Prospects for Higgs CP property measurements at the LHC

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Introduction

- After the Higgs was discovered in 2012, understanding its properties, and looking for any possible deviations from the SM prediction, becomes a very important task of LHC

  - Understanding the Higgs spin: scalar (spin-0) or tensor (spin-2)
  - Measuring its mass precisely: vacuum stability, cosmology
  - Flavor sector: Does it gives rise to flavor changing effect (e.g., LFV) ?
  - Other exotic decays (e.g., $H \to$invisible) ?
  - Understanding its CP property: related to matter-antimatter imbalance in the universe

    1) If Higgs is in a pure CP eigen state: is it CP even or odd ?
    2) If Higgs is in a CP mixture: gives rise to CP violation. This is a more exciting scenario, as the current known CP violation source (a single complex phase in CKM) is too small to explain the matter-antimatter imbalance

Higgs CP in Run-1

[EPJC 75 (2015) 476]
[Phys. Rev. D 92 (2015) 012004]

- ATLAS uses Effective Field Theory (EFT) to parametrize the HVV vertex:

$$\begin{aligned}\mathcal{L}_0^V = \quad & \Big\{c_\alpha \kappa_{\rm SM}\left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right] \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & -\tfrac{1}{2}\tfrac{1}{\Lambda}\left[c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + s_\alpha \kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Big\} X_0\end{aligned}$$

- CMS uses a similar EFT expression (show ZZ terms only):

$$L(\mathrm{HVV}) \sim \underbrace{a_1 \frac{m_Z^2}{2} \mathrm{HZ}^\mu \mathrm{Z}_\mu}_{\text{SM}} - \underbrace{\frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \mathrm{HZ}_\mu \Box \mathrm{Z}^\mu - \frac{1}{2} a_2 \mathrm{HZ}^{\mu\nu} \mathrm{Z}_{\mu\nu}}_{\text{BSM CP-even}} - \underbrace{\frac{1}{2} a_3 \mathrm{HZ}^{\mu\nu} \tilde{\mathrm{Z}}_{\mu\nu}}_{\text{BSM CP odd}} + \ldots$$

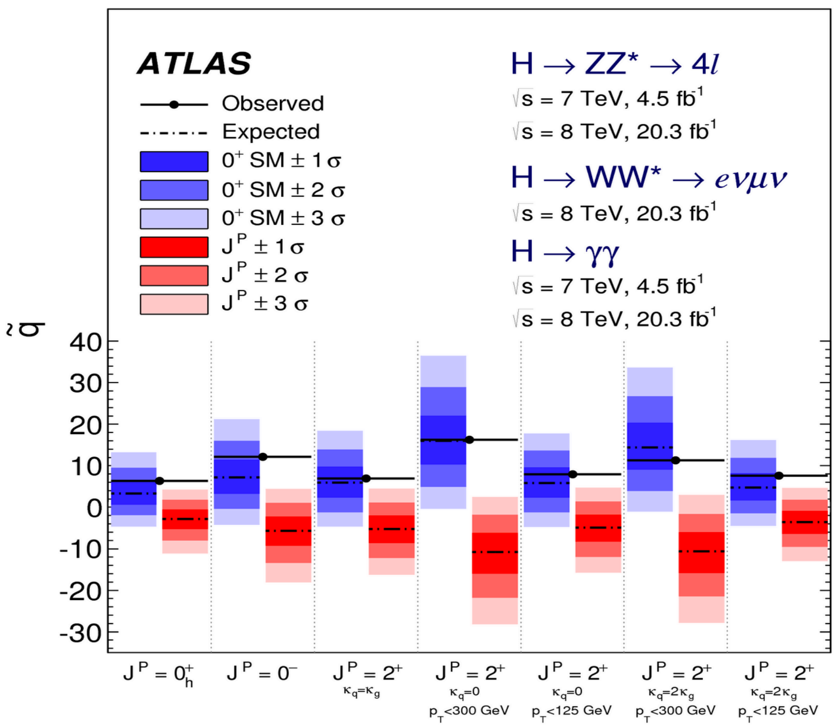
- The definition of the pure Higgs CP states (ATLAS):

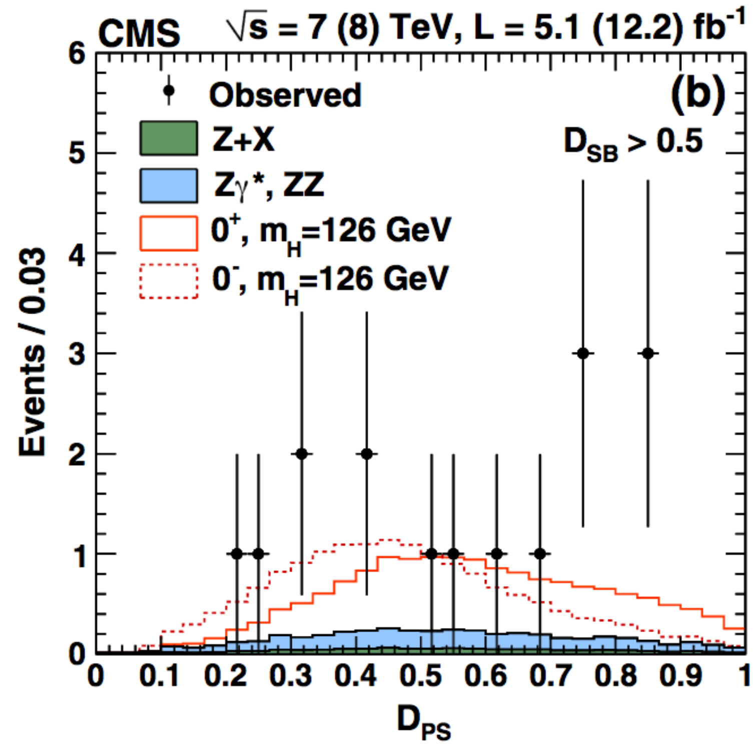
J^P	Model	Choice of tensor couplings			
		$\kappa_{\rm SM}$	κ_{HVV}	κ_{AVV}	α
0^+	Standard Model Higgs boson	1	0	0	0
0_h^+	BSM spin-0 CP-even	0	1	0	0
0^-	BSM spin-0 CP-odd	0	0	1	$\pi/2$

Higgs CP in Run-1

[EPJC 75 (2015) 476]
[Phys. Rev. Lett. 110 (2013) 081803]

- Test the CP states against alternatives assuming Higgs in a pure CP state:
  - Both ATLAS and CMS used a Matrix Element method to test $J^P=0^+$ vs 0^-
  - ATLAS combined three channels: $WW \to e\nu\mu\nu$ 0-jet category, $\gamma\gamma$ and $ZZ \to 4l$
  - CMS used only $ZZ \to 4l$





The CP odd 0^- model is excluded at CL better than 99.9% by both ATLAS and CMS

Mixed CP test

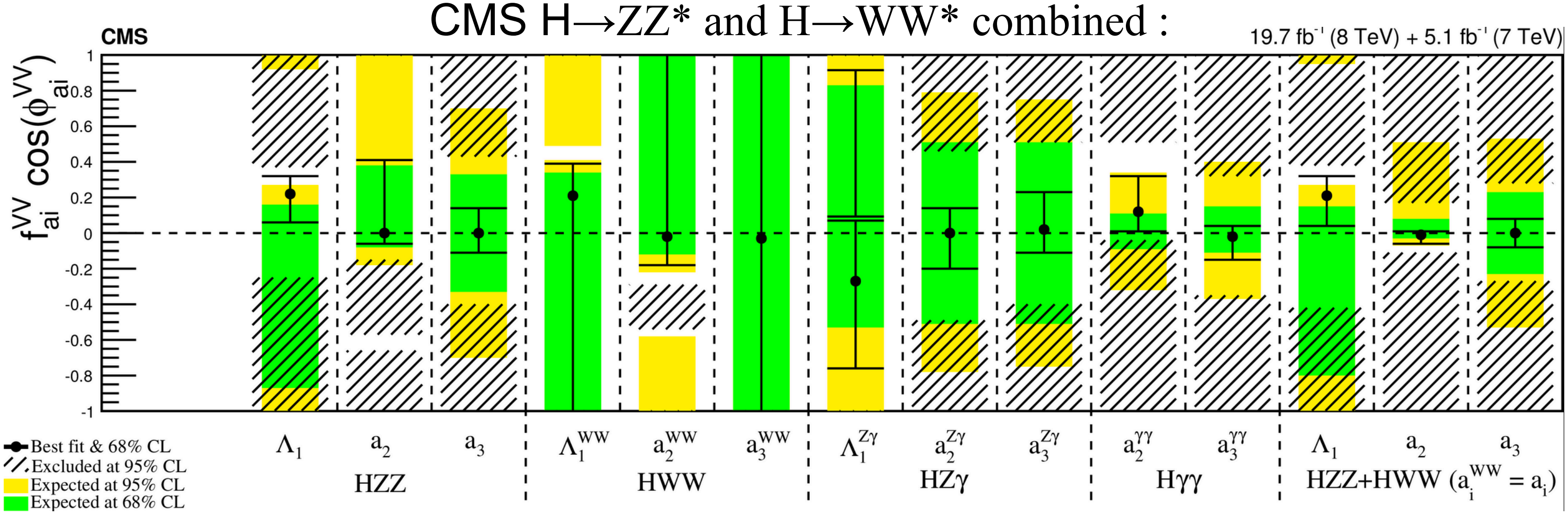
[EPJC 75 (2015) 476]
[Phys. Rev. D 92 (2015) 012004]

