Determination of the CP parity of Higgs bosons in their tau decay channels at the LHC

Stefan Berge
Johannes Gutenberg-University Mainz

23. 9. 2013
Würzburg

PRiSMA

JG|U
JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Introduction

- LHC: At least one scalar boson, probably Spin-0, with $m_h = 126$ GeV
- If it is one boson: h^0, H^0 (CP-even), A^0 (CP-odd) or h_1 (CP-mixed) state
  - It is not a pure CP-odd state A^0 ($h \to ZZ$: CMS-PAS-HIG-13-002, ATLAS-CONF-2013-013; and 1211.1980)
  - No large anamolous $A^0 ZZ$ coupling (because of $h \to ZZ$)
- If there is more than one Higgs boson (2HDM), degenerated in mass
  - E.g. A^0 and H^0
  - E.g. h^0 and H^0 or several CPmix states
- $\to h \to \tau\tau$ ideal channel to measure CP

Higgs decay into tau lepton pairs

- Consider Lagrangian: $\mathcal{L}_Y = -\,N\,(\cos\phi\,\bar\tau\tau + \sin\phi\,\bar\tau i\gamma_5\tau)\,h$

Normalization

CP mixing angle

- Higgs decays via $h \to \bar\tau\tau$,
  where the $\bar\tau\tau$ pair has
  $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

- if $\tau\bar\tau$ is in $^1S_0$ state :
  $\to\ J^{PC} = 0^{-+}$
  $\to\ A^0$
  $\to \langle s_{\tau^-}\cdot s_{\tau^+}\rangle = -\dfrac{3}{4}$
  $\to \phi = \dfrac{\pi}{2}$

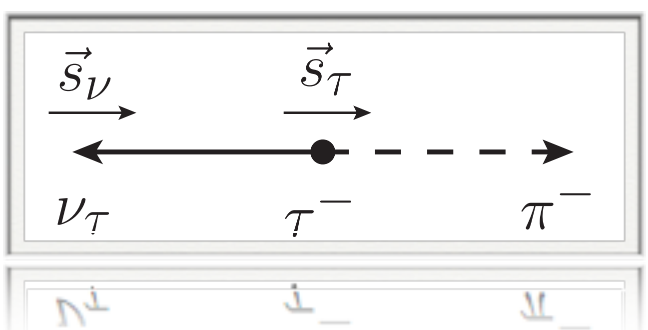
- if $\tau\bar\tau$ is in $^3P_0$ state :
  $\to\ J^{PC} = 0^{++}$
  $\to\ H^0, h^0$
  $\to \langle s_{\tau^-}\cdot s_{\tau^+}\rangle = \dfrac{1}{4}$
  $\to \phi = 0$

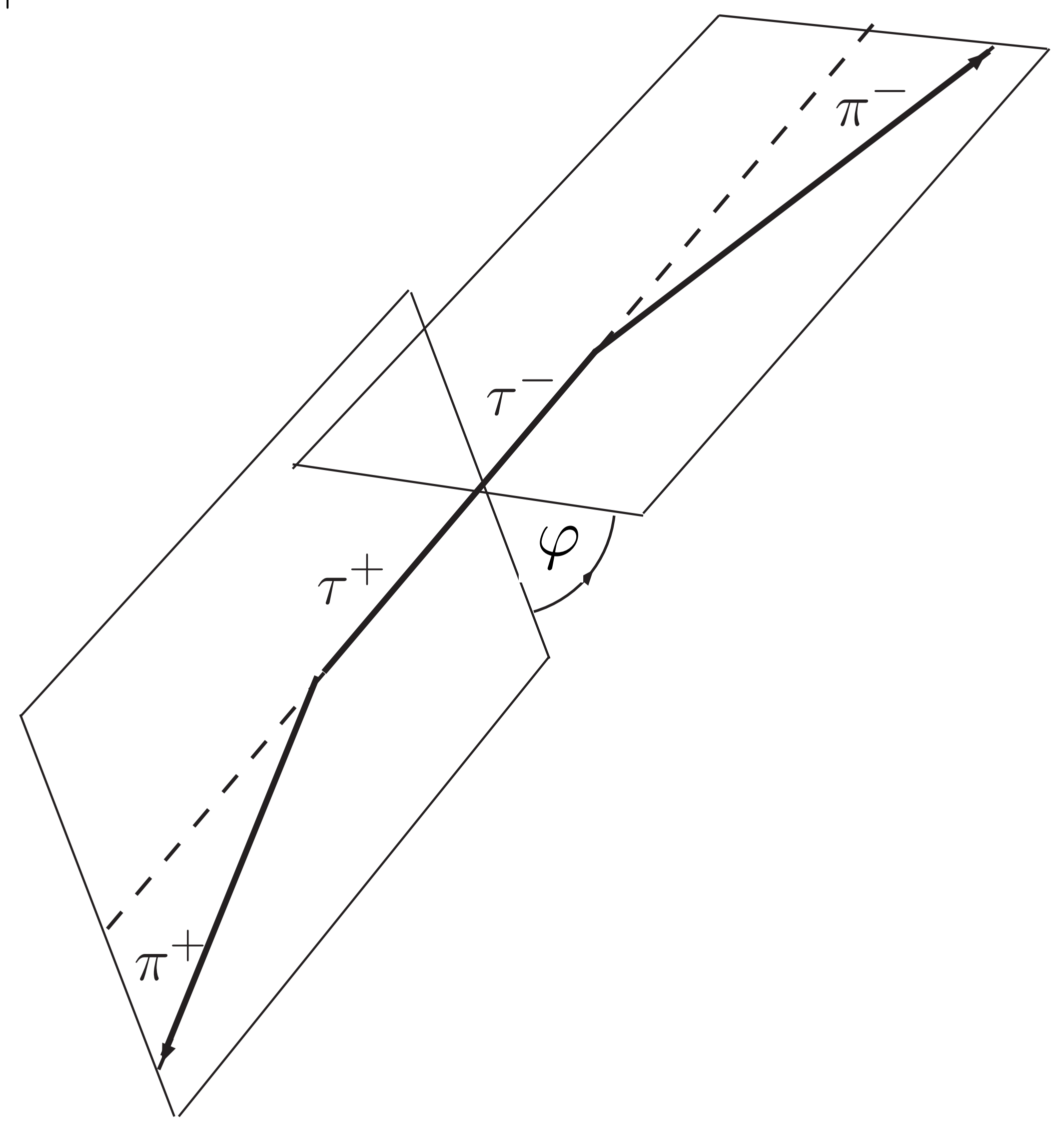
Higgs decay into tau lepton pairs

- Consider $\tau^- \to \pi^- + \nu_\tau$:
  Higgs decay probability can be written as *(Barger et al. '79)*

  $$\Gamma(H, A \to \tau^-\tau^+) \;\sim\; 1 - s_z^{\tau^-} s_z^{\tau^+} \pm s_T^{\tau^-} s_T^{\tau^+}$$

- Pion is preferably emitted
  in the direction of the
  tau-Spin in the tau rest frame





