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Search for lepton flavor violation in Higgs and Z′ decays with the ATLAS detector at the LHC

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On behalf of the ATLAS collaboration

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Outline

- Motivation
- LFV search with Z′ model
- LFV search with BSM Higgs model
- A bit more on other models
- Summary

Motivation

- Lepton Flavor Violation (LFV) is highly suppressed in the SM, an observation of LFV would most likely mean new physics
- LFV has not yet been observed among charged leptons
- LFV is permitted in many extensions of the SM


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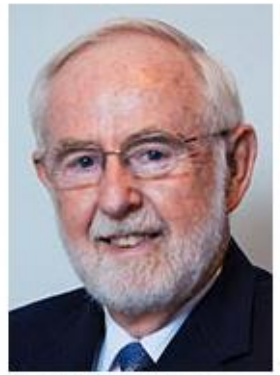
Takaaki Kajita
Prize share: 1/2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Arthur B. McDonald
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The Nobel Prize in Physics 2015

- Takaaki Kajita
- Arthur B. McDonald

"for the discovery of neutrino oscillations"

Heavy Z boson -- Z′

Beyond SM Higgs

SUSY RPV τ sneutrino

Quantum Black Hole

…

Overview of LFV searches at ATLAS

- Z′ boson LFV decay search
  - ✓ to eμ final states with 7 TeV data (EPJC Vol.71, 12(2011)1809)
  - ✓ to $e\mu/e\tau_{had}/\mu\tau_{had}$ final states with 8 TeV (Phys. Rev. Lett. 115 031801 (2015)) and 13 TeV data (accepted by EPJC, arXiv:1607.08079v1)

- Higgs LFV decay search
  - ✓ to eτ/μτ final states with 8 TeV data (submitted to EPJC, arXiv:1604.07730v1 & JHEP 1511 (2015) 211)

- SUSY RPV τ sneutrino search
  - ✓ to $e\mu/e\tau_{had}/\mu\tau_{had}$ final states with 7/8/13 TeV data (same as Z′)

- QBH search
  - ✓ to $e\mu/e\tau_{had}/\mu\tau_{had}$ final states with 13 TeV data (same as Z′)

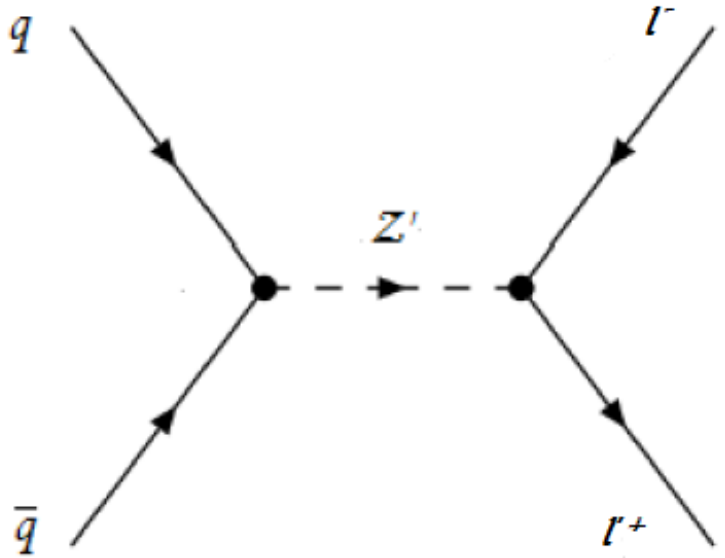
- tau→3μ search (submitted to EPJC, arXiv:1601.03567), Z→μτ search (same as Higgs)
  ≥4 lepton search (JHEP12(2012)124), displaced vertex search (Physics Letters B 719 (2013) 280) …

Z′ boson Search – Model

- Extended SSM Z′
  - ✓ the same couplings as the SM Z boson
  - ✓ extend to allow for LFV couplings:

    Q_{12}, Q_{13} and Q_{23}

$$\sigma(Z' \to l_i l'_j) \propto \frac{g'^2_Z Q^2_{ij} M^2_{ll'}}{(M^2_{ll'} - M^2_{Z'})^2 + M^2_{Z'} \Gamma^2_{Z'}}$$



- ✓ A general search for heavy resonance
- ✓ Relatively small background due to 2 different flavor leptons

l = e, μ or τ_{had}

Signal: Pythia8

Z′ boson Search – Data and objects

◆ **Data sample :** 25 ns data in 2015, Luminosity = 3.2 fb^{-1}

◆ **MC sample :** ATLAS fully simulated samples with all necessary corrections

◆ **Objects**

➢ Electrons

- Kinematic: pT> 65 GeV
  $|\eta|< 2.47$ (no crack region)
- Track and calo quality
- Isolated

➢ Muons

- Kinematic: pT> 65 GeV
  $|\eta|< 2.5$
- Combined track quality
- Isolated

➢ Taus

- Kinematic: pT> 40 GeV
  $|\eta|< 2.47$
- 1 and 3 prongs
- Track and calo quality
- Overlap removal with e and μ

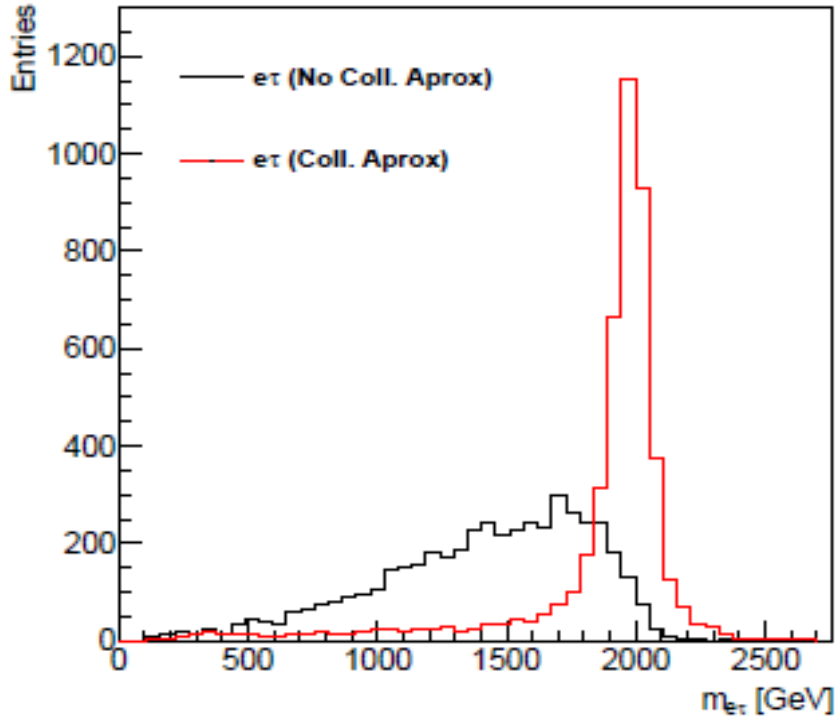
➢ MET: calculated with calibrated objects

