Physics Potential of the CEPC

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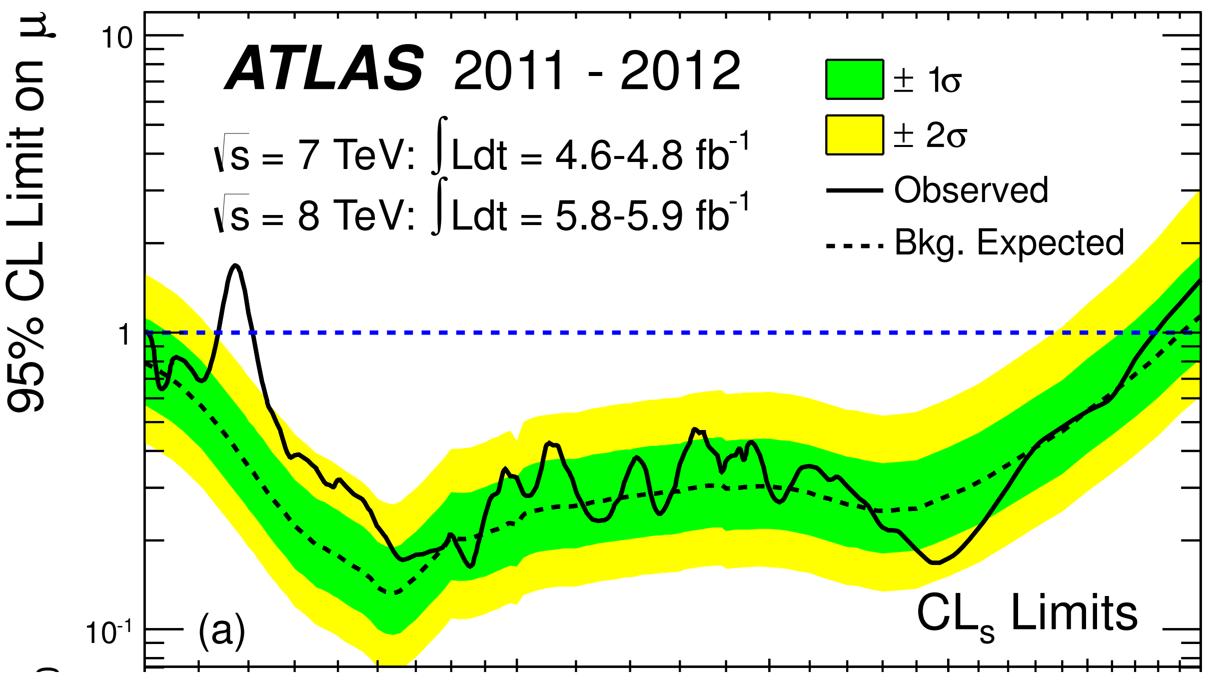
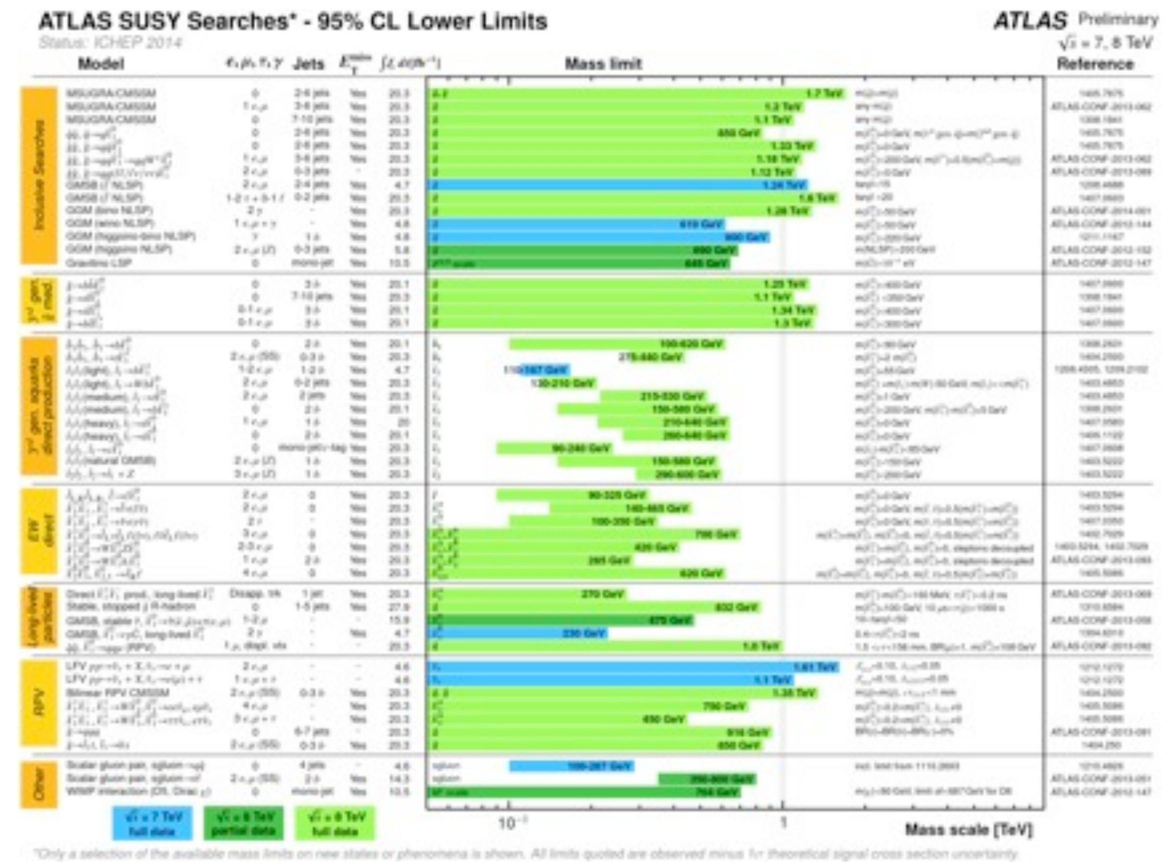
Particle physics in 2015.

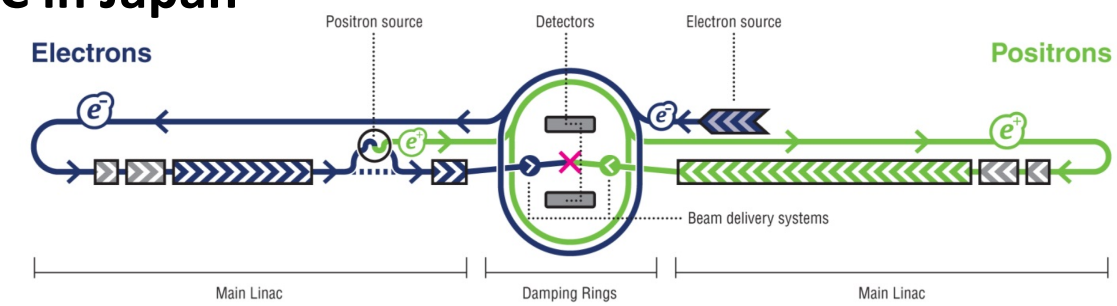


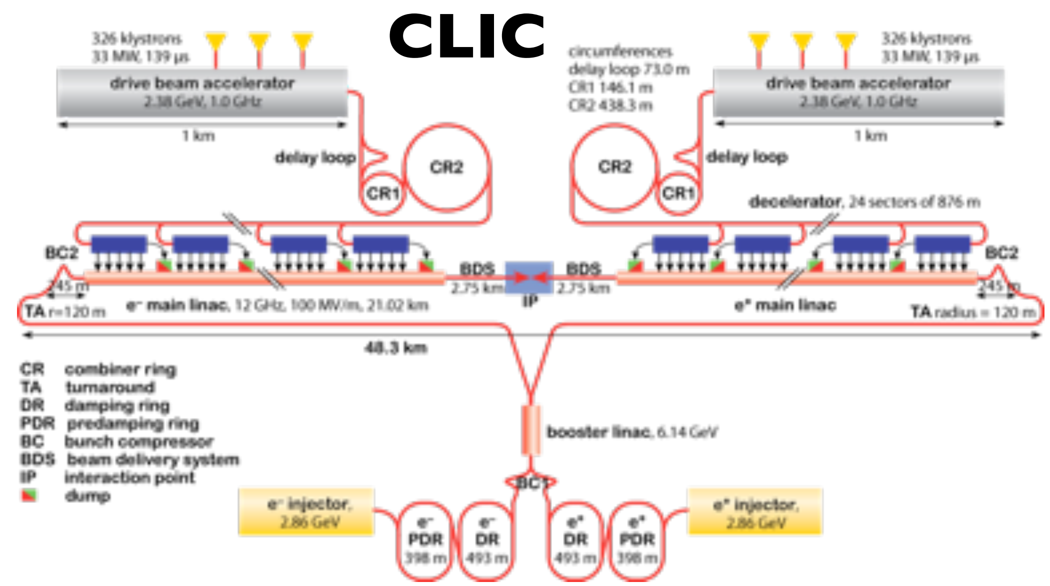


- LHC-8 discovered Higgs, covered a lot of ground.
- LHC-13 will start, may teaches us a lot more.
- At the same time, next step beyond LHC?