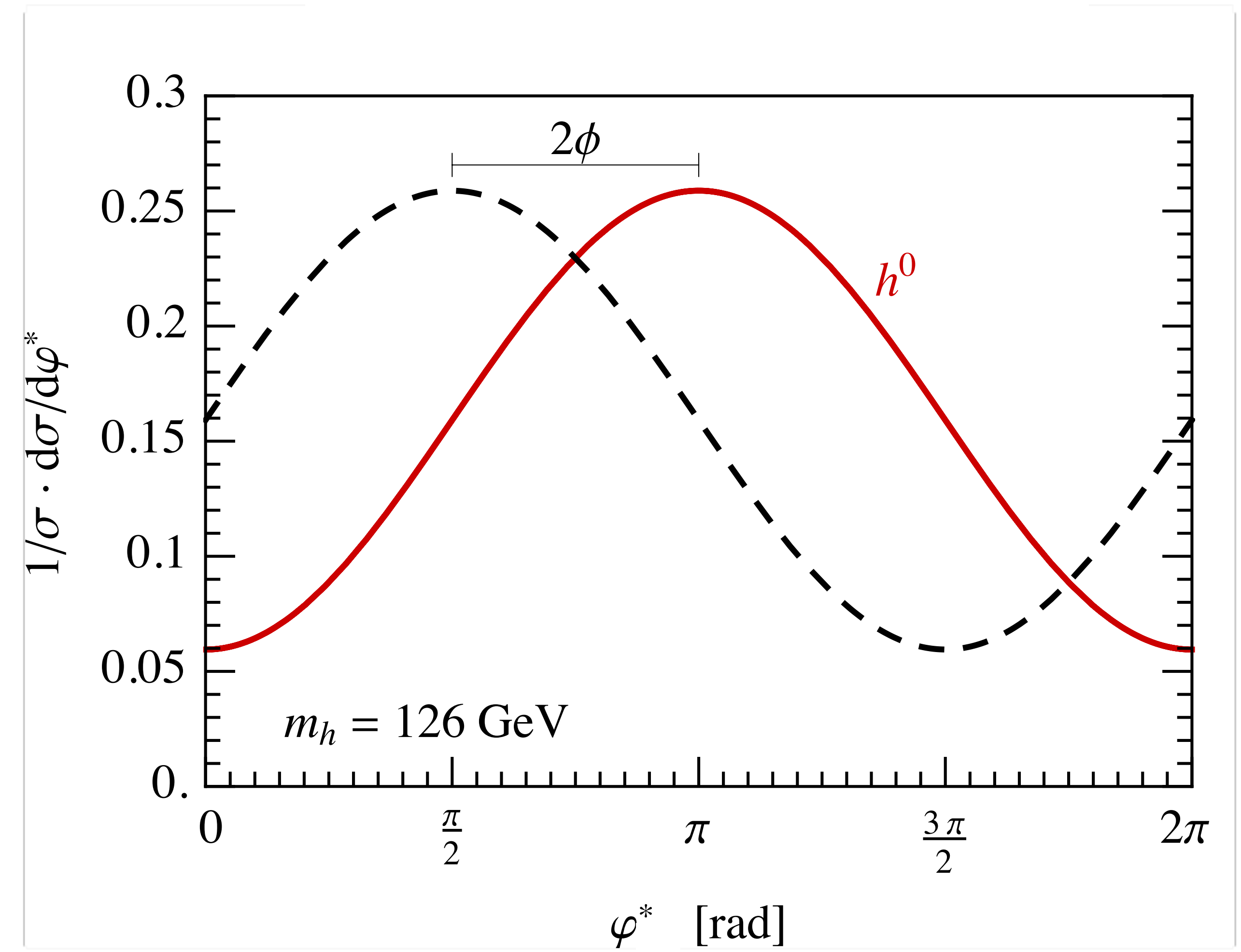
- φ is sensitive to
  $\tau\tau$ spin correlation

Higgs decay into tau lepton pairs

- $$\frac{1}{\Gamma}\frac{d\Gamma(h\to\pi^+\pi^-+2\nu)}{d\varphi^*} = \frac{1}{2\pi}\left[1-\frac{\pi^2}{16}\cos(\varphi^*-2\phi)\right]$$

- $\varphi^* = \varphi^+ - \varphi^-$

  with $\varphi^\pm$ the azimuthal angles of the $\pi^\pm$ defined in their respective $\tau^\pm$ rest frames



- Define Asymmetry for h^0:

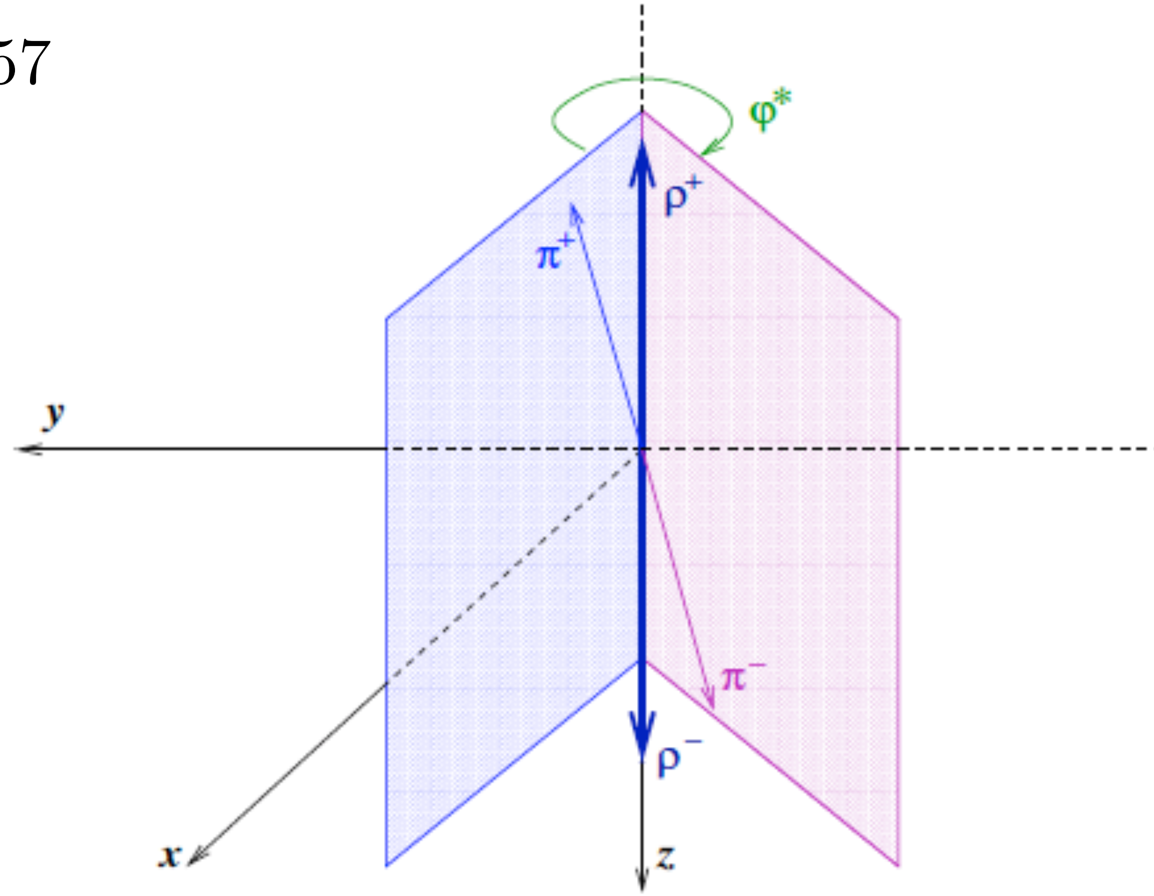
  $$A^{h^0} = \frac{\sigma(\cos\varphi^* < 0) - \sigma(\cos\varphi^* > 0)}{\sigma}$$