Z′ boson Search – Event selection

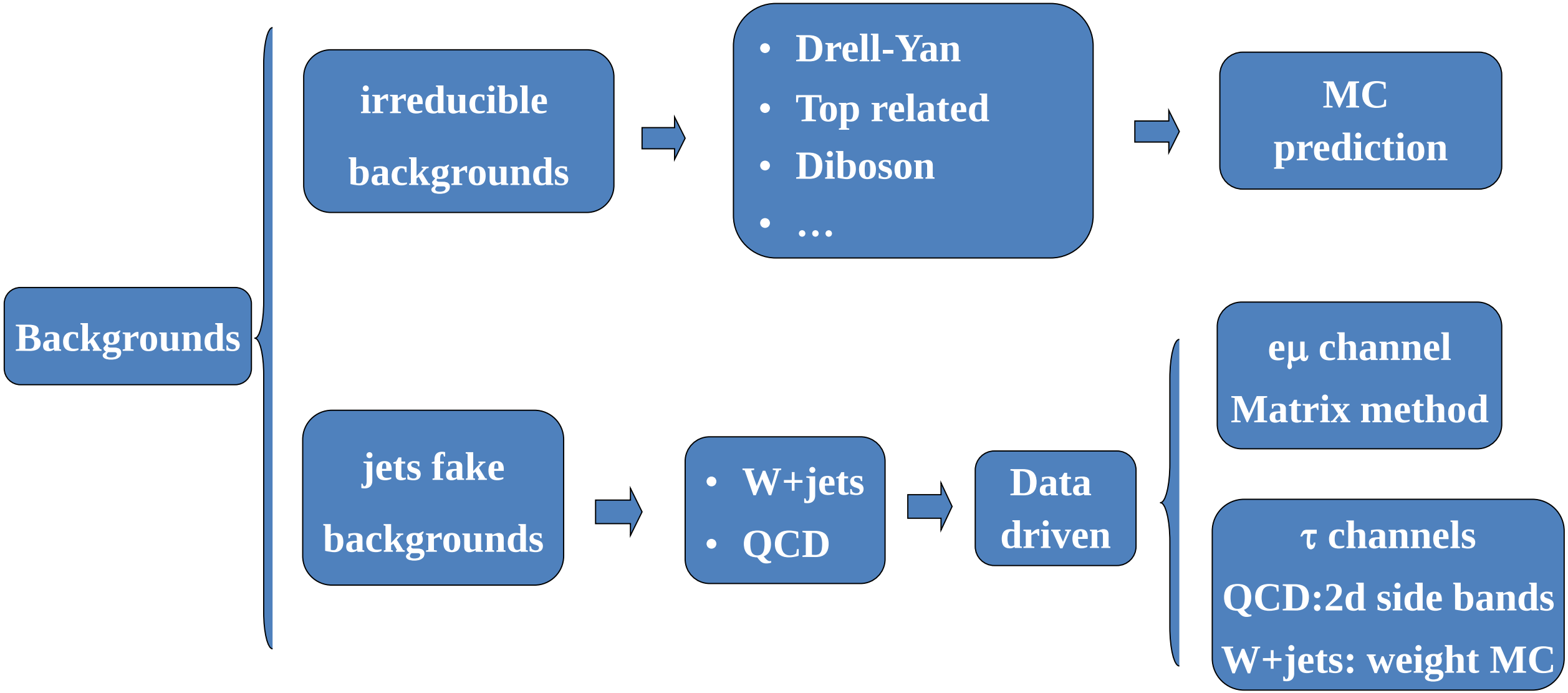
- single electron or muon trigger
- 2 “good” different flavor leptons
- back-to-back: $\Delta\phi(l, l') > 2.7$
- $M_{ll'} > 600$GeV as “signal region”

$M_{l\tau}$ invariant mass reconstruction

- ✓ taus are heavily boosted, so are their decay products
- ✓ ν and those visible hadronic tau decay products are ~ collinear
- ✓ assume $\eta(\nu) = \eta(\tau_{had})$
- ✓ improved peak resolution



