Search for CP violation in Higgs sector at LHC

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Why CPV interesting?

- Baryon genesis: why more matter than anti-matter?
- Sakharov's conditions
  1. Baryon number violation
  2. C and CP violations
  3. Departure from the equilibrium

Why CPV interesting?

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

- Sakharov's conditions

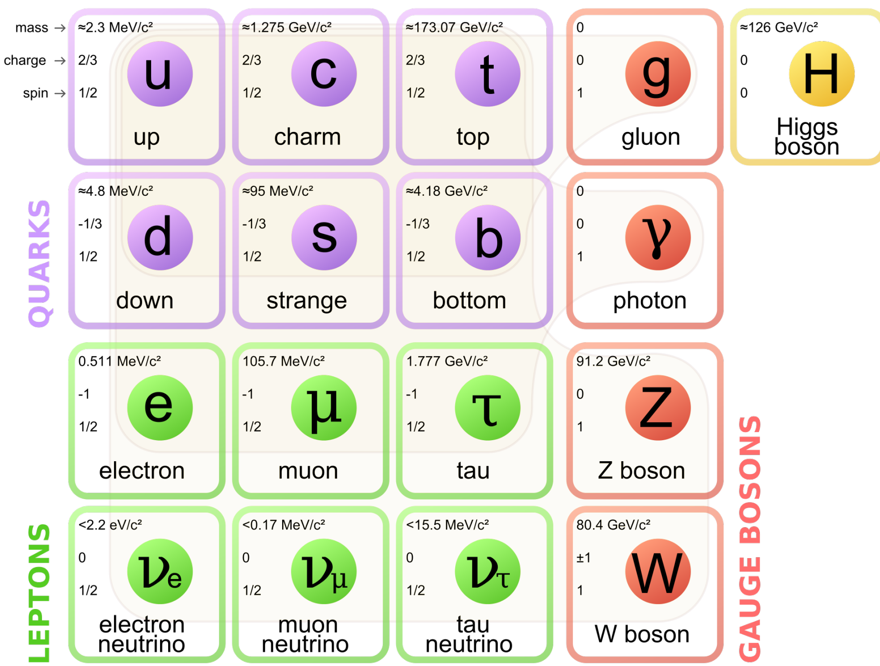
Sakharov's conditions	Standard Model
1. Baryon number violation	✓
2. C and CP violations	✗
3. Departure from the equilibrium	✗

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



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

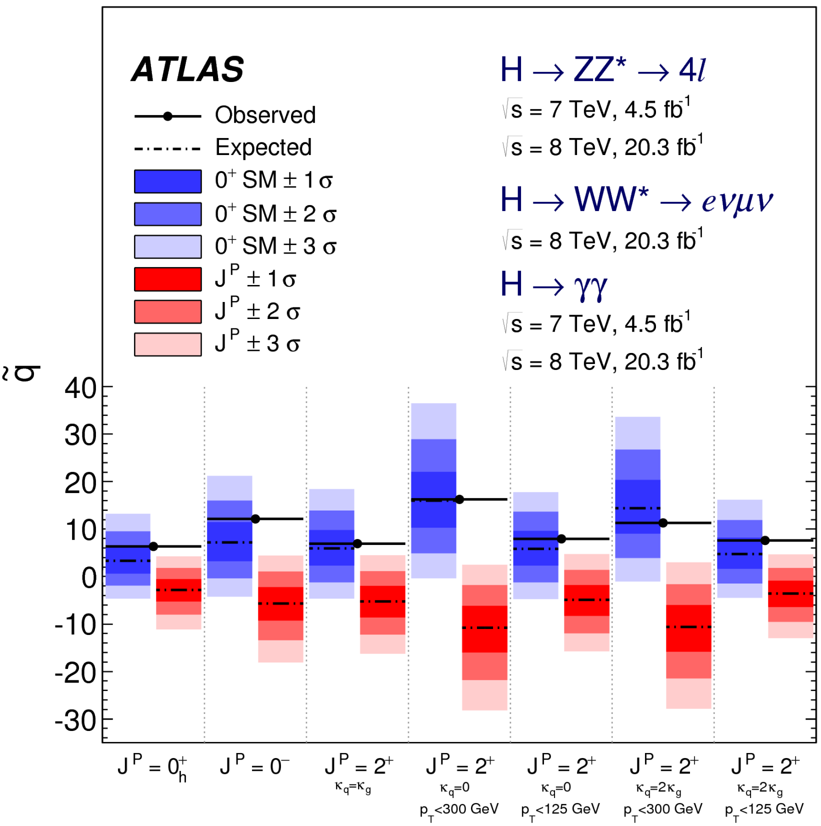
Higgs boson open the door

- 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

Higgs boson open the door

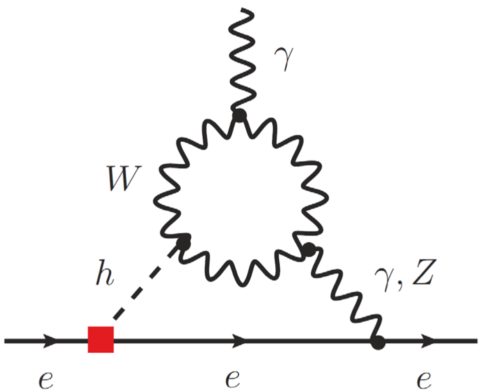
- Higgs boson is found a CP-even scalar, as SM prediction
  - $J^P=0^+$ compared with alternative spin-model

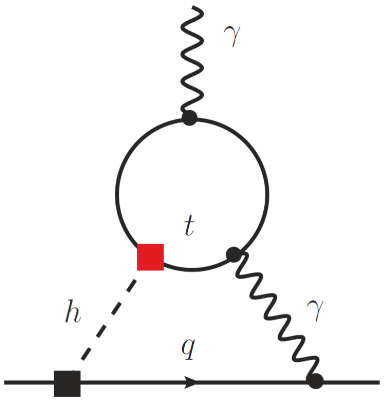


- But, mixing between CP-even and CP-odd is still allowed, which could lead to CP violation

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

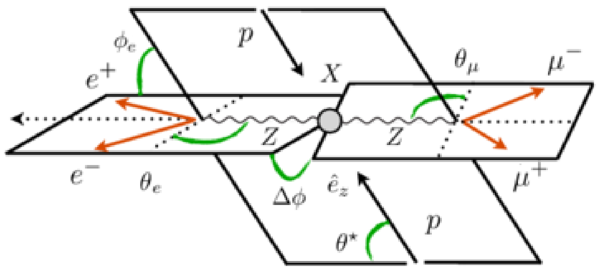
$$|\tilde{\kappa}_e| \lesssim 1.7 \times 10^{-2}$$
$$|\tilde{\kappa}_t| \lesssim 1.0 \times 10^{-2}$$

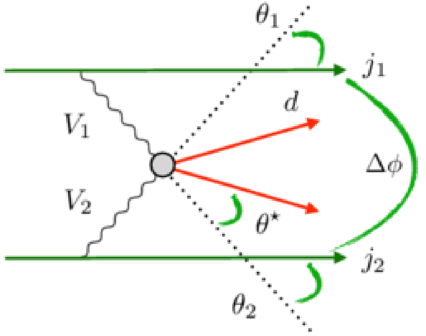
- But, very model dependent
  - Gauge-dependent contributions, UV-divergent diagrams

CP violation in Higgs sector

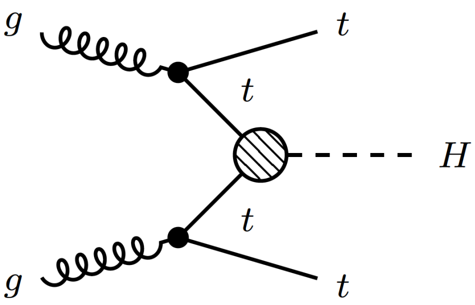
- General methodology:
  - using event topology to build some CP sensitive angle

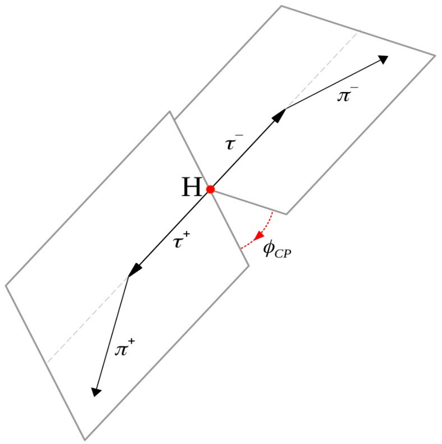
Higgs coupling to vector bosons (HVV)





Higgs coupling to fermions (Yukawa coupling: Hff)





- Via gluon-gluon fusion loop (not fucus of this talk)

Outline

- **CP structure in Higgs-Vector boson coupling**
  - **$H \rightarrow ZZ \rightarrow 4l$, Vector Boson Fusion (VBF)**
- **CP structure in Higgs-fermion Yukawa coupling**
  - **to quark: ttH, to lepton: $H \rightarrow \tau^+\tau^-$**

This talk only focus some direct searches

Contributions from LHC-China

- **CP structure in Higgs-Vector boson coupling**
    - $H \to ZZ \to 4l$, Vector Boson Fusion (VBF)

LZ, 方亚泉，刘波 in IHEP: VBF $H \to \gamma\gamma$ at ATLAS (in progress)

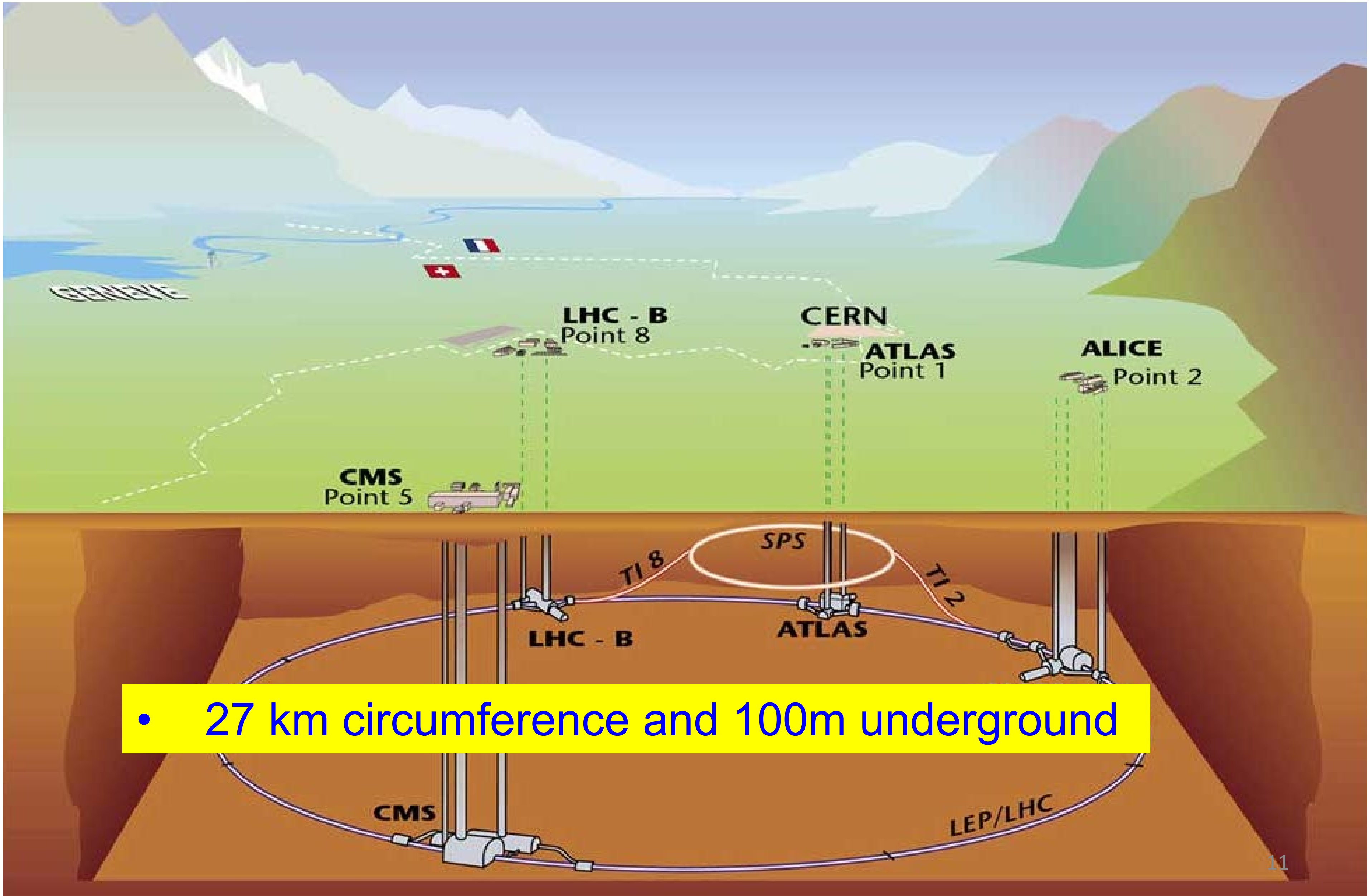
- **CP structure in Higgs-fermion Yukawa coupling**
    - to quark: ttH, to lepton: $H \to \tau^+\tau^-$

LZ: $H \to \tau^+\tau^-$ at ATLAS (in progress)

杨洪洮, USTC (at ATLAS)

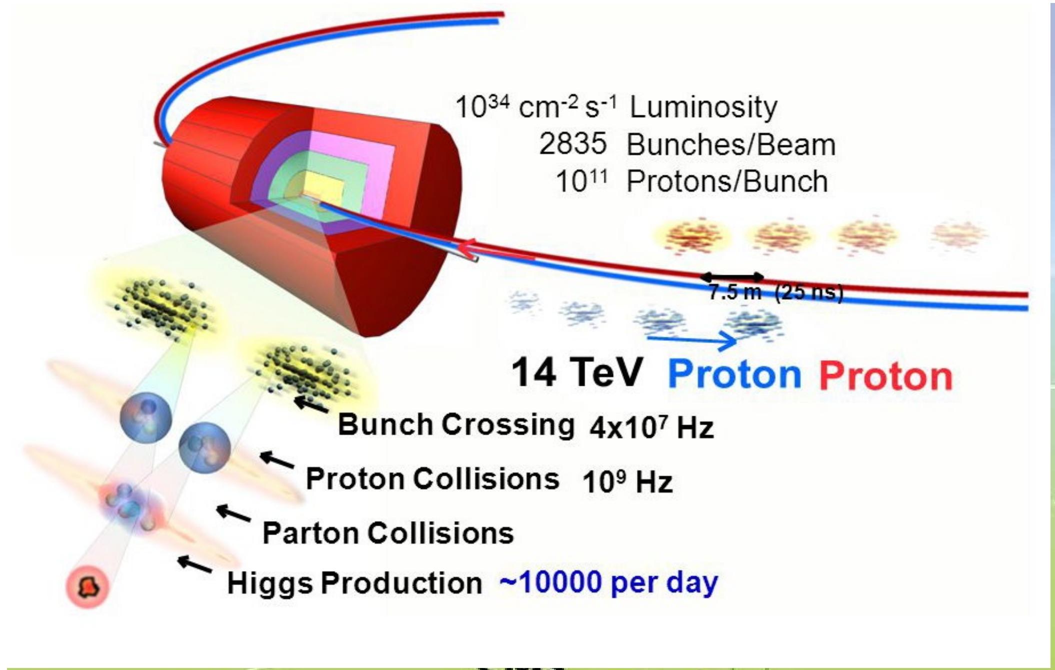
肖朦, ZJU (at CMS)

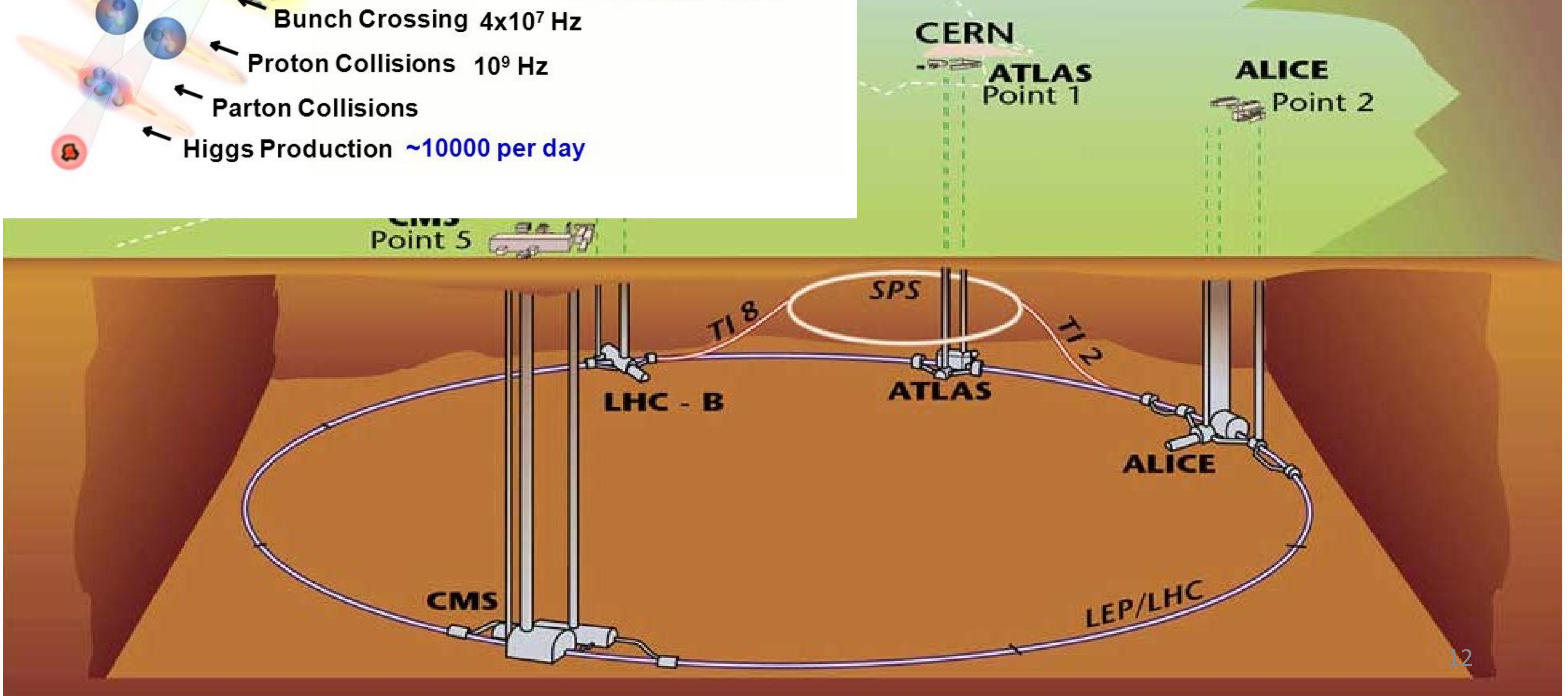
Large Hadron Collider (LHC)



