How to pin down the CP parity of a Higgs boson in its tau decays at the LHC

Werner Bernreuther
RWTH Aachen

S. Berge, W. B., Phys. Lett. **B671** (2009) 470. [arXiv:0812.1910 [hep-ph]].
S. Berge, W. B., J. Ziethe, Phys. Rev. Lett. **100** (2008) 171605. [arXiv:0801.2297 [hep-ph]].
S. Berge, W. B., B. Niepelt, H. Spiesberger, arXiv:1108.0670 [hep-ph]]

Expectation:

Problem # 1 of particle physics:

"Which mechanism breaks the electroweak gauge symmetry?"

will be experimentally clarifed, hopefully already @ LHC

$\longrightarrow$ search for spin 0 resonances

Many concepts/models discussed:

elementary Higgs field(s),
condensation of (new) fermions, e.g. techniquarks $\longrightarrow$ Higgs-like bound states,
Higgsless models, ...

Assume here: elementary or composite Higgs particles exist

Some arguments in favor of EWSB sector being more complex than in SM
$\longrightarrow$ Higgs particle spectrum larger than just one $J^{PC} = 0^{++}$ state.

Suppose a neutral spin 0 resonance ϕ will be discovered at LHC.

Next step would be determination of its properties:
- branching fractions,...
- spin from polar angle distributions, $\phi \to VV$, $f\bar{f}$
- determination of CP parity of ϕ – scalar, pseudoscalar, or CP mixture ?

As to the latter, many prosals & suggestions for various final states:

$\phi \to ZZ$
2-jet correlations in $\phi\, \mathrm{jet\, jet}$
$\phi \to \tau\tau$
....

Consider in the following most general couplings of spin zero Higgs resonance to quarks, leptons f:

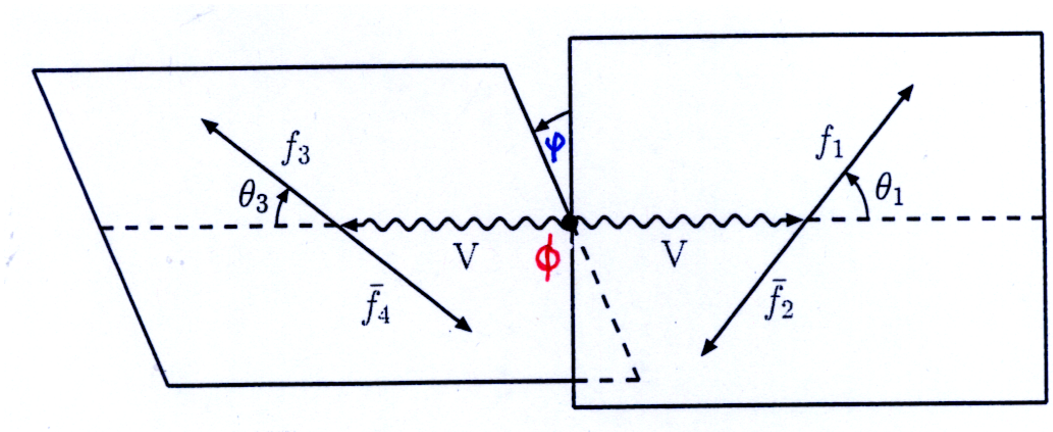
$$\mathcal{L}_Y = -(\sqrt{2}G_F)^{1/2} m_f(\mathbf{a_f}\bar{f}f + \mathbf{b_f}\bar{f}i\gamma_5 f)\,\phi\ ,$$

$\mathbf{a_f}$ and $\mathbf{b_f}$ model-dependent reduced scalar and pseudoscalar Yukawa couplings.
For SM Higgs, $\mathbf{a_f} = 1$ and $b_f = 0$.

Determination of CP parity of ϕ

For instance, in "golden channel"

$$pp \to \phi \to ZZ \to \ell^- \ell^+ \ \ell'^- \ell'^+$$



Adaption of classic determination of CP parity of π^0

Dell'Aquila, Nelson (1986), Barger et al. (1994), Buszello et al. (2004), ...

If $\phi = 0^{++}$ $\Rightarrow$ ZZ wave function $\epsilon_1 \cdot \epsilon_2$ $\Rightarrow$ planes tend to be $\|$

If $\phi = 0^{-+}$ $\Rightarrow$ ZZ wave function $(\epsilon_1 \times \epsilon_2) \cdot \mathbf{k}$ $\Rightarrow$ planes tend to be $\perp$

However, if ϕ is a CP mixture: $|\phi\rangle = c_1|H\rangle + c_2|A\rangle$

only $CP = +1$ component $|H\rangle$ expected to have sizeable coupling to ZZ

Decays $\phi \to f\bar{f}$

$f\bar{f}$ spin correlations in $\phi \to f\bar{f}$ strongly discriminate
between scalar, pseudoscalar, and CP mixture.

Exploitable only for $f = \tau$, and if ϕ is heavy enough, also for $f = t$ quark

Dell'Aquila, Nelson (1989); W.B., Brandenburg (1992), Grzadkowski, Gunion (1995), ...

