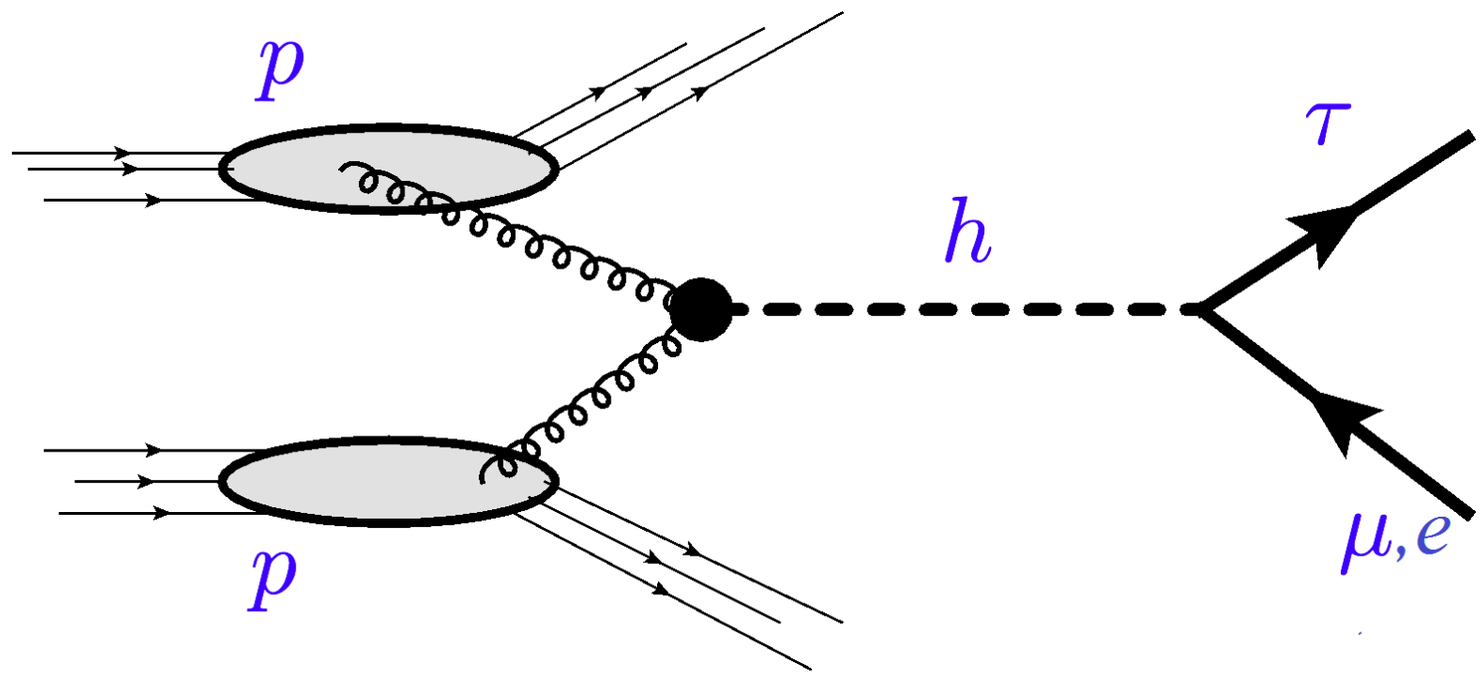
Search for lepton-flavor-violating decays of the Higgs boson with the ATLAS experiment



ATANU PATHAK

UNIVERSITY OF LOUISVILLE

2017 Meeting of the APS Division of Particles and Fields (DPF 2017)
31 July - 4 August, 2017.
Fermi National Accelerator Laboratory

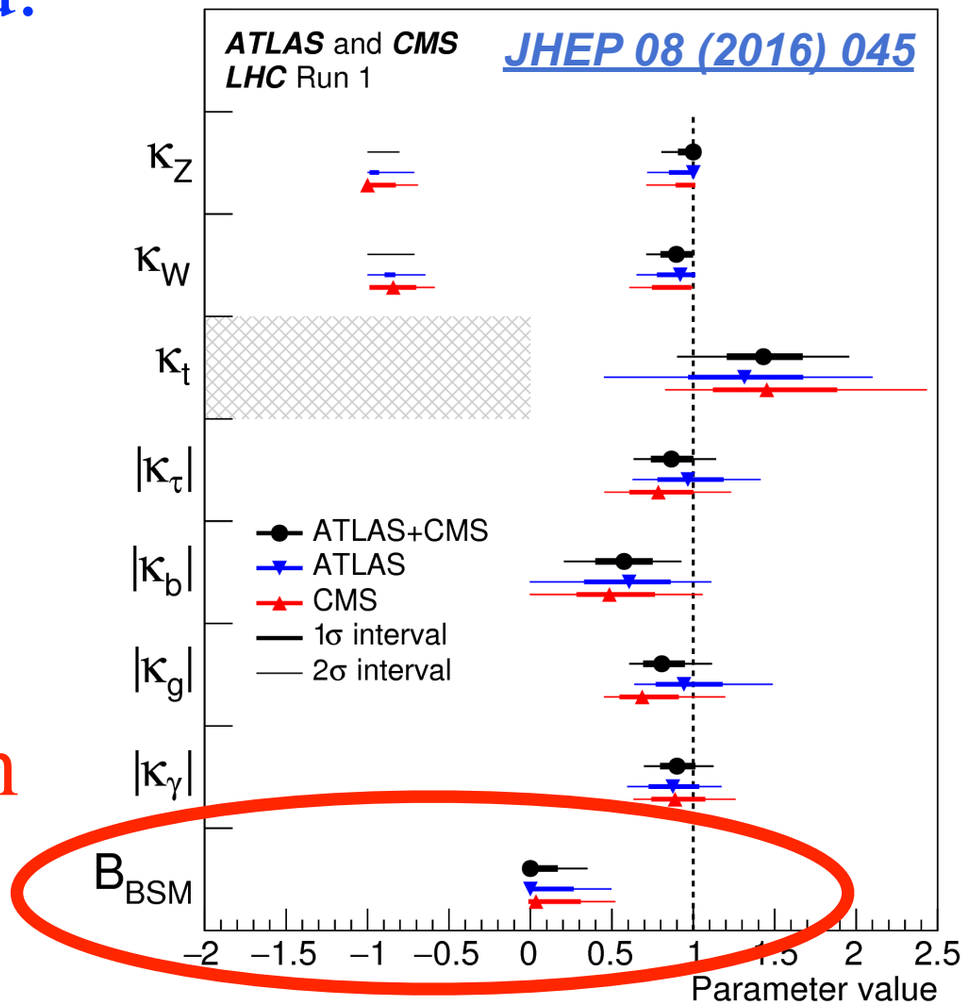
Lepton flavor violating decays of Higgs boson

- In Standard Model (SM), lepton flavor violation (LFV) is not allowed in the decays of the Higgs boson with mass ≈ 125 GeV.
- Many new physics models predict LFV in $\mu \to e$, $\tau \to e$, $\tau \to \mu$
- LHC presents unique opportunity to search for $H \to e\mu$, $e\tau$, $\mu\tau$
- Interesting indirect limits are predicted:
  - $\mathscr{B}(\mu \to e\gamma) < 10^{-13}$ (MEG, SINDRUM)

    $\Rightarrow \mathscr{B}(H \to e\mu) < 10^{-8}$
  - $\mathscr{B}(\tau \to e/\mu\,\gamma) < 10^{-8}$ (BaBar, Belle)

    $\Rightarrow \mathscr{B}(H \to e/\mu\tau) < 10\%$

  (G. Blankenburg, J. Ellis, and G. Isidori: 1202.5704)
  (R. Harnik, J. Kopp, and J. Zupan: 1209.1397)



- Beyond SM contributions to rare and exotic decays of the Higgs boson from Run 1 combination of ATLAS+CMS inputs are allowed at the level of 20%.

