Experimental overview of Higgs LFV decays

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Overview

- In parallel to precision measurements of Higgs boson couplings, searches for non-SM Higgs decays reach unprecedented sensitivity at the LHC

- Searches for H(125)→$e\tau/\mu\tau$ decays are the most sensitive probes of $Y_{e\tau/\mu\tau}$
  - Experimental challenges: large backgrounds, poor reconstructed mass resolution

- Searches for H(125)→$e\mu$ also performed at the LHC:
  - Very good mass resolution but huge backgrounds

- Searches for LFV decays of lighter or heavier Higgs bosons:
  - LHCb contributes at low mass, ATLAS and CMS at high mass

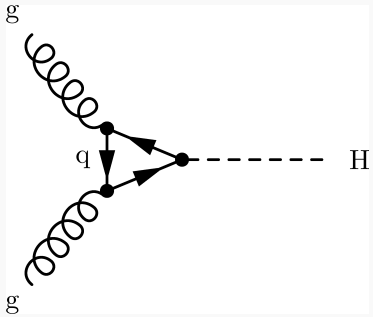
H(125)→eτ/μτ

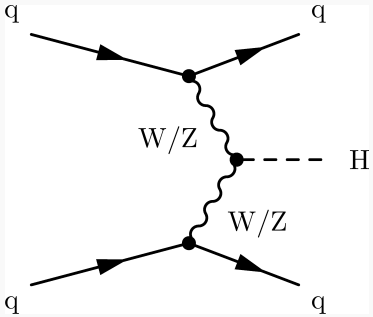
CMS, 36 fb^{-1} at 13 TeV: arXiv:1712.07173

ATLAS, 36 fb^{-1} at 13 TeV: arXiv:1907.06131

Signature

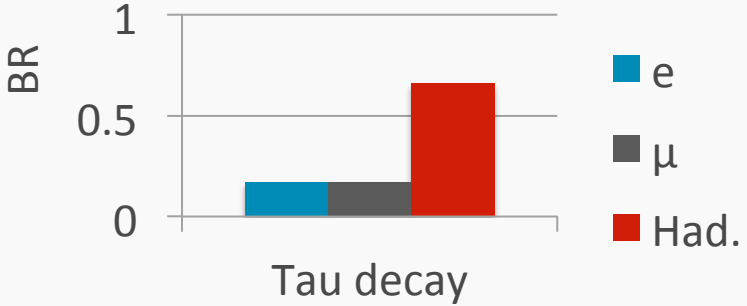
- Production:
  - ggH or VBF





  - VBF: select 2 jets with large mass and/or large pseudorapidity difference

- Decay:
  - $\tau \rightarrow \tau_e$, τ_μ, or τ_h



  - $e + \tau_e$ and $\mu + \tau_\mu$ not studied because of large $Z \rightarrow ee/\mu\mu$ bkg
  - $e+\tau_\mu$: electron expected to be harder
  - $\mu+\tau_e$: muon expected to be harder

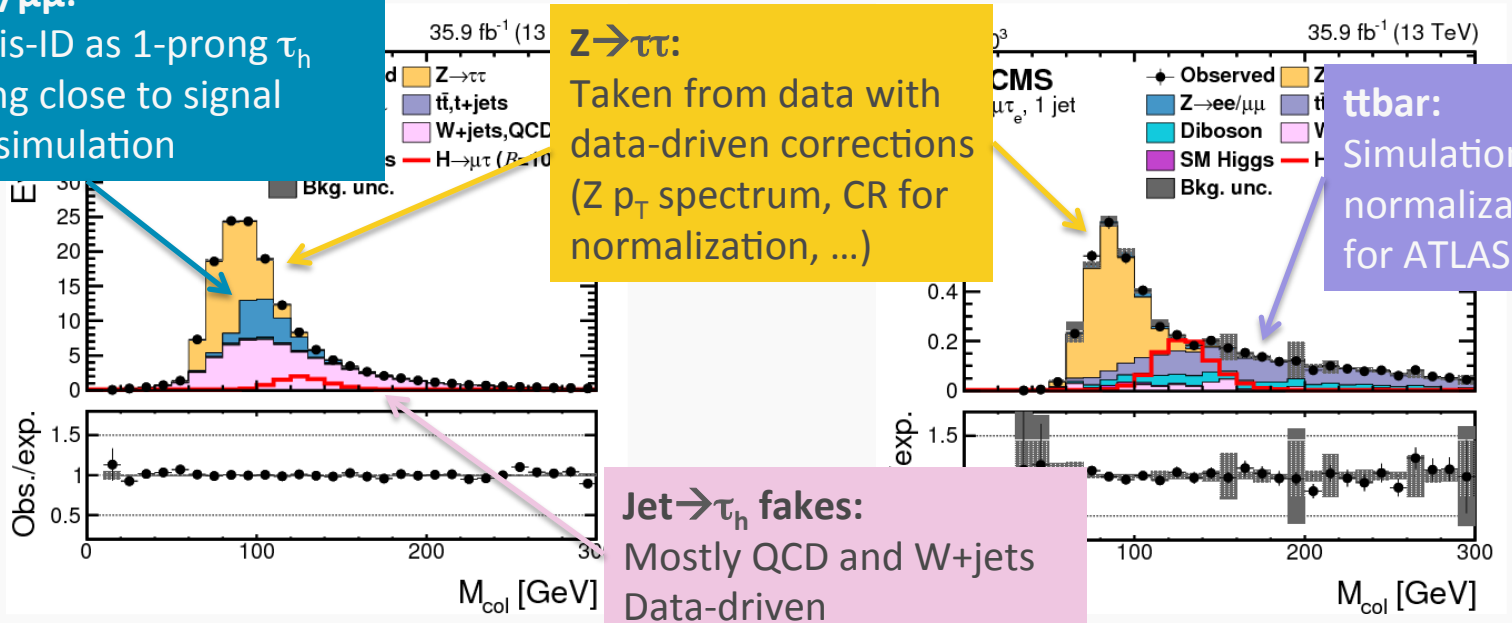
Background composition

- Final states with a τ_h
- e+μ final state

Z→ee/μμ:
e/μ mis-ID as 1-prong τ_h
Peaking close to signal
From simulation

Z→ττ:
Taken from data with data-driven corrections (Z p_T spectrum, CR for normalization, …)

ttbar:
Simulation, normalization from CR for ATLAS

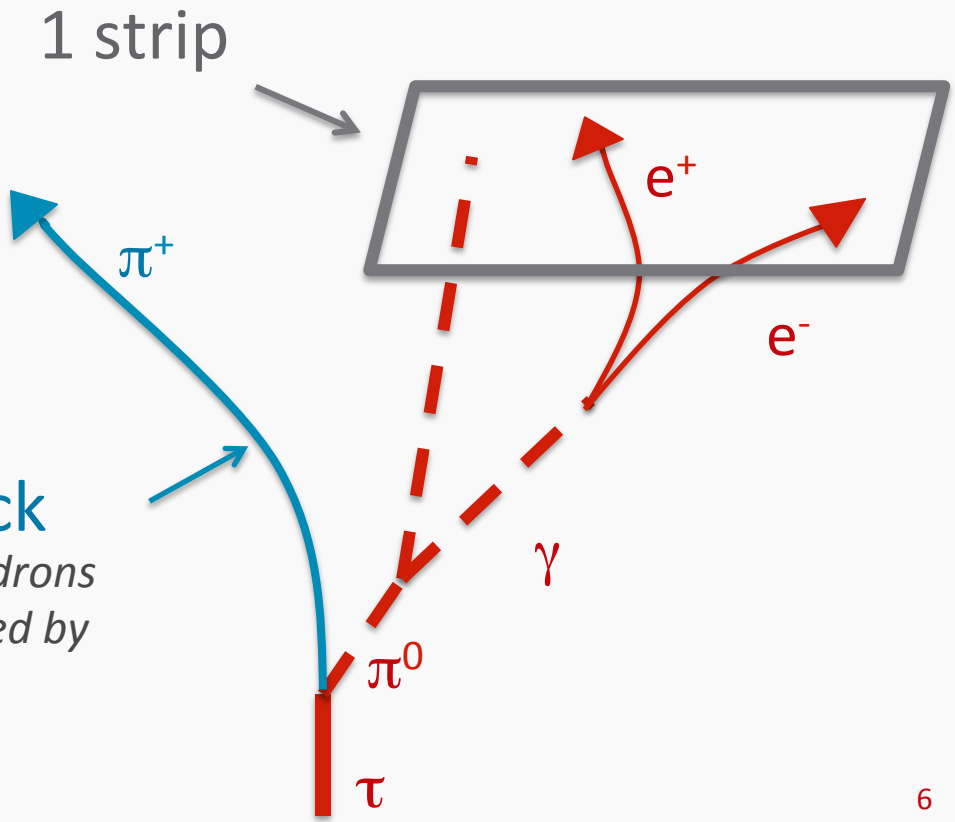


Jet→τ_h fakes:
Mostly QCD and W+jets
Data-driven

Reconstructing τ_h candidates at CMS

Neutral pions reconstructed from strips of energy deposit in the electromagnetic calorimeter

