ATLAS EXPERIMENT

CMS Compact Muon Solenoid

POSTERA CRESCAM LAUDE

THE UNIVERSITY OF MELBOURNE

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

Measurement of Higgs Boson couplings and CP Structure using tau leptons at LHC

Daniele Zanzi
on behalf of the ATLAS and CMS Collaborations

14th International Workshop on Tau Lepton Physics (Tau2016)
21/09/2016, IHEP Beijing

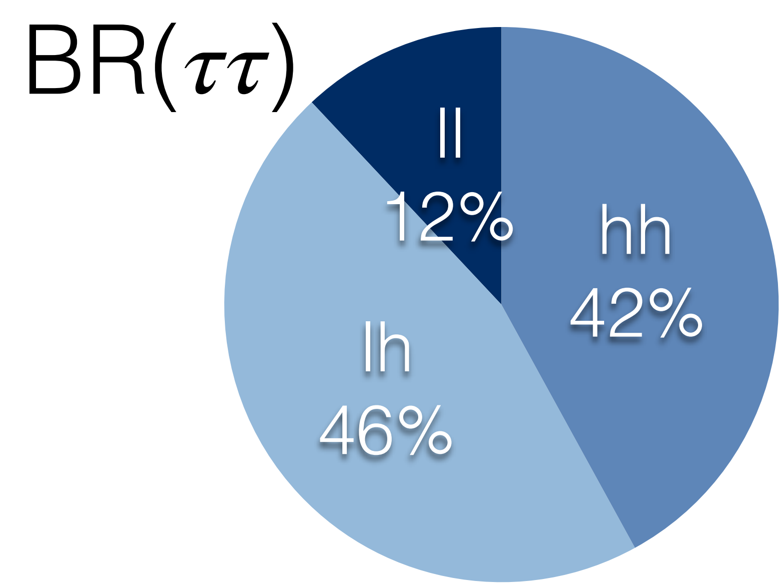
Outline

- This talk is focused on the potential for the measurement of CP violation in the Higgs boson couplings using H→$\tau\tau$ events
- Content:
  - main features of H→$\tau\tau$ channel and H$\tau\tau$ coupling measurement in Run-I
  - CP invariance in VBF H→$\tau\tau$
  - CP invariance in H→$\tau\tau$ decay: no estimate with full detector simulation yet. Overview of observables and final states and focus on experimental issues
- Related talks this week:
  - "Tau reconstruction at ATLAS" by Cristina GALEA/Daniele ZANZI
  - "Tau trigger and Identification at CMS in Run II" by Olivier DAVIGNON
  - "Higgs decays to tau leptons in the Standard Model and beyond" by Laura DODD
  - "Perspective for a measurement of tau-Polarisation in Z --> tau tau with CMS" by Vladimir CHEREPANOV
  - "Search for the Standard Model Higgs boson in the di-tau decay channel with the ATLAS detector" by Dugan O'NEIL

Higgs Boson Couplings

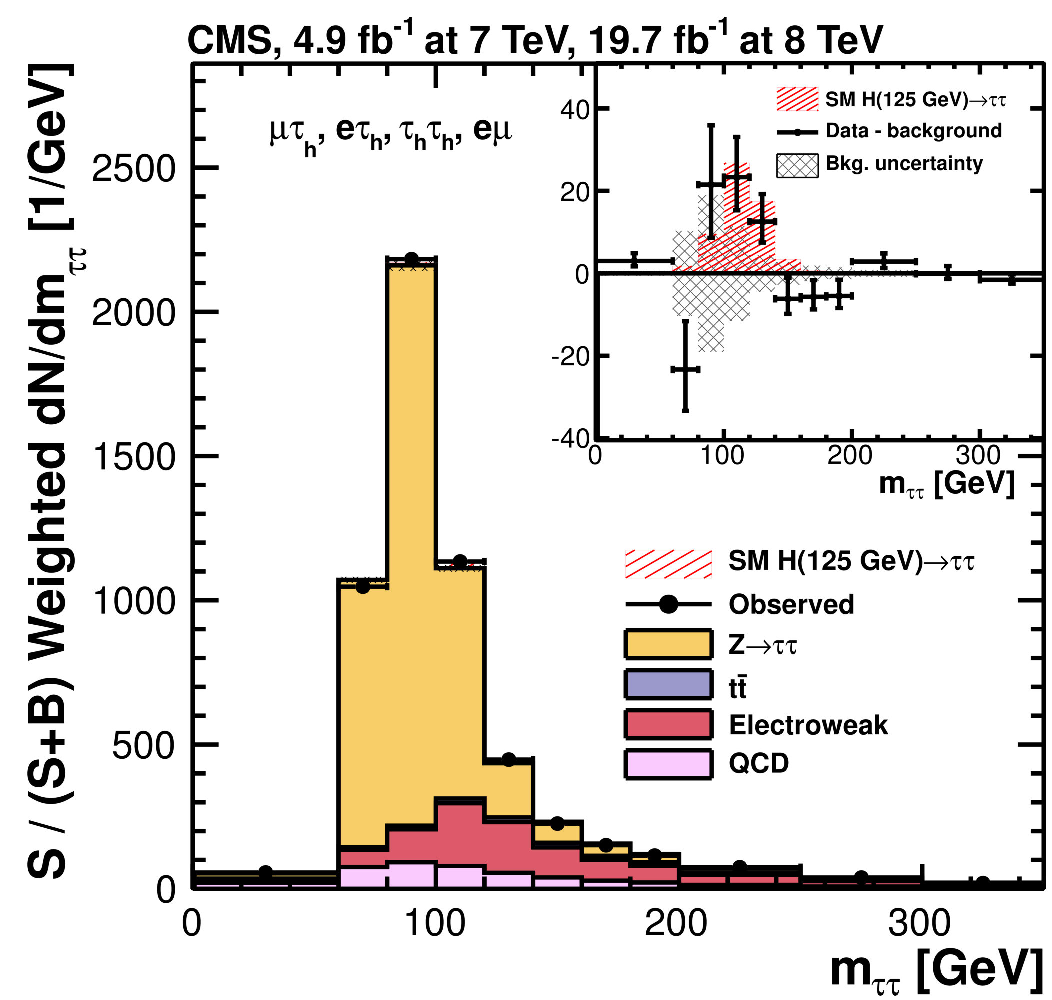
- Importance of measuring CP violation in Higgs boson couplings
  - lack of sources of CP violation in the SM to explain observed baryon asymmetry
  - no observable effect of CP violation expected in production or decay of SM Higgs boson
- Any observation of CP violation involving the observed Higgs boson is an unequivocal sign of physics beyond the SM
- Maybe one of the few chances to get direct hints for new physics at LHC if the new physics mass scale is too high for direct production

The H→$\tau\tau$ Channel



- Most sensitive fermionic channel (BR=6.3%)
- One of the most sensitive final states for VBF production at LHC
- Bulk of the sensitivity in events with $p^{\tau\tau}_T \gtrsim 100$ GeV
- Large irreducible background from Z→$\tau\tau$
- 10-20% m(τ,τ) mass resolution due to the presence of at least two neutrinos in final state
- Low-pt electrons, muons and hadronically-decaying tau difficult to trigger on

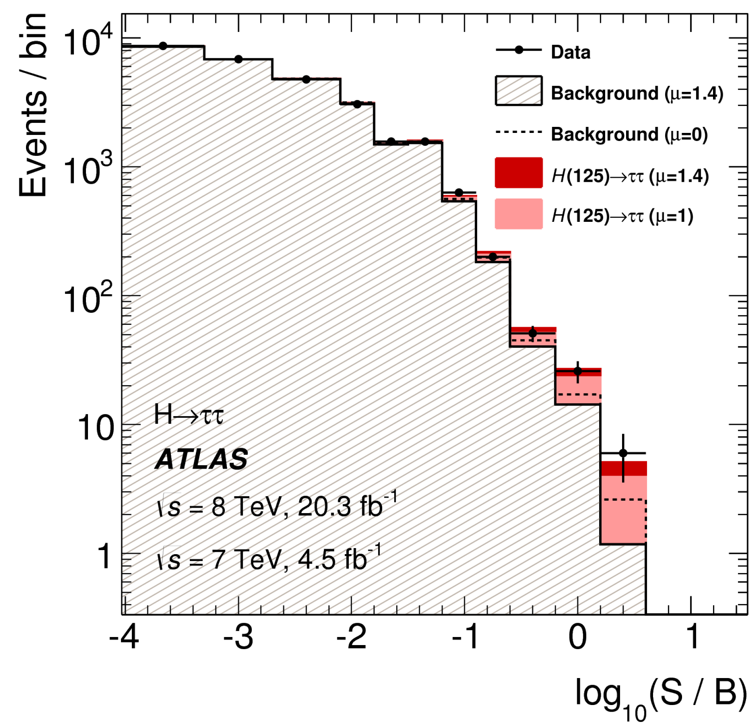
Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other modes with hadrons		3.2
All modes containing hadrons		64.8