Z′ boson Search – Backgrounds

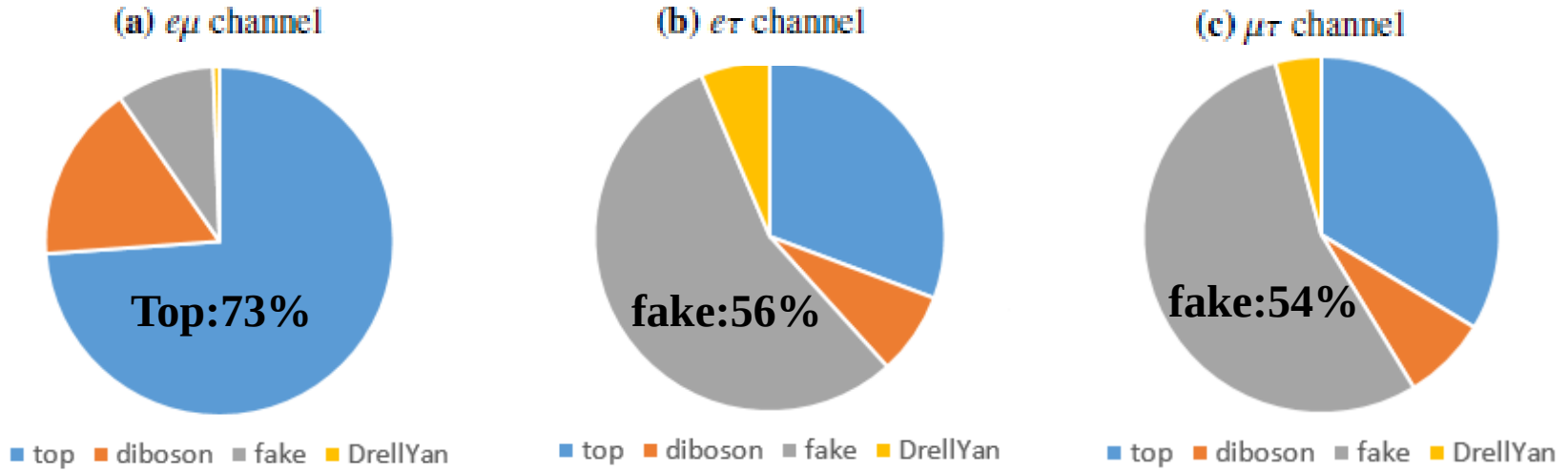


Z′ boson Search – Event yields

- $M_{ll'}$<600GeV: validation region; $M_{ll'}$ >600GeV: signal region

Process	$m_{e\mu} < 600$ GeV	$m_{e\mu} > 600$ GeV	$m_{e\tau} < 600$ GeV	$m_{e\tau} > 600$ GeV	$m_{\mu\tau} < 600$ GeV	$m_{\mu\tau} > 600$ GeV
Top quark	1190 ± 140	22 ± 5	790 ± 190	25 ± 9	580 ± 140	21 ± 7
Diboson	159 ± 17	4.9 ± 0.9	109 ± 26	6.2 ± 1.9	84 ± 20	4.8 ± 1.4
Multi-jet and W+jets	55 ± 11	2.7 ± 1.7	3200 ± 800	45 ± 14	1900 ± 500	34 ± 12
$Z/\gamma^* \to \ell\ell$	14.5 ± 2.0	0.18 ± 0.04	1030 ± 240	5.2 ± 1.4	610 ± 140	2.6 ± 0.7
Total SM background	1410 ± 150	30 ± 7	5200 ± 1300	81 ± 25	3200 ± 800	63 ± 20
SM+Z' ($M_{Z'} = 2$ TeV)	-	75 ± 13	-	185 ± 34	-	130 ± 28
SM+$\tilde{\nu}_\tau$ ($M_{\tilde{\nu}_\tau} = 2$ TeV)	-	40 ± 8	-	105 ± 27	-	78 ± 22
SM+QBH RS $n = 1$ ($M_{th} = 2$ TeV)	-	44 ± 9	-	122 ± 28	-	90 ± 23
Data	1463	25	5416	111	3239	48

- For signal region



Z′ boson Search – Systematics

Source	$m_{\ell\ell'}$ = 1 TeV		
	$e\mu$	$e\tau$	$\mu\tau$
PDF uncertainty	17%	15%	15%
Luminosity	5%	5%	5%
Statistical	18%	11%	15%
Reducible background	5%	29%	40%
Top quark production modelling	5%	3%	4%
Electron trigger efficiency	1%	1%	N/A
Electron identification	2%	2%	N/A
Electron energy scale and resolution	3%	3%	N/A
Muon reconstruction efficiency	2%	N/A	2%
Muon scale and resolution	4%	N/A	4%
Muon trigger efficiency	2%	N/A	2%
Tau identification	N/A	4%	4%
Tau reconstruction	N/A	3%	3%
Tau energy calibrations	N/A	2%	2%
Total	27%	35%	44%
SM Background in $m_{\ell\ell'} \pm 0.1 \cdot m_{\ell\ell'}$	3.9	11.9	11.4

