CP violation in Higgs sector

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Why CPV interesting?

- Baryon genesis: why more matter than anti-matter?

- Sakharov's conditions

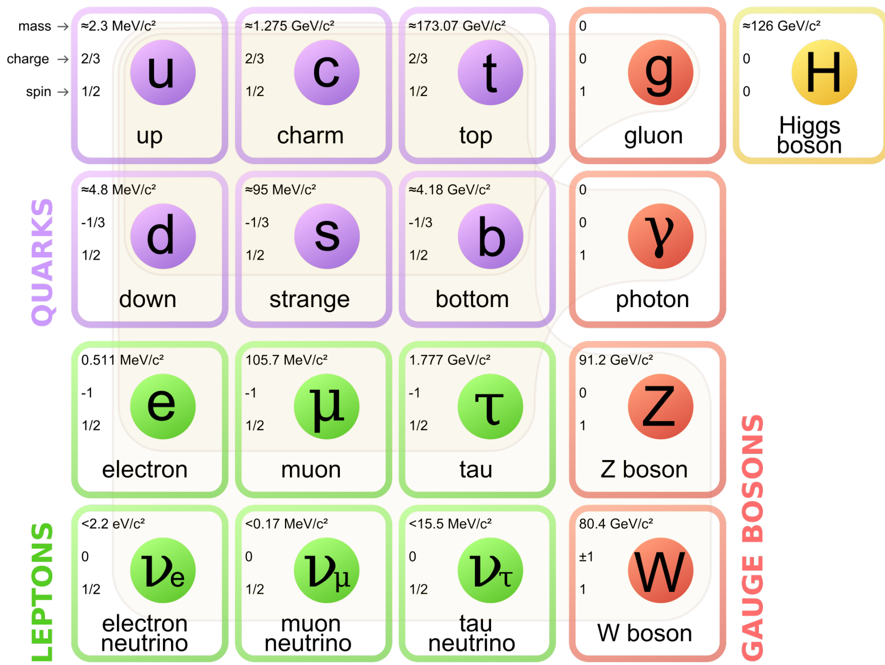
Sakharov's conditions	Standard Model
1. Baryon number violation	✓
2. C and CP violations	✗
3. Departure from the equilibrium	✗

In SM

- Sphaleron process can lead B violation. But,
- CKM, only CPV source in SM, is not enough
- Higgs mechanism in SM is too smooth

Higgs boson open the door

- The discovery of Higgs boson open a new sector
  - Many BSM, e.g. 2HDM, provide new CP violation sources and strong phase transition at Higgs sector



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i\bar{\psi}\not{D}\psi + h.c.$$

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

Higgs boson open the door

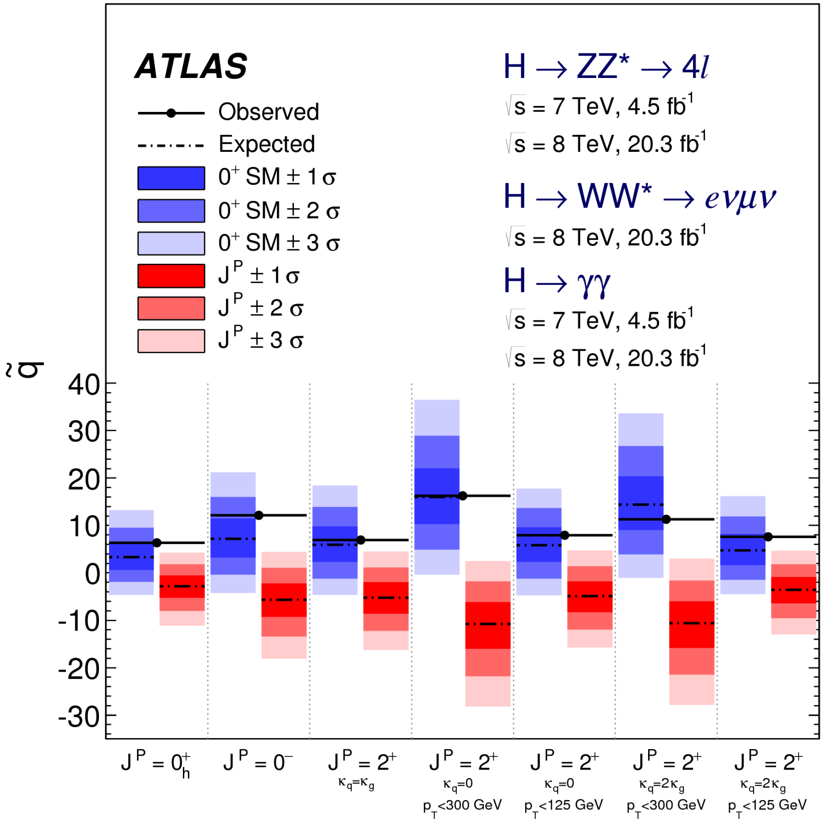
- The discovery of Higgs boson open a new sector
  - Many BSM, e.g. 2HDM, provide new CP violation sources and strong phase transition at Higgs sector

- LHC Higgs physics program
  - Is there CP violation in Higgs coupling
  - EW symmetry breaking the 1st or 2nd order phase transition

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

Higgs boson open the door

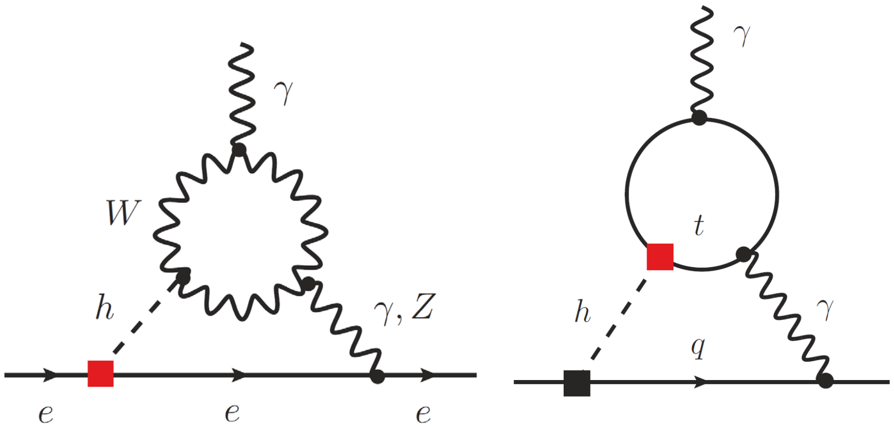
- Higgs boson is found a CP-even scalar, as SM prediction
  - $J^P=0^+$ compared with alternative spin-model



- But, mixing between CP-even and CP-odd, which could lead to CP violation, is still allowed

Indirect constraint

- Low energy experiments, e.g. electron EDM, can constrain the Higgs CP indirectly



$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i \tilde{\kappa}_f \bar{f} \gamma_5 f \right) h$$

ACME collaboration:

eEDM<1.1×10^{-29} e·cm

$$|\tilde{\kappa}_e| \lesssim 1.7 \times 10^{-2}$$
$$|\tilde{\kappa}_t| \lesssim 1.0 \times 10^{-2}$$

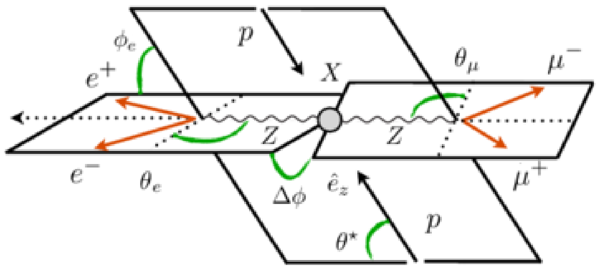
- But, very model dependent
  - Gauge-dependent contributions, UV-divergent diagrams, etc.

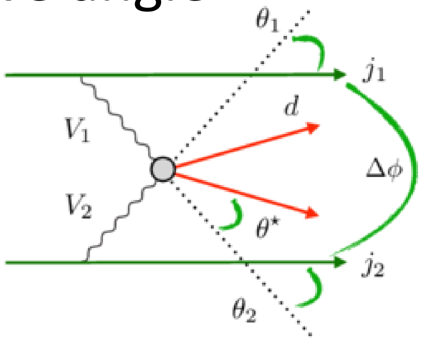
From J. Brod at Higgs 2020

CP violation in Higgs sector

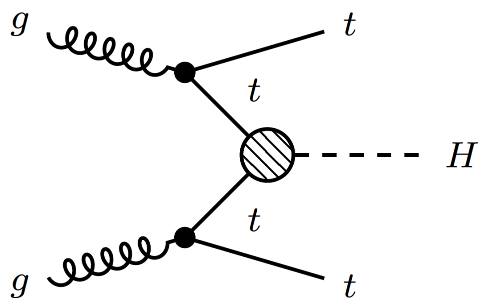
- General methodology:
  - using event topology to build some CP sensitive angle

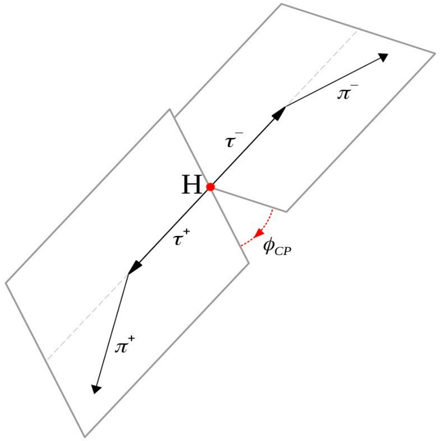
Higgs coupling to vector bosons (HVV)





Higgs coupling to fermions (Yukawa coupling: Hff)





- Indirect measurements not discussed here
  - e.g. ggf loop, cross section, etc

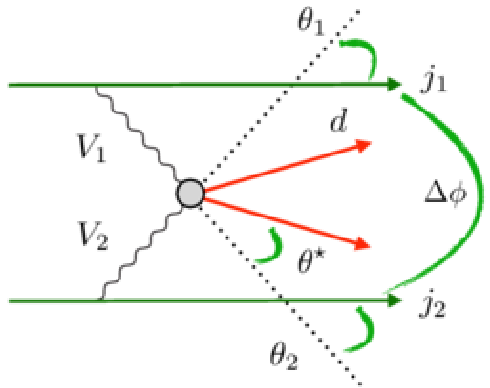
- **ATLAS public results:** https://twiki.cern.ch/twiki/bin/view/AtlasPublic

New results from ATLAS

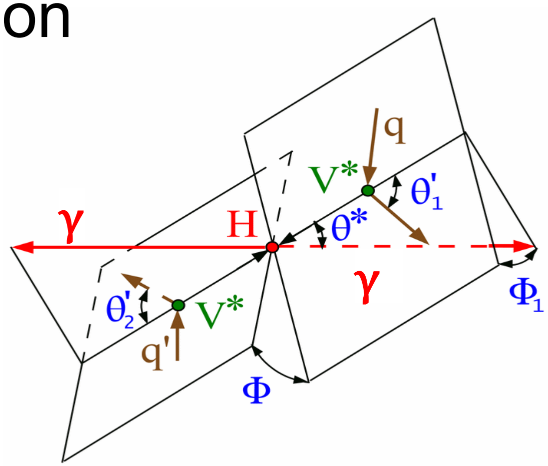
- **CP structure in Higgs-Vector boson coupling**
  - **Vector Boson Fusion (VBF) with $H\to\gamma\gamma$**
  - arXiv:2208.02338, accepted by PRL
  - Main collaborators: Y. Fang, B. Liu, F. Guo, H. Chen, A. Tarek, etc.
- **CP structure in Higgs-fermion Yukawa coupling**
  - **Higgs decay to lepton: $H\to\tau^+\tau^-$**
  - arXiv:2208.02338, accepted by EPJC
  - Main collaborators: H. Li, A. De Maria, K. Lie, T. Cheng, etc.

