Higgs boson properties with $H \to \tau\tau$ decays using the CMS detector

Particle and Astroparticle Physics Division seminar, IFJ PAN
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Higgs physics after discovery

- Directions of Higgs boson studies after its discovery
  - **Precision measurements:**
    cross-section & couplings,
    mass & width
  - **Direct observation of couplings to fermions (3^{rd} generation):**
    $H \to \tau\tau$, $H \to bb$, ttH processes
  - **Rare processes:**
    coupling to 2^{nd} generation: $H \to \mu\mu$, $H \to cc$,
    self coupling (HH),
    H->Zγ/γγ* (BSM in loops),
    “Invisible” decays
  - **BSM searches:**
    additional Higgs bosons,
    exotic decays,
    anomalous couplings

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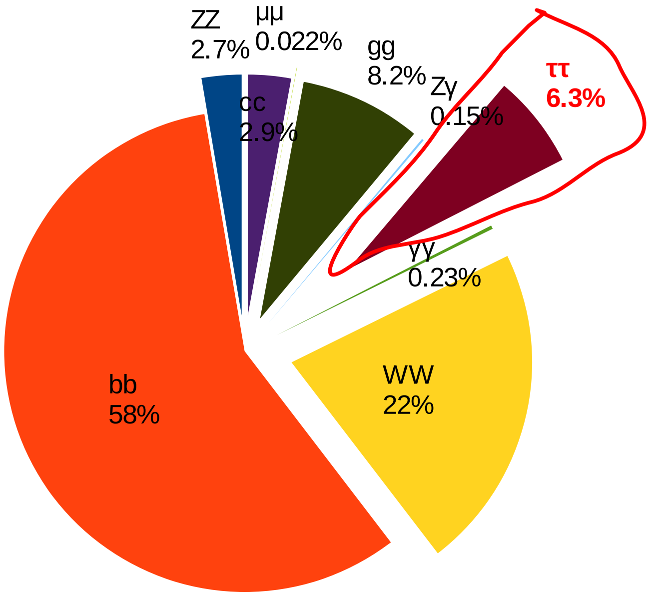

- $H\to\tau\tau$ important in this programme:
  - **Reasonable purity & Br~6%:** cross-section at high-p_T(H) and of VBF (HVV coupling)
  - **Probe Yukawa coupling**
  - **$H\to\tau\tau$ can be enhanced in BSM** (also additional Higgs bosons)

- H → ττ important in this programme:
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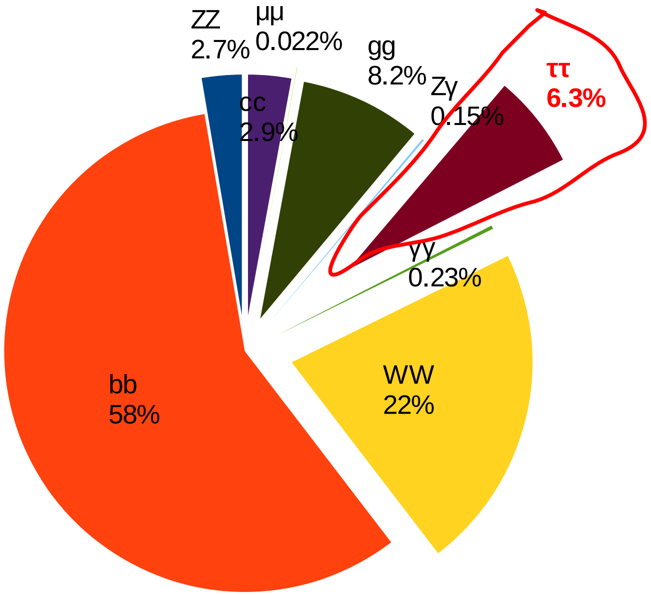
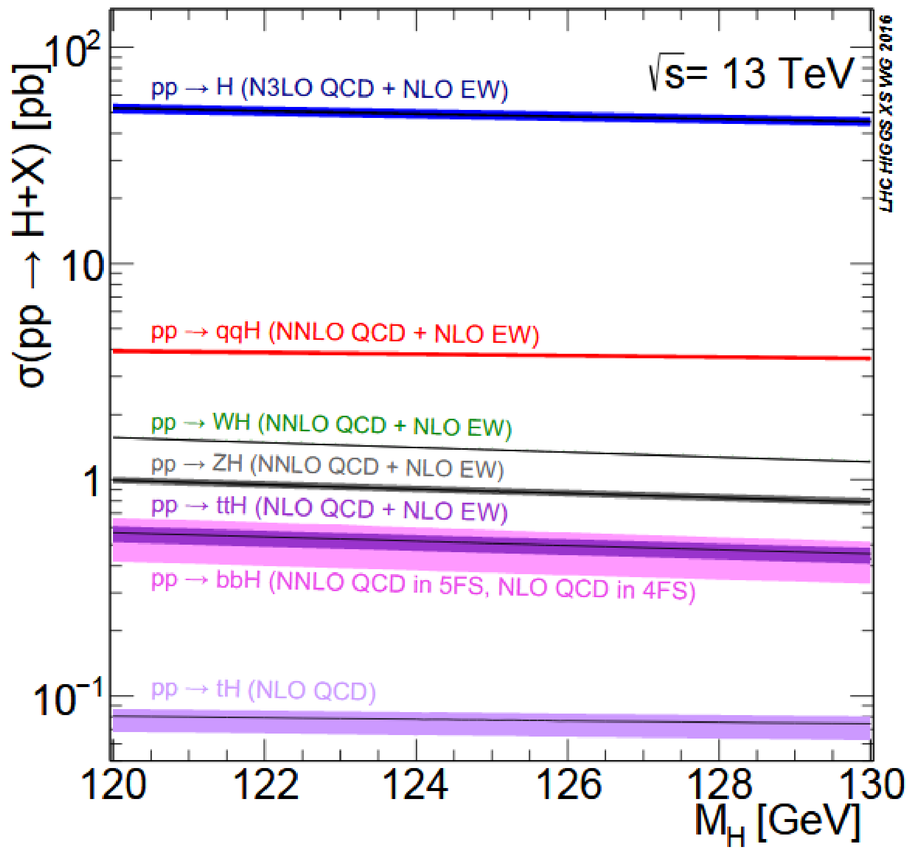


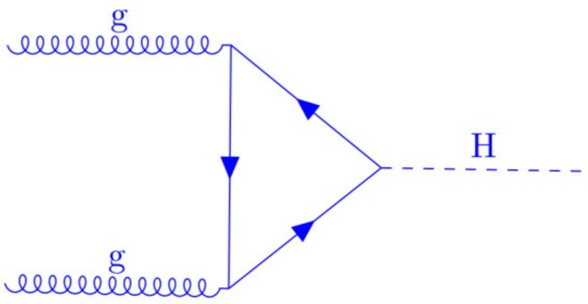
Outline

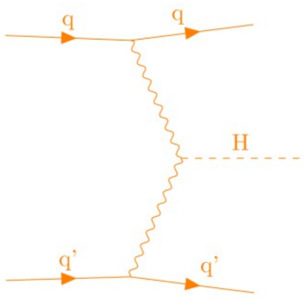
- Anatomy of H → ττ measurements
- Higgs boson cross-section with H → ττ
- Probing CP structure of tau Yukawa coupling

Higgs boson production at LHC

- Dominant production mode is gg → H
  σ~49pb at 13TeV
  (mostly via t-quark loop)
- VBF and VH production modes
  - Cross-section O(10) times smaller than for gg → H
    σ~3.8pb (VBF), ~1.4pb (WH), ~0.9pb (ZH) at 13TeV
  - Characteristic signatures: jets, leptons, p_T^{miss}
    (from V or scattering quarks)
- ttH & tH production
  σ~0.5pb (ttH), ~0.08pb (tH) at 13TeV



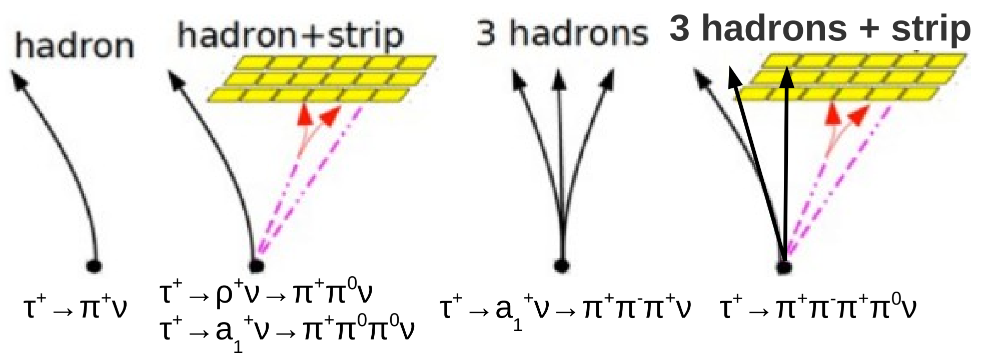




Anatomy of $H \to \tau\tau$ measurements

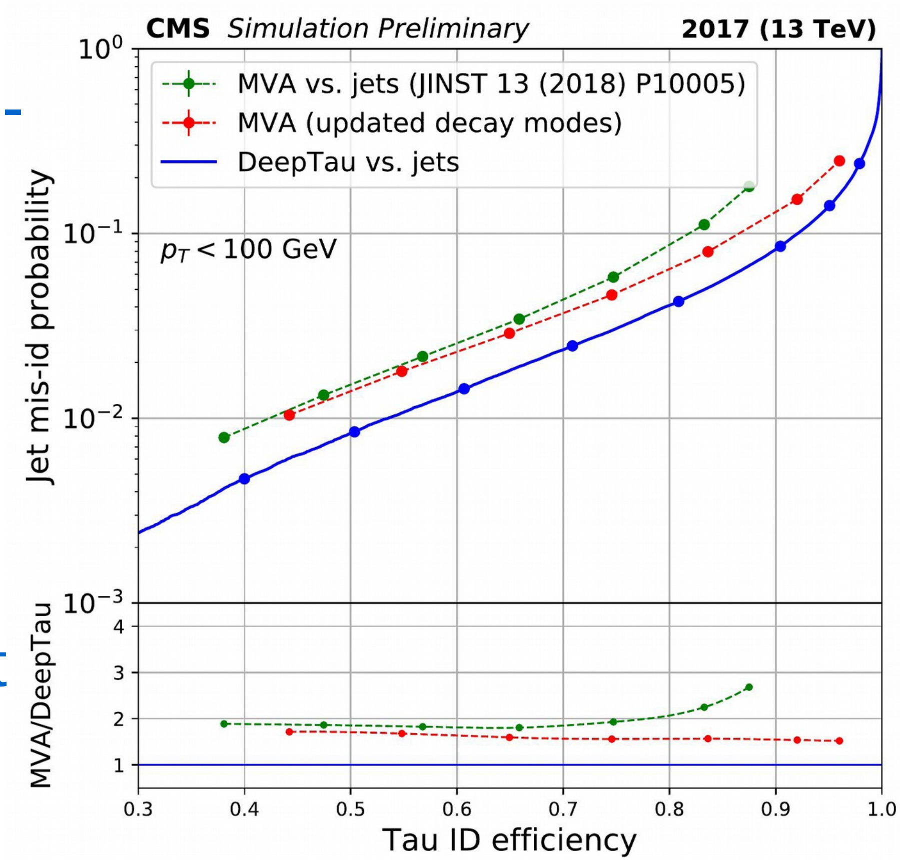
τ reconstruction in CMS

- Only visible τ decay products reconstructed
  - νs contribute to p_T^{miss}



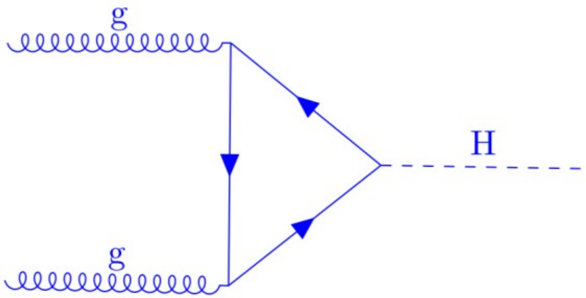
- Leptonic decays undistinguishable from prompt e and μ
- Decays to hadrons+ν (τ_h) with hadron-plus-stips (HPS) algorithm
  - Main decay modes
- Further identification with DNN
  - τ_h quantities & quantities of particles around τ_h (global and per-particle)

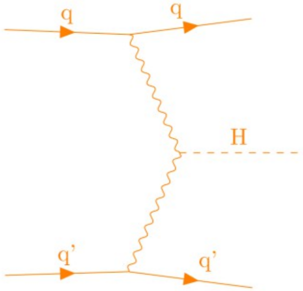
=> significant gain in performance wrt previous tauID



Anatomy of H → ττ measurements

- Use the $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, and eμ
- Exploit event topology
  - Production: 0-, 1- and 2-jet (VBF)
  - p_T of the di-τ+MET (Higgs)
  - VH(ττ) channels analysed separately