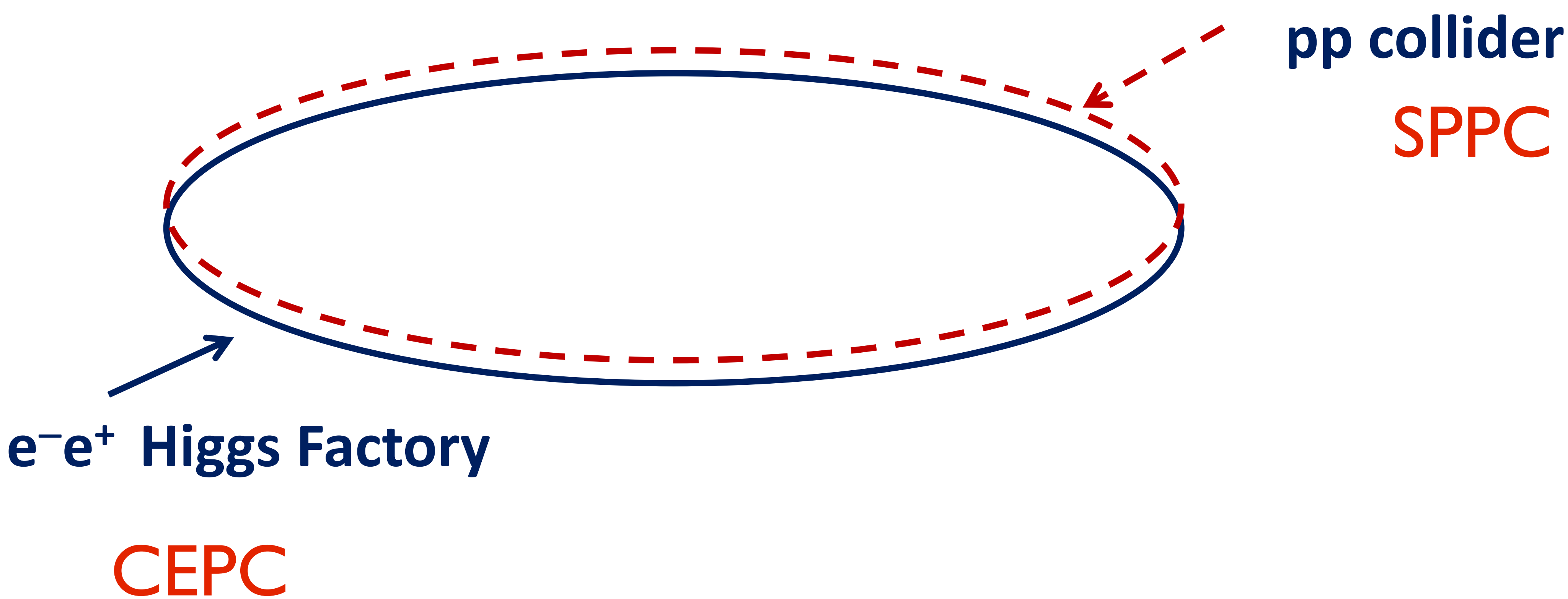
Further down the road

ILC in Japan

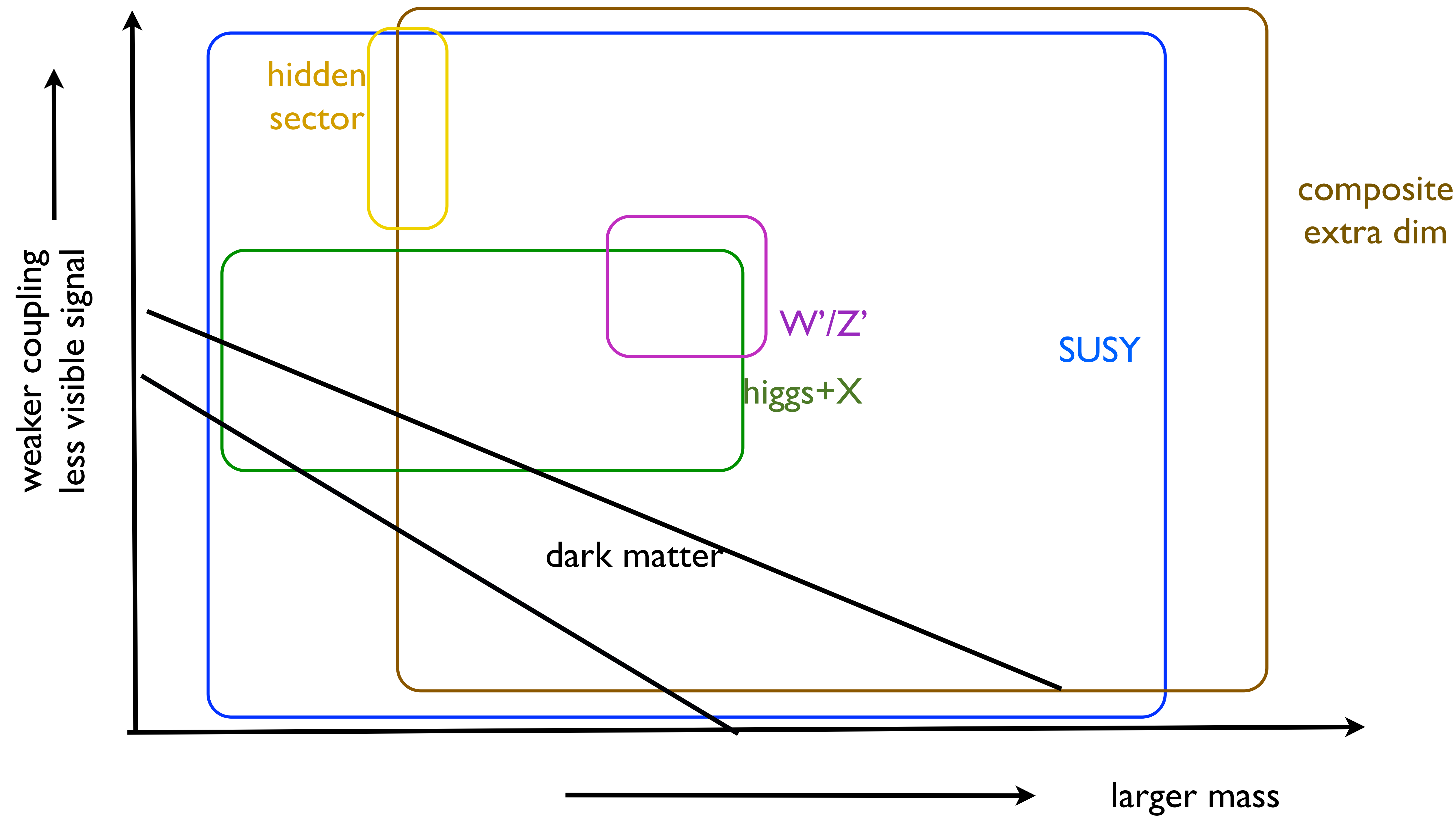




Circular. “Scale up” LEP+LHC



Exploring new physics with colliders



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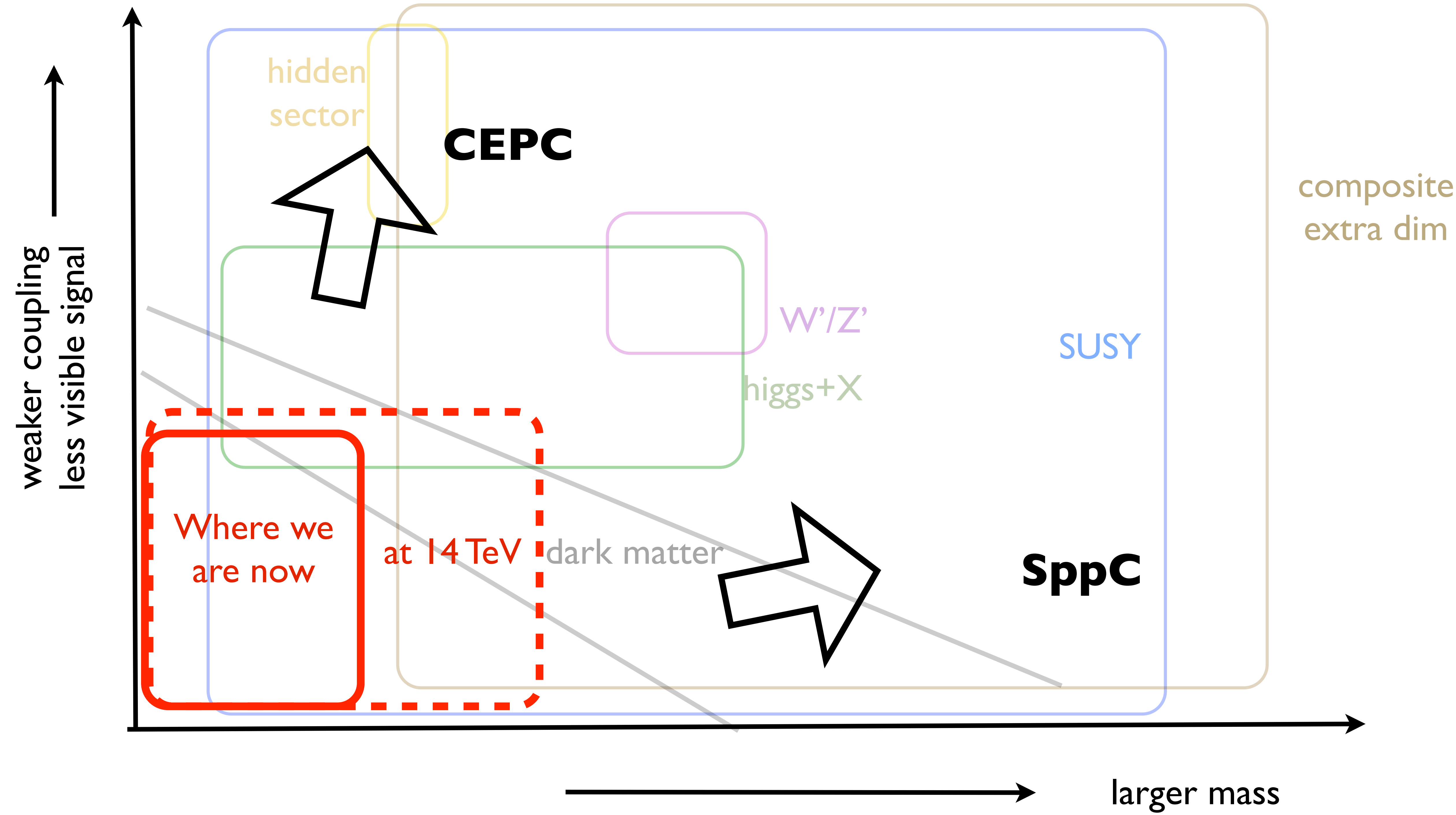
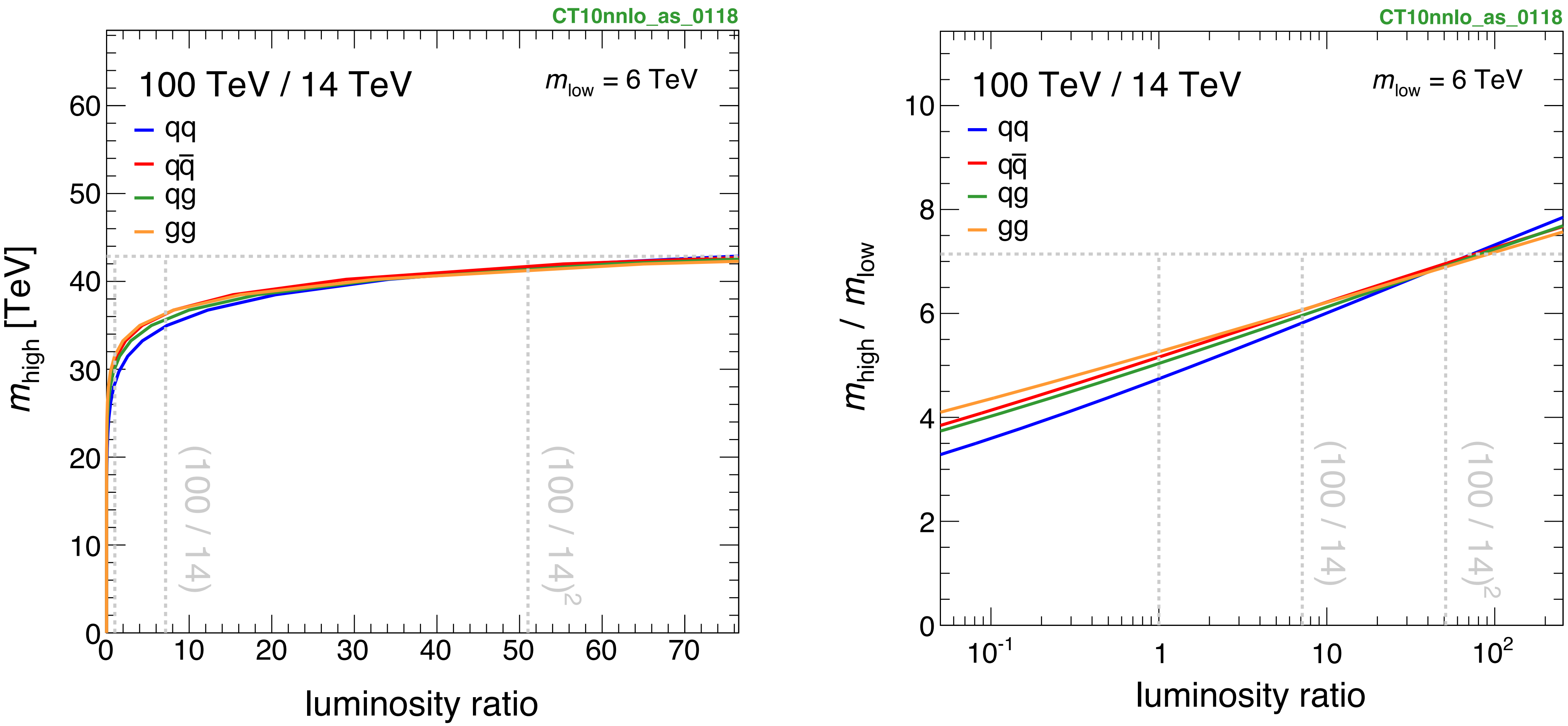


Direct production of new physics

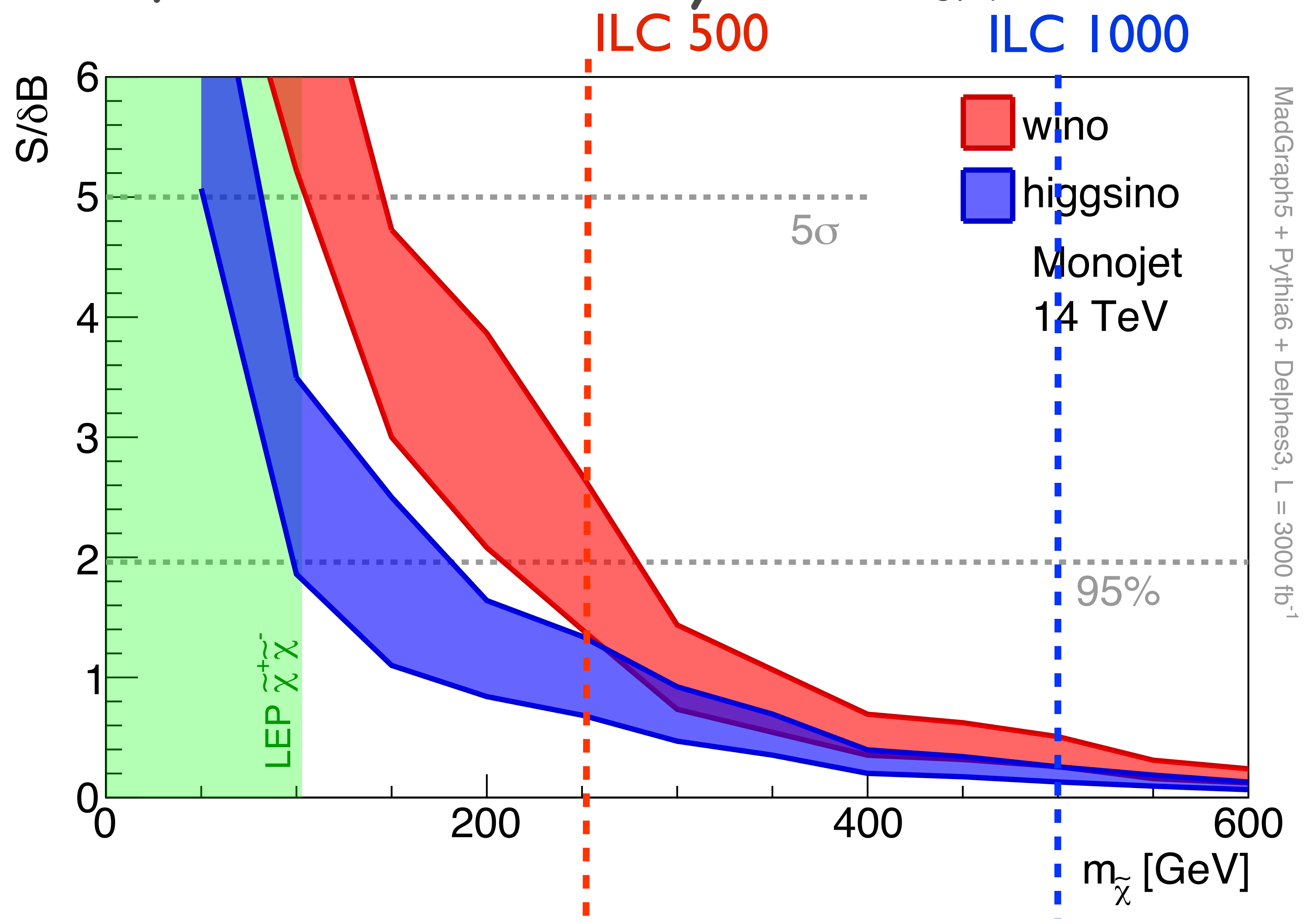
High energy hadron collider.

- Direct production of new physics particles.
- Reach proportional to E_{CM} .
- 14 ⇒ 100, a factor 5 gain quickly.
- Slow gain with increasing luminosity, eventually reach a factor of 7.



Lepton collider, direct production

- Can see difficult signal (mono-photon example below).
- However, reach limited by the E_{CM}.



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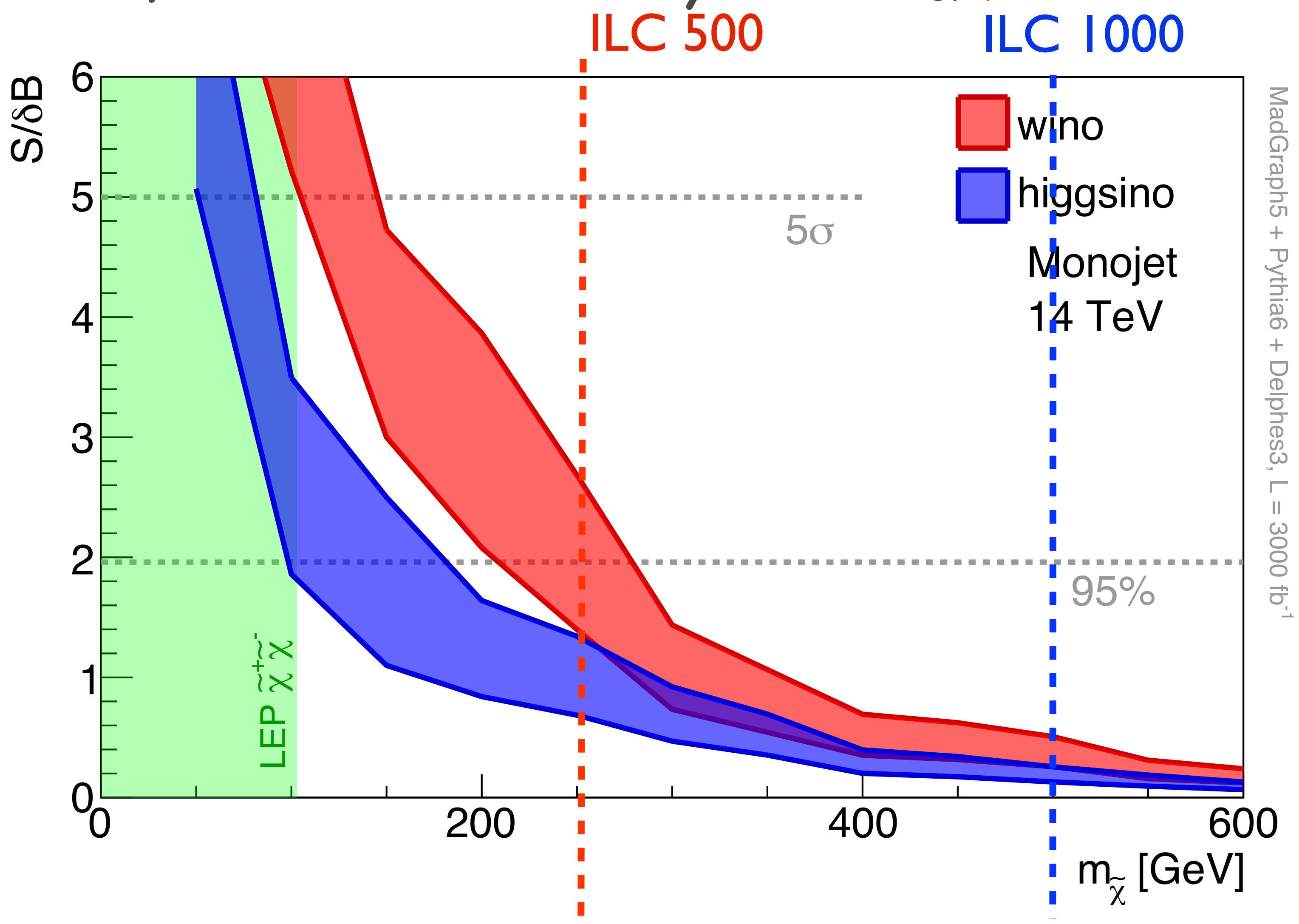
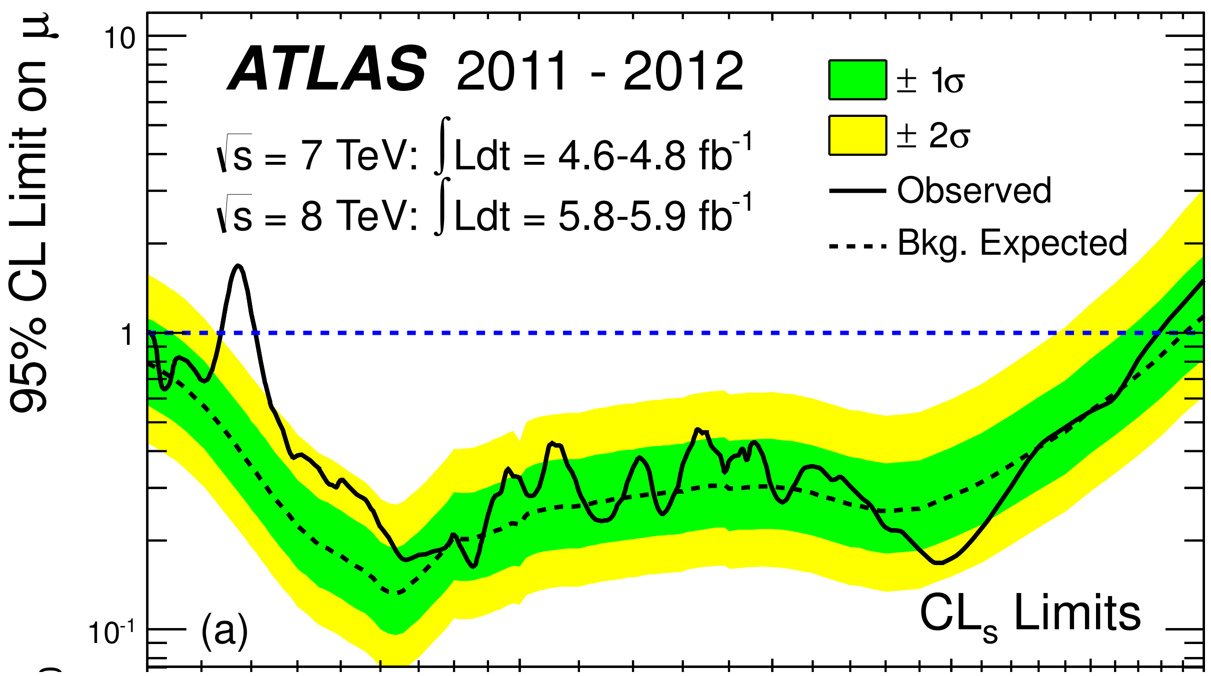
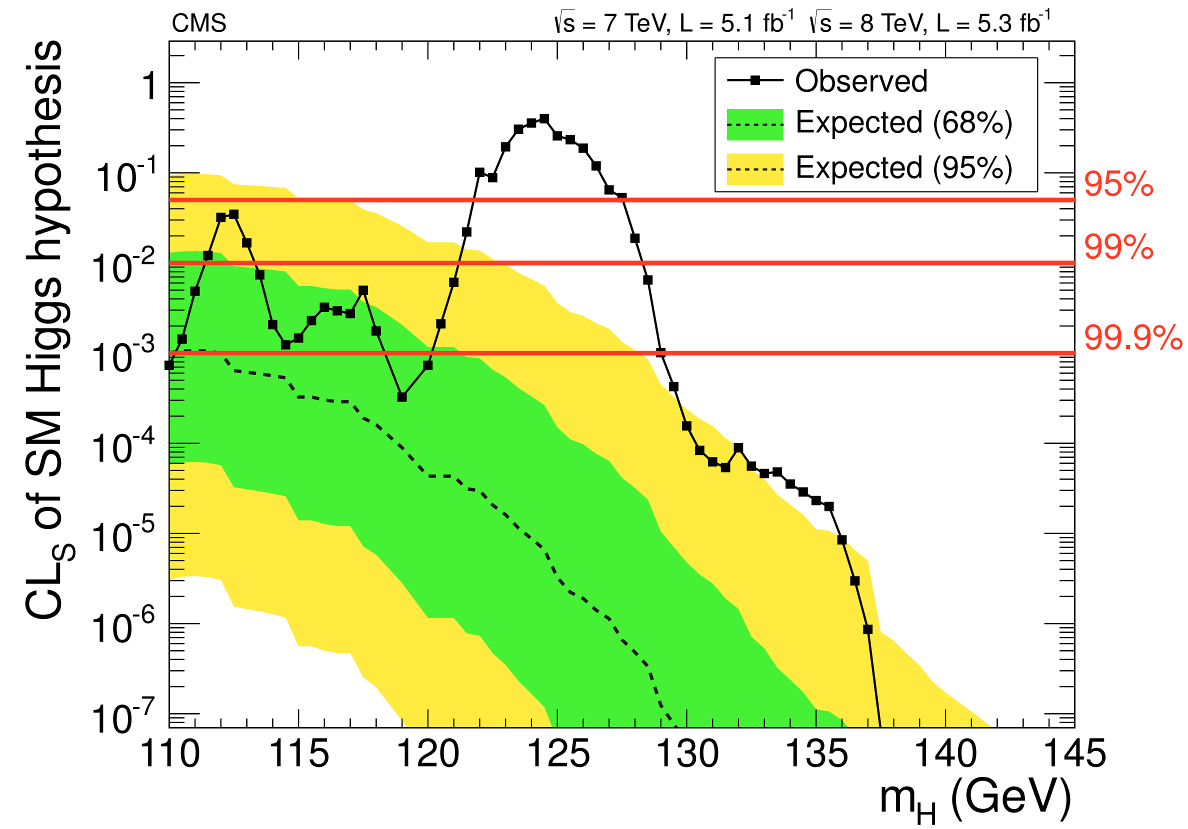


Strength is in precision measurements

Higgs Physics

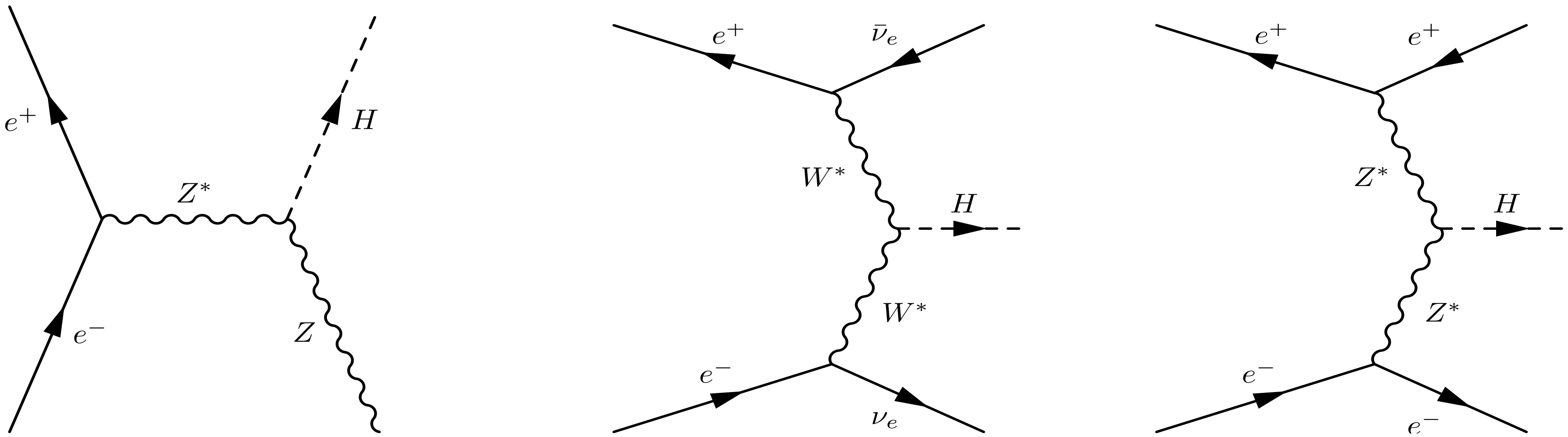
Discovery! July 4th, 2012

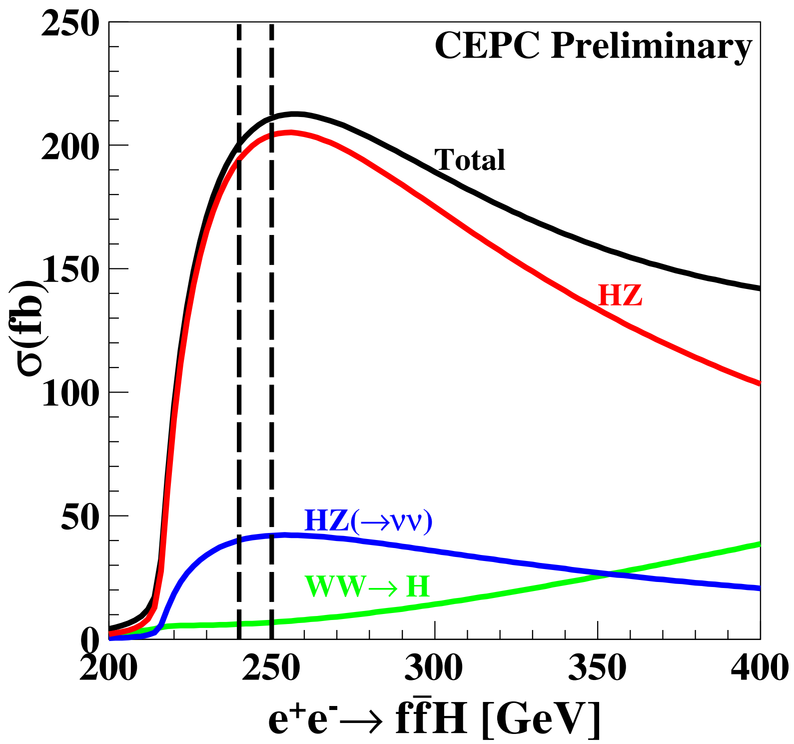




- $m_h \approx 125$ GeV, Standard Model like couplings.

