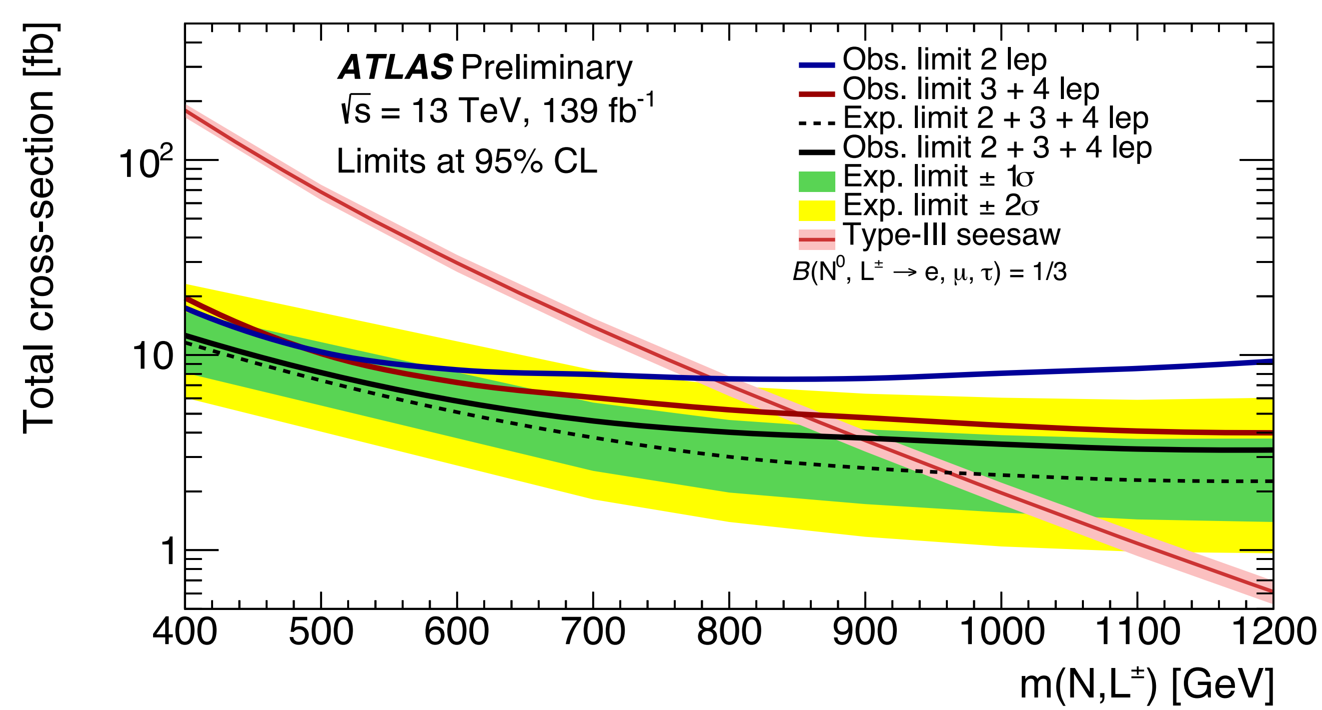


Search for Heavy Leptons





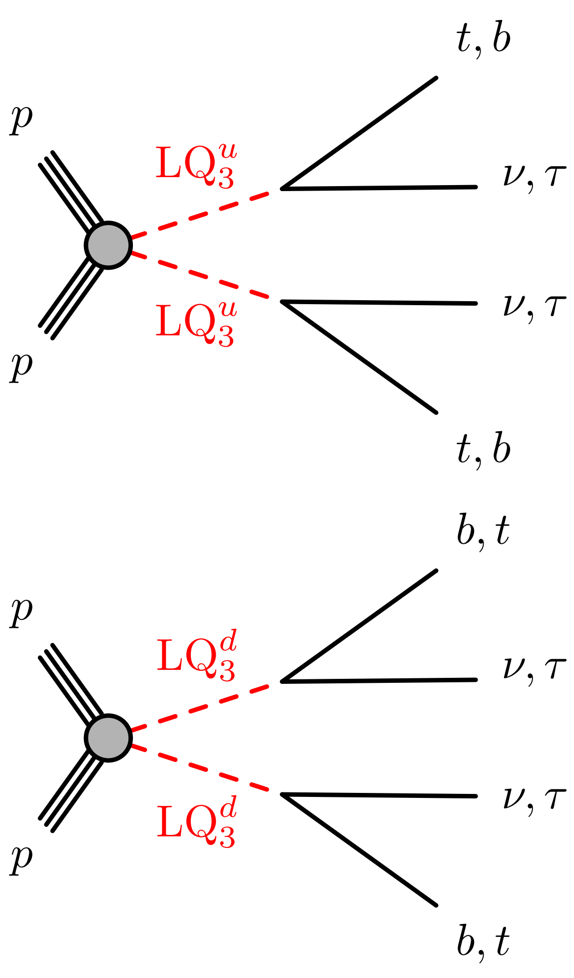
- Statistical uncertainties dominant in SRs
- Results combined with similar search in 2-lepton events [Eur. Phys. J. C 81 (2021) 218]
- Exclusion limits at $m(N, L^{\pm}) > 910$ GeV
- Most stringent limits on type-III seesaw models at LHC



Search for LQ

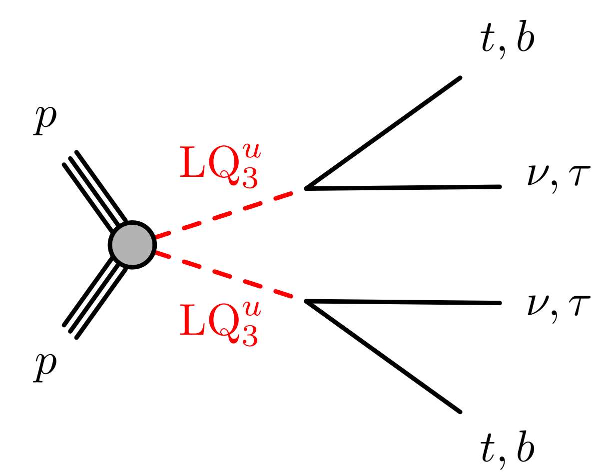
Search for LQ

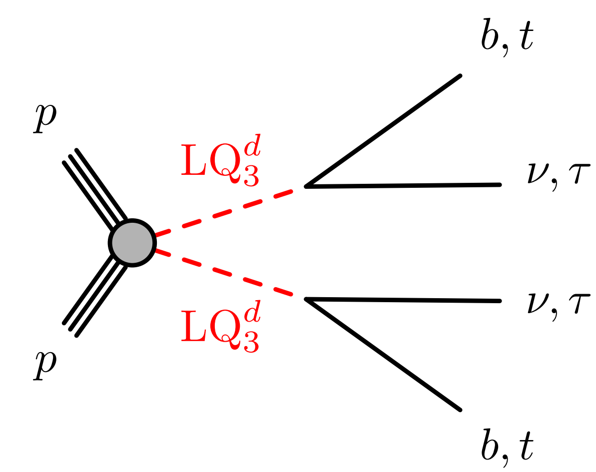
- Leptoquarks (LQ) are **scalar or vector bosons** with non-zero baryon and lepton quantum numbers, charged under all SM gauge groups
- Can violate LFU and explain flavour anomalies, if they have **cross-generational** couplings
- Minimal Buchmüller-Rückl-Wyler (BRW) model
  [*Phys.Lett.B* 191 (1987) 442-448, *Phys.Lett.B* 448 (1999) 320-320 (erratum)]
  - Yukawa-type couplings to $q\ell$ or $q\nu$



Search for LQ

- **Scalar** 3rd-generation leptoquarks [Phys. Rev. D 93, 035018 (2016)]
  - $\mathrm{LQ}_3^u \to t\nu/b\tau\,(|q| = 2/3)$ and $\mathrm{LQ}_3^d \to b\nu/t\tau\,(|q| = 1/3)$
- **Vector** 3rd-generation leptoquarks $\mathrm{LQ}_3^{\mathrm{V}}$ * [Eur.Phys.J. C79 (2019) 4, 334]
  - Same charge and decay mode as LQ_3^u
  - Minimal-coupling (MC): $\mathrm{LQ}_3^{\mathrm{V}}$ couples SM gauge bosons through covariant derivative
  - Yang-Mills (YM): $\mathrm{LQ}_3^{\mathrm{V}}$ is massive gauge boson with additional couplings to SM gauge bosons
- Model parameters: $m(\mathrm{LQ})$ and $\mathscr{B}(\mathrm{LQ} \to \mathrm{q}\ell)$
- Pair-production cross section depends only on $m(\mathrm{LQ})$
  - $\sigma_{\mathrm{YM}}(\mathrm{LQ}_3^{\mathrm{V}}) \sim 5\sigma_{\mathrm{MC}}(\mathrm{LQ}_3^{\mathrm{V}}) \sim 20\sigma(\mathrm{LQ}_3^{u/d})$ at $m(\mathrm{LQ}) = 1.5$ TeV
- For $\mathscr{B}(\mathrm{LQ} \to \mathrm{q}\tau) \sim 0.5$, most events have 1 τ, 2 b-jets and large E_T^{miss}





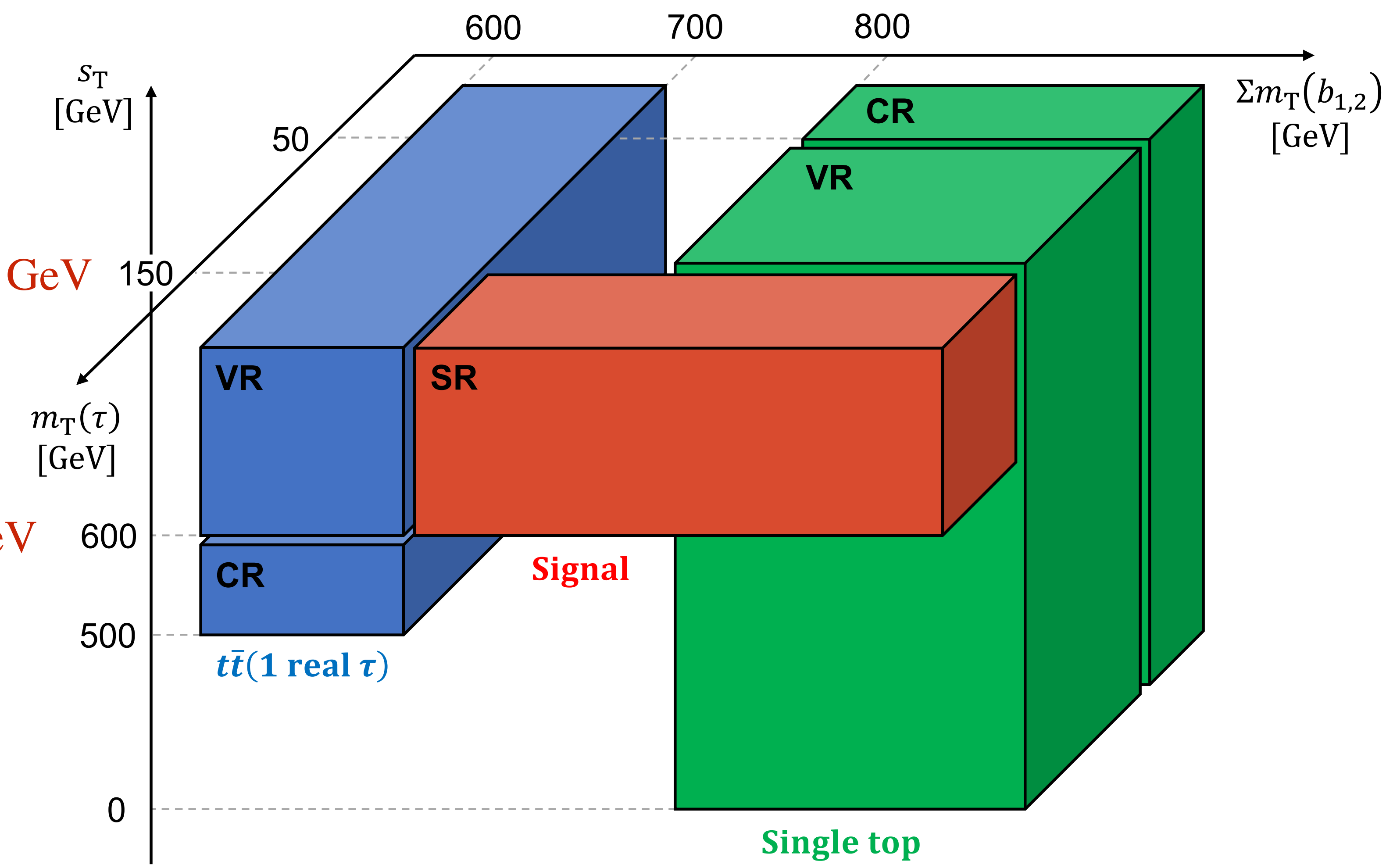
(*) Additional vector states needed for a realistic extension of the SM (colour singlet Z' and colour octet G'), but these are not included in the model