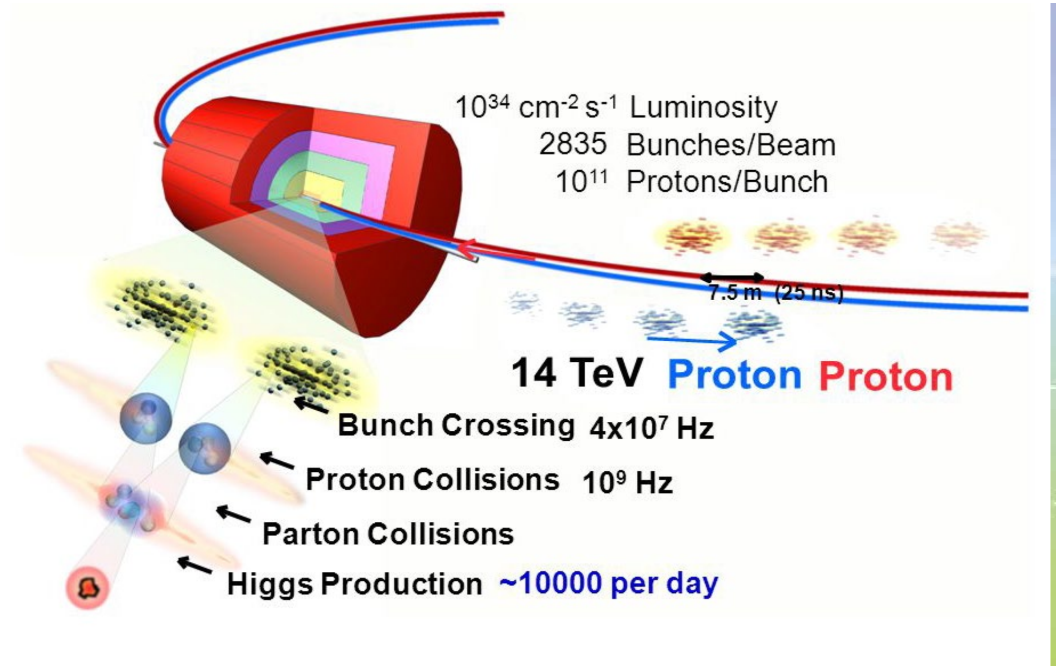
- 27 km circumference and 100m underground

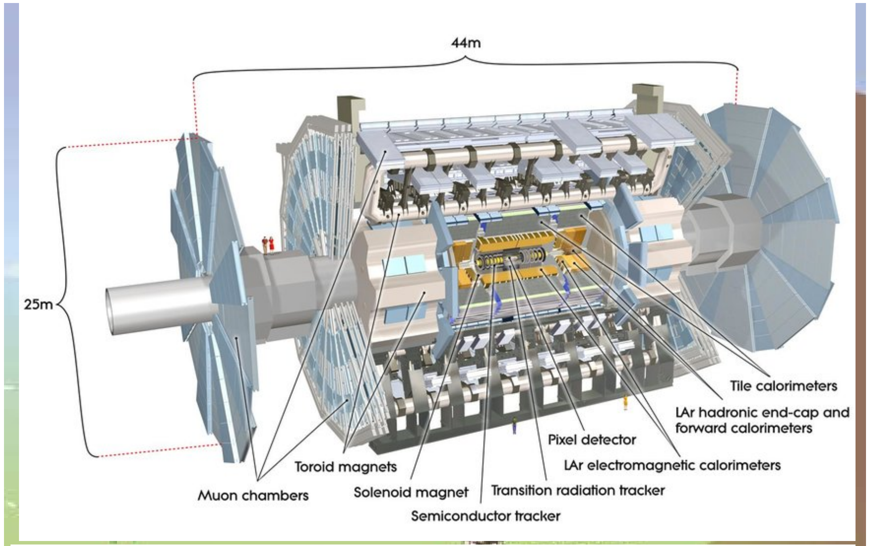
Large Hadron Collider (LHC)

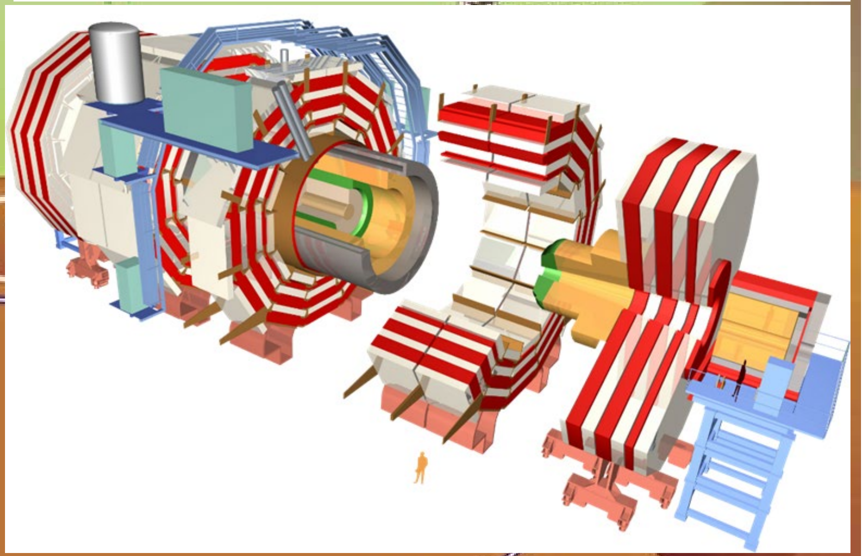


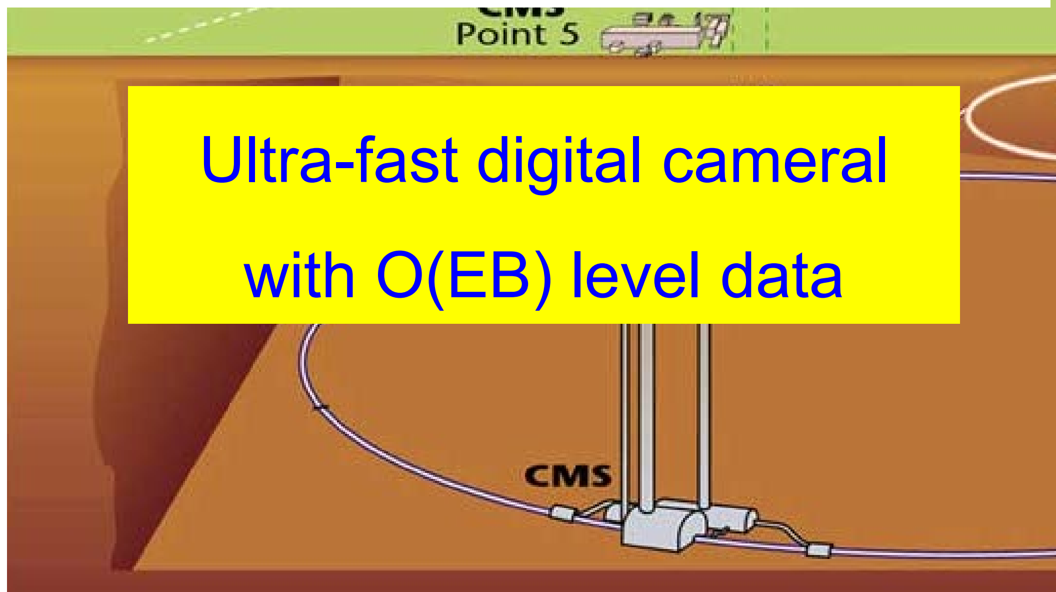


Large Hadron Collider (LHC)





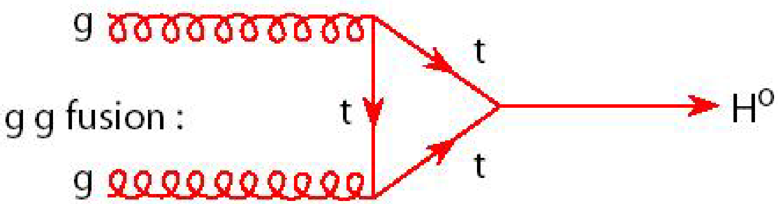


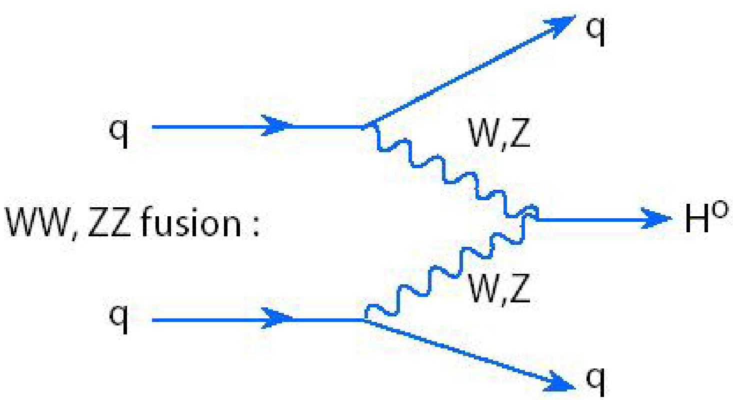


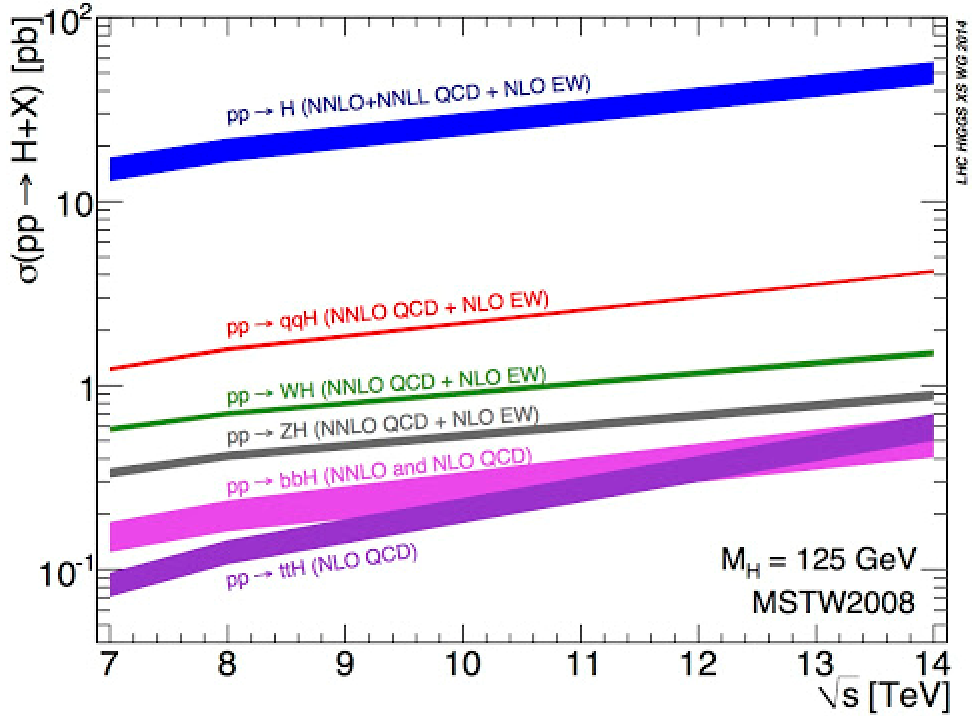
Ultra-fast digital cameral

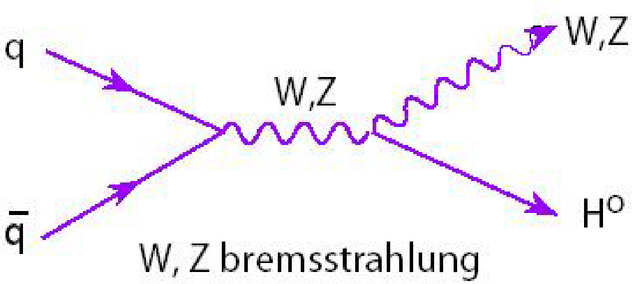
with O(EB) level data

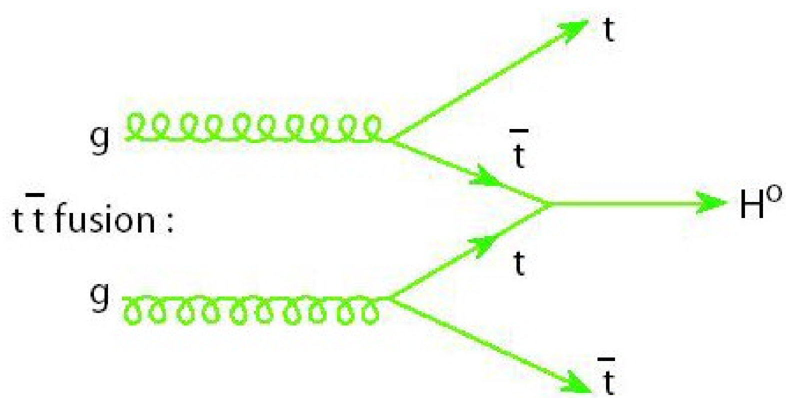
Higgs production at LHC



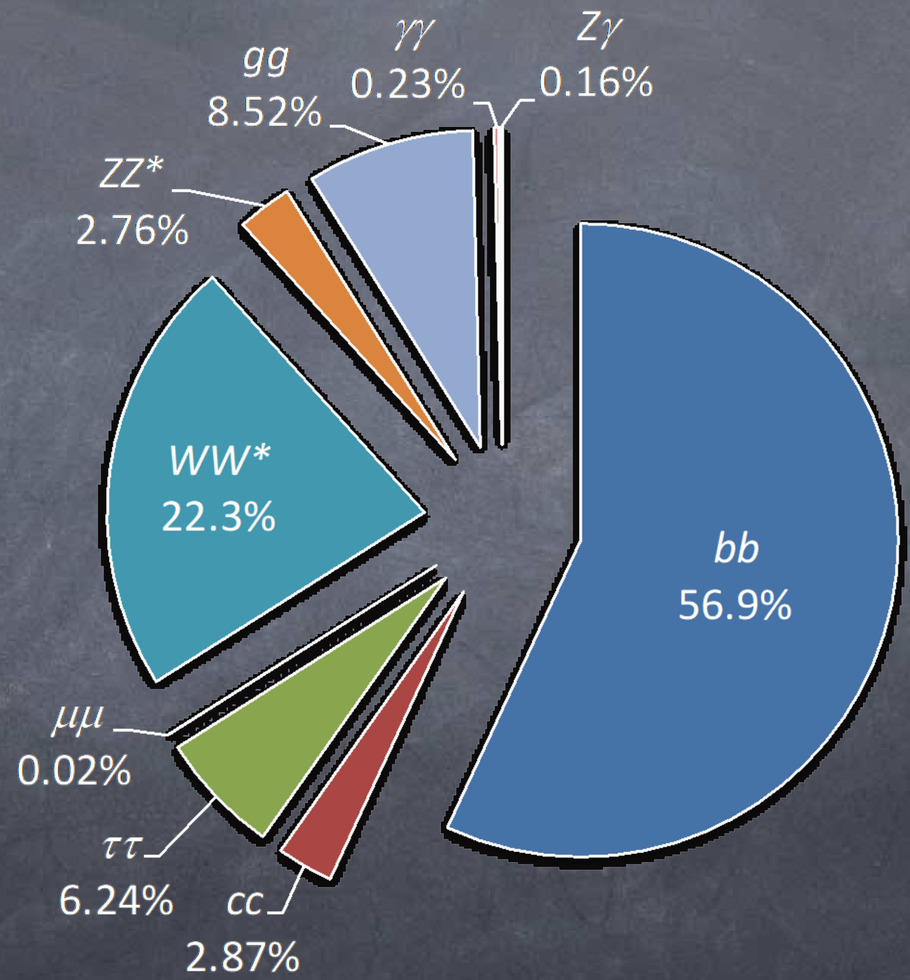




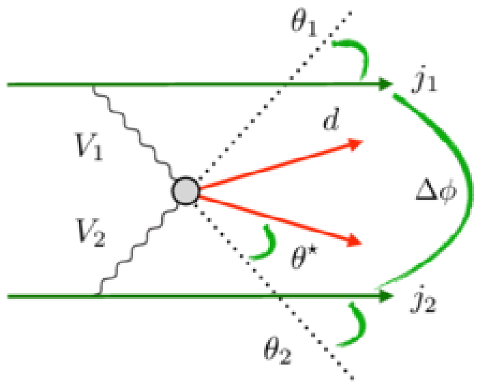




Higgs boson decays



Study HVV CP in VBF production



- HVV vertex in VBF Higgs production
- Independent from Higgs decay
  - Use H→ττ (H→γγ in progress), assume SM Br
- HISZ EFT basis implemented in HAWK
  - After EW symmetry breaking

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

$$\tilde{g}_{HAA} = \frac{g}{2m_W}(\tilde{d}\sin^2\theta_W + \tilde{d}_B\cos^2\theta_W)$$
$$\tilde{g}_{HAZ} = \frac{g}{2m_W}\sin 2\theta_W(\tilde{d} - \tilde{d}_B)$$
$$\tilde{g}_{HZZ} = \frac{g}{2m_W}(\tilde{d}\cos^2\theta_W + \tilde{d}_B\sin^2\theta_W)$$
$$\tilde{g}_{HWW} = \frac{g}{m_W}\tilde{d},$$

