Prospects of constraining the Higgs CP nature in the tau decay channel at the LHC

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arXiv:1510.03850

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Contents

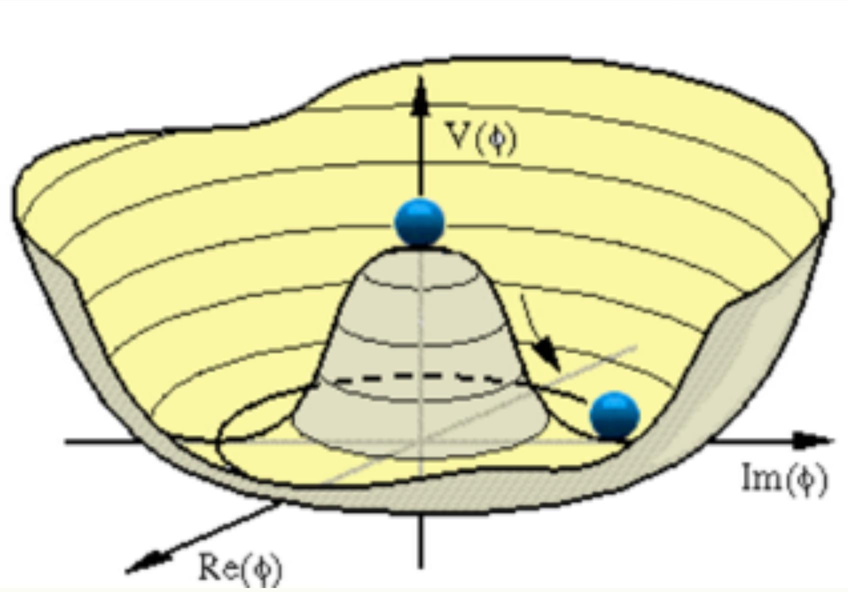
- Higgs sector CP violation
- Determination of φ_τ at the LHC:
  - Impact parameter method
  - ρ-decay plane method
  - Combination of the methods
- Conclusion

Standard Model Higgs Mechanism

- SM includes one Higgs doublet field: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$

- Lagrangian of Higgs sector:

$$\mathcal{L}_{Higgs} = (D_\mu \Phi^\dagger)(D^\mu \Phi) + \mu^2 \Phi^\dagger \Phi - \frac{\lambda}{4}(\Phi^\dagger \Phi)^2$$



- Spontaneous symmetry breaking results in one physical Higgs boson h^0 and massive $W^\pm$ and Z^0 vector bosons.

- h^0 must be CP-even to couple to $Z^0 Z^0$ at tree level

Higgs sector CP violation

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CP violation

- SM contains only one Higgs boson that therefore needs to be CP even

- Is there CP violation in addition to the CKM phase - as a hint for new physics ?

- Different extended Models with CP violation have different impact on Higgs to SM-particle interactions:

  E.g. effects could show up in hZZ-coupling or in $h\tau\tau$ coupling or in htt coupling

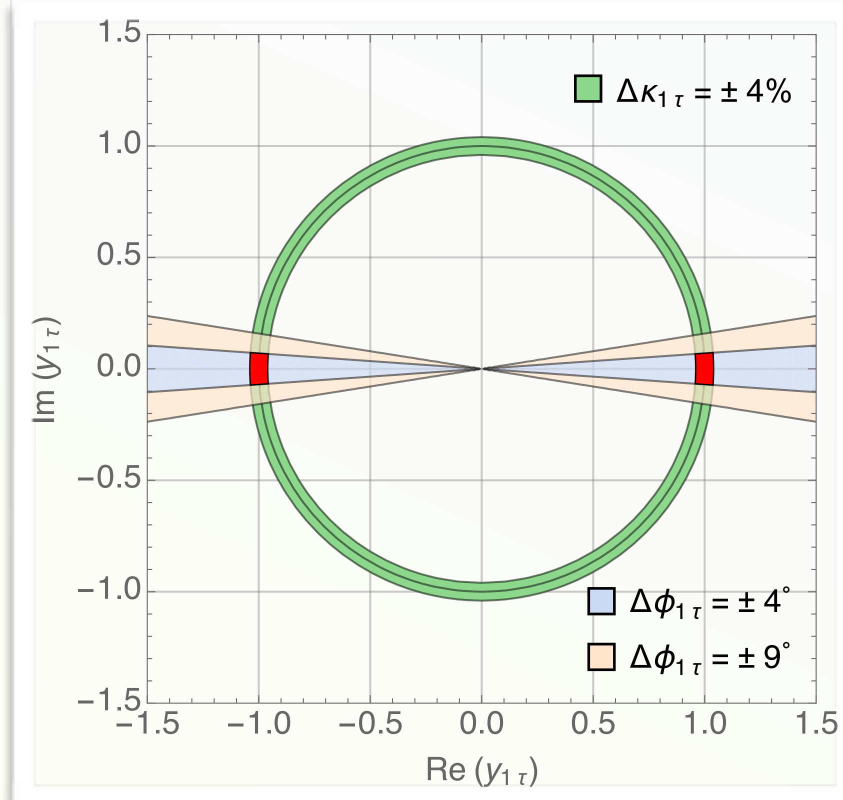
- CP measurement in $h \to ZZ$ can exclude a CP-odd Higgs boson, but not CP-mixing

- That also means that a complete exclusion of CP violation in the Higgs sector is complicated

CP violation in h-tautau coupling

- CP violation could show up in the h-$\tau\tau$ coupling at the leading order:

- General Lagrangian:



$$\mathcal{L}_Y = -\frac{m_\tau}{\mathrm{v}}\,\kappa_\tau\,(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)\,h\,,$$

$$= -\frac{m_\tau}{\mathrm{v}}\,(\mathrm{Re}(y_{i\tau})\;\bar{\tau}\tau + \mathrm{Im}(y_{i\tau})\;\bar{\tau}i\gamma_5\tau)\,h_i$$

- κ_τ can is determined by branching ratio measurements

- ϕ_τ can be measured using the $\tau\tau$ spin correlations

- Using κ_τ and ϕ_τ - specific models can be constrained

CP violation in 2 Higgs Doublet Models

- 2HD Models $\to$ two Higgs doublets Φ_1, Φ_2. Choosing the Higgs basis (only Φ_1 has a non-zero vacuum expectation value):

$$\Phi_1 = \left(G^+, (\mathrm{v} + S_1 + iG^0)/\sqrt{2}\right)^T , \qquad \Phi_2 = \left(H^+, (S_2 + iS_3)/\sqrt{2}\right)^T$$

- G^+, G^0 - Goldstone fields, H^+ - charged Higgs-boson field, S_1, S_2 and S_3 neutral fields, which are CP-even and -odd

- Fields in mass basis h_1, h_2, h_3

$$(h_1, h_2, h_3)^T = R(S_1, S_2, S_3)^T \tag{1}$$

  R - real orthogonal 3×3 matrix, depends on the Higgs potential

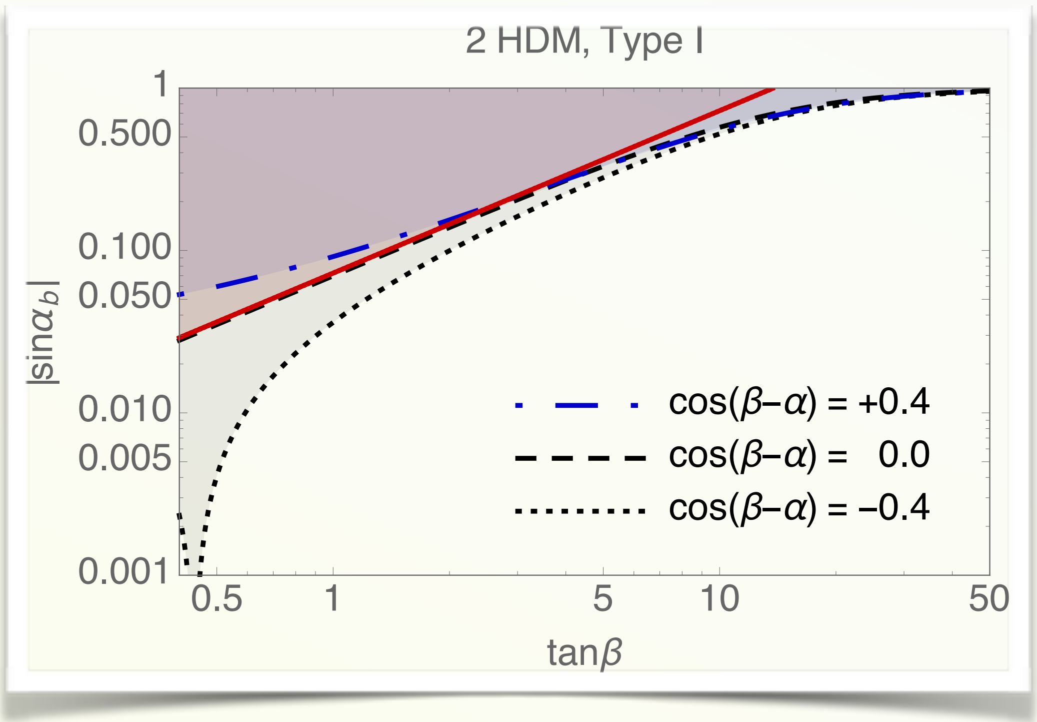
- Yukawa interactions to quarks/leptons in the aligned 2HDM (0908.1554):

$$\begin{aligned} y_{id,l} &= R_{i1} + (R_{i2} + iR_{i3})\zeta_{d,l} \, , \\ y_{iu} &= R_{i1} + (R_{i2} - iR_{i3})\zeta_u^* \end{aligned}$$