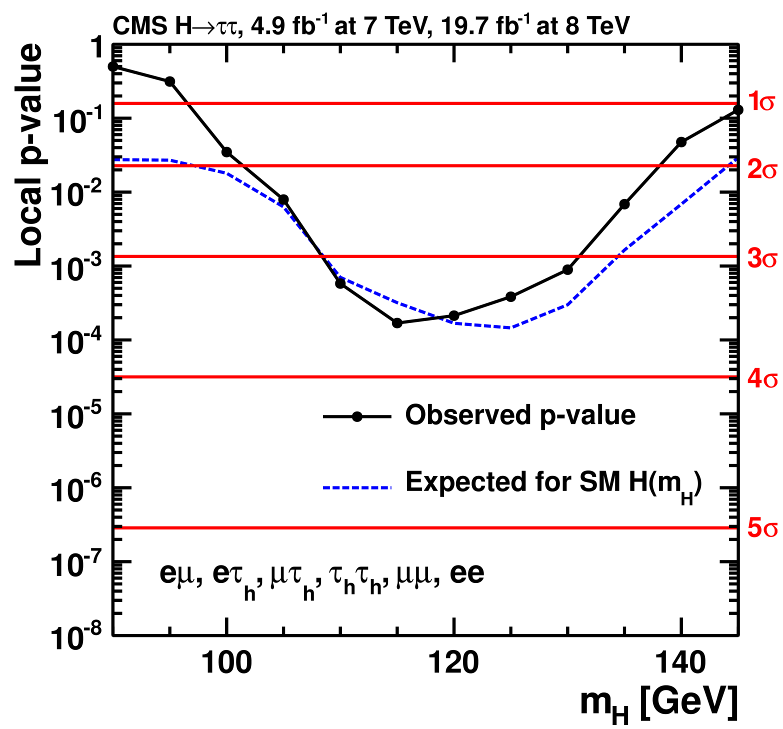


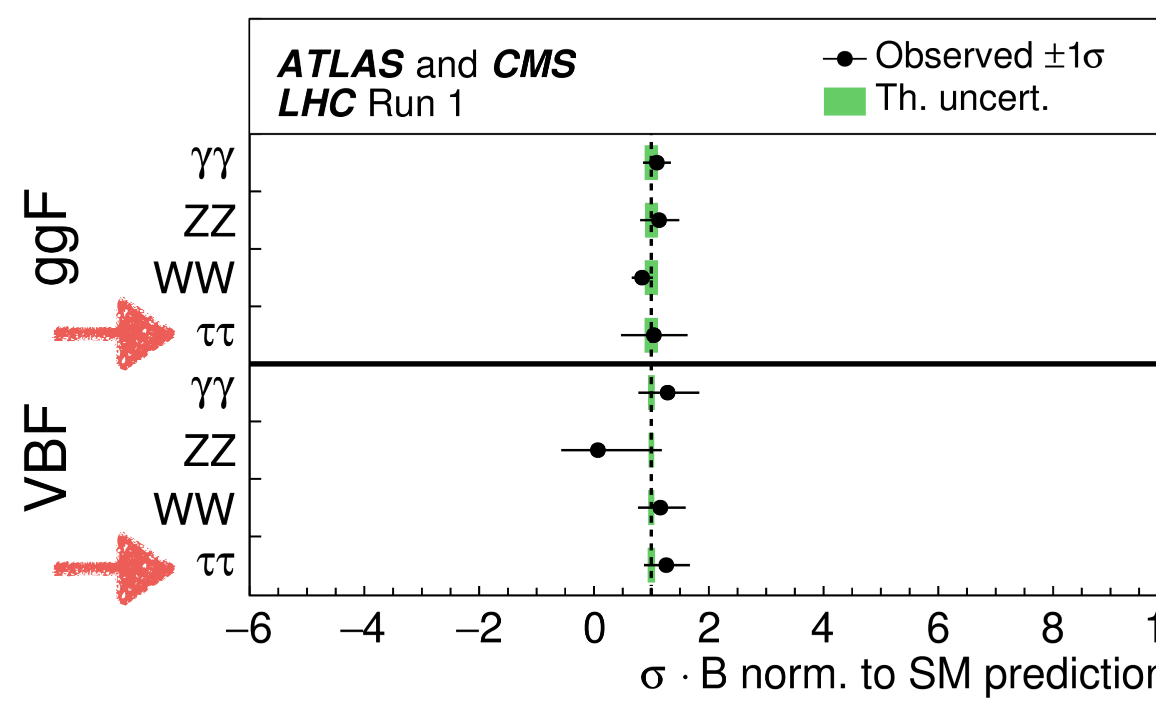
Run-I Legacy

ATLAS: JHEP04(2015)117, CMS: JHEP05(2014)104, ATLAS and CMS: arxiv:1606.02266 (submitted to JHEP)

- ATLAS and CMS results based on full Run-I dataset at 7 and 8 TeV
  - very similar selected phase spaces targeting VBF and ggH+jet productions
  - similar background estimates
  - different signal extraction methods (cut-based and MVA)
- Sensitivity dominated by VBF event categories
- ATLAS+CMS combination: >5sigma observation (H->tautau)







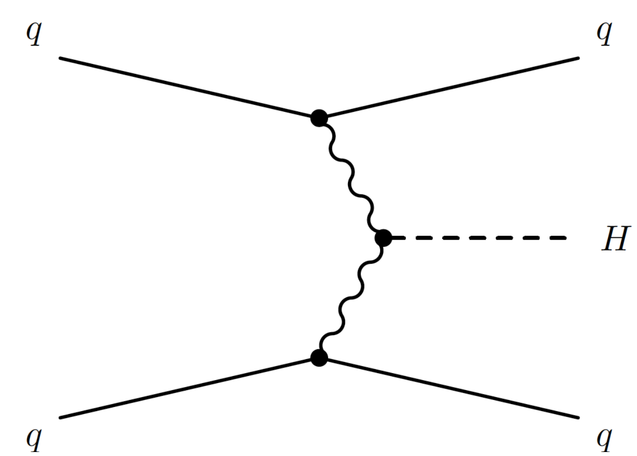
	ATLAS	CMS	ATLAS+CMS
$\mu^{\tau\tau}$	$1.41^{+0.40}_{-0.36}$	$0.88^{+0.30}_{-0.28}$	$1.11^{+0.24}_{-0.22}$
Obs. (Exp.) p0	4.4(3.3)	3.4(3.7)	5.5(5.0)

CP Invariance in **VBF** H→$\tau\tau$

CP Invariance in VBF H→$\tau\tau$

ATLAS: arxiv:1602.04516
(submitted to EPJC)

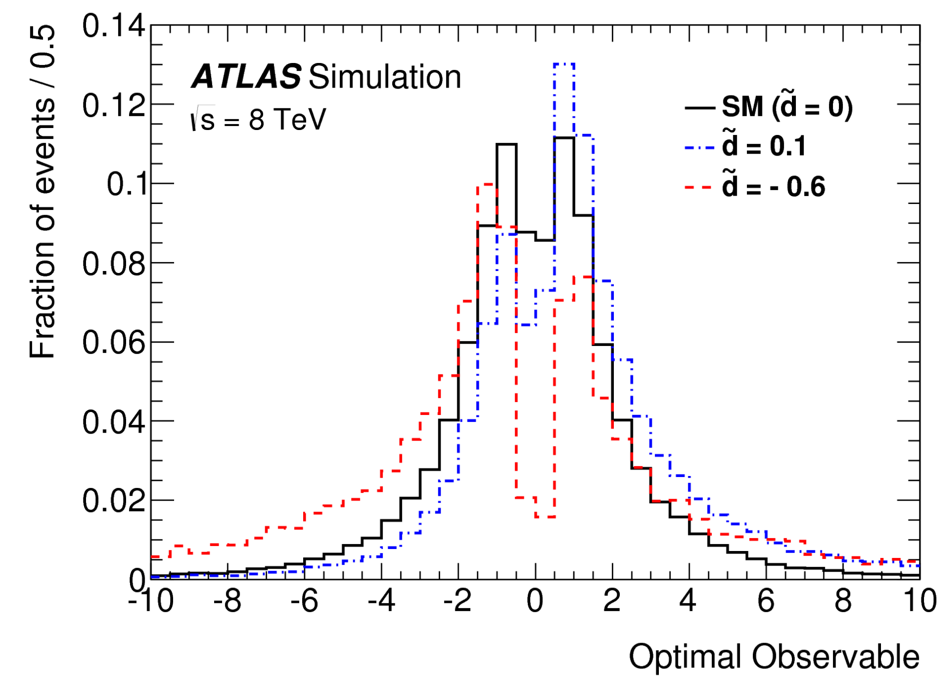
- **Direct test of CP invariance** in the VBF Higgs boson production
- Test of CP-violating contributions in HVV coupling. Independent of Higgs decay mode
- Exploit statistical power of VBF in H→$\tau\tau$ channel: O(10) signal events and s/b~0.3
- Limits set on CP-violating effects in EFT framework
- EFT Lagrangian with up to mass dimension six CP-violating operators parametrised by dimensionless coupling $\tilde{d}$:



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{HAZ} = 0$$

- CP-odd *Optimal Observable* defined as ratio of interference term in ME to the SM contribution



$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

$$\mathcal{OO} = \frac{2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$$

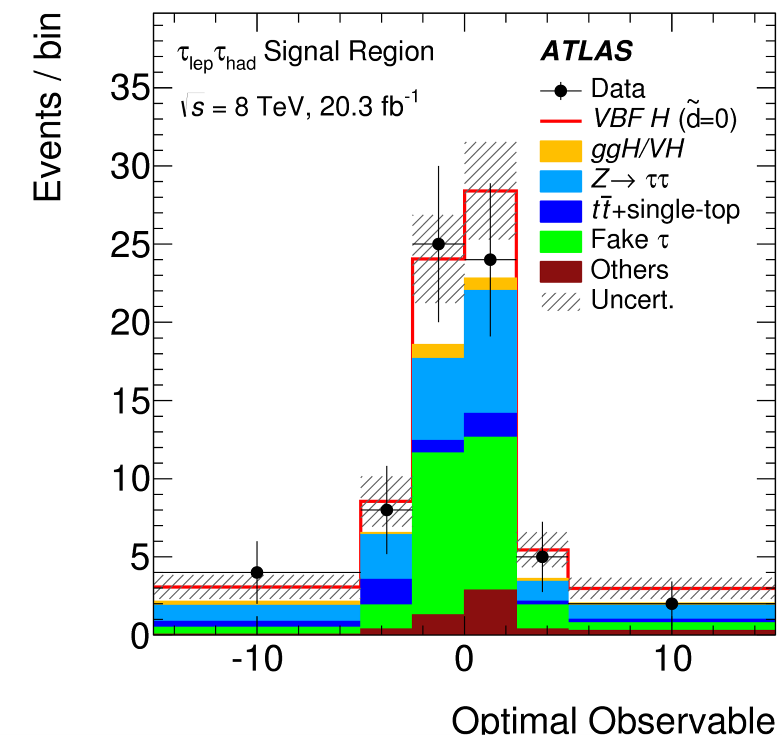
CP Invariance in VBF $H \to \tau\tau$

ATLAS: arxiv:1602.04516 (submitted to EPJC)

