Imperial College
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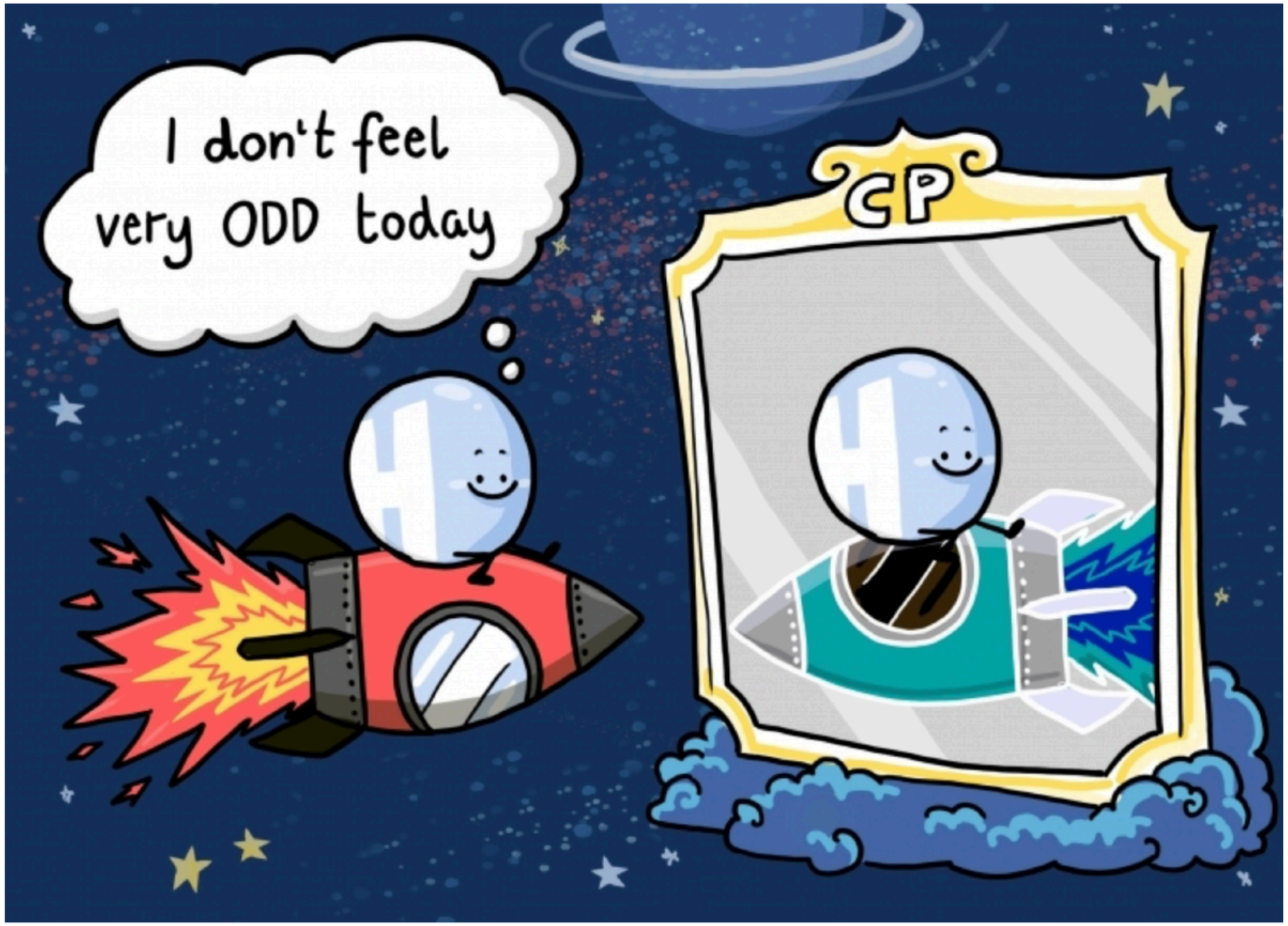
CMS

Measuring the Higgs boson's CP-properties using H→$\tau\tau$ decays



KIT particle physics colloquium 17/11/22

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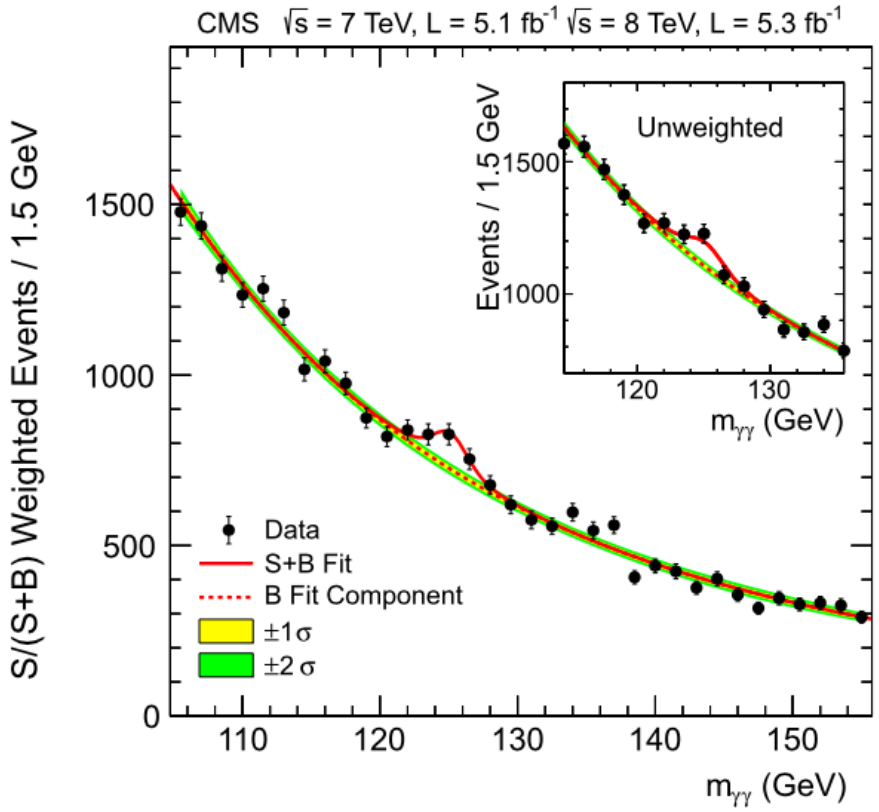
Overview

- This year marks the 10th anniversary of the Higgs boson discovery
- Since its discovery we have entered the era of precision measurements where we want to measure Higgs coupling and properties precisely
- In today seminar I will discuss the latest measurements by the CMS Collaboration of the Higgs boson CP properties



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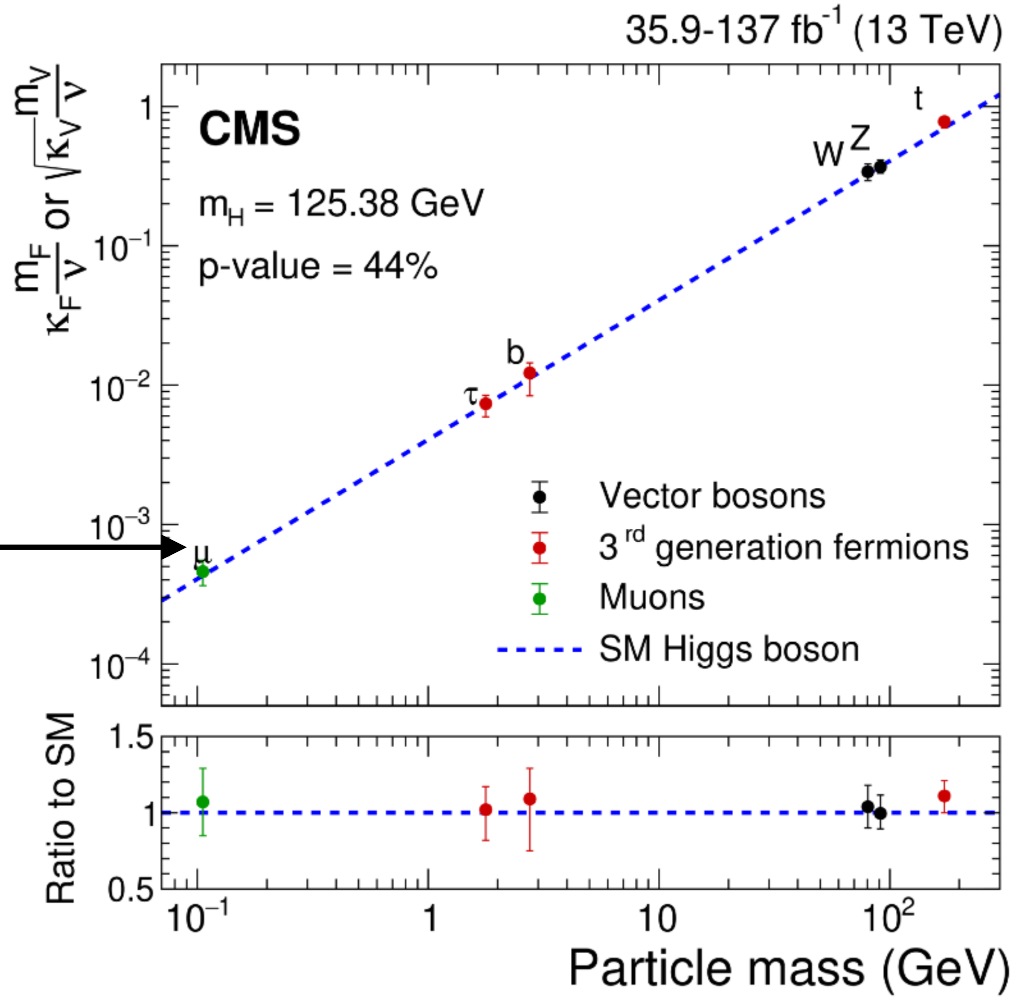
Success of the standard model

- The standard model (SM) of particle physics is incredibly successful at describing many experimental observables
- E.g electron magnetic dipole moment measured to within 1 part in 10^{12}
- The Higgs boson was the last missing piece of the SM
    - Discovered by ATLAS and CMS in 2012
    - Good agreement with SM predictions



Phenomena not explained by the SM

- Hierarchy problem - Higgs boson is unnaturally light
- Does not contain a dark matter candidate
- No explanation for dark energy, neutrino masses
- Does not describe gravity
- Matter anti-matter asymmetry - does not account for the observed Baryon asymmetry of the universe (BAU)

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This talk!

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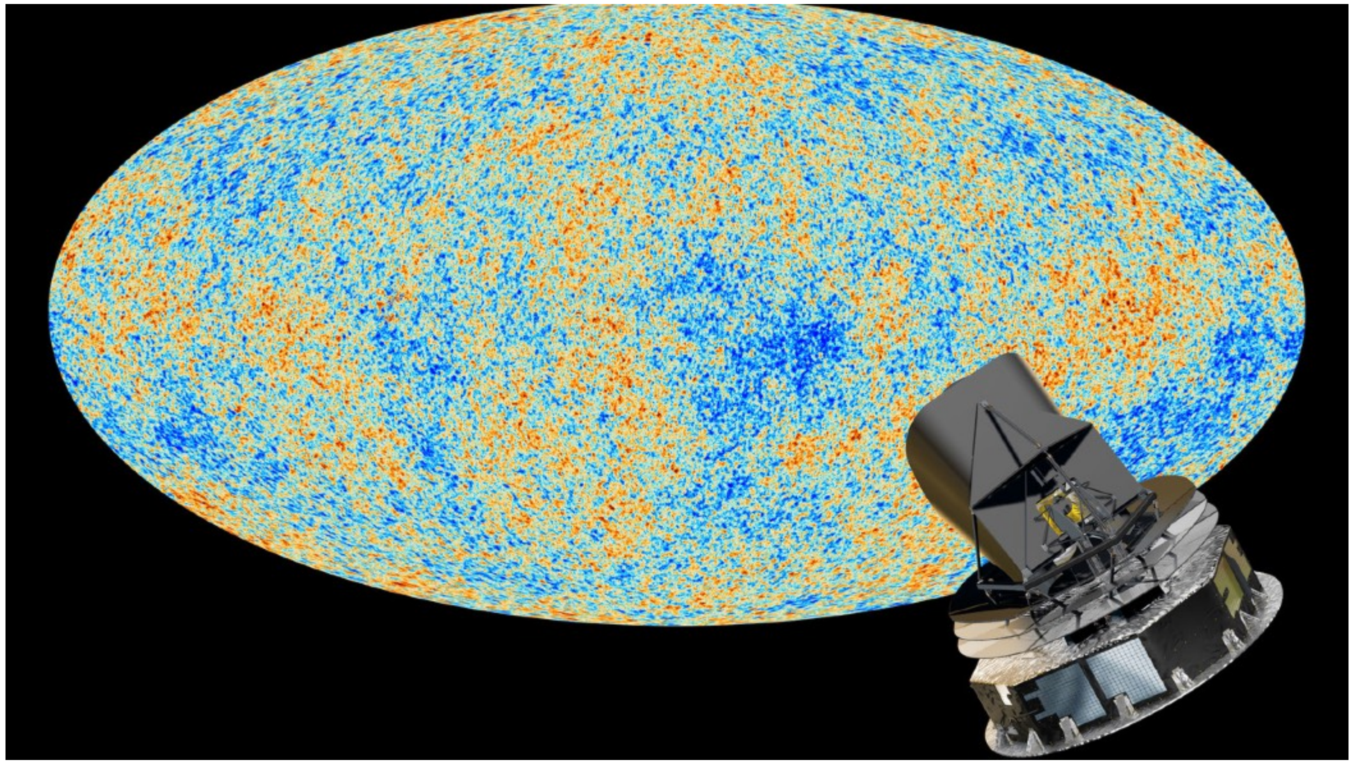
What is the BAU problem?

- The BAU is measured by Planck from the CMB to be:

$$Y_B^{\text{obs}} = (8.59 \pm 0.08) \times 10^{-11}$$

- Corresponds to a small preference for matter over antimatter

- What is the reason for this preference of matter over antimatter?



Sakharov conditions

1. Baryon number violation
2. C-symmetry and CP-symmetry violation
3. Departure from thermal equilibrium

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Sakharov conditions

1. Baryon number violation

- In SM baryon number (B) conserved classically
- But quantum effects give rise to chiral anomaly and violate B conservation 😃

Sakharov conditions

2. C-symmetry and CP-symmetry violation

- C violation in SM (SM is a chiral theory) 😃

- CP violation in SM as well - CP violating phase δ in quark mixing (CKM matrix)

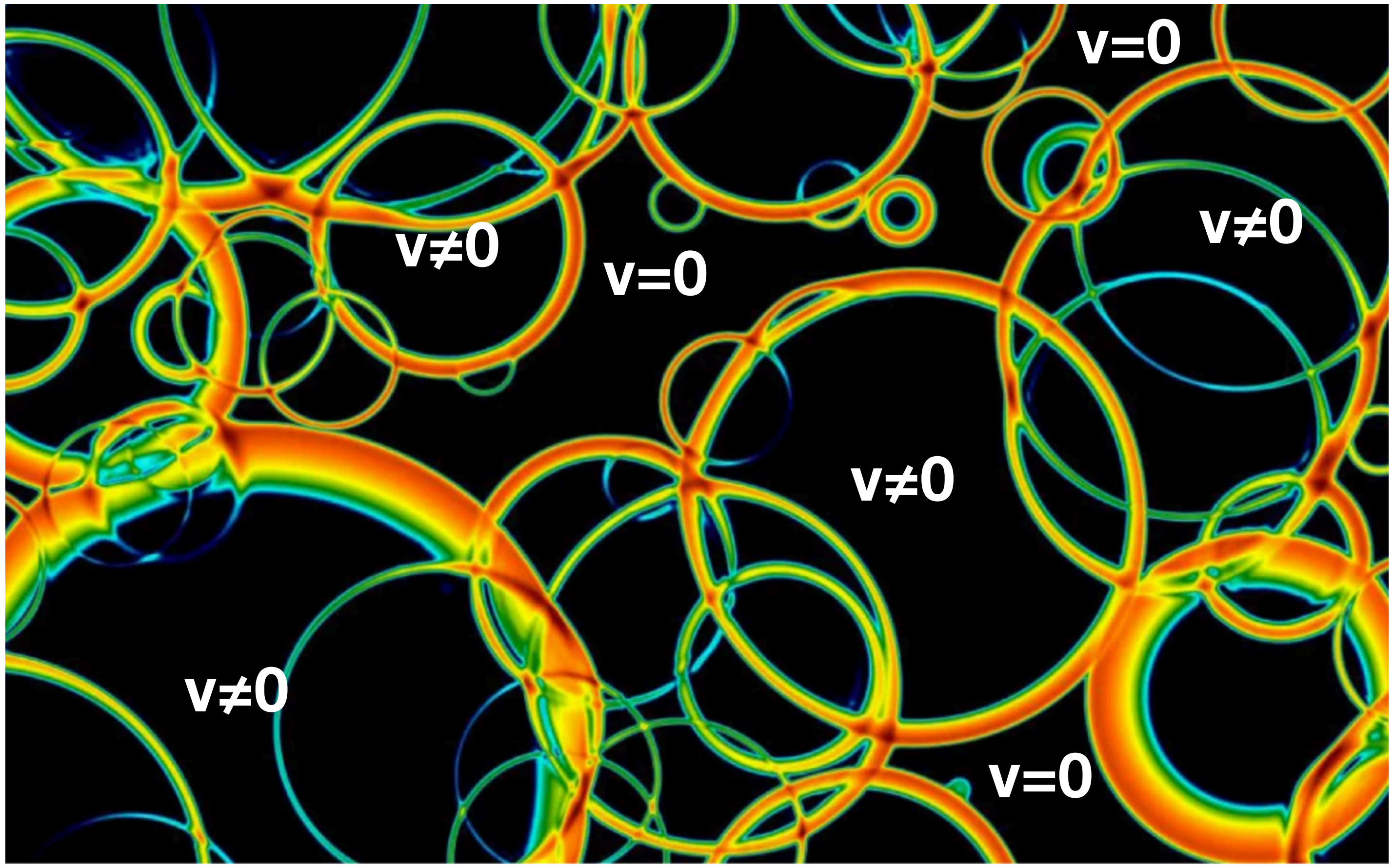
$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{\boxed{-i\delta}} \\ 0 & 1 & 0 \\ -s_{13}e^{\boxed{i\delta}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- **But** amount of CP violation in SM is about 10 orders of magnitude too small to explain BAU… ☹️

Sakharov conditions

3. Departure from thermal equilibrium

- **Electroweak baryogenesis**: Baryon generation at the electroweak phase transition
- If electroweak phase transition is first order, universe tunnels from v=0 to v≠0 vacuum via bubble nucleation
- Processes near bubble wall highly out of equilibrium



Sakharov conditions

3. Departure from thermal equilibrium

- But to give first order phase transition require Higgs mass < 75 GeV
- SM Higgs boson is too heavy to give first order phase transition 🙁
- To make electroweak baryogenesis work we need BSM to give additional sources of CP violation and first order phase transition

Sakharov conditions

3. Departure from thermal equilibrium

- But to give first order phase transition require Higgs mass < 75 GeV
- SM Higgs boson is too heavy to give first order phase transition ☹
- To make electroweak baryogenesis work we need BSM to give additional sources of CP violation and first order phase transition

This talk!

CP violation in the Higgs sector

- SM Higgs sector only contains 1 CP-even Higgs boson
- No CP odd component to Higgs couplings
- However, many BSM Higgs scenarios where additional CP-violating interactions are possible
- Most simple example complex two Higgs doublet model (C2HDM)
- Other examples such as NMSSM
- These extended Higgs sectors can also give first order phase transition

C2HDM: overview

- Compared to SM Higgs sector has one additional doublet

- 4 allowed types depending on which doublet the fermions couple to:

	u-type	d-type	Leptons
Type 1	ϕ_2	ϕ_2	ϕ_2
Type 2	ϕ_2	ϕ_1	ϕ_1
Lepton-specific	ϕ_2	ϕ_2	ϕ_1
Flipped	ϕ_2	ϕ_1	ϕ_2

- Potential looks like:

$$V = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - \left(\boxed{m_{12}^2}\Phi_1^\dagger\Phi_2 + \mathrm{h.c.}\right) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2$$
$$+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \left[\boxed{\frac{\lambda_5}{2}}(\Phi_1^\dagger\Phi_2)^2 + \mathrm{h.c.}\right] .$$

- Complex parameters m_{12}^2 and λ_5 allow CP-violation

- H bosons: H_1, H_2, H_3, H^+, H^- → neutral Higgs bosons not CP eigenstates!

Motivation for CP violation in H fermion couplings

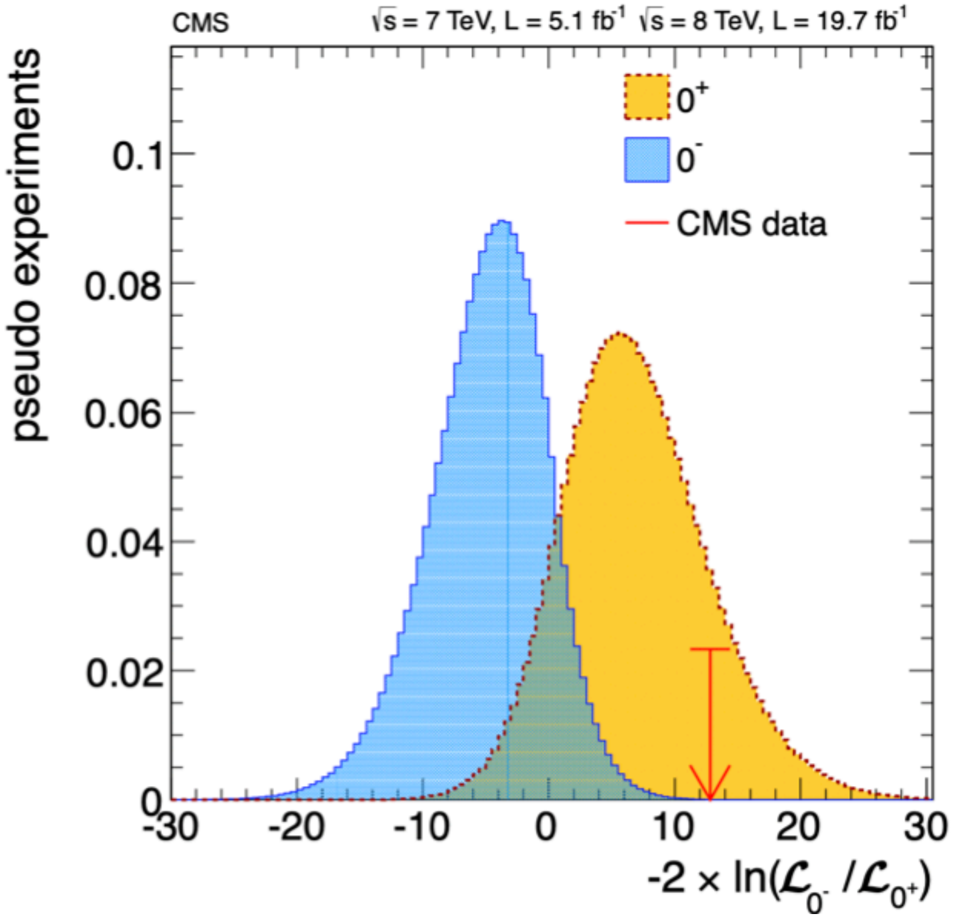
- Since Run 1 H CP properties have been measured

- CP-odd strongly disfavoured

- But possible H isn't CP eigenstate

- Previous measurements are based on HVV couplings **but** CP-odd HVV coupling typically suppressed (no tree level coupling) → current bounds actually quite weak

- Hff couplings well motivated because CP-odd coupling at tree-level → not suppressed like HVV!



Parameterisation of Hff CP properties

- Parameterise Lagrangian in terms of CP-even and CP-odd Yukawa couplings:

$$\mathcal{L}_Y = -\frac{m_\mathrm{f}}{v}(\boxed{\kappa_\mathrm{f}\bar{f}f} + \boxed{\tilde{\kappa}_\mathrm{f}\bar{f}i\gamma_5 f})h \qquad \kappa_\mathrm{f} = y_\mathrm{f}/y_\mathrm{f}^{SM}$$

- Define mixing angle as:

$$\tan\alpha^{\mathrm{Hff}} = \frac{\tilde{\kappa}_\mathrm{f}}{\kappa_\mathrm{f}}$$

- CP-even: $\alpha^{\mathrm{Hff}} = 0^\circ$, CP-odd: $\alpha^{\mathrm{Hff}} = 90^\circ$, CP-mixed: $0^\circ < |\alpha^{\mathrm{Hff}}| < 90^\circ$

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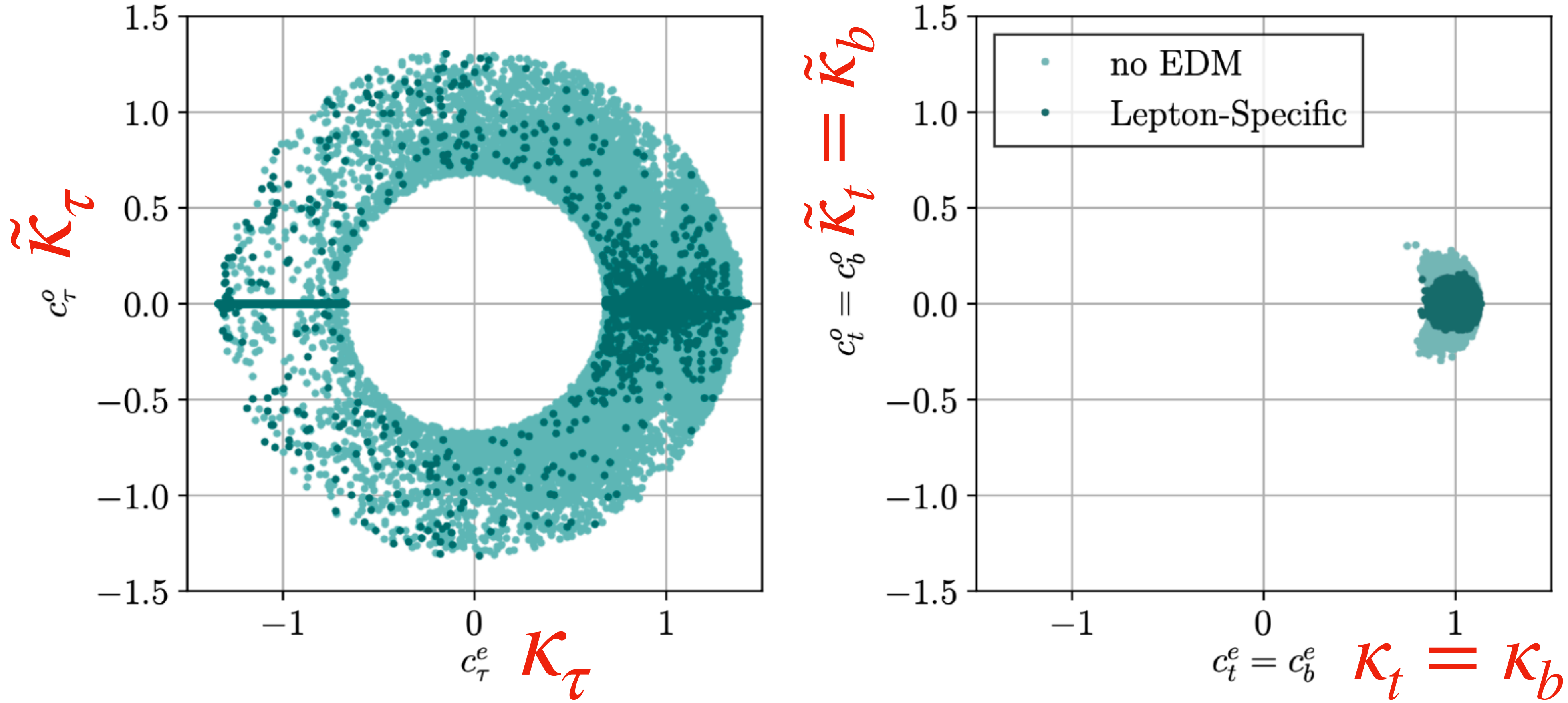
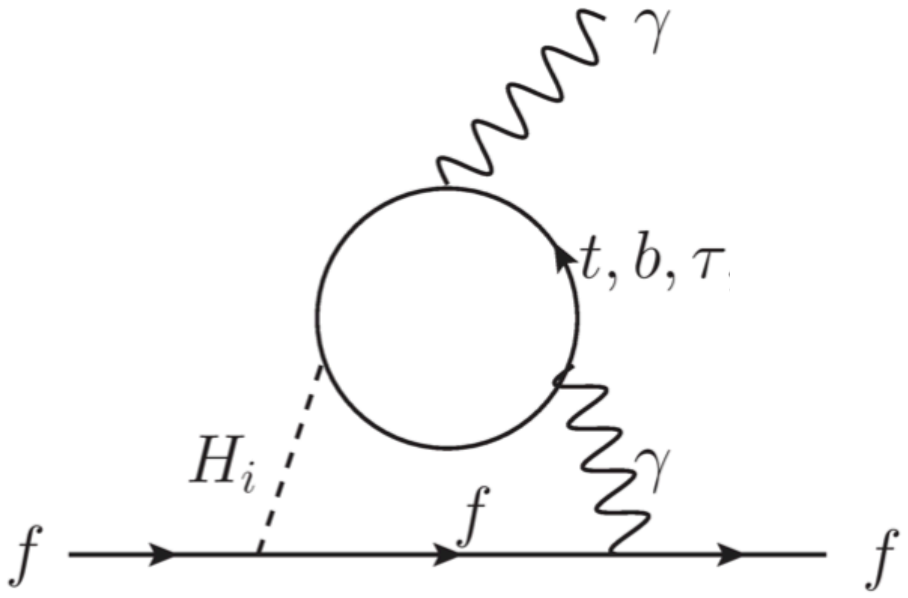
C2HDM

- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios
  - light points allowed by all constraints except EDMs, dark points show points also passing EDM constraints
- Lots of points even for large scenarios $\tilde{\kappa}_\tau$ for lepton-specific 2HDM - similar situation for Type 2



