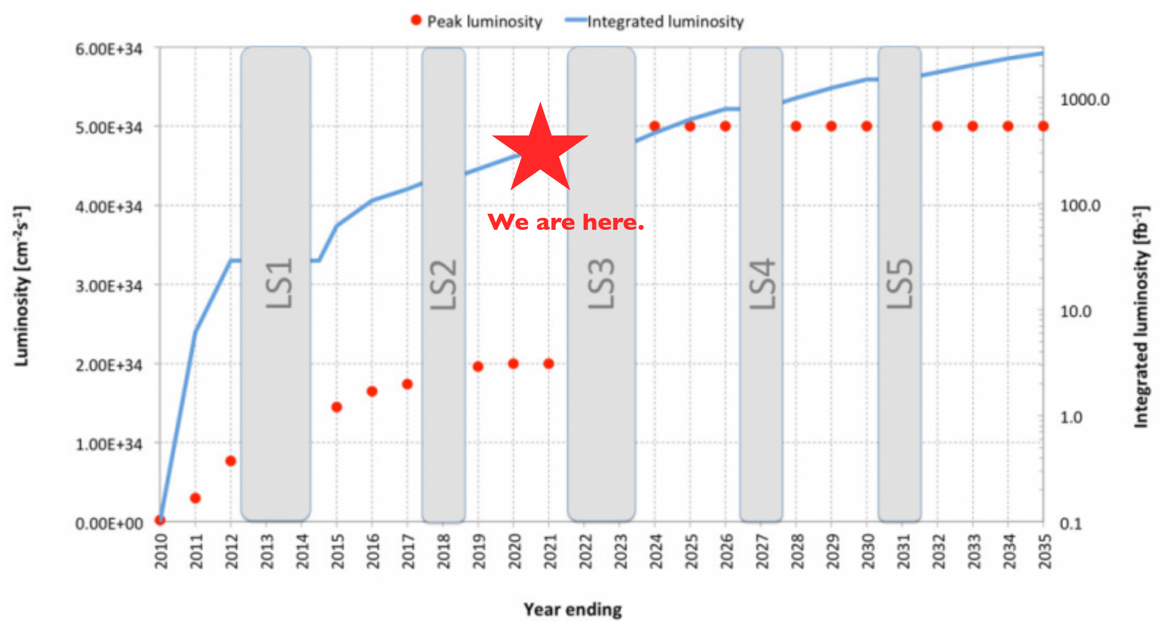
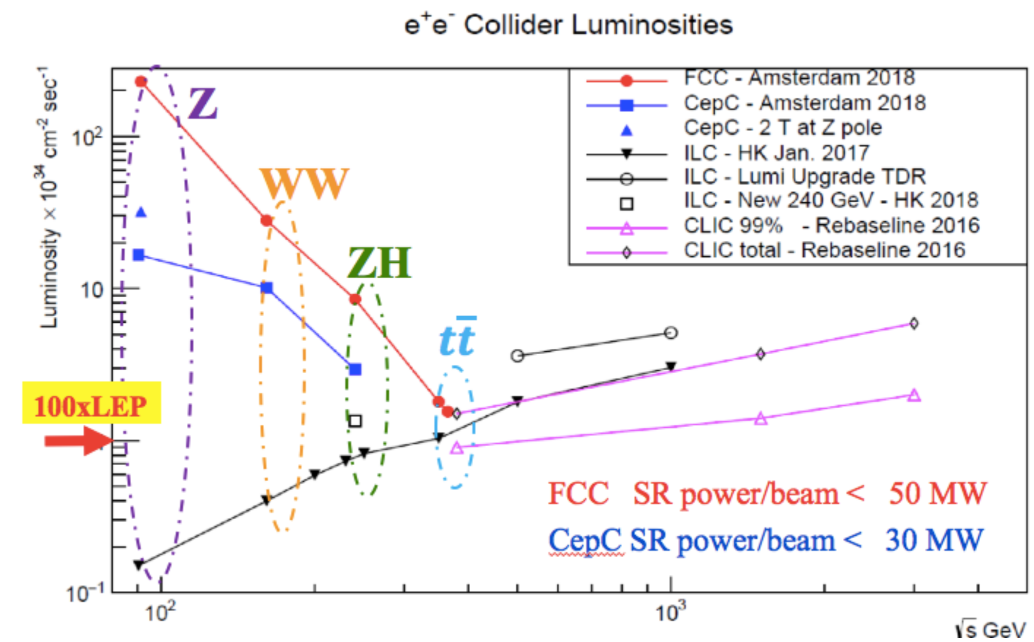
CEPC physics goals

LianTao Wang
Univ. of Chicago

Joint workshop of the CEPC physics, software and new detector design, April 14. Yang Zhou.

The coming decades

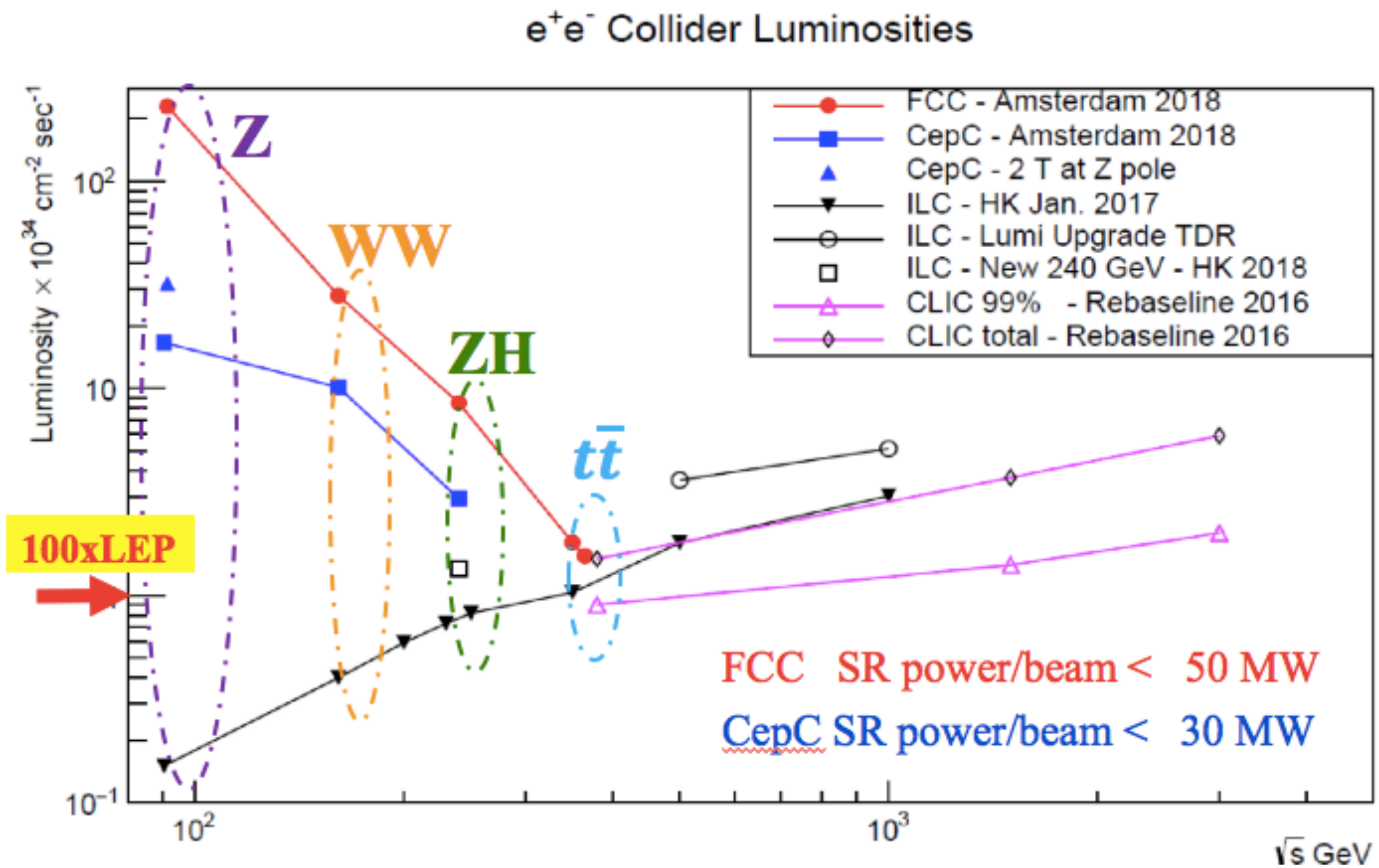




- More data, cleaner collisions.
- Main target: precision, rare processes.

History on our side

- First signal of something new are often “indirect”.
  - Beta decay: W (1933)
  - Kaon rare decay: charm (1970)
  - Neutrino scattering: Z (1973)
  - Electroweak precision: top and Higgs (1980s-1990s)
  - ....
- We expect an equally fruitful journey from now on.



Main goal of the physics studies:

How to fully realize the physics potential of data?

My talk

- The main physics case:
  - Higgs, Electroweak + opportunities of exotic searches
- Clearly laid out in the Conceptual Design Report
  - Will be brief on these familiar points.
- I will try to highlight new developments opportunities for further studies.

A lot of on-going work

Higgs boson CP properties at CEPC

Meng Xiao (ZJU) Xin Shi (IHEP)
Yanxi Gu (UCSD) Mengyao Liu (SDU)

Measurement of Bs → $\pi^0\pi^0$ at CEPC

Yuexin Wang, Manqi Ruan
2020.11.27

Exclusive hadronic Z decays

Shan Cheng

In collaboration with Qin Qin, Man-qi Ruan and Fu-sheng Yu

December 18, 2020

Effective mixing angle($\sin^2\theta_W^{eff}$) measurement at CEPC

Zhenyu Zhao, Siqi Yang, Minghui Liu, Liang Han

2020.11.27

Probing bino NLSP at lepton colliders

Chengcheng Han(韩成成)
Sun Yat-Sen university(中山大学)

Based arXiv-2101.12131 (today)
With Junmou Chen, Jin Min Yang, Mengchao Zhang

CEPC Snowmass
2021.1.29

Measurement of H->ZZ* at the CEPC

Ryuta Kiuchi , Yanxi Gu , Min Zhong, Shih-Chieh Hsu, Xin Shi, Kaili Zhang

2020-01-29 1

Stimulated by the Snowmass white paper activities organized by Manqi Ruan

My talk

- Precision measurements: Higgs and beyond
- Gateway to new physics
  - A possible new physics scenario

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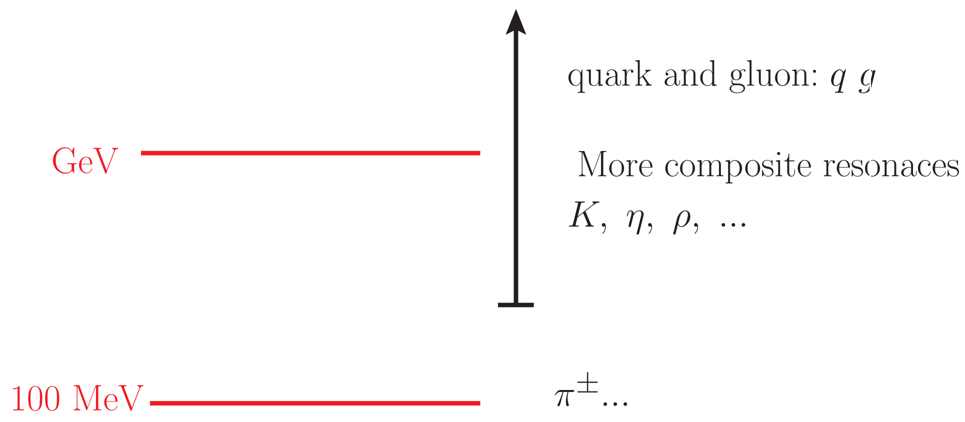
Big question: why Higgs?

- Spin 0 elementary particle, unique one of its kind.
- We have seen spin-0 particles.
  - They are composite, with other states around.



Higgs looks very different.

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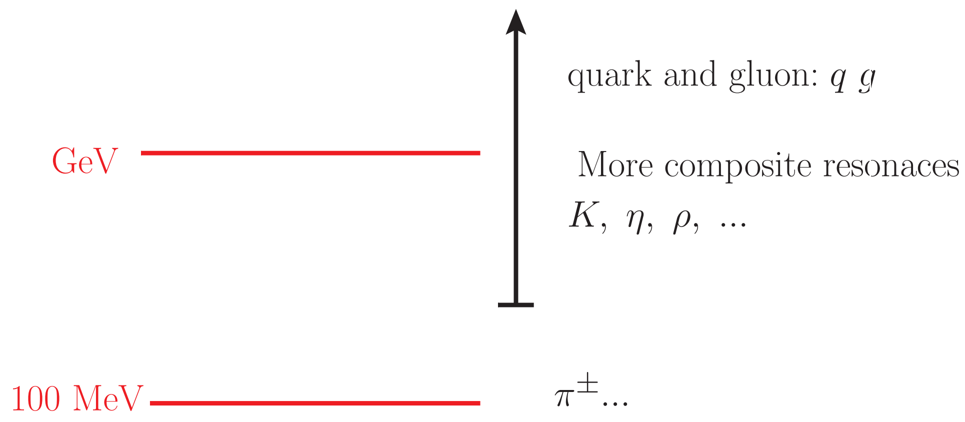
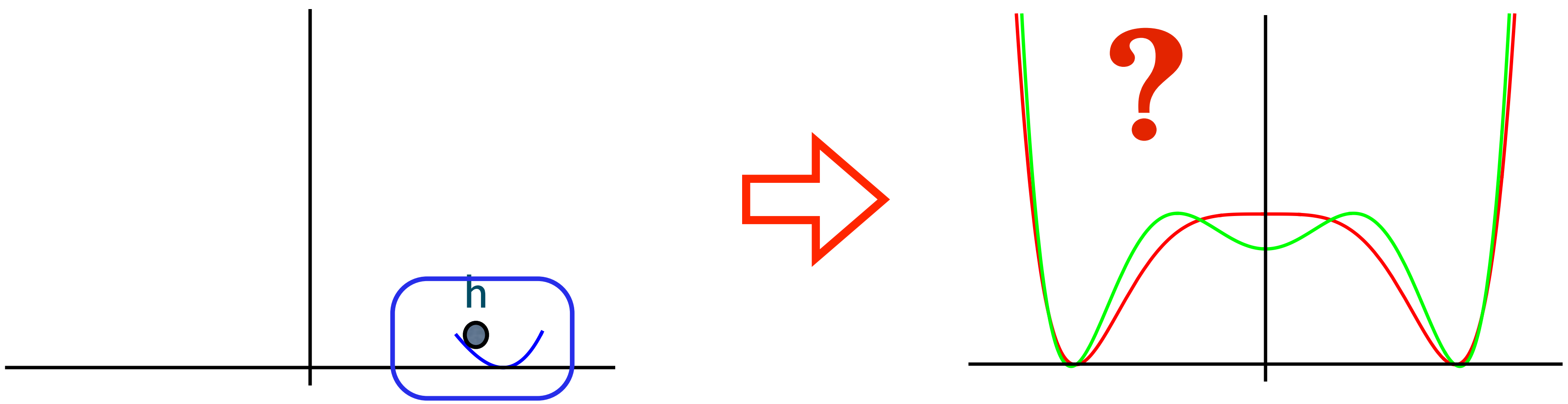


Higgs looks very different.

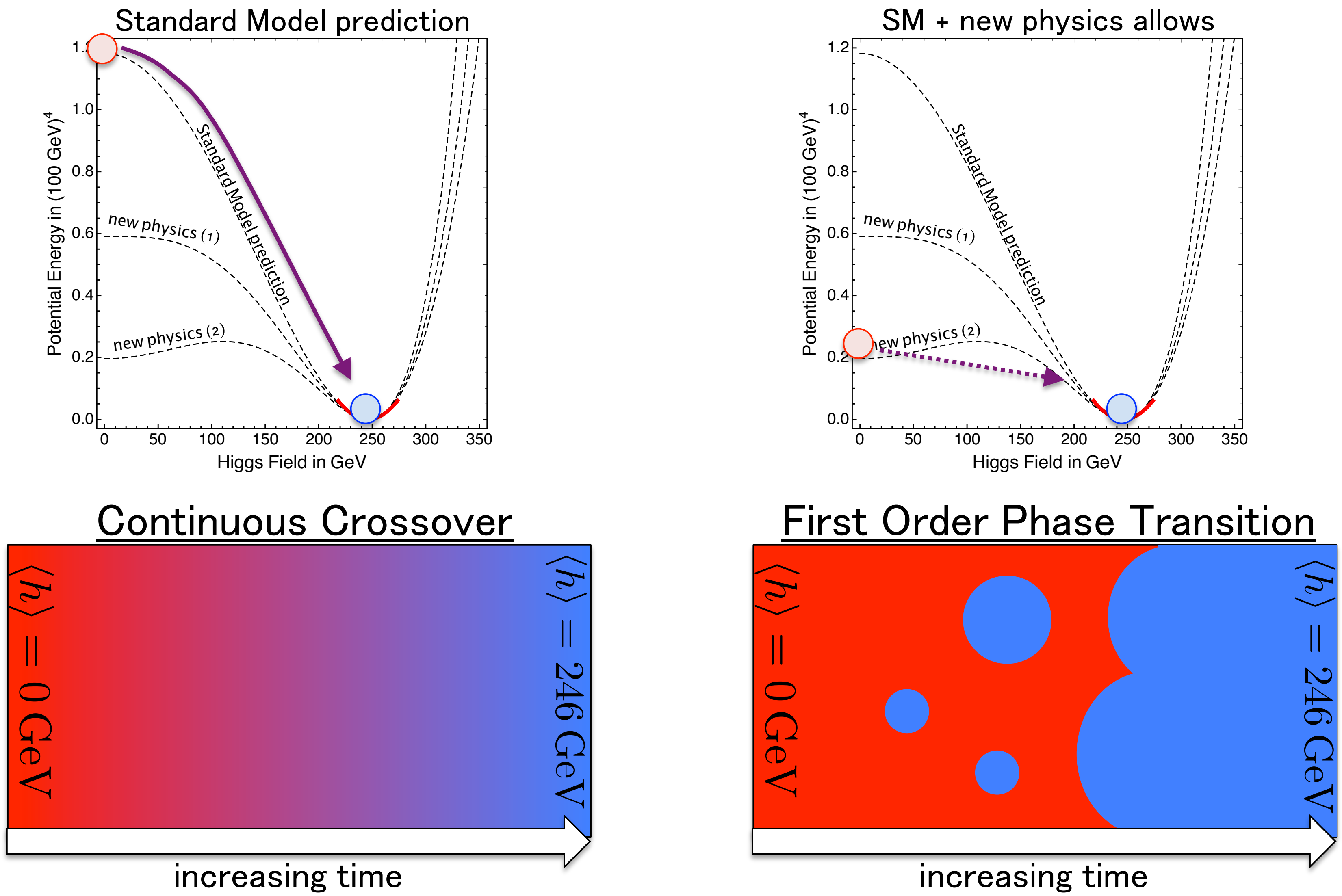
- So, where does the Higgs come from?