  E.g. $A(h^0\to\pi^+\pi^-+2\nu) = 40\%$

Higgs decay into tau lepton pairs

- Desch, Was, Worek, Phys.Lett. B579 (2004) 157
- $h \to \tau\tau \to \rho^+\rho^- + 2\nu$ decay channel
- Reconstruction of ρ-momenta necessary (separation of π^+ and π^0)
- Boost into the $\rho^+\rho^-$ rest frame
- In this frame measure the angle between the planes of the $\rho^+\pi^+$ and the plane of $\rho^-\pi^-$
- Respect the sign of $\pi^- \cdot (\pi^+ \times \rho^+$
- Separate events with $y_1 y_2 > 0$ and $y_1 y_2 < 0$

$$y_1 = \frac{E_{\pi^+} - E_{\pi^0}}{E_{\pi^+} + E_{\pi^0}}, \qquad y_2 = \frac{E_{\pi^-} - E_{\pi^0}}{E_{\pi^-} + E_{\pi^0}}$$



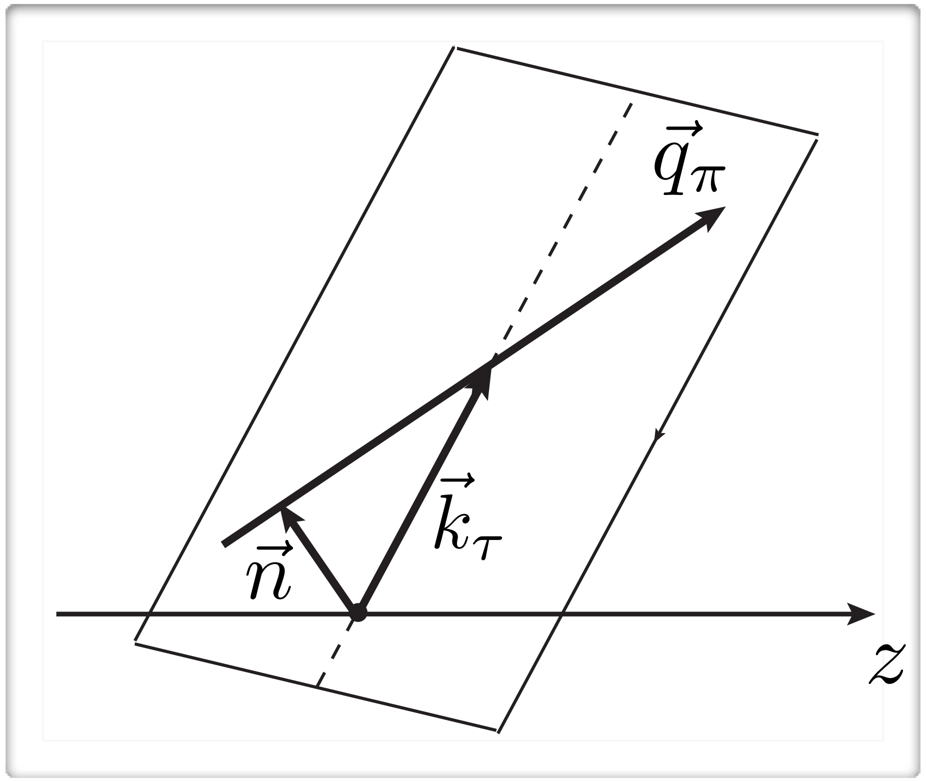
(taken from 0307331)

- Primulando et al., arXiv:1308.1094
- Improved observable for $h \to \tau\tau \to \rho^+\rho^- + 2\nu$ if neutrino moment a known (ILC)
- Use collinear approximation $\to$ reduces to φ^* of Worek et al.

Our method:

(Phys.Lett. B671 (2009) 470-476 [arXiv: 0812.1910])

- No reconstruction of τ rest frames
- Use impact parameter vectors $\hat{n}_-$, $\hat{n}_+$
  $\varphi \sim acos(\hat{n}_- \cdot \hat{n}_+)$
- Boost $\hat{n}_\pm$ into $\pi^-\pi^+$-ZMF (denoted by $*$)
  $(n^\mu n_\mu = -1)$:
- $\varphi^* = \mathrm{acos}(\hat{n}^*_{-\perp} \cdot \hat{n}^*_{+\perp})$
- Measurement of primary vertex (PV) necessary
  (additional tracks/underlying event)



$m_h = 126$ GeV

$\rightarrow \ \gamma \approx 35$

$< ct >_\tau \cdot\gamma \approx 3$ mm

$n_\perp^{max} \approx 43\ \mu$m

Definition of observables

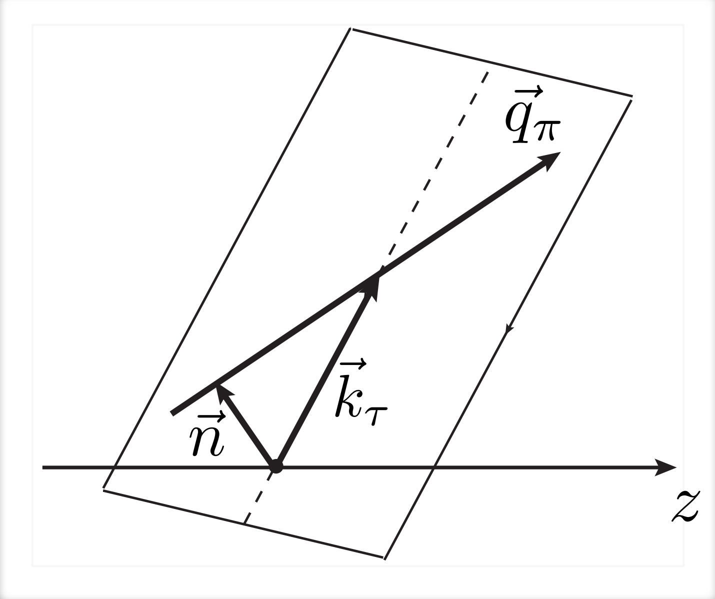
$$\mathcal{O}_3 = s_{\tau^-} \cdot s_{\tau^+}$$

$$\varphi^* = \mathrm{acos}(\hat{n}^*_{-\perp} \cdot \hat{n}^*_{+\perp})$$

$$\mathcal{O}_2 = \hat{k}_{\tau^-} \cdot (s_{\tau^-} \times s_{\tau^+})$$

$$\mathcal{O}_2^* = \hat{q}^*_{\pi^-} \cdot (\hat{n}^*_{-\perp} \times \hat{n}^*_{+\perp}) = \sin\varphi^*_{CP}$$