Consider here $pp \to \phi + X$ and decay

$$\phi \to \tau^- \tau^+$$

Scalar vs. pseudoscalar with τ spin correlation $S = \mathbf{s}_\tau \cdot \mathbf{s}_{\bar{\tau}}$

If $\phi = 0^{++} \quad \Rightarrow \quad \tau^-\tau^+$ in ${}^3P_0$ state $\quad \Rightarrow \quad \langle S \rangle_{\tau\tau} = 1/4$
if $\phi = 0^{-+} \quad \Rightarrow \quad \tau^-\tau^+$ in ${}^1S_0$ state $\quad \Rightarrow \quad \langle S \rangle_{\tau\tau} = -3/4$
if ϕ is CP mixture $\quad \Rightarrow \quad \langle S \rangle_{\tau\tau} = (a_\tau^2 - 3b_\tau^2)/(4a_\tau^2 + 4b_\tau^2)$

CP-odd correlation $S_{CP} = \hat{\mathbf{k}}_\tau \cdot (\mathbf{s}_\tau \times \mathbf{s}_{\bar{\tau}}) \quad \Rightarrow \quad \langle S_{CP} \rangle_{\tau\tau} = -a_\tau b_\tau/(a_\tau^2 + b_\tau^2)$

$\langle S_{CP} \rangle_{\tau\tau} \neq 0 \quad \Rightarrow \quad$ **CPV**; $\qquad$ for instance $|\langle S_{CP} \rangle_{\tau\tau}| = 1/2$ for ideal CP mixture

For $\phi \to \tau^-\tau^+$, $\quad \tau^\pm \to$ 1 charged prong $= e^\pm$, $\mu^\pm$, $\pi^\pm$ $\quad$ (72 % of all $\tau\tau$ events)

$$\phi \; \to \; \tau^-(\mathbf{k}_\tau) \; + \; \tau^+(\mathbf{k}_{\bar{\tau}}) \to \; a(\mathbf{p}_1) \; + \; \bar{b}(\mathbf{p}_2) \; + \; X$$

Spin correlation $\langle S \rangle_{\tau\tau}$ leads to a non-isotropic distribution in $\cos\varphi$, where $\varphi = \angle(\mathbf{p_1}, \mathbf{p_2})$.

$$\frac{1}{\Gamma_{a\bar{b}}} \frac{d\Gamma_{a\bar{b}}}{d\cos\varphi} = \frac{1}{2}\left(1 - D_{a\bar{b}} \, \cos\varphi\right) \; , \quad D_{a\bar{b}} = -\frac{4}{3}\, \kappa_a \kappa_{\bar{b}} \, \langle S \rangle_{\tau\tau} \; . \tag{1}$$

κ_a is τ-spin analyzing power of particle a.
$\Gamma_a^{-1} d\Gamma_a(\tau^- \to a + X)/d\cos\theta_a = (1 + \kappa_a \, \cos\theta_a)/2$, where $\theta_a = \angle(\mathbf{s}_\tau, \mathbf{p}_1)$

For instance, if $\tau^\mp \to \pi^\mp$ directly $\quad \Rightarrow \quad \kappa_a = 1$ and $\kappa_{\bar{b}} = -1$
then

$$D_{\pi\pi} = +0.33 \quad \text{for} \quad \phi = 0^{++}, \qquad D_{\pi\pi} = -1 \quad \text{for} \quad \phi = 0^{-+}$$

Distribution of $\mathcal{O}_{CP} = (\hat{\mathbf{k}}_\tau - \hat{\mathbf{k}}_{\bar{\tau}}) \cdot (\hat{\mathbf{p}}_2 \times \hat{\mathbf{p}}_1)/2$ tests for **CPV**

Alternatively: Correlation of decay-planes in, e.g., $\phi \to \tau^- + \tau^+ \to \pi^- \pi^+ + \nu_\tau + \bar{\nu}_\tau$

$$\Gamma^{-1}\frac{d\Gamma}{d\varphi} = \frac{1}{2\pi}[1 - \frac{\pi^2}{16}(c_1 \cos\varphi + c_2 \sin\varphi)]\,, \qquad (*)$$

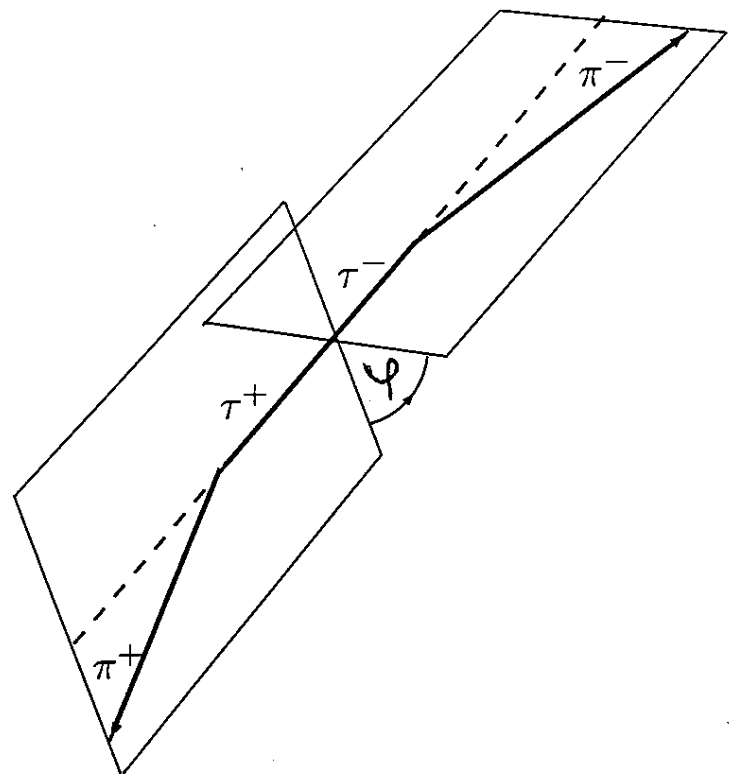
where $\varphi = \angle(\mathbf{n}_-, \mathbf{n}_+)$, $\mathbf{n}_\pm$ **signed** normal vectors, $0 \leq \varphi < 2\pi$ and

$$c_1 = \frac{a_\tau^2 - b_\tau^2}{a_\tau^2 + b_\tau^2}\,,\;\; c_2 = -\frac{2a_\tau b_\tau}{a_\tau^2 + b_\tau^2}\,.$$

If φ and $2\pi - \varphi$ cannot be distinguished

then $\Gamma^{-1}\frac{d\Gamma}{d\varphi} = \frac{1}{\pi}(1 - \frac{\pi^2}{16}c_1 \cos\varphi)$

where $0 \leq \varphi < \pi$



Side remark: in e^+e^- production, e.g. $e^+e^- \to Z\phi$, $\phi \to \tau^-\tau^+$

