Studies of the Higgs boson CP property in the fermionic couplings using $H \to \tau\tau$ events with the CMS experiment

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Physics at the Terascale

Motivation

Unraveling properties of the new boson h of $m_h \simeq 125$ GeV

couplings spin parity **CP**

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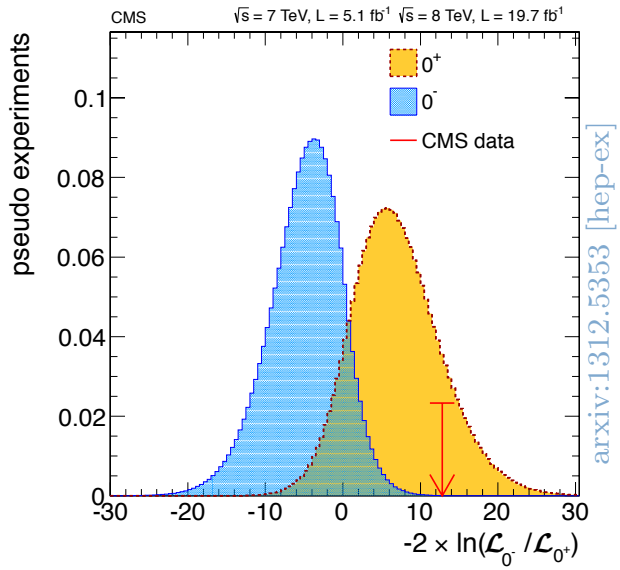
- LHC data $\Rightarrow J^P = 0^+$

  $h \to ZZ$ arxiv:1312.5353 [hep-ex]
- CP-odd component not yet excluded

  Phys. Rev. D 87, 055014



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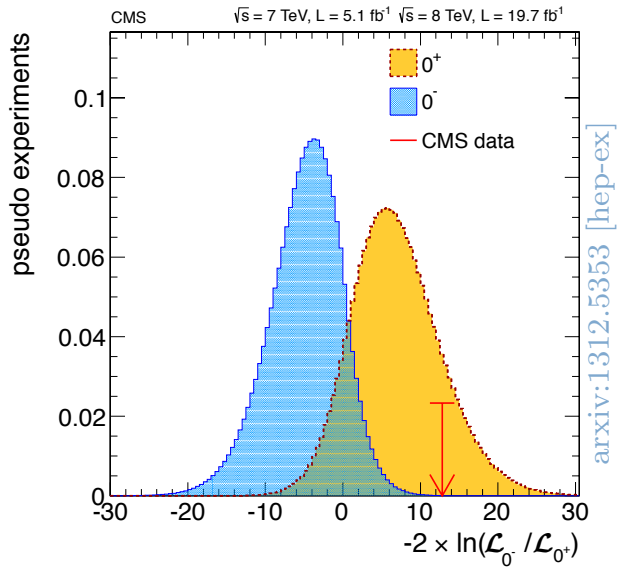


CP study in interactions with fermions

- Sensitive to CP-even and CP-odd components

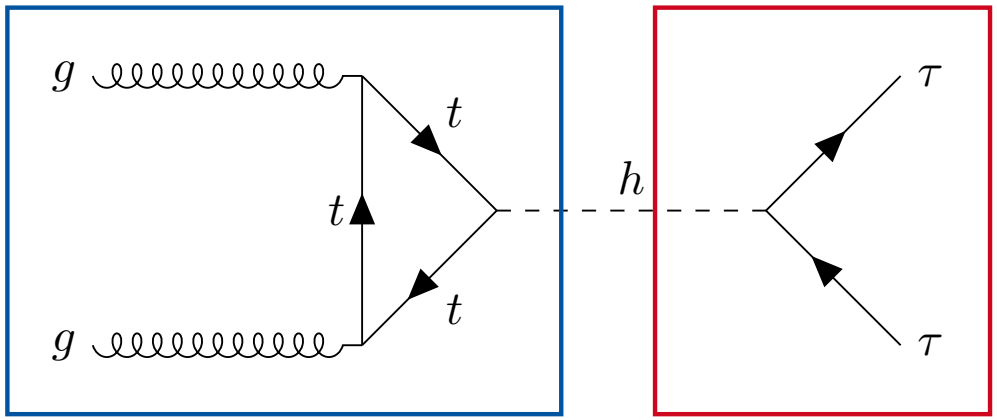
Strategies

- Studies in the production mode of the Higgs boson

- Studies in the decay mode of the Higgs boson

Strategies

- Studies in the production mode of the Higgs boson



CP-sensitive observable Higgs event selection

J. Degens

L. Wiens

D. Wolfschläger

- Studies in the decay mode of the Higgs boson

Strategies

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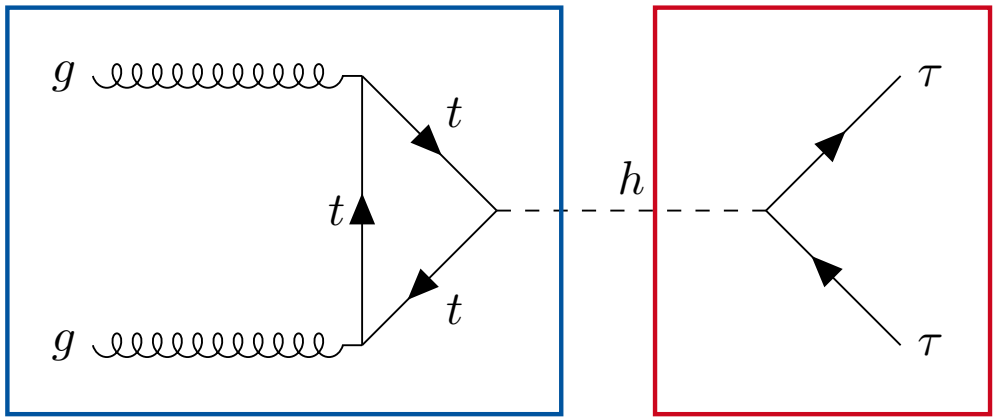

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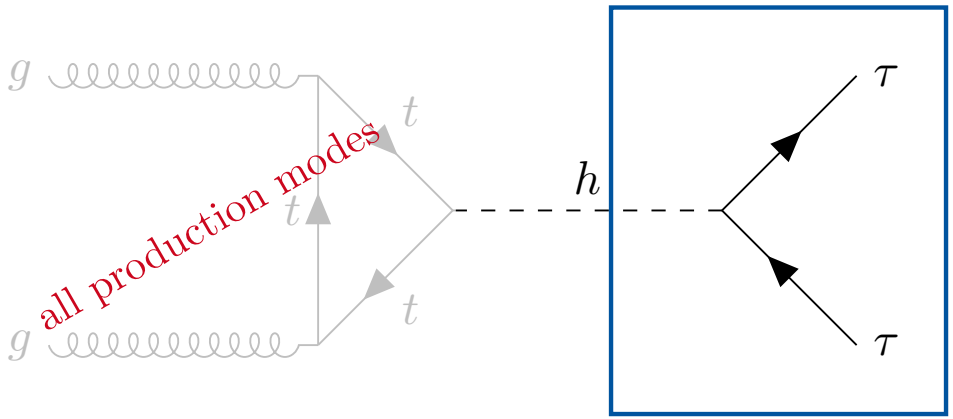


CP-sensitive observable

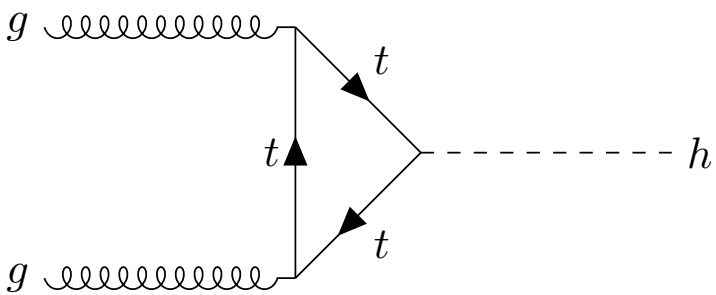
C. Pistone

Production mode studies

Higgs production via gluon-gluon fusion

[arxiv:1406.3322]

$$\mathcal{L}_{hff} = g_f \left(\underbrace{\cos\alpha_f \bar{f} f}_{\text{CP-even}} + \underbrace{\sin\alpha_f \bar{f} i\gamma_5 f}_{\text{CP-odd}} \right) h$$