Direct searches more constraining at LHC

Run 1: CMS & ATLAS found mild differences in $H \to \mu\tau$

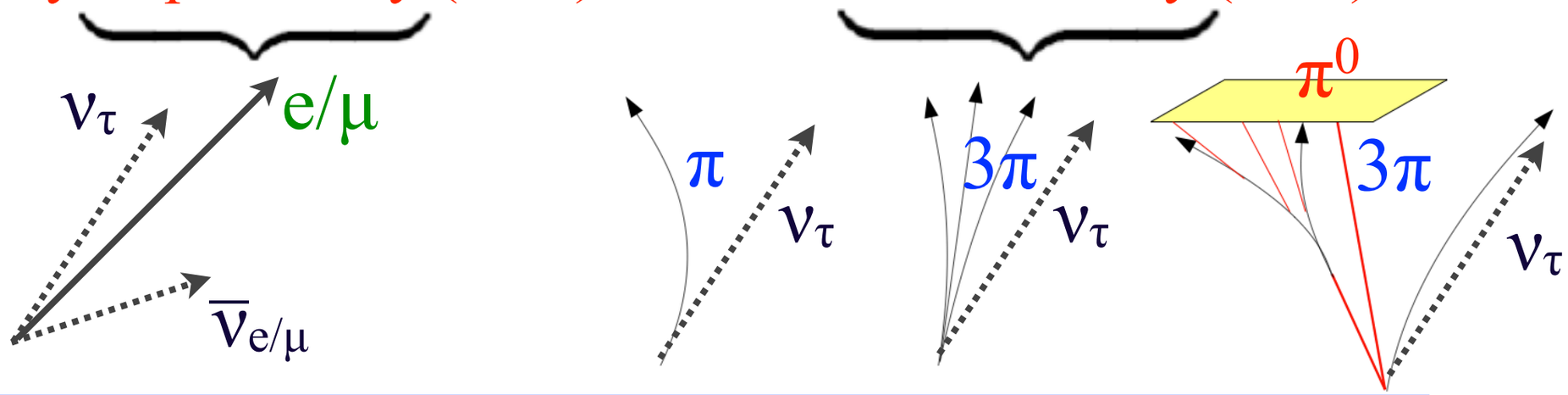
$H \to$	Experiment	$\sqrt{s}$ (TeV)	$\int L$ (fb $^{-1}$)	Upper Limits at 95% CL		Best Fit Value (Branching Fraction)	Significance (Observed)
				Expected	Observed		
$\mu\tau$	CMS (2012 Data) PLB749 (2015) 337 [1502.07400]	8	19.7	$(0.75 \pm 0.38)\%$	1.51%	$(0.84\ ^{+0.39}_{-0.37})\%$	2.4 σ
	ATLAS (2012 Data) EPJC77 (2017) 70 [1604.07730]	8	20.3	$(1.01^{+0.40}_{-0.29})\%$	1.43%	$(0.53 \pm 0.51)\%$	1 σ
$e\tau$	CMS (2012 Data) PLB763 (2016) 472 [1607.03561]	8	19.7	$(0.75\ ^{+0.32}_{-0.22})\%$	0.69%	$(-0.10\ ^{+0.37}_{-0.36})\%$	
	ATLAS (2012 Data) EPJC77 (2017) 70 [1604.07730]	8	20.3	$(1.21\ ^{+0.49}_{-0.34})\%$	1.04%	$(-0.34\ ^{+0.64}_{-0.66})\%$	
$e\mu$	CMS (2012 Data) PLB763 (2016) 472 [1607.03561]	8	19.7	0.048%	0.035%		

Run 2 (LHCP, May2017): CMS found slight difference in $H \to e\tau$

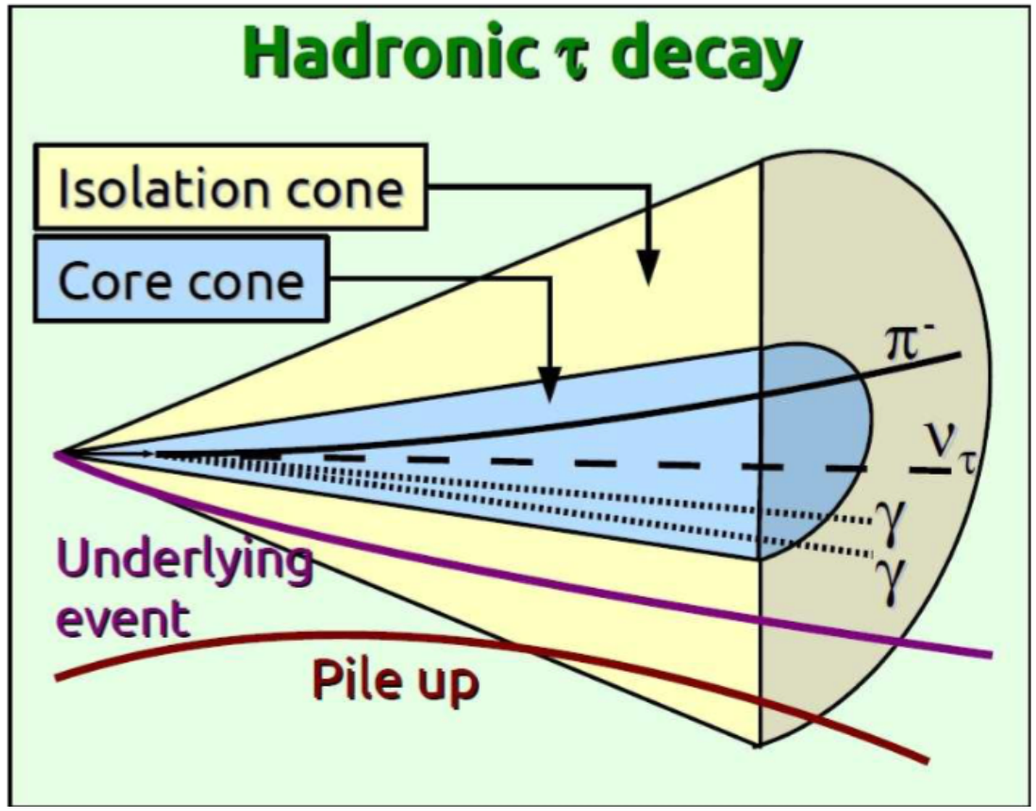
$H \to$	Experiment	$\sqrt{s}$ (TeV)	$\int L$ (fb $^{-1}$)	Upper Limits at 95% CL		Best Fit Value (Branching Fraction)	Significance (Observed)
				Expected	Observed		
$\mu\tau$	CMS (2015-16 Data) PAS HIG-17-001	13	35.9	0.25%	0.25%	$(0.00 \pm 0.12)\%$	
$e\tau$	CMS (2015-16 Data) PAS HIG-17-001	13	35.9	0.37%	0.61%	$(0.30\ ^{+0.19}_{-0.18})\%$	1.6 σ

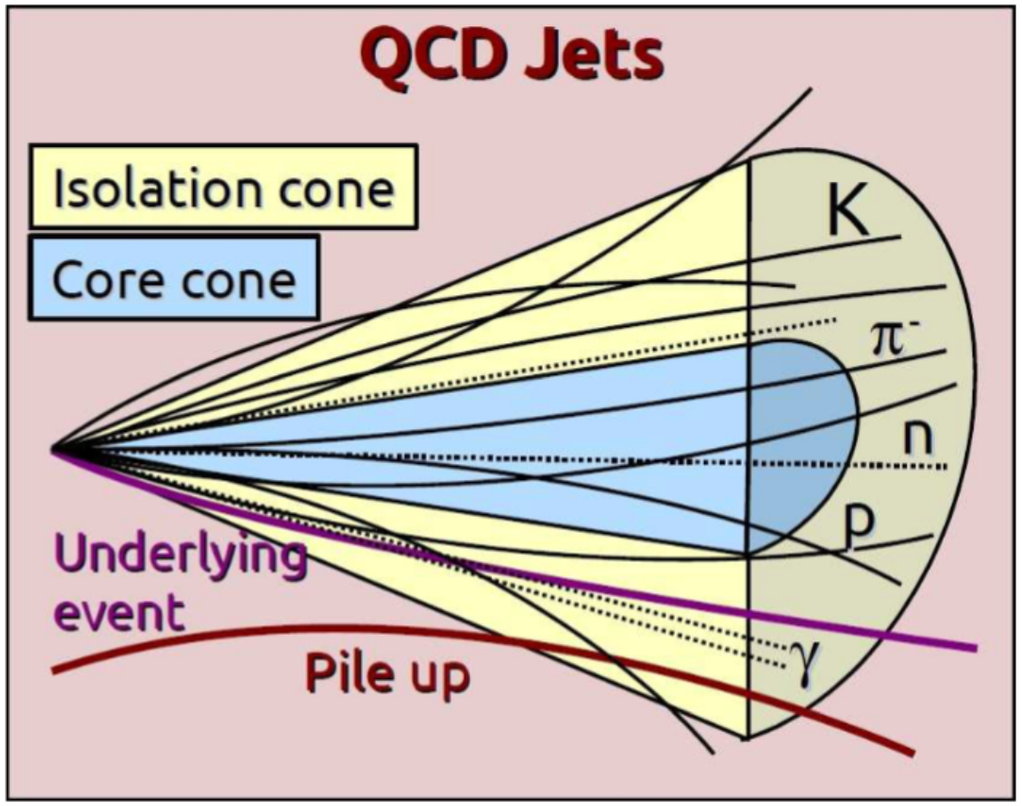
Tau decays at LHC

Tau (τ) decays leptonically (35%) as well as hadronically (65%)

