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Institute of High Energy Physics Chinese Academy of Sciences

INSTITUTE OF HIGH ENERGY PHYSICS · CAS · THEORETICAL PHYSICS DIVISION

Measuring Phase Angle in the Higgs-bottom Yukawa Interaction at Higgs Factory

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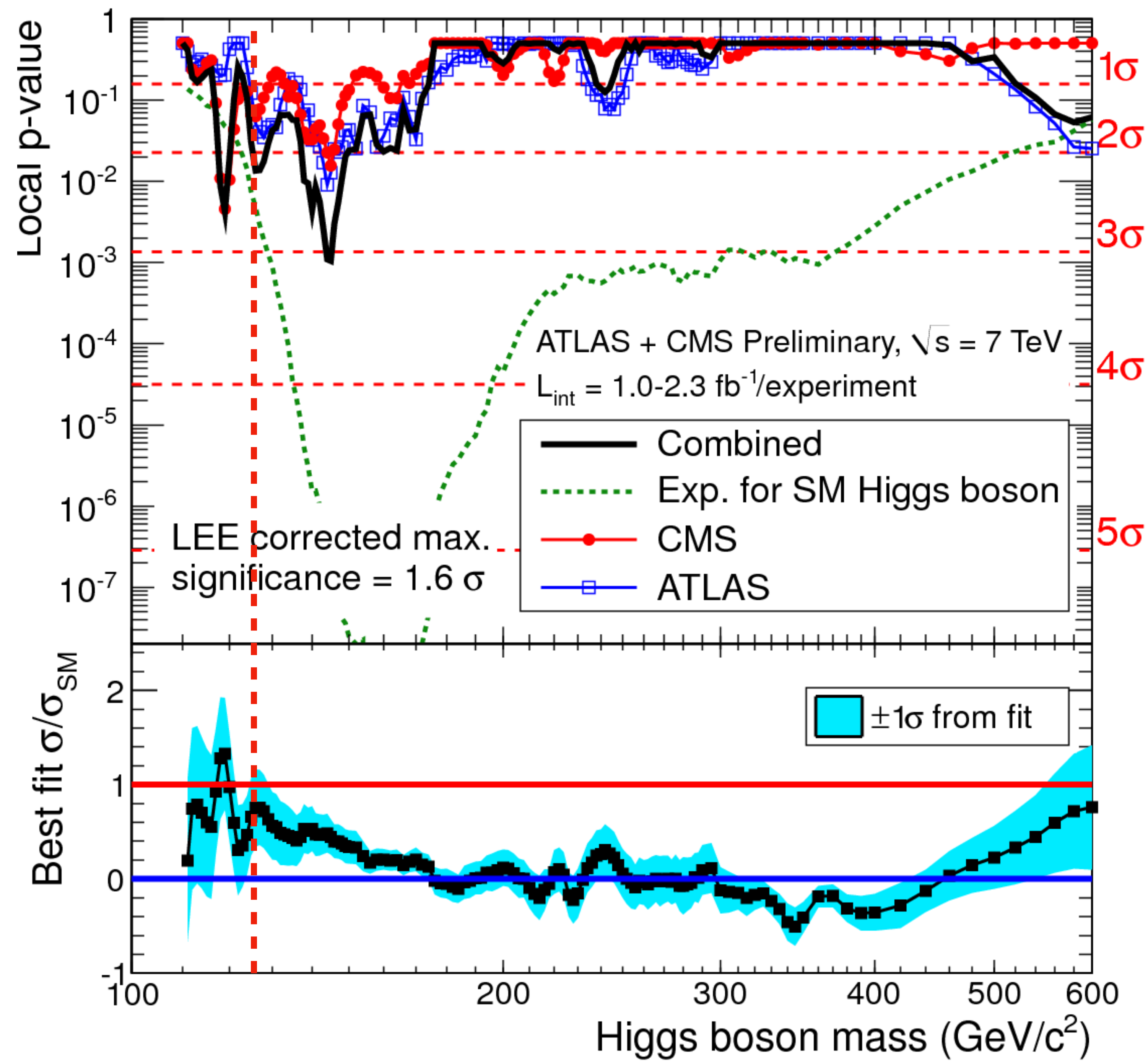
Based on work in collaboration with Edmond L. Berger, Qi Bi, Kangyu Chai, Jun Gao and Yiming Liu

Introduction

An Era of Precisely Higgs Physics

- From 2011 to 2019

At the end of 2011, there was no evidence of the new scalar boson. Did you guess the correct mass of the SM-like Higgs boson from the information shown in this figure?

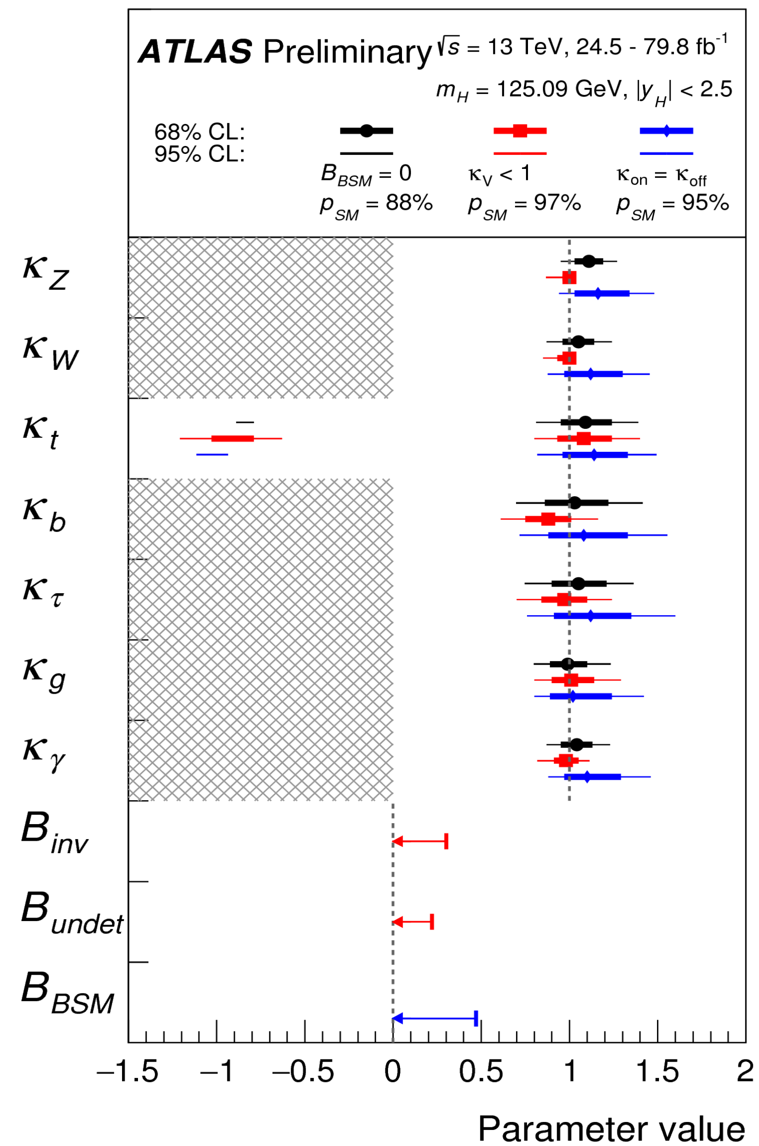


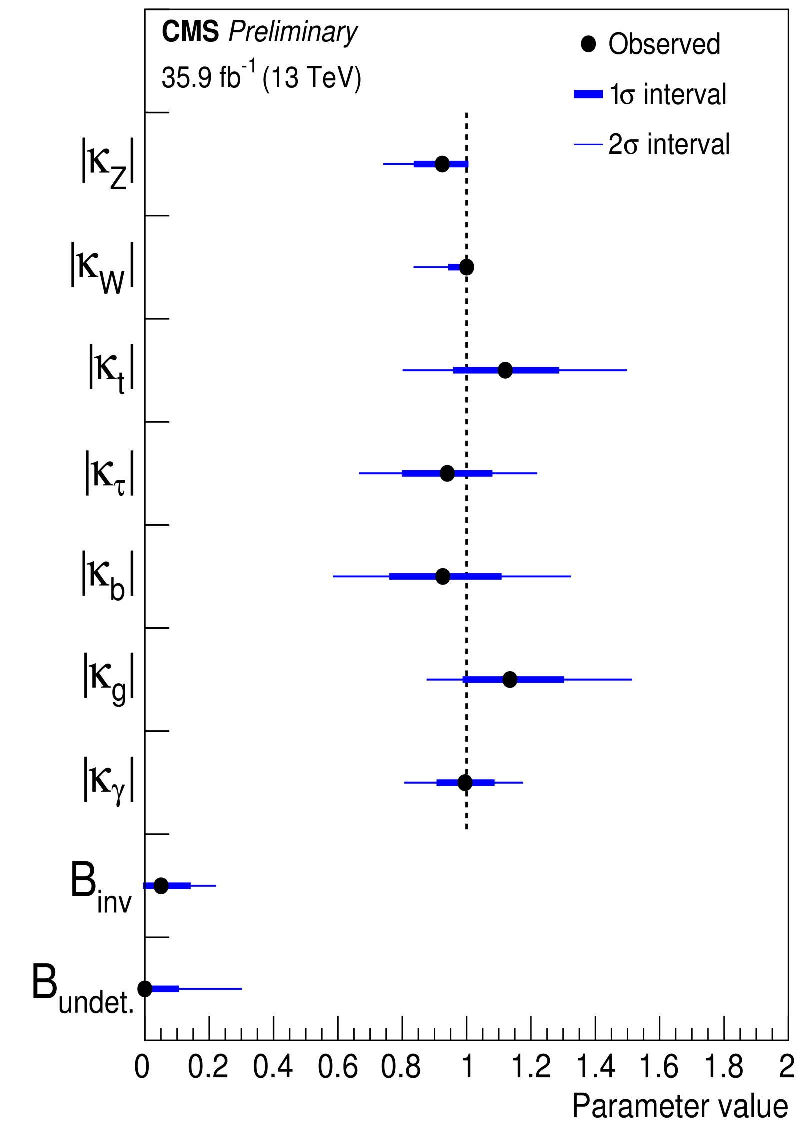
ATLAS and CMS Collaboration, ATLAS-CONF-2011-157, CMS PAS HIG-11-023.

An Era of Precisely Higgs Physics

- From 2011 to 2019

With 80 fb^{-1} integrated luminosity, the κ parameters are measured with ~20% accuracy.

