Higgs or sƃƃıH
Good Old Standard Model or Something New?

DESY Summer Student Program 2024

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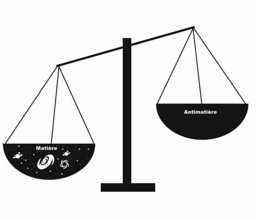
Why are we interested in the CP violation?

We see our universe made almost entirely of matter

- The Big Bang should have created **equal amounts** of matter and antimatter
- What tipped the **balance**?
- Why did a tiny portion of matter survive? $\sim \mathbf{1 : 10^9}$

Sakharov's solution: CP violation



Few sources of CP violation exist already in the Standard Model: CKM, PMNS matrices

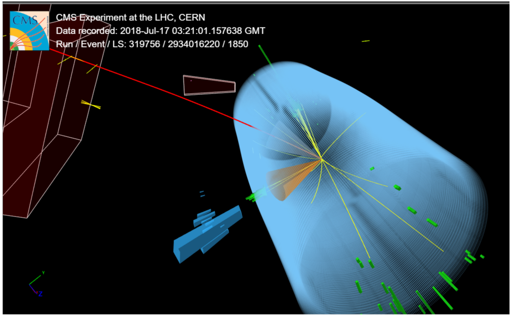
- They are significantly **insufficient** to account for the baryon asymmetry

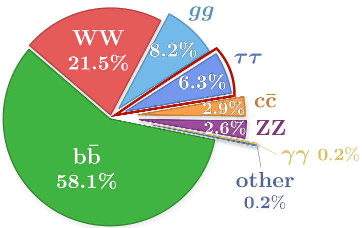
Additional **CP violating sources** are necessary

CP violation in the Higgs sector

One possibility: CP violation in the Higgs sector!

- SM Higgs boson is **CP-even** $J^{CP} = 0^{++}$
- **CP admixture** couplings are still allowed experimentally





> **Why look at the tau?**

- It carries **spin** information of the Higgs
- b-quarks hadronize
- Muons cross the detectors
- W/Z bosons have no CP-odd tree-level coupling

Yukawa Coupling and CP Violation

How to measure CP properties?

- Take a look at Lagrangian: $\mathcal{L}_Y = \frac{m_\tau}{v}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)H$

We need a **CP-sensitive** observable

> The measurement of $\varphi_{\tau\tau}$ is performed by studying the cross-section of the $H \to \tau\tau$:

$$\frac{d\sigma_{H\to\tau\tau}}{d\phi_{CP}} \propto \text{const} - \cos(\phi_{CP} - 2\varphi_{\tau\tau})$$

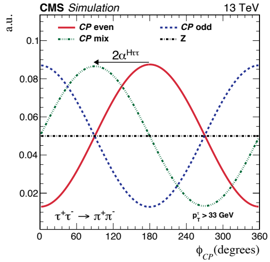
> CP-mixing modify the **spin correlation** between τ

> The correlation carries over to the τ **decay products**

> ϕ_{CP} can be defined as the angle between τ **decay planes**

CP-mixing encoded into reduced Yukawa couplings

- $\kappa_\tau = \sqrt{\mu^{\tau\tau}} \cos(\varphi_{\tau\tau})$
- $\tilde{\kappa}_\tau = \sqrt{\mu^{\tau\tau}} \sin(\varphi_{\tau\tau})$



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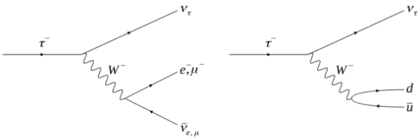
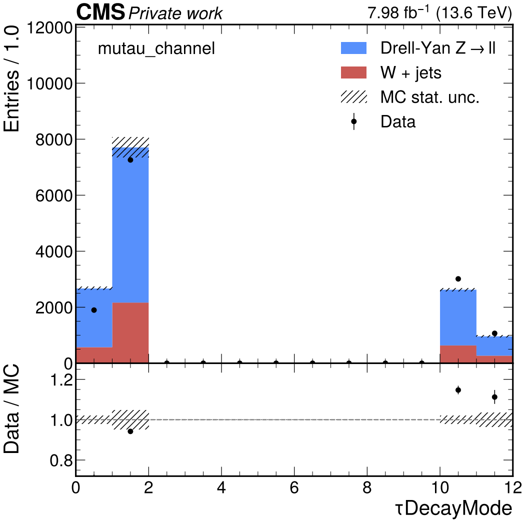
Tau Lepton