ϕ rest frame and τ momenta can be reconstructed $\to$ (*) applicable

Back to Higgs production @ LHC:

$$p\,p \;\rightarrow\; \phi \,+\, X \;\rightarrow\; \tau^-(\mathbf{k}_\tau) \,+\, \tau^+(\mathbf{k}_{\bar\tau}) \,+\, X \;\rightarrow\; a(\mathbf{q}_1) \,+\, \bar{b}(\mathbf{q}_2) \,+\, X\,,$$

Determination of correlations discussed above requires knowledge of $\tau^\pm$ momenta
$\tau^\pm$ **momenta cannot be reconstructed in these reactions.**

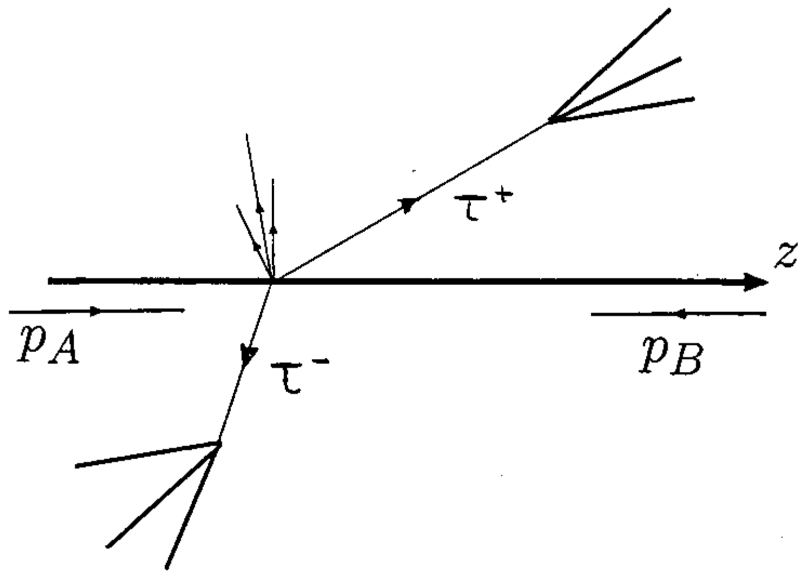
Consider first direct $\tau^\mp \rightarrow \pi^\mp$:

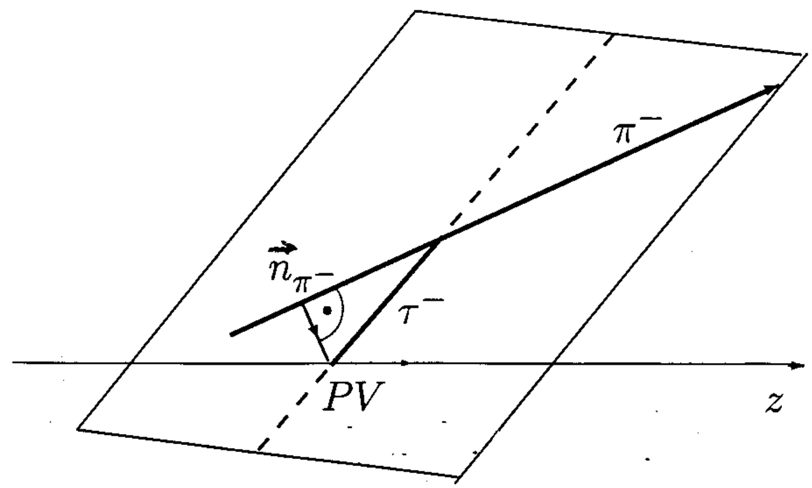
$$\tau^- \, \tau^+ \rightarrow \pi^- \, \pi^+ + \nu_\tau \nu_{\bar\tau}$$

Notice: above decay-plane correl. invariant under change of frame, e.g.

$$\phi \text{ rest frame} = \tau^-\tau^+ \text{ ZMF} \longrightarrow \pi^-\pi^+ \text{ ZMF}$$

Consider $\tau^{\pm} \to \pi^{\pm}$ in **lab frame**





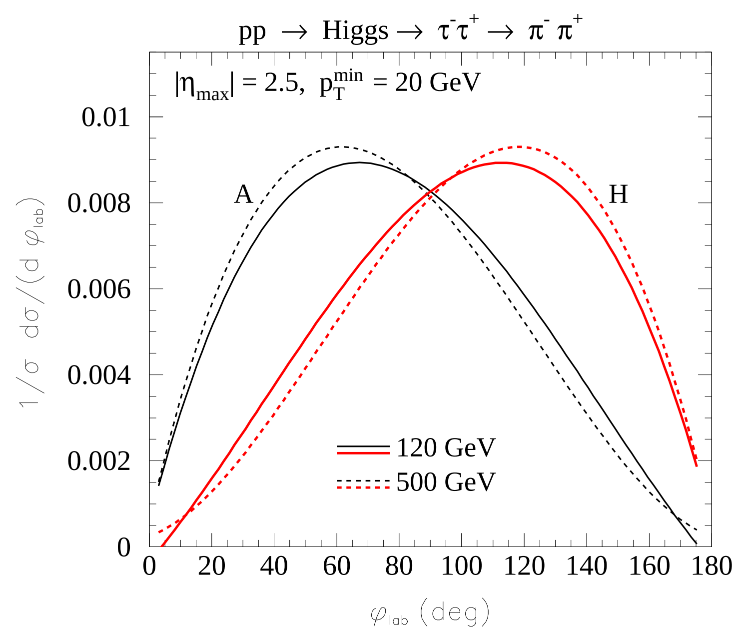
PV $= \phi$ prod. vertex $\cong \tau^-\tau^+$ prod. vertex