- ATLAS/CMS considered the mixture of SM and BSM CP even/odd in the HVV tensor structure, using either ME-based variables or templates

ATLAS H→ZZ* and H→WW* combined :

Coupling ratio	Best fit value		95% CL Exclusion Regions	
Combined	Expected	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	0.0	−0.48	$(-\infty, -0.55] \bigcup [4.80, \infty)$	$(-\infty, -0.73] \bigcup [0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	0.0	−0.68	$(-\infty, -2.33] \bigcup [2.30, \infty)$	$(-\infty, -2.18] \bigcup [0.83, \infty)$

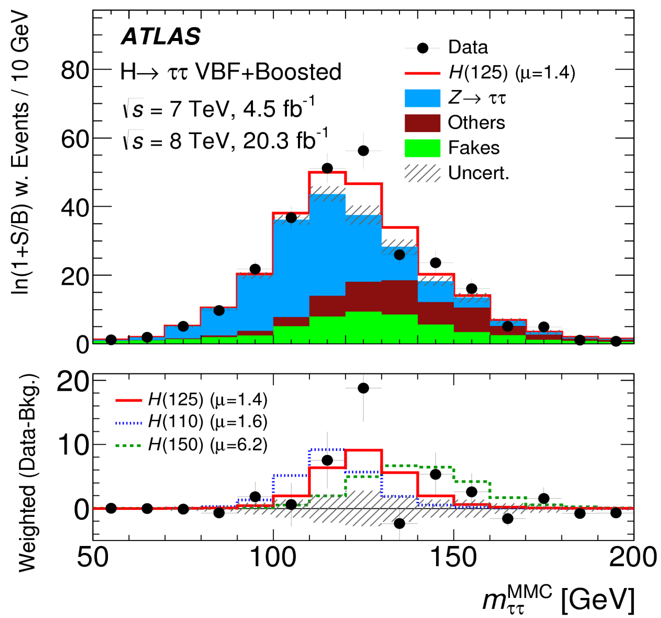
CMS H→ZZ* and H→WW* combined :

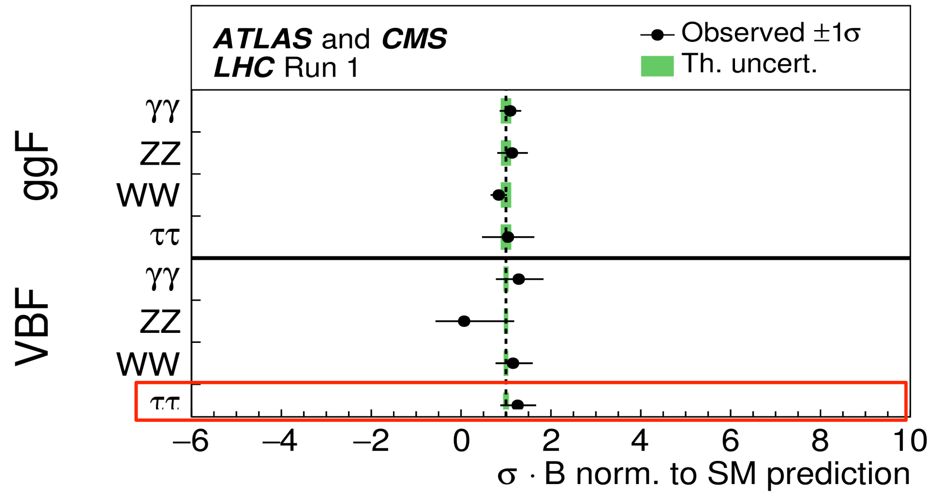


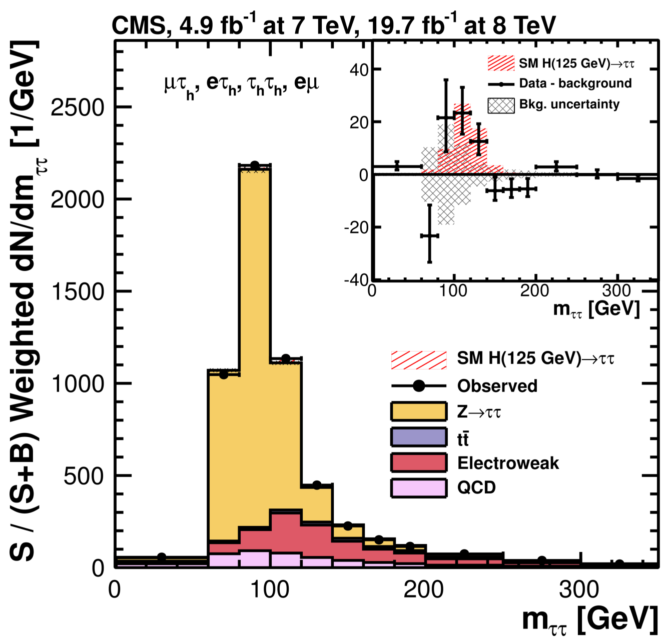
The non-SM tensor couplings are consistent with zero for both ATLAS and CMS

The H→ττ search channel

[JHEP 04 (2015) 117]
[JHEP 05 (2014) 104]
[JHEP 08 (2016) 045]







- Combined run-1 sensitivity of ATLAS/CMS already exceeds 5σ:

	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)

- H→ττ is one of the best channels to search for VBF production. It is a very sensitive channel for CP in both HVV and Hff couplings
- In the 2HDM model, the H→ττ rate is often enhanced, and Higgs can also have mixed CP. This makes the H→ττ channel very special

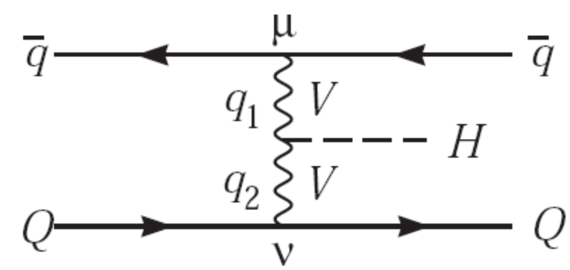
CP test in VBF Higgs production

- The CP nature of the HVV coupling can be tested in the VBF production of the Higgs boson. Effective Lagrangian (SM + CP-violating operators):

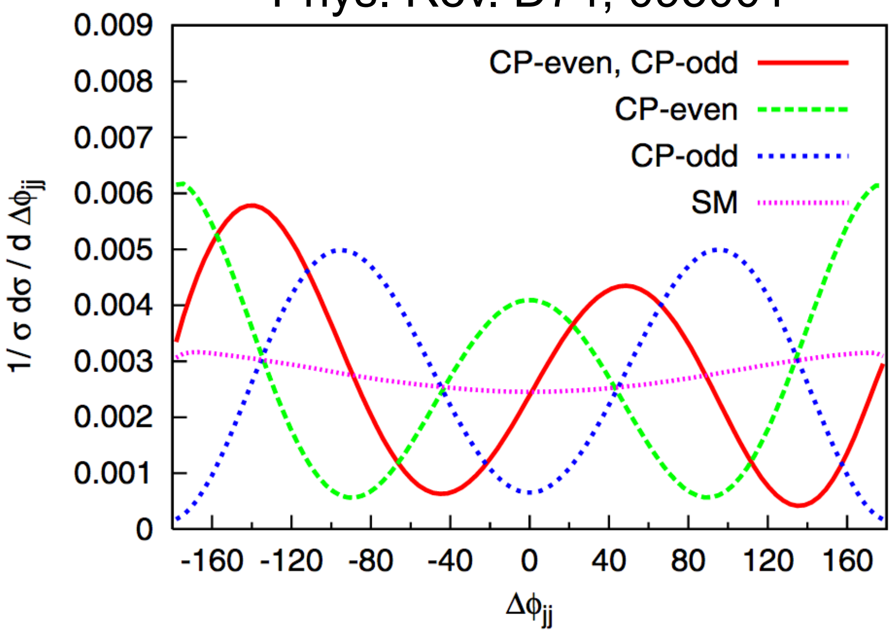
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \tilde{g}_{HAA} H \tilde{A}_{\mu\nu} A^{\mu\nu} + \tilde{g}_{HAZ} H \tilde{A}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HZZ} H \tilde{Z}_{\mu\nu} Z^{\mu\nu} + \tilde{g}_{HWW} H \tilde{W}^{+}_{\mu\nu} W^{-\mu\nu}$$

with the following assumed:

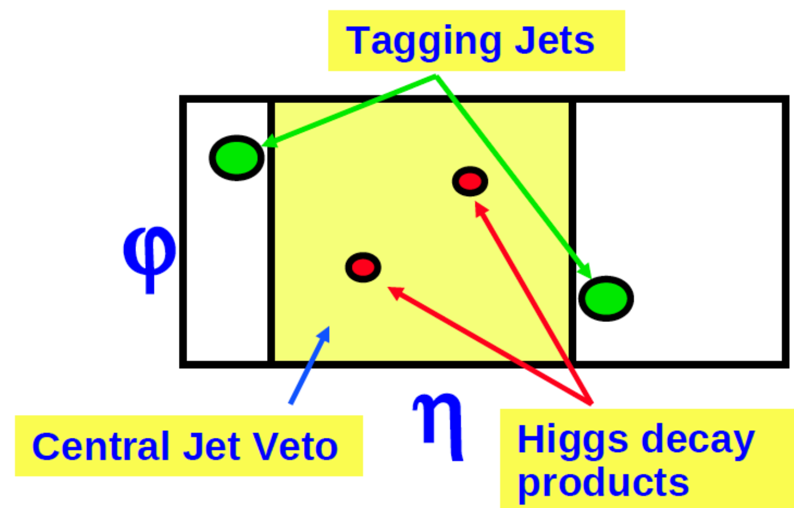
$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{HAZ} = 0$$



Phys. Rev. D74, 095001



Traditionally proposed variable: signed ΔΦ between the two tagging:



CP test in VBF $H\to\tau\tau$ with ATLAS

[arXiv:1602.04516 (accepted to EPJC)]

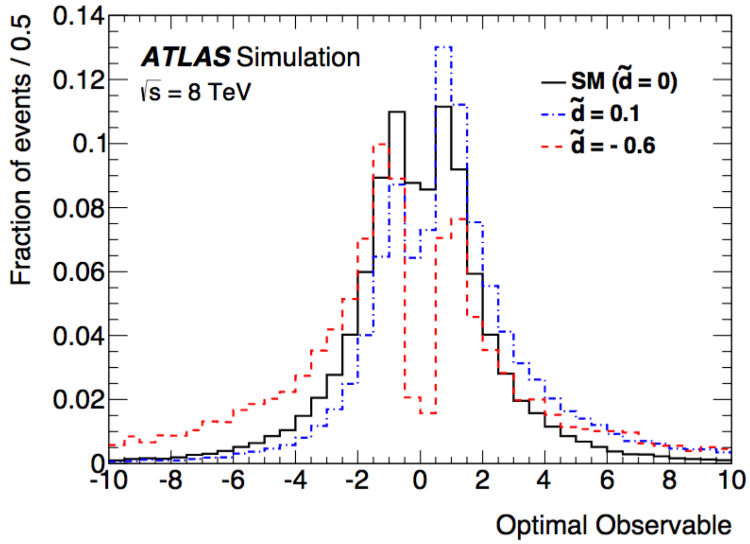
- The Optimal Observable (OO) is expected to perform better than $\Delta\Phi$. It is defined as: $OO = \frac{2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}})}{|\mathcal{M}_{\mathrm{SM}}|^2}$

  with the Matrix Element for VBF production being

$$\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \tilde{d}\cdot\mathcal{M}_{\mathrm{CP\text{-}odd}}$$

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

- With all 4-momenta of the final state particles (Higgs and two tagging jets) measured (not possible with $H\to WW^*$), the LO ME of SM and CP-odd can be calculated from HAWK, and then OO can be calculated per event



For no CP violation, the mean of OO distribution should be 0

For positive (negative) CP-odd component (determined by $\tilde{d}$), its mean will be shifted to positive (negative) values

The OO approach is more sensitive than $\Delta\Phi$, and can be used in other decays such as $H\to\gamma\gamma$

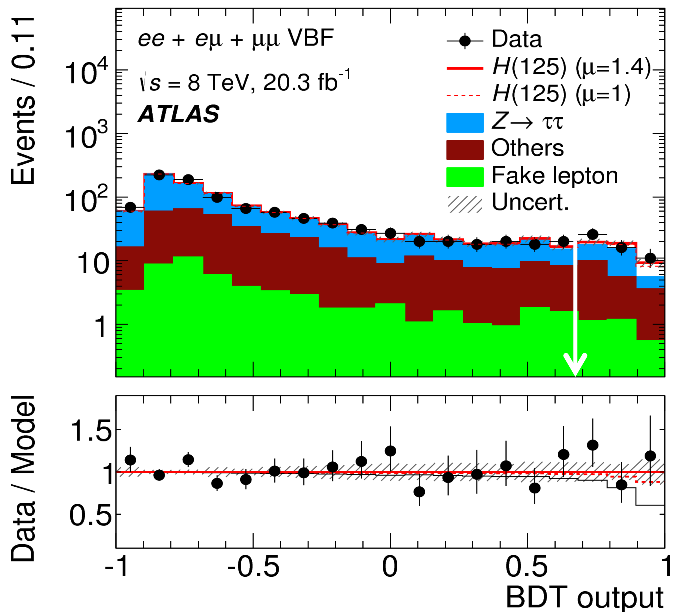
CP test in VBF H→ττ with ATLAS

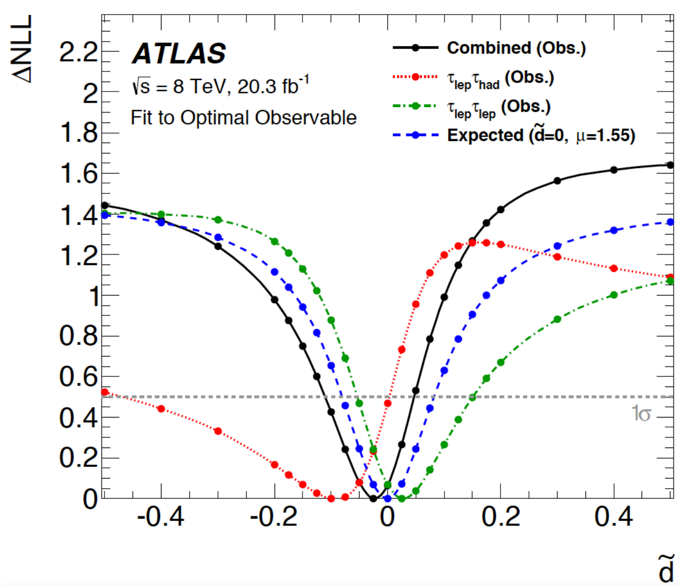
[arXiv:1602.04516 (accepted to EPJC)]

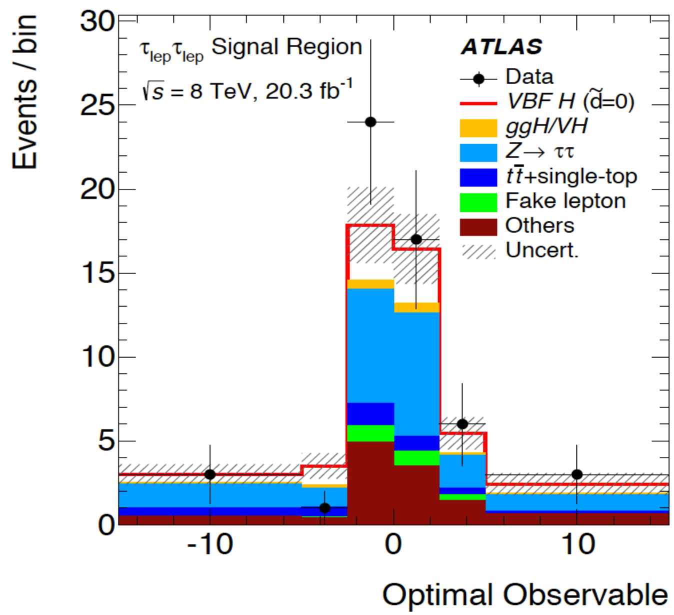
- Cut at high Boosted Decision Tree (MVA analysis) values to get more pure signal events (S/B ~ 0.3)
- A likelihood fit to the OO distribution is performed to find the best $\tilde{d}$, which is found to be consistent with 0 – no sign of CPV

$$-0.11 < \tilde{d} < 0.05 \quad \text{(68\% CL)}$$

- The 1σ bound is a factor 10 better than the HVV CP in decay (c.f. slide 5)

