Searches for lepton flavour universality violation with the ATLAS detector

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On behalf of the ATLAS Collaboration

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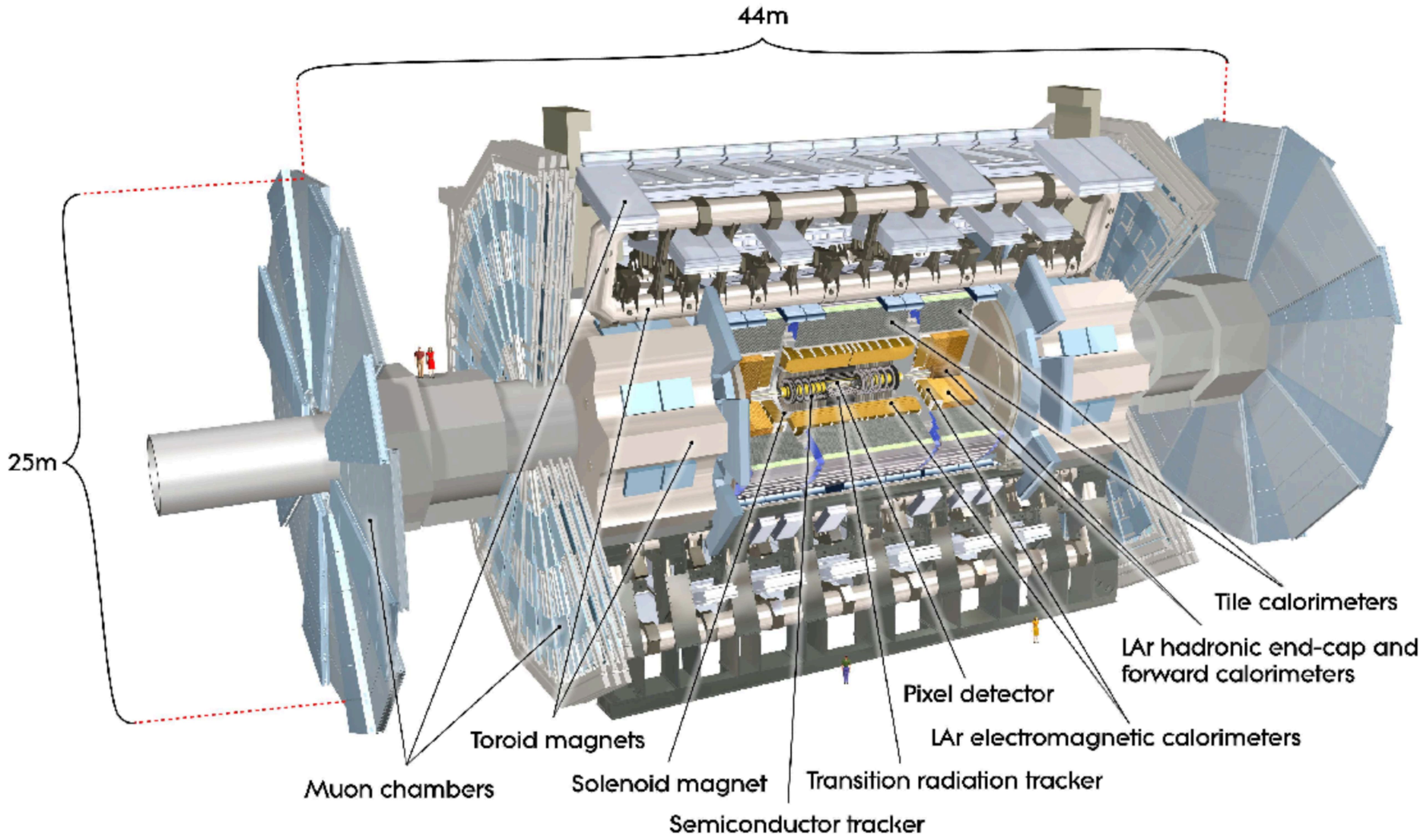
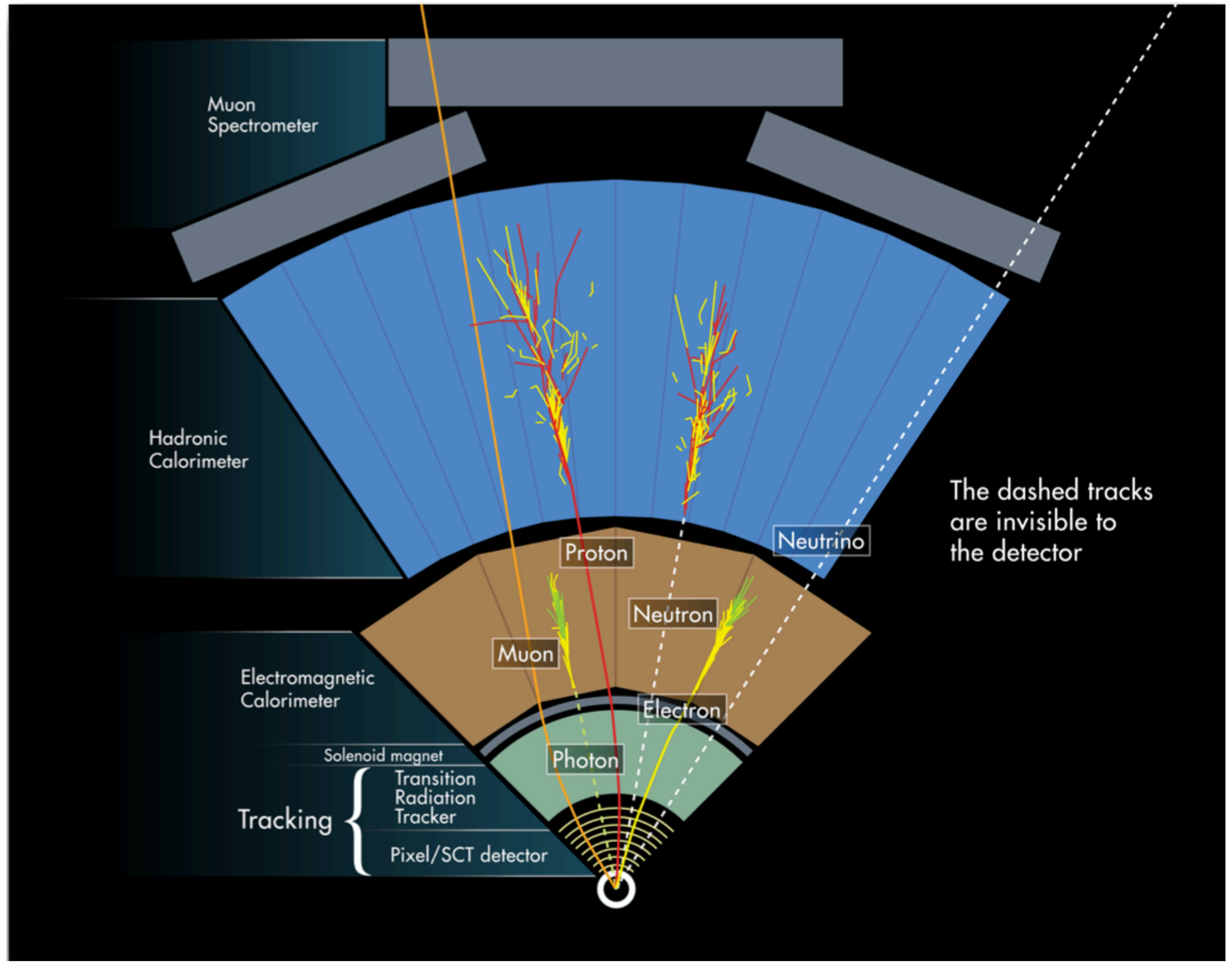
Outline

- The observation of neutrino oscillations indicates that **Lepton Flavour Violation** is realised in nature and that lepton flavour is not an exact symmetry.
  - ✓ LFV in **Z** boson decay
  - ✓ LFV in **Higgs** boson decay
  - ✓ LFV in high-mass dilepton search
- **Lepton Flavour Universality** is a fundamental prediction of the SM, search the violation of LFU for the BSM
  - ✓ asymmetry dilepton(eμ) search
  - ✓ rare B-decays
  - ✓ leptoquarks

ATLAS detector





- The ATLAS detector consists of an inner tracking detector, calorimeters and a muon spectrometer, which could provide good measurement of leptons
- ATLAS has collected lots of data 140 fb^{-1} at Run2

Z boson -> eμ

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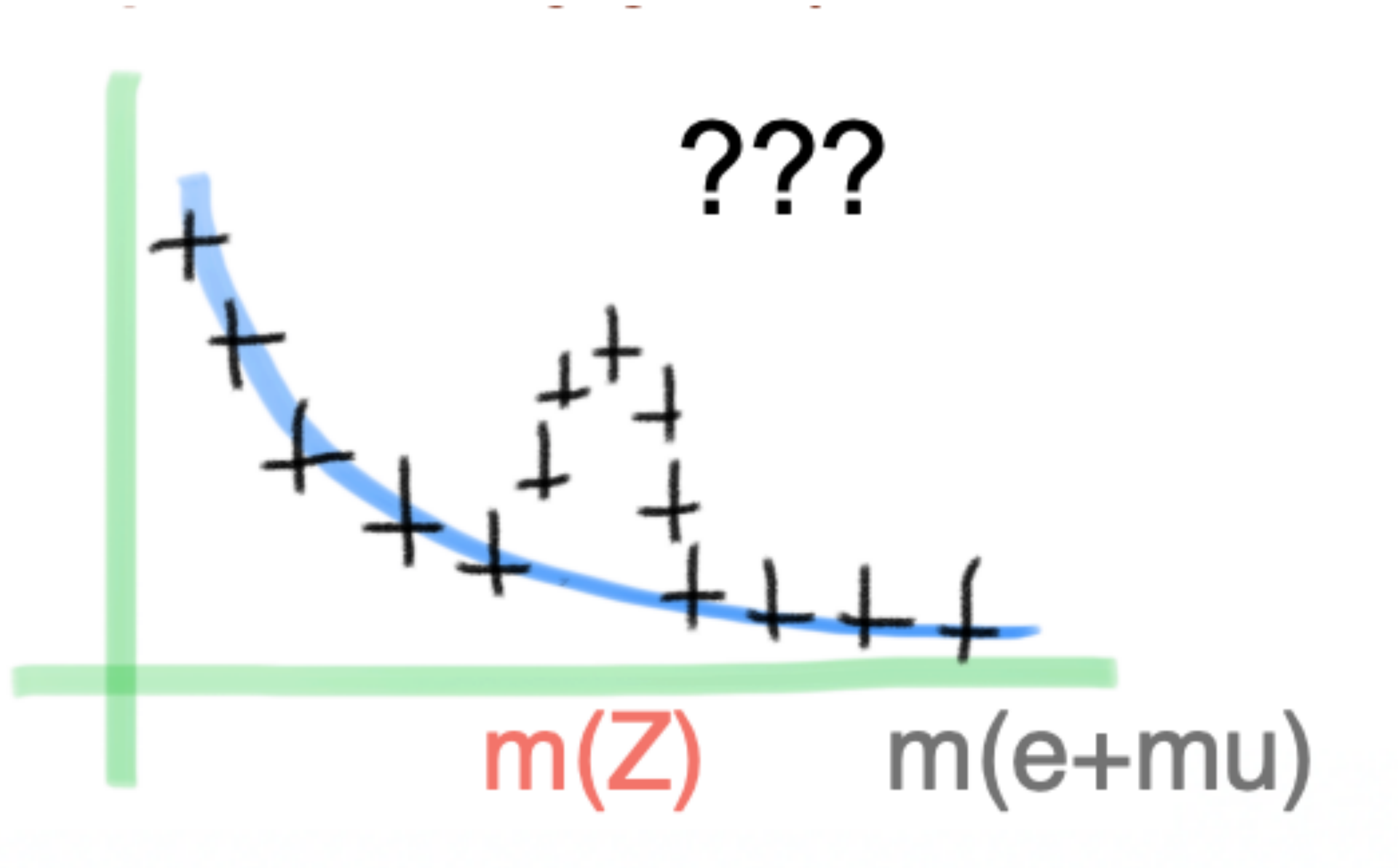
- Search for Z boson decay into e+μ using full Run-2 data
- Two high-p_T, isolated opposite charged tracks identified as two different flavour e+μ

- Main backgrounds:
  - Z -> $\tau\tau$ -> e$\mu\nu\nu\nu\nu$
  - Z -> $\mu\mu$ with one μ is misidentified as an electron
  - Diboson(WW->e$\mu\nu\nu$) or ttbar(tt->e$\mu\nu\nu$+bb) or W+jets…

- Little jet activity
  - Veto b-Jets, small p_T of Leading jet..
- Little missing Energy



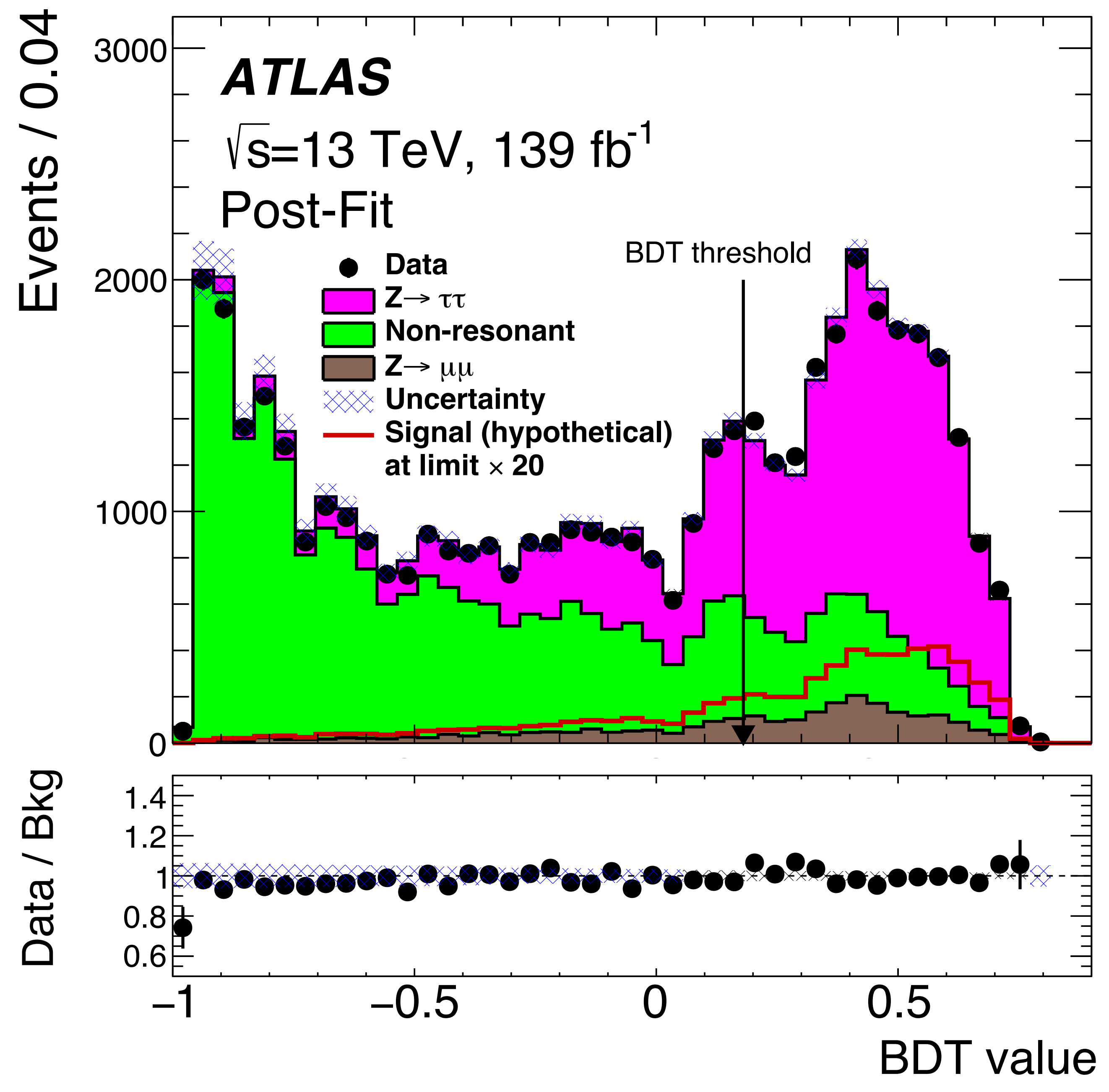
- Looking for peak structure on the smooth falling backgrounds
- Using MC study for efficiency/model

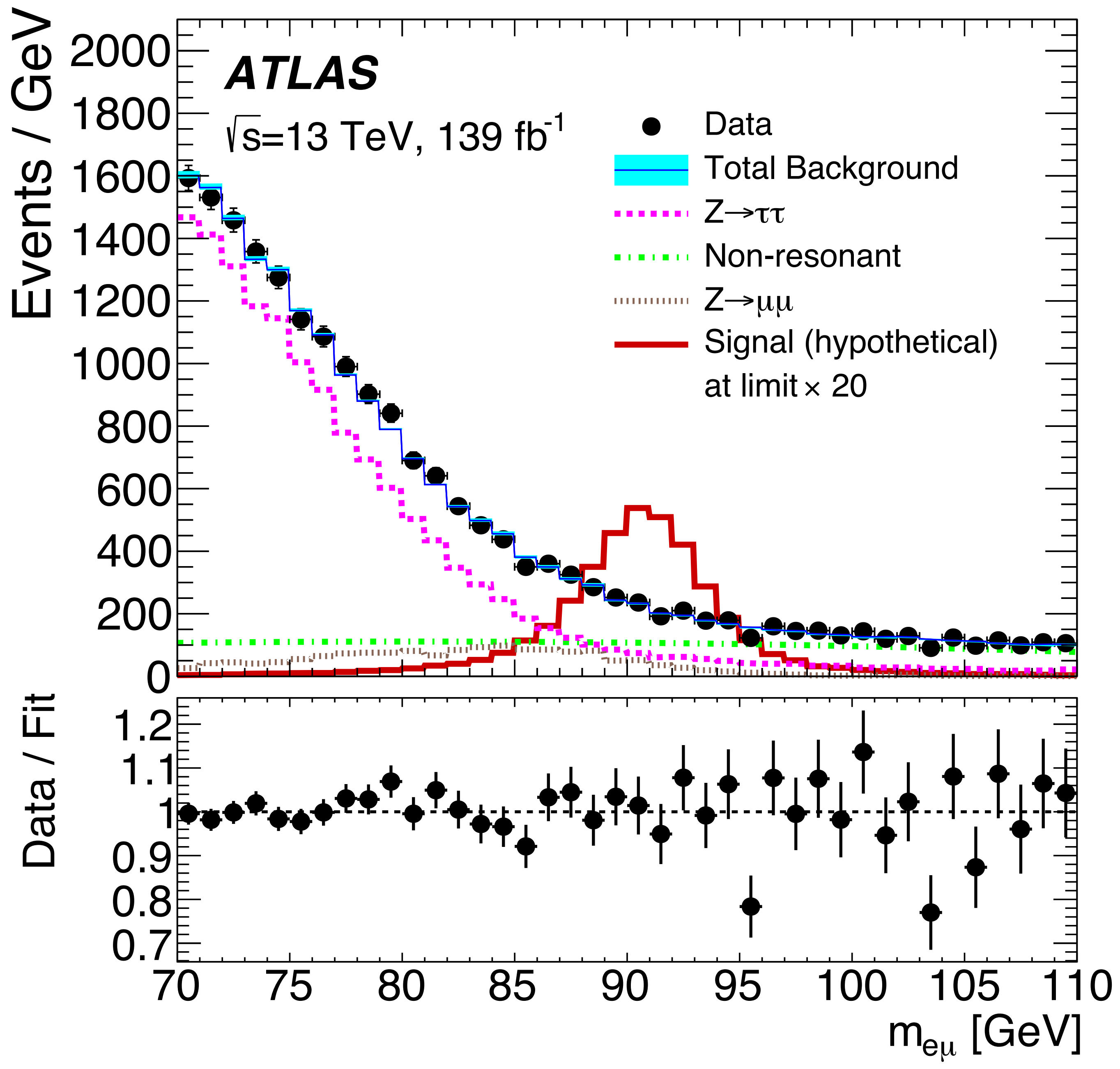
Z boson -> eμ

- Using BDT to further reduce the backgrounds
  - input variables: E_T^{miss} p_T^Z p_T of leading jet
- performed a likelihood fit
  - signal: peaking hist PDF from MC sample
  - Z->$\tau\tau$ Backgrounds
  - Z->$\mu\mu$ Backgrounds
  - Combinatorial Backgrounds described by a second order polynomial function

$$\mathcal{L} = \prod_{i=1}^{N} \left[N_{\text{sig}} \cdot F_{\text{sig}} + N_{\tau\tau} \cdot F_{\tau\tau} + N_{\mu\mu} \cdot F_{\mu\mu} + N_{\text{cmb}} \cdot F_{\text{cmb}} \right]$$

- Using the Signal acceptance and efficiency and expected number of Z boson to calculate the upper limit
  - B(Z->eμ) < 2.62*10^{-7} at 95% CL



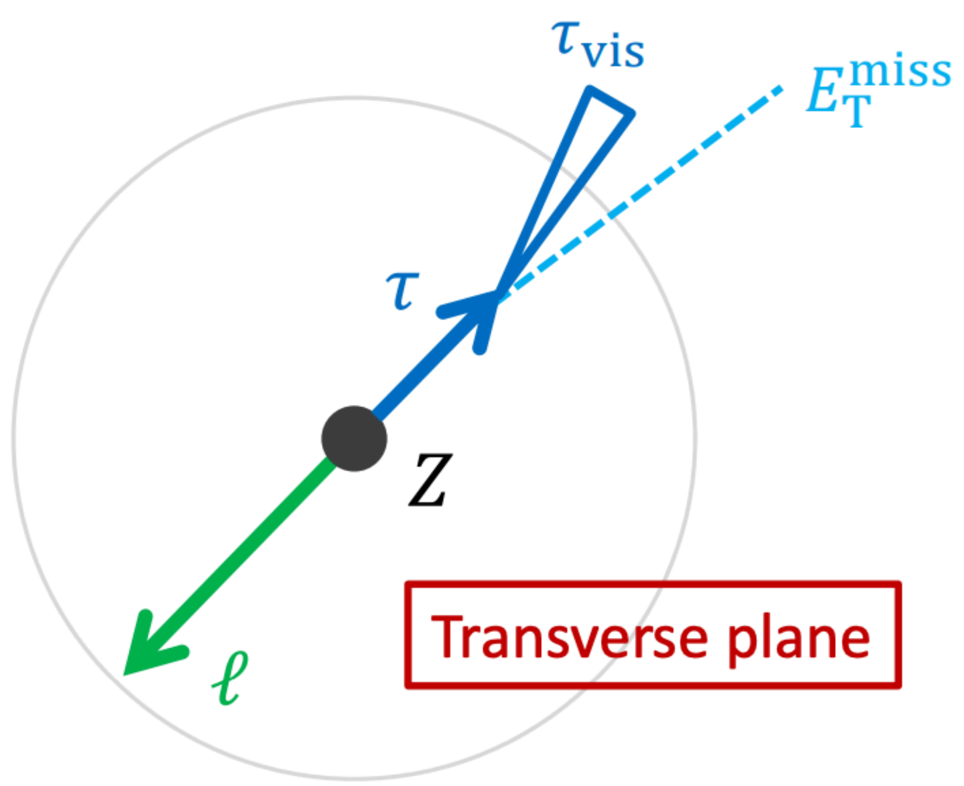


Z boson -> eτ or $\mu\tau$

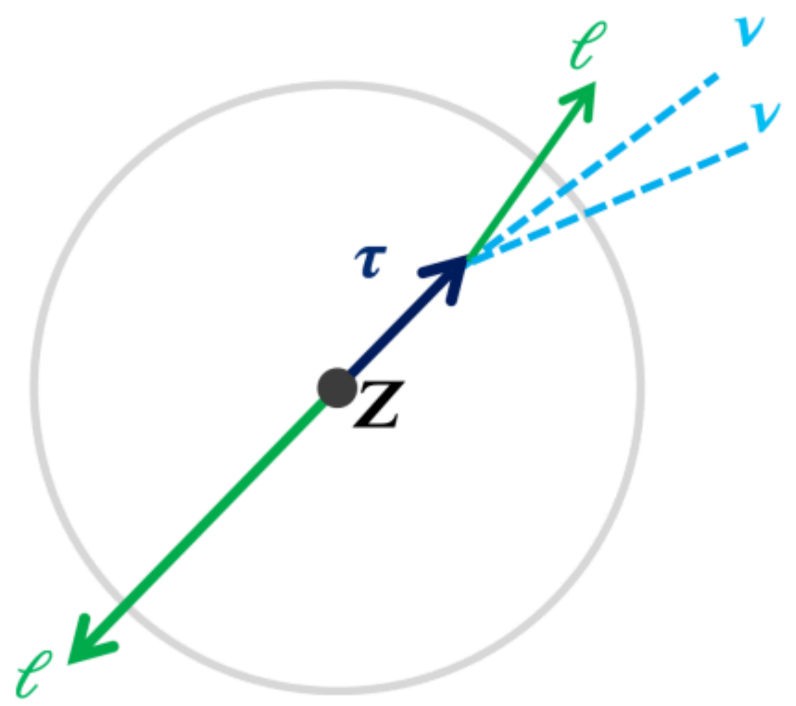
Page Link had decay

Page Link lep dacay

- Search for Z boson decay into lep+τ with τ leptonic decay or hadronic decay
- Main backgrounds
  - Z boson: Z -> $\tau\tau$ or Z->leplep
    MC based estimation + data-driven corrections to reduce theory uncertainties
  - Jet-> τ fakes: W+jets, QCD multijet, Z+jets
    Data-Driven fake factor method
  - other backgrounds: top, diboson, Higgs
    MC based estimation