likewise $\tau^+ \to \pi^+$ in lab frame

impact parameter vectors $\mathbf{n}_{\pm}$

distribution of $\varphi_{lab} = \arccos(\mathbf{n}_+ \cdot \mathbf{n}_-)$

has some discriminating power $H \leftrightarrow A$



Much higher sensitivity is achieved by following **proposal:** **S. Berge, W.B. (2009)**
measured pion (charged prong) lab. 4-momenta $p^\mu_\mp = (E_\mp, \mathbf{p}_\mp)$
measured normalized impact parameter vectors $\hat{\mathbf{n}}_\pm$
Define two spacelike 4-vectors $n^\mu_\pm = (0, \hat{\mathbf{n}}_\pm)$

$$\text{boost to } \pi^-\pi^+ \text{ ZMF: } n^\mu_\pm \longrightarrow n^{*\mu}_\mp = (n^*_{0\mp}, \mathbf{n}^*_\mp)\ ,$$
$$p^\mu_\mp \longrightarrow (E^*_\mp,\ \mathbf{p}^*_\mp) \text{ where } \mathbf{p}^*_+ = -\mathbf{p}^*_-\ .$$

Decompose spatial parts $\mathbf{n}^*_\mp$ into components $\|$ and $\perp$ to the respective pion 3-momentum $\mathbf{p}^*_\mp$:

$$\mathbf{n}^*_\mp = r^\mp_\perp \hat{\mathbf{n}}^{*\mp}_\perp + r^\mp_\| \hat{\mathbf{n}}^{*\mp}_\|\ ,$$

In this way unit vectors $\hat{\mathbf{n}}^{*\mp}_\perp$ are obtained, which are orthogonal to $\mathbf{p}^*_\mp$, respectively, for each event in a unique fashion.
The angle, which takes the role of the true angle in $\pi\pi$ ZMF between the unsigned normal vectors of the decay planes, is defined by

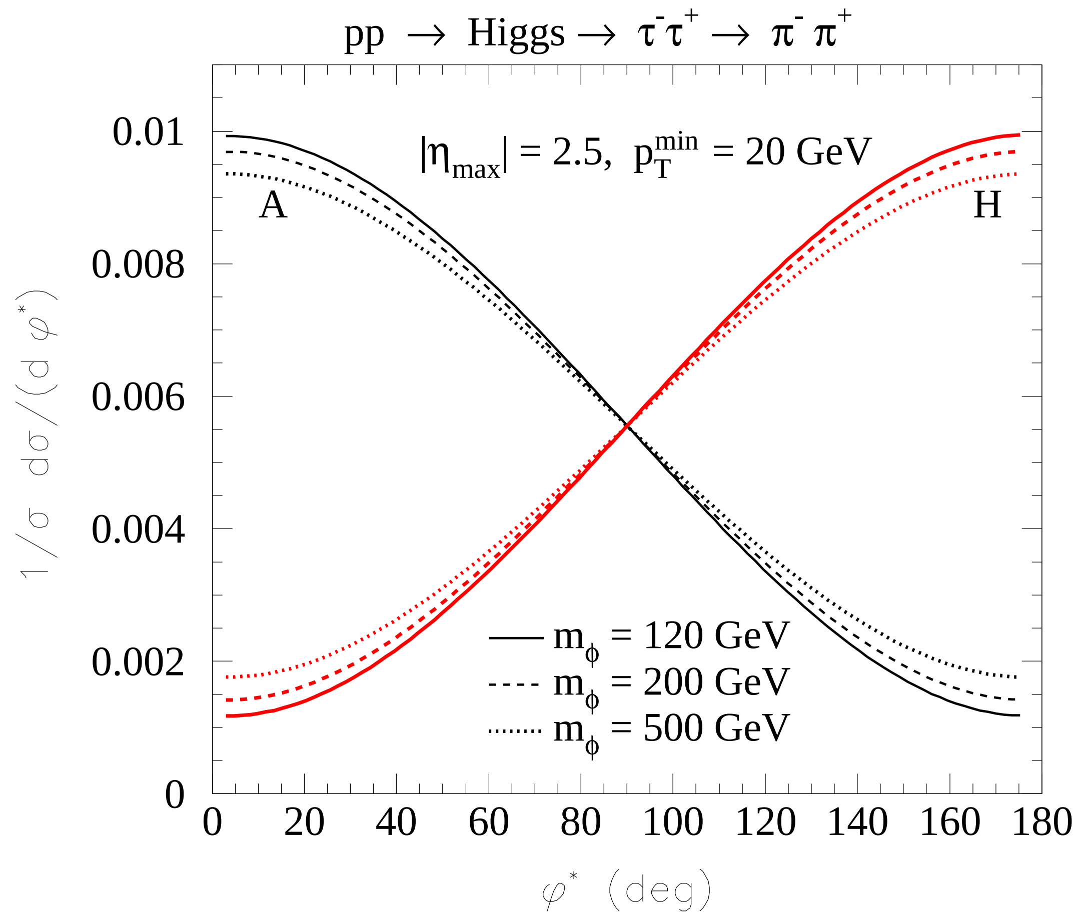
$$\varphi^* = \arccos(\hat{\mathbf{n}}^{*+}_\perp \cdot \hat{\mathbf{n}}^{*-}_\perp)\ ,$$

where $0 \le \varphi^* < \pi$. In addition, the CP-odd and T-odd triple correlation, respectively angle

$$\mathcal{O}^*_{CP} = \hat{\mathbf{p}}^*_- \cdot (\hat{\mathbf{n}}^{*+}_\perp \times \hat{\mathbf{n}}^{*-}_\perp) \longrightarrow \psi^*_{\mathbf{CP}} = \arccos(\hat{\mathbf{p}}^*_- \cdot (\hat{\mathbf{n}}^{*+}_\perp \times \hat{\mathbf{n}}^{*-}_\perp))$$