$M_{ll'}$ **at 1TeV region**

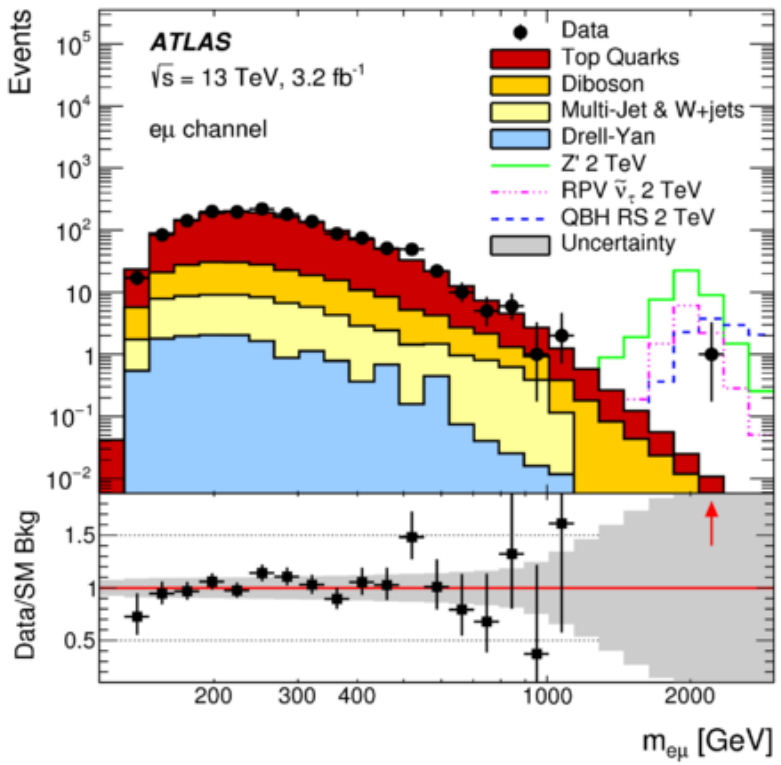
eμ channel: PDF + stat

eτ channel: PDF + stat + fake estimate

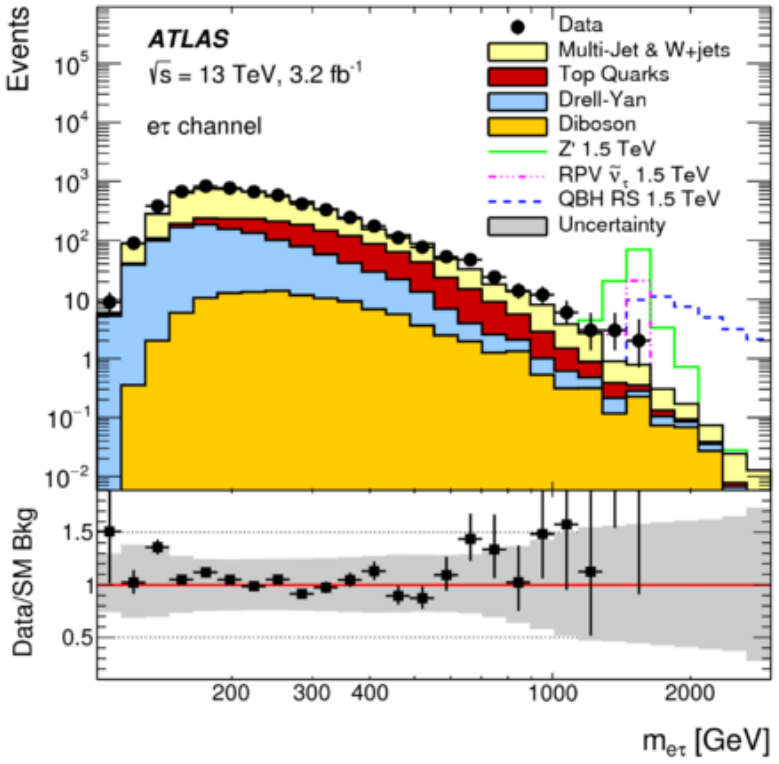
μτ channel: PDF + stat + fake estimate

Z′ boson Search – $M_{ll'}$ discriminant

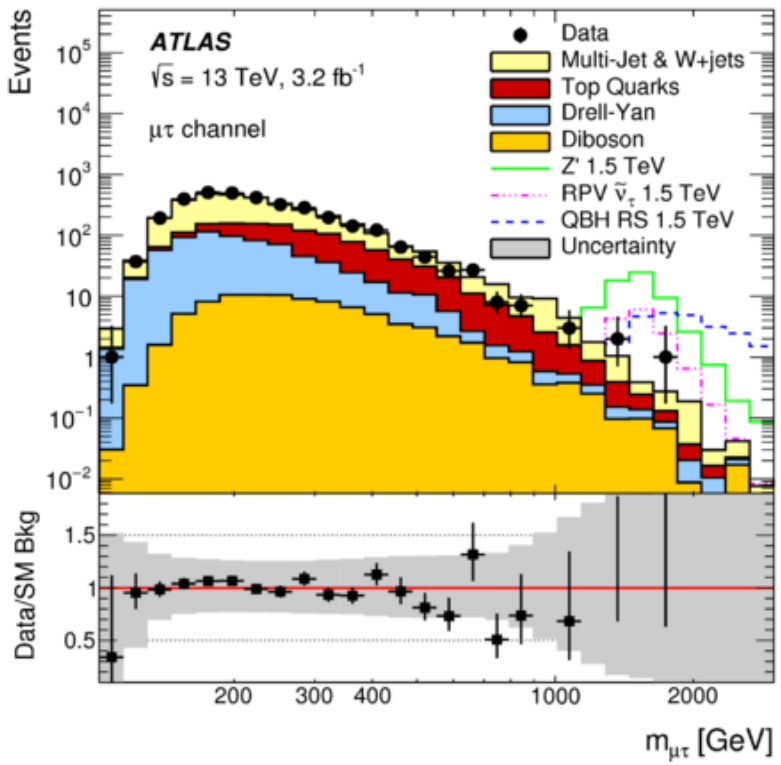
Dilepton invariant mass



Dominant: Top backgrounds



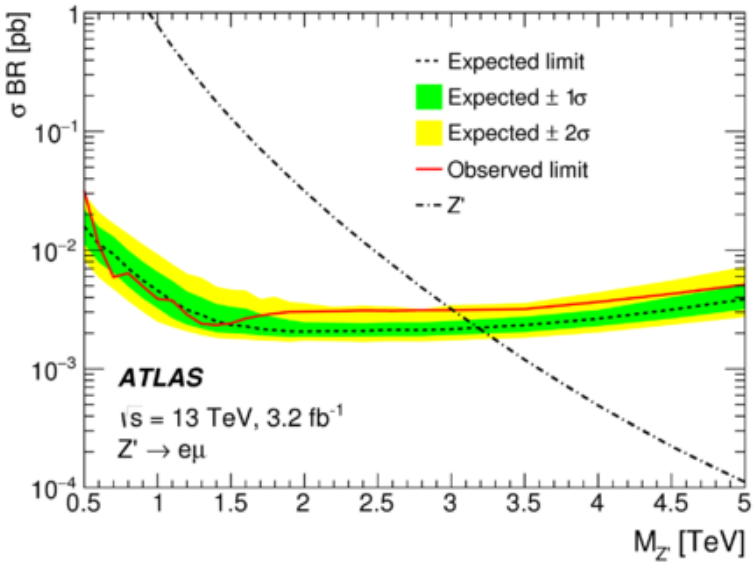
Dominant: Top + jet fake



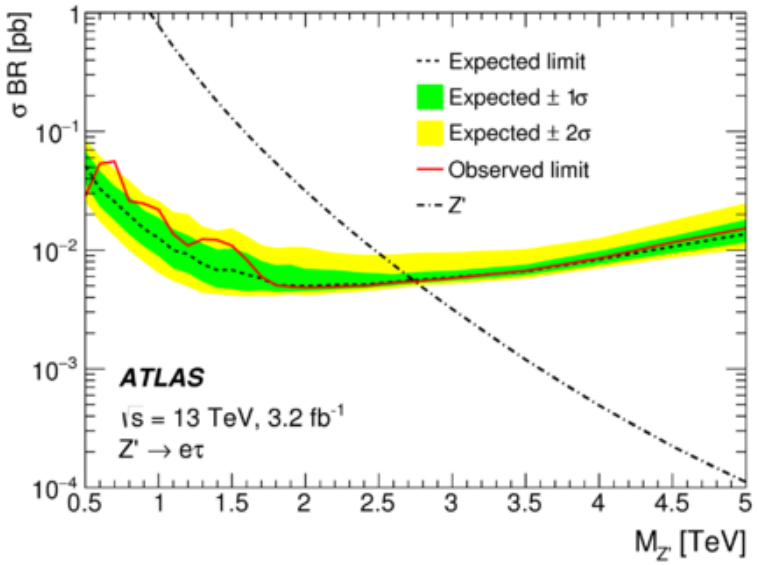
Dominant: Top + jet fake

Z′ boson Search – Limit plots

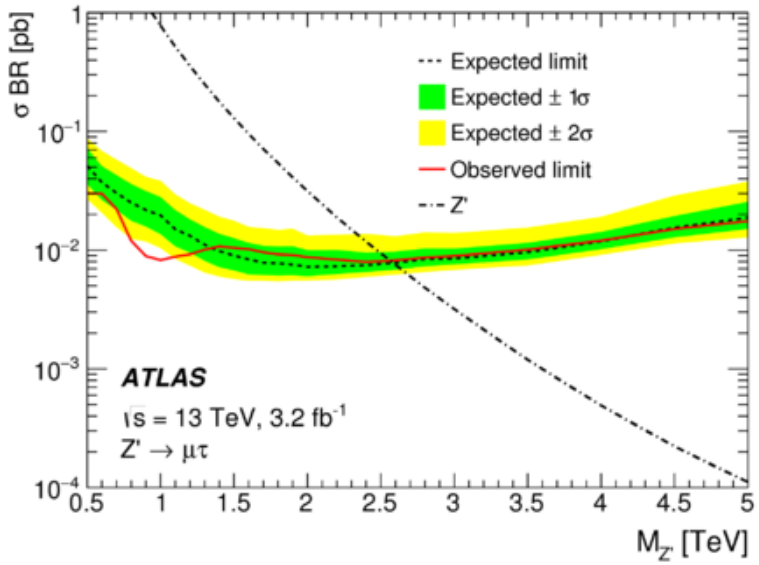
eμ channel



eτ channel



μτ channel



Mass exclusion

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

Z′ boson Search – Conclusion

Conclusion

- A search for LFV Z’ is performed in eμ, eτ or μτ final states
- No significant data excess is observed compared to SM expectation
- New limits considerably extend the previous ATLAS results

BSM Higgs Search – Introduction

Both ATLAS and CMS support the observation of 125GeV "Higgs"

Coupling not very different from SM "Higgs"

Any non-SM property ?

