Studying the interaction properties of the Higgs boson at the LHC and future colliders

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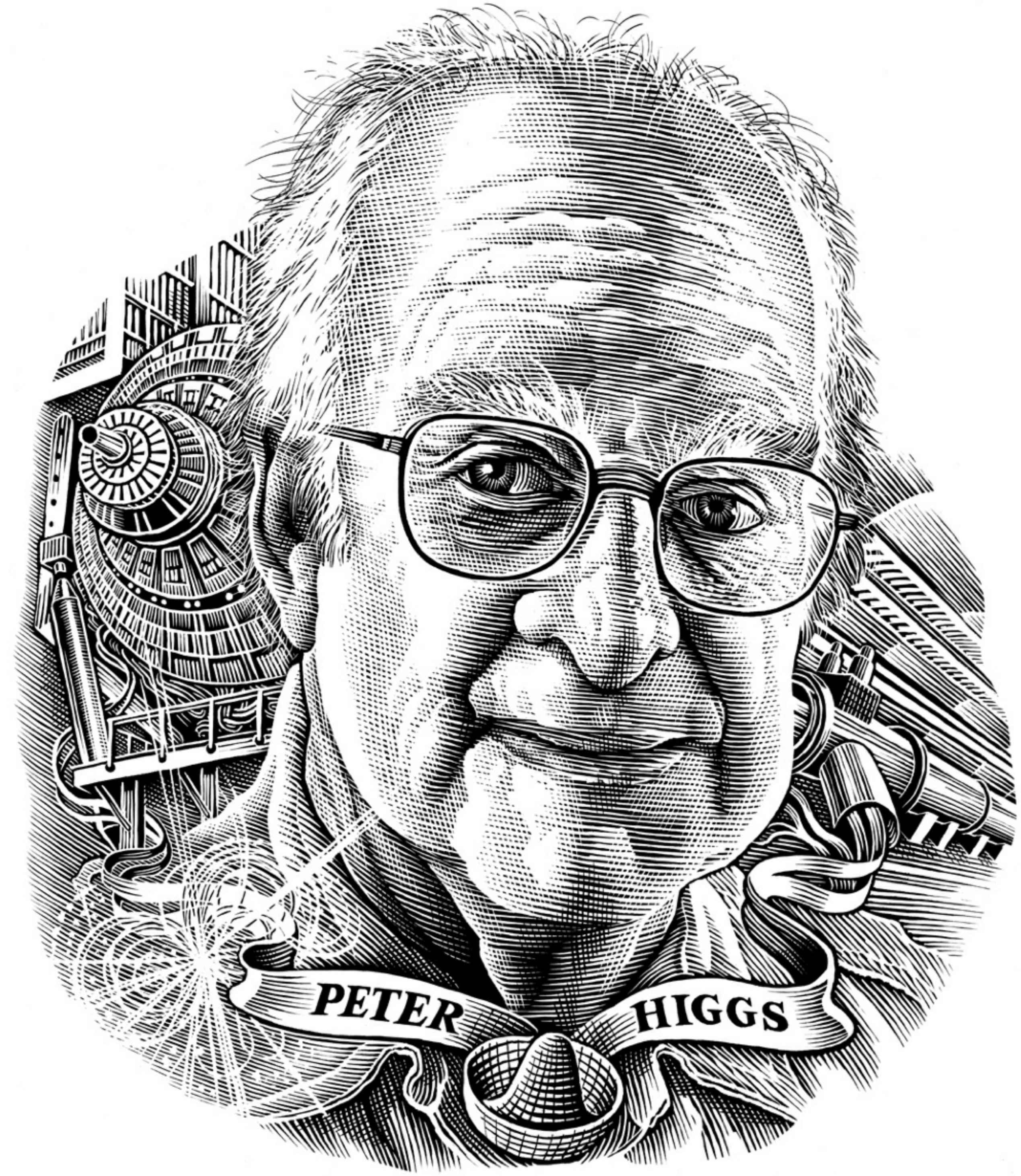
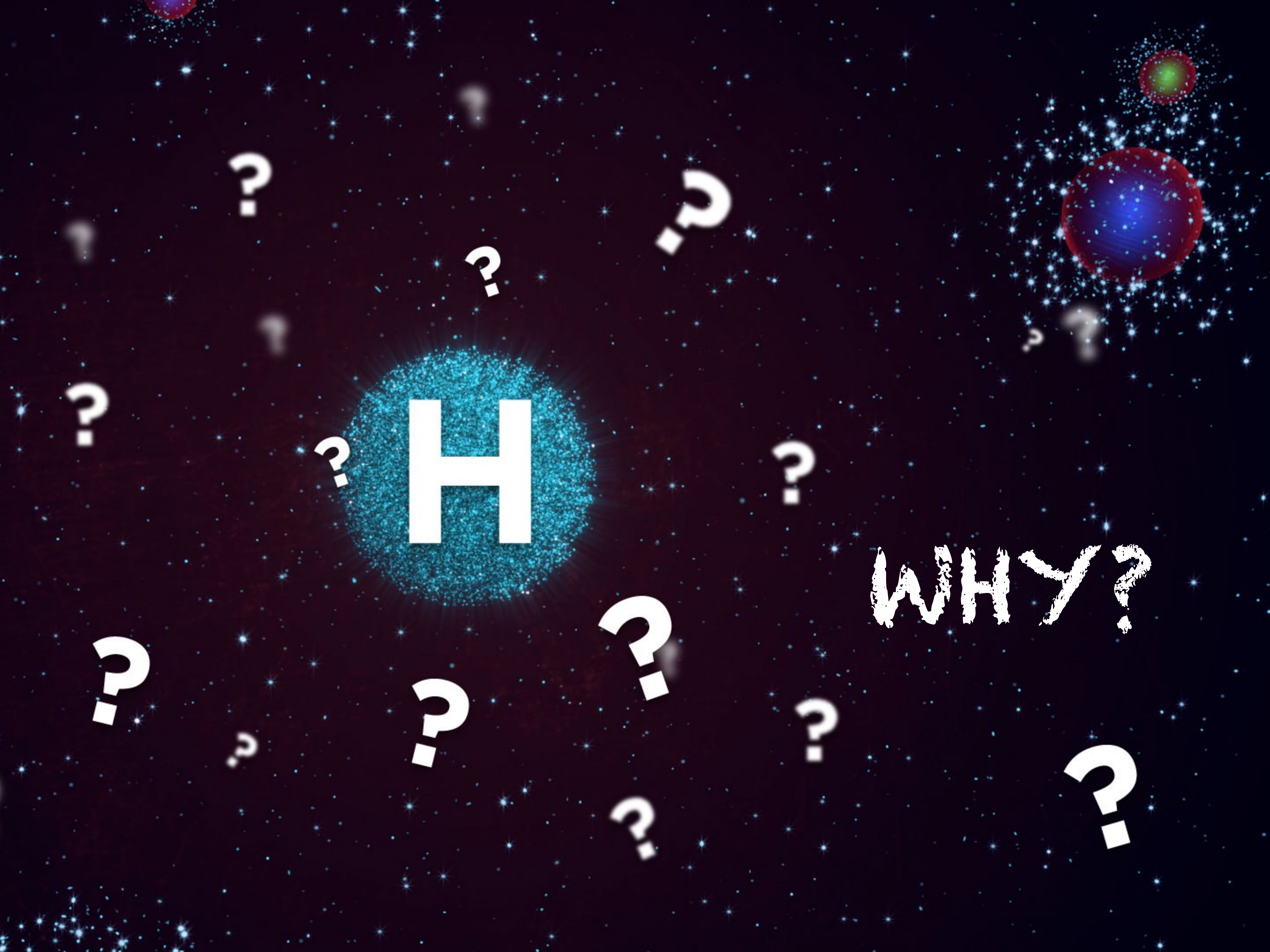
WHY?

WHAT?



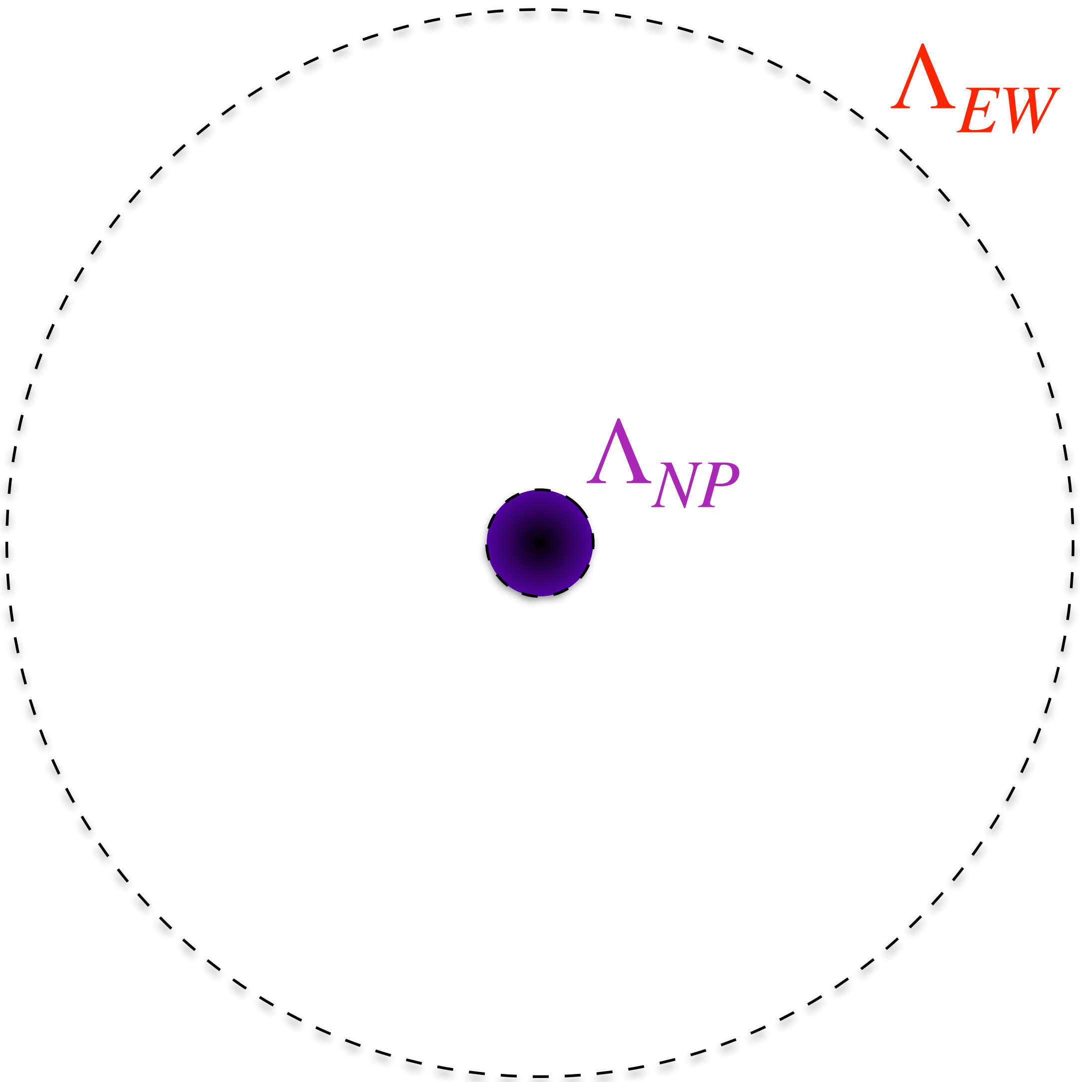
WHERE?

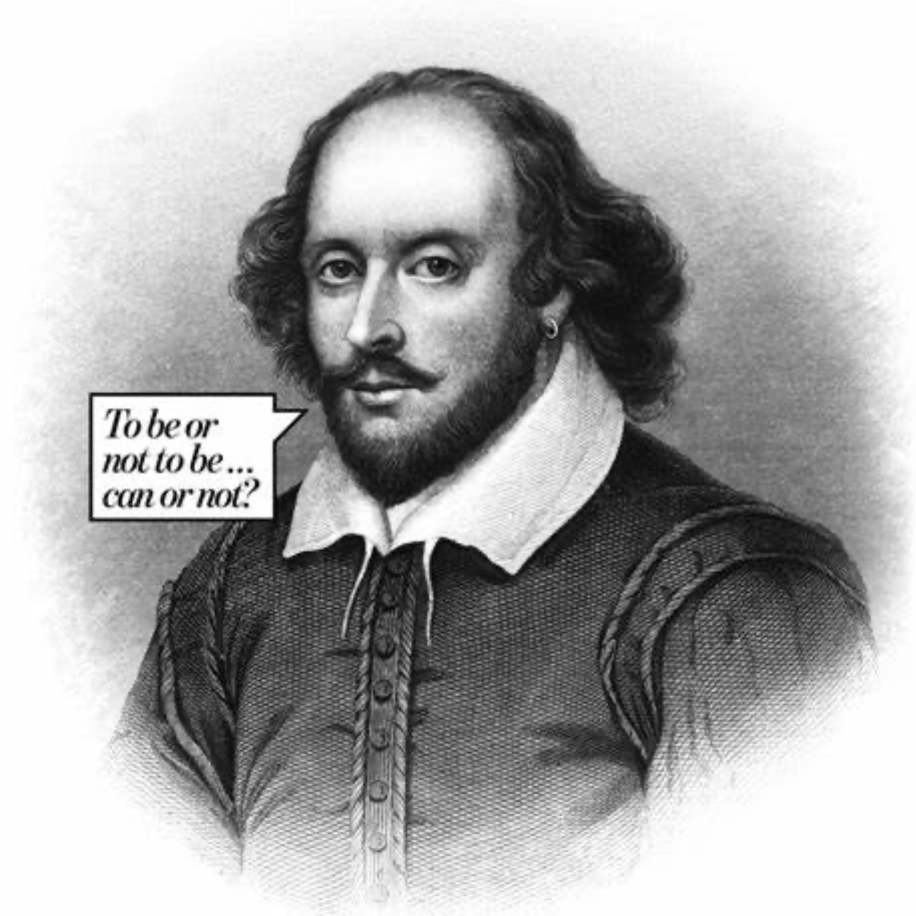

H
WHY?

