Determination of the CP quantum numbers of neutral Higgs bosons at Linear Colliders

Stefan Berge
Johannes Gutenberg-University Mainz

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Introduction

- If only one Higgs boson will be found at LHC
  - maybe SM with one Higgs double: $$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

- or a 2-Higgs doublet Model maybe realized and found at LHC/LC
  - 5 physical higgs bosons $$\begin{pmatrix} \phi_1^0 \\ \phi_1^- \end{pmatrix}, \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

  - CP is approximately conserved (e.g. MSSM)

$$\begin{aligned} &2\ CP\text{-even states: } h^0,\ H^0 \\ &1\ CP\text{-odd state: } A^0 \\ &2\ \text{charged states: } H^\pm \end{aligned}$$

  - CP is violated, neutral states mix: $h_1,\ h_2,\ h_3$

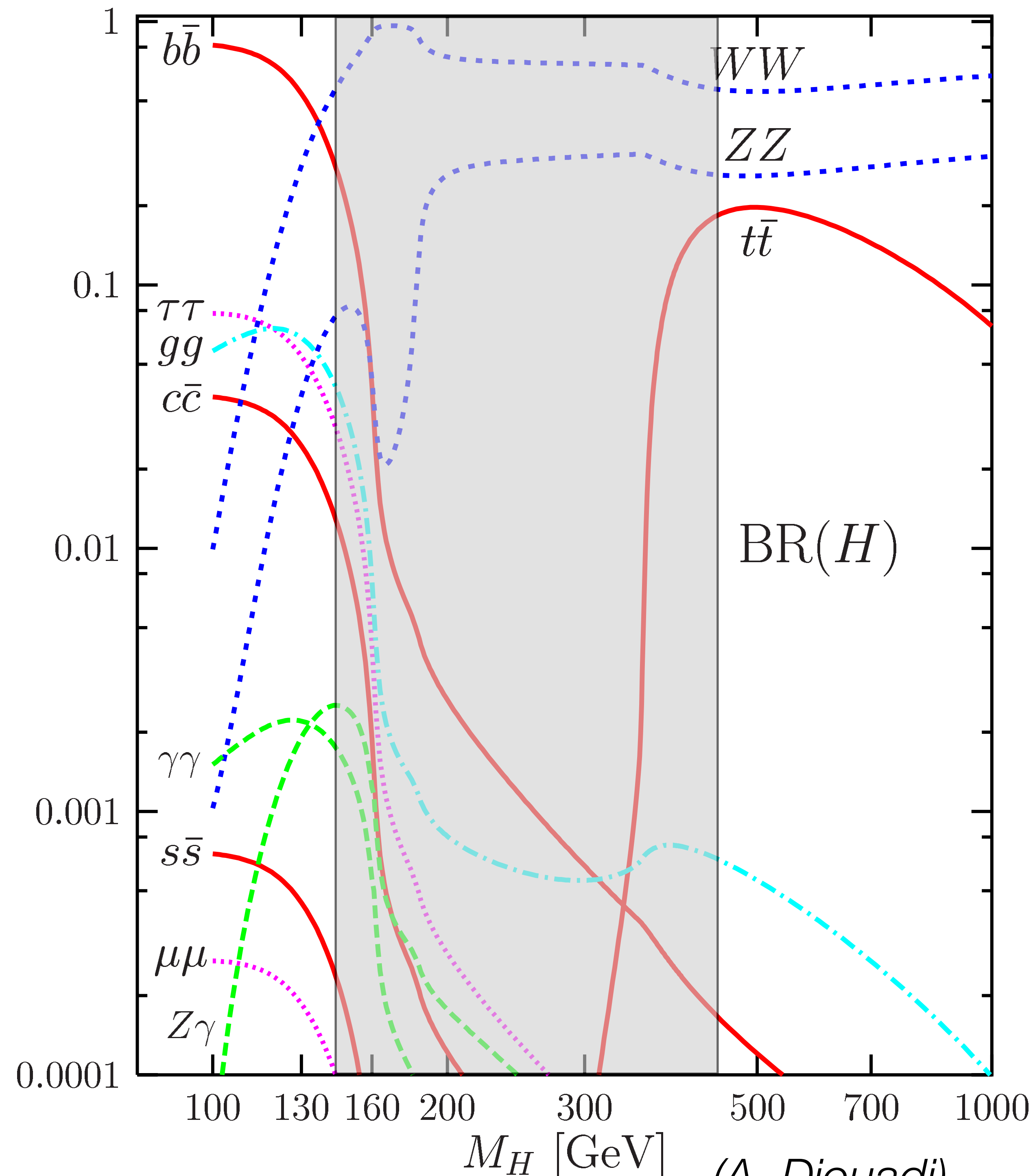
Introduction

- For neutral Spin-0 resonances: what is it's CP quantum number?

  2-Higgs doublet model:
  h, H, A: CP-even? CP-odd?
  mass degeneracy: CP violation?

- If CP is measured in the tau-tau decay, any production mode at LHC/ILC can be used, if the Higgs production vertex can be reconstructed

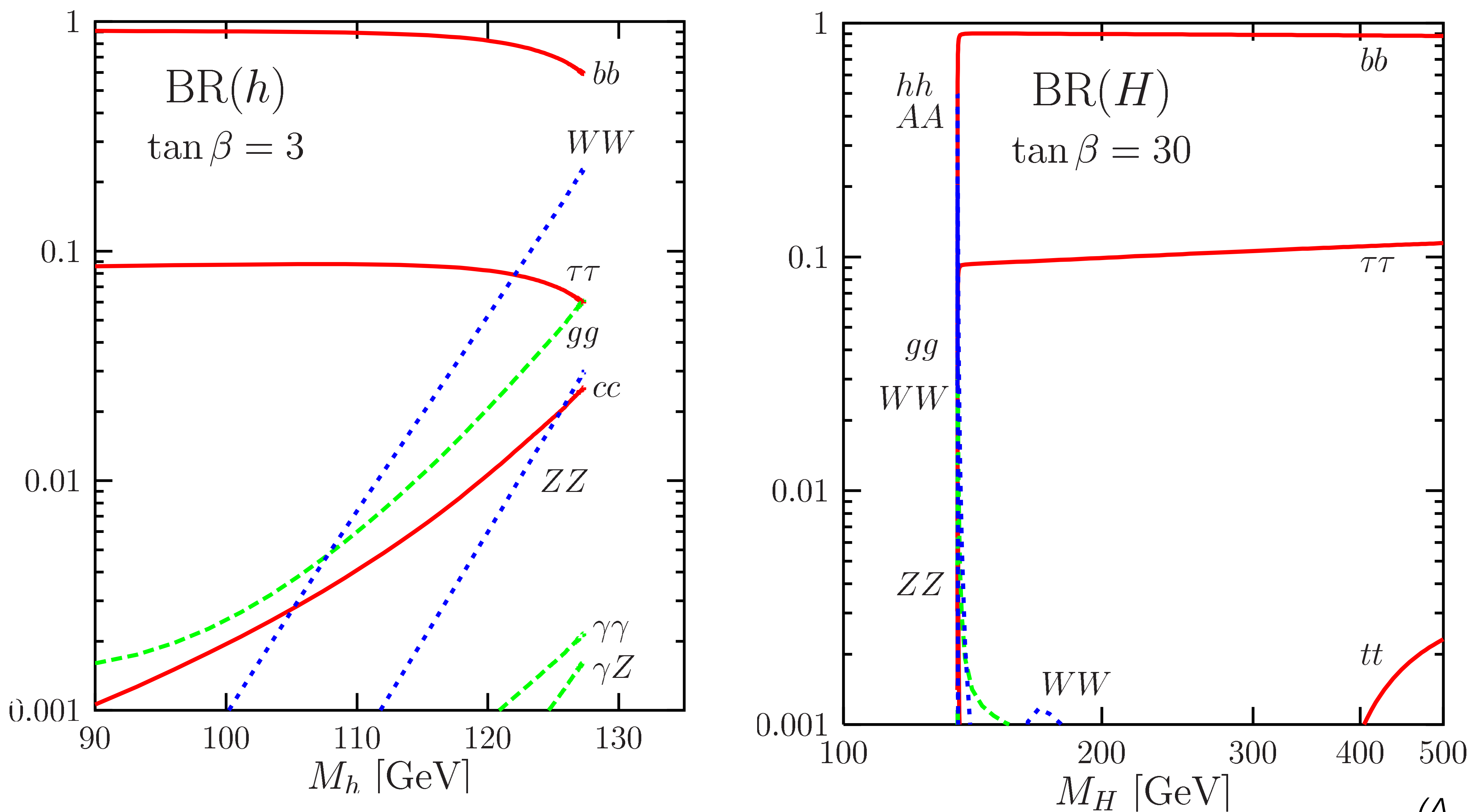
- Branching Ratio, SM:



(A. Djouadi)

Introduction

- Branching Ratio, MSSM, CP-even Higgs bosons



(A. Djouadi)

Introduction

- CP quantum numbers and possible CP violation of neutral Higgs bosons can be measured in a variety of Higgs decays or Higgs production processes, (*see also hep-ph/0608079*)

- $e^+e^- \to Z\Phi \to Z + \tau\bar{\tau}$ and $\tau \to \rho + \nu$ — *(Desch, Was, Worek '03) uses 6.3% of events*
- $e^+e^- \to Z\Phi \to Z + \tau\bar{\tau}$ and $\tau \to \pi + \nu$ — *Kramer et al. '94, Kühn, Wagner '84, Kühn '93)*
- $e^+e^- \to Z\Phi \to Z + \tau\bar{\tau}$ and $\tau \to \text{hadrons}$ — *(A. Rouge, '05) uses 23% of events; small Higgs width*

$\Phi \to f\bar{f}$ decay

- Consider the Lagrangian: $\mathcal{L}_Y = -\frac{m_f}{v}\left(a \cdot \bar{f}f + b \cdot i\bar{f}\gamma_5 f\right)\phi$
- If Higgs decays into a fermion-antifermion pair $\phi^0 \to f\bar{f}$

  $f\bar{f}$ pair has $P = (-1)^{L+1}$ and $C = (-1)^{L+S}$

  with total Spin S and orbital angular momentum L

- if $f\bar{f}$ is in ${}^1S_0$ state :
  - $\to\ J^{PC} = 0^{-+}$
  - $\to\ A^0$
  - $\to \langle \mathbf{s}_1 \cdot \mathbf{s}_2 \rangle = -\frac{3}{4}$
  - $\to a = 0, b = 1$

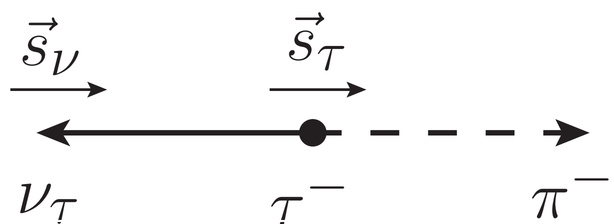
  if $f\bar{f}$ is in ${}^3P_0$ state :
  - $\to\ J^{PC} = 0^{++}$
  - $\to\ H^0, h^0$
  - $\to \langle \mathbf{s}_1 \cdot \mathbf{s}_2 \rangle = \frac{1}{4}$
  - $\to a = 1, b = 0$

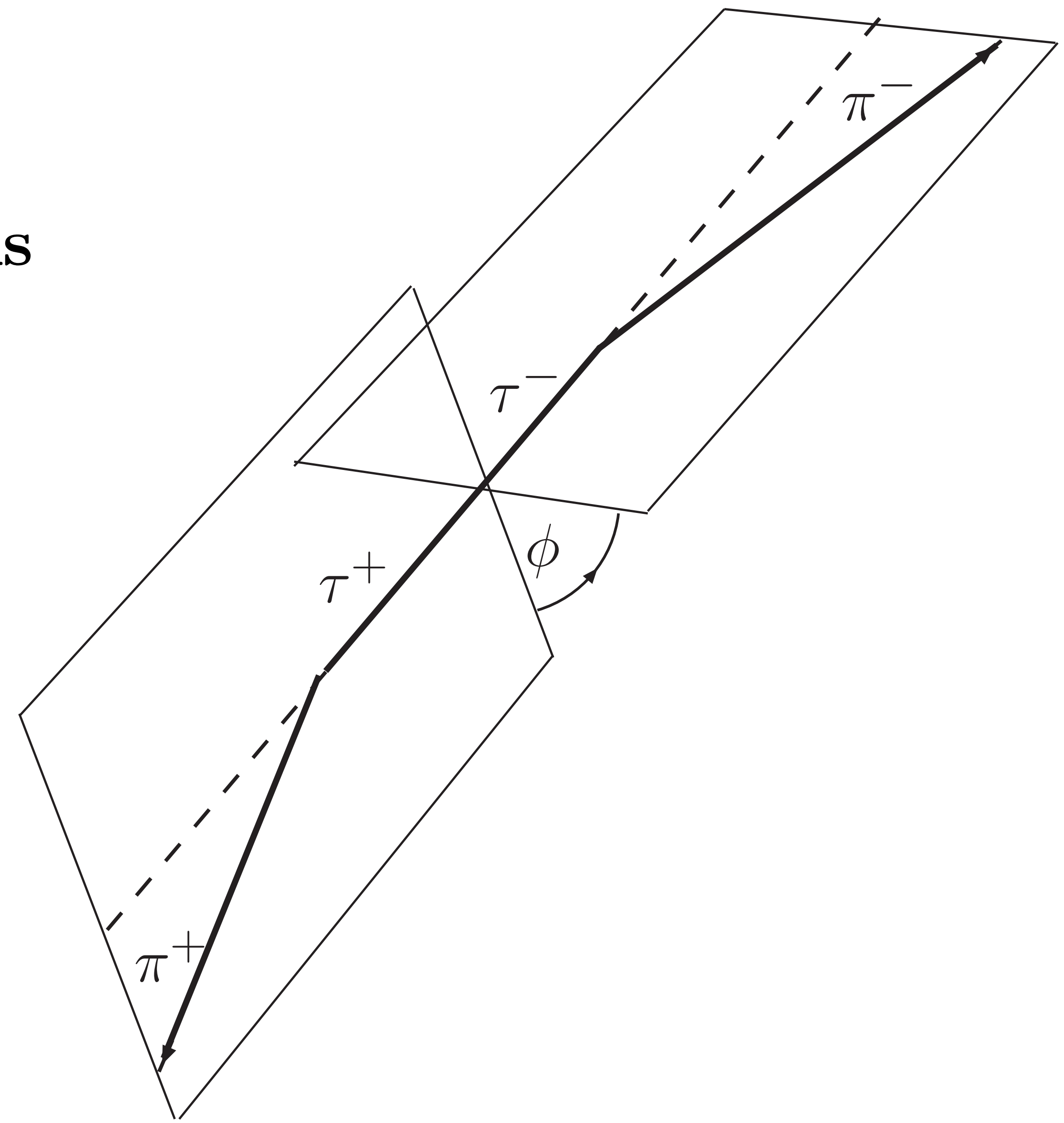
$\Phi \to \tau\tau$ decay

- **How to measure tau spins?**
  Consider: $\tau^- \to \pi^- + \nu_\tau$
- **Decay probability can be written as** ***(Barger et al. '79)***

  $$\Gamma(H, A \to \tau^-\tau^+) \sim 1 - \mathbf{s}_\mathbf{z}^- \, \mathbf{s}_\mathbf{z}^+ \pm \mathbf{s}_\mathbf{T}^- \, \mathbf{s}_\mathbf{T}^+$$