Study HVV CP in VBF production

- HVV vertex in VBF Higgs production



To Higgs rest frame



- Independent from Higgs decay: here, use $H\to\gamma\gamma$ (SM Br)
- EFT interpretation: two bases used

Warsaw: $\mathcal{L}_{\rm SMEFT}^{\rm CP-odd} \supset \frac{c_{H\tilde{W}}}{\Lambda^2} H^\dagger H \tilde{W}^I_{\mu\nu} W^{\mu\nu I} + \frac{c_{H\tilde{B}}}{\Lambda^2} H^\dagger H \tilde{B}^A_{\mu\nu} B^{\mu\nu} + \frac{c_{H\tilde{W}B}}{\Lambda^2} H^\dagger \sigma^I H \tilde{W}^I_{\mu\nu} B^{\mu\nu}$

HISZ:

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

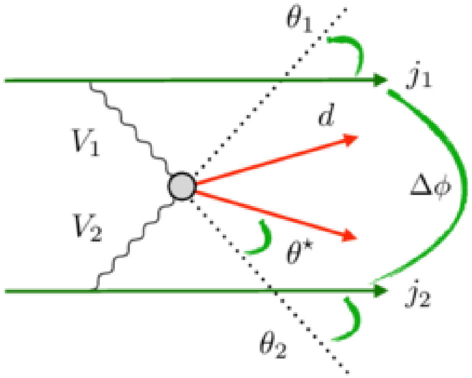
$$\tilde{d} = -\frac{m_W^2}{\Lambda^2} c_{\tilde{W}W}$$

Optimal Observable

- Single CP sensitive observable
  - combine kinematics information of VBF jets and Higgs, to constrain Wilsonian coefficient, e.g. $\tilde{d}$ and $c_{h\widetilde{W}}$

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

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



- Evaluated with
  - momentum fraction of initial-state parton $x1(x2)$, four-momenta of Higgs boson and two VBF jets
  - At rec. level, $x_{1,2}^{\rm reco} = \frac{m_{Hjj}}{\sqrt{s}} e^{\pm y_{Hjj}}$

m_{Hjj} (y_{Hjj}): invariant mass (rapidity) of Higgs and VBF jet system

Optimal Observable

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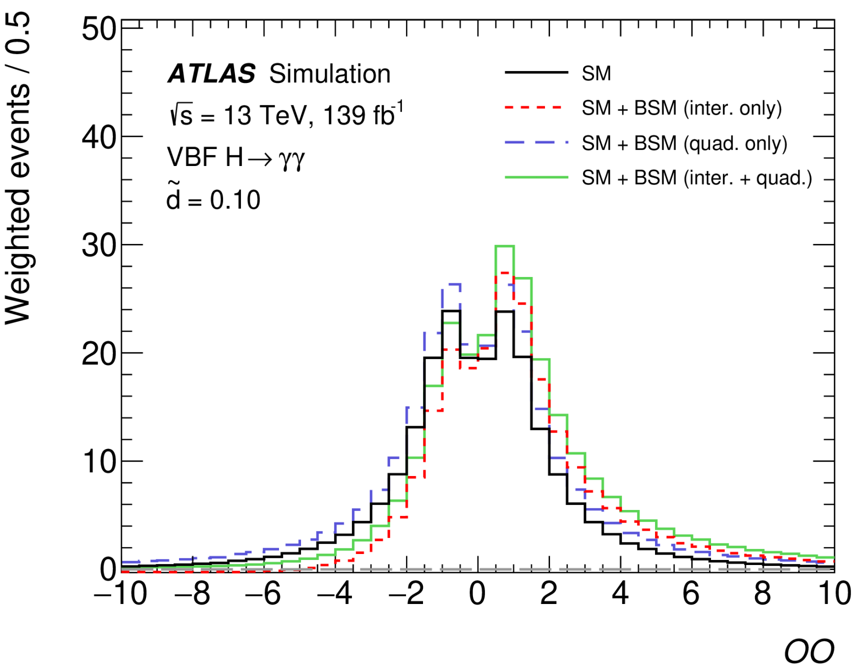
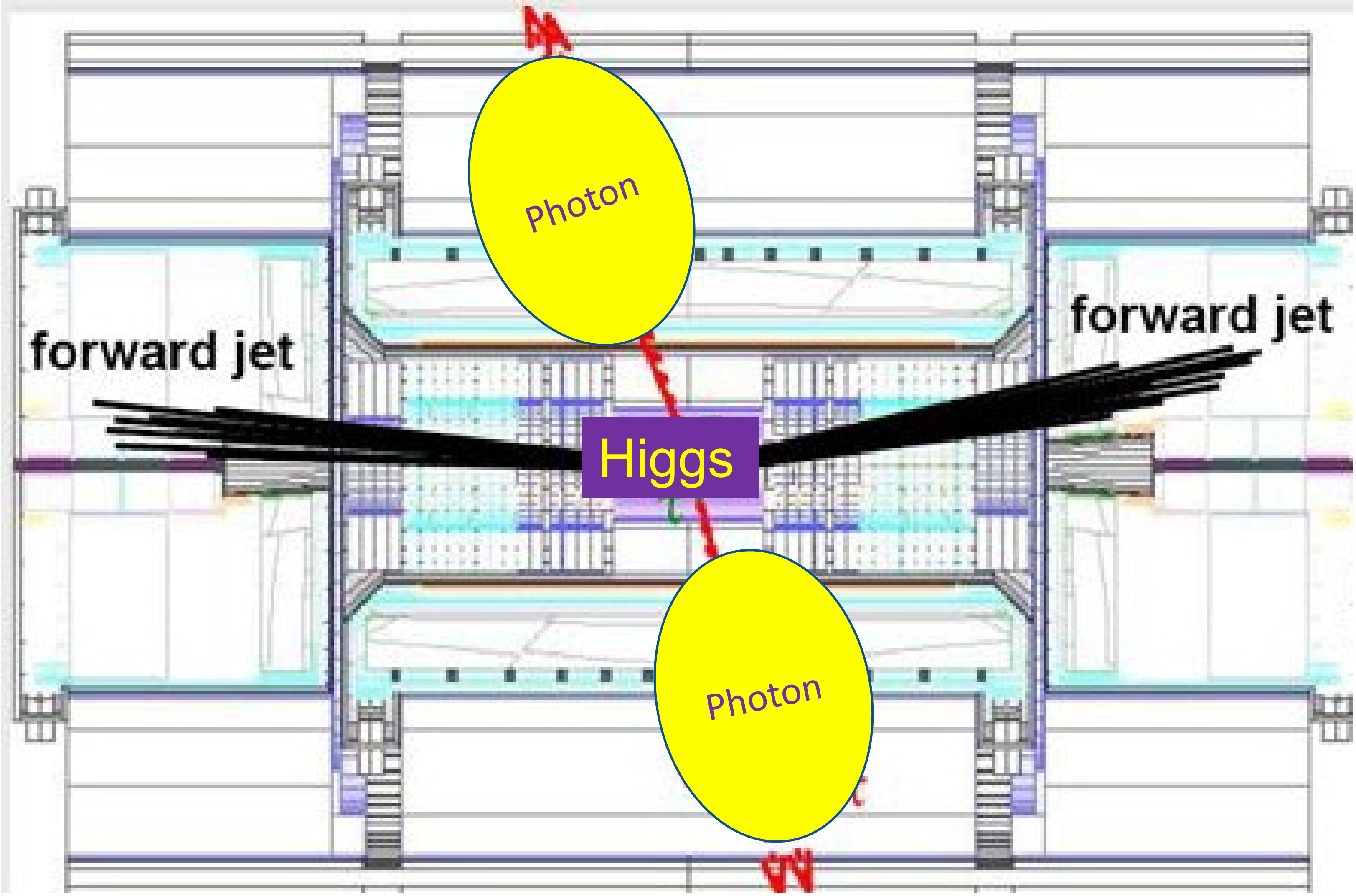
$$|\mathcal{M}|^2 = |\mathcal{M}_{\text{SM}}|^2 + \tilde{d} \cdot 2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

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

- Phenomenon
  - Inter. : asymmetry, direct CPV
  - Quad. : over cross section



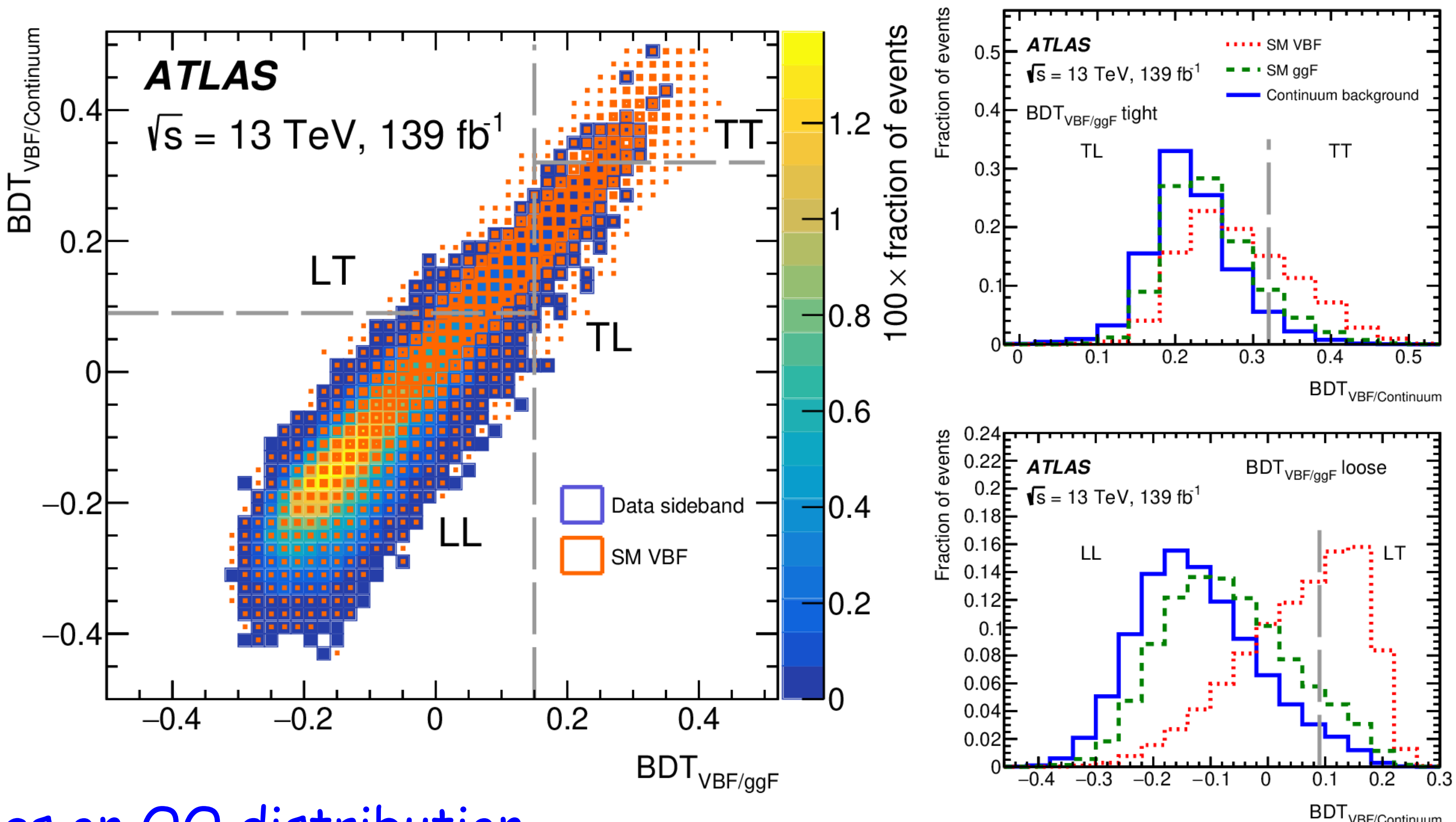
VBF signature at detector



Illustrative figure

VBF: $H\to\gamma\gamma$

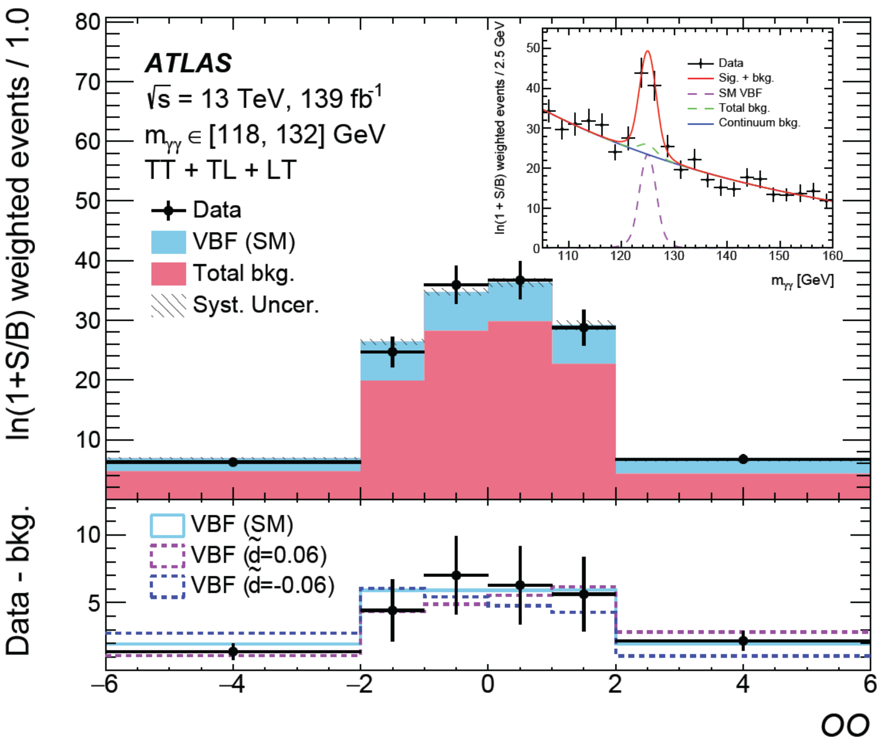
- Events selection
  - $N_{jets} \geq 2$ and $H\to\gamma\gamma$ final states
  - Two BDTs: **VBF v.s. ggF** and **VBF $H\to\gamma\gamma$ v.s. continuum**