Higgs sector — A bridge to NP

- Hierarchy "problem"

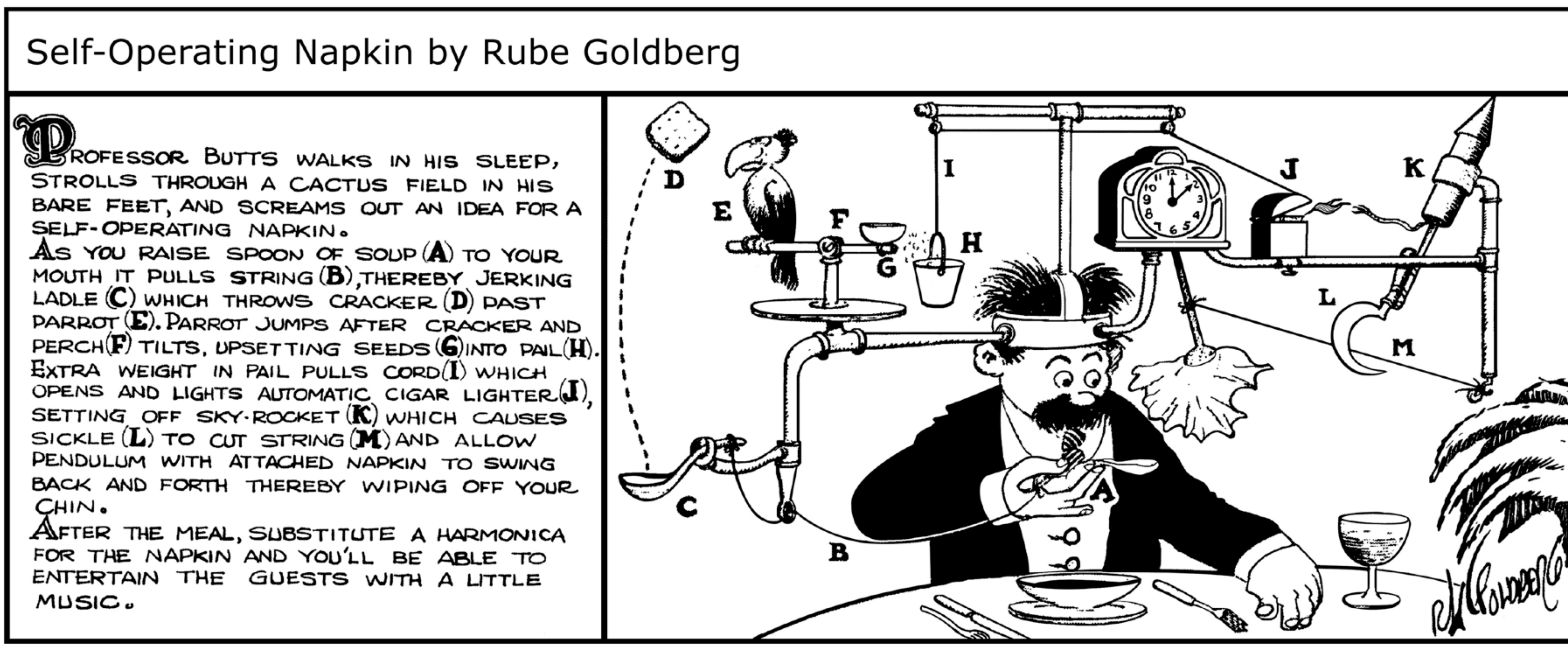
- New Physics: to be or not to be?





Higgs sector — A bridge to NP

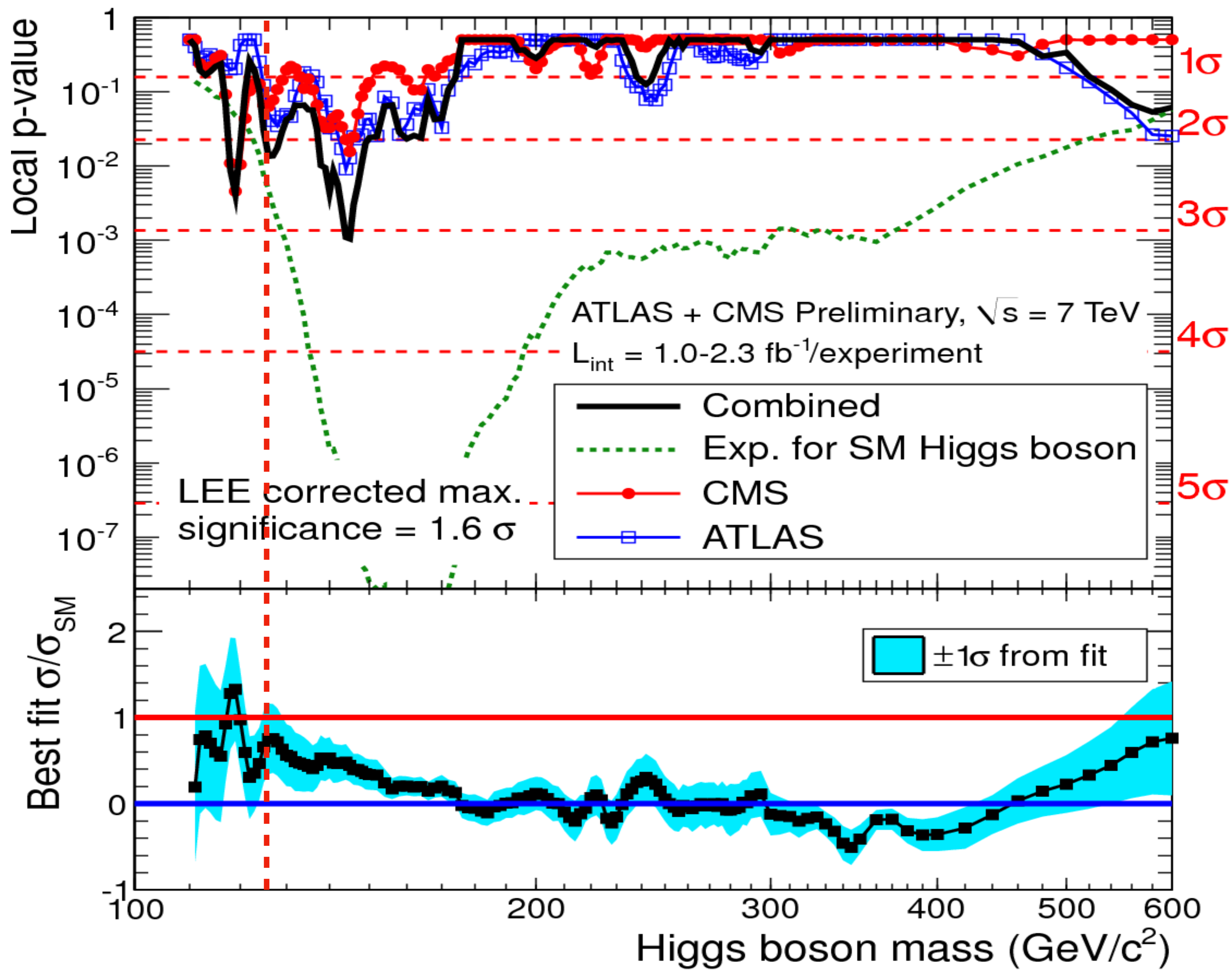
- Hierarchy "problem"
- New Physics: to be or not to be?
- Standard Model: a precisely designed model!



Self-Operating Napkin by Rube Goldberg

An Era of Precisely Higgs Physics

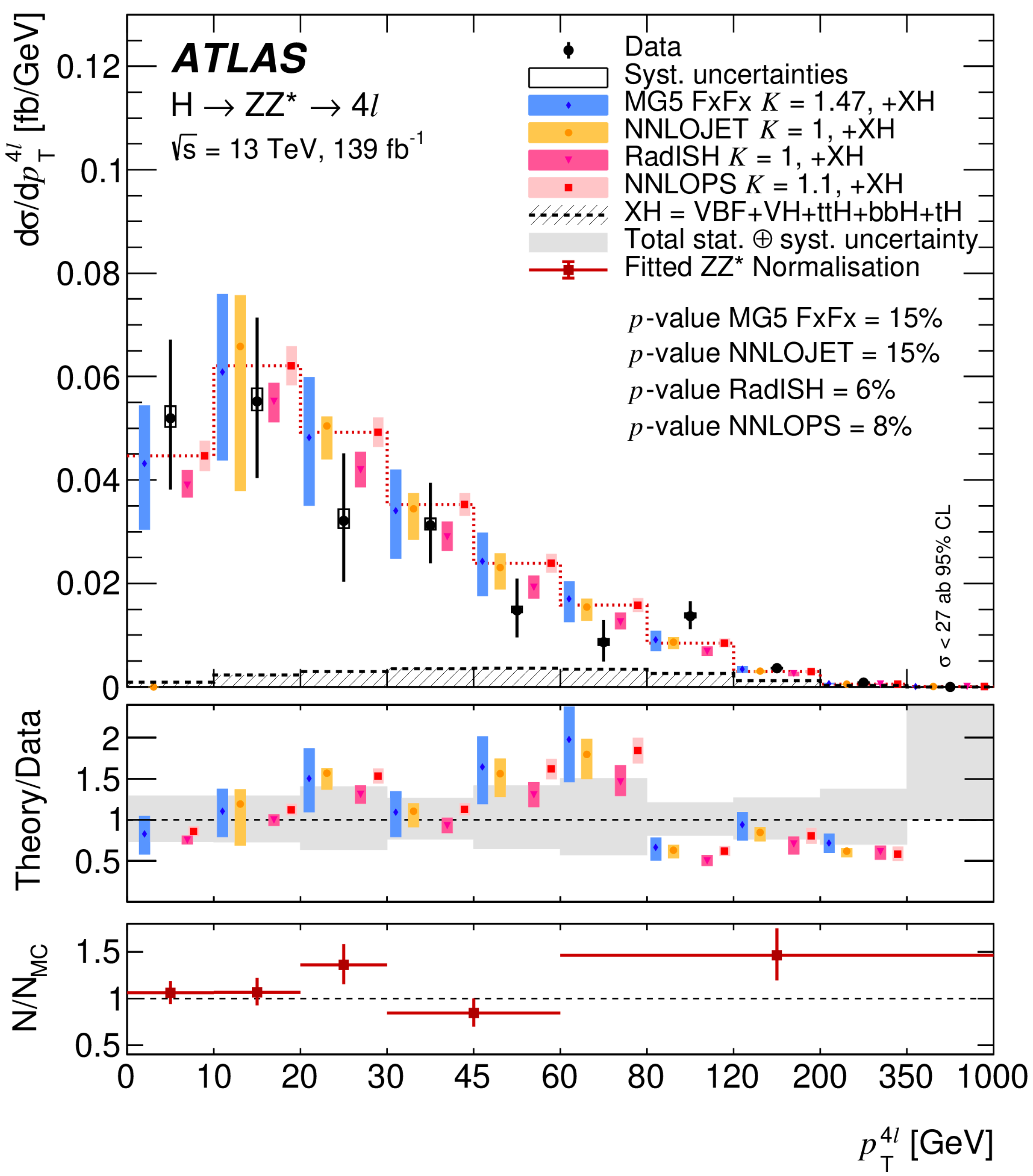
- From 2011 to 2021 (2019)

