Determination of the Higgs CP mixing angle in the tau decay channels

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CP measurements at the LHC

- $h^0 \to ZZ^* \to 4l$ (Choi et al.'02, Buszello et al. '02, Godbole '07, Koval'chuk '08)
- $pp \to h^0 + 2$ jet (Plehn '01, Hankele, Klämke, Zeppenfeld '06 Dolan et al. 1406.3322)
- $pp \to h^0 t\bar{t}$ (Ellis, Hwang, Sakurai, Takeuchi, arXiv:1312.5736)
- $h^0 \to \gamma\gamma$ with converted photons (Bishara et al., arXiv:1312.2955)
- $h^0 \to \gamma Z$ (Korchin, Kovalchuk, arXiv:1303.0365)
- Model dependent parameter fits including EDM's: e.g. arXiv:1403.4775
- $h^0 \to \tau\bar{\tau}$ (Bernreuther et al. '97, S.B., W. Bernreuther '08, S.B., Bernreuther, Niepelt, Spiesberger '11 Harnik, Martin, Okui, Primulando, Yu, arXiv:1308.1094)

Measuring the Higgs CP mixing angle in the tau decay channel

Higgs decay into tau lepton pairs

Advantage of $h \to \tau\tau$ decay channel:

- Large branching fraction
- Radiative corrections of $h \to \tau\tau$ are small ($\leq 1\%$, 9701347)
- Couples to CP even as well as CP-odd Higgs components at leading order $\to$ direct test of Higgs CP nature
- Degenerated states of scalar and pseudo-scalar bosons can be distinguished from a single CP-mix state

Disadvantage of $h \to \tau\tau$ decay channel:

- Large background from $Z \to \tau\tau$ (and QCD)

Higgs decay into tau lepton pairs

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

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 :
  $\to\ J^{PC} = 0^{-+}$
  $\to\ A^0$
  $\to \langle s_{\tau^-}\cdot s_{\tau^+}\rangle = -\frac{3}{4}$
  $\to \phi_h = \frac{\pi}{2}$

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

Higgs decay into tau lepton pairs

- Higgs decay probability ($\beta_\tau = 1$):

$$\Gamma_{h\to\tau^-\tau^+} \;\sim\; 1 - \vec{s}_z^{\,-}\vec{s}_z^{\,+} + \cos(2\phi_h)(\vec{s}_T^{\,-}\vec{s}_T^{\,+}) - \sin(2\phi_h)[\,(\vec{s}_T^{\,-}\times\vec{s}_T^{\,+})\cdot\hat{k}^{\tau^-}]$$

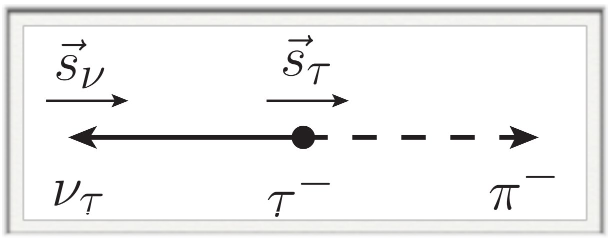
CP even   CP odd

- $\vec{s}^{\,\pm}_{z,T}$ - longitudinal, transverse vectors of $\tau^\pm$ spin in its rest frame with respect to $\hat{k}^{\tau^-} = \hat{e}_z$
- Higgs CP information encoded in the transverse component

Higgs decay into tau lepton pairs

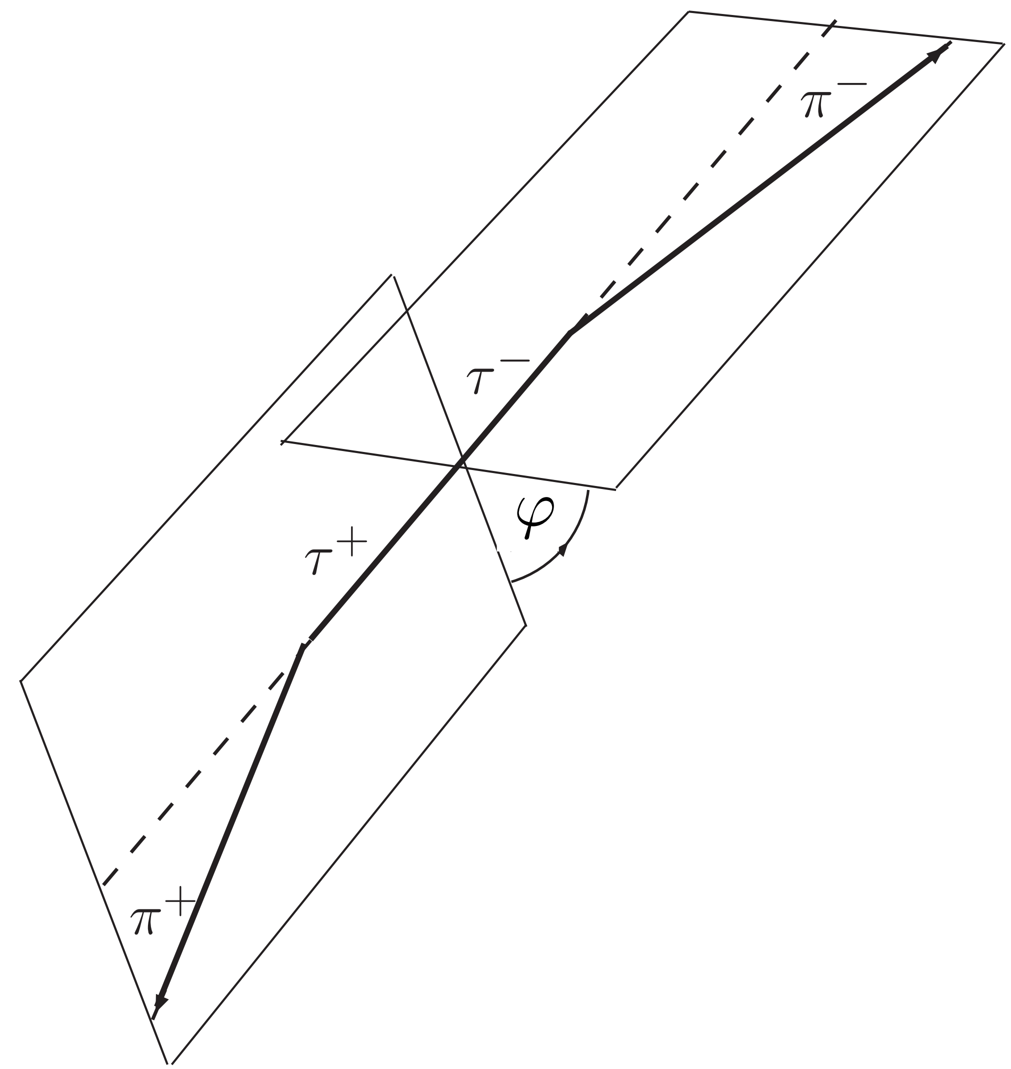
- The maximum asymmetry is obtained for $\tau^- \to \pi^- + \nu_\tau$:

  π^- is emitted in the direction of the τ^--Spin in the τ^- rest frame (spin analyzer quality of 1)

  (π^+ in opposite direction of τ^+ spin in τ^+ rest frame

  $\to$ reason for the additional minus sign above



- $$\frac{1}{\Gamma}\frac{d\Gamma(h \to \pi^+\pi^- + 2\nu)}{d\varphi_{CP}} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\cos(\varphi_{CP} - 2\phi_h)\right]$$ (Dell'Aquila, Nelson, 1989)

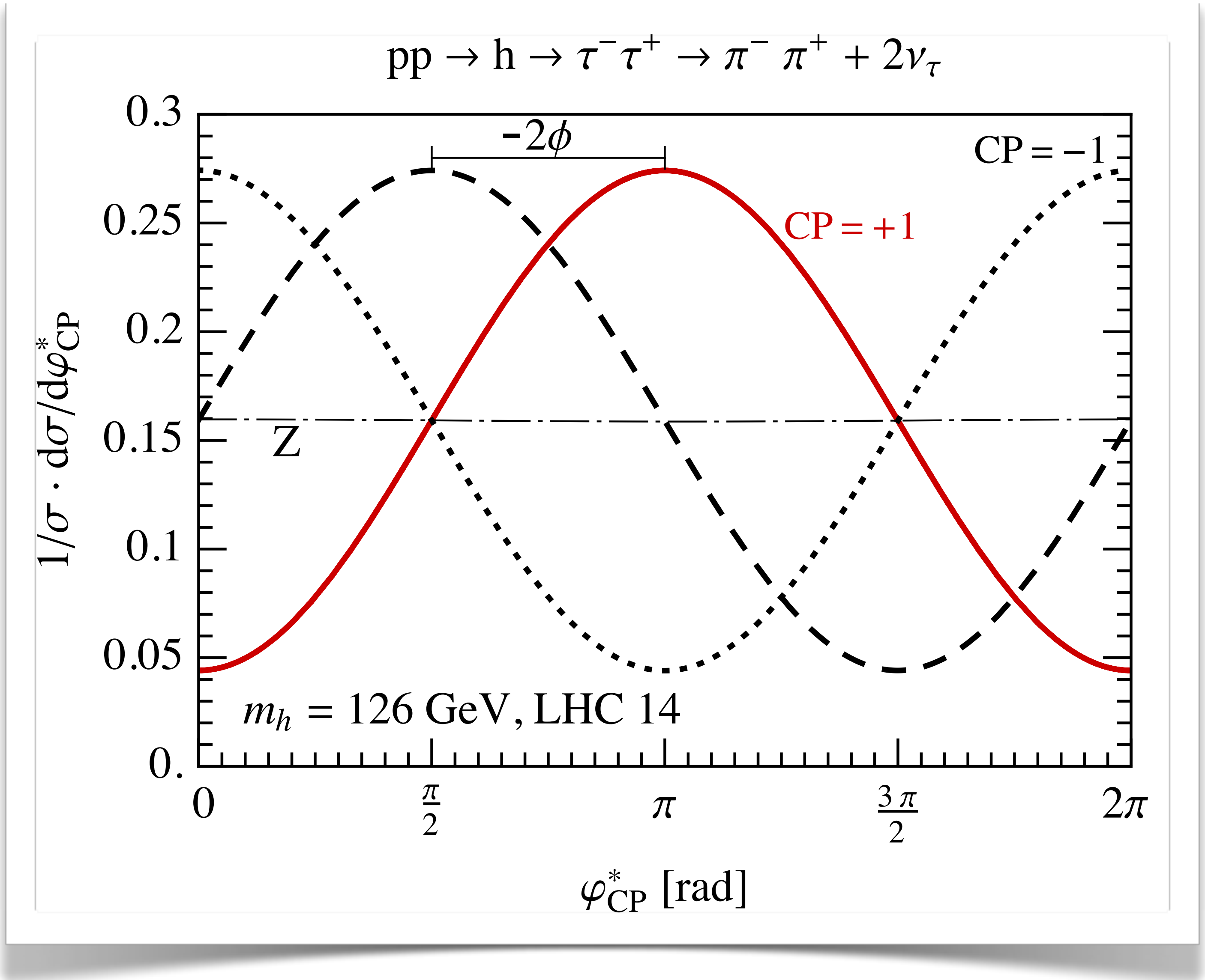
  φ_{CP} is defined in the interval $0 \leq \varphi_{CP} \leq 2\pi$

CP measurement using the tau impact parameter

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

- $2\phi_h$ can be determined from the shift of the fitted φ_{CP} distribution with respect to the red curve for which $\phi_h = 0$.

- Precision on ϕ_h depends on the number of events and the size of the amplitude



CP measurement using the tau impact parameter

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- Define Asymmetry:

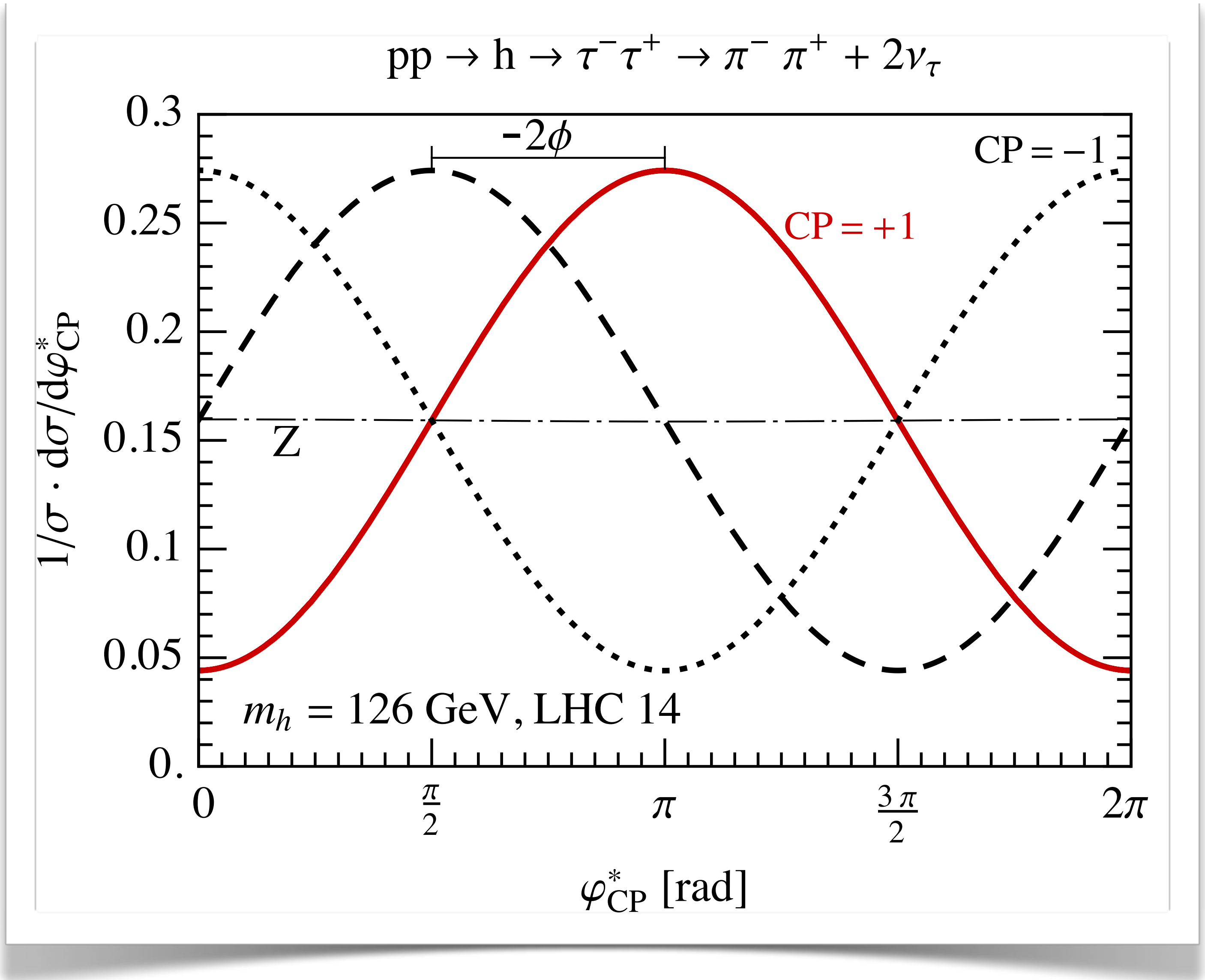
$$A = \frac{\sigma_{up}-\sigma_{low}}{\sigma}$$

where

$$\sigma_{up} = \sigma(\cos(\varphi_{CP}-2\phi_h)>0)$$
$$\sigma_{low} = \sigma(\cos(\varphi_{CP}-2\phi_h)<0)$$

- Integrated over all $\theta_\pm$:

$A = 39.3\%$



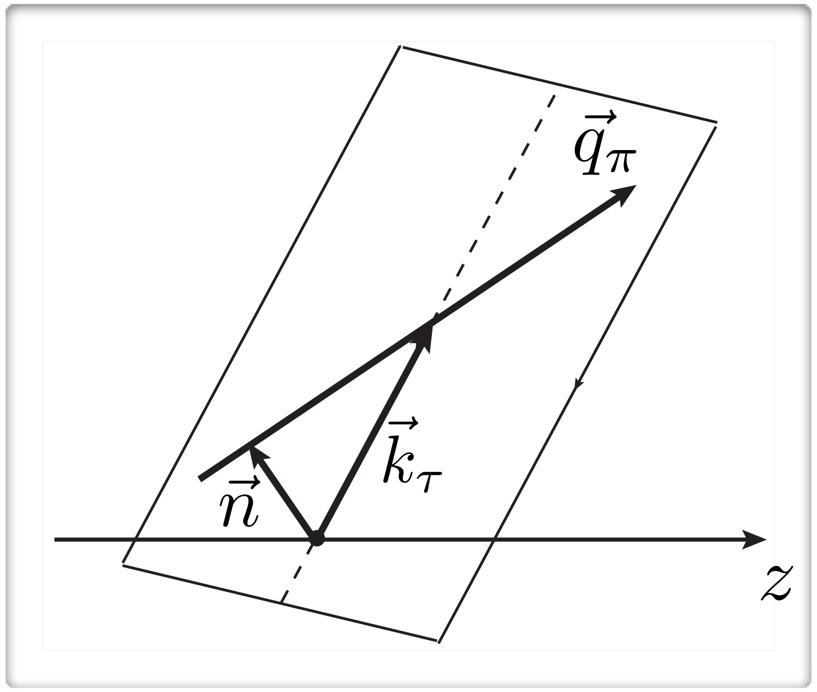
Higgs CP measurements using the tau impact parameter information

S.B., W. Bernreuther, arXiv: 0812.1910
S.B., W. Bernreuther, B. Niepelt, H. Spiesberger, arXiv: 1108.0670
sse also: S.B., W. Bernreuther, H. Spiesberger, arXiv: 1308.2674
S.B., W. Bernreuther, S. Kirchner, in preparation

CP measurement using the tau impact parameter

- Determine normalized impact parameter vectors in lab frame: $\hat{n}_-$, $\hat{n}_+$

- Boost $n^\mu_\pm = (0, \hat{n}_\pm)$ into zero momentum frame of charged prongs, e.g. $\pi^-\pi^+$-ZMF. Use transverse components with respect to $\vec{q}_-^{\,*}$, e.g. the π^- momentum in that frame: $\hat{n}_\perp^{*\pm}$



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

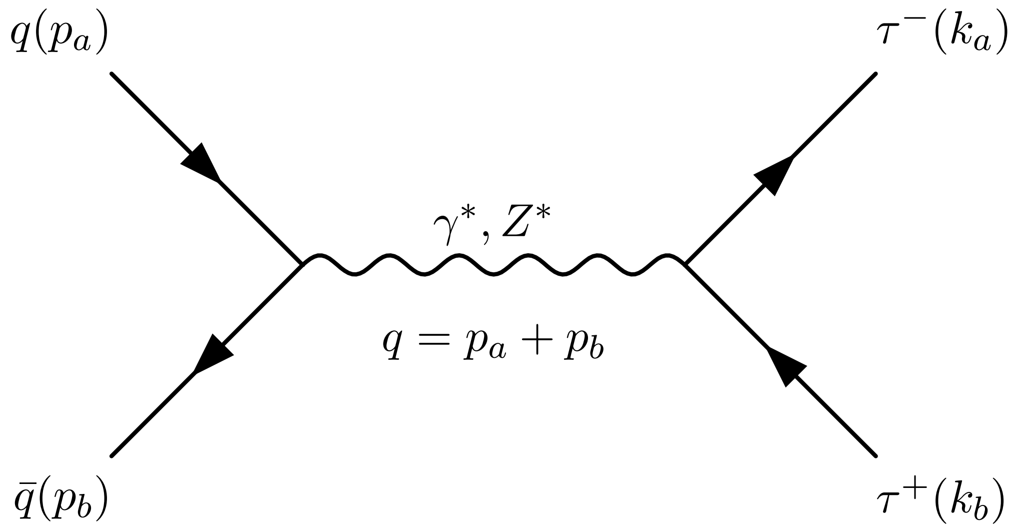
  where $\varphi^* = \arccos(\hat{n}_\perp^{*+} \cdot \hat{n}_\perp^{*-})$
  and $\mathcal{O}^*_{CP} = \hat{q}^*_- \cdot (\hat{n}_\perp^{*+} \times \hat{n}_\perp^{*-})$