EW phase transition



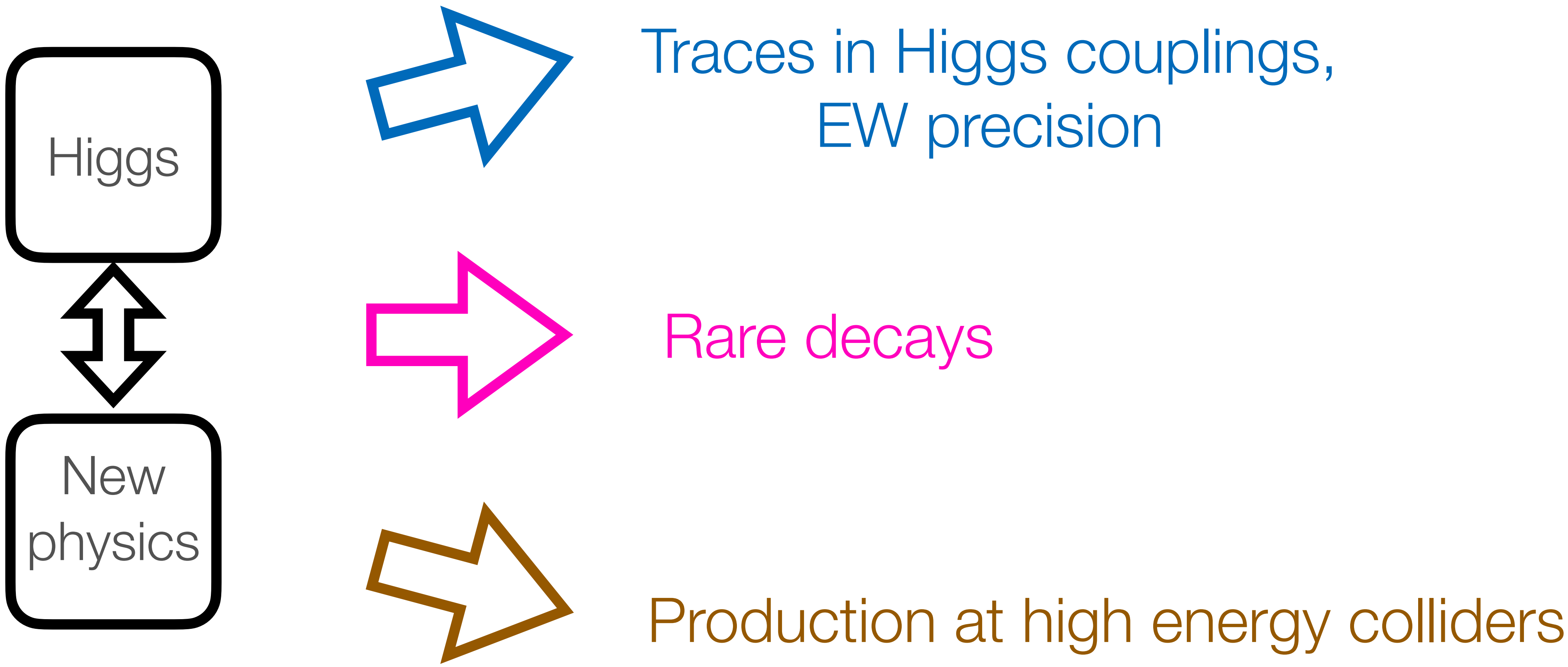
What we know from LHC
LHC upgrades won't go much further

Early universe



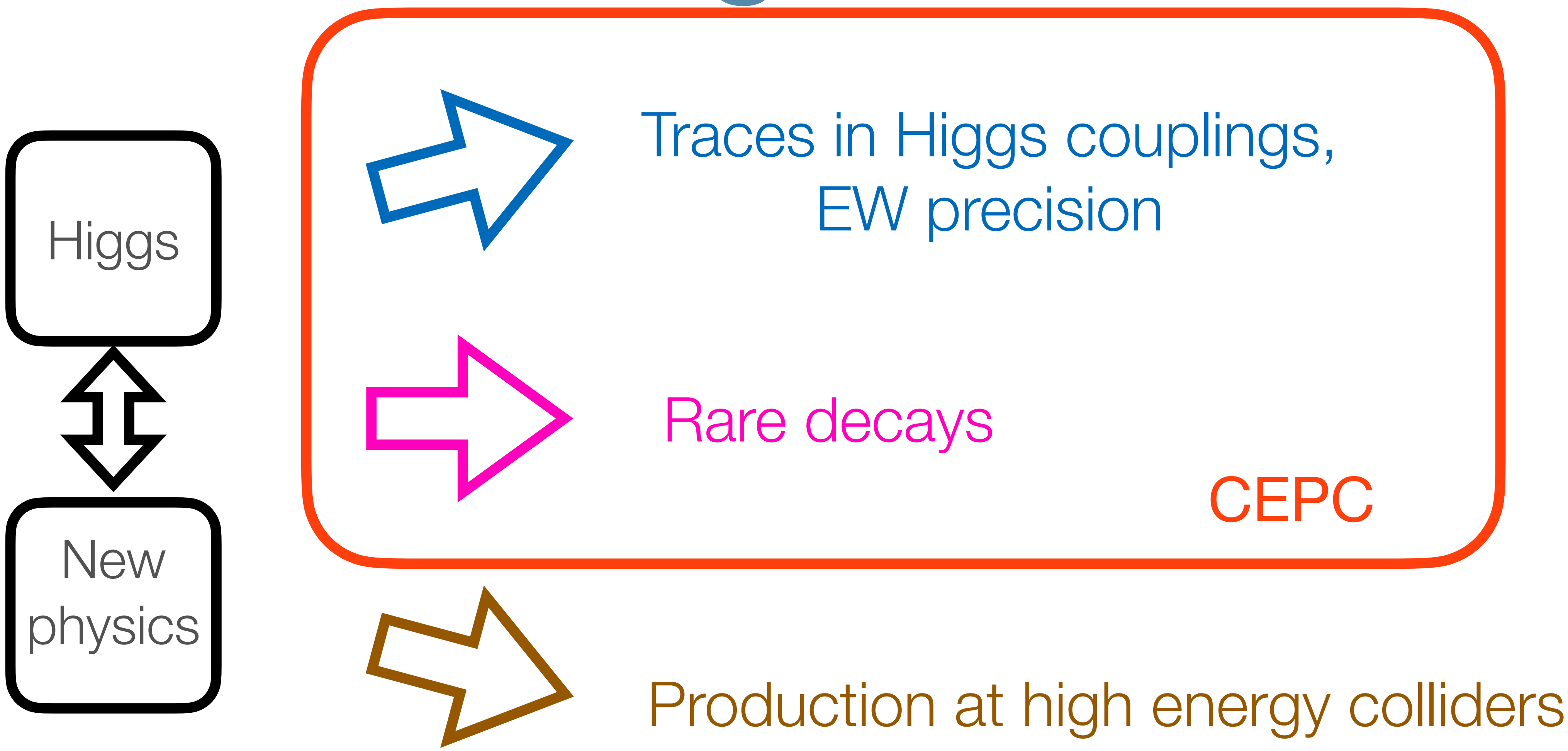
- How does Higgs evolve in the early universe?

Possible new signals



- New physics must couple to the Higgs.
- We will seek answers from the Higgs as well.

Possible new signals



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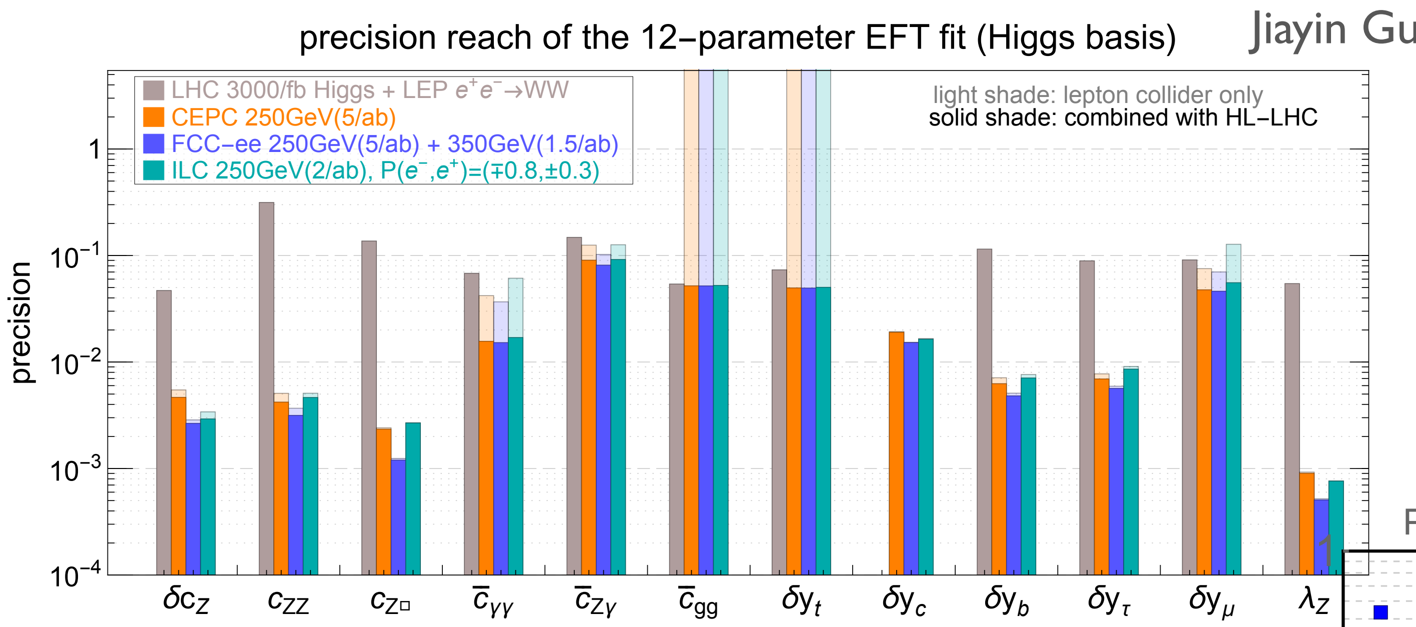
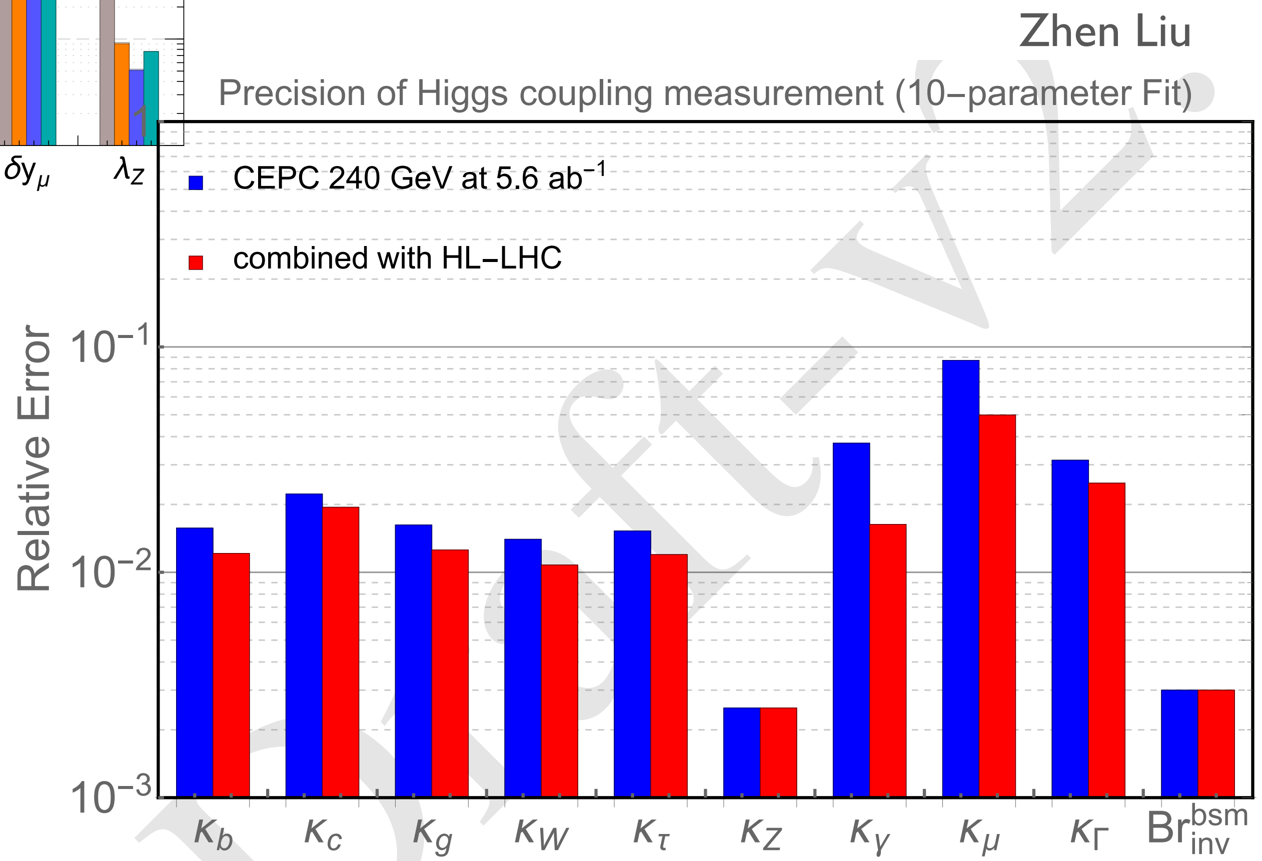
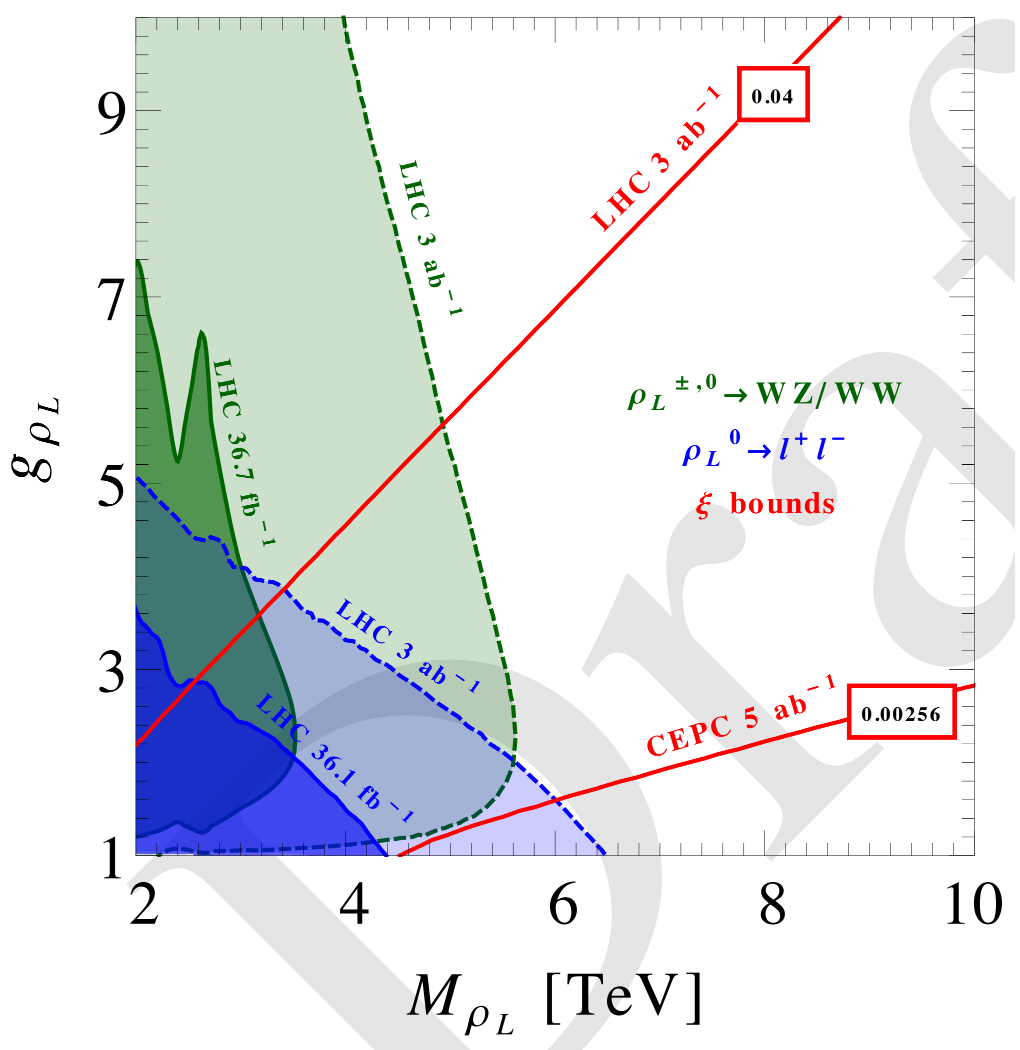
Higgs coupling

