Reconstruction of tau lepton decay planes for analysing the Higgs CP at CMS

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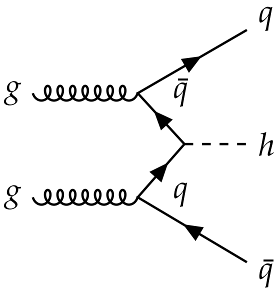
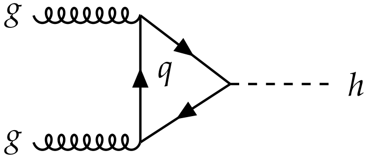
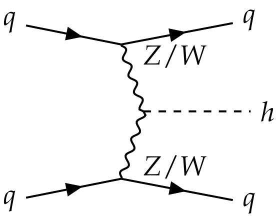
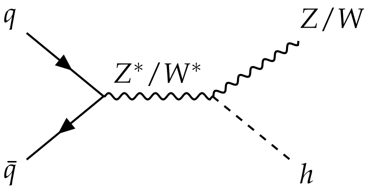
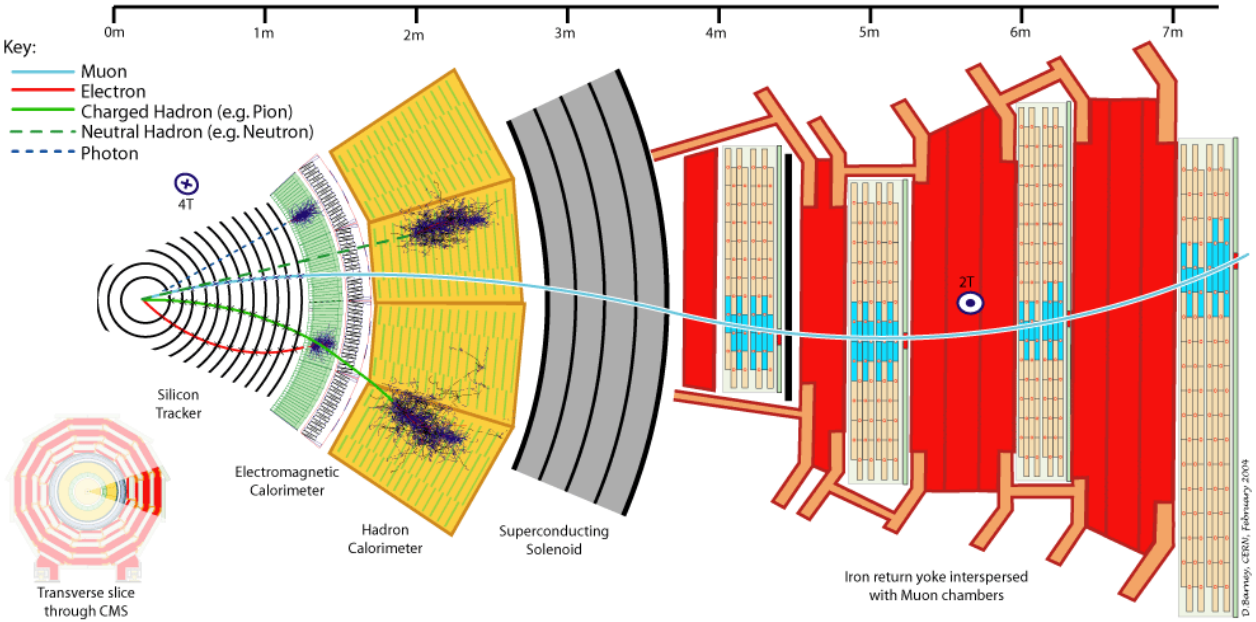
Higgs Production at the CMS Experiment











The $\mathcal{CP}$ property of the Higgs-boson

The Yukawa Lagrangian describes the interaction of a neutral spin-zero Higgs boson of any $\mathcal{CP}$ nature

$$\mathcal{L}_Y = -\left(\sqrt{2}G_F\right)^{\frac{1}{2}} \sum_{j,f} m_f \left(a_{jf}\bar{f}f + b_{jf}\bar{f}i\gamma_5 f\right) h_j$$

It can be rewritten as an effective Lagrangian for $h \rightarrow \tau^+\tau^-$

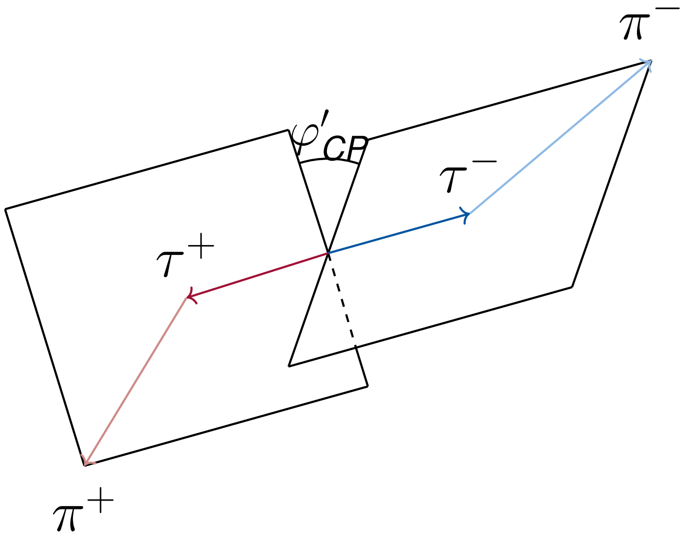
$$\mathcal{L}_Y = -g_\tau \left(\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau}i\gamma_5\tau\right) h$$

ϕ_τ is the mixing angle

$$|\psi\rangle = \cos\phi_\tau \, |\psi_{even}\rangle + \sin\phi_\tau \, |\psi_{odd}\rangle$$