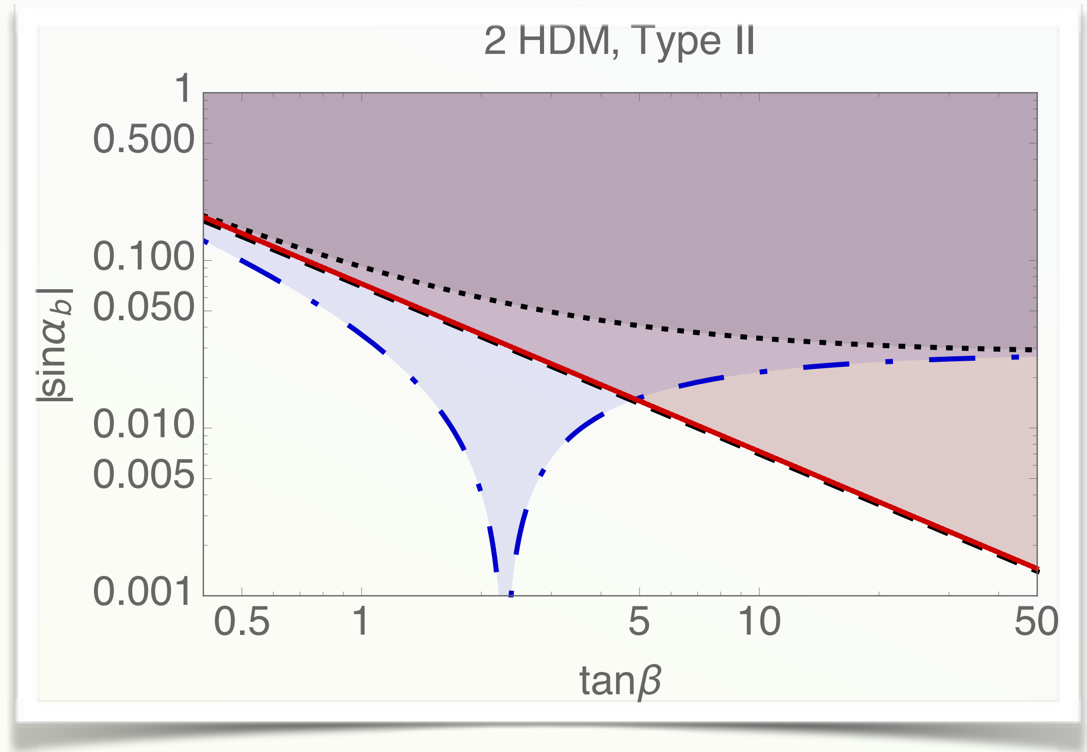
- Additional CP violation due to the parameters $\zeta_{d,l}$ and ζ_u.

- $\to$ CP violation in $h\tau\tau$-coupling is different from CP violation in htt-coupling

CP violation in 2 Higgs Doublet Models, Example

- 

Type I



Type II

- Exclusion ranges, assuming $\phi_{1\tau} = 0^\circ \pm 4^\circ$ and $\kappa_\tau = 1 \pm 0.04$.
- Exclusion of solid red lines is independent of mixing angle α.
- Dot-dashed blue, dashed black, and dotted black lines correspond to $\cos(\beta - \alpha) = 0.4, 0,$ and -0.4

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Determination of ϕ_τ at the LHC

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CP measurement in $h \to \tau^+\tau^-$

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

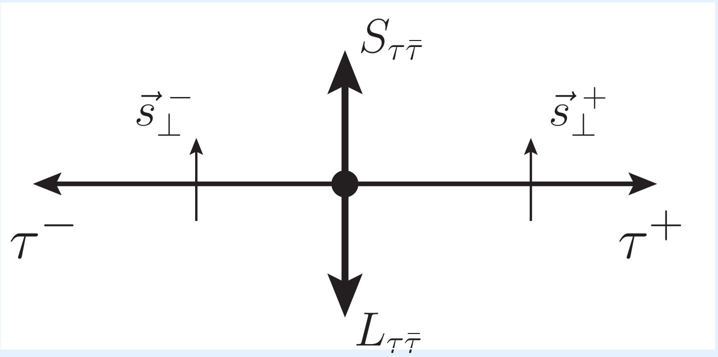
h^0

CP-even (SM), $\phi_\tau = 0$

$\mathcal{L}_{h^0\tau\tau} = -g_\tau \cdot \bar{\tau}\tau h$

$J^{PC} = 0^{++}$

$L_{\tau\bar{\tau}} = 1,\ S_{\tau\bar{\tau}} = 1$



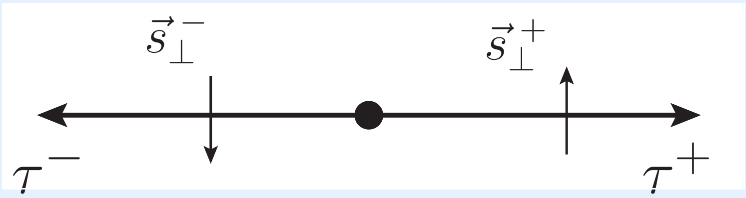
A^0

CP-odd, $\phi_\tau = \frac{\pi}{2}$

$\mathcal{L}_{A^0} = -g_\tau \cdot \bar{\tau} i\gamma_5 \tau h$

$J^{PC} = 0^{-+}$

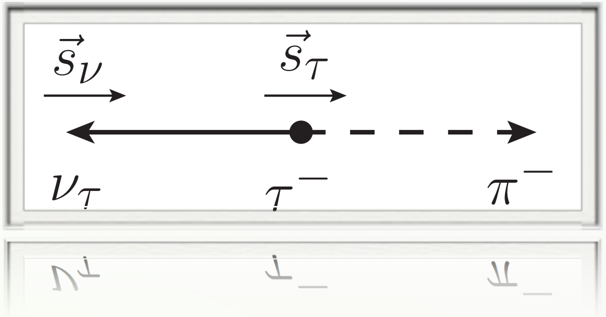
$L_{\tau\bar{\tau}} = 0,\ S_{\tau\bar{\tau}} = 0$



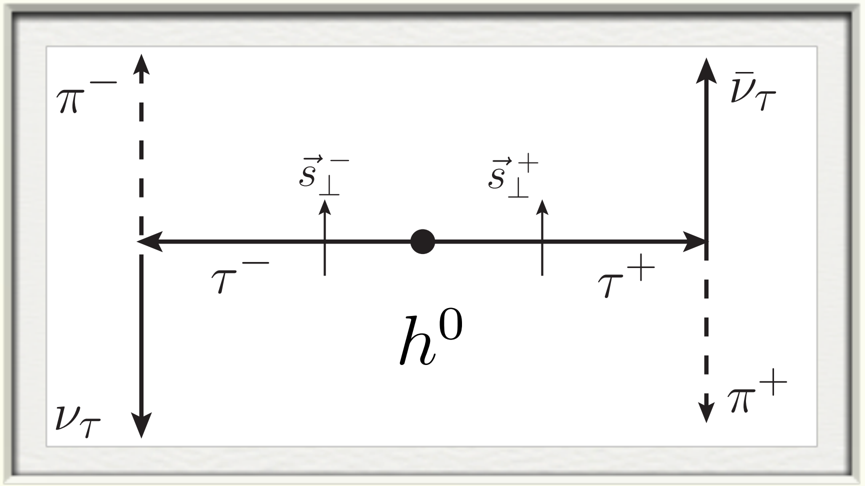
Parity and charge conjugation property of a fermion-anti-fermion wave function:
$P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

CP measurement in $h \to \tau^+\tau^-$

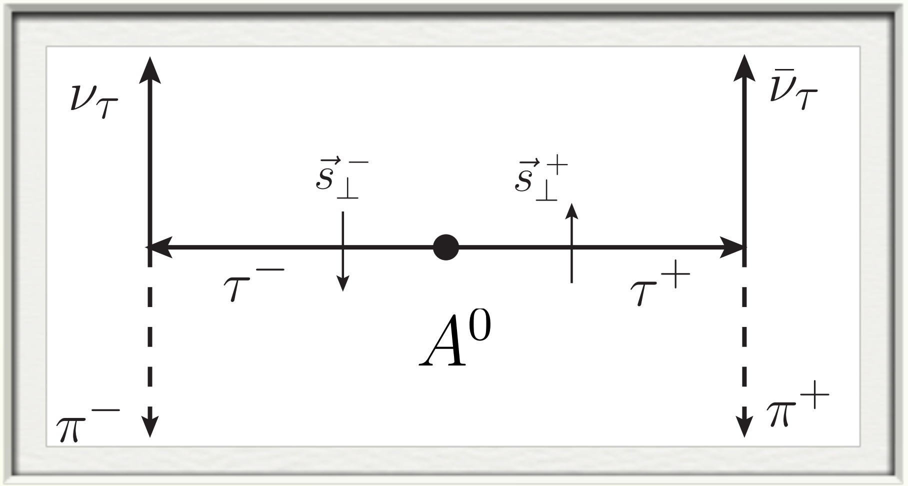
- π^- is emitted in the direction of the τ^--Spin in the τ^- rest frame (spin analyzer quality of 1)