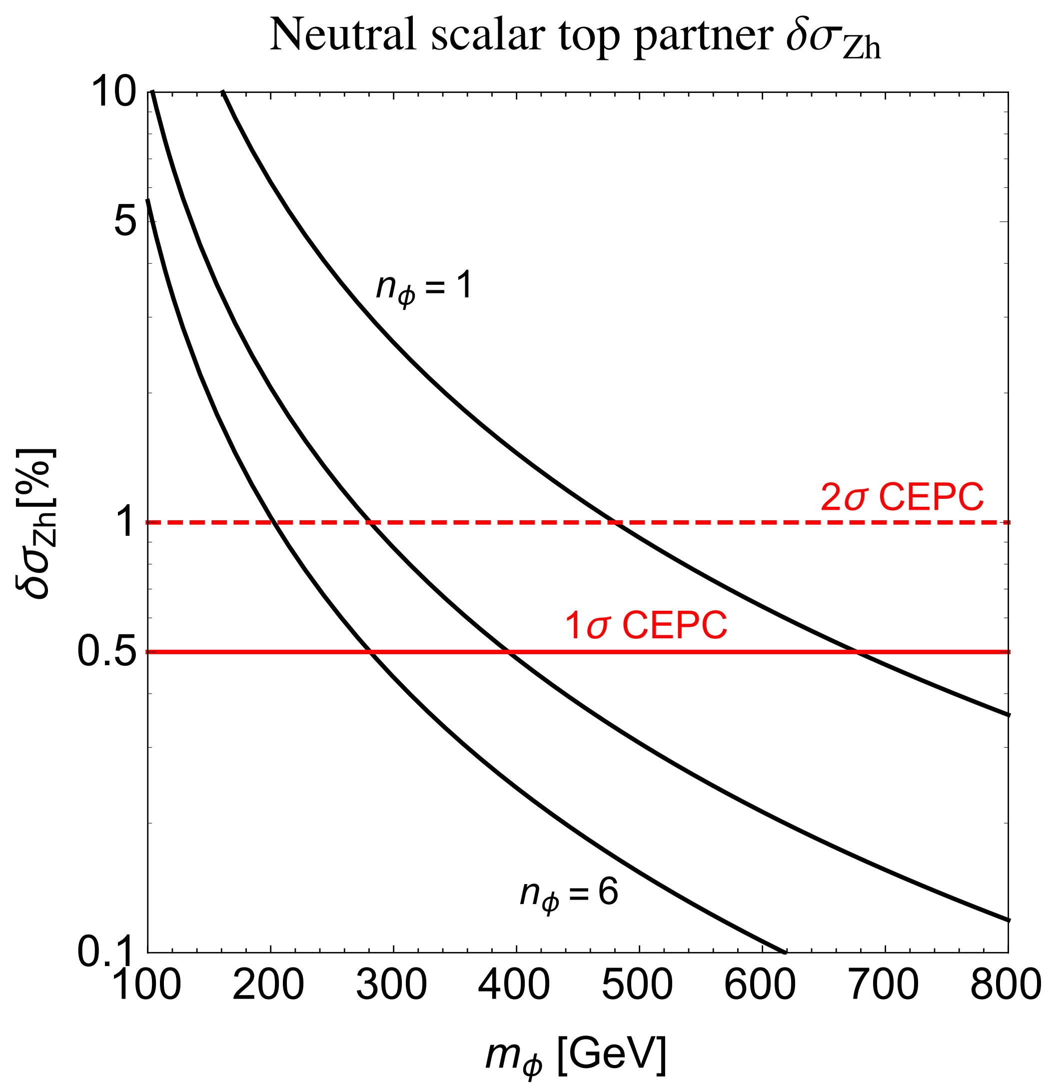


Most sensitive probes in the coming decades!



Example: naturalness

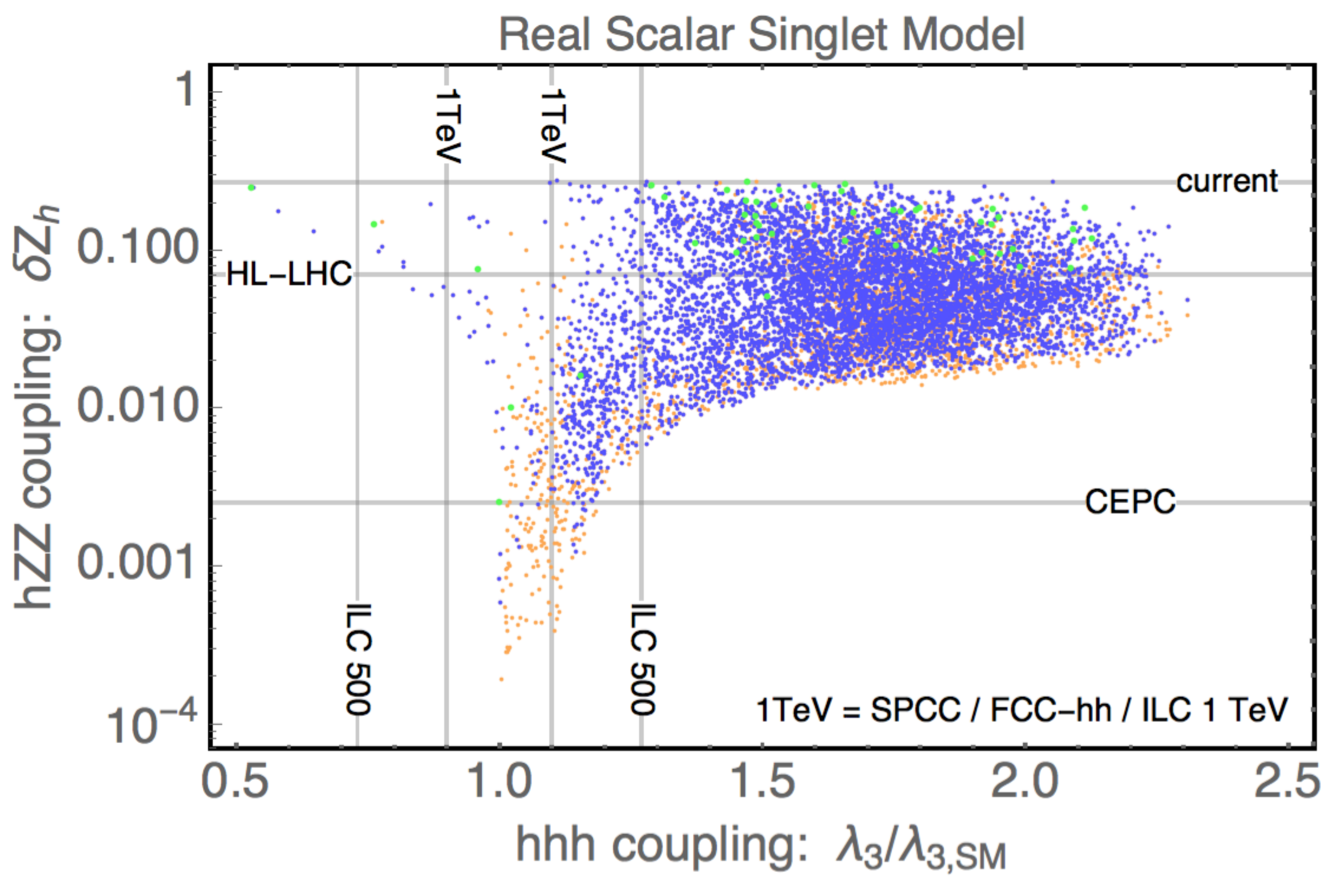




Composite Higgs

Neutral naturalness

Example: EW phase transition



Orange = first order phase transition, $v(T_c)/T_c > 0$
Blue = "strongly" first order phase transition, $v(T_c)/T_c > 1.3$
Green = very strongly 1PT, could detect GWs at eLISA

Huang, Long, LTW, 1608.06619

More models, possible connection with matter anti-matter asymmetry
Further exploration underway.

Beyond CDR studies

- Refinement of Higgs coupling measurements.

  Ryuta Kiuchi, Yanxi Gu, Min Zhong, Shih-Chieh Hsu, Xin Shi, Kaili Zhang…

- CP properties of the Higgs.

  Yaquan Fang, Gangyi Guo, Gang Li, Qiyu Sha, Xinchou Lou
  Meng Xiao, Xin Shi
  …

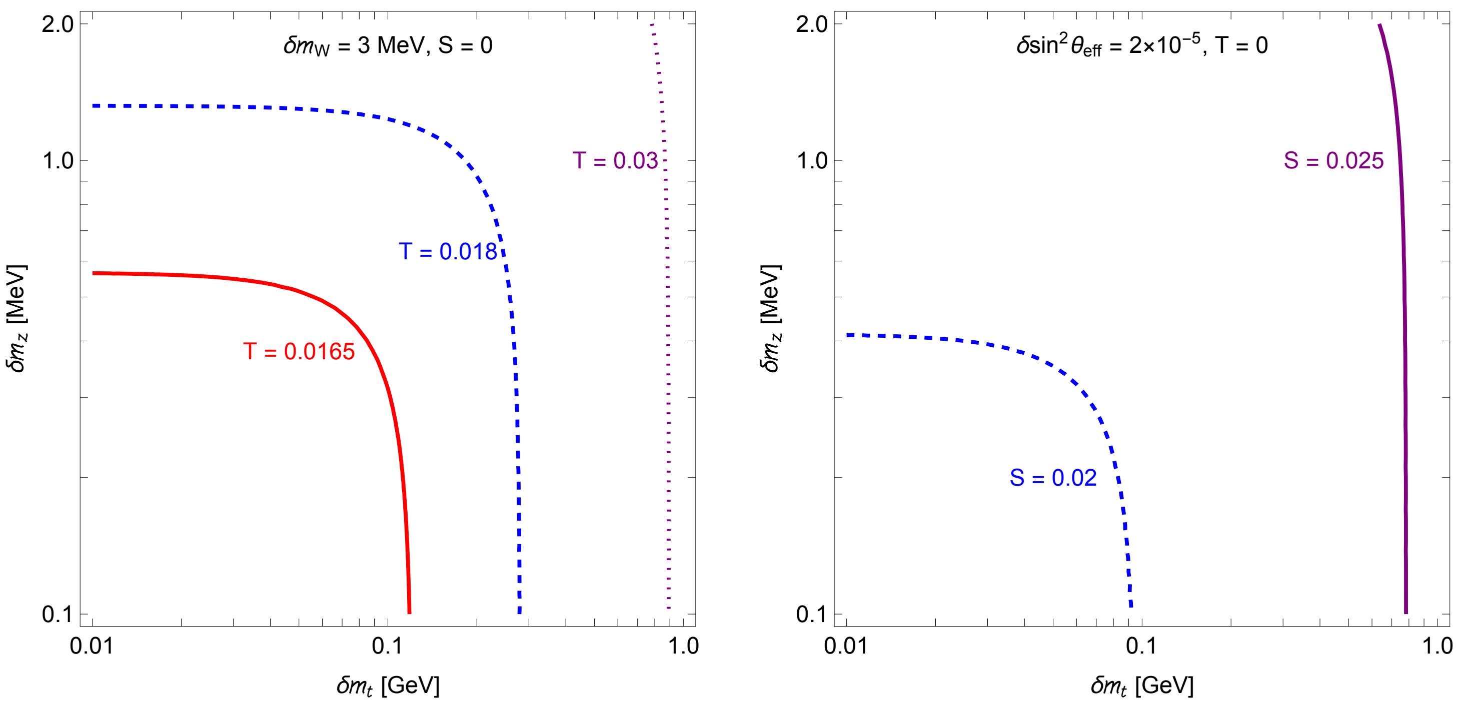
- EW precision

  Liang Han, Zhijun Liang, Minghui Liu, Siqi Yang, Zhenyu Zhao, …

For details, see the talks later in this meeting.

Gains from run at ttbar

- Top mass a key input for electroweak precision.



Parameter	Current	CEPC baseline	Improved m_t
S	3.4×10^{-2}	8.1×10^{-3}	6.6×10^{-3}
T	2.8×10^{-2}	9.2×10^{-3}	6.5×10^{-3}

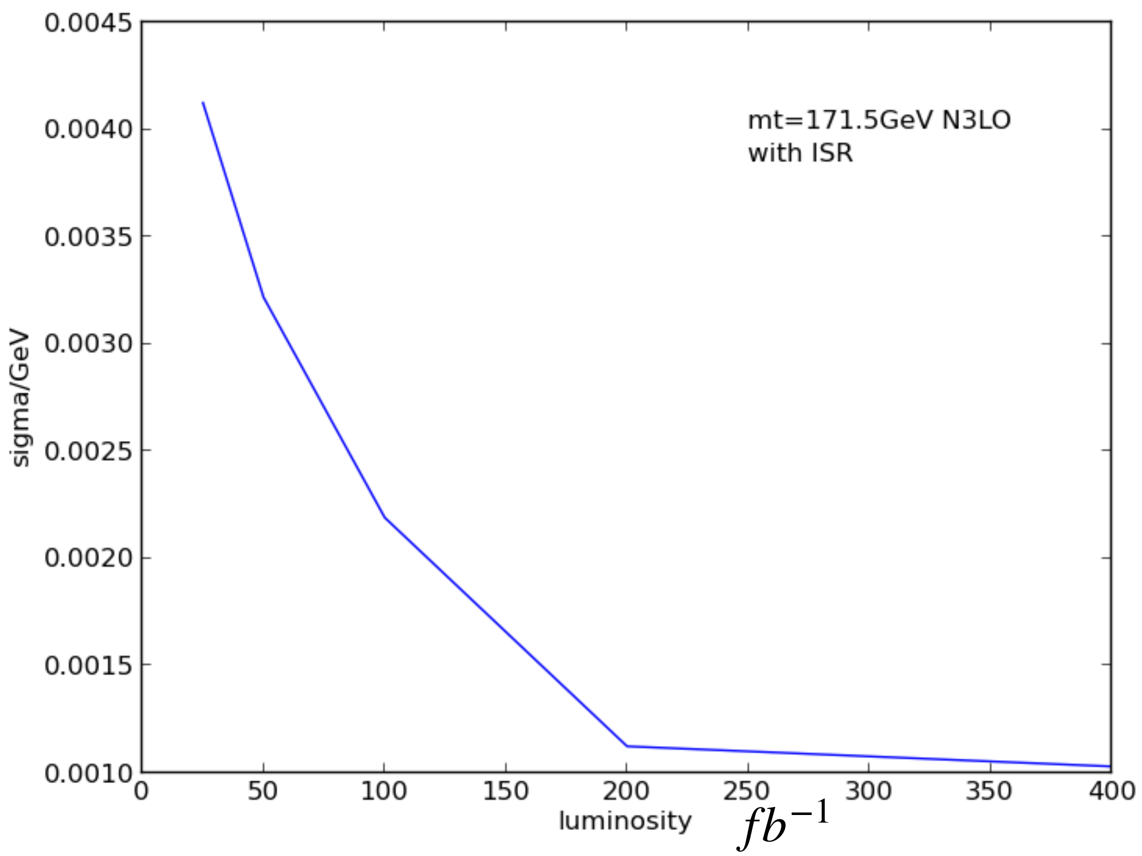
CEPC studies

Gang Li, Zhan Li, Zhijun Liang, Yaquan Fang, Xiaohu Sun, Shudong Wang, Yiwei Wang, Shuiting Xin, Hao Zhang

See Xiaohu Sun's talk for details.

Threshold scans

- 4-$\sqrt{s}$ scheme = {341.5,342.5,343,344.5} GeV
- 6-$\sqrt{s}$ scheme = {341,342,342.5,343,343.5,344.5} GeV
- 8-$\sqrt{s}$ scheme = {340,341,342,342.5,343,343.5,344.5,345} GeV



Great precision possible.

Beyond top mass

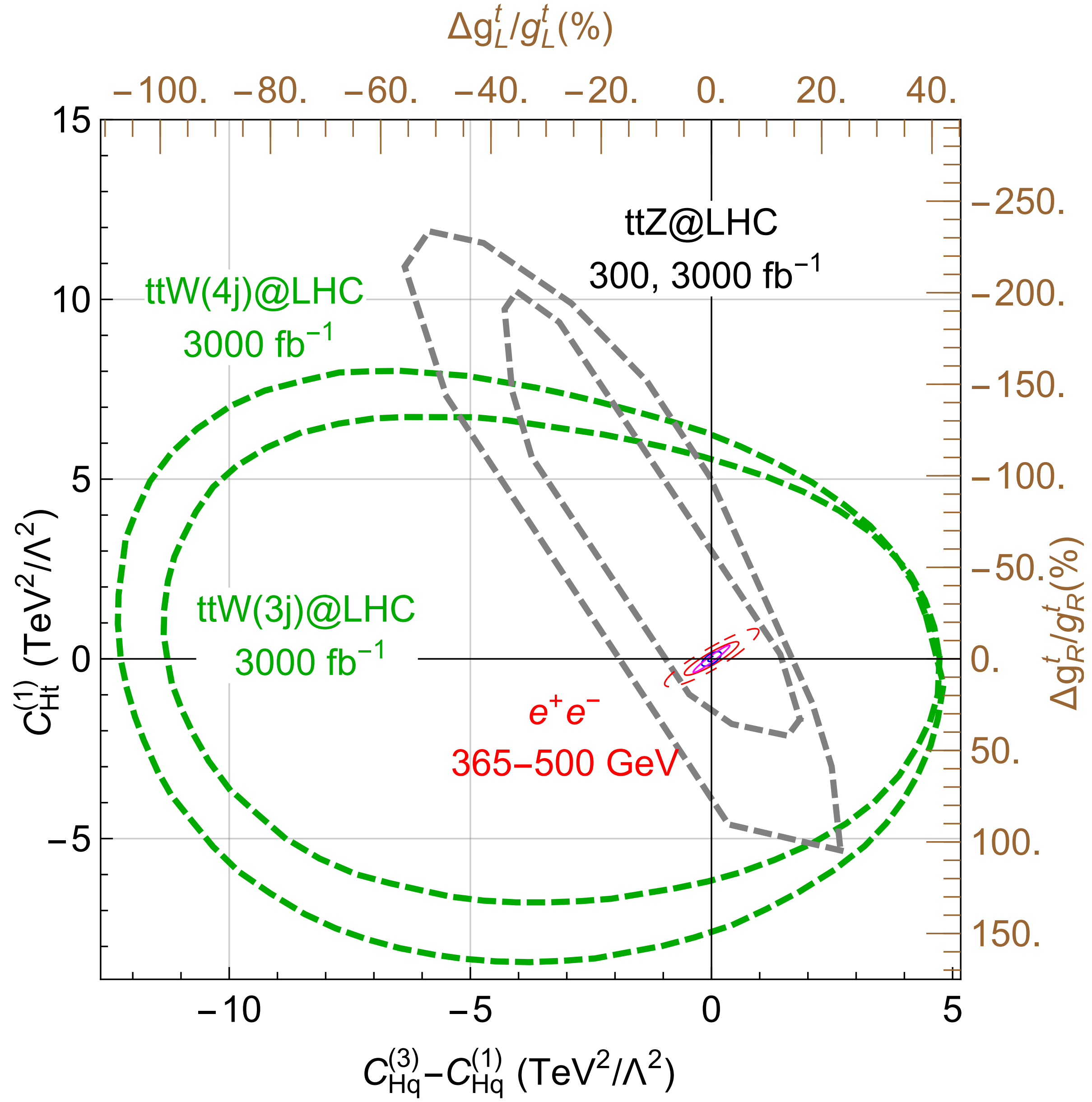
$$\mathcal{O}_{Hq}^{(1)} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu q_L),$$
$$\mathcal{O}_{Hq}^{(3)} = \frac{i}{\Lambda^2}(H^\dagger \tau^I \overleftrightarrow{D}_\mu H)(\bar{q}_L \gamma^\mu \tau^I q_L)$$
$$\mathcal{O}_{Ht} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{t}_R \gamma^\mu t_R),$$
$$\mathcal{O}_{Hb} = \frac{i}{\Lambda^2}(H^\dagger \overleftrightarrow{D}_\mu H)(\bar{b}_R \gamma^\mu b_R),$$