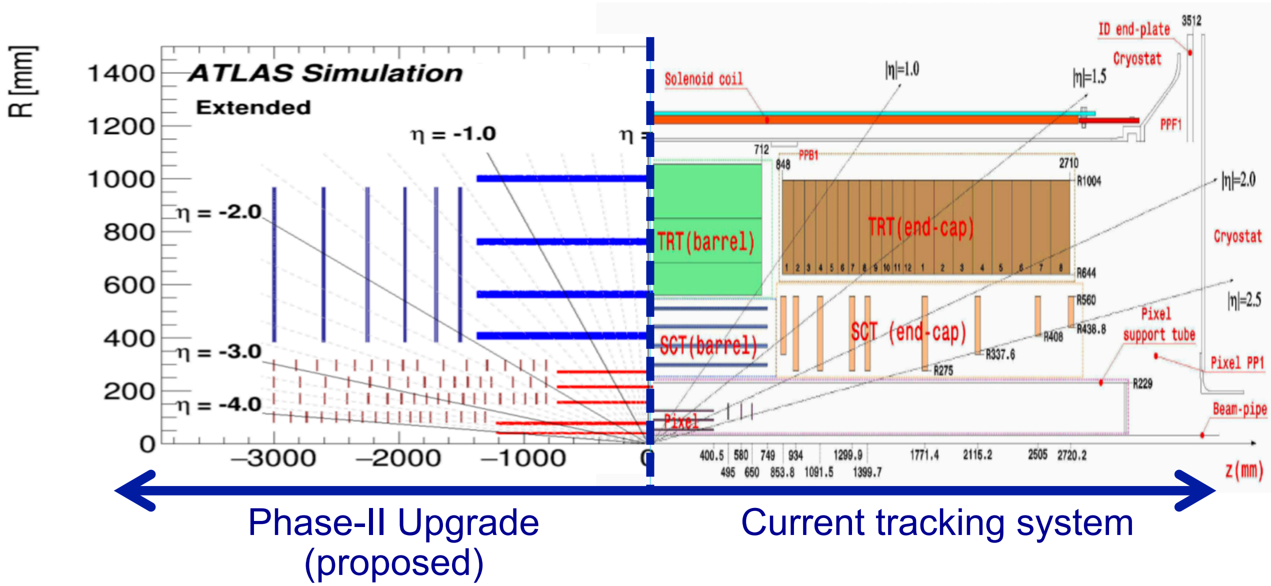


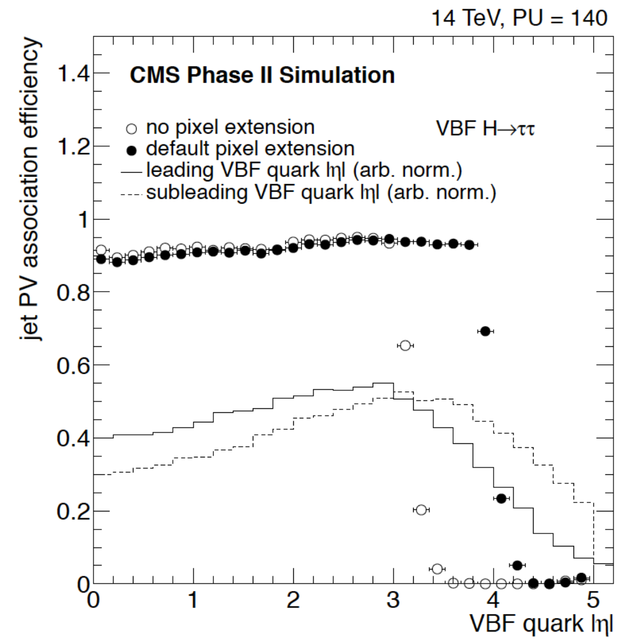




VBF $H\rightarrow\tau_l\tau_h$ in HL-LHC

[ATL-PHYS-PUB-2014-018]
[CERN-LHCC-2015-010]





ATLAS

forward pile-up jet rejection	50%	75%	90%
forward tracker coverage	$\Delta\mu$		
Run-I tracking volume	0.24		
$\lvert\eta\rvert < 3.0$	0.18	0.15	0.14
$\lvert\eta\rvert < 3.5$	0.18	0.13	0.11
$\lvert\eta\rvert < 4.0$	0.16	0.12	0.08

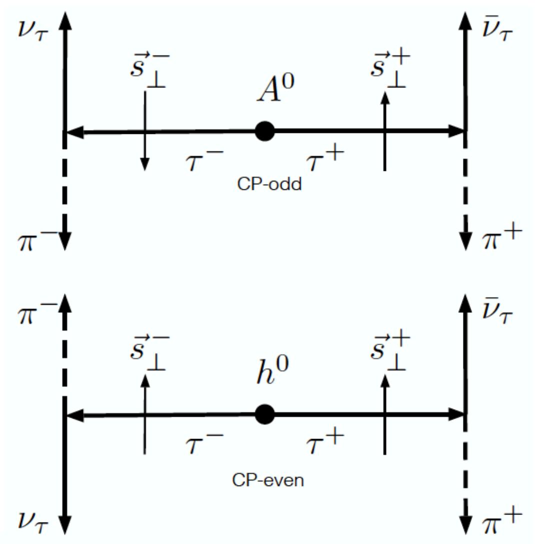
- Missing Transverse Energy and $\tau\tau$ mass resolution will degrade as the pileup increases
- The signal-background discrimination increases with the tracking coverage (VBF forward jets)
- Assuming zero theory uncertainty, the uncertainty on the signal strength μ at 8-18% (2-5%) can be achieved with ATLAS $\tau_l\tau_h$ alone (CMS $\tau\tau$ inclusive)
- Would expect a corresponding increase in precision for the VBF CP

CP test in H→ττ decay

- CP-odd Yukawa coupling can enter the Lagrangian at dim-4, thus sensitive at tree-level rather than with the dim-6 operators in HVV

$$-g_\tau\left(\cos\phi\bar{\tau}\tau+\sin\phi\bar{\tau}i\gamma_5\tau\right)h$$

Φ is the mixing angle. Φ=0 (Φ=π/2) means SM (CP odd)



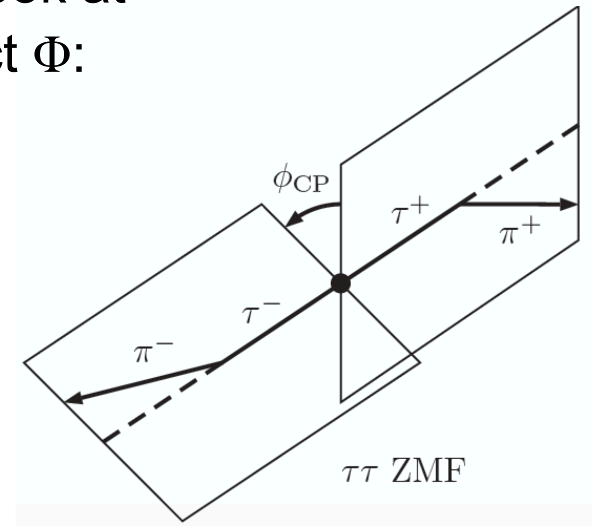
- CP of Hττ coupling can be distinguished by the transverse tau spin correlations

$$\Gamma(H,A\to\tau^-\tau^+)\sim 1-s_z^{\tau^-}s_z^{\tau^+}\boxed{\pm s_T^{\tau^-}s_T^{\tau^+}}$$

Sensitive to CP (H vs A)

- For example, with the τ→πν decay, one can look at the angle between tau decay planes to extract Φ:

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



- It is experimentally challenging because the neutrinos are not reconstructed

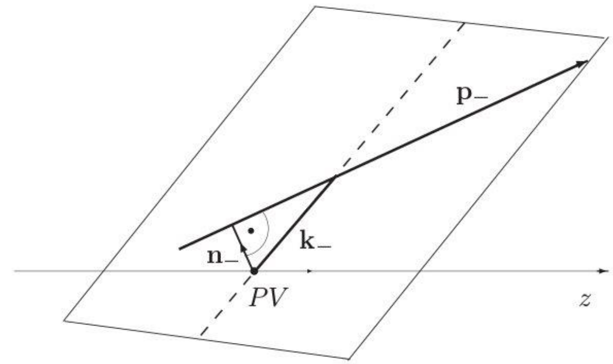
CP test in H→ττ decay

- There are two methods to extract CP from H→ττ decay:

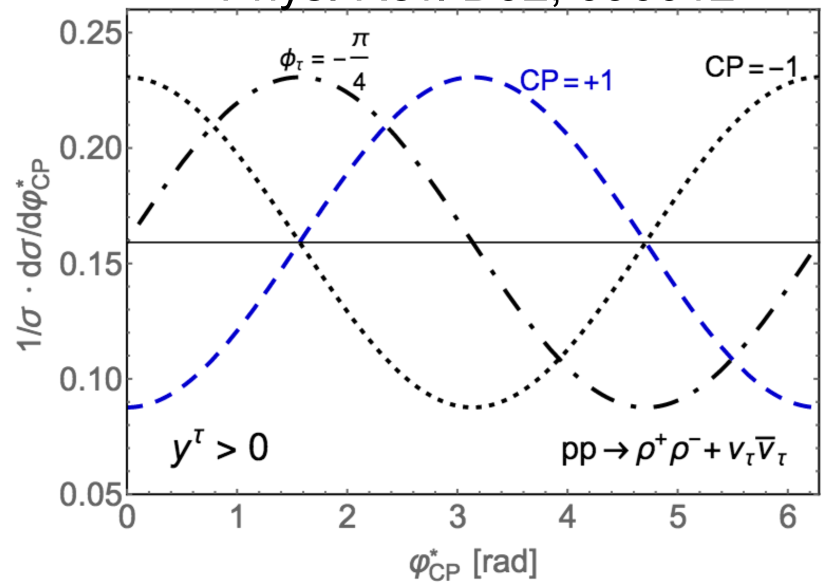
  Impact Parameter (IP) method:
  - Approximately reconstruct the tau decay plane from its leading track and IP
  - Best for the $\tau\to\pi\nu$ decay. The analyzing power is compromised for other tau decays

