Searches for lepton flavour violation at ATLAS

Geert-Jan Besjes *(Niels Bohr Institute, University of Copenhagen)*

On behalf of the ATLAS collaboration

19th International Workshop on Neutrinos from Accelerators
Uppsala, 26 September 2017

ATLAS EXPERIMENT

Overview

- Standard Model: 3 generations of fermions
- Fermions can change flavour:
  - CKM matrix (quarks)
  - PMNS matrix (leptons, spec. neutrinos)

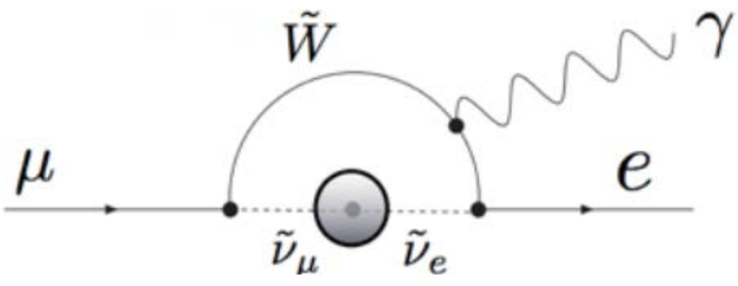
- *Charged* lepton flavour violation?
- Not observed yet!

- Neutrino oscillations imply **flavour violation in loops allowed in the SM**

- However, implied charged lepton flavour violation ***very* strongly constrained due to GIM mechanism**
- Several BSM scenarios raise the branching ratios to levels reachable at the LHC
- **Any observation is a discovery!**

- Spoiler: no such observations as of this conference

$\mu \to e\gamma$ in the SM…



…cannot be seen at the LHC:

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{M^2_W}\right|^2 \sim 10^{-54}$$

The diagram can be rotated to obtain e.g. LFV Z decays

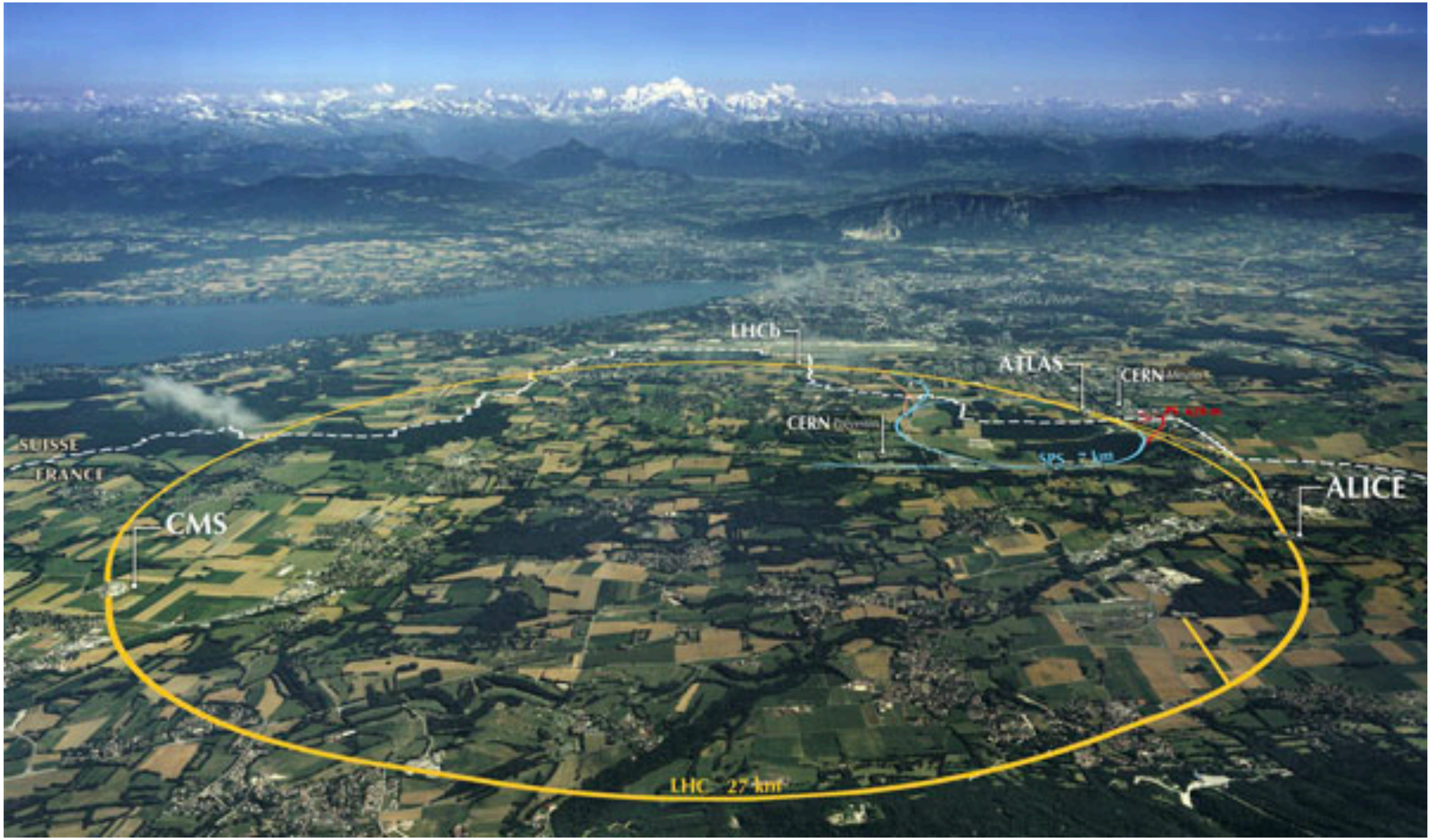
Lepton flavour violation at the LHC

- Lepton flavour violation at the LHC focuses on objects as result from p-p collisions

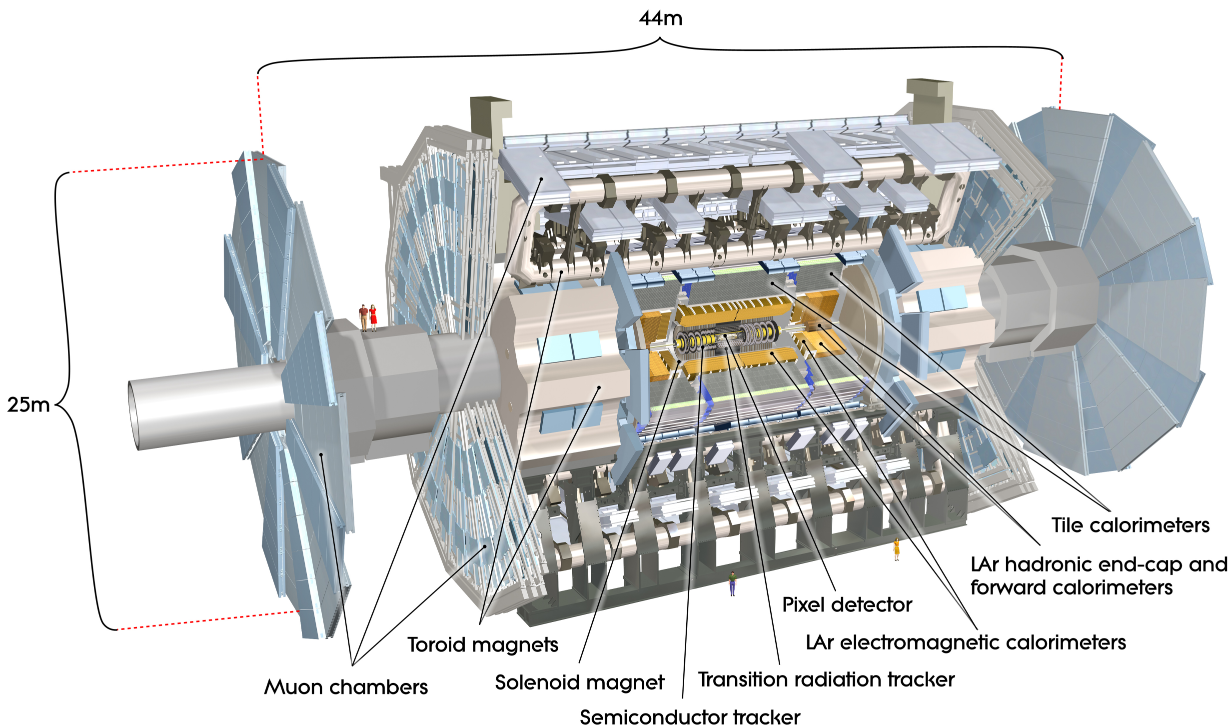
- Muon decays:
  - $\mu \to e\gamma$
  - $\mu \to 3e$
  - $\mu \to e$ conversion
- Tau decays:
  - $\tau \to e\gamma$
  - $\tau \to 3l$
- Meson decays:
  - $B^0/D^0 \to e\mu$

- In ATLAS, focus on:
  - Decays of Standard Model bosons (Z, Higgs)
  - Decays of heavy (neutral) particles (Z', ...)
  - $\tau \to 3\mu$

The Large Hadron Collider



The ATLAS experiment



- **High precision tracking system** (silicon pixels/strips and a transition radiation tracker), with **new 4th pixel layer: insertable b-layer (IBL)**
- **Two calorimeters** (EM: liquid Ar; hadronic: scintillating tiles + LAr endcaps)
- **Muon spectrometer** for muon identification (combined with tracker)
- **Two large magnet systems** (toroidal and solenoidal)
- **An efficient trigger/DAQ system to make the most of our data**

arXiv:1408.5774
arXiv:1604.07730

LFV decays of the SM Z boson

- Searches divided into fully leptonic channel and channels with taus ($Z \rightarrow e\mu$ and $Z \rightarrow \tau l$)
- Uses the full 2012 20.3 fb^{-1} dataset at $\sqrt{s} = 8$ TeV

- Channel-dependent strategies required, depending on presence of tau

- Without taus:
  - Find an excess on the Z peak $m(e\mu)$
  - Need to reject events with missing transverse energy
  - Major background $Z \rightarrow ll$ decays and leftover leptonic $Z \rightarrow \tau\tau$ events

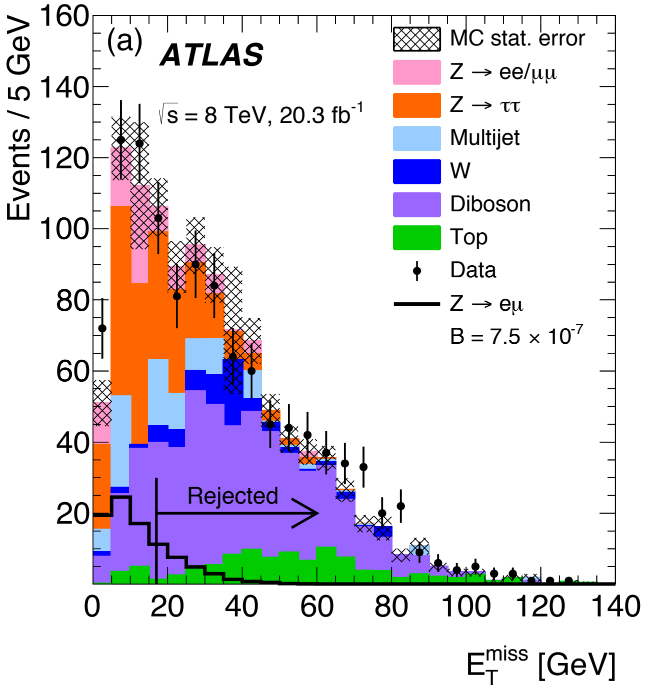
- With taus:
  - Focus on hadronic tau decays; split between flavours of lepton
  - Major background becomes $Z \rightarrow \tau\tau$ events
    - Missing transverse energy can no longer be straightforwardly exploited
    - Data driven techniques to estimate taus faked by jets
    - Clever techniques needed to separate $Z \rightarrow \tau_{lep}\tau_{had}$ from signal
  - No result on $Z \rightarrow \tau e$ channel