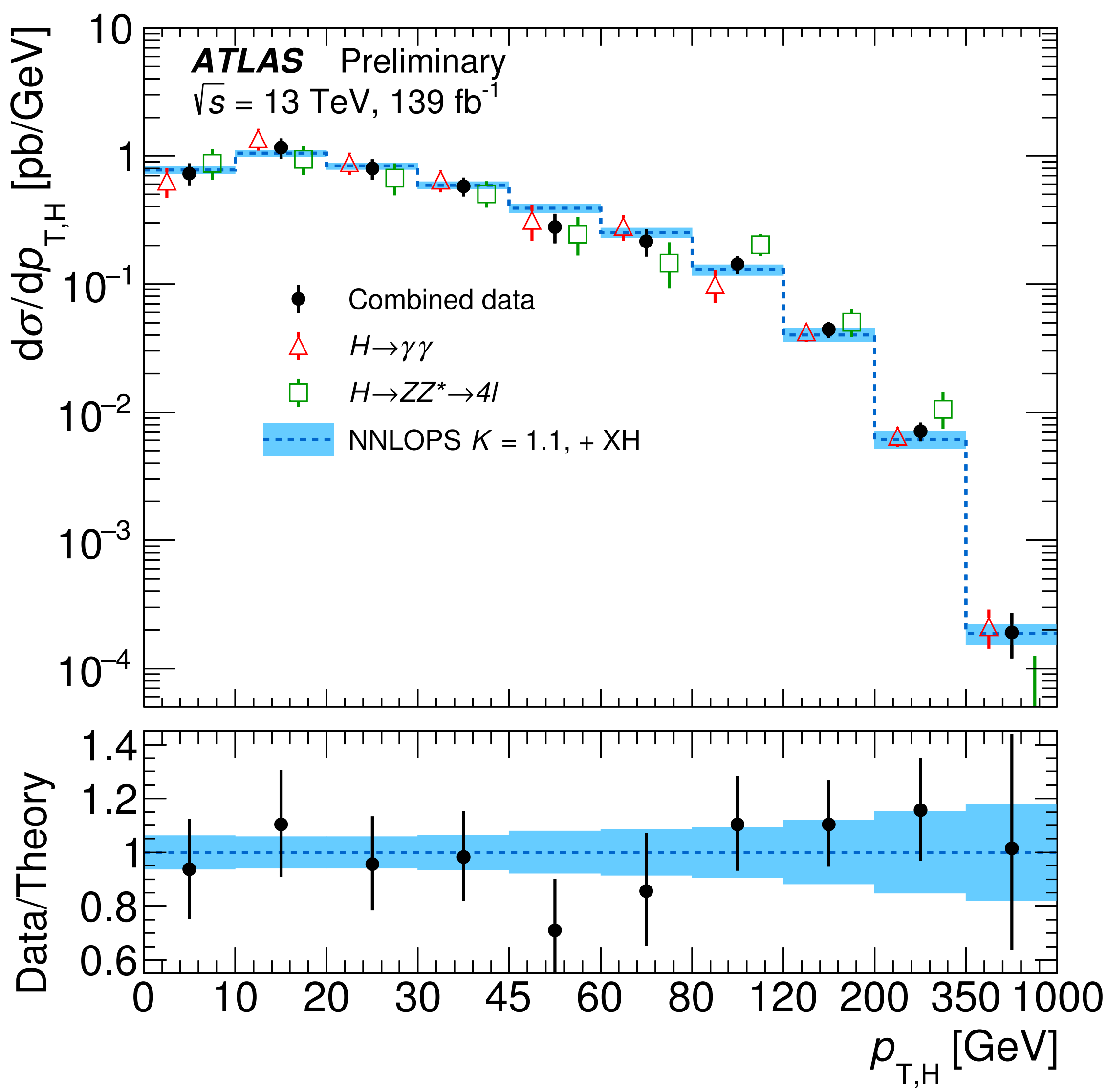


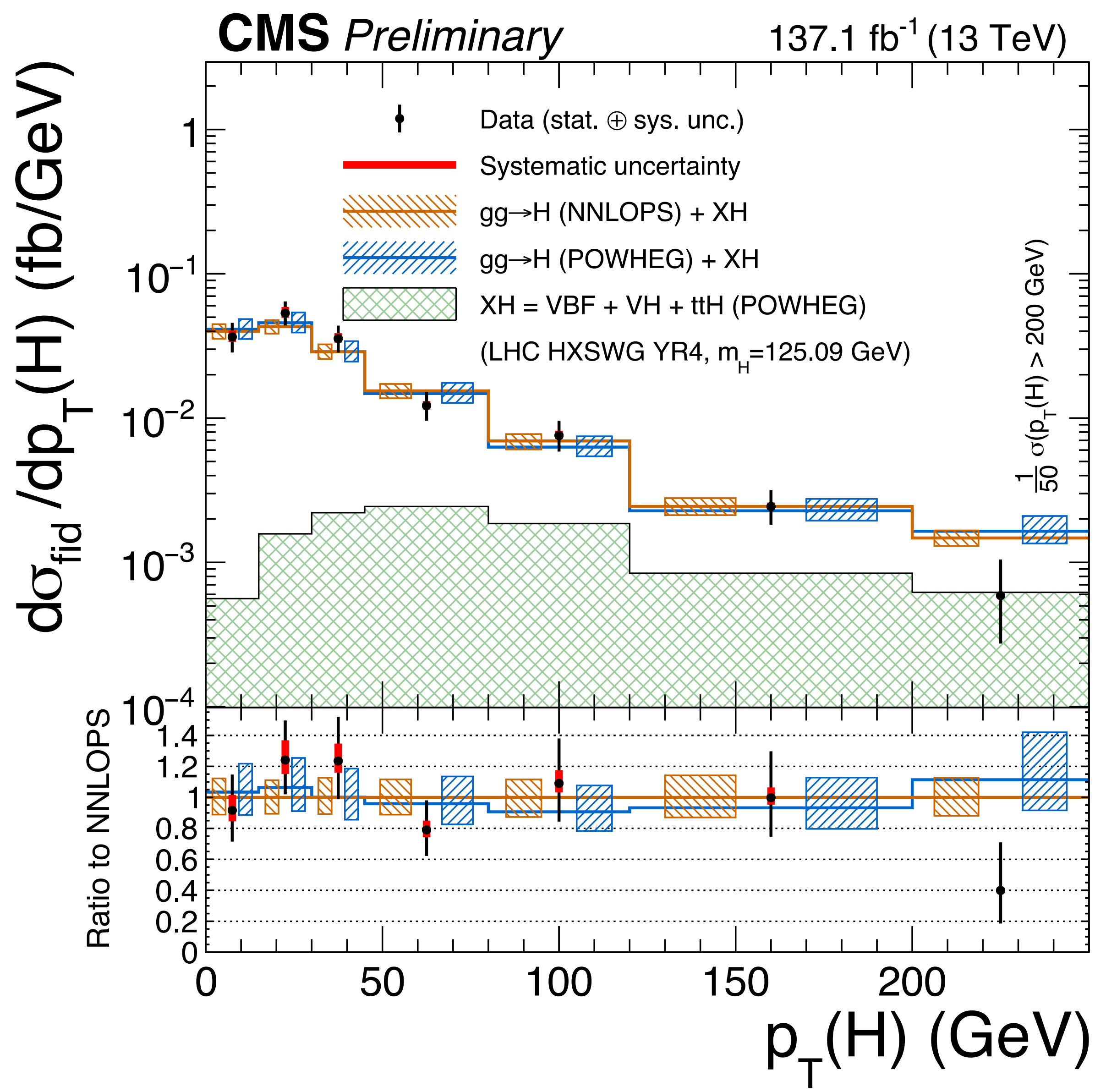


ATLAS Collaboration, arXiv:1909.02845[hep-ex];
CMS Collaboration, CMS-PAS-HIG-17-031.

An Era of Precisely Higgs Physics

- More information: go beyond the κ-scheme!

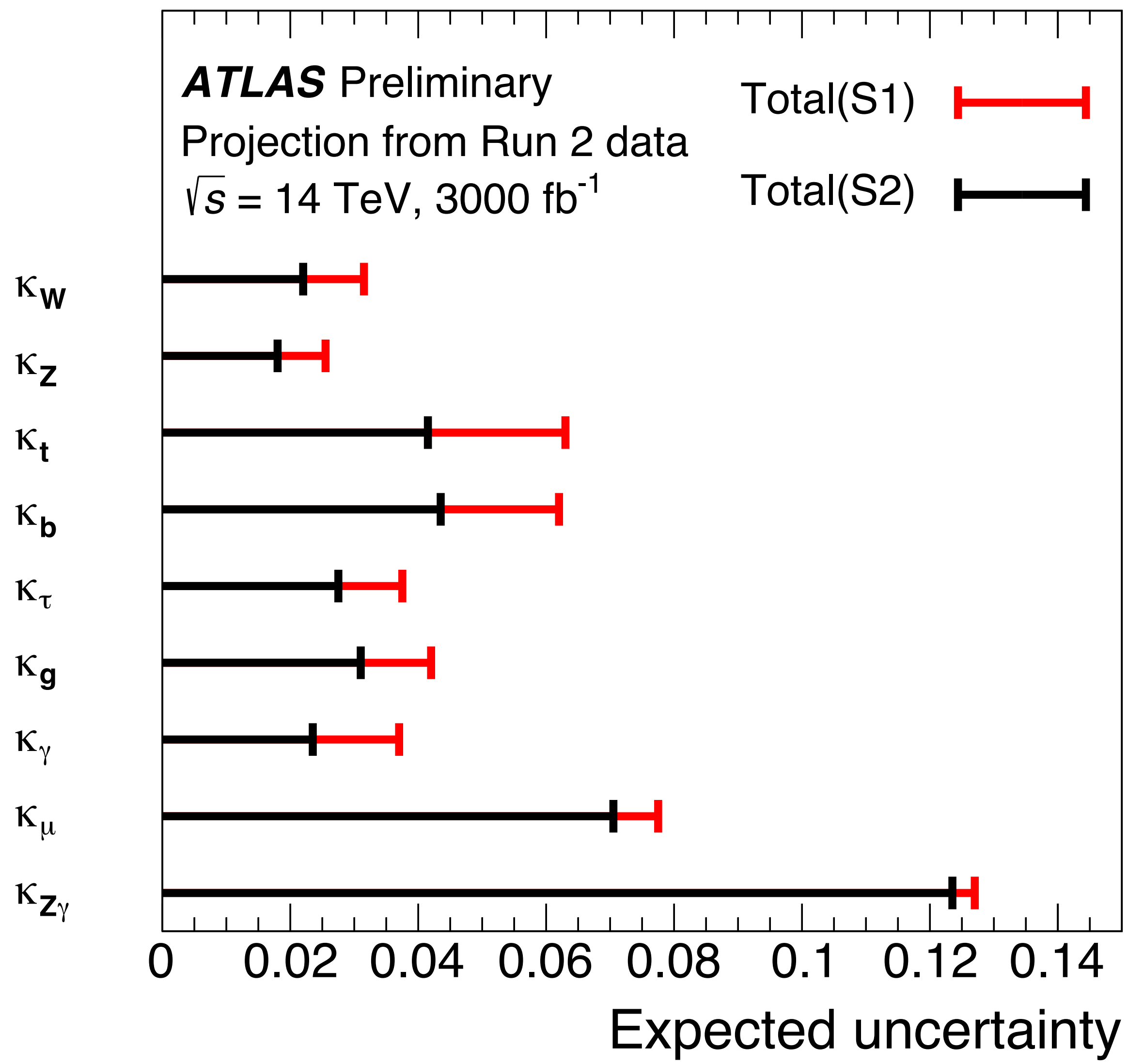


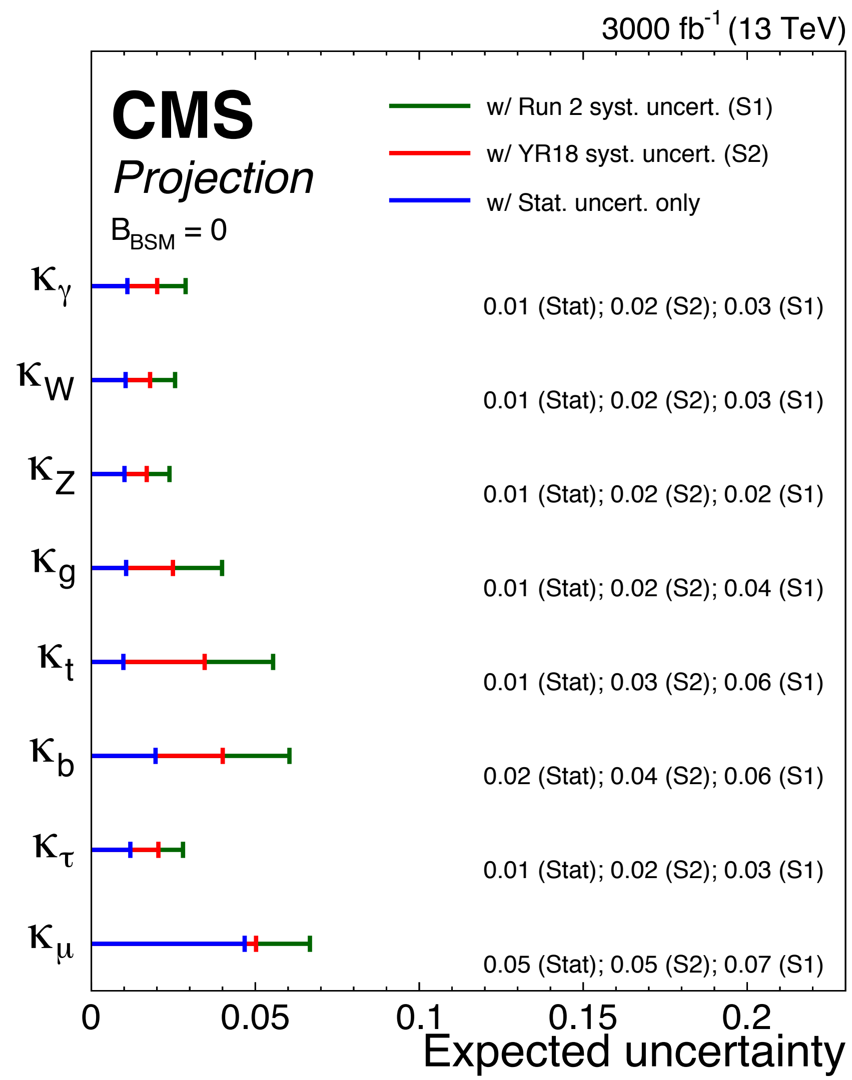


ATLAS Collaboration, ATLAS-CONF-2019-032;
CMS Collaboration, CMS-PAS-HIG-19-001.

