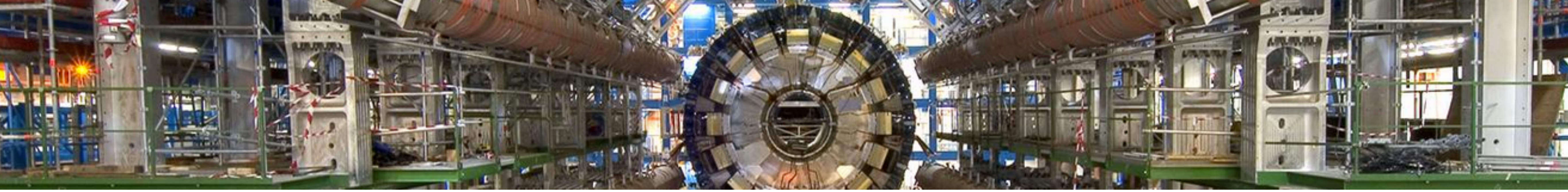

Search for Lepton Flavour Violation with the ***ATLAS*** detector

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on behalf of the ***ATLAS*** collaboration

Introduction

In SM, LFV is highly suppressed.

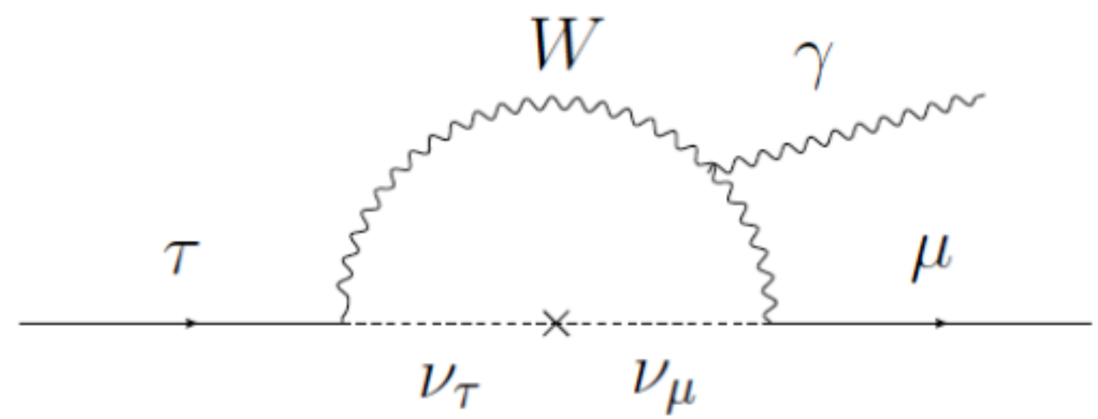
Many BSM models predict LFV in some manner (e.g 2HDM, Randall-Sundrum, composite Higgs)

Direct decays of leptons ($\ell \rightarrow \ell'\gamma$, $\ell \rightarrow 3\ell'$) measured with precision experiments.

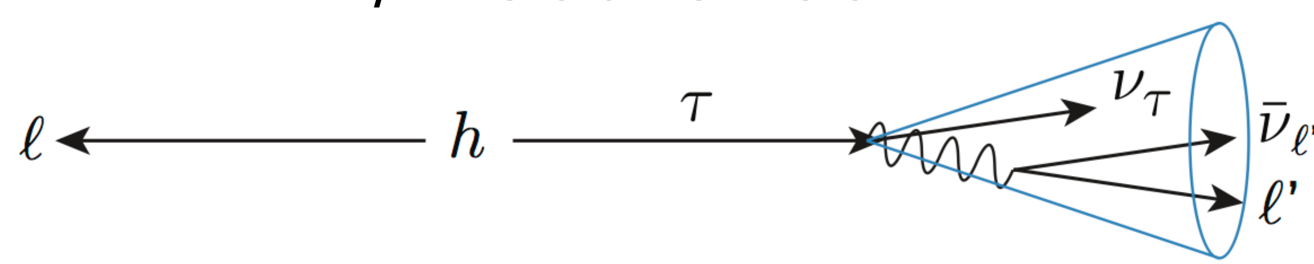
ATLAS can probe more specific couplings than these broader searches.

Main searches are neutral boson decays (focus on τ decay). Also in top quark decays (NEW) and τ→3μ (see Matteo's poster).

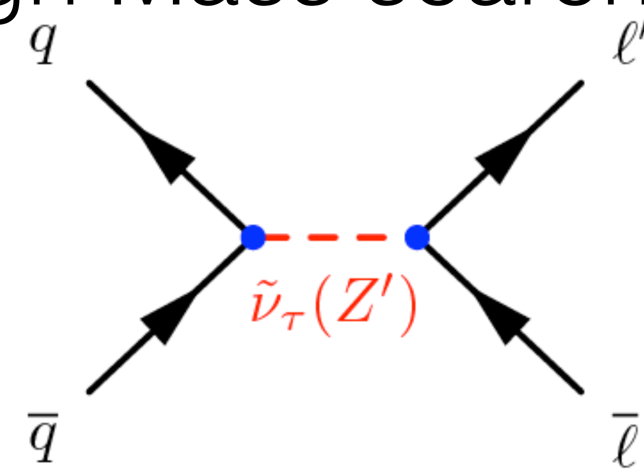
Low energy (precision)



H/Z searches



High Mass searches



Summary

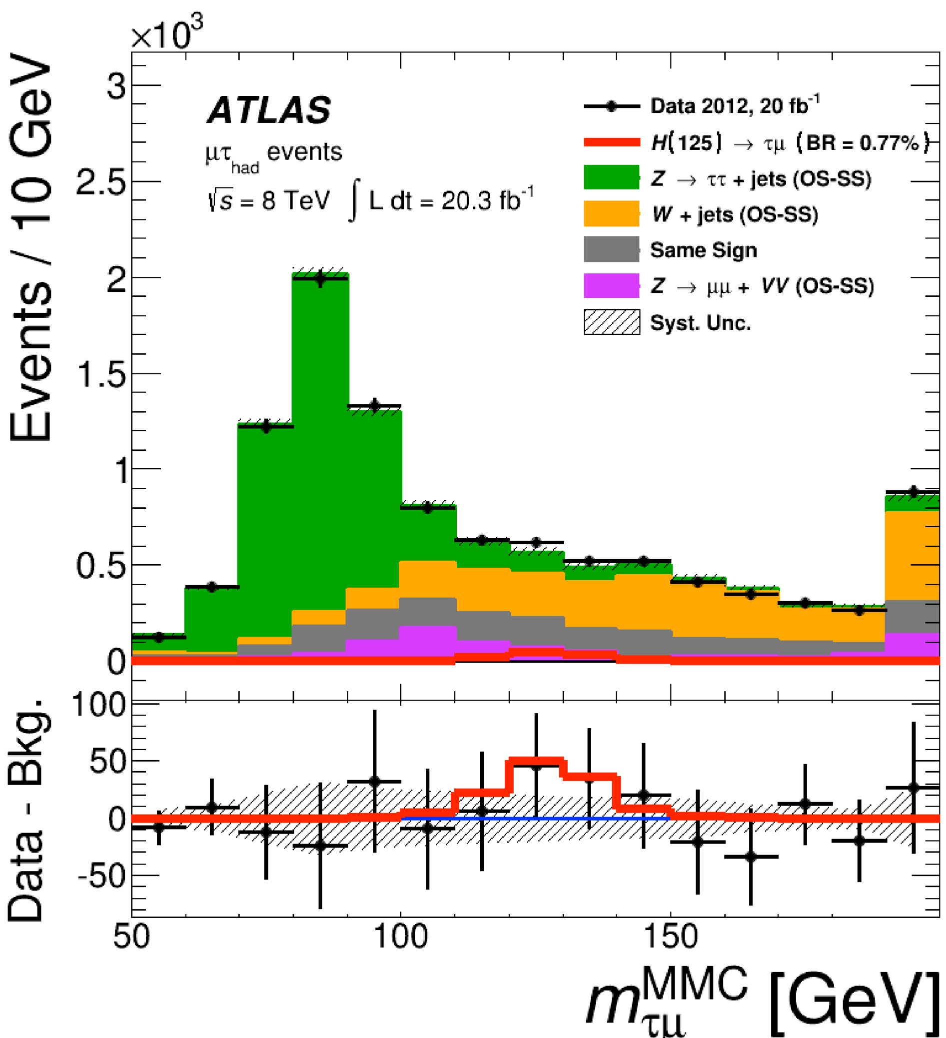
- We have a new measurement for Z decays (incl. eτ) with 13 TeV data
- Also updated High Mass result with 13 TeV dataset
- Higgs results still under study (but we are working hard to get results public)
- New measurement involving top quark decays (ATLAS-CONF-2018-044)

		Higgs boson	Z boson	High Mass
8 TeV	eτ	1604.07730 1.04%	-	1503.04430
	μτ	1508.03372 & 1604.07730 1.43%	1604.07730 1.69×10^{-5}	
13 TeV	eτ	In progress	1804.09568 5.8×10^{-5}	1807.06573
	μτ		1804.09568 1.3×10^{-5}	

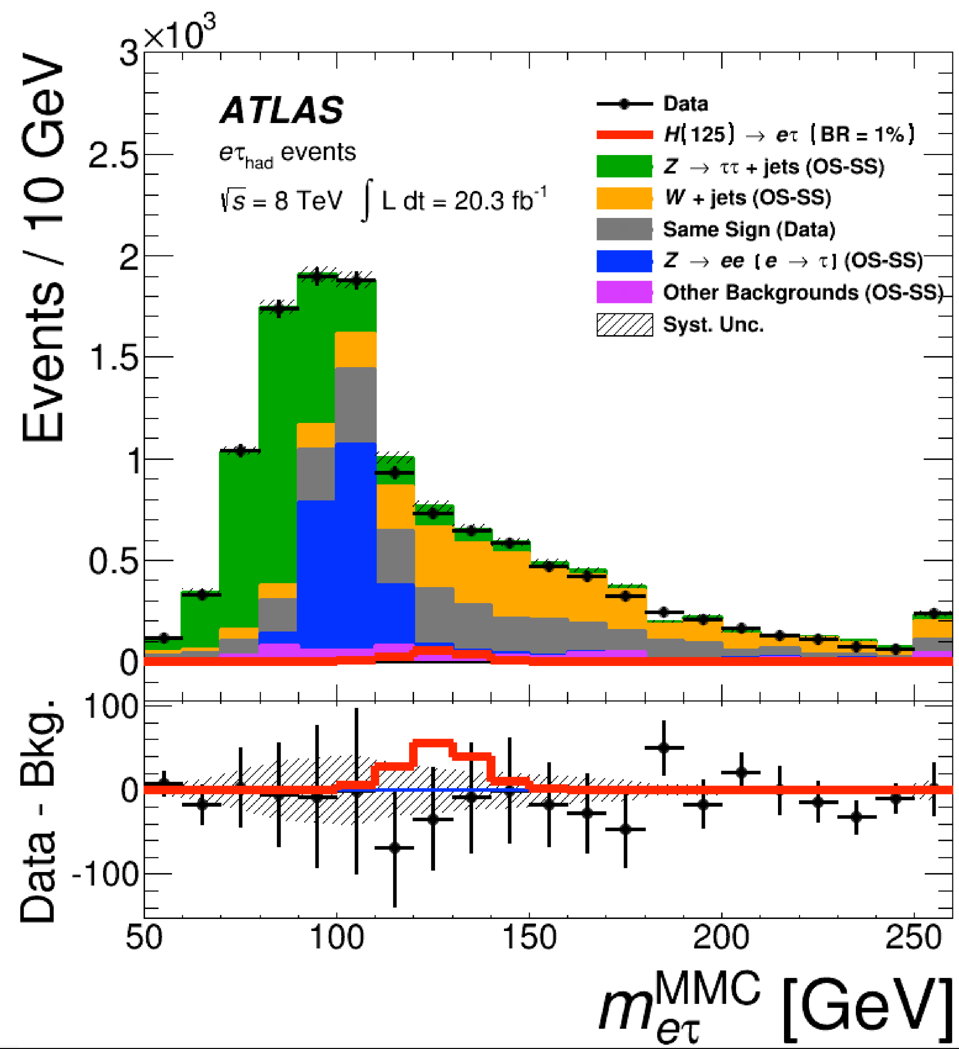
Higgs boson decays (8 TeV)

- Higgs boson decays sensitive to new Yukawa type couplings
- Search in all eτ, μτ modes (leptonic and hadronic decays)
- Signal separated per channel (not necessarily correlated)

- Hadronic channel major backgrounds:
  - SM Z→ττ decays
  - Misidentified τ_{had} candidates