Anatomy of $H \rightarrow \tau\tau$ measurements

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  - Production: 0-, 1- and 2-jet (VBF)
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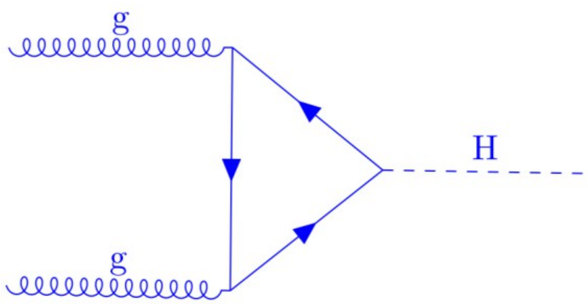
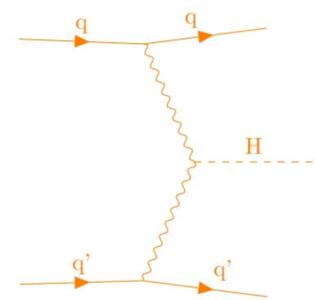
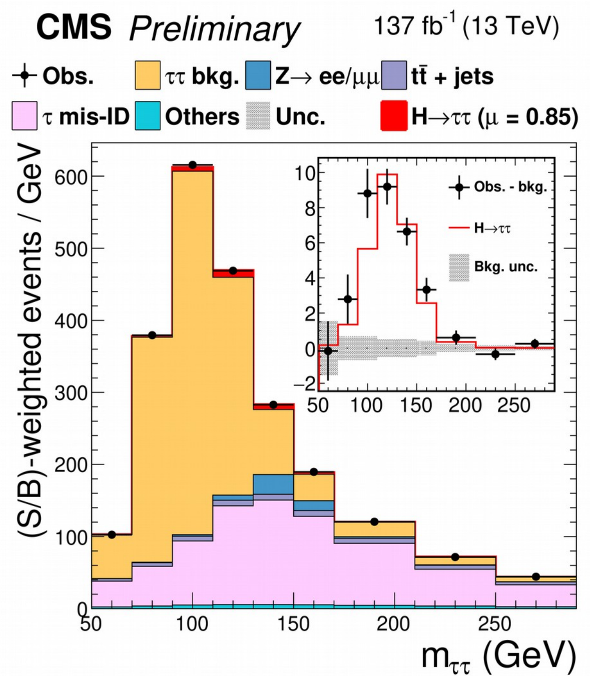
- Fully reconstructed $m_{\tau\tau}$ (res. of ~20%)
  - max likelihood based







CMS-HIG-PAS-19-010

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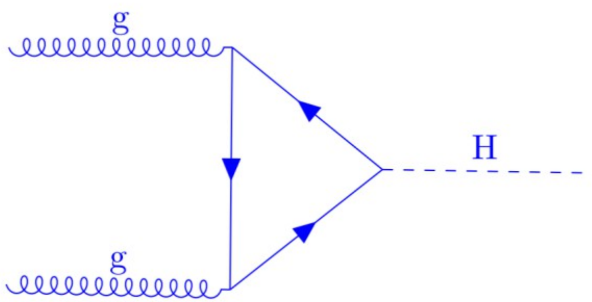
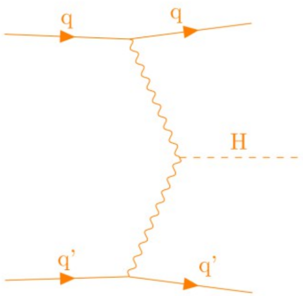
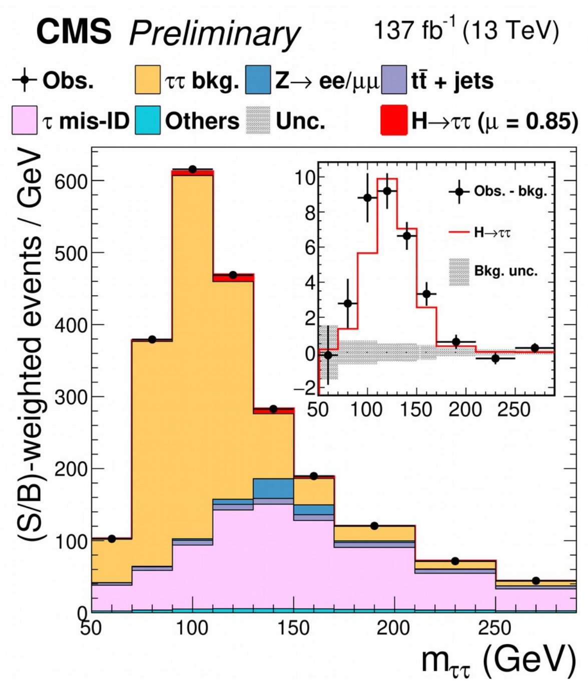
  => Cut-based or MVA-based event categories with different yields & S/B
- Fit S&B expectations to data to find event yields
  - All categories fit simultaneously
  - Systematics as nuisance parameters







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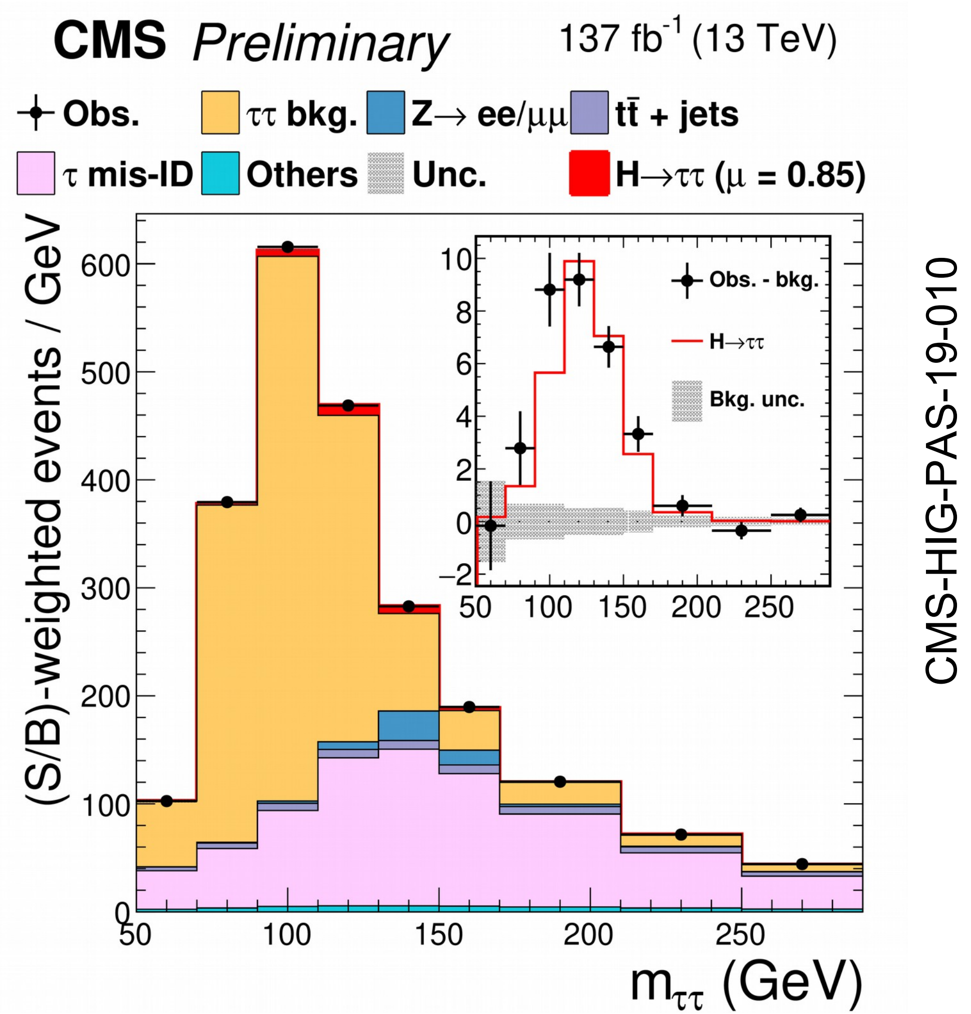
Background in H → ττ measurements

Z/γ* → ττ
Embedding technique:
Replace μs in Z/γ* → μμ data by simulated τs

Mis-ID τs (fakes)
Mainly: QCD jets, W+jets w/ jet → τ
Fake factors technique:
Apply mis-ID probability to τ-free events

Z/γ* → ee/μμ,
tt+jets,
Others (VV, single-t, ...)
Simulation (with MC/data corrections)



Higgs boson cross-section with H → ττ

CMS-HIG-PAS-19-010

Simplified template cross-section

- Simplified template cross-section (STXS):
  - generic fiducial volume (y_H<2.5)
  - specific production modes
  - mutually exclusive regions of phase-space

=> Sensitive fain-grained measurements

=> Reduced theory uncertainties

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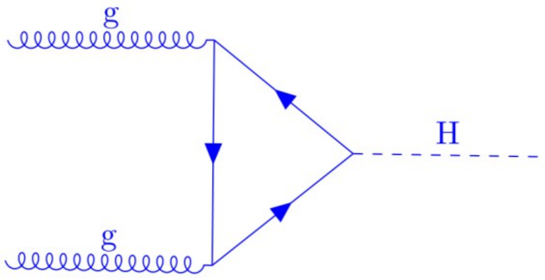
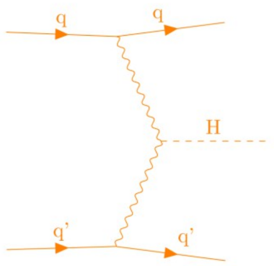
- Inclusive: total x-sec
- Stage 0: production processes (gg→H, VBF)





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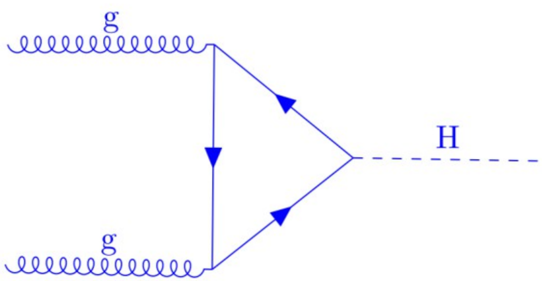
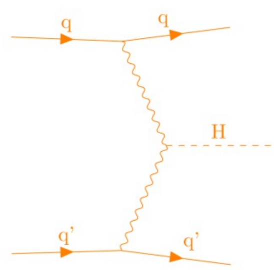
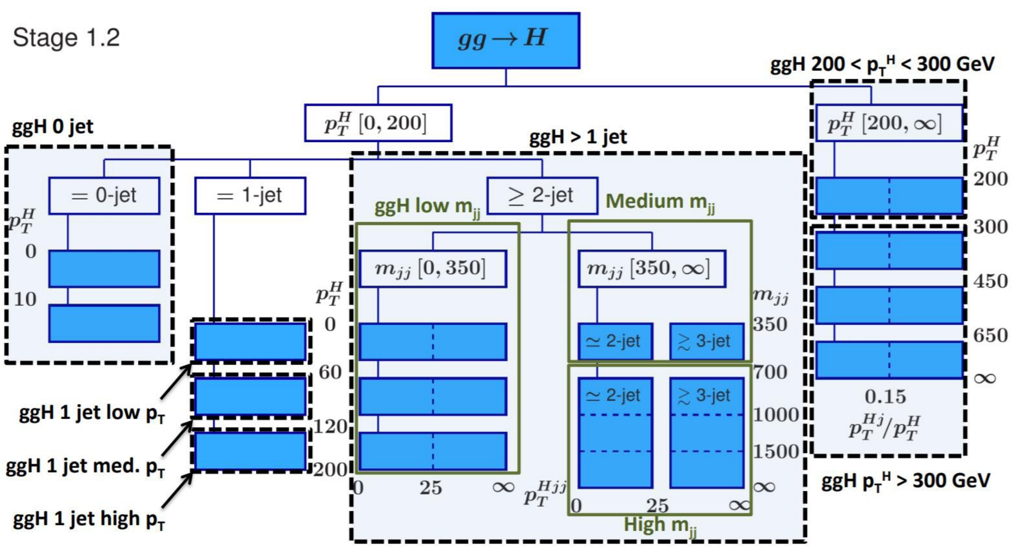
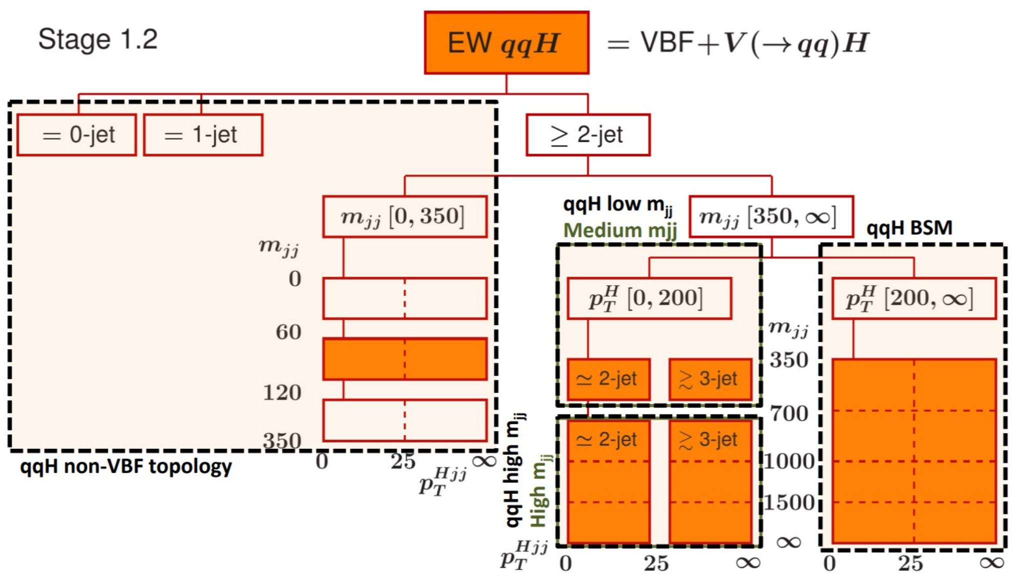
- Stage 0: production processes ($gg \rightarrow H$, VBF)
- Stage 1.2: additional divisions (below), #jet, p_T(H), mjj, ...