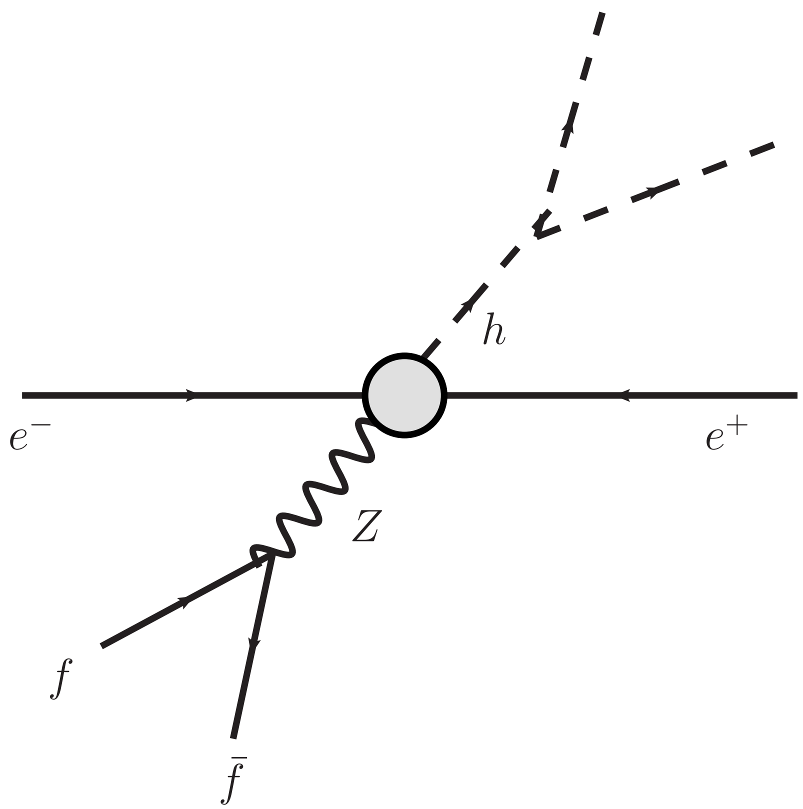
CEPC Higgs program

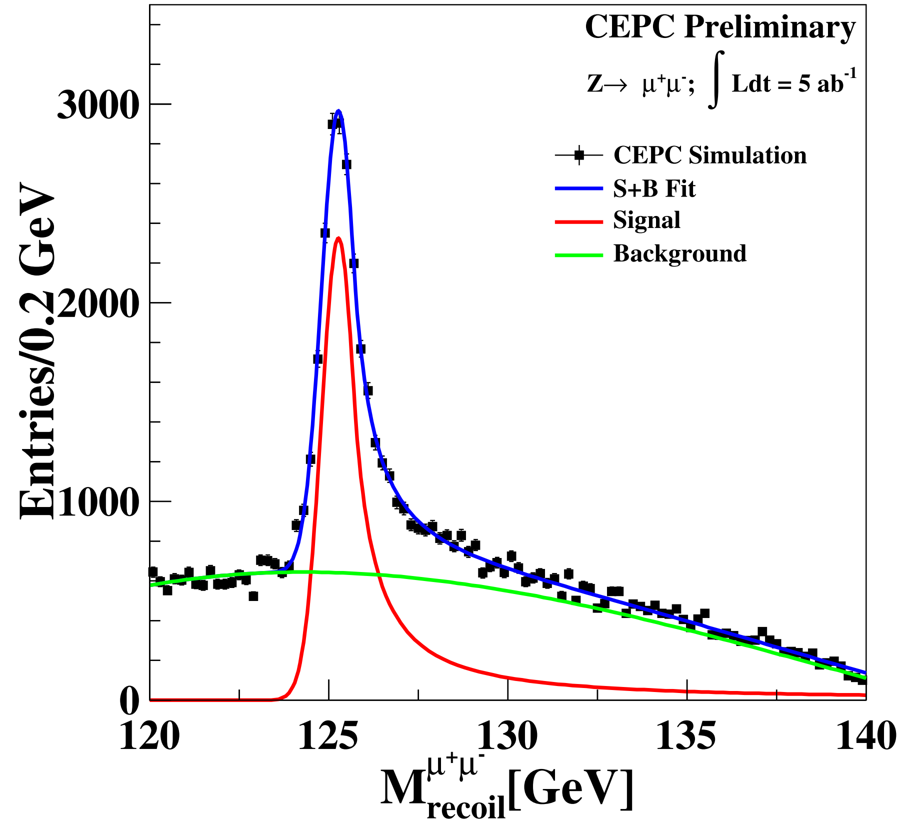




Process	Cross section	Nevents in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\nu H$	6.72	3.36×10^4
$e^+e^- \to eeH$	0.63	3.15×10^3
Total	219	1.10×10^6

Zh cross section





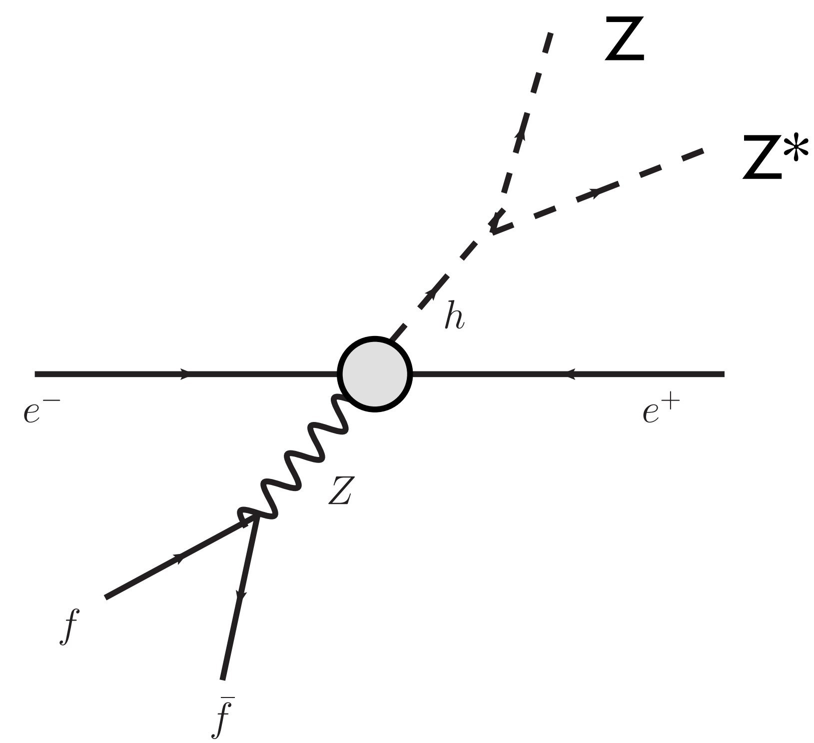
$$M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

Can use recoil mass to identify Zh process, independent of Higgs decay

⇒ inclusive measurement of Zh cross section

Higgs width.

Unique capability of lepton colliders.



$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$

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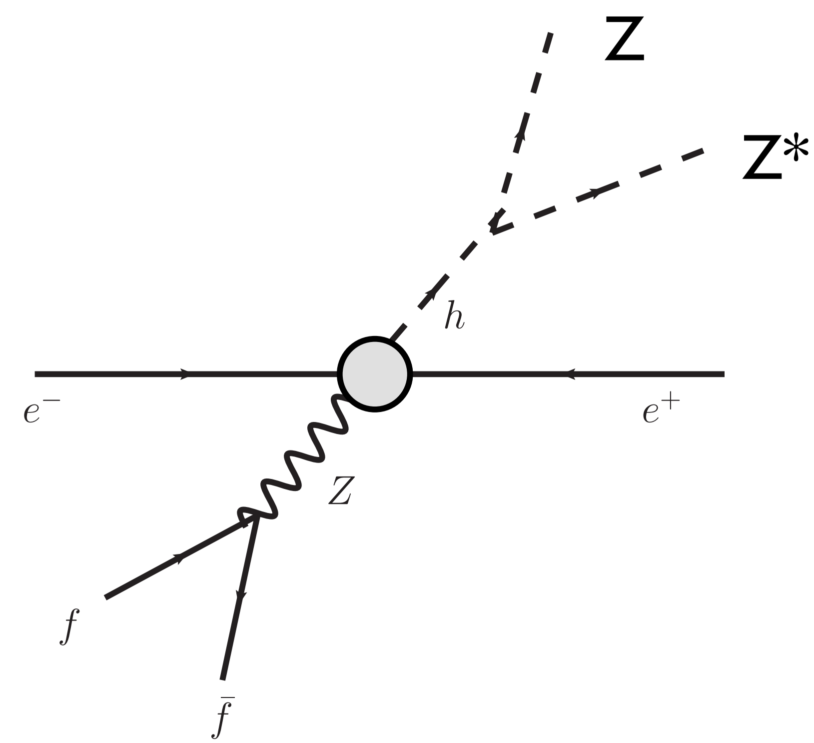

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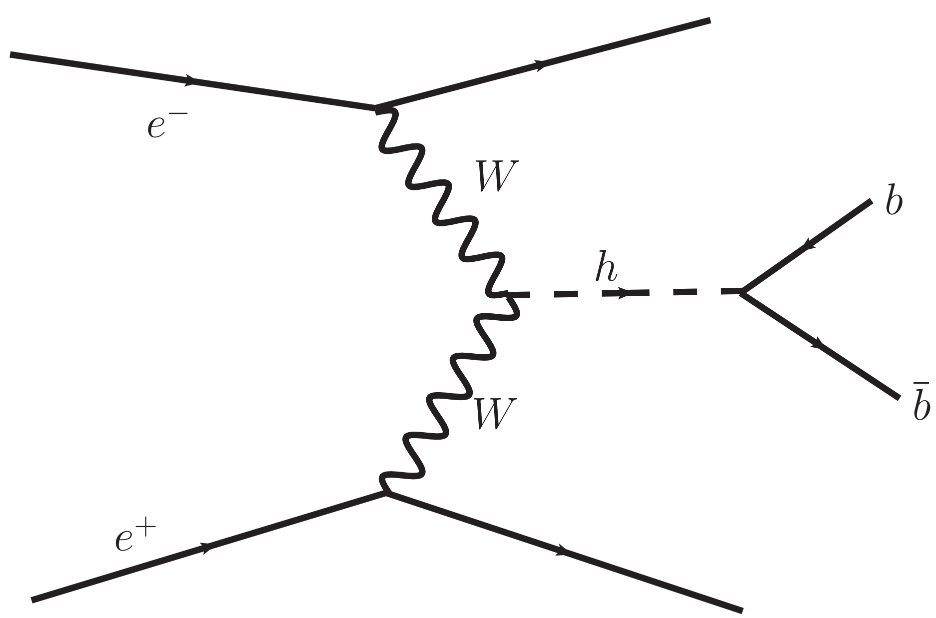


$$\Gamma_H \propto \frac{\Gamma(H \to bb)}{\mathrm{BR}(H \to bb)} \propto \frac{\sigma(\nu\nu H \to \nu\nu bb)}{\mathrm{BR}(H \to bb) \cdot \mathrm{BR}(H \to WW^*)}$$

Impressive capability cross the board

ΔM_H	Γ_H	$\sigma(ZH)$	$\sigma(\nu\nu H) \times \mathrm{BR}(H \to bb)$
5.9 MeV	2.7%	0.51%	2.8%

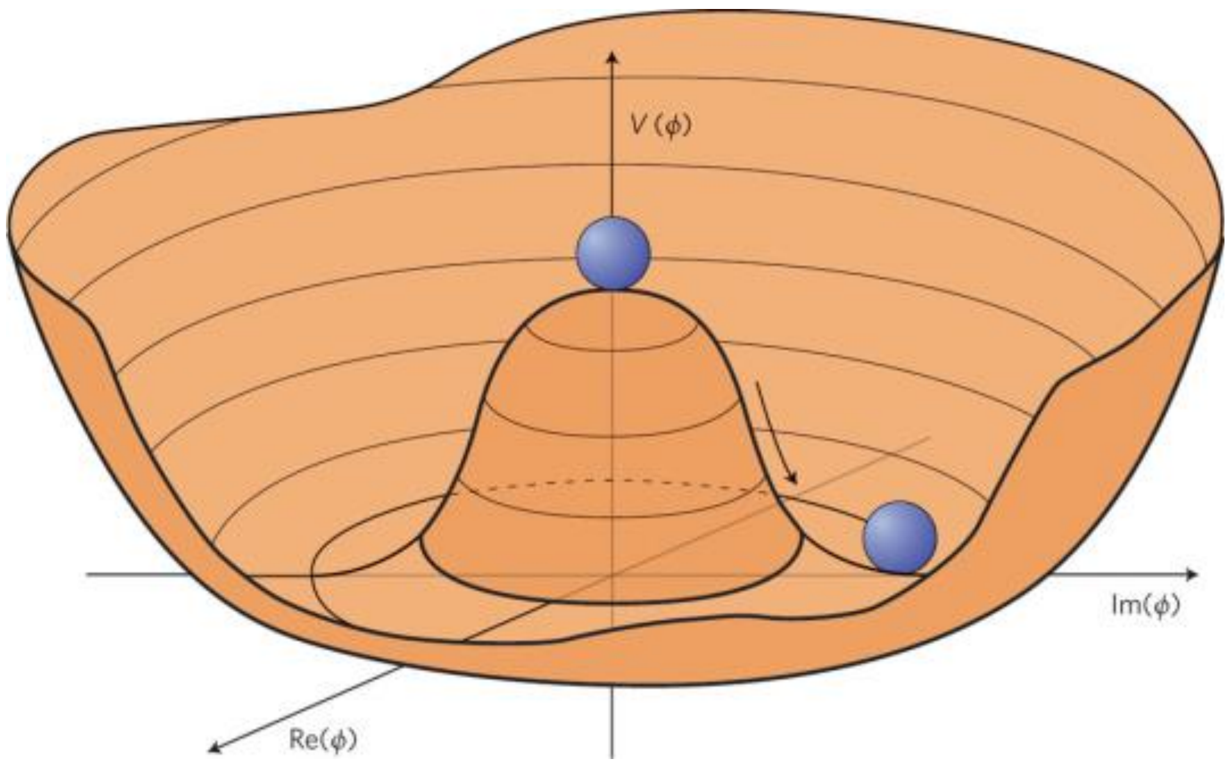
Decay mode	$\sigma(ZH) \times \mathrm{BR}$	BR
$H \to bb$	0.28%	0.57%
$H \to cc$	2.2%	2.3%
$H \to gg$	1.6%	1.7%
$H \to \tau\tau$	1.2%	1.3%
$H \to WW$	1.5%	1.6%
$H \to ZZ$	4.3%	4.3%
$H \to \gamma\gamma$	9.0%	9.0%
$H \to \mu\mu$	17%	17%
$H \to \mathrm{inv}$	–	0.28%

Why do we want to know more about Higgs?

particle	spin
quark: u, d,...	1/2
lepton: e...	1/2
photon	1
W,Z	1
gluon	1
Higgs	0

h: a new kind of
elementary particle

“Simple” picture: Mexican hat



$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

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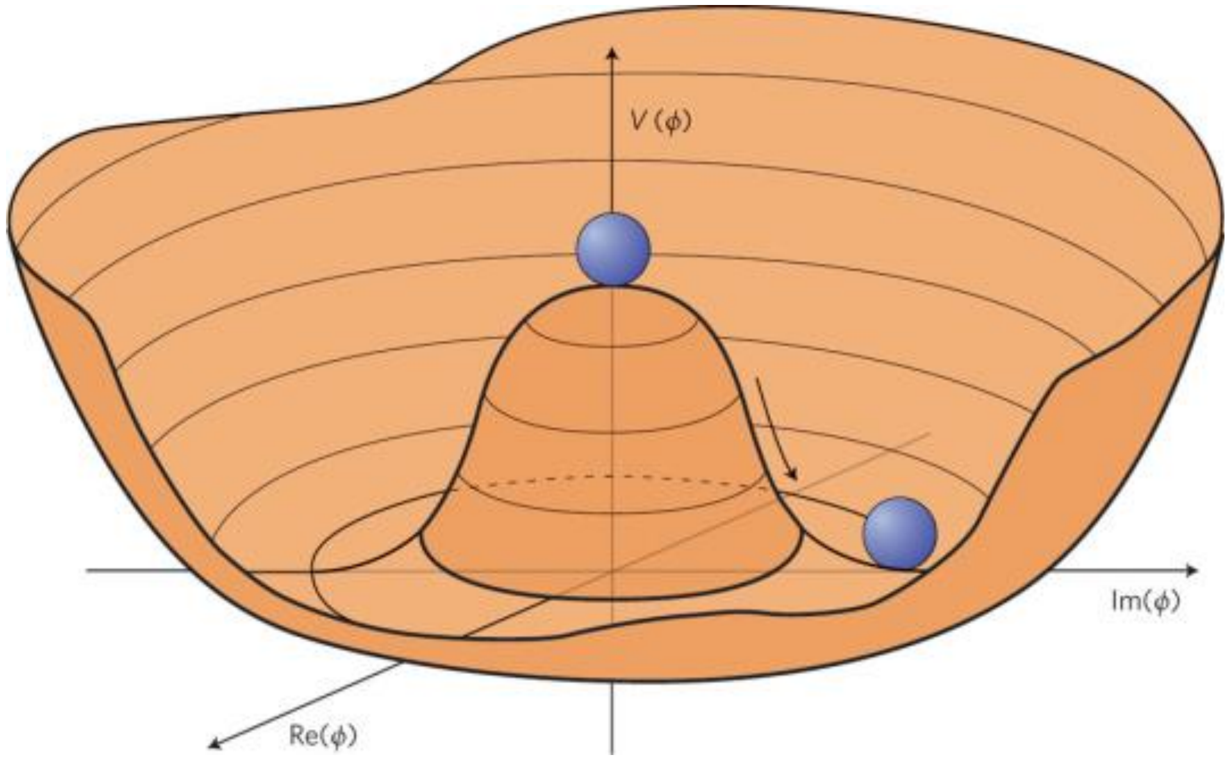