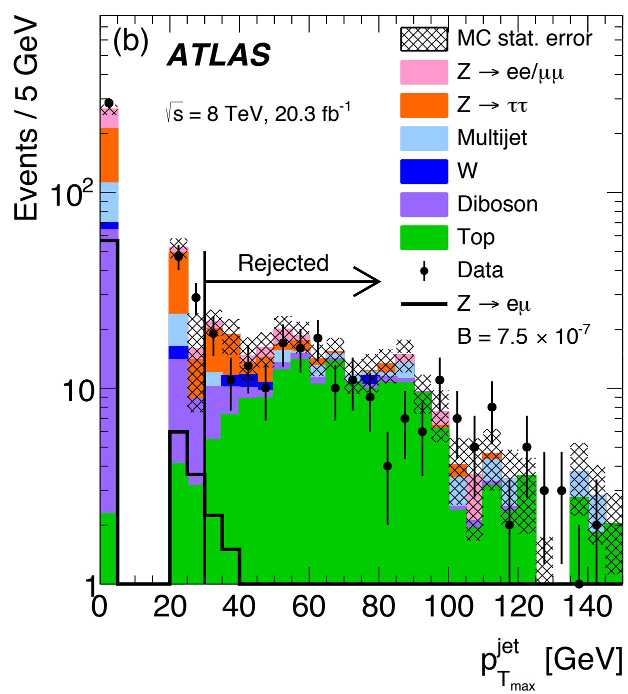
ATLAS EXPERIMENT

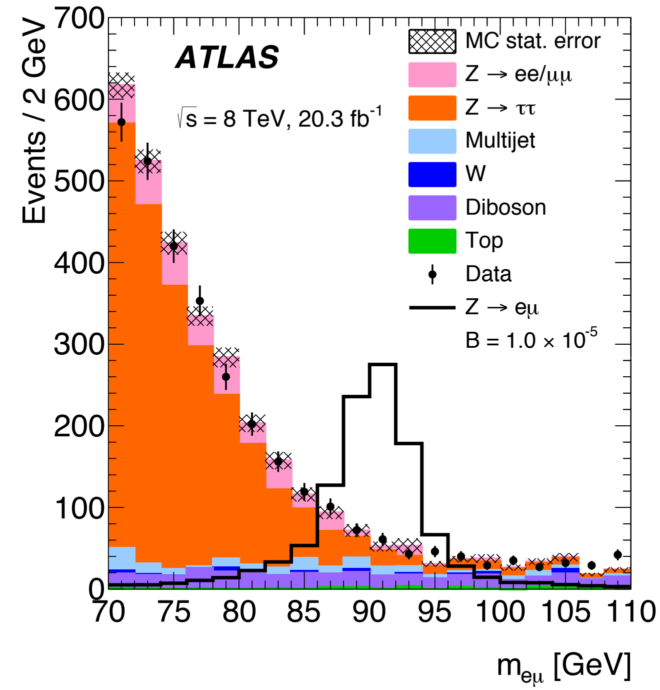
arXiv:1408.5774

LFV decays of the SM Z boson: $Z \rightarrow e\mu$

- **Require two opposite-charge different-flavour leptons**
- Reject events with high missing transverse momentum (e.g. WW, Ztautau)
- Reject events with high-pT jet activity (e.g. ttbar)
- This way, obtain a "clean" invariant mass spectrum
- **3rd order Chebychev polynomial fit to background**







Left two figures shown for 85 GeV < m(eμ) < 95 GeV

arXiv:1408.5774

LFV decays of the SM Z boson: Z → eμ

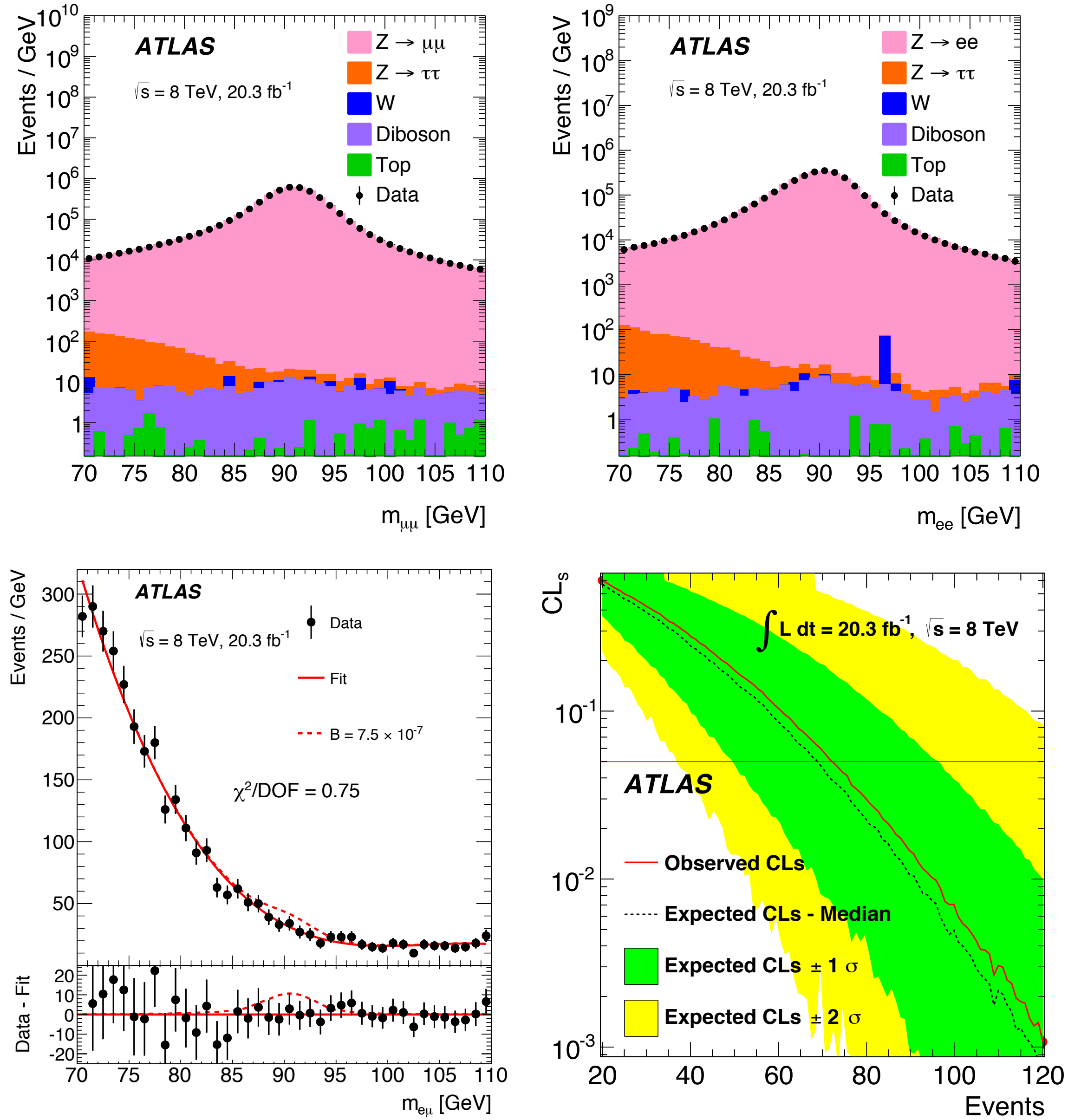
- Branching ratio estimate as ratio of 95% limit on Z → eμ events and total Z production:

$$\mathrm{BR}(Z \to e\mu) < \frac{N_{95\%}}{\epsilon_{e\mu} N_Z}$$

- N_Z estimated as weighted average from dilepton decays
- Relative ratios Z → ee and Z → μμ from events in window between 70 and 110 GeV

- Resulting limit:

$$\mathrm{BR}(Z \to e\mu) < 7.5 \times 10^{-7}$$



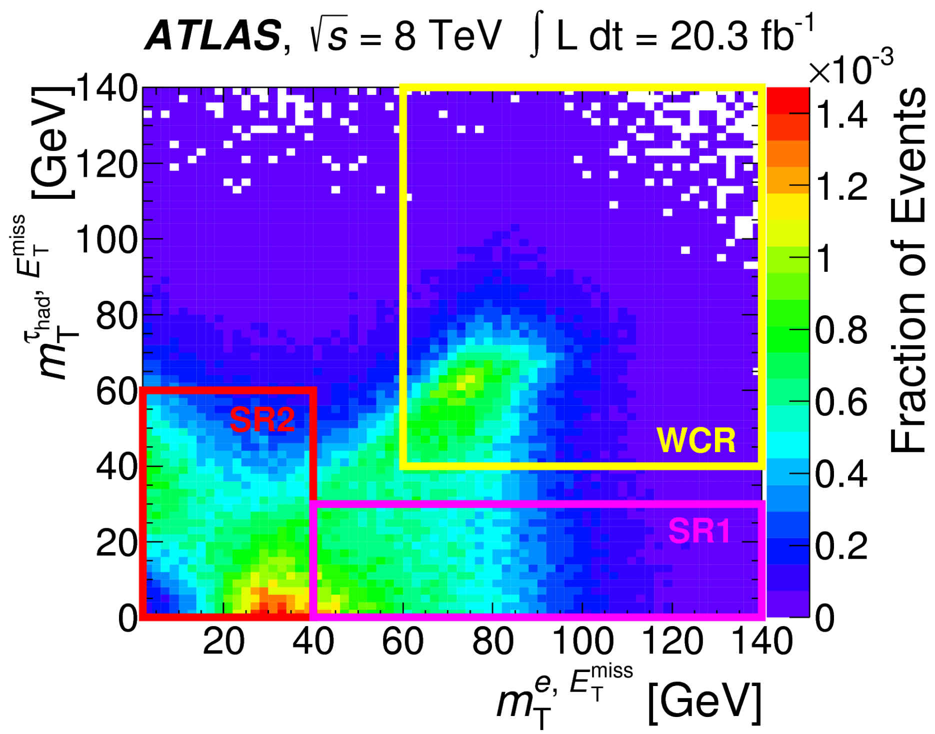
ATLAS EXPERIMENT

arXiv:1604.07730

LFV decays of the SM Z boson: $Z \rightarrow \tau_{had}\mu$

- Exploit fact that hadronic decay of tau lepton leads to missing energy
  - Can construct transverse mass of τ-MET and lepton-MET systems
  - In case missing transverse energy aligned with tau, mT(τ, MET) is small
  - Signal dominated by low mT(τ, MET) and moderate mT(lepton, MET)
  - Rectangular selections in two dimensional phase space define regions

- Reject events with b-jets and require $|\eta(\tau) - \eta(l)| < 2$ to reject W+jets and multijet events
- Irreducible backgrounds: $Z \rightarrow \tau\tau$, diboson (WW), $H \rightarrow \tau\tau$ and top



arXiv:1604.07730

LFV decays of the SM Z boson: Z → $\tau_{had}\mu$

- Events then categorised using Missing Mass Calculator (MMC)
- Attempts to minimise likelihood functions to take into account missing energy from neutrino
- Adapted parametrisation from H → ττ searches