- It is the heaviest lepton and it is reconstructed based on its **decay products**



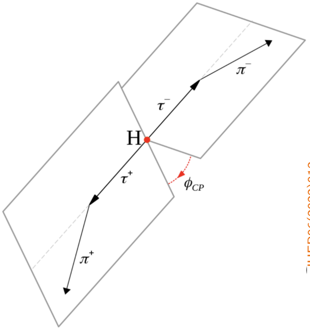
> **Leptonic** $\sim 35\%$ **Hadronic** $\sim 65\%$

- **DM 0:** 1 prong $(\tau^\pm \to \pi^\pm \nu_\tau)$
- **DM 1:** 1 prong$+\pi^0$ $(\tau^\pm \to \rho^\pm \nu_\tau \to \pi^\pm \pi^0 \nu_\tau)$
- **DM 10:** 3 prong $(\tau^\pm \to a_1^\pm \nu_\tau \to \pi^\pm \pi^\mp \pi^\pm \nu_\tau)$
- **DM 11:** 3 prong$+\ \pi^0$



The Acoplanarity angle

- The CP-mixing angle arises as a phase-shift in the **acoplanarity angle ϕ_{CP}** distribution
- Considering the decay $H \to \tau^+\tau^- \to \pi^+\pi^-\nu_\tau\bar{\nu}_\tau$ in Higgs rest frame:
  - > Tau **direction of flight** $\vec{p}_\tau^{\pm}$
  - > Pion **momentum** $\vec{p}_\pi^{\pm}$
- ϕ_{CP} can be defined as the angle between τ **decay planes**



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Presence of **neutrinos** in τ decay: approximated methods are needed!

$\Longrightarrow$

Substitute $\vec{p}_\tau^{\pm}$ with the **Impact Parameter** of its charged decay product

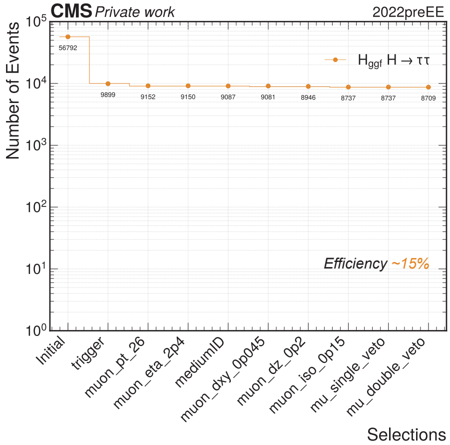
Analysis

Event Selection $H \to \tau\tau(\tau_\mu \tau_h)$

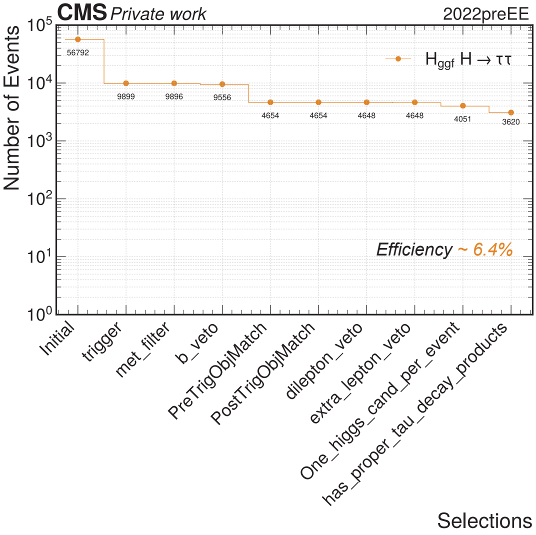
How to select the candidates for the measurement?