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



π^- and π^+ are preferably antiparallel



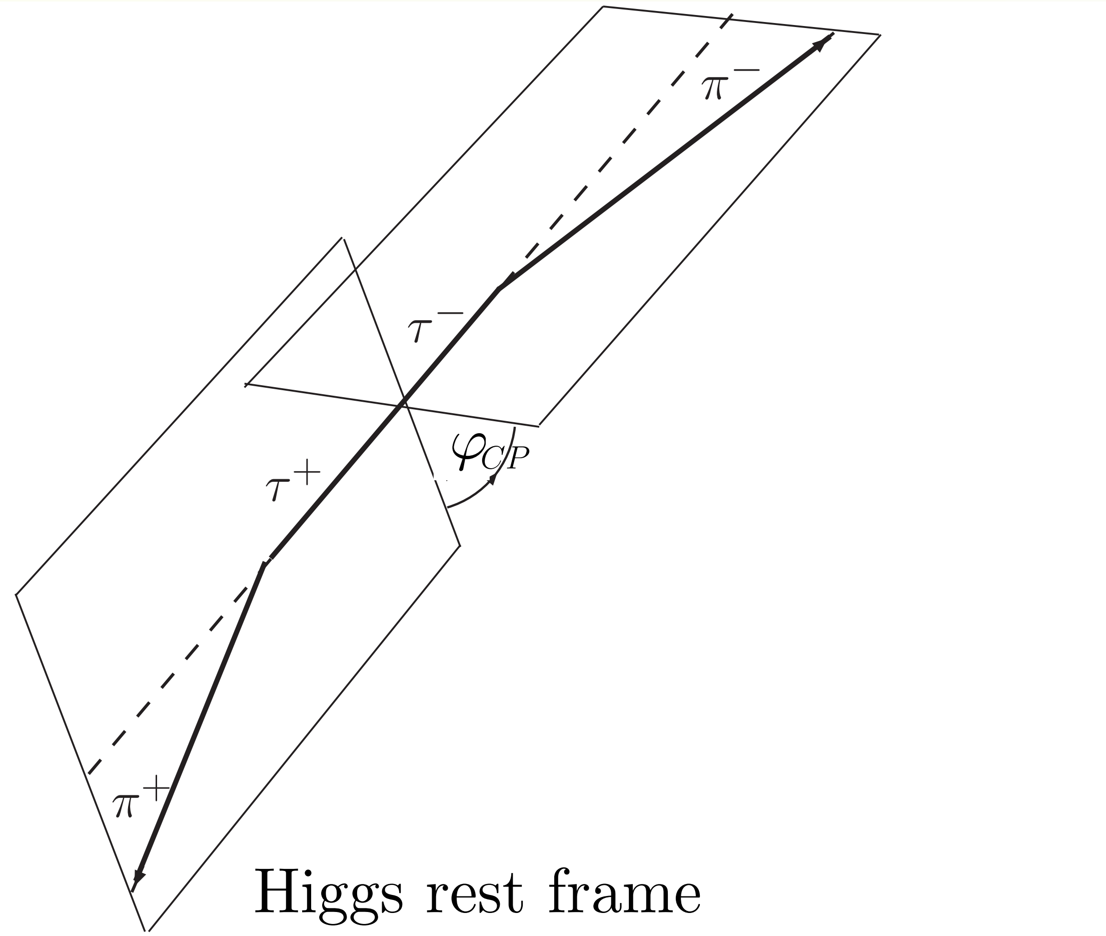
π^- and π^+ are preferably parallel

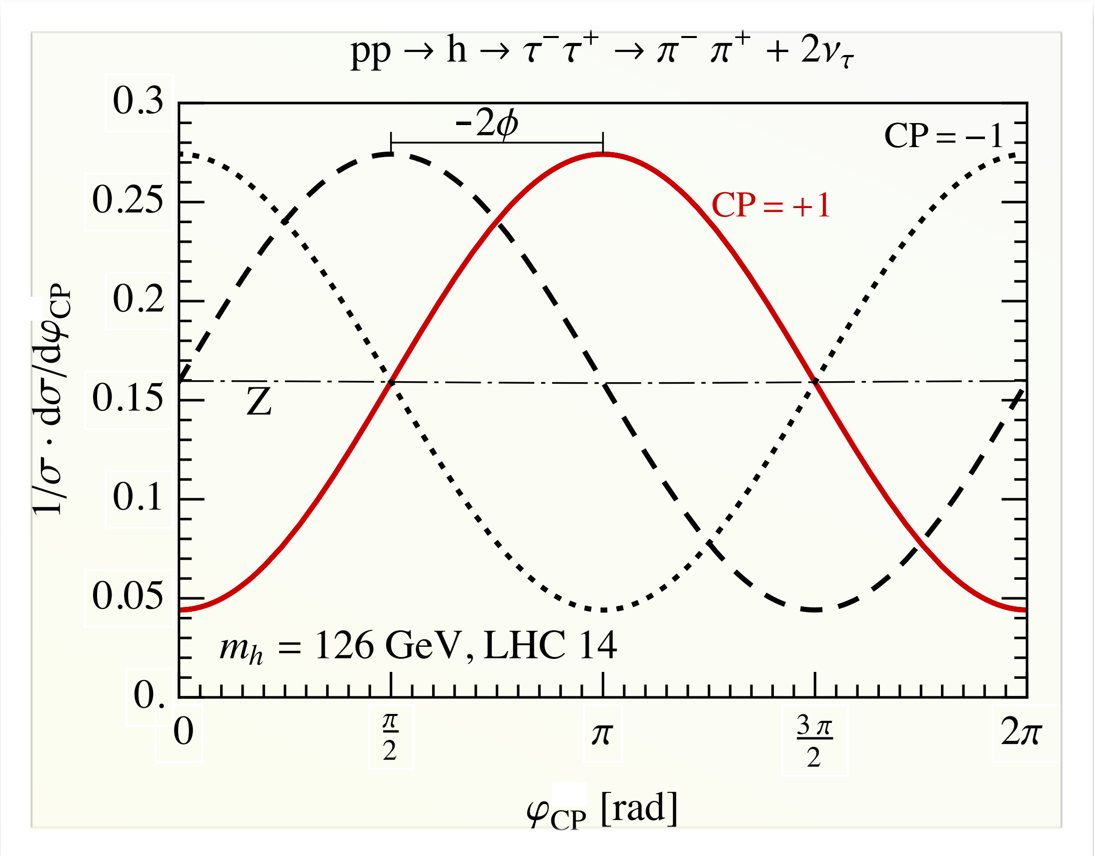
CP measurement in $h \to \tau^+\tau^-$

- $$\frac{1}{\Gamma}\frac{d\Gamma(h \to \pi^+\pi^- + 2\nu)}{d\varphi_{CP}} = \frac{1}{2\pi}\left[1 - \frac{\pi^2}{16}\cos(\varphi_{CP} - 2\phi_\tau)\right]$$

(Dell'Aquila, Nelson, 1989)

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





$A_{nocut} = 40\%$

CP measurement in $h \to \tau^+\tau^-$

- We analyze all major 1- and 3-prong tau decay modes:

$$
\begin{aligned}
\tau &\to l + \nu_l + \nu_\tau \\
\tau &\to a_1 + \nu_\tau \to \pi + 2\pi^0 + \nu_\tau \\
\tau &\to a_1^{L,T} + \nu_\tau \to 2\pi^\pm + \pi^\mp + \nu_\tau \\
\tau &\to \rho + \nu_\tau \to \pi + \pi^0 + \nu_\tau \\
\tau &\to \pi + \nu_\tau
\end{aligned}
$$

- The differential τ decay width for any τ decay channel can be written as:

$$
\mathrm{d}\Gamma\left(\tau^-(\hat{\mathbf{s}}^-)\right) = \frac{1}{2m_\tau}|\overline{\mathcal{M}}|^2\left[1 - \mathbf{h}^-\hat{\mathbf{s}}^-\right] d\Phi
$$

Impact parameter method

Phys.Lett. B671, 470 (2009), Phys.Rev. D84, 116003 (2011),
Eur. Phys. J. C74, 3164 (2014), Phys.Lett. B727, 488 (2013)

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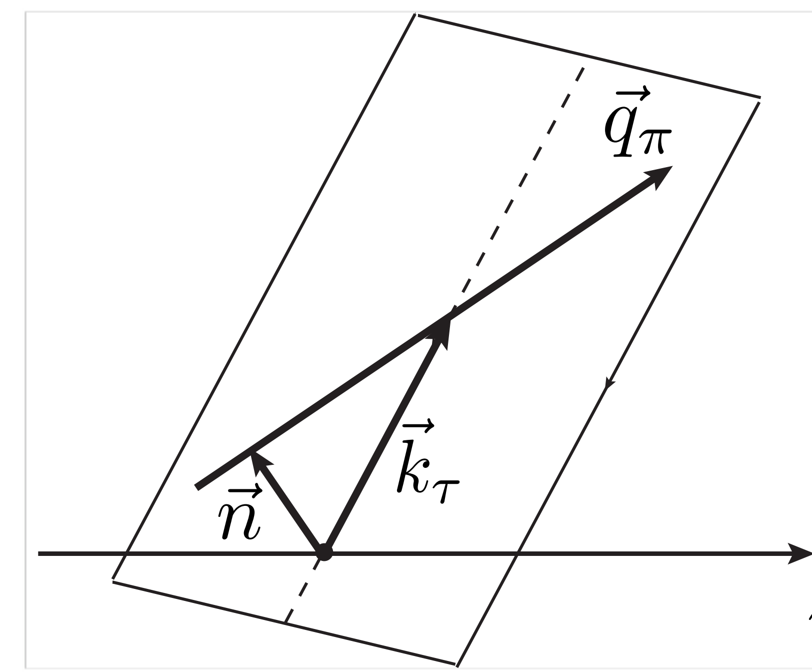
CP measurement using the $\tau^{\pm}$ impact parameters

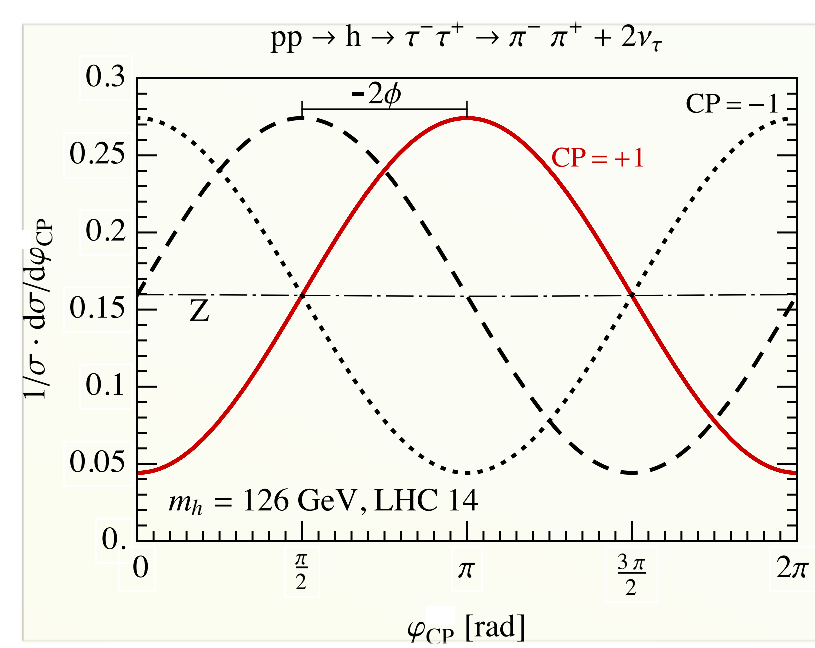
- Determine normalized impact parameter vectors in lab frame: $\hat{n}_-$, $\hat{n}_+$