No bias on OO distribution

Optimal Observable

- Events further categorized into six OO bins
  - VBF Higgs signal extracted by a simultaneous fit on diphoton mass



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

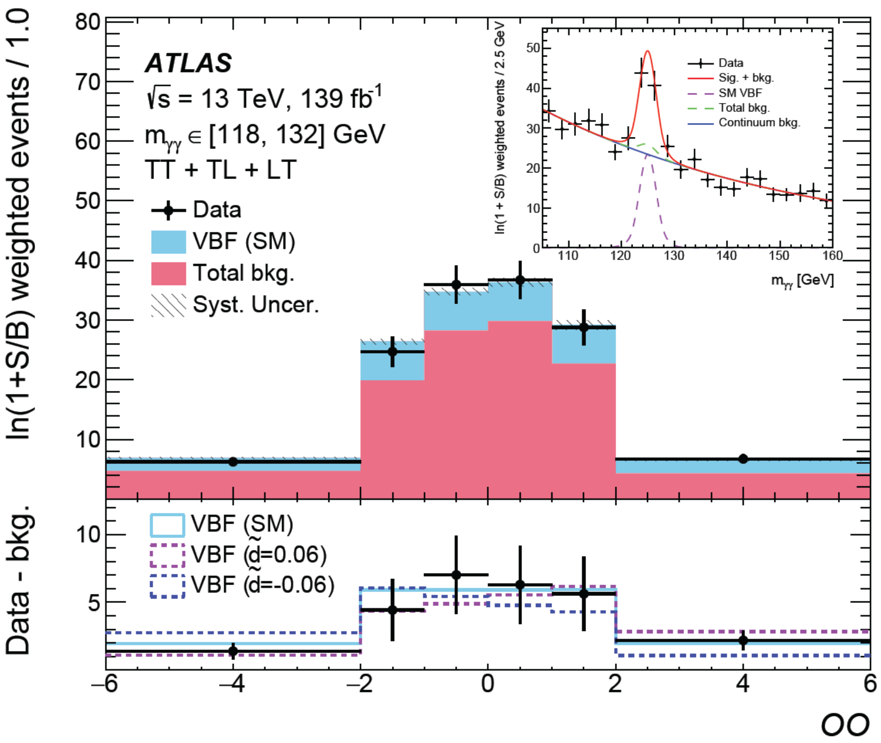
Interpretation

1. Interference only:

   factor out the impact on overall cross section and only sensitive to the CP violation.

Optimal Observable

- Events further categorized into 6 OO bins
  - VBF Higgs signal extracted by a simultaneous fit on diphoton mass



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

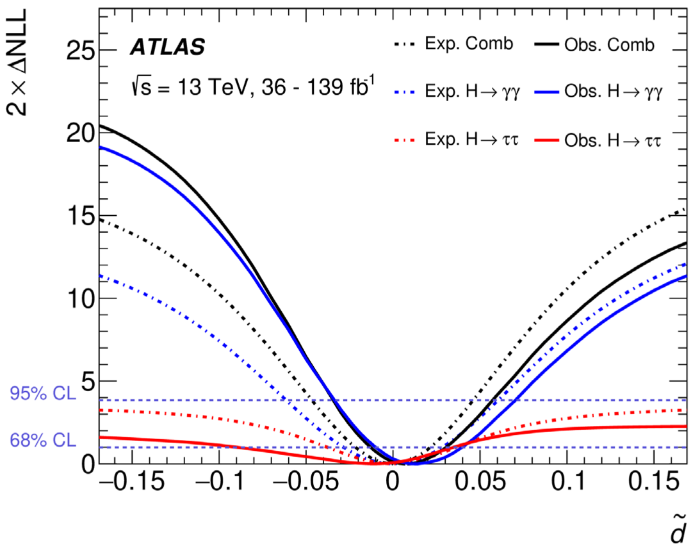
Interpretation

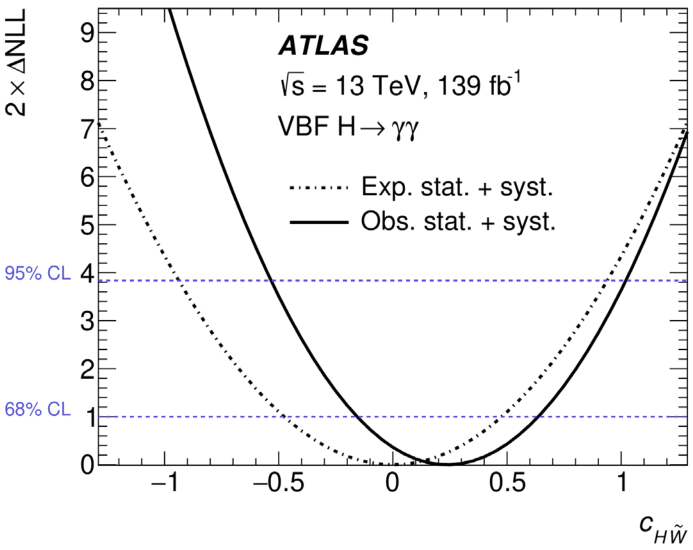
2. Interference + quadrature:

   For completeness, to compare with other analyses

Constrain CP-odd in HVV coupling

- CP-odd operators in two EFT bases constrained
  - HISZ basis: $\tilde{d}$;   Warsaw basis: $c_{h\widetilde{W}}$
  - $\tilde{d}$ further constrained by combining with H→ττ previous results





- Results compatible with SM and no CP violation observed
- The most stringent constraints on CP-violating effects in the HVV coupling so far

Constrain CP-odd in HVV coupling

	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

- CP-odd operators in two EFT bases constrained
  - $\tilde{d}$ in HISZ basis: 95% confidence interval(CI), achieved for the first time
  - $c_{h\widetilde{W}}$ in Warsaw basis: 95% CI, five times better than$H$->$\gamma\gamma$ differential measurement (arXiv:2202.00487)
- Combination with previous H→ττ results on $\tilde{d}$

CPV in Yukawa coupling

- CP-odd HVV coupling is high dimension operators, usually arisen at one loop, e.g. 2HDM prediction:

$$\mathcal{L}_{\rm eff} \supset -\frac{\tilde{g}_{hZZ}}{2}\, hZ_{\mu\nu}\tilde{Z}^{\mu\nu} - \tilde{g}_{hWW}\, hW^{+}_{\mu\nu}\tilde{W}^{-\mu\nu}$$

$$\tilde{g}_{hZZ} \simeq -\frac{\sin\alpha_2}{\tan\beta}\,\frac{1}{6\times 10^5\ \mathrm{GeV}}$$

$$\tilde{g}_{hWW} \simeq \frac{\sin\alpha_2}{\tan\beta}\,\frac{1}{5\times 10^5\ \mathrm{GeV}}$$

- LHC constraint
  - (137 fb^{-1}, CMS PAS HIG-19-009) $\quad \tilde{g}_{hZZ} \lesssim \frac{1}{3\times 10^3\ \mathrm{GeV}}$
  - (HL-LHC, 1902.00134) $\quad \tilde{g}_{hZZ} \lesssim \frac{1}{8\times 10^3\ \mathrm{GeV}}$

- CP-odd in Higgs Yukawa coupling to fermion Hff coupling
  - Can be arisen at tree level in, e.g. 2HDM

$$\mathcal{L}_{\rm Yuk} \supset -\frac{m_f}{v}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

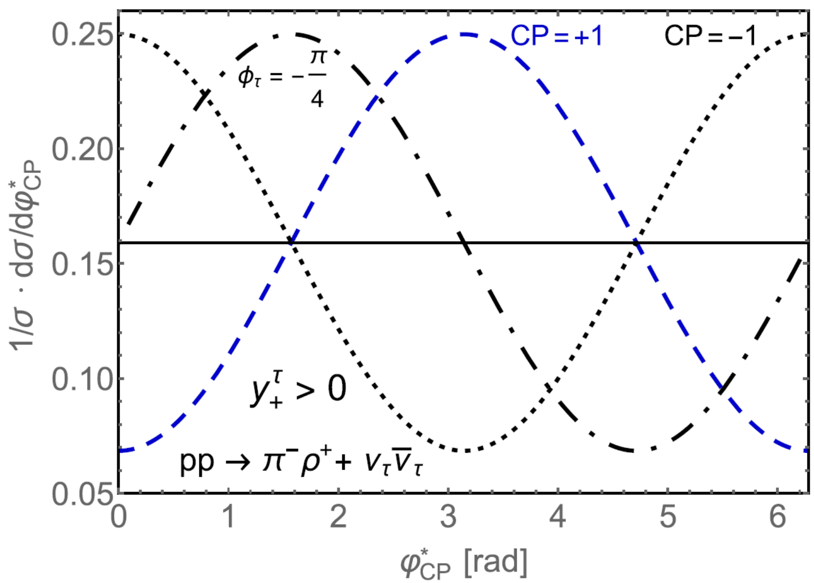
CP structure of H→ττ coupling

- CP-mixing of Higgs to τ lepton yukawa coupling
  - φ^*_{CP} : angle between **two τ decay planes** encodes spin correlation
  - Propagated to the tau decay products

$$\mathcal{L}_Y = -\frac{m_\tau}{\mathrm{v}}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)h$$

1. CP mixing parametrized by ϕ_τ

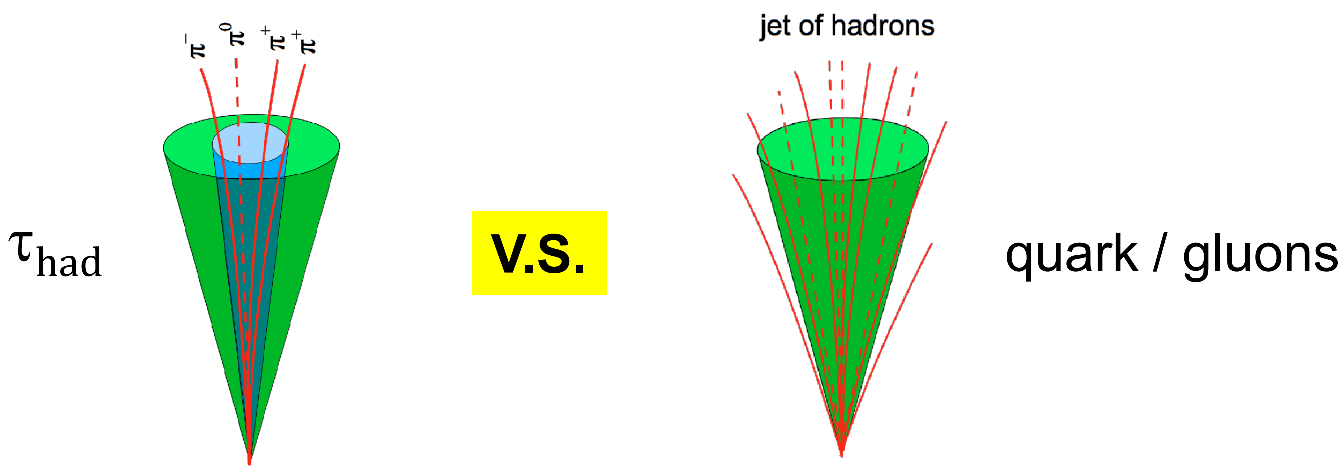
$$\frac{d\Gamma}{d\phi_{CP}}(H\to\tau^+\tau^-) \sim 1 - s_z\bar{s}_z + R(2\alpha^{H\tau\tau})\cdot s_\perp\bar{s}_\perp \sim 1 - \frac{\pi^2}{16}b(E^+)b(E^-)\cdot\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$



2. ϕ_τ measured as modulation, or phase shift, in φ^*_{CP} distribution.