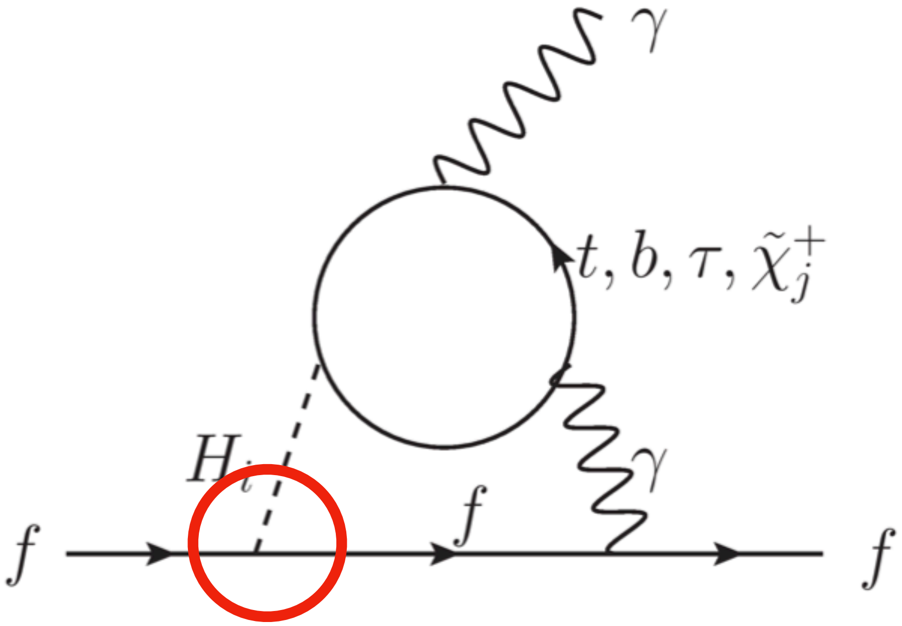
Indirect measurements: EDMs



- CP-violating H couplings can lead to the generation of electric dipole moment (EDMs)
- Measurements of EDMs therefore allow indirect constraints to be set on H CP properties
- Tightest bound come from electron EDM measurements:
  - $d_e \sim 10^{-29}$ *e* cm (ACME Coll., 2018)

Indirect measurements EDMs

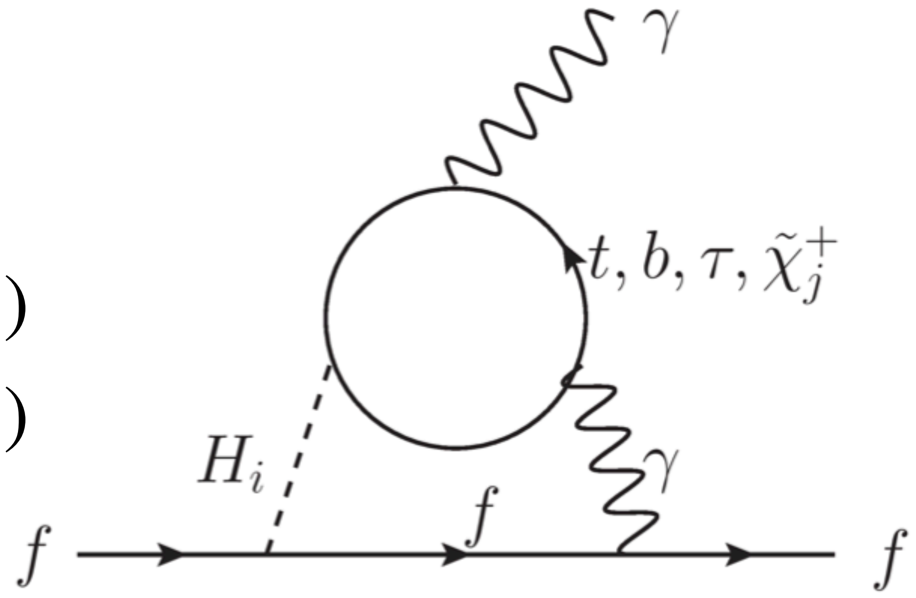
- **But** such constraints are model-dependent
  - Have to assume something about coupling of other particles to the H-boson e.g H→ee
  - For some models get additional diagrams contributing which change EDMs



Constrains from EDMs / BAU

- In simple models electron EDM scales with couplings like:

$$|d_e/d_e^{\mathrm{ACME}}| = \kappa_e(870.0\tilde{\kappa}_t + 3.9\tilde{\kappa}_b + 3.4\tilde{\kappa}_\tau + 2.8\tilde{\kappa}_c + \ldots) \\ +\tilde{\kappa}_e(610.1\kappa_t + 3.1\kappa_b + 2.8\kappa_\tau + 2.3\kappa_c + \ldots)$$



- We also get an bound from BAU models (e.g PhysRevLett.124.181801):

$$Y_B/Y_B^{\mathrm{obs}} = 28\tilde{\kappa}_t - 11\tilde{\kappa}_\tau - 0.2\tilde{\kappa}_b + \ldots$$

Formulas from arXiv:2202.11753

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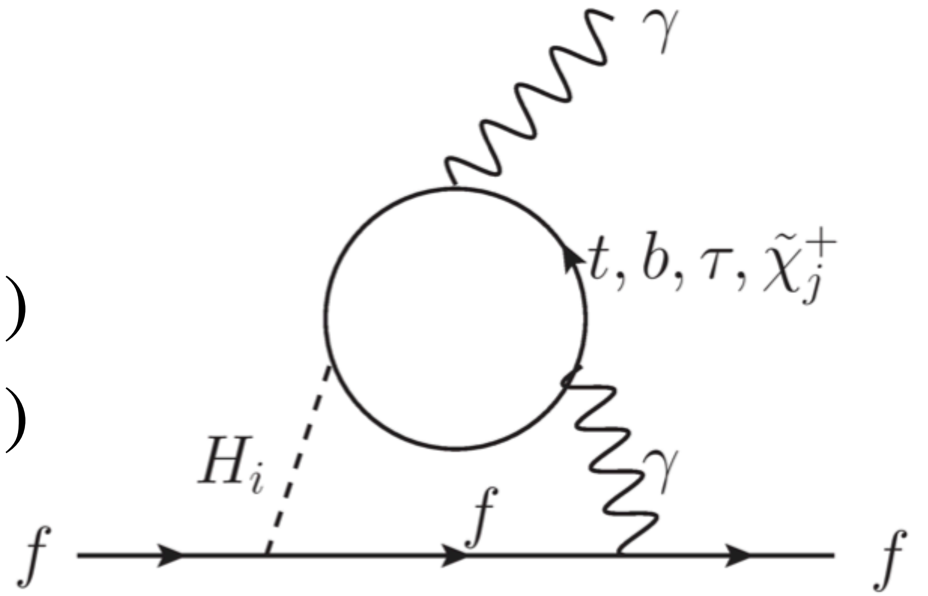

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Both top and τ can give large contributions to BAU

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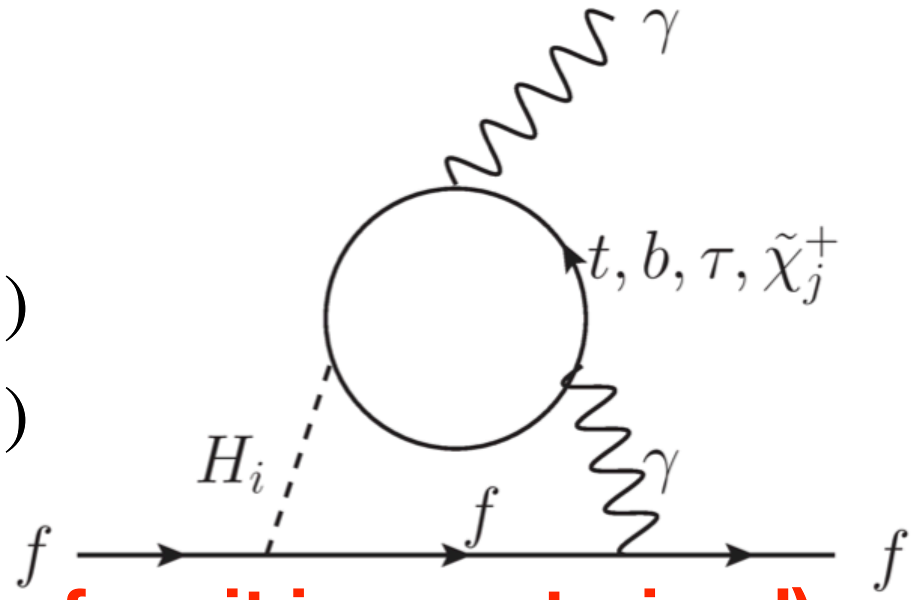


$$
\begin{aligned}
|d_e/d_e^{\text{ACME}}| = \kappa_e(870.0\tilde{\kappa}_t + 3.9\tilde{\kappa}_b + 3.4\tilde{\kappa}_\tau + 2.8\tilde{\kappa}_c + \dots) \\
+\tilde{\kappa}_e(610.1\kappa_t + 3.1\kappa_b + 2.8\kappa_\tau + 2.3\kappa_c + \dots)
\end{aligned}
$$

BUT top coupling modify EDMs significantly (therefore it is constrained) - not the case for the τ though

- We also get an bound from BAU models (e.g PhysRevLett.124.181801):

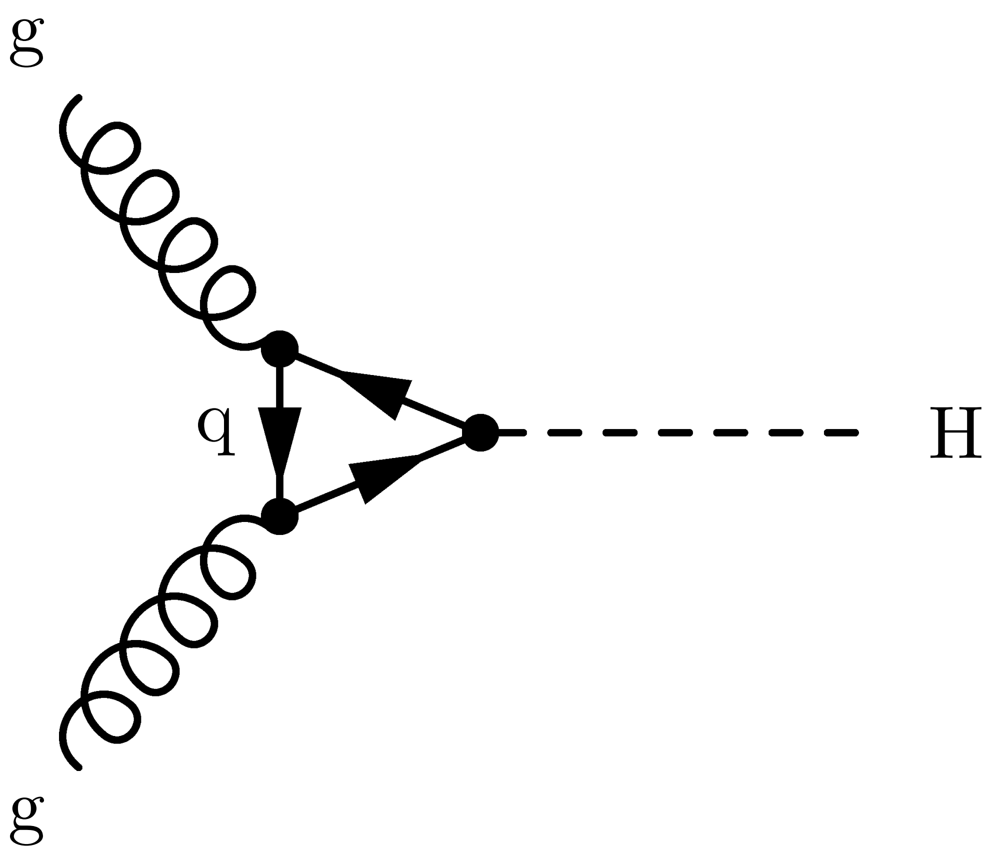
$$Y_B/Y_B^{\text{obs}} = \boxed{28\tilde{\kappa}_t - 11\tilde{\kappa}_\tau} - 0.2\tilde{\kappa}_b + \dots$$

Both top and τ can give large contributions to BAU

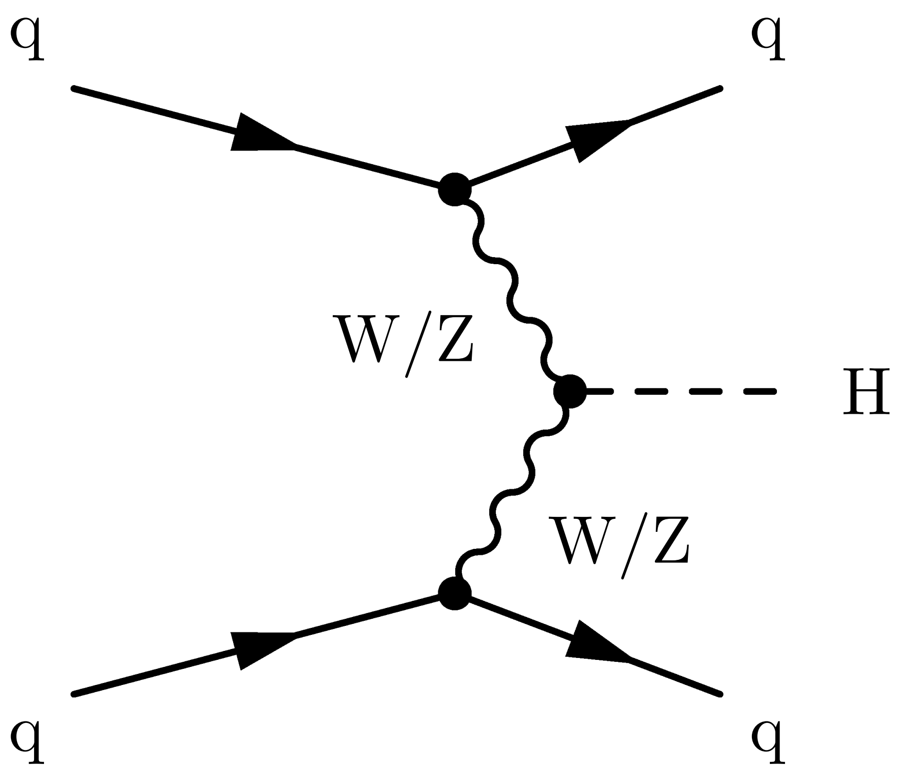
Formulas from arXiv:2202.11753

Higgs production at the LHC

- Most sensitive production modes are ggH and VBF
    - ggH has ~ 10 times larger cross section but VBF has additional jet topology to tag events
    - When we put both together we get about same sensitivity to both processes



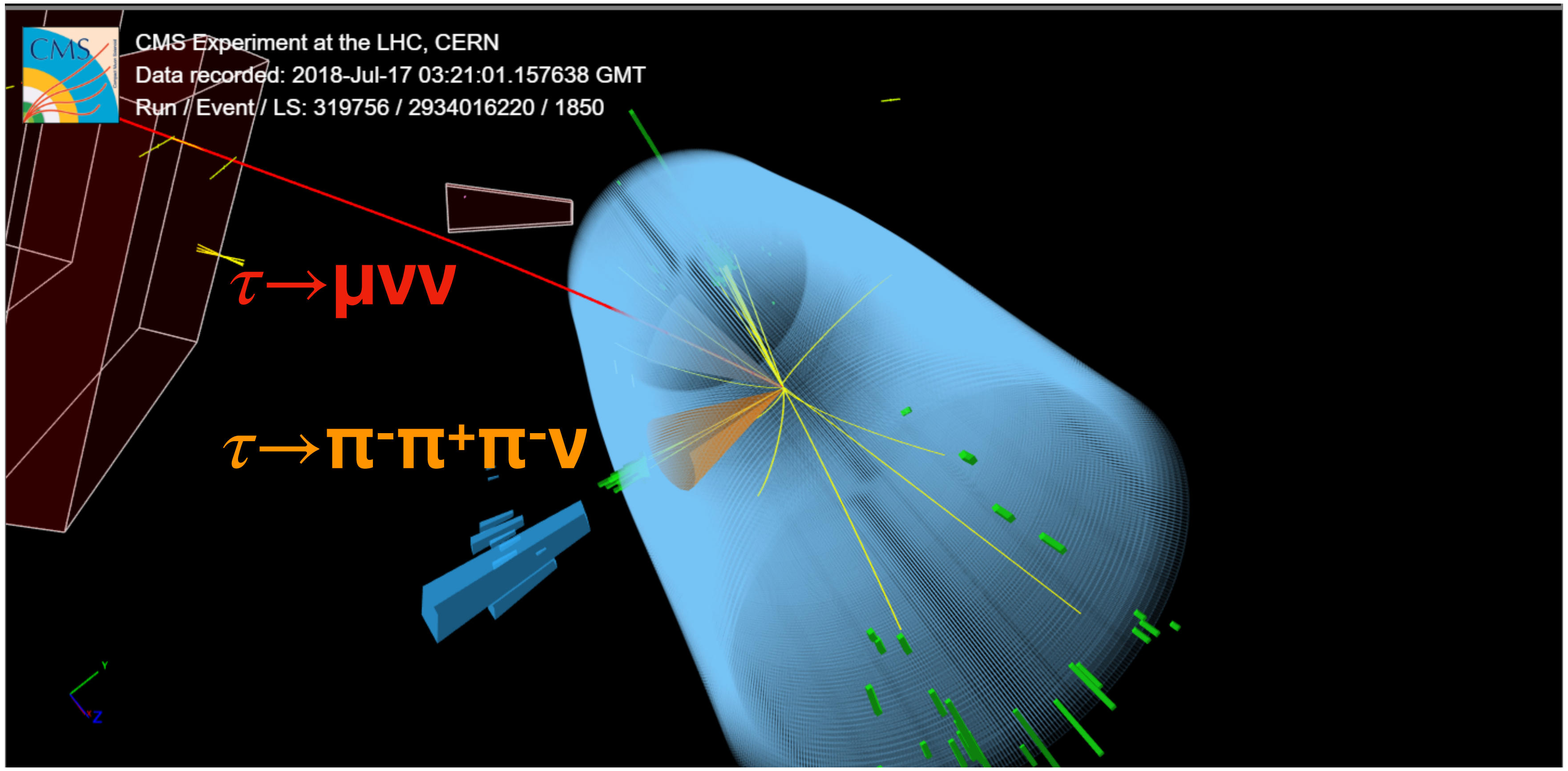
ggH



VBF

H→$\tau\tau$ decays

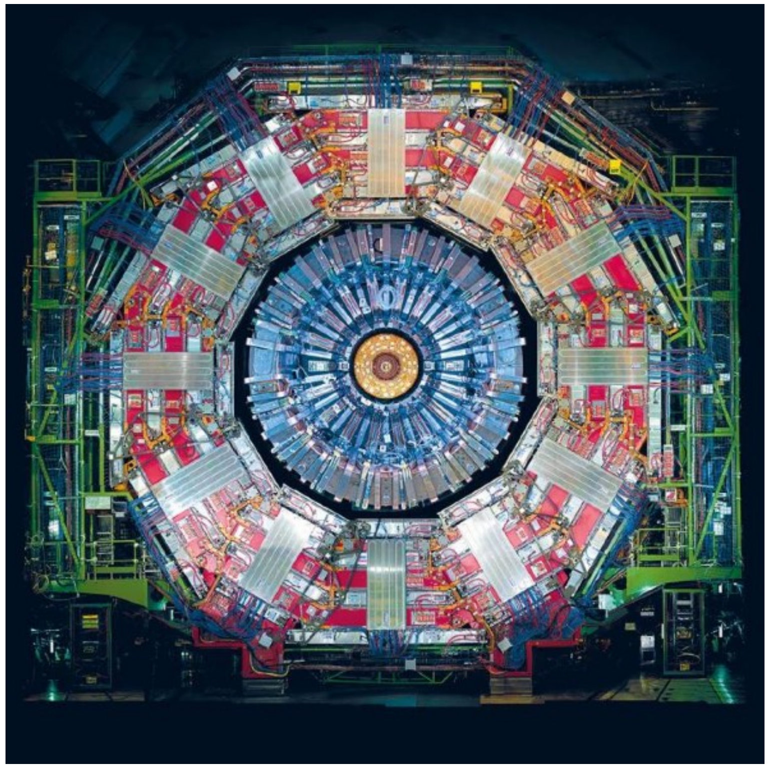
- H→$\tau\tau$ has fairly large branching fraction ~ 6%
- Taus unstable, decay close to primary vertex
- Don't reconstruct them directly but from their decay product: $\tau\rightarrow\mu\nu\nu$, $\tau\rightarrow e\nu\nu$, $\tau\rightarrow\pi^-\nu$, $\tau\rightarrow\pi^-\pi^0\nu$, $\tau\rightarrow\pi^-\pi^+\pi^-\nu$, …
- Neutrinos undetected → indirect constraint from missing transverse momentum

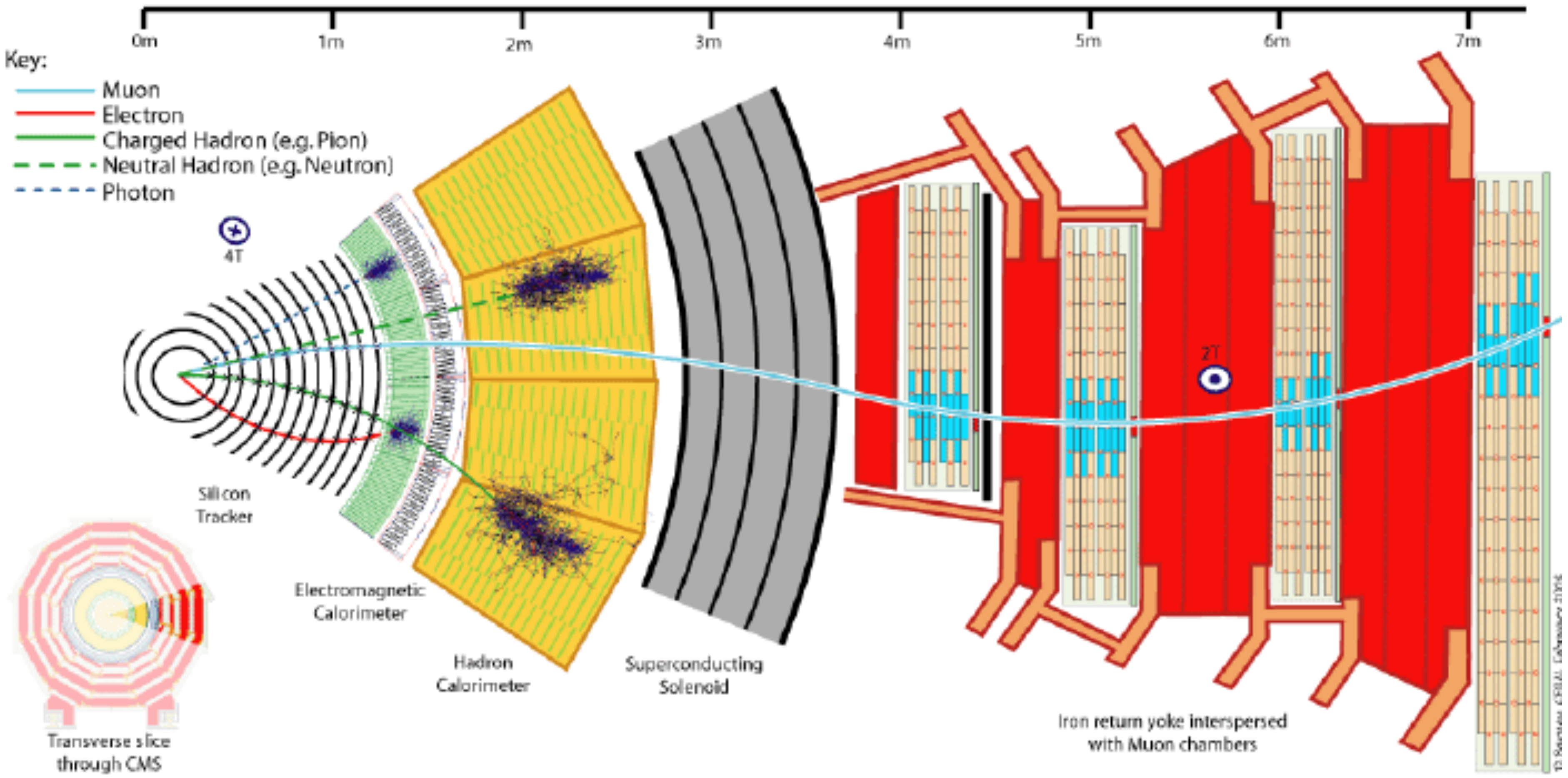


The CMS experiment

- LHC delivered proton-proton collisions at C.O.M energy = 13 TeV between 2015-2018

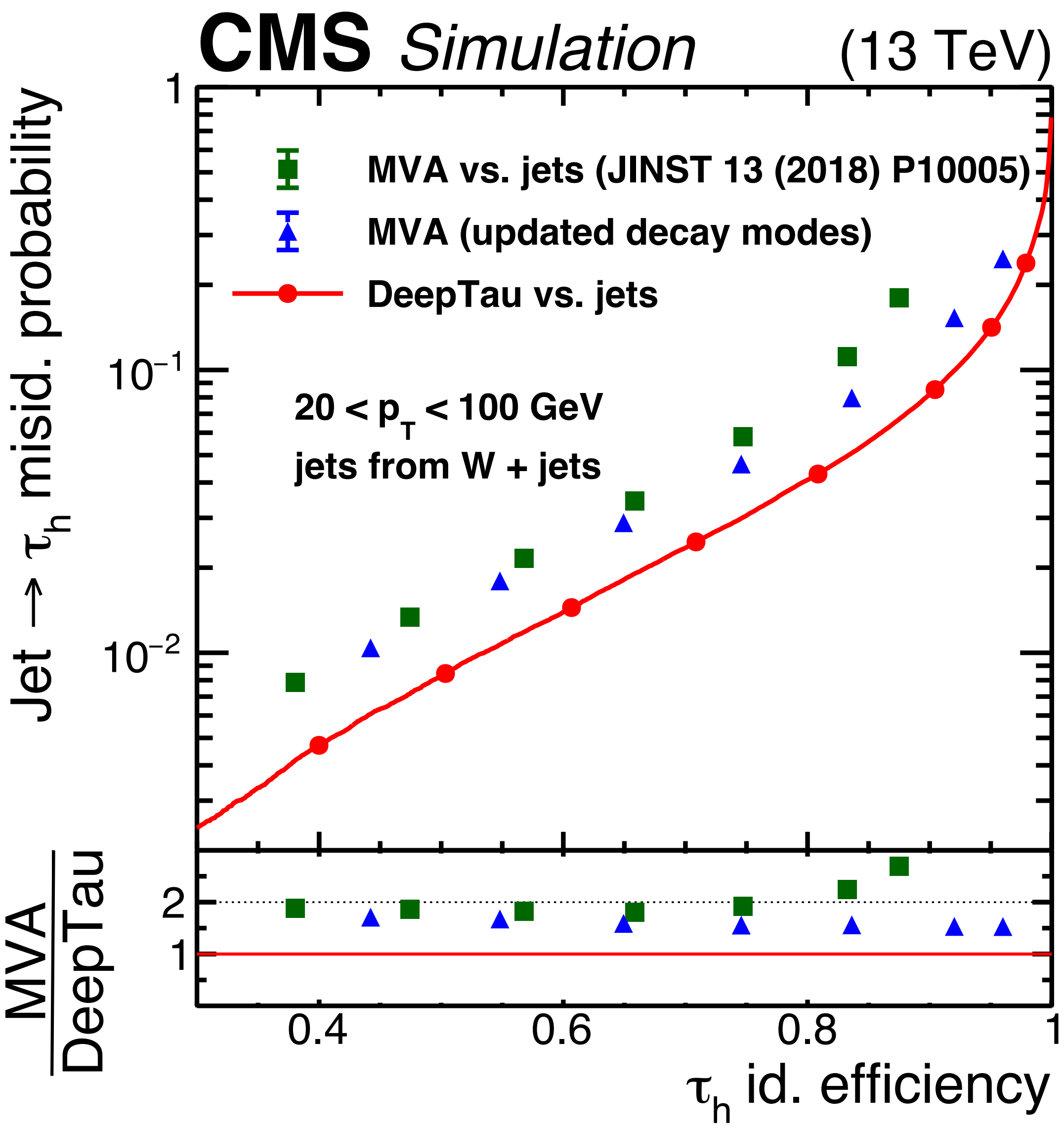
- CMS recorded 137/fb of collision data between 2016-2018 (so called “Run 2”)





Tau reconstruction and identification

- Leptonically decaying taus reconstructed with standard CMS electron / muon identification
- Hadronic tau reconstruction based on hadron plus strips algorithm (HPS)
  - Charged hadrons
  - Strips = rectangular clusters of e/ɣ's aiming to reconstruct π^0's ($\pi^0 \rightarrow \gamma\gamma$)
- "DeepTau" ID in CMS uses deep neural networks including a mix of low level information and high level variables
  - such as tau lifetimes, isolation, intermediate resonances etc



CMS-TAU-20-001

Observables sensitive to $\alpha^{H\tau\tau}$

- Measure $H\tau\tau$ coupling properties using $H\rightarrow\tau\tau$ decays

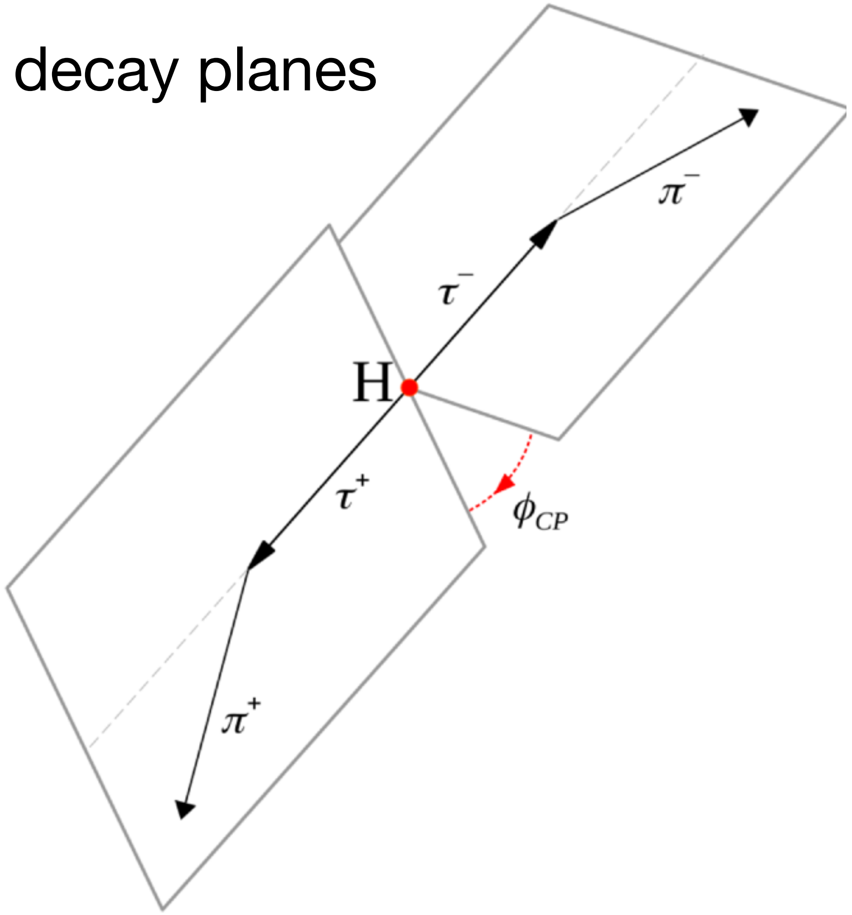
- Transverse spin correlations manifest as angular correlations of τ decay products