- 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: $\hat{n}_\perp^{*\pm}$



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

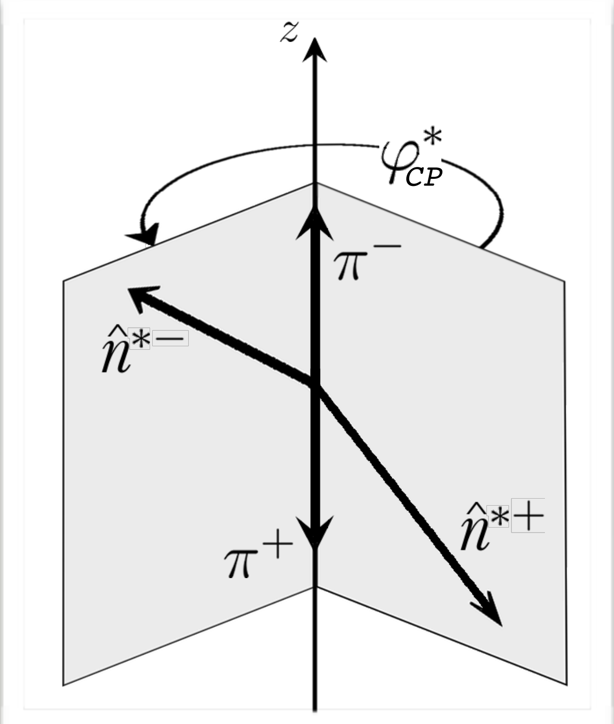
  where $\varphi^* = \arccos(\hat{n}_\perp^{*+} \cdot \hat{n}_\perp^{*-})$
  and $\mathcal{O}^*_{CP} = \hat{q}_-^* \cdot (\hat{n}_\perp^{*+} \times \hat{n}_\perp^{*-})$



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

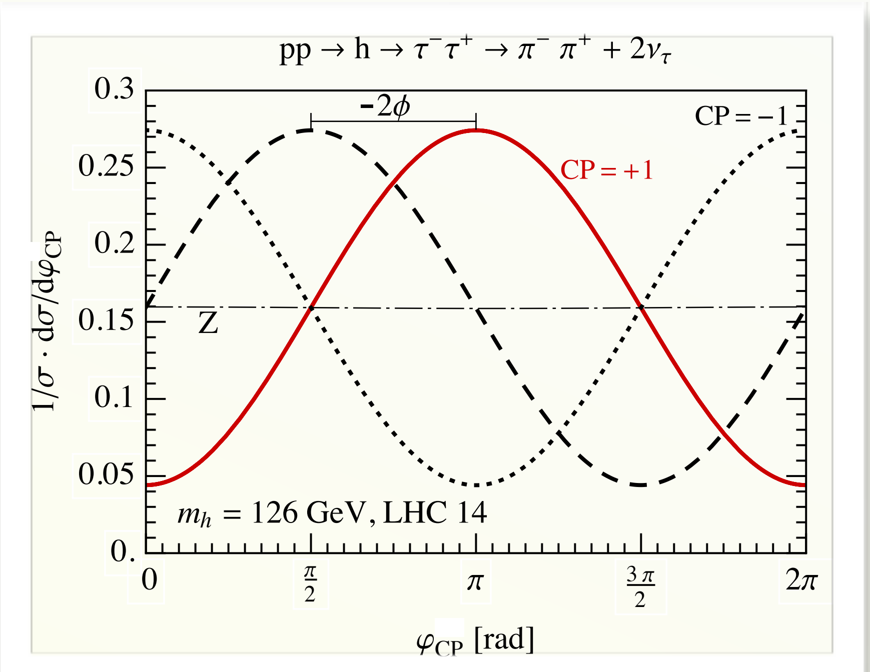
CP measurement using the $\tau^{\pm}$ impact parameters

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



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

Determination of ϕ_τ using reconstruction of ρ momenta

hep-ph/0204292, hep-ph/0302046, hep-ph/0307331, hep-ph/0202007, hep-ph/0305082

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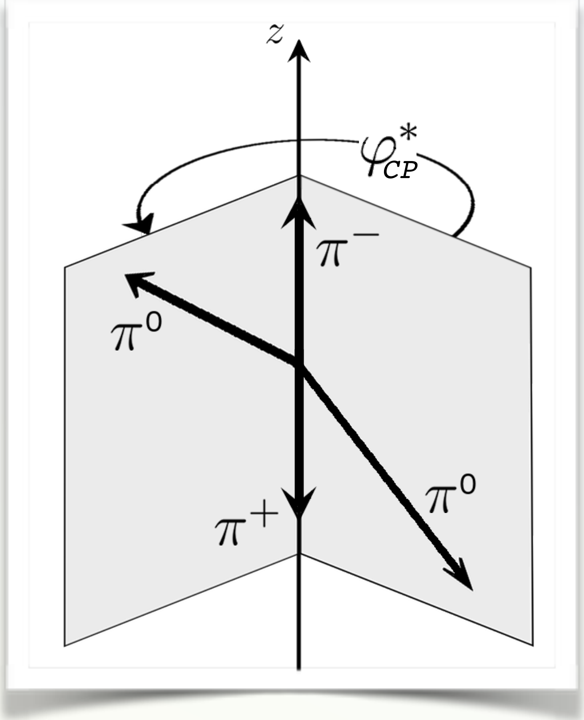
CP measurement in $h \to \tau^+\tau^- \to \rho^+\rho^- + 2\nu$ at the LHC

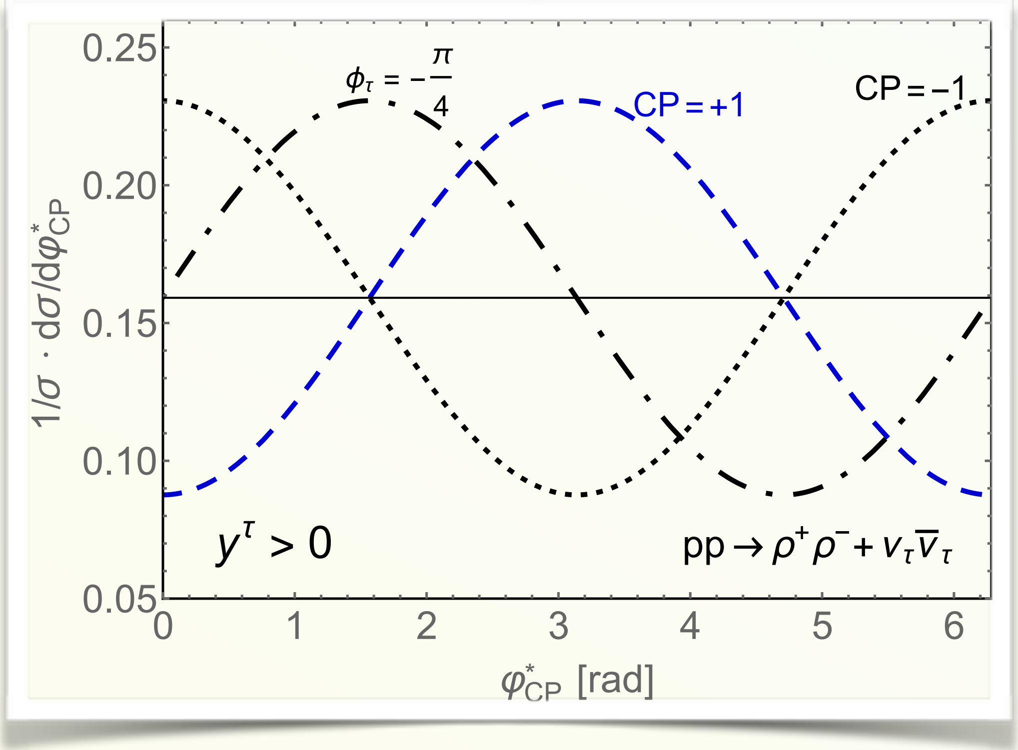
- Desch, Imhof, Was, Worek, hep-ph/0307331
  Harnik et al. arXiv:1308.1094



- Decay channel: $h \to \tau^+\tau^- \to \rho^+\rho^- + 2\nu$

- Reconstruction of ρ-momenta necessary (separation of $\pi^\pm$ and π^0)

- Boost all momenta into the $\pi^+\pi^-$-ZMF (denoted by $*$). This is different from the original method

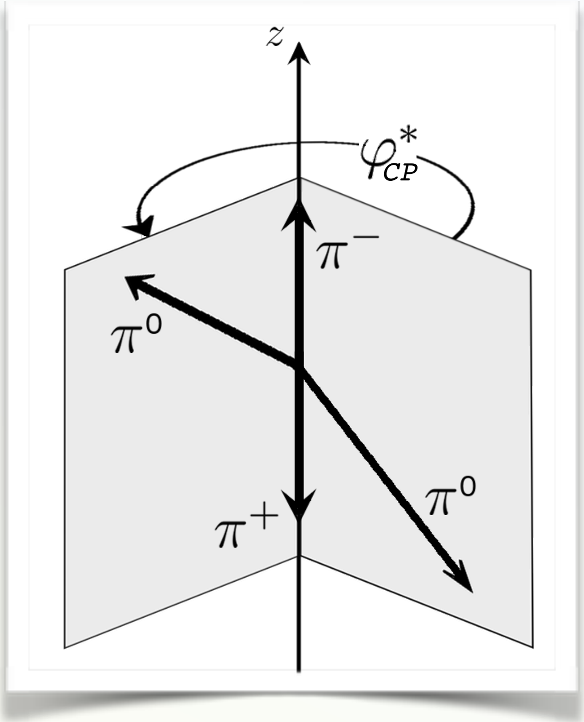


- In the $\pi^+\pi^-$-ZMF, calculate $\hat{q}^{*0-}$ and $\hat{q}^{*0+}$, the normalized transverse vectors of the π^0 with respect to their corresponding charged π

CP measurement in $h \to \tau^+\tau^- \to \rho^+\rho^- + 2\nu$ at the LHC

- Defining:

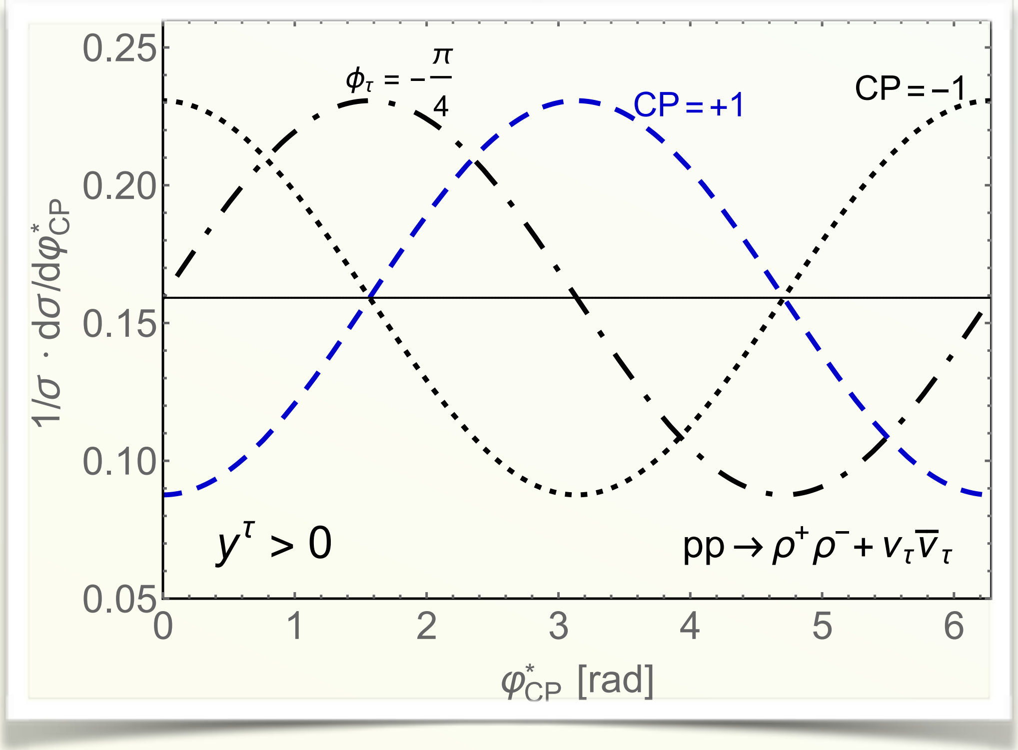
$$\varphi^* = \arccos\left(\hat{\mathbf{q}}_\perp^{*0+} \cdot \hat{\mathbf{q}}_\perp^{*0-}\right)$$
$$\mathcal{O}^* = \hat{\mathbf{q}}^{*-} \cdot \left(\hat{\mathbf{q}}_\perp^{*0+} \times \hat{\mathbf{q}}_\perp^{*0-}\right)$$



- Then φ^*_{CP} is defined:

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

$A = 28\%$



- Events need to be separated using

$$y_-^\tau = \frac{(E_{\pi^-} - E_{\pi^0})}{(E_{\pi^-} + E_{\pi^0})} \quad , \quad y_+^\tau = \frac{(E_{\pi^+} - E_{\pi^0})}{(E_{\pi^+} + E_{\pi^0})}$$

and selecting

$$y^\tau > 0 \text{ or } y^\tau < 0 \qquad \text{where} \quad y^\tau = y_-^\tau y_+^\tau$$

Combination of impact-parameter and ρ - decay plane method

arXiv:1510.03850

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Combination of methods

- Consider the decay channel $h \to \tau^-\tau^+ \to \pi^-\rho^+$:

- Determine impact parameter $\hat{n}_-$ and ρ^+ decay particle momenta π^0, π^+ in Lab frame

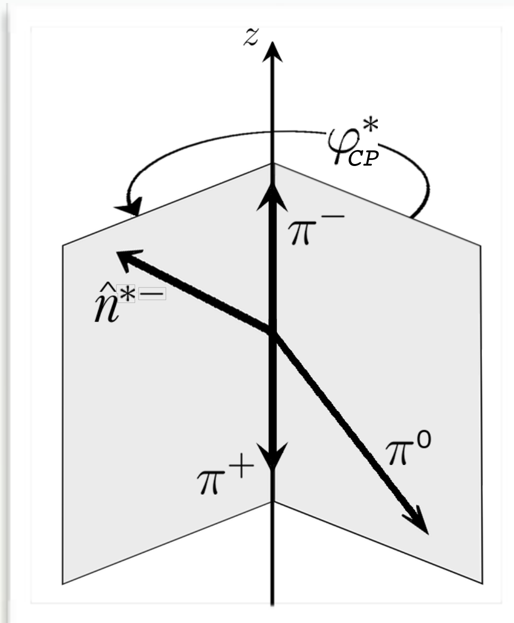
- Boost $n_-^\mu = (0, \hat{n}_-)$ and momenta into $\pi^-\pi^+$ ZMF (denoted by *)

- Calculate in this frame the transverse components $\hat{n}_\perp^{*-}$ and $\hat{q}_\perp^{*0+}$. Using

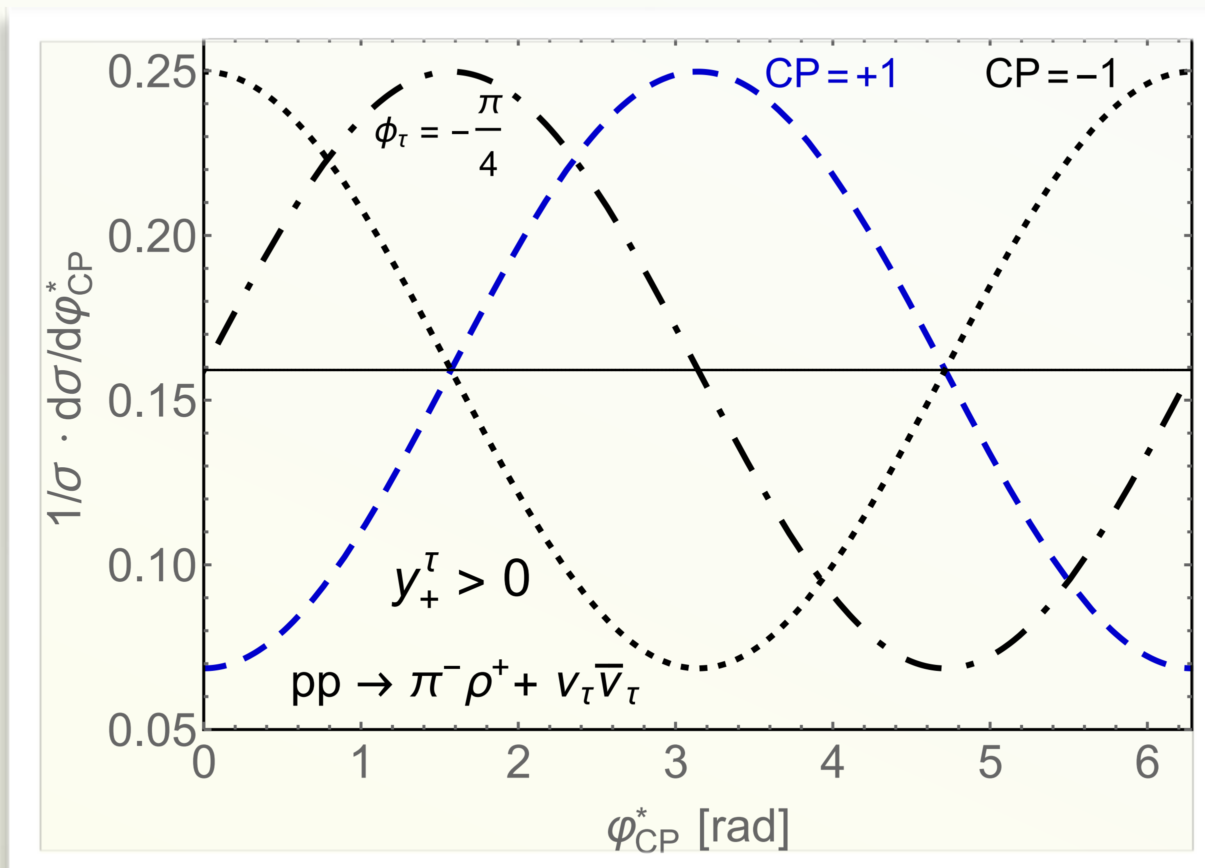
$$\varphi^* = \arccos\left(\hat{\mathbf{q}}_\perp^{*0+} \cdot \hat{\mathbf{n}}_\perp^{*-}\right)$$
$$\mathcal{O}^* = \hat{\mathbf{q}}^{*-} \cdot \left(\hat{\mathbf{q}}_\perp^{*0+} \times \hat{\mathbf{n}}_\perp^{*-}\right)$$

- then φ_{CP}^* is defined:

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



$$y_+^\tau = \frac{E_{\pi^+}^\tau - E_{\pi^0}^\tau}{E_{\pi^+}^\tau + E_{\pi^0}^\tau}$$



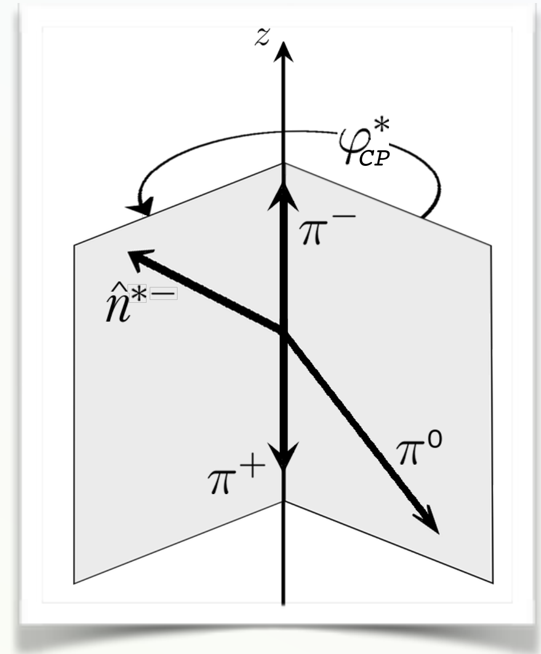
Combination of methods

- General structure in $\pi^-\pi^+$ ZMF:

  $\hat{q}^{*-}$ is the normalized π^- momentum

  $\hat{p}_\perp^{*+}$ is either $\hat{q}_\perp^{*0+}$ or $\hat{n}_\perp^{*+}$

  $\hat{p}_\perp^{*-}$ is either $\hat{q}_\perp^{*0-}$ or $\hat{n}_\perp^{*-}$



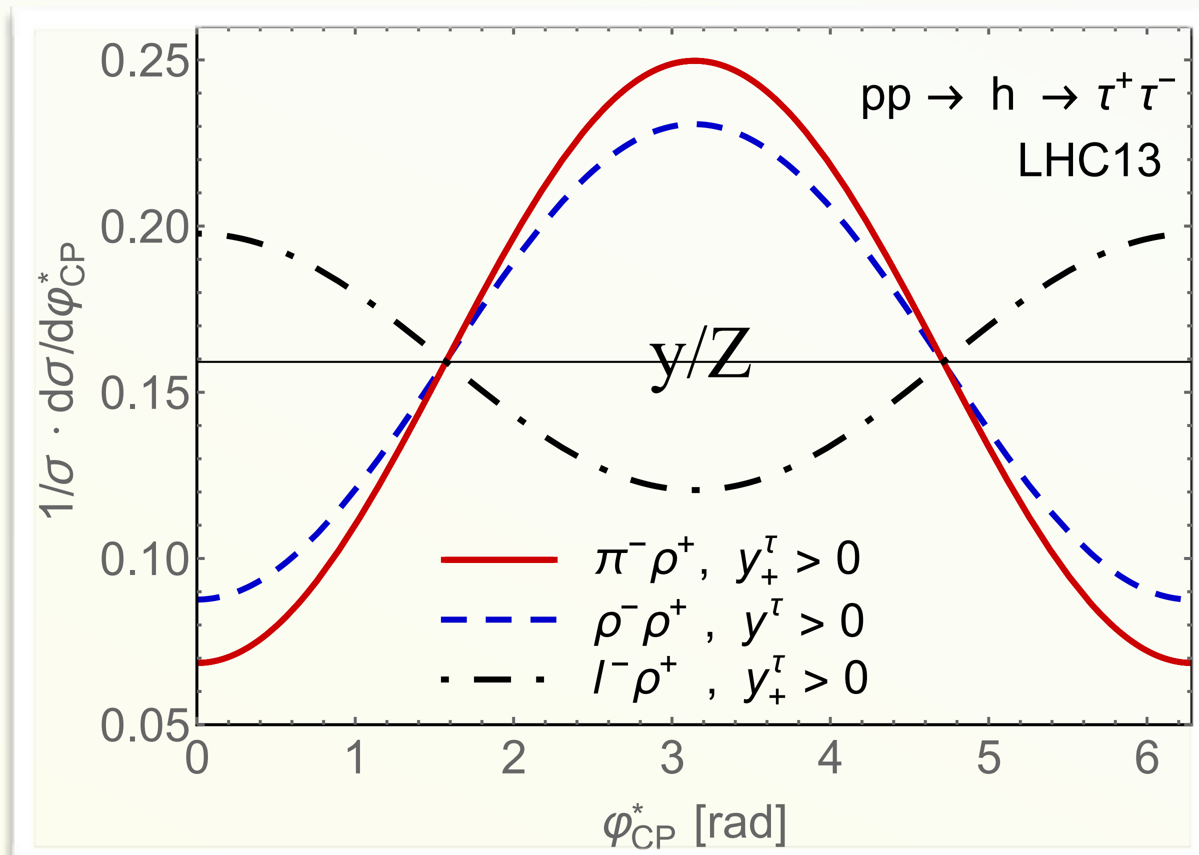
- Then one can write the definition as:

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

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

and φ^*_{CP} is defined as

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



Conclusion: Estimation of the expected precision

- Included all decay channels and all methods for gluon-gluon fusion process
- LHC 13 TeV, $M_{\tau\tau} > 100$ GeV and detector cuts
- Included simple Detector smearing
- Assumed 2 reconstructed signal+background events ($pp \to h/y/Z \to \tau\tau$) per fb
- $\to \phi_\tau$ can be measured with an uncertainty of 15° (9°) for an integrated luminosity of $150\,\mathrm{fb}^{-1}$ ($500\,\mathrm{fb}^{-1}$)
- Eventually with a luminosity of $3\,\mathrm{ab}^{-1}$ one may reach $\phi_\tau = 3.6^\circ$

$\tau\tau$ decay channel	A_S [%]	$\frac{S}{S+B}$	A_{S+B} [%]
hadron-hadron	16.2	0.5	8.1
lepton-hadron	9.4	0.5	4.7
lepton-lepton	4.5	1/3	1.5

Backup slides

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CP measurement in $h \to \tau^+\tau^- \to \rho^+\rho^- + 2\nu$ at the LHC

- The differential τ decay width for any τ decay channel can be written as:

$$d\Gamma\left(\tau^-(\hat{\mathbf{s}}^-)\right) = \frac{1}{2m_\tau}|\overline{\mathcal{M}}|^2\left[1 - \mathbf{h}^-\hat{\mathbf{s}}^-\right] d\Phi$$

- Consider the $\tau^- \to \rho^- + \nu_\tau$ decay channel:

  $\mathbf{h} = \mathcal{N}\left(2\left(q \cdot N\right) \cdot \mathbf{q} + q^2\mathbf{N}\right)$

  with $q = q^- - q_{\pi^0}$.

  In the τ rest frame it is: $q \cdot N = (E_{\pi^\pm} - E_{\pi^0})m_\tau$

  Separate events with positive and negative spin analyser using:

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

Drell-Yan background

S. B., W. Bernreuther, and S. Kirchner, arXiv:1408.0798

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Z, γ boson background

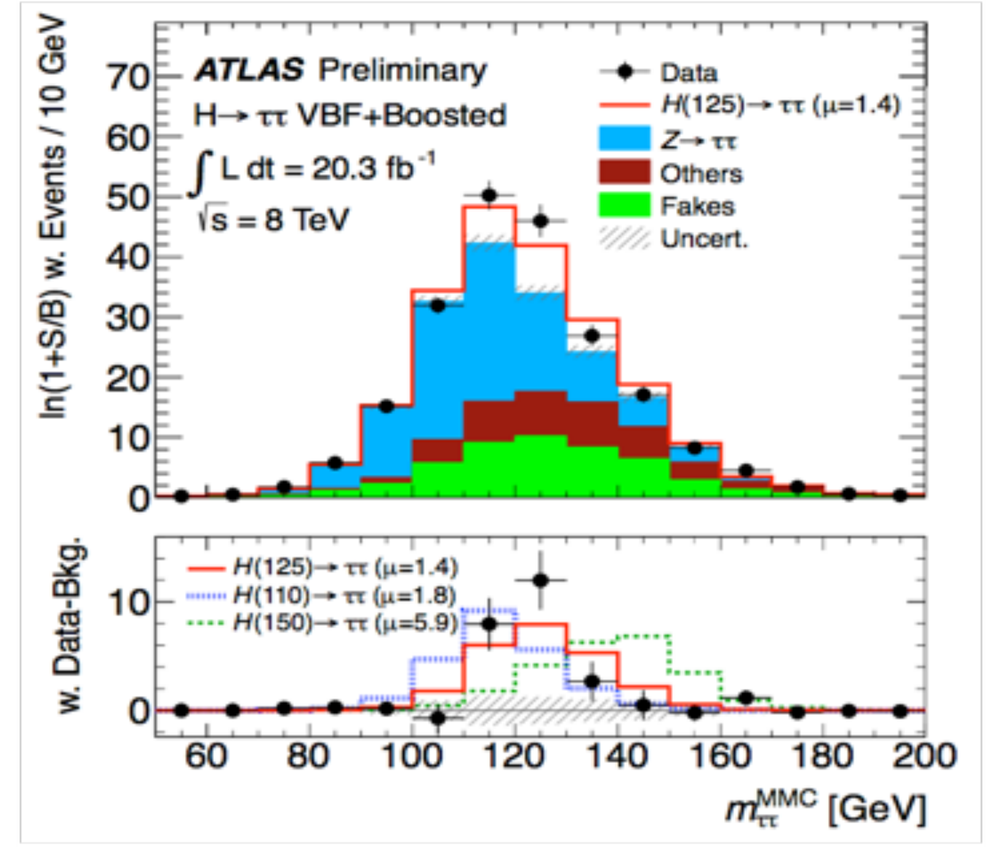
- Drell-Yan and $Z^*/\gamma^* + jets$ represent major and overwhelming background to the $h \to \tau^+\tau^-$ signal

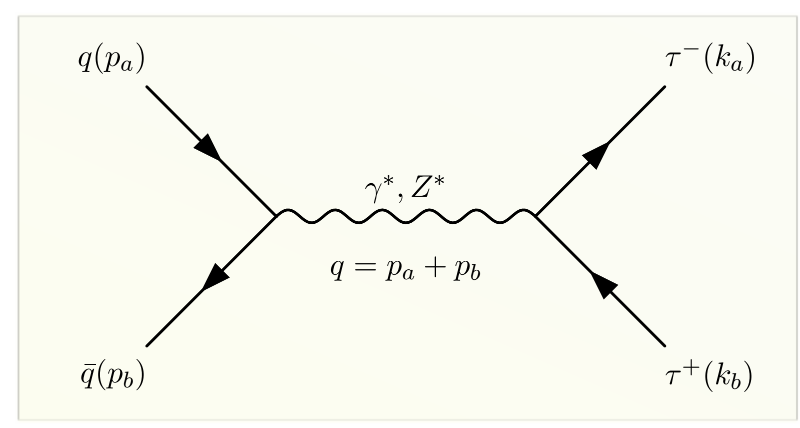
- The production of Z^*/γ^* and its decay into a pair of τ leptons does not factorize as for the Higgs signal process