An Era of Precisely Higgs Physics

- More precisely result in near future.

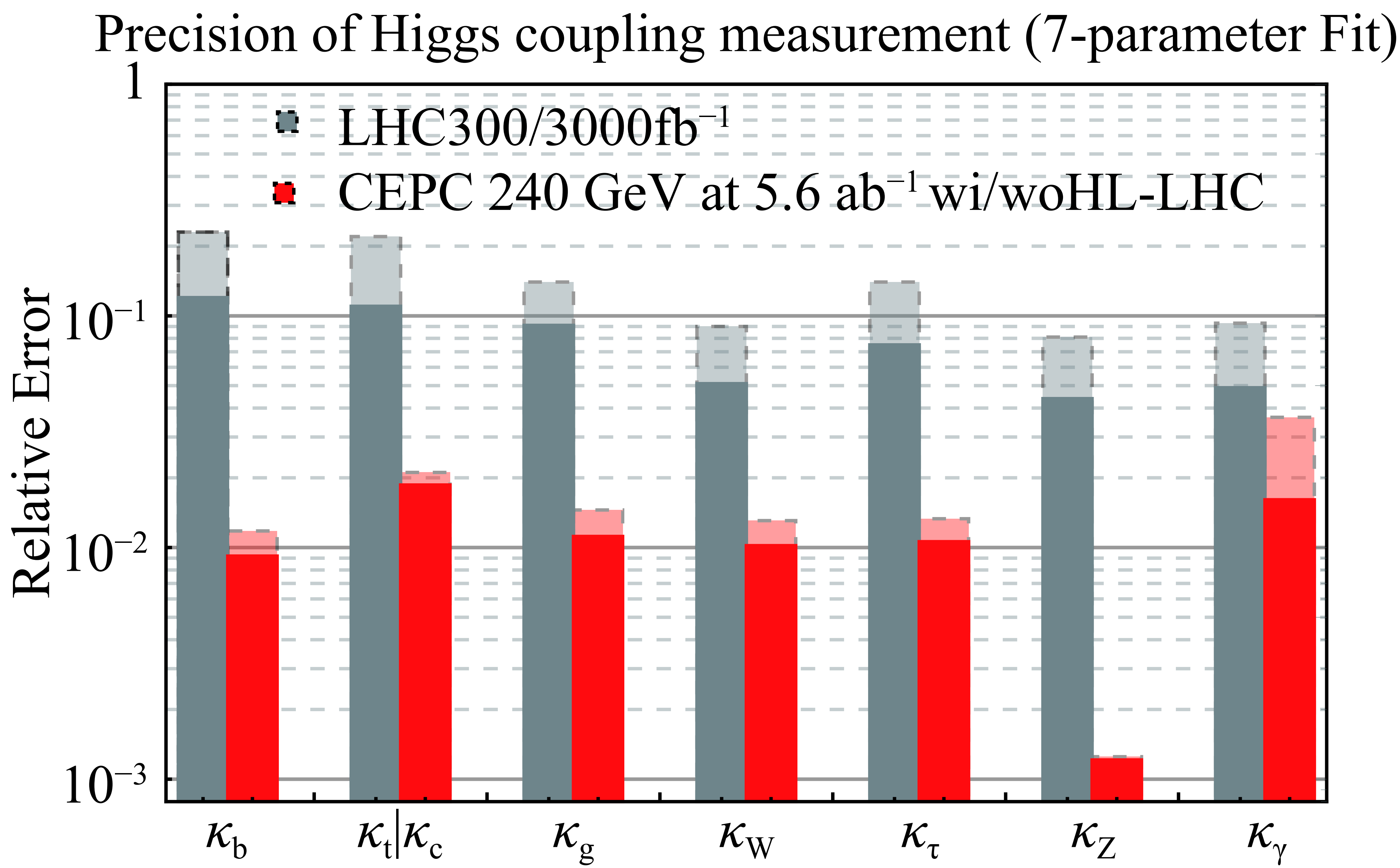




ATLAS Collaboration, ATLAS-PHYS-PUB-2018-054;
CMS Collaboration, CMS PAS FTR-18-011.

An Era of Precisely Higgs Physics

- More results with Higgs factory.

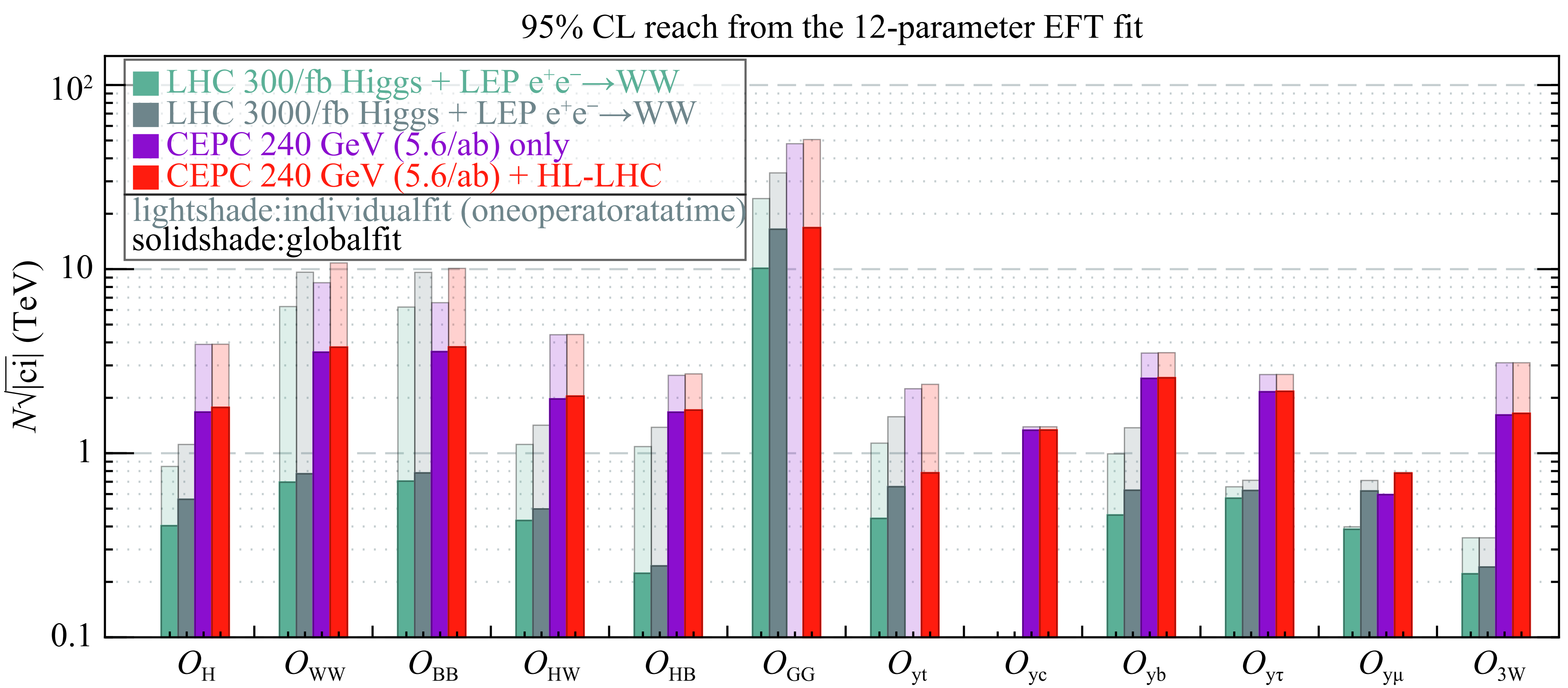


F. An, et al, Chin. Phys. C43 (2019) 043002

An Era of Precisely Higgs Physics

- Go beyond the “signal strength”.

1. Effective Field Theory (theories?) method



F. An, et al, Chin. Phys. C43 (2019) 043002; etc (too many to be listed fairly)

An Era of Precisely Higgs Physics

- Go beyond the “signal strength”.

1. Effective Field Theory (theories?) method

    - Advantages: model-independent, self-consistent, …

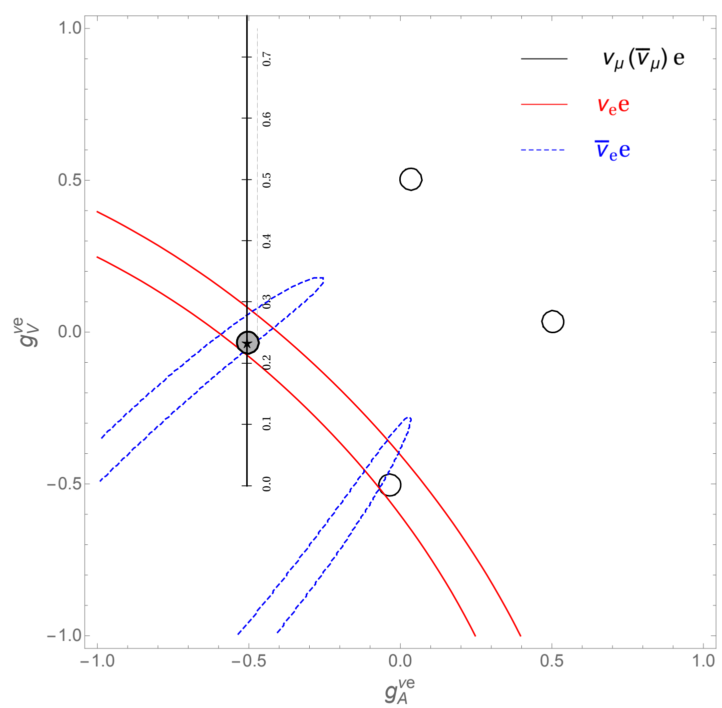
    - Need helps from traditional method: too many parameters …

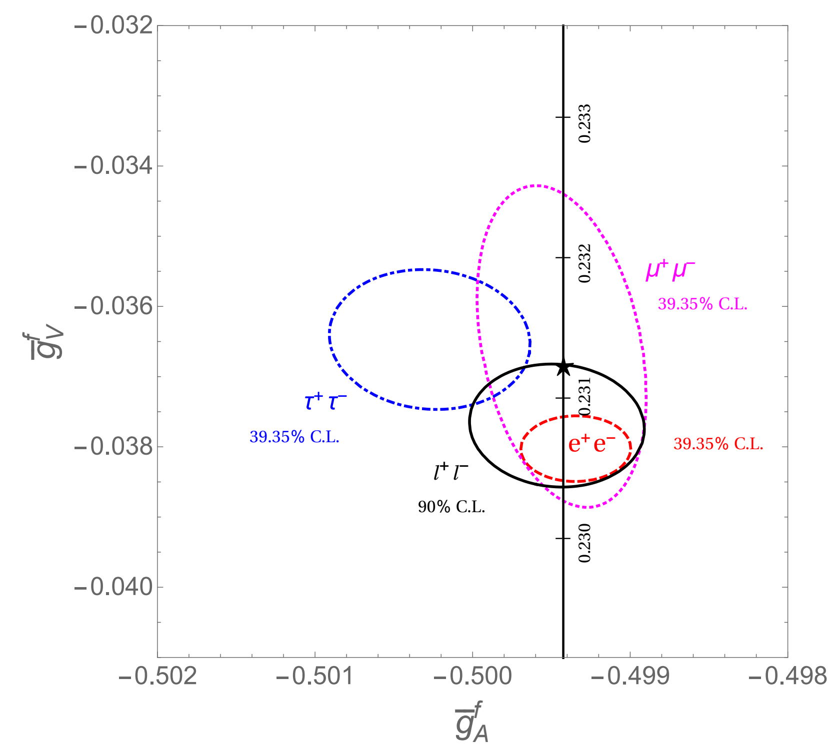
An Era of Precisely Higgs Physics

- Go beyond the “signal strength”.