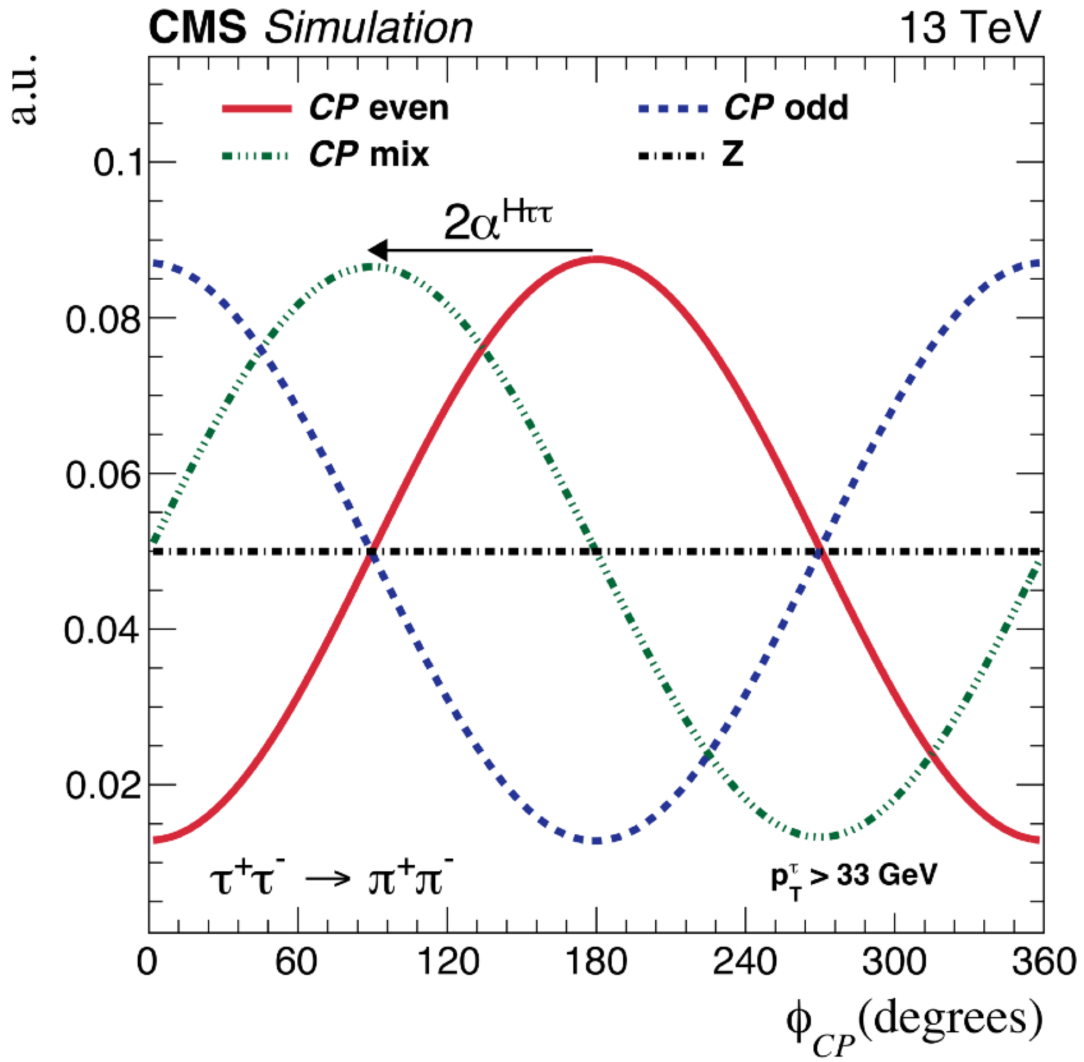
- Most simple 2-body decay: $\tau\rightarrow\pi^{-}\nu$

- Partial decay width looks like:

$$d\Gamma = \propto 1 - C\cdot\cos(\phi_{CP} - 2\alpha^{H\tau\tau})$$

ϕ_{CP} is angle between τ decay planes in H rest frame



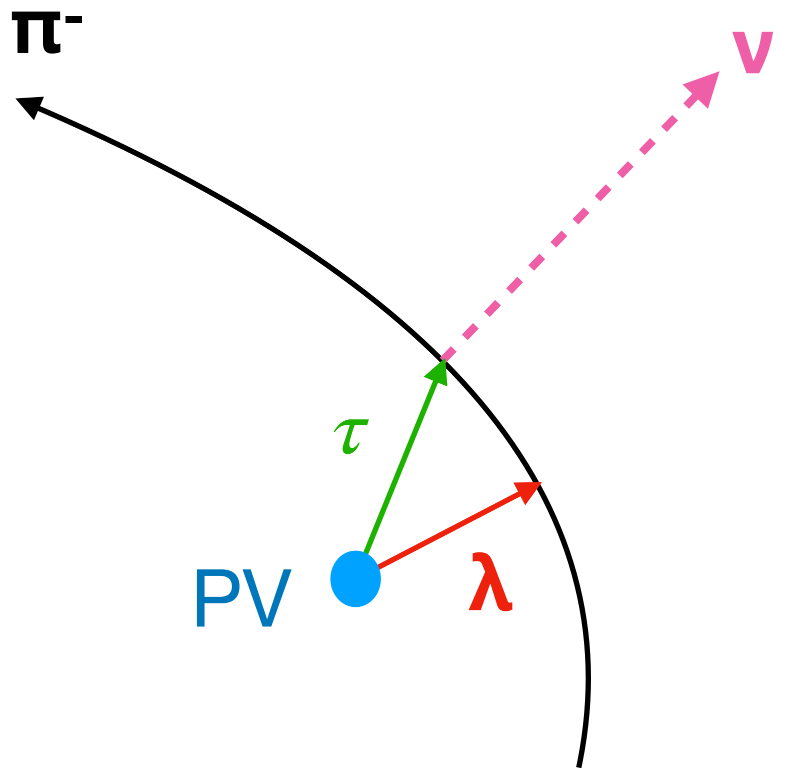


Impact parameters

- Charged tracks from tau decays do not originate exactly from PV

- Can define IP by minimising distance between PV and track

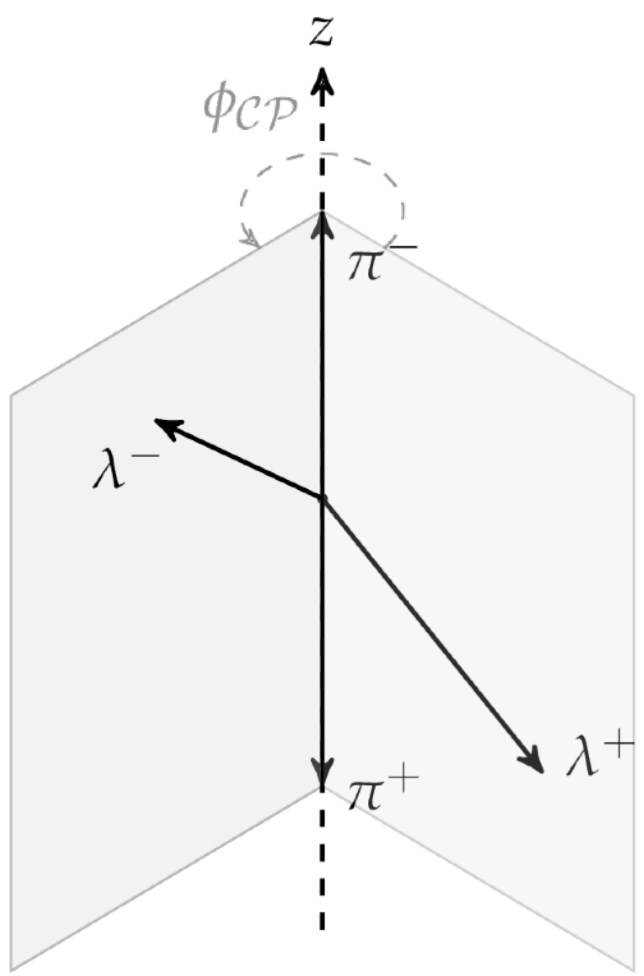
- IP is the vector that points from the primary vertex (PV) to the point of closest approach to the charged particle track

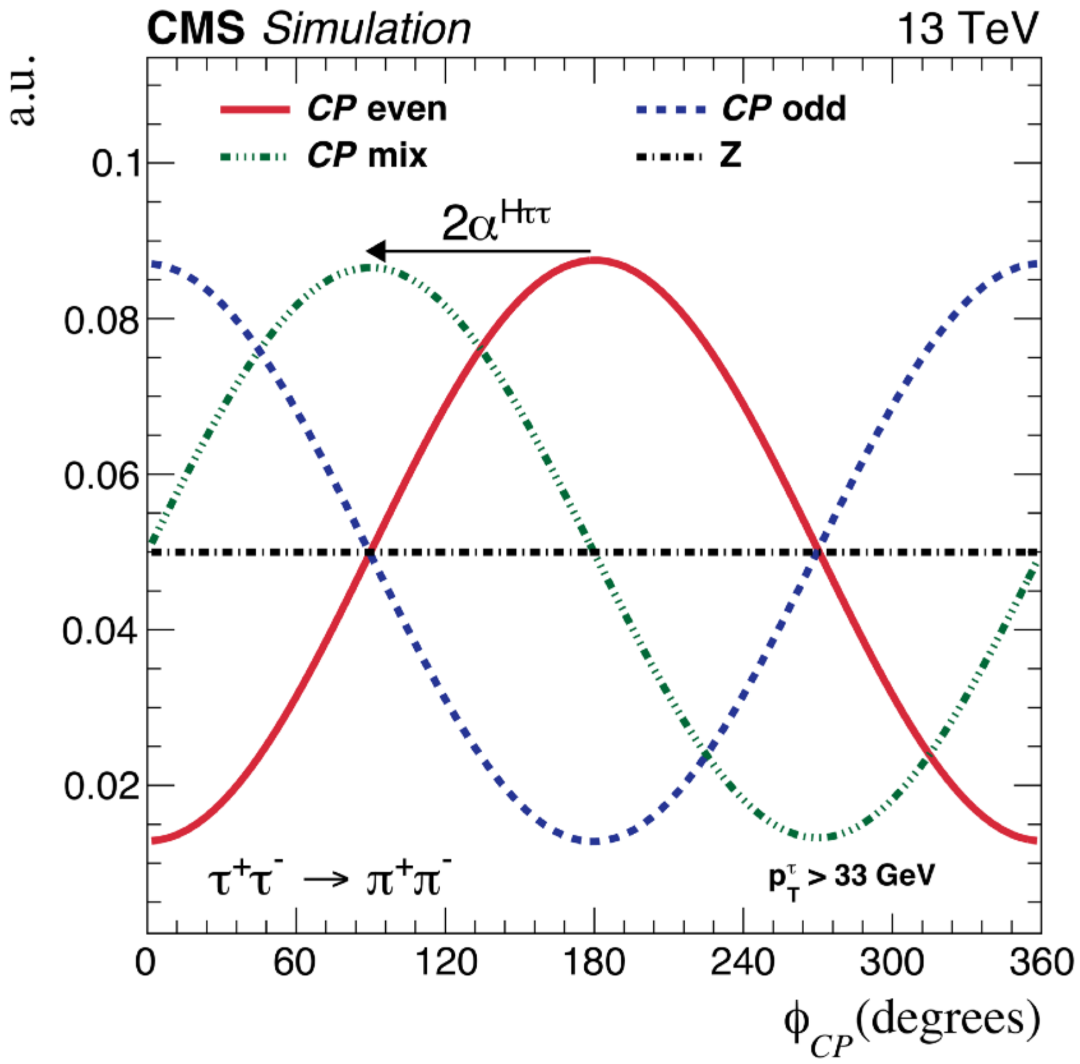


The IP method

- In practise the ϕ_{CP} defined on the previous slide cannot be well measured at a hadron collider due to the neutrinos

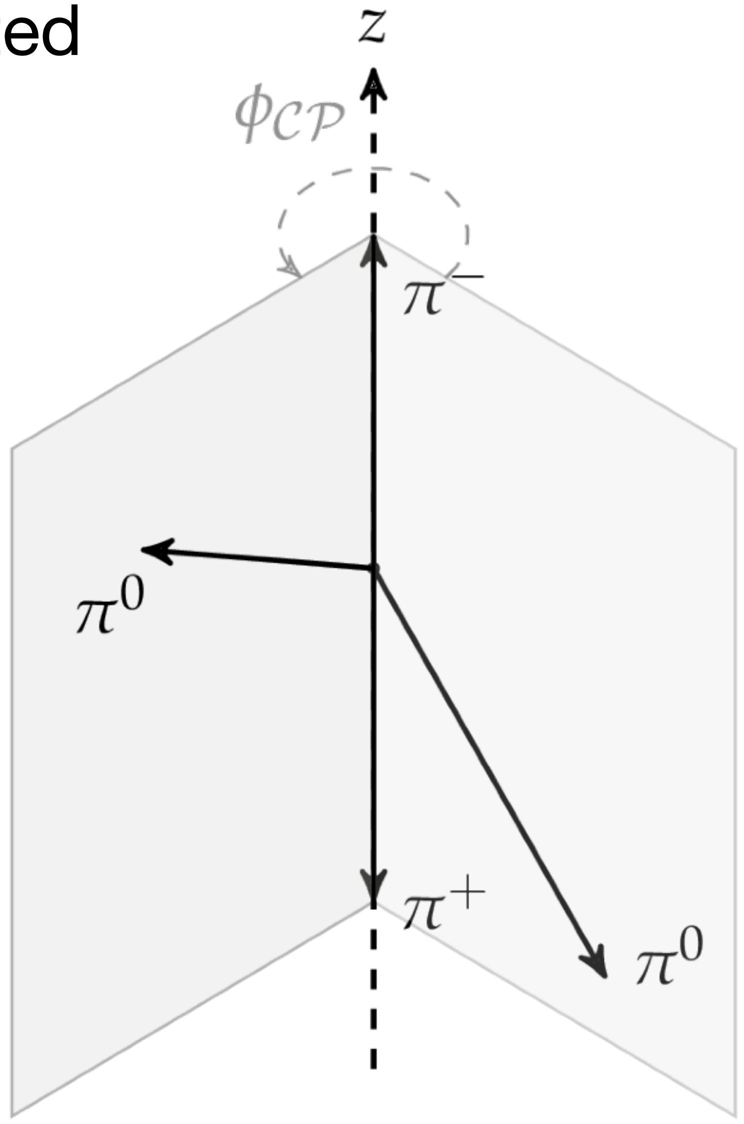
- But we can measure the impact parameter (IP) λ of the charged particle
  - IP is the vector that points from the primary vertex (PV) to the point of closest approach to the charged particle track

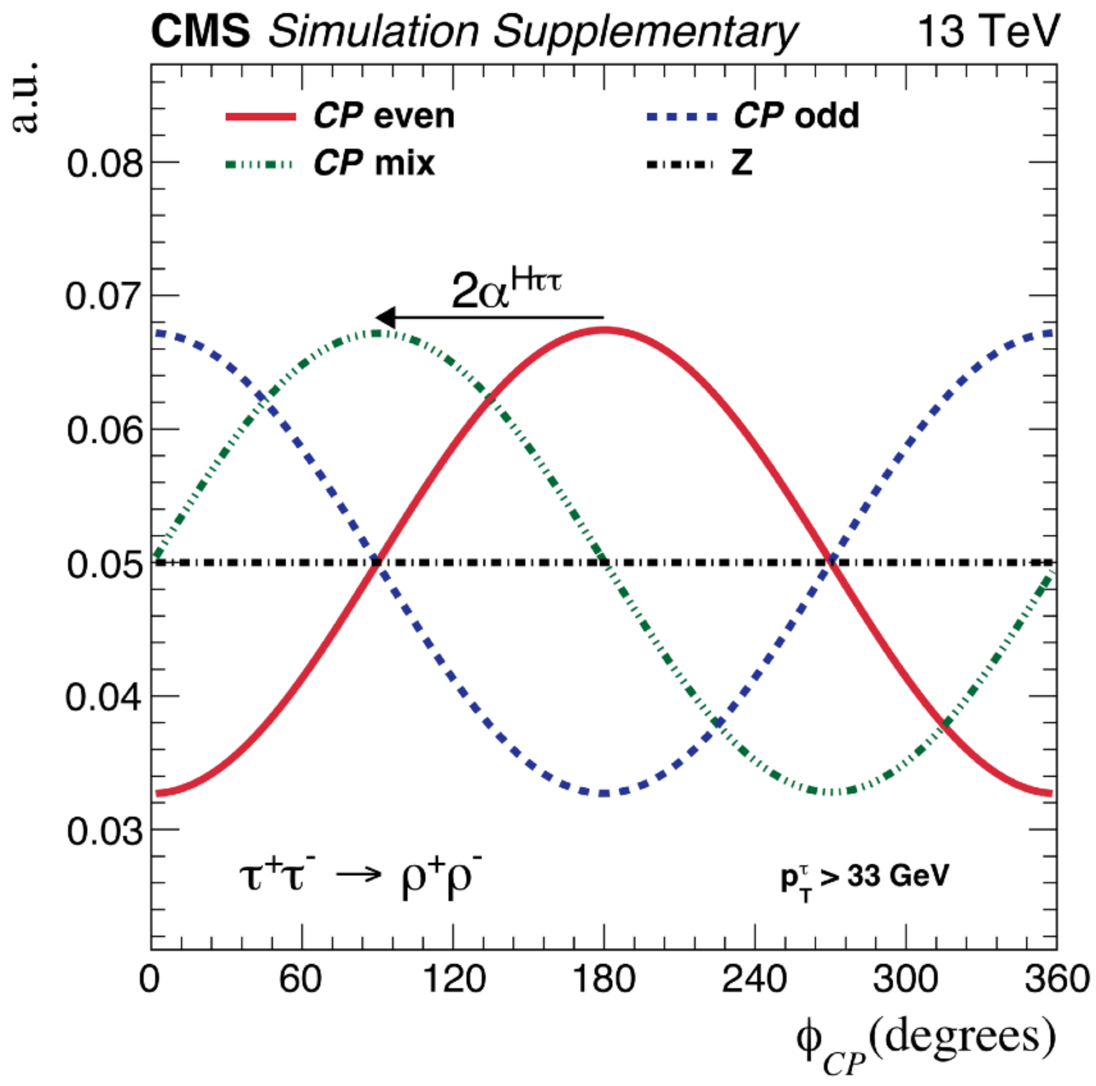




The π^0 method

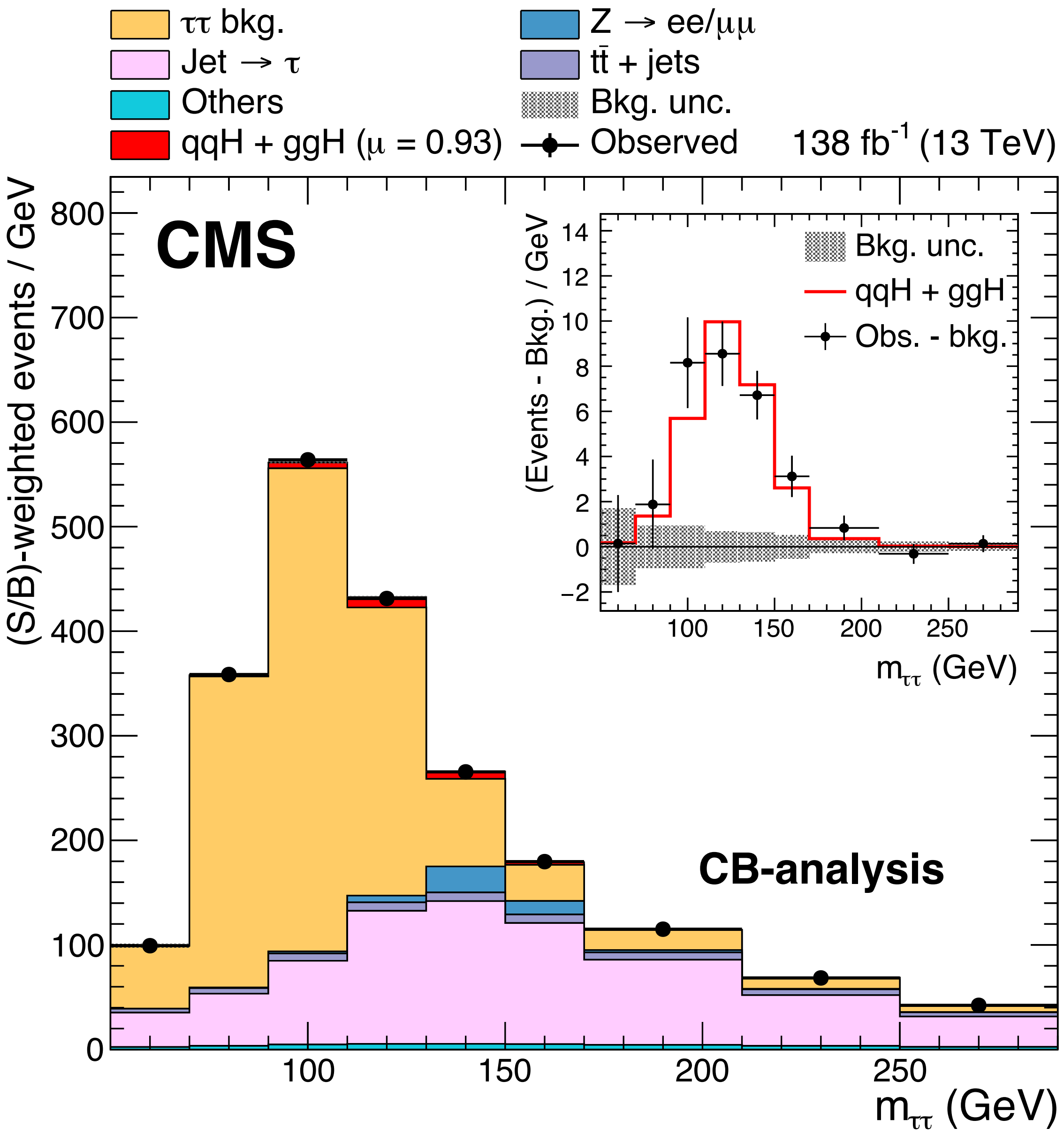
- For events with an intermediate resonances we can define a variable using only visible decay products
  - e.g $\tau\tau \rightarrow \rho^+\nu\rho^-\nu \rightarrow \pi^+ \pi^0\nu\ \pi^- \pi^0\ \nu$
- This avoids using the IP which is quite short compared to tracker resolution so is imprecisely reconstructed





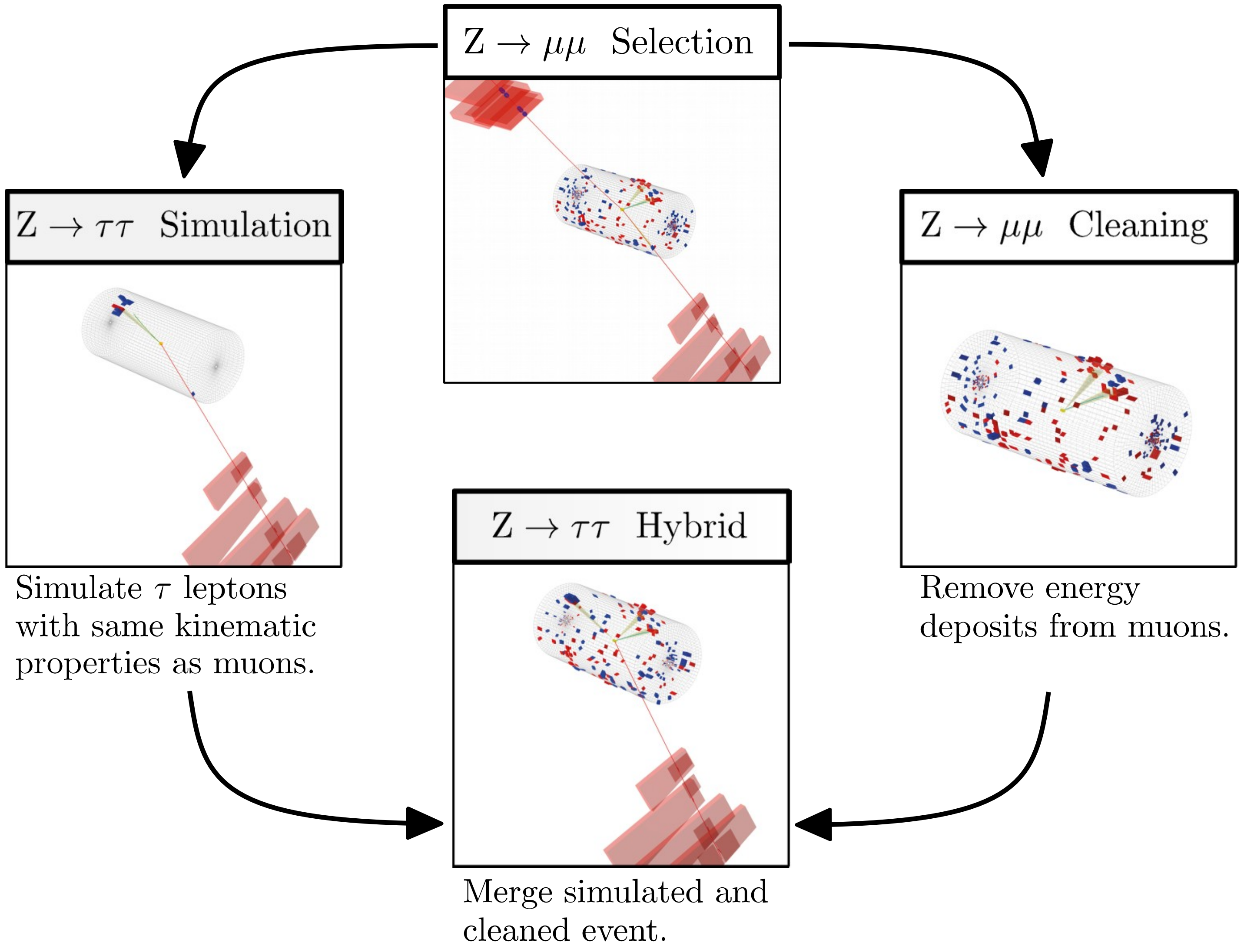
Backgrounds

- Two largest contributions to background are Z→$\tau\tau$ and jets faking hadronic taus (j→τ_h)
- We use data-driven method to estimate these processes
- This has advantaged such as reduced systematic uncertainties
- Statistics can be very large compared to MC simulations



Modelling Z→$\tau\tau$: The embedding method

- Method exploits lepton universality in Z decays
- Replace muons selected in data with simulated tau leptons
- Bulk of events content (e.g jets, PU, UE, …) comes directly from data so described perfectly
- Full details in JINST 14 (2019) P06032



$Z \to \mu\mu$ Selection

$Z \to \tau\tau$ Simulation

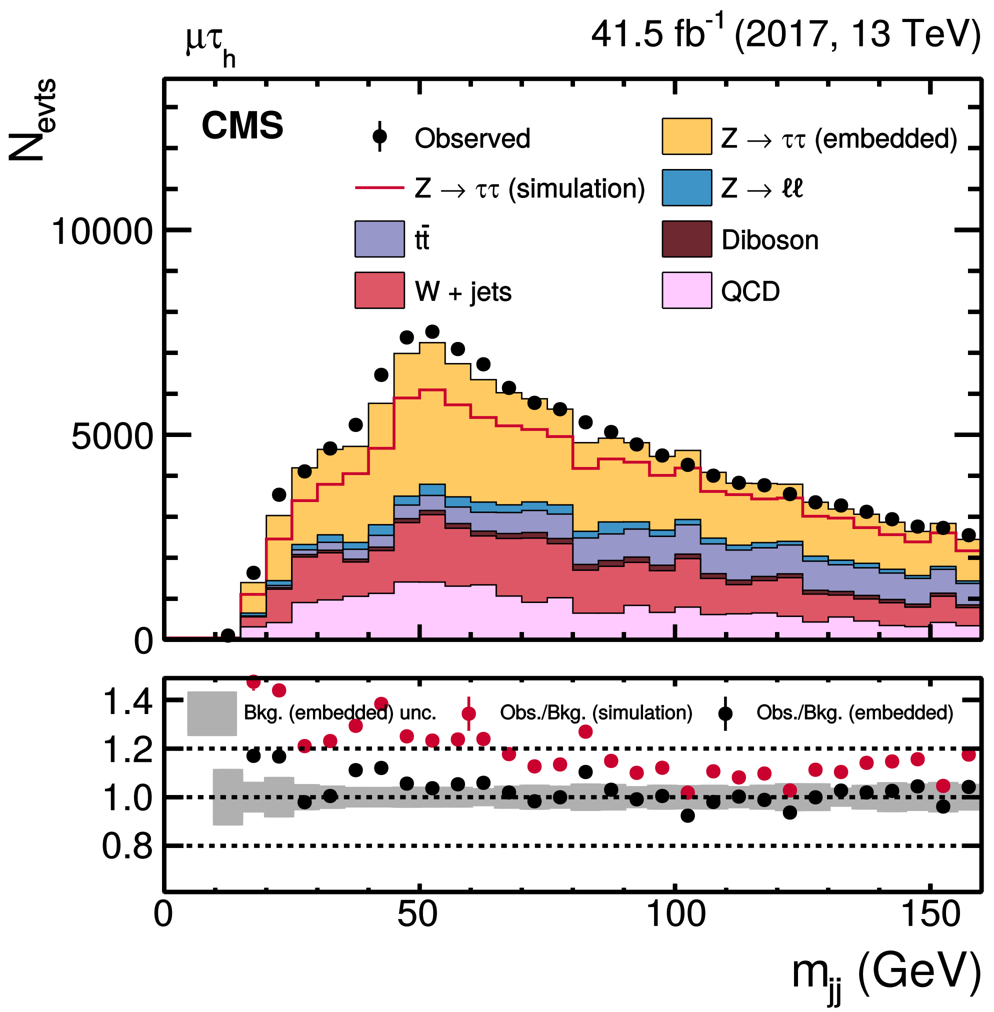
Simulate τ leptons with same kinematic properties as muons.

$Z \to \mu\mu$ Cleaning

Remove energy deposits from muons.

$Z \to \tau\tau$ Hybrid

Merge simulated and cleaned event.



