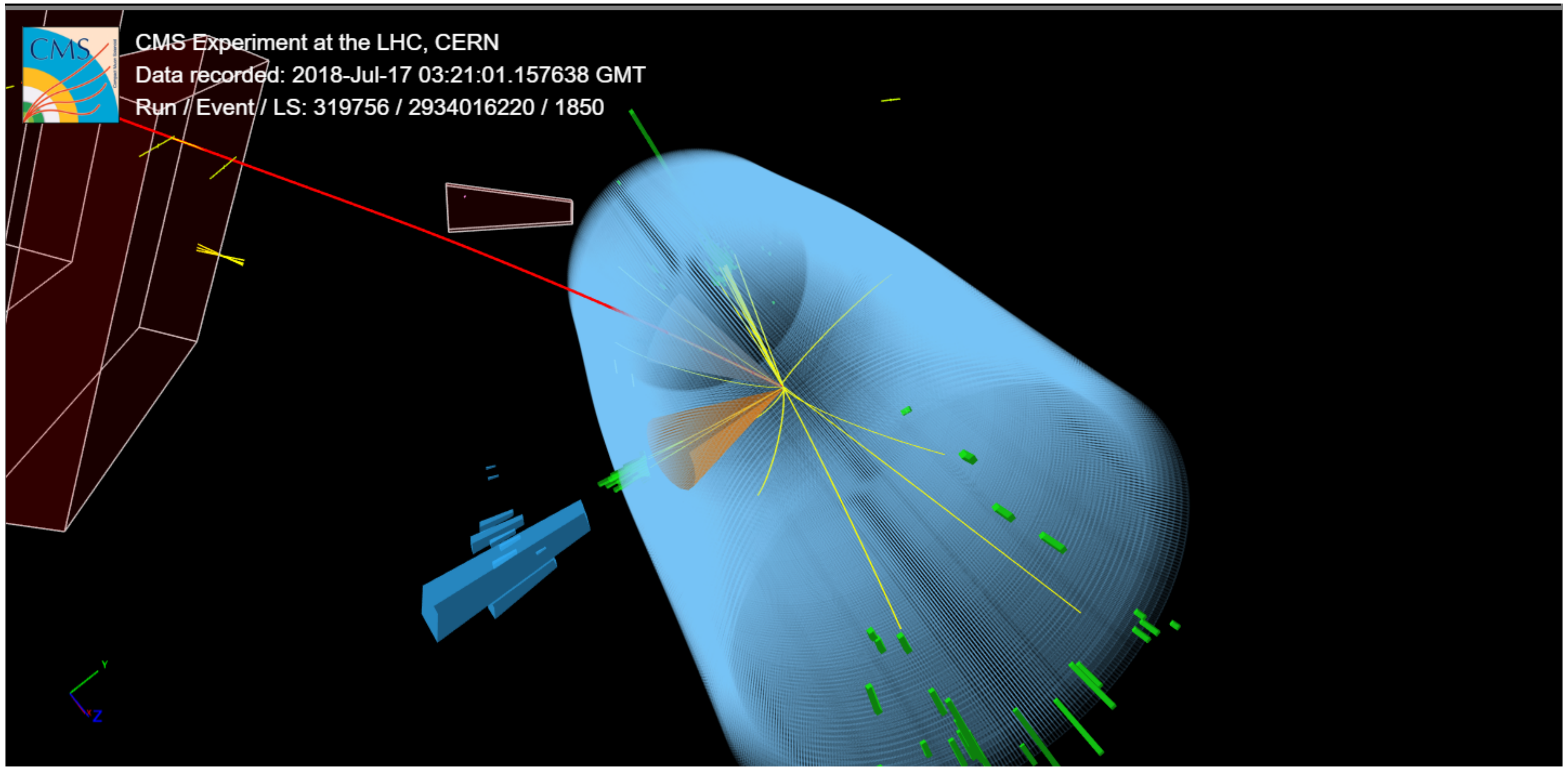
Measuring the SM-scalar CP-properties using the H→$\tau\tau$ decay channel



HEP@VUB Seminar 27/05/21

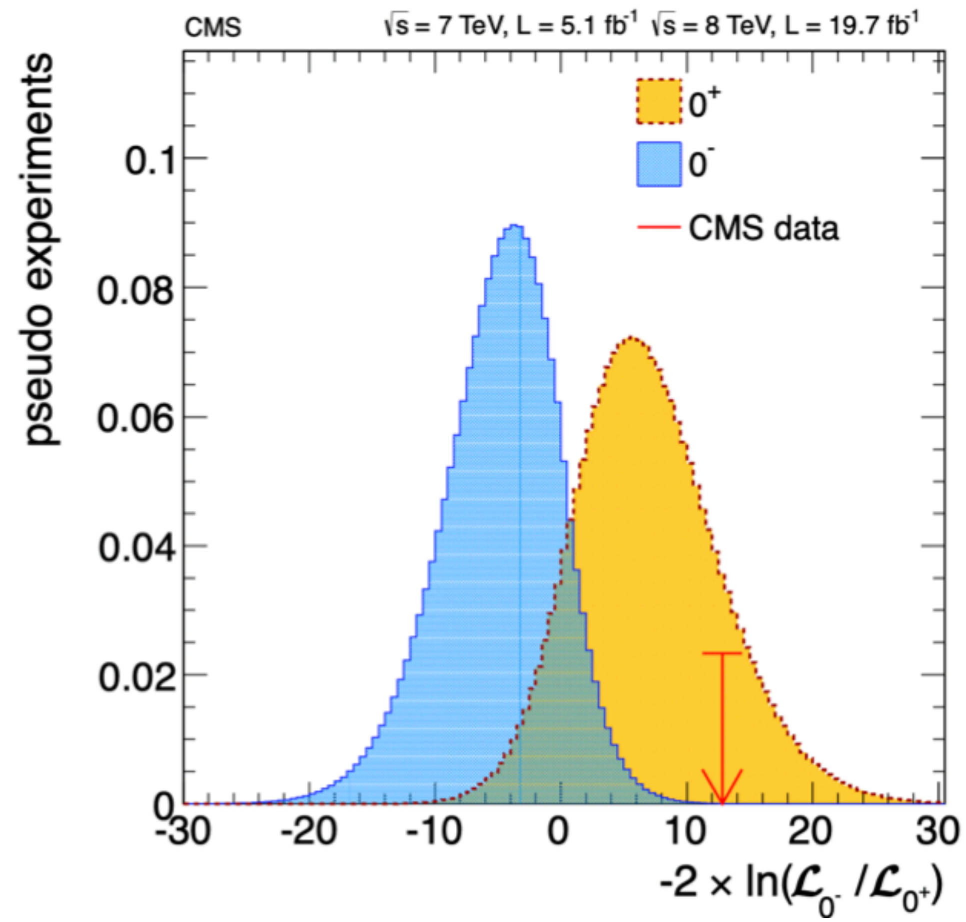
Daniel Winterbottom
d.winterbottom15@imperial.ac.uk

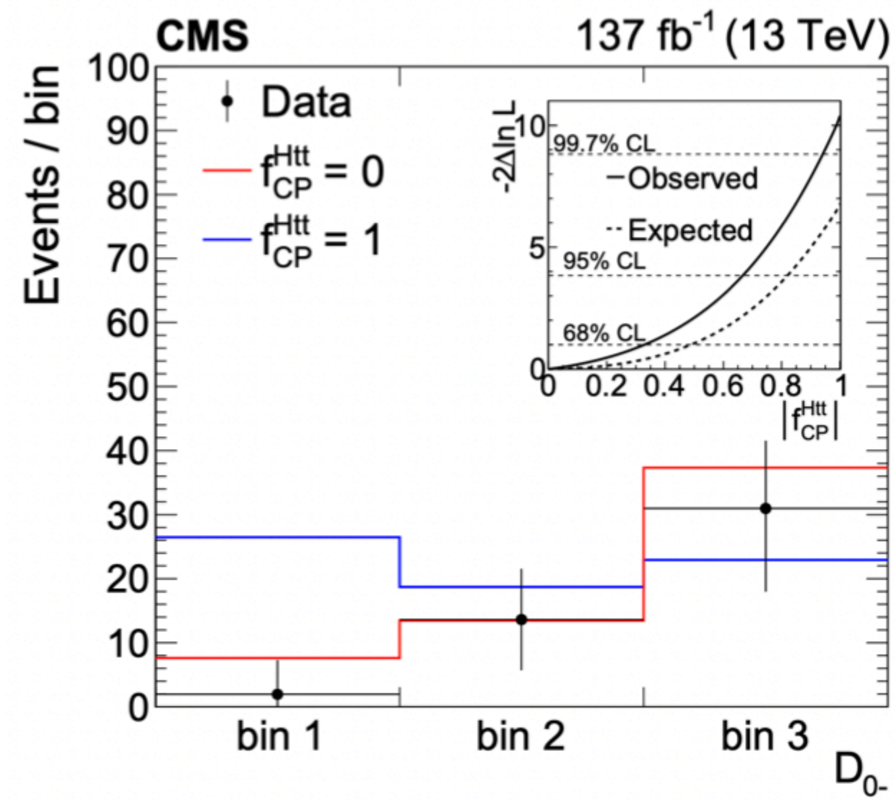
Overview

- Motivations
- EDM constraints
- Examples of BSM BEH sectors with CP-violation
- Overview of measurement strategies at colliders
- Latest CMS results
- Future prospects
- Conclusions

Motivations

- In the SM BEH sector the BEH-boson (H) is a CP-even state (0^+)
- Extended Brout-Englert-Higgs (BEH) sectors predict modified properties of the 125 GeV BEH-boson and/or new observable states in the scalar sector
- Discovery of such a extended BEH sector would be evidence for new physics beyond the standard model (BSM)
- One such class of extensions include additional CP phases in the BEH sector
- Such models can help explain observed matter-antimatter asymmetry in the universe
- The BEH-boson CP properties are well measured in HVV couplings **but** CP-odd HVV coupling typically suppressed (no tree level coupling) → current bounds actually quite weak
- H→ff couplings well motivated because CP-odd coupling at tree-level → not suppressed like HVV!
- Measurements of Htt CP-properties by CMS (arXiv:2003.10866) and ATLAS (arXiv:2004.04545)
- In this talk: first measurement of $H\rightarrow\tau\tau$ CP-properties: results presented at ICHEP 2020 conference (CMS-PAS-HIG-20-006)





Parameterisation of H→$\tau\tau$ CP properties

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

$$\mathscr{L}_Y = -\frac{m_\tau}{v}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau)h \qquad \kappa_i = y_i / y_i^{SM}$$

- Define mixing angle as:

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

- CP-even: $\phi_{\tau\tau} = 0^o$, CP-odd: $\phi_{\tau\tau} = 90^o$, CP-mixed: $0^o < |\phi_{\tau\tau}| < 90^o$

- Can write partial decay width as:

$$d\Gamma \sim 1 - s_z^- s_z^+ + \cos(2\phi_{\tau\tau})(\mathbf{s}_T^- \cdot \mathbf{s}_T^+) + \sin(2\phi_{\tau\tau})\left[(\mathbf{s}_T^- \times \mathbf{s}_T^+) \cdot \hat{k}^-\right]$$

- s=spin → transverse spin correlations sensitive to $\phi_{\tau\tau}$

S. Berge, et al.

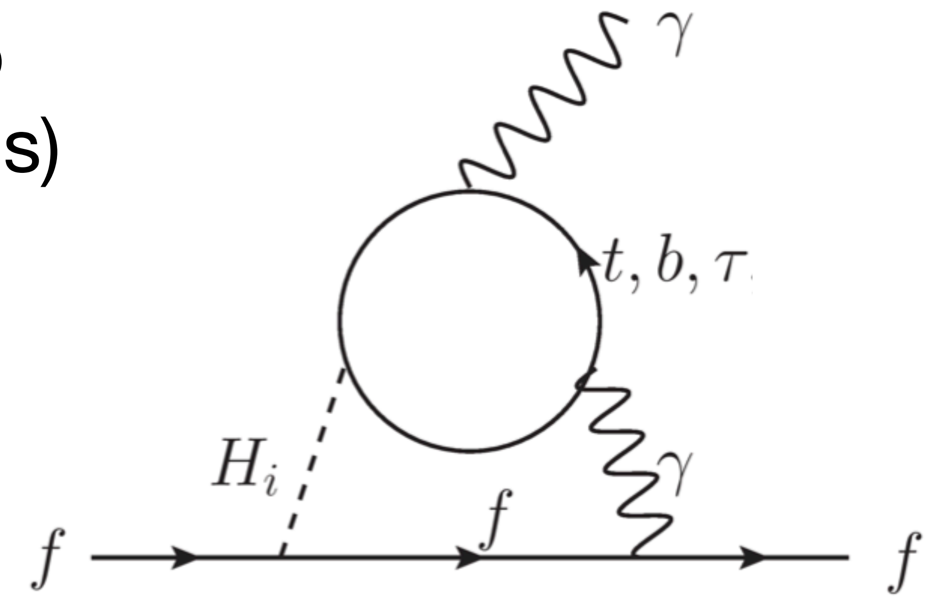
Indirect measurements EDMs

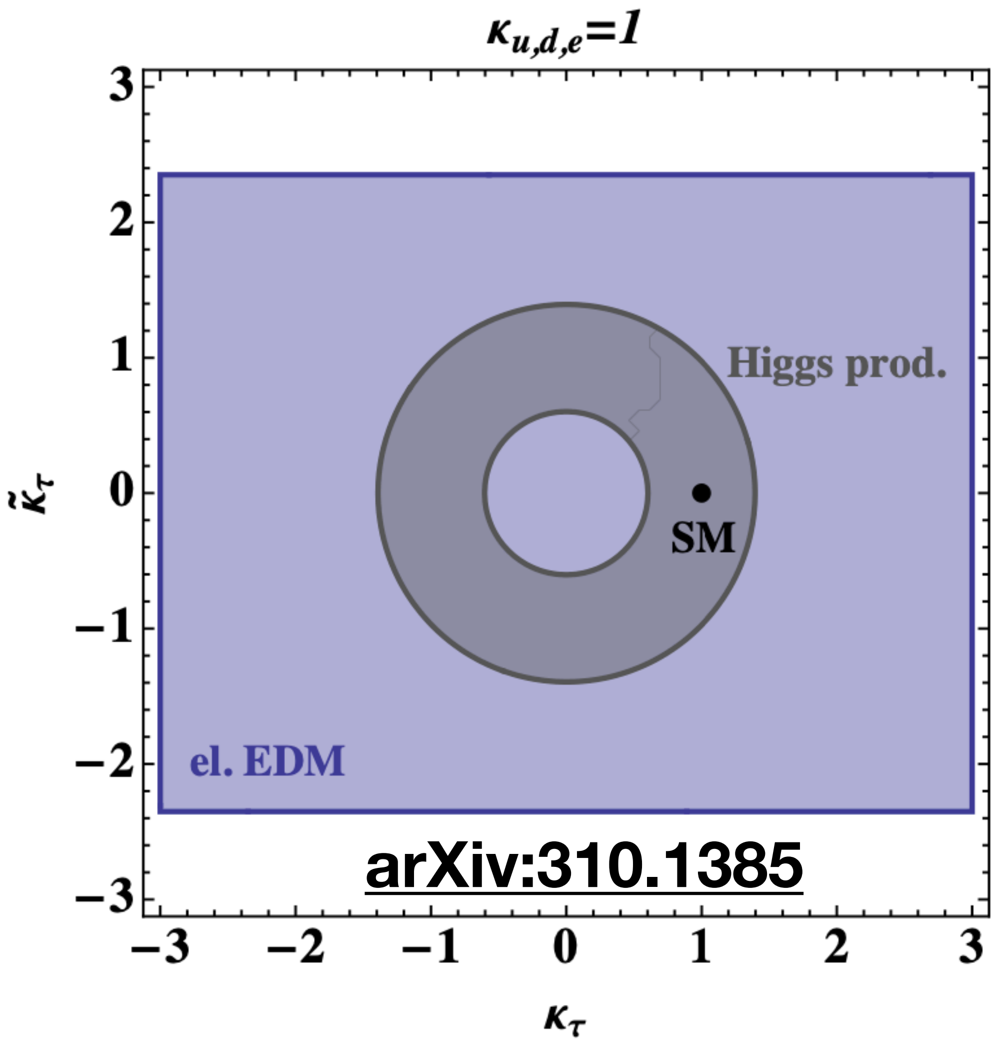
- CP-violating BEH-boson couplings can lead to the generation of electric dipole moment (EDMs) from diagrams such as those shown right

- Measurements of EDMs can therefore allow indirect constraints to be set on H→$\tau\tau$ CP properties

- Tightest bound come from electron EDM measurements:
  - ~ 10^{-28} *e* cm (ACME Coll., 2013)
  - ~ 10^{-29} *e* cm (ACME Coll., 2018)

- Note most model dependent bounds show in the next slides use 2013 measurement so are actually tighter than what is shown

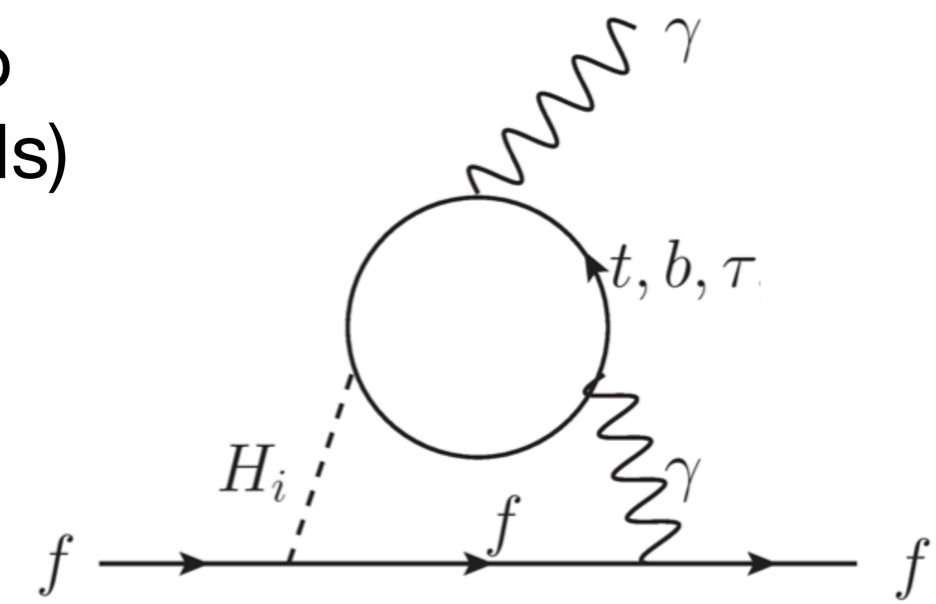




arXiv:310.1385

Indirect measurements EDMs

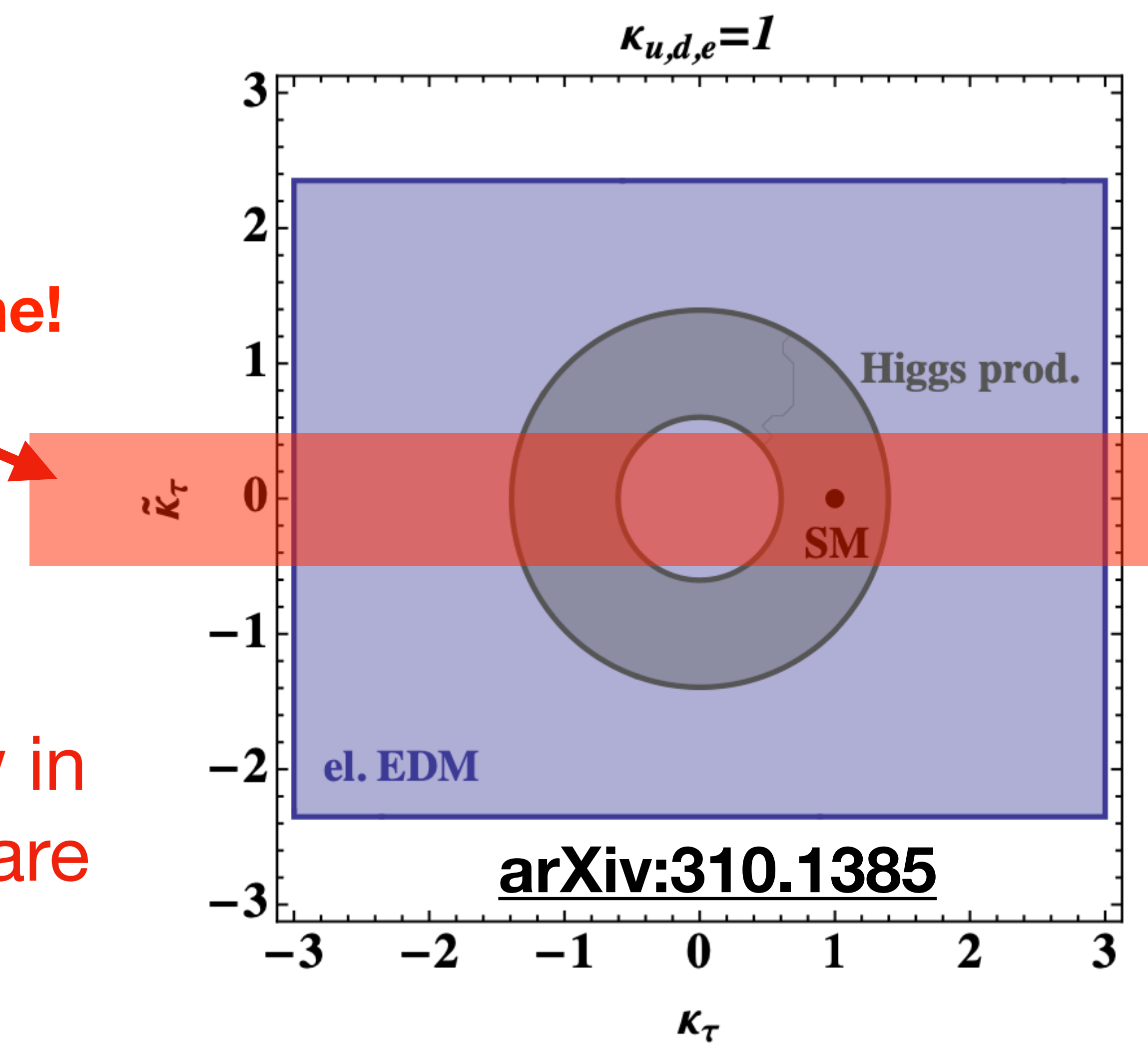
- CP-violating BEH-boson couplings can lead to the generation of electric dipole moment (EDMs) from diagrams such as those shown right



- Measurements of EDMs can therefore allow indirect constraints to be set on H→$\tau\tau$ CP properties

- Tightest bound come from electron EDM measurements:
  - ~ 10^{-28} *e* cm (ACME Coll., 2013)
  - ~ 10^{-29} *e* cm (ACME Coll., 2018)

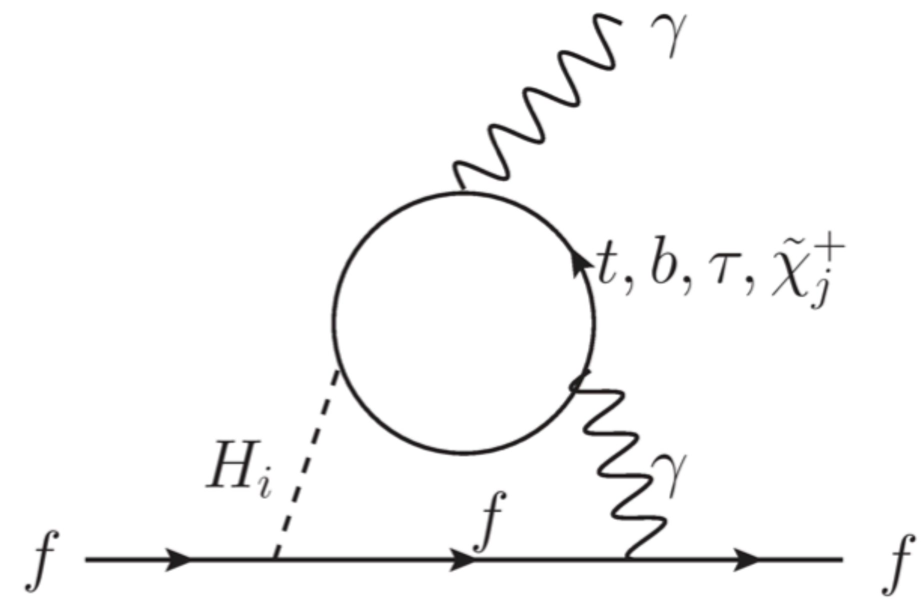
Including this one!