Higgs LFV decay :

Considered Lagrangian for the Yukawa interactions

$$-\mathcal{L}_Y = \frac{c_{ij}}{\sqrt{2}} h \bar{\ell}_L^i \ell_R^j + \text{h.c.}, \quad i,j = e,\mu,\tau \text{, where } c_{ij}^{SM} = \delta_{ij}\sqrt{2}m_i/v \text{ and } v = 246 \text{ GeV}.$$

- ✓ A complementary to SM Higgs measurement
- ✓ Well motivated by theory
- ✓ Stringent limits on H→eμ from low energy tau decay experiments, but less stringent limits on H→eτ or μτ

Higgs(125GeV)→ eτ or μτ : τ can decay both hadronically and leptonically

BSM Higgs Search – Data and objects

◆ **Data sample :** 8 TeV pp data in 2012, Luminosity = 20.3 fb^{-1}

◆ **MC sample :** ATLAS full simulated samples with all necessary corrections

◆ **Objects**

➢ Electrons

- Kinematic: pT> 26 GeV
  $|\eta|< 2.47$ (no crack region)
- Track and calo quality
- Isolated

➢ Muons

- Kinematic: pT> 26 GeV
  $|\eta|< 2.4$
- Combined track quality
- Isolated

➢ Taus (had)

- Kinematic: pT> 45 GeV
  $|\eta|< 2.47$
- 1 and 3 prongs
- Track and calo quality
- Overlap removal with e and μ

➢ MET: calculated with calibrated objects

BSM Higgs Search – Event selection: τ_{had} channel

2 SRs are introduced to maximize the sensitivity

SR1: dominant bkgd W+jets

SR2: dominant bkgd Z+jets

2 VRs are introduced to validate the dominant backgrounds

WCR: validate modelling of Wjets

TCR: validate modelling of top

Criterion	SR1	SR2	WCR	TCR
$p_T(\mu)$ or $E_T(e)$	>26 GeV	>26 GeV	>26 GeV	>26 GeV
$p_T(\tau_{had})$	>45 GeV	>45 GeV	>45 GeV	>45 GeV
$\lvert\eta(\text{lep}) - \eta(\tau_{had})\rvert$	<2	<2	<2	<2
$m_T(\text{lep}, E_T^{miss})$	>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

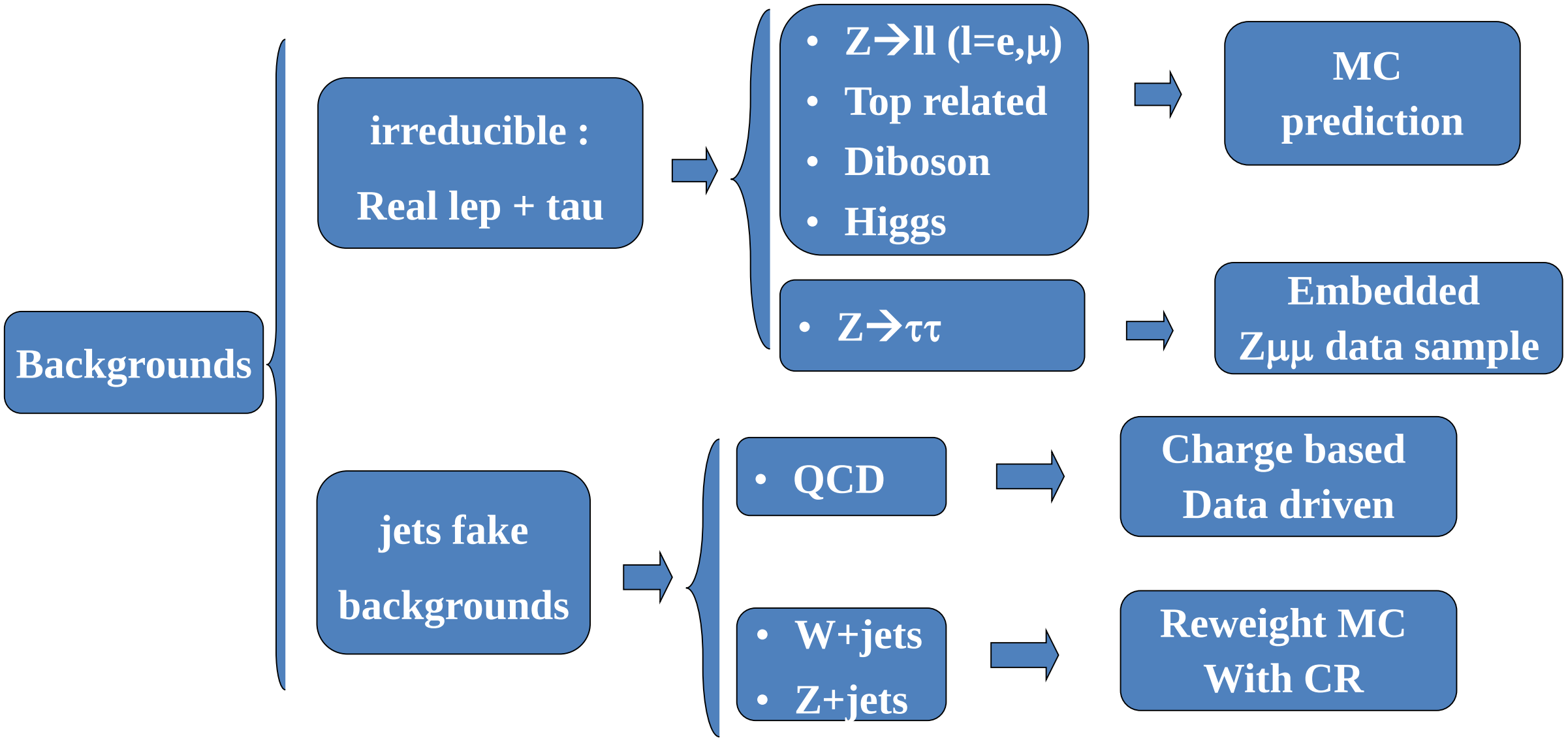
M(l,τ) is reconstructed similar as Z′, and is used for signal search