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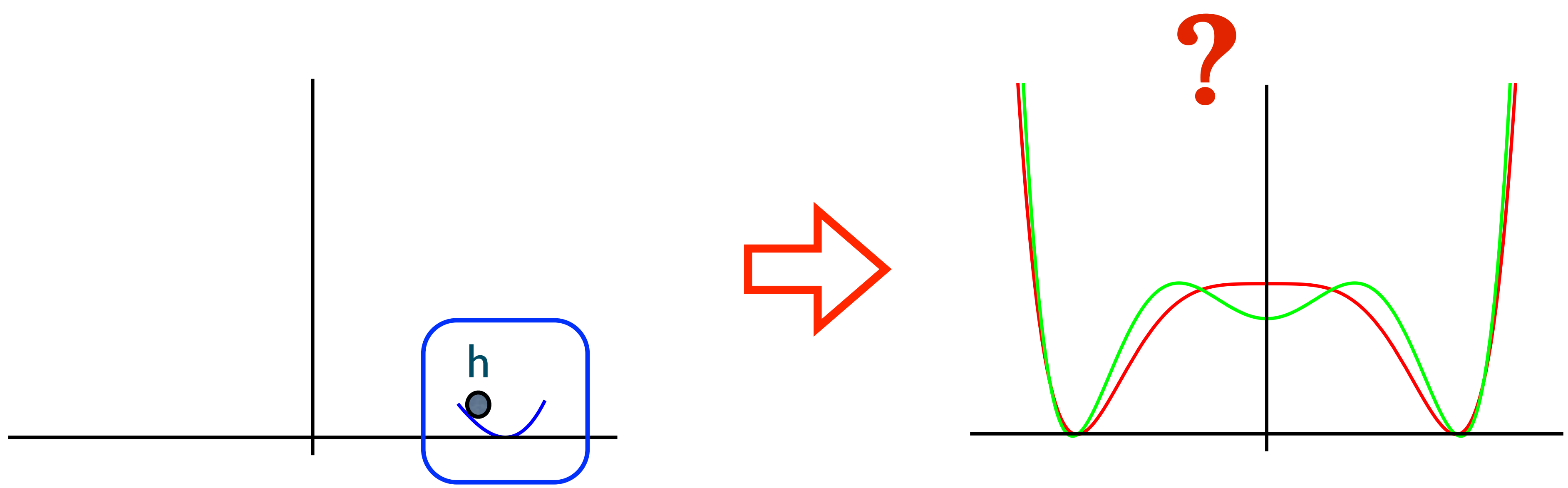
However, this simplicity is deceiving.
Parameters not predicted by theory. Can not be the complete picture.

We know very little about Higgs, not even sure about "Mexican hat".

$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$ or $V(h) = \frac{1}{2}\mu^2 h^2 - \frac{\lambda}{4} h^4 + \frac{1}{\Lambda^2} h^6$



What we know now

Is the EW phase transition first order?

Where do we start?

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Is Higgs really the simple elementary particle?
Or, is it something more complicated?

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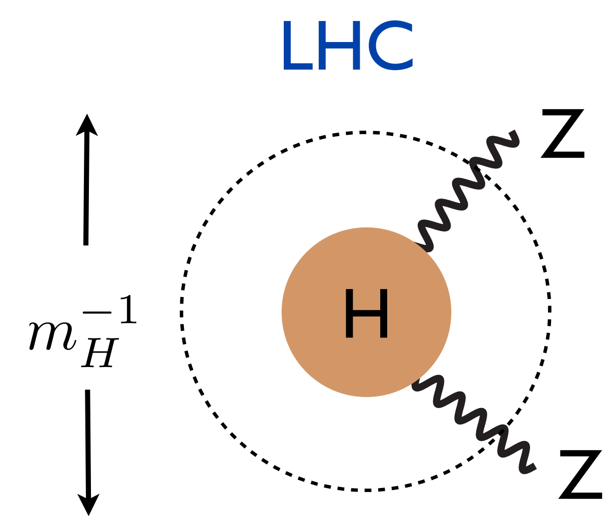

Visualize as the "size" of the particle
Complicated: size = mass^{-1} (just like proton)
Simple: point-like

Why complicated? An example:
Landau-Ginzburg replaced by BCS, more complicated!

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Is Higgs really the simple elementary particle?
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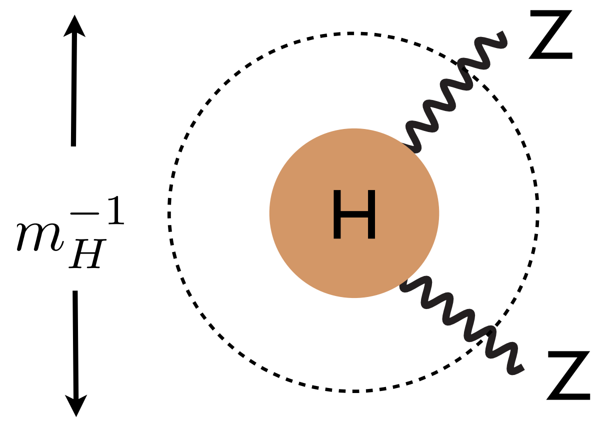


Why complicated? An example:
Landau-Ginzburg replaced by BCS, more complicated!

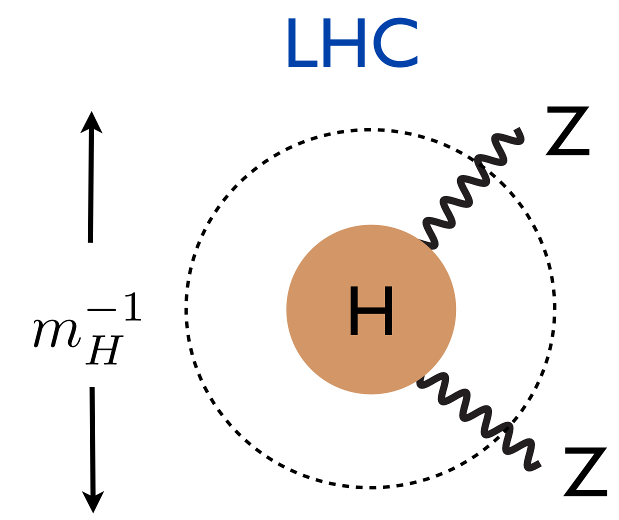
LHC results so far: point like, "sort of",
but not conclusive.

Need to look at couplings in greater detail.

How well do we need to know?

In general, the deviation from the simple picture can be parameterized as

$$\delta = c\frac{m_W^2}{M_{\rm NP}^2},\ \ c = \mathcal{O}(1)$$



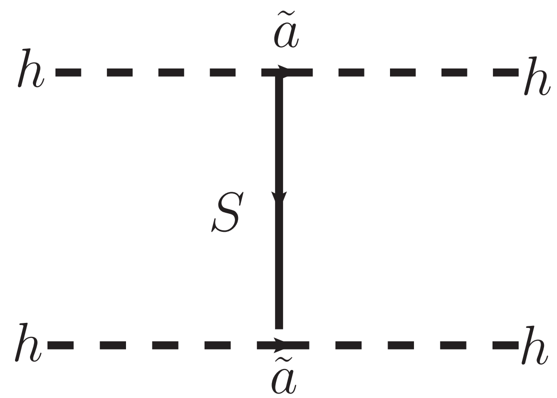
LHC will search new physics particles directly with mass $M_{NP} \lesssim$ TeV.

Therefore, deviation more than a few % unlikely

To be comparable or go beyond, need to measure Higgs coupling to % level or better

Consider a simple model

$$m^2 h^\dagger h + \tilde{\lambda}(h^\dagger h)^2 + m_S^2 S^2 + \tilde{a} S h^\dagger h + \tilde{b} S^3 + \tilde{\kappa} S^2 h^\dagger h + \tilde{h} S^4$$



shift in h-Z coupling > 0.5%

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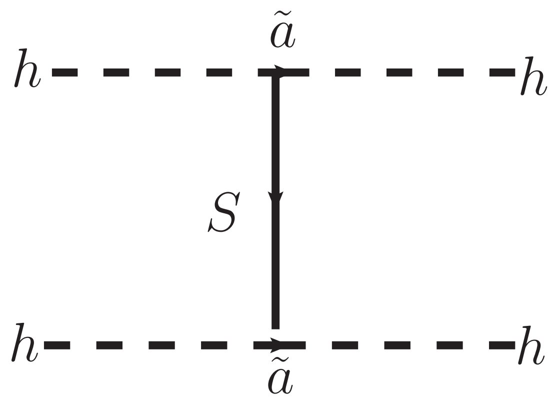
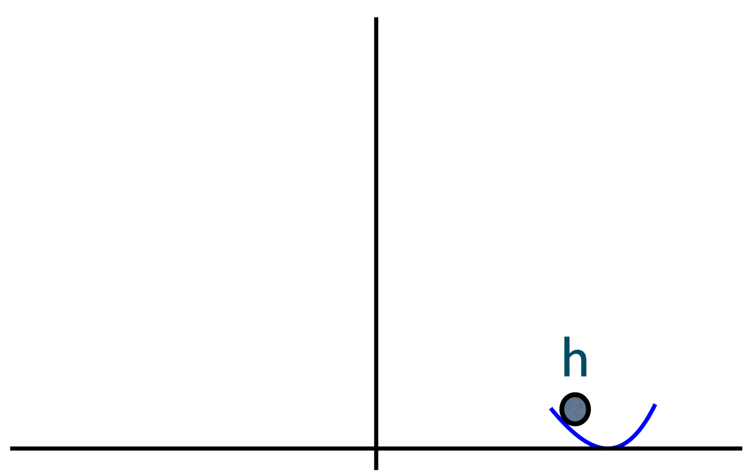
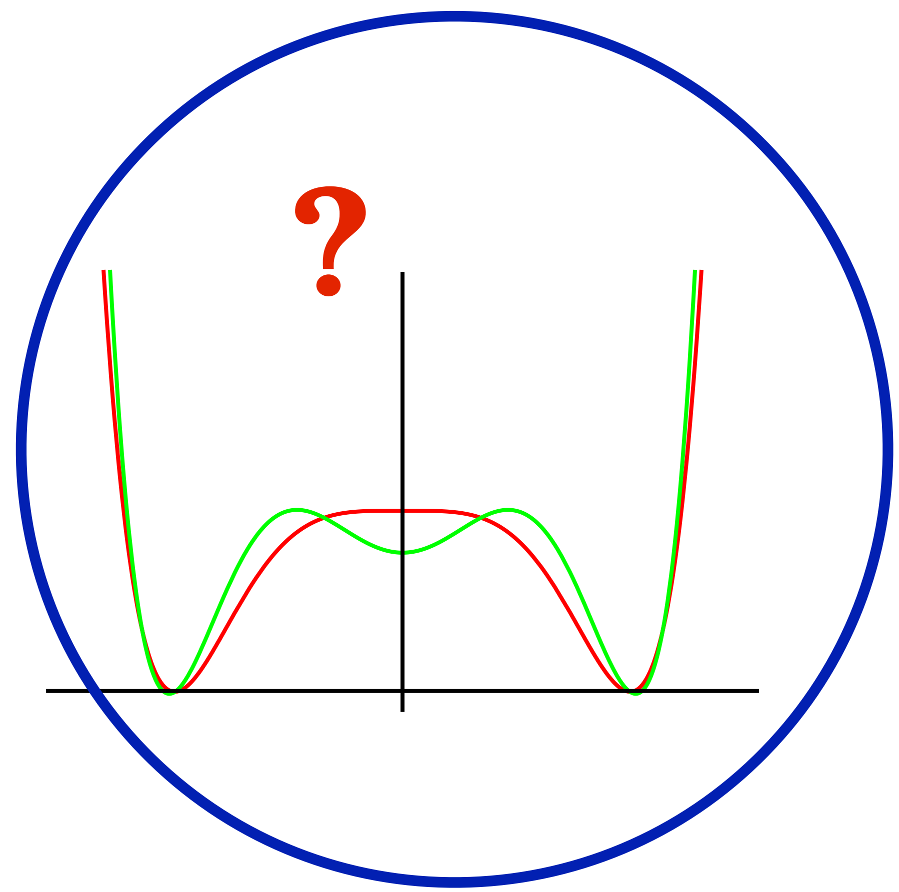


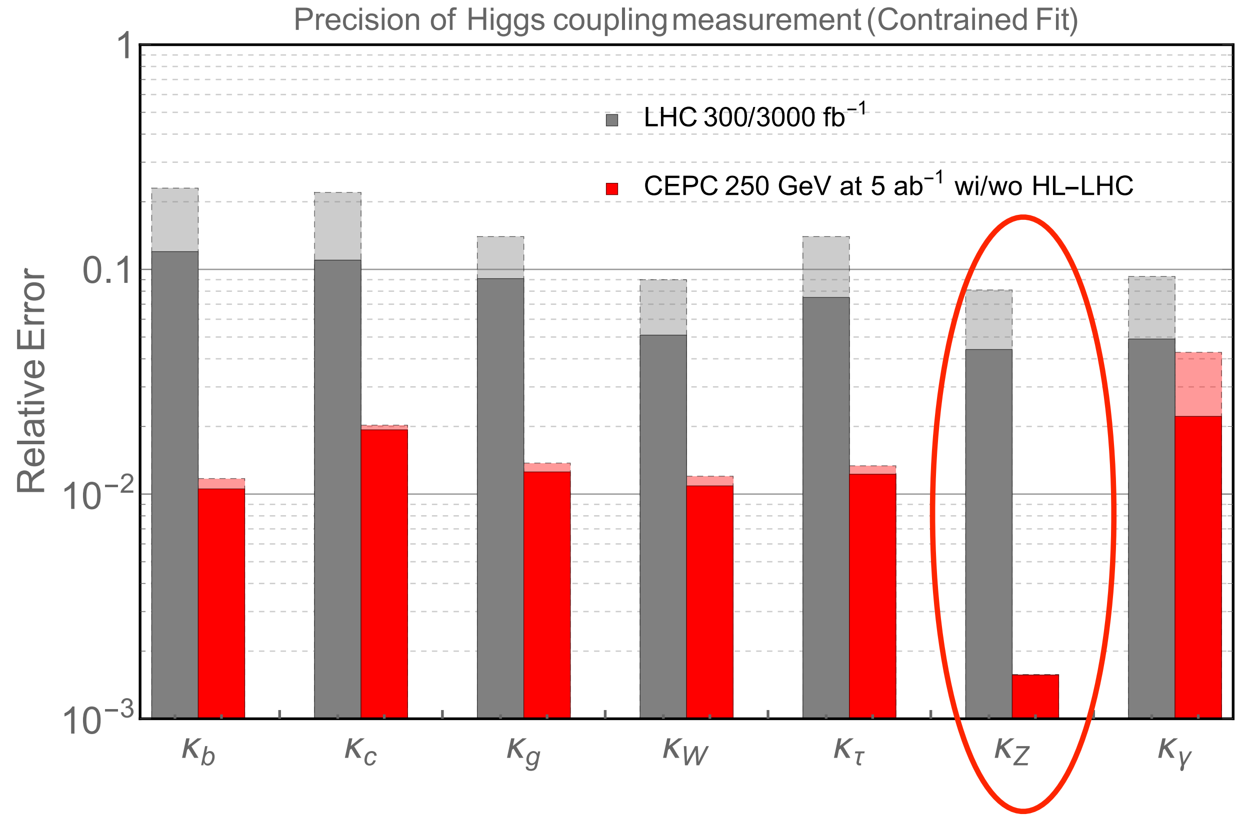
shift in h-Z coupling > 0.5%

Measuring it well is crucial to answer this question.

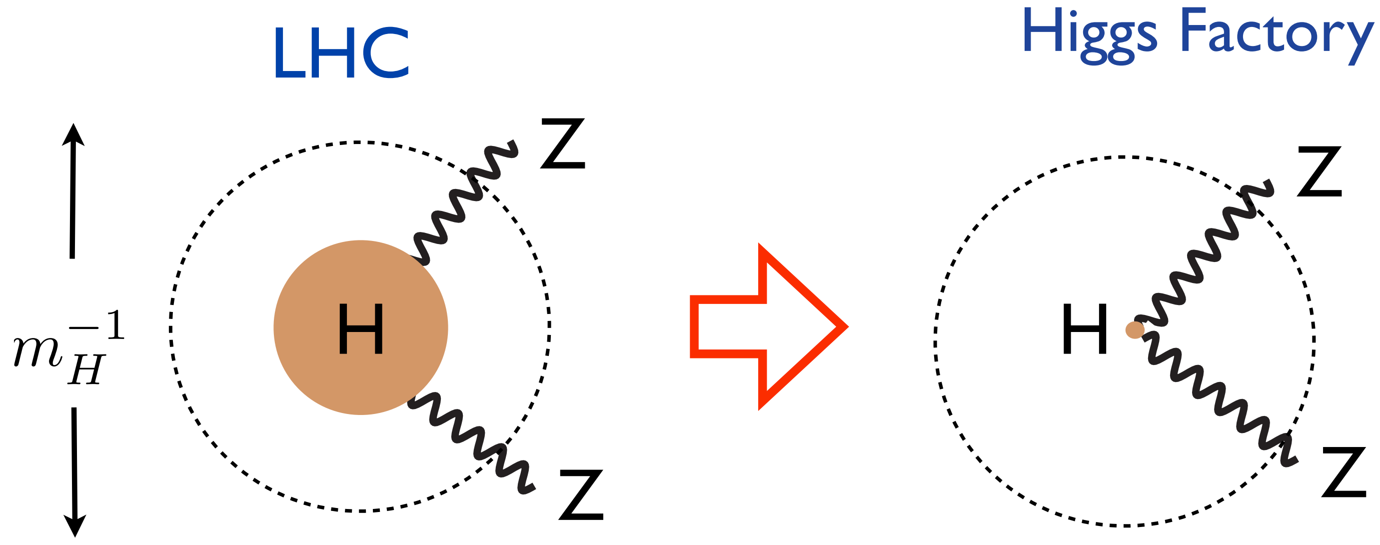




How well can we do?