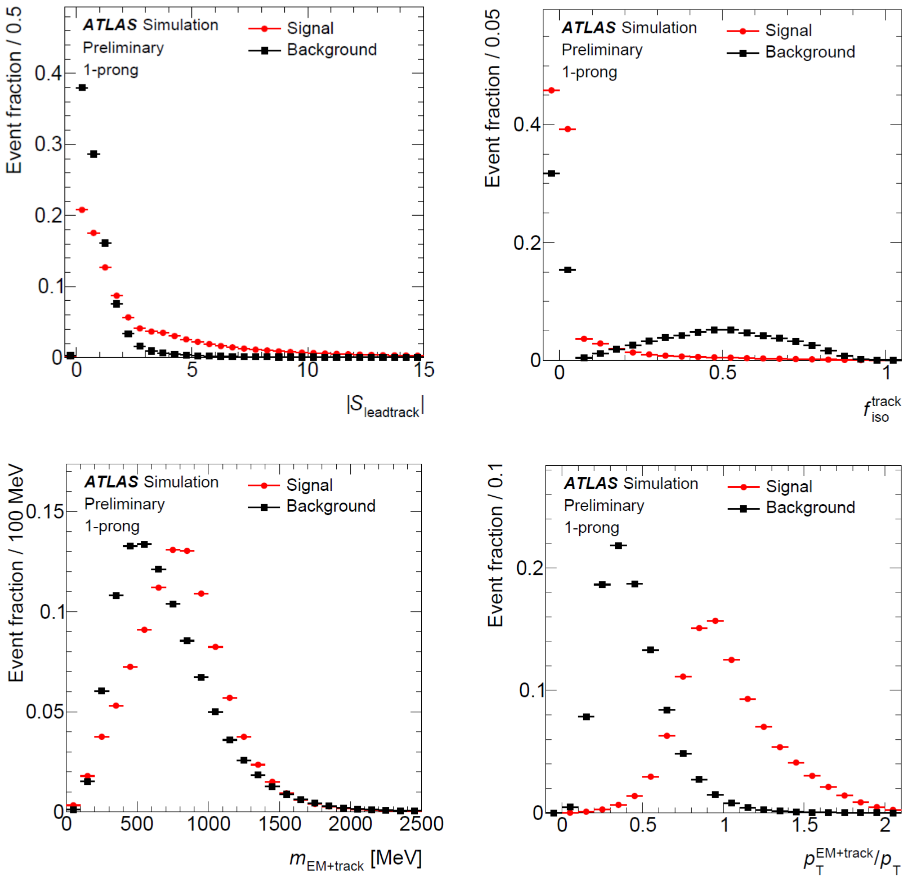
How to detect tau lepton

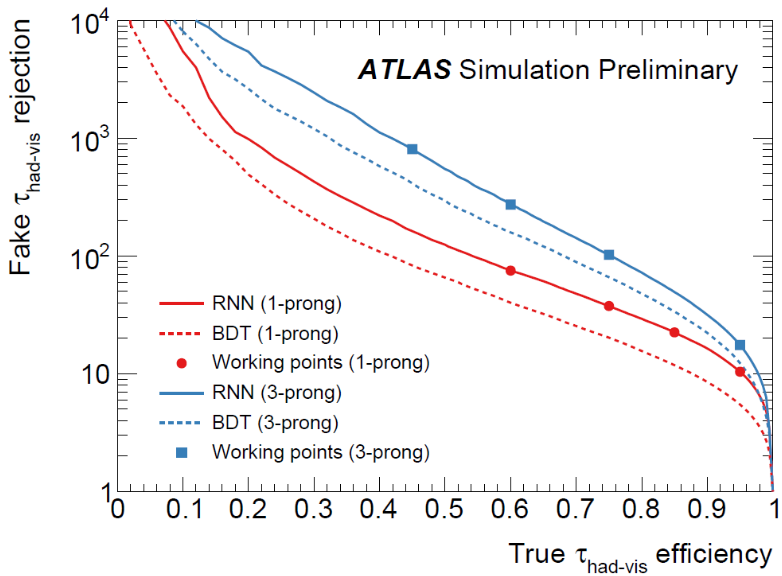
- Tau lepton
  - Heaviest lepton: 1.777 GeV, Decay length: $c\tau \approx 87\ \mu m$
  - ~ 35% to e or μ, ~ 65% to hadrons
- Experimental signature
  - Tau decay to e or μ looks like prompt e or μ
  - τ_{had} has a narrower energy deposit at calorimeter and finite number of tracks



τ_{had} identification

- Multi-Variate Analysis to combine all detector information





ATL-PHYS-PUB-2019-033

Tau decay mode classification

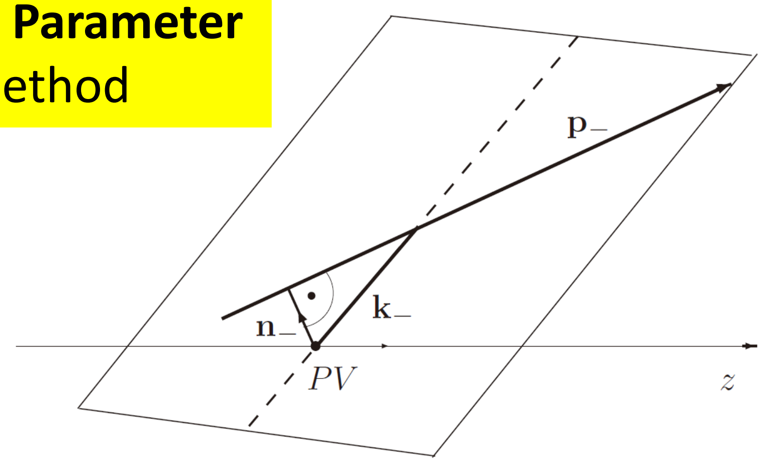
- Two methods to build τ decay plane

Notation	Decay mode	Branching fraction
ℓ	$\ell^{\pm}\bar{\nu}\nu$	35.2%
1p0n	$h^{\pm}\nu$ $(\pi^{\pm}\nu)$	11.5% (10.8%)
1p1n	$h^{\pm}\pi^{0}\nu$ $(\pi^{\pm}\pi^{0}\nu)$	25.9% (25.5%)
1pXn	$h^{\pm} \geq 2\pi^{0}\nu$ $(\pi^{\pm}2\pi^{0}\nu)$	10.8% (9.3%)
3p0n	$3h^{\pm}\nu$ $(3\pi^{\pm}\nu)$	9.8% (9.0%)

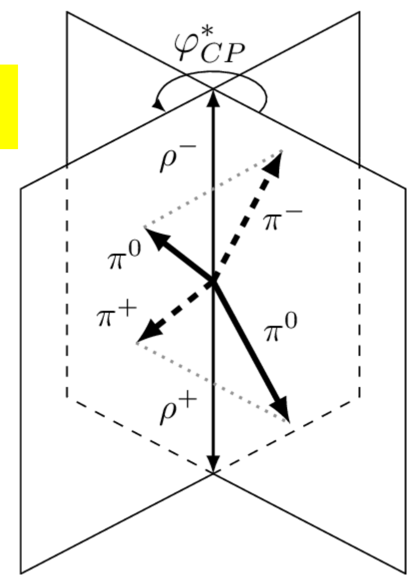
Impact Parameter (IP) method

Rho method

Impact Parameter method

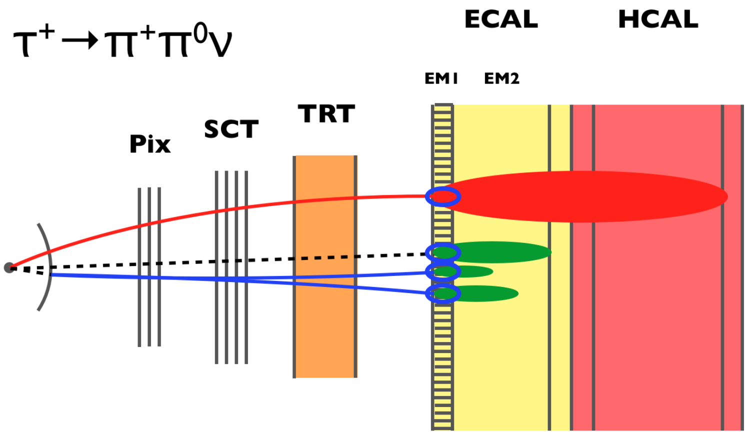


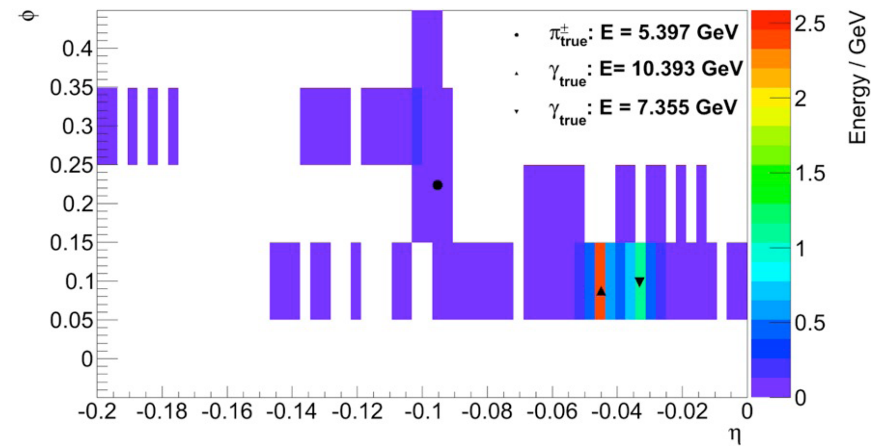
Rho method



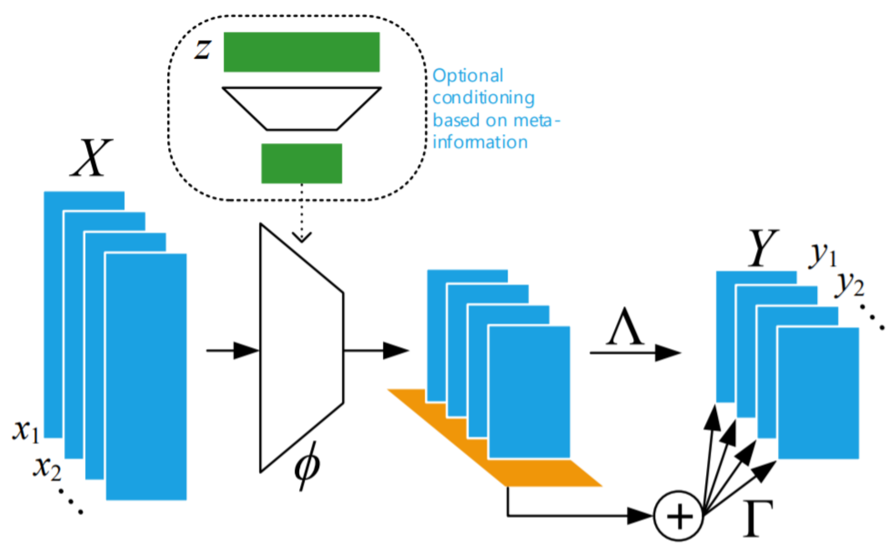
Tau decay mode classification

- Identify π^0 in hadron collider





- Deep NN: Deep Set



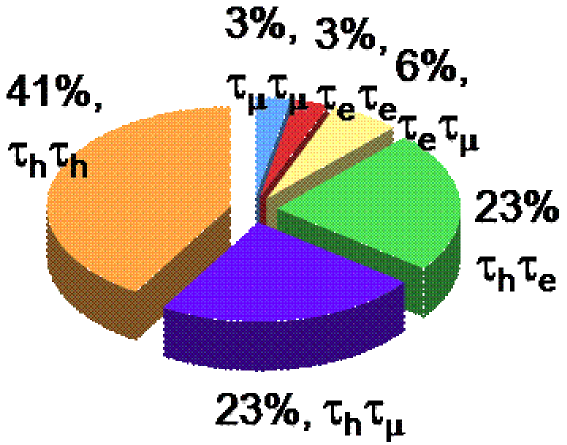
Efficiency migration matrix

ATLAS Simulation Internal — Diagonal: 81.9% Efficiency

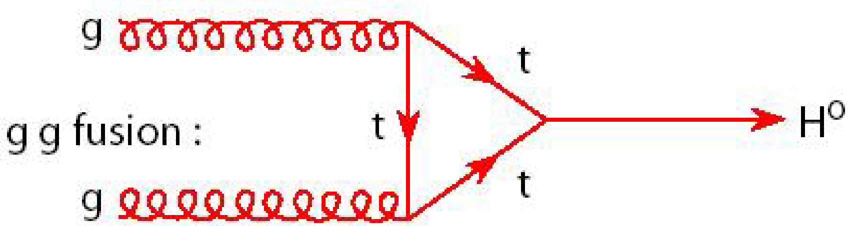
Reco Tau Decay Mode \ True Tau Decay Mode	1p0n	1p1n	1pXn	3p0n	3pXn
3pXn	0.0	0.6	0.5	3.4	68.5
3p0n	0.1	0.1	0.0	93.4	26.2
1pXn	0.6	5.8	56.0	0.1	1.0
1p1n	9.8	85.8	42.0	1.1	3.8
1p0n	89.5	7.8	1.5	2.0	0.4

