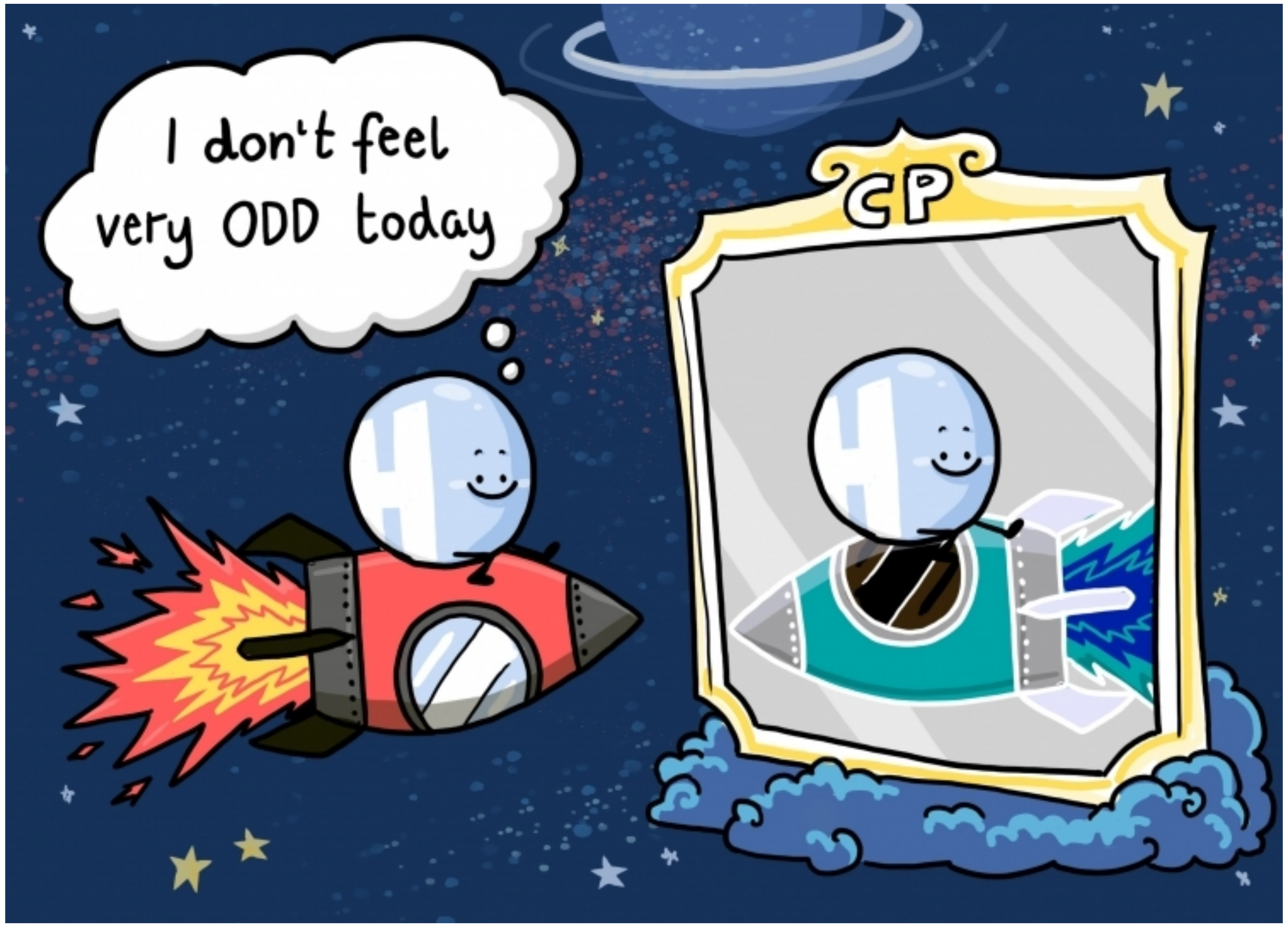
IMPERIAL

Searching for CP violation in the Higgs sector using the H→ττ decay channel



Daniel Winterbottom
d.winterbottom15@imperial.ac.uk

Overview

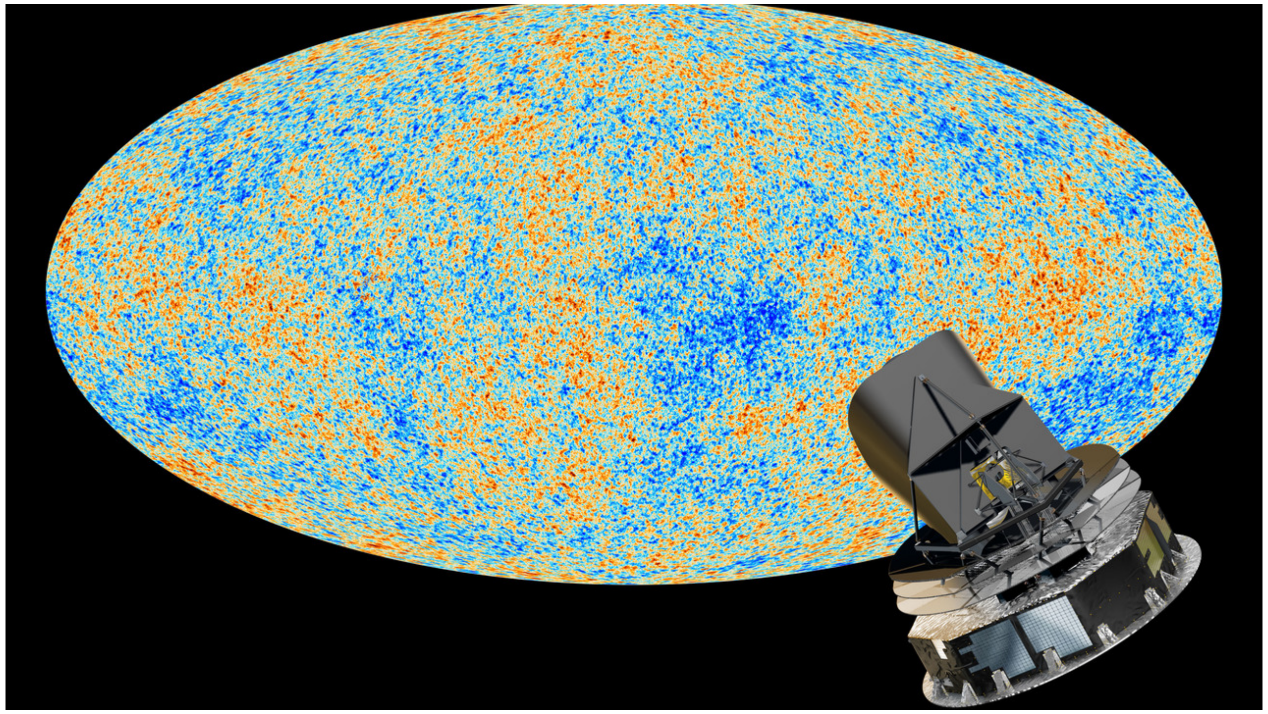
- Motivation for CP violation (CPV) in the Higgs sector
- How to measure CPV in $H \rightarrow \tau\tau$ decays
- Latest results
- Projection to HL-LHC
- Going further than projections

What is the BAU problem?

- The Baryon Asymmetry of the Universe (BAU) is measured by Planck from the CMB to be:

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

- Corresponds to a small preference for matter over antimatter
  - About 1 surviving matter particle for each matter-antimatter pair
- What is the reason for this preference of matter over antimatter?



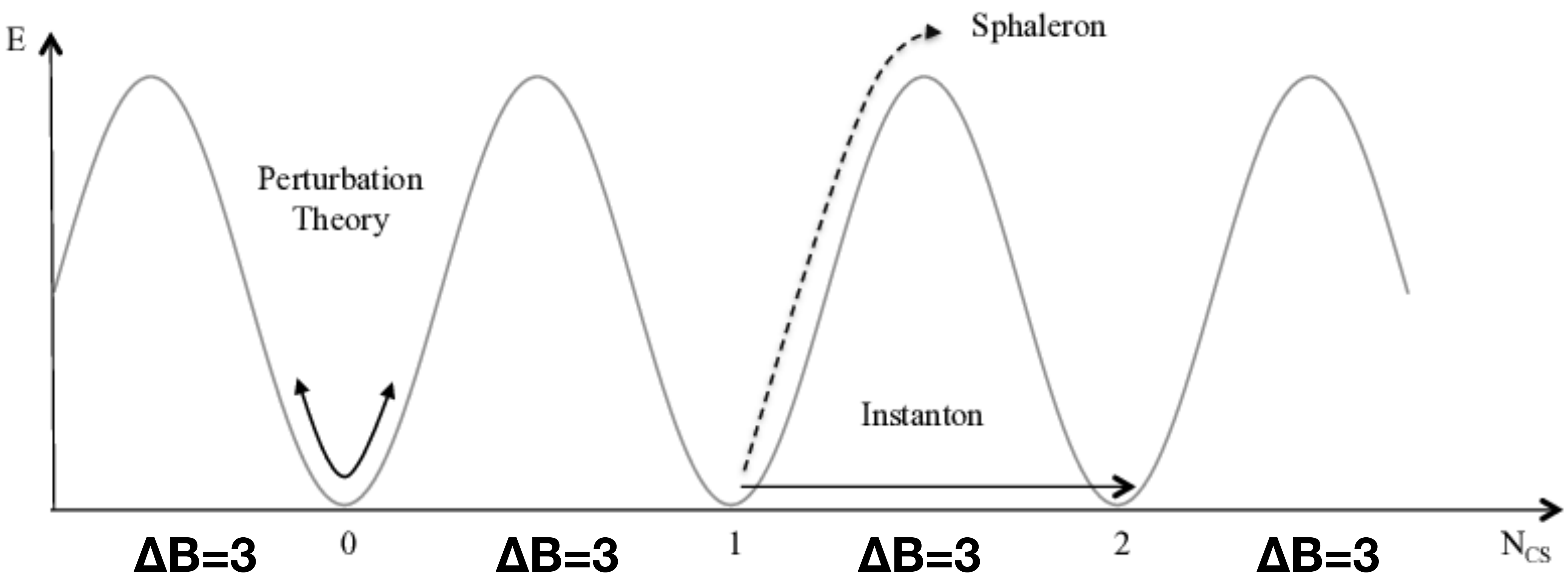
Sakharov conditions

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

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
  - Via transitions between degenerate vacua (sphalerons), not in perturbation theory
- B−L remains exactly conserved; only B+L is violated



2. C-symmetry and CP-symmetry violation

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

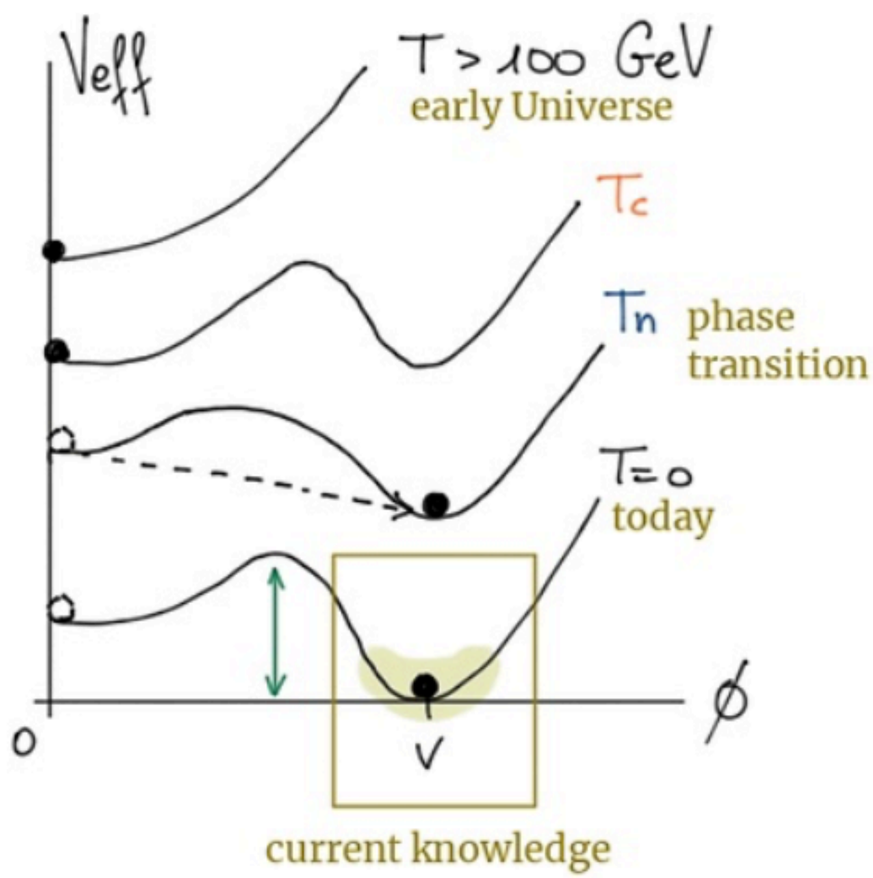
- CP violation in SM as well - CP violating phase δ in quark mixing (CKM matrix)

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

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

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



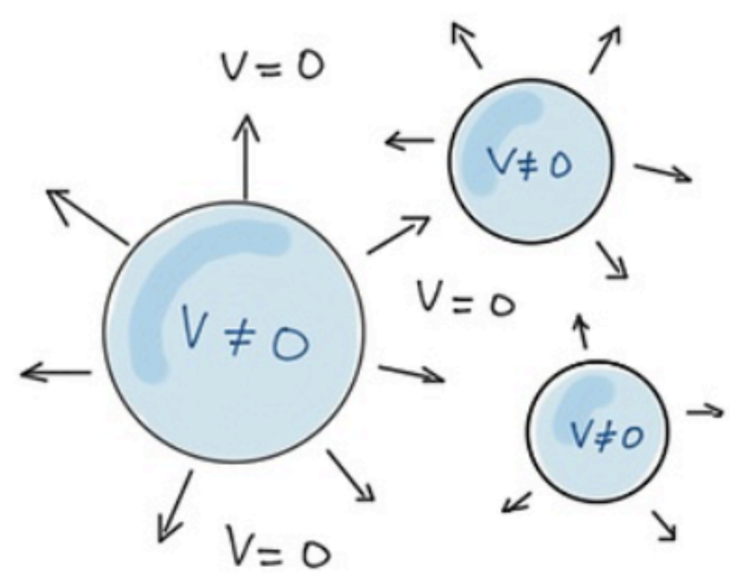


Photo: Kateryna Radchenko Serdula

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

3. Departure from thermal equilibrium

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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:

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

- Complex parameters m_{12}^2 and λ_5 allow CP-violation
- H bosons: H_1, H_2, H_3, H^+, H^- → neutral Higgs bosons not CP eigenstates!

Motivation for CP violation in H fermion couplings

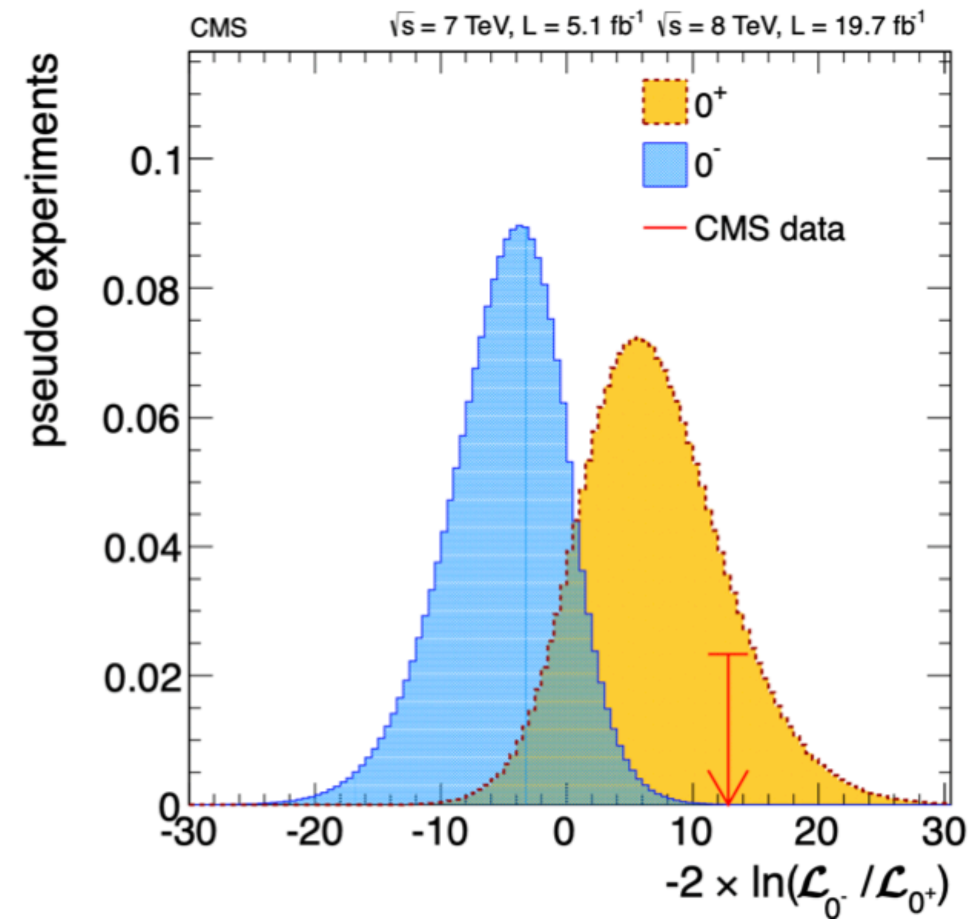
- Since Run 1 H CP properties have been measured

- 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

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

$$\mathscr{L}_Y = -\frac{m_\tau}{v}(\kappa_f \bar{f}f + \tilde{\kappa}_f \bar{f} i\gamma_5 f)h \qquad \kappa_f = y_f / y_f^{SM}$$

- Define mixing angle as:

$$\tan\alpha^{Hff} = \frac{\tilde{\kappa}_f}{\kappa_f}$$

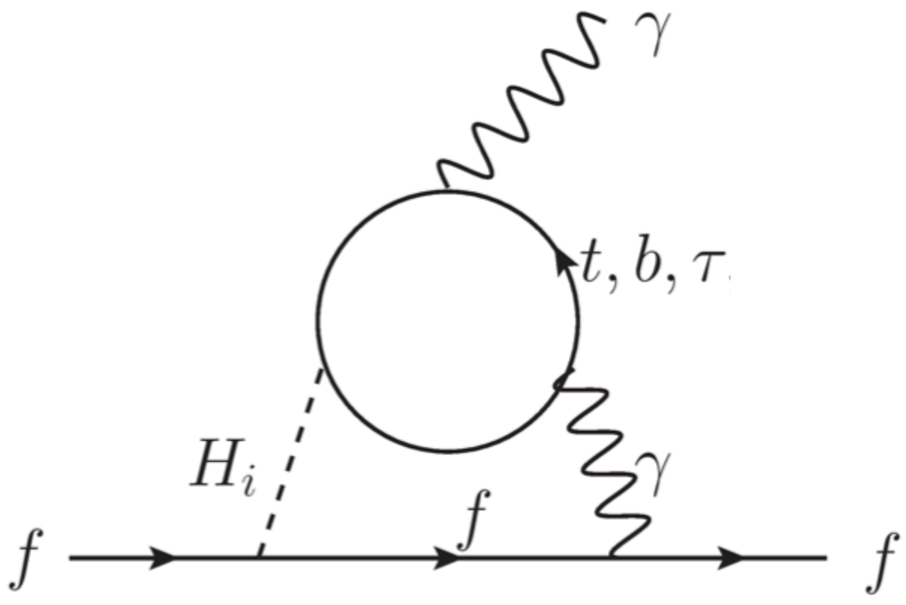
- CP-even: $\alpha^{Hff} = 0^o$, CP-odd: $\alpha^{Hff} = 90^o$, CP-mixed: $0^o < |\alpha^{Hff}| < 90^o$

Previous results

- First direct CP measurement in $H \to \tau\tau$ using Run-2 LHC data 138 fb^{-1} at 13 TeV arXiv:2110.04836
  - $\alpha^{H\tau\tau} = (-1 \pm 19)^\circ$, expected $(0 \pm 21)^\circ$
  - Projection to HL-LHC: $\alpha^{H\tau\tau} = (0 \pm 5)^\circ$
- ATLAS performed independent measurement with their equivalent Run-2 dataset arXiv:2212.05833
  - $\alpha^{H\tau\tau} = (9 \pm 16)^\circ$, expected $(0 \pm 28)^\circ$

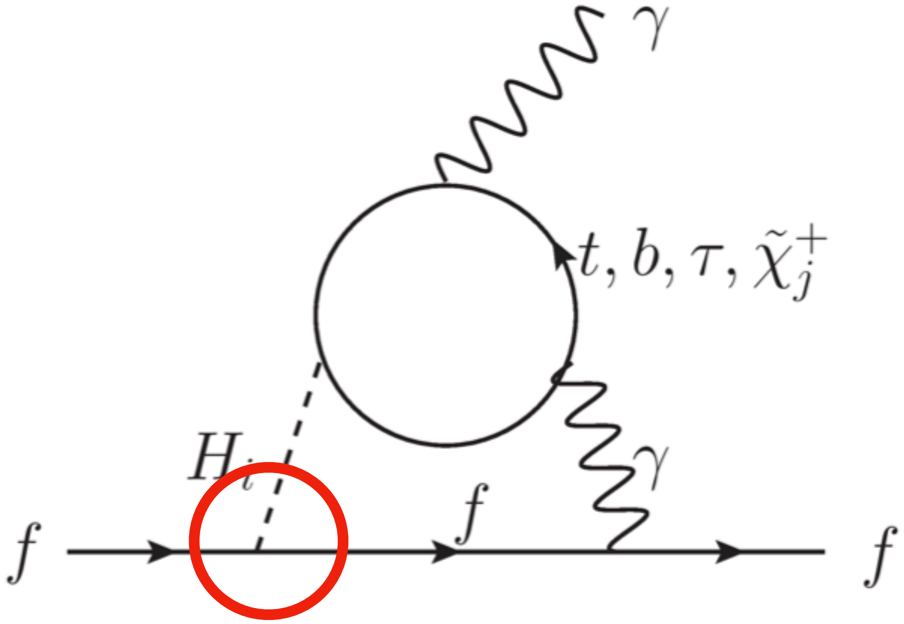
Indirect measurements: EDMs

- 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:
    - $d_e < 10^{-30}$ e cm at 90% CL (JILA, 2023)



Indirect measurements EDMs

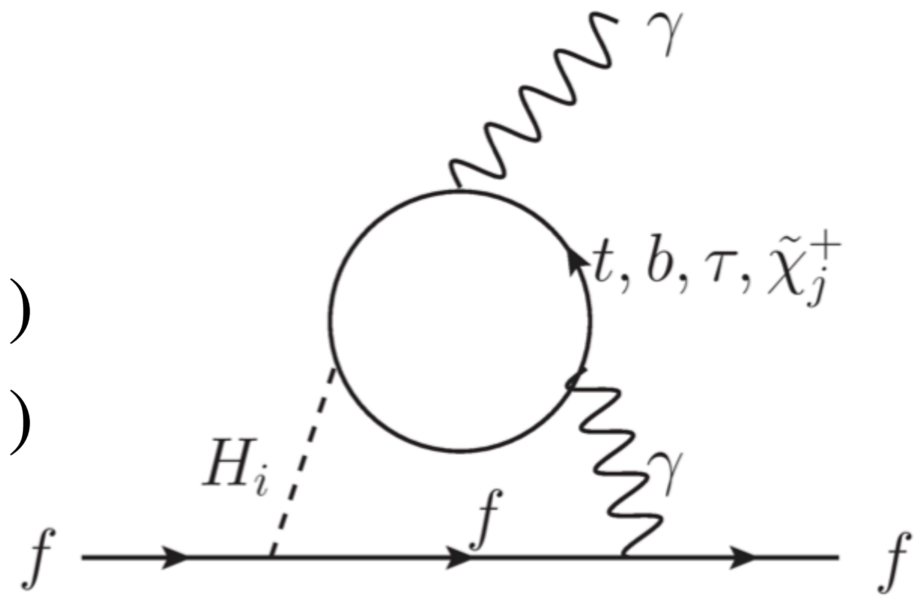
- **But** such constraints are model-dependent
  - Have to assume something about coupling of other particles to the H-boson e.g H→ee
  - For some models get additional diagrams contributing which change EDMs



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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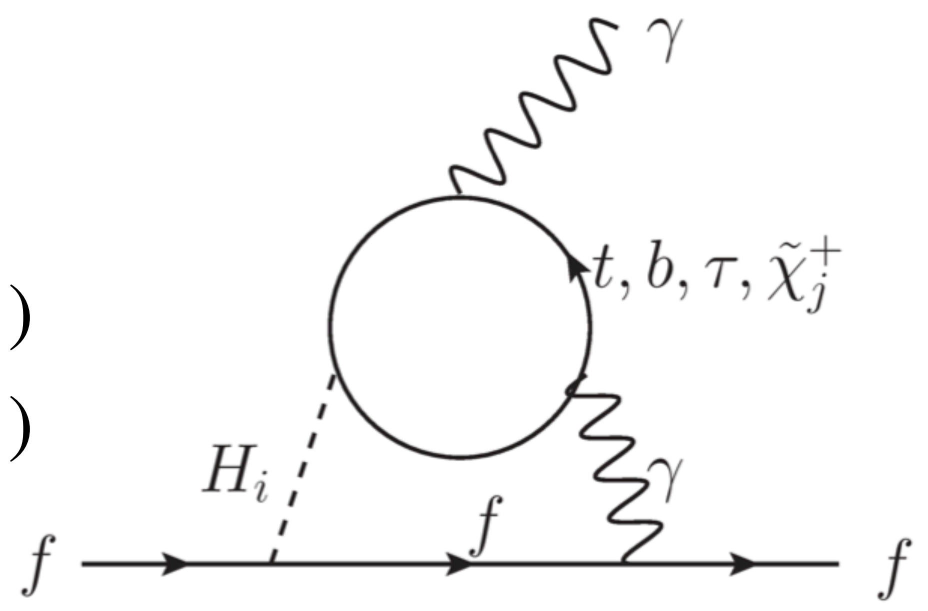