$m_h = 126$ GeV
$\rightarrow \gamma \approx 35$
$\gamma < ct >_\tau \approx 3$ mm
$< n_\perp >_\tau \approx 43\,\mu$m

- Measurement of primary vertex (PV) necessary (additional tracks/underlying event)

Z boson background

Z, γ boson background



- Consider $\tau\tau$ production via γ, Z exchange
- Total angular momentum for γ, Z is 1 $\rightarrow \tau\tau$ spins preferably parallel
- NLO QCD corrections included in numerical evaluation
- Consider analytic form of LO differential cross section for $q\bar{q} \rightarrow Z, \gamma \rightarrow \tau^+\tau^- \rightarrow \pi^+ + \pi^- + 2\nu$ decay:

Z, γ boson background

- LO differential cross section can be written in $\tau\bar{\tau}$ rest frame for $q\bar{q} \to Z, \gamma \to \tau^+\tau^- \to \pi^+ + \pi^- + 2\nu$ decay ($\beta_\tau = 1$):
  (Bernreuther, Nachtmann, Overmann, 1993)

- $$d\sigma_{Z,\gamma} \sim v_\tau^{B1} v_\tau^{B2} \left[1 - \cos\theta_+ \cos\theta_- - \frac{1}{2}\sin\theta_+ \sin\theta_- \cos(\varphi_+ + \varphi_-)\right]$$
  $$+ a_\tau^{B1} a_\tau^{B2} \left[1 - \cos\theta_+ \cos\theta_- + \frac{1}{2}\sin\theta_+ \sin\theta_- \cos(\varphi_+ + \varphi_-)\right]$$
  $$+ \left(a_\tau^{B1} v_\tau^{B2} + a_\tau^{B2} v_\tau^{B1}\right) \left(\cos\theta_+ - \cos\theta_-\right)$$

$Z\tau\tau$ and $\gamma\tau\tau$ couplings

Result of parity violating Z interaction

$\cos\theta_\pm, \varphi_\pm$: polar and azimuthal angle of pions in their respective τ rest frame with $\hat{k}_{\tau^-} = \hat{e}_z$