- We are looking for an **isolated muon** and a **hadronically** decaying tau in the event

1. **High Level Trigger**: at least an isolated global muon reconstructed with $p_T > 24$ GeV
2. **Muon conditions**:
   - $p_T > 26$ GeV and $|\eta| < 2.4$
   - $I_{rel} < 0.15$
   - It must match the one that fired the trigger ($\Delta R < 0.5$)
3. **Tau conditions**:
   - $p_T > 20$ GeV and $|\eta| < 2.3$
   - It must pass a threshold for the CNN DeepTau classifiers



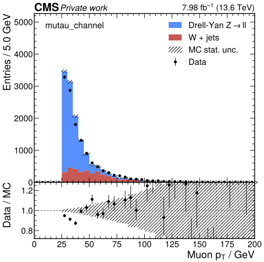
Event Selection $H \rightarrow \tau\tau(\tau_\mu \tau_h)$

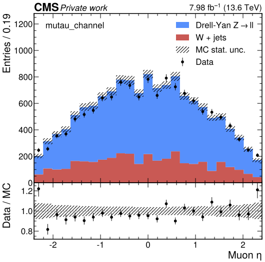


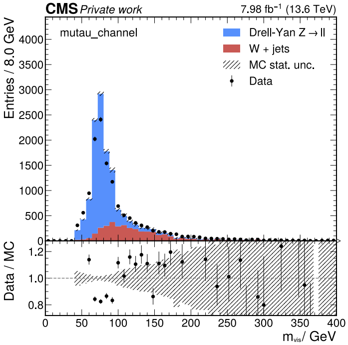
- An event is **selected** if at least a **pair** is found: they must have opposite charge and $\Delta R > 0.5$
- An event is **discarded** if:

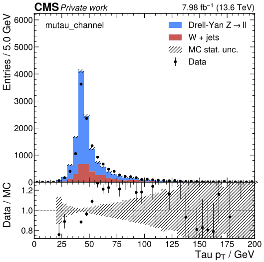
1. **b-jet veto**: it contains a b-jet
2. **Extra lepton veto**: it contains a third lepton with certain kinematics properties
3. **Di-lepton veto**: it contains dilepton pairs

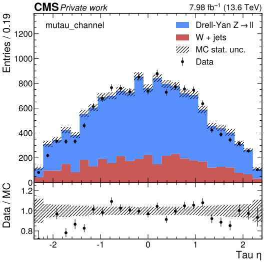
Kinematic variables: control plots







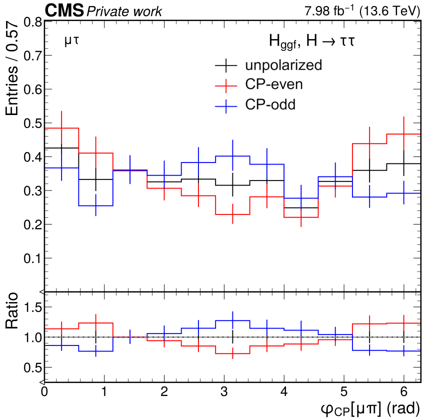


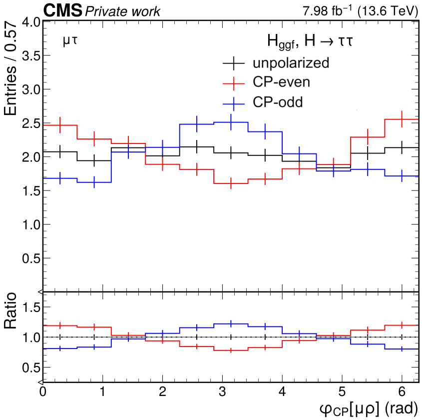


> Okay agreement between **Data/MC** even without all the backgrounds :)

Results for the signal $H \to \tau\tau \, (\tau_\mu \tau_h)$

Starting from the Monte Carlo simulation of the **unpolarized signal** we can create the decay template that encodes the **spin-correlation** for: CP-even $(\varphi_{\tau\tau} = 0)$, CP-odd $(\varphi_{\tau\tau} = \pi/2)$

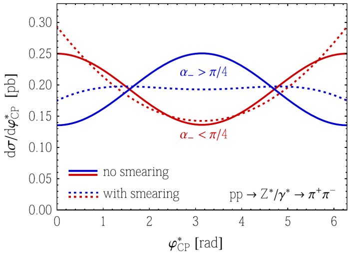




Drell-Yan Background $Z \to \tau\tau$

> The **Drell-Yan process** $Z \to \tau\tau$ is an irreducible background

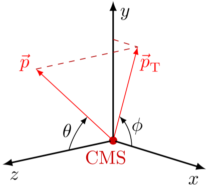
> The cross-section involves terms of the form $\cos(2\phi^+ - \phi_{CP})$ which go to **zero** integrating over ϕ in $[0, 2\pi] \implies$ The acoplanarity angle distribution is **flat**



How to recover the dependence on ϕ_{CP} ?

