BSM prospects at future colliders

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Rencontres de Blois, May 30, 2017

This talk

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- Assuming no discovery of new particle at the LHC.
  - If there is a discovery at the LHC, what to do next would be obvious.

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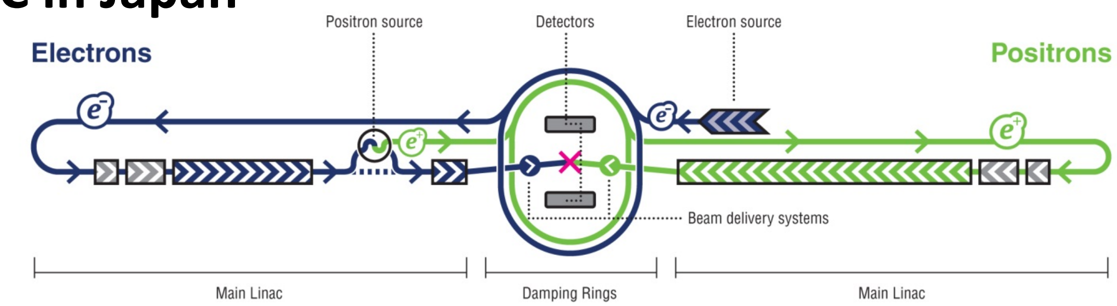
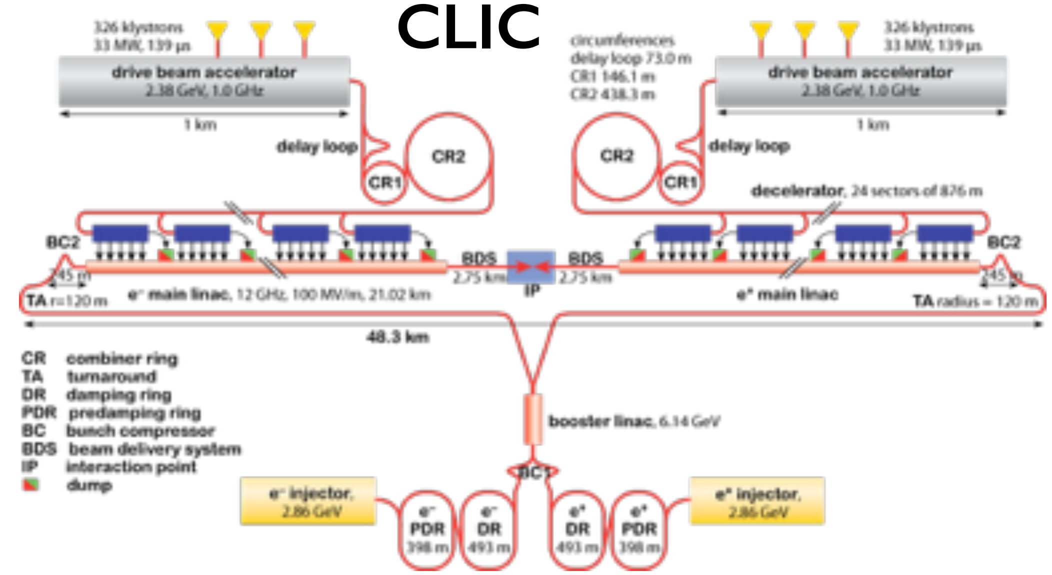
- Assuming no discovery of new particle at the LHC.
  - If there is a discovery at the LHC, what to do next would be obvious.
- Physics case for future colliders
  - Cover significant ground beyond the LHC.
  - Answering important questions beyond the reach of the LHC

Beyond the LHC, future facilities

ILC in Japan



CLIC

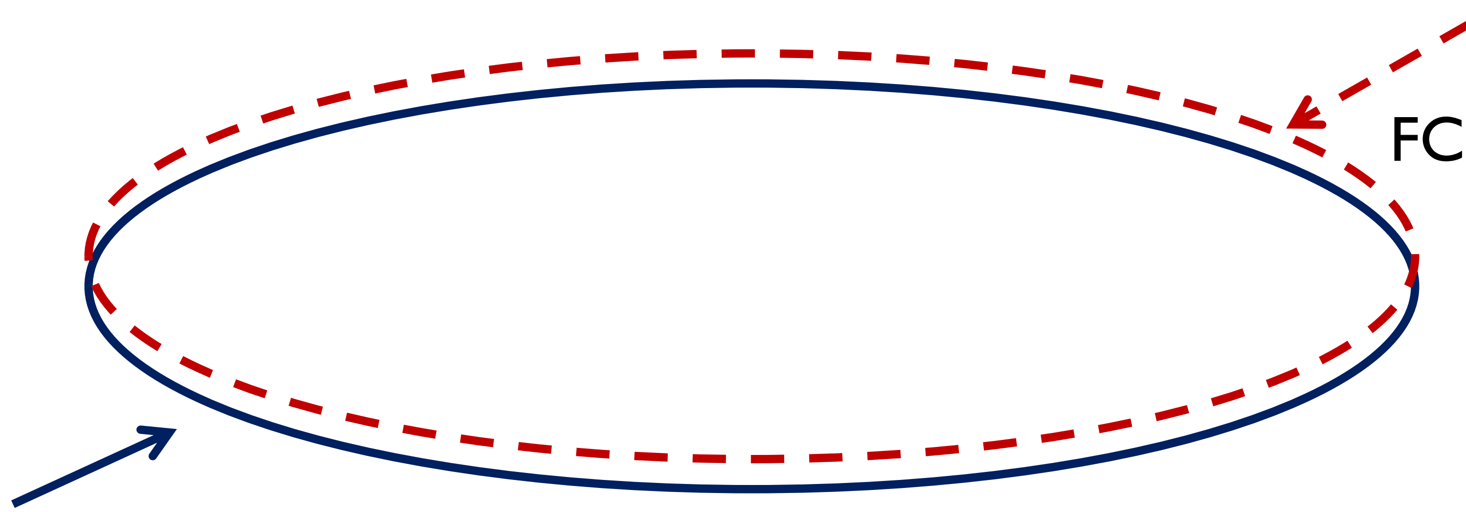


Circular. "Scale up" LEP+LHC

~100 TeV

pp collider

FCC-hh (CERN), SppC(China)



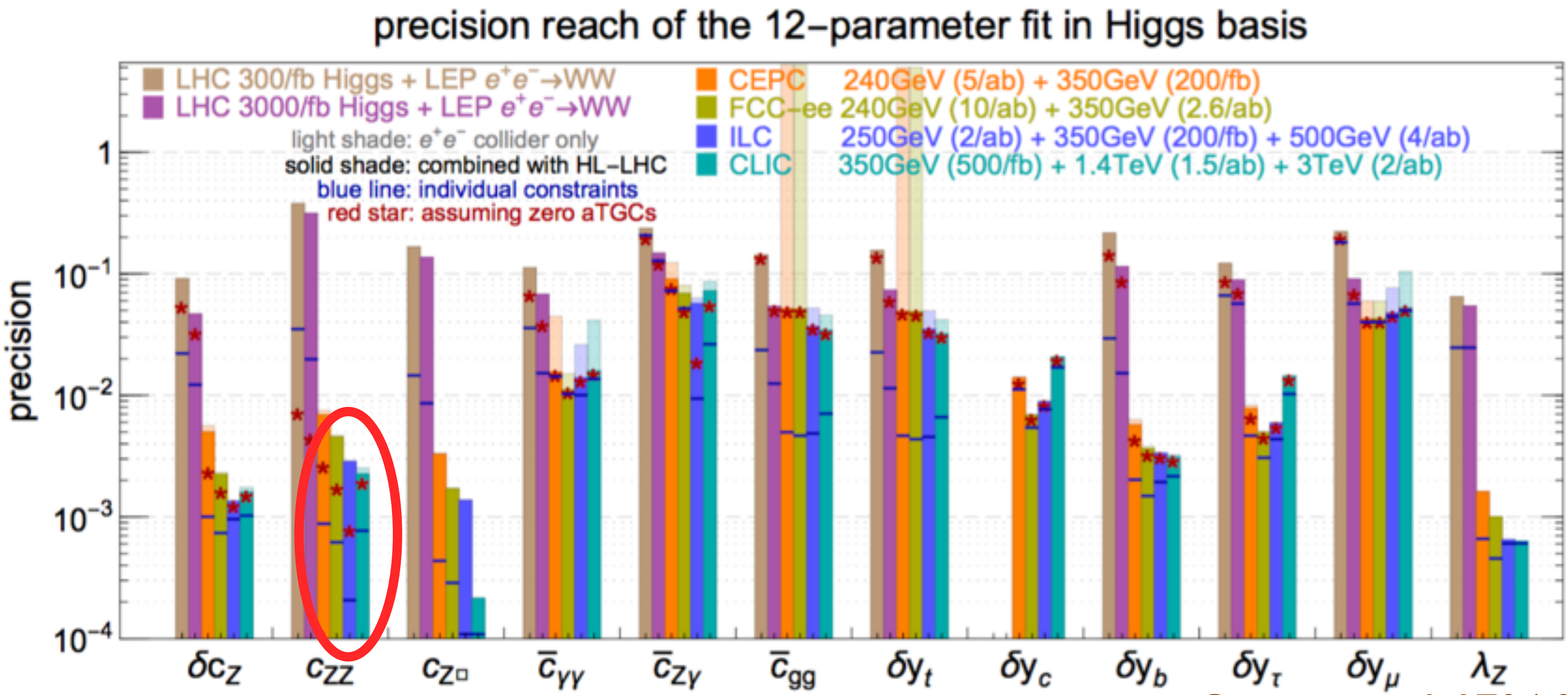
250 GeV **e^-e^+ Higgs Factory**

FCC-ee (CERN), CEPC(China)

Lepton colliders as Higgs factories

- Physics case relatively independent of the outcome of the LHC.
  - Reach further than the LHC.
  - Address questions that LHC can't answer.

Lepton colliders and precision measurements



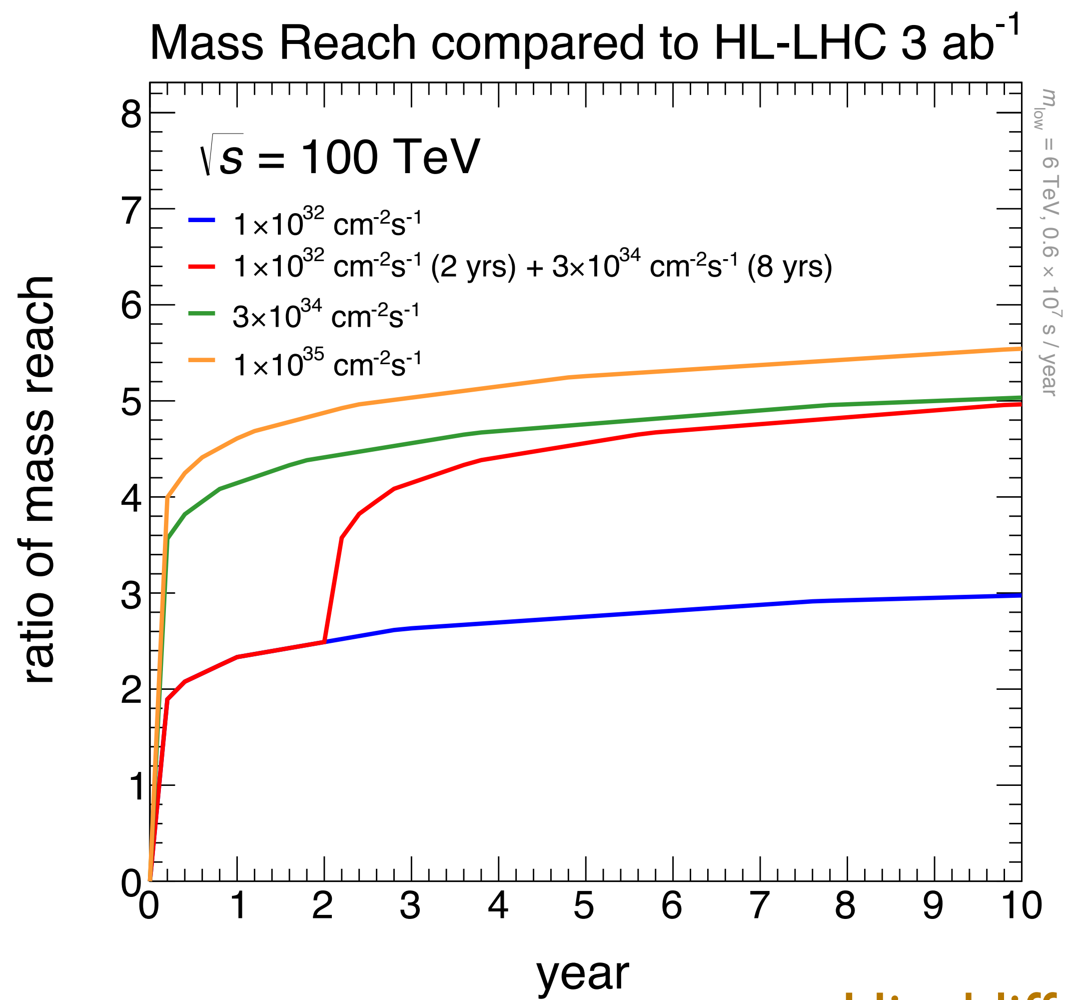
Grojean et al. 1704.02333

New physics with mass M_{NP} can affect Higgs coupling as

$$\delta \sim \frac{m_W^2}{M_{\rm NP}^2}$$

Sub percent precision, reach to new physics at multi-TeV scale.
Far beyond the reach of LHC.

100-ish TeV pp collider



Hinchliffe, Kotwal, Mangano, Quigg, LTW

A factor of at least 5 increase in reach beyond the LHC, with modest luminosity

On future hadron colliders

On future hadron colliders

- Physics case "obvious". The energy frontier.

On future hadron colliders

- Physics case "obvious". The energy frontier.
- Without LHC discovery.
  - Physics case for a 100 TeV pp collider stronger than HE-LHC at 28 TeV.
  - Cost+technological challenge. Perhaps easier to "sell" only as a second step of a circular Higgs factory in longer term.

SM cannot be the final story

- Electroweak symmetry breaking.
- Dark matter.
- Flavor
- CP
- ...

SM cannot be the final story

- Electroweak symmetry breaking.
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My focus here

Electroweak symmetry breaking

Fundamental interactions in the SM

Electromagnetism: Coulomb $\sim \dfrac{\alpha}{r}$

QCD: confinement $\sim r$

Weak interaction: Higgs $\sim \dfrac{e^{-m_{\mathrm{W}} \cdot r}}{r}$

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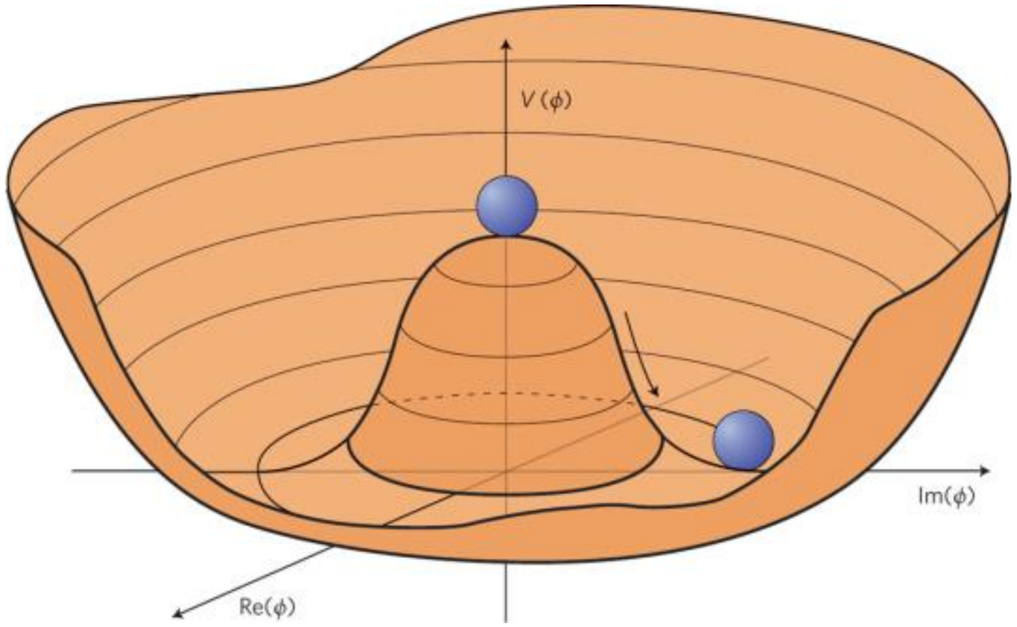
Weak interaction: Higgs $\sim \dfrac{e^{-m_{\mathrm{W}} \cdot r}}{r}$

A very different type of interaction.
With a spin-0 Higgs boson, different from all other particles.
We have just barely started to study it, much to learn.

Mysteries of the electroweak scale.



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

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

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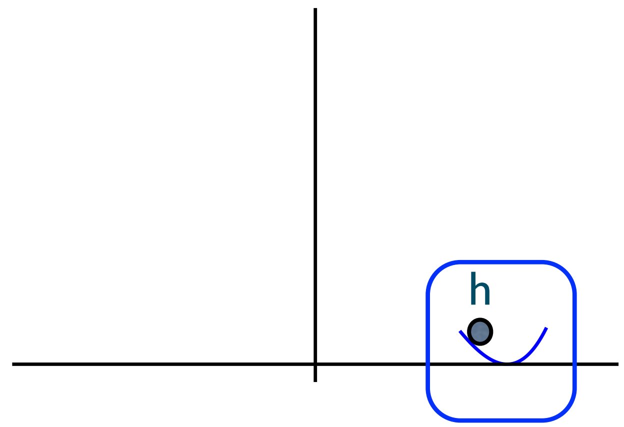
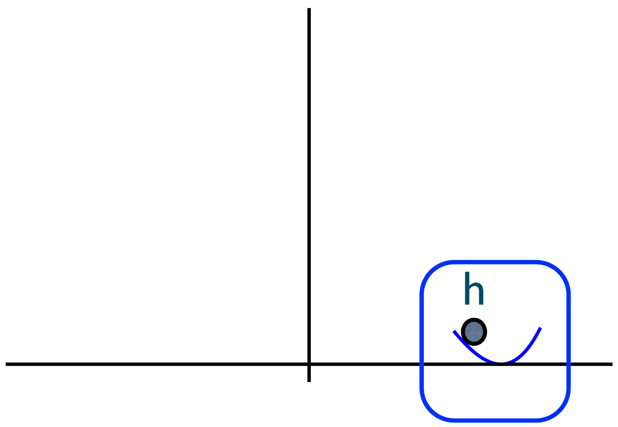


What we know now

- How to predict/calculate Higgs mass?
- What does the rest of the Higgs potential look like? Nature of electroweak phase transition.
- Is it connected to the matter anti-matter asymmetry?

Mysteries of the electroweak scale.



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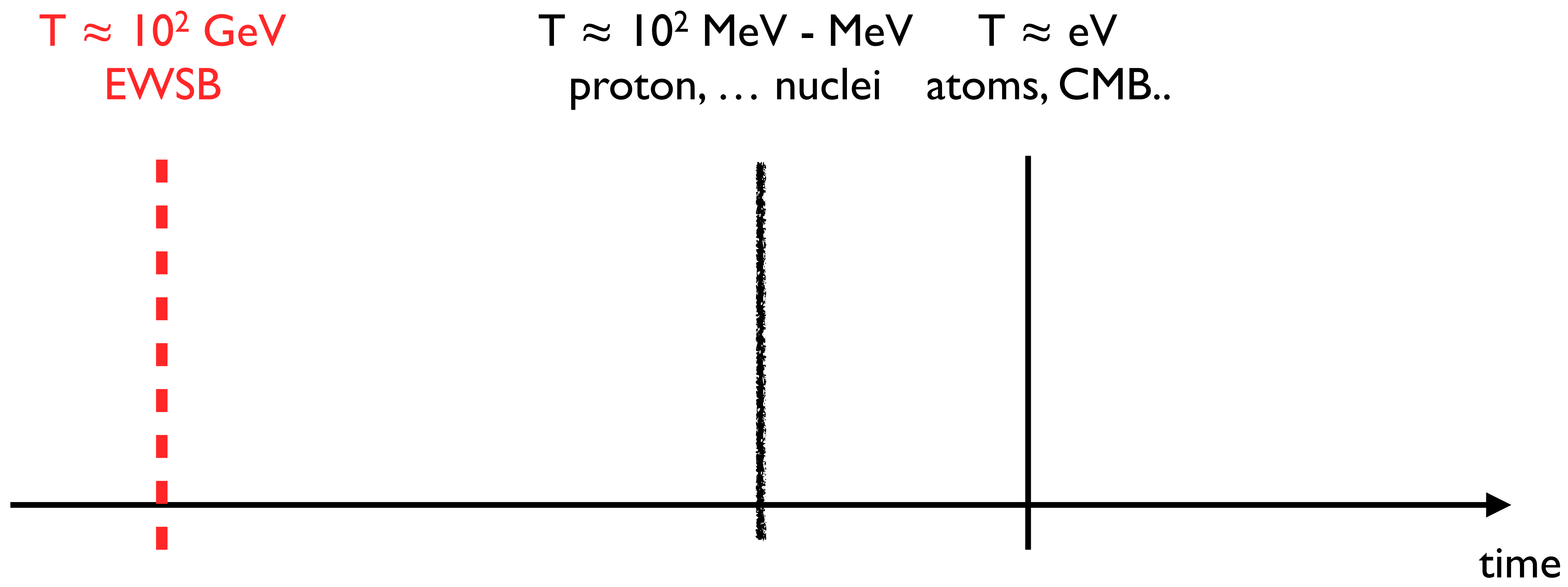
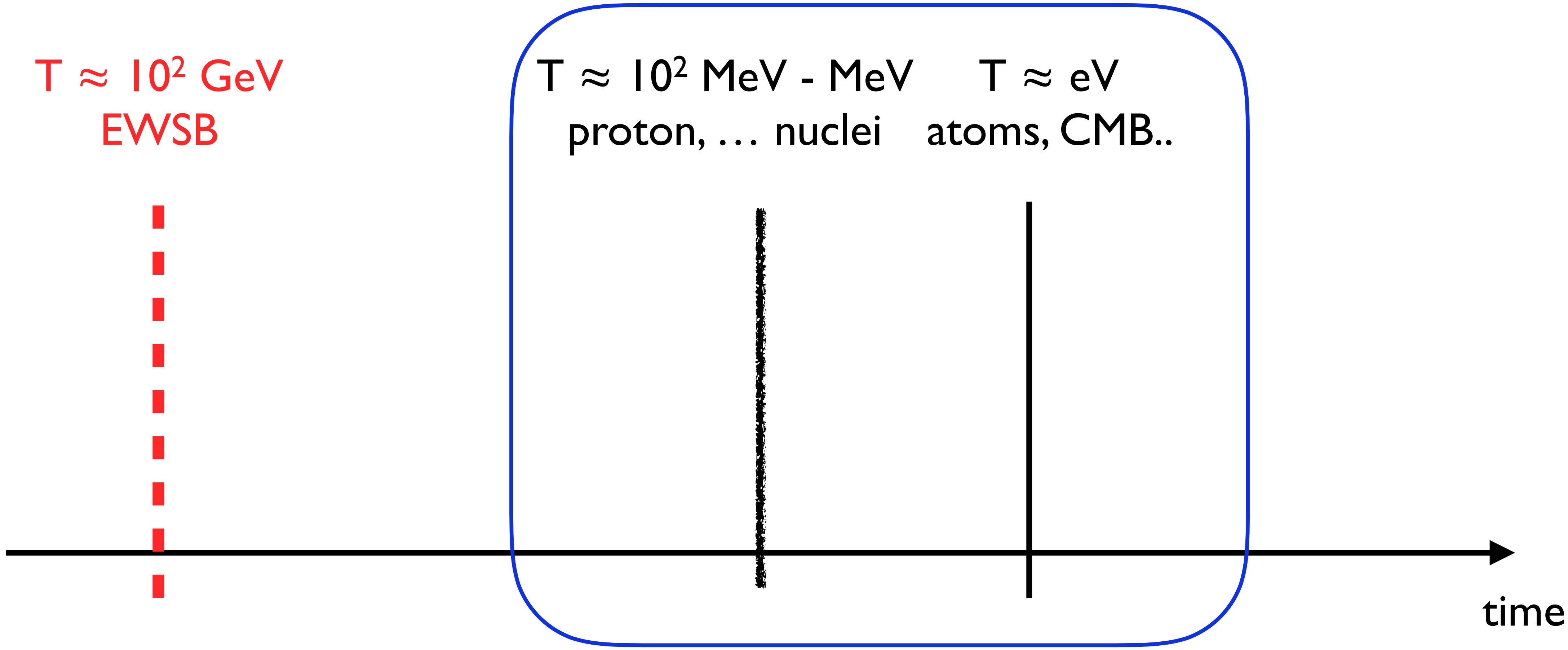
Milestones in cosmology



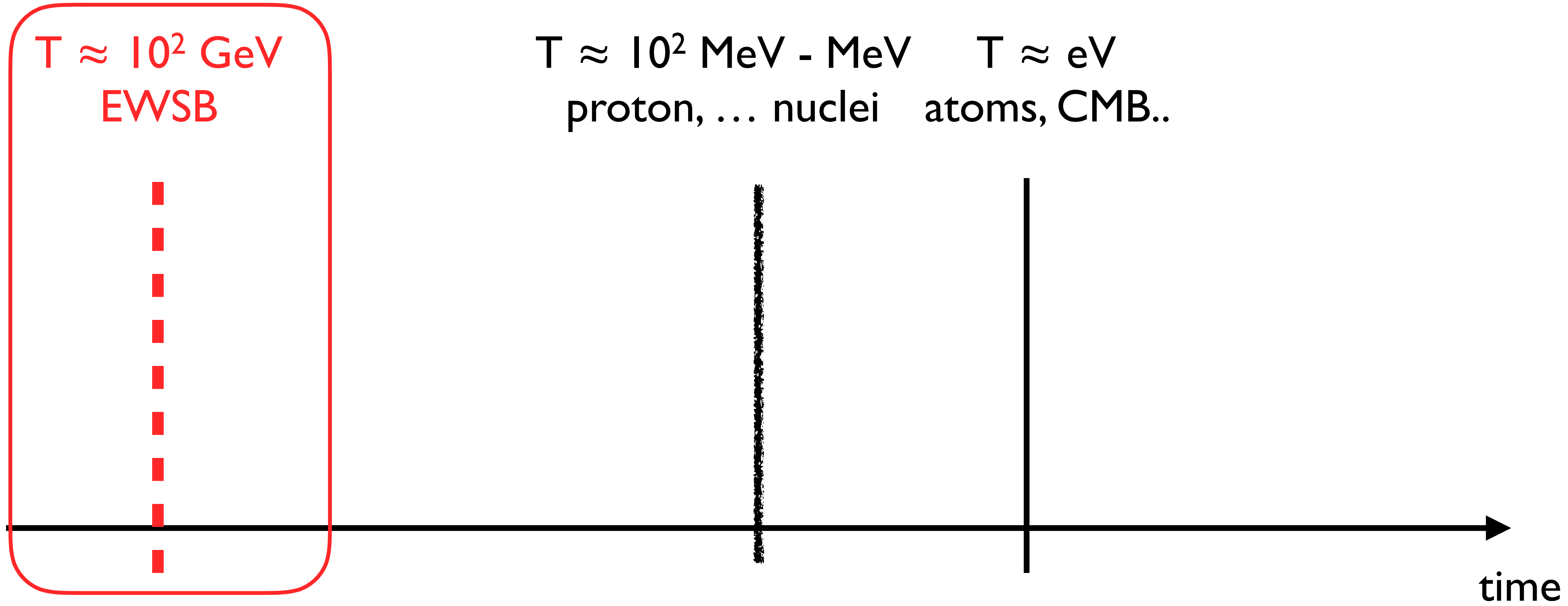
Milestones in cosmology



Well understood through both astrophysical observation and laboratory measurements of particle properties.

Lead to the establishment of modern cosmology

Milestones in cosmology

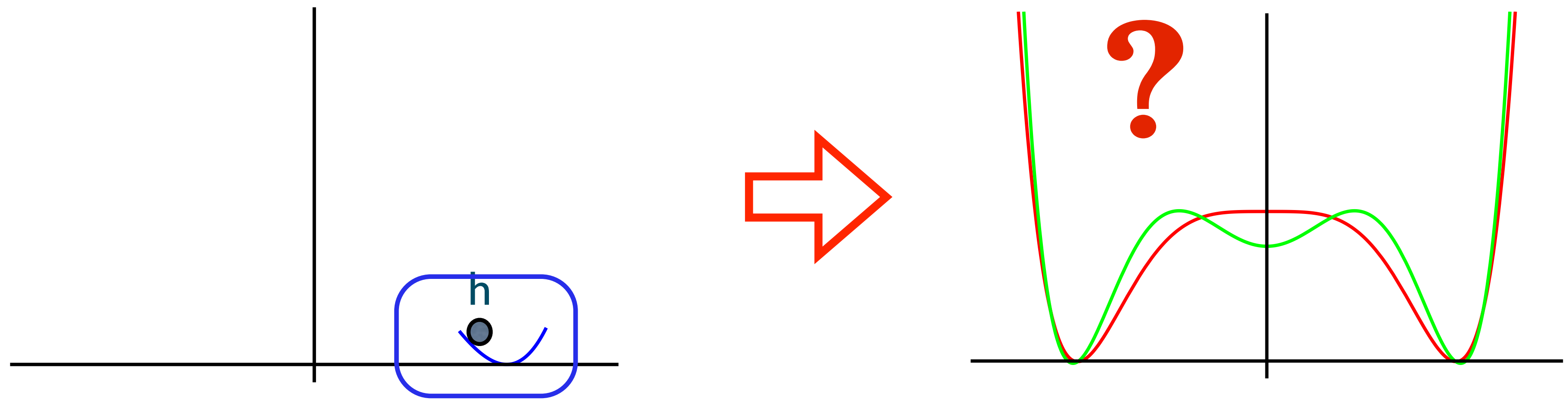


A monumental event. Set stage for later evolution.
W/Z/h and SM matter acquire masses.

Phase transition can lead to matter anti-matter asymmetry.

Yet, our experimental probe has just begun.
Lab measurement of Higgs properties instrumental.

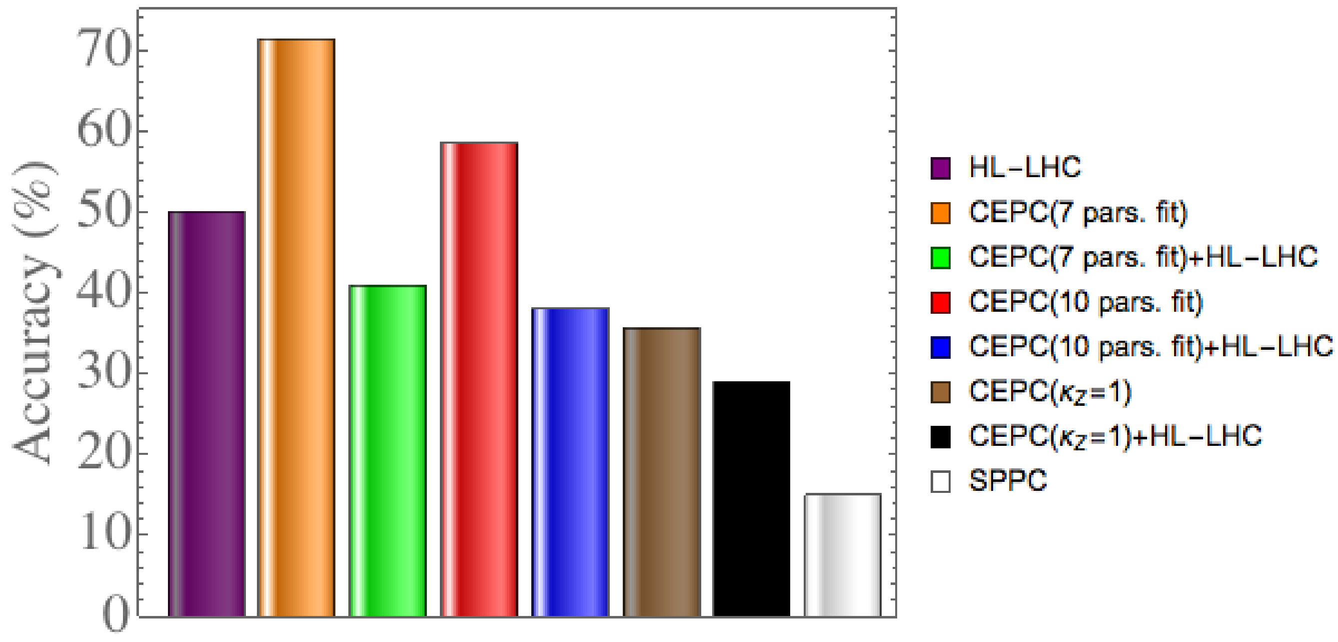
Nature of EW phase transition



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

"wiggles" in Higgs potential

Big difference in triple Higgs coupling



Triple Higgs coupling at 100 TeV pp collider

30 ab^{-1}

$$\frac{\lambda}{\lambda_{\rm SM}} \in \begin{cases} [0.891, 1.115] & \text{no background syst.} \\ [0.882, 1.126] & 25\%\ hh, 25\%\ hh + \text{jet} \\ [0.881, 1.128] & 25\%\ hh, 50\%\ hh + \text{jet} \end{cases}$$

Barr, Dolan, Englert, de Lima, Spannowsky

ILC 500: 27%

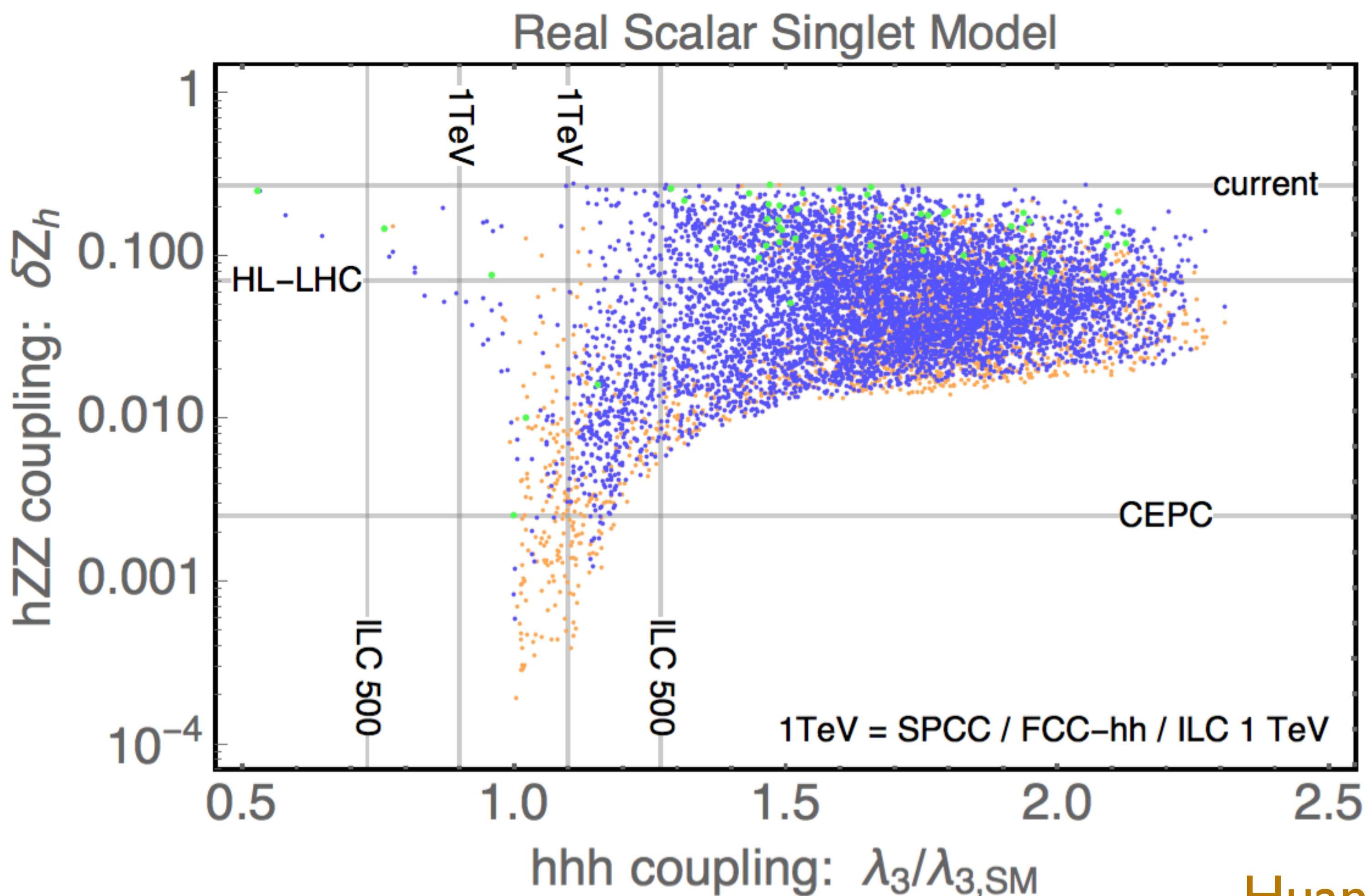
ILC ultimate, 1 TeV 5 ab-1: 10%

But, there should be more

$$V(h) = \frac{m^2}{2} h^2 + \lambda h^4 + \frac{1}{\Lambda^2} h^6 + \ldots$$

- 1st order EW phase transition means there is new physics close to the weak scale.
- Can be difficult to discover at the LHC.
  - Maybe only couple weakly to the Higgs.
- Will leave more signature in Higgs coupling.

Probing EWSB at higgs factories

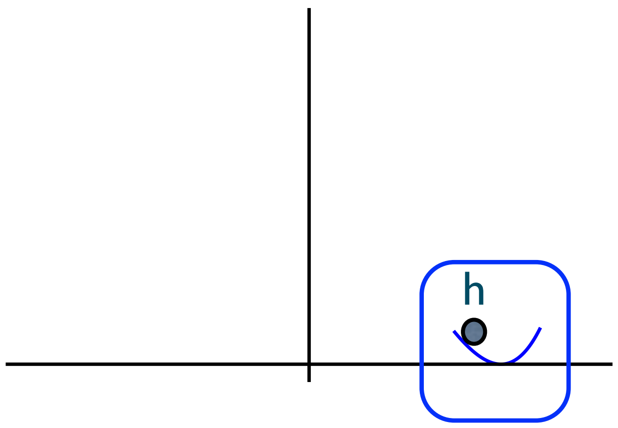


Huang, Long, LTW, 1608.06619

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

Good coverage in model space

Mysteries of the electroweak scale.



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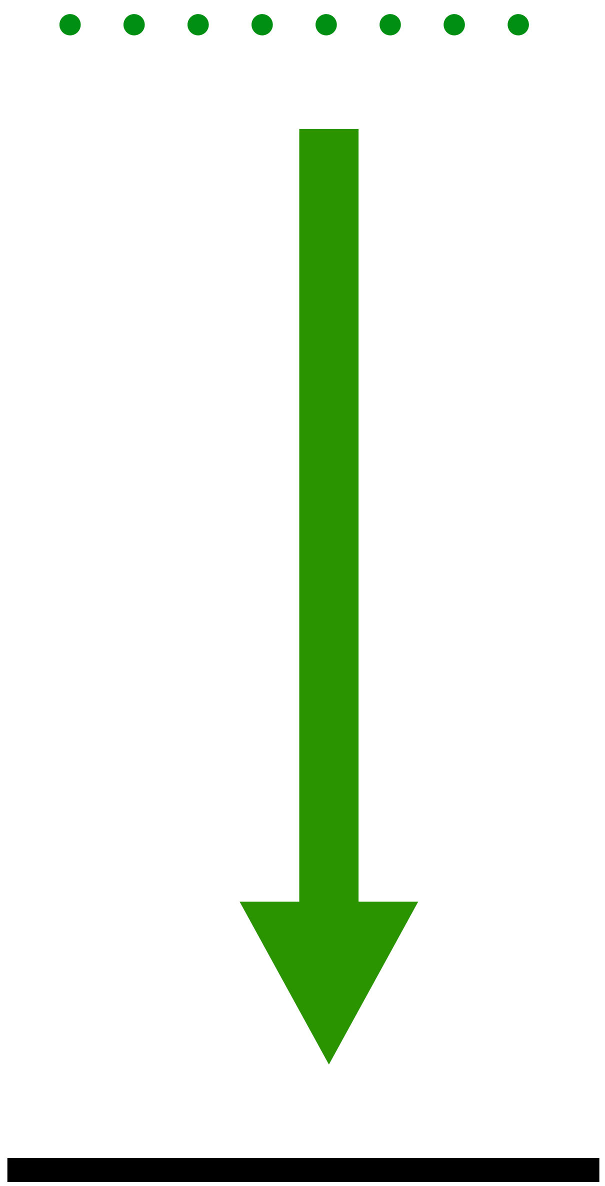
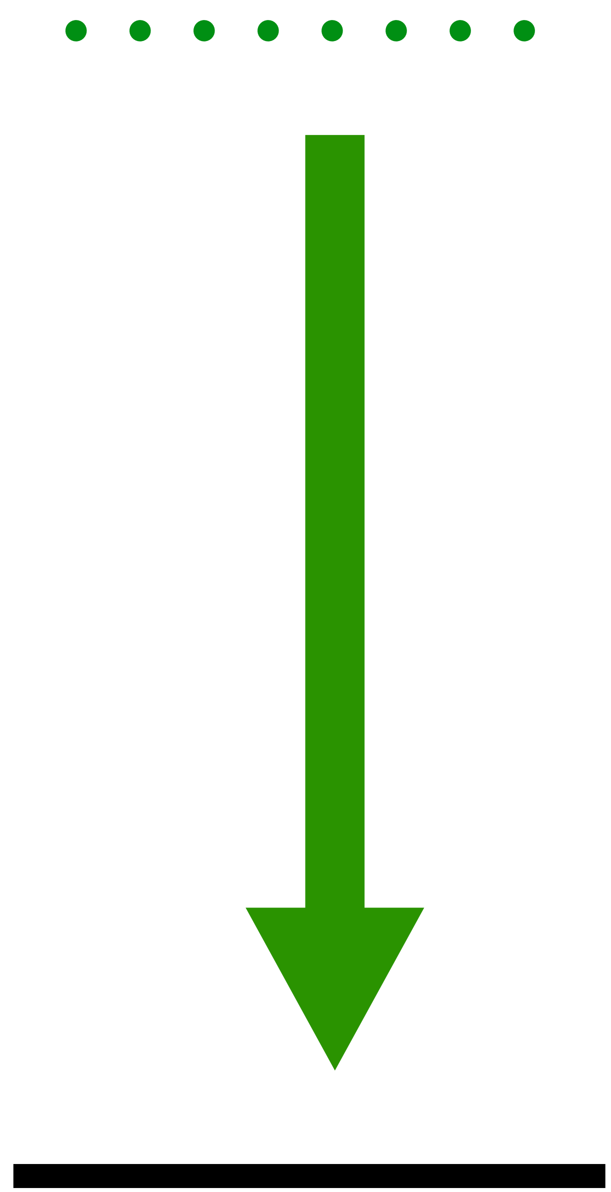
How to predict Higgs mass?



The energy scale of new physics
responsible for EWSB

Electroweak scale, 100 GeV.
m_h , m_W …

How to predict Higgs mass?



The energy scale of new physics
responsible for EWSB

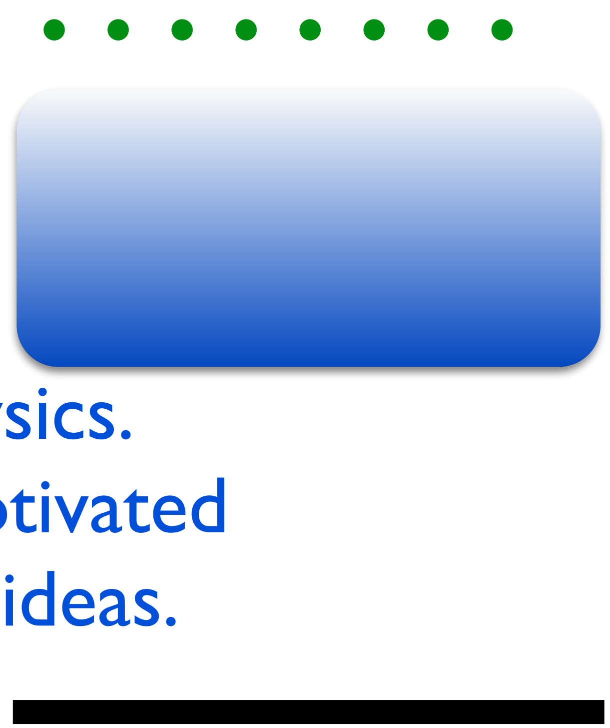
What is this energy scale?
$M_{Planck} = 10^{19}$ GeV, …?

If so, why is so different from 100 GeV?
The so called naturalness problem

Electroweak scale, 100 GeV.
m_h , m_W …

Naturalness of electroweak symmetry breaking

The energy scale of new physics
responsible for EWSB

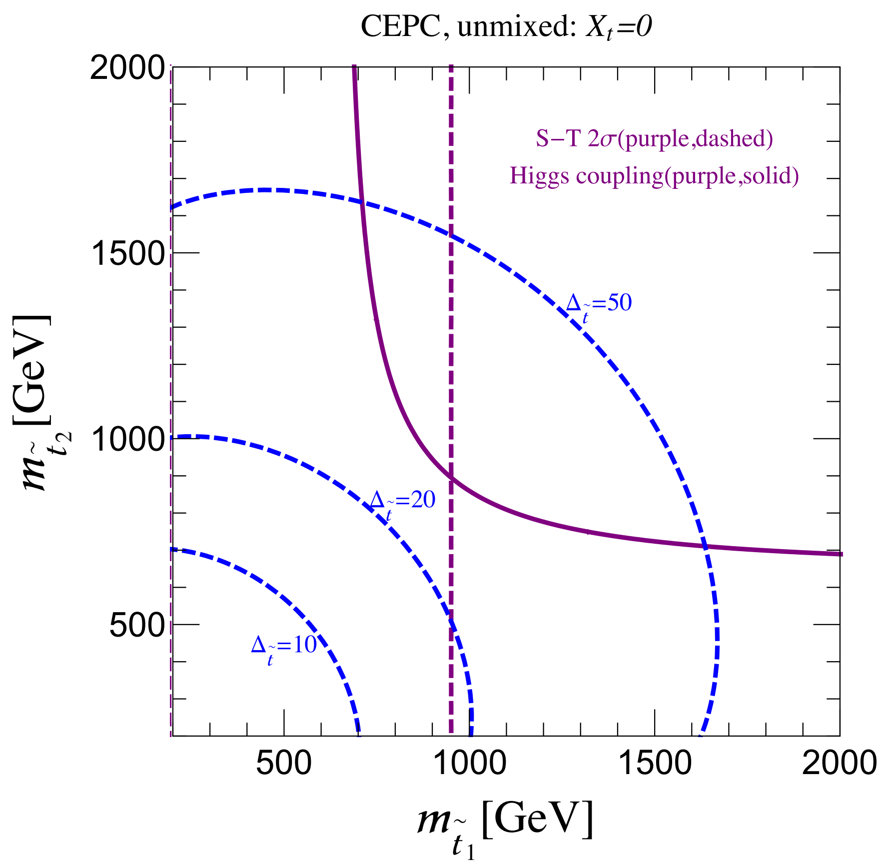


TeV new physics.
Naturalness motivated
Many models, ideas.

Electroweak scale, 100 GeV.
m_h , m_W ...

Naturalness in SUSY

- LHC searches model dependent, many blind spots.



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

- Testing fine-tuning down to percent level.

- Higgs coupling and precision at CEPC provides a powerful and complementary probe.

Composite Higgs at lepton collider

Higgs is not (quite) elementary, will have deviations in Higgs couplings.

$$\delta W_h \sim \delta Z_h \sim \frac{v^2}{f^2}$$

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

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

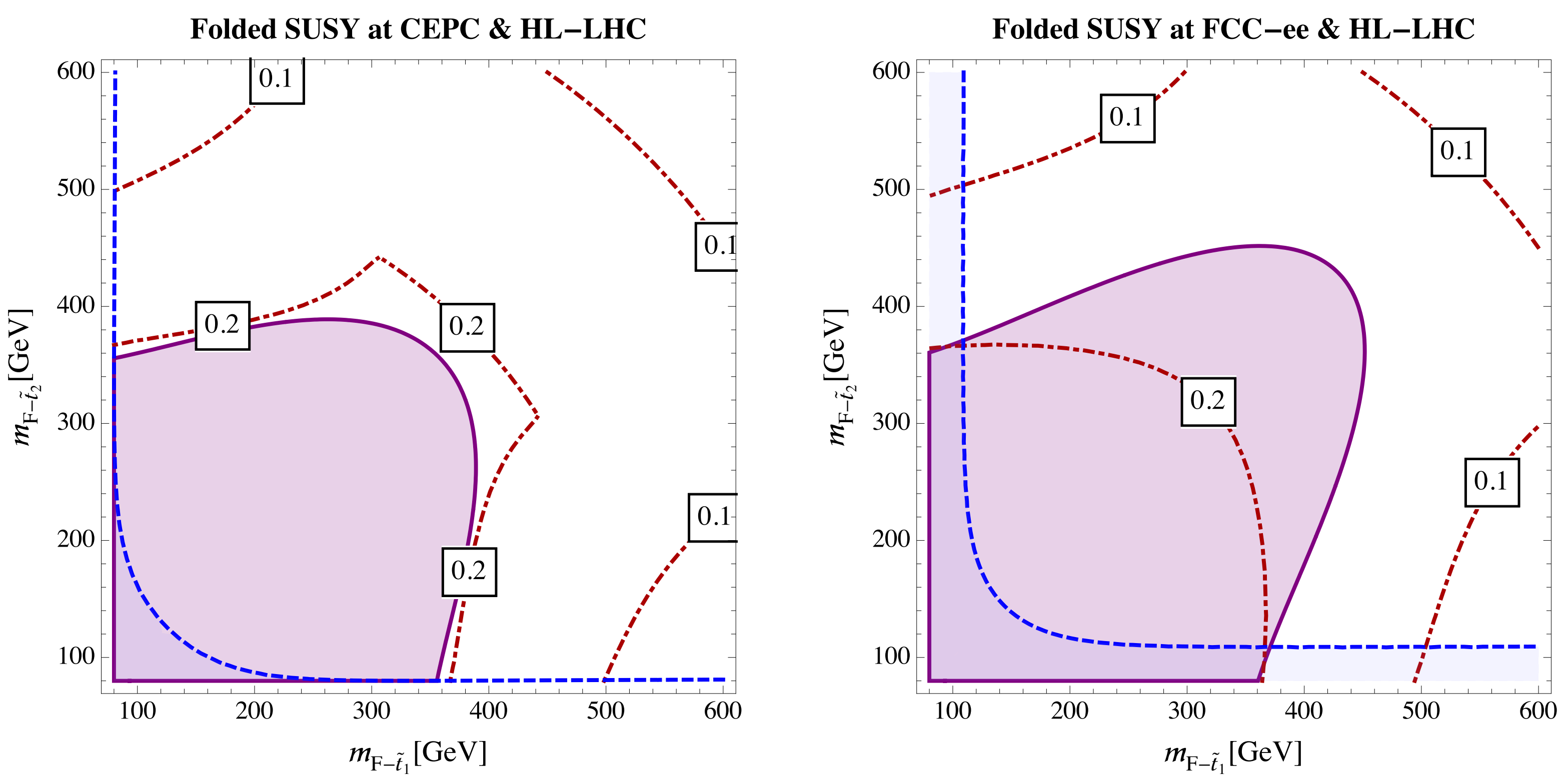
Experiment	κ_Z (68%)	f (GeV)
HL-LHC	3%	1.0 TeV
ILC500	0.3%	3.1 TeV
ILC500-up	0.2%	3.9 TeV
CEPC	0.2%	3.9 TeV
TLEP	0.1%	5.5 TeV

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

Lesson: when both type of corrections generated at the same order, Higgs coupling measurement is typically stronger.

More exotic ideas: Folded SUSY

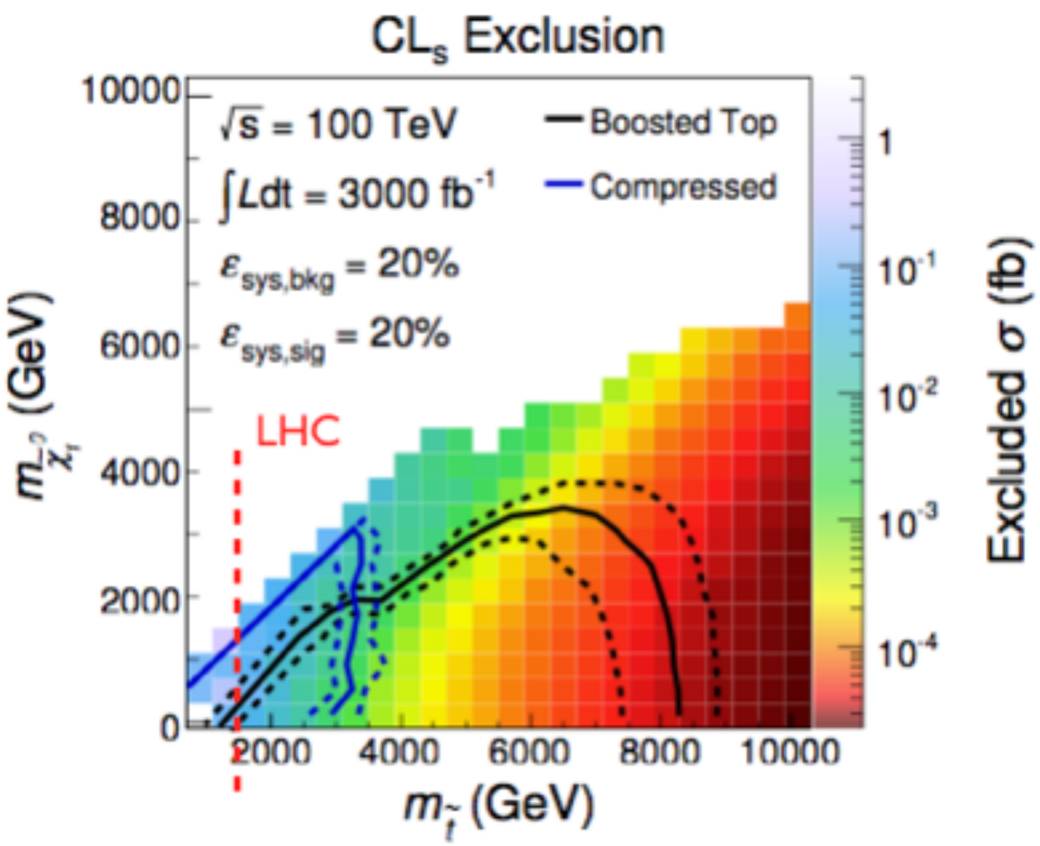
- Top partner has SM electroweak couplings only.
- Deviations in $h \to \gamma\gamma$.



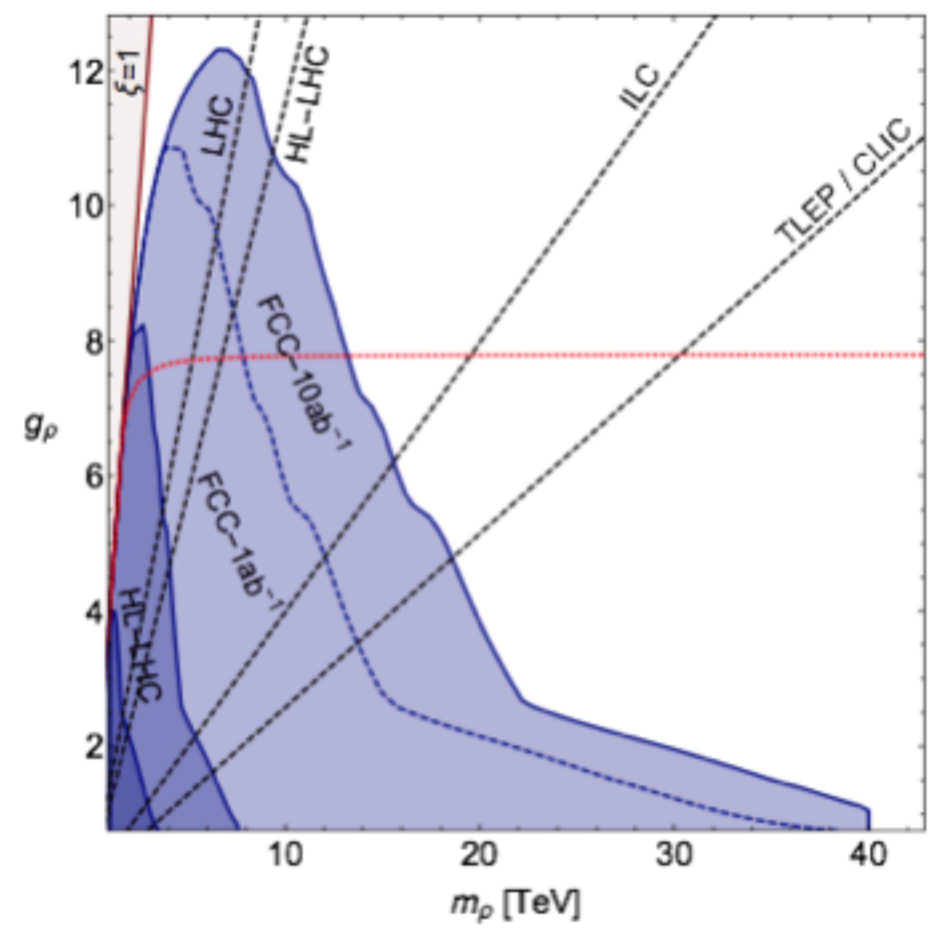
J. Fan, M. Reece, LTW, 1412.3107

Testing naturalness at 100 TeV pp collider

Cohen et. al., 2014



Pappadopulo, Thamm, Torre, Wulzer, 2014

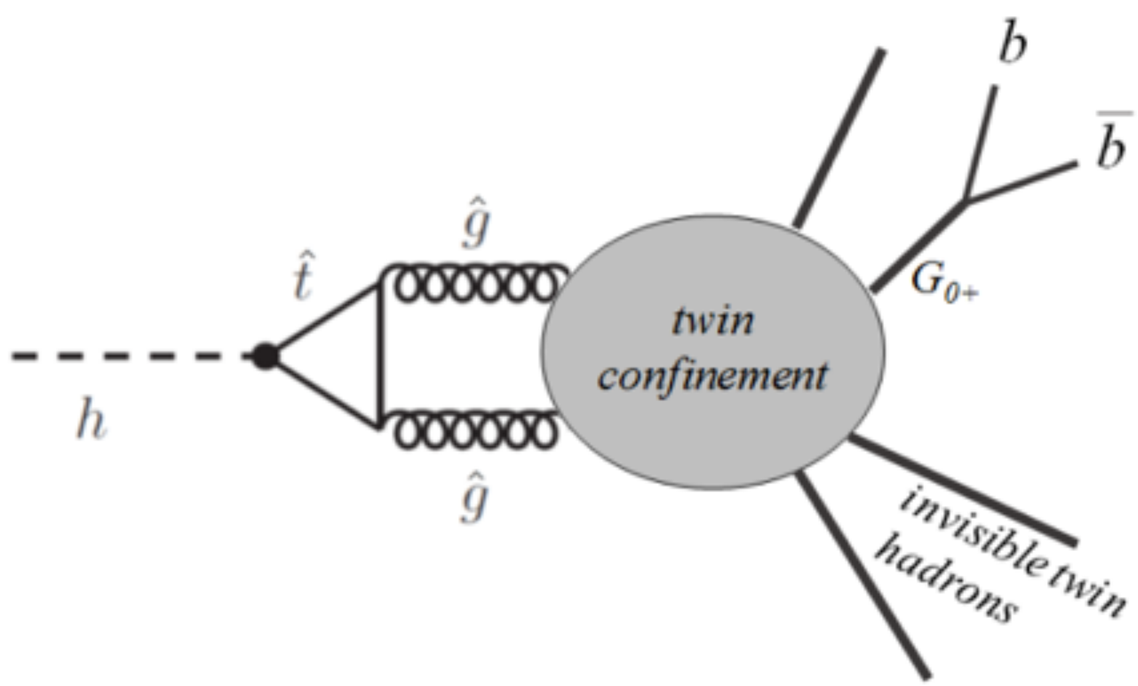


Fine tuning: $(M_{NP})^{-2}$

Stealthy top partner. “twin”

Chacko, Goh, Harnik

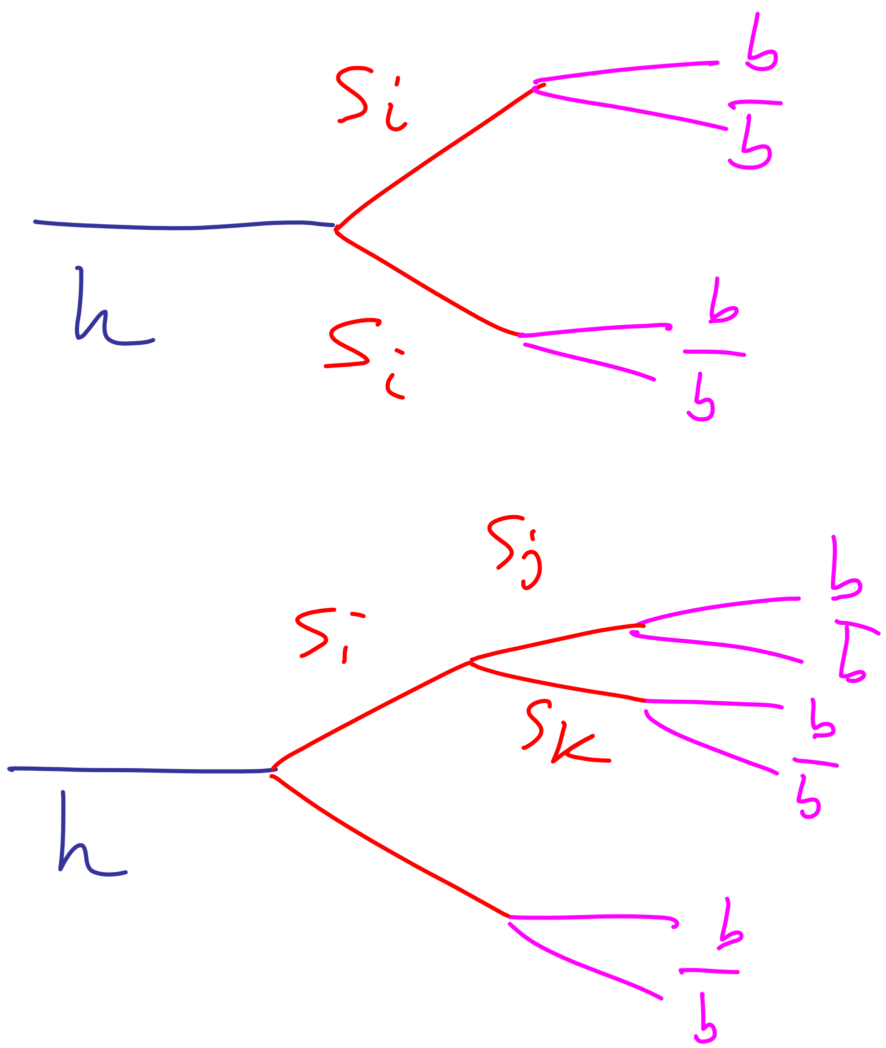
Craig, Katz, Strassler, Sundrum



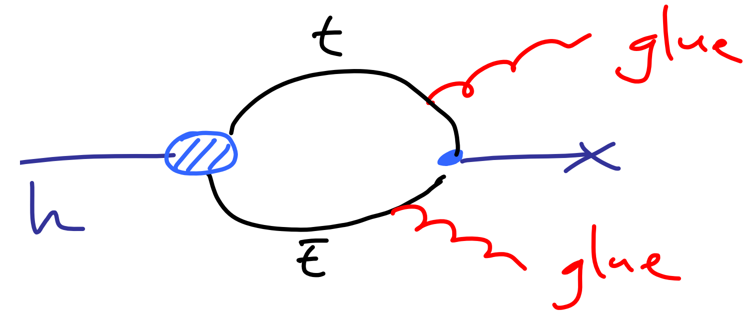
- Top partner not colored. Higgs decay through hidden world and back.
- Lead to Higgs rare decays.

More alternatives

More relevant without discovery at the LHC



Indirect: CEPC



$K_g \sim \left(\frac{m_t^2}{\Lambda^2}\right) \sim 10\%$ Easy @CEPC

$K_\gamma \sim$ few % Possible@ CEPC

Low scale landscape

Higgs rare decay.

"fat" Higgs

Higgs coupling

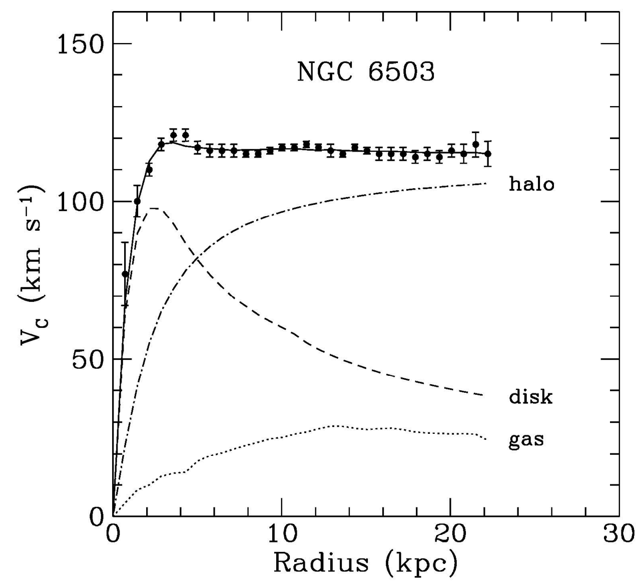
Can't hide from the Higgs.

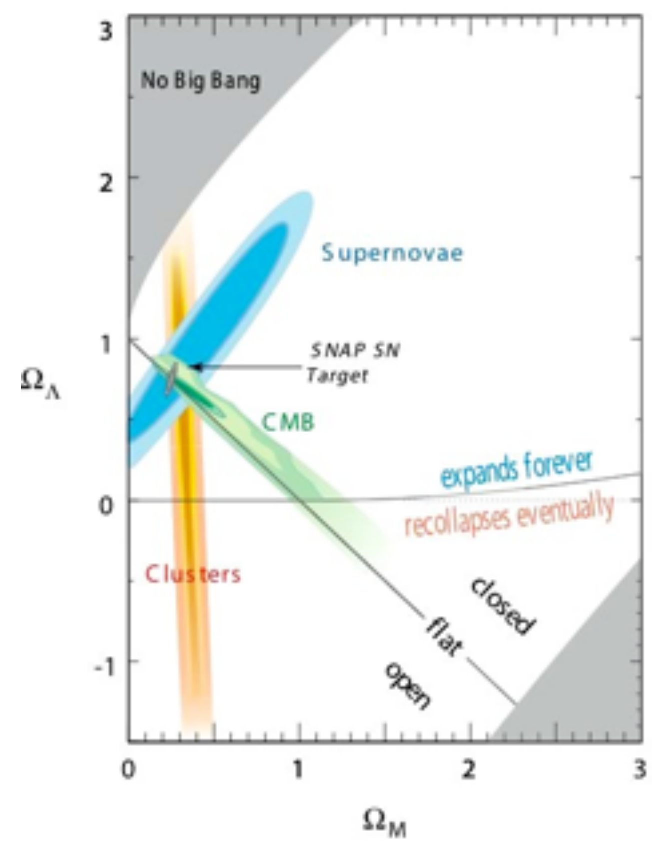
Talk by Arkani-Hamed CEPC workshop Sept. 2016

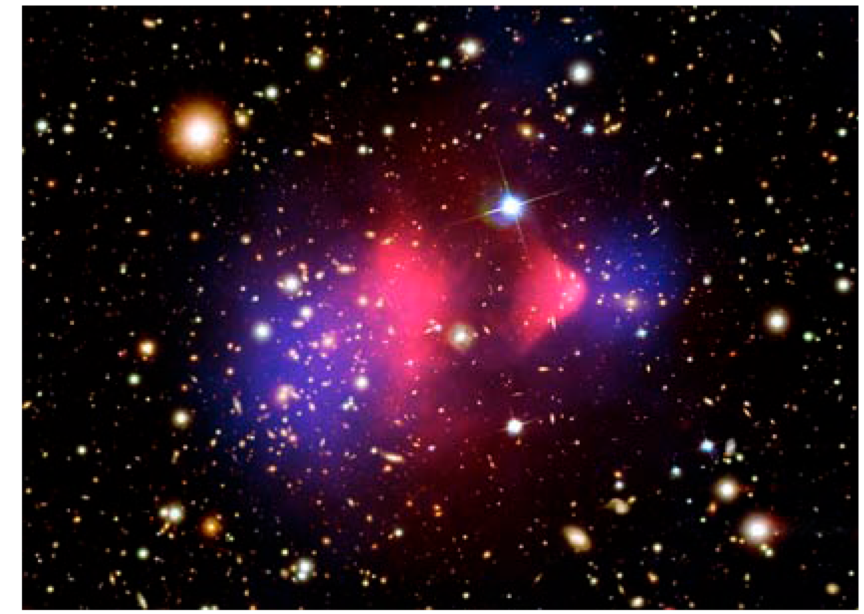
Bottom line

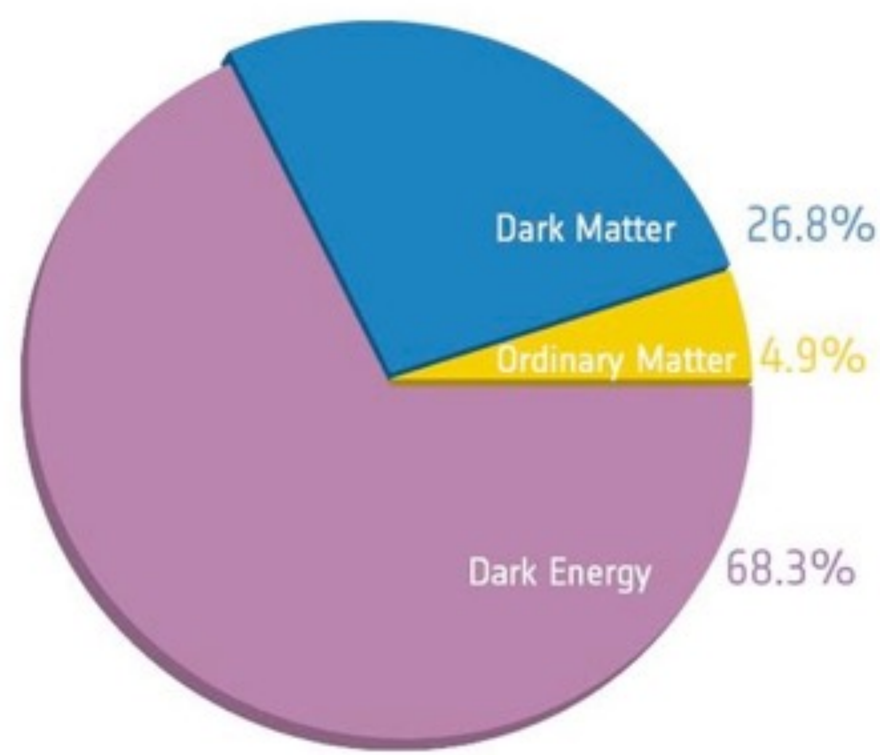
- Naturalness is the most pressing question of EWSB.
  - How should we predict the Higgs mass?
- We may not have the right idea. No confirmation of any of the proposed models.
- Need experiment!
- Fortunately, with Higgs, we know where to look.
- And, the clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

Dark matter





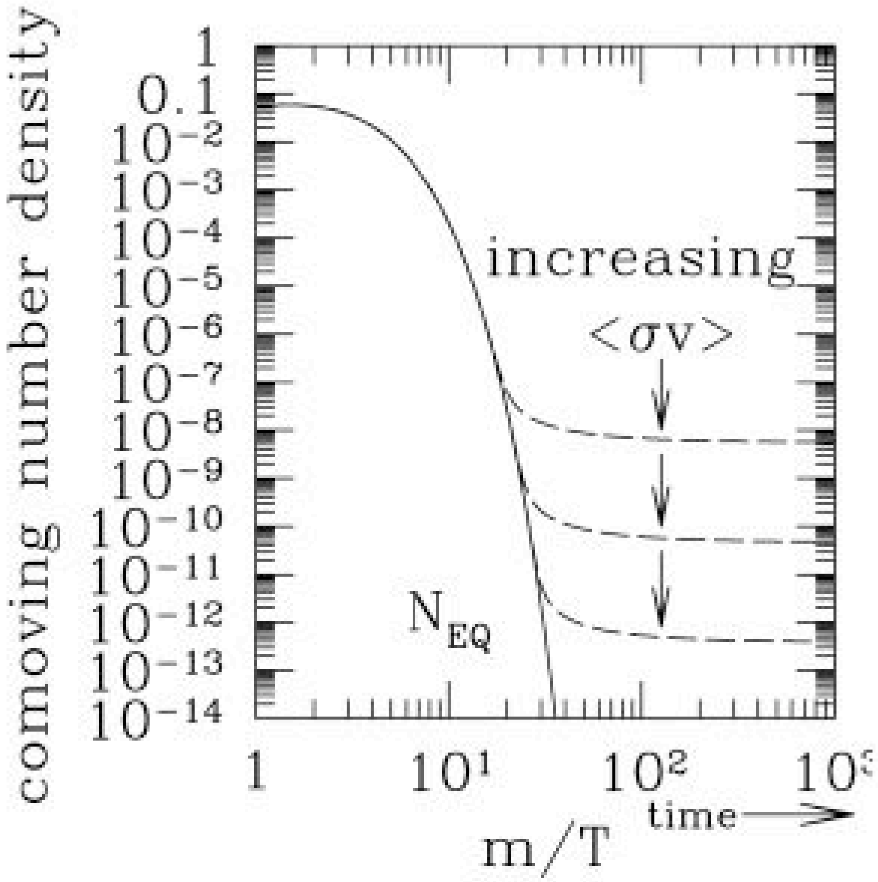


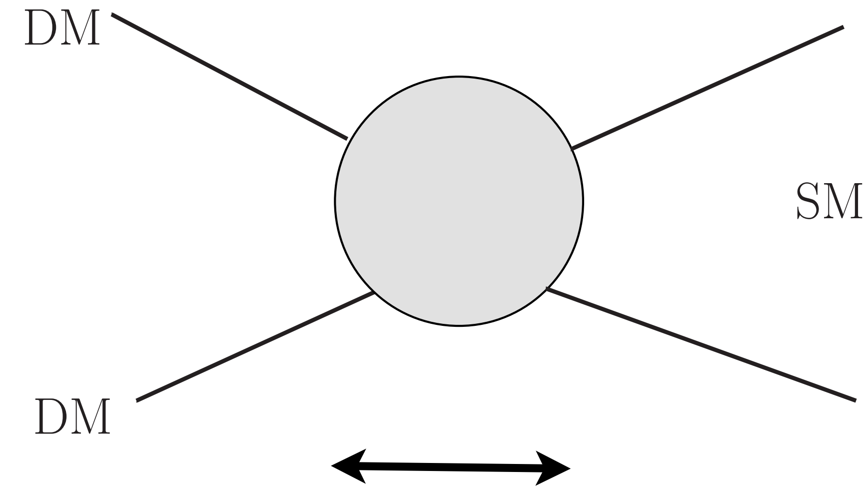


It is there.
Only seen its gravitational interaction.

We have to understand them better.
Collider search is a key approach.

WIMP miracle





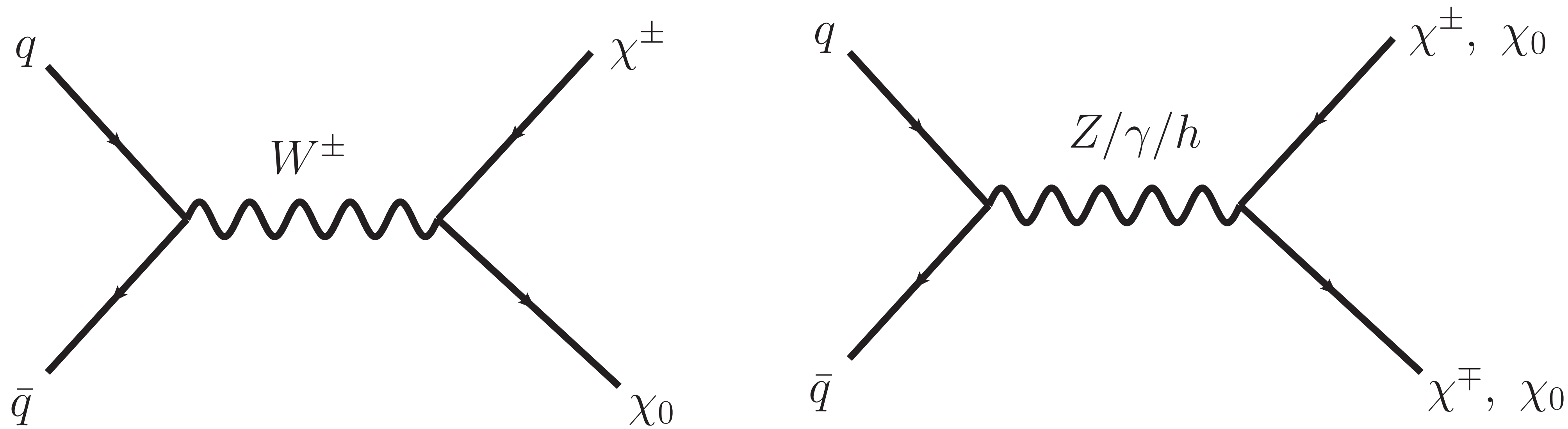
$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- Thermal equilibrium in the early universe.

- If $g_D \sim 0.1$ $M_D \sim$ 10s GeV - TeV
  - We get the right relic abundance of dark matter.

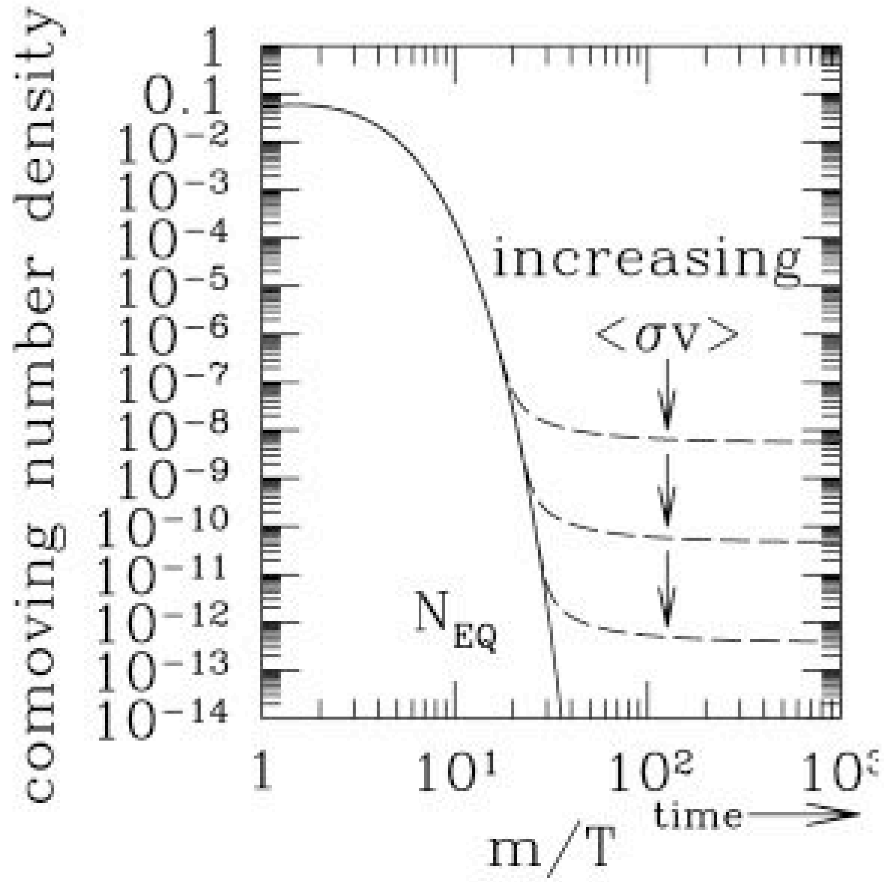
- Major hint for weak scale new physics!

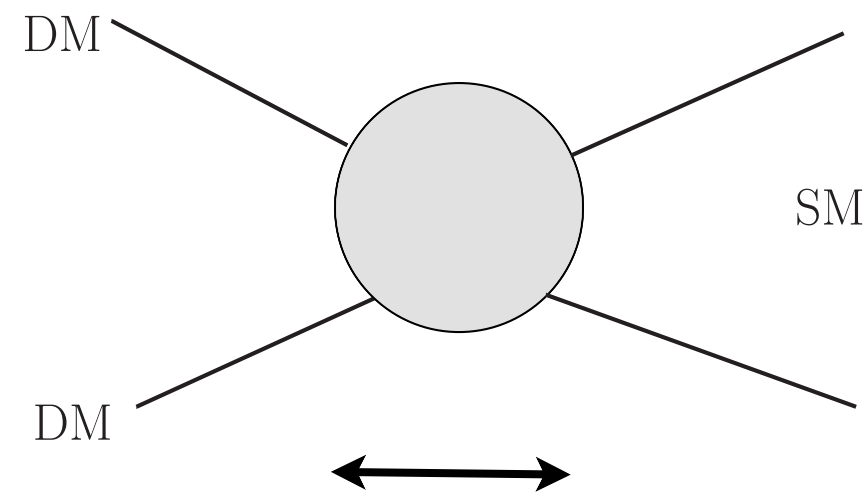
Simplest WIMP: part of weak multiplet



- Mediated by W/Z/h.
- Predictive, no unkown particle as mediator.
- The original WIMP proposal.

WIMP mass





$$\langle \sigma v \rangle \sim \frac{g_{\mathrm{D}}^4}{m_{\mathrm{DM}}^2}$$

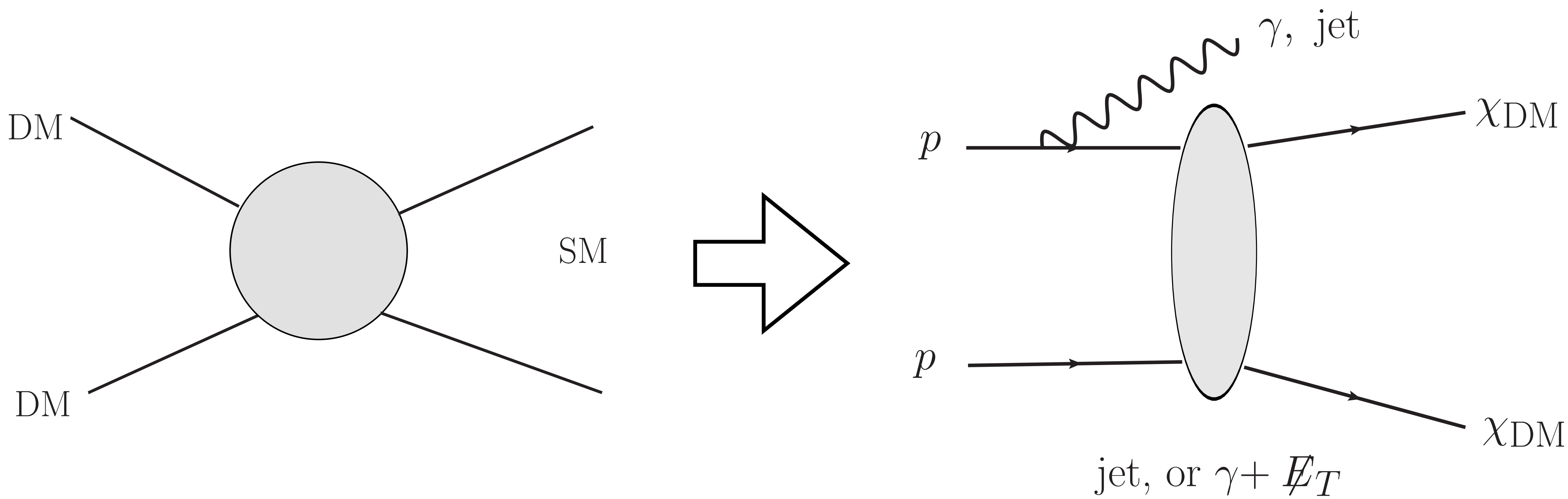
– More precisely, to get the correct relic abundance

$$M_{\mathrm{WIMP}} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3} \right)$$

TeV-ish in simplest models

Basic channel

- pair production + additional radiation.

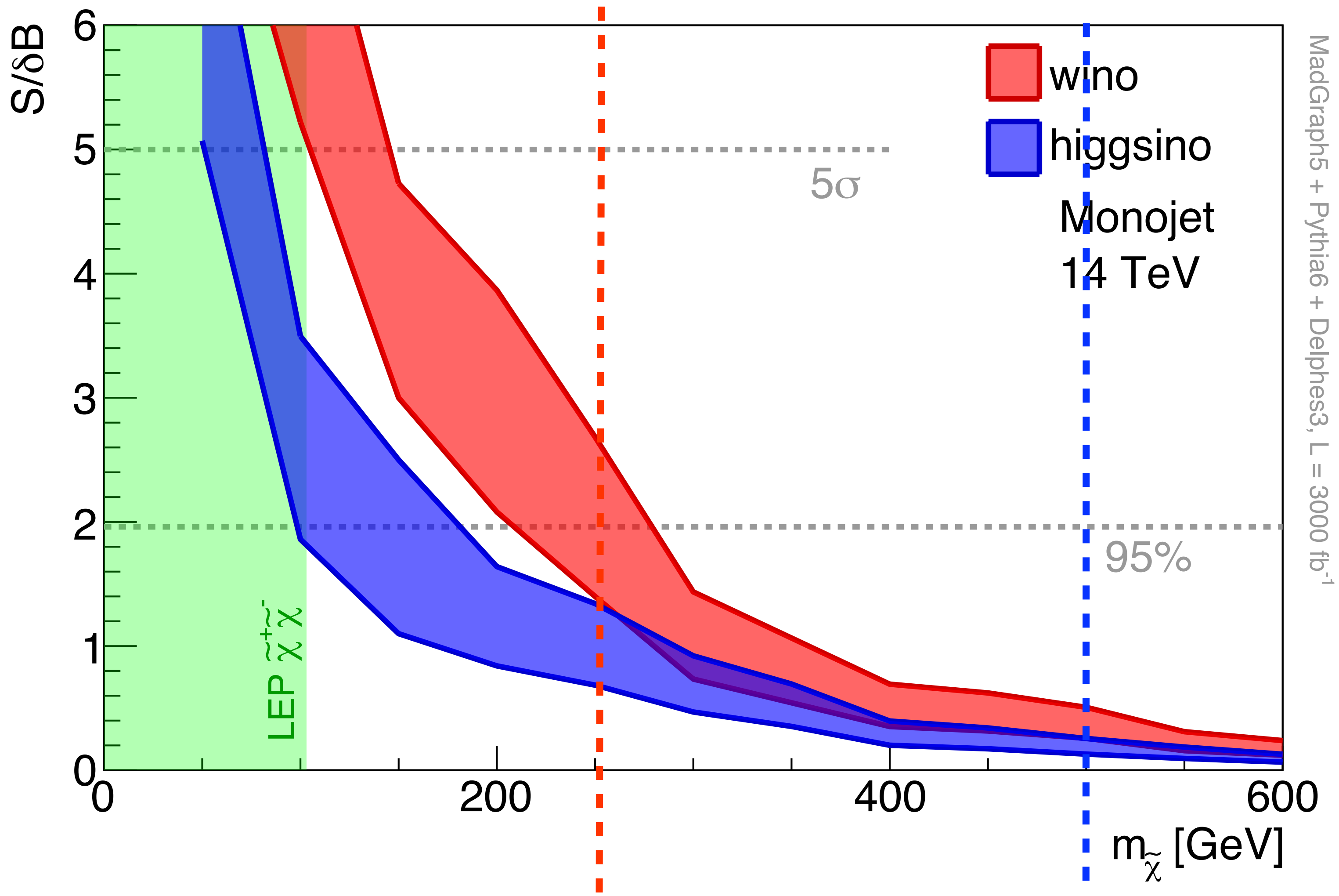


- Mono-jet, mono-photon, mono-...

- Have become "Standard" LHC searches.

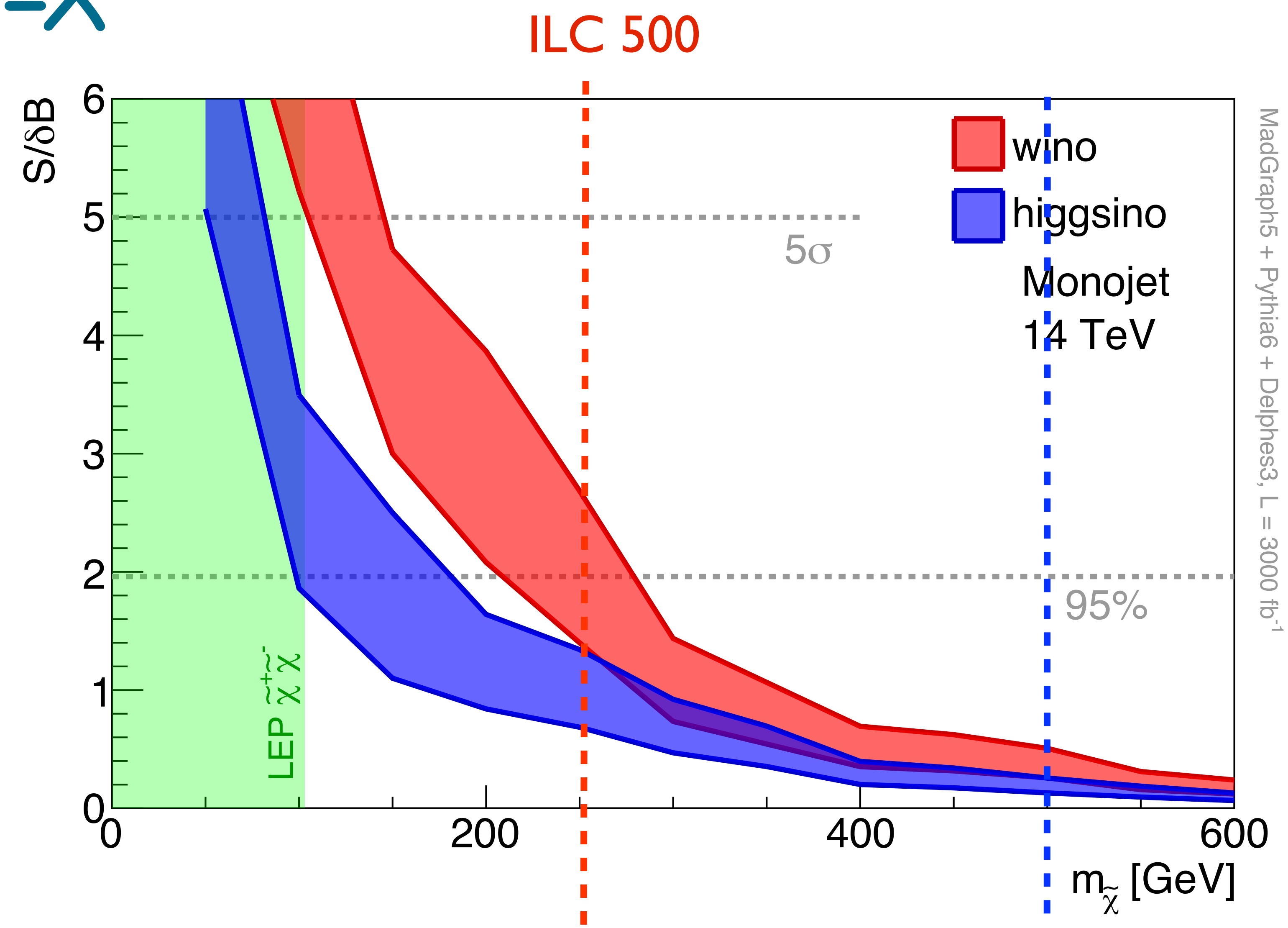
- Very challenging, systematics dominated

Mono-X



- Very challenging. Systematics dominated
  - No limit from the 8 TeV run.
  - Very weak discovery reach at 14 TeV, 3 ab^{-1} .
- Reach at lepton collider, about 1/2 E_{CM}.

Mono-X



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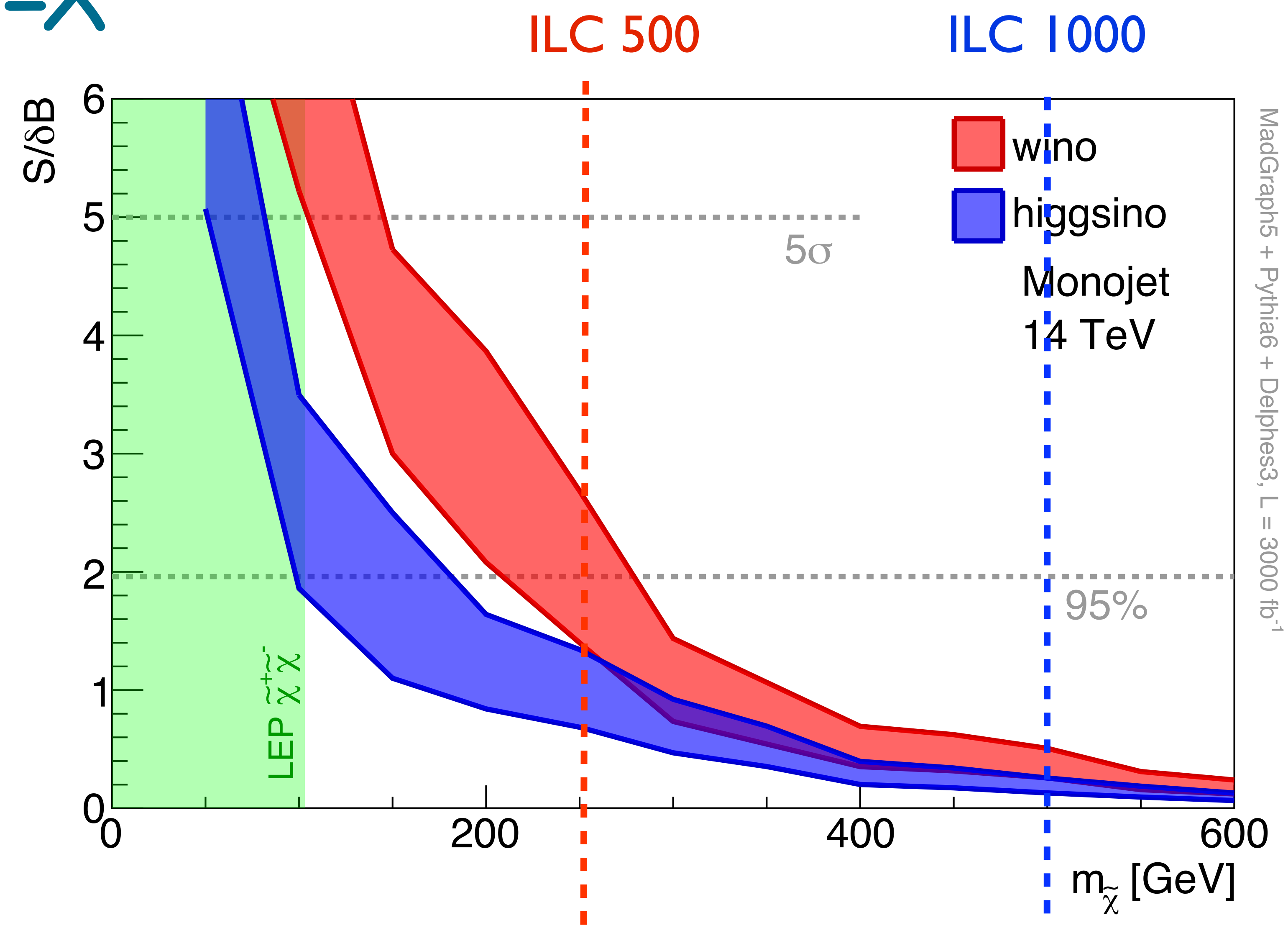

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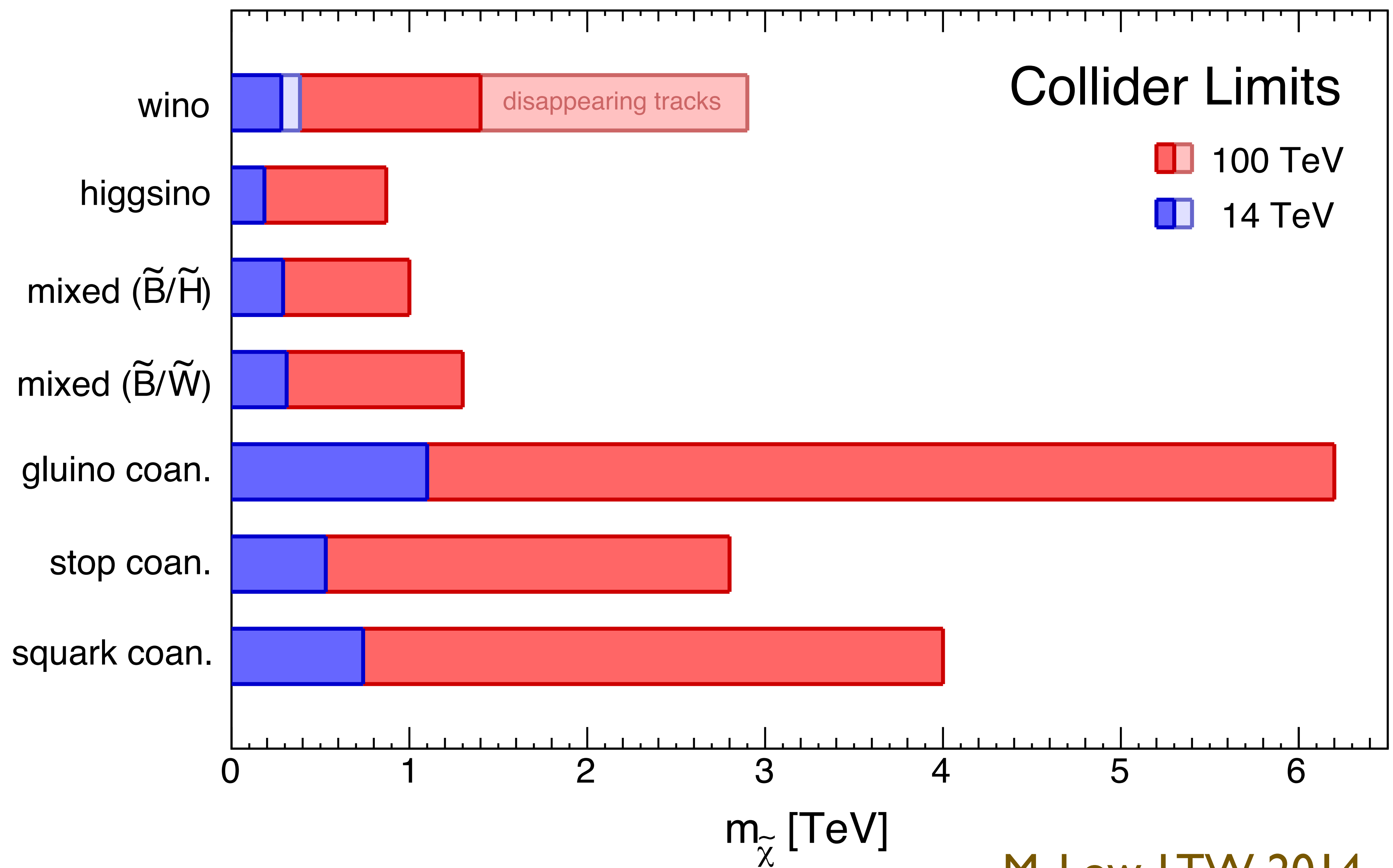
Dark matter with Mono-jet



M. Low, LTW 2014

$$M_{\rm WIMP} \leq 1.8 \text{ TeV} \left(\frac{g^2}{0.3}\right)$$

A lot more

- A Z-pole program, >10^3 Zs than LEP 1. Push EW precision measurement by at least one order of magnitude.
- Flavor physics at both e+e- and pp.
- ep, heavy ion...

Conclusion

- Physics case for the Higgs factories very strong.
  - More straightforward to push.
- Intense (and very exciting) work ahead to make it happen as soon as possible.
- 100 TeV pp collider as a promising second step (longer term)
- An LHC discovery can certainly change things dramatically.

Probing NP with precision measurements

- CEPC: clean environment, good for precision.

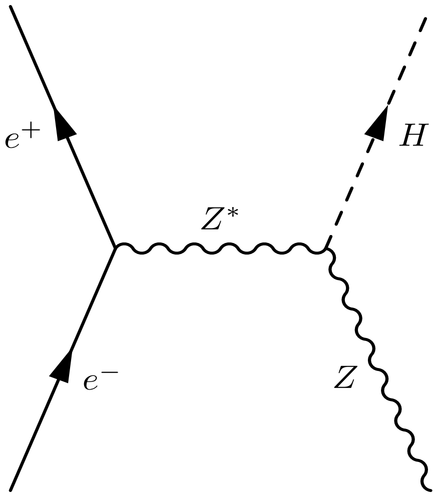
- We are going after deviations of the form

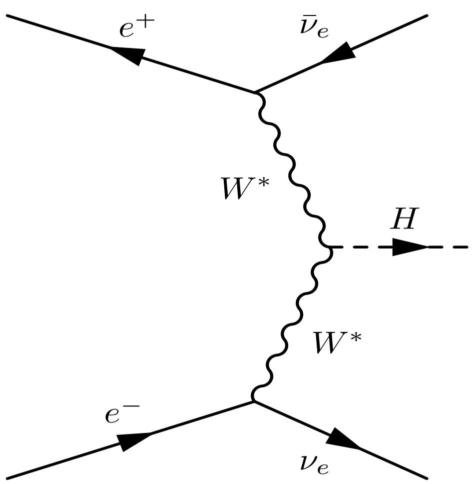
$$\delta \simeq c \frac{v^2}{M_{\mathrm{NP}}^2}$$

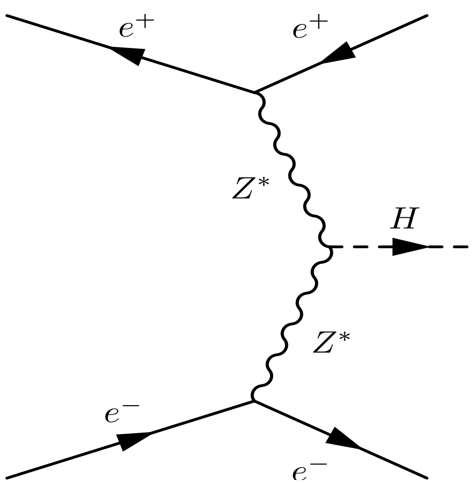
M_{NP} : mass of new physics
c: $O(1)$ coefficient

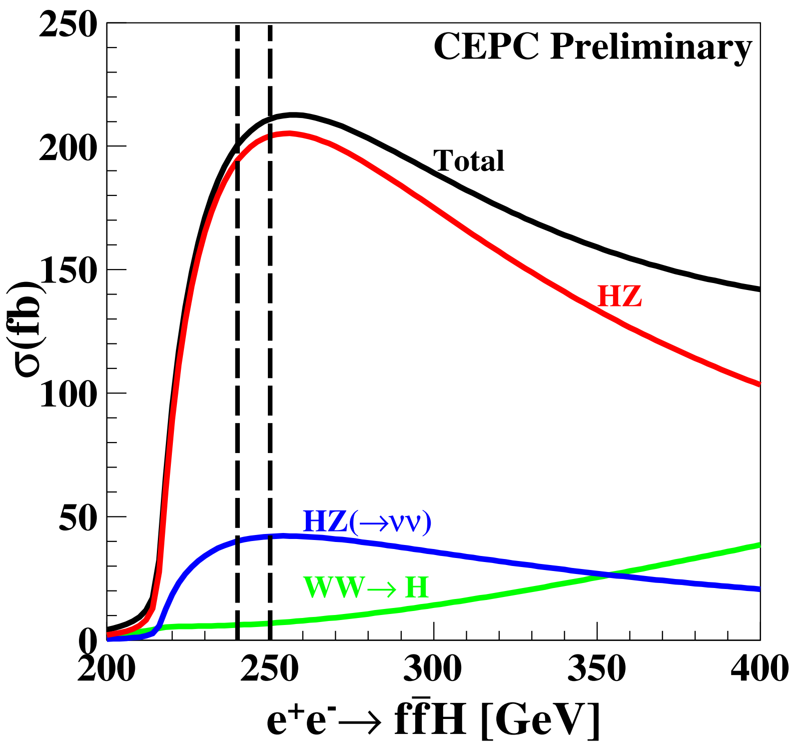
- Take for example the Higgs coupling.
  - LHC precision: 5-10% $\Rightarrow$ sensitive to M_{NP} < TeV
  - However, M_{NP} < TeV largely excluded by direct NP searches at the LHC.
  - To go beyond the LHC, need 1% or less precision.

Higgs factory processes



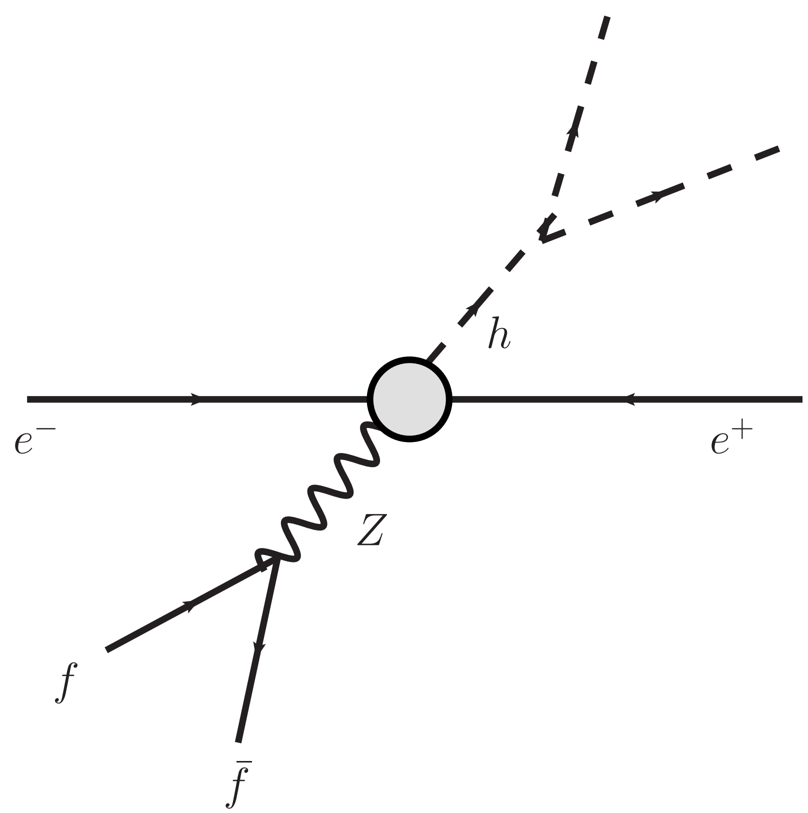


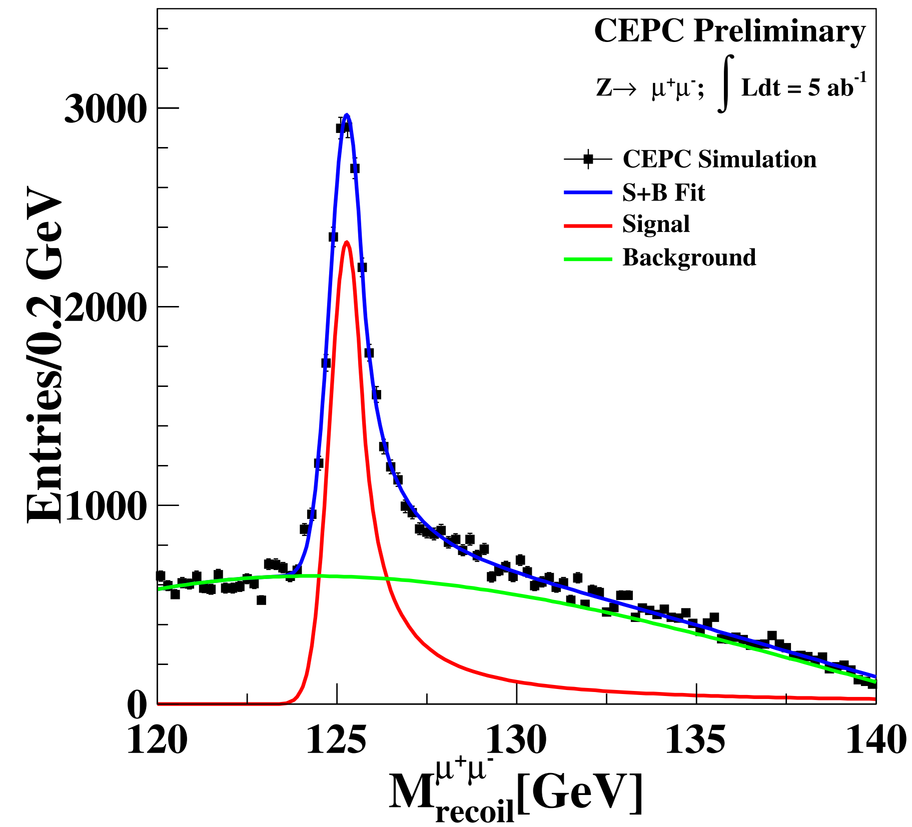




Process	Cross section	Nevents in 5 ab^{-1}
Higgs boson production, cross section in fb		
$e^+e^- \to ZH$	212	1.06×10^6
$e^+e^- \to \nu\nu H$	6.72	3.36×10^4
$e^+e^- \to eeH$	0.63	3.15×10^3
Total	219	1.10×10^6

Zh cross section



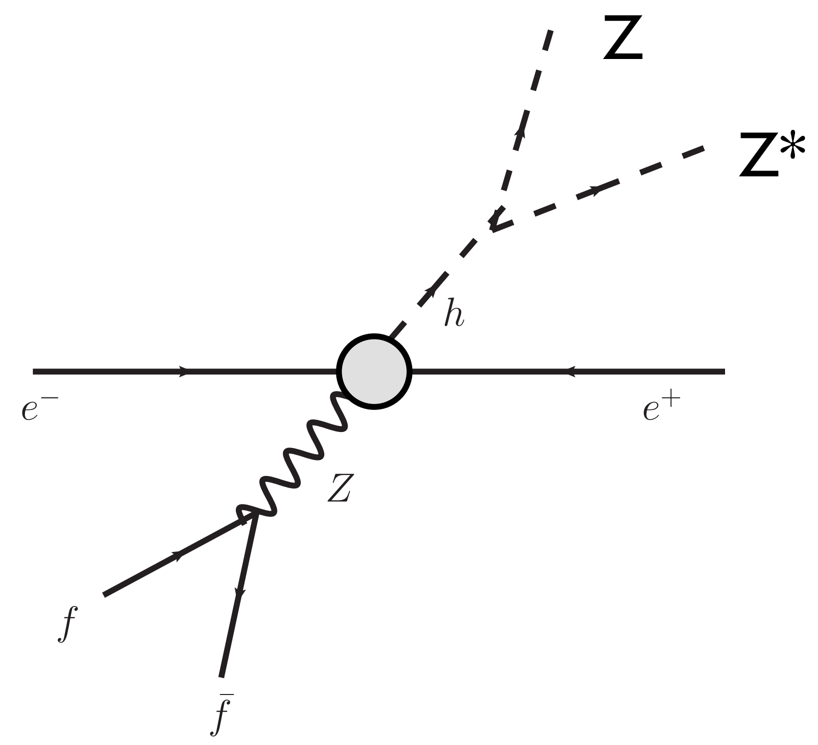


$$M^2_{\text{recoil}} = (\sqrt{s} - E_{ff})^2 - p^2_{ff} = s - 2E_{ff}\sqrt{s} + m^2_{ff}$$

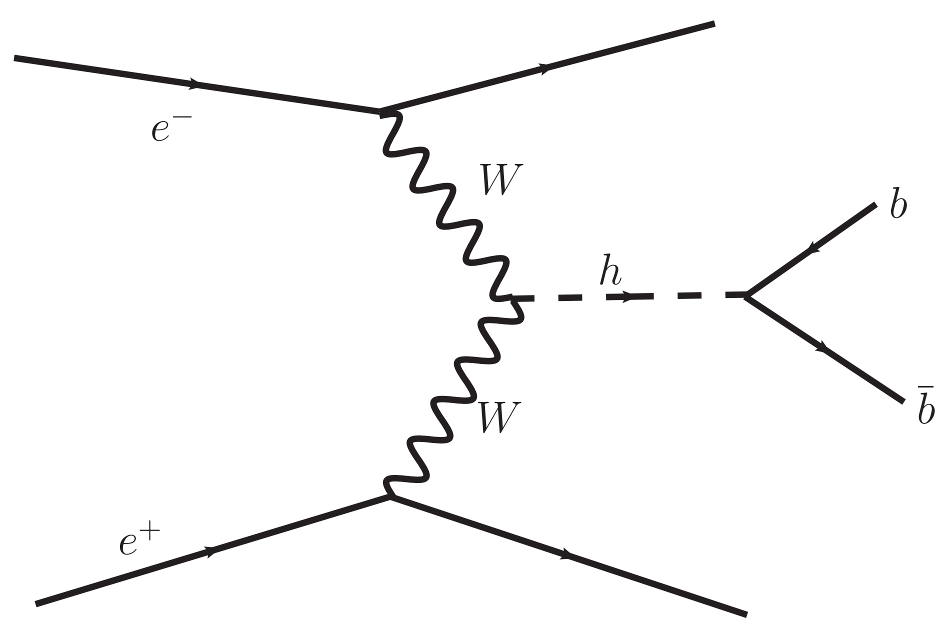
Can use recoil mass to identify Zh process, independent of Higgs decay

⇒ inclusive measurement of Zh cross section

Higgs width. Unique capability of lepton colliders.

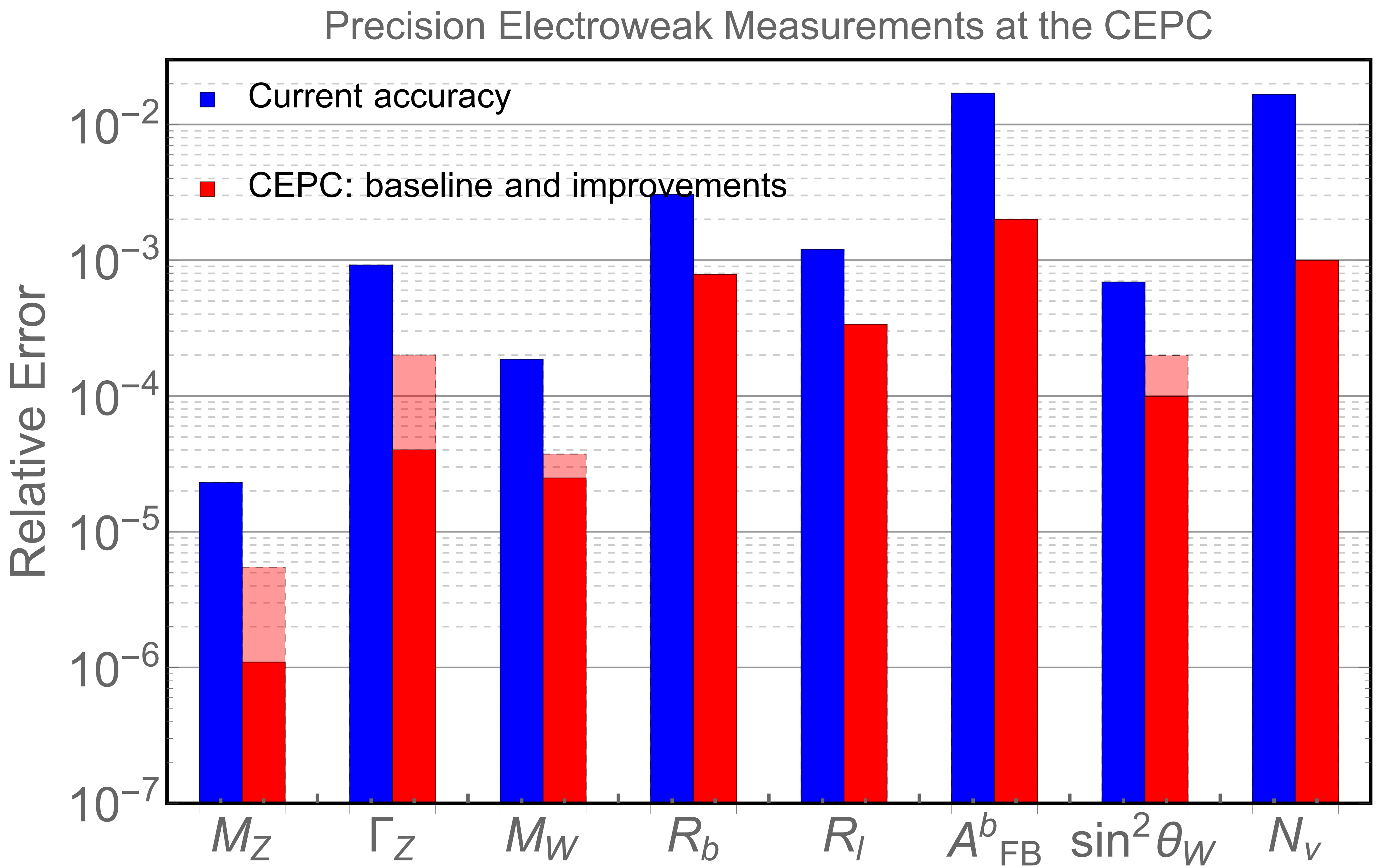


$$\Gamma_H \propto \frac{\Gamma(H \to ZZ^*)}{\mathrm{BR}(H \to ZZ^*)} \propto \frac{\sigma(ZH)}{\mathrm{BR}(H \to ZZ^*)}$$



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

Big advance in electroweak precision



Large improvements across the board

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	$(\pm 2.3_{\rm exp} \pm 1.5_{\rm th}) \times 10^{-5}$	$(\pm 1_{\rm exp} \pm 0.8_{\rm th}) \times 10^{-4}$	$\pm 0.03_{\rm exp} \pm 0.1_{\rm th}$

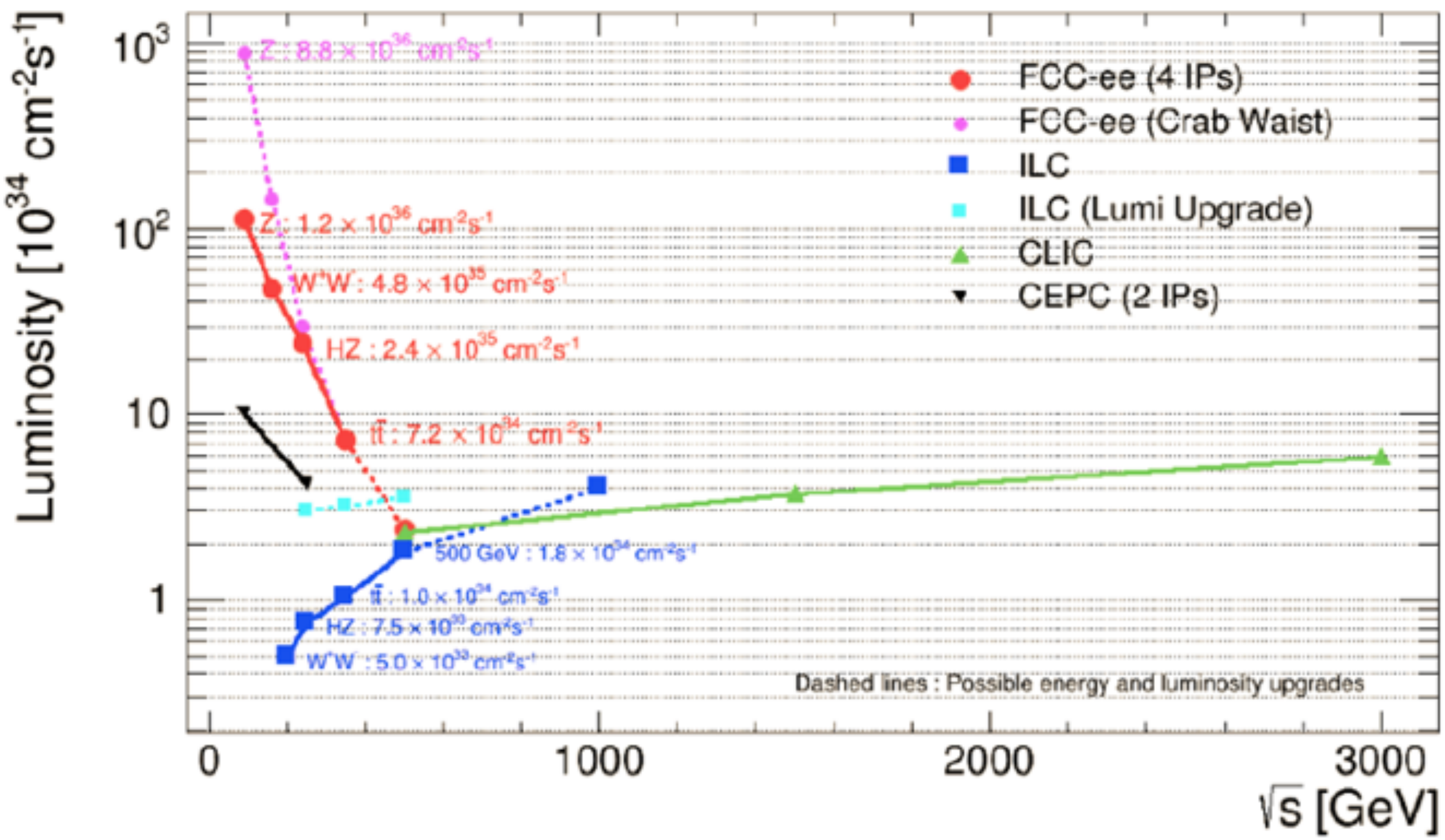
x4 statistics off Z-pole

energy calibration

ILC?

CEPC design goal

- Limit SR power to 50 MW per beam
- CEPC: single ring, head-on collision, up to 250 GeV
- FCC-ee: double ring, large crossing angle, up to 350 GeV



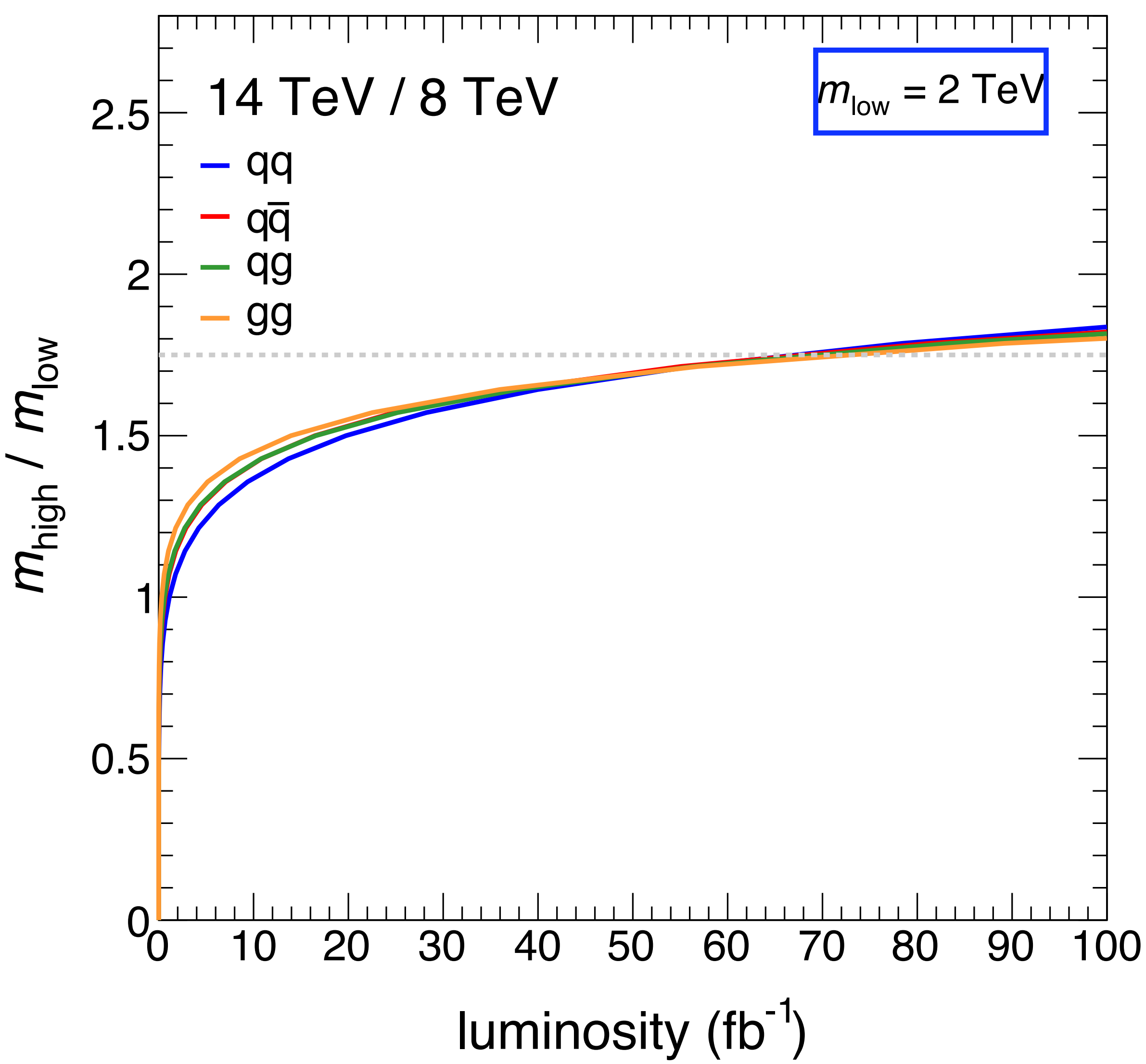
CEPC:
- 10^6 Higgs
- 10^{10} Z

FCC-ee:
- 10^7 Higgs
- $10^{12\text{-}13}$ Z

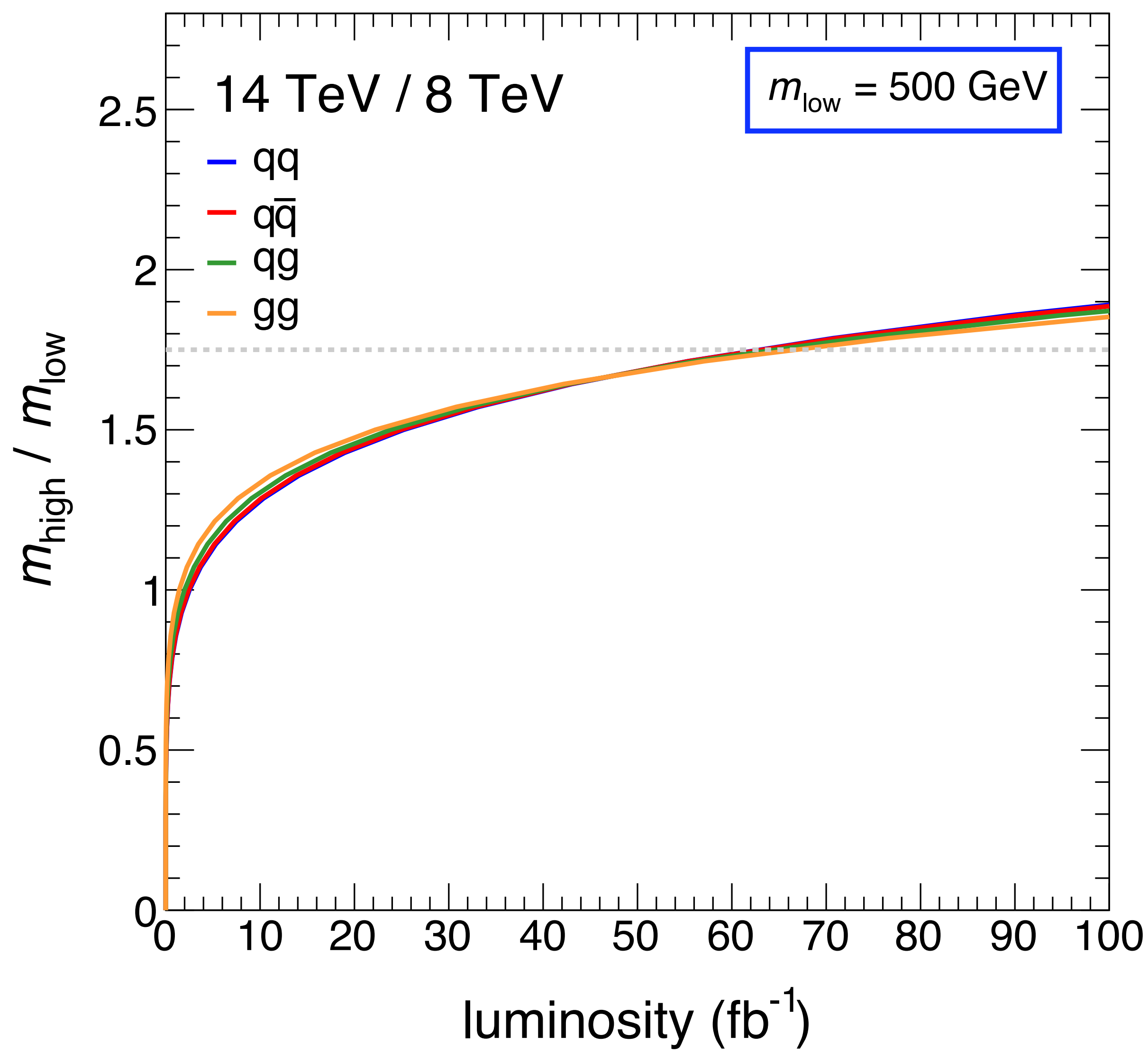
X. Lou

As data accumulates

Run 1 limit 2 TeV, e.g. pair of 1 TeV gluino.



500 GeV, e.g. pair of 250 GeV electroweak-ino



Rapid gain initial 10s fb^{-1}, slow improvements afterwards.

Reaching the "slow" phase after Moriond 2017