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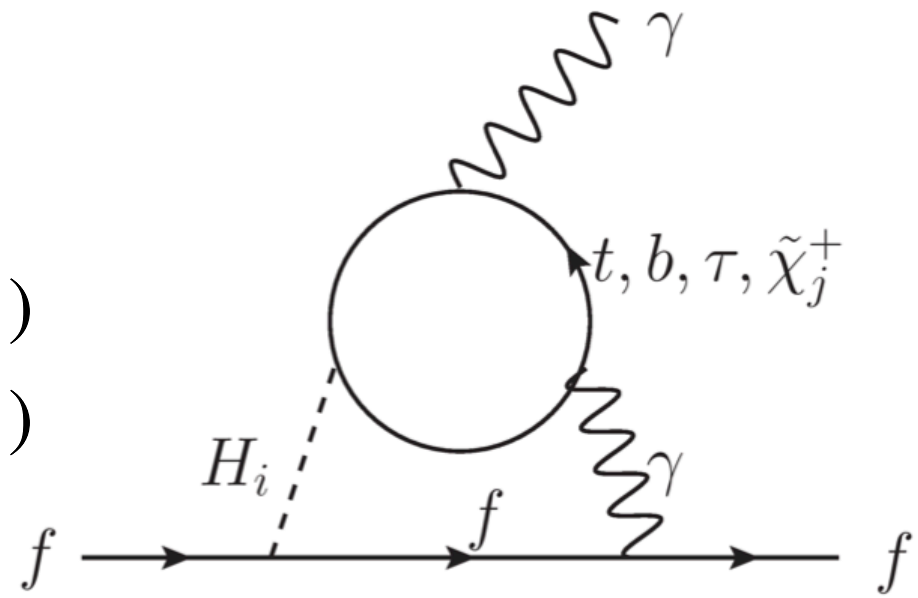

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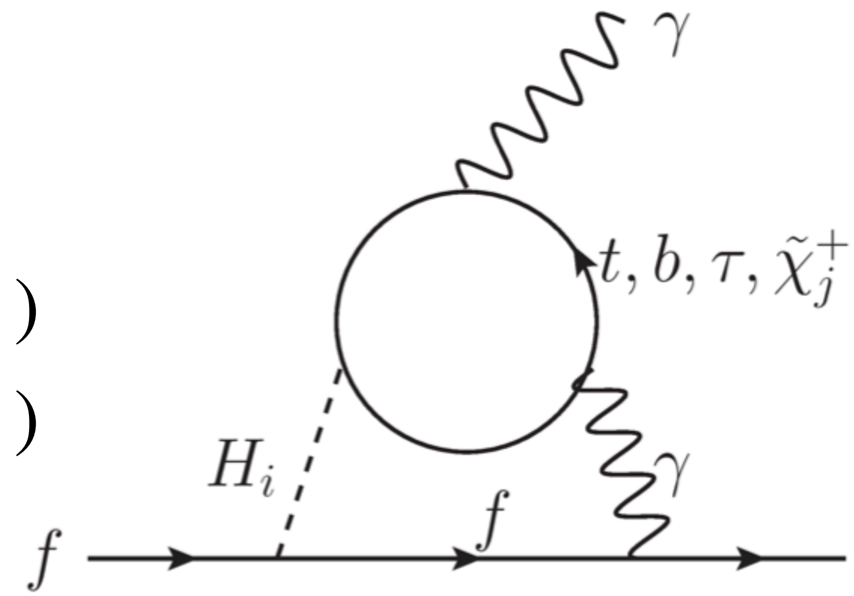


BUT top coupling modifies EDMs significantly (therefore it is constrained) - not the case for the τ

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

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

Generating the observed BAU requires $\alpha^{H\tau\tau} \gtrsim 5^o$

Both top and τ can give large contributions to BAU

Formulas from arXiv:2202.11753

Measuring $\alpha^{H\tau\tau}$ at the LHC

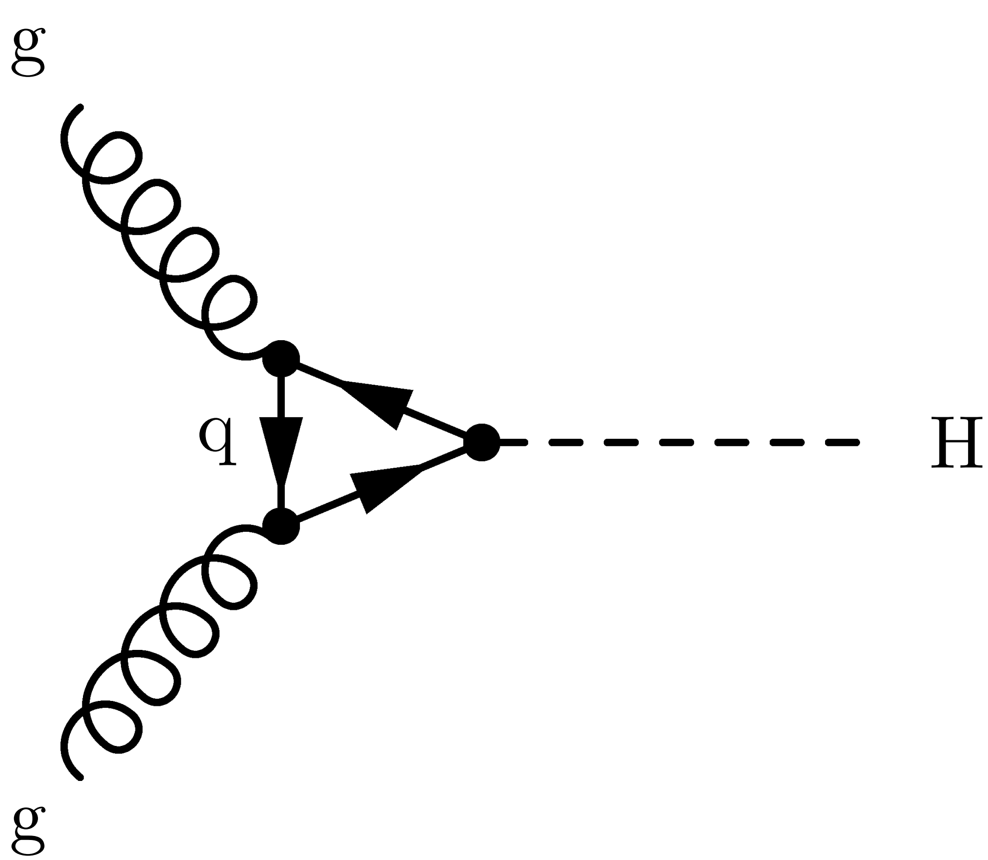
1. Produce Higgs bosons

2. Tag their decay into tau lepton pairs

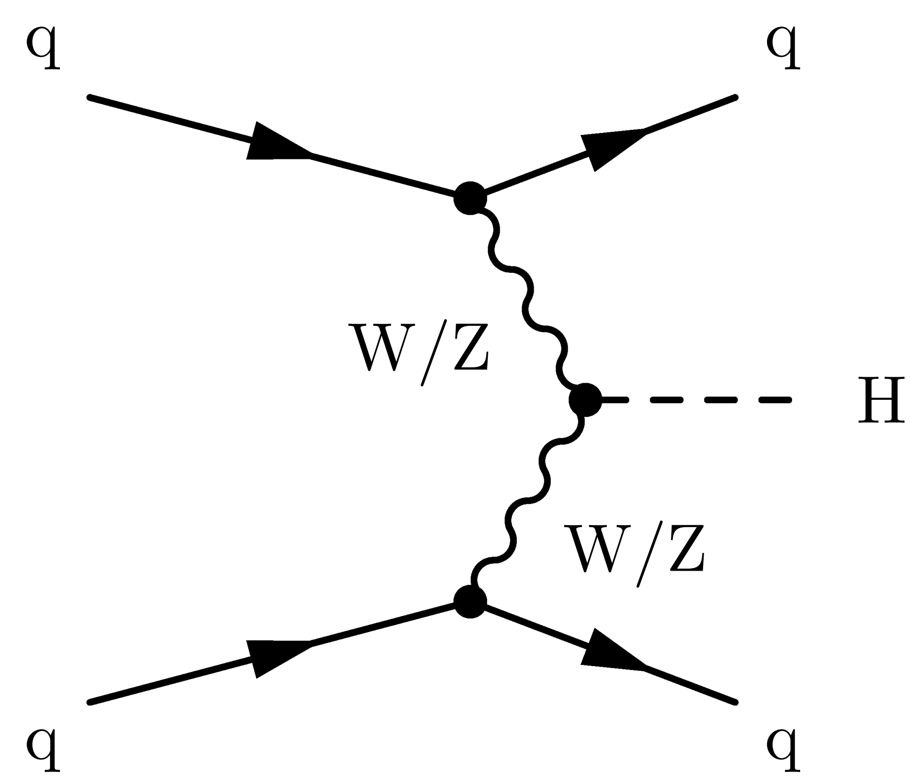
3. Suppress backgrounds

4. Measure CP-sensitive observables

- 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



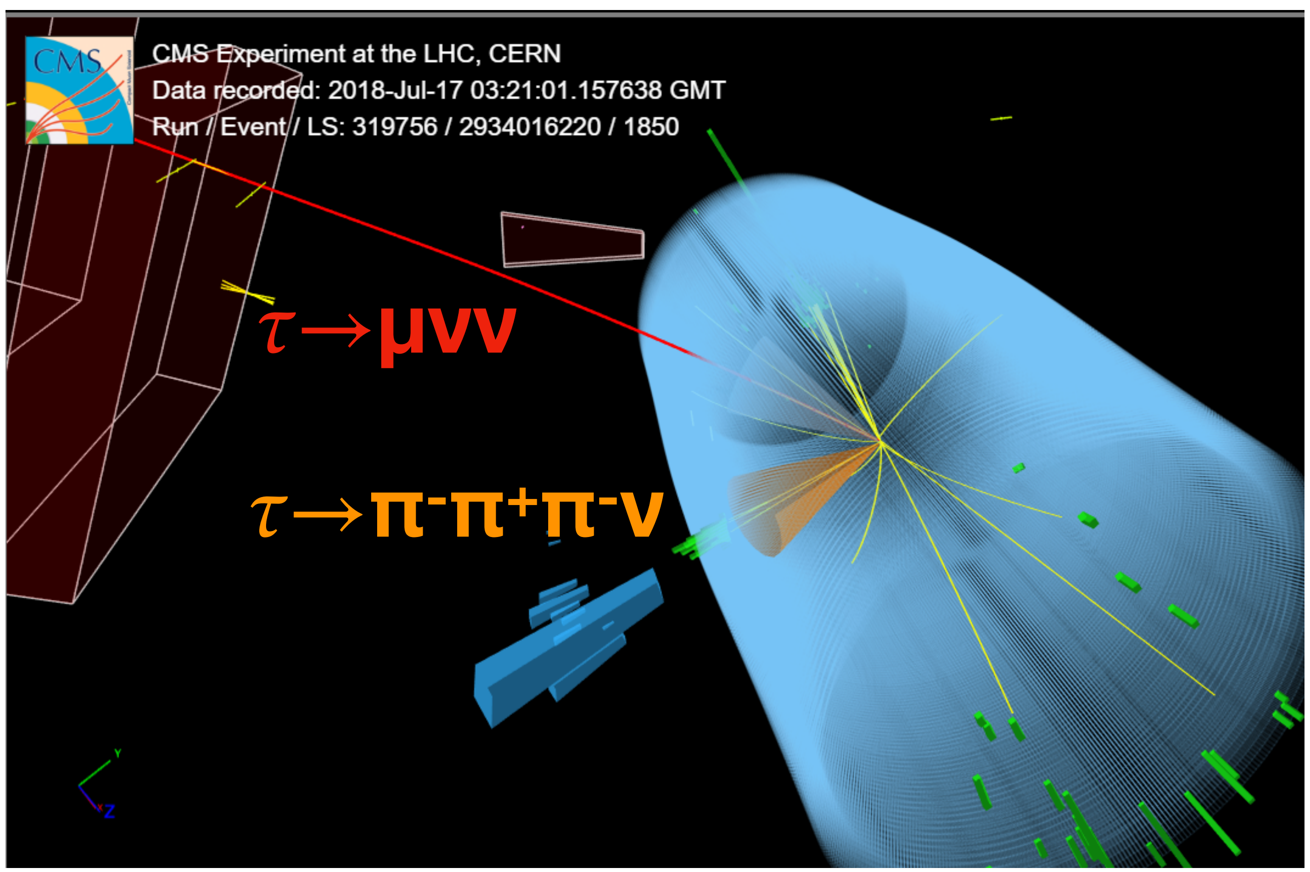
ggH



VBF

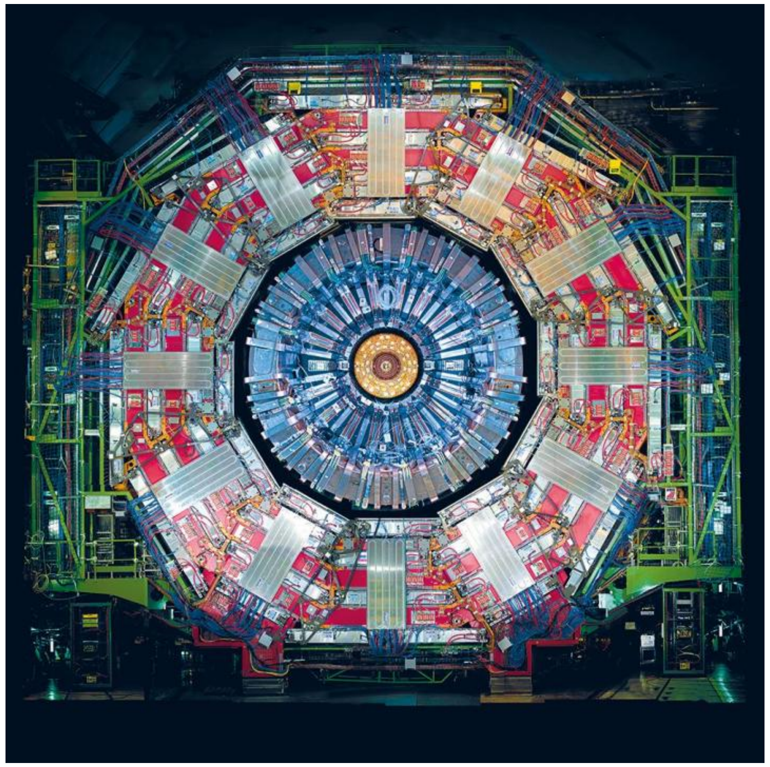
H→$\tau\tau$ decays

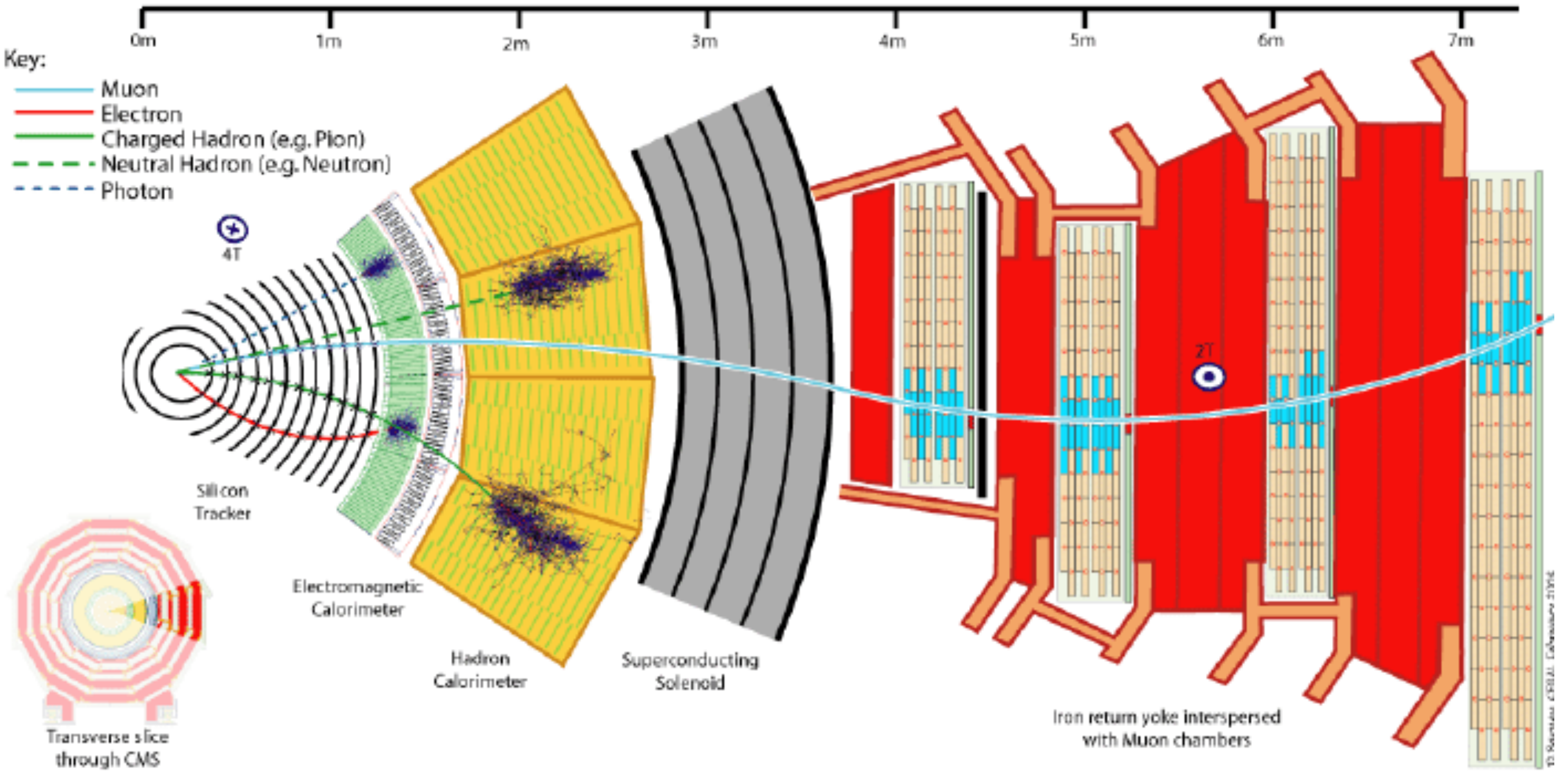
- H→$\tau\tau$ has fairly large branching fraction ~ 6%
- Taus unstable, decay close to primary vertex
- Don't reconstruct them directly but from their decay product: $\tau\to\mu\nu\nu$, $\tau\to e\nu\nu$, $\tau\to\pi^-\nu$, $\tau\to\pi^-\pi^0\nu$, $\tau\to\pi^-\pi^+\pi^-\nu$, …
- Neutrinos undetected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



Decay mode	Resonance	$\mathcal{B}$ (%)	
Leptonic decays		35.2	
$\tau^- \to e^-\overline{\nu}_e\nu_\tau$			17.8
$\tau^- \to \mu^-\overline{\nu}_\mu\nu_\tau$			17.4
Hadronic decays		64.8	
$\tau^- \to h^-\nu_\tau$			11.5
$\tau^- \to h^-\pi^0\nu_\tau$	$\rho(770)$		25.9
$\tau^- \to h^-\pi^0\pi^0\nu_\tau$	$a_1(1260)$		9.5
$\tau^- \to h^-h^+h^-\nu_\tau$	$a_1(1260)$		9.8
$\tau^- \to h^-h^+h^-\pi^0\nu_\tau$			4.8
Other			3.3

The CMS experiment

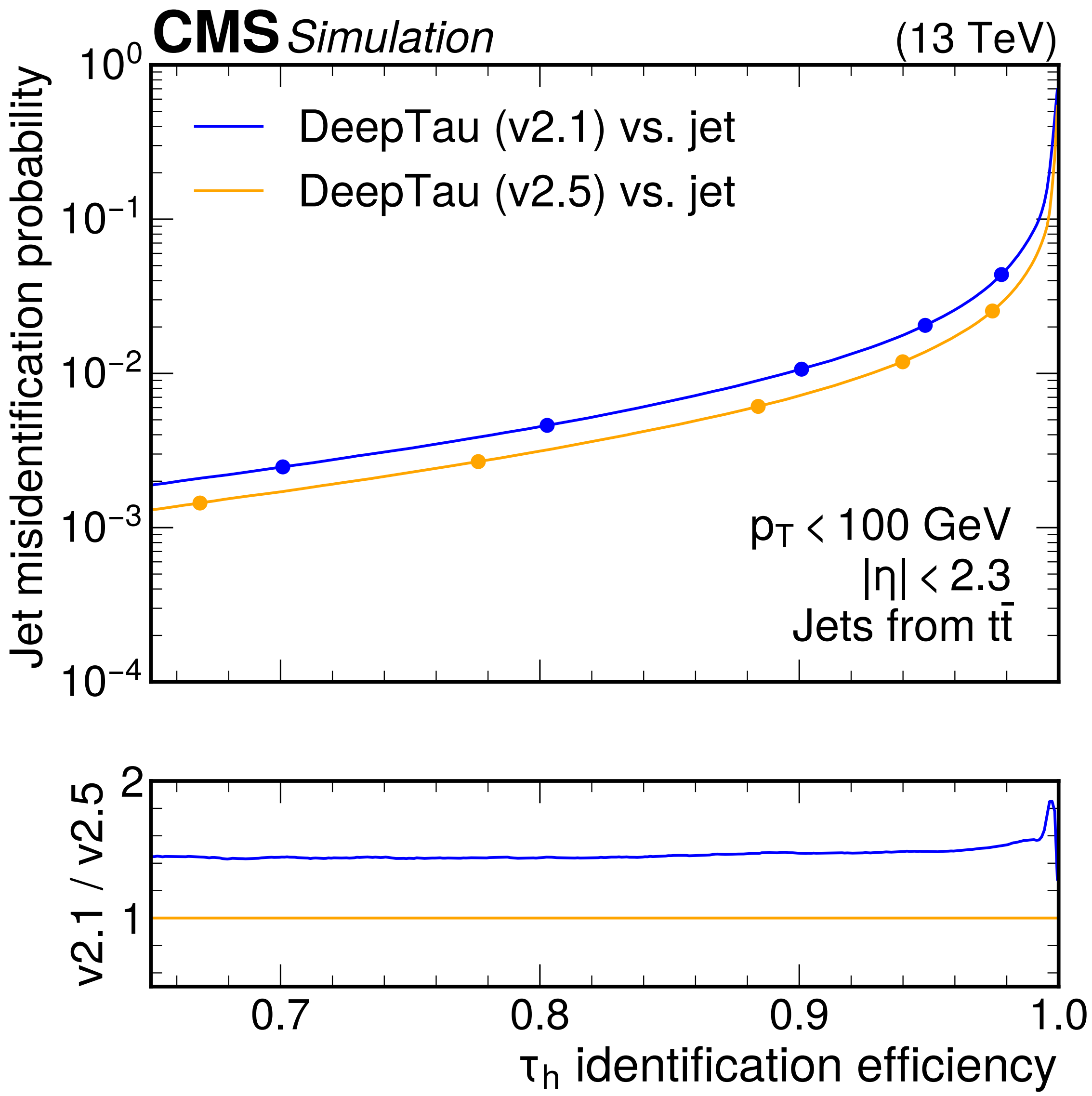




- Two-stage trigger: Level-1 (L1) Hardware trigger, then software-based High-Level Trigger (HLT)

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-24-001

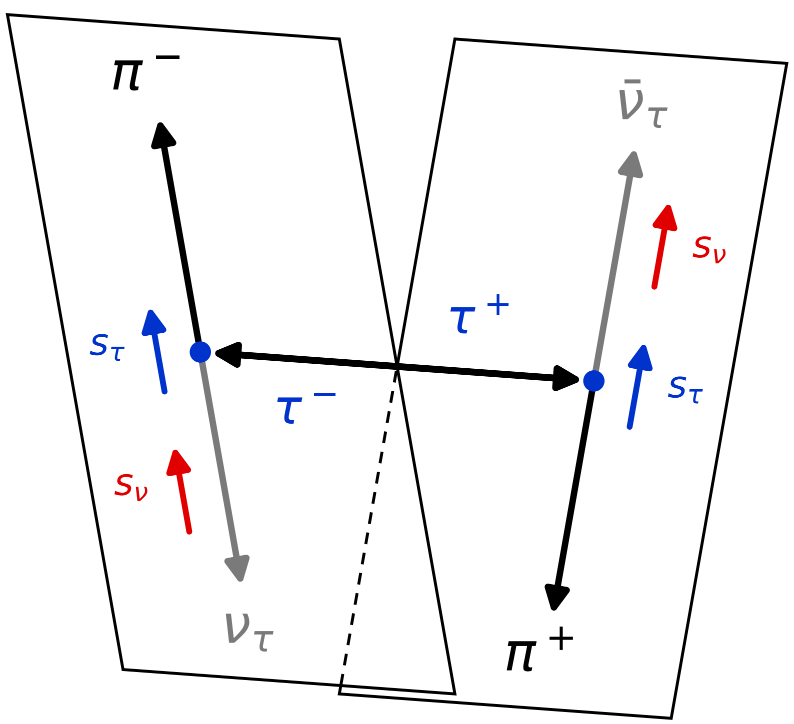
- Two taus, each spin-1/2
- Two possibilities for total spin S: 0, or 1