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





- **Then,** $\varphi = acos\left(\hat{\vec{q}}_{\pi^-} \cdot \hat{\vec{q}}_{\pi^+}\right)$ **is sensitive to** $\tau\tau$ **spin correlation (**$\hat{\vec{q}}_{\pi^\pm}$ **defined in** $\tau^\pm$ **rest frame)**

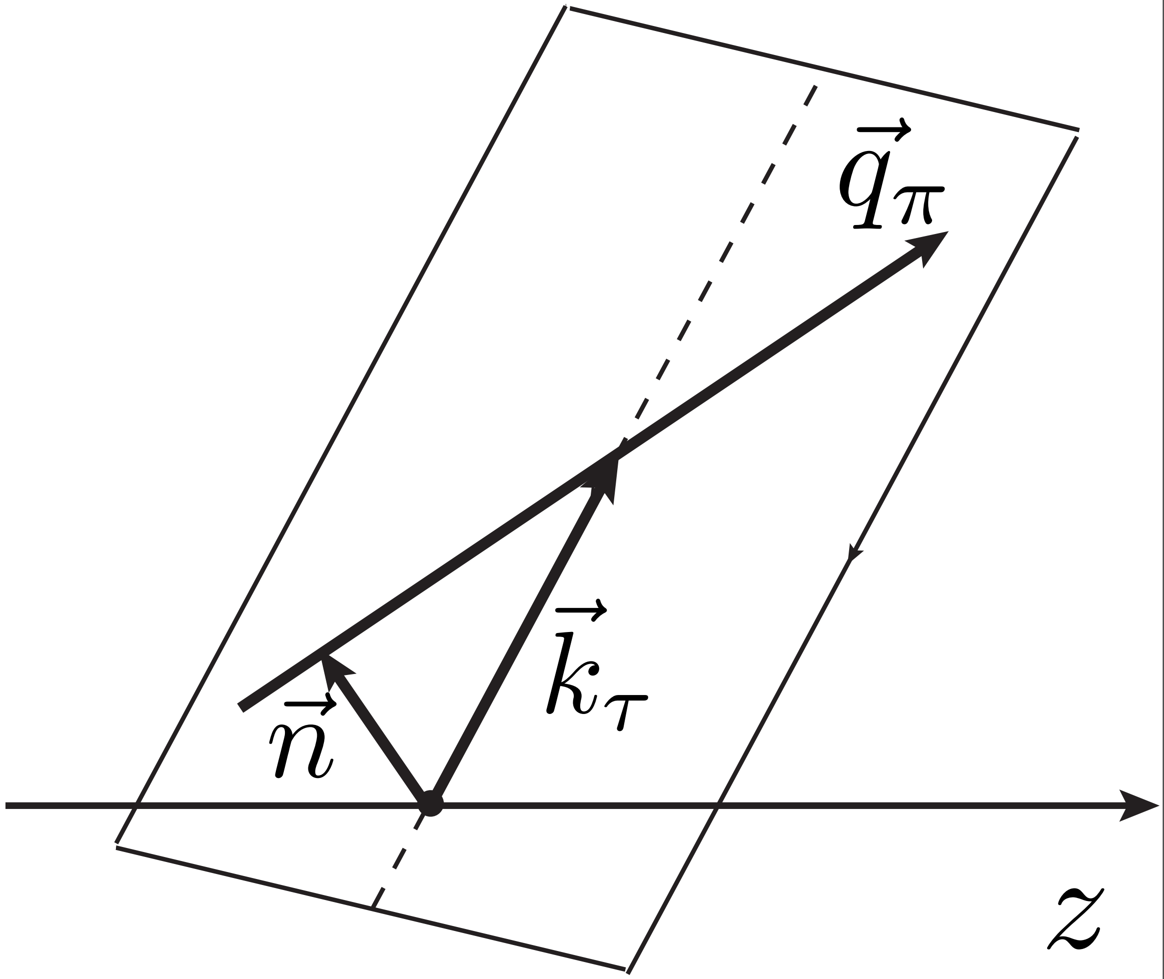
$\Phi \to \tau\tau$ decay

- **Instead of $\hat{\vec{q}}_\pi$ use reconstructed impact parameter vectors**
  $\varphi = acos(\hat{\mathbf{n}}_- \cdot \hat{\mathbf{n}}_+)$

- **Boost $\hat{\vec{n}}_\pm$ into $\pi^-\pi^+$-ZMF ($n^\mu n_\mu = -1$):**

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

  Same distribution as in $\tau\tau$ - ZMF.



$\to$ **Measurement of PV necessary (from $Z \to e^+e^-$)**

$\to$ **Due to boost into $\pi^-\pi^+$-ZMF, no reconstruction of τ rest frames necessary.**

