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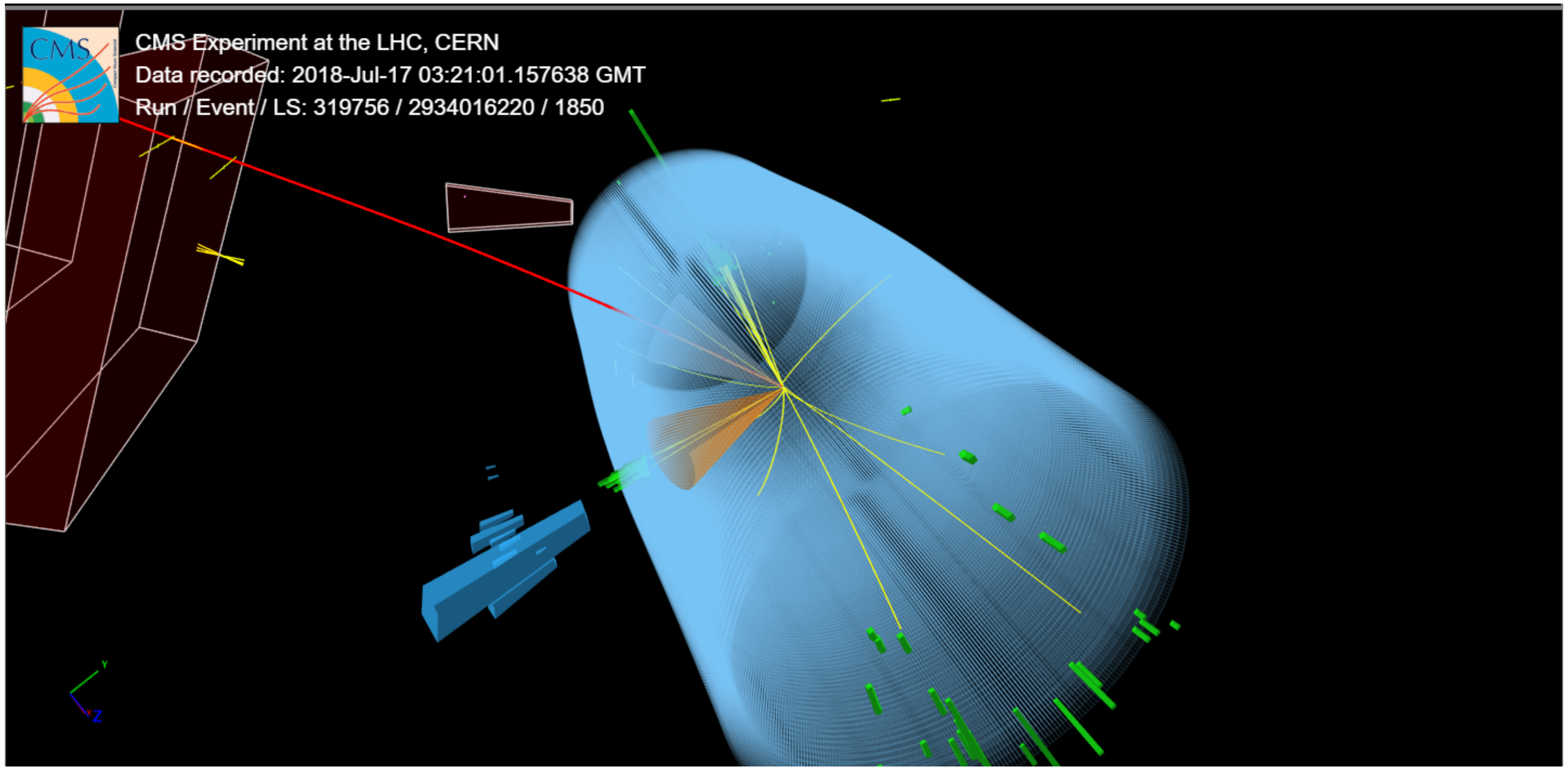
Measuring Higgs couplings and properties in the H→$\tau\tau$ decay channel



University of Birmingham Particle Physics group seminar 09/06/21

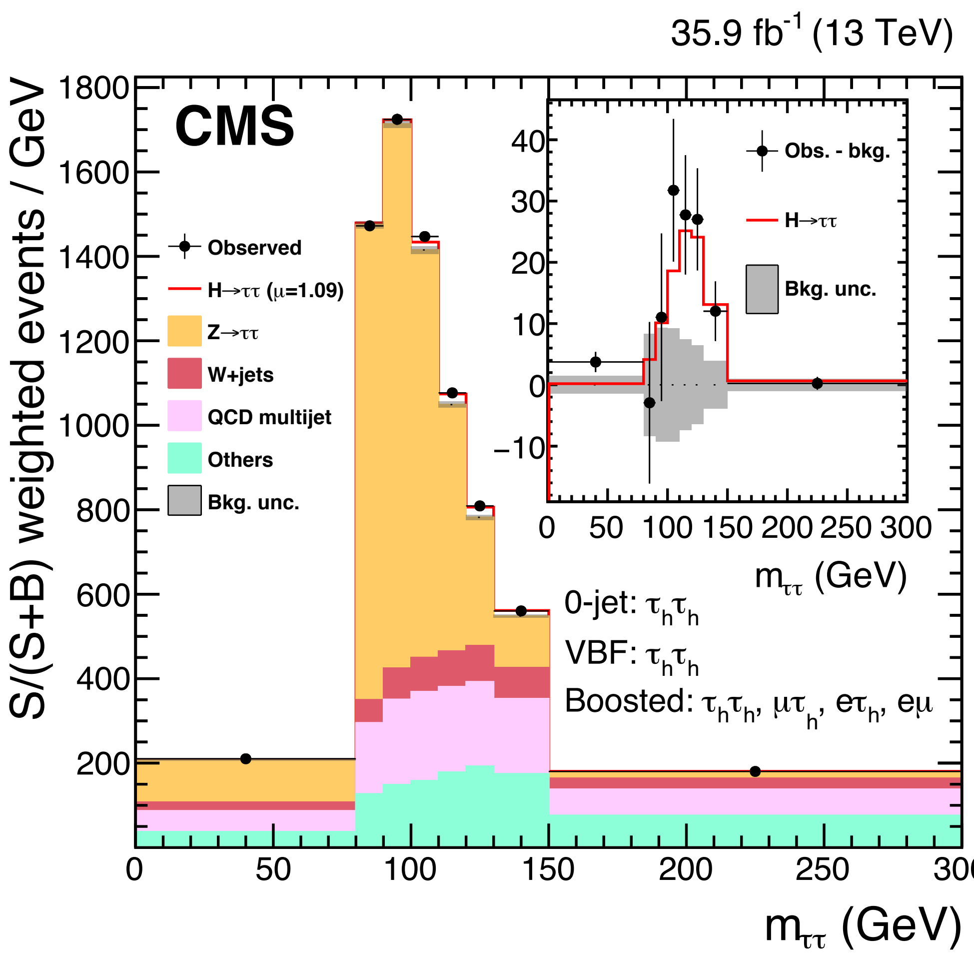
Daniel Winterbottom
d.winterbottom15@imperial.ac.uk

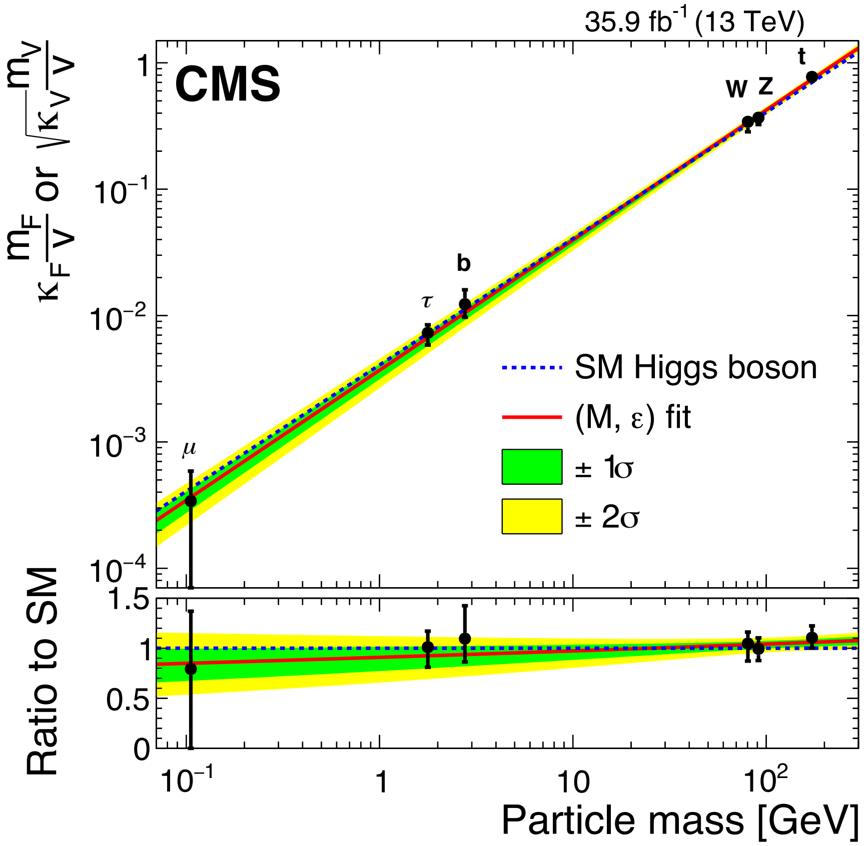
Overview

- A brief history of H→$\tau\tau$ + motivations
- Common components to H→$\tau\tau$ analyses
- Measurements of cross sections and couplings
- Measurement of the Higgs CP properties
- Conclusions

A brief history of H→$\tau\tau$ in CMS

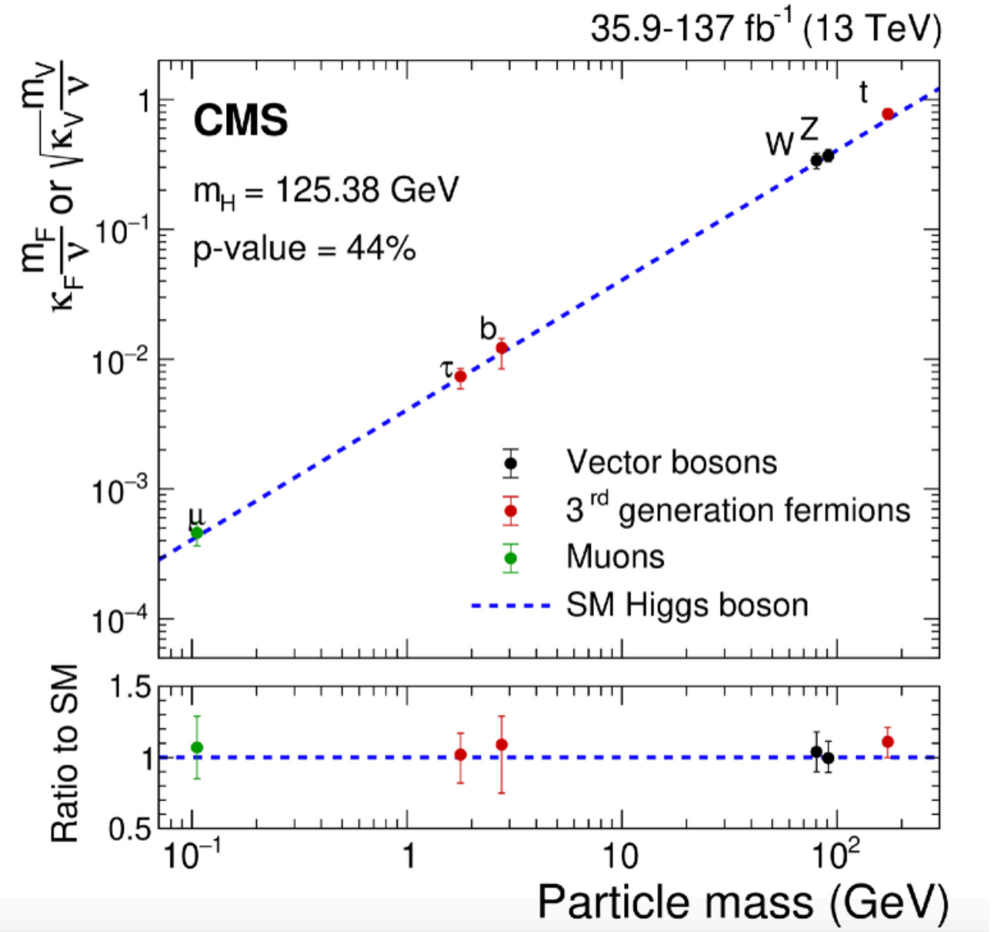
- 2012: Discovery of the Higgs Boson
- 2016: Observation of the H→$\tau\tau$ process
- 2018: Combined CMS coupling measurement extracting y_τ coupling





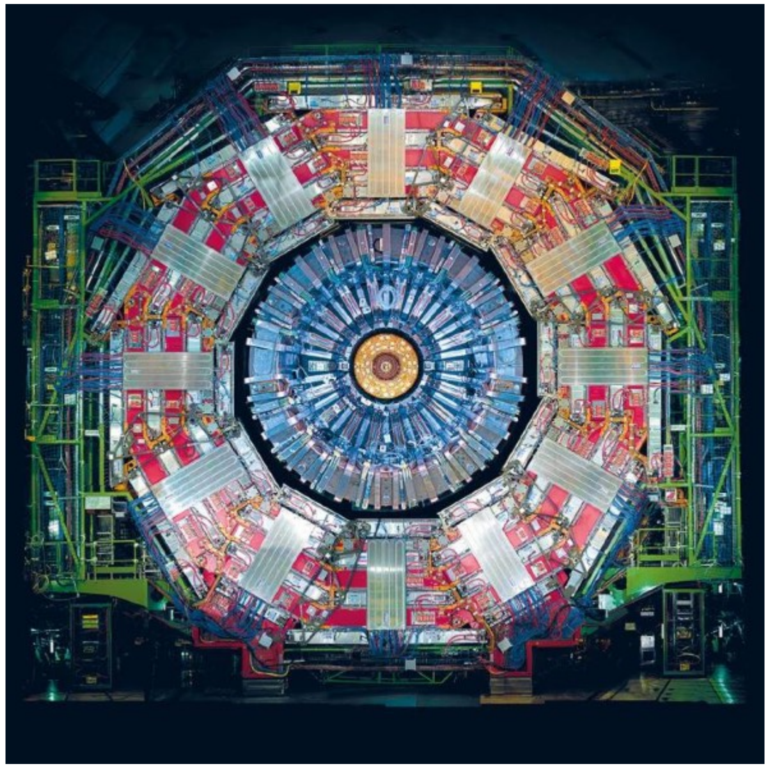
Motivations for H→$\tau\tau$ measurements

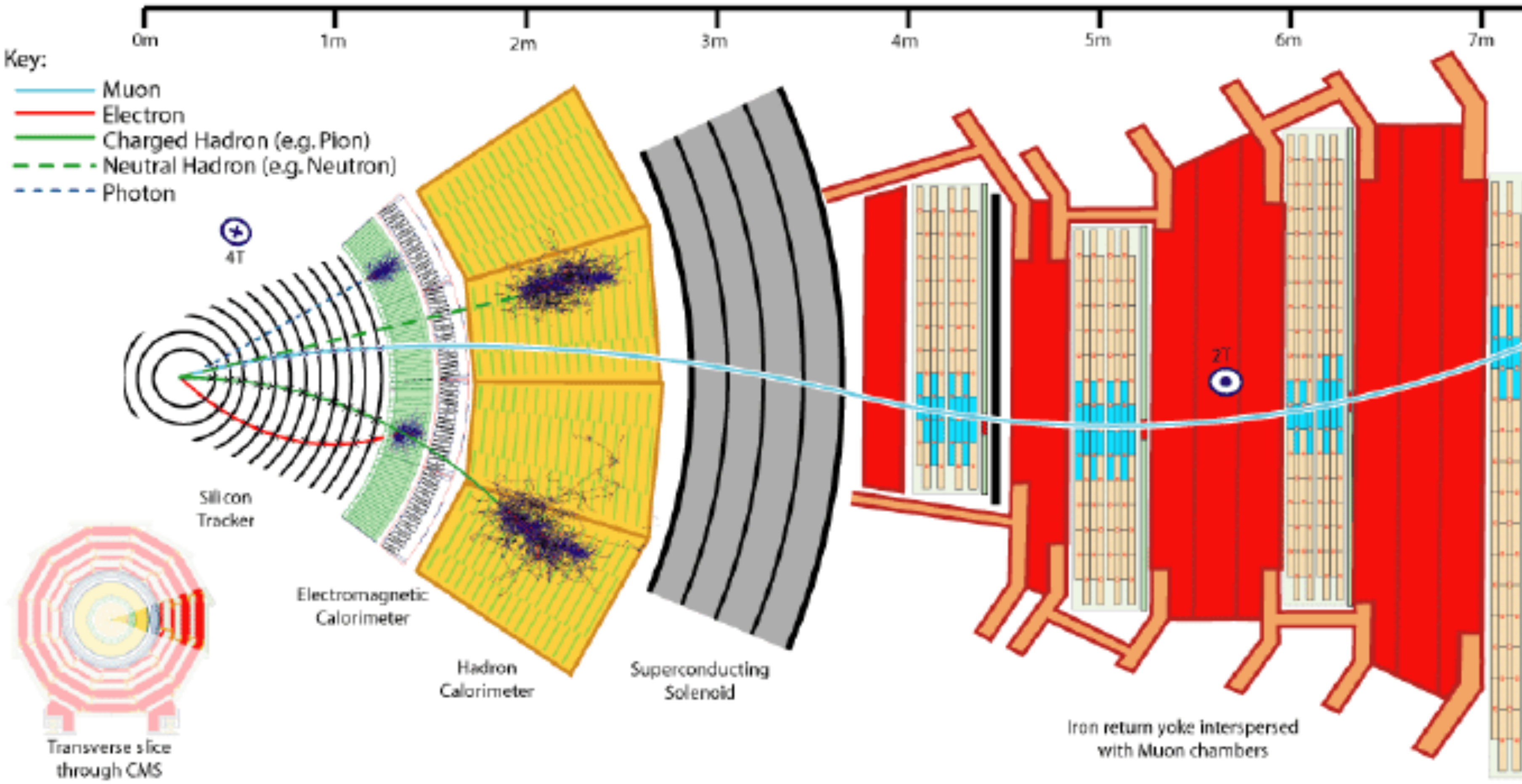
- Since observation real shift in focus from "search-mode" to "precision-mode"
- We want to measure cross-sections, couplings, and properties precisely
- We have also started to perform differential measurements
  - Highly motivated as we can expect BSM effects to show up predominantly in certain regions of the phase space - e.g boosted events
- For property measurements H→$\tau\tau$ decays can be used to determine Higgs CP state



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)





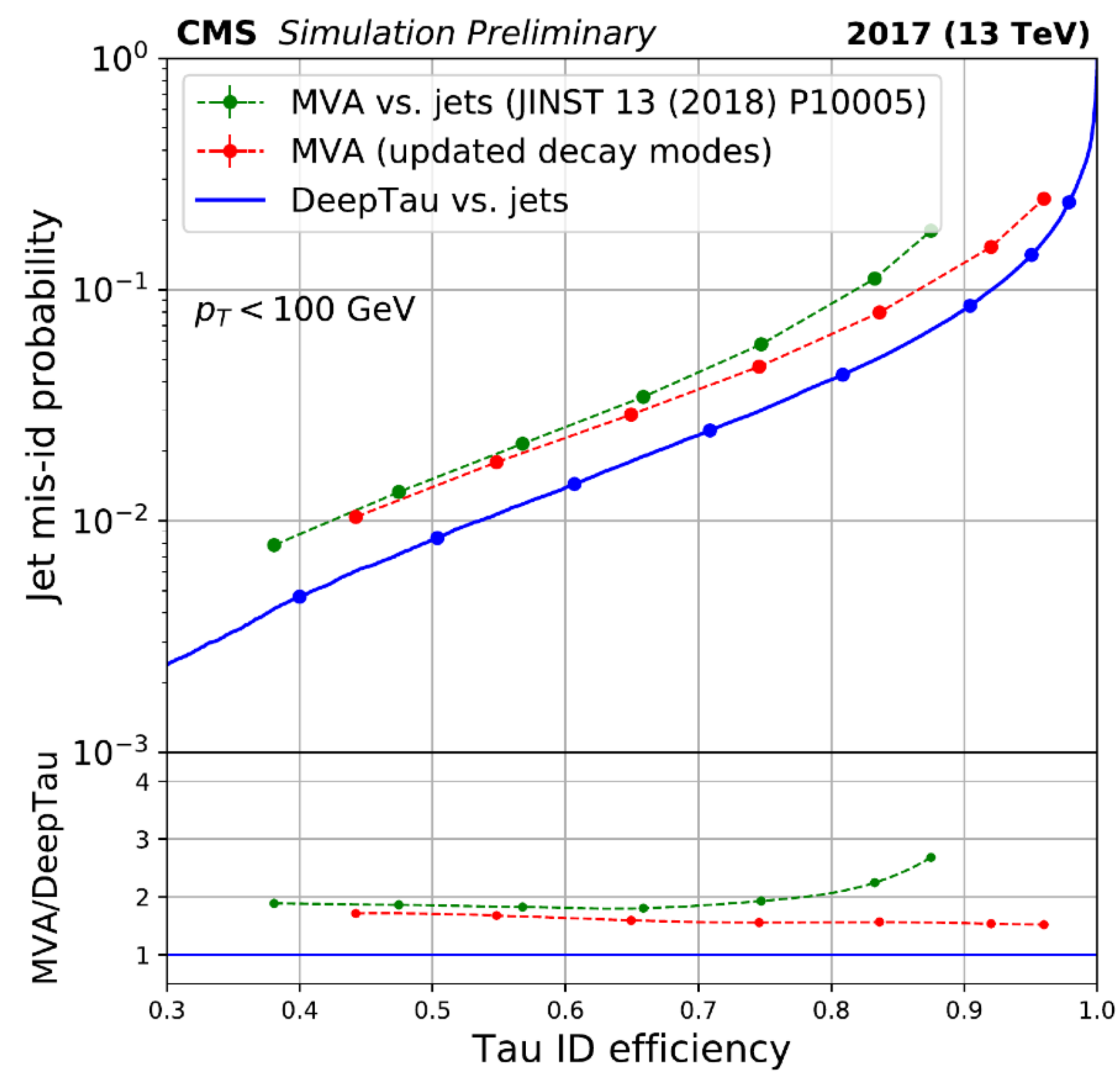
Common components to $H \rightarrow \tau\tau$ analyses

Challenges with the H→$\tau\tau$ channel

- Tau leptons are unstable, they decay very close to the primary interaction point in the beam pipe to leptons or hadrons + neutrinos
  - $\tau \to \mu\nu\nu$ / $e\nu\nu$ ~ 35%
  - $\tau \to N \times h^- + M \times \pi^0 + \nu$ [N = 1, 3, .. ; M ≥0] ~ 65%
  - Neutrinos are undetectable but can partially reconstruct them due to transverse momentum imbalance (MET)
  - In order to maximise selection efficiencies we need to consider as many tau decay modes as possible - both leptonic and hadronic decays!
  - Hadronic decays (τ_h) are not as distinct as electrons/muons, we need to avoid being overwhelmed with j→τ_h fakes from multijet QCD events
- Significant backgrounds due to several processes: e.g Drell-Yan, QCD
  - Shapes are complicated so require template fitting
  - Associated systematic uncertainties with MC simulations can be large - need to reduce these
  - Statistical populations of templates can be problematic
- Due to MET we cannot reconstruct H system fully → need to improve mass resolution

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



Background modelling

- Two largest contributions to background are Z→$\tau\tau$ and jets faking hadronic taus (j→τ_h)

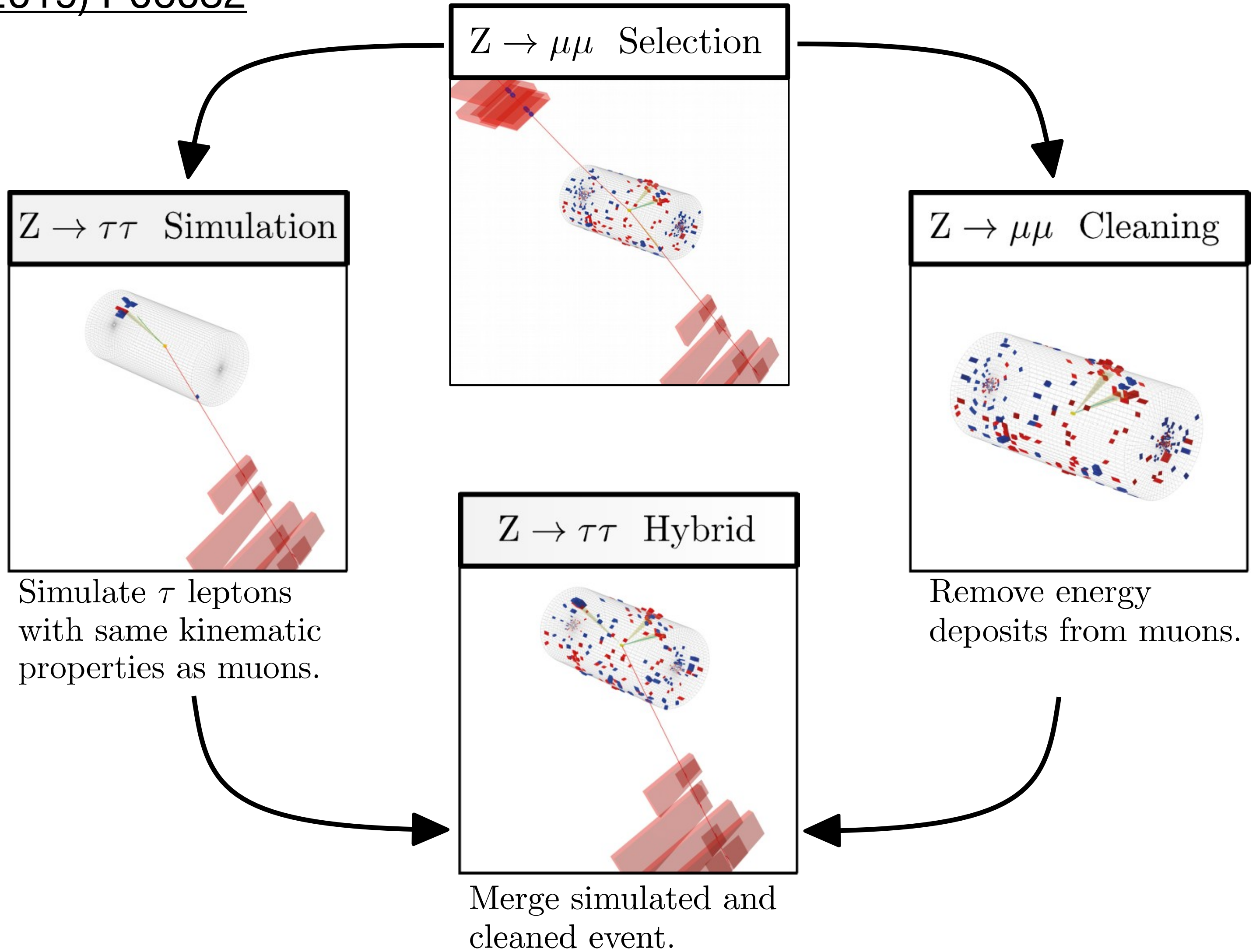
- We use data-driven method to estimate these processes

- This has advantaged such as reduced systematic uncertainties
  - 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

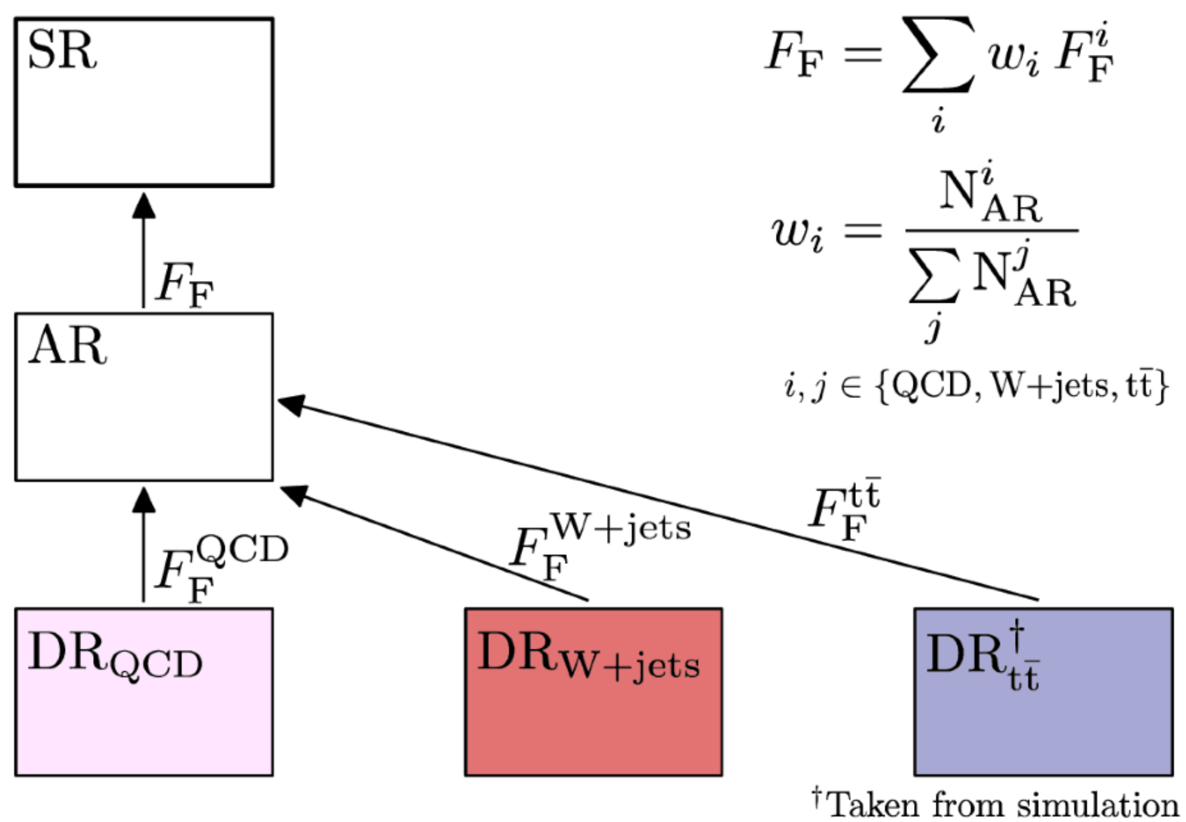
The embedding method

- Used to estimate backgrounds with real di-tau pairs - mainly Z→$\tau\tau$
- 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



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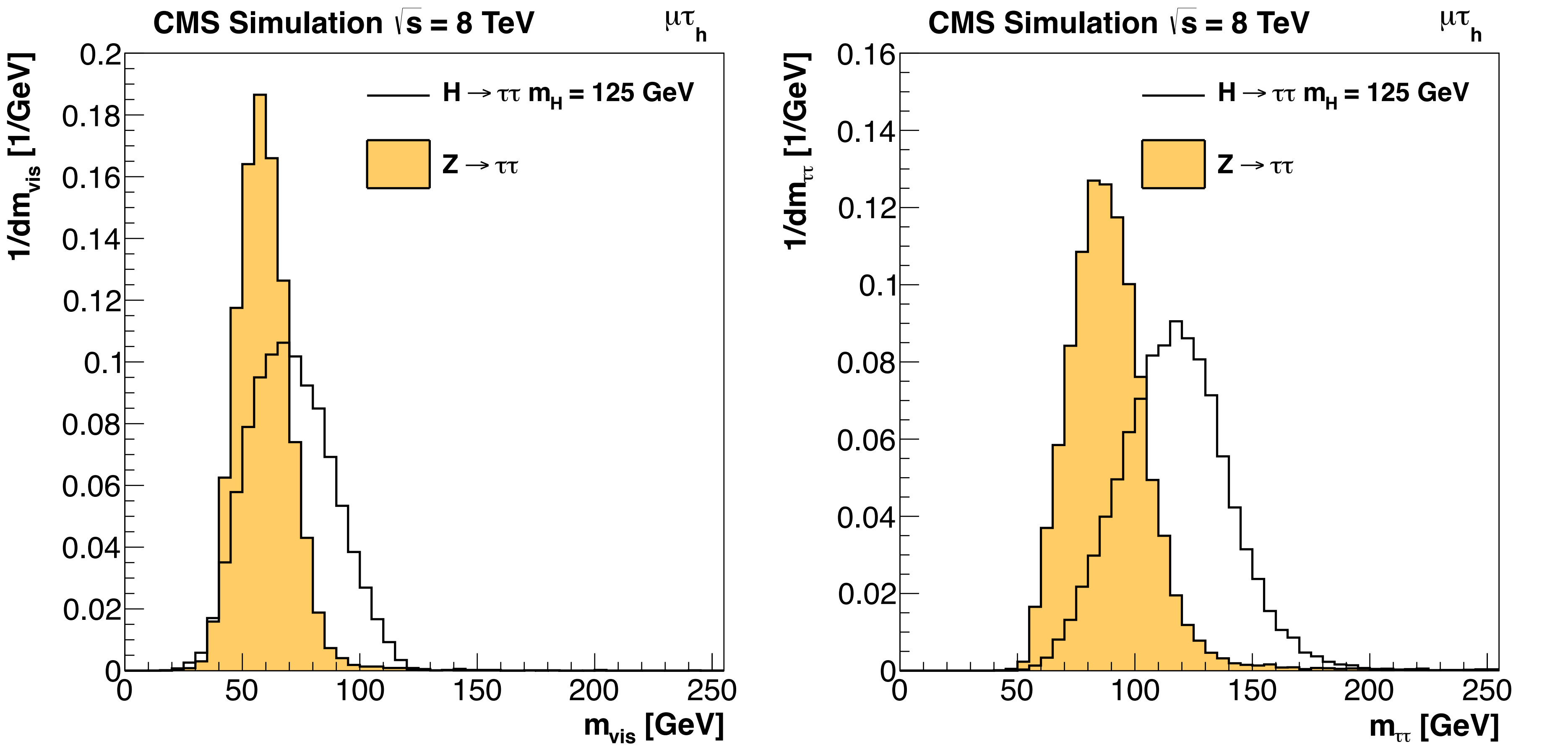
Mass estimates: the SVFit algorithm

- 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,

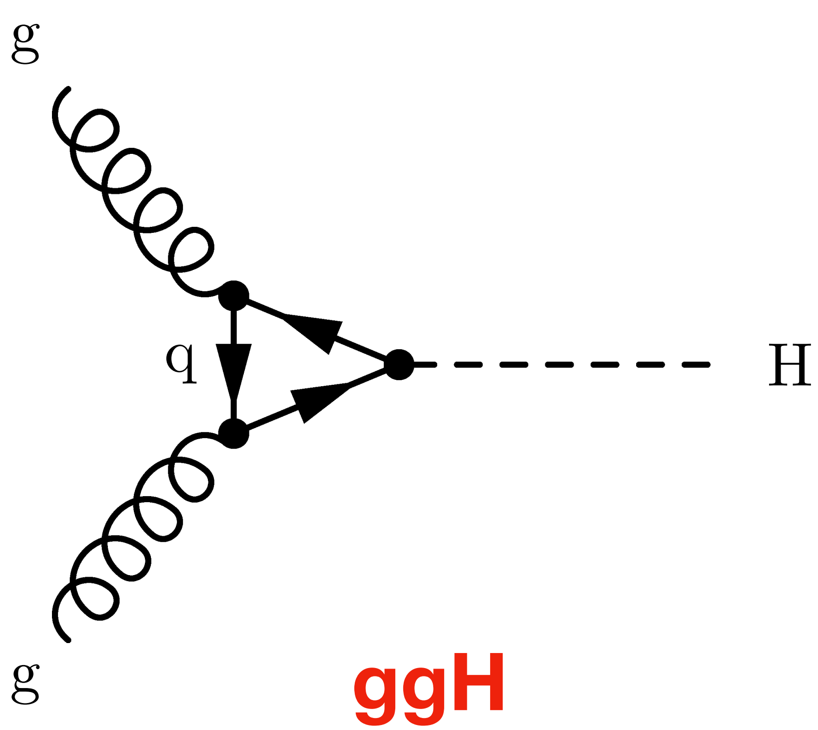
- Gives a significant improvement over using only the visible 4-vectors (m_{vis})