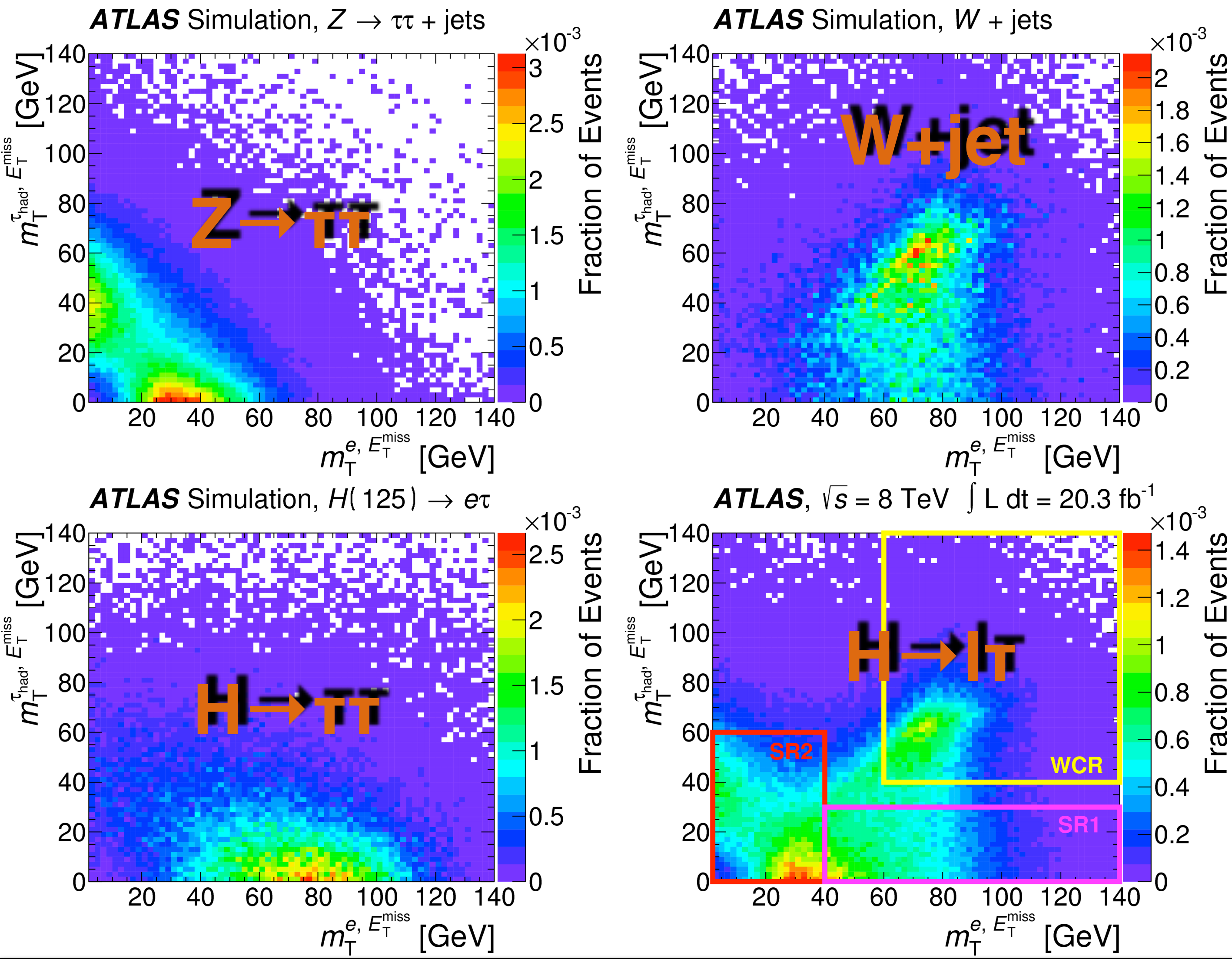
μτ



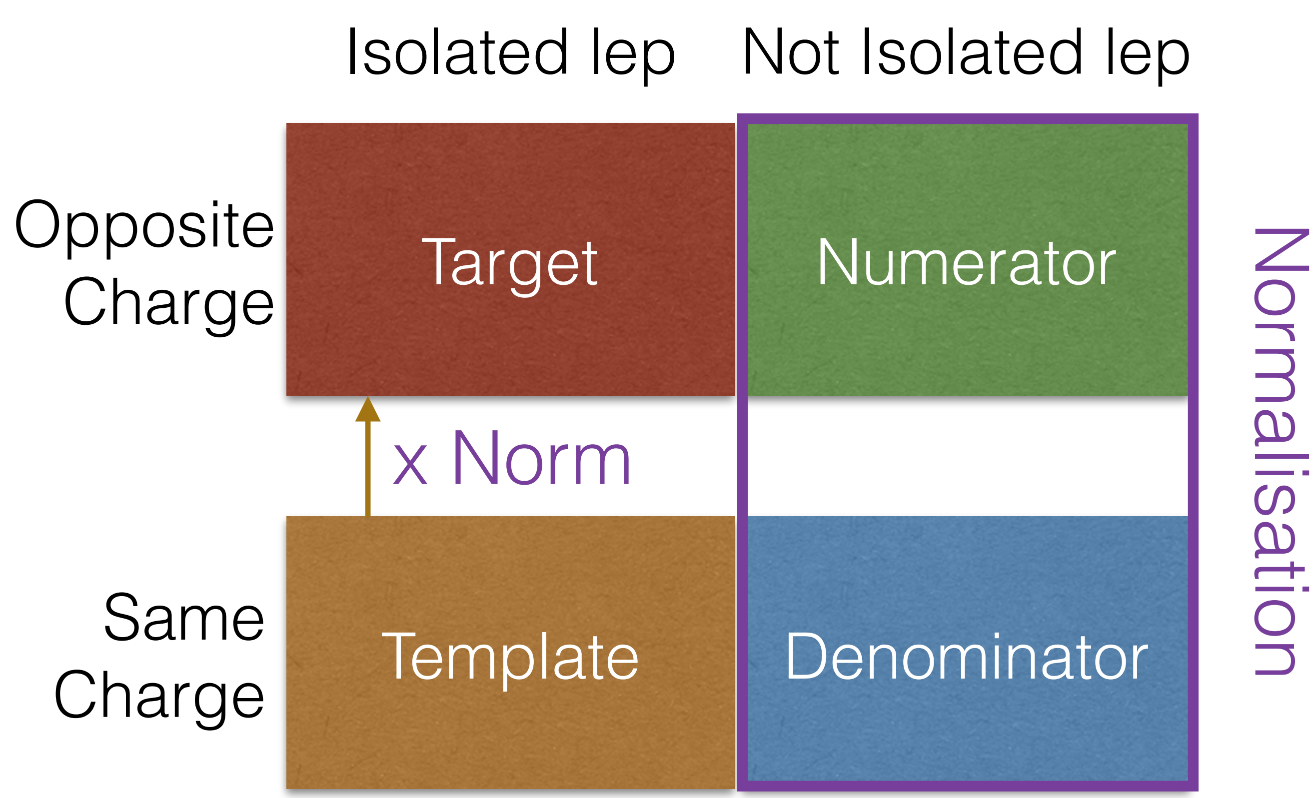
eτ

H→lτ$_{had}$ decays

- Two signal regions used to select against two major backgrounds
  - SR1 selects against Z events
  - SR2 selects against W+jets events

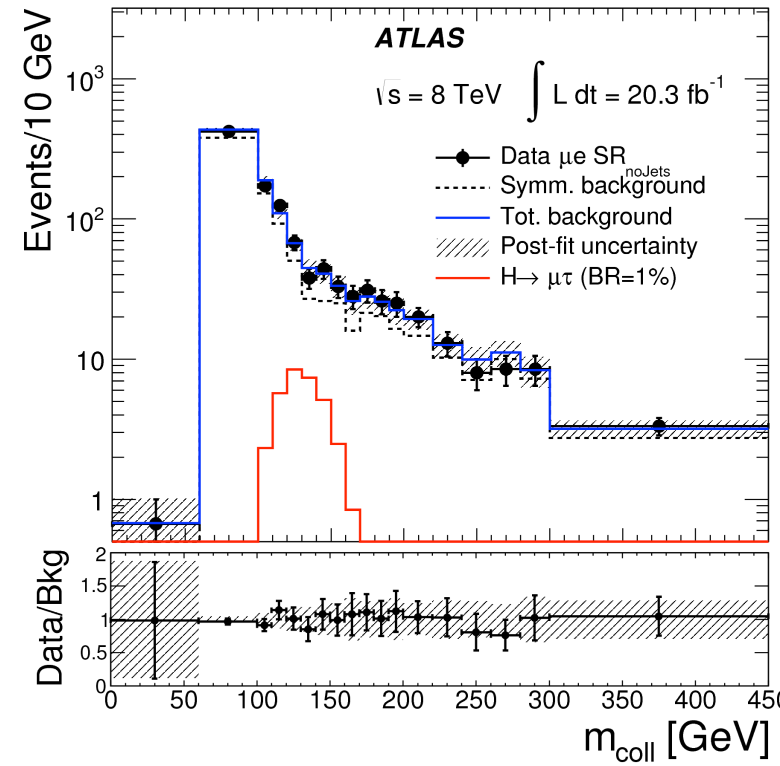


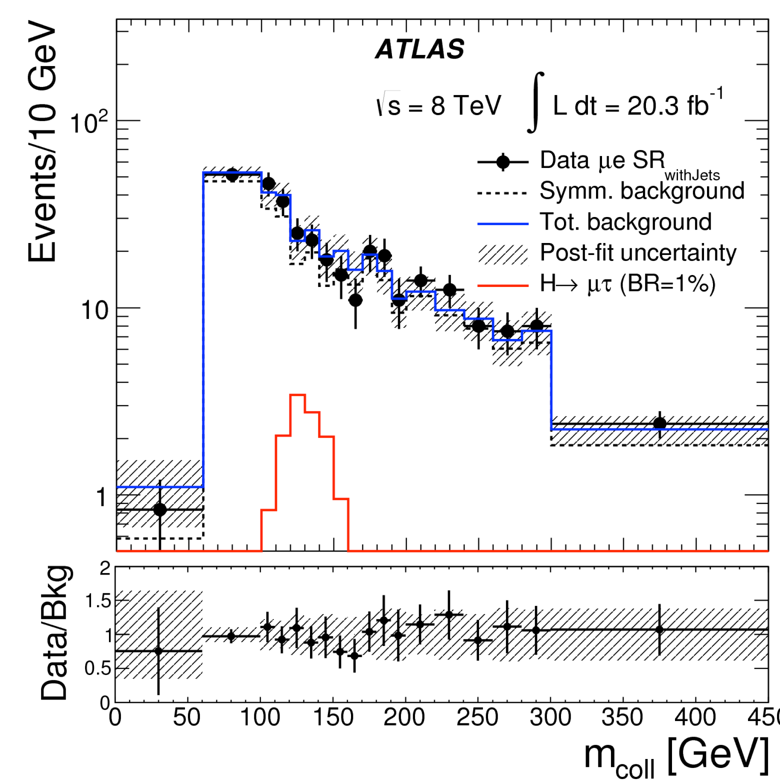
- Misidentified τ$_{had}$ modelled with a data-driven background estimation
  - Multijet modelled from same charged jet events
- Z→ττ modelled with an embedding method