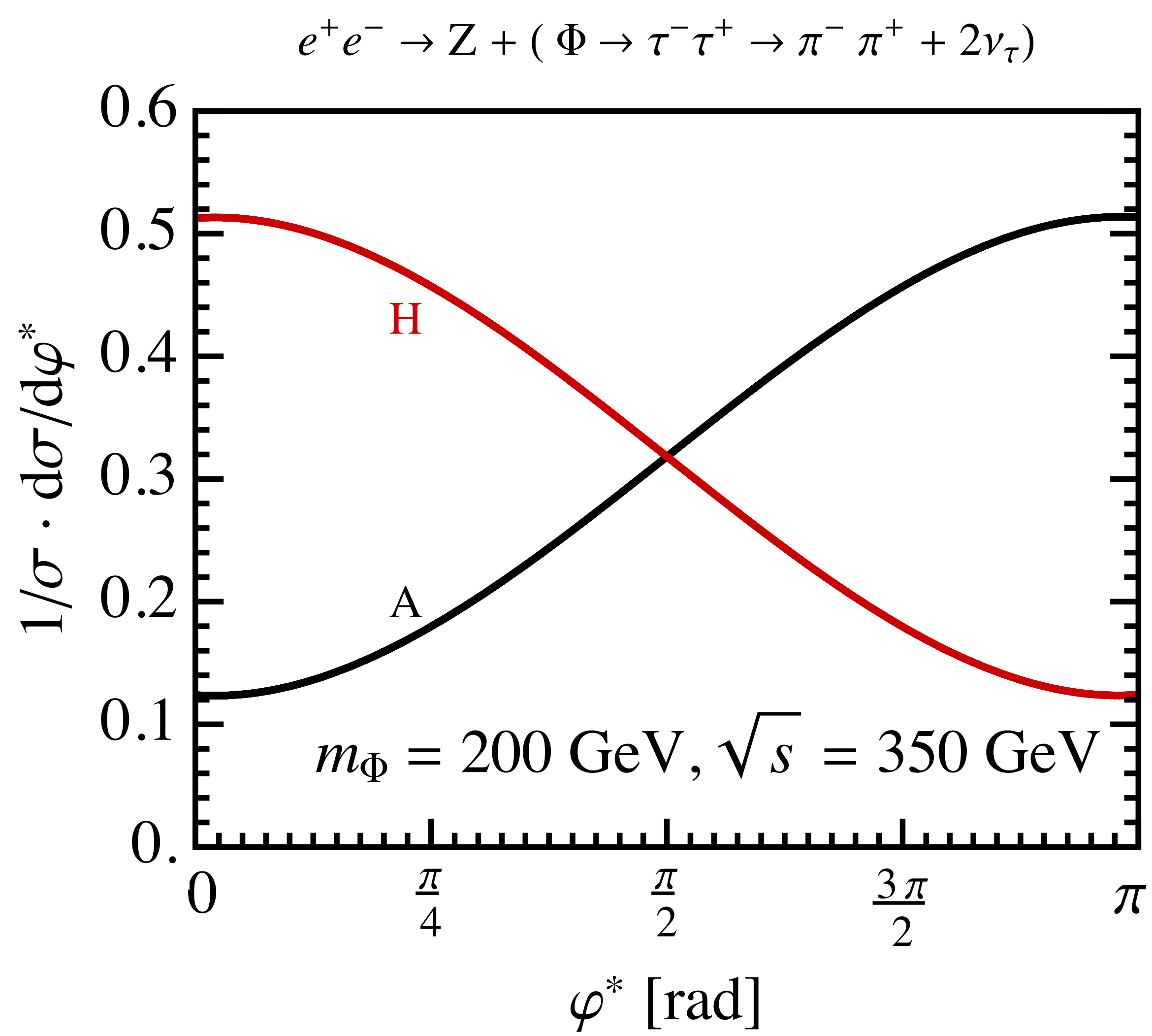
$\Phi \to \tau\tau$ decay

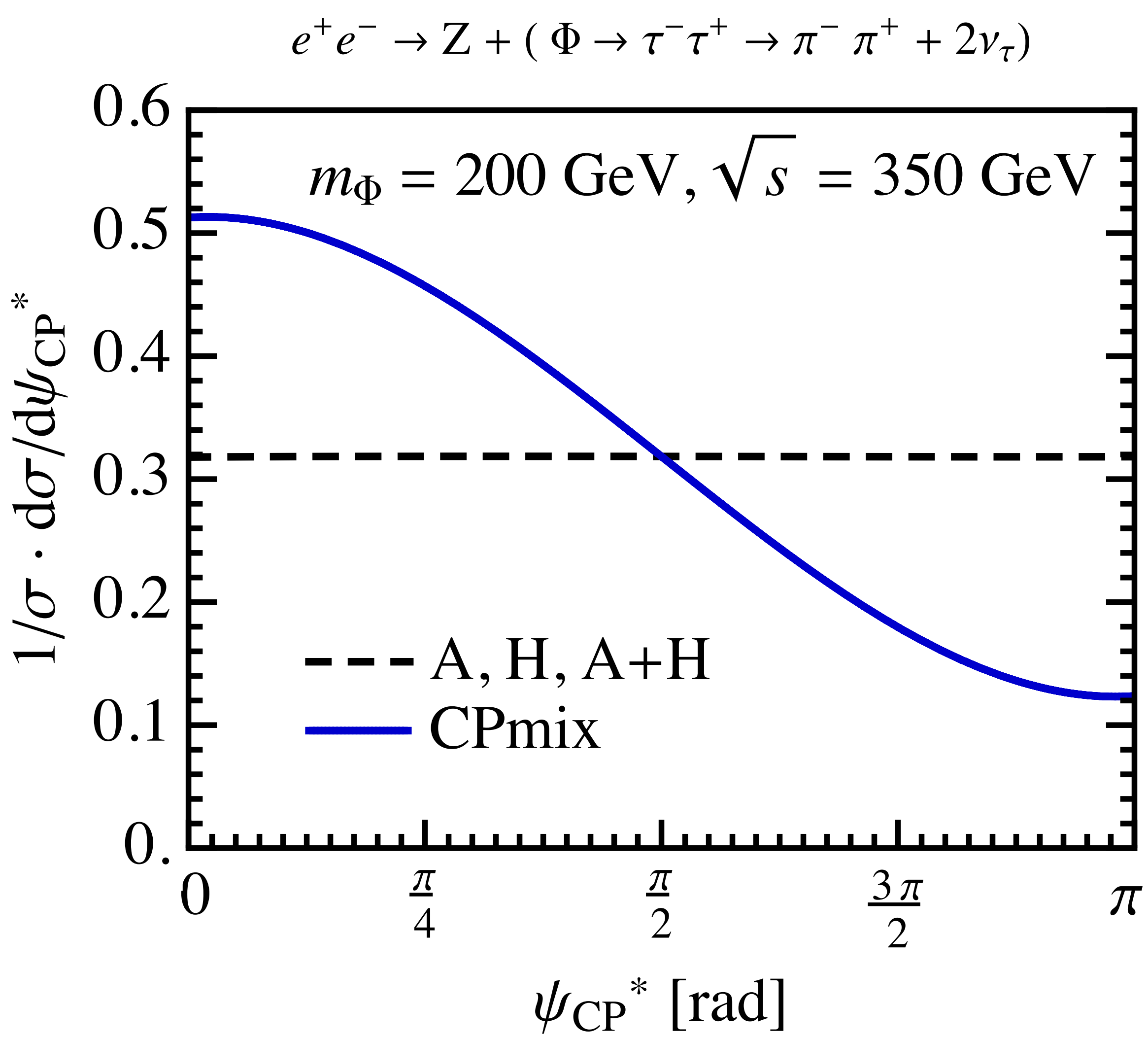
$$\mathcal{O}_2 = \hat{\mathbf{k}}_1 \cdot (\mathbf{s}_1 \times \mathbf{s}_2)$$

$$\mathcal{O}_3 = \mathbf{s}_1 \cdot \mathbf{s}_2$$

$$\psi^*_{CP} = acos(\hat{\mathbf{q}}^*_1 \cdot (\hat{\mathbf{n}}^*_{1\perp} \times \hat{\mathbf{n}}^*_{2\perp}))$$

$$\varphi^* = acos(\hat{\mathbf{n}}^*_{1\perp} \cdot \hat{\mathbf{n}}^*_{2\perp})$$