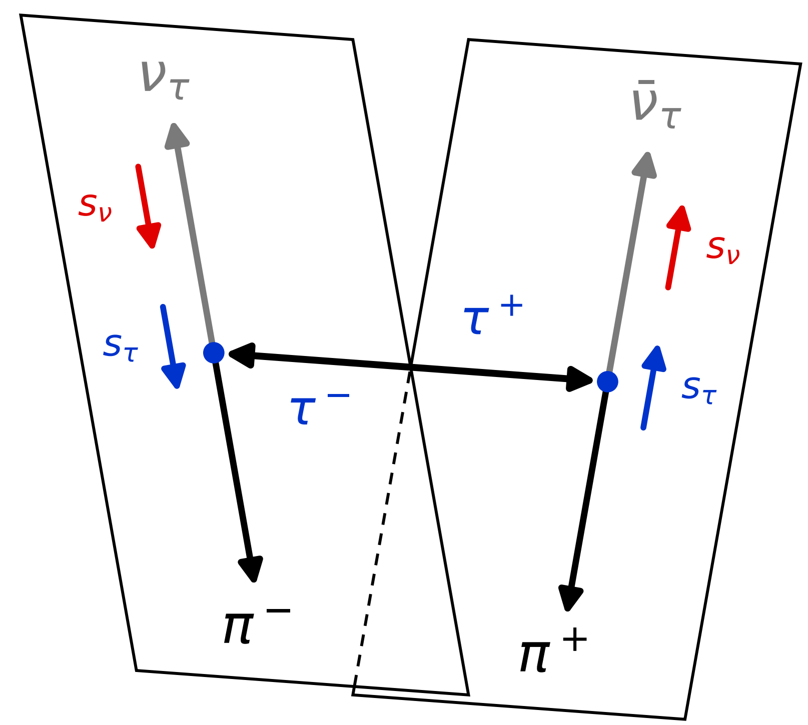
CP-even (S=1)

$$|1,0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle + |\downarrow\downarrow\rangle\right)$$

CP-odd (S=0)

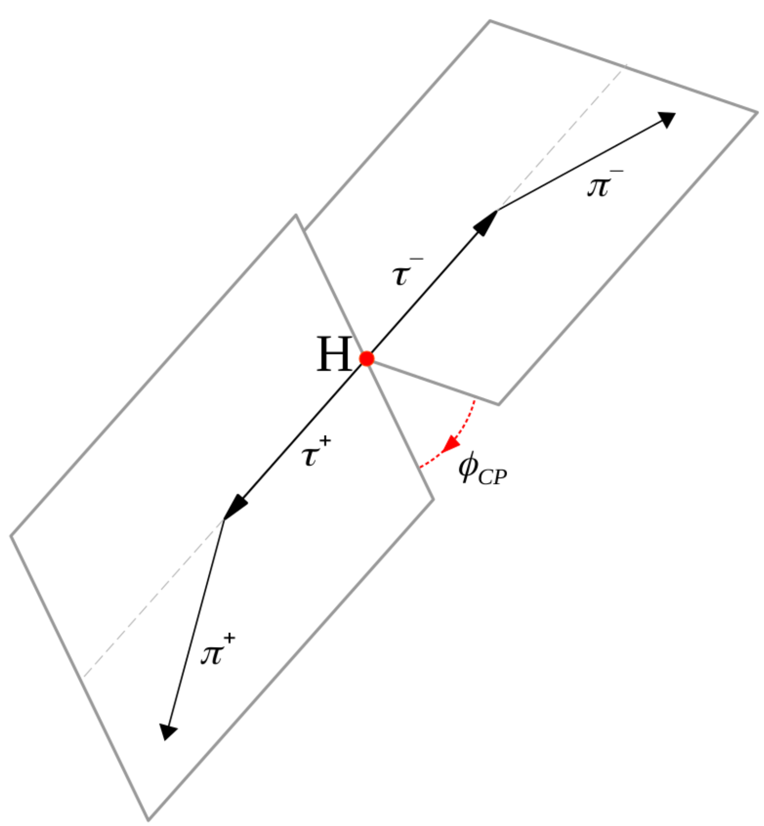
$$|0,0\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle\right)$$

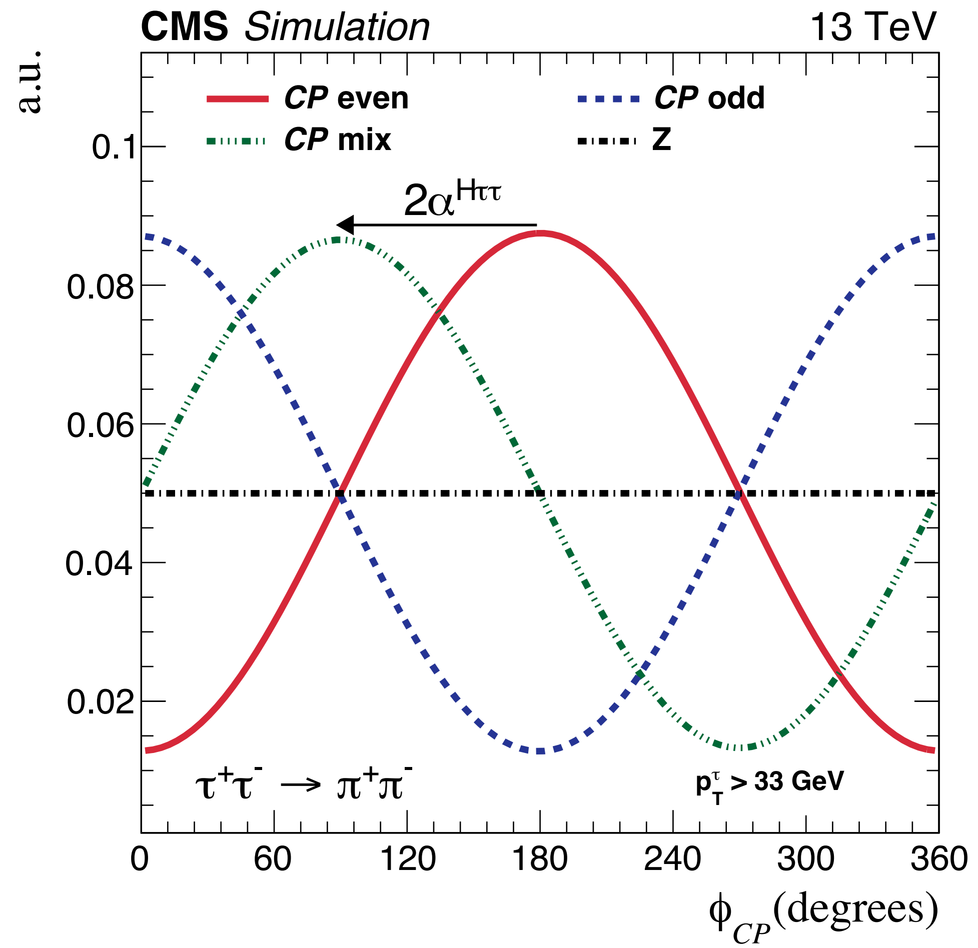




CP observables

- Exploit differences in spin alignment to define CP sensitive variable ϕ_{CP}
- For most simple 2-body decay $\tau \rightarrow \pi^{-}\nu$ just angle between τ-π planes
  - For other decays more complicated formula that depends on tau decay products





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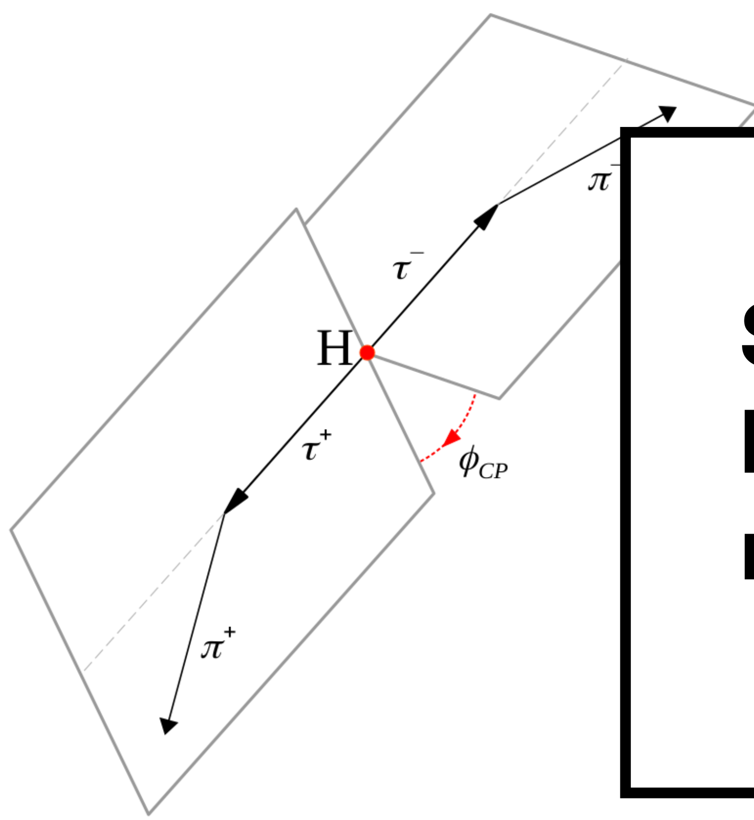
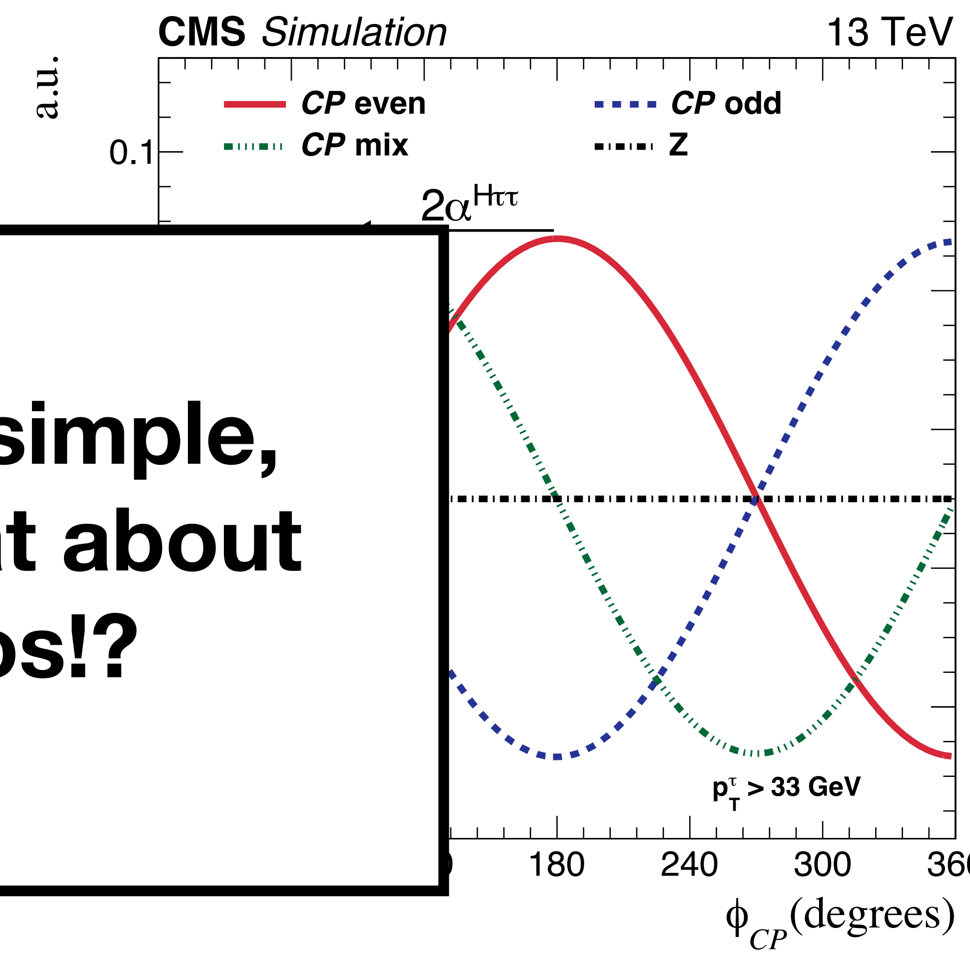
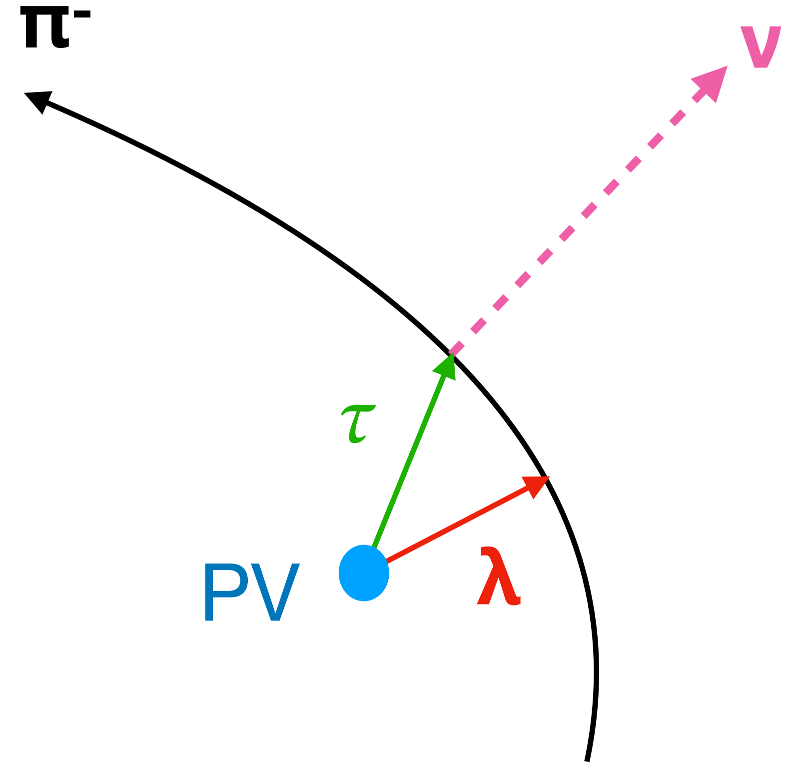


Seems simple, but what about neutrinos!?



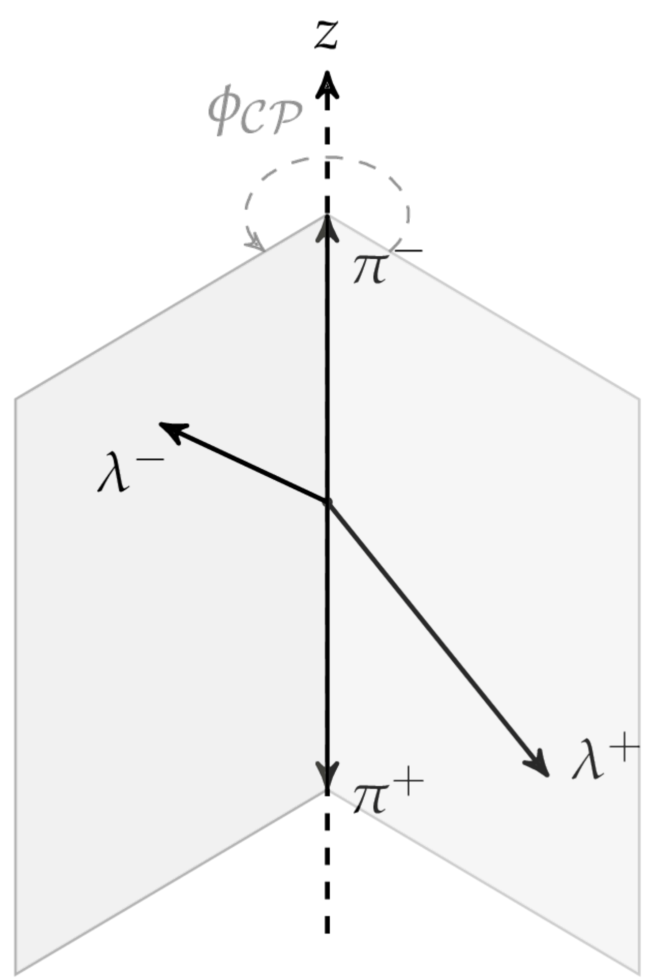
The Impact parameter method

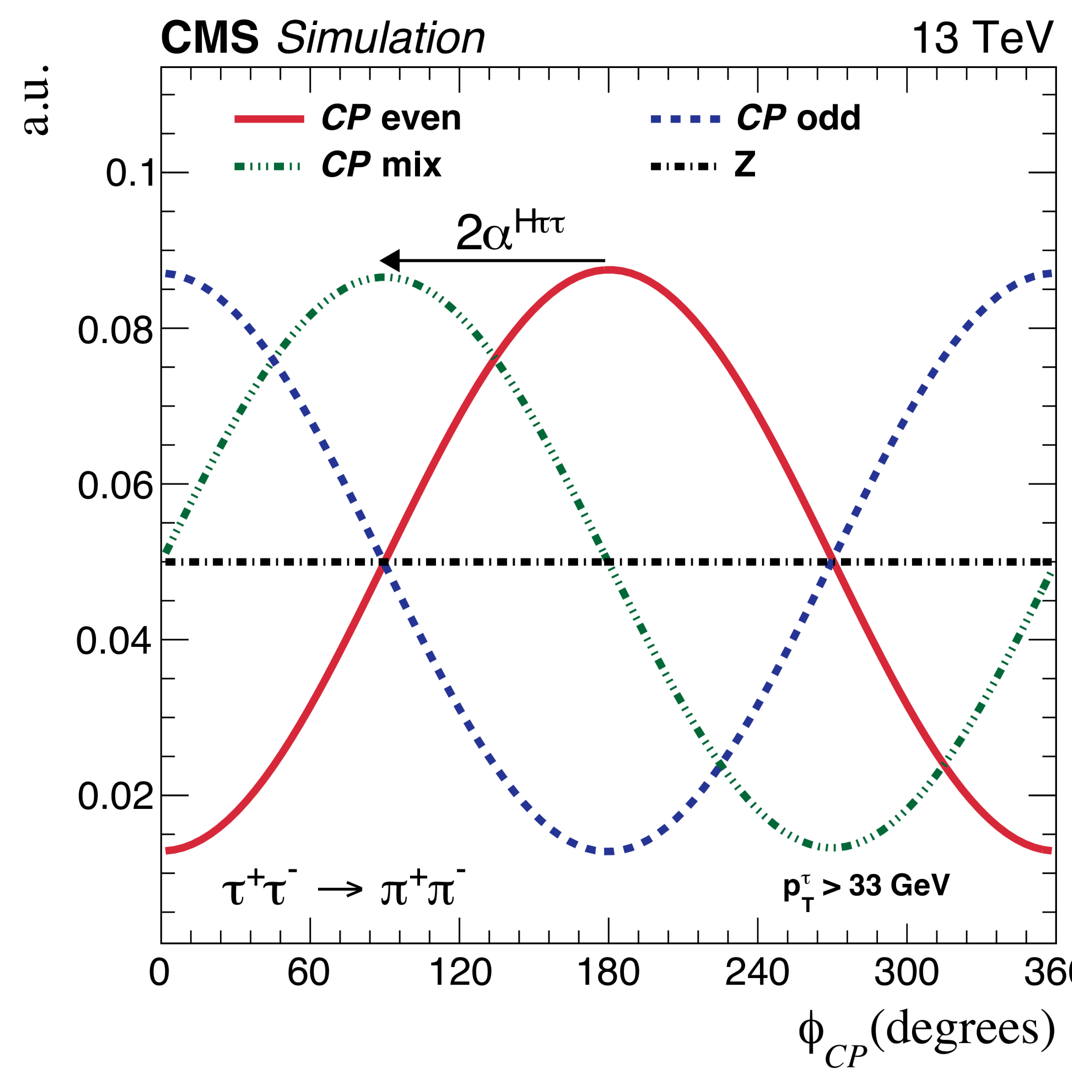
- Charged tracks from tau decays do not originate exactly from the primary vertex (PV)
- Can define impact parameter (IP) by minimising distance between PV and track
- IP is the vector that points from the PV to the point of closest approach to the charged particle track
- Pion track and IP tend to lie on the same plane as the tau and the pion!



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

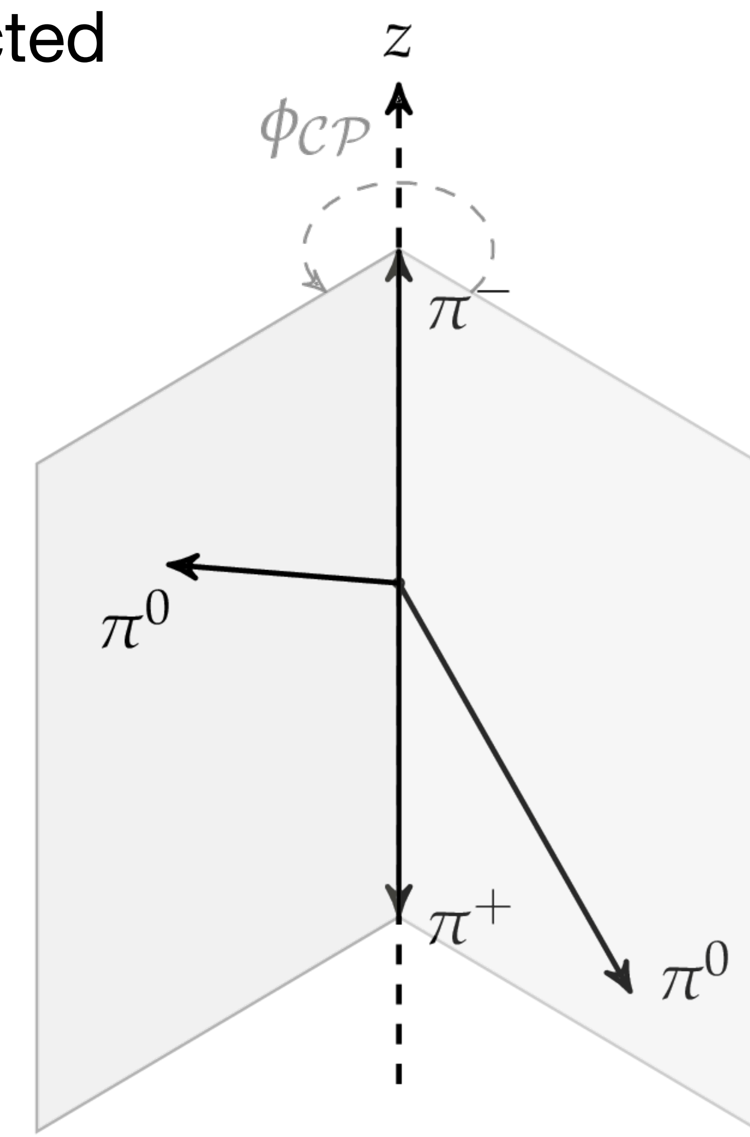
- But we can measure the impact parameter (IP) λ of the charged particle
  - IP is the vector that points from the primary vertex (PV) to the point of closest approach to the charged particle track