Search for LQ

$$\Sigma m_T(b_1, b_2) = m_T(b_1) + m_T(b_2) > 700\,\text{GeV}$$

$$m_T(\tau) = \sqrt{2p_T(\tau)E_T^{\text{miss}}(1 - \cos\Delta\phi(\tau, E_T^{\text{miss}}))} > 150\,\text{GeV}$$

$$s_T = p_T(\tau) + p_T(\text{jet}_1) + p_T(\text{jet}_2) > 600\,\text{GeV}$$

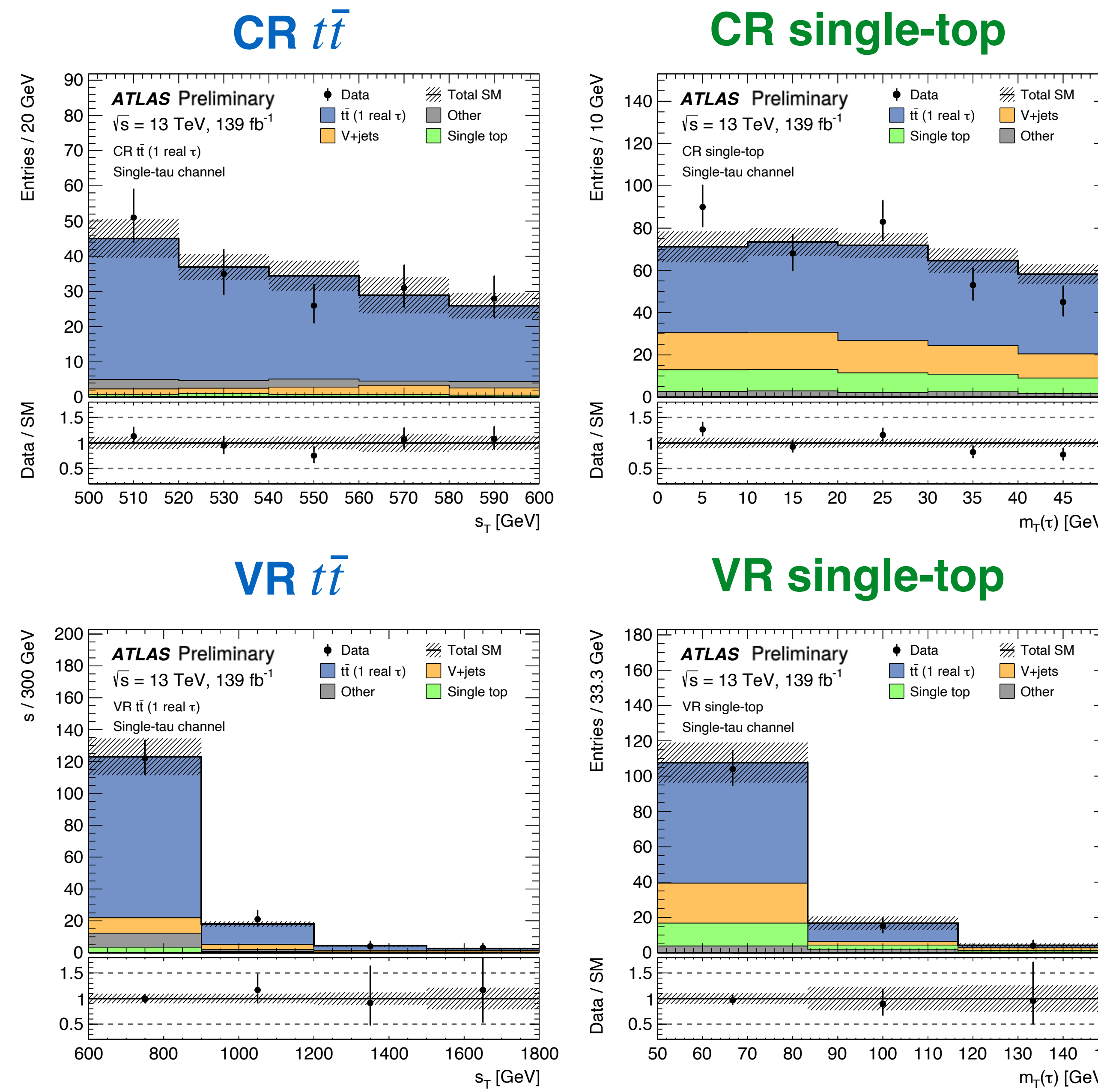


- SRs:
  - E_T^{miss} trigger, offline E_T^{miss}>280 GeV, $1\ \tau_{\text{had-vis}}$, $\geq 2\ b$-jet, no leptons
  - one-bin SR for model-independent fit
  - **multi-bin SR** for model-dependent fit
- Dominant $t\bar{t}$ **(1 real τ)** and **single-top** backgrounds estimated from dedicated CRs and extrapolated to SRs via MC predictions

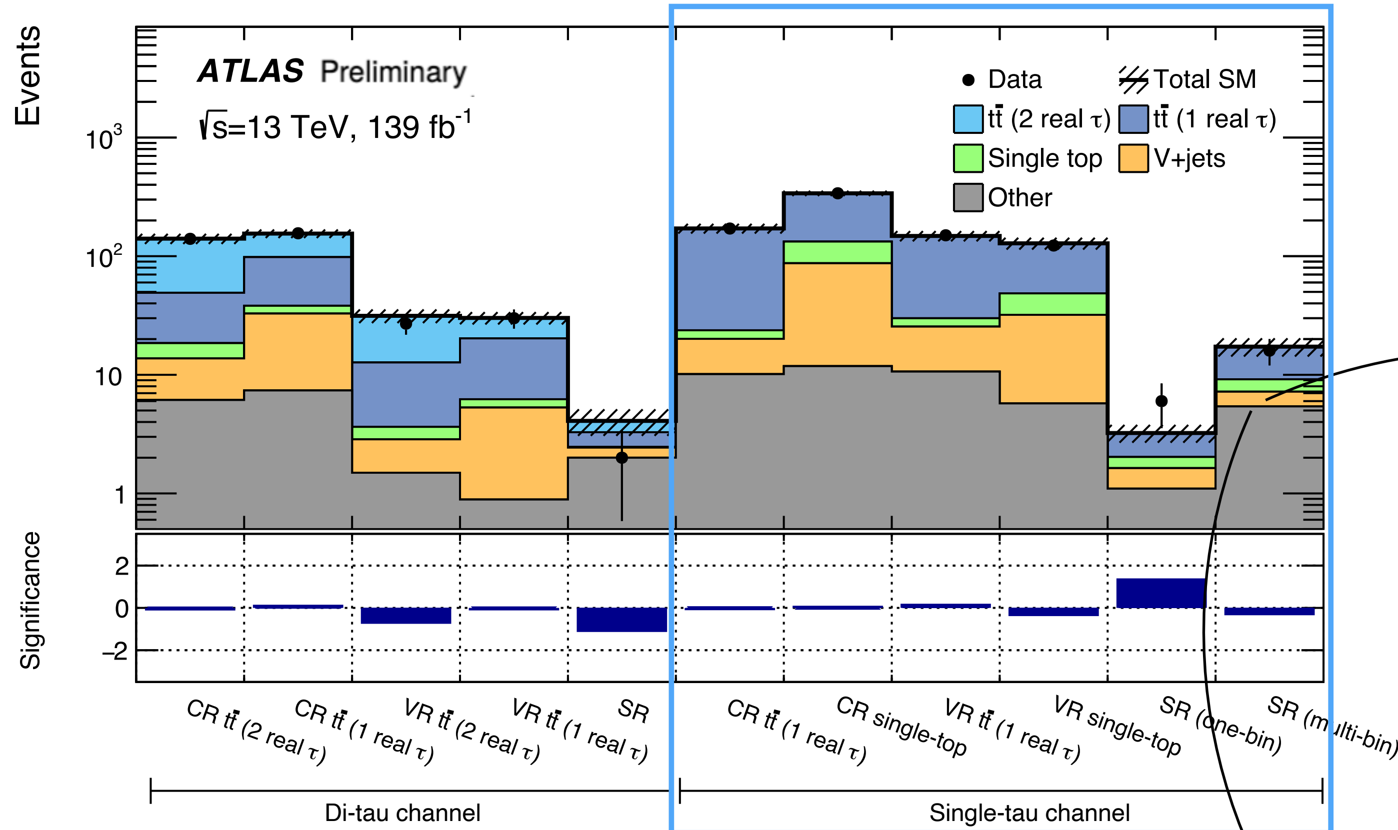
Search for LQ

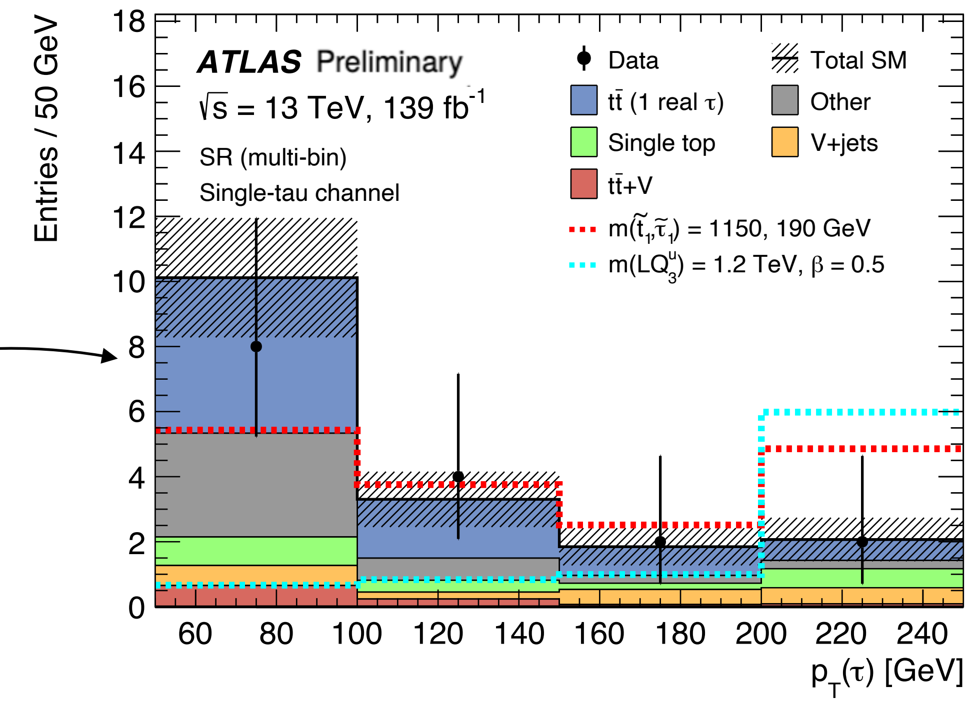
- Normalisation corrections wrt predictions:
  - $t\bar{t}$ (1 real τ): $0.84^{+0.21}_{-0.17}$
  - single-top: $0.18^{+0.19}_{-0.16}$
    - due to modelling of interference with $t\bar{t}$
    - alternative diagram removal scheme yields normalisation corrections larger than 1
    - CR->SR extrapolations are compatible
- Largest systematic uncertainties on background normalisations and on $t\bar{t}$ and single-top theoretical modelling