1. Effective Field Theory (theories?) method

2. Traditional method: from signal strength to Lorentz structures.





J. Erler and A. Freitas, Phys. Rev. D98 (2018) 030001 (PDG2018)

An Era of Precisely Higgs Physics

- Example: generic form of the SFF interaction

$$\mathscr{L} = y_f h \bar{f}(\cos\alpha_f + i\gamma_5 \sin\alpha_f) f$$

$$y_f \in \mathbb{R}^+, \quad \alpha_f \in (-\pi, \pi]$$

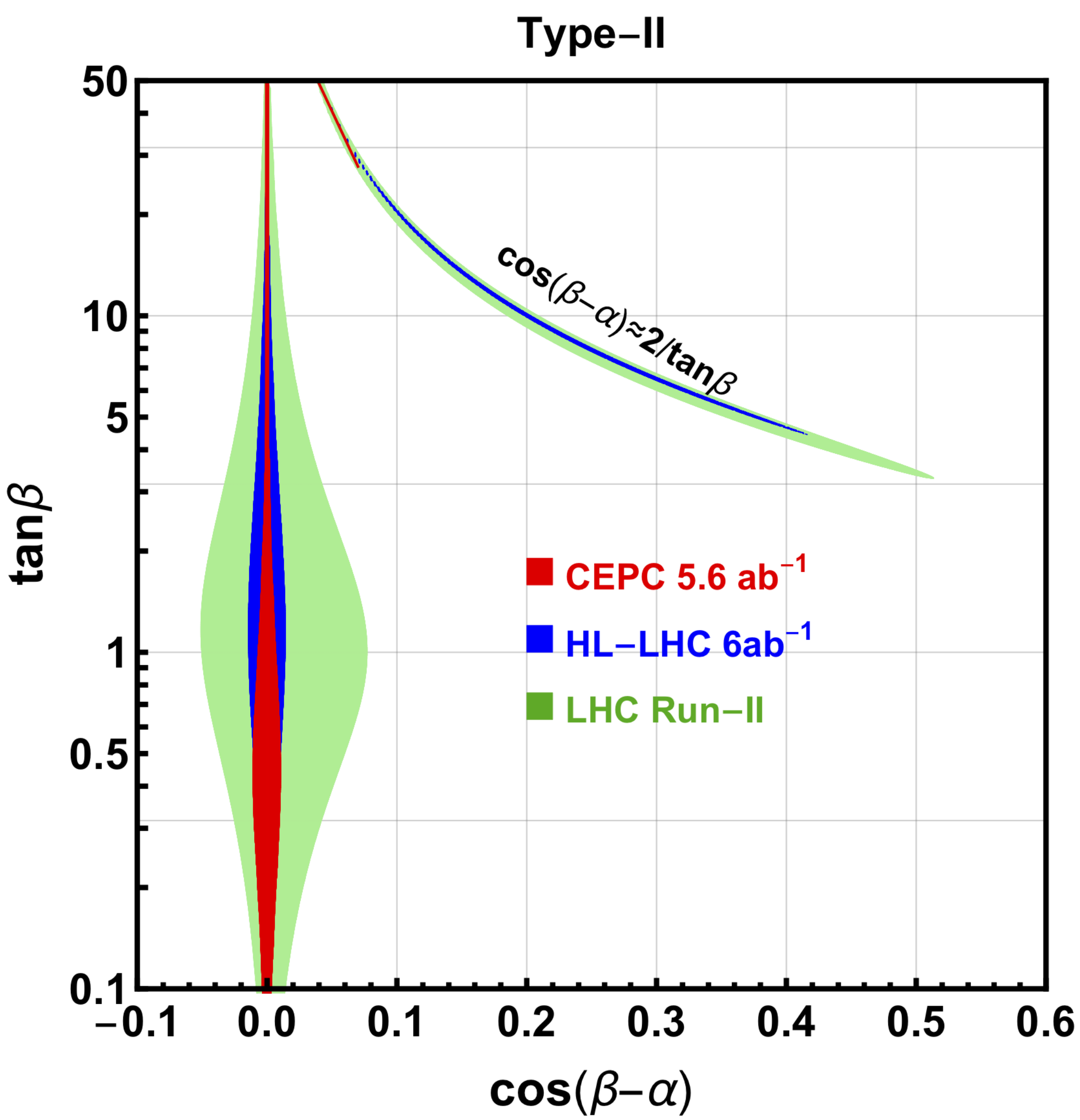
- The non-zero phases in the Yukawa interactions are evidence of new sources of EWSB and might be important for us to understand the matter-antimatter asymmetry in our universe.

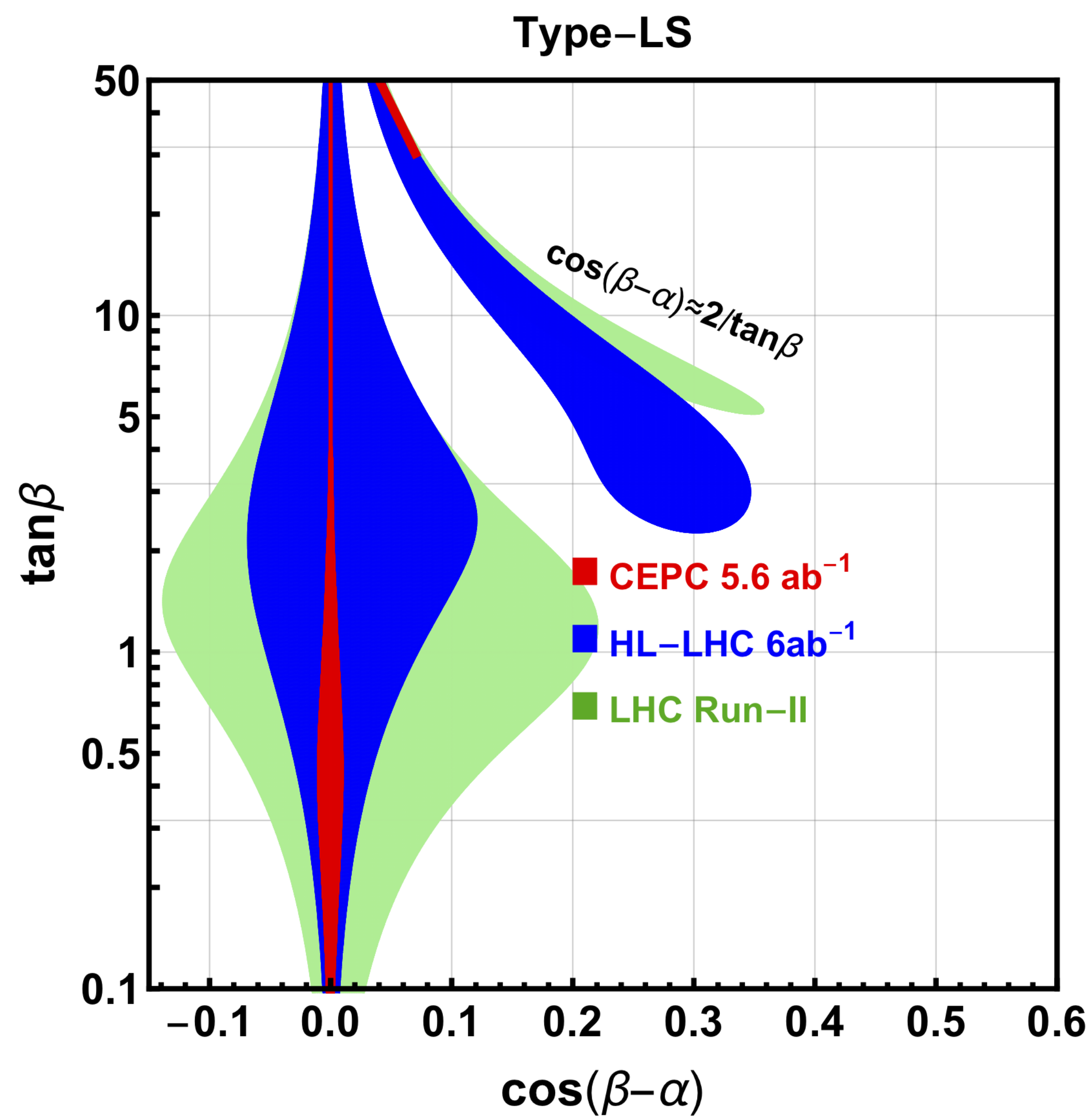
- Can we measure the α_f ?

Phase in bottom-quark Yukawa interaction

Phase in bottom-quark Yukawa Interactions

- Very interesting parameter.
- Exp: 2HDMs

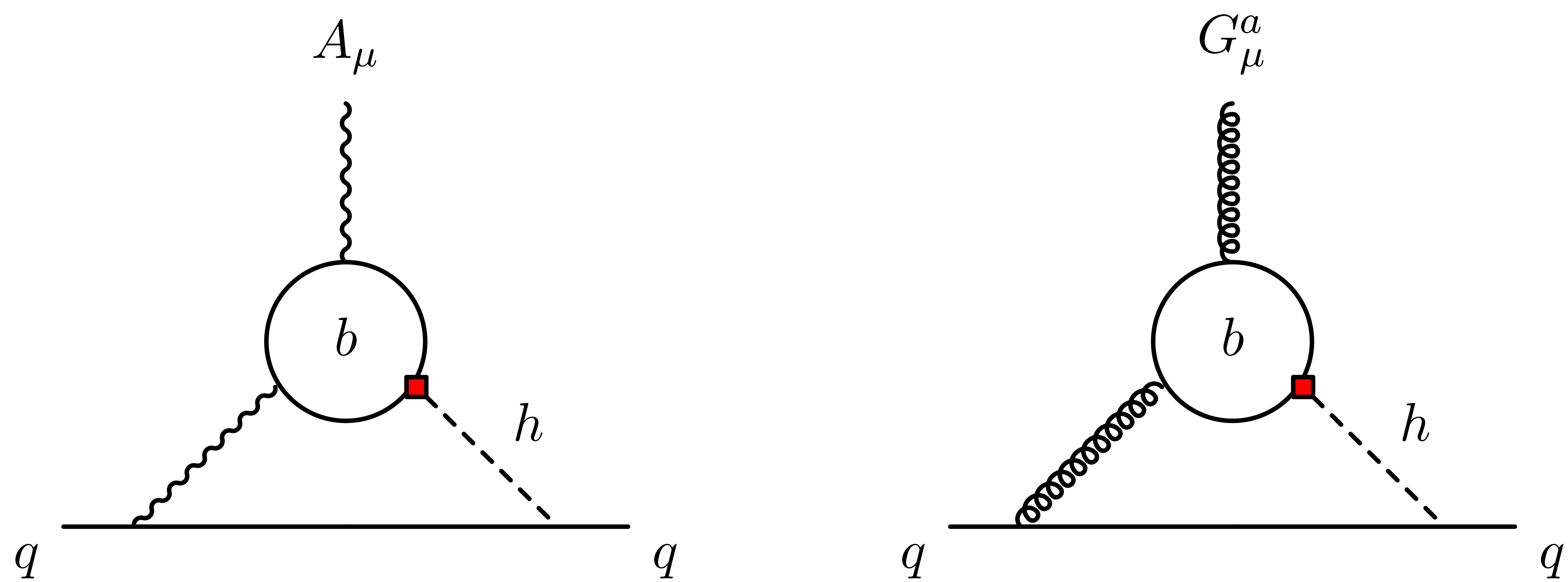




Wei Su, arXiv:1910.06269[hep-ph].

Phase in bottom-quark Yukawa Interactions

- Indirect measurement (e.g. EDM).



$$\mathscr{L}_{\rm eff} = -d_q \frac{i}{2}\,\bar{q}\sigma^{\mu\nu}\gamma_5 q\, F_{\mu\nu} - \tilde{d}_q \frac{ig_s}{2}\,\bar{q}\sigma^{\mu\nu}T^a\gamma_5 q\, G^a_{\mu\nu}$$

$$d_q \simeq -12eQ_qQ_b^2 \frac{\alpha}{(4\pi)^3}\sqrt{2}G_F m_q\,\kappa_b \sin\phi_b\, x_b \left(\log^2 x_b + \frac{\pi^2}{3}\right) ,$$

$$\tilde{d}_q \simeq 2\frac{\alpha_s}{(4\pi)^3}\sqrt{2}G_F m_q\,\kappa_b \sin\phi_b\, x_b \left(\log^2 x_b + \frac{\pi^2}{3}\right) ,$$

J. Brod and E. Stamou, arXiv:1810.12303[hep-ph].

Phase in bottom-quark Yukawa Interactions

- Indirect measurement (e.g. EDM).