$m_{l\tau}^{MMC}$

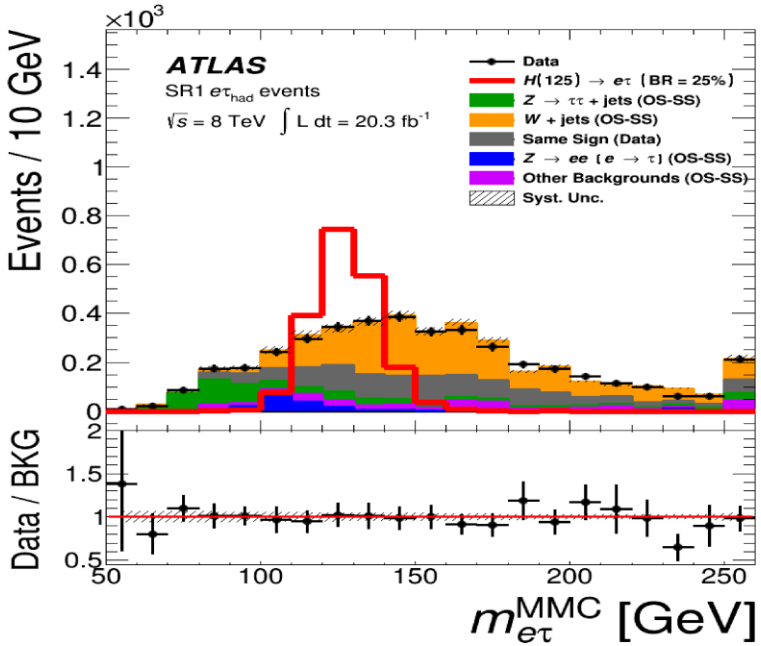
lep = e or μ

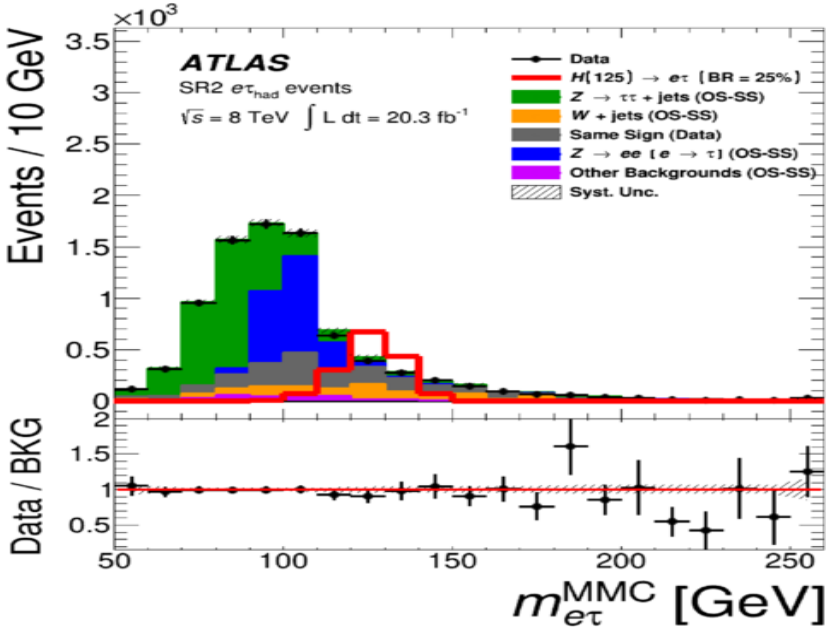
Nucl. Instrum. Meth. A 654 (2011) 481

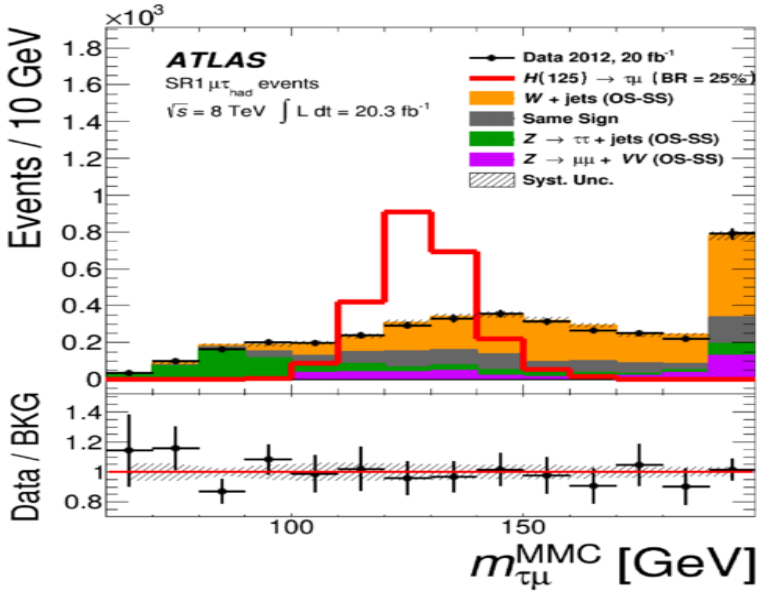
BSM Higgs Search – Backgrounds: τ_{had} channel

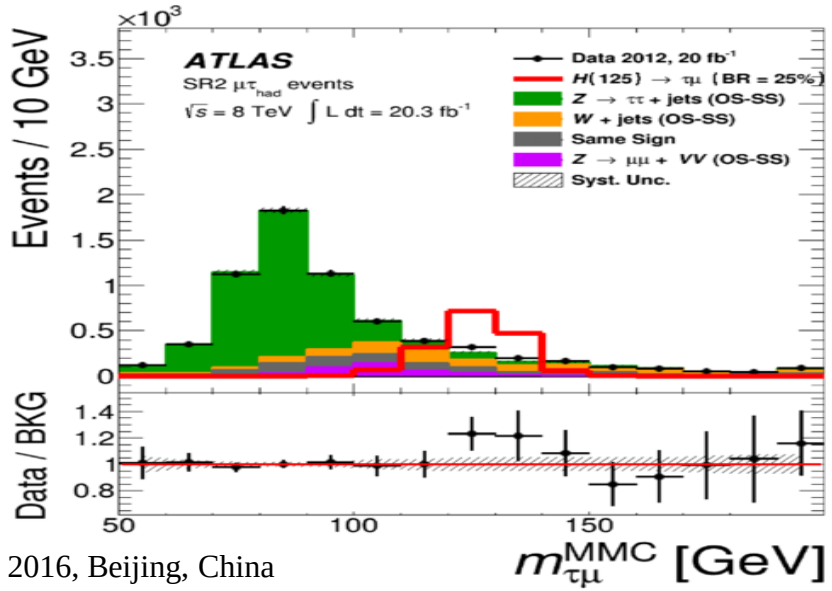


BSM Higgs Search – Control plots: τ_{had} channel









Up: eτ channel

Down: μτ channel

Left: SR1

Right: SR2

BSM Higgs Search – Event selection: τ_{lep} channel

2 SRs are defined to maximize the sensitivity

SR1: with no central ($|\eta|<2.4$) light jet

SR2: with ≥ 1 central light jet

Search variables

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

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

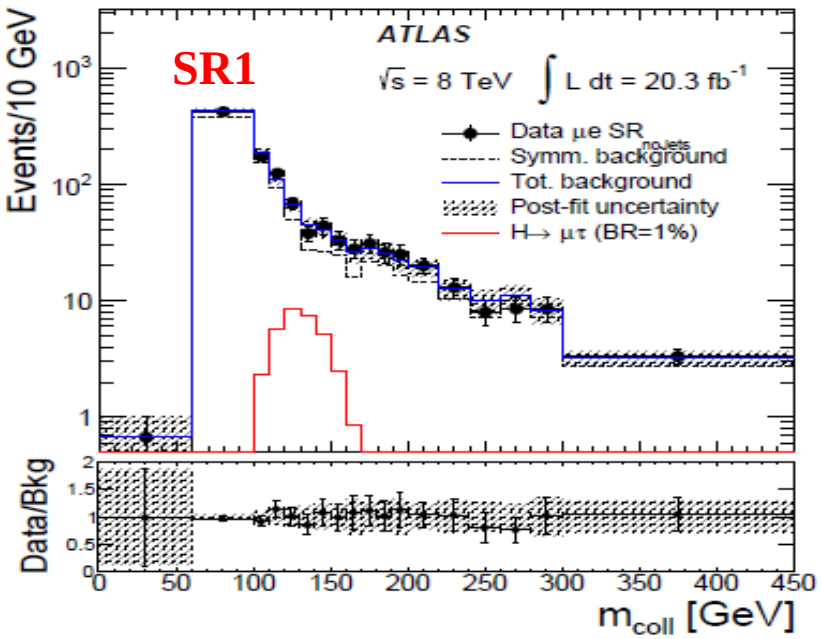
BSM Higgs Search – Backgrounds: τ_{lep} channel