  Using the $\tau\to\rho\nu\to\pi^{\pm}\pi^{0}\nu$ decay:
  - The tau decay plane can be approximately reconstructed by the track and neutral pion
  - However, the relative energy of $\pi^{\pm}$, π^{0} need to be classified in order to maximize the analyzing power

- In order to use the two methods, the tau decay modes (substructure) need to be well differenciated (next few slides)



Phys. Rev. D92, 096012



A few extra references:
EPJC 74 (2014) 3164, Phys. Rev. D88 076009,
Phys. Lett. B579 (2004) 157, Phys. Lett. B543 (2002) 227

Tau substructure in ATLAS

[EPJC 76(5) (2016) 1]

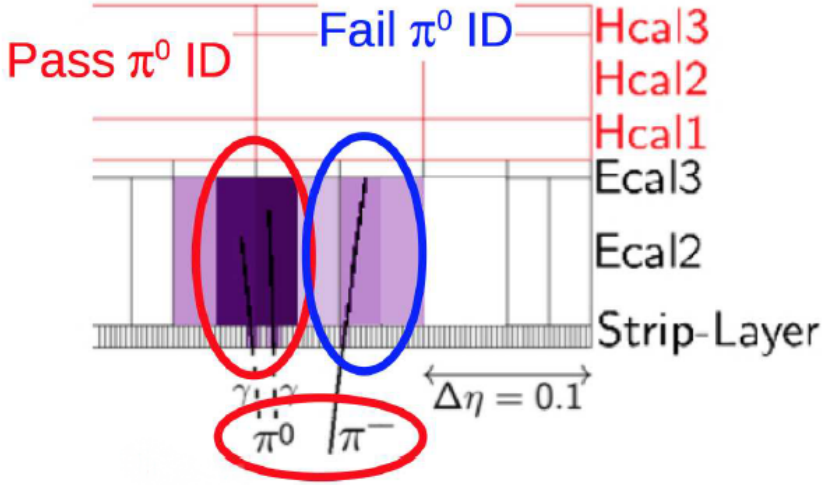
- After initial Tau reconstruction and ID, the hadronic tau candidate is further analyzed with a particle-flow algorithm to better reconstruct and differenciate the neutral pions π^0
- The energy in calorimeter deposited by $\pi^{\pm}$ is subtracted, and the remaining energy cluster is reconstructed as π^0 and identified with BDT
- The final decay mode classification is done with another BDT

Single tau efficiency:

Decay mode	$\mathcal{B}$ [%]	$\mathcal{A} \cdot \varepsilon_{\mathrm{reco}}$ [%]	$\varepsilon_{\mathrm{ID}}$ [%]
$h^{\pm}$	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

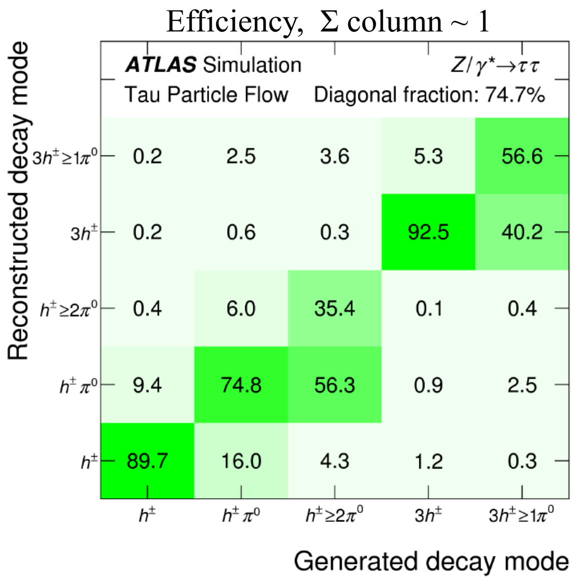
Ditau efficiency (BR*Reco*ID)

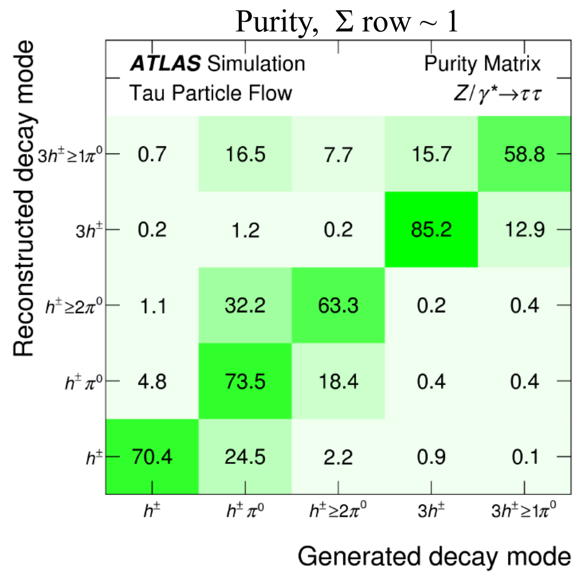
Effi. (%)	π^+	$\pi^+\pi^0$	$\pi^+{+}\geq 2\pi^0$	$3\pi^{\pm}$
π^-	0.08			
$\pi^-\pi^0$	0.30	0.30		
$\pi^-{+}\geq 2\pi^0$	0.10	0.20	0.03	
$3\pi^{\pm}$	0.19	0.37	0.12	0.12

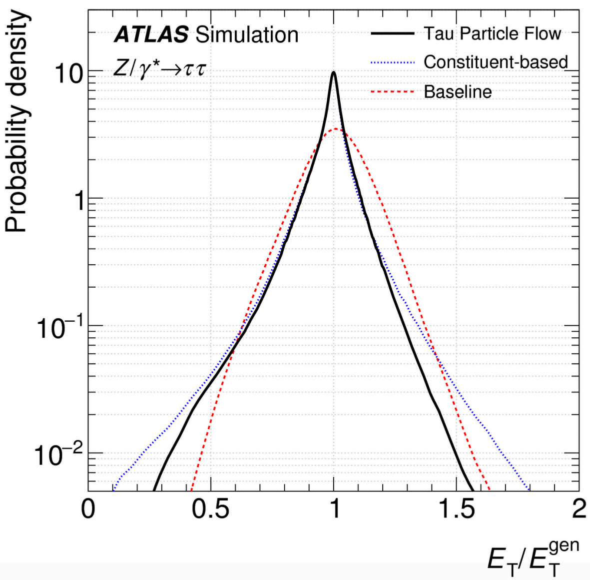


Tau substructure in ATLAS

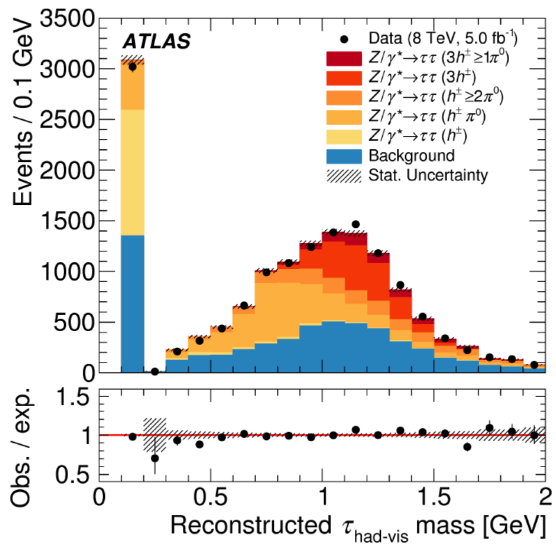
[EPJC 76(5) (2016) 1]