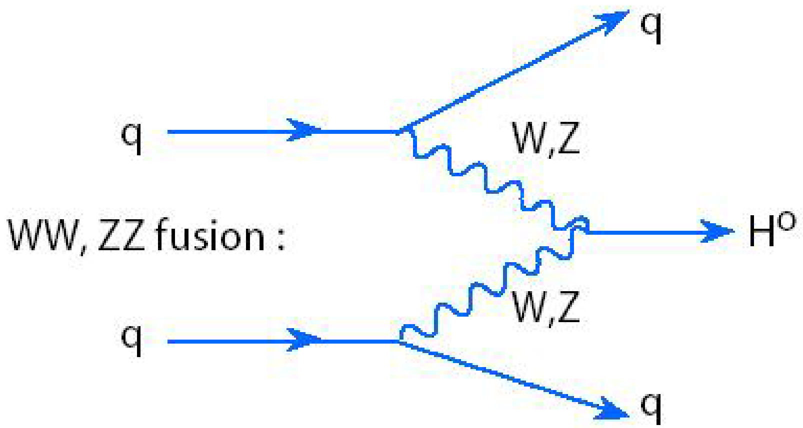
Overview of $H \to \tau\tau$ analysis

- Br($H \to \tau\tau$) $\approx$ 6%
- 2 final states: $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$



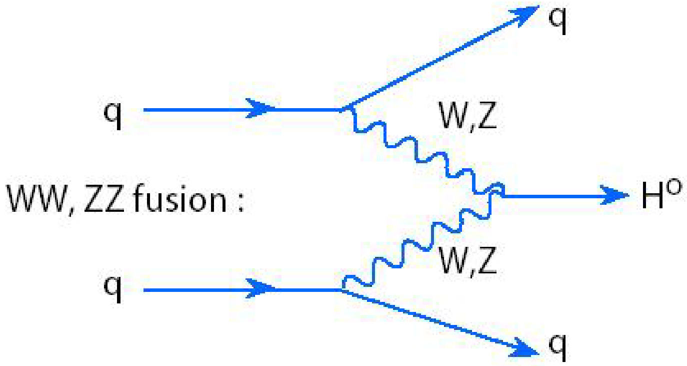
- Production modes: ggF and VBF

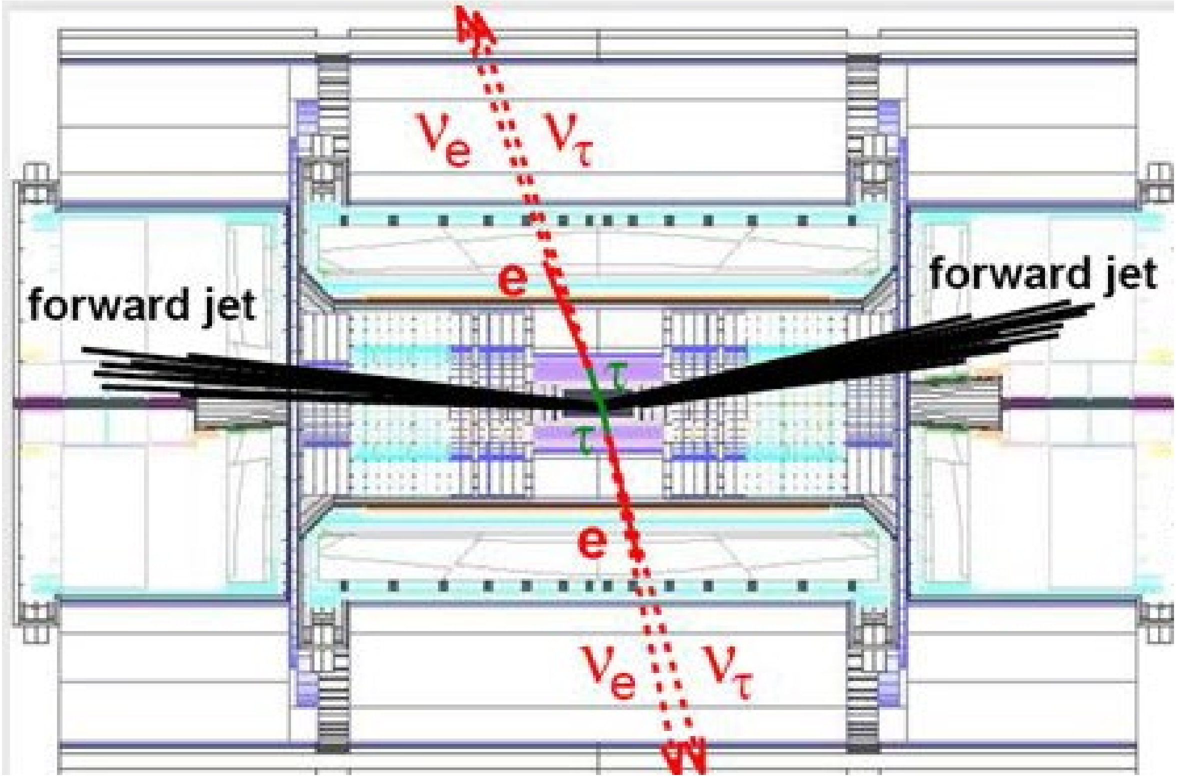




$H \to \tau\tau$: VBF

- VBF: tag two forward high p_T jets
  - High di-jet invariant mass: m_{jj}
  - Large separation: $\Delta\eta_{jj}$

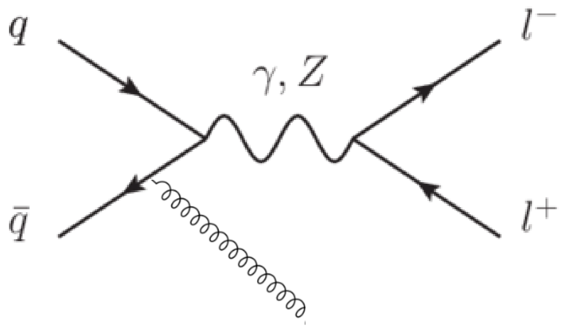


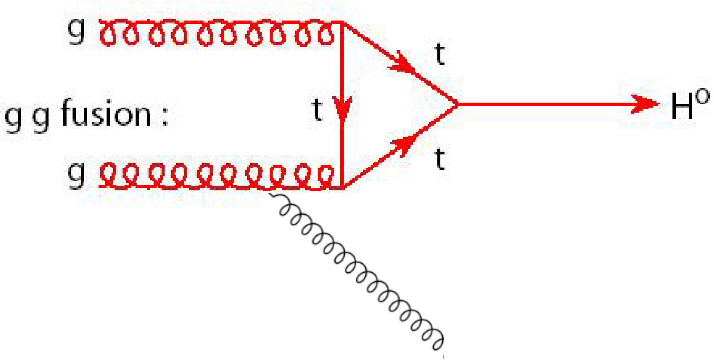


Illustrative Figure

$H \rightarrow \tau\tau$: ggH

- VBF: tag two forward high p_T jets
- ggH: larger color factor than quark initiated $Z \rightarrow \tau\tau$
  - more high p_T gluon radiation





Color factor: $C_g = 3$ v.s. $C_q = 4/3$

Event categorization

- Improve $H \to \tau\tau$ significance

VBF	Boost
$p_T^{j_2} > 30$ GeV $m_{jj} > 400$ GeV $\lvert\Delta\eta_{jj}\rvert > 3.0$ $\eta_{j_1} \cdot \eta_{j_2} < 0$ Central τ-leptons	Not VBF $p_T^{\tau\tau} > 100$ GeV

Signal region ($110 < m_{\tau\tau}^{MMC} < 150$ GeV)			
VBF_1	VBF_0	Boost_1	Boost_0
BDT(VBF) > 0	BDT(VBF) < 0	$\Delta R_{\tau\tau} < 1.5$ and $p_T^{\tau\tau} > 140$ GeV	$\Delta R_{\tau\tau} > 1.5$ or $p_T^{\tau\tau} < 140$ GeV

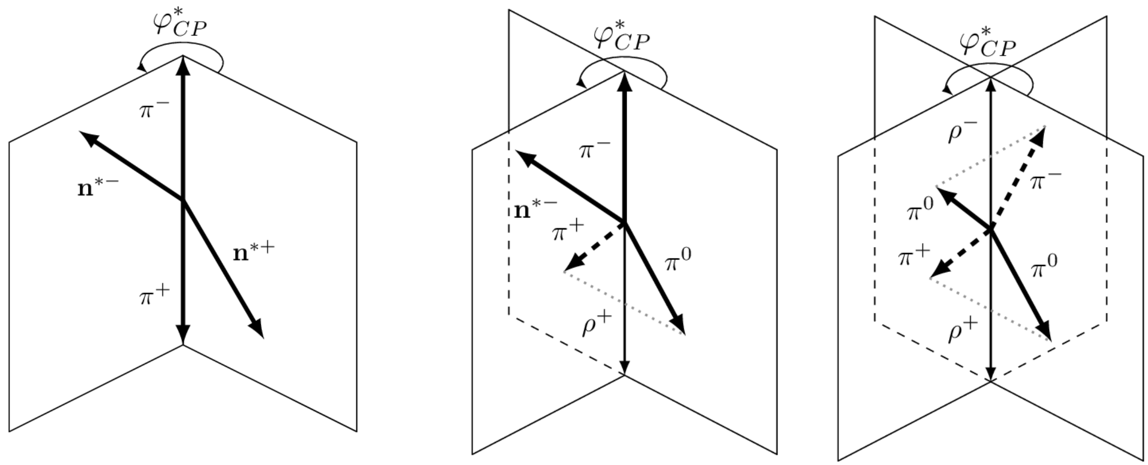
$Z \to \tau\tau$ control regions ($60 < m_{\tau\tau}^{MMC} < 110$ GeV)			
VBF_1 Z CR	VBF_0 Z CR	Boost_1 Z CR	Boost_0 Z CR

CP sensitive observable

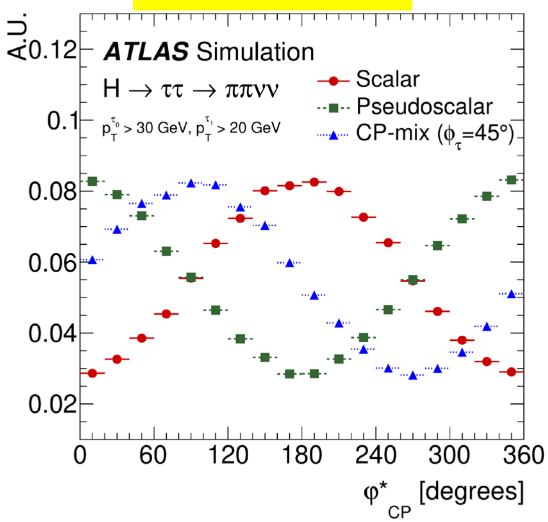
- φ^*_{CP} : angle between two tau decay planes, sensitive to ϕ_τ

  - **Combinations:**

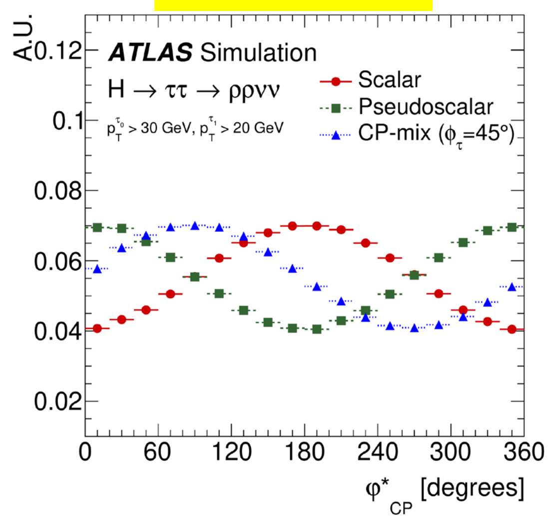
    1p0n–1p0n, ℓ–1p0n,
    1p0n–1p1n, ℓ–1p1n,
    1p1n–1p1n etc.