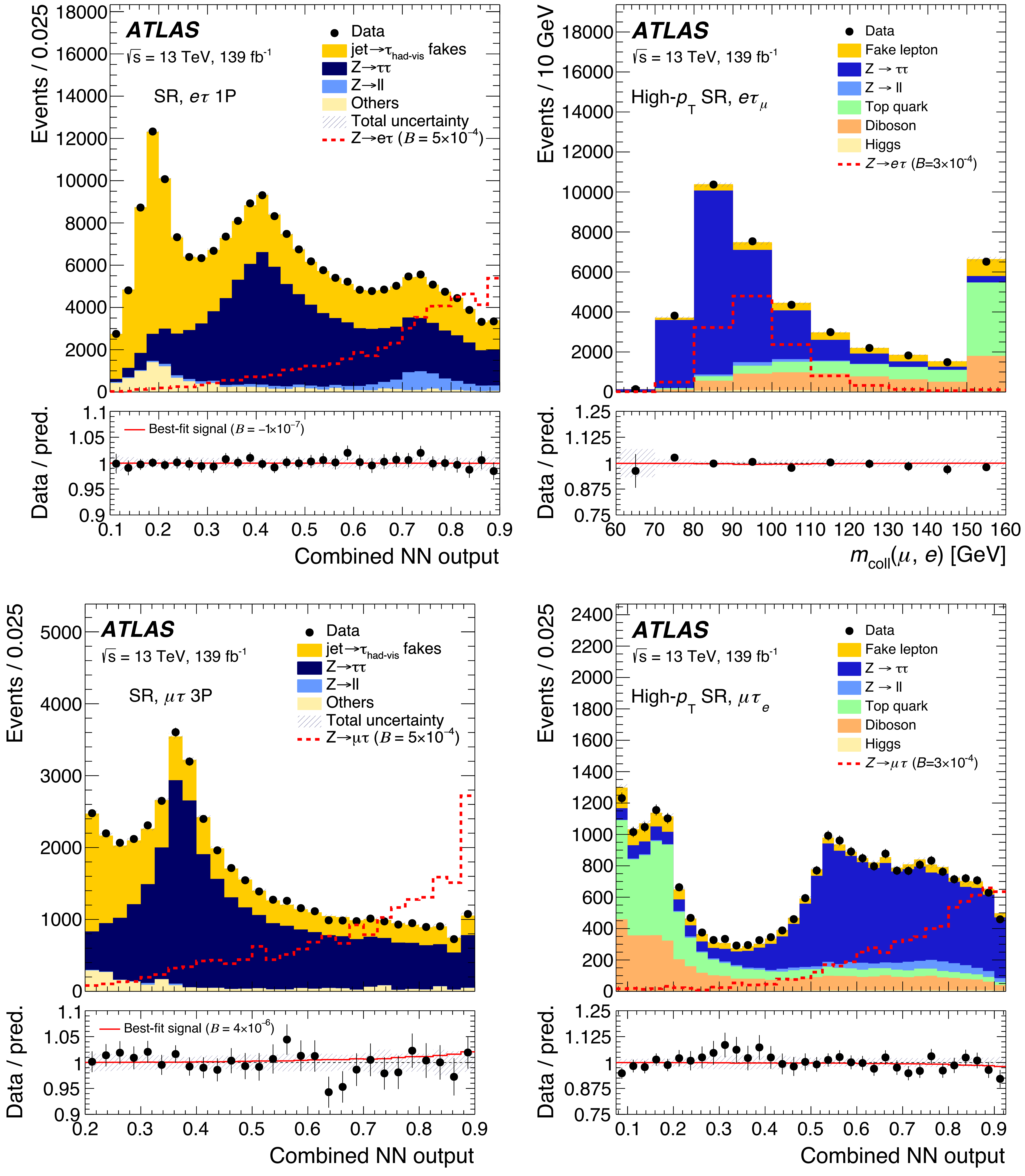
- Event selection / sig-bkg separation
  - unique signal topology and Z mass resonance
  - SR with relatively loose kinematic selection
  - Further separation using neural network
- Statistical interpretation
  - Fit NN output in SR and m_{coll} in Z -> $\tau\tau$ CR to data
  - Data-model compatibility quantified using frequentist CLs method
  - Exclusion limit set by inverted CLs hypothesis tests



Z boson -> eτ or $\mu\tau$

- τ polarization reweighting
- Validation in the Same-Sign SR
- Mixture of low- and high-level variables for the neural network
- Combining individual output scores to a single one
- Fit split in 1prong/3prong(τ hadronic) or two p_T^{l2} regions(τ leptonic)
- Fit in SR and CR simultaneously

	Observed (expected) upper limit on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$]	
Final state, polarization assumption	$e\tau$	$\mu\tau$
$\ell\tau_{\text{had}}$ 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)	9.8 (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)



τ hadronic decay τ leptonic decay

Higgs boson -> eτ or $\mu\tau$

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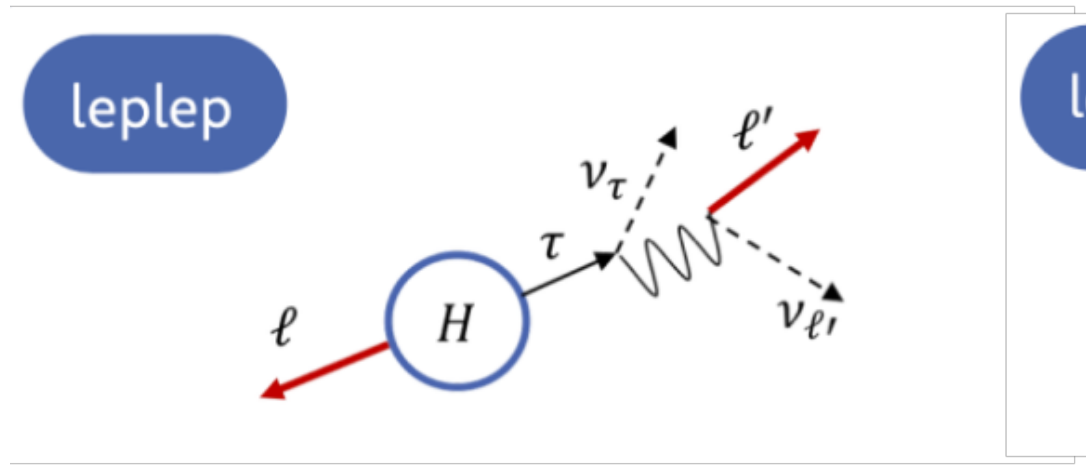
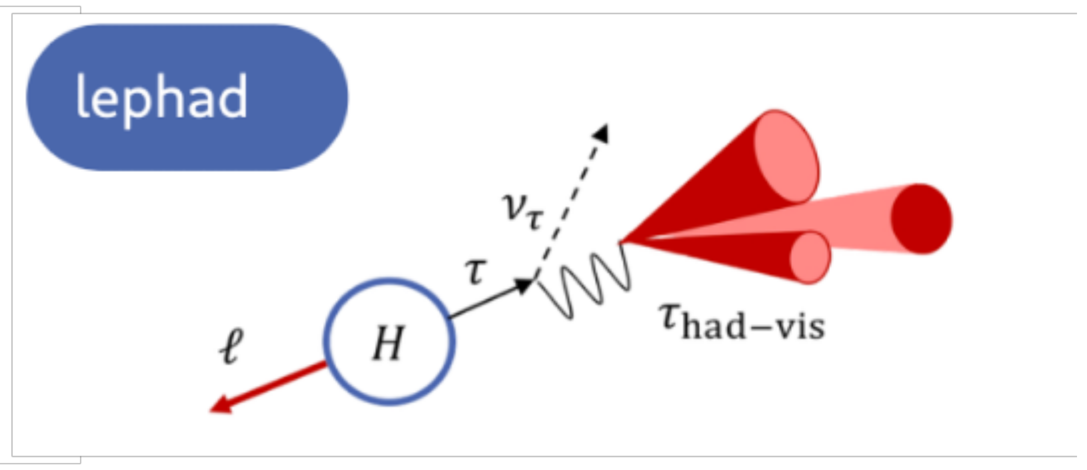
- Search for **H** $\rightarrow e\tau$ and **H**$\rightarrow \mu\tau$, two independent signals. Analysis targets leptonic tau decays and hadronic tau decays.
- Main Higgs boson production modes considered for LFV signal (ggH, VBF, VH).
- Categorisation: loose preselection(baseline) and further split into **VBF and non-VBF** regions.
- **MVA** used to enhance sensitivity. Final discriminants are the MVA scores.
- Statistical analysis for signal strength $\mu = B(H\rightarrow l\tau)$ extraction with Maximum Binned Likelihood fit using TRExFitter





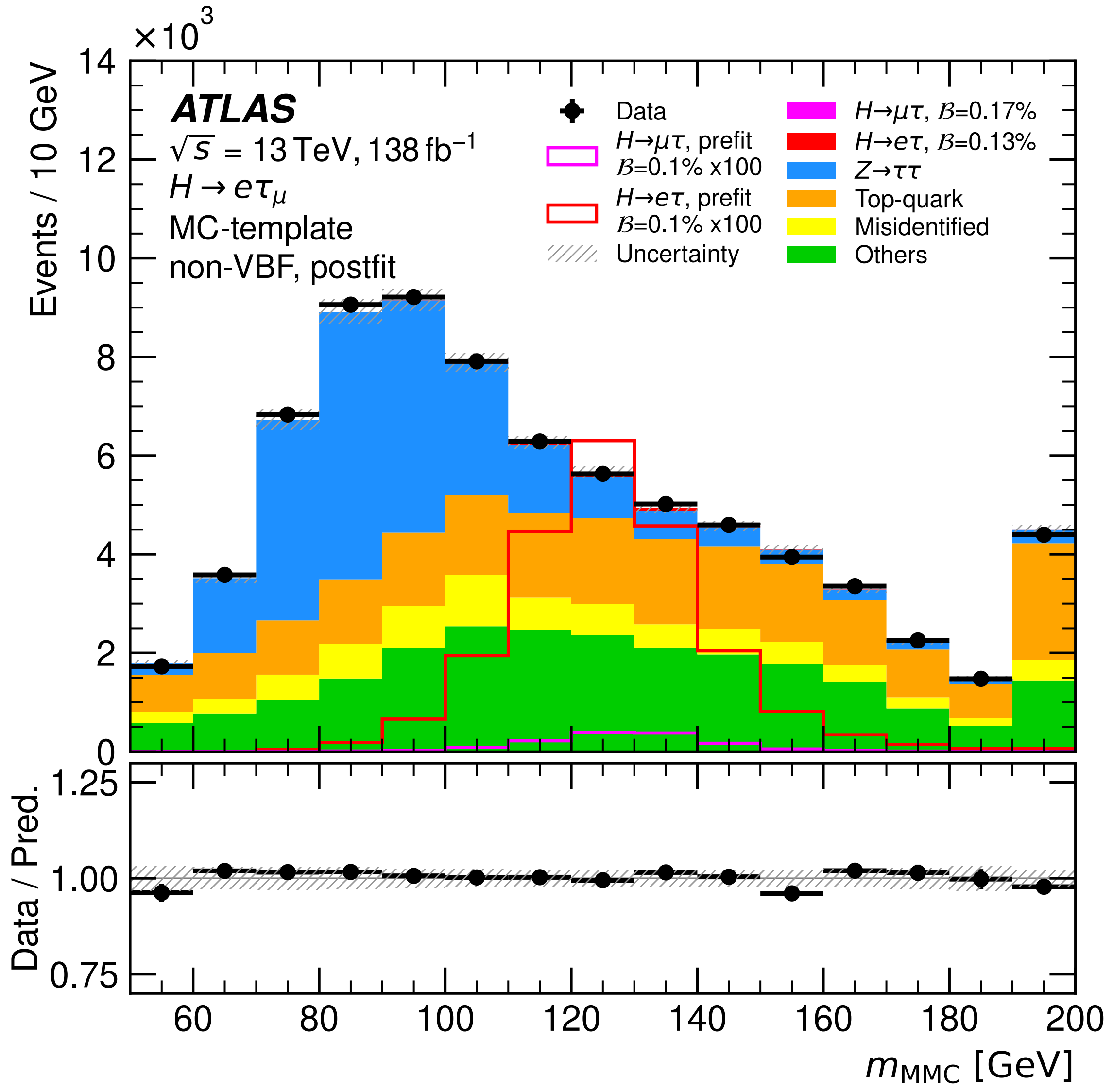
Lep-lep final states with one electron and one muon.
Channel classification ($e\tau_\mu$ or $\mu\tau_e$) based on p_T ordering in the approx Higgs frame: $p_T(l_H) > p_T(l_\tau)$.
Two background estimation method:
•**Symmetry based leplep**
Fake background data-driven. Other backgrounds estimated mainly data-driven via symmetry method
•**MC-template leplep**
Fake background data-driven. Other backgrounds estimated with MC templates and normalisation of main backgrounds data-driven from CRs

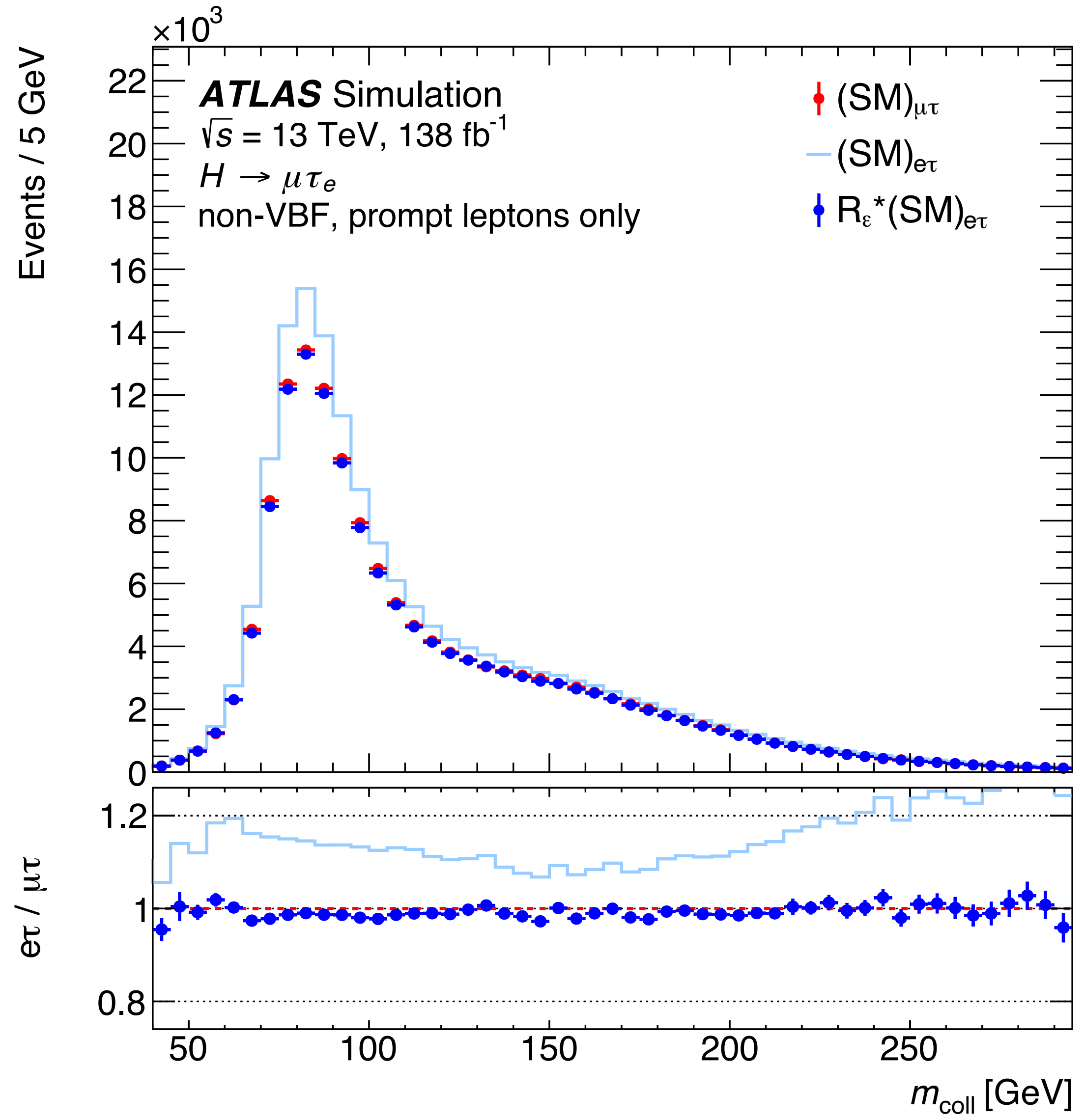
Lep-Had final states with one lepton and one hadronic tau (ethad or muthad):
Only one background estimation is used:
•**MC-template lephad**
Fake background data-driven. Other backgrounds estimated through MC

Higgs boson -> eτ or $\mu\tau$

- **Symmetry method** : LFV H decays break the SM symmetry if B(H→ $\mu\tau$) ≠ B(H→eτ), Data of each of the two channels can serve as background prediction for the other channel.

- **MC-template** method uses simulation to estimate Z→$\tau\tau$, Top, Diboson, Higgs….use data-driven to estimate fakes





•**Symmetry method, leplep**: **NNs trained with Keras**, Separate training for non-VBF and VBF, but common for eτ_μ and $\mu\tau_e$

  •Non-VBF: 1 Multiclassifier NN with 3 output nodes. Signal node is used for fit.

  •VBF: 3 NNs, combined linearly. LFV vs (Z$\tau\tau$+H$\tau\tau$+MC fakes) / (Top+VV+HWW) / Fakes

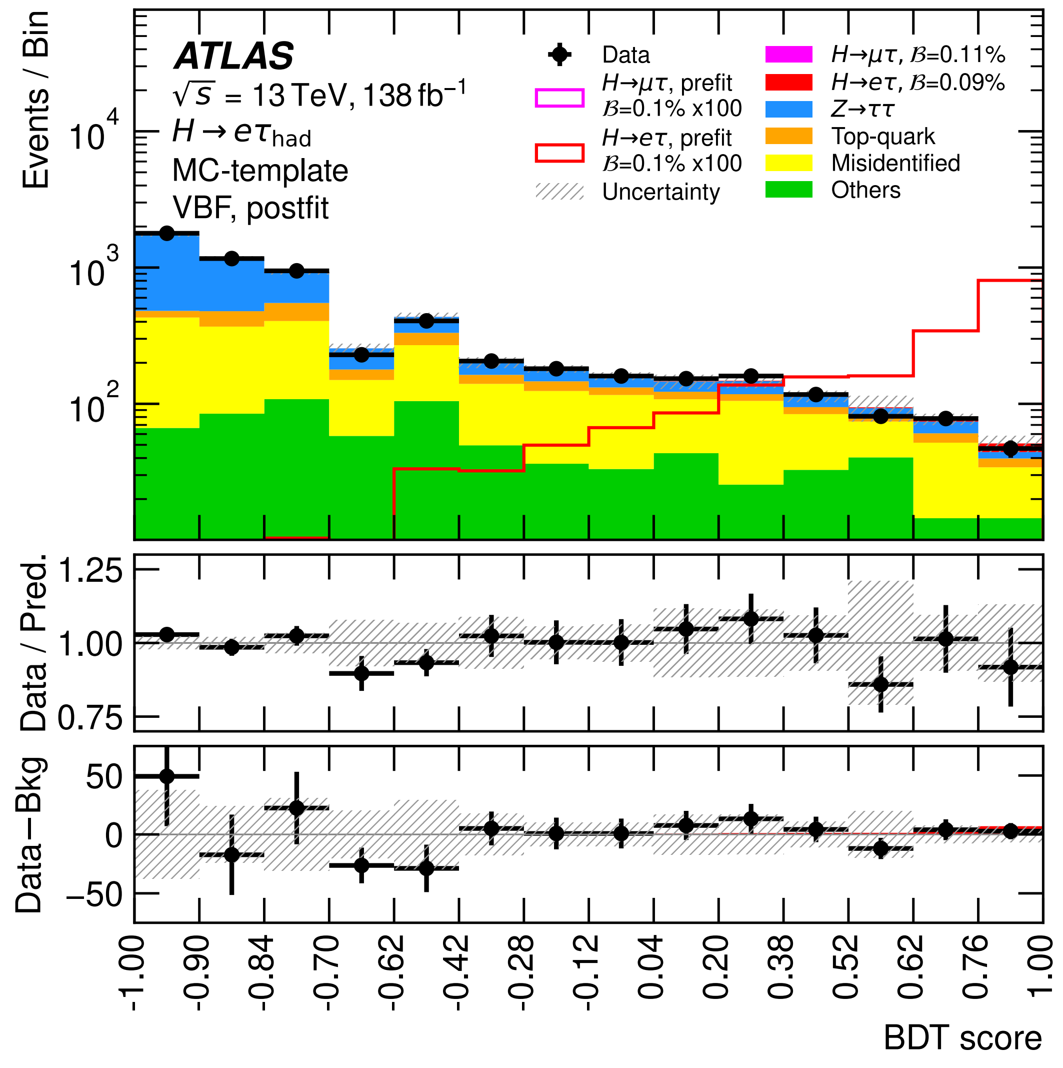
•**MC-template method, leplep**: **BDTs with TMVA**, Separate training for non-VBF and VBF, but common for eτ_μ and $\mu\tau_e$

  •Non-VBF and VBF: 3 BDTs, combined linearly. LFV vs (Z$\tau\tau$+H$\tau\tau$+Zleplep) / (Top+VV+HWW) / Fakes

•**MC-template method, lephad**: **BDTs with TMVA**, Separate training for non-VBF and VBF and for eτ_{had} and $\mu\tau_{had}$

  •Non-VBF eτ_{had} : 3 BDTs, combined linearly. LFV vs Z$\tau\tau$ / Fakes / rest of bkgs

  •VBF and non-VBF $\mu\tau_{had}$: 2 BDTs, combined linearly for non-VBF $\mu\tau_{had}$ and quadratically for VBF.   LFV vs Ztt / rest of bkgs



Higgs boson -> eτ or $\mu\tau$

1 POI Fit results: B(H→eτ)=0 when fitting B(H→ μτ) and viceversa.

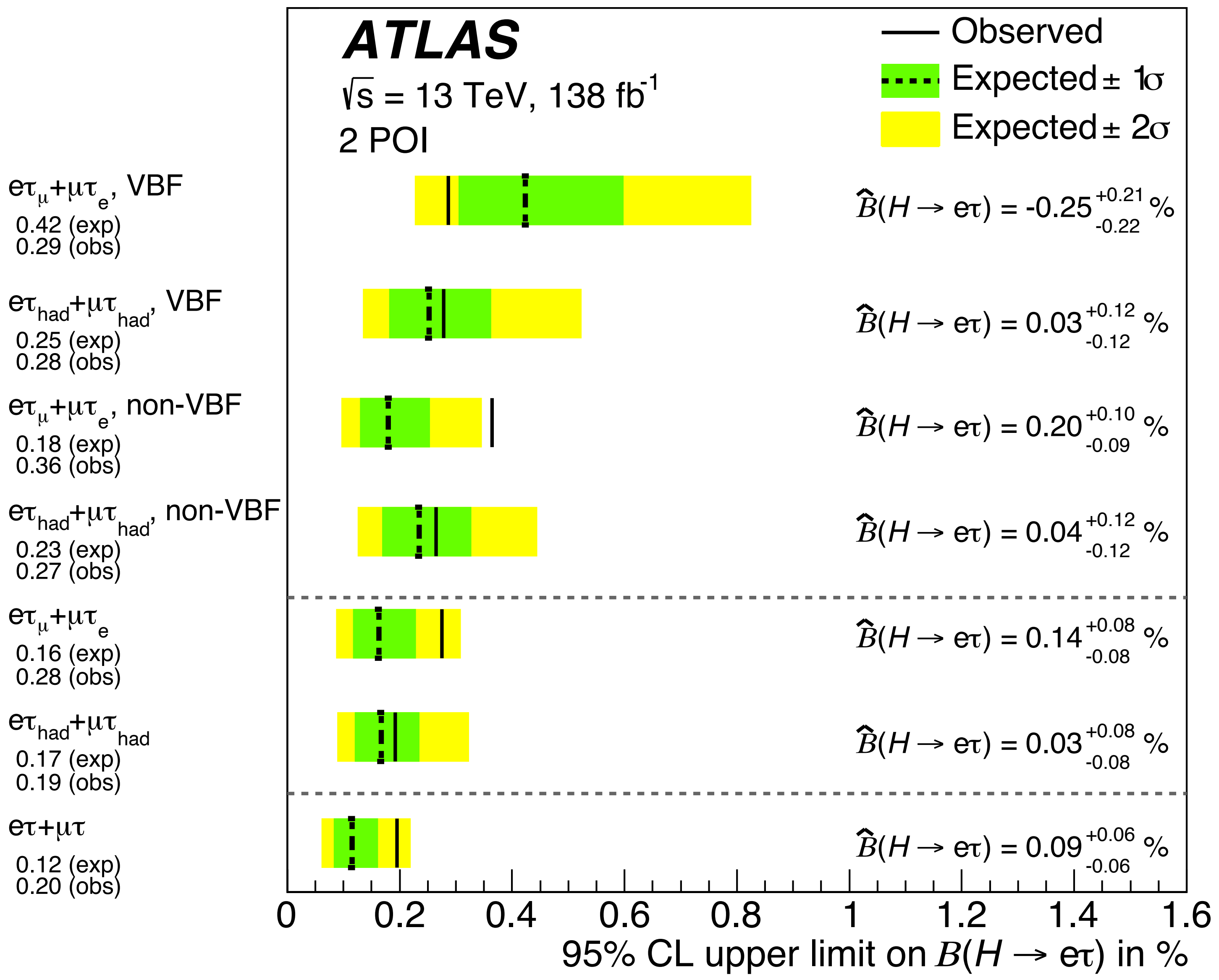
- Observed limits are above expected ones: **2.2σ** excess seen for B (H→eτ) and **1.9σ** for B(H→ μτ).