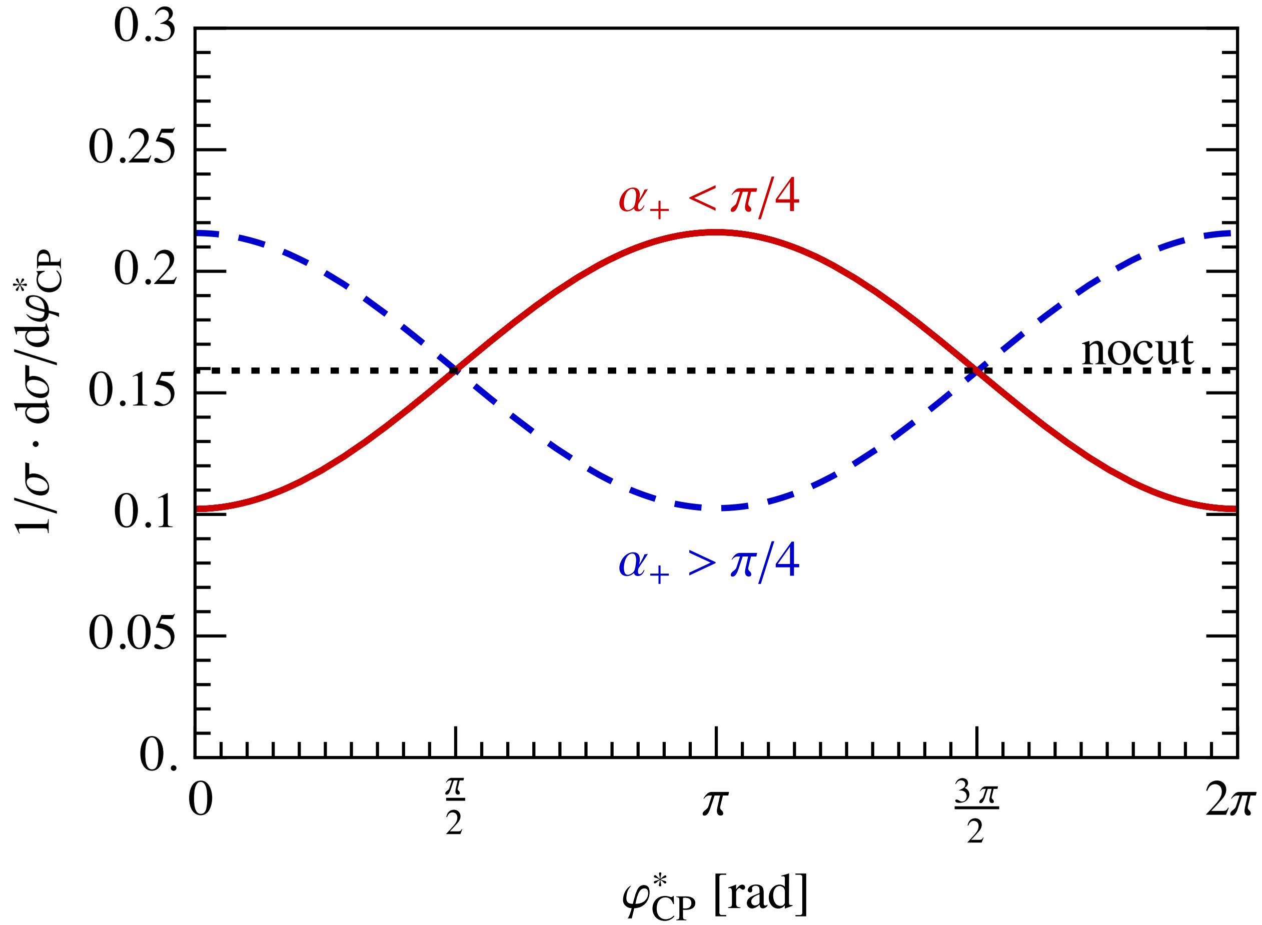
Z, γ boson background

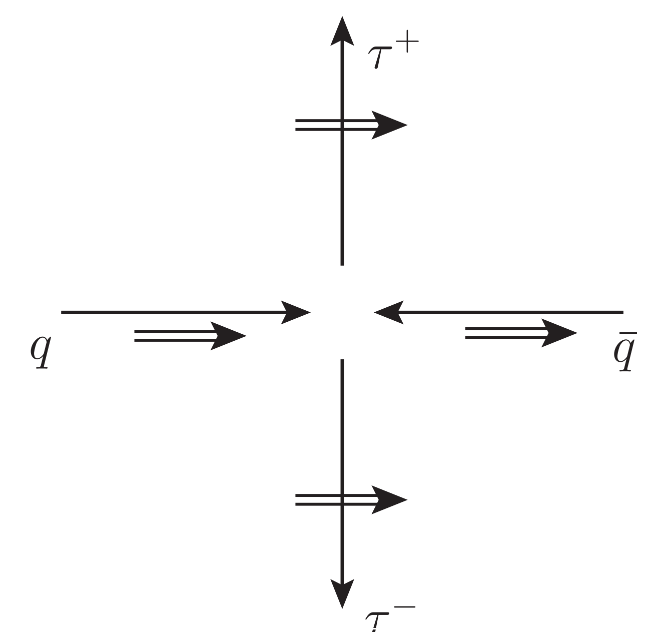
- α_+ measures the angle of the π^+ momentum with respect to the $pp \to \tau^+\tau^-$ production plane

- Red line: π^+ momentum in production plane,
  $\to \tau$ spins parallel, sum up to 1
  $\to \pi$ preferably antiparallel

- Blue line: π^+ momentum perpendicular to production plane,
  $\to \tau$ spins antiparallel and sum up to 0
  $\to \pi$ preferably parallel

- γ^*, Z^* production channel can be used to calibrate the Higgs CP measurement





Estimate of the precision

on the Higgs CP mixing angle

Estimate of the precision of ϕ_h

- Assume ATLAS+CMS ~ 2.1 events per fb^{-1} (based on ATLAS highest BDT score, VBF, $S/(S+B) = 0.43$, $S+B = 21$ for $\mathcal{L} = 20 fb^{-1}$)

- Demand $\hat{n}_{\pm} \geq 20\mu$m $\rightarrow$ 55% of events remain.

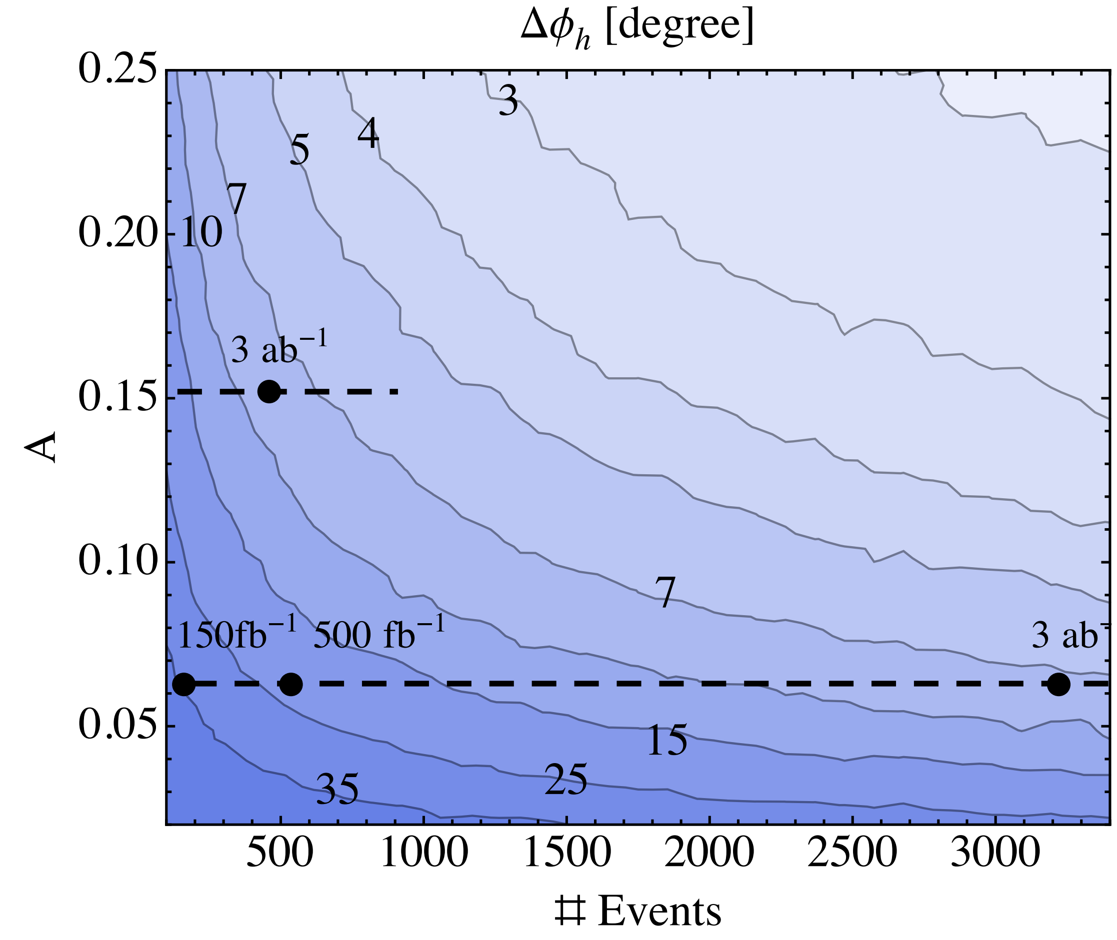
- Assuming an asymmetry reduction due to smearing effects of 0.9

- Use all hadronic τ decays: $A_{S+B} = 6.3\%$

  \# Events $= \{161, 537, 3222\}$

  for $\mathcal{L} = \{150 fb^{-1}, 500 fb^{-1}, 3ab^{-1}\}$

  $\rightarrow \Delta\phi_h = \{35°, 20°, 7°\}$



Concluding Remarks

- Determination of the Higgs CP mixing angle is possible in the tau decay channel at the LHC, using the φ^*_{CP} distribution.

- The appropriate φ^*_{CP} distribution for γ, Z boson background processes can be use to calibrate the measurement.

