Higgs Sector CP Violation in Diffraction at the LHC

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- **Radiative Higgs Sector CP Violation in the MSSM**
- **Luminosity for Exclusive Double Diffractive Higgs Production at the LHC**
- **Diffraction as a CP and Lineshape Analyzer for a Strongly Coupled Higgs Boson System**
- **Future Prospects**

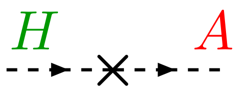
*Talk based on:

B.E. Cox, J.R. Forshaw, J.S. Lee, J.W. Monk and A.P., Phys. Rev. **D68** (2003) 075004;

J. Ellis, J.S. Lee and A.P., hep-ph/0502251.

• Higgs Sector CP Violation

- Explicit or spontaneous CP violation in the Higgs potential at the tree level, e.g. 2HDM. [T.D. Lee, PRD**8** (1973) 1226; S. Weinberg, PRL**37** (1976) 657; G.C. Branco, PRL**44** (1980) 504, . . .]



The CP-violating HA mixing occurs at the tree level, but generically $M_H \not\sim M_A$.

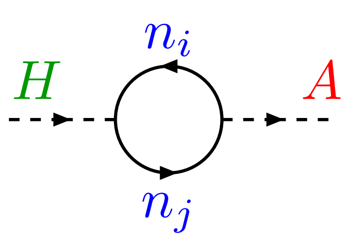
- Spontaneous or explicit radiative CP violation in the Higgs potential.

  – Spontaneous radiative CP violation: it generically leads to a very light 'CP-odd' scalar, with $M_A \lesssim 40$ GeV, and is phenomenologically highly disfavoured.

  [H. Georgi, G. Pais, PRD**10** (1974) 1246; J.C. Romao, PLB**173** (1986) 309]

  – Explicit radiative CP violation:

  (i) Through loop effects of heavy Majorana neutrinos in a constrained 2HDM potential [A.P., PRL**77** (1996) 4996.]



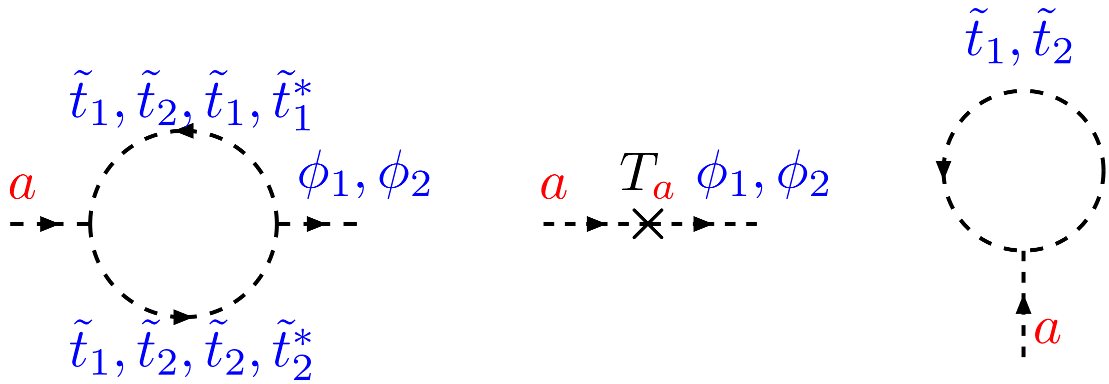
Resonant CP-violating scenarios, with $M_H - M_A \sim \Gamma_{H,A}$.

  (ii) Through radiative effects of stops/sbottoms in the MSSM. [A.P., PRD**58** (1998) 096010; PLB**435** (1998) 88]

• Radiative Higgs Sector CP Violation in the MSSM

Two major effects of CP violation on the Higgs sector:
– CP-violating self-energy effects
– CP-violating vertex effects

– CP-violating self-energy effects:



$$\mathcal{M}^2_{SP} \sim \frac{m_t^4}{v^2}\,\frac{\mathrm{Im}\,(\mu A_t)}{32\pi^2 Q_t^2} \times \left(1,\ \frac{|A_t|^2}{Q_t^2},\ \frac{|\mu|^2}{\tan\beta\ Q_t^2},\ \frac{2\mathrm{Re}\,(\mu A_t)}{Q_t^2}\right) \lesssim (100\ \mathrm{GeV})^2$$

[A.P., PR**D58** (1998) 096010; PL**B435** (1998) 88;
A.P., C.E.M. Wagner, NP**B553** (1999) 3; D.A. Demir, PR**D60** (1999) 055006;
M. Carena, J. Ellis, A.P., C.E.M. Wagner, NP**B586** (2000) 92;
S.Y. Choi, M. Drees, J.S. Lee, PL**B481** (2000) 57;
T. Ibrahim and P. Nath, hep-ph/0008237 $\cdots$]

The mixing of the three neutral Higgs bosons

$$\begin{pmatrix} \phi_1 \\ \phi_2 \\ a \end{pmatrix} = O \begin{pmatrix} H_1 \\ H_2 \\ H_3 \end{pmatrix}$$

O is a 3×3 orthogonal matrix which also describes the mixing of the Higgs bosons with different CP parities.