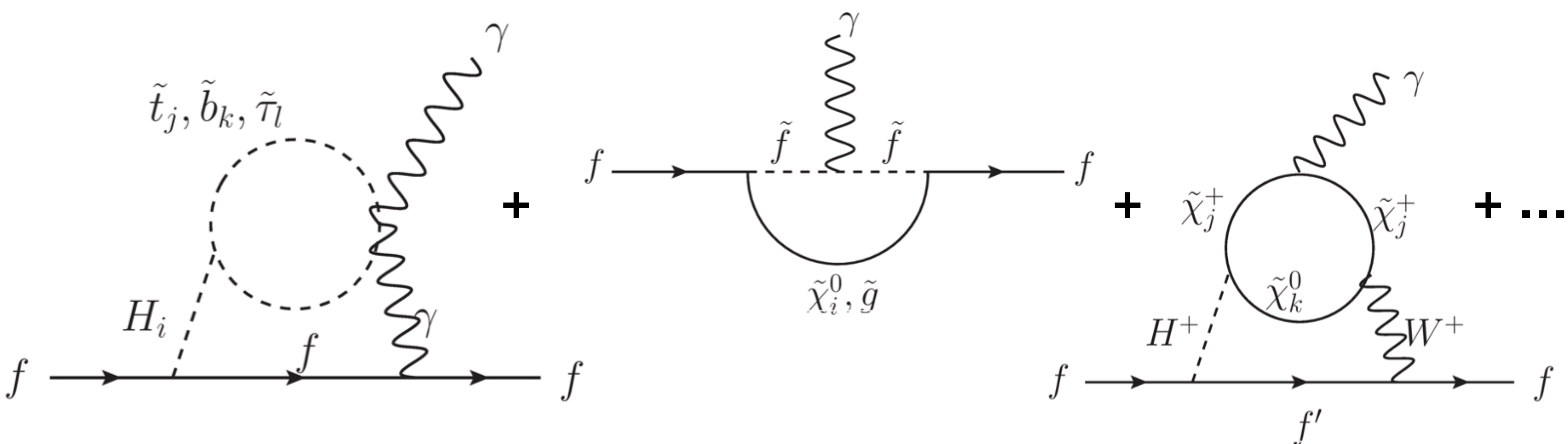


arXiv:310.1385

- Note most model dependent bounds show in the next slides use 2013 measurement so are actually tighter than what is shown

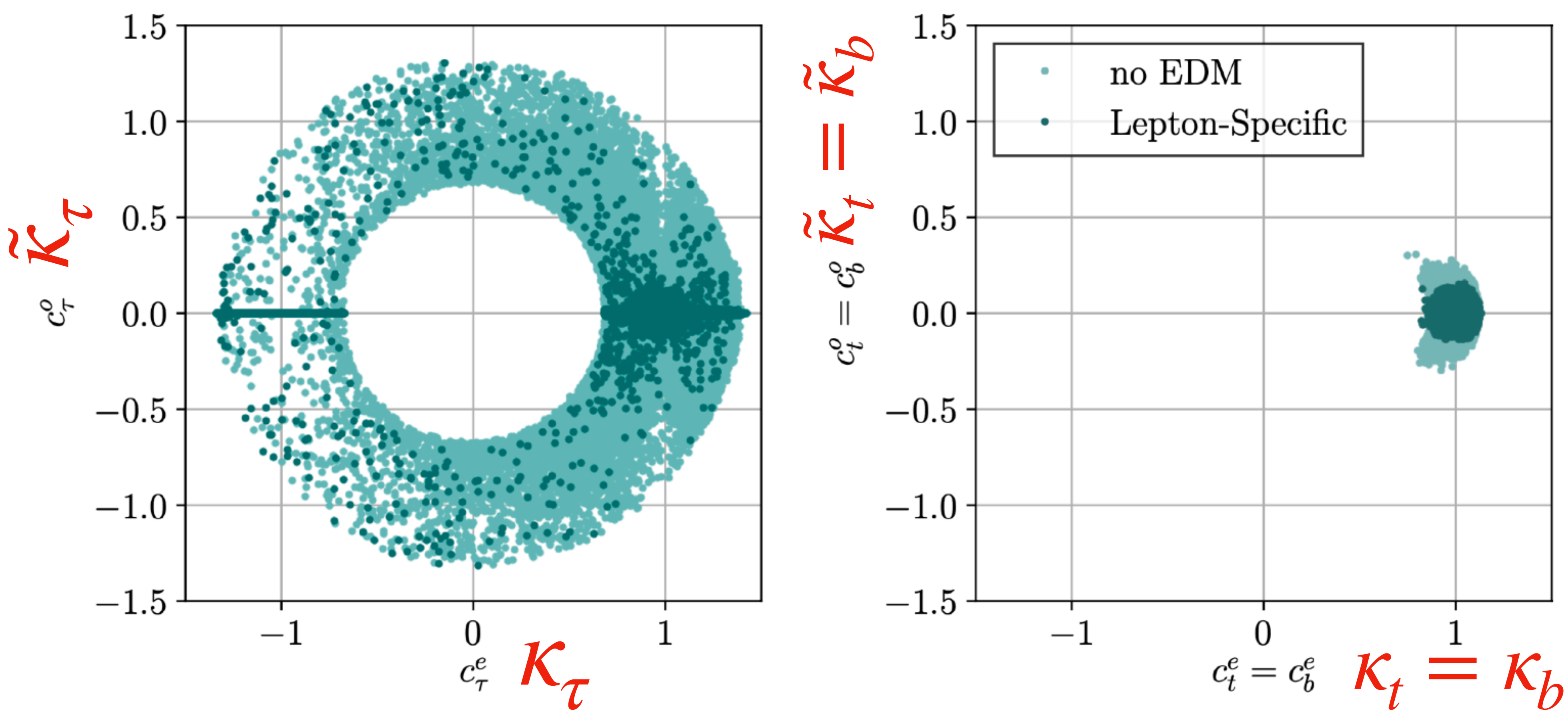
- **But** such constraints are model-dependent
  - Have to assume something about coupling of other particles to the BEH-boson e.g H→ee coupling
  - For some models e.g SUSY get additional diagrams contributing - can change EDMs





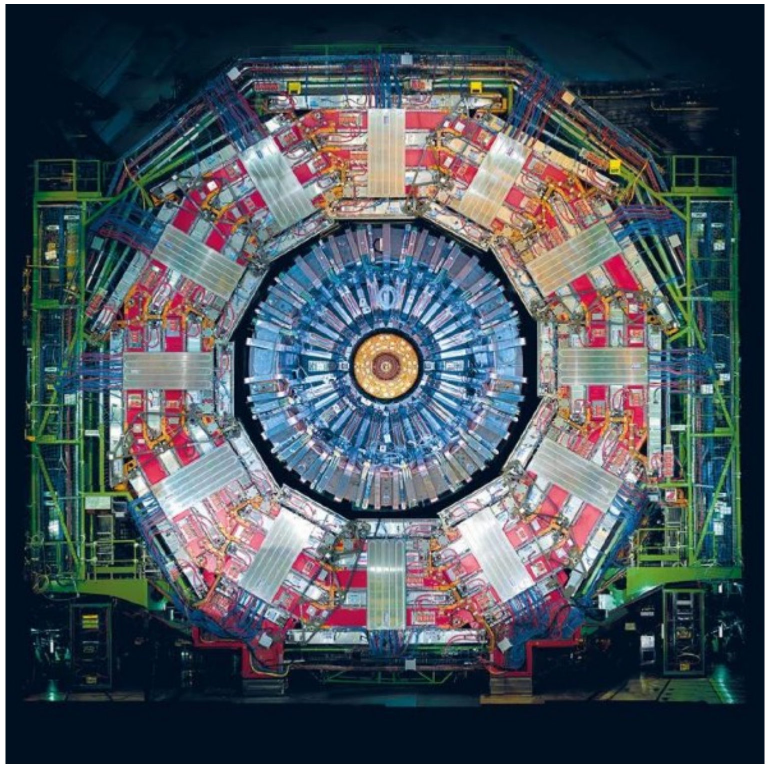
C2HDM

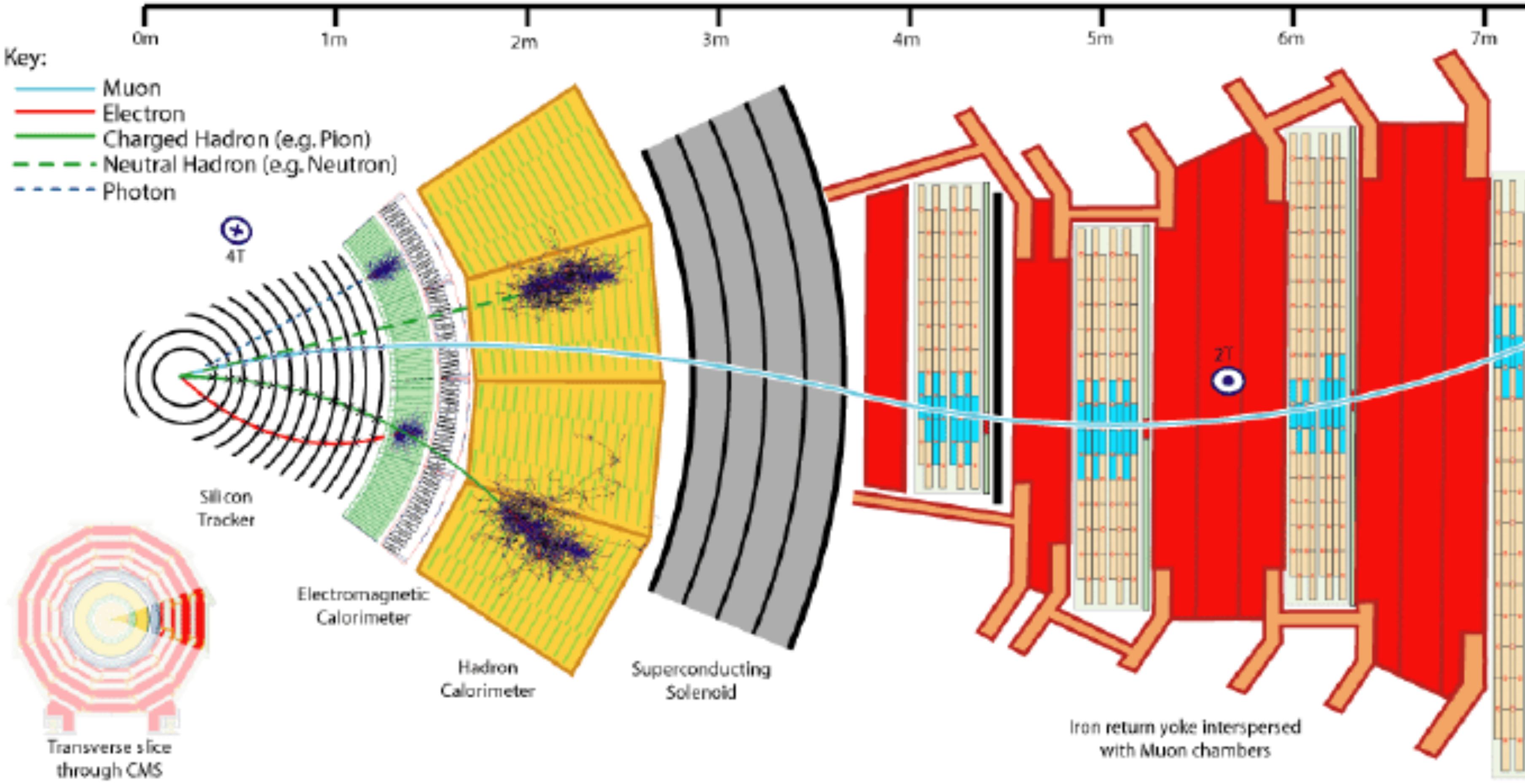
- Simplest extension that allows for CP-violation in BEH sector - complex two BEH doublet model (C2HDM)
- 4 additional BEH-bosons H_1, H_2, H_3, $H^{\pm}$ → one of H_i is the 125 GeV boson
- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios - light points allowed by all constraints 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
- More constrained for Type I and flipped scenarios

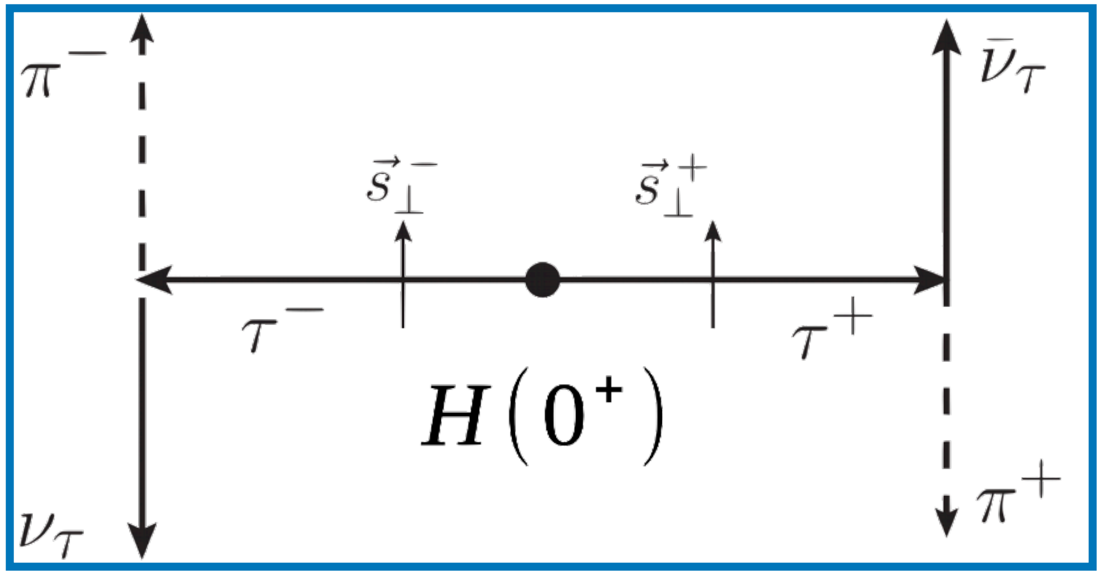


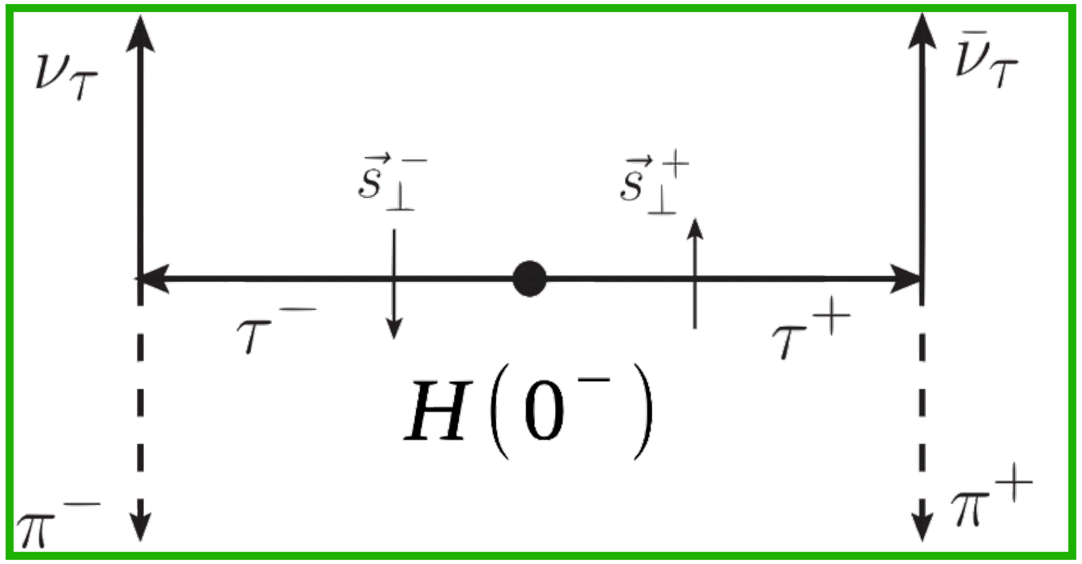
The CMS experiment

- 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)





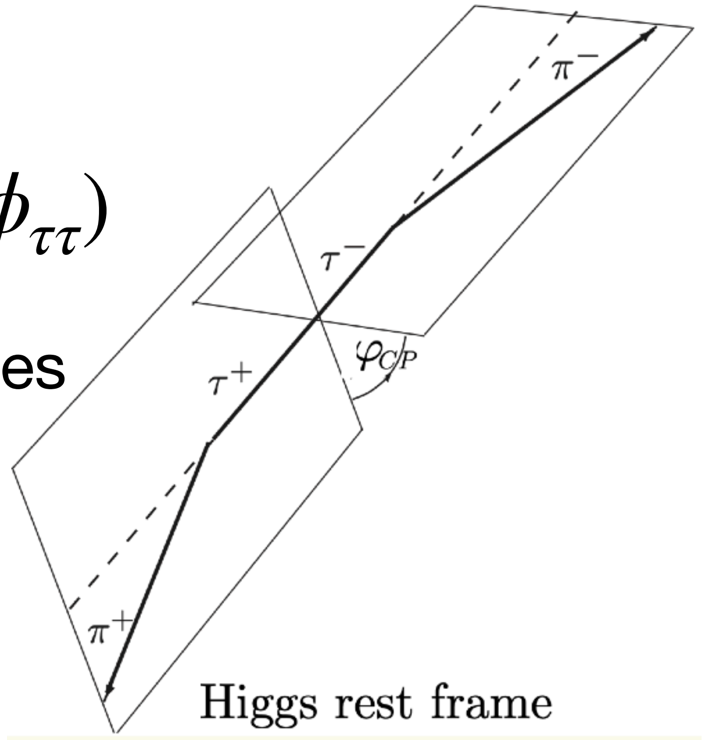


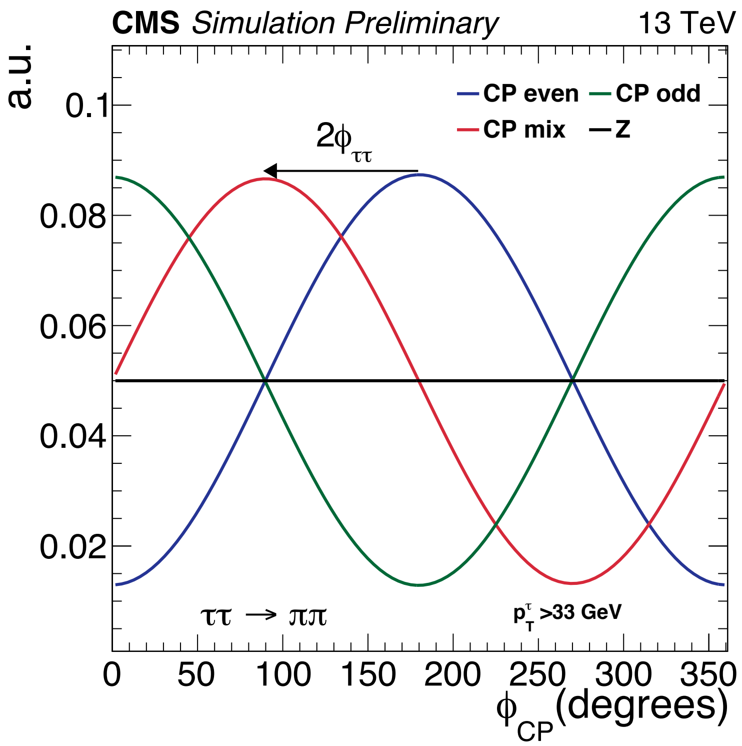


- Transverse spin correlations manifest as angular correlations of τ decay products
- Most simple 2-body decay: $\tau \rightarrow \pi^- \nu$
- Partial decay width looks like:

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

ϕ_{CP} is angle between τ decay planes in BEH-boson rest frame





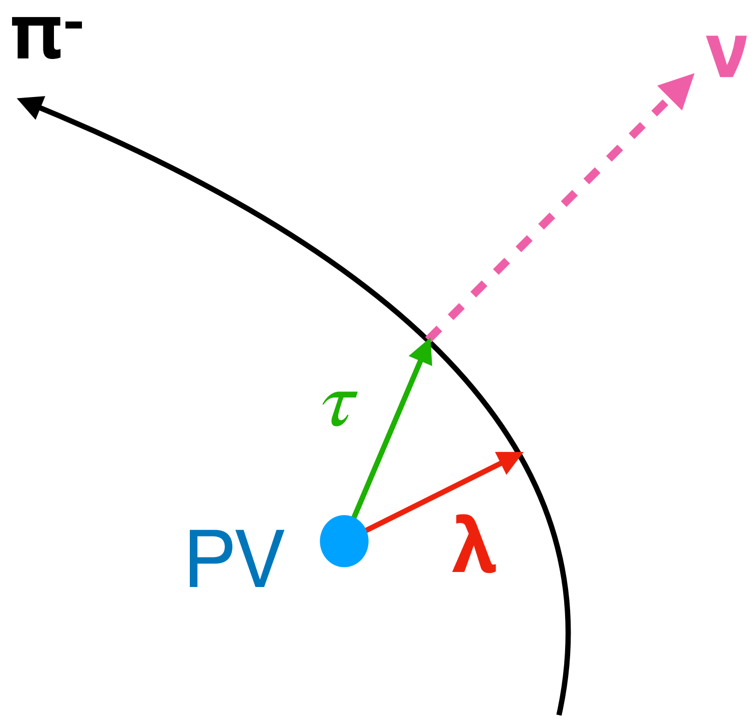
Plots courtesy of S. Berge

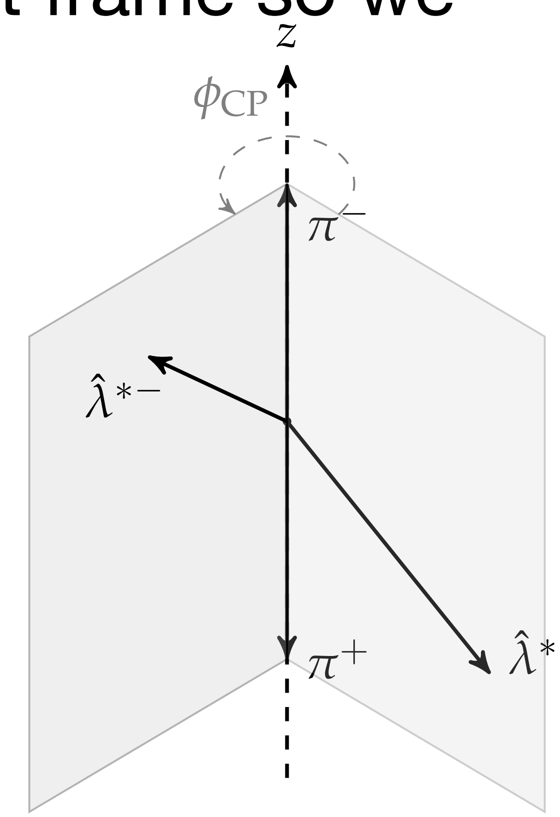
The IP method

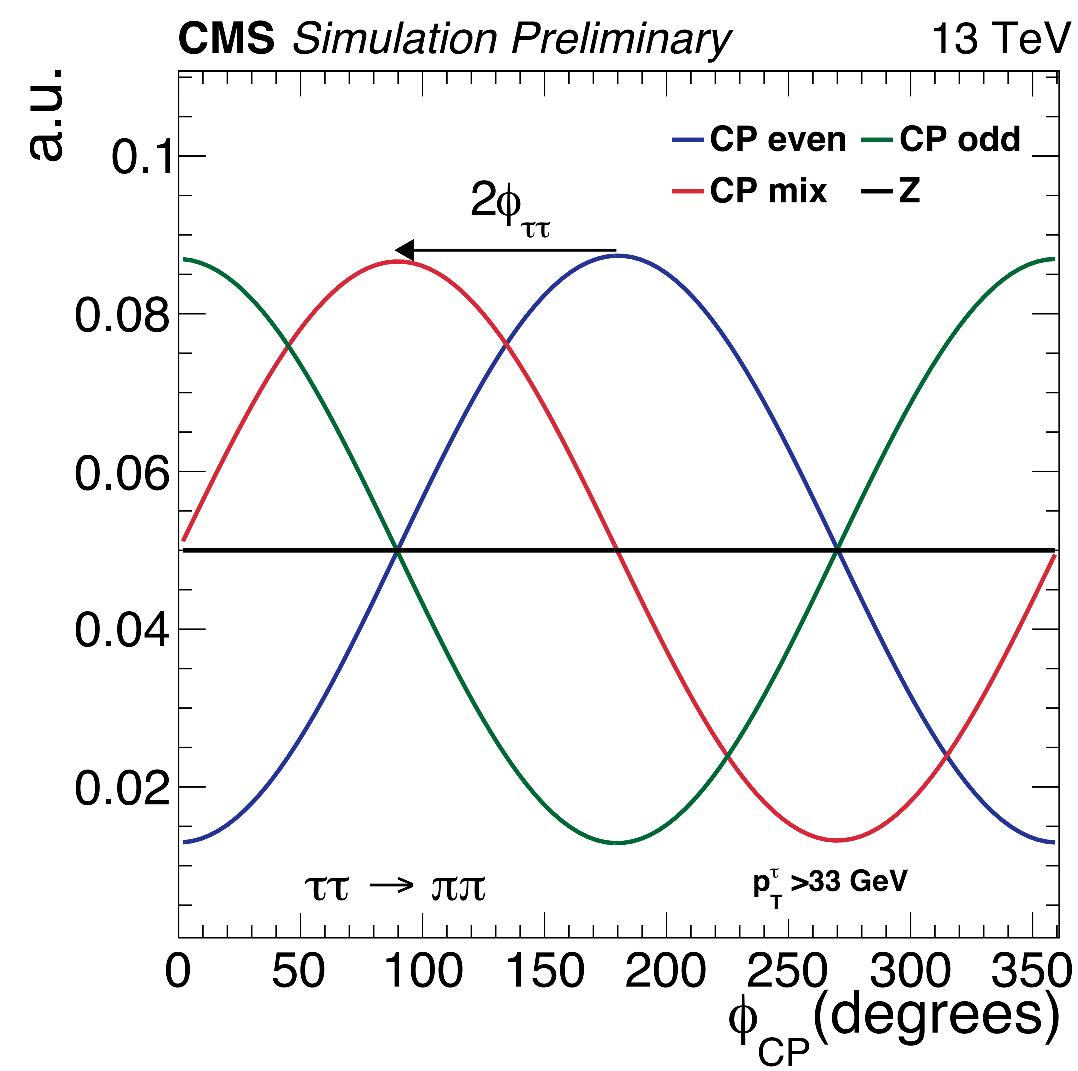
- In practise the ϕ_{CP} defined on the previous slide cannot be well measured at a hadron collider due to the neutrinos