- Background modelling combination of MC and data-driven corrections
  - Dedicated control regions used to use normalise real backgrounds
  - Multijets and fakes from data using opposite- minus same-sign method:

$$N_{\mathrm{OS}}^{\mathrm{bkg}} = r_{\mathrm{QCD}} \cdot N_{\mathrm{SS}}^{\mathrm{data}} + \sum_{i\in\mathrm{bkg}} N_{\mathrm{OS-SS}}^{\mathrm{i}}$$

same-sign data sample that accounts for fakes

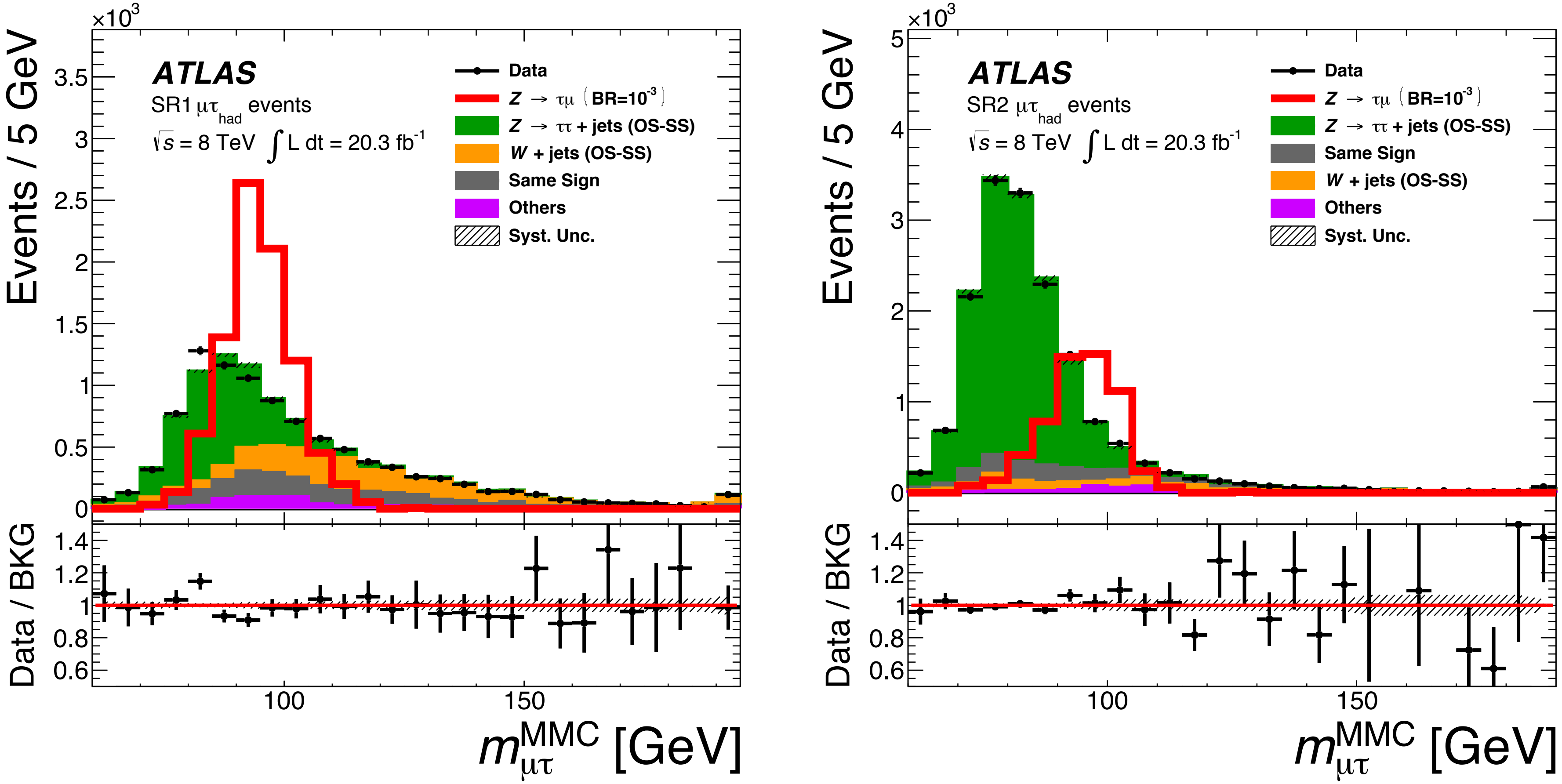
for every background, a "add-on" term of OS-SS events from MC normalised to data

  - Correction factor rQCD is ratio OS/SS measured in dedicated multijet control region

- Simultaneous likelihood fit of signal region plus W and top control regions to extract signal
- No Z control region: Z → ττ taken from embedded sample of Z → ττ data
  - *Embedding*: replace muons with simulated taus

arXiv:1604.07730

LFV decays of the SM Z boson: $Z \rightarrow \tau_{had}\mu$



$Br(Z \rightarrow \mu\tau)[10^{-5}]$	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	$-2.1^{+1.2}_{-1.3}$	$2.6^{+2.9}_{-2.6}$	$-1.6^{+1.3}_{-1.4}$

arXiv:1508.03372

arXiv:1604.07730

LFV decays of the Higgs boson

- Part of an effort to study Higgs properties
- LFV couplings can be introduced through effective field theories

- Searches can be categorised as $H \to e\mu$, and $H \to \tau\mu$ and $H \to \tau e$
- No published ATLAS result on the first channel
- Results with taus use the full 2012 20.3 fb^{-1} dataset at $\sqrt{s}$ = 8 TeV

- Leptonic tau decays also considered
  - Exploit angular separation between leptons
  - Collinear mass approximation for lepton from tau decay

- Strategy with hadronic taus very similar to searches for Z decays
  - Kinematic windows shift towards higher invariant mass
  - Fewer $Z \to \tau\tau$ events as background
  - $H \to \tau\tau$ events become relevant
  - Sources of reducible backgrounds remain the same

- Results in more stringent limits than indirect searches!

arXiv:1604.07730

LFV decays of the Higgs boson: H → τ_{lep}e, H → $\tau_{lep}\mu$

- Events selected an opposite-sign electron-muon pair
  - Highest-p_T object labelled l_1, the other l_2
  - Used to define eμ and eμ categories

- Two exclusive signal regions: with no central jets, or at least one central jet
- Collinear mass approximation used to reconstruct Higgs mass:

$$m_{\text{coll}} = \sqrt{2p_{\text{T}}^{\ell_1}\left(p_{\text{T}}^{\ell_2} + E_{\text{T}}^{\text{miss}}\right)\left(\cosh\Delta\eta - \cos\Delta\phi\right)}$$

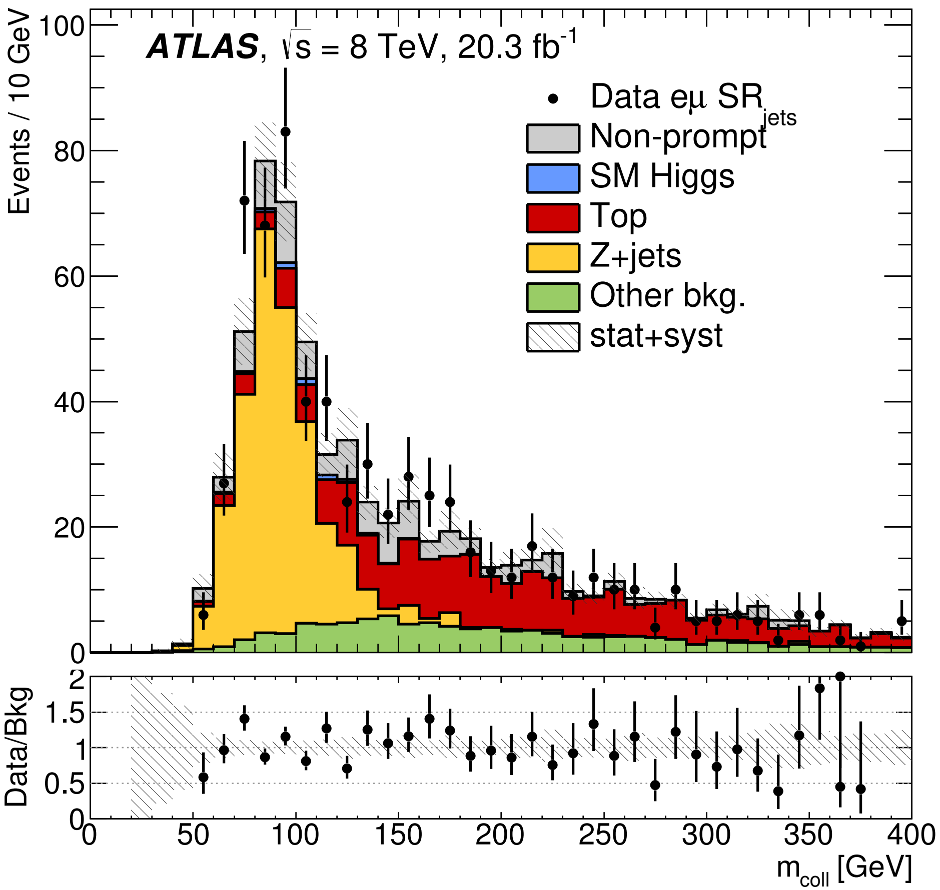
- Correction factors for asymmetry between categories derived
  - Non-prompt leptons
    - Estimated using a matrix method
    - Efficiencies for prompt and non-prompt estimated using tag-and-probe method
  - Different trigger and reconstruction efficiencies
    - Since leading lepton is on trigger plateau, factorises to a function of $pT(l_2)$
    - Determined in 3 bins: 12 to 20 GeV, 20 to 30 GeV, and above 30 GeV

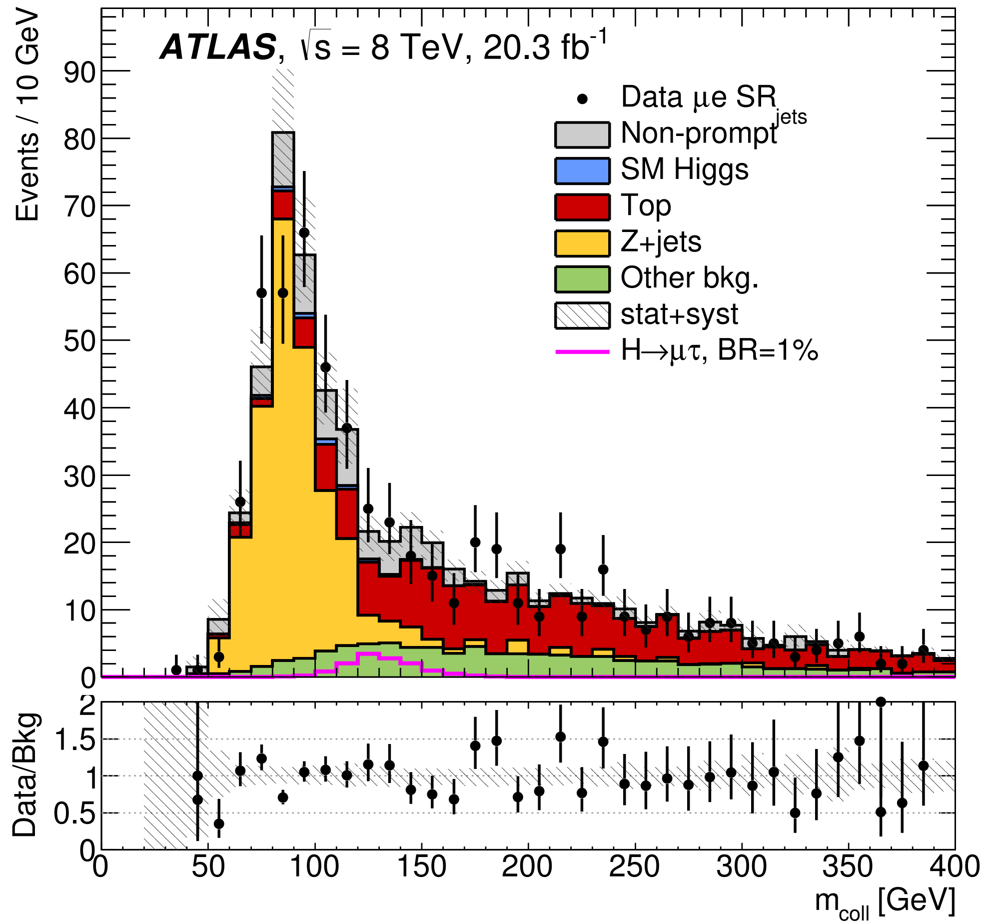
- Combined statistical model fits the symmetric component, non-prompt contributions