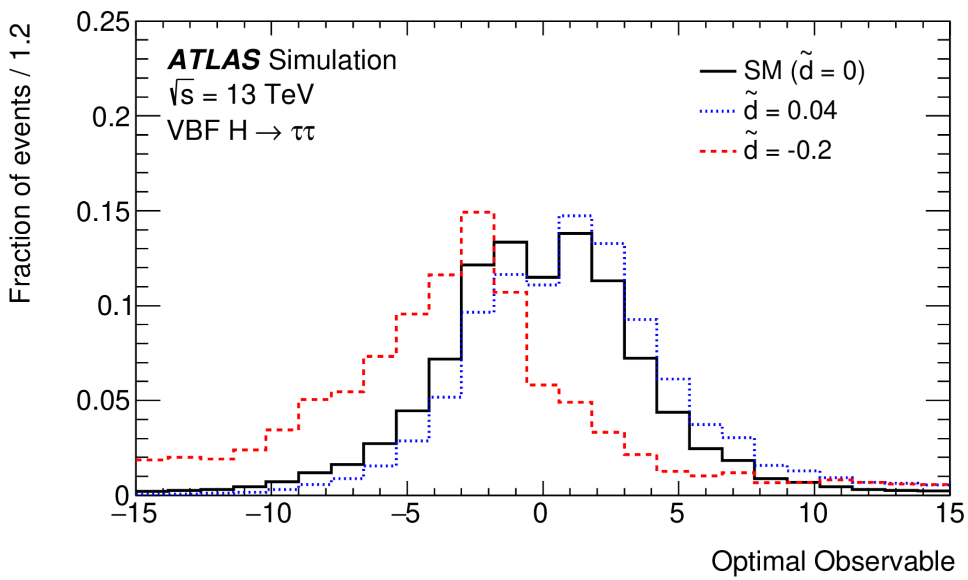
  - Assumption: $\tilde{d} = \tilde{d}_B$

Study HVV CP in VBF production

- Analysis strategy: to constrain $\tilde{d}$
  - Build CP sensitive observable **Optimal Observable**
  - Using ME calculated in HAWK, combining kinematics information of VBF jets and Higgs into a single observable

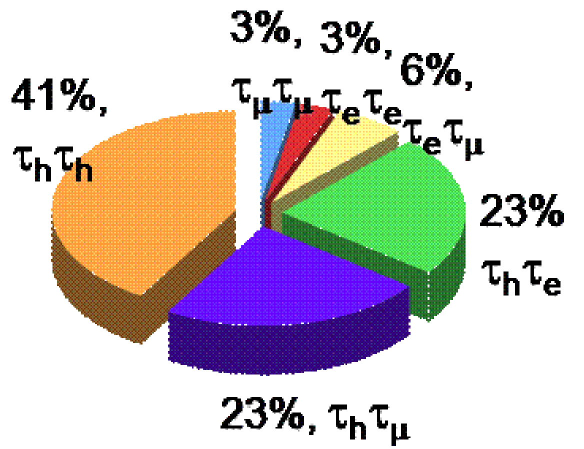
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{d} \cdot 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{CP\text{-}odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\mathrm{CP\text{-}odd}}|^2$$

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

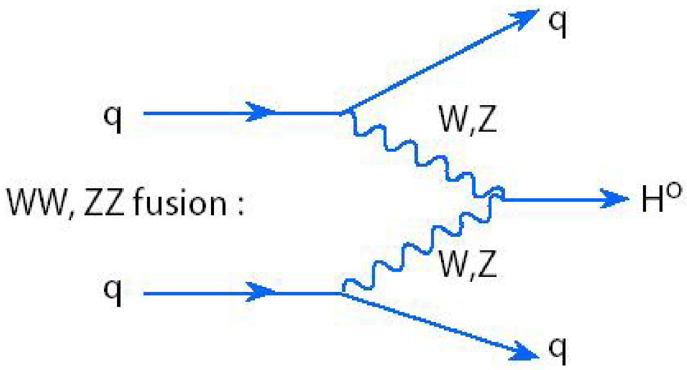


$H\rightarrow\tau\tau$: overview

- Branching fraction: ≈ 6%
- 3 final states:
  - $\tau_{lep}\tau_{lep}$, $\tau_{lep}\tau_{had}$, $\tau_{had}\tau_{had}$

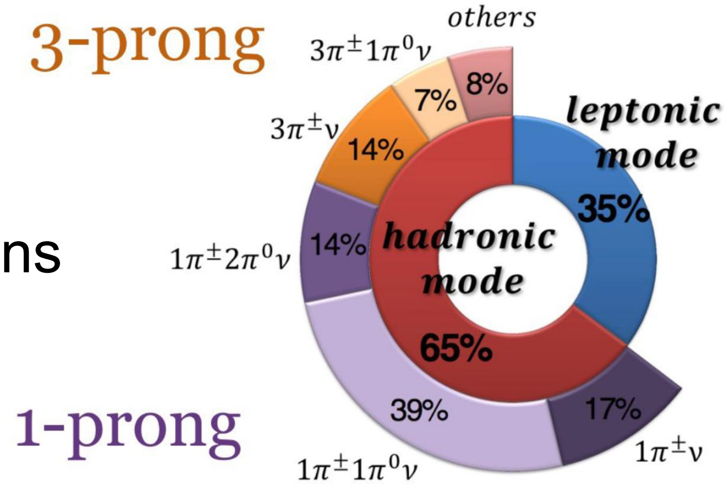


- VBF: tag two forward high pT jets
  - High di-jet invariant mass: m_{jj}
  - Large separation: $\Delta\eta_{jj}$

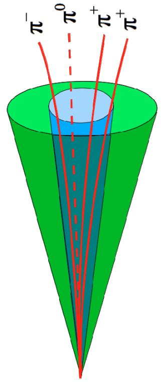


How to detect tau lepton

- Tau lepton
  - Heaviest lepton: 1.777 GeV
  - Decay length: ct ≈ 87 μm
  - ~ 35% to e or μ, ~ 65% to hadrons

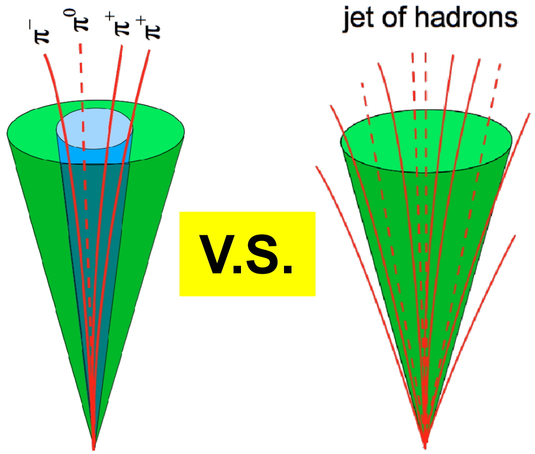


- Experimental signature
  - Tau decay to e or μ looks like prompt e or μ
  - τ_{had} has a narrower energy deposit at calorimeter

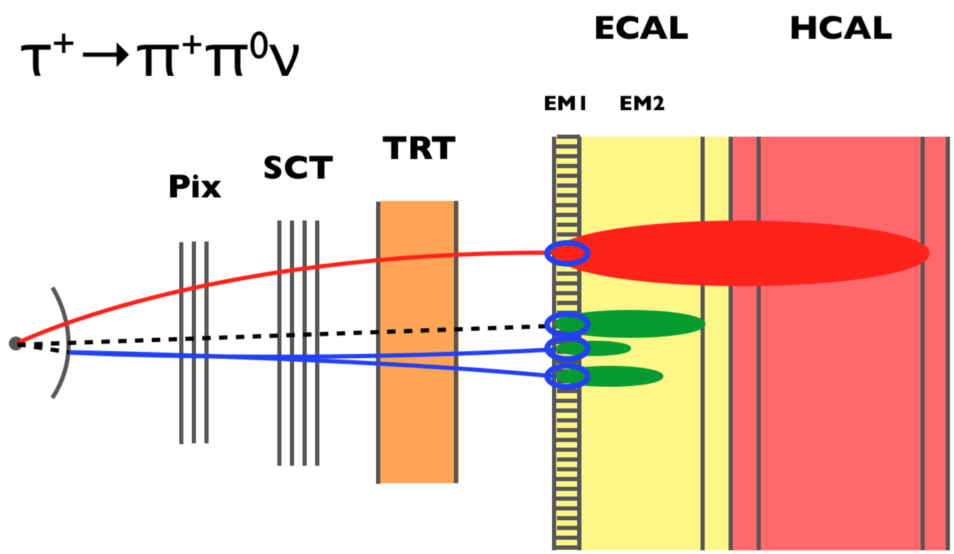


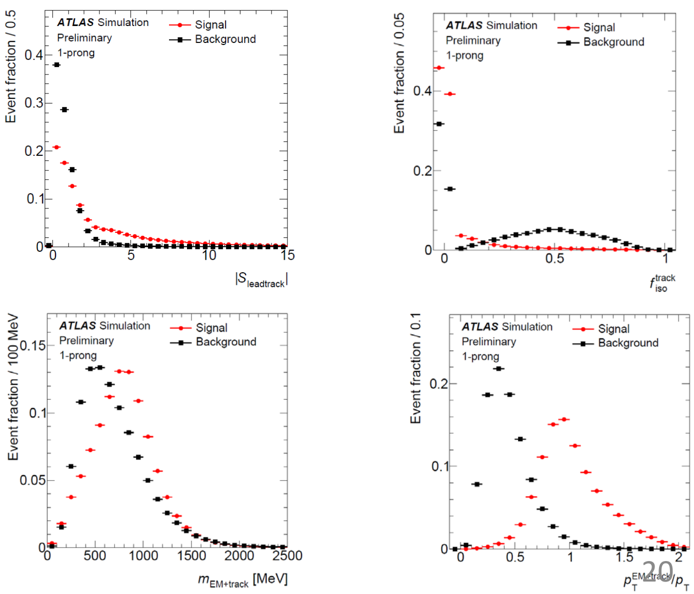
τ_{had} identification

- Identify τ_{had} from quark and gluons
  - Finite impact parameter of tracks
  - Narrow calorimeter energy deposit



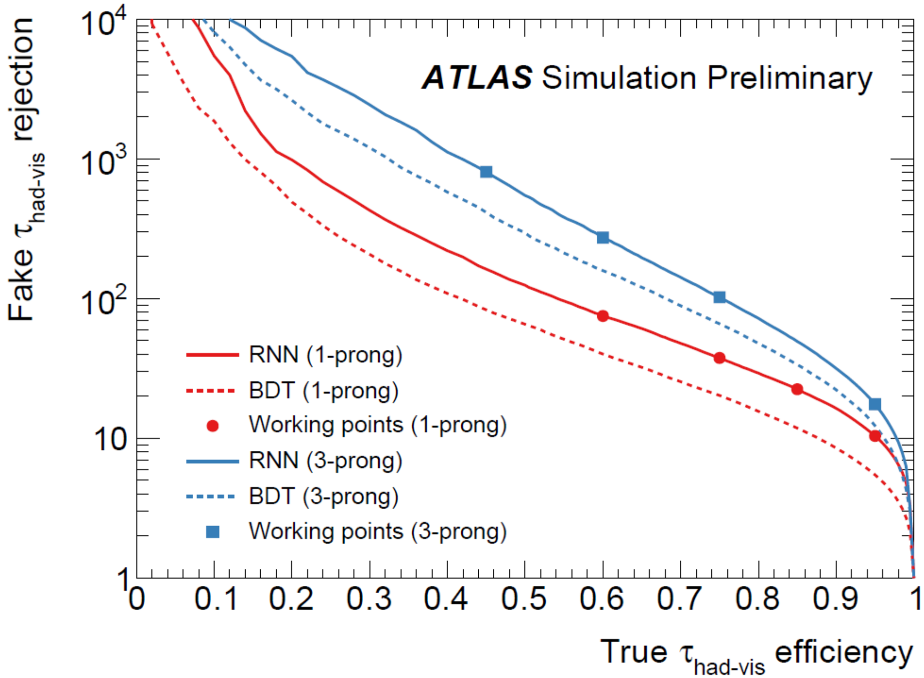
- Multi-Variate Analysis to combine all detector information





Machine learning tau ID

- Multi-Variate Analysis used widely
  - e.g. Boosted Decision Tree (BDT), etc.
- Recent trend: Deep Learning
  - E.g. Recurrent NN (RNN)



	Observable	1-prong	3-prong
Track inputs	$p_T^{\text{seed jet}}$	•	•
	p_T^{track}	•	•
	$\Delta\eta^{\text{track}}$	•	•
	$\Delta\phi^{\text{track}}$	•	•
	$\lvert d_0^{\text{track}}\rvert$	•	•
	$\lvert z_0^{\text{track}} \sin\theta\rvert$	•	•
	$N_{\text{IBL hits}}$	•	•
	$N_{\text{Pixel hits}}$	•	•
	$N_{\text{SCT hits}}$	•	•
Cluster inputs	$p_T^{\text{jet seed}}$	•	•
	E_T^{cluster}	•	•
	$\Delta\eta^{\text{cluster}}$	•	•
	$\Delta\phi^{\text{cluster}}$	•	•
	λ_{cluster}	•	•
	$\langle\lambda^2_{\text{cluster}}\rangle$	•	•
	$\langle r^2_{\text{cluster}}\rangle$	•	•
High-level inputs	$p_T^{\text{uncalibrated}}$	•	•
	f_{cent}	•	•
	$f^{-1}_{\text{leadtrack}}$	•	•
	ΔR_{max}	•	•
	$\lvert S_{\text{leadtrack}}\rvert$	•	
	S_T^{flight}		•
	$f_{\text{iso}}^{\text{track}}$	•	•
	$f_{\text{track}}^{\text{EM}}$	•	•
	$p_T^{\text{EM+track}}/p_T$	•	•
	$m^{\text{EM+track}}$	•	•
	m^{track}		•

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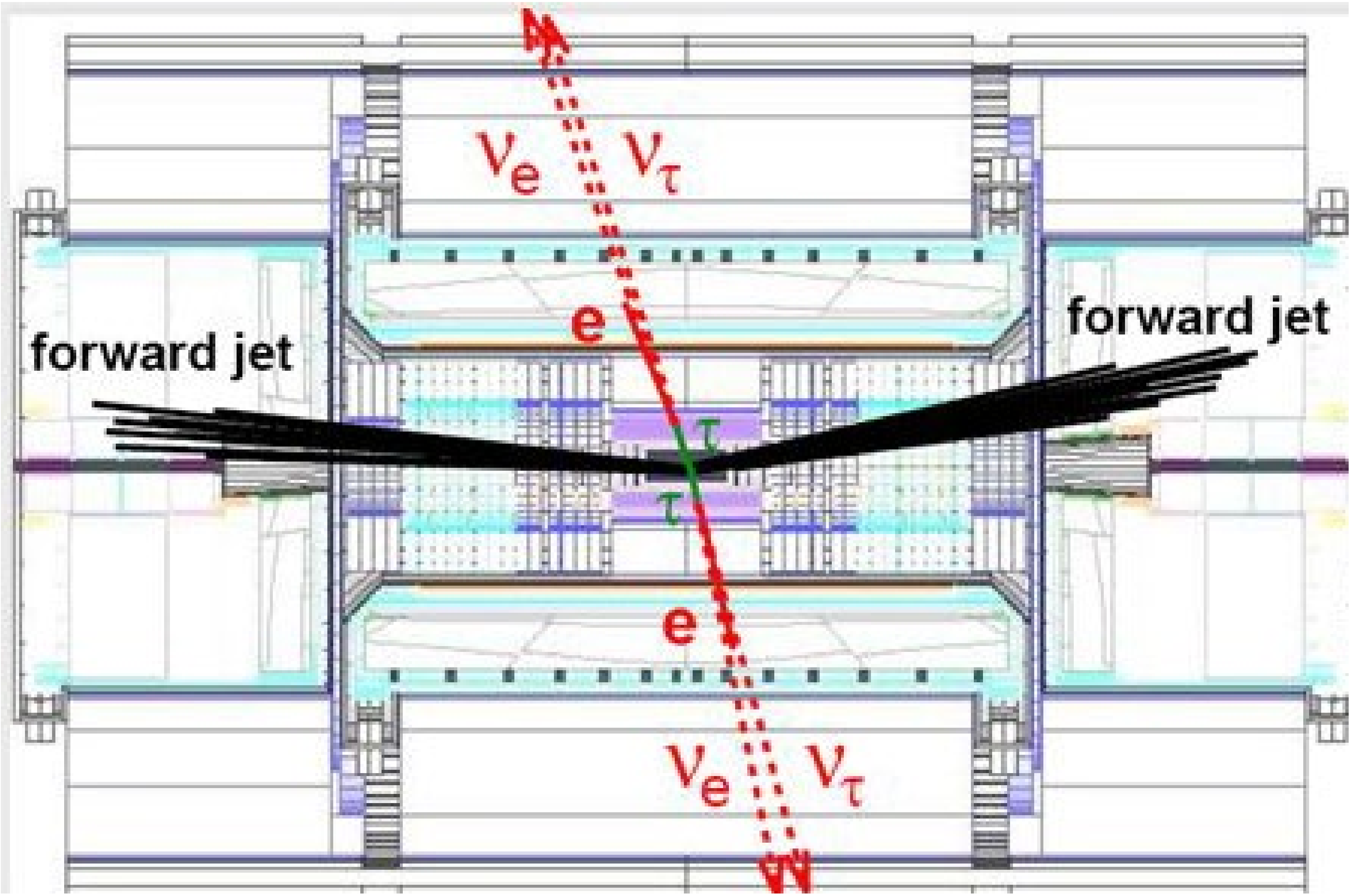
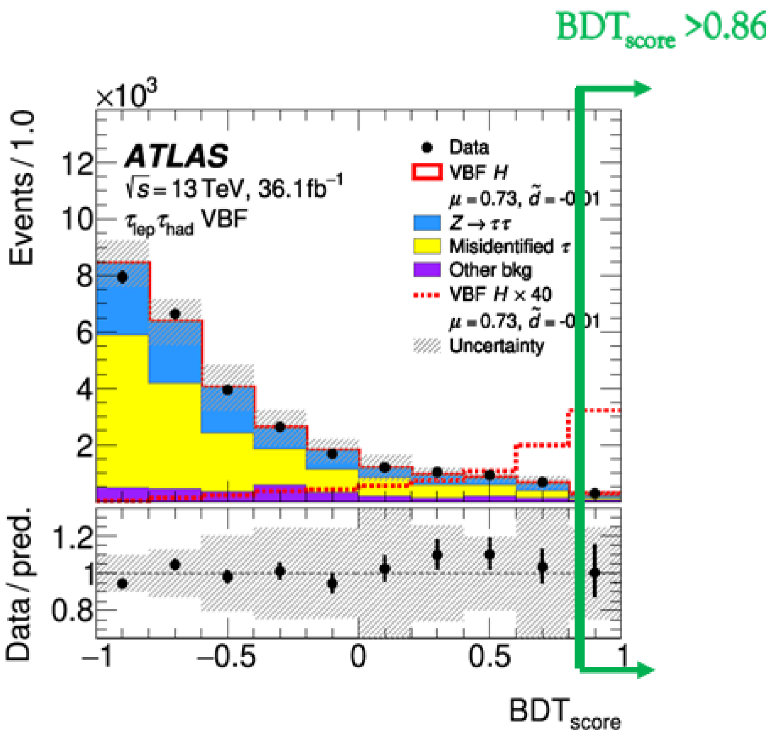
$H \to \tau\tau$: VBF