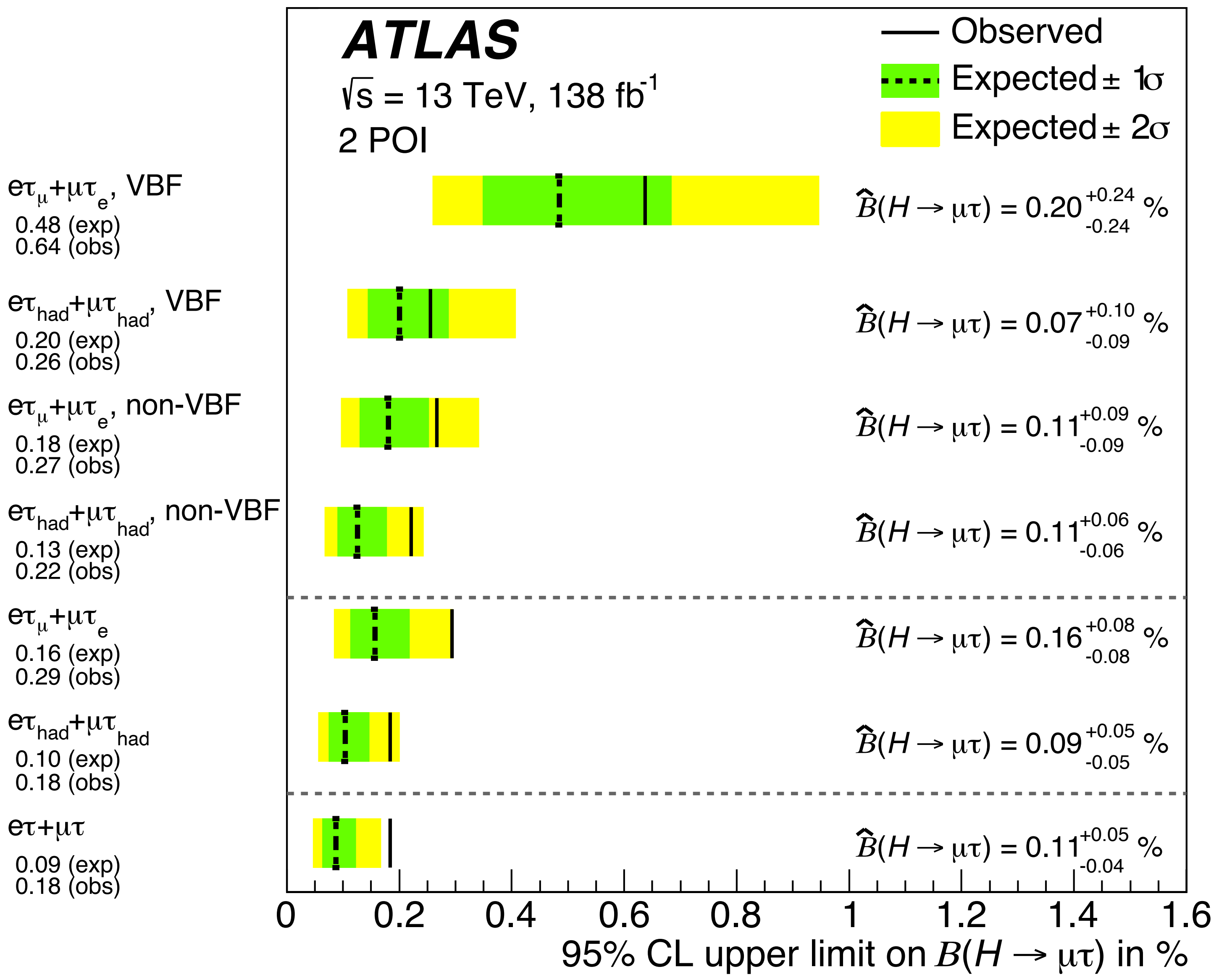
2 POI Fit results: fit two channel simultaneously

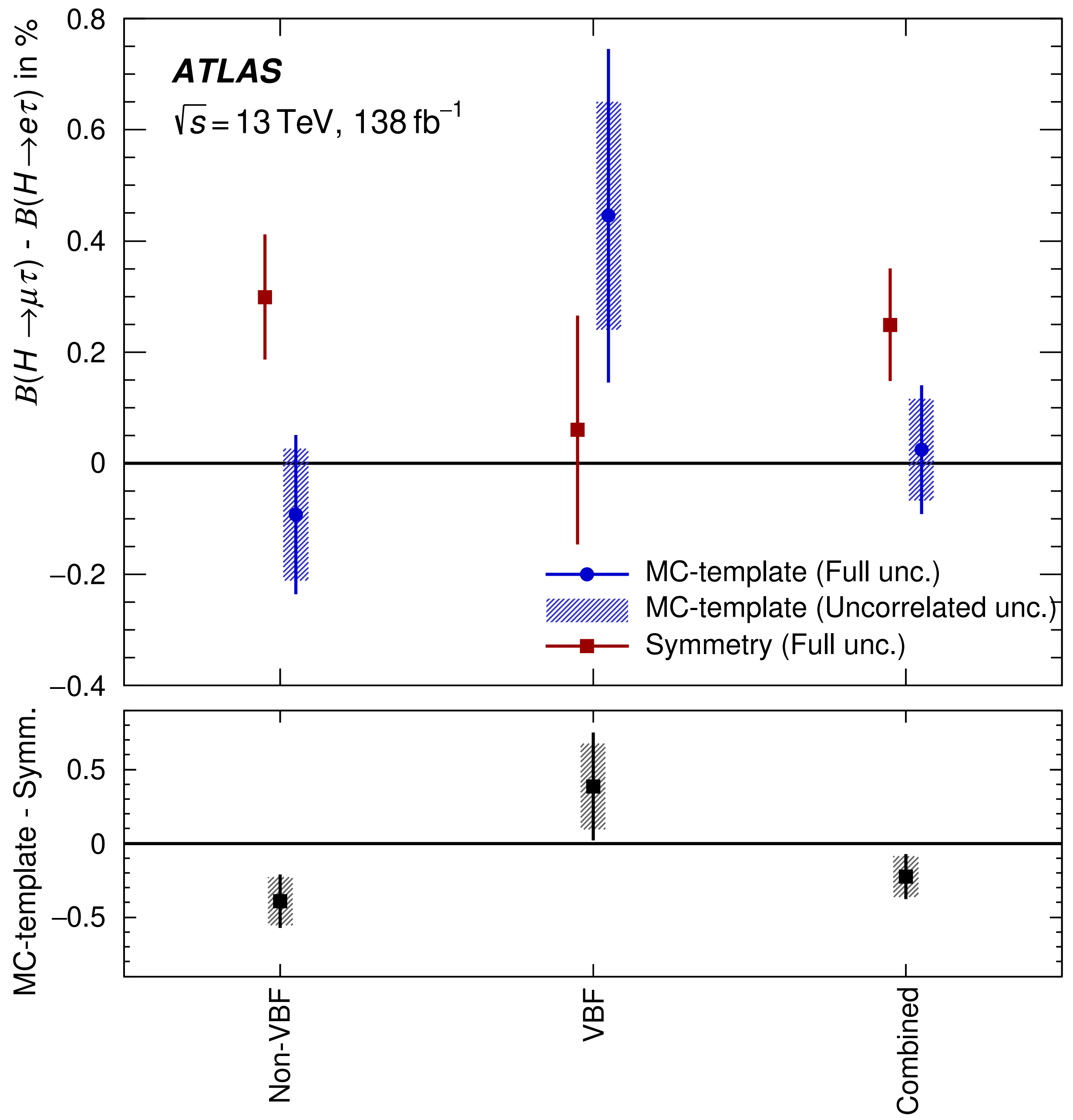
- **1.6σ** excess seen for B (H→eτ) and **2.5σ** for B(H→ μτ). Compatibility with SM within **2.17σ**.

Symmetry method measures difference B(H→ μτ)-B(H→eτ)

- Compatibility is found to be within **2.3σ** (within **1.3σ** if combined fit results are used).







high-mass dilepton final states

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Search for Charged lepton flavour violation at TeV scale:

- LFV Z' : same quark couplings and chiral structure as the SM Z boson
- Quantum Black Hole: the extradimensional Planck Scale is reached, might violate LFC
- R-Parity Violating SUSY: τ-sneutrino decay

3 channels: $e\mu$, $e\tau_{had}$, $\mu\tau_{had}$ with two opposite leptons which are back-to-back in phi

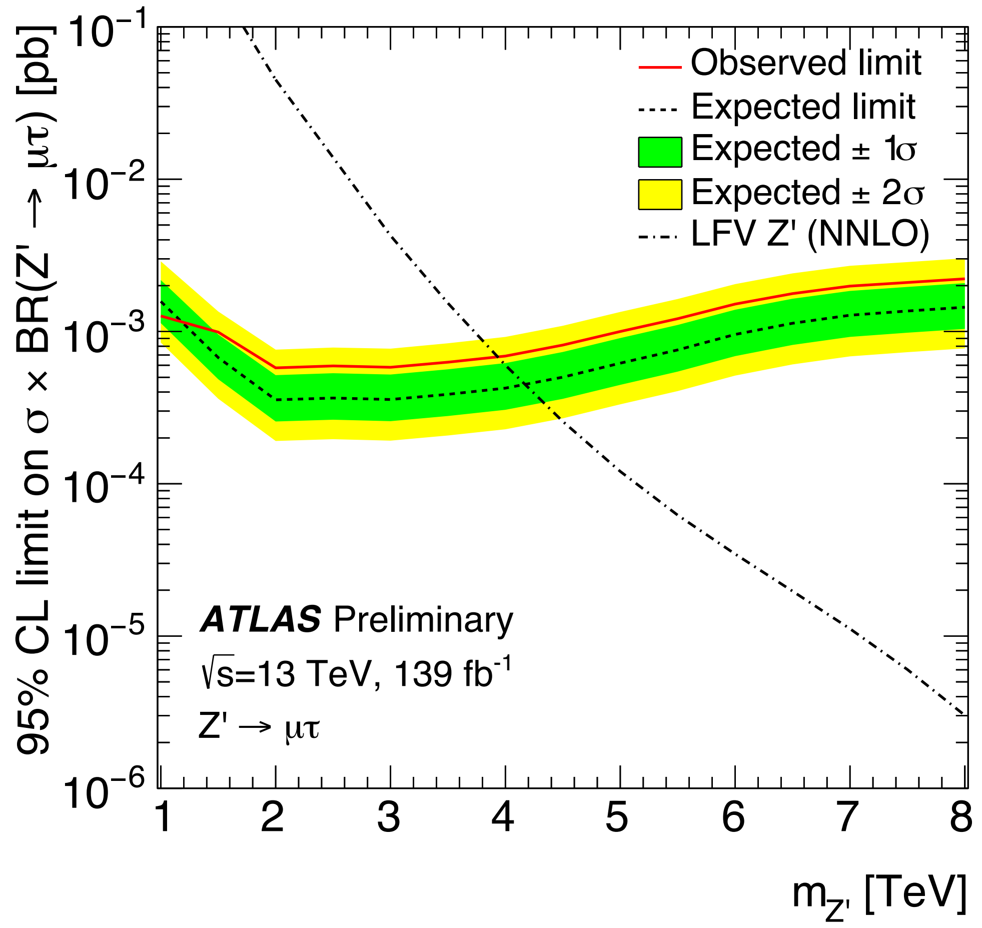
tau-neutrino is reconstructed from MET and the direction of tau-hadronic

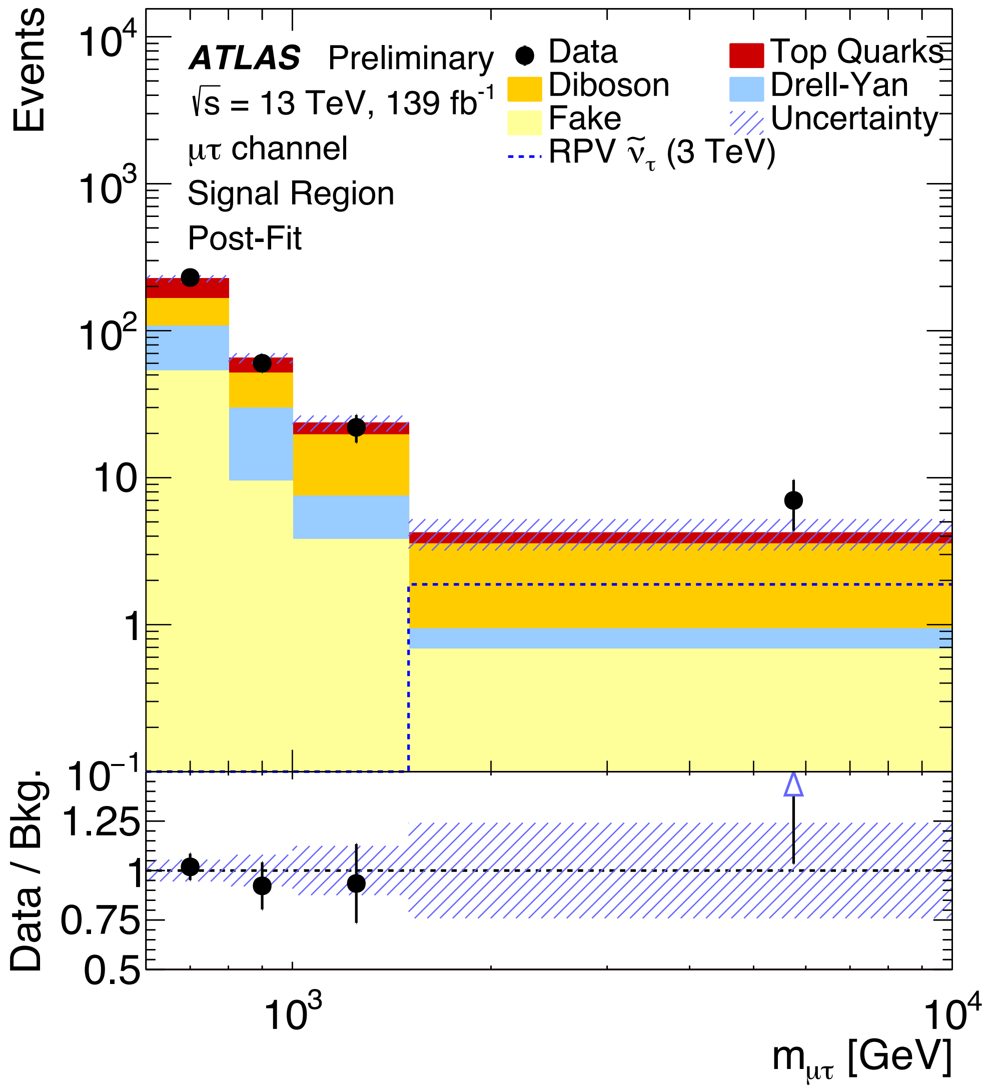
SR: mll>600GeV

BKG:

- Irreducible backgrounds: ttbar, single top, diboson, $Z \rightarrow ll$ -> MC simulation
- Reducible backgrounds : mainly refer to Wjets and QCD -> Data-driven method

Model	Observed (expected) limit [TeV]		
	$e\mu$ channel	$e\tau$ channel	$\mu\tau$ channel
LFV Z'	5.0 (4.8)	4.0 (4.3)	3.9 (4.2)
RPV SUSY $\tilde{\nu}_\tau$	3.9 (3.7)	2.8 (3.0)	2.7 (2.9)
QBH ADD $n = 6$	5.9 (5.7)	5.2 (5.5)	5.1 (5.2)
QBH RS $n = 1$	3.8 (3.6)	3.0 (3.3)	3.0 (3.1)





unexpected asymmetry of eμ

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$$\rho = e^+\mu^- / e^-\mu^+$$

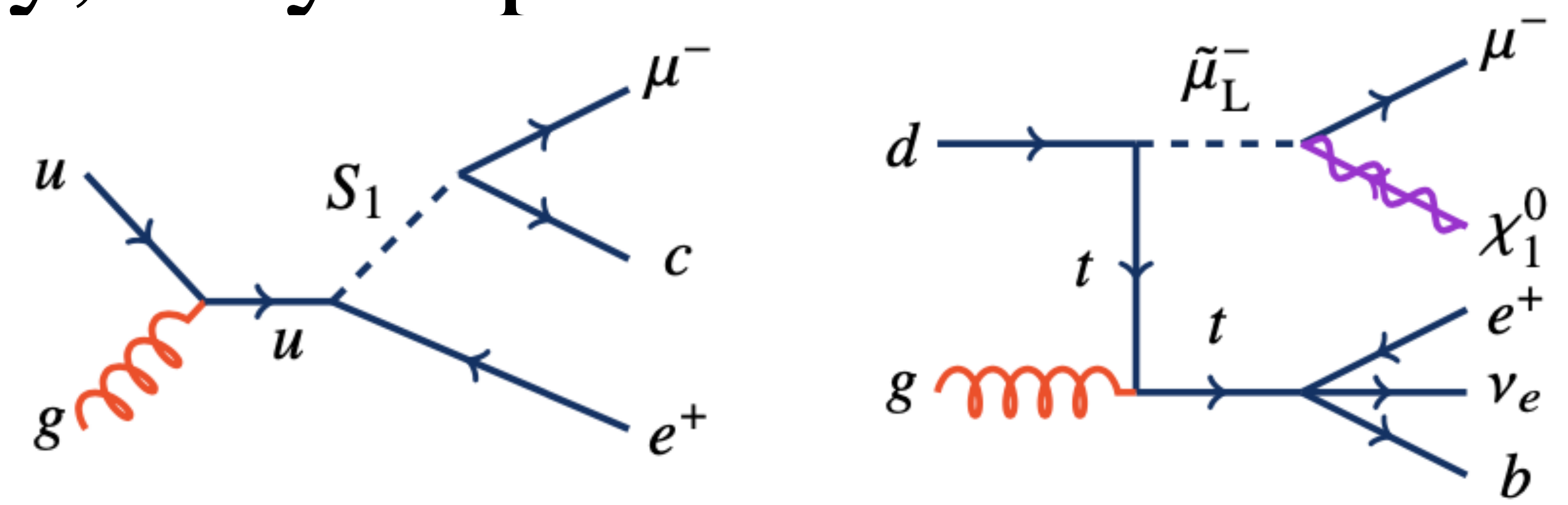
Not charge OR flavour symmetry, but the combination of both: a SM property that is yet untested.

SM pp->emu processes ρ~1

- ttbar, VV,… LO symmetric
- From phase space reasons slight bias for $\rho < 1$

If ρ> **1**, significantly, only explanation BSM.

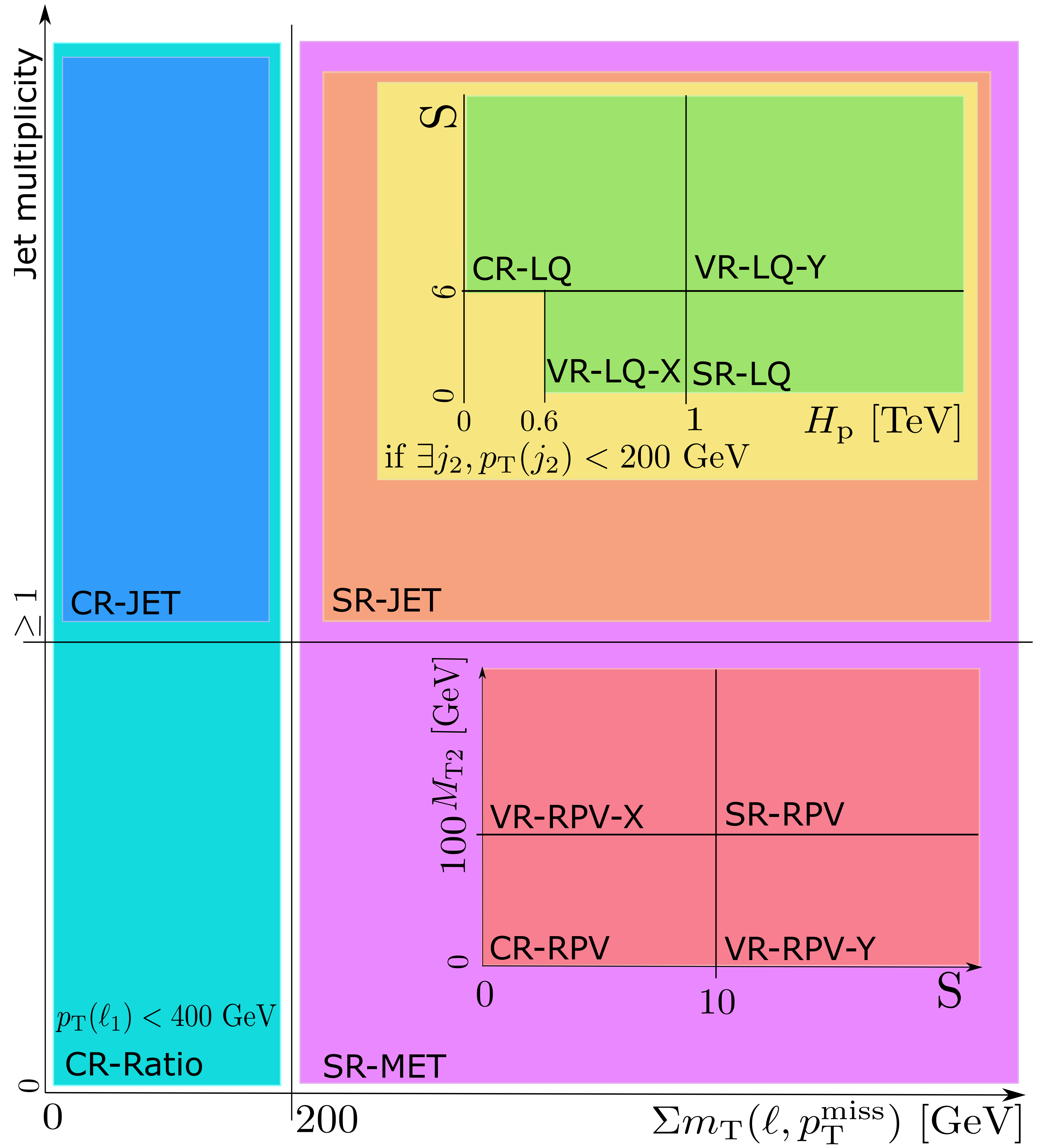
- Scalar leptoquark
- R-parity-violation



Bias:

Various detector effects can make $\boldsymbol{\rho}$ smaller than 1

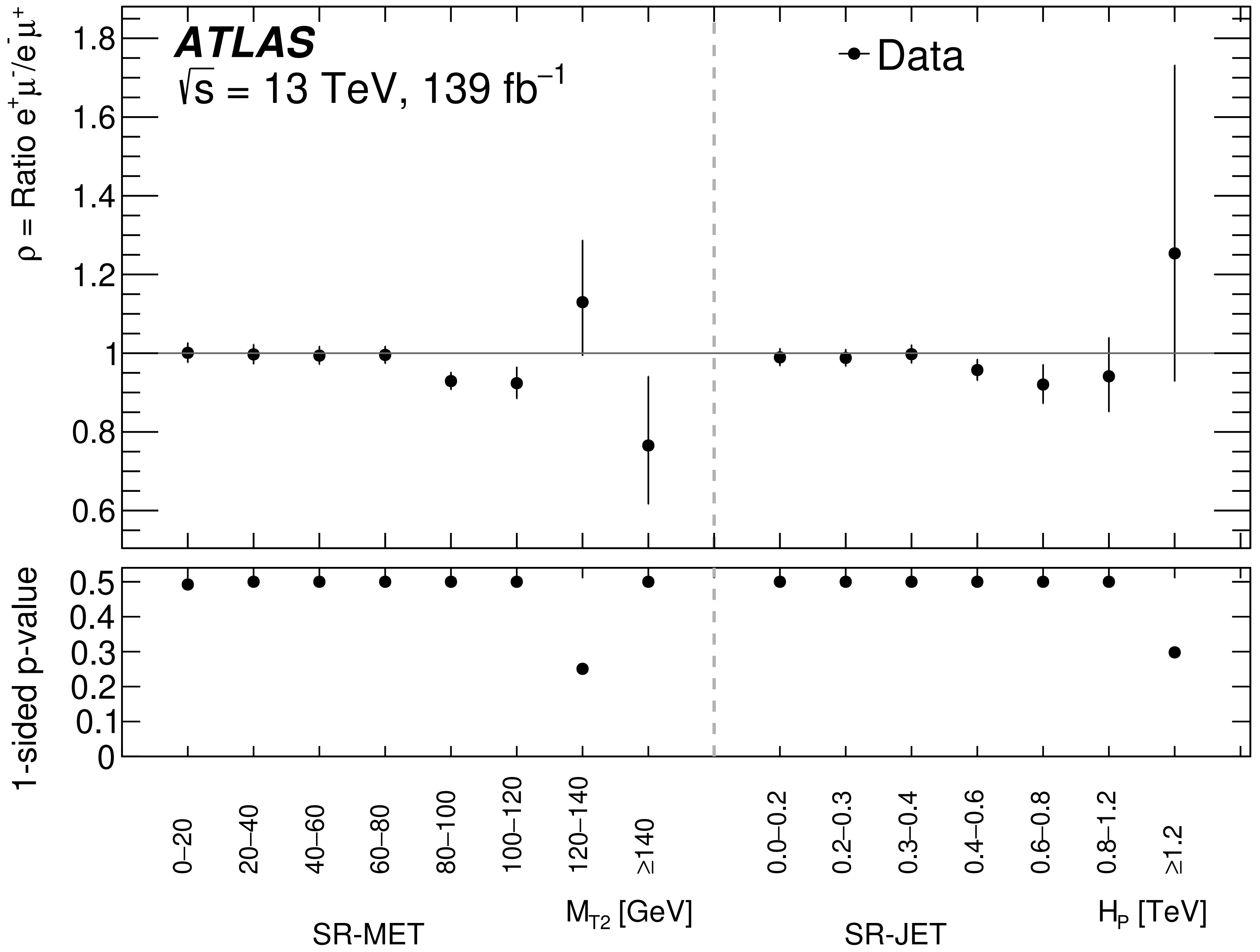
- Muon Sagitta
  - just using MCP recommended data correction + unc.
  - Tiny correction
- Electrons
  - ChargeID correction Tool used.
  - CP uncs. applied as instructed by EGamma group cover any charge bias.
- Fake leptons
- Muon efficiency charge-bias corrections (affect $\boldsymbol{\rho}$ either way)

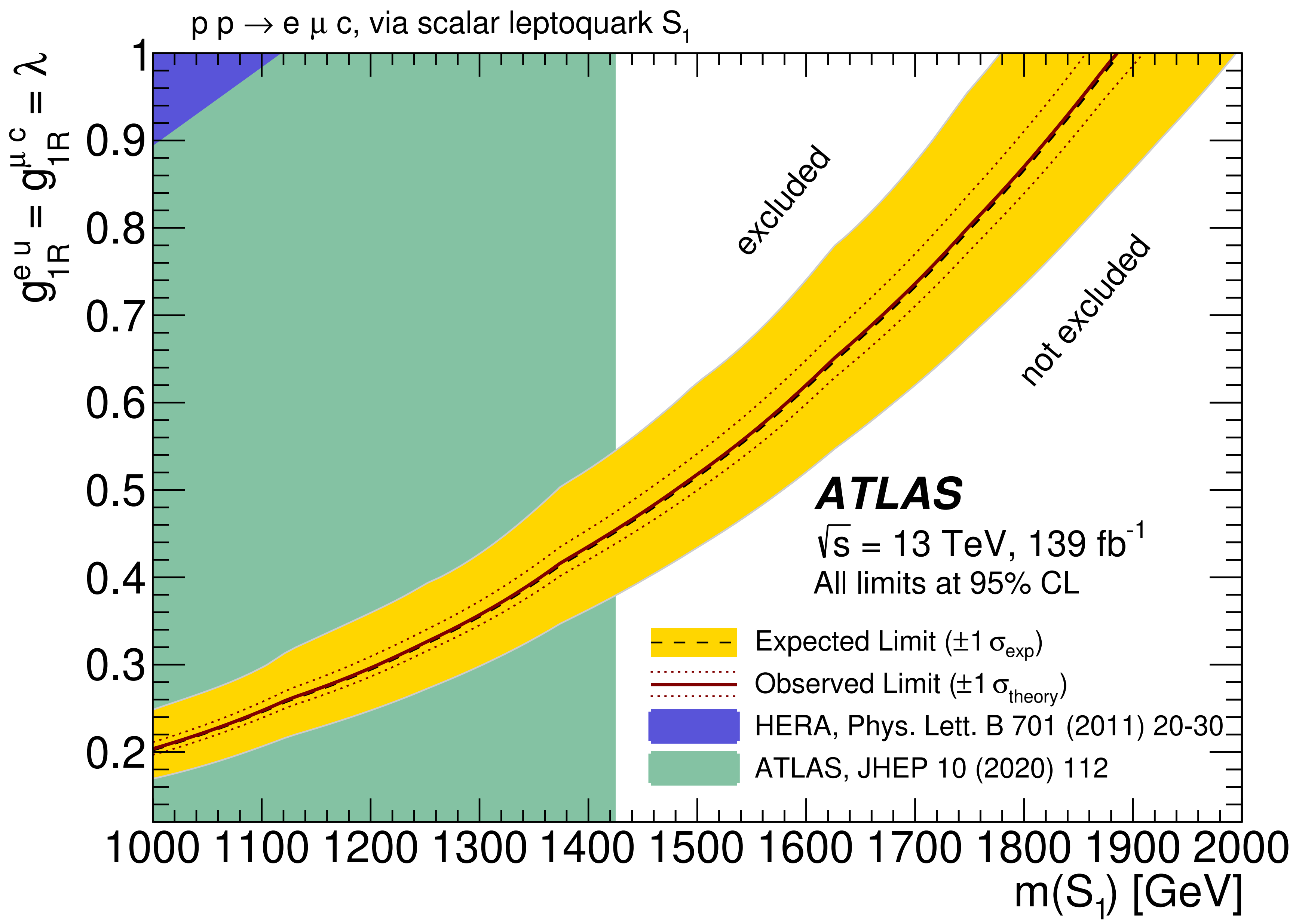


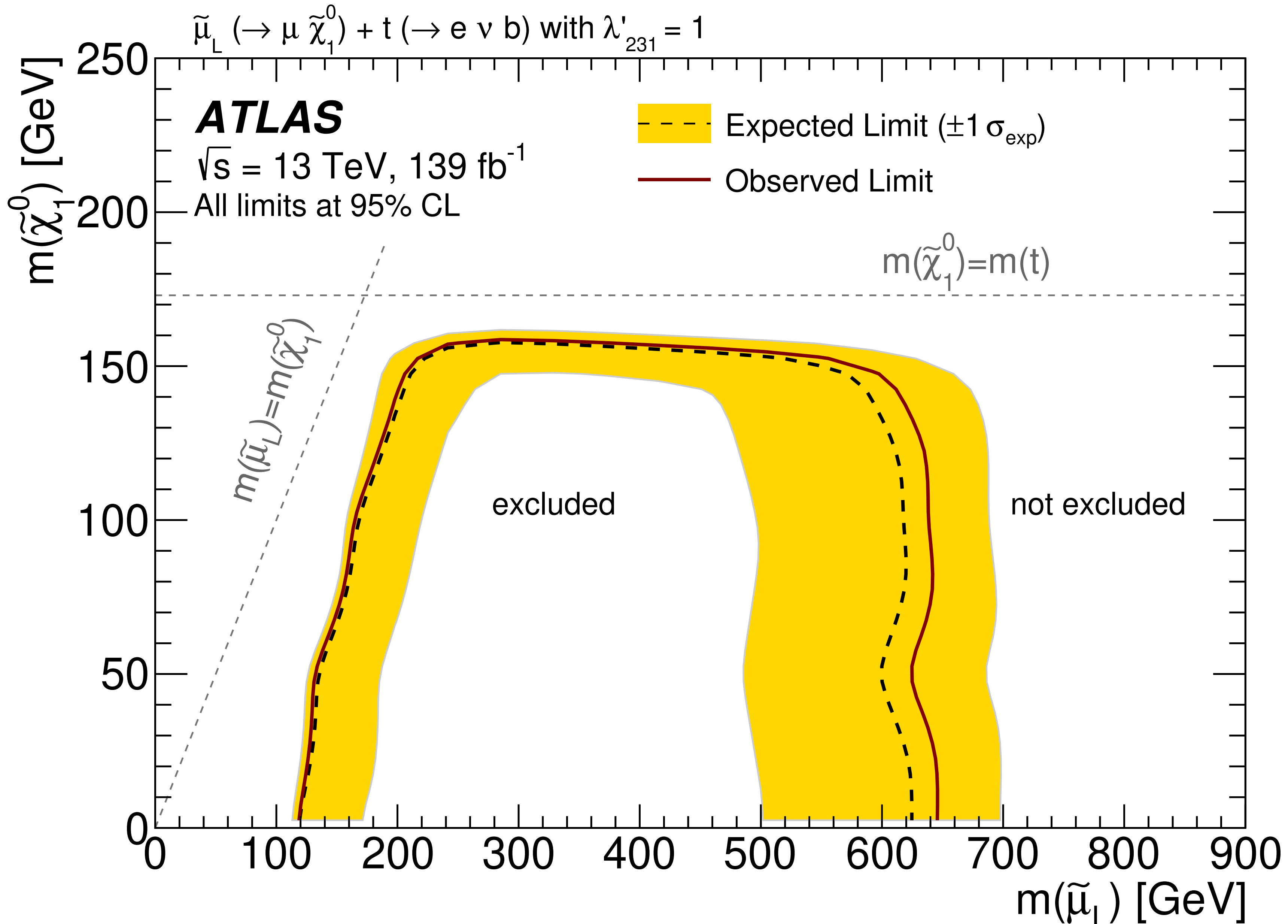
unexpected asymmetry of eμ

No significant model-independent evidence for $\rho > \mathbf{1}$ was seen

Set the exclusion limits for the two model







	SR-RPV $e^+\mu^-$	SR-RPV $e^-\mu^+$	SR-LQ $e^+\mu^-$	SR-LQ $e^-\mu^+$
$M(\tilde{\chi}_1^0, \tilde{\mu}) = (0, 500)$ GeV, $\lambda'_{231} = 1$	191 ± 23	46.8 ± 7.7		
$M(\tilde{\chi}_1^0, \tilde{\mu}) = (50, 250)$ GeV, $\lambda'_{231} = 1$	1160 ± 130	361 ± 97		
$M(S_1) = 1$ TeV, $\lambda = 0.5$			214 ± 15	14.5 ± 1.8
$M(S_1) = 1.25$ TeV, $\lambda = 1.0$			356 ± 53	22.9 ± 3.7
Data	489 ± 22	510 ± 23	60.9 ± 7.8	69.1 ± 8.3
Total SM expectation	503 ± 48	510 ± 26	61 ± 15	69 ± 12
• part due to real leptons	473 ± 47	479 ± 24	47 ± 13	47 ± 11
• part due to fake leptons	29.4 ± 8.2	30.3 ± 8.3	14.1 ± 6.5	22.1 ± 6.6