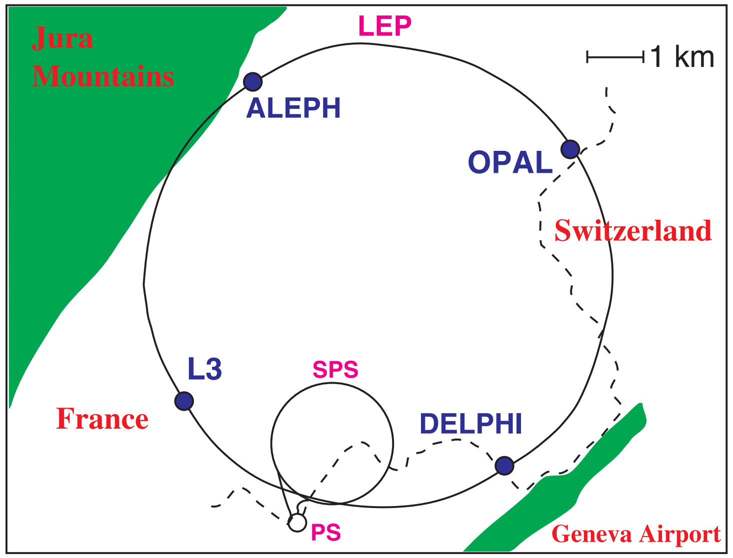
$$\kappa_Z = \frac{g_{hZ}(\text{Measured})}{g_{hZ}(\text{SM})}$$

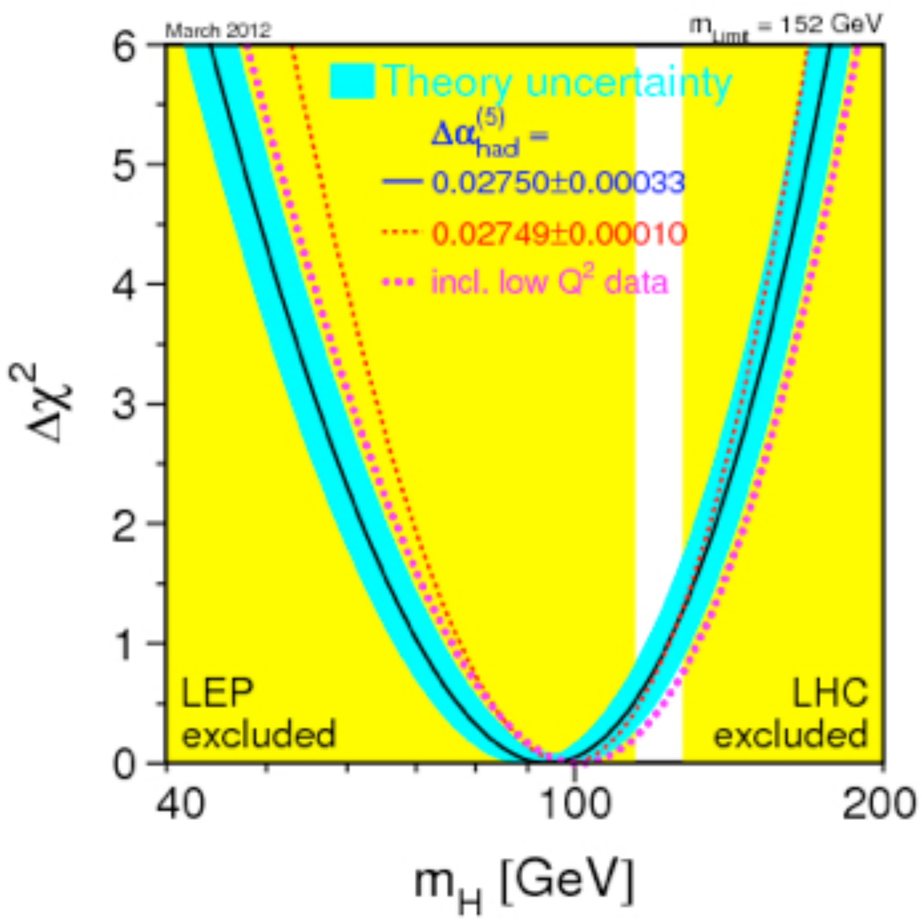


CEPC has what it takes!

Electroweak Precision

CEPC will build on the success





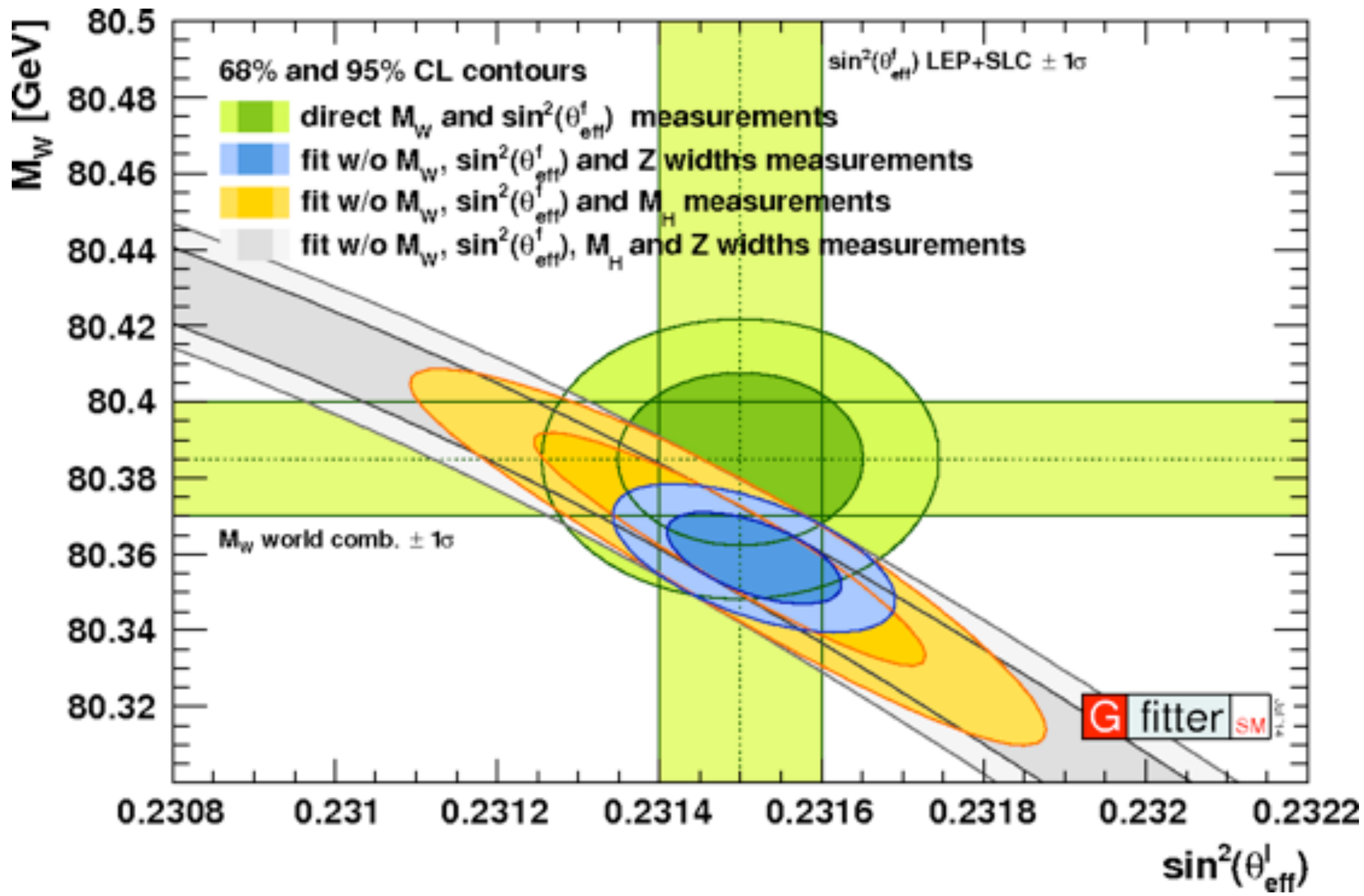
LEP I, 17 million Z decays

Understood the properties of the W,Z-boson well enough to

Nail the range of the Higgs mass

Guide the quest of BSM new physics.

EW precision will continue to be relevant



Open questions in the SM center on electroweak symmetry breaking ⇒ expecting new physics here.

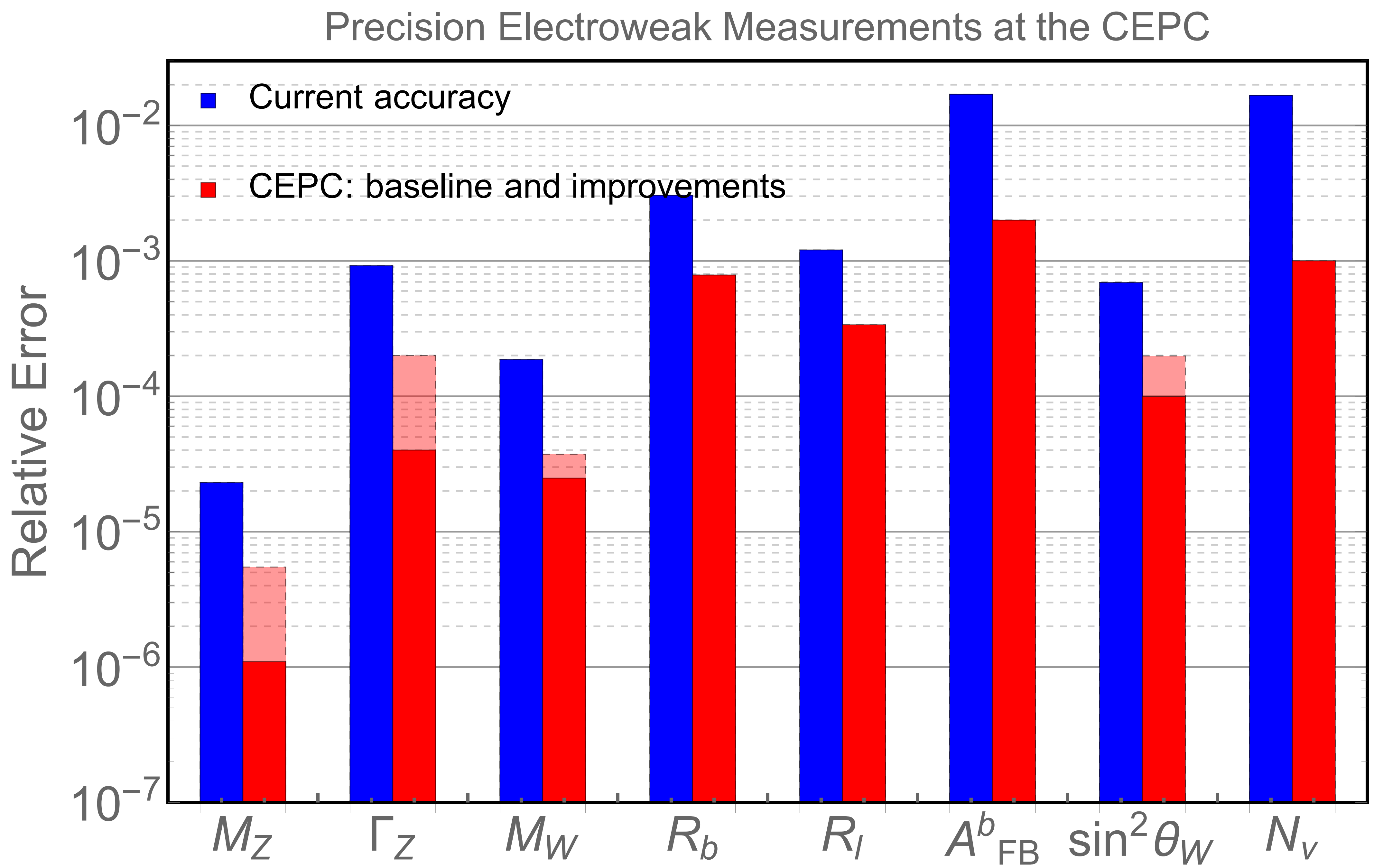
Higgs discovery only sharpened them.

Measuring EW sector better will certainly teach us a lot.

EW program at the CEPC

- Z-pole.
  - Planning at preliminary stage.
  - Will use 1 year, 2 detector and 100s fb^{-1} here.
  - A factor of 100 more Zs than LEP-I
- WW
  - Threshold. 100s fb^{-1}
  - Continuum WW production in Higgs factory mode.

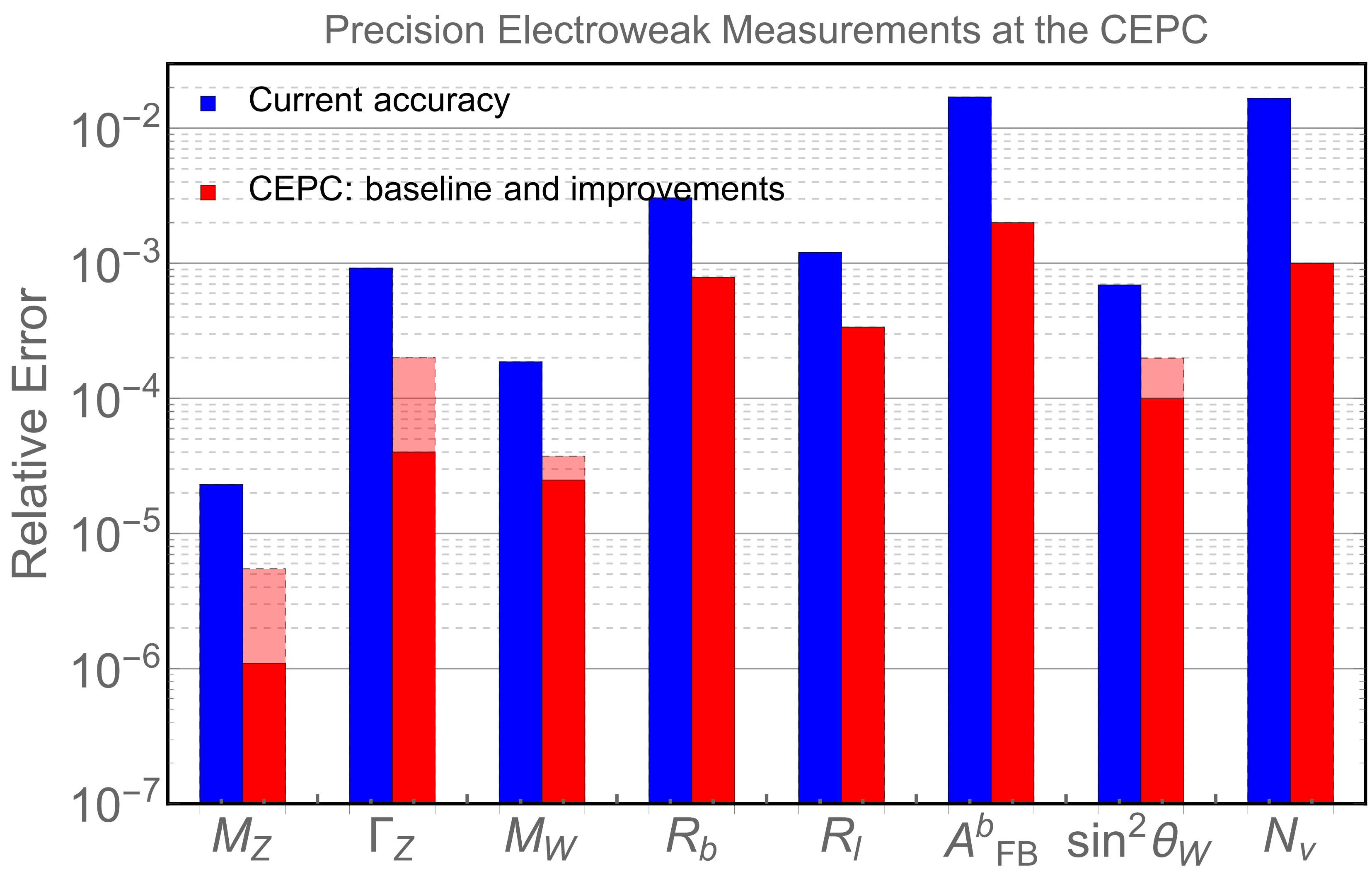
A big step forward



Large improvements across the board

A big step forward

Based on estimates from Zhijun Liang



Estimate preliminary.

Mostly Systematics dominated. (estimate conservative)

Baseline (conservative): 100 fb^{-1} on Z-pole, 60 fb^{-1} around Z-pole scan

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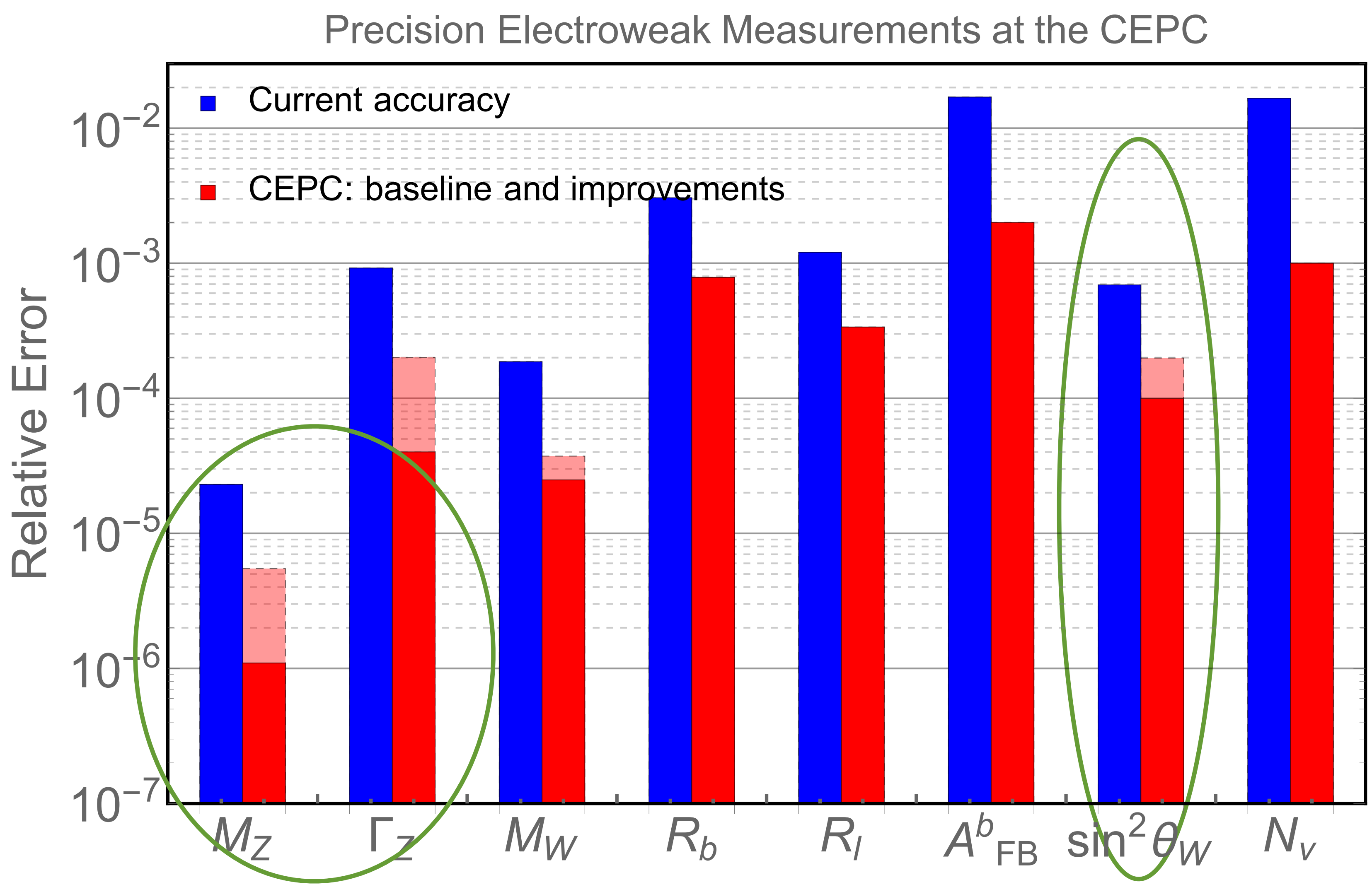

Estimate preliminary.