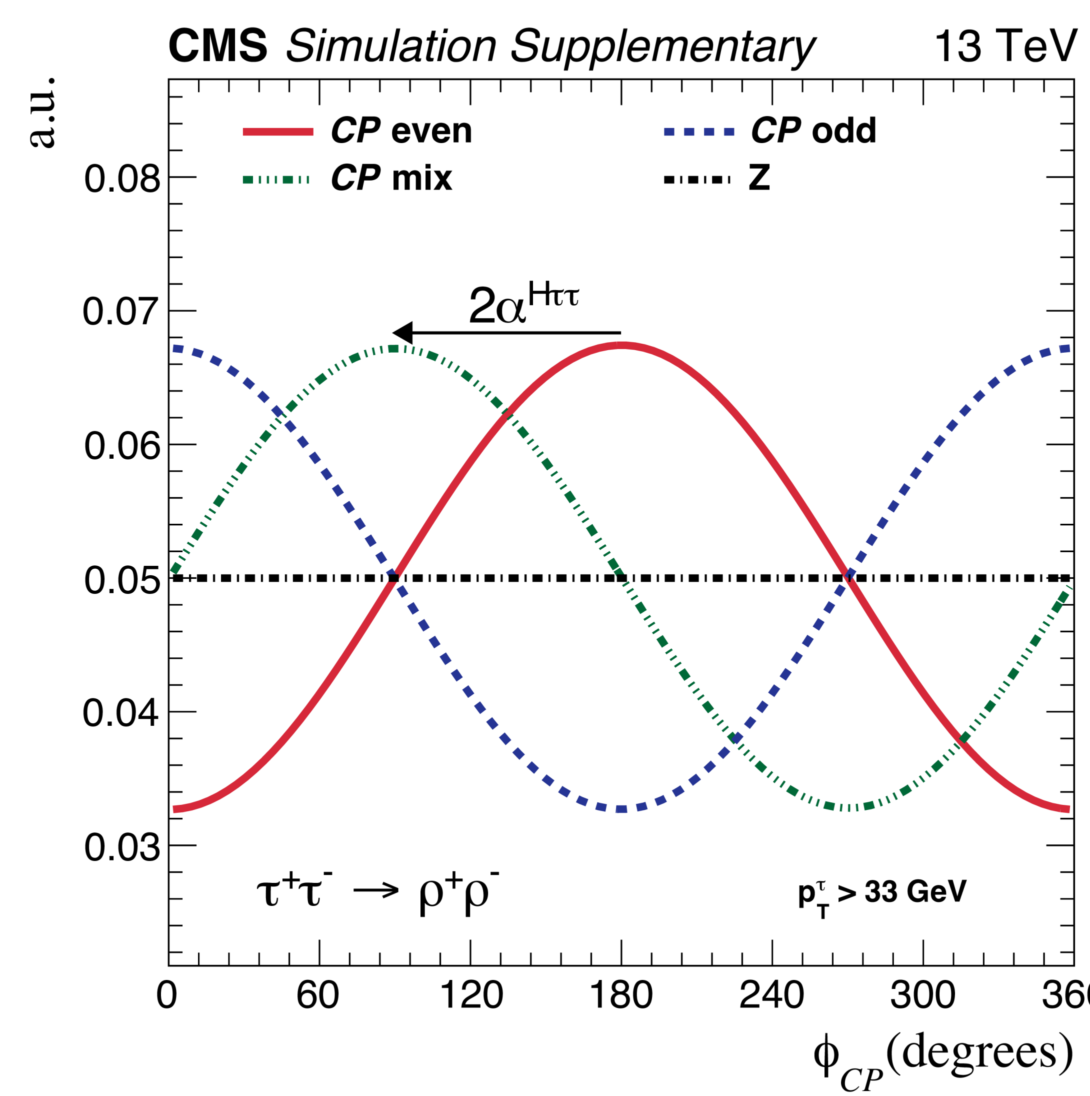




The π^0 method

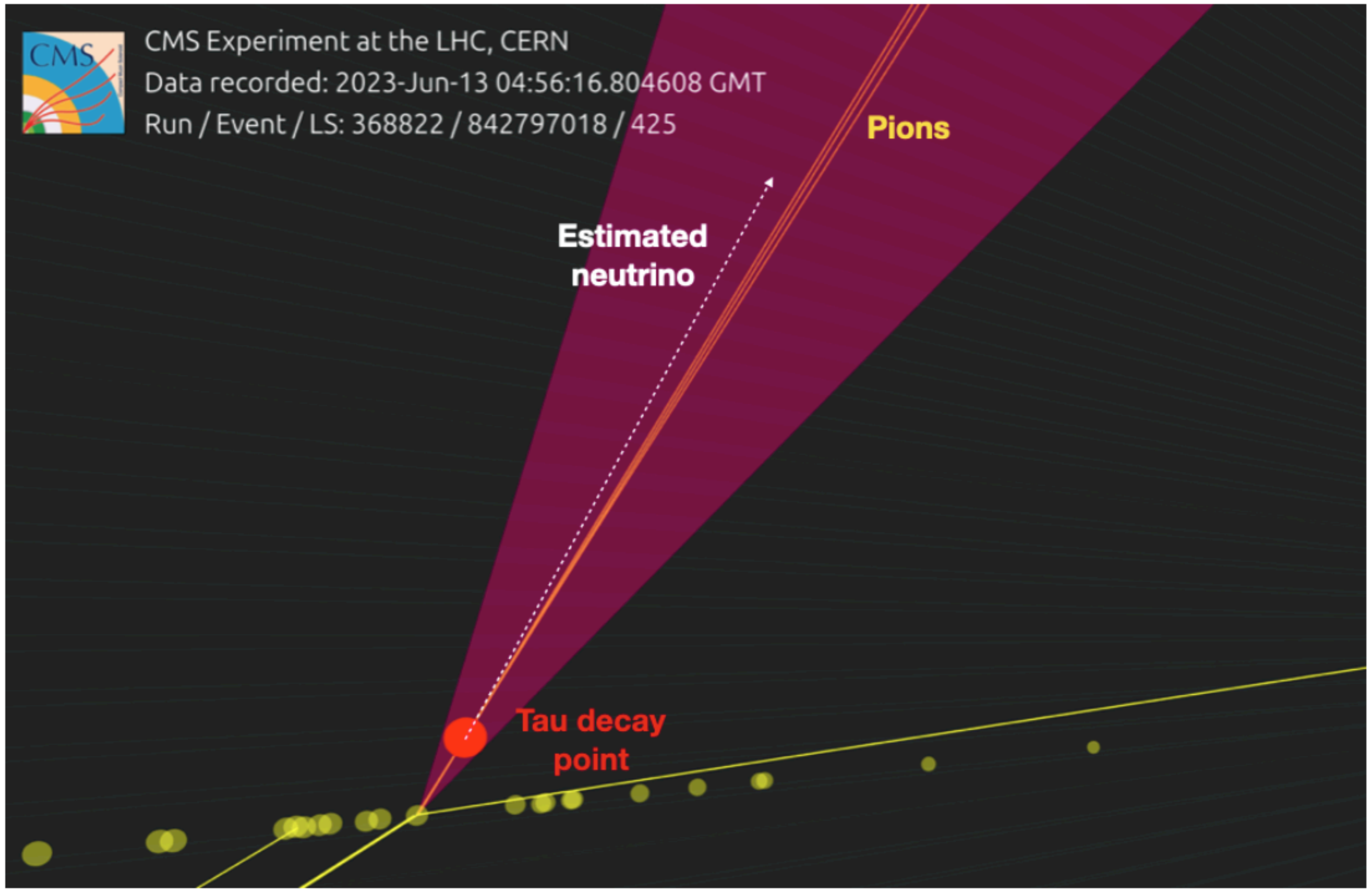
- For events with an intermediate resonances we can define a variable using only visible decay products
  - e.g $\tau\tau \rightarrow \rho^+\nu\rho^-\nu \rightarrow \pi^+ \pi^0\nu\ \pi^- \pi^0\ \nu$
- This avoids using the IP which is quite short compared to tracker resolution so is imprecisely reconstructed





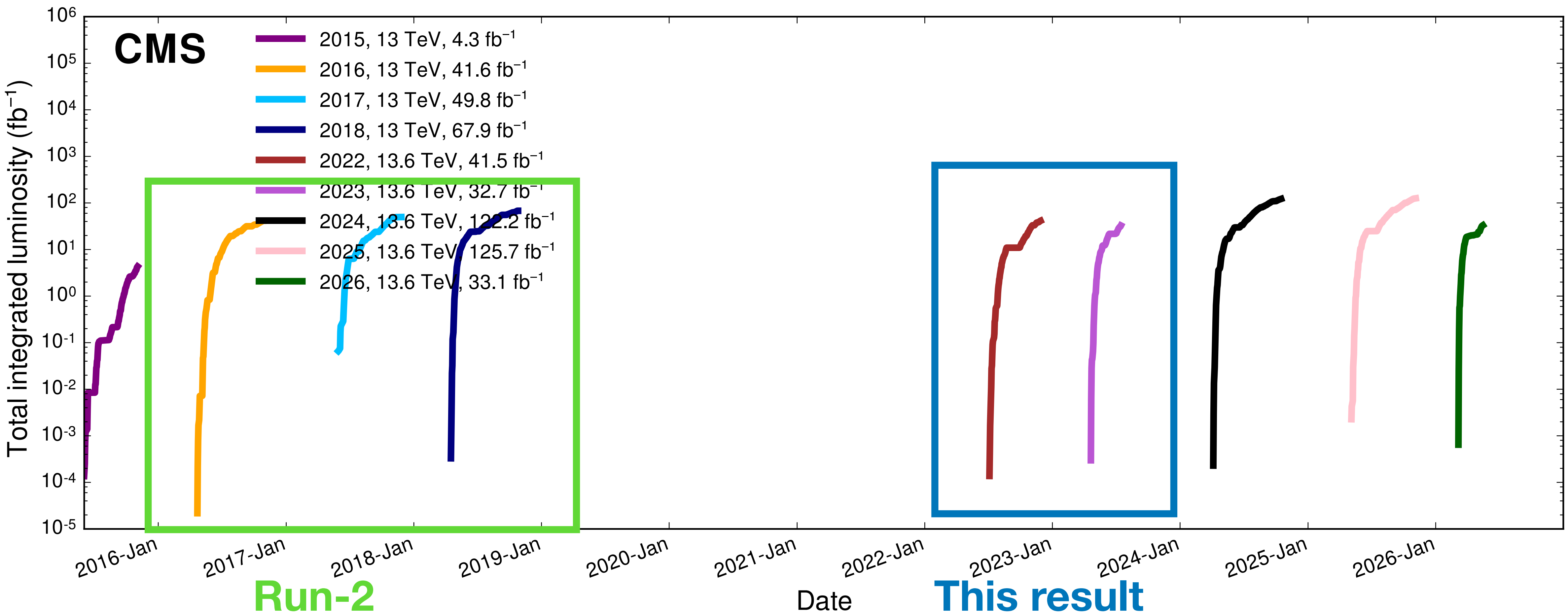
phiCP definition: a1 method

- We get some tau decays into 3 charged pions via a1 resonance: $\tau^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu$
- Reconstruct secondary vertex to the tau (where 3 tracks intersect)
  - Constrains tau flight direction
  - Combine with estimate of tau p from “Fast-MTT” algorithms (based on collinear-approximation), neutrino p then follows



LHC data exploited

- For the latest measurement presented here we used the data collected at 13.6 TeV in 2022—2023: 62.4 fb^{-1}
  - Another ~250 fb^{-1} to be analysed soon!
- Less than half the luminosity compared to Run-2 (138 fb^{-1} at 13 TeV), but….



Improvements compared to Run-2

- The a1 method disused previous is new ~10% improvement
- Improved tau identification ~ 5% improvement
- New triggers (inc using DeepTau in HLT) ~ 15% improvement
- Larger cross-section at 13.6 TeV vs 13 TeV ~ 5% improvement
- New selections introduced to discard poorly reconstructed events ~20% improvement
- Also better classification of tau decay modes
- With these improvements we expect better sensitivity than Run-2 despite having less than half the luminosity!

Event selections

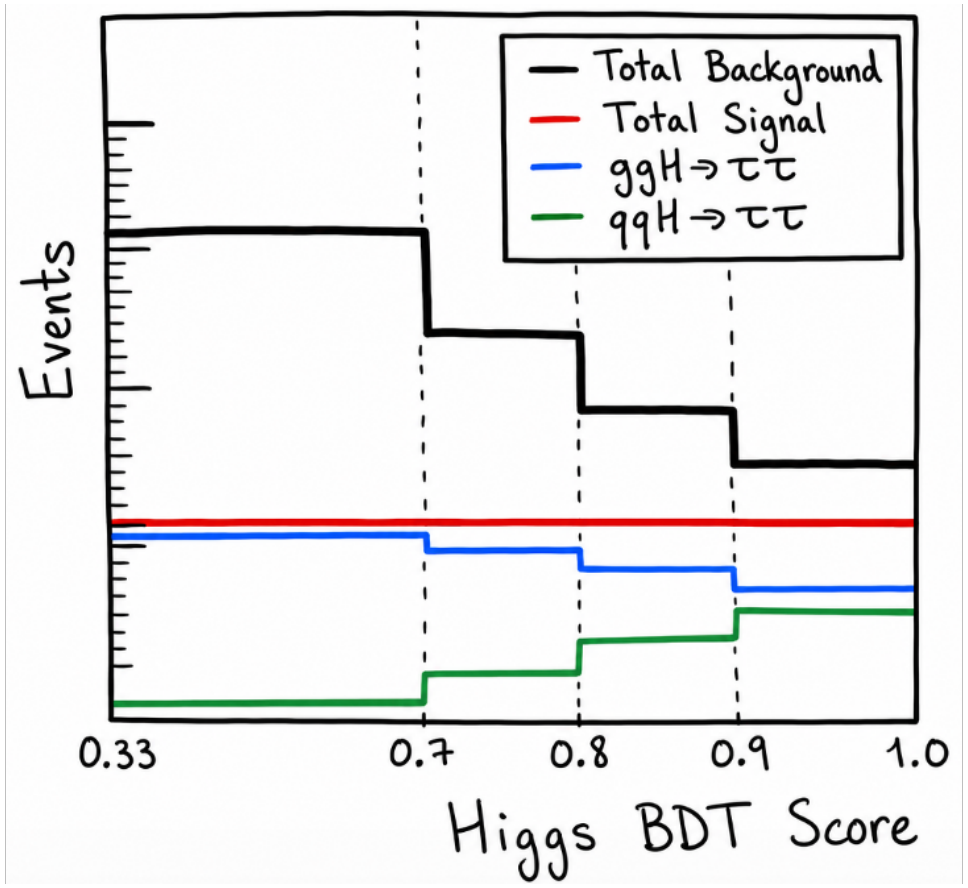
- We select di-tau events in the fully hadronic final state ($\tau_h\tau_h$) and two semi-leptonic final state ($\tau_e\tau_h$ and $\tau_\mu\tau_h$)

- 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, or with transverse mass m_T > 65 GeV

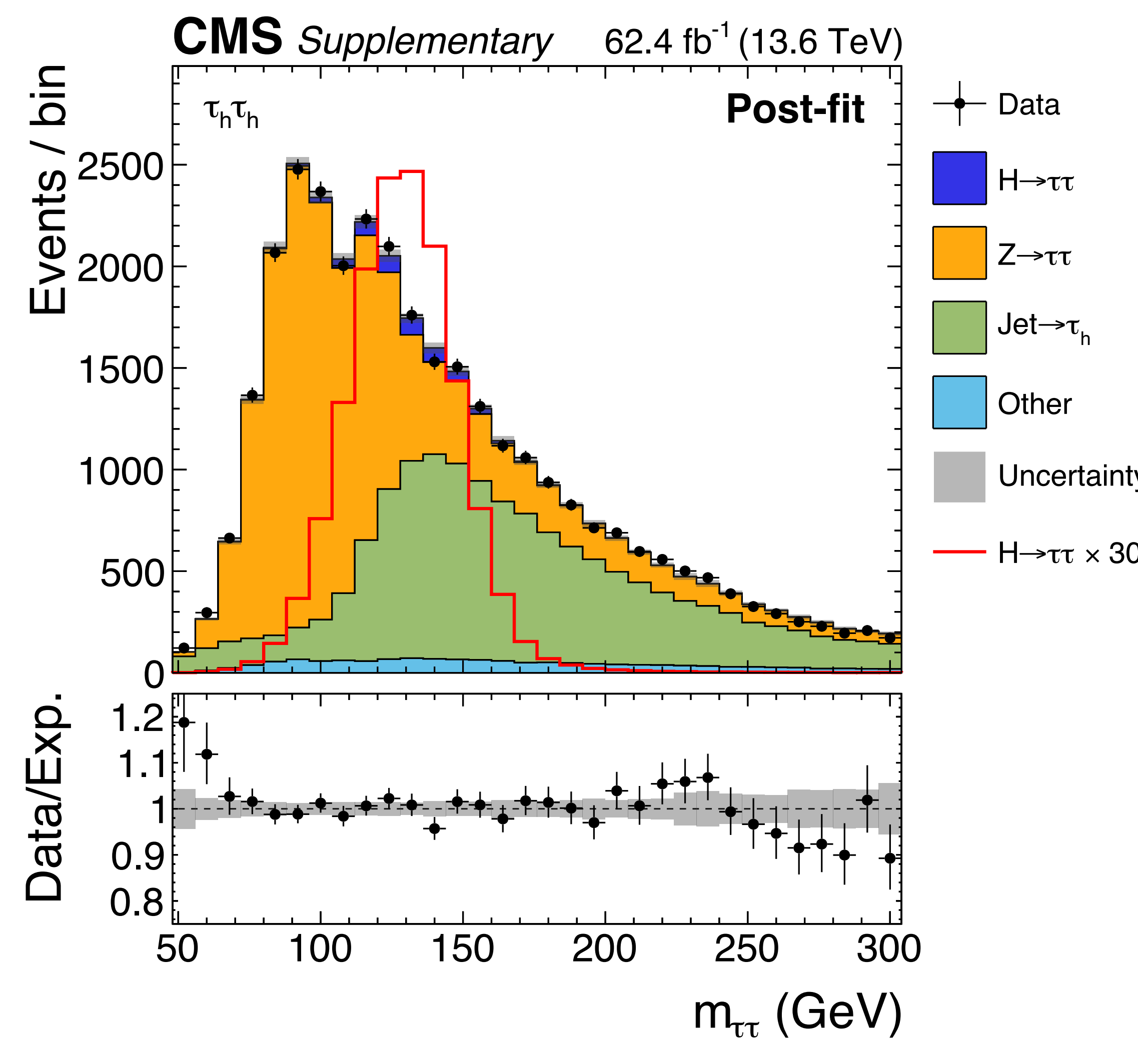
Background suppression

- Train multi class BDT to separate signal from main background
  - Classes: mis-ID background, genuine tau background, Higgs signal
- BDT does not attempt to separate VBF from ggH production but get some separation as VBF peaks more sharply at high Higgs BDT score
- Input variables include: $m_{\tau\tau}$ (estimated with FastMTT algorithm); p_T and η of taus and jets; missing transverse momentum variables; dijet variables for tagging VBF e.g dijet mass



Background modelling

- Largest background from Z→ττ
- Model using MC (MadGraph @ NLO)
  - Merge Z+Nj samples for N=0,1,2
  - Gives better modelling of VBF-like phase space
- Several corrections applied to improve modelling



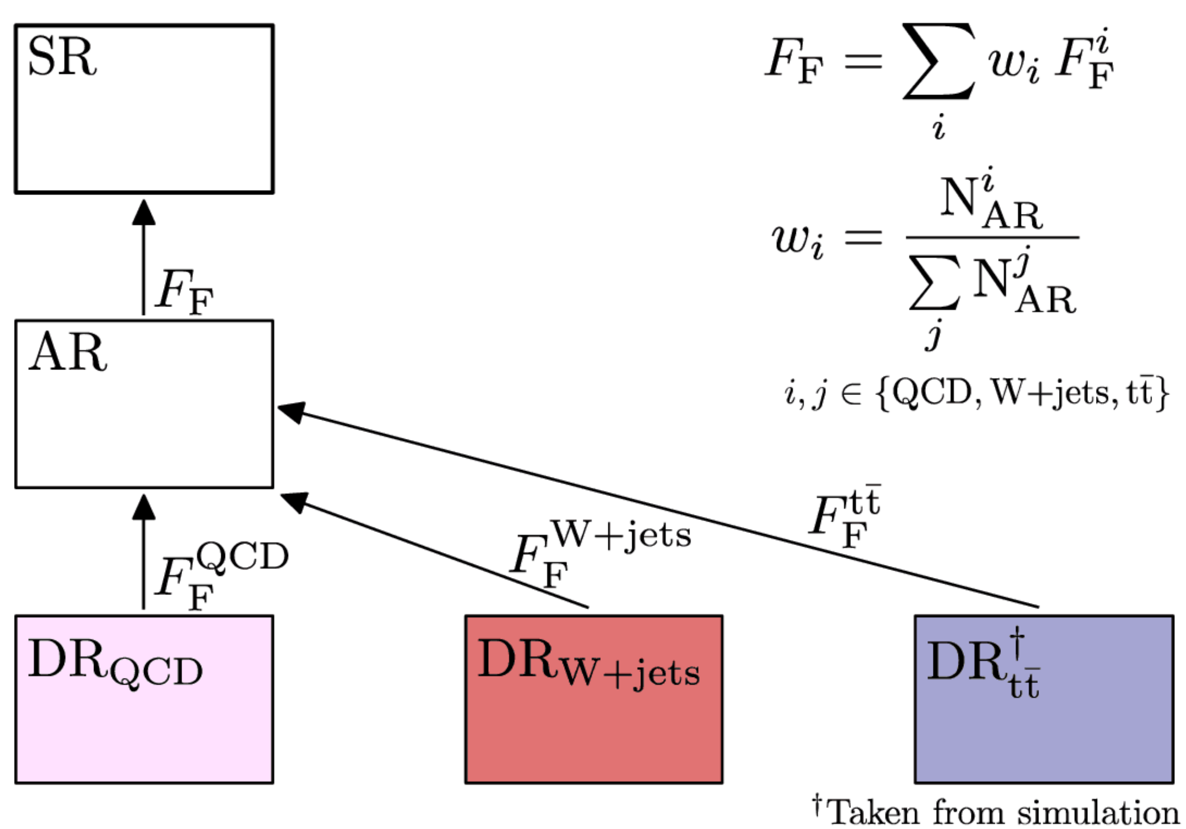
Background modelling: mis-ID background

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

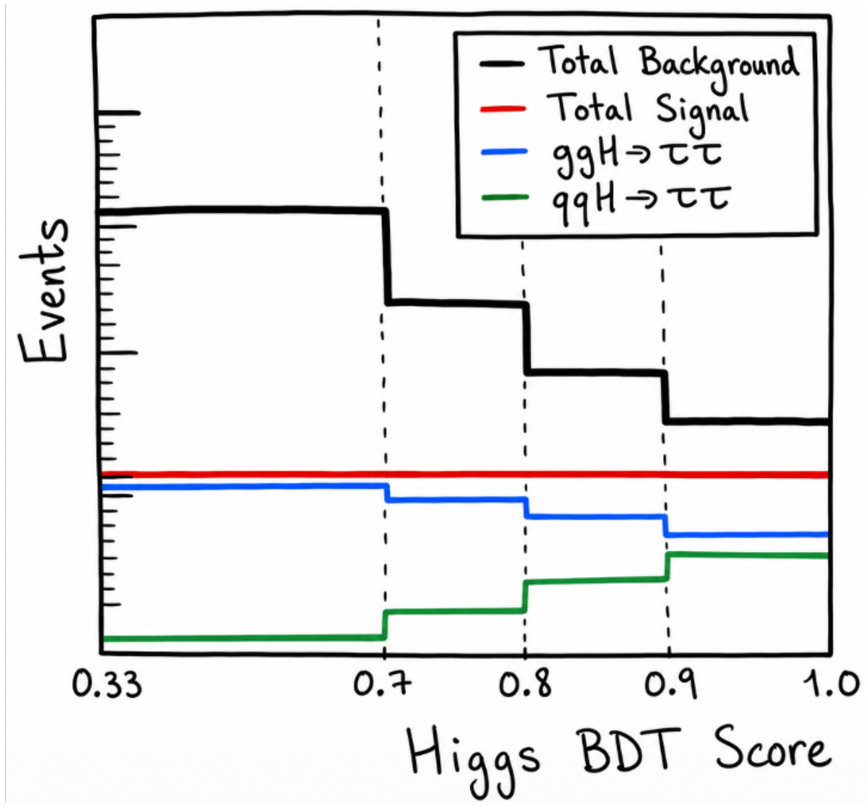
- We select events in a sideband region failing nominal tau ID requirements but passing a relaxed selection

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

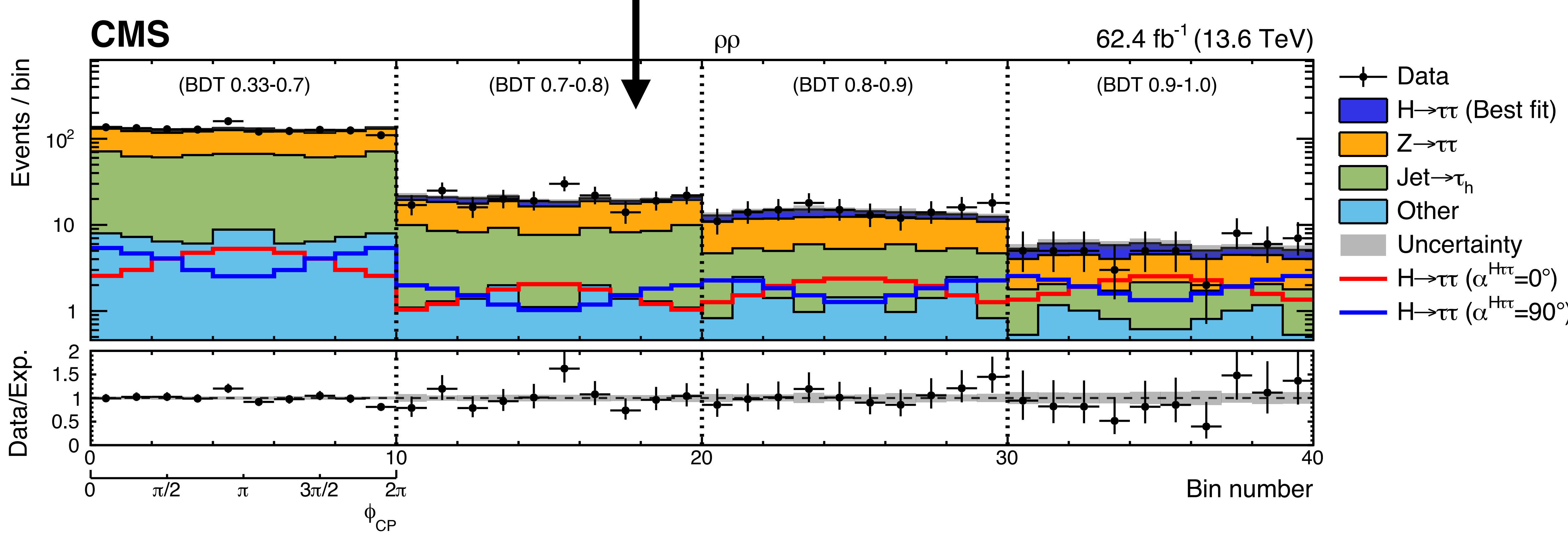
- Dominant processes are:
  QCD and W+jets