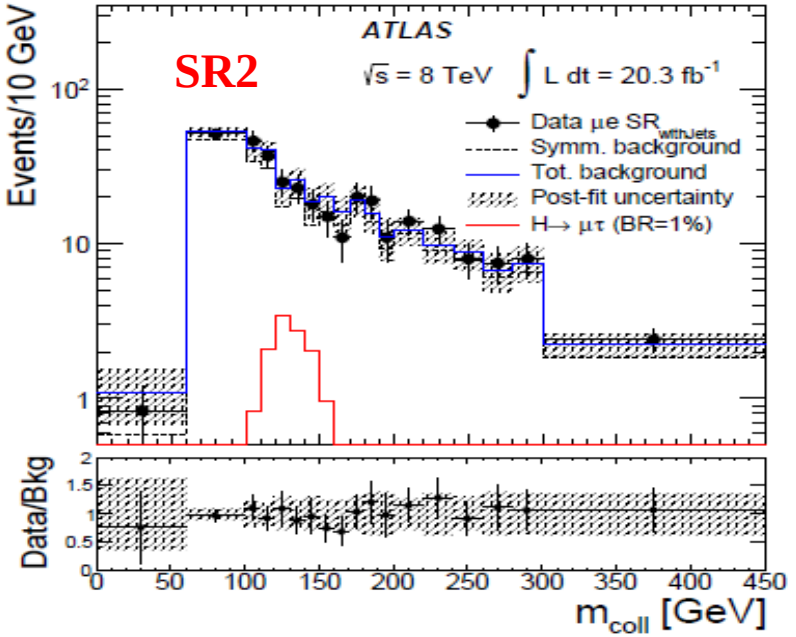
Phys. Rev. D 90, (2014) 015025

Backgrounds are estimated with an e-μ symmetry method by assuming:

- ✓ SM processes in data are symmetric under the exchange of prompt e with prompt μ
- ✓ Higgs LFV decay breaks this symmetry

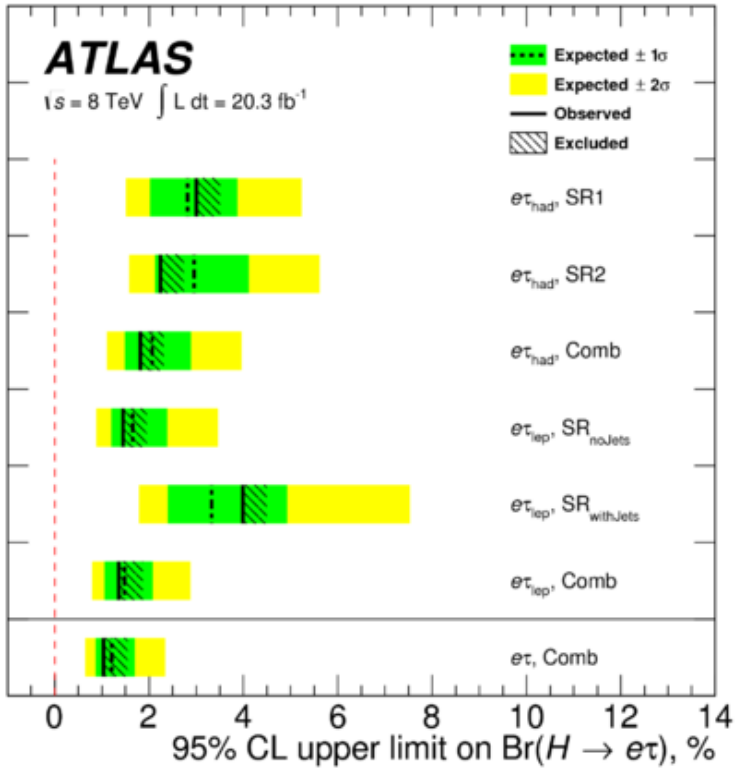
Effects from non-prompt e/μ & efficiency difference are corrected



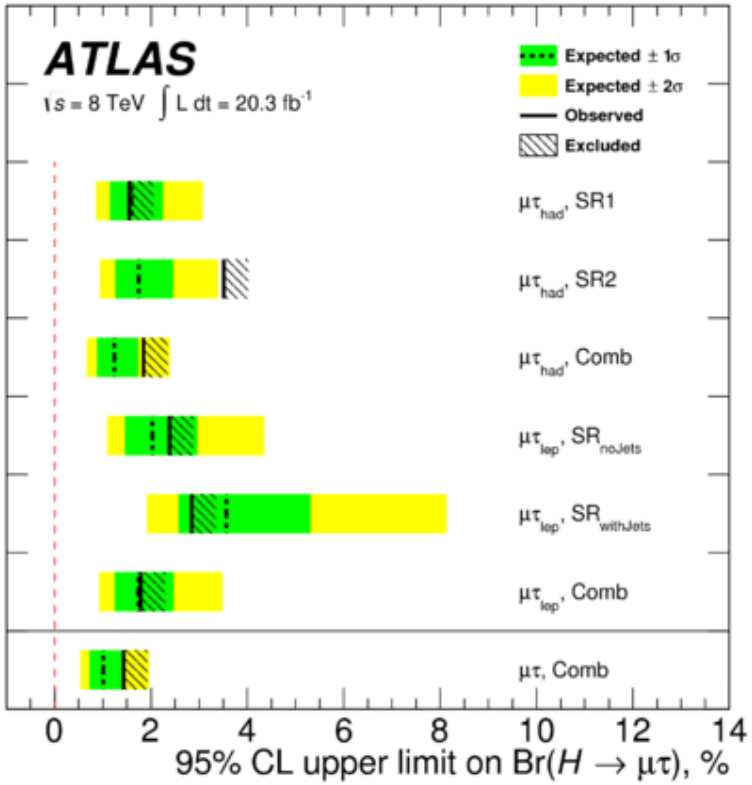


BSM Higgs Search – Results

- No statistically significant deviations of the data from bkgd prediction are observed
- 95% CL upper limits on LFV Higgs decay Branching ratio is placed with a frequentist method assuming m_H = 125GeV