Mostly Systematics dominated.
(estimate conservative)

energy calibration

x4 statistics

Some potential improvements

Baseline (conservative): 100 fb^{-1} on Z-pole, 60 fb^{-1} around Z-pole scan

Inputs for the further study

Baseline option

	Present data	CEPC fit
$\alpha_s(M_Z^2)$	0.1185 ± 0.0006 [17]	$\pm 1.0 \times 10^{-4}$ [18]
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	$(276.5 \pm 0.8) \times 10^{-4}$ [19]	$\pm 4.7 \times 10^{-5}$ [20]
m_Z [GeV]	91.1875 ± 0.0021 [21]	$\pm\mathbf{0.0005}$
m_t [GeV] (pole)	$173.34 \pm 0.76_{\rm exp}$ [22] $\pm 0.5_{\rm th}$ [20]	$\pm 0.6_{\rm exp} \pm 0.25_{\rm th}$ [20]
m_h [GeV]	125.14 ± 0.24 [20]	$< \pm 0.1$ [20]
m_W [GeV]	$80.385 \pm 0.015_{\rm exp}$ [17]$\pm 0.004_{\rm th}$ [23]	$(\pm\mathbf{3}_{\rm exp} \pm 1_{\rm th}) \times 10^{-3}$ [23]
$\sin^2\theta_{\rm eff}^{\ell}$	$(23153 \pm 16) \times 10^{-5}$ [21]	$(\pm\mathbf{4.6}_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$ [24]
Γ_Z [GeV]	2.4952 ± 0.0023 [21]	$(\pm\mathbf{5}_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$ [25]
$R_b \equiv \Gamma_b/\Gamma_{\rm had}$	0.21629 ± 0.00066 [21]	$\pm\mathbf{1.7} \times 10^{-4}$
$R_\ell \equiv \Gamma_{\rm had}/\Gamma_\ell$	20.767 ± 0.025 [21]	$\pm\mathbf{0.007}$

With possible improvements.

CEPC	$\sin^2\theta_{\rm eff}^{\ell}$	Γ_Z [GeV]	m_t [GeV]
Improved Error	$(\pm 2.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$	$\pm 0.03_{\rm exp} \pm 0.1_{\rm th}$

x4 statistics off Z-pole

energy calibration

ILC?

Electroweak precision at CEPC

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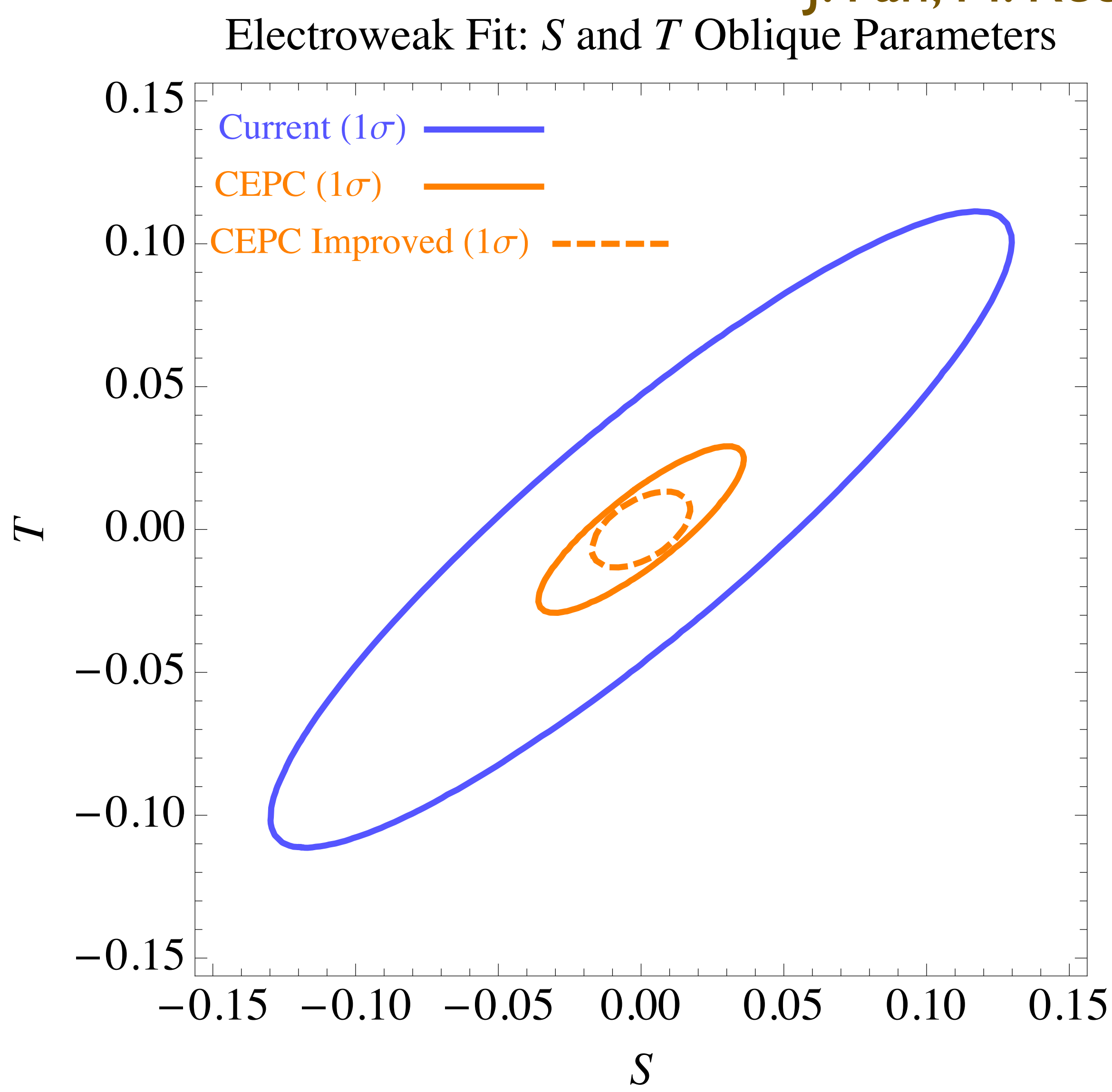
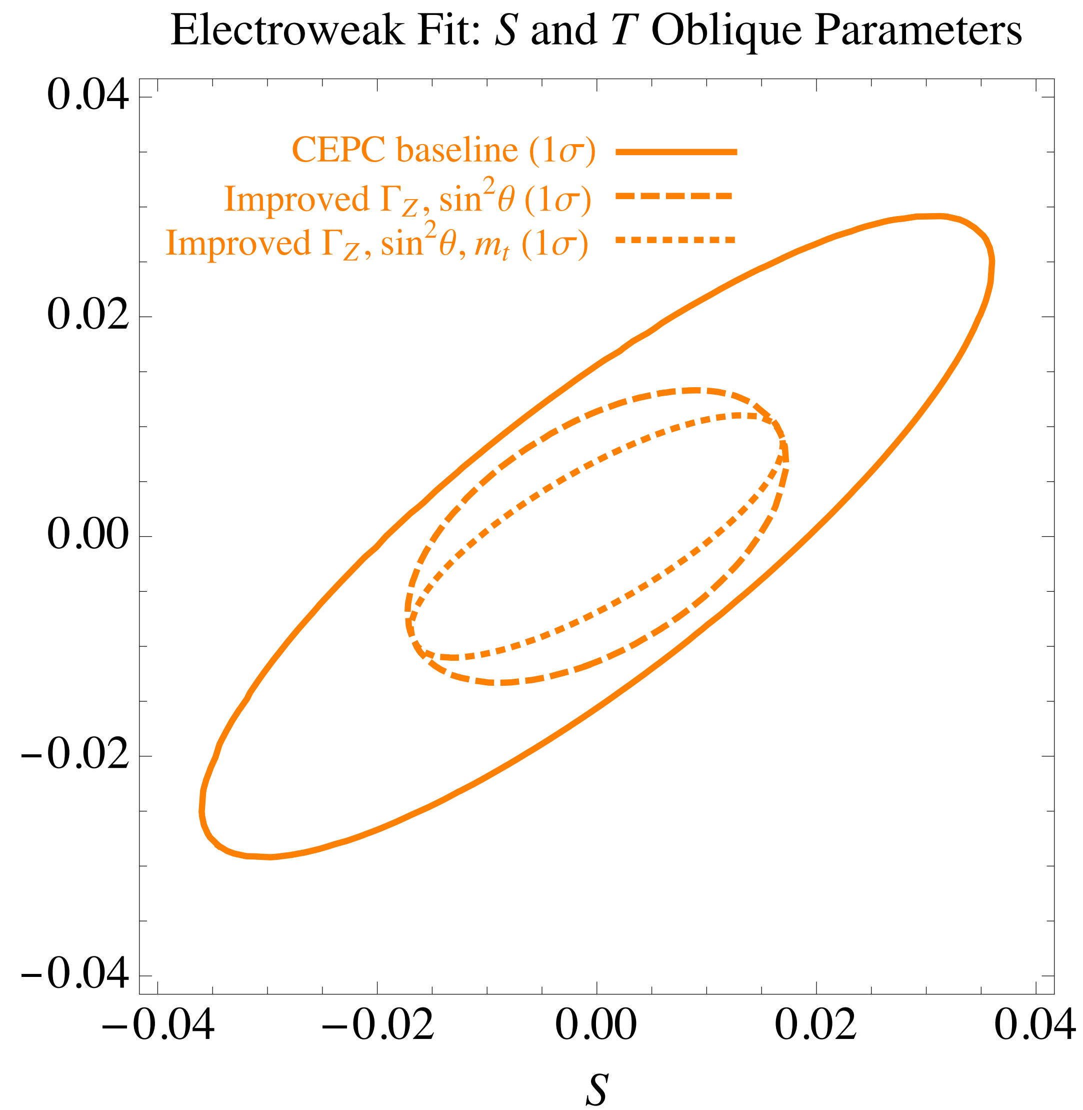
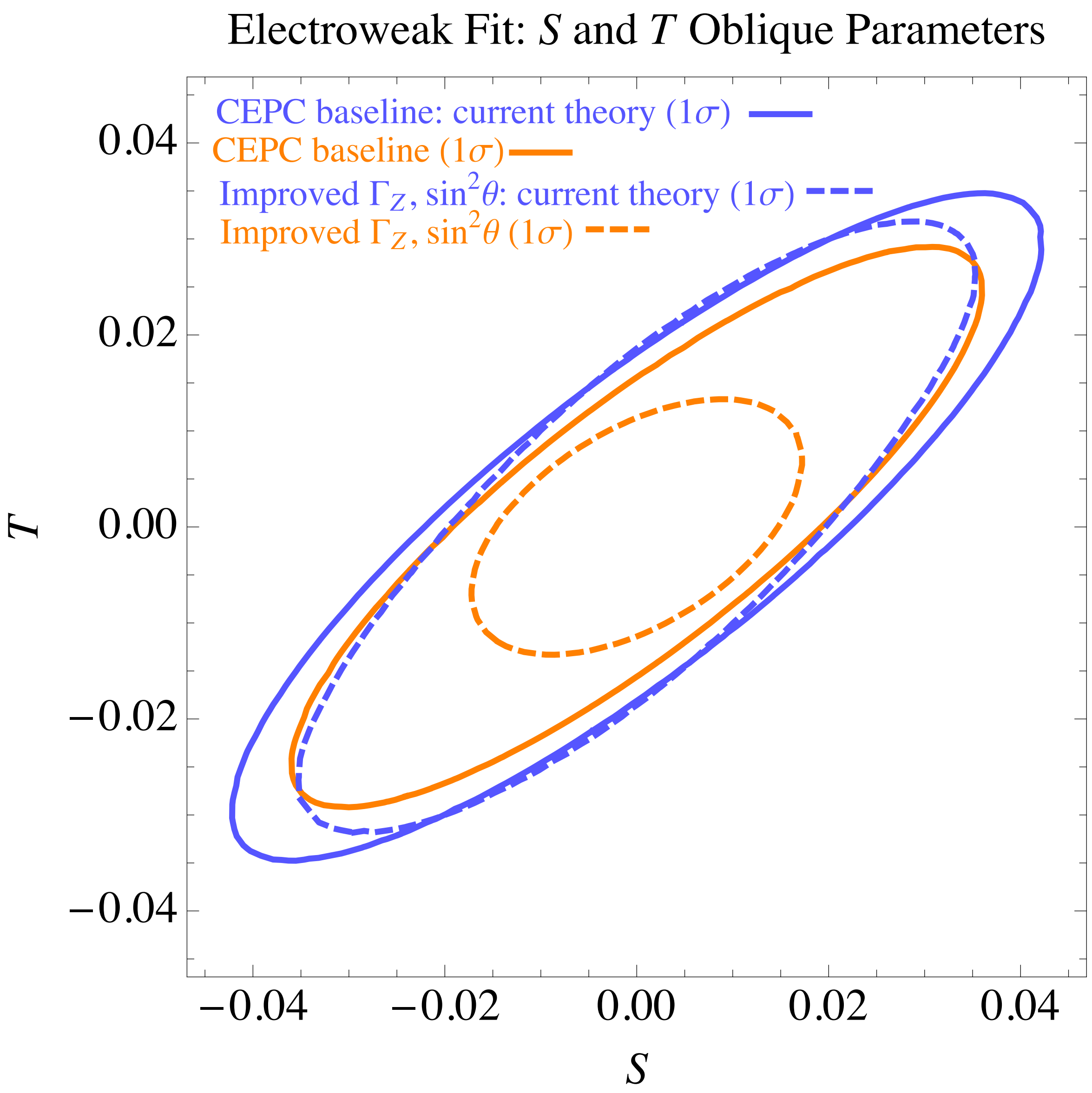




Parameter	Current	CEPC baseline	Improved $\Gamma_Z, \sin^2\theta$	Also improved m_t
S	3.6×10^{-2}	1.3×10^{-2}	9.7×10^{-3}	7.1×10^{-3}
T	3.1×10^{-2}	1.0×10^{-2}	7.5×10^{-3}	4.6×10^{-3}

Challenge (opportunity) for theorists



Our main result (orange contour) assumes completion of most electroweak 3 loop calculations.

Pushing beyond current status by at least one order is crucial.

Targets of a successful EW program

- $\delta m_W < 5$ MeV
- $\delta \sin^2\theta_{eff} < 2\times10^{-5}$ (and/or Γ_Z about 100 keV)
- $\delta m_Z < 500$ keV
- $\delta m_t < 100$ MeV
- Better measurements + theory for $\Delta\alpha_{had}$.
- Higher order calculations.

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Probing New Physics

Probing new physics: Higgs coupling vs electroweak precision

New physics effect at lepton colliders can be parameterized as two classes of effective operators

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$$(\partial_\mu h^\dagger h),\ (h^\dagger h) h f f^c,\ (h^\dagger h) F_{\mu\nu}^2,\ (h^\dagger h)^3,\ \ldots$$

Does not break any SM symmetry. Higgs coupling measurement gives stronger bounds.
Only feed into EW precision at higher order.

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Higgs coupling vs electroweak precision

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Only feed into EW precision at higher order.

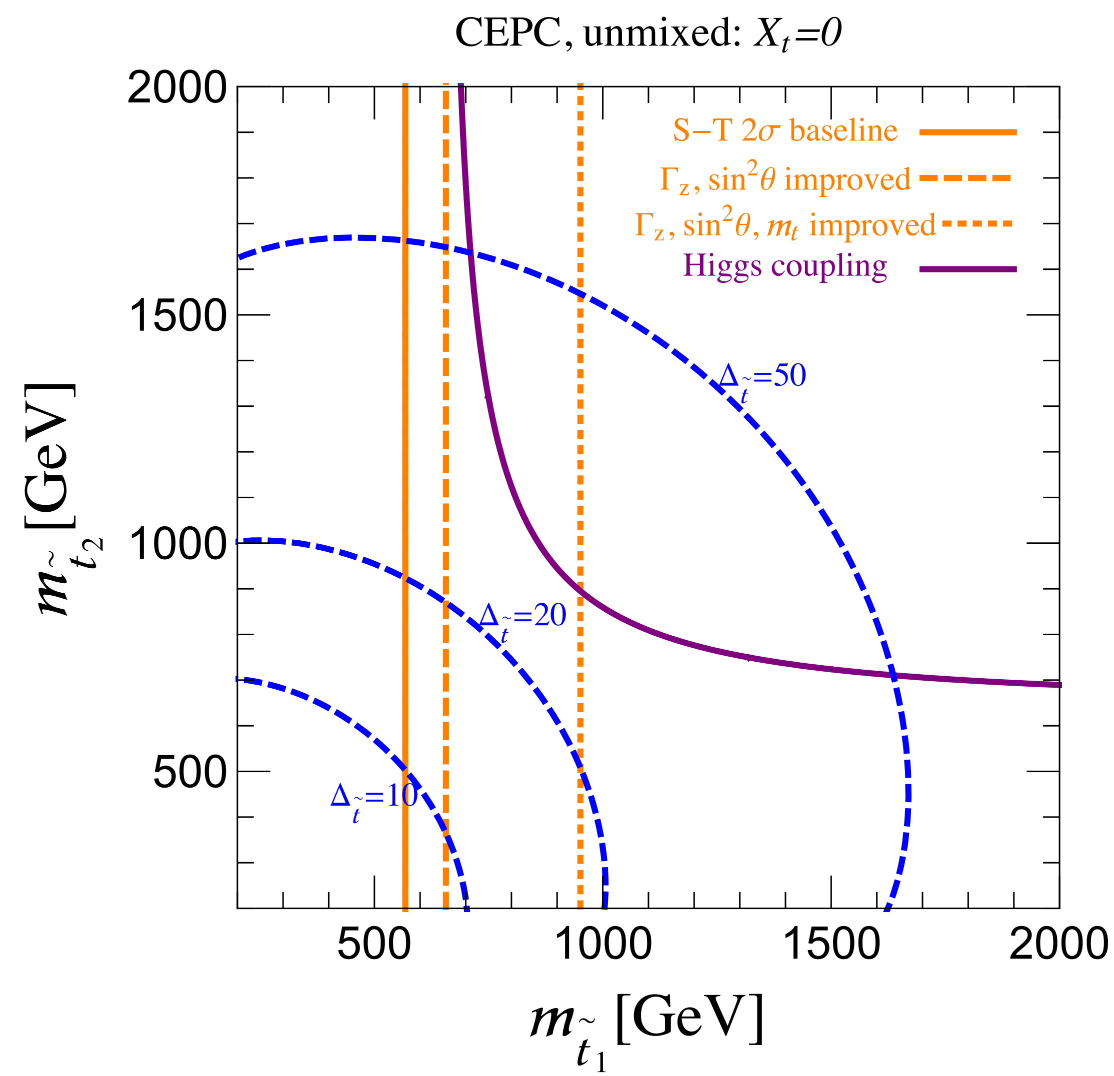
$$h^\dagger D^\mu h \bar{f} \bar{\sigma}_\mu f,\ (h^\dagger D_\mu h)^2,\ h^\dagger W^{\mu\nu} h B_{\mu\nu}, \ldots$$

Breaks SM symmetry, EW precision tests have better sensitivity.

Naturalness, fine-tuning

- Outstanding mystery: huge difference between W/Z/h masses and M_{Planck}, 16 order of magnitude!
- Many models to address this question. Most prominently: Supersymmetry and composite Higgs.
- LHC searches model dependent, many blind spots.
- Precision measurement at CEPC provides a powerful and complementary probe.