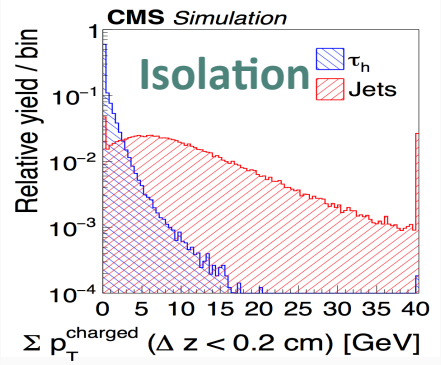
- Combination of 1 or 3 tracks with or without strips
- Decay modes = 1 prong, 1 prong + π^0, 3 prongs

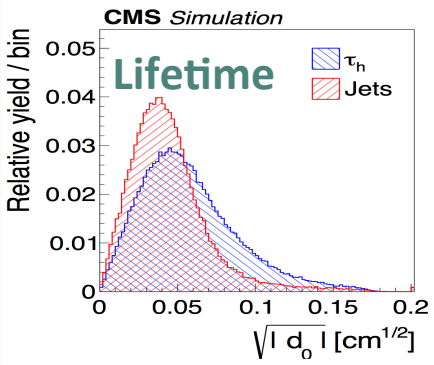


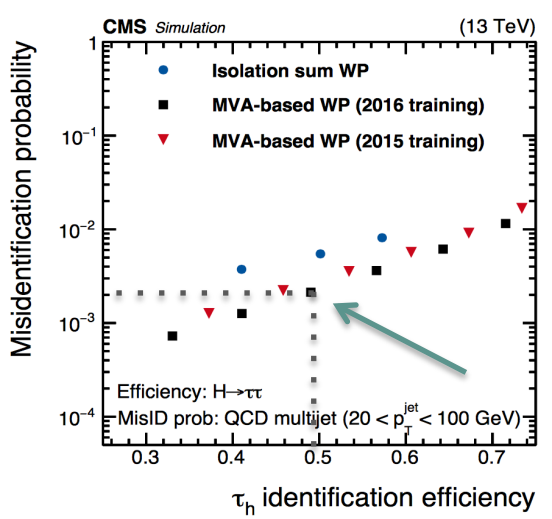
Identifying τ_h candidates at CMS

- MVA identification to reject quark/gluon jet → τ_h fakes, based on:
  - **Isolation** variables (jets are surrounded by more hadronic activity)
  - **Lifetime** variables (taus are displaced)

- ~50% efficiency for real τ_h, ~0.2% misidentification rate for jets

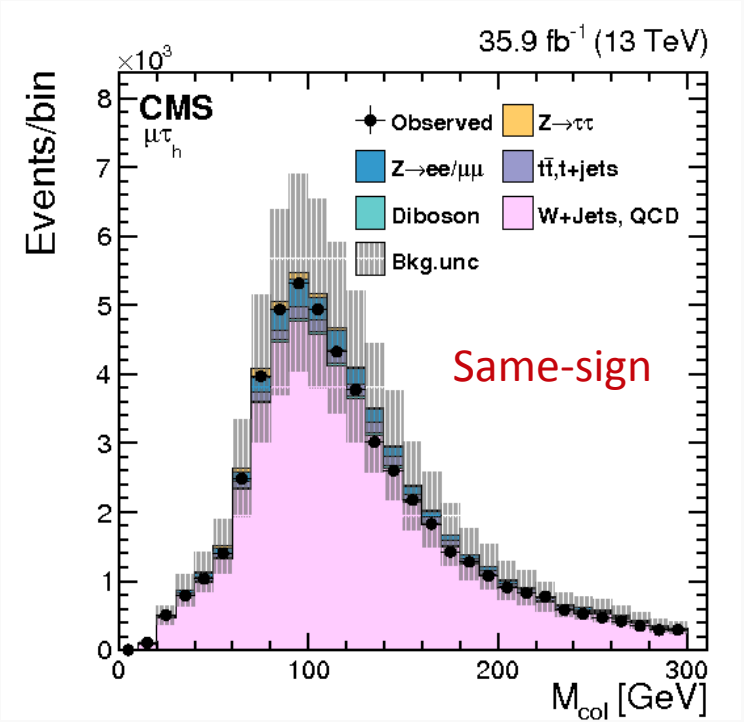






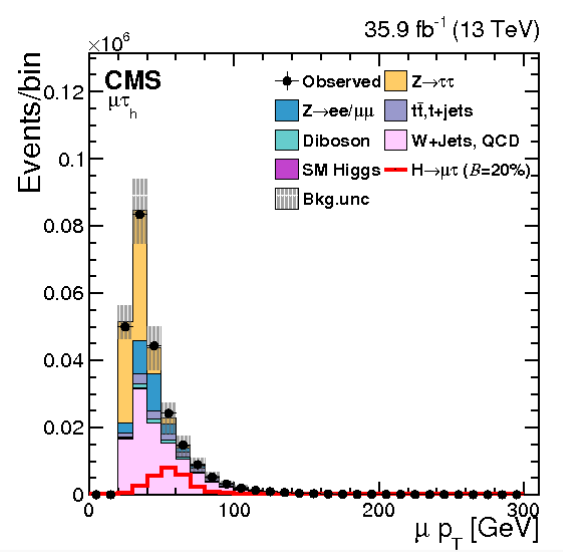
jet→τ_h background estimation

- Mostly W+jets and QCD multijet events
- Estimated from events where the τ_h passes some loose isolation but not the tight working point used in the SR ("anti-isolated")
- Probabability for jets passing the loose isolation to pass the tight one measured in Z→μμ + jets events, used to reweigh anti-isolated events to predict bkg in signal region
- Validated in various control regions



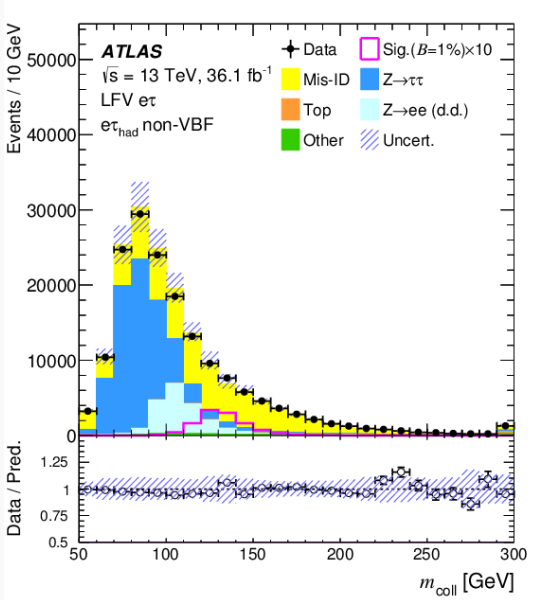
Discriminative variables

- Leading lepton p_T



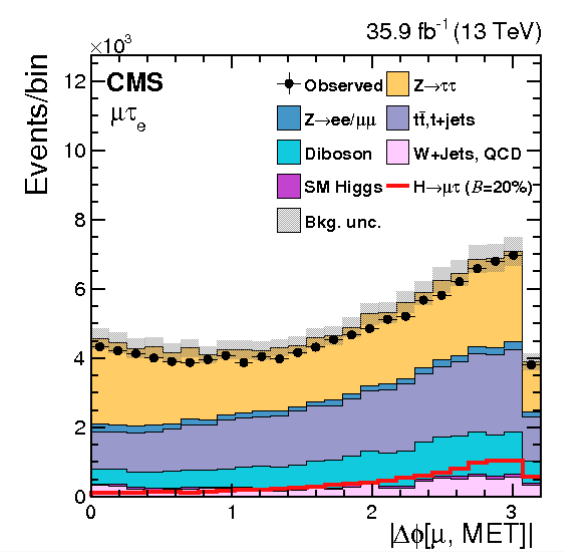
Signal: prompt lepton
Z→ττ: lepton from τ decay
QCD: fake lepton