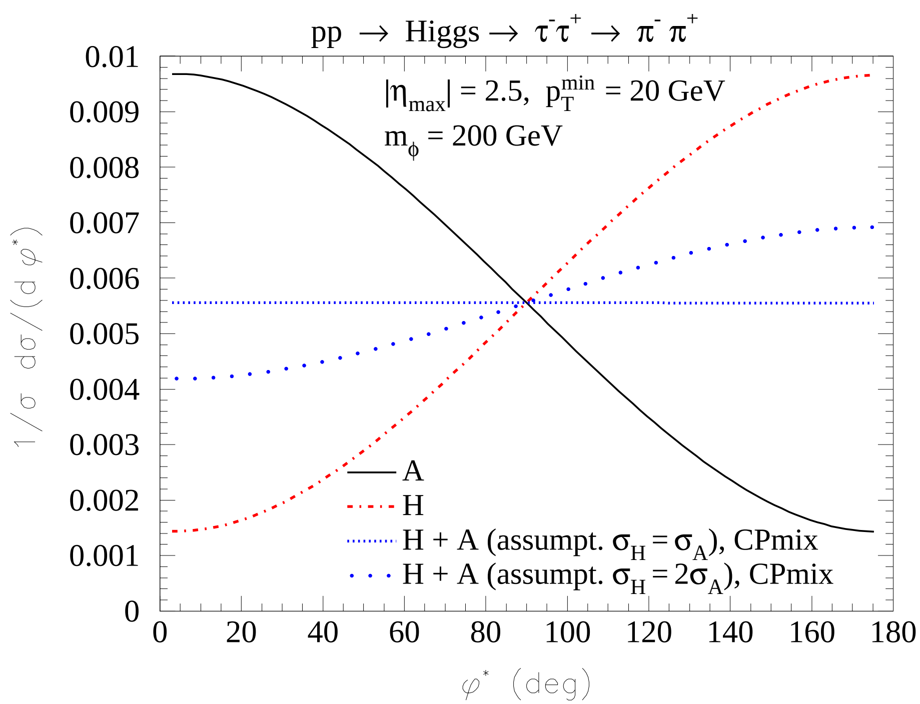
appropriate tool for distinguishing between CP invariance and CPV in Higgs-boson decay.

Distribution of "decay-plane" angle φ^* for several Higgs masses $\phi = H, A$ and $\pi^\pm$ acceptance cuts

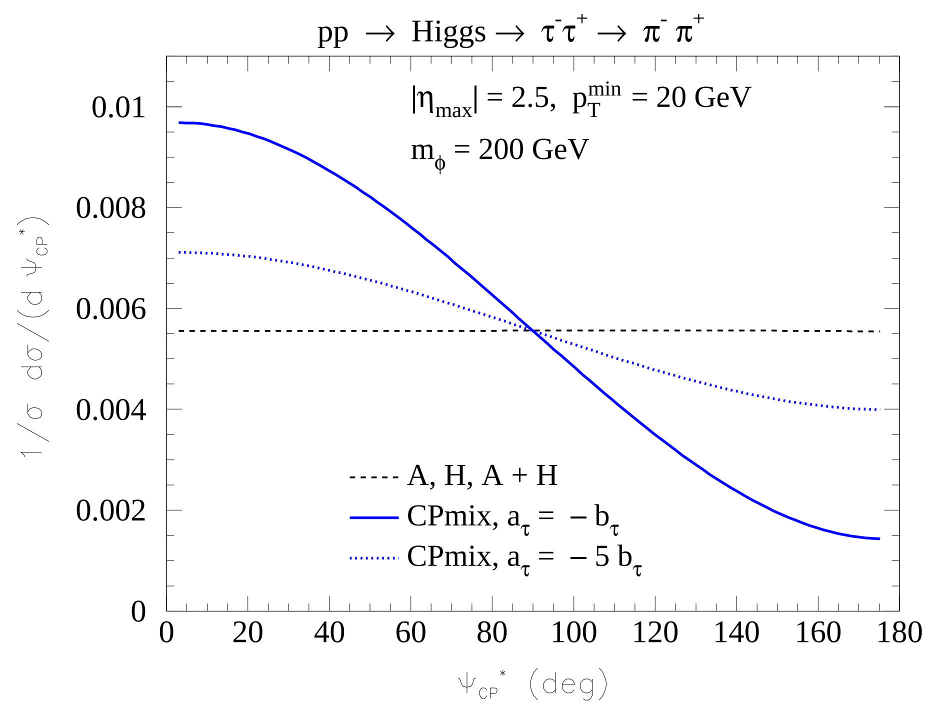


Several Scenarios:

production of pure H, production of pure A
production of (nearly) mass-degenerate H and A: same σ and different σ
versus production of CP mixture ϕ: $|a_\tau| = |b_\tau|$ and $|a_\tau| = \sqrt{2}|b_\tau|$



angle φ^*



CP angle $\psi^*_{\mathbf{CP}}$

φ^* and of ψ^*_{CP} can be determined also for

- the other major 1-prong τ decays:

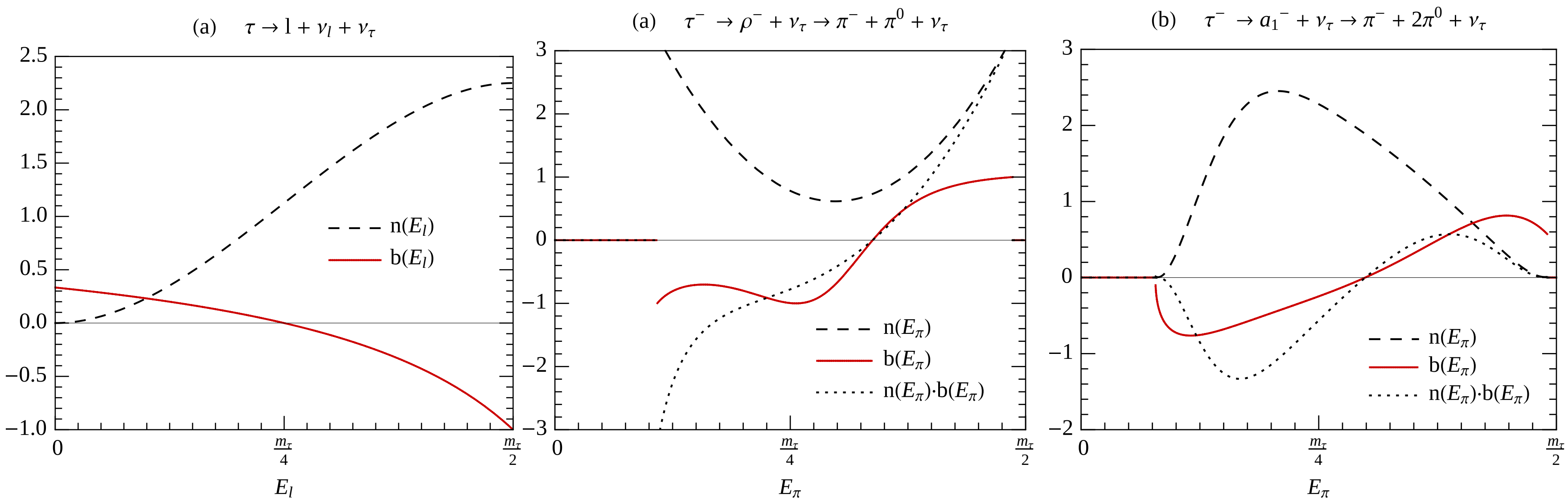
$$\tau \to \ell \nu_\tau \bar{\nu}_\ell,$$
$$\tau^\mp \to \rho^\mp \nu_\tau \to \pi^\mp \pi^0 \nu_\tau \ ,$$
$$\tau^\mp \to a_1^\mp \nu_\tau \to \pi^\mp 2\pi^0 \nu_\tau \ ,$$

$$pp \to \Phi + X \to \tau^- \tau^+ + X \to \begin{cases} \ell^- \ \ell'^+ + X, & \ell, \ell' = e, \mu, \\ \ell^- \pi^+ + X \quad \text{and} & \pi^- \ell^+ + X, \\ \pi^- \pi^+ + X \,. & \end{cases}$$

- the 3-prong τ decays

Distributions of polarized τ decays $\tau \to \ell$ and $\tau \to \rho, a_1 \to \pi$:

$$\tau \text{ rest frame :} \qquad 4\pi\Gamma^{-1}\mathrm{d}\Gamma\left(\tau \to a\right)/\mathrm{d}E_a\mathrm{d}\Omega_a = n(E_a)\left(1 \pm b(E_a)\,\hat{\mathbf{s}}\cdot\hat{\mathbf{q}}\right)$$