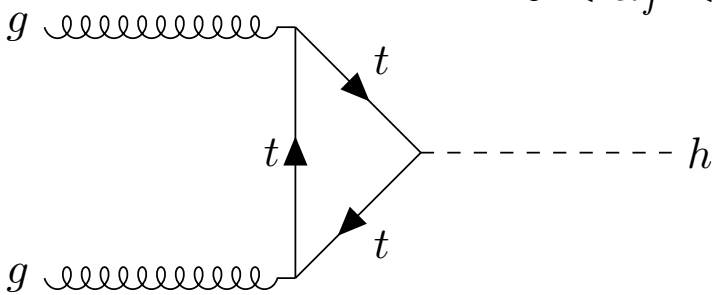


Higgs production via gluon-gluon fusion

[arxiv:1406.3322]

$$\mathcal{L}_{hgg} = \underbrace{\cos\alpha_f \frac{\alpha_s}{12\pi v} h G^a_{\mu\nu} G^{a\,\mu\nu}}_{\text{CP-even component}} + \underbrace{\sin\alpha_f \frac{\alpha_s}{8\pi v} h G^a_{\mu\nu} \epsilon_{\mu\nu\rho\sigma} G^{a\,\rho\sigma}}_{\text{CP-odd component}}$$

$\alpha_f = 0$	CP-even
$\alpha_f = \frac{\pi}{2}$	CP-odd
$0 < \alpha_f < \frac{\pi}{2}$	CP violation



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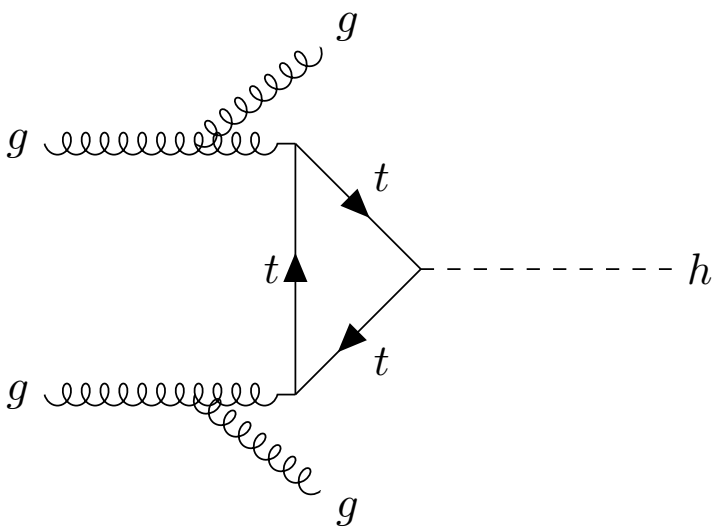

- Opposite hemisphere:
  $y_j \equiv y_{j1} = -y_{j2}$
- Lab frame ≡ centre-of-mass frame:
  $\vec{p} = \pm E_{\text{CM}} \hat{z}$

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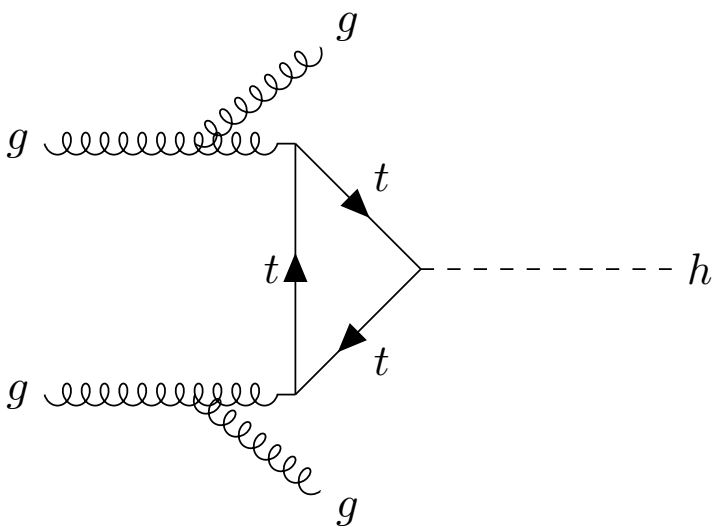

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$$|\mathcal{M}^2|_{\pm} \sim exp(4y_j)\,(A \pm B\cos(2\Delta\phi_{jj}))$$

with A, B and ξ functions of E_{CM} and m_h

Higgs production via gluon-gluon fusion

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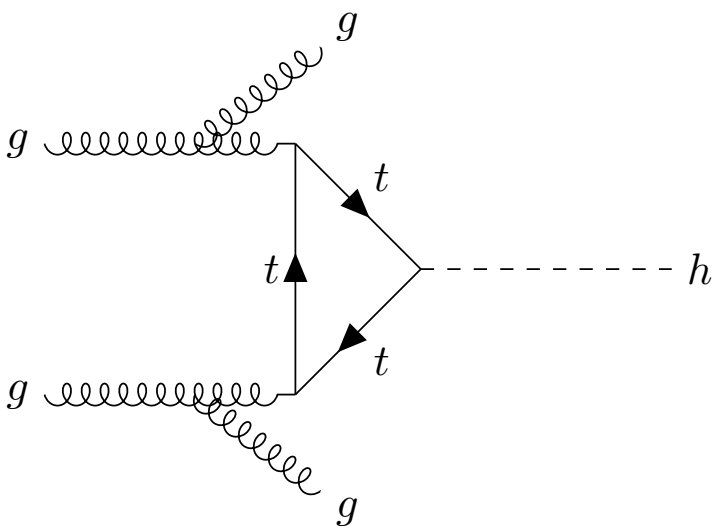