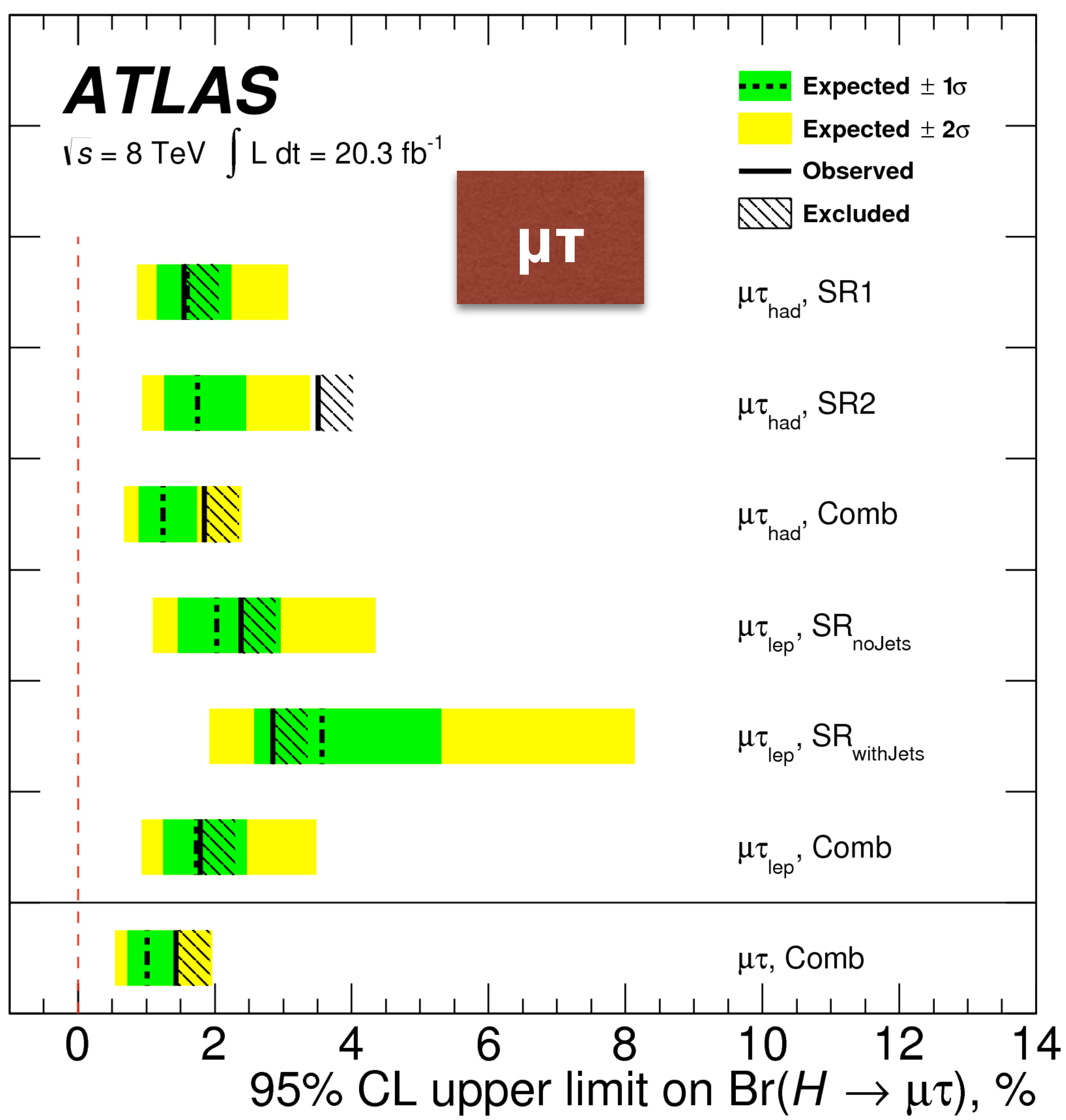
$H \to l\tau_{lep}$ decays

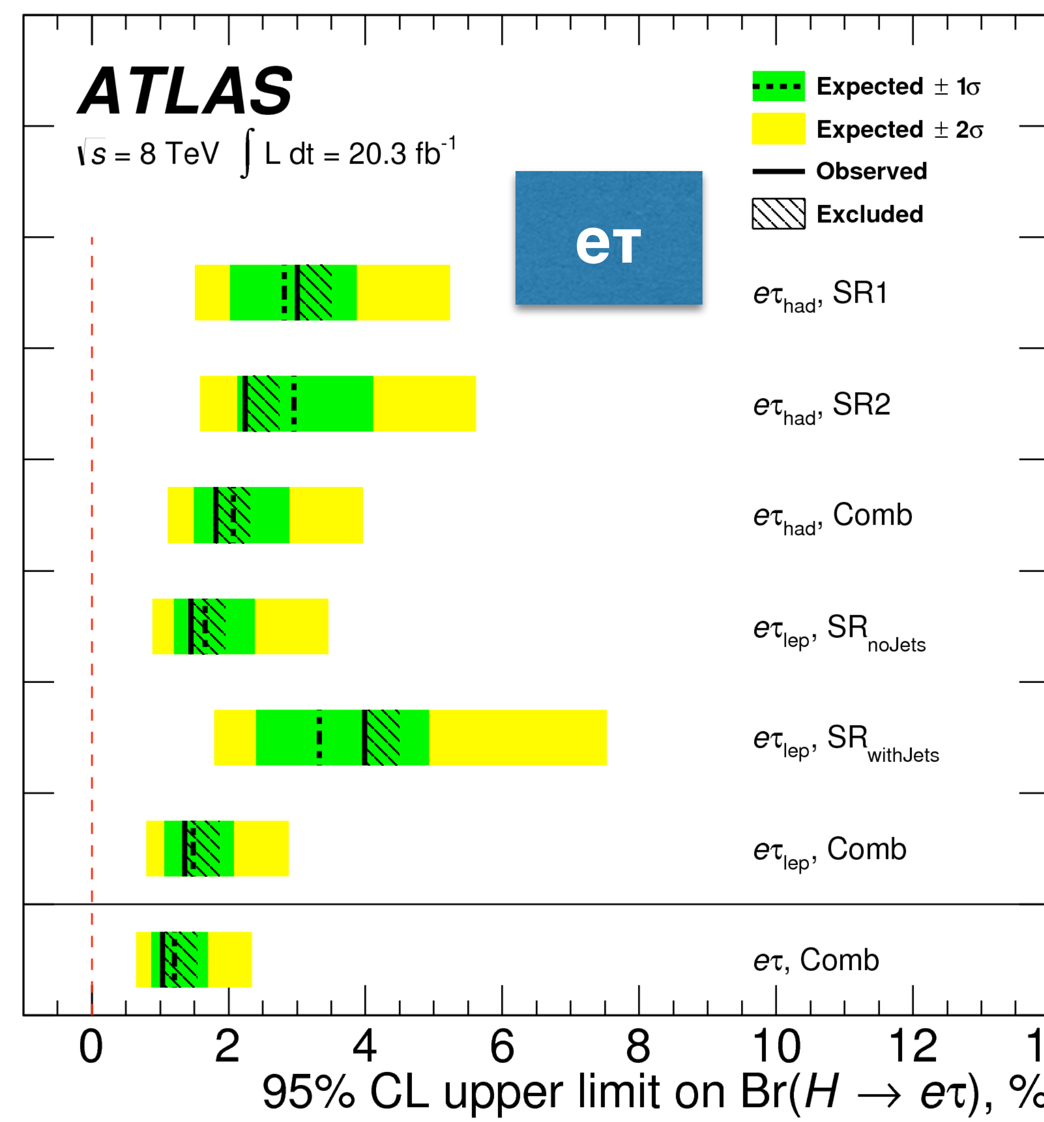
- Novel search for leptonic channel
- Background estimation exploits symmetry under e/μ interchange in SM (LFV decays break this)
- Differences in efficiencies in lepton reco/selections accounted for
- Signal extracted from fit to collinear mass distribution
    - Two regions defined (with/without jets)
- No excess found





$H \to l\tau$ decays



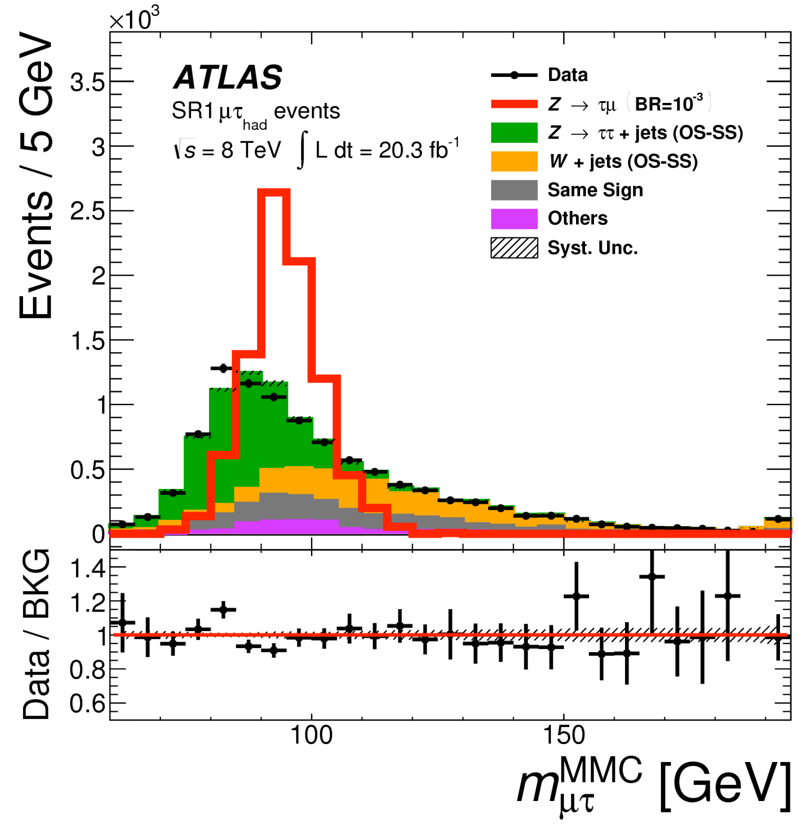


- Upper limits set to 1.04% and 1.43% of H branching ratio for eτ and μτ
- Best fit branching ratio is $-0.34^{+0.64}_{-0.66}$ and $0.53^{+0.51}_{-0.51}$ for eτ and μτ

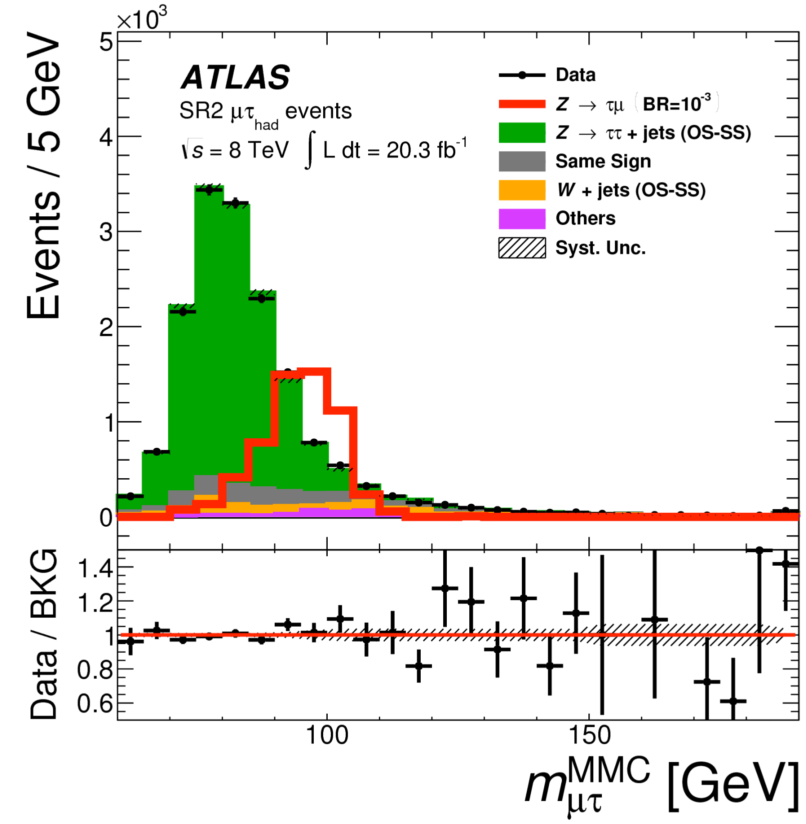
Z boson decays (8 TeV)

- Only searched for $Z \to \mu\tau_{had}$ decays
- Major backgrounds:
  - SM $Z \to \tau\tau$ decays
  - Misidentified τ_{had} candidates
- Modelled with same background estimation as Higgs measurement
- Signal extraction via fit to MMC mass in two signal sensitive regions

SR1



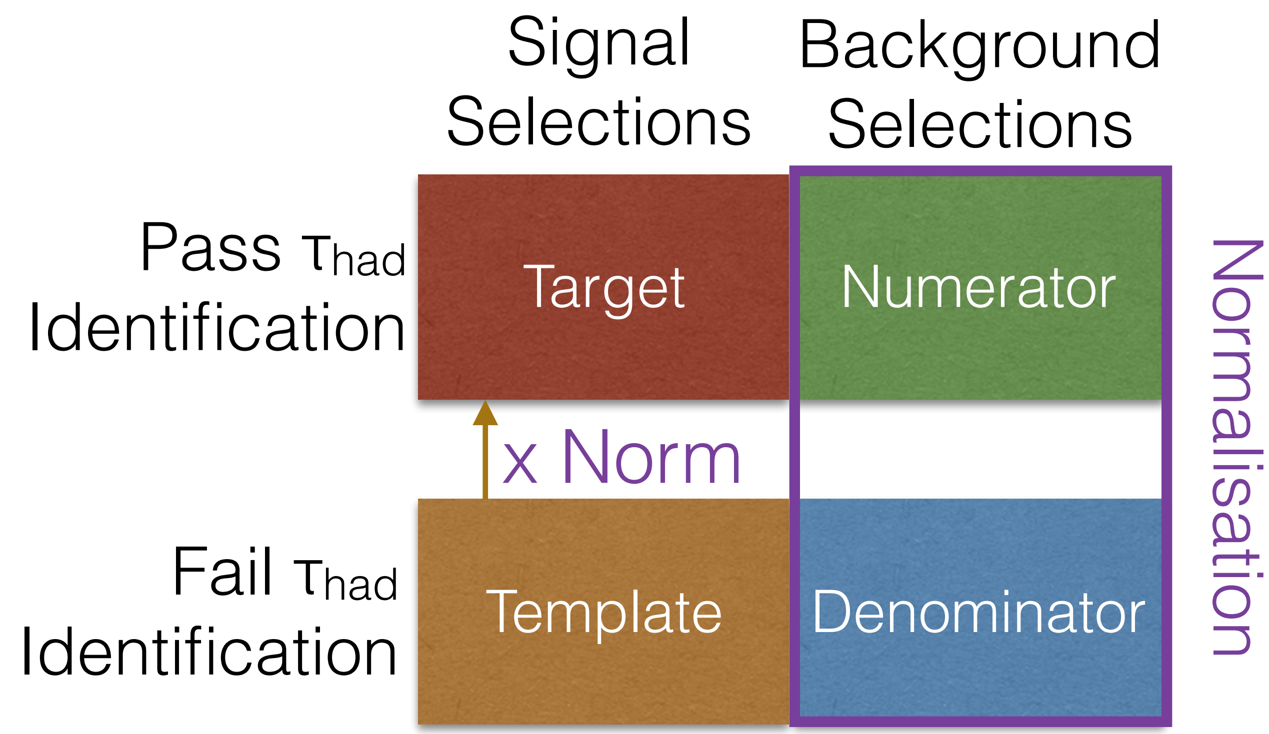
SR2

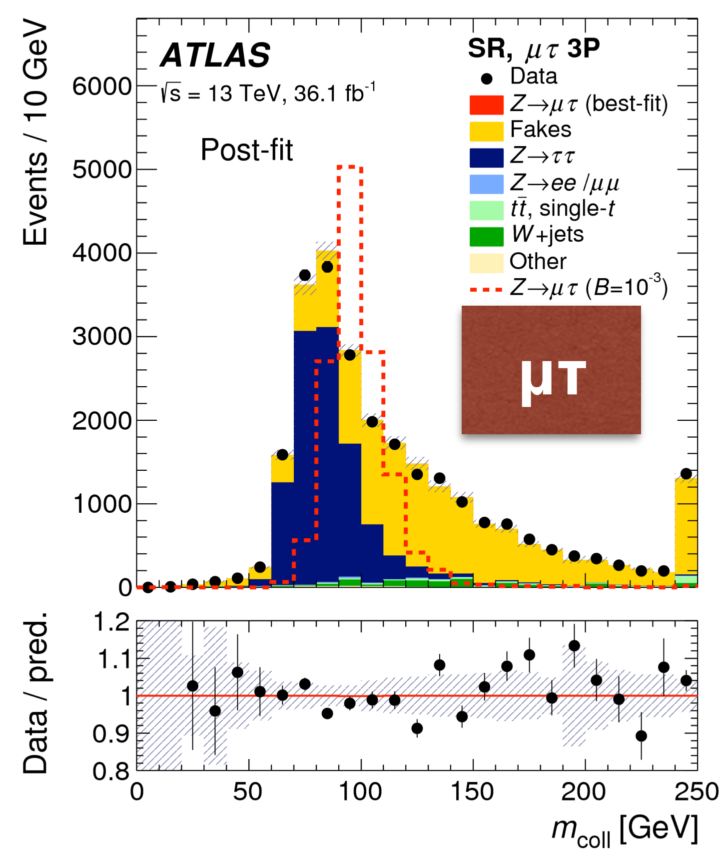


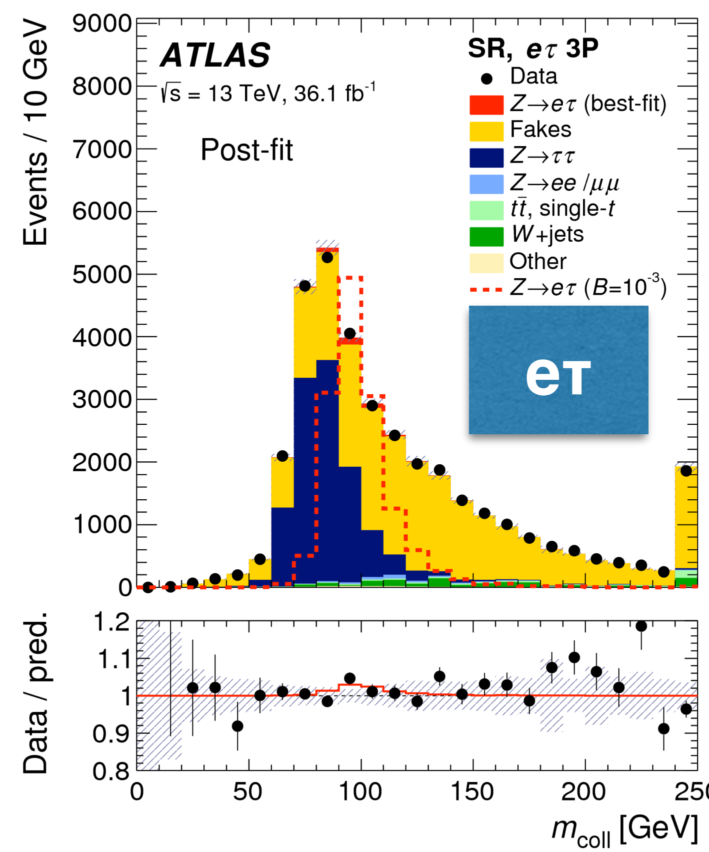
$\mathrm{Br}(Z \to \mu\tau)[10^{-5}]$	SR1	SR2	Combined
Expected limit	$2.6^{+1.1}_{-0.7}$	$6.4^{-1.8}_{+2.8}$	$2.6^{+1.1}_{-0.7}$
Observed limit	1.5	7.9	1.7
Best fit	$-2.1^{+1.2}_{-1.3}$	$2.6^{+2.9}_{-2.6}$	$-1.6^{+1.3}_{-1.4}$