- The achievable precision on ϕ_h at the LHC should be about 20° for $\mathcal{L} \leq 500\, fb^{-1}$ and about 7° for $\mathcal{L} \leq 3\, ab^{-1}$

Backup slides

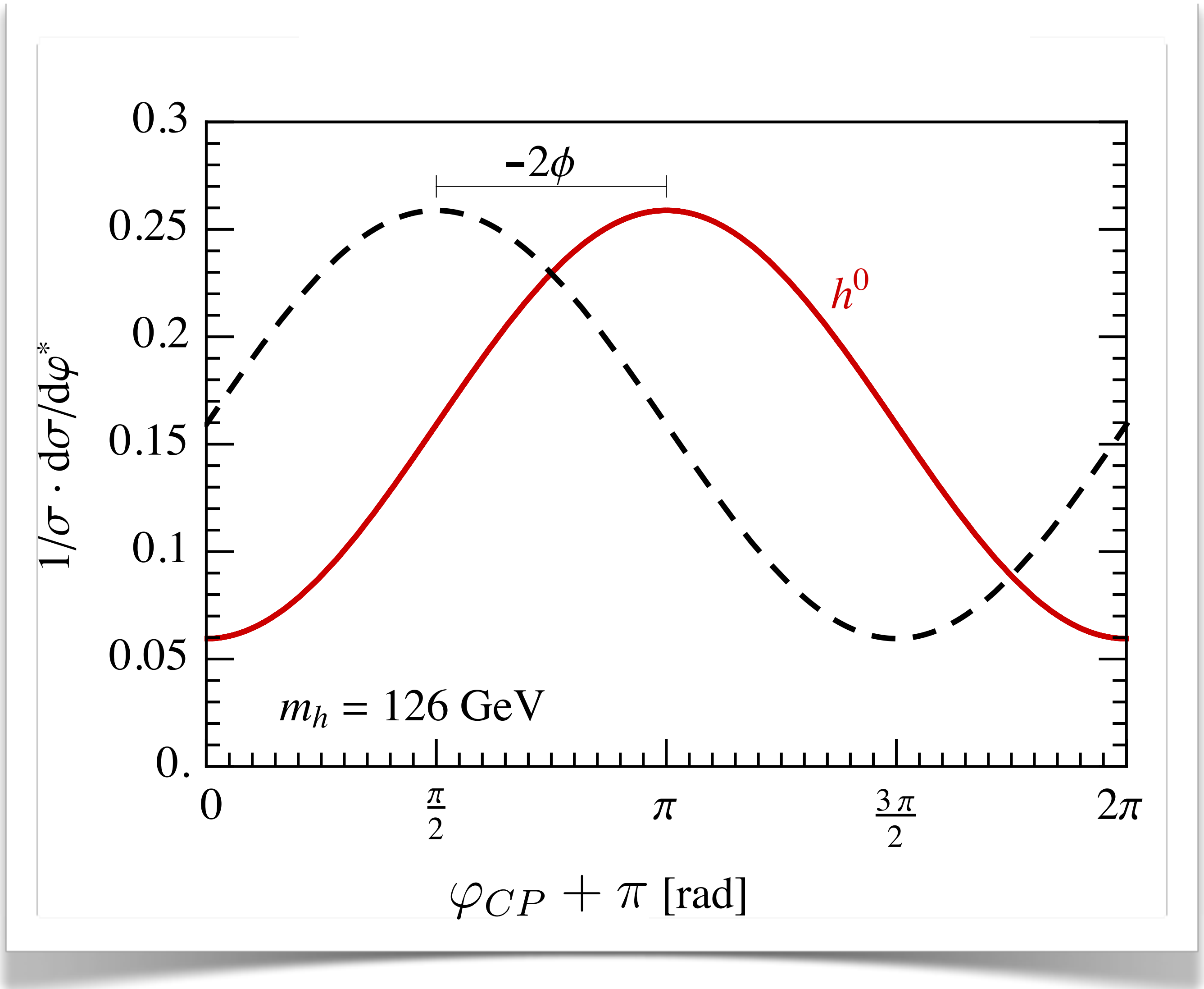
Higgs decay into tau lepton pairs

- Higgs decay probability with $\cos\theta_{s^-} = s_z^-, \cos\theta_{s^+} = s_z^+$ and $\varphi_{CP} = \varphi_- - \varphi_+$ using polar coordinates and $\hat{k}^{\tau^-} = \hat{e}_z$):

$$\Gamma_{h\to\tau^-\tau^+} \sim 1 - \cos\theta_{s^-}\cos\theta_{s^+} + \sin\theta_{s^-}\sin\theta_{s^+}\cos(\varphi_{CP} - 2\phi_h)$$

- $2\phi_h$ can be determined from the shift of the fitted φ_{CP} distribution with respect to the red curve for which $\phi_h = 0$.

- Precision on ϕ_h depends on the number of events and the size of the amplitude



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- Integrated over all $\theta_\pm$:

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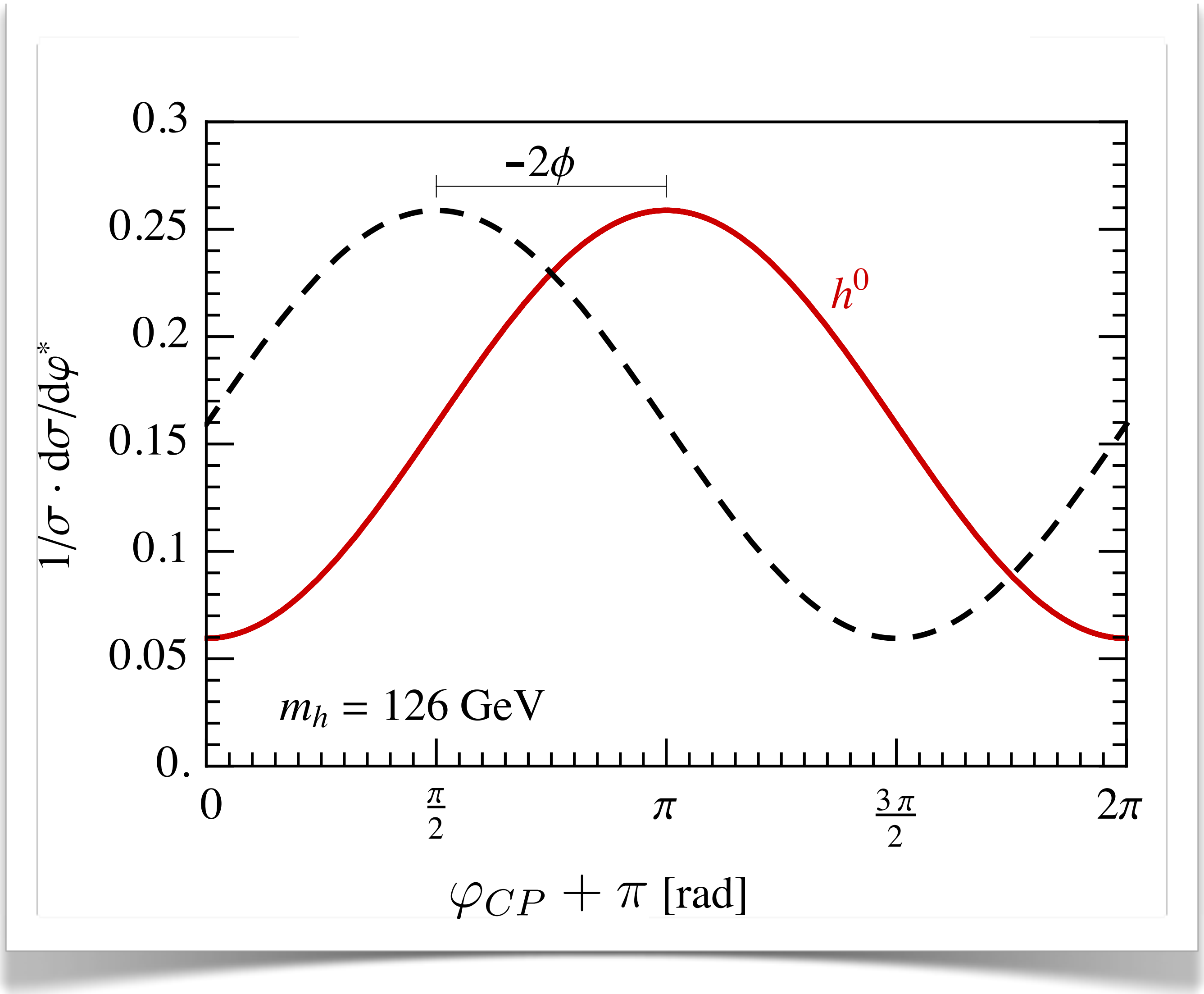
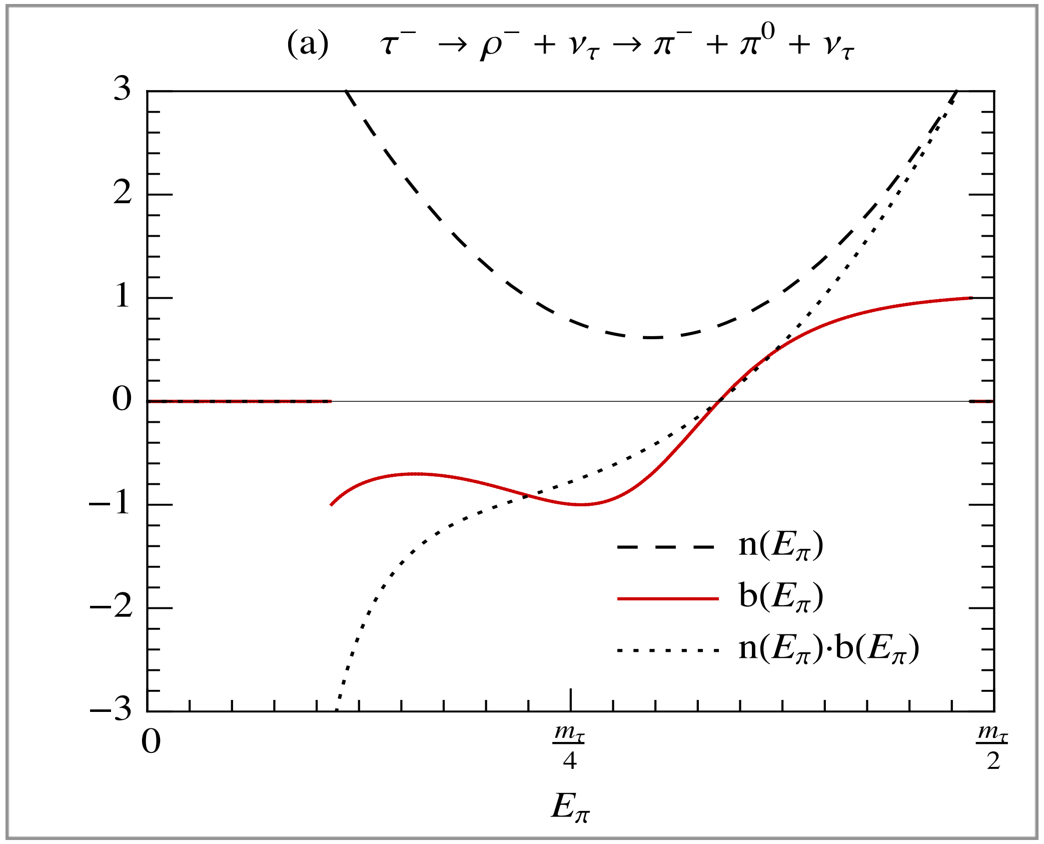


CP measurement using the tau impact parameter

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

- 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

CP measurement using the tau impact parameter

- Differential cross section for general decay $h \to \tau\bar{\tau} \to a^- + a'^+ + X$:

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

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

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

- Asymmetry, characterizing expected precision:

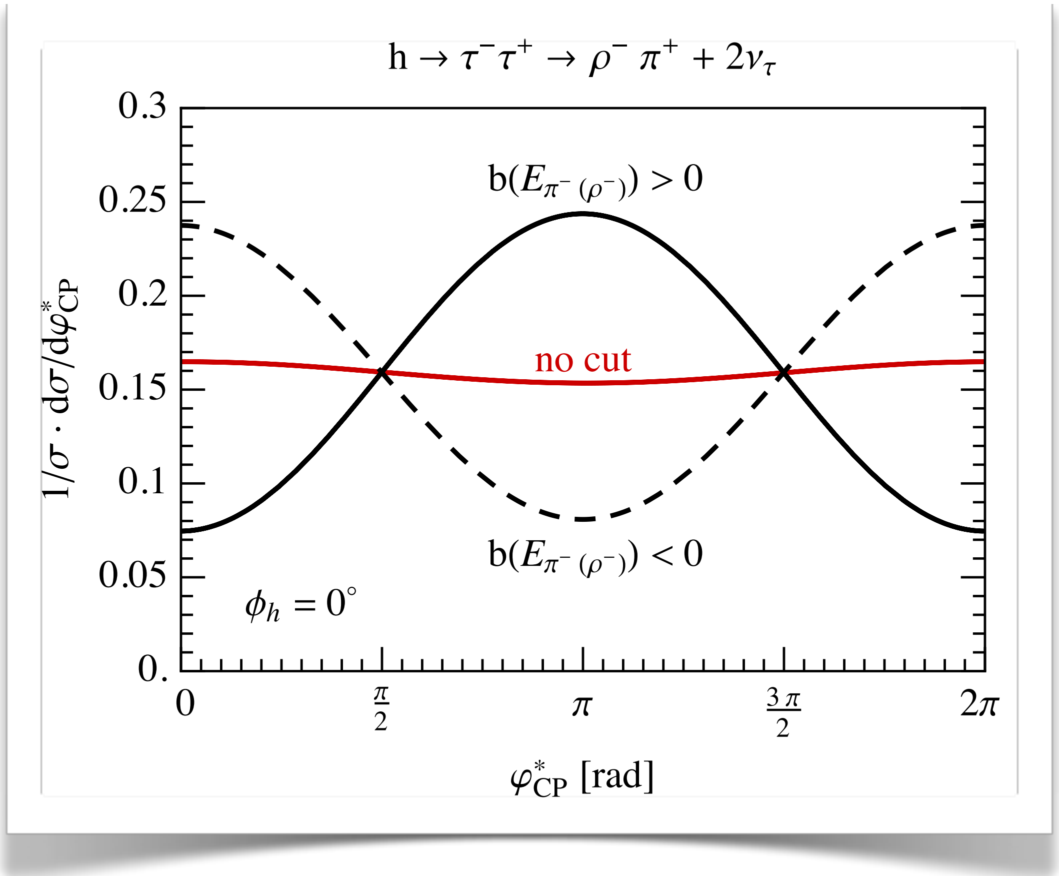
$$A = \frac{-\,4u}{2\pi v}$$

$\rightarrow$ All τ decay channels can be included

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

$\rightarrow$ Energies of a^- and a'^+ in τ rest frames and in Higgs rest frame are related by a boost