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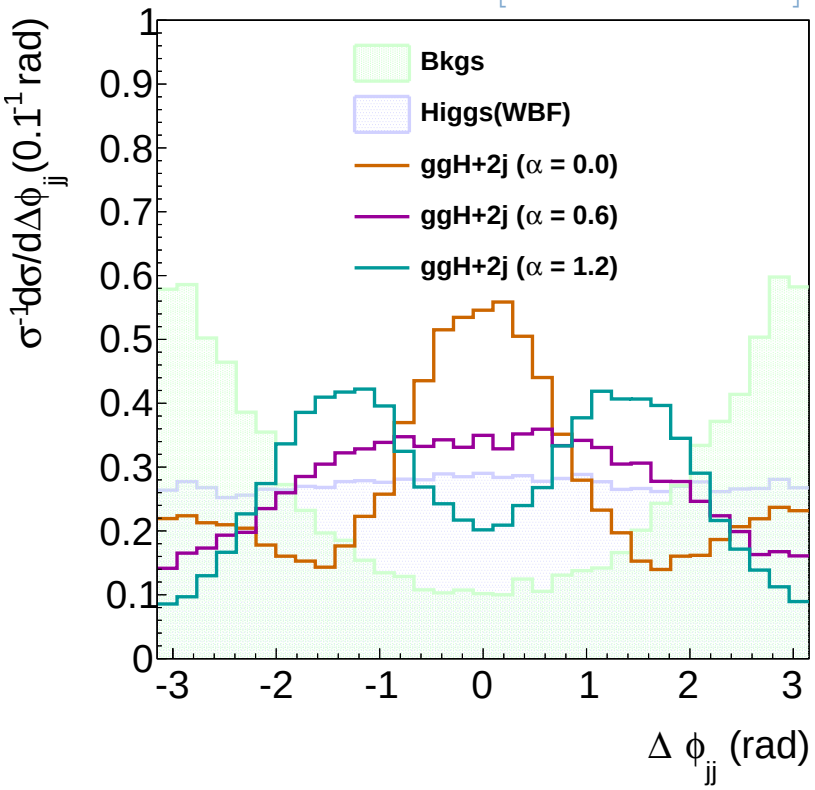
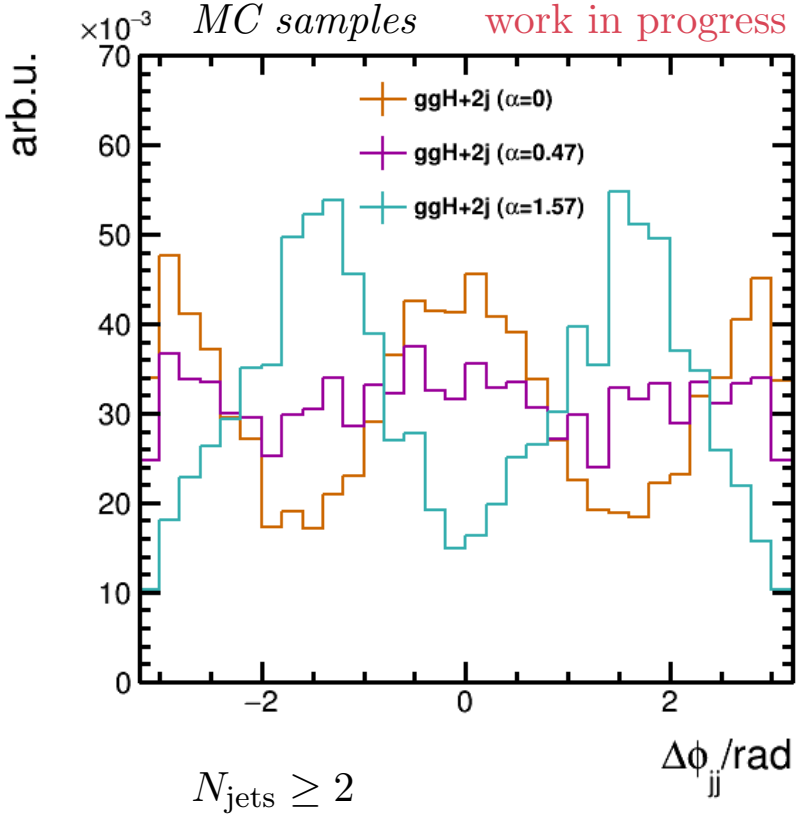
CP-sensitive observable

with A, B and ξ functions of E_{CM} and m_h

Distribution of the observable for signal samples

[arxiv:1406.3322]





$N_{\text{jets}} \geq 2$

$m_{jj} > 500$ GeV

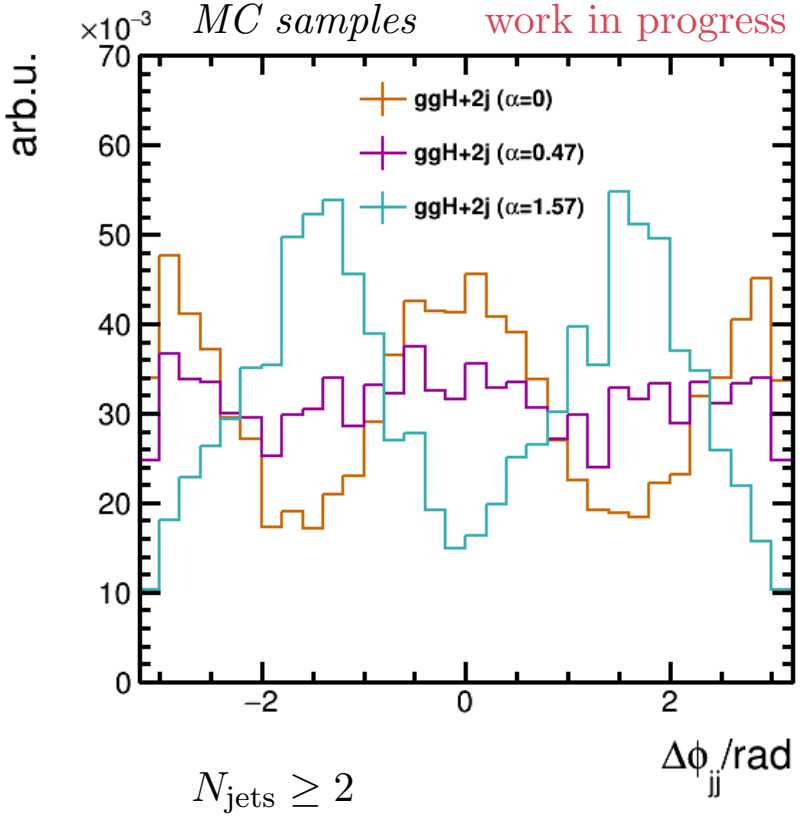
$\eta_{j1} \cdot \eta_{j2} < 0$ and $|\Delta\eta_{jj}| > 3.5$

Distribution of the observable for signal samples

- Available MC samples:
  CP-even state
- Simulating many different CP states:
  unfeasible

⇒ MC reweighting technique:

$$\mathcal{W}_{\alpha=x} = \frac{|\mathcal{M}_{\alpha=x}|^2}{|\mathcal{M}_{\alpha=0}|^2}\mathcal{W}_{\alpha=0}$$



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Sensitivity

- SM $H \to \tau\tau$ selection: CMS-HIG-16-043

  $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h\tau_h$

  Inherited systematic uncertainties

  No shape uncertainties

- Further selection cuts:

  $N_{\text{jets}} \geq 2$

  $m_{jj} > 200$ GeV

  $\eta_{j1} \cdot \eta_{j2} < 0$ and $|\Delta\eta_{jj}| > 2$

- Categories:

  $m_{jj} < 500$ GeV

  $m_{jj} > 500$ GeV

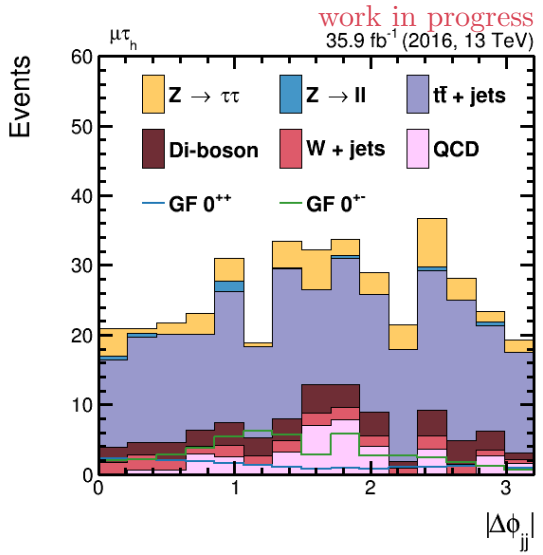
  $p_T^h > 150$ GeV and $m_{\text{sv}} > 100$ GeV

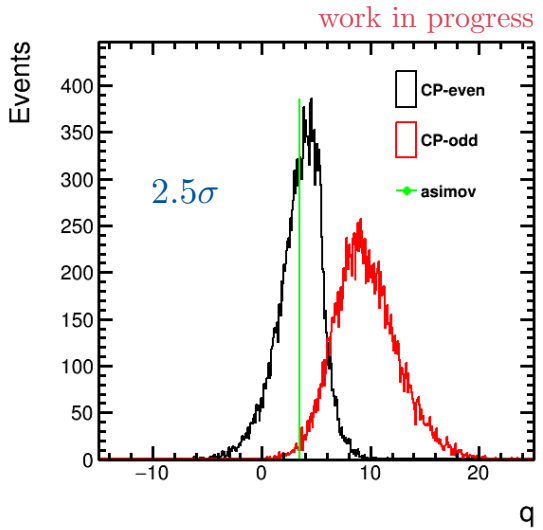
  $p_T^h < 150$ GeV

  $m_{\text{sv}} < 100$ GeV

  $m_{\text{sv}} > 100$ GeV

Test statistic with Asimov datasets ($L = 35.9$ fb^{-1})