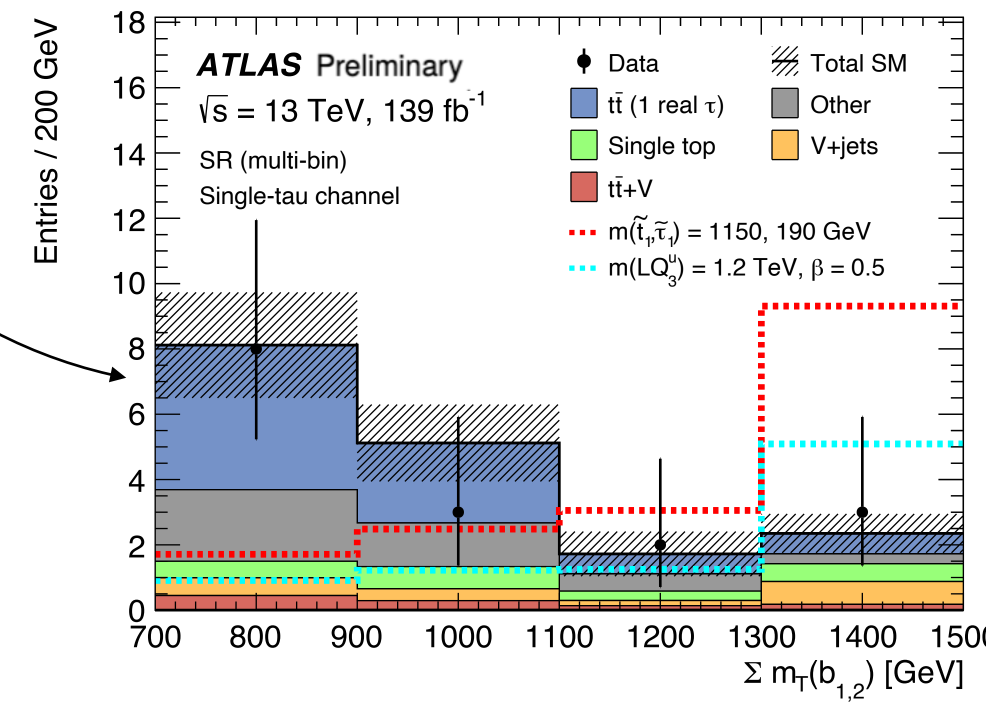
Systematic uncertainty	Single-tau one-bin SR	Single-tau multi-bin SR
Total	17 %	17 %
Jet-related	4.2 %	3.9 %
Tau-related	5.5 %	4.3 %
Other experimental	1.0 %	0.8 %
Theoretical modelling	17 %	19 %
MC statistics	7.5 %	4.4 %
Normalisation factors	15 %	16 %
Luminosity	0.5 %	0.4 %



Search for LQ



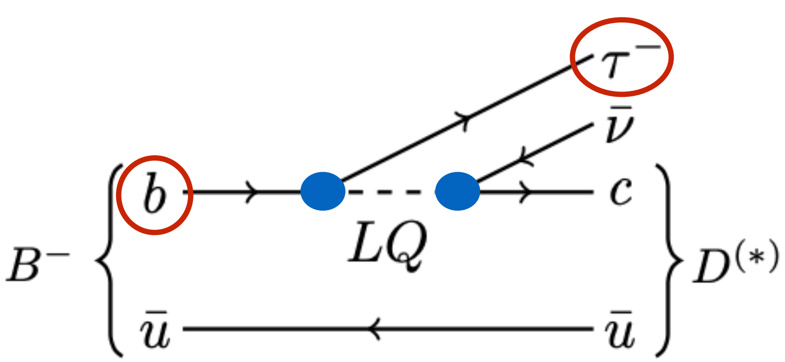




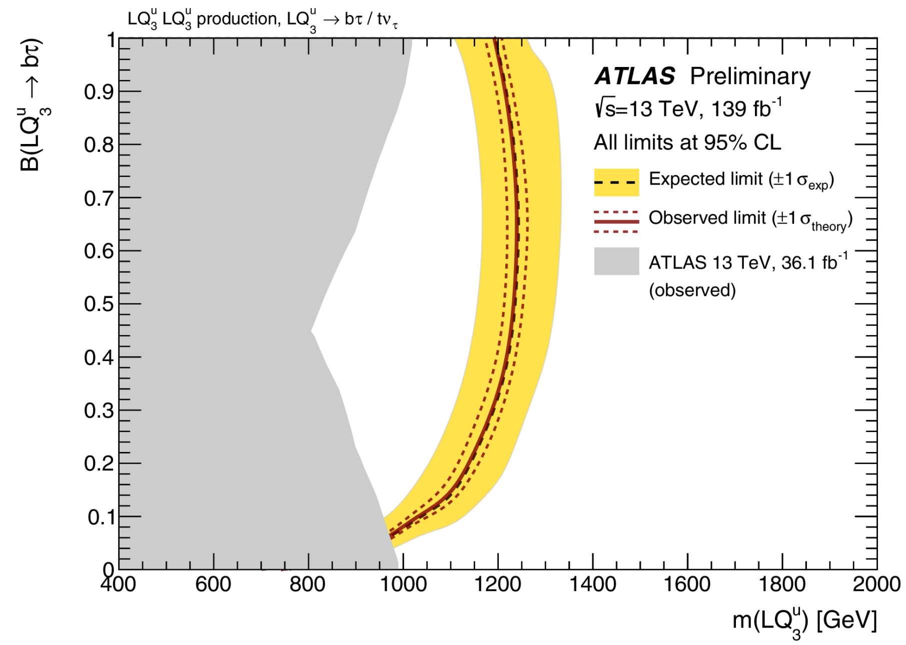
- Analysis includes also di-tau event categories targetting SUSY $\tilde{t} \rightarrow b\nu\tilde{\tau}(\rightarrow \tau\tilde{G})$ pair production

Search for LQ

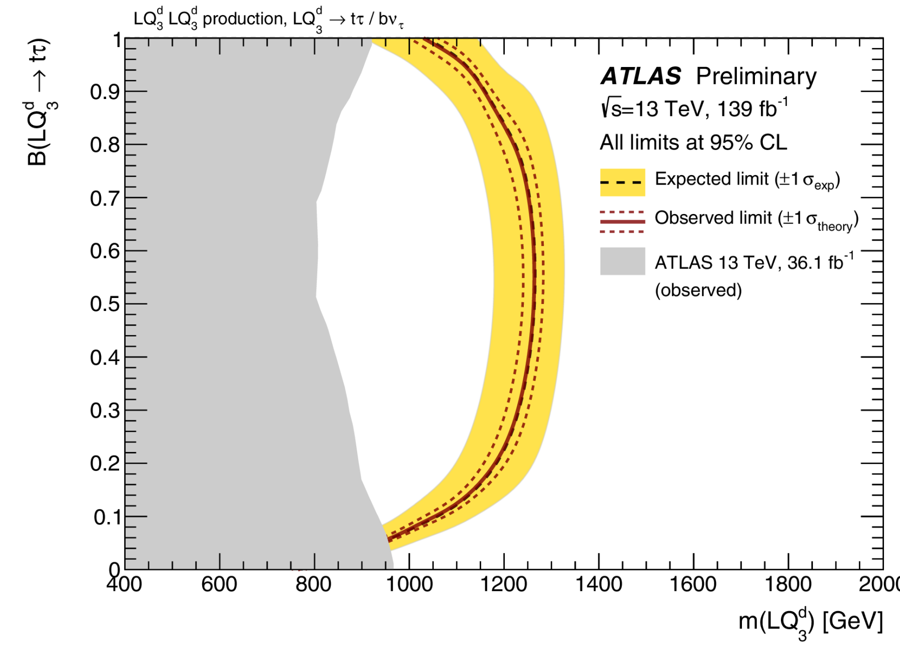
- Strongest limits on pair-produced 3rd-generation scalar LQs for $\mathscr{B}(\mathrm{LQ}_3^{\mathrm{u/d}} \rightarrow \mathrm{q}\tau) \sim 0.5$
- For first time in ATLAS, interpretation for vector LQs