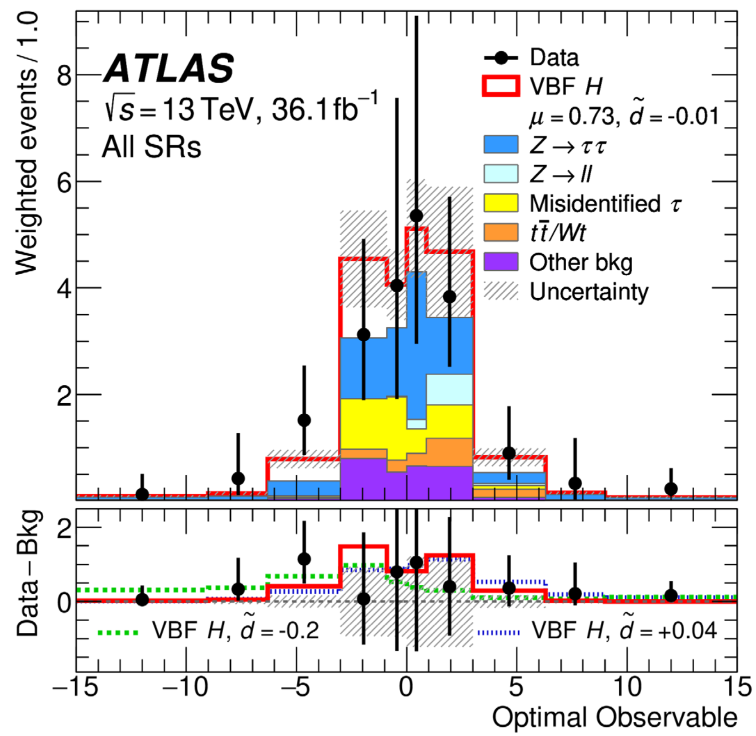


Illustrative figure

Study HVV CP in VBF production

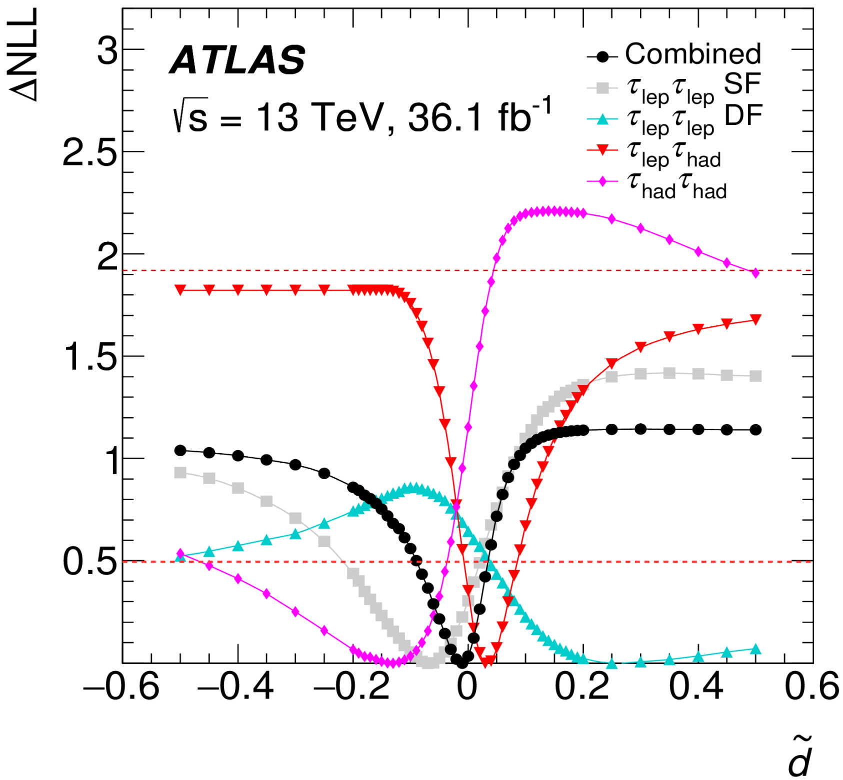
- VBF events selection
  - $N_{jets} \geq 2$ and $H \rightarrow \tau\tau$ final states
  - BDT to discriminate VBF v.s. backgrounds, not bias OO distribution
-





Study HVV CP in VBF production

- Results: 68% Confidence Interval of $\tilde{d}$
  - Expected: [−0.035,0.033], Observed: [−0.090,0.035]



Study HVV CP in H→ZZ decay

- Generic $H \rightarrow VV$ (V=W,Z,g,γ) amplitude:

$$\mathscr{A}(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

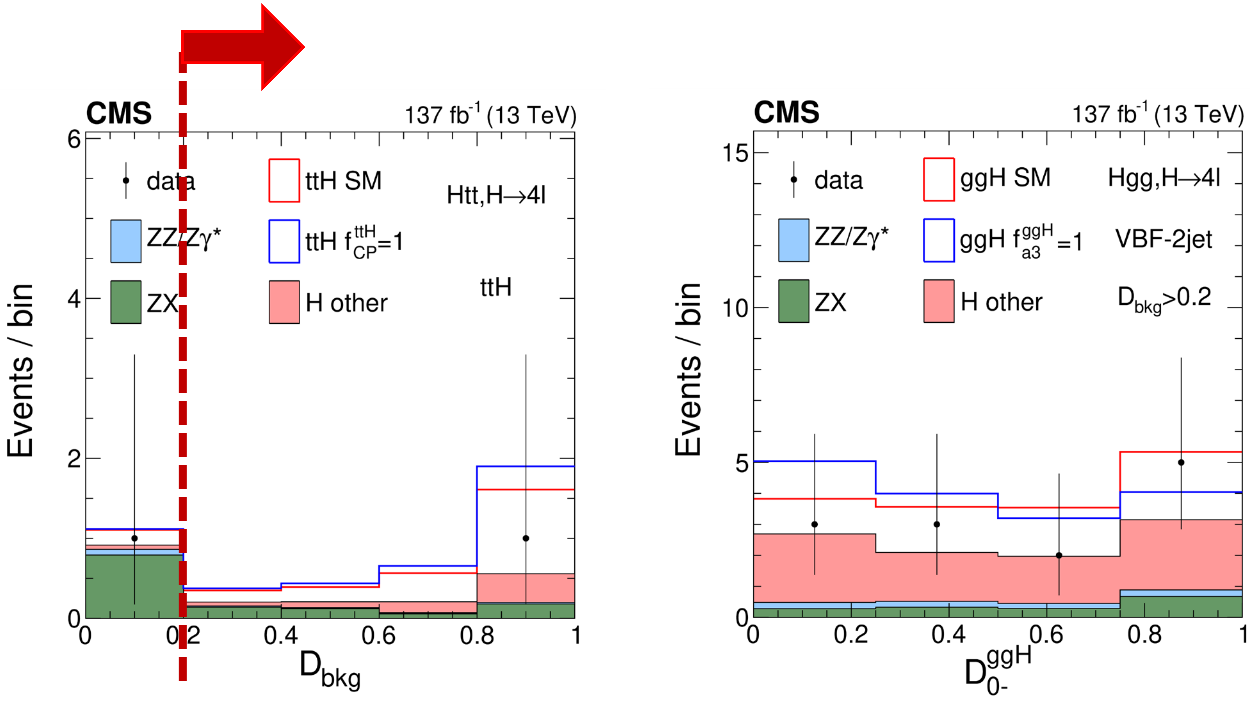
- For the V=W,Z we have:
  - **a_1 = CP-even couplings (SM-like)**
  - a_2, κ_1, $\kappa_2^{Z\gamma}$ = CP-even anomalous couplings
  - **a_3 = CP-odd coupling**

- Two approaches to relate ZZ and WW couplings:
  - Approach 1: $a_i^{ZZ} = a_i^{WW}$, $\kappa_1^{WW} = \kappa_1^{ZZ}$
  - Approach 2: SU(2) X U(1) - SMEFT

Study HVV CP in H→ZZ decay

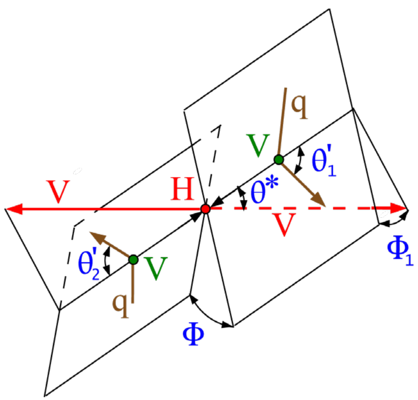
- H→4e, 4μ, 2e2μ decays, via ggH, VBF+VH, and ttH
- Matrix element variables (MELA) used to exploit production and decay information:

$$\mathcal{D}_{\text{alt}}(\boldsymbol{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega})}{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega}) + \mathcal{P}_{\text{alt}}(\boldsymbol{\Omega})} \qquad \mathcal{D}_{\text{int}}(\boldsymbol{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\boldsymbol{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\boldsymbol{\Omega})\mathcal{P}_{\text{alt}}(\boldsymbol{\Omega})}} \rightarrow \mathcal{D}_{CP}$$

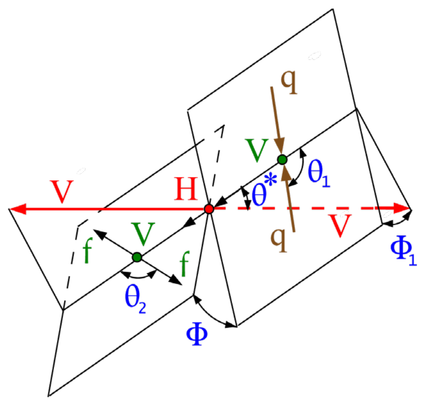


Study HVV CP in H→ZZ decay

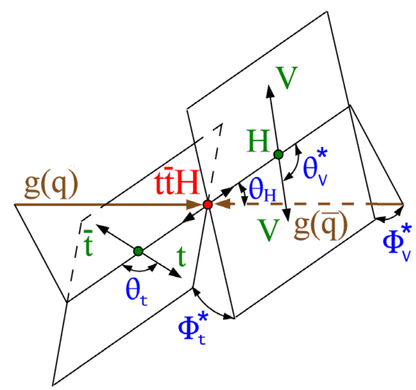
- Very rich physics program in CMS results
  - Four production modes explored for CP structure of HVV, Htt, and H to gluon effective coupling



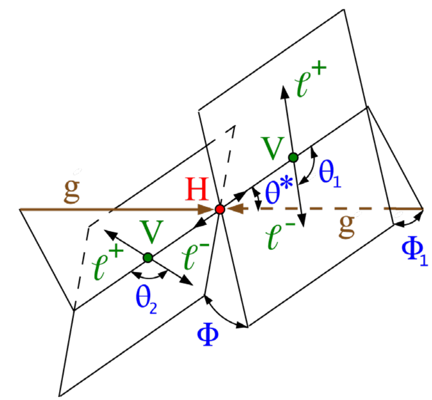
VBF



VH

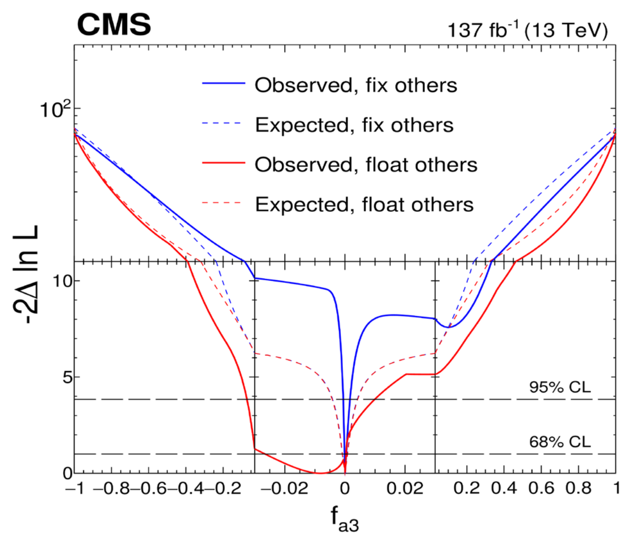


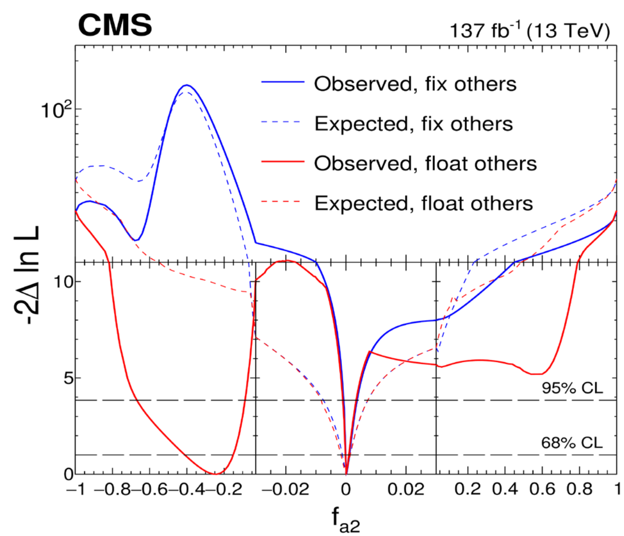
ttH



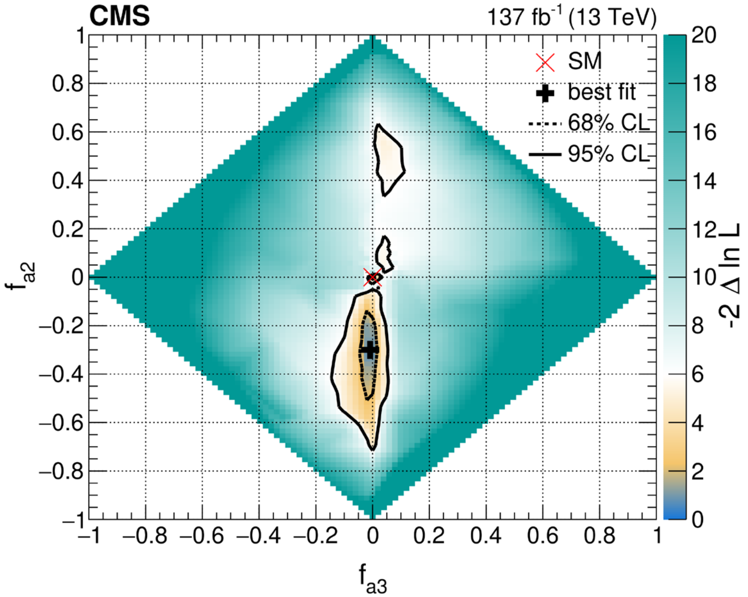
ggH

Generic amplitude Interpretation

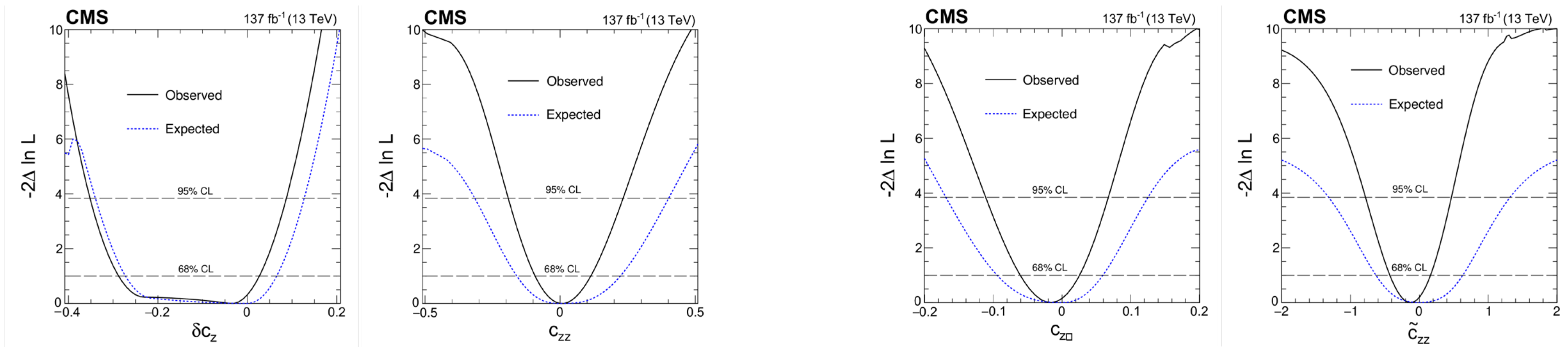




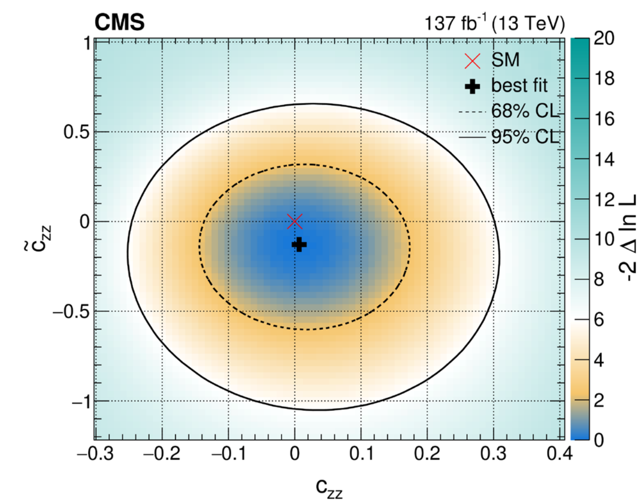
- Scans of cross section fraction (f) in Generic Amplitude