Modifies Vqq couplings

Also qqVh, little impact on Higgs coupling fits

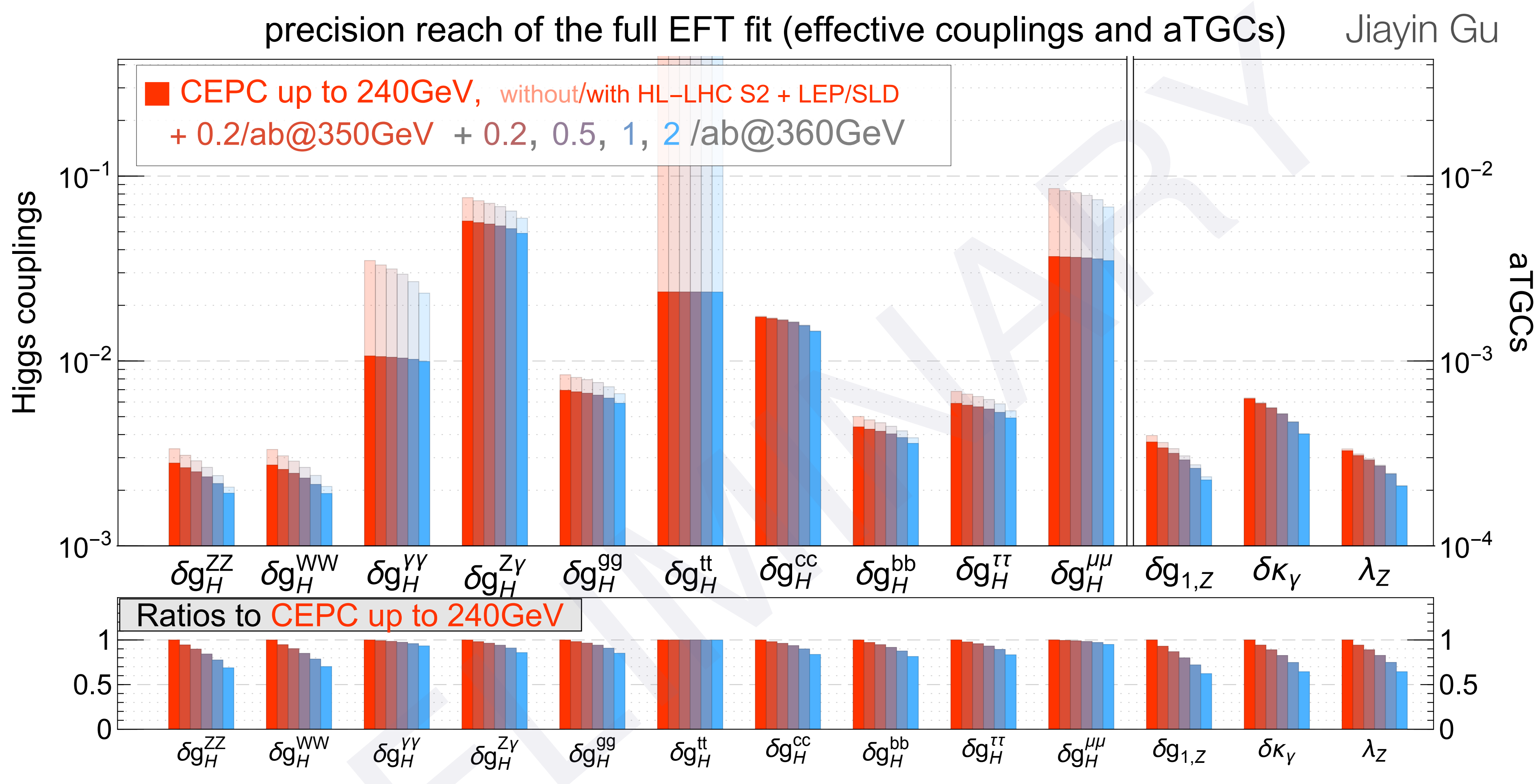
Better sensitivities to these running at the ttbar energies

Better sensitivities at ttbar



Probed by $e^+ e^- \to Z^* \to tt$

Better at higher energies



Gain up to a factor of a few

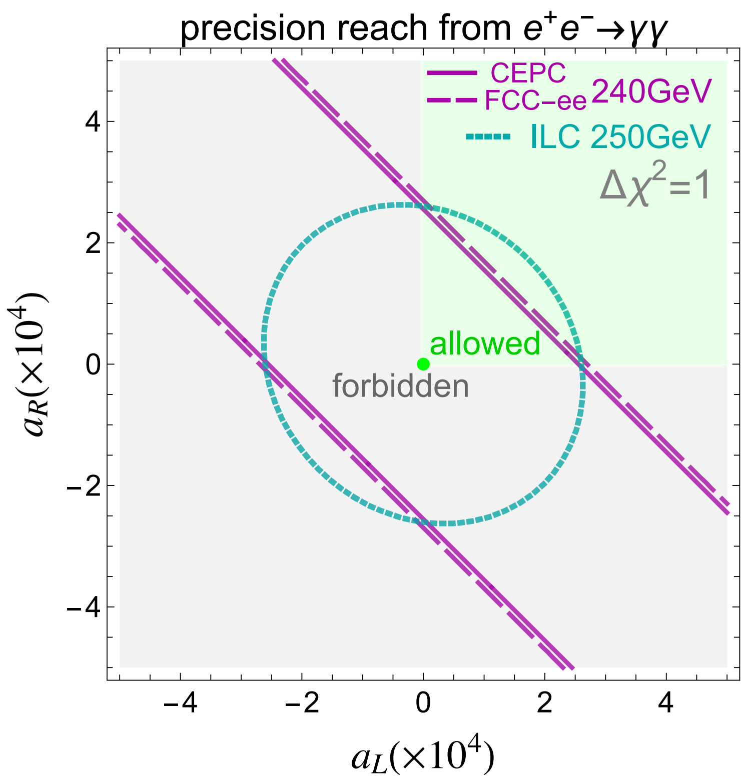
Even better if one can run at even higher energies.

Checking the foundation

- Testing quantum mechanics, relativity, locality…

$$\sigma(e^+e^- \to \gamma\gamma) \geq \sigma_{\rm SM}(e^+e^- \to \gamma\gamma)$$

An unambiguous prediction following from basic rules of quantum field theory

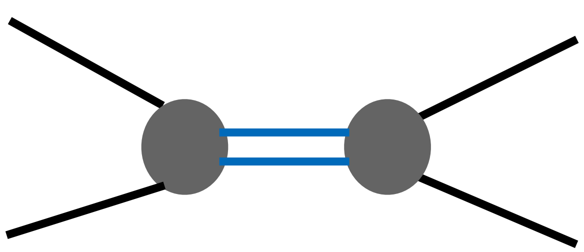


J. Gu, C. Zhang and LTW, 2011.03055

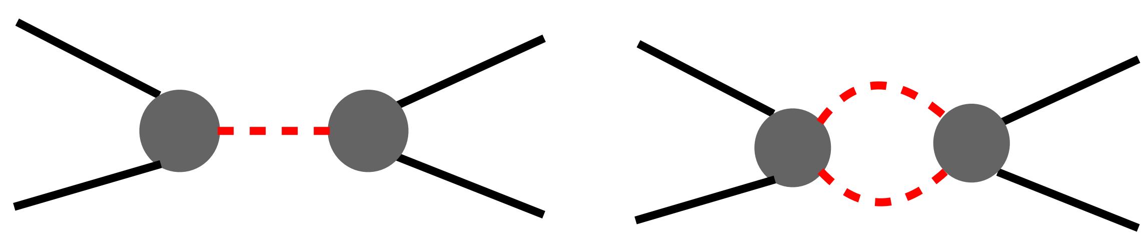
EFT and beyond

- Effective field theory has been widely used to characterize new physics effects.
- There could be important exceptions.

New physics effects beyond the simple EFT parameterization



Strongly coupled, continuum



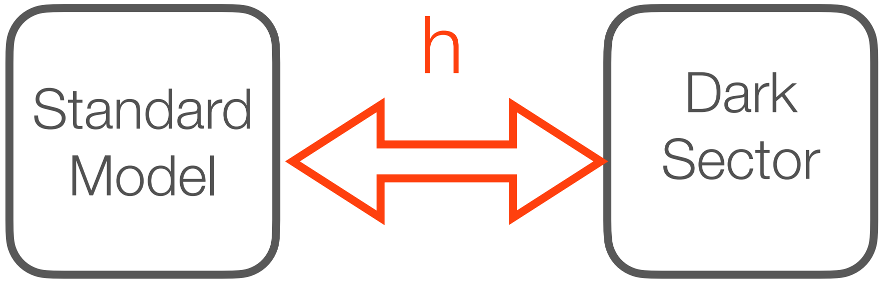
Light new physics

It would useful to look at several benchmark scenarios.

My talk

- Precision measurements: Higgs and beyond
- Gateway to new physics
    - A possible new physics scenario

Higgs portal



- Dark sector coupling to the SM

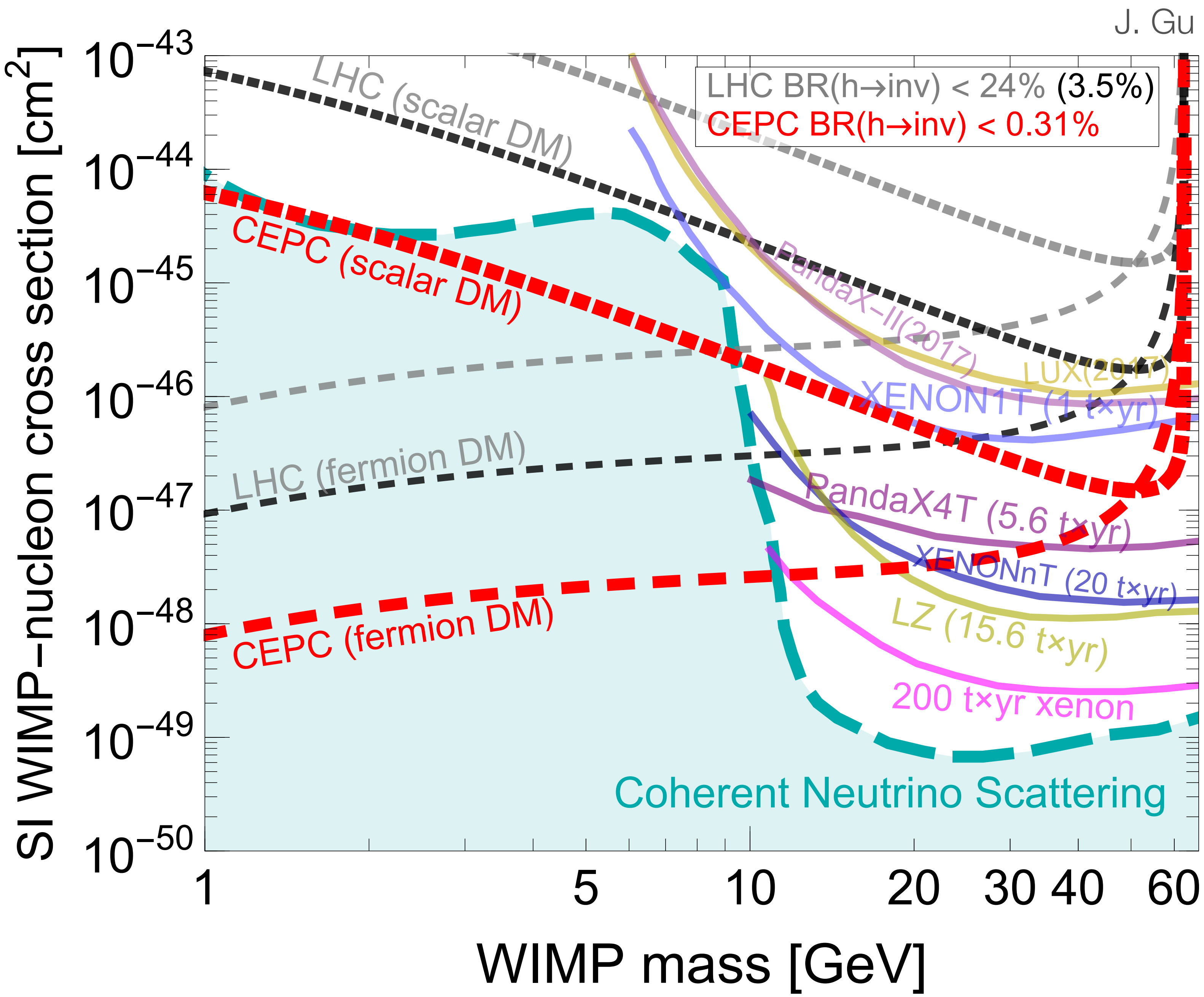
$$\mathcal{O}_{\mathrm{SM}} \cdot \mathcal{O}_{\mathrm{dark}}$$

$\mathcal{O}_{\mathrm{SM}}$: gauge inv. SM operator $\mathcal{O}_{\mathrm{dark}}$: dark sector operator

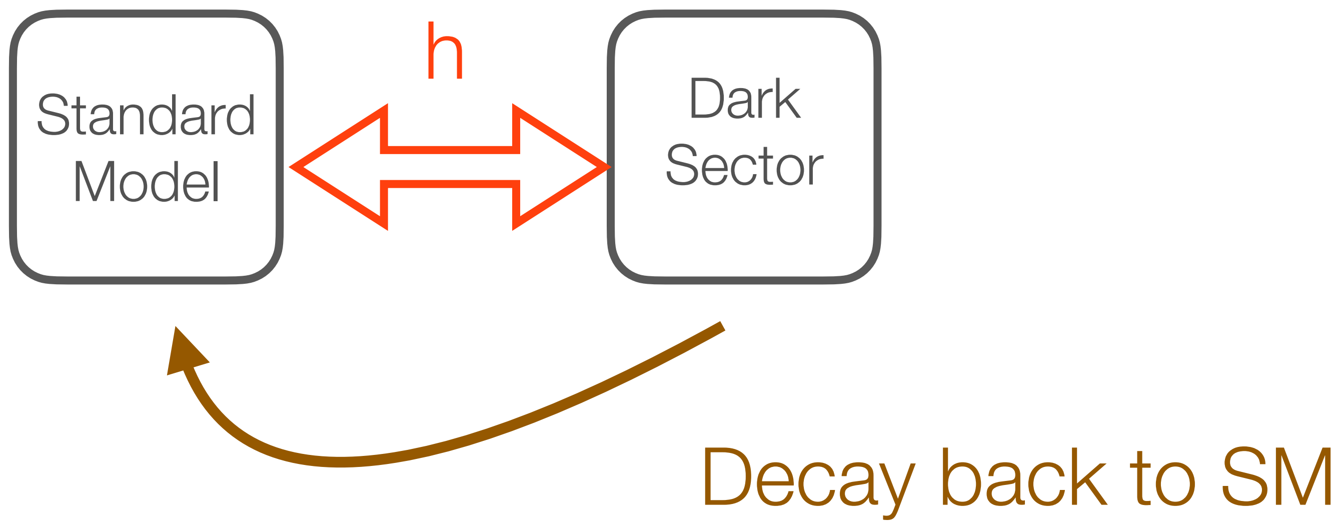
- More relevant coupling ⇔ lowest dim operator
  - Unique choice: $O_{SM} = HH^{\dagger}$. Higgs portal.

Higgs portal dark matter

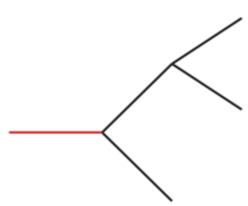
$$\mathcal{O} = H^\dagger H X_{\rm dm} X_{\rm dm} \quad \Rightarrow \quad h \to X_{\rm dm} X_{\rm dm}$$



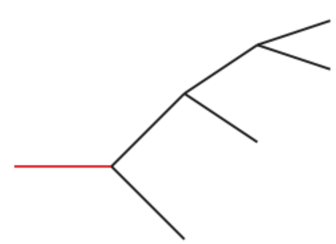
Higgs rare decay



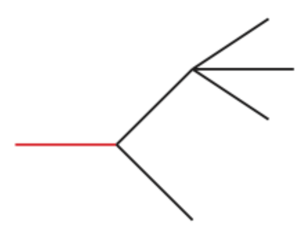
$h \to 2 \to 3$



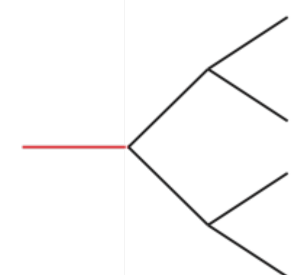
$h \to 2 \to 3 \to 4$



$h \to 2 \to (1 + 3)$



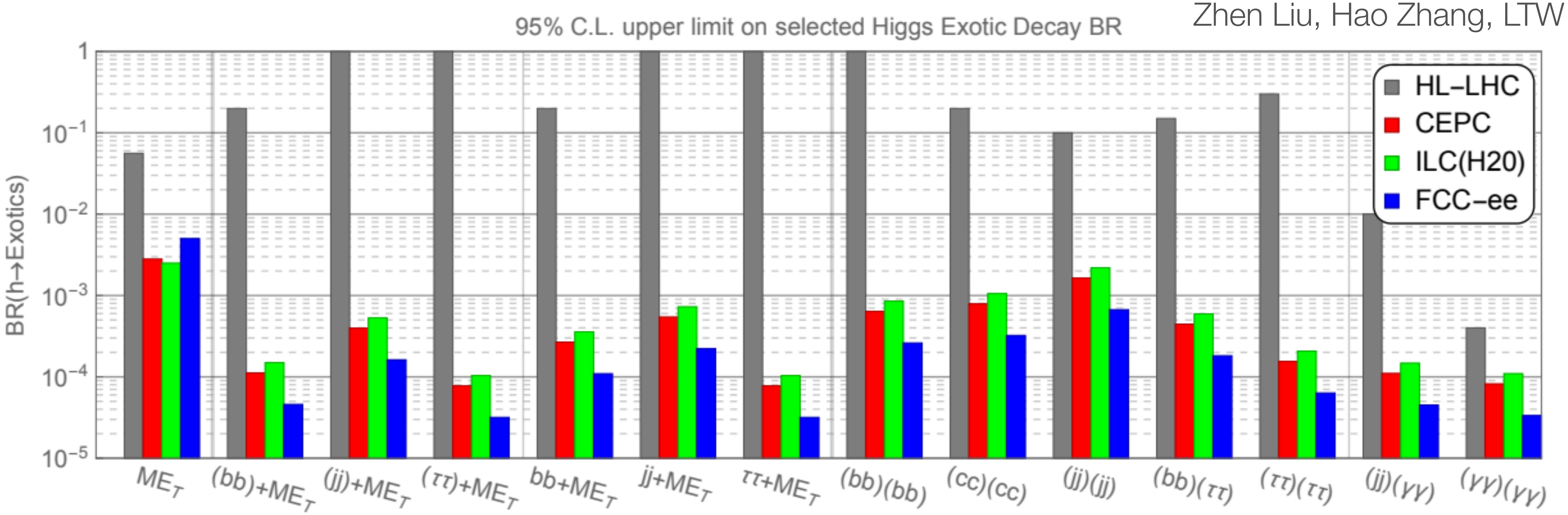
$h \to 2 \to 4$



....