- $pp \to \tau^+\tau^-$ spin density matrix needs to be calculated

- Included NLO QCD corrections in calculation of the Drell-Yan spin density matrix using standard techniques

ATLAS-CONF-2013-108



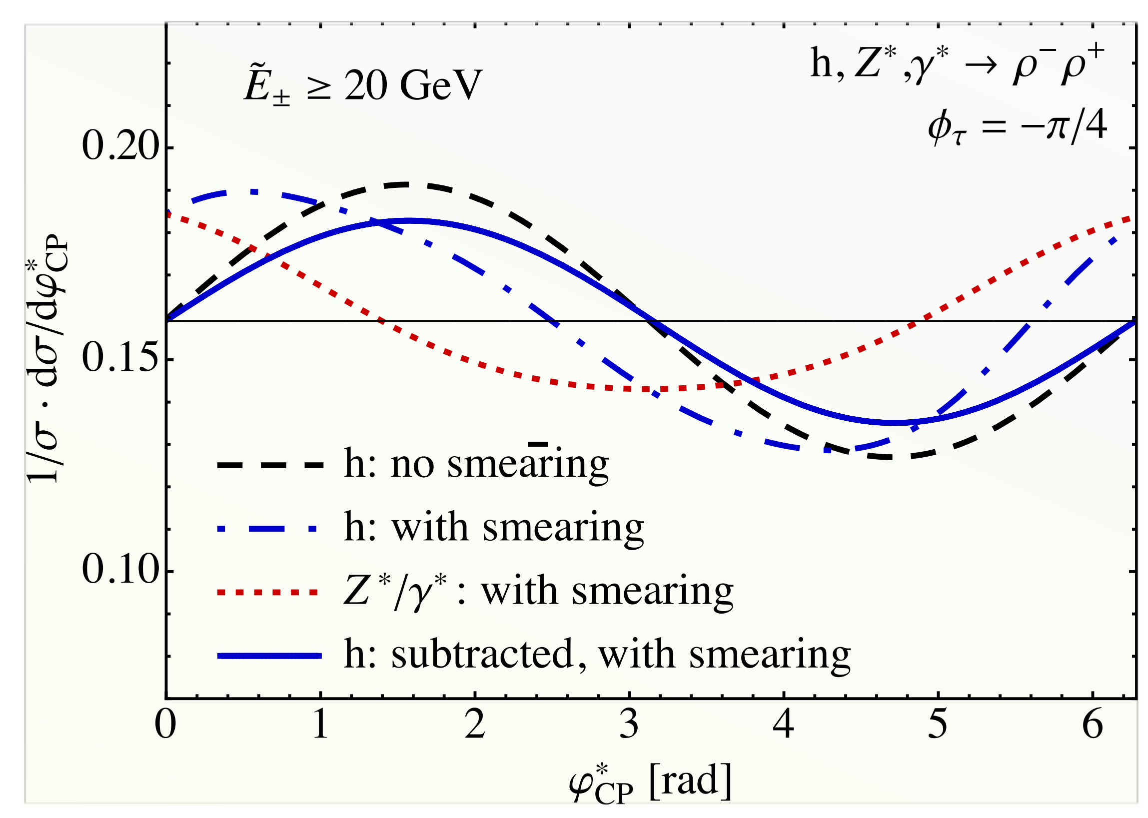


Z, γ boson background

- In dependence of $\varphi^*_{CP} = \varphi_- - \varphi_+$ (integrate out φ_+): $\frac{d\sigma_{Z,\gamma}}{d\varphi^*_{CP}} \sim 1$
- No φ^*_{CP} dependence.
- No φ^*_{CP} dependence,
  if p_T cuts are applied.
- No φ^*_{CP} dependence
  at NLO QCD.
- φ^*_{CP} is affected by
  measurement uncertainties:

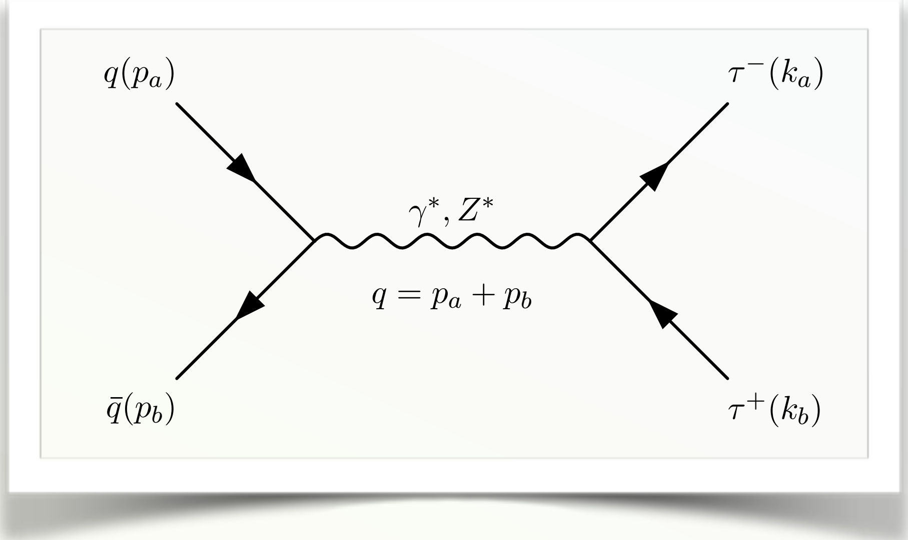
  i) Primary vertex resolution (z-direction)

  ii) Other smearing effects.
- Signal and background affected similarly



Drell-Yan background

- Drell-Yan LO cross section for $\tau^\mp \to \pi^\mp + \nu_\tau/\bar{\nu}_\tau$ decay



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

$Z\tau\tau$ 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 $\hat{k}_{\tau^-} = \hat{e}_z$

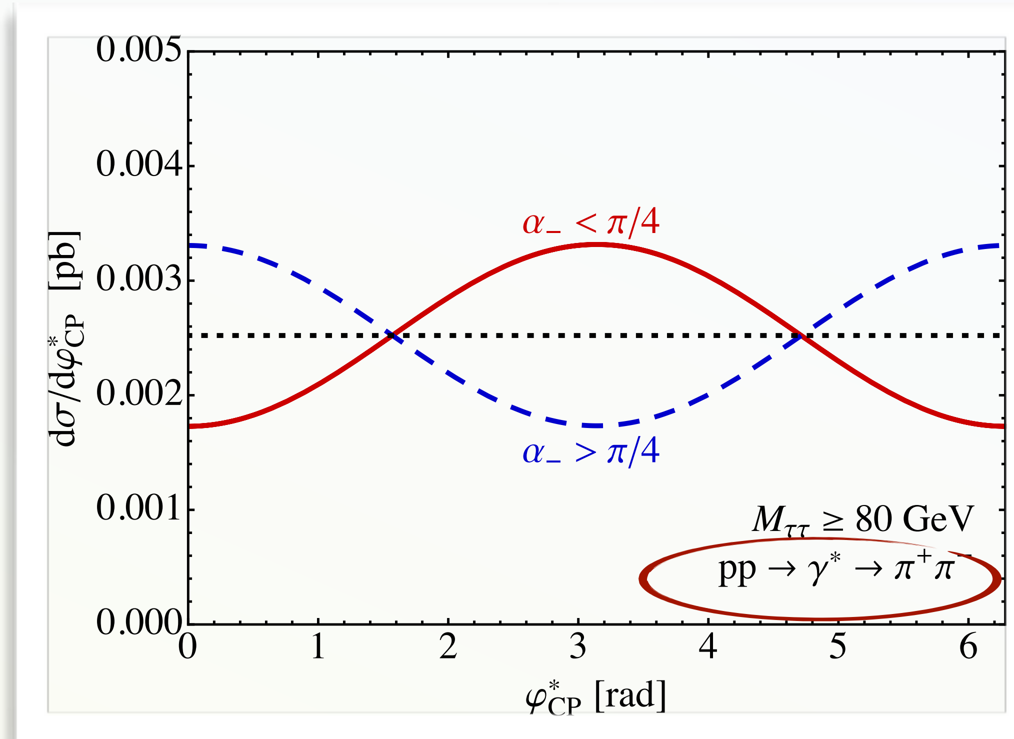
Photon background for impact parameter method1

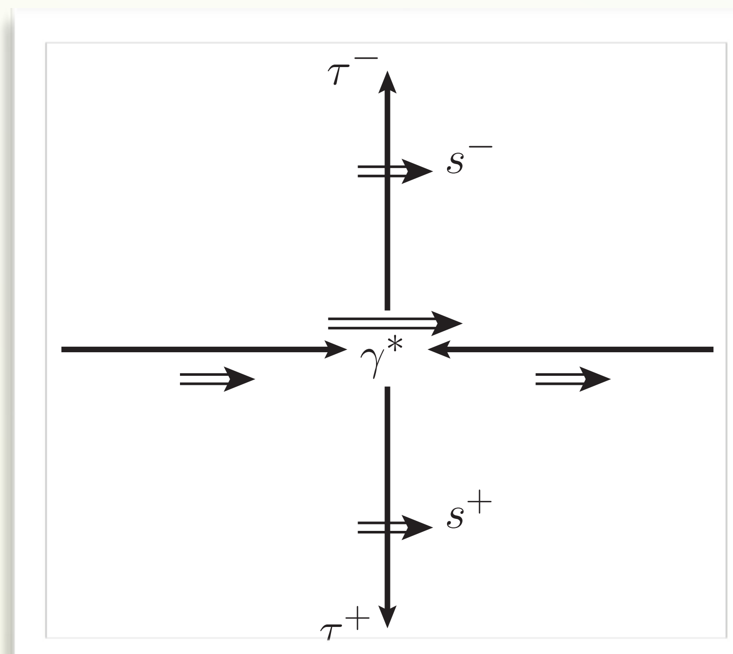
- Red line denotes events where π^- momentum is preferably parallel ($\alpha_- < \pi/4$) to $pp \to \tau^+\tau^-$ production plane.
- Blue line: events where π^- momentum is preferably perpendicular ($\alpha_- > \pi/4$).

$$\cos\alpha_- = \left| \frac{\hat{\mathbf{e}}_\mathbf{z} \times \hat{\mathbf{p}}^{\pi^-}}{|\hat{\mathbf{e}}_\mathbf{z} \times \hat{\mathbf{p}}^{\pi^-}|} \cdot \frac{\hat{\mathbf{n}}_- \times \hat{\mathbf{p}}^{\pi^-}}{|\hat{\mathbf{n}}_- \times \hat{\mathbf{p}}^{\pi^-}|} \right|$$

- Distribution opposite for Z^* exchange; Z^* dominates.