Z boson decays (13 TeV)

- Search in the $Z \to e\tau_{had}$ (new!) and $Z \to \mu\tau_{had}$ channels (see Terry's poster)
- Modelling updated (see Lara's talk):
  - Misidentified τ_{had} are estimated from events where candidate fails identification
    - p_T dependent reweighting based on data-driven (mis)identification probability
    - Rates measured separately for 1p and 3p taus
  - $Z \to \tau\tau$ estimation is purely MC based and normalisation from fit







Signal Extraction (Z 13 TeV)

- Signal extraction is done using a multivariate approach (split into 1P and 3P):
  - Train three sets of Neural Networks to separate signal from Z→ττ, Z→ll (1P only) and the W+jets backgrounds
- Fit performed on the combined classifier score

$$\text{combined output(1P)} = 1 - \sqrt{(1-\text{output}_{\text{W}})^2 + (1-\text{output}_{\text{Z}})^2 + (1-\text{output}_{\text{Zll}})^2}/\sqrt{3}.$$

- Inputs were:
  - Four vectors (boosted, rotated and scaled for consistency)
  - Higher level mass variables (lab frame)
  - Vectorial p_T and $\Delta\alpha$ variable (lab frame)

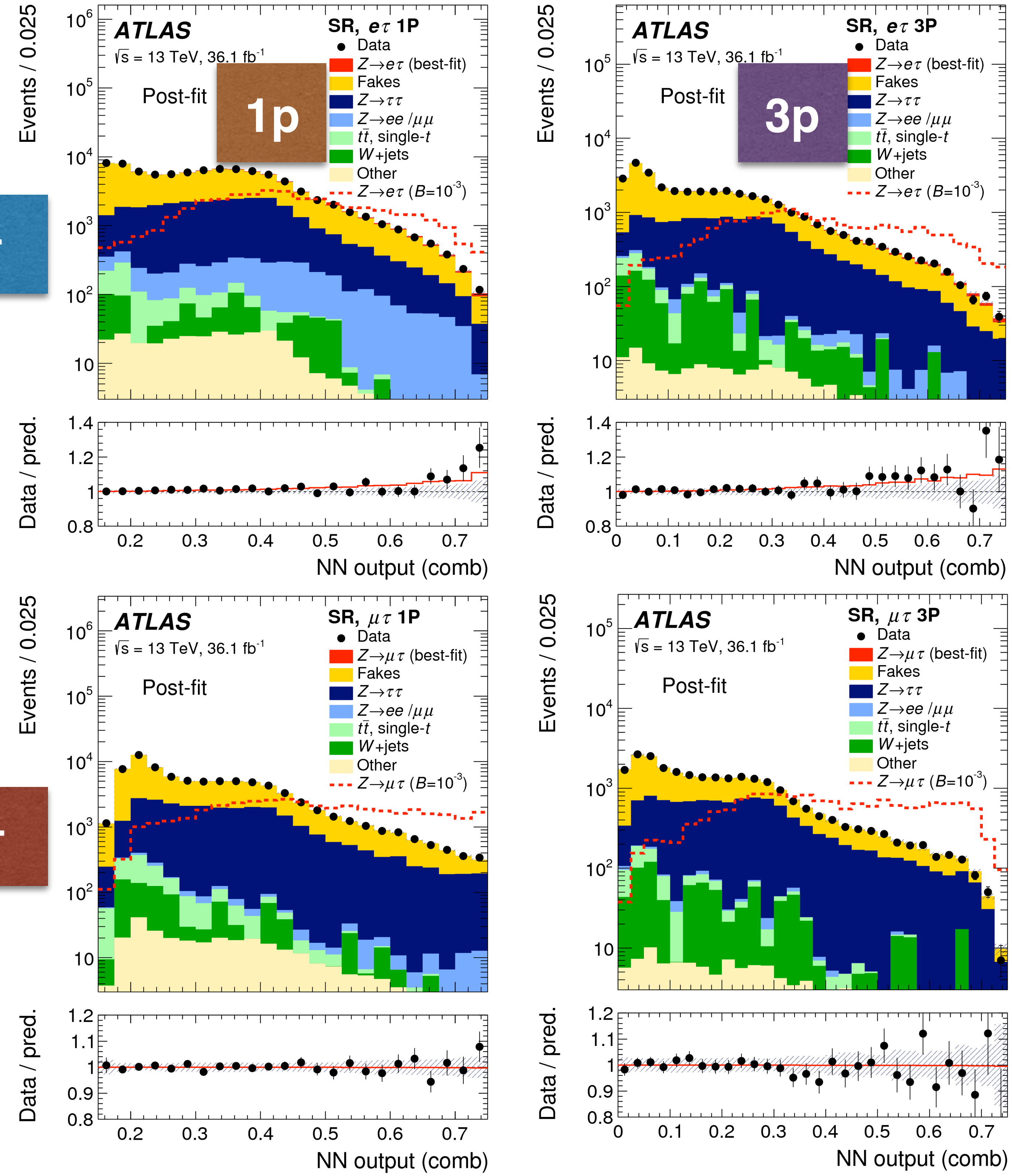
Variable	Description	Z NN	Zll NN	W NN
$\hat{E}^{\text{lep}}$	light-lepton energy	✓	✓	✓
$\hat{p}_x^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_x	✓	✓	✓
$\hat{p}_z^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ p_z	✓	✓	✓
$\hat{E}^{\tau_{\text{had-vis}}}$	$\tau_{\text{had-vis}}$ energy	✓	✓	✓
$\hat{p}_z^{\text{miss}}$	$E_{\text{T}}^{\text{miss}}$ component along z-axis	✓	✓	✓
$\hat{E}^{\text{miss}}$	magnitude of $E_{\text{T}}^{\text{miss}}$	✓	✓	✓
$p_{\text{T}}^{\text{tot}}$	transverse component of total momentum	✓	✓	✓
m_{coll}	collinear mass	✓	✓	✓
$\Delta\alpha$	see Eq. (1) [47]	✓	✓	✓
$m(\ell, \tau_{\text{had-vis}})$	invariant mass of light lepton and $\tau_{\text{had-vis}}$		✓	

Z boson decays (13 TeV)

- Results show slight excess in Z→eτ channel (2.3σ over background)
    - Best fit **BR = $(3.3^{+1.5}_{-1.4})\times10^{-5}$**
    - First ATLAS limits set on Z→eτ **BR 5.8×10^{-5}**
- No excess in Z→μτ.
    - Best fit **BR = $(-0.1^{+1.2}_{-1.2})\times10^{-5}$**
    - Limit on Z→μτ branching ratio (combined with the 8 TeV dataset) is **1.3×10^{-5}** which is competitive with LEP at 1.2×10^{-5}

eτ

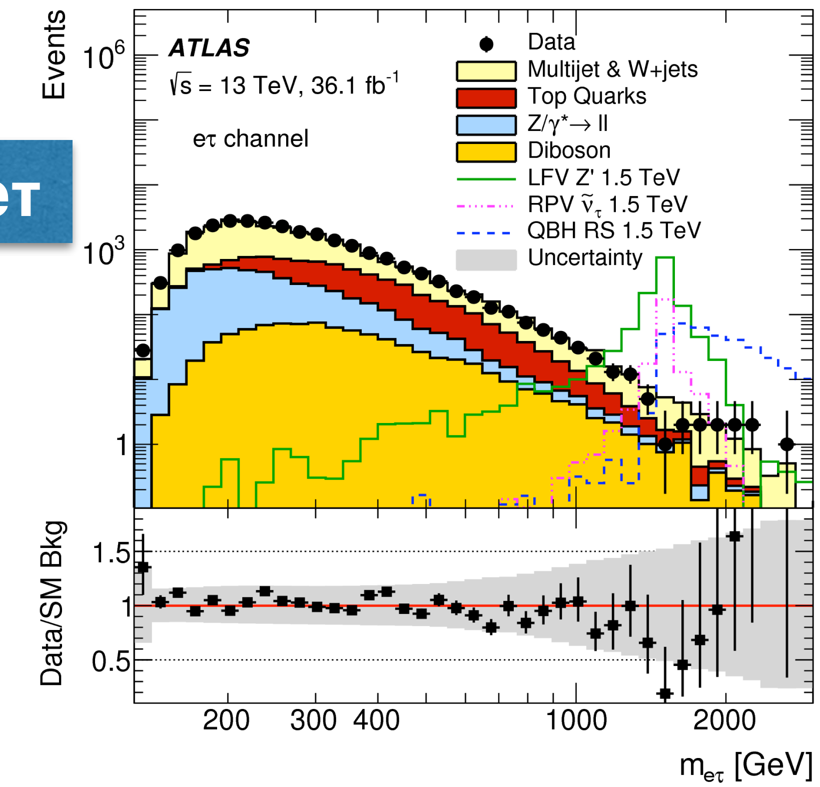
μτ



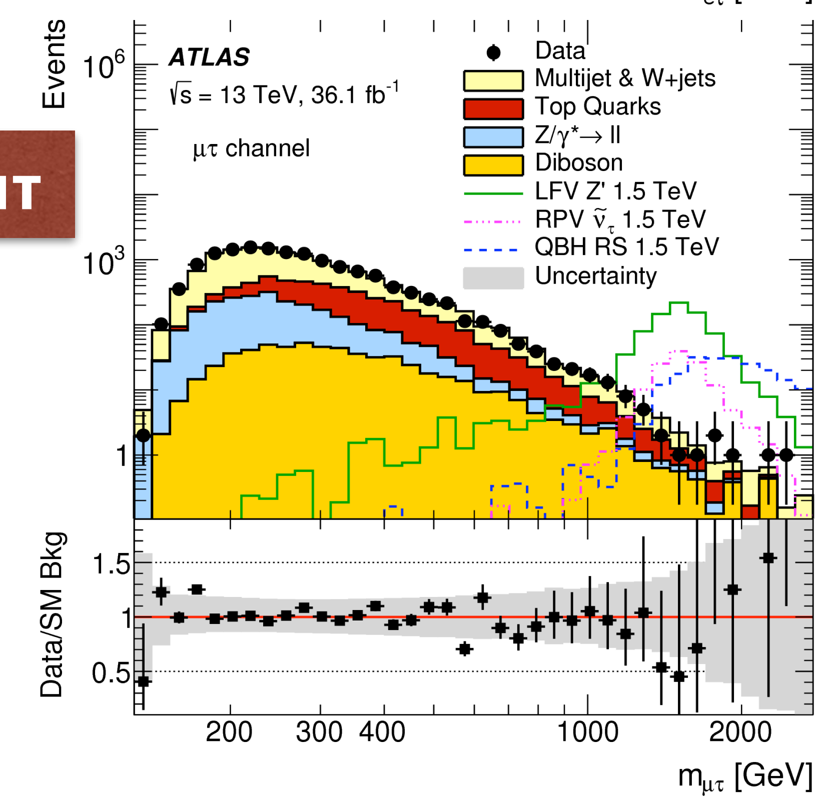
High mass search (13 TeV)