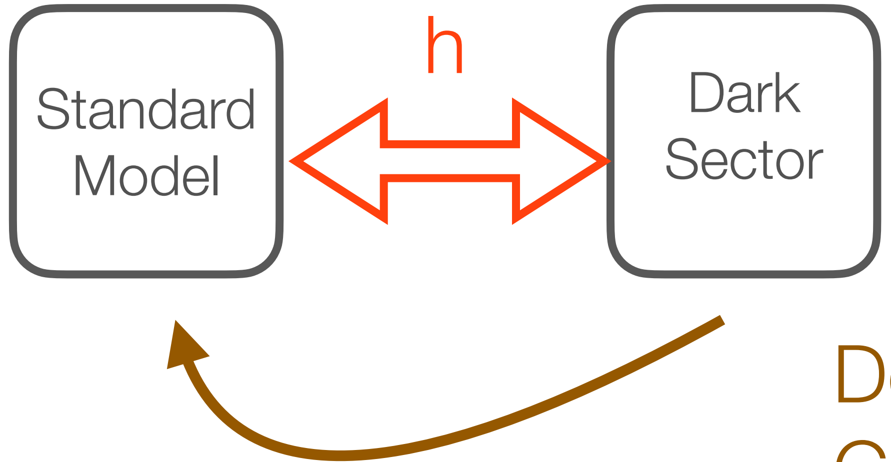
Higgs exotic decay

Zhen Liu, Hao Zhang, LTW

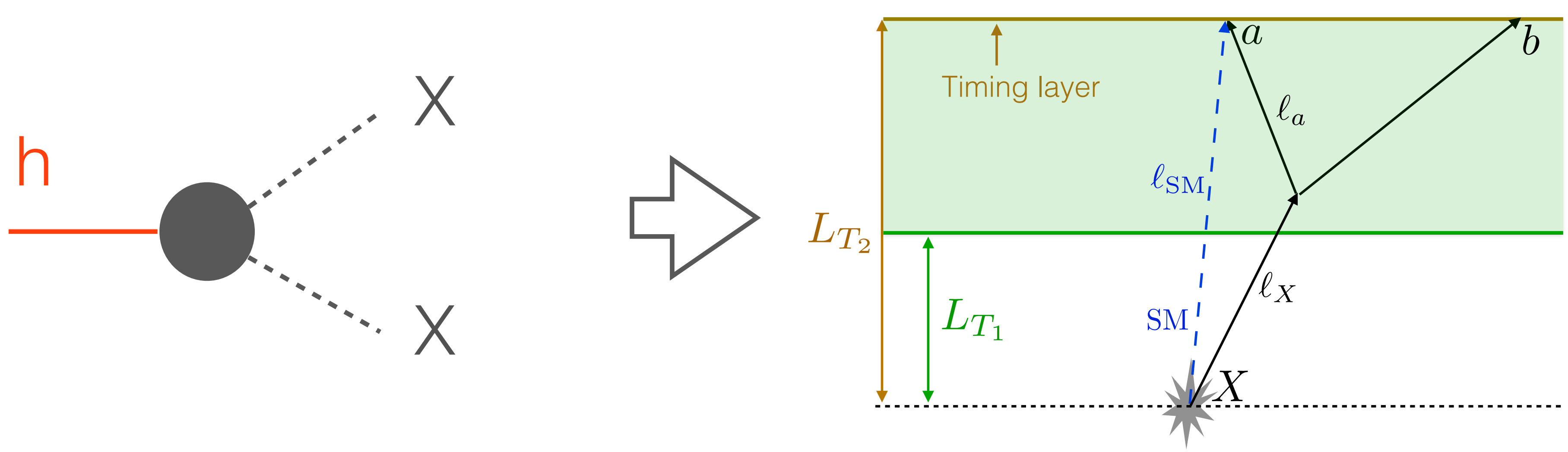


Complementary to hadron collider searches

Long lived particle?

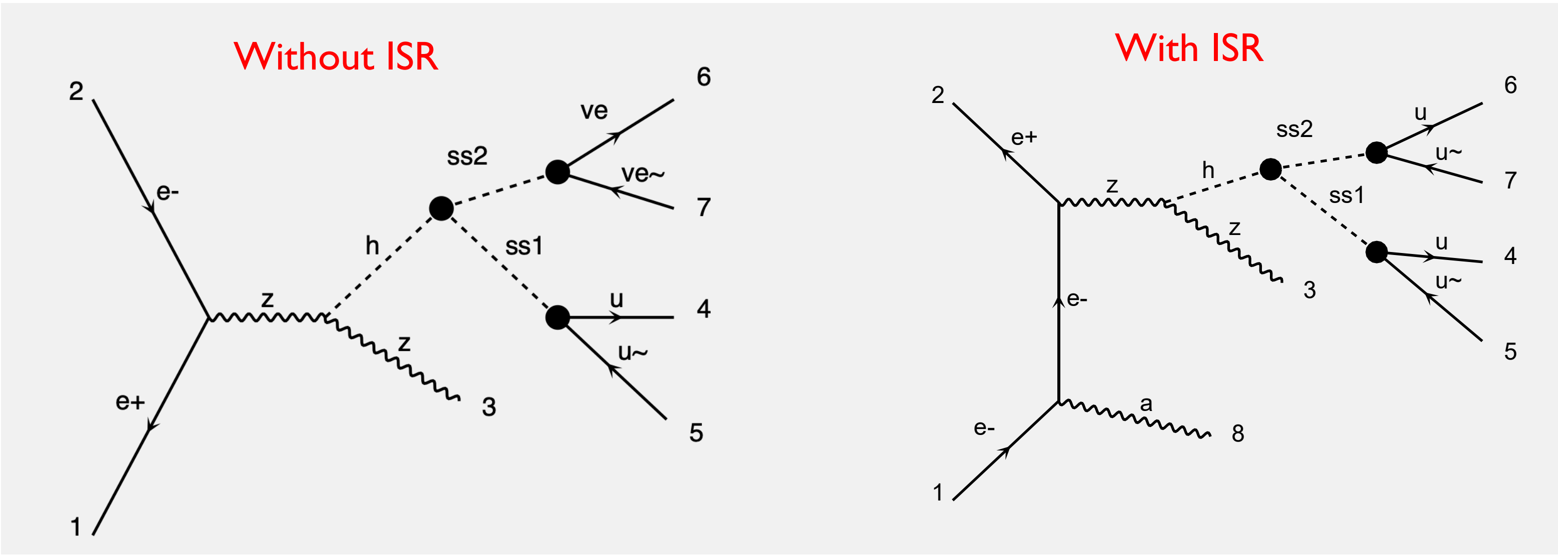


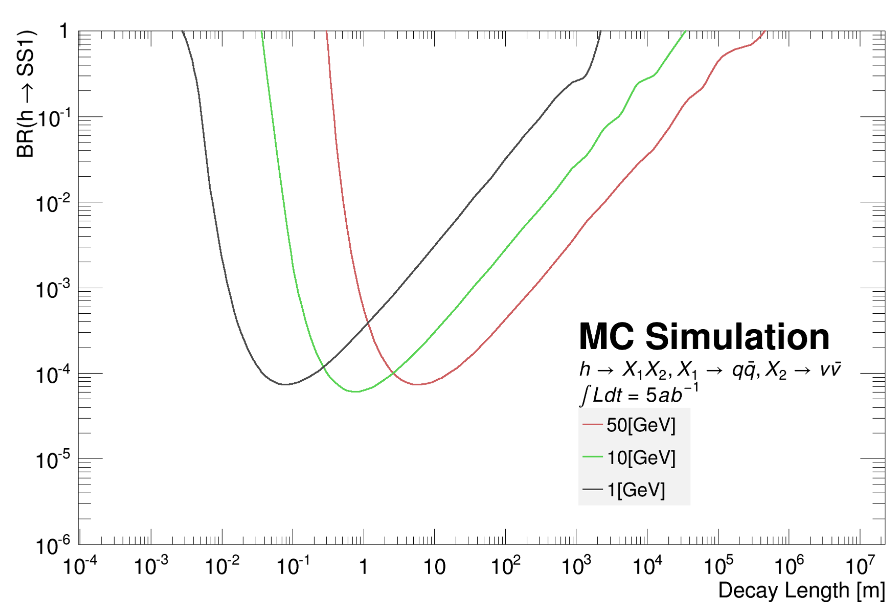
Decay back to SM
Can be long lived.
cτ can be 1 km or more

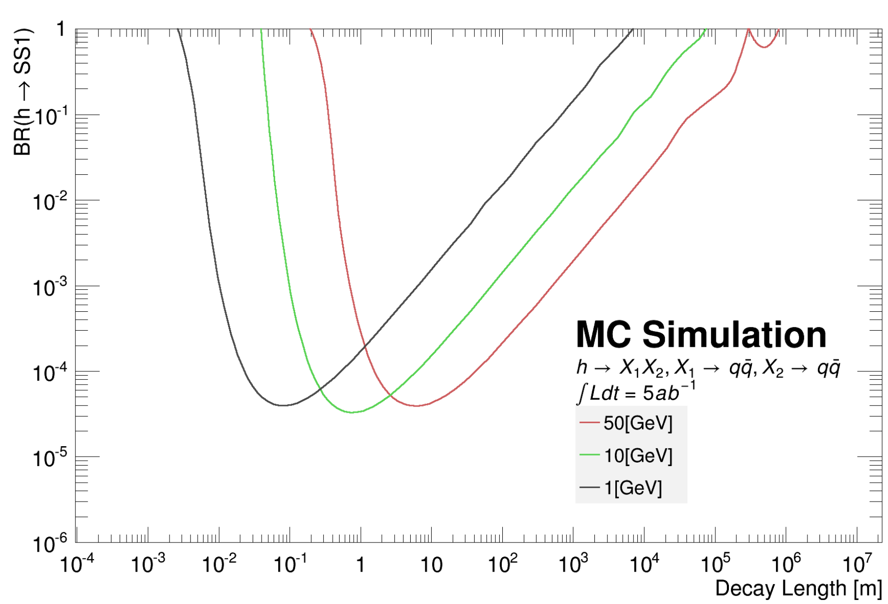


A recent study for CEPC

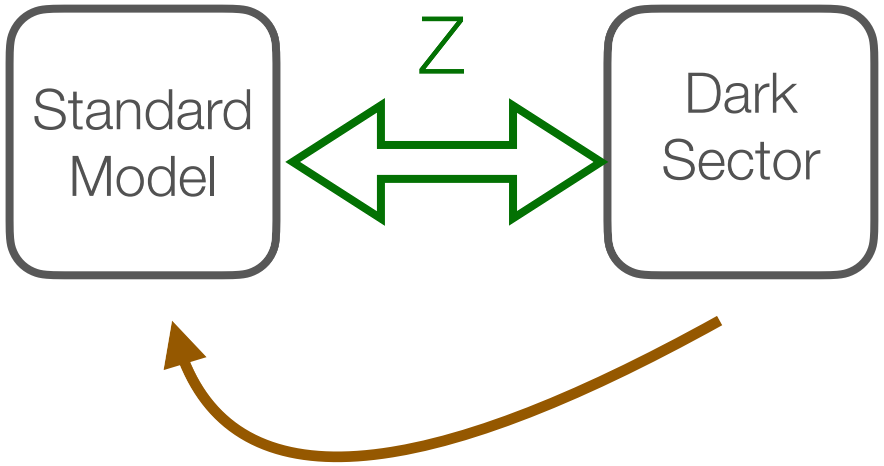
Yuelei Zhang, Xiang Chen, Jifeng Hu, Liang Li







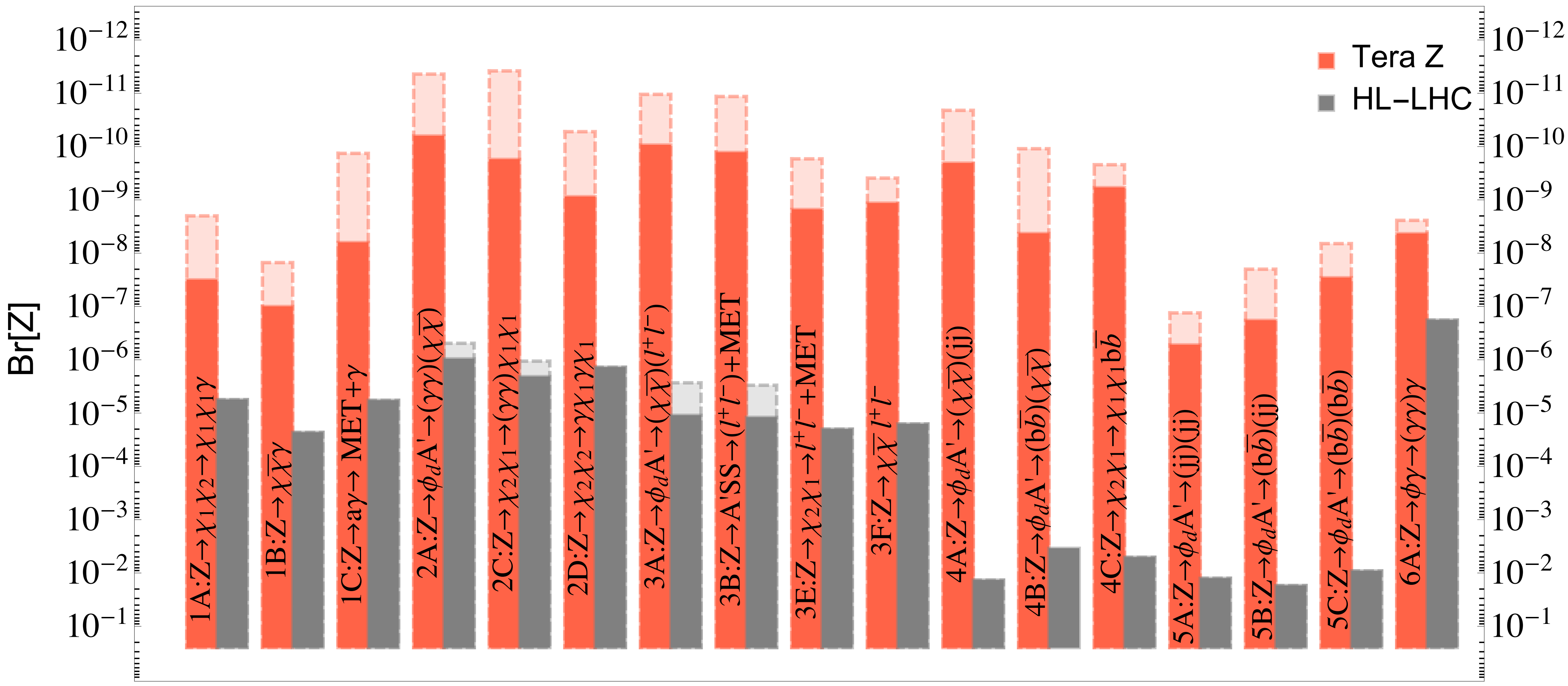
Z decay



- 10^{12} Zs at the CEPC goes a long way in probing the dark sector.