- 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

- Cannot use BEH-boson rest frame so we use $\pi^+\pi^-$ rest frame

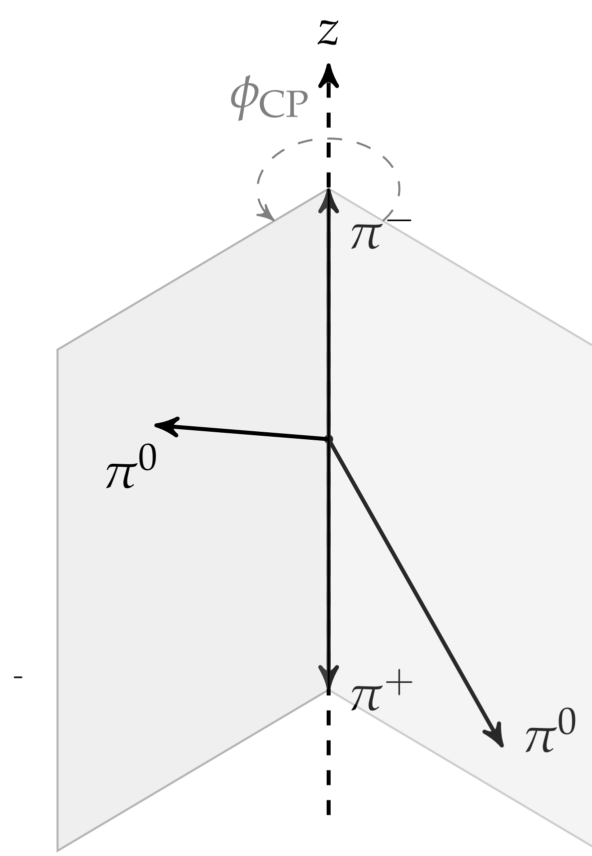


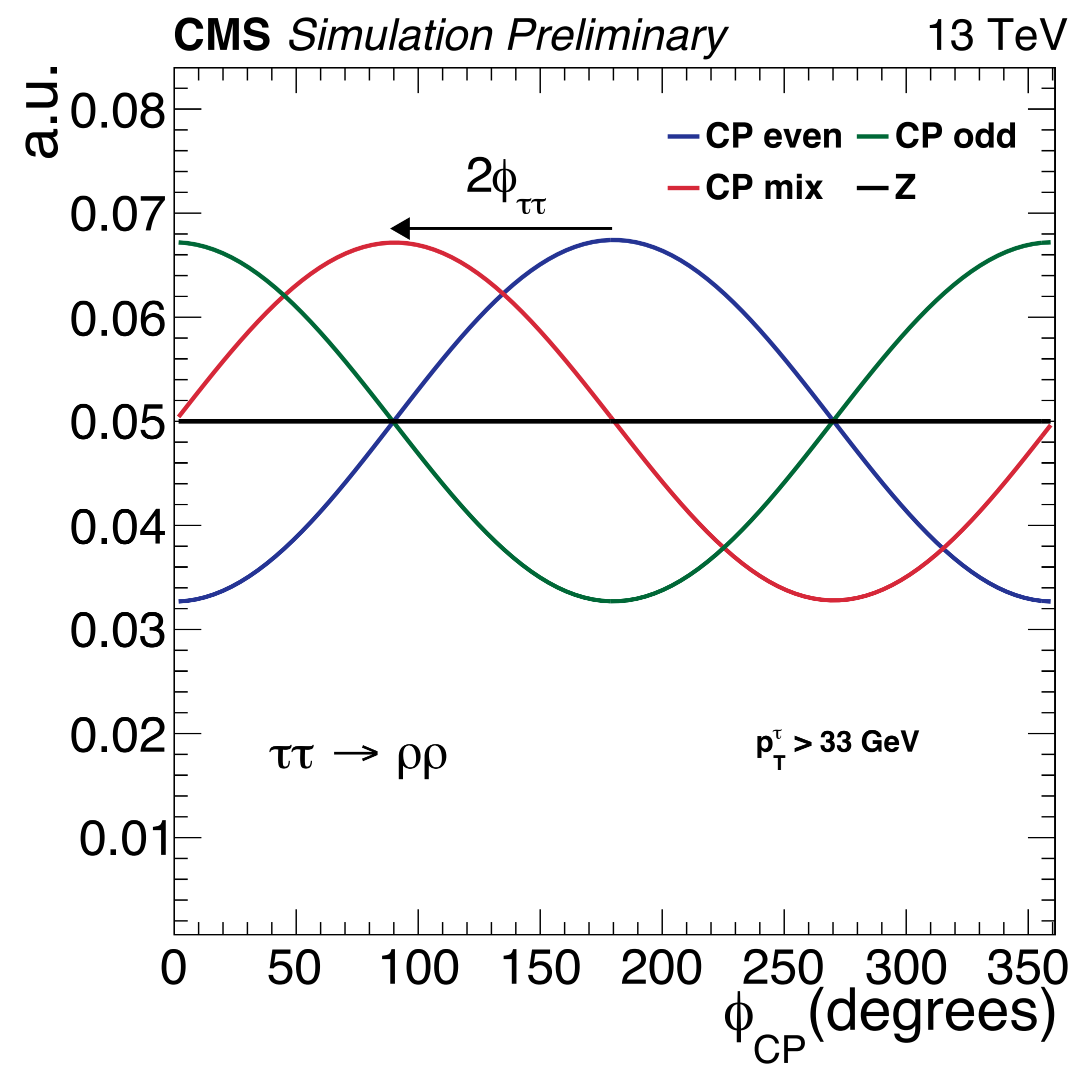




The π^0 method

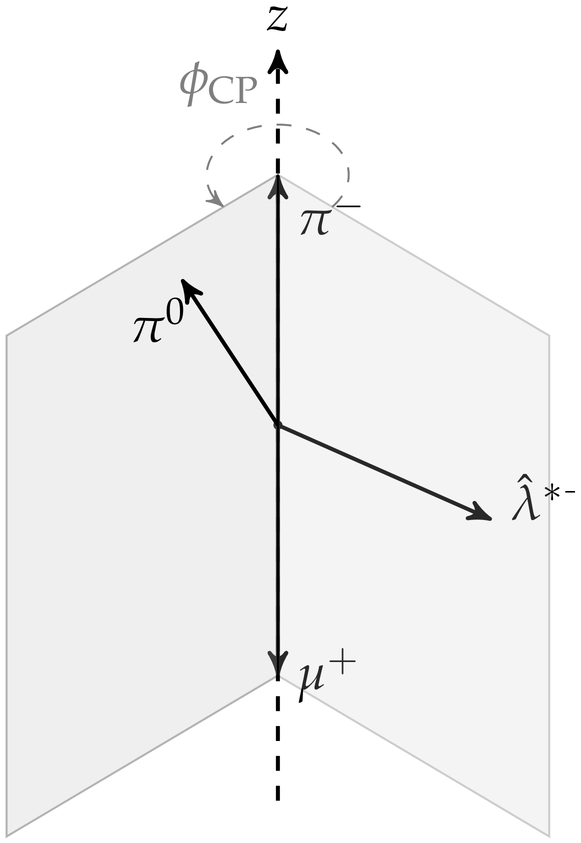
- For events with an intermediate resonances we can define a variable using only visible decay products
  - e.g $\tau\tau \rightarrow \rho^+\nu\rho^-\nu \rightarrow \pi^+ \pi^0\nu\ \pi^- \pi^0\ \nu$
- This avoids using the IP which is quite short compared to tracker resolution so is imprecisely reconstructed
- In this case we define ϕ_{CP} similar to previous but use π^0 vector instead of IP

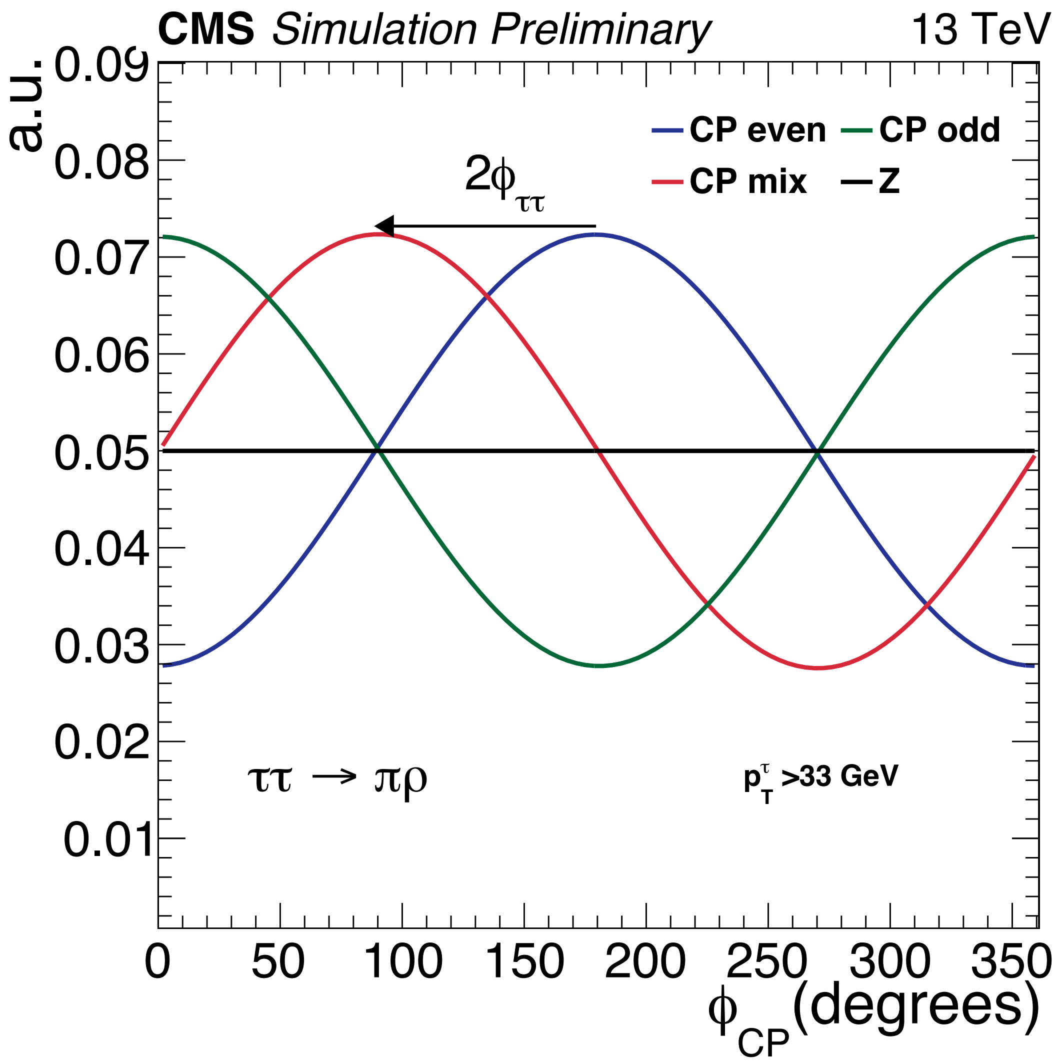




The "mixed" method

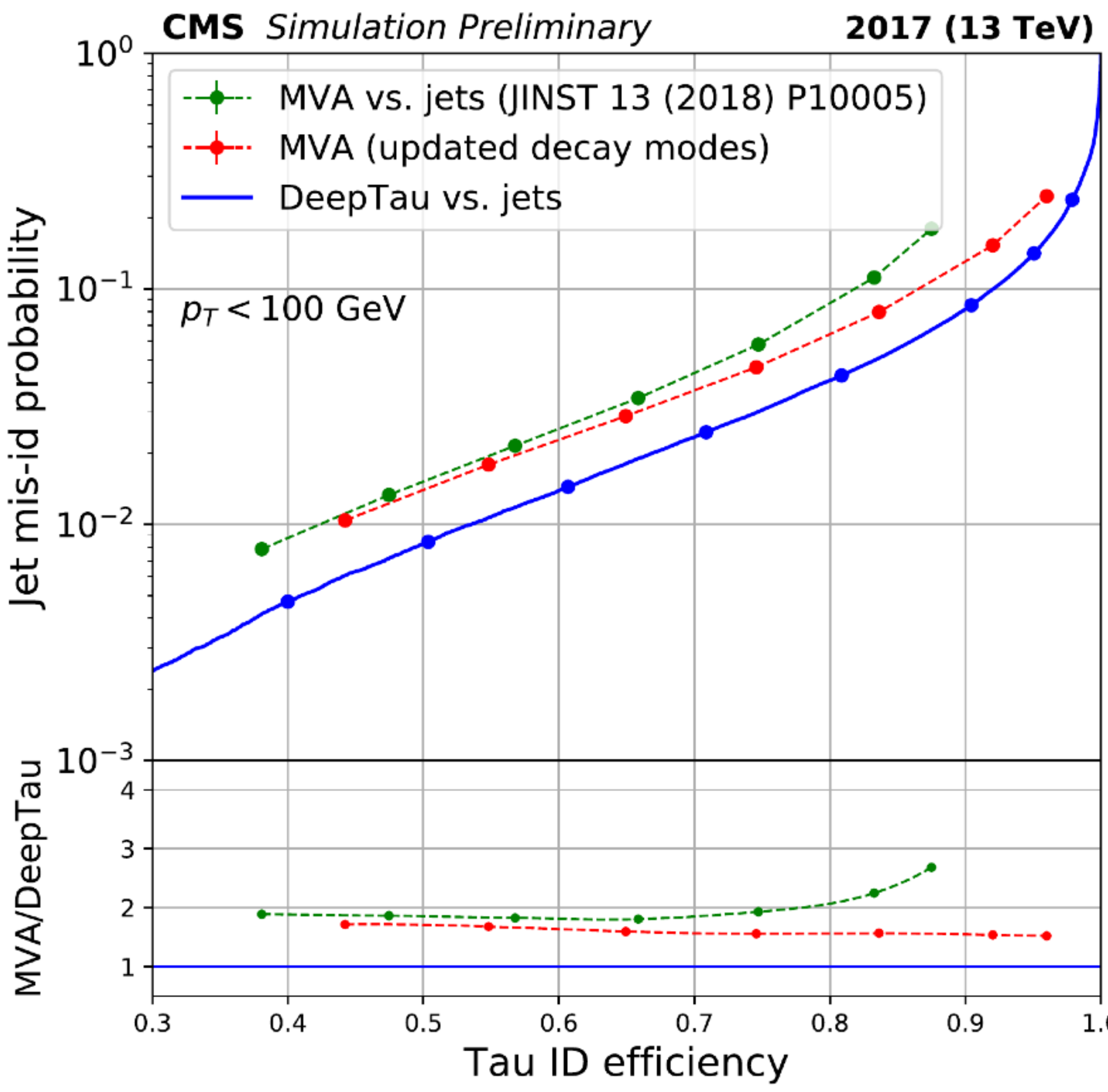
- Can also define ϕ_{CP} using a so-called "mixed" method when we have a neutral pion from 1 tau decay only
- E.g for a $H \rightarrow \tau\tau \rightarrow \rho^{+}\nu\mu^{-}\nu \rightarrow \pi^{+}\pi^{0}\nu\mu^{-}\nu\nu$





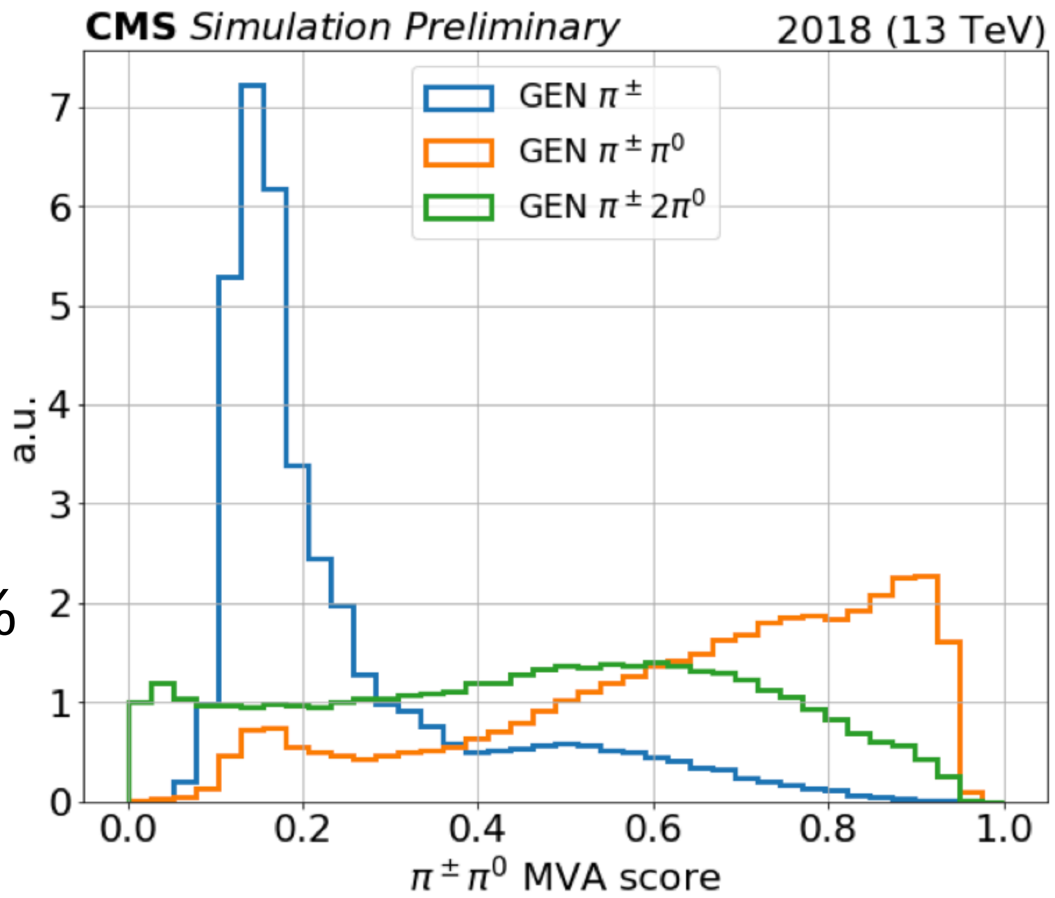
Tau reconstruction and identification

- Leptonically decaying taus reconstructed with standard CMS electron / muon identification
- Hadronic tau reconstruction based on hadron plus strips algorithm (HPS)
  - Charged PF candidates = hadrons
  - Strips = rectangular clusters of e/ɣ's aiming to reconstruct π^0's
- After reconstruction we want to perform tau identification to reduce background from jet and lepton fakes
- State of the art tau ID in CMS uses deep neural networks including a mix of low level information (PF candidates), and high level variables sensitive to properties such as tau lifetimes, isolation, intermediate resonances etc
- Significant improvement over previous tau ID using BDTs
- More details on Deeptau in CMS-DP-2019-033



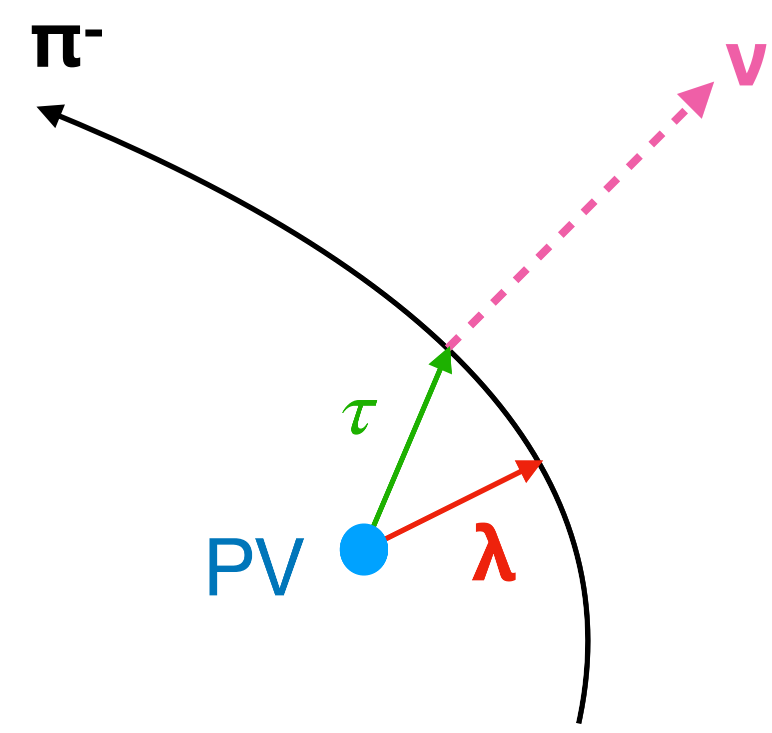
Tau decay mode selection

- The analysis is very sensitive to proper identification of the various hadronic decay modes
- For example a $\tau \rightarrow \rho \rightarrow \pi^- \pi^0$ looks a lot like a $a_1 \rightarrow \pi^- 2\pi^0$ as two π^0 tend to be merged by π^0 reconstruction algorithm
- But the CP separation (i.e the amplitude of the ϕ_{CP} distribution) 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 $N_ɣ$
- Improvement to final sensitivity using this BDT is ~ 25%
- CMS released a DPS with more details: CMS-DP-2020-041



Primary vertex and impact parameters

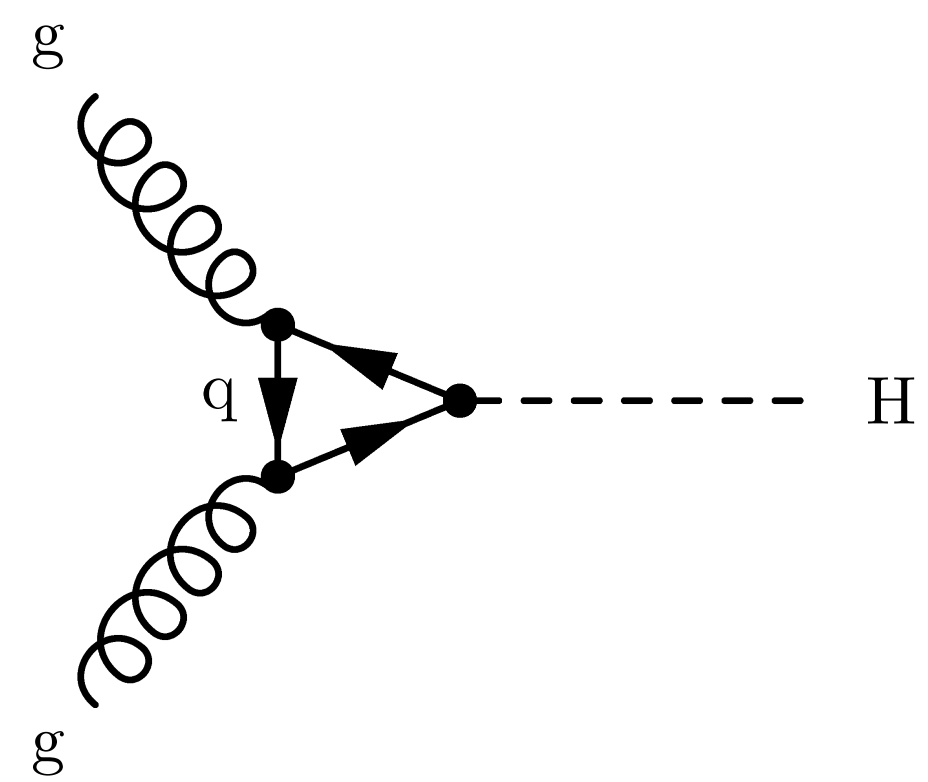
- Charged tracks from tau decays do not originate exactly from PV
  - We exclude these tracks and refit the vertex
- We also include an additional constraint from the LHC luminous region (so-called beam spot)

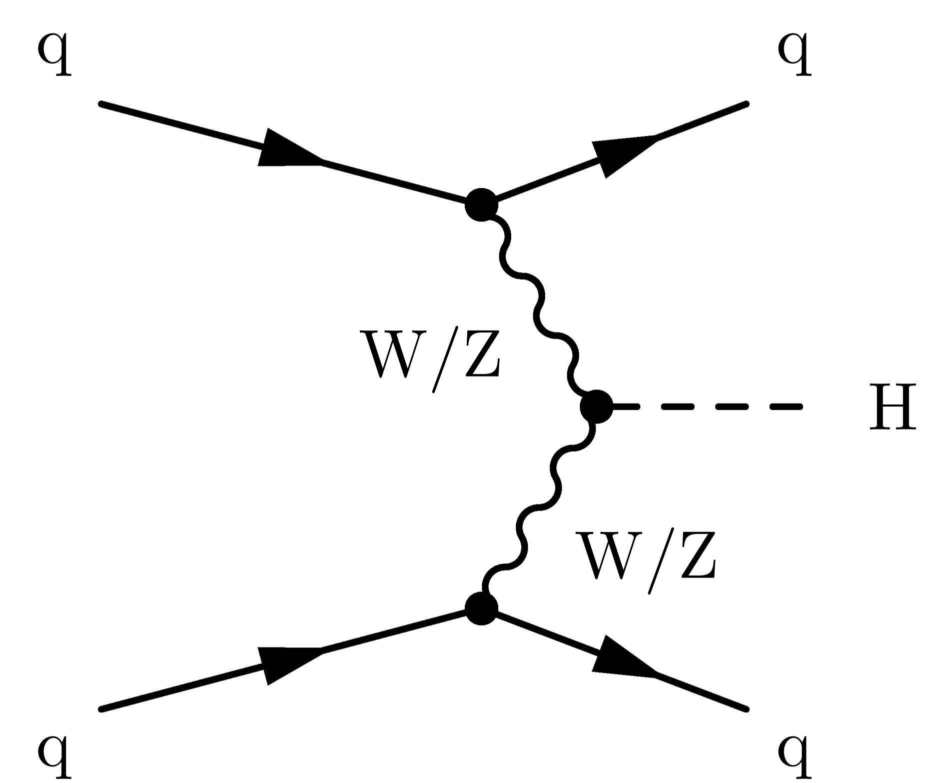


- To find IP we minimise distance between PV and track in 3D
- Out IP method also allows us to propagate uncertainties on the track and PV to define a significance $\delta_{IP} = |\boldsymbol{\lambda}|/\sigma_{IP}$
- We reject events with $\delta_{IP} < 1.5$ → gives about a 15% improvement in the final sensitivity