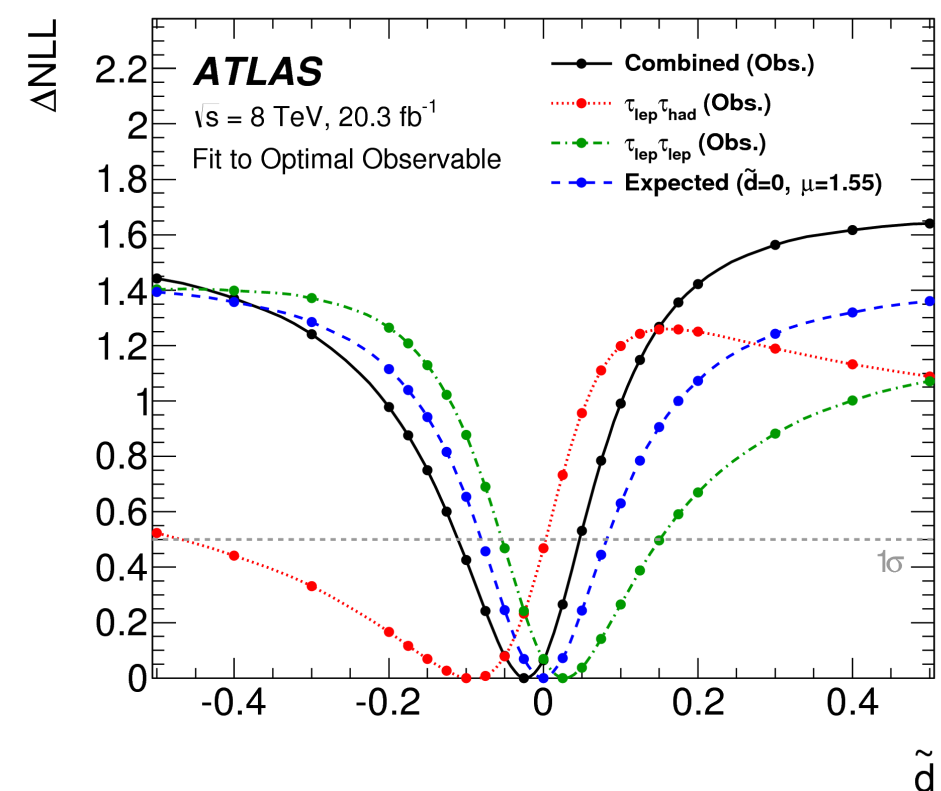
- Spin-off of the ATLAS Run-I VBF MVA analysis in ll and lh channels:
  - same selections and background estimates
  - fit of the events selected in the most sensitive BDT-score bins
- The **observed <OO> is consistent with zero** within statistical uncertainties. No hints for CP-violation:
  - ll: $\langle OO \rangle = 0.3 \pm 0.5$
  - lh: $\langle OO \rangle = -0.3 \pm 0.4$
- 68% CL limits on $\tilde{d}$:

$$-0.11 < \tilde{d} < 0.05$$

- 68% CL limits 10 times better than previous results from H→VV channels. No sensitivity yet for 95% CL interval



Process	$\tau_{lep}\tau_{lep}$	$\tau_{lep}\tau_{had}$
Data	54	68
VBF $H \to \tau\tau/WW$	9.8±2.1	16.7±4.1
$Z \to \tau\tau$	19.6±1.0	19.1±2.2
Fake lepton/τ	2.3±0.3	24.1±1.5
$t\bar{t}$ +single-top	3.8±1.0	4.8±0.7
Others	11.5±1.7	5.3±1.6
ggH/VH, $H \to \tau\tau/WW$	1.6±0.2	2.5±0.7
Sum of backgrounds	38.9±2.3	55.8±3.3



CP Invariance in H→$\tau\tau$ **Decay**

CP Invariance in H→ττ Decay

- Unique chance for **model-independent direct measurement** for CP-violating Yukawa couplings (Higgs production independent)
- Unlike for *HVV* coupling, SM Lagrangian can be extended with **tree-level** CP-odd Yukawa couplings:

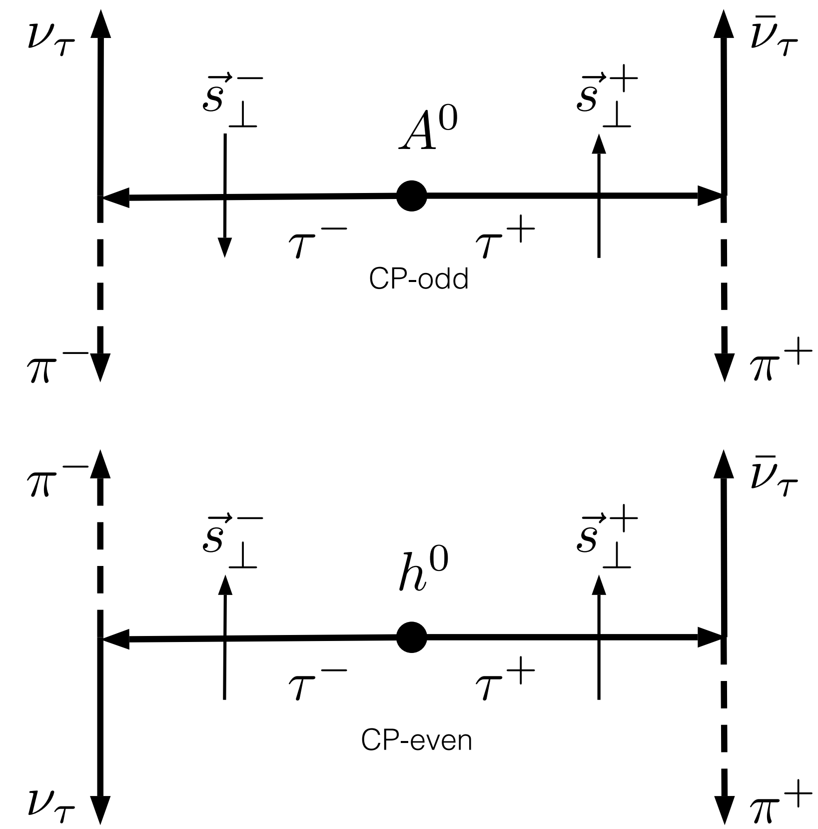
$$\mathcal{L}_{h\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\underbrace{\cos\phi_\tau \bar{\tau}\tau}_{\text{CP-even}} + \underbrace{\sin\phi_\tau \bar{\tau} i\gamma_5 \tau}_{\text{CP-odd}})h$$

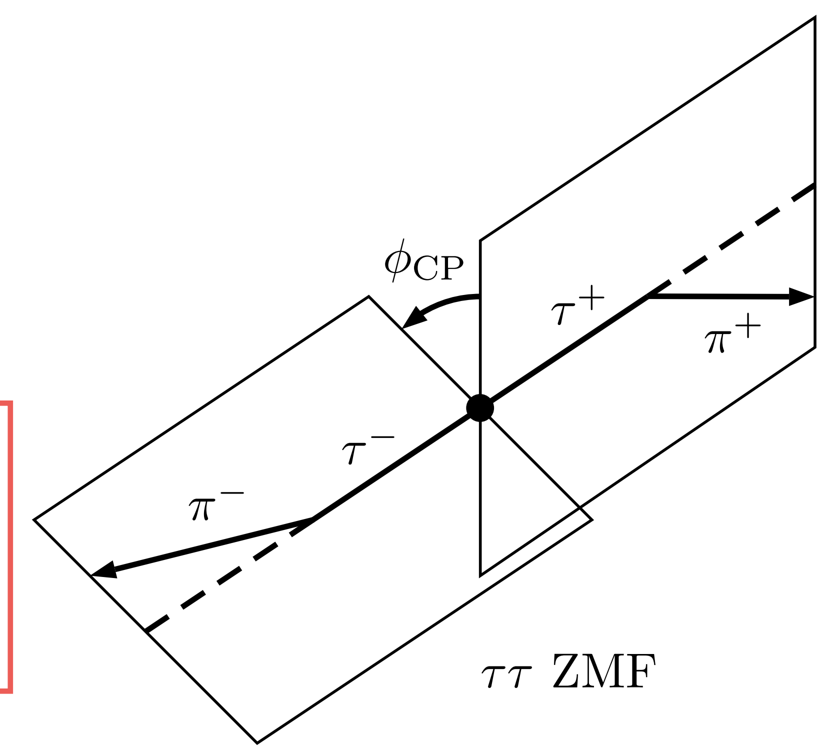
$$\text{SM}: \phi_\tau = 0$$
$$\text{CP-odd}: \phi_\tau = \pi/2$$

- CP-violating H$\tau\tau$ coupling experimentally accessible from transverse tau spin correlations and angular distributions of tau decay products in the Higgs rest frame

$$\frac{1}{\Gamma}\frac{d\Gamma(h \to \tau\tau \to \pi^+\pi^- + 2\nu)}{d\phi_{CP}} \propto 1 - \frac{\pi^2}{16}\cos(\phi^*_{CP} - 2\phi_\tau)$$

- CP-mixing angle ϕ_τ accessible looking at the signed angle of the tau decay planes
- Experimentally challenging: not possible to reconstruct tau momenta and Higgs rest frame, $\tau\tau$ Zero-Momentum-Frame (ZMF)





Short literature review:
Berge et al. [Phys.Rev.D92, 096012, EPJC(2014)74:3164, Phys.Lett.B727(2013)488–495]
Primulando et al. [Phys.Rev.D88,076009]
Desch et al. [Phys.Lett.B579(2004)157–164]
Was et al. [Phys.Lett.B543(2002)227-234, arxiv:1608.02609]