Measurement strategy

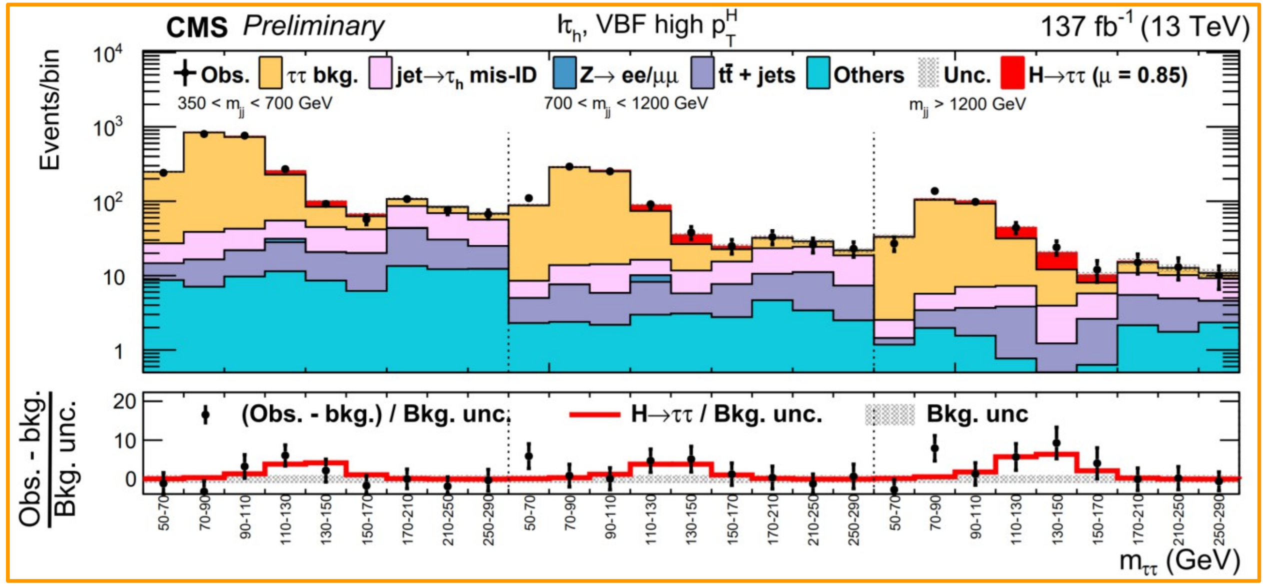
- Full Run-2 data of 137/fb
- Five event categories
  (motivated by STXS bins)
  2D fit in each ($m_{\tau\tau}$ & other):

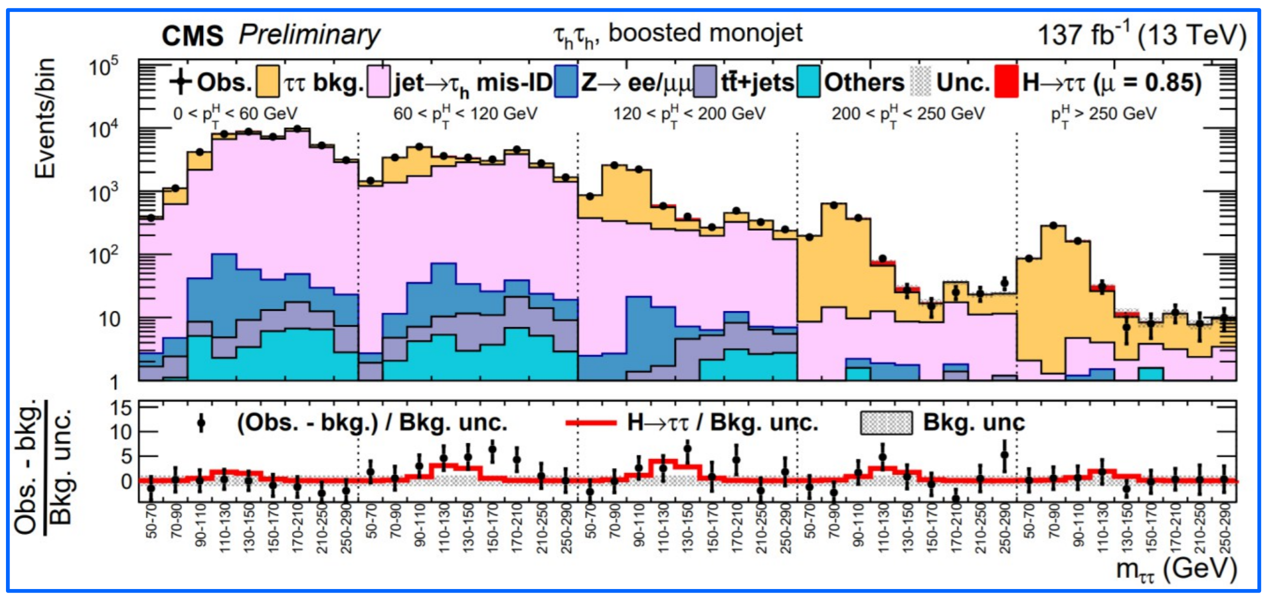
VBF, low & high $p_T(H)$; m_{jj}

0-jet; $p_T(\tau_h)$

Boosted: 1-jet, ≥2-jets; $p_T(H)$

- **Highest sensitivity at high $p_T(H)$ and for VBF topology**



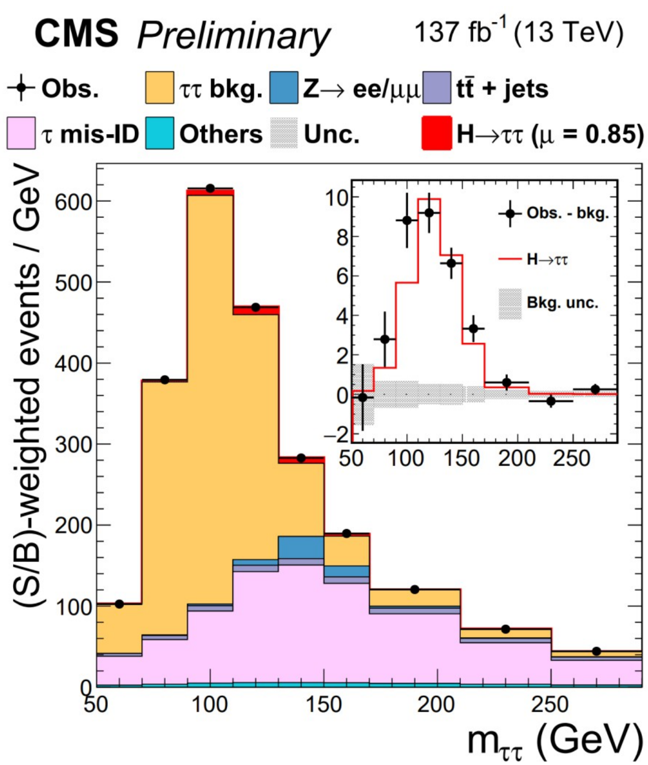


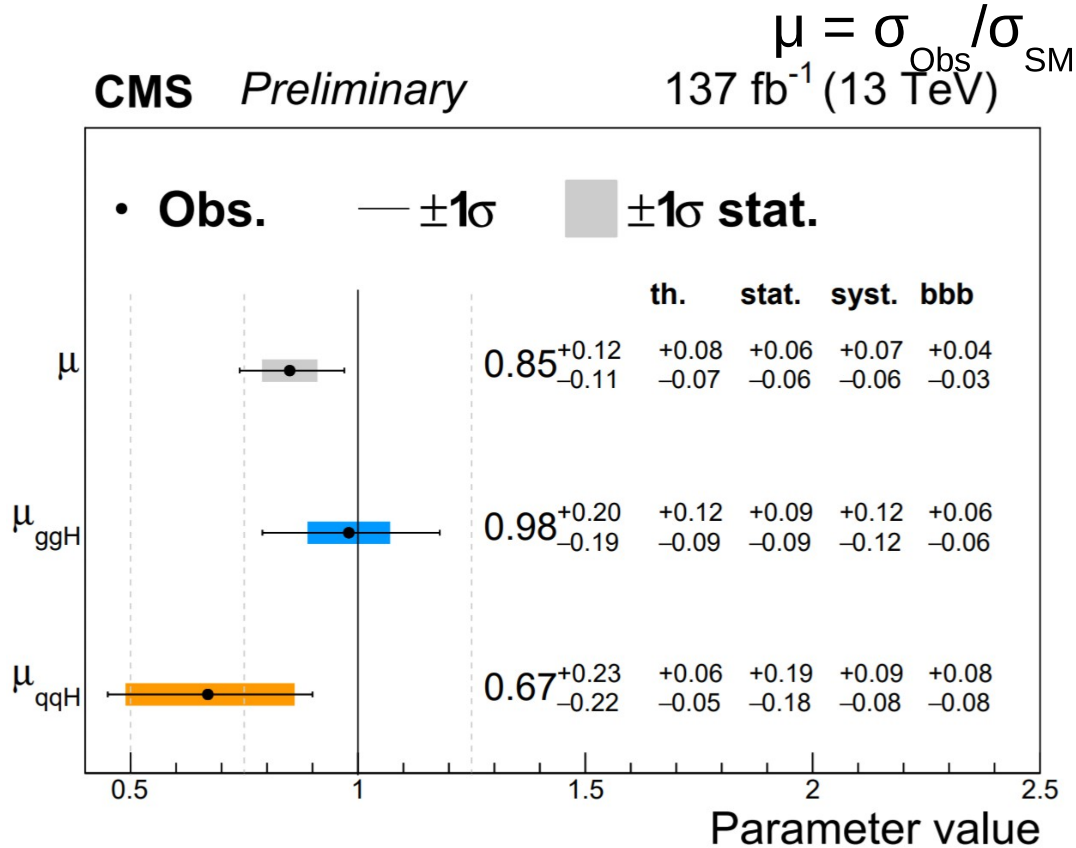
Results: inclusive & stage 0

- Inclusive and gg→H **not** dominated by stat. unc. Experimental unc. of
  - ~10% for inclusive
  - ~20% for gg→H
  - ~30% for VBF (qqH)
- In agreement with SM predictions

$\sigma\mathcal{B}(\mathrm{H}\to\tau\tau)$ (fb)

Process	Measured	SM Prediction
Inclusive	2960^{+394}_{-370}	3422^{+172}_{-172}
ggH	3060^{+592}_{-552}	3051^{+160}_{-160}
qqH	$221^{+75.3}_{-73.3}$	$329^{+9.67}_{-9.67}$

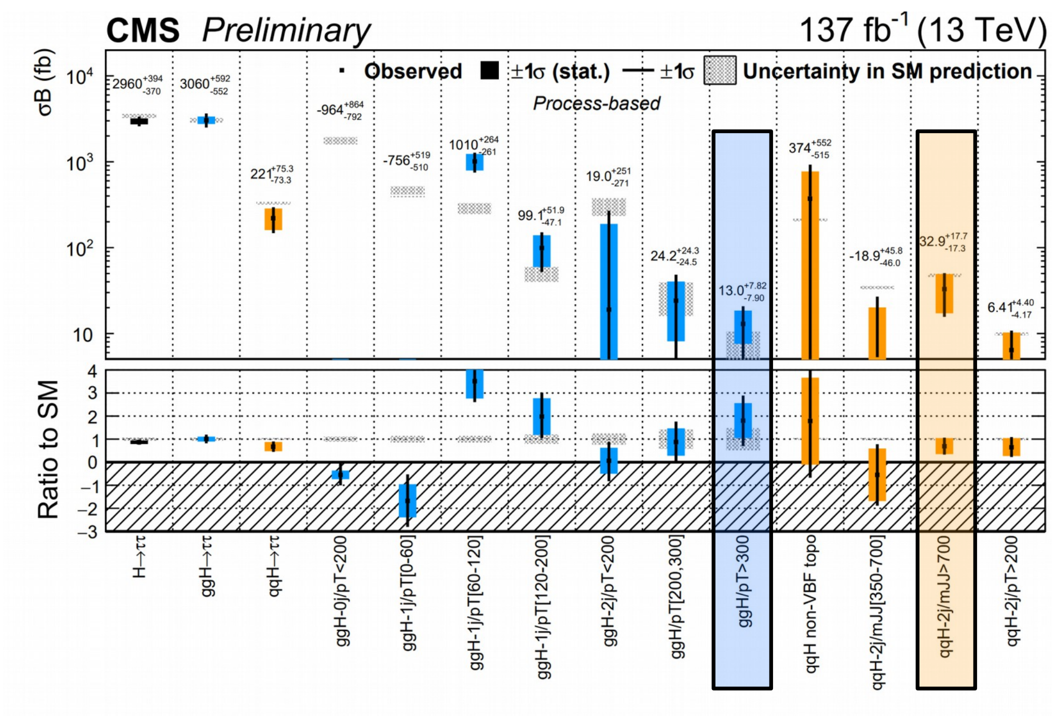


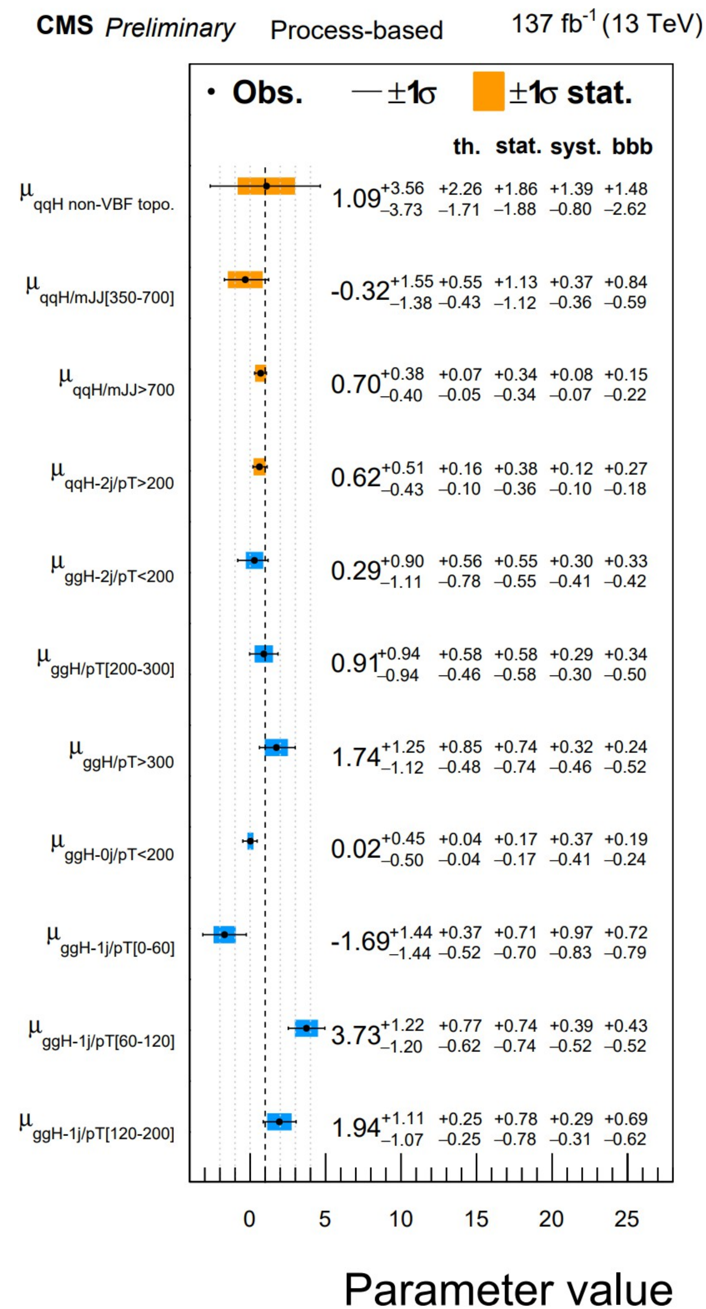


Results: stage 1.2

$\mu = \sigma_{Obs}/\sigma_{SM}$

- Result using "bin-merging schemes" when
  - Poor per-process sensitivity
  - Correlation due to limited resolution
- Two schemas
  - Process-based (here)
  - Topology-based (backup)
- Highest sensitivity at high p_T(H) and for VBF topologies (inaccessible with other decays)