Supersymmetry: stop

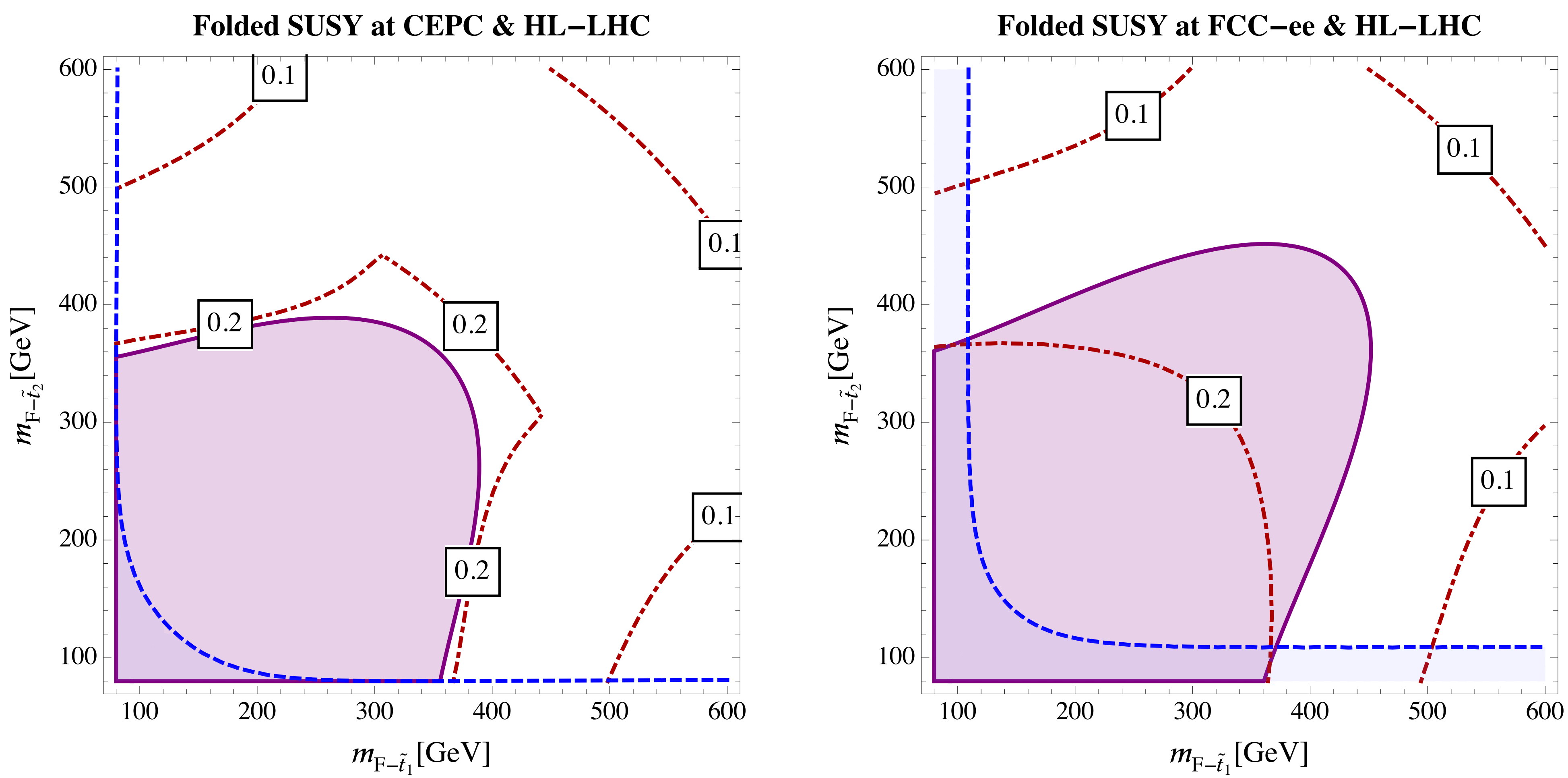


J. Fan, M. Reece, LT Wang, 1412.3107

- Both Higgs coupling and EW precision important.
- Model independent testing fine-tuning down to percent level.

Can SUSY be hidden from the LHC?

- Folded SUSY.
- Top partner has SM electroweak couplings only.
- No hgg. Only hγγ. Weak limit from Higgs coupling measurements.



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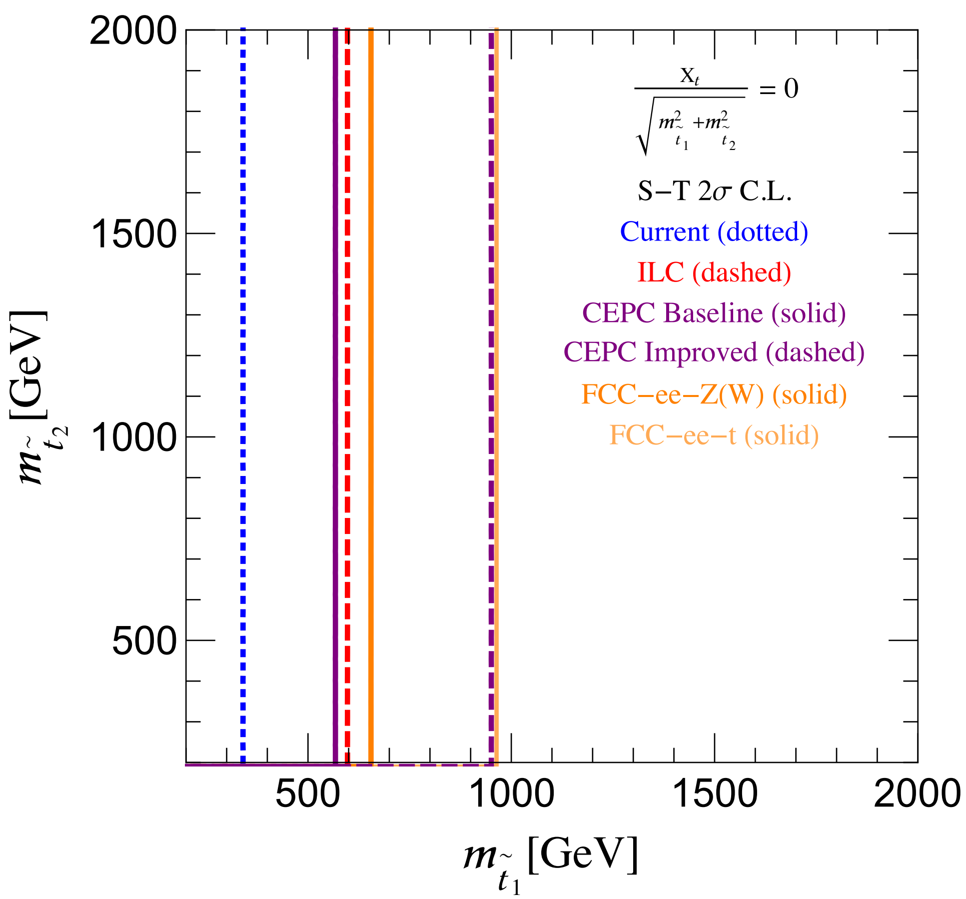
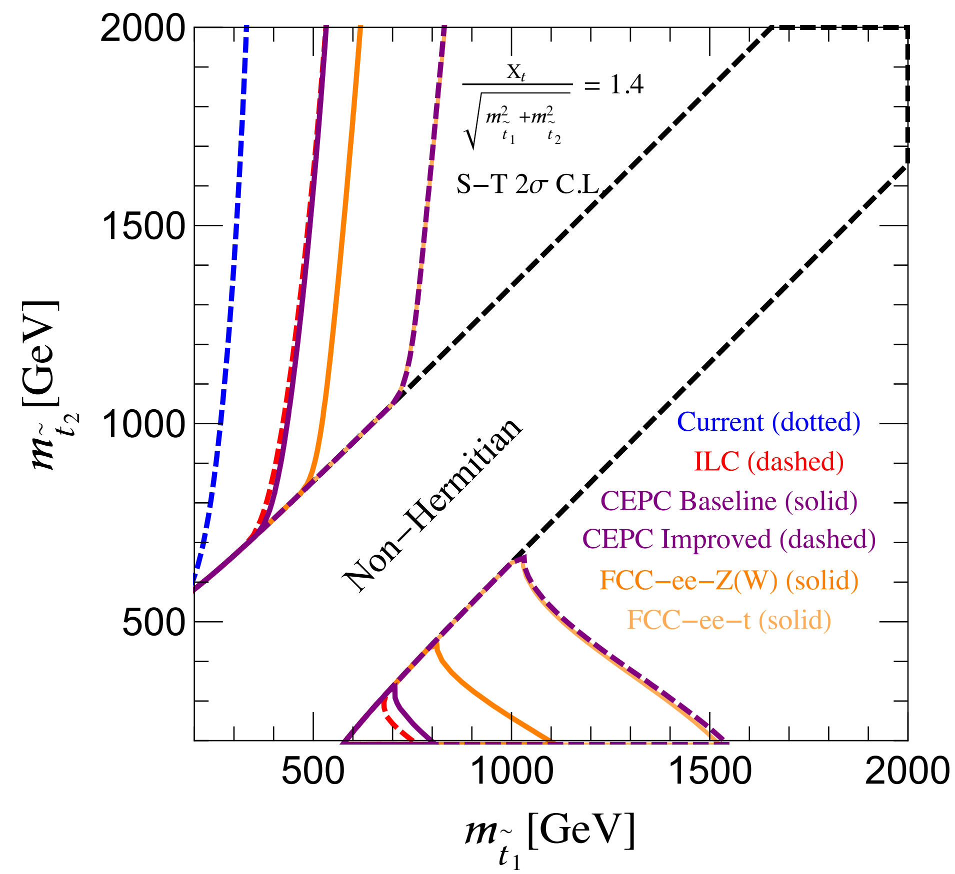
Folded SUSY

- However, they do introduce correction in EW precision observables.
- Leads to stronger limit.





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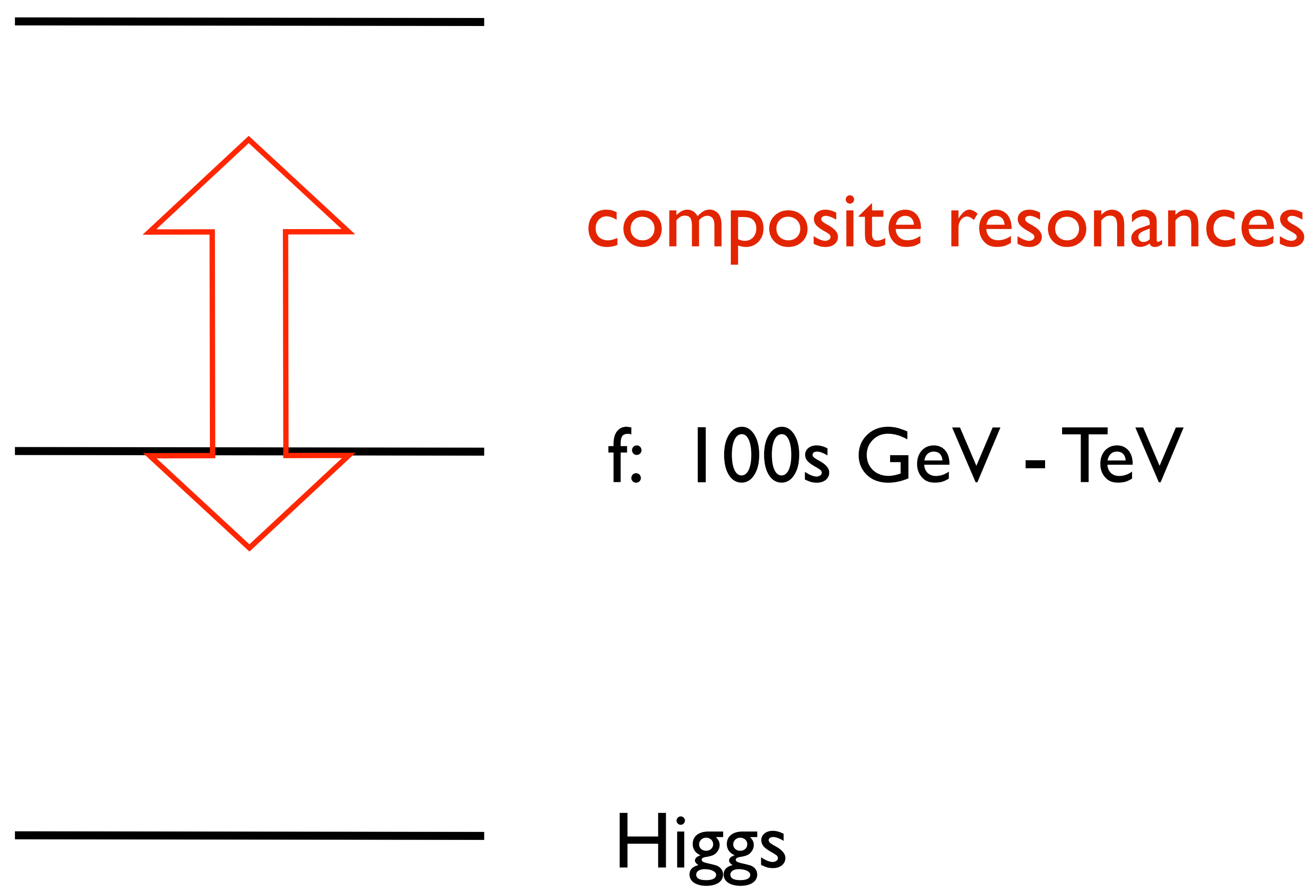
Is the Higgs composite?



LHC searches can go up to f = (a couple of) TeV.

Composite Higgs at CEPC

Experiment	κ_Z (68%)	f (GeV)	κ_g (68%)	$m_{\tilde{t}_L}$ (GeV)
HL-LHC	3%	1.0 TeV	4%	430 GeV
ILC500	0.3%	3.1 TeV	1.6%	690 GeV
ILC500-up	0.2%	3.9 TeV	0.9%	910 GeV
CEPC	0.2%	3.9 TeV	0.9%	910 GeV
TLEP	0.1%	5.5 TeV	0.6%	1.1 GeV

By measuring Higgs coupling.

Composite Higgs at CEPC

Composite resonances couples to W and Z. Will give rise to deviation in EW precision observables.

$$S \simeq \frac{N}{4\pi}\frac{v^2}{f^2}$$

Experiment	S (68%)	f (GeV)
ILC	0.012	1.1 TeV
CEPC (opt.)	0.02	880 GeV
CEPC (imp.)	0.014	1.0 TeV
TLEP-Z	0.013	1.1 TeV
TLEP-t	0.009	1.3 TeV

Higgs portal.

$$\frac{1}{\Lambda} H^\dagger H \bar{\chi}\chi \qquad \boldsymbol{\chi}\text{: new fermions}$$

Among simplest possible new physics couplings.

Present in many interesting contexts:
Dark matter, composite top partner, ...

What can precision measurements tell us about new physics at scale Λ?

Need to consider different kinds of possible new physics.

UV completions of Higgs portal

New physics (I): a new scalar particle

$$\mathcal{L}_{\rm EFT} \supset -\frac{a\kappa_S}{m_S} H^\dagger H \bar{\chi}\chi + \frac{a^2}{m_S^2}\frac{1}{2}(\partial_\mu |H|^2)^2 + \cdots$$

Tree level corrections to the Higgs couplings.

UV completions of Higgs portal

New physics (I): a new scalar particle

$$\mathcal{L}_{\text{EFT}} \supset -\frac{a\kappa_S}{m_S} H^\dagger H \bar{\chi}\chi + \frac{a^2}{m_S^2}\frac{1}{2}(\partial_\mu |H|^2)^2 + \cdots$$

Tree level corrections to the Higgs couplings.

New physics (II): a new fermion doublet

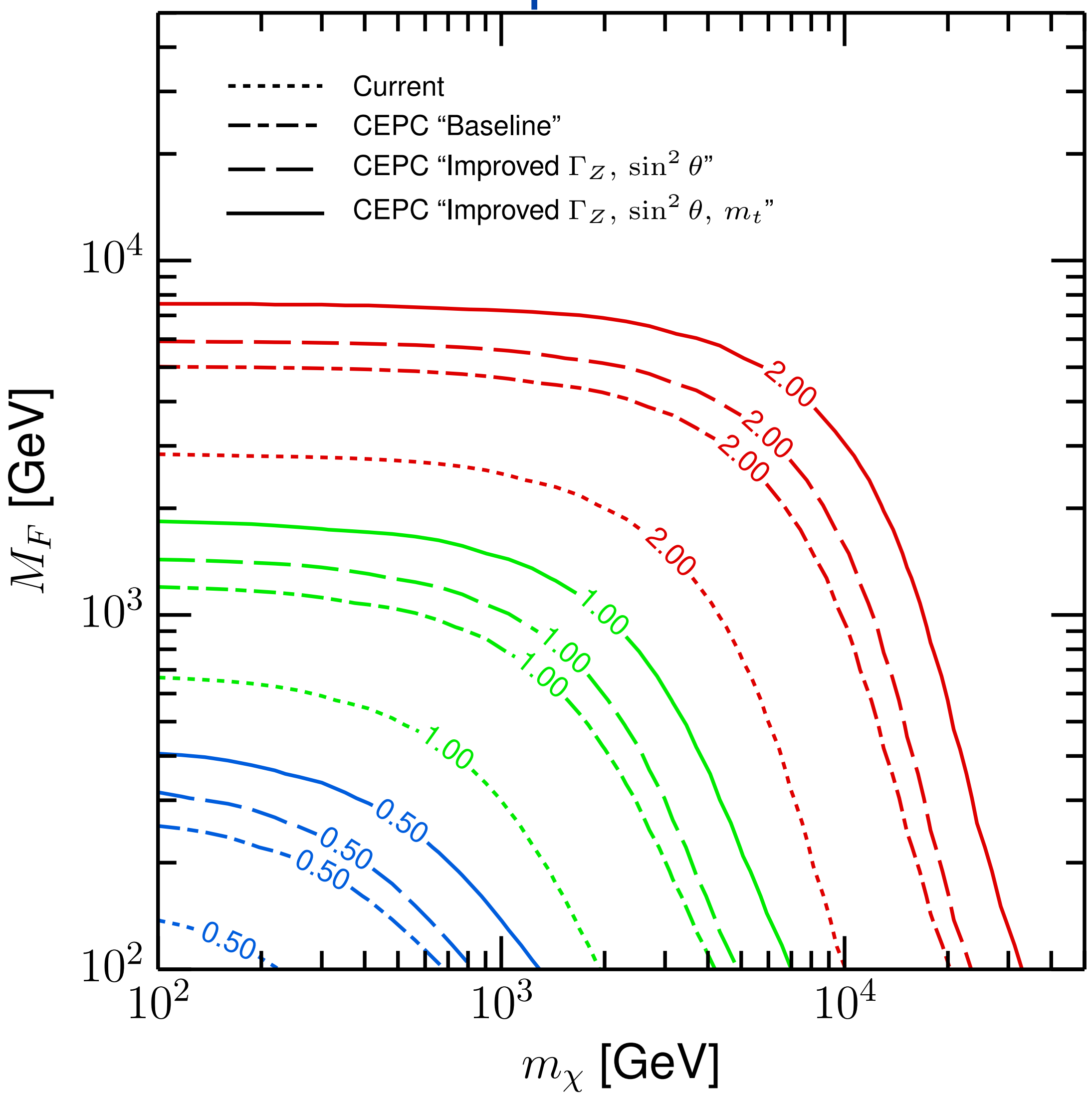
$$F \sim (\mathbf{1}, \mathbf{2}, +1/2) \qquad\qquad - M_F \bar{F}F - \kappa \bar{F} H \chi - \kappa \bar{\chi} H^\dagger F.$$

Breaks SM custodial SU(2) symmetry.