$H \rightarrow e\tau$ hypothesis



$H \rightarrow \mu\tau$ hypothesis

BSM Higgs Search – Conclusion

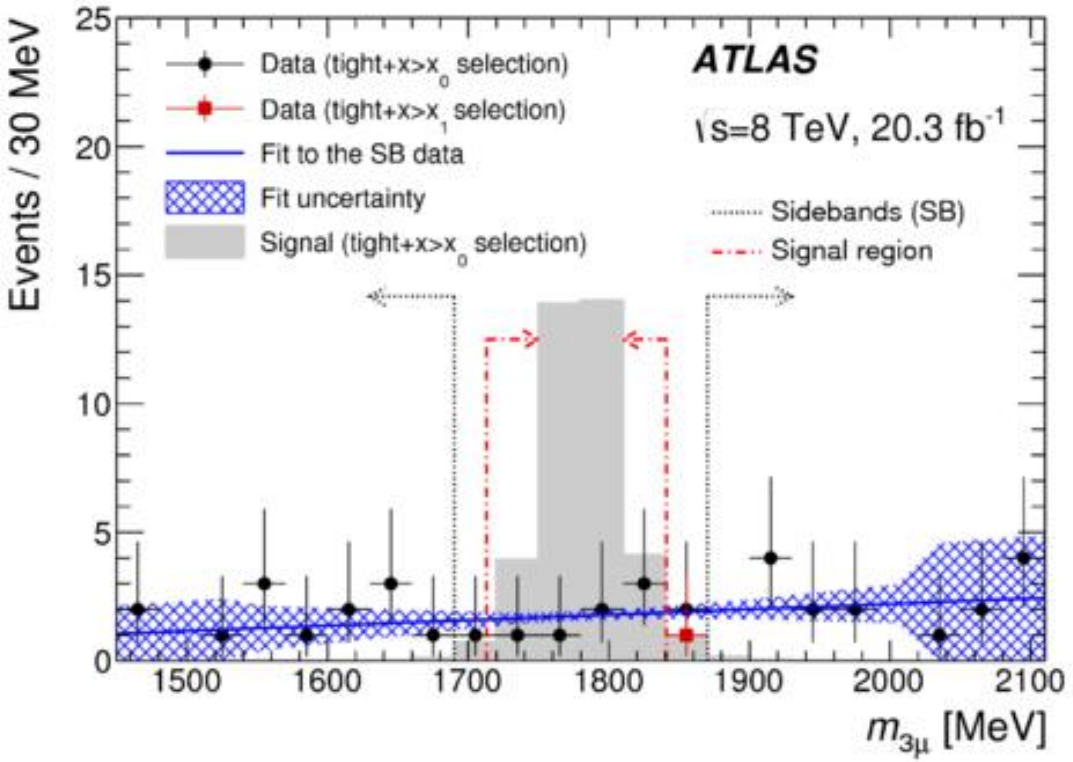
- A search for H→eτ or H→μτ LFV decay is performed, with τ decays both leptonically and hadronically
- No obvious data excesses over SM background prediction are observed
- 95% CL upper limits on LFV Higgs decay Br are placed

$$\mathrm{Br}(H \to e\tau) < 1.04\%, \mathrm{Br}(H \to \mu\tau) < 1.43\%$$

Other searches -- τ→3μ

Submitted to: Eur. Phys. J. C. arXiv:1601.03567v2

- A search for **τ→3μ** is made with 8TeV 20.3/fb dataset using W→**τν** events at ATLAS
- Dominant systematics are from muon recon and trigger



- No events are observed in signal region , while 0.2 bkgd events are expected
- The observed upper limits of Br(**τ→3μ**) is 3.76×10^{-7} at 90% CL.
- Demonstrate the potential of LHC as a probe of LFV in τ decay
- Expect significantly improved sensitivity with more data

Other searches

- Quantum black hole search
- SUSY RPV tau sneutrino search

Submitted to: EPJC arXiv:1607.08079

Share exactly the same strategy as Z′ search and will be published together with Z′ on EPJC

Model	Expected Limit [TeV]			Observed Limit [TeV]		
	$e\mu$	$e\tau$	$\mu\tau$	$e\mu$	$e\tau$	$\mu\tau$
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

- Z→μτ LFV decay measurement

Submitted to: EPJC arXiv:1604.07730v1

Share similar strategy as H→μτ search and will be published together with Higgs search on EPJC

$$\mathrm{Br}(Z \to \mu\tau) < 1.69 \times 10^{-5}.$$

Summary

- Several analyses searching for LFV in the charged lepton sector are performed by ATLAS
- No significant data excess over SM expectation is observed in any channel
- Limits are put on the σ x Br or Br, which considerably extend the previous ATLAS results

Backup slides

Statistical analysis for Z′ search

- Reasonable agreement between observation and expectation
- 95% CL level Limits are put on the **σ x Br** of Z′ model
- Bayesian method is used to set limits

$$\mathcal{L}(n_{\rm obs}|\theta,\hat{\Omega}) = \prod_{k=1}^{N_{\rm bins}} \frac{\mu_k^{n_{{\rm obs}_k}} e^{\mu_k}}{n_{{\rm obs}_k}!} \prod_{i=1}^{N_{\rm Sys}} G(\Omega_i,0,1)\ , \qquad \mu_k = N_{{\rm bkg}_k} + N_{{\rm sig}_k}(\theta)$$

where $N(\theta)$ is the total number of expected events as a function of the parameter of interest, ϵ_{ij} is the relative change in event yields for signal (j=1) and background (j=2) due to the systematic uncertainty i and $G(\Omega_i, 0, 1)$ is a unit Gaussian assumed to be the probability density function for the nuisance parameter Ω_i. All systematic errors are assumed to be Gaussian in nature.

BSM Higgs Search – Results

- No statistically significant deviations of the data from bkgd prediction are observed
- 95% CL upper limits on LFV Higgs decay Branching ratio is placed with a frequentist method assuming m_H = 125GeV

Channel	Category	Expected limit [%]	Observed limit [%]	Best fit Br [%]
$H \to e\tau_{had}$	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	$-0.47^{+1.08}_{-1.18}$
$H \to e\tau_{lep}$	SR_{noJets}	$1.66^{+0.72}_{-0.46}$	1.45	$-0.45^{+0.89}_{-0.97}$
	$SR_{withJets}$	$3.33^{+1.60}_{-0.93}$	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	$-0.34^{+0.64}_{-0.66}$

Channel	Category	Expected limit [%]	Observed limit [%]	Best fit Br [%]
$H \to \mu\tau_{had}$	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	$0.77^{+0.62}_{-0.62}$
$H \to \mu\tau_{lep}$	SR_{noJets}	$2.03^{+0.93}_{-0.57}$	2.38	$0.31^{+1.06}_{-0.99}$
	$SR_{withJets}$	$3.57^{+1.74}_{-1.00}$	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	$0.53^{+0.51}_{-0.51}$