b -> s lep lep

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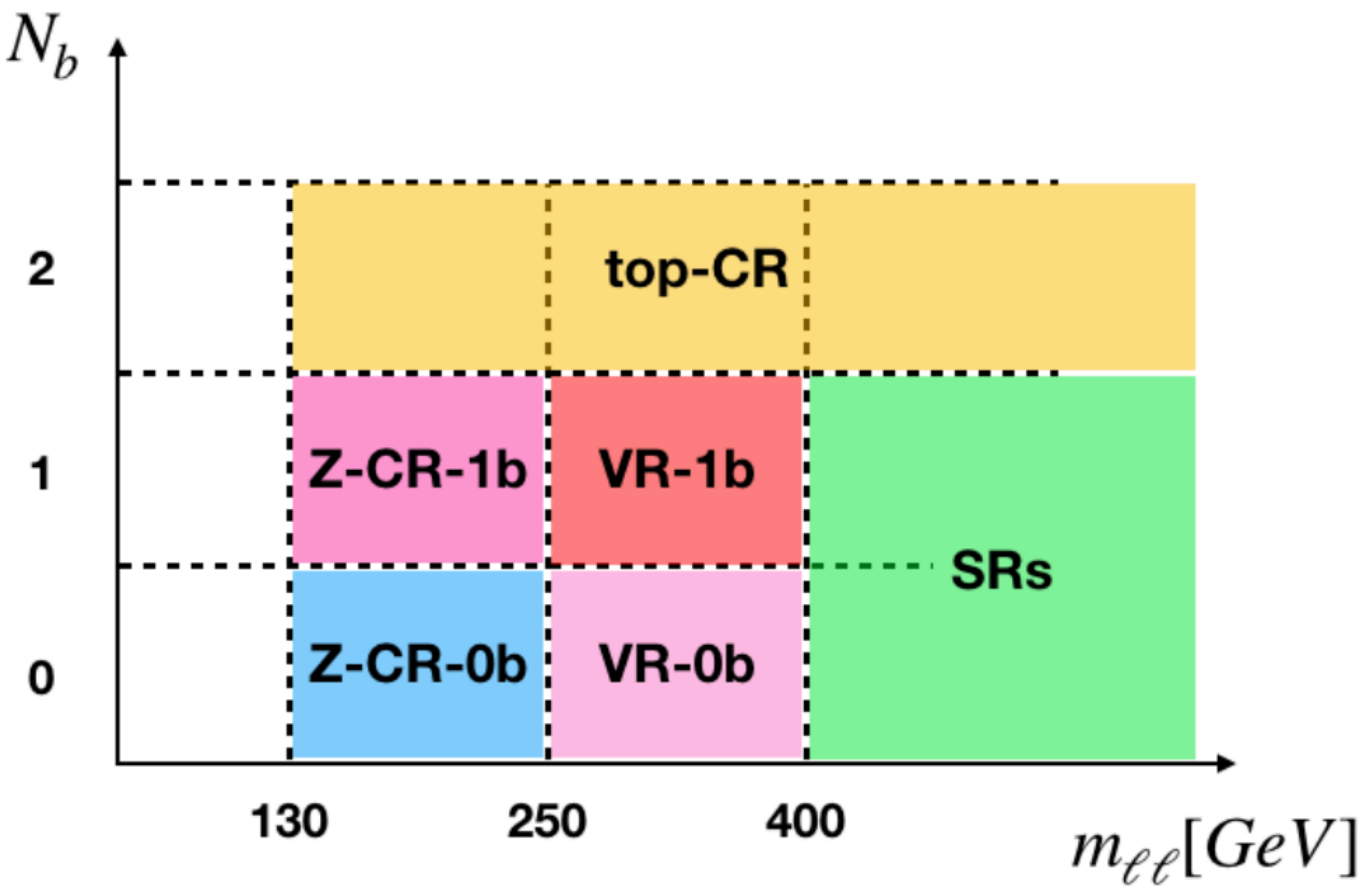
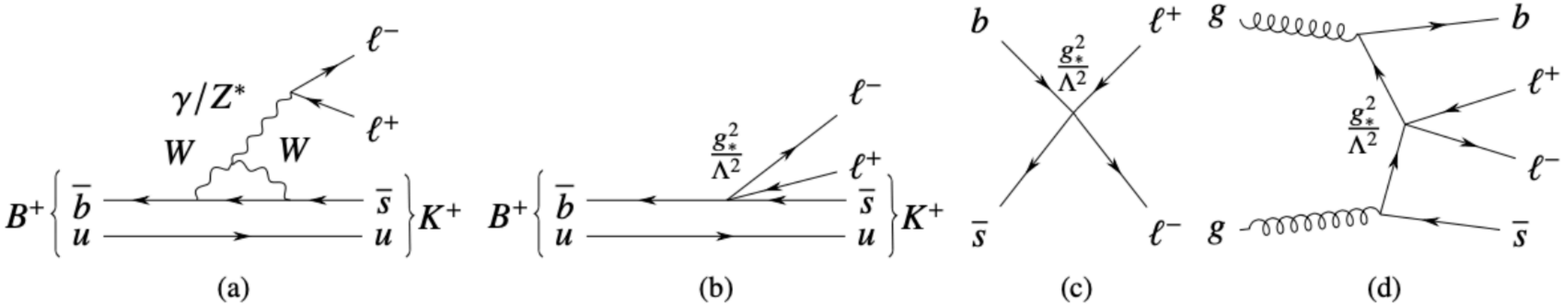
- Several measurements hint at a possible violation of LFU in rare *B*-meson decays into a *K* meson and a pair of muons or electrons.
- modeled using an effective field theory with a four-point contact interaction between the fermions involved
- two opposite-charge and same-flavor leptons produced in association with exactly one *b* quark or without any *b* quarks
- correspond to a *bs*ll operator with $\Lambda/g \approx 30$ TeV



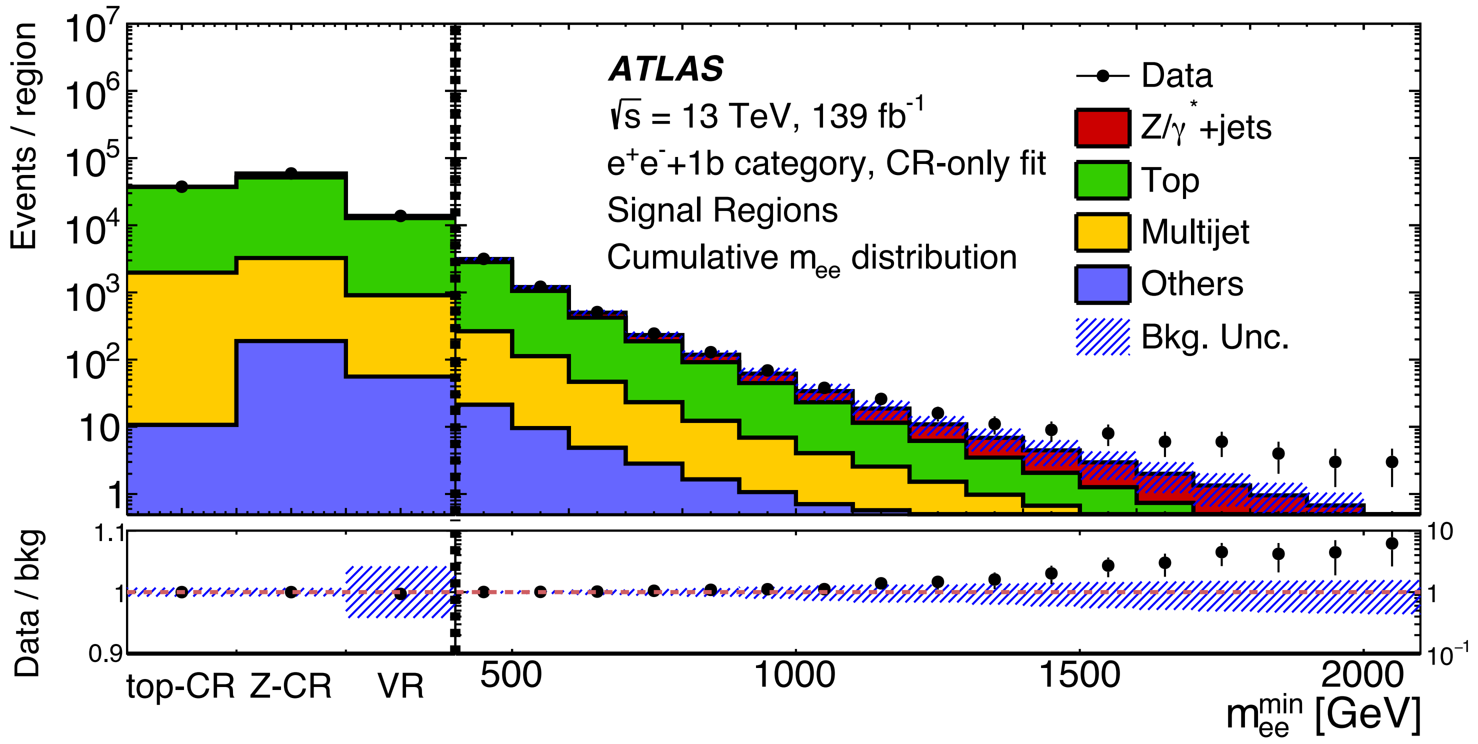


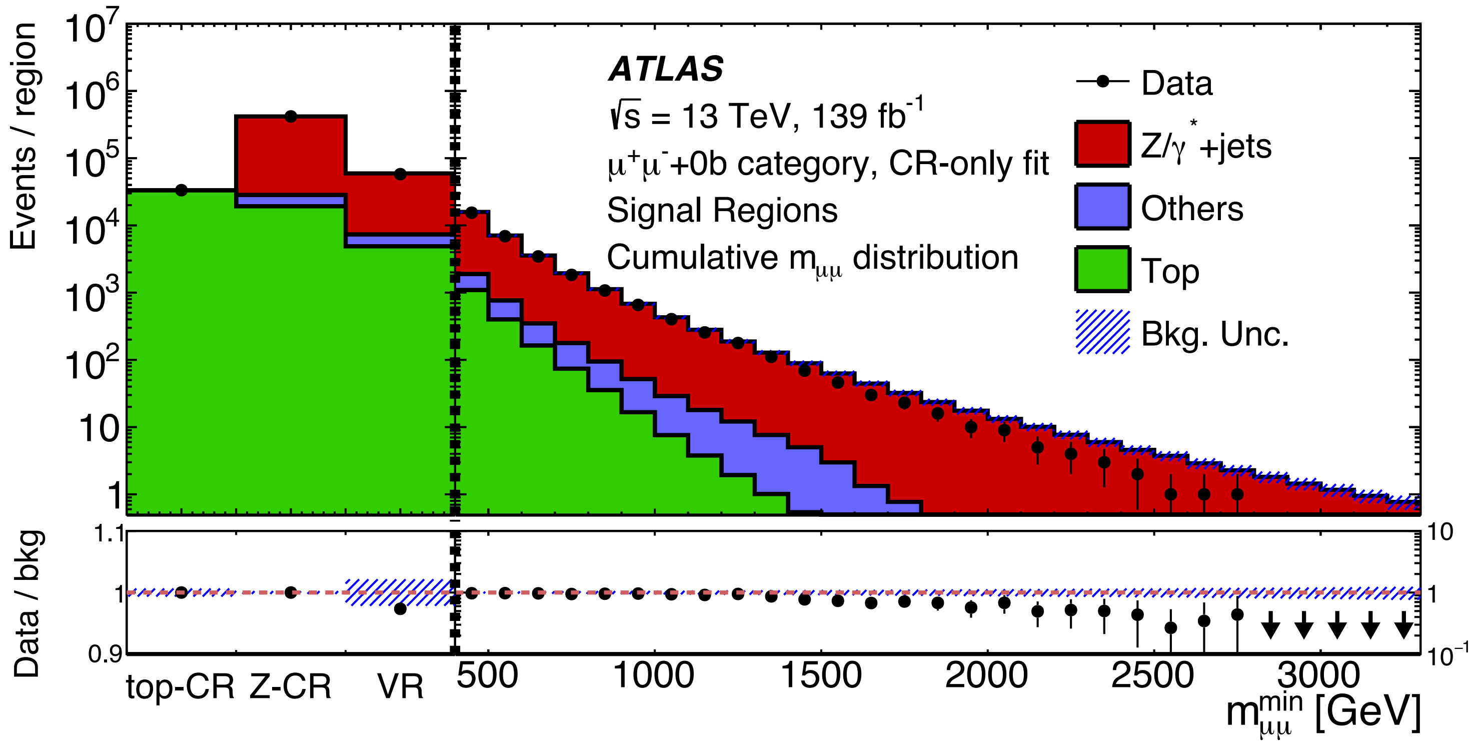
b -> s lep lep

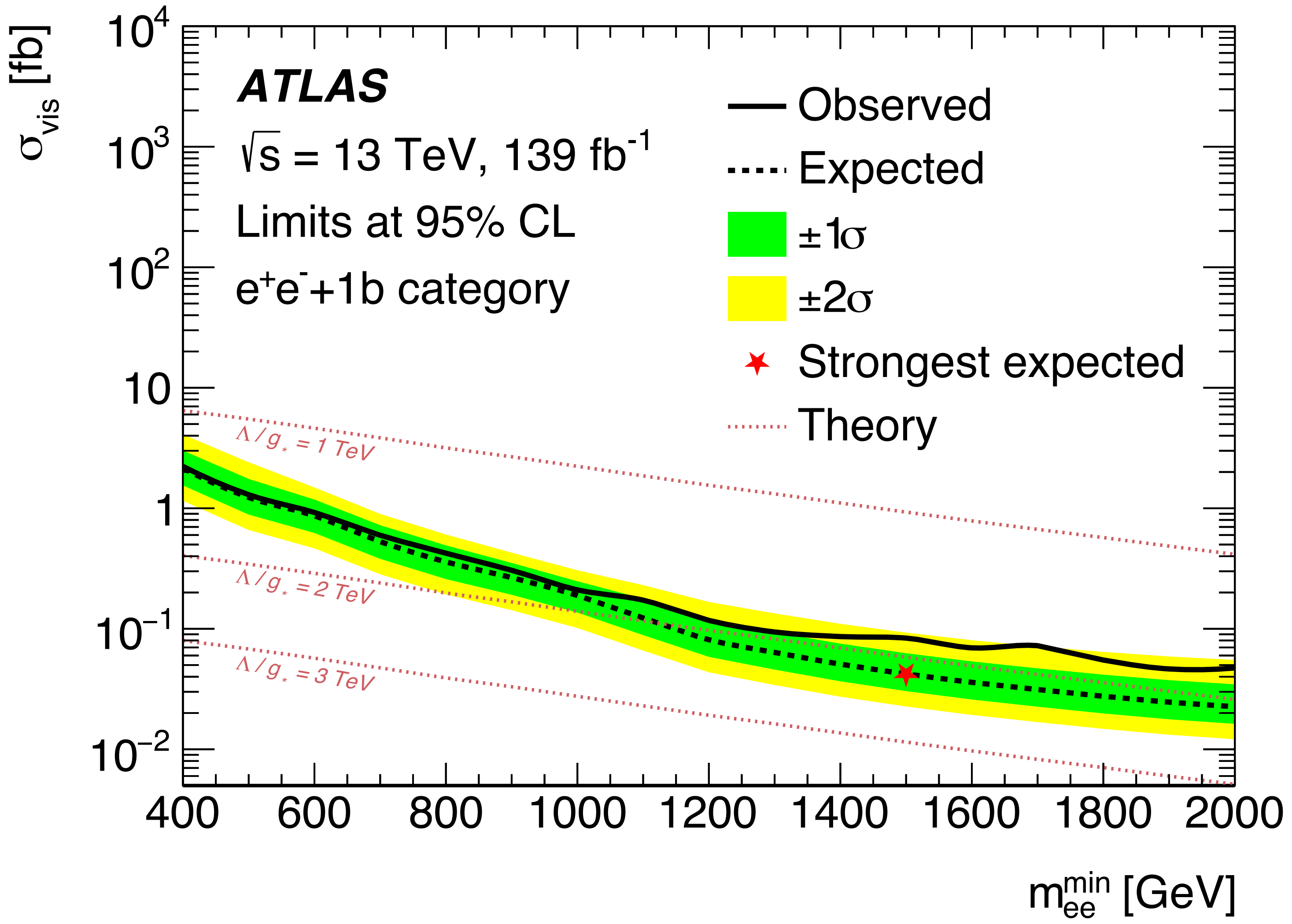
Z + jets samples are good statistics.
Top samples suffer from low statistics at the tail
- extrapolation.
Background of misidentified objects (electron channel only):
- Use data-driven Matrix Method
- Extrapolation is necessary for the high mass bins.

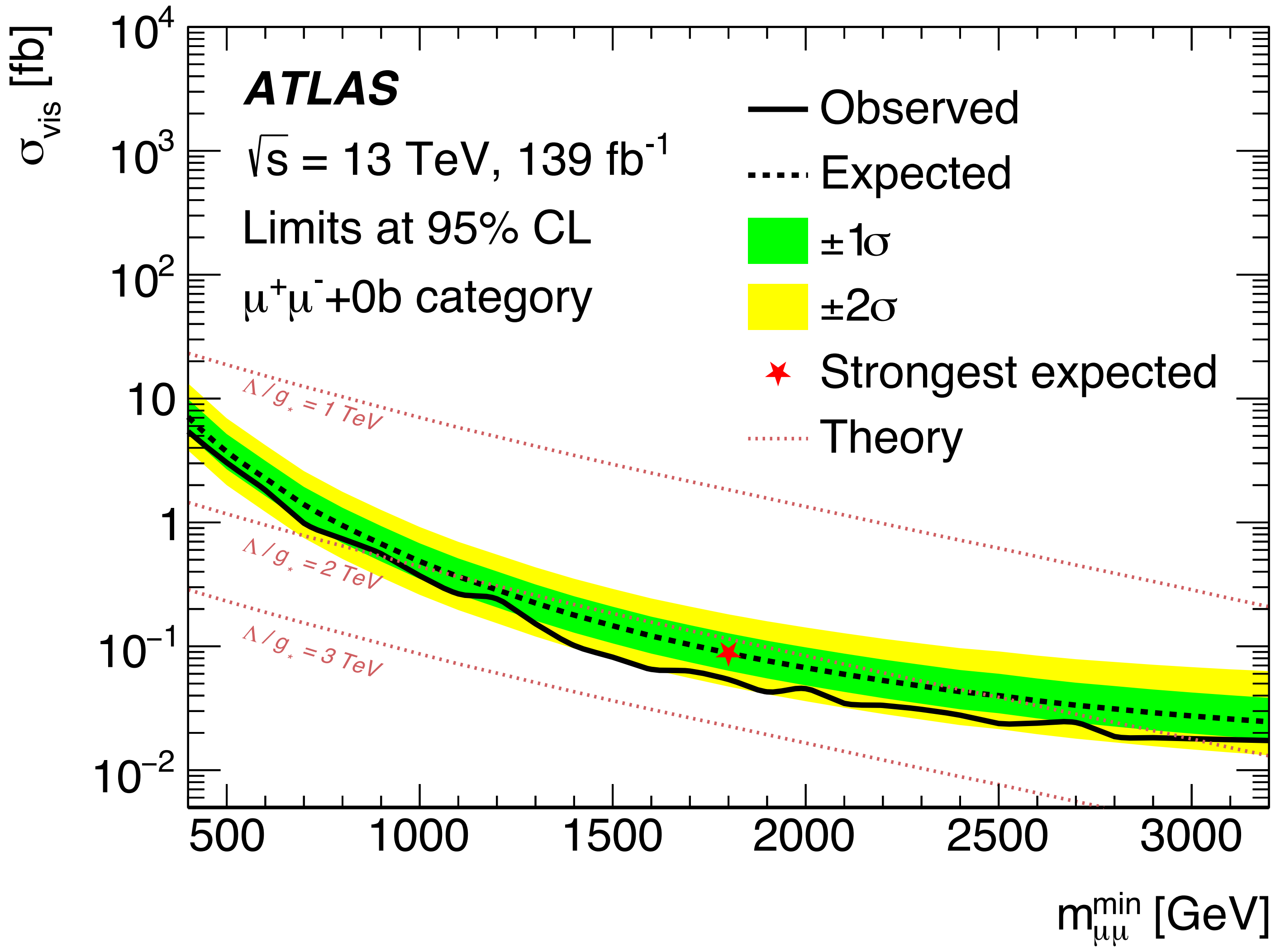
The cumulative mass m_{ll}^{min} is considered
- contact interactions expect a m_{ll} tail.

Contact interactions with Λ/g_* lower than 2.0 (2.4) TeV are excluded for electrons (muons) at the 95% CL , still far below the value which is favored by the B-meson decay anomalies.