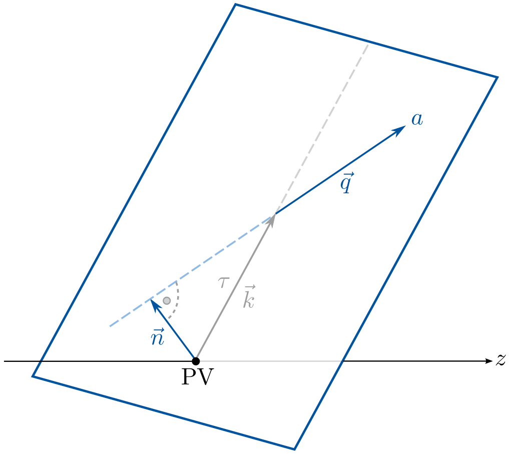
Any mixture of $|\psi_{even}\rangle$ and $|\psi_{odd}\rangle$ is a sign for $\mathcal{CP}$-violation which is required for Baryogenesis

The $\mathcal{CP}$ Sensitive Variable φ^*_{CP}

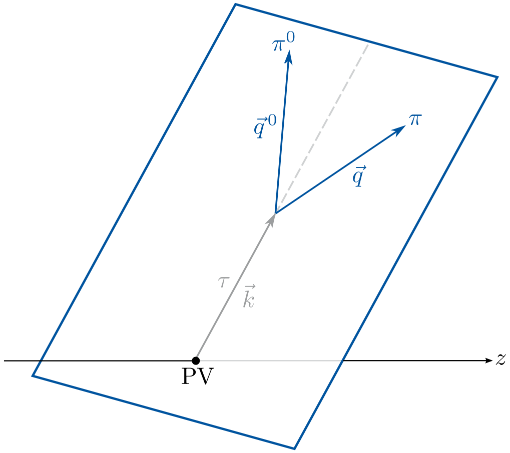


φ'_{CP} is $\mathcal{CP}$ sensitive
but inaccessible at CMS

Impact Parameter Method



Rho Method



The $\mathcal{CP}$ Sensitive Variable φ^*_{CP}

$\hat{n}_\perp$: Normal vector of plane reconstructed via IP method

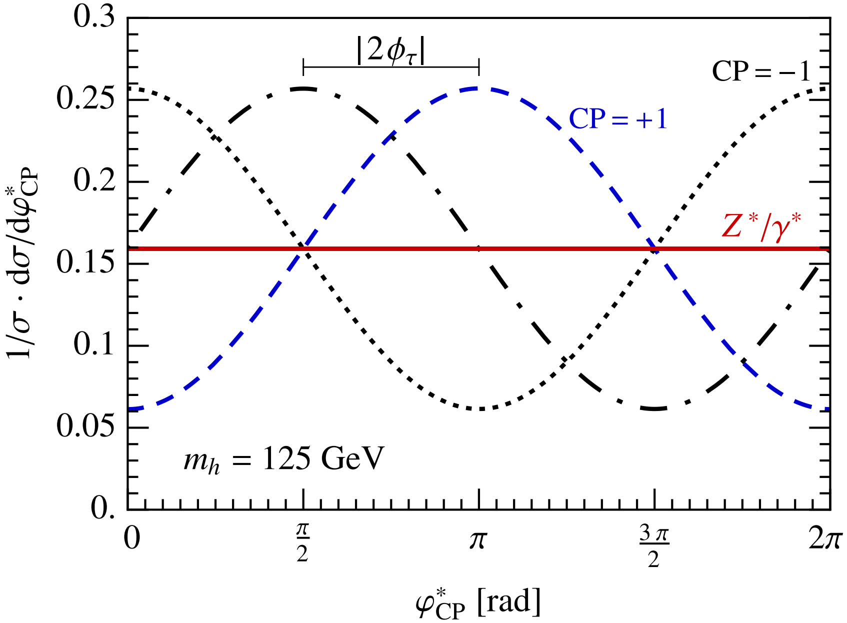
$h \rightarrow \tau\tau \rightarrow \mu\pi + 2\nu$

$$\varphi^* = \arccos\left(\hat{n}^+_\perp \cdot \hat{n}^-_\perp\right)$$

$$\mathcal{O}^*_{CP} = \hat{p}_{L^-} \cdot \left(\hat{n}^+_\perp \times \hat{n}^-_\perp\right)$$