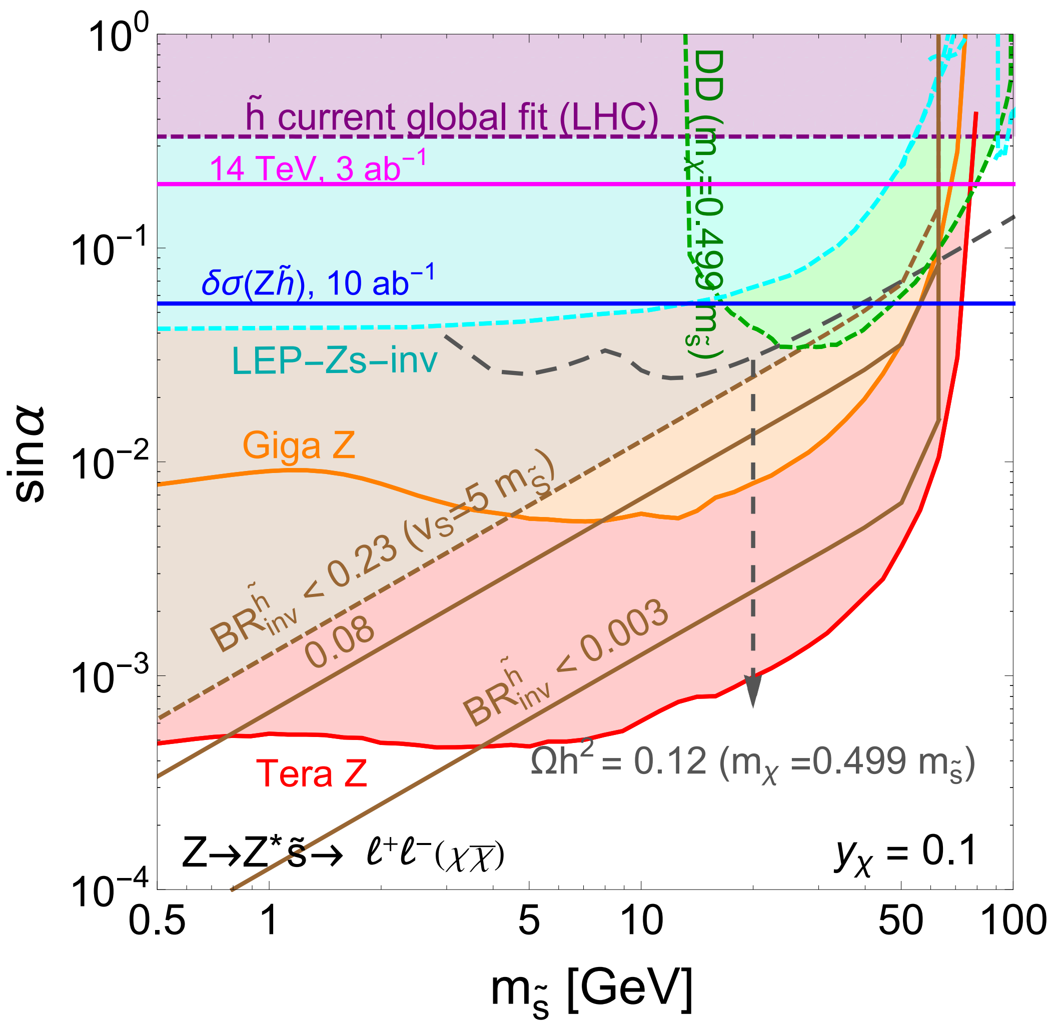
Rare Z decay

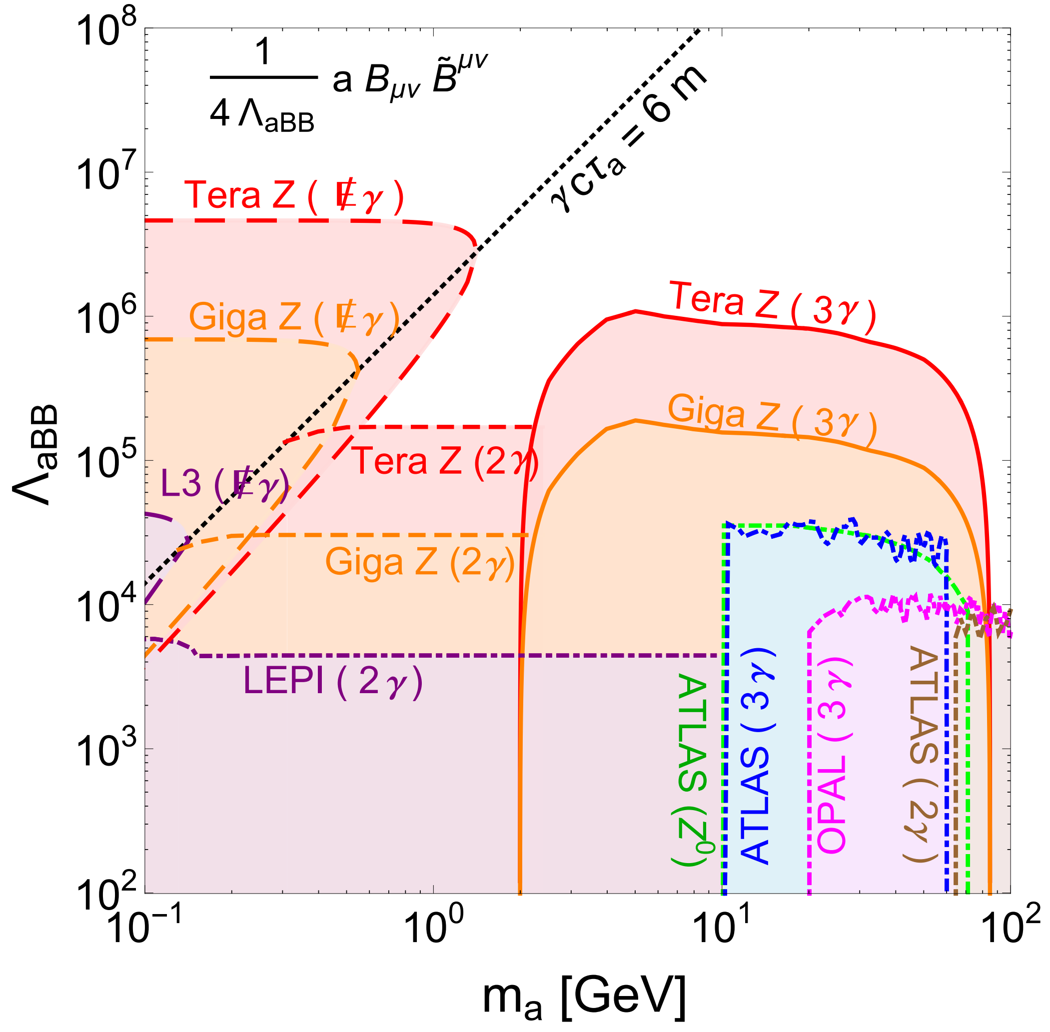
J. Liu, X.P. Wang, W. Xue, LTW



Window into dark sector

J. Liu, X.P. Wang, W. Xue, LTW





There are certainly many more scenarios to explore here.

B, charm, hadron, τ

Particle production

Particle	@ Tera-Z	@ Belle II		@ LHCb
***b* hadrons**				
B^+	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B^0	6×10^{10}	3×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	3×10^{13}
B_s	2×10^{10}	3×10^{8}	$(5\,\mathrm{ab}^{-1}$ on $\Upsilon(5S))$	8×10^{12}
b baryons	1×10^{10}			1×10^{13}
Λ_b	1×10^{10}			1×10^{13}
***c* hadrons**				
D^0	2×10^{11}			
D^+	6×10^{10}			
D_s^+	3×10^{10}			
Λ_c^+	2×10^{10}			
τ^+	3×10^{10}	5×10^{10}	$(50\,\mathrm{ab}^{-1}$ on $\Upsilon(4S))$	

From CEPC's CDR using fragmentation ratios from Amhis et al, 17

- Similar statistical sample of $B^{0,\pm}$, τ's at Belle 2 and CEPC
- Two order of magnitude more B_s at CEPC wrt to Belle 2
- b-baryon physics possible at the CEPC
- Limited possibilities for charm physics at Belle 2

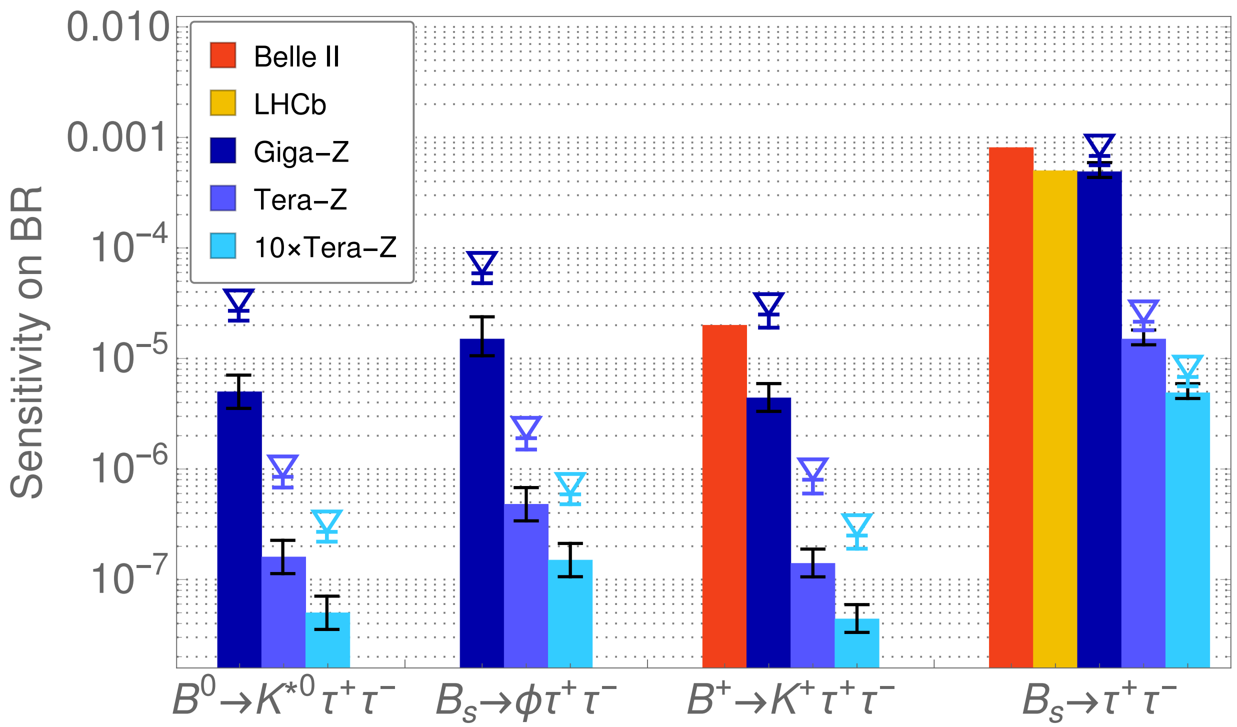
Great place to probe rare flavor processes!

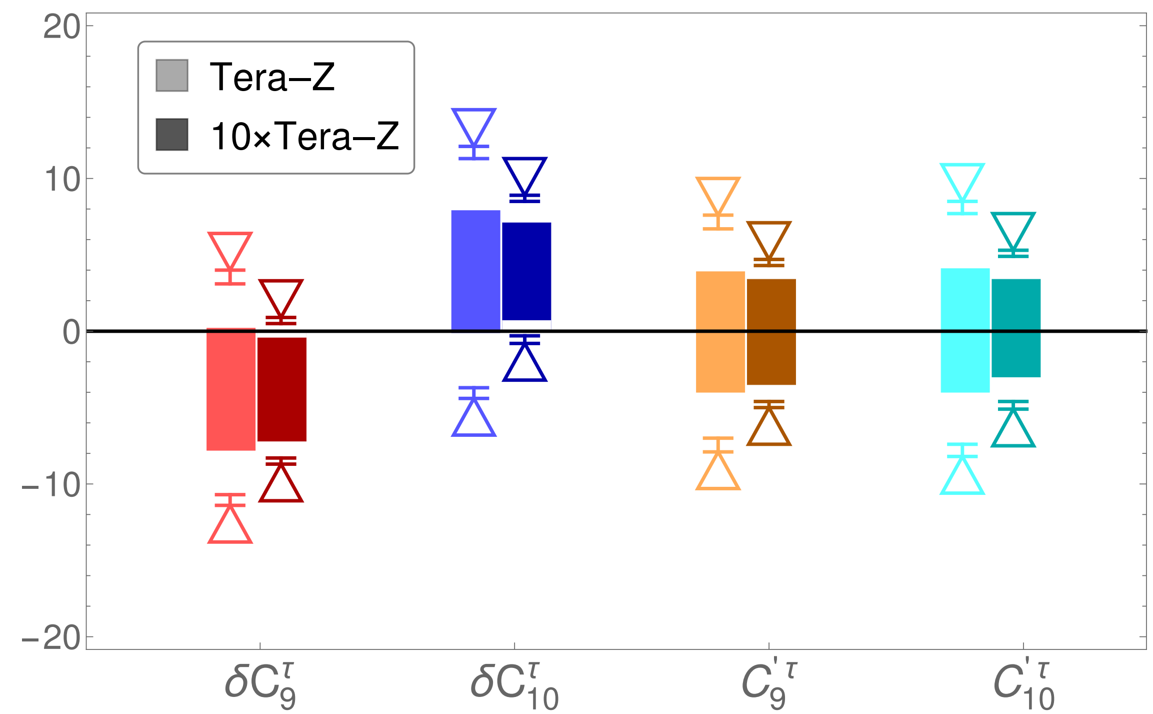
Naive estimates:

Observable	Current sensitivity	Future sensitivity	Tera-Z sensitivity
$\mathrm{BR}(B_s \to ee)$	2.8×10^{-7} (CDF) [10]	$\sim 7 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \mu\mu)$	0.7×10^{-9} (LHCb) [8]	$\sim 1.6 \times 10^{-10}$ (LHCb) [18]	$\sim$ few $\times 10^{-10}$
$\mathrm{BR}(B_s \to \tau\tau)$	5.2×10^{-3} (LHCb) [9]	$\sim 5 \times 10^{-4}$ (LHCb) [18]	$\sim 10^{-5}$
R_K, R_{K^*}	$\sim 10\%$ (LHCb) [5, 4]	$\sim$few% (LHCb/Belle II) [18, 40]	$\sim$few %
$\mathrm{BR}(B \to K^* \tau\tau)$	–	$\sim 10^{-5}$ (Belle II) [40]	$\sim 10^{-8}$
$\mathrm{BR}(B \to K^* \nu\nu)$	4.0×10^{-5} (Belle) [44]	$\sim 10^{-6}$ (Belle II) [40]	$\sim 10^{-6}$
$\mathrm{BR}(B_s \to \phi\nu\bar{\nu})$	1.0×10^{-3} (LEP) [15]	–	$\sim 10^{-6}$
$\mathrm{BR}(\Lambda_b \to \Lambda\nu\bar{\nu})$	–	–	$\sim 10^{-6}$
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BaBar) [24]	$\sim 10^{-9}$ (Belle II) [40]	$\sim 10^{-9}$
$\mathrm{BR}(\tau \to 3\mu)$	2.1×10^{-8} (Belle) [37]	$\sim$ few $\times 10^{-10}$ (Belle II) [40]	$\sim$ few $\times 10^{-10}$
$\frac{\mathrm{BR}(\tau\to\mu\nu\bar{\nu})}{\mathrm{BR}(\tau\to e\nu\bar{\nu})}$	3.9×10^{-3} (BaBar) [23]	$\sim 10^{-3}$ (Belle II) [40]	$\sim 10^{-4}$
$\mathrm{BR}(Z \to \mu e)$	7.5×10^{-7} (ATLAS) [3]	$\sim 10^{-8}$ (ATLAS/CMS)	$\sim 10^{-9} - 10^{-11}$
$\mathrm{BR}(Z \to \tau e)$	9.8×10^{-6} (LEP) [17]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-11}$
$\mathrm{BR}(Z \to \tau\mu)$	1.2×10^{-5} (LEP) [13]	$\sim 10^{-6}$ (ATLAS/CMS)	$\sim 10^{-8} - 10^{-10}$

Lepton universality

Lingfeng Li, Tao Liu, 2012.00665



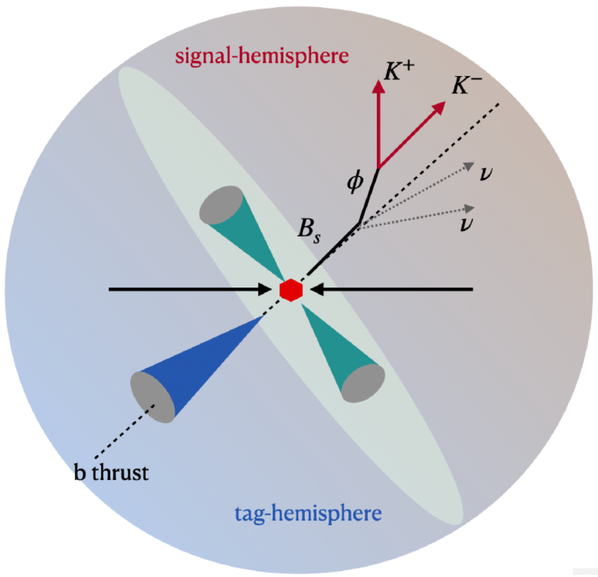


Intriguing connection with some recently anomalies, such as R_D.

Another important channel

$$B_s \to \phi\nu\nu$$

	Experimental	SM Prediction
$\text{BR}(B^0 \to K^0\nu\bar{\nu})$	$< 2.6 \times 10^{-5}$	$(2.17 \pm 0.30) \times 10^{-6}$
$\text{BR}(B^0 \to K^{*0}\nu\bar{\nu})$	$< 1.8 \times 10^{-5}$	$(9.48 \pm 1.10) \times 10^{-6}$
$\text{BR}(B^\pm \to K^\pm\nu\bar{\nu})$	$< 1.6 \times 10^{-5}$	$(4.68 \pm 0.64) \times 10^{-6}$
$\text{BR}(B^\pm \to K^{*\pm}\nu\bar{\nu})$	$< 4.0 \times 10^{-5}$	$(10.22 \pm 1.19) \times 10^{-6}$
$\text{BR}(B_s \to \phi\nu\bar{\nu})$	$< 5.4 \times 10^{-3}$	$(11.84 \pm 0.19) \times 10^{-6}$



Full sim based study in progress

The preliminary cut chain

	N_S	N_B	S/sqrt(B)	sqrt(S+B)/S
Total	180000	1.5e+11	0.46	2.15
$N_\phi > 0$	6.78e4	4.82e+09	0.98	1.02
$E_l < 1$ GeV	5.55e4	2.05e9	1.22	0.82
$E^{ISO}_{Neutral} < 2.7$ GeV	4.59e4	6.91e8	1.75	0.57
$E^{ISO}_{track} < 4$ GeV	4.25e4	4.17e8	2.08	0.48
$\alpha < 0.8$	1.71e4	5.77e+5	22.52	0.045
Efficiency	0.095	3.85e-06		