- Collinear mass



Supposes visible tau and ν are aligned
Unbiased Z/H mass estimator

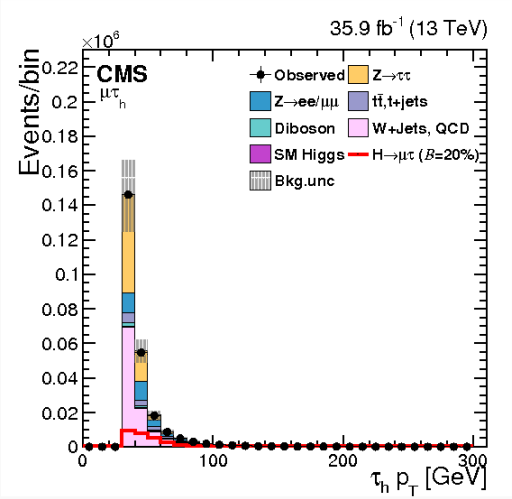
- $\Delta\phi(l_1,MET)$



Signal: MET from 1 τ decay, opposed to lepton
Z→ττ: both taus create MET

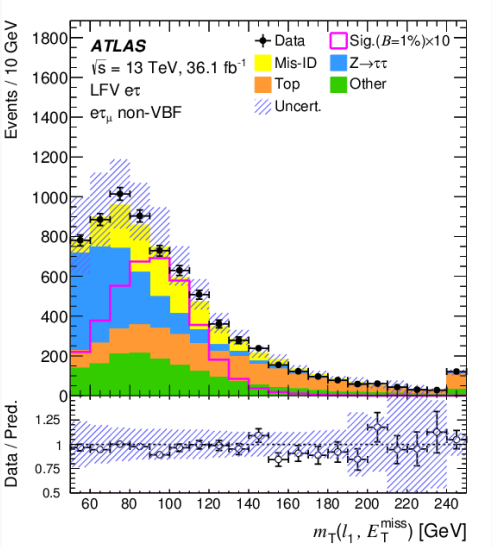
Discriminative variables

- τ_h p_T



Larger jet→τ_h misidentification at low p_T

- $m_T(l_1,MET)$



Signal: MET from τ, peak below H mass
Z→ττ/fake: limited MET
Top: large MET wo correlation with l_1

+ plenty of other variables, with different degrees of correlation…:

MET, DR between the objects, jet kinematics, lepton kinematics, …

Analysis strategy

- ATLAS way:
  - Make 2 signal regions: VBF-like (2 jets with high mass and large η separation)
  - Cut on some variables to create 2 orthogonal background control regions (top, Z)
  - Train BDT and simultaneously fit BDT output in SRs with CRs

VBF SR | Non-VBF SR | Top CR | $Z \rightarrow \tau\tau$ CR

- CMS way:
  - Make 4 signal regions based on number of jets
  - Train BDT and fit BDT output (MVA-approach)
  - Or, alternatively, apply tighter selection criteria and fit reconstructed Higgs mass (cut-based (CB) approach)

0 jet | 1 jet | 2 jets non-VBF | 2 jets VBF

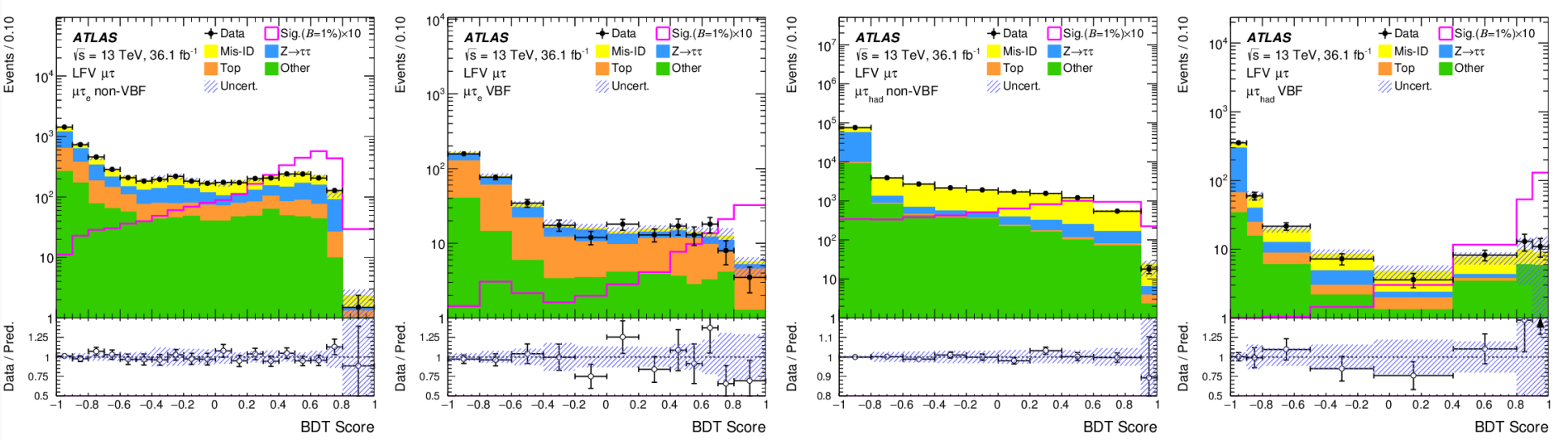
ATLAS final distributions (μτ)

Mixture of mis-ID (= QCD, W, semi-leptonic ttbar), Z→ττ, ttbar, VV

Large ttbar bkg High signal purity at high BDT score

Mixture of mis-ID (= QCD, W) and Z→ττ

High signal purity at high BDT score Remaining mis-ID



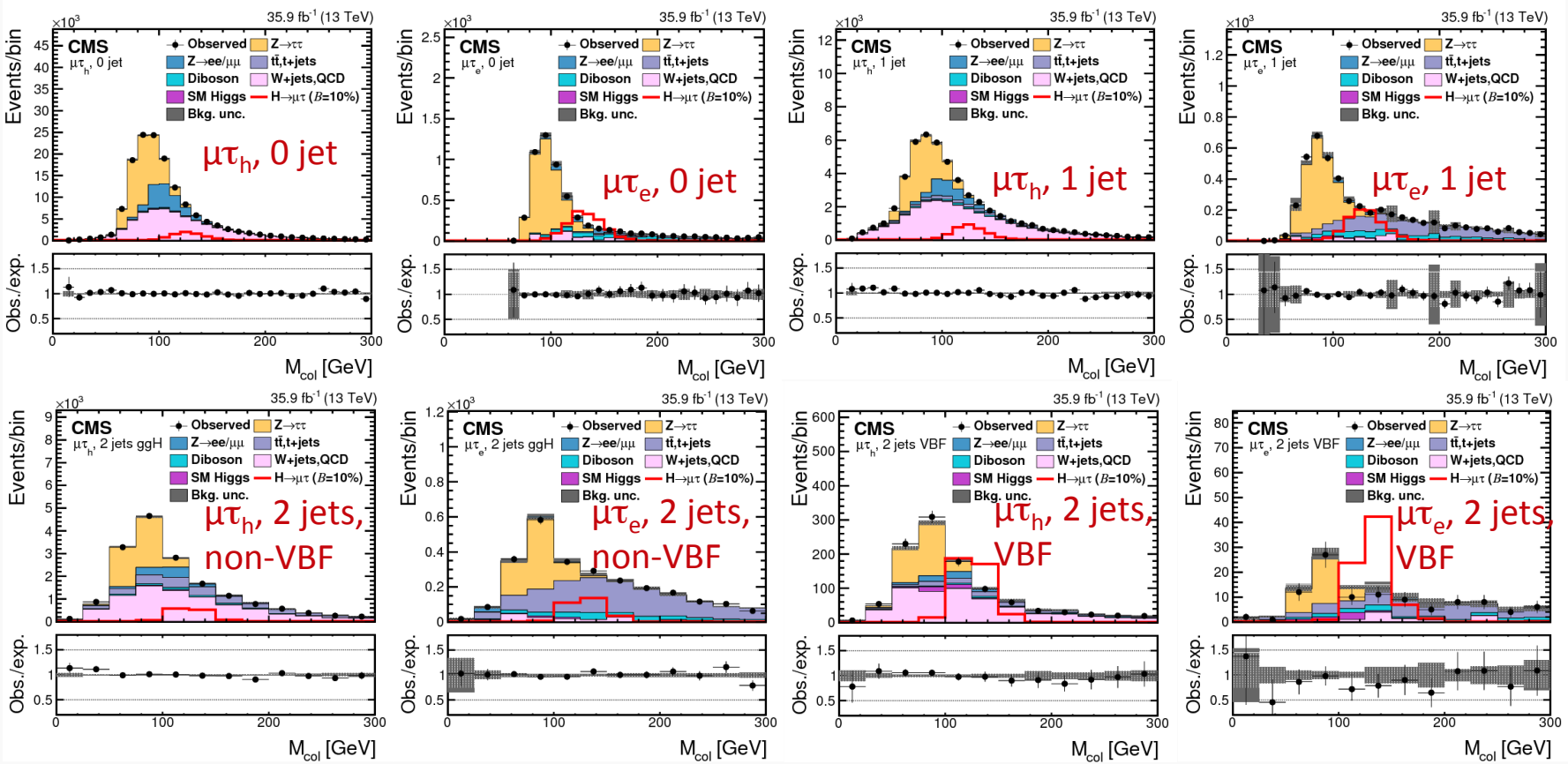
$\mu\tau_e$, non-VBF

$\mu\tau_e$, VBF

$\mu\tau_h$, non-VBF

$\mu\tau_h$, VBF

CMS distributions (μτ, CB analysis)



Systematics (ATLAS)