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

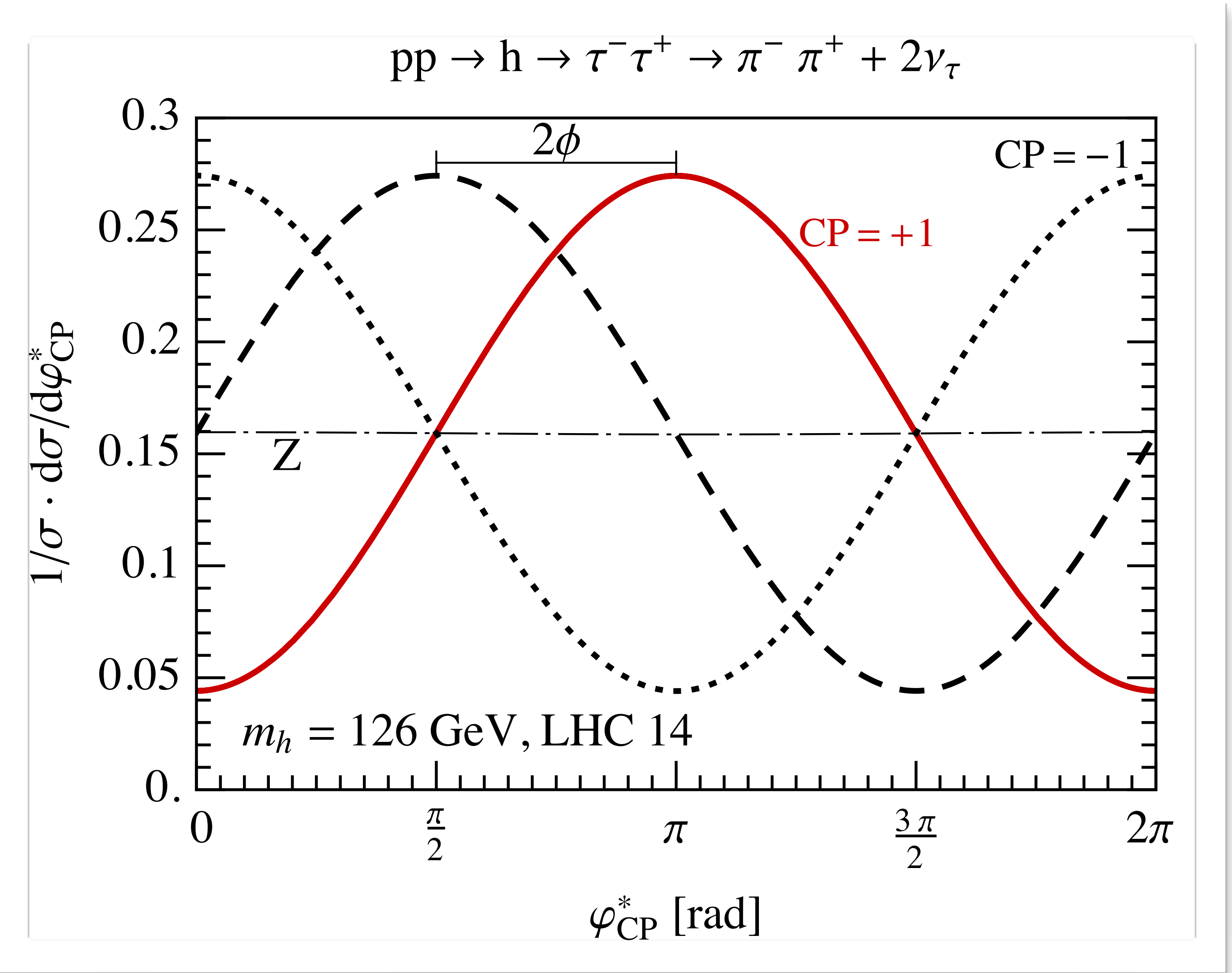


Differential distribution

- $$\frac{1}{\Gamma}\frac{d\Gamma(h\to\pi^+\pi^-+2\nu)}{d\varphi^*_{CP}} = \frac{1}{2\pi}\left[1-\frac{\pi^2}{16}\cos(\varphi^*_{CP}-2\phi)\right]$$

- $Z\to\tau\tau$ background (dot-dashed line) has a flat distribution

- h^0+A^0 has flat distribution if $\sigma_{h^0}=\sigma_{A^0}$

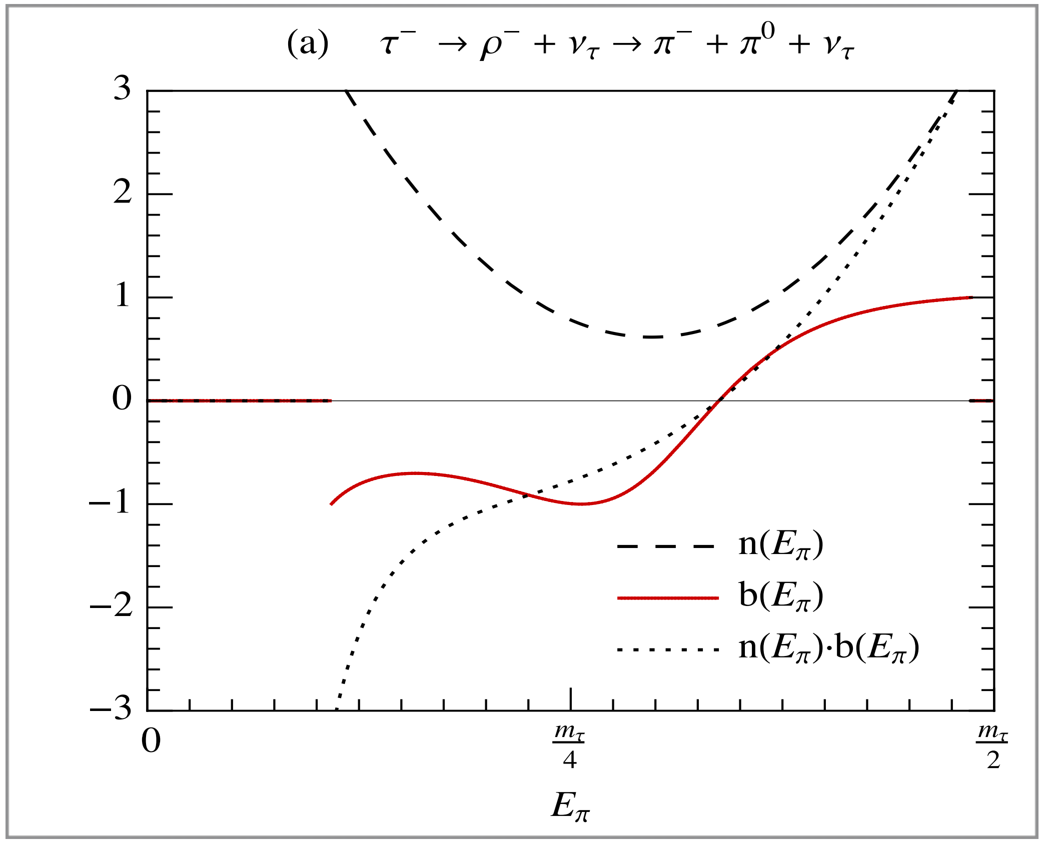


Usable tau decay modes

- Differential decay width: $\frac{d\Gamma(\tau(k,s)\to i(q)+X)}{\Gamma/(4\pi)\ dE_i d\Omega_i} = n(E_i)\left(1 + b(E_i)\ \hat{s}\cdot\hat{q}\right)$

- Branching ratios:

decay mode	BR_{PDG} [%]
$\tau^- \to \pi^-$	11
$\tau^- \to \rho^- \to \pi^-\pi^0$	25.5
$\tau^- \to a_1^- \to \pi^- 2\pi^0$	9.3
$\tau^- \to a_1^- \to \pi^-\pi^+\pi^-$	9
$\tau^- \to e^-, \mu^-$	35.2



- Energy variable in 3-body decay modes: $\tau^\pm \to l^\pm + X$ and $\tau^\pm \to \rho^\pm / a_1^\pm + X \to \pi^\pm + X$

- $b(E)$ determines spin analyzer quality

- $n(E)$ determines relativ contribution to σ

Differential distribution

- Differential cross section:

$$d\sigma \sim \; d\Omega_\tau \; dE_{a^-} \; dE_{a'^+} d\varphi^*_{CP} \boxed{\left[v + u \cdot \cos\left(\varphi^*_{CP} - 2\phi\right)\right]}$$

$$u = -n\left(E_{a^-}\right) b\left(E_{a^-}\right) n\left(E_{a'^+}\right) b\left(E_{a'^+}\right) \frac{\pi^2 p_h^2}{8} \frac{g_\tau^2}{\sqrt{2} G_F m_\tau^2}$$