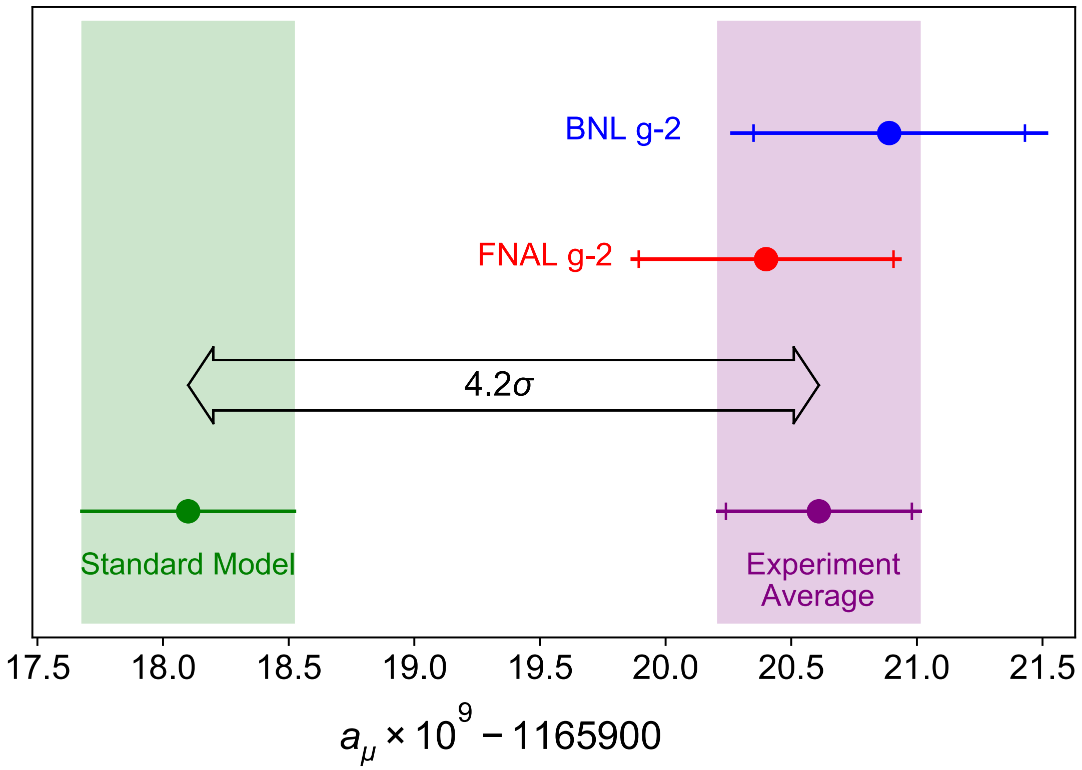
Yudong Wang, Lingfeng Li, Manqi Ruan, Yanyun Duan, Tao Liu, Taifan Zheng

My talk

- Precision measurements: Higgs and beyond
- Gateway to new physics
  - A possible new physics scenario

IF:

Muon g-2



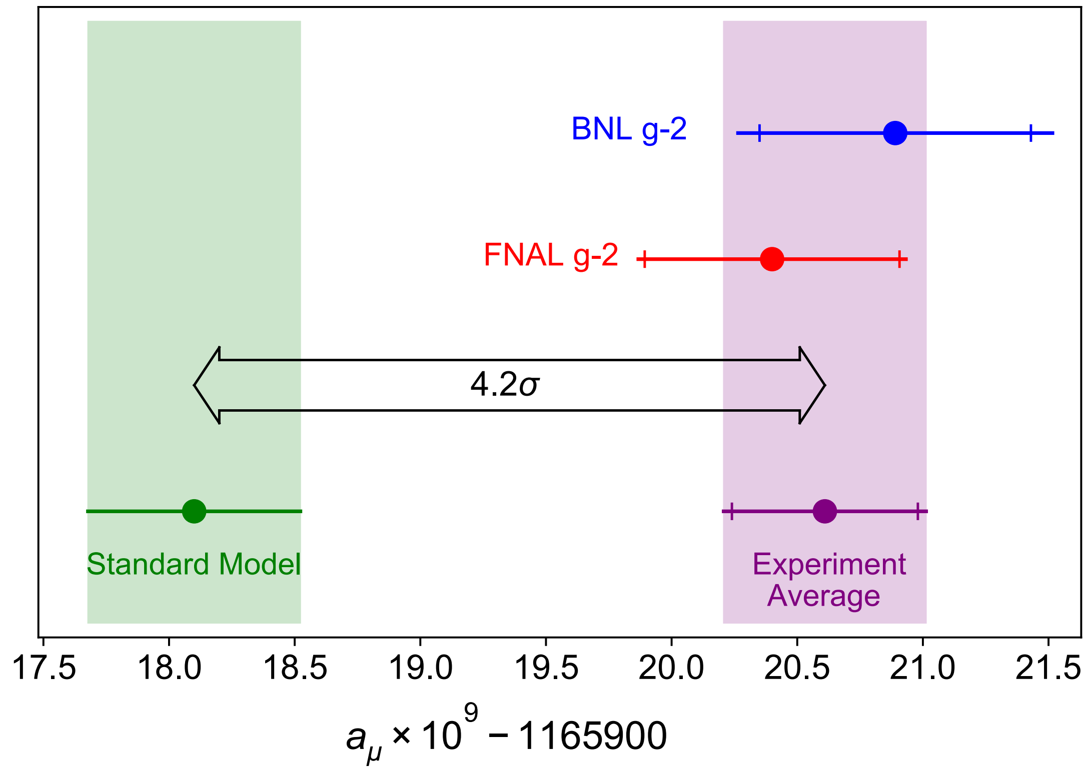
$$\mathscr{L} \supset \frac{e}{16\pi^2}\frac{m_\mu}{M_{\rm NP}^2} H\bar{L}\sigma_{\mu\nu}\mu_R F^{\mu\nu} \;\rightarrow\; \delta a_\mu \simeq \frac{e}{16\pi^2}\frac{m_\mu^2}{M_{\rm NP}^2}$$

Disagreement with SM ⇒ (1-loop) $M_{\rm NP} \sim 300$ GeV.

Or, with 2-loop contribution, $M_{\rm NP} \sim 30$ GeV.

IF:

Muon g-2



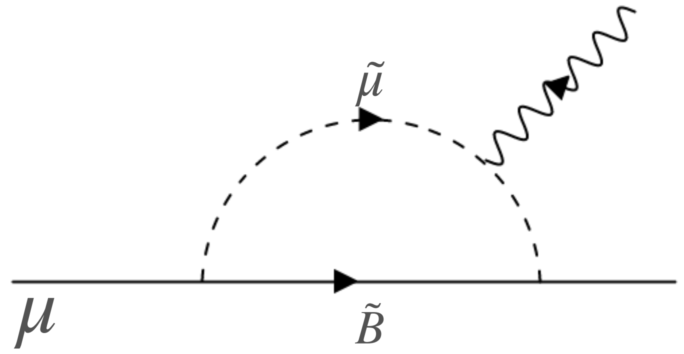
$$\mathscr{L} \supset \frac{e}{16\pi^2}\frac{m_\mu}{M_{\rm NP}^2} H\bar{L}\sigma_{\mu\nu}\mu_R F^{\mu\nu} \;\rightarrow\; \delta a_\mu \simeq \frac{e}{16\pi^2}\frac{m_\mu^2}{M_{\rm NP}^2}$$

Disagreement with SM ⇒ (1-loop) $M_{NP} \sim 300$ GeV.

Or, with 2-loop contribution, $M_{NP} \sim 30$ GeV.

A suite of sensitive searches and measurement at CEPC

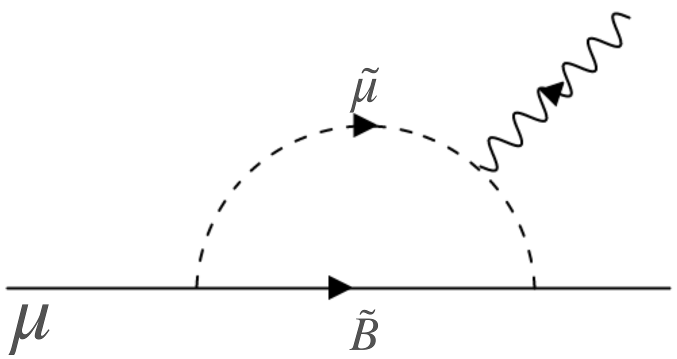
NP at 1-loop



$$m_{\tilde{\mu}} \sim m_{\tilde{B}} \sim 100 - 500 \text{ GeV}$$

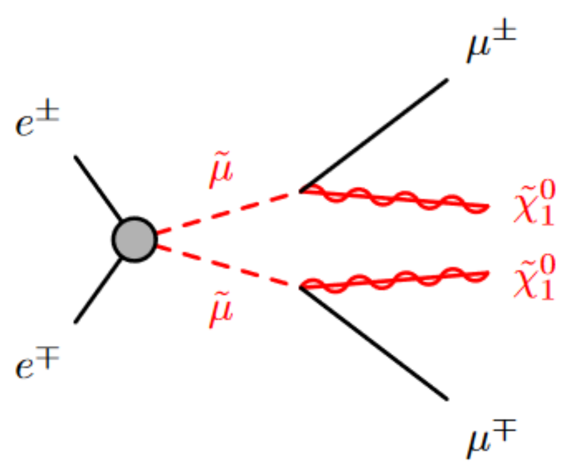
Probably within the LHC reach

NP at 1-loop

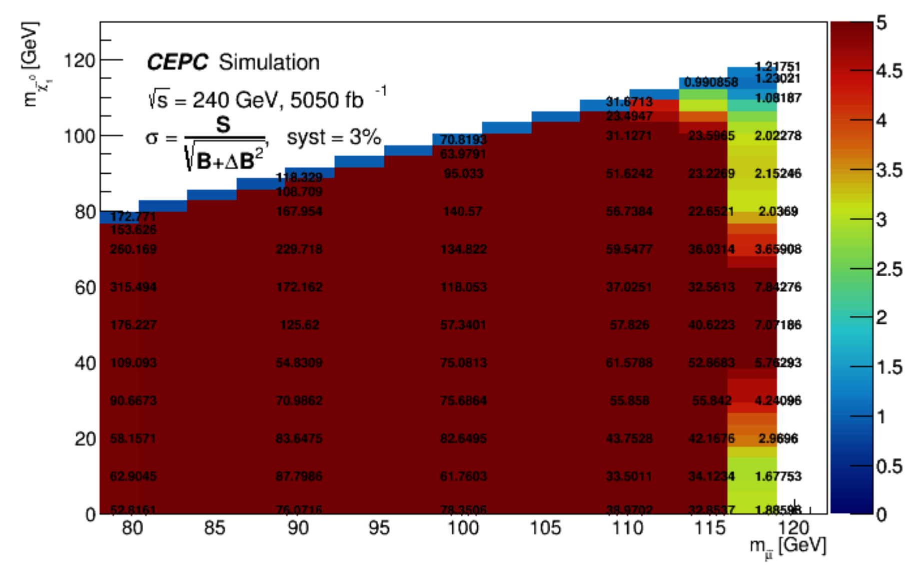


$$m_{\tilde{\mu}} \sim m_{\tilde{B}} \sim 100 - 500\ \text{GeV}$$

Probably within the LHC reach

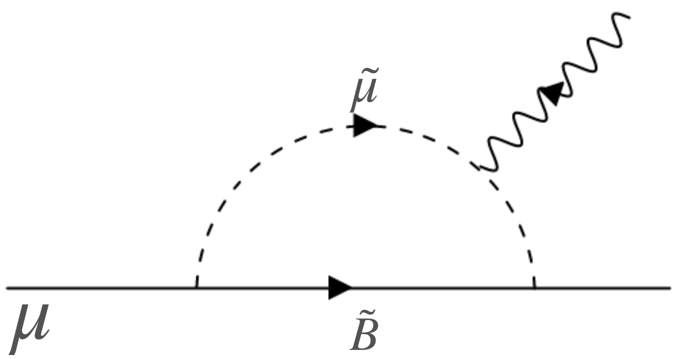


From Jiarong Yuan's slide



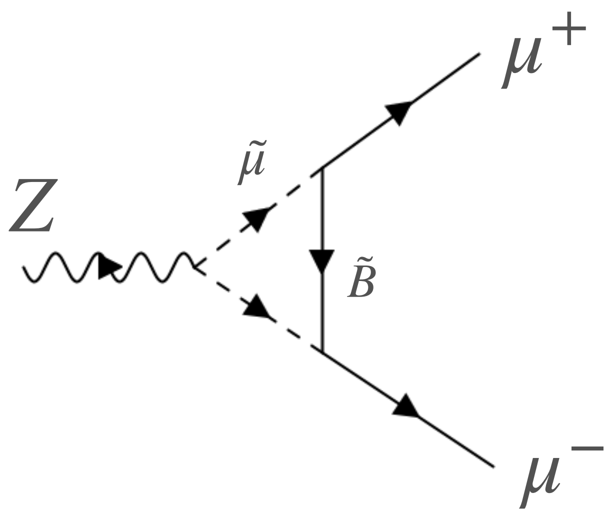
Direct search limited by E_{CM} (extra motivation for ttbar) .

NP at 1-loop



$m_{\tilde{\mu}} \sim m_{\tilde{B}} \sim 100 - 500$ GeV

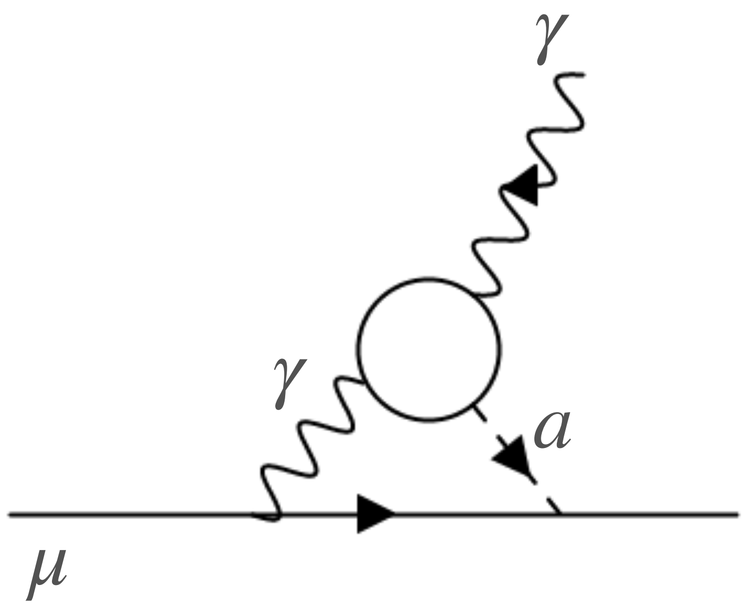
Probably within the LHC reach



$$\frac{\delta\Gamma_\mu}{\Gamma_\mu} \sim 10^{-4} - 10^{-5}$$

Precision Z-decay measurement could provide complementary information.

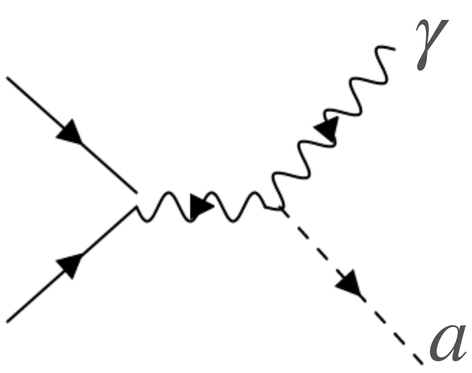
2-loop

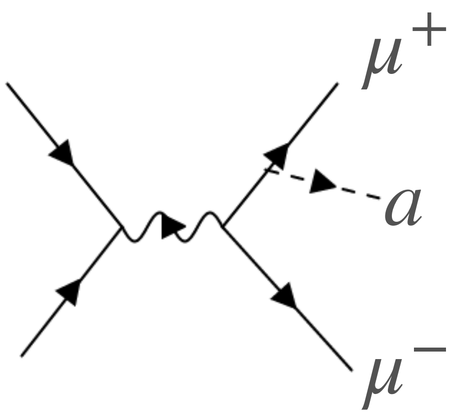


a : axion-like particle, pseudo-scalar Higgs, …

$m_a < 100$ GeV

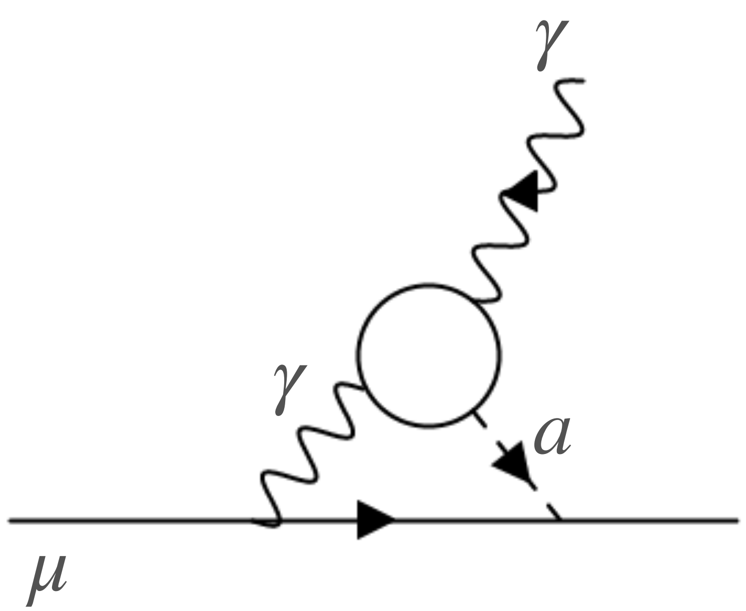
LHC discovery difficult.





Tiny rate, large background

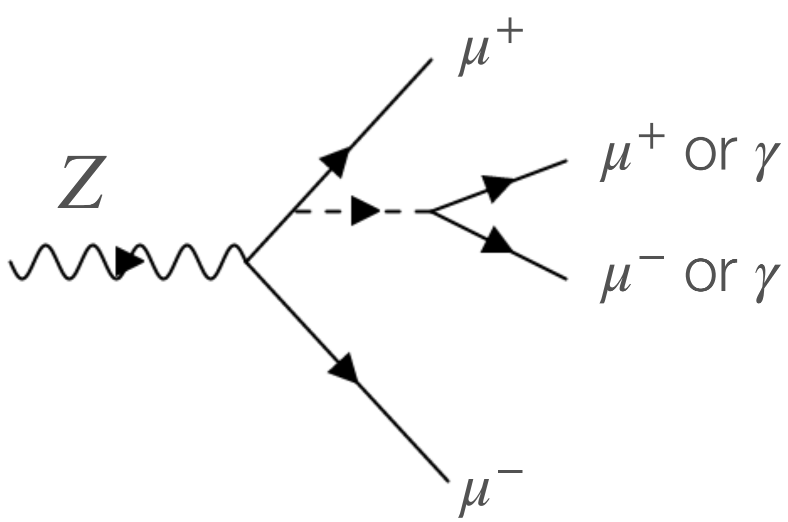
2-loop



a : axion-like particle, pseudo-scalar Higgs, …

$m_a < 100$ GeV

CEPC:



BR($Z \to 4\mu$ or $2\mu 2\gamma$) $\sim 10^{-7}$

Within the reach of Tera Z.

Pseudo scalar Higgs constrained by EW precision tests, flavor physics at CEPC

Conclusions

- The main physics goal: precision measurement of Higgs.
  - Well documented in the CDR.
  - Refinement underway.
- Physics potential in new physics searches still has many open topics.
  - Great opportunities to make progresses.