Statistical inference

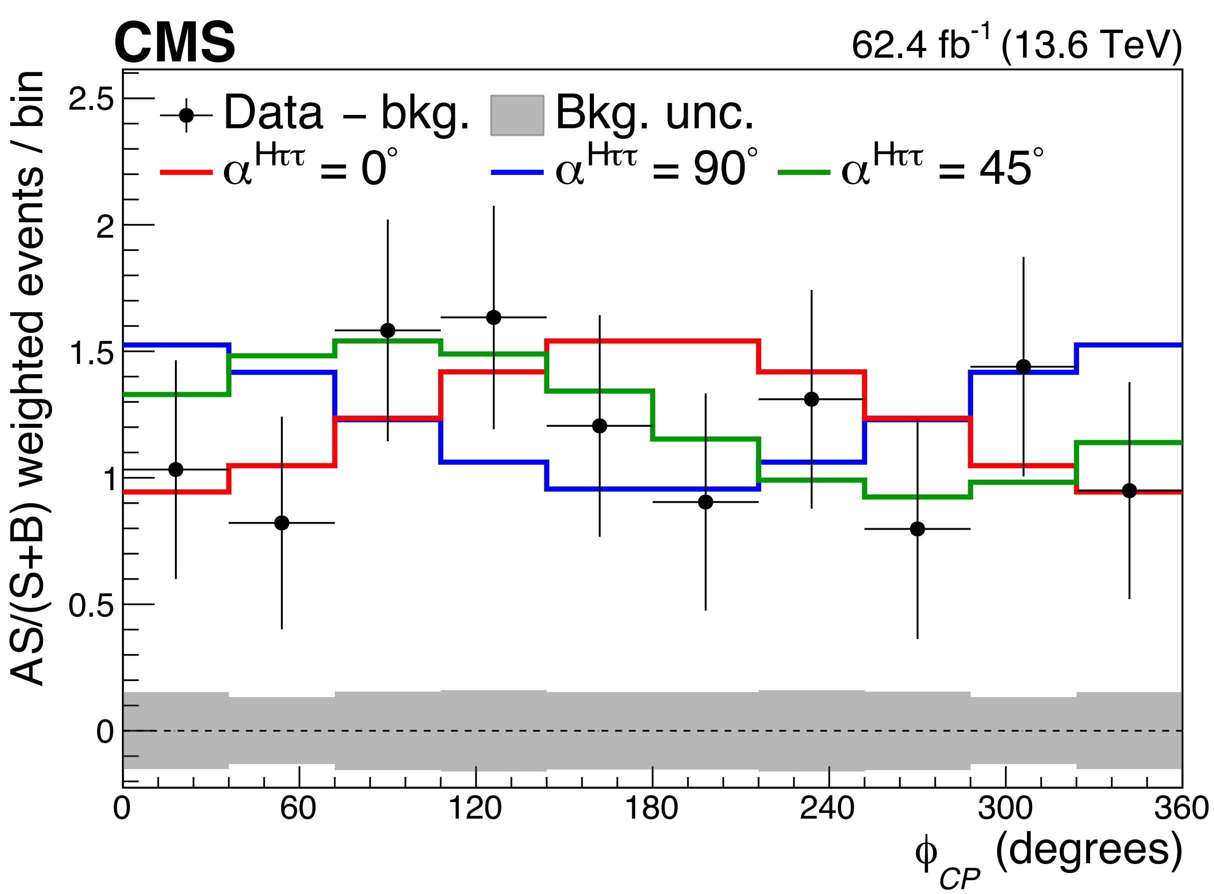


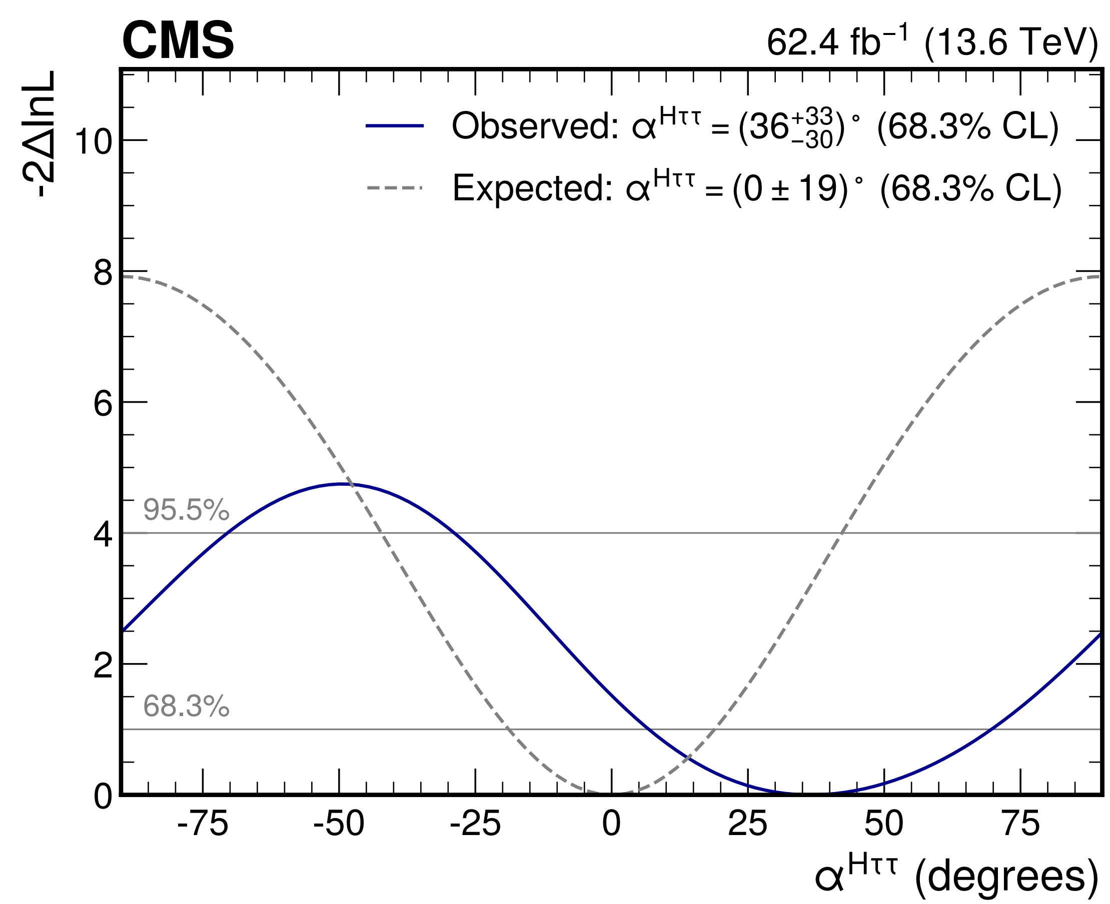
- Binned 2-D maximum likelihood fit
- Bin events in BDT score to separate Higgs from background
- In each BDT window fit ϕ_{CP}



Results

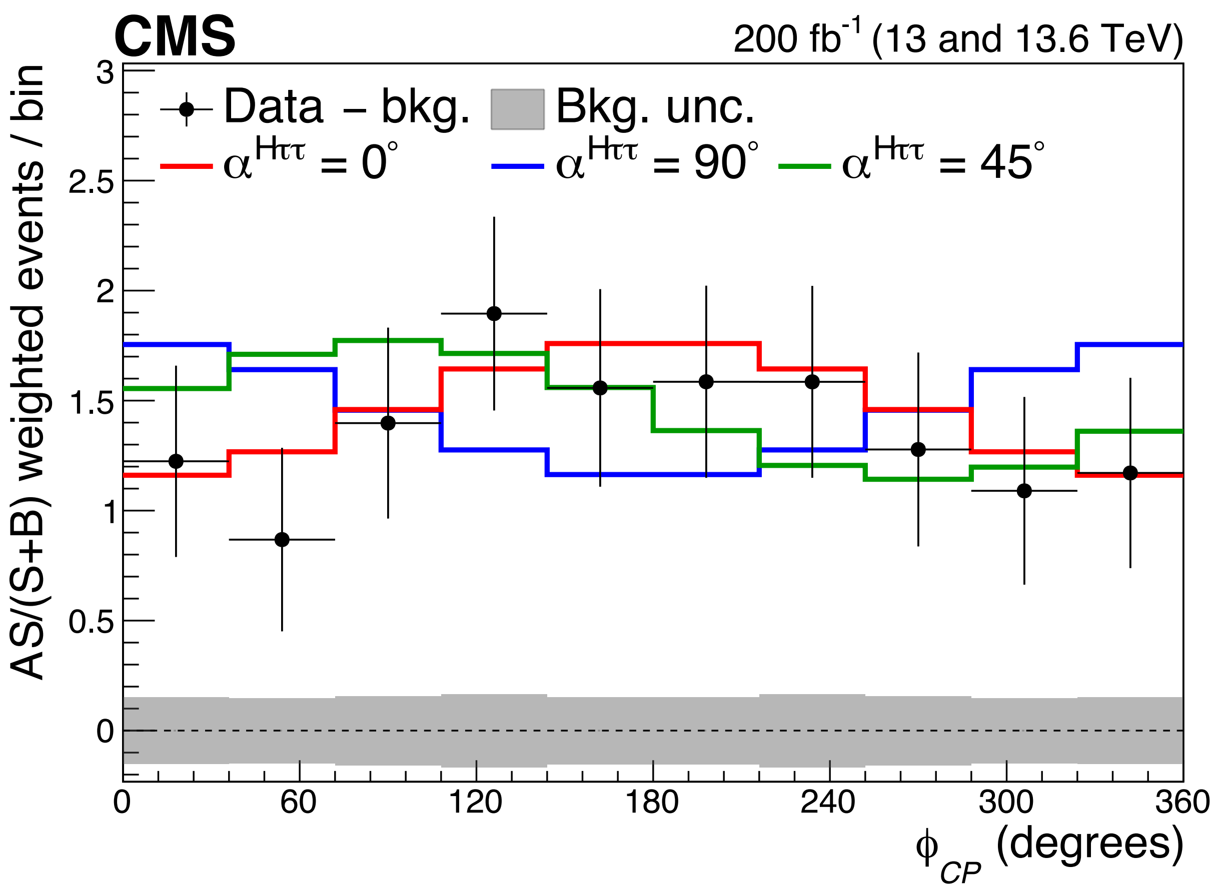
- Weight events by sensitivity to visualise ϕ_{CP} (left)
- Data slightly favour CP-violating scenario → non-zero $\alpha^{\mathrm{H}\tau\tau}$ (right)
  - Best fit: $\alpha^{\mathrm{H}\tau\tau} = (36^{+33}_{-30})^{\circ}$; Expected: $\alpha^{\mathrm{H}\tau\tau} = (0 \pm 19)^{\circ}$

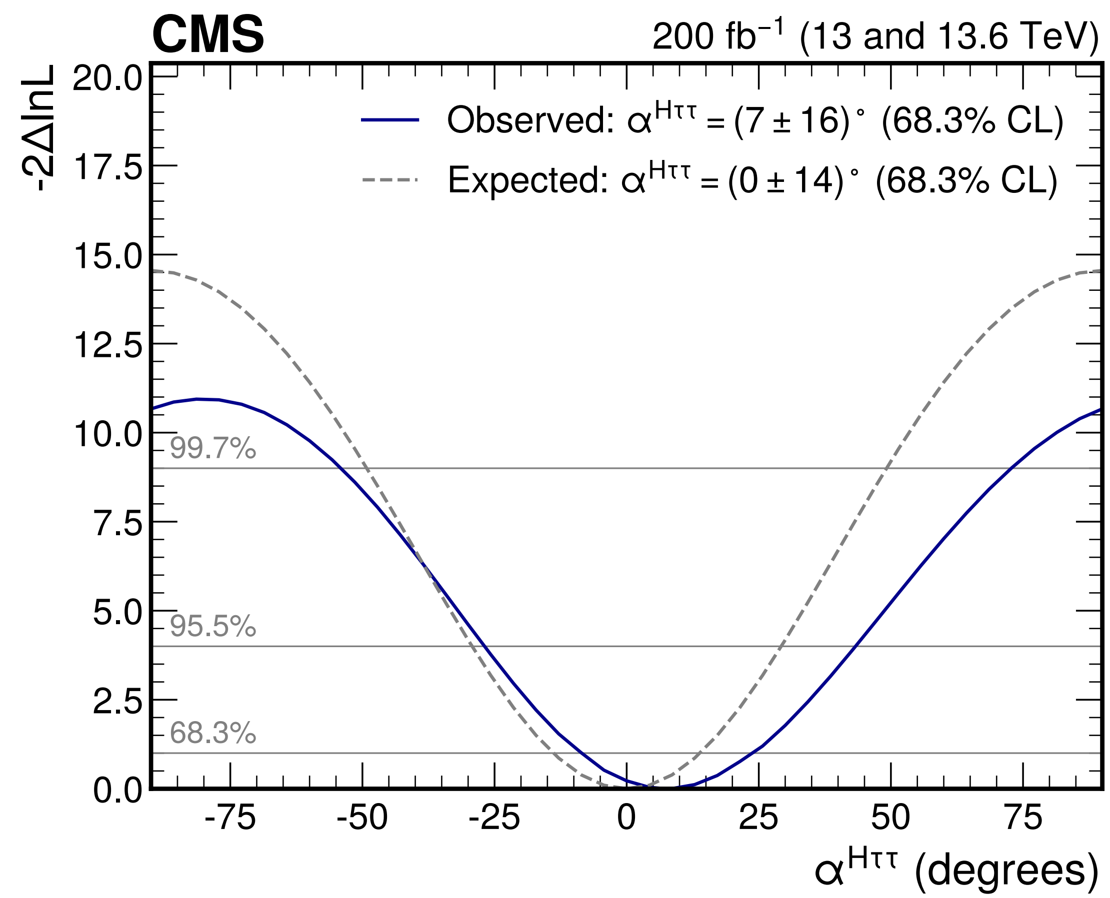




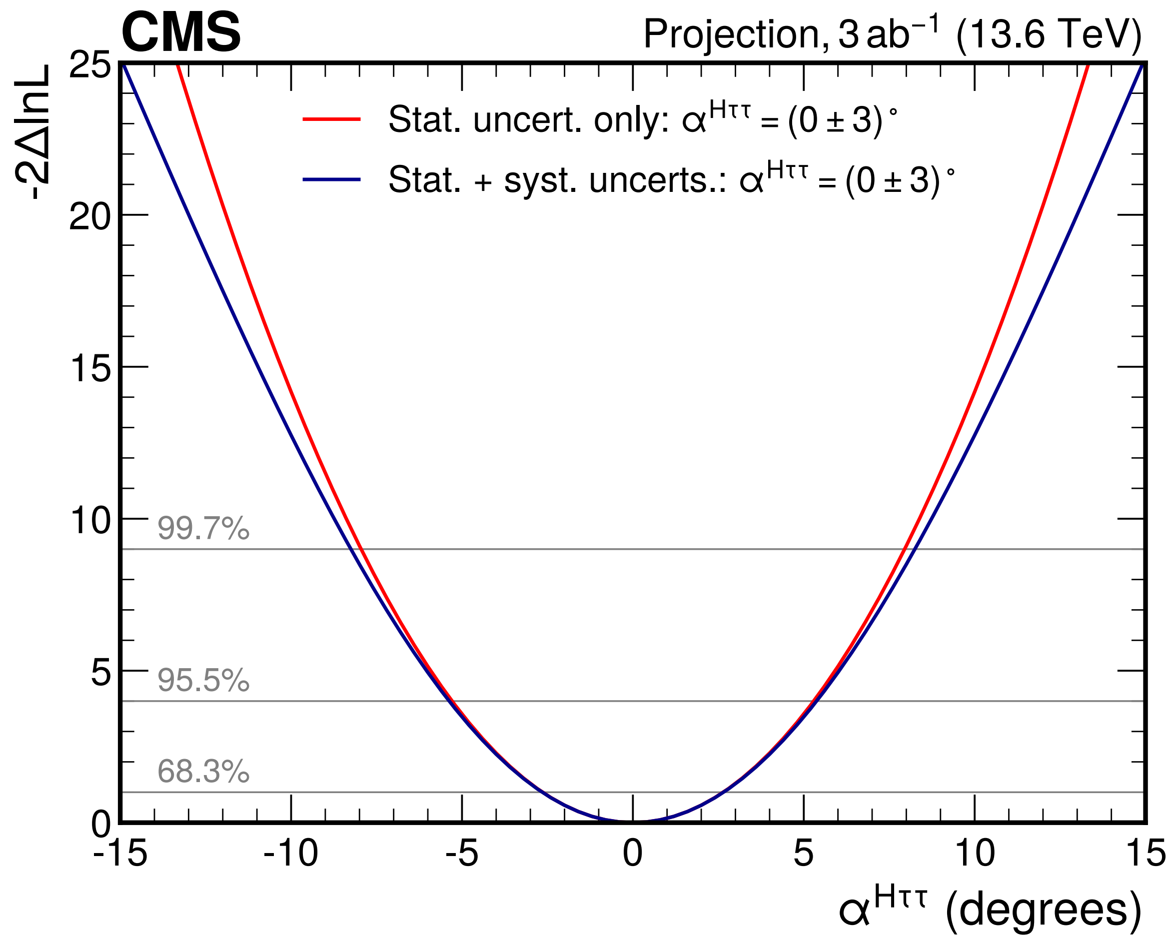
Run-2 + Run-3 Results

- Combined with Run-2 measurement: $\alpha^{H\tau\tau} = (-1 \pm 19)^{\circ}$
- Overall looks closer to CP-even
- Combined best fit: $\alpha^{H\tau\tau} = (7 \pm 16)^{\circ}$; Expected: $\alpha^{H\tau\tau} = (0 \pm 14)^{\circ}$





- Projection to end of HL-LHC (3000 $fb^{-1}$by 2042)
  - Scale luminosity from 62 fb^{-1} to 3000 fb^{-1}
  - Assume same acceptance and systematics as Run-3
- Expect to reach 3^{o} uncertainty → Can we do better?



Reconstructing neutrinos with ML

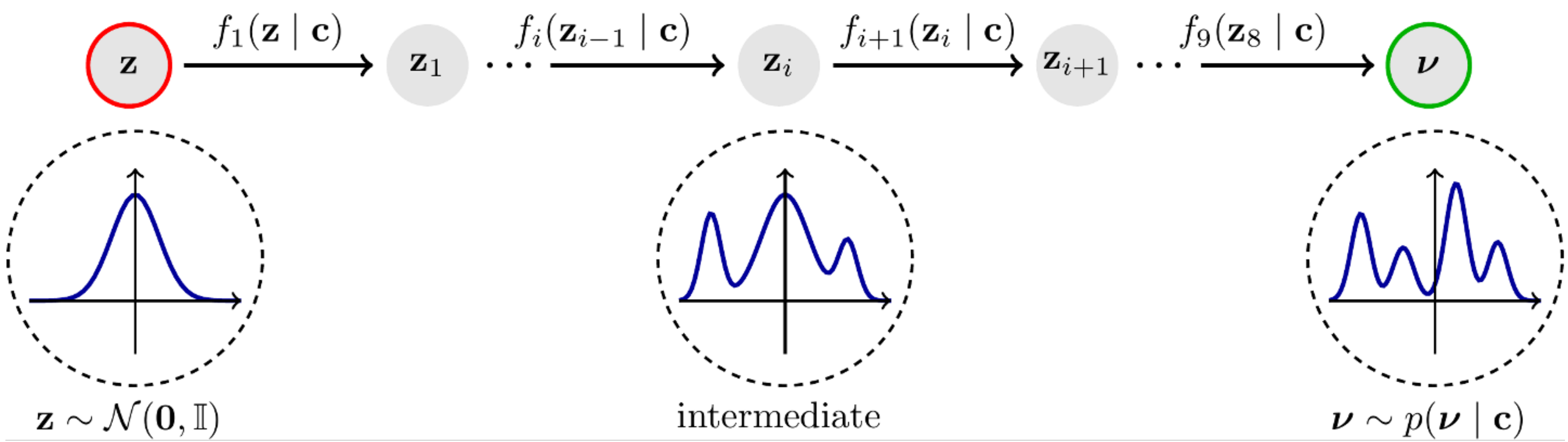
- Current CP measurements use somewhat crude approximation for the neutrinos
- Can we improve this using machine learning (ML)?
- Given indirect constraints on the neutrinos c what is their most likely momenta?
  - Constraints: Visible decay products kinematics, Track impact parameters / SVs, missing transverse momentum, mass constraints $m_{\tau1}$~$m_{\tau2}$~1.8 GeV , $m_{\tau\tau}$ =125 GeV
- TauPolaris (arXiv:2608.10961) tool uses a normalising flow to estimate most likely momenta of tau neutrinos
  - Determine density p(v | c), then find maximum to determine v

Normalising flows overview

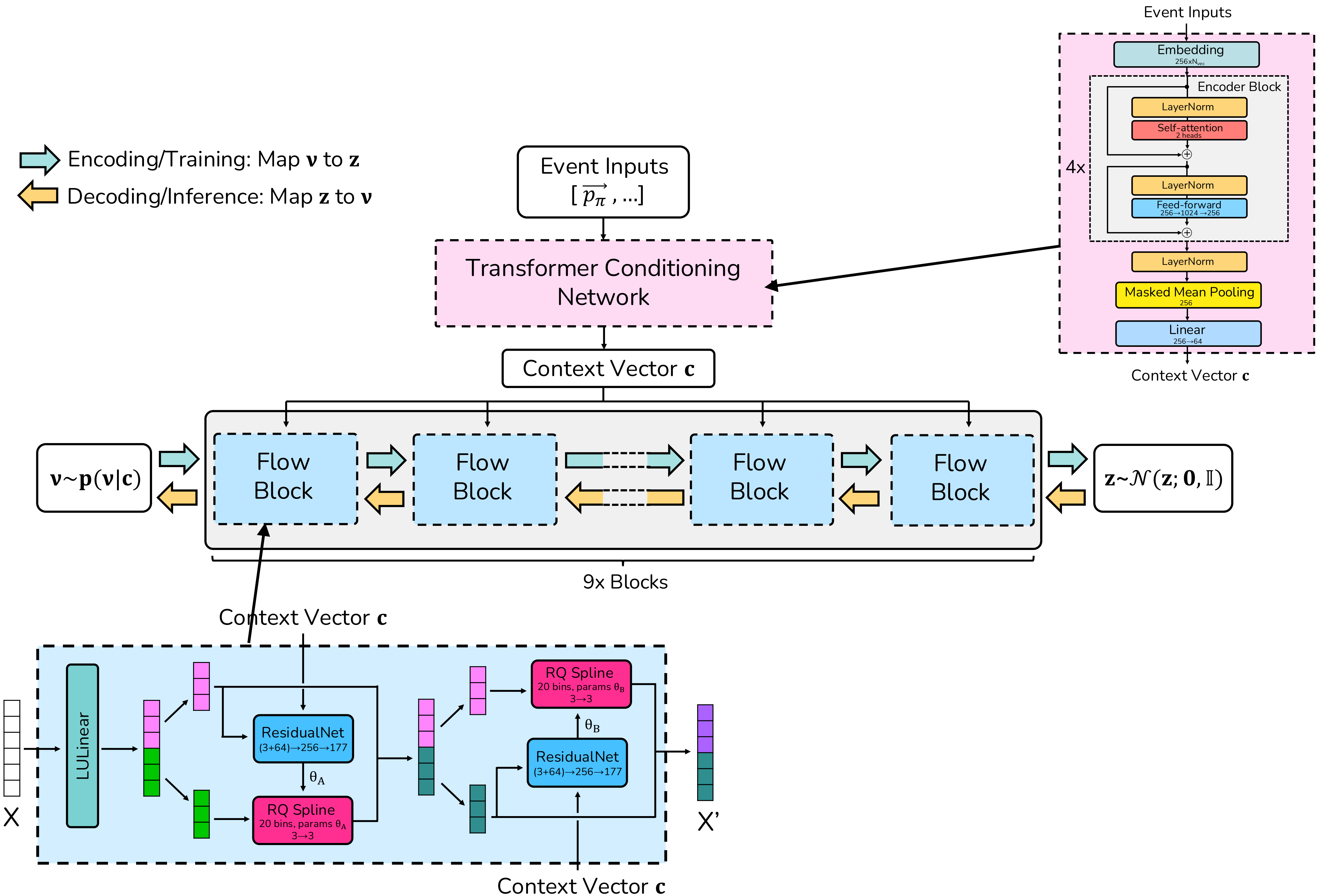
- Normalising flows learn a transformation between simple base distribution (Gaussian) and a complex target distribution
- Since Gaussian density is know can use change of variables formula to compute the target density:

$$\log p(\boldsymbol{\nu} \mid \mathbf{c}) = \log \mathcal{N}\big(\mathbf{z};\, \mathbf{0}, \mathbb{I}\big) + \log \left| \det J_f(\boldsymbol{\nu} \mid \mathbf{c}) \right|$$

- The Jacobian term corrects for the change in volume under the map — where volume grows the density thins out, where volume shrinks the density piles up.
- Needs transformation to be invertible and differentiable - apply chain of simpler transformations
    - Easier to guarantee inevitability and differentiability for simple transformation
    - By chaining many transformation we build up expensiveness