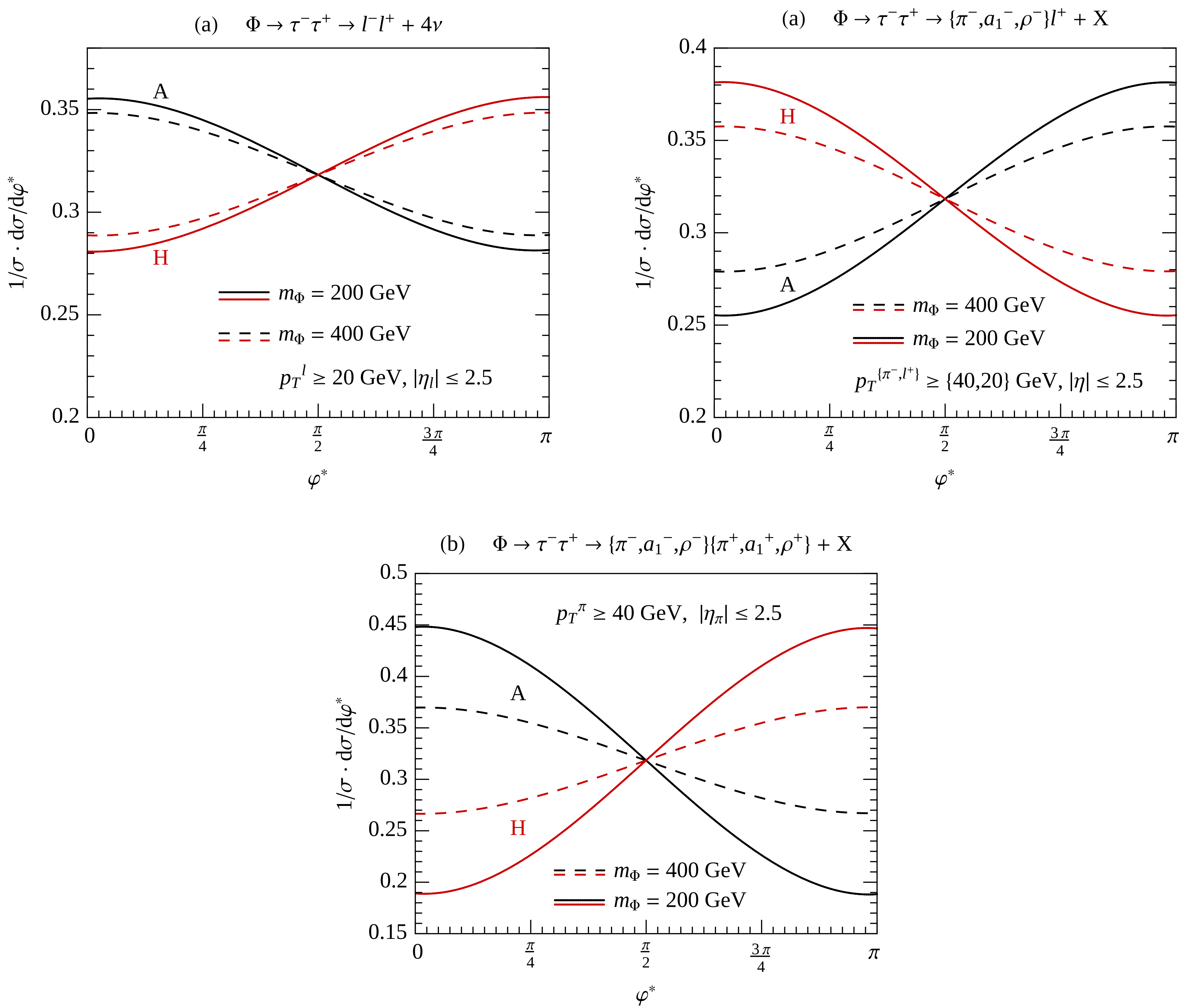


Integrated τ-spin analyzing power of ℓ, resp. π form ρ, a_1 is rather poor
However, acceptance cuts in laboratory frame, for instance

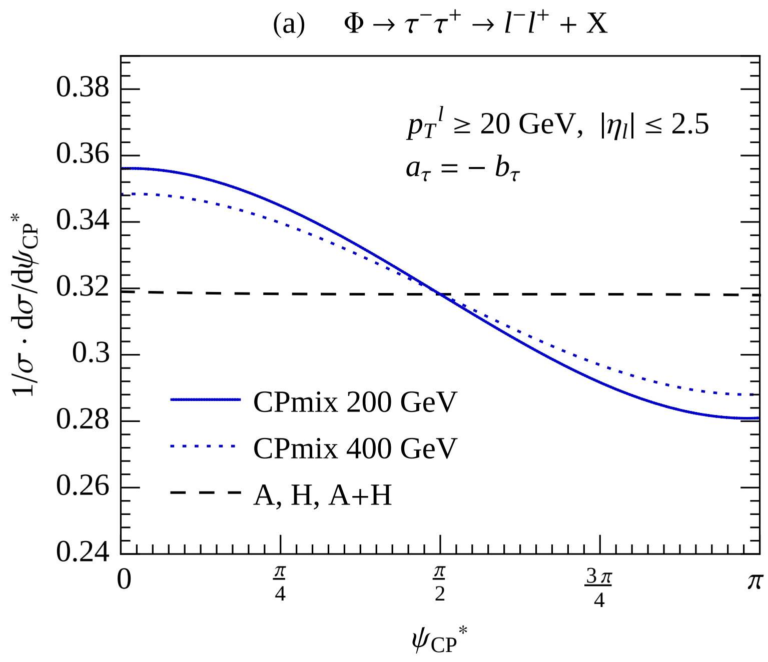
$$p_T^\ell \geq 20\,\mathrm{GeV}, \quad |\eta_\ell| \leq 2.5, \qquad p_T^\pi \geq 40\,\mathrm{GeV}, \quad |\eta_\pi| \leq 2.5,$$

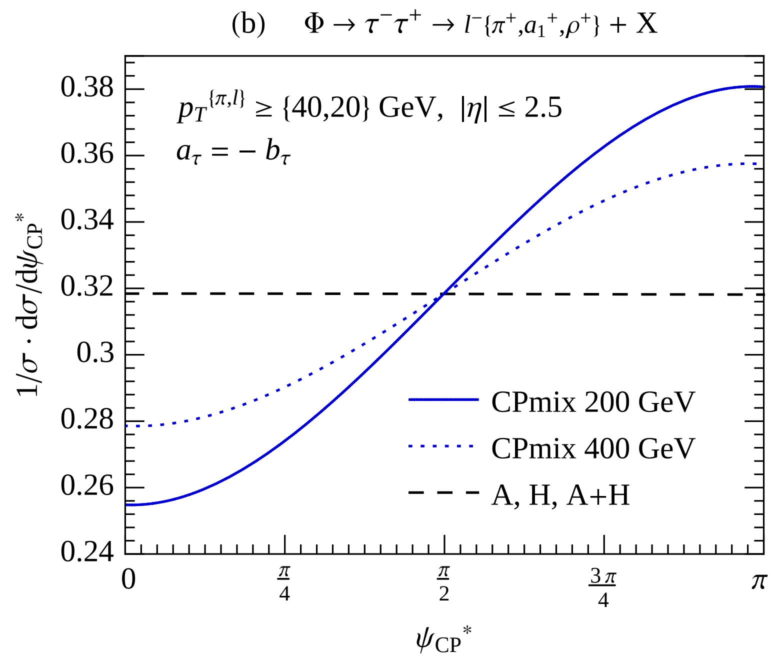
select high-energy part of spectra $\Rightarrow$ **significantly enhance τ-spin analyzing power**

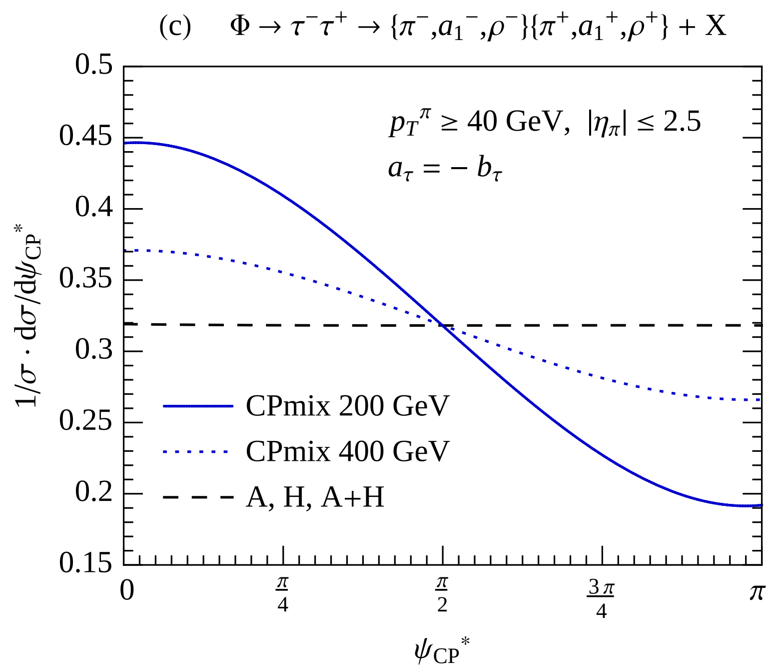
The $\varphi*$ distributions for $\ell\ell$, ℓ-had. and had.-had. final states