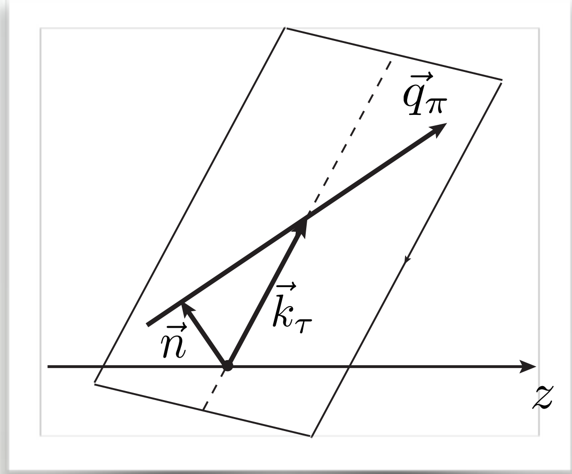
$\hat{e}_z$ … beam axis
$\hat{n}_-$ … normalized π^- impact parameter in Lab frame
$\hat{p}^{\pi^-}$ … normalized π^- momentum in Lab frame





Drell-Yan background for $\tau^{\pm}$ impact parameter method

- Split events into two classes, where the π^- momentum is either parallel or perpendicular to the $pp \to \tau^+\tau^-$ production plane:

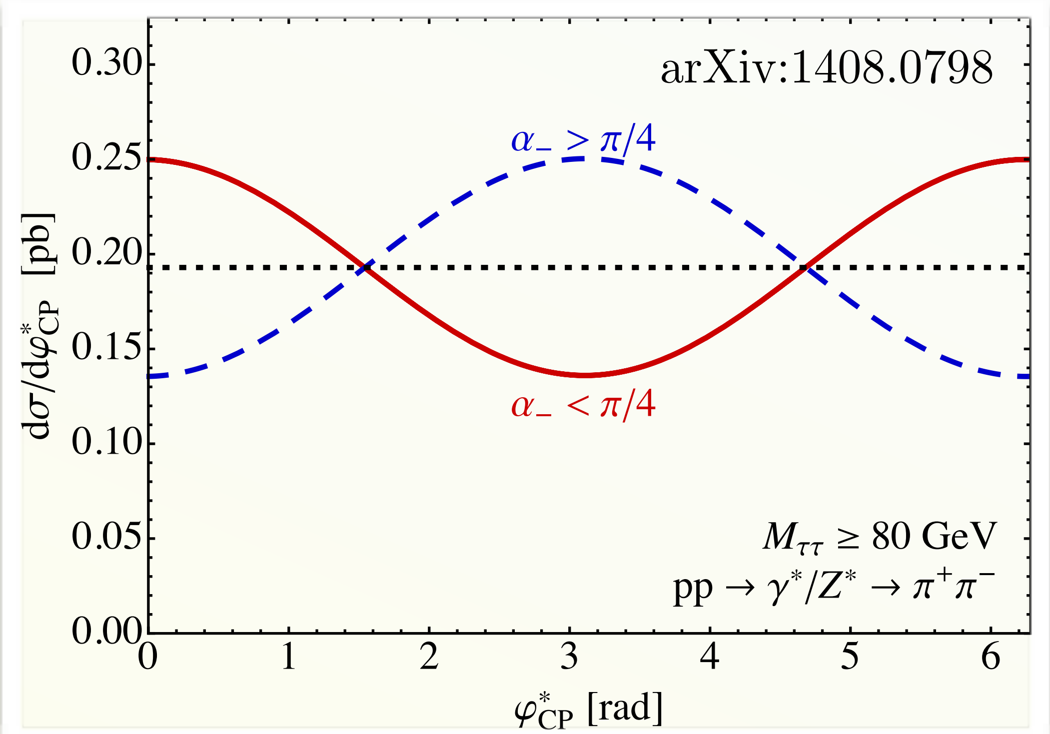


$$\cos\alpha_- \quad = \quad \left| \frac{\hat{\mathbf{e}}_\mathbf{z} \times \hat{\mathbf{p}}^{\pi^-}}{|\hat{\mathbf{e}}_\mathbf{z} \times \hat{\mathbf{p}}^{\pi^-}|} \cdot \frac{\hat{\mathbf{n}}_- \times \hat{\mathbf{p}}^{\pi^-}}{|\hat{\mathbf{n}}_- \times \hat{\mathbf{p}}^{\pi^-}|} \right|$$

- Red line denotes event where π^- momentum is preferably parallel ($\alpha_- < \pi/4$)

- Dashed blue line denotes event where π^- is preferably perpendicular ($\alpha_- > \pi/4$)

- Distribution dominated by Z^* exchange



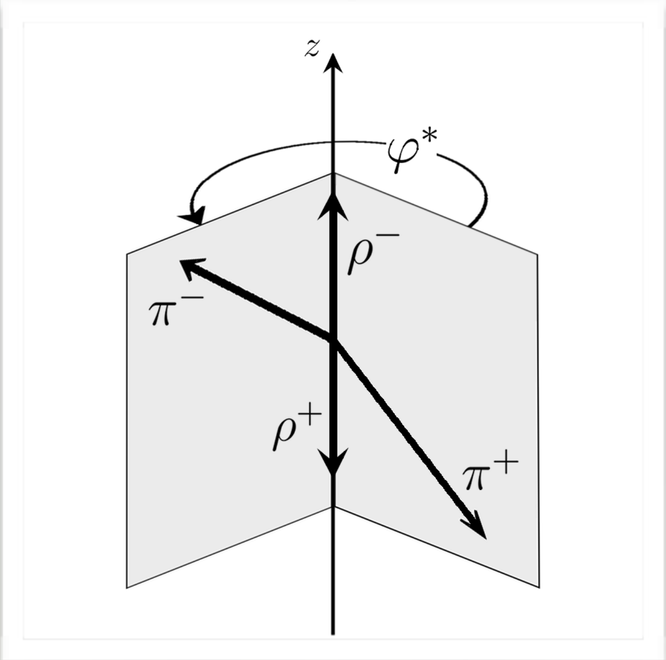
$A = 19\%$

$\hat{e}_z$ ... beam axis
$\hat{n}_-$ ... normalized π^- impact parameter in Lab frame
$\hat{p}^{\pi^-}$ ... normalized π^- momentum in Lab frame

Drell-Yan background $pp \to \tau^+\tau^- \to \rho^+\rho^- + 2\nu$ at LHC

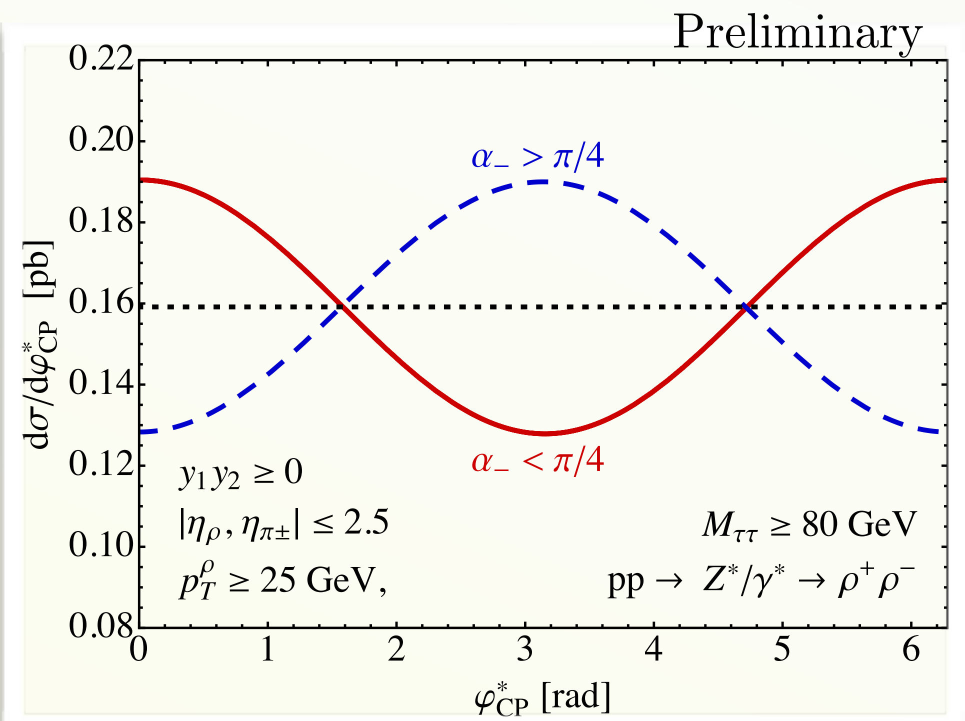
- Similar for $Z^*/\gamma^* \to \rho^+\rho^-$ decay channel, however, use ρ^- and π^- momenta:

$$\cos\alpha_- = \left| \frac{\hat{\mathbf{e}}_\mathbf{z} \times \hat{\mathbf{p}}^{\rho-}}{|\hat{\mathbf{e}}_\mathbf{z} \times \hat{\mathbf{p}}^{\rho-}|} \cdot \frac{\hat{\mathbf{p}}^{\pi-} \times \hat{\mathbf{p}}^{\rho-}}{|\hat{\mathbf{p}}^{\pi-} \times \hat{\mathbf{p}}^{\rho-}|} \right|$$



- Red line denotes event where π^- momentum is preferably parallel ($\alpha_- < \pi/4$)

- Dashed blue line denotes event where π^- is preferably perpendicular ($\alpha_- > \pi/4$)



$\hat{e}_z$ ... beam axis
$\hat{p}^{\pi^-}$ ... normalized π^- momentum in Lab frame
$\hat{p}^{\rho^-}$ ... normalized ρ^- momentum in Lab frame

$A = 12\%$