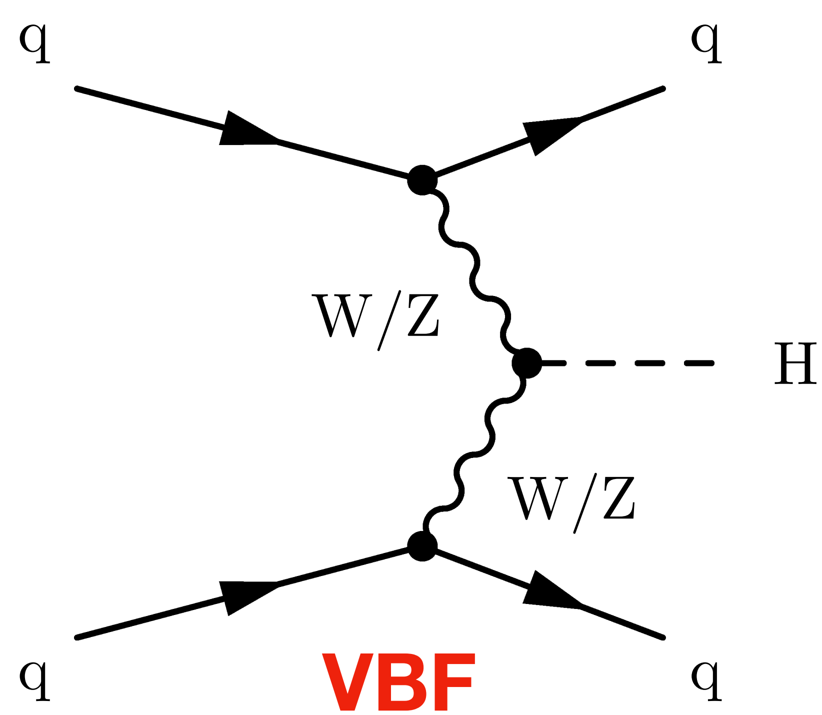


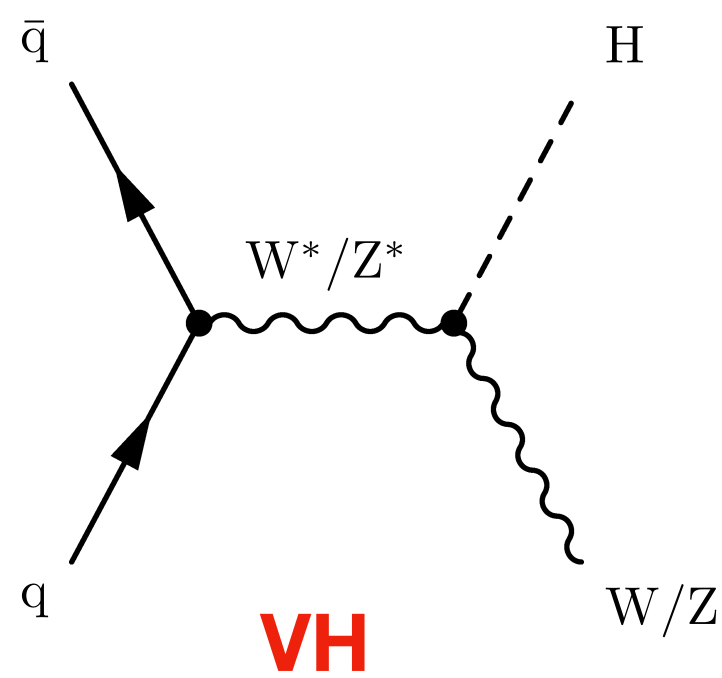
Cross section and STXS measurements

Considered signal productions

- The analysis targets mainly the gluon fusion (ggH) and vector boson fusion (VBF) processes, and pick up a smaller amount of the VH production with V→hadron decays
- We have separate dedicated analyses to target other production modes: ttH and VH (V→leptons)
- Largest cross section ggH (48 pb), then VBF (4 pb), then VH (2 pb)
- Although ggH is largest other production modes have additional jet topologies that make them more distinct from backgrounds
  - e.g VBF we get 2 additional jets in the forward detector regions, tend to be well separated in η and have large invariant mass
  - The result is H→$\tau\tau$ tends to be ~ equally sensitive to ggH and VBF production



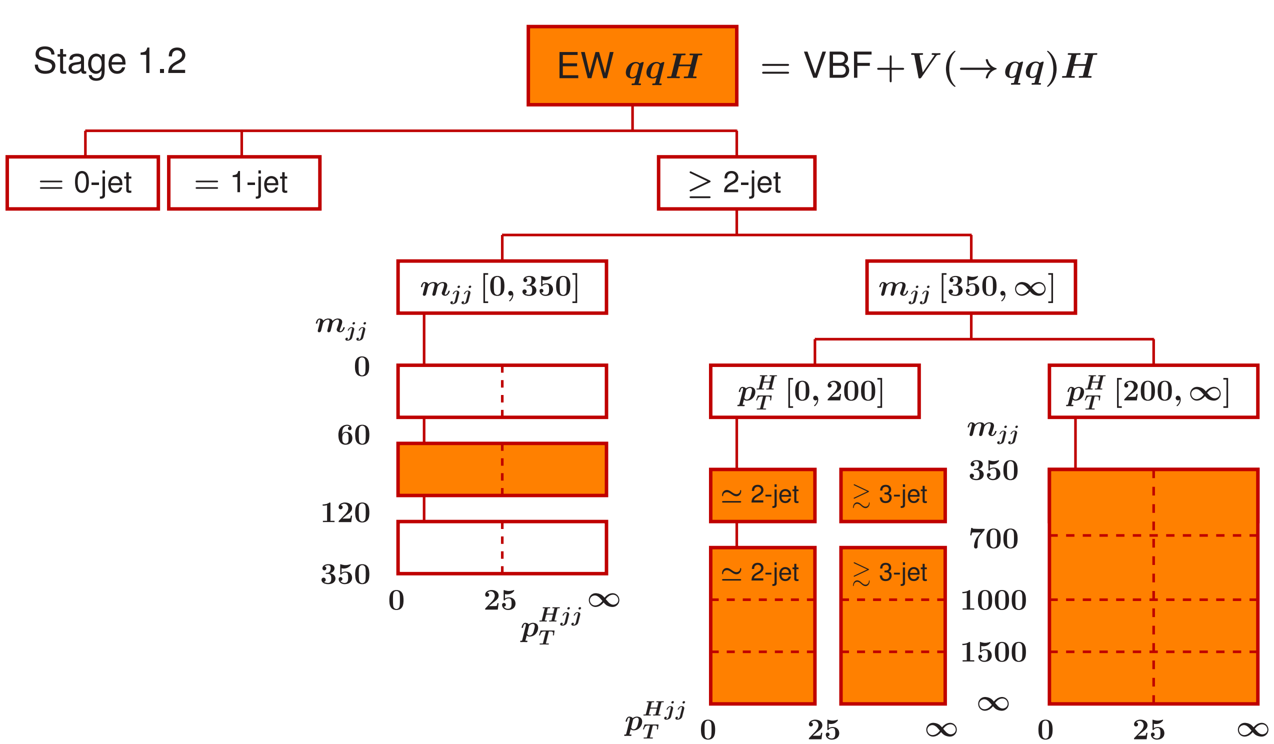


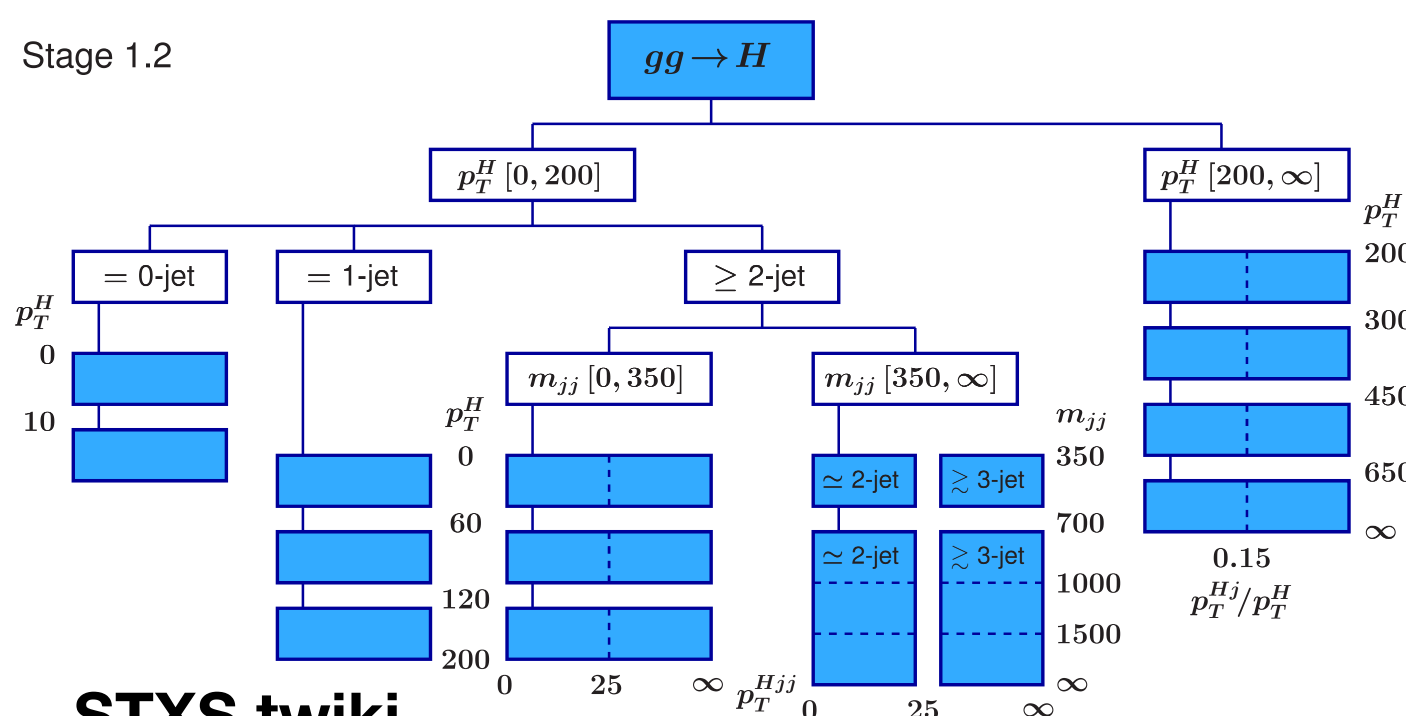


STXS overview

- In Run 2 there has been a move towards differential Higgs measurements

- The Simplified Template Cross Section (STXS) scheme is an example of framework for such measurements, its aims are to :
  - Provide granular measurements for individual Higgs production modes
  - Reduce theoretical uncertainties that are directly folded into the measurements





STXS twiki

d.winterbottom@imperial.ac.uk

Event selections

- We select oppositely charged pairs of hadronic taus (τ_h), electrons (e), and muons (μ)

- Events grouped into channels depending on pairs
  - We use only the 4 most sensitive channels: $\tau_h\tau_h$, $e\tau_h$, $\mu\tau_h$, and eμ

- Electron, muons, and taus are required to pass ID discriminants and be isolated

- We apply additional vetos on events with additional leptons and bjets to reduce background such a Drell-Yan and ttbar

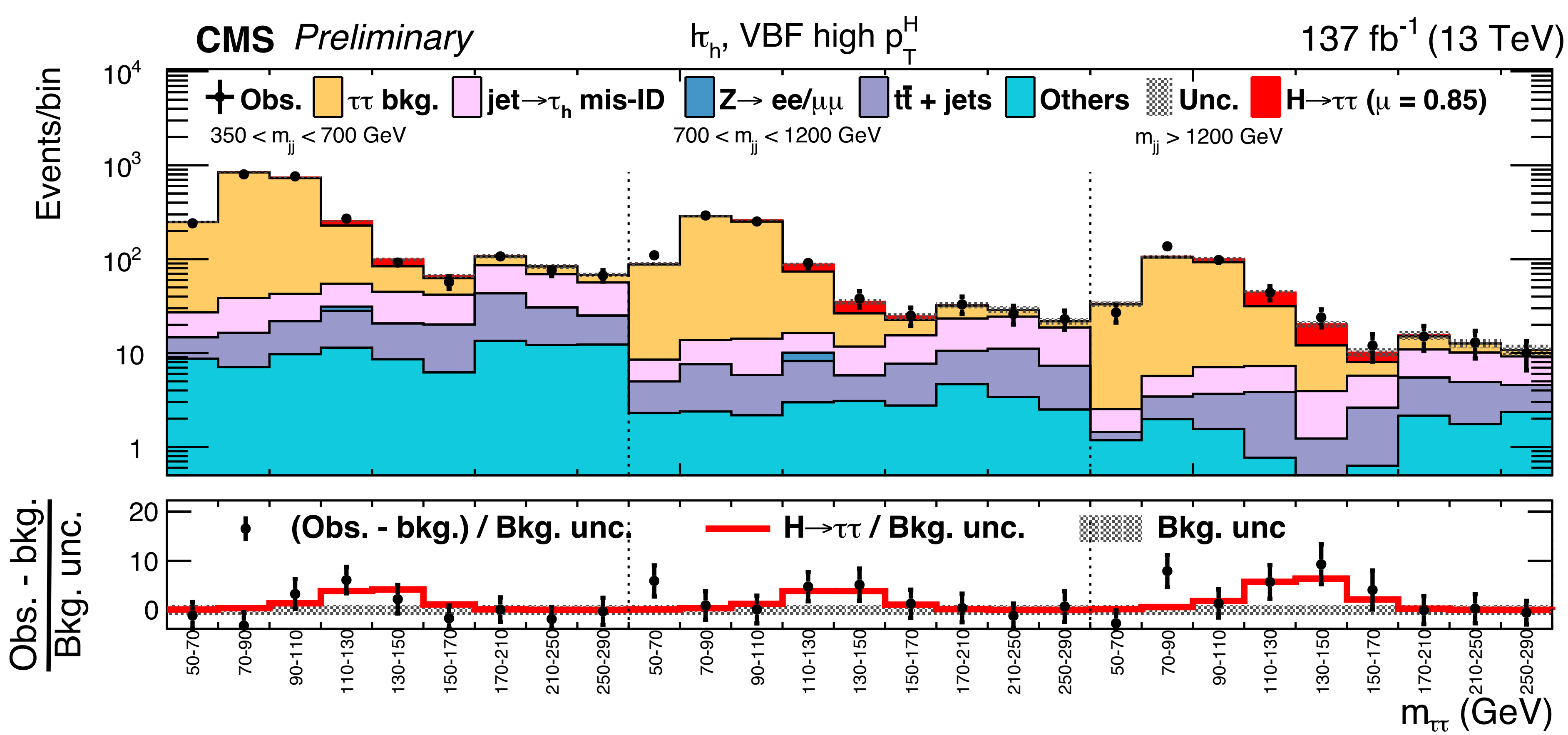
- In the semi-leptonic channels we also require the transverse mass of the lepton+MET system to be $<$ 50 GeV to reduce the W+jets background

Event categorisation

- We first split events into 3 categories to target different productions processes:
    - 0-jet: No jets with p_T > 30 GeV - targets mainly ggH
    - VBF: 2 or more jets with m_{jj} > 300 GeV ($|\Delta\eta|_{jj}$ > 2.5 and p_T^H>100 GeV) for the $e\tau_h$, $\mu\tau_h$, and eμ ($\tau_h\tau_h$) channels - targets VBF events
    - Boosted: 1-jets events or 2+ jets events failing VBF cuts - selects boosted ggH+j events, VH, and some VBF
- We then further categorise events based on p_T^H and N_{jets} and to align with STXS bin boundaries
    - VBF: split into two categories with p_T^H>200 GeV and p_T^H< 200 GeV
    - Boosted: split into two categories with N_{jets}=1 and N_{jets}>1
- Gives 5 categories in total

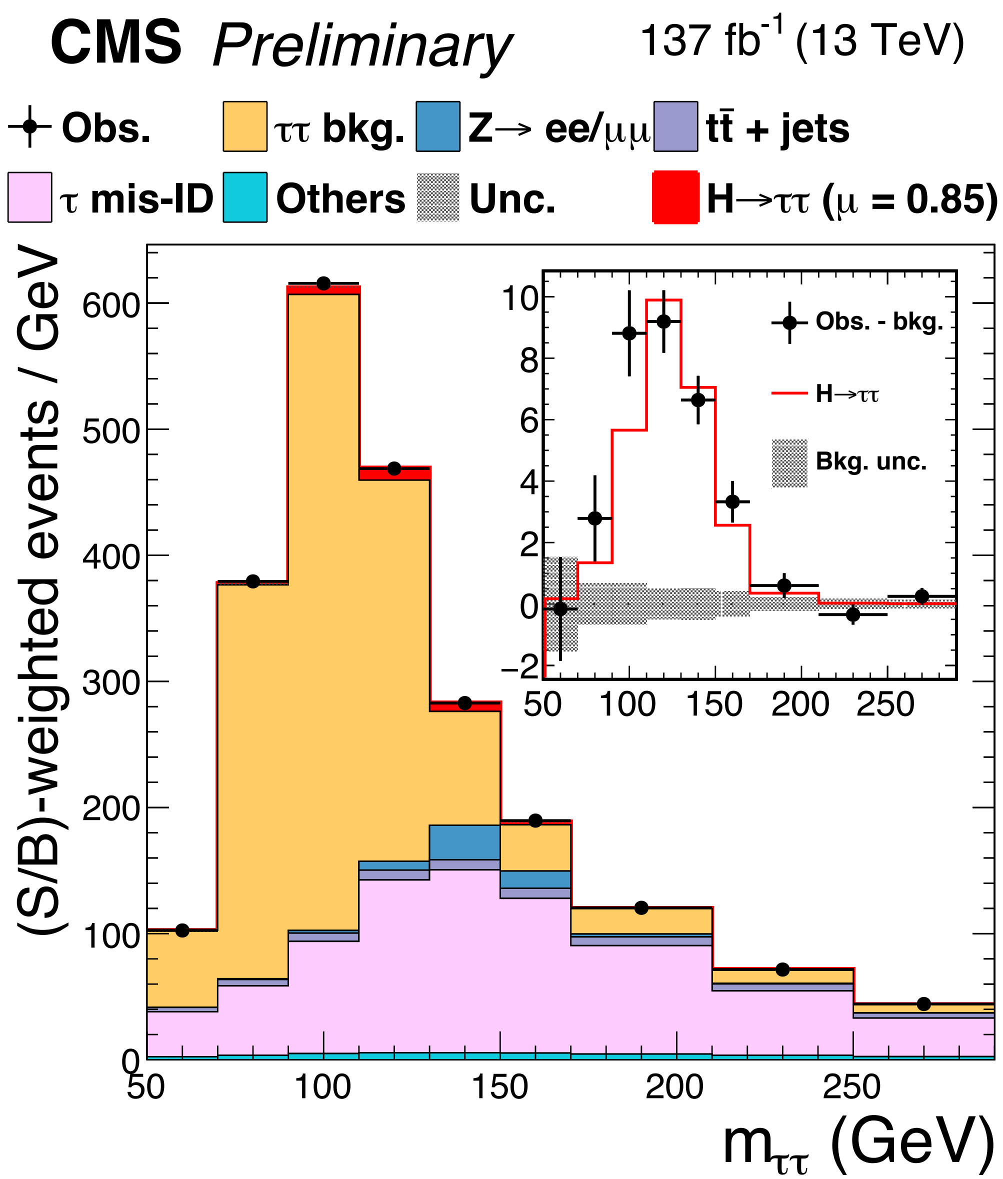
Signal extraction

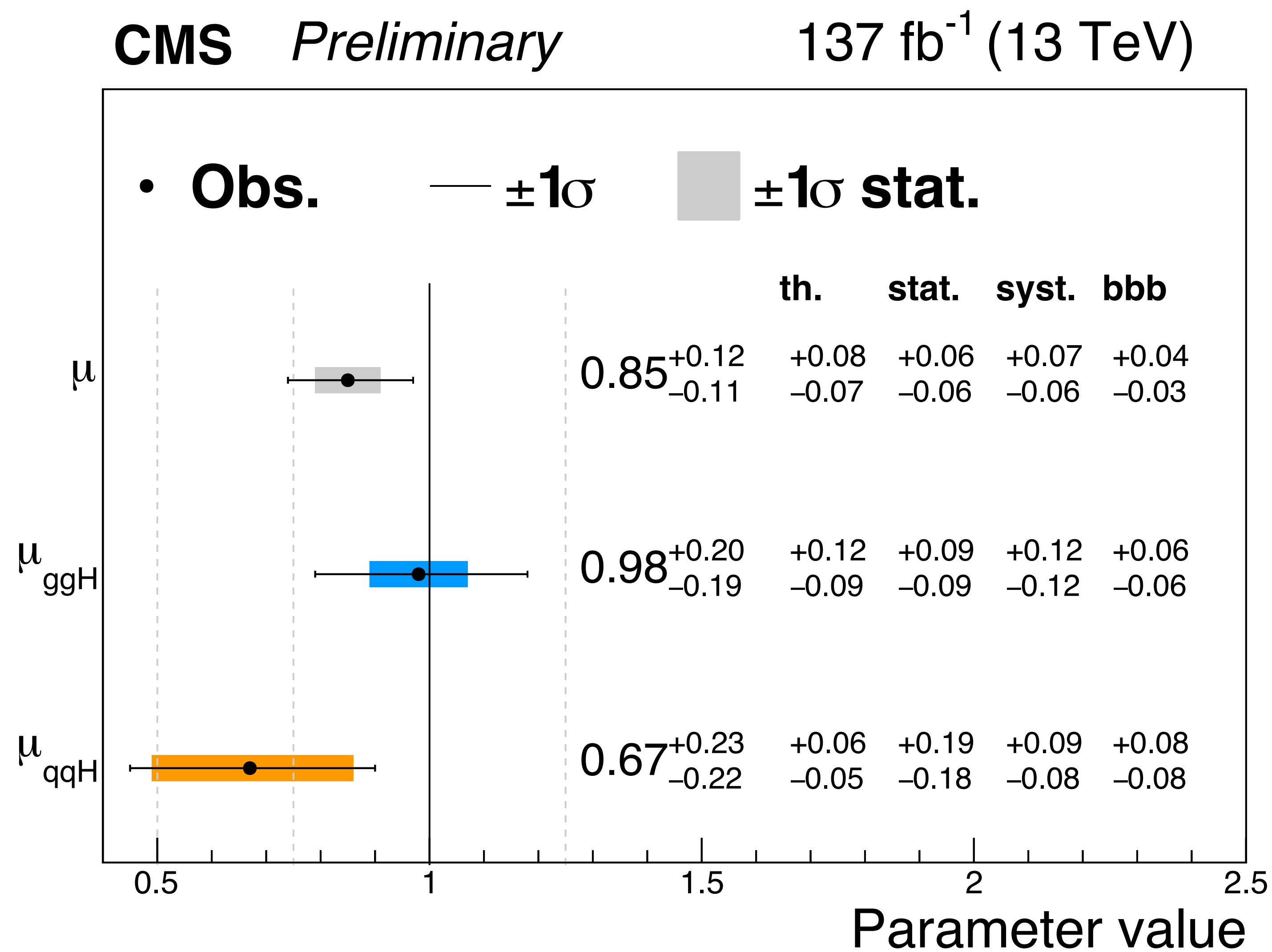
- In each category a 2D (or 1D) distributions is built:
  - 0-jet: $m_{\tau\tau}$ vs p_T (2D) for $e\tau_h$, $\mu\tau_h$; $m_{\tau\tau}$ for $\tau_h\tau_h$ and eμ (1D)
  - Boosted: $m_{\tau\tau}$ vs p_T^H
  - VBF : $m_{\tau\tau}$ vs m_{jj}
- We perform a binned maximum likelihood fit combining all channels and categories to extract the results



Results: inclusive cross sections

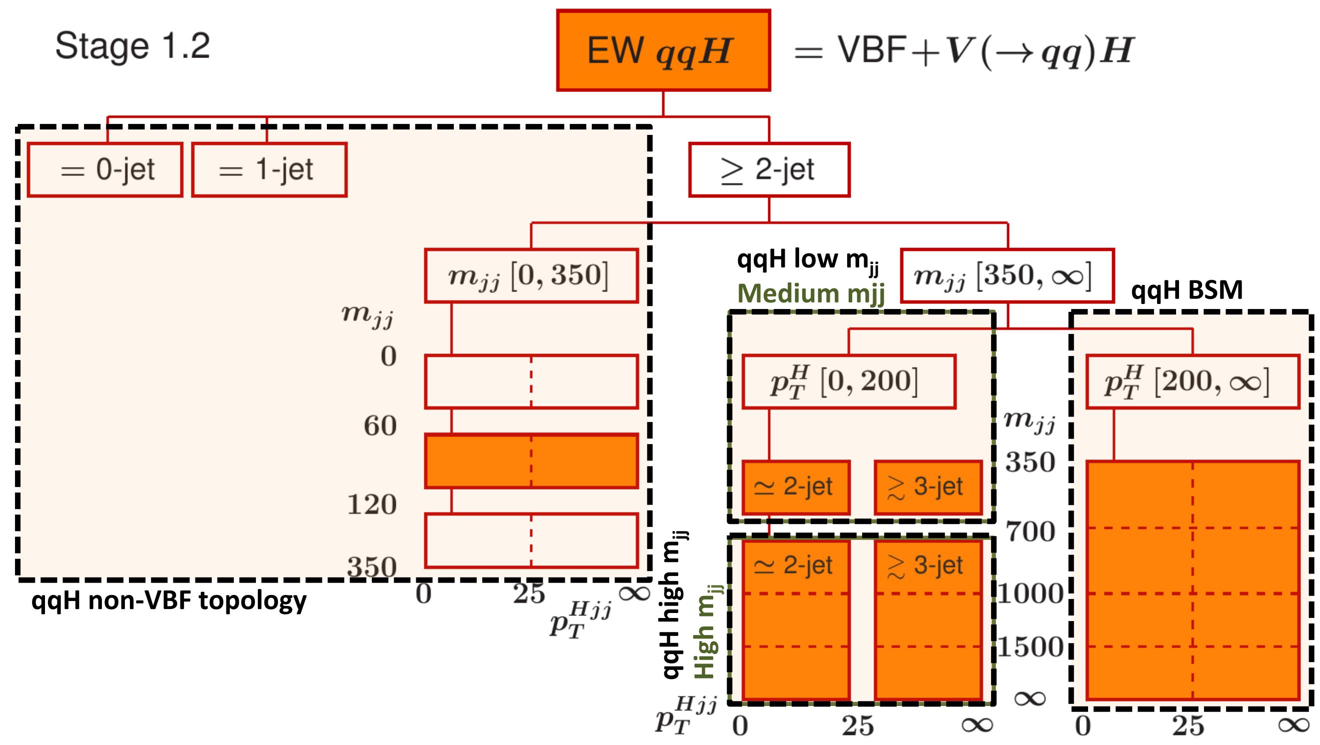
- Inclusive Higgs cross section measured (all production modes collectively)
- ggH and qqH (VBF+VH) cross sections also measured separately

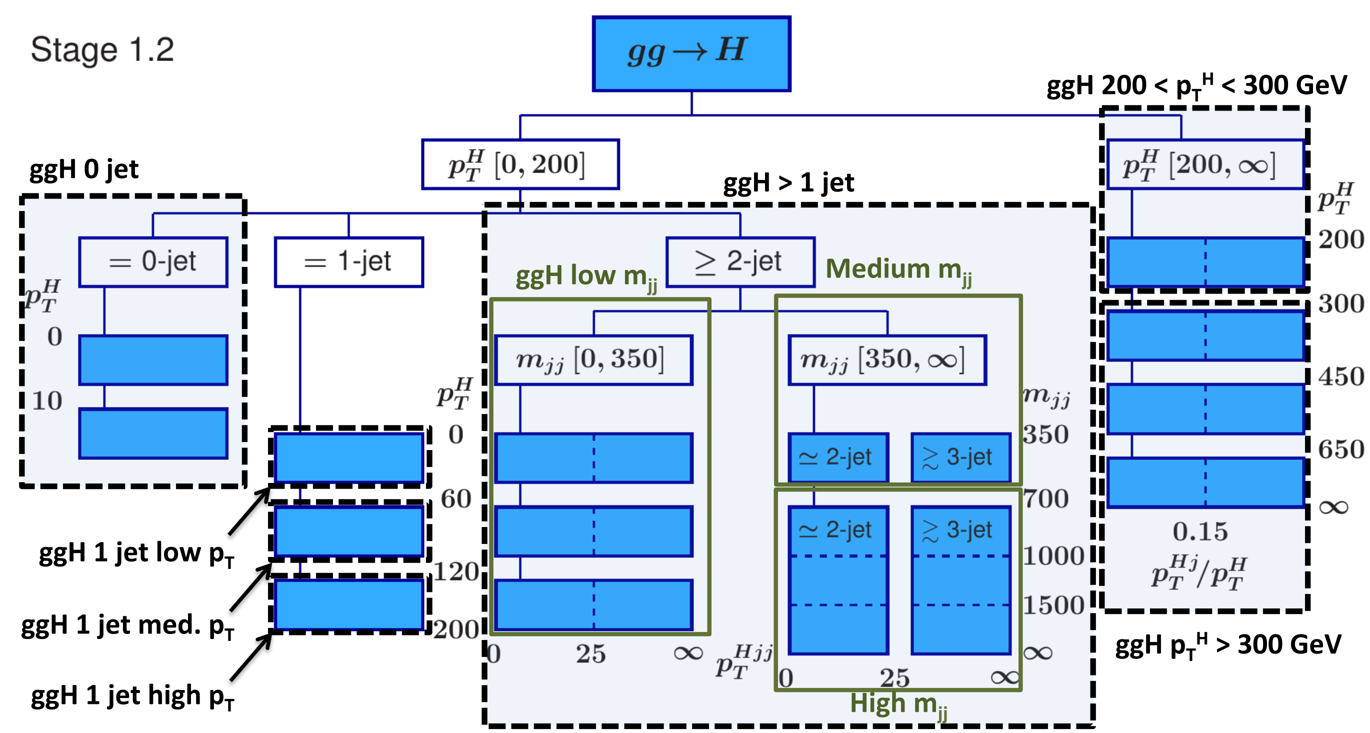




STXS bin merging

- In the $H \rightarrow \tau\tau$ analysis alone we are not sensitive to every STXS bin
- Some would have very large uncertainties or strong correlations with neighbours
- We thus merge such bins
- Two merging schemes are used:
  - Process based: ggH and qqH treated separately, some neighbouring bins merged
  - Topology based: ggH and qqH tied together for VBF-like topology bins, some bins also merged for non-VBF bins but ggH and qqH kept separate

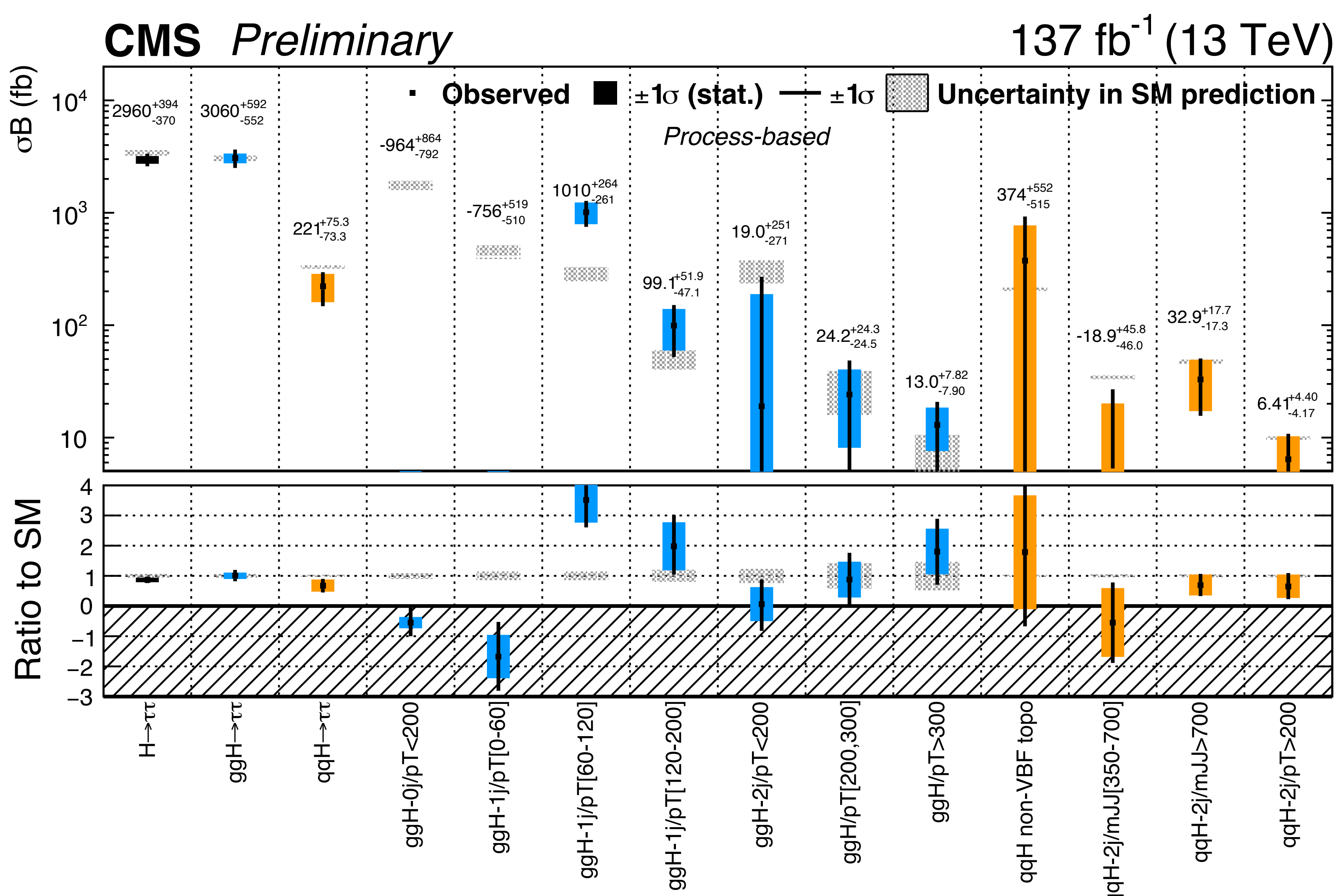


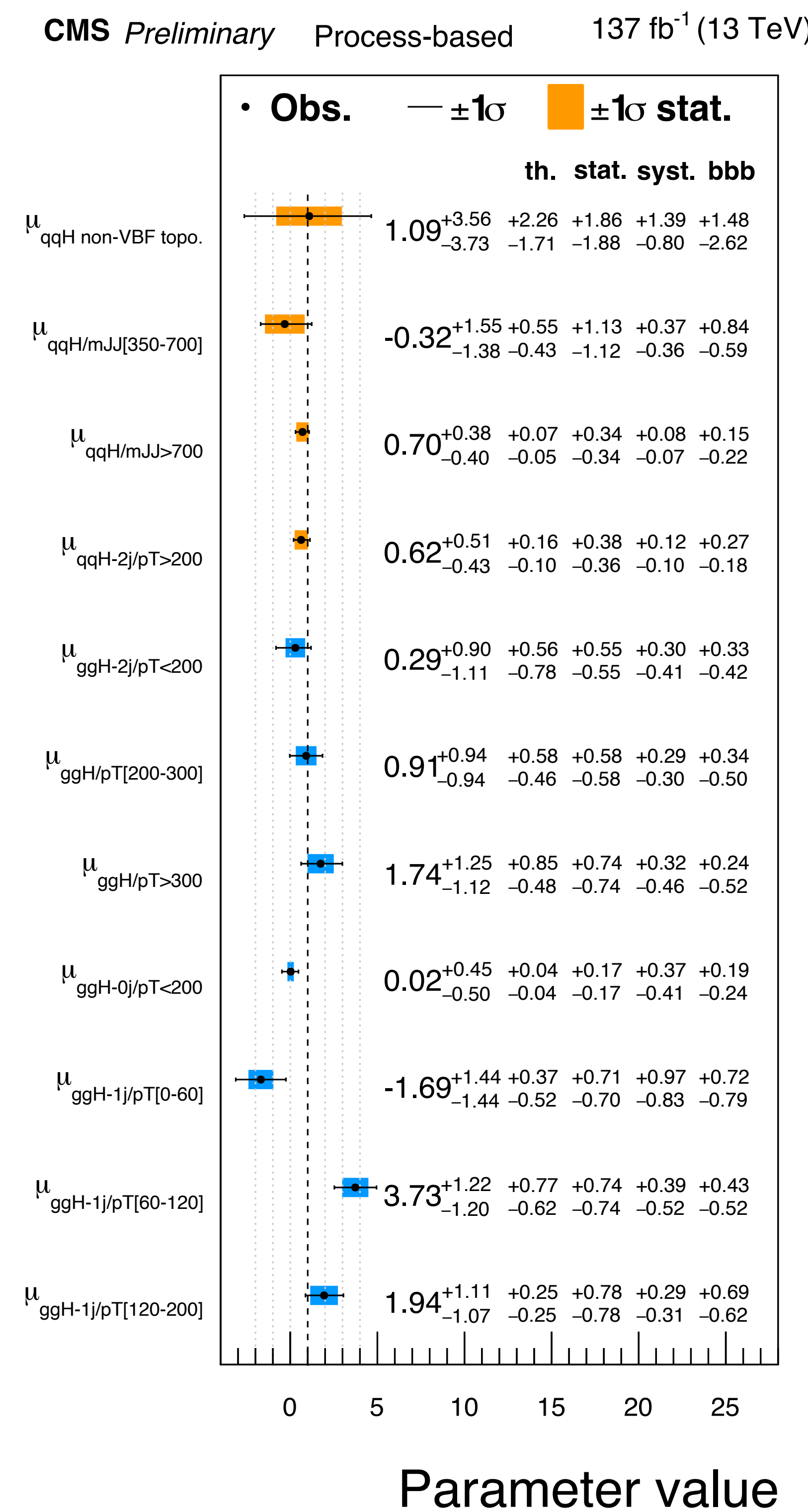


dashed-back = process based
solid green=topology-based

Results: STXS measurements (process based)