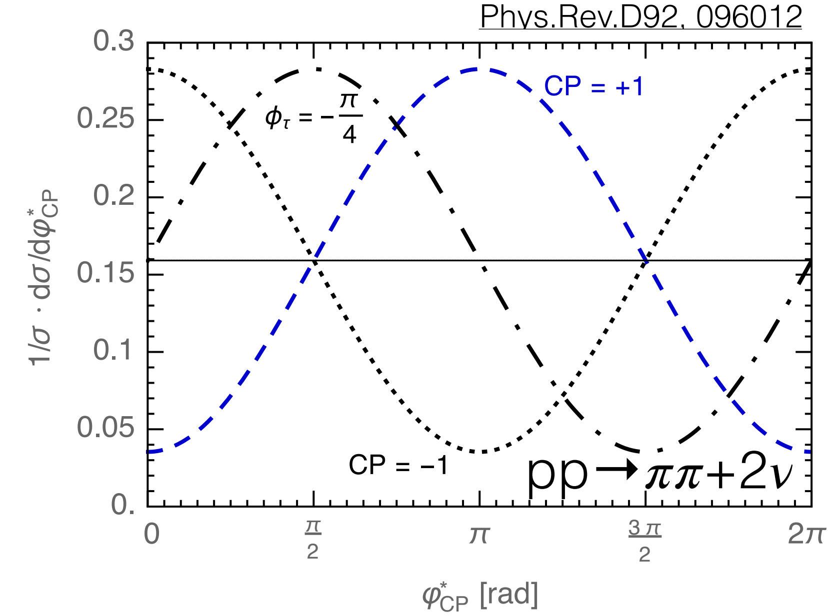
Final states and Observables

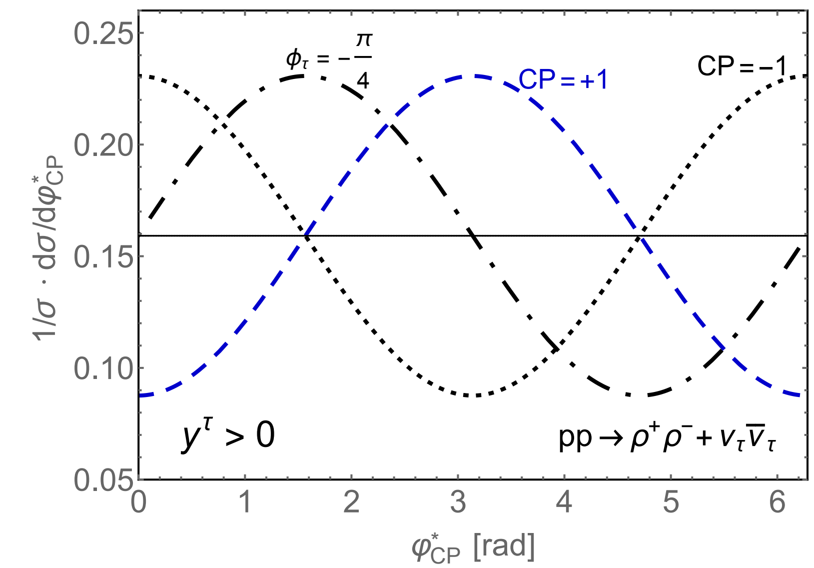
- Sensitivity to ϕ_τ using visible tau decay products and without reconstruction of Higgs rest frame
- Because of only one neutrino, hadronic decays expected to have higher sensitivity to tau spin than leptonic decays
- ***Impact Parameter* (IP) method** [Phys.Lett.B727(2013)488–495]:
  - decay plane from the tau leading track and its IP from the primary vertex
  - works for every decay (including leptonic), but best for direct decays $\tau^\pm \rightarrow \pi^\pm \nu$. For non-direct decays, tune of tau lower pt cut needed due to sign flip in spin analysing power
- ***ρ* method** [Phys.Lett.B579(2004)157–164]:
  - tau decay plane spanned by the track and neutral pion in $\tau^\pm \rightarrow \rho^\pm(770) \rightarrow \pi^\pm \pi^0 \nu$
  - decays need to be classified based on the $\pi^\pm$-π^0 energy difference in the $\rho\rho$ rest frame

$$y_\pm = \frac{E_{\pi^\pm} - E_{\pi^0}}{E_{\pi^\pm} + E_{\pi^0}}$$

- Effectiveness of observable depends also on:
  - how well it combines with other observables for mixed $\tau\tau$ decays
  - how different is its distribution in mis-classified decays (can cancel out modulation in correctly classified decays!)

Phys.Rev.D92, 096012





Tau Decay Reconstruction

ATLAS: EPJC(2016)76:295; CMS: JINST11(2016)P01019, CMS-DP-2016-015

- Experimental needs: **high reco*ID efficiency** and **high purity** in decay mode classification, **good pi0 momentum resolution**
- π-decay has low BR, but high reco efficiency. Electron/muon fake contamination
- ρ-decay has high BR and high reco efficiency. High contamination of $\pi^{\pm}2\pi^0$

BR($\tau\tau$) [%]	lep	π^+	$\pi^+\pi^0$	$\pi^+ \geq 2\pi^0$	$3\pi^+ \geq 0\pi^0$
lep	12				
π^-	8	1			
$\pi^-\pi^0$	18	6	7		
$\pi^- \geq 2\pi^0$	8	3	6	1	
$3\pi^- \geq 0\pi^0$	11	4	8	4	3

45% 43%

EPJC(2016)76:295

Decay mode	$\mathcal{B}$ [%]	$\mathcal{A} \cdot \varepsilon_{reco}$ [%]	ε_{ID} [%]
$h^{\pm}$	11.5	32	75
$h^{\pm}\pi^0$	30.0	33	55
$h^{\pm} \geq 2\pi^0$	10.6	43	40
$3h^{\pm}$	9.5	38	70
$3h^{\pm} \geq 1\pi^0$	5.1	38	46

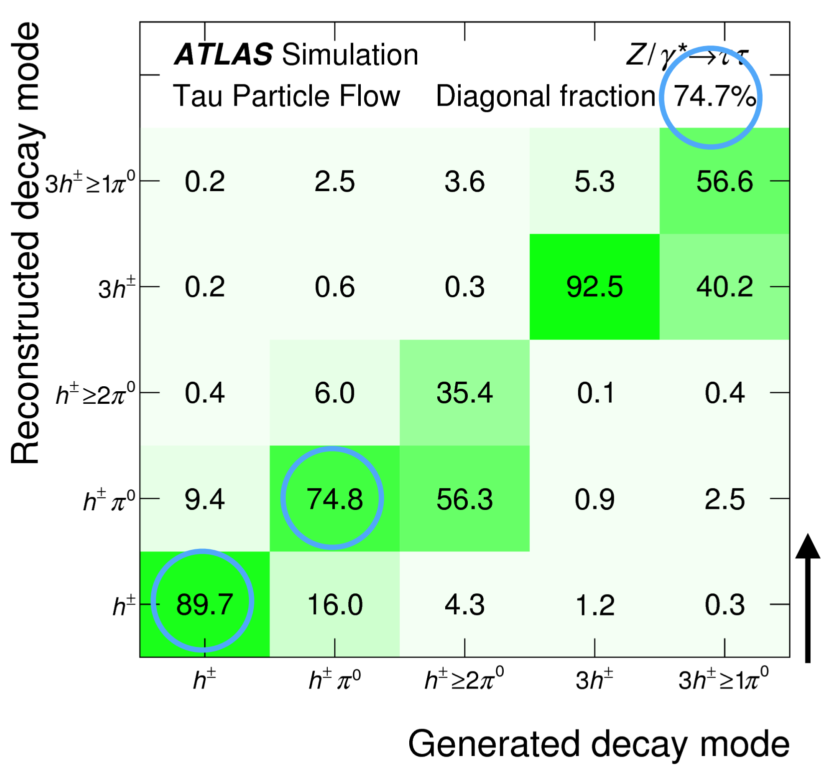
BR*Reco*ID[%]	π^+	$\pi^+\pi^0$	$\pi^+ \geq 2\pi^0$	$3\pi^+ \geq 0\pi^0$
π^-	0.08			
$\pi^-\pi^0$	0.30	0.30		
$\pi^- \geq 2\pi^0$	0.10	0.20	0.03	
$3\pi^- \geq 0\pi^0$	0.16	0.30	0.10	0.07

Tau Decay Reconstruction

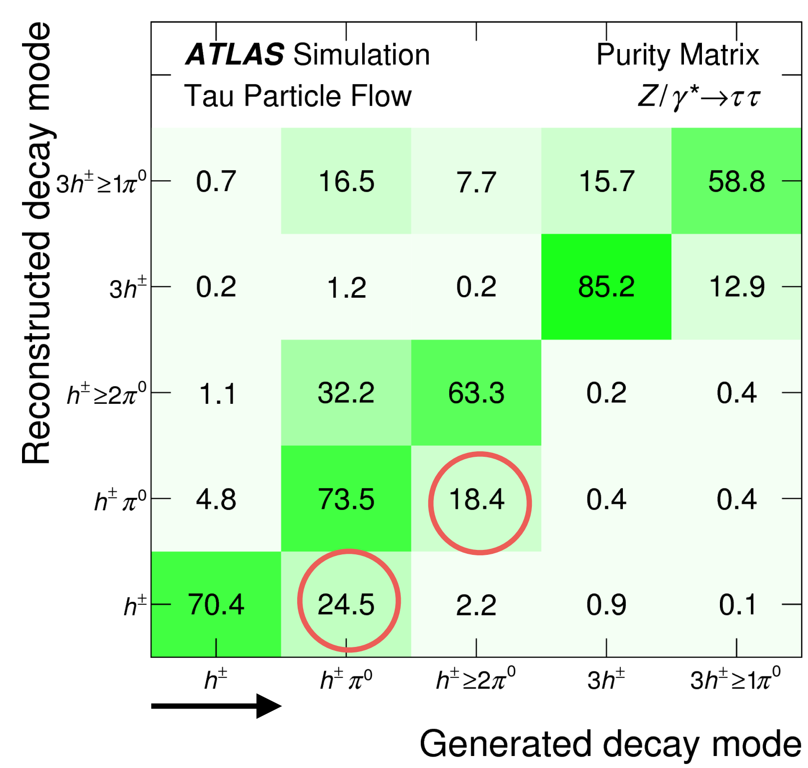
ATLAS: EPJC(2016)76:295; CMS: JINST11(2016)P01019, CMS-DP-2016-015

- Experimental needs: **high reco*ID efficiency** and **high purity** in decay mode classification, **good pi0 momentum resolution**
- π-decay has low BR, but high reco efficiency. Electron/muon fake contamination
- ρ-decay has high BR and high reco efficiency. High contamination of $\pi^{\pm}2\pi^{0}$

Classification efficiency:

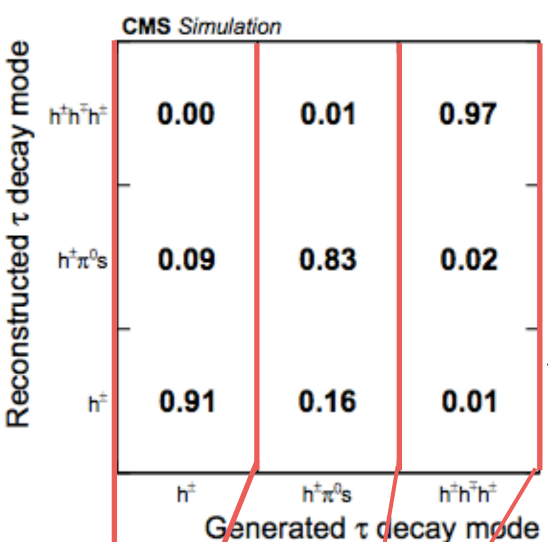


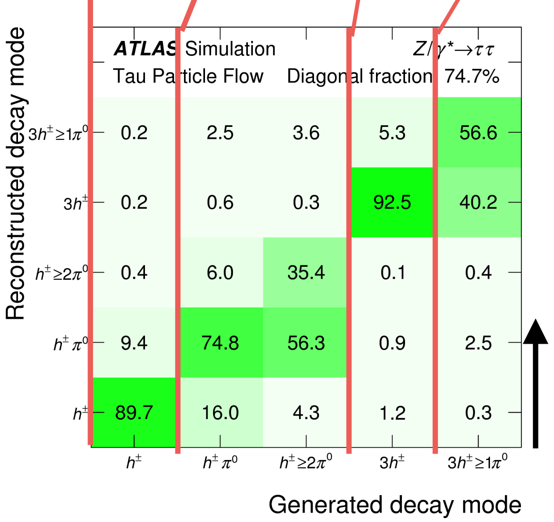
Decay mode purity:

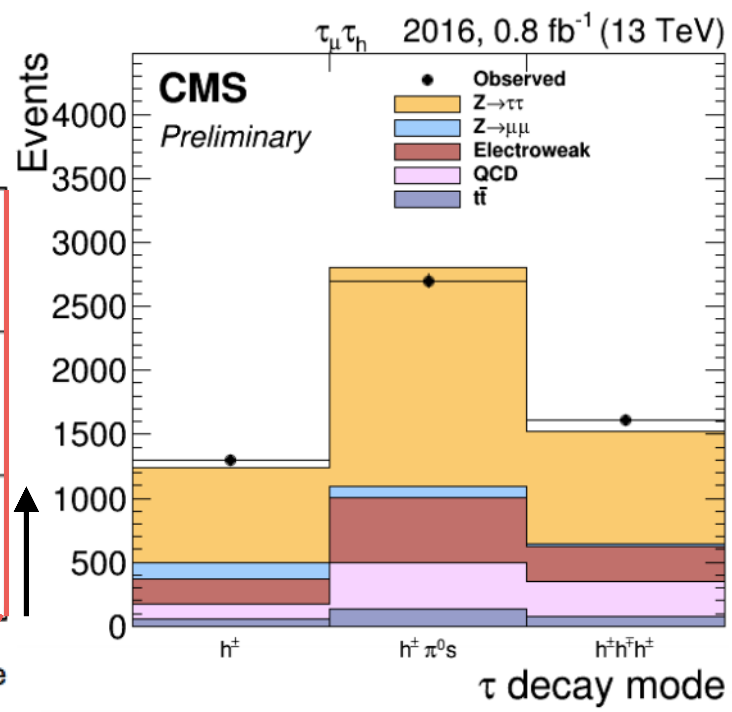


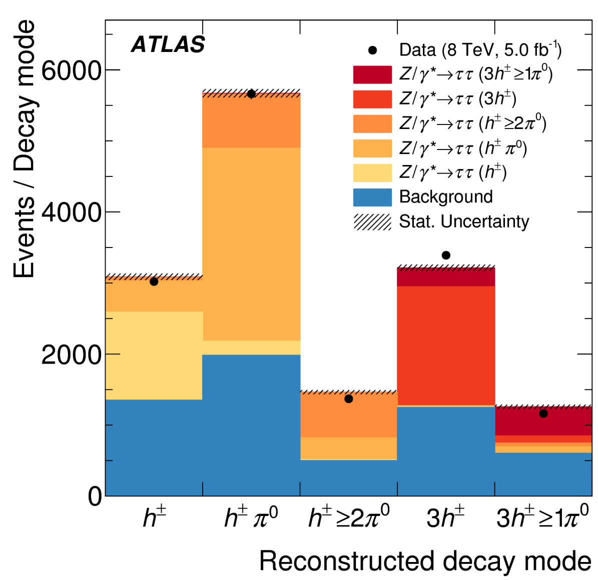
Tau Decay Reconstruction

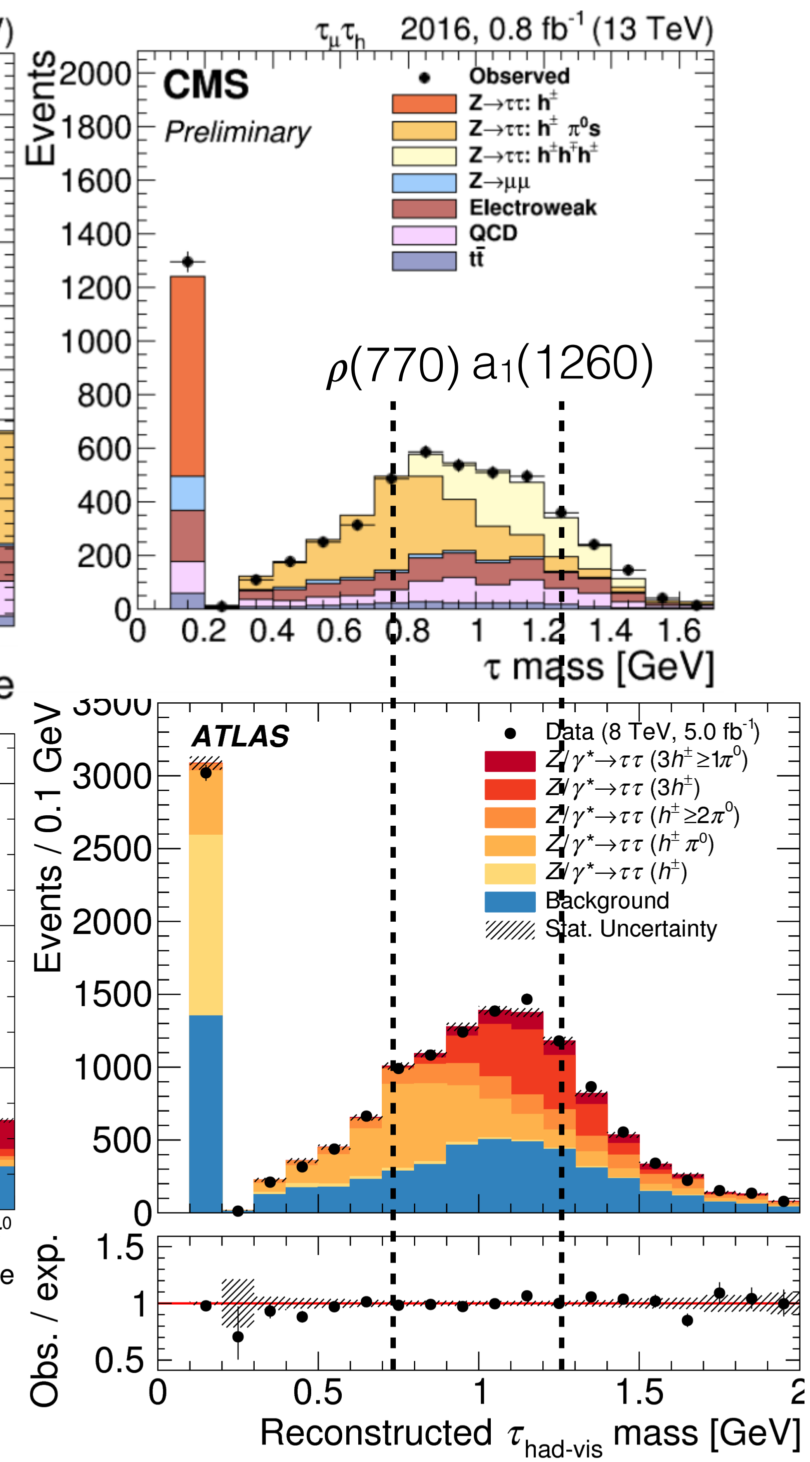
ATLAS: EPJC(2016)76:295; CMS: JINST11(2016)P01019, CMS-DP-2016-015