EFT interpretation



- 1D and 2D scans of EFT couplings
  - Other couplings are profiled in the fit



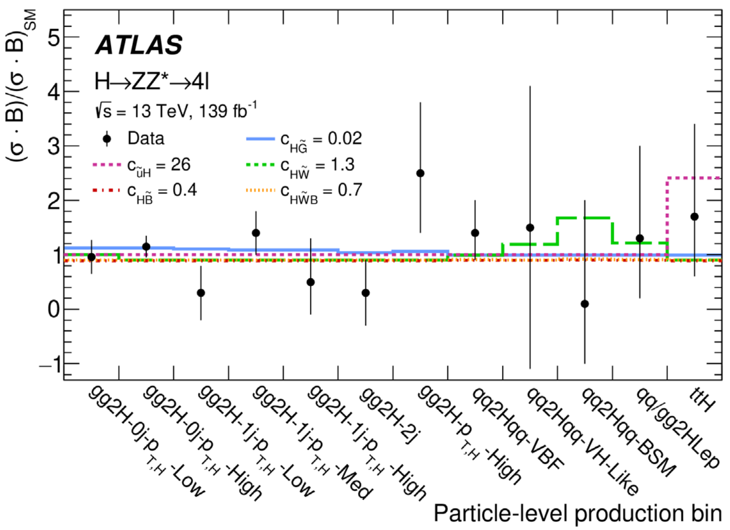
- HVV amplitude parameters related to EFT couplings by:

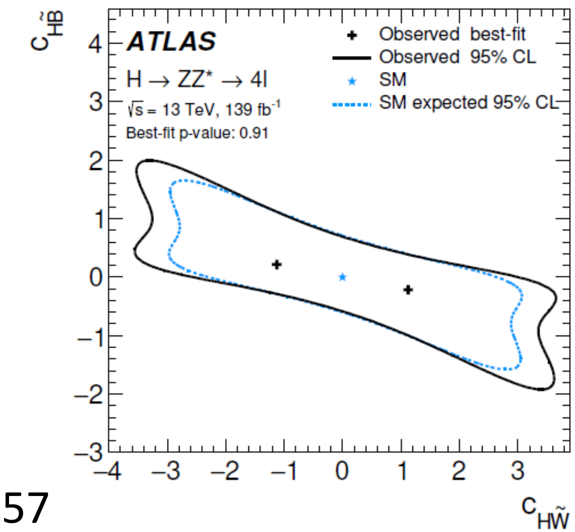
$$\delta c_Z = \frac{1}{2}a_1 - 1 \qquad c_{Z\Box} = \frac{m_Z^2 s_W^2}{4\pi\alpha}\frac{\kappa_1}{(\Lambda_1)^2} \qquad c_{ZZ} = -\frac{s_W^2 c_W^2}{2\pi\alpha}a_2 \qquad \tilde{c}_{ZZ} = -\frac{s_W^2 c_W^2}{2\pi\alpha}a_3$$

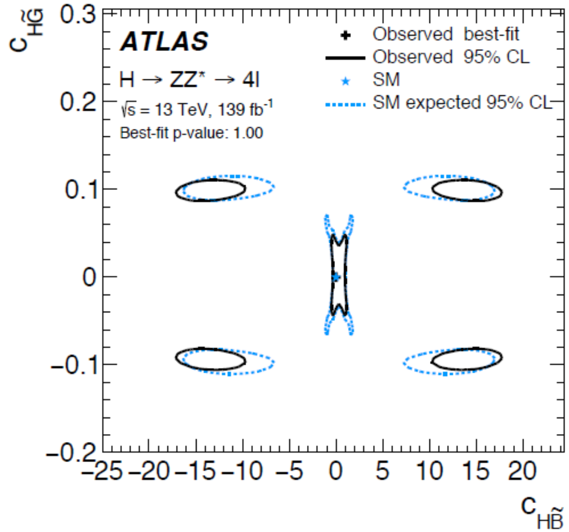
ATLAS H→ZZ→4l EFT results

- Probe CP-odd HVV coupling in EFT via STXS measurement

- Various CP-odd operators constrained
  - Correlation can be resolved in other measurement





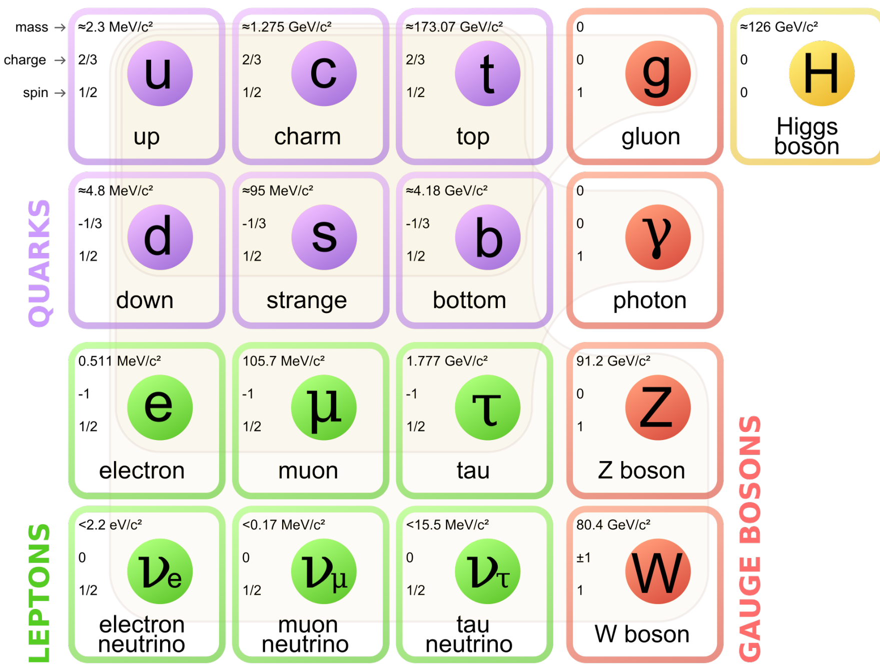


Eur. Phys. J. C 80 (2020) 957

CP structure in Higgs to fermion Yukawa coupling

All Yukawa couplings are created equal.

By this Author



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

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

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

CP structure in Higgs to fermion Yukawa coupling

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

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

$$\tilde{g}_{hZZ} \simeq -\frac{\sin\alpha_2}{\tan\beta}\,\frac{1}{6\times10^5\ \text{GeV}} \qquad \tilde{g}_{hWW} \simeq \frac{\sin\alpha_2}{\tan\beta}\,\frac{1}{5\times10^5\ \text{GeV}}$$

LHC constraint

- (137 fb−1, CMS PAS HIG-19-009) $\tilde{g}_{hZZ} \lesssim \frac{1}{3\times10^3\ \text{GeV}}$
- (HL-LHC, 1902.00134) $\tilde{g}_{hZZ} \lesssim \frac{1}{8\times10^3\ \text{GeV}}$

CP structure in Higgs to fermion Yukawa coupling

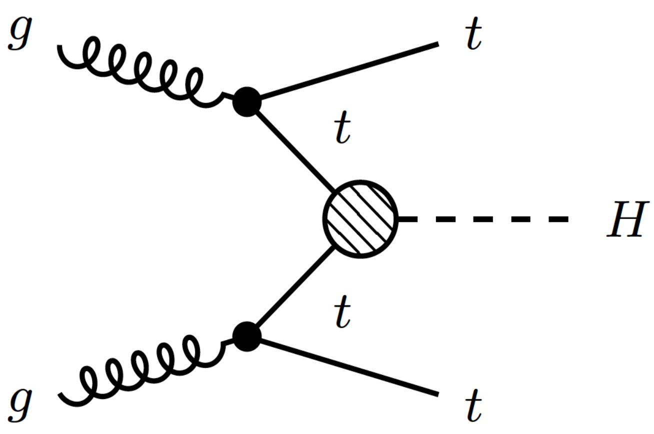
$$\mathcal{L}_{\rm Yuk} \supset -\frac{m_f}{v}\left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

- Can be arised at tree level in, e.g. 2HDM

	Type I	**Type II**
$\tilde{\kappa}_u$	$-\frac{s_{\alpha_2}}{t_\beta}$	$-\frac{s_{\alpha_2}}{t_\beta}$
$\tilde{\kappa}_{d,\ell}$	$\frac{s_{\alpha_2}}{t_\beta}$	$-s_{\alpha_2} t_\beta$

Study of ttH vertex in H→γγ

- Probe CP of top Yukawa coupling via ttH production

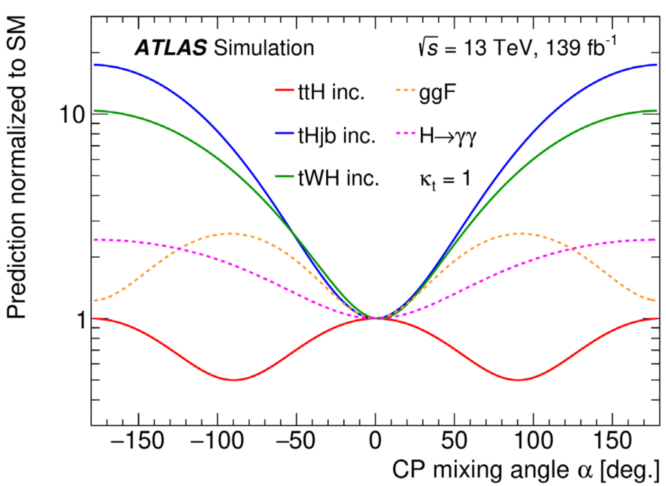


- EFT-inspired Lagrangian

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t \kappa_t [\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

Top Yukawa coupling

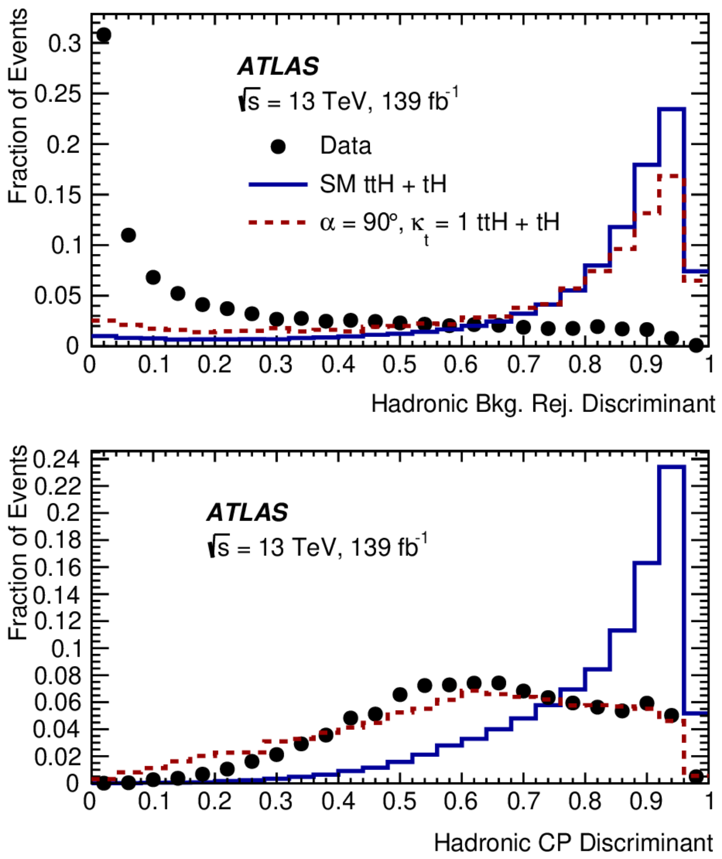
CP-mixing angle

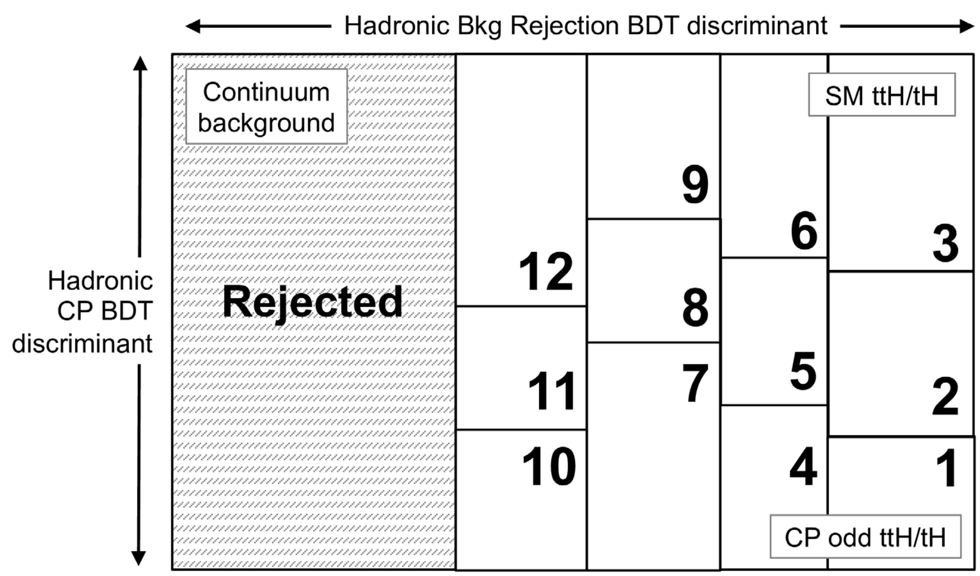


Phys. Rev. Lett. 125 (2020) 061802

Study of ttH vertex in H→γγ

- Two BDTs to categorize events
  - ttH signal v.s. background and CP-even v.s. CP-odd

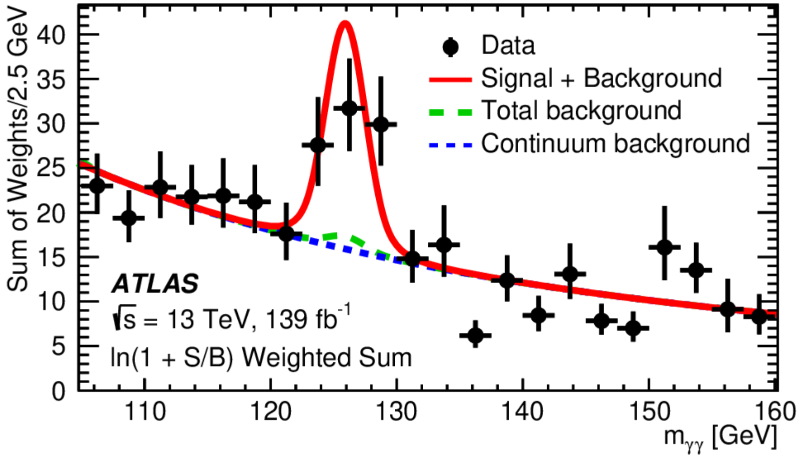




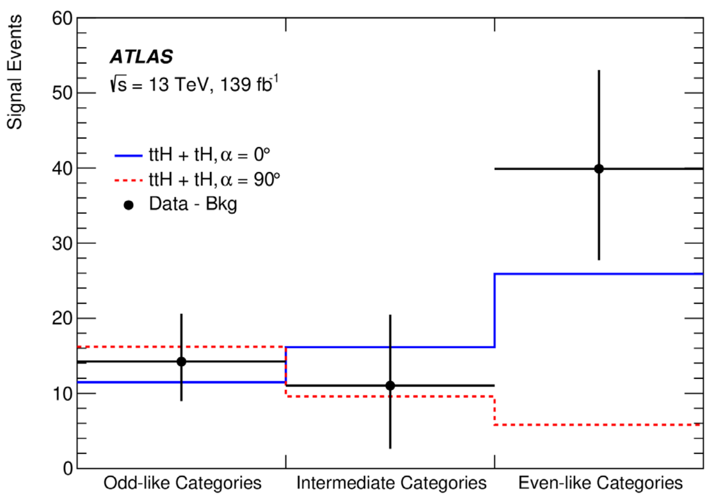
Phys. Rev. Lett. 125 (2020) 061802

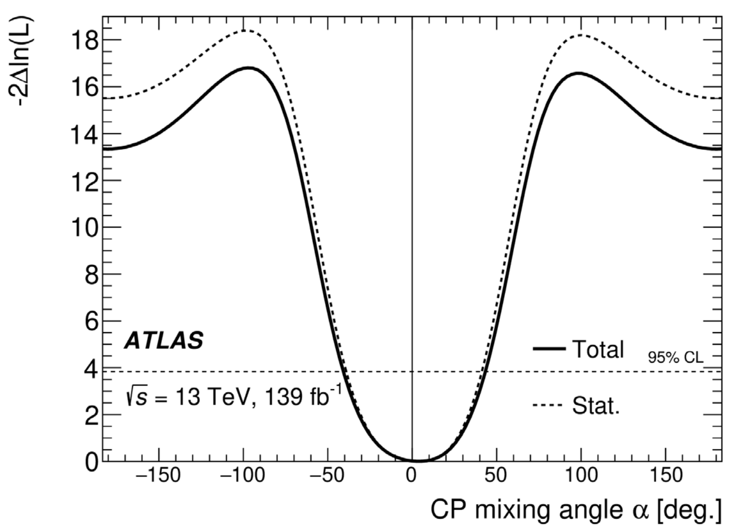
Study of ttH vertex in H→γγ

- Simultaneous fit on $m_{\gamma\gamma}$ to extract Higgs events



- Data favor CP-even state
  - Limit on CP-mixing angle |α| < 43^0 (56^0) at 95% C.L.