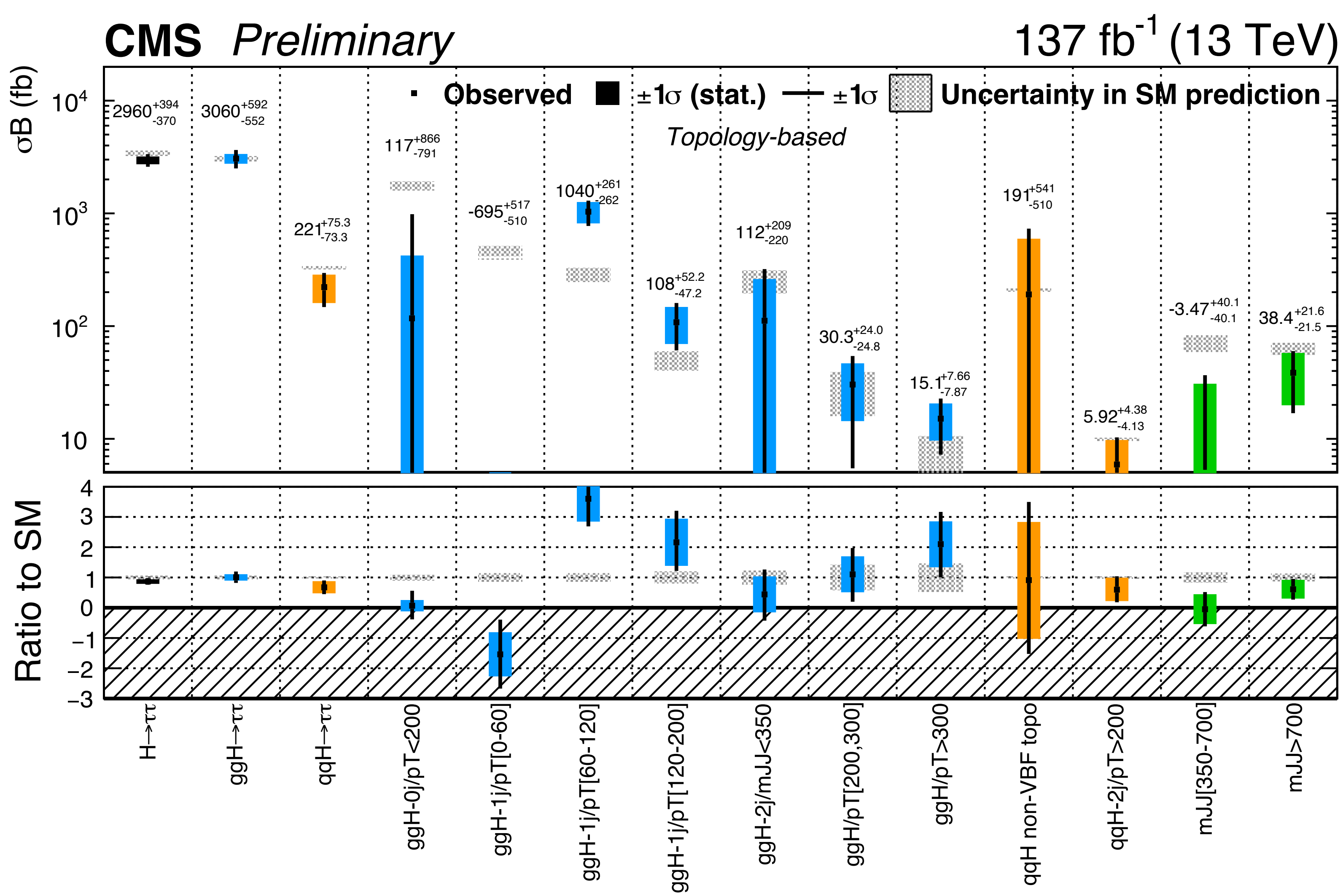
- The STXS results for process based merging scheme
- Some small tensions in low p_T bins but altogether compatible with the expectation

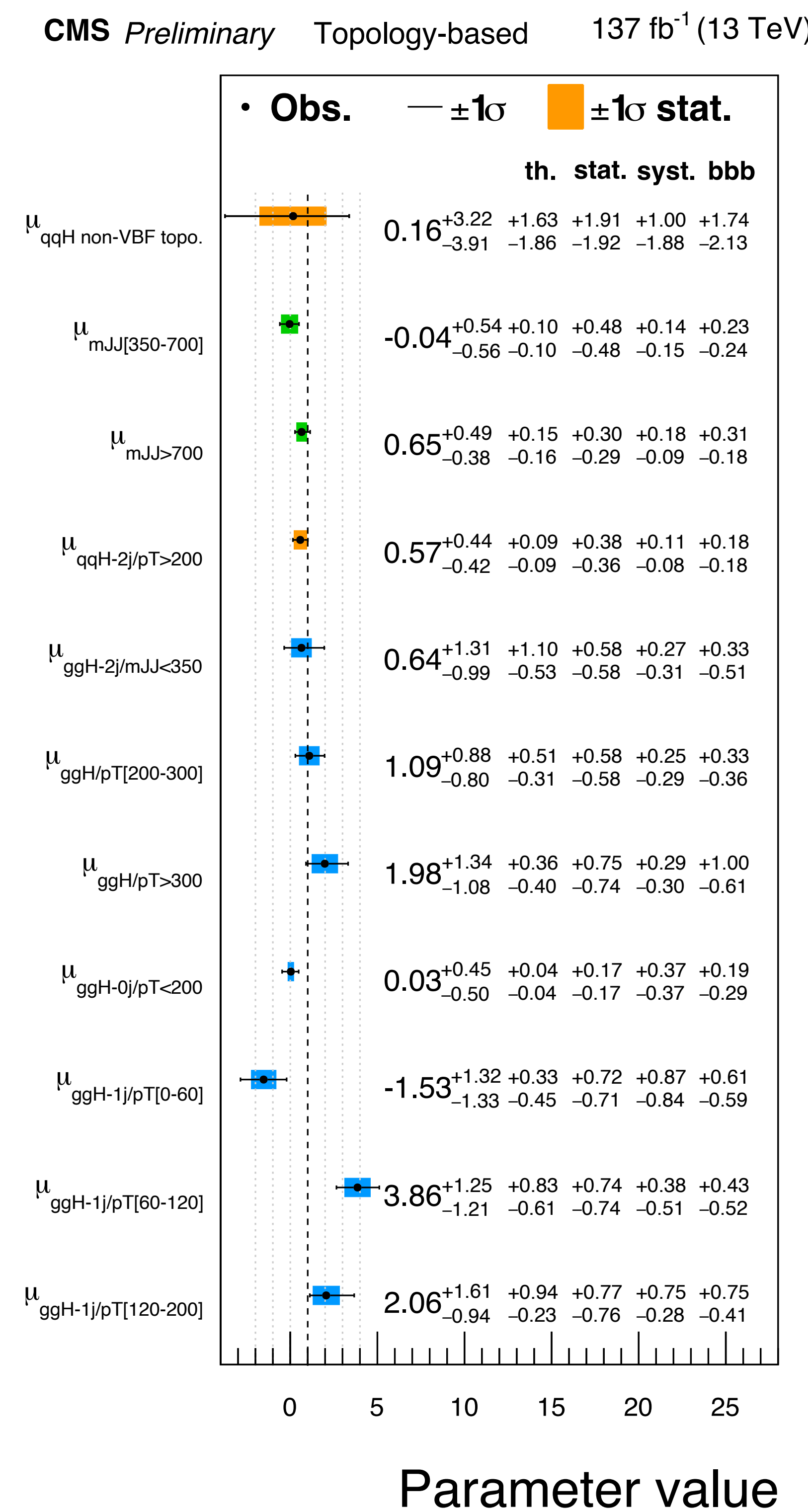




Results: STXS measurements (topology-based)

- The STXS results for topology based merging scheme
- Some small tensions in low p_T bins but altogether compatible with the expectation

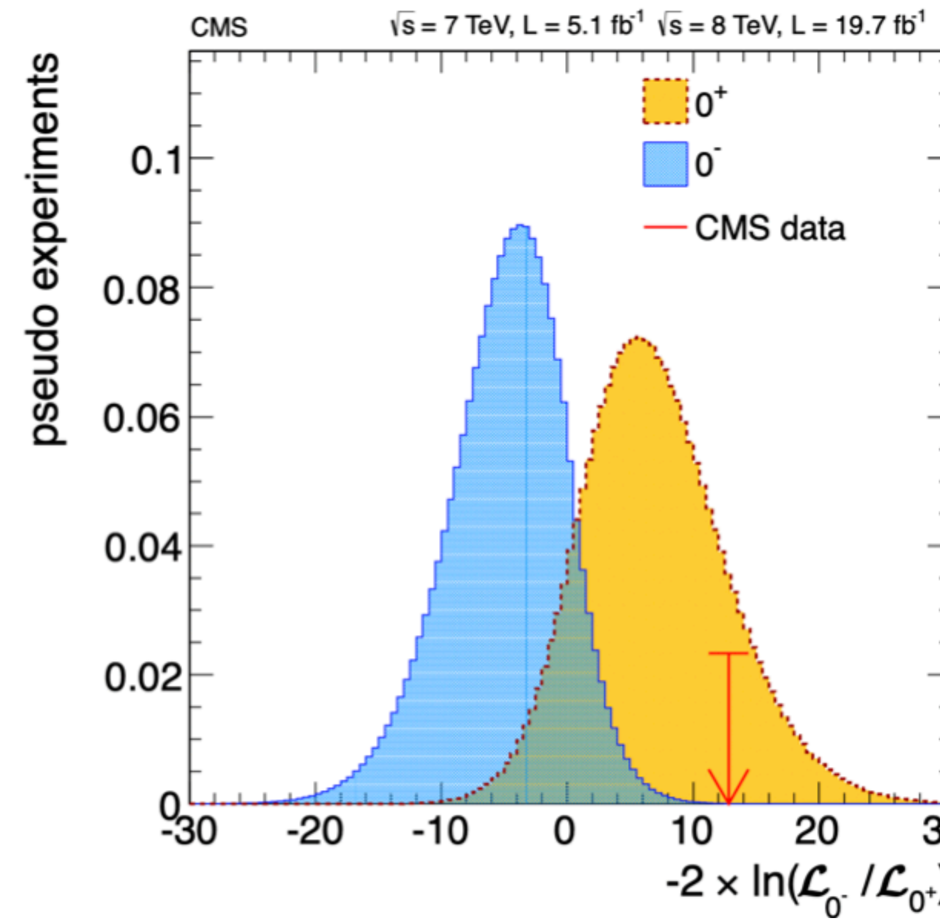


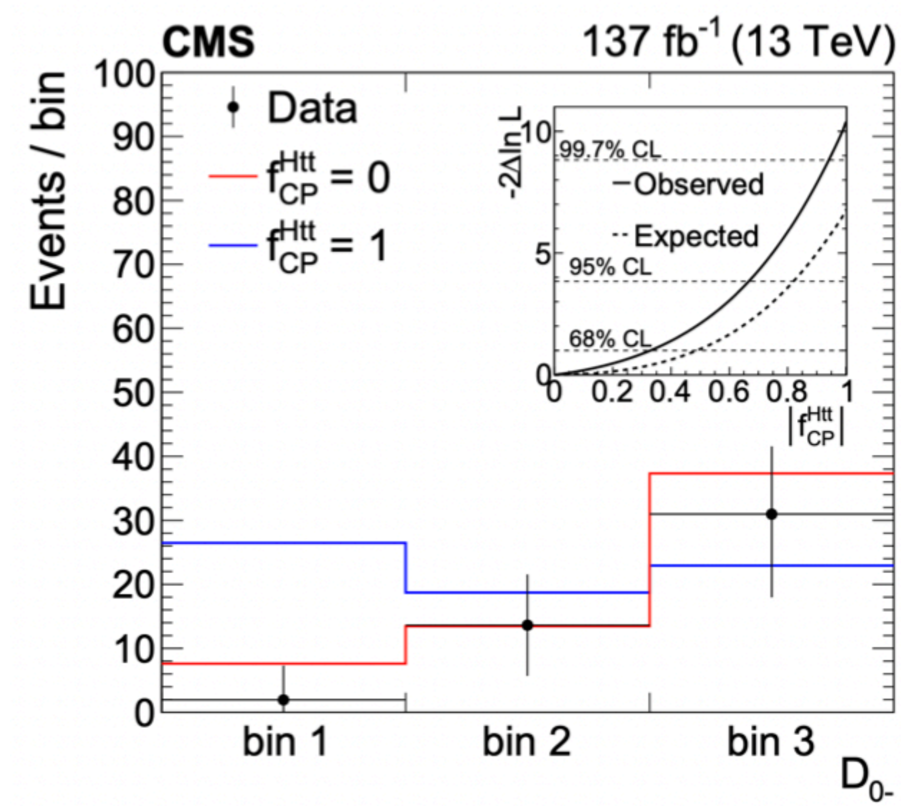


CP measurements

Motivations for CP measurements

- In the SM Higgs sector Higgs bosons is a CP-even state (0^+)
- Extended Higgs sectors predict modified properties of the 125 GeV Higgs boson and/or new observable states in scalar sector
- Discovery of such a extended Higgs sector would be evidence for new physics beyond the standard model (BSM)
- One such class of extensions include additional CP phases in the Higgs sector
- Such models can help explain observed matter-antimatter asymmetry in the universe
- Higgs CP properties 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)





- 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:

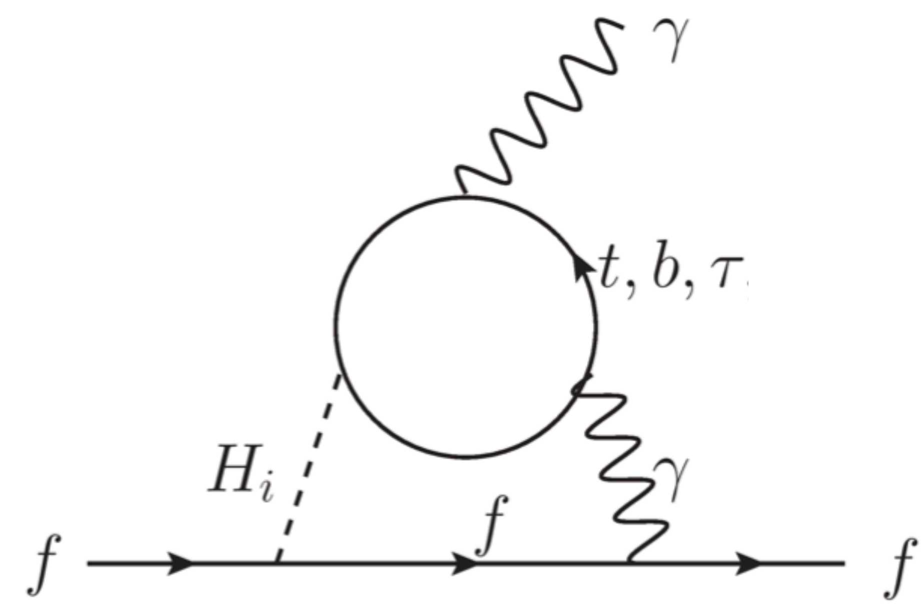
$$d\Gamma \sim 1 - s_z^- s_z^+ + \cos(2\phi_{\tau\tau})(\mathbf{s}_T^- \cdot \mathbf{s}_T^+) + \sin(2\phi_{\tau\tau})\left[(\mathbf{s}_T^- \times \mathbf{s}_T^+) \cdot \hat{k}^-\right]$$

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

S. Berge, et al.

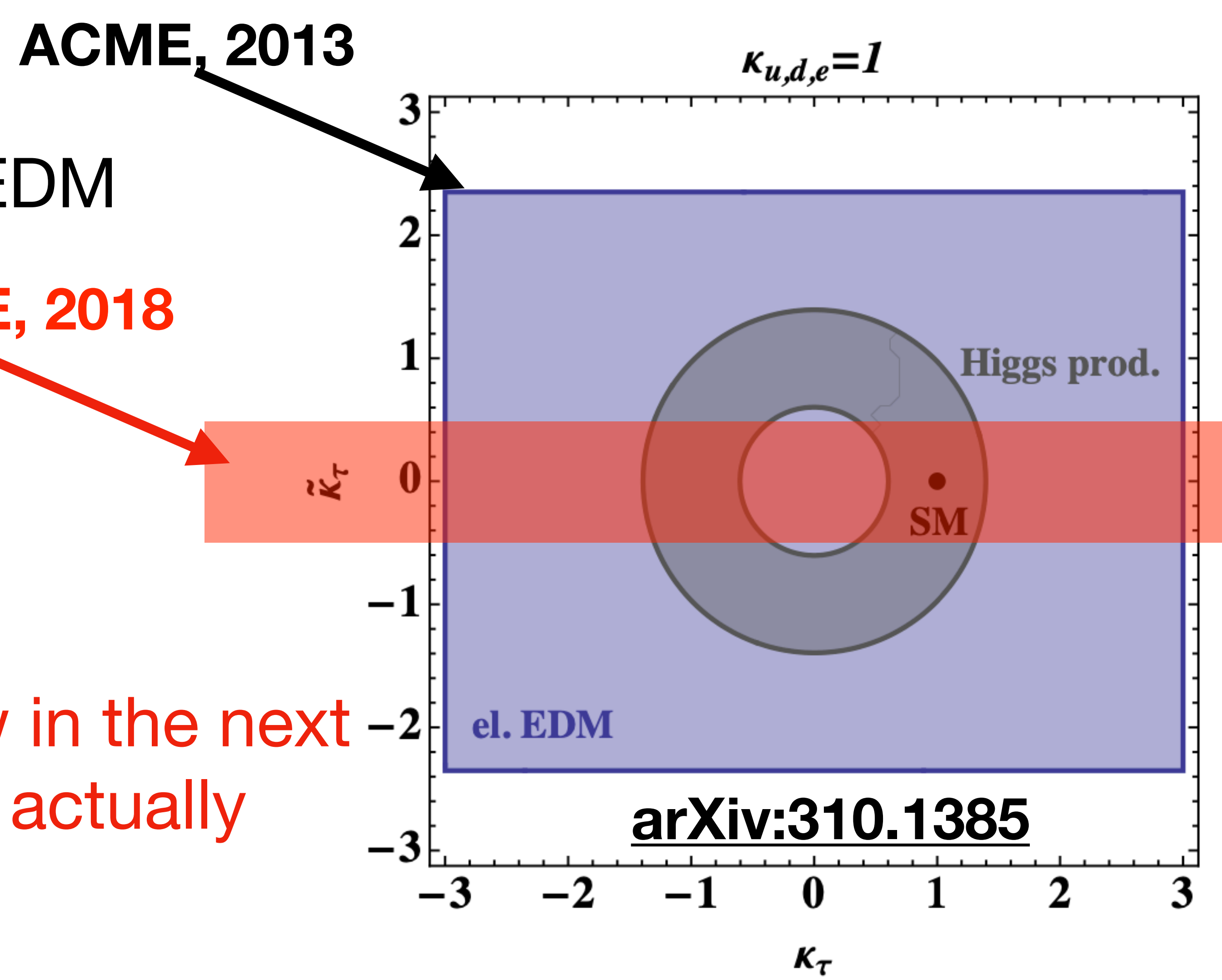
Indirect measurements EDMs

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



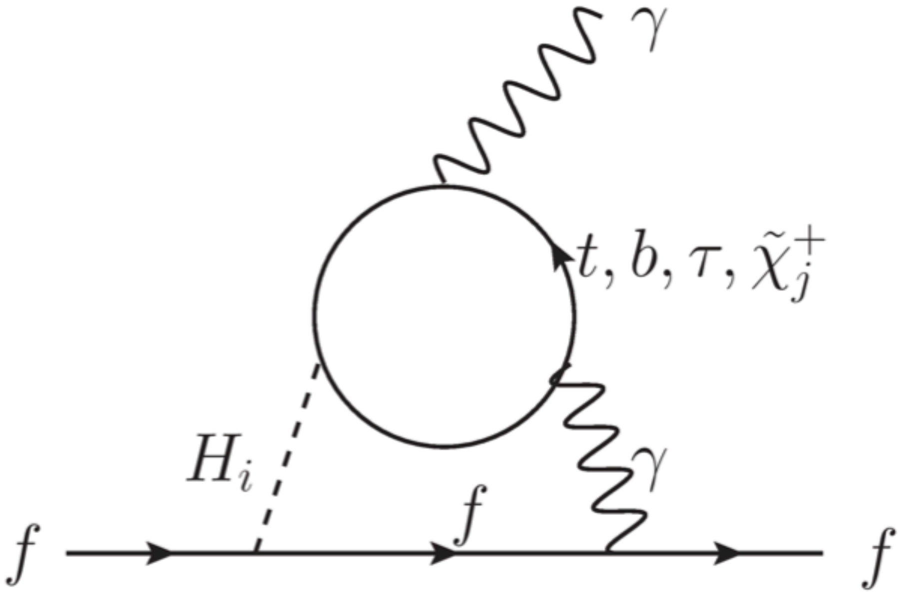
- Measurements of EDMs can therefore allow indirect constraints to be set on H→$\tau\tau$ CP properties

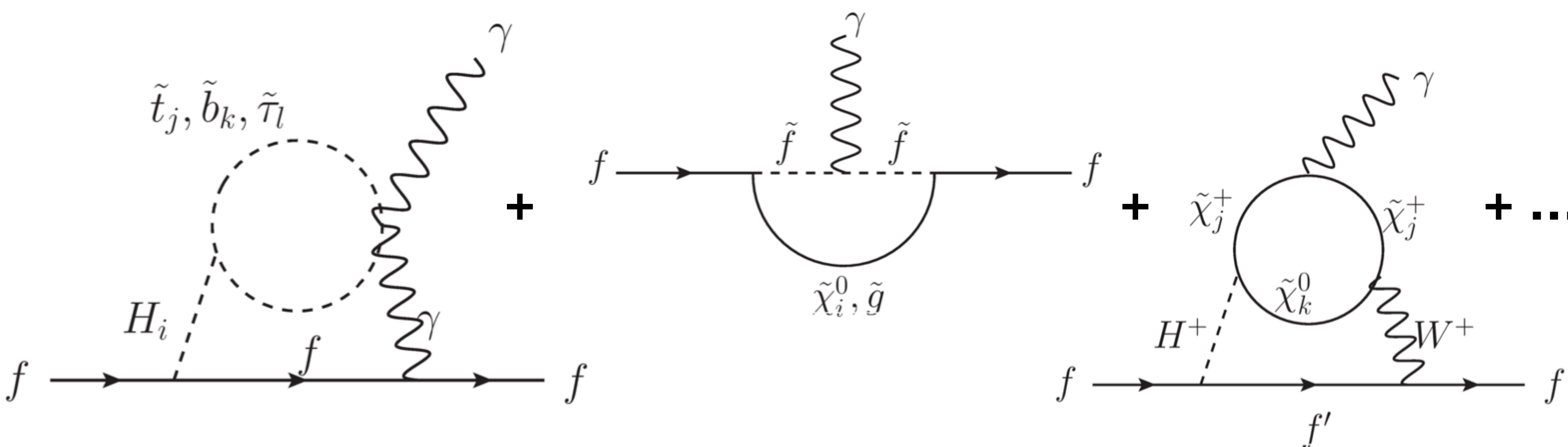
- Tightest bound come from electron EDM measurements:
  - ~ 10^{-28} *e* cm (ACME Coll., 2013)
  - ~ 10^{-29} *e* cm (ACME Coll., 2018)



- Note 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 Higgs e.g H→ee coupling
  - For some models e.g SUSY get additional diagrams contributing - can change EDMs





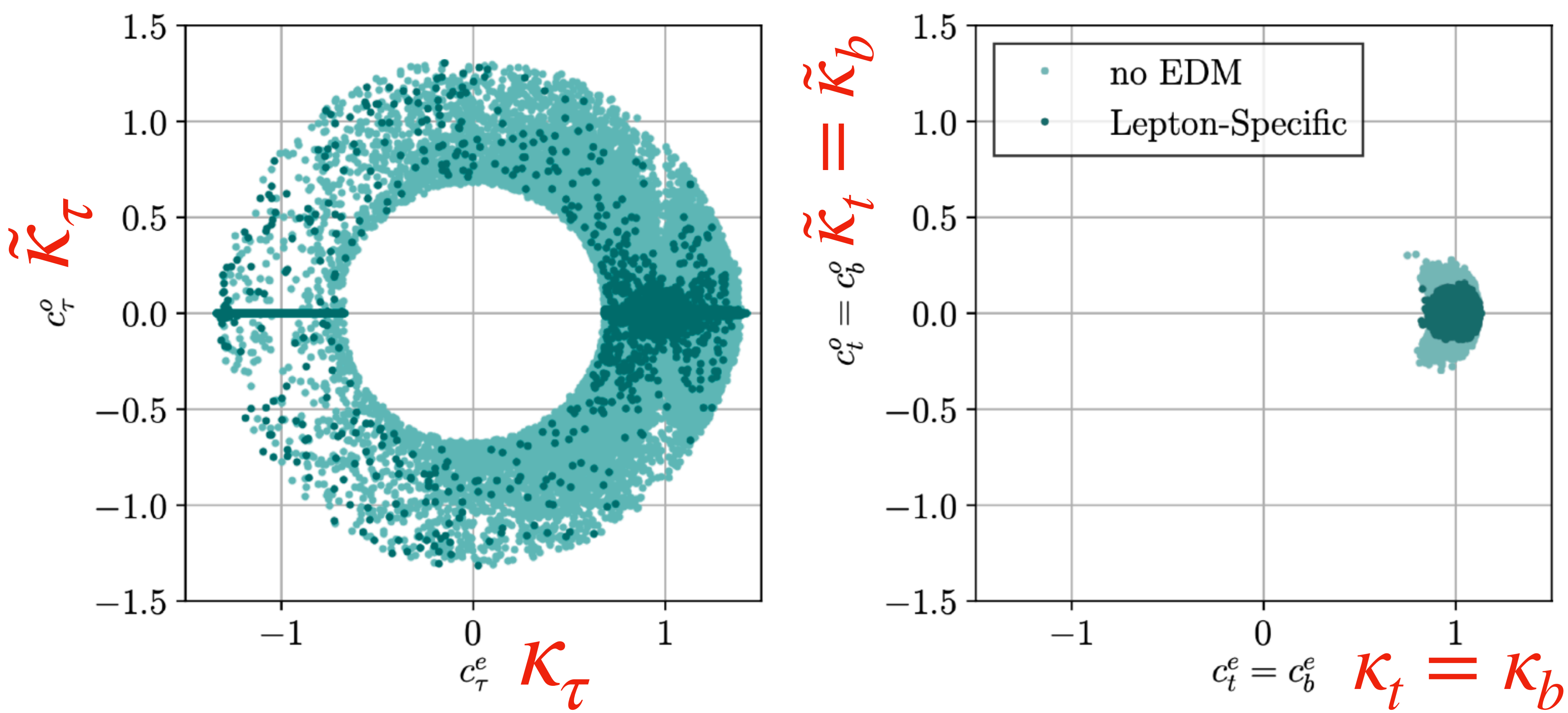
Two Higgs doublet models

- SM Higgs sector has one Higgs doublet
- Two Higgs doublet models (2HDM) introduce an additional Higgs doublet
- Results in 4 additional Higgs bosons: in CP-conserving case h, H, A, $H^{\pm}$ → one of h, H is the 125 GeV boson
- Several different types of 2HDM possible depending on which doublet the fermions couple to, including (not not limited 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
Type 3	ϕ_1, ϕ_2	ϕ_1, ϕ_2	ϕ_1, ϕ_2

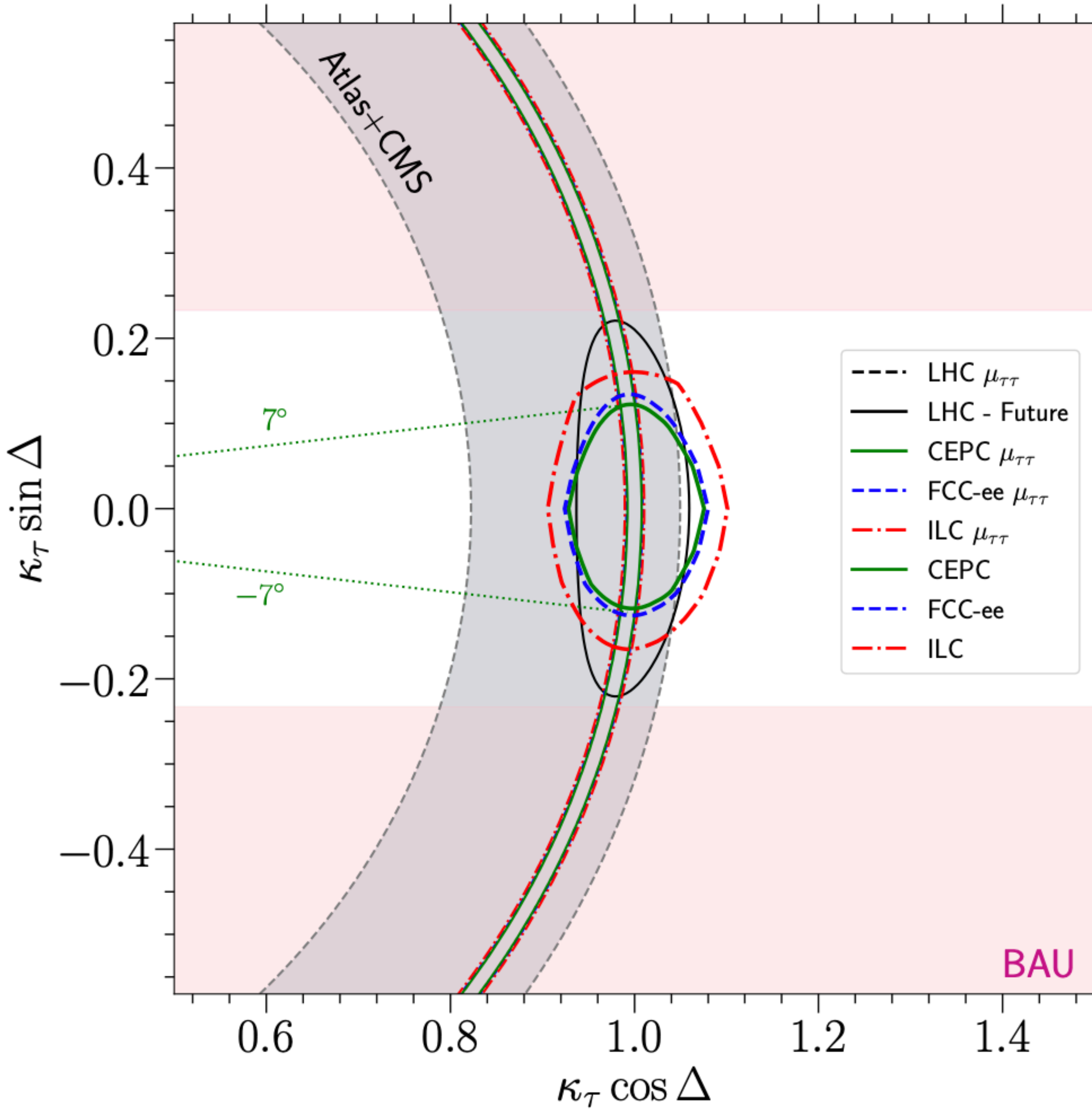
C2HDM

- 2HDM simplest extension that allows for CP-violation in Higgs sector - complex 2HDM (C2HDM)
- 4 additional Higgs 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 $\bar{\kappa}_\tau$ for lepton-specific 2HDM - similar situation for Type 2
- More constrained for Type I and flipped scenarios