Signal modelling

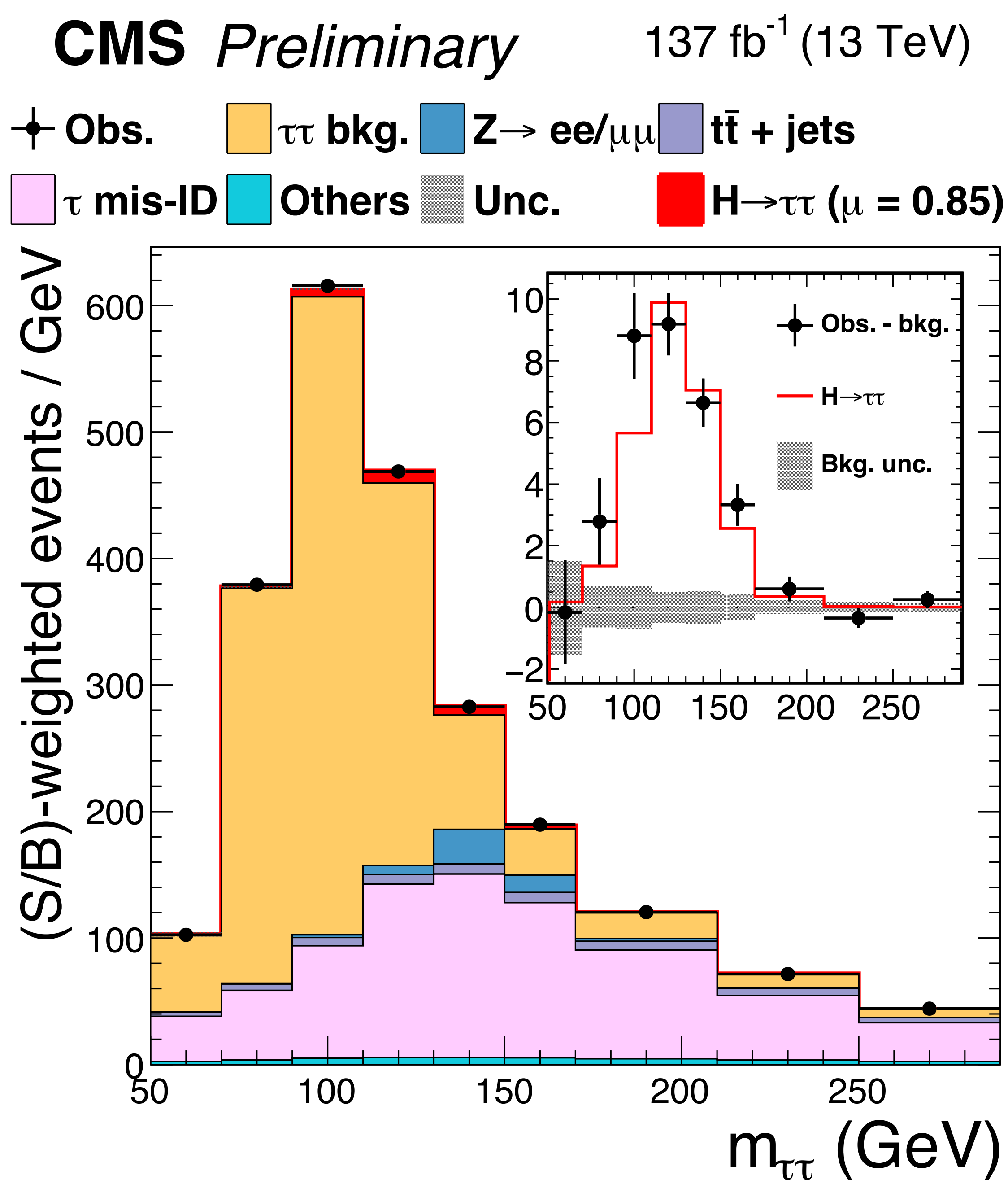
- H→$\tau\tau$ has relatively sizeable branching ratio and is relatively clean
- Most sensitive production modes are ggH and VBF
  - ggH has larger cross section but VBF has additional jet topology to tag events
  - When we put both together we get about same sensitivity to both processes
- We assume production kinematics are SM-like and produce scalar BEH-bosons with POWHEG-BOX-V2
- H→$\tau\tau$ decays handled by Pythia 8.2
  - We force taus to decay without spin correlations
  - Spin effects then added back using weights computed with TauSpinner (arXiv:1802.05459)
  - This has advantage that we can use a single MC sample to model any generic CP scenario





Backgrounds

- Two largest contributions to background are $Z \rightarrow \tau\tau$ jets faking hadronic taus ($j \rightarrow \tau_h$)
- We use data-driven method to estimate these processes
- This has advantaged such as reduced systematic uncertainties
  - For example objects such as jets can come directly from data so we aren't sensitive to data vs simulation differences in jet energy scale / resolution
- Statistics can be very large compared to MC simulations so help reduce statistical uncertainties considerably



Event selections

- We select di-tau events in the fully hadronic final state ($\tau_h\tau_h$) and one semi-leptonic final state ($\tau_\mu\tau_h$)
  - collectively these channel include ~ 55% of all di-tau decay, and include all the most sensitive channels
- For $\tau_h\tau_h$ we require:
  - Two opposite-sign τ_h candidates passing HPS and deepTau ID
  - Taus should be desperate by $\Delta R > 0.5$ and have $p_T > 40$ GeV
  - Pass the double-tau trigger (with p_T threshold of 35 GeV)
  - Veto events with additional light leptons
- For $\tau_\mu\tau_h$ we require:
  - A τ_h candidate with $p_T > 20$ GeV passing HPS and deepTau ID
  - A isolated μ passing identification and with $p_T > 23$ (25) GeV for 2016 (2017 and 2018)
  - The τ_h and μ should have opposite sign charges and be separated by $\Delta R > 0.5$
  - Event should pass either a single muon trigger (p_T threshold between 23-27 GeV) or muon+tau trigger
  - Veto events with additional light leptons, b-jets, or with transverse mass $m_T > 50$ GeV

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 $\tau_h\tau_h$ ($\tau_\mu\tau_h$) channel we use BDT (NN)

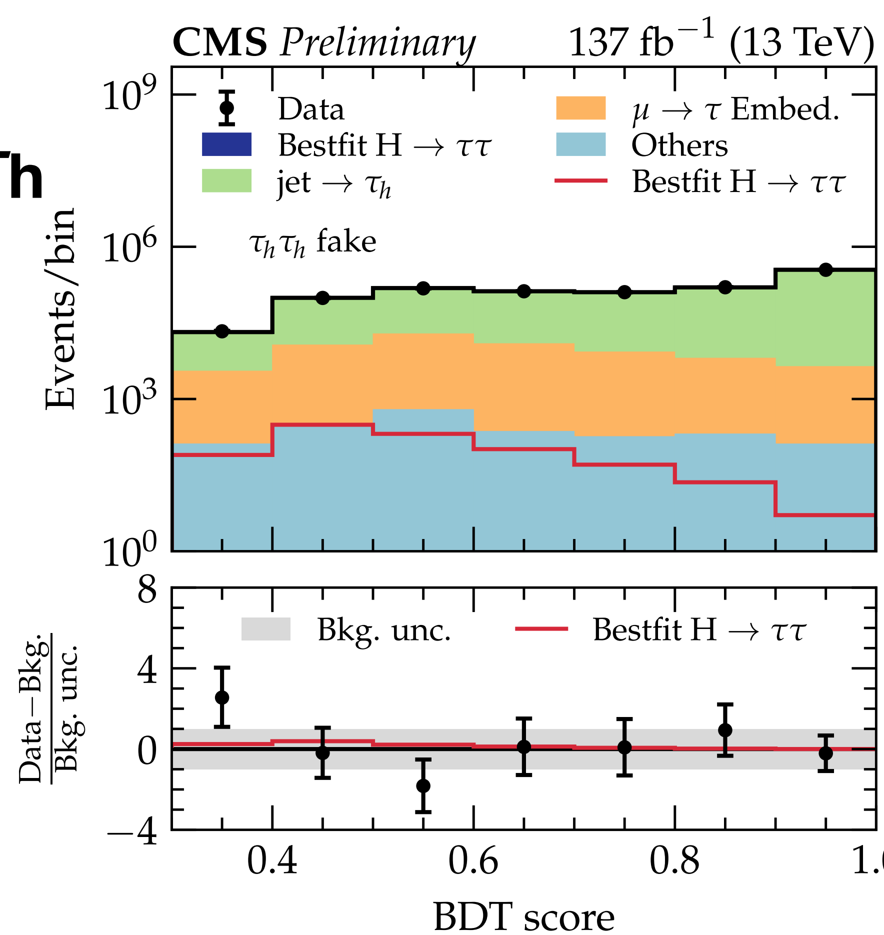
  - Includes several variables such as: p_T's, $m_{\tau\tau}$, Njets, m_{jj}, ..

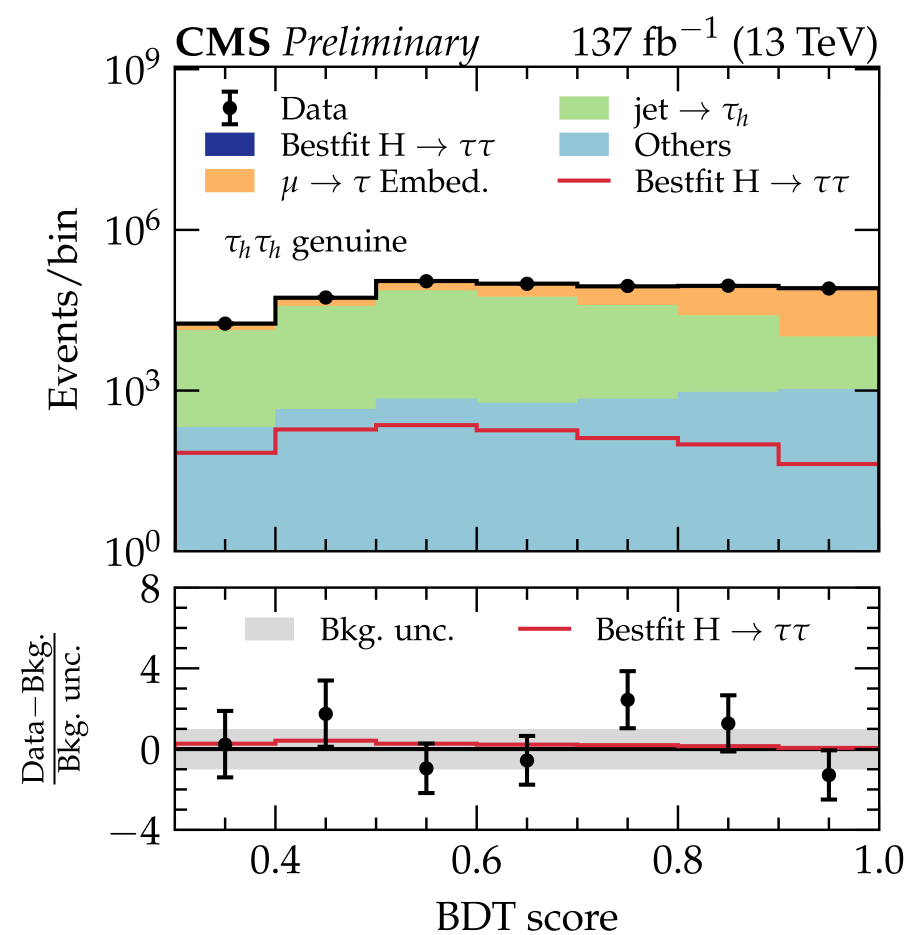
  - $m_{\tau\tau}$ most important variable - because of neutrinos we estimate using SV-fit algorithm (J. Phys. Conf. Ser. 513 022035)

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
- In each category we then fit the corresponding score as a discriminating variable

fake-τ_h



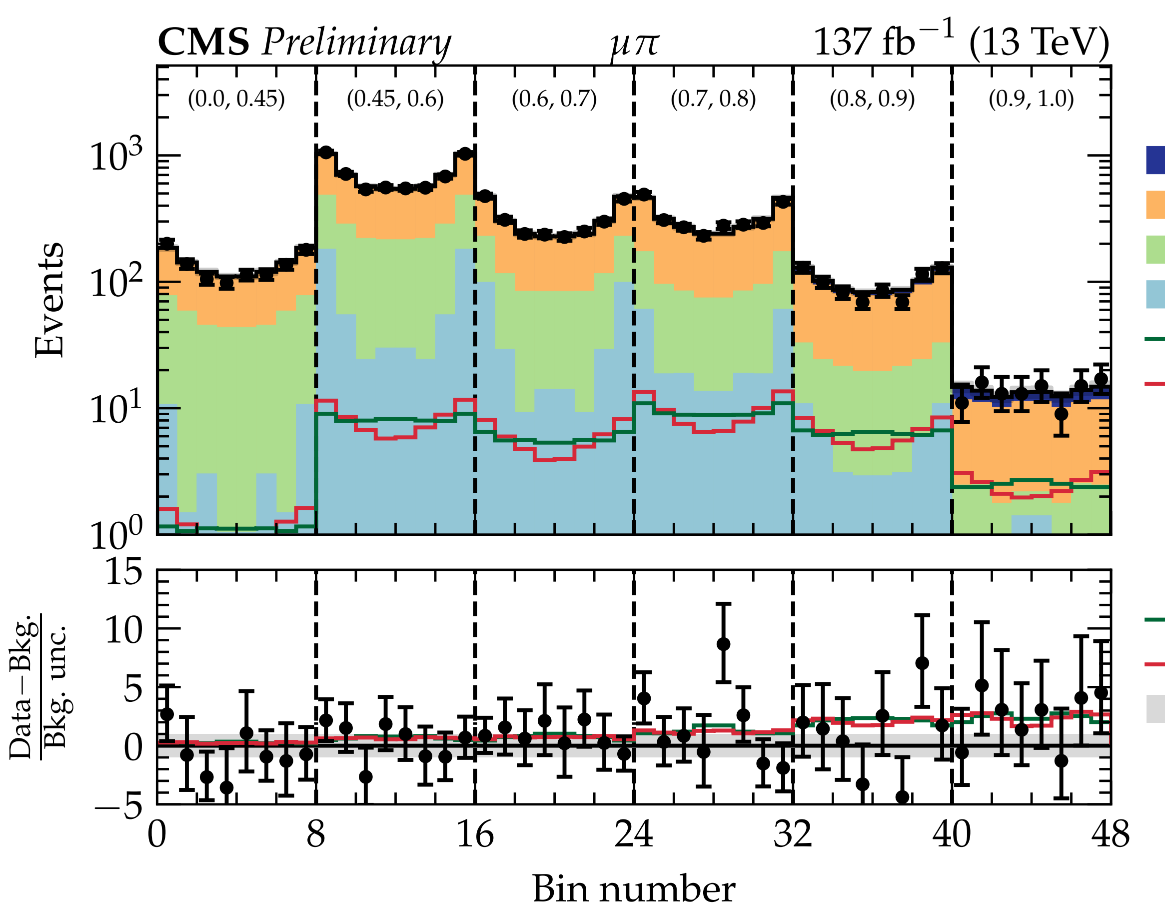


genuine-τ_h

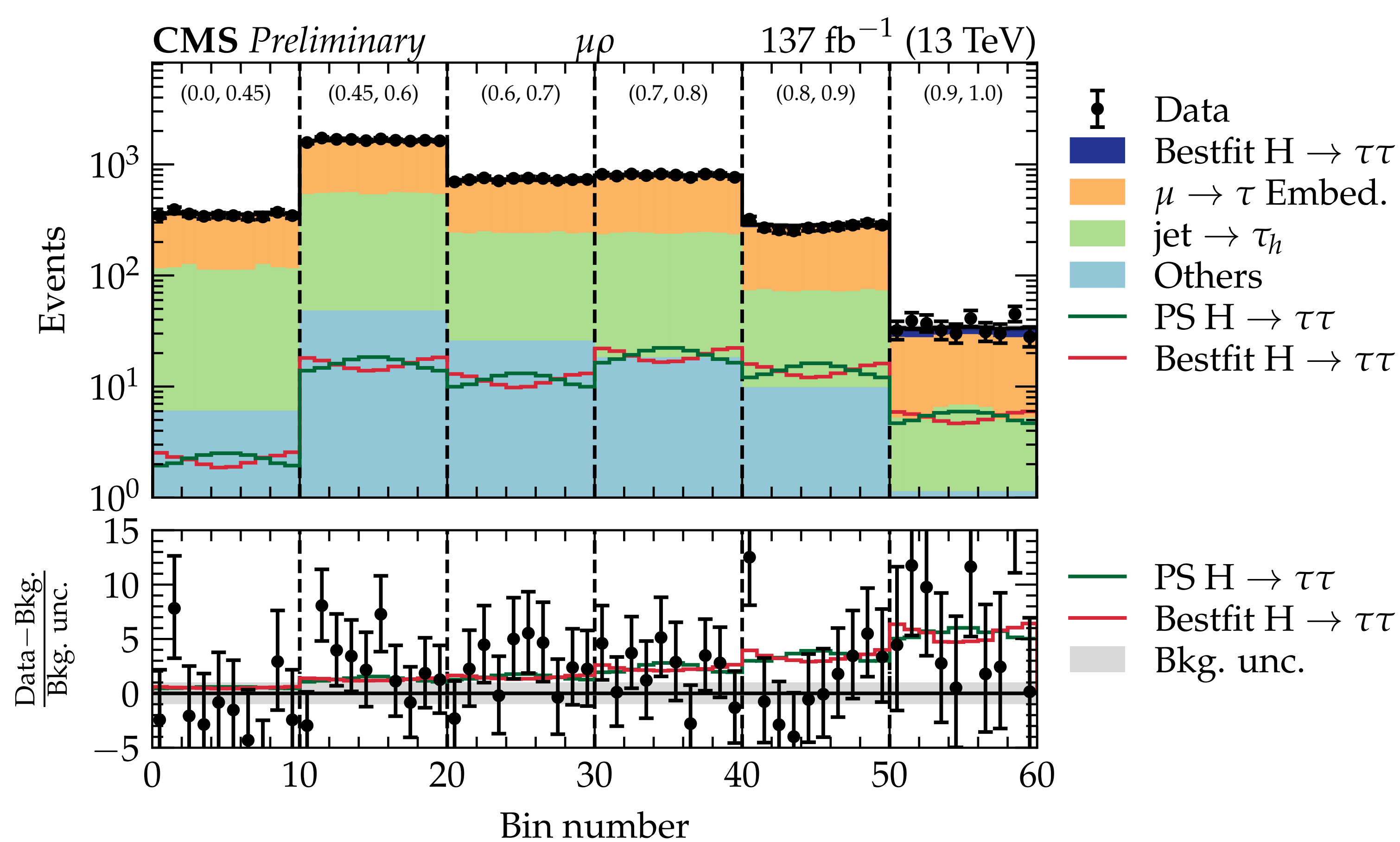
Signal categories

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

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

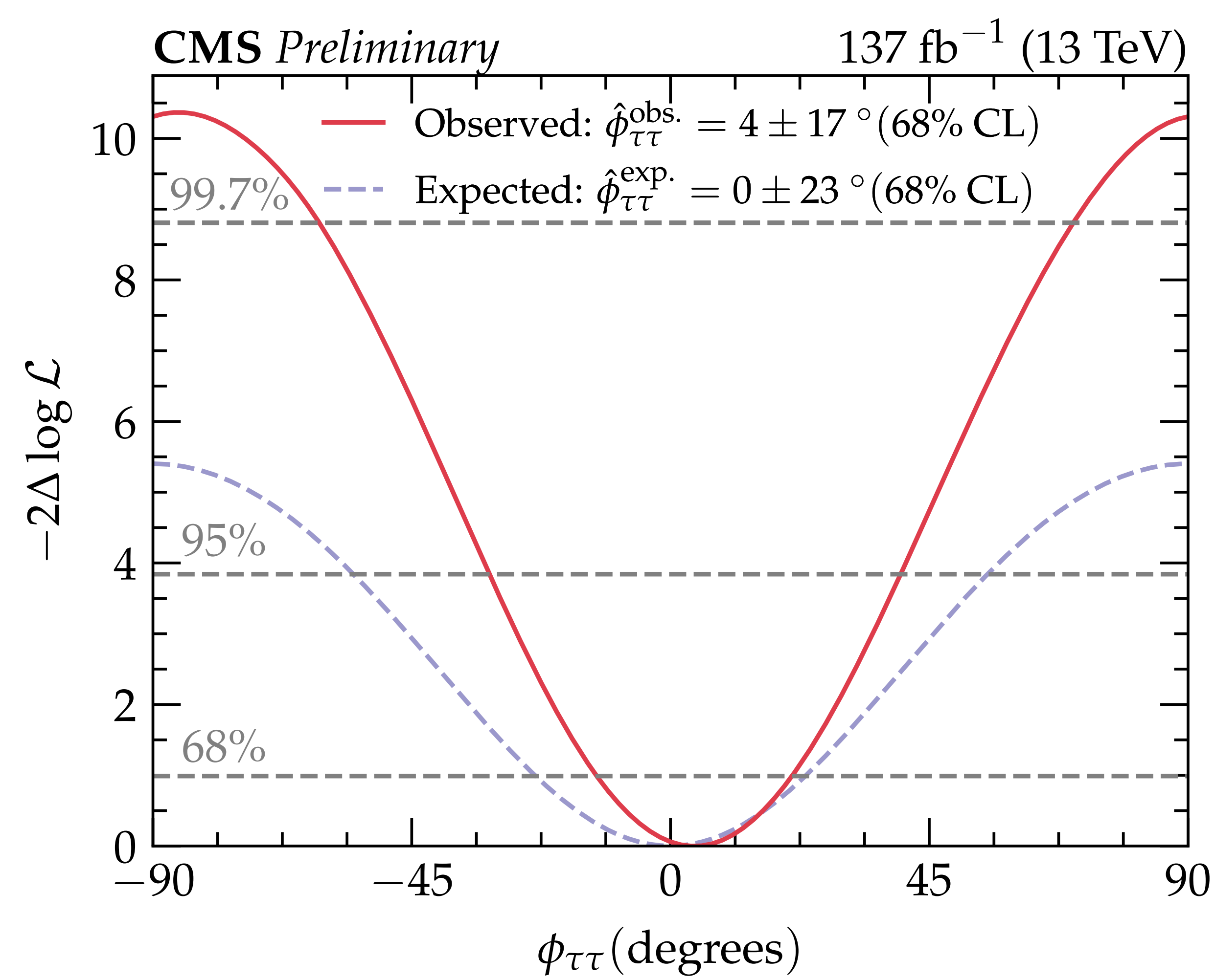


$\tau_\mu \tau_h$, $\tau_h \rightarrow \rho^- \nu$



Results

- We extract out results by means of a binned maximum likelihood fit combining all channels and categories
- The observed (red) and expected (blue) -2Δlog(L) scan is shown below
- The best fit value and uncertainty is 4 ±17° compared to an expected value of 0 ± 23°
- Results are therefore in agreement with the SM although uncertainties are large so there is still lots of room for new physics
- Due to a slight upwards fluctuation we are able to exclude the pure CP-odd hypothesis at the 3σ level

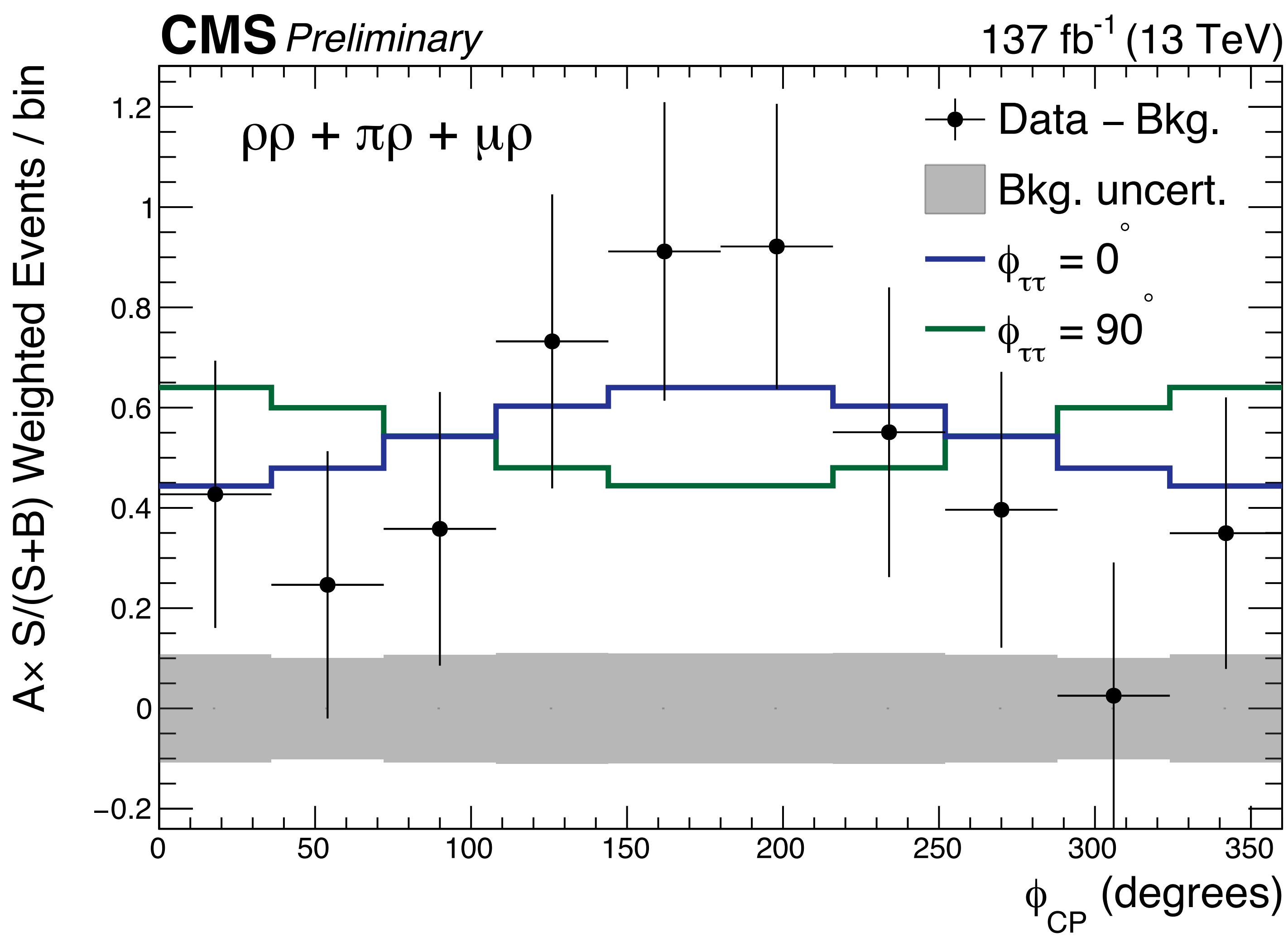


Results: ϕ_{CP} distribution

- For a visual representation of the measurement we produce a double weighted distribution of the muon sensitive categories