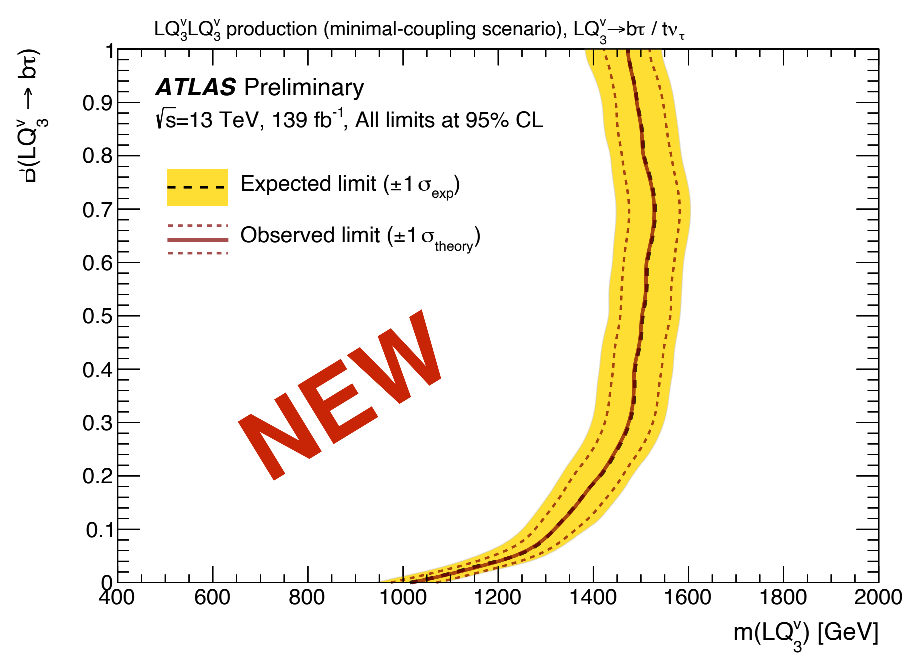
Scalar up-type



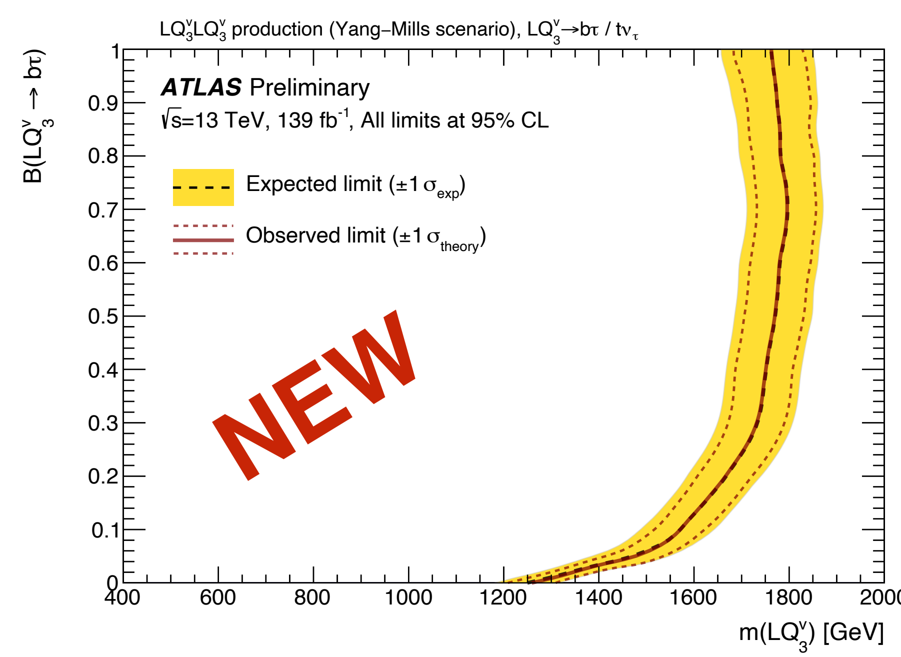
Scalar down-type



Vector MC

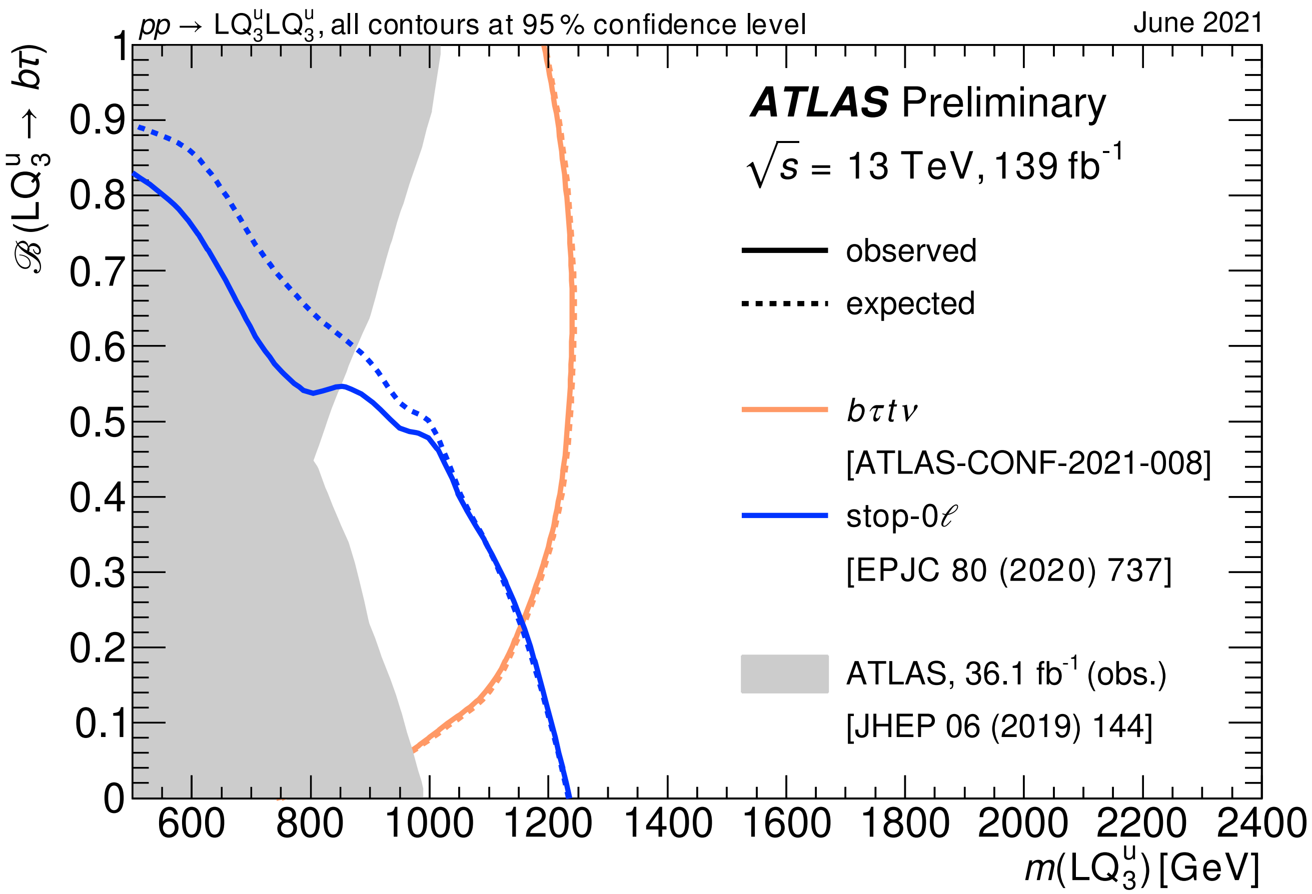


Vector YM

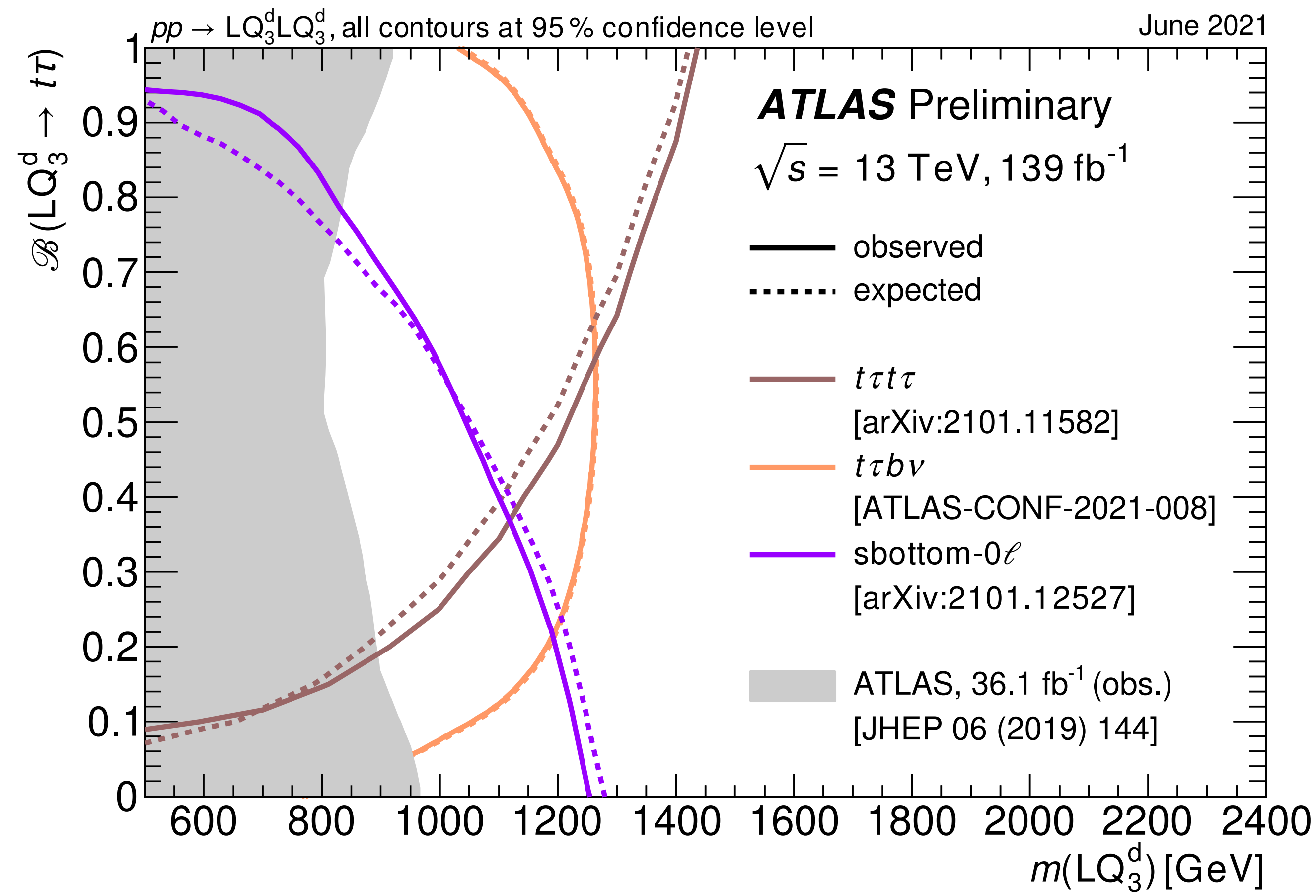


Search for LQ

Scalar up-type

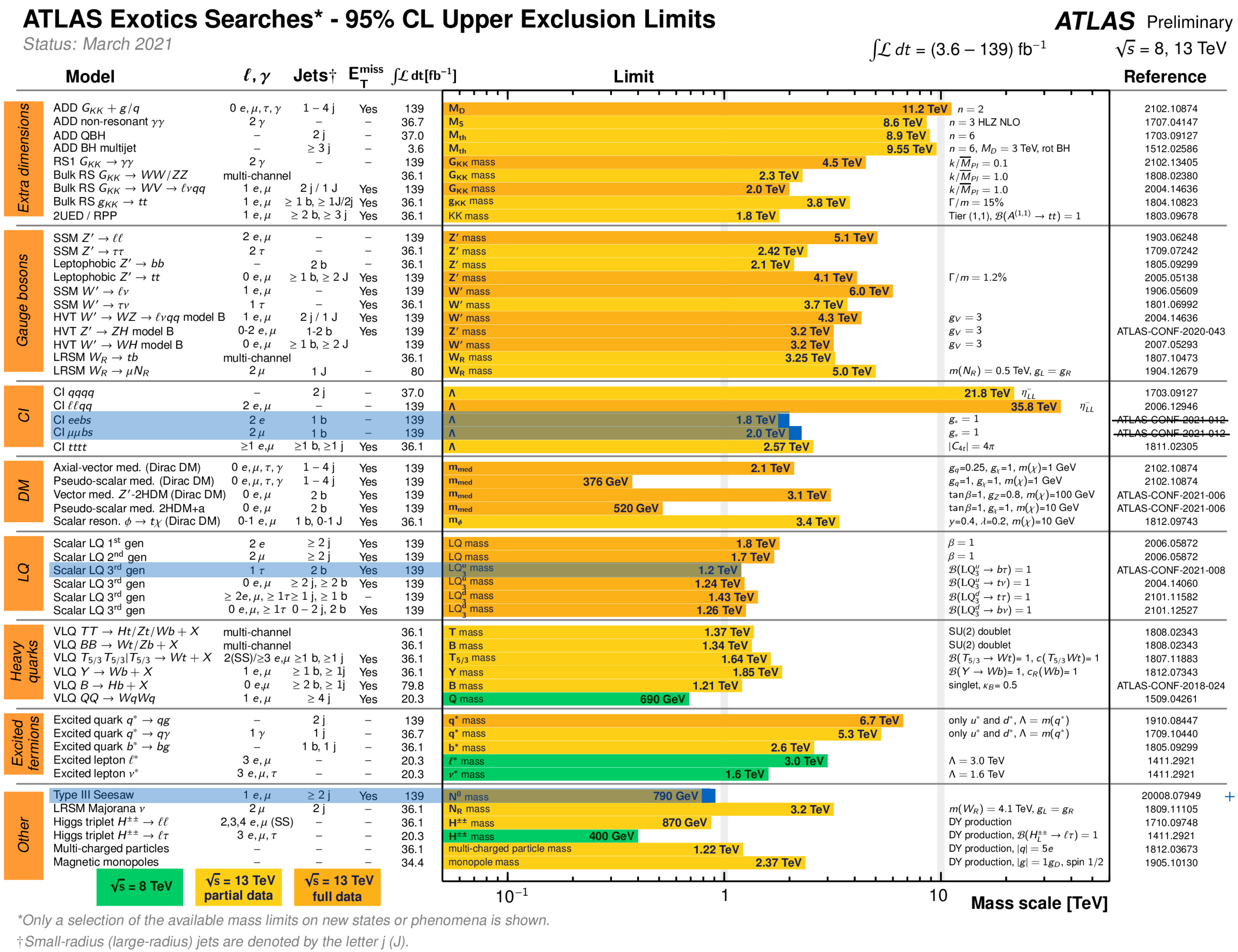


Scalar down-type



- Summary of ATLAS exclusion limits for scalar 3rd-generation LQs
- More on other LQ searches in seminar by Tamara Vazquez Schroeder (link)