CP structure of Y_τ coupling

CMS-HIG-PAS-20-006

Tau Yukawa coupling (Y_τ)

- Yukawa coupling: CP-odd term can occur at tree level (no suppression by NP scale!)

$$\mathcal{L}_Y = -\frac{m_\tau H}{v}\left(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau\right)$$

CP-even (scalar)

CP-odd (pseudoscalar)

- Parametrisation: effective CP mixing angle:

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

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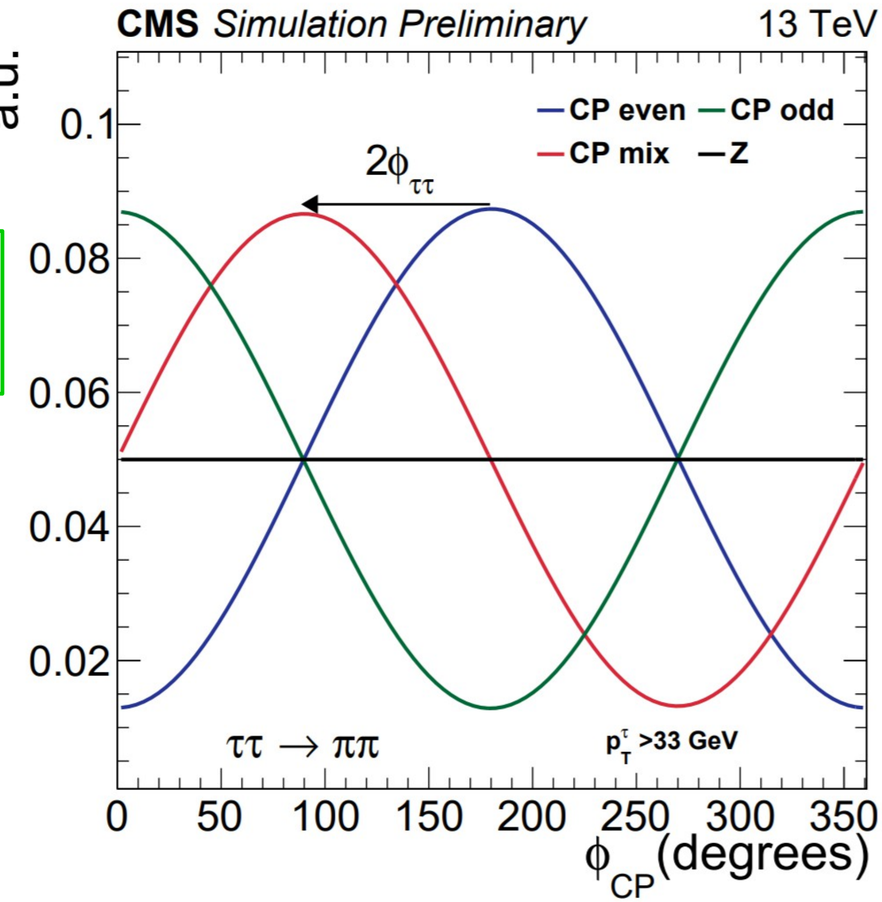


- Parametrisation: effective CP mixing angle:

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

- H $\to\tau\tau$ decay rate in a function of angle between τ-decay planes (φ_{CP}) sensitive on $\varphi_{\tau\tau}$

$$d\Gamma(H \to \tau^+\tau^-) \approx 1 - b(E^+)b(E^-)\frac{\pi^2}{16}\cos(\phi_{CP} - 2\phi_{\tau\tau})$$

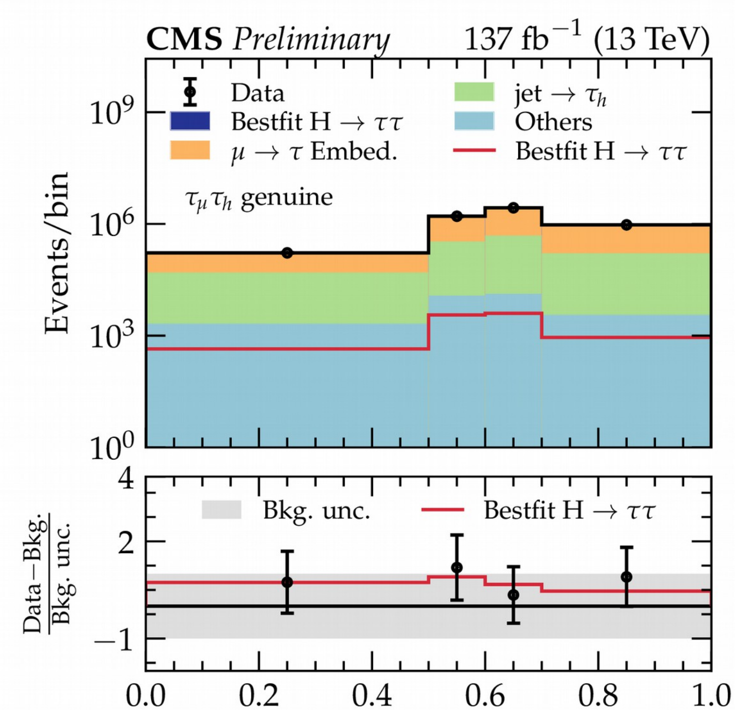
Strategy

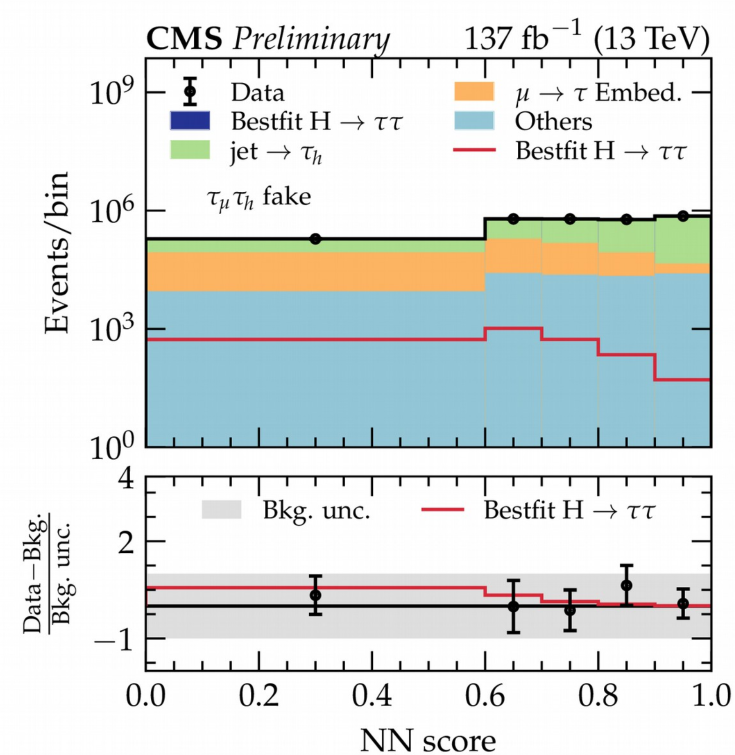
- Full Run-2 data of 137/fb
- Most sensitive channels: $\mu\tau_h$ & $\tau_h\tau_h$ (~50% of all ττ final states)

Mode	$\mu^\pm$	$\pi^\pm$	$\rho^\pm \to \pi^\pm\pi^0$	$a_1^\pm \to \pi^\pm\pi^0\pi^0$	$a_1^\pm \to \pi^\pm\pi^\mp\pi$
$\mathcal{B}(\%)$	17.4	11.5	25.9	9.5	9.8
Symbol	μ	π	ρ	a_1^{1pr}	a_1^{3pr}

- Three event categories with ML (muli-class NN/BDT):
  - H → ττ signal
  - Genuine ττ (mainly Z/γ* → ττ)
  - Fakes (mainly QCD multi-jets & W+jets)

  => Use $m_{\tau\tau}$ and event topology & kinematics
- Reconstruct decay planes (signal cat.)
- Fit expectation to data in all categories
  - 2D fit in signal category: φ_{CP} vs ML score





Decay plane reconstruction

- In LHC generally not possible
  - Momentum carried by υs, not known Higgs rest frame

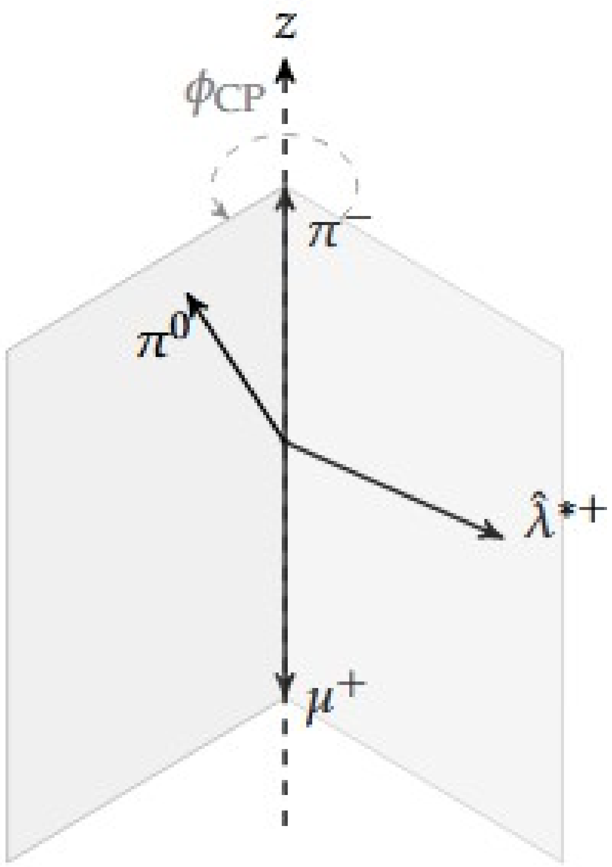
  => use approximated methods
- Impact parameter method for single charged particle ($\mu^{\pm}$, $\pi^{\pm}$)

  (by S.Berge et al)

  Plane spanned by IP and momentum of charged particle
- Neutral pion method (ρ, a_1^{1pr}, a_1^{3pr})

  (by Z.Wąs et al)

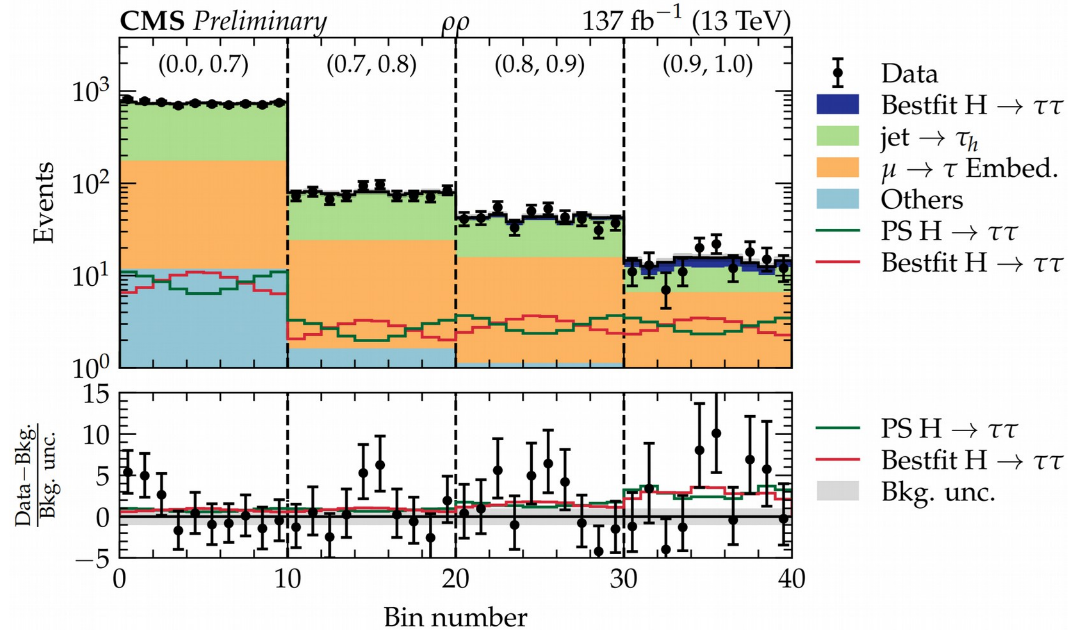
  Plane spanned by momentum of charged and neutral particle
  - a_1^{1pr}: momenta of $2\pi^0$ summed up
  - a_1^{3pr}: find pair compatible with ρ and use instead of π^0
- Combine planes in zero momentum frame (ZMF) of two charged particles