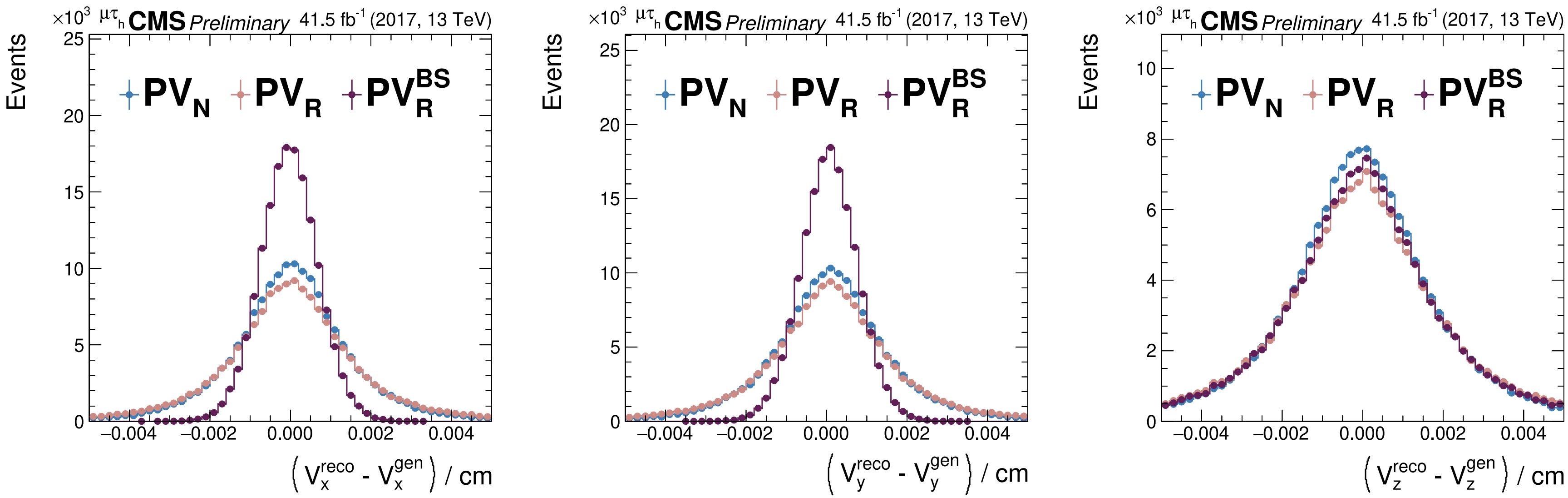
$$\varphi^*_{CP} = \begin{cases} \varphi^* & \text{, if } \mathcal{O}^*_{CP} \geq 0 \\ 2\pi - \varphi^* & \text{, if } \mathcal{O}^*_{CP} < 0 \end{cases}$$

[arXiv:1408.0798] by Berge and Bernreuther from RWTH



The Primary Vertex

There are currently 3 methods of calculating the primary Vertex $\vec{V}$



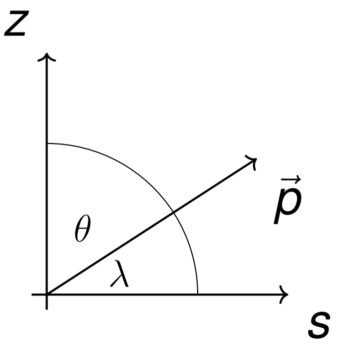
PV_N: include all tracks associated with the event

PV_R: exclude tau daughter tracks

PV_R^{BS}: exclude tau daughter tracks and uses beam spot as an initial estimate

Reconstruction of the Particle Trajectory

- $\frac{q}{p}$: signed inverse momentum of the charged particle
- λ: angle of momentum with respect to xy-plane
- ϕ: azimuthal angle with respect to x-axis
- d_{xy}:shortest distance from BS to track in xy-plane
- d_{sz}:shortest distance from BS to track in sz-plane



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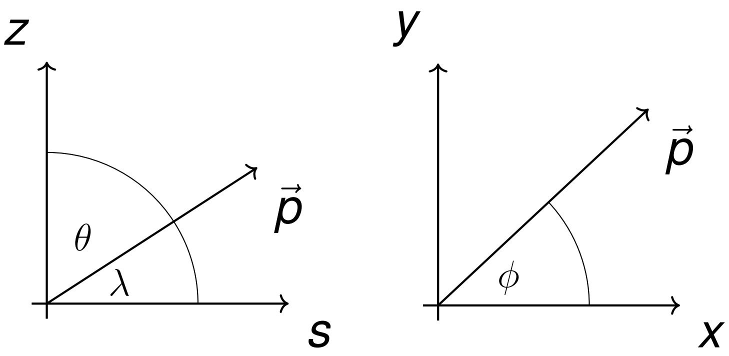

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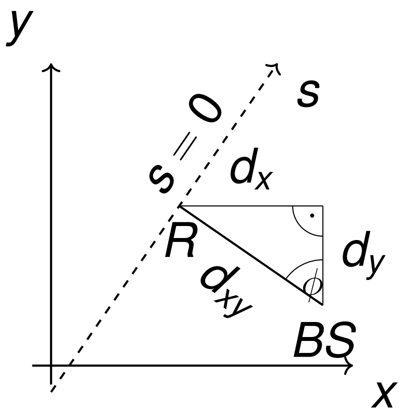