Object reconstruction, up to 10% for complex objects

Bkg and signal prediction, from data or simulation

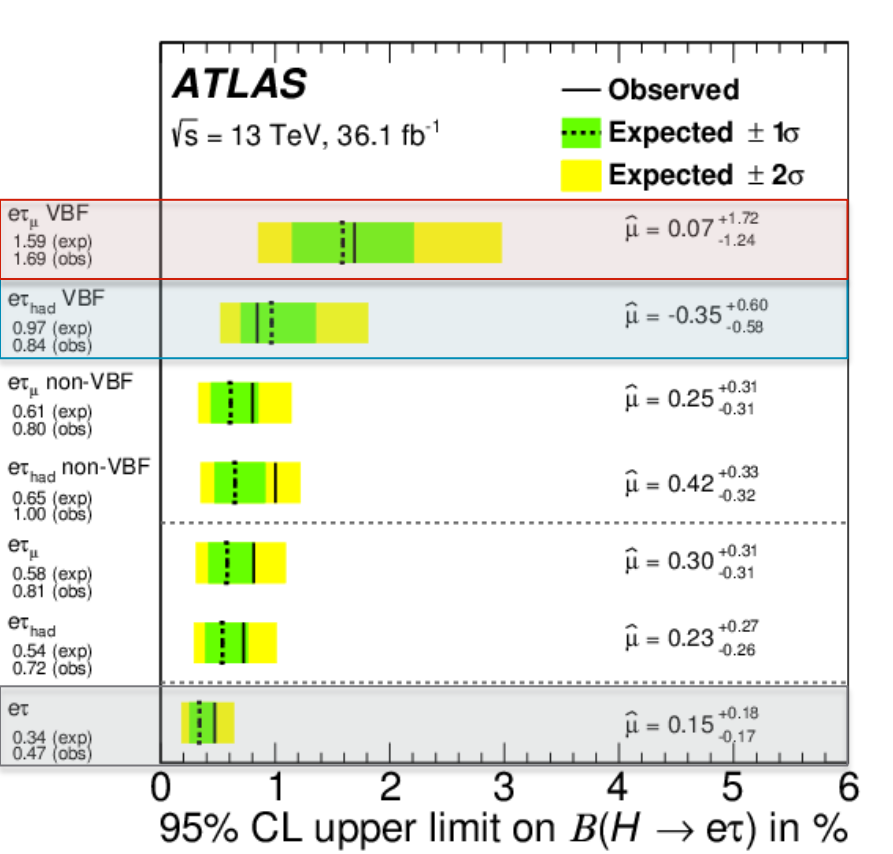
Systematic uncertainties dominate, but some scale with luminosity

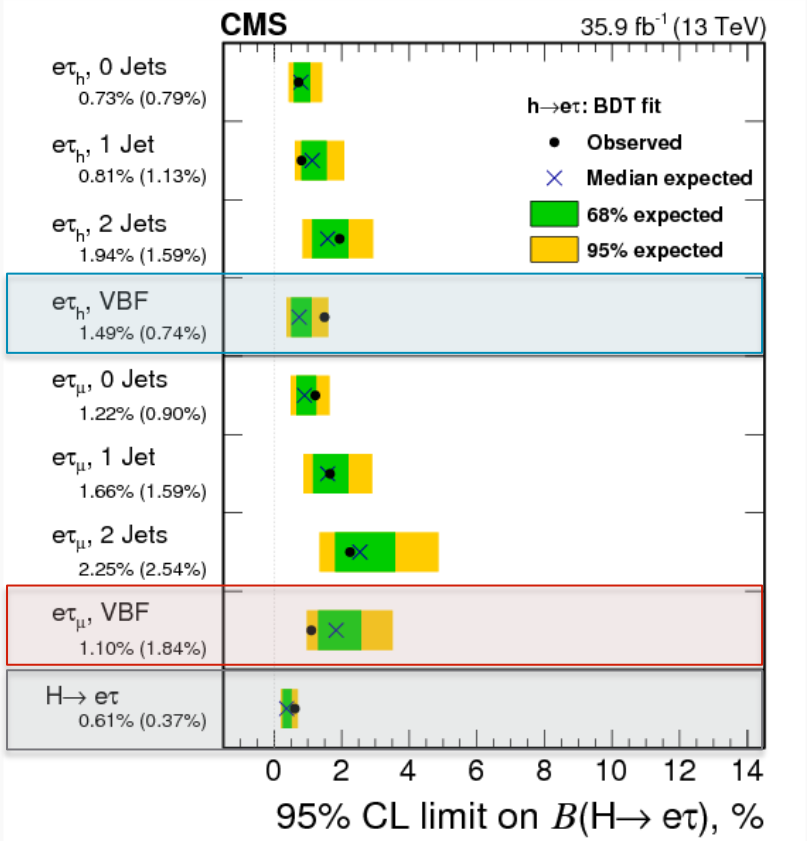
Source of uncertainty	Impact on $\mathcal{B}(H \to e\tau)$ [%]		Impact on $\mathcal{B}(H \to \mu\tau)$ [%]	
	Measured	Expected	Measured	Expected
Electron	+0.05/−0.05	+0.06/−0.06	+0.03/−0.03	+0.02/−0.02
Muon	+0.04/−0.04	+0.04/−0.04	+0.10/−0.10	+0.08/−0.10
$\tau_{\text{had-vis}}$	+0.02/−0.02	+0.02/−0.02	+0.04/−0.04	+0.04/−0.05
Jet	+0.09/−0.08	+0.09/−0.09	+0.11/−0.12	+0.11/−0.12
$E_{\text{T}}^{\text{miss}}$	+0.02/−0.02	+0.02/−0.03	+0.05/−0.08	+0.03/−0.05
b-tag	+0.02/−0.03	+0.03/−0.03	+0.01/−0.01	+0.01/−0.01
Mis-ID backg. ($\ell\tau_{\ell'}$)	+0.08/−0.07	+0.09/−0.08	+0.07/−0.07	+0.07/−0.07
Mis-ID backg. ($\ell\tau_{\text{had}}$)	+0.12/−0.11	+0.11/−0.12	+0.11/−0.11	+0.10/−0.10
Pile-up modelling	+0.02/−0.01	+0.01/−0.01	+0.05/−0.03	+0.08/−0.06
Luminosity	< 0.01	< 0.01	< 0.01	< 0.01
Background norm.	+0.05/−0.04	+0.05/−0.03	+0.04/−0.02	+0.05/−0.03
Theor. uncert. (backg.)	+0.04/−0.03	+0.04/−0.03	+0.08/−0.07	+0.09/−0.09
Theor. uncert. (signal)	+0.01/−0.01	+0.01/−0.01	+0.04/−0.02	+0.02/−0.02
MC statistics	+0.04/−0.04	+0.03/−0.03	+0.04/−0.04	+0.05/−0.04
Full systematic	+0.17/−0.16	+0.17/−0.17	+0.18/−0.18	+0.19/−0.20
Data statistics	+0.07/−0.07	+0.07/−0.07	+0.07/−0.07	+0.08/−0.08
Total	+0.18/−0.17	+0.18/−0.18	+0.19/−0.19	+0.20/−0.21