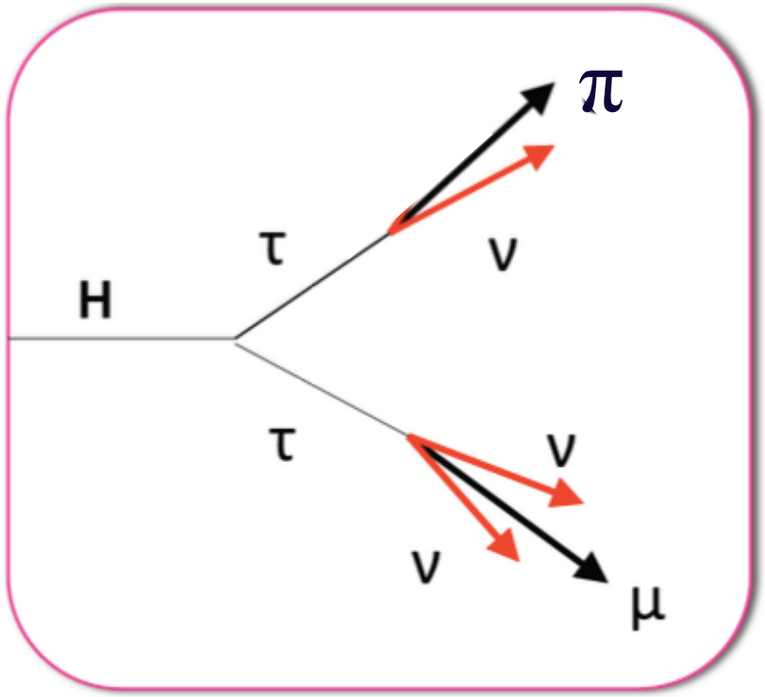


In this analysis, only hadronic decays of the τ lepton is studied.
Such decays are reconstructed as "tau-jets" in the ATLAS detector.

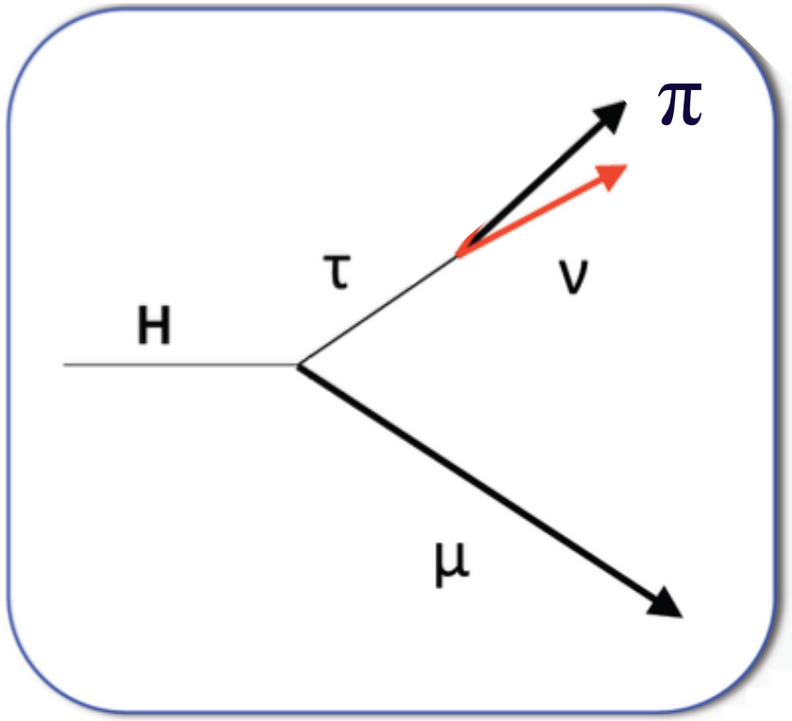




Signal characteristics



$H \rightarrow \tau\tau$



$H \rightarrow \mu\tau$

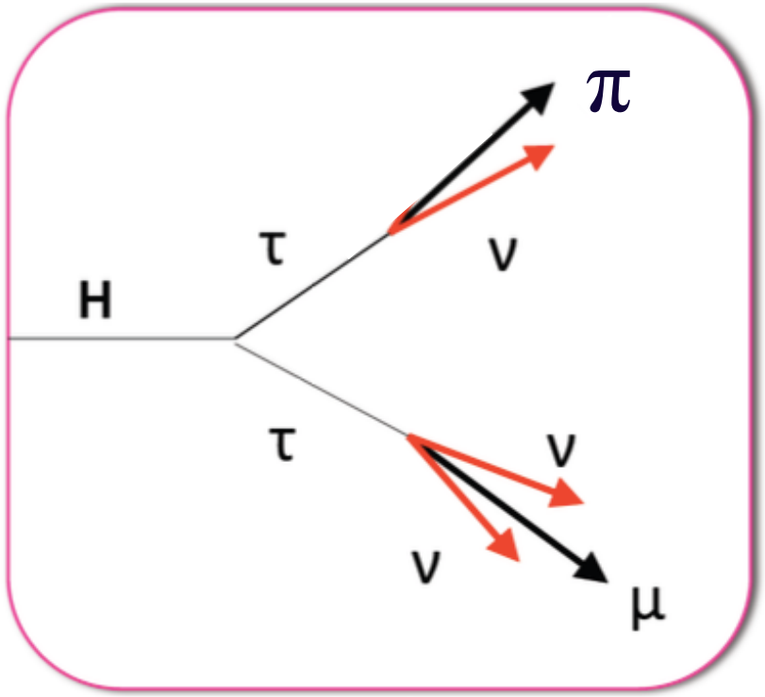
SM Process

- **SM Process: $H \rightarrow \tau_{\mu}\tau_{had}$**
- **Branching ratio of $H \rightarrow \tau\tau$ is 6.3% at m_H = 125 GeV.**
- **More than one neutrino in final state**

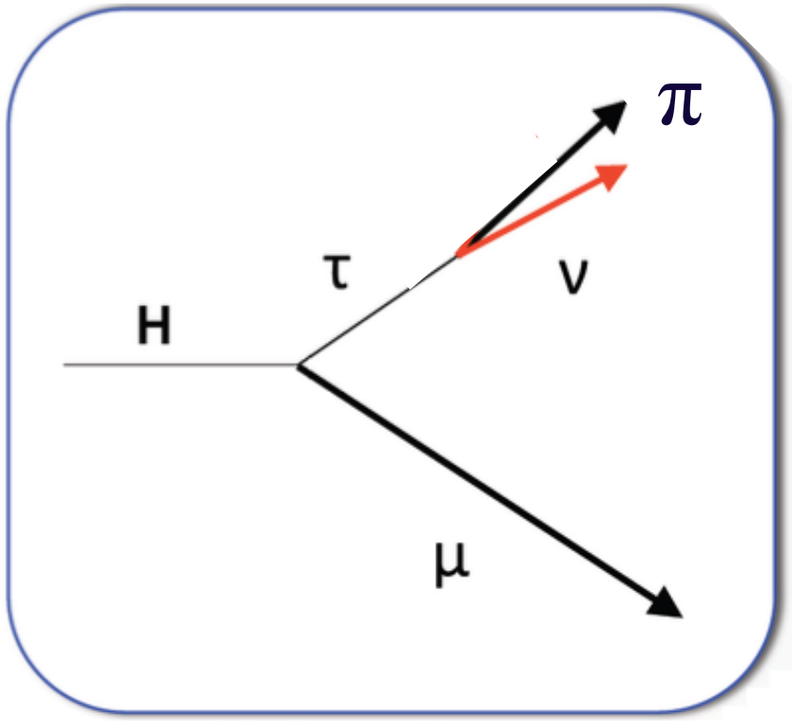
LFV Process

- **Beyond SM Process: $H \rightarrow \mu\tau_{had}$**
- **Branching ratio up to 10%, based on indirect predictions.**
- **One neutrino in final state, larger visible mass than SM process.**