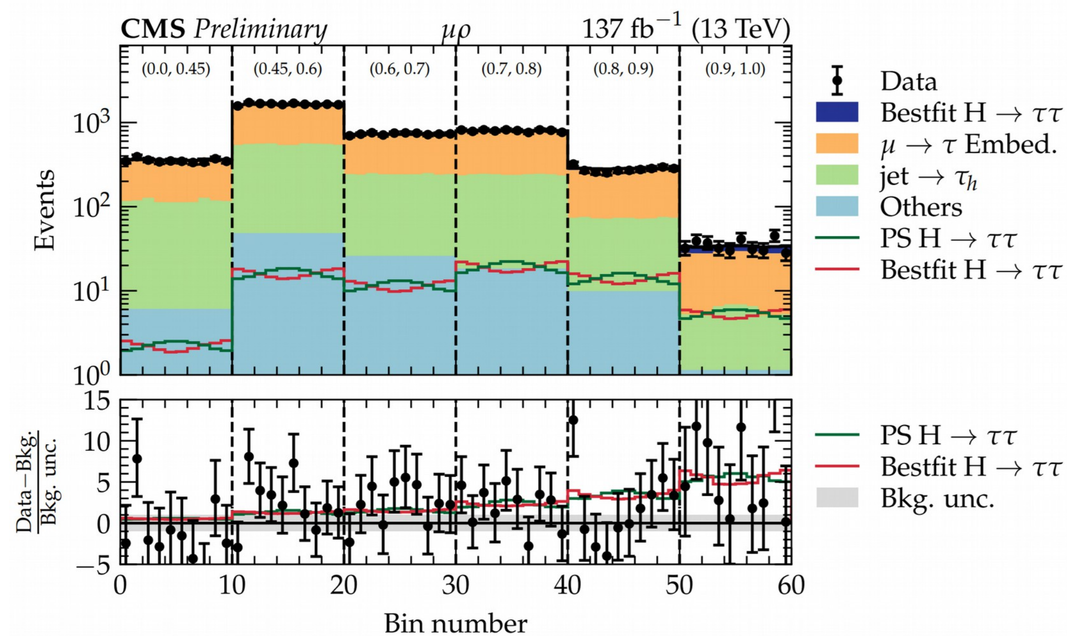


Example signal categories: ρρ, μρ

Optimise sensitivity

- Dedicated BDT for τ_h decay-mode identification (on top of HPS) => reduces smearing due to incorrect decay-mode assignment (improvement of 15-20% over HPS)
- Impact parameters estimated with 3D helical track extrapolation towards PV => more precise IP and its uncertainty





Most sensitive channels: ρρ, πρ, μρ

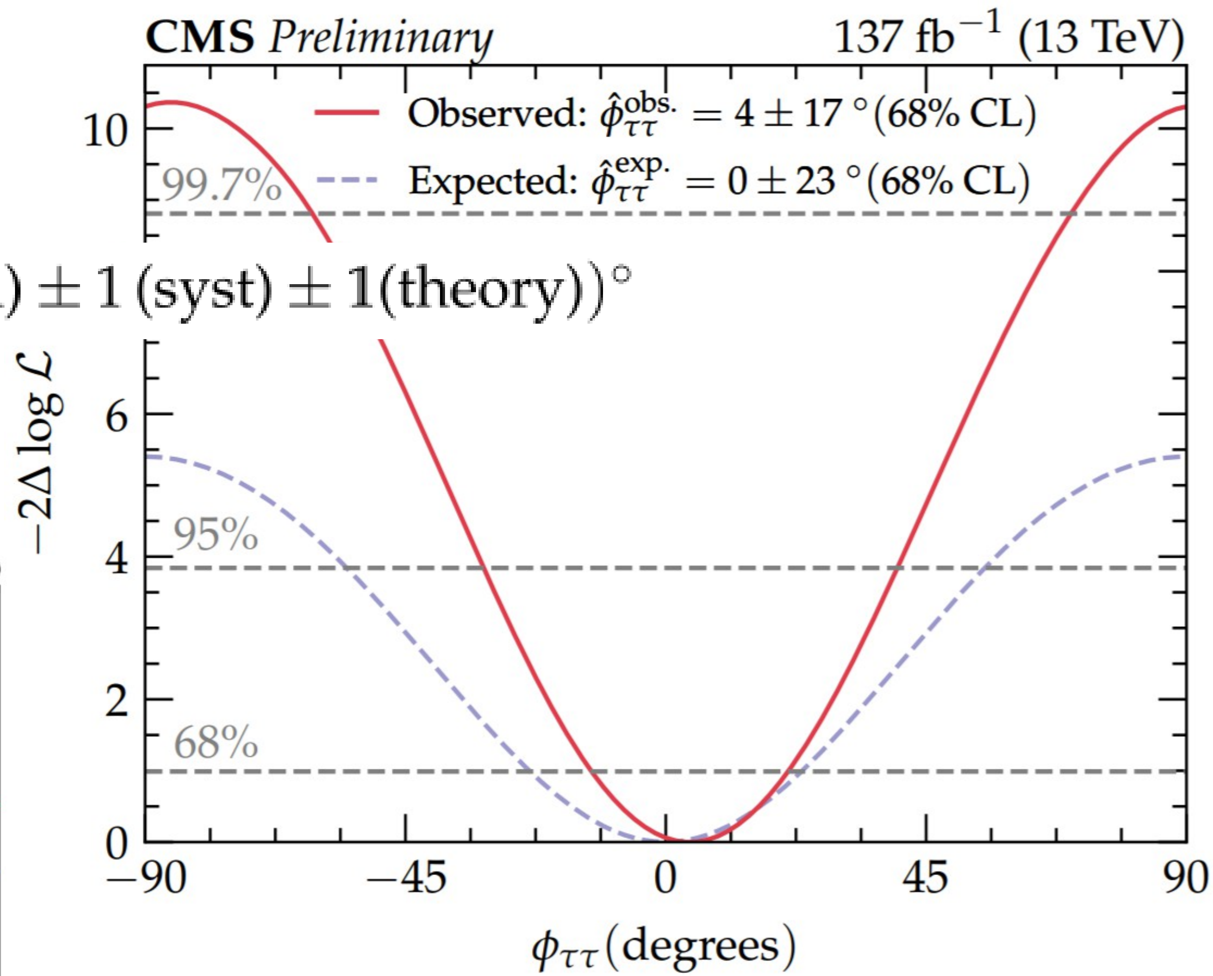
- each with ~1σ separation between CP-even and -odd

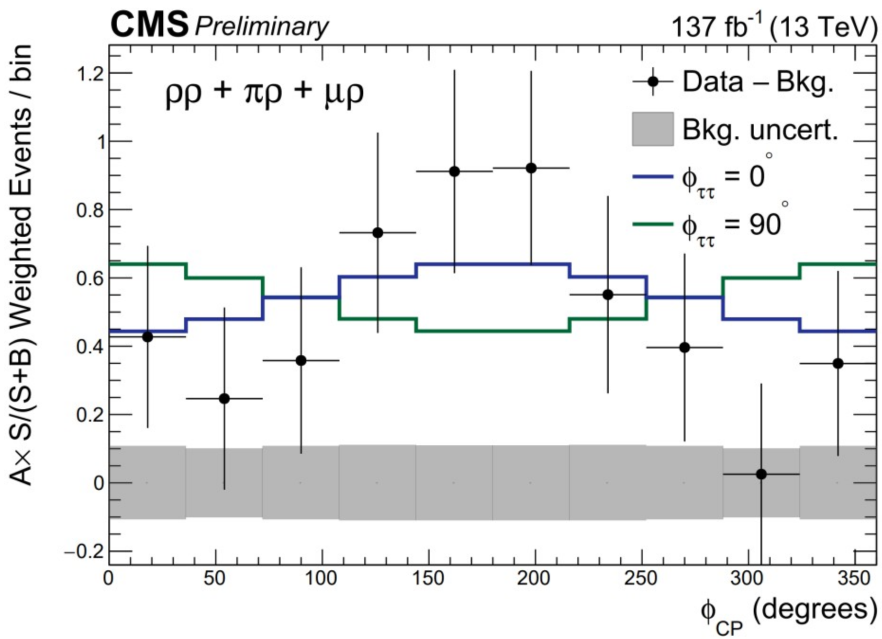
Results: $\varphi_{\tau\tau}$

- 1st measurement of CP structure of Y_τ
- Consistent with SM: CP-even preferred over CP-odd with 3.2σ

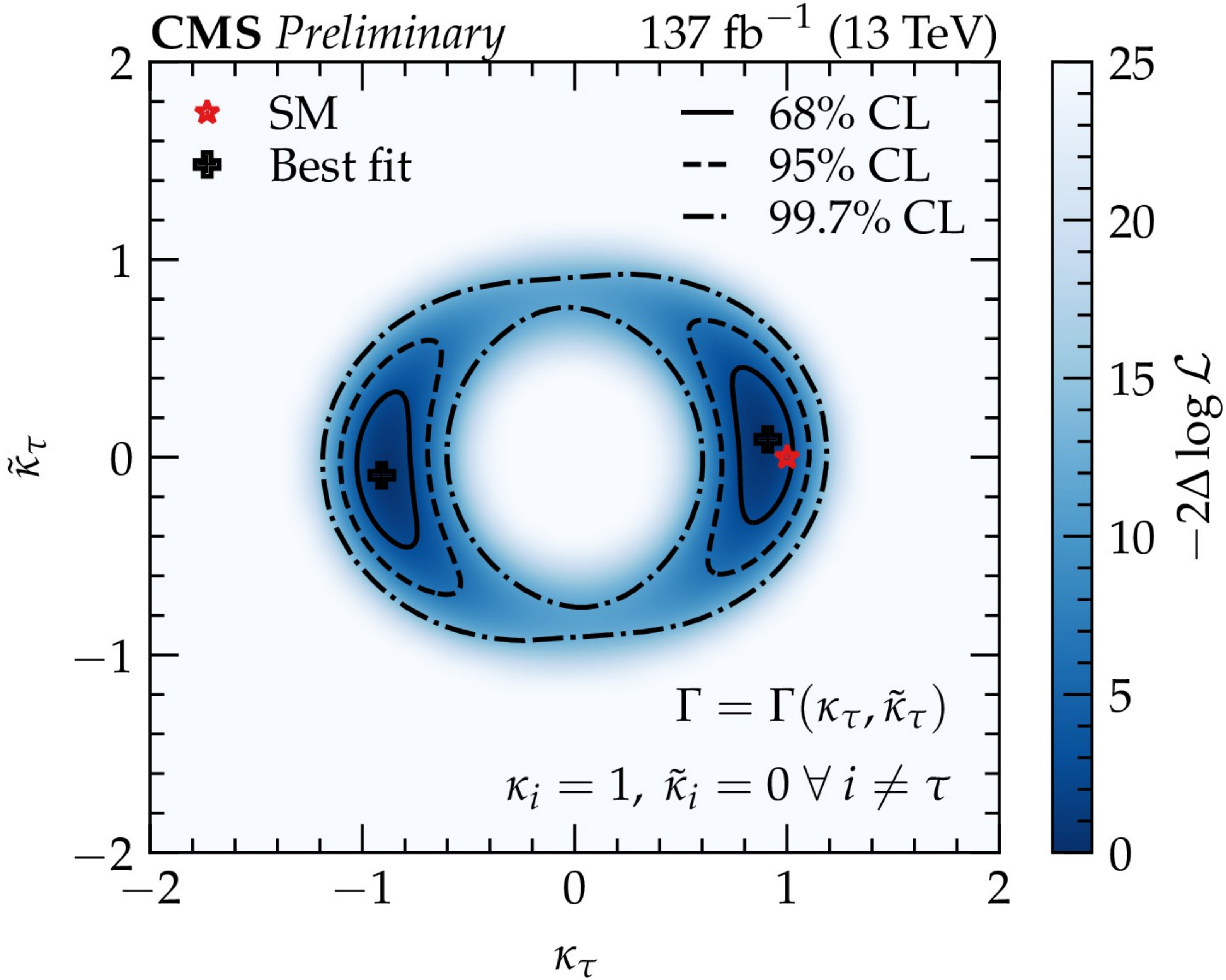
$$\phi_{\tau\tau} = (4 \pm 17\,(\text{stat}) \pm 2(\text{bin-by-bin}) \pm 1\,(\text{syst}) \pm 1(\text{theory}))^\circ$$

- Uncertainty dominated by statistic





Results: reduced couplings

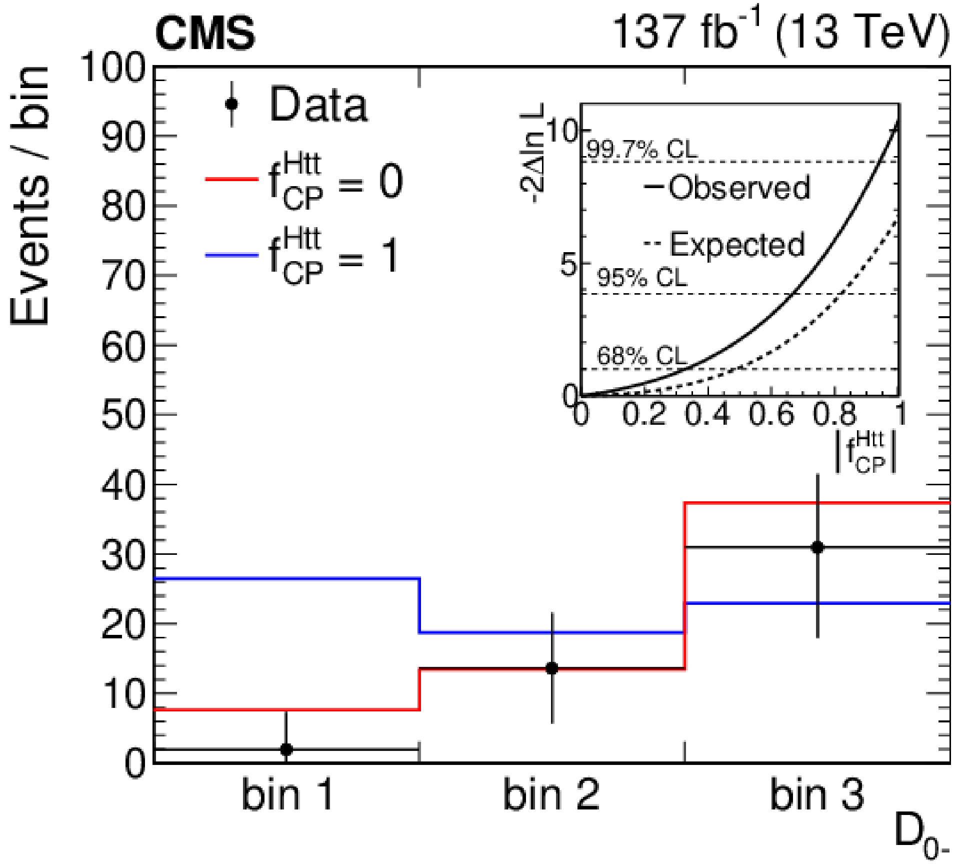


Excursion: Y_t measurement

- Same coupling structure
- Parametrised by

$$f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2} \,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$$