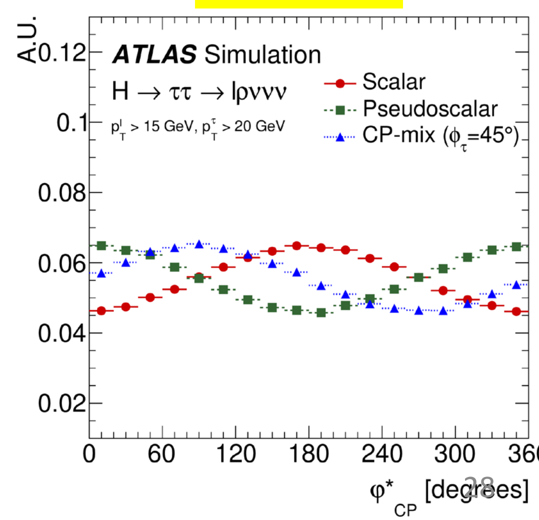
1p0n–1p0n



1p1n–1p1n



ℓ–1p1n



Event categorization

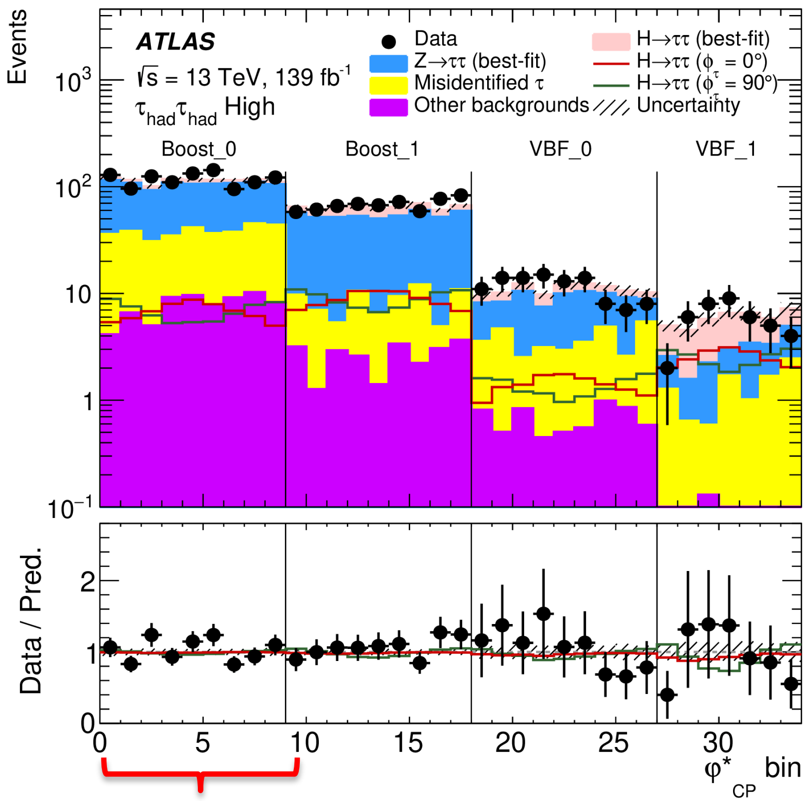
- Improve significance on ϕ_τ
  - Impact Parameter significance: $d_0^{sig} = {}^{d_0}/_{\sigma}$
  - τ spin-analyzing functions: $y_\pm^{\rho/a_1}$ from ρ or $a1$ meson decays

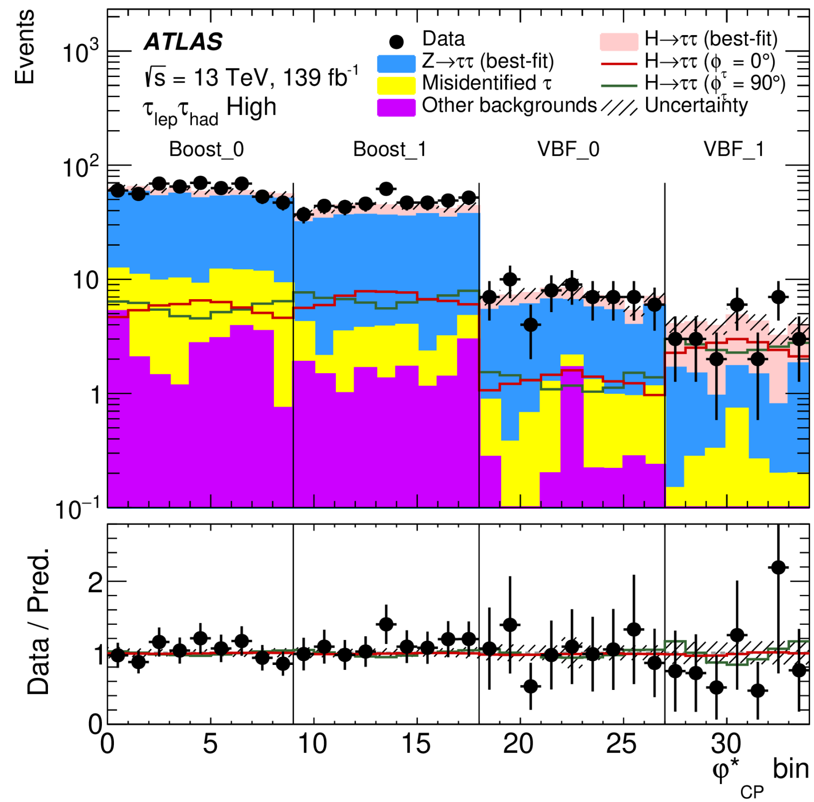
$$y_\pm^\rho = (E_{\pi^\pm} - E_{\pi^0})/(E_{\pi^\pm} + E_{\pi^0}) \qquad y_\pm^{a_1} = \frac{E_{2\pi} - E_{\pi_1^\pm}}{E_{2\pi} + E_{\pi_1^\pm}} - \frac{m_{3\pi}^2 - m_{\pi_1^\pm}^2 + m_{2\pi}^2}{2m_{3\pi}^2}$$

Channel	Signal region	Decay mode combination	Selection criteria
$\tau_{\rm had}\tau_{\rm had}$	High	1p0n–1p0n	$\lvert d_0^{\rm sig}(\tau_1)\rvert > 1.5$ $\lvert d_0^{\rm sig}(\tau_2)\rvert > 1.5$
		1p0n–1p1n	$\lvert d_0^{\rm sig}(\tau_{\rm 1p0n})\rvert > 1.5$ $\lvert y^\rho(\tau_{\rm 1p1n})\rvert > 0.1$
		1p1n–1p1n	$\lvert y^\rho(\tau_1) y^\rho(\tau_2)\rvert > 0.2$
	Medium	1p0n–1pXn	$\lvert d_0^{\rm sig}(\tau_{\rm 1p0n})\rvert > 1.5$ $\lvert y^\rho(\tau_{\rm 1pXn})\rvert > 0.1$
		1p1n–1pXn	$\lvert y^\rho(\tau_{\rm 1p1n}) y^\rho(\tau_{\rm 1pXn})\rvert > 0.2$
		1p1n–3p0n	$\lvert y^\rho(\tau_{\rm 1p1n})\rvert > 0.1$ $\lvert y^{a_1}(\tau_{\rm 3p0n})\rvert > 0.6$
	Low	All above	Not satisfying selection criteria

CP structure of H→ττ coupling

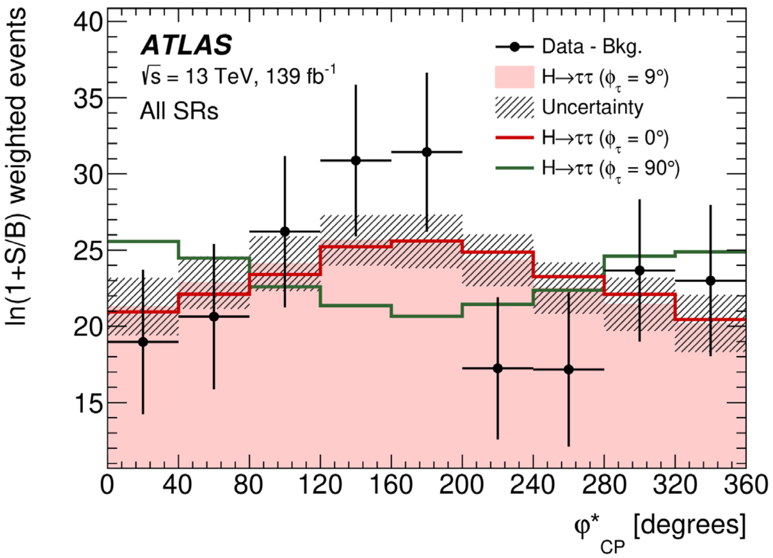
- Analysis strategy:
  - Simultaneous fit on φ^*_{CP} to extract the CP mixing angle

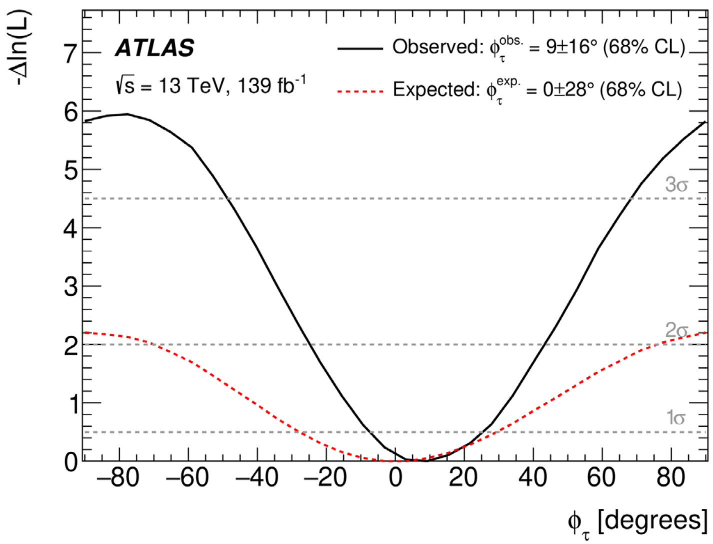




φ^*_{CP} distribution

CP structure of H→ττ coupling





- Observed (expected) $\phi_\tau \approx 9° \pm 16°$ ($0° \pm 28°$) at the 68% CL
  - Results compatible with SM expectation within uncertainties
  - Excluded pure CP-odd state at 3.4σ significance

Summary

- CP violation is one of the most interesting and profound topics in particle physics, where Higgs sector is a new field to look into
- Two new results from ATLAS experiment presented
  - for CP in the Higgs coupling to vector bosons and fermions.
  - New techniques: decay plane building, Optimal Observable (Matrix Element method), MVA method widely used in CPV
- Diverse theoretical frameworks: EFT based, Amplitude, etc.
- Both analyses still statistically limited. More data in Run 3 will definitely help