In analogy to the case of neutrinos and quarks, Higgs bosons with mixed CP parities are ordered according to their weights:

$$M_{H_1} \leq M_{H_2} \leq M_{H_3}$$

At the one-loop level, M_{H_i} (with $i = 1, 2, 3$) and O are analytically determined by the input parameters:

$$M_{H^+}(m_t)\,, \quad \tan\beta(m_t)\,,$$

$$\mu(Q_{tb})\,, \quad A_t(Q_{tb})\,, \quad A_b(Q_{tb})\,,$$

$$\widetilde{M}^2_Q(Q_{tb})\,, \quad \widetilde{M}^2_t(Q_{tb})\,, \quad \widetilde{M}^2_b(Q_{tb})\,.$$

CP-conserving versus CP-violating MSSM parameters:

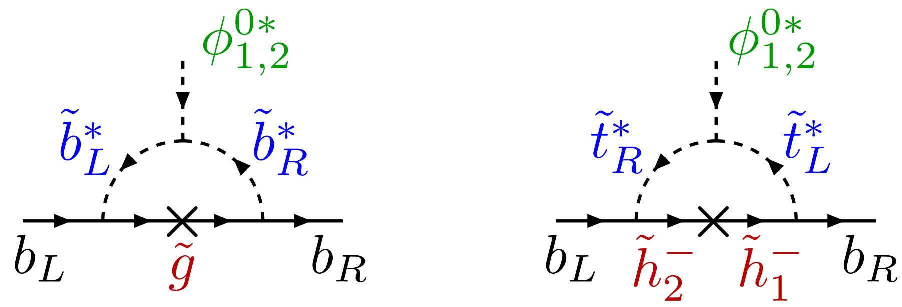
CP-conserving:	CP-violating:
$\tan\beta$	$\tan\beta$, with $\xi = 0$
$\widetilde{M}_Q^2$, $\widetilde{M}_t^2$, $\widetilde{M}_b^2$	$\widetilde{M}_Q^2$, $\widetilde{M}_t^2$, $\widetilde{M}_b^2$
μ	$\lvert\mu\rvert$, $\arg(\mu)$
$A_{t,b}$	$\lvert A_{t,b}\rvert$, $\arg(A_{t,b})$
M_A	M_{H^+}

At two loops:

$m_{\tilde{g}}$	$\lvert m_{\tilde{g}}\rvert$ and $\arg(m_{\tilde{g}})$

– CP-violating vertex effects:

Effective $H_1 bb$-coupling



$$-\mathcal{L}^{\rm eff}_{\phi^0\bar{b}b} = (h_b + \delta h_b)\,\phi_1^{0*}\,\bar{b}_R b_L + \Delta h_b\,\phi_2^{0*}\,\bar{b}_R b_L \;+\; \text{h.c.}$$

with

$$\frac{\delta h_b}{h_b} \sim -\frac{2\alpha_s}{3\pi}\,\frac{m^*_{\tilde{g}} A_b}{\max\,(Q_b^2, |m_{\tilde{g}}|^2)} - \frac{|h_t|^2}{16\pi^2}\,\frac{|\mu|^2}{\max\,(Q_t^2, |\mu|^2)}$$

$$\frac{\Delta h_b}{h_b} \sim \frac{2\alpha_s}{3\pi}\,\frac{m^*_{\tilde{g}}\mu^*}{\max\,(Q_b^2, |m_{\tilde{g}}|^2)} + \frac{|h_t|^2}{16\pi^2}\,\frac{A_t^*\mu^*}{\max\,(Q_t^2, |\mu|^2)}$$

and

$$h_b = \frac{g_w m_b}{\sqrt{2} M_W \cos\beta\,[\,1 + \delta h_b/h_b + (\Delta h_b/h_b)\tan\beta\,]}$$

[M. Carena, J. Ellis, A.P., C. Wagner '00]

– Implications of CPV Higgs physics:

- **2-loop Higgs-mediated EDMs**

  [D. Chang, W.-Y. Keung, A.P., PRL **82** (1999) 900; A.P., NP**B644** (2002) 263.]

- **FCNC observables:**
  $\Delta M_{K,B}$, ϵ_K, ϵ'/ϵ, $\mathcal{B}(B_{d,s} \to \ell^+\ell^-)$,
  $\mathcal{A}_{\rm CP}(B_{d,s} \to \ell^+_{L(R)}\ell^-_{L(R)})$, with $\ell = \mu\,,\tau$,
  $\mathcal{B}(B \to X_s\gamma)$, . . .

  [E.g. A. Dedes and A.P., PR**D67** (2003) 015012.]

- **Dark Matter**

  [P. Gondolo and K. Freese, hep-ph/990839; T. Falk, A. Ferstl and K.A. Olive, Astropart. Phys. **13** (2000) 301; M. Gomez, T. Ibrahim, P. Nath and S. Skadhauge, PR**D70** (2004) 035014; C. Balazs, M. Carena, A. Menon, D. Morrissey, C. Wagner, hep-ph/0412264.]

- **Electroweak Baryogenesis**

  [E.g. M. Carena, J.M. Moreno, M. Quiros, M. Seco and C. Wagner, NP**B599** (2001) 158.]

- **Higgs phenomenology at LEP2, Tevatron and LHC**

  [E.g. S.Y. Choi, K. Hagiwara, J.S. Lee, PR**D64** (2001) 032004; M. Carena, J. Ellis, S. Mrenna, A.P., C.E.M. Wagner, NP**B659** (2003) 145.]