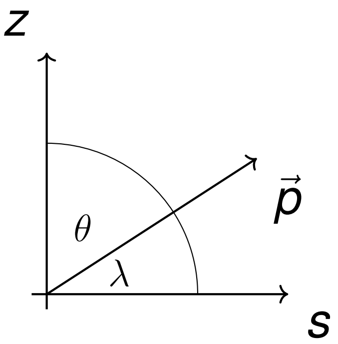

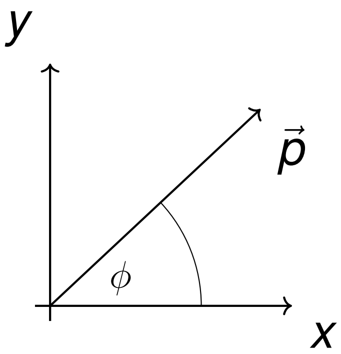

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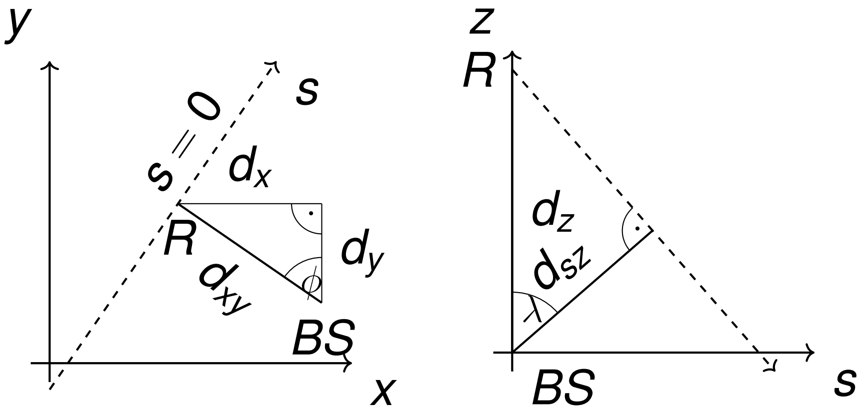
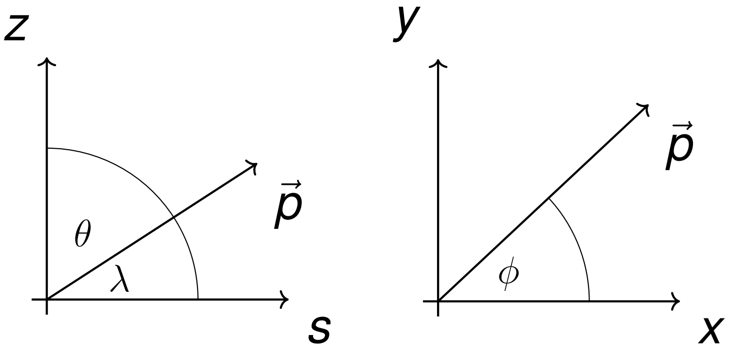
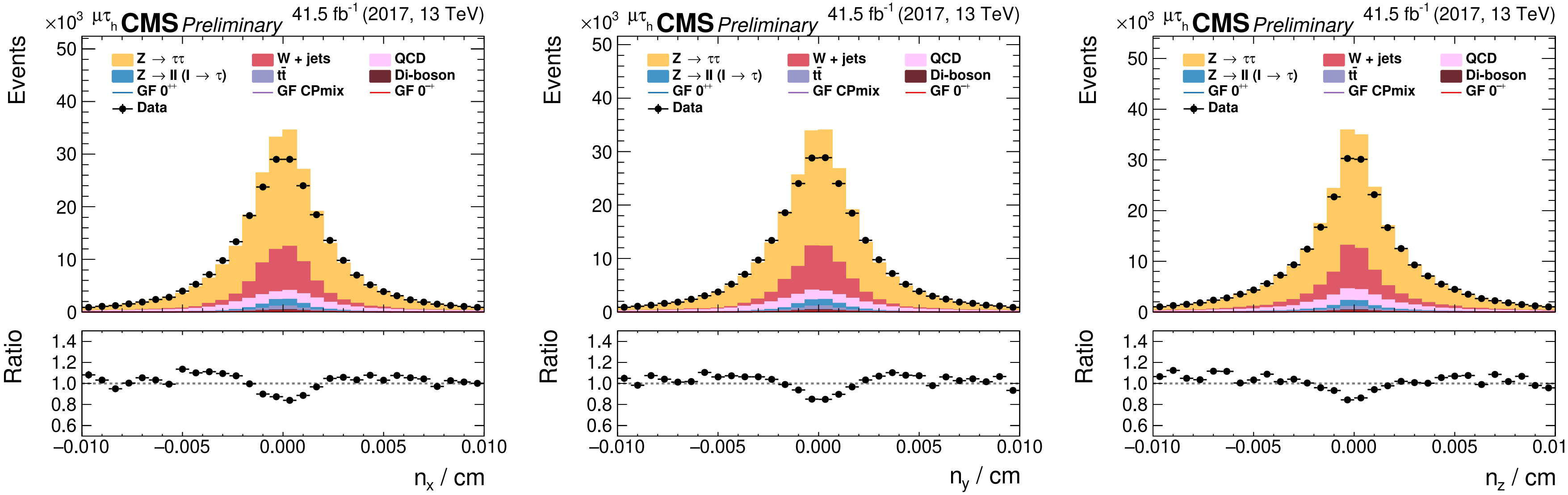




The Impact Parameter

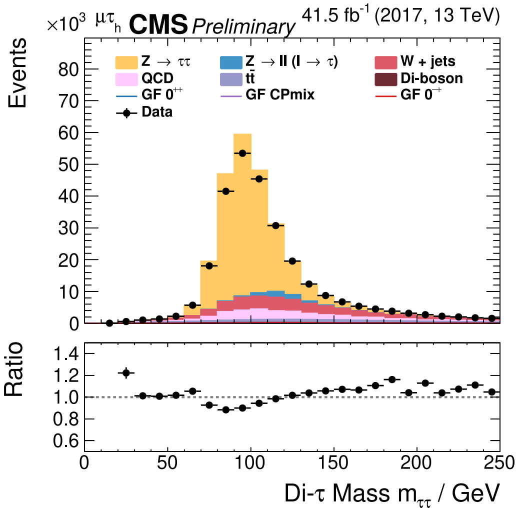
$$\vec{x}(t) = \vec{h} + \begin{pmatrix} r\cos(\omega t - \alpha) \\ -r\sin(\omega t - \alpha) \\ v_z t \end{pmatrix}$$

$$\delta(t) = \left|\vec{x}(t) - \vec{V}\right|^2 \xrightarrow{t'\to t_{min}} \vec{n} = \vec{x}(t_{\mathrm{min}}) - \vec{V}$$