ATLAS EXPERIMENT

arXiv:1604.07730

LFV decays of the Higgs boson: $H \to \tau_{lep} e$, $H \to \tau_{lep} \mu$

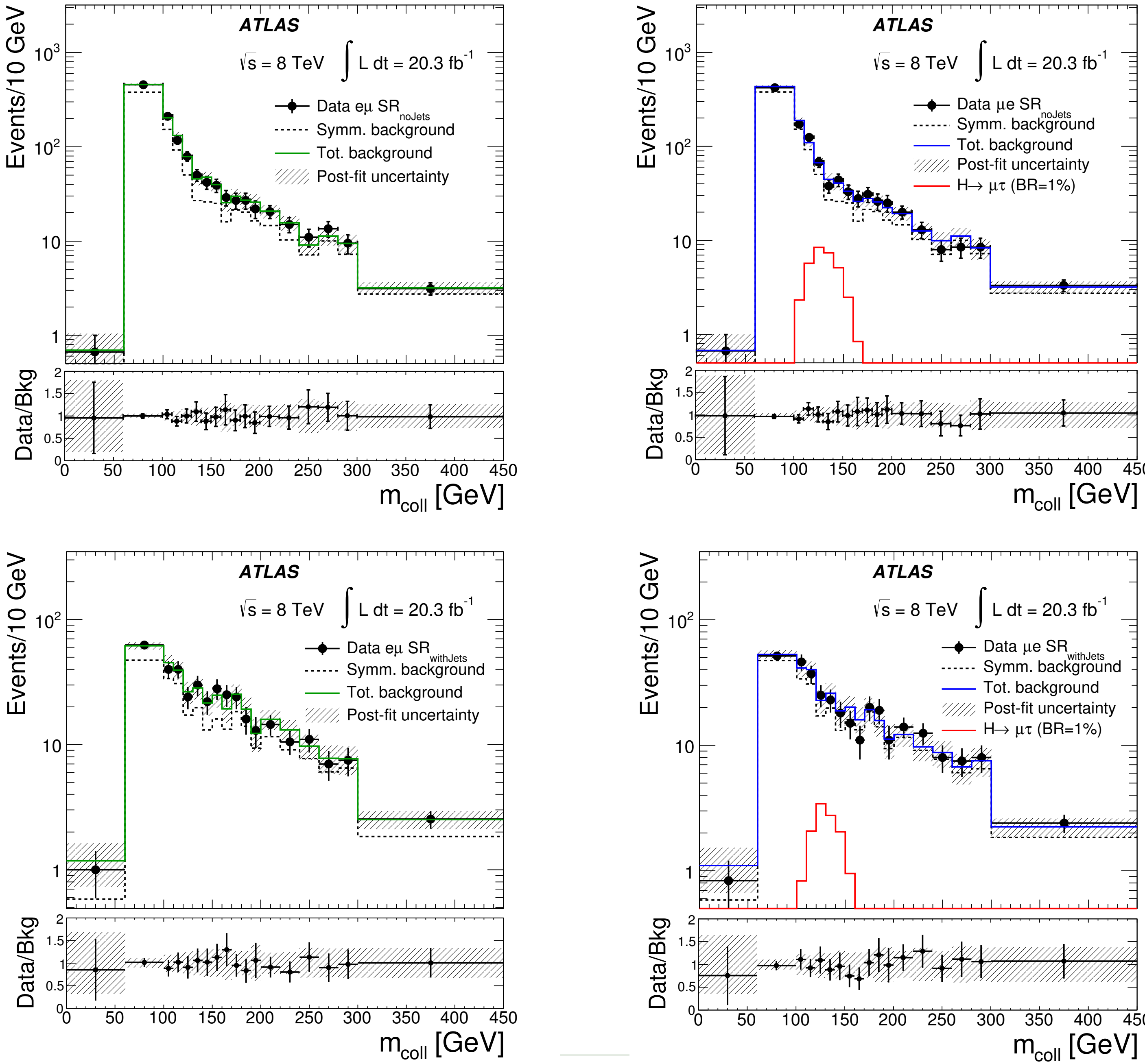




Background modelling before asymmetry corrections

arXiv:1604.07730

LFV decays of the Higgs boson: $H \to \tau_{lep} e$, $H \to \tau_{lep} \mu$



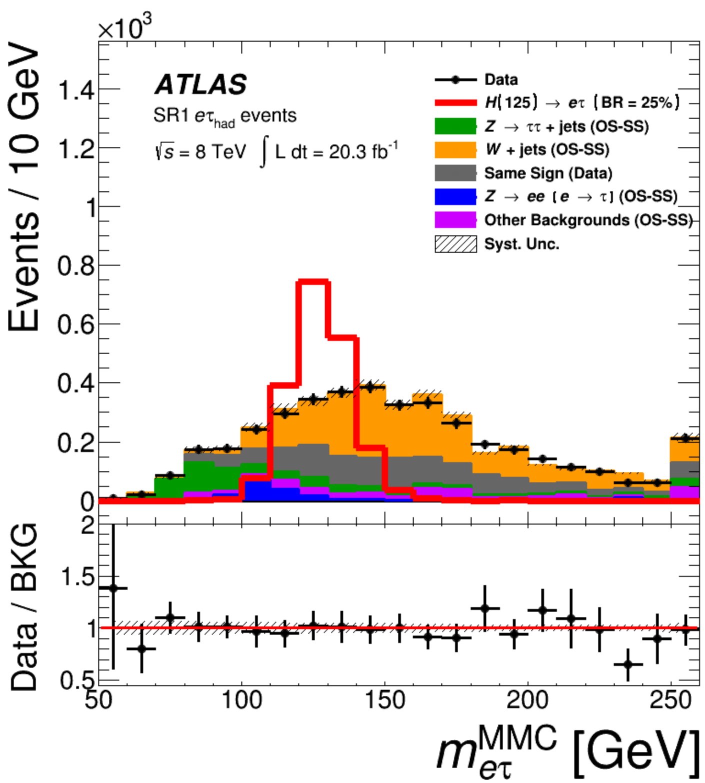
arXiv:1508.03372

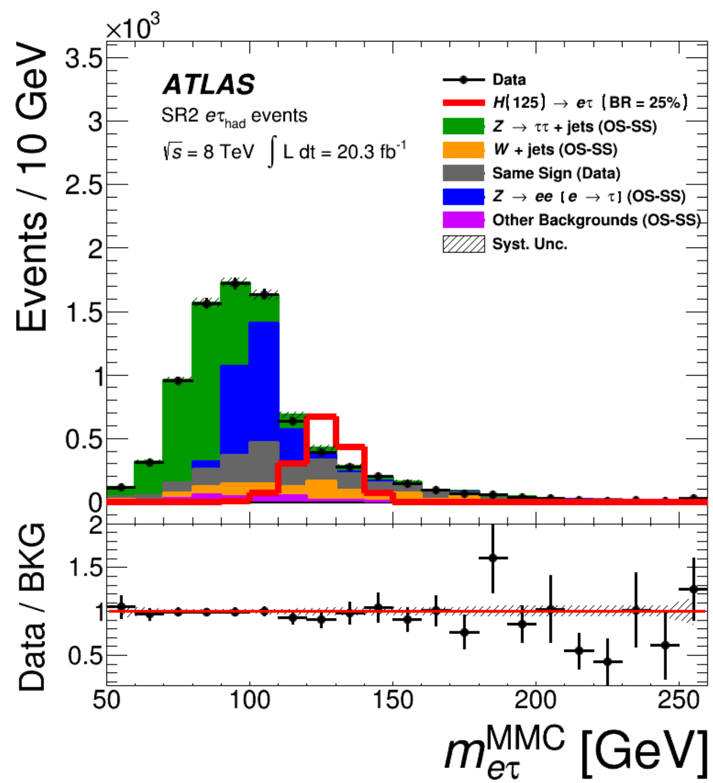
arXiv:1604.07730

LFV decays of the Higgs boson: $H \rightarrow \tau_{had}e$, $H \rightarrow \tau_{had}\mu$

- Very similar methodology to analysis in Z channel
  - Slightly different kinematic selections due to m(H) versus m(Z)
  - Again two signal regions per lepton flavour defined