- **CPsuperH:** [J.S. Lee, A.P., M. Carena, S.Y. Choi, M. Drees, J. Ellis, C. Wagner, CPC**156** (2004) 283.]

- **Resonant CP Violation at LHC and $\gamma\gamma$ colliders.**

  [A.P., NP**B504** (1997) 61; J. Ellis, J.S. Lee, A.P., PR**D70** (2004) 075010; hep-ph/0411379; R. Godbole, S. Kraml and R. Singh, hep-ph/0409199; hep-ph/0501027.]

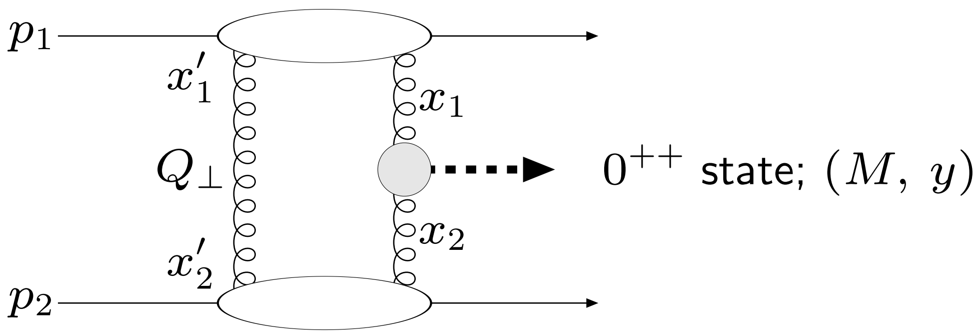
$\longrightarrow$ **Diffraction as a CP and Lineshape Analyzer for a Strongly Coupled Higgs Boson System**

[B.E. Cox, J.R. Forshaw, J.S. Lee, J.W. Monk and A.P., PR**D68** (2003) 075004; J. Ellis, J.S. Lee and A.P., hep-ph/0502251.]

- **Luminosity for Exclusive Double Diffractive Higgs Production at the LHC**

Missing mass method in $pp \to p + H + p$

[V. Khoze, A. Martin, M. Ryskin, '00]



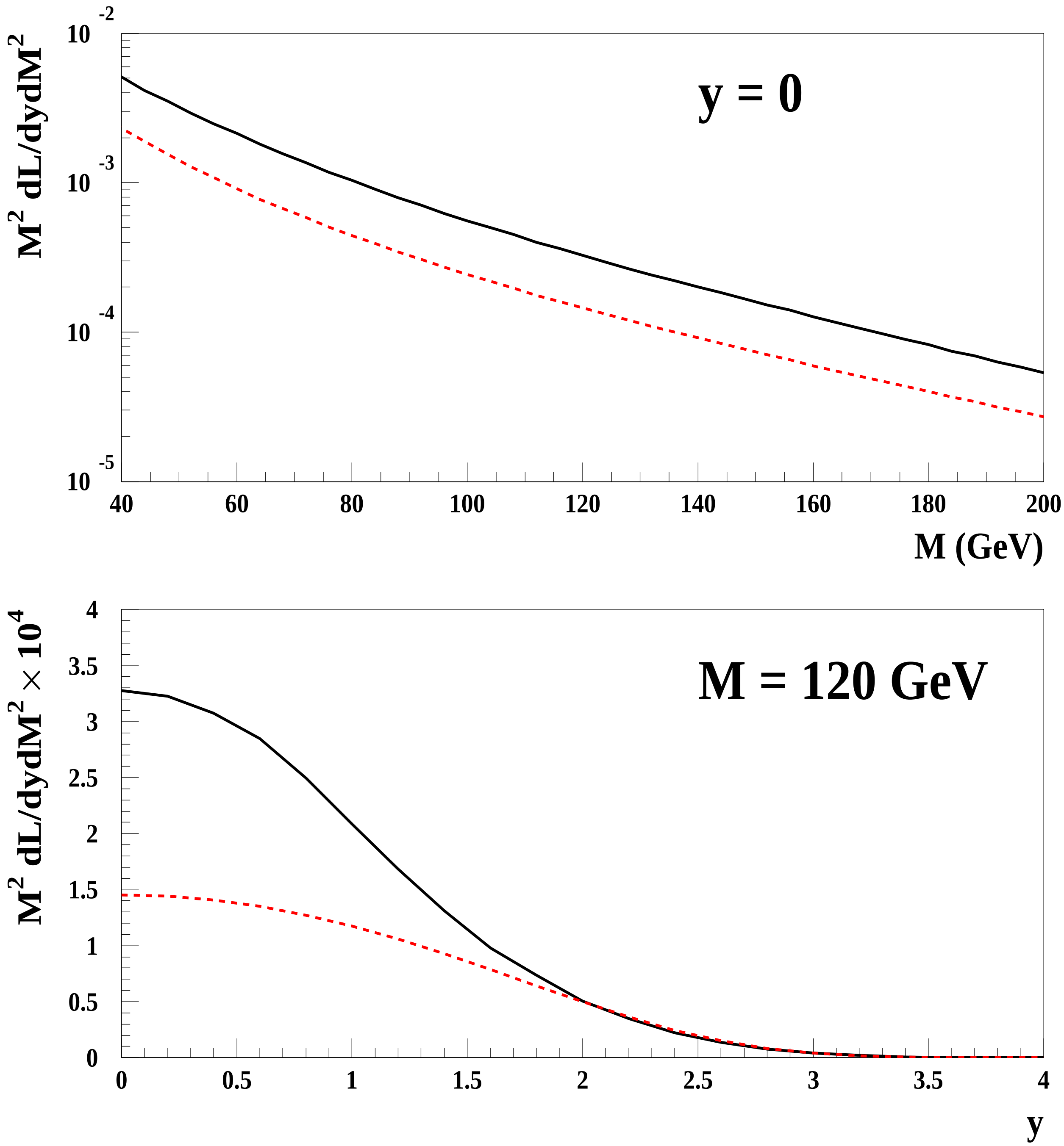
Expected mass resolution $\delta M \sim 1$ GeV!