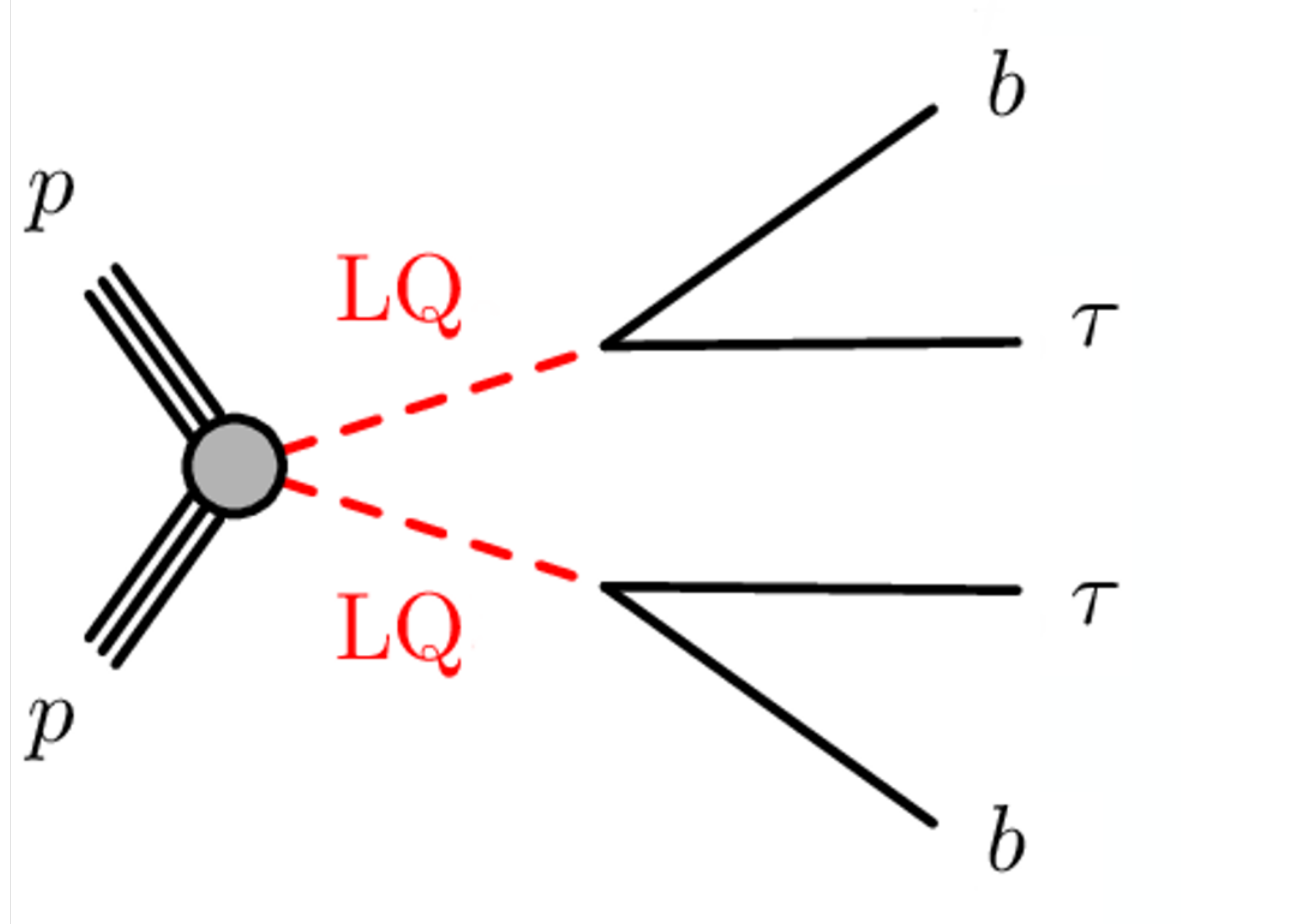






search for leptoquarks

[pair btau Page Link]



- Leptoquarks (LQ) could explain the anomalies of LFU in B-physics.
- Target pair-produced up-type LQs with B(LQ → bτ) = 1.0
  ✓ Scalar and Vector (Yang-Mills and Minimal) are considered.
- Two channels: $\tau_{had}\tau_{had}$, $\tau_{had}\tau_{lep}$ (lep = e, μ), ≥2 jets, ≥1 b-jet
- parametric neural network used as a discriminator

Signal:

Scalar LQ: Coupling parameters are set as $\lambda = 0.3$, $\beta = 0.5$

Vector LQ: Minimal coupling scenario and Yang-Mills coupling scenario, $\beta = 0.5$

Backgrounds:

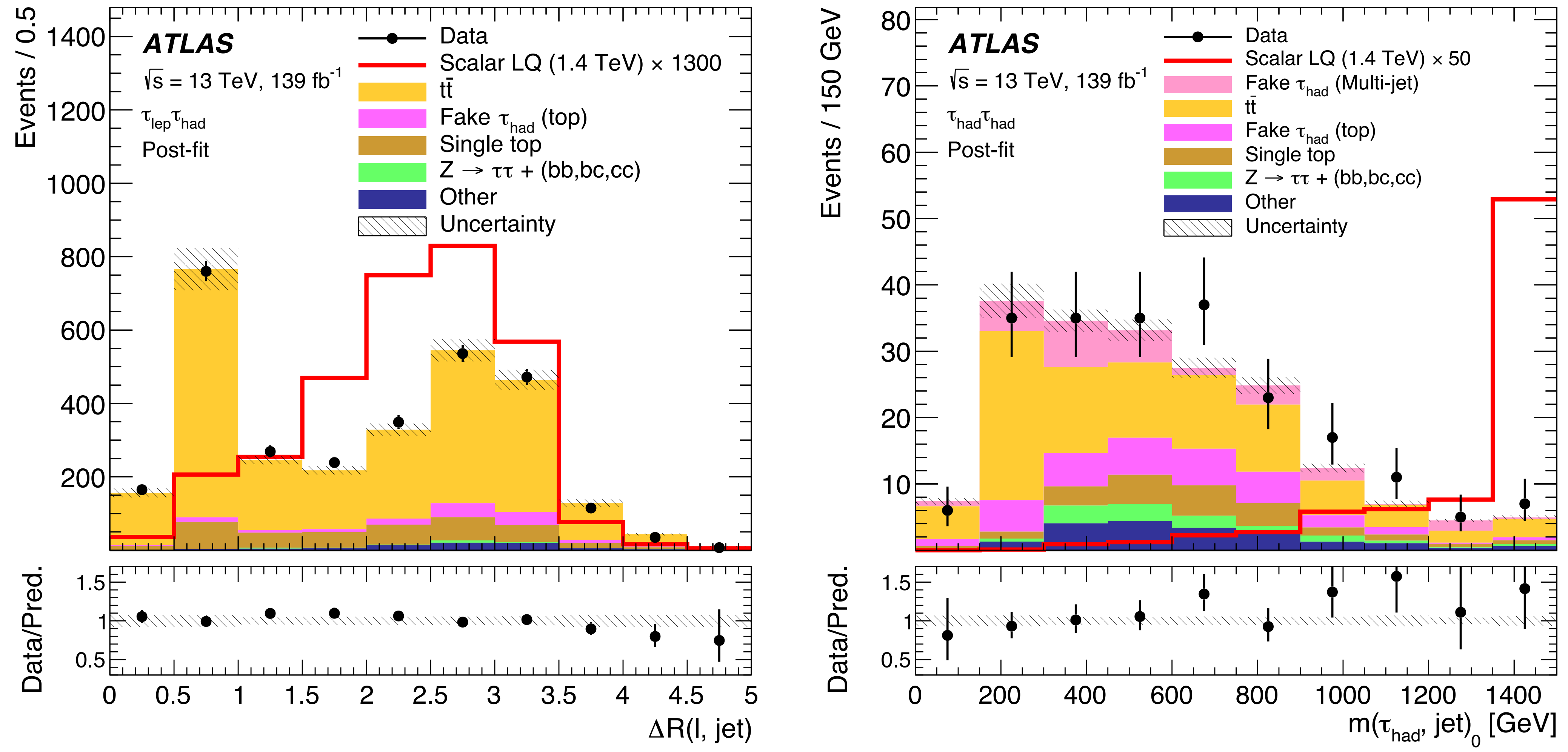
✓Z, W + jets, diboson, SM Higgs (MC)

✓ttbar/single-top: sT dependent Reweighting

✓Multi-jet with fake τ_{had} :

negligible. (lephad channel)

Estimated by Fake-Factor method. (hadhad channel)



PNN input variables distribution

search for leptoquarks

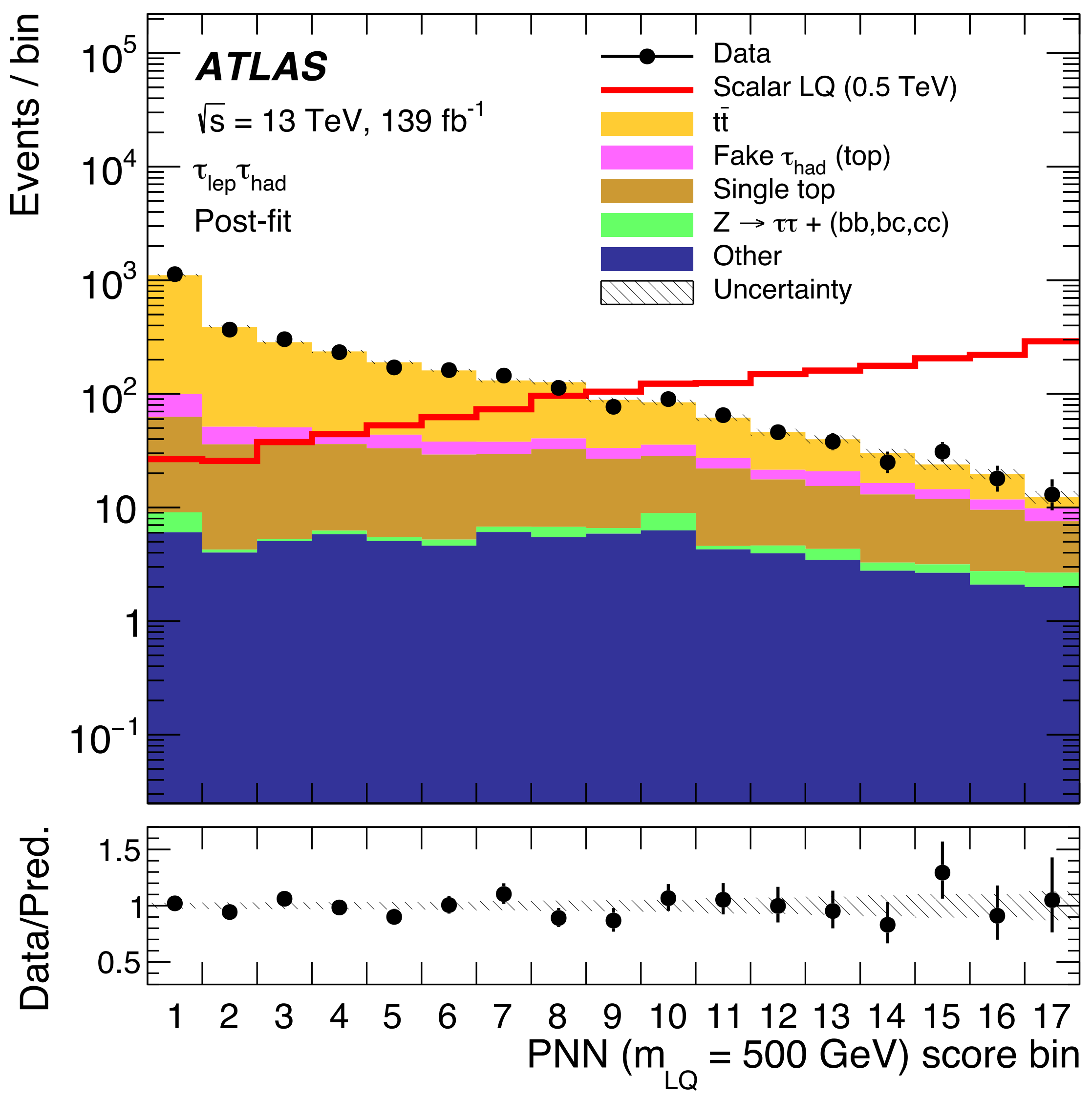
PNN is used to further separate signal and background.

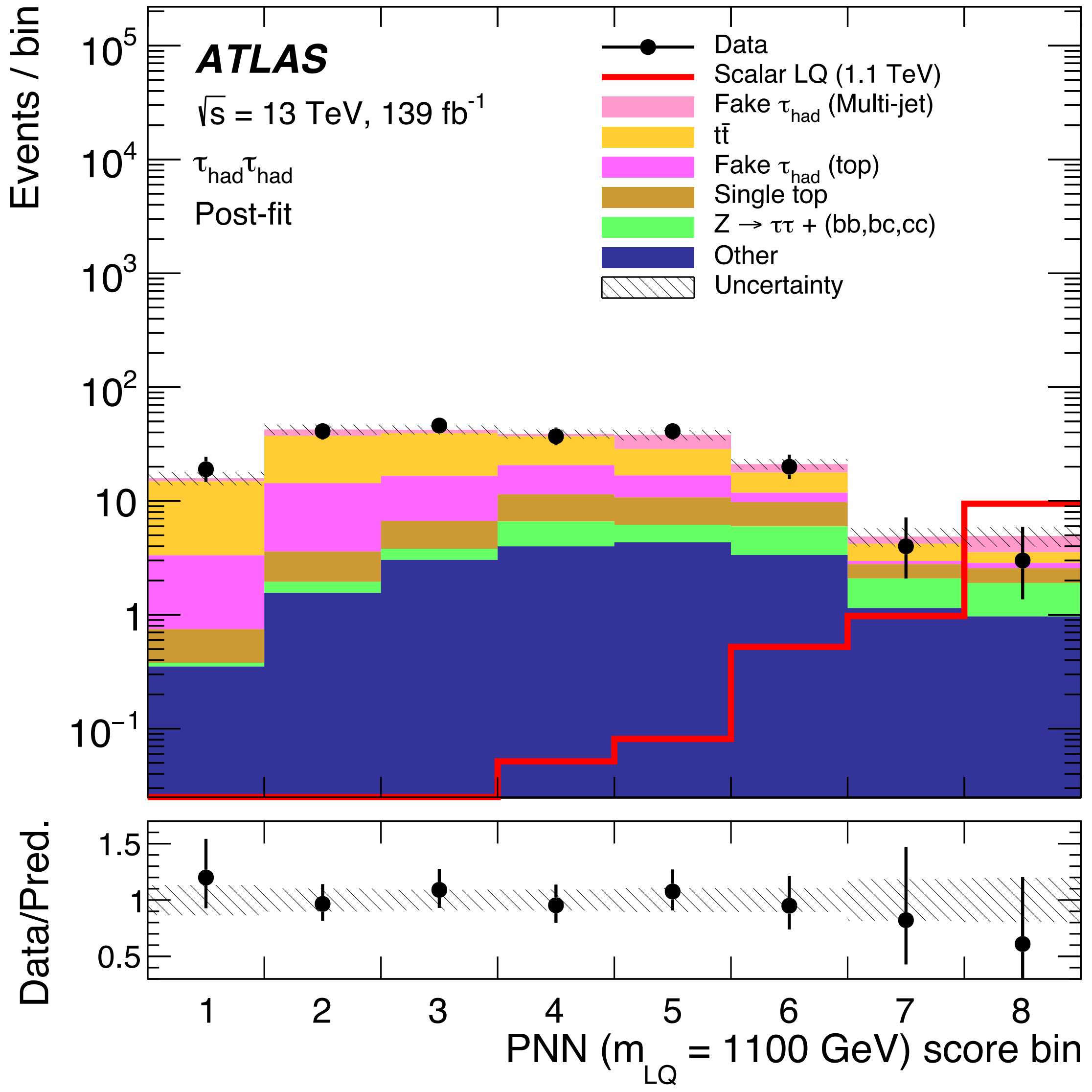
- Signal: each mass point of LQ
- BKG: ttbar and single top for both true and fake taus for training

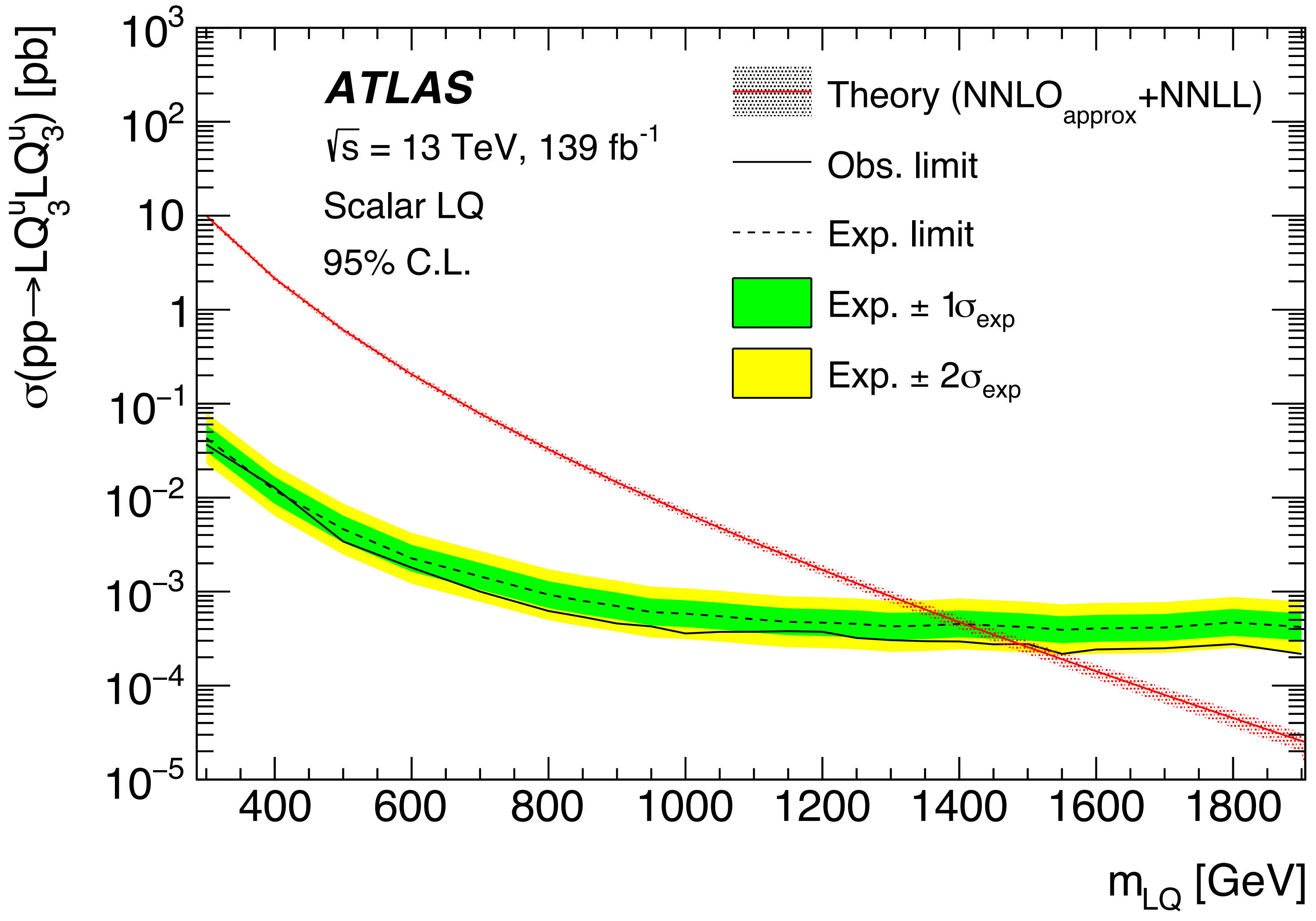
bτ combination is taken by minimizing difference of m(b, τ) between both pairs.

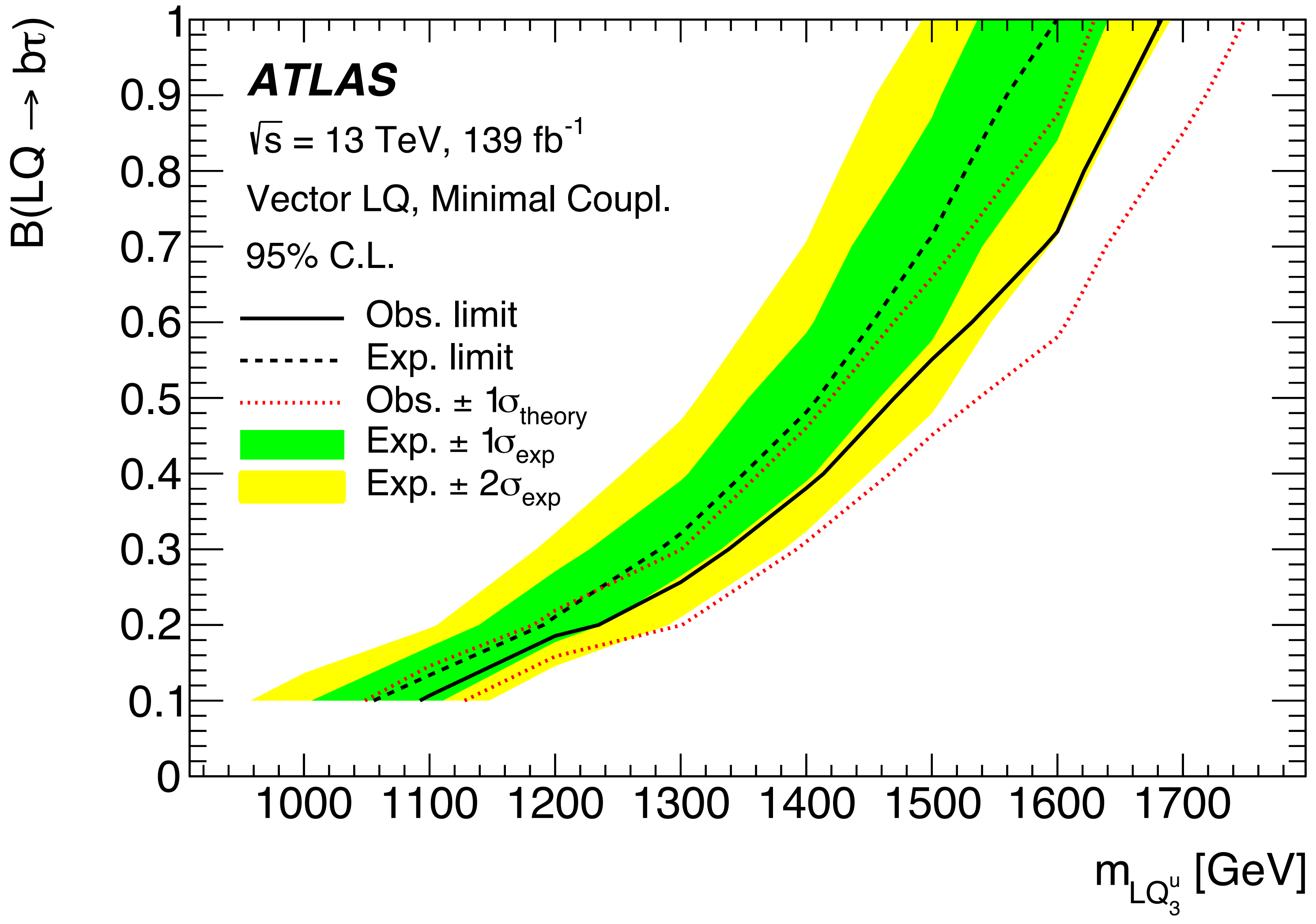
Binned profile likelihood fit is performed on PNN distribution

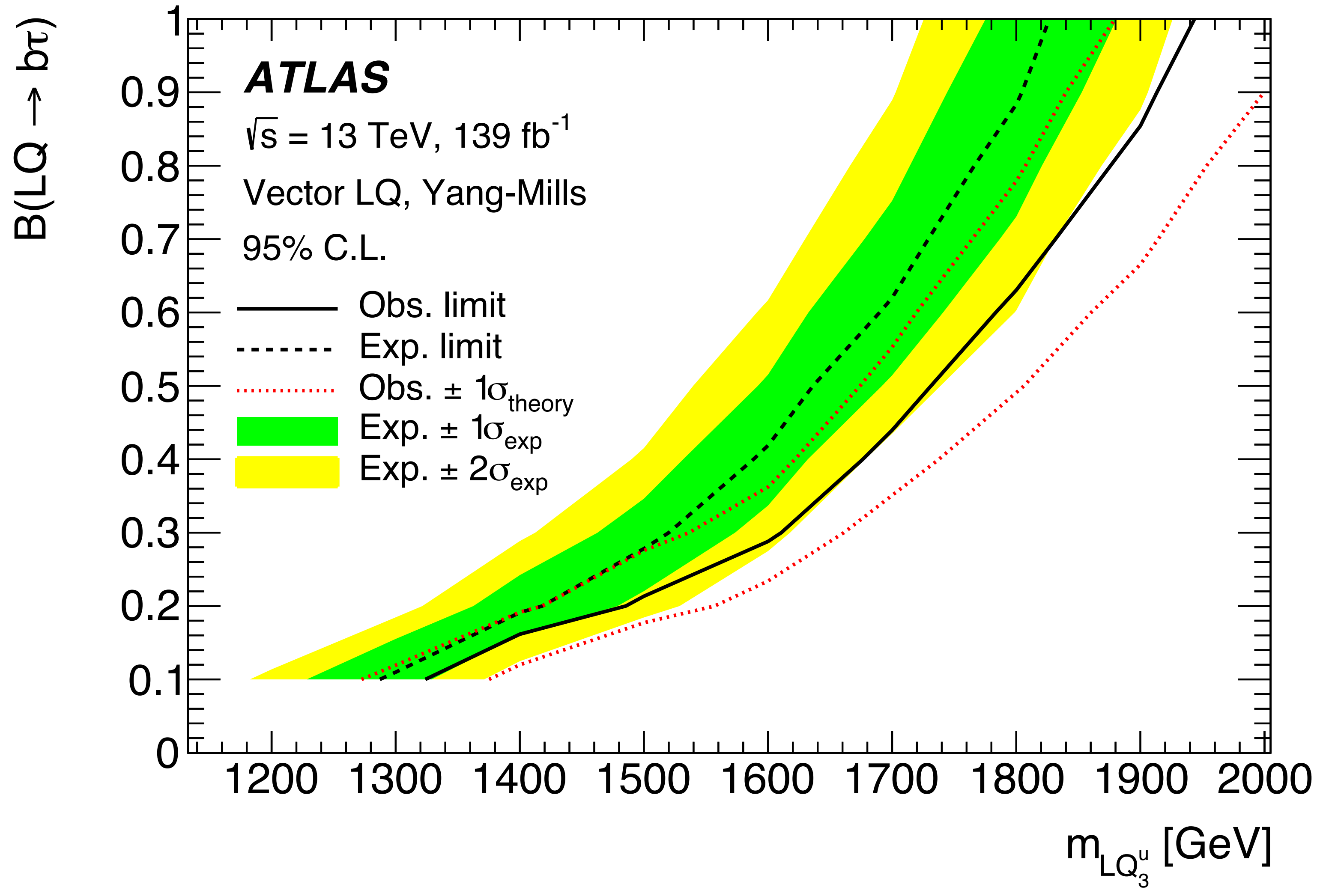
	Obs. limit [GeV]	Exp. limit [GeV]
Scalar LQ	1490	1410
Vector LQ (minimal-coupling)	1690	1600
Vector LQ (Yang–Mills)	1960	1840