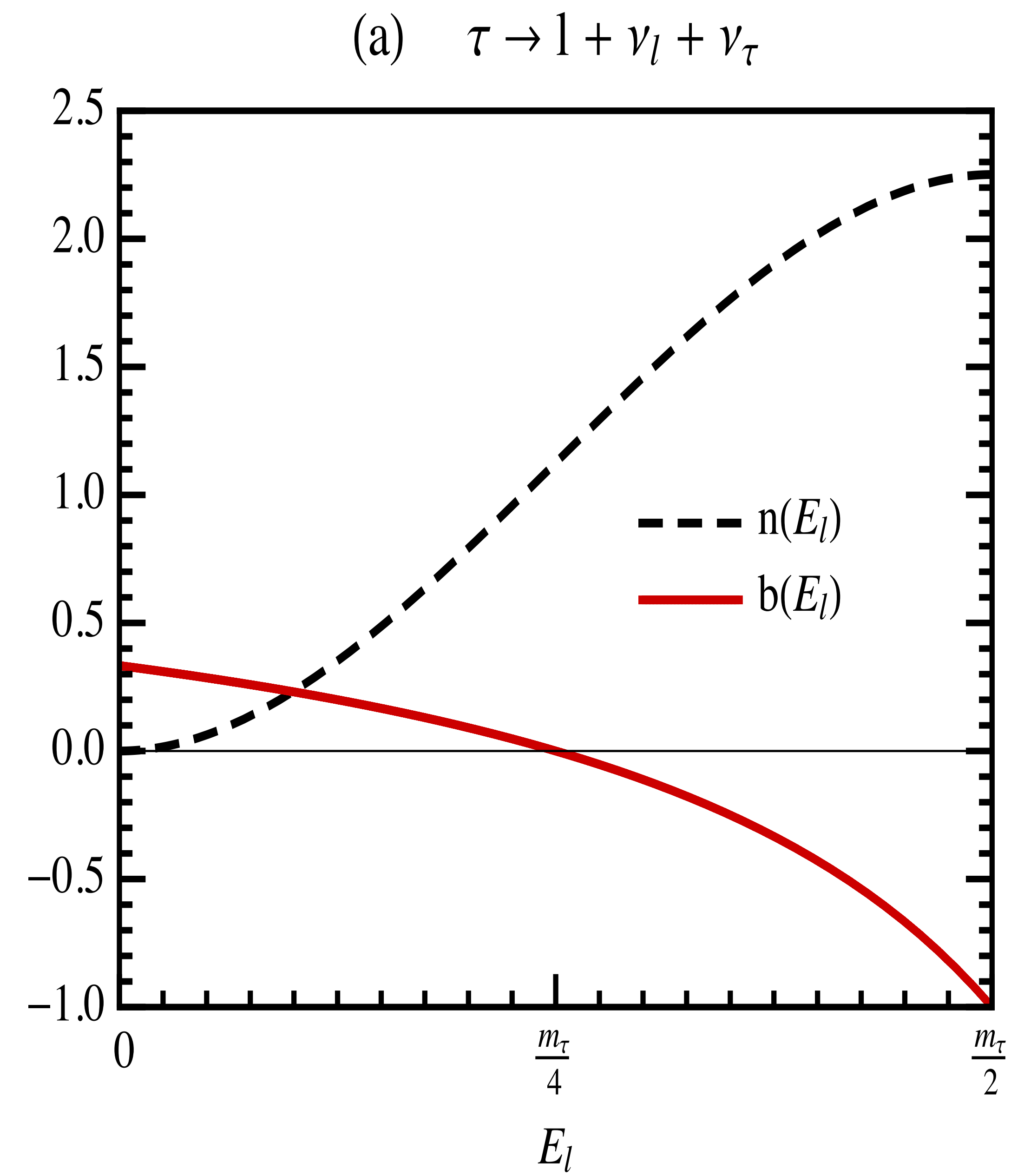




$\Phi \to \tau\tau$ decay

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

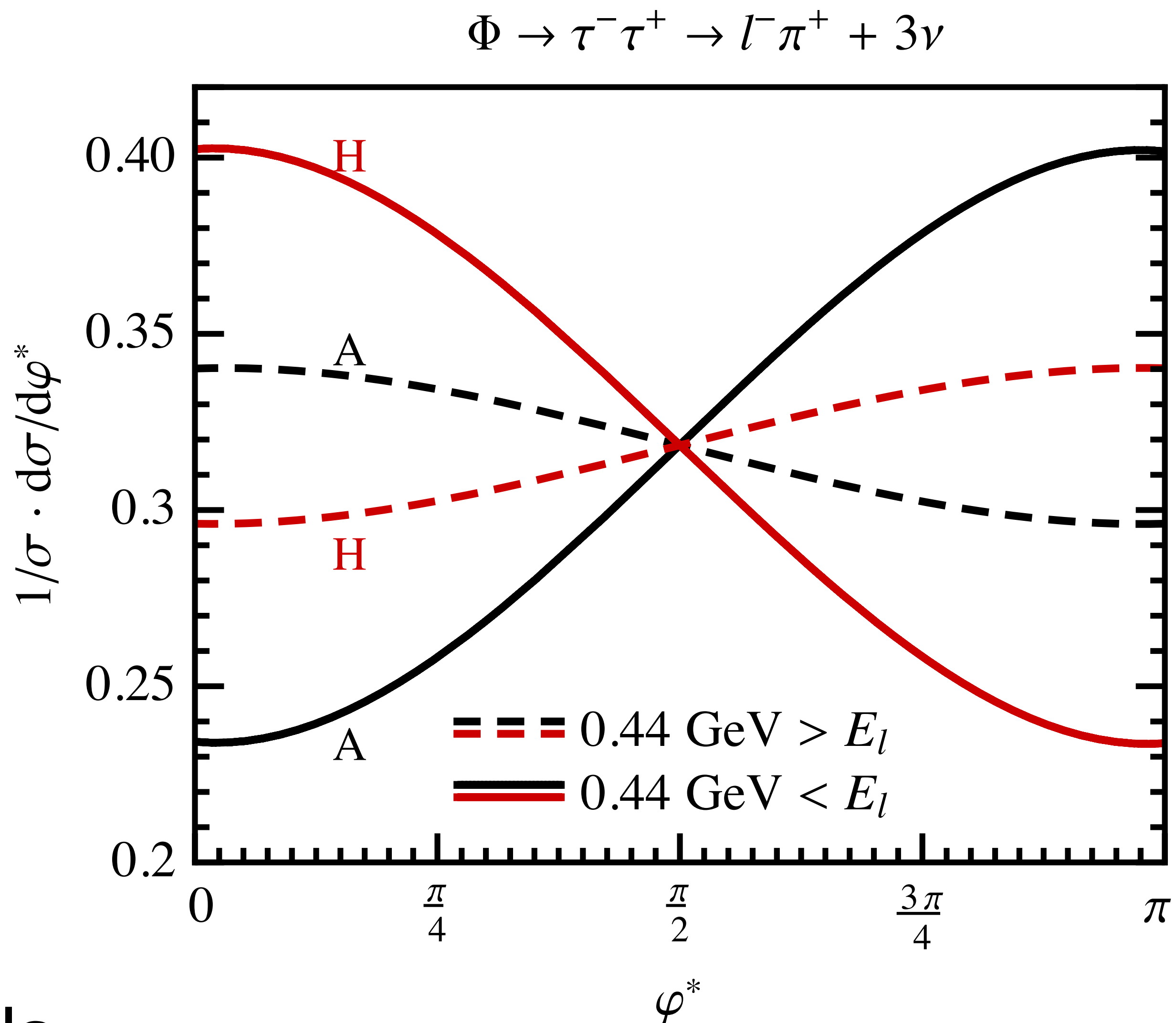
decay mode	BR_{PDG} [%]
$\tau^- \to \pi^-$	11
$\tau^- \to \rho^- \to \pi^-\pi^0$	25.5
$\tau^- \to a_1^- \to \pi^- 2\pi^0$	9.3
$\tau^- \to a_1^- \to \pi^-\pi^+\pi^-$	9
$\tau^- \to e^-, \mu^-$	35.2



- Energy not fixed in lepton, rho, a1 decay channel
- $b(E_l)$ determines spin analyzer quality
- $n(E_l)$ determines overall contribution to cross section