- Measured with ttH→γγ
- BDT (estimate of optimal D_{0-} variable) used; it exploits:
  - jet kinematics & b-tagging,
  - γγ kinematics (w/ mass),
  - lepton kinematics & multiplicity
- $m_{\gamma\gamma}$ fit in D_{0-} bins
- Results:
  - Obs: $f_{CP}^{Htt} = 0.00 \pm 0.33$ at 68% CL
  - Exp: $f_{CP}^{Htt} = 0.00 \pm 0.49$
  - CP-even preferred over CP-odd with 3.2σ (exp. 2.6σ)



- Translates on
  - Obs: $\varphi_{tt} < 35$ deg
  - Exp: $\varphi_{tt} < 44$ deg
- Similar sensitivity by ATLAS

Summary

- Run-2 opens era of precise measurements of the Higgs boson
- Measurements with $H \rightarrow \tau\tau$ decays provides unique opportunities:
  - Production cross-section measurements at high $p_T(H)$ and high m_{jj} (VBF topology)
    - Measured in STXS framework;
    - Measurement of differential cross-sections ongoing
  - **Probing of CP structure of tau Yukawa coupling**
    - CMS measurement (1st of this type!) agrees with SM and excludes pure CP-odd coupling at 3.2σ
    - Inclusion of $e+\tau_h$ and other analysis improvements will increase sensitivity of the measurement by ~10%

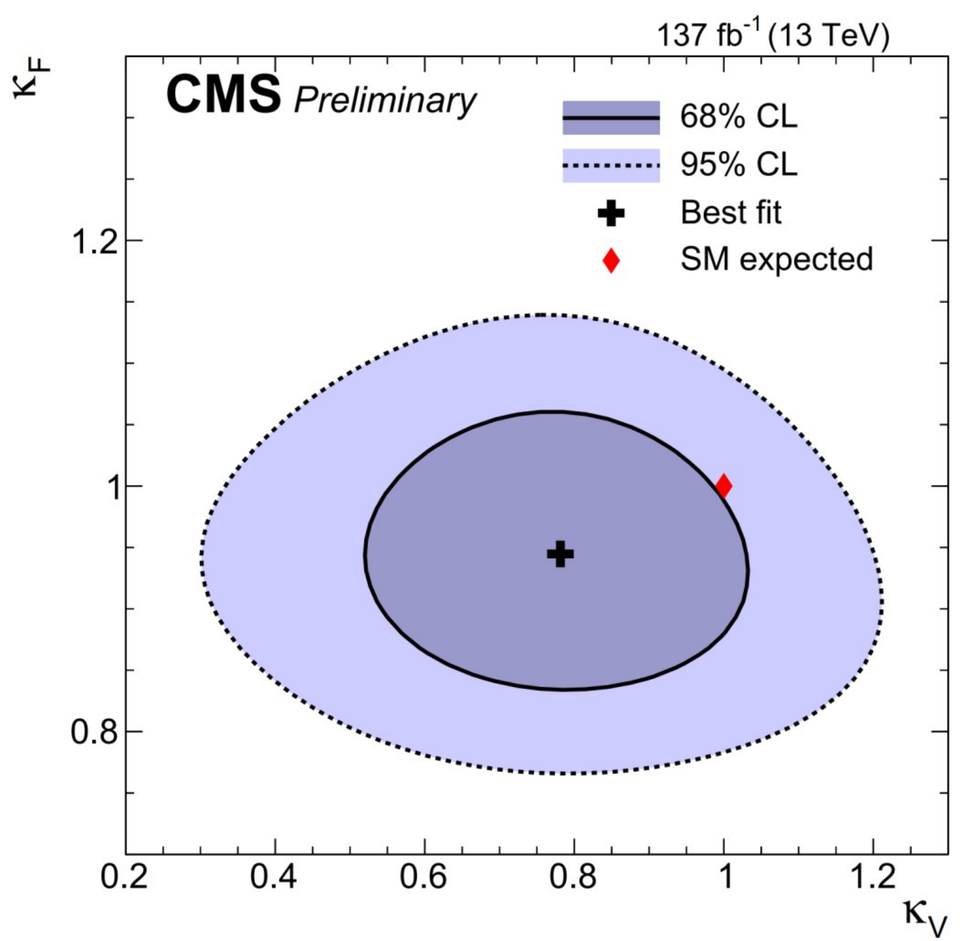
=> The boson looks like **the** (minimal) **SM Higgs boson** (at least with current precision)

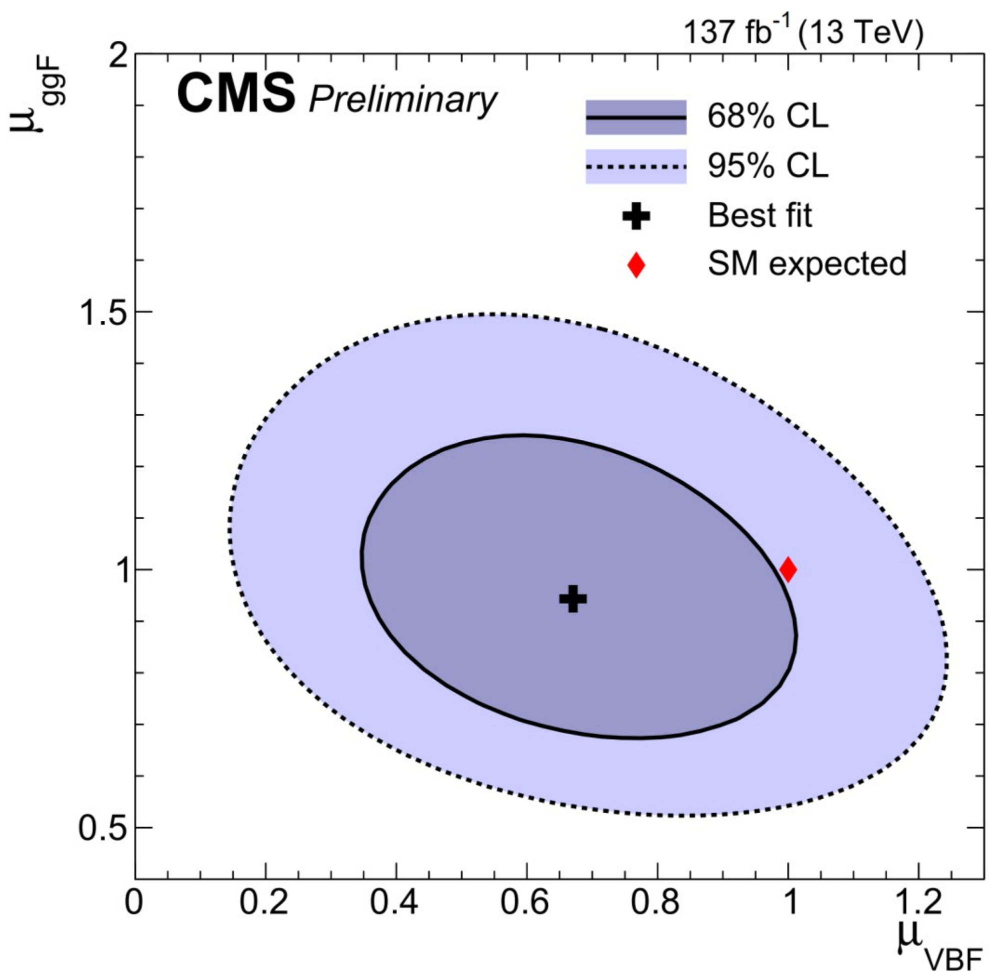
Thank you!

Additional material

Results: gg → H vs VBF

- Close to 1 sigma agreement with SM
  - Presented as signal strengths ($\mu = \sigma_{Obs}/\sigma_{SM}$) and coupling modifiers (κ)