[B. Cox, hep-ph/0501064.]

Effective Luminosity:

$$M^2 \frac{\partial^2 \mathcal{L}}{\partial y \partial M^2} = 4 \times 10^{-4} \left(\frac{\int_{\ln Q_{\min}}^{\ln \mu} F_g(x_1, x_2, Q_T, \mu) \, \mathrm{d}\ln Q_T}{\mathrm{GeV}^{-2}} \right)^2 \times \left(\frac{\hat{S}^2}{0.02} \right) \left(\frac{4}{b \ \mathrm{GeV}^2} \right)^2 \left(\frac{R_g}{1.2} \right)^4$$

Effective luminosity for $\sqrt{s} = 14$ TeV



Solid (dashed) lines are obtained using CTEQ6M (MRST2004NNLO), with $Q_{\rm min} = 1.0$ GeV.

Predictions using other PDFs lie between the above two extreme cases [J. Forshaw, `http://agenda.cern.ch/fullAgenda.php?ida=a045699`]

- **Diffraction as a CP and Lineshape Analyzer for a Strongly Coupled Higgs Boson System**

Higgs Tri-mixing Scenario of the CPV MSSM:

$$\tan\beta = 50, \quad M_{H^\pm}^{\rm pole} = 155 \;\; {\rm GeV},$$
$$M_{\tilde{Q}_3} = M_{\tilde{U}_3} = M_{\tilde{D}_3} = M_{\tilde{L}_3} = M_{\tilde{E}_3} = 0.5 \;\; {\rm TeV},$$
$$|\mu| = 0.5 \;\; {\rm TeV}, \quad |A_{t,b,\tau}| = 1 \;\; {\rm TeV},$$
$$|M_{1,2}| = 0.3 \;\; {\rm TeV}, \qquad |M_3| = 1 \;\; {\rm TeV},$$

For CP-odd phases:

$$\Phi_\mu = 0^\circ, \quad \Phi_{A_t,A_b,A_\tau} = 90^\circ, \quad \Phi_{1,2} = 0^\circ, \quad \Phi_3 = -10^\circ,$$

CPsuperH gives (in GeV)

$$M_{H_1} = 120.2, \quad M_{H_2} = 121.4, \quad M_{H_3} = 124.5,$$
$$\Gamma_{H_1} = 1.19, \quad \Gamma_{H_2} = 3.42, \quad \Gamma_{H_3} = 3.20,$$

and branching ratios:

$$B(H_1 \to b\bar{b}/\tau^+\tau^-) = 0.81/0.19$$
$$B(H_2 \to b\bar{b}/\tau^+\tau^-) = 0.81/0.19$$
$$B(H_3 \to b\bar{b}/\tau^+\tau^-) = 0.80/0.19$$

For CP-odd phases:

$$\Phi_\mu = 0^\circ, \quad \Phi_{A_t,A_b,A_\tau} = 90^\circ, \quad \Phi_{1,2} = 0^\circ, \quad \Phi_3 = -90^\circ,$$

CPsuperH gives (in GeV)

$$M_{H_1} = 118.4, \quad M_{H_2} = 119.0, \quad M_{H_3} = 122.5,$$
$$\Gamma_{H_1} = 3.91, \quad \Gamma_{H_2} = 6.02, \quad \Gamma_{H_3} = 6.34,$$

and branching ratios:

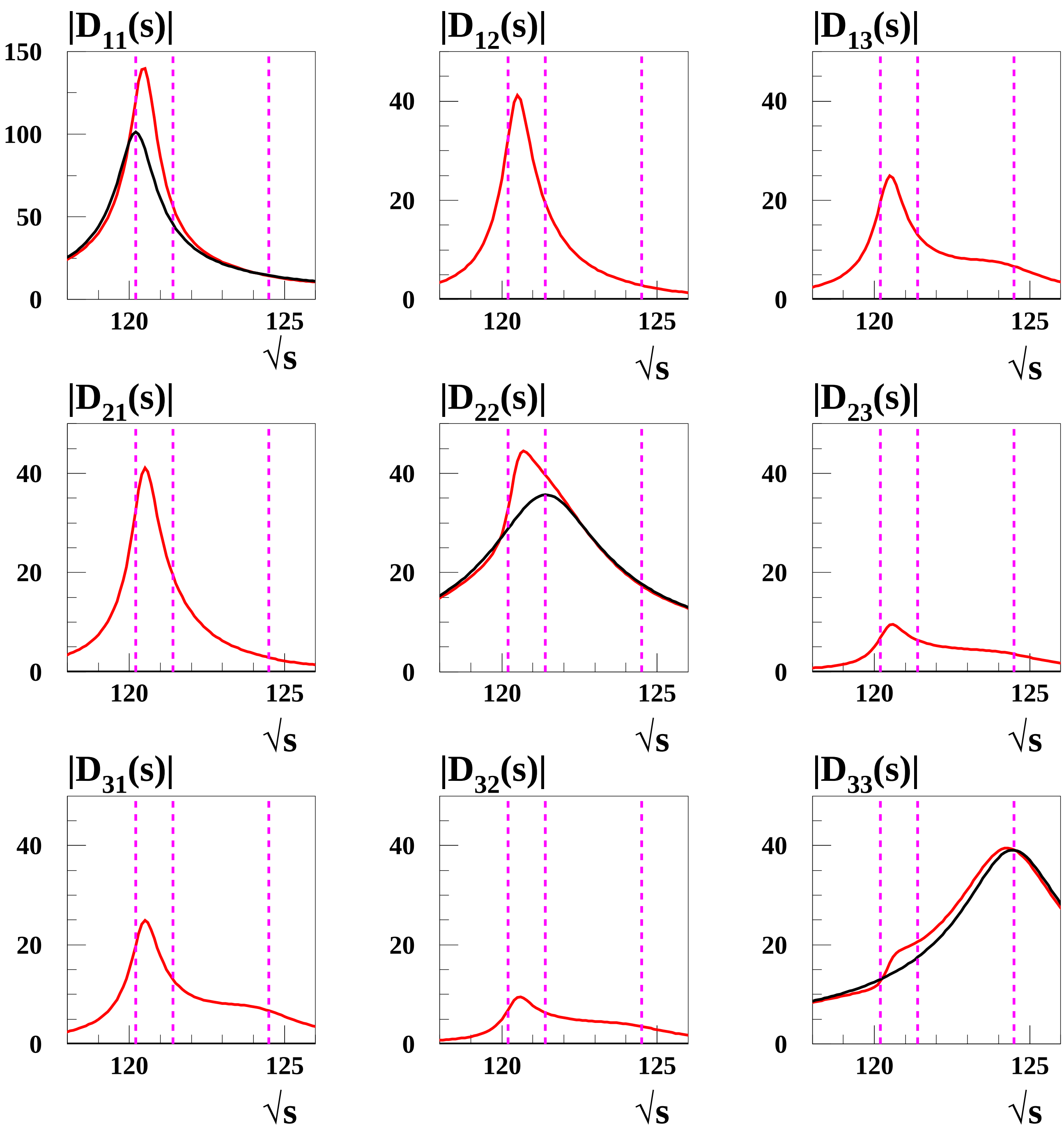
$$B(H_1 \to b\bar{b}/\tau^+\tau^-) = 0.91/0.1$$
$$B(H_2 \to b\bar{b}/\tau^+\tau^-) = 0.91/0.1$$
$$B(H_3 \to b\bar{b}/\tau^+\tau^-) = 0.91/0.1$$