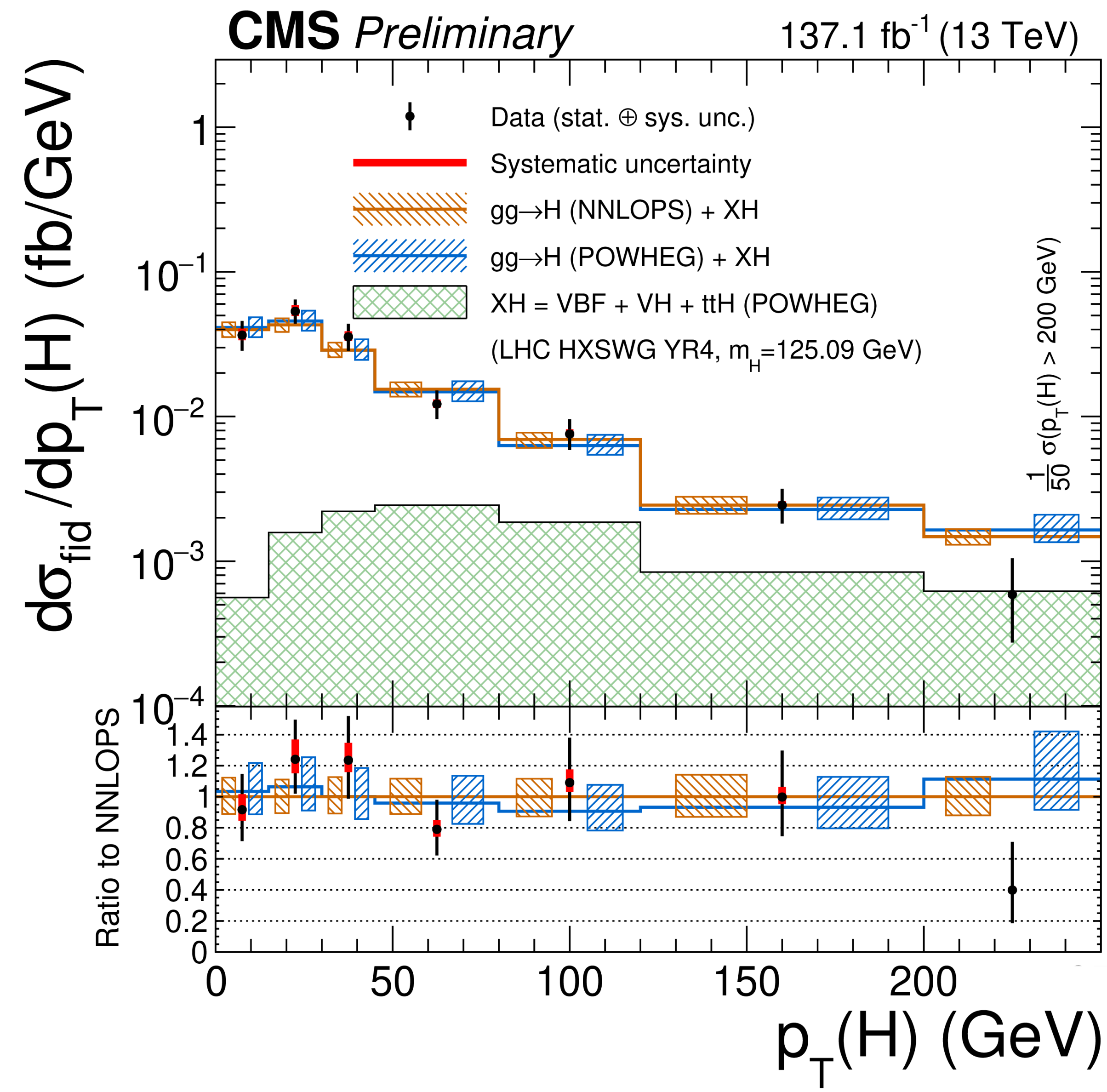


ATLAS and CMS Collaboration, ATLAS-CONF-2011-157, CMS PAS HIG-11-023.

An Era of Precisely Higgs Physics

- More information: go beyond the κ-scheme!

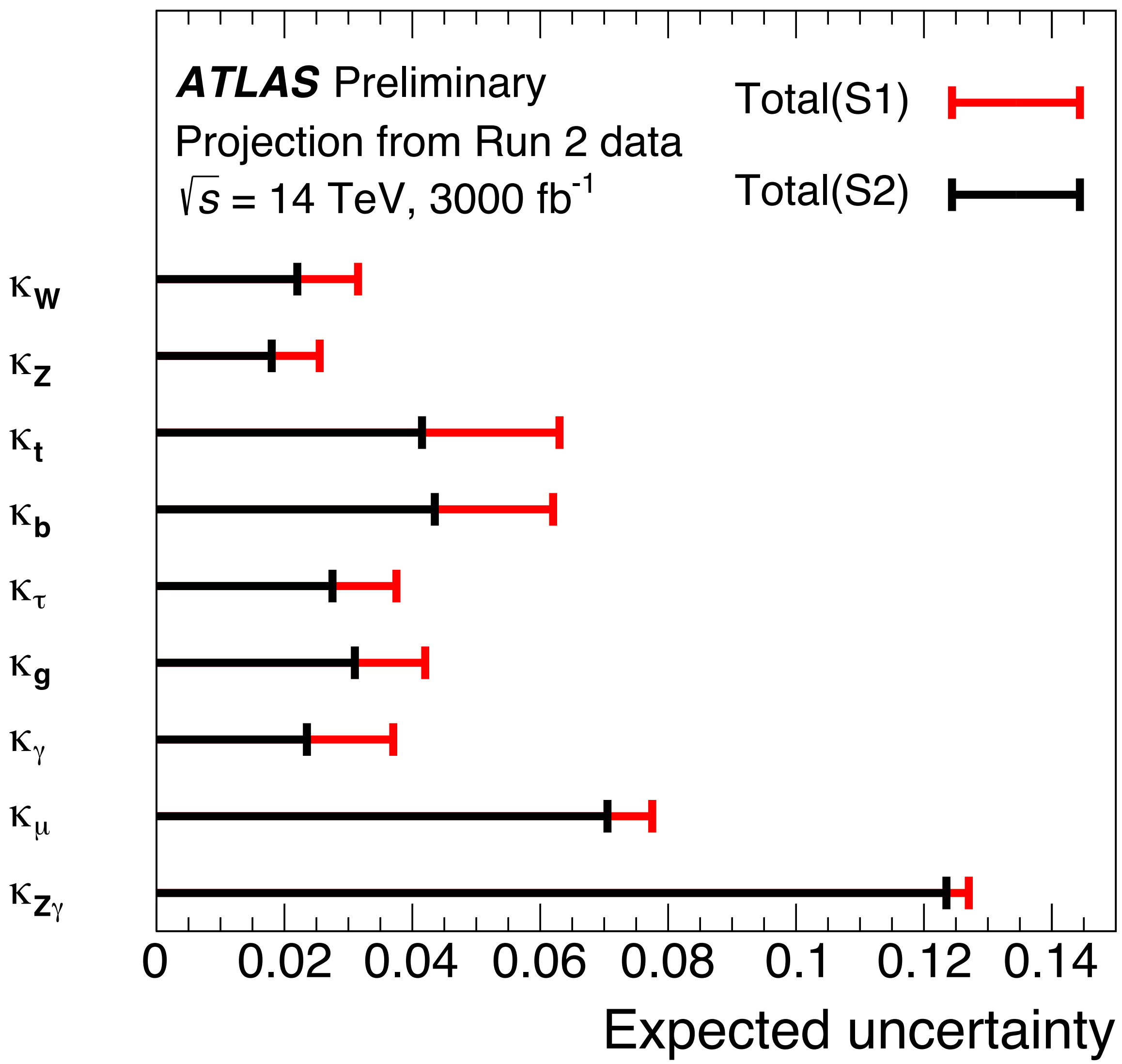


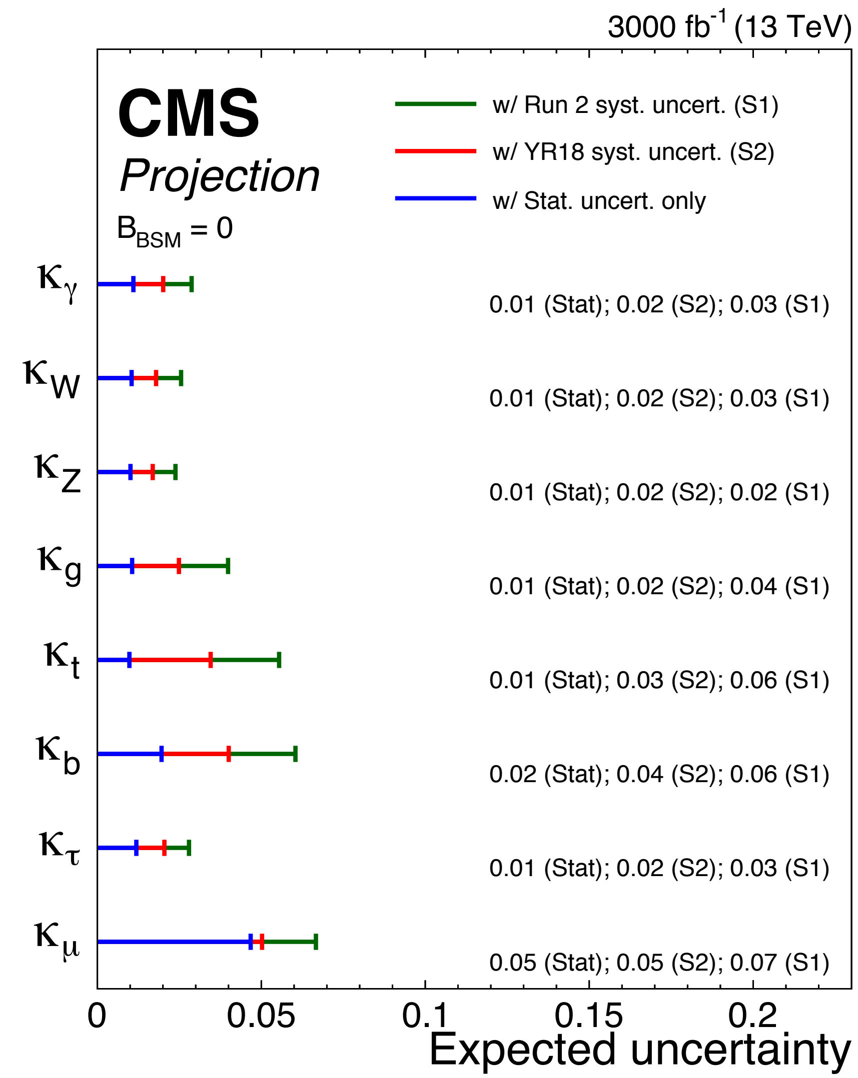


From Andrea Gabrielli's slides.

An Era of Precisely Higgs Physics

- More precisely result in near future.