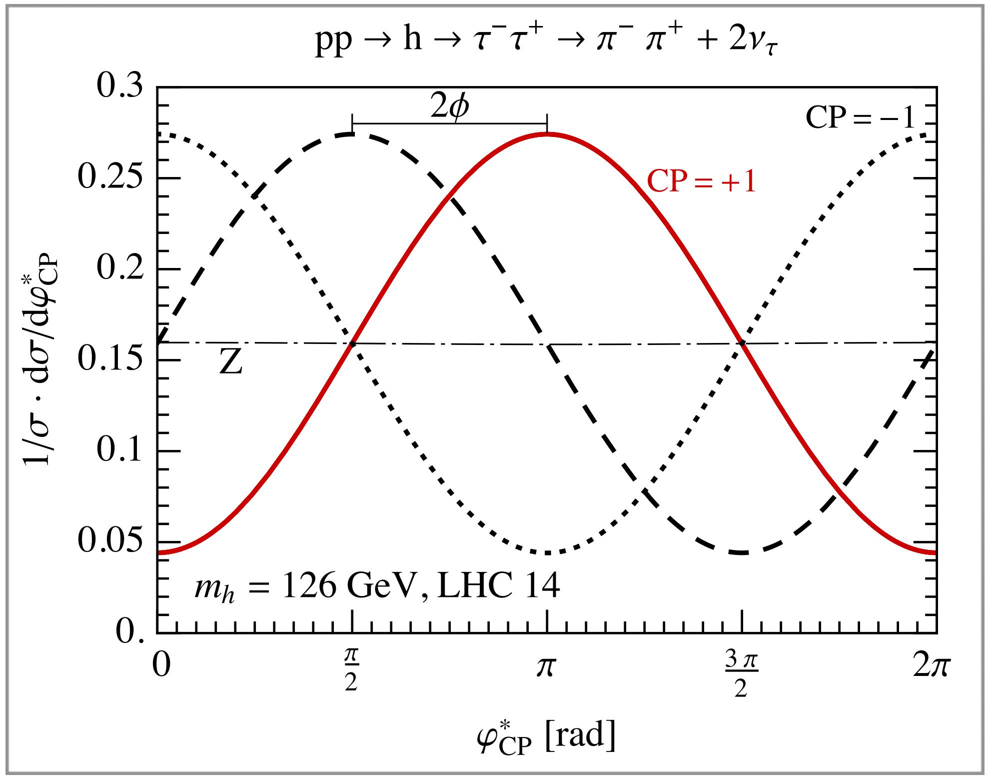
$$v = 4n\left(E_{a^-}\right) n\left(E_{a'^+}\right) \; N$$

- Asymmetry, characterizing expected precision:

$$\boxed{A \; = \; \frac{-\,4u}{2\pi v}}$$

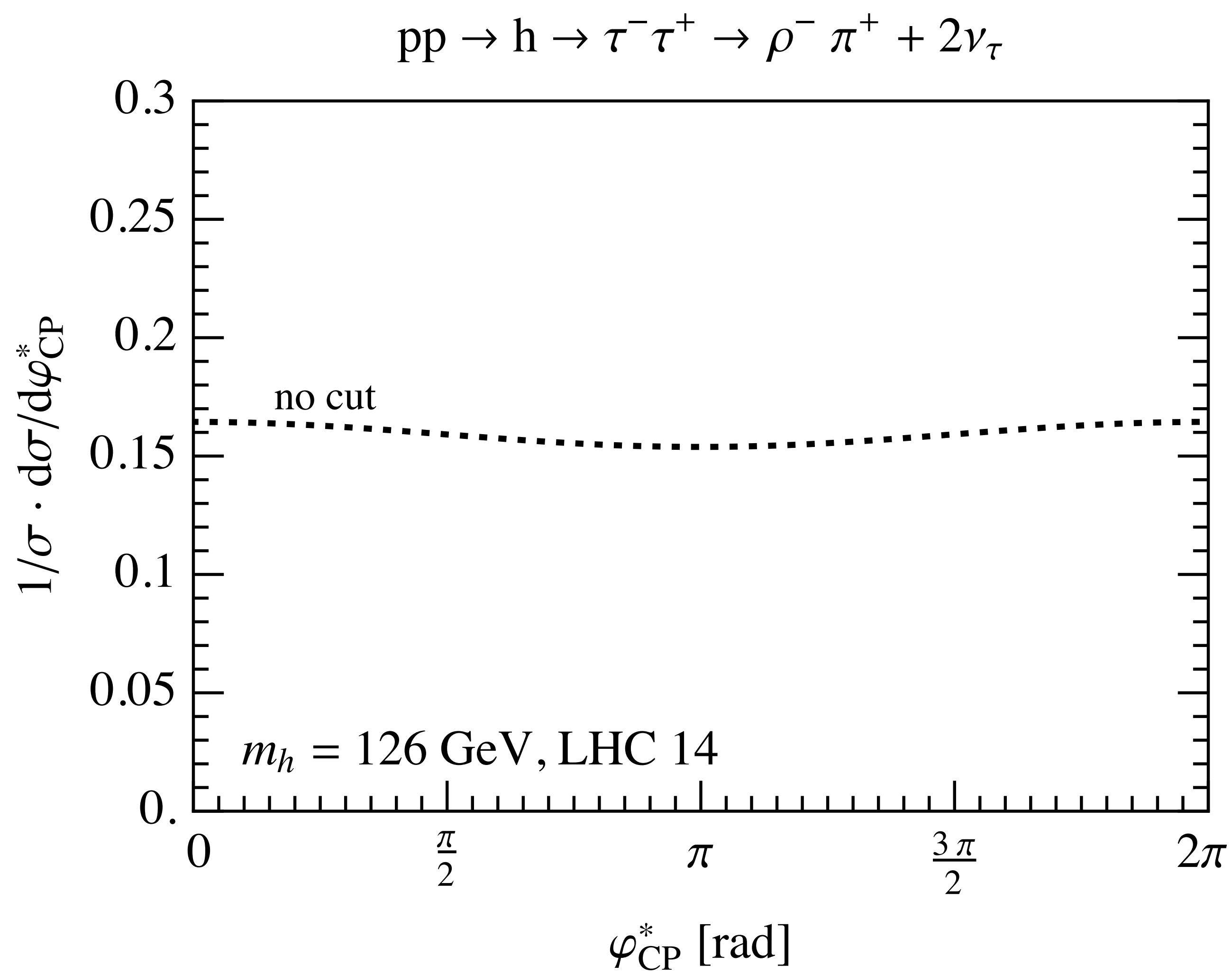
$\rightarrow$ Large spin analyzer functions $b(E)$ generate large asymmetries.

$\rightarrow$ Need to separate $b(E) > 0$ and $b(E) < 0$ contributions.