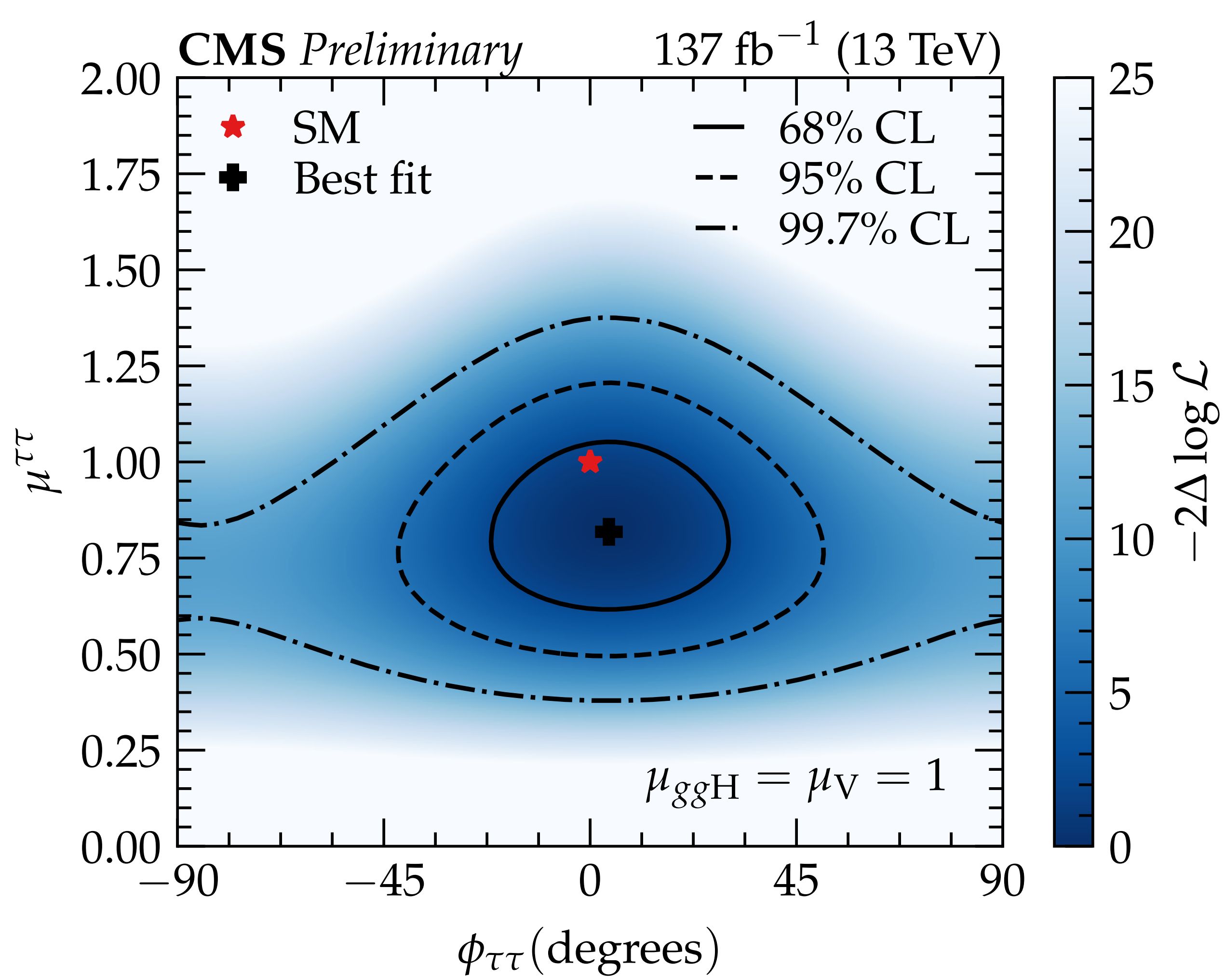
- Weight by S/(S+B) and the parameter A

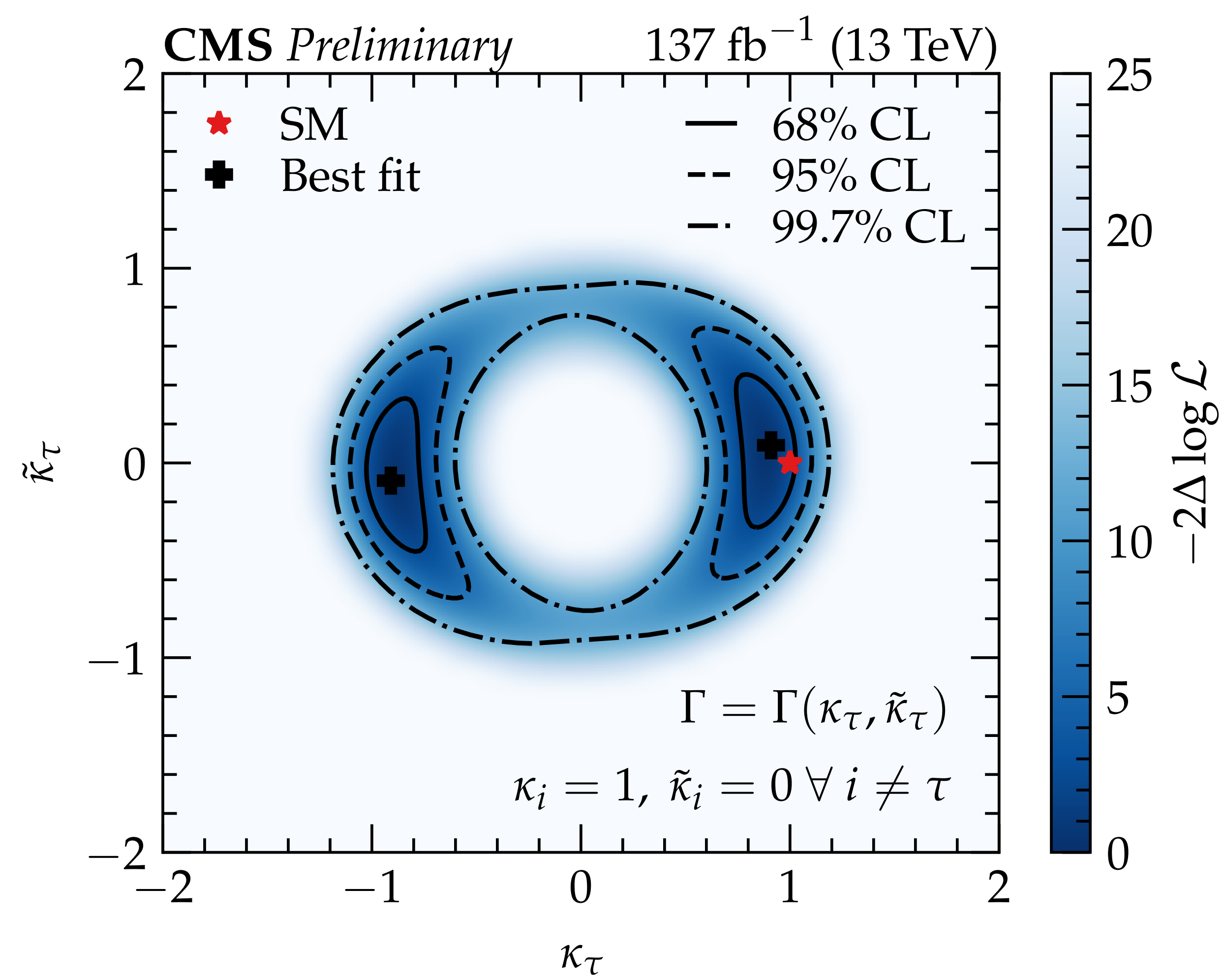
- A is the "average asymmetry" = sum of absolute differences between CP-even and CP-odd for all bins / N_{bins}



2D scans and coupling measurements

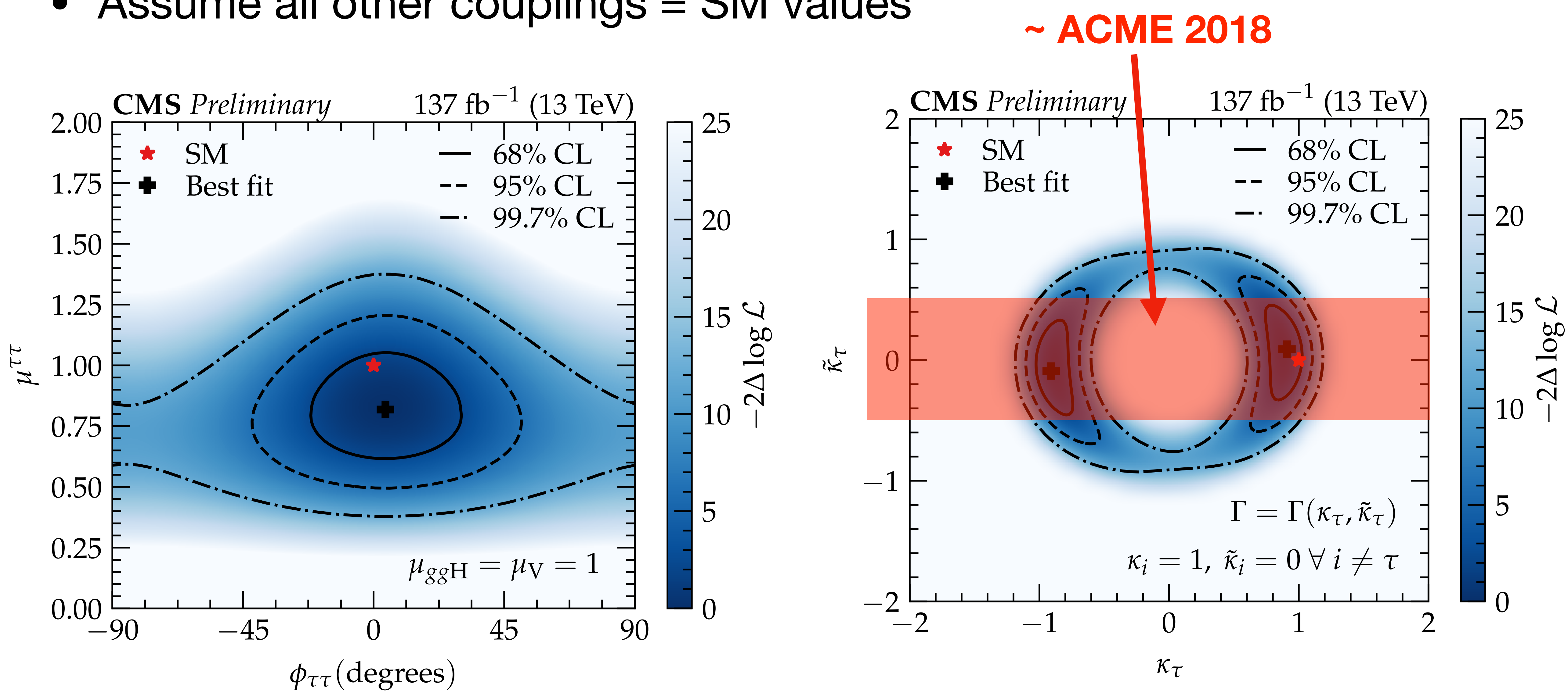
- Plot 2D scan of branching ratio modified $\mu_{\tau\tau}$ vs $\phi_{\tau\tau}$ (left)
- Also interpret results in terms of couplings: κ_τ and $\bar{\kappa}_\tau$ (right)
  - Assume all other couplings = SM values





2D scans and coupling measurements

- Plot 2D scan of branching ratio modified $\mu_{\tau\tau}$ vs $\phi_{\tau\tau}$ (left)
- Also interpret results in terms of couplings: κ_τ and $\bar{\kappa}_\tau$ (right)
  - Assume all other couplings = SM values



Future measurements: LHC

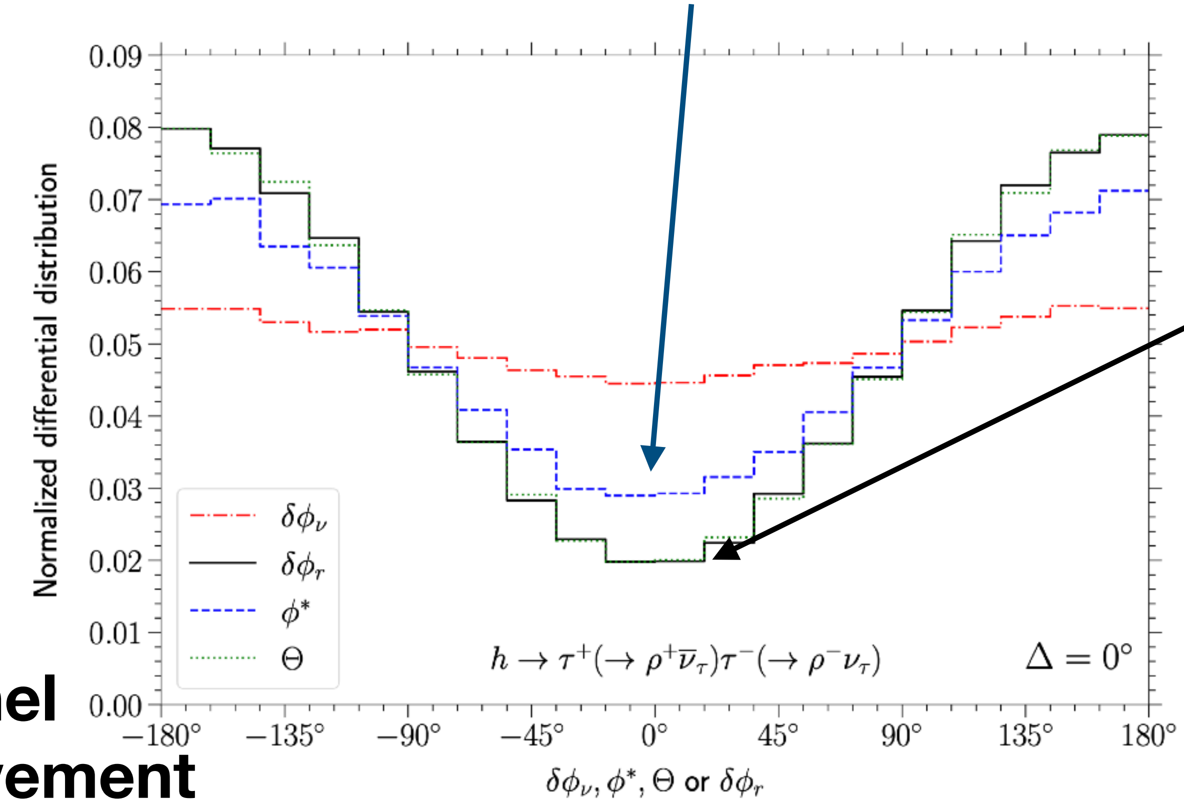
- Even shorter term (~ spring/summer 2021):
  - Add more channels e.g eρ eπ ea_1
  - Likely bring ~ 10-15% improvement in sensitivity
- Medium term (LHC Run 3 ~ 2025):
  - Take into account more information/variables to constrain the $\tau\tau$ system e.g missing energy, secondary vertices, impacts parameters (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 ~ 2037)
  - Breakdown of expected statistical and systematic uncertainties
    $\phi_{\tau\tau} = 0 \pm 23$ (stat.) + 2 (syst.) $^{\circ}$
  - Very naive prediction for HL-LHC (3/ab): scale statistical error by $1/(3000/137)^{0.5}$:

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

Future measurements: lepton colliders

- Lepton colliders have advantage of being able to constrain BEH-boson 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°

ρρ channel ~ 30% improvement

Results here take into account ρρ, πρ, and ππ channels only

Conclusions

- Introduced extended BEH sectors with additional CP-violation in BEH-boson couplings
- Discussed measurements of CP-properties of $H \rightarrow \tau\tau$ coupling
- Indirect constraints from EDMs
- Presented the latest results from the CMS collaboration using Run2 data (2016-2018)
  - Current best measurement: $\phi_{\tau\tau} = 4 \pm 17^{\circ}$
  - Pure CP-odd hypothesis excluded at 3σ level
- Discussed prospects for future measurements at LHC and future ee colliders

Thanks for your attention!

Backup

C2HDM: overview

- Compared to SM BEH 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:

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

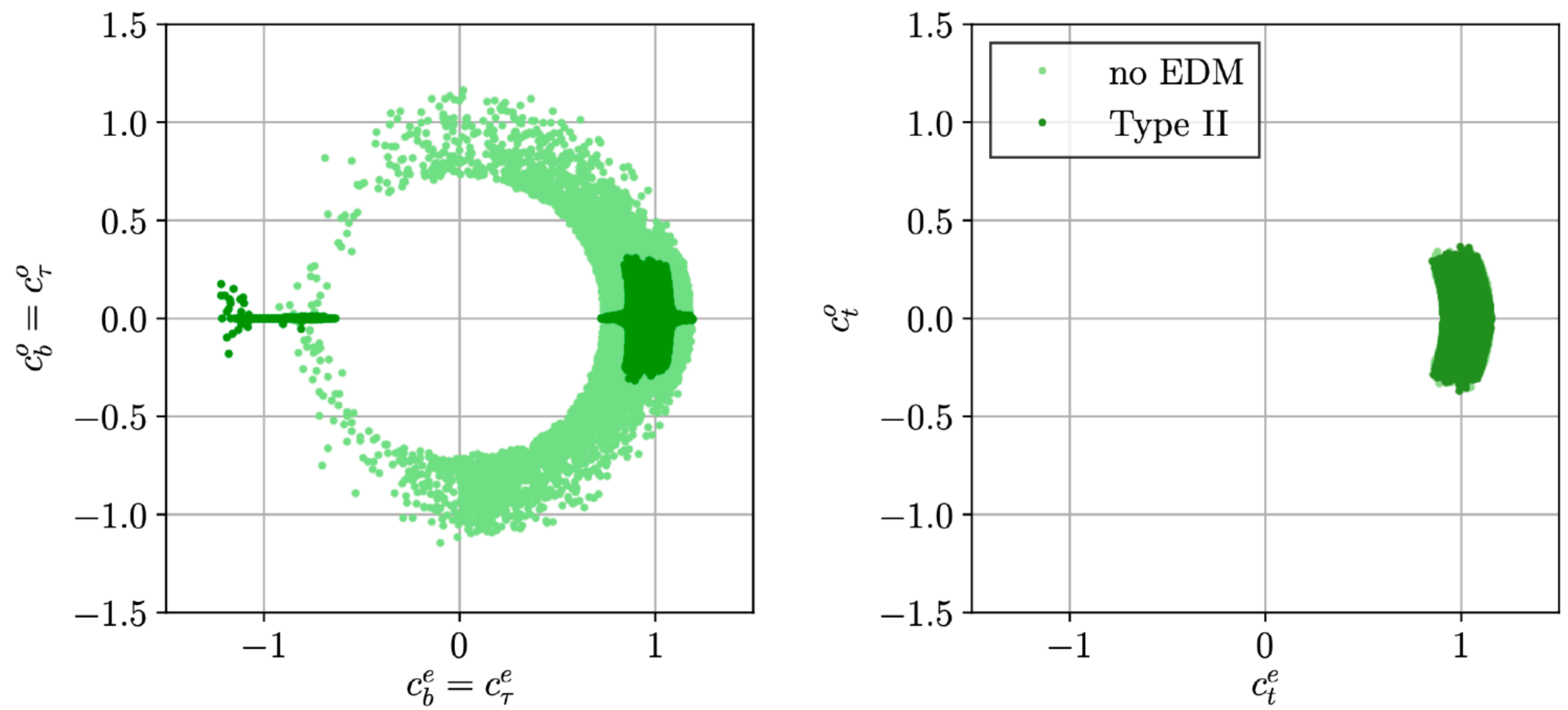
- Complex parameters m_{12}^2 and λ_5 allow CP-violation

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
  - BEH-boson (125 GeV) coupling constraints
  - HiggsBounds (searches for additional bosons)

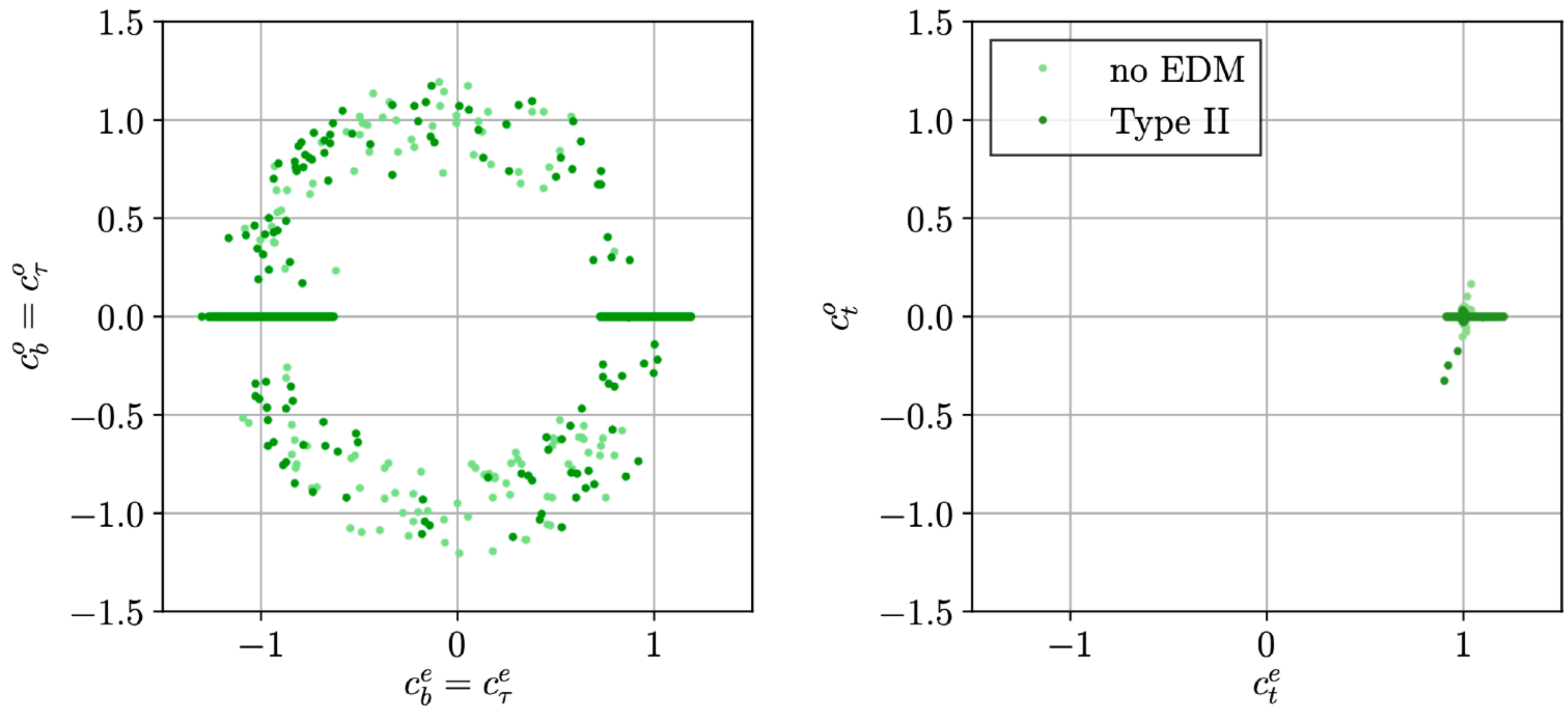
C2HDM: Type 2

- 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



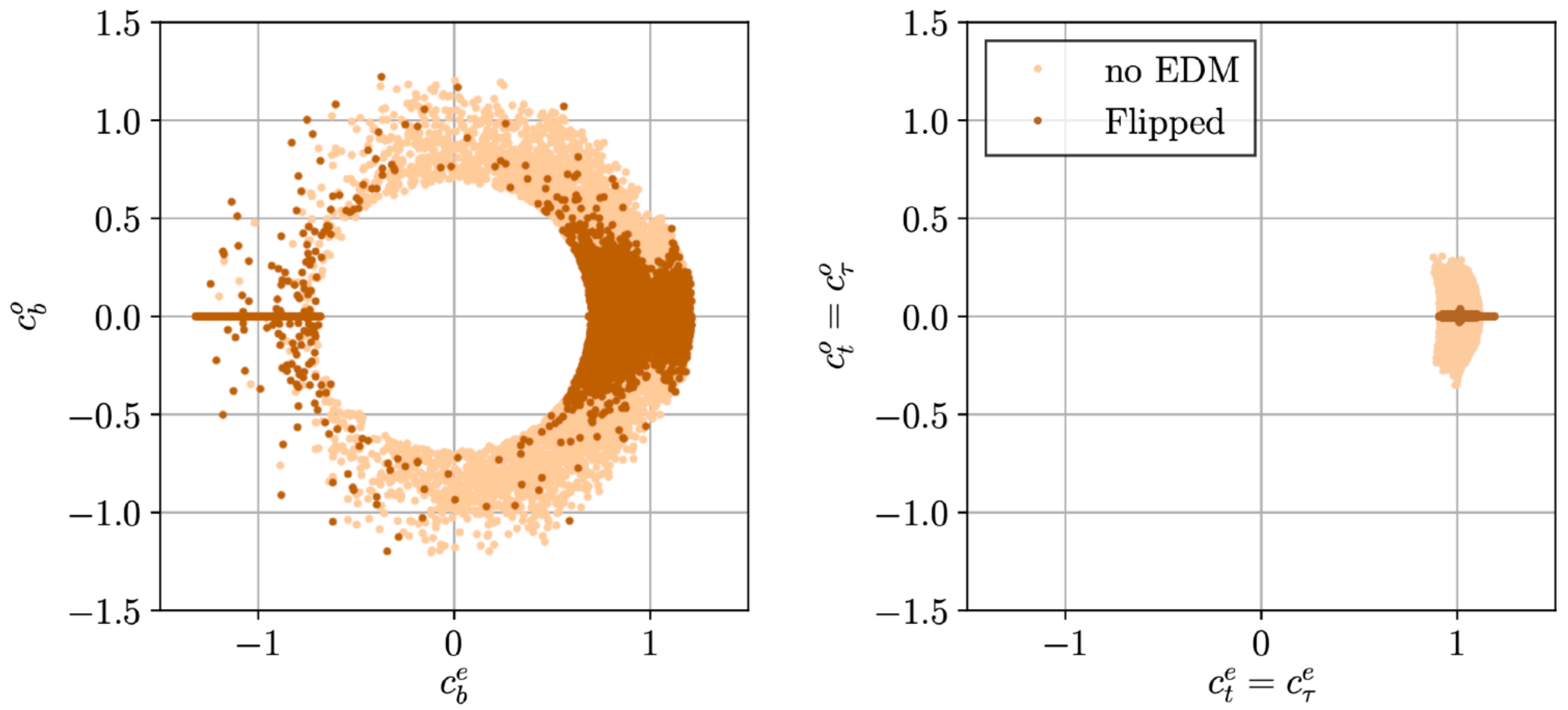
- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios

- In Type 2 2HDM can also get points with larger $\bar{\kappa}_\tau$ not excluded for cases where H_2 = 125 GeV boson



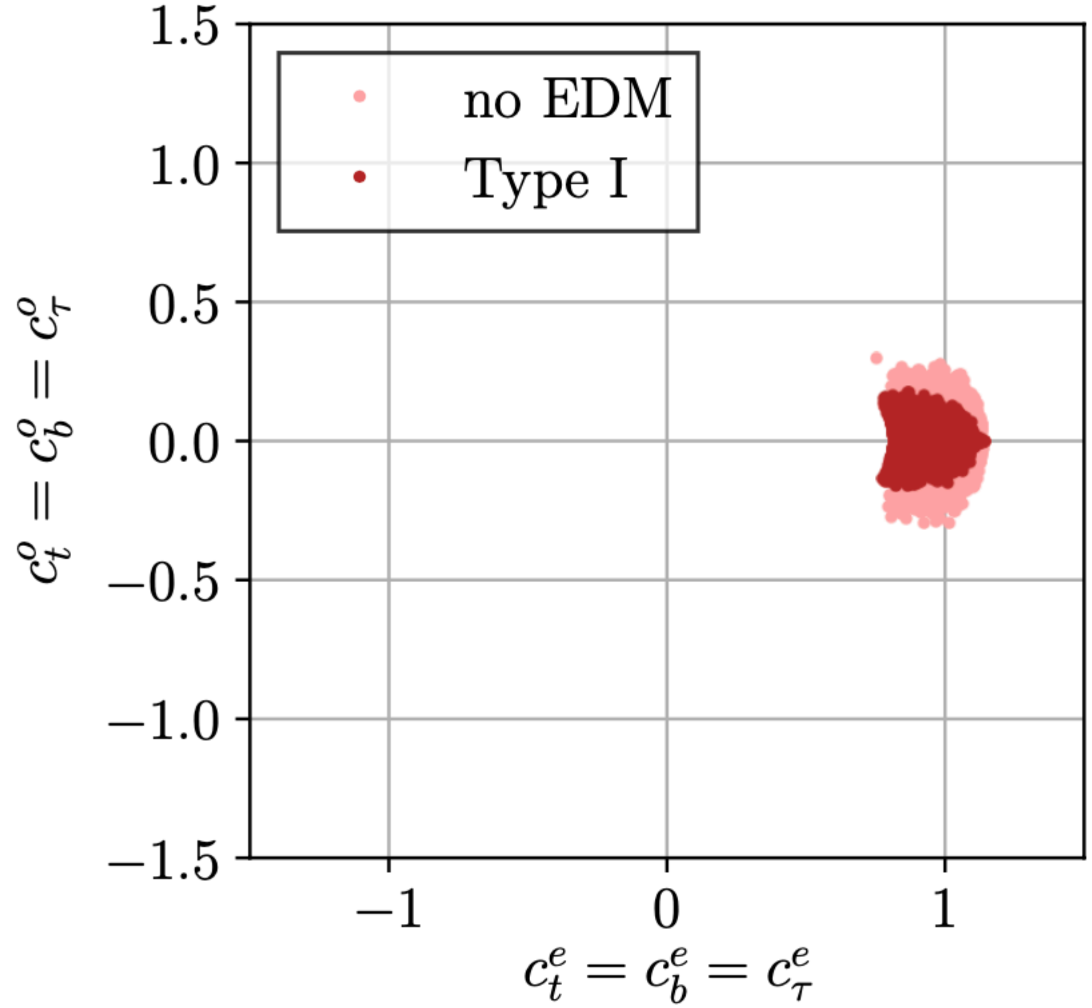
C2HDM: Type-Y

- 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



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

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

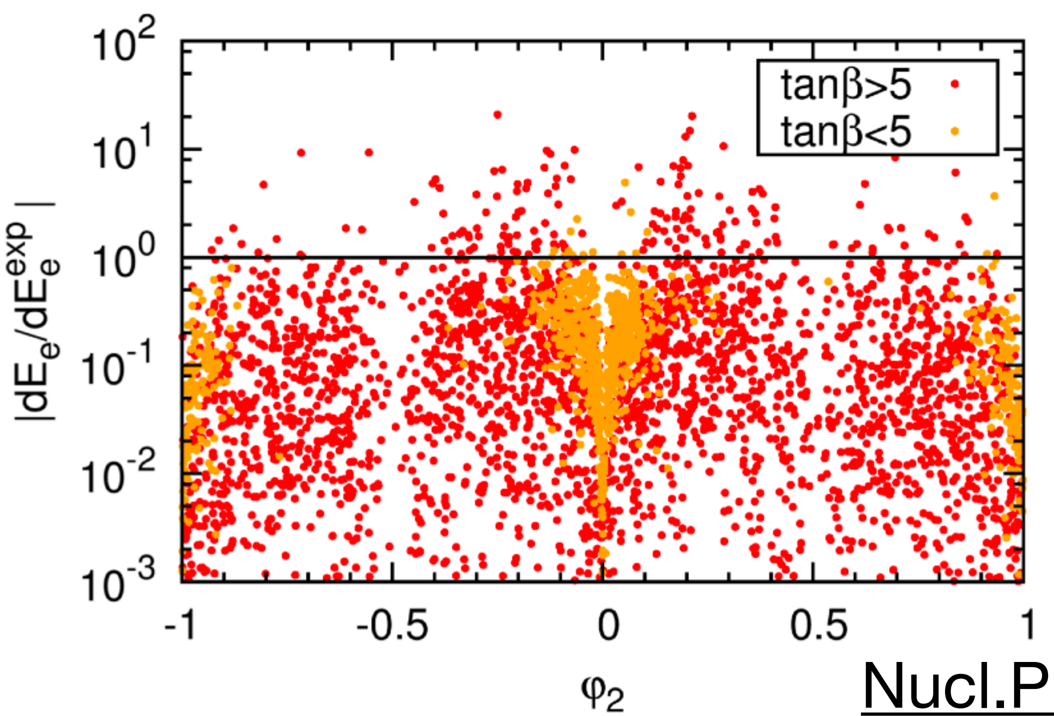
$$W_{NMSSM} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \kappa \hat{S}^3$$

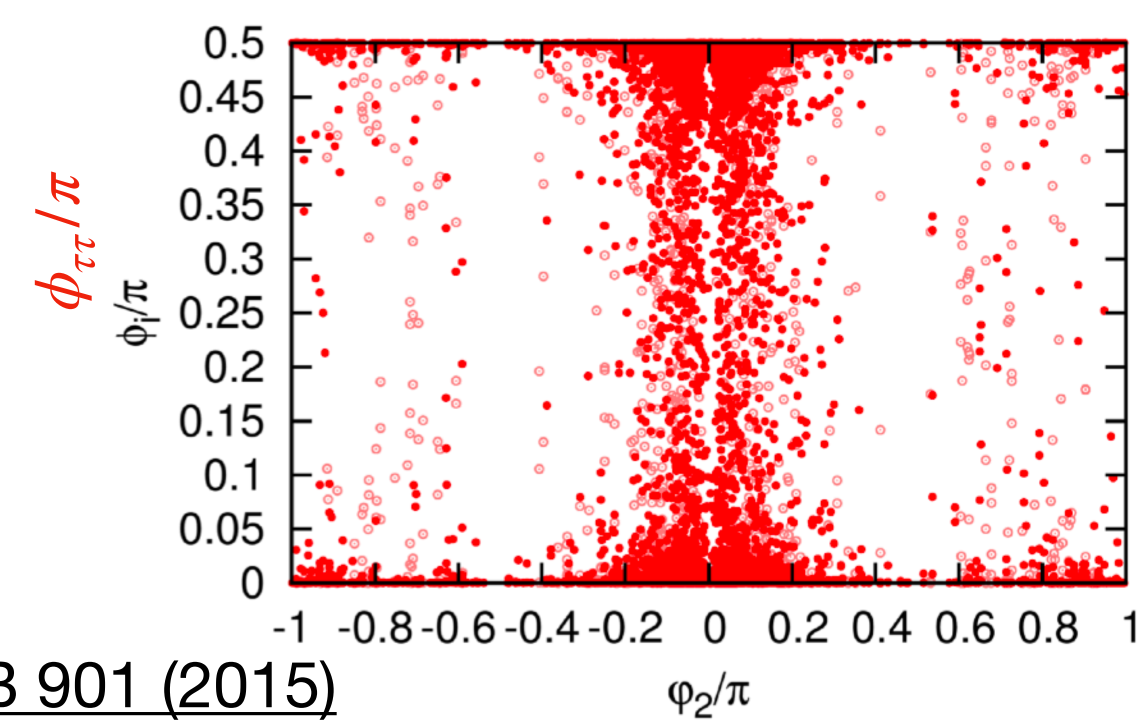
- In NSSM the μ parameter is generated as the vacuum expectation value of S

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

NMSSM

- BEH 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 BEH sector is extended with additional complex singlet
- 7 BEH-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° - using uses older ACME 2013 EDM constraints

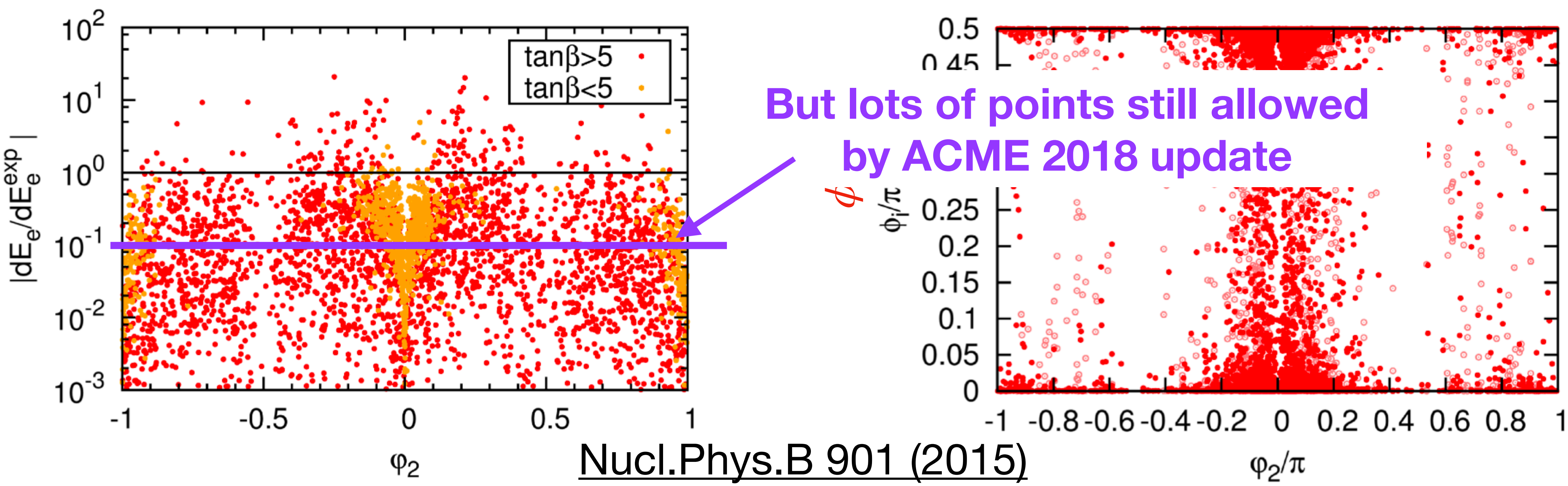




Nucl.Phys.B 901 (2015)

NMSSM

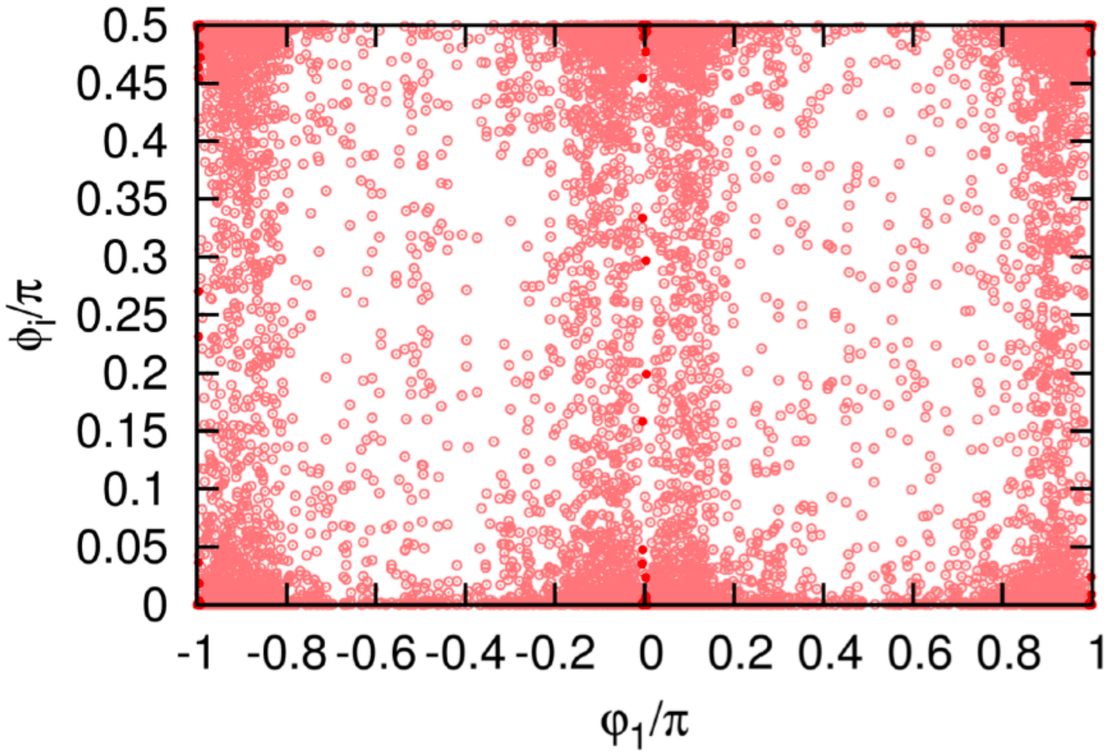
- BEH sector in MSSM is a type 2 2HDM
  - But additional constraints on parameters means there is no CP-violation at tree level (can get CP violation at higher orders but suppressed)
  - CP-violation in MSSM probably not observable from H125 measurements
- In NMSSM BEH sector is extended with additional complex singlet
- 7 BEH-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 $\phi_{\tau\tau} \sim 27^{o}$ - using uses older ACME 2013 EDM constraints

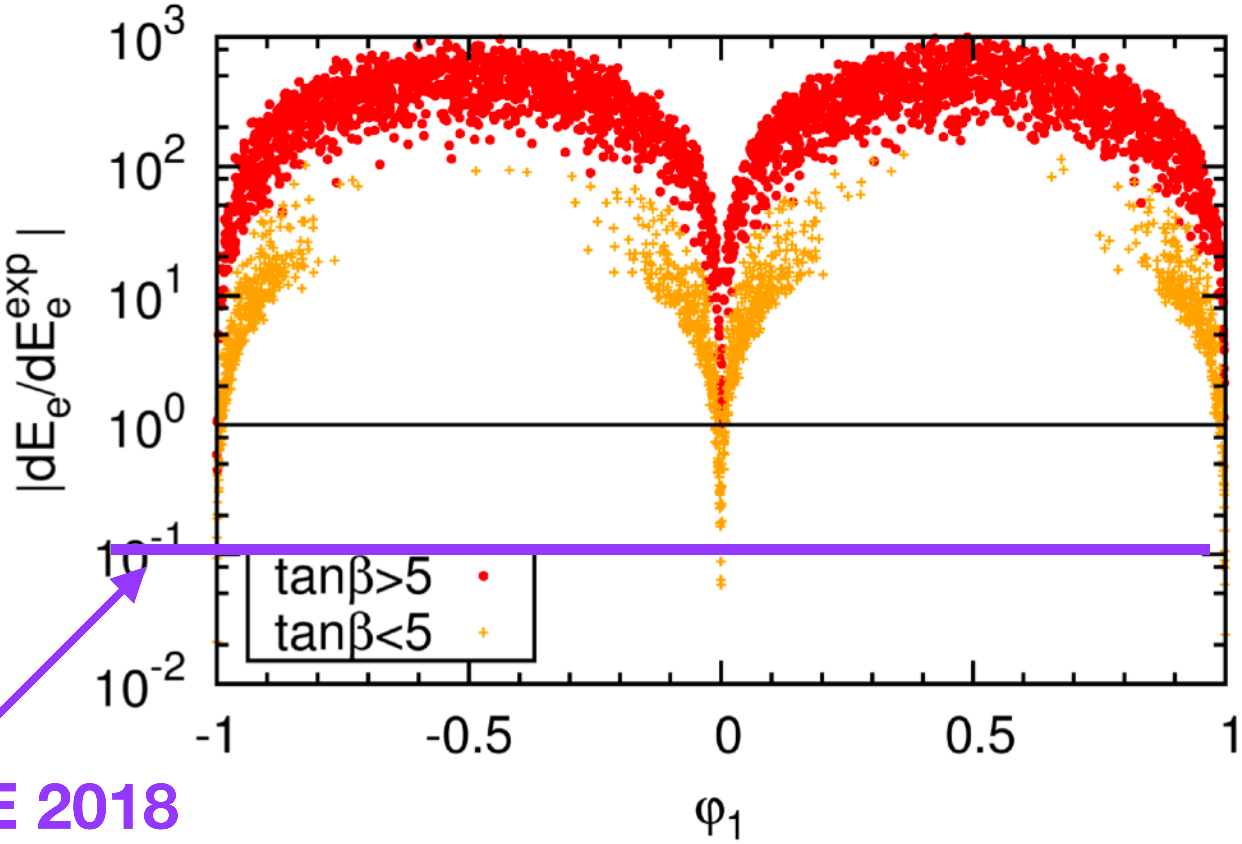


Nucl.Phys.B 901 (2015)

NMSSM: MSSM-type

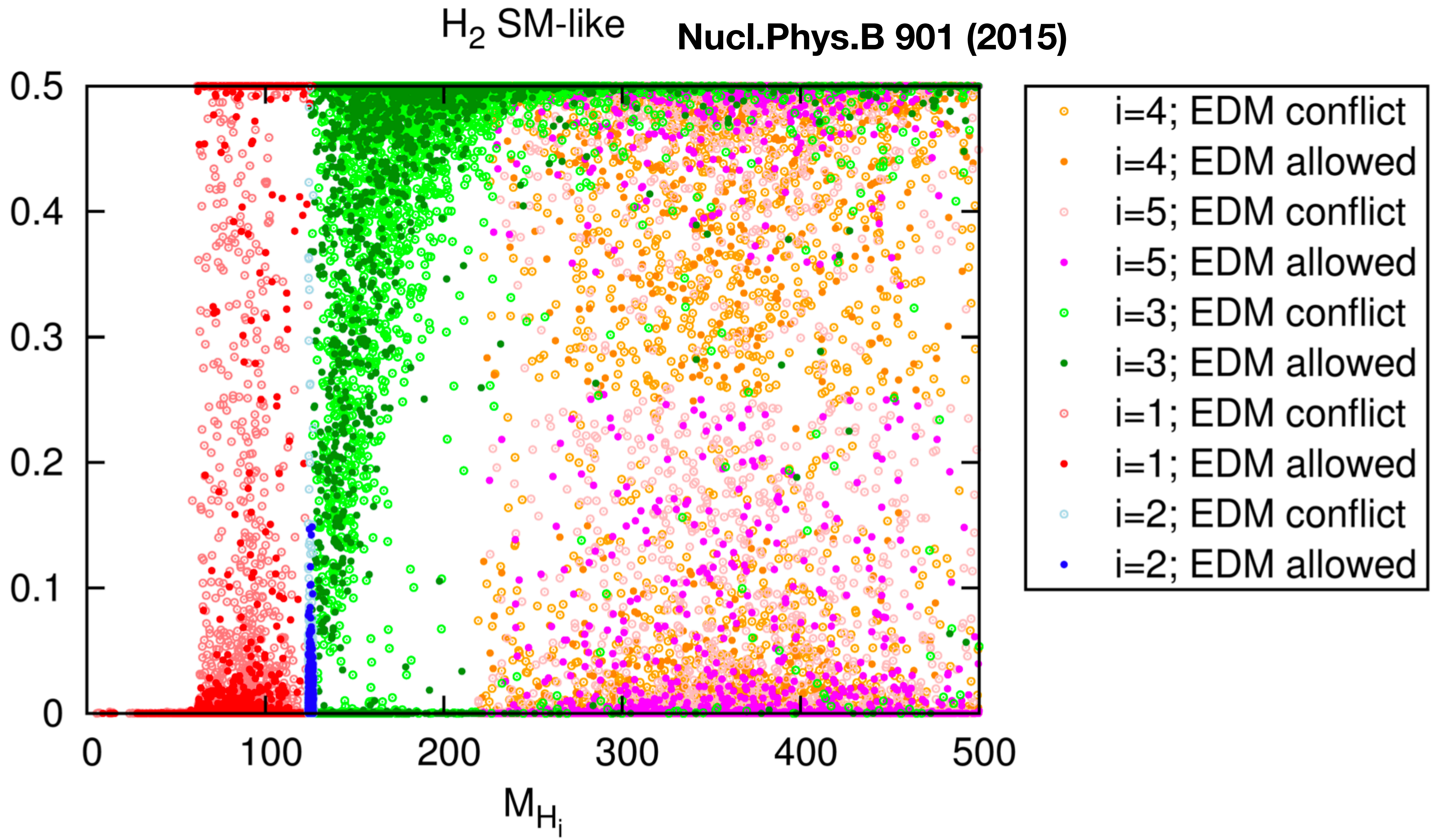
- MSSM-type CP-violation tightly constrained by EDMs
  - not many open points in left plot
  - Most points below EDM limit in right plot





Nucl.Phys.B 901 (2015)

- Allowed H_i masses



ϕ_{CP} formulas

- Formulas for IP-IP method:

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

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

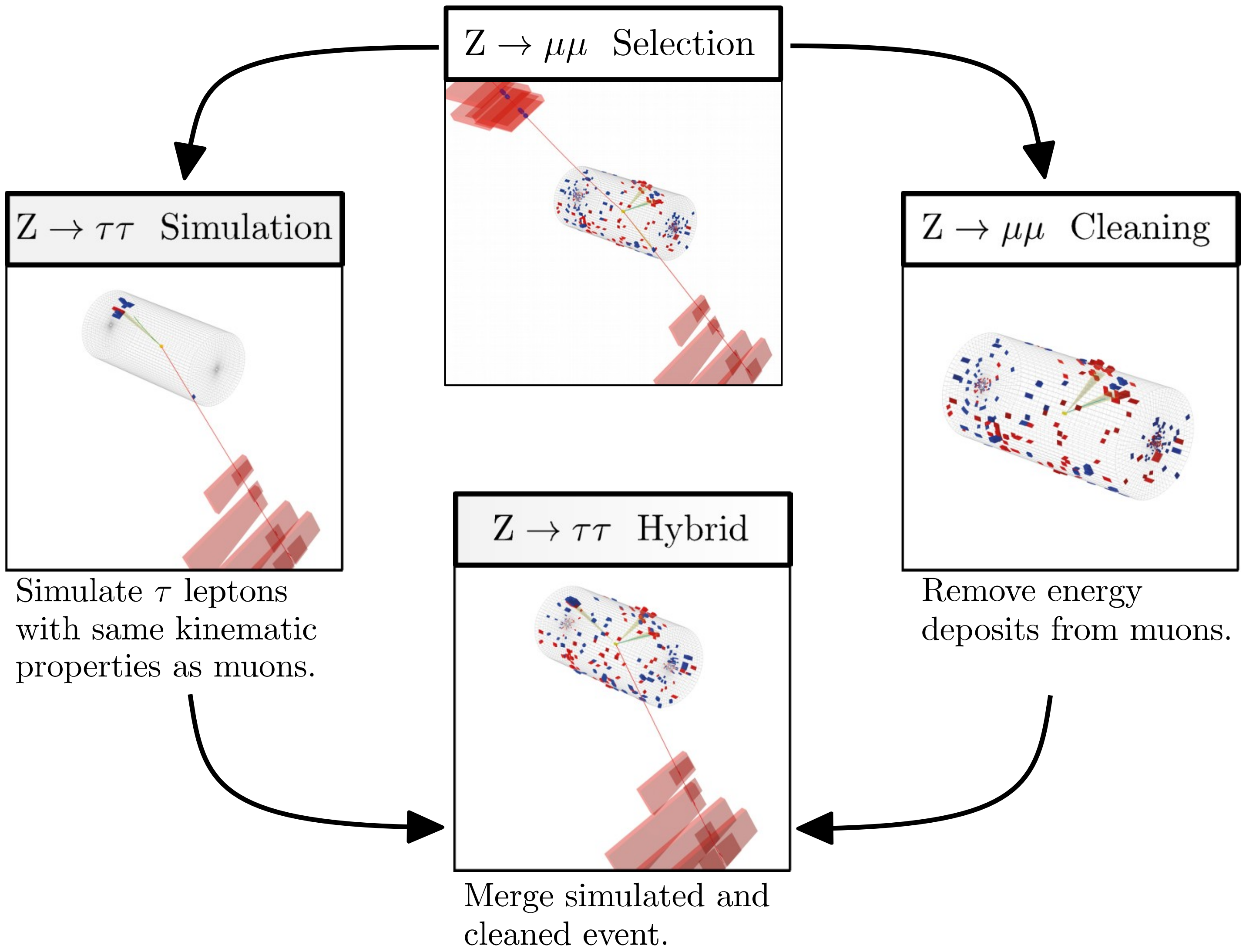
$$\phi_{CP} = \phi^*, \text{ if } O^* \geq 0$$