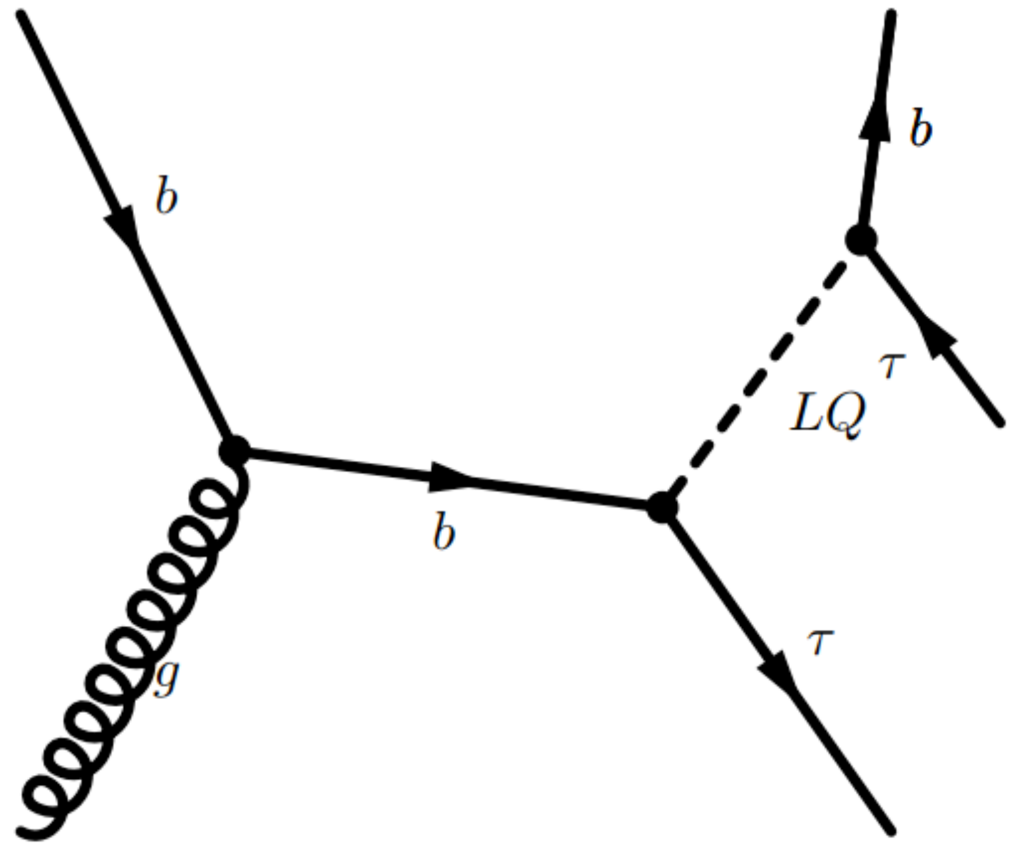


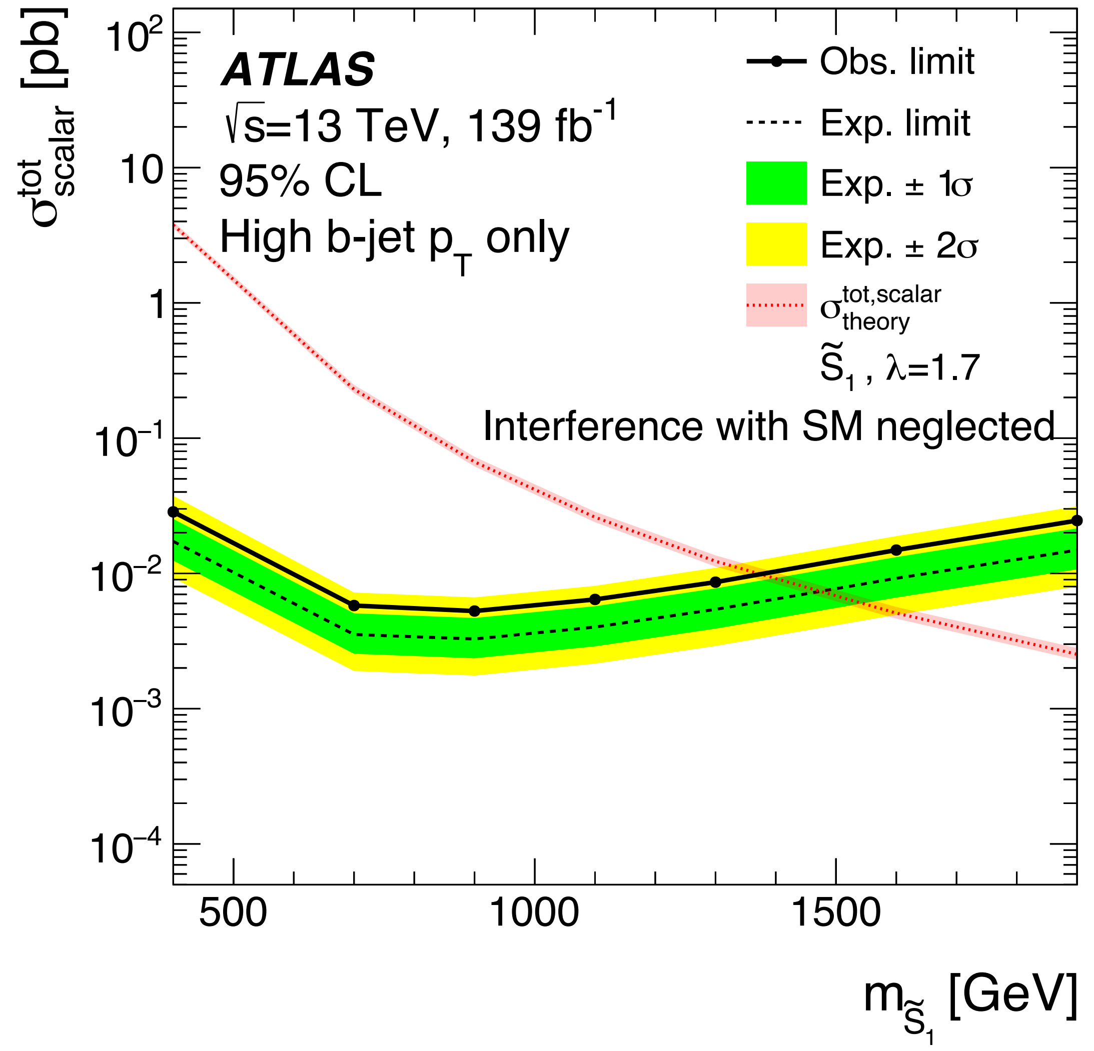


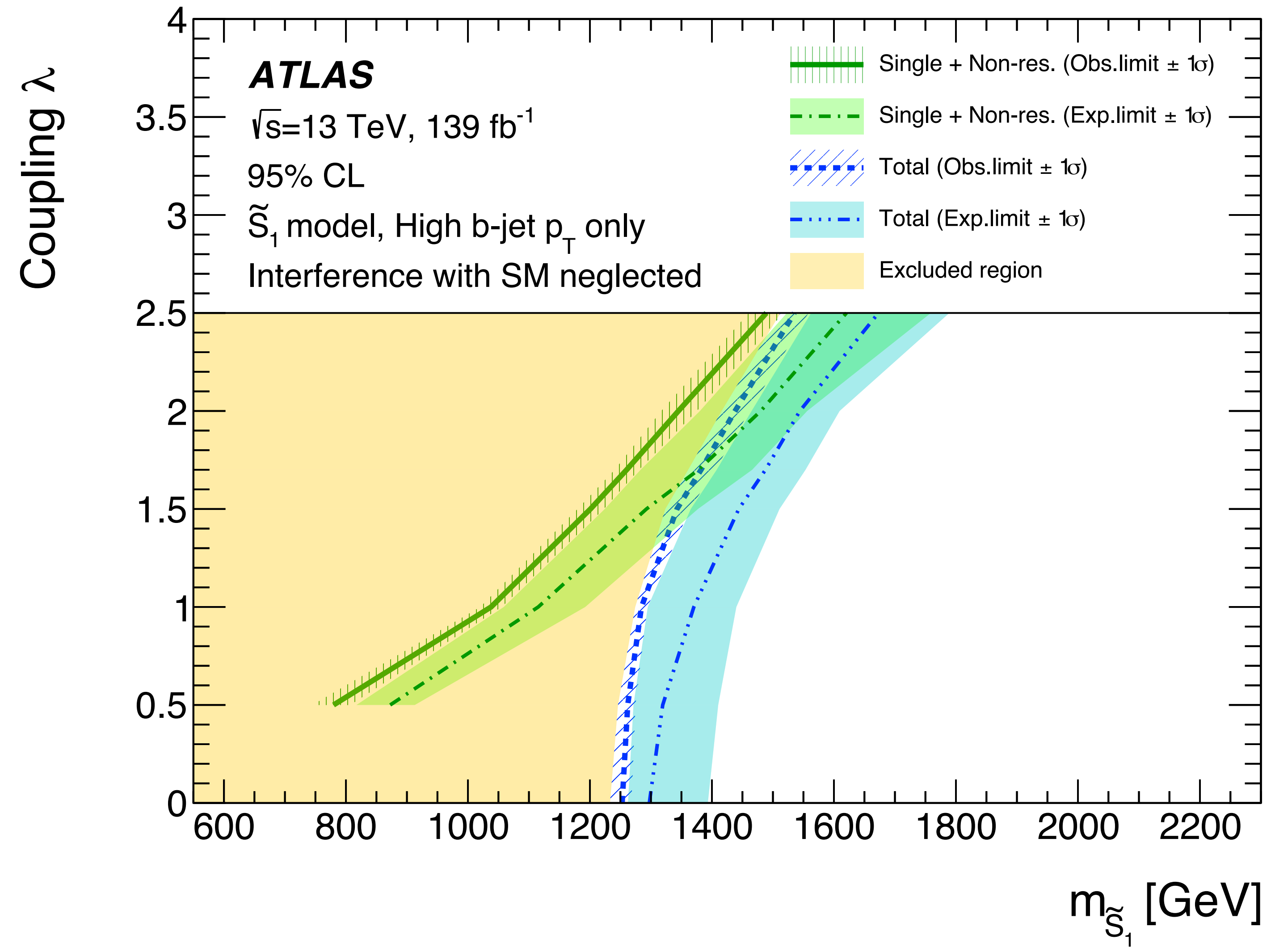
search for leptoquarks

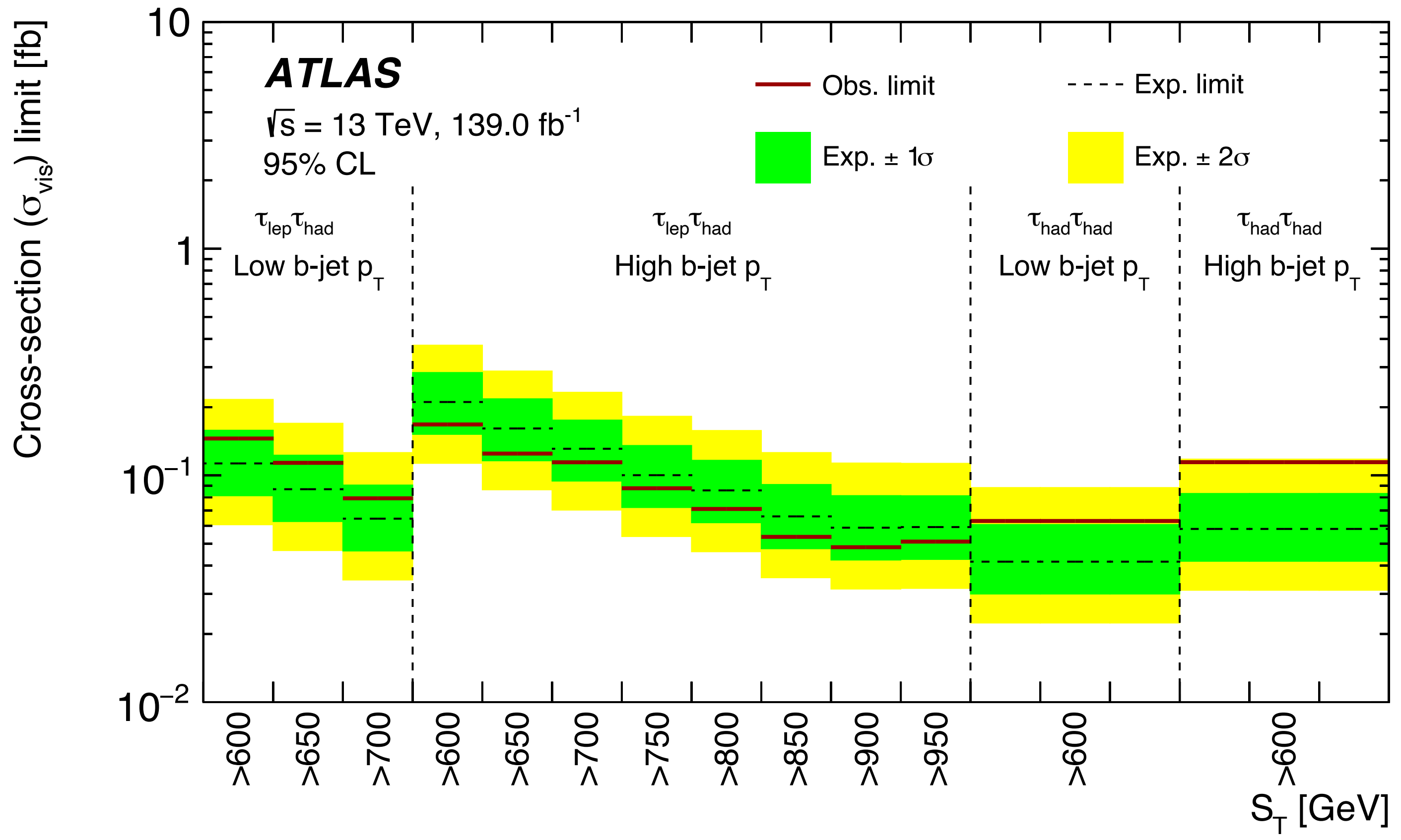
[tau btau Page Link]

Search for LQ in bττ final states, with all prod. modes included
Two channels: $\tau_{had}\,\tau_{had}$ and $\tau_{lep}\,\tau_{had}$
Divided in b-jets pT
Binned likelihood function in bins of sT
Simultaneous fit by combining
$\tau_{had}\,\tau_{had}$ and $\tau_{lep}\,\tau_{had}$ / high pT and low pT
No significant excess observed in data









Model	$\lambda = 1.0$	$\lambda = 1.7$	$\lambda = 2.5$
Single+non-resonant $U_1^{\rm YM}$ production	1.31 (1.43)	1.59 (1.73)	2.03 (2.27)
Single+non-resonant $U_1^{\rm MIN}$ production	1.15 (1.24)	1.45 (1.58)	1.98 (2.26)
Single+non-resonant+pair $U_1^{\rm YM}$ production	1.58 (1.64)	1.70 (1.81)	2.05 (2.28)
Single+non-resonant+pair $U_1^{\rm MIN}$ production	1.35 (1.44)	1.52 (1.63)	1.99 (2.26)
Single+non-resonant $\tilde{S}_1$ production	1.04 (1.11)	1.26 (1.38)	1.49 (1.62)
Single+non-resonant+pair $\tilde{S}_1$ production	1.28 (1.37)	1.38 (1.49)	1.53 (1.67)

Summary

- Recent studies of lepton flavour universality (LFU) violation on the ATLAS detector are shown
- No significant evidence of the BSM is observed
- Look forward to Run3 and HL-LHC with much more data!

Thank you !

Back up

Z boson -> eμ

Fit model

$$\mathcal{L} = \prod_{i=1}^{N} P_i = \prod_{i=1}^{N} \frac{\mu_i^{n_i} e^{-\mu_i}}{n_i!}$$

$$= \prod_{i=1}^{N} \frac{(N_{\text{sig}} \cdot F_{\text{sig}} + N_{\tau\tau} \cdot F_{\tau\tau} + N_{\mu\mu} \cdot F_{\mu\mu} + N_{\text{cmb}} \cdot F_{\text{cmb}})_i^{n_i} e^{-(N_{\text{sig}} \cdot F_{\text{sig}} + N_{\tau\tau} \cdot F_{\tau\tau} + N_{\mu\mu} \cdot F_{\mu\mu} + N_{\text{cmb}} \cdot F_{\text{cmb}})_i}}{n_i!},$$

$$Br(Z \rightarrow e\mu) = \frac{N_{signal}}{\varepsilon_{sig} \times N_Z} \quad N_Z = \sqrt{\left(\frac{N_{ee}^{Data}}{\varepsilon_{ee} Br(Z \rightarrow ee)} \times \frac{N_{\mu\mu}^{Data}}{\varepsilon_{\mu\mu} Br(Z \rightarrow \mu\mu)}\right)}$$

	Best-fit contribution in mass window	
Background	[70, 110] GeV	[85, 95] GeV
$Z \rightarrow \tau\tau$	13716 ± 185	951 ± 13
$Z \rightarrow \mu\mu$	1557 ± 209	533 ± 72
Non-resonant	4105 ± 259	1075 ± 68

Three kinds of **systematic uncertainties:**

- From experimental object: jet, electron, muon, MET, pileup, btag
    - Affect the $Z \rightarrow e\mu/ee/\mu\mu$ efficiency(cancel each other in the ratio) and the signal/background shape
- Statistical fluctuation due to the limit size of MC sample for each bin from signal/background model template
    - Affect the signal&background shape
- Other uncertainties:
    - Uncertainties from reweighting: to cancel theory/model uncertainties from the ratio
    - Uncertainties from Z boson number
    - From MC, <0.1%

Source of uncertainty	Degradation of $\mathcal{B}^{95\%\text{CL}}(Z \rightarrow e\mu)$
Statistical uncertainty in MC samples	9.5%
$Z \rightarrow \tau\tau$	4.7%
$Z \rightarrow \mu\mu$	6.1%
All other sources	2.4%
Jet energy scale and resolution	1.2%
Pileup	1.2%
Electron energy scale and resolution	0.8%
Lepton efficiency	0.7%
b-tagging	0.6%
Muon resolution and bias correction	0.6%

Z boson -> eτ or $\mu\tau$ lep channel

Fake Factor method

Estimate fakes of the subleading-pT ℓ2 with fake factor method in same-sign region

Pass or fail isolation (FCTight) for ℓ2 (ℓ1 always required to pass isolation)

NN:

- Trained against the dominant backgrounds: Z → τ τ , di-boson, and tt̄+single-t
- Combining individual output scores to a single score used in the fitting
- Low-level variables: four-momenta of the two leptons and E miss T
- High-level variables: m(e, μ), mcoll(e, μ), Δα(e, μ)

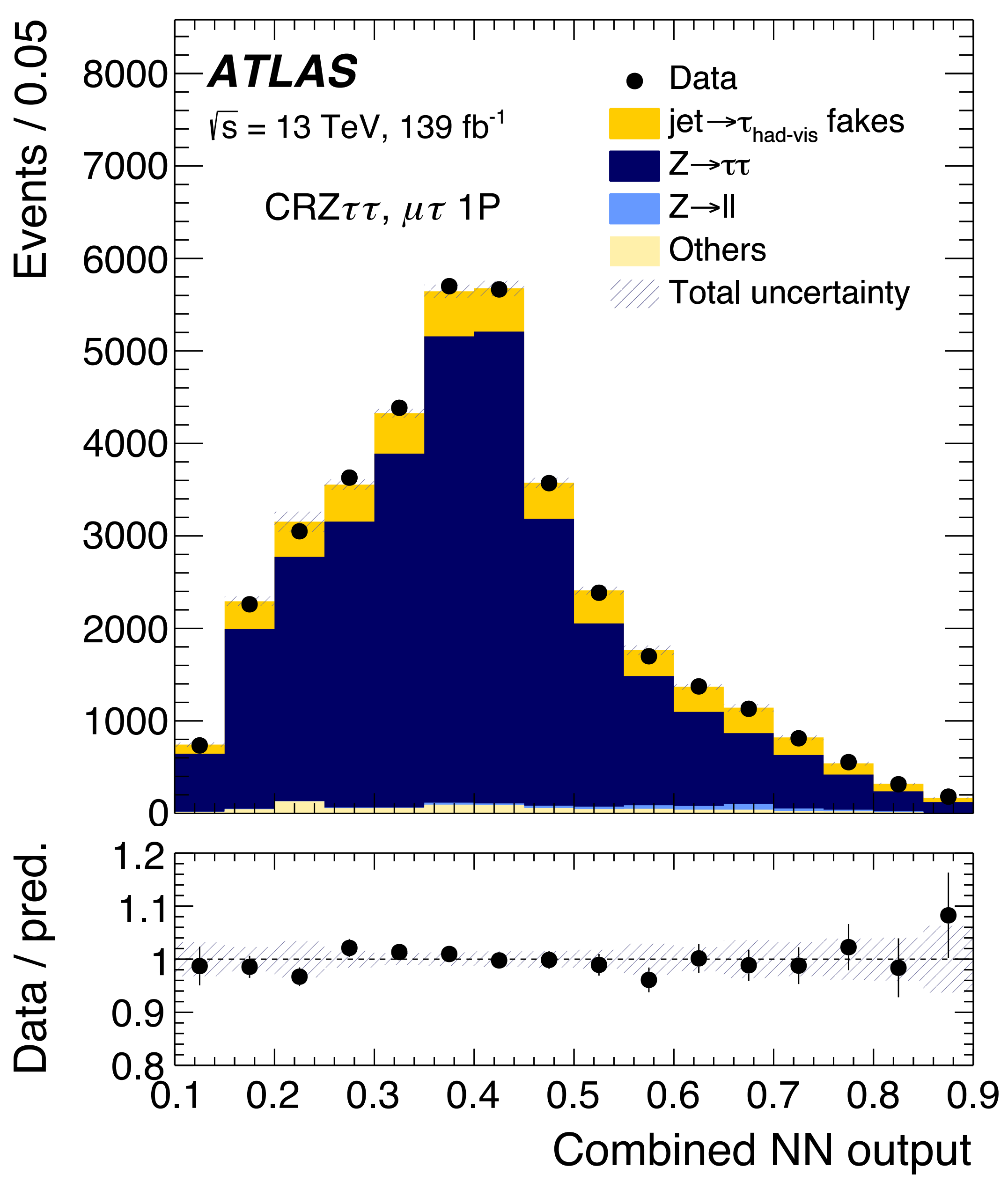
$$\text{combined NN output} = 1 - \sqrt{\frac{1}{3}\sum_{i=1}^{3}(1-\text{NN}_i)^2}\,.$$

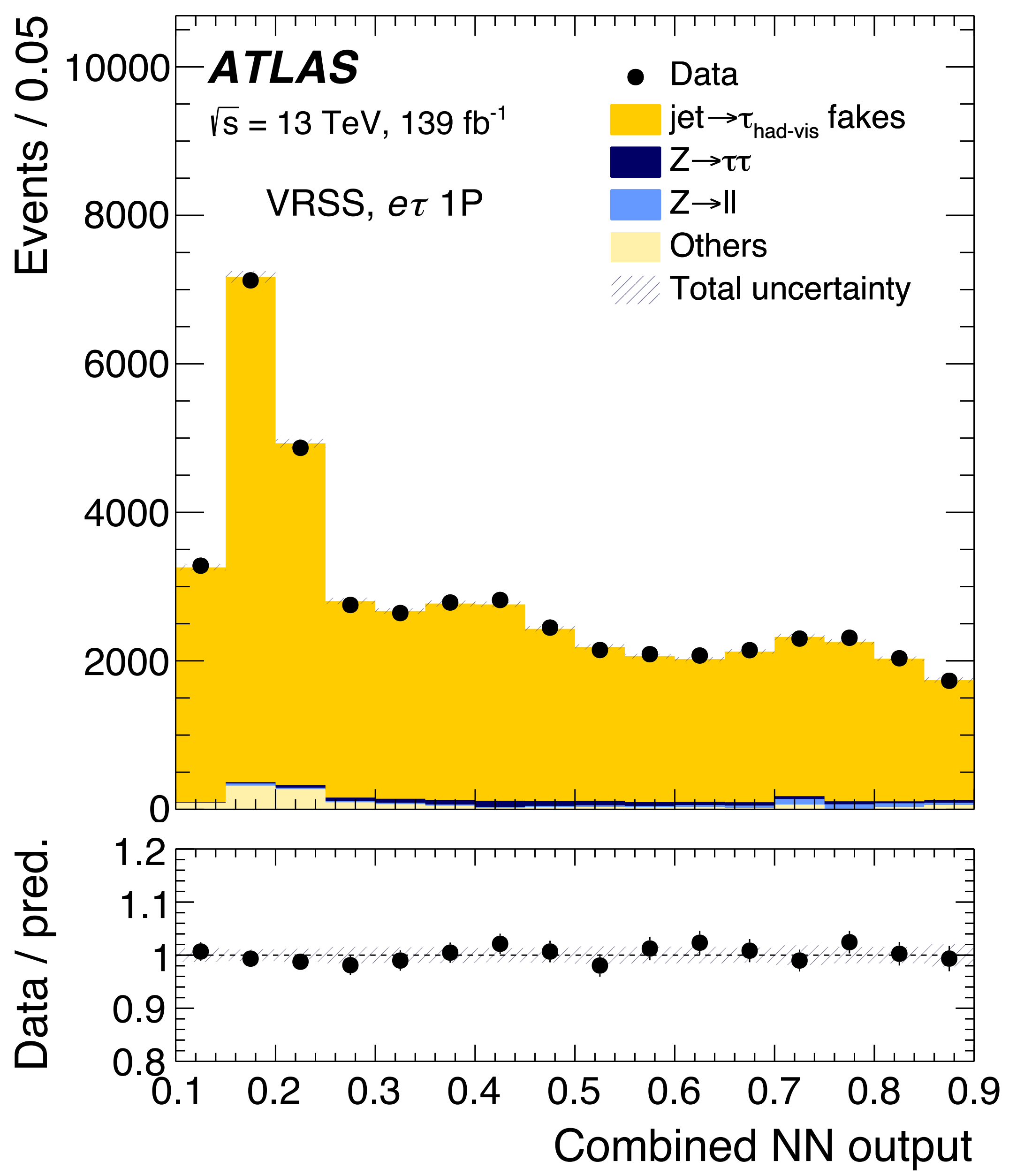
Selection criterion	Purpose
Exactly two isolated light leptons (ℓ_0, ℓ_1) with opposite electric charge and different flavor (e or μ); $p_T(\ell_0) > p_T(\ell_1)$	Select events consistent with signal decays.
No $\tau_{\text{had-vis}}$ candidate	Complementarity to the $\ell\tau_{\text{had}}$ channel.
Transverse mass[1] $m_T(\ell_1, \boldsymbol{E}_T^{\text{miss}}) < 35$ GeV $\lvert\Delta\phi(\ell_0, \boldsymbol{E}_T^{\text{miss}})\rvert > 1$ rad No b-tagged jets (using the 77% efficiency working point)	Reject top-quark and diboson events.
Invariant mass of the ℓ_0–ℓ_1 pair $m(\ell_0, \ell_1) > 40$ GeV	Reject events incompatible with Z-boson decays.
Neural network (optimized for signal vs. $Z \to \tau\tau$) output > 0.2	Complementarity to the CRZ$\tau\tau$ region.
In $\mu\tau_e$ channel: $p_T^{\text{track}}(e)/E_T^{\text{cluster}}(e) < 1.1$	Reject $Z \to \mu\mu$ events.