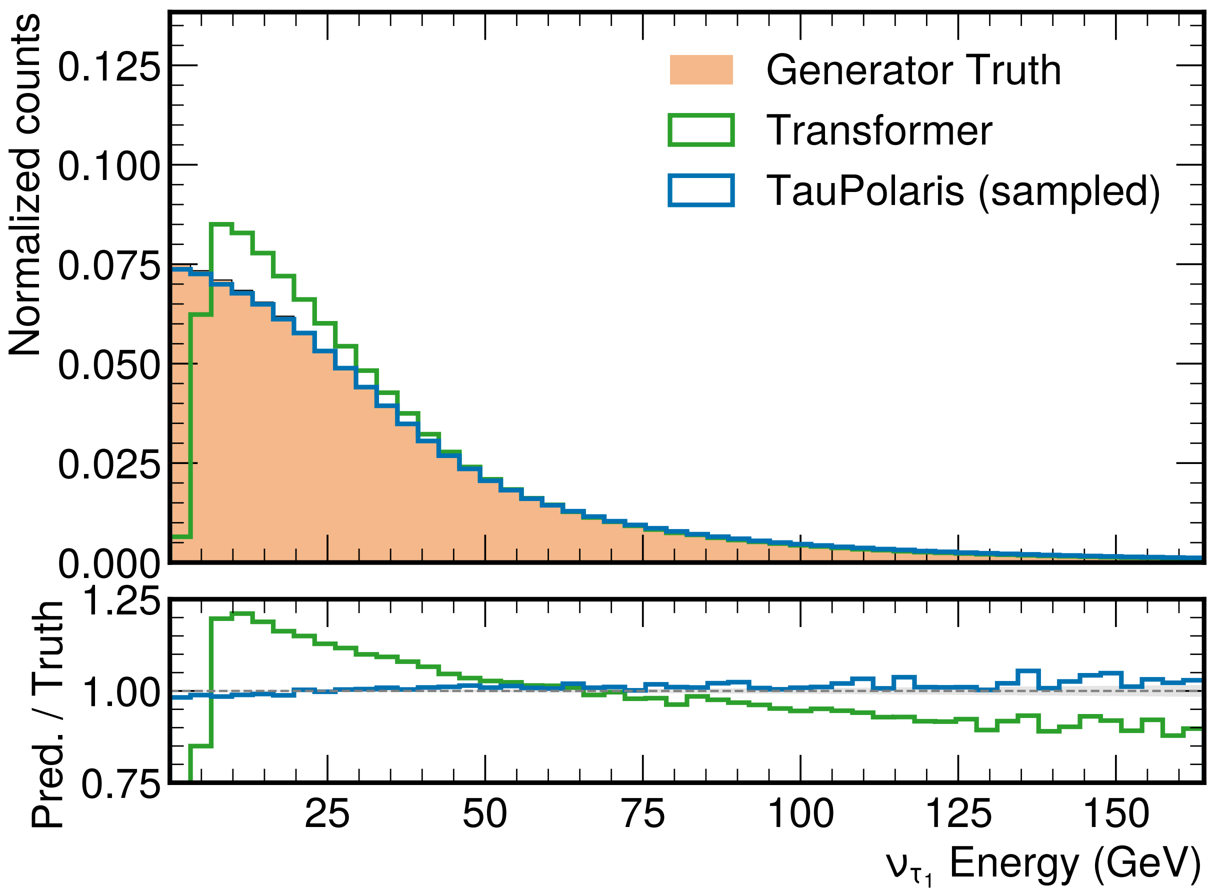
TauPolaris Architecture

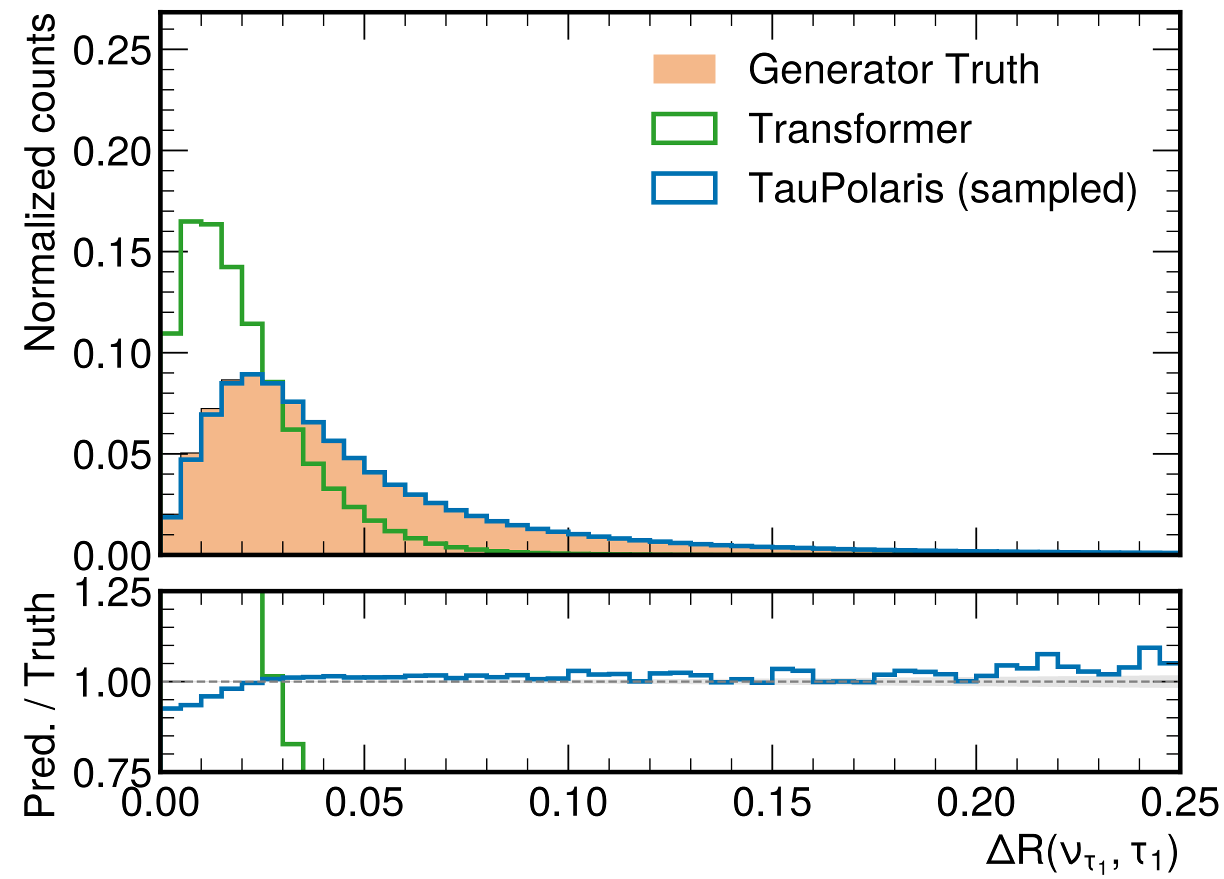


Validating the reconstructed kinematics

- We can sample the flow to reproduce the generator-level neutron distributions e.g Energy and ΔR from undecayed tau

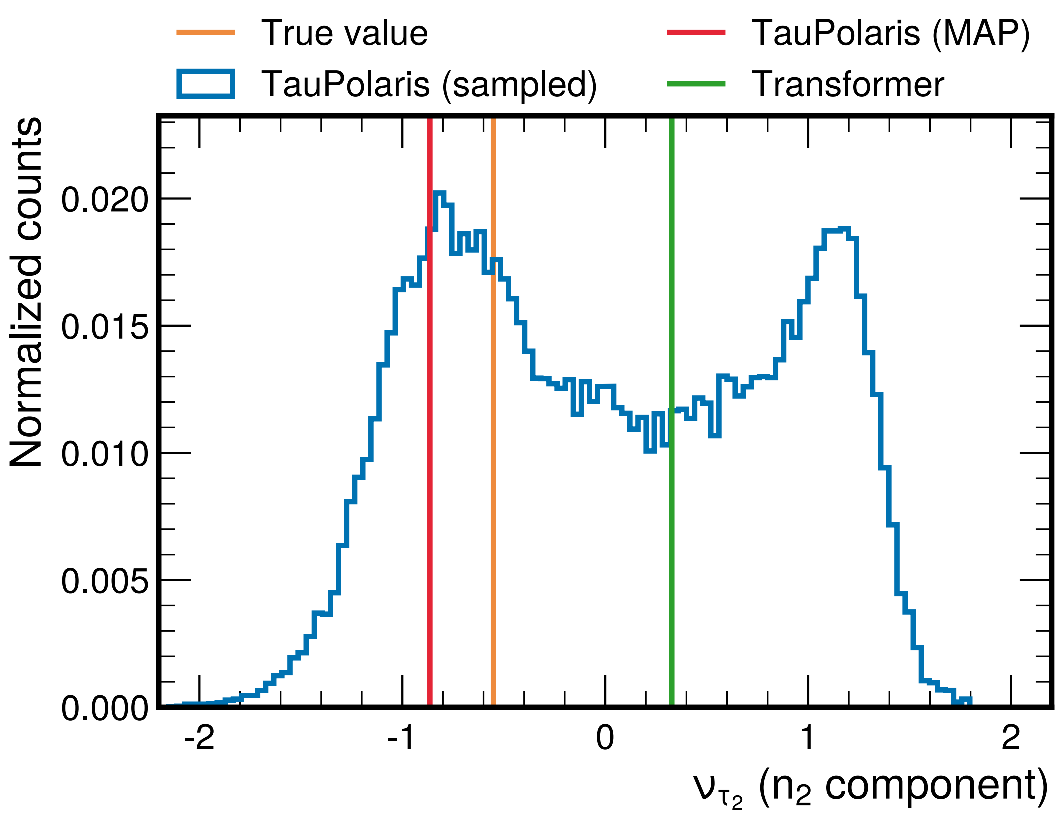
- Comparing this to a standard ML-regression method e.g transformer trained with mean squared error (MSE) loss
  - MSE-based regression tends to incorrectly predict neutrino is more collinear with the tau

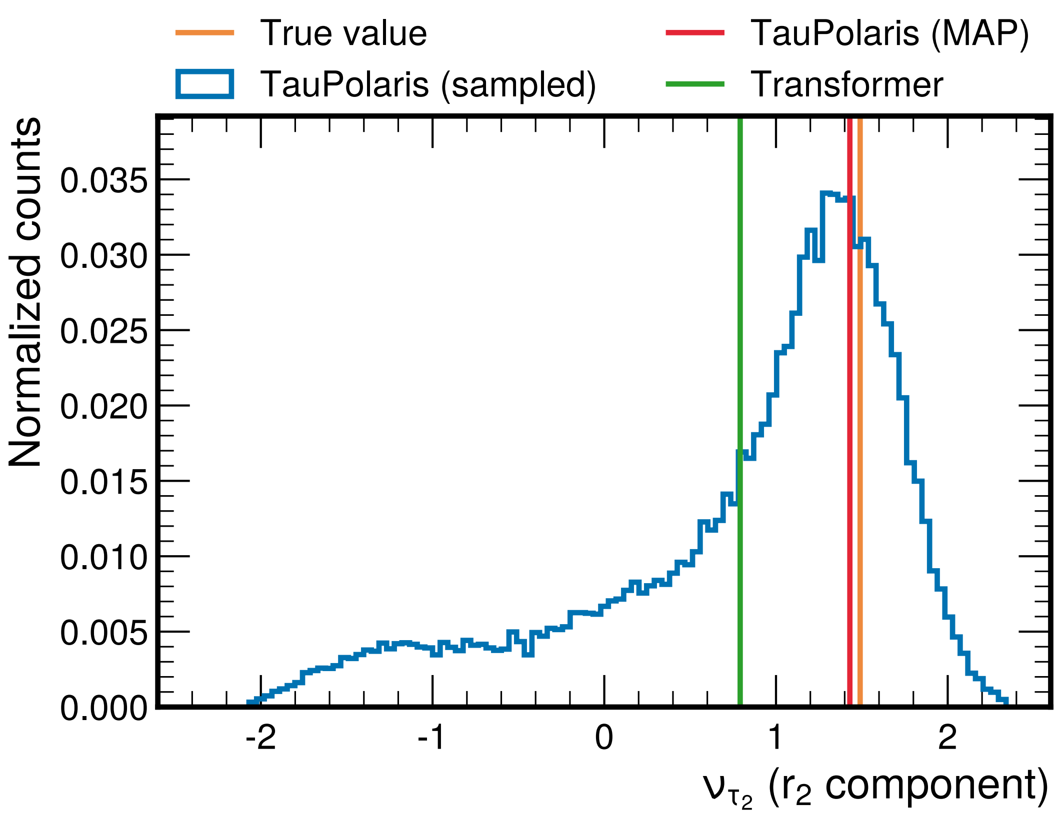




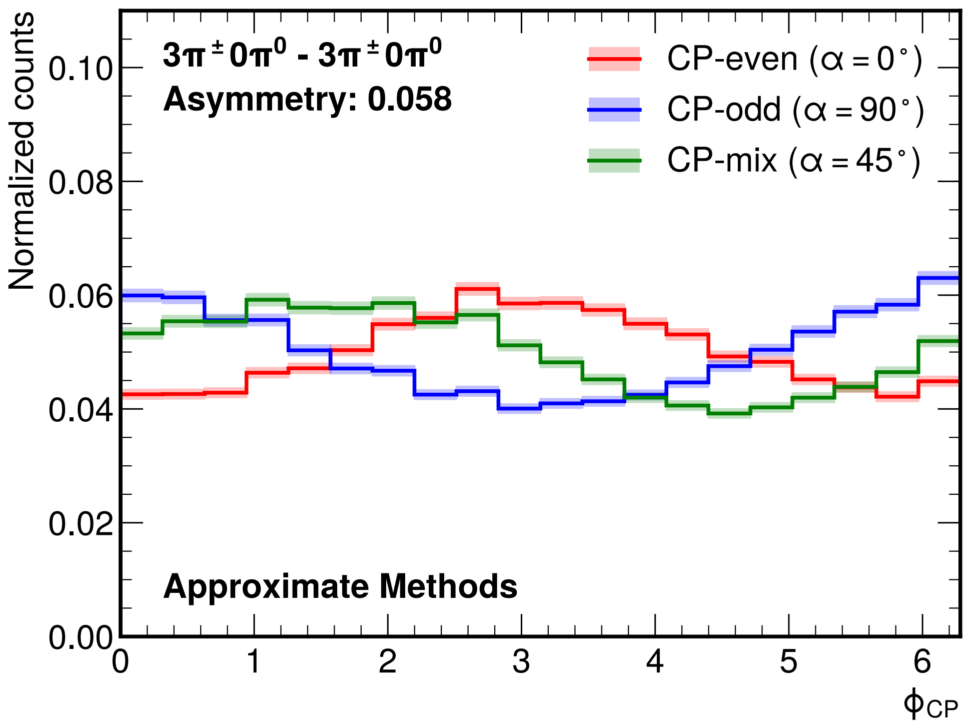
Looking at individual events

- Two example events showing the pdf (blue) evaluated using the flow vs the transformer estimate
  - n and r are transverse components of neutrino momentum wrt tau
- Any MSE-based regression tends to learn the mean of the density
  - This is problematic when distribution is multimodal - mean can fall in region with low probability

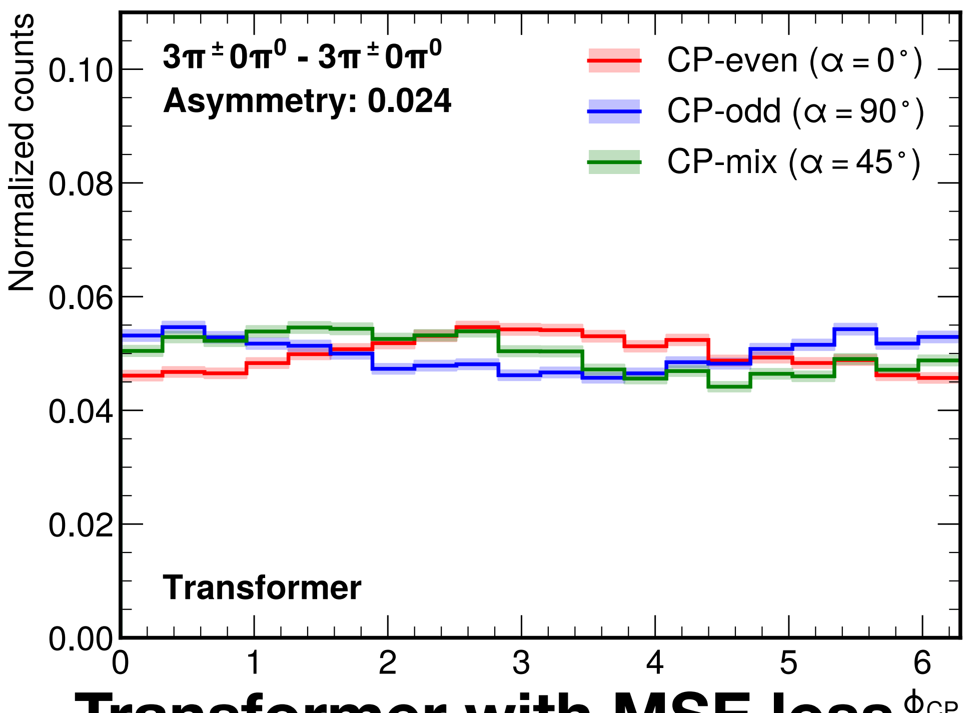




Improvements to sensitivity

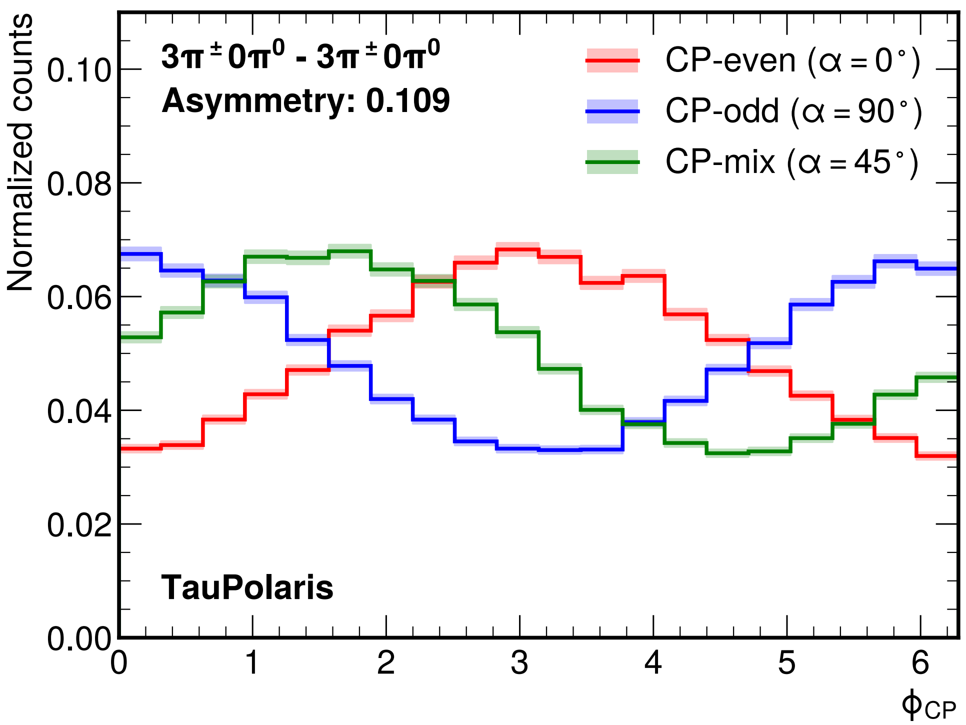


Run-3 method



Transformer with MSE loss

+90% improvement!



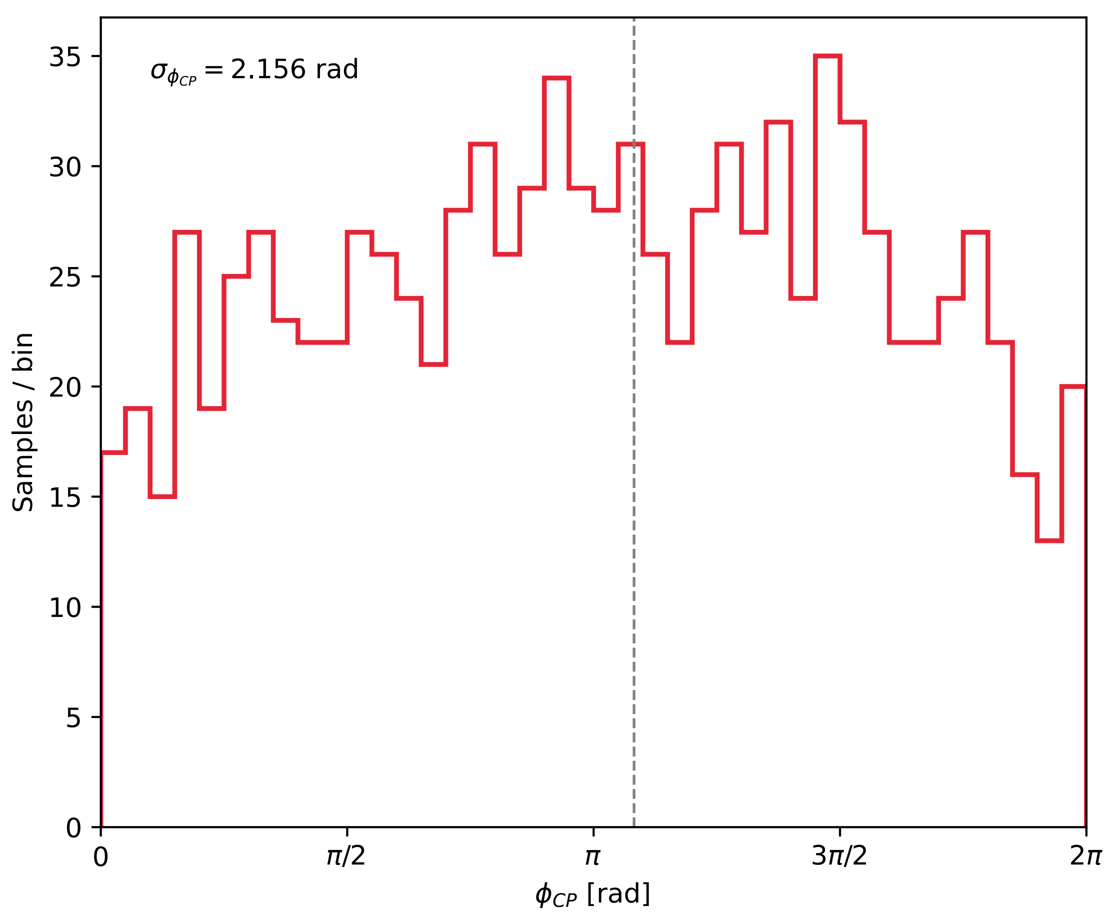
Normalising Flow

Improvements to sensitivity

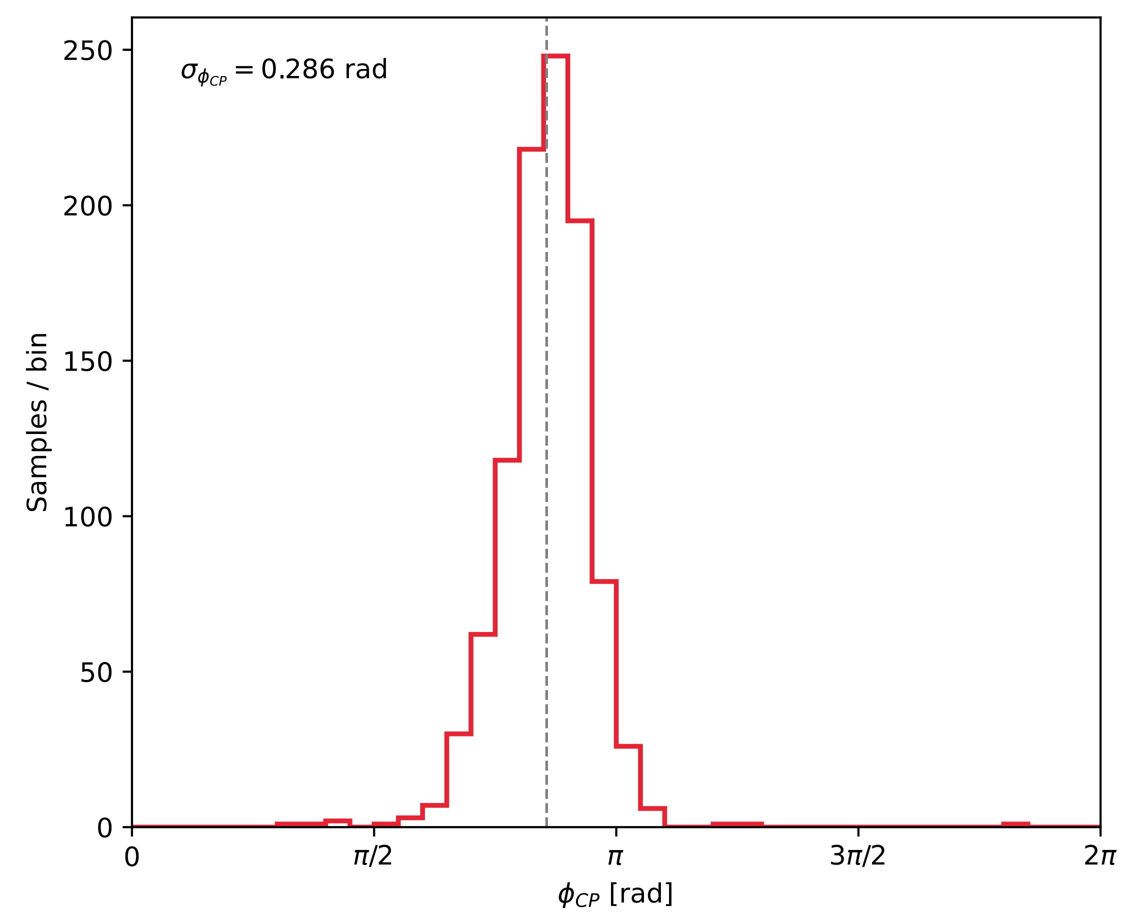
- More modest gain in other channels but still a significant improvement and more to come in future versions