H→eτ results

CMS MVA-results shown

CB results worse by a factor of ~2





H→μτ results

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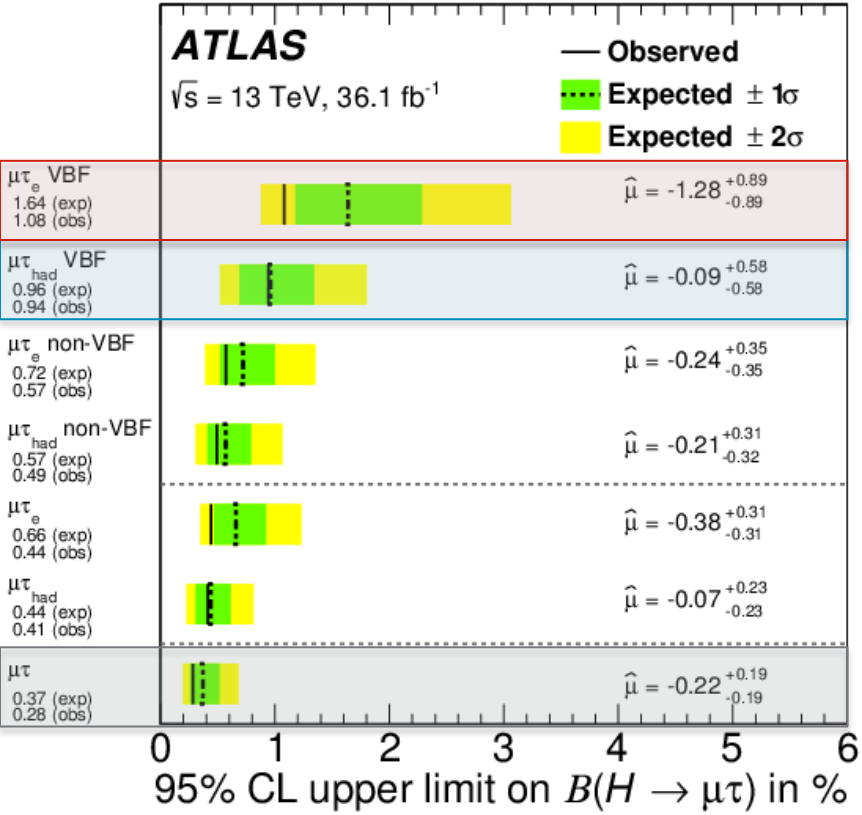
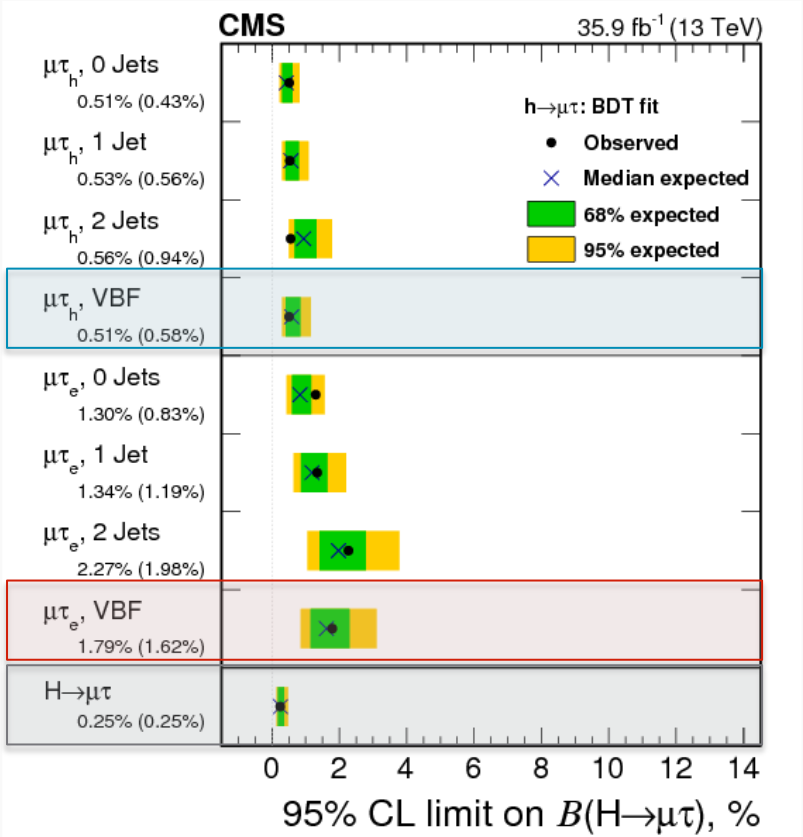
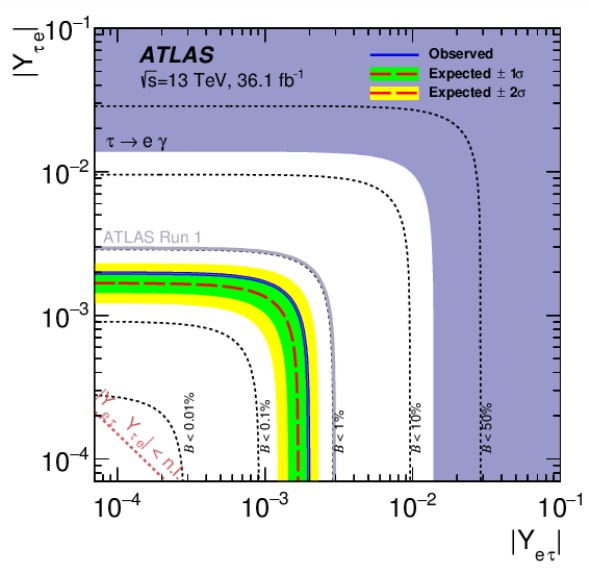


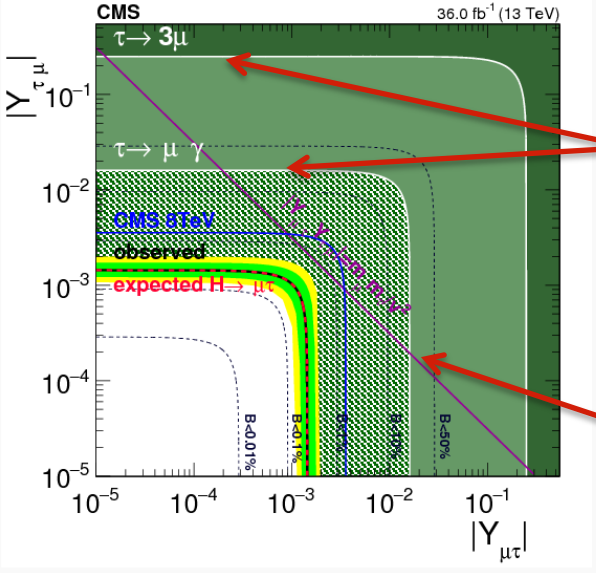


Results in terms of $Y_{l\tau}$

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

- Results on BR can be converted to results in the $Y_{l\tau}$-$Y_{\tau l}$ plane





Direct searches for $\tau\to 3\mu$ and $\tau\to\mu/e\,\gamma$ much less sensitive to $Y_{l\tau}/Y_{\tau l}$

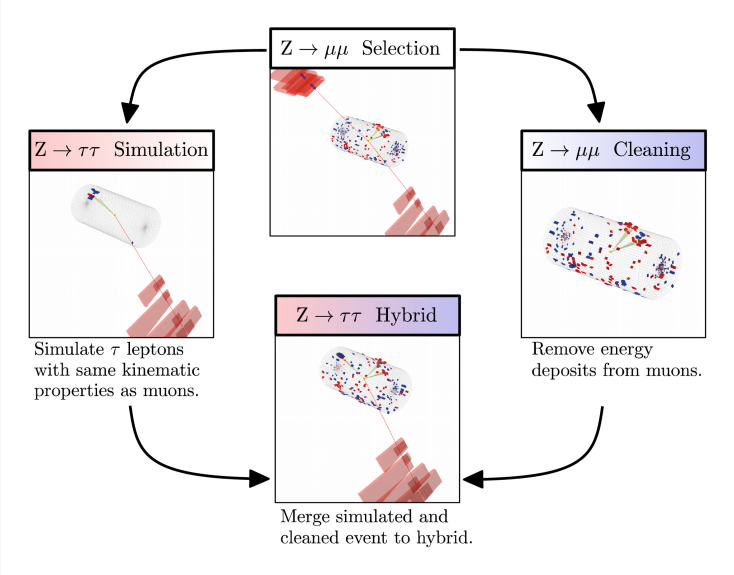
Yukawa-like relationship $|Y_{\mu\tau}\,Y_{\tau\mu}| = (m_\mu\, m_\tau)\,/\,v^2$

What to expect in the near future?

- No LFV Higgs result based on the full Run-2 dataset (x 4 luminosity) … yet
- But conclusions can be drawn from SM H→ττ analysis (*CMS-PAS-HIG-19-010*)
  - Significance increased from 5 to 10 sigmas: larger improvement than luminosity scaling. **How?**

Embedded Z→ττ samples:

Z→μμ events in data, reconstructed muons replaced by simulated taus
Reduction of experimental and theoretical uncertainties: jet-related variables, MET, Z p_T, …



Hadronic tau identification:

Deep neural network training reduces the fake background by a factor of ~2 for a same efficiency

What to expect in the far future?

- 3000 fb^{-1} at the HL-LHC
- No dedicated projection but resources from YR (*arXiv:1902.00134*)

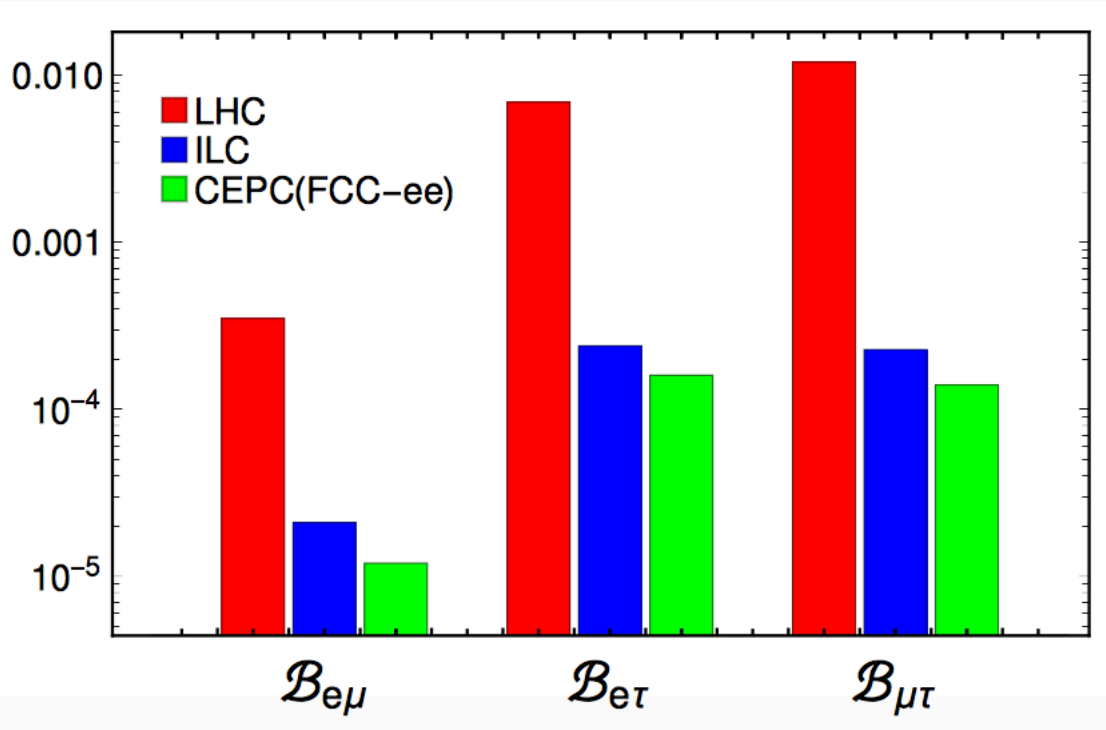
- Systematic uncertainties in object reconstruction reduced (back-up)
- Expected improvements in background estimation methods because of larger statistics
- Expected improvement in theory uncertainties (mostly for the signal)
- With larger statistics and many years ahead of us, very likely to improve the analysis strategy (deep learning?, more clever variables?, more clever categories?, very pure categories?, …)