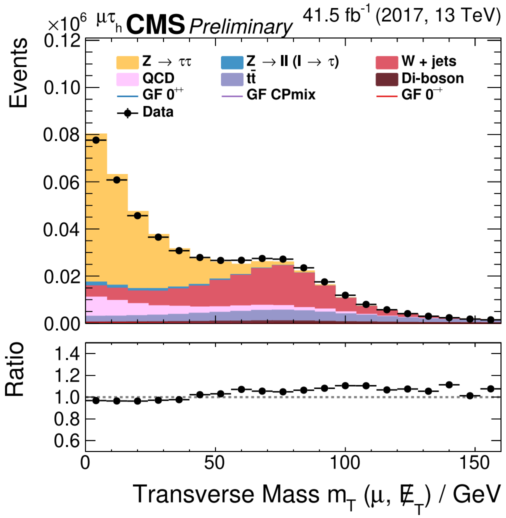


Find a Drell-Yan Control region

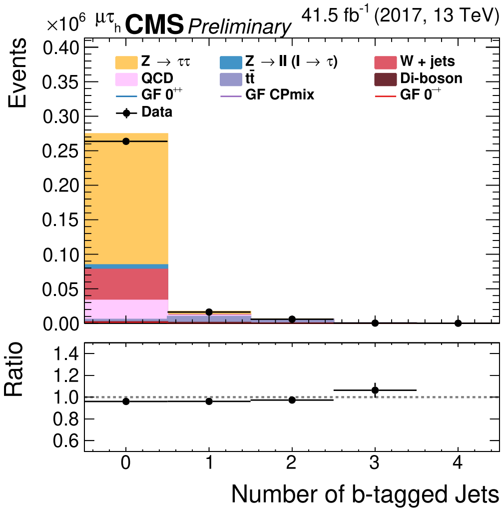
- Exclude $H \to \tau^+\tau^-$ events
- Exclude W+jets events
- Exclude $t\bar{t}$ events