Coupled-channel analysis for neutral Higgs bosons

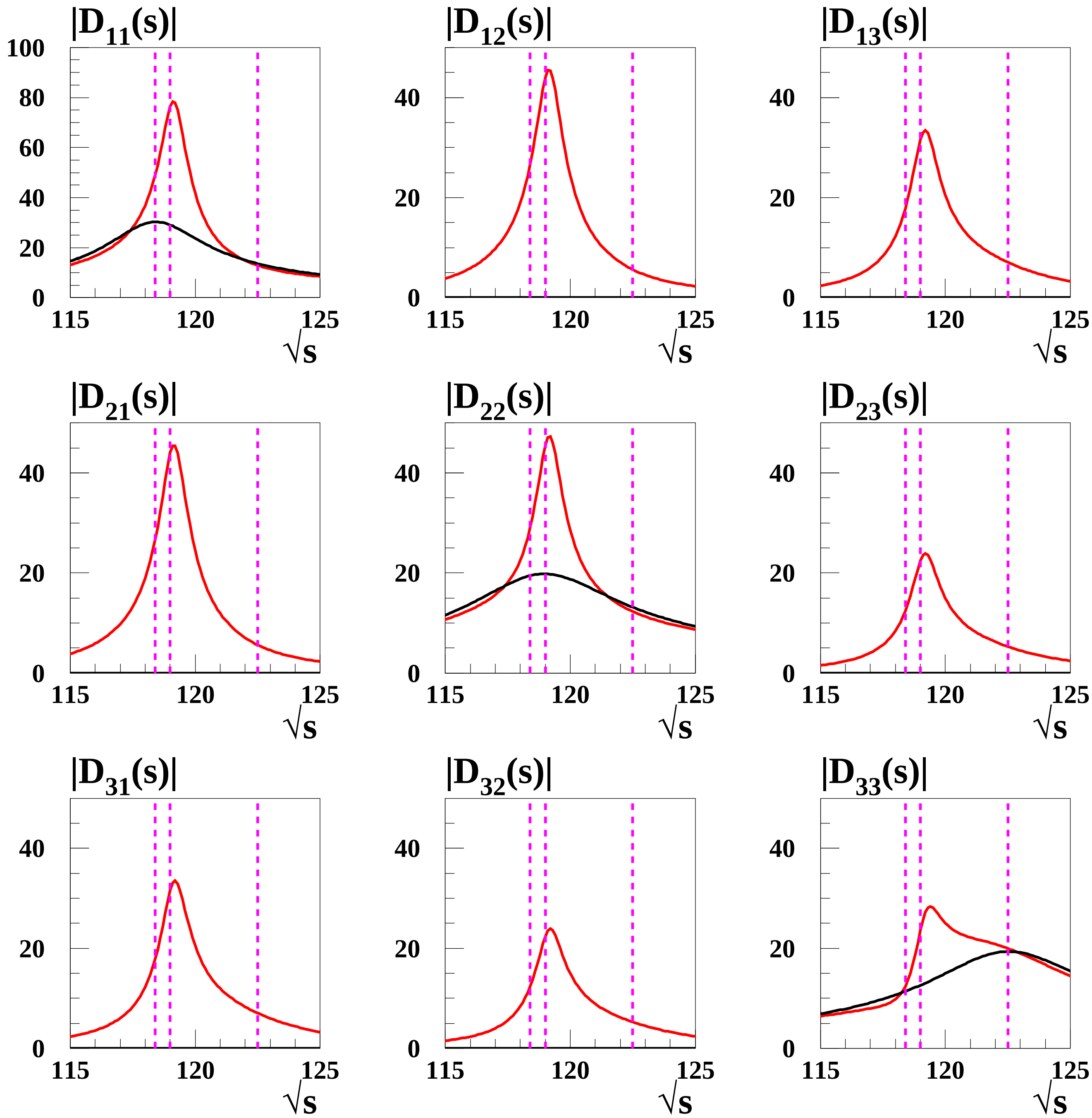
– $\mathrm{Im}\,\widehat{\Pi}_{ij} = 0$, when $i \neq j$

– Complete 3×3 Higgs-boson propagator matrix $D(\hat{s})$
[A.P., NP**B504** (1997) 61; J. Ellis, J.S. Lee, A.P., PR**D70** (2004) 075010.]

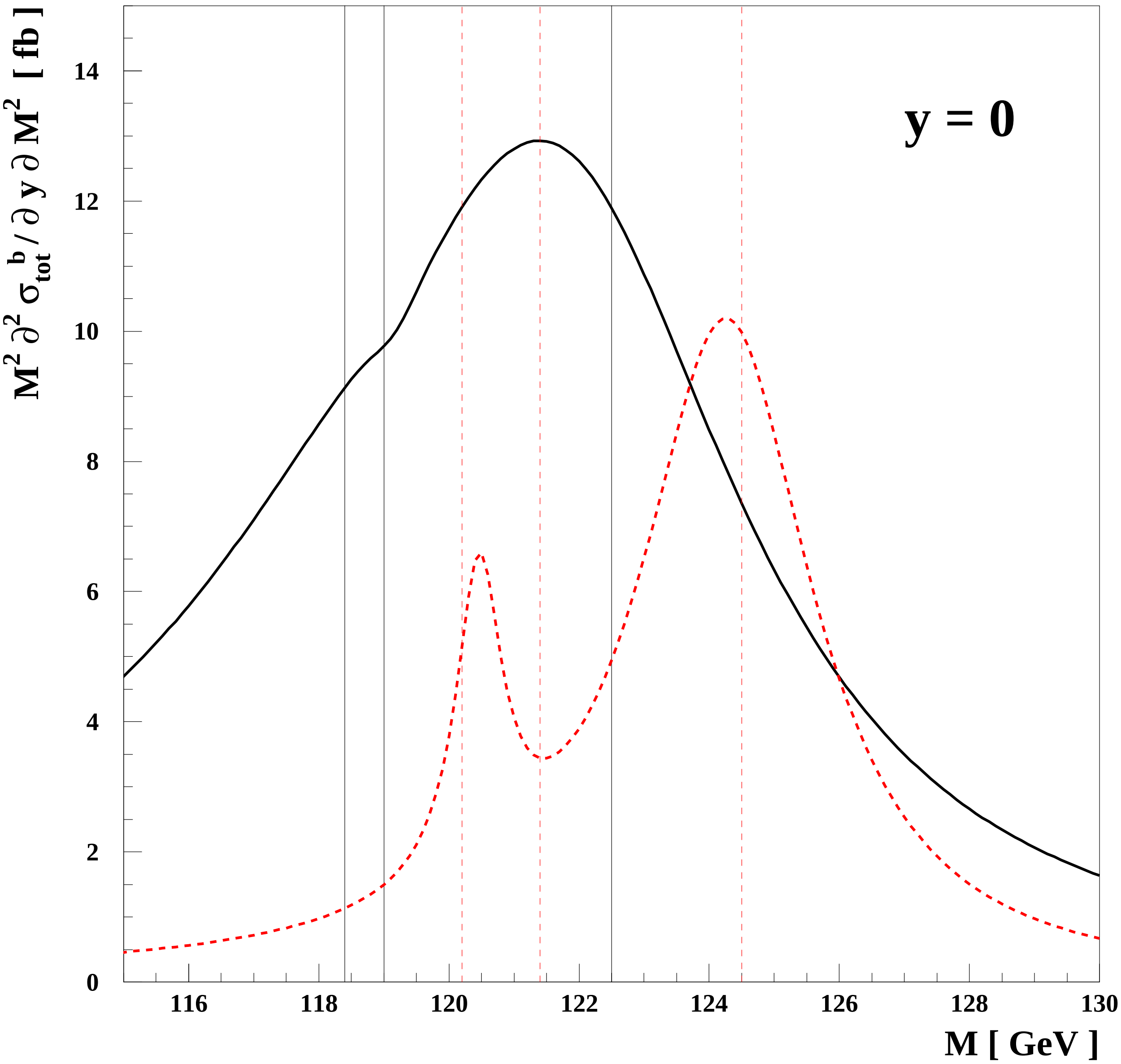
Higgs Tri-mixing scenario with $\Phi_3 = -10^\circ$:



Higgs Tri-mixing scenario with $\Phi_3 = -90°$:



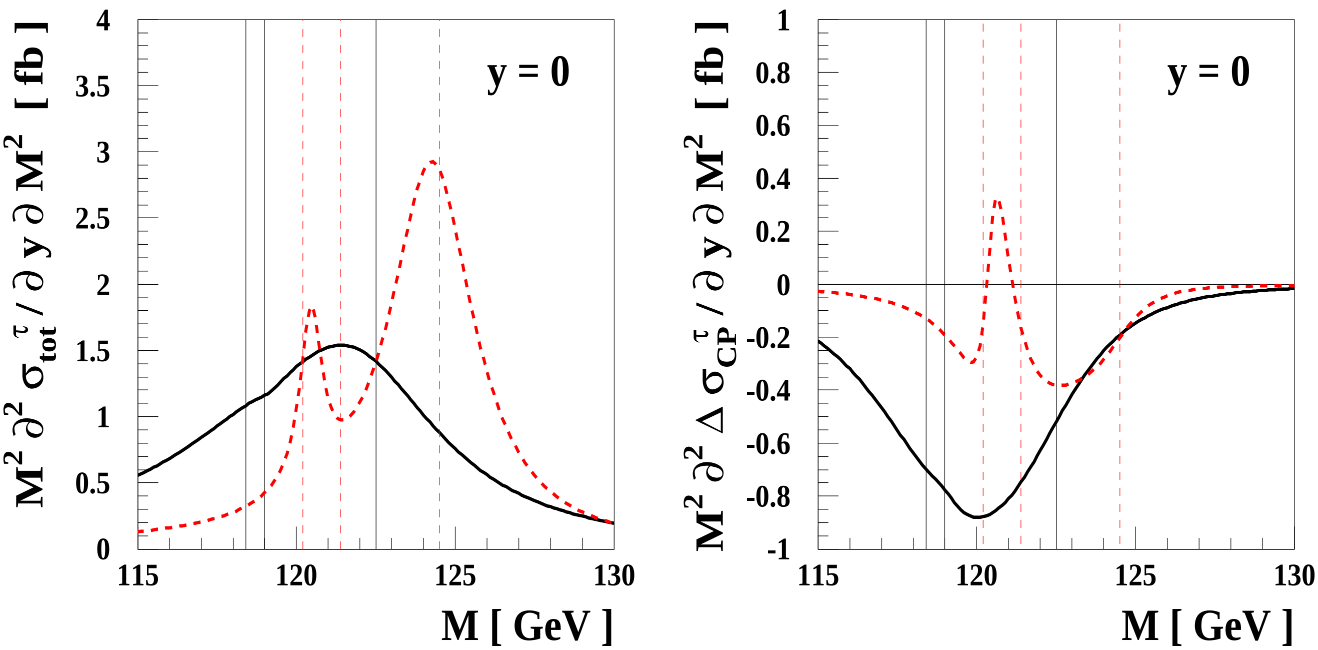
$pp \to p + H_i + p \to p + [b(\sigma)\bar{b}(\bar{\sigma})] + p$



$M^2 \frac{\partial^2 \sigma^b_{\rm tot}}{\partial y \partial M^2}$ versus M, using CTEQ6M PDFs.

Higgs tri-mixing scenarios with $\Phi_3 = -90^\circ$ (solid lines) and $\Phi_3 = -10^\circ$ (dotted lines). The vertical lines indicate the three Higgs-boson pole-mass positions.

$$pp \rightarrow p + H_i + p \rightarrow p + [\tau^-(\sigma)\tau^+(\bar{\sigma})] + p$$