- *Could probably reach limits $B(H \rightarrow \mu\tau) < 0.01\text{-}0.05\%$ (or a discovery!), assuming S/B ratio similar to LHC Run-2 (requires trigger and reco improvements)*

What to expect in the far future?

arXiv:1711.07243

- The ILC and CEPC would also be sensitive to LFV H decays
- Much cleaner environment than LHC:
  - O(10) bkg events expected
- Could reach limits on B(H→eτ/μτ) around 0.01%.



H(125)→eμ

ATLAS, 139 fb^{-1} at 13 TeV: arXiv:1909.10235

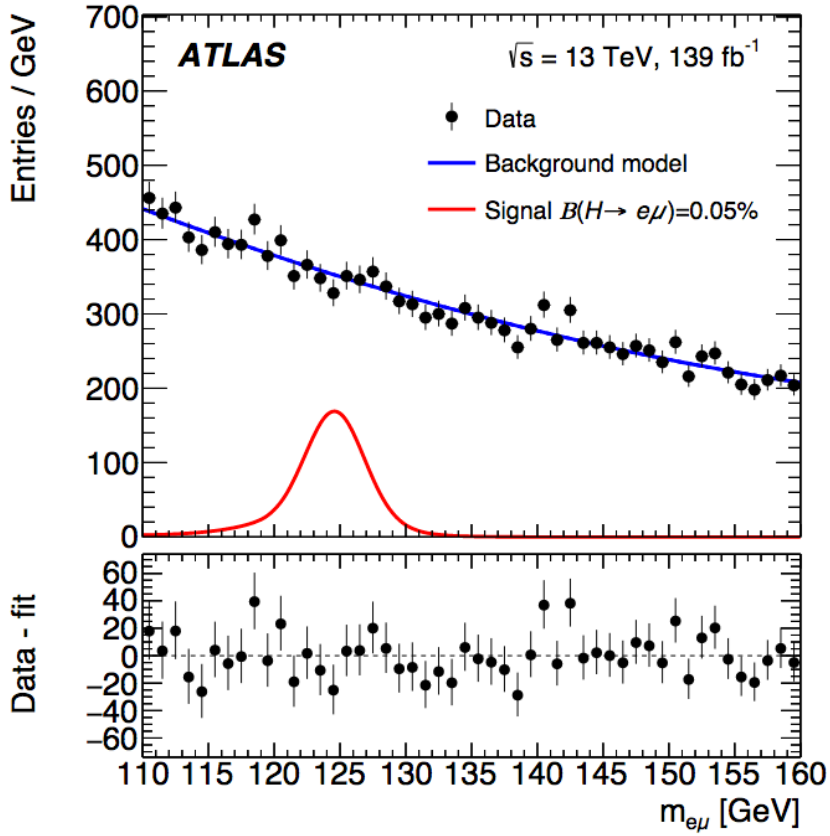
ATLAS H→eμ, 139 fb^{-1}

- Strong constraints on $Y_{e\mu}$ from μ→eγ measurement and electron dipole moment, but assumptions involved

- Unbinned fit of a narrow resonance over a smooth decreasing background

- B(H→eμ) < 6.2 x 10^{-5}
- 8 TeV CMS: B(H→eμ) < 3.4 x 10^{-5}

arXiv:1909.10235



LFV decays of lighter/heavier H

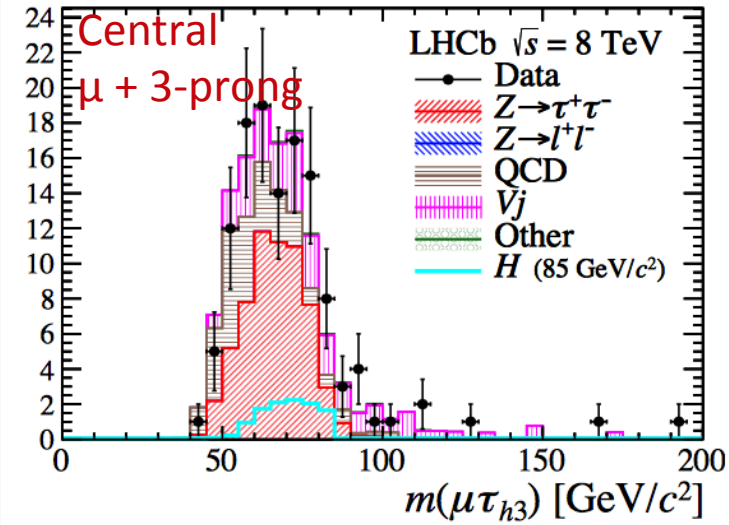
CMS, 36 fb^{-1} at 13 TeV: arXiv:1911.10267

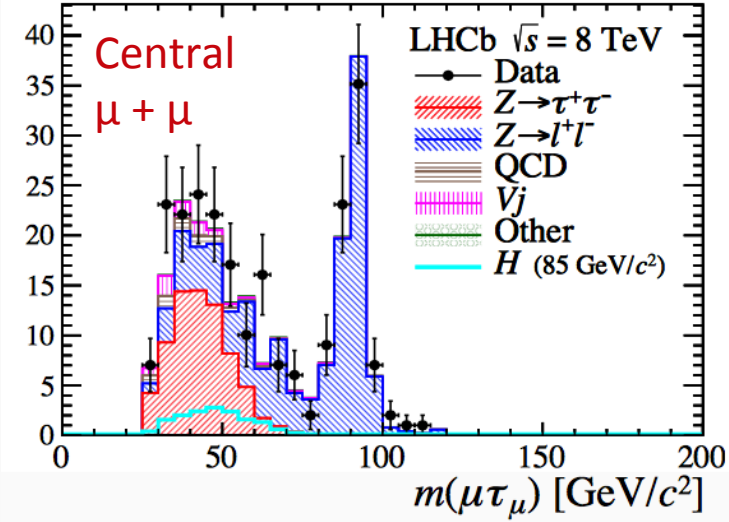
LHCb, 2 fb^{-1} at 8 TeV: arXiv:1808.07135

LHCb search for h→μτ

- 8 TeV search, *arXiv:1808.07135*
- Light 2HDM Higgs boson with LFV decays, 45 < m < 195 GeV
- Probing forward rapidity region
- Targeting ggH production

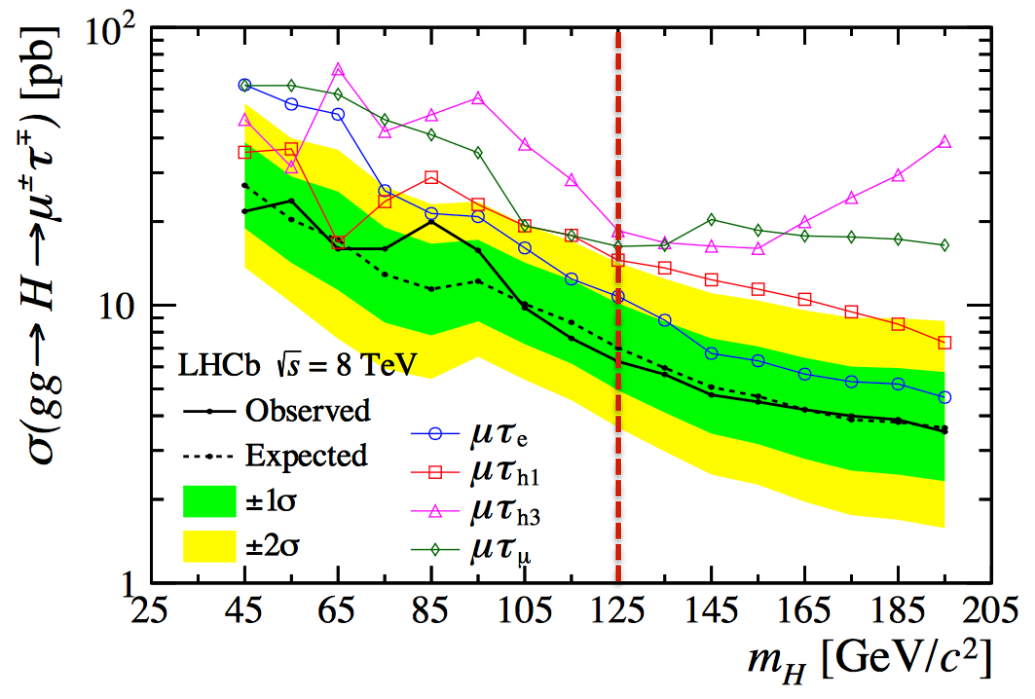
- 4 decay channels studied: $\mu\tau_e$, $\mu\tau_\mu$, $\mu\tau_{1prong}$, $\mu\tau_{3prong}$
- 3 categories: low (optimal for m < 75 GeV), central, high (m > 85 GeV)
- QCD and Vj backgrounds taken from data