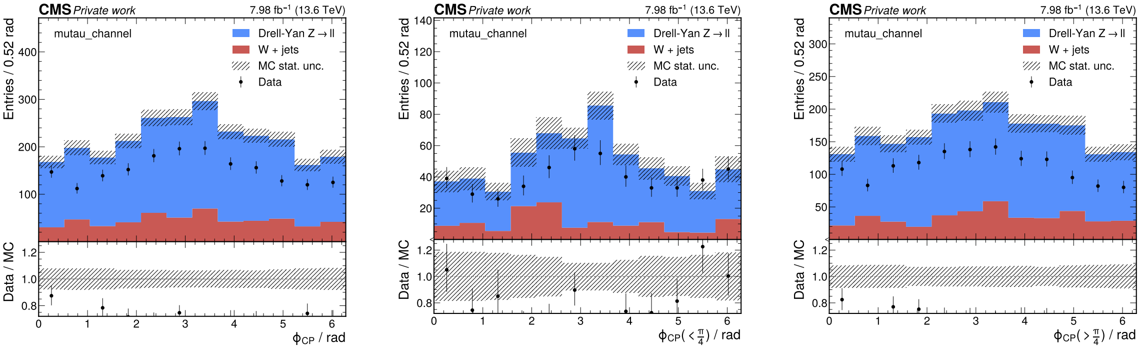
> Considering the positive beam direction $\hat{z}$ and the τ^- direction of flight

$$\cos\alpha = \left| \frac{\hat{z} \times \vec{P}_-}{|\hat{z} \times \vec{P}_-|} \cdot \frac{\vec{R}_- \times \vec{P}_-}{|\vec{R}_- \times \vec{P}_-|} \right|$$



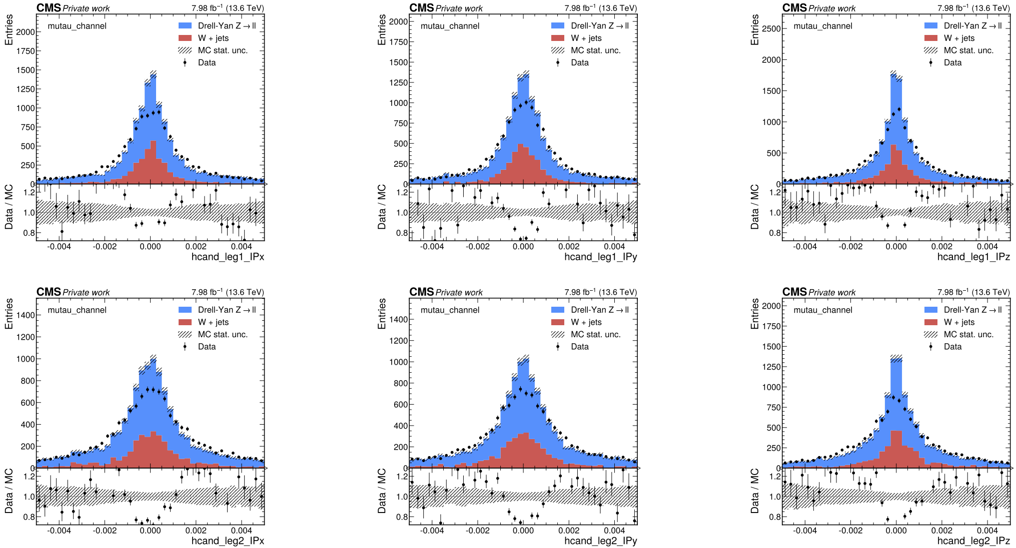
This discriminant can be used to split the events

Validation of the method using DY dataset ($\mu^{\mp}\pi^{\pm}$)

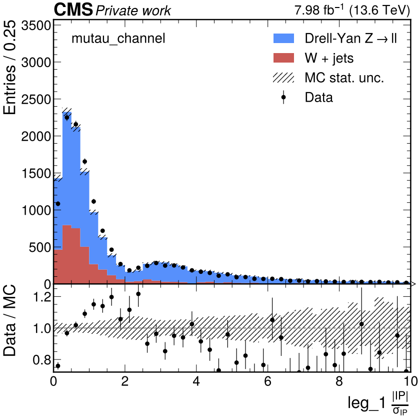


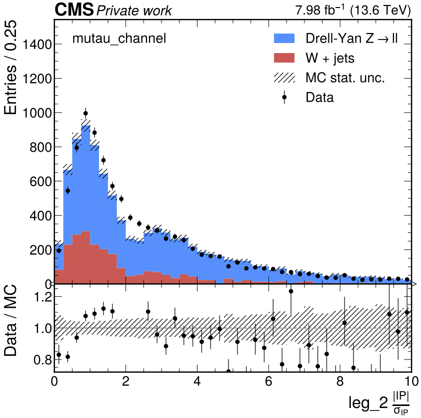
> Something is missing, trying to look somewhere else...