The ψ^*_{CP} distributions for $\ell\ell$, ℓ-had. and had.-had. final states







Asymmetries:

$$A_{\varphi^*} = \frac{N(\varphi^* > \pi/2) - N(\varphi^* < \pi/2)}{N_> + N_<)}$$

estimate of event numbers: $H \leftrightarrow A$ with 3 σ

m_Φ [GeV]	dilepton	lepton-pion	two-pion
200	770	240	100
400	1200	670	420

$$A_{\psi^*_{CP}} = \frac{N(\psi^*_{CP} > \pi/2) - N(\psi^*_{CP} < \pi/2)}{N_> + N_<)}$$

Estimate of event numbers: ideal CP mixture with 3 σ

m_Φ [GeV]	dilepton	lepton-pion	two-pion
200	3000	1000	230
400	4800	2700	1400

Conclusions

If spin-zero resonance will be discovered at LHC
and will also be seen in in $\phi \to \tau\tau$

proposed method to determine CP parity of ϕ can be applied to any 1-prong τ-decay mode

- standard selection cuts enhance discriminating power of observables φ^* and ψ^*_{CP}

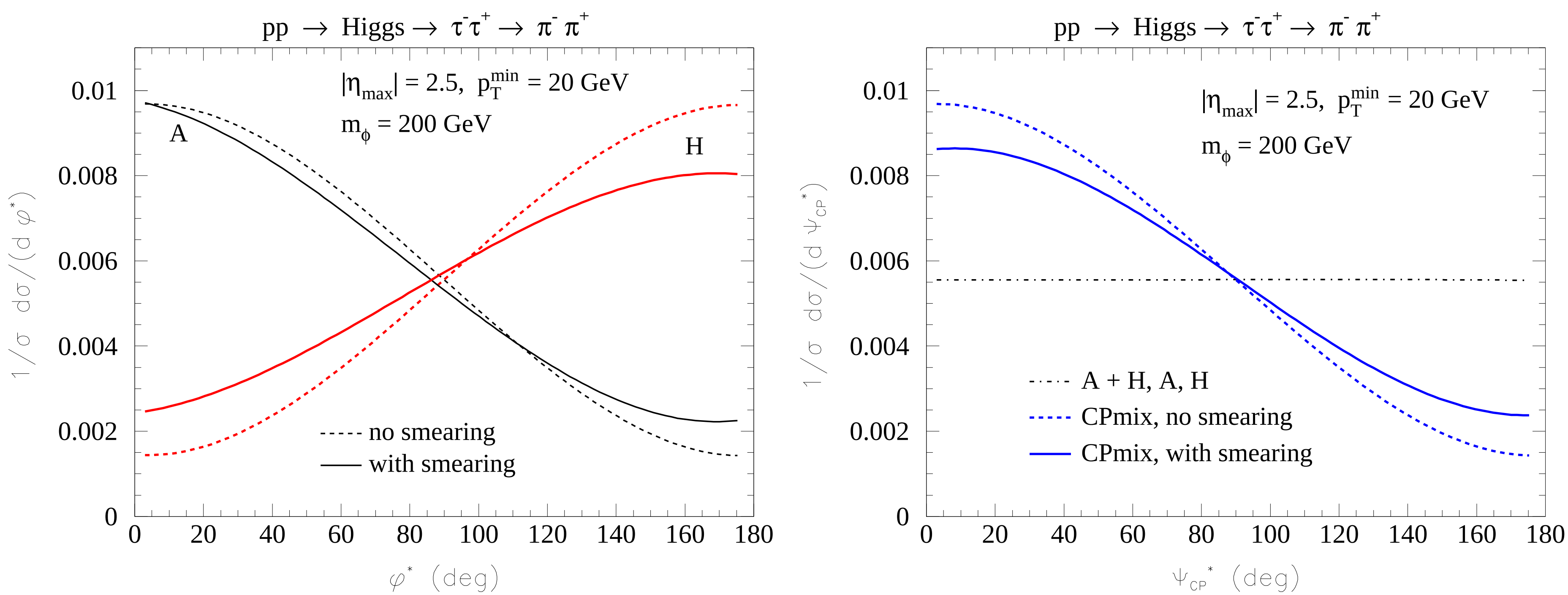
- simulation of measurement uncertainities (“smearing”)
  $\longrightarrow$ distributions are experimentally robust

- method, of course, also applicable to e^+e^- production of ϕ

Backup slides

Distributions with smearing of PV and of tracks of charged prongs

"smear" PV coordinates and of $\pi^{\pm}$ momenta & energies with Gaussian $\exp(-X^2/2\sigma_X^2)$



angle φ^* CP angle $\psi^*_{\mathbf{CP}}$

$\sigma_z^{PV} = 30\,\mu\mathrm{m}$, $\sigma_{tr}^{PV} = 10\,\mu\mathrm{m}$, $\sigma_{tr}^{\pi} = 10\,\mu\mathrm{m}$, $\sigma_{\theta}^{\pi} = 1\,\mathrm{mrad}$, $\Delta E^{\pi}/E^{\pi} = 5\%$.
average τ decay length $c\tau_\tau = 87\ \mu\mathrm{m}$, $|\mathbf{n}| \sim 80\ \mu\mathrm{m}$,