$70\,\text{GeV} < m_{\tau\tau} < 110\,\text{GeV}$



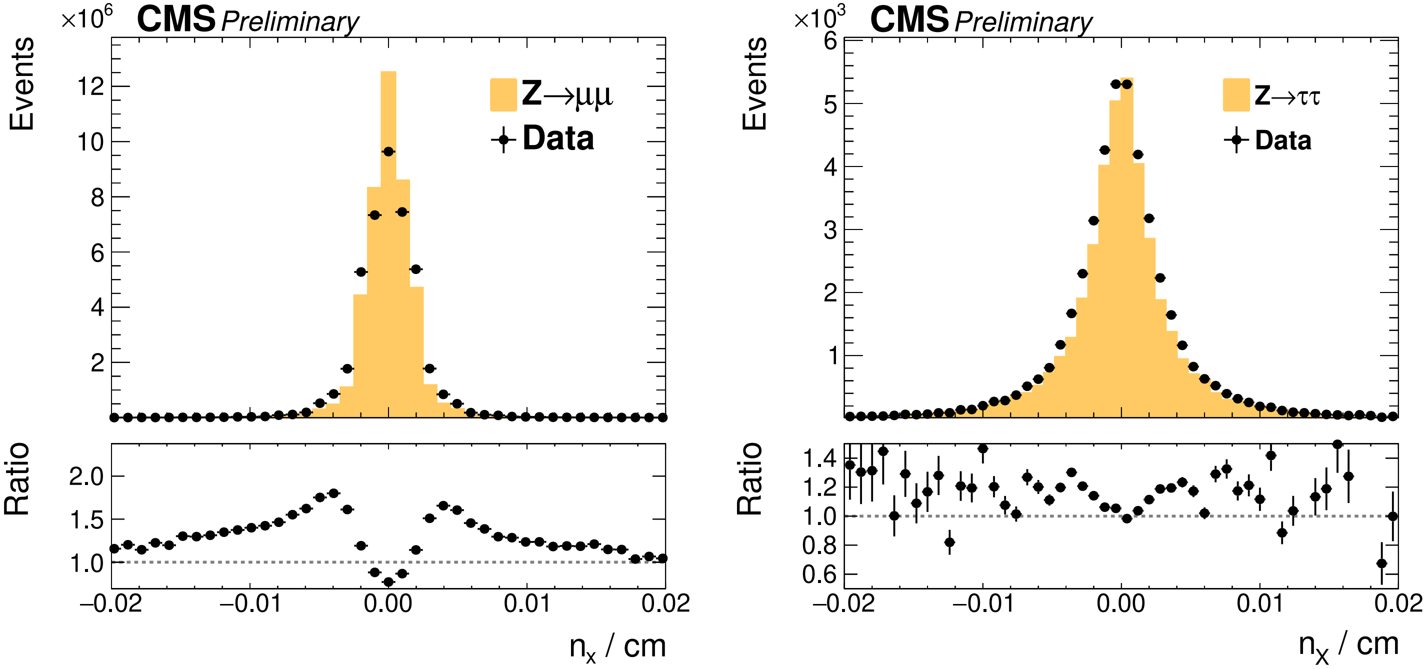
$m_T < 80\,\text{GeV}$



$n_b < 1$

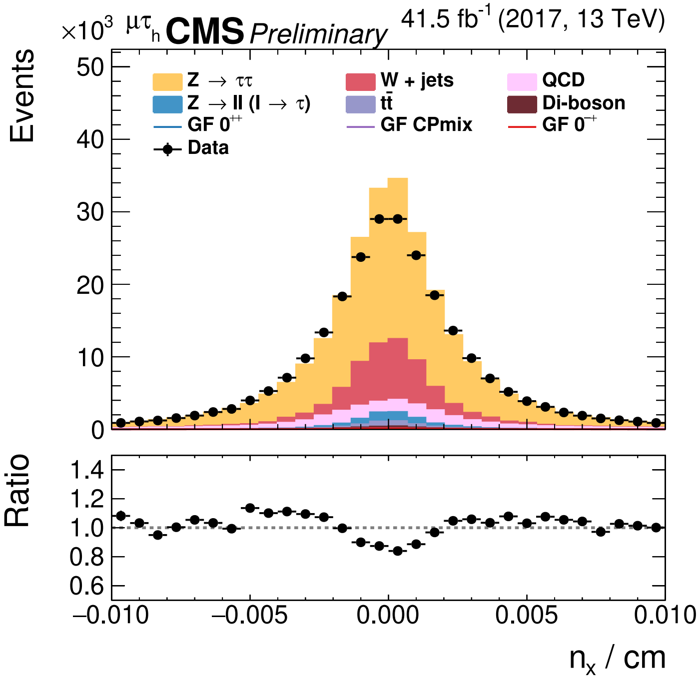
Quantile Mapping - Strategy

- Calibration is done in DY control region
- Use $Z \to \mu\mu$ samples to calibrate prompt decays (mostly W+jets)
- Use $Z \to \tau\tau \to \mu\tau_h + 2\nu_\tau$ samples to calibrate non prompt decays
- Subtract backgrounds other than DY from data (calibrate prompt IPs first)
- $n_i^{QM} = F_{data}^{-1}(F_{MC}(n_i))$ for i in $[x, y, z]$

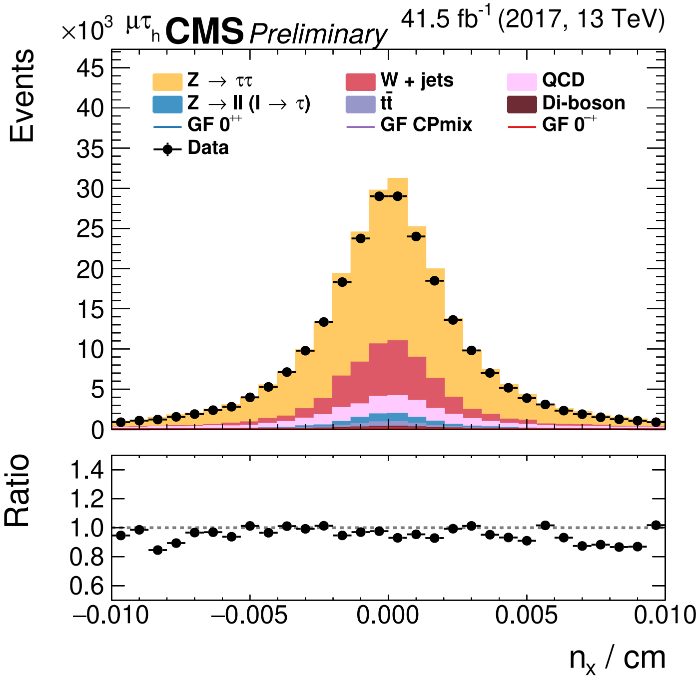


Calibrated Reconstructed IP for muons - $\mu\tau_h$ channel

uncalibrated:



calibrated:



- Agreement vastly improves

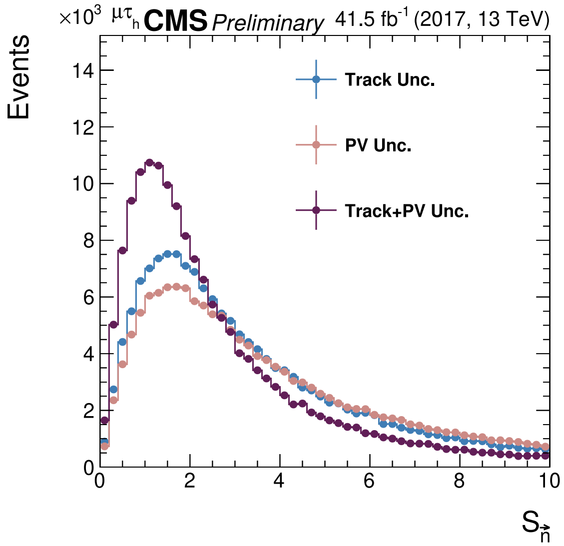
Impact Parameter Significance

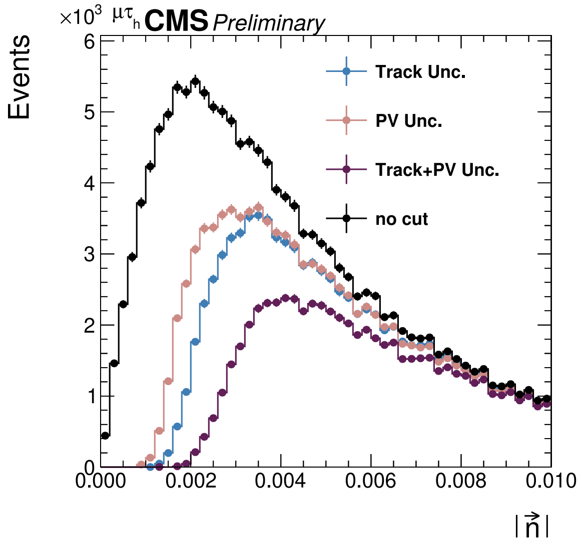
$\Sigma_{\vec{x}}$: Track Covariance Matrix