Signal characteristics



$H \rightarrow \tau\tau$



$H \rightarrow \mu\tau$

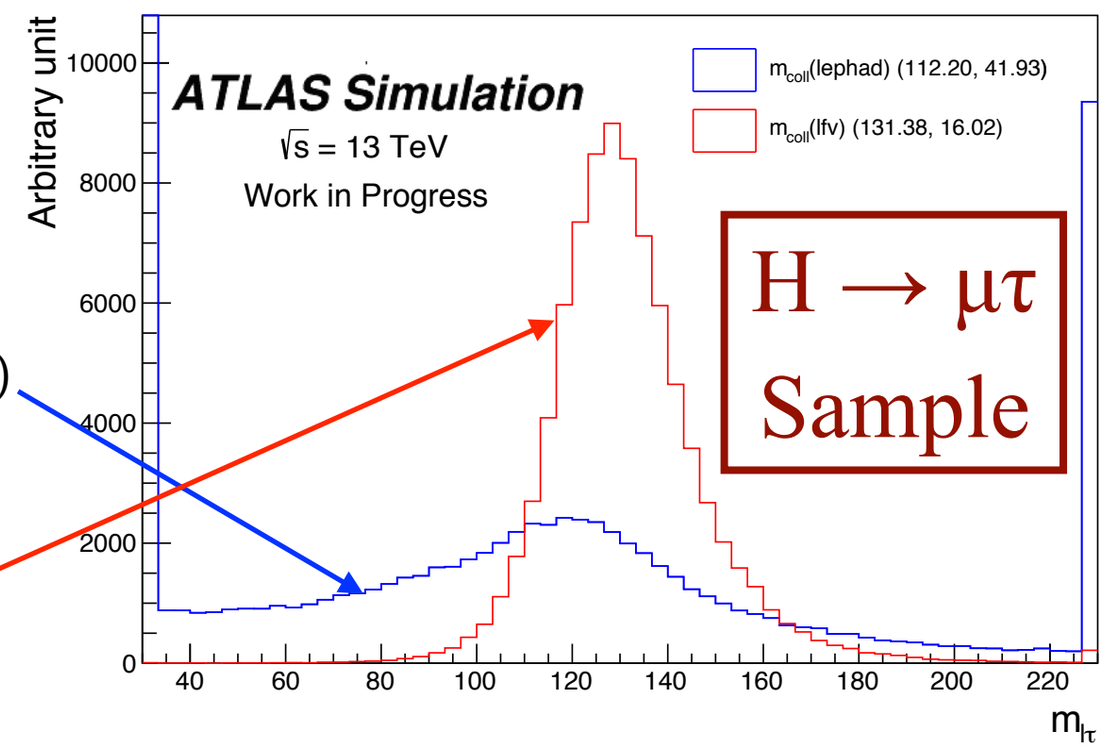
Collinear mass definition:

for $H \rightarrow \tau\tau$ analysis

$$m_{\tau\tau} = m_{vis}/\sqrt{x_1 x_2} \text{ with } x_{1,2} = p_{vis1,2}/(p_{vis1,2} + p_{mis1,2})$$

for $H \rightarrow l\tau$ analysis

$$m_{l\tau} = m_{vis}/\sqrt{x} \text{ with } x = p_{tau}/(p_{tau} + p_{mis})$$



$H \rightarrow \mu\tau$ Sample

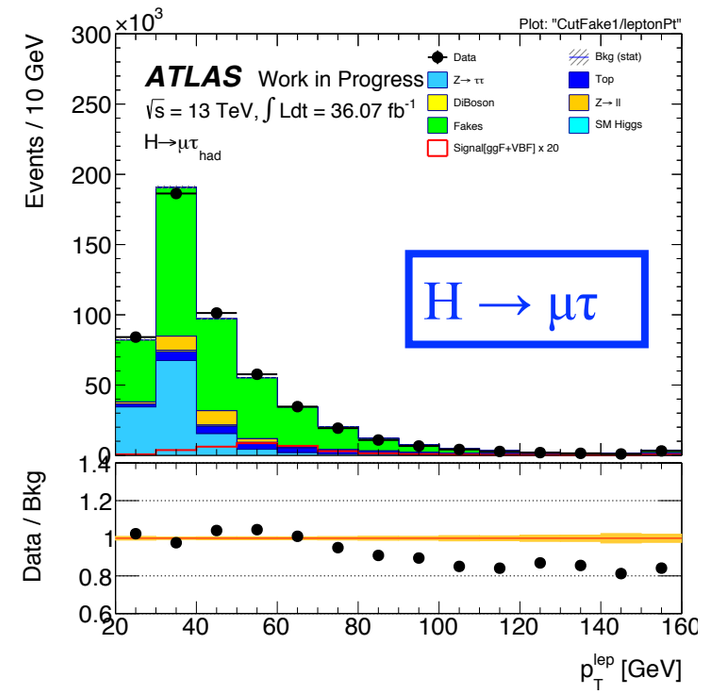
Background composition

Preselection

- **1 charged lepton with $p_T > 27$ GeV and 1 oppositely charged tau with $p_T > 25$ GeV**
- **$|\Delta\eta(\ell, \tau)| < 2$**
- **$n_{b\text{-jets}} = 0$ with $p_T > 20$ GeV**

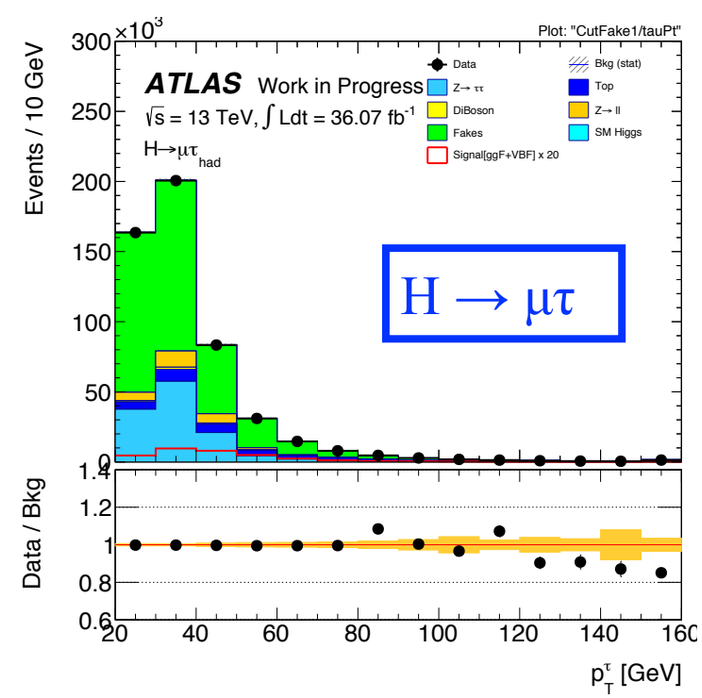
$\sqrt{s}$ = 13 TeV, $\mathscr{L}$=36 fb^{-1}, 2015-2016 data

	e ATL-COM-PHYS-2016-1702	μ Eur. Phys. J. C76 (2016) 292	τ ATLAS-CONF-2017-02
Efficiency	88%	99%	75 (60)% for 1 (3) tracks
Inverse background efficiency	250	100	50 (500) for 1 (3) tracks



Main backgrounds

Monte Carlo prediction	Data-driven estimate (Fake factor method)
• $Z \to \tau\tau$ • $Z \to \ell\ell$ • Single-top/$t\bar{t}$ • Di-boson (WW, WZ, ZZ, Wγ, Zγ)	• QCD • W+jets