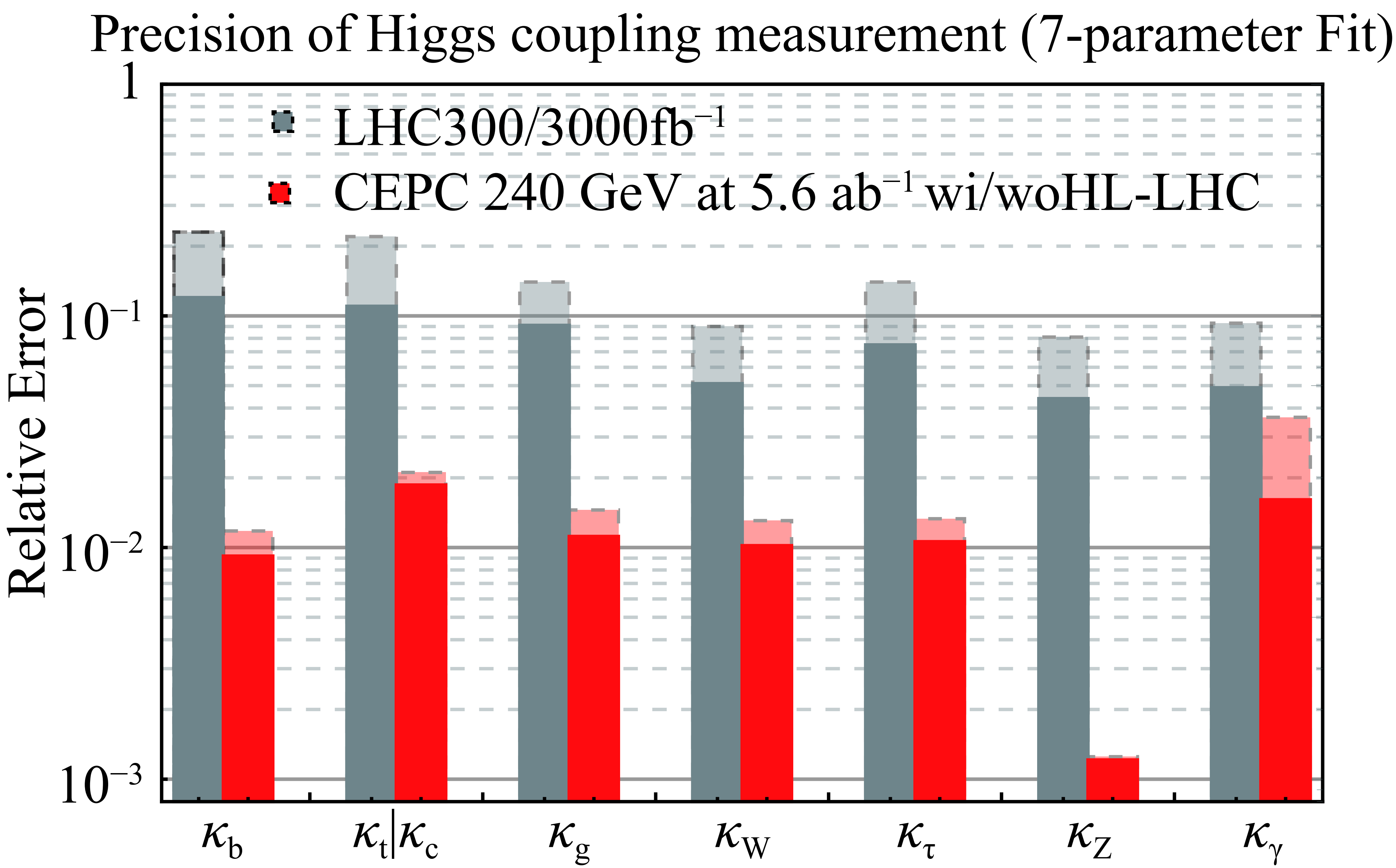




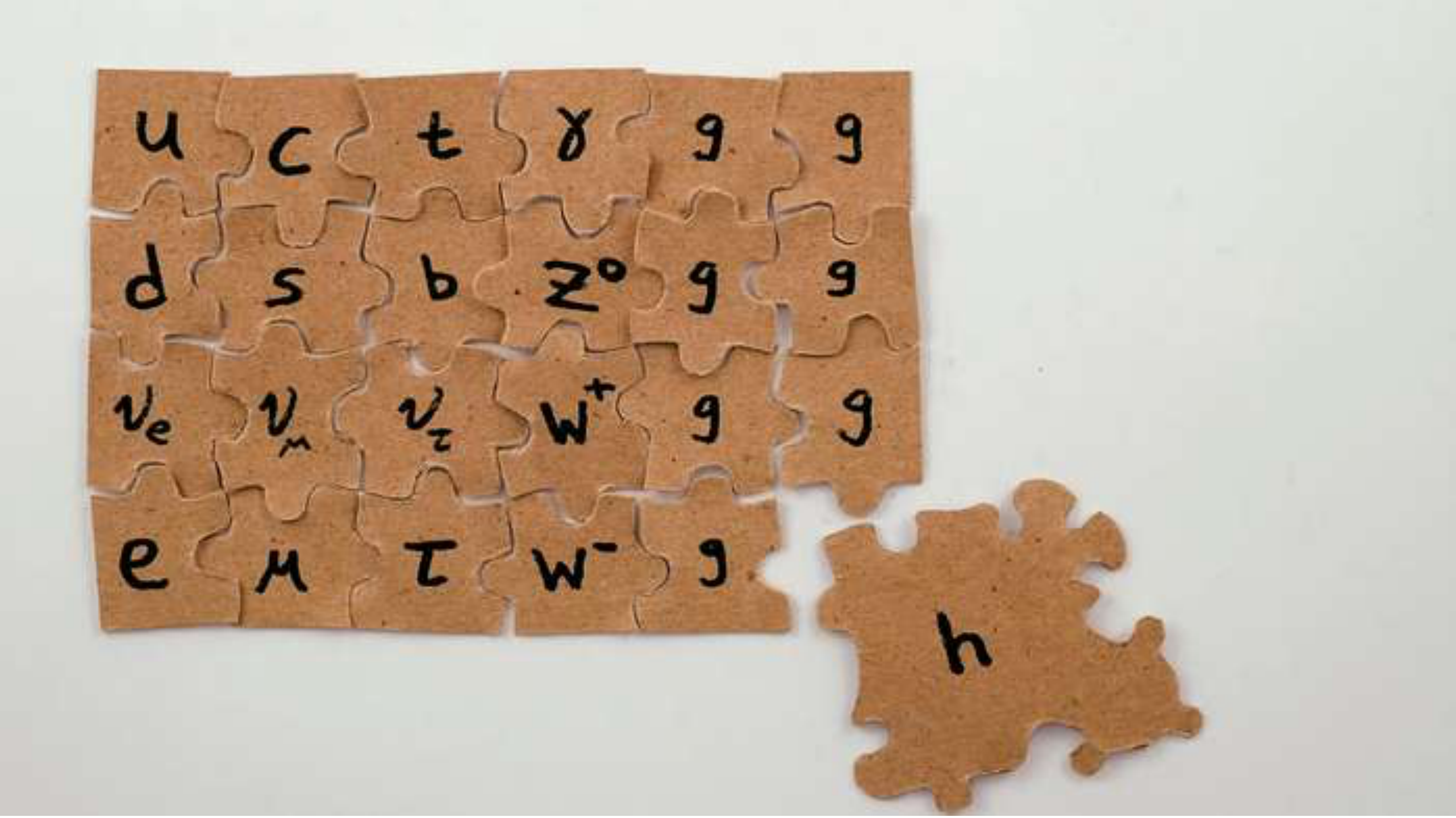
ATLAS Collaboration, ATLAS-PHYS-PUB-2018-054;
CMS Collaboration, CMS PAS FTR-18-011.

An Era of Precisely Higgs Physics

- More results with Higgs factory.



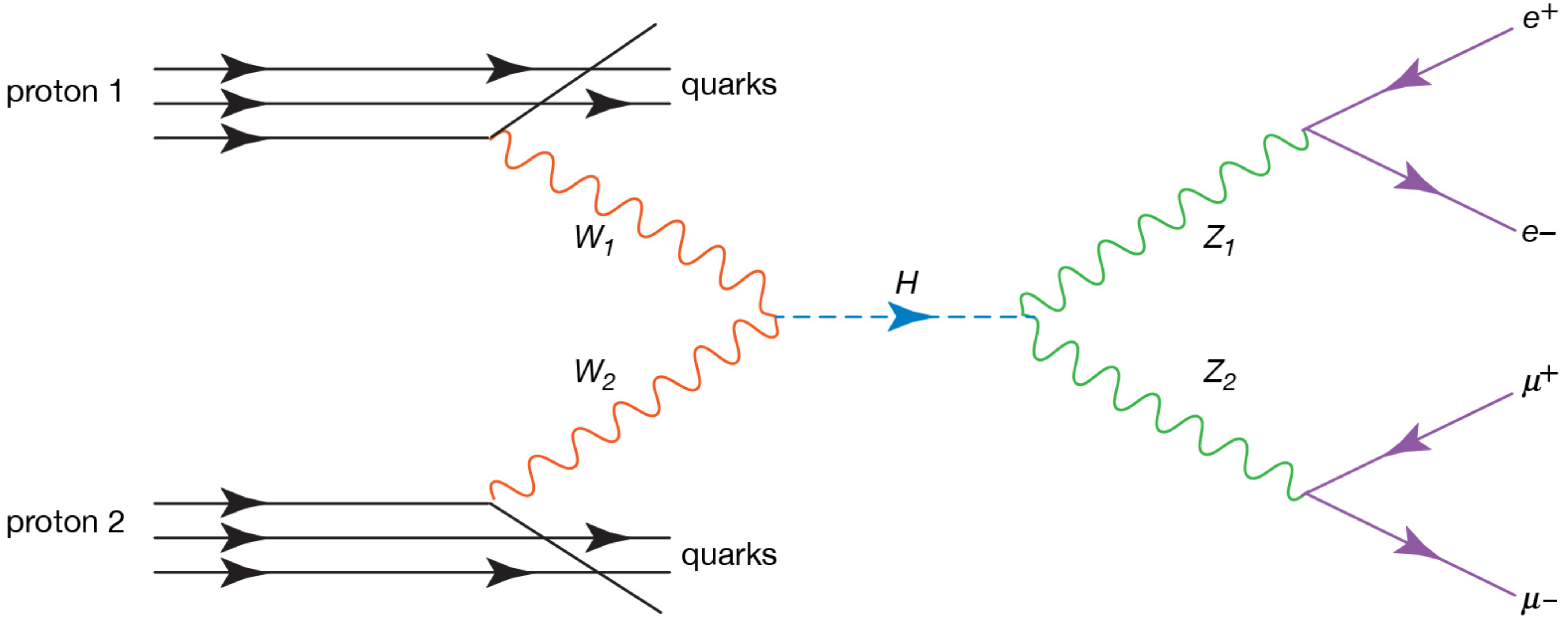
F. An, et al, Chin. Phys. C43 (2019) 043002



WHAT?

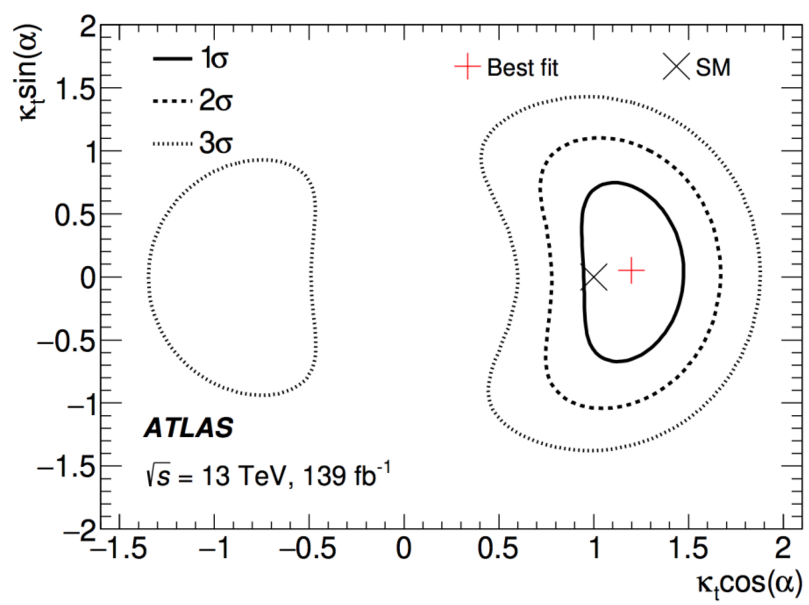
Higgs interactions in the SM

- Gauge interaction: unitarity and gauge boson mass.

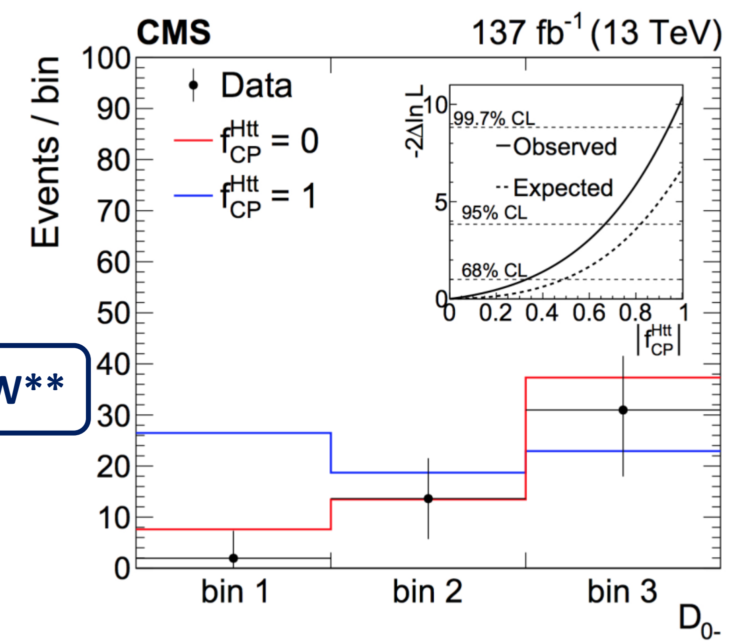


Higgs interactions in the SM

- Gauge interaction: unitarity and gauge boson mass.
- Yukawa interaction: fermion mass, CP violation.



NEW



ATLAS

→ The Higgs boson coupling modifiers k_γ and k_g are constrained to the combination result .

→ κ_t is left free to float in the fit.

- $|\alpha| > 43^o\ (63^o)$ obs. (exp) exclusion at 95% CL
- Obs. (Exp.) pure CP-odd coupling excluded at **3.9 σ (2.5 σ)**

CMS

→ The Higgs boson couplings to other particles constrained to SM.

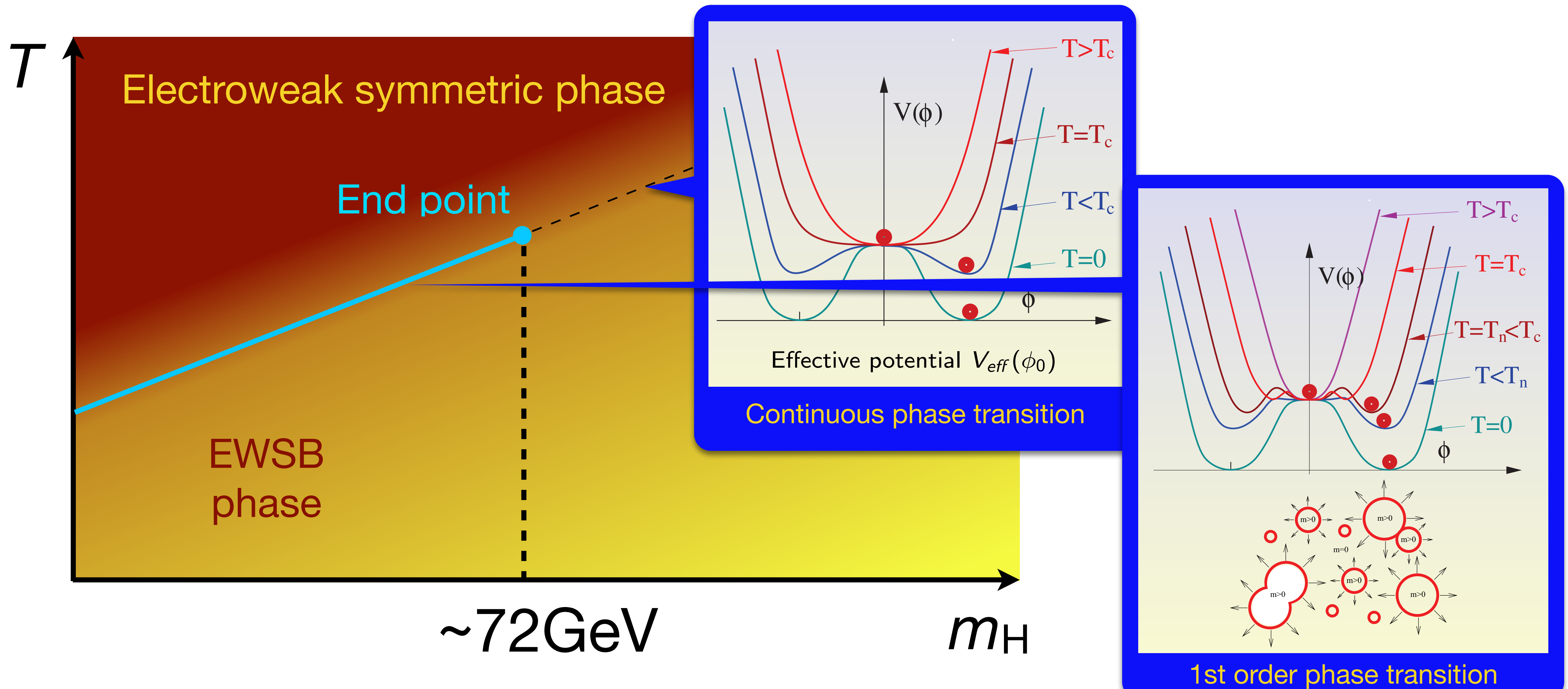
→ μ_{ttH} and $|f^{Htt}_{CP}|$ are free to float in the fit.