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 charged leptons	±0.4	±0.4
$\boldsymbol{E}_T^{\text{miss}}$	±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

Z boson -> eτ or $\mu\tau$ had channel

- Five NN classifiers trained in each channel for signal vs the major backgrounds:
  - 1P $Z \to \tau\tau$, 1P W+jets (fakes), 1P $Z \to \ell\ell$
  - 3P $Z \to \tau\tau$, 3P W+jets (fakes)
- Training samples
  - MC samples in SR without $m$vis and NN output cuts
  - For samples with real taus ($Z \to \tau\tau$ and signal), tau ID is relaxed (Tight $\to$ Loose)
- Inputs: Mix of low- and high-level kinematic variables
  - Low-level: 4-momenta of ℓ, τ and ET miss (boosted and rotated to remove symmetries)
  - High-level: $m$vis, $m$coll, $\Delta\alpha$ (and m ℓ, τ track for the $Z \to \ell\ell$ classifier)
- Final discriminant created by combining the different classifier outputs
  - Outputs of different classifiers are weighted differently ($w$bkg's)
  - Improve separation of different backgrounds along the NN output : 1. better handle of each background. 2. lower post-fit uncertainty 3.better sensitivity
  - Optimised by a grid search that looks for best expected limit
- Modelling of the NN output distribution
  - Validated in CRZ$\tau\tau$ (for $Z \to \tau\tau$) and VRSS (for fakes) [VRSS = SR but with same-sign $\ell\tau$ pair (renamed from SS SR)]





Z boson -> eτ or $\mu\tau$ had channel

The fake factor (FF) method:

○ Process-specific fake factors ($F p$) derived in four fakes-enriched regions (FR)

○ W+jets ; pure-QCD multijet ; $Z \rightarrow \ell\ell$ +jets ; ttћ(in descending order of importance in SR)

○ $F p$ is the ratio of events passing τ ID (Tight) to those failing (Loose but not Tight)

○ The final (region-specific) fake factor (Fr) is the weighted average of F

Main selection criteria	**Purpose**
At least one $\tau_{\text{had-vis}}$ candidate Exactly one isolated light lepton Opposite-sign charged ℓ–$\tau_{\text{had-vis}}$ pair	Select events with ℓ–τ pair candidate
$m_{\text{T}}(\tau_{\text{had-vis}}, E_{\text{T}}^{\text{miss}}) < 35$ GeV	Reject $Z \to \tau\tau$ and W+jets events
$m_{\text{vis}}(\ell, \tau_{\text{had-vis}}) > 60$ GeV	Invariant mass of the ℓ–$\tau_{\text{had-vis}}$ pair. Reject events incompatible with ℓ–τ pairs from Z-boson decays
No tagged b-hadron jets	Reject $t\bar{t}$ and single-top-quark events
Combined neural network output > 0.1 (0.2) for events with 1P (3P) $\tau_{\text{had-vis}}$ candidates	Reject background-like events
NN (optimized for signal versus $Z \to \ell\ell$) output > 0.2	Ensure orthogonal region for correcting $Z \to \ell\ell$ simulation (ℓ misidentified as 1P $\tau_{\text{had-vis}}$ candidate, see Section **??**)

Fit Model

○ Four unconstrained normalisation factors (NF):

○ μS : signal strength modifier ∝ BR $Z \rightarrow \ell\tau$ (parameter of interest)

○ μ Z : normalisation of Z samples with real $\ell\tau$had final state ($Z \rightarrow \tau\tau$ and $Z \rightarrow \ell\tau$)

○ μ 1P fakes /μ 3P fakes : normalisation of 1-prong / 3-prong fakes

○ Fit Regions:

○ SR: binned in combined NN output score ○ Low-score bins: constrain backgrounds ○ High-score bins: constrain signal

○ CRZ$\tau\tau$: binned in $m$coll ○ Helps constrain normalisations and TES systematics

○ Independent fits for $e\tau$ and $\mu\tau$

○ 1P and 3P events are separated but fitted simultaneously

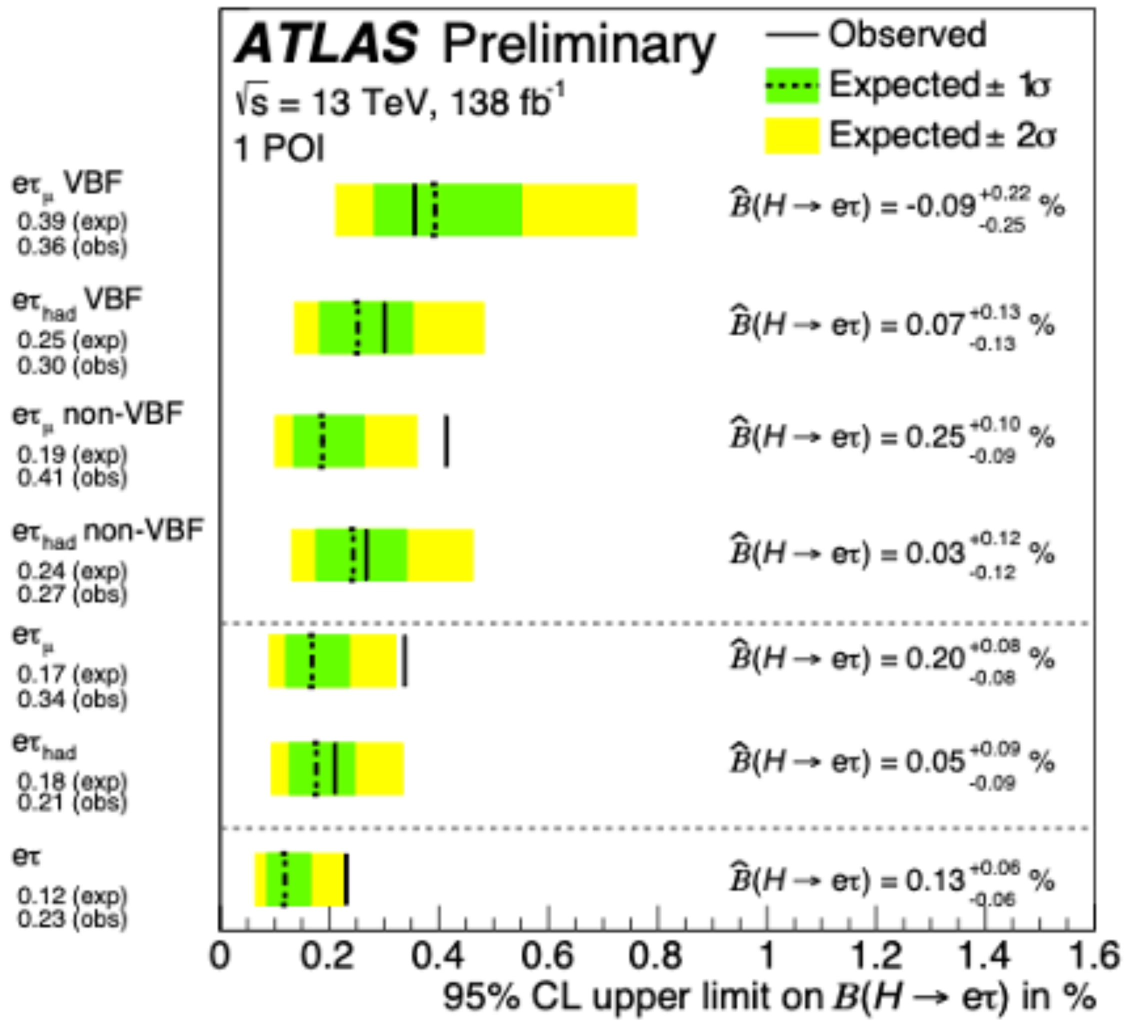
	Uncertainty on $\mathcal{B}(Z \to \ell\tau)$ [$\times 10^{-6}$]	
Source of uncertainty	$\boldsymbol{e\tau}$	$\boldsymbol{\mu\tau}$
Statistical	±3.5	±2.8
Systematic	±2.3	±1.6
τ leptons	±1.9	±1.5
Energy calibration	±1.3	±1.4
Jet rejection	±0.3	±0.3
Electron rejection	±1.3	
Light leptons	±0.4	±0.1
$E_{\text{T}}^{\text{miss}}$, 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

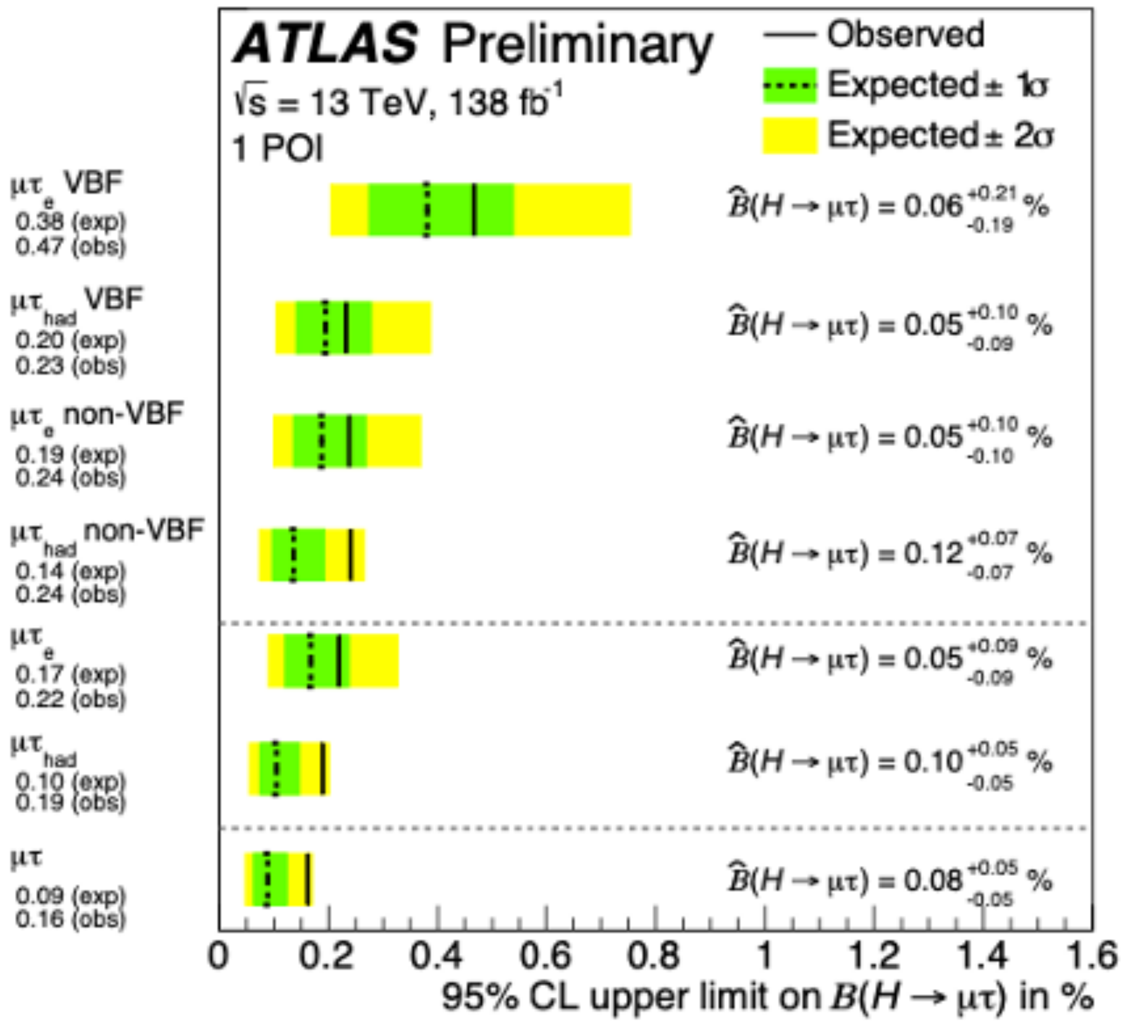
Higgs boson -> eτ or $\mu\tau$

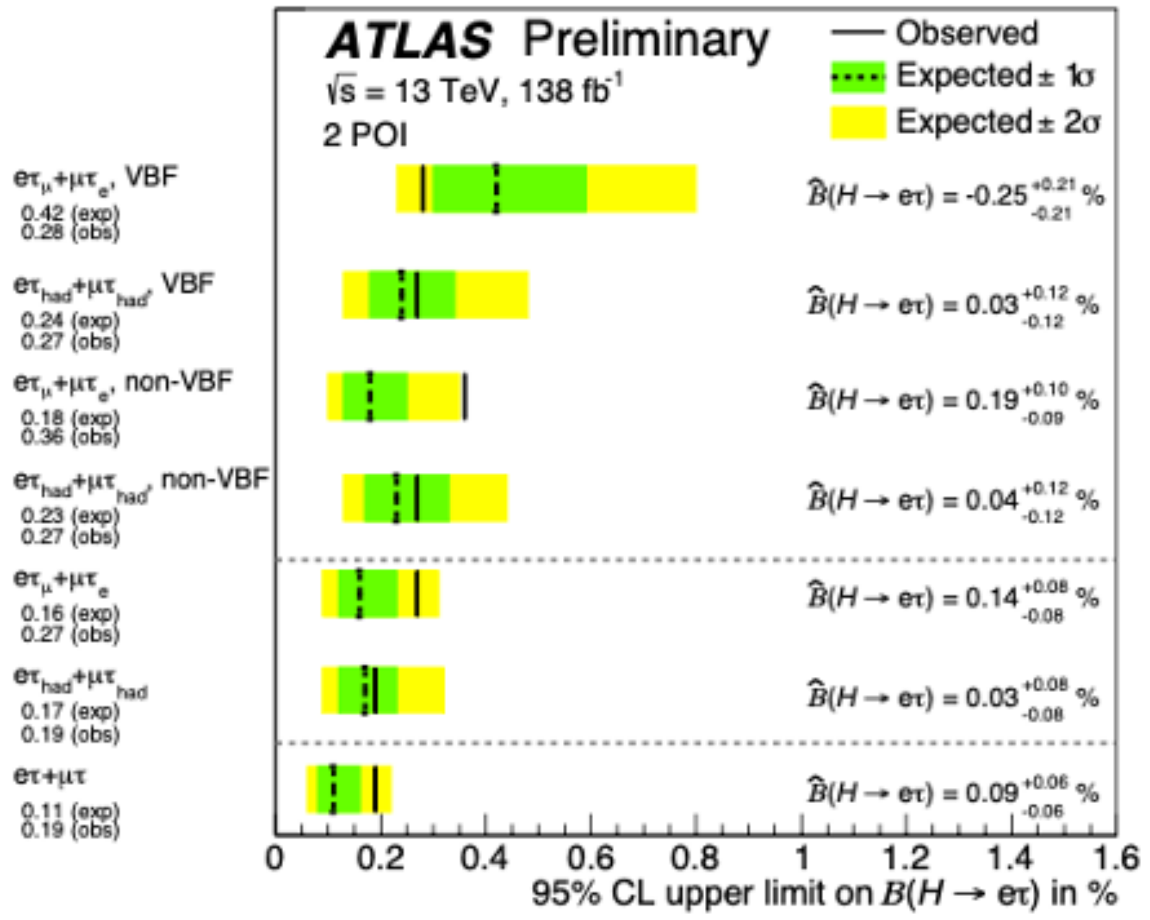
Selection	$\ell\tau_{\ell'}$	$\ell\tau_{\text{had}}$
Baseline	exactly $1e$ and 1μ, OS τ_{had}-veto b-veto $p_T^{\ell_1} > 45\,(35)$ GeV MC-template (Symmetry method) $p_T^{\ell_2} > 15$ GeV $30\text{ GeV} < m_{\ell_1\ell_2} < 150$ GeV $0.2 < p_T^{\text{track}}(\ell_2 = e)/p_T^{\text{cluster}}(\ell_2 = e) < 1.25$ (MC-template) track d_0 significance requirement (see text) $\lvert z_0 \sin\theta\rvert < 0.5$ mm	exactly 1ℓ and $1\tau_{\text{had-vis}}$, OS τ_{had} Tight ID Medium eBDT ($e\tau_{\text{had}}$) b-veto $p_T^{\ell} > 27.3$ GeV $p_T^{\tau_{\text{had-vis}}} > 25$ GeV, $\lvert\eta^{\tau_{\text{had-vis}}}\rvert < 2.4$ $\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_T^{\text{miss}}) > -0.35$ $\lvert\Delta\eta(\ell, \tau_{\text{had-vis}})\rvert < 2$
VBF	*Baseline* ≥ 2 jets, $p_T^{j_1} > 40$ GeV, $p_T^{j_2} > 30$ GeV $\lvert\Delta\eta_{jj}\rvert > 3$, $m_{jj} > 400$ GeV	
non-VBF	*Baseline* plus fail *VBF* categorisation – –	 veto events if $90 < m_{\text{vis}}(e, \tau_{\text{had-vis}}) < 100$ GeV

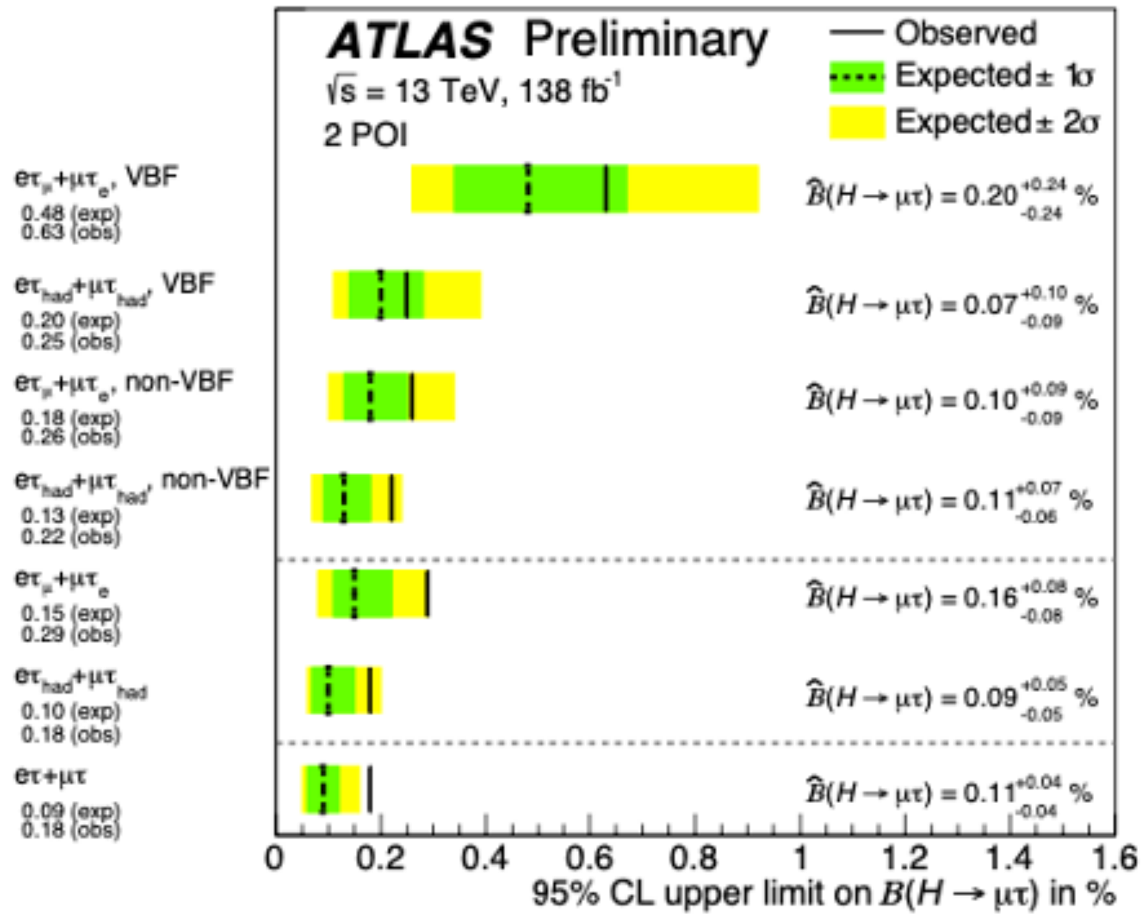
- VBF and non-VBF categories as well as lep-lep and lep-had channels are mutually exclusive
- Selection is as similar as possible between MC-template and Symmetry, differences related to the symmetry assumption and definition of CRs.