Event selections

- We select di-tau events in the fully hadronic final state ($\tau_h\tau_h$) and two semi-leptonic final state ($\tau_e\tau_h$ and $\tau_\mu\tau_h$)

- For $\tau_h\tau_h$ we require:
    - Two opposite-sign τ_h candidates passing HPS and DeepTau ID
    - Veto events with additional light leptons

- For $\tau_l\tau_h$ we require:
    - A τ_h candidate passing HPS and DeepTau ID
    - A isolated e/μ passing identification
    - The τ_h and e/μ should have opposite sign charges
    - Veto events with additional light leptons, b-jets, or with transverse mass $m_T > 50$ GeV

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MVA signal vs background

- Event after apply previous event selections the background is significantly larger than the signal (S/B ~ 0.006)

- We use multi-class MVAs to improve separation between the backgrounds

  - 2 background classes: genuine-τ_h and fake-τ_h, + 1 inclusive signal class

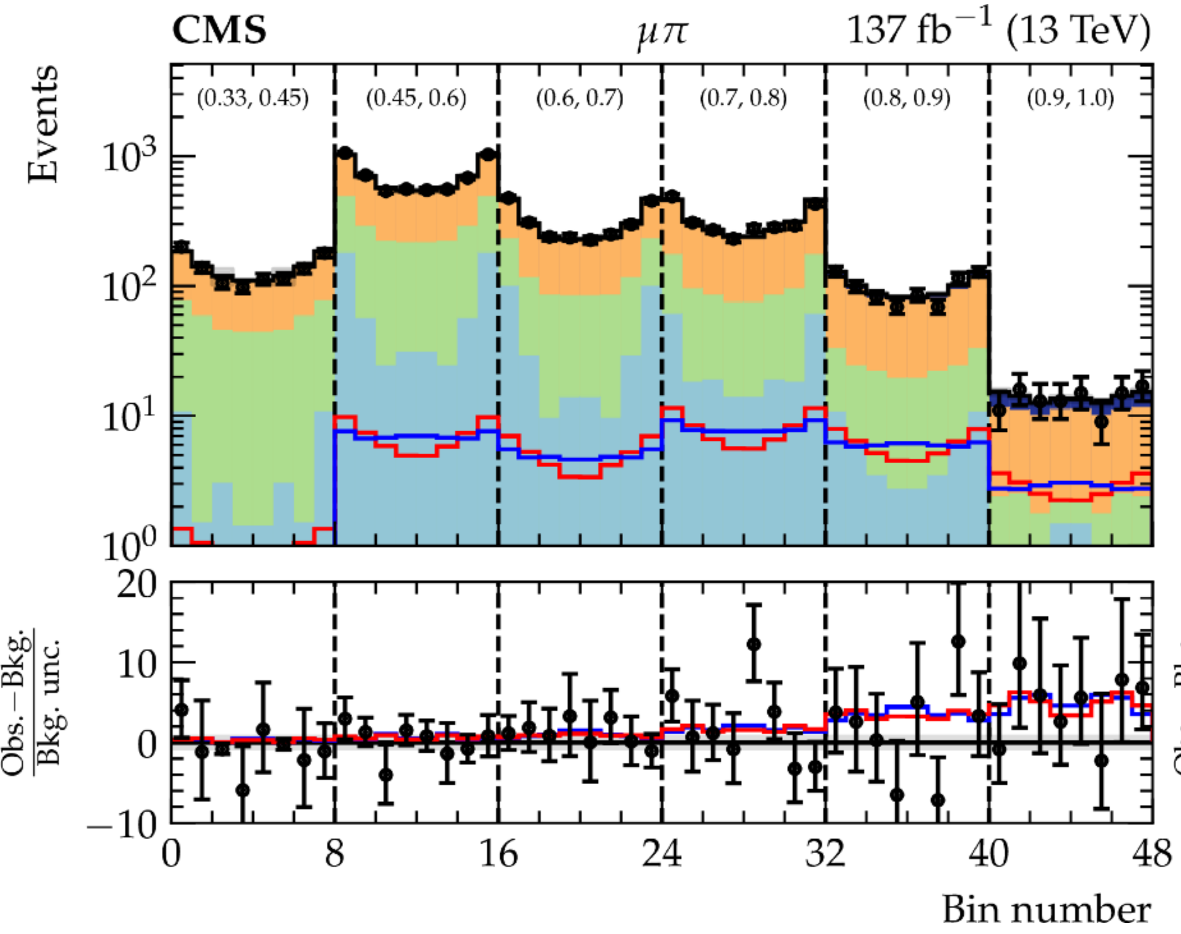
- For $\tau_h\tau_h$ ($\tau_l\tau_h$) channel(s) we use BDT (NN)

  - $m_{\tau\tau}$ most important variable - because of neutrinos we estimate using SV-fit algorithm (J. Phys. Conf. Ser. 513 022035)

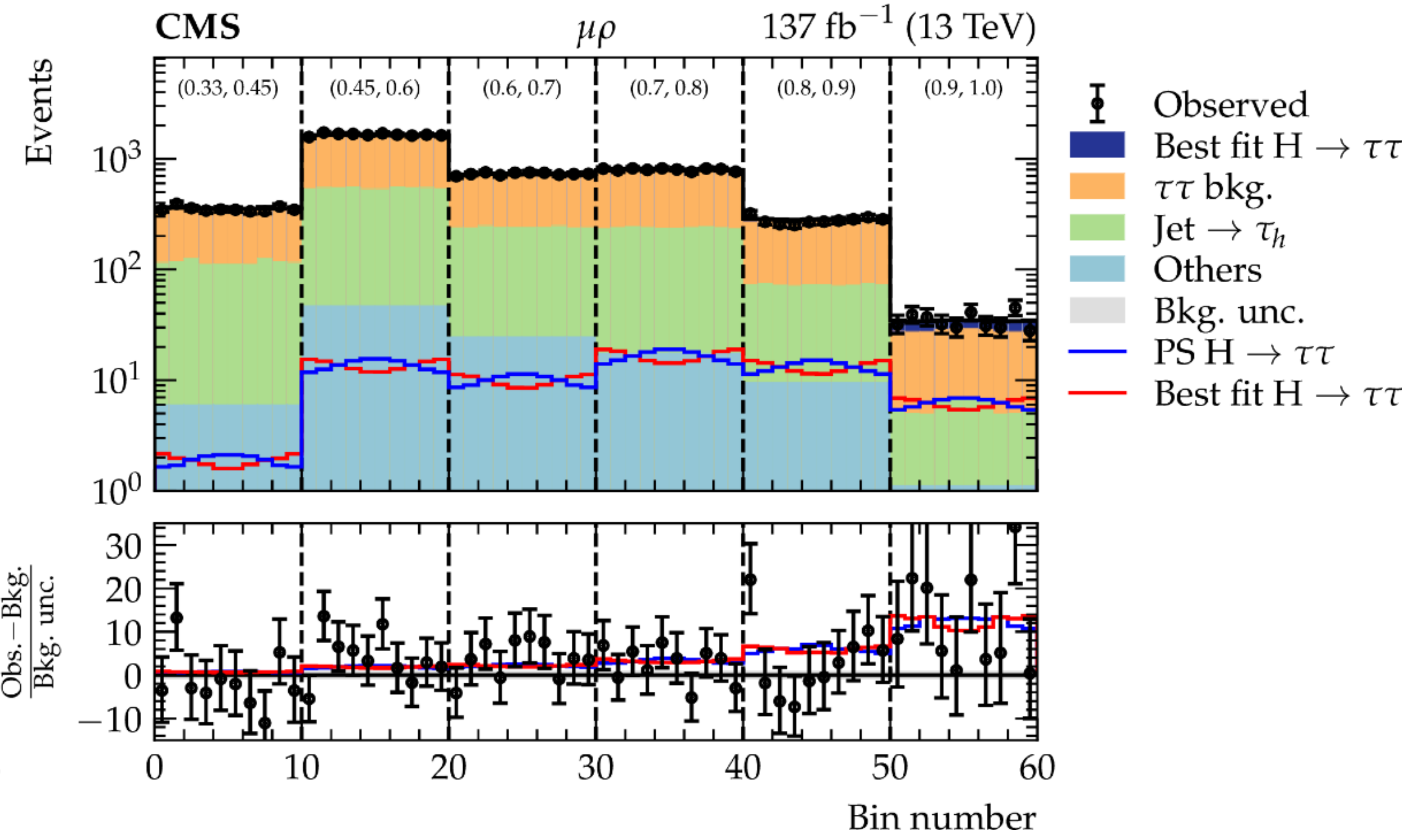
Signal categories

- For the signal-like events we divide events depending on the τ_h decay mode
- We fit 2D variables: 1 variable is the MVA score, the second is ϕ_{CP}

$\tau_\mu\tau_h$, $\tau_h \to \pi^- \nu$



$\tau_\mu\tau_h$, $\tau_h \to \rho^- \nu$



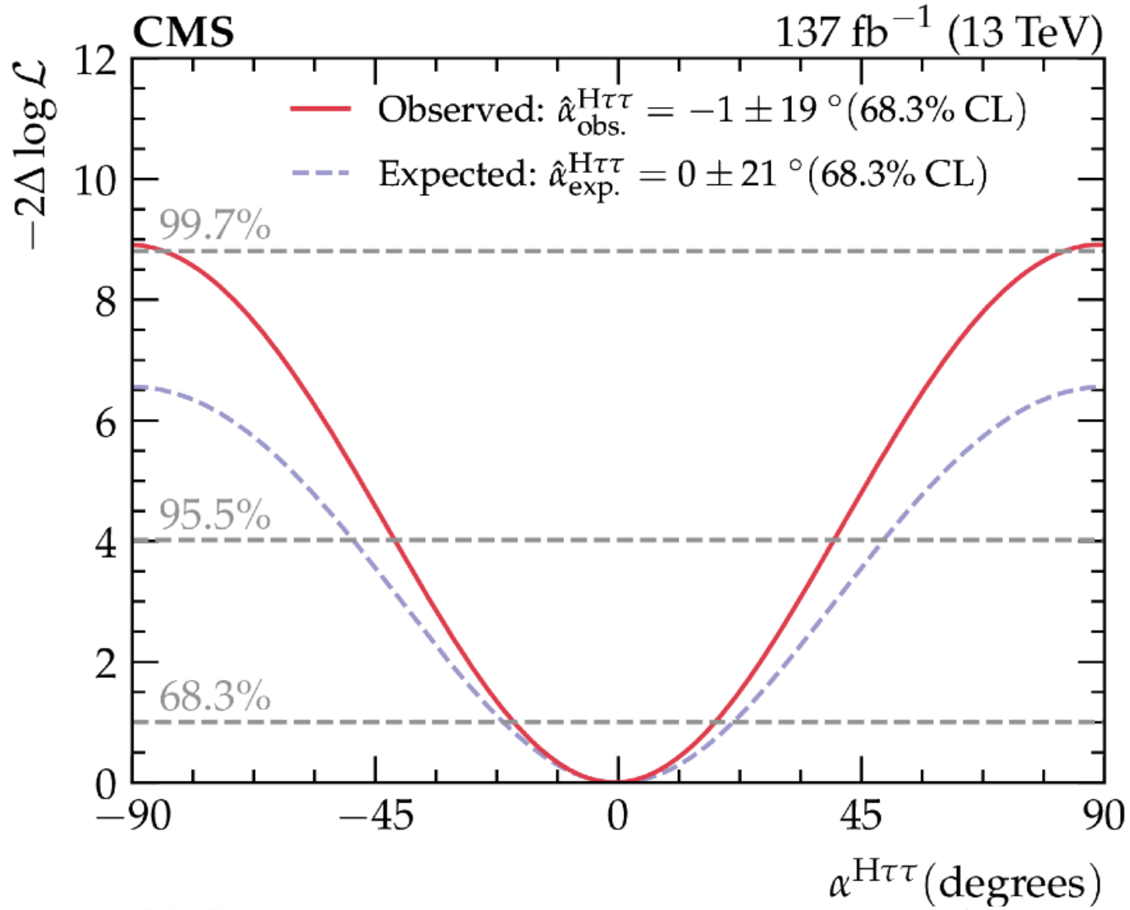
Results

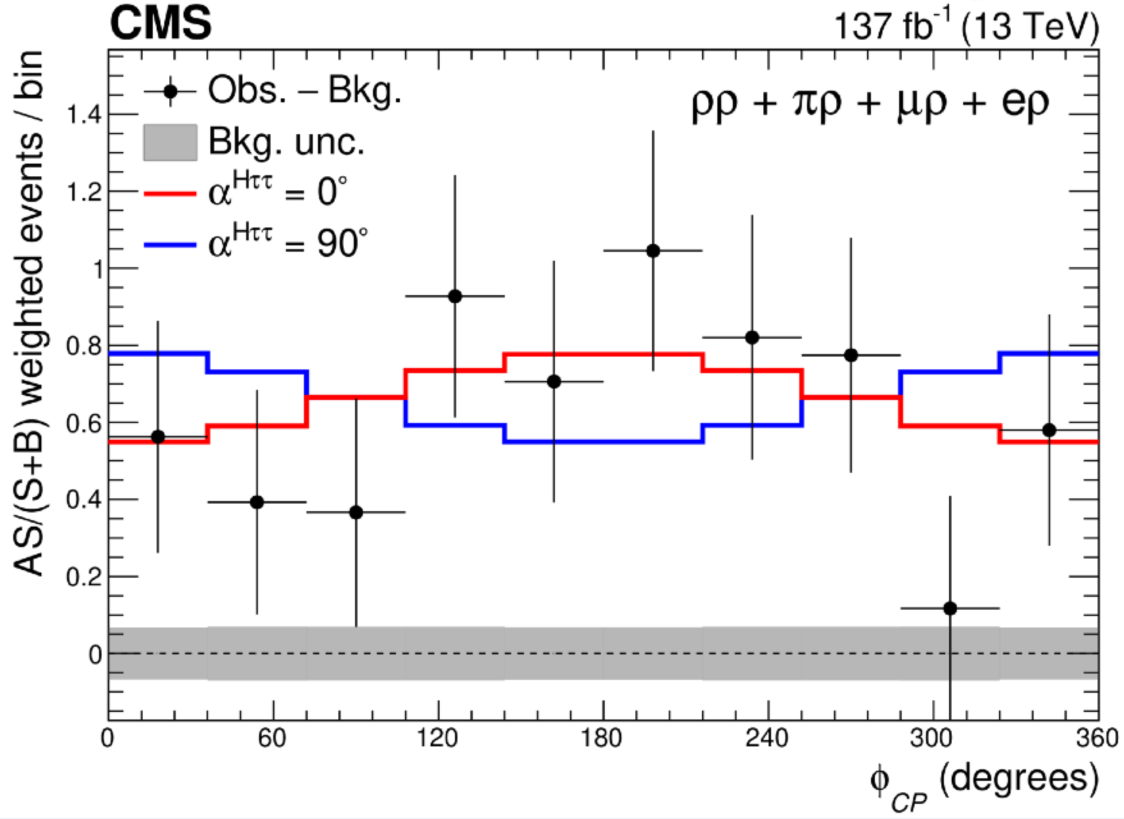
- The observed (red) and expected (blue) -2Δlog(L) scan is shown below

- The best fit value and uncertainty is $\alpha^{H\tau\tau} = -1 \pm 19^{o}$

- Results are in agreement with the SM

- We exclude the pure CP-odd hypothesis at the 3σ level

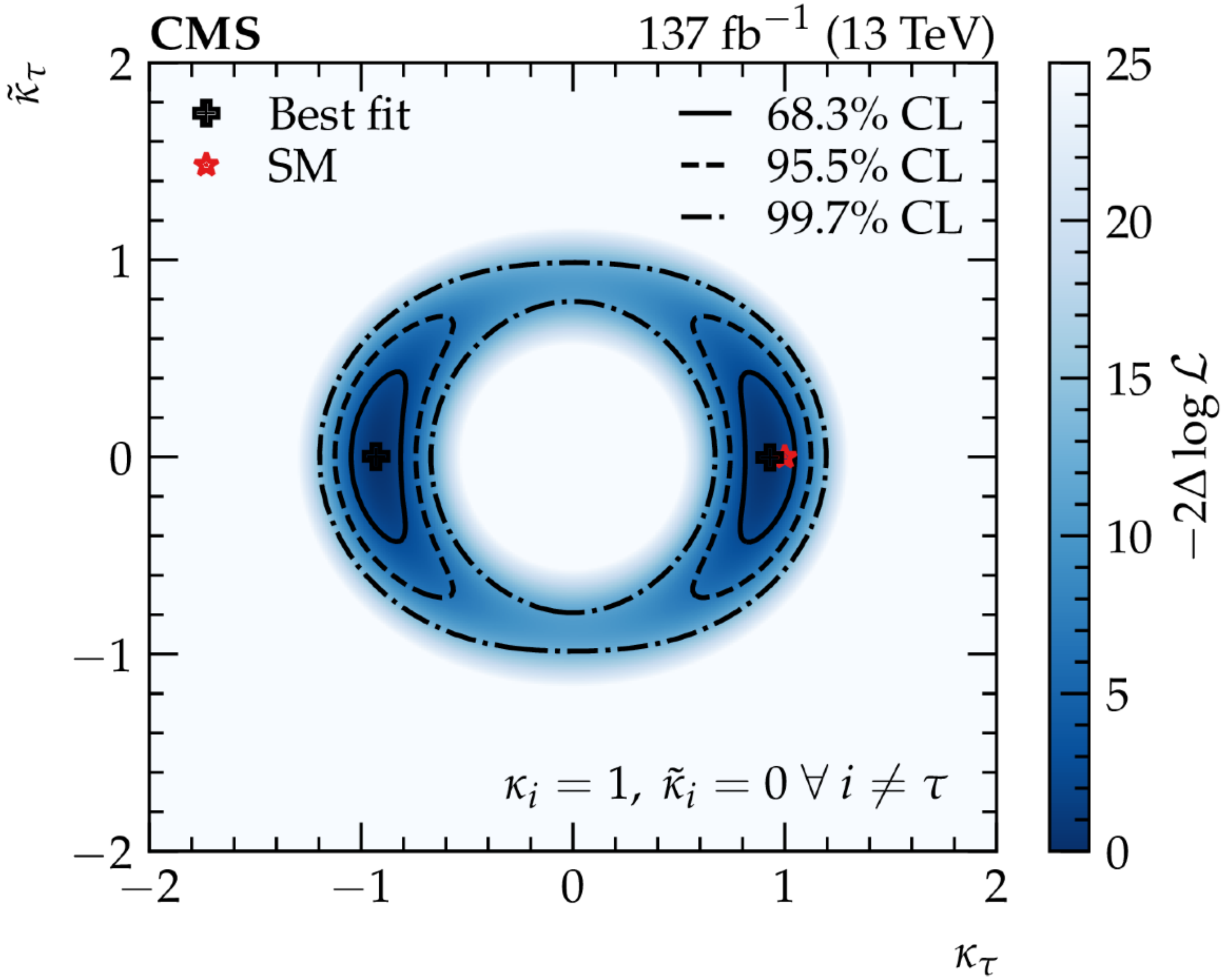




Coupling measurements

- Also interpret results in terms of couplings: κ_τ and $\tilde{\kappa}_\tau$

- Assume all other couplings = SM values

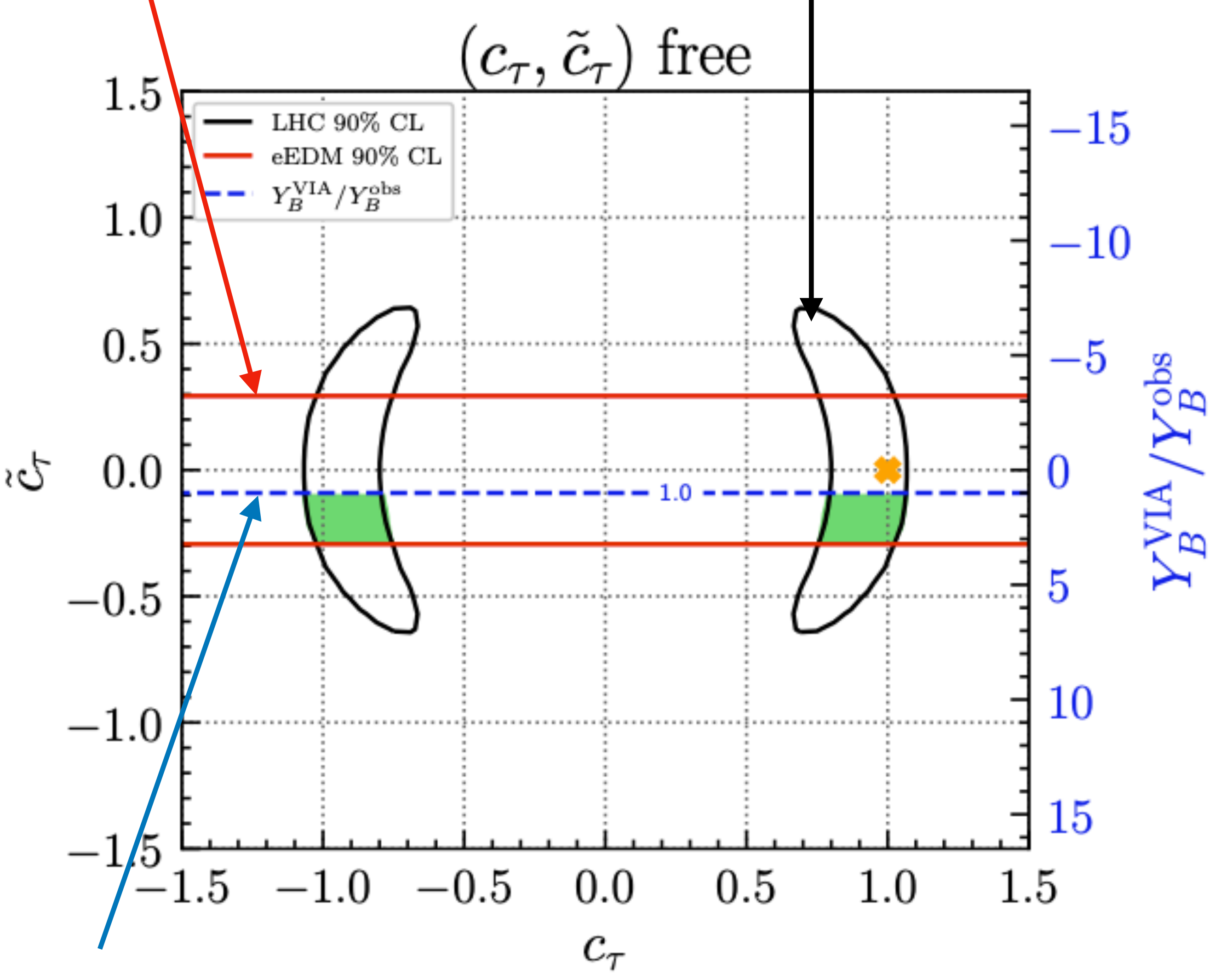


Comparison with indirect constraints

- Consider simplified model:
  - Only SM particles contributing
  - All other couplings = SM expectations
- CMS measurement able to probe regions of parameter space uncovered by EDMs that can explain BAU

CMS direct measurement

EDM bound



BAU

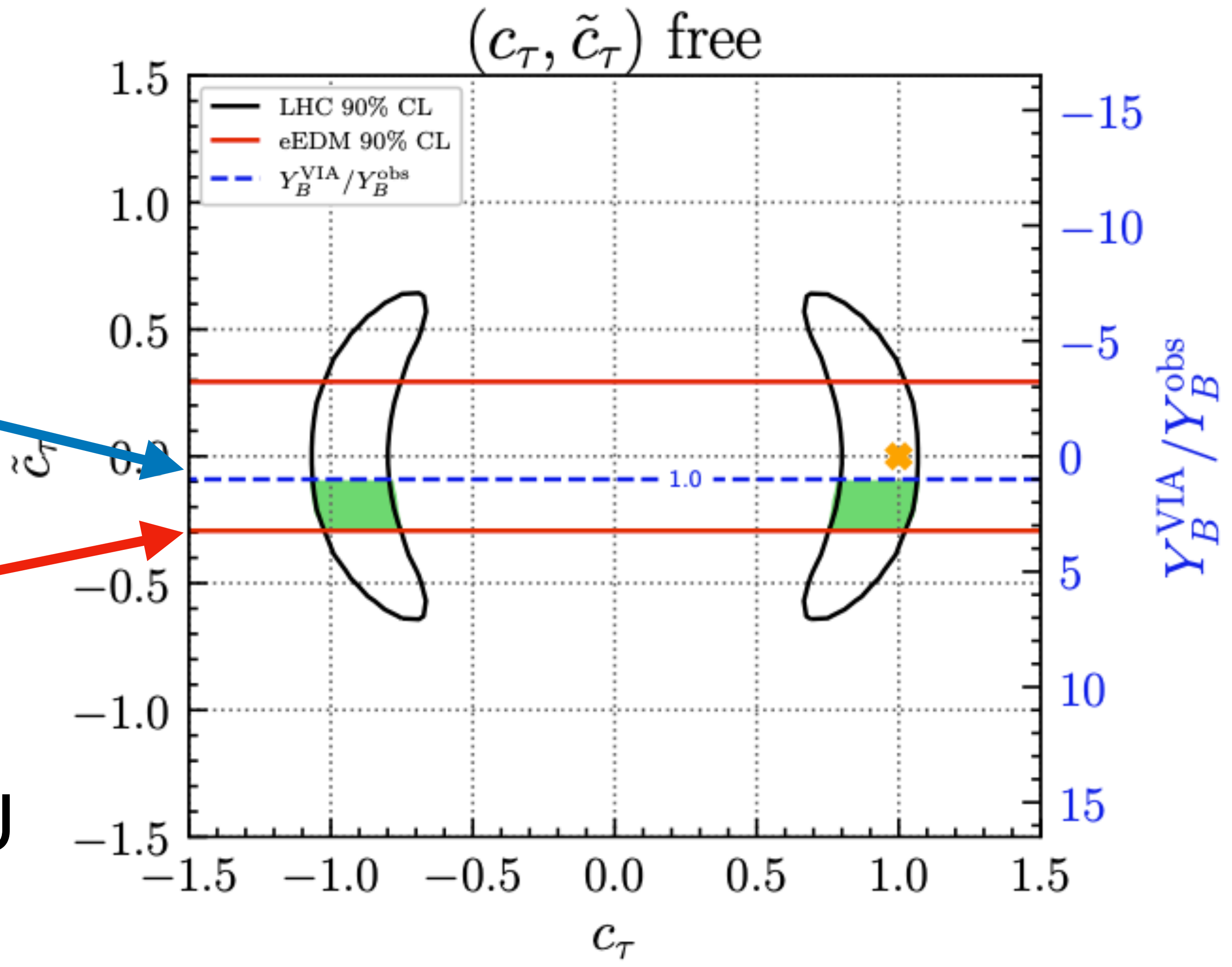
Plot from arXiv:2202.11753

The ultimate goal

Plot from arXiv:2202.11753

$\alpha^{H\tau\tau} \sim -6^{o}$

$\alpha^{H\tau\tau} \sim -17^{o}$



- $\alpha^{H\tau\tau}$ bounded by EDMs and BAU

- Most interesting to race to explore: $-17^{o} < \alpha^{H\tau\tau} < -6^{o}$

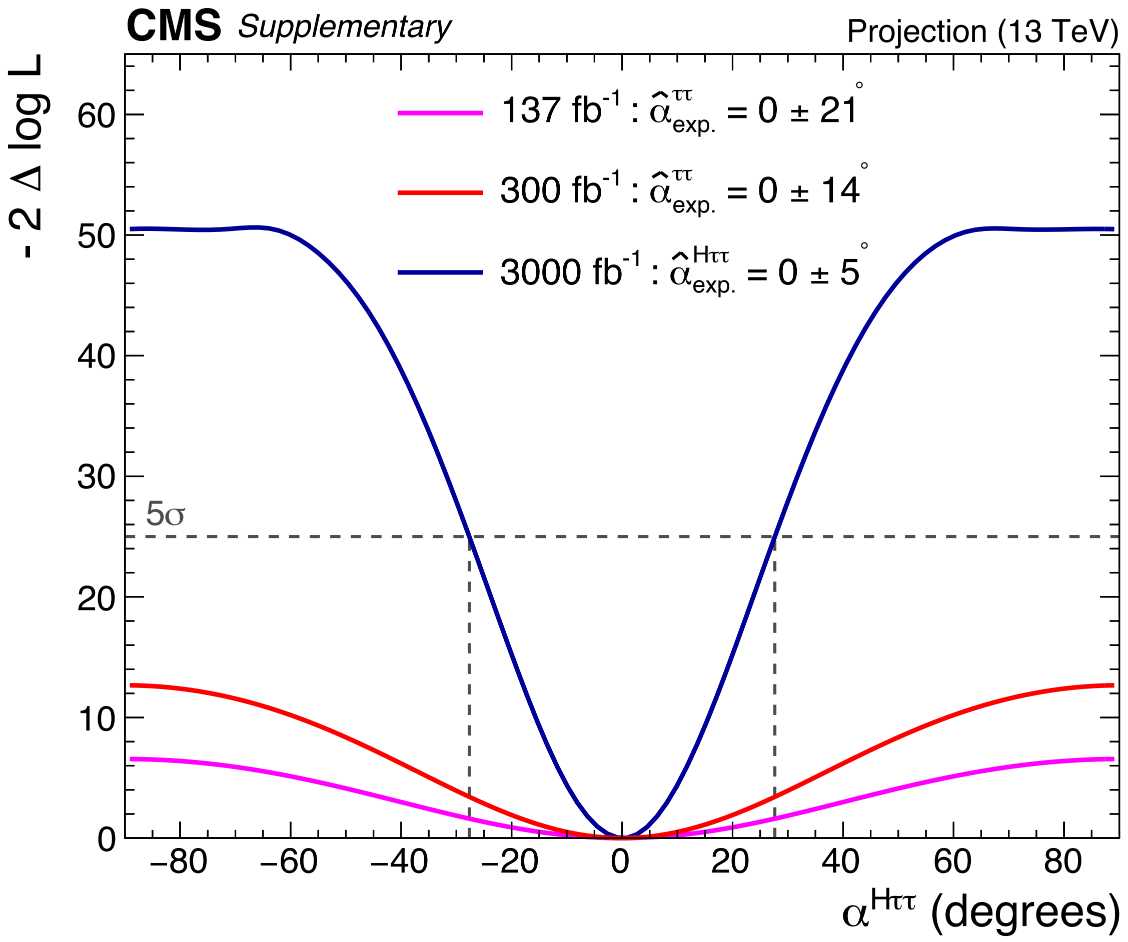
- What are the prospects for this?