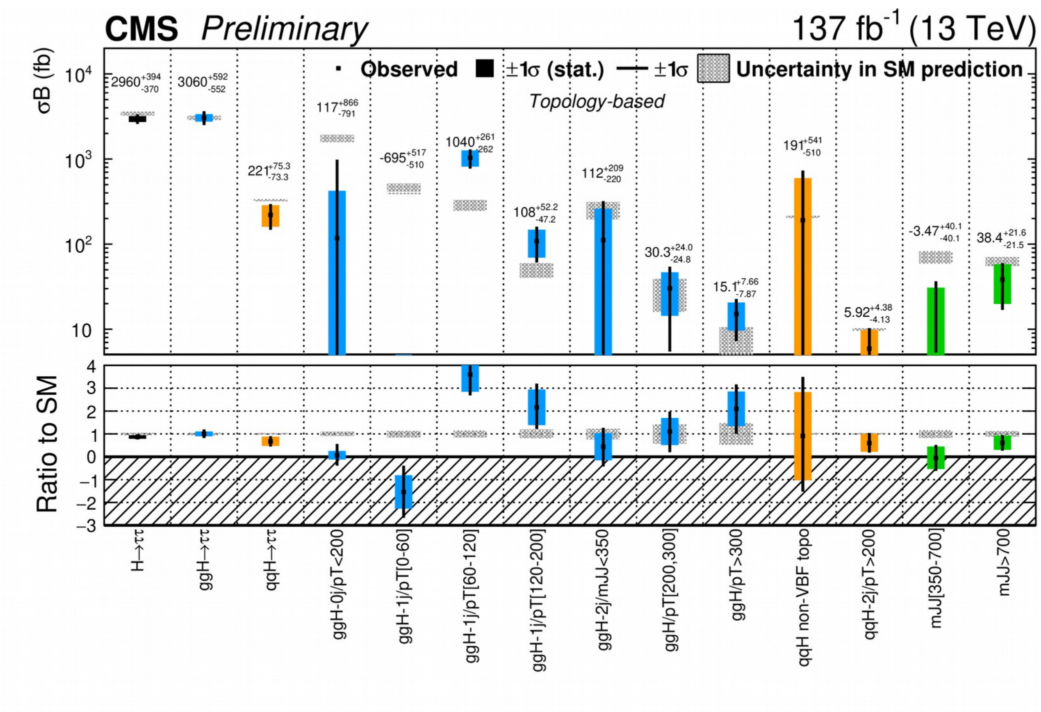


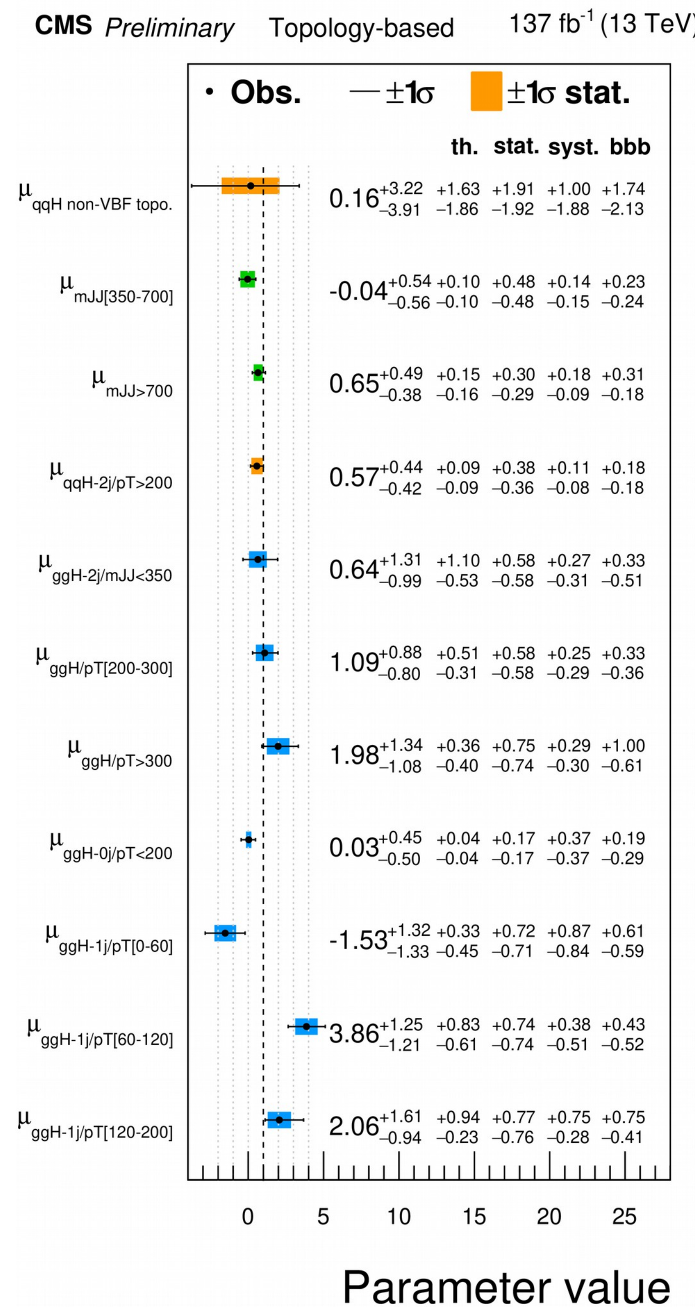


Results: stage 1.2

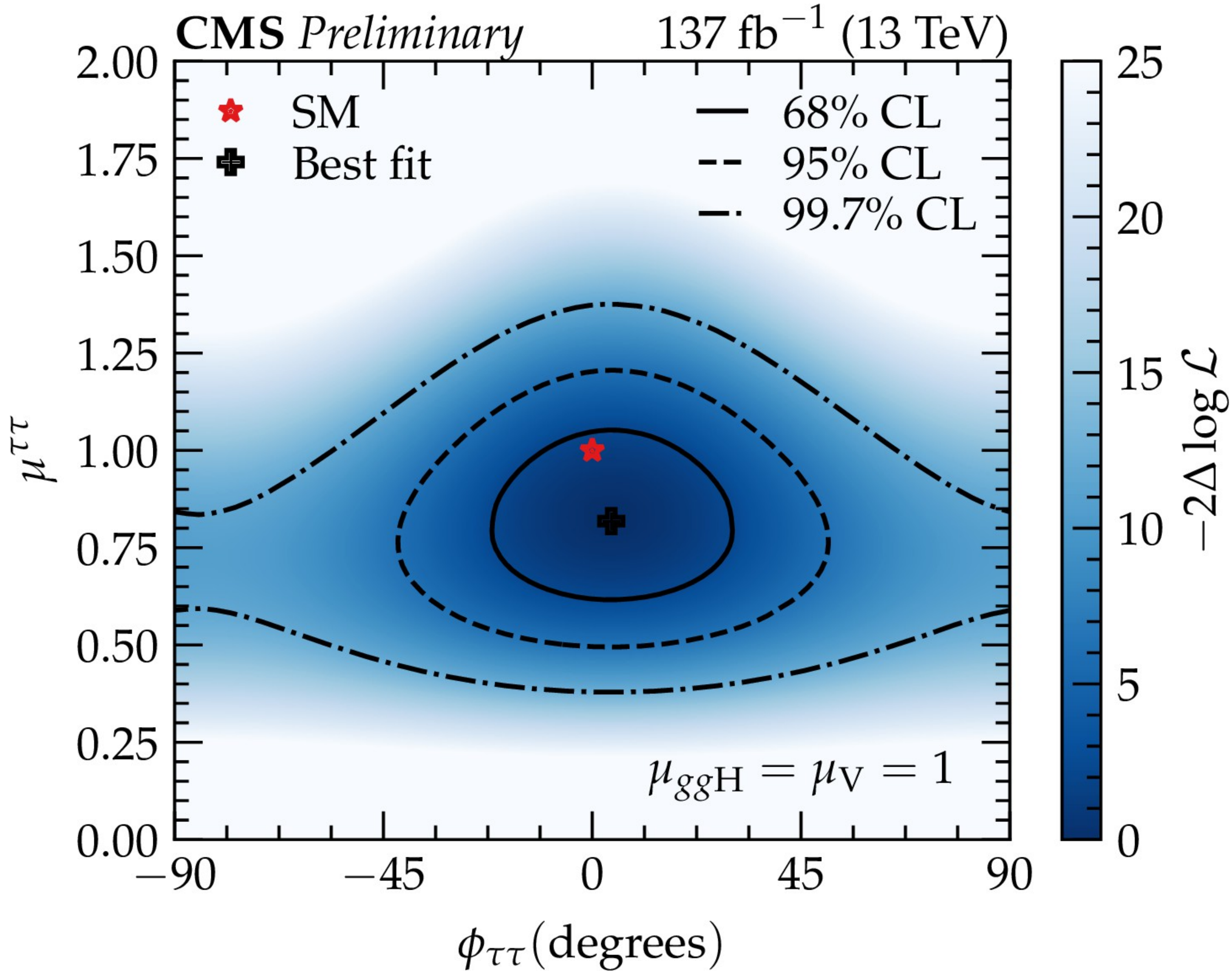
$\mu = \sigma_{Obs}/\sigma_{SM}$

- Result using topology-based merging
- Highest sensitivity at high $p_T(H)$ and for VBF topologies (inaccessible with other decays)





$\Phi_{\tau\tau}$ vs signal strength



MVA τ_h decay-mode ID

Decay mode migrations lead to incorrect φ_{CP} estimates

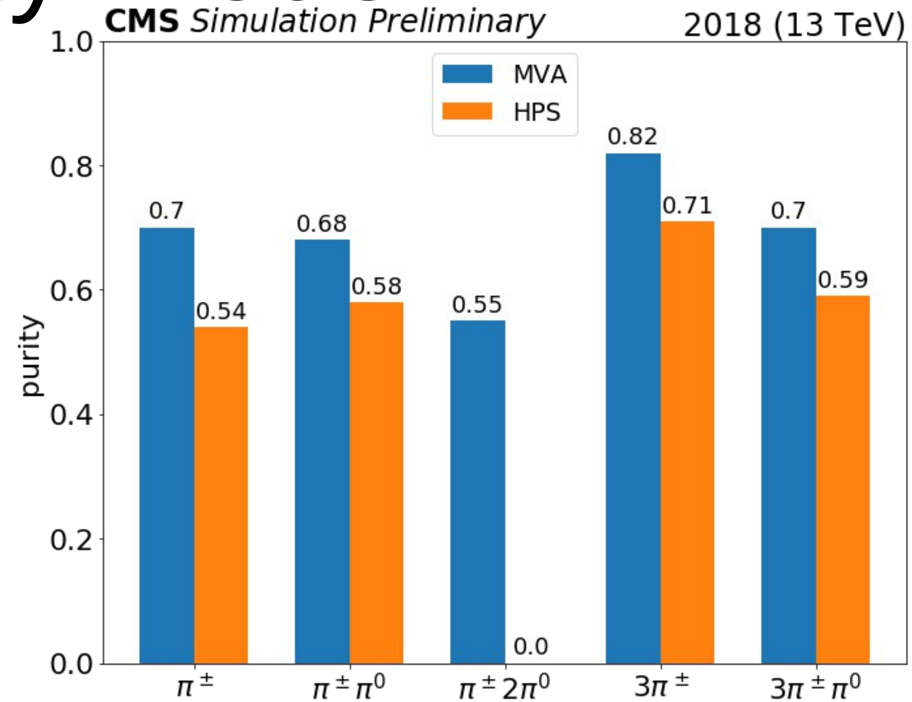
=> Dedicated BDT developed to improve decay mode identification on top of HPS

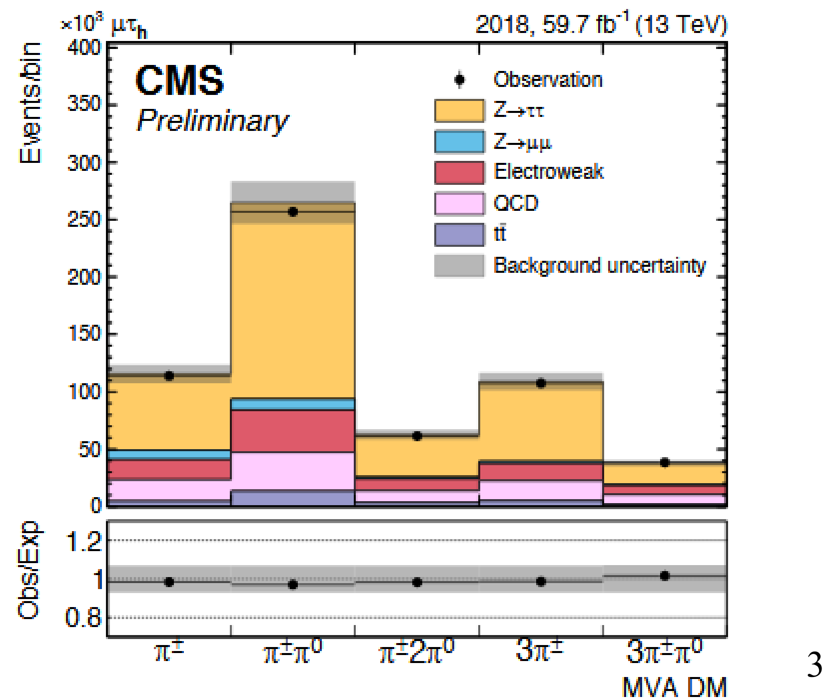
Inputs include:

- Inv. masses of tau decay products,
- angular distribution of photons in strips,
- HPS decay mode

Substantial gain in purity and Efficiency => Improves φ_{CP} sensitivity by ~15-20%

CMS-DP-2020-041





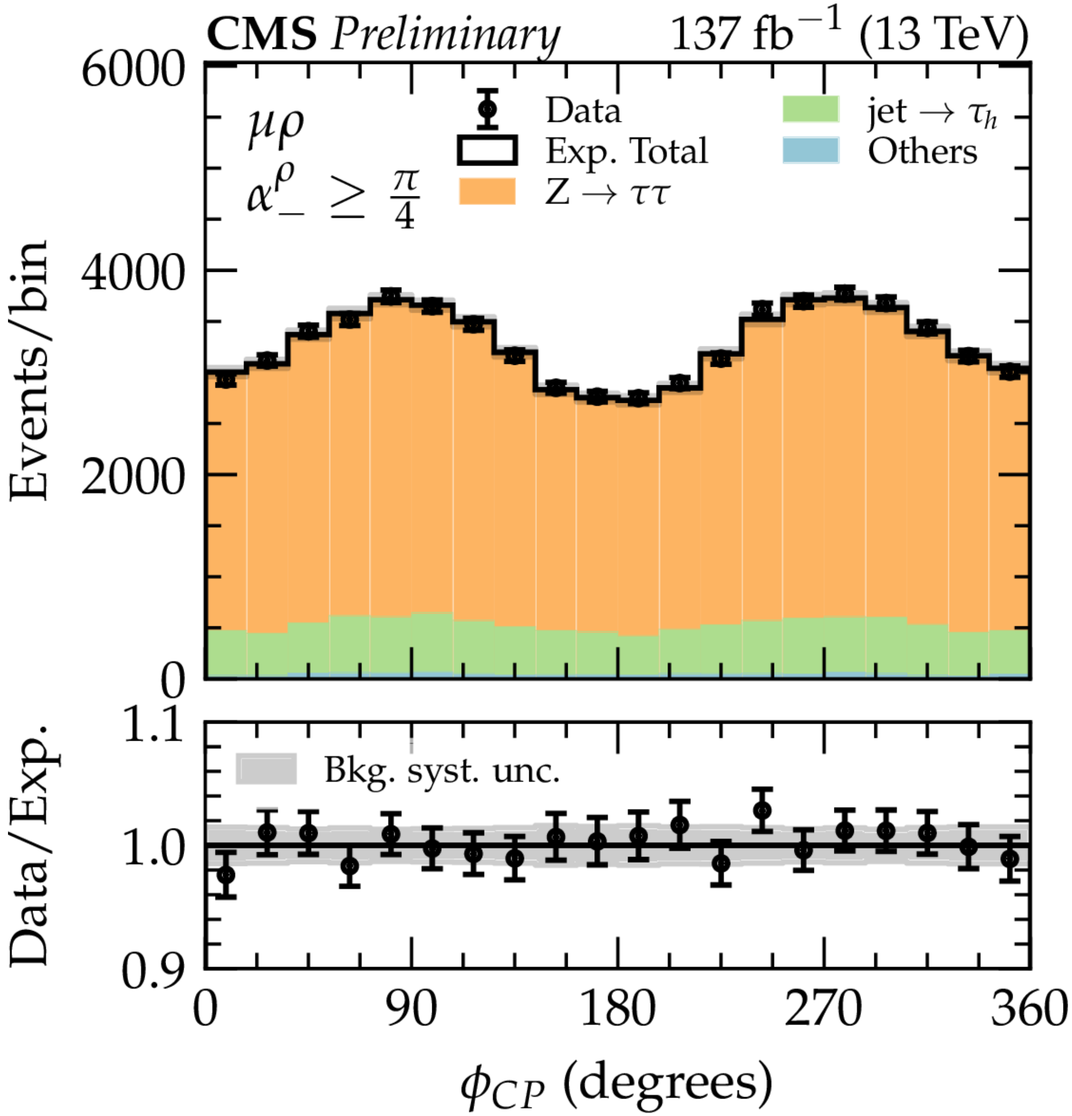
Check with $Z \to \tau\tau$

φ_{CP} flat for $Z \to \tau\tau$, but can be modulated when events "nearly perpendicular" ($\alpha>\pi/4$, here) or "nearly coplanar" ($\alpha<\pi/4$) to $q\tau$ production plane are selected

- cf. S.Berge et al, arXiv:1410.6362

Can be used to check data/MC of φ_{CP} with $Z \to \tau\tau$ enriched sample

- **Observed agreement is very good**



CP structure of HVV coupling with H $\rightarrow$ ττ

Phys. Rev. D 100 (2019), 112002 (HIG-17-034)

HVV coupling

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

m_V, q_V, ε_V – mass, 4-momentum and polarization of V boson,

$f^{\mu\nu} = \varepsilon_V^{\mu} q^{\nu} - \varepsilon_V^{\mu\nu} q^{\mu}$ – field strength tensor