- $f^{Htt}_{CP} = 0.00 \pm 0.33$ **at 68% CL**
- Limit at 95% CL : $|f^{Htt}_{CP}| < 0.67$
- Obs. (Exp.) pure CP-odd coupling excluded at **3.2 σ (2.6 σ)**

From Rajdeep Chatterjee's slides

Higgs interactions in the SM

- Gauge interaction: unitarity and gauge boson mass.
- Yukawa interaction: fermion mass, CP violation.
- Higgs self-coupling: origin of the EWSB and EWPT.

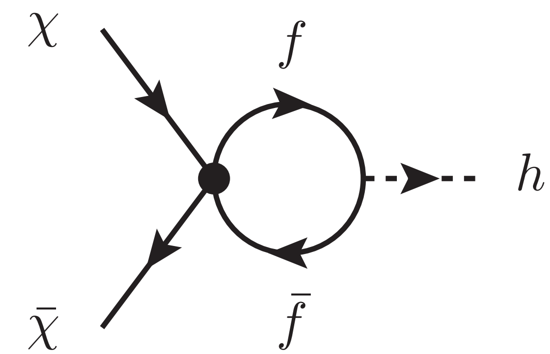


Higgs interactions beyond the SM

- Model building: extended Higgs sector, Higgs portal, …

- EFT: neutrino mass, bridge to dark sector, …

Name	Operator	Coefficient
S	$\bar{\chi}\chi\bar{f}f$	m_f/Λ^3
PS	$\bar{\chi}\gamma^5\chi\bar{f}f$	im_f/Λ^3
SP	$\bar{\chi}\chi\bar{f}\gamma^5 f$	im_f/Λ^3
P	$\bar{\chi}\gamma^5\chi\bar{f}\gamma^5 f$	m_f/Λ^3




t-channel
W- boson decay
gg fusion
s-channel
WW,ZZ fusion
W+ boson decay
tt̄ fusion
decay to leptons
W- boson decay
decay to four gluons
two photon-two gluon decay
tW-channel
decay to four photons
WZ bremsstrahlung
WW,ZZ fusion

WHERE?

An example

- Example: generic form of the SFF interaction

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

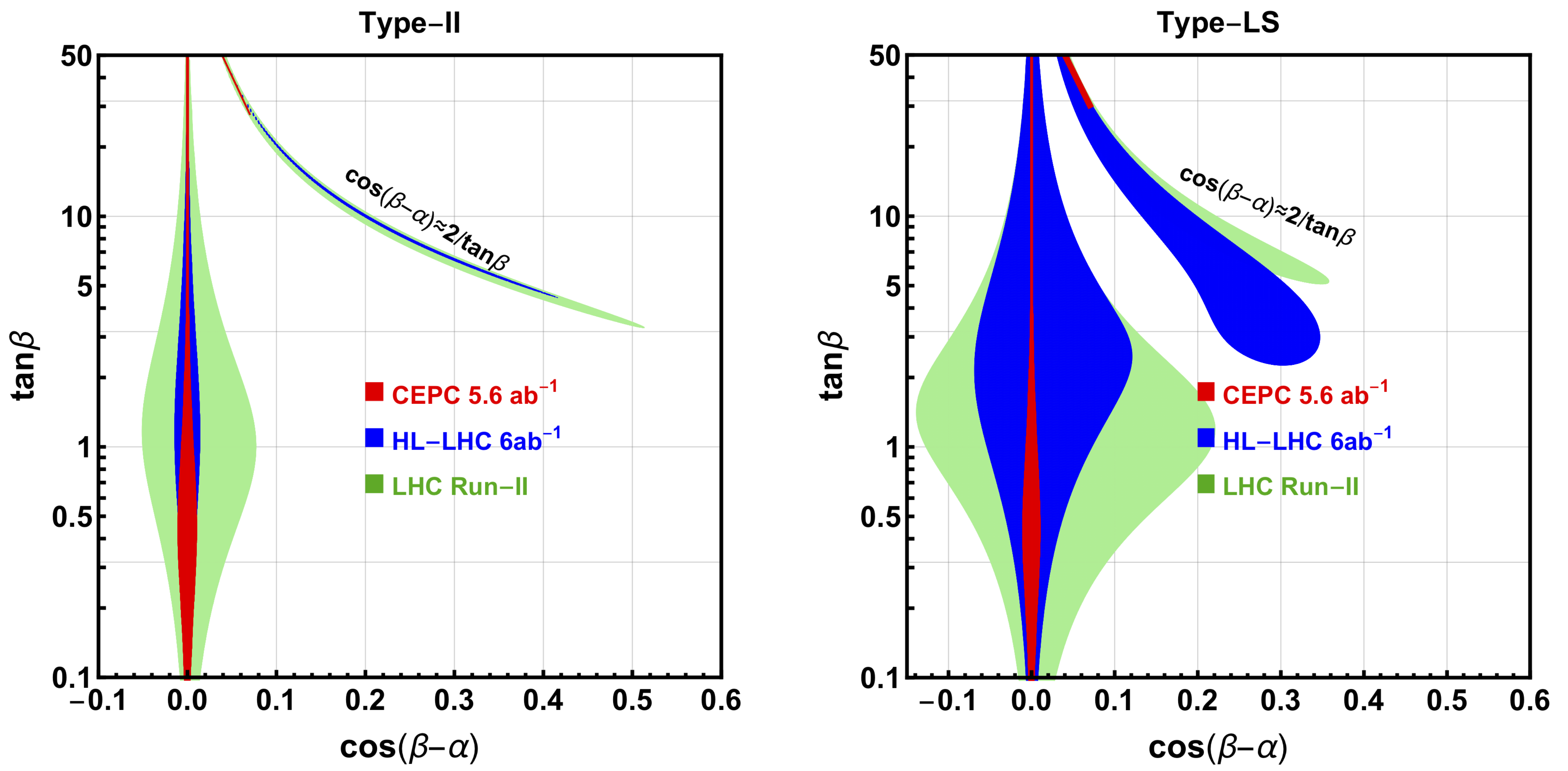
$$y_f \in \mathbb{R}^+, \quad \alpha_f \in (-\pi, \pi]$$

- Can we measure the α_f ?

- Is there any new CP (P) violation effect in the Yukawa interactions?

Phase in bottom-quark Yukawa Interactions

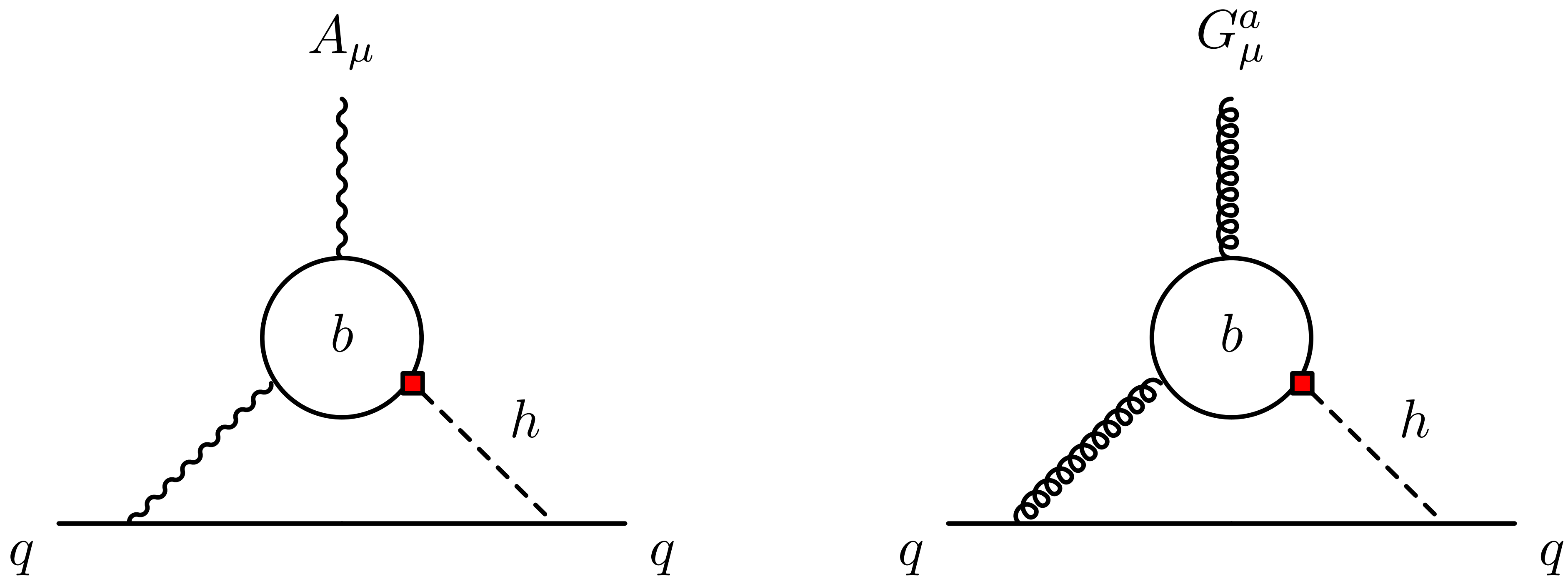
- Very interesting parameter.
- Exp: 2HDMs



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

Phase in bottom-quark Yukawa Interactions

- Indirect measurement (e.g. EDM).



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

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

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

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

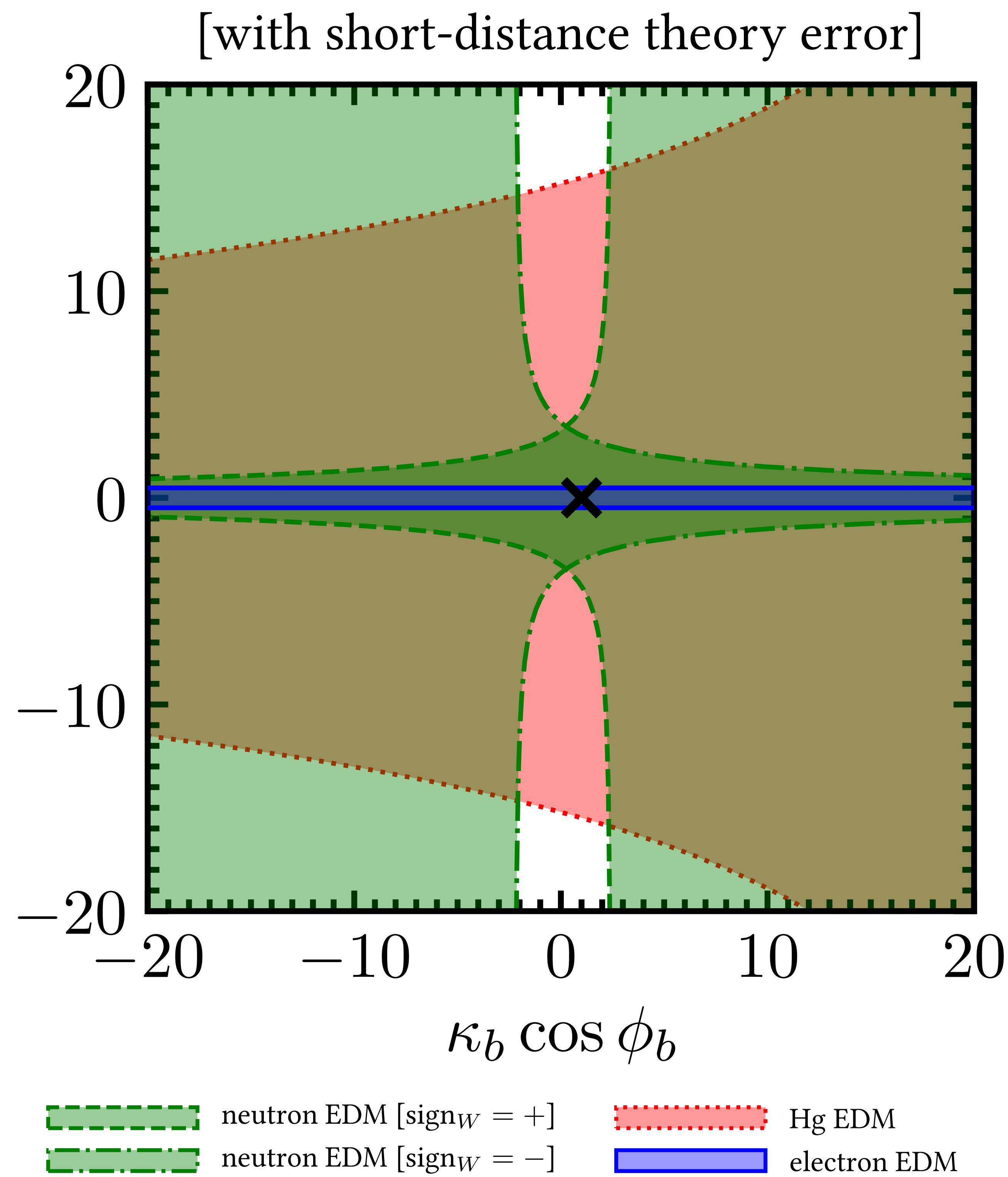
Phase in bottom-quark Yukawa Interactions