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

- 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

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



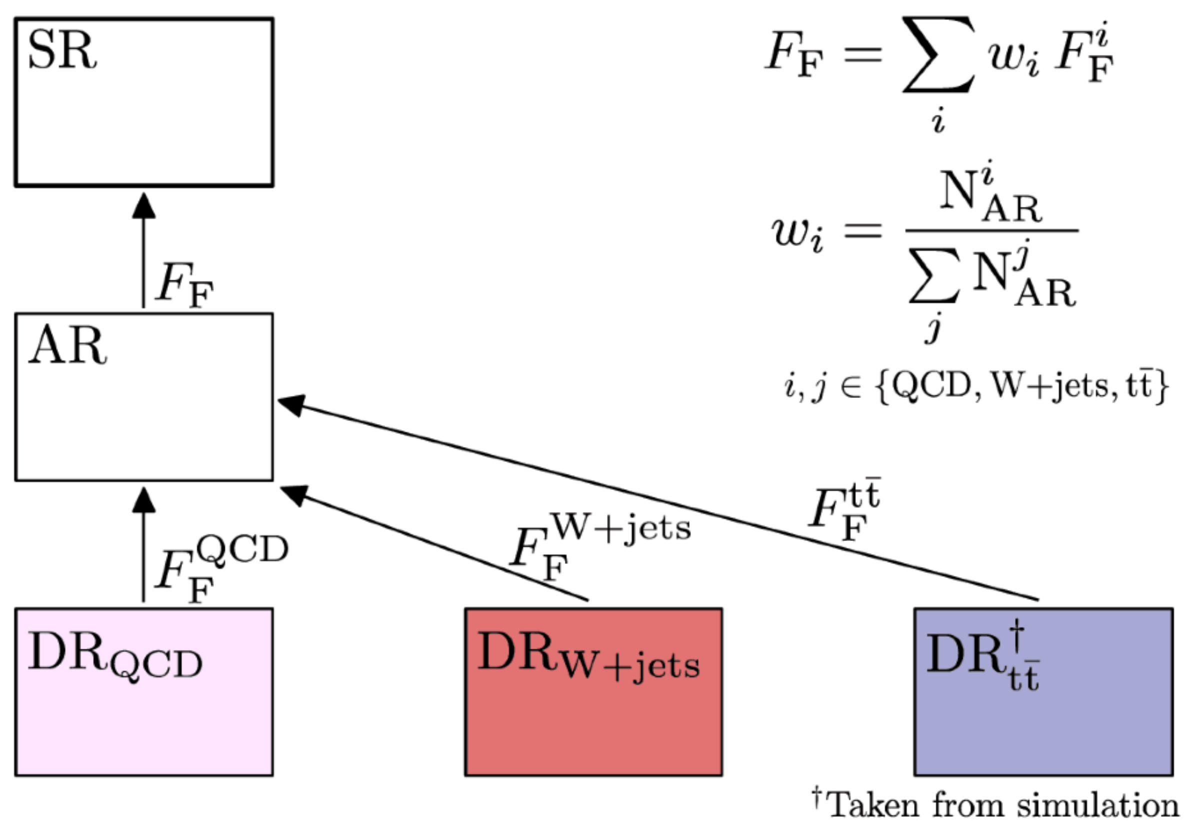
The fake factor method

- 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

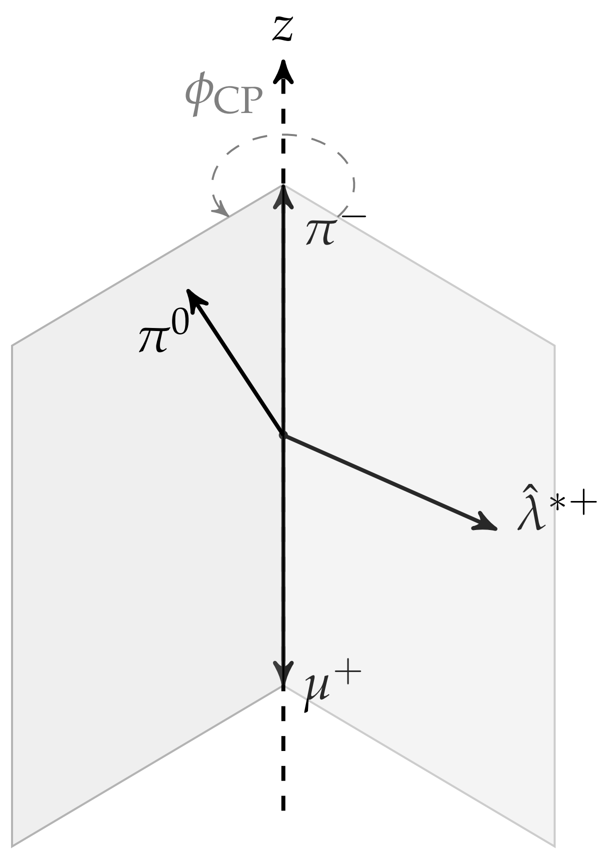
- Scale events by ratios:
  FF = (nominal ID) /(relaxed ID)
  which we call fake factors

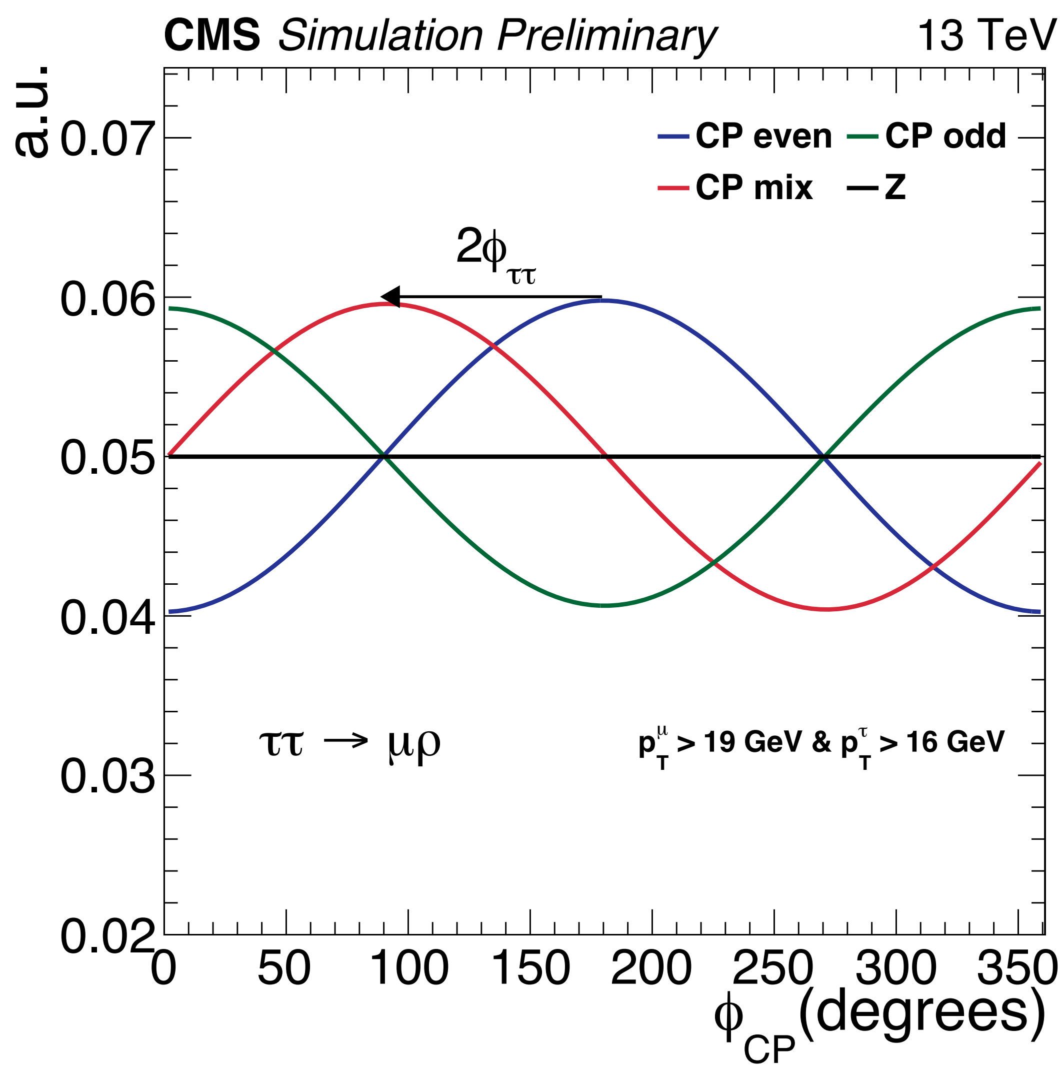
- Dominant processes are:
  QCD and W+jets



JHEP 09 (2018)007

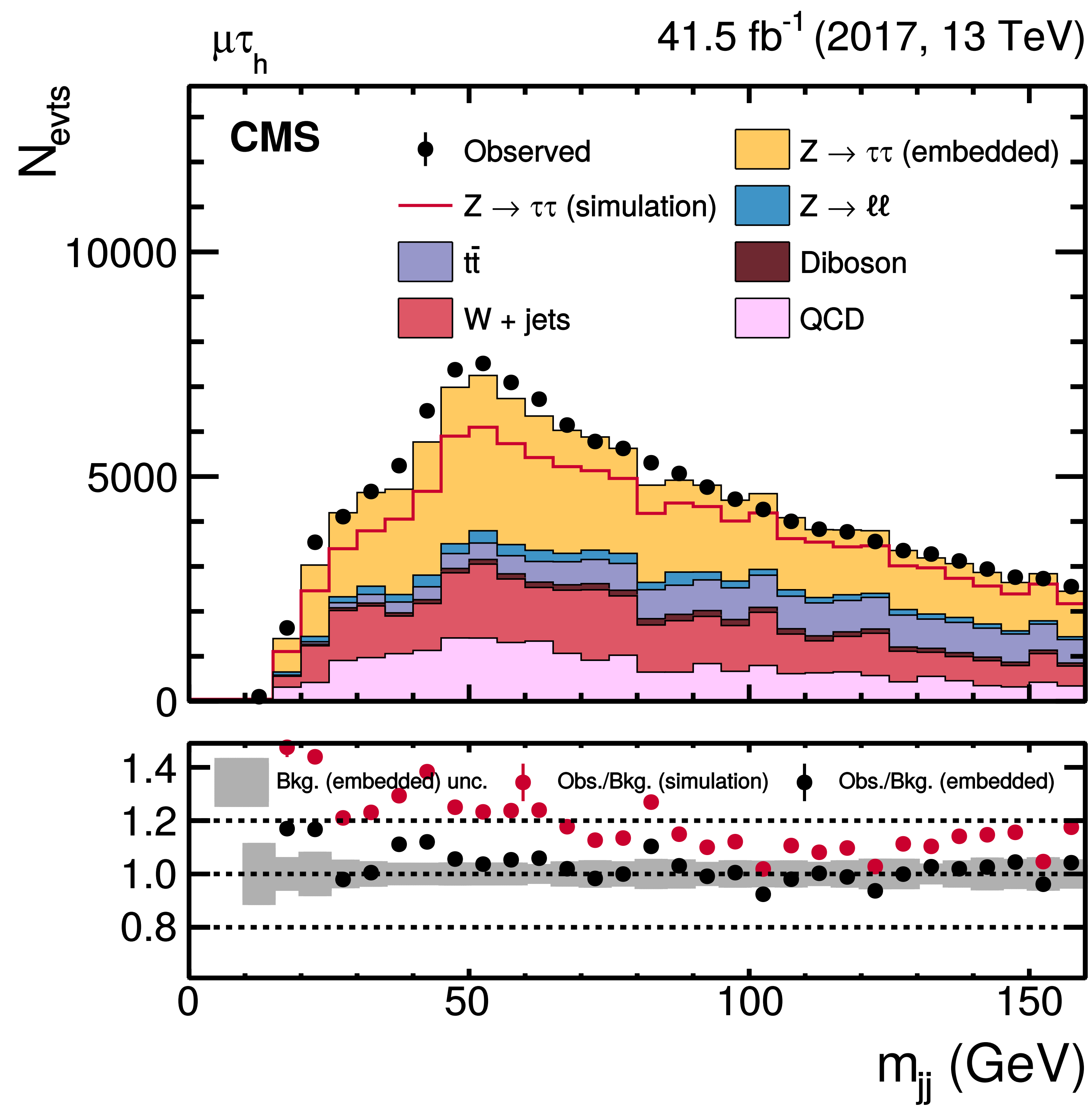
- Replacing $\tau\rightarrow\pi\nu$ with $\tau\rightarrow\mu\nu\nu$ we can define equivalent CP sensitive variables for $\tau_\mu\tau_h$ channel





Embedding method vs pure MC simulations

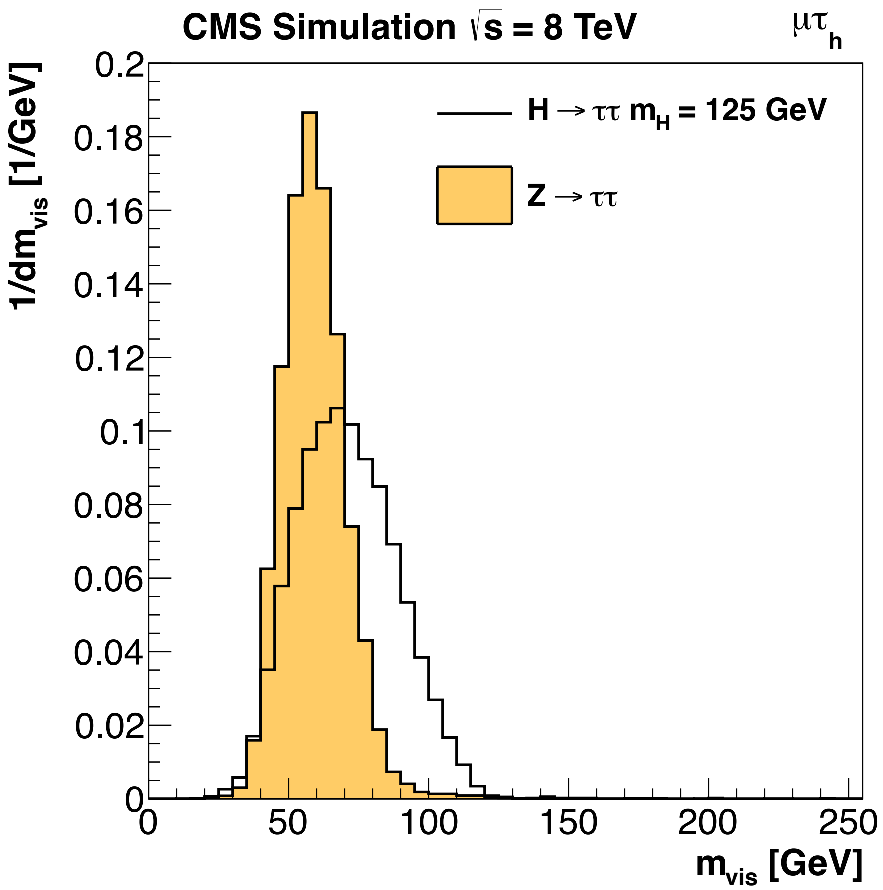
- Embedding method brings improvements in description of the data
- All objects except simulated tau leptons come from real data events so are described perfectly (e.g jets)
- For example the di-jet invariant mass distribution (right) is described much better for embedding (black points) vs pure MC simulations (red points)

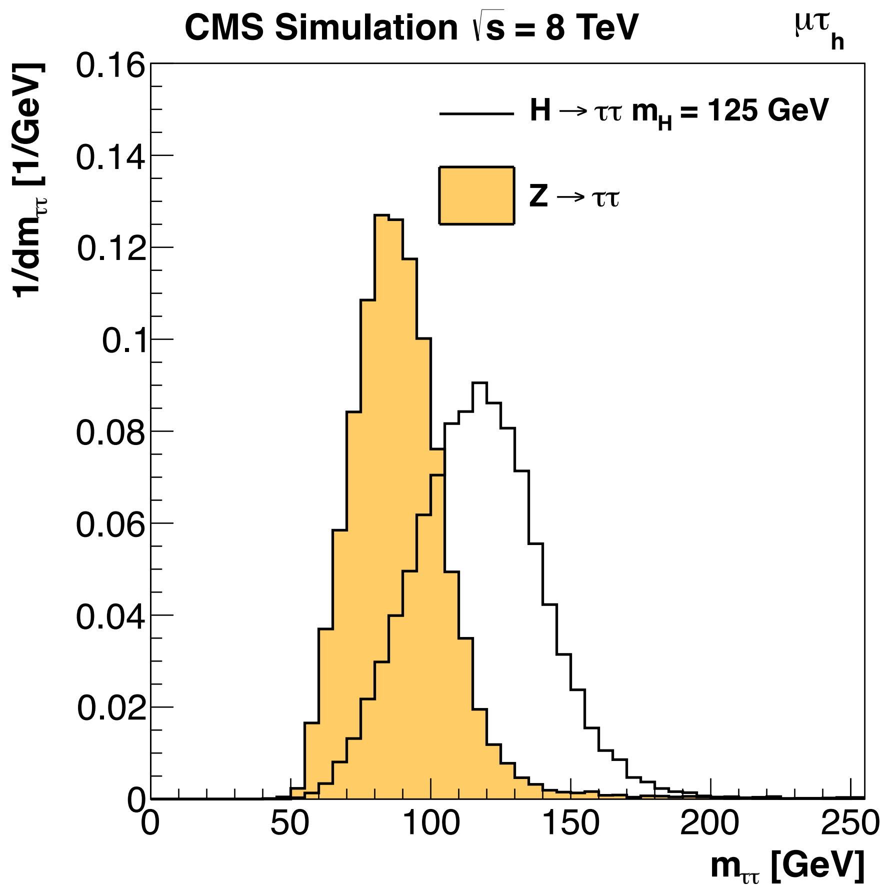


SVFit algorithm

- 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})

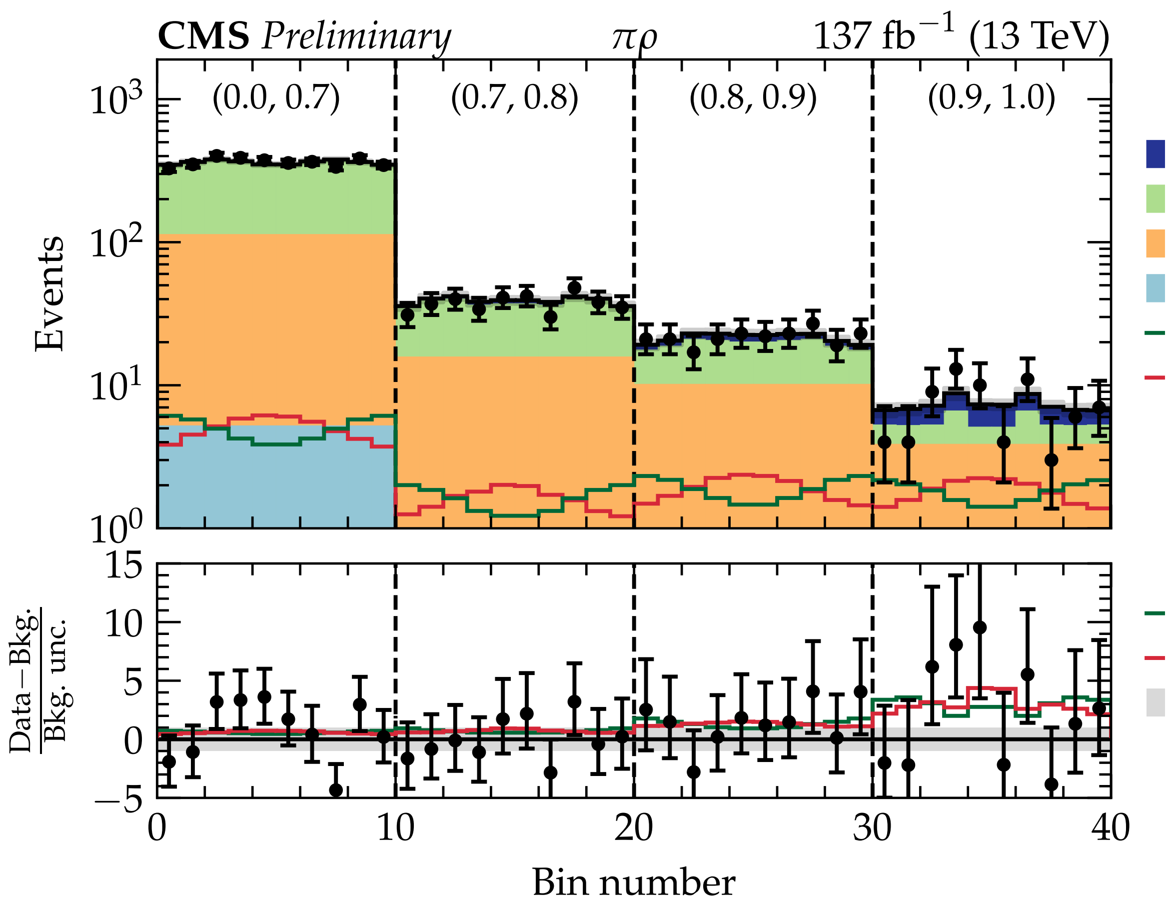




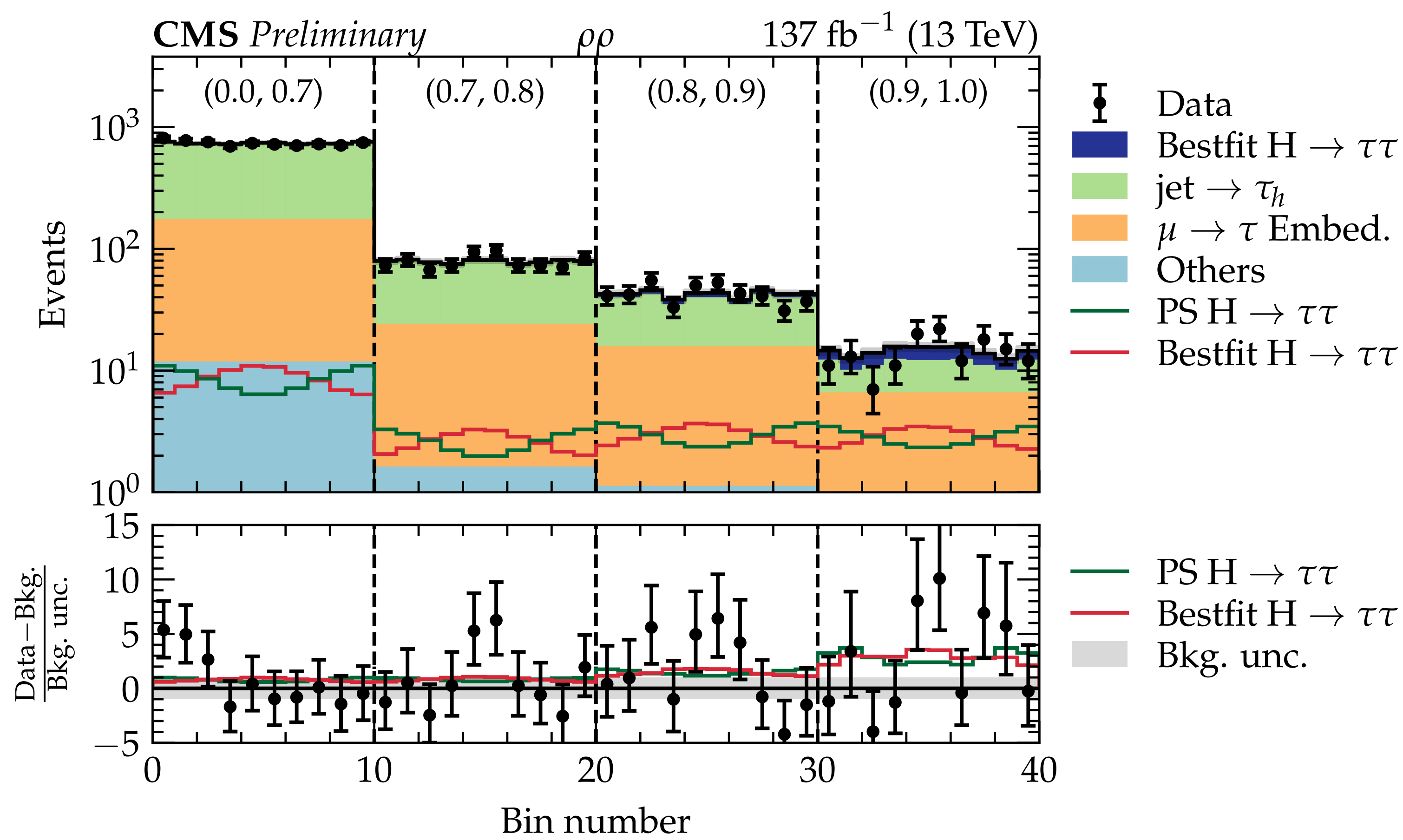
More examples of signal categories

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

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

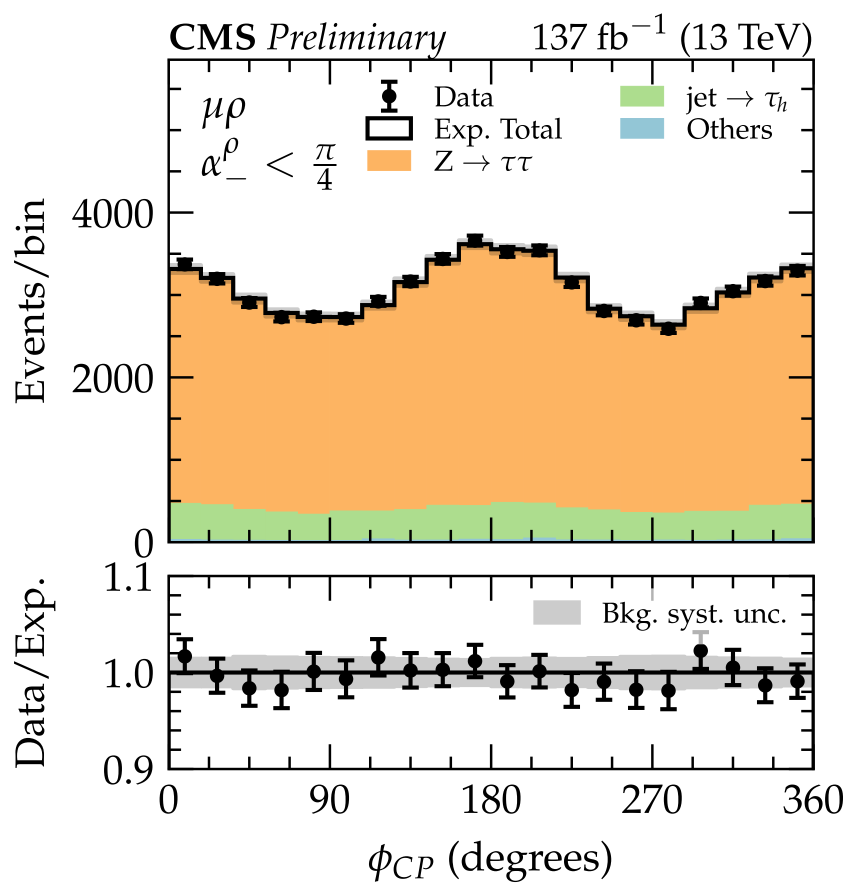


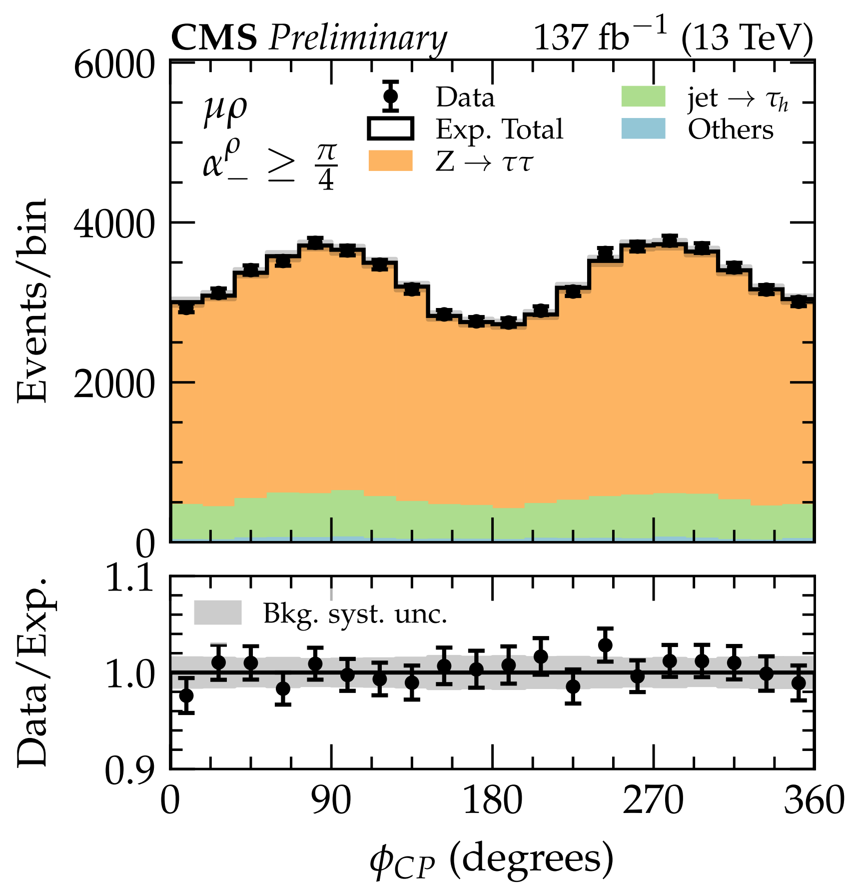
$\tau_h\tau_h \rightarrow \rho^-\nu\rho^-\nu$