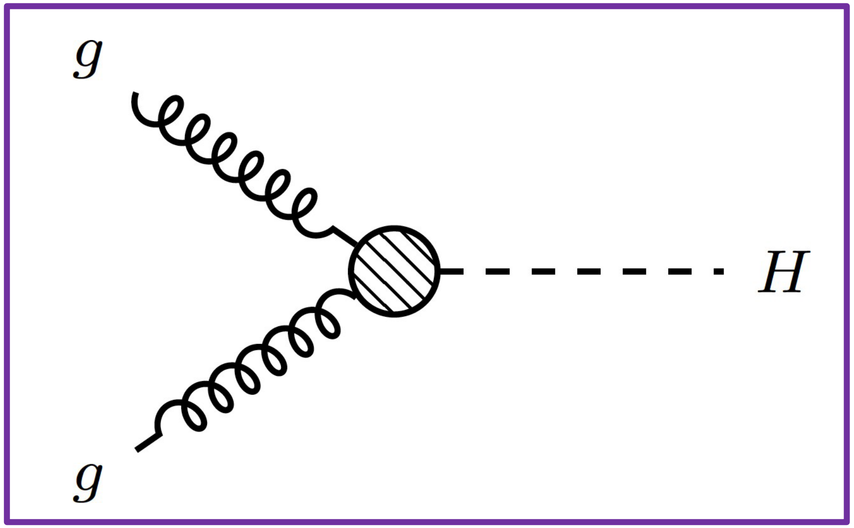
Backup

Study HVV CP in H→ZZ decay

- Parameterize in terms of cross section fractions, f_{ai}
- For the V=W,Z,

$$f_{ai} = \frac{|a_i|^2 \sigma_i}{|a_1|^2 \sigma_1 + |a_2|^2 \sigma_2 + |a_3|^2 \sigma_3 + |\kappa_1|^2 \sigma_{\Lambda 1} + |\kappa_1^{Z\gamma}|^2 \sigma_{\Lambda 1}^{Z\gamma}} \operatorname{sgn}\left(\frac{a_i}{a_1}\right)$$

- Four fractions: f_{a2}, f_{a3}, $f_{\Lambda 1}$, and $f_{\Lambda 1}^{Z\gamma}$


g
g
H

Studies of ggH vertex in H→WW

CP properties of the Higgs boson in the effective Higgs – gluon coupling

- Production mode: ggH
    - In the large top quark mass limit: the CP structure of the top-quark Yukawa coupling is inherited by the effective Higgs – gluon interaction
    - Assumption: SM-like HVV coupling

- Theoretical framework: EFT with Higgs Characterization

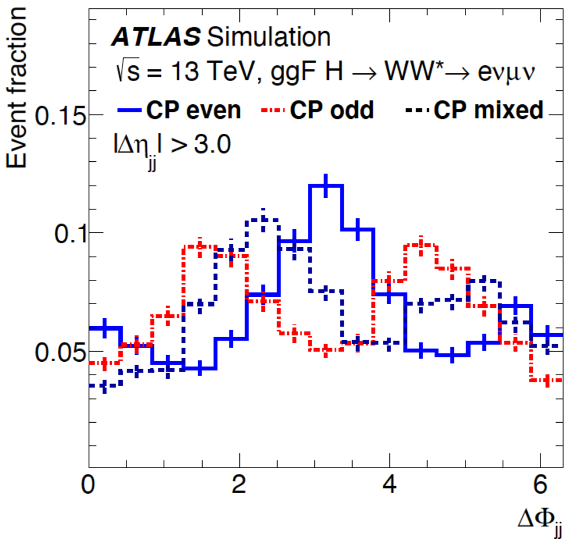
$$\mathcal{L}_0^{\text{loop}} = -\frac{g_{Hgg}}{4}\left(\kappa_{gg}\cos(\alpha)G^a_{\mu\nu}G^{a,\mu\nu} + \kappa_{gg}\sin(\alpha)G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right)H$$

Effective coupling   CP-mixing angle

- Target: constrain the CP-mixing angle α
- Sensitive observable: signed-$\Delta\phi_{jj}$

Signed difference in ϕ of the leading and subleading jets for events with at least two jets

- Shape sensitive to CP effects



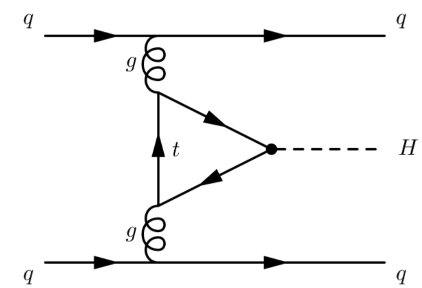
CP – even: κ_{gg} = 1 ; cos(α) = 1

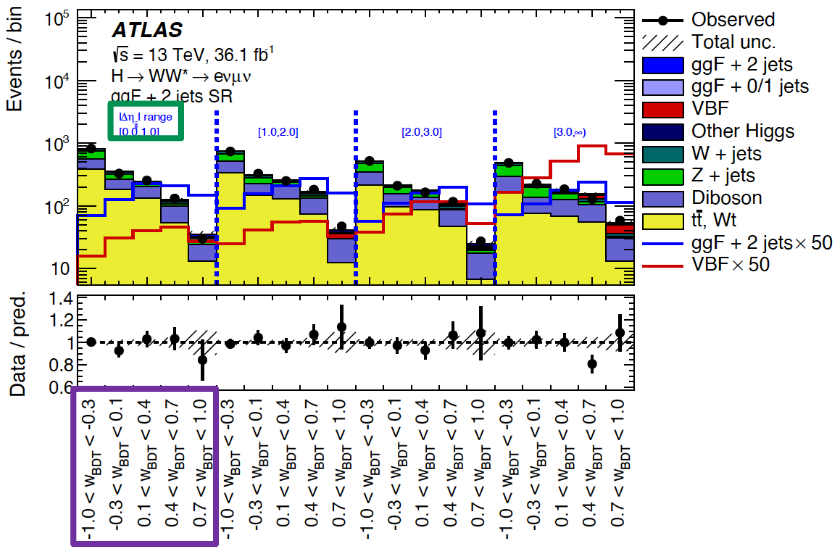
CP – odd: κ_{gg} = 1 ; cos(α) = 0

CP – mixed: κ_{gg} = 1 ; cos(α) = 1/√2

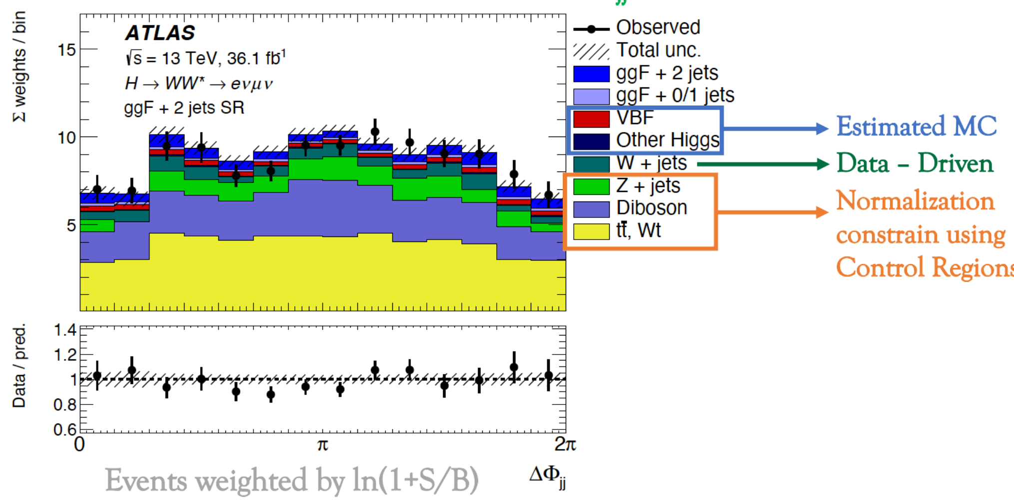
Studies of ggH vertex in H→WW

- Select ggF +2 jets events
- BDT to discriminate H→WW signal from the main backgrounds
- Build 12 categories in the 2D space BDT vs $\Delta\eta_{jj}$
  - BDT score split: maximize the signal/bkg ratio
  - $\Delta\eta_{jj}$ split: separation between different CP hypotheses for $\Delta\phi_{jj}$ increase at high $\Delta\eta_{jj}$
  - Perform a fit on signed-$\Delta\phi_{jj}$





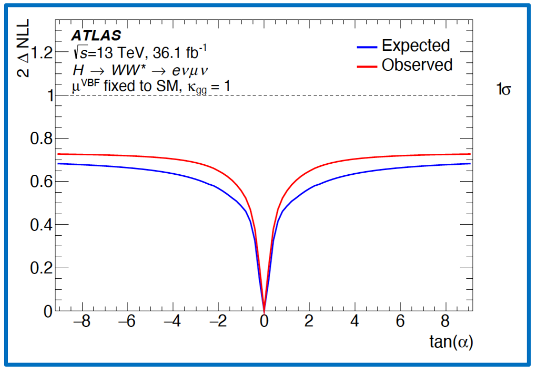
Post – fit distribution of signed-$\Delta\phi_{jj}$



arXiv:2109.13808v1

Studies of ggH vertex in H→WW

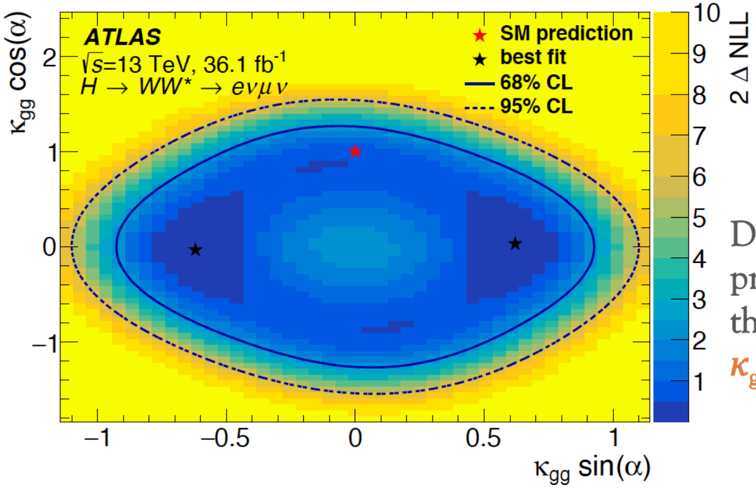
- Perform a fit on signed-$\Delta\phi_{jj}$
  - Two approaches:
    - Exploits only shape information: best isolation of CP-dependence
      - Lower sensitivity → does not reach 1σ confidence level



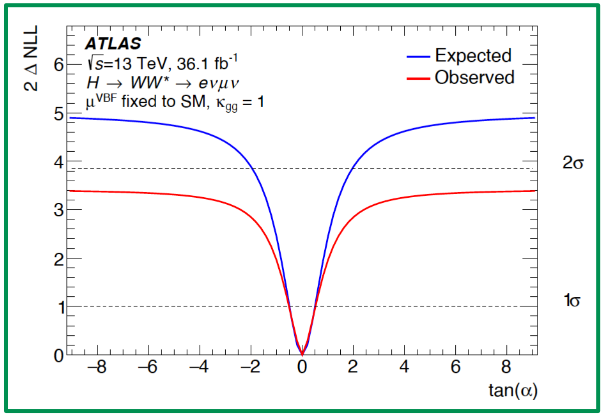
    - Both shape and rate are considered: best sensitivity
      - Observed sensitivity worse than the expected → signal strength of the ggF + 2 jets process lower then expected:

$\mu^{ggF+2j} = 0.5 \pm 0.4\,(\text{stat.})^{+0.7}_{-0.6}\,(\text{syst.})$

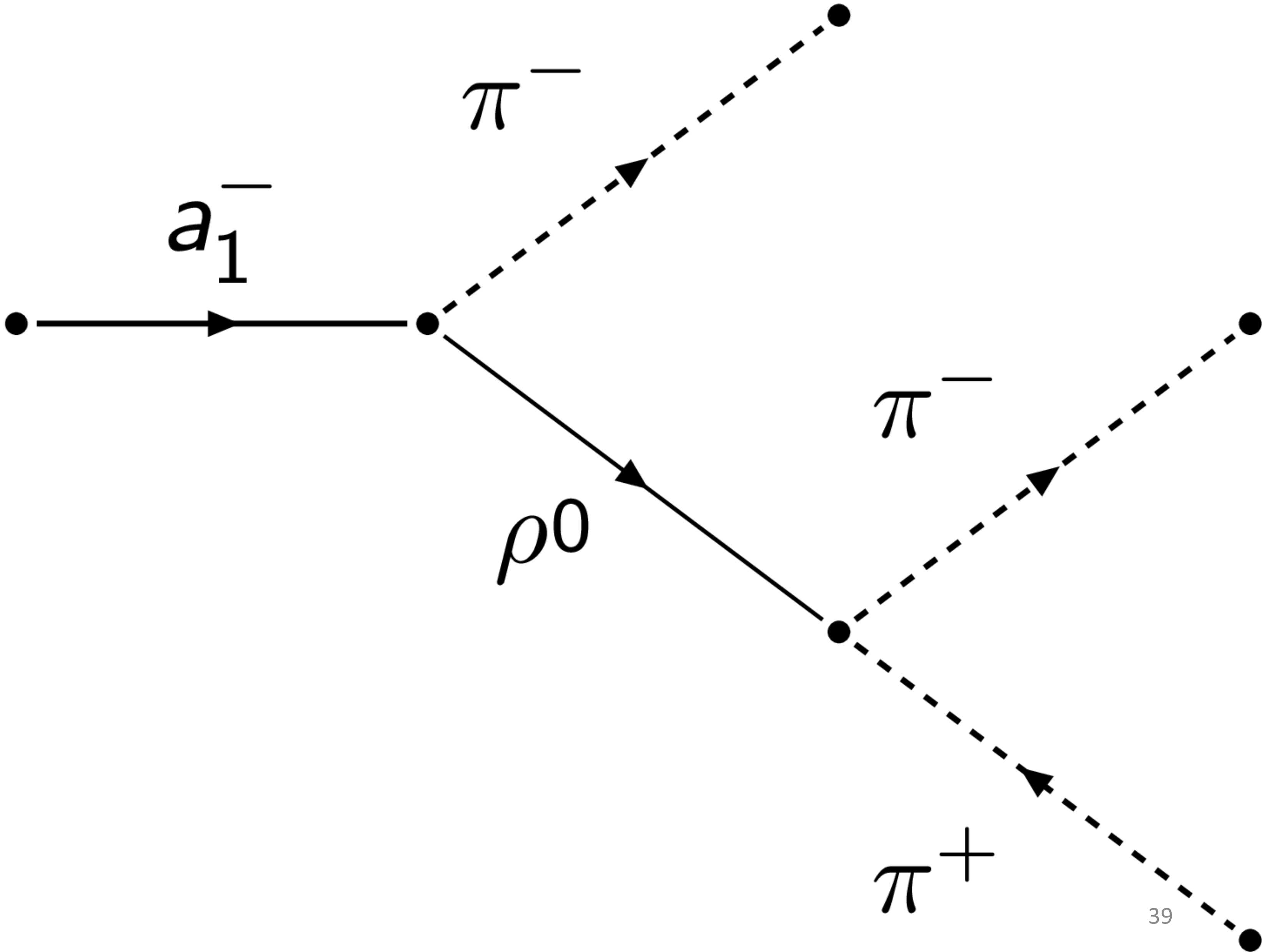
- Simultaneous fit of the coupling strength scale factors



Data consistent with SM prediction within 1σ and the excluded limit $\kappa_{gg}\cos(\alpha)$ vs. $\kappa_{gg}\sin(\alpha)$ at 2σ



$\tan(\alpha) = 0.0 \pm 0.4\,(\text{stat.}) \pm 0.3\,(\text{syst.})$


π^-
a_1^-
π^-
$\rho 0$
π^+

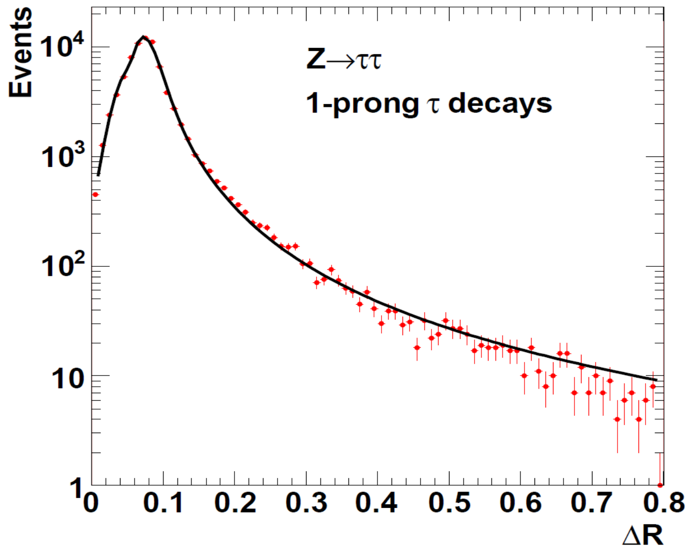
Reconstruct di-tau mass

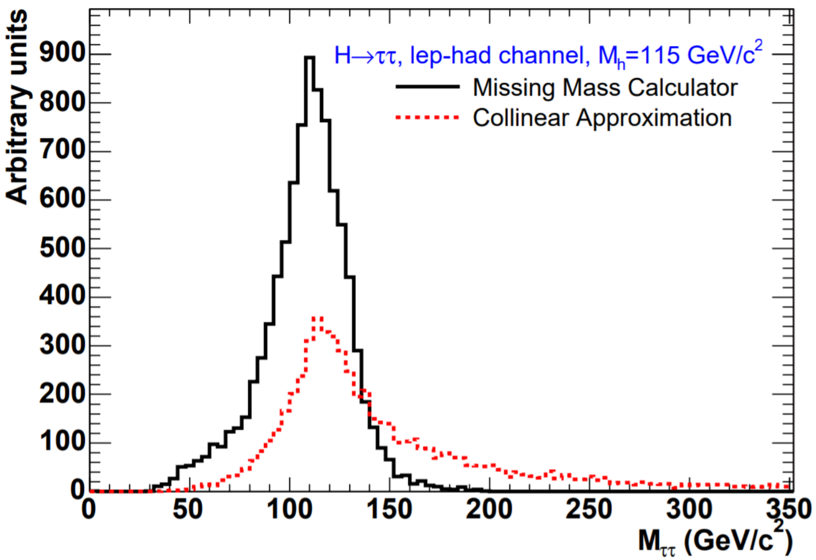
- Likelihood based method to recover neutrinos
  - Simulate kinematics: $\mathrm{Prob}(\Delta R, p_\tau)$
  - Include measured information

$$\mathcal{P}(\not{E}_{\mathrm{T}\,x,y}) = \exp\left(-\frac{(\Delta \not{E}_{\mathrm{T}\,x,y})^2}{2\sigma^2}\right)$$

- Final LLH

$$\mathcal{L} = -\log\left(\mathcal{P}(\Delta R_1, p_{\tau 1}) \times \mathcal{P}(\Delta R_2, p_{\tau 2}) \times \mathcal{P}(\Delta \not{E}_{\mathrm{T}\,x}) \times \mathcal{P}(\Delta \not{E}_{\mathrm{T}\,y})\right)$$





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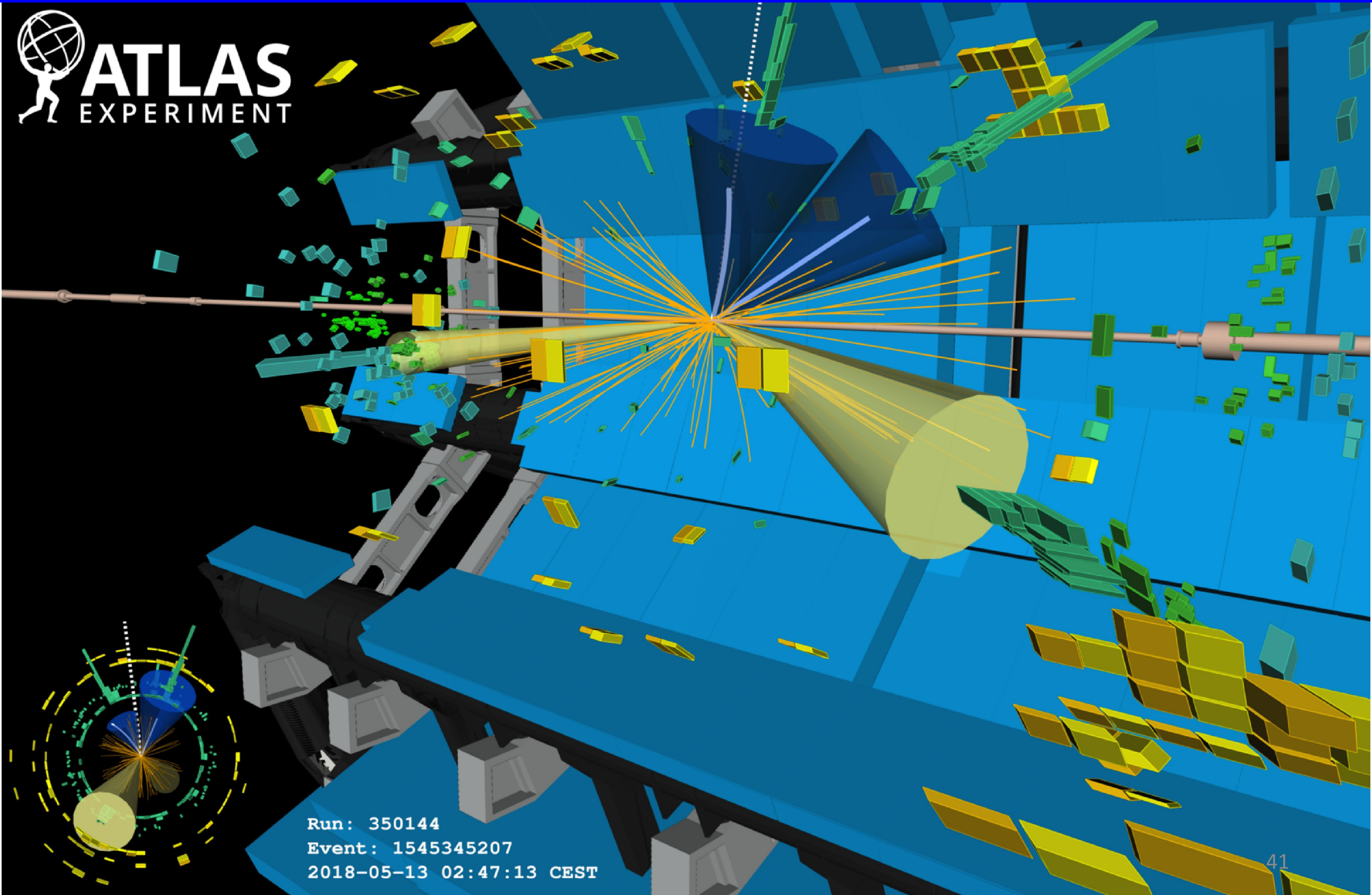
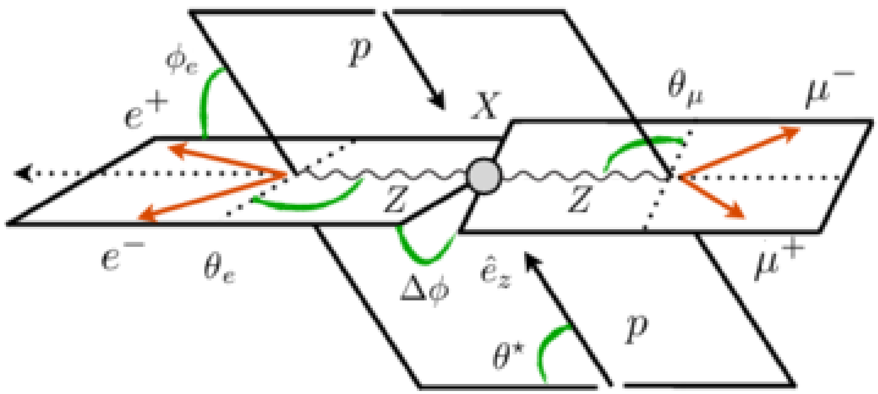
CP structure of H→ττ coupling



HVV CP in H→ZZ



As already mentioned above, we analyze all major 1- and 3-prong tau decay modes:

$$\tau \to l + \nu_l + \nu_\tau\,, \tag{3}$$

$$\tau \to a_1 + \nu_\tau \to \pi + 2\pi^0 + \nu_\tau\,, \tag{4}$$

$$\tau \to a_1^{L,T} + \nu_\tau \to 2\pi^\pm + \pi^\mp + \nu_\tau\,, \tag{5}$$

$$\tau \to \rho + \nu_\tau \to \pi + \pi^0 + \nu_\tau\,, \tag{6}$$

$$\tau \to \pi + \nu_\tau\,. \tag{7}$$

We call the decay mode $\tau \to a_1^{L,T} + \nu_\tau$ in (5) also '1-prong', because the 4-momentum of $a_1^\pm$ can be obtained from the measured 4-momenta of the 3 charged pions. The longitudinal (L) and transverse (T) helicity states of the a_1 resonance can be separated by using known kinematic distributions [22–25].