- Also relies on the MMC to extract a signal



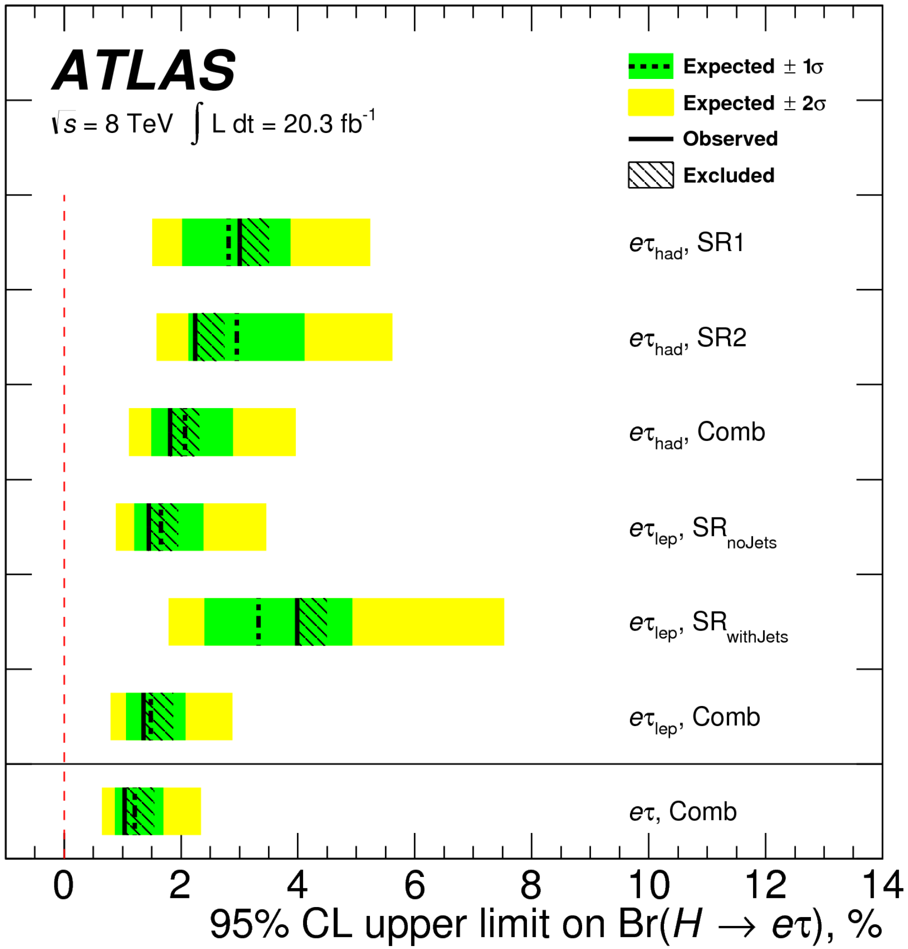


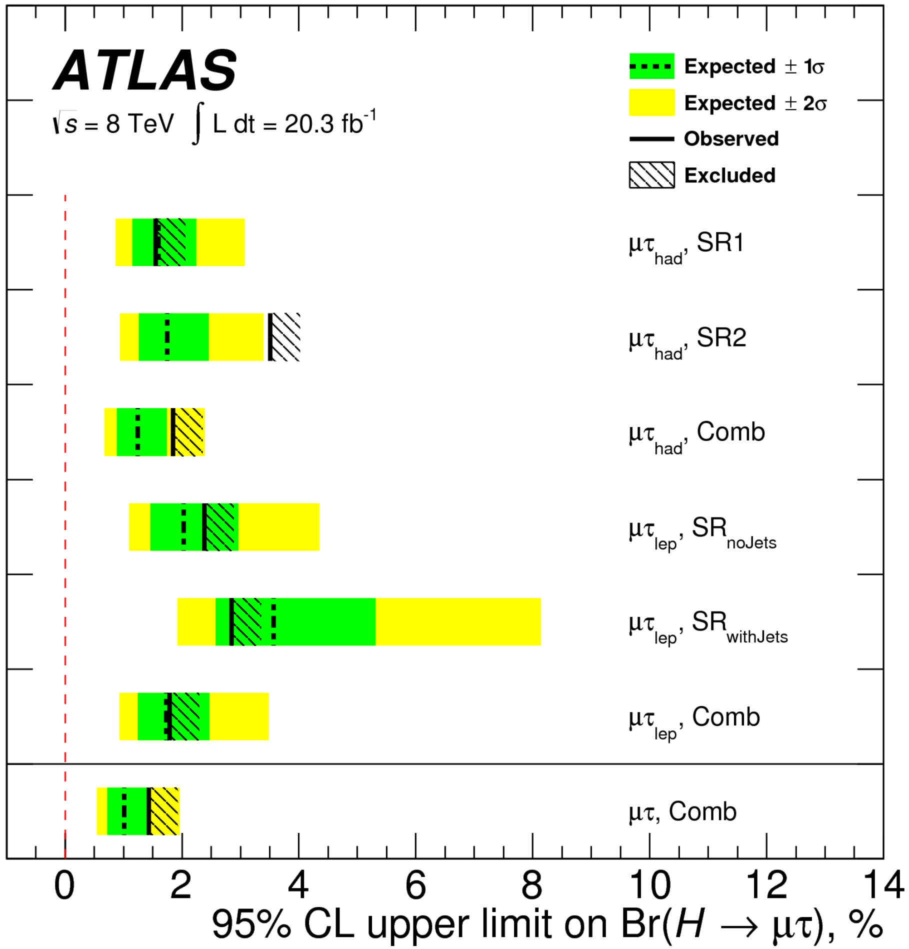
ATLAS EXPERIMENT

arXiv:1508.03372

arXiv:1604.07730

LFV decays of the Higgs boson





arXiv:1601.03567

High-mass dilepton searches

- **LFV processes could involve decaying heavy particles**
- These lead to high-mass different-flavour dilepton events
- Uses the run-2 dataset from 2015 ($\sqrt{s}$ = 13 TeV) of 3.2 fb-1

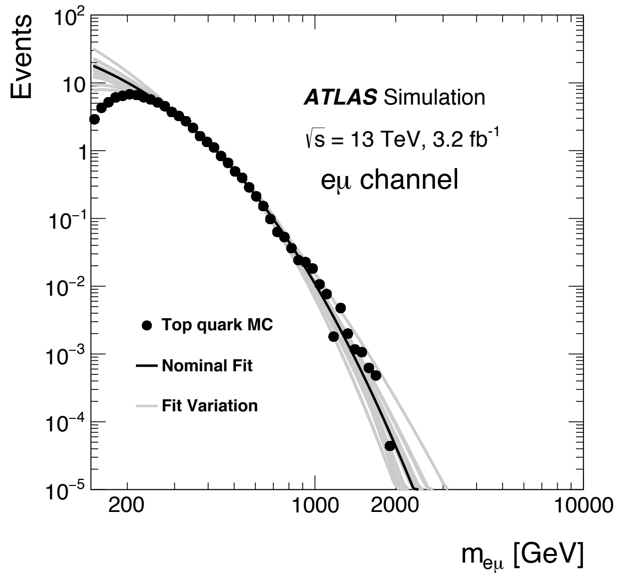
- **Basic strategy:**
  - Select two events with different flavours of leptons in 3 channels
  - Construct invariant mass distribution,
    taking fake taus into account
  - Extrapolate top background to high mass
  - Top quark background dominates eμ channel;
    W+jets in channels with taus

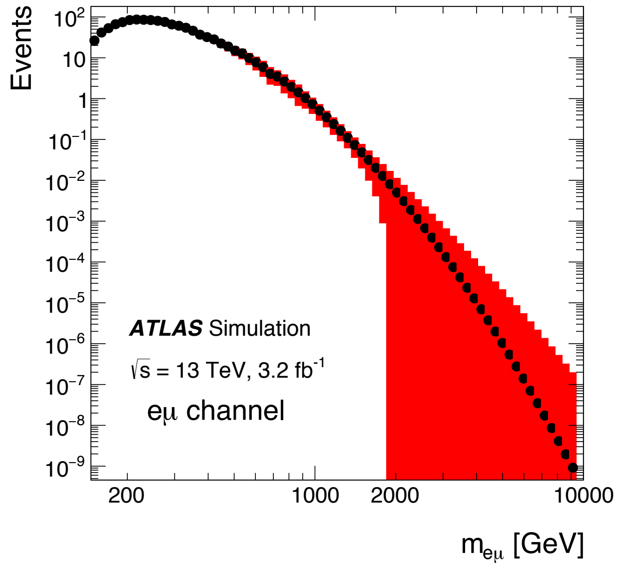
- **Interpretations in three models using a Bayesian method** (binned marginal likelihood):
  - *Z'*: heavy gauge boson with same quark couplings as Z and LFV couplings Q_{ij}
  - *Quantum Black Holes*: QBHs produced at Plank scale;
    could violate lepton flavour in decay
  - *RPV SUSY*: most SUSY models introduce *R-parity* to prevent proton decay;
    however, R-parity violating SUSY could still violate lepton *or* baryon number separately

arXiv:1607.08079

High-mass dilepton searches

- Backgrounds involve:
  - top (ttbar, single-t), DY → ll, diboson (MC);
  - W+jets (MC+data-driven);
  - and multijet events (data-driven)
- Tau fake rate measured in data in a W+jets control region; applied as weight to W+jets
  - Normalisation estimated in signal-free subset of signal region with MET > 30 GeV and pT(tau) < 150 GeV
- Top background extrapolated to high mass through fit for each channel
  - Dependency on fit range is source of systematic error



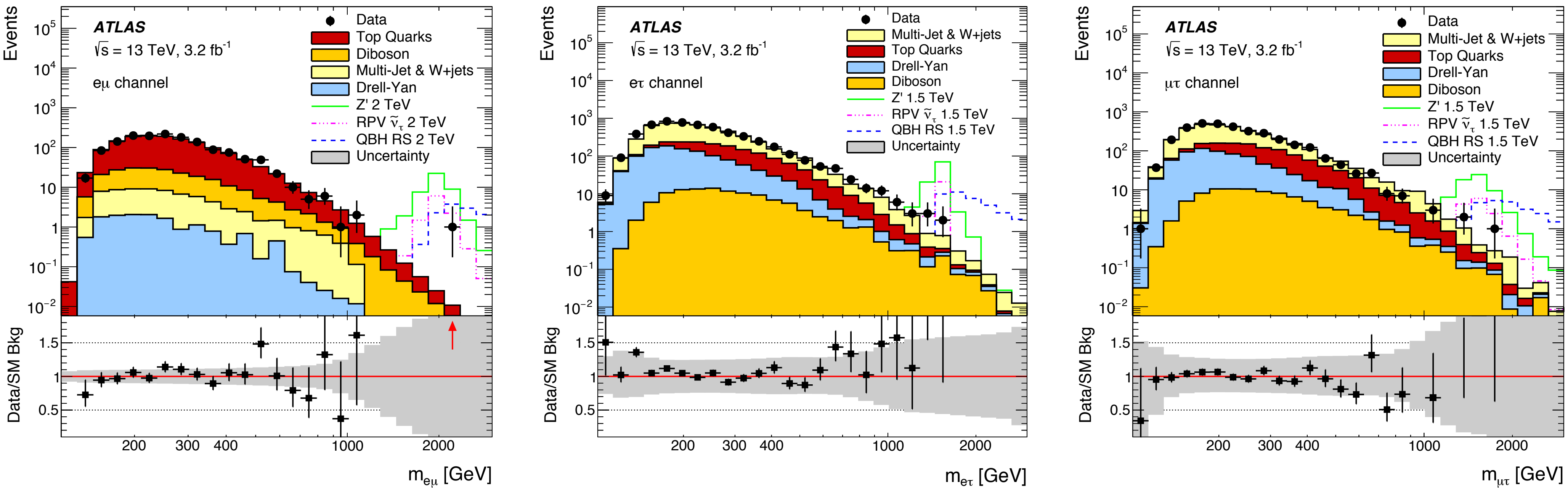


Process	$m_{e\mu} < 600$ GeV	$m_{e\mu} > 600$ GeV
Top quark	1190 ± 140	22 ± 5
Diboson	159 ± 17	4.9 ± 0.9
Multi-jet and W+jets	55 ± 11	2.7 ± 1.7
$Z/\gamma^* \to \ell\ell$	14.5 ± 2.0	0.18 ± 0.04
Total SM background	1410 ± 150	30 ± 7
SM+Z' ($M_{Z'} = 2$ TeV)	-	75 ± 13
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau} = 2$ TeV)	-	40 ± 8
SM+QBH RS $n = 1$ ($M_{\text{th}} = 2$ TeV)	-	44 ± 9
Data	1463	25

(a) $e\mu$ channel

arXiv:1607.08079

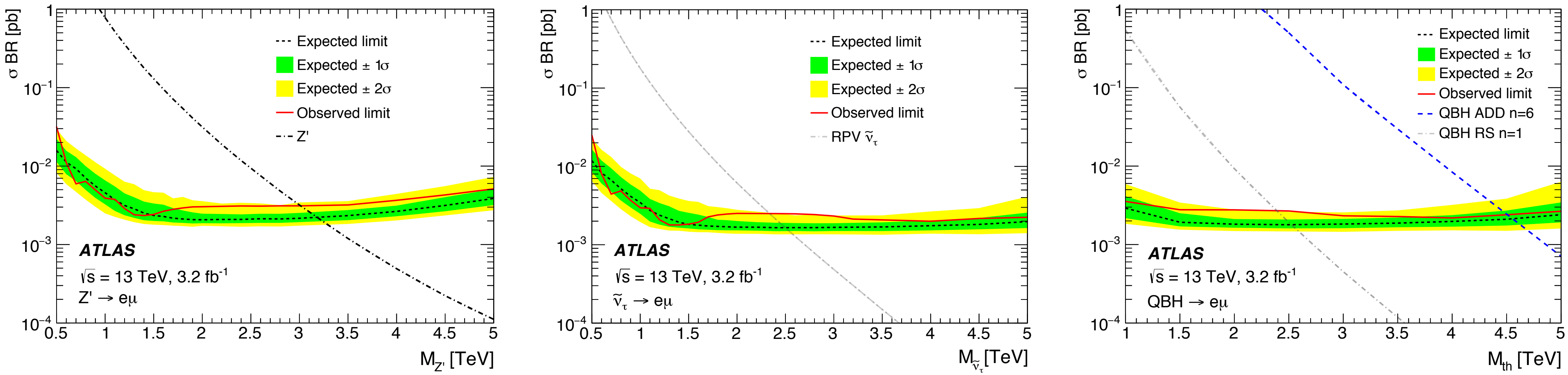
High-mass dilepton searches



- No significant deviations from the SM observed
- Slight deficit in tau-muon channel
- Single event at 2.1 TeV in the electron-muon channel

arXiv:1607.08079

High-mass dilepton searches



Model	Expected Limit [TeV]			Observed Limit [TeV]		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
Z'	3.2	2.7	2.6	3.0	2.7	2.6
RPV SUSY $\tilde{\nu}_\tau$	2.5	2.1	2.0	2.3	2.2	1.9
QBH ADD $n = 6$	4.6	4.1	3.9	4.5	4.1	3.9
QBH RS $n = 1$	2.5	2.2	2.1	2.4	2.2	2.1

For Z', only one decay allowed at the same time.