- 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.):

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



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

Phase in bottom-quark Yukawa Interactions

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

Phase in bottom-quark Yukawa Interactions

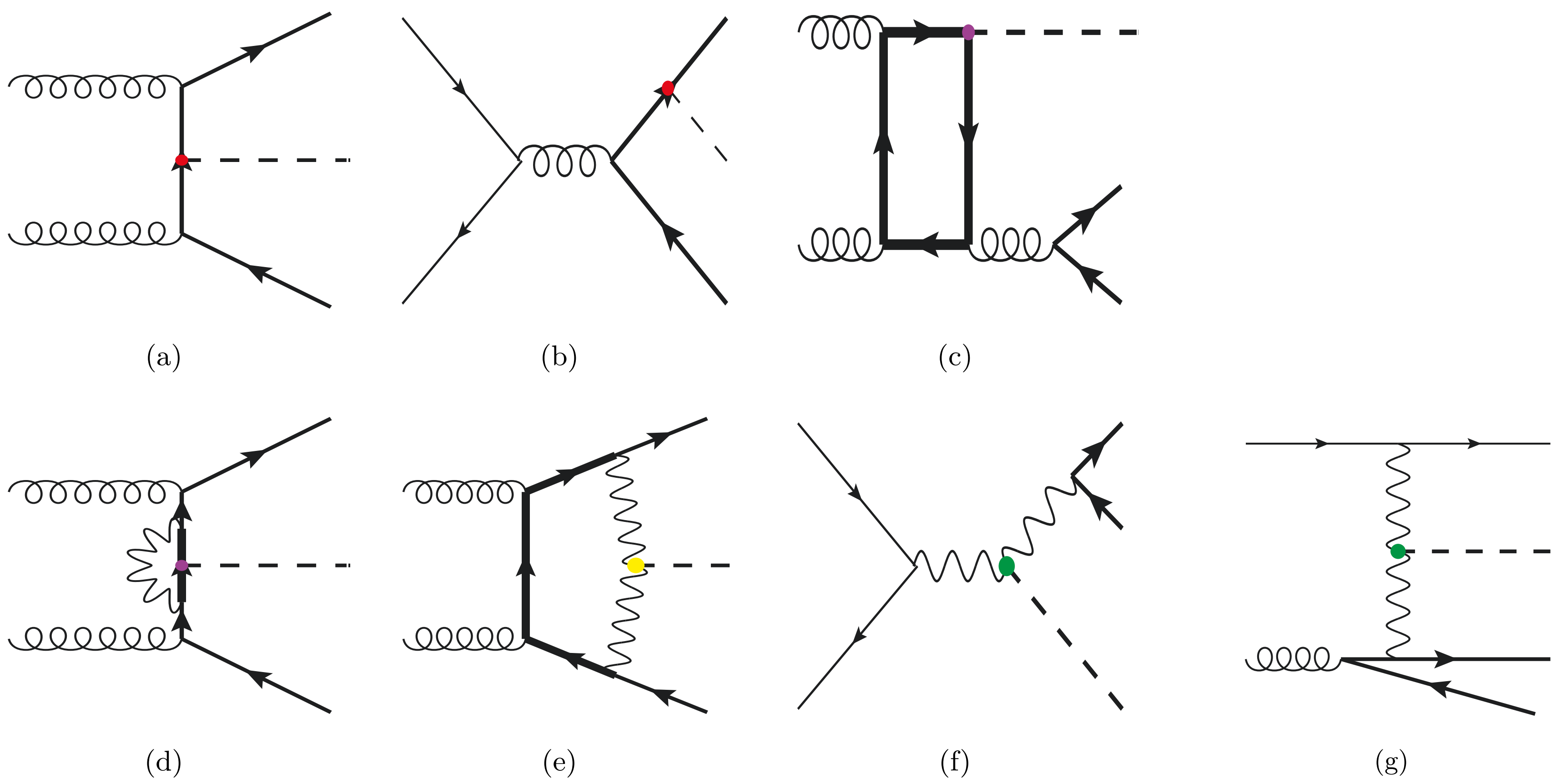
- Indirect measurement (e.g. EDM).
- But difficult at the LHC!
- Indirect: small contribution to gluon fusion process due to tiny coupling constant.

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

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

Phase in bottom-quark Yukawa Interactions

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



D. Pagani, H.-S Shao, M. Zaro, JHEP 2011 (2020) 036.

Phase in bottom-quark Yukawa Interactions

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

Channel	LO σ (fb)	NLO-k-fact	$6\,\mathrm{ab}^{-1}$ [#evt]	$2b$-jets[%]
y_b^2	0.0648	1.5	583	7.7%
$y_b y_t$	-0.00829	1.9	-95	4.0%
y_t^2	0.123	2.5	1,840	12%
Zh	0.0827	1.3	645	21%
$\sum b\bar{b}h$	0.262	-	2,970	-
$b\bar{b}\gamma\gamma$	12.9	1.5	116,000	14%

C. Grojean, A. Paul, Z. Qian, JHEP 2104 (2021) 139.

Phase in bottom-quark Yukawa Interactions

- But possible at Higgs factory.

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

- Small bottom mass, 0.25% modulation of the partial width.

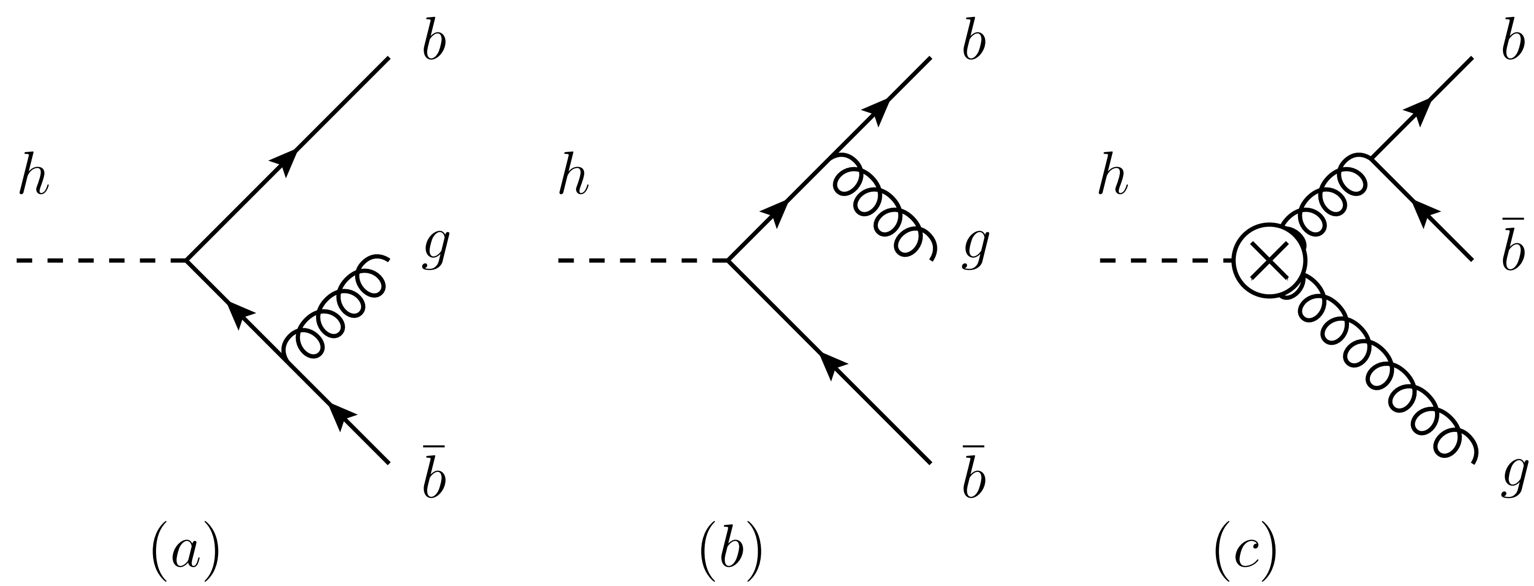
- Sensitivity of the partial width: ~0.3%.

- 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

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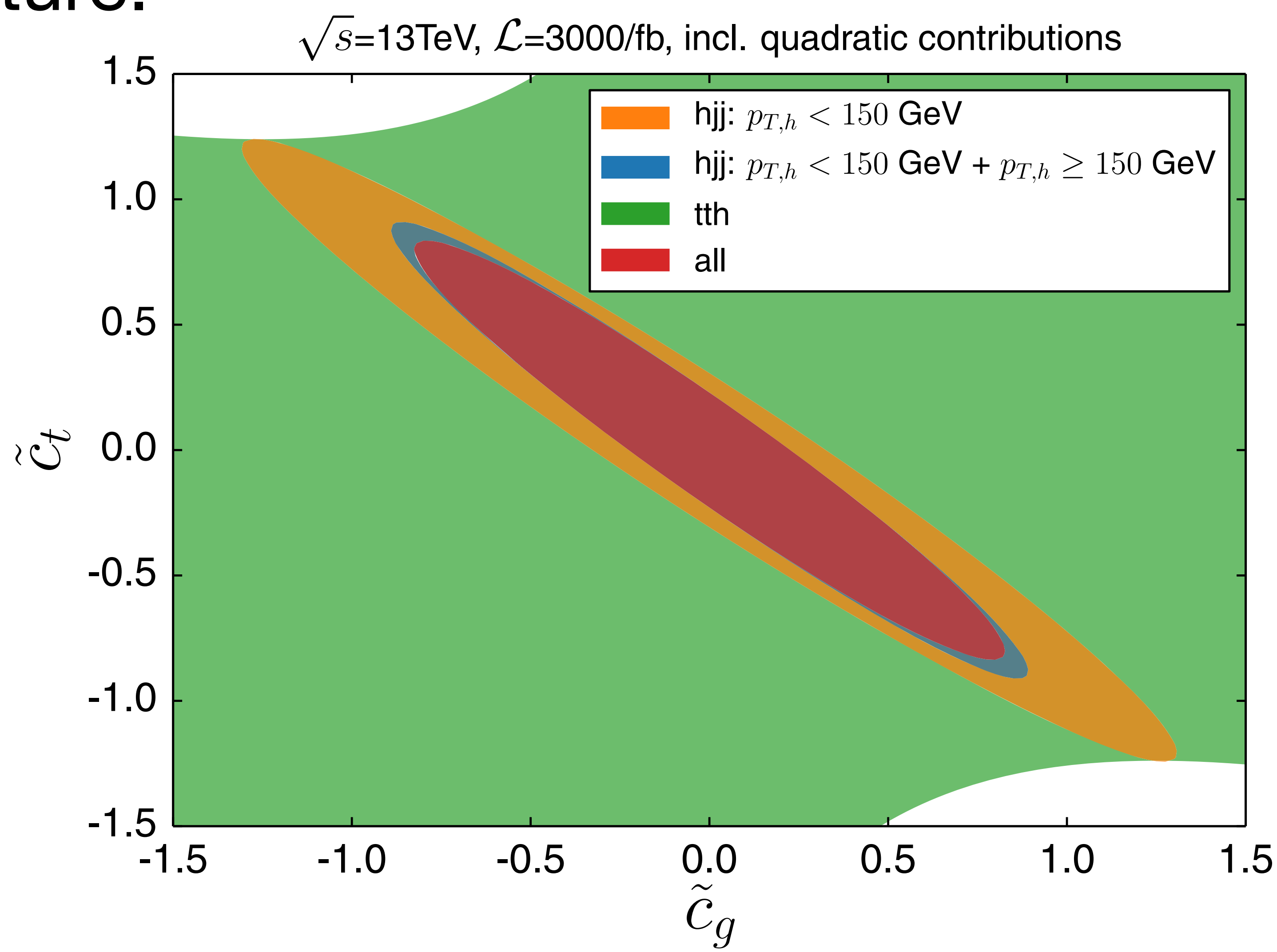
$$\tilde{O}_g = \frac{\alpha_s}{8\pi v} G^a_{\mu\nu} \tilde{G}^{a\mu\nu} h,$$
$$\tilde{O}_t = i\bar{t}\gamma_5 t h,$$