$\Phi \to \tau\tau$ decay

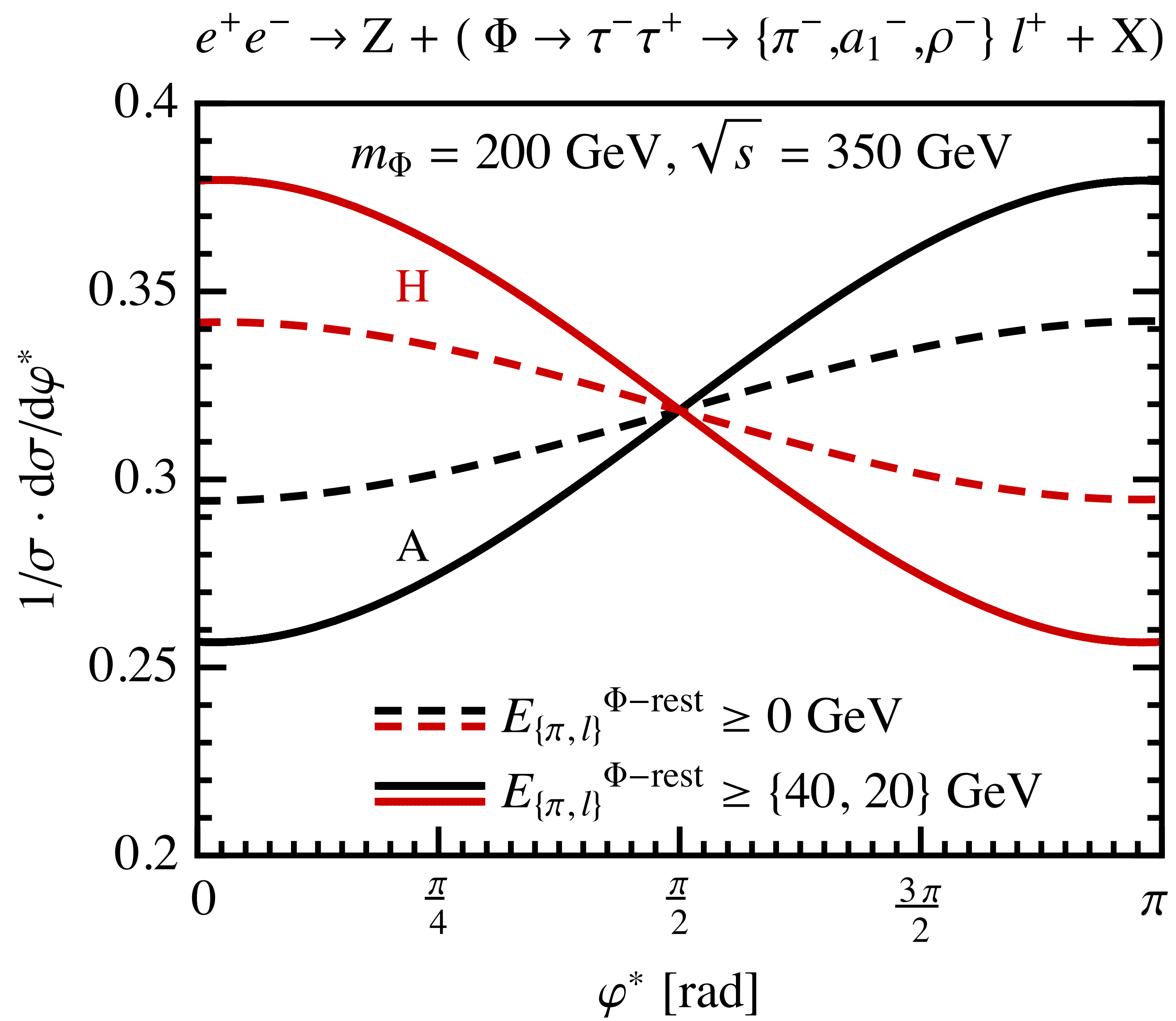
- Leptonic decay: $\tau^- \to l^- + \nu_\tau + \bar{\nu}_l$
- Assume theoretical cut at $E_l = \frac{m_\tau}{2}$
- Slopes are opposite for E<0.44 GeV and E>0.44 GeV
- Discrimination power deceases when integrated over whole range
- Behavior worse for hadronic channels $b(E_{a_1,\rho})$ opposite to leptonic decay
- Needs to separate small and large El



$\Phi \to \tau\tau$ decay

Combined hadron-lepton channel

$$\tau^+\tau^- \to \{a_1, \rho, \pi\}^+ + l^- + X$$



- Events with small Energy in the Higgs rest frame have preferably small energy in the corresponding tau rest frame

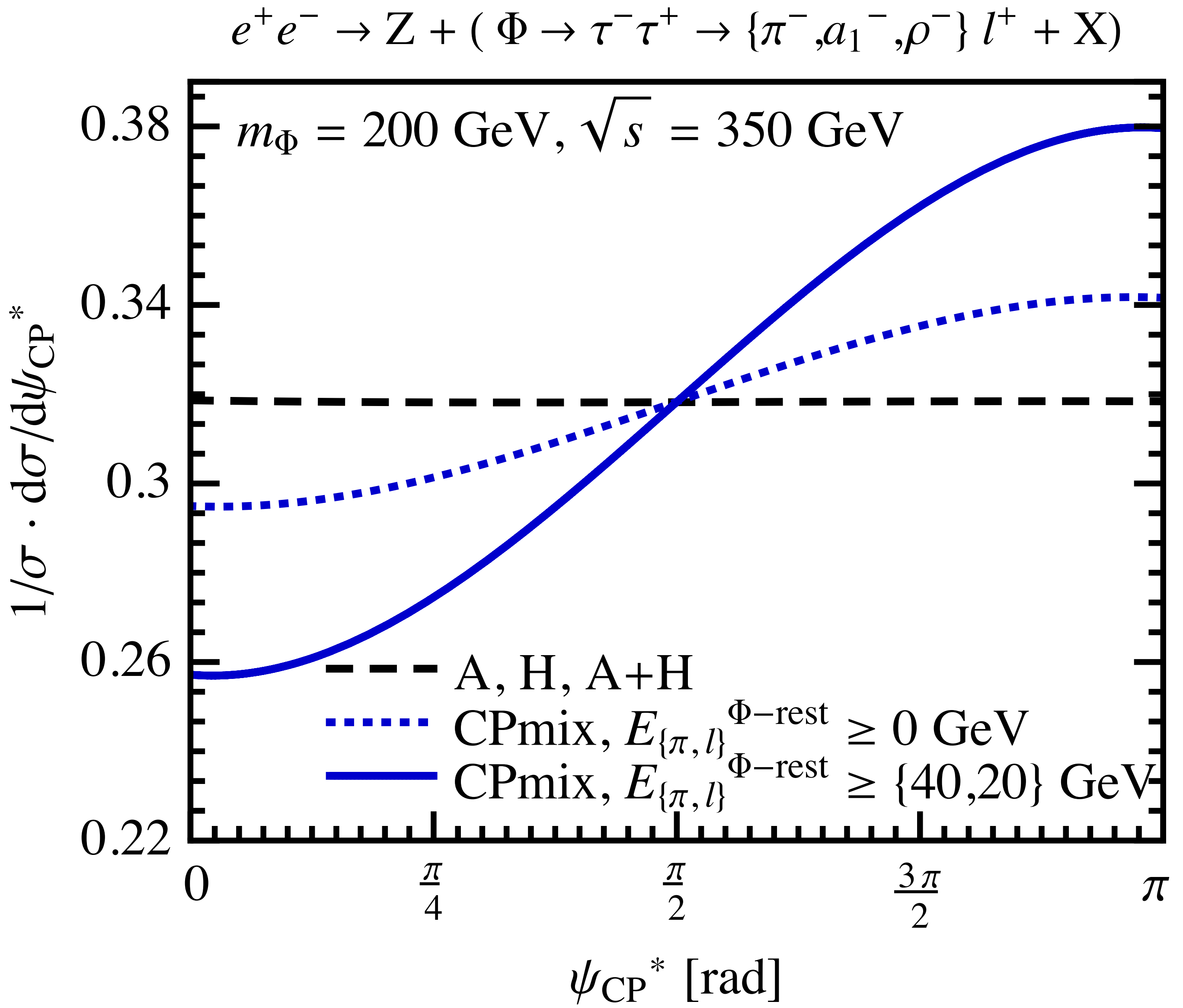
- Discrimination power can be improved, by cuts on the lepton/pion energy in the Higgs rest frame