For RPV, identical coupling to tau sneutrino for all channels.

arXiv:1601.03567

Neutrinoless $\tau \to 3\mu$ decays

- Decays involving tau leptons and muons are golden channels for LFV searches

- In the SM, BR($\tau \to 3\mu$) is approx 10^{-14}
- BSM scenarios increase the branching ratio to 10^{-10} to 10^{-8}
- Current limits from b-physics (Babar, Belle, LHCb) at 10^{-8}

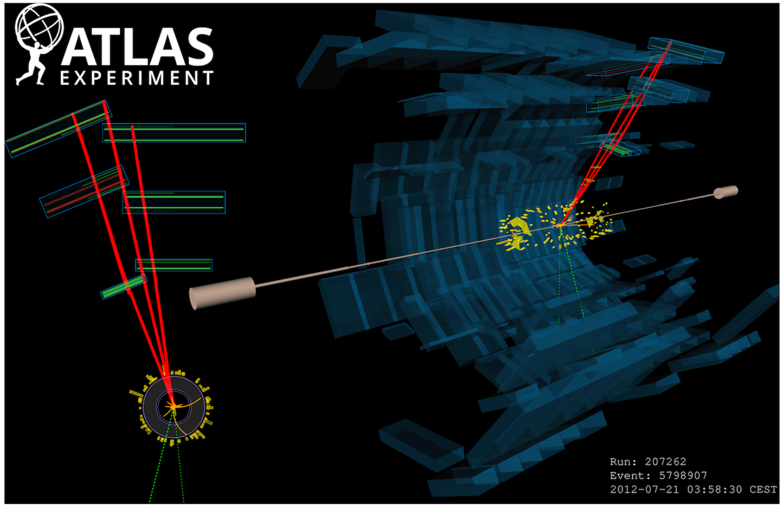
- Difficult search to perform at hadron colliders: very low energy muons
- Need to exploit multi-object triggers to record enough data
- Uses the full 20.3 fb^{-1} dataset at $\sqrt{s}$ = 8 TeV

- Basic strategy:
  - select 3 muons from the same vertex;
  - categorise the events according to the 3-muon invariant mass;
  - fit sidebands to obtain yield in mass window;
  - extract a limit at 90% CL

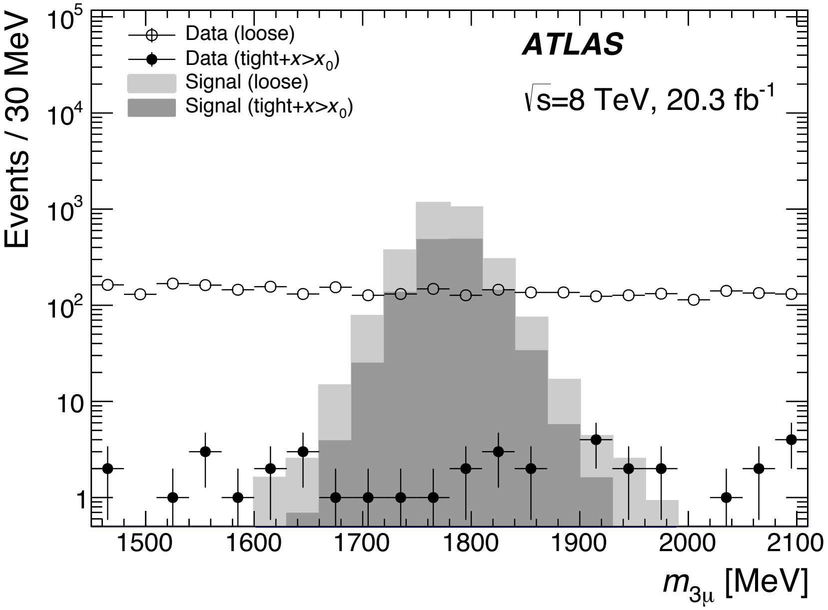
arXiv:1601.03567

Neutrinoless τ → 3μ decays

- Use decays W → τν → 3μν
  - Tau lepton produced with a transverse momentum, typically 25 to 50 GeV
  - Muons from tau decay close in space
  - Neutrino carries away missing transverse energy
- Basic selection: 3 muons from same vertex with |m(3μ) – m(τ)| < 1 GeV
  - Require m(3μ) < 2.5 GeV; pT(μ) > 2.5 GeV
  - Rely on several multi-muon triggers
- Events then categorised according to m(3μ)
  - Loose selection to train BDT
  - Study rejection in sidebands; tighter selection defined through optimisation on limit



Region	Range in $m_{3\mu}$ [MeV]
Signal region	[1713, 1841]
Blinded region	[1690, 1870]
Sideband region	[1450, 1690] and [1870, 2110]
Training region	[750, 1450] and [2110, 2500]



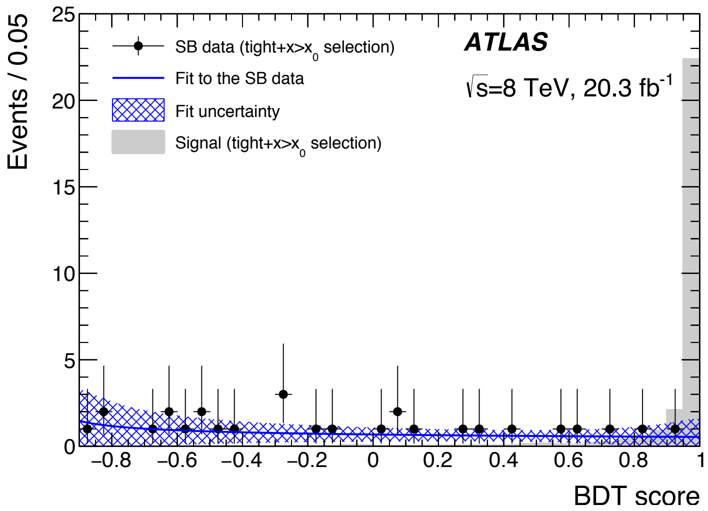
arXiv:1601.03567

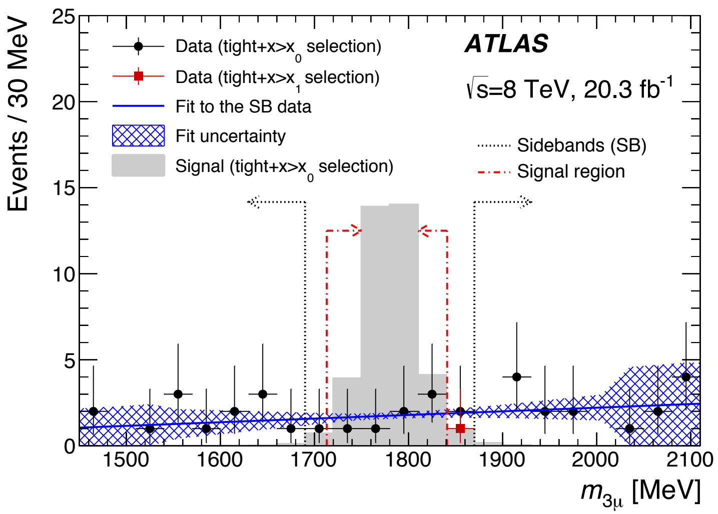
Neutrinoless $\tau \rightarrow 3\mu$ decays

- Loose selection used to train BDT
- Tighter selection adds several additional selections and a loose BDT score requirement x_0
- BDT score fit in looser category; fraction of selected events used for scaling mass distributions
  - Events with $x > x_0$ used for fit
  - Scales background with fraction of events with tighter selection $x > x_1$
- Background rejection as function of score optimised by maximising expected exclusion limit

- Single event with 1860 MeV observed
- 90% CL limit BR($\tau \rightarrow 3\mu$) < 3.76×10^{-7}
- Not competitive yet with LHCb or b-factories; shows potential in ATLAS for such searches with larger dataset
- Expect to be competitive with Belle at the end of run 2 (data taking up to end 2018)

BDT score in sideband region



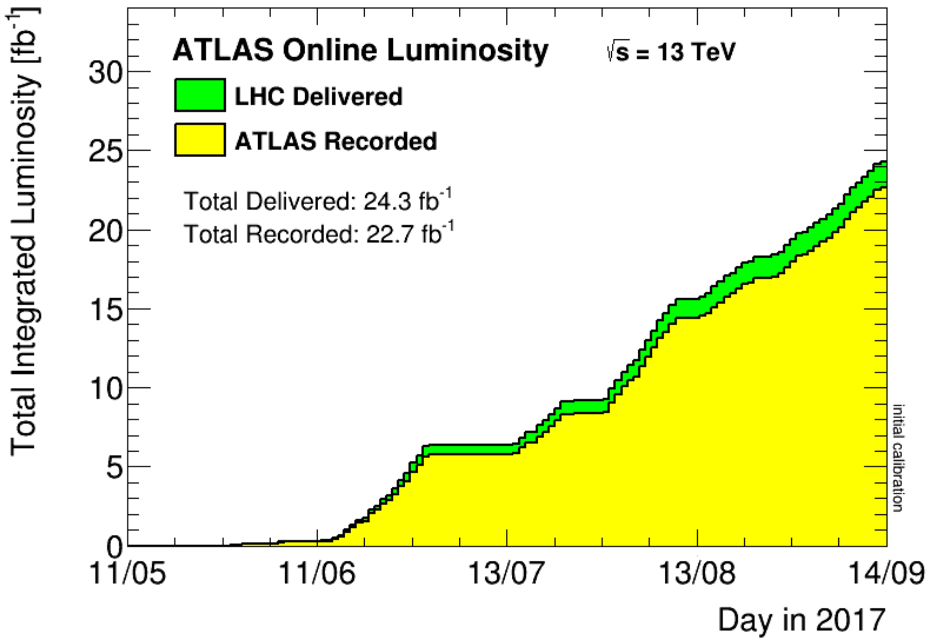


Summary

- Presented several searches at 8 and 13 TeV
- No evidence or discovery of LFV processes (yet?)

- Many more searches using the full 2015+2016 dataset in progress…
- …as well as ongoing preparations to exploit the entire run-2 dataset (expect around $100fb^{-1}$)

- Stay tuned for updates of several of these searches!