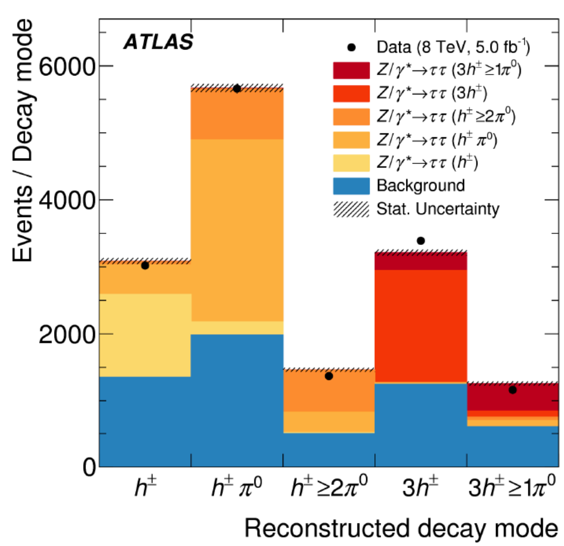




In general, non-negligible fraction of 2/1 π^0 reconstructed as 1/0 π^0



Good reconstruction of tau mass in different decay modes



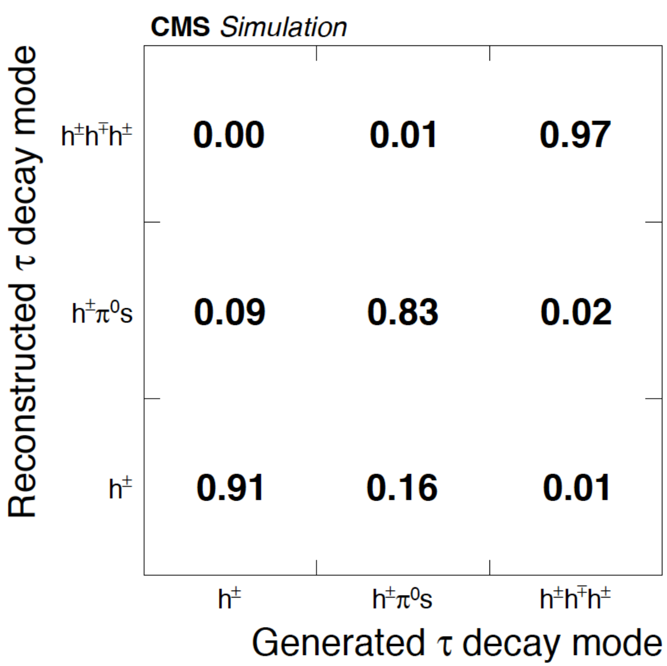
Good tau decay classification

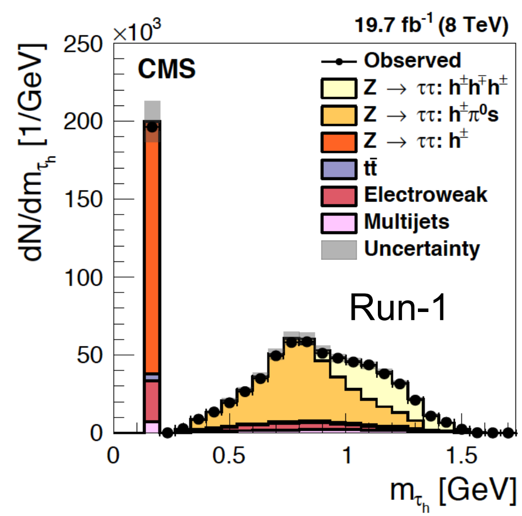
- With the substructure, a factor of 2 improvement of tau energy w.r.t. the calo-based at low p_T (~0.16 for neutral π^0)
- A factor of 5 improvement in the angular resolution
  - neutral π^0 η : ~0.006
  - neutral π^0 Φ : ~0.012

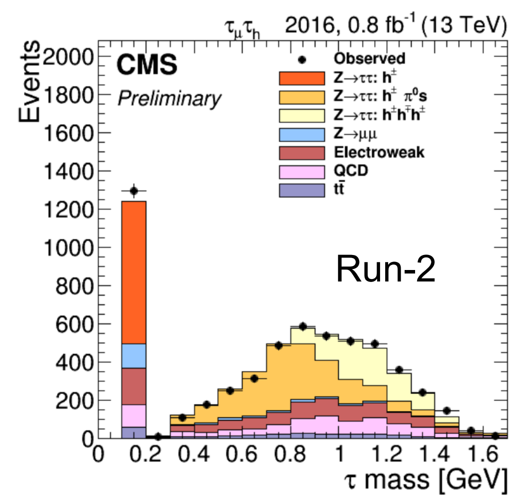
Tau decay reconstruction in CMS

[JINST11 (2016) P01019]
[CMS-DP-2016-016]

- CMS also uses the particle-flow constituents (charged and neutral particles) to reconstruct taus. Discriminants are then applied to reject jets and leptons (MVA-based tau ID)
- Multiple τ_h hypotheses for each jet are constructed (a combinatorial approach). The one passing all cuts and with the highest p_T is selected as the decay mode for the tau candidate

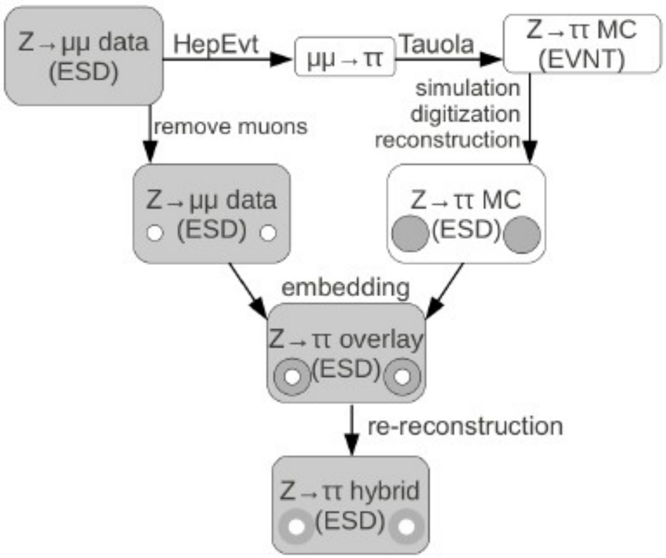






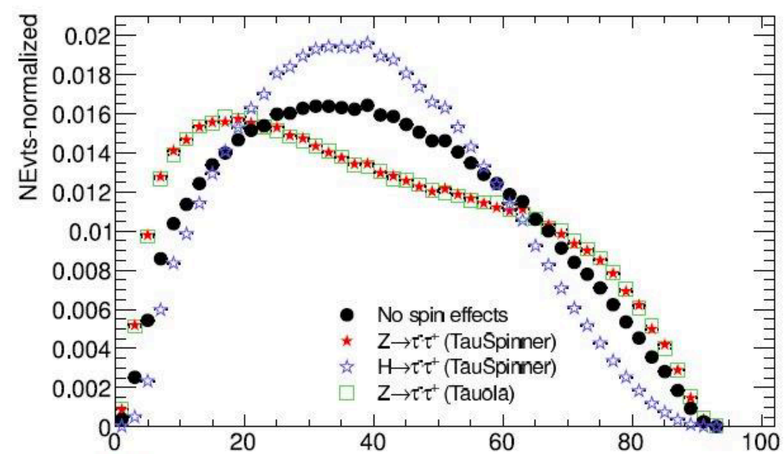
- ❖ Have less decay modes classified than ATLAS, but the cross-talk among different modes is also smaller
- ❖ Tau decay modes and mass have good agreement with data (though W+jets and QCD are higher in run-2 than in run-1)

Z→ττ background



- Z→ττ is a dominant background for H→ττ search. Both ATLAS and CMS use embedding to simulate this background (reduced systematics):
  - Replace muons from Z→μμ data by simulated taus and decay the taus
  - Embed the simulated tau decay products into the original real data event

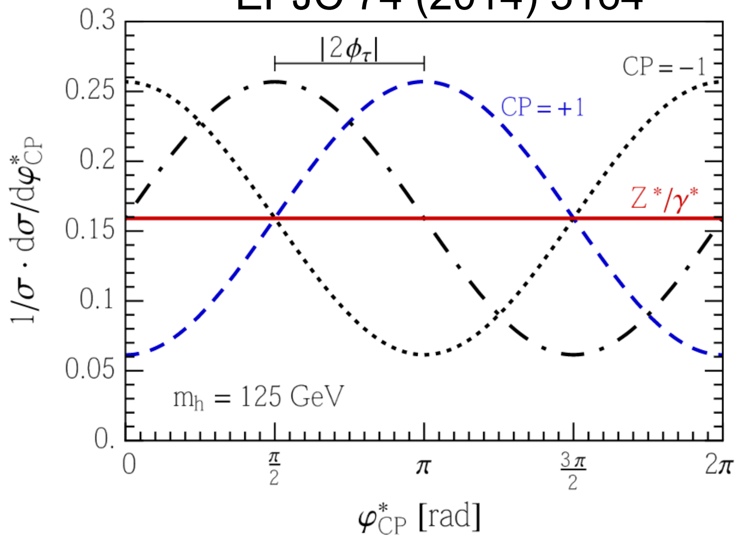
CERN-PH-TH/2011-307



(b)

Visible mass of the two hadrons in the channel where both τ leptons decay to $\pi^- \nu$.