- Motivated by three main models:
    - Z’ (same quark couplings, only one LFV coupling)
    - RPV SUSY (τ sneutrino, coupling to 1st gen quarks)
    - Quantum Black Holes (QBH)
- Search channels eμ, eτ, μτ (won’t talk about eμ here)
- Main backgrounds:
    - W+jets estimated with MC, with data-driven fake rate
    - Multijet estimated in similar way to H/Z 8 TeV search (same charged jet events)
    - Top estimated with MC extrapolated to high mass region with fit

eτ



μτ

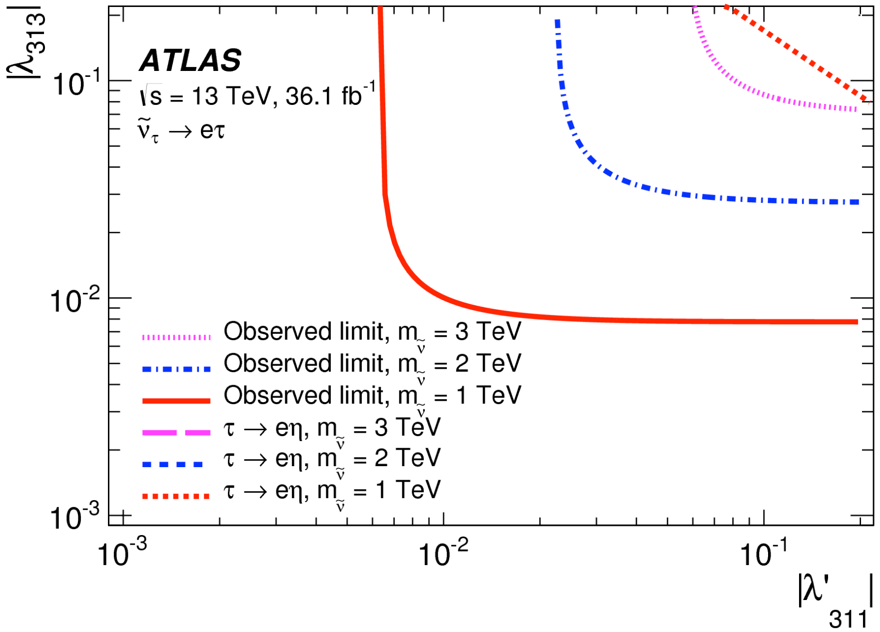


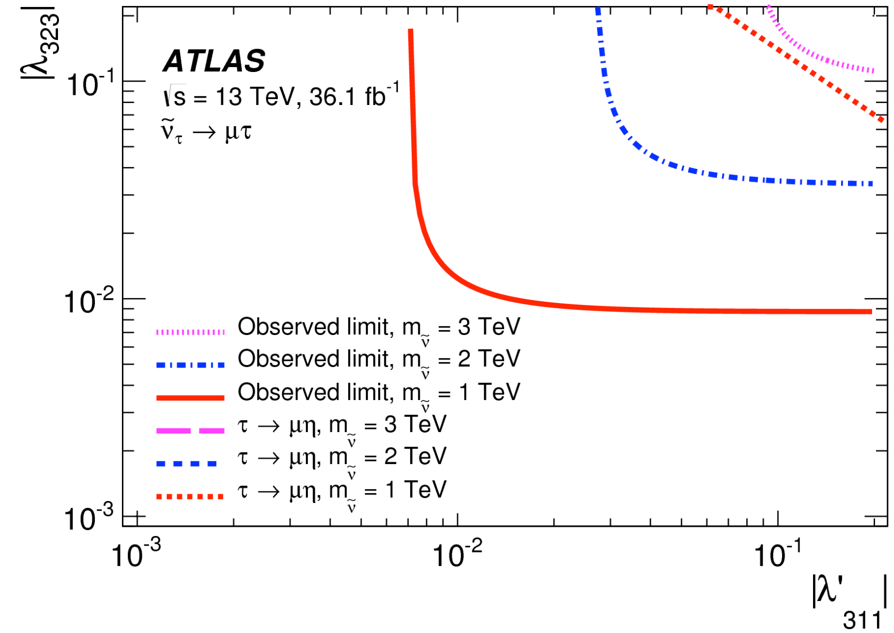
Limits on couplings in New Models

eτ

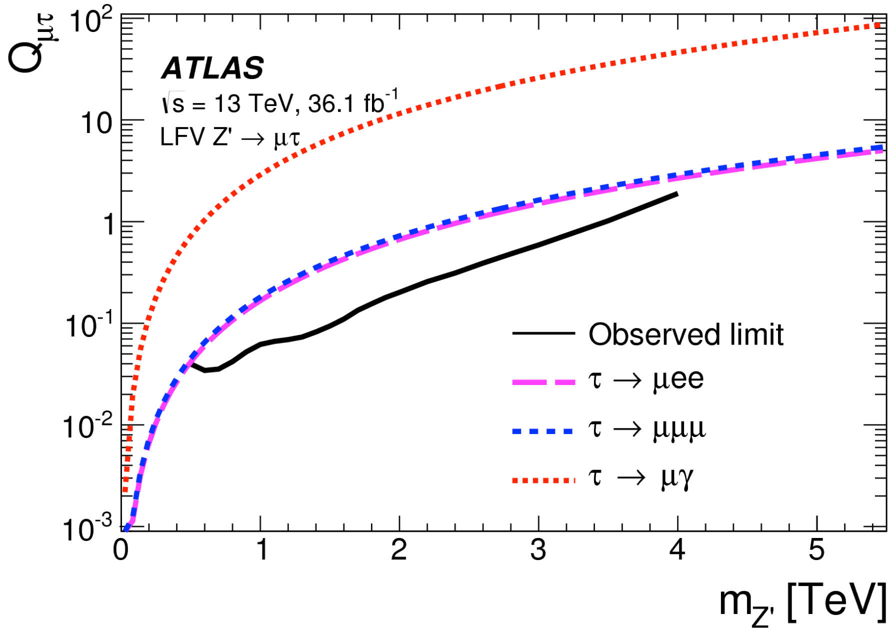
μτ

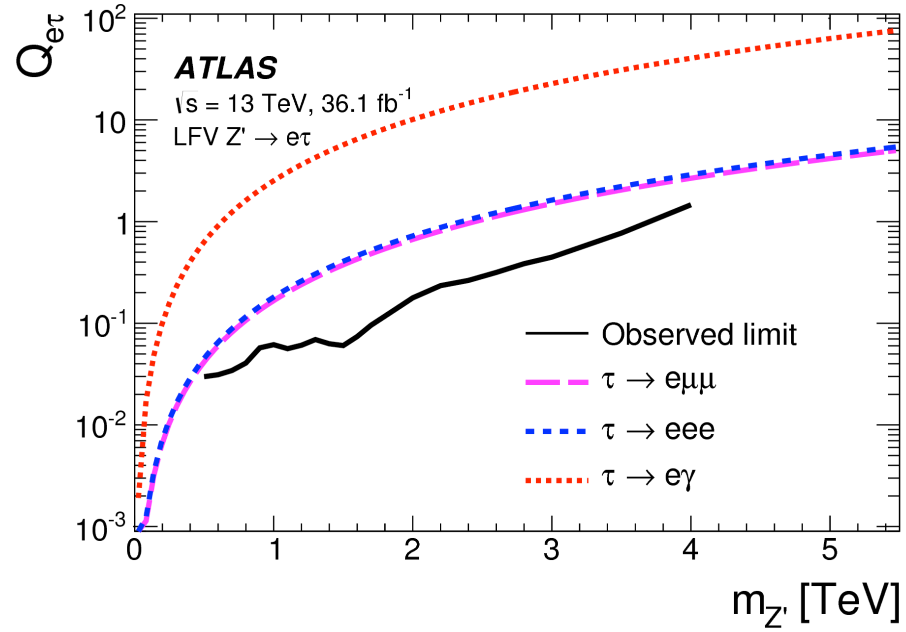
Sneutrino





Z'

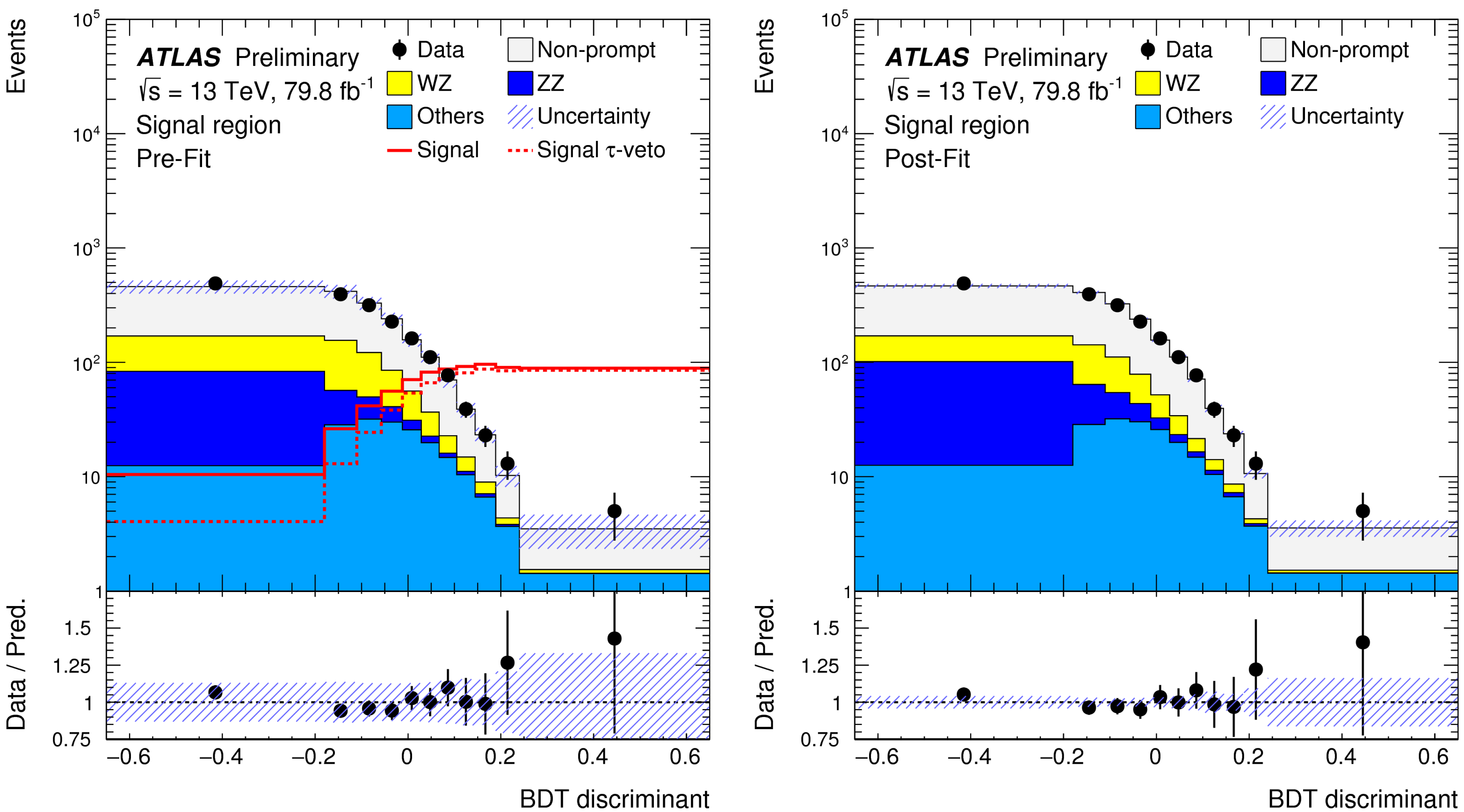




- Comparing limits from precision experiments, this measurement is now more sensitive for Z' models above 0.5 TeV and $|\lambda_{3x3}|$ couplings for τ sneutrino model

Top Quark Decays

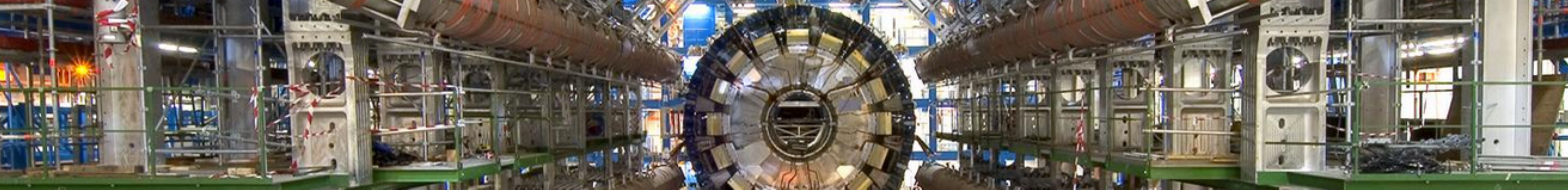
- Probing dimension 6 operators through top pair production with decay via $t \rightarrow e\mu q$ (where q=u or c)
- Matrix method used for background estimation of non-prompt lepton
- Signal extraction via a BDT trained on 13 input variables
- Slight fluctuation seen in last two bins, not statistically significant (0.9σ)



- First direct search for LFV in top quark decays places strong limits
  - BR < 1.86×10^{-5} including leptonic τ decays cf 10^{-3} from indirect measurements

Conclusion

- Updated search for LFV Z decays:
  - First limits for $Z \to e\tau$ with ATLAS have been set!
  - $Z \to \mu\tau$ limits now competitive with LEP!
- Moving forward with $H \to e\tau$ and $H \to \mu\tau$ searches with 13 TeV dataset
  - Keep an eye out!
- High mass searches with 13 TeV dataset are now able to constrain LFV couplings in Z' and RPV SUSY models better than low energy measurements
- Brand new search places strong constraints on lepton flavour violation in top quark physics!
  - Still to analyse the hadronic τ decay mode



BACKUP

Higgs: Selections

$\mu\tau_{had}$

Cut	SR1	SR2	WCR	TCR
$p_{\mathrm{T}}(\mu)$	>26 GeV	>26 GeV	>26 GeV	>26 GeV
$p_{\mathrm{T}}(\tau_{\mathrm{had}})$	>45 GeV	>45 GeV	>45 GeV	>45 GeV
$m_{\mathrm{T}}(\mu, E_{\mathrm{T}}^{\mathrm{miss}})$	>40 GeV	<40 GeV	>60 GeV	–
$m_{\mathrm{T}}(\tau_{\mathrm{had}}, E_{\mathrm{T}}^{\mathrm{miss}})$	<30 GeV	<60 GeV	>40 GeV	–
$\lvert\eta(\mu) - \eta(\tau_{\mathrm{had}})\rvert$	<2	<2	<2	<2
N_{jet}	–	–	–	>1
$N_{b-\mathrm{jet}}$	0	0	0	>0