Backup

$Z \to \tau_{had}\,\mu/e$: signal and control regions

Cut	SR1	SR2	WCR	TCR
$p_T(\mu)$	>30 GeV	>30 GeV	>30 GeV	>30 GeV
$p_T(\tau_{had})$	>30 GeV	>30 GeV	>30 GeV	>30 GeV
$\lvert\eta(\mu) - \eta(\tau_{had})\rvert$	<2	<2	<2	<2
$m_T^{\mu,E_T^{miss}}$	>30 GeV and <75 GeV	<30 GeV	>60 GeV	–
$m_T^{\tau_{had},E_T^{miss}}$	<20 GeV	<45 GeV	>40 GeV	–
N_{jet}	–	–	–	>1
N_{b-jet}	0	0	0	>0

$Z \rightarrow \tau_{had}\, \mu/e$: signal region yields

	SR1	SR2
Signal	86 ± 2 ± 22	56± 2± 18
$Z \rightarrow \tau\tau$	3260 ± 30 ± 60	7060± 40±150
W+jets	1350 ± 70 ±110	590± 50± 70
Same–Sign events	1110 ± 40 ±100	930± 30± 90
$VV + Z \rightarrow \mu\mu$	410 ± 60 ± 50	240± 60± 60
$H \rightarrow \tau\tau$	25.1± 0.5± 3.0	41± 1± 5
Top	22 ± 4 ± 4	15± 4± 4
Total background	6170 ±100 ±100	8880±100±140
Data	6134	8982

$H \to \tau_{had}\,\mu/e$: signal and control regions

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

$H \to \tau_{had}\,\mu/e$: signal region yields

	SR1			SR2		
LFV signal (Br($H \to e\tau$) = 1.0%)	75	± 1	± 8	59	± 1	± 8
W+jets	740	±80	±110	370	±60	±70
Same-Sign events	390	±20	± 60	570	±30	±80
$Z \to \tau\tau$	116	± 8	± 11	245	±11	±20
VV and $Z \to ee(jet \to \tau_{\text{had}}^{\text{misid}})$	71	±31	± 30	60	±20	±40
$Z \to ee(e \to \tau_{\text{had}}^{\text{misid}})$	69	±17	± 11	320	±40	±40
$t\bar{t}$ and single top	18	± 5	± 4	10.2	± 2.6	± 2.2
$H \to \tau\tau$	4.6	± 0.2	± 0.7	10.5	± 0.3	± 1.5
Total background	1410	±90	± 70	1590	±80	±70
Data	1397			1501		

H → μe: signal regions

	$\mathrm{SR}_{\mathrm{noJets}}$	$\mathrm{SR}_{\mathrm{withJets}}$
Light leptons	$e^{\pm}\mu^{\mp}$	$e^{\pm}\mu^{\mp}$
τ_{had} leptons	veto	veto
Central jets	0	≥ 1
b-jets	0	0
$p_{\mathrm{T}}^{\ell_1}$	≥ 35 GeV	≥ 35 GeV
$p_{\mathrm{T}}^{\ell_2}$	≥ 12 GeV	≥ 12 GeV
$\lvert\eta^{e}\rvert$	≤ 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
$\Delta p_{\mathrm{T}}(\ell_1, \ell_2)$	≥ 7 GeV	≥ 1 GeV

H → μe: fit results

SR_{noJets}					
$p_T^{\ell_2}$ bin [GeV]	$f\left(p_T^{\ell_2}\right)$		LFV Signal, Br=1%	Total Backg.	Observed
12–20	1.11 ± 0.06	$e\mu$	14.9 ± 0.4 ± 2.7	1219 ± 24 ±27	1212
		μe	10.7 ± 0.4 ± 2.3	1033 ± 25 ±20	1035
20–30	1.07 ± 0.08	$e\mu$	15.1 ± 0.4 ± 2.7	998 ± 22 ±25	995
		μe	12.4 ± 0.4 ± 2.2	950 ± 23 ±21	950
≥ 30	1.01 ± 0.07	$e\mu$	12.5 ± 0.4 ± 2.2	455 ± 17 ±16	452
		μe	11.4 ± 0.4 ± 2.0	458 ± 16 ±14	457
$SR_{withJets}$					
$p_T^{\ell_2}$ bin [GeV]	$f\left(p_T^{\ell_2}\right)$		LFV Signal, Br=1%	Total Backg.	Observed
12–20	1.07 ± 0.10	$e\mu$	5.9 ± 0.3 ± 1.1	222 ± 10 ±11	220
		μe	3.9 ± 0.2 ± 0.9	181 ± 10 ± 9	182
20–30	1.24 ± 0.16	$e\mu$	5.4 ± 0.2 ± 1.1	187 ± 9 ±11	187
		μe	4.5 ± 0.2 ± 0.9	161 ± 9 ± 9	161
≥ 30	1.13 ± 0.10	$e\mu$	5.5 ± 0.2 ± 1.0	251 ± 11 ±12	250
		μe	4.9 ± 0.2 ± 0.9	229 ± 11 ±11	229

LFV Higgs results

Channel	Category	Expected limit [%]	Observed limit [%]	Best fit Br [%]
$H \to e\tau_{\mathrm{had}}$	SR1	$2.81^{+1.06}_{-0.79}$	3.0	$0.33^{+1.48}_{-1.59}$
	SR2	$2.95^{+1.16}_{-0.82}$	2.24	$-1.33^{+1.56}_{-1.80}$
	Combined	$2.07^{+0.82}_{-0.58}$	1.81	$-0.47^{+1.08}_{-1.18}$
$H \to e\tau_{\mathrm{lep}}$	$\mathrm{SR}_{\mathrm{noJets}}$	$1.66^{+0.72}_{-0.46}$	1.45	$-0.45^{+0.89}_{-0.97}$
	$\mathrm{SR}_{\mathrm{withJets}}$	$3.33^{+1.60}_{-0.93}$	3.99	$0.74^{+1.59}_{-1.62}$
	Combined	$1.48^{+0.60}_{-0.42}$	1.36	$-0.26^{+0.79}_{-0.82}$
$H \to e\tau$	Combined	$1.21^{+0.49}_{-0.34}$	1.04	$-0.34^{+0.64}_{-0.66}$
$H \to \mu\tau_{\mathrm{had}}$	SR1	$1.60^{+0.64}_{-0.45}$	1.55	$-0.07^{+0.81}_{-0.86}$
	SR2	$1.75^{+0.71}_{-0.49}$	3.51	$1.94^{+0.92}_{-0.89}$
	Combined	$1.24^{+0.50}_{-0.35}$	1.85	$0.77^{+0.62}_{-0.62}$
$H \to \mu\tau_{\mathrm{lep}}$	$\mathrm{SR}_{\mathrm{noJets}}$	$2.03^{+0.93}_{-0.57}$	2.38	$0.31^{+1.06}_{-0.99}$
	$\mathrm{SR}_{\mathrm{withJets}}$	$3.57^{+1.74}_{-1.00}$	2.85	$-1.03^{+1.66}_{-1.82}$
	Combined	$1.73^{+0.74}_{-0.49}$	1.79	$0.03^{+0.88}_{-0.86}$
$H \to \mu\tau$	Combined	$1.01^{+0.40}_{-0.29}$	1.43	$0.53^{+0.51}_{-0.51}$

High-mass LFV: results eμ

Process	$m_{e\mu} < 600$ GeV	$m_{e\mu} > 600$ GeV
Top quark	1190 ± 140	22 ± 5
Diboson	159 ± 17	4.9 ± 0.9
Multi-jet and W+jets	55 ± 11	2.7 ± 1.7
$Z/\gamma^* \to \ell\ell$	14.5 ± 2.0	0.18 ± 0.04
Total SM background	1410 ± 150	30 ± 7
SM+Z' ($M_{Z'} = 2$ TeV)	-	75 ± 13
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau} = 2$ TeV)	-	40 ± 8
SM+QBH RS $n = 1$ ($M_{\text{th}} = 2$ TeV)	-	44 ± 9
Data	1463	25

High-mass LFV: results eτ

Process	$m_{e\tau} < 600$ GeV	$m_{e\tau} > 600$ GeV
Top quark	790 ± 190	25 ± 9
Diboson	109 ± 26	6.2 ± 1.9
Multi-jet and W+jets	3200 ± 800	45 ± 14
$Z/\gamma^* \to \ell\ell$	1030 ± 240	5.2 ± 1.4
Total SM background	5200 ± 1300	81 ± 25
SM+Z' ($M_{Z'} = 1.5$ TeV)	-	185 ± 34
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau} = 1.5$ TeV)	-	105 ± 27
SM+QBH RS $n = 1$ ($M_{\text{th}} = 1.5$ TeV)	-	122 ± 28
Data	5416	111

High-mass LFV: results μτ

Process	$m_{\mu\tau} < 600$ GeV	$m_{\mu\tau} > 600$ GeV
Top quark	580 ± 140	21 ± 7
Diboson	84 ± 20	4.8 ± 1.4
Multi-jet and W+jets	1900 ± 500	34 ± 12
$Z/\gamma^* \to \ell\ell$	610 ± 140	2.6 ± 0.7
Total SM background	3200 ± 800	63 ± 20
SM+Z' ($M_{Z'} = 1.5$ TeV)	-	130 ± 28
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau} = 1.5$ TeV)	-	78 ± 22
SM+QBH RS $n = 1$ ($M_{\mathrm{th}} = 1.5$ TeV)	-	90 ± 23
Data	3239	48