$\rightarrow$ Cut on a^- and a'^+ Energies in (approximated) Higgs rest frame

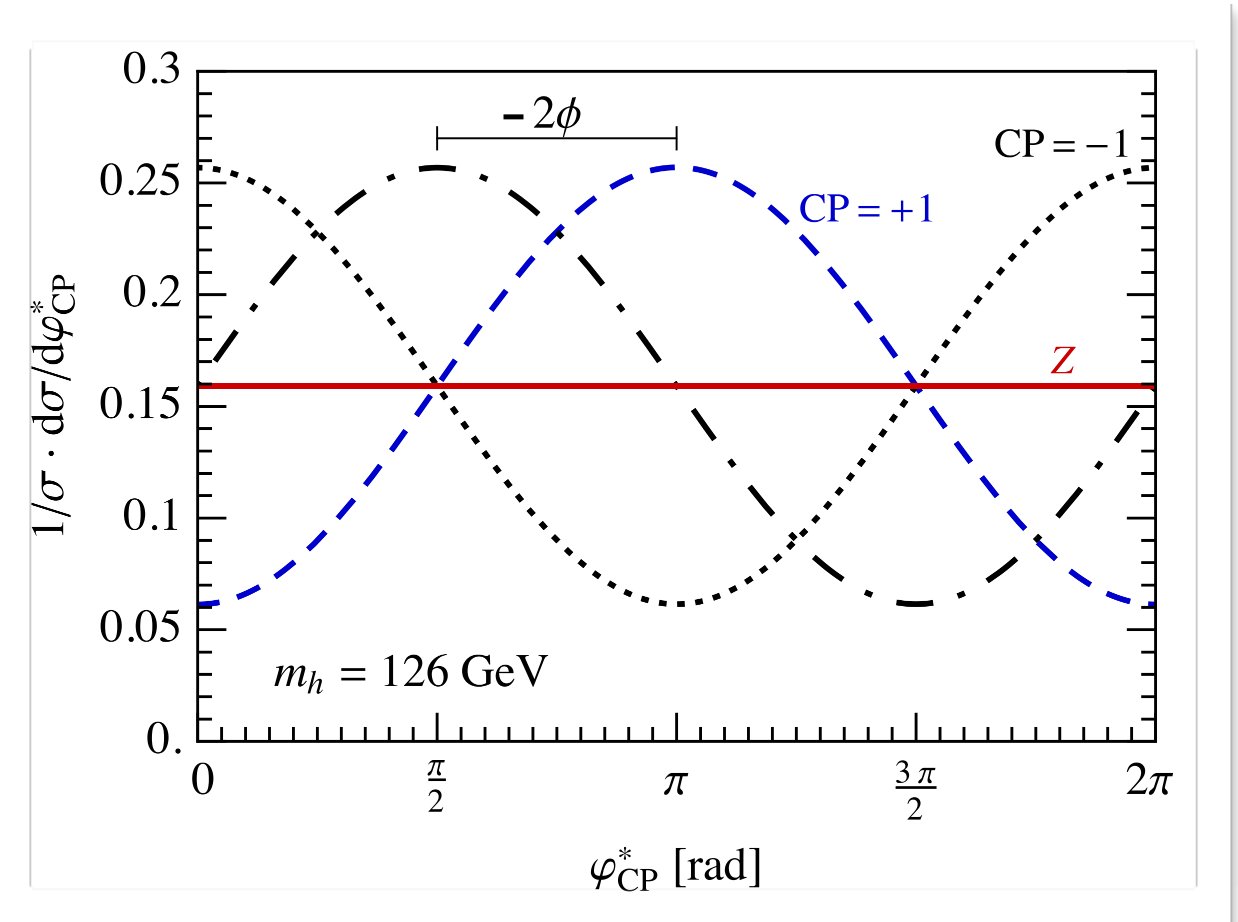


Z, γ boson background

- In dependence of $\varphi_{CP} = \varphi_- - \varphi_+$ (integrate out φ_+):

$$\frac{d\sigma_{Z,\gamma}}{d\varphi_{CP}} \sim \left(v_\tau^{B1} v_\tau^{B2} + a_\tau^{B1} a_\tau^{B2}\right) \left[1 - \cos\theta_+ \, \cos\theta_-\right] + \left(a_\tau^{B1} v_\tau^{B2} + a_\tau^{B2} v_\tau^{B1}\right) \left(\cos\theta_+ - \cos\theta_-\right)$$

- No φ_{CP} dependence !
- No φ_{CP} dependence if transverse momentum or rapidity cuts are applied on the final charged pions.
- No φ_{CP} dependence at NLO QCD



Backup slides

$\tau\tau$-decay channel	$A\,[\%]$	# of events for $\mathscr{L} = 1\,\text{ab}^{-1}$	$\Delta\phi\ [^\circ]$ $\mathscr{L} = 1\,\text{ab}^{-1}$	$\Delta\phi\ [^\circ]$ $\mathscr{L} = 500\,\text{fb}^{-1}$	$\Delta\phi\ [^\circ]$ $\mathscr{L} = 300\,\text{fb}^{-1}$
$(\pi + a_1^\lambda)(\pi + a_1^\lambda)$	28.9	269	5.5	7.9	10
$\rho\rho$	18.0	443	7.0	10	13
$\rho(\pi + a_1^\lambda)$	22.8	686	4.4	6.3	8.2
$a_1(\pi + a_1^\lambda)$+ρa_1+$a_1 a_1$	10	638	11	18	23
all had-had:			3.0	4.3	5.5
ll	4.8	454	30	36	39
$l(\pi + a_1^\lambda)$	11.8	706	8.7	13	18
$l\rho$	6.0	723	19	27	31
la_1	3.4	292	38	42	44
all lep-had:			7.7	11	15
all:			2.8	4.0	5.1