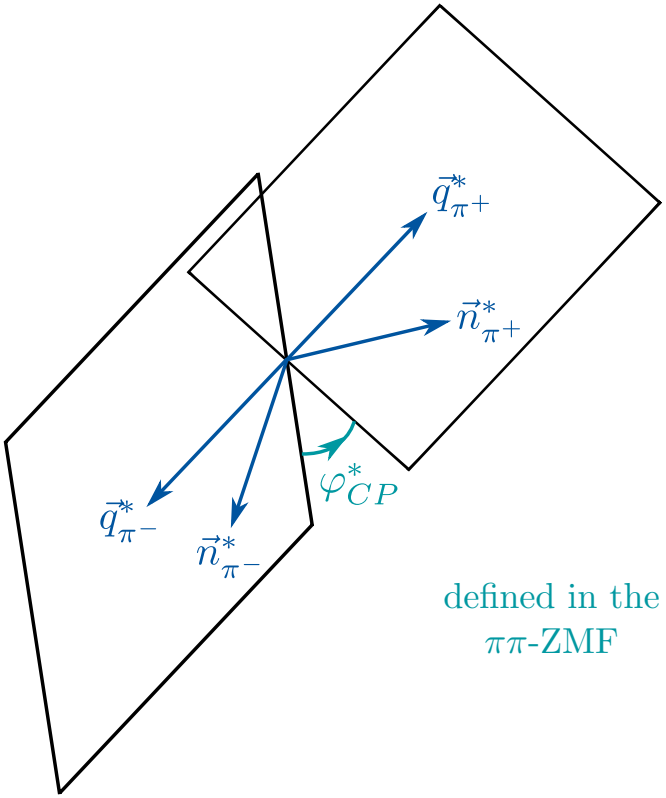


Decay mode studies

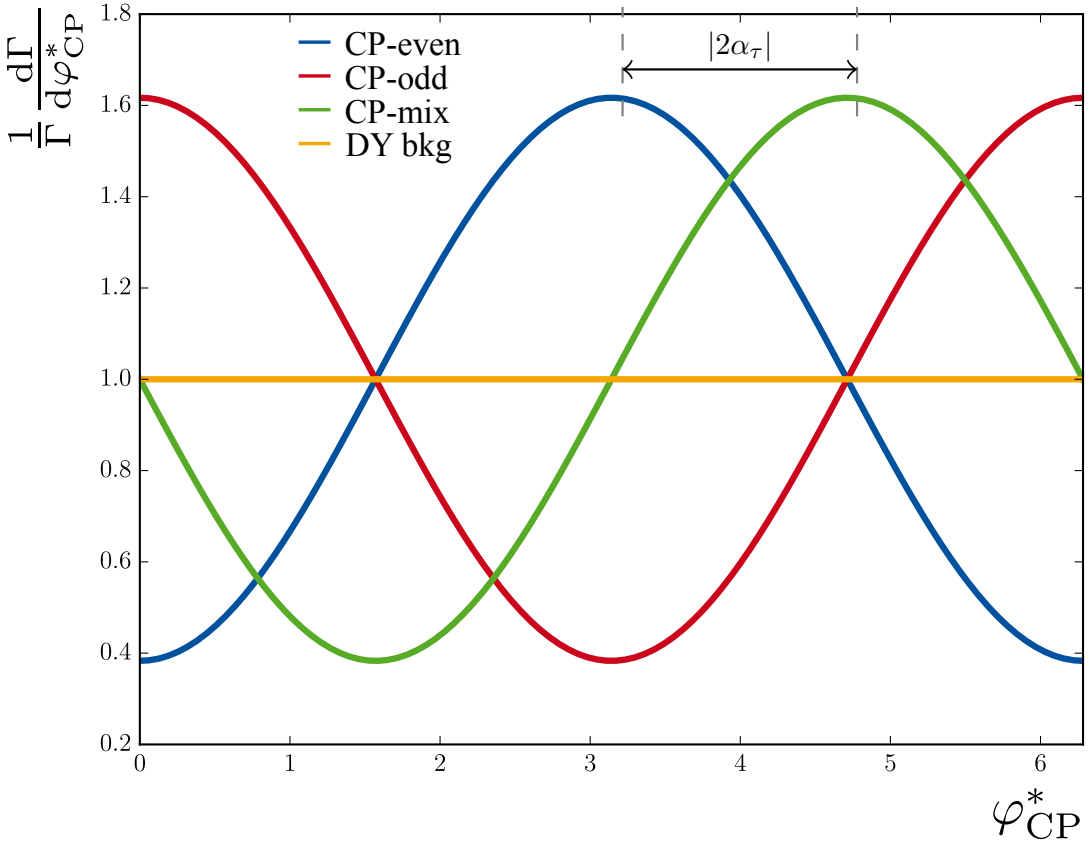
CP-sensitive observable

arxiv:1408.0798 [hep-ph]

$$\mathcal{L}_{h\tau\tau} = g_\tau \left(\underbrace{\cos\alpha_\tau \bar{\tau}\tau}_{\text{CP-even}} + \underbrace{\sin\alpha_\tau \bar{\tau} i\gamma_5 \tau}_{\text{CP-odd}}\right) h$$



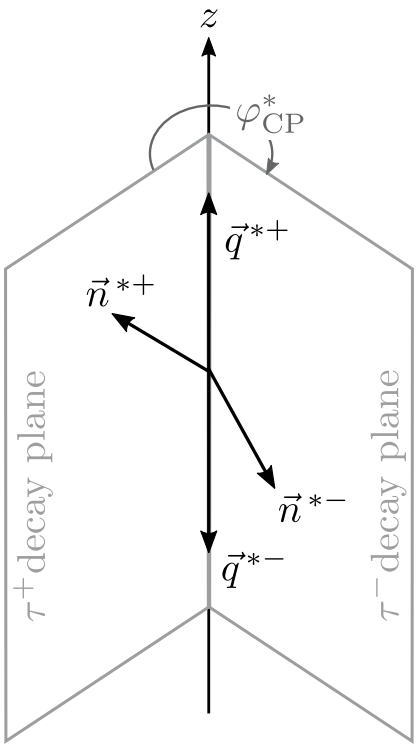
defined in the $\pi\pi$-ZMF



Methods of reconstructing φ^*_{CP}

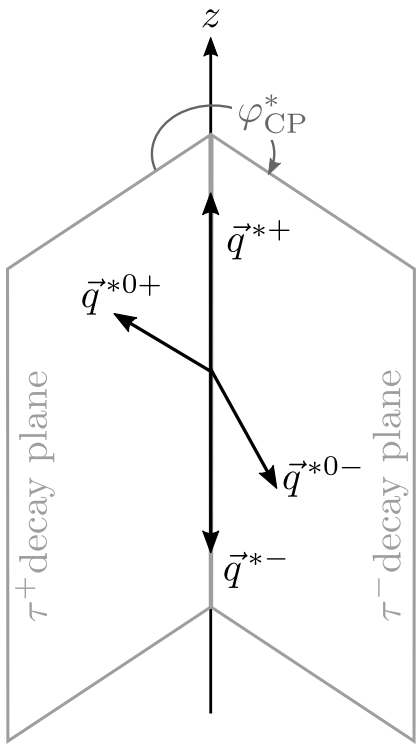
impact parameter (IP) method

arvix:1408.0798 [hep-ph]



ρ-decay plane method

arvix:1510.03850 [hep-ph]



Methods of reconstructing φ^*_{CP}

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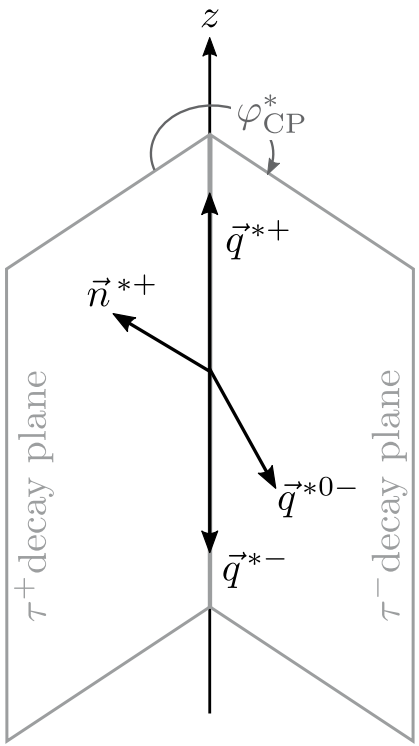
combined method
arvix:1510.03850 [hep-ph]