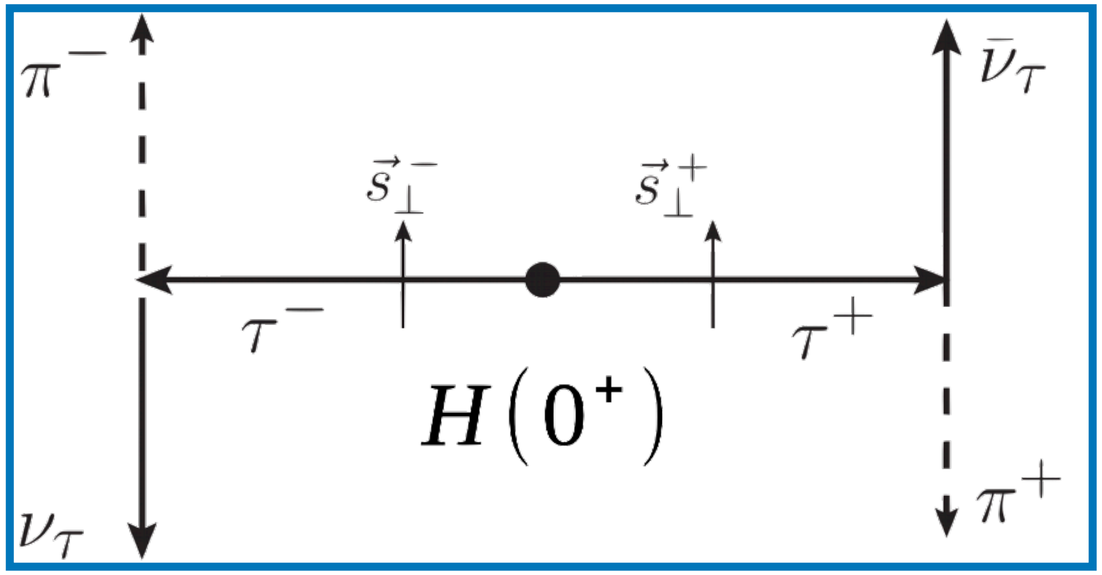


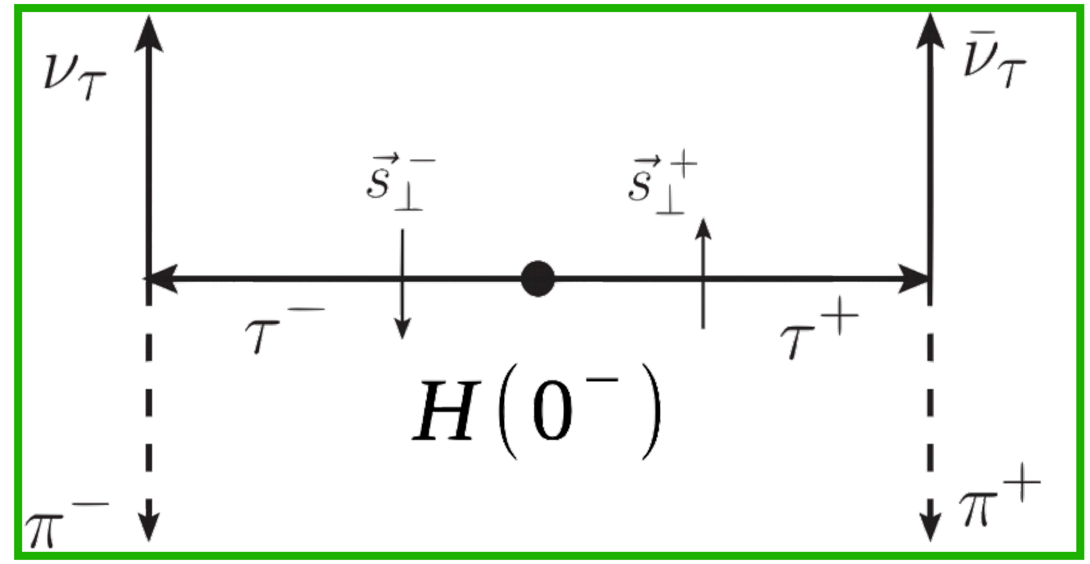
Matter-Antimatter asymmetry

- Models with CP violation in the Higgs sector that can explain matter-antimatter asymmetry can predict a measurable value of $\phi_{\tau\tau}$
- For example Phys. Rev. D 103, 095021 they compare the expected precision of various colliders with the minimum value of $\phi_{\tau\tau}$ (13°) in a Type III 2HDM model that can explain the matter antimatter asymmetry
- This means that measurements of $\phi_{\tau\tau}$ to within a precision of ~ a few degrees could establish evidence for or even an observation of such models



Observables sensitive to $\phi_{\tau\tau}$

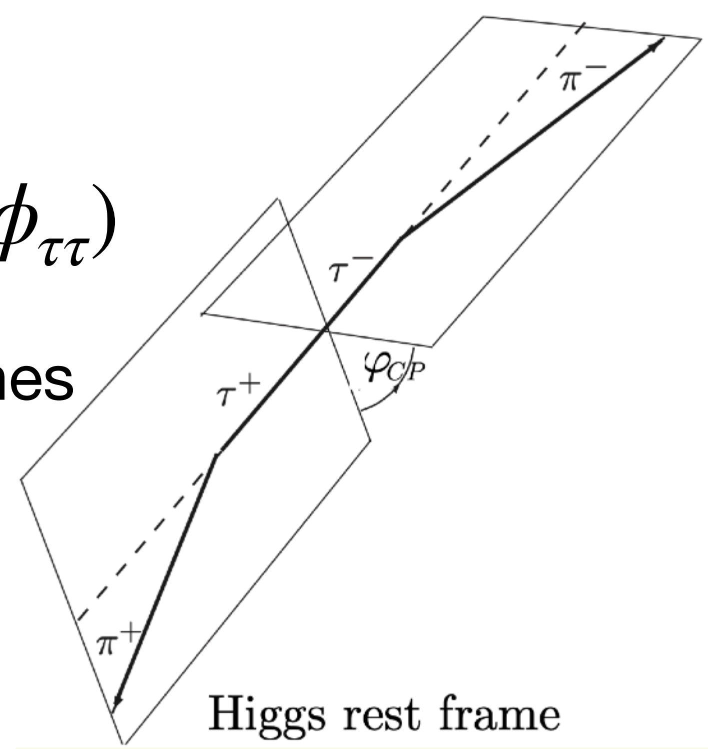


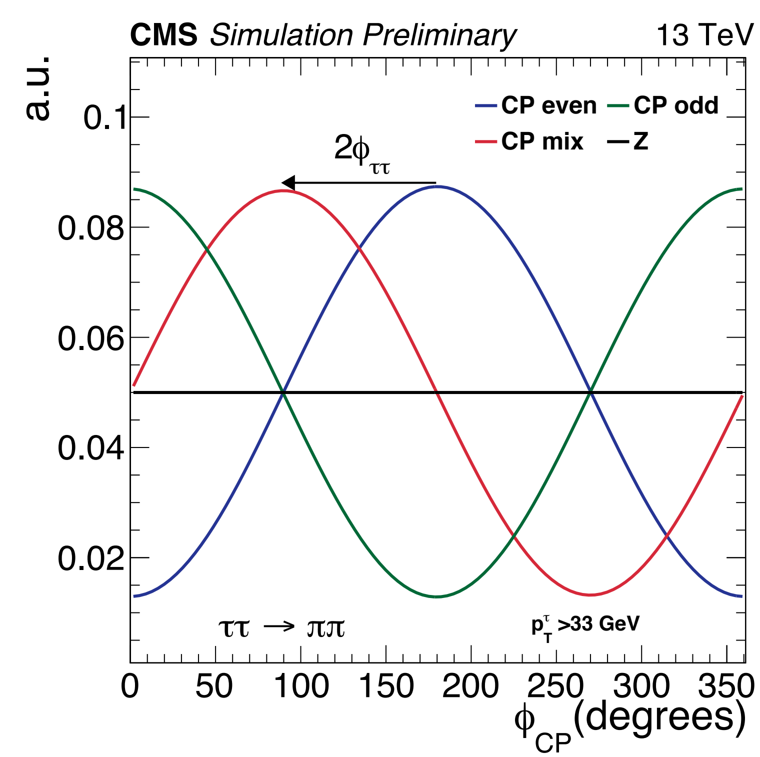


- Transverse spin correlations manifest as angular correlations of τ decay products
- Most simple 2-body decay: $\tau \to \pi^- \nu$
- Partial decay width looks like:

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

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





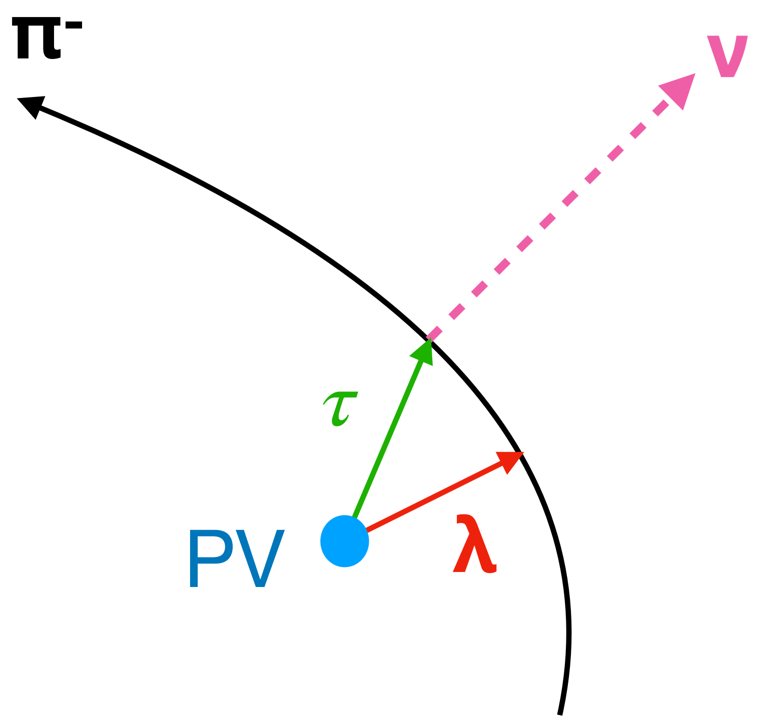
Plots courtesy of S. Berge

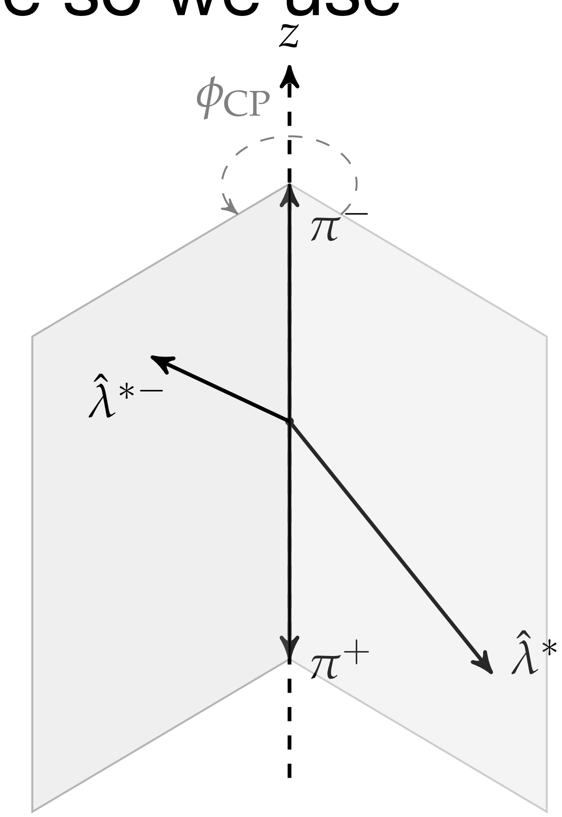
The IP method

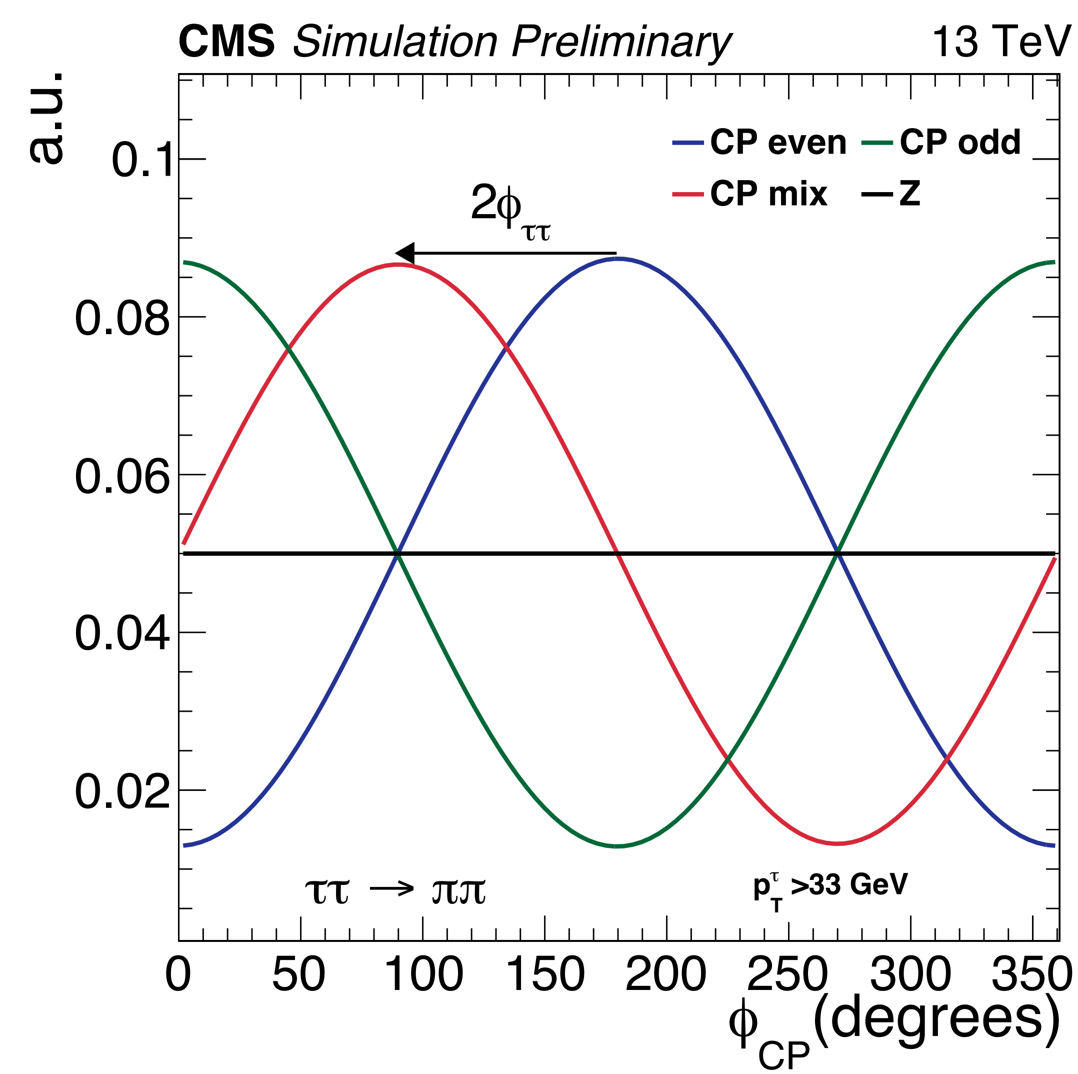
- In practise the ϕ_{CP} defined on the previous slide cannot be well measured at a hadron collider due to the neutrinos

- 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 Higgs rest frame so we use $\pi^+\pi^-$ rest frame

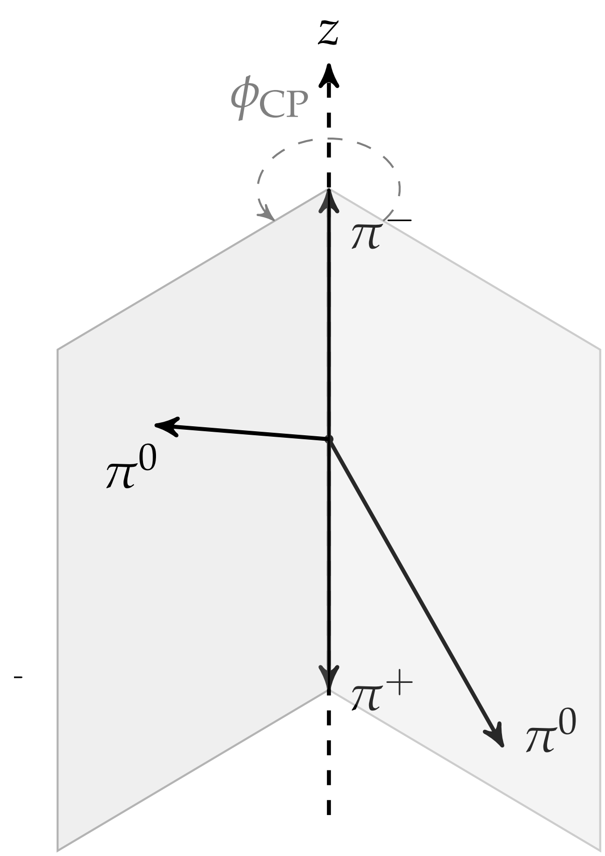


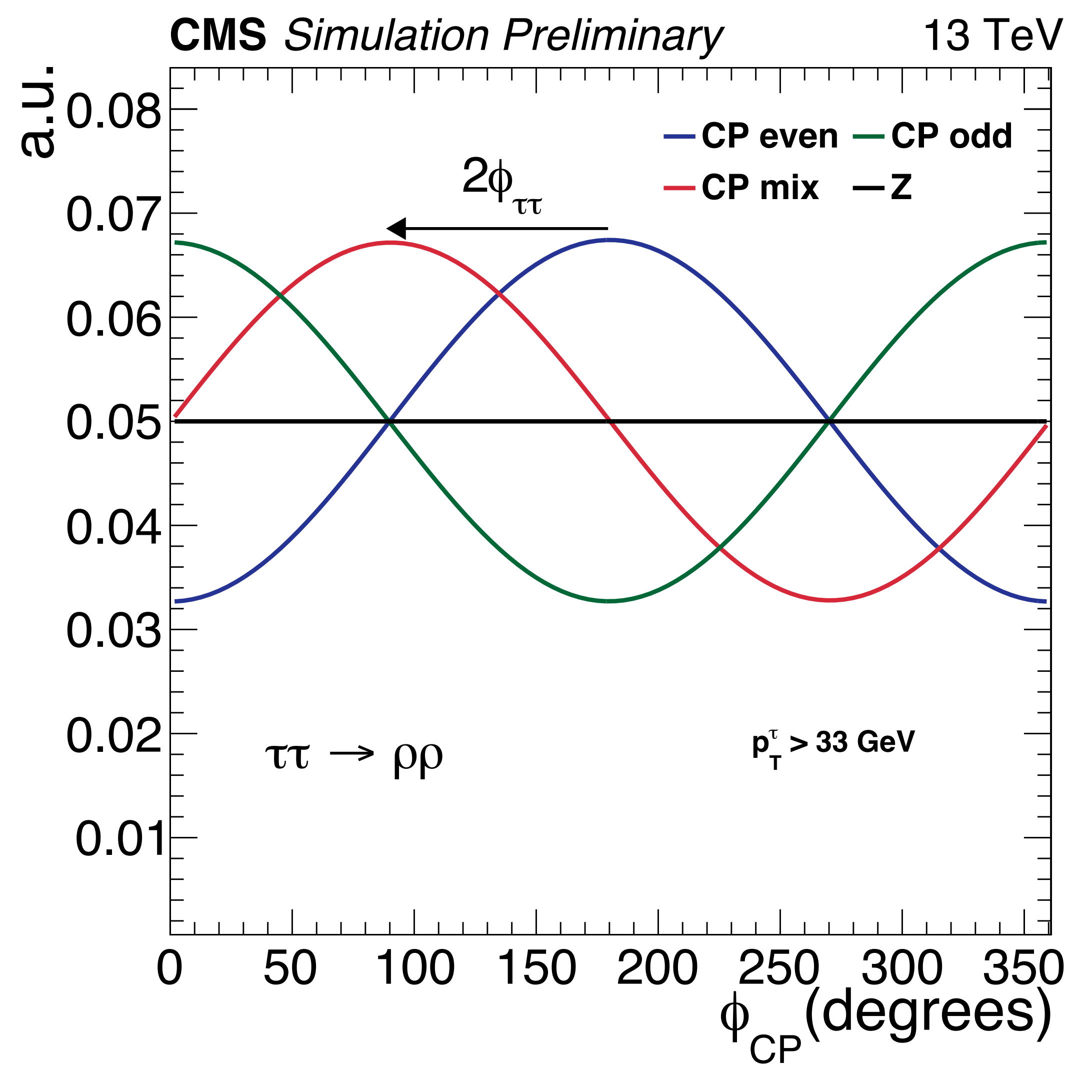




The π^0 method

- For events with an intermediate resonances we can define a variable using only visible decay products
  - e.g $\tau\tau \to \rho^+\nu\rho^-\nu \to \pi^+ \pi^0\nu\ \pi^- \pi^0\ \nu$
- 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

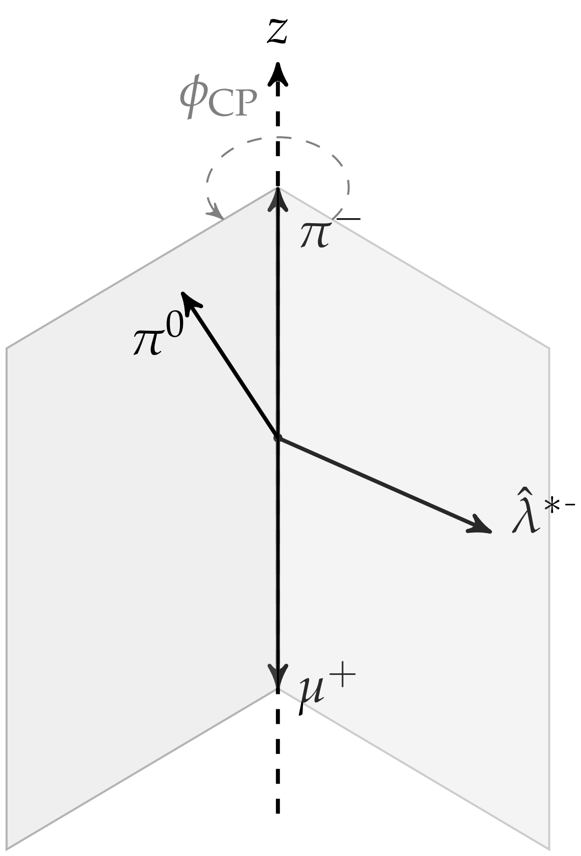


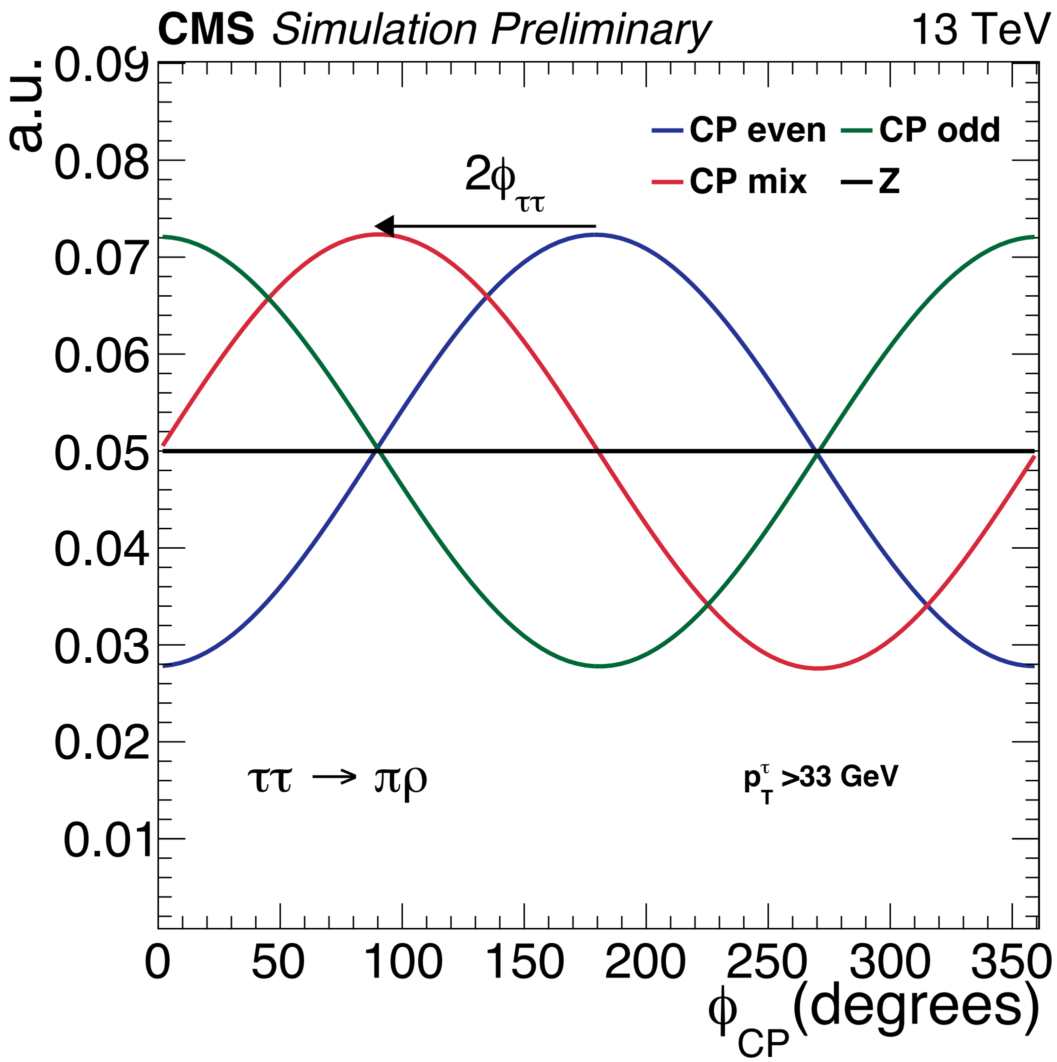


The “mixed” method

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

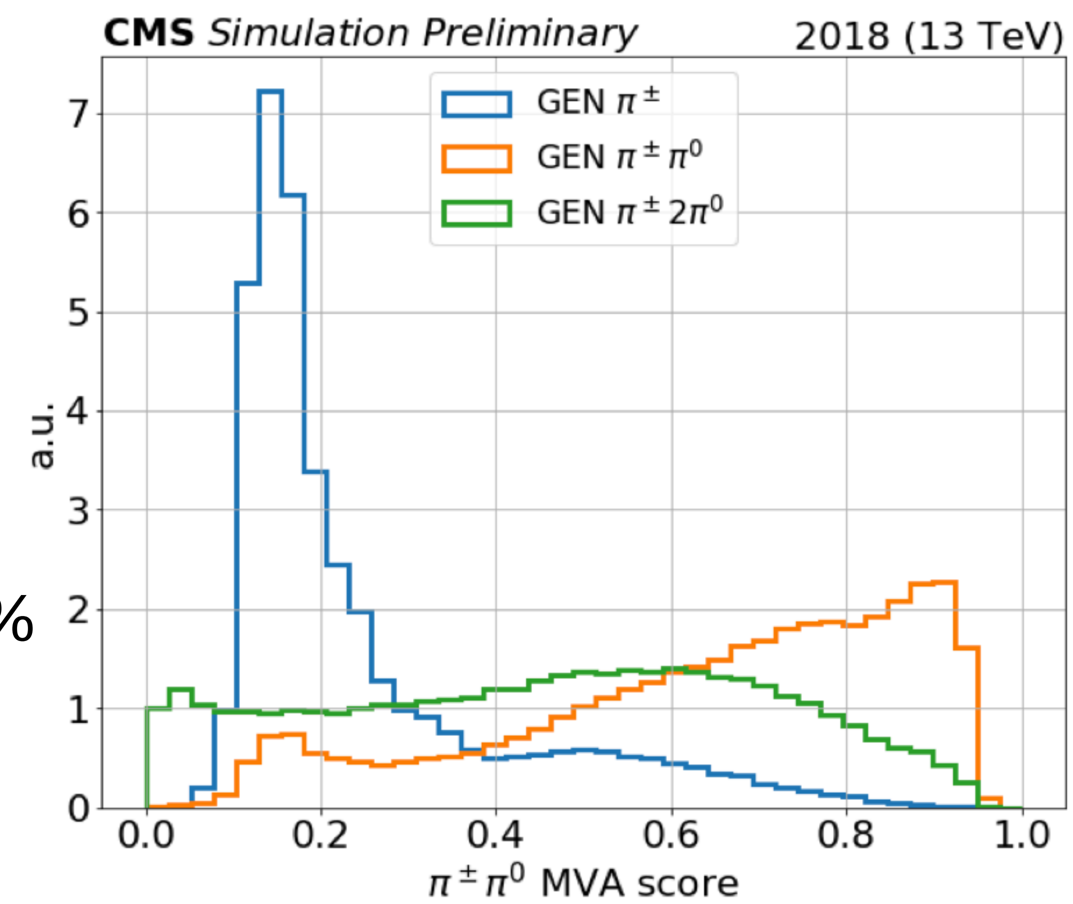
- E.g for a $H \rightarrow \tau\tau \rightarrow \rho^+ \nu \mu^- \nu \rightarrow \pi^+ \pi^0 \nu \mu^- \nu\nu$





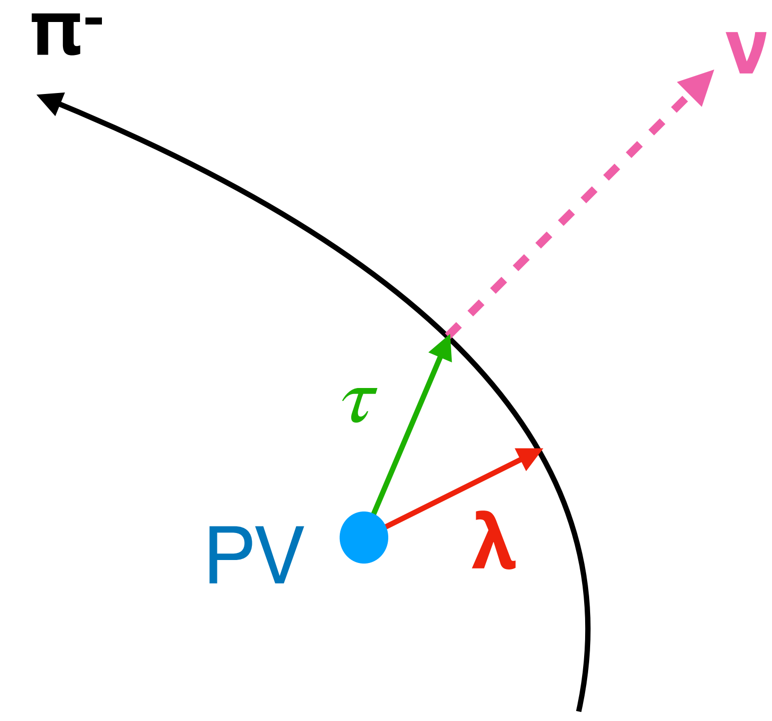
Tau decay mode selection

- 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, γ pT; angular observables; variables sensitive to γ density such as N_γ
- 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

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

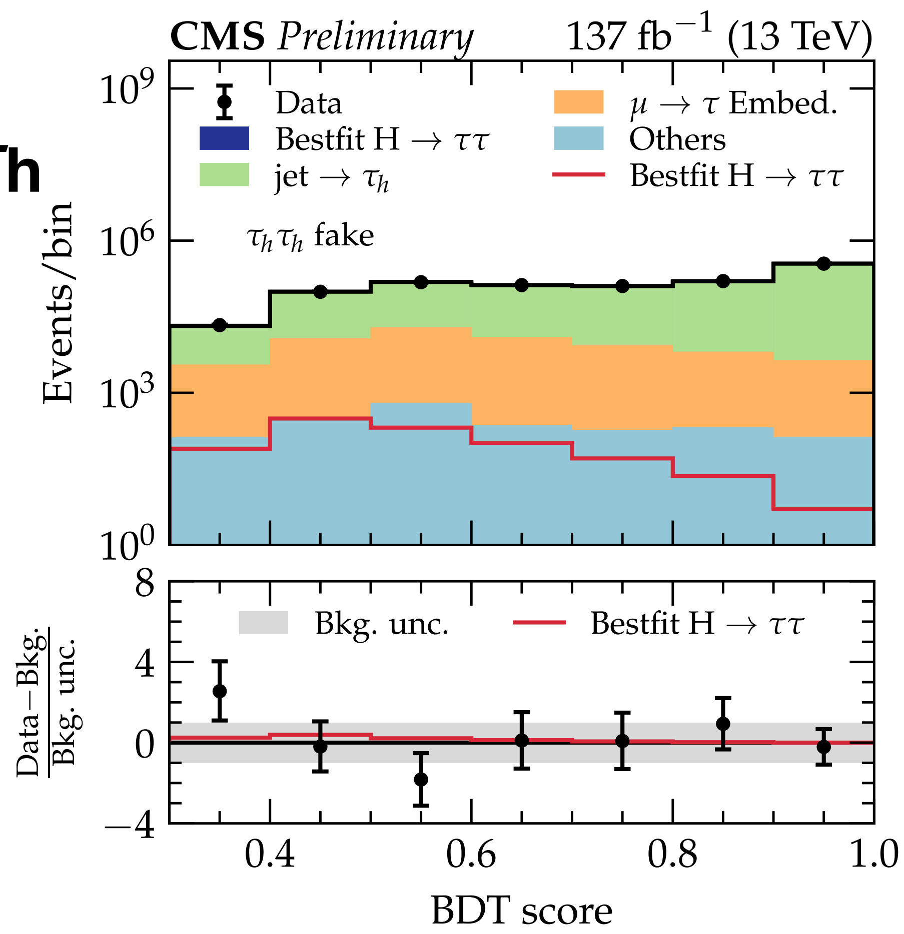
MVA signal vs background

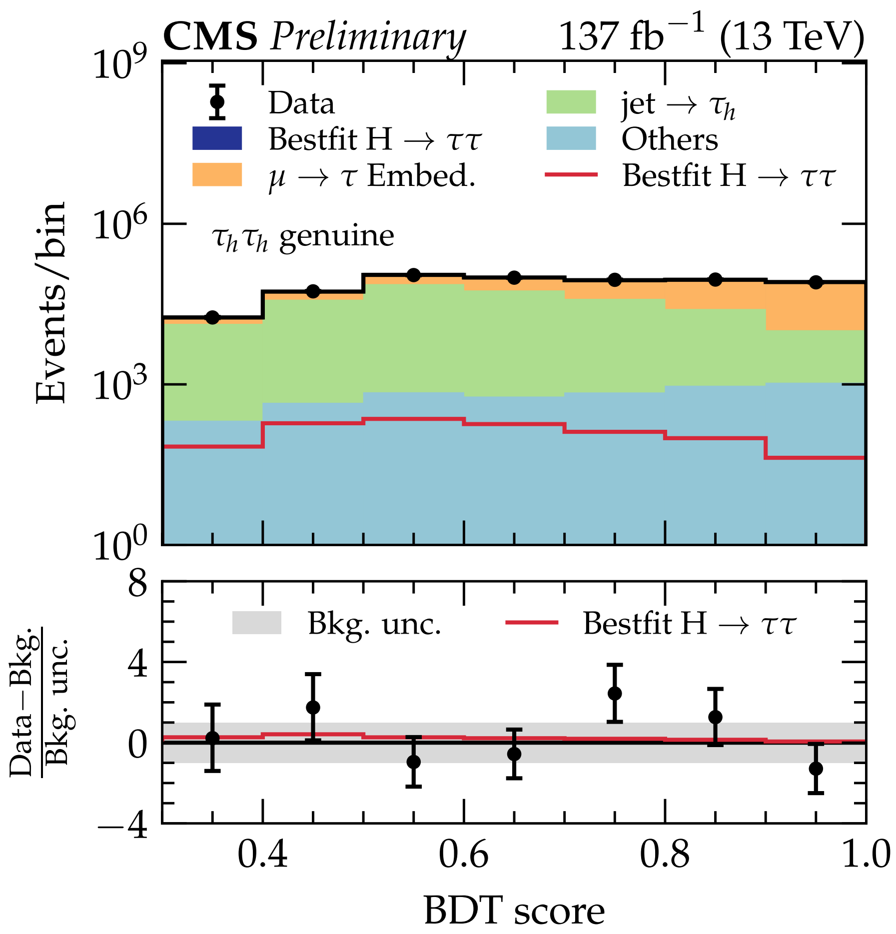
- Event after apply previous event selections the background is significantly larger than the signal (S/B ~ 0.006)
- We use multi-class MVAs to improve separation between the backgrounds
  - 2 background classes: genuine-τ_h and fake-τ_h, + 1 inclusive Higgs signal class
- For $\tau_h\tau_h$ ($\tau_\mu\tau_h$) channel we use BDT (NN)
  - Includes several variables such as: p_T's, $m_{\tau\tau}$, N_{jets}, 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