ATLAS Exotics Summary



arXiv:2105.13847

+ vector interpretation

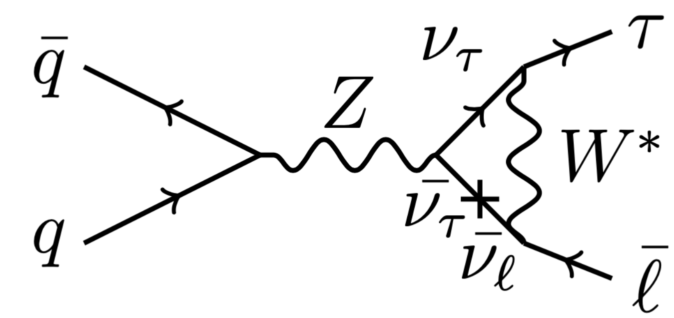
+ ATLAS-CONF-2021-023

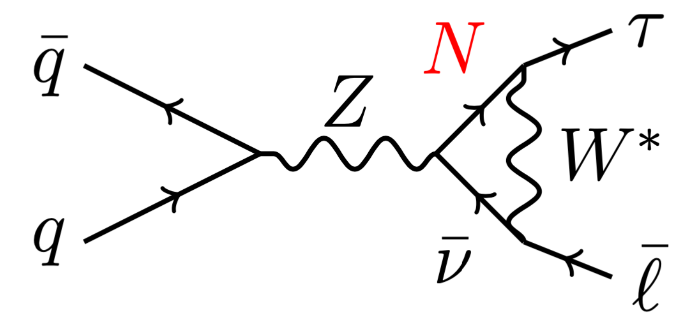
D. Zanzi

Search for LFV $Z \to \ell\tau$ decays

Search for $Z \to \ell\tau$

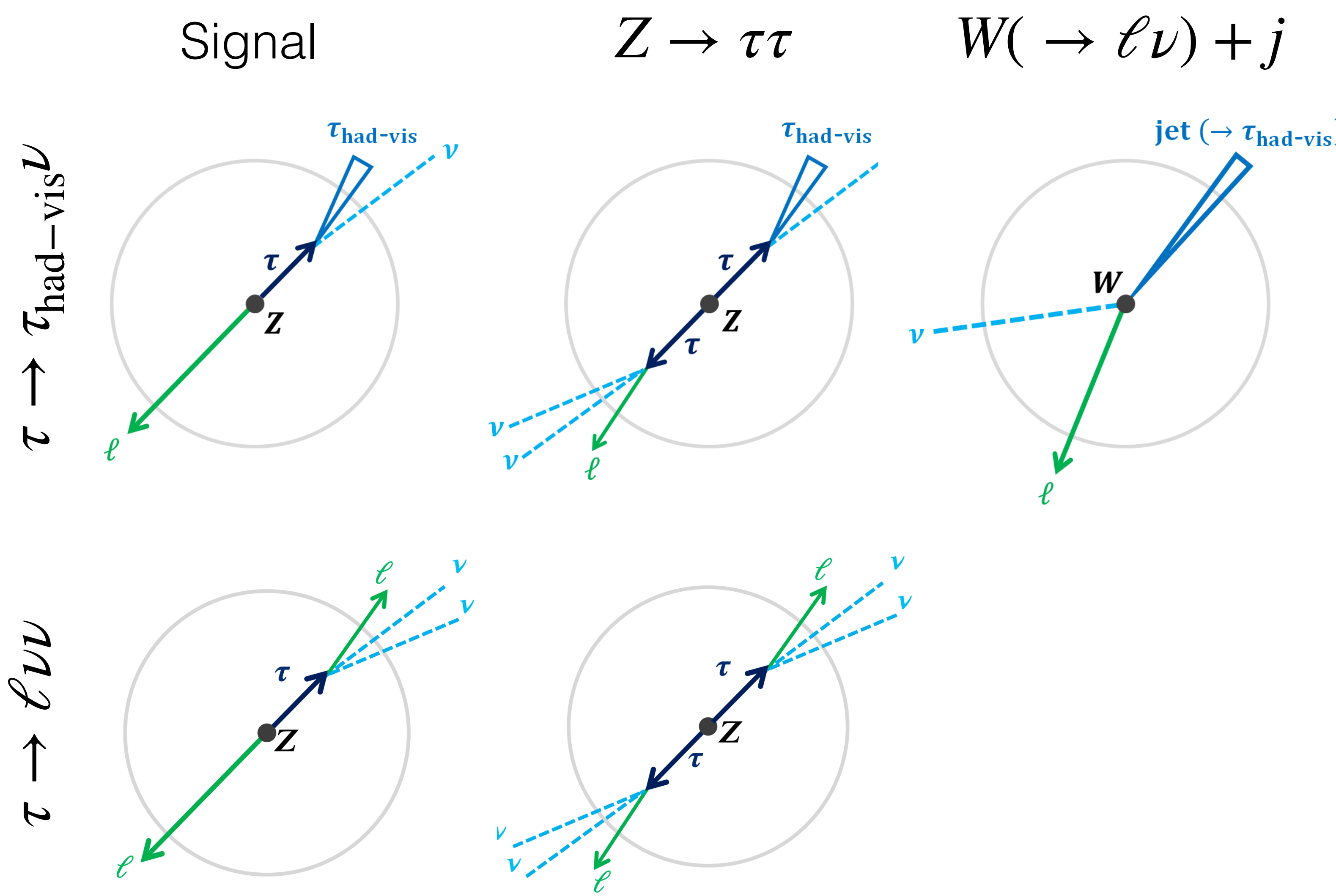
- Lepton flavour conservation is an accidental symmetry in SM
- Violation of lepton flavour conservation (LFV) not forbidden by any fundamental symmetry
  - Only "broken" by neutrino oscillations (massive neutrinos)
  - In SM, LFV processes with charged leptons can occur via ν-oscillation at $\mathscr{B}(Z \to \ell\tau) \approx 10^{-54}$
- Prime place to look for new phenomena in lepton interactions. **Any observation is a clear indication of NP!**
- Search for $Z \to \ell\tau$ complementary to low-energy searches, eg $\tau \to \gamma\mu, 3\mu$ (sensitive to eff vertices at higher energies)
- Challenge: look for tiny signal $\mathscr{B}(Z \to \ell\tau) \lesssim 10^{-5}$ (LEP limits) in huge background
  $\mathscr{B}(Z \to \tau(\to \ell\nu)\tau) = 2.4 \times 10^{-2}$
- Due to excellent LHC and ATLAS performance in Run-2, we can analyse 8×10^{9} Z decays!





Search for $Z \to \ell\tau$

- Search for $Z \to \ell\tau \, (\ell = e, \mu)$ decays in events with
  - **hadronic τ decays**
    $\mathscr{B}(\tau \to \tau_{had-vis}\nu) = 65\,\%$
    (Nature Physics (2021))
  - **leptonic τ decays**
    $\mathscr{B}(\tau \to \ell\nu\nu) = 35\,\%$
    (2105.12491 submitted to PRL)
- Key feature:
  - **event classification** based on decay kinematic properties of final state particles and E_T^{miss}
  - precise **determination of background**



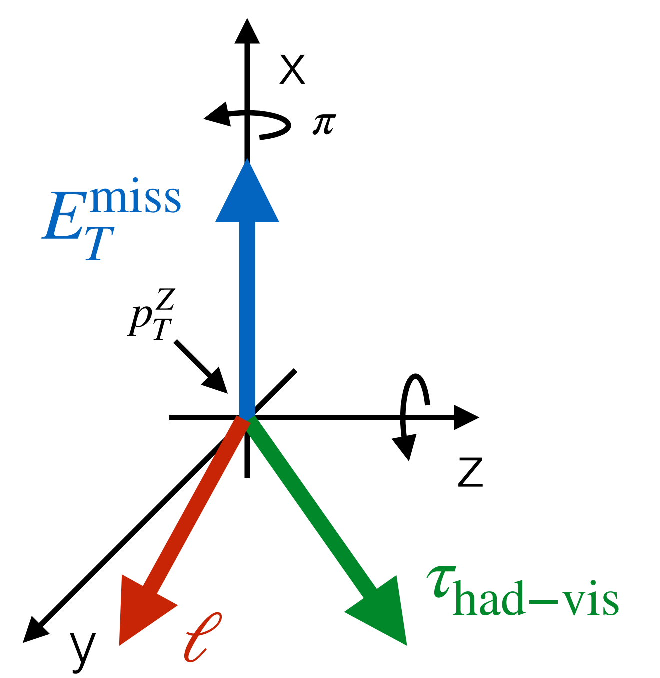
Search for $Z \to \ell\tau$

- Deep neural networks with **full kinematic information** (4-momentum components) of particles
- Inputs:
  - Removal of physical symmetries via rotation and Lorentz-boost. Reduction from 12 to **6 independent momentum components**, hence reduced set of NN inputs (smaller network, good given limited statistics for training)
  - Addition of **high-level variables** (eg masses) to aid training

Variable	Description
$p_z(\ell)$	z-component of the light lepton's momentum.
$E(\ell)$	Energy of the light lepton.
$p_x(\tau_{\text{had-vis}})$	x-component of the $\tau_{\text{had-vis}}$ candidate's momentum.
$p_z(\tau_{\text{had-vis}})$	z-component of the $\tau_{\text{had-vis}}$ candidate's momentum.
$E(\tau_{\text{had-vis}})$	Energy of the $\tau_{\text{had-vis}}$ candidate.
$E_{\text{T}}^{\text{miss}}$	The missing transverse momentum.
$m_{\text{vis}}(\ell,\tau)$	The visible mass: the invariant mass of the ℓ–$\tau_{\text{had-vis}}$ system.
$m_{\text{coll}}(\ell,\tau)$	The collinear mass: the invariant mass of the ℓ–$\tau_{\text{had-vis}}$–ν system, where the ν is assumed to have a momentum that is equal in the transverse plane to the measured $E_{\text{T}}^{\text{miss}}$ and collinear in η with the $\tau_{\text{had-vis}}$ candidate.
$m(\ell,\tau \text{ track})$	The invariant mass of the light lepton and the track associated with the $\tau_{\text{had-vis}}$ candidate (only used by the $Z \to \ell\ell$ classifier).
$\Delta\alpha$	A kinematic discriminant sensitive to the different fractions of τ-lepton four-momentum carried by neutrinos in signal and background [7].