Decay modes	Approximate	Transformer	TauPolaris	$\Delta_{\text{Approx.}}$ (%)	$\Delta_{\text{Transf.}}$ (%)
$1\pi^{\pm}0\pi^{0}$–$1\pi^{\pm}0\pi^{0}$	0.084	0.090	0.080	−5	−11
$1\pi^{\pm}0\pi^{0}$–$1\pi^{\pm}1\pi^{0}$	0.077	0.061	0.082	+6	+34
$1\pi^{\pm}0\pi^{0}$–$1\pi^{\pm}2\pi^{0}$	0.054	0.040	0.060	+11	+50
$1\pi^{\pm}0\pi^{0}$–$3\pi^{\pm}0\pi^{0}$	0.062	0.039	0.090	+45	+131
$1\pi^{\pm}1\pi^{0}$–$1\pi^{\pm}1\pi^{0}$	0.080	0.052	0.093	+16	+79
$1\pi^{\pm}1\pi^{0}$–$1\pi^{\pm}2\pi^{0}$	0.056	0.034	0.068	+21	+100
$1\pi^{\pm}1\pi^{0}$–$3\pi^{\pm}0\pi^{0}$	0.066	0.031	0.101	+53	+226
$1\pi^{\pm}2\pi^{0}$–$1\pi^{\pm}2\pi^{0}$	0.040	0.022	0.050	+25	+127
$1\pi^{\pm}2\pi^{0}$–$3\pi^{\pm}0\pi^{0}$	0.047	0.019	0.073	+55	+284
$3\pi^{\pm}0\pi^{0}$–$3\pi^{\pm}0\pi^{0}$	0.058	0.024	0.109	+88	+354
$1\pi^{\pm}0\pi^{0}$–$3\pi^{\pm}1\pi^{0}$	–	0.019	0.051	–	+168
$1\pi^{\pm}1\pi^{0}$–$3\pi^{\pm}1\pi^{0}$	–	0.015	0.057	–	+280
$1\pi^{\pm}2\pi^{0}$–$3\pi^{\pm}1\pi^{0}$	–	0.011	0.040	–	+264
$3\pi^{\pm}0\pi^{0}$–$3\pi^{\pm}1\pi^{0}$	–	0.011	0.064	–	+482
$3\pi^{\pm}1\pi^{0}$–$3\pi^{\pm}1\pi^{0}$	–	0.009	0.040	–	+344
τ_{ℓ}–$1\pi^{\pm}0\pi^{0}$	0.041	0.044	0.042	+2	−5
τ_{ℓ}–$1\pi^{\pm}1\pi^{0}$	0.044	0.036	0.049	+11	+36
τ_{ℓ}–$1\pi^{\pm}2\pi^{0}$	0.032	0.022	0.037	+16	+68
τ_{ℓ}–$3\pi^{\pm}0\pi^{0}$	0.036	0.024	0.052	+44	+117
τ_{ℓ}–$3\pi^{\pm}1\pi^{0}$	–	0.003	0.006	–	+100

- Because the flow learns the full probability density we can also estimate an uncertainty on ϕ_{CP}
  - Sample the pdf → spread gives you the uncertainty (use circular standard deviation)



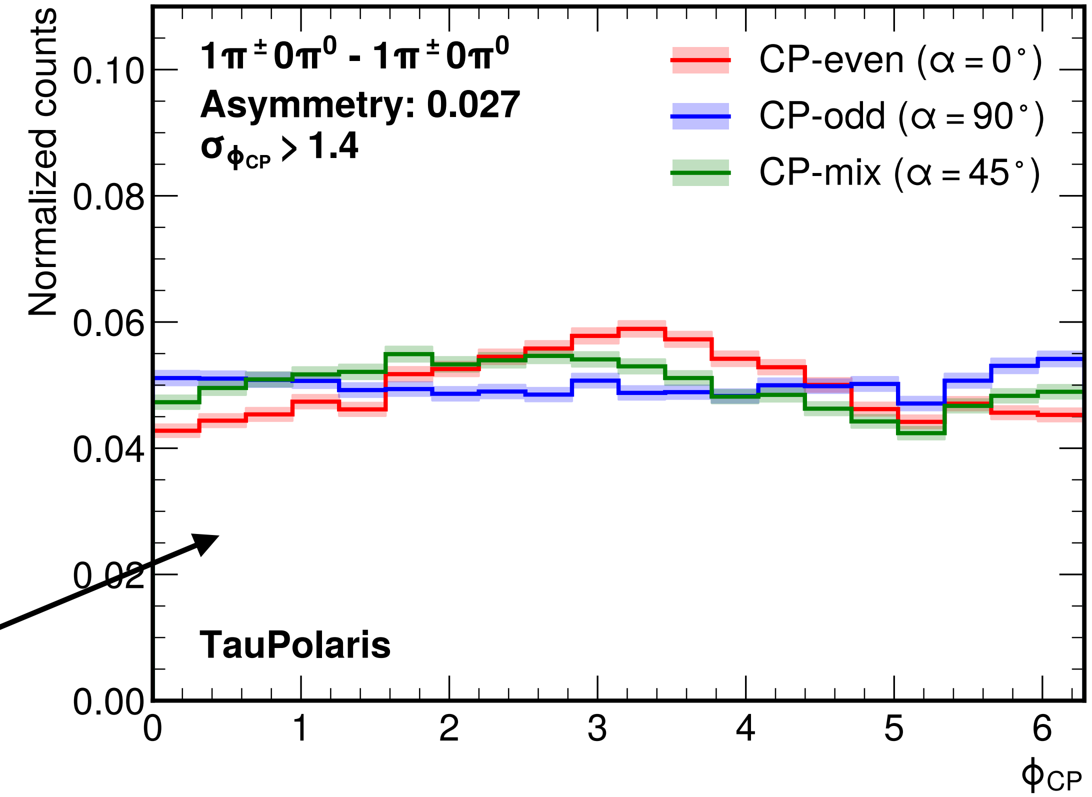
A poorly reconstructed event



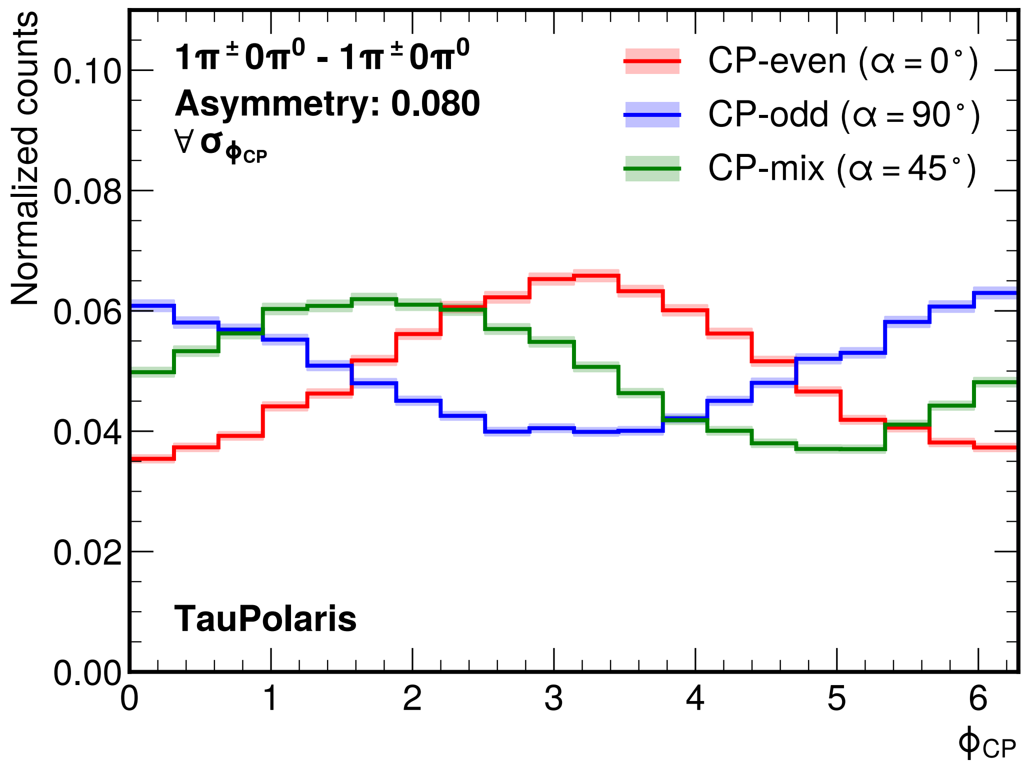
A well reconstructed event

Using the uncertainty

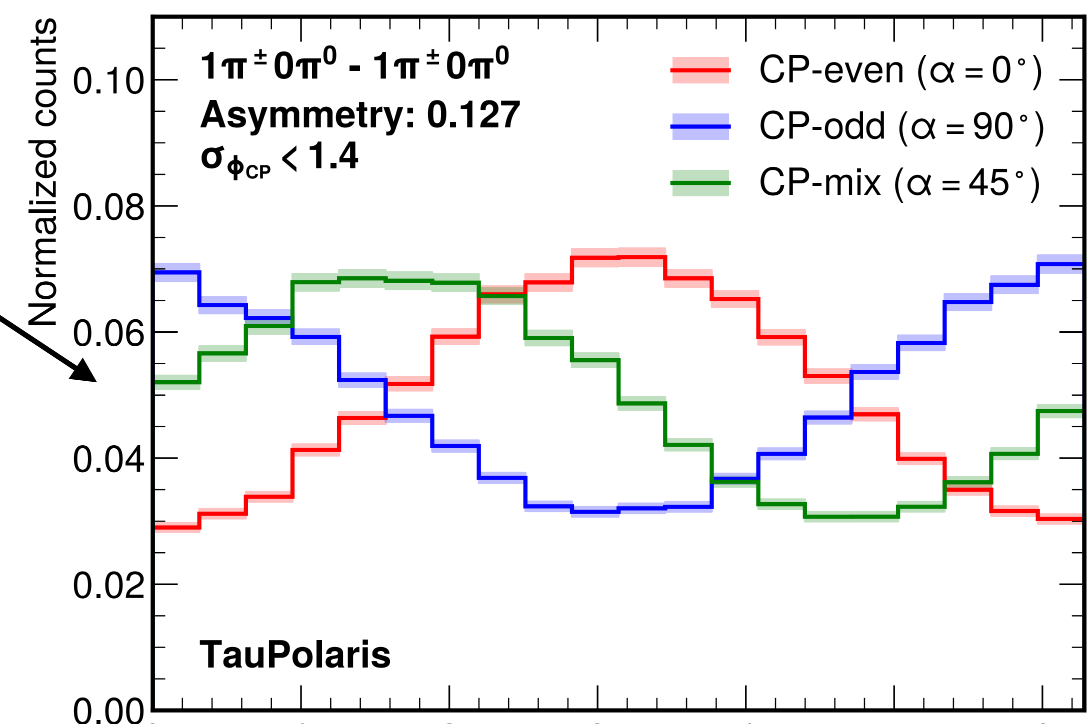
- Uncertainty gives you a handle for separating well reconstructed events
  - Either discard bad events or categorise



poorly reconstructed events



All events



Well reconstructed events

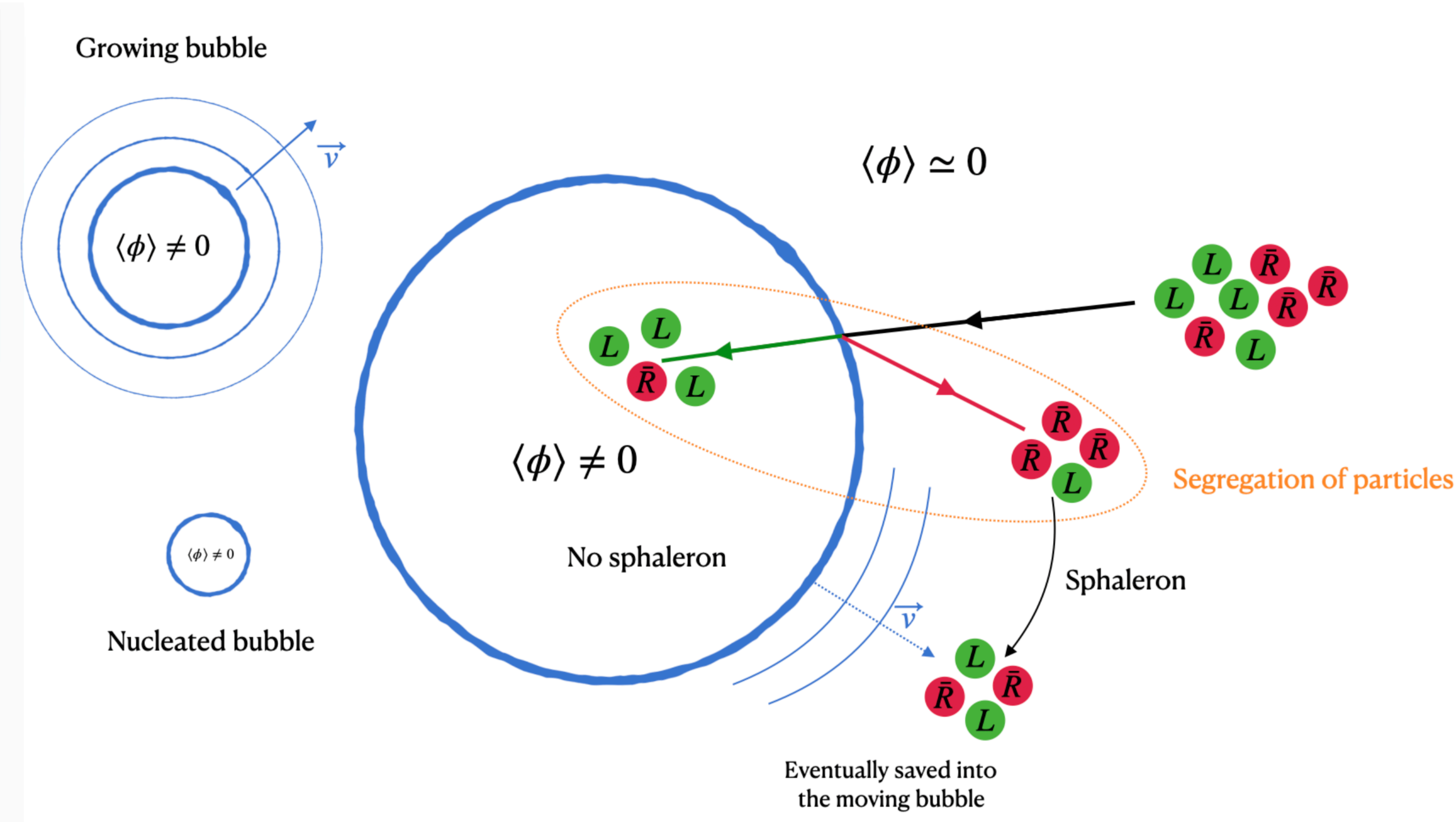
Conclusions

- Presented the latest CMS measurements of the Higgs boson CP properties
    - Preprint: arXiv:2606.03510 (Accepted by JHEP)
- Thanks to several improvements we were able to achieve a better expected result than Run-2 despite using less than half the amount of data
- Another ~250 fb^{-1} of data has been recorded by CMS and will be analysed in the next year or so
- Lots of prospects to improve measurements at the HL-LHC

Thanks for your attention!

Backup

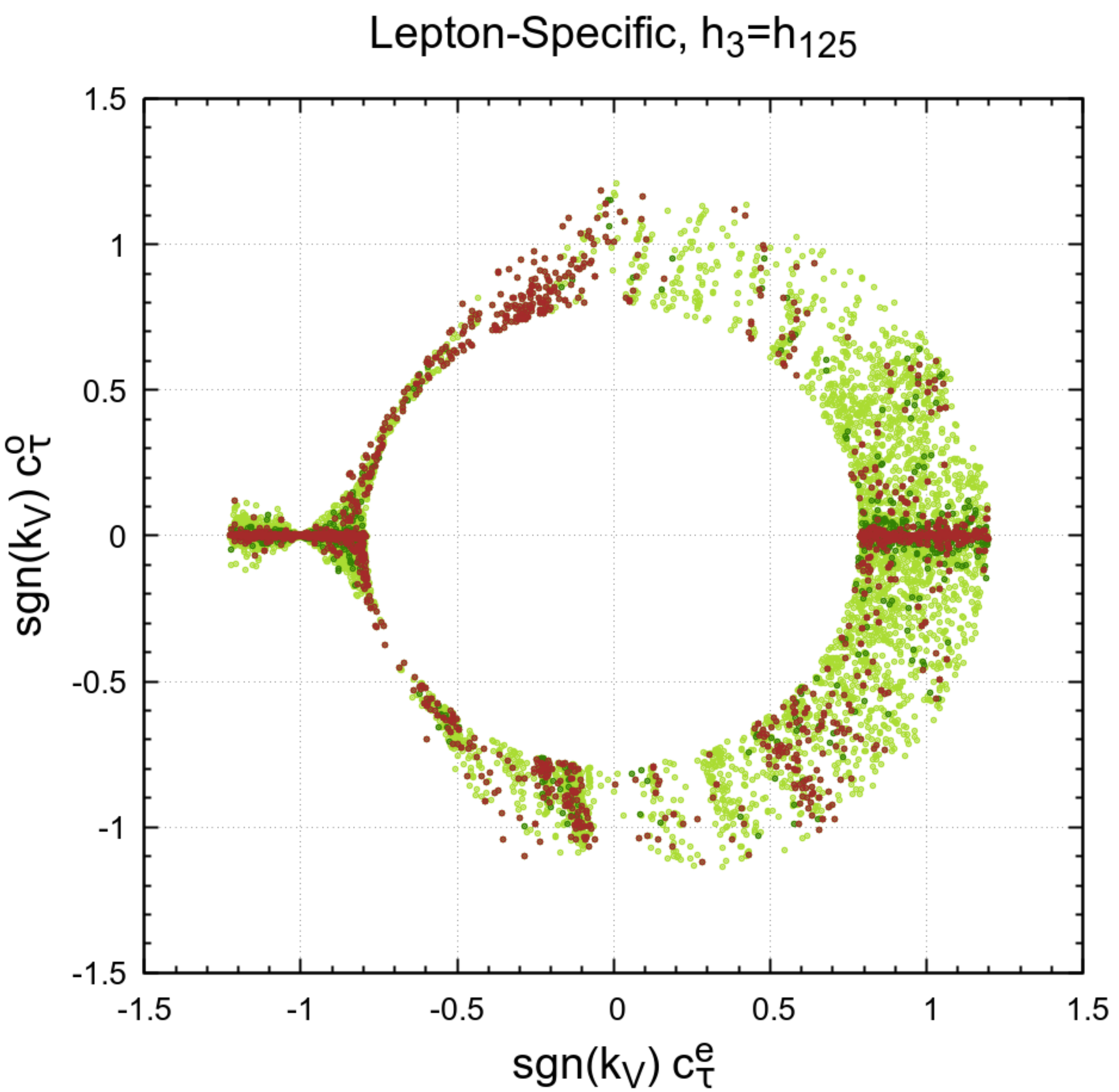
Electroweak Baryogengesis



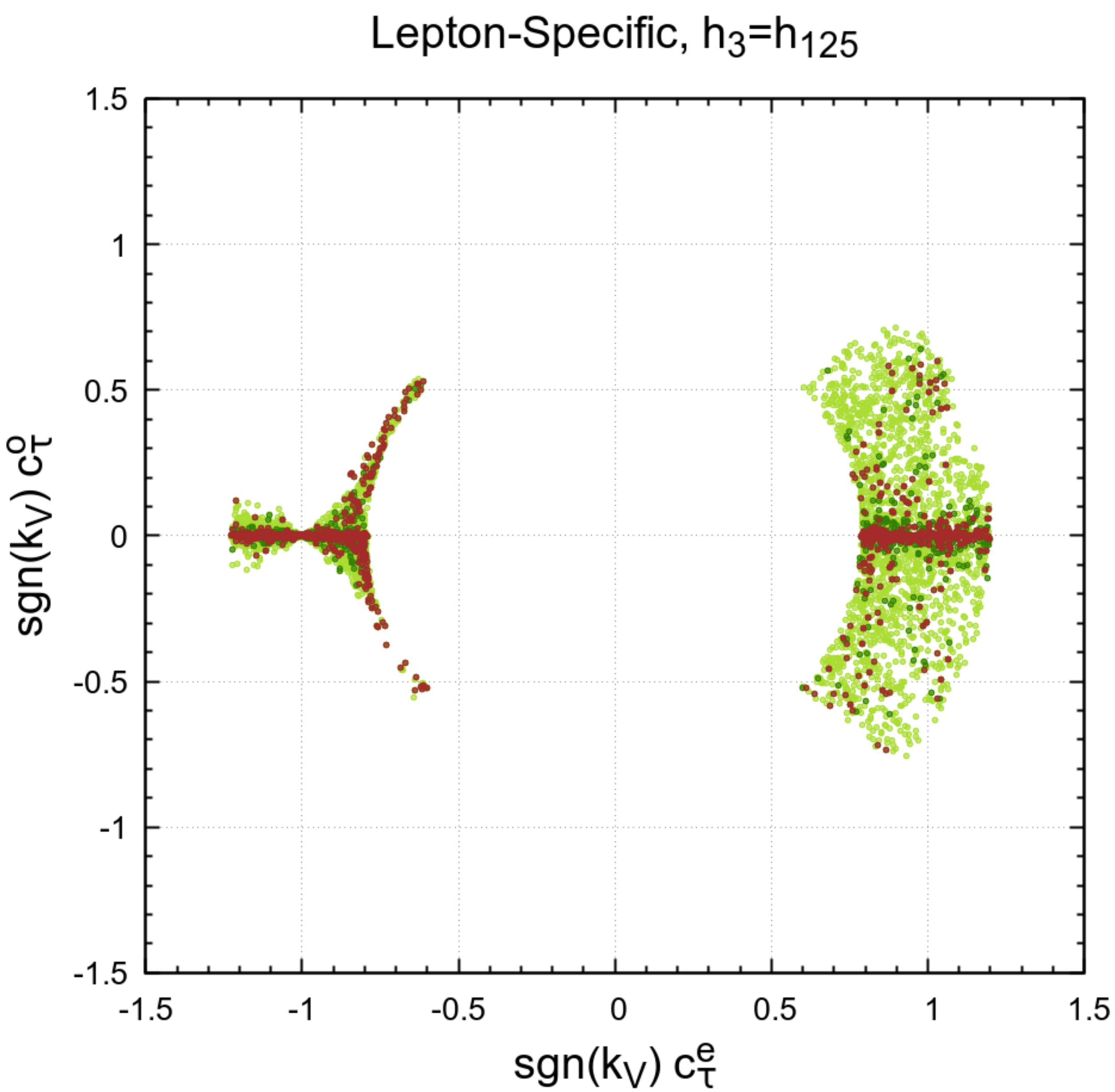
Taken from https://www.mdpi.com/2075-4434/10/6/116

C2HDM bounds

- Red points pass latest eEDM bounds (green older bounds)



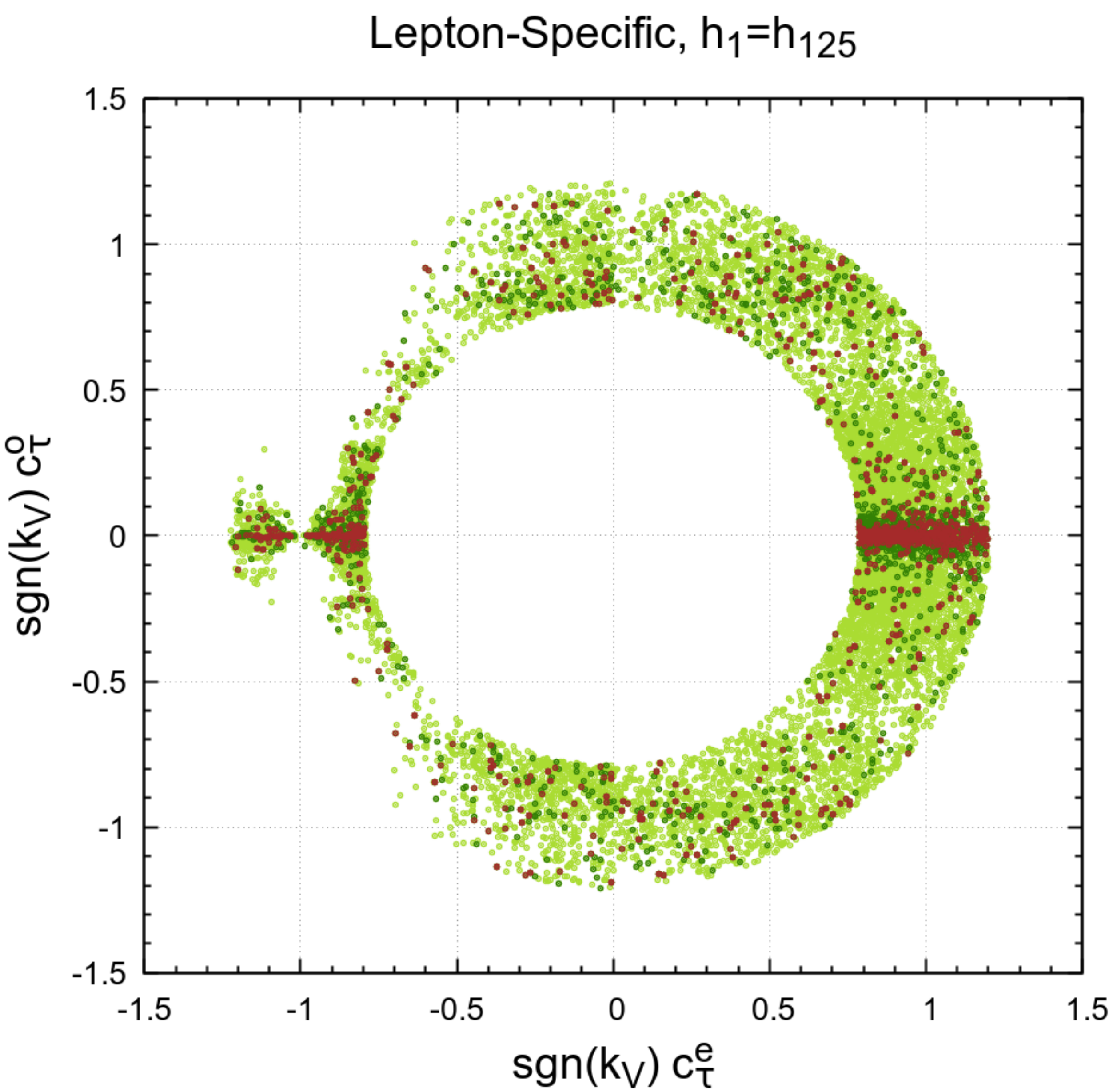
No direct $\alpha^{H\tau\tau}$ measurements