- Hadronic EDMs (90% C.L.):

$$\frac{y_b}{y_b^{\mathrm{SM}}} |\sin \alpha_b| < 5$$

- Electron EDM (90% C.L.):

$$\frac{y_b}{y_b^{\mathrm{SM}}} |\sin \alpha_b| < 0.4$$

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- But indirectly measurements are suffered by the NP contributions to the loop…

J. Brod and E. Stamou, arXiv:1810.12303[hep-ph].

Phase in bottom-quark Yukawa Interactions

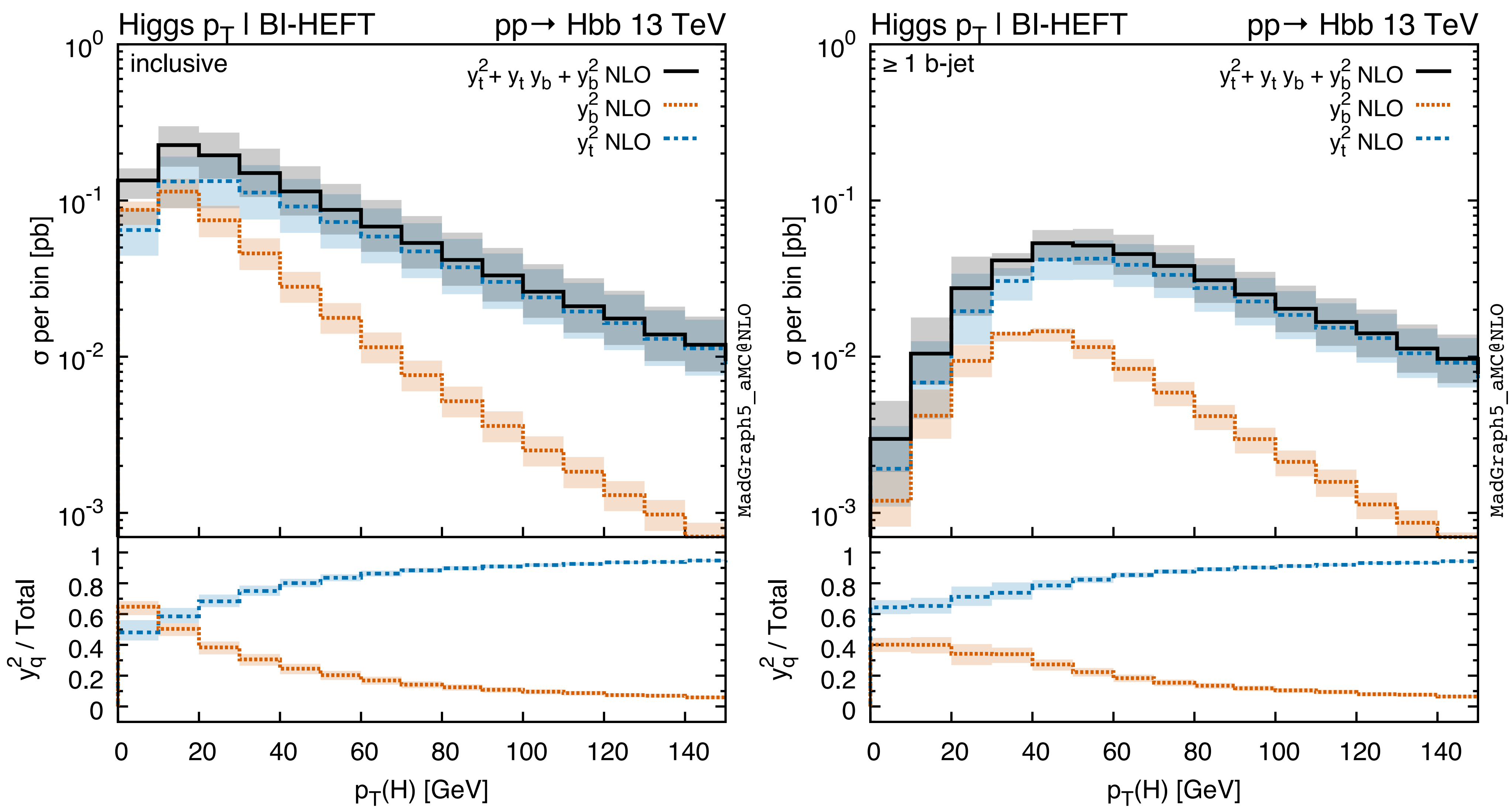
- Indirect measurement (e.g. EDM).
- But difficult at the LHC!
- Indirect: small contribution to gluon fusion process due to tiny coupling constant.

$$\sigma(gg \to H) \sim 1.04\kappa_t^2 + 0.002\kappa_b^2 - 0.04\kappa_t\kappa_b$$

ATLAS Collaboration, arXiv:1909.02845[hep-ex].

Phase in bottom-quark Yukawa Interactions

- Very difficult at the LHC!
- Direct: large background, large contribution from Hgg.



N. Deutschmann, F. Maltoni, M. Wiesemann and Marco Zaro, JHEP 1907 (2019) 054.

Phase in bottom-quark Yukawa Interactions

- But possible at Higgs factory.

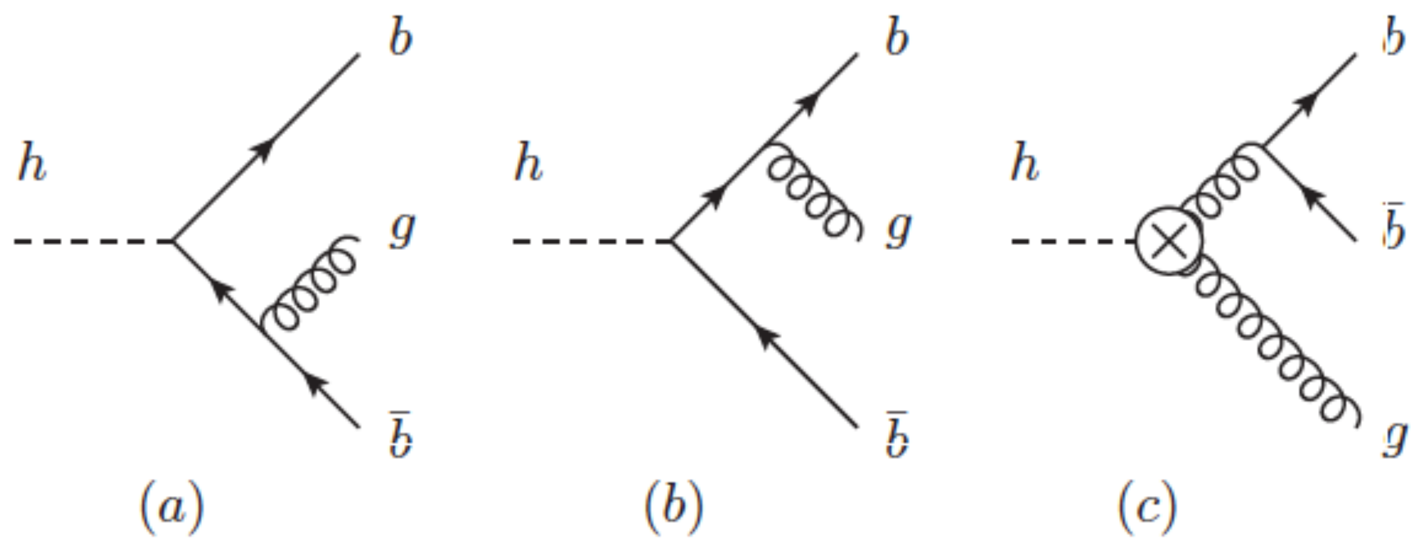
$$\Gamma(h \to b\bar{b}) = \Gamma(h \to b\bar{b})^{\rm SM} \left(\frac{y_b^{\rm SM}}{y_b}\right)^2 \left(\cos^2\alpha_b + \beta_b^{-2}\sin^2\alpha_b\right)$$

- Small bottom mass, 0.25% modulation of the partial width.
- Sensitivity of the partial width: ~0.3%.
- We need other method.

F. An, et al, Chin. Phys. C43 (2019) 043002;

Phase in bottom-quark Yukawa Interactions

- Interference in Higgs decay:



- Advantage: the Hgg interaction can be well measured at both the LHC and the Higgs factory, with the information of the Lorentz structure.

$$hG^a_{\mu\nu}G^{a,\mu\nu} \quad \textbf{vs} \quad hG^a_{\mu\nu}\tilde{G}^{a,\mu\nu}$$

Phase in bottom-quark Yukawa Interactions

- Interference in Higgs decay:

$$d\Gamma \sim y_b^2 \alpha_s d\Gamma_{11} + y_b \alpha_s^2 \frac{m_b}{m_h} d\Gamma_{12} + \alpha_s^3 d\Gamma_{22}$$

- Chirality analysis.

- Symmetry $\quad \psi_f \to e^{-i\alpha_f \gamma_5/2} \psi_f$

$$\bar{\psi}_f e^{i\alpha_f \gamma_5} \psi_f \to \psi_f^\dagger e^{i\alpha_f \gamma_5/2} \gamma^0 e^{i\alpha_f \gamma_5} e^{-i\alpha_f \gamma_5/2} \psi_f$$
$$= \psi_f^\dagger \gamma^0 e^{-i\alpha_f \gamma_5/2} e^{i\alpha_f \gamma_5} e^{-i\alpha_f \gamma_5/2} \psi_f = \bar{\psi}_f \psi_f$$

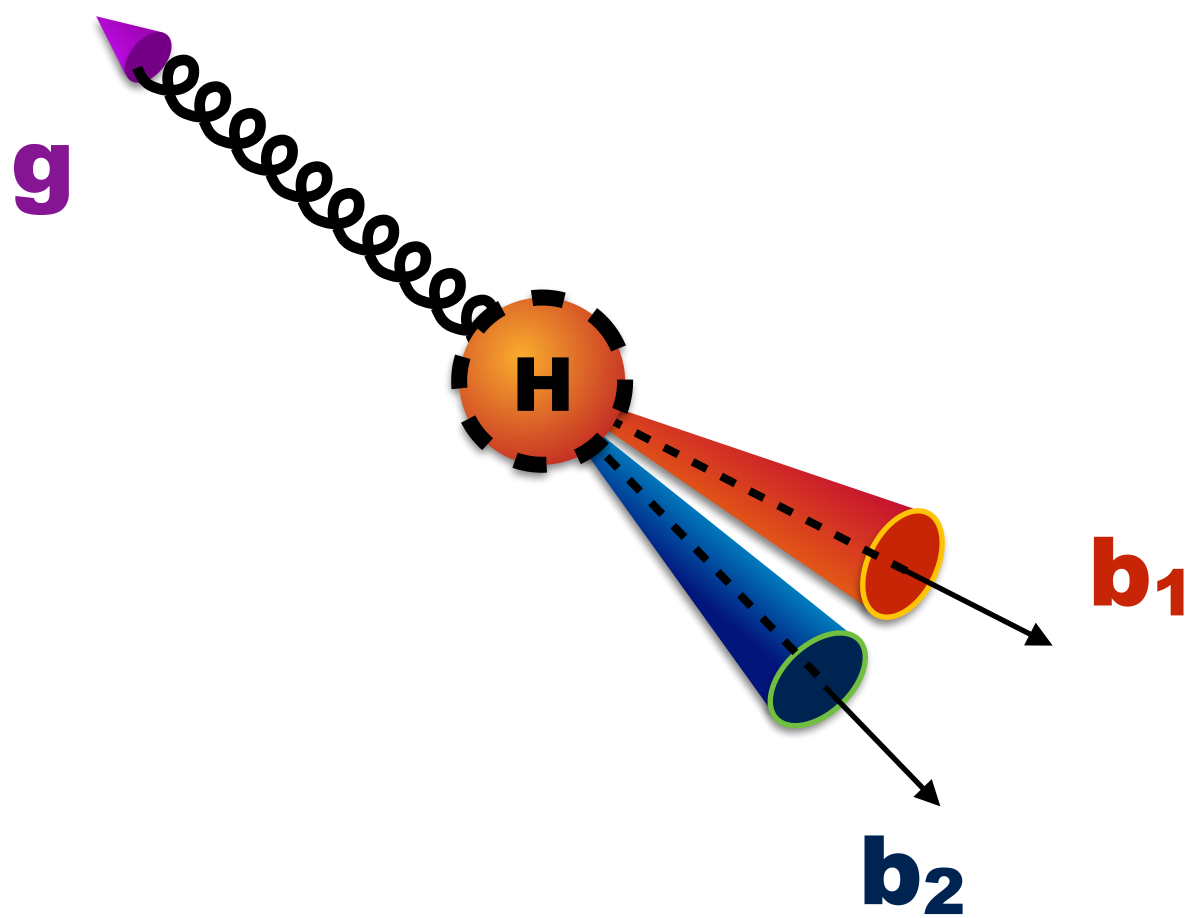
$$m_f \bar{\psi}_f \psi_f \to m_f \psi_f^\dagger e^{i\alpha_f \gamma_5/2} \gamma^0 e^{-i\alpha_f \gamma_5/2} \psi_f = m_f \bar{\psi}_f e^{-i\alpha_f \gamma_5} \psi_f$$