In transformed frame

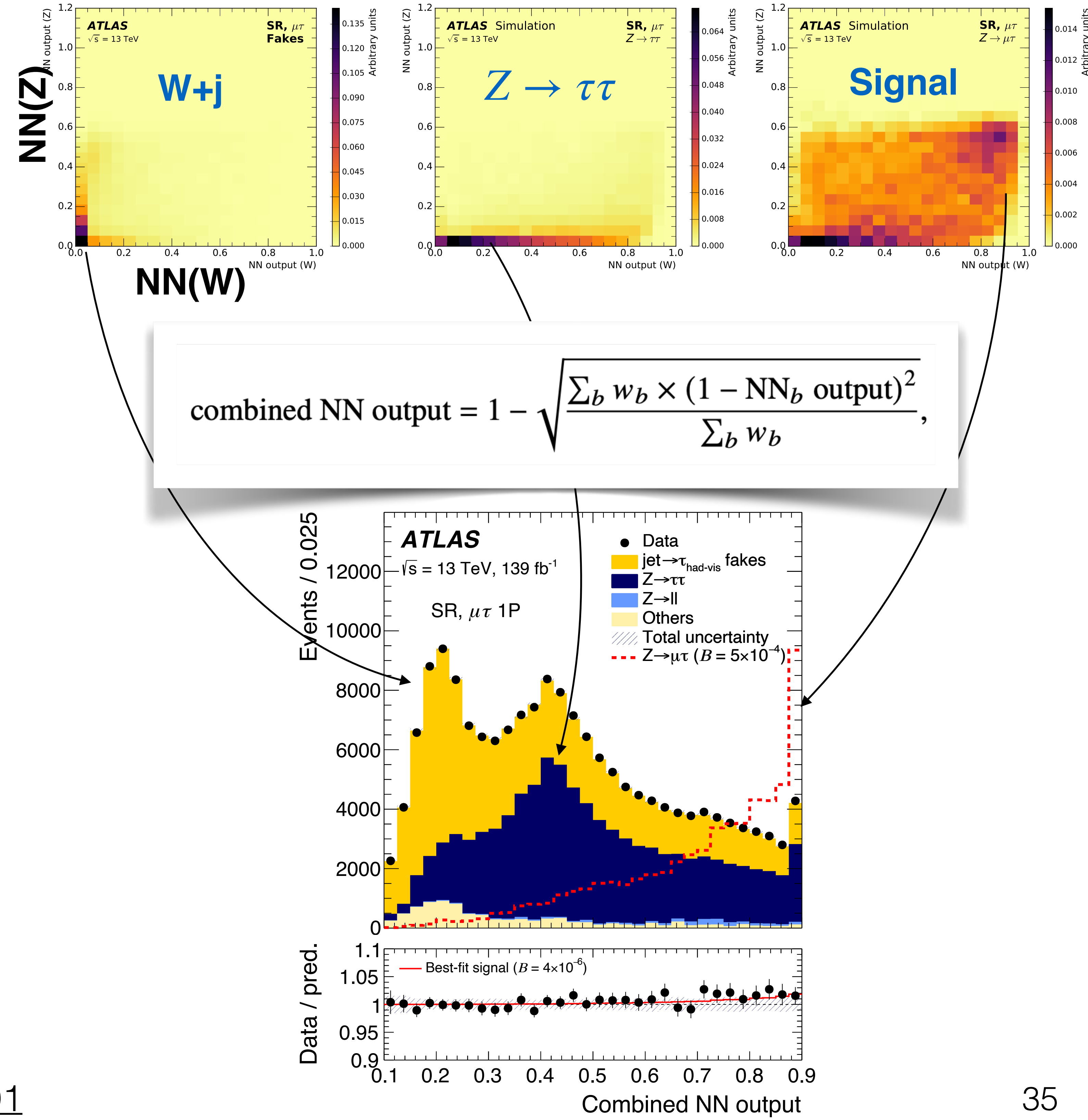
Similar set for leptonic channel



Search for $Z \to \ell\tau$

Phys. Rev. D 98 (2018) 092010

- One binary NN classifier trained against each main background
  - Had channel: $Z \to \tau\tau$, $W + j$, $Z \to \ell\ell$
  - Lep channel: $Z \to \tau\tau$, $t\bar{t}$, VV
- **NN outputs combined** exploiting different correlations of these for different processes
- Different source of backgrounds separated from signal but also among themselves
- Shape fit of full combined NN output spectrum able to **better constrain each individual background contribution**, hence better sensitivity

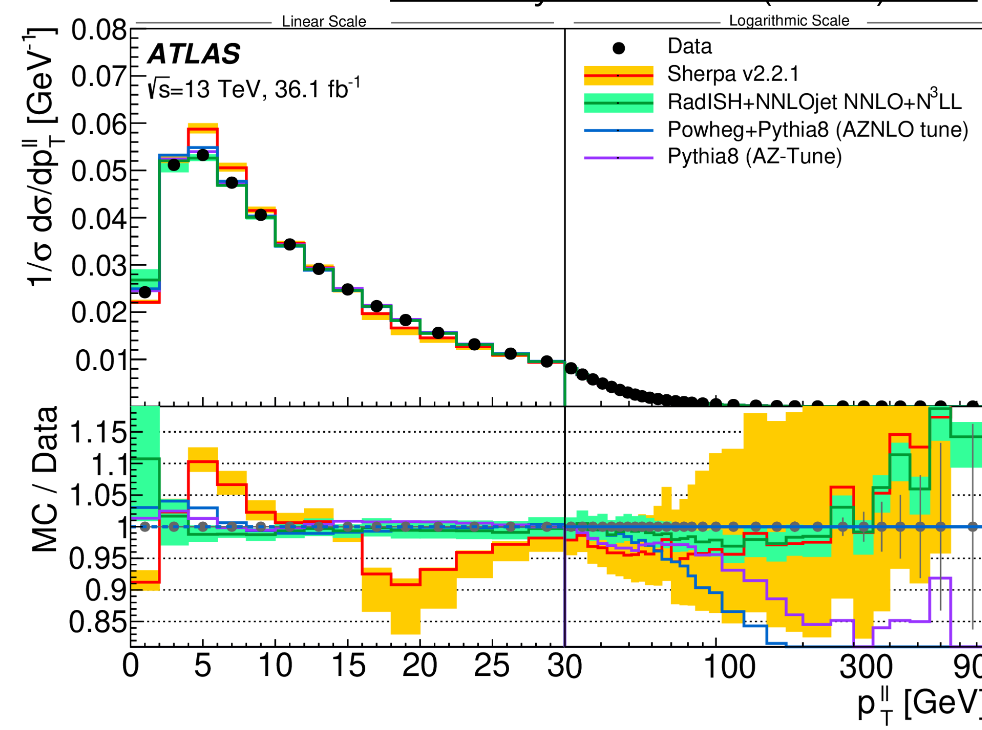


$$\text{combined NN output} = 1 - \sqrt{\frac{\sum_b w_b \times (1 - \text{NN}_b \text{ output})^2}{\sum_b w_b}},$$

Search for $Z \to \ell\tau$

- Modelling of **Z production**:
  - Signal (Pythia) and $Z \to \tau\tau$ (Sherpa) events reweighed to fiducial Z production cross section measurement by ATLAS to reduce theory uncertainties
- **Common normalisation factor** on signal and $Z \to \tau\tau$ determines $\sigma_Z \times A(\ell\tau)$ from data and reduces experimental systematics uncertainties
- Events with mis-identified objects ($j \to \tau_{\mathrm{had-vis}}$ fakes and non-prompt electrons and muons) modelled from data

Eur. Phys. J. C 80 (2020) 616



Leptonic channel

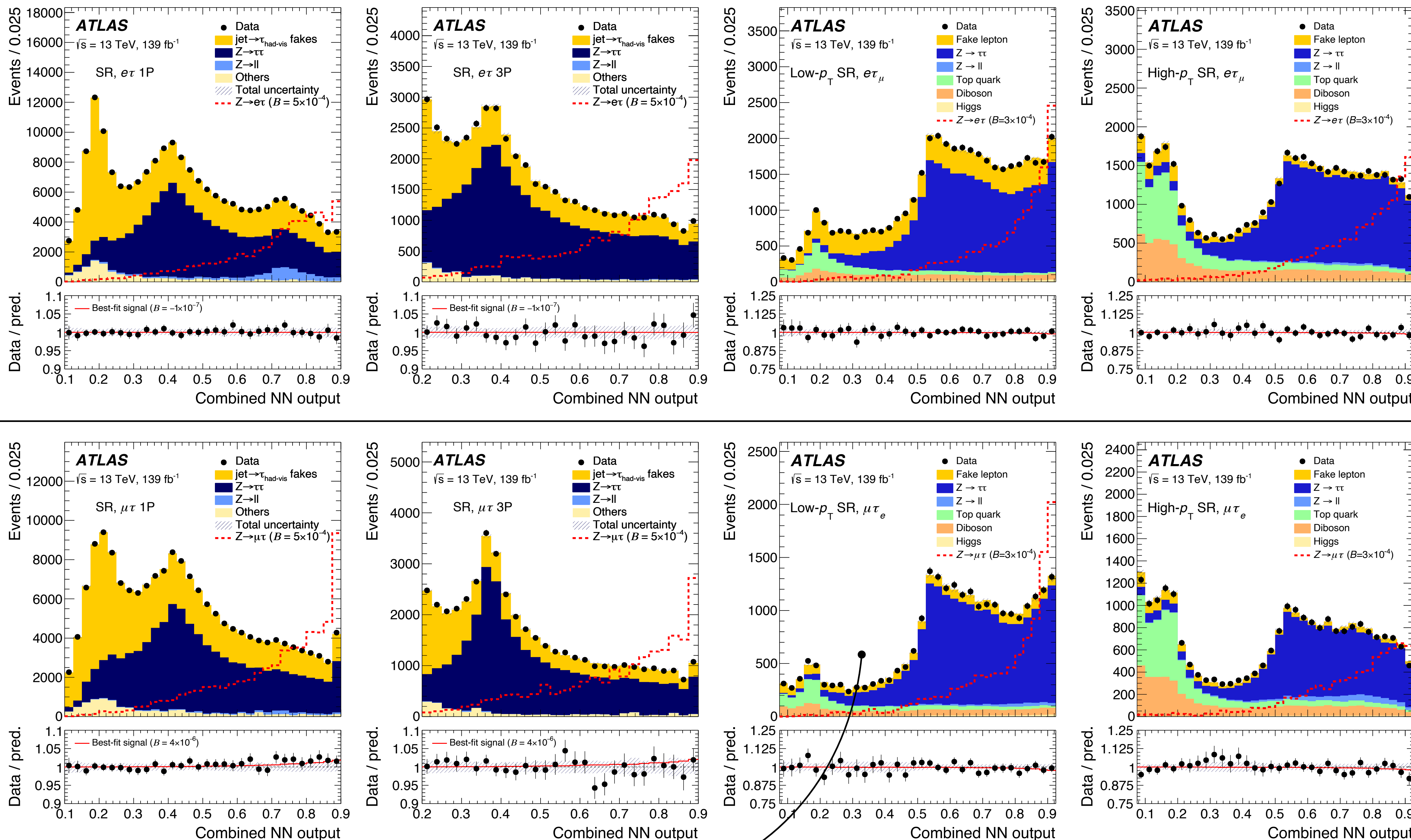
Source of uncertainty	Uncertainty in $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±3.9
Fake leptons (statistical)	±0.1	±0.1
Systematic	±2.7	±3.4
Light leptons	±0.4	±0.4
E_T^{miss}, jets and flavor tagging	±2.1	±2.4
E_T^{miss}	±0.4	±0.8
Jets	±1.9	±2.2
Flavor tagging	±0.5	±0.9
Z-boson modeling	<0.1	±0.1
$Z \to \mu\mu$ yield	–	±0.8
Other backgrounds	±0.1	±0.6
Fake leptons (systematic)	±0.4	±0.9
Total	±4.4	±5.2

Hadronic channel

Source of uncertainty	Uncertainty on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
Statistical	±3.5	±2.8
Systematic	±2.3	±1.6
τ-leptons	±1.9	±1.5
Energy calibration	±1.3	±1.4
Jet rejection	±0.3	±0.3
Electron rejection	±1.3	
Light leptons	±0.4	±0.1
E_T^{miss}, jets and flavour tagging	±0.6	±0.5
Z-boson modelling	±0.7	±0.3
Luminosity and other minor backgrounds	±0.8	±0.3
Total	±4.1	±3.2

Search for $Z \to \ell\tau$

	$\ell\tau_{had-vis}$ (1prong)	$\ell\tau_{had-vis}$ (3prong)	$\ell\tau_{\ell'}$ (low-pt l')	$\ell\tau_{\ell'}$ (high-pt l')
Search for $Z \to e\tau$				
Search for $Z \to \mu\tau$				