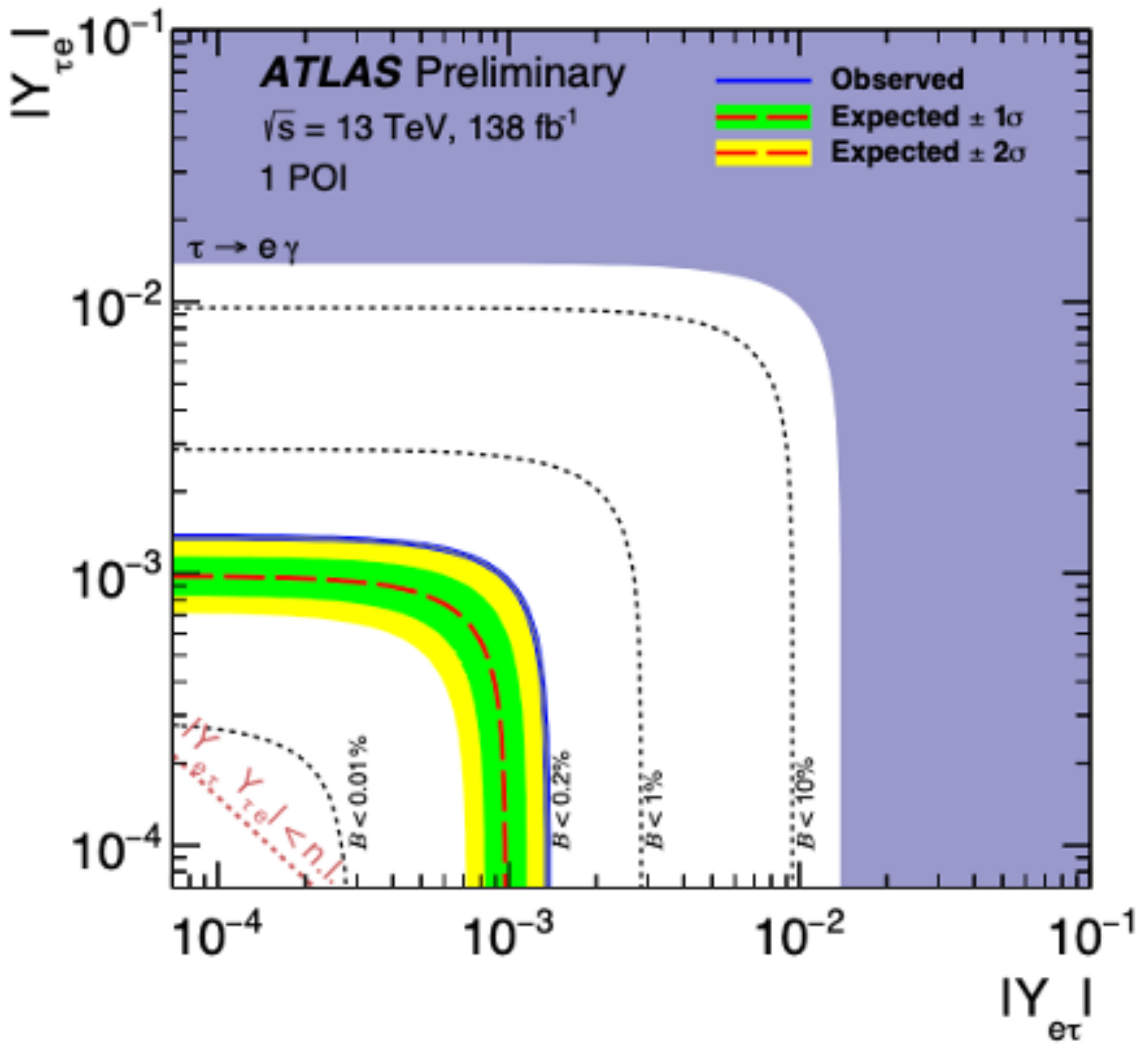
Higgs boson -> eτ or $\mu\tau$

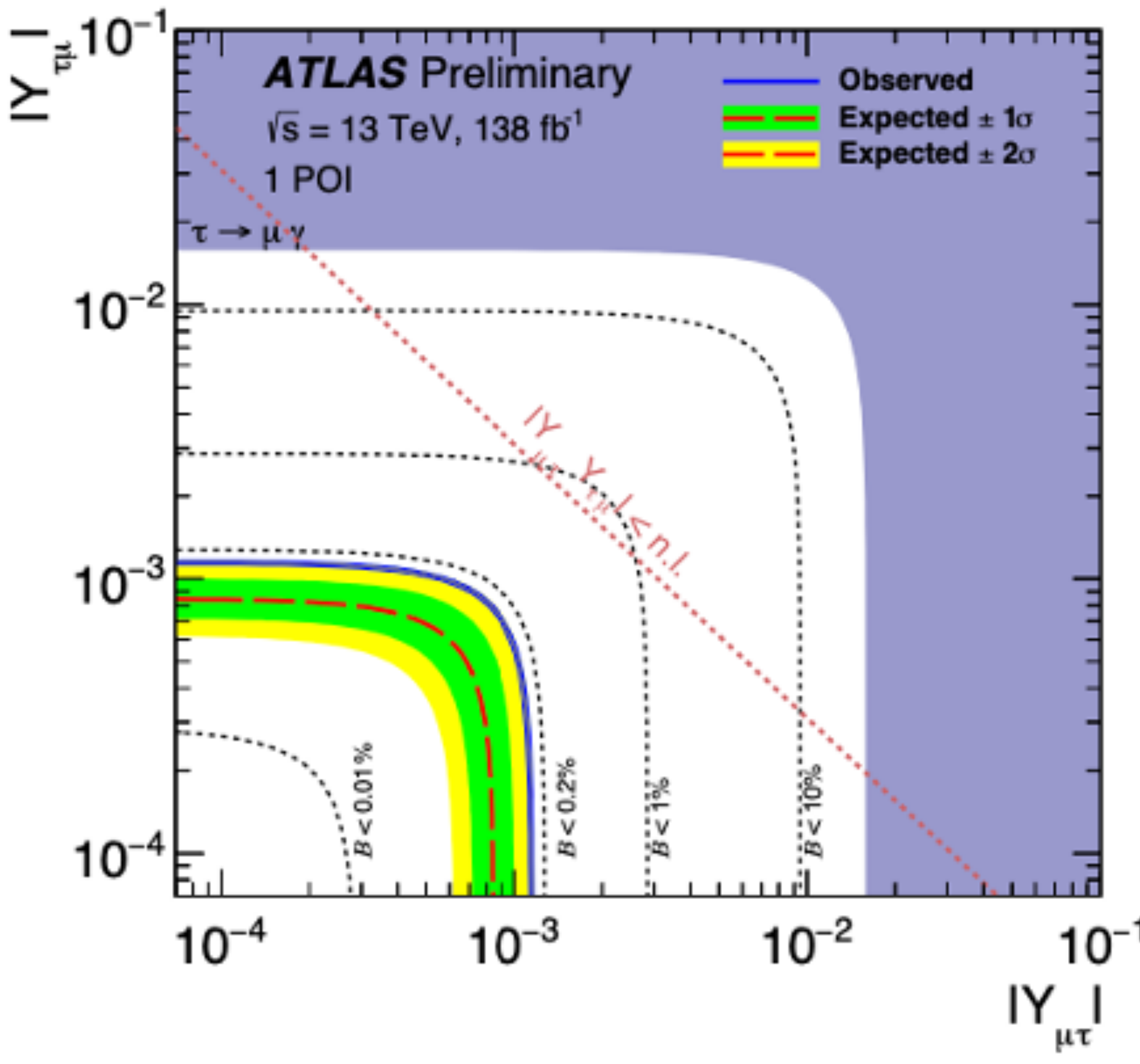


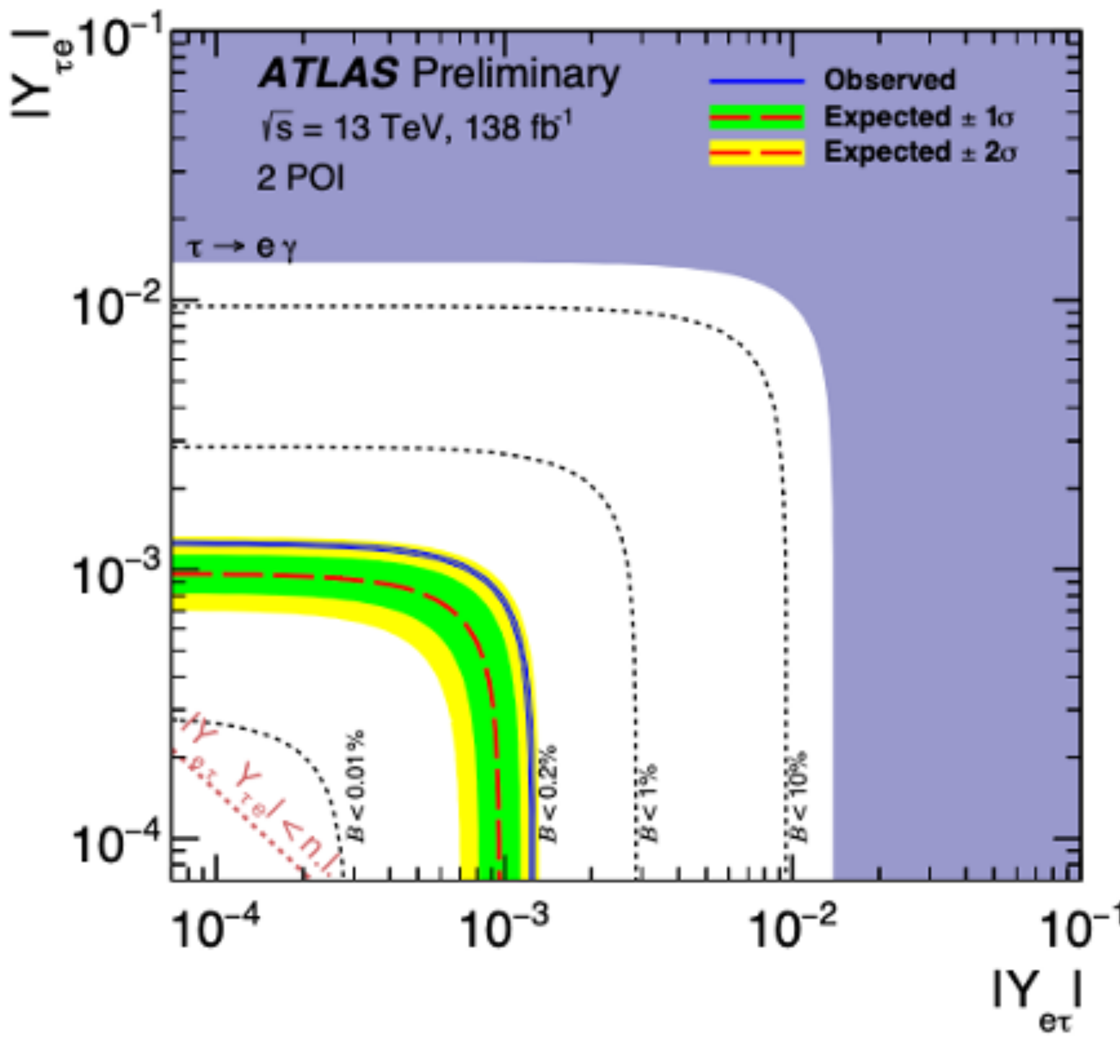


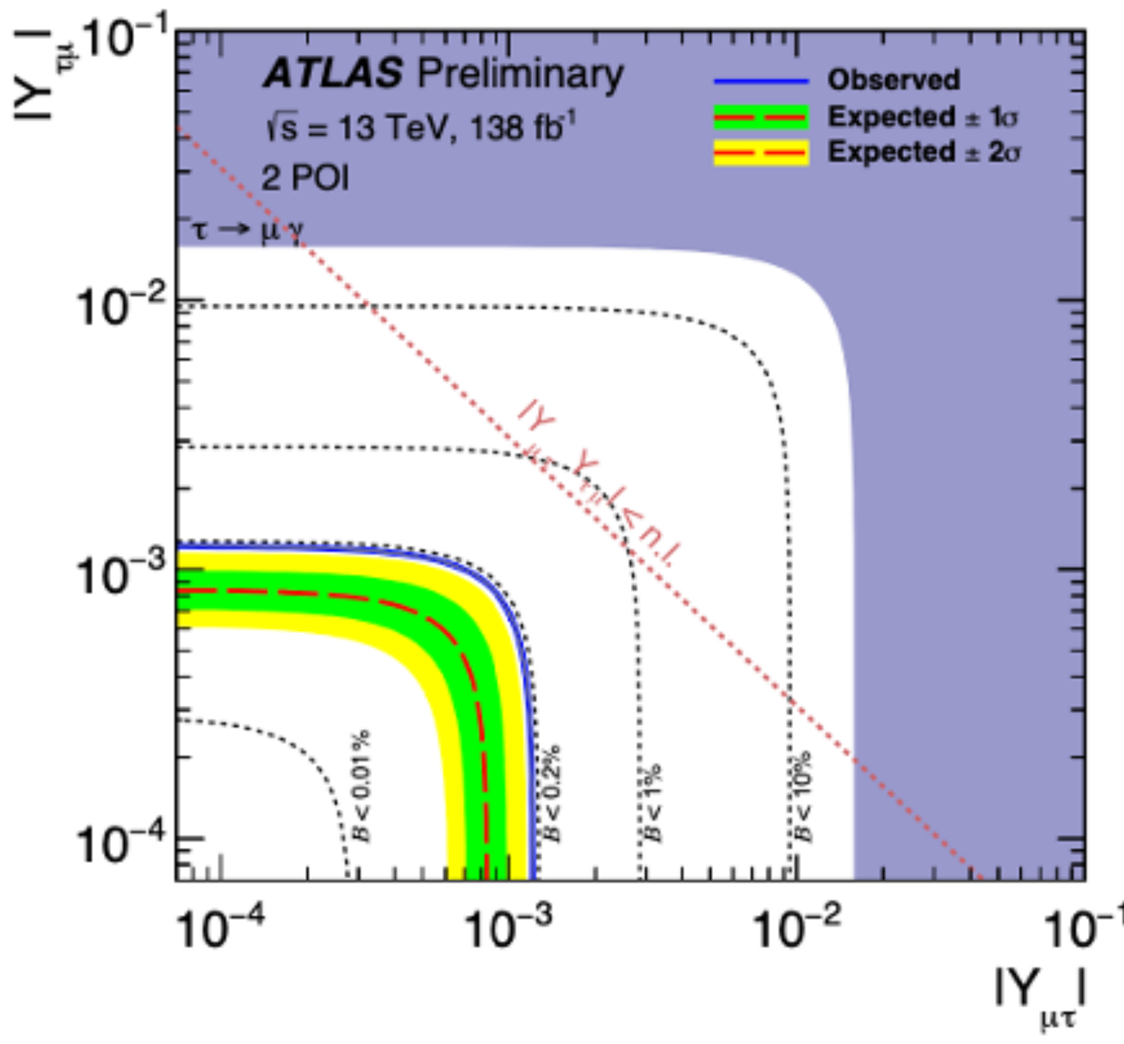












$$|Y_{\ell\tau}|^2 + |Y_{\tau\ell}|^2 = \frac{8\pi}{m_H}\frac{\mathcal{B}(H\to\ell\tau)}{1-\mathcal{B}(H\to\ell\tau)}\Gamma_H(\mathrm{SM})$$

high-mass dilepton final states

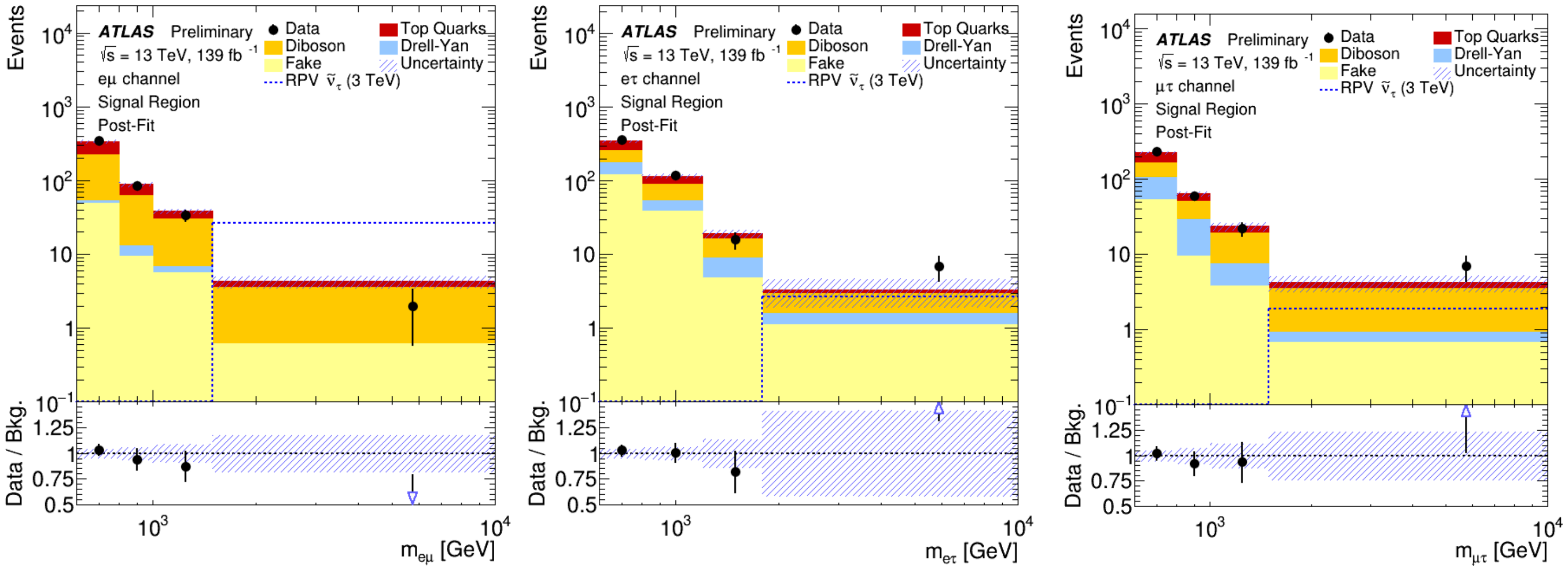
Matrix Method

$$\begin{bmatrix} N_{\mathrm{TT}} \\ N_{\mathrm{LT}} \\ N_{\mathrm{TL}} \\ N_{\mathrm{LL}} \end{bmatrix} = \begin{bmatrix} r_e r_\mu & f_e r_\mu & r_e f_\mu & f_e f_\mu \\ (1-r_e) r_\mu & (1-f_e) r_\mu & (1-r_e) f_\mu & (1-f_e) f_\mu \\ r_e(1-r_\mu) & f_e(1-r_\mu) & r_e(1-f_\mu) & f_e(1-f_\mu) \\ (1-r_e)(1-r_\mu) & (1-f_e)(1-r_\mu) & (1-r_e)(1-f_\mu) & (1-f_e)(1-f_\mu) \end{bmatrix} \begin{bmatrix} N_{\mathrm{RR}} \\ N_{\mathrm{FR}} \\ N_{\mathrm{RF}} \\ N_{\mathrm{FF}} \end{bmatrix}$$

- The goal of the matrix method is to estimate the fraction of events in the data sample with a “real” electron and a “real” muon (N_{RR}), events with a jet faking an electron (“fake” electron) and a “fake” muon (N_{FF}), and events with one “real” lepton and one “fake” lepton (N_{RF} and N_{FR}).
- Two selection criteria are defined: “Tight” and “Loose” for muons (electrons) based on their lepton quality (identification and isolation) respectively.
- “*r*” refers to the probability of a “Loose” lepton matched to a true lepton to pass the “Tight” quality selection, defined as the “real efficiency”. It is evaluated from $Z \to \mathrm{ll}'$ simulated events. The “ f ” refers to the probability that a jet is misidentified as a “Tight” quality lepton, so called “fake rate” which is determined in a multijet-enriched data sample.

high-mass dilepton final states

Source of uncertainty (in percentage)	Impact on observed $\mu_{RPV}^{e\mu}$	Impact on observed $\mu_{RPV}^{e\tau}$	Impact on observed $\mu_{RPV}^{\mu\tau}$
Flavor tagging	2.1	<0.1	0.11
fake backgrounds	0.57	3.2	9.7
Jet and E_T^{miss}	2.1	0.75	0.81
Electrons	2.2	0.85	-
Muons	2.8	-	4.4
τ-leptons	-	9.7	11
Other (luminosity, JVT, pile-up)	0.59	0.39	0.66
Background modelling	9.6	2.1	7.3
Top and Diboson normalisations	8.7	1.6	1.8
Signal statistics	0.36	0.66	0.76
Background statistics	28	9.6	15
Total systematic uncertainty	32	14	23
Data statistics	53	48	71
Total	62	50	74



(a) (b) (c)

unexpected asymmetry of eμ

S is the so-called 'object-based pTmiss significance' It is a dimensionless measure of the degree to which the apparent missing transverse momentum in the event is 'real' (i.e. attributable to momentum carried away by invisible particles) rather than due to object mismeasurement or pile-up.

$$\mathcal{S}^2 = \frac{\left|\boldsymbol{E}_{\mathrm{T}}^{\mathrm{miss}}\right|^2}{\sigma_{\mathrm{L}}^2\left(1-\rho_{\mathrm{LT}}^2\right)}.$$

$$M_{\mathrm{T2}} \equiv \min_{\vec{a}+\vec{b}=\vec{p}_{\mathrm{T}}^{\mathrm{miss}}} \max\left[m_{\mathrm{T}}(e,\vec{a}), m_{\mathrm{T}}(\mu,\vec{b})\right]$$

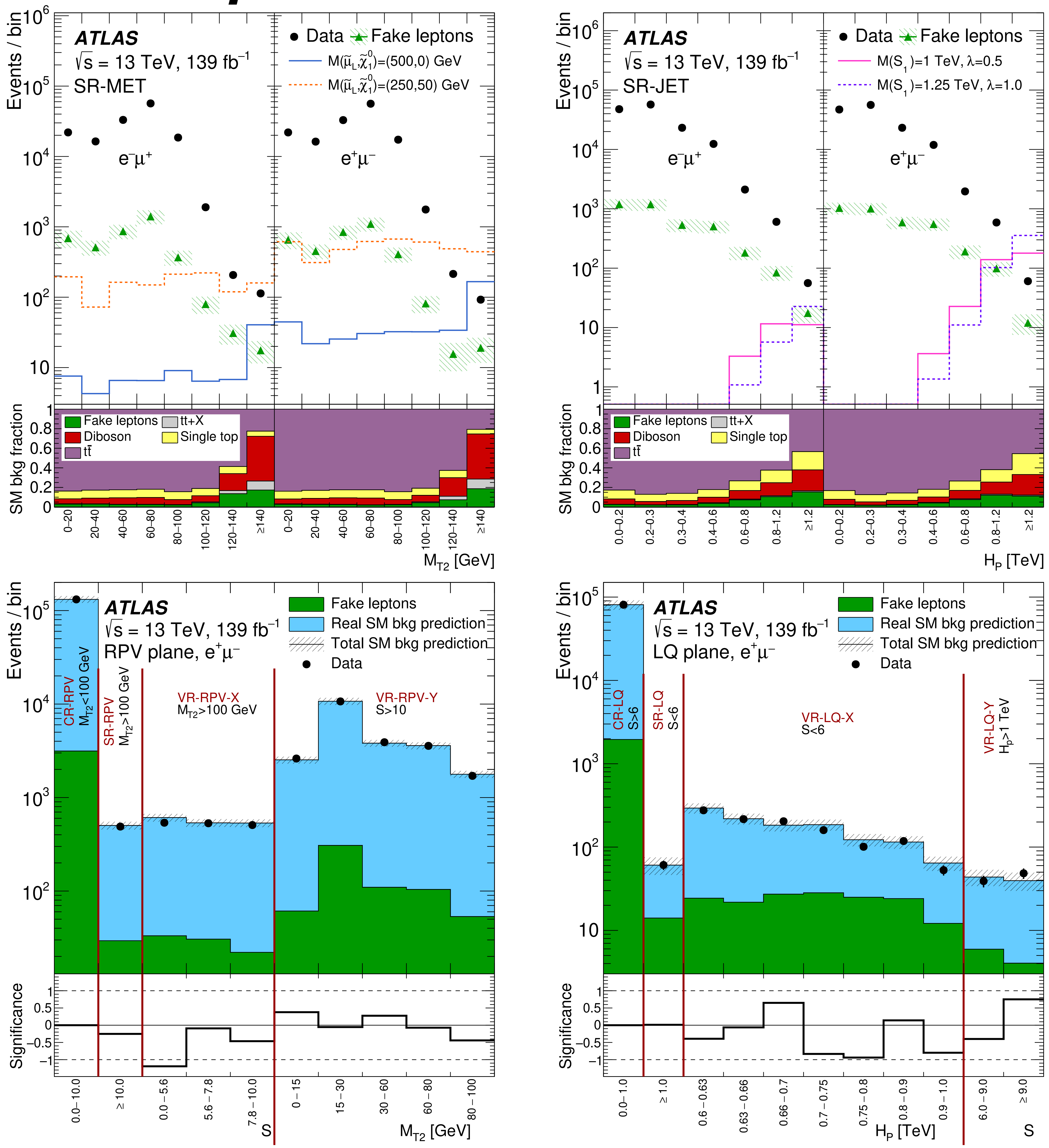
where a and b represent the contributions to p^{miss} from each semi-leptonic decay of a pair-produced particle, and all possible values that sum to the observed p^{miss} are minimised over.

$$H_{\mathrm{P}} \equiv |\vec{p}_{\mathrm{T}}^{\,e}| + |\vec{p}_{\mathrm{T}}^{\,\mu}| + |\vec{p}_{\mathrm{T}}^{\,j_1}|$$

Hp is a simple sum of the magnitudes of the transverse momenta of the two leptons and the most energetic jet in the event.

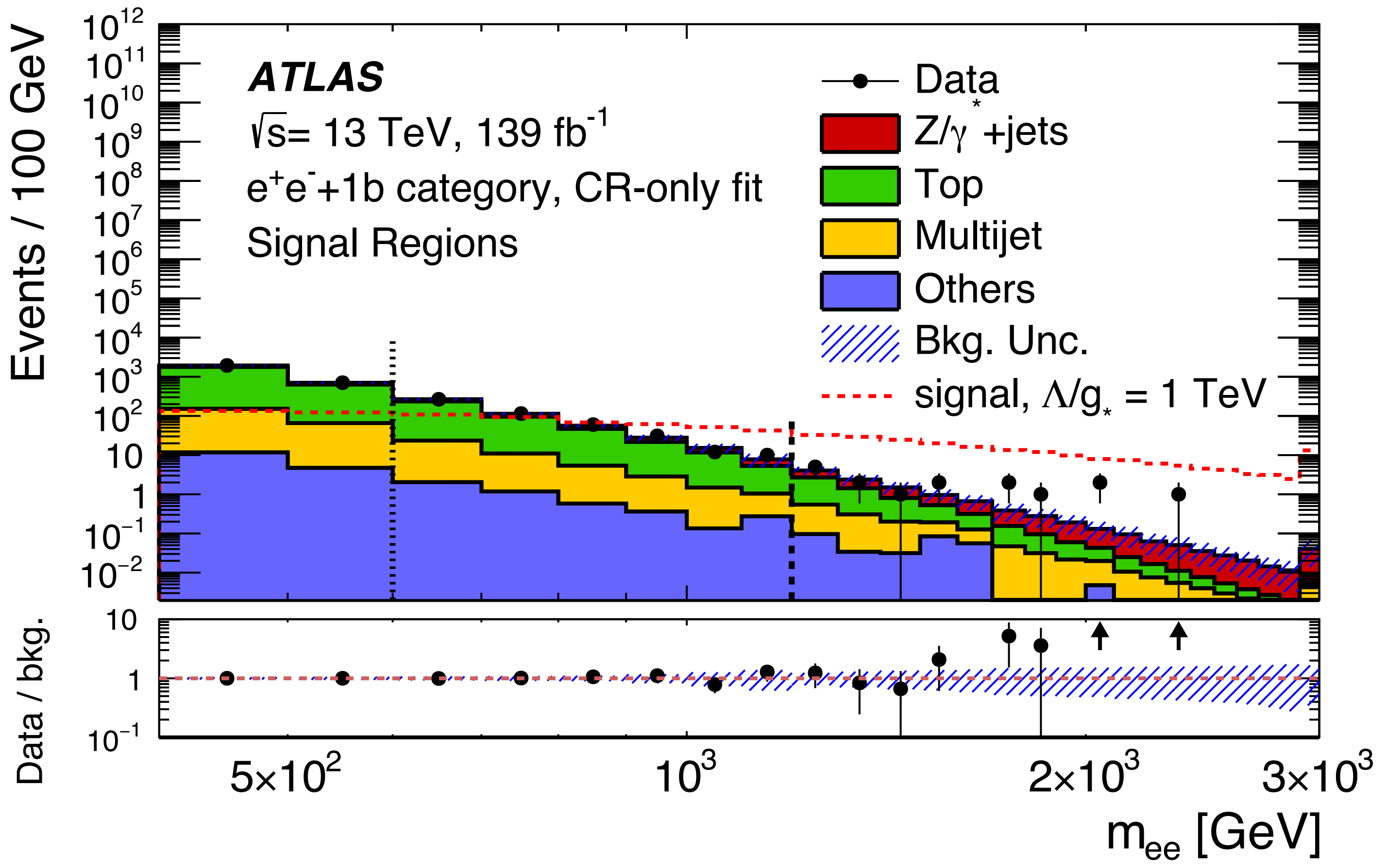
unexpected asymmetry of $e\mu$

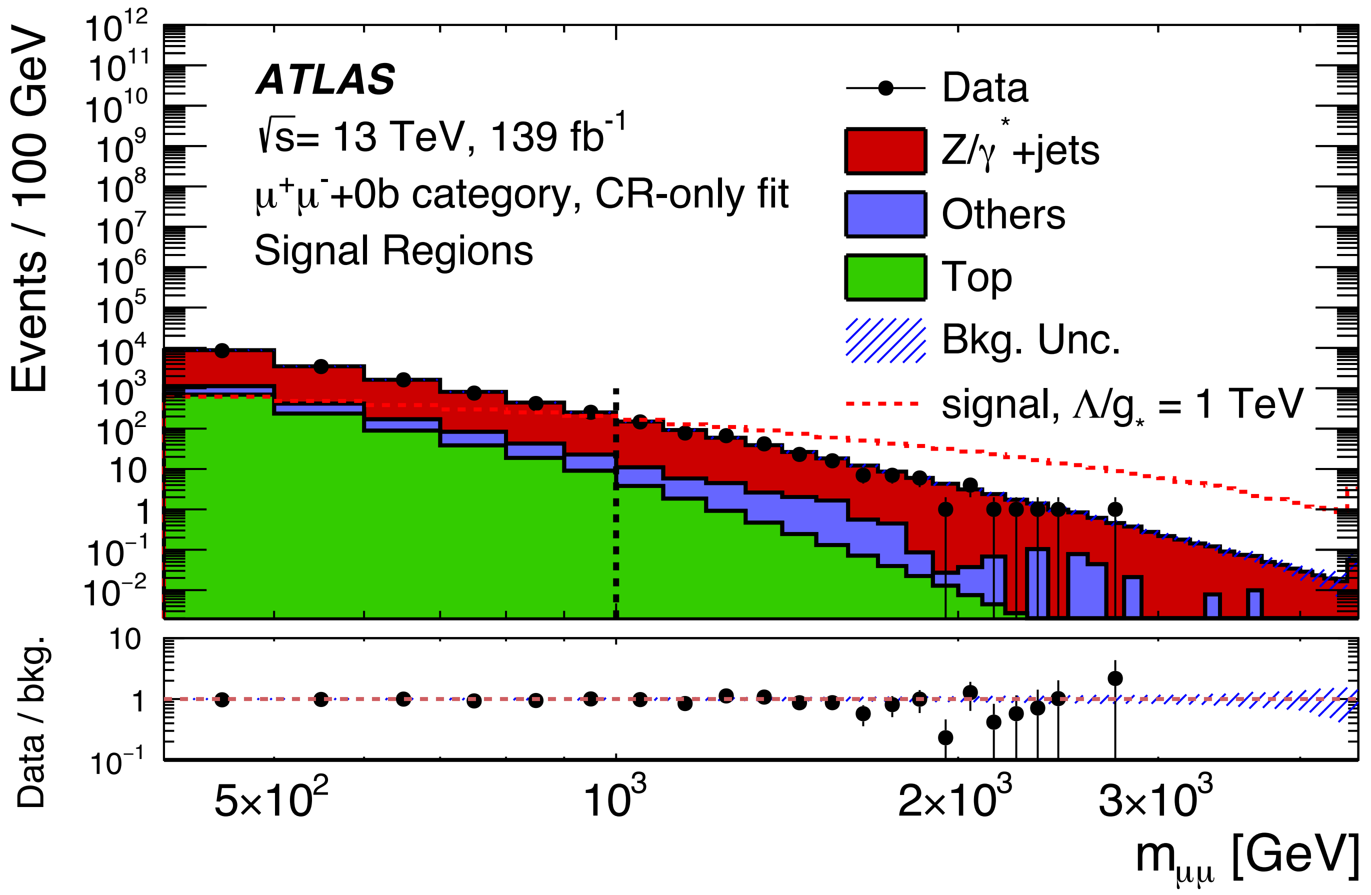
$$\mathcal{L}(\vec{N}_{\mathrm{obs}}^{+-/-+}|\vec{\theta},\vec{\alpha},\vec{\rho}) = \prod_{i\in \mathrm{bins}}\Big[\mathrm{Pois}(N^{-+}_{\mathrm{obs},i}|w_i^{-+}(\vec{\theta})N_{\mathrm{exp},i}+F_i^{-+}(\vec{\alpha})) \times \mathrm{Pois}(N^{+-}_{\mathrm{obs},i}|\rho_i w_i^{+-}(\vec{\theta})N_{\mathrm{exp},i}+F_i^{+-}(\vec{\alpha}))\Big] \times \prod_{k\in\text{ fake lepton uncertainties}} \mathrm{Gaus}(0|\alpha_k,1) \times \prod_{j\in\text{ data uncertainties}}\mathrm{Gaus}(0|\theta_j,1).$$

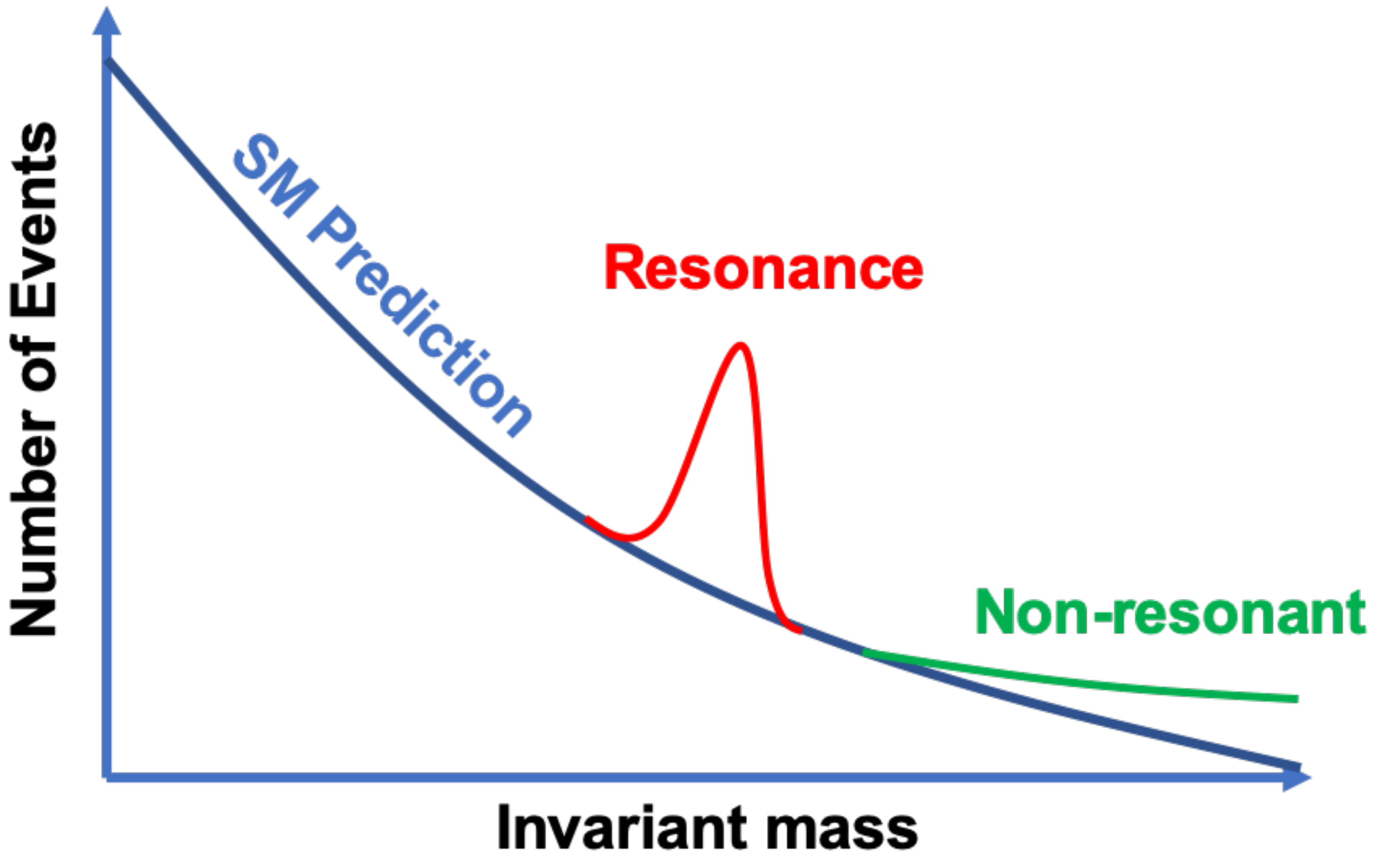


b -> s lep lep

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)







search for leptoquarks

	$\tau_{lep}\tau_{had}$ 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	

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