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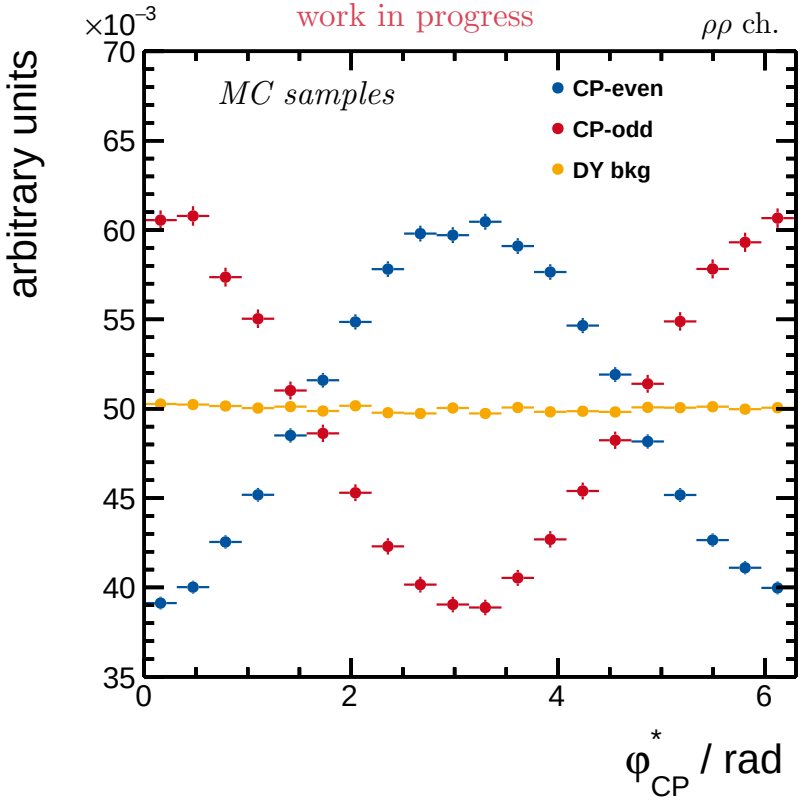
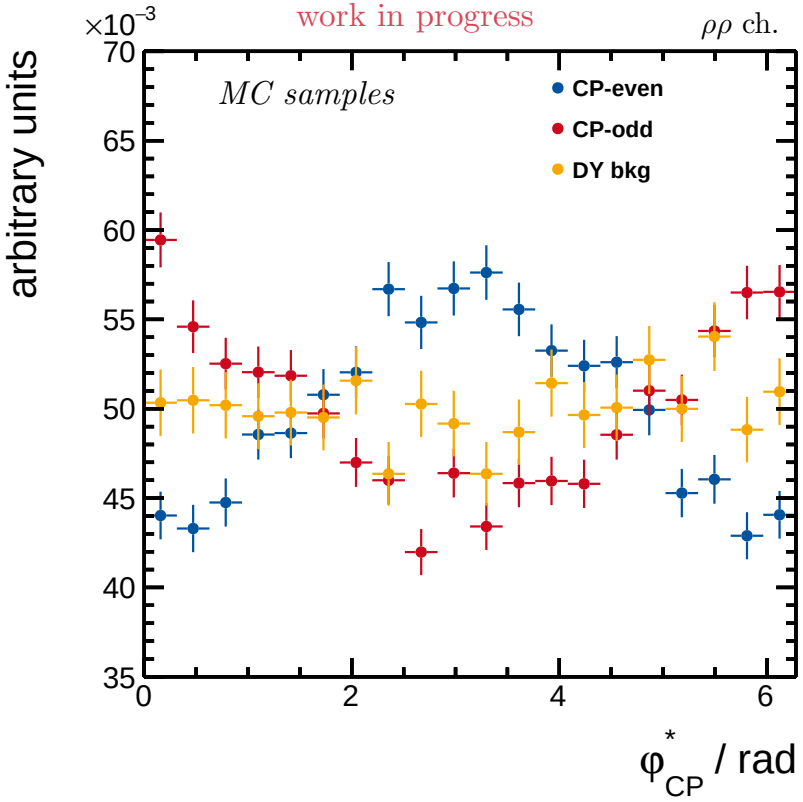
ρ-decay plane method

generator level

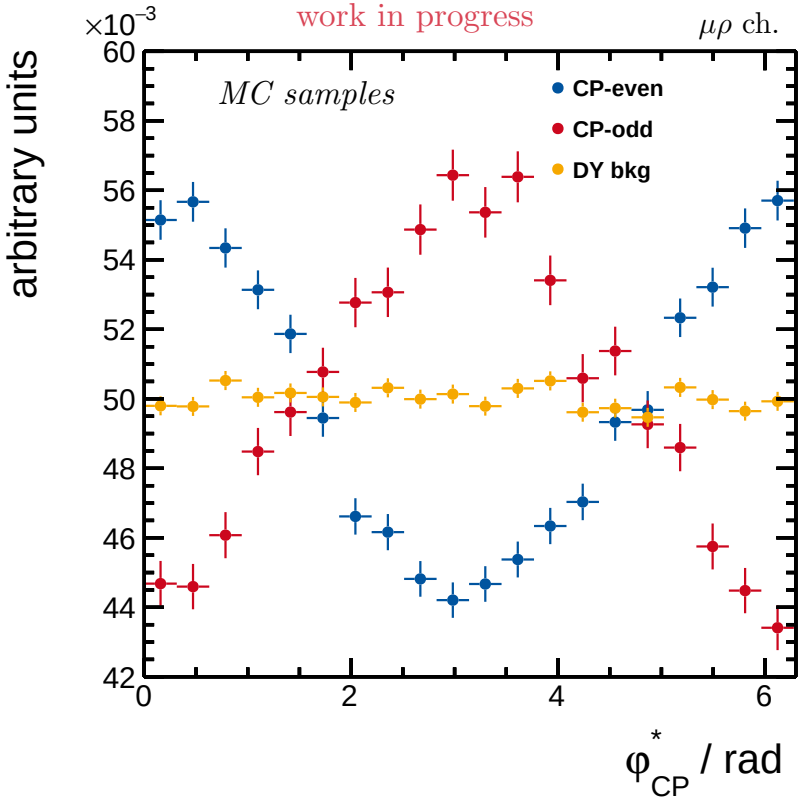


reconstruction level

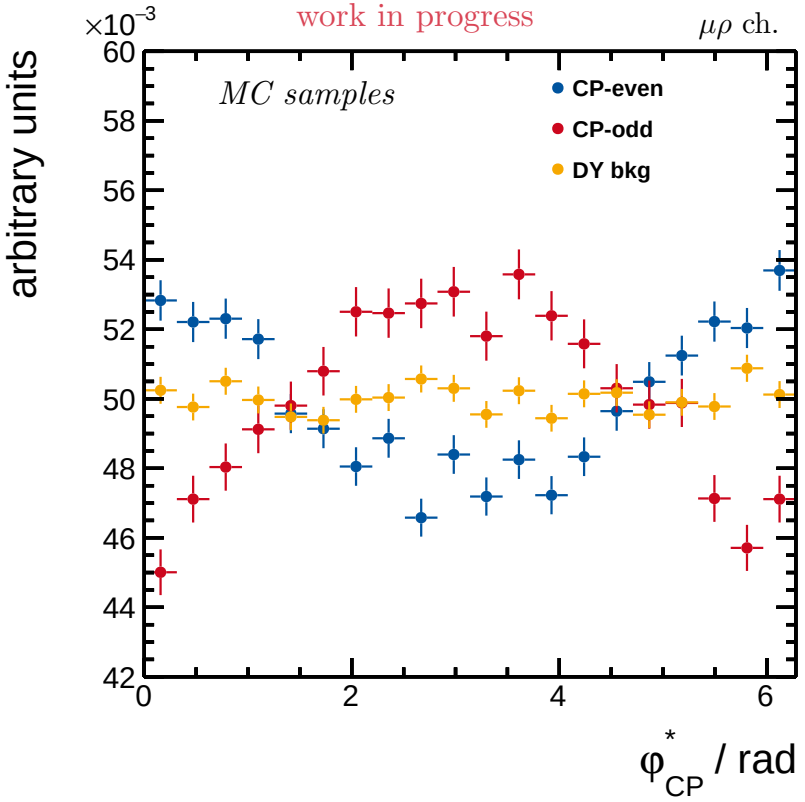


Combined method

generator level



reconstruction level



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  Inherited systematic uncertainties