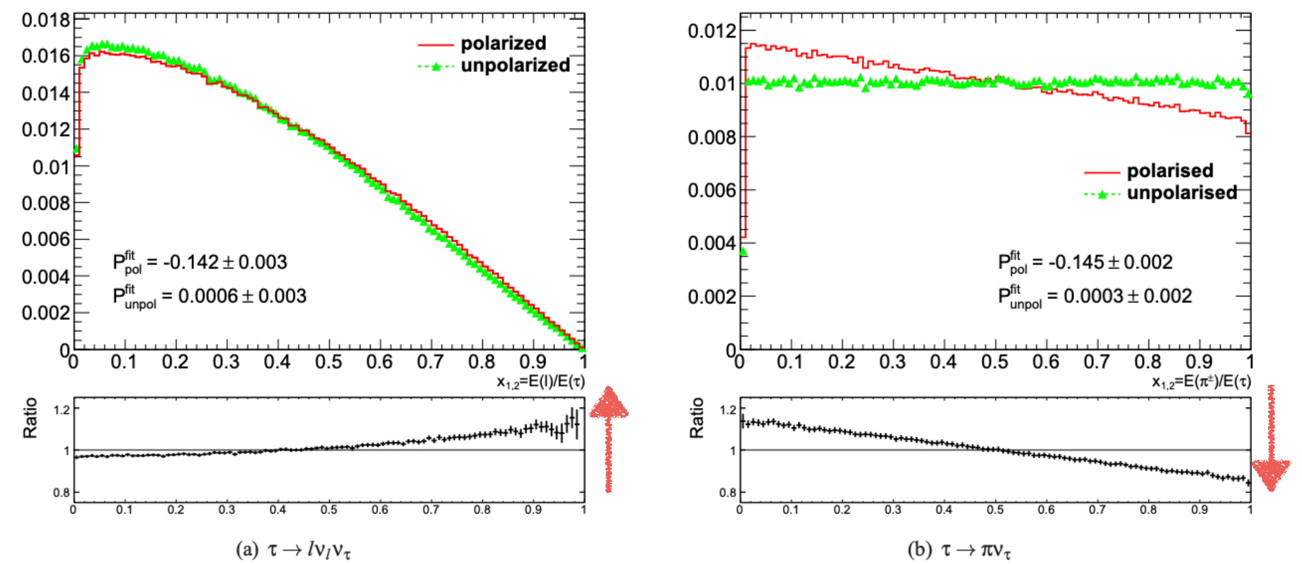
Bulk of $Z \to \tau\tau$ events fitted in separate Z-CRs

SRs divided by p_T of subleading lepton to improve categorisation of fakes background

Search for $Z \to \ell\tau$

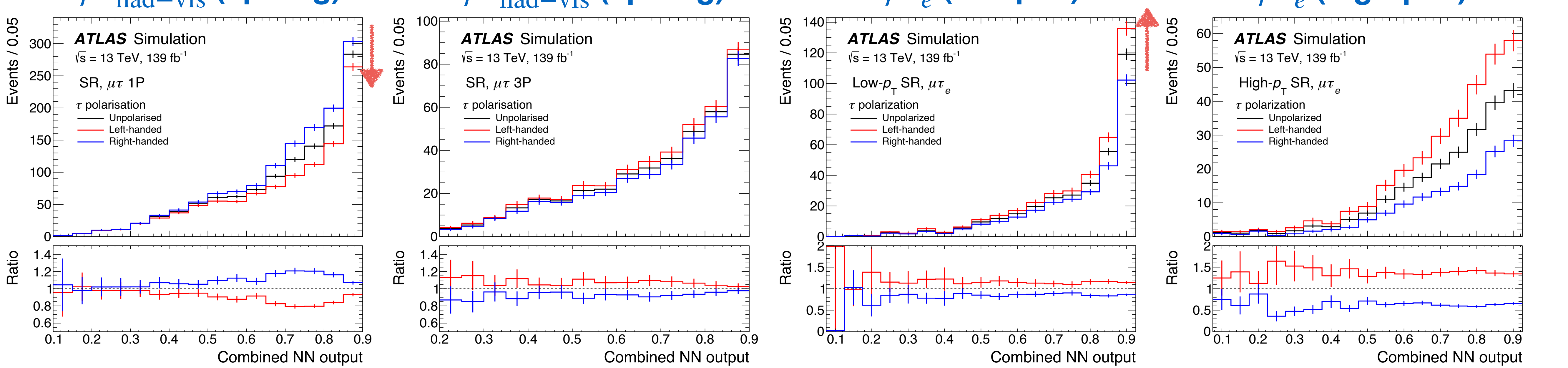
- Limits on $\mathcal{B}(Z \to \ell\tau)$ for unpolarised and maximally polarised τ leptons
- Due to spin correlations, same polarisation has opposite effects on the energy fraction of the visible decay products in leptonic and hadronic decays
- **Combined results are almost independent of polarisation hypothesis**

$\tau \to \ell\nu\nu$ $\tau \to \pi\nu$



Acta Phys.Polon.B 45 (2014) 10, 1921-1946

$\mu\tau_{\rm had-vis}$ **(1prong)** $\mu\tau_{\rm had-vis}$ **(3prong)** $\mu\tau_e$ **(low-pt e)** $\mu\tau_e$ **(high-pt e)**



D. Zanzi

Nat. Phys. (2021), arXiv:2105.12491

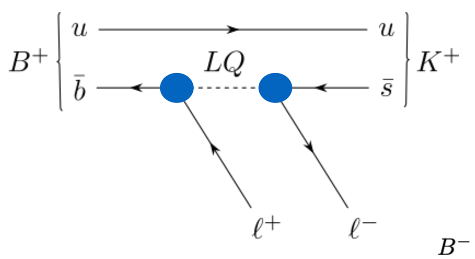
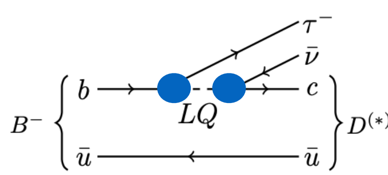
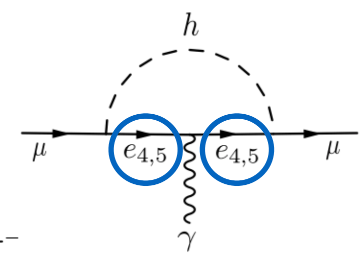
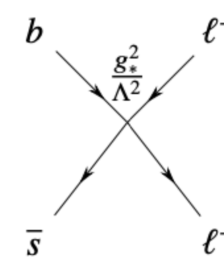
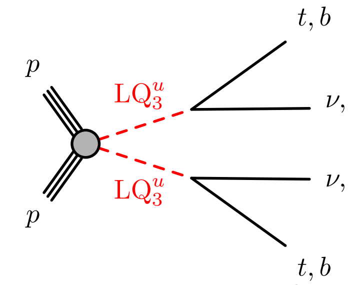
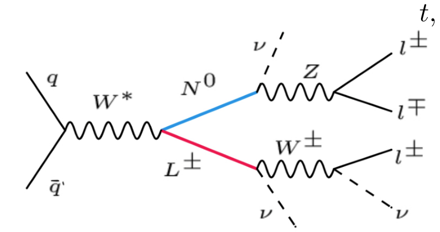
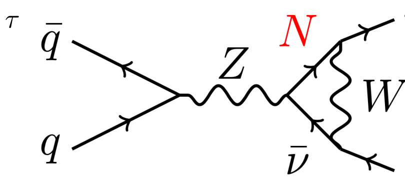
Search for $Z \to \ell\tau$

Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ Run 1 + Run 2, unpolarized τ	8.1 (8.1)	9.5 (6.1)
$\ell\tau_{\text{had}}$ Run 2, left-handed τ	8.2 (8.6)	9.5 (6.7)
$\ell\tau_{\text{had}}$ Run 2, right-handed τ	7.8 (7.6)	10 (5.8)
$\ell\tau_{\ell'}$ Run 2, unpolarized τ	7.0 (8.9)	7.2 (10)
$\ell\tau_{\ell'}$ Run 2, left-handed τ	5.9 (7.5)	5.7 (8.5)
$\ell\tau_{\ell'}$ Run 2, right-handed τ	8.4 (11)	9.2 (13)
Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
Combined $\ell\tau$ Run 2, left-handed τ	4.5 (5.7)	5.6 (5.3)
Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)
LEP OPAL, unpolarised τ [10]	9.8	17
LEP DELPHI, unpolarised τ [11]	22	12

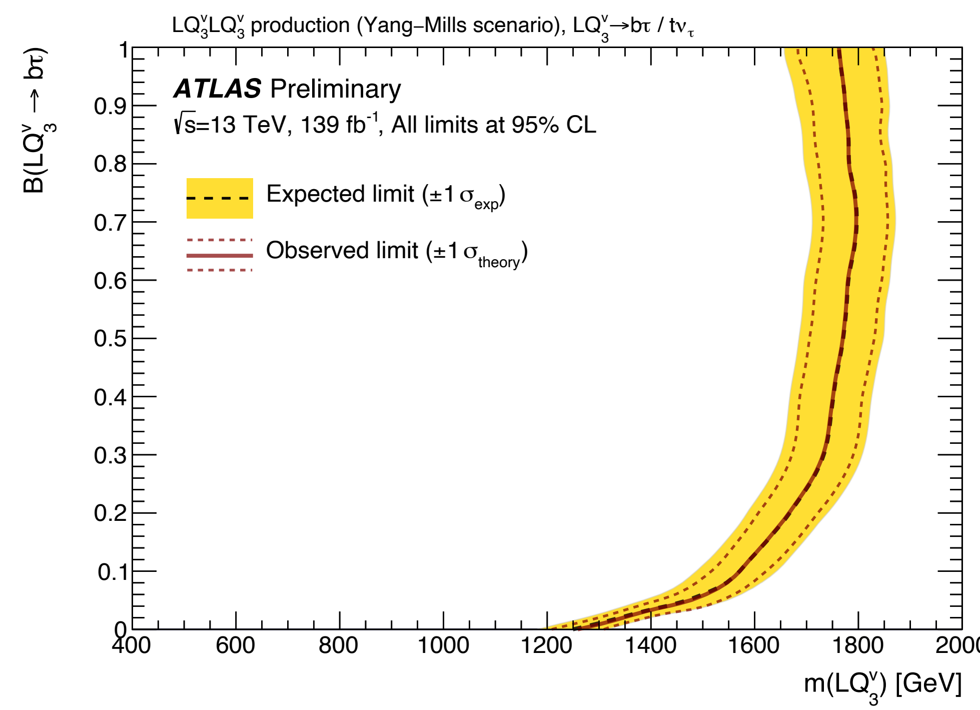
- Best-fit:
  - $\mathcal{B}(Z \to e\tau) = (-1.4 \pm 2.5(\text{stat}) \pm 1.8(\text{sys})) \times 10^{-6}$
  - $\mathcal{B}(Z \to \mu\tau) = (+1.7 \pm 2.2(\text{stat}) \pm 1.6(\text{sys})) \times 10^{-6}$
- World-best upper limits, **2x** improvement on limits by LEP!

nature physics ARTICLES
https://doi.org/10.1038/s41567-021-01225-z
Check for updates
OPEN
Search for charged-lepton-flavour violation in *Z*-boson decays with the ATLAS detector
ATLAS Collaboration*

Summary

- Many open questions on lepton interactions
- **Growing evidence for LFU violation** in B decays
  - difficult to explain all anomalies at once without contradicting current experimental data
- **New experimental data needed from complementary frontiers**, not only from B-decays
- ATLAS is pushing the search for new phenomena in lepton interactions on several fronts
  - Milestone reached by overtaking longstanding LEP legacy
- Searches largely limited by **stat uncertainties**, also for high-background searches like $Z \to \ell\tau$
- High expectation on what we can learn in Run-3+