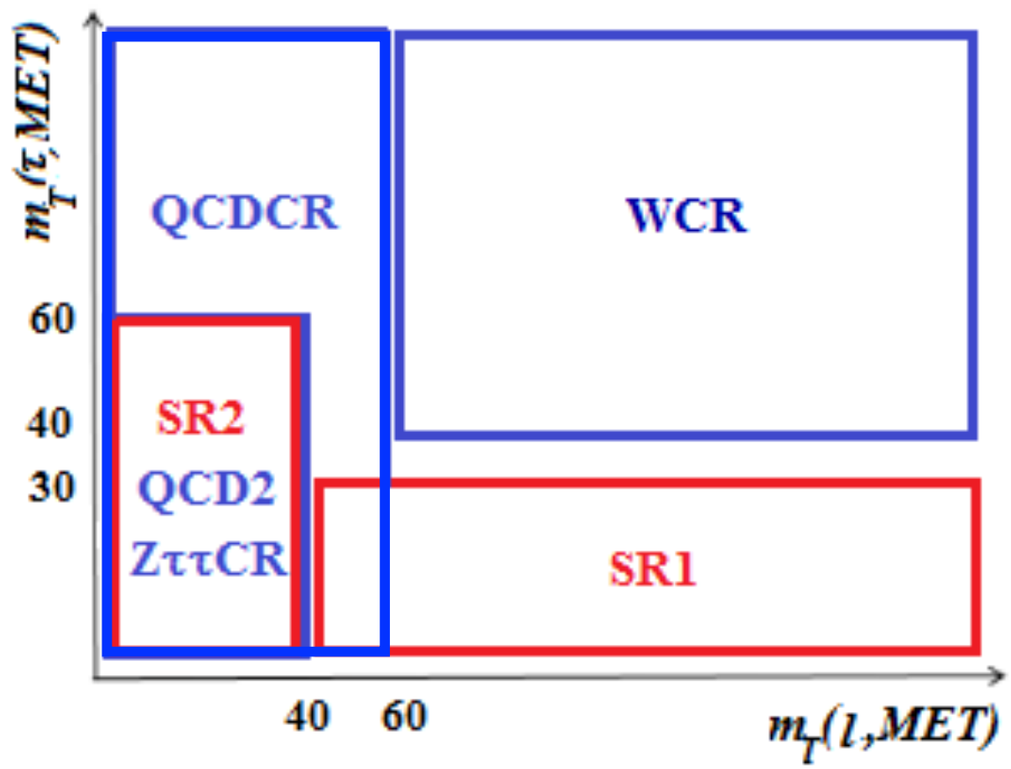


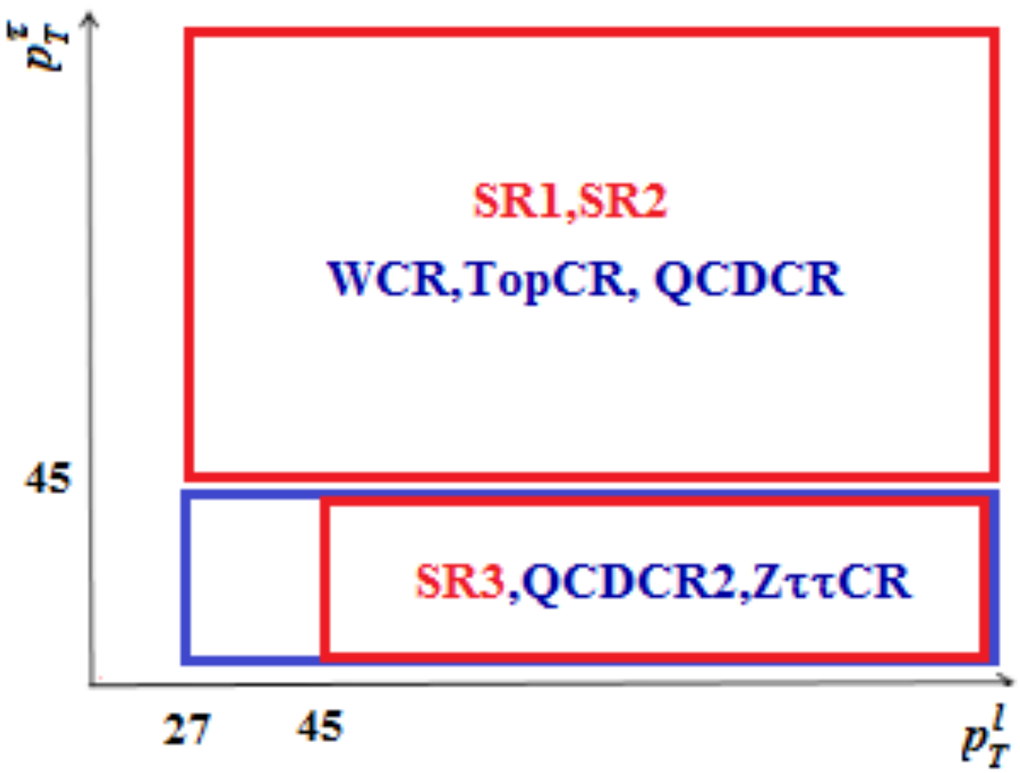
Background characteristics

Regions defined in terms of the *transverse mass*

$$m_{\mathrm{T}}^{\ell, E_{\mathrm{T}}^{\mathrm{miss}}} \equiv \sqrt{2 p_{\mathrm{T}}^{\ell} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi)} \quad (\text{where } \ell = e, \tau_{\mathrm{had}})$$

with $\Delta\phi$ angle between ℓ and the direction of $E_{\mathrm{T}}^{\mathrm{miss}}$





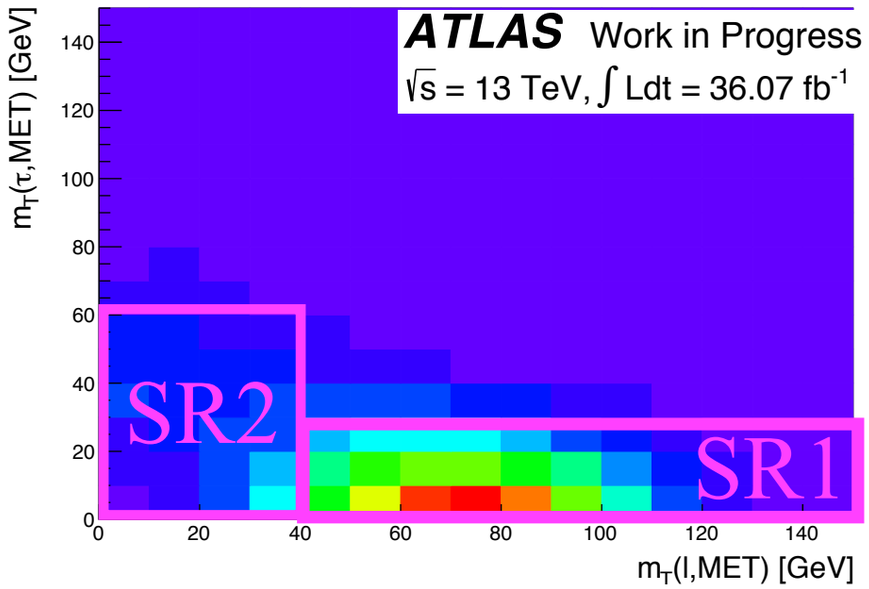
- SR1 dominated by W+jets, whereas SR2 dominated by Z+jets.
- Both SR1 & SR2 have $p_{\mathrm{T}}^{\tau} > 45$ GeV.
- Introduce new SR3 w.r.t Run 1, $p_{\mathrm{T}}^{\ell} > 45$ GeV, $25 < p_{\mathrm{T}}^{\tau} < 45$ GeV.

Signal vs. background characteristics

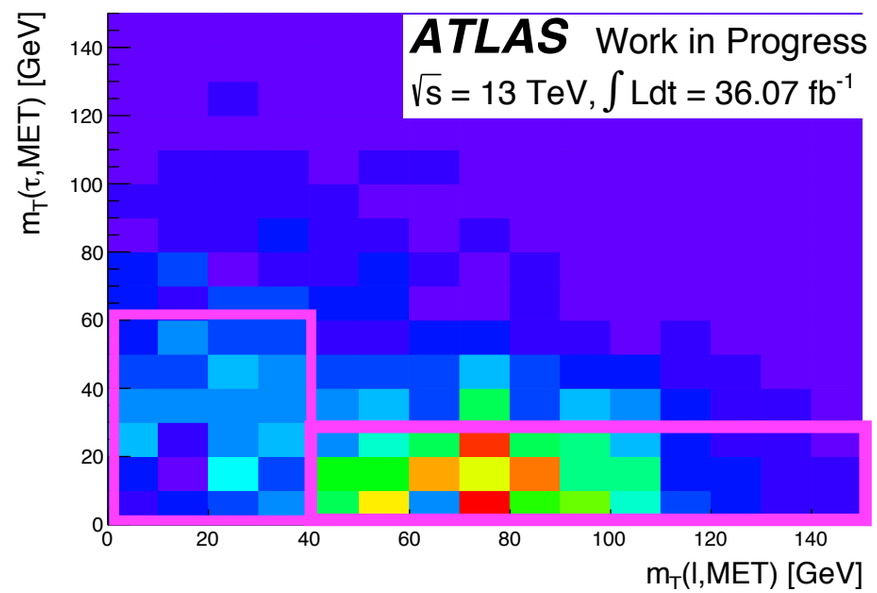
$\mu\tau$ preselection (m_T^l vs m_T^τ)

$H \rightarrow \mu\tau$

Signal



W+jets



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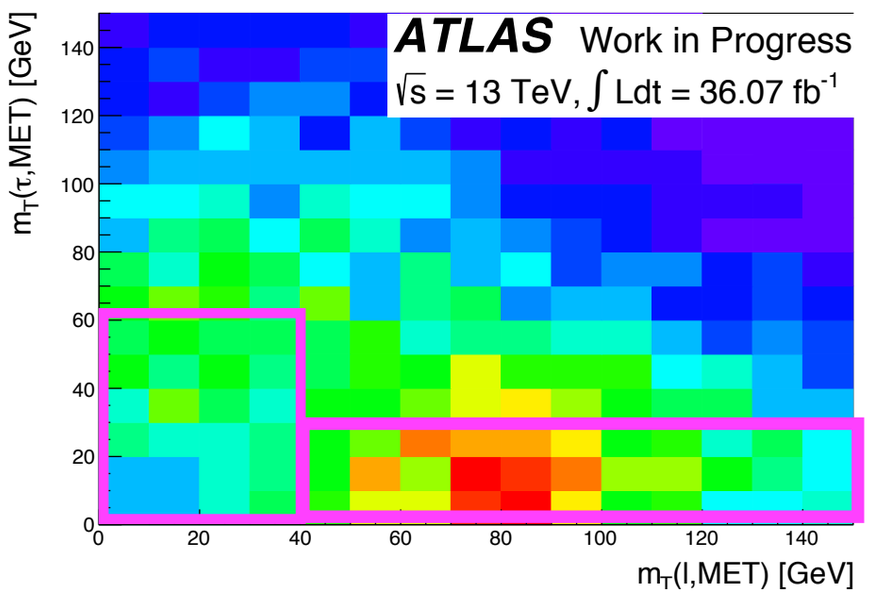
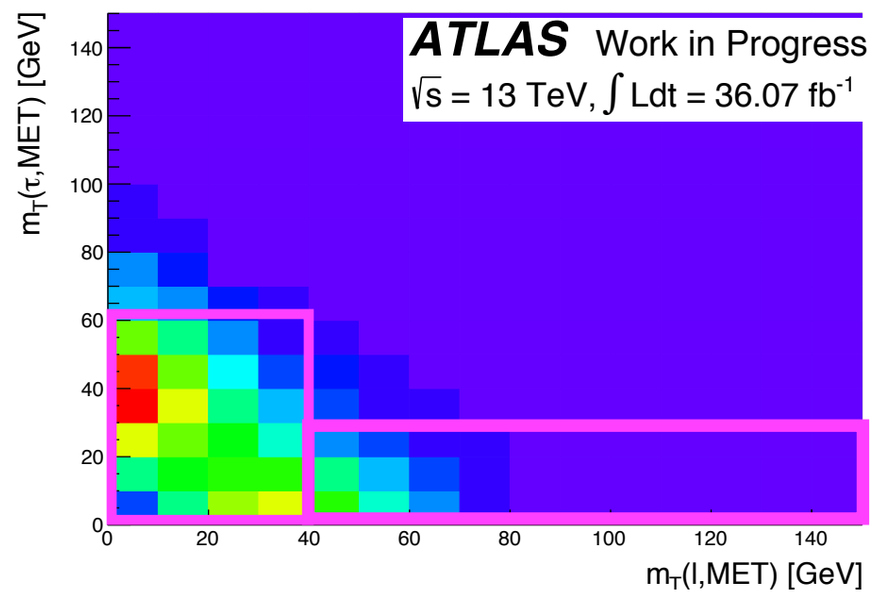