$\Sigma_{\vec{V}}$: Primary Vertex Covariance Matrix

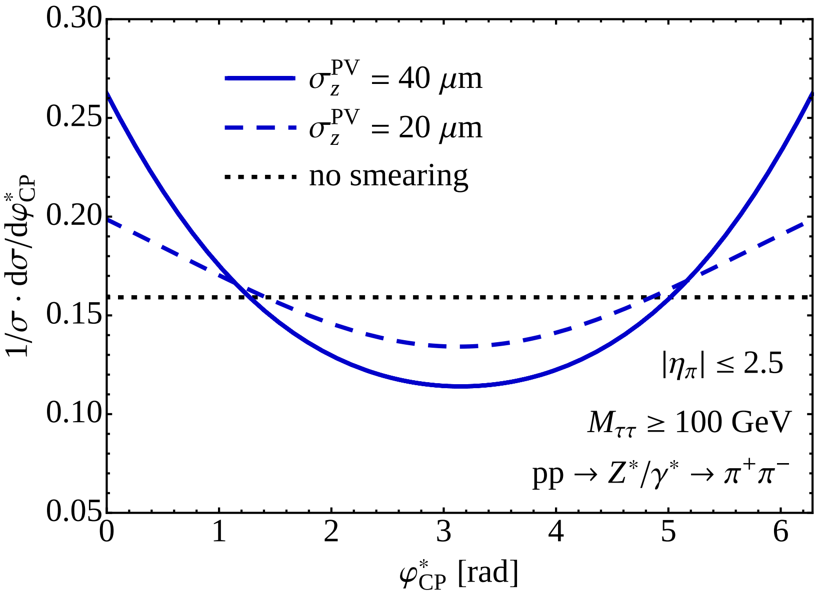
$$\Sigma_{\vec{n}} = J_{\vec{n}} \begin{pmatrix} \Sigma_{\vec{x}} & 0 \\ 0 & \Sigma_{\vec{V}} \end{pmatrix} J_{\vec{n}}^{T} \qquad \Rightarrow \qquad S_{\vec{n}} = \frac{|\vec{n}|}{\sigma_{|\vec{n}|}}$$

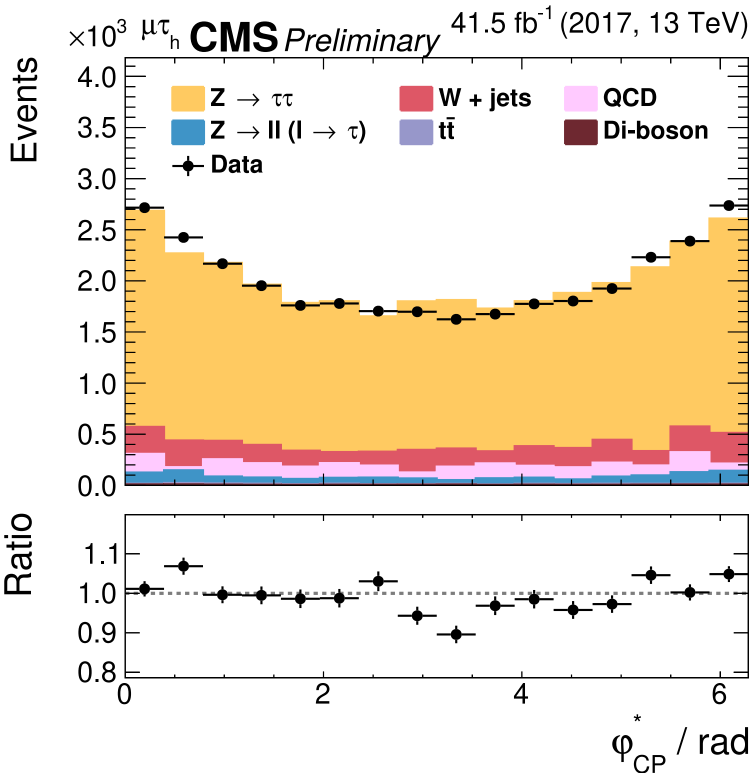
$$S_{\vec{n}} > 1:$$





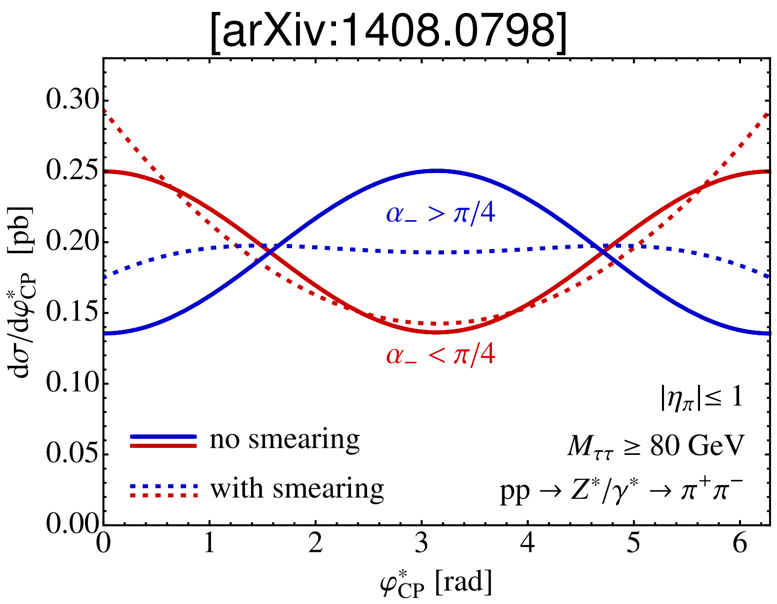
DY Modulation of φ^*_{CP} - Pure Impact Parameter Method





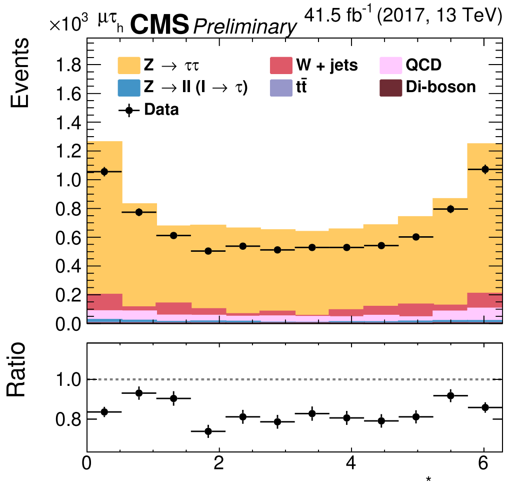
$\mu\pi$ final state

DY Modulation of φ^*_{CP} - Pure Impact Parameter Method

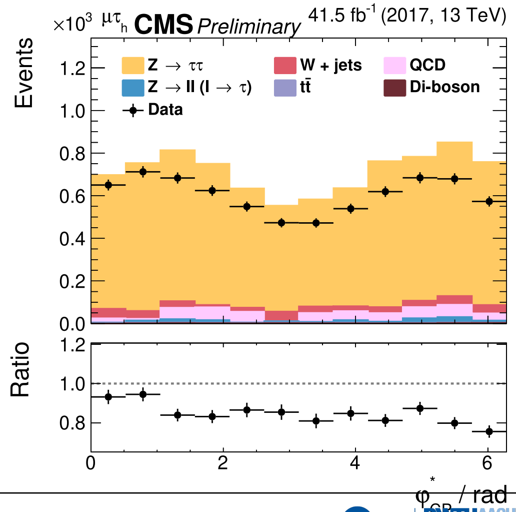


$$\cos(\alpha_-) = \left| \frac{\vec{e}_z \times \vec{p}_{L-}}{|\vec{e}_z \times \vec{p}_{L-}|} \cdot \frac{\vec{n}_- \times \vec{p}_{L-}}{|\vec{n}_- \times \vec{p}_{L-}|} \right|$$

$\alpha_- < \pi/4$:



$\alpha_- > \pi/4$:



Conclusion and Outlook

- A framework for calculating the 3D impact parameter and the full impact parameter covariance matrix has been provided
- This is used in the $\mathcal{CP}$ analysis at CMS
- The cut on the impact parameter significance selects well reconstructed impact parameters
- A calibration method has been presented to improve agreement of impact parameters
- Another calibration method was developed by working group and will be used instead
- The $\mathcal{CP}$ Analysis is moving forward and on its way to publish a paper

BACKUP

BACKUP

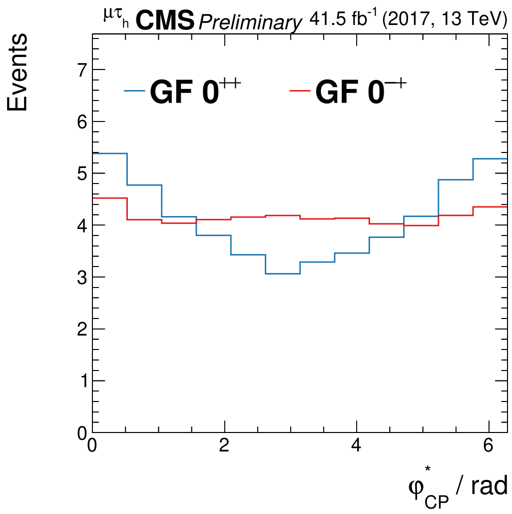
The particle Trajectory in terms of the helix parameters

$$t \rightarrow t'/\omega$$

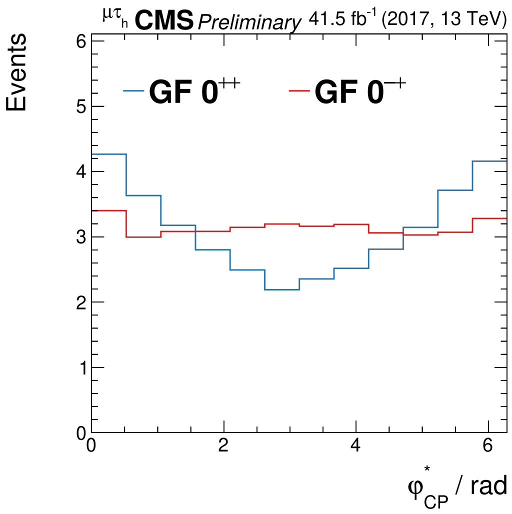
$$\vec{x}(t') = \vec{b} + \begin{pmatrix} -d_{xy} \cdot \sin\phi + \frac{\cos(\lambda)}{B\cdot\left|\frac{q}{p}\right|} \cdot [\sin\phi\,(1 - \cos t') + \cos\phi \sin t'] \\ d_{xy} \cdot \cos\phi + \frac{\cos(\lambda)}{B\cdot\left|\frac{q}{p}\right|} \cdot [\sin\phi \sin t' - \cos\phi\,(1 - \cos t')] \\ d_{sz}/\cos\lambda + \frac{\sin(\lambda)}{B\cdot\left|\frac{q}{p}\right|} \cdot t' \end{pmatrix}$$

Looking at the modulation of φ^*_{CP} - Impact Parameter Method

no cut



$S_{\vec{n}} > 1$:



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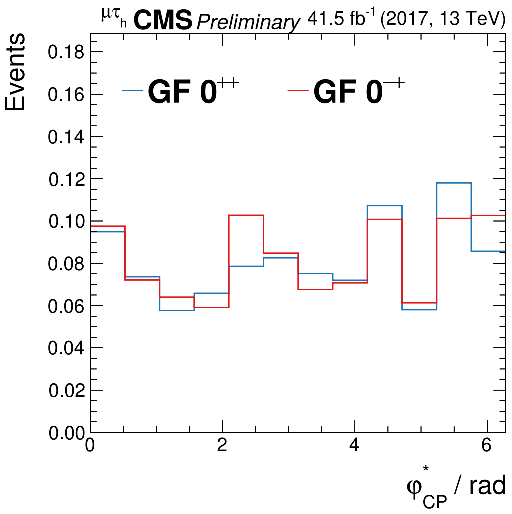

- Gluonfusion signal sample was used in the $\mu\pi$ final state
- Modulation is visible without any cut
- Amplitude is enhanced by selecting well reconstructed impact parameters
- Modulation is not visible by selecting only badly reconstructed impact parameters