$e\tau_{had}$

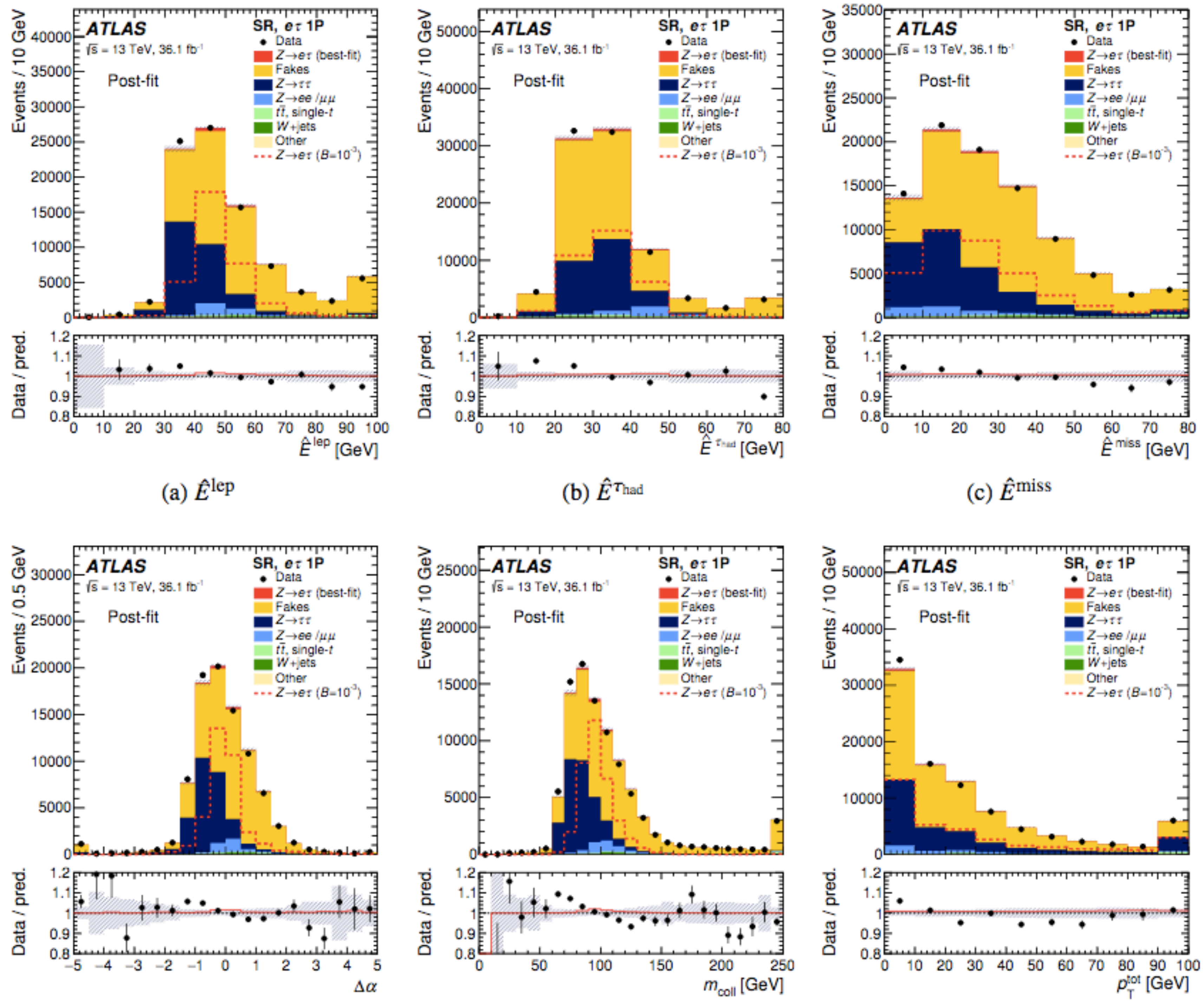
Criterion	SR1	SR2	WCR	TCR
$E_{\mathrm{T}}(e)$	>26 GeV	>26 GeV	>26 GeV	>26 GeV
$p_{\mathrm{T}}(\tau_{\mathrm{had}})$	>45 GeV	>45 GeV	>45 GeV	>45 GeV
$\lvert\eta(e) - \eta(\tau_{\mathrm{had}})\rvert$	<2	<2	<2	<2
$m_{\mathrm{T}}^{e,E_{\mathrm{T}}^{\mathrm{miss}}}$	>40 GeV	<40 GeV	>60 GeV	–
$m_{\mathrm{T}}^{\tau_{\mathrm{had}},E_{\mathrm{T}}^{\mathrm{miss}}}$	<30 GeV	<60 GeV	>40 GeV	–
N_{jet}	–	–	–	≥2
$N_{b-\mathrm{jet}}$	0	0	0	≥1

$e\mu$

	$\mathrm{SR}_{\mathrm{noJets}}$	$\mathrm{SR}_{\mathrm{withJets}}$
Light leptons	$e^{\pm}\mu^{\mp}$	$e^{\pm}\mu^{\mp}$
τ leptons	veto	veto
Central jets	0	≥ 1
b-jets	0	0
$p_{\mathrm{T}}^{\ell_1}$	$\geq 35GeV$	$\geq 35GeV$
$p_{\mathrm{T}}^{\ell_2}$	$\geq 12GeV$	$\geq 12GeV$
$\lvert\eta^{e}\rvert$	≤ 2.4	≤ 2.4
$\lvert\eta^{\mu}\rvert$	≤ 2.4	≤ 2.4
$\Delta\phi(\ell_2, E_{\mathrm{T}}^{\mathrm{miss}})$	≤ 0.7	≤ 0.5
$\Delta\phi(\ell_1, \ell_2)$	≥ 2.3	≥ 1.0
$\Delta\phi(\ell_1, E_{\mathrm{T}}^{\mathrm{miss}})$	≥ 2.5	≥ 1.0
$\Delta p_{\mathrm{T}}(\ell_1, \ell_2)$	$\geq 7GeV$	$\geq 1GeV$

NN inputs (eτ 1p)

$$\Delta\alpha = \frac{1}{2}\frac{m_Z^2 - m_\tau^2}{p(\tau_{\text{had-vis}})\cdot p(\ell)} - \frac{p_T(\ell)}{p_T(\tau_{\text{had-vis}})}$$



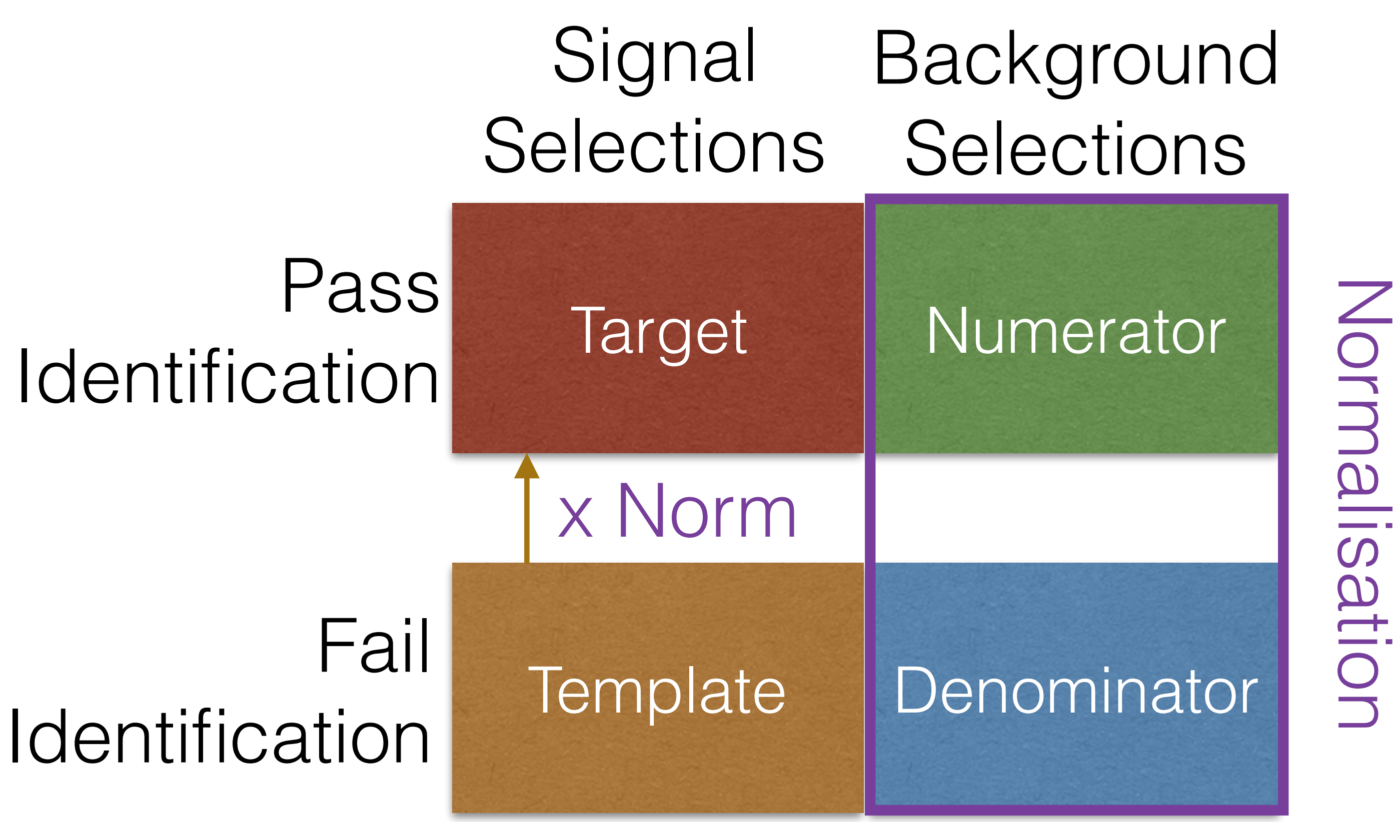
(a) $\hat{E}^{\text{lep}}$ (b) $\hat{E}^{\tau_{\text{had}}}$ (c) $\hat{E}^{\text{miss}}$

(d) $\Delta\alpha$ (e) m_{coll} (f) p_T^{tot}

Z: Background

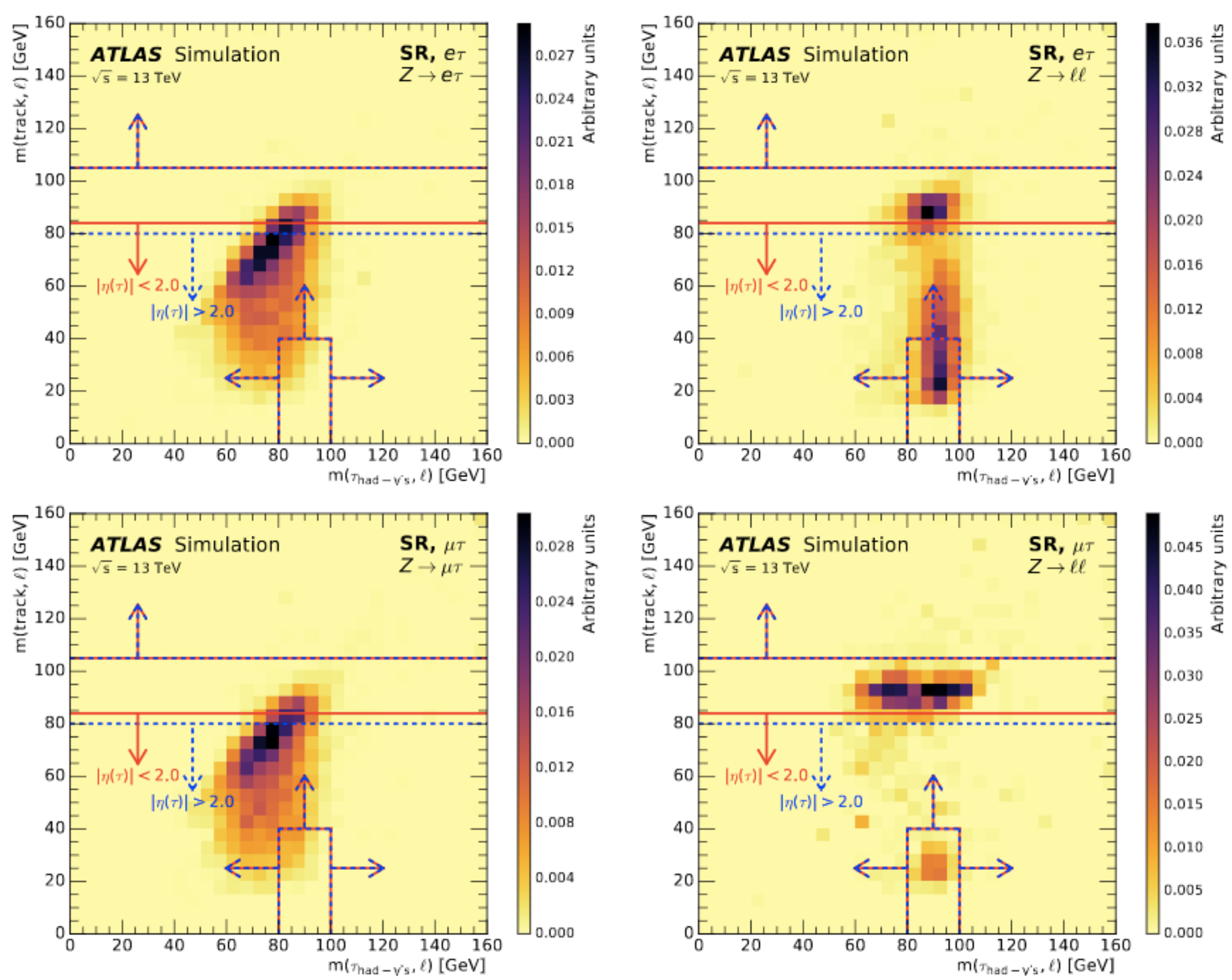
Region	Change relative to SR selection	Purity [%] $e\tau$	Purity [%] $\mu\tau$
CRZll	Two same-flavor opposite-charge light leptons with $81 < m_{\ell\ell} < 101$ GeV	98	98
CRW	$m_{\mathrm{T}}(\ell, E_{\mathrm{T}}^{\mathrm{miss}}) > 40$ GeV and $m_{\mathrm{T}}(\tau_{\text{had-vis}}, E_{\mathrm{T}}^{\mathrm{miss}}) > 35(30)$ GeV in $e\tau$ ($\mu\tau$) events	84	85
CRT	$N_{b\text{-jets}} \geq 2$	98	98
CRQ	Inverted light-lepton isolation	75	37

$$N_{\mathrm{SR}}^{\mathrm{fake}} = \sum_{k} \left(N_{\mathrm{SR,data}}^{\mathrm{fail}} - N_{\mathrm{SR,MC,not\ jet}\rightarrow\tau}^{\mathrm{fail}} \right)_k \times F_k$$