  No shape uncertainties

- Example with ρ-decay plane + combined methods

  Categories: $N_{\text{jets}} = \{0, 1, 2\}$, $m_{\text{sv}} > 100$ GeV

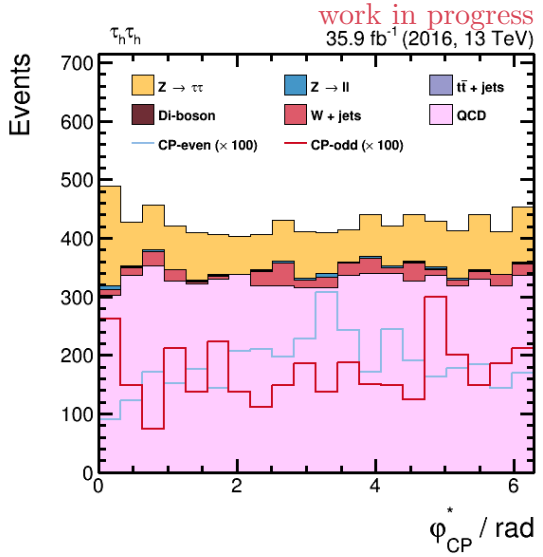
- Categorization still work in progress:

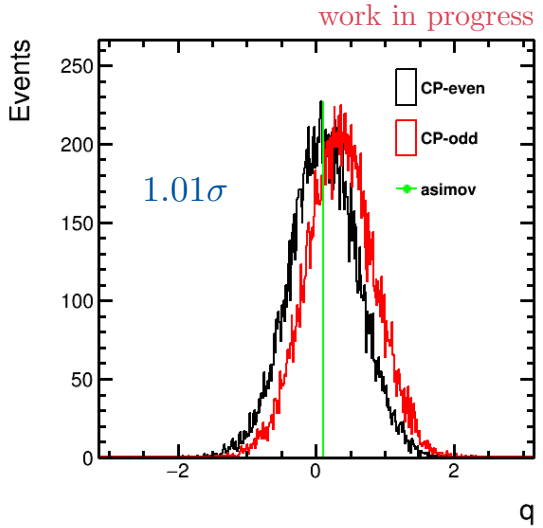
  $N_{\text{jets}} = \{0, 1, 2\}$

  $m_{\text{sv}} < 100$ GeV

  $m_{\text{sv}} > 100$ GeV

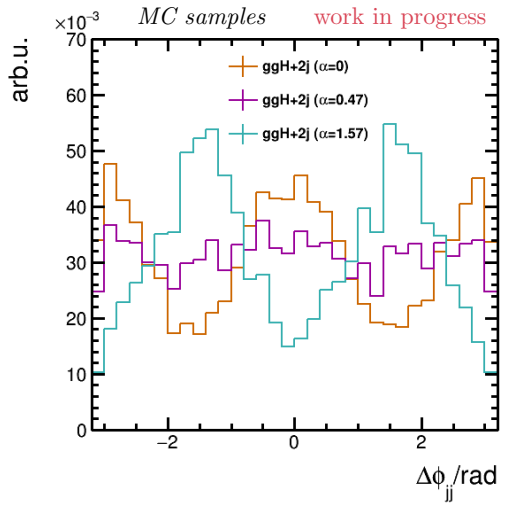
Test statistic with Asimov datasets ($L = 35.9$ fb^{-1})

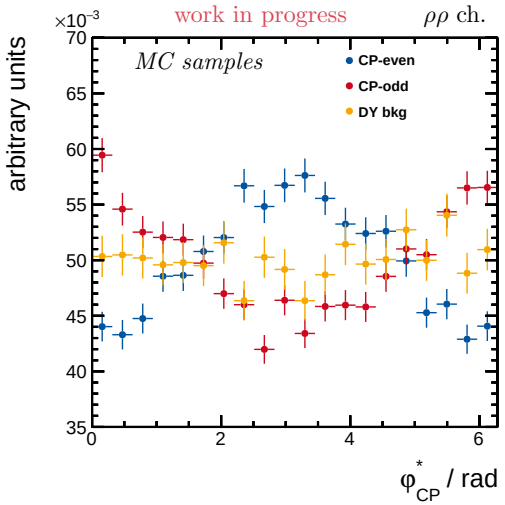




Summary

- Production mode strategy
  - Possibility to set limits in the near future
- Decay mode strategy
  - Less sensitivity
  - Best with ρ-decay plane and combined methods
  - Attempts to improve sensitivity of the IP method (e.g. primary vertex refitting)
  - Expected improvements of the IP method with new pixel detector
- Tools and analysis ready to be used in data