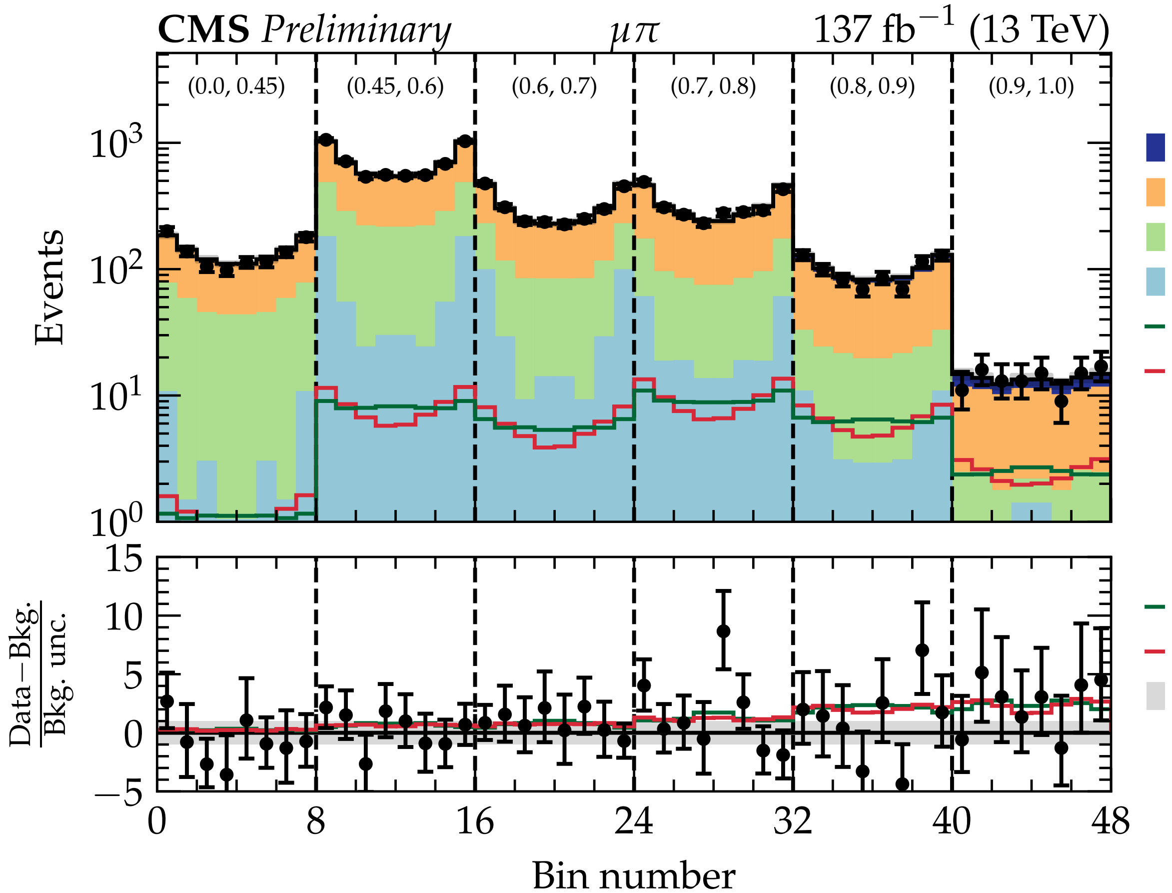
genuine-τ_h

Signal categories

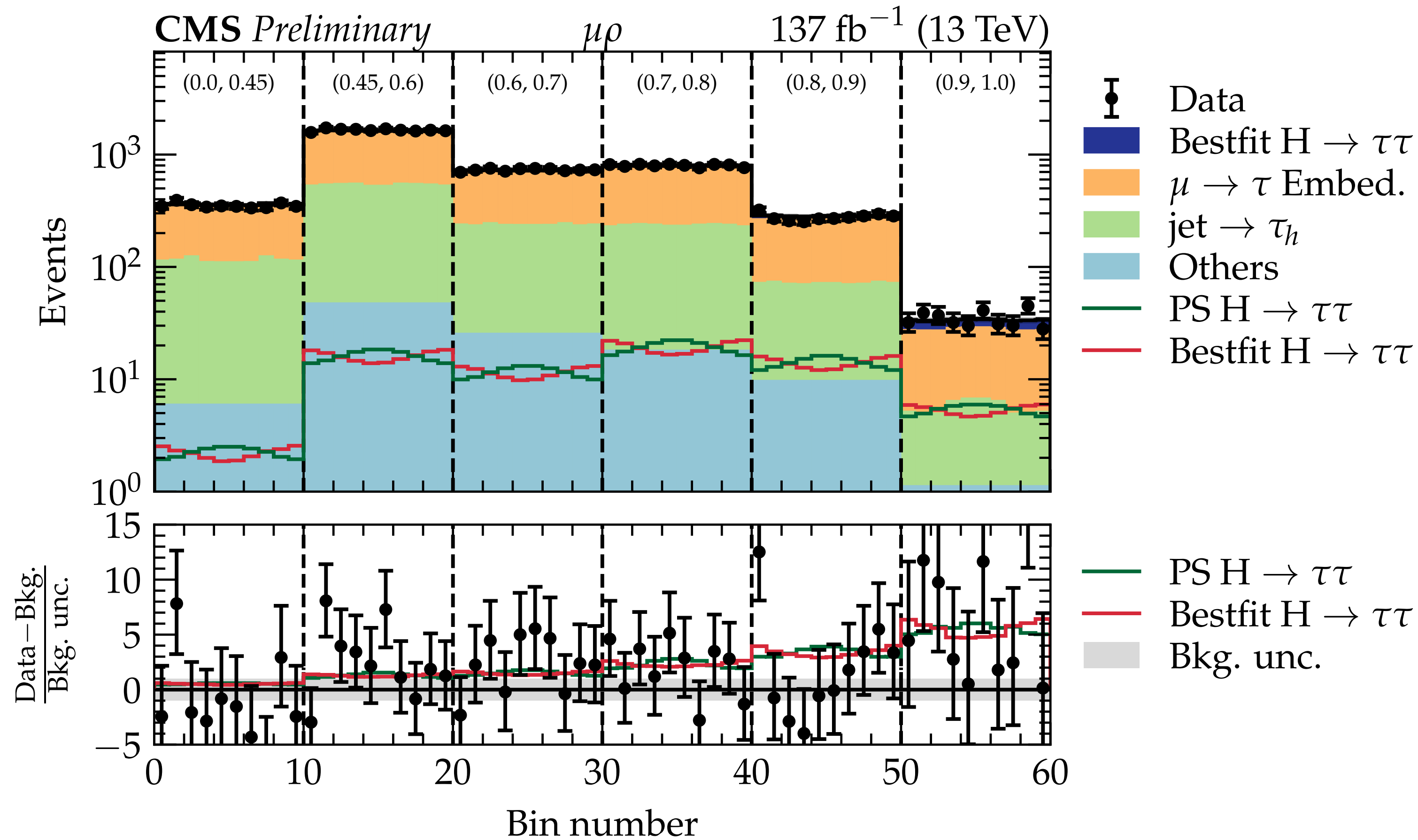
- For the Higgs signal category we further divide events depending on the τ_h decay mode

- We fit 2D variables: 1 variable is the MVA score, the second is ϕ_{CP}

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

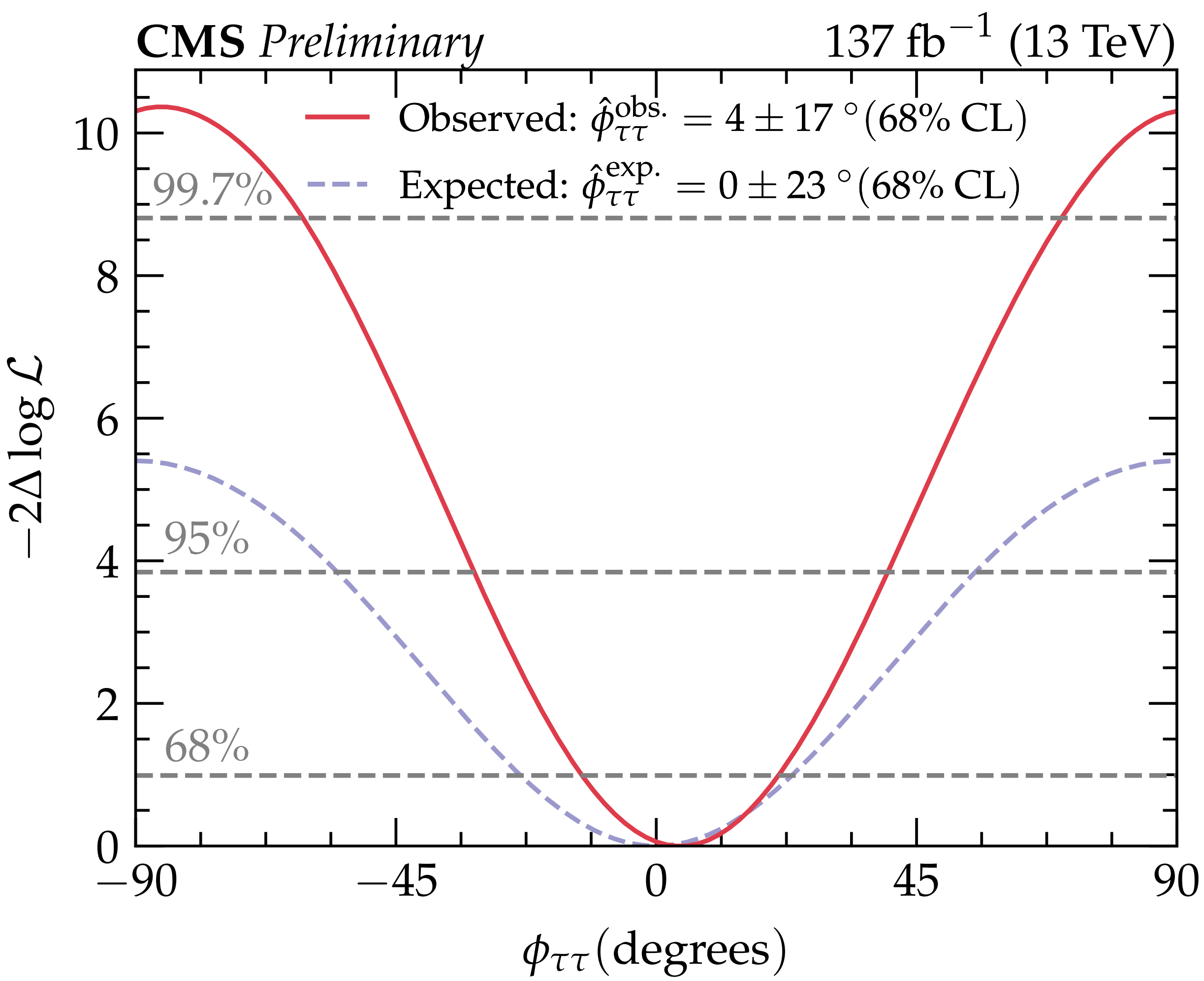


$\tau_\mu\tau_h$, $\tau_h \rightarrow \rho^-\nu$



Results

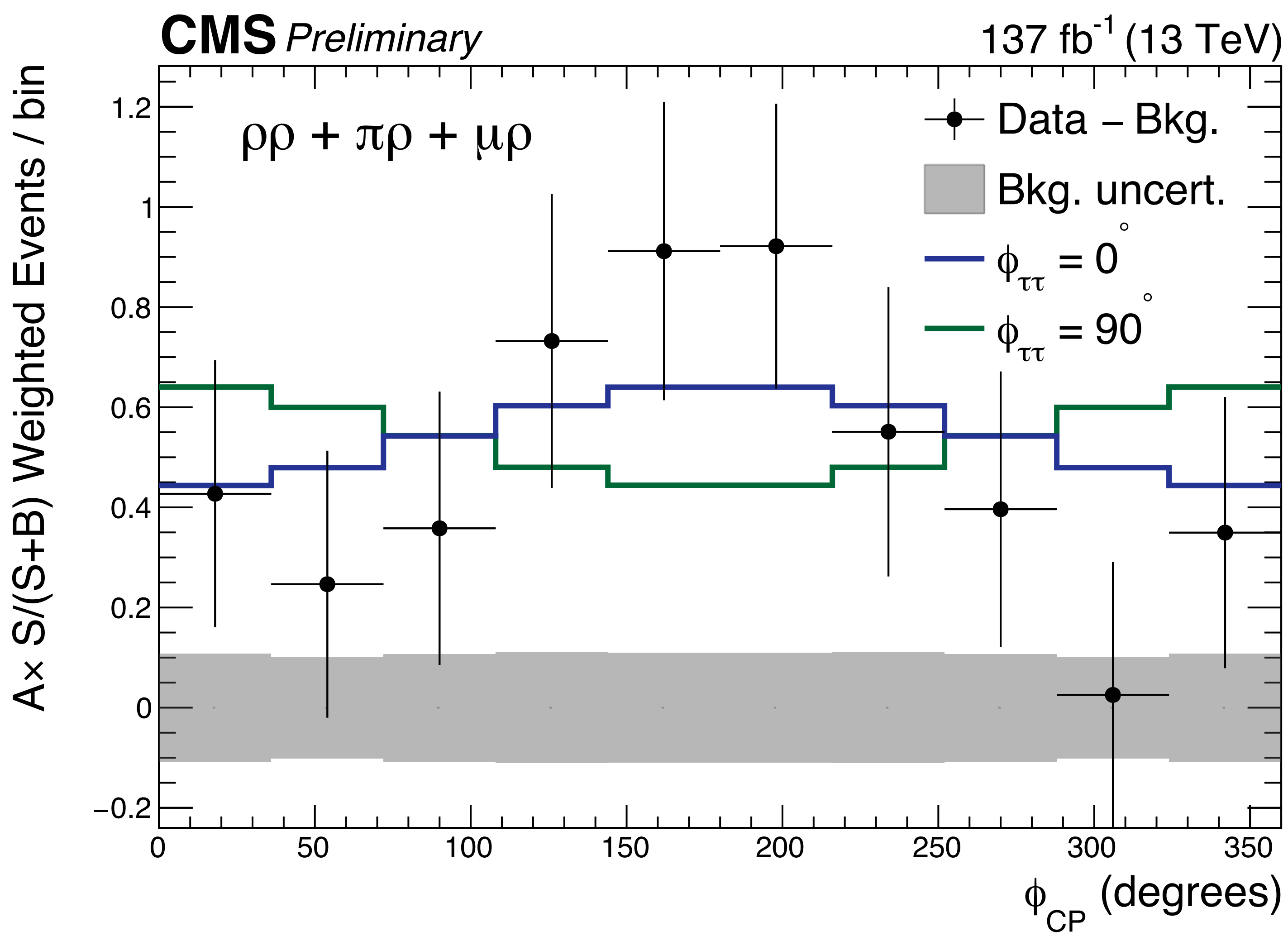
- We extract out results by means of a binned maximum likelihood fit combining all channels and categories
- The observed (red) and expected (blue) -2Δlog(L) scan is shown below
- The best fit value and uncertainty is 4 ±17^{o} compared to an expected value of 0 ± 23^{o}
- Results are therefore in agreement 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



- 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

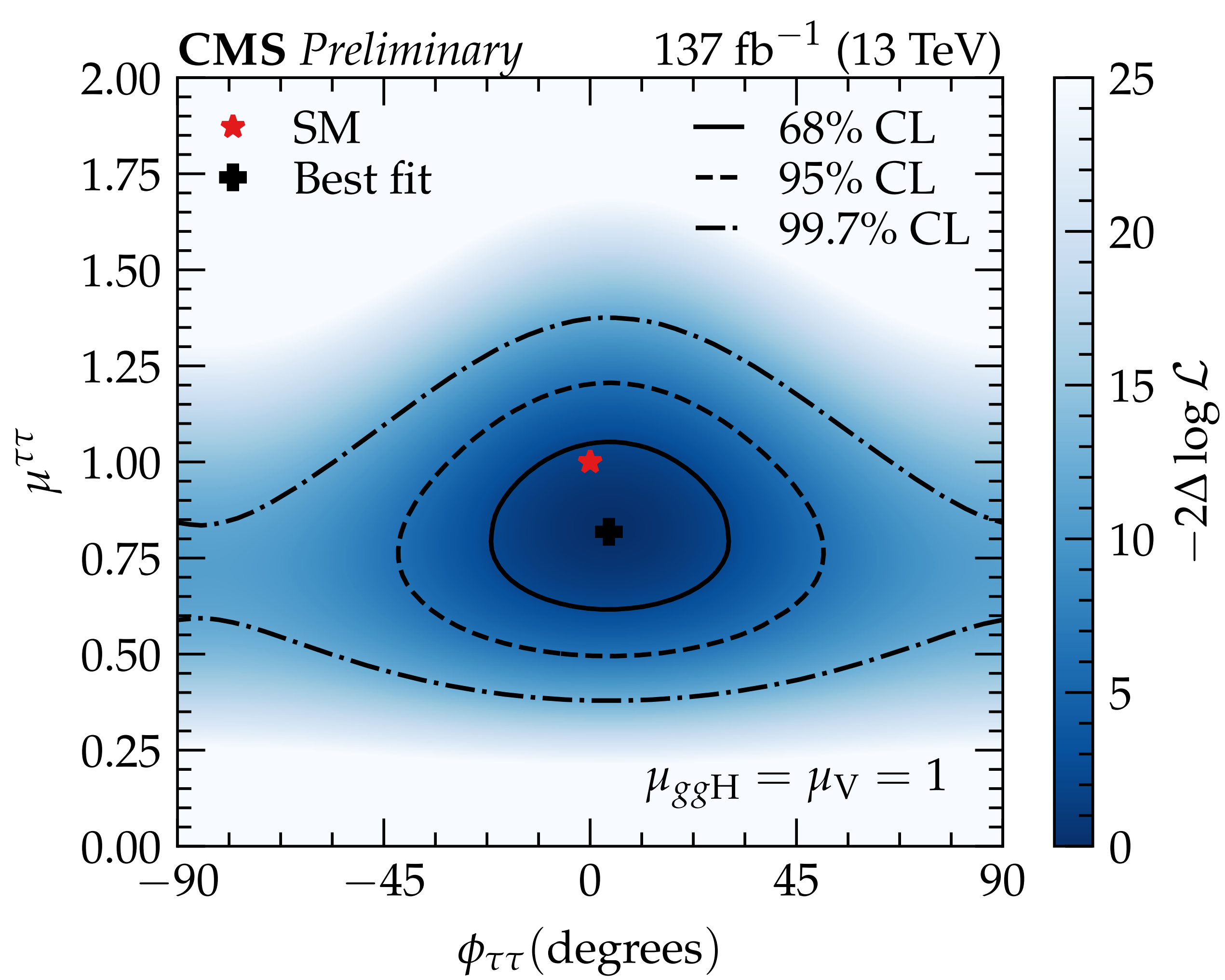
- A is the "average asymmetry" = sum of absolute differences between CP-even and CP-odd for all bins / N_{bins}

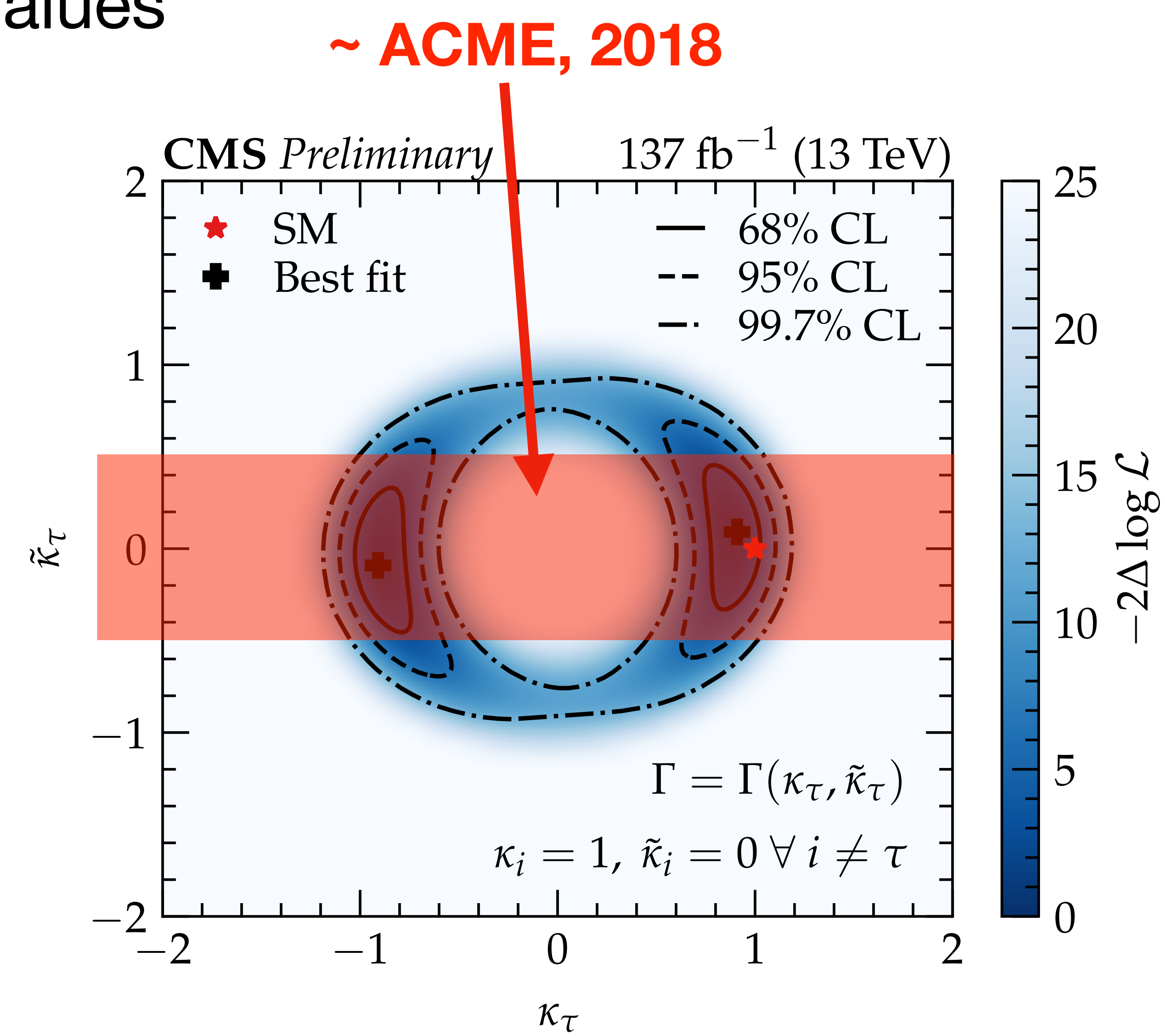


2D scans and coupling measurements

- 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





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°

Conclusions

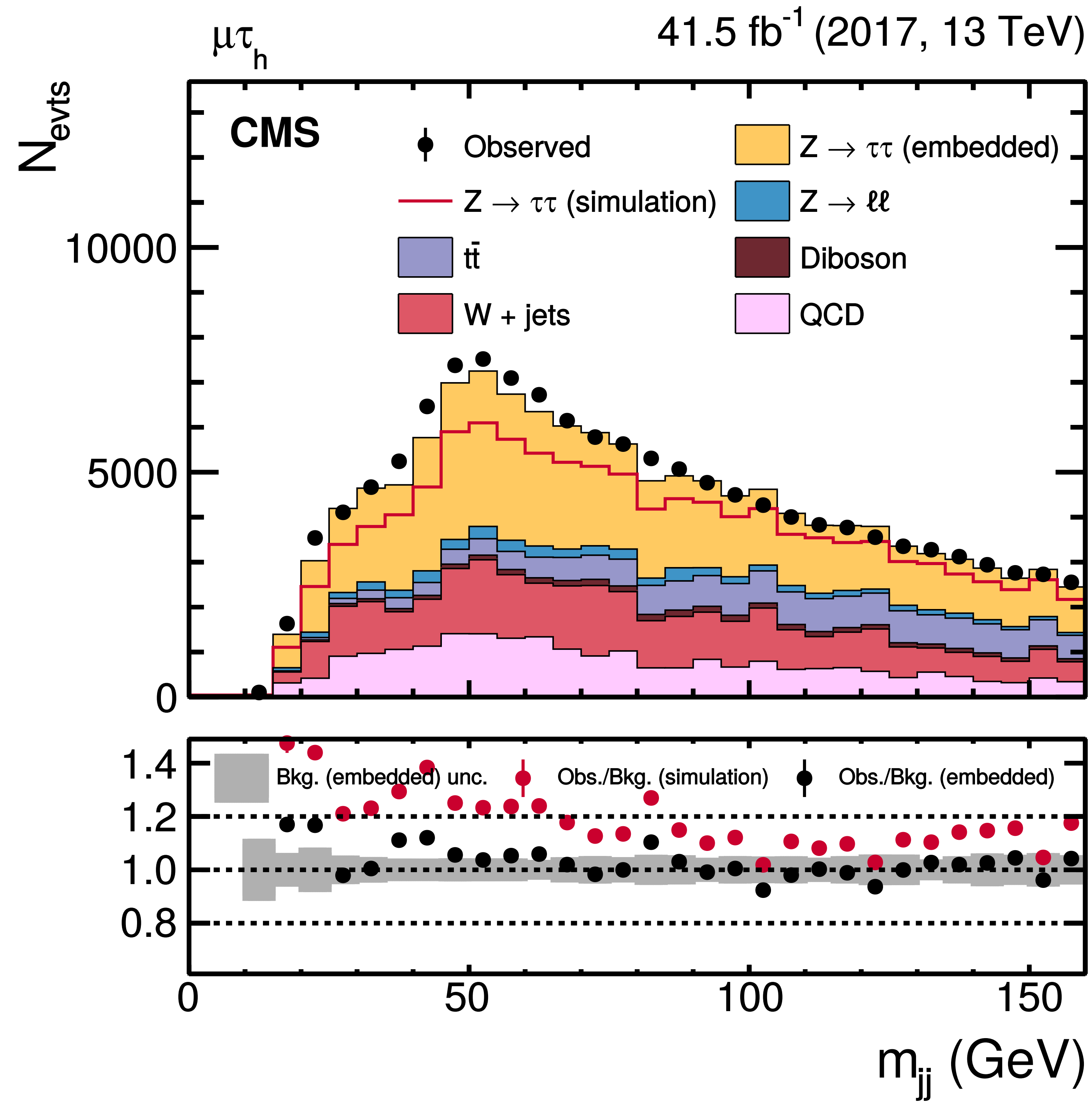
- The latest Higgs cross section and coupling measurements by the CMS experiment have been presented
- Current best fit value of Higgs production cross section is 0.85 ± 0.12 times the SM expectation
- Presented the first CP property results from the CMS collaboration using Run 2 data (2016-2018)
  - Current best measurement: $\phi_{\tau\tau} = 4 \pm 17^{o}$
  - Pure CP-odd hypothesis excluded at 3σ level

Thanks for your attention!

Backup

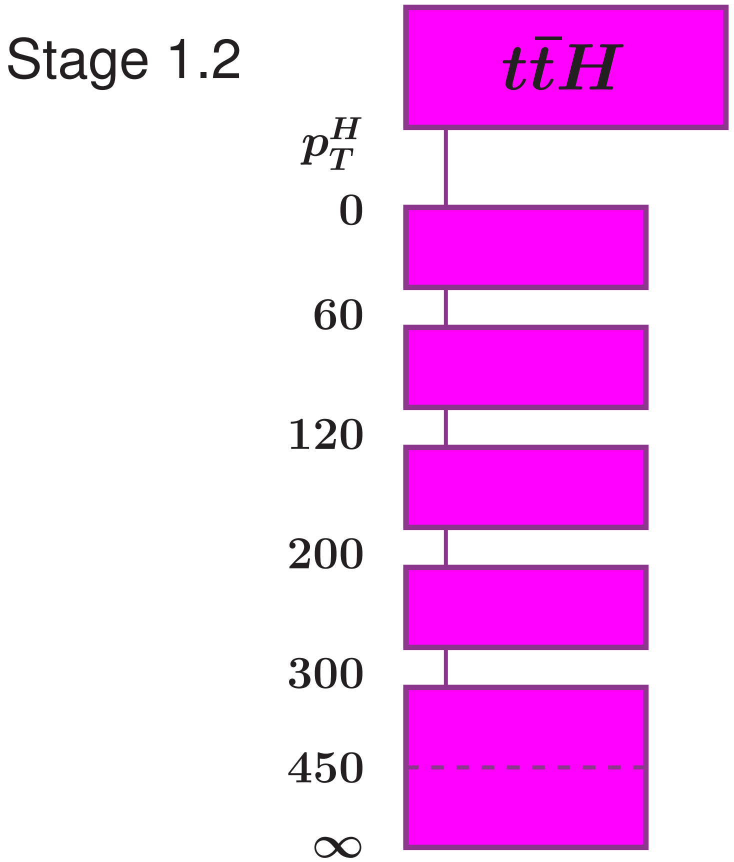
Embedding method vs pure MC simulations

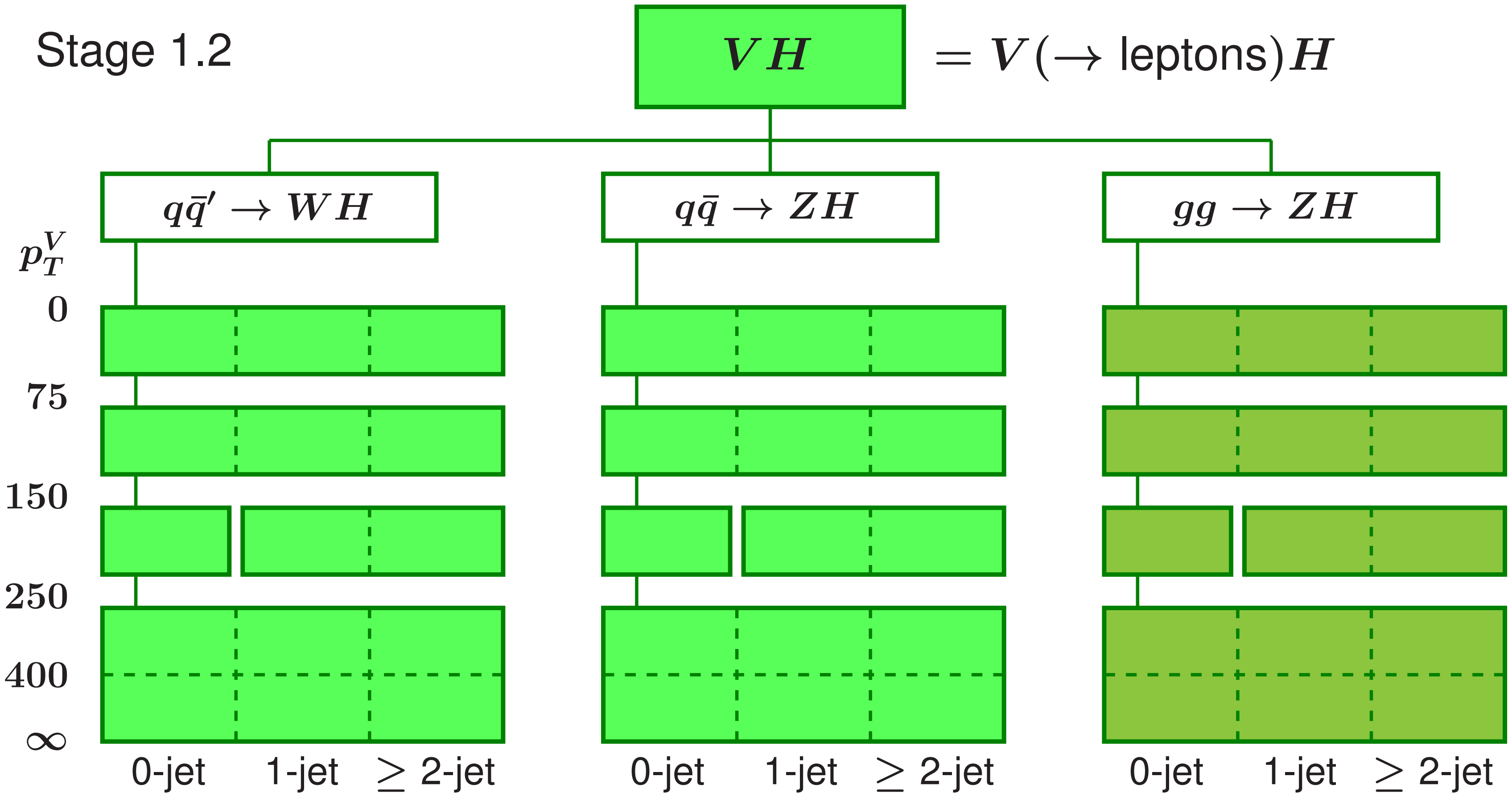
- Embedding method brings improvements in description of the data
- All objects except simulated tau leptons come from real data events so are described perfectly (e.g jets)
- For example the di-jet invariant mass distribution (right) is described much better for embedding (black points) vs pure MC simulations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



STXS: ttH and VH

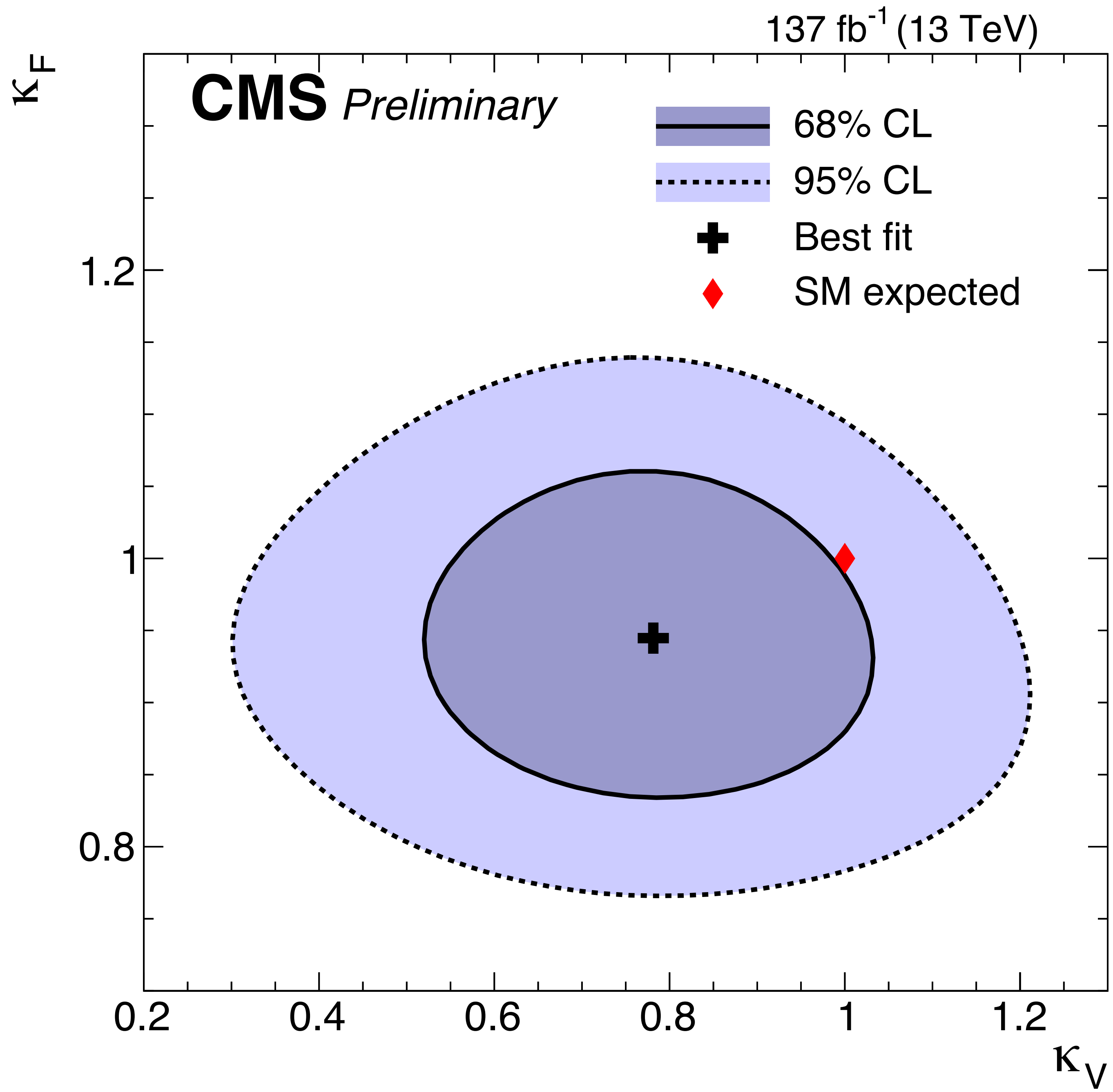
- Also STXS bins defined for VH (V→leptons), and ttH