Example: $h \to \tau\bar{\tau} \to \rho^- + \pi^+ + 2\nu$

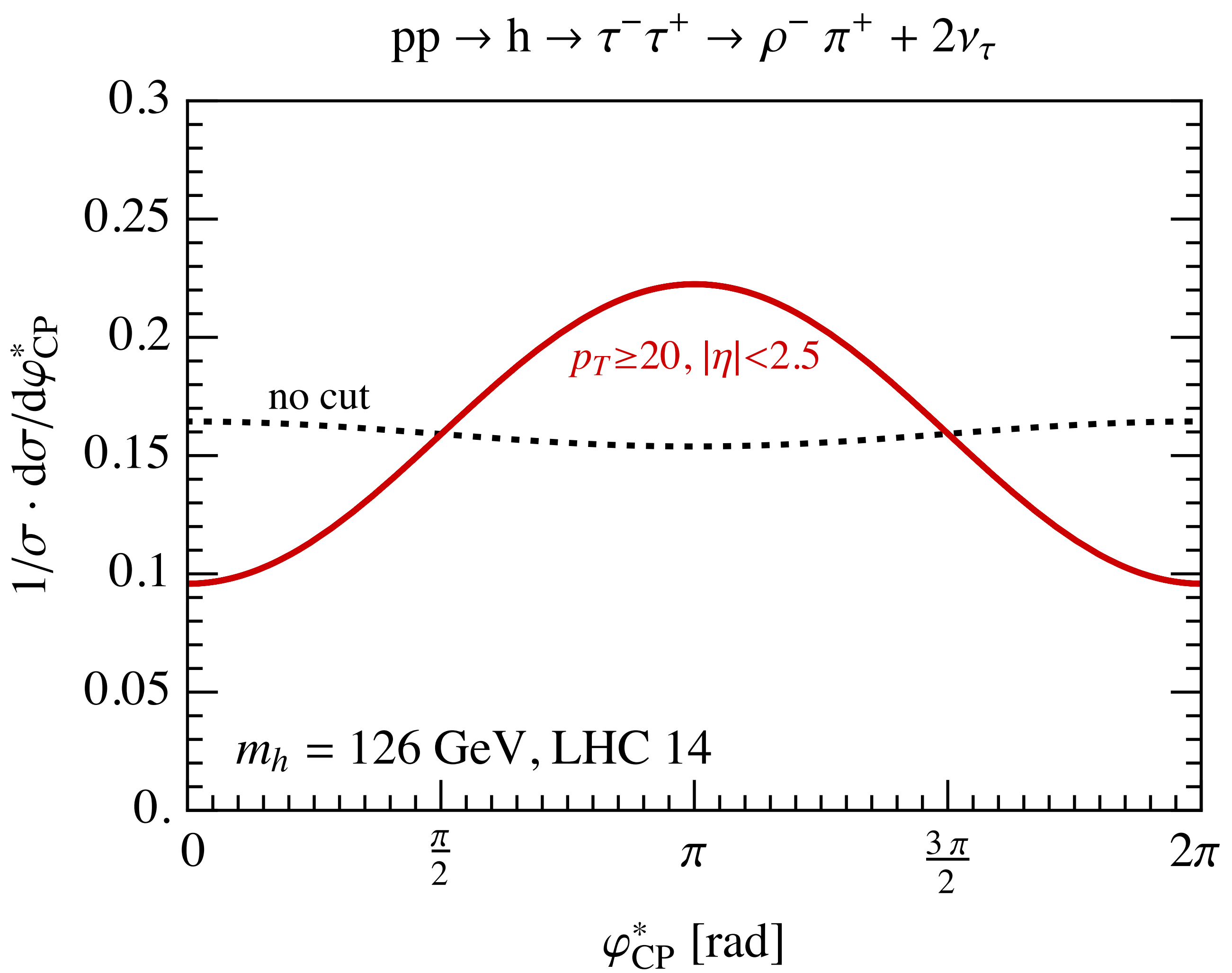
- LHC for $m_h = 126$ GeV
  assuming $gg \to h$ at LO



$A(\text{no cut}) = -2\%$

Example: $h \to \tau\bar{\tau} \to \rho^- + \pi^+ + 2\nu$

- LHC for $m_h = 126$ GeV assuming $gg \to h$ at LO
- $p_T^\pi \geq 20$ GeV cut selects π with large energy in the τ rest frame

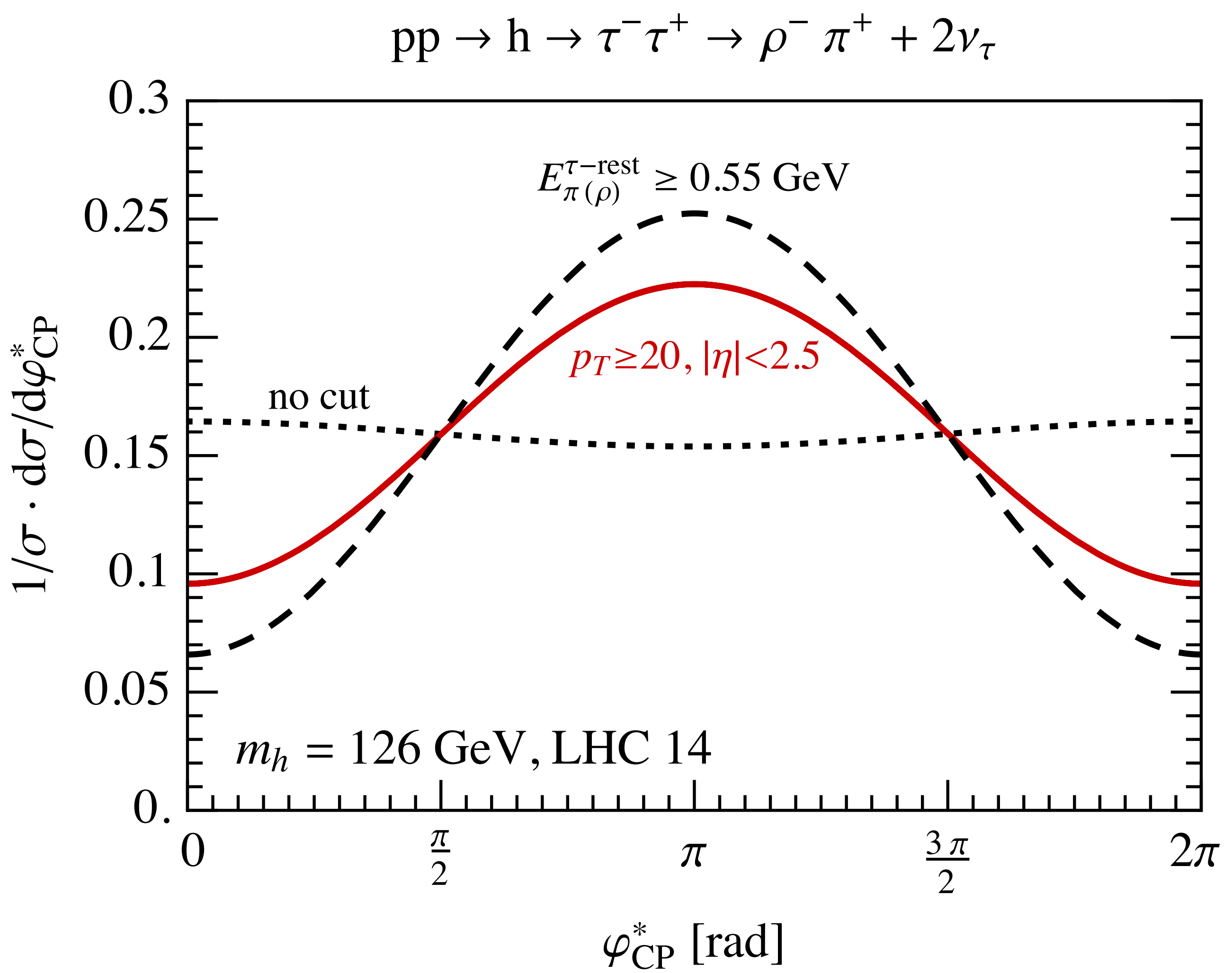


$$A(\text{no cut}) = -2\%$$

$$A(p_T \geq 20\text{GeV}) = 25\%$$

Example: $h \to \tau\bar{\tau} \to \rho^- + \pi^+ + 2\nu$

- LHC for $m_h = 126$ GeV assuming $gg \to h$ at LO
- $p_T^\pi \geq 20$ GeV cut selects π with large energy in the τ rest frame
- Theoretical cut $E_{\pi(\rho)}^{\tau-restframe} \geq 0.55$ GeV selects events with $b(E_{\pi(\rho)}^{\tau-restframe}) > 0$