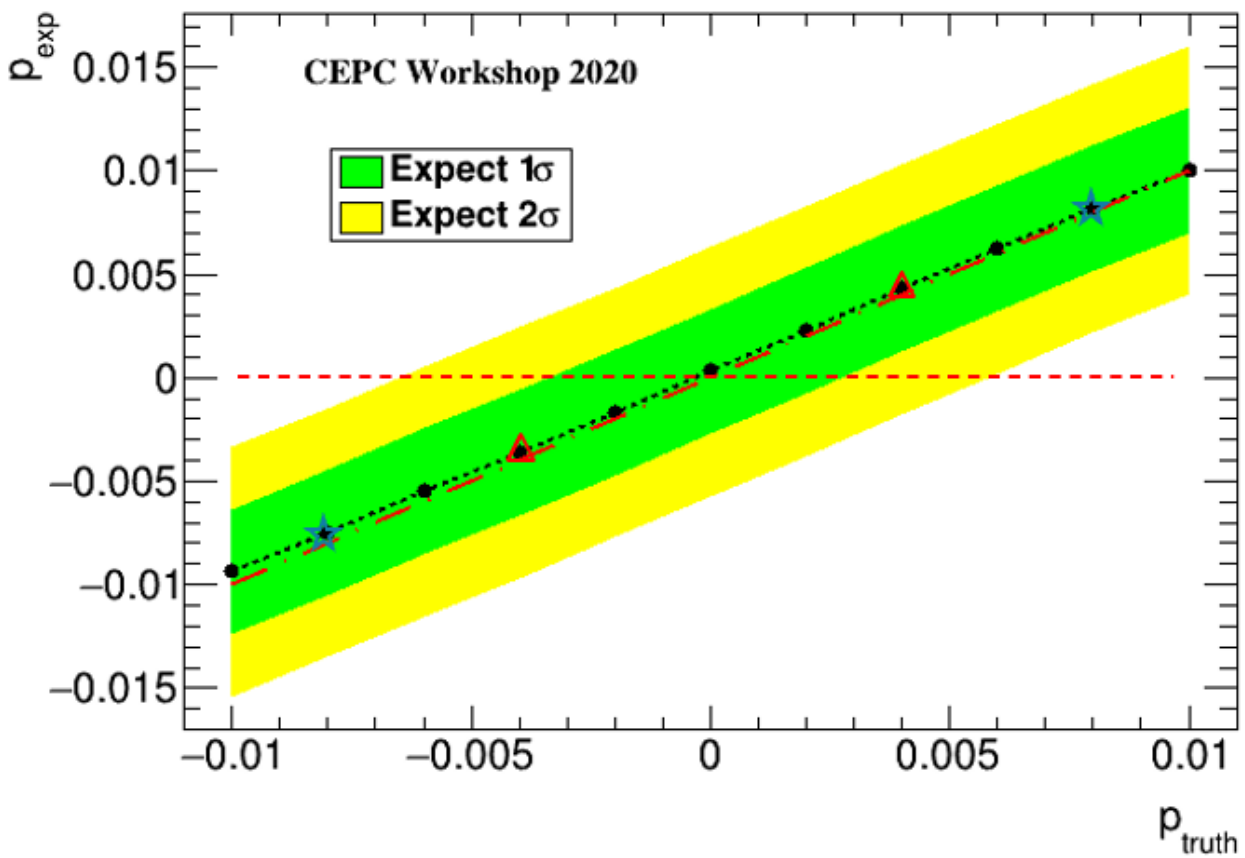
CP of Higgs

Yaquan Fang, Gangyi Guo, Gang Li, Qiyu Sha, Xinchou Lou

See Ke Li and Qiyu Sha's talk for details.

Another fundamental property of the Higgs which is not completely nailed.

For other CP-mixing p hypothesis, a similar result could be derived with ω



△ 1σ exceed beyond SM

☆ 2σ exceed beyond SM

A bit shift in input truth p and measured p. Needs some further understanding.

Slides from Qiyu Sha

Higgs portal

$$\lambda O_{\rm SM} \cdot O_{\rm dark} \rightarrow \left(\lambda \frac{m_W}{g}\right) h \cdot O_{\rm dark}$$

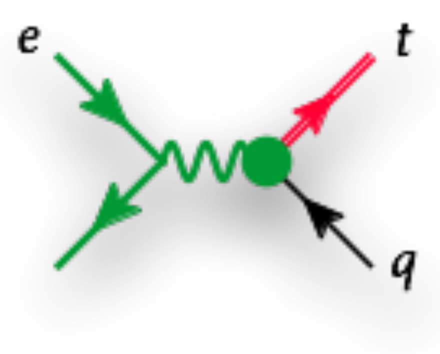
- Producing dark sector particles through the Higgs portal.
- Higgs rare decays:
  - Higgs → invisible at LHC can constrain down to a few percent.
  - A lot of room for exotic decay:

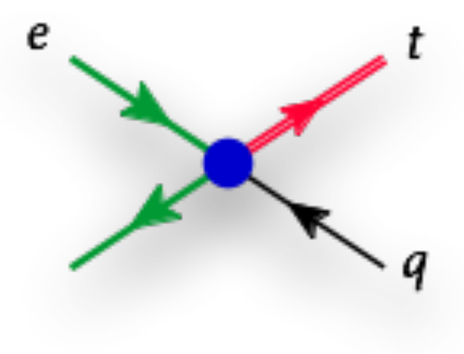
$$O_{\rm dark} = \bar{\psi}_{\rm dark}\psi_{\rm dark}, \quad \lambda = \frac{1}{\Lambda}$$

$$\Lambda \sim 10 \ \text{TeV} \ \rightarrow \ \text{BR}(h \rightarrow \bar{\psi}_{\rm dark}\psi_{\rm dark}) \leq 10^{-2}$$

Higgs-top couplings: FCNC

Cen Zhang

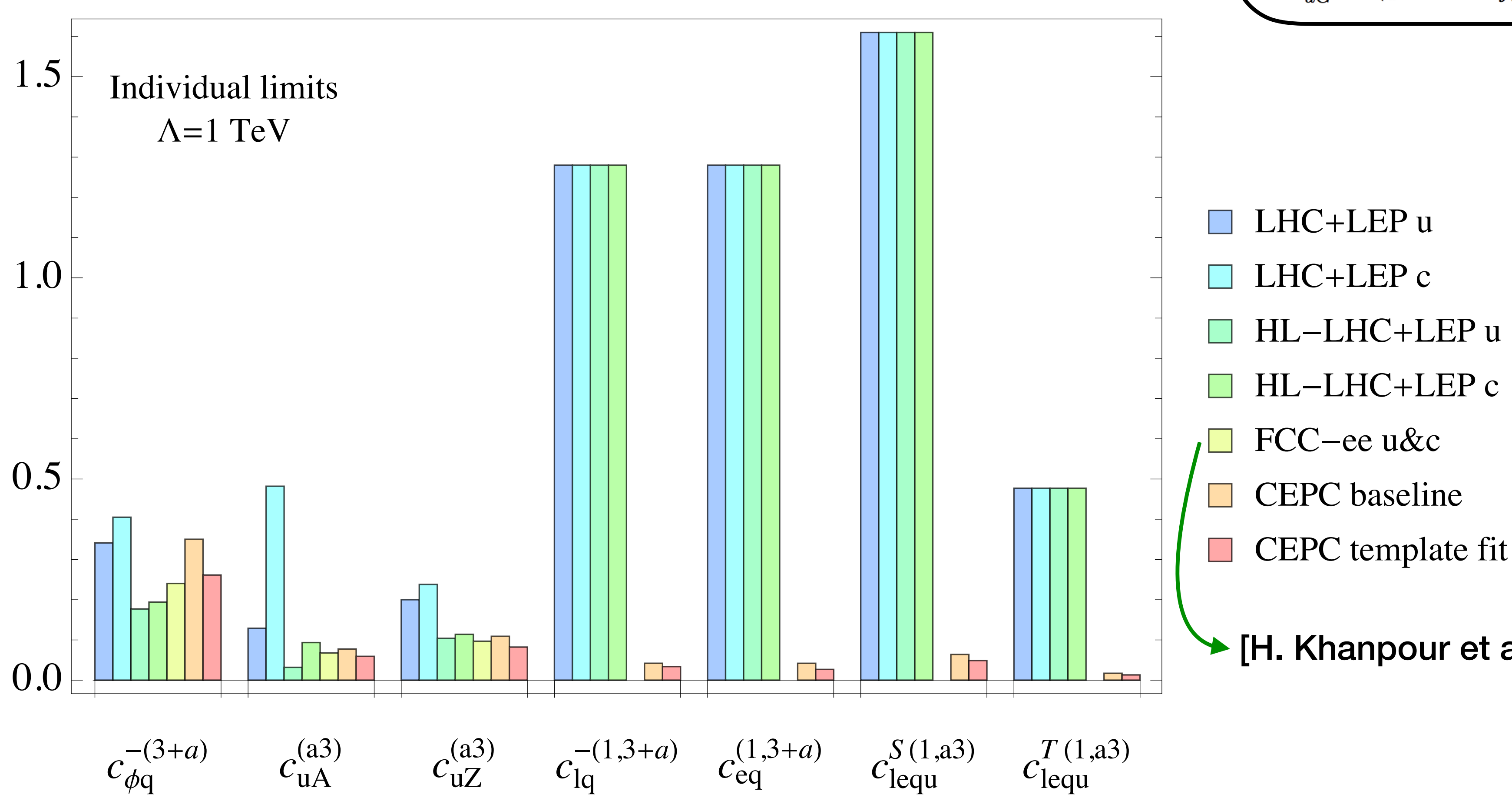




Warsaw basis operators

[B. Grzadkowski et al. 10]

$$O_{u\varphi}^{(ij)} = \bar{q}_i u_j \tilde{H}\,(H^\dagger H),$$
$$O_{\varphi q}^{1(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_i \gamma^\mu q_j),$$
$$O_{\varphi q}^{3(ij)} = (H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_i \gamma^\mu \tau^I q_j),$$
$$O_{\varphi u}^{(ij)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_i \gamma^\mu u_j),$$
$$O_{\varphi ud}^{(ij)} = (\tilde{H}^\dagger i D_\mu H)(\bar{u}_i \gamma^\mu d_j),$$
$$O_{uW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I u_j)\,\tilde{H} W^I_{\mu\nu}$$
$$O_{dW}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} \tau^I d_j)\,H W^I_{\mu\nu},$$
$$O_{uB}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} u_j)\tilde{H} B_{\mu\nu},$$
$$O_{uG}^{(ij)} = (\bar{q}_i \sigma^{\mu\nu} T^A u_j)\,\tilde{H} G^A_{\mu\nu}.$$
$$O_{lq}^{1(ijkl)} = (\bar{l}_i \gamma^\mu l_j)(\bar{q}_k \gamma^\mu q_l),$$
$$O_{lq}^{3(ijkl)} = (\bar{l}_i \gamma^\mu \tau^I l_j)(\bar{q}_k \gamma^\mu \tau^I q_l),$$
$$O_{lu}^{(ijkl)} = (\bar{l}_i \gamma^\mu l_j)(\bar{u}_k \gamma^\mu u_l),$$
$$O_{eq}^{(ijkl)} = (\bar{e}_i \gamma^\mu e_j)(\bar{q}_k \gamma^\mu q_l),$$
$$O_{eu}^{(ijkl)} = (\bar{e}_i \gamma^\mu e_j)(\bar{u}_k \gamma^\mu u_l),$$
$$O_{lequ}^{1(ijkl)} = (\bar{l}_i e_j)\;\varepsilon\;(\bar{q}_k u_l),$$
$$O_{lequ}^{3(ijkl)} = (\bar{l}_i \sigma^{\mu\nu} e_j)\;\varepsilon\;(\bar{q}_k \sigma_{\mu\nu} u_l),$$
$$O_{ledq}^{(ijkl)} = (\bar{l}_i e_j (\bar{d}_k q_l)(\bar{u}_k \gamma^\mu u_l),$$



[H. Khanpour et al. '14]

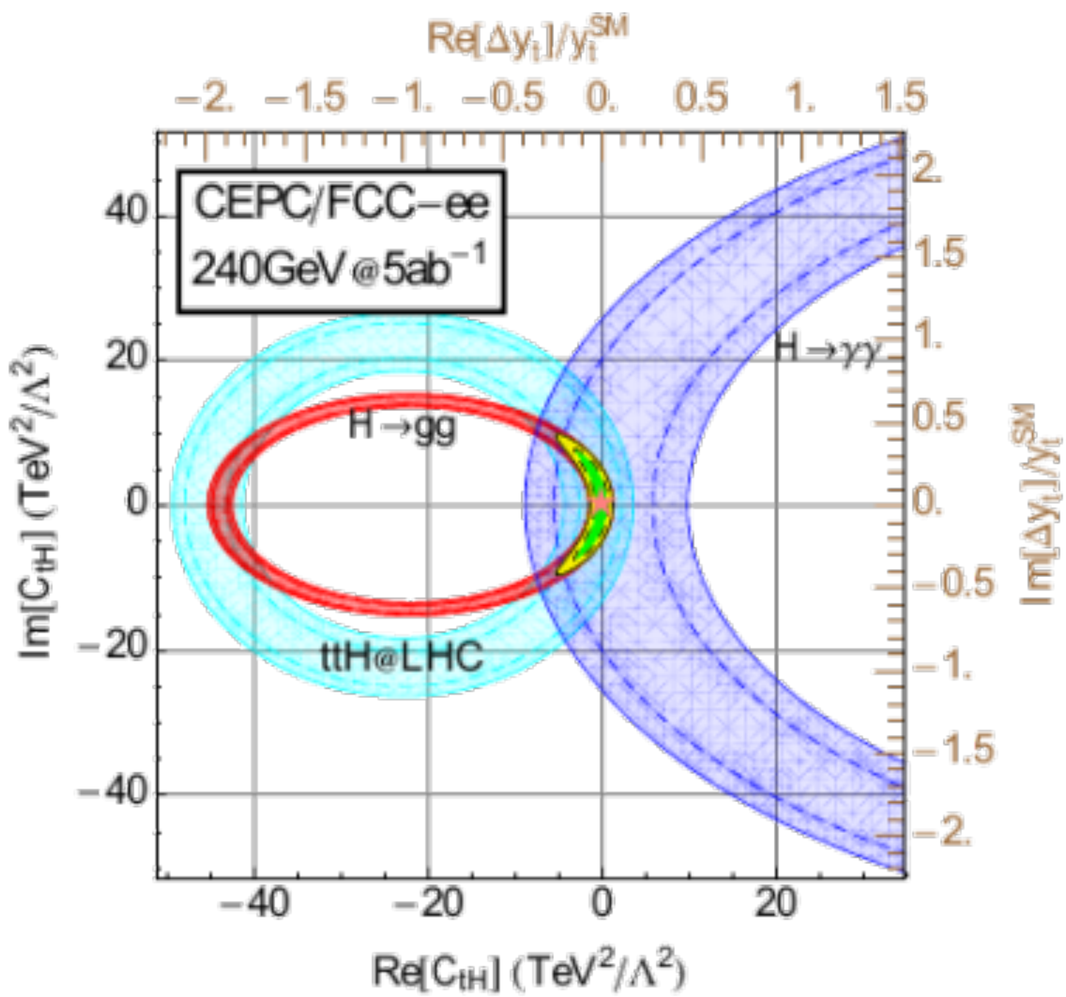
Higgs-top couplings: Yukawa

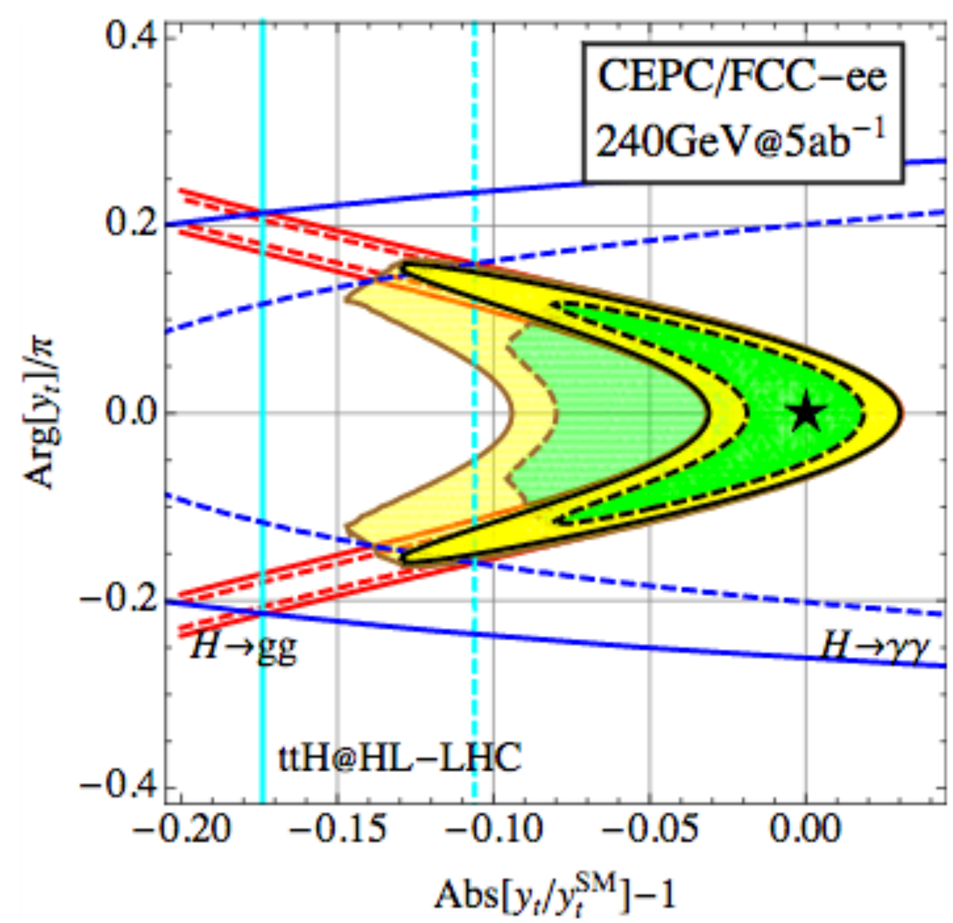
Zhen Liu

$$\mathcal{O}_{tH} = \frac{1}{\Lambda^2}(H^\dagger H)(\bar{q}_L \tilde{H} t_R),$$

Modifies top Yukawa,
both real and imaginary parts.

Main observables: h→γγ, h→gg





Extra