Z: Selections

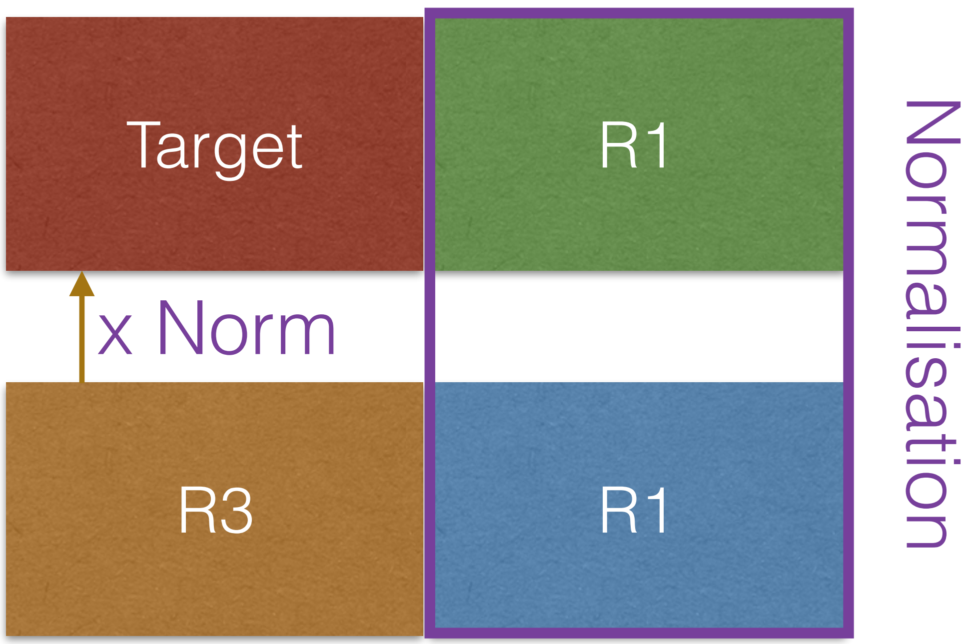
Preselection	one isolated tight light lepton with $p_T > 30$ GeV matched to a lepton selected at trigger level leading $\tau_{\text{had-vis}}$ with $p_T > 20$ GeV, $N_\tau^{\text{tracks}} = 1$ or 3 and passing tight identification if $N_\tau^{\text{tracks}} = 1$: $0.0(0.1) < \lvert\eta_\tau\rvert < 1.37$ or $1.52 < \lvert\eta_\tau\rvert < 2.2(2.5)$ in $e\tau(\mu\tau)$ events if $N_\tau^{\text{tracks}} = 3$: $0.0 < \lvert\eta_\tau\rvert < 1.37$ or $1.52 < \lvert\eta_\tau\rvert < 2.5$ $q_\ell \times q_\tau = -1$ no b-jet, no additional light lepton
Signal Region	$m_T(\tau_{\text{had-vis}}, E_T^{\text{miss}}) < 35(30)$ GeV in $e\tau$ $(\mu\tau)$ events if $N_\tau^{\text{tracks}} = 1$ and $\lvert\eta_\tau\rvert < 2.0$: $m(\text{track}, \ell) < 84$ GeV or $m(\text{track}, \ell) > 105$ GeV if $N_\tau^{\text{tracks}} = 1$ and $\lvert\eta_\tau\rvert > 2.0$: $m(\text{track}, \ell) < 80$ GeV or $m(\text{track}, \ell) > 105$ GeV if $N_\tau^{\text{tracks}} = 1$ and $80 < m(\tau_{\text{had-vis}}, \ell) < 100$ GeV: $m(\text{track}, \ell) > 40$ GeV



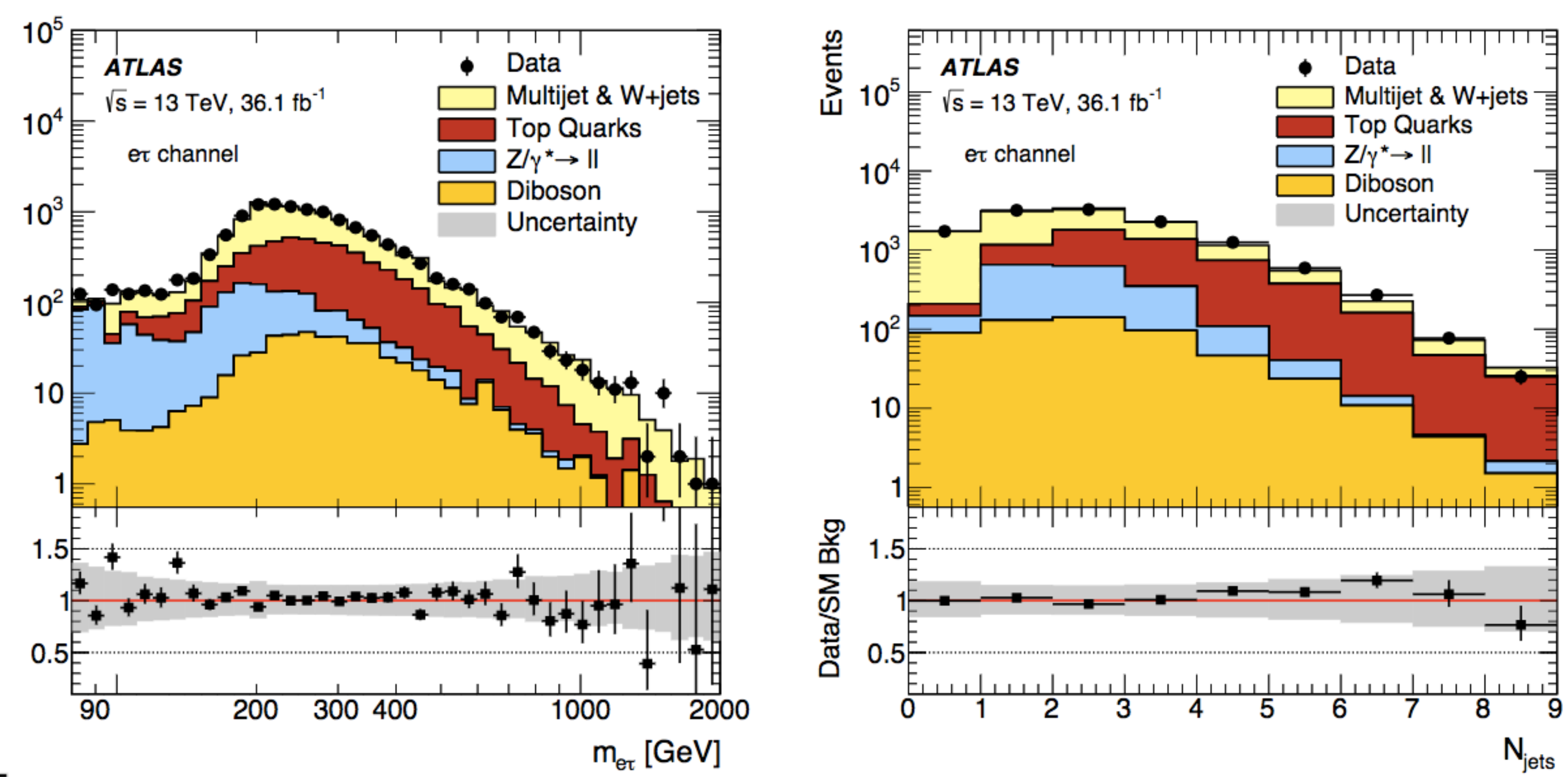
High Mass: Background

Multijet estimation

	Object selection	Lepton-pair charges
R_1	Non-isolated e/μ & $\tau_{\text{had-vis}}$ failing τ ID requirements (p_{T_ℓ} & p_{T_τ} < 200 GeV)	Same-charge
R_2	Isolated e/μ & pass ID $\tau_{\text{had-vis}}$ (p_{T_ℓ} & p_{T_τ} < 200 GeV)	Same-charge
R_3	Non-isolated e/μ & $\tau_{\text{had-vis}}$ failing τ ID requirements	Same-charge + Opposite-charge



W+jets CR

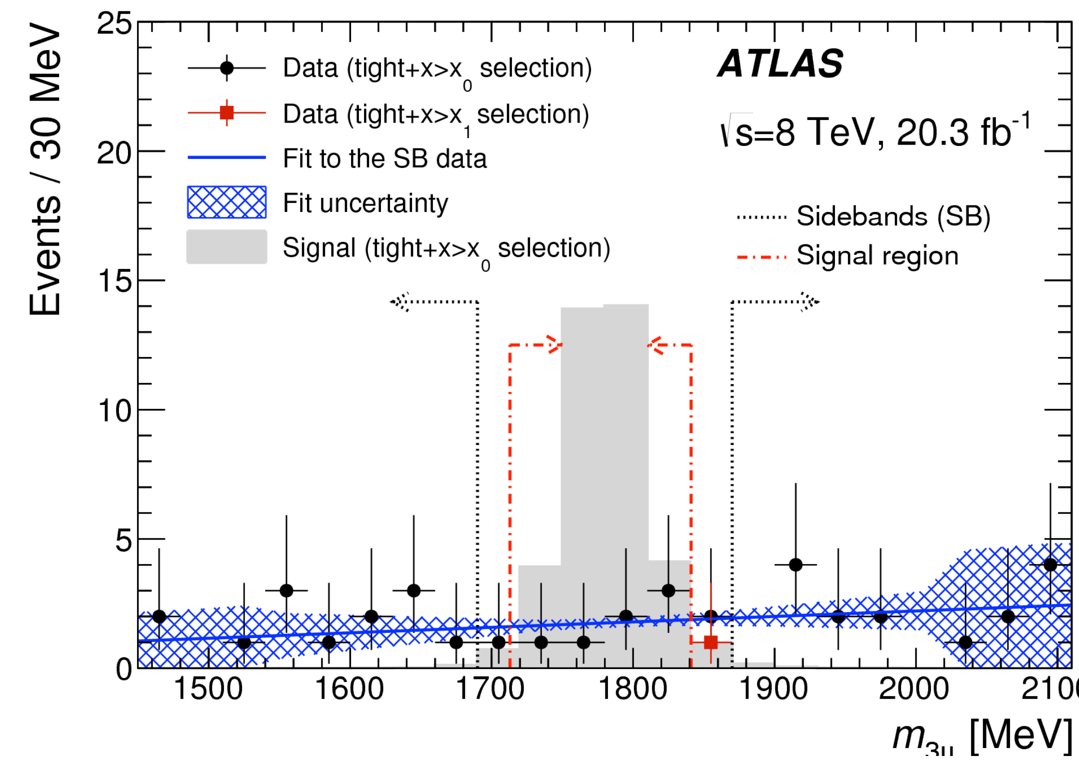


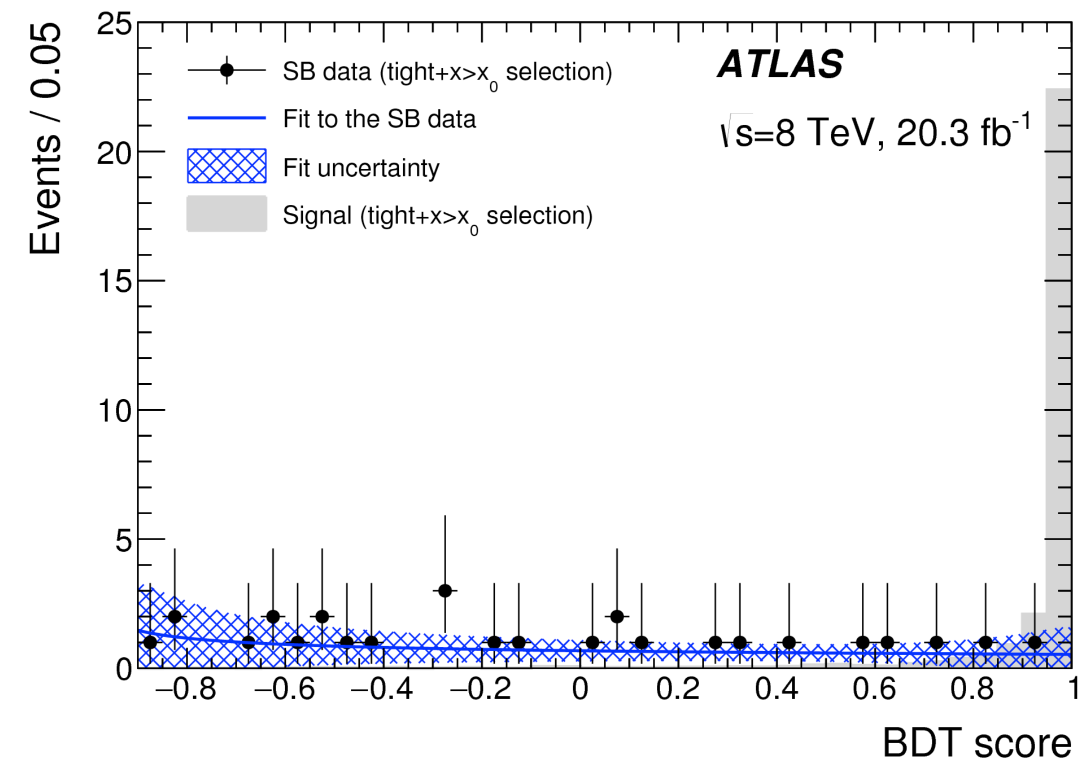
Top: Fit function

$$a \cdot m_{\ell\ell'}^{b} \cdot m_{\ell\ell'}^{c \cdot \ln(m_{\ell\ell'})} \quad \text{and} \quad \frac{a}{(m_{\ell\ell'} + b)^{c}}$$

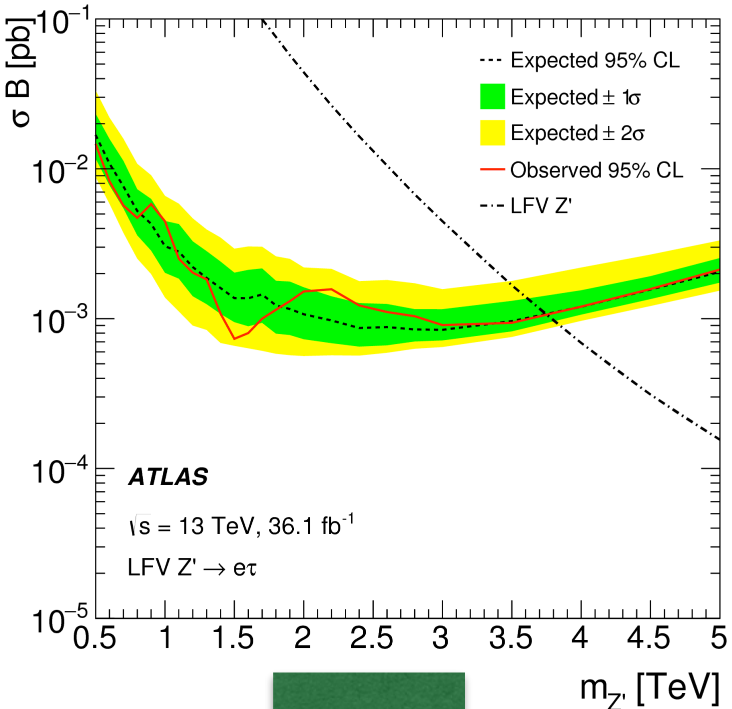
τ→3μ Search (1601.03567)