C. Englert, P. Galler, A. Pilkington, M. Spannowsky, Phys. Rev. D 99 (2019) 095007;

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

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

Phase in bottom-quark Yukawa Interactions

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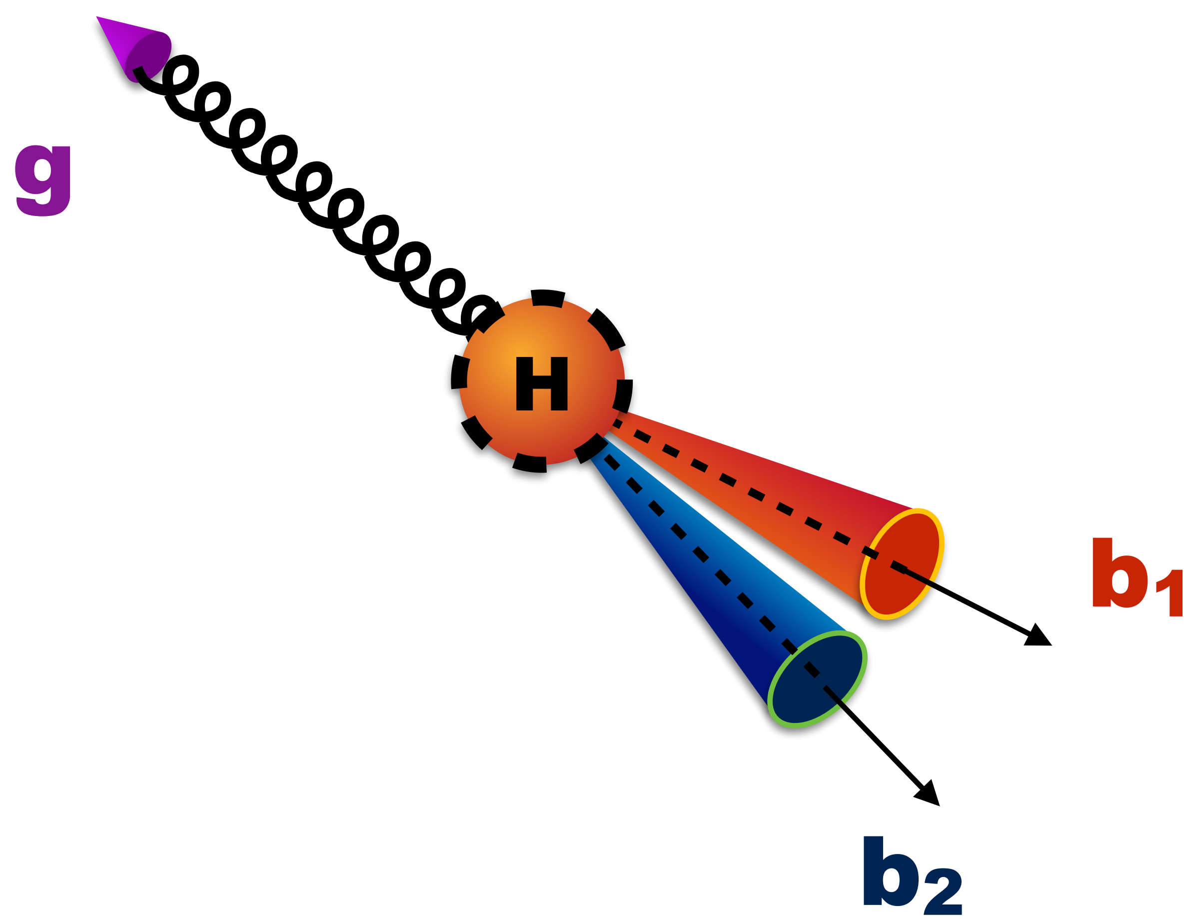
$$m_f\bar{\psi}_f\psi_f \to m_f\psi_f^\dagger e^{i\alpha_f\gamma_5/2}\gamma^0 e^{-i\alpha_f\gamma_5/2}\psi_f = m_f\bar{\psi}_f e^{-i\alpha_f\gamma_5}\psi_f$$

Phase in bottom-quark Yukawa Interactions

- Interference in Higgs decay:

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

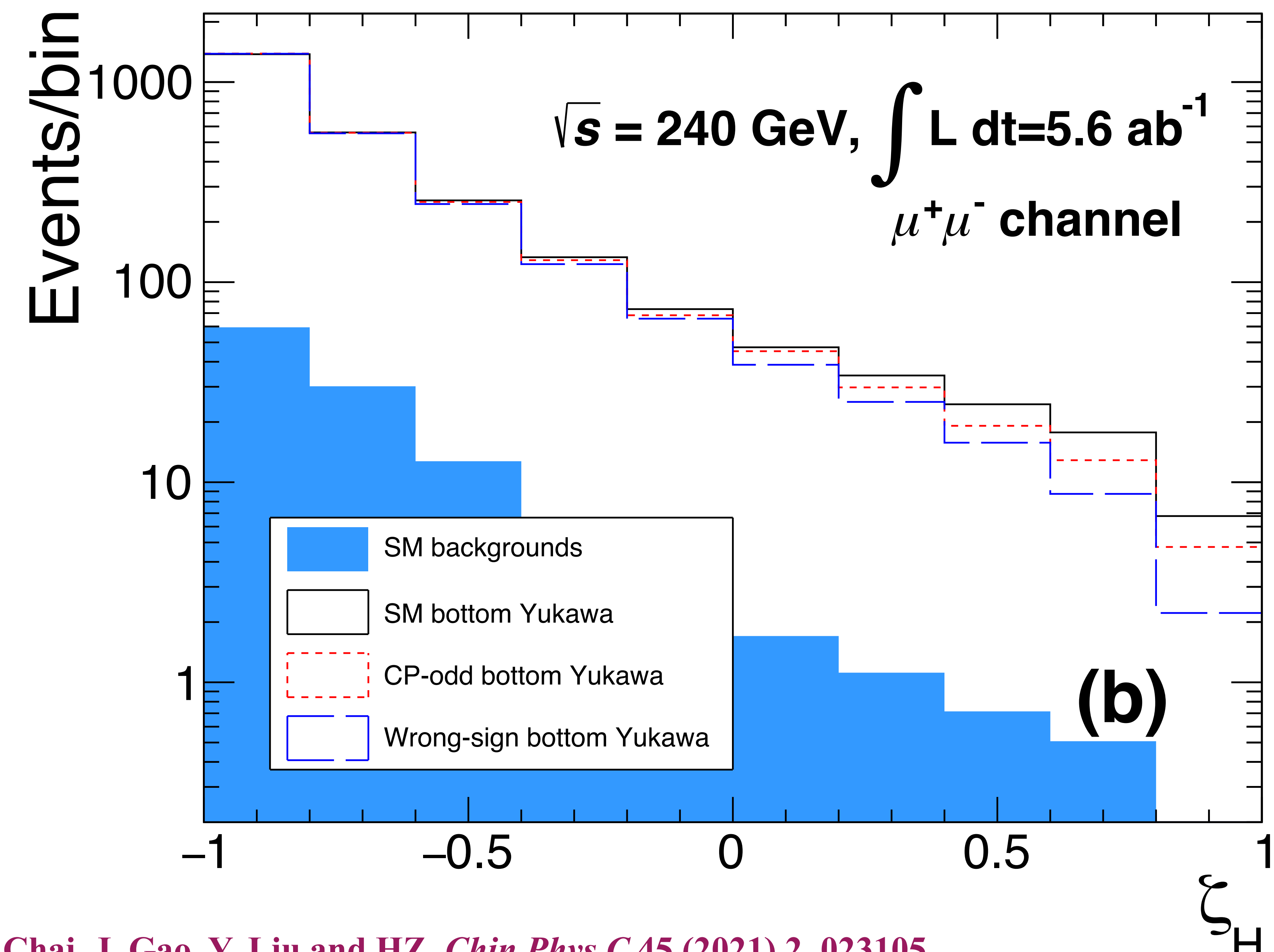
- To enhance the interference effect:



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

Collider Simulation

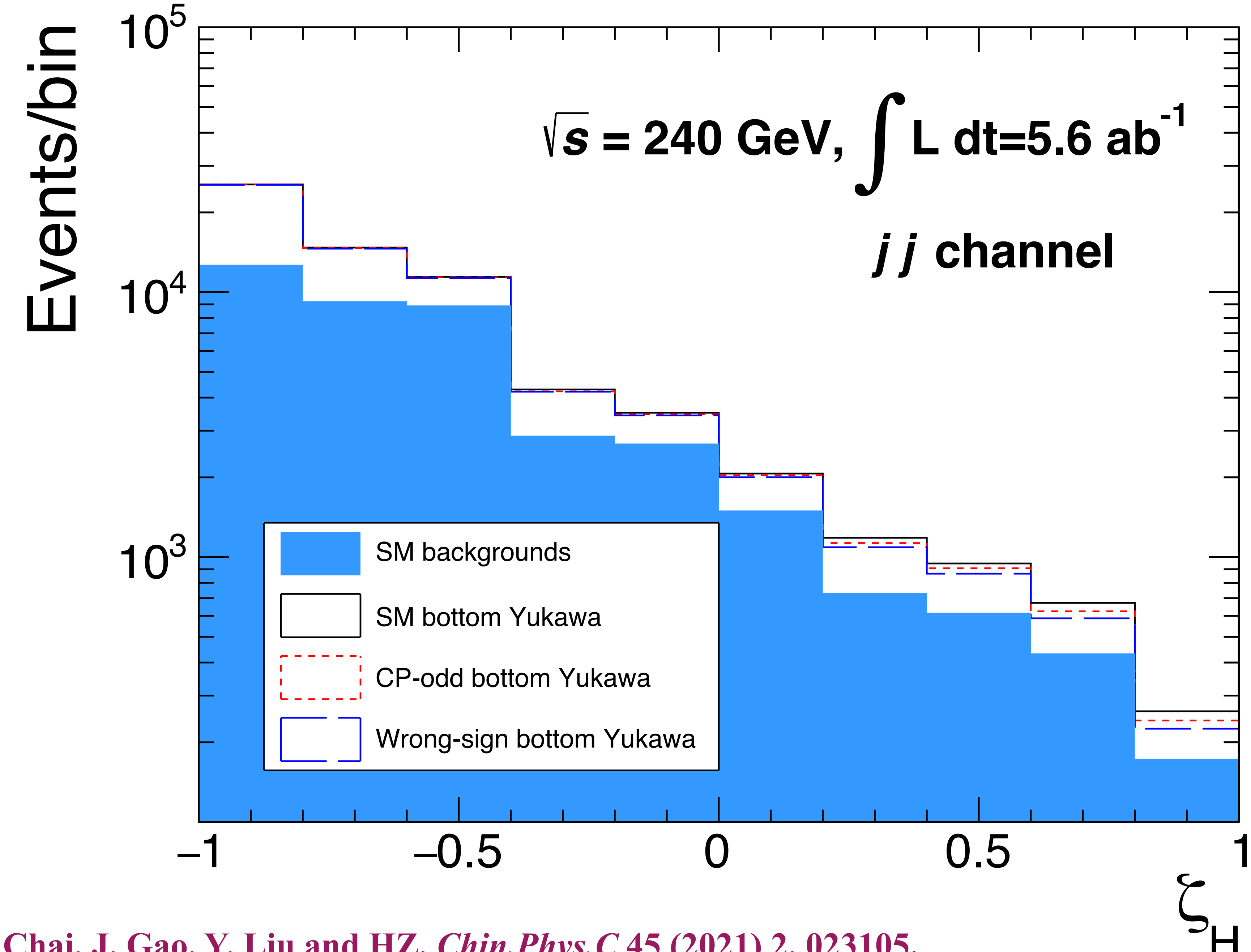
- Interference in Higgs decay:



Q. Bi, K. Chai, J. Gao, Y. Liu and HZ, *Chin.Phys.C* 45 (2021) 2, 023105.

Collider Simulation

- Interference in Higgs decay:



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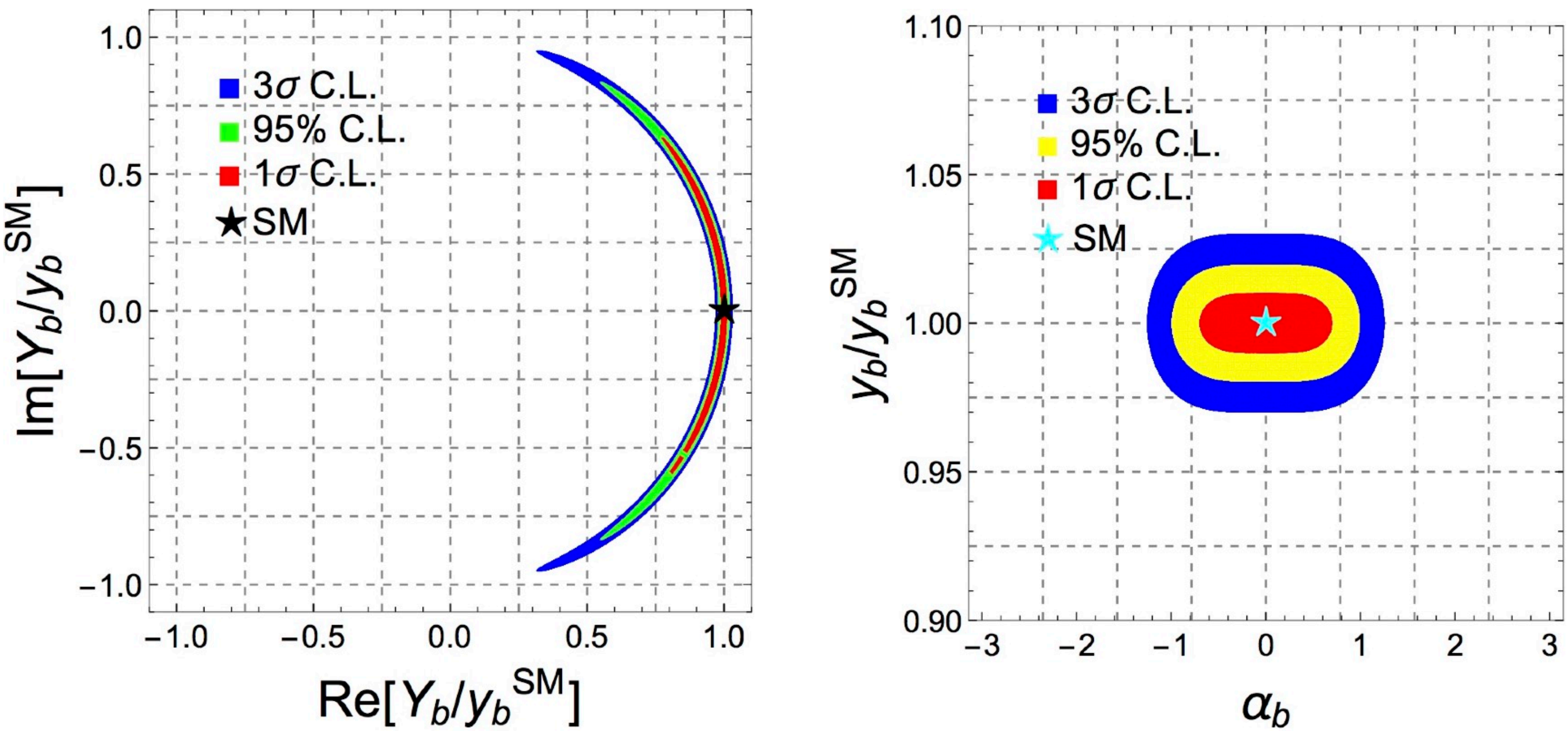
Results