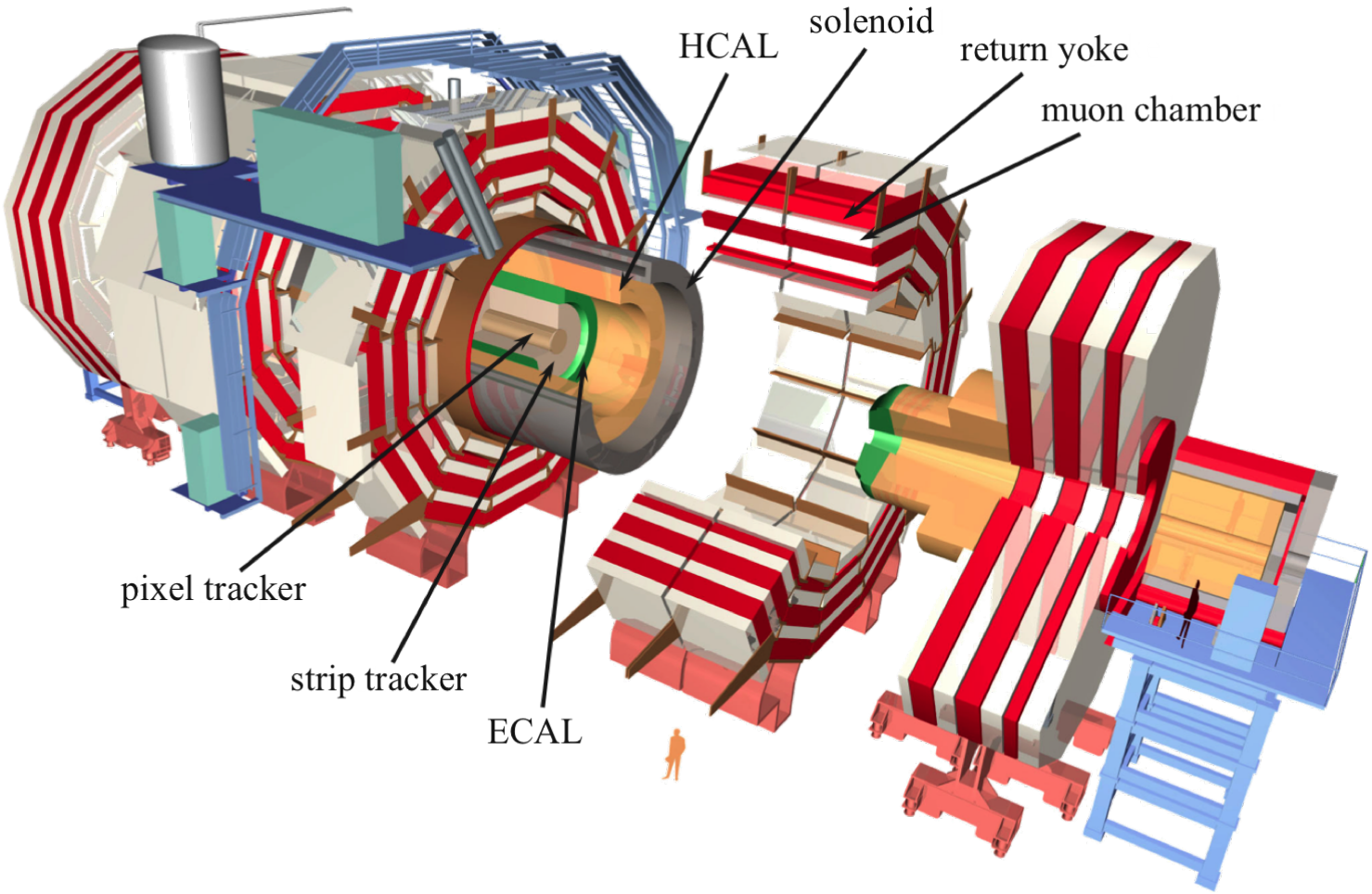




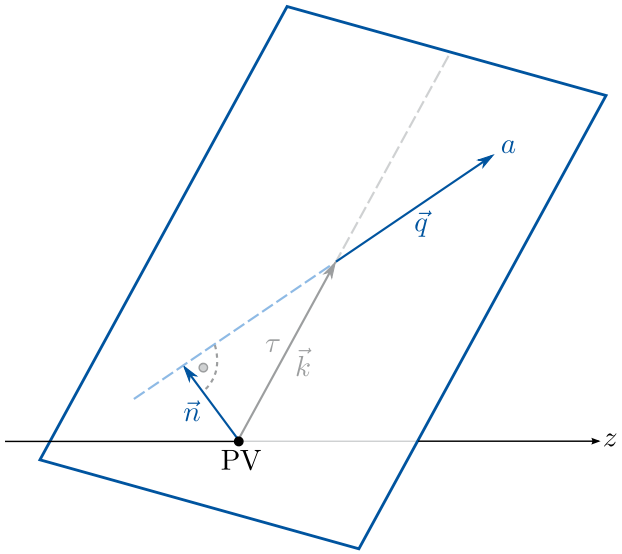
Thanks for your attention!

Backup slides

CMS detector



IP method

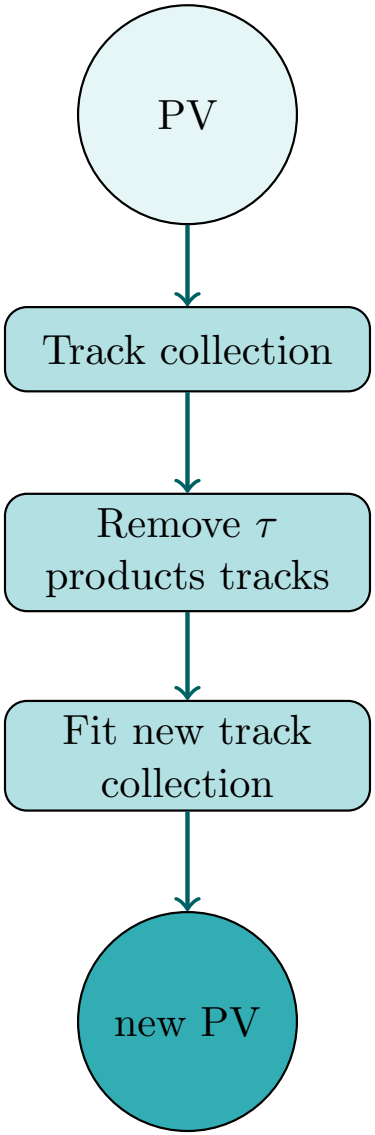


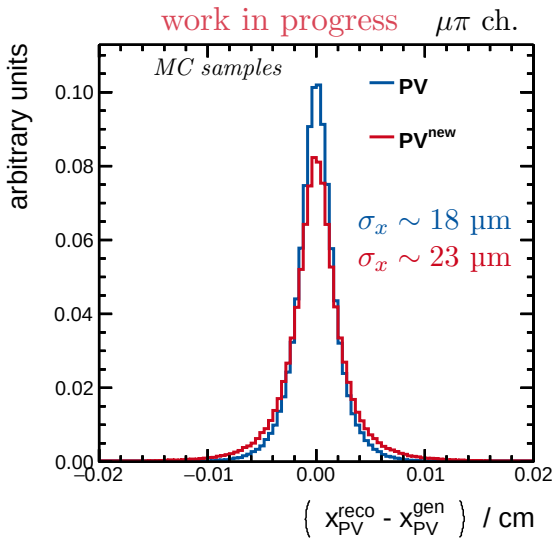
- Momenta and IP vectors of the τ daughters
- Boost into the ZMF of the τ daughters
- Reconstruction of φ^*_{CP}

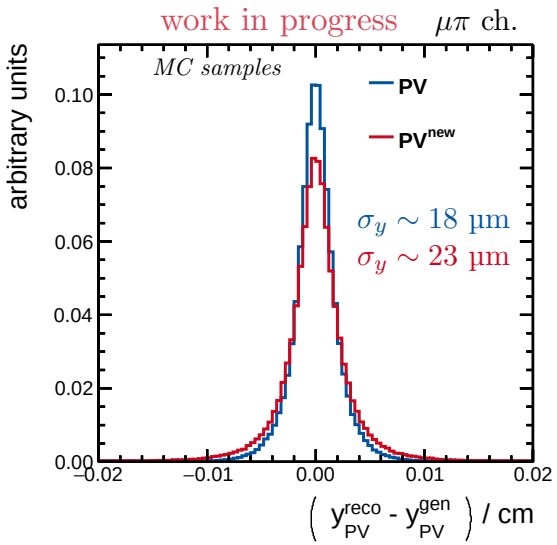
Crucial points for the analysis

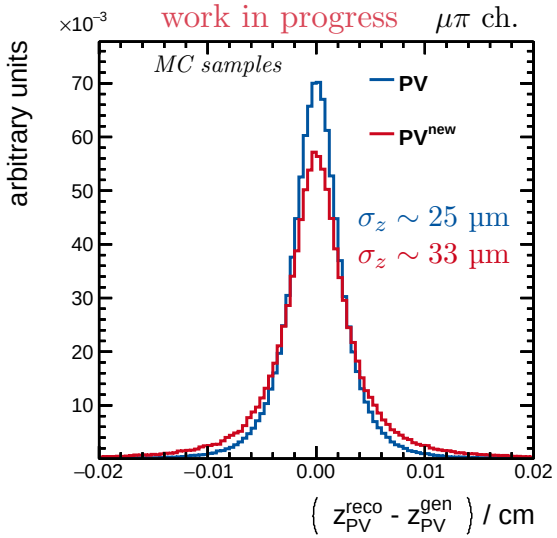
- Reconstruction of the primary vertex
- Reconstruction of the impact parameter vector