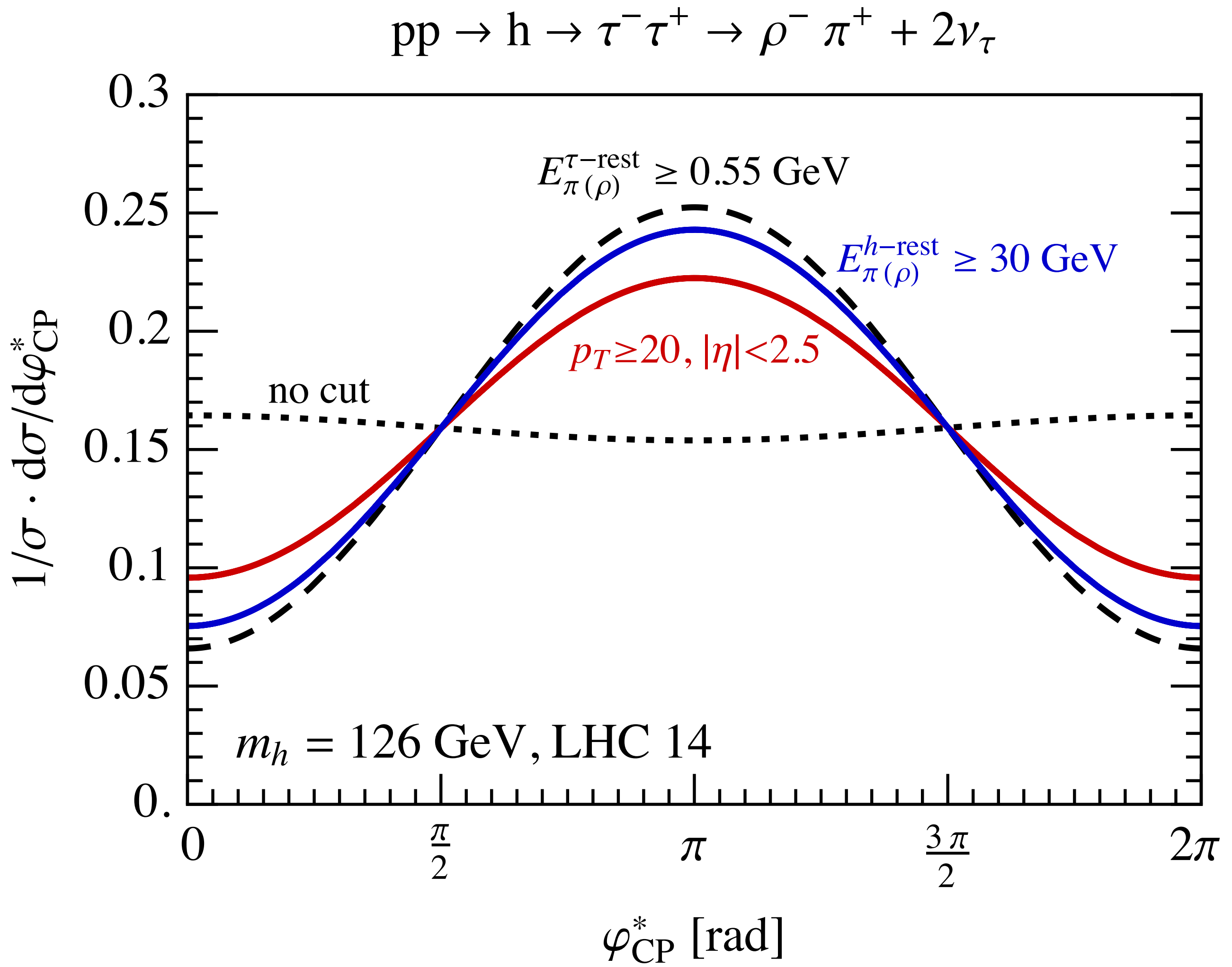
$$A(\text{no cut}) = -2\%$$

$$A(p_T \geq 20\text{GeV}) = 25\%$$

$$A(E_{\pi(\rho)}^{\tau-restframe} \geq 0.55\,\text{GeV}) = 37\%$$

Example: $h \to \tau\bar{\tau} \to \rho^- + \pi^+ + 2\nu$

- LHC for $m_h = 126$ GeV assuming $gg \to h$ at LO
- $p_T^\pi \geq 20$ GeV cut selects π with large energy in the τ rest frame
- Theoretical cut $E_{\pi(\rho)}^{\tau-restframe} \geq 0.55$ GeV selects events with $b(E_{\pi(\rho)}^{\tau-restframe}) > 0$
- Minimum cut on $E_{\pi(\rho)}^{Higgs-restframe}$ in reconstructed Higgs rest frame (collinear approximation) selects events with $b(E_{\pi(\rho)}^{\tau-restframe}) > 0$