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

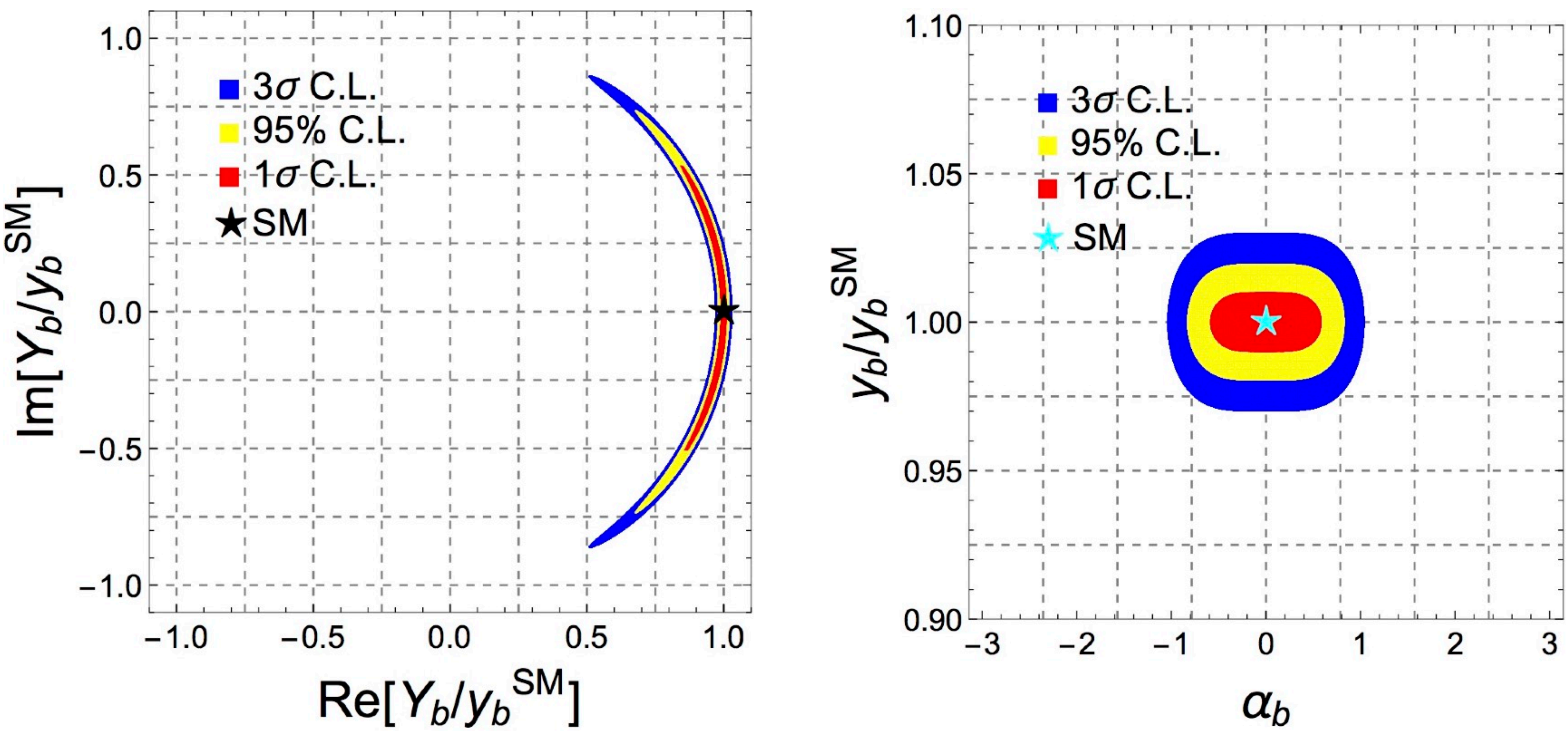


$\delta\alpha_b \sim \pm 40^\circ$

Q. Bi, K. Chai, J. Gao, Y. Liu and HZ, *Chin.Phys.C* 45 (2021) 2, 023105.

Results

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

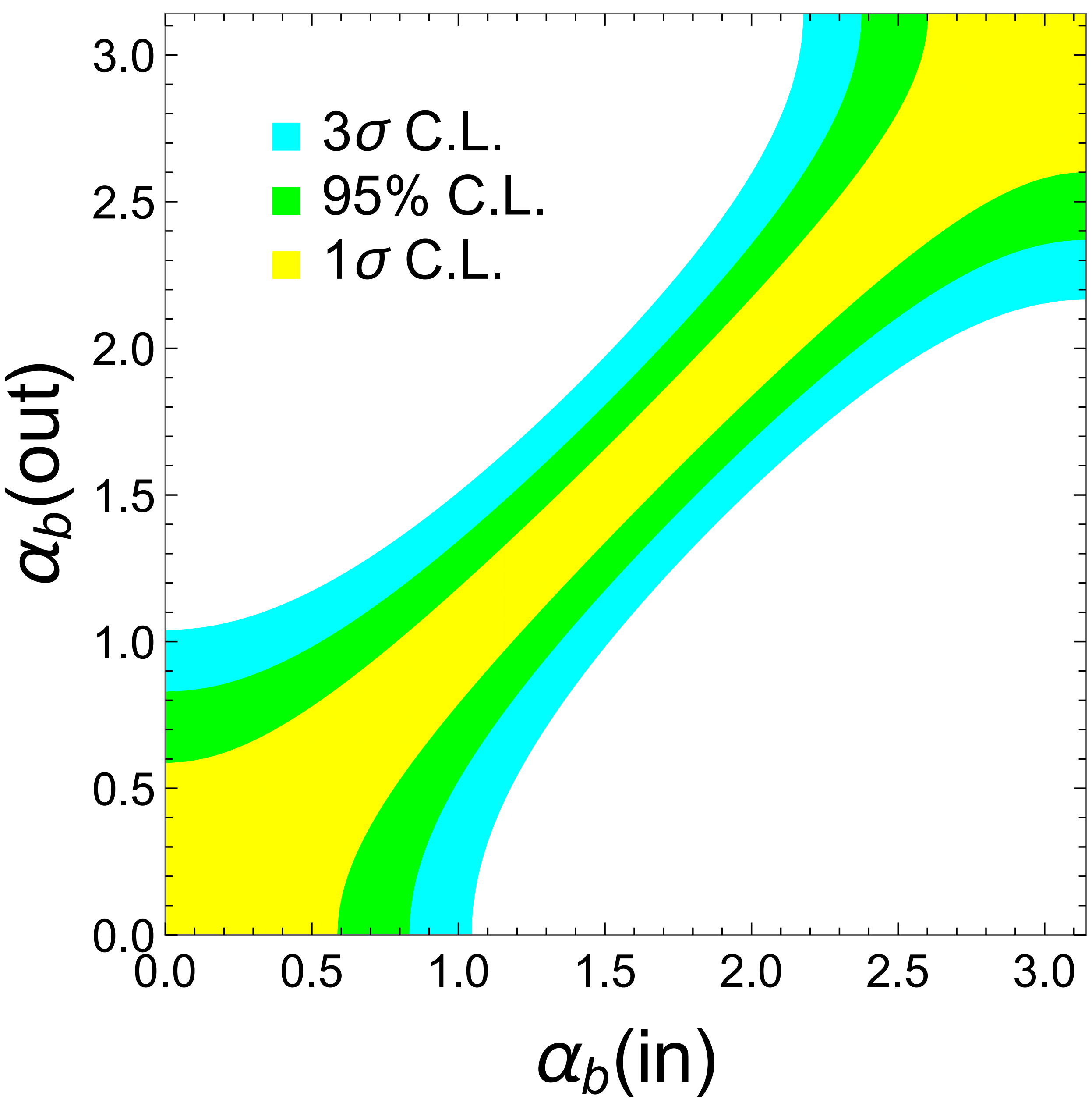


$\delta\alpha_b \sim \pm 34^\circ$

Q. Bi, K. Chai, J. Gao, Y. Liu and HZ, *Chin.Phys.C* 45 (2021) 2, 023105.

Results

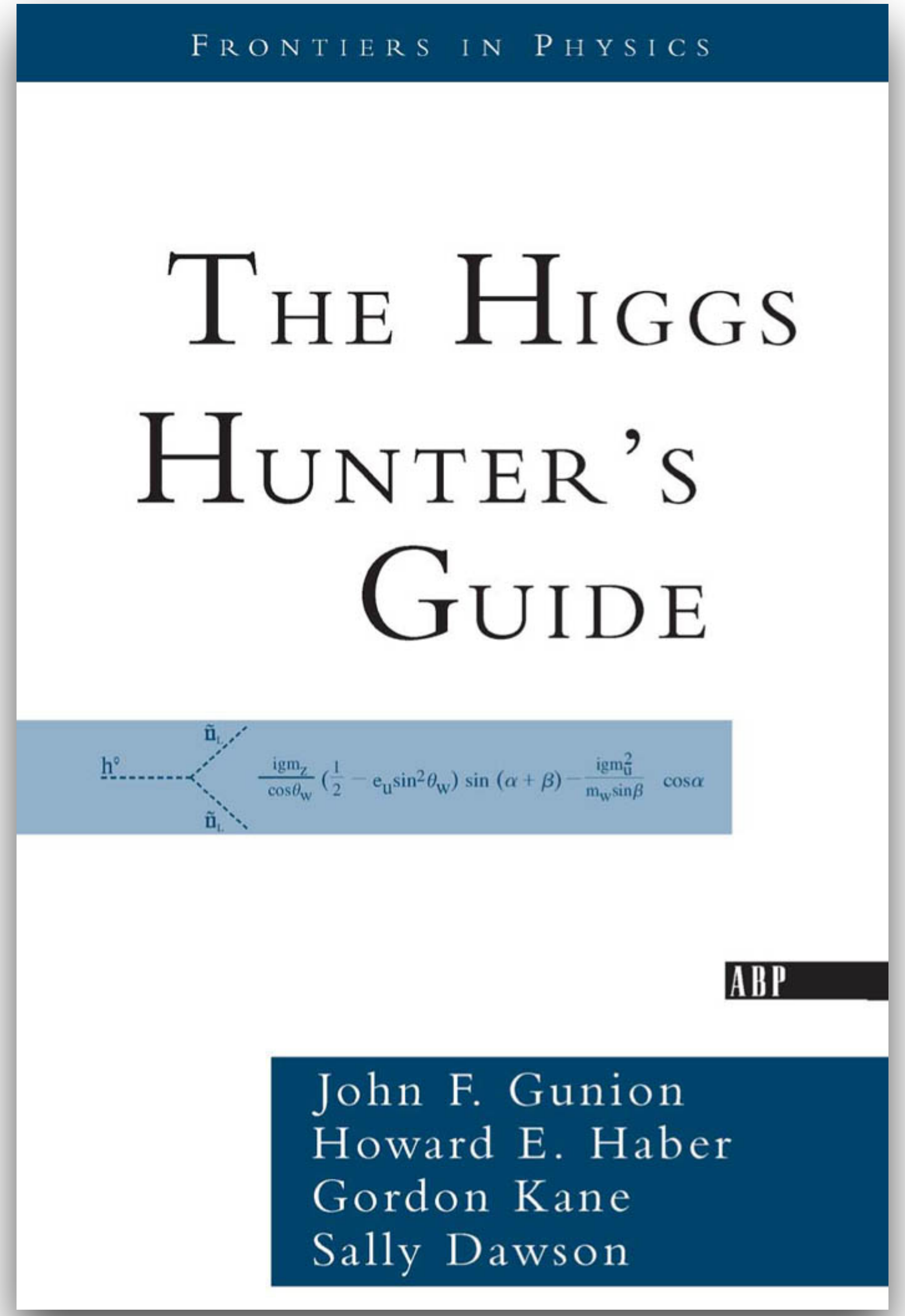
- 240GeV Higgs factory with 5.6ab^{-1} integrated luminosity+ 365GeV Higgs factory with 1.5ab^{-1} integrated luminosity.



Q. Bi, K. Chai, J. Gao, Y. Liu and HZ, *Chin.Phys.C* 45 (2021) 2, 023105.

Summary

- LHC and future colliders will bring us to an era of precisely Higgs physics.
- Experimentalists have already measured a lot of important properties of the SM-like Higgs boson.
- We need to understand the details of the Higgs boson as we did for the Z boson at LEP.
- We show an example of studying the CP property of the Higgs-bottom-quark Yukawa interaction.



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First paperback printing, June 2000

PERSEUS POD ON DEMAND

We hunted the Higgs Boson for more than 50 years. What should we do after getting it?

Domesticating it!

Backup Slides

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

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

- 240GeV leptonic decaying Z

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

- 240GeV hadronic decaying Z

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

Collider Simulation

- Hadronic decaying Z: likelihood method.

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

- We reconstruct Z and H with minimizing the discriminator

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