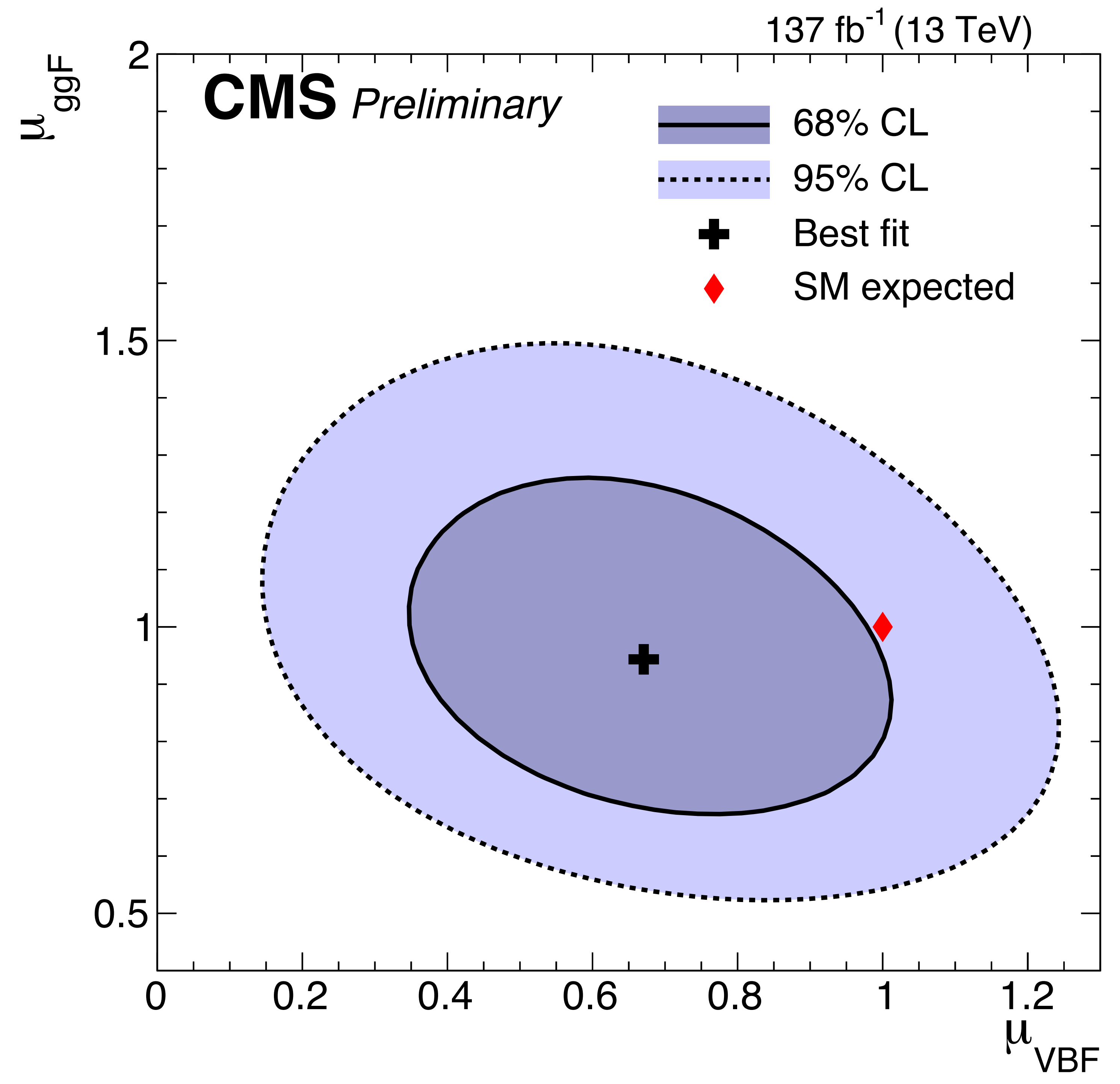


Results: coupling measurements

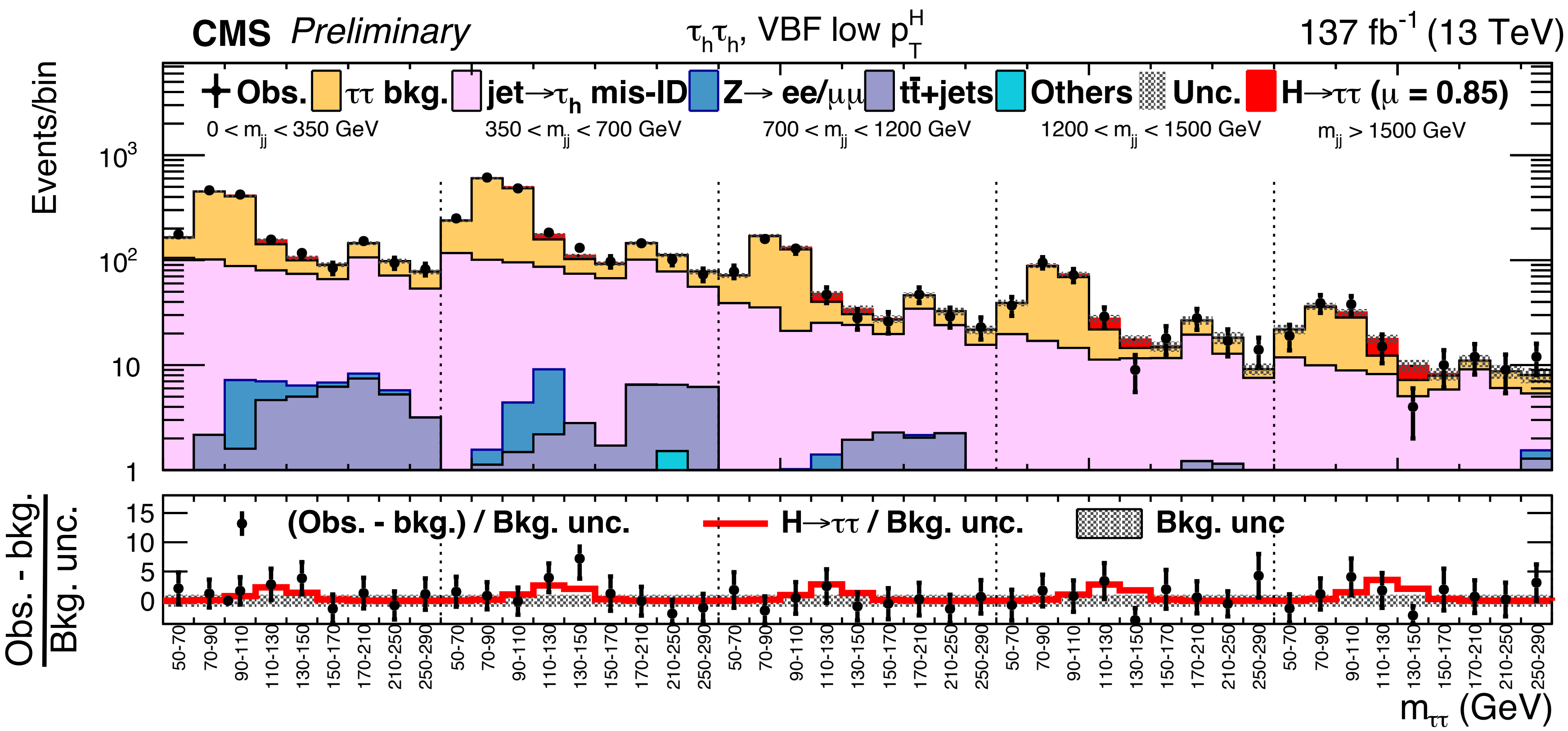
- The results are also interpreted in terms of coupling strength modifiers
- Here we assume common coupling modifiers for fermions (κ_f) and bosons (κ_V)
- Coupling strength modifiers = coupling relative to the SM expectation e.g $\kappa_\tau = y_\tau / y_\tau^{SM}$

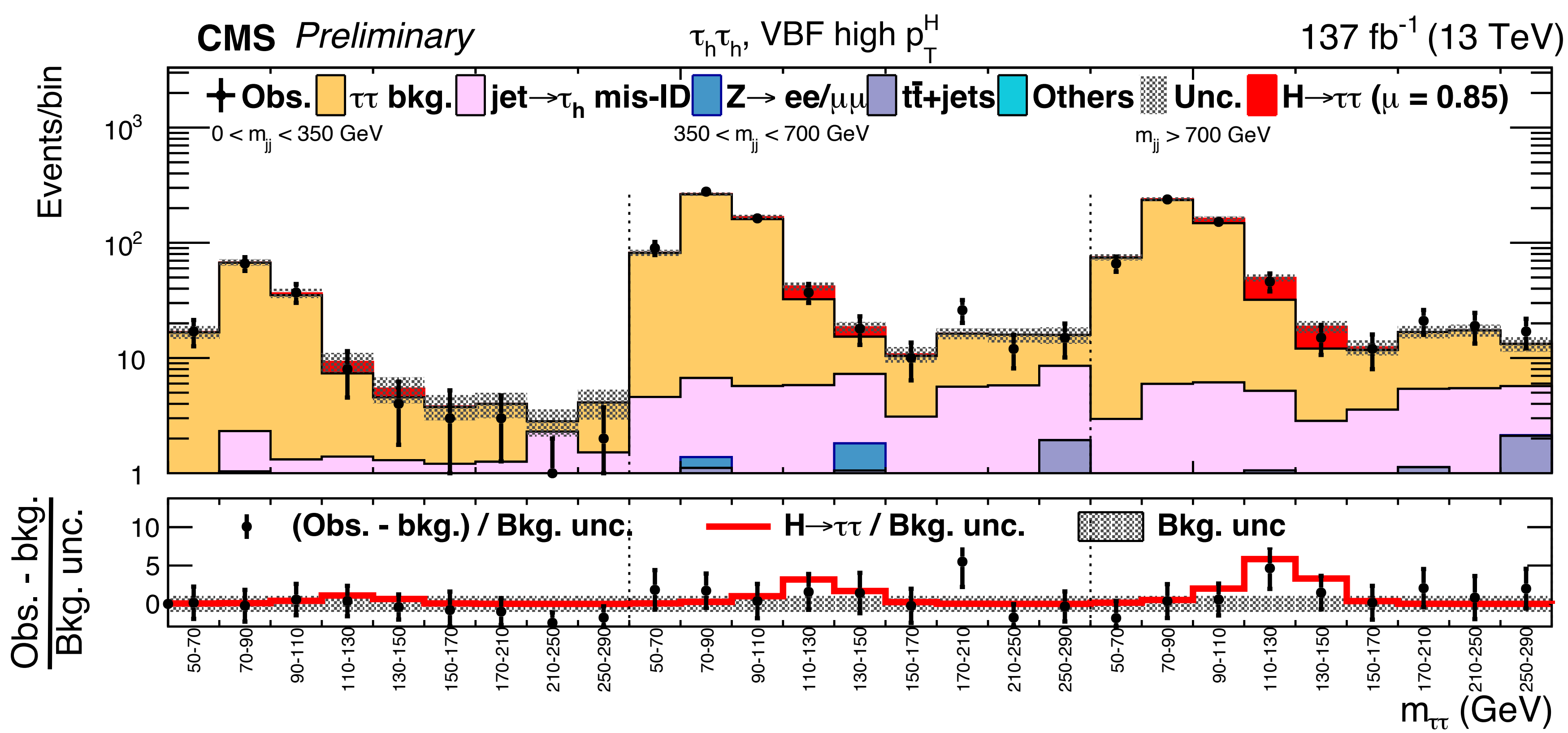


2D scans of ggH and VBF cross sections



Signal extraction: additional examples of fitted distributions





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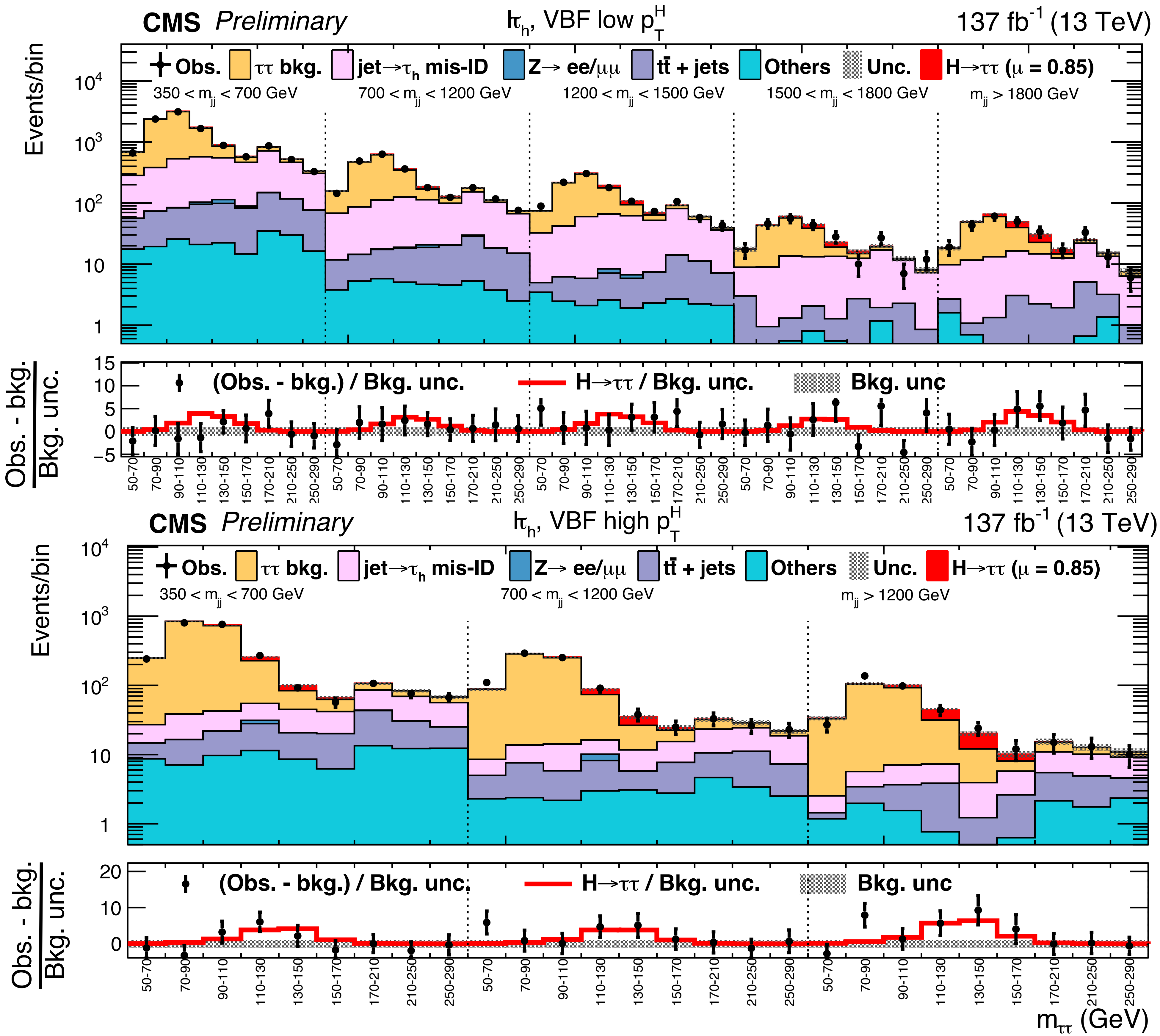


C2HDM: overview

- Compared to SM Higgs sector has one additional doublet

- 4 allowed types depending on which doublet the Higgs couples 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:

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

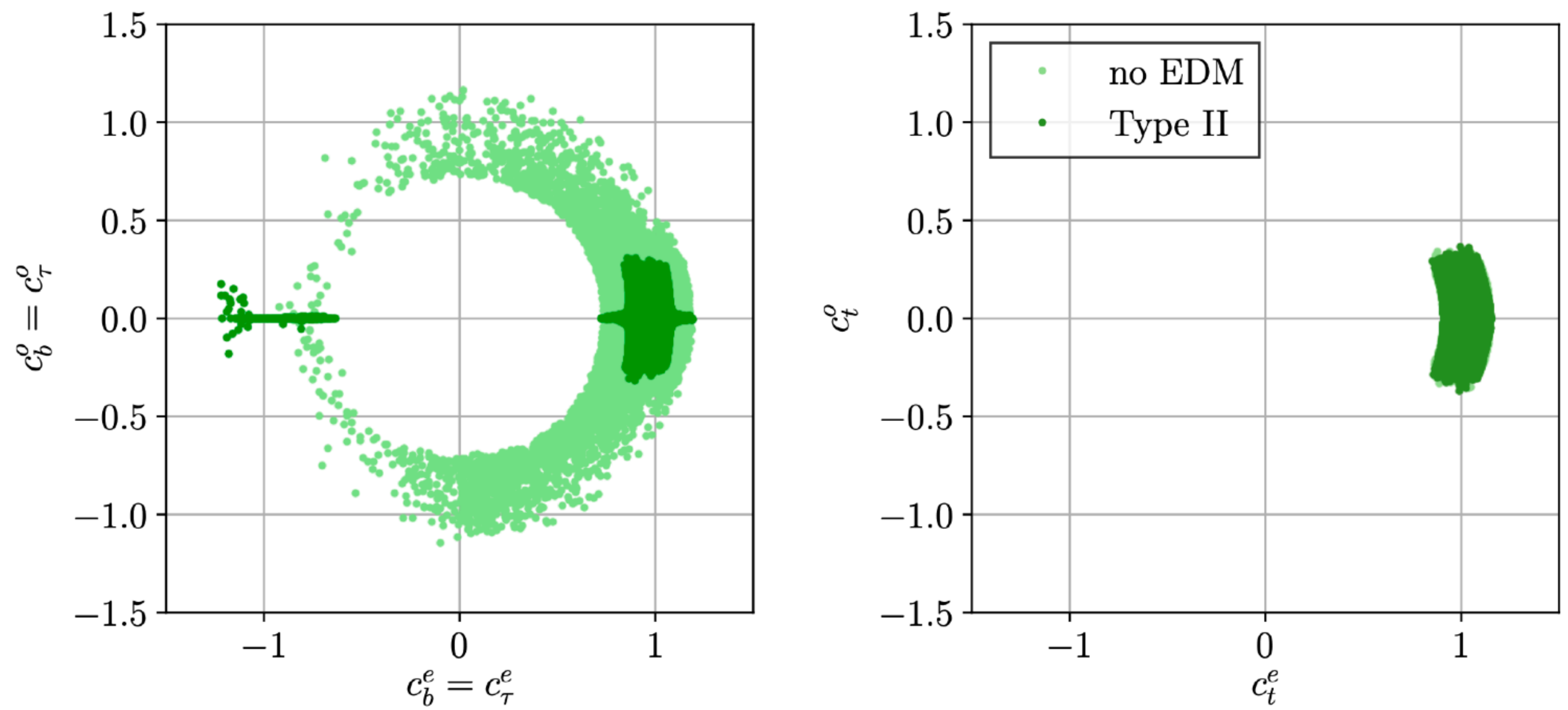
- Complex parameters m_{12}^2 and λ_5 allow CP-violation

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

C2HDM: Type 2

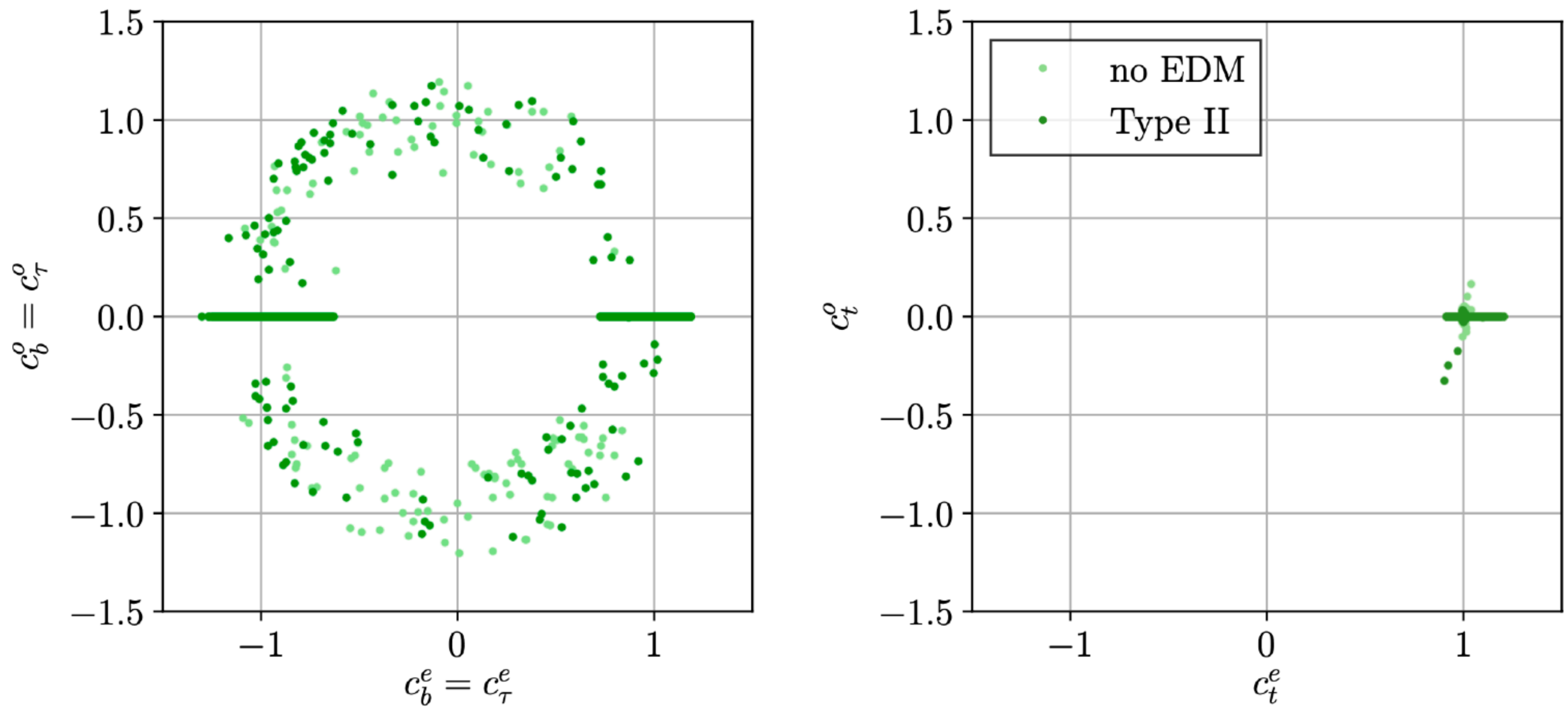
- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios
- In Type 2 2HDM where H_1 = 125 GeV boson
- EDMs constrain scenarios with large-iso $\bar{\kappa}_\tau$ quite alot



C2HDM: Type 2

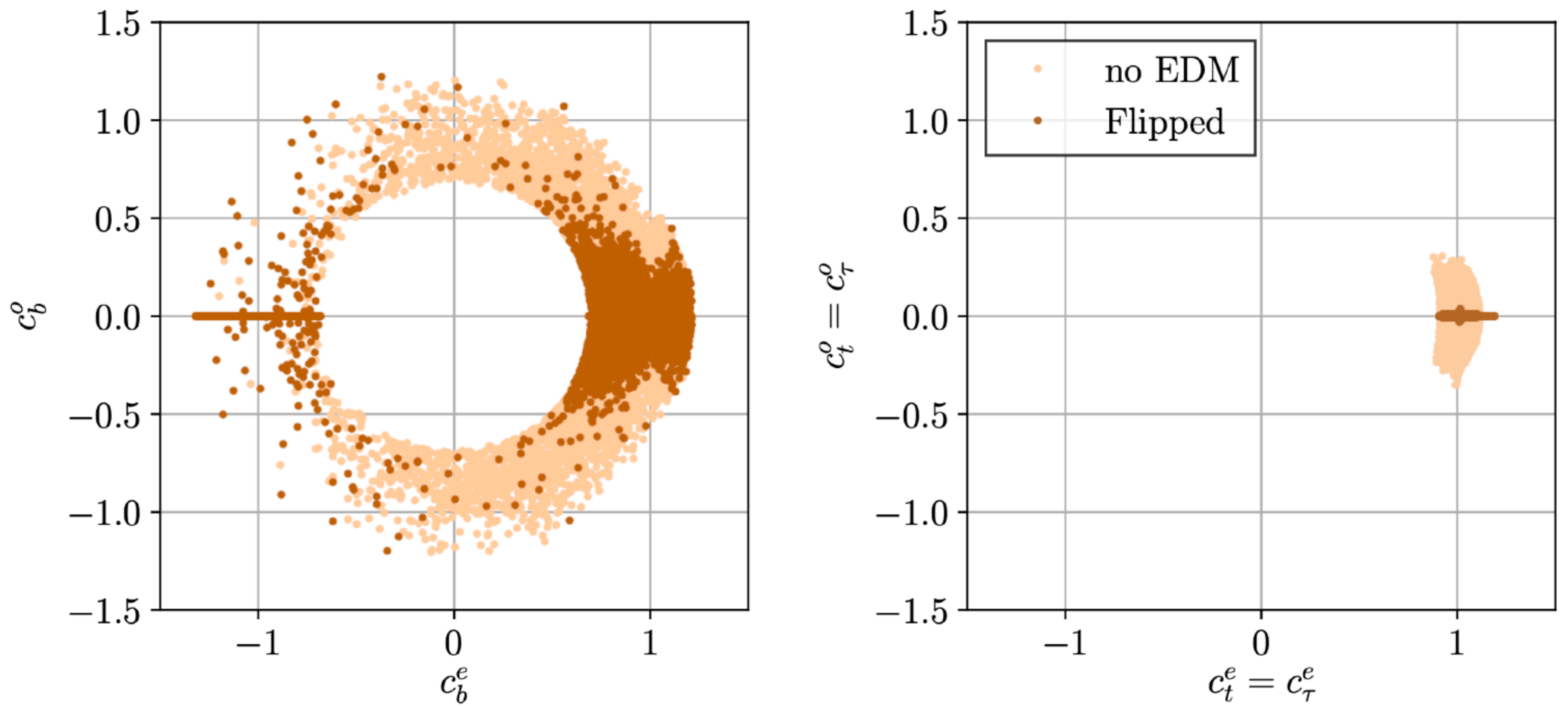
- In JHEP 02 (2018)073 they show allowed points for various 2HDM scenarios

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



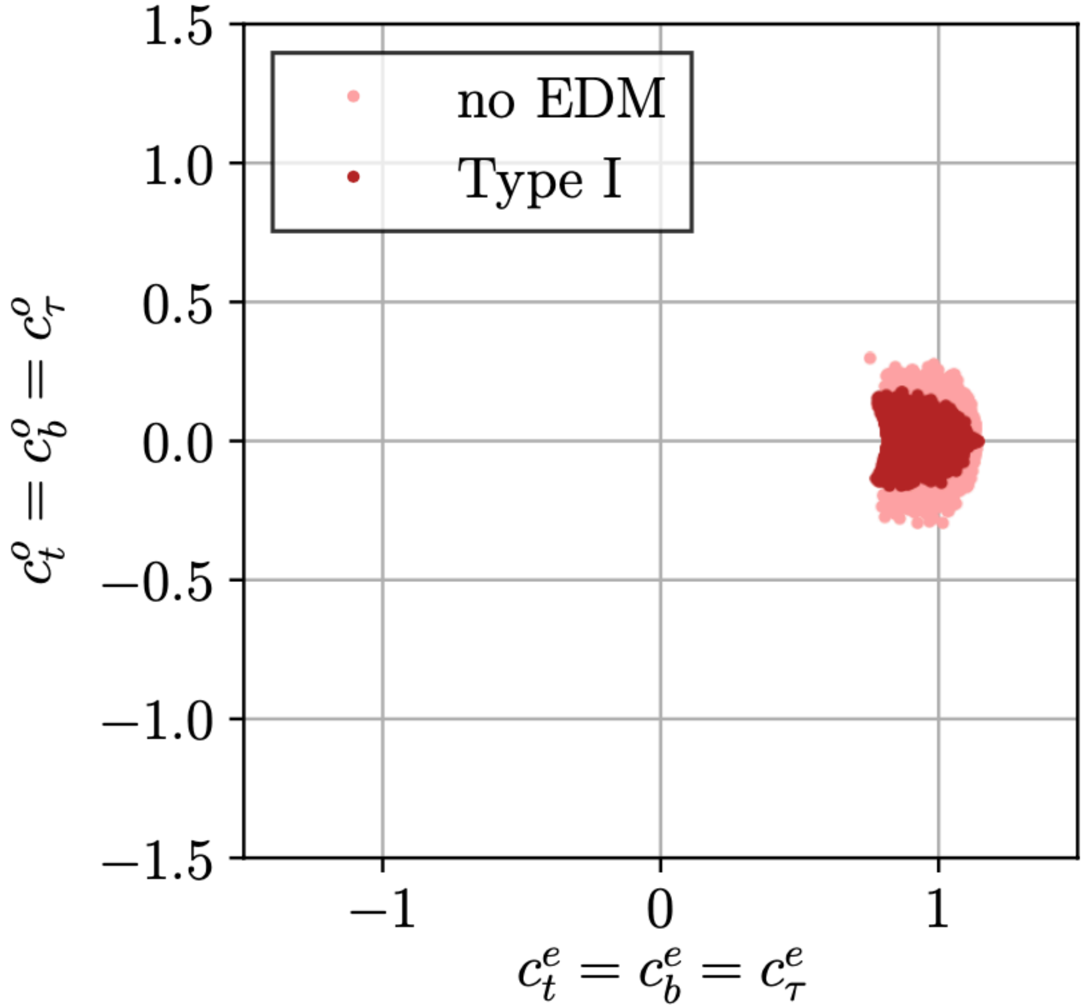
C2HDM: Type-Y

- 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



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

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

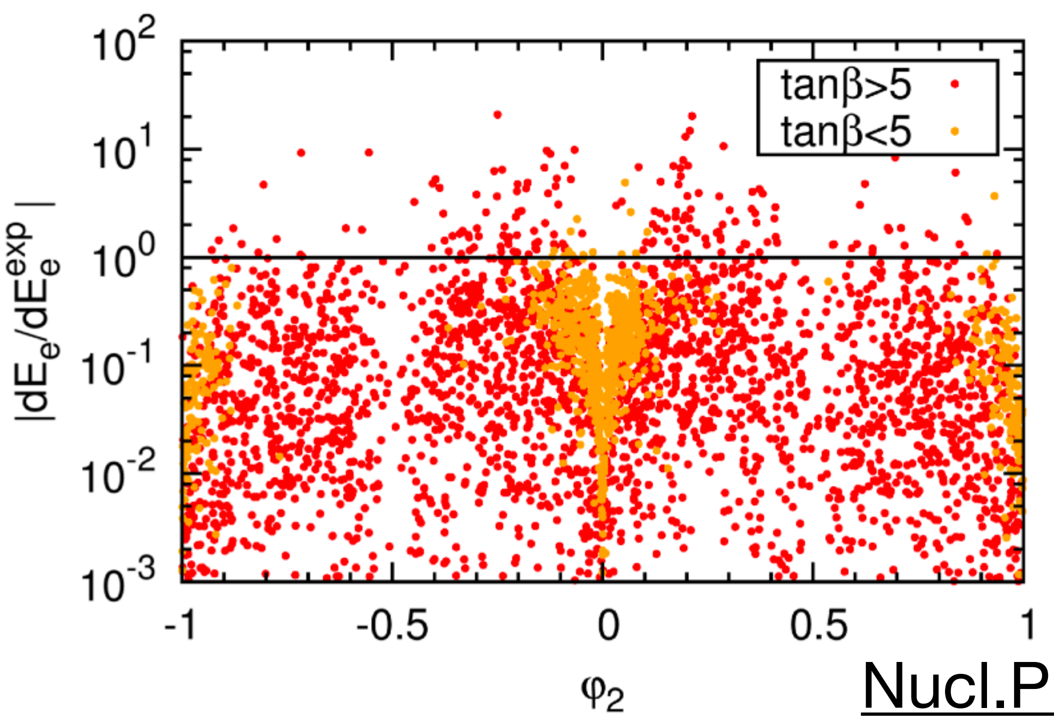
$$W_{NMSSM} = \lambda \hat{S} \hat{H}_u \hat{H}_d + \kappa \hat{S}^3$$

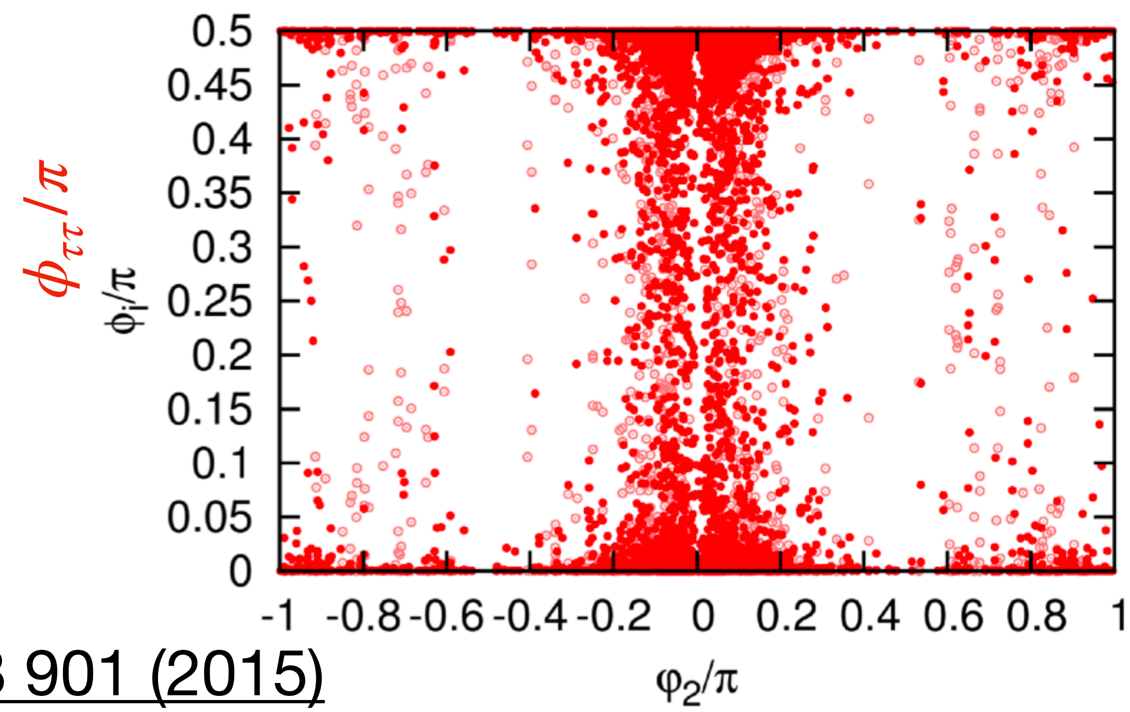
- In NSSM the μ parameter is generated as the vacuum expectation value of S