Impact Parameter components



Impact Parameter significance





Summary

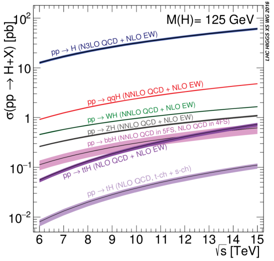
- Studied a new BSM scenario related to the **Higgs's CP-properties**
- Followed the main steps of the **tau reconstruction** pipeline
- Calculated the **acoplanarity angle** for the signal dataset
- Looked at the **validation** of the model in $Z \to \tau\tau$

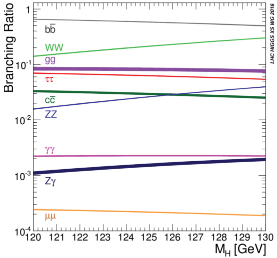
- Further investigation are necessary for the missing modulation in the validation dataset

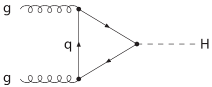
Thank you for your attention

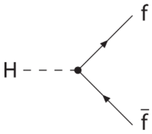
Backup

The Higgs Boson









> Main **production mechanisms**:
- gluon-gluon Fusion
- Vector Boson Fusion
- associated production with a W/Z
- top quark pair production

> Different **decay channels**:
- $H \to b\bar{b}$: 58.2%
- $H \to W^+W^-$: 21.4%
- $H \to \tau^+\tau^-$: 6.3%
- $H \to \gamma\gamma$: 0.23%

H$\rightarrow\tau\tau$: current status

CMS Run2 result is: $\alpha^{\mathrm{H}\tau\tau} = -1 \pm 19(\text{stat.}) \pm 1(\text{syst.}) \pm 2(\text{bin-by-bin}) \pm 1(\text{theo.})^{\circ}$ @ 68.3% CL

- This result has a statistically-dominated uncertainty
- $\leq 7^{\circ}$ uncertainty on $\alpha^{\mathrm{H}\tau\tau}$ required to probe BSM scenarios
- Run3 campaign will double the statistics
- We expect statistical uncertainty for Run2 + Run3 to reduce by 40%

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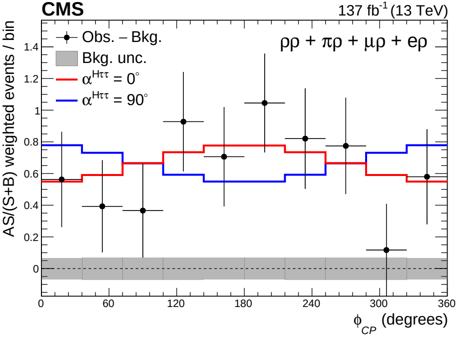
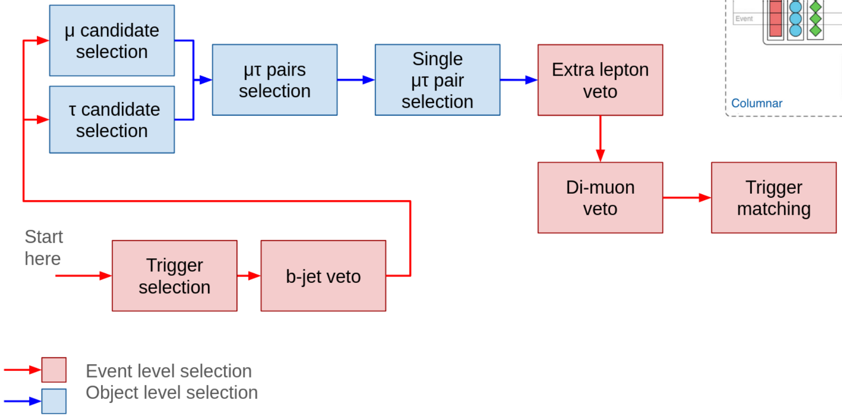
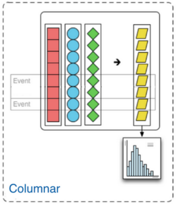
Current result