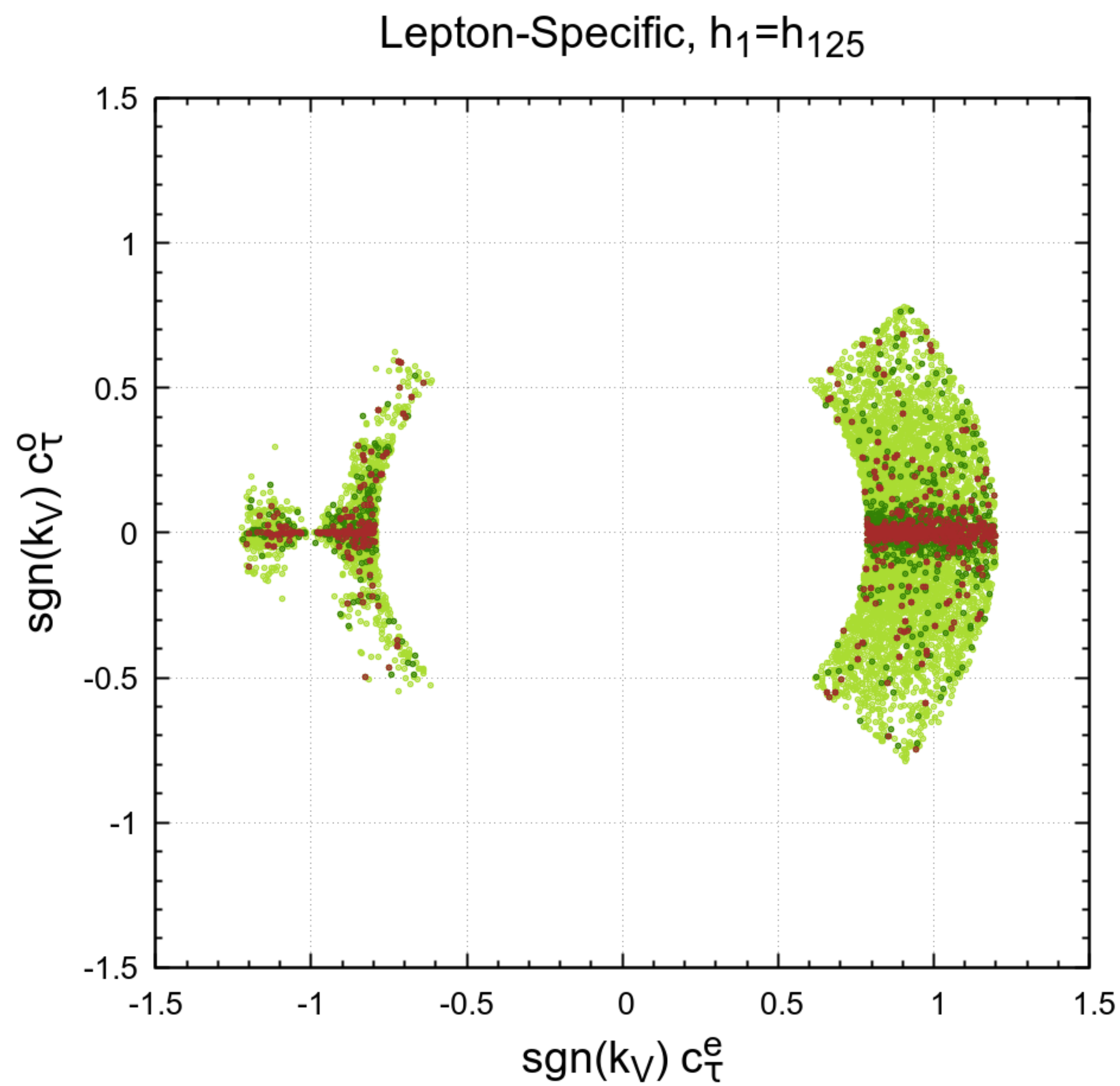
With direct $\alpha^{H\tau\tau}$ measurements

C2HDM bounds

- Red points pass latest eEDM bounds (green older bounds)

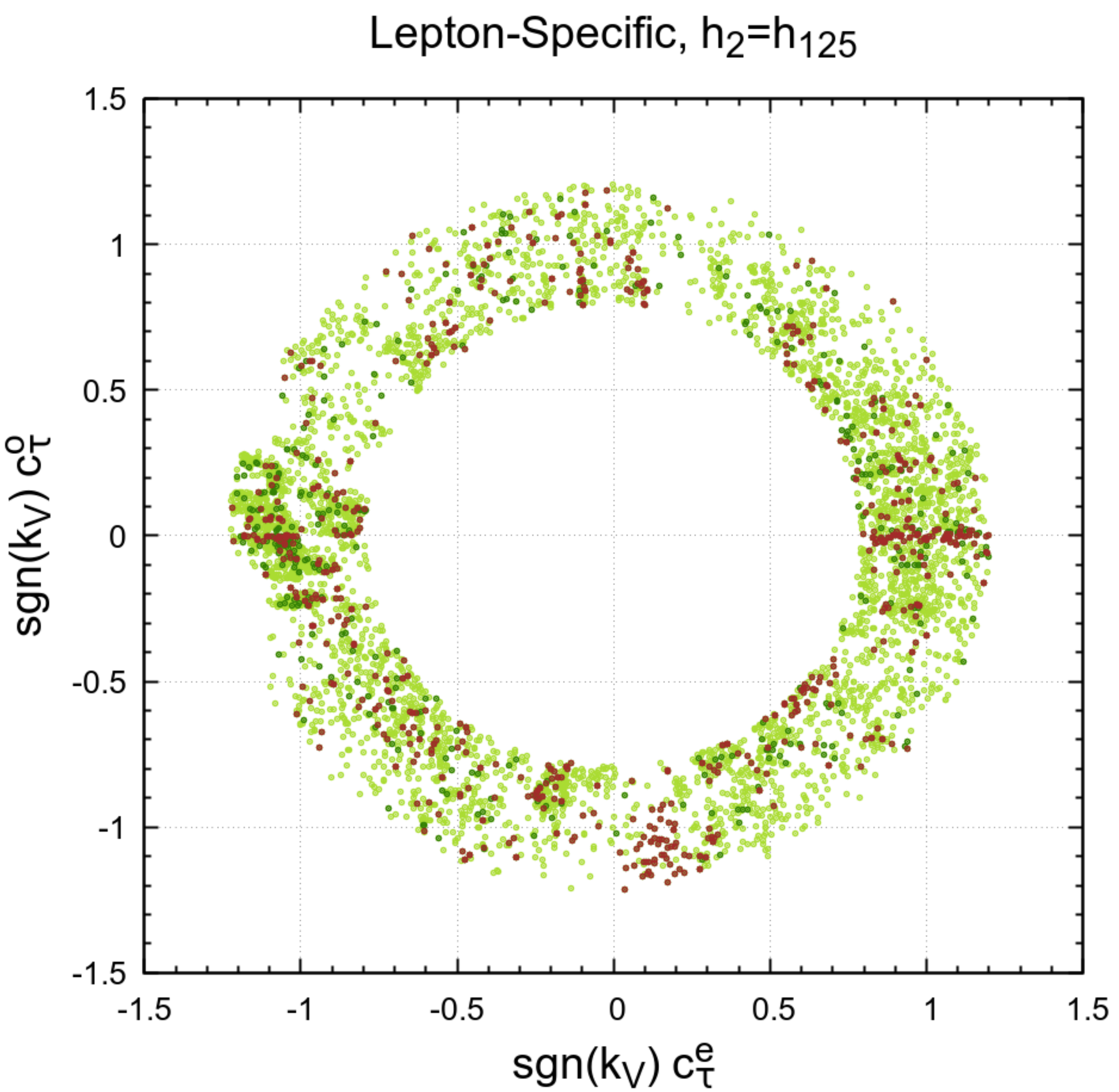


No direct $\alpha^{H\tau\tau}$ measurements

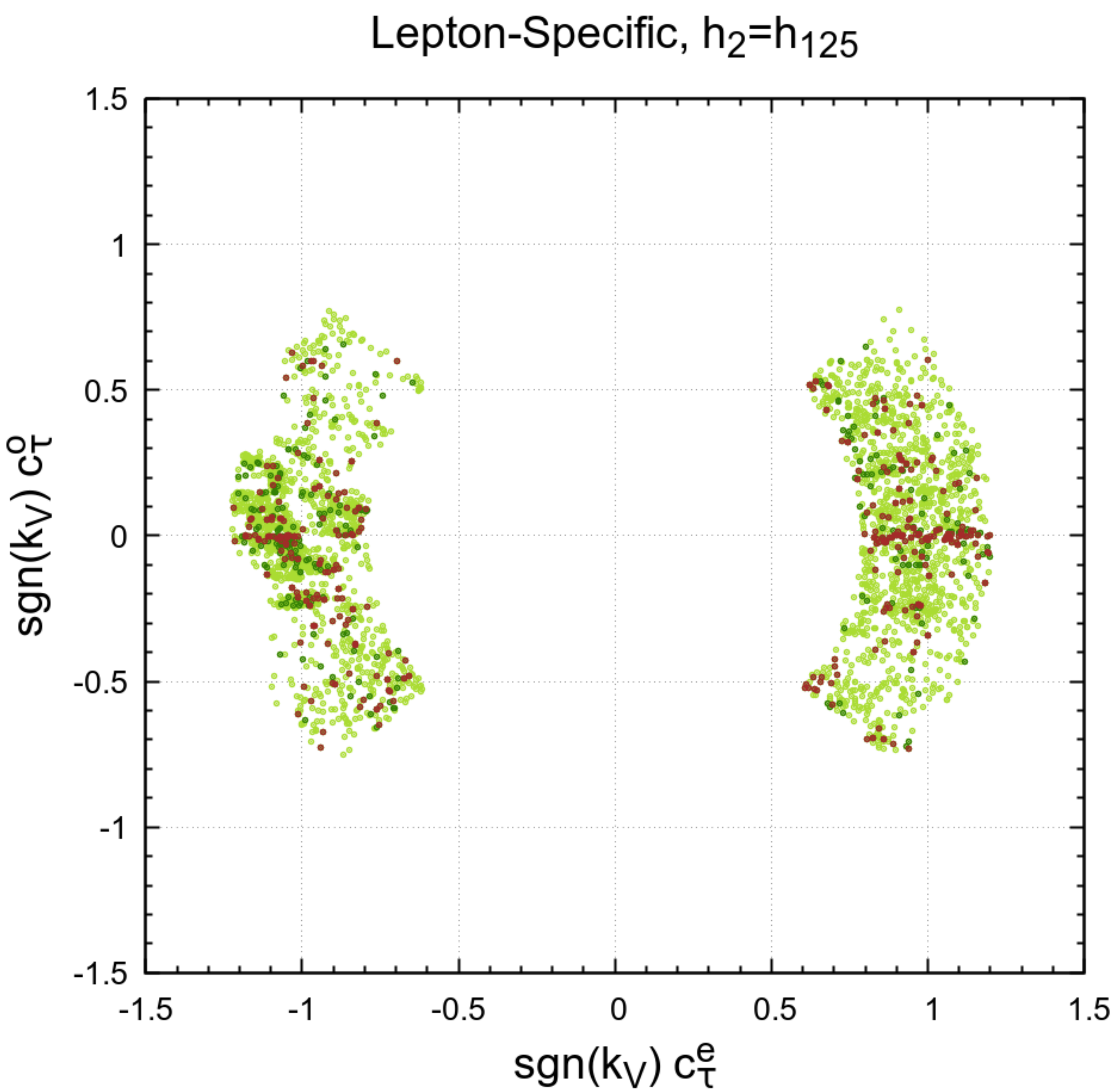


With direct $\alpha^{H\tau\tau}$ measurements

- Red points pass latest eEDM bounds (green older bounds)



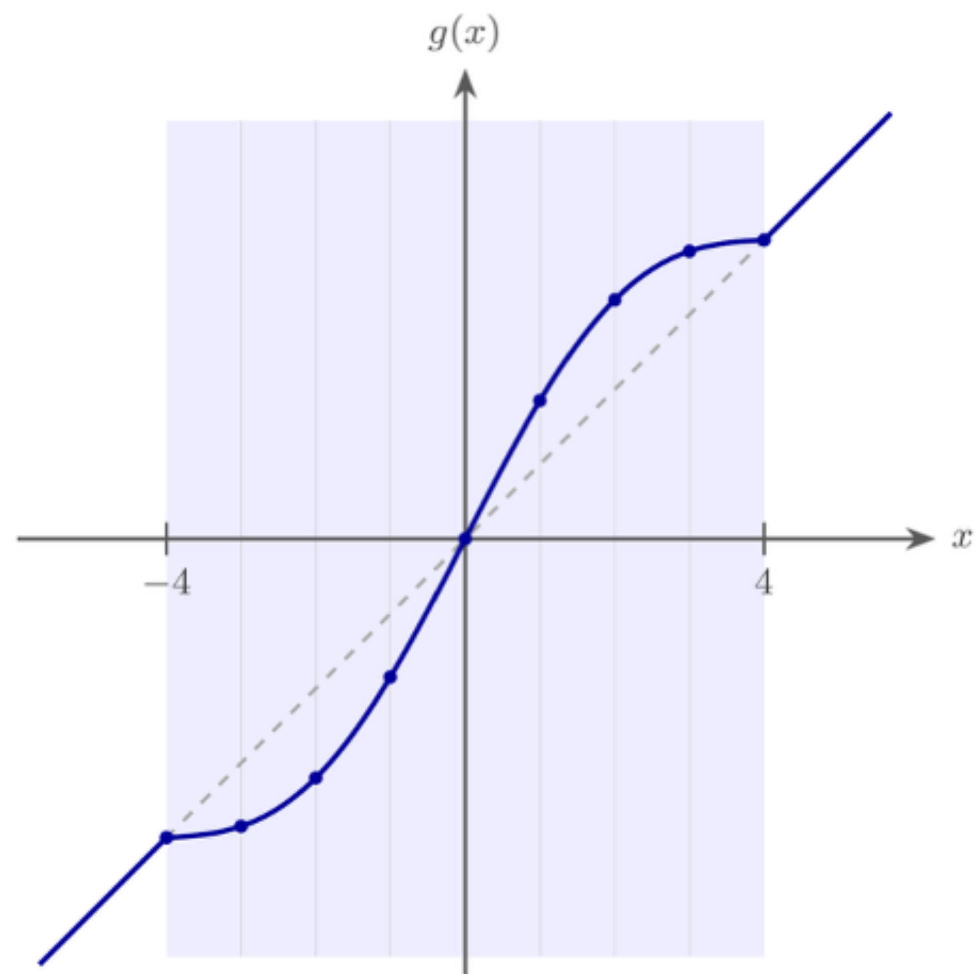
No direct $\alpha^{H\tau\tau}$ measurements

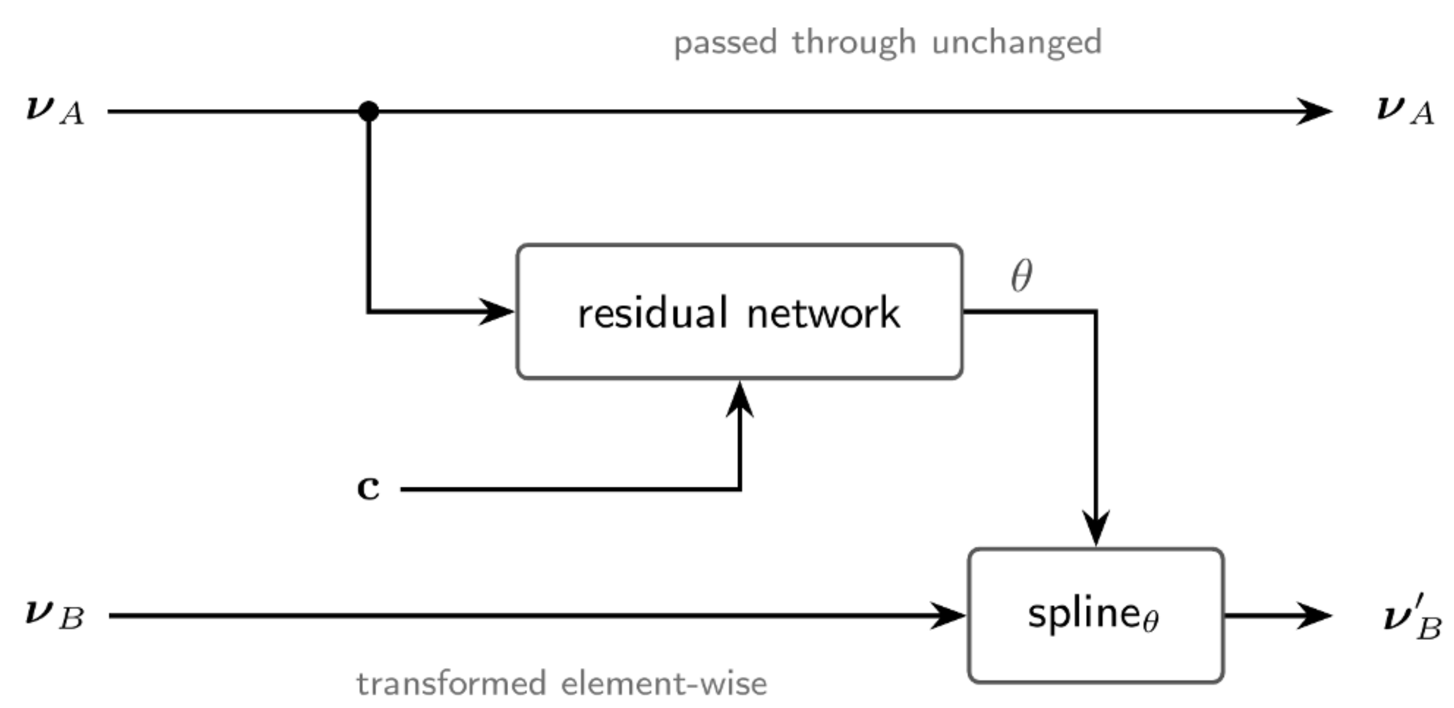


With direct $\alpha^{H\tau\tau}$ measurements

Rational-quadratic splines for transformations

- Split v into halves v_A and v_B: v_A passes through unchanged and, with c, sets the parameters θ of a spline applied to v_B
  - Invertible as v_A is unchanged so can use it to compute θ during inverse - the network is never inverted and can be arbitrarily complex
  - Jacobian is triangular so determinant is just product of diagonals - easy to compute
- Force splines to be monotonic which ensures transformation is invertible
- Rational quadratic ensures evaluating the inverse involves solving a quadratic which is done analytically





Normalising flows extra

- **Invertible** — so that every value has one, and only one, corresponding point in the Gaussian space. Without that, the density becomes an unworkable sum over multiple points.

- **Differentiable** — because the correction term in the formula *is* a derivative (the Jacobian). No derivative, no formula.

- Jacobian definition:

$$J_f(\boldsymbol{\nu} \mid \mathbf{c}) = \frac{\partial \mathbf{z}}{\partial \boldsymbol{\nu}} = \begin{pmatrix} \frac{\partial z_1}{\partial \nu_1} & \cdots & \frac{\partial z_1}{\partial \nu_D} \\ \vdots & \ddots & \vdots \\ \frac{\partial z_D}{\partial \nu_1} & \cdots & \frac{\partial z_D}{\partial \nu_D} \end{pmatrix}$$

- Total Det(J) = product of Det(Ji)

Sensitivity by channel

- Main improvements in Run-3 to $\tau_h\tau_h$ channel

Decay mode	Expected sensitivity (σ)
$\tau_e\tau_h$	0.99
$e\rho$	0.57
$e\pi$	0.54
ea_1^{3pr}	0.38
ea_1^{1pr}	0.17
$\tau_\mu\tau_h$	1.47
$\mu\rho$	1.16
$\mu\pi$	0.71
μa_1^{3pr}	0.51
μa_1^{1pr}	0.24
$\tau_h\tau_h$	1.85
$\rho\rho$	1.10
$\rho\pi$	1.08
ρa_1^{3pr}	0.65
$\pi\pi$	0.39
πa_1^{3pr}	0.48
$a_1^{1pr}\rho$ and $a_1^{1pr}a_1^{1pr}$	0.30
πa_1^{1pr}	0.23
$a_1^{3pr}a_1^{3pr}$	0.28
$a_1^{3pr}a_1^{1pr}$	0.13
Combined	2.6

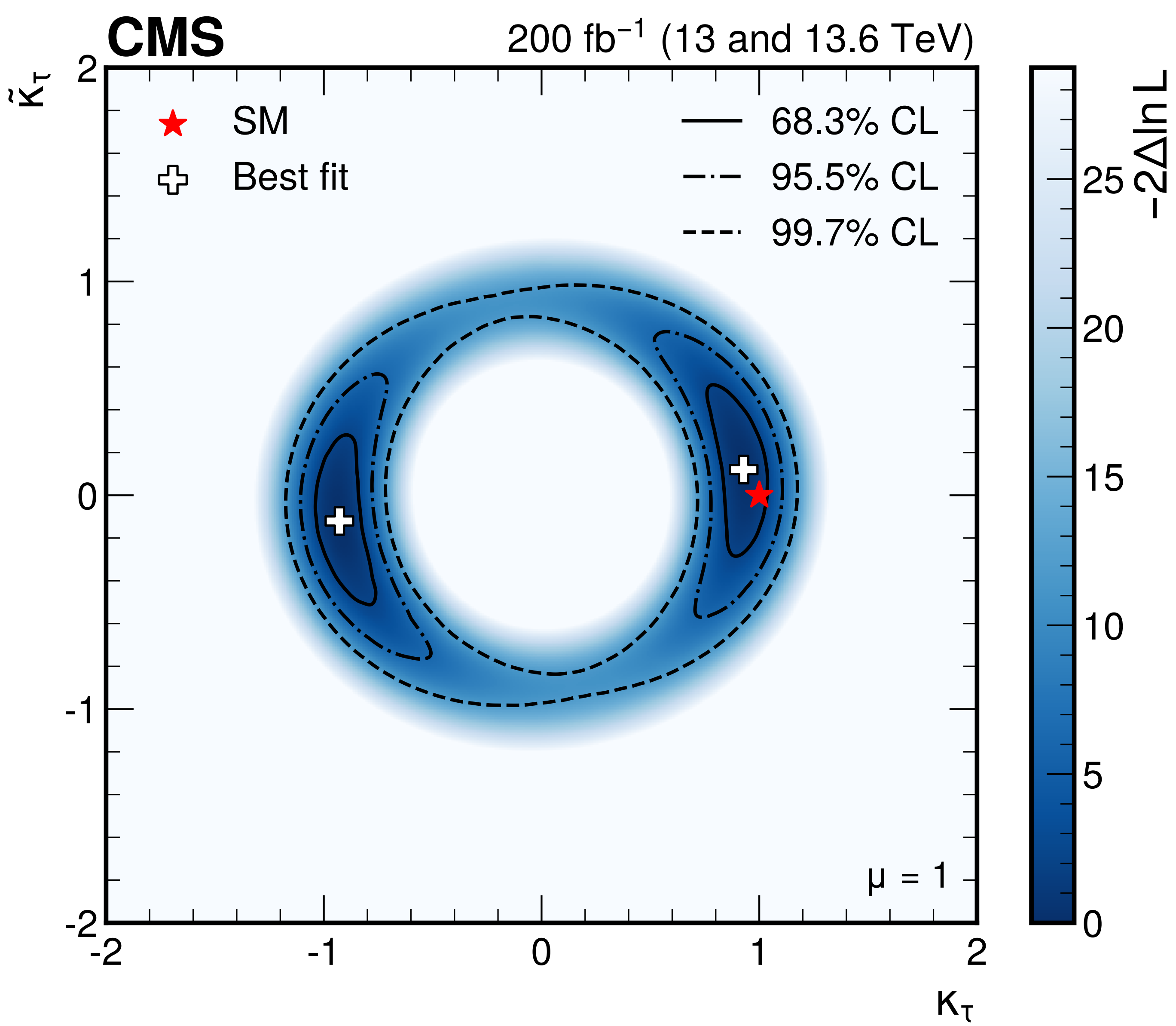
Run-2

Decay mode	Expected sensitivity (σ)
$\tau_h\tau_h$	2.38
$\rho\rho$	1.31
$\rho\pi$	1.18
ρa_1^{3pr}	1.17
πa_1^{3pr}	0.70
$\pi\pi$	0.43
$a_1^{1pr}\rho$ and $a_1^{1pr}a_1^{1pr}$	0.47
$a_1^{3pr}a_1^{3pr}$	0.41
πa_1^{1pr}	0.29
$a_1^{3pr}a_1^{1pr}$	0.27
$\tau_\mu\tau_h$	1.34
$\mu\rho$	1.00
$\mu\pi$	0.58
μa_1^{3pr}	0.61
μa_1^{1pr}	0.24
$\tau_e\tau_h$	0.66
$e\rho$	0.47
$e\pi$	0.31
ea_1^{3pr}	0.34
ea_1^{1pr}	0.09
Combined	2.82

Run-3

Coupling scan

- Assume Higgs cross-sections = SM-values and modify only $\Gamma(\mathrm{H} \rightarrow \tau\tau)$ partial width with tau Yukawa couplings and set bound on CP-even and CP-odd Yukawa couplings



τ mass reconstruction

- This can lead an MSE-based regressor to “pick” unlikely or even unphysical values
- Variables that are very sensitive to correlations between neutrinos and visible tau components are largely effected e.g tau mass below
- CP variables also strongly impacted as they are basically describing angular correlations between the decay products