CP structure of $H\to\tau\tau$ coupling

- CP-mixing of Higgs to tau lepton Yukawa coupling

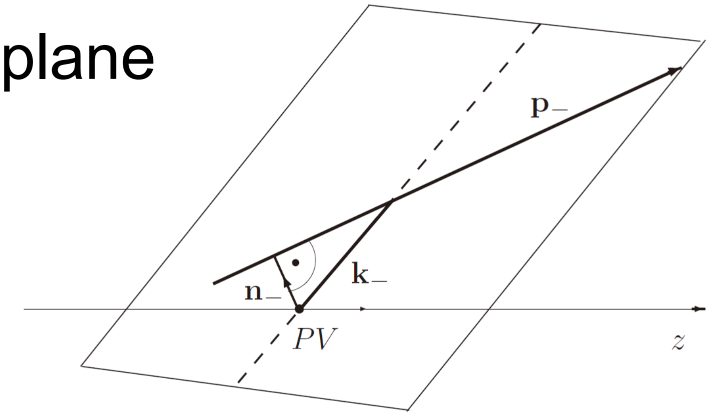
$$\mathcal{L}_Y = -\frac{m_\tau}{\mathrm{v}}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)h$$

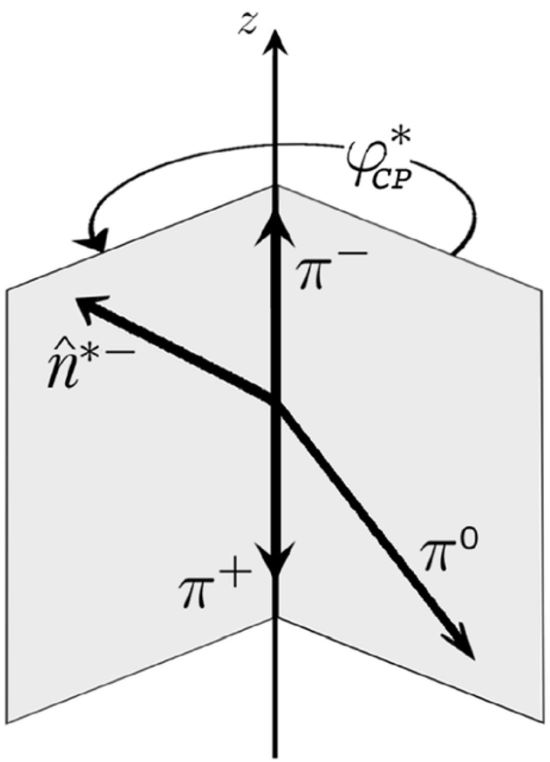
- Spin correlation encoded in the angle between two τ decay planes, and propagated to the tau decay products

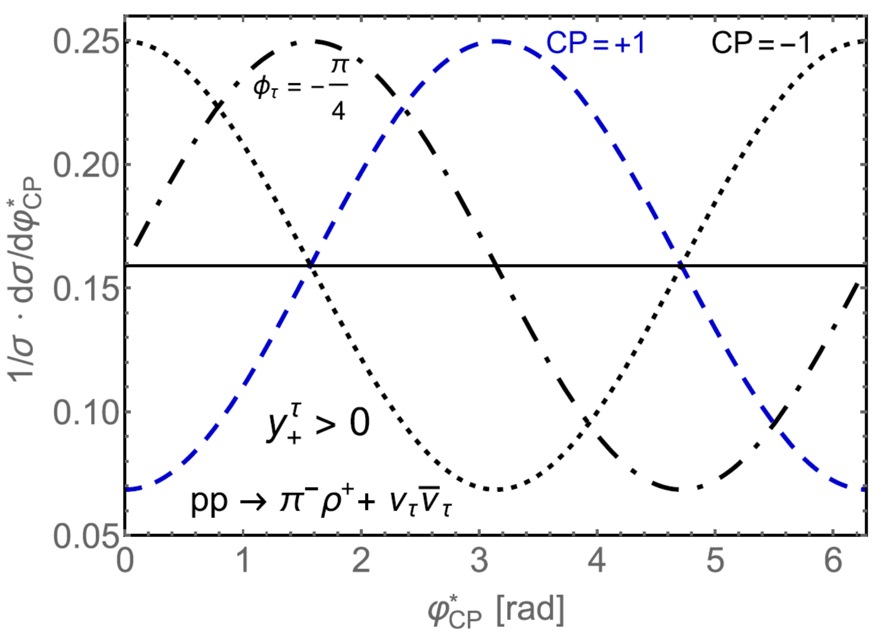
$$\frac{d\Gamma}{d\phi_{CP}}(H\to\tau^+\tau^-) \sim 1 - s_z\bar{s}_z + R(2\alpha^{H\tau\tau})\cdot s_\perp\bar{s}_\perp \sim 1 - \frac{\pi^2}{16}b(E^+)b(E^-)\cdot\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

CP structure of H→ττ coupling

- Two methods to build the τ decay plane
  - **Impact Parameter** method
  - **Rho** method

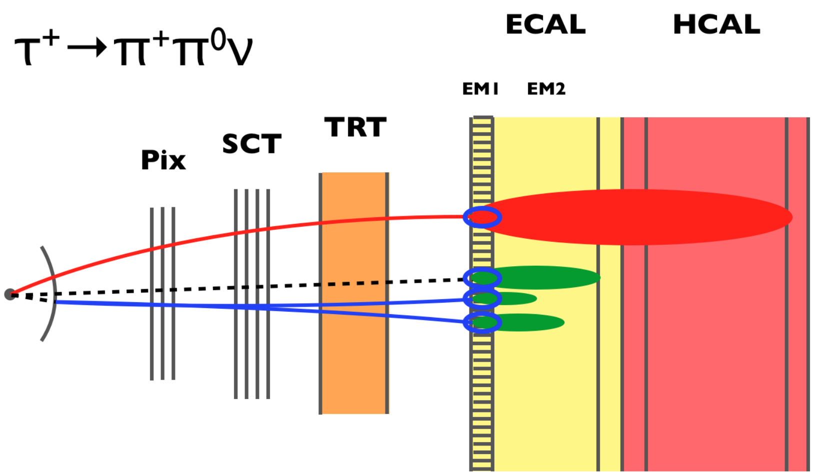


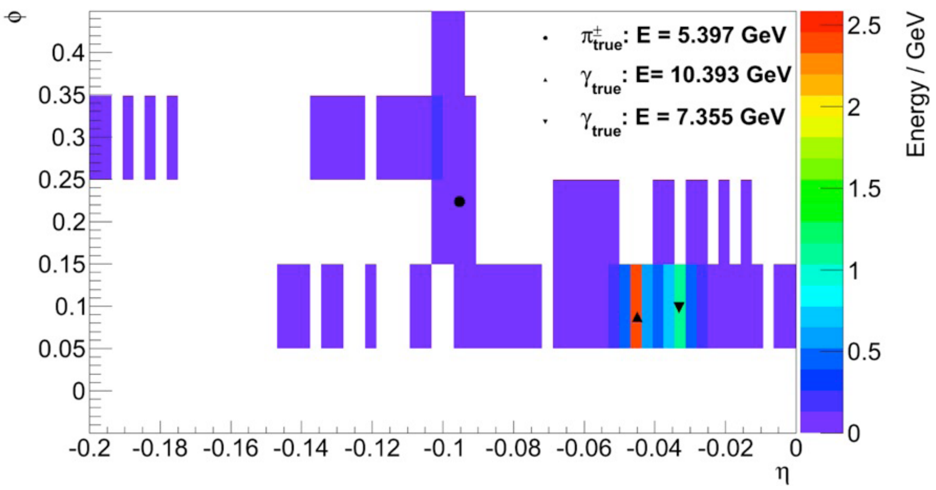




Tau decay mode classification

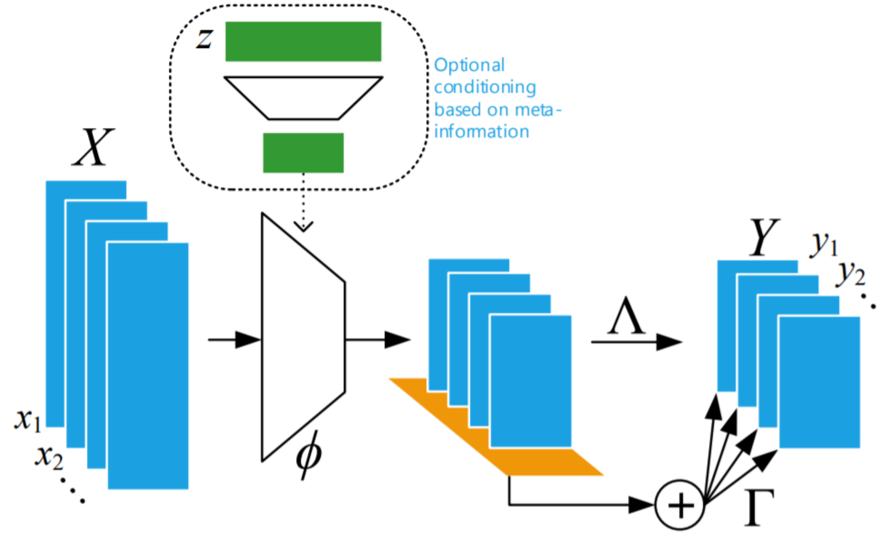
Decay mode	Meson resonance	$\mathcal{B}$ [%]
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	26.0
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	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





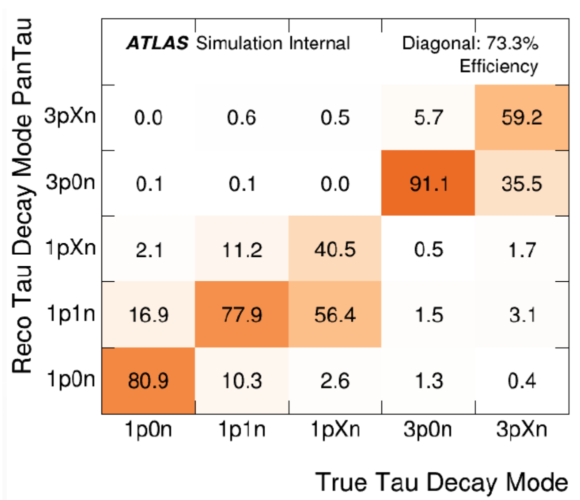
Deep NN classification

- Tracks and π^0s used as input in the Deep Set neural network

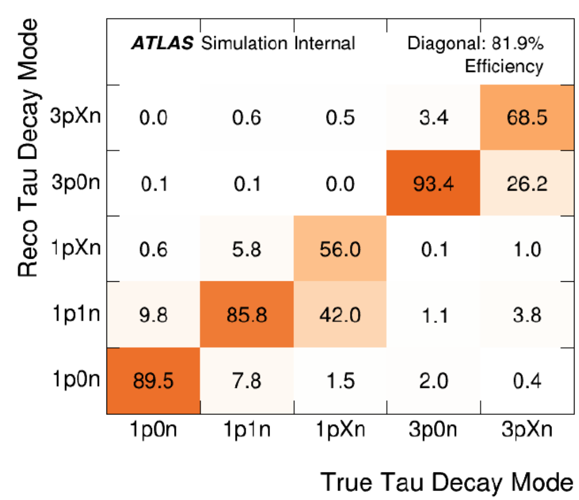


- Efficiency migration matrix

BDT



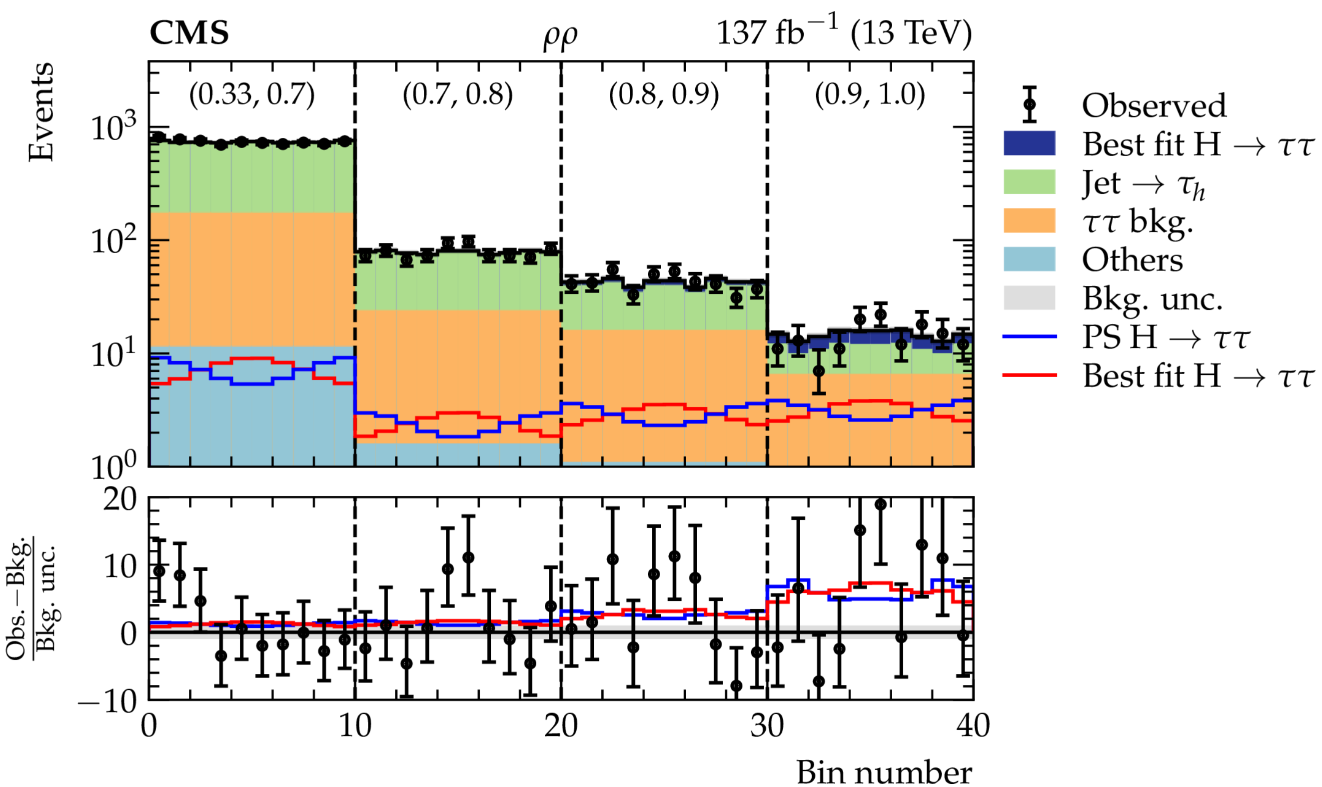
DNN



CP structure of H→ττ coupling

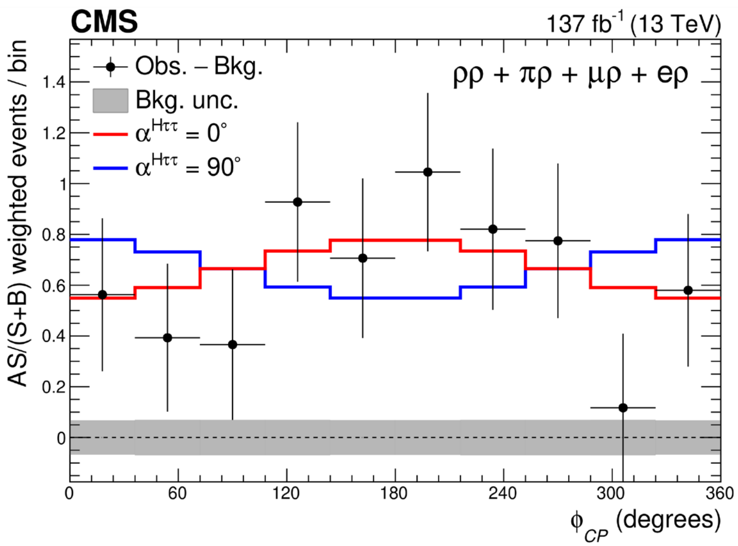
arXiv:2110.04836

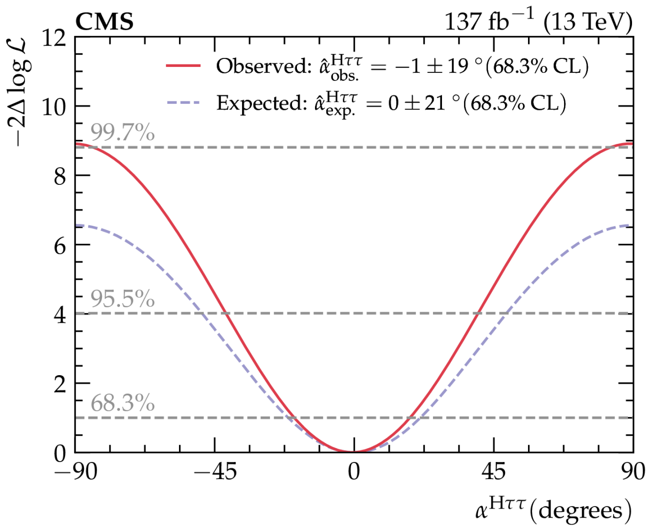
- Analysis strategy:
  - BDT trained against backgrounds, and further categories events
  - Simultaneous fit on ϕ_{CP} to extract the CP mixing angle



CP structure of H→ττ coupling

arXiv:2110.04836





- CP-odd scenario excluded at 3.0σ
- Best fit value of $\alpha_{H\tau\tau}$ is -1±19 ^{0}

Theoretical Impact

Search for tth, h→γγ: $\left|\frac{\tilde{\kappa}_t}{\kappa_t}\right| \lesssim 0.93$ (139 fb^{-1}, ATLAS, 2004.04545; CMS, 2003.10866)

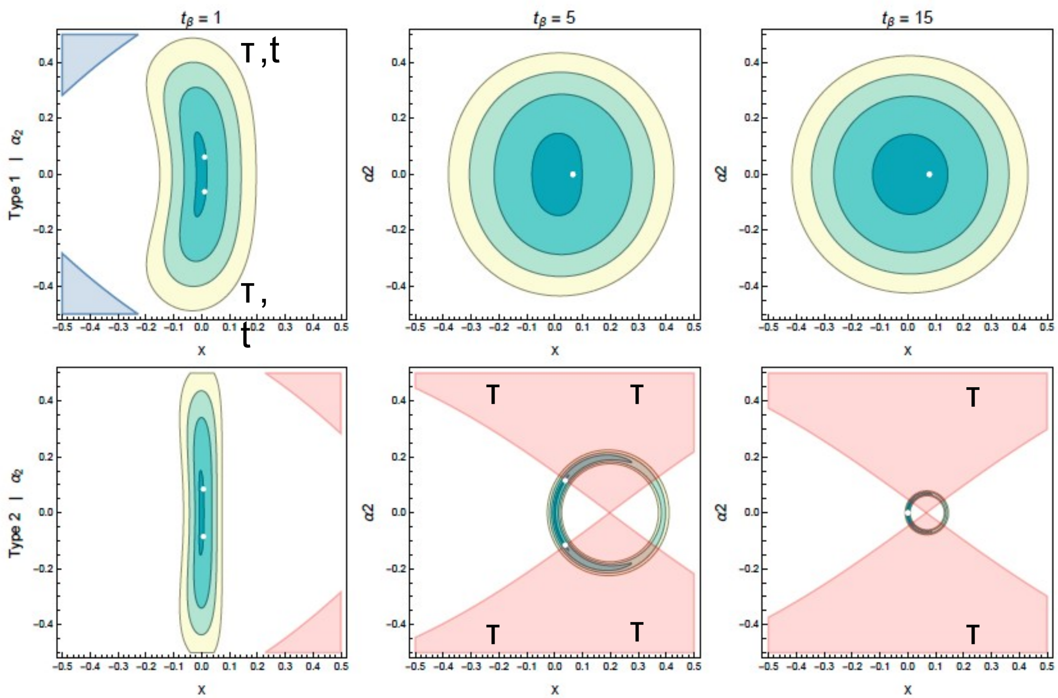
Search for H→ττ: $\left|\frac{\tilde{\kappa}_\tau}{\kappa_\tau}\right| \lesssim 0.73$ (137 fb^{-1}, CMS PAS HIG-20-006)