Selection pipeline





Acoplanarity angle reconstruction - Unified notation

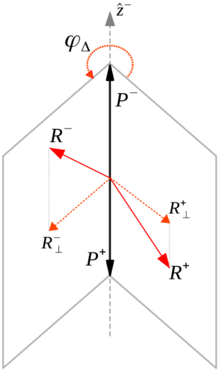
> A **Zero Momentum Frame ZMF** is defined by two momenta and in this frame they are co-axial $\vec{P}_+ + \vec{P}_- = 0$

> A **reference vector** $\vec{R}_\pm$ boosted in the ZMF, which is not parallel to $\vec{P}_\pm$

> A **phase-shift** of π is applied if needed

$$\phi_{CP} = \begin{cases} \varphi^* & \text{if } \mathcal{O} \geq 0 \\ 2\pi - \varphi^* & \text{if } \mathcal{O} < 0 \end{cases} \qquad \varphi^* = \arccos\left(\frac{\vec{R}_\perp^+}{|\vec{R}_\perp^+|} \cdot \frac{\vec{R}_\perp^-}{|\vec{R}_\perp^-|} \right)$$

$$\mathcal{O} = (\vec{R}_\perp^+ \times \vec{R}_\perp^-) \cdot \vec{P}^- \qquad \vec{R}_\perp^\pm = \vec{R}^\pm - (\vec{R}^\pm \cdot \vec{P}^\pm) \frac{\vec{P}^\pm}{|\vec{P}^\pm|^2}$$



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Acoplanarity angle reconstruction - Unified notation

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Channel	P1	R1	P2	R2	π Phase-Shift
$\tau_{\mu,e,\pi} \times \tau_{\mu,e,\pi}$	$\vec{p}_{\mu,e,\pi}$	$\overrightarrow{IP}_{\mu,e,\pi}$	$\vec{p}_{\mu,e,\pi}$	$\overrightarrow{IP}_{\mu,e,\pi}$	-
$\tau_{\mu,e,\pi} \times \tau_{\rho}$	$\vec{p}_{\mu,e,\pi}$	$\overrightarrow{IP}_{\mu,e,\pi}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^0}$	$y_\rho < 0$
$\tau_{\mu,e,\pi} \times \tau_{a_1^{1Pr}}$	$\vec{p}_{\mu,e,\pi}$	$\overrightarrow{IP}_{\mu,e,\pi}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^0\pi^0}$	$y_{a_1^{1Pr}} < 0$
$\tau_{\mu,e,\pi} \times \tau^{\pm}_{a_1^{3Pr}}$	$\vec{p}_{\mu,e,\pi}$	$\overrightarrow{IP}_{\mu,e,\pi}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^\mp}$	$y_{a_1^{3Pr}} < 0$
$\tau_{\rho} \times \tau_{\rho}$	$\vec{p}_{\pi}$	$\vec{p}_{\pi^0}$	$\vec{p}_{\pi}$	$\vec{p}_{\pi^0}$	$y_\rho \cdot y_\rho < 0$
$\tau_{\rho} \times \tau_{a_1^{1Pr}}$	$\vec{p}_{\pi}$	$\vec{p}_{\pi^0}$	$\vec{p}_{\pi}$	$\vec{p}_{\pi^0\pi^0}$	$y_\rho \cdot y_{a_1^{1Pr}} < 0$
$\tau_{\rho} \times \tau^{\pm}_{a_1^{3Pr}}$	$\vec{p}_{\pi}$	$\vec{p}_{\pi^0}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^\mp}$	$y_\rho \cdot y_{a_1^{3Pr}} < 0$
$\tau_{a_1^{1Pr}} \times \tau^{\pm}_{a_1^{3Pr}}$	$\vec{p}_{\pi}$	$\vec{p}_{\pi^0\pi^0}$	$\vec{p}_{\pi^\pm}$	$\vec{p}_{\pi^\mp}$	$y_{a_1^{1Pr}} \cdot y_{a_1^{3Pr}} < 0$
$\tau_{a_1^{3Pr}} \times \tau_{a_1^{3Pr}}$	$\vec{p}_{\tau}$	$\vec{h}$	$\vec{p}_{\tau}$	$\vec{h}$	-

$$y_\rho = \frac{E_\pi - E_{\pi^0}}{E_\pi + E_{\pi^0}}, \quad y_{a_1^{1Pr}} = \frac{E_\pi - E_{\pi^0\pi^0}}{E_\pi + E_{\pi^0\pi^0}}, \quad y_{a_1^{3Pr}} = \frac{E_{\pi^\pm} - E_{\pi^\mp}}{E_{\pi^\pm} + E_{\pi^\mp}}.$$