High-mass LFV: uncertainties

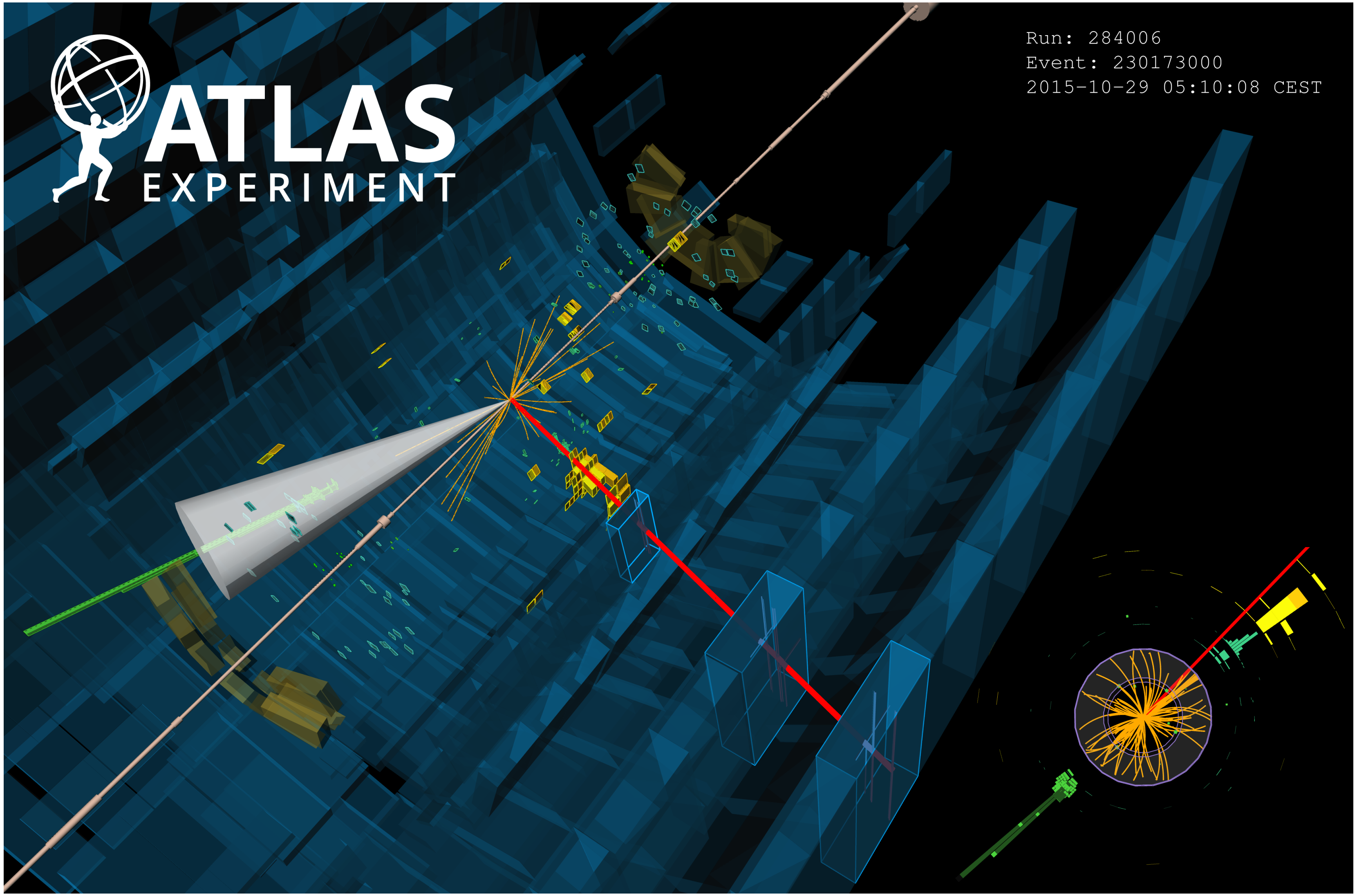
Source	$m_{\ell\ell'} = 1$ TeV			$m_{\ell\ell'} = 2$ TeV			$m_{\ell\ell'} = 3$ TeV		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
PDF uncertainty	17%	15%	15%	35%	38%	35%	70%	75%	70%
Luminosity	5%	5%	5%	5%	5%	5%	5%	5%	5%
Statistical	18%	11%	15%	80%	27%	27%	120%	28%	30%
Reducible background	5%	29%	40%	5%	35%	75%	5%	45%	85%
Top quark production modelling	5%	3%	4%	12%	4%	5%	15%	10%	8%
Electron trigger efficiency	1%	1%	N/A	1%	1%	N/A	1%	1%	N/A
Electron identification	2%	2%	N/A	2%	2%	N/A	2%	2%	N/A
Electron energy scale and resolution	3%	3%	N/A	3%	3%	N/A	3%	3%	N/A
Muon reconstruction efficiency	2%	N/A	2%	4%	N/A	4%	6%	N/A	6%
Muon scale and resolution	4%	N/A	4%	12%	N/A	12%	20%	N/A	20%
Muon trigger efficiency	2%	N/A	2%	2%	N/A	2%	2%	N/A	2%
Tau identification	N/A	4%	4%	N/A	5%	5%	N/A	6%	6%
Tau reconstruction	N/A	3%	3%	N/A	4%	4%	N/A	4%	4%
Tau energy calibrations	N/A	2%	2%	N/A	3%	3%	N/A	4%	4%
Total	27%	35%	44%	90%	59%	90%	140%	90%	120%
SM Background in $m_{\ell\ell'} \pm 0.1 \cdot m_{\ell\ell'}$	3.9	11.9	11.4	0.09	0.55	0.49	0.002	0.014	0.017

ATLAS EXPERIMENT

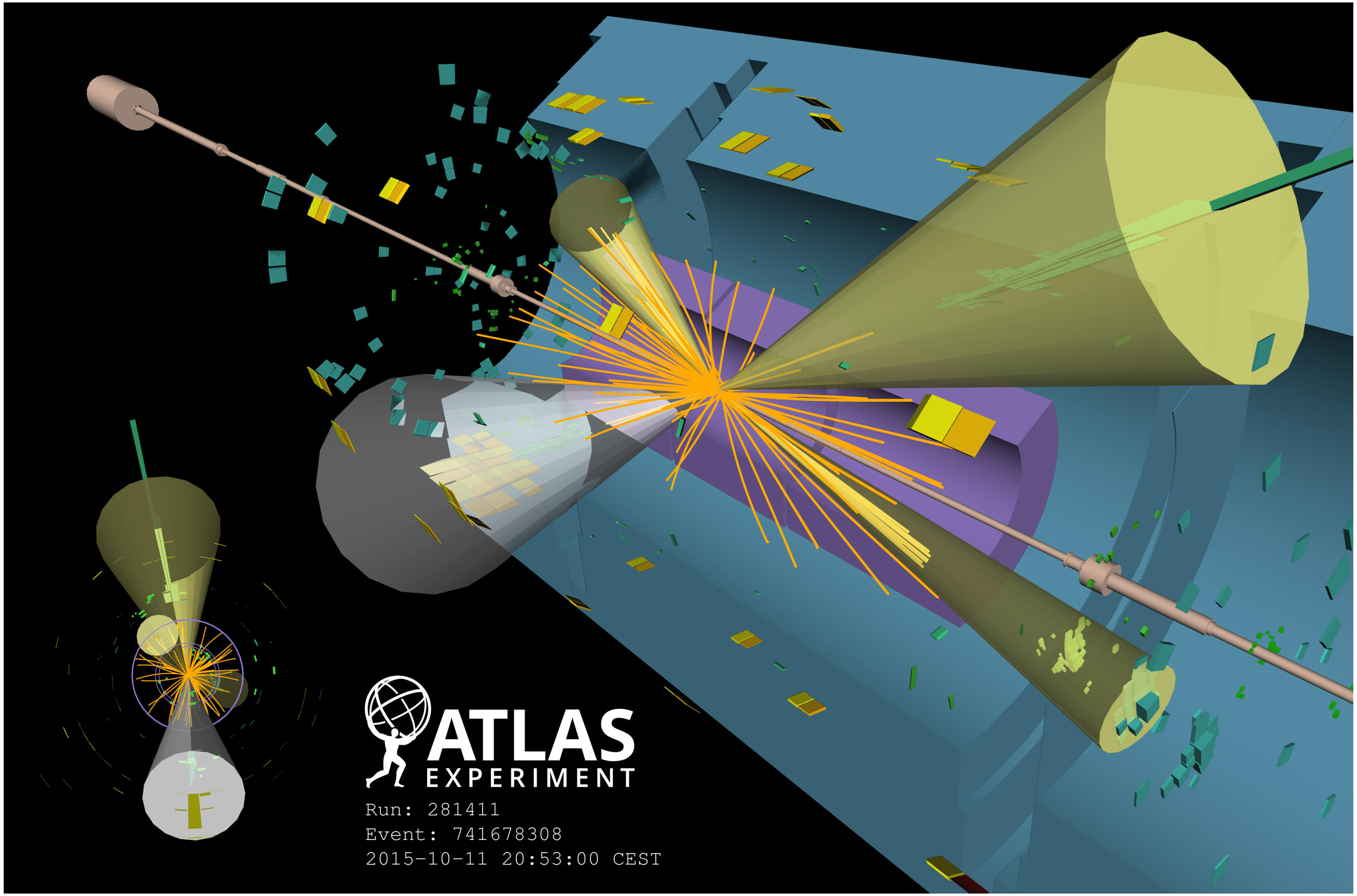
High-mass LFV: highest event masses

Channel	$m_{\ell\ell'}$ [GeV]	E_T^{miss} [GeV]	Lepton type	p_{T_ℓ} [GeV]	η_ℓ	ϕ_ℓ
$e\mu$	2088.7	72	μ^+ e^-	617 1164	0.29 1.64	0.4 -2.8
$e\tau$	1633.8	8.5	e^- τ^+	412 409	-1.26 1.33	1.8 -1.5
$\mu\tau$	1665.7	130.5	μ^+ τ^-	159 81	2.20 -2.19	2.7 -0.5

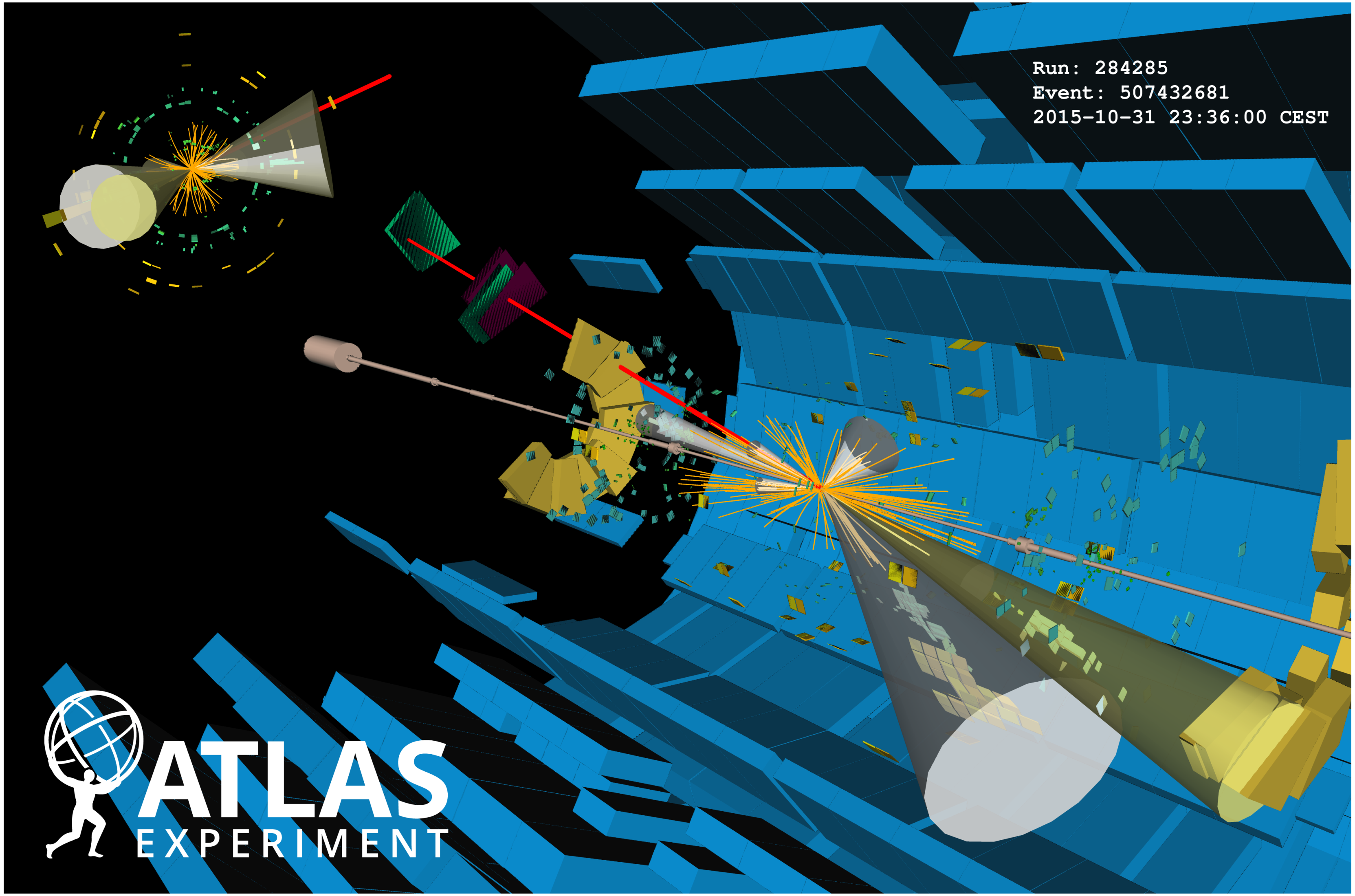
High-mass LFV: event display eμ



High-mass LFV: event display eτ



High-mass LFV: event display μτ



High-mass LFV: acceptance * efficiency