1804.01241

ILC, 250 GeV, 2ab^{-1}: angle can be measured with a 4.3^0 precision

1703.04855

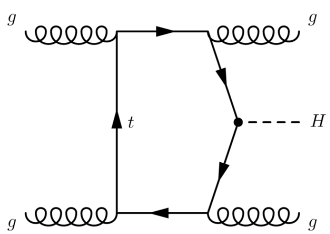
CEPC, 250 GeV, 5ab^{-1}: angle can be measured with a 2.9^0 precision

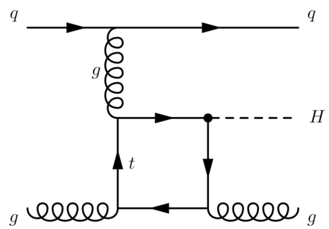


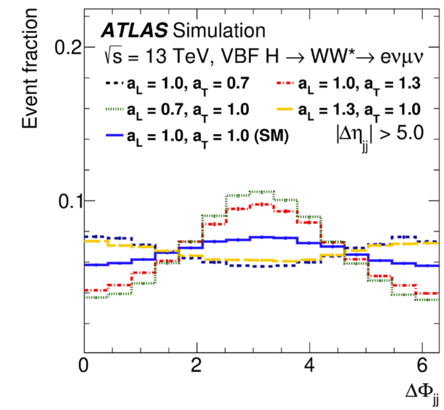
S. Gori's talk in Higgs Hunting 2021

Other measurements

$gg \rightarrow H \rightarrow WW* \rightarrow e\nu\mu\nu$ + 2 jets

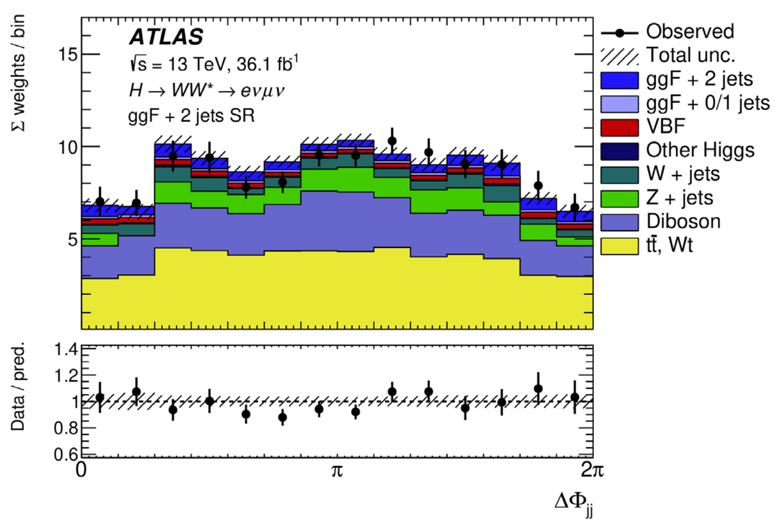


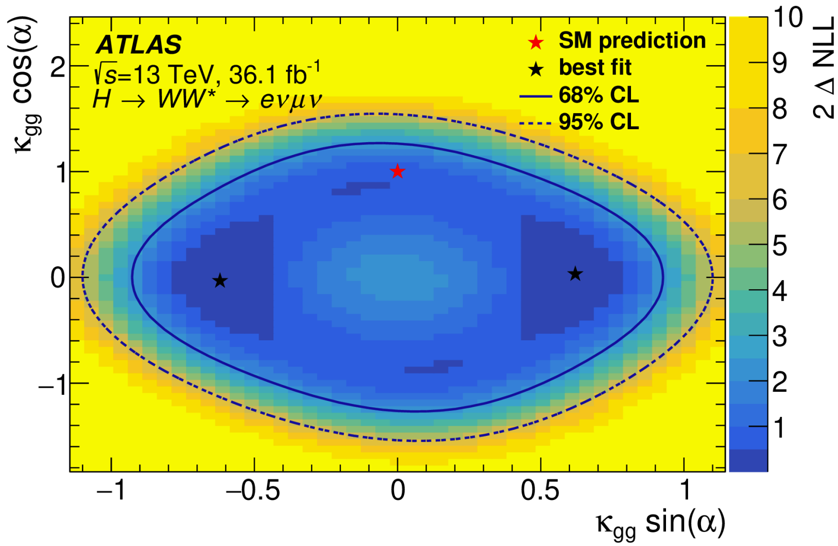




Effective Lagrangian

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





Summary

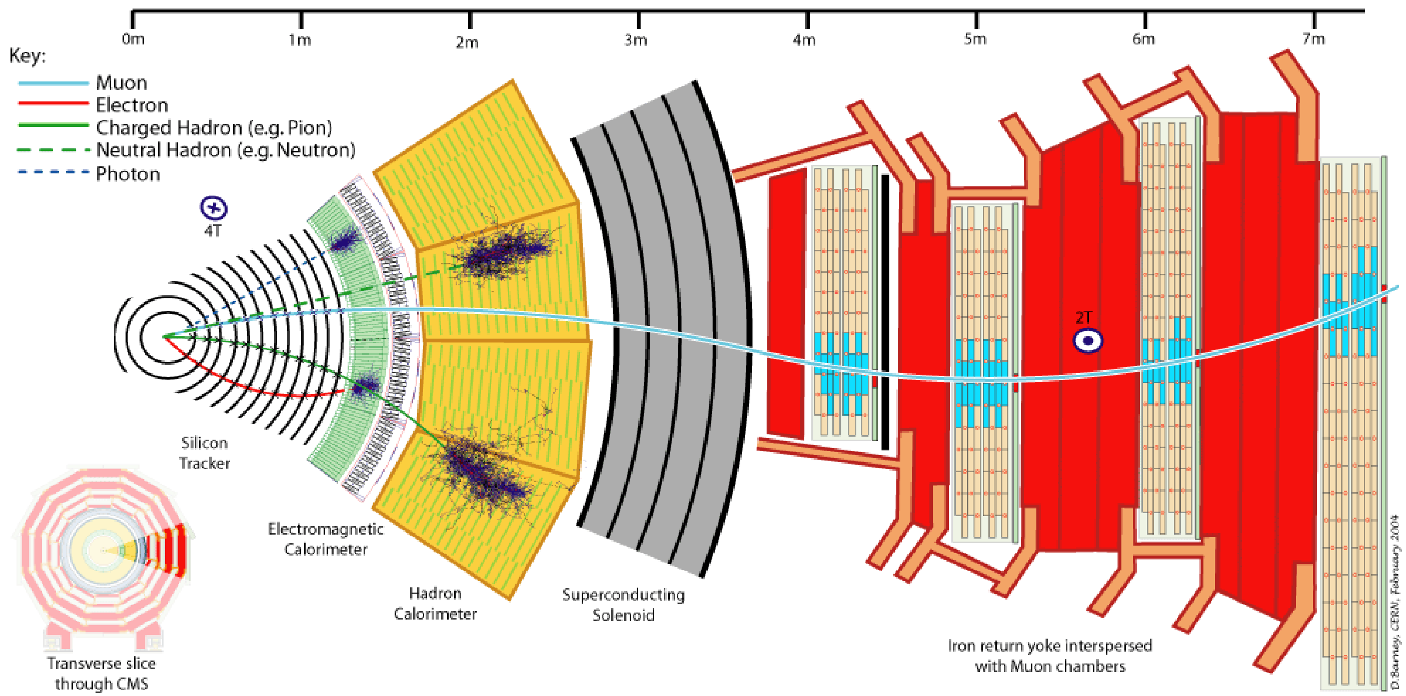
- CP violation is one of the most interesting and profound question in particle physics, where Higgs sector is a new field to look into
- ATLAS and CMS experiments performed an extensive search for CP in the Higgs coupling to vector bosons and fermions.
- New techniques: decay plane building, Optimal Observable (Matrix Element method), MVA method widely used in CPV
- Diverse theoretical frameworks: EFT based, Amplitude, etc.



南京大學
NANJING UNIVERSITY

Backup

探测粒子



内径迹探测器　电磁量能器　强子量能器　缪子径迹探测器

(大约) **精度**　<1%　~1-2%　~10-20%　~1%

LHC前已知基本粒子

轻子

ν_e	ν_μ	ν_τ
e	μ	τ

夸克

u	c	t
d	s	b

规范玻色子

W	Z	γ	g

费米子探测

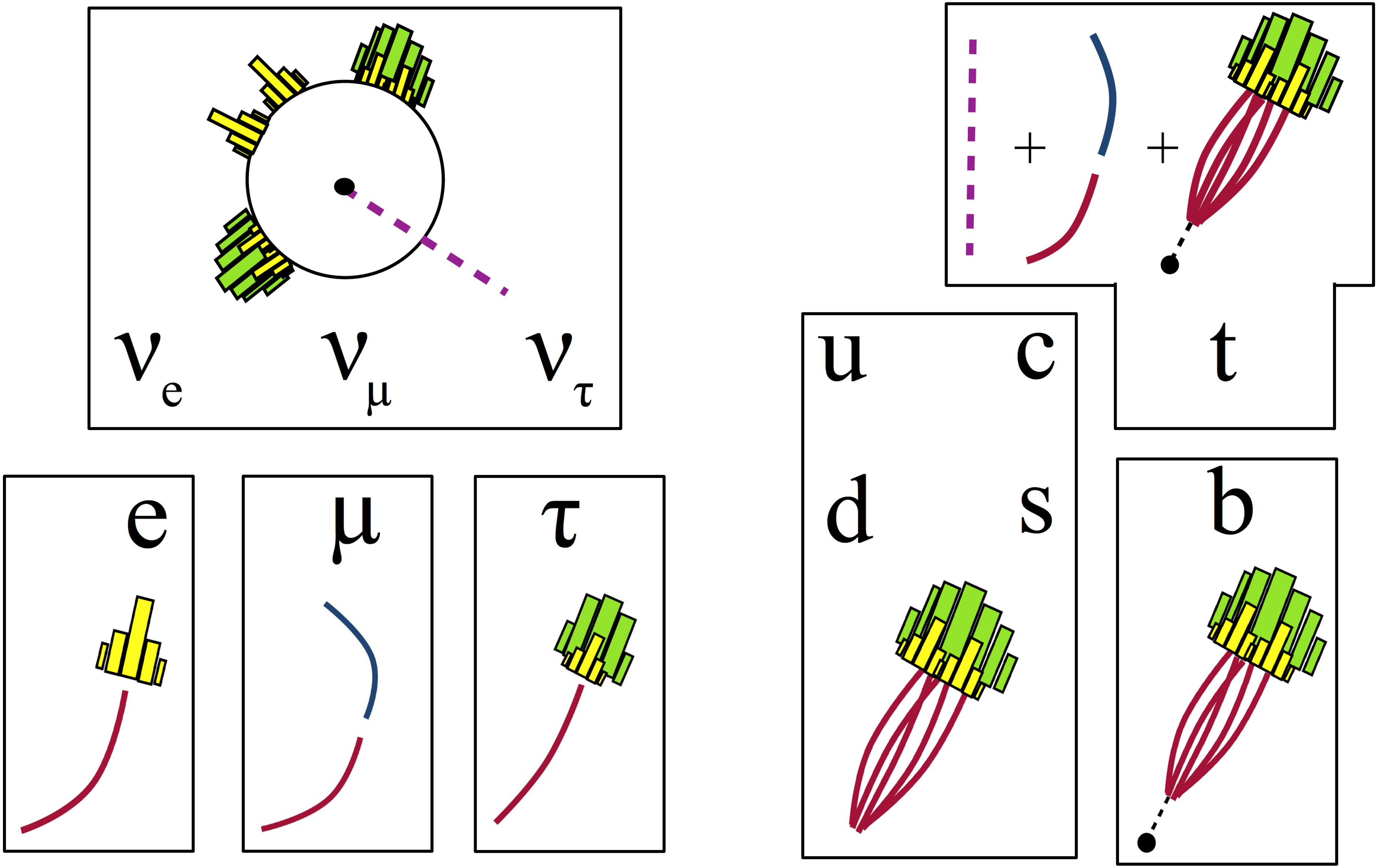
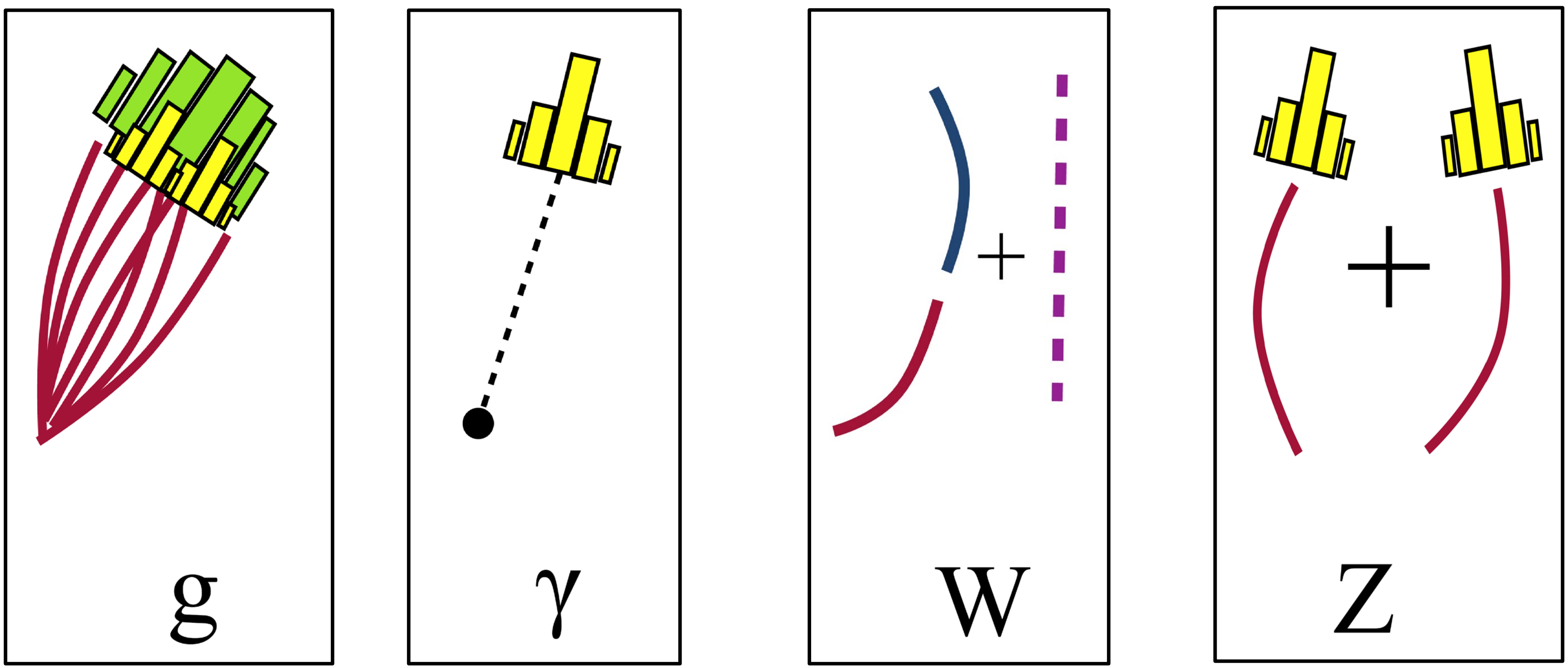


Illustration idea from John Allison

规范玻色子探测

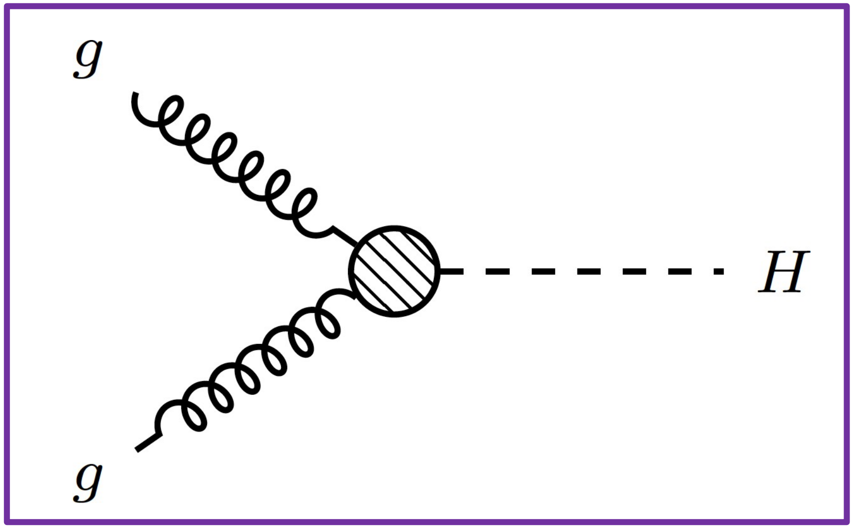


Study HVV CP in $H\rightarrow ZZ$ decay

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

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

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


g
g
H

arXiv:2109.13808v1

Studies of ggH vertex in H→WW

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

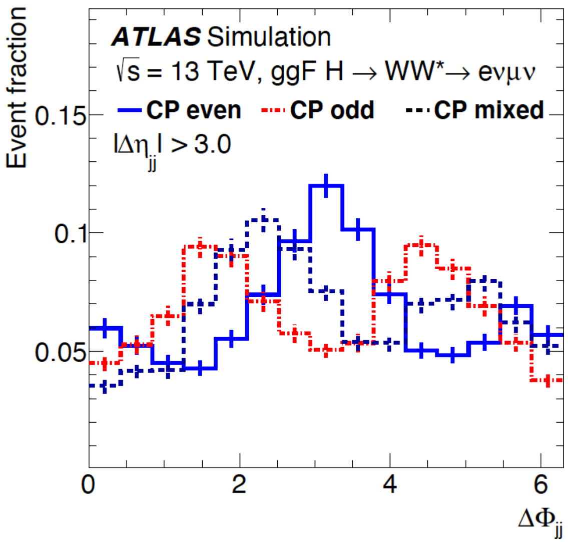
- Production mode: ggH
    - In the large top quark mass limit: the CP structure of the top-quark Yukawa coupling is inherited by the effective Higgs – gluon interaction
    - Assumption: SM-like HVV coupling
- Theoretical framework: EFT with Higgs Characterization