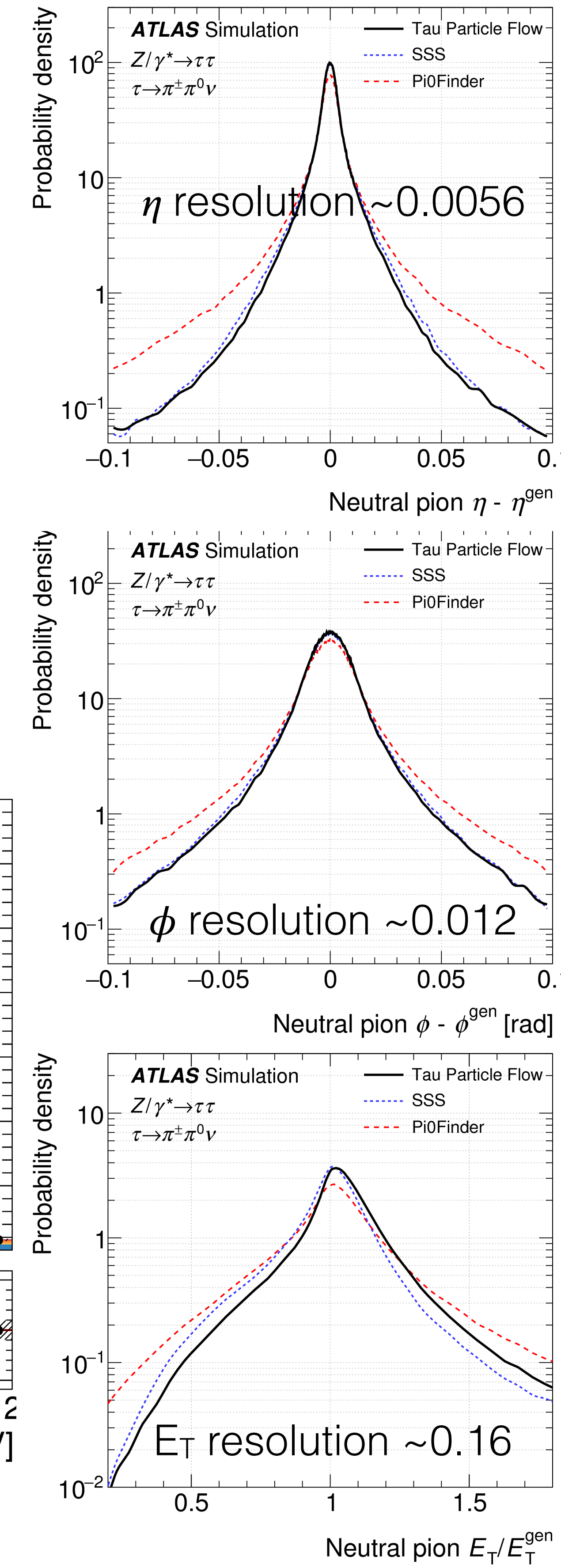








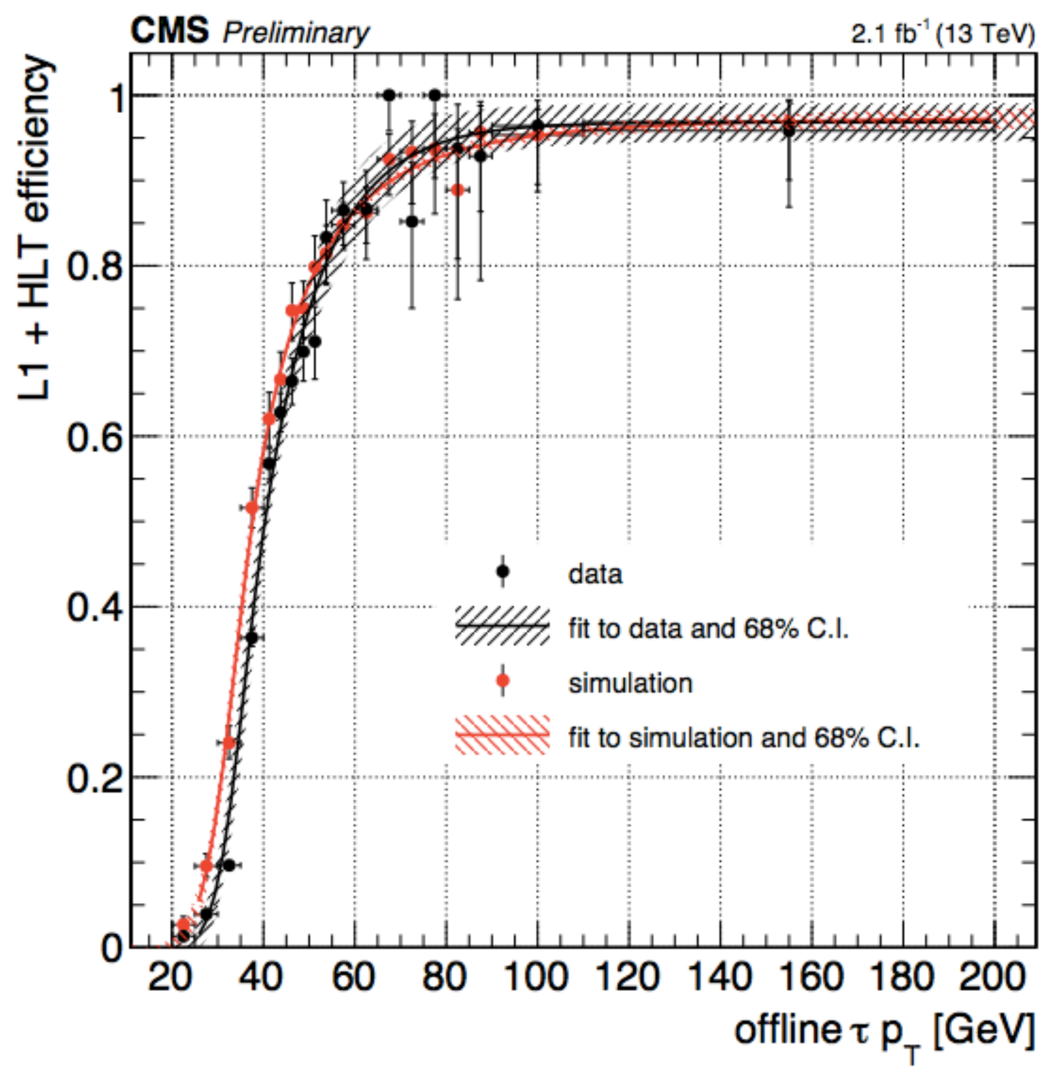


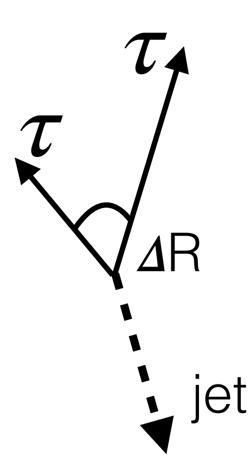


Tau Trigger

CMS: CMS-DP-2016-037; ATLAS: ATLAS TauTriggerPublicResults

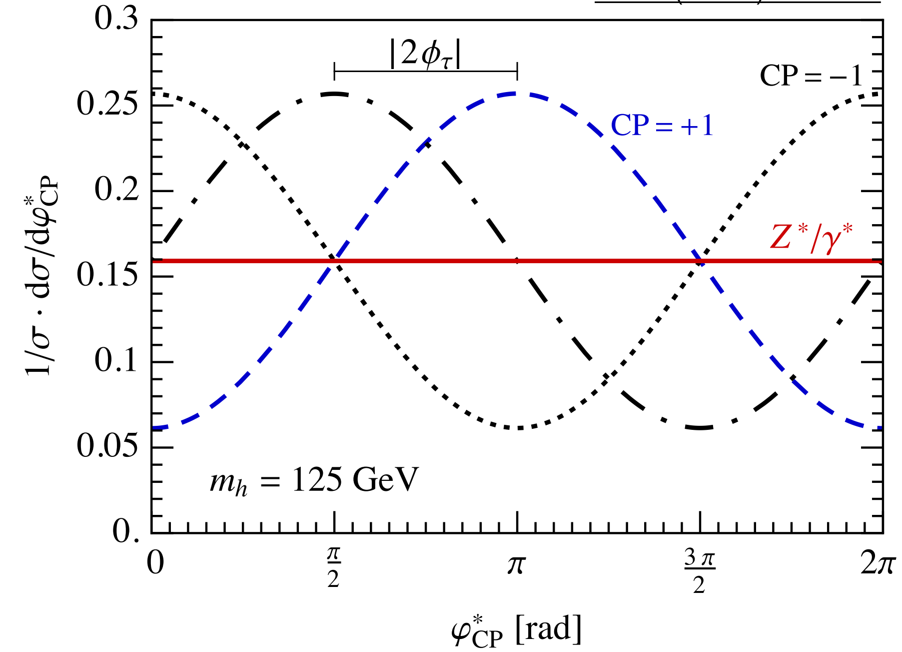
- **L1 bottleneck for hh**:
  - at L1, taus are pure calorimeter signatures. Very expensive as luminosity and pileup increases
  - efficiency curve driven by L1 energy resolution
- To reduce rate, additional requirements like **extra jets** or **$\Delta R(\tau,\tau)$** (see new ATLAS L1Topo HW) are used to select the boosted phase space used by $H\rightarrow\tau\tau$





$Z/\gamma^* \rightarrow \tau\tau$ Background

EPJC(2014)74:3164



- ϕ_{CP} distribution expected to be **flat** as taus are mostly longitudinally polarised
  - is ϕ_{CP} distribution still flat in boosted Z+j events ($p_T^{\tau\tau}$>100GeV)?
  - are tau spin correlations in mass tail with 110<$m_{\tau\tau}$<140 GeV significantly different?

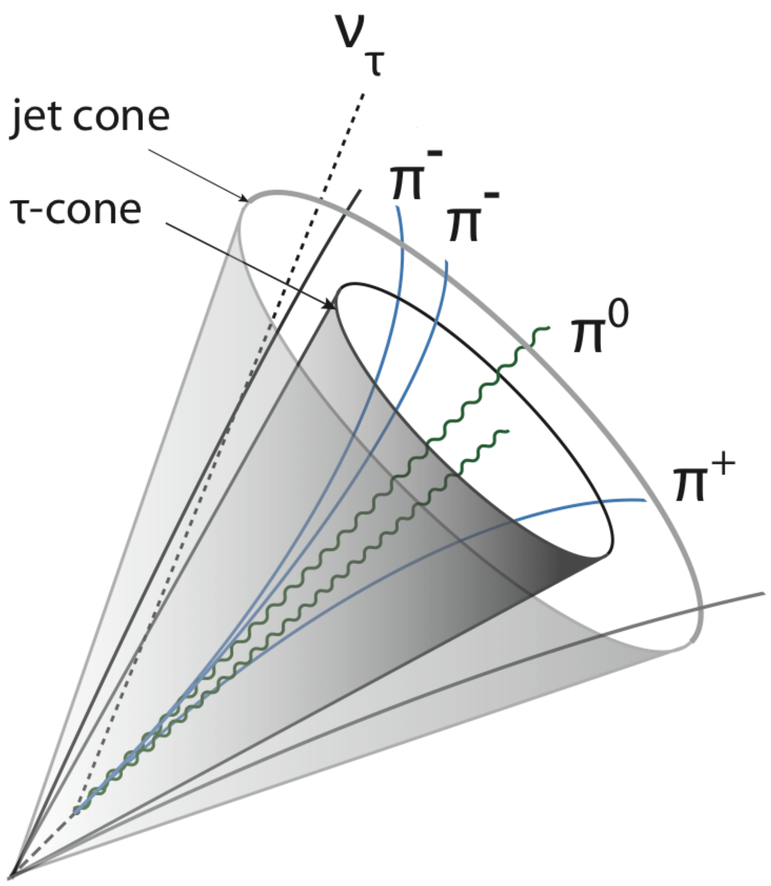
- Current methods to model the $Z \rightarrow \tau\tau$ background is via:
  - MC, tau decays are performed either inside ME calculation or outside. **Sherpa** includes the tau decay in the ME with the full helicity matrix, while MadGraph/Powheg use **TAUOLA/TauSpinner** which simulates longitudinal and transverse tau spin correlations as expected in DY events
  - Embedded $Z \rightarrow \mu\mu$ data events, where muons are replaced by taus whose decays is simulated by TAUOLA/TauSpinner

- In Run-I, both ATLAS and CMS used **embedded events** to reduce theory systematic uncertainties on Z+j,2j productions

- If there are no significant effects that require full Z+j simulation as in Sherpa, we can profit from high statistics and reduce systematics in embedded events

Fakes

- Contamination from jets faking taus not negligible, especially in interesting $m_{\tau\tau}$ mass range
- Distributions expected flat, but can be sculpted by detector effects
- In hh in Run-I, both ATLAS and CMS used **anti-isolated taus** to model the multi-jet background
    - anti-isolation means different numbers of neutral and charged pions, that is different decay modes
- For CP measurement, need to have a model for jets faking hadronic taus with the same decay mode as signal
    - may need to use anti-ID'ed taus corrected by fake rates. This is challenging given the not well-defined multi-jet production processes (successfully used in lh channel)
- In general, studies of multi-jet background based on MC are very hard