Phase in bottom-quark Yukawa Interactions

- Interference in Higgs decay:

$$d\Gamma \sim y_b^2 \alpha_s d\Gamma_{11} + y_b \alpha_s^2 \frac{m_b}{m_h} d\Gamma_{12} + \alpha_s^3 d\Gamma_{22}$$

- To enhance the interference effect:



$$\zeta_H \equiv \frac{2E_{b_1}E_{b_2}}{\sqrt{E_{b_1}^2 + E_{b_1}^2}} \cos\theta_{b_1 b_2},$$

Collider Simulation

- We analyze the signal and backgrounds at 240GeV Higgs factory and 365GeV electron-positron collider.
- Results from different decay modes of the Z-boson are combined.
- Both signal and background events are produced with MadGraph5. ISR effect and NNLO k-factor are included.
- The detector effect is simulated with Gaussian smearing effect.

F. An, et al, Chin. Phys. C43 (2019) 043002; C. Chen, Z. Cui, G. Li, Q. Li, M. Ruan, L. Wang, Q.-s. Yan, arXiv:1705.04486[hep-ph]; Q.-F. Sun, F. Feng, Y. Jia, W.-L. Sang, Phys. Rev. D96 (2017) 051301; Y. Gong, Z. Li, X. Xu, L. L. Yang, X. Zhao, Phys. Rev. D95 (2017) 093003

Collider Simulation

- The detector effect is simulated with Gaussian smearing effect.

$$
\begin{aligned}
\frac{\sigma(E_j)}{E_j} &= \frac{0.60}{\sqrt{E_j/\mathrm{GeV}}} \oplus 0.01, \\
\frac{\sigma(E_{e^\pm,\gamma})}{E_{e^\pm,\gamma}} &= \frac{0.16}{\sqrt{E_{e^\pm,\gamma}/\mathrm{GeV}}} \oplus 0.01, \\
\sigma\left(\frac{1}{p_{\mathrm{T},\mu^\pm}}\right) &= 2\times 10^{-5}\ \mathrm{GeV}^{-1} \oplus \frac{0.001}{p_{\mu^\pm}\sin^{3/2}\theta_{\mu^\pm}},
\end{aligned}
$$

- The b-tagging efficiency is set to be 80% for channels with leptonic decaying Z boson, and 60% for channels with hadronic decaying Z boson.

- Charm quark jet mis-tagging rate is set to be 10%, light jets mis-tagging rates is set to be 1%.

Collider Simulation

- Pre-selection cuts

$$|\eta_{j,\ell^\pm}| < 2.3,\ \Delta R_{ij} > 0.1, \Delta R_{i\ell} > 0.2,$$
$$E_j > 10\mathrm{GeV},\ E_{\ell^\pm} > 5\mathrm{GeV}.$$

- 240GeV leptonic decaying Z

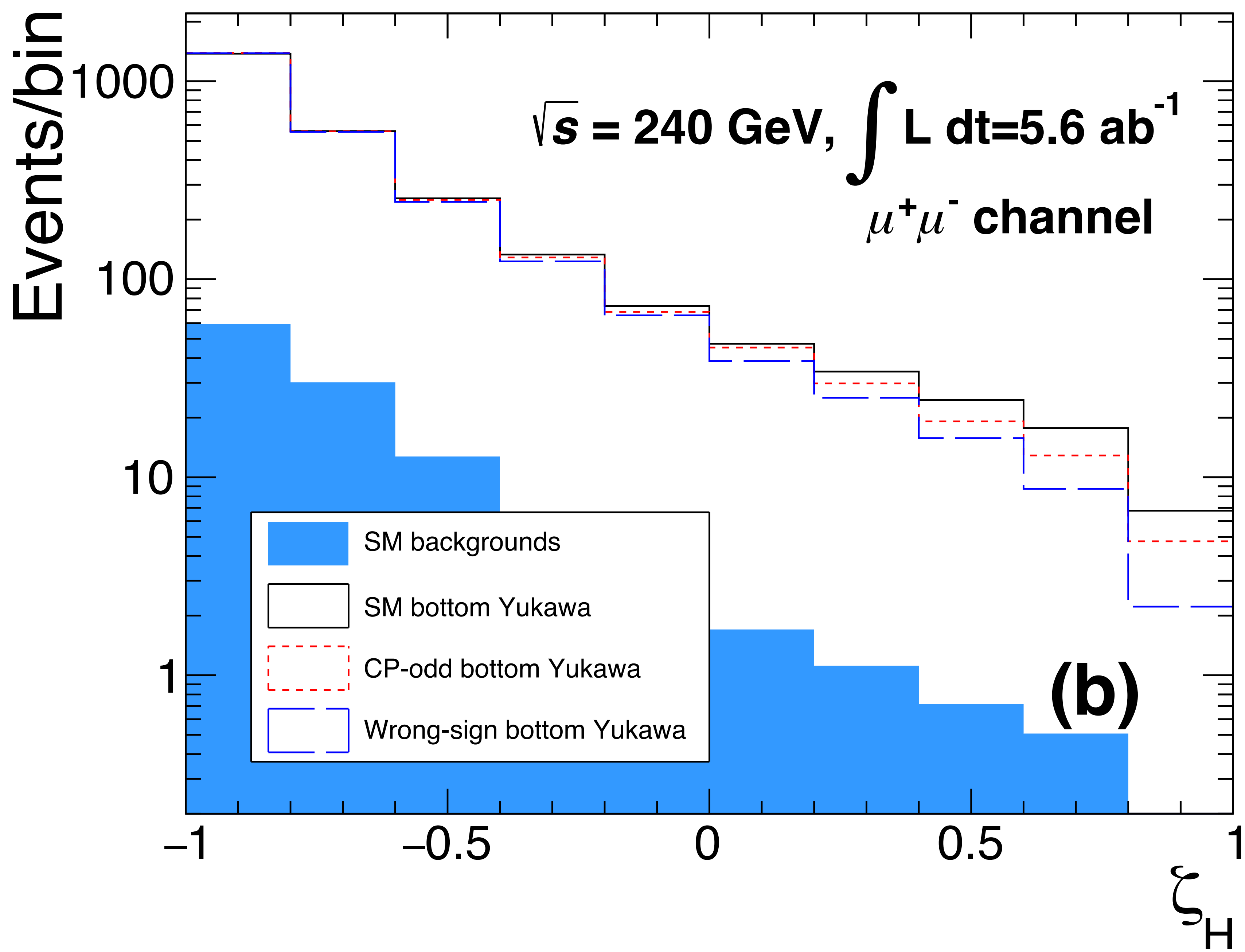
$$|m_{\mu^+\mu^-} - m_Z| < 10\mathrm{GeV},\quad |m_{e^+e^-} - m_Z| < 15\mathrm{GeV},$$
$$\theta_{\ell^+\ell^-} > 80^\circ,\qquad \not{E}_\mathrm{T} < 10\mathrm{GeV},$$
$$124.5\mathrm{GeV} < m_\mathrm{recoil} < 130\mathrm{GeV},\ \text{for } \mu^+\mu^- \text{ channel},$$
$$118\ \mathrm{GeV} < m_\mathrm{recoil} < 140\mathrm{GeV},\ \text{for } e^+e^- \text{ channel},$$

- 240GeV hadronic decaying Z

$$|\cos\theta_i| < 0.98,\ d_{ij} > 0.002, E_j > 15\mathrm{GeV}, \not{E}_\mathrm{T} < 10\mathrm{GeV}.$$

Collider Simulation

- Interference in Higgs decay:



Collider Simulation

- Hadronic decaying Z: likelihood method.

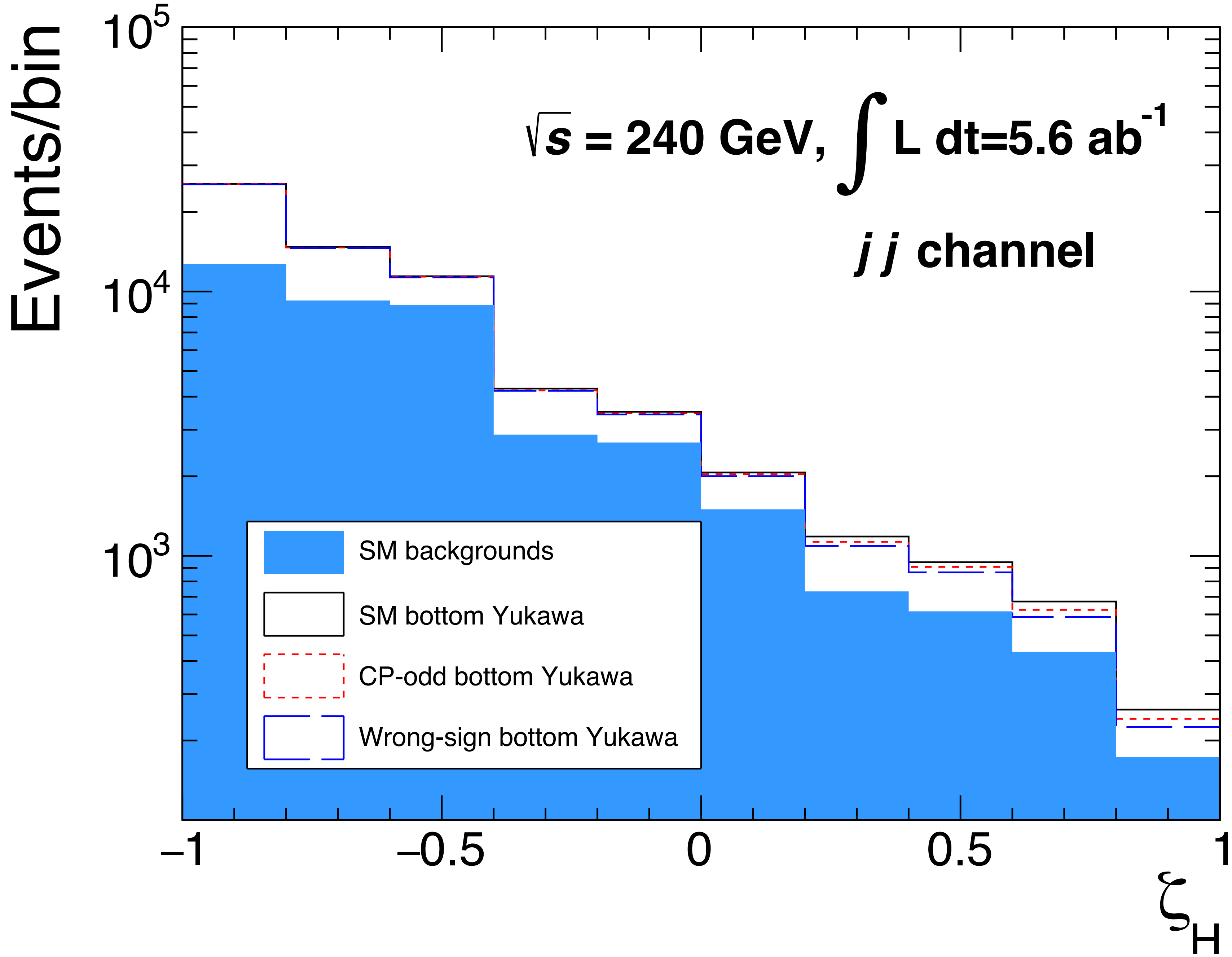
$$
\begin{aligned}
L_Z(m) &= P(m; 91.0\mathrm{GeV}, 6.19\mathrm{GeV}), \\
L_h(m) &= P(m; 125.3\mathrm{GeV}, 6.54\mathrm{GeV}), \\
L_{rZ}(m) &= P(m; 126.7\mathrm{GeV}, 8.43\mathrm{GeV}), \\
L_{rh}(m) &= P(m; 93.0\mathrm{GeV}, 10.56\mathrm{GeV}),
\end{aligned}
$$