- In SM only $a_1^{ZZ} \neq 0$ and $a_1^{WW} \neq 0$ at tree level, assumed $a_1 \equiv a_1^{ZZ} = a_1^{WW}$
- a_3 – CP-odd => CPV via interference with CP-even
- Assuming constant and real couplings (sensible for $m_{BSM} >> m_H$) it is eqiv. to eff. Lagrangian:

$$L(\mathrm{HVV}) \sim a_1 \frac{m_Z^2}{2} \mathrm{H} Z^{\mu} Z_{\mu} - \frac{\kappa_1}{(\Lambda_1)^2} m_Z^2 \mathrm{H} Z_{\mu} \Box Z^{\mu} - \frac{1}{2} a_2 \mathrm{H} Z^{\mu\nu} Z_{\mu\nu} - \frac{1}{2} a_3 \mathrm{H} Z^{\mu\nu} \tilde{Z}_{\mu\nu}$$
$$+ a_1^{\mathrm{WW}} m_{\mathrm{W}}^2 \mathrm{H} W^{+\mu} W_{\mu}^- - \frac{1}{(\Lambda_1^{\mathrm{WW}})^2} m_{\mathrm{W}}^2 \mathrm{H} \left(\kappa_1^{\mathrm{WW}} W_{\mu}^- \Box W^{+\mu} + \kappa_2^{\mathrm{WW}} W_{\mu}^+ \Box W^{-\mu}\right)$$
$$- a_2^{\mathrm{WW}} \mathrm{H} W^{+\mu\nu} W_{\mu\nu}^- - a_3^{\mathrm{WW}} \mathrm{H} W^{+\mu\nu} \tilde{W}_{\mu\nu}^-$$
$$+ \frac{\kappa_2^{Z\gamma}}{\left(\Lambda_1^{Z\gamma}\right)^2} m_Z^2 \mathrm{H} Z_{\mu} \partial_{\nu} F^{\mu\nu} - a_2^{Z\gamma} \mathrm{H} F^{\mu\nu} Z_{\mu\nu} - a_3^{Z\gamma} \mathrm{H} F^{\mu\nu} \tilde{Z}_{\mu\nu} - \frac{1}{2} a_2^{\gamma\gamma} \mathrm{H} F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} a_3^{\gamma\gamma} \mathrm{H} F^{\mu\nu} \tilde{F}_{\mu\nu},$$

cf. CMS Collaboration, Phys. Rev. D 92, 072010 (2015)

HVV coupling

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

m_V, q_V, ε_V – mass, 4-momentum and polarization of V boson,

$f^{\mu\nu}=\varepsilon_V^{\mu} q^{\nu} - \varepsilon_V^{\mu\nu} q^{\mu}$ – field strength tensor

- In SM only $a_1^{ZZ}\neq 0$ and $a_1^{WW}\neq 0$ at tree level,
- assumed $a_1 \equiv a_1^{ZZ} = a_1^{WW}$ (custodial sym.)

  same also for $a_i \equiv a_i^{ZZ} = a_i^{WW}$ (kin. not affected, results can be reinterpreted)
- a_3 – CP-odd => CPV via interference with CP-even
- Parametrise using fractional cross-section (uncerts. cancel out):

$$fai = \frac{|a_i^2|\sigma_i}{\sum_j |a_j^2|\sigma_j} \qquad \varphi_{ai} = arg\left(\frac{a_i}{a_1}\right)$$

where σ_i cross section (decay rate) for $a_i = 1, a_{j\neq i} = 0$

Probing HVV coupling w/ MELA

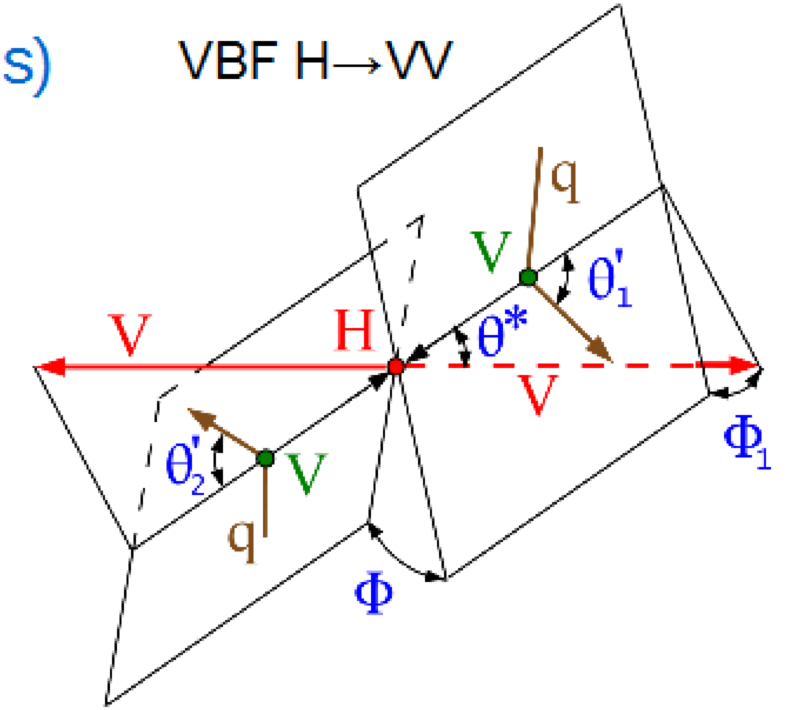
- MELA (Matrix Element Likelihood Analysis)
  - Two types of discriminants

$$\mathcal{D}_{\text{alt}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})}{\mathcal{P}_{\text{sig}}(\mathbf{\Omega}) + \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}$$

$$\mathcal{D}_{\text{int}}(\mathbf{\Omega}) = \frac{\mathcal{P}_{\text{int}}(\mathbf{\Omega})}{2\sqrt{\mathcal{P}_{\text{sig}}(\mathbf{\Omega})\ \mathcal{P}_{\text{alt}}(\mathbf{\Omega})}}$$

  - D_{alt} distinguishes between signal (*sig*) and alternative (*alt*) model
    - *alt* can be alternative production (to categorise events) or background or coupling model
  - D_{int} accounts for interference
  - Signal distributions with JHUgen

VBF H→VV

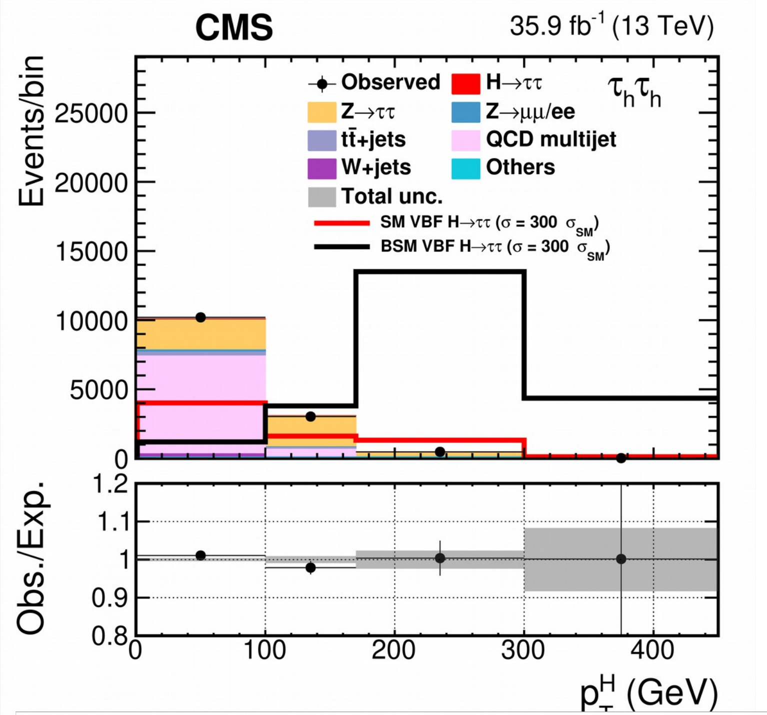


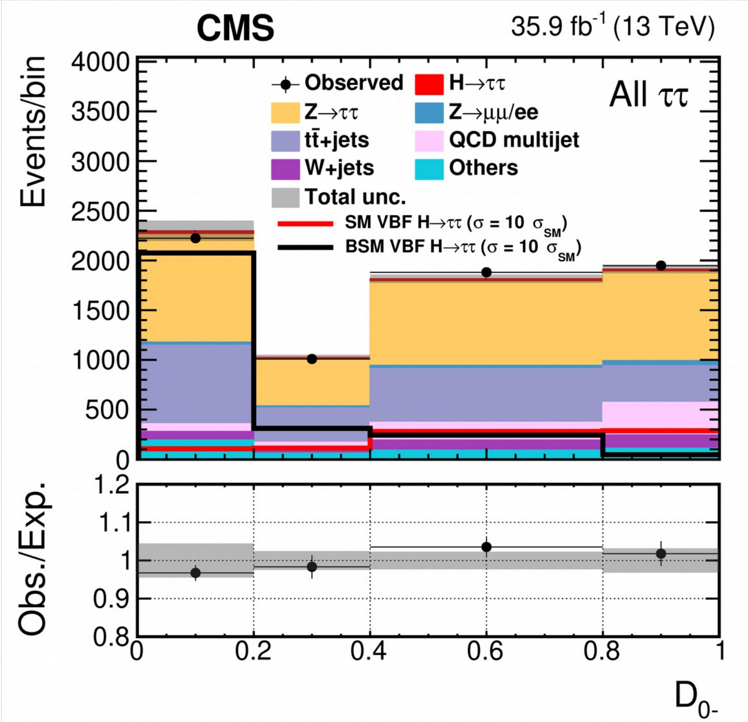
$$P(\Omega) = P(\Theta_1^*, \Theta_1, \Theta_2, \Phi_1, \Phi_2, \ldots)$$

cf. CMS Collaboration, Phys. Rev. D 99, 112003 (2019)

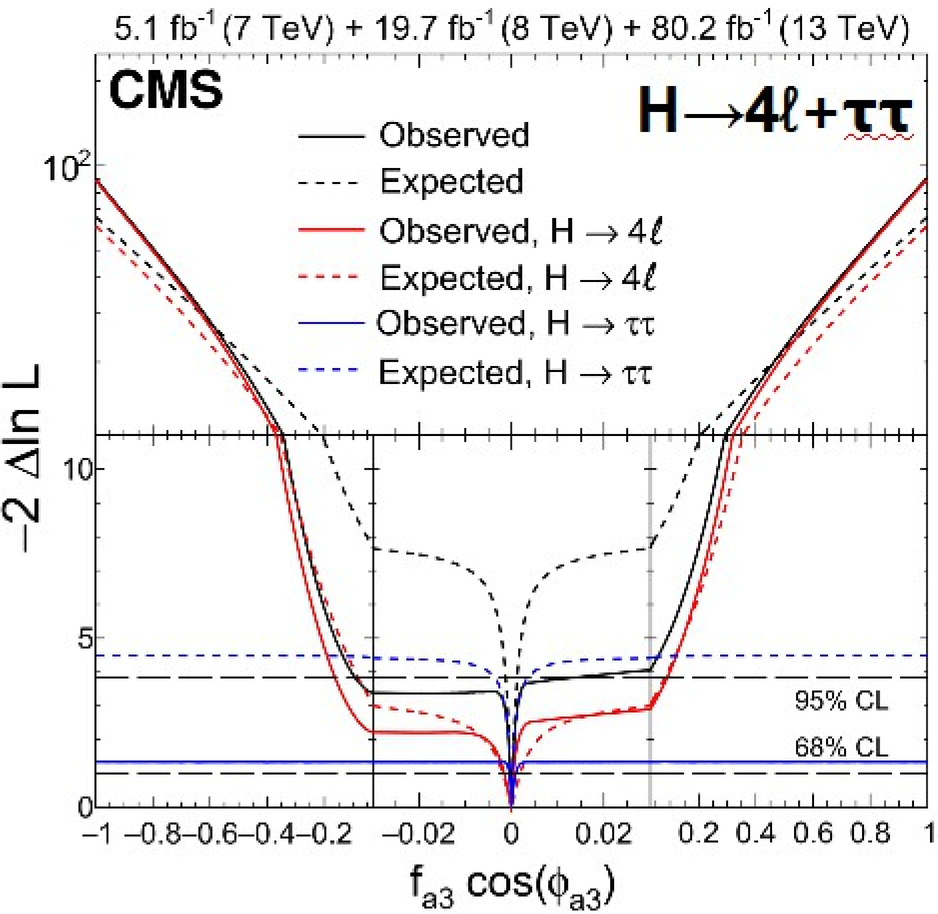
Analysis strategy

- Used 36/fb (2016 data)
- $H\rightarrow\tau\tau$: $\tau_h\tau_h$, $\mu\tau_h$, $e\tau_h$, $e\mu$
  - Categories (production) using kinematic cuts
    - VBF category (2-jet, high mjj, ...)
    - boosted category (1-jet or 2-jets no-VBF)
    - 0-jets category
- Production info & H kinematics
  - $m_{\tau\tau}$ (+ other quantity deepened on channel) in 0-jets category
  - $m_{\tau\tau}$, p_T^H in boosted category
  - $m_{\tau\tau}$, m_{jj}, D_{0-} (a_3 contr.), D_{CP} ($a_1 - a_3$ interf.) in VBF category
  - and signal strength modifiers μ_F, μ_V





Results (combined with H → 4l)



Parameter	Observed / (10^{-3})		Expected / (10^{-3})	
	68% CL	95% CL	68% CL	95% CL
$f_{a3}\cos(\phi_{a3})$	0.00 ± 0.27	$[-92, 14]$	0.00 ± 0.23	$[-1.2, 1.2]$
$f_{a2}\cos(\phi_{a2})$	$0.08^{+1.04}_{-0.21}$	$[-1.1, 3.4]$	$0.0^{+1.3}_{-1.1}$	$[-4.0, 4.2]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.00^{+0.53}_{-0.09}$	$[-0.4, 1.8]$	$0.00^{+0.48}_{-0.12}$	$[-0.5, 1.7]$
$f_{\Lambda1}^{Z\gamma}\cos(\phi_{\Lambda1}^{Z\gamma})$	$0.0^{+1.1}_{-1.3}$	$[-6.5, 5.7]$	$0.0^{+2.6}_{-3.6}$	$[-11, 8.0]$

f_{ai} agree with 0 (SM) with 10^{-3} – 10^{-2} precision at 95% CL

95%CL

Parameter	Observed	Expected
a_3/a_1	$[-0.81, 0.31]$	$[-0.090, 0.090]$
a_2/a_1	$[-0.055, 0.097]$	$[-0.11, 0.11]$
$(\Lambda_1\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda1})$ (GeV)	$[-\infty, -650] \cup [440, \infty]$	$[-\infty, -610] \cup [450, \infty]$
$(\Lambda_1^{Z\gamma}\sqrt{\lvert a_1\rvert})\cos(\phi_{\Lambda1}^{Z\gamma})$ (GeV)	$[-\infty, -400] \cup [420, \infty]$	$[-\infty, -360] \cup [390, \infty]$

a_i/a_1 agree with 0 (SM) with 10^{-1} precision

- Production dominates low f_{ai}, while decay high f_{ai}