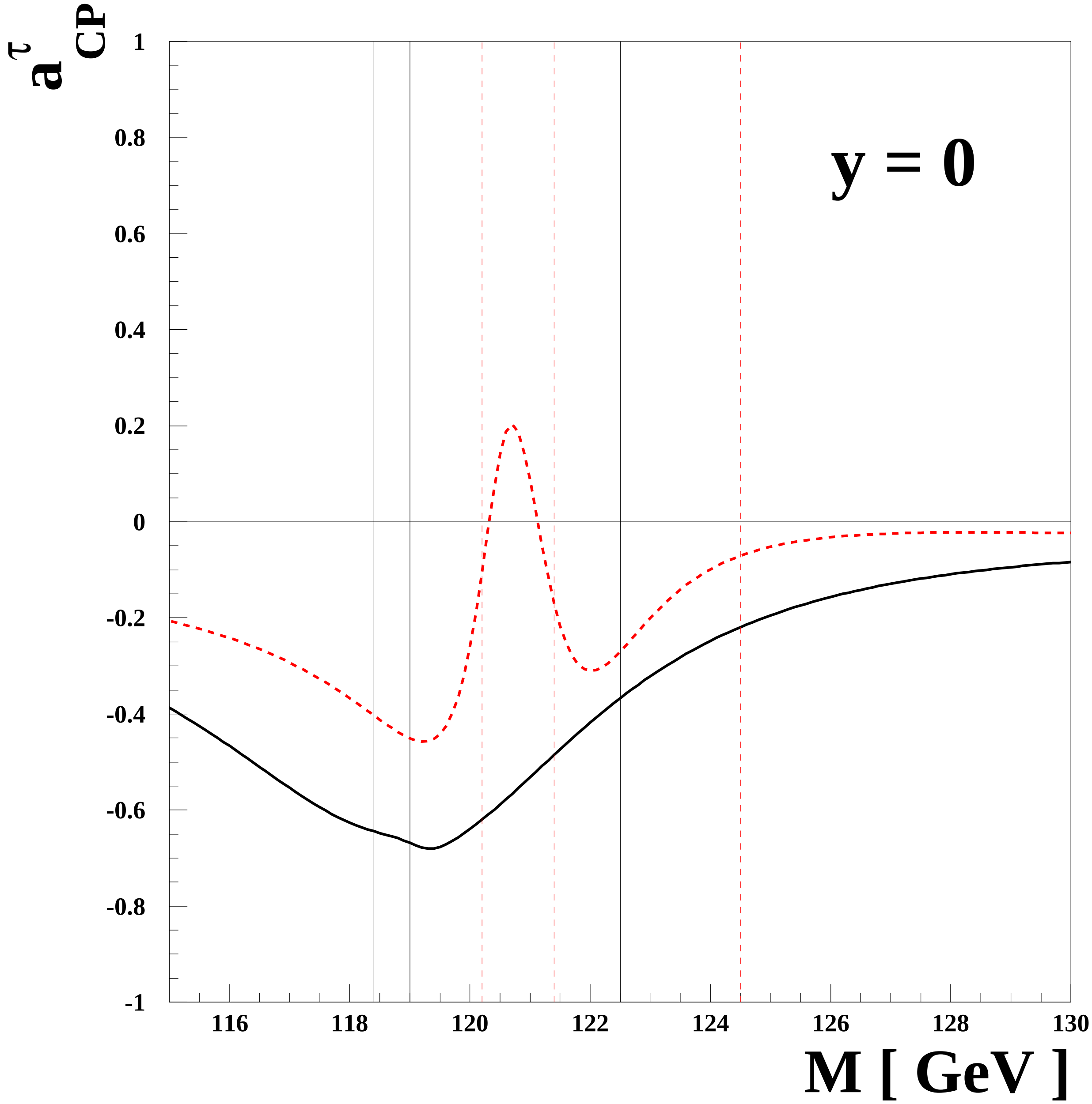


$M^2\frac{\partial^2\sigma^\tau_{\rm tot}}{\partial y\partial M^2}$ (left) and $M^2\frac{\partial^2\Delta\sigma^\tau_{\rm CP}}{\partial y\partial M^2}$ (right) versus M, using CTEQ6M PDFs, where

$$\Delta\sigma^\tau_{\rm CP} \equiv \sigma(pp \rightarrow pH_ip;\ H_i \rightarrow \tau^+_R\tau^-_R) - \sigma(pp \rightarrow pH_ip;\ H_i \rightarrow \tau^+_L\tau^-_L)$$

Higgs tri-mixing scenarios with $\Phi_3 = -90^\circ$ (solid lines) and $\Phi_3 = -10^\circ$ (dotted lines). The vertical lines indicate the three Higgs-boson pole-mass positions.

CP Asymmetry in Higgs Tri-mixing Scenarios



$$a^{\tau}_{\rm CP} \equiv \frac{M^2 \, \frac{\partial^2 \Delta\sigma^{\tau}_{\rm CP}}{\partial y \partial M^2}}{M^2 \, \frac{\partial^2 \sigma^{\tau}_{\rm tot}}{\partial y \partial M^2}}$$

• Future Prospects

- The CP-violating MSSM predicts naturally 3 nearly degenerate neutral Higgs bosons for $M_{H^+} \sim 140$–170 GeV and large $\tan\beta \gtrsim 40$, where all 3 Higgs bosons mix strongly with each other. We term such a scenario the Higgs Tri-mixing Scenario of the CP-violating MSSM.

- Diffraction at the LHC offers unique capabilities to analyze the CP properties and the lineshape of a strongly coupled Higgs-boson system, through the missing-mass method, with expected missing-mass resolution $\Delta M \sim 1$ GeV.

- Further studies on the dynamics and phenomenology of diffraction are needed:

  (i) Reduce the theoretical uncertainties.

  (ii) Study other possible channels.

  (iii) Explore other observables, e.g. in inclusive diffractive processes.