- We reconstruct Z and H with minimizing the discriminator

$$
\begin{aligned}
\Delta = & -2\ln L_Z(m_{i_1 i_2}) - 2\ln L_h(m_{i_3 i_4 i_5}) - 2\ln L_{rZ}(m^{\mathrm{recoil}}_{i_1 i_2}) \\
& -2\ln L_{rh}(m^{\mathrm{recoil}}_{i_3 i_4 i_5}) - 70B(i_3) - 70B(i_4) \\
& +100B(i_5), \qquad (24)
\end{aligned}
$$

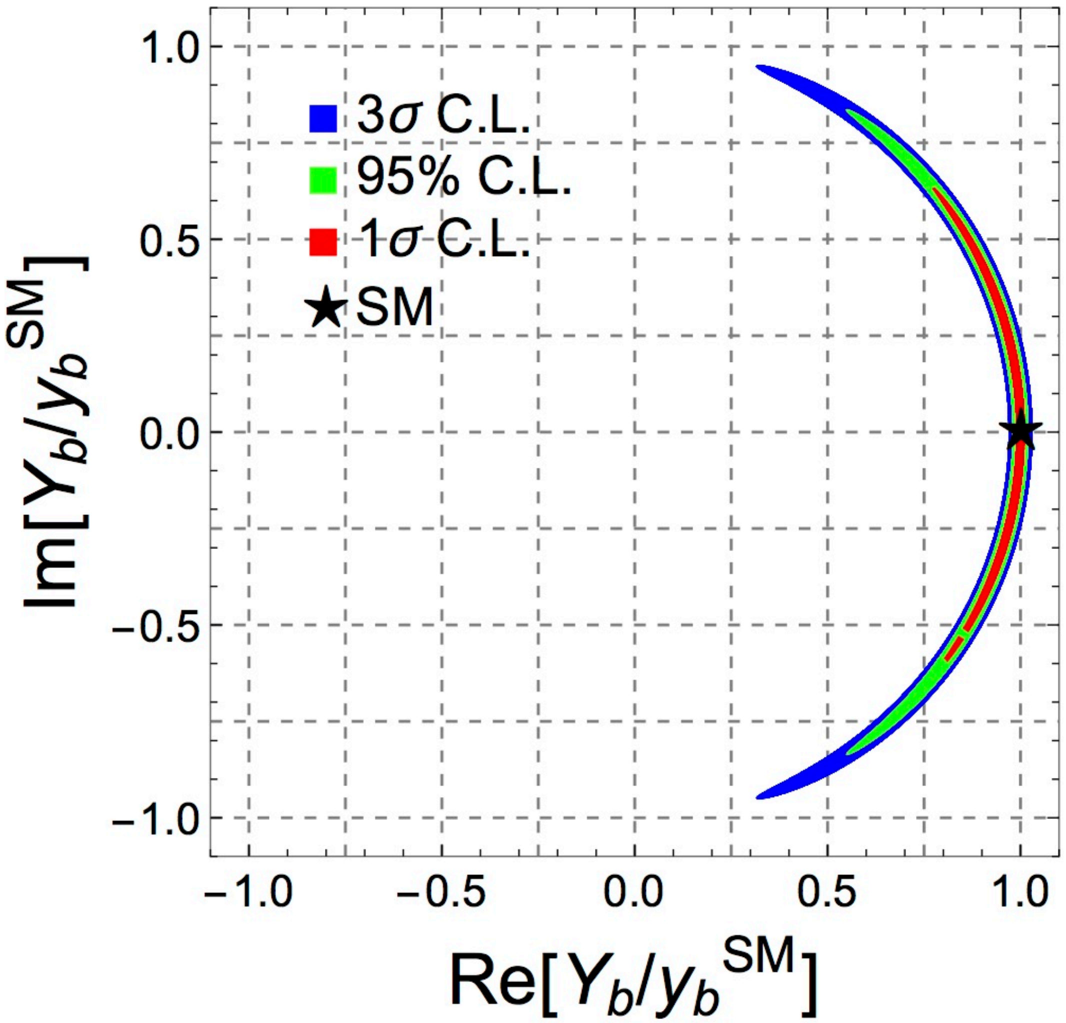
Collider Simulation

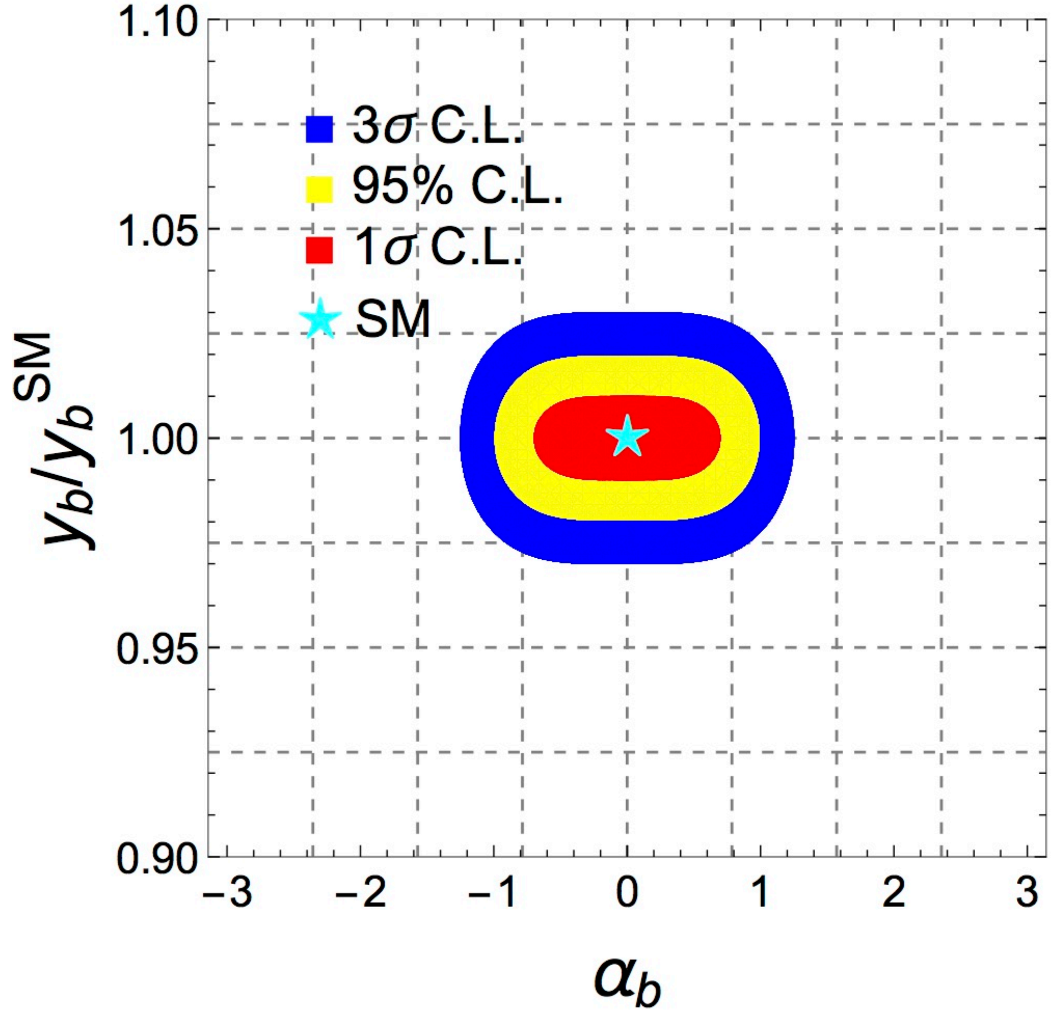
- Interference in Higgs decay:



Results

- 240GeV Higgs factory with 5.6ab^{-1} integrated luminosity.





$\delta\alpha_b \sim 40°$

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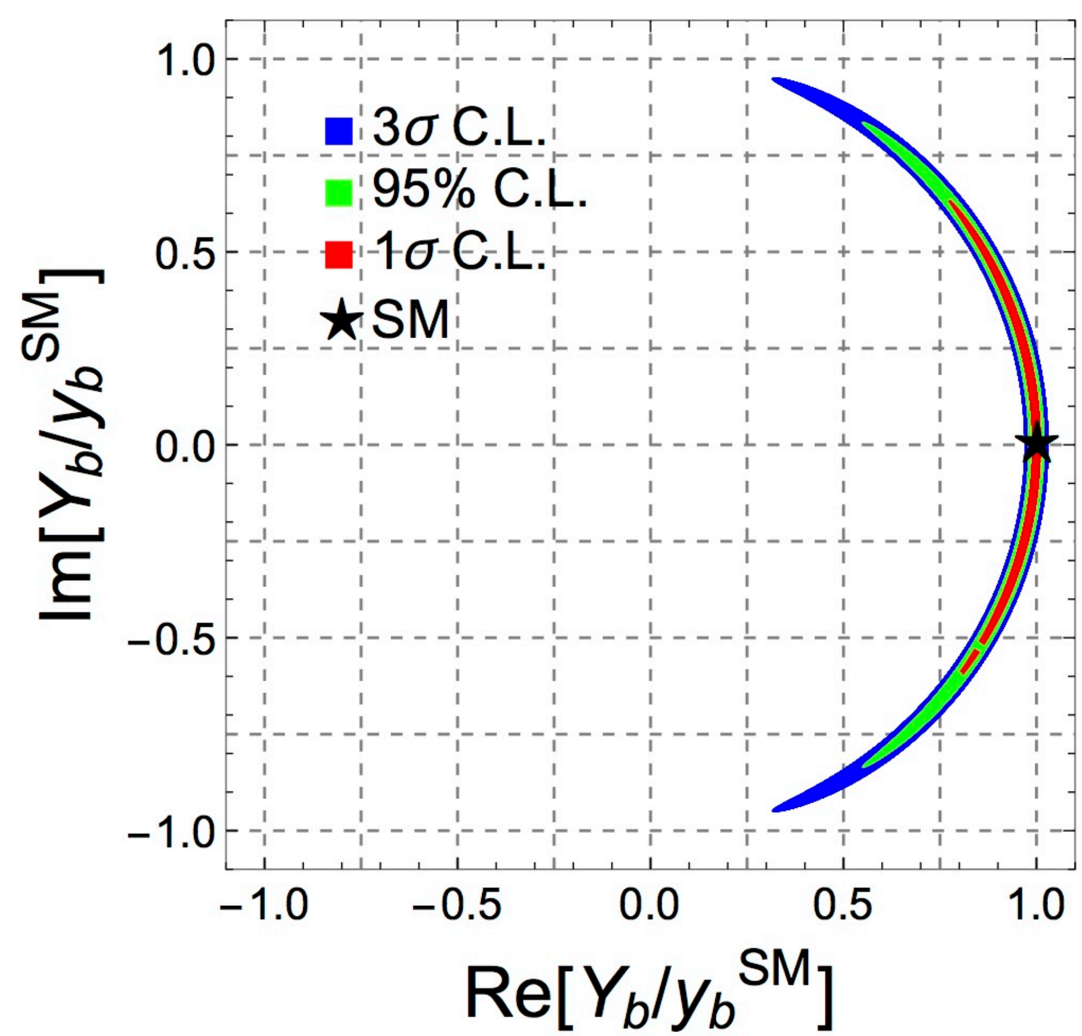
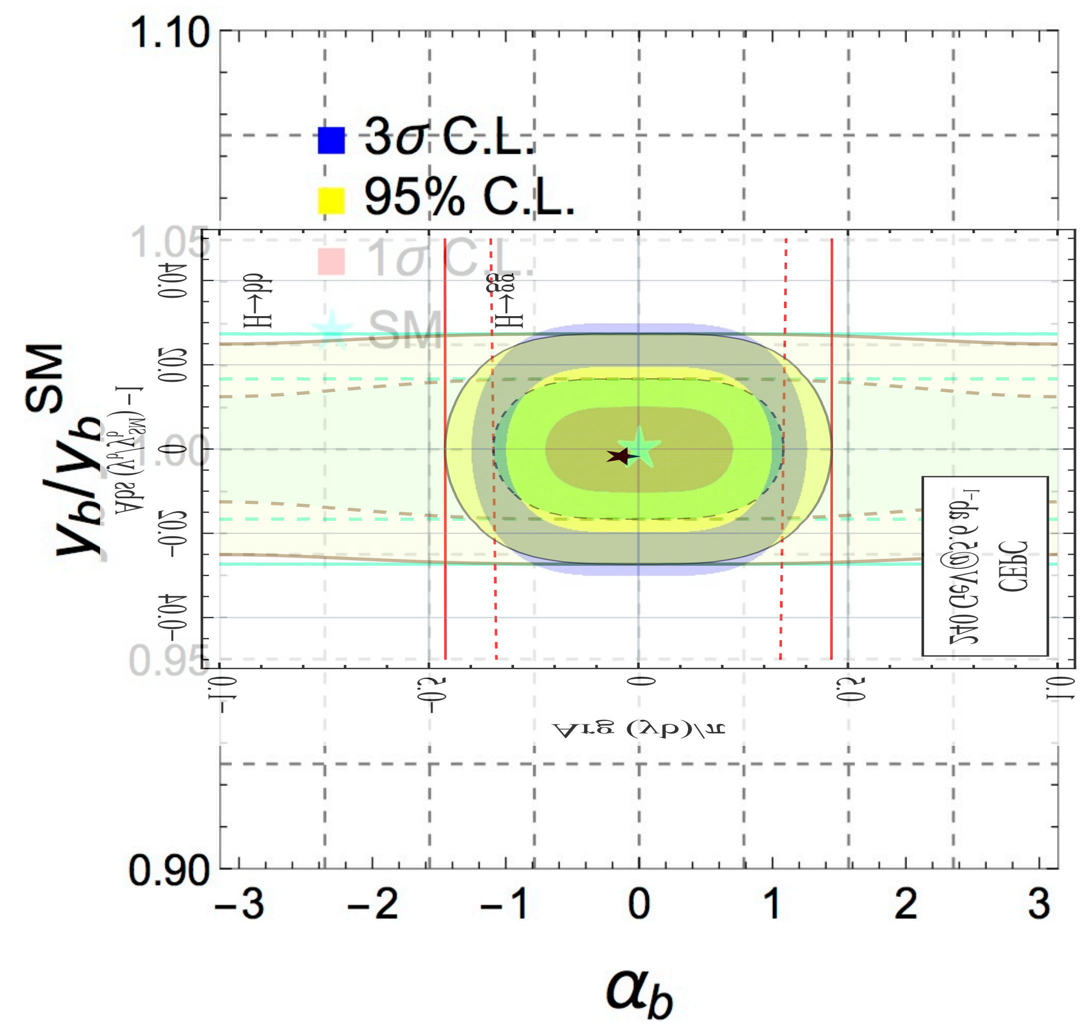