$\Phi \to \tau\tau$ decay

- Testing CP mixed states

$$\psi^*_{CP} = acos(\, \hat{\mathbf{q}}^*_1 \cdot (\hat{\mathbf{n}}^*_{1\perp} \times \hat{\mathbf{n}}^*_{2\perp})\,)$$

- Fig.: maximal mixing a = - b
- Black-dashed for CP eigen-states and degenerated mass
- Opposite slope for
  1) ll, hadron-hadron channel
  2) a = b

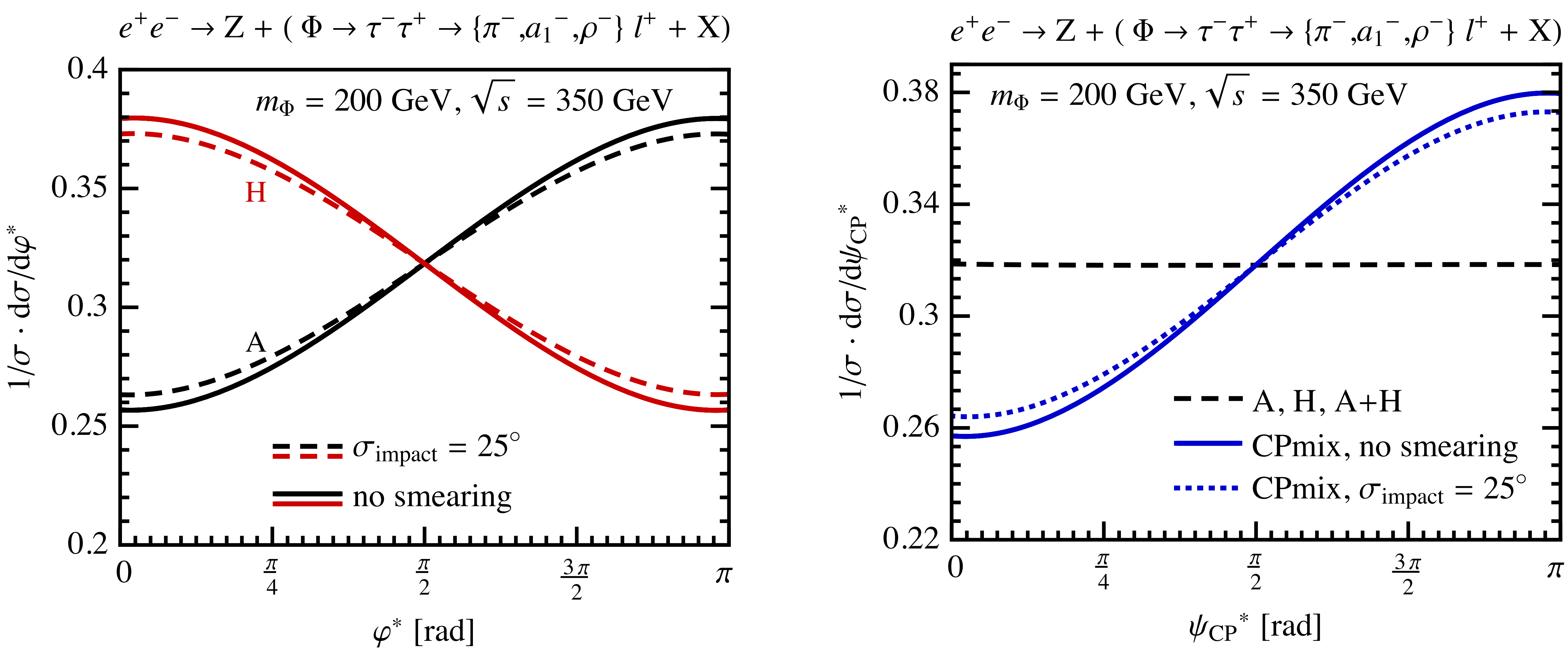


$\Phi \to \tau\tau$ decay

Combined hadron-lepton channel

$$\tau^+\tau^- \to \{a_1, \rho, \pi\}^+ + l^- + X$$

- Gaussian smearing of impact parameter measurement with $\sigma_{impact} = 25^o$ suggest in *worek '03*



Conclusion

- Determination of the CP quantum number of a neutral, Spin-0 resonances is possible in the $\tau\tau$ decay channel, where all dominant tau-decay channels can be included

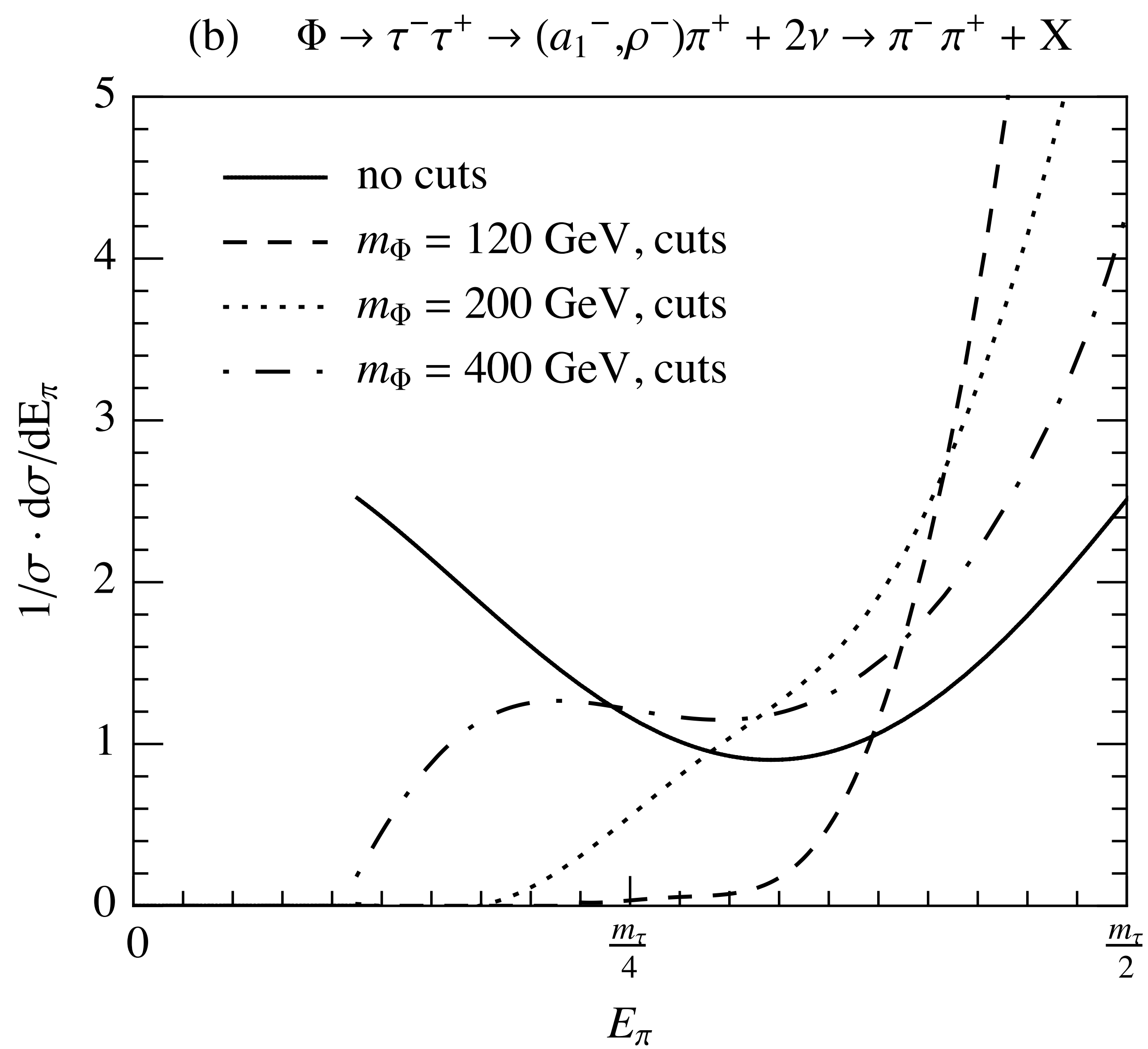
  -> Important: no reconstruction of tau 4-momenta necessary