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

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° - using uses older ACME 2013 EDM constraints





Nucl.Phys.B 901 (2015)

NMSSM

- Higgs sector in MSSM is a type 2 2HDM
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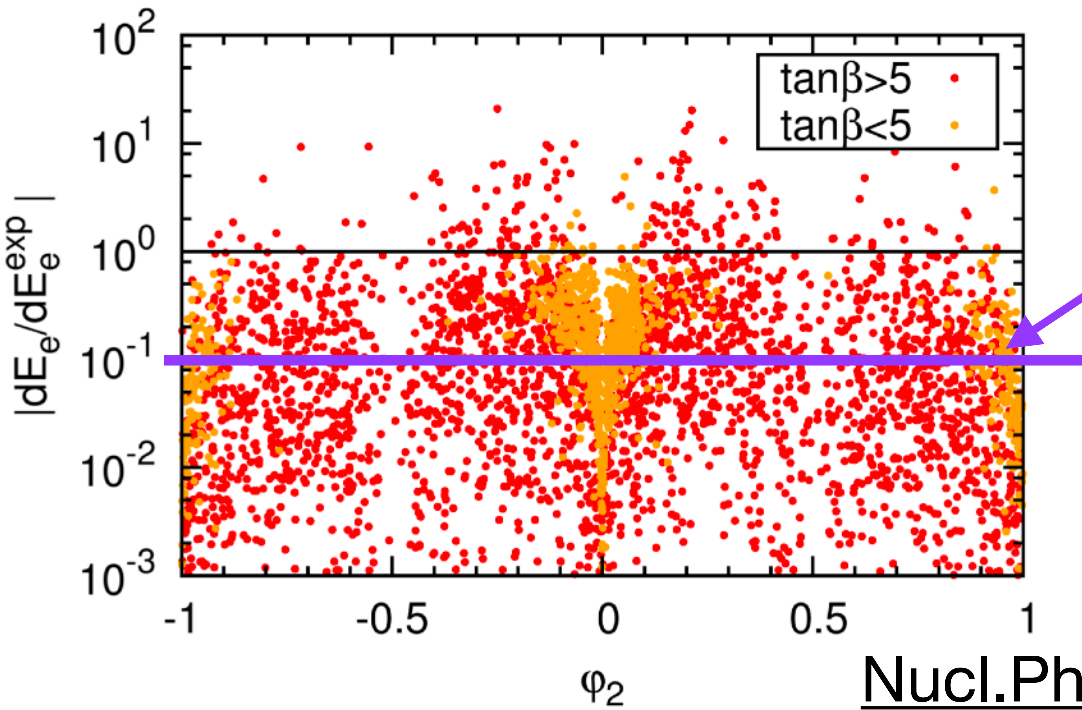
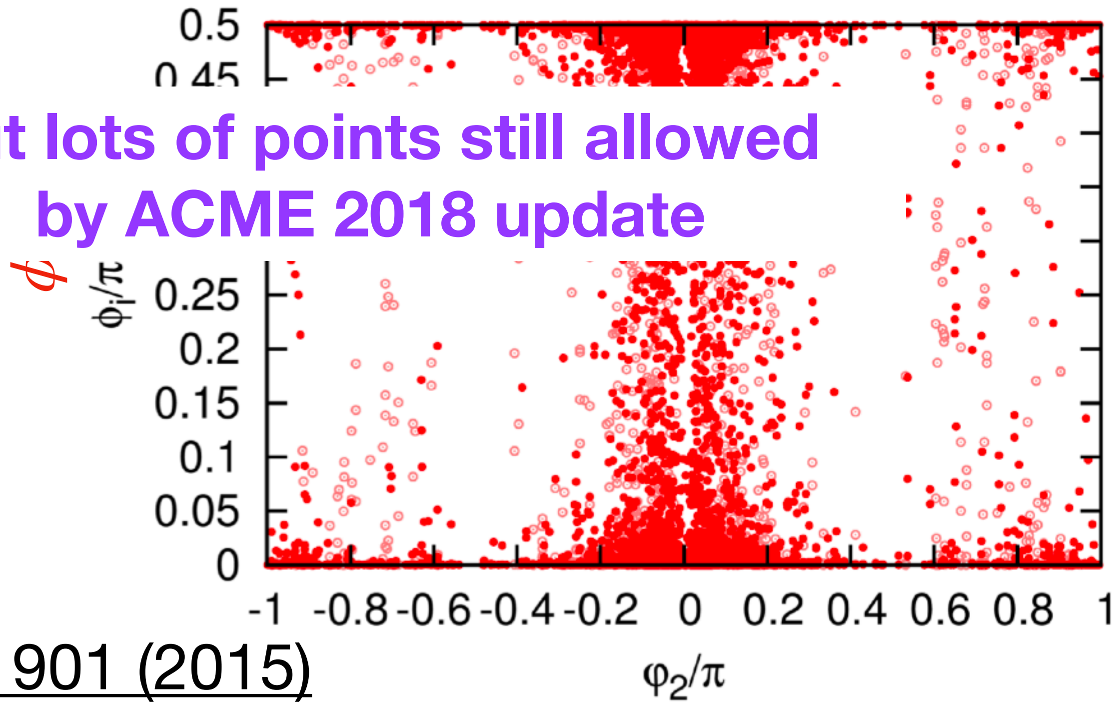
- In examples below solid points not excluded by theory/experiment including EDMs, open points = conflict with EDMs
  - Lots of points still allowed up to $\phi_{\tau\tau} \sim 27^o$ - using uses older ACME 2013 EDM constraints

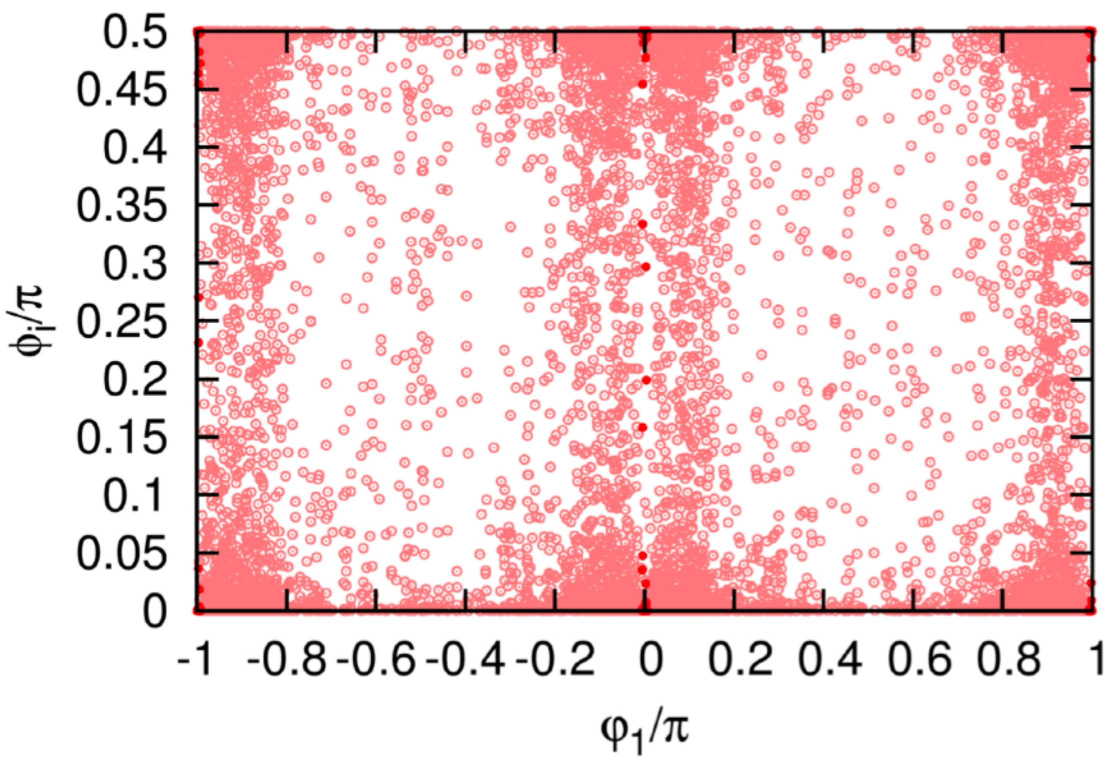


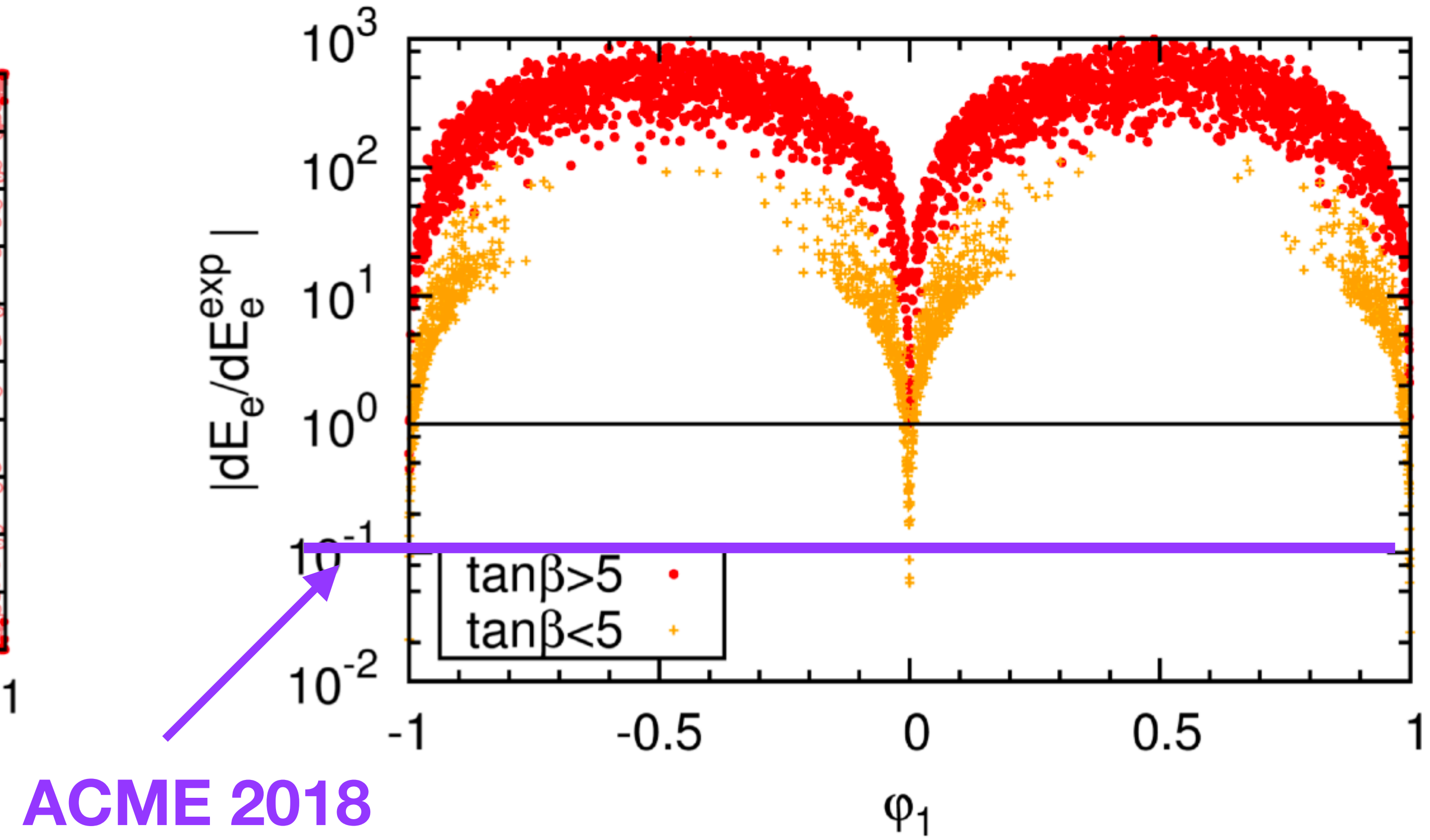
But lots of points still allowed by ACME 2018 update



Nucl.Phys.B 901 (2015)

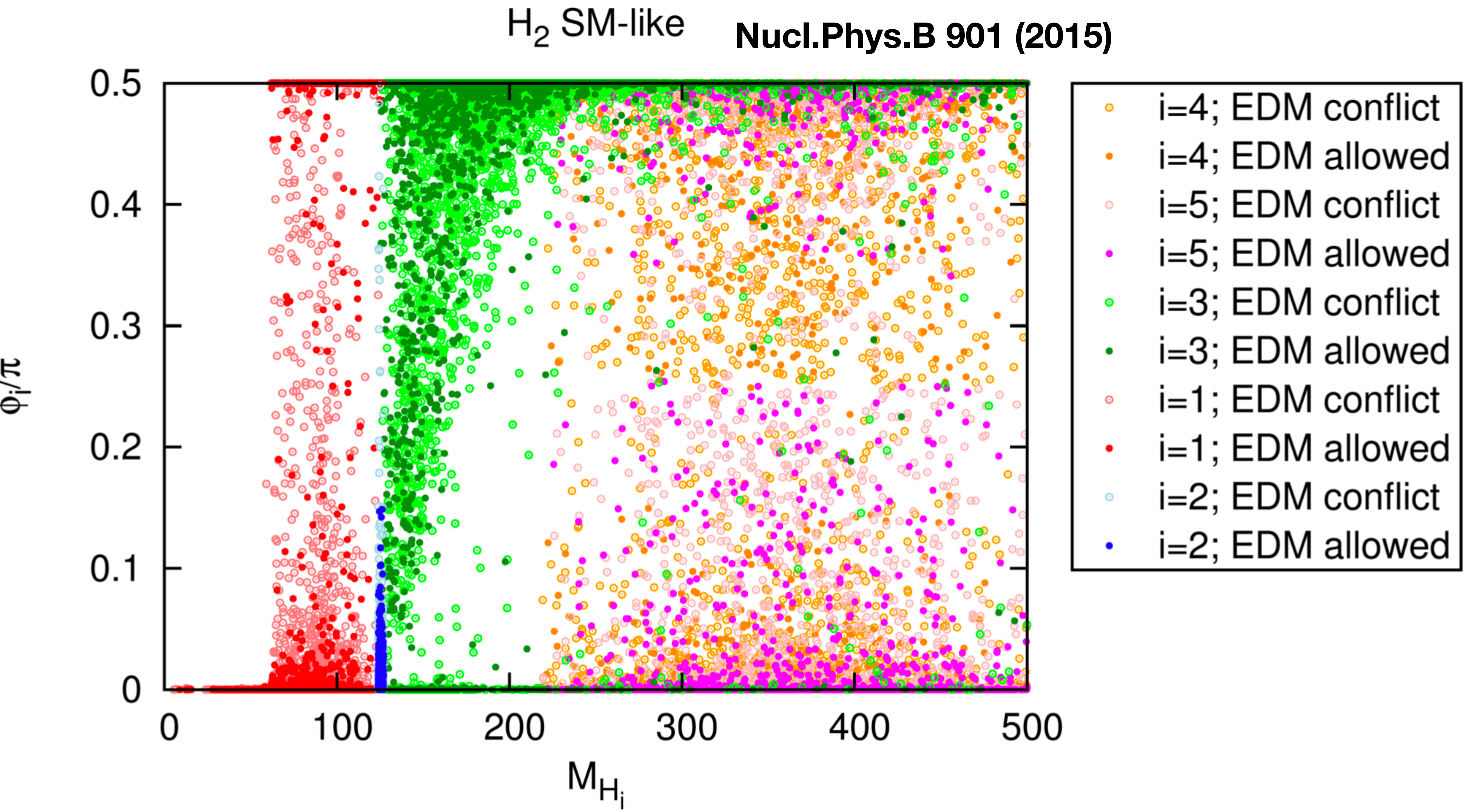
- MSSM-type CP-violation tightly constrained by EDMs
  - not many open points in left plot
  - Most points below EDM limit in right plot





Nucl.Phys.B 901 (2015)

- Allowed H_i masses



ϕ_{CP} formulas

- Formulas for IP-IP method:

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

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

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

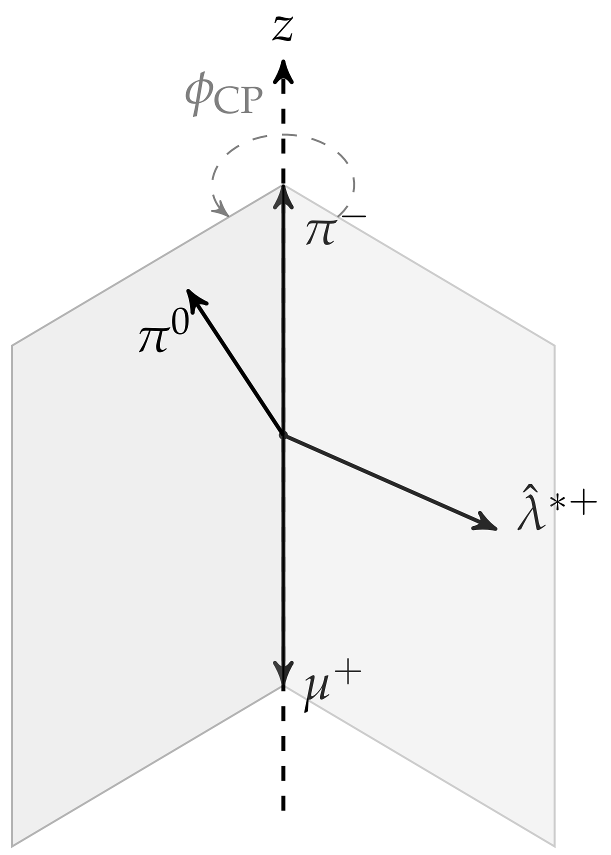
$$\phi_{CP} = 360^\circ - \phi^*, \text{ if } O^* < 0$$

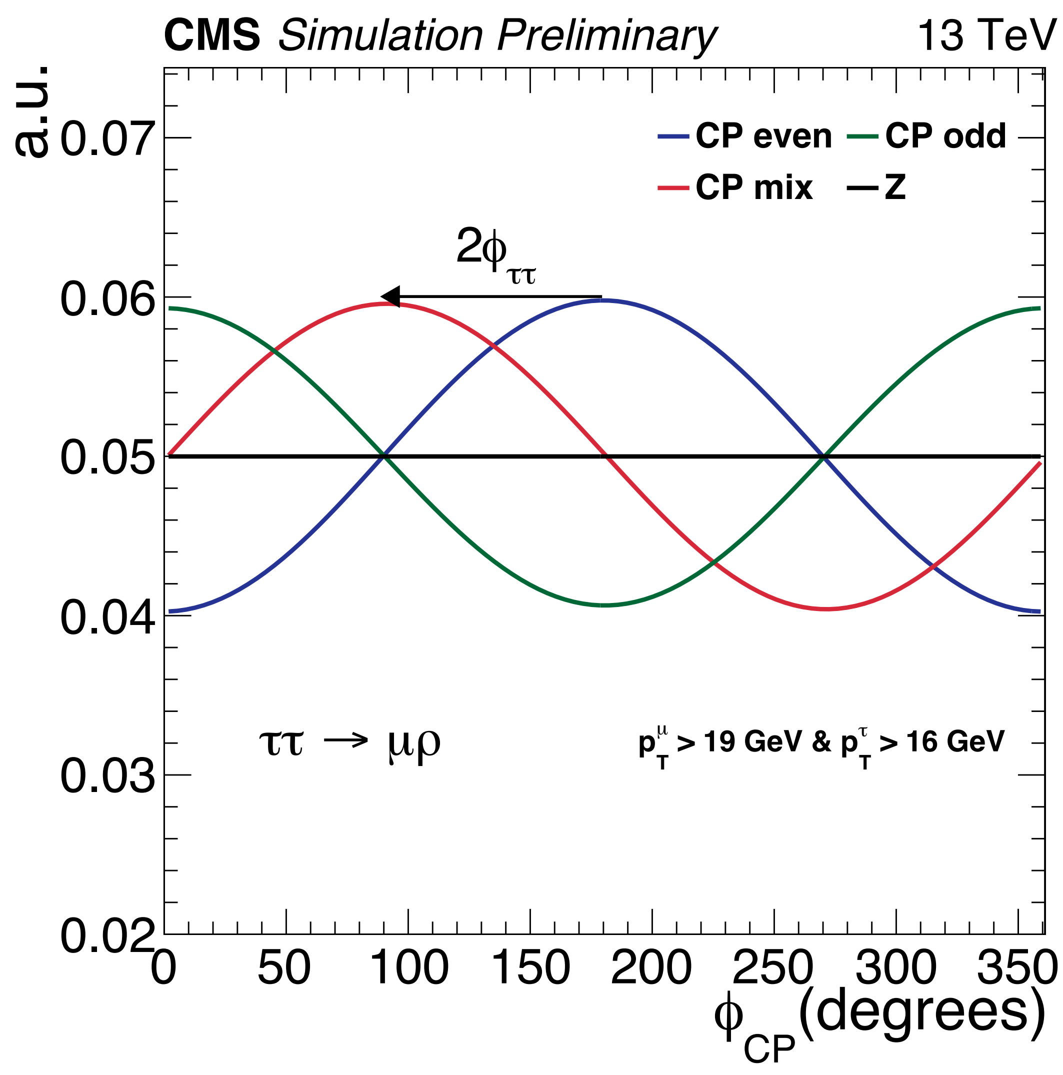
- λ are IP vectors perpendicular to $\pi^\pm$, q is $\pi^\pm$ direction vector

- “*” 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

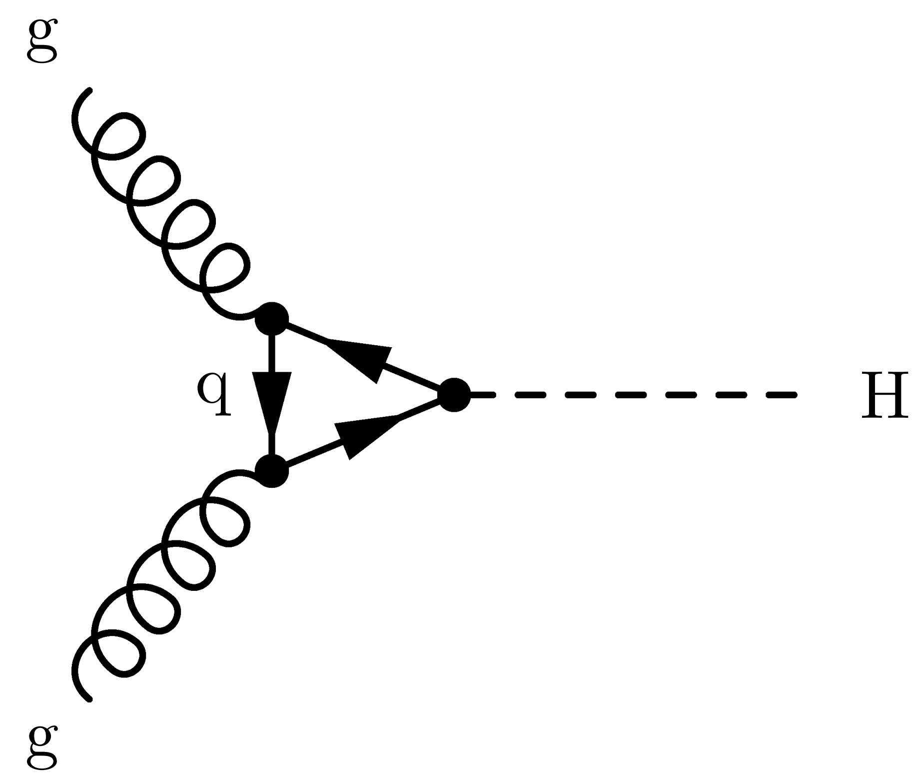
- Replacing $\tau\rightarrow\pi\nu$ with $\tau\rightarrow\mu\nu\nu$ we can define equivalent CP sensitive variables for $\tau_\mu\tau_h$ channel

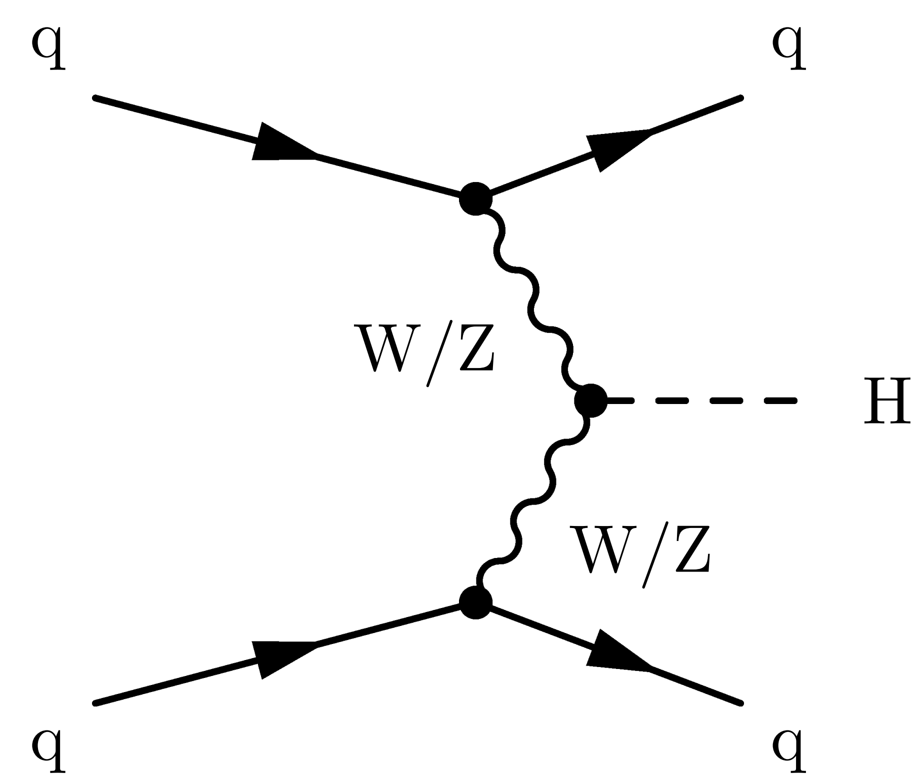




Signal modelling

- 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 H 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

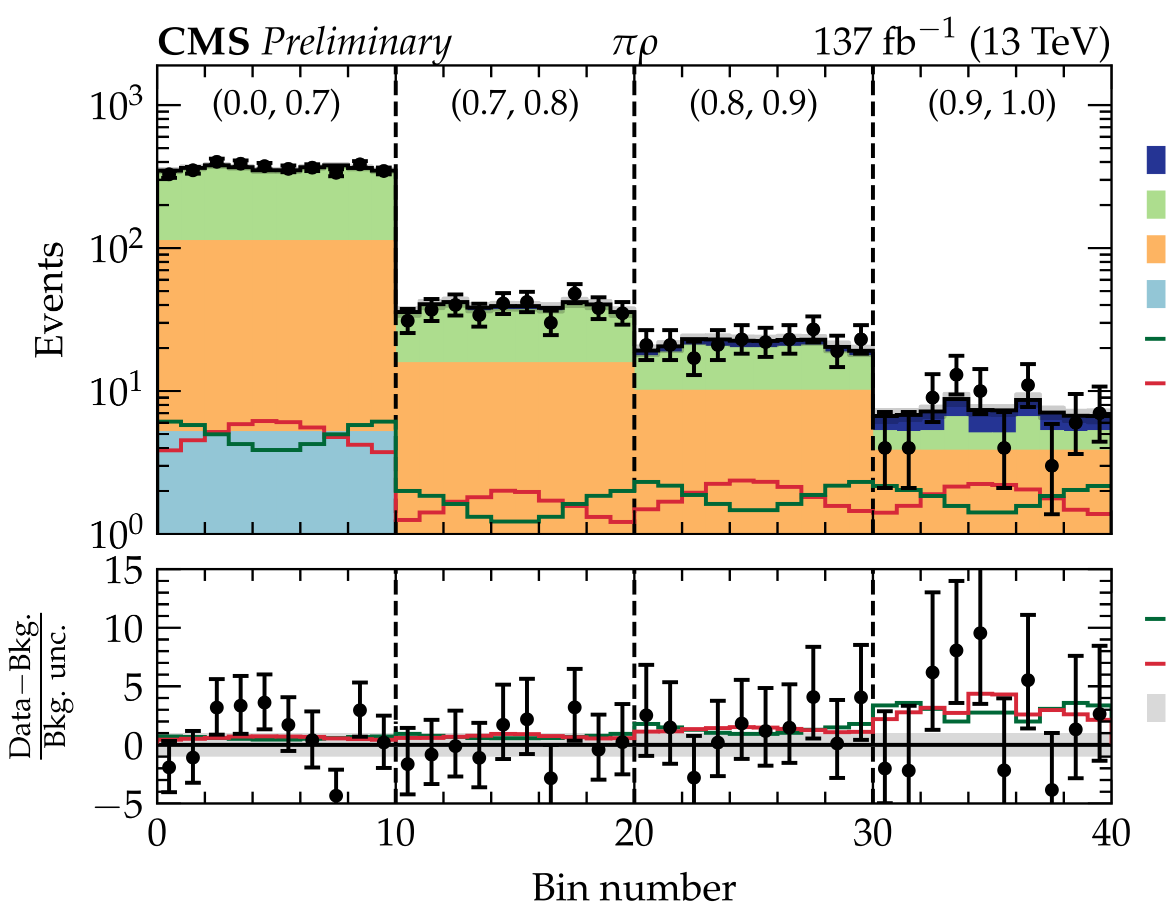




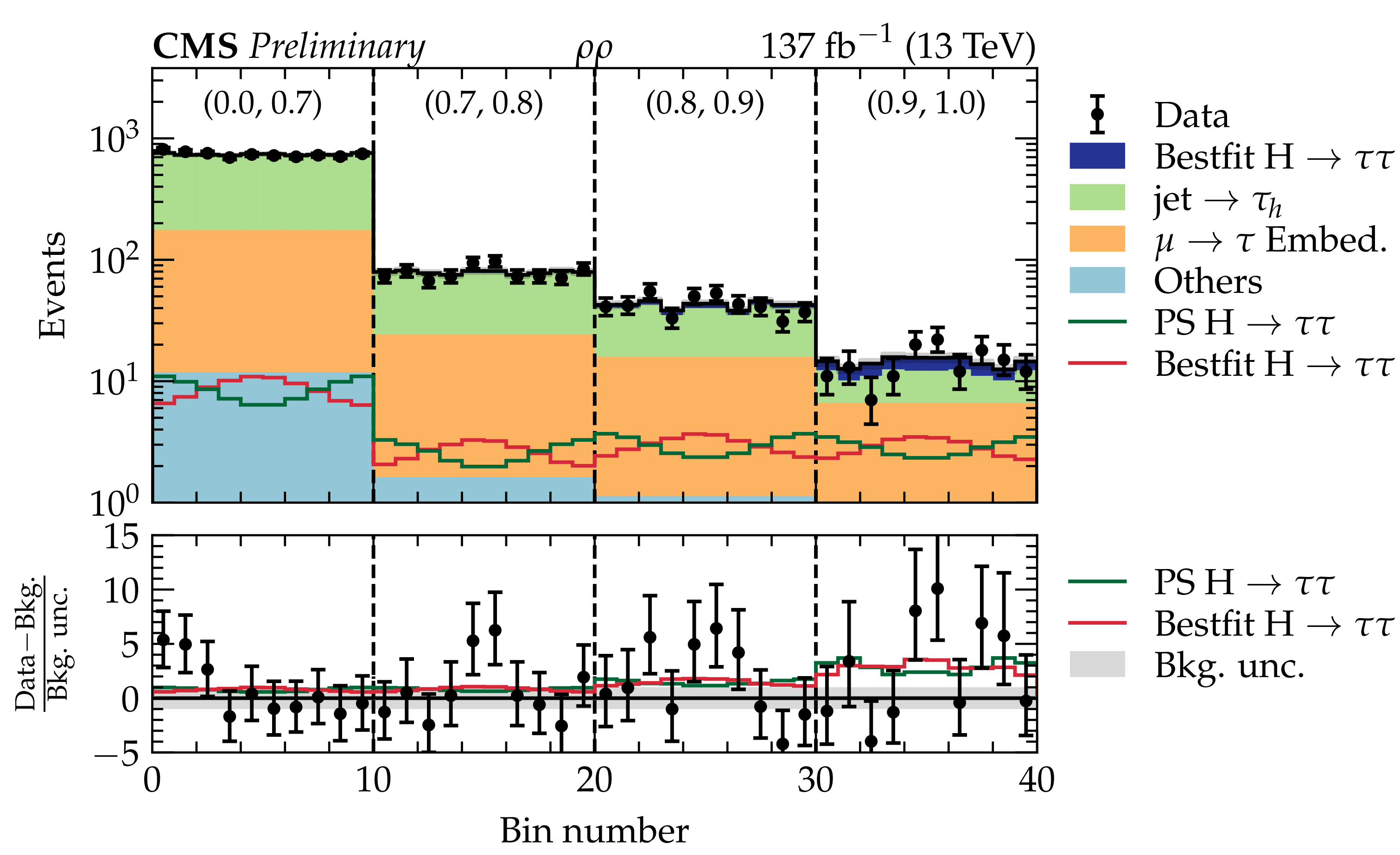
More examples of signal categories

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

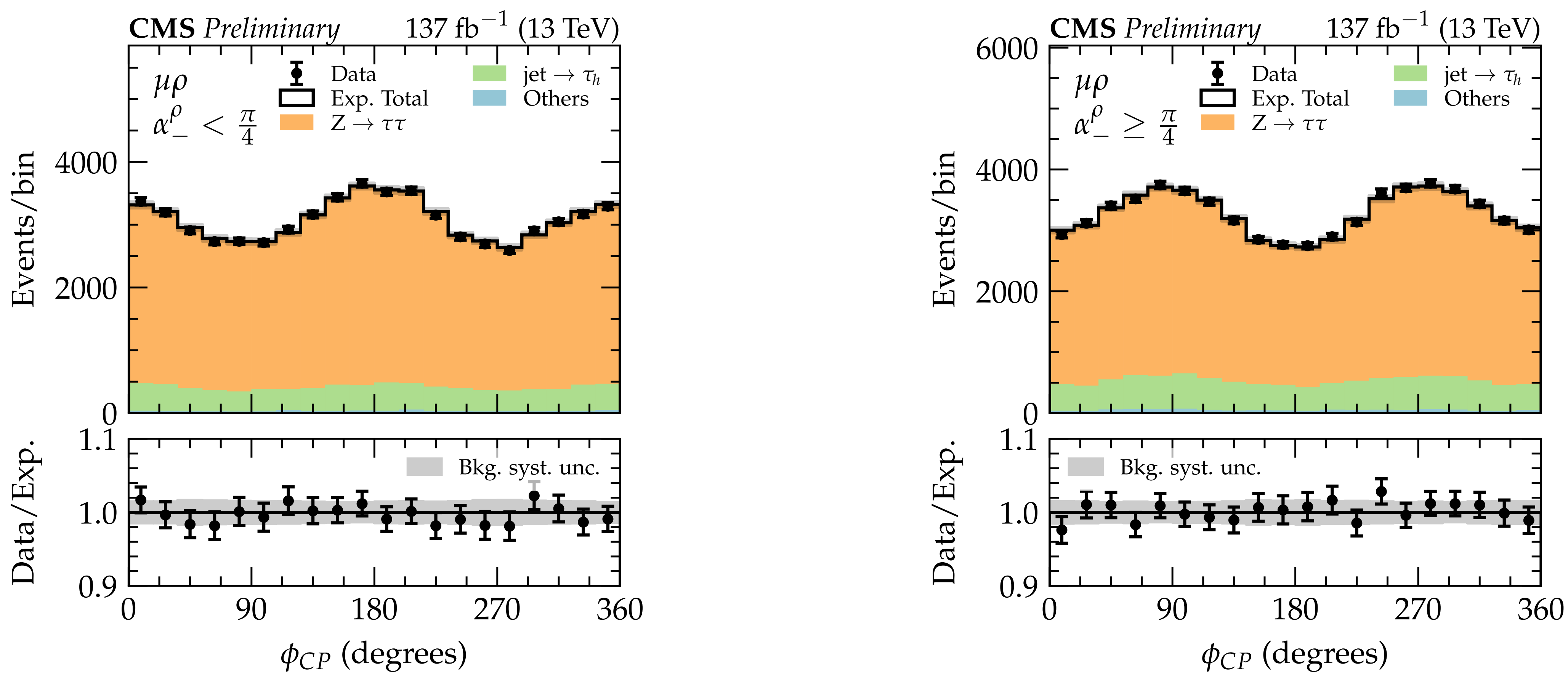
$\tau_h\tau_h \rightarrow \pi^- \nu \rho^- \nu$