Future measurements at the LHC

- Short term (LHC Run 3 ~ 2026):
  - Take into account more information/variables to constrain the $\tau\tau$ system e.g missing energy, secondary vertices, impacts parameters (where not already used e.g ρρ channel)
  - Improvements in signal vs background separation can help as well
  - Should improve sensitivity compared to current analysis but by how much remains to be seen
- Long term (end of HL-LHC data taking ~ 2040)
  - Breakdown of expected statistical and systematic uncertainties
    $\phi_{\tau\tau} = 0 \pm 21$ (stat.) + 2 (syst.) $^{\circ}$
  - Prediction for HL-LHC (3/ab):.5:

    $\phi_{\tau\tau} = 0 \pm 5$ (stat.) + 2 (syst.) $^{\circ}$
    - remains stats. Limited with total error ~ 5°

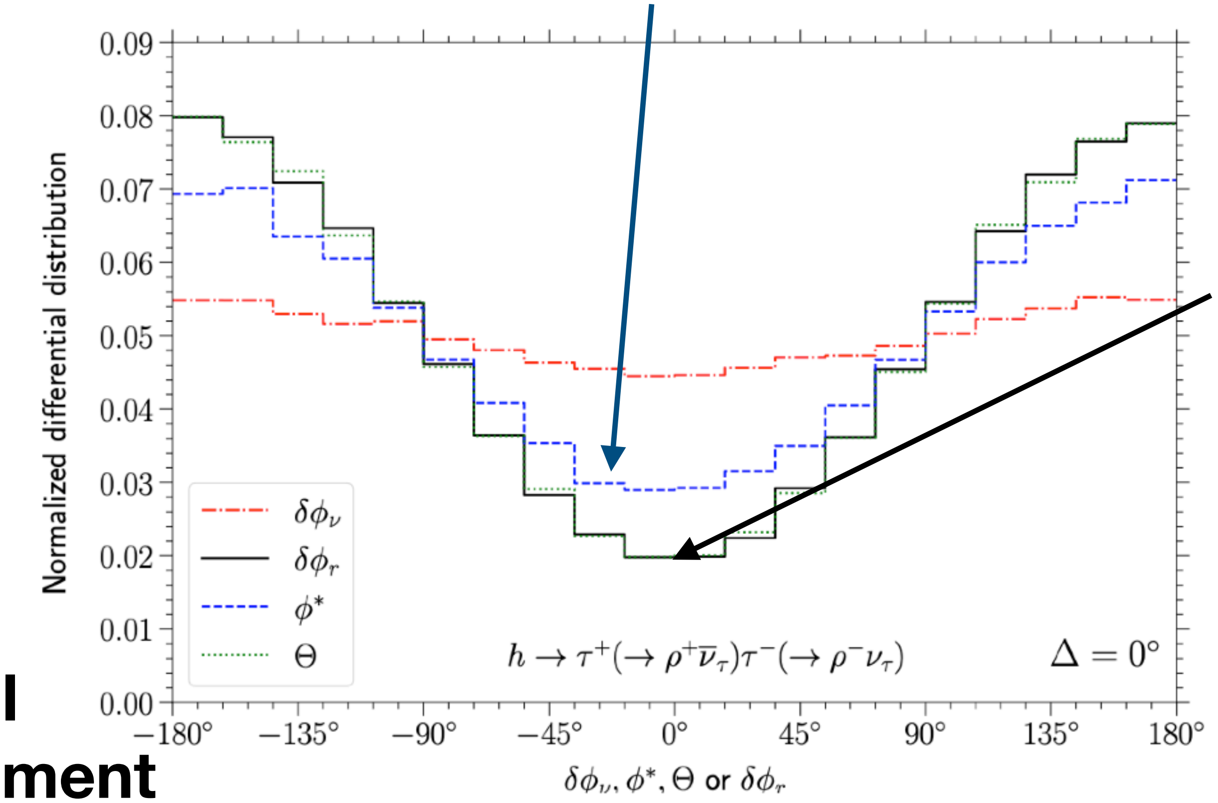
But we can develop the analysis techniques to bring further improvements!



Future measurements: lepton colliders

- Lepton colliders have advantage of being able to constrain H 4-vector in both transverse and longitudinal directions
  - Much cleaner environment which is good for precision measurements
  - Can fully constrain system (i.e estimate neutrinos) in several channels
  - Once system is constrained can estimate polarimetric vector, **h**, for each taus - **h** points in most likely direction of tau spin
  - Angle between **h**'s, $\delta\phi_r$, sensitive to $\phi_{\tau\tau}$
- Several publications out there that estimate sensitivity at ee colliders e.g arXiv:2012.13922 - summarised below

ϕ_{CP} - as used by CMS



$\delta\Phi_r$

	68% C.L. for $m = 1$
CEPC	2.9°
FCC-ee	3.2°
ILC	3.8°

Results here take into account ρρ, πρ, and ππ channels only
For LHC we gain ~ 60% from adding other channels

ρρ channel
~ 30% improvement

Conclusions

- Presented the latest CMS measurements of the Higgs boson CP properties
- CP properties of Higgs couplings to tau leptons measured for the first time
- All measurements consistent with SM expectations but reduce the allowed parameter space for BSM physics
- Lots of prospect to improve measurements in future LHC runs!

Thanks for your attention!

d.winterbottom@imperial.ac.uk 17/11/22

Backup

C2HDM: bounds

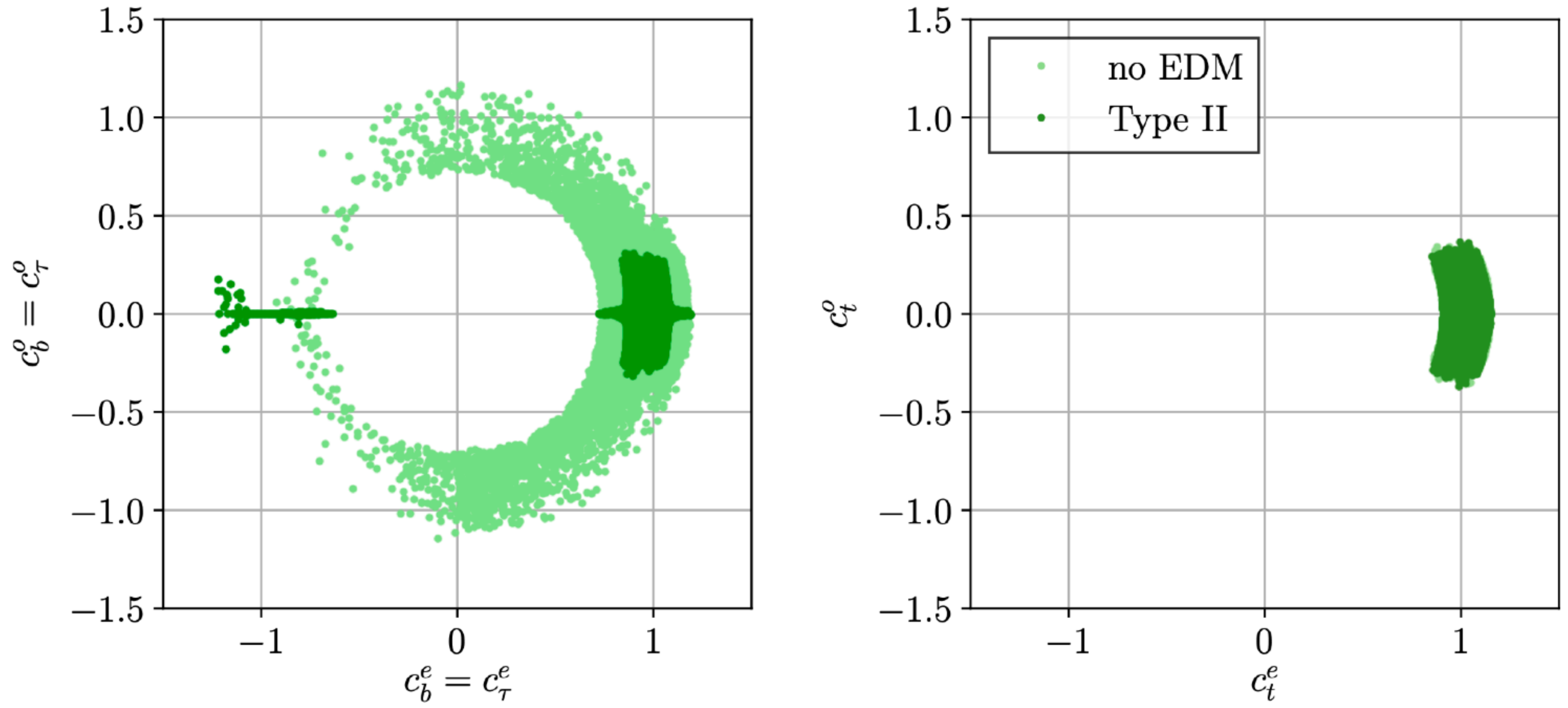
- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios considering several bounds:
  - Electron EDMs (ACME 2013)
  - Theoretical bounds: boundless from below and perturbative unitarity
  - Electroweak precision data
  - Flavour physics
  - H-boson (125 GeV) coupling constraints
  - HiggsBounds (searches for additional bosons)

C2HDM: Type 2

- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios

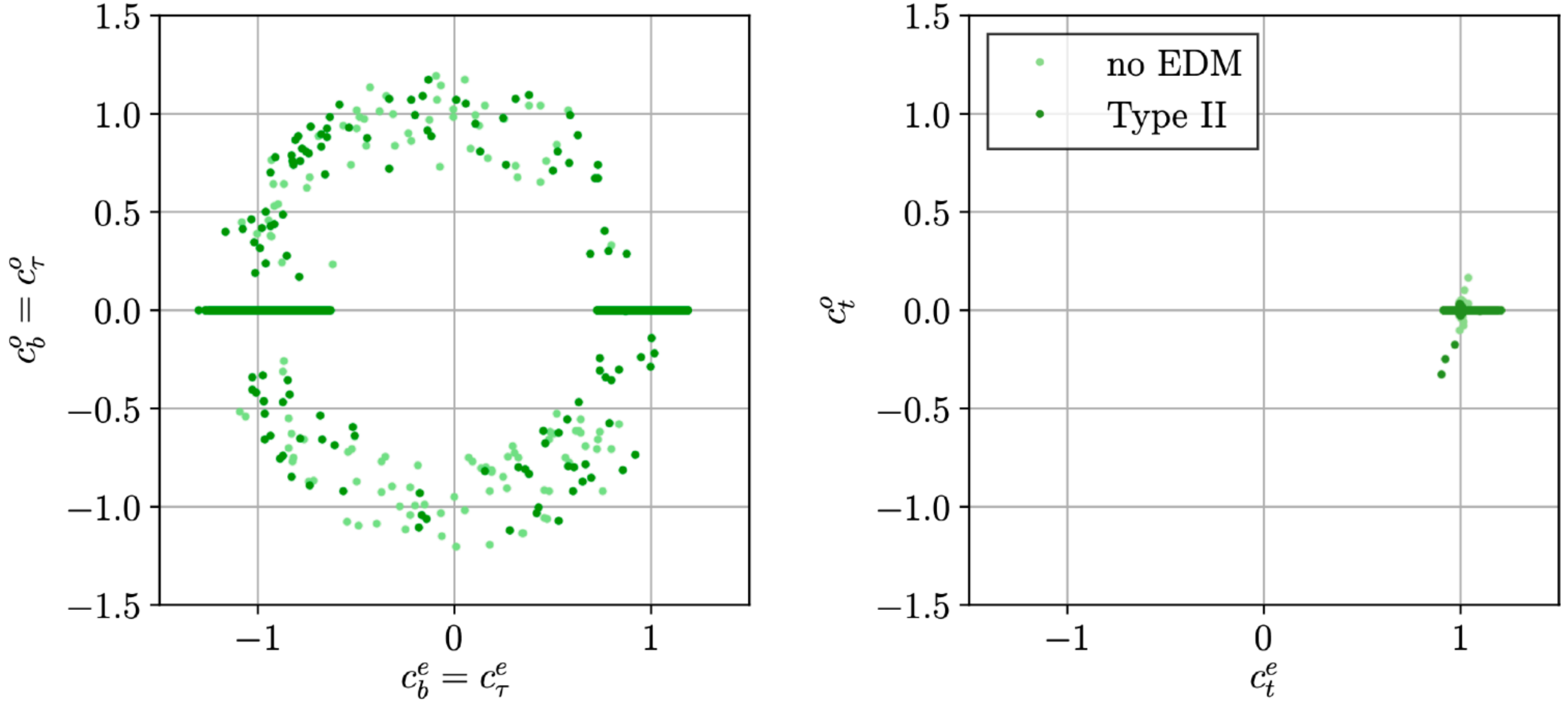
- In Type 2 2HDM where H_1 = 125 GeV boson

- EDMs constrain scenarios with large-iso $\bar{\kappa}_\tau$ quite alot



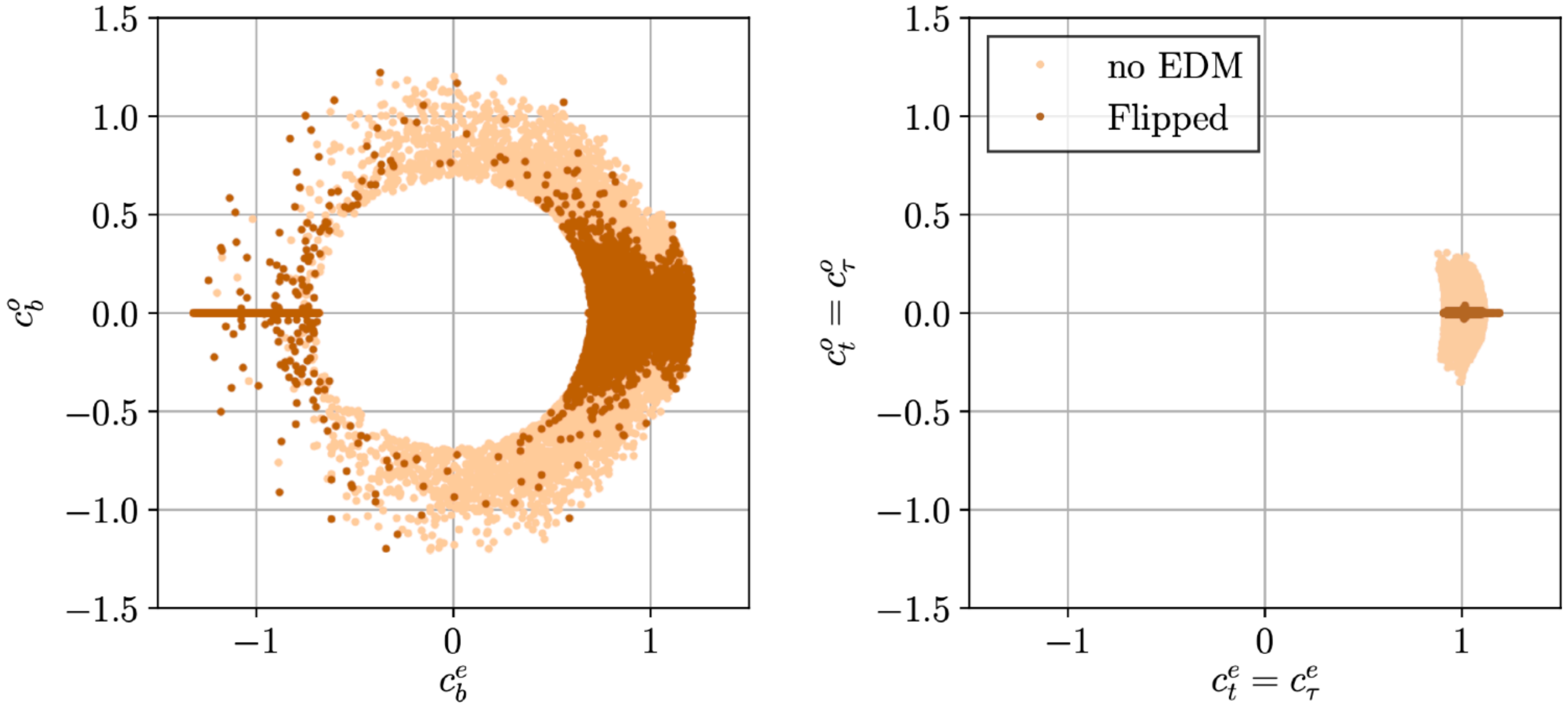
C2HDM: Type 2

- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios
- In Type 2 2HDM can also get points with larger $\bar{\kappa}_\tau$ not excluded for cases where H_2 = 125 GeV boson



C2HDM: Type-Y

- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios
- In Type-Y (flipped) 2HDM where H_1 = 125 GeV boson
- EDMs constrain scenarios with large $\bar{\kappa}_\tau$ significantly
- But lots of points still unexploded if we could measure $\bar{\kappa}_b$

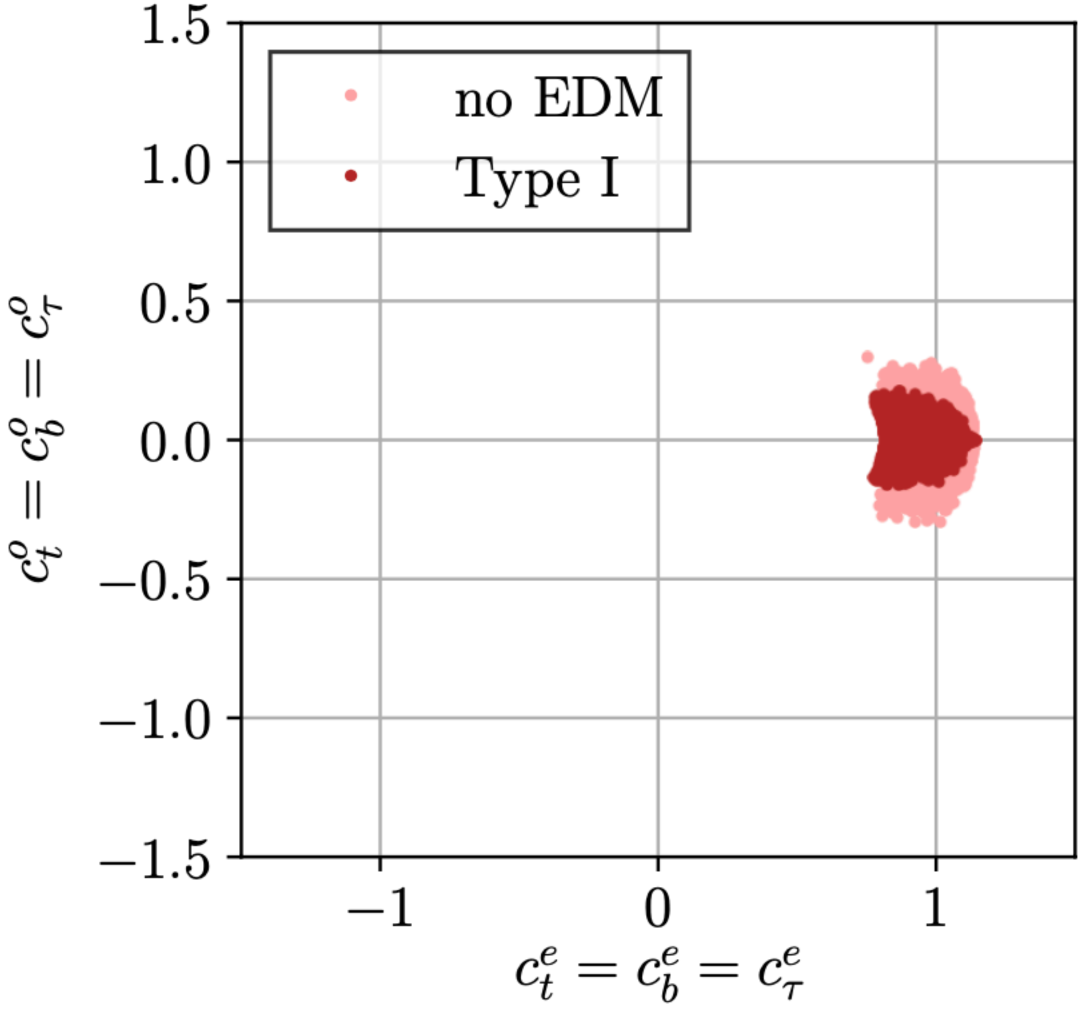


C2HDM: Type 1

- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios

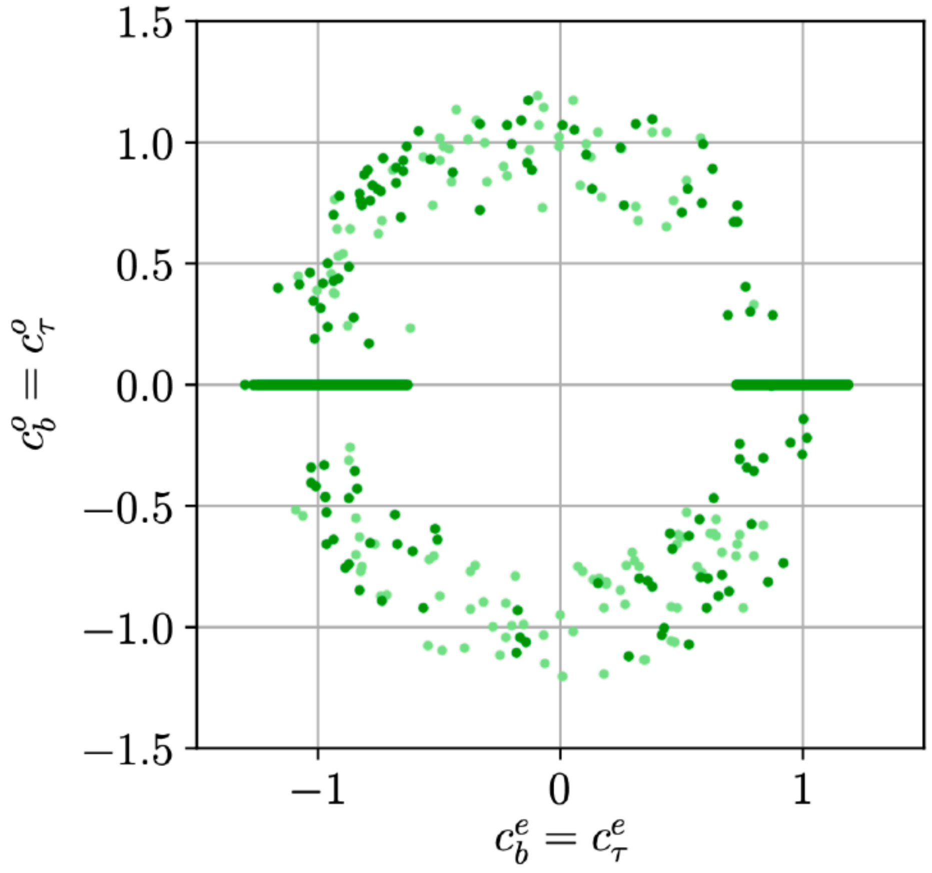
- In Type 1 2HDM where H_1 = 125 GeV boson

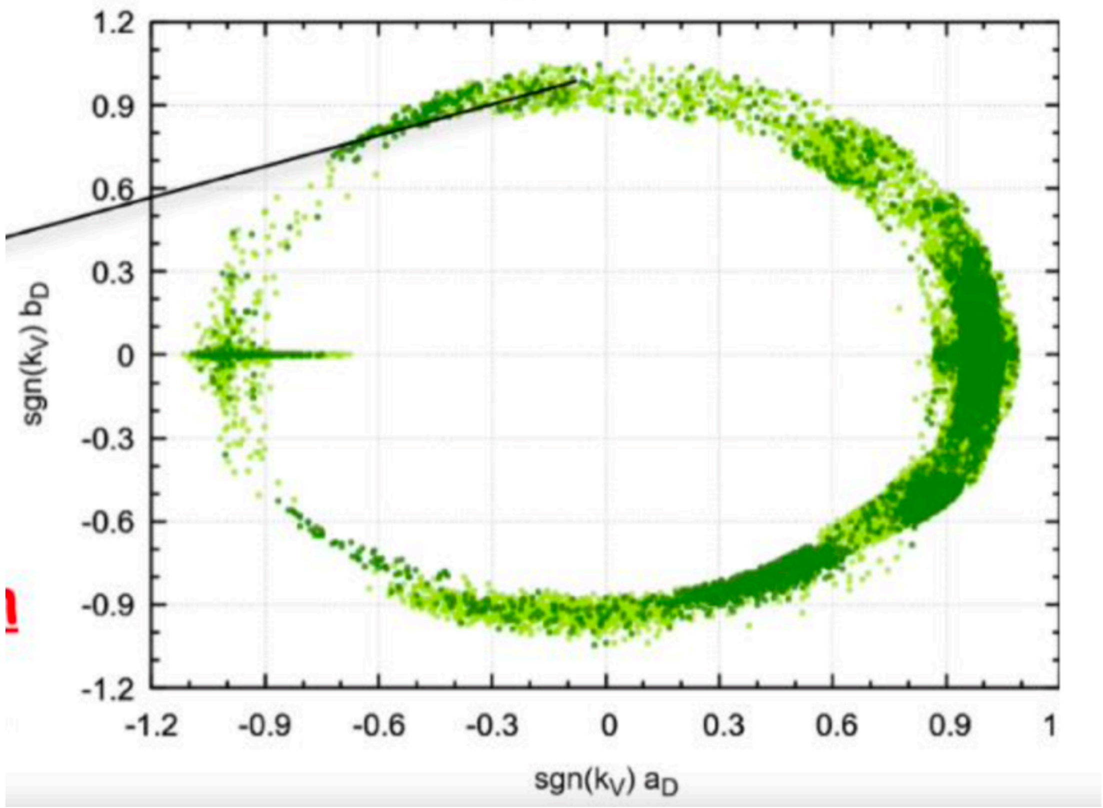
- Most tightly constrained



C2HDM: Type 2

- In JHEP 02 (2018)073 EDM constraints based off older measurement of electron EDMs
- But authors confirmed via private communication that points are still allowed even with new EDM bounds





Private communication with Rui Santos

NMSSM: the μ-problem

- The Higgsino mass parameter, μ, is constrained to be of order the weak scale (~ 200 GeV) by the SM phenomenology
- But naturally μ is expected to be of order the Planck scale (10^{19} GeV) → why is μ so small?
- The NMSSM solves the μ-problem by introducing an additional complex singlet, S

$$W_{MSSM} = \mu \hat{H}_u \hat{H}_d$$

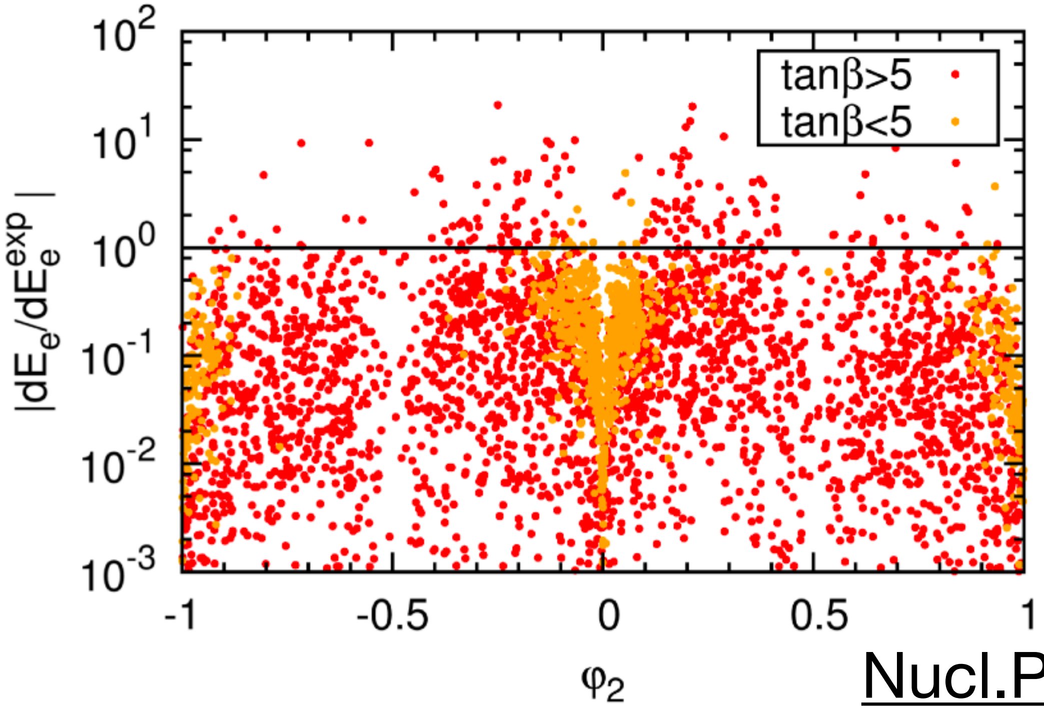
$$W_{NMSSM} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \kappa \hat{S}^3$$

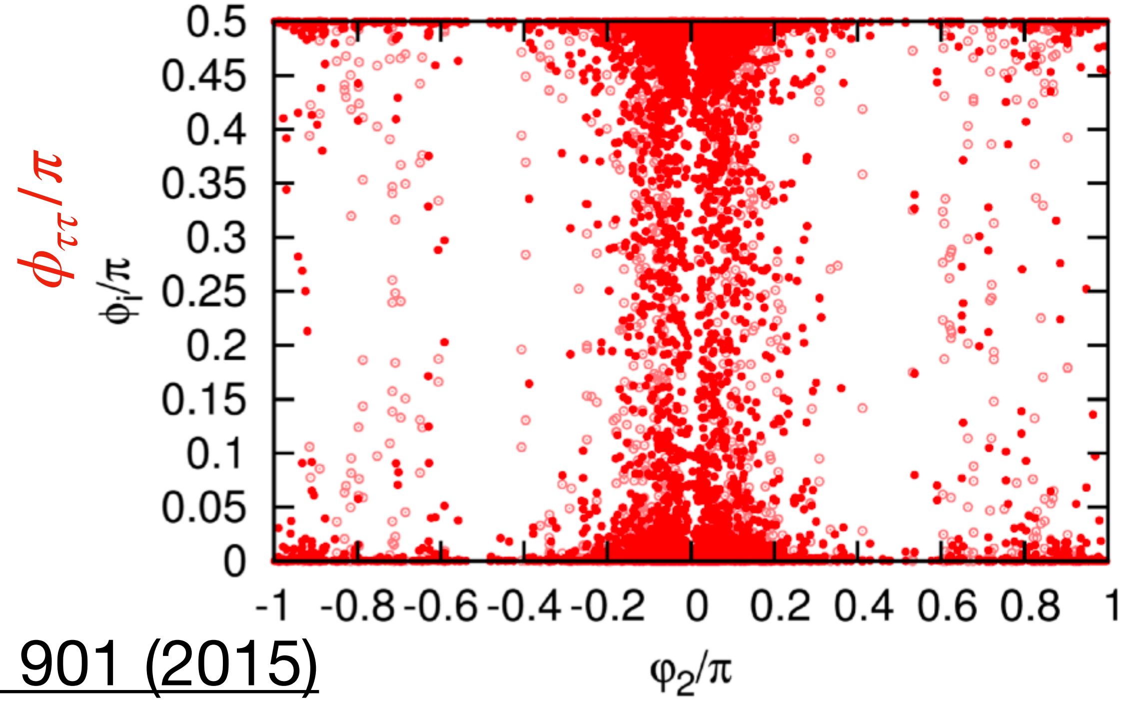
- In NSSM the μ parameter is generated as the vacuum expectation value of S

$$\mu = \lambda \langle \hat{S} \rangle$$

NMSSM

- Higgs sector in MSSM is a type 2 2HDM
    - But additional constraints on parameters means there is no CP-violation at tree level (can get CP violation at higher orders but suppressed)
    - CP-violation in MSSM probably not observable from H125 measurements
- In NMSSM Higgs sector is extended with additional complex singlet
- 7 Higgs bosons: 5 neutral + 2 charged
- Two CP-phases φ_1 (“MSSM-like” - tightly constrained) and φ_2 (“NMSSM-like” largely unconstrained)
- In examples below solid points not excluded by theory/experiment including EDMs, open points = conflict with EDMs
    - Lots of points still allowed up to $\phi_{\tau\tau}$ ~ 27^{o} - using uses older ACME 2013 EDM constraints





Nucl.Phys.B 901 (2015)