Impact Parameter method

- Used when there are **one prong** decays, both tau leptons decay to a single charged particle
- The two charged particles define the **ZMF**
- The tau momentum is replaced by the **impact parameter** of its charged decay product (IP)
- The vector connecting the **primary vertex** (PV) to the **point of closest approach** (PCA) is used to approximate the tau **direction-of-flight**

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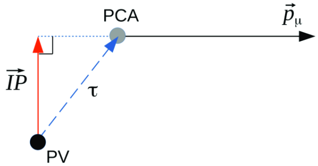
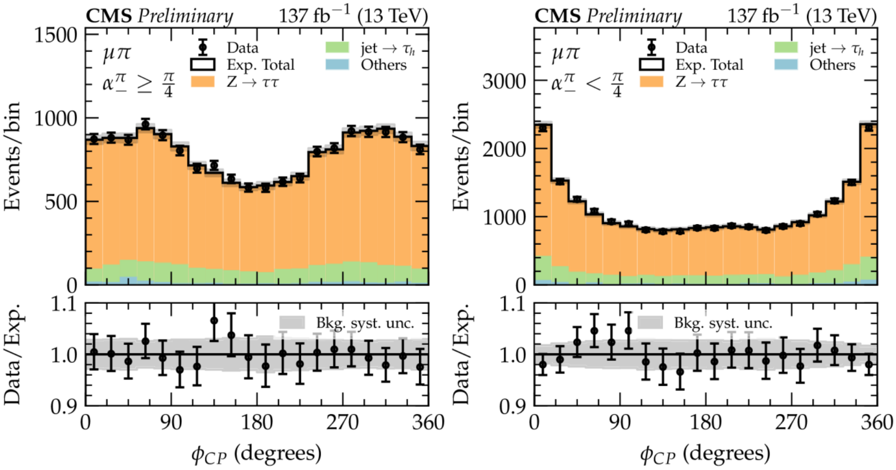


$$\phi_{CP} = \begin{cases} \varphi^* & \text{if } \mathcal{O} \geq 0 \\ 2\pi - \varphi^* & \text{if } \mathcal{O} < 0 \end{cases} \qquad \varphi^* = \arccos\left(\vec{IP}^+_\perp \cdot \vec{IP}^-_\perp\right) \qquad \mathcal{O} = (\vec{IP}^+_\perp \times \vec{IP}^-_\perp) \cdot \frac{\vec{p}^-_p}{|\vec{p}^-_p|}$$

Drell-Yan Background $Z \to \tau\tau$

$$\mathrm{d}\sigma_{DY}/\mathrm{d}\cos(\theta^+)\,\mathrm{d}\cos(\theta^-)\,\mathrm{d}\cos(\phi^+)\,\mathrm{d}\varphi_{CP}\,\mathrm{d}E^+\mathrm{d}E^- \propto \sum_{B_1,B_2=Z,\gamma} a(B_1,B_2)$$
$$\times\Big\{V_\tau^{B_1}V_\tau^{B_2}\big[1-\big(\cos(\theta^+)\cos(\theta^-)+\frac{1}{2}\sin(\theta^+)\sin(\theta^-)\cos(2\phi^+-\varphi_{CP})\big)\big]$$
$$+A_\tau^{B_1}A_\tau^{B_2}\big[1-\big(\cos(\theta^+)\cos(\theta^-)-\frac{1}{2}\sin(\theta^+)\sin(\theta^-)\cos(2\phi^+-\varphi_{CP})\big)\big]$$
$$+\left(a^{B_1}V_\tau^{B_2}+V_\tau^{B_1}A_\tau^{B_2}\right)\left(\cos(\theta^+)-\cos(\theta^-)\right)\Big\}$$

Drell-Yan Background $Z \to \tau\tau$ Run2



Folding procedure φ_{CP}