EPJC 74 (2014) 3164



Although the CP angle distribution is expected to be flat for Z→ττ (mostly longitudinally polarized), Tauola/TauSpinner ensures the correct Z polarization and ditau spin correlation

Summary

Testing the CP nature of Higgs is one of the important tasks after its discovery. The diboson decays of Higgs are good probes of CP

With the diboson channels ($H\rightarrow\gamma\gamma$, ZZ, WW), and assuming pure CP state for the Higgs, the CP even state is favored by data

With the diboson channels, the tensor structure of HVV coupling can also be probed for mixed CP scenarios. No significant CP mixing effect is observed and limits are set on the CP-odd terms in EFT

The $H\rightarrow\tau\tau$ channel is ideal for probing CP with HVV coupling through Vector Boson Fusion, or through the $H\tau\tau$ Yukawa coupling. Combined sensitivity of ATLAS and CMS already exceeds 5σ with Run-1 data

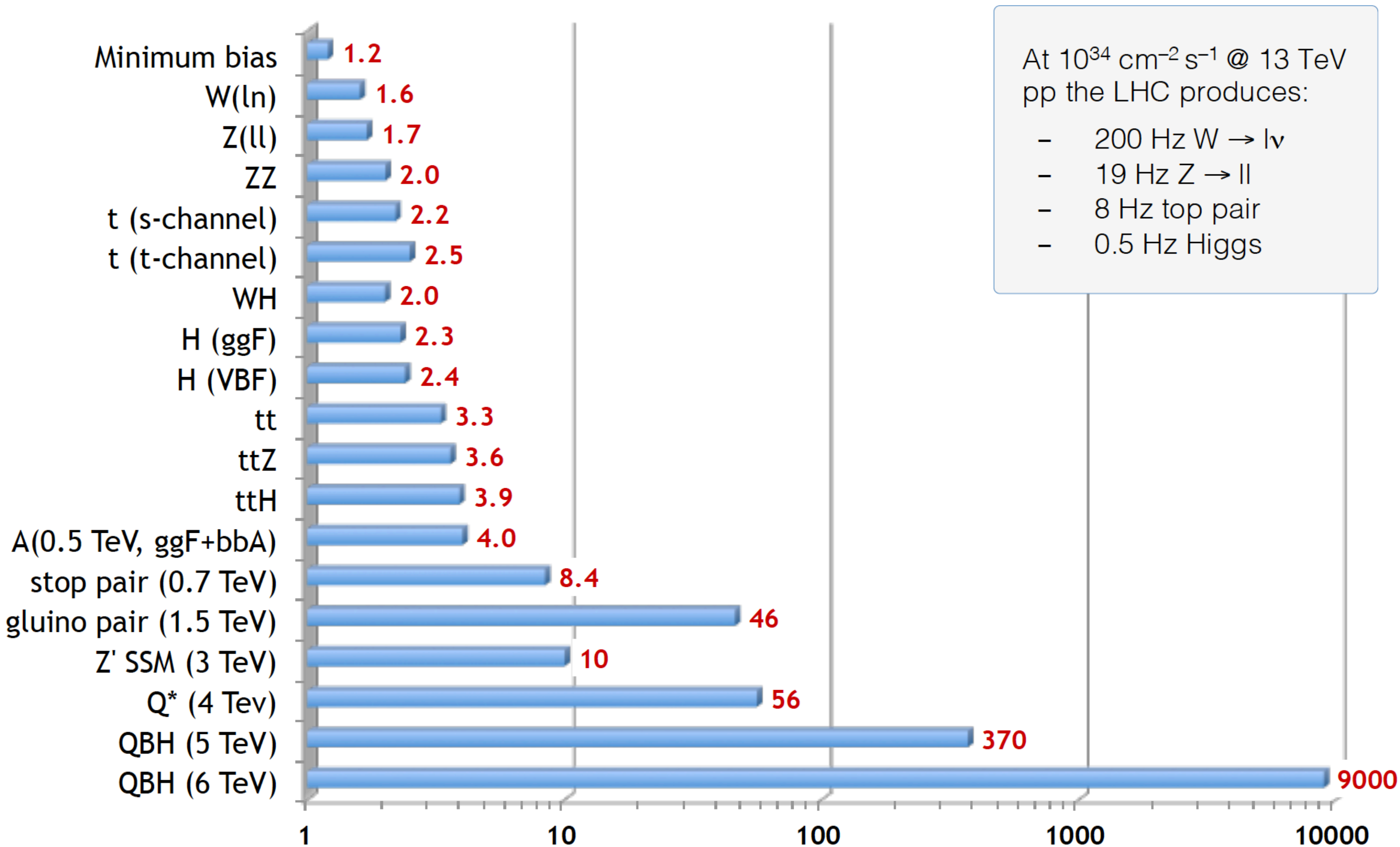
ATLAS has results with VBF $H\rightarrow\tau\tau$ with Run-1 data. The CP-mixing parameter in the VBF production is consistent with zero

CP mixing in $H\rightarrow\tau\tau$ decay can be large in theory, but experimentally very challenging. Both ATLAS and CMS have refined the tau reconstruction with substructure information, which is essential for the CP study in tau decays. A lot of work is still ongoing, and some first results are expected soon

The CP test precision will improve with the HL-LHC data. Just a few % uncertainty on the $H\rightarrow\tau\tau$ signal strength is expected

Extra Slides

Scaling factors from 8 to 13 TeV



Higgs tensor coupling

[EPJC 75 (2015) 476]

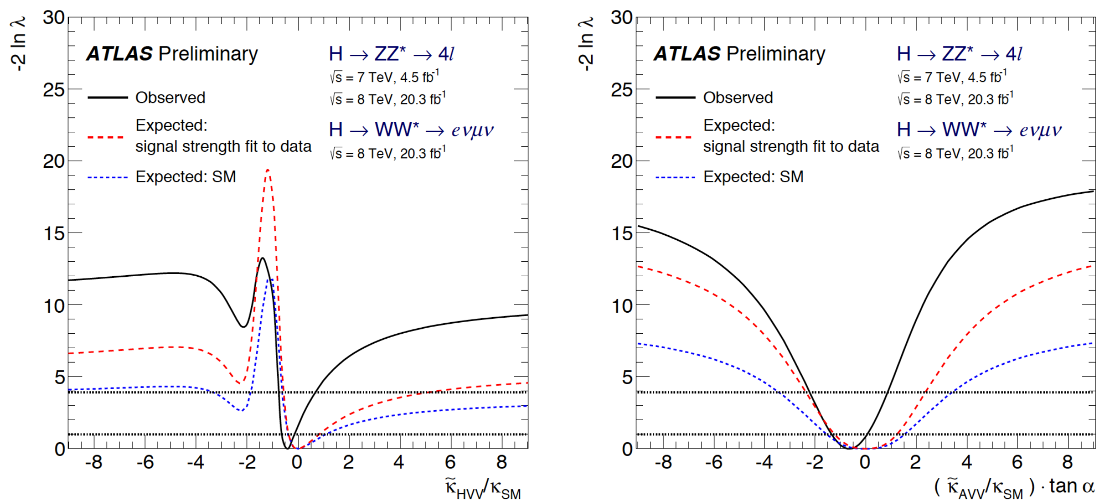
Use Effective Field Theory to probe Higgs HVV tensor structure (for spin-0):

$$\begin{aligned}\mathcal{L}_0^V = & \Big\{c_\alpha \kappa_{SM}\Big[\boxed{\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}}\Big] \\ & -\tfrac{1}{4}\tfrac{1}{\Lambda}\Big[\boxed{c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu}} + \boxed{s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu}}\Big] \\ & -\tfrac{1}{2}\tfrac{1}{\Lambda}\Big[\boxed{c_\alpha \kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu}} + \boxed{s_\alpha \kappa_{AWW} W^+_{\mu\nu} \tilde{W}^{-\mu\nu}}\Big]\Big\} X_0\end{aligned}$$

where $\tilde{V}^{\mu\nu} = \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}V_{\rho\sigma}$ is the dual tensor, and α is the mixing angle: $c_\alpha = \cos\alpha$, $s_\alpha = \sin\alpha$

SM 0^+ BSM CP-even 0_h^+ BSM CP-odd 0^-

Mixed CP Higgs tests:



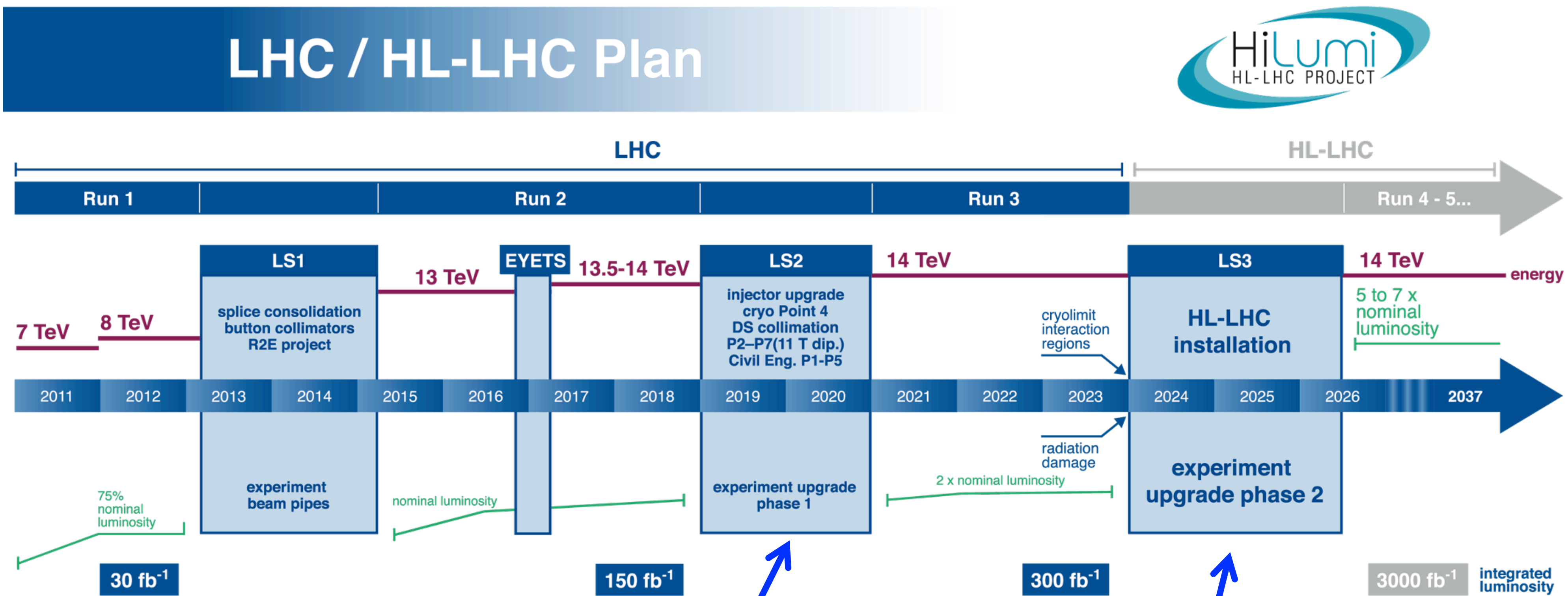
Combined 3 channels: WW→eνμν, γγ, ZZ→4l. Limits on the BSM and SM coupling ratio can be set:

$$\tilde{\kappa}_{AVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{AVV}$$

$$\tilde{\kappa}_{HVV} = \frac{1}{4}\frac{v}{\Lambda}\kappa_{HVV}$$

Coupling ratio	Best fit value		95% CL Exclusion Regions	
Combined	Expected	Observed	Expected	Observed
$\tilde{\kappa}_{HVV}/\kappa_{SM}$	0.0	−0.48	$(-\infty, -0.55]\bigcup[4.80, \infty)$	$(-\infty, -0.73]\bigcup[0.63, \infty)$
$(\tilde{\kappa}_{AVV}/\kappa_{SM}) \cdot \tan\alpha$	0.0	−0.68	$(-\infty, -2.33]\bigcup[2.30, \infty)$	$(-\infty, -2.18]\bigcup[0.83, \infty)$

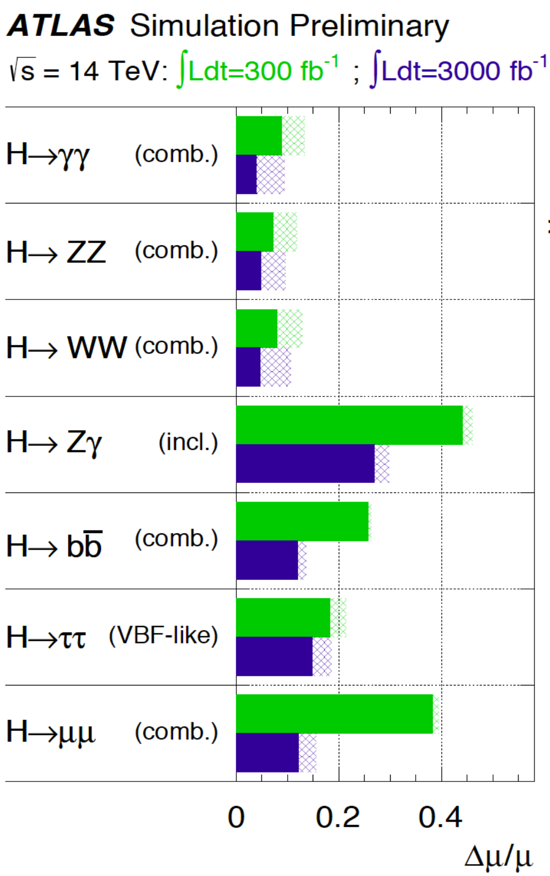
LHC plans for future runs



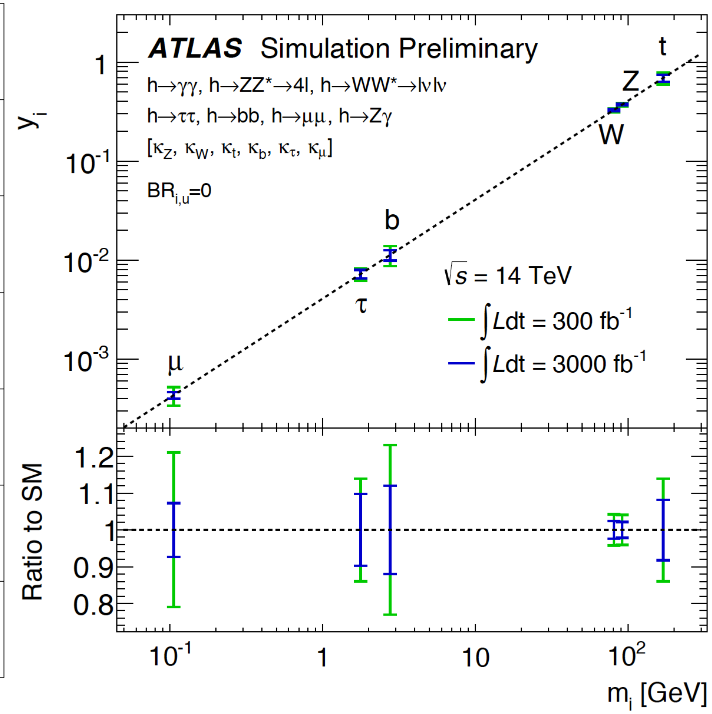
Phase-1 Upgrade for
$L=2\text{-}3\times10^{34}\ cm^{-2}s^{-1}$
In the advanced
stages… starting
production

Phase-II Upgrade for
$L=5\text{-}7.5\times10^{35}\ cm^{-2}s^{-1}$
In the design and
prototyping stage

Higgs prospects for HL-LHC [ATL-PHYS-PUB-2014-016/017]



Coupling versus mass:

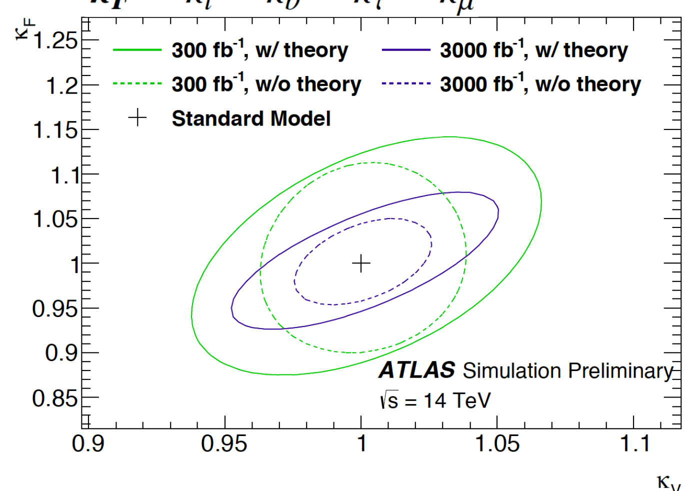


Errors on individual factors:

Nr.	Coupling	300 fb^{-1} Theory unc.: All	Half	None
8	κ_Z	8.1%	7.9%	7.9%
	κ_W	9.0%	8.7%	8.6%
	κ_t	22%	21%	20%
	κ_b	23%	22%	22%
	κ_τ	14%	14%	13%
	κ_μ	21%	21%	21%
	κ_g	14%	12%	11%
	κ_γ	9.3%	9.0%	8.9%
	$\kappa_{Z\gamma}$	24%	24%	24%

$$\kappa_V = \kappa_Z = \kappa_W$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_\mu$$



More precise measurements of Higgs production and decay rates: ~10% (~20%) for the boson (fermion) decay

More precise determination of the Higgs mass and width

Test of the SM in the Higgs sector and probe for new physics such as MSSM, rare/new/invisible Higgs decay

Use EFT and differential variables for advanced Higgs property tests