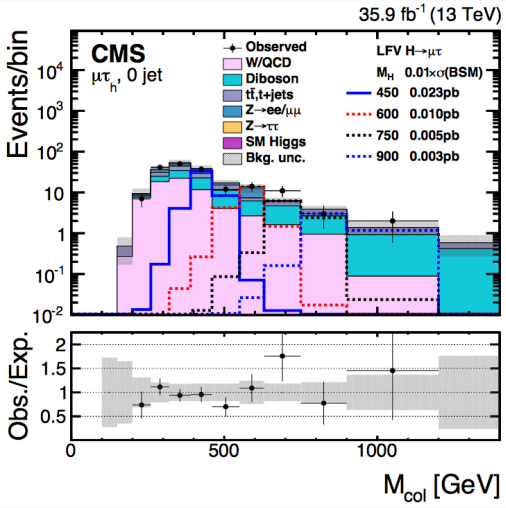
LHCb search for h→μτ, 8 TeV

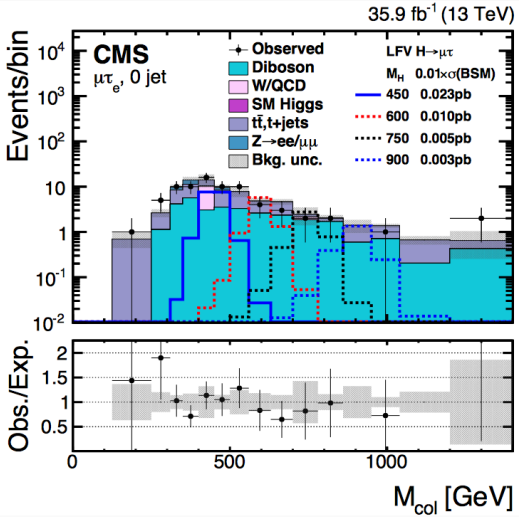
- No significant excess
- Contributions from decay channels depend on mass
- Complementary to ATLAS and CMS:
  - At 125 GeV: B(h→μτ) < 26%
  - But exploring low mass region too

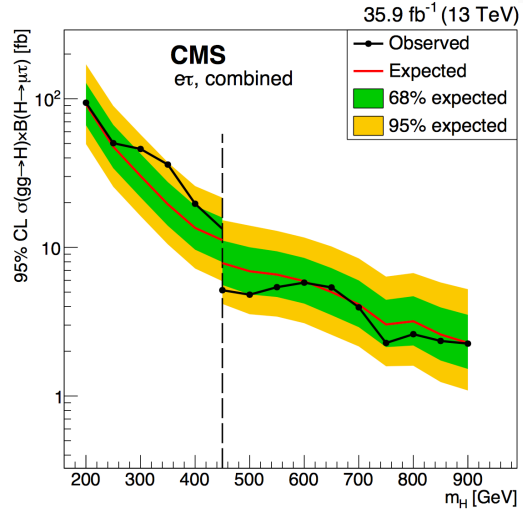


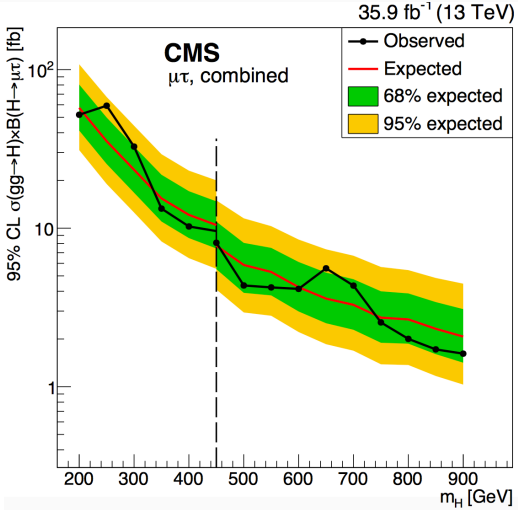
LFV decays of heavy Higgs bosons

- Mass range probed: 200-900 GeV
- Categories based on the number of jets
- Special attention to the description of the collinear mass spectrum, even in the tails
- No significant excess observed at any mass









Summary

Summary

- $H \rightarrow \mu\tau/e\tau$ searches performed at the LHC are complex and already exclude BR below the percent level
- Searches for lighter or heavier LFV Higgs boson decays, or for LFV decays in the $e\mu$ final state are also performed

- In the short term (Run-2), we can expect significant improvements from larger integrated luminosity, and improved background methods and object reconstruction
- In the longer term (HL-LHC), constraints could go down to $O(10^{-4})$ because of large datasets, reduced systematics, and analysis improvements

Backup

HL-LHC systematic uncertainties

Source	Component	Run 2 unc.	Projection minimum unc.
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic τ ID		6%	Same as Run 2
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy resolution		Varies with p_T and η	Half of Run 2
$\vec{p}_T^{miss}$ scale		Varies with analysis selection	Half of Run 2
b-tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated luminosity		2.5%	1%

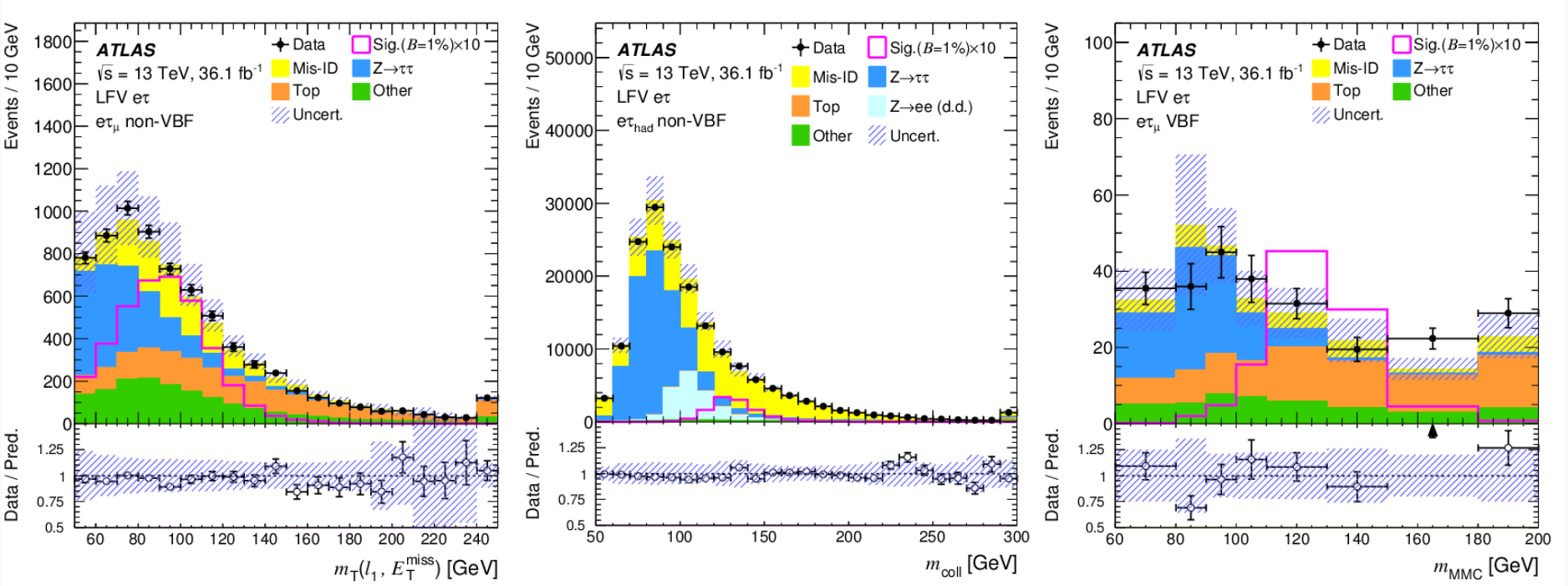
Simulations ATLAS H→eτ/μτ

Table 1: Generators used to describe the signal and background processes, parton distribution function (PDF) sets for the hard process, and models used for parton showering, hadronization and the underlying event (UEPS). The orders of the total cross-sections used to normalize the events are also given. More details are given in Ref. [17].