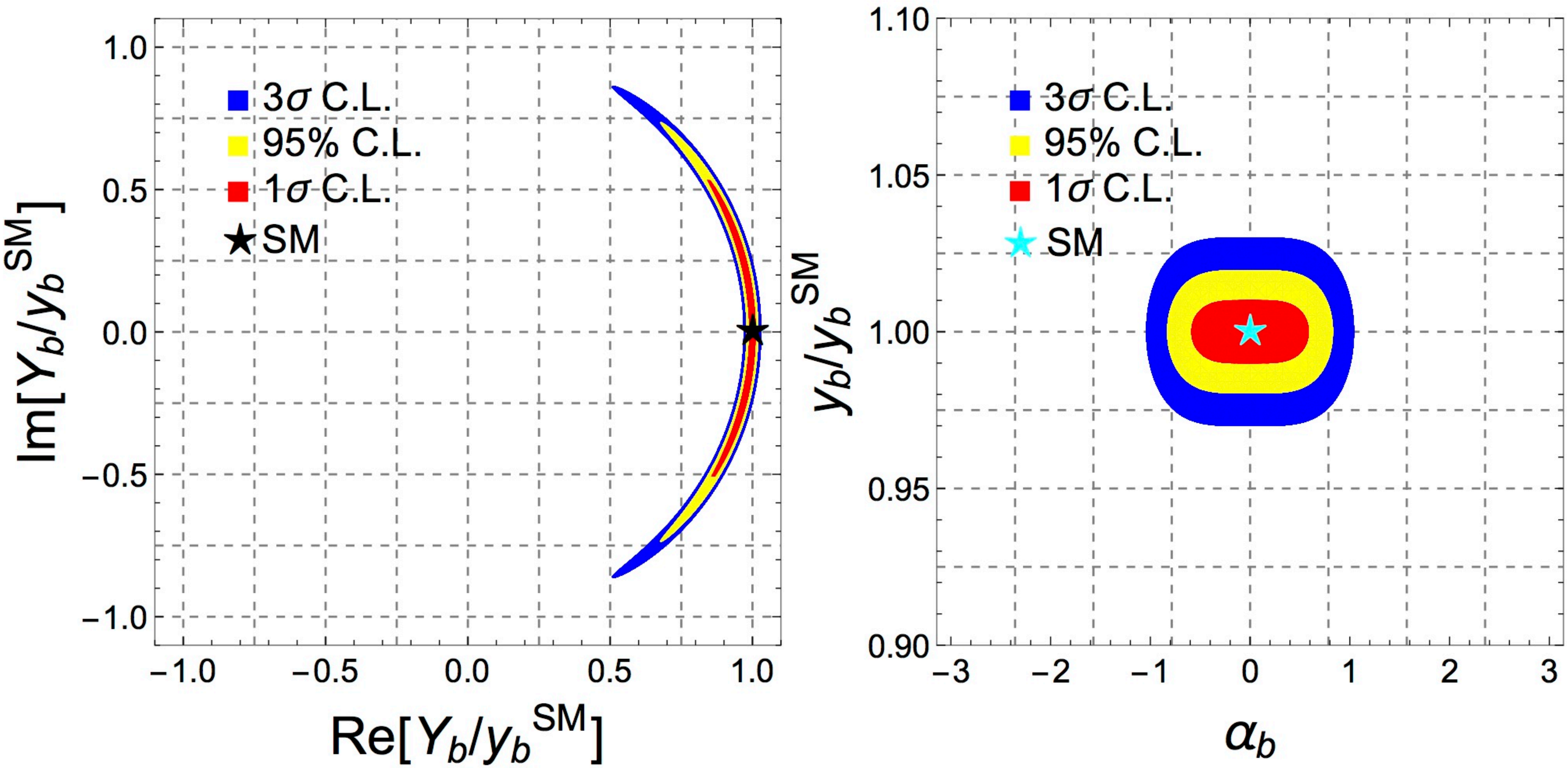


$\delta\alpha_b \sim 40^{\circ}$

F. An, et al, Chin. Phys. C43 (2019) 043002;

Results

- 240GeV Higgs factory with 5.6ab^{-1} integrated luminosity+ 365GeV Higgs factory with 1.5ab^{-1} integrated luminosity.

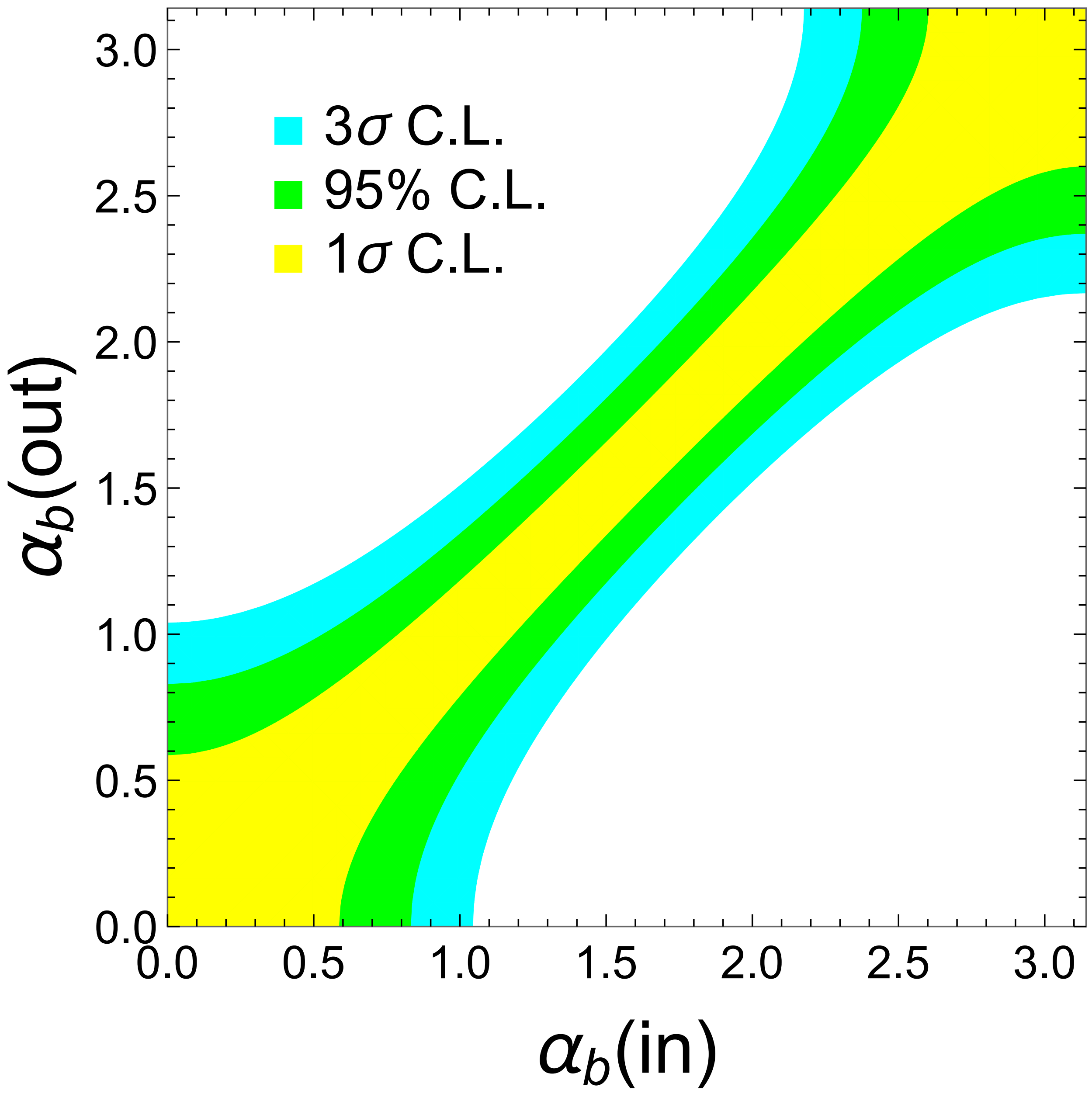


Ed L. Berger, Q. Bi, K. Chai, J. Gao, Y. Liu and HZ, to be appeared.

$\delta\alpha_b \sim 34^\circ$

Results

- 240GeV Higgs factory with 5.6ab^{-1} integrated luminosity+ 365GeV Higgs factory with 1.5ab^{-1} integrated luminosity.



Ed L. Berger, Q. Bi, K. Chai, J. Gao, Y. Liu and HZ, to be appeared.

Summary

Conclusion

- The non-SM Yukawa interactions between the Higgs boson and SM fermions are definitely new physics beyond the SM.

- The phases in the Yukawa interactions are evidence of new sources of EWSB and might be important for us to understand the matter-antimatter asymmetry in our universe.

- We propose a method for measuring the phases for the bottom-quark Yukawa interaction directly at Higgs factory.

Thank you!