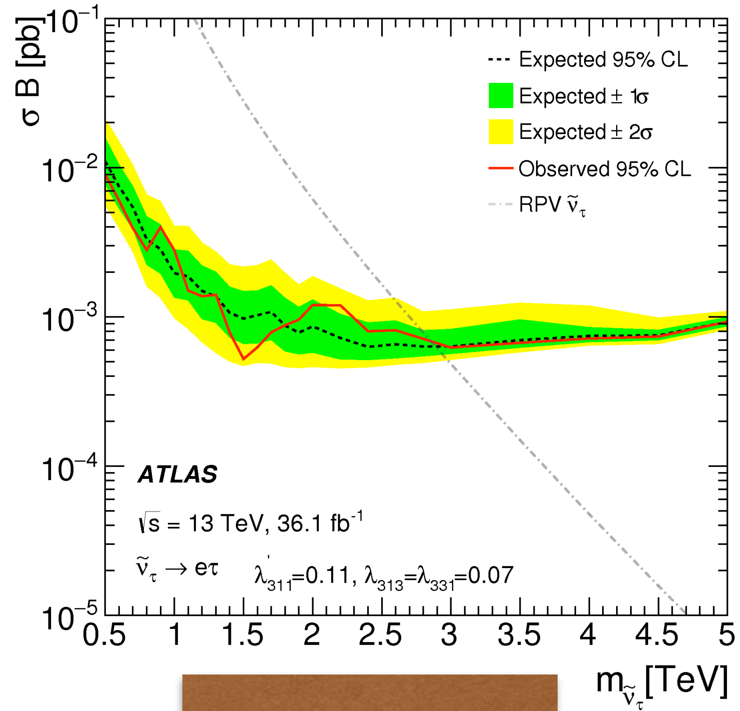
- τ→3μ measurement is possible via W→τ(→3μ)ν decay
- Very low background measurement
  - Estimated in sidebands
- Boosted decision tree trained on a loose selection (16 input variables)
- Signal extraction on fit of BDT score with tighter requirements
  - Limit is 3.76x10^{-7} of BR of τ decay

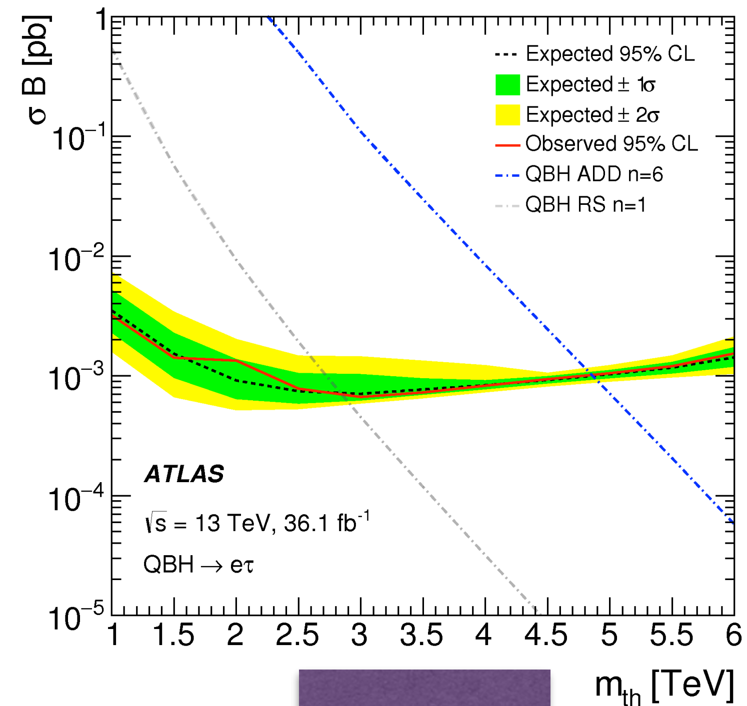




High mass limits





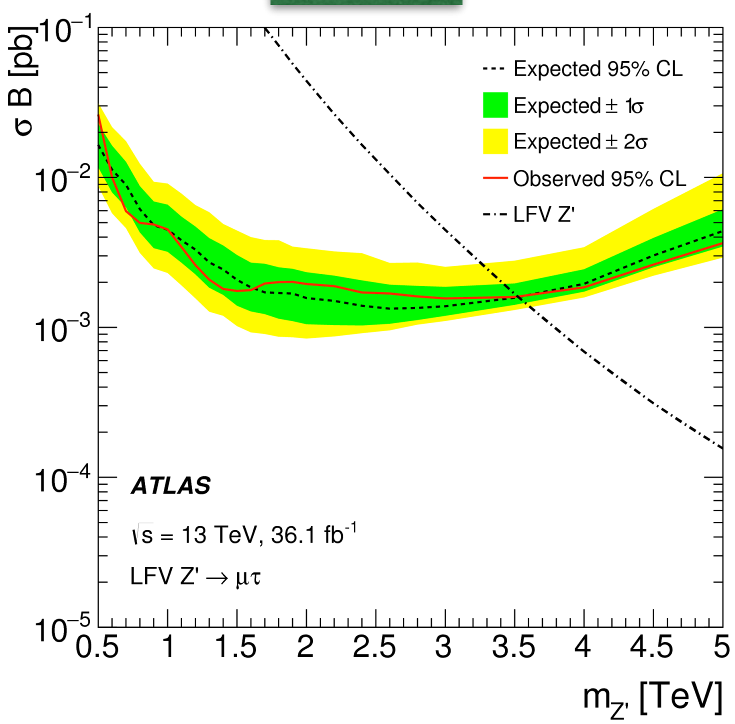


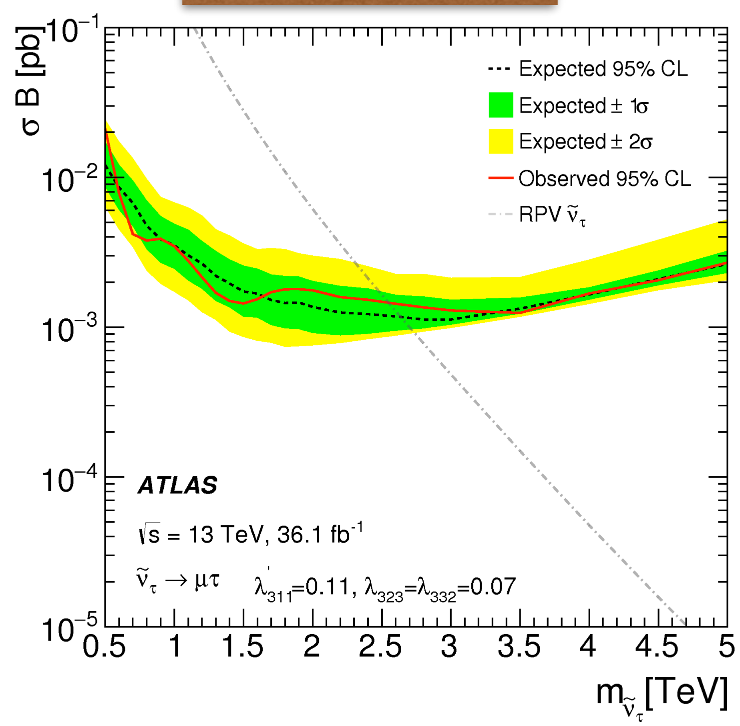
eτ

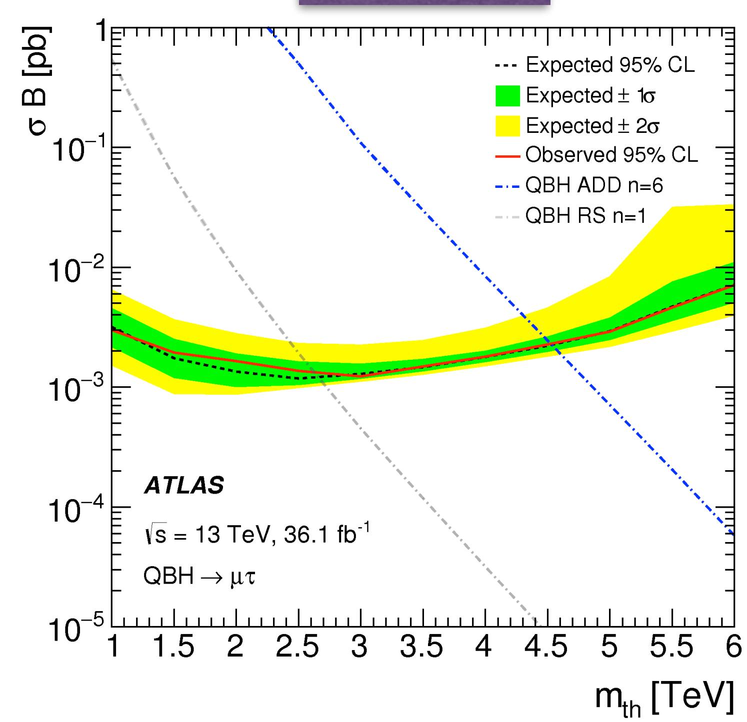
Z'

Sneutrino

QBH

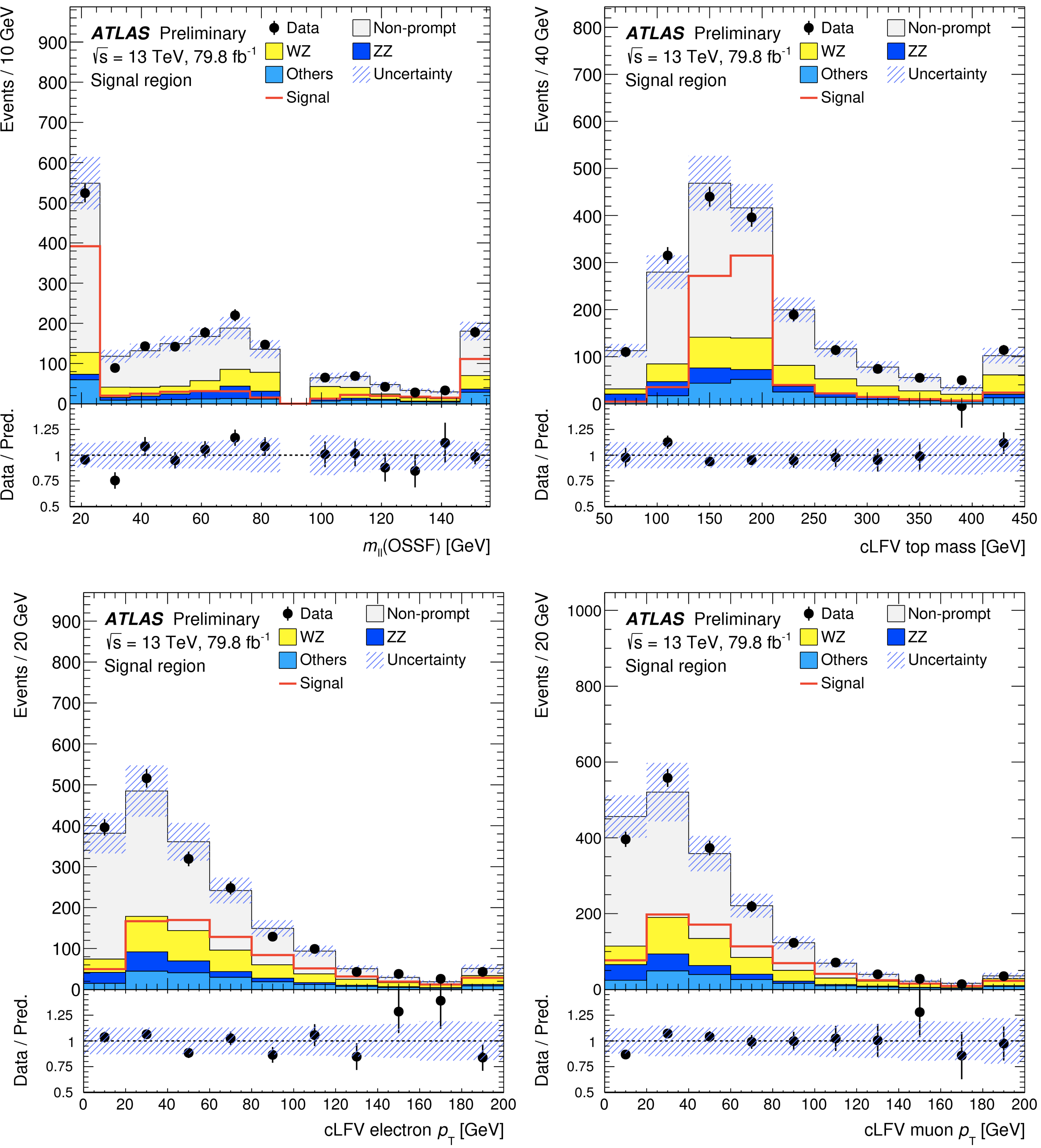






μτ

Top Quark Decays (BDT inputs)



Variable	Separation (%)
OSSF lepton pair invariant mass	11
cLFV top mass	10
p_T of the electron associated to the cLFV decay	9.1
p_T of the muon associated to the cLFV decay	8.5
p_T of the lepton associated to the SM decay	8.3
Scalar mass of all jets and leptons in the event	7.6
Same-sign electron pair invariant mass	6.9
Missing transverse momentum	6.8
Number of b-jets	6.7
W transverse mass associated to the SM top lepton	6.6
ΔR between the cLFV electron and the cLFV light jet	6.5
SM top mass	6.4
ΔR between the cLFV muon and the cLFV light jet	6.3
BDT discriminant	44