Summary

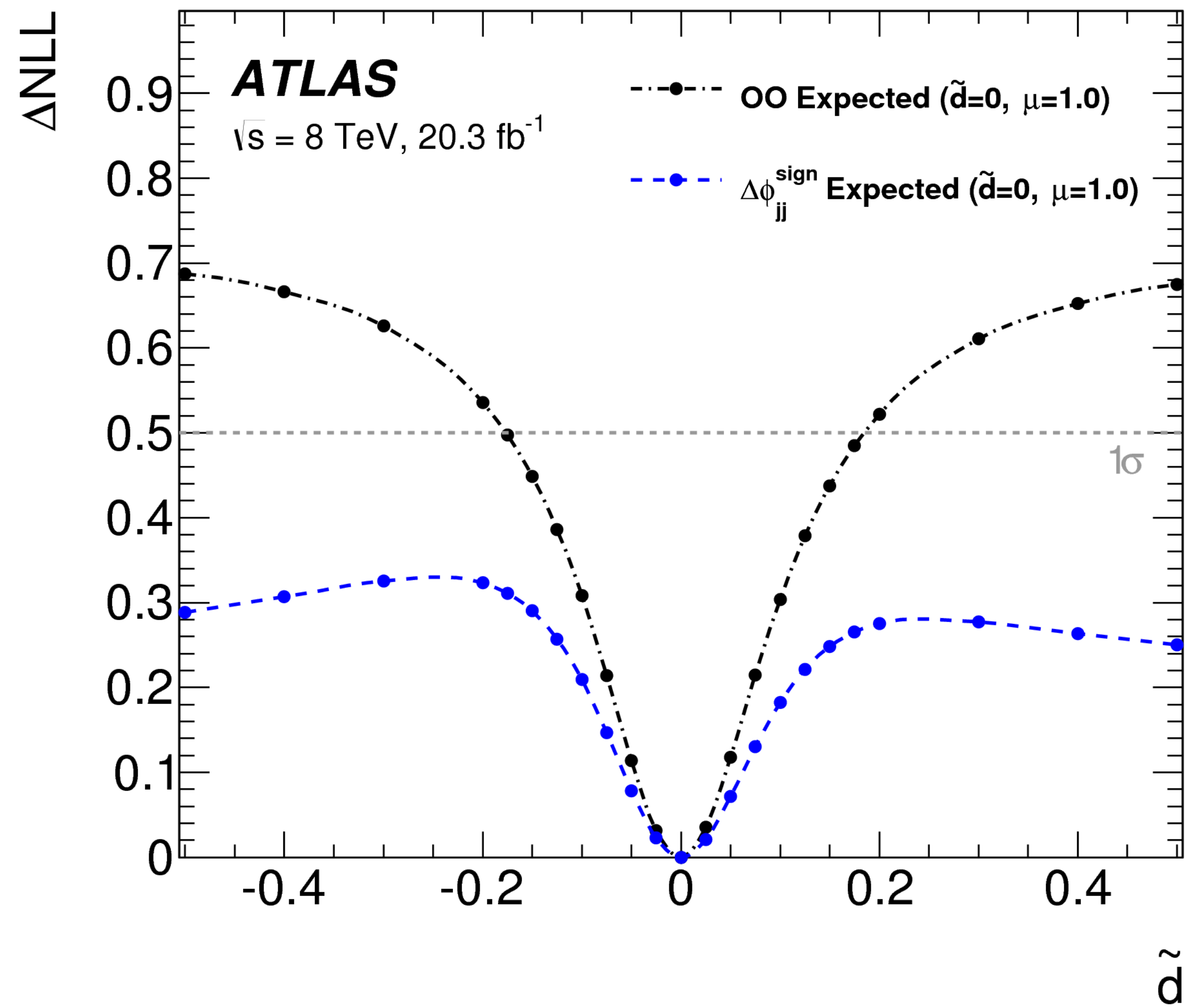
- Great potential for direct measurement of CP violation using H→$\tau\tau$ events, both in Higgs production and decay:
  - 5σ observation for H→$\tau\tau$ decays from ATLAS+CMS combination in Run-I
  - [-0.11, 0.05] limits at 68% CL on CP-mixing parameter $\tilde{d}$ in VBF production
- Test of CP violation in H→$\tau\tau$ decays very promising, but experimentally challenging. No estimate yet with full detector simulation. I've tried to present some of the experimental issues
  - sensitive phase spaces at $p^{\tau\tau}_T \gtrsim$ 100 GeV, especially in VBF topology
  - need to use as many decay modes as possible with observables robust against limited detector resolution and little sensitive to misclassified decays
  - focus on getting good pion angular and energy resolutions, low decay mode misclassification rate, and high decay reconstruction and identification efficiency
  - Z→$\tau\tau$ and multi-jets backgrounds may need special treatment for CP analyses
- Work ongoing on all these points

Additional Material

CP Invariance in VBF H→$\tau\tau$

ATLAS: arxiv:1602.04516
(submitted to EPJC)

- Alternative observable is signed $\Delta\phi$ between VBF jets, but the sensitivity is lower
- Possible extensions: idea to probe ggH coupling in ggH+2j events (arxiv:1406.3322)



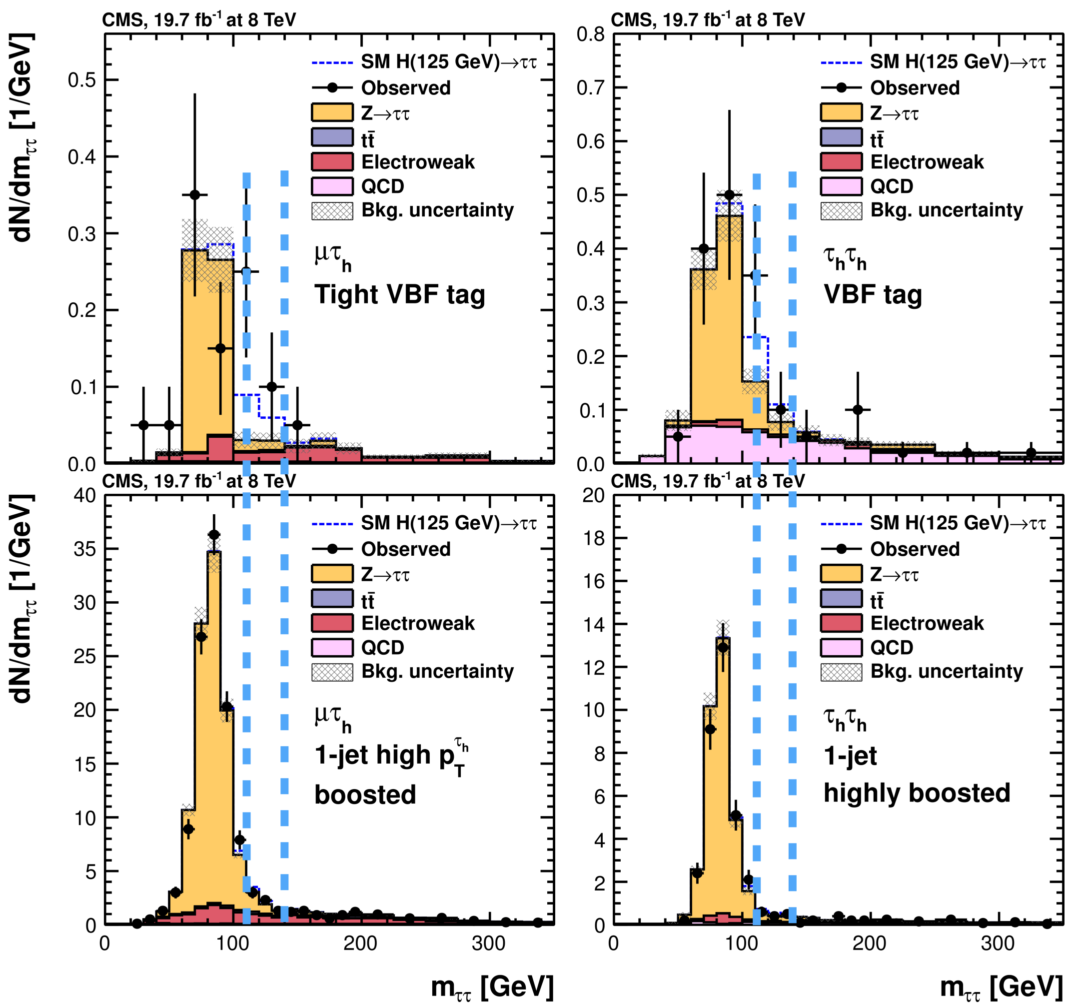
Final states and Observables

- For **3-tracks** decays, method proposed based on secondary vertex reconstruction (experimentally challenging) or extension of ρ method based on NN [arxiv:1608.02609]