NMSSM

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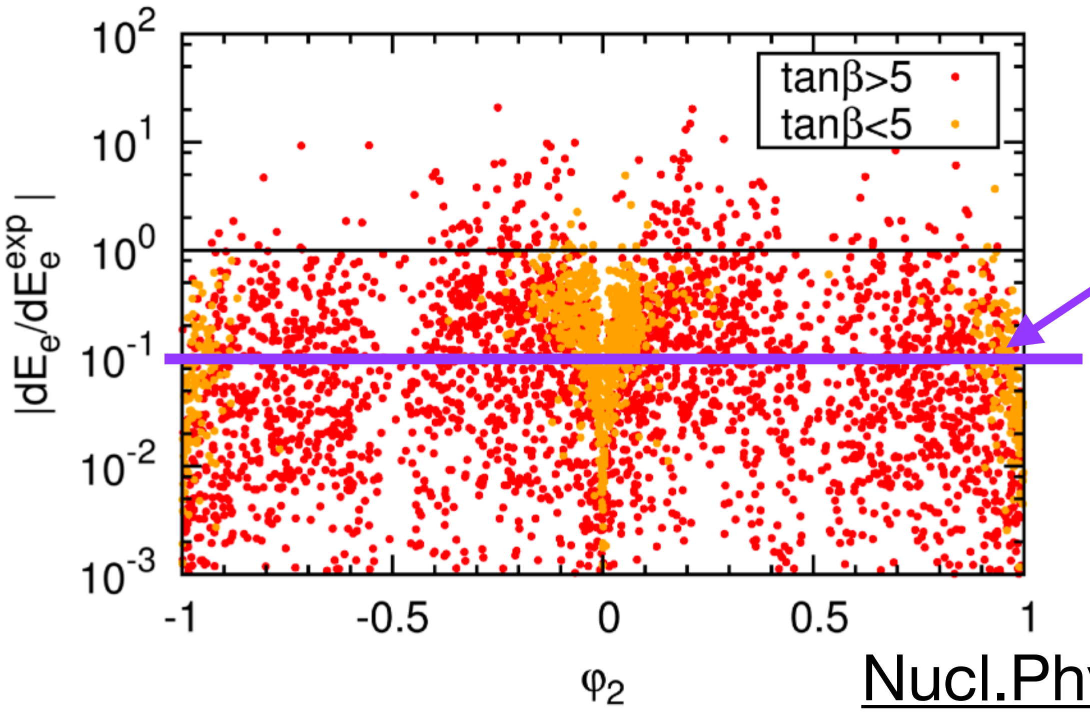
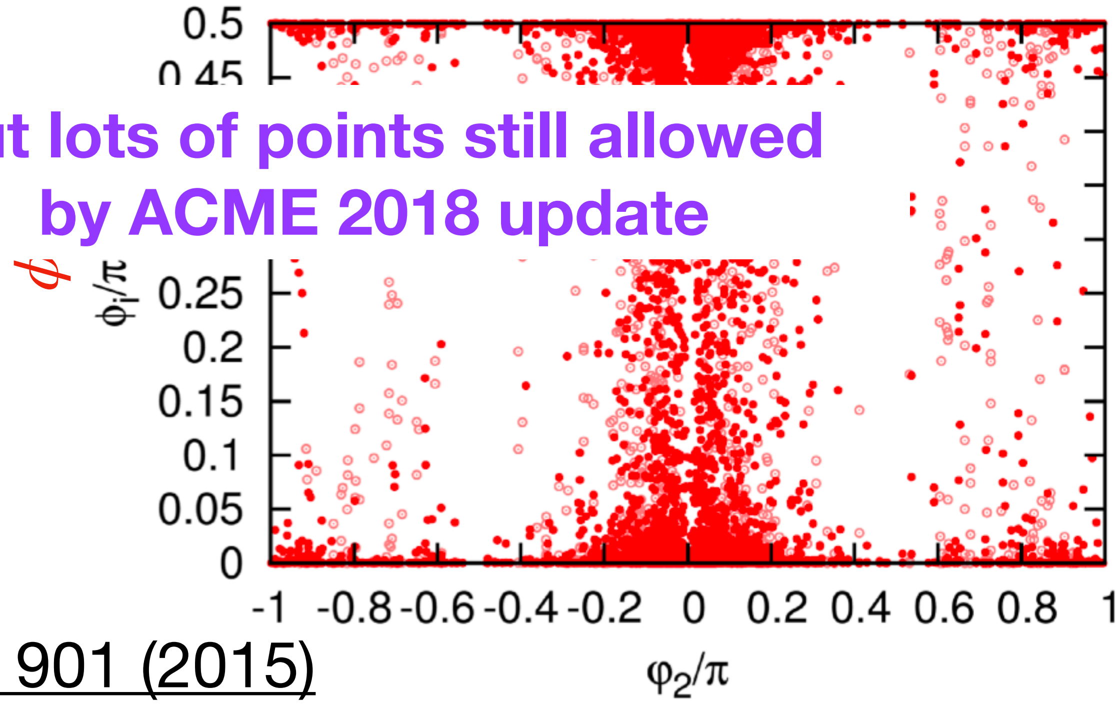


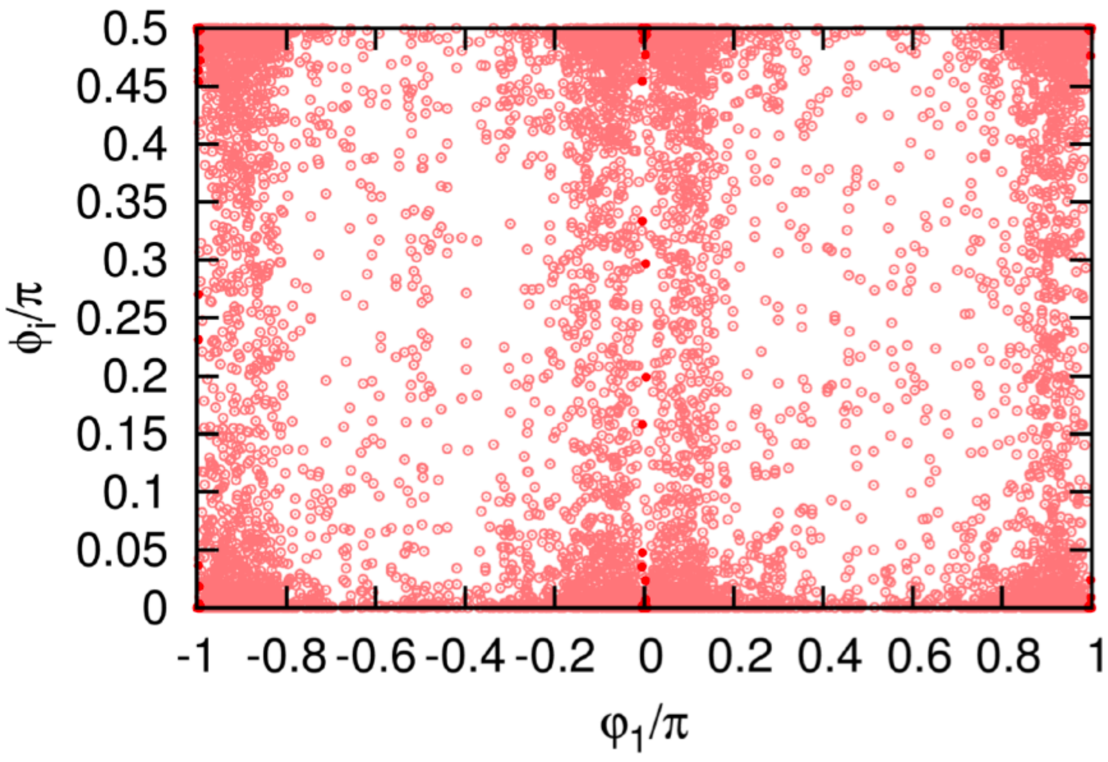


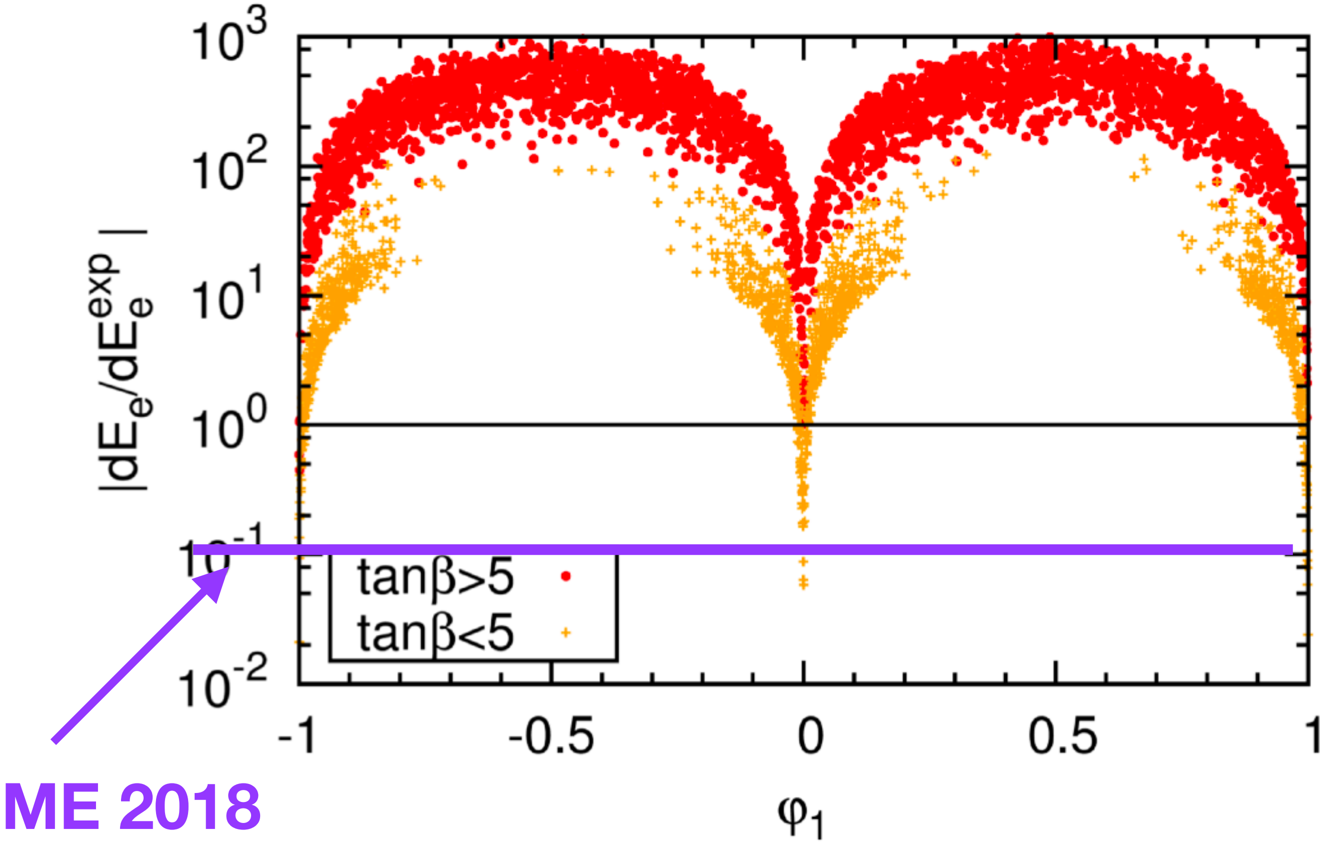
But lots of points still allowed by ACME 2018 update

Nucl.Phys.B 901 (2015)

NMSSM: MSSM-type

- MSSM-type CP-violation tightly constrained by EDMs
  - not many open points in left plot
  - Most points below EDM limit in right plot



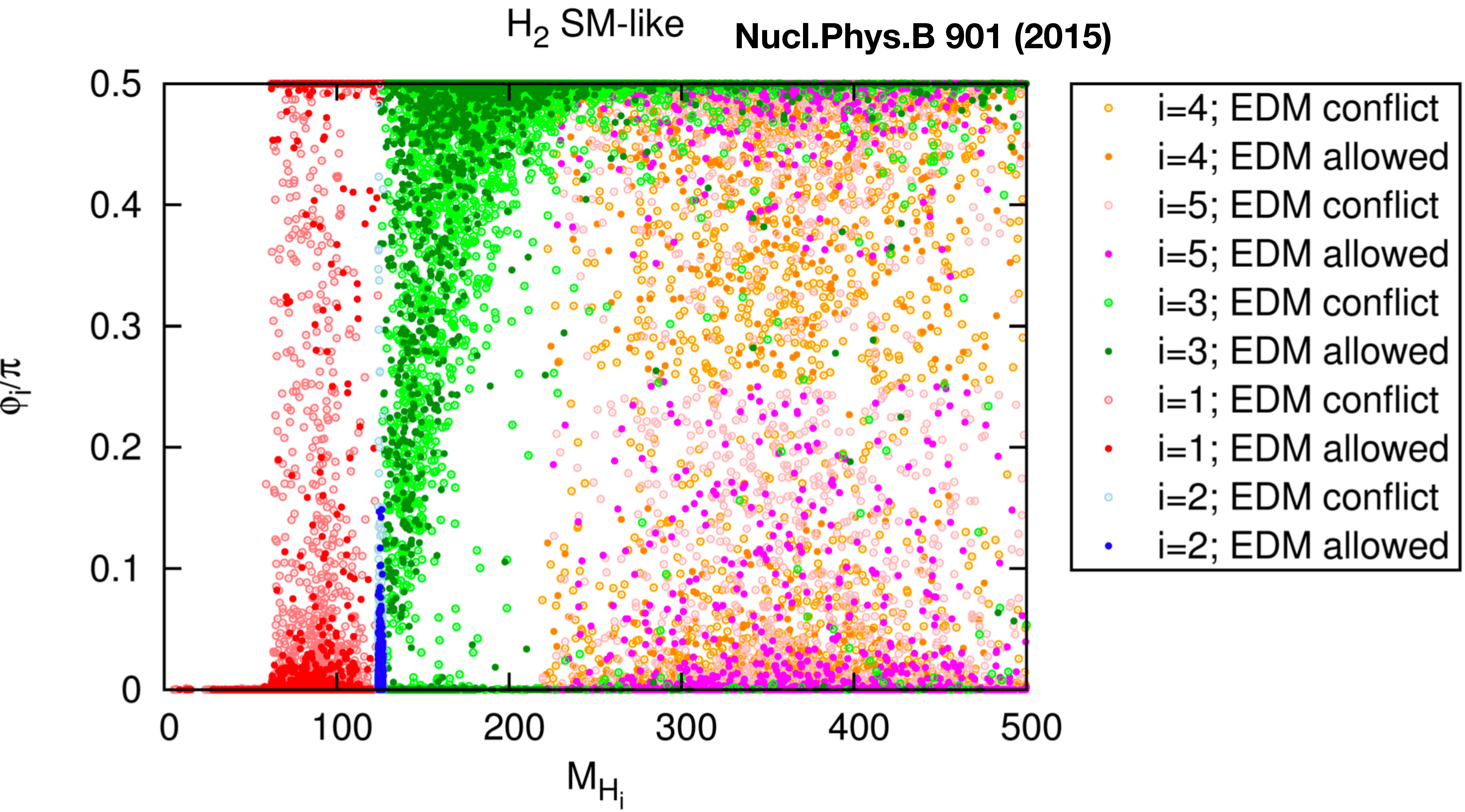


ACME 2018

Nucl.Phys.B 901 (2015)

NMSSM: Allowed H_i masses

- Allowed H_i masses



Nucl.Phys.B 901 (2015)

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ϕ_{CP} formulas

- Formulas for IP-IP method:

$$\phi^* = \arccos(\hat{\lambda}_\perp^{+*} \cdot \hat{\lambda}_\perp^{-*})$$

$$O^* = \hat{q}^{-*} \cdot (\hat{\lambda}_\perp^{+*} \times \hat{\lambda}_\perp^{-*})$$

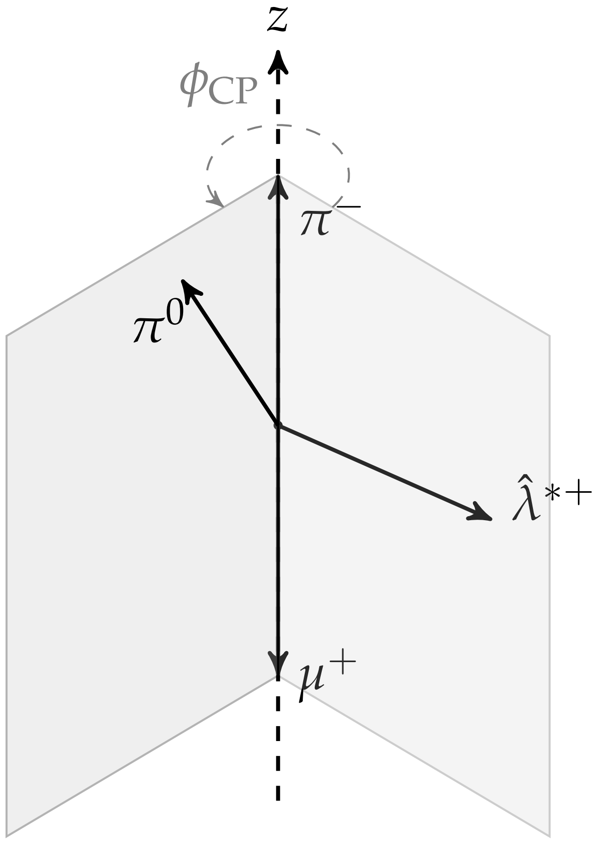
$$\phi_{CP} = \phi^*, \text{ if } O^* \geq 0$$

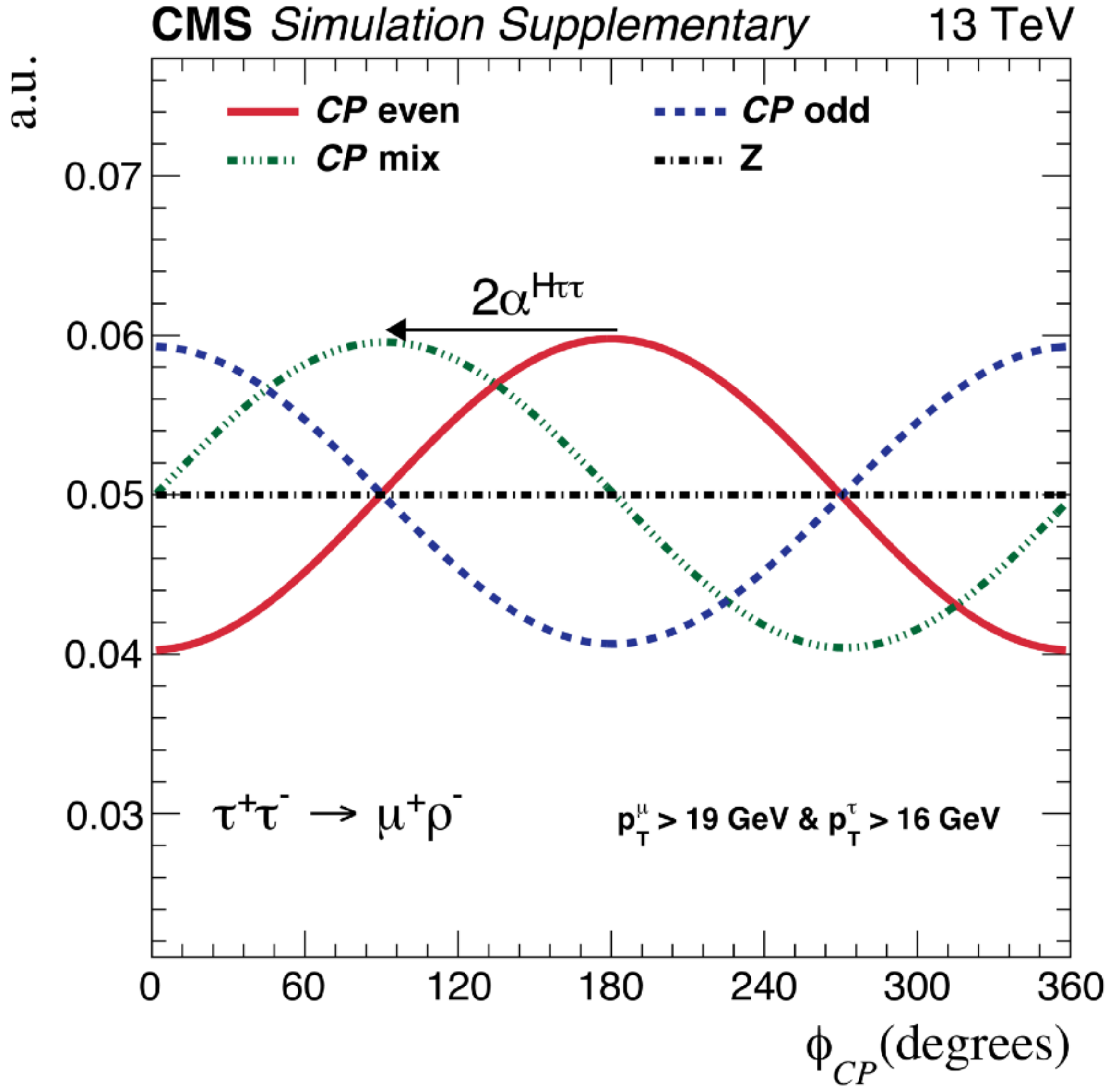
$$\phi_{CP} = 360^\circ - \phi^*, \text{ if } O^* < 0$$

- λ are IP vectors perpendicular to $\pi^\pm$, q is $\pi^\pm$ direction vector
- "*" means we are boosted into the charged pion rest frame
- For π^0 -method and mixed-method the same formulas are uses except λ is substituted with π^0 4-vectors

CP sensitive variables for $\tau_\mu\tau_h$ events

- Replacing $\tau\to\pi\nu$ with $\tau\to\mu\nu\nu$ we can define equivalent CP sensitive variables for $\tau_\mu\tau_h$ channel

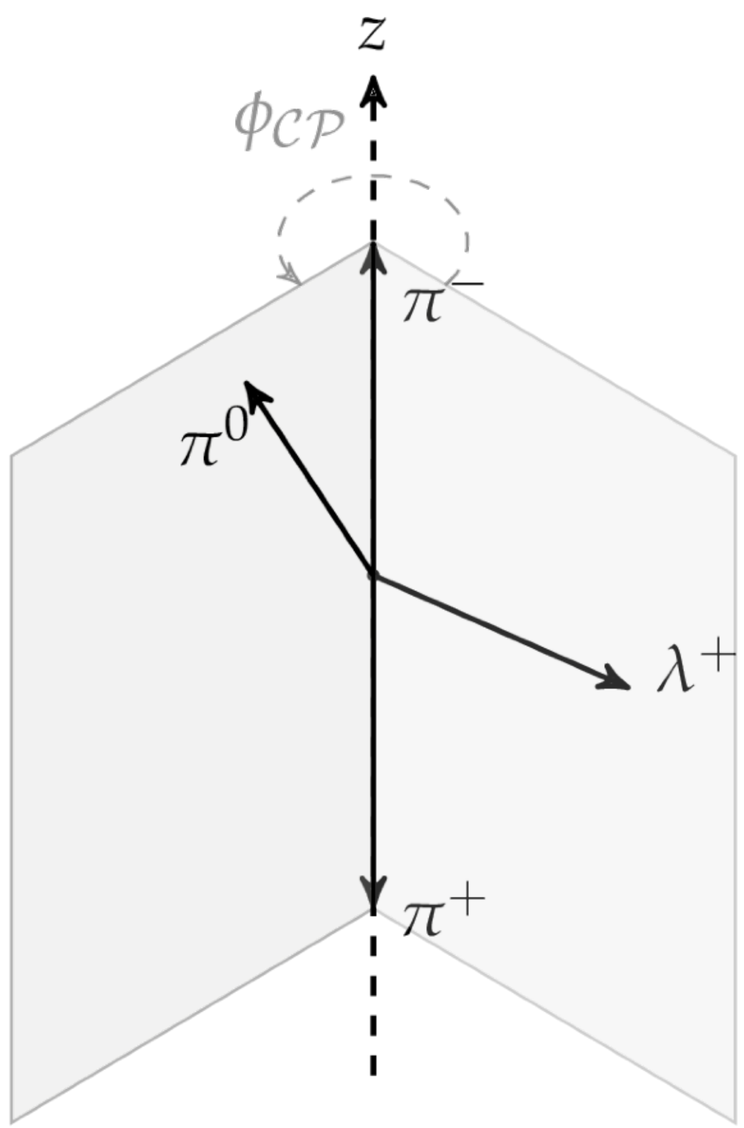


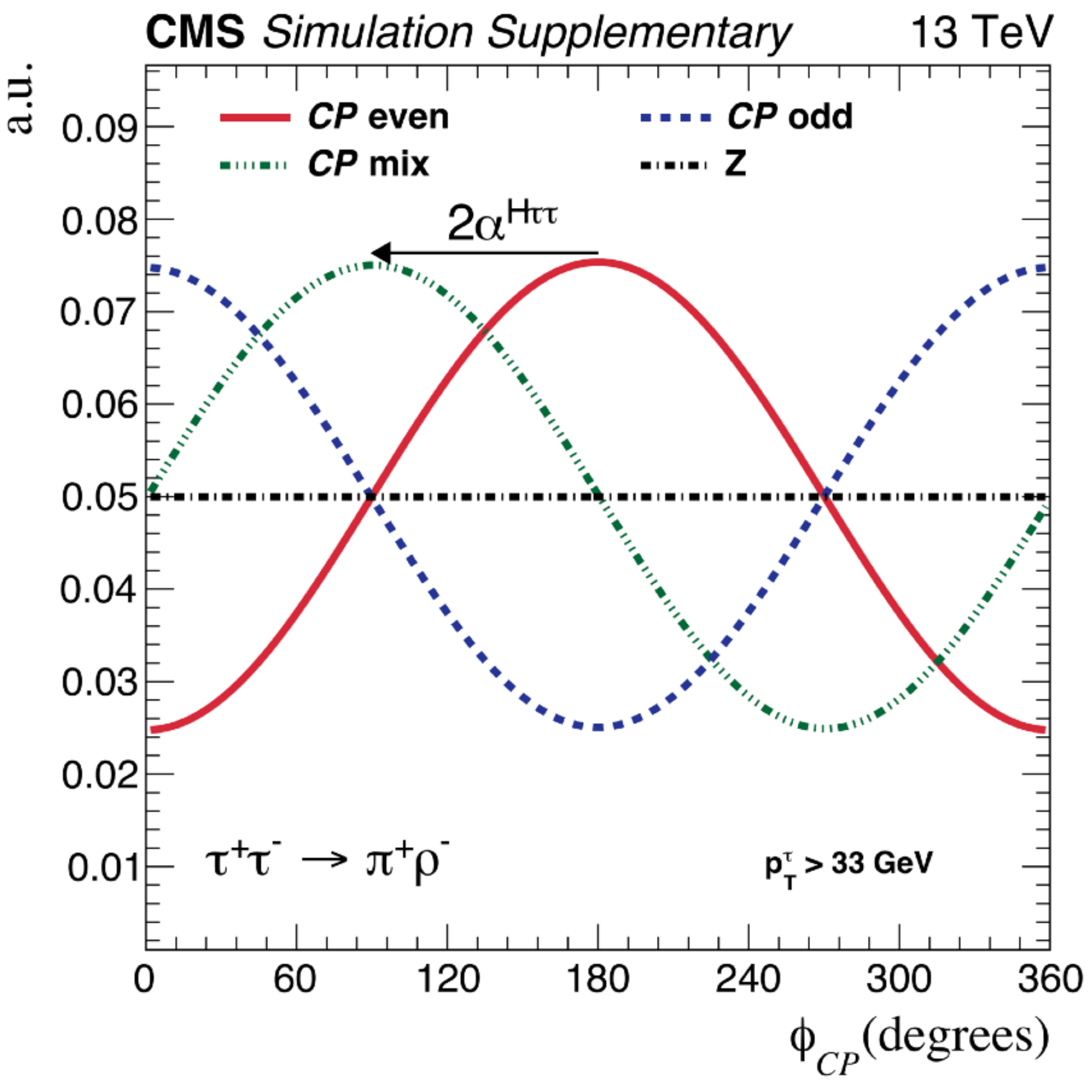


The “mixed” method

- Can also define ϕ_{CP} using a so-called “mixed” method when we have a neutral pion from 1 tau decay only

- E.g for a $H\rightarrow\tau\tau\rightarrow \rho^{+}\nu\mu^{-}\nu \rightarrow \pi^{+}\pi^{0}\nu\,\mu^{-}\nu\nu$





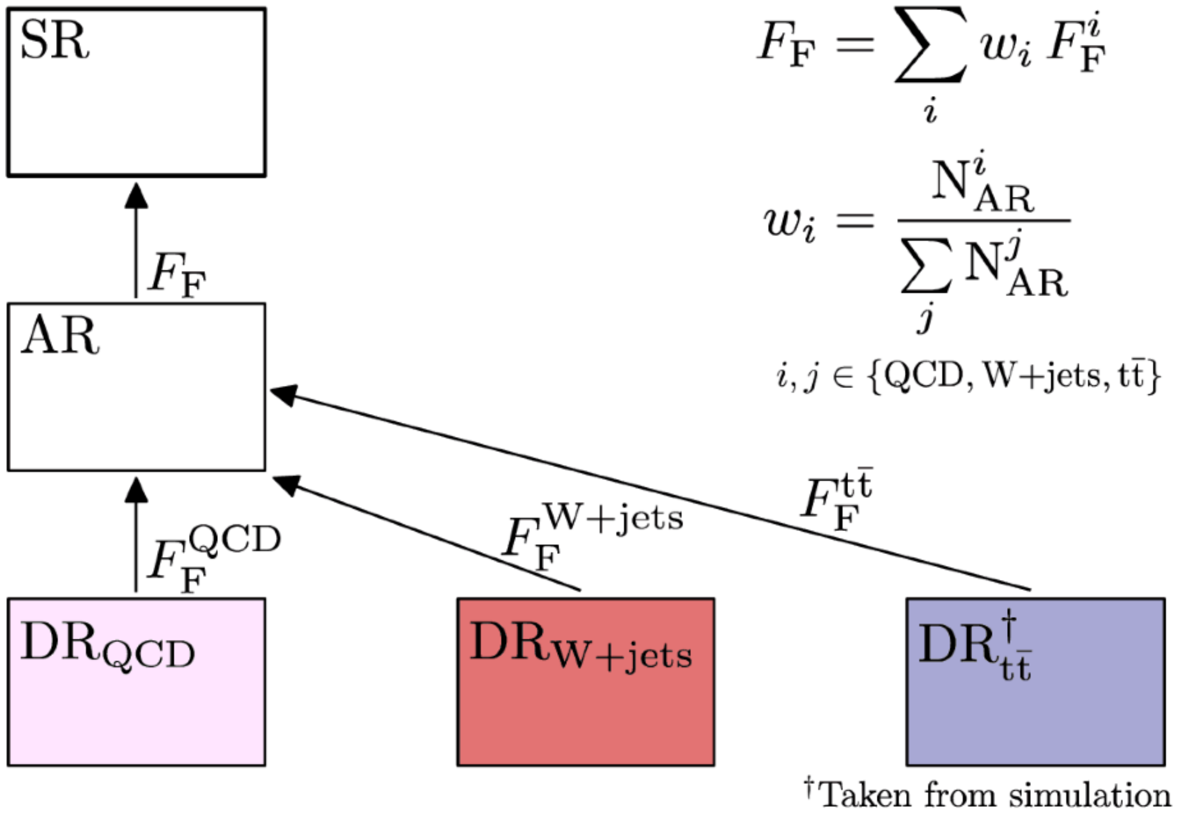
Modelling j→τ_h: The fake factor method

- The “fake factor” method is used to estimate all background with jets faking hadronic taus (j→τ_h)