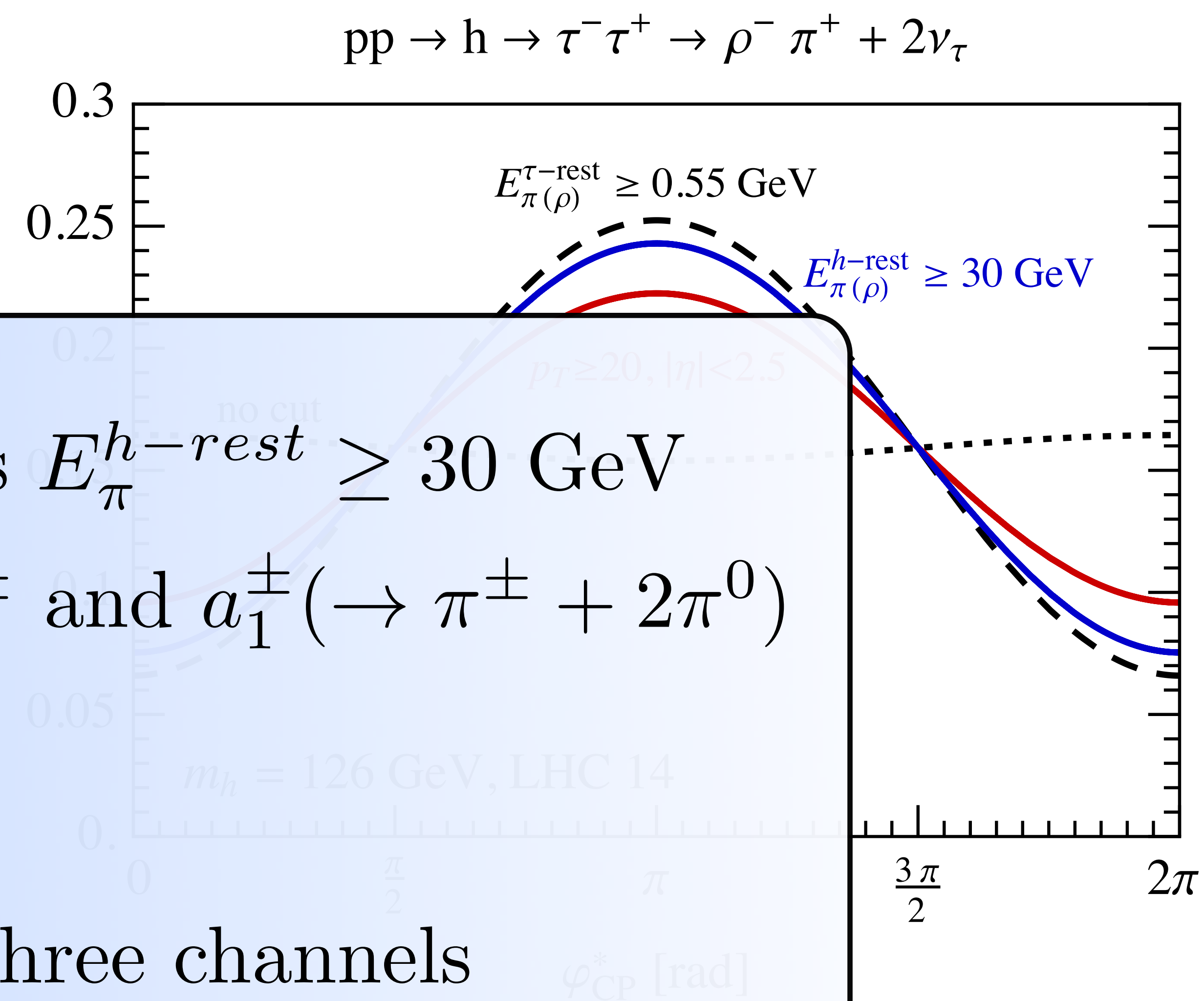
$$A(\text{no cut}) = -2\%$$

$$A(p_T \geq 20\text{GeV}) = 25\%$$

$$A(E_{\pi(\rho)}^{\tau-restframe} \geq 0.55\,\text{GeV}) = 37\%$$

$$A(E_{\pi(\rho)}^{h^0-restframe} \geq 30\,\text{GeV}) = 34\%$$

Example: $h \to \tau\bar{\tau} \to \rho^- + \pi^+ + 2\nu$



- LHC for $m_h = 126$ GeV assuming $gg \to h$ at LO
- $p_T^\pi \geq 20$ GeV cut selects π with large ... τ rest frame
- Theoretical cut $E_{\pi(\rho)}^{\tau-restframe} \geq 0.55$ GeV selects events with $b(E_{\pi(\rho)}^{\tau-restframe}) > 0$
- Minimum cut on $E_{\pi(\rho)}^{Higgs-restframe}$ in reconstructed Higgs rest frame (collinear approximation) selects events with $b(E_{\pi(\rho)}^{\tau-restframe}) > 0$

Notice: If one demands $E_\pi^{h-rest} \geq 30$ GeV no separation of $\pi^\pm, \rho^\pm$ and $a_1^\pm (\to \pi^\pm + 2\pi^0)$ necessary, because

$b(E_{\pi^\pm}^{\tau-rest}) > 0$ for all three channels

$$A(\text{no cut}) = -2\%$$
$$A(p_T \geq 20\text{GeV}) = 25\%$$
$$A(E_{\pi(\rho)}^{\tau-restframe} \geq 0.55\,\text{GeV}) = 37\%$$
$$A(E_{\pi(\rho)}^{h^0-restframe} \geq 30\,\text{GeV}) = 34\%$$

Asymmetry and Precision

- Example: 400 Events

  $A = 20\%$

  20 bins

  $\phi = -\pi/8$

- Fit distribution:

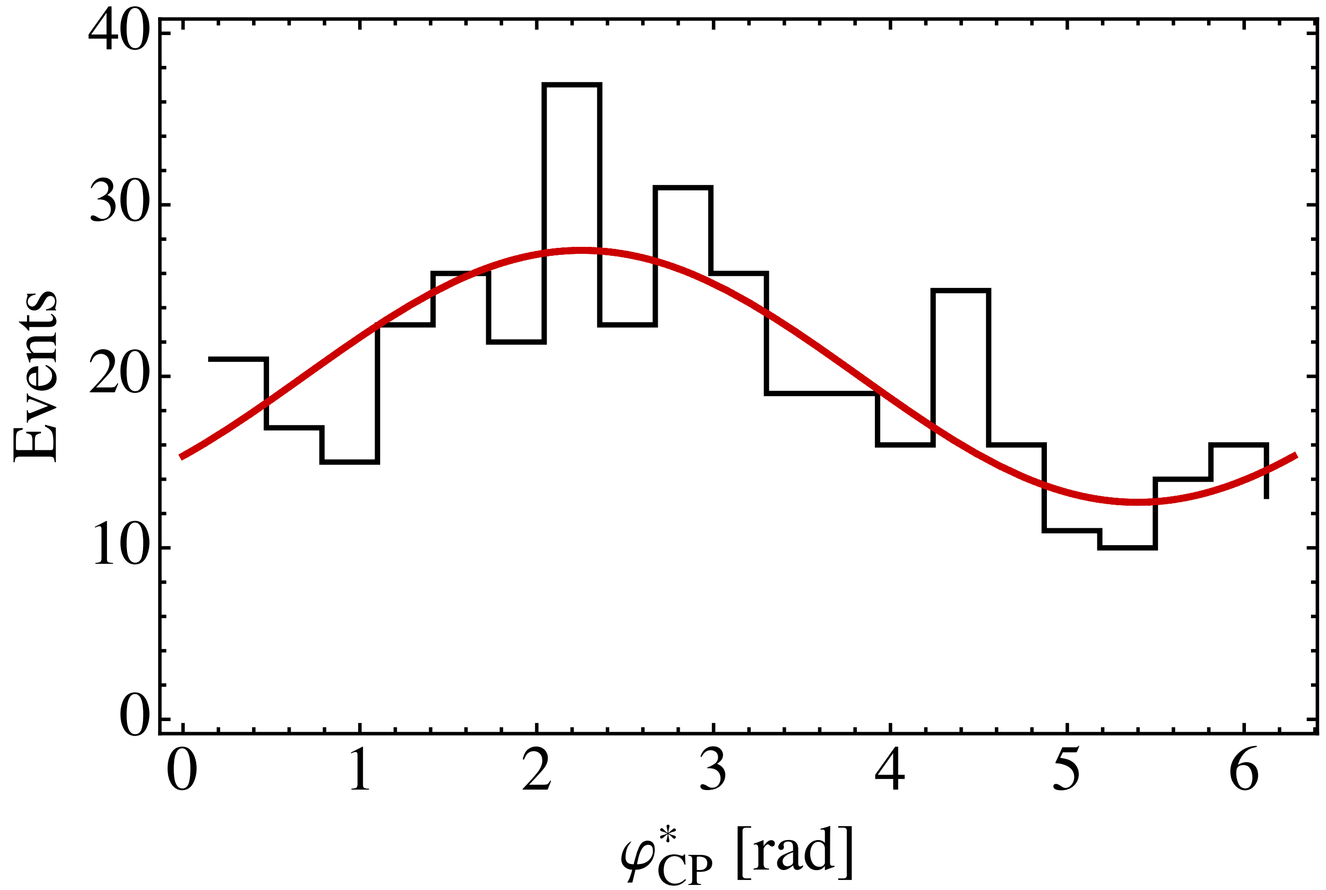
  $u \cdot \cos(\varphi^*_{CP} - 2\phi) + v$

- Expected Precision on ϕ:

  $A = 10\% \quad \rightarrow \quad \Delta\phi = 15.5^\circ$

  $A = 15\% \quad \rightarrow \quad \Delta\phi = 9.0^\circ$

  $A = 20\% \quad \rightarrow \quad \Delta\phi = 6.6^\circ$



- $h\tau\tau$-coupling:

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

References

- LHC defining the impact parameter method: Phys.Lett. B671 (2009) 470-476 [arXiv: 0812.1910]
- LHC, all tau decay channels: Phys.Rev. D84 (2011) 116003 [arXiv: 1108.0670]
- Definition of the φ^*_{CP} distribution for LC: arXiv:1308.2674
- Definition of the φ^*_{CP} distribution for LHC: this talk

Concluding Remarks

- Determination of the CP quantum numbers of neutral, Spin-0 resonances is possible in the tau decay channel at the LHC, where all dominant tau-decay channels can be included
- Our method uses the impact paramter measurement of the charged τ decay products.
- An estimate of the precision on ϕ strongly depends on the expected precision of the impact parameter measurement and the expected background.