$Z\tau\tau$

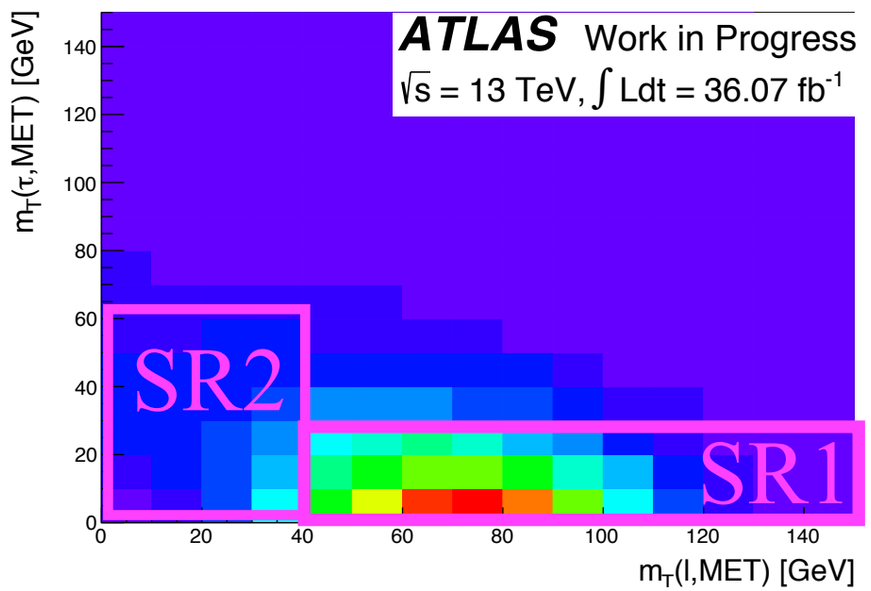


Signal vs. background characteristics

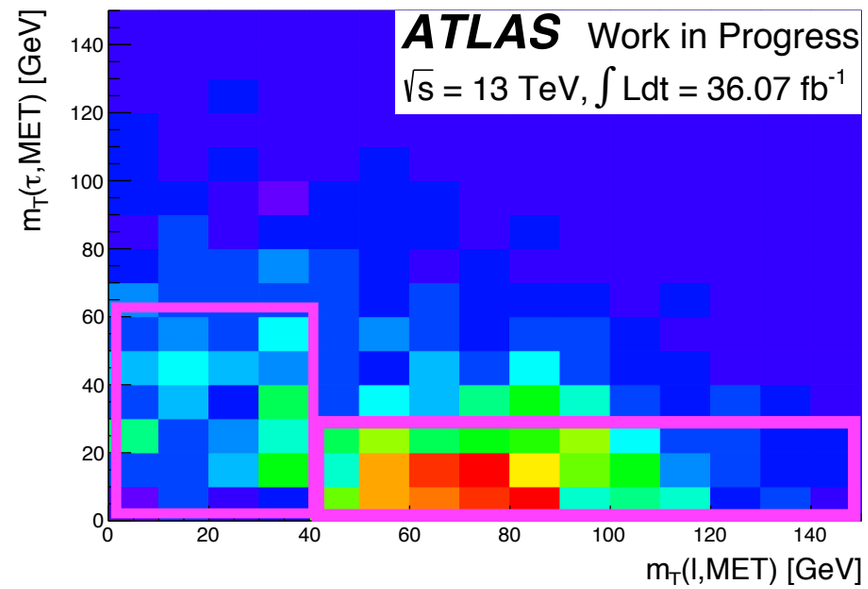
$e\tau$ preselection (m_T^l vs m_T^τ)

$H \rightarrow e\tau$

Signal



W+jets



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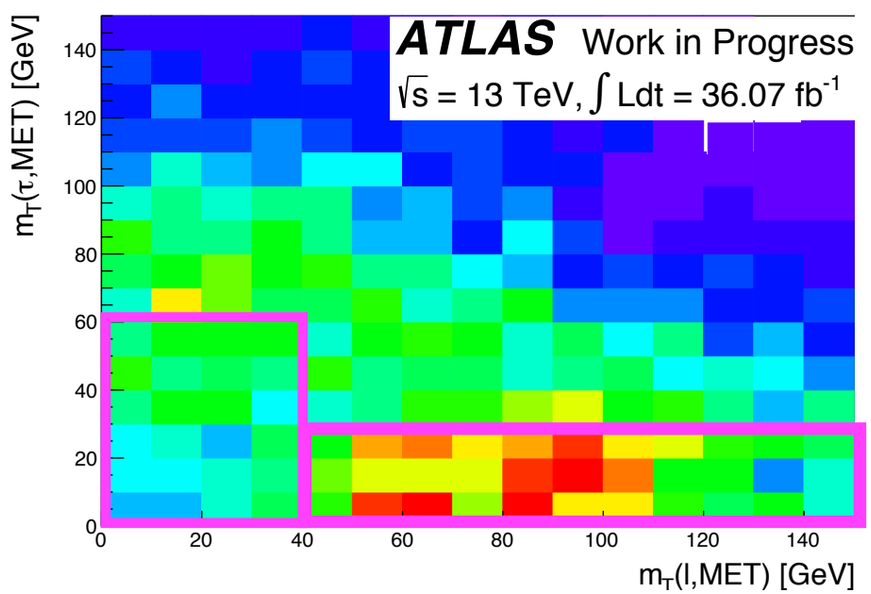
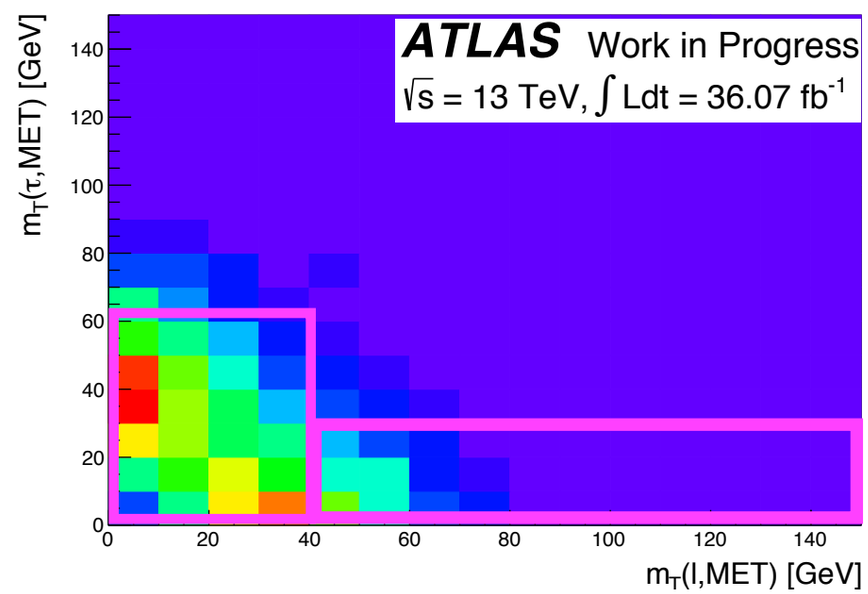