- We select events in a sideband region failing nominal tau ID requirements but passing a relaxed selection

- Scale events by ratios:
  FF = (nominal ID) /(relaxed ID)
  which we call fake factors

- Dominant processes are:
  QCD and W+jets



$$F_F = \sum_i w_i F_F^i$$

$$w_i = \frac{N_{AR}^i}{\sum_j N_{AR}^j}$$

$$i, j \in \{QCD, W{+}jets, t\bar{t}\}$$

†Taken from simulation

JHEP 09 (2018)007

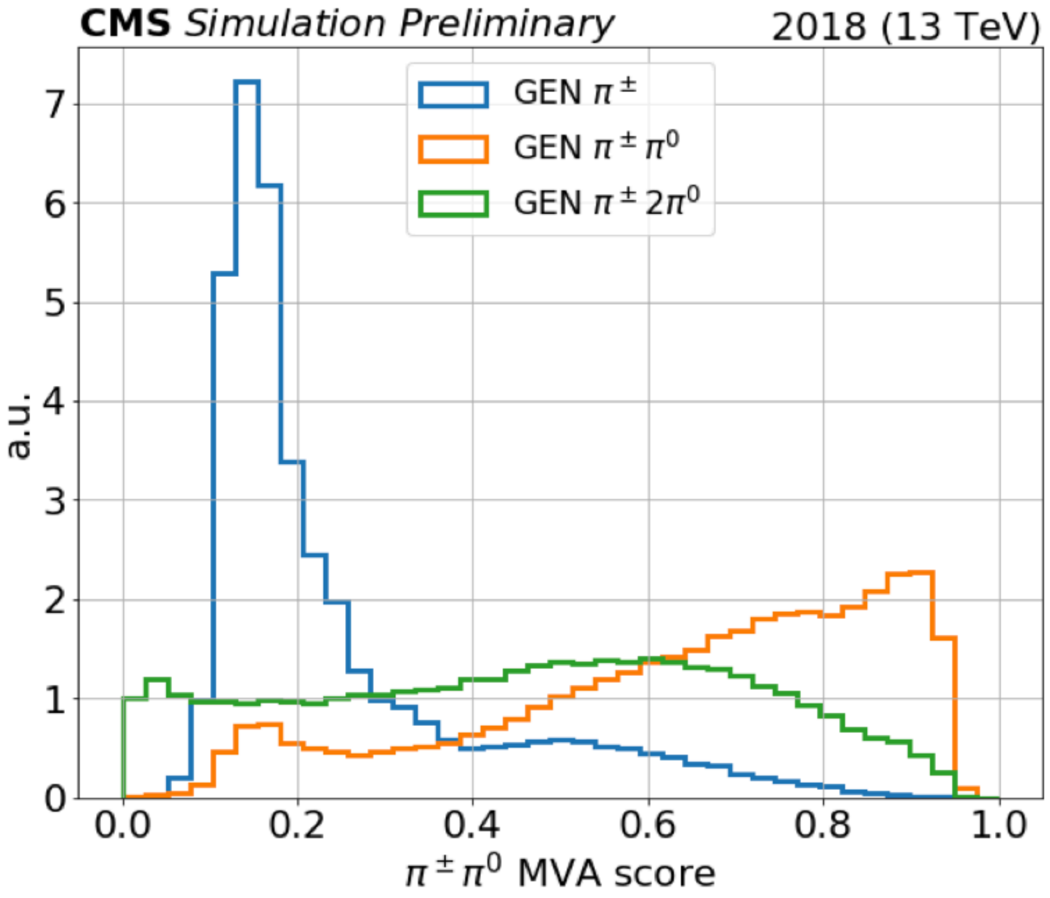
Tau decay mode selection

- The analysis is very sensitive to proper identification of the various hadronic decay modes

- E.g a $\tau \to \rho \to \pi^- \pi^0$ looks a lot like a $a_1 \to \pi^- 2\pi^0$ as two π^0 tend to be merged

- But the CP separation is very different for these two cases

- We improve the separation between modes using a dedicated BDT
  - Variables include kinematic variables such as masses, ɣ pT; angular observables; variables sensitive to ɣ density such as N_γ

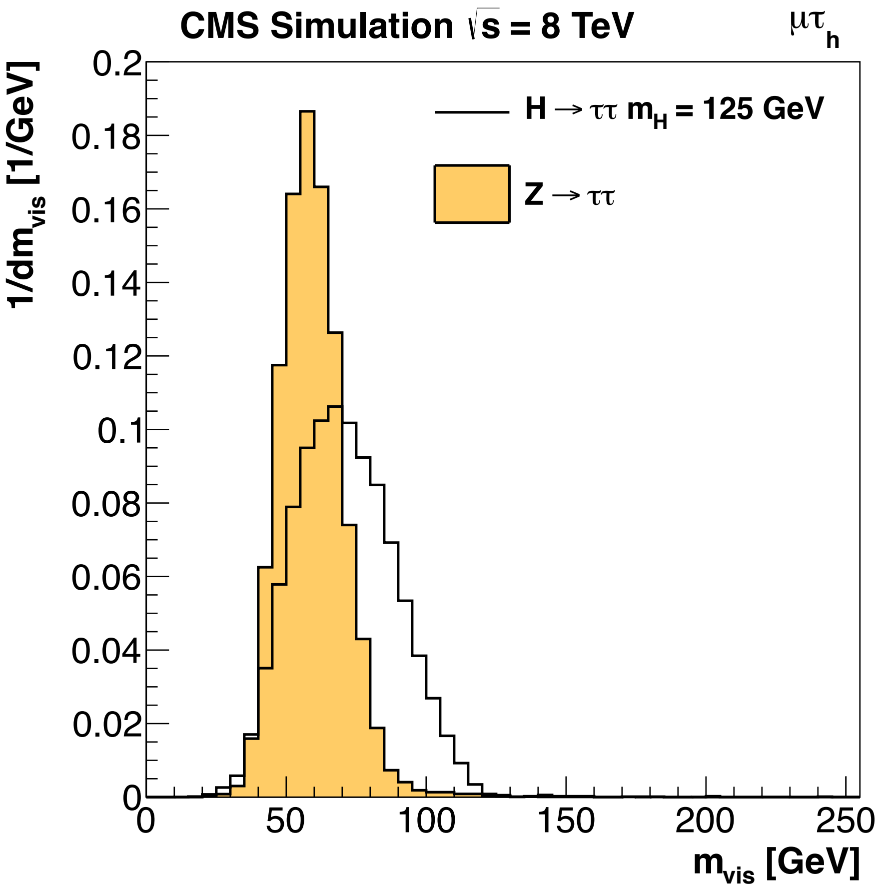


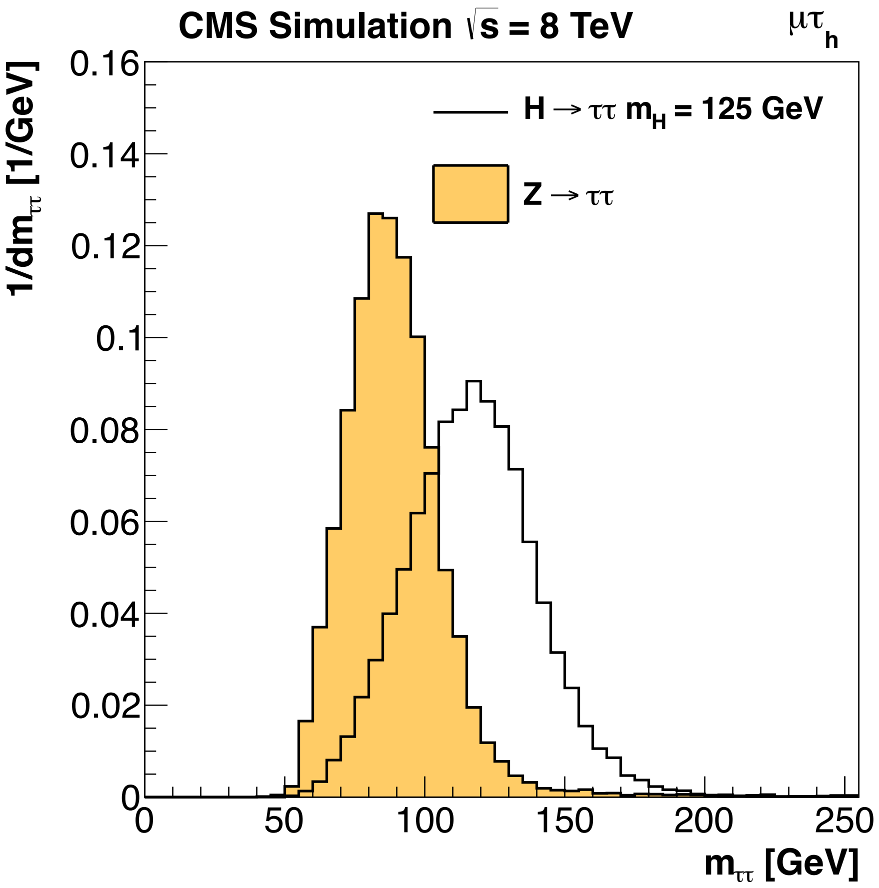
CMS-DP-2020-041

SVFit algorithm

- The SV-Fit algorithm is a simplified matrix element method that combines the missing transverse momentum vector + corresponding uncertainties with the 4-vectors of the visible decay products to calculate the parent boson mass

- Gives a significant improvement over using only the visible 4-vectors (m_{vis})



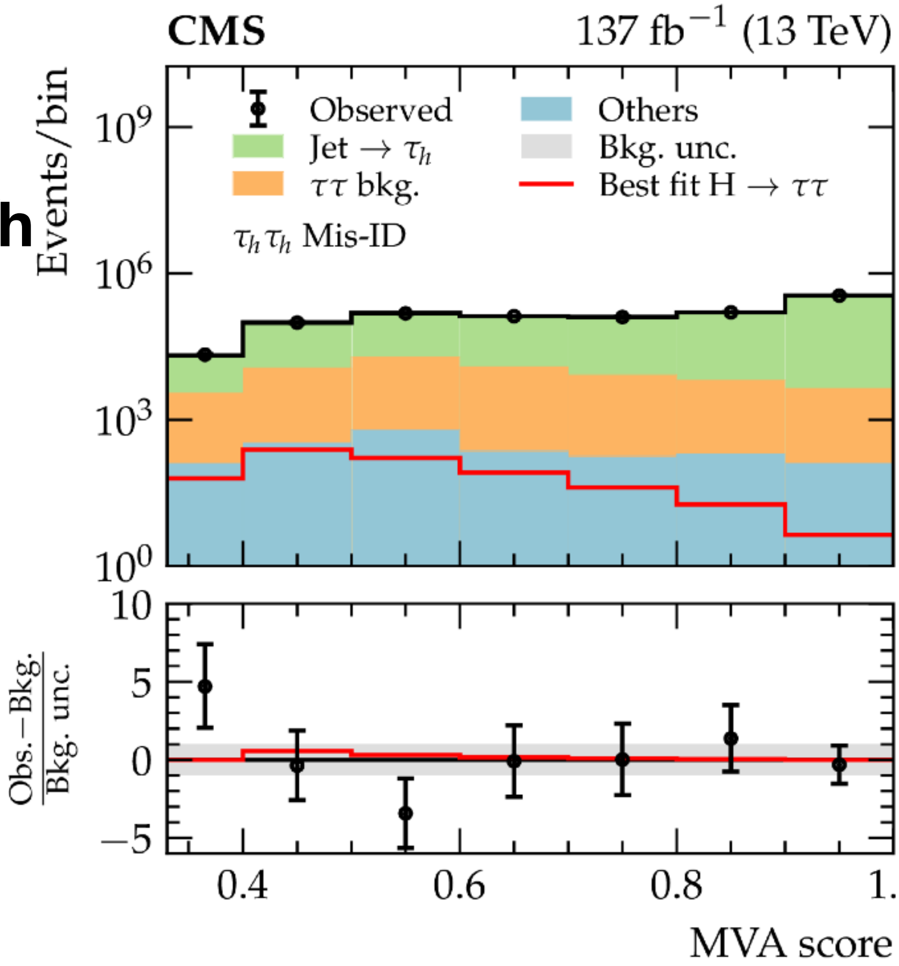


Background categories

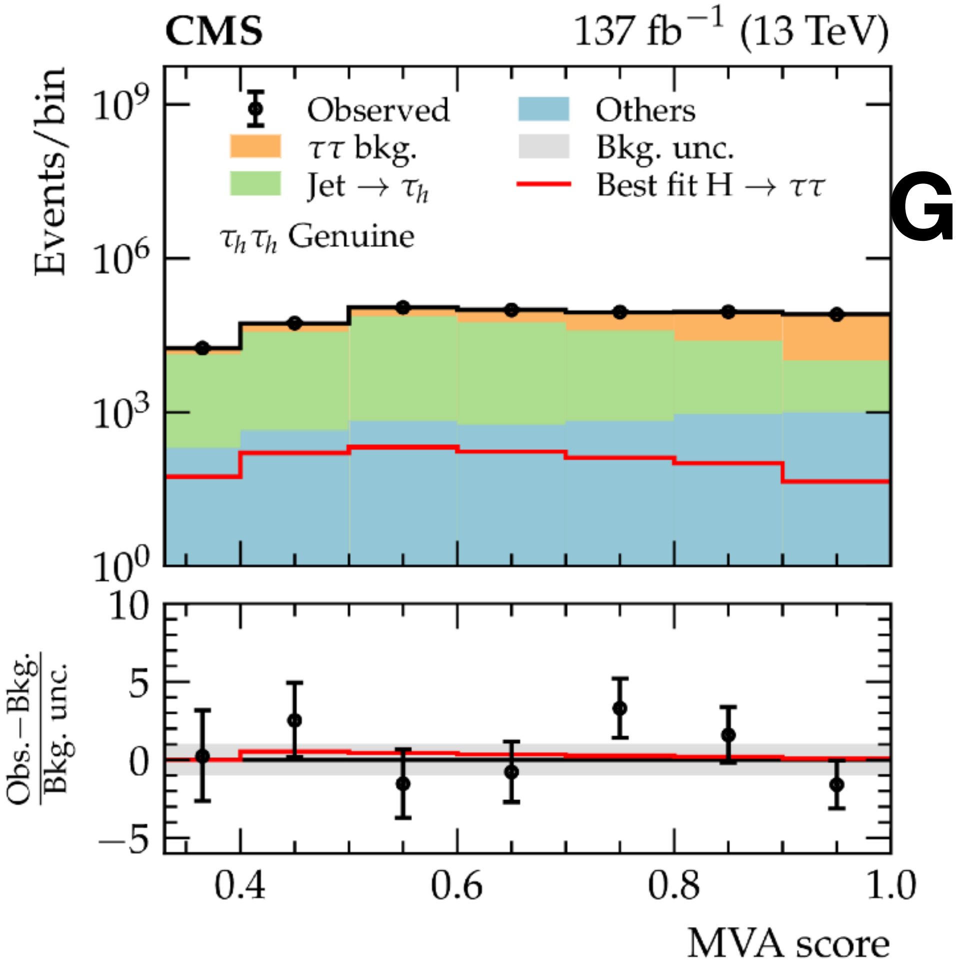
- Output of MVAs are three scores (or “probabilities”) that sum to 1, 1 score per class

- We sort events into signal and background categories based on which score is the largest

Mis-ID τ_h



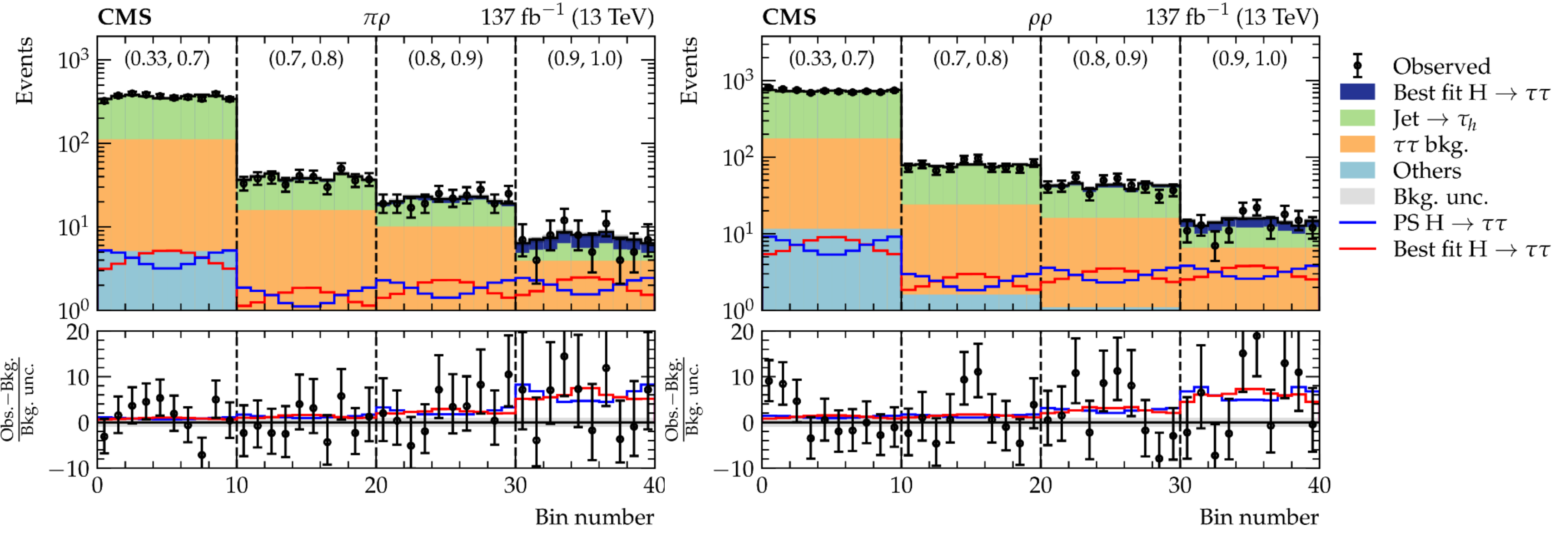
Genuine-τ_h



More examples of signal categories

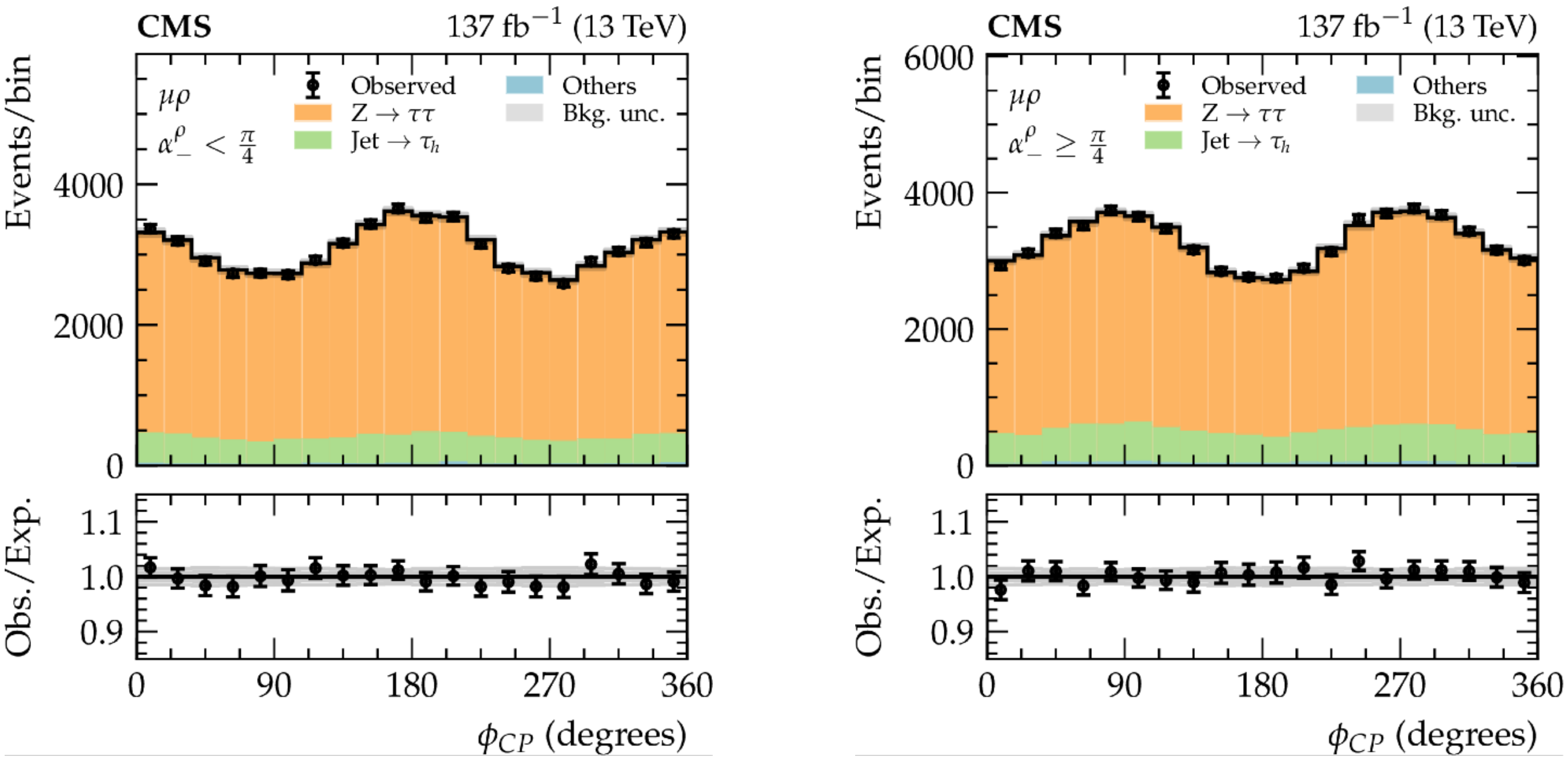
- Two more examples of signal categories for $\tau_h\tau_h$ final states

$\tau_h\tau_h \rightarrow \pi^-\nu\rho^-\nu$ $\tau_h\tau_h \rightarrow \rho^-\nu\rho^-\nu$



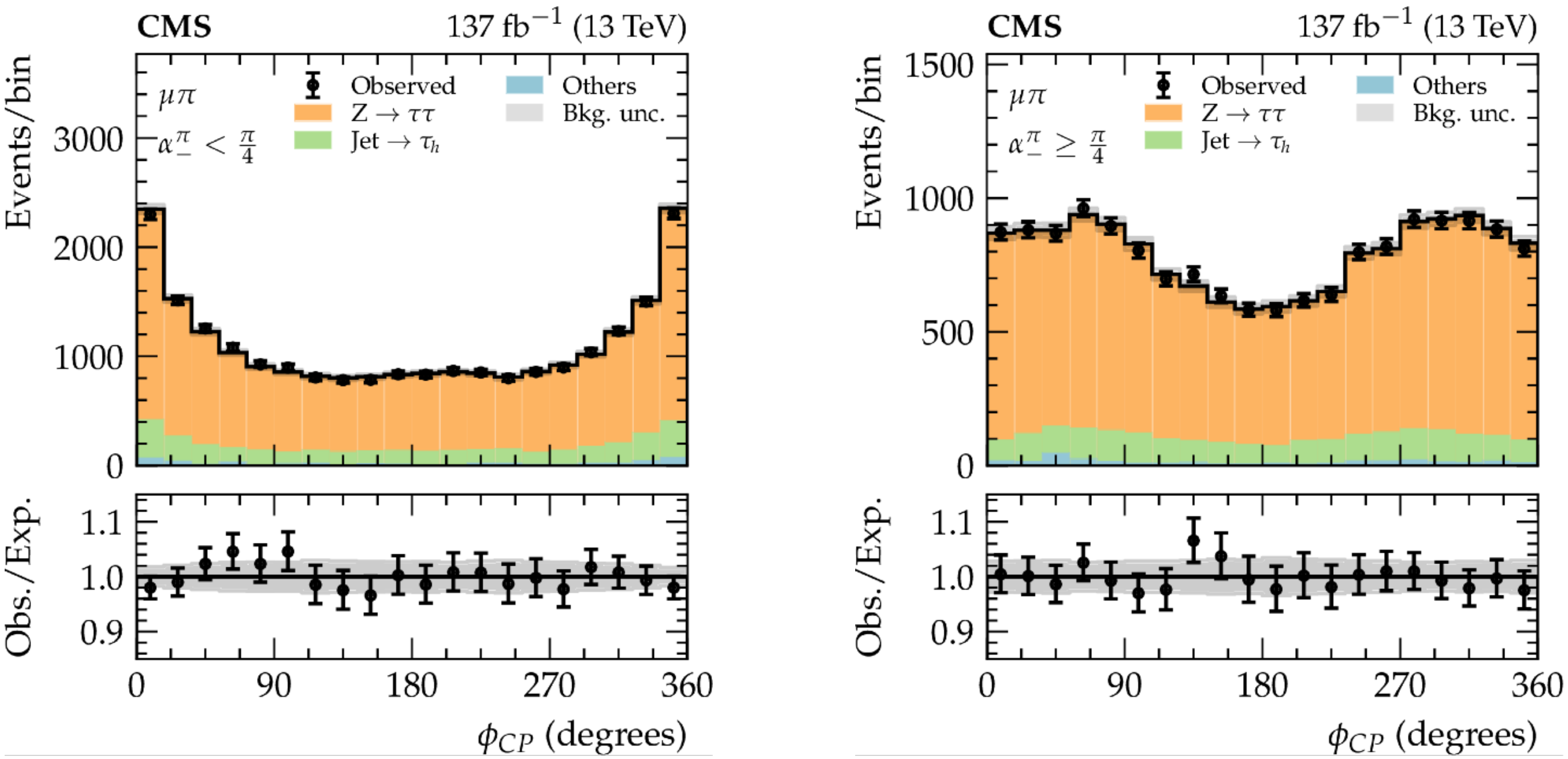
Checks using Z→$\tau\tau$

- All H→$\tau\tau$ analyses use qq̄→Z→ττ events as “standard candle” to validate MC description of data
- Same for the CP-analysis except as Z→ττ has ~ flat distribution of $\phi_{\tau\tau}$
- But we can split into two sinusoidal contributions using α_- variable
  - Separates events into those “nearly coplanar” ($\alpha_- < \pi/4$) and “nearly perpendicular” ($\alpha_- > \pi/4$) to qτ plane in lab frame
- Definition in paper by [Stefan Berge et al.](#)



Checks using Z→$\tau\tau$: τ_h→$\pi^-\nu$

- Check of Z→ττ using α_- splitting for τ_h→πν
- Definition in paper by [Stefan Berge et al.]()



Polarimetric vectors

- Polarimetric vectors for $\tau_h \rightarrow \pi^- \nu$ and $\tau_h \rightarrow \rho^- \nu$ decays

$$\tau^\pm \rightarrow \pi^\pm \nu : \vec{h} = -\vec{n}_\pi$$

$$\tau^\pm \rightarrow \rho^\pm \nu \rightarrow \pi^\pm \pi^0 \nu : \vec{h} = m_\tau \frac{2(qN)\vec{q} - q^2 \vec{N}}{2(qN)(qP) - q^2(NP)}$$

$$m_\tau : \tau \ mass$$

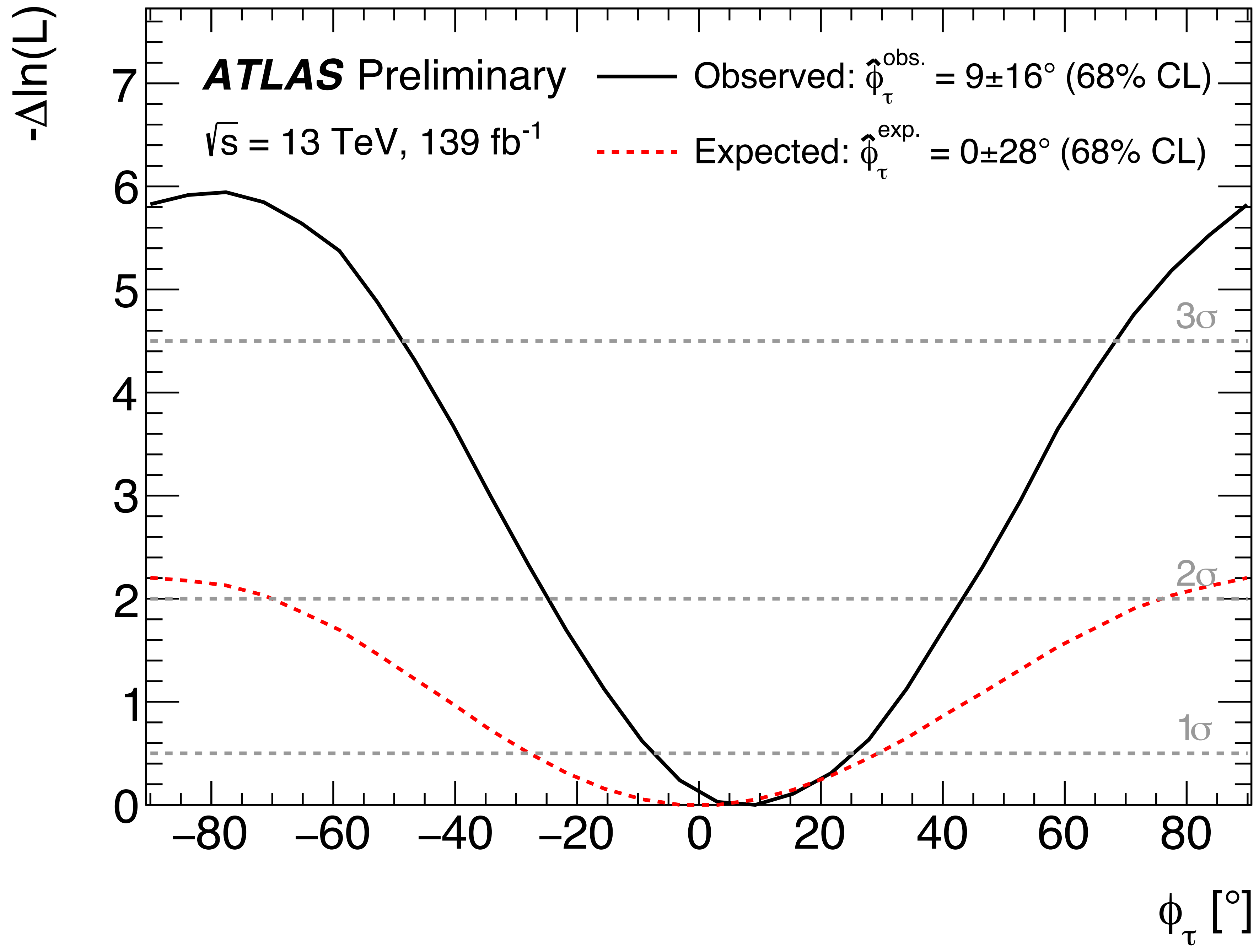
$$\left.\begin{array}{l} q : \pi^\pm - \pi^0 \\ N : \nu = \tau^\pm - \pi^\pm - \pi^0 \\ P : \tau^\pm \end{array}\right\} \text{4-vectors}$$

- Defined in rest frame of τ's

- More complicated for a1 decays but parameterisation from the CLEO collaboration exists (Phys. Rev. D61 (2000) 012002)

ATLAS results

- Similar measurement has been done by ATLAS: https://cds.cern.ch/record/2809728



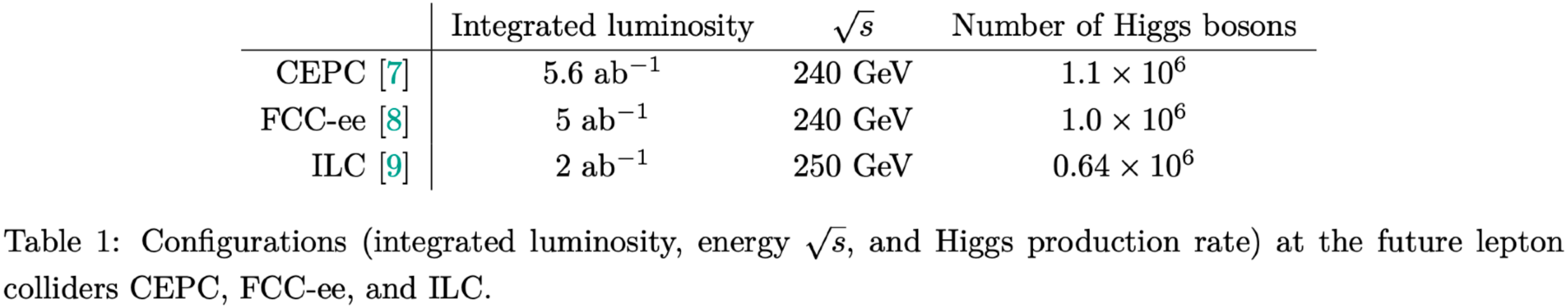
Future ee colliders

- Circular Electron-Positron Collider (CEPC): arXiv:811.10545

- Future Circular Collider (FCC)-ee: Eur. Phys. J. ST 228, no.2, 261-623 (2019)

- International Linear Collider: arXiv.org:1306.6352

- Integrated luminosities / energies used to compute sensitivities in arXiv:2012.13922:



	Integrated luminosity	$\sqrt{s}$	Number of Higgs bosons
CEPC [7]	5.6 ab^{-1}	240 GeV	1.1×10^6
FCC-ee [8]	5 ab^{-1}	240 GeV	1.0×10^6
ILC [9]	2 ab^{-1}	250 GeV	0.64×10^6

Table 1: Configurations (integrated luminosity, energy $\sqrt{s}$, and Higgs production rate) at the future lepton colliders CEPC, FCC-ee, and ILC.