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

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

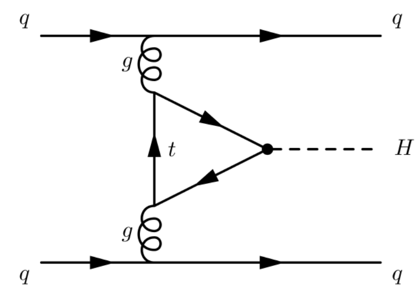
CP – odd: κ_{gg} = 1 ; cos(α) = 0

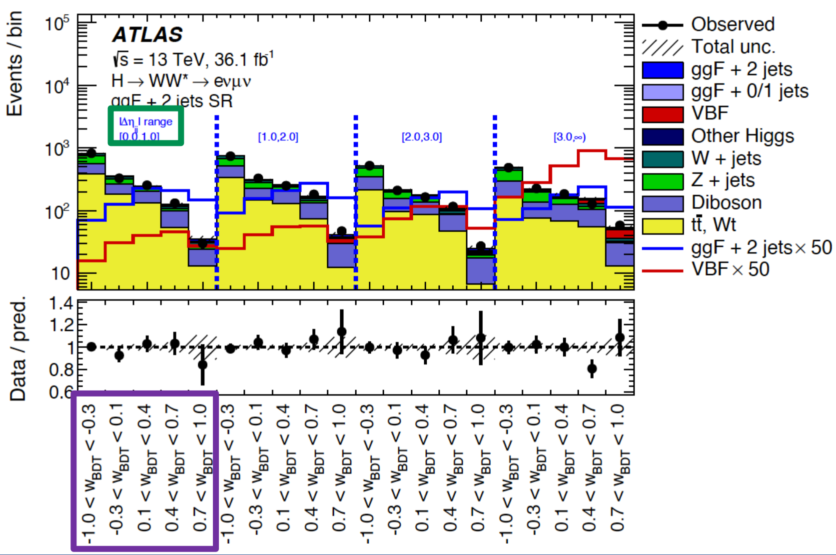
CP – mixed: κ_{gg} = 1 ; cos(α) = $1/\sqrt{2}$

arXiv:2109.13808v1

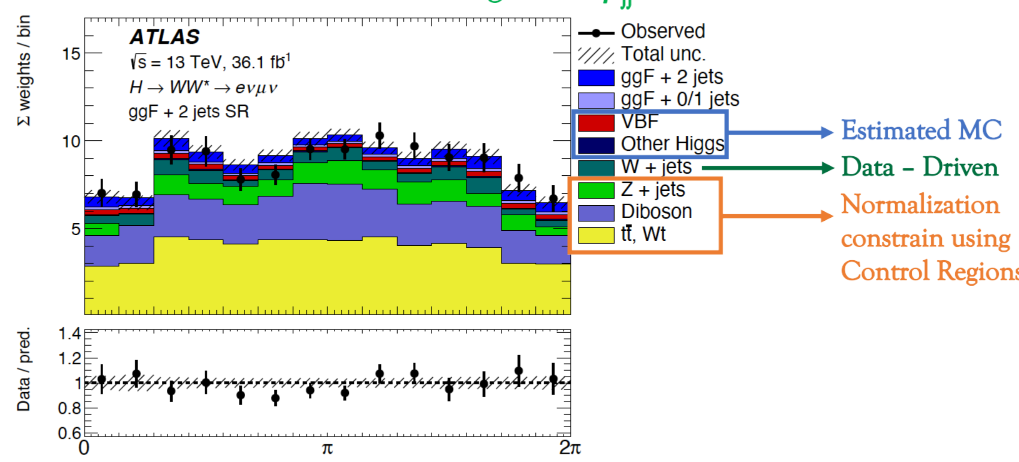
Studies of ggH vertex in H→WW

- 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-$\Delta\phi_{jj}$

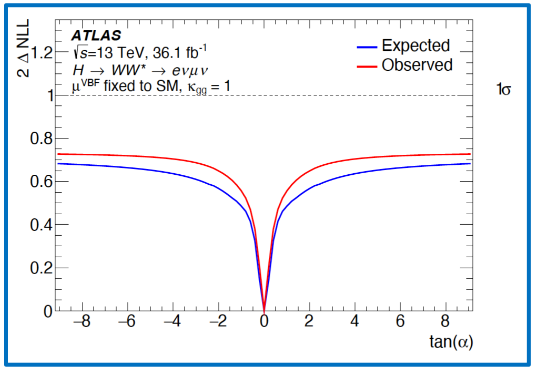


Events weighted by ln(1+S/B)

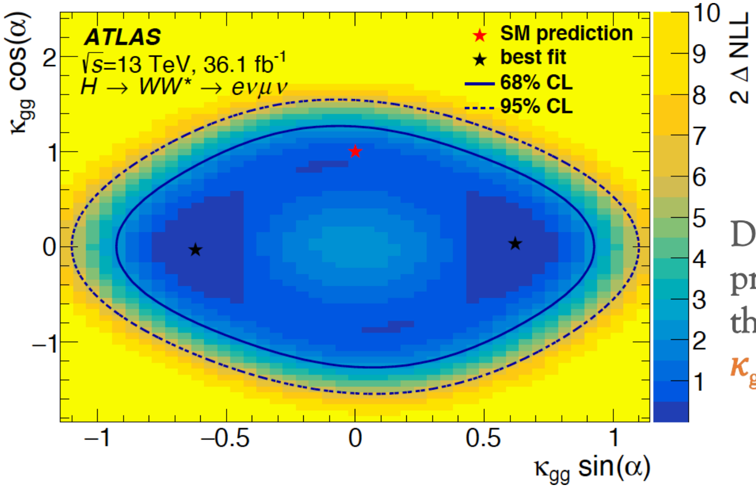
arXiv:2109.13808v1

Studies of ggH vertex in H→WW

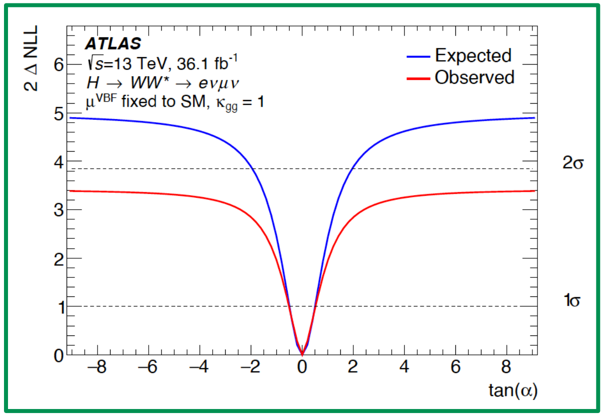
- Perform a fit on signed-$\Delta\phi_{jj}$
  - Two approaches:
    - Exploits only shape information: best isolation of CP-dependence
      - Lower sensitivity → does not reach 1σ confidence level
    - Both shape and rate are considered: best sensitivity
      - Observed sensitivity worse than the expected → signal strength of the ggF + 2 jets process lower then expected: $\mu^{ggF+2j} = 0.5 \pm 0.4\,(\text{stat.})^{+0.7}_{-0.6}\,(\text{syst.})$



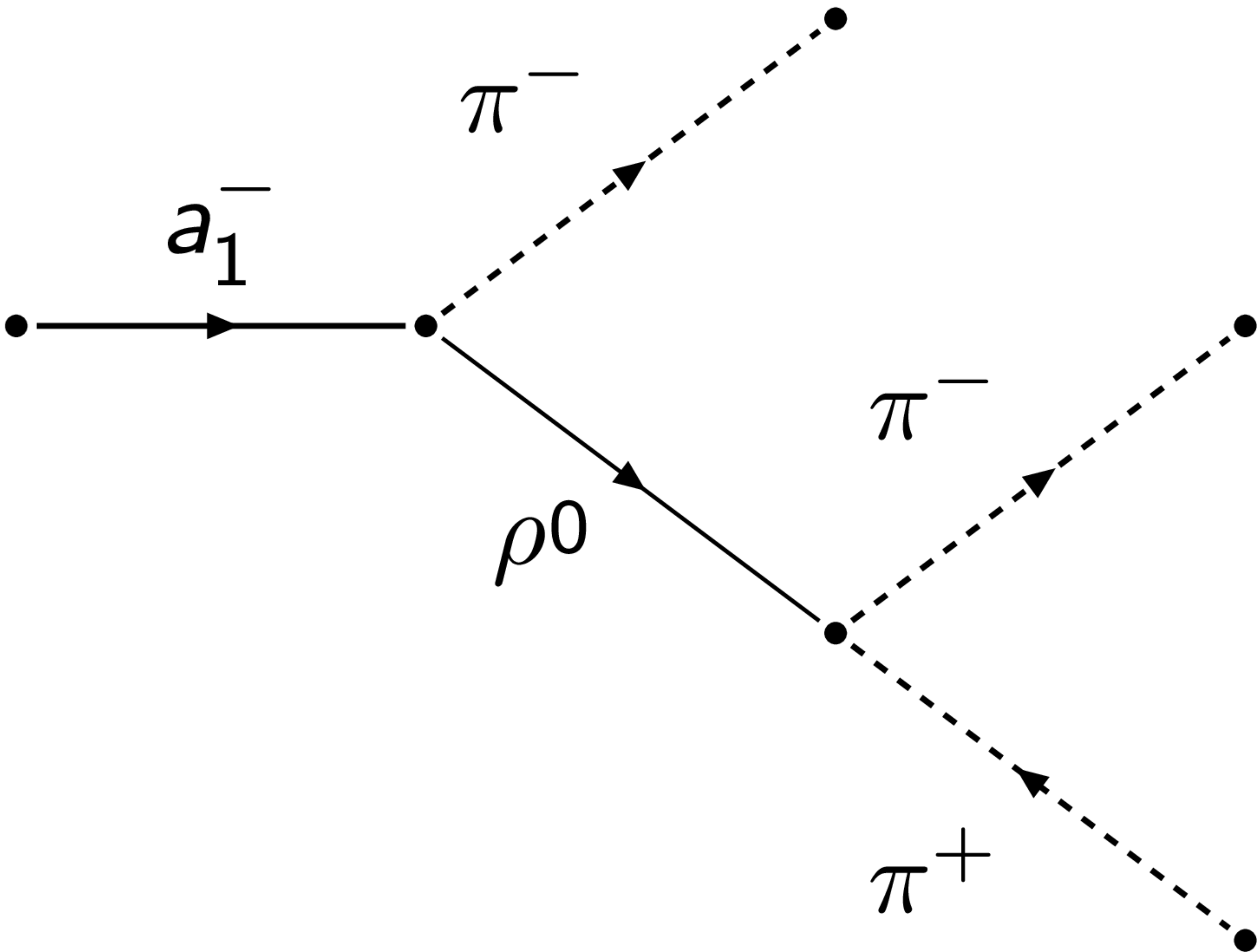
- Simultaneous fit of the coupling strength scale factors



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



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

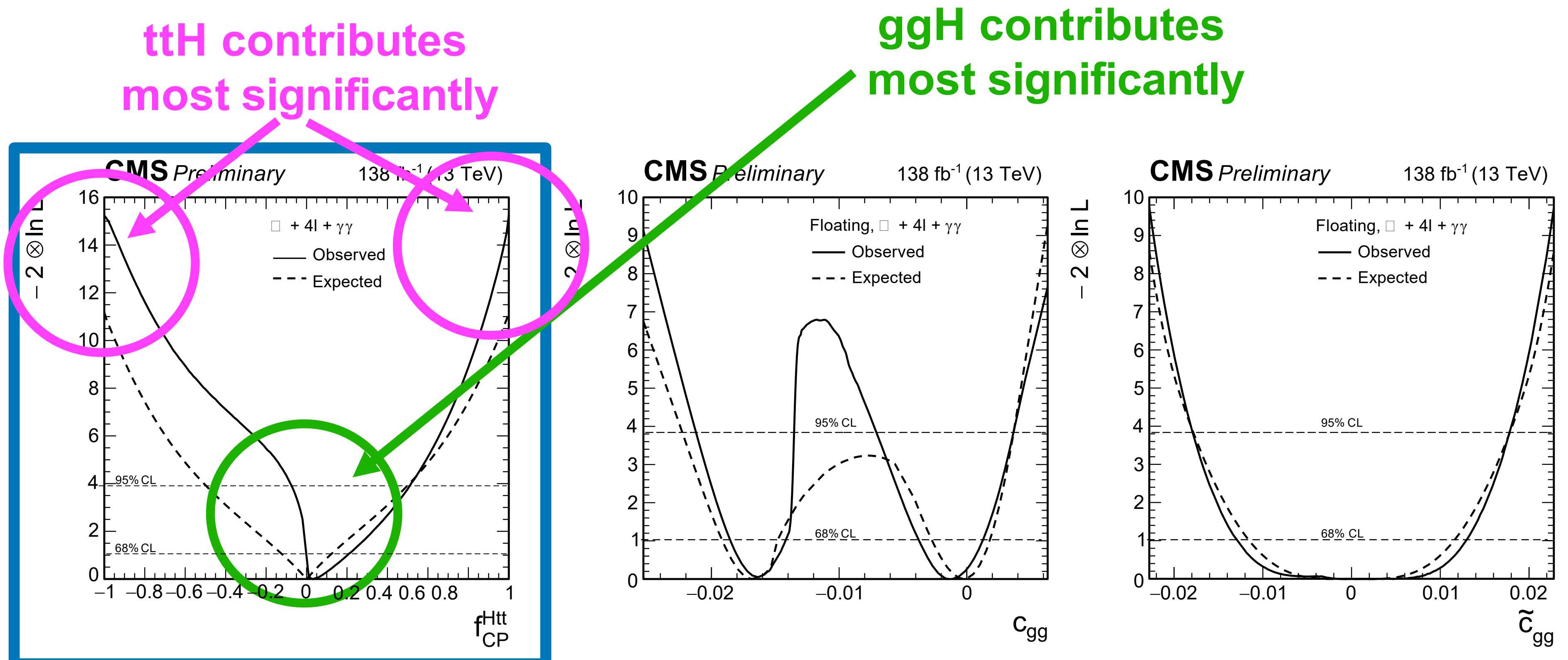


a_1^-
π^-
$\rho 0$
π^-
π^+

Tautau, gamgam, ZZ combination

- Assuming the ggH loop is dominated by the top quark we measure f_{CP}^{Htt} combining ggH, ttH, and tH

- The c_{gg} and $\tilde{c}_{gg}$ parameters are also measured with κ_t and $\tilde{\kappa}_t$ constrained by the ttH(→ZZ/γγ)



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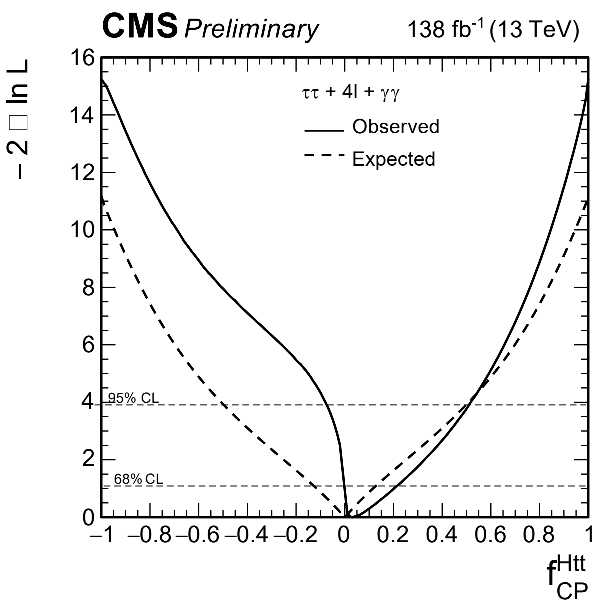

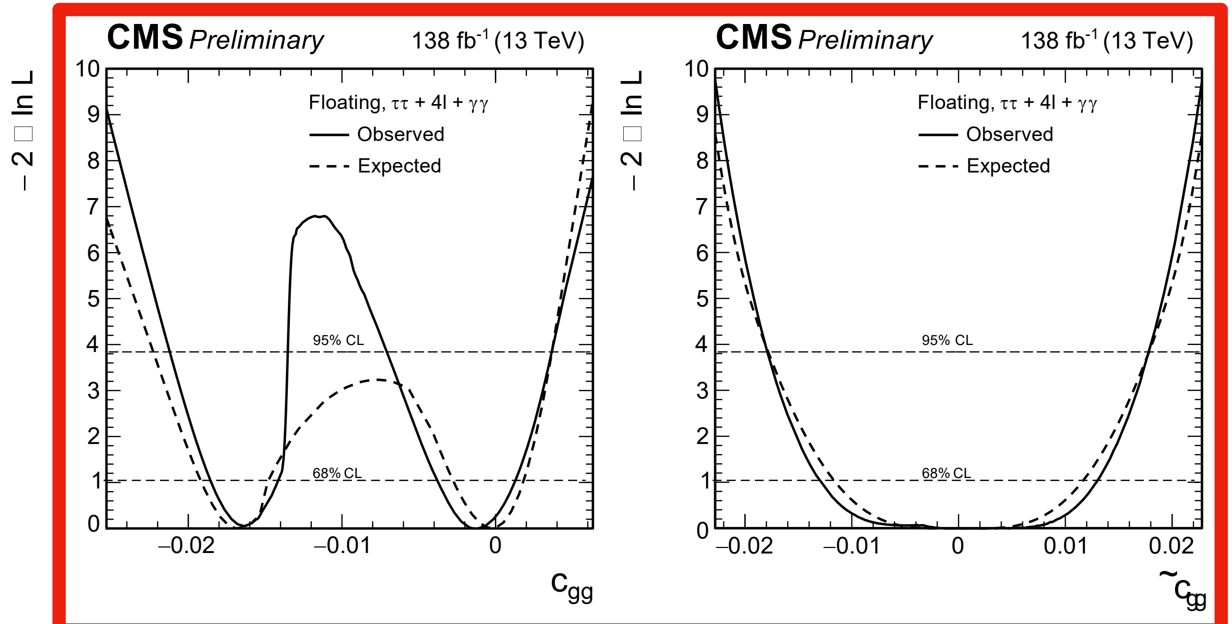

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