Final state, polarization assumption	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$] $e\tau$	$\mu\tau$
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Combined $\ell\tau$ Run 1 + Run 2, unpolarized τ	5.0 (6.0)	6.5 (5.3)
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Combined $\ell\tau$ Run 2, right-handed τ	5.4 (6.2)	7.7 (5.3)
LEP OPAL, unpolarised τ [10]	9.8	17
LEP DELPHI, unpolarised τ [11]	22	12

Additional Material

Leptoquarks Models

The U_1 simplified model

C. Cornella (LHCP'21)

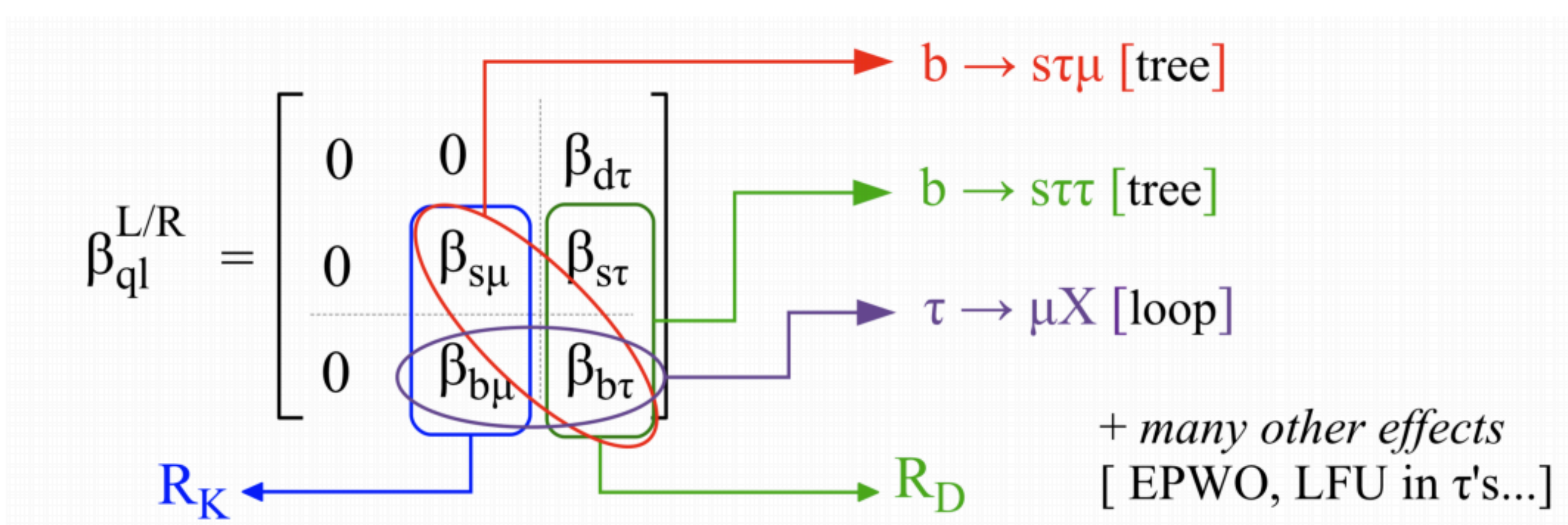
The **vector leptoquark** is the only single mediator solution:

- ✓ no tree-level contribution to $b \to s\nu\bar{\nu}$, protected from proton decay
- ! does not come alone: additional massive vectors (Z', G'), vector-like fermions

Stick to simplified model:

$$\mathscr{L} \supset \frac{g_U}{\sqrt{2}} U_1^\mu \left[\beta_L^{i\alpha} (\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha} (\bar{d}_R^i \gamma_\mu e_R^\alpha)\right] + \mathrm{h.c.} \qquad U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

Good description of all low-energy data with a "natural" flavor structure:



$\beta_{b\tau}^L = 1$

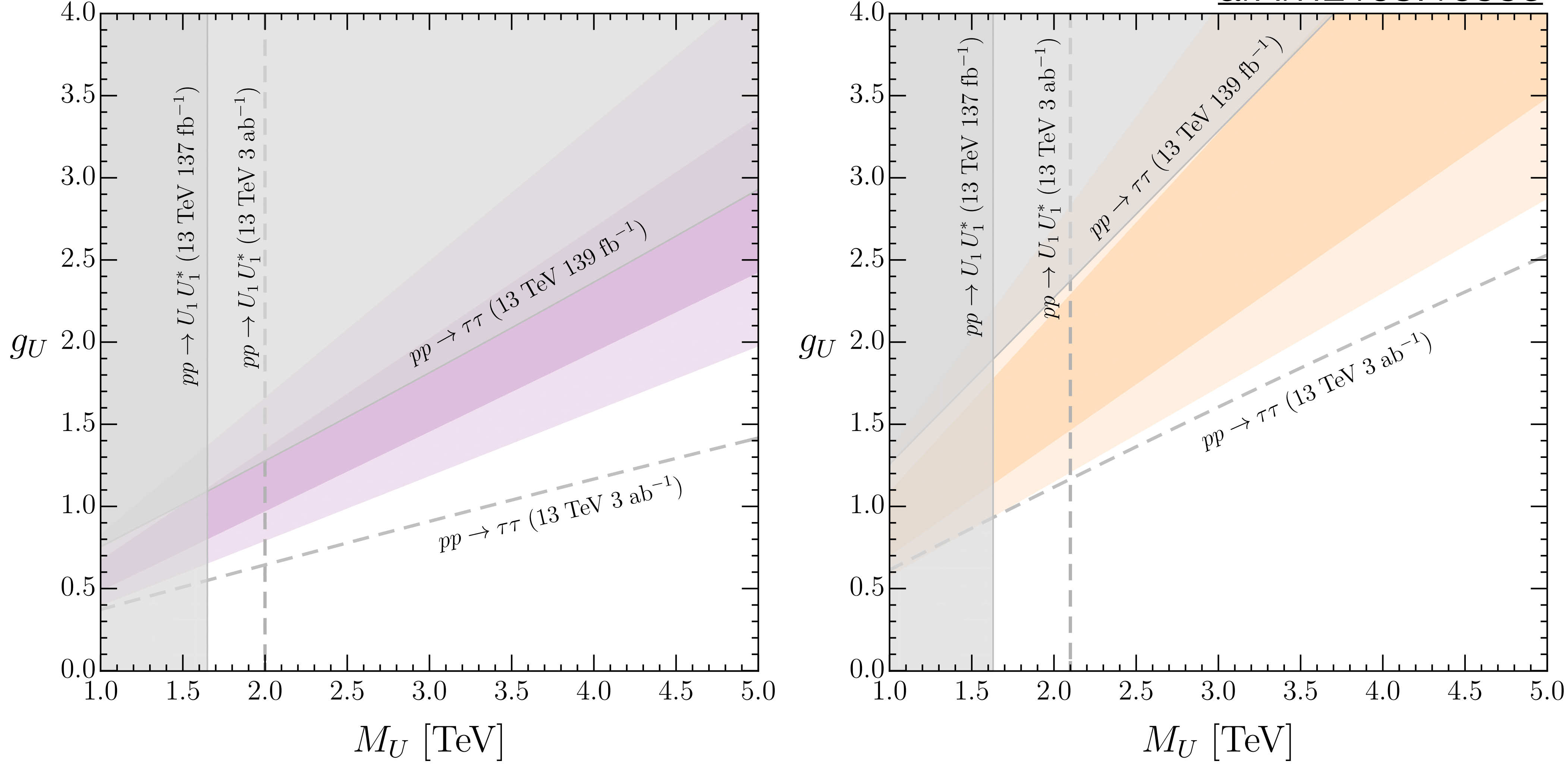
$\beta_{b\tau}^R \sim \mathcal{O}(1)$

$\beta_{s\tau}^L, \beta_{b\mu}^L \sim \mathcal{O}(0.1)$

$\beta_{s\mu}^L, \beta_{d\tau}^L \sim \mathcal{O}(0.01)$

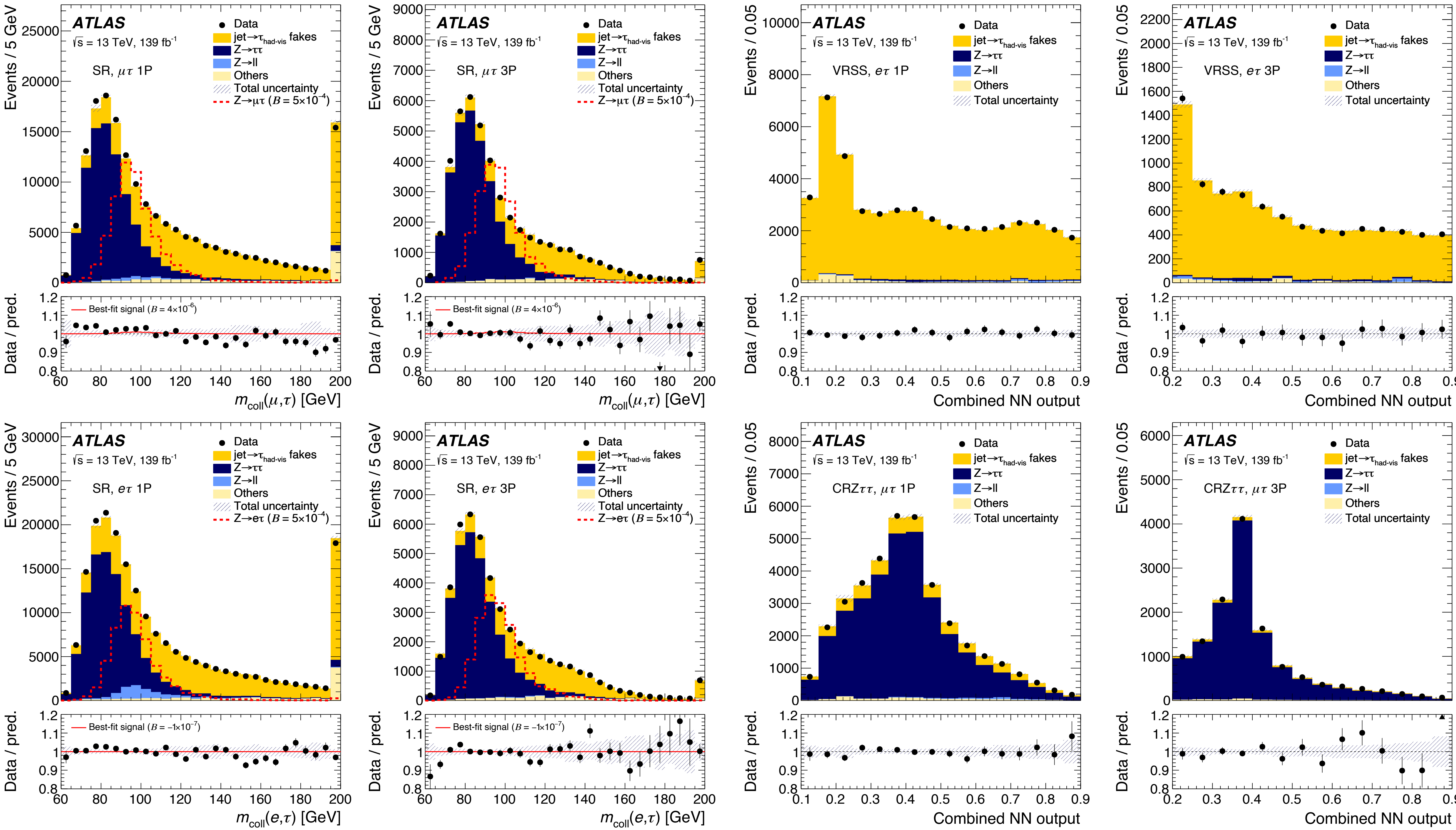
Leptoquarks Models

[arXiv:2103.16558]



- Reach of LHC constraints for vector LQ models compared to the compared to the M/g scale indicated by the B-anomalies

$Z \rightarrow \ell\tau$ Validation



$Z \rightarrow \ell\tau$ Validation