Comparing indirect constraints for Htt and H$\tau\tau$

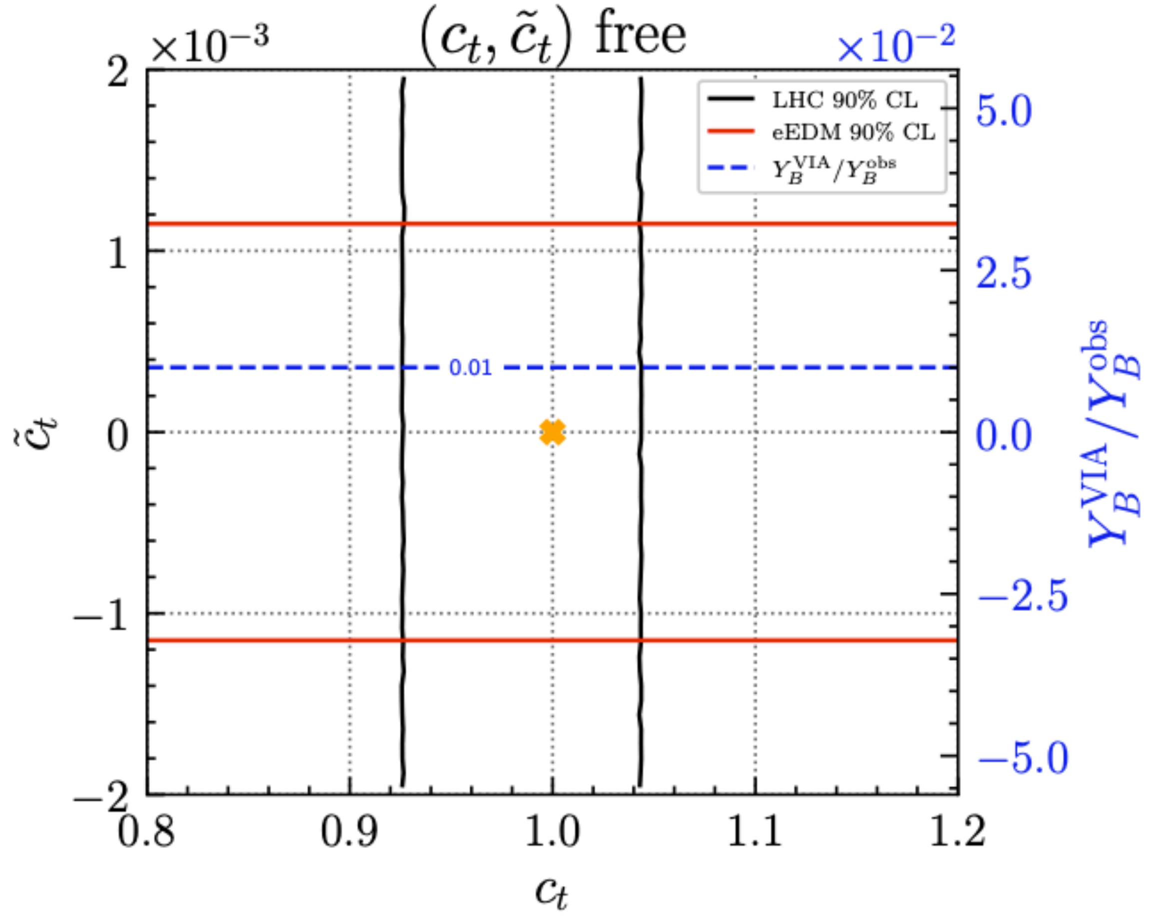
- In contrast Htt coupling in simplified model tightly constrained by EDMs

- However, the conclusions about Htt depend heavily on the assumption made about the other couplings, Hee coupling = SM expectation

- Hee coupling is not measured experimentally

- Can avoid bounds if Hee is non SM

- → Important to measure Htt CP properties directly still

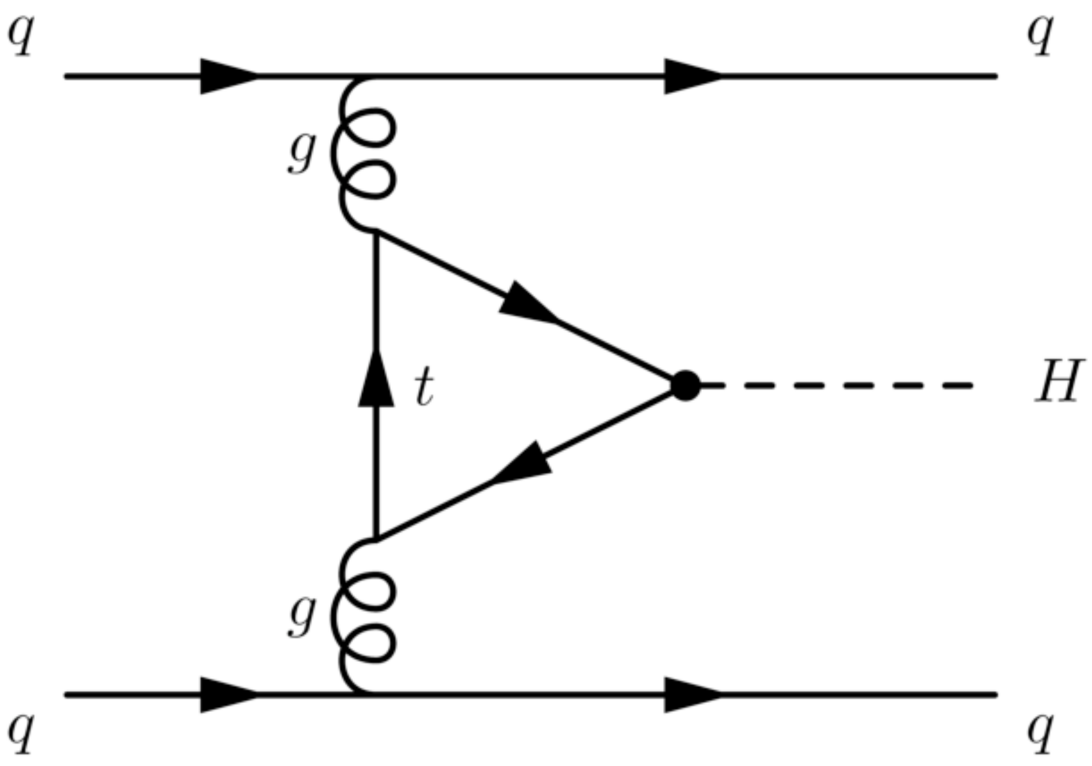


Htt

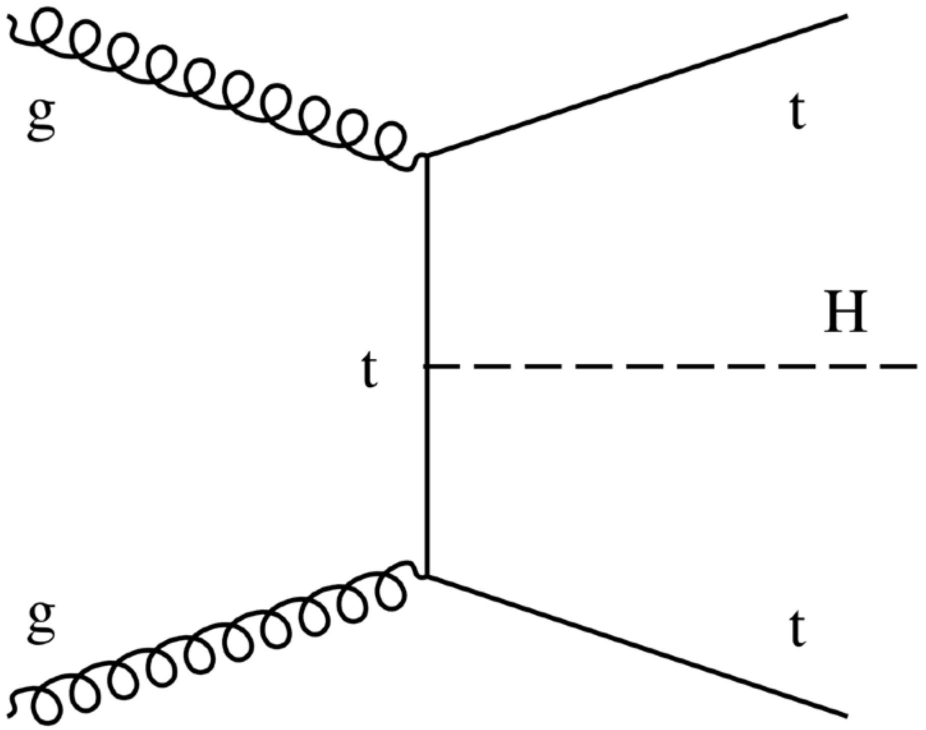
Plot from arXiv:2202.11753

Measuring CP properties of Htt coupling

- Since $m_H < 2m_{top}$ can't measure Htt coupling using decay process
- But can probe coupling using production by ggH or top associated production (ttH)



ggH



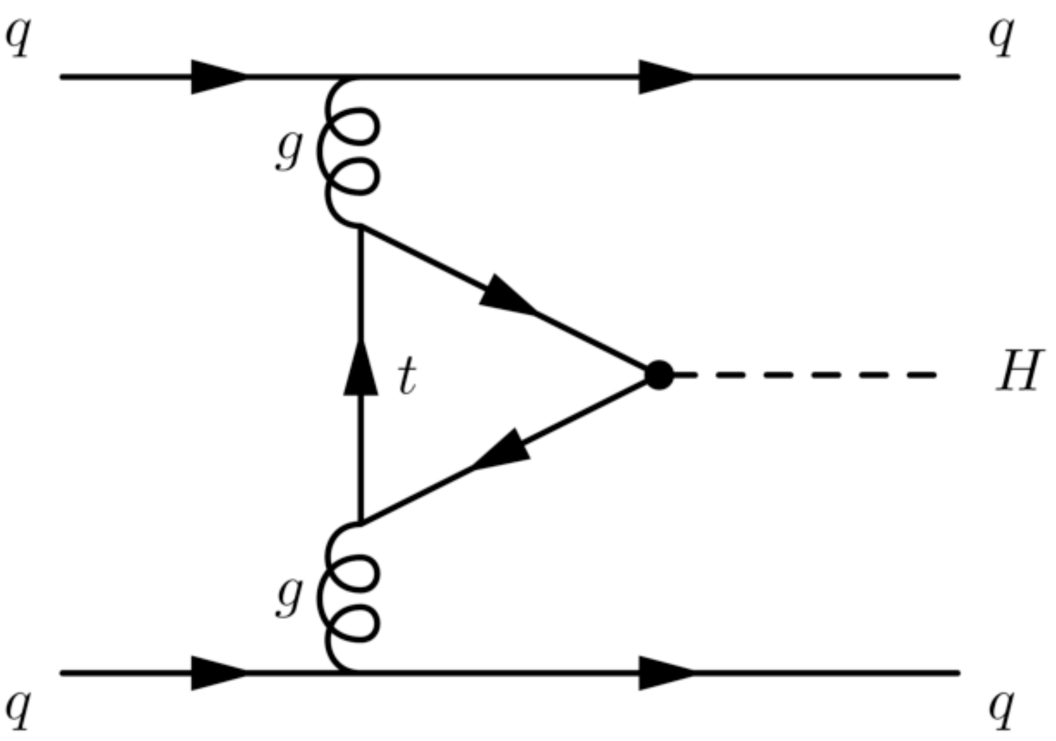
ttH

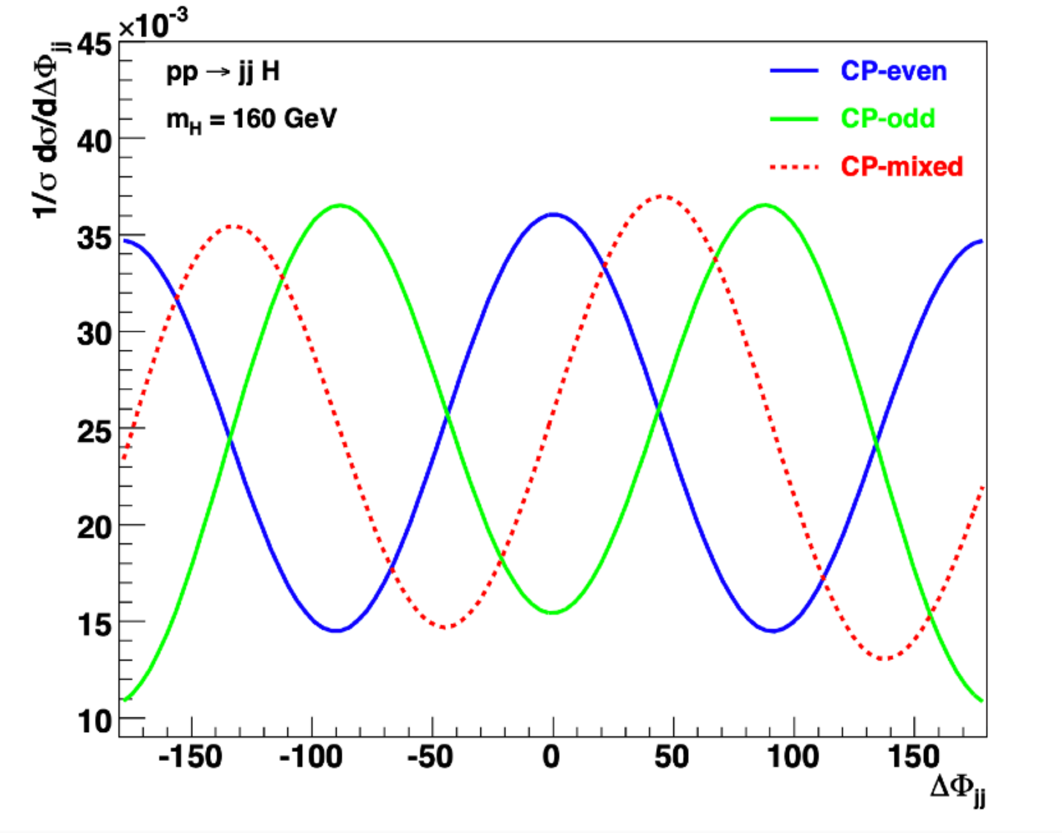
ggH CP measurements

- For ggH production angular correlations between associated jets produced in ggH+2j events are sensitive to CP

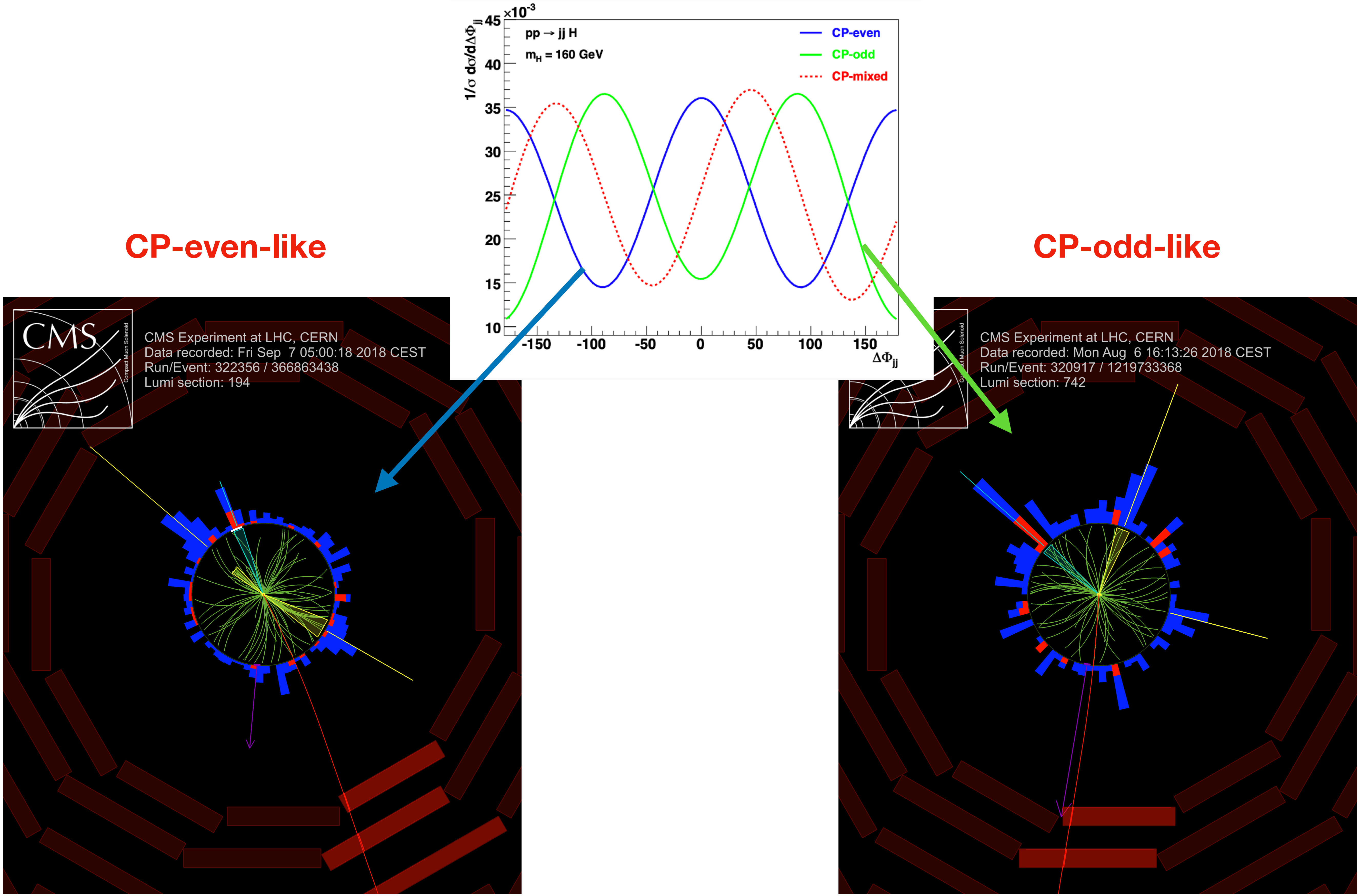
- Most information encoded in azimuthal angular seperation, $\Delta\phi_{jj}$

- ggH events with VBF like topology are most sensitive to CP
  - e.g large di-jet invariant masses





ggH CP measurements



CP-even-like

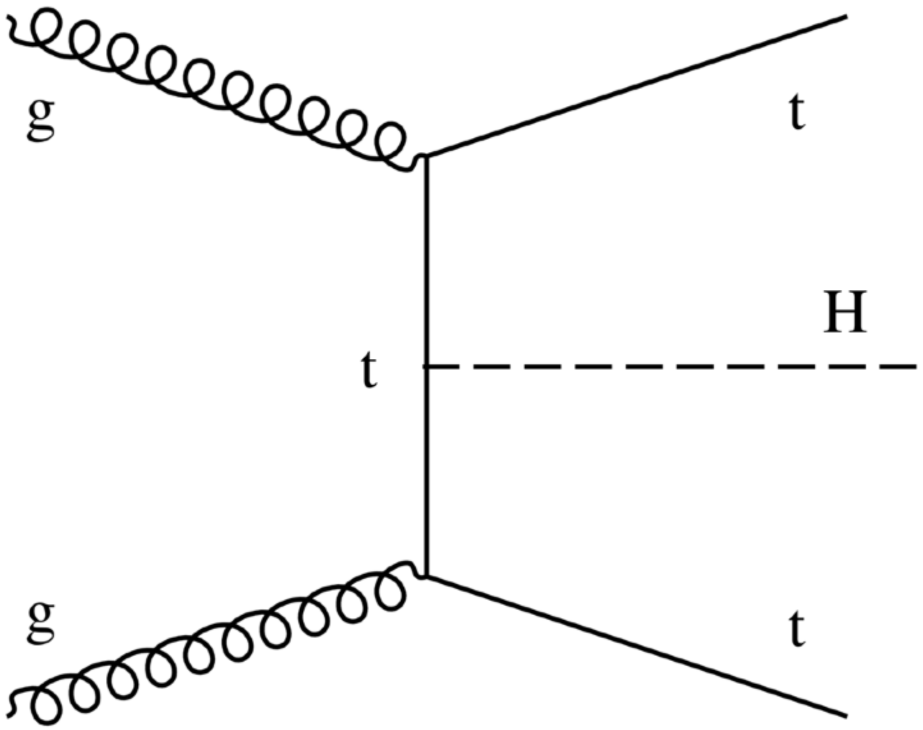
CP-odd-like

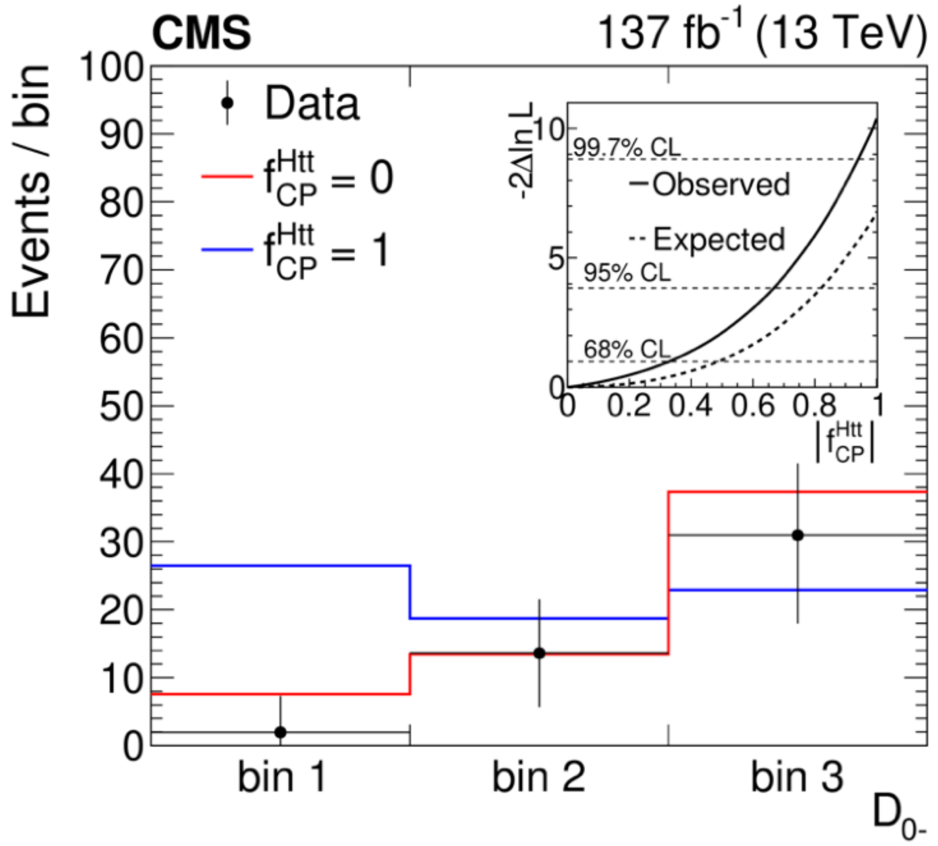
ttH CP measurment

- For ttH CP properties manifest in several observables

- We therefore build a BDT based discriminant taking several kinematic variables as inputs
  - Kinematics of up to 6 jets, leptons from semi-leptonic top decays, Higgs decay products

- We call our BDT discriminant D_{0-}

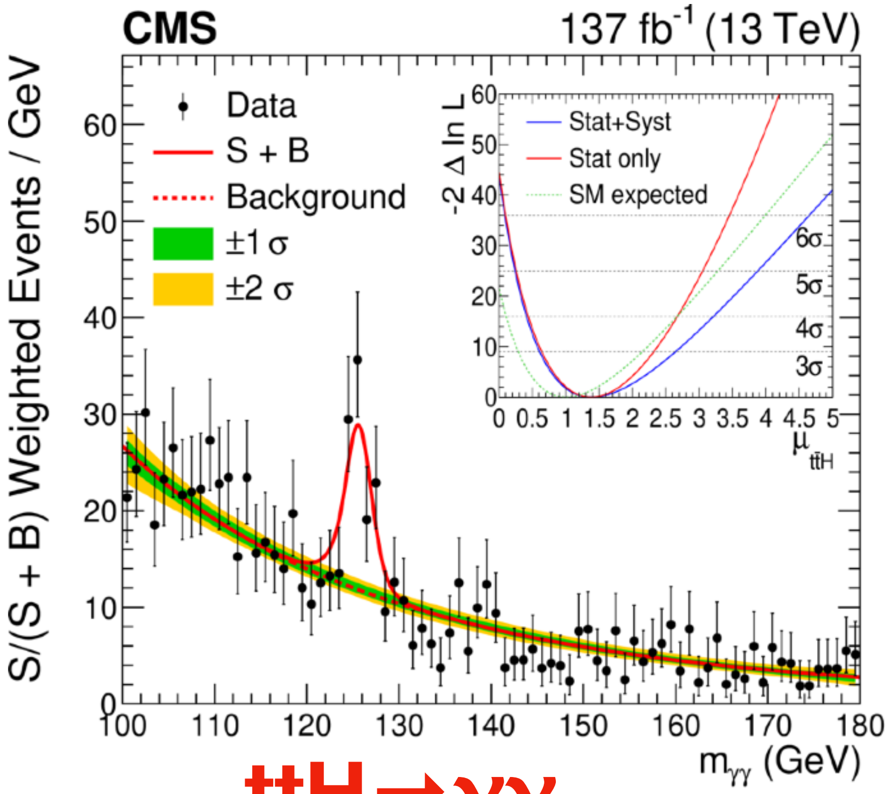




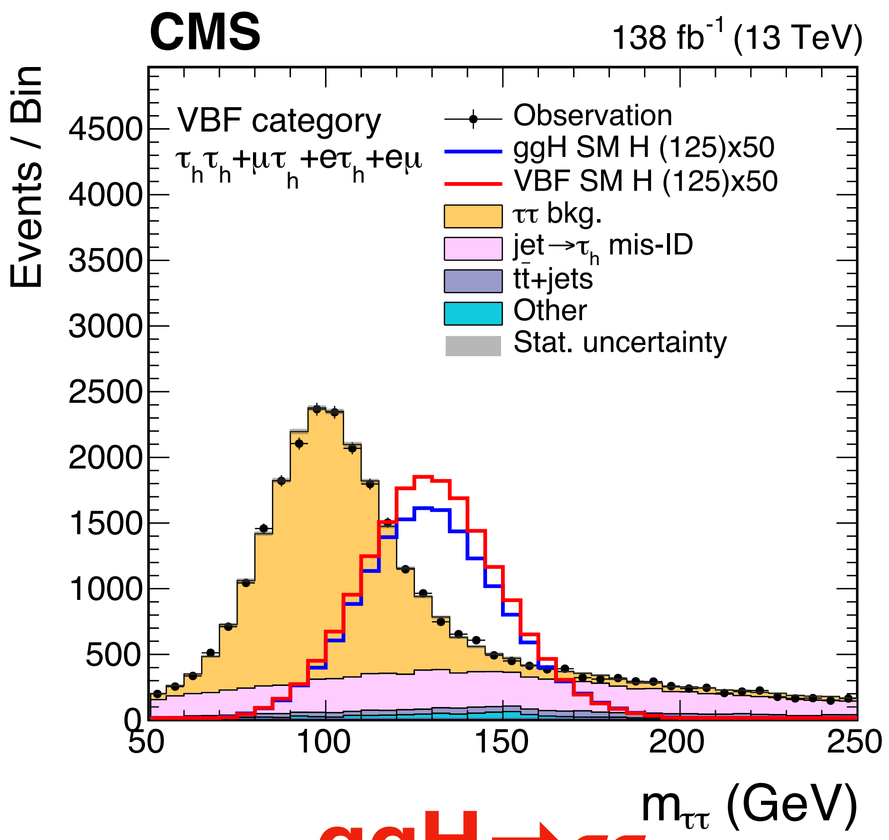
Combining ttH and ggH

- Best sensitivity from combining ttH and ggH results using as many H final states as possible

- Current best measurement from CMS uses:
    - ttH in the H→γγ and H→ZZ final states
    - ggH in the H→$\tau\tau$ and H→ZZ final states



ttH→γγ



ggH→$\tau\tau$

Htt CP results

- Measured value of mixing angle:

$$\alpha^{\mathrm{Htt}} = 2^{+10}_{-2}\,^{\circ}$$

- In agreement with SM

- Pure CP-odd hypothesis excluded at 3.9σ