Higgs and BSM

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University of Chicago

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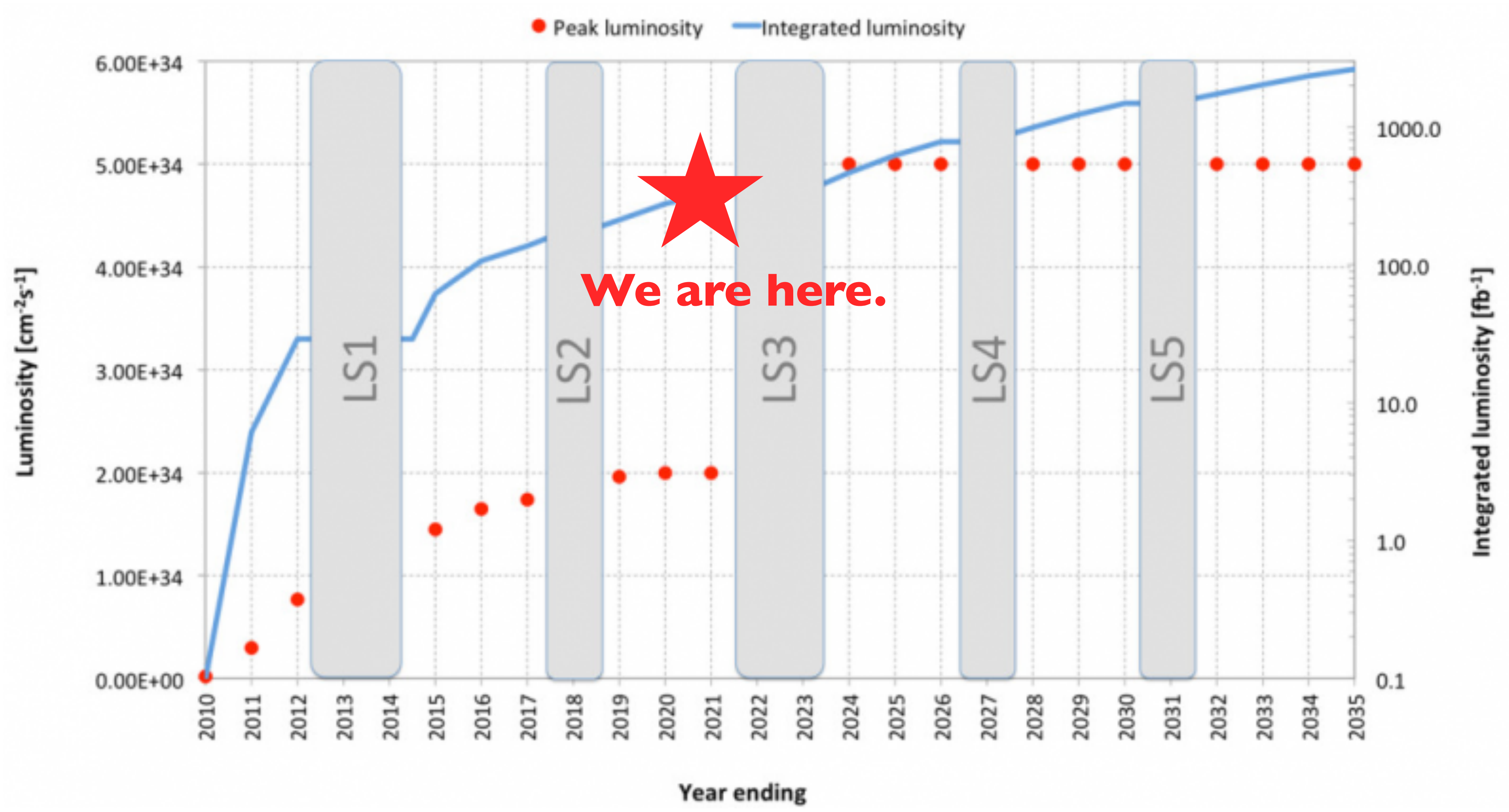
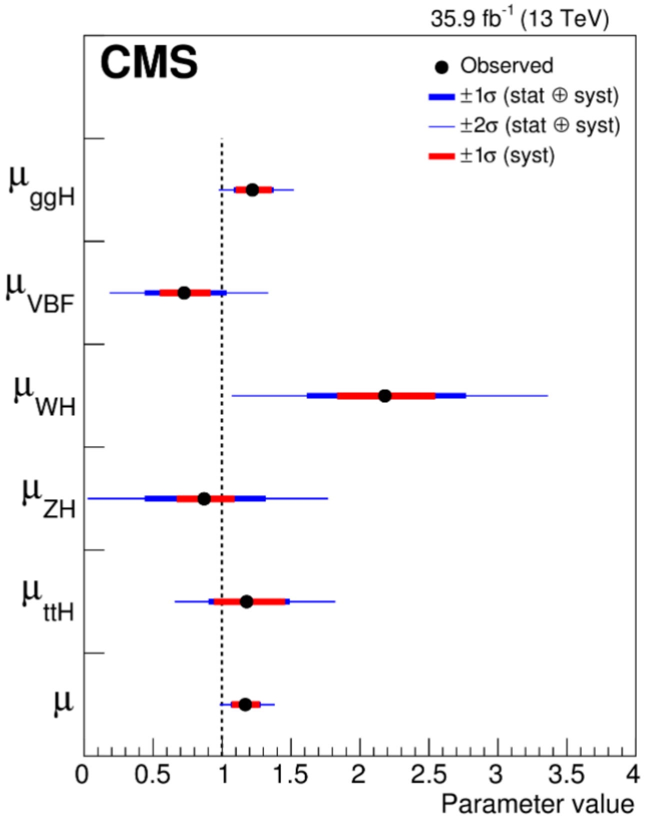
Our immediate future

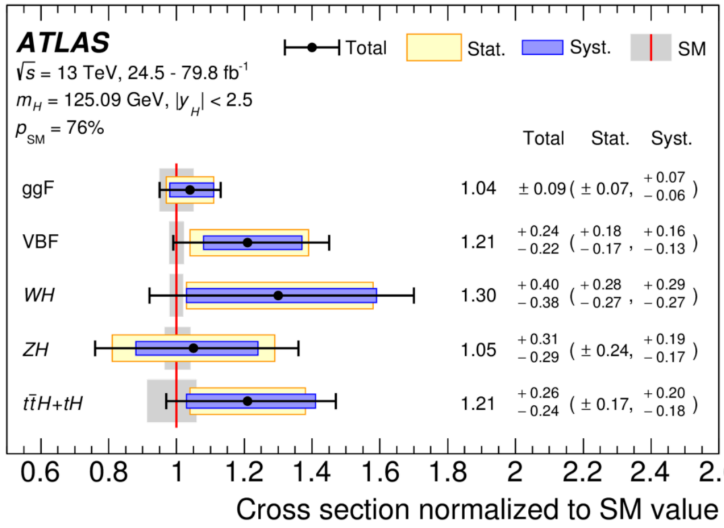


Still about 10 times amount of data to come.

Most immediate question:
How to fully realize the potential of the LHC?

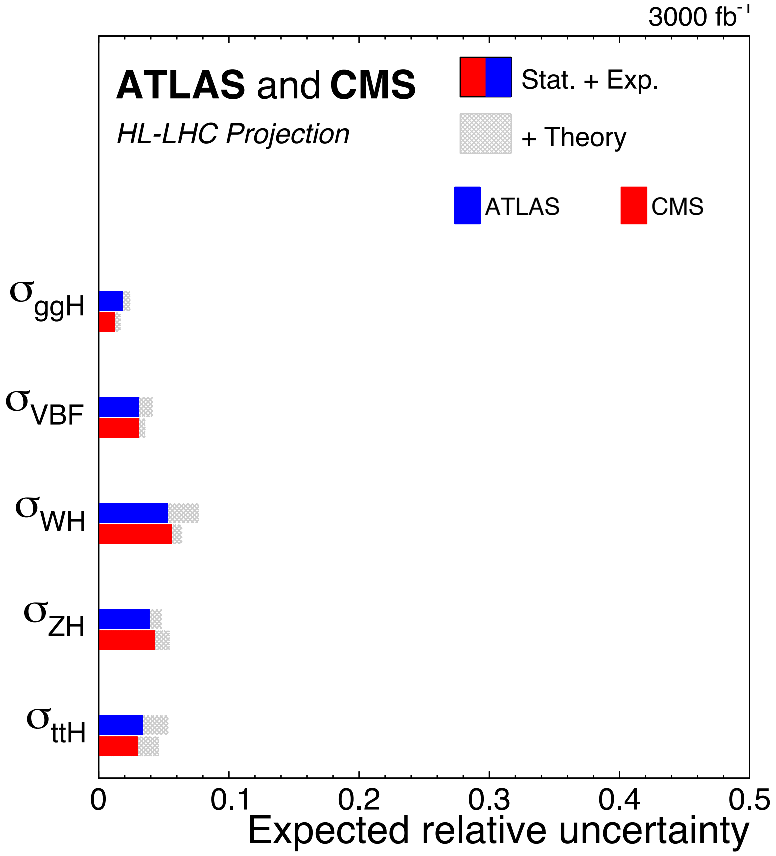
All eyes are on the Higgs





Current precision: 10(s)%

A few Percent by the end of the LHC



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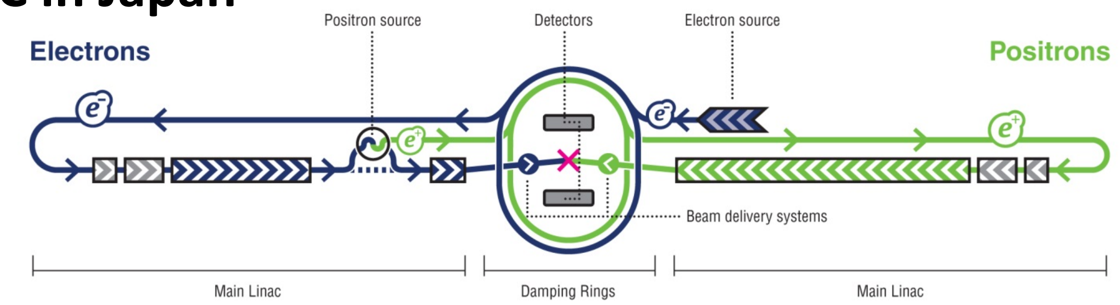
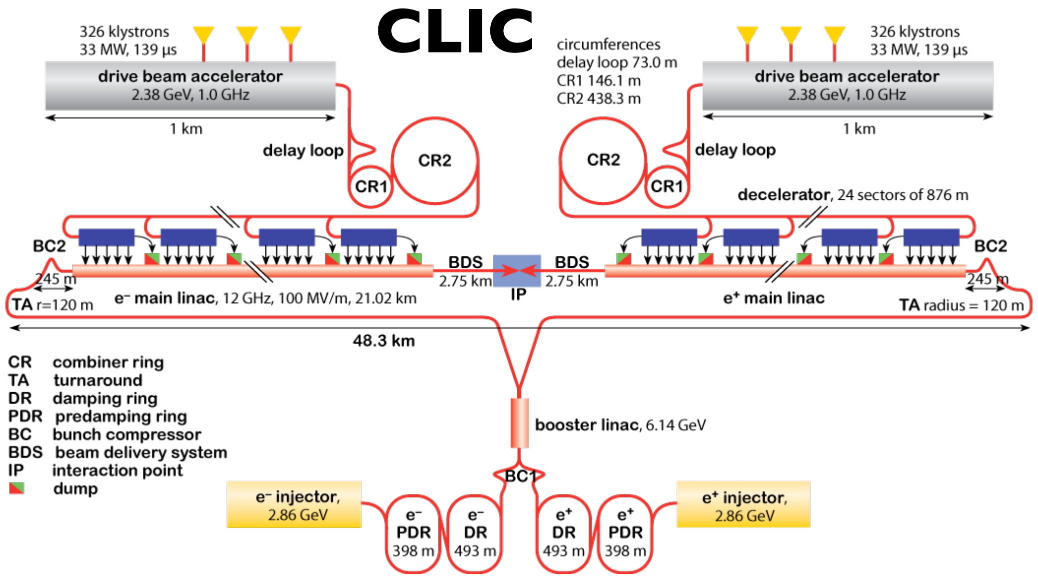
Future Colliders

ILC in Japan





Circular. “Scale up” LEP+LHC

pp collider ~100 TeV

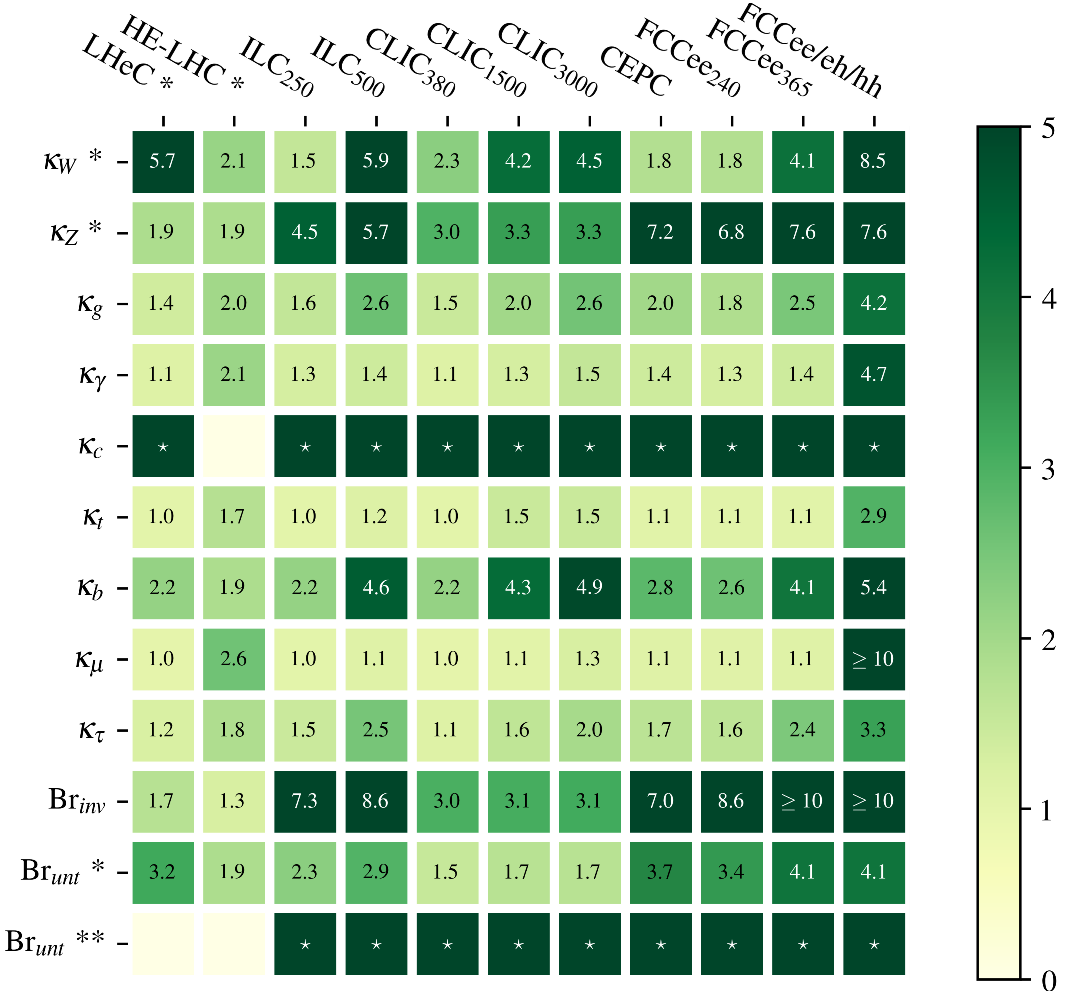
FCC-hh (CERN), SppC(China)

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

FCC-ee (CERN), CEPC(China)

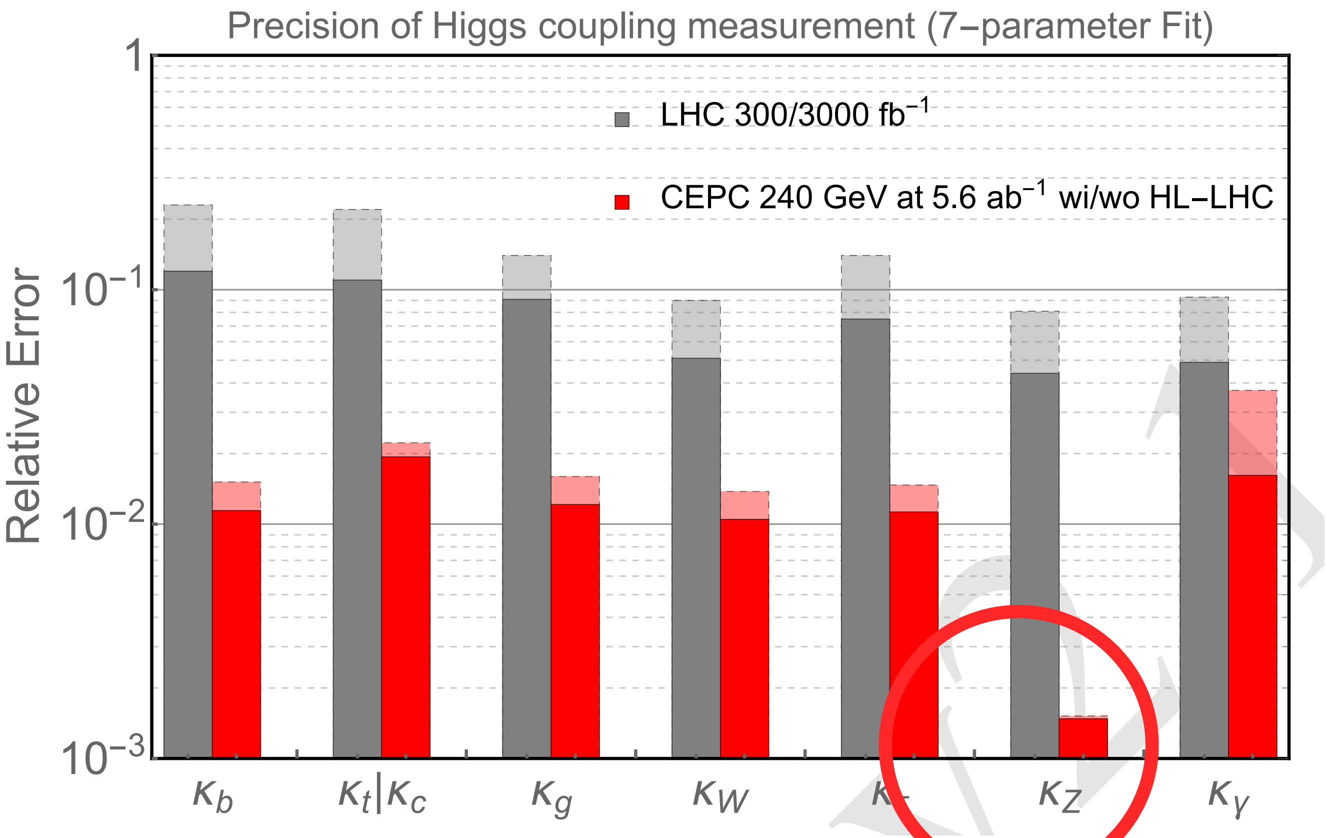
Likely to get a precision machine first!

Higgs coupling at future colliders



	LHeC *	HE-LHC *	ILC_{250}	ILC_{500}	CLIC_{380}	CLIC_{1500}	CLIC_{3000}	CEPC	FCCee_{240}	FCCee_{365}	FCCee/eh/hh
κ_W *	5.7	2.1	1.5	5.9	2.3	4.2	4.5	1.8	1.8	4.1	8.5
κ_Z *	1.9	1.9	4.5	5.7	3.0	3.3	3.3	7.2	6.8	7.6	7.6
κ_g	1.4	2.0	1.6	2.6	1.5	2.0	2.6	2.0	1.8	2.5	4.2
κ_γ	1.1	2.1	1.3	1.4	1.1	1.3	1.5	1.4	1.3	1.4	4.7
κ_c	⋆		⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆
κ_t	1.0	1.7	1.0	1.2	1.0	1.5	1.5	1.1	1.1	1.1	2.9
κ_b	2.2	1.9	2.2	4.6	2.2	4.3	4.9	2.8	2.6	4.1	5.4
κ_μ	1.0	2.6	1.0	1.1	1.0	1.1	1.3	1.1	1.1	1.1	≥ 10
κ_τ	1.2	1.8	1.5	2.5	1.1	1.6	2.0	1.7	1.6	2.4	3.3
Br_{inv}	1.7	1.3	7.3	8.6	3.0	3.1	3.1	7.0	8.6	≥ 10	≥ 10
Br_{unt} *	3.2	1.9	2.3	2.9	1.5	1.7	1.7	3.7	3.4	4.1	4.1
Br_{unt} **			⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆	⋆

(*) $|\kappa_V| \leq 1$ applied for hadron colliders (**) Not requiring $|\kappa_V| \leq 1$ (⋆) Not measured in HL-LHC



- A large step beyond the HL-LHC.
  - Can achieve per-mil level measurement.
  - Determination of the Higgs width.

For the coming couple of decades:

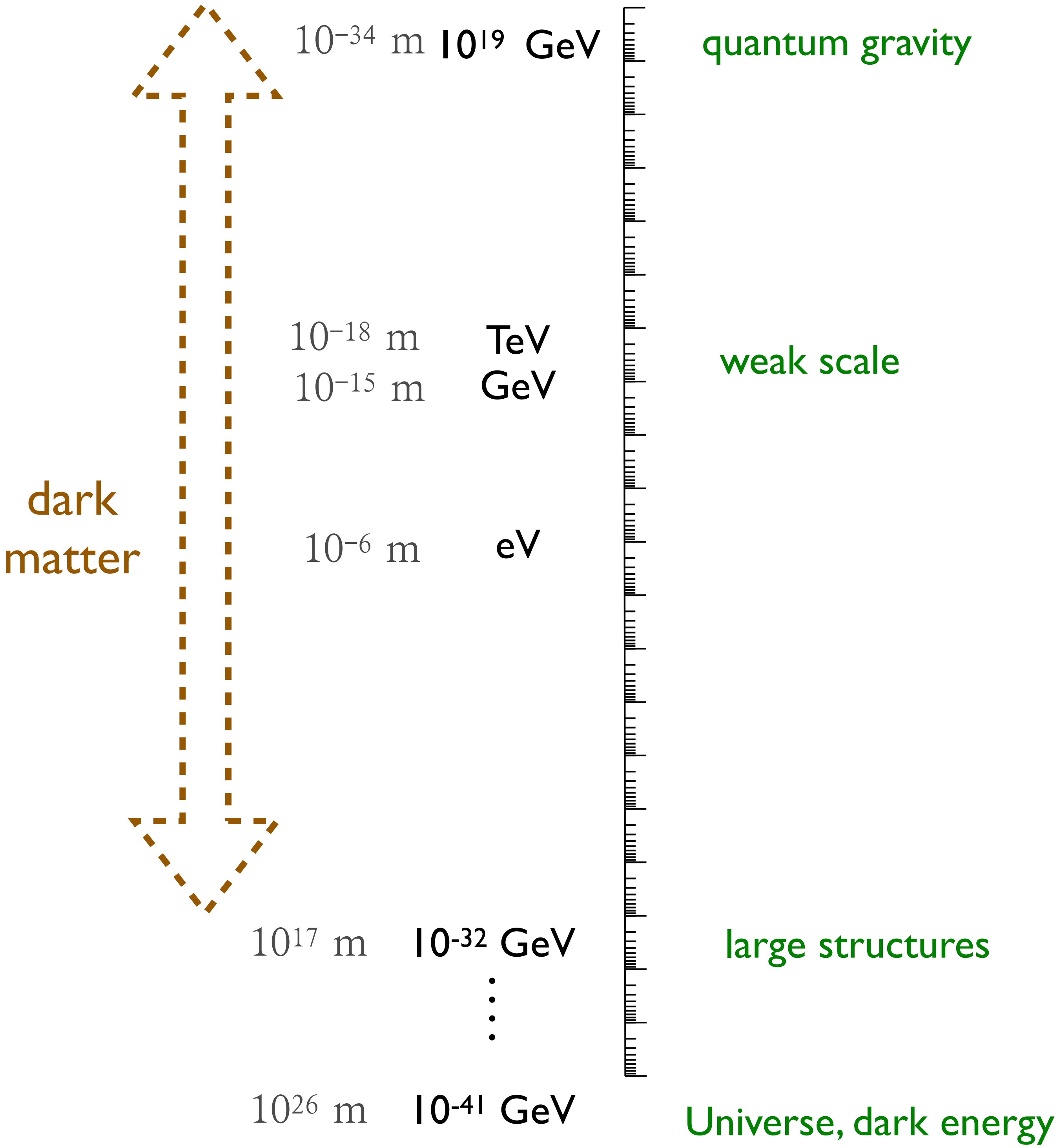
Most of the progresses at the colliders will be made on precision measurements.

One of the main targets is the Higgs boson.

This talk:

- What’s the connection between the Higgs and BSM new physics?
  - Focus on motivation rather than model details.

Our world



10^{-34} m 10^{19} GeV quantum gravity

10^{-18} m TeV

10^{-15} m GeV

weak scale

dark matter

10^{-6} m eV

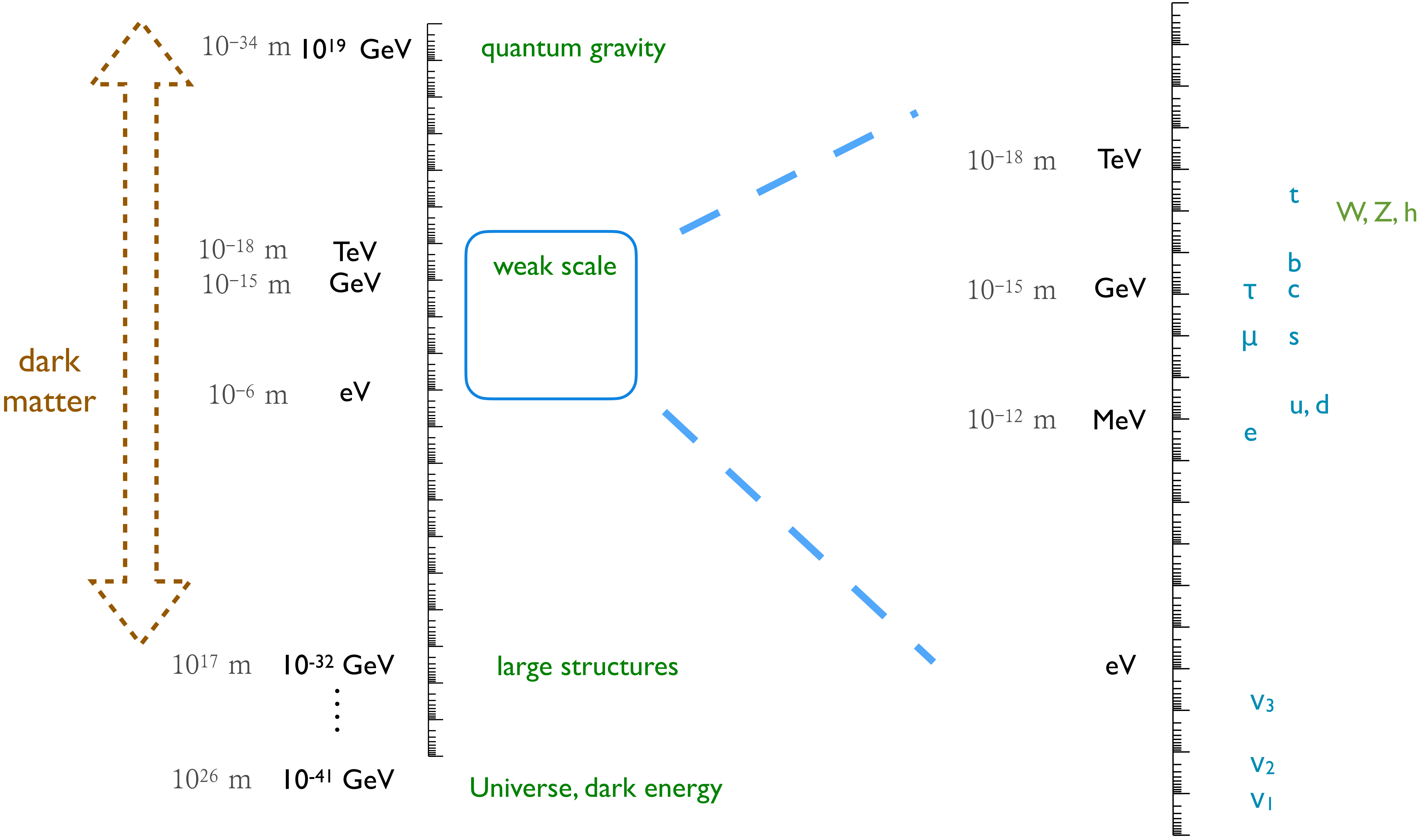
10^{17} m 10^{-32} GeV large structures

⋮

10^{26} m 10^{-41} GeV Universe, dark energy

Amazing progresses in the last ~100 years

Our world



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t

W, Z, h

b

10^{-15} m GeV

τ c

μ s

10^{-12} m MeV

u, d

e

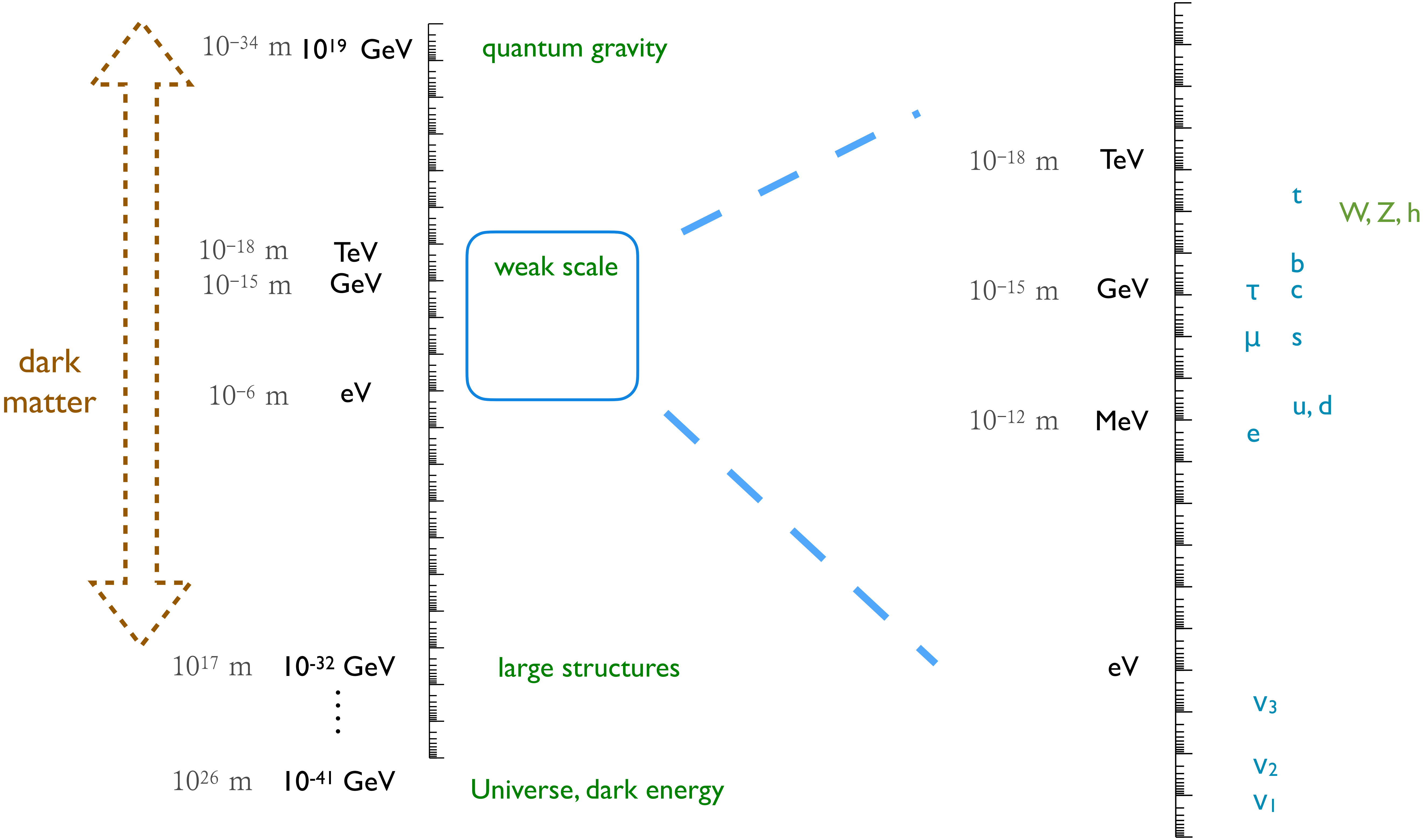
eV

ν_3

ν_2

ν_1

Our world



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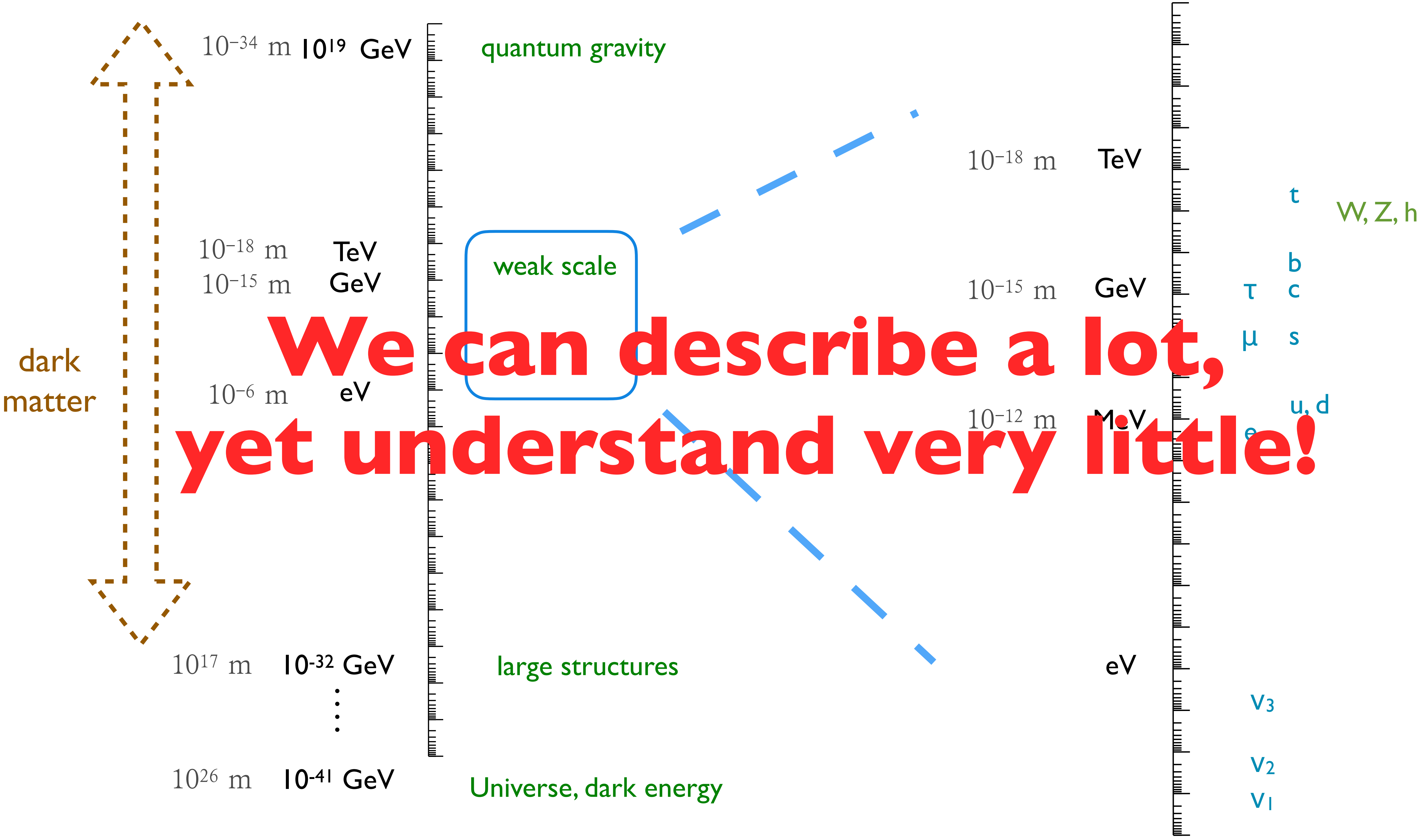
A lot of structure, multitudes of scales, but why?

Our world



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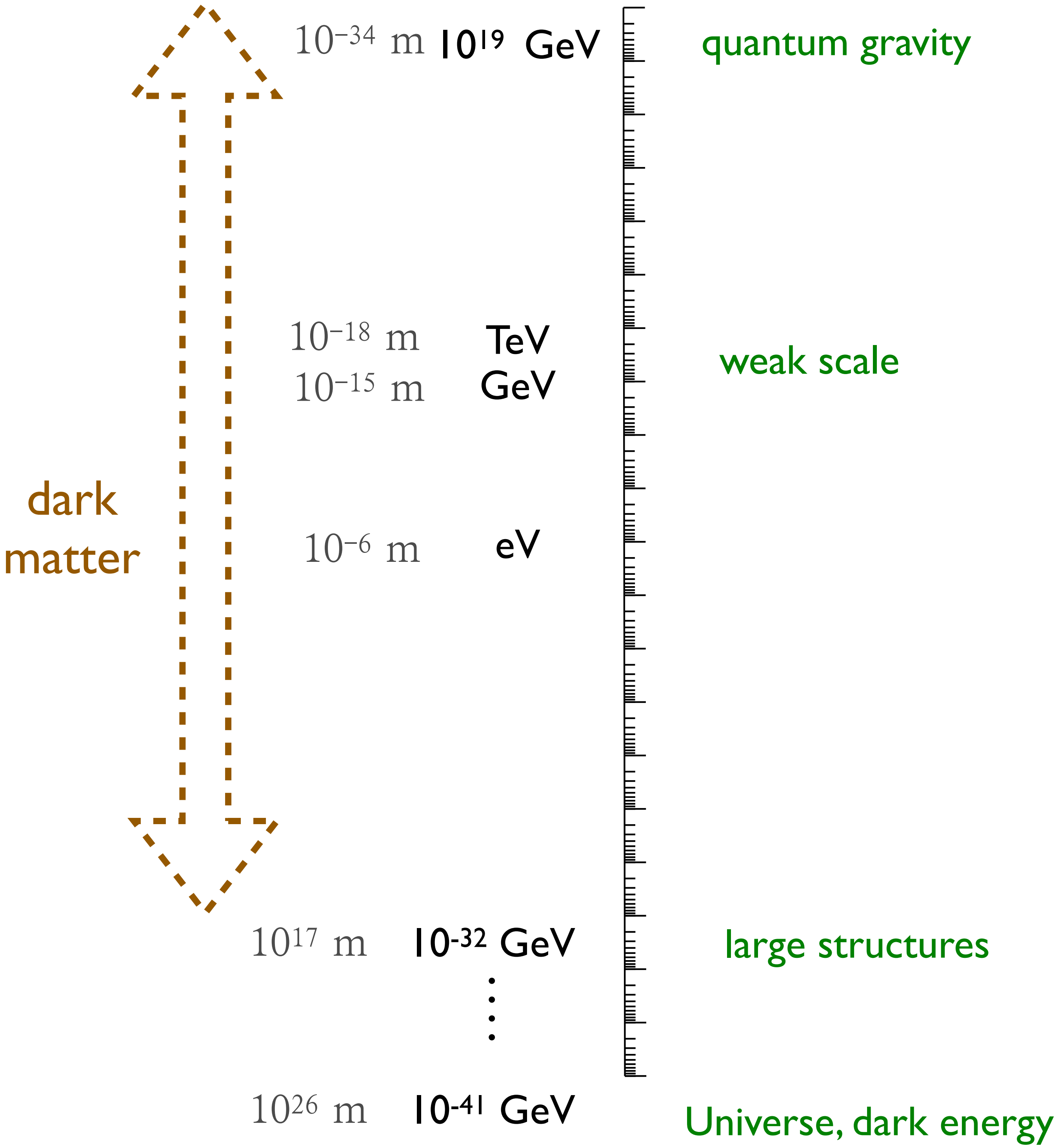
We can describe a lot, yet understand very little!

Beginning of an new era



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dark matter

In particular

Why all the different scales?

Why are there 4 interactions?

Why are they so different?

Why 3 families?

why are they so different?

Why more matter than anti-matter?

Dark matter?

Dark energy? ...

Electroweak symmetry breaking

Fundamental interactions in the SM

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

QCD: confinement $\sim r$

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

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Well understood with many decades of exp study.

Lead to numerous breakthroughs, including the establishing QM and QFT

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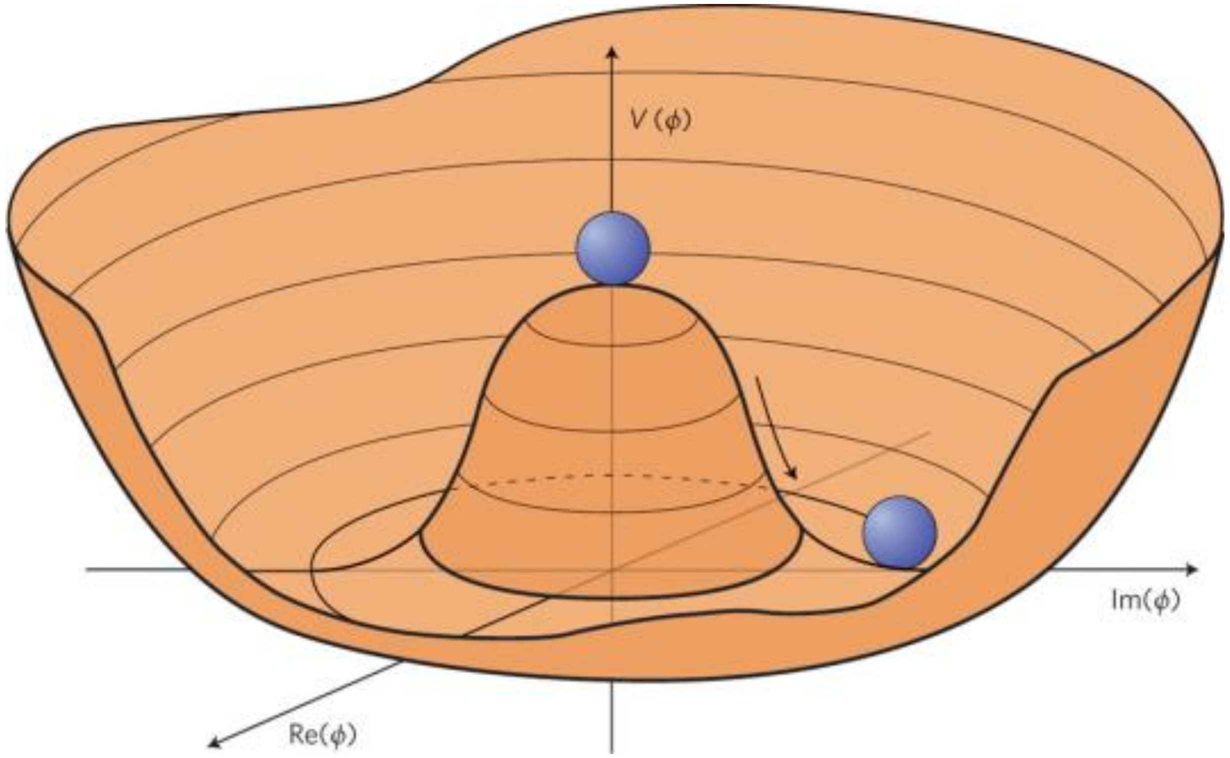
Weak interaction: Higgs $\sim \frac{e^{-m_{\mathrm{W}} \cdot r}}{r}$

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.

“Simple” picture:

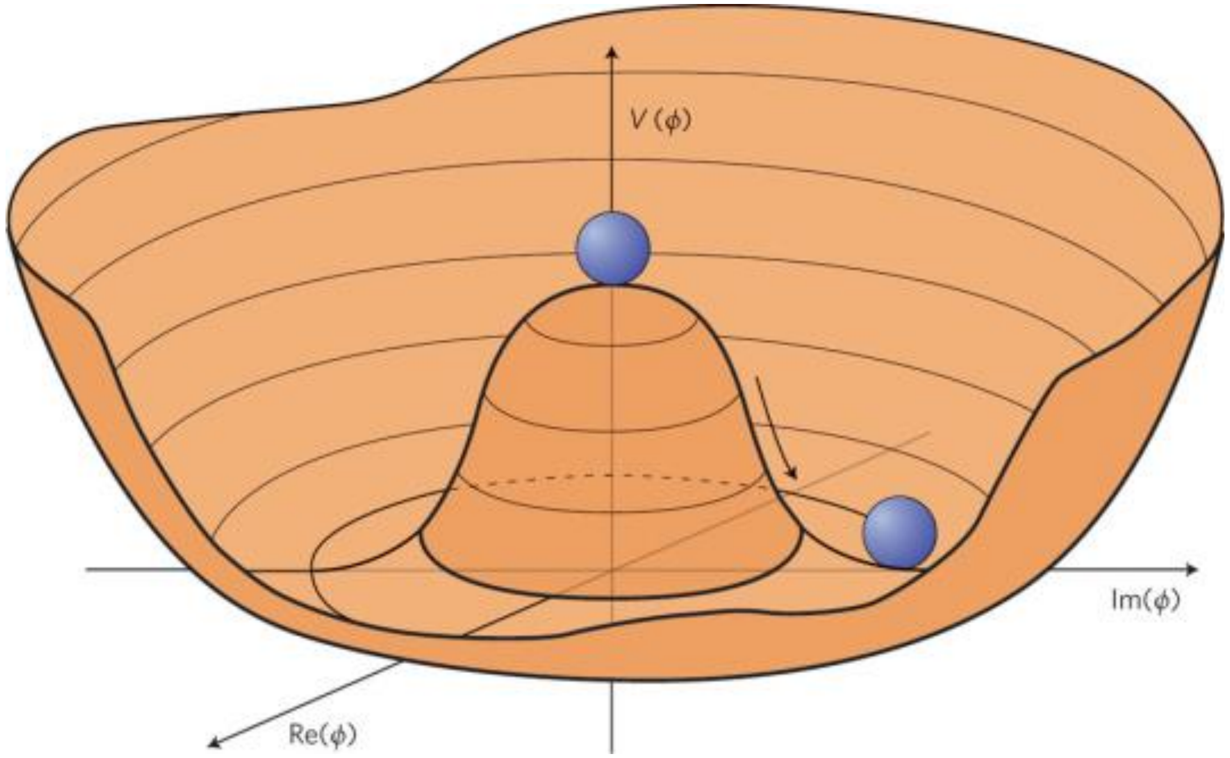


$$V(h) = \frac{1}{2}\mu^2 h^2 + \frac{\lambda}{4} h^4$$

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

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

“Simple” picture:



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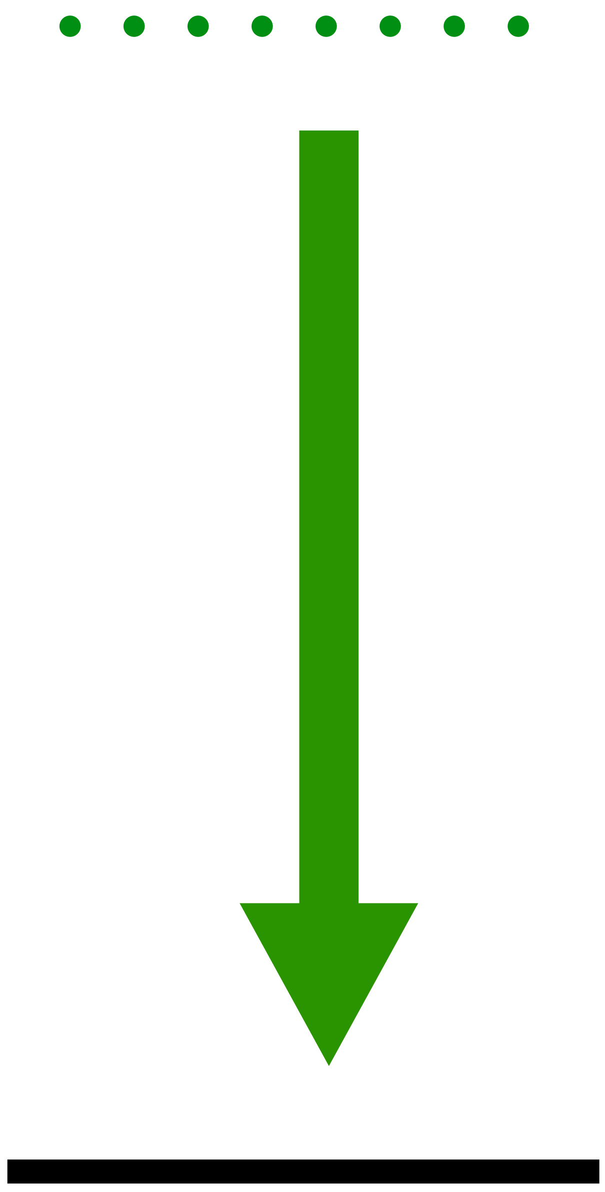
Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

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