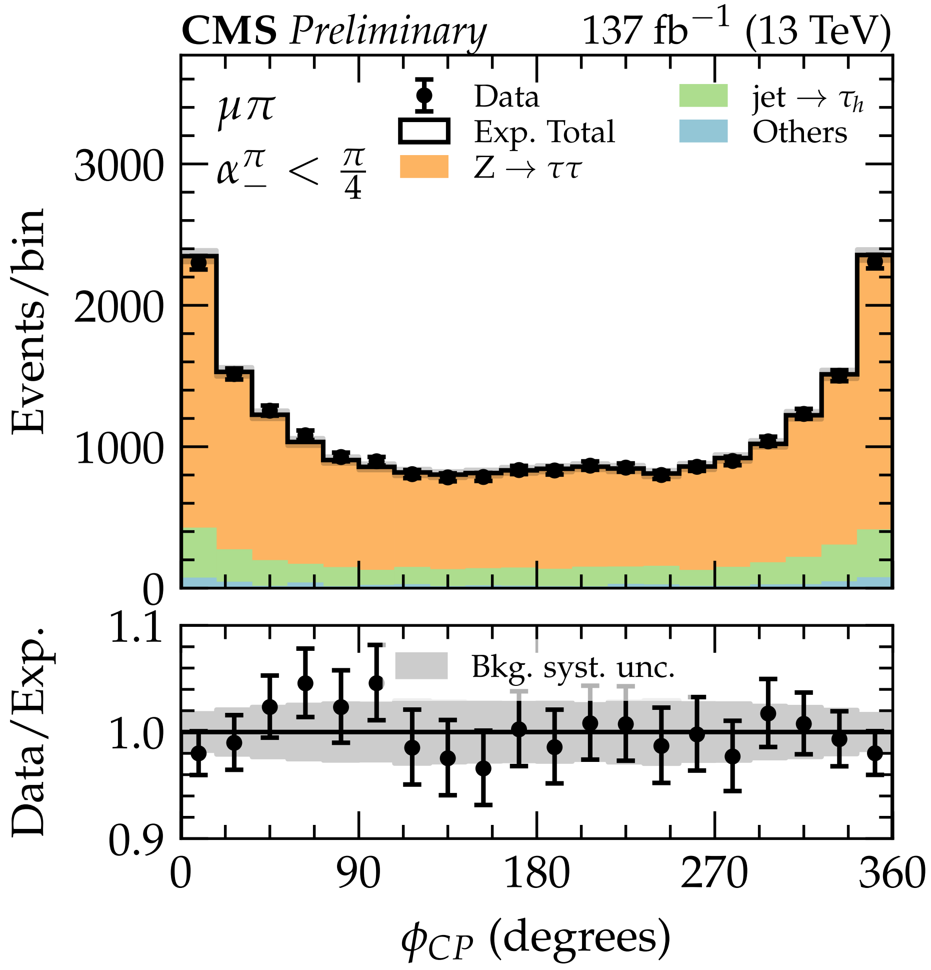
$\tau_h\tau_h \rightarrow \rho^- \nu \rho^- \nu$

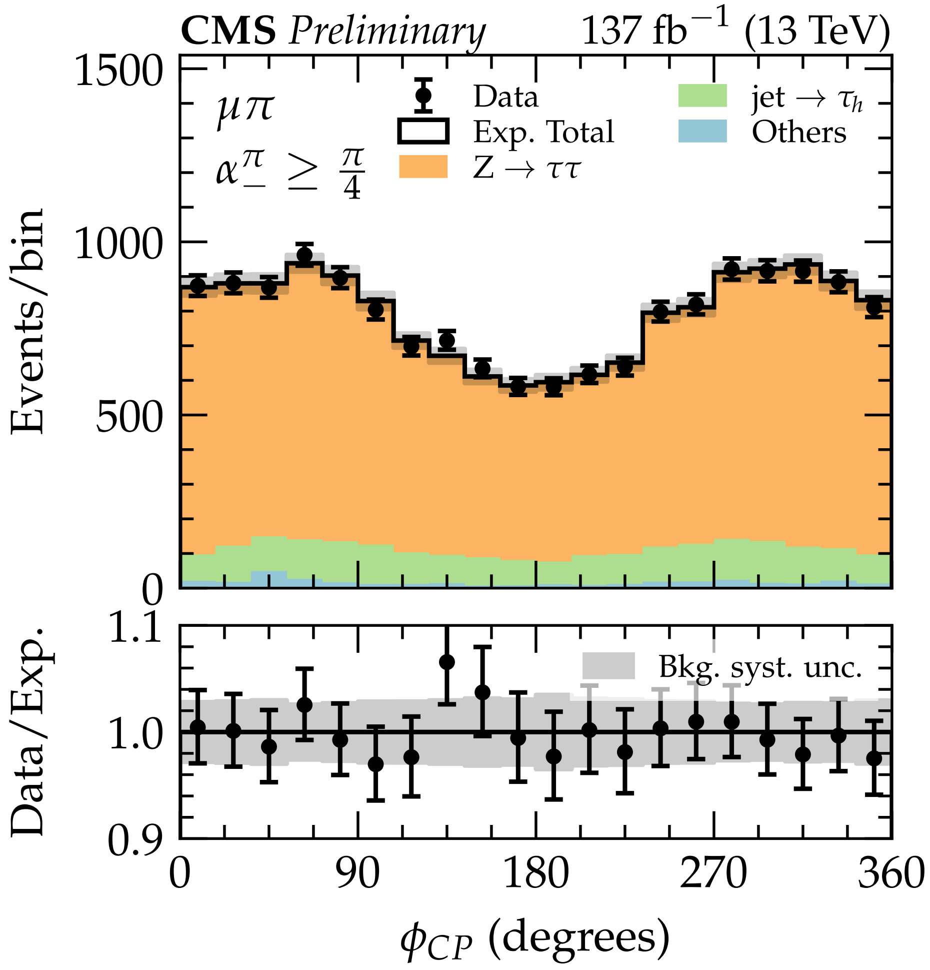


- All H→$\tau\tau$ analyses use $q\bar{q}$→Z→$\tau\tau$ events as "standard candle" to validate MC description of data
- Same for the CP-analysis except as Z→$\tau\tau$ has ~ flat distribution of $\phi_{\tau\tau}$
- But we can split into two sinusoidal contributions using α_- variable
  - Separates events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



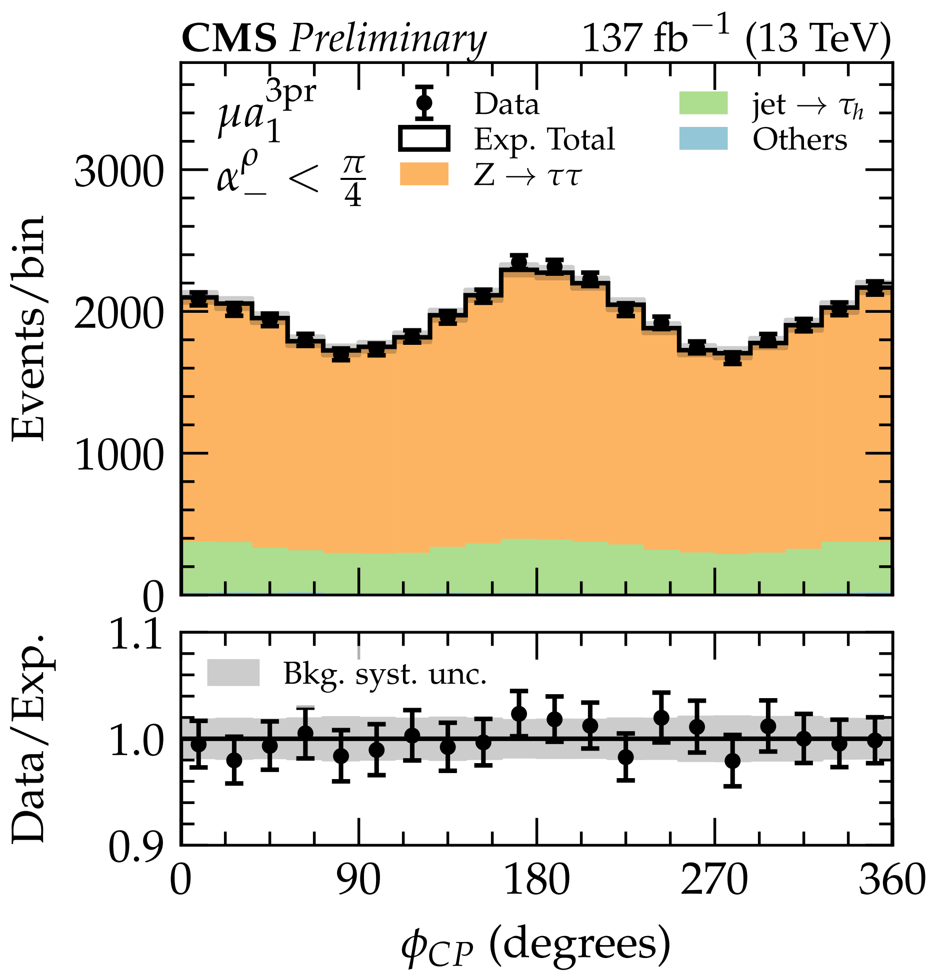
- Check of Z→ττ using α_- splitting for τ_h→πν
- Definition in paper by Stefan Berge et al.

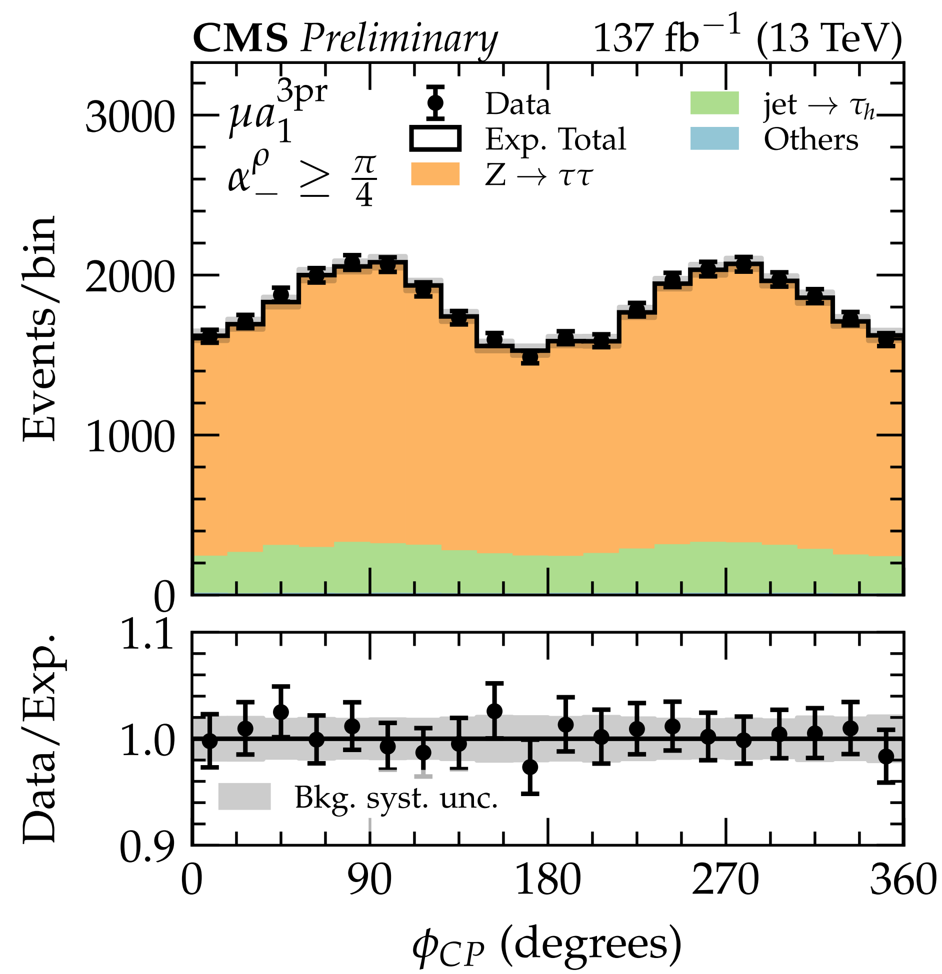




Checks using Z→$\tau\tau$: τ_h→a1ν →π⁻π⁻π⁺ν

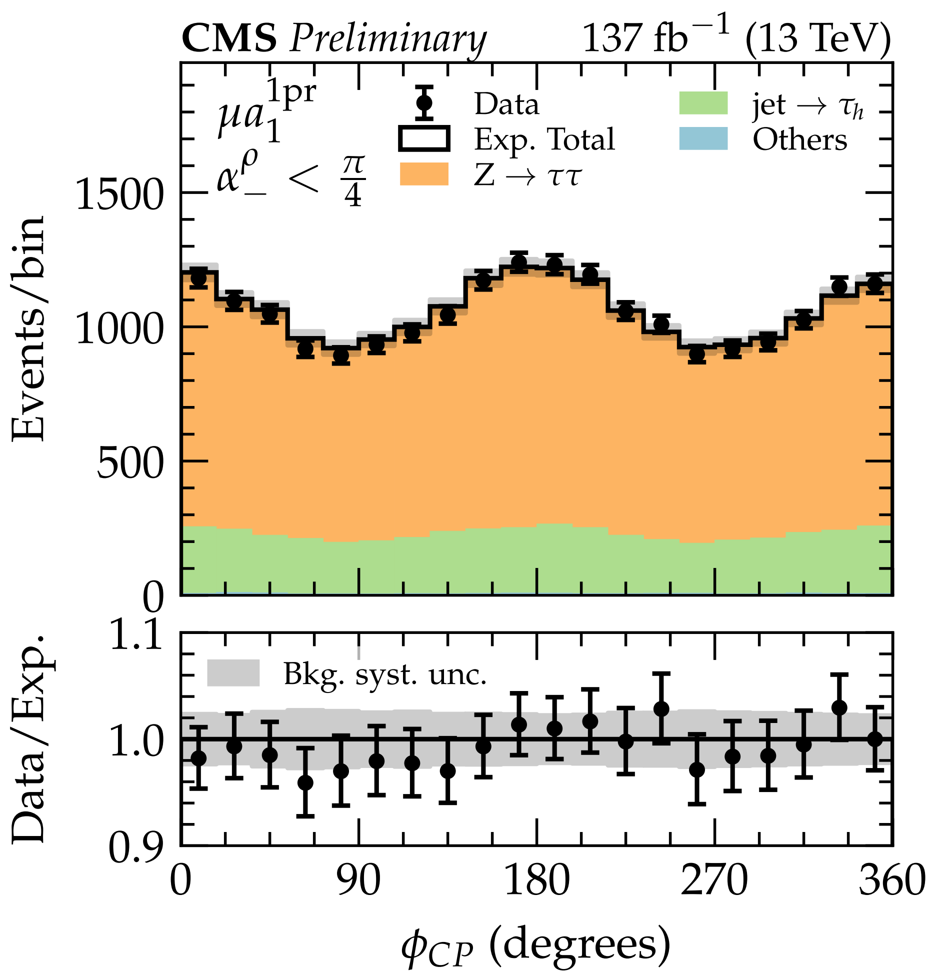
- Check of Z→ττ using α₋ splitting for $\tau_h \to a_1 \nu \to \pi^- \pi^- \pi^+ \nu$
- Definition in paper by Stefan Berge et al.

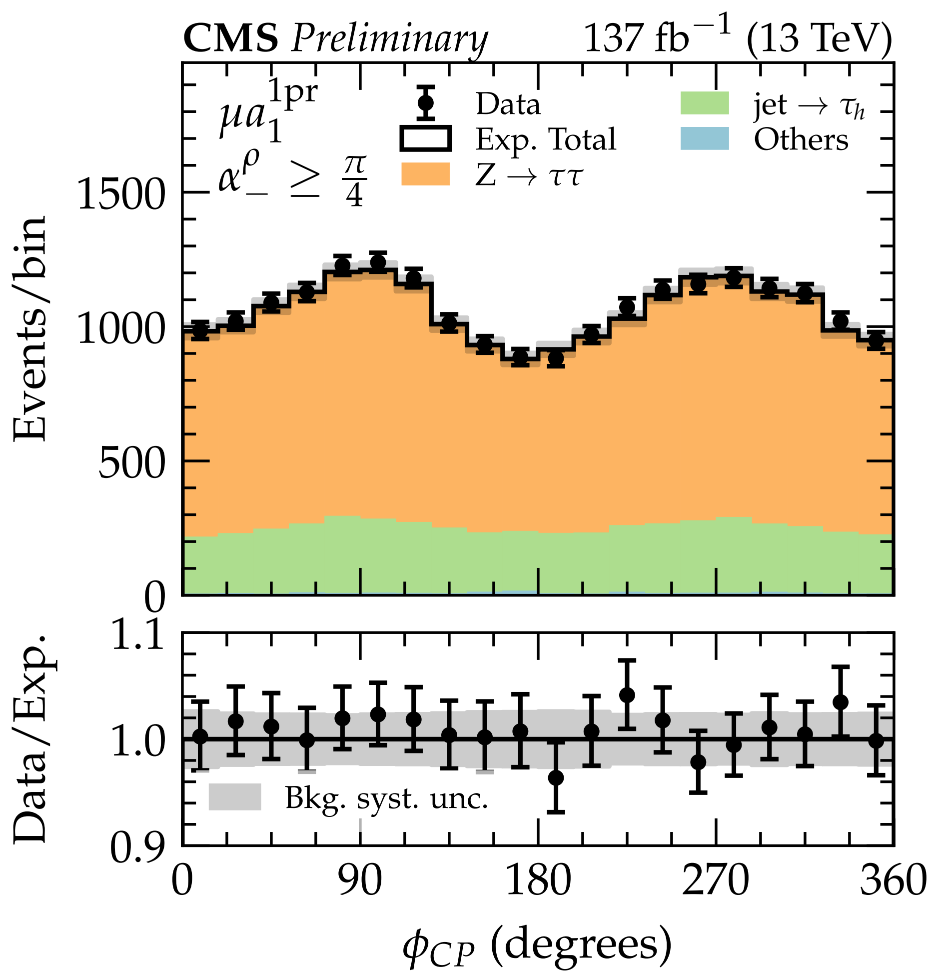




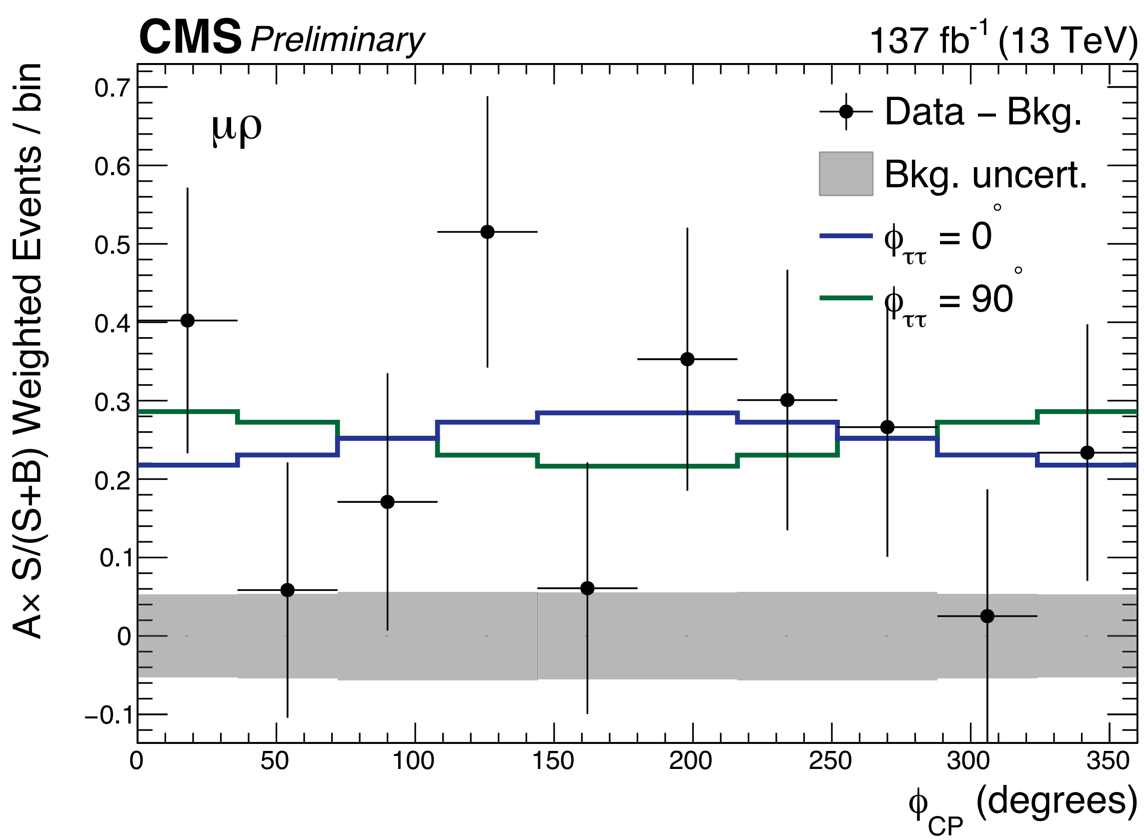
Checks using Z→$\tau\tau$: τ_h→a1ν →π⁻π⁻π⁺ν

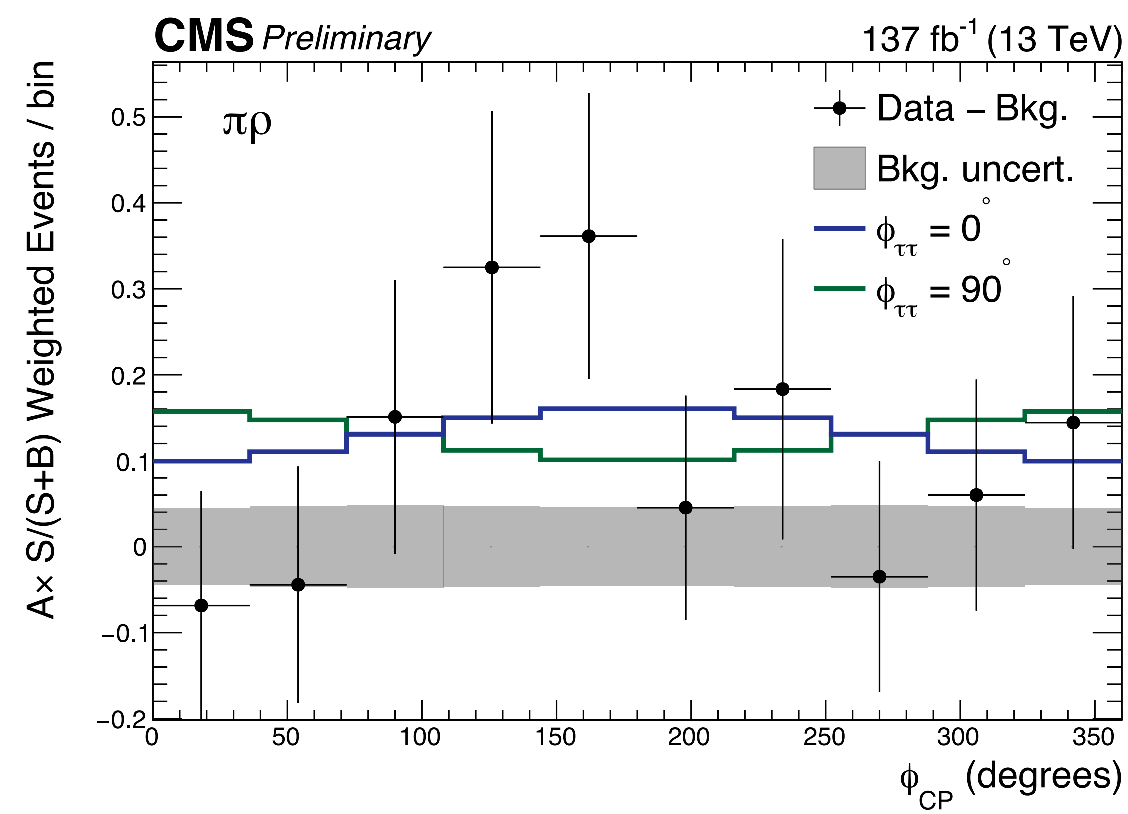
- Check of Z→ττ using α₋ splitting for $\tau_h \rightarrow a_1\nu \rightarrow \pi^-\pi^0\pi^0\nu$
- Definition in paper by Stefan Berge et al.

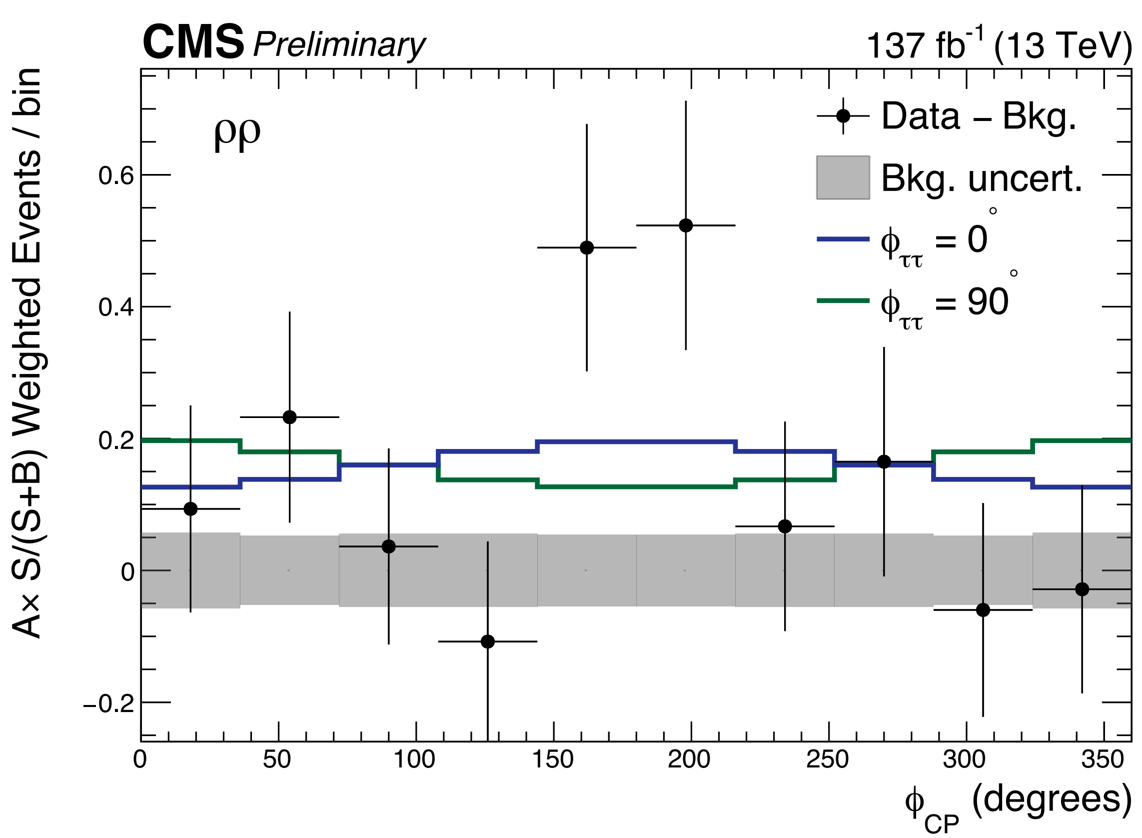


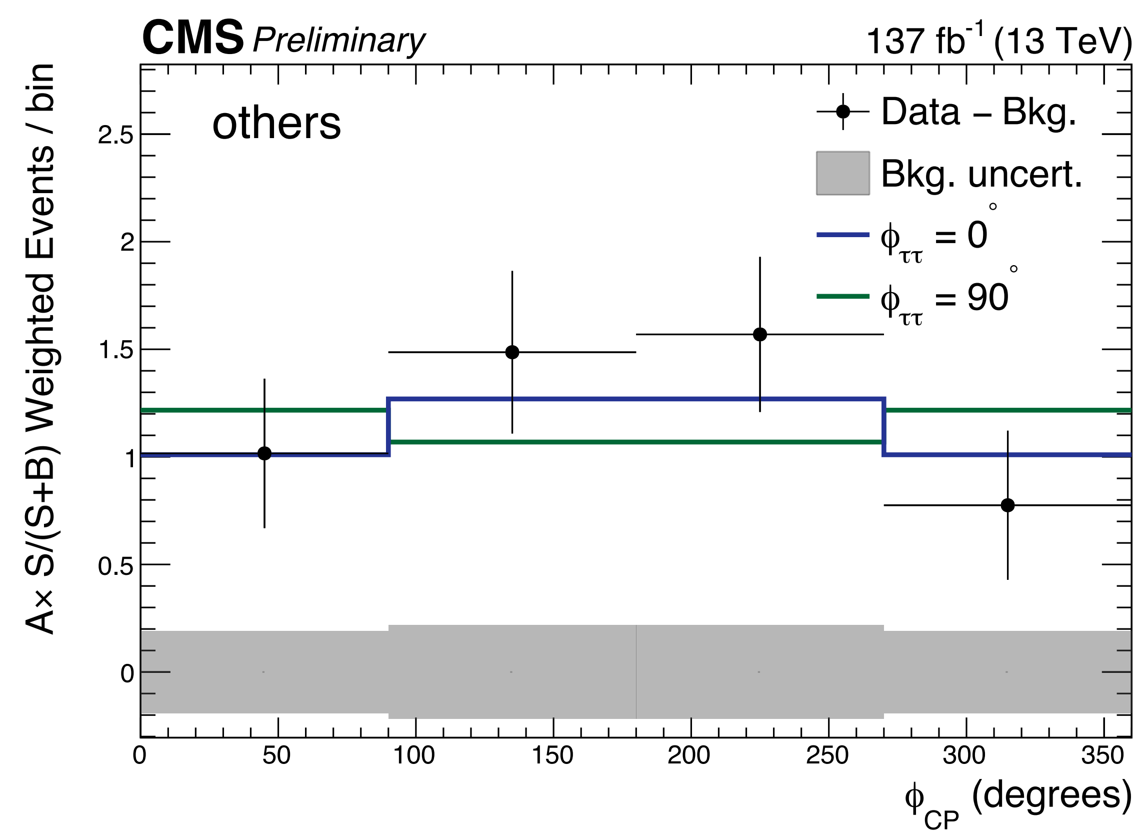


ϕ_{CP} distribution by channel









Polarimetric vectors

- Polarimetric vectors for $\tau_h \rightarrow \pi^- \nu$ 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*

4-vectors:

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

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

$P : \tau^\pm$

- 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:

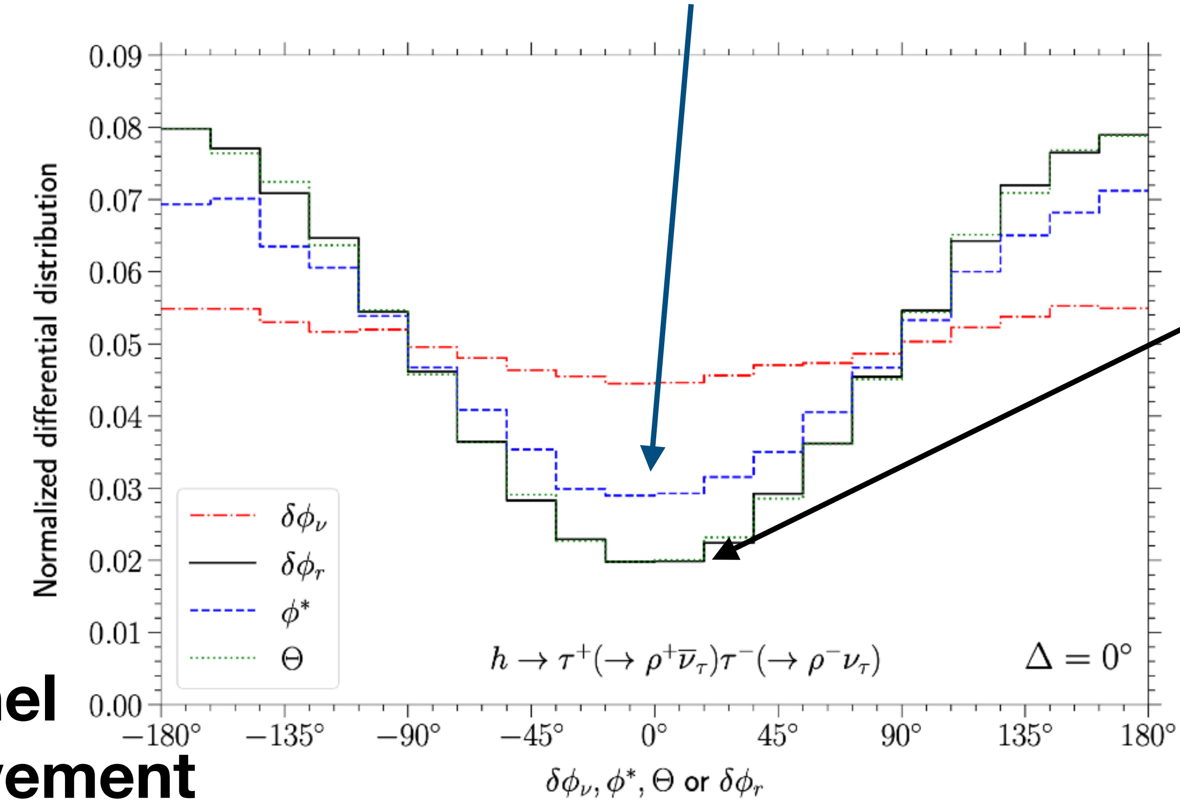
	Integrated luminosity	$\sqrt{s}$	Number of Higgs bosons
CEPC [7]	$5.6\ ab^{-1}$	240 GeV	1.1×10^6
FCC-ee [8]	$5\ ab^{-1}$	240 GeV	1.0×10^6
ILC [9]	$2\ ab^{-1}$	250 GeV	0.64×10^6

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

Future measurements: lepton colliders

- Lepton colliders have advantage of being able to constrain Higgs 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