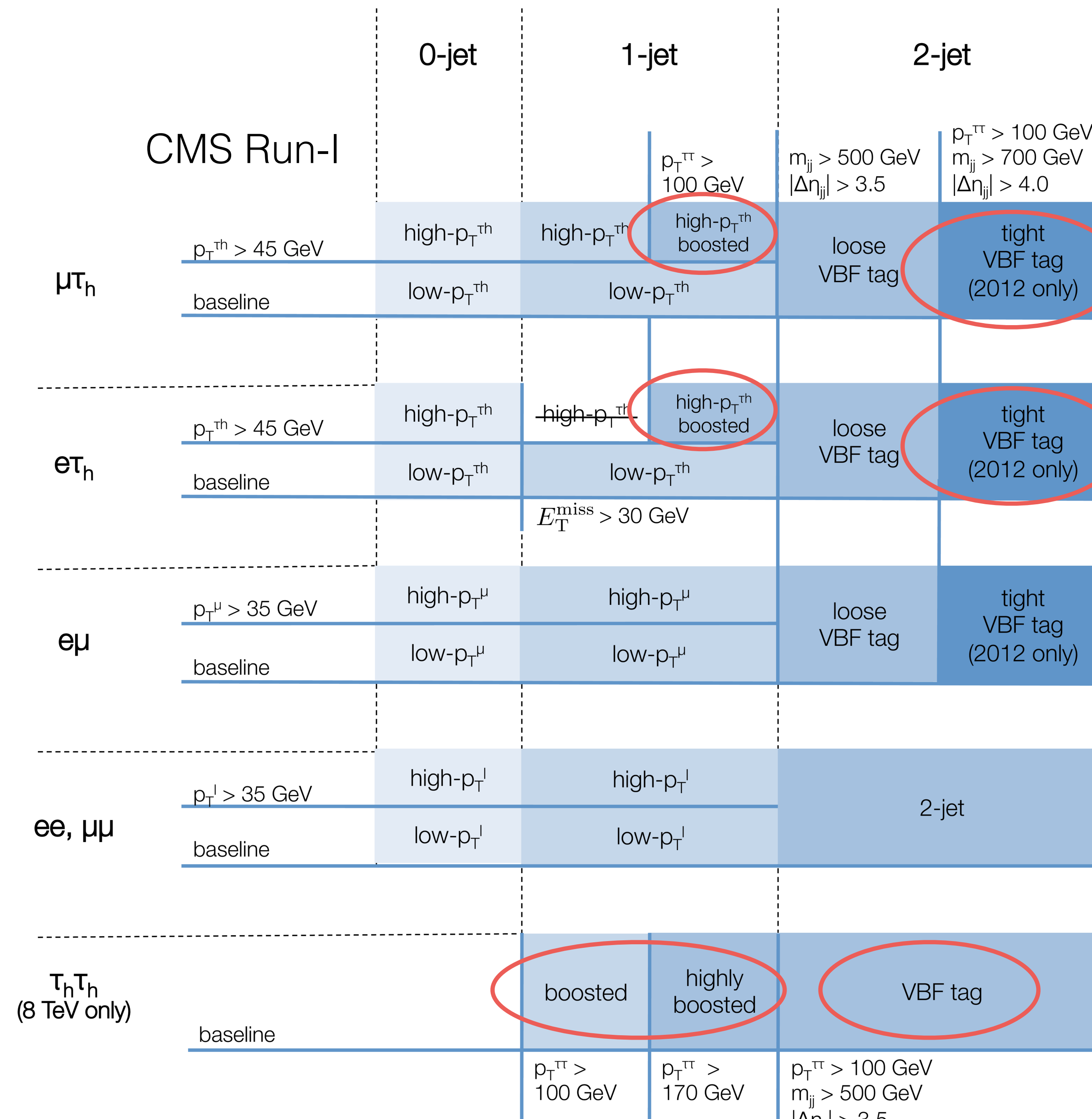
Event Categorisation

ATLAS: JHEP04(2015)117; CMS: JHEP05(2014)104

- In ATLAS and CMS cut-based analysis, most sensitive categories have at least **$p_T^{\tau\tau}$ > 100 GeV**, both for VBF and ggF production
- In 110<$m_{\tau\tau}$<140 GeV, good s/b (~1 in VBF, ~0.1 in 1jet), but large part of the bkg are fakes. Large stat. uncertainty in VBF



Event Category (8 TeV)	Signal	$\frac{S}{S+B}$
$\mu\tau$ Tight VBF	2.4 ± 0.2	0.49
$\tau\tau$ VBF	3.0 ± 0.3	0.32
$\mu\tau$ 1-jet high-p_T boosted	16.5 ± 2.6	0.07
$\tau\tau$ 1-jet highly boosted	8.4 ± 1.2	0.14



Event Categorisation

- CP measurement done in similar phase spaces as $H\rightarrow\tau\tau$ search to retain sensitivity to Higgs signal → Measurement to be performed in several event categories (or with MVA selection)
- In addition, if the observables have different distributions for different decay modes, each event category may need to be split per $\tau\tau$ decay mode and fitted independently
- This can easily lead to several signal regions with very signal little yields. Important to **exploit as much BR($\tau\tau$) as possible**
- For the IP- and ρ-methods, classifying events based on **IP significance** and **$y_{\pm}$ magnitude** may improve sensitivity, but this doubles the amount of categories to fit
- The large number of categories would probably require very **high statistics of simulated** events
  - investigating use of **MC event filters** for both tau decays and event topologies
  - use of **fast simulation** may be beneficial even though not much used yet in analysis with hadronic taus

Tau Trigger

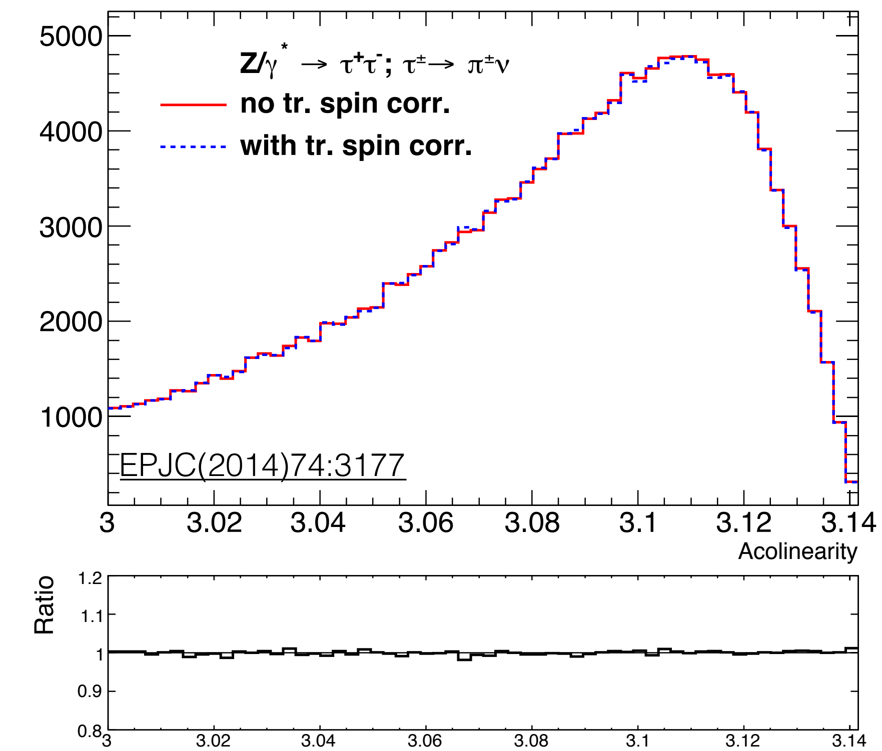
- For a precise measurement of CP violation in $H\tau\tau$ Yukawa, the full HL-LHC dataset will be needed and high trigger efficiency is required
- ATLAS and CMS are upgrading their TDAQ systems to cope with higher luminosity and pileup
- Trigger systems will be more and more reliant on **tracking** rather than calorimeter signatures
- Development of new hardware for tracking (see ATLAS FTK, L1Track, FTK++) and new tracking detector with improved FE (see CMS new tracker with self-seeding track trigger)
- More at DAQ@LHC'16

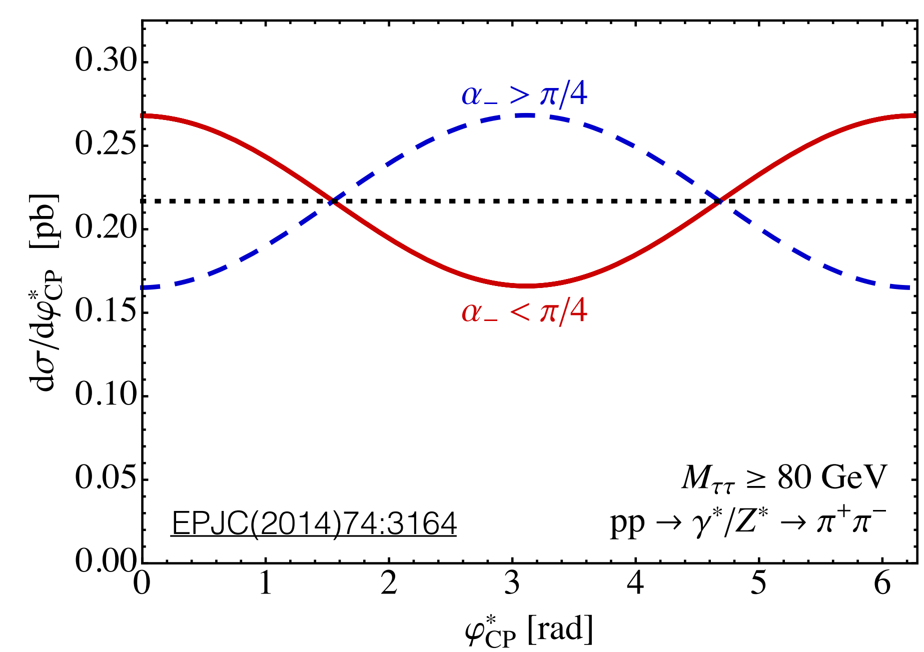
ATLAS PhaseII Scoping Document, CERN-LHCC-2015-020

Item	Offline p_T Threshold [GeV]	Offline $\|\eta\|$	L0 Rate [kHz]	L1 Rate [kHz]	EF Rate [kHz]
isolated Single e	22	< 2.5	200	40	2.20
forward e	35	$2.4 - 4.0$	40	8	0.23
single γ	120	< 2.4	66	33	0.27
single μ	20	< 2.4	40	40	2.20
di-γ	25	< 2.4	8	4	0.18
di-e	15	< 2.5	90	10	0.08
di-μ	11	< 2.4	20	20	0.25
$e - \mu$	15	< 2.4	65	10	0.08
single τ	150	< 2.5	20	10	0.13
di-τ	40,30	< 2.5	200 !!	30	0.08
single jet	180	< 3.2	60	30	0.60*
fat jet	375	< 3.2	35	20	0.35*
four-jet	75	< 3.2	50	25	0.50*
H_T	500	< 3.2	60	30	0.60*
E_T^{miss}	200	< 4.9	50	25	0.50*
jet + E_T^{miss}	140,125	< 4.9	60	30	0.30*
forward jet**	180	3.2 - 4.9	30	15	0.30*
Total			~1000	~400	~10

$Z/\gamma^* \rightarrow \tau\tau$ Background

- In DY events, effects from transverse spin correlations on ϕ_{CP}-sensitive distributions look negligible (EPJC(2014)74:3177). Is this the case also for Z+j events?
- Important to compare
  - Sherpa and TAUOLA/TauSpinner in events with same initial state
  - predictions with data enhancing sensitivity to transverse spin correlations with kinematic cuts (EPJC(2014)74:3164)





Systematic Uncertainties

- $Z \rightarrow \tau\tau$ data, both in low-$p_T^{\tau\tau}$ regions and in the signal region sidebands (eg $80 < m_{\tau\tau} < 110$ GeV), offers good chance to constrain:
  - theoretical systematic uncertainty on Z+j cross section
  - experimental systematic uncertainty on tau decay mode reconstruction and identification
  - neutral pion momentum and impact parameter resolution
- Systematics which may be more challenging to control:
  - modelling of transverse spin correlations in Z+j events
  - tau decay mode purity