$Z\tau\tau$



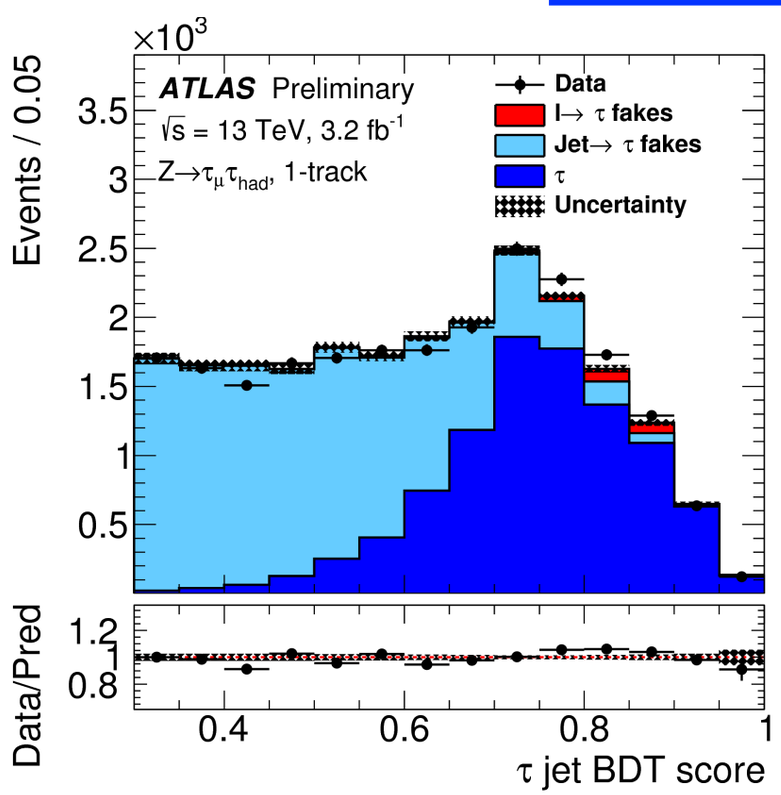
Fake factor background estimation

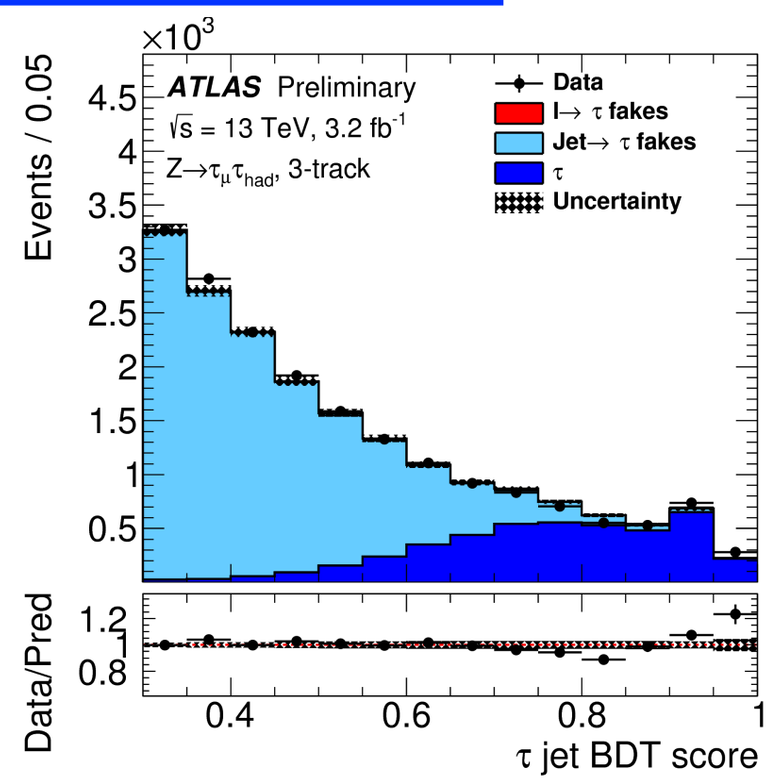
- Events failing tau-ID are weighted by fake factors to predict fake backgrounds in signal (tau-ID) region for W+jets, QCD

$$N_{fake}^{ID} = (N_{data}^{anti-ID} - N_{MC,others}^{anti-ID}) \times FF$$

$$FF = \sum_i R_i \times FF_i$$

$$FF_i = \frac{N_{data,CRi}^{ID} - N_{MC,others,CRi}^{ID}}{N_{data,CRi}^{anti-ID} - N_{MC,others,CRi}^{anti-ID}}$$





ATLAS-CONF-2017-029 (May 2017)

Tau-ID is based on BDT scores, which are well modeled in Run 2 (13 TeV)

Fake factor background estimation

- Fake factors are estimated for each components separately (W+jet, QCD)

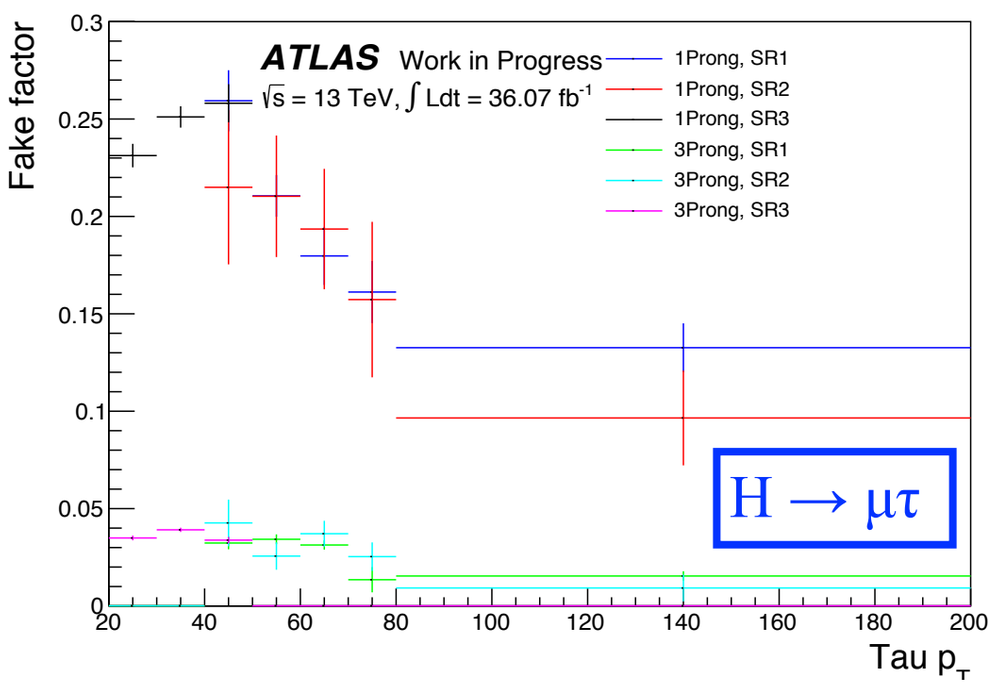
$$FF = \sum_i R_i \times FF_i$$

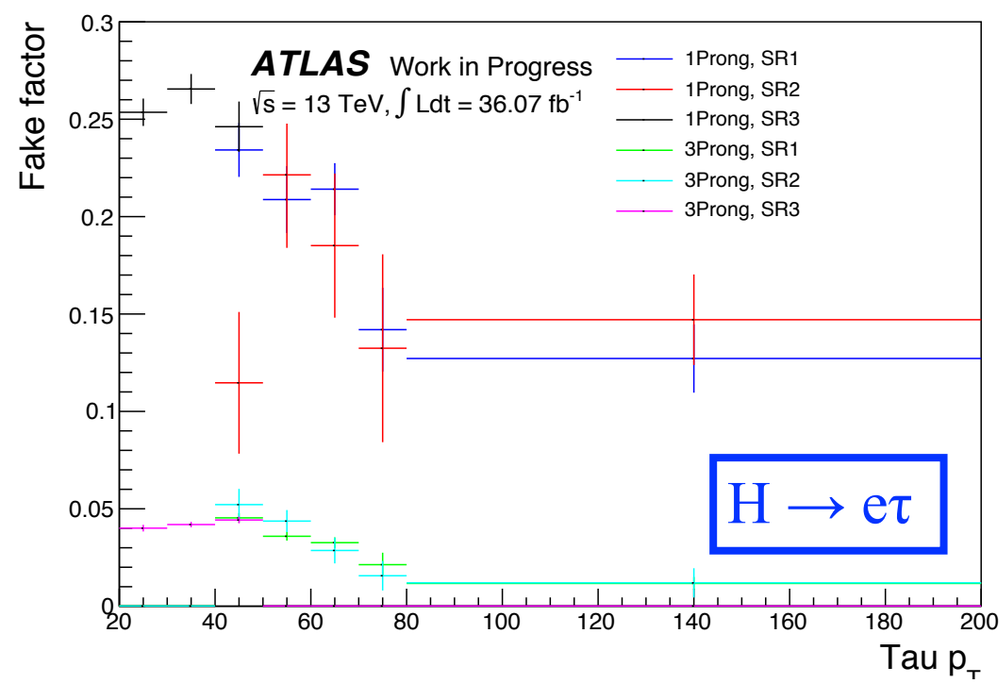
- **Relative contributions**

$$R_i = k_i \frac{N_{MC,i}^{anti-ID}}{N_{data}^{anti-ID} - N_{MC,others}^{anti-ID}}$$