- CP-odd and CP-even eigenstates can be distinguished in this decay mode by measuring the $\varphi^* = acos(\hat{\mathbf{n}}^*_{1\perp} \cdot \hat{\mathbf{n}}^*_{2\perp})$ distribution

- CP mixed Higgs boson states can be measured in the decay to tau-tau by determining the triple product $\psi^*_{CP} = acos(\hat{\mathbf{q}}^*_1 \cdot (\hat{\mathbf{n}}^*_{1\perp} \times \hat{\mathbf{n}}^*_{2\perp}))$

$\Phi \to \tau\tau$ decay

- Hadronic decay channel
  $$\tau^- \to \{a_1^-, \rho^-\} + \nu_\tau \to \pi^- + X$$
- Events with small Energy in the Higgs rest frame have preferably small energy in the corresponding tau rest frame
- Effect more pronounced as lighter the Higgs mass is
- Direct pion decay energy fixed



$\Phi \;\rightarrow\; f\bar{f}$ decay

- Lagrangian: $\mathcal{L}_Y = -\frac{m_f}{v}\left(a\cdot\bar{f}f + b\cdot i\bar{f}\gamma_5 f\right)\phi$

- Spin-density matrix: $$R_{\alpha_1\alpha_2,\beta_1\beta_2}(\vec{k}) = \sum_X \langle f(k_1,\alpha_1),\bar{f}(k_2,\beta_1),X|\mathcal{T}|\phi(q)\rangle \langle f(k_1,\alpha_1),\bar{f}(k_2,\beta_1),X|\mathcal{T}|\phi(q)\rangle^*$$

- Decomposition in spin space of f and $\bar{f}$ in $f\bar{f}$ center of mass system:

$$R = A\cdot\mathbb{1}\otimes\mathbb{1} + \vec{B}^+\cdot\boldsymbol{\vec{\sigma}}\otimes\mathbb{1} + \mathbb{1}\otimes\boldsymbol{\vec{\sigma}}\cdot\vec{B}^- + C_{ij}\,\sigma_i\otimes\sigma_j$$

refers to spin space of f

spin space of $\bar{f}$

- with $\vec{B}^\pm = b^\pm\,\hat{k}_1$

$$C_{ij} = c_1\,\delta_{ij} + c_2\,\hat{k}_{1i}\hat{k}_{1j} + c_3\epsilon_{ijk}\,\hat{k}_{1k}$$

- $A,\ b^\pm,\ c_1,\ c_2,\ c_3$ can be determined by a set of observables (and calculated)

$\Phi \to f\bar{f}$ decay

- Define observables *(Bernreuther et al. hep-ph/9701347)*

$$
\begin{aligned}
\mathcal{O}_0 &= \hat{\mathbf{k}}_1 \cdot (\mathbf{s}_1 + \mathbf{s}_2) \\
\mathcal{O}_1 &= \hat{\mathbf{k}}_1 \cdot (\mathbf{s}_1 - \mathbf{s}_2) \\
\mathcal{O}_2 &= \hat{\mathbf{k}}_1 \cdot (\mathbf{s}_1 \times \mathbf{s}_2) \\
\mathcal{O}_3 &= \mathbf{s}_1 \cdot \mathbf{s}_2 \\
\mathcal{O}_4 &= (\hat{\mathbf{k}}_1 \cdot \mathbf{s}_1)(\hat{\mathbf{k}}_1 \cdot \mathbf{s}_2)
\end{aligned}
$$

$$\langle \mathcal{O}_i \rangle = \frac{Tr\{R \cdot \mathcal{O}_i\}}{Tr\{R\}}$$

$$
\begin{aligned}
\langle \mathcal{O}_0 \rangle &= \frac{2(b^+ + b^-)}{4A} \\
\langle \mathcal{O}_1 \rangle &= \frac{2(b^+ - b^-)}{4A} \\
\langle \mathcal{O}_2 \rangle &= \frac{2c_3}{4A} \\
\langle \mathcal{O}_3 \rangle &= \frac{3c_1 + c_2}{4A} \\
\langle \mathcal{O}_4 \rangle &= \frac{c_1 + c_2}{4A}
\end{aligned}
$$

- $\mathbf{s}_1 = \frac{1}{2}\sigma \otimes \mathbb{1}$ and $\mathbf{s}_1 = \frac{1}{2}\mathbb{1} \otimes \sigma$ are the spin operators of f and $\bar{f}$

	c_1	c_2	c_3
CP	c_1	c_2	$-c_3$

$\Phi \to f\bar{f}$ decay

- Define observables *(hep-ph/9701347)*

$$\begin{aligned}
\mathcal{O}_0 &= \hat{\mathbf{k}}_1 \cdot (\mathbf{s}_1 + \mathbf{s}_2) \\
\mathcal{O}_1 &= \hat{\mathbf{k}}_1 \cdot (\mathbf{s}_1 - \mathbf{s}_2) \\
\mathcal{O}_2 &= \hat{\mathbf{k}}_1 \cdot (\mathbf{s}_1 \times \mathbf{s}_2) \\
\mathcal{O}_3 &= \mathbf{s}_1 \cdot \mathbf{s}_2 \\
\mathcal{O}_4 &= (\hat{\mathbf{k}}_1 \cdot \mathbf{s}_1)(\hat{\mathbf{k}}_1 \cdot \mathbf{s}_2)
\end{aligned}$$

$$\langle \mathcal{O}_i \rangle = \frac{Tr\{R \cdot \mathcal{O}_i\}}{Tr\{R\}}$$

$$\begin{aligned}
\langle \mathcal{O}_0 \rangle &= \frac{2(b^+ + b^-)}{4A} \\
\langle \mathcal{O}_1 \rangle &= \frac{2(b^+ - b^-)}{4A} \\
\langle \mathcal{O}_2 \rangle &= \frac{2c_3}{4A} \\
\langle \mathcal{O}_3 \rangle &= \frac{3c_1 + c_2}{4A} \\
\langle \mathcal{O}_4 \rangle &= \frac{c_1 + c_2}{4A}
\end{aligned}$$

- $\mathbf{s}_1 = \frac{1}{2}\sigma \otimes \mathbb{1}$ and $\mathbf{s}_1 = \frac{1}{2}\mathbb{1} \otimes \sigma$
  are the spin operators of f and $\bar{f}$

	c_1	c_2	c_3
CP	c_1	c_2	$-c_3$

$\Phi \to \tau\tau$ decay

- Similar for $\tau \to \rho + \nu_\tau$
  $\tau \to a_1 + \nu_\tau$

- $b(E_{a_1,\rho})$ opposite to leptonic decay
- $n(E_{a_1,\rho})$ equally important for small and large pion energies in tau rest frame

- φ^* horizontal line at 0 if integrated over whole spectrum (no cuts)

- Energy for direct decay fixed