Process	Generator	PDF	UEPS	Cross-section order
ggF	Powheg-Box v2 [26–30] NNLOPS [31]	PDF4LHC15 [32] NNLO	Pythia 8.212 [25]	N^3LO QCD + NLO EW [33–36]
VBF	Powheg-Box v2 MiNLO [30]	PDF4LHC15 NLO	Pythia 8.212	~NNLO QCD + NLO EW [37–39]
WH, ZH	Powheg-Box v2 MiNLO	PDF4LHC15 NLO	Pythia 8.212	NNLO QCD + NLO EW [40–42]
W/Z+jets	Sherpa 2.2.1 [43]	NNPDF30NNLO [44]	Sherpa 2.2.1 [45]	NNLO [46, 47]
$VV/V\gamma^*$	Sherpa 2.2.1	NNPDF30NNLO	Sherpa 2.2.1	NNLO
$t\bar{t}$	Powheg-Box v2 [26–28, 48]	CT10 [49]	Pythia 6.428 [50]	NNLO+NNLL [51]
Single t	Powheg-Box v1 [52, 53]	CT10	Pythia 6.428	NLO [54–56]

$\ell\tau_{\ell'}$			$\ell\tau_{\text{had}}$		
Variable	VBF	non-VBF	Variable	VBF	non-VBF
m_{MMC}	HR	HR	m_{coll}	HR	HR
$p_{\text{T}}^{\ell_1}$	•	•	p_{T}^{ℓ}	•	HR
$p_{\text{T}}^{\ell_2}$	HR	HR	$p_{\text{T}}^{\tau_{\text{had-vis}}}$	•	HR
$\Delta R(\ell_1, \ell_2)$	HR	•	$\Delta R(\ell, \tau_{\text{had-vis}})$	•	•
$m_{\text{T}}(\ell_1, E_{\text{T}}^{\text{miss}})$	•	HR	$m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}})$	HR	•
$m_{\text{T}}(\ell_2, E_{\text{T}}^{\text{miss}})$	HR	•	$m_{\text{T}}(\tau_{\text{had-vis}}, E_{\text{T}}^{\text{miss}})$	HR	HR
$\Delta\phi(\ell_1, E_{\text{T}}^{\text{miss}})$	•	•	$\Delta\phi(\ell, E_{\text{T}}^{\text{miss}})$	HR	•
$\Delta\phi(\ell_2, E_{\text{T}}^{\text{miss}})$		HR	$\Delta\phi(\tau_{\text{had-vis}}, E_{\text{T}}^{\text{miss}})$	•	
$m(\text{j}_1, \text{j}_2)$	•		$m(\text{j}_1, \text{j}_2)$	•	
$\Delta\eta(\text{j}_1, \text{j}_2)$	HR		$\Delta\eta(\text{j}_1, \text{j}_2)$	•	
$p_{\text{T}}^{\tau}/p_{\text{T}}^{\ell_1}$		HR	$\sum_{i=\ell,\tau_{\text{had-vis}}} \cos\Delta\phi(i, E_{\text{T}}^{\text{miss}})$	•	•
			$E_{\text{T}}^{\text{miss}}$	HR	•
			m_{vis}		HR
			$\Delta\eta(\ell, \tau_{\text{had-vis}})$		•
			η^{ℓ}		•
			$\eta^{\tau_{\text{had-vis}}}$		•
			ϕ^{ℓ}		•
			$\phi^{\tau_{\text{had-vis}}}$		•
			$\phi(E_{\text{T}}^{\text{miss}})$		•

ATLAS discriminative variables

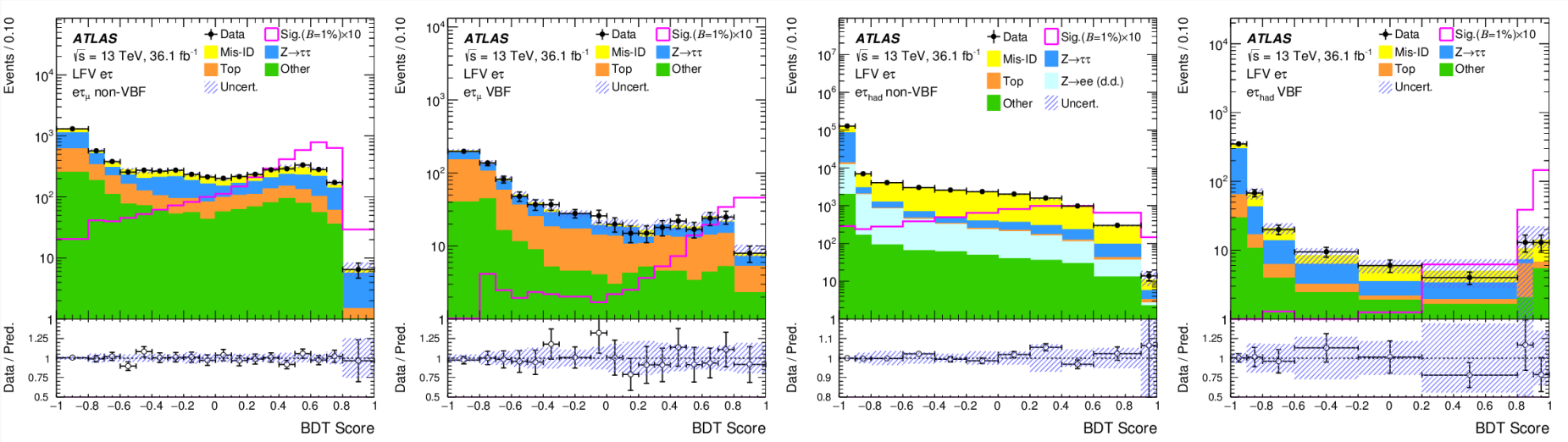


LHCb selection and systematics

Selection set	Variable	$\mu\tau_e$	$\mu\tau_{h1}$	$\mu\tau_{h3}$	$\mu\tau_\mu$
All	$p_T(\tau)$ [GeV/c]	> 5	> 10	> 12	> 5
	$p_T(\tau_{h3}^{\text{prong1}})$ [GeV/c]	—	—	> 1	—
	$p_T(\tau_{h3}^{\text{prong2}})$ [GeV/c]	—	—	> 1	—
	$p_T(\tau_{h3}^{\text{prong3}})$ [GeV/c]	—	—	> 6	—
	$p_T(\mu) - p_T(\tau)$ [GeV/c]	> 0	—	—	—
	$m(\tau_{h3})$ [GeV/c^2]	—	—	0.7–1.5	—
	$m_{\text{corr}}(\tau_{h3})$ [GeV/c^2]	—	—	> 3	—
	Time-of-flight (τ_{h3}) [fs]	—	—	> 30	—
	IP(τ) [μm]	> 10	> 10	—	> 50
	IP(μ) [μm]	< 50	< 50	< 50	< 50
	$\Delta\phi$ [rad]	> 2.7	> 2.7	> 2.7	> 2.7
	$\hat{I}_{p_T}(\tau)$	> 0.9	> 0.9	> 0.9	> 0.9
	$\hat{I}_{p_T}(\mu)$	> 0.9	> 0.9	> 0.9	> 0.9
L-selection	$p_T(\mu)$ [GeV/c]	> 20	> 20	> 20	> 20
	A_{p_T}	< 0.6	< 0.4	—	> 0.3
	$I_{p_T}(\tau)$ [GeV/c]	< 2	< 2	< 2	< 2
	$I_{p_T}(\mu)$ [GeV/c]	< 2	< 2	< 2	< 2
C-selection	$p_T(\mu)$ [GeV/c]	> 30	> 30	> 30	> 30
	A_{p_T}	—	< 0.5	—	> 0.3
H-selection	$p_T(\tau)$ [GeV/c]	> 20	> 20	> 20	—
	$p_T(\mu)$ [GeV/c]	> 40	> 40	> 40	> 50
	A_{p_T}	—	—	—	> 0.4

	$\mu\tau_e$	$\mu\tau_{h1}$	$\mu\tau_{h3}$	$\mu\tau_\mu$
Luminosity	1.16	1.16	1.16	1.16
Tau branching fraction	0.22	0.18	0.48	0.23
PDF	2.6–7.1	3.5–7.2	2.6–7.3	3.0–7.9
Scales	0.9–1.9	0.8–1.7	0.9–1.7	0.9–1.9
Reconstruction efficiency	1.8–3.6	1.9–5.4	3.3–7.1	1.5–3.3
Selection efficiency	2.5–6.0	1.9–4.1	4.0–9.3	3.8–8.5

ATLAS eτ final distributions



eτ$_\mu$, non-VBF

eτ$_\mu$, VBF

eτ$_h$, non-VBF

eτ$_h$, VBF

Tau lepton decays

- Taus decay almost immediately in the detector

- **Leptonic decays**: 1 electron or 1 muon (+ 2 neutrinos)
- **Semi-hadronic decays (τ_h)**: charged hadrons + neutral hadrons (+ 1 neutrino)

Decay mode	Resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(260)$	10.9
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other hadronic modes		1.8