$\sum_i R_i = 1$ and k_i's are normalization factors

- Fake factors as functions of tau p_T, number of prongs and m_T (τ,MET)

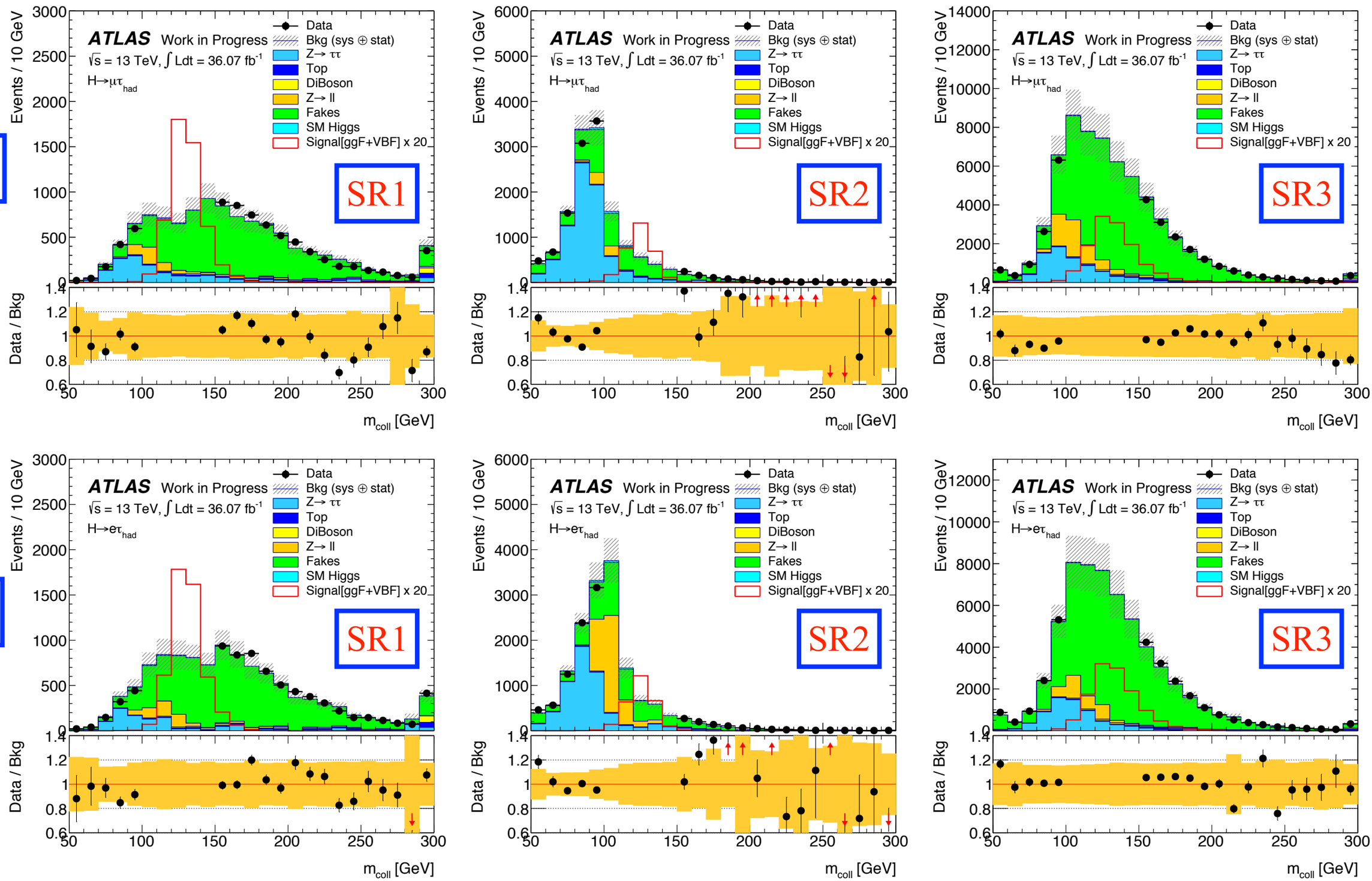




Discriminating variable: collinear mass

$H \rightarrow \mu\tau$

$H \rightarrow e\tau$



- Mass variables are blinded in the window 100 GeV $< m <$ 150 GeV

Systematic uncertainties

Fake background systematics

- vary FF_W and FF_{QCD} by $\pm 1\ \sigma$
- vary R_W and R_{QCD} by $\pm 1\ \sigma$
- vary non-fake MC subtracted

Include all other systematics following standard prescriptions by ATLAS performance groups.

Include theory uncertainties ~ 7% following LHC Higgs XS group.

	Rel. diff. to nom. (%)			Rel. diff. to nom. (%)		
	SR1	SR2	SR3	SR1	SR2	SR3
Nominal	$H \to \mu\tau$			$H \to e\tau$		
FF Stat. Unc. (up)	10	10	15	10	11	14
FF Stat. Unc. (down)	-10	-10	-14	-11	-11	-15
R_W (up)	2	2	4	2	3	5
R_W (down)	-2	-2	-4	-2	-3	-6
MC subtraction (up)	4	6	5	4	7	6
MC subtraction (down)	-4	-6	-5	-4	-7	-6

Systematics	Uncertainty
Luminosity	2−3%
Fakes	15−20%
JES	4−5%
E_T^{miss}	1−2%
Tau ID	3−4%
Lepton ID	2%
B-tag	2%
Theory	7%

$H \rightarrow \mu\tau$: expected sensitivity

- Comparison of results with and without systematics

		Significance				Upper limits at 95% CL			
		SR1	SR2	SR3	Combined	SR1	SR2	SR3	Combined
$H \rightarrow \mu\tau_{had}$	Without Systematics	2.79 σ	2.19 σ	1.98 σ	4.07 σ	$(0.70\ ^{+0.28}_{-0.20})\%$	$(0.90\ ^{+0.35}_{-0.25})\%$	$(0.99\ ^{+0.39}_{-0.28})\%$	$(0.48\ ^{+0.19}_{-0.13})\%$
	With Systematics	2.40 σ	1.73 σ	1.60 σ	3.66 σ	$(0.82\ ^{+0.32}_{-0.23})\%$	$(1.12\ ^{+0.44}_{-0.31})\%$	$(1.25\ ^{+0.49}_{-0.38})\%$	$(0.56\ ^{+0.22}_{-0.16})\%$

- Comparison of sensitivity between Run 1 and Run 2

	Significance		Upper limits at 95% CL		
	Run 1	Run 2	Run 1		Run 2
	Observed	Expected	Observed	Expected	Expected
$H \rightarrow \mu\tau_{had}$	1.3 σ	3.66 σ	1.85%	$(1.24\ ^{+0.50}_{-0.35})\%$	$(0.56\ ^{+0.22}_{-0.16})\%$

Significance numbers are calculated assuming $B(H \rightarrow \ell\tau)=1\%$

$H \rightarrow e\tau$: expected sensitivity

- Comparison of results with and without systematics

		Significance				Upper limits at 95% CL			
		SR1	SR2	SR3	Combined	SR1	SR2	SR3	Combined
$H \rightarrow e\tau_{had}$	Without Systematics	2.76 σ	1.89 σ	1.96 σ	3.88 σ	$(0.71\ ^{+0.28}_{-0.21})\%$	$(1.04\ ^{+0.41}_{-0.29})\%$	$(1.00\ ^{+0.39}_{-0.28})\%$	$(0.51\ ^{+0.20}_{-0.14})\%$
	With Systematics	2.38 σ	1.72 σ	1.48 σ	3.28 σ	$(0.82\ ^{+0.32}_{-0.23})\%$	$(1.12\ ^{+0.44}_{-0.31})\%$	$(1.27\ ^{+0.49}_{-0.38})\%$	$(0.58\ ^{+0.23}_{-0.17})\%$

- Comparison of sensitivity between Run 1 and Run 2

	Significance		Upper limits at 95% CL		
	Run 1	Run 2	Run 1		Run 2
	Observed	Expected	Observed	Expected	Expected
$H \rightarrow e\tau_{had}$	0.89 σ	3.28 σ	1.81%	$(2.07\ ^{+0.82}_{-0.58})\%$	$(0.58\ ^{+0.23}_{-0.17})\%$

Significance numbers are calculated assuming $B(H \rightarrow \ell\tau)=1\%$

Summary and outlook

- Search for lepton flavor violating decays of the Higgs boson has been performed with Run 2 data at 13 TeV using 36 fb^{-1} of data collected by the ATLAS detector at LHC.

- Analysis of only hadronic decays of tau is presented here.

- Expected significance ~ 3σ obtained assuming $B(H \rightarrow \ell\tau)=1\%$.

- The expected ATLAS limits at Run 2 are around 0.6%, which are factor of 2 to 3 more stringent than those obtained at Run 1.