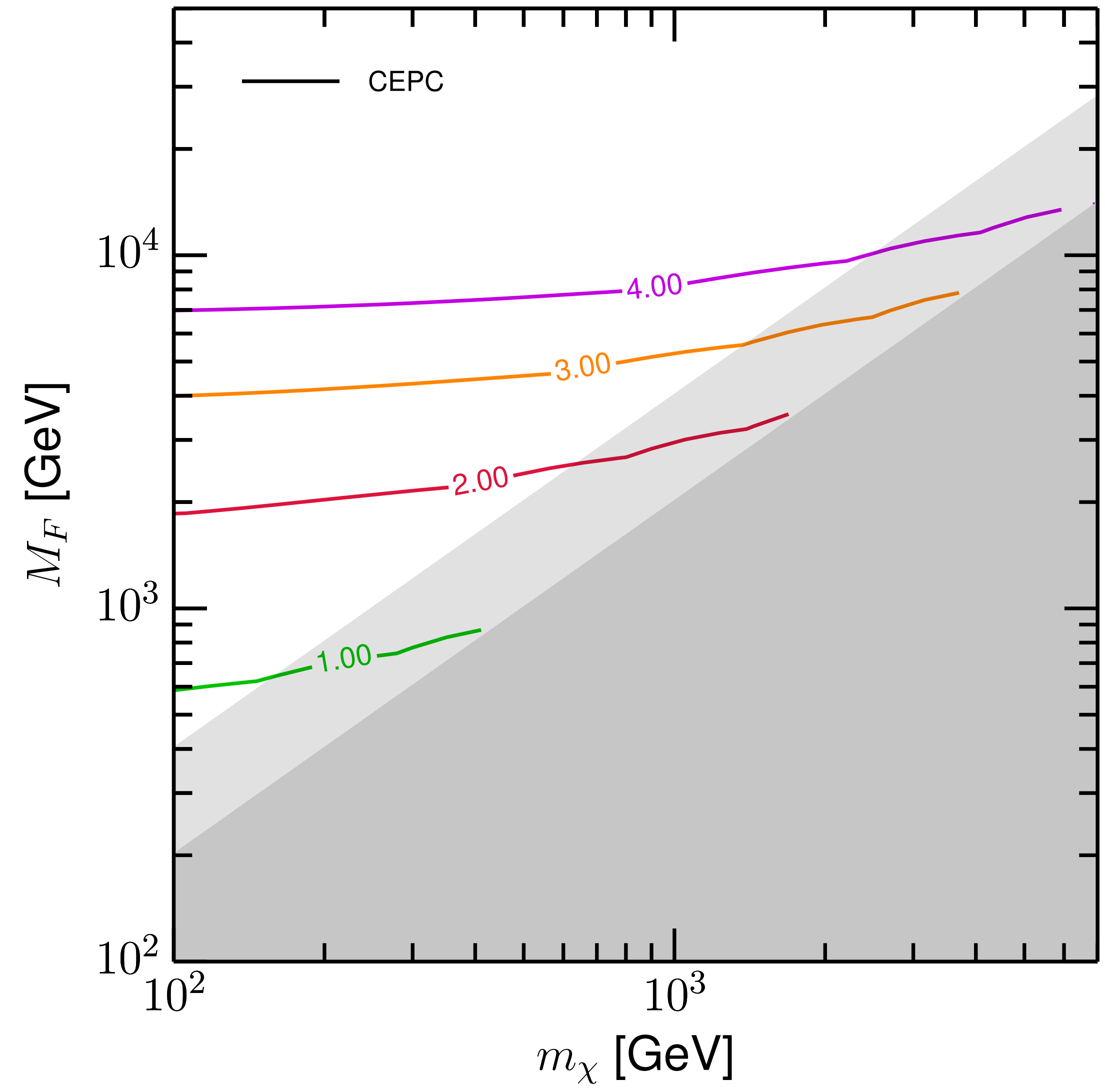
One-loop correction to both T-parameter and Higgs couplings.

Reach at CEPC

EW precision



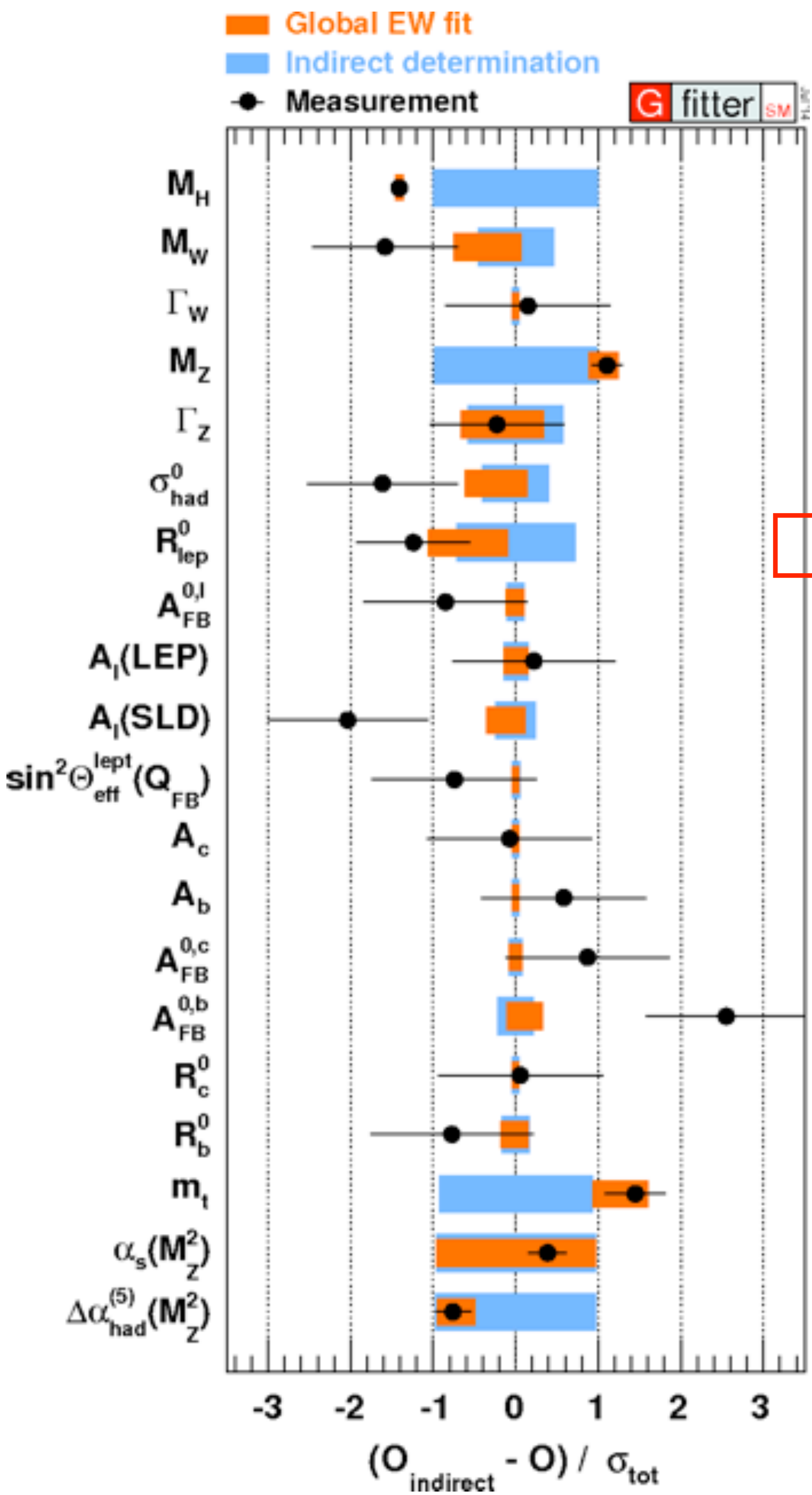
Higgs coupling

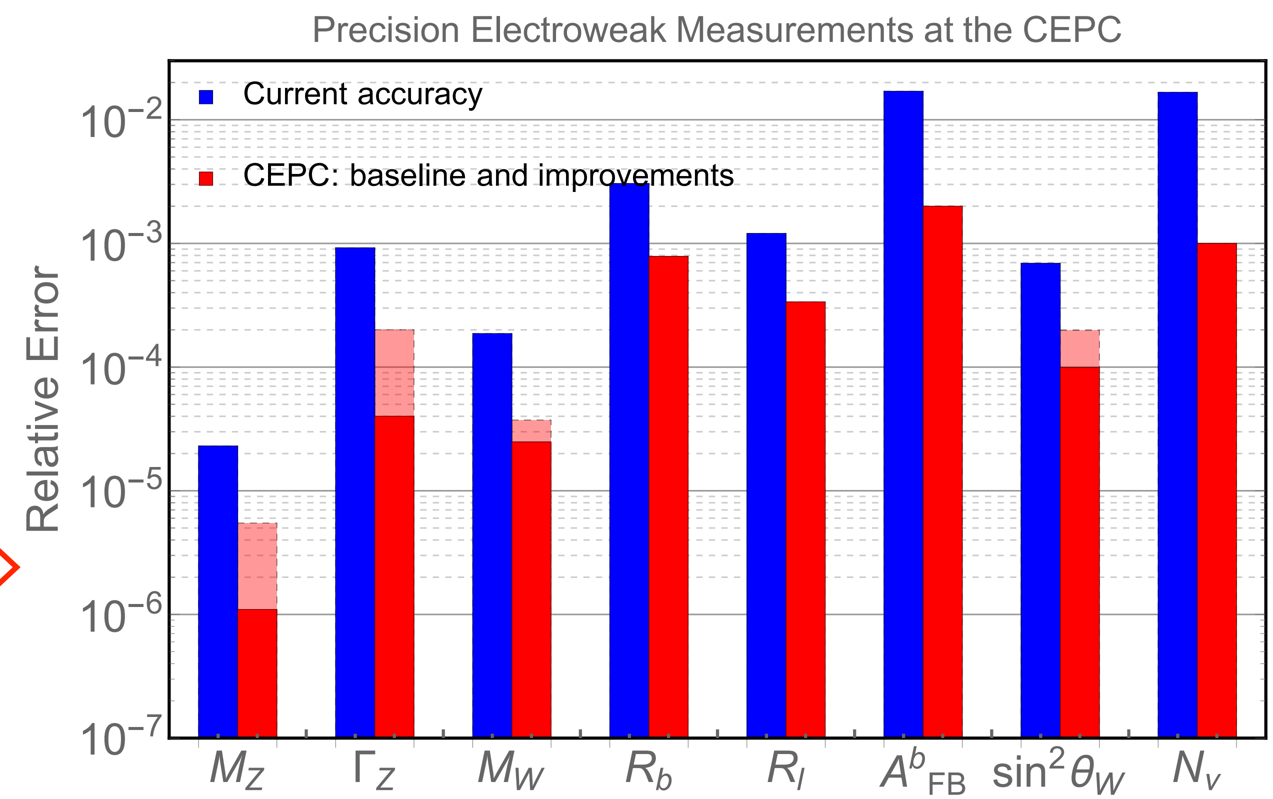


Z-pole has better sensitivity.

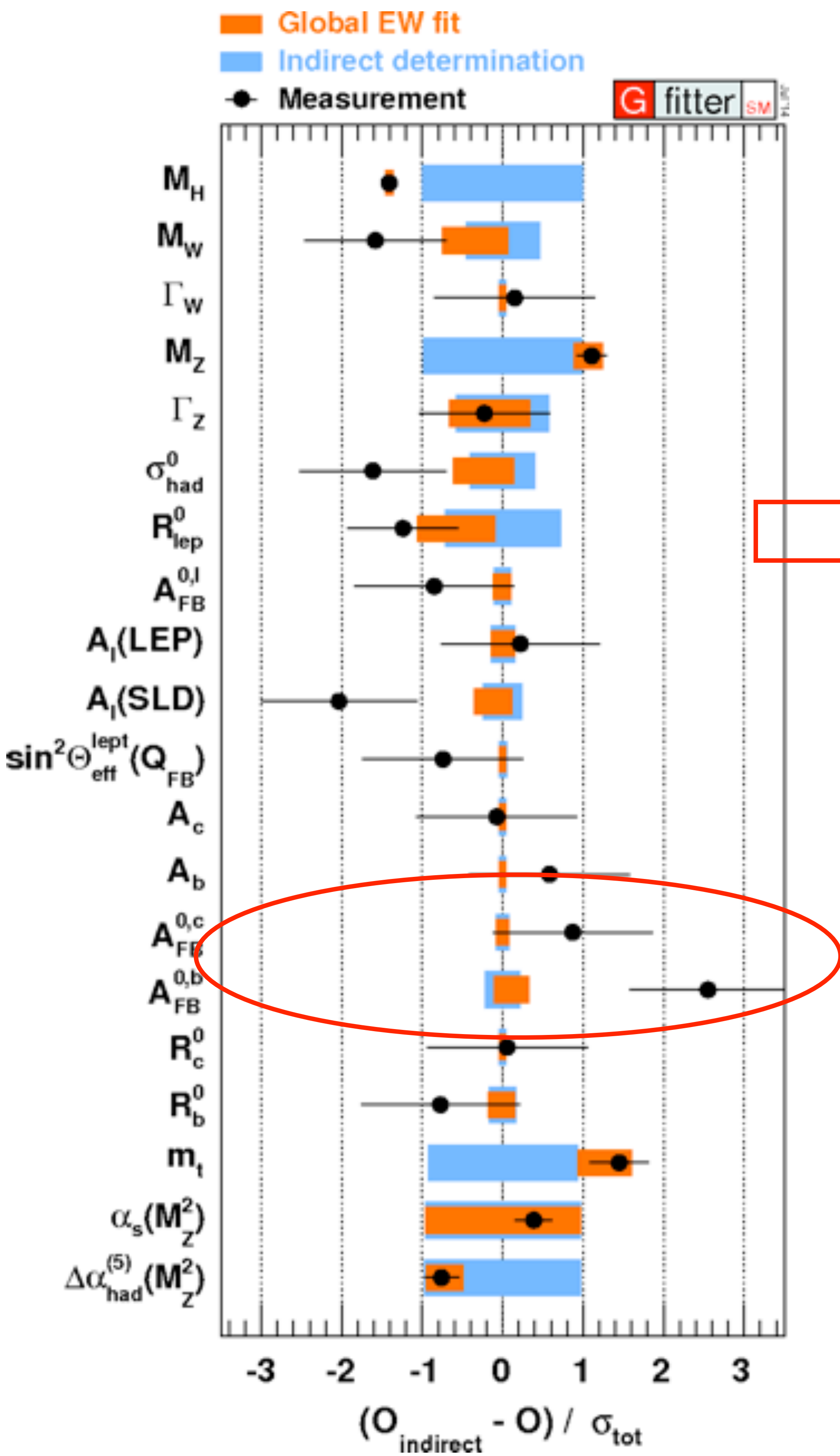
Higgs coupling complementary. Will be the leading channel if UV completion preserves custodial SU(2).

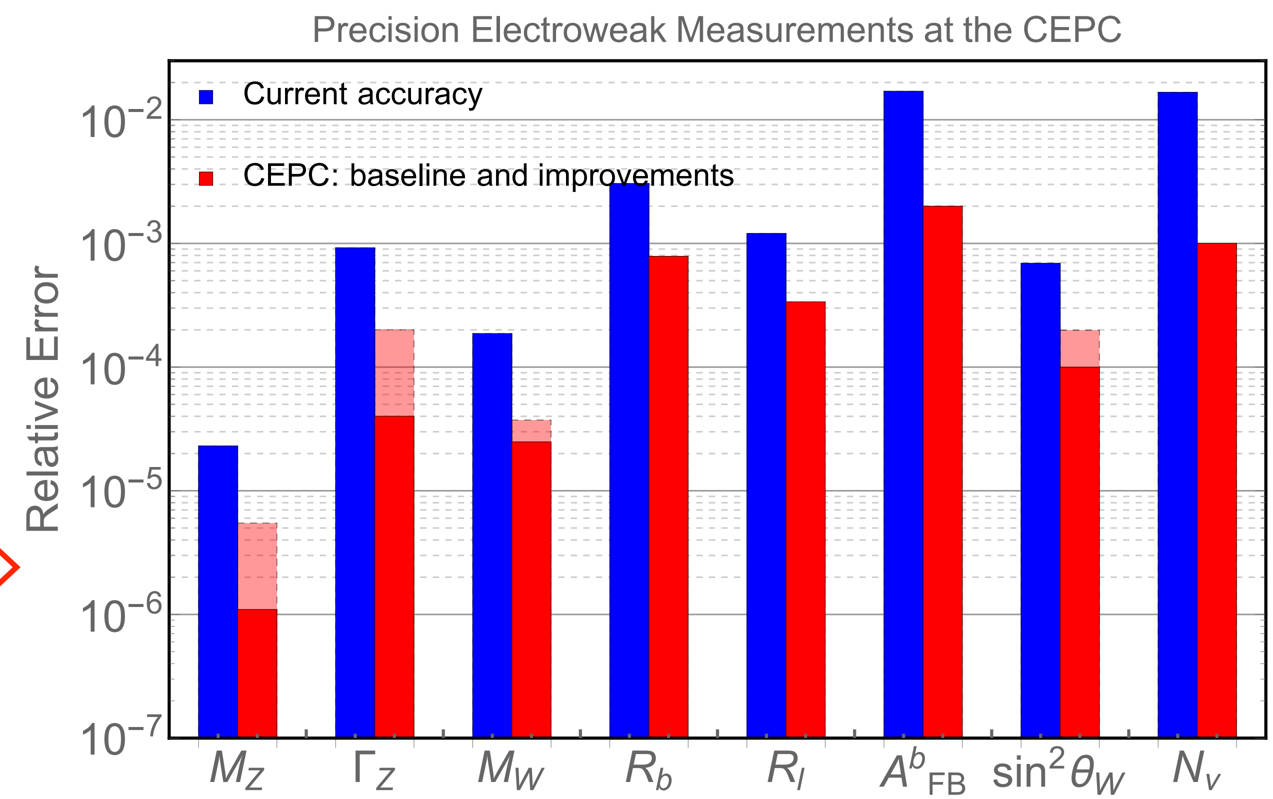
A much better microscope





A much better microscope





New physics?
We will find out.

Conclusions.

- CEPC is a big step forward in terms of precision measurements: both Higgs and electroweak
- Great potential in probing a wide range of important new physics.
- Complementary to direct searches at colliders.
- We have just started to explore the potential of the EW program. Much more to be done.

Z-pole program of CEPC

10^2 (s) fb^{-1} planned, > 10^3 times more Zs than LEP

Observable	LEP precision	CEPC precision	CEPC runs	$\int \mathcal{L}$ needed in CEPC
m_Z	2 MeV	0.5 MeV	Z threshold scan runs	$> 150\text{fb}^{-1}$
m_W	33 MeV	3 MeV	ZH runs	$> 100\text{fb}^{-1}$
A^b_{FB}	1.7%	0.15%	Z threshold scan runs	$> 150\text{fb}^{-1}$
$\sin^2\theta_W^{\text{eff}}$	0.07%	0.02%	Z threshold scan runs	$> 150\text{fb}^{-1}$
R^b	0.3%	0.08%	Z pole	$> 100\text{fb}^{-1}$
N^ν (direct measurement)	1.7%	0.2%	ZH runs	$> 100\text{fb}^{-1}$
N^ν (indirect measurement)	0.27%	0.1%	Z threshold scan runs	$> 150\text{fb}^{-1}$
R^μ	0.2%	0.05%	Z pole	$> 100\text{fb}^{-1}$
R^τ	0.2%	0.05%	Z pole	$> 100\text{fb}^{-1}$

Baseline option