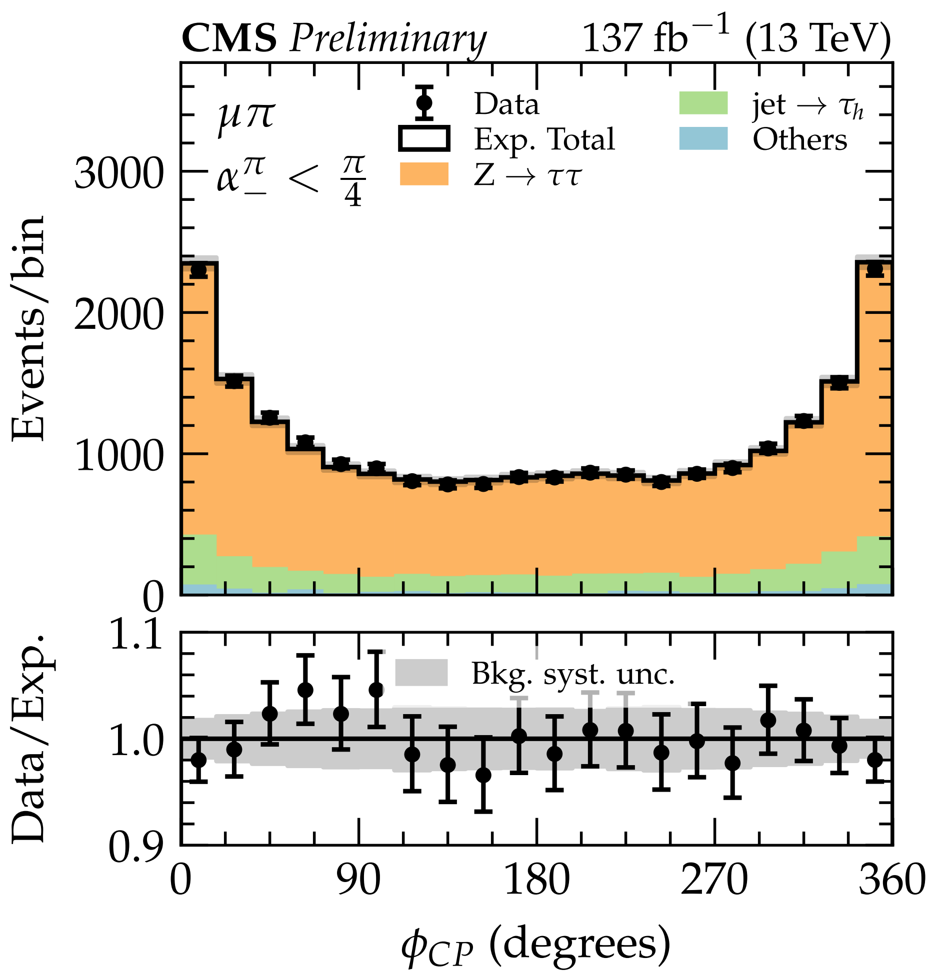
Checks using Z→$\tau\tau$

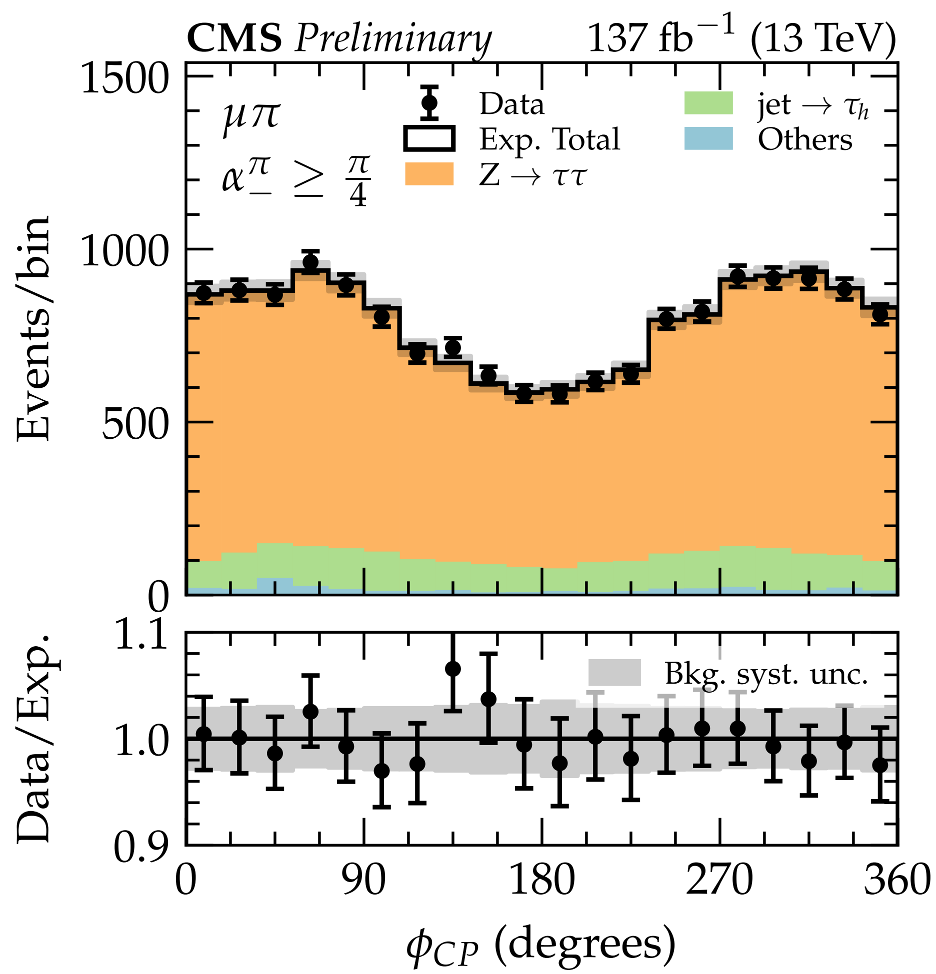
- All H→$\tau\tau$ analyses use q$\bar{q}$→Z→$\tau\tau$ events as "standard candle" to validate MC description of data
- Same for the CP-analysis except as Z→$\tau\tau$ has ~ flat distribution of $\phi_{\tau\tau}$
- But we can split into two sinusoidal contributions using α_- variable
  - Separates events 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.





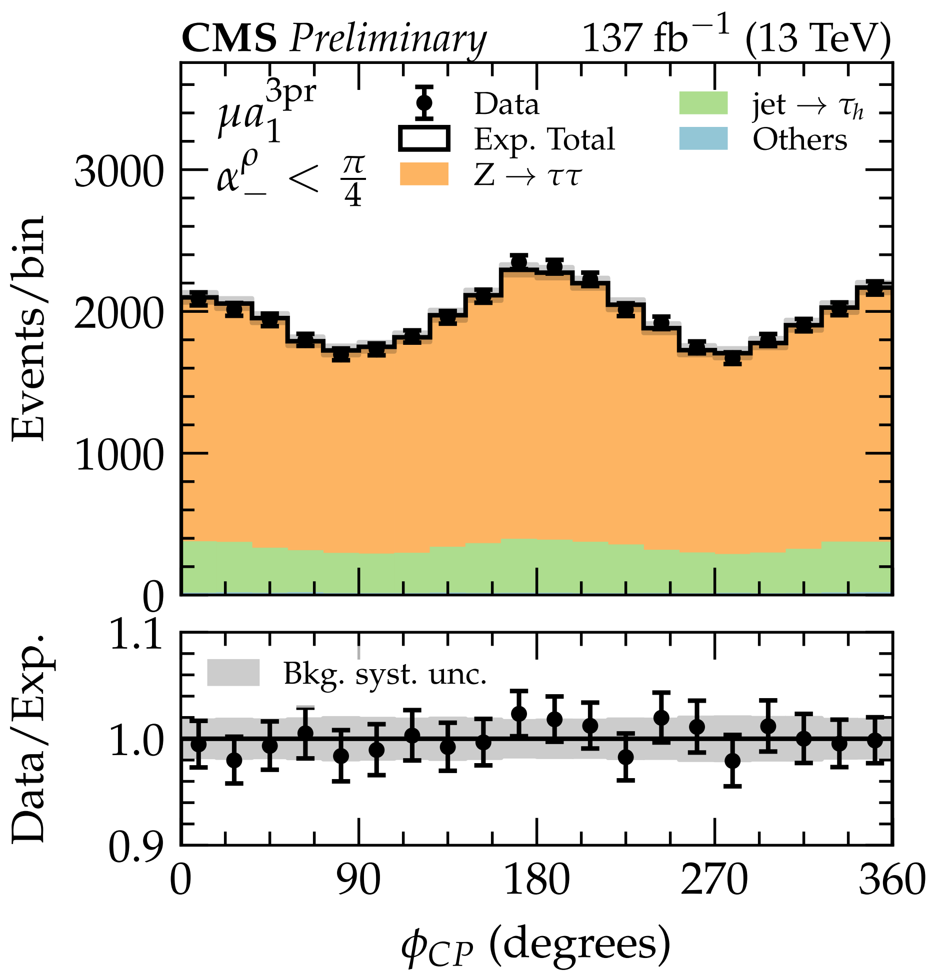
- Check of Z→ττ using α₋ splitting for τ_h→πν
- Definition in paper by Stefan Berge et al.

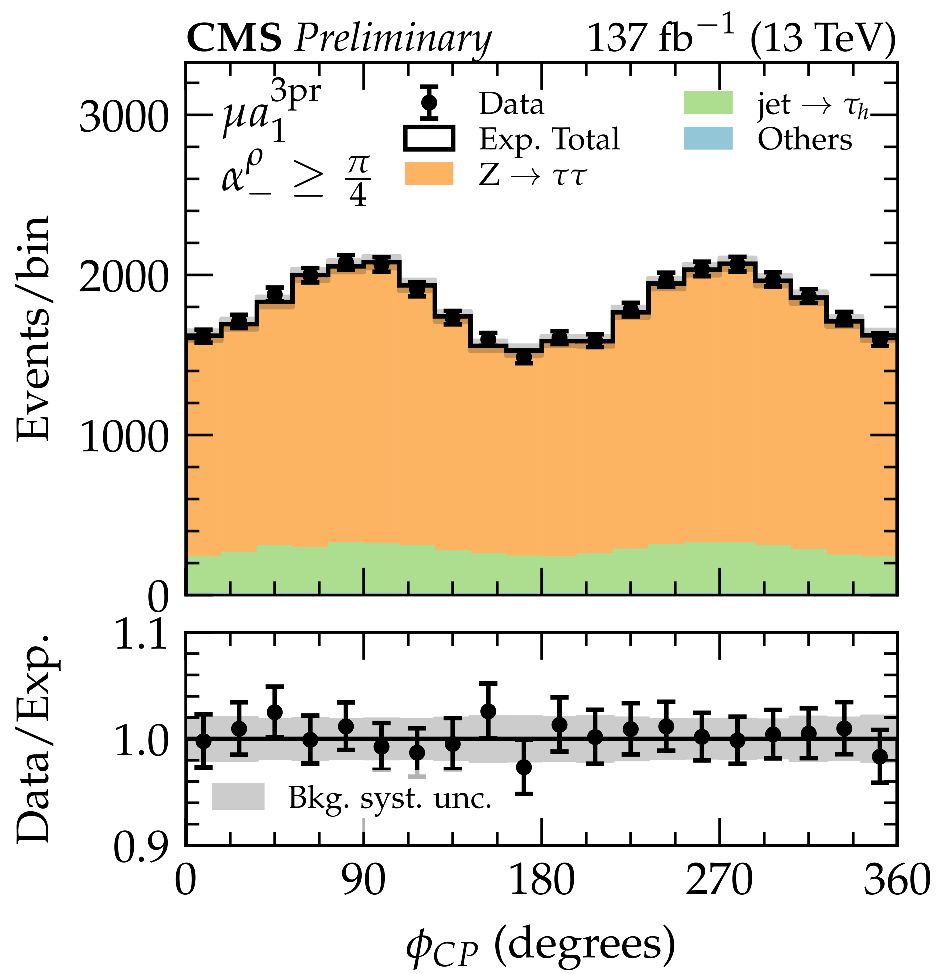




Checks using Z→$\tau\tau$: τ_h→a1ν →π⁻π⁻π⁺ν

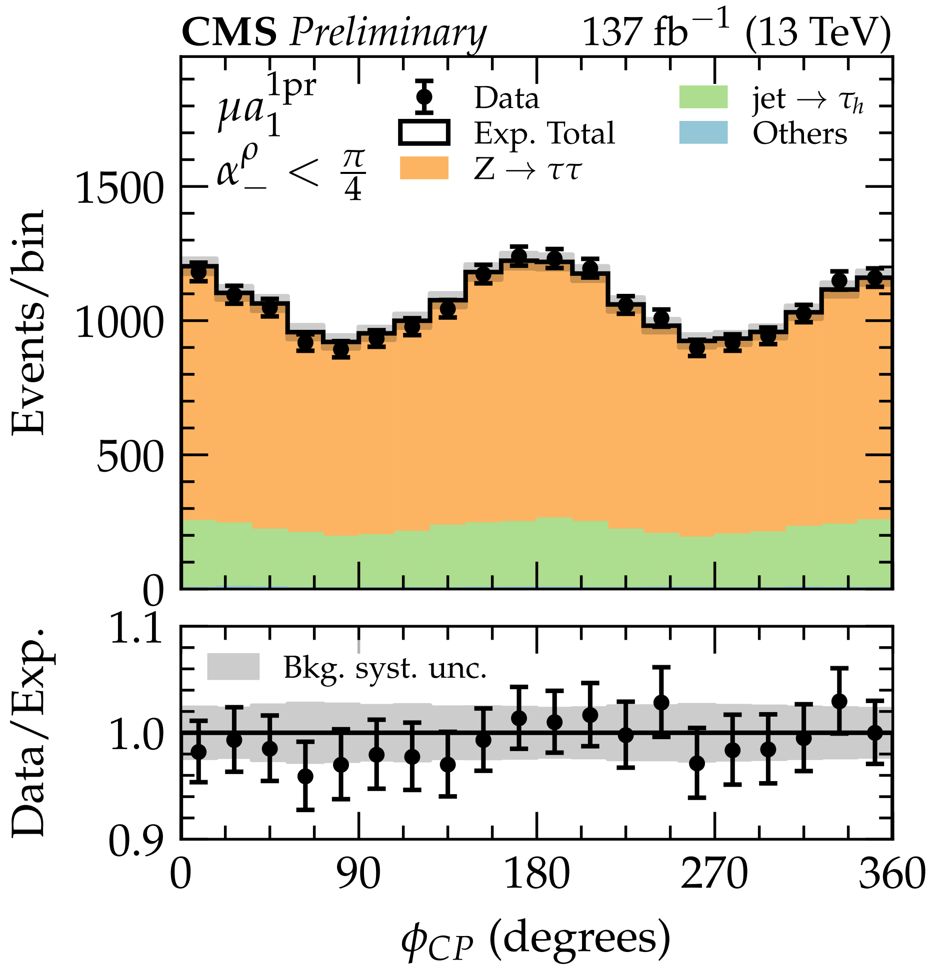
- Check of Z→ττ using α₋ splitting for $\tau_h \to a_1 \nu \to \pi^- \pi^- \pi^+ \nu$
- Definition in paper by Stefan Berge et al.

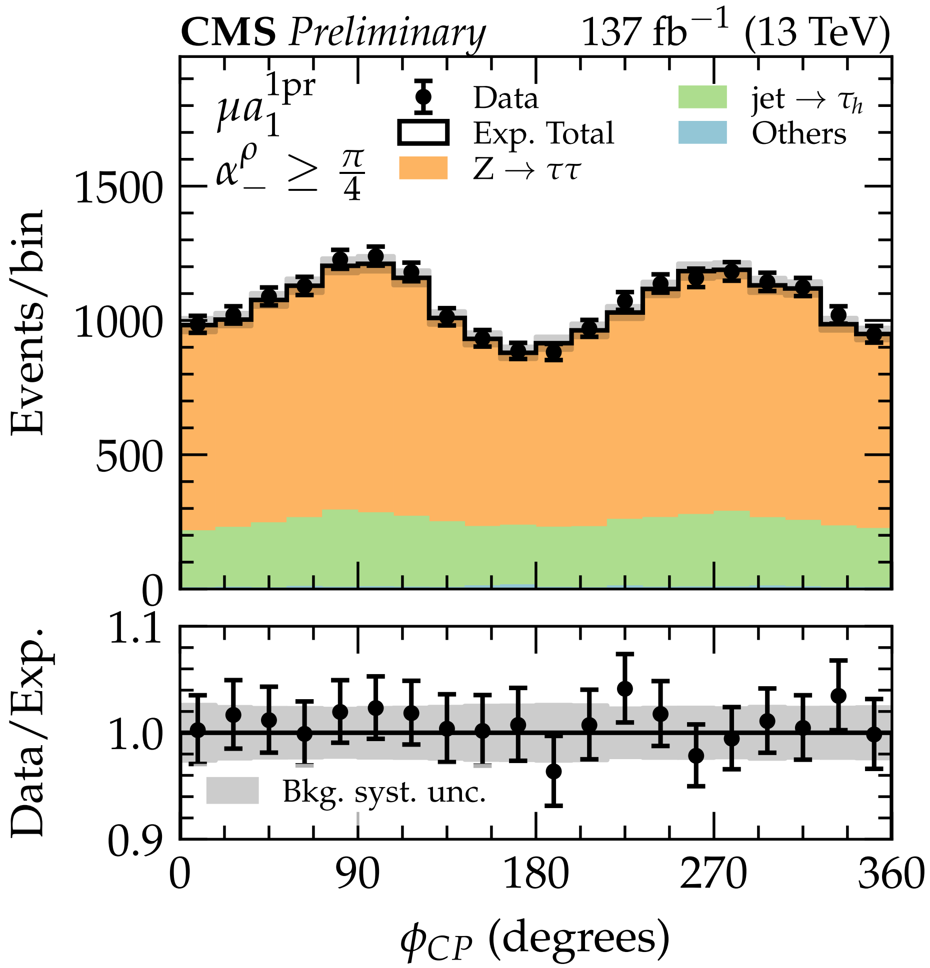




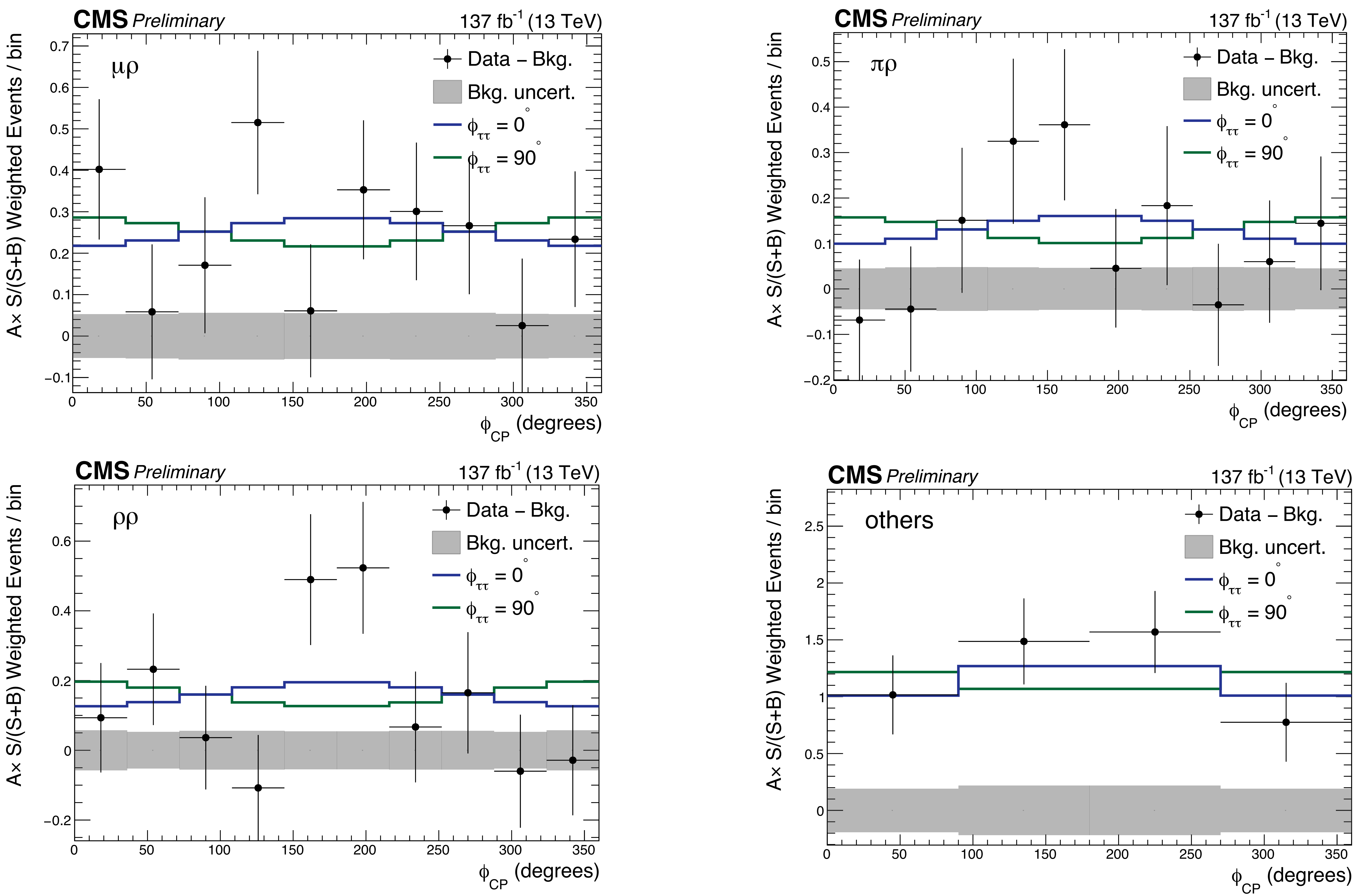
Checks using Z→$\tau\tau$: τ_h→a1ν →π⁻π⁻π⁺ν

- Check of Z→ττ using α₋ splitting for $\tau_h \rightarrow a_1 \nu \rightarrow \pi^- \pi^0 \pi^0 \nu$
- Definition in paper by Stefan Berge et al.





ϕ_{CP} distribution by channel



Polarimetric vectors

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

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

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

$m_\tau : \tau \ mass$

$q : \pi^\pm - \pi^0$

$N : \nu = \tau^\pm - \pi^\pm - \pi^0$

$P : \tau^\pm$

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)

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.