PV refitting





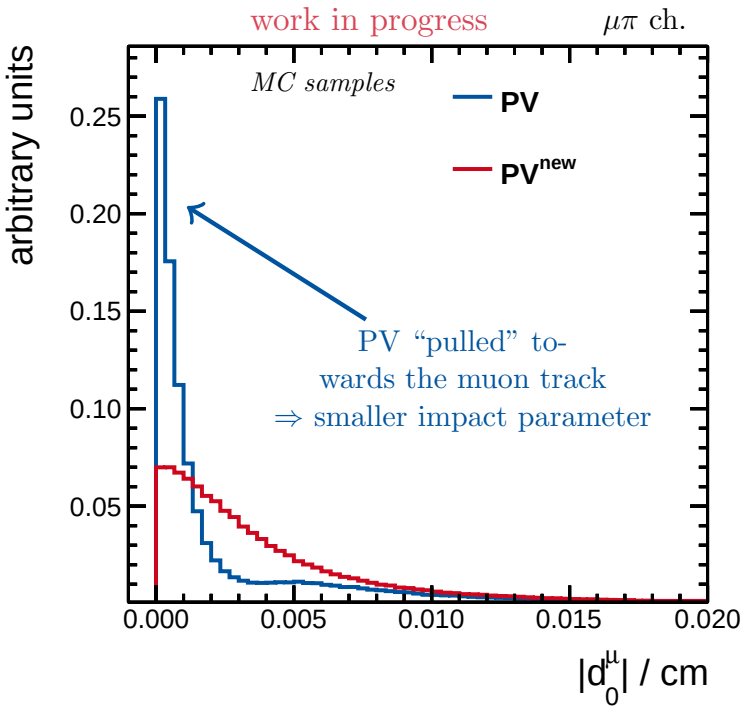




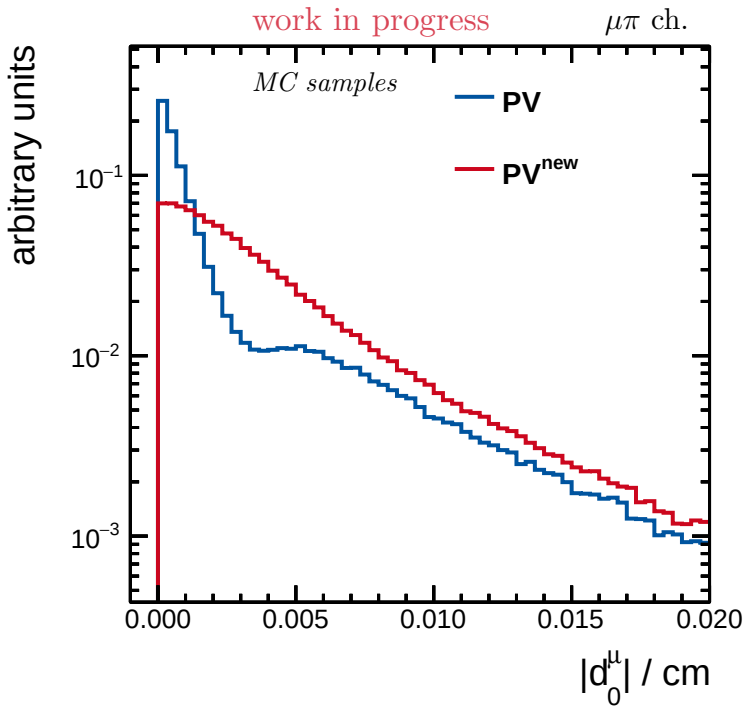
removed largest p_T tracks
$\Rightarrow$ worsening of resolution
(expected!)

Transverse impact parameter d_0

linear scale

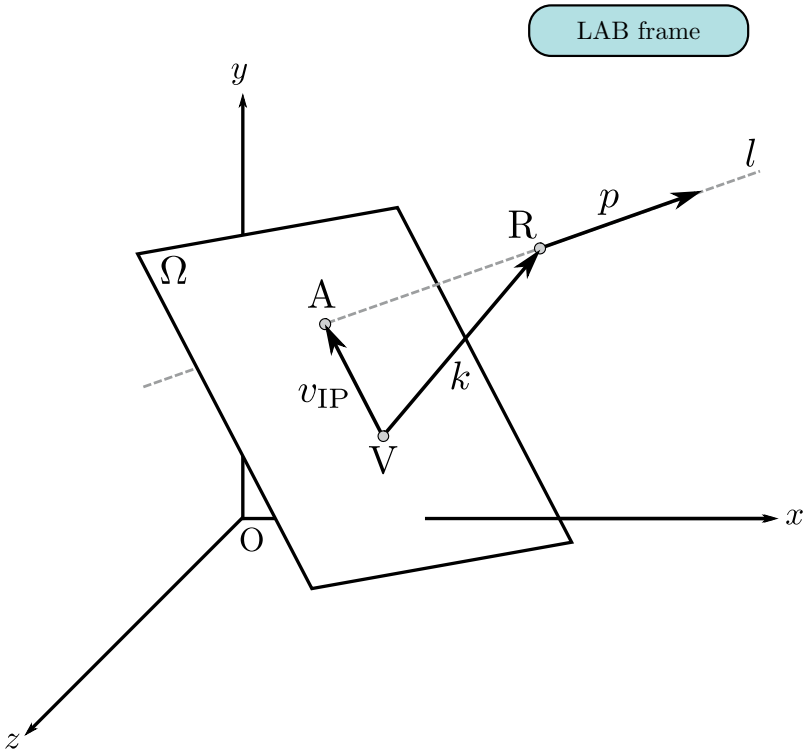


log scale



PV^{new} gives the right impact parameter distribution

Impact parameter vector reconstruction



$\vec{p}$ = momentum of the τ daughter

R = reference point of the track

V = reconstructed vertex

$\vec{k} = \vec{\mathrm{R}} - \vec{\mathrm{V}}$

$\vec{v}_{\mathrm{IP}} = \vec{\mathrm{A}} - \vec{\mathrm{V}}$

$\mathrm{A} = \ell \wedge \Omega$

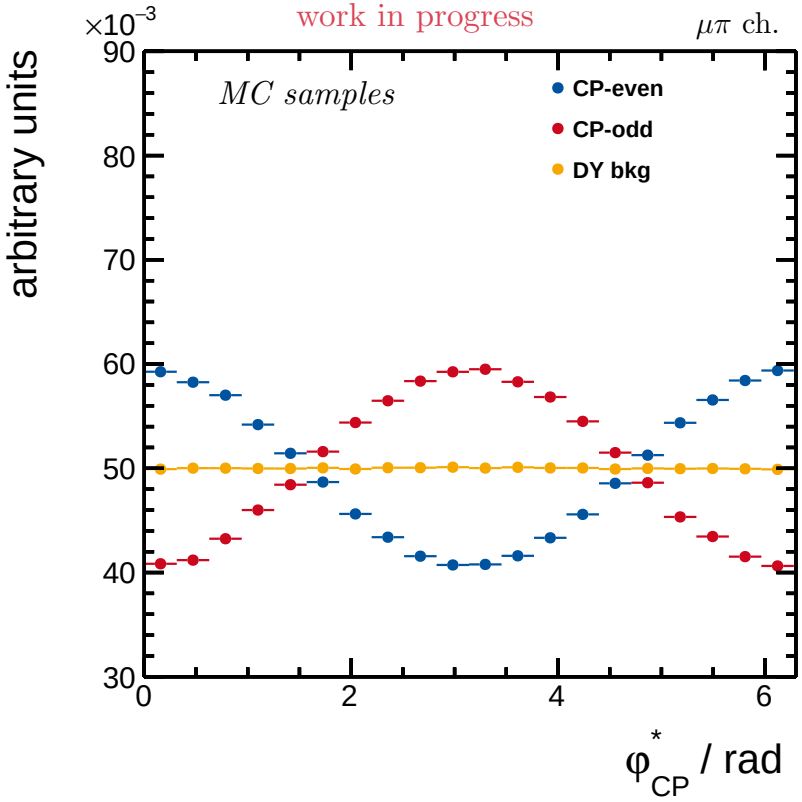
with $\ell : x \mapsto \vec{x} = \vec{\mathrm{R}} + a\,\vec{p}$

and $\Omega : x \mapsto \vec{p} \cdot \left(\vec{x} - \vec{\mathrm{V}}\right) = 0$

$$\Rightarrow \vec{v}_{\mathrm{IP}} = \vec{k} - \frac{\vec{k}\cdot\vec{p}}{|\vec{p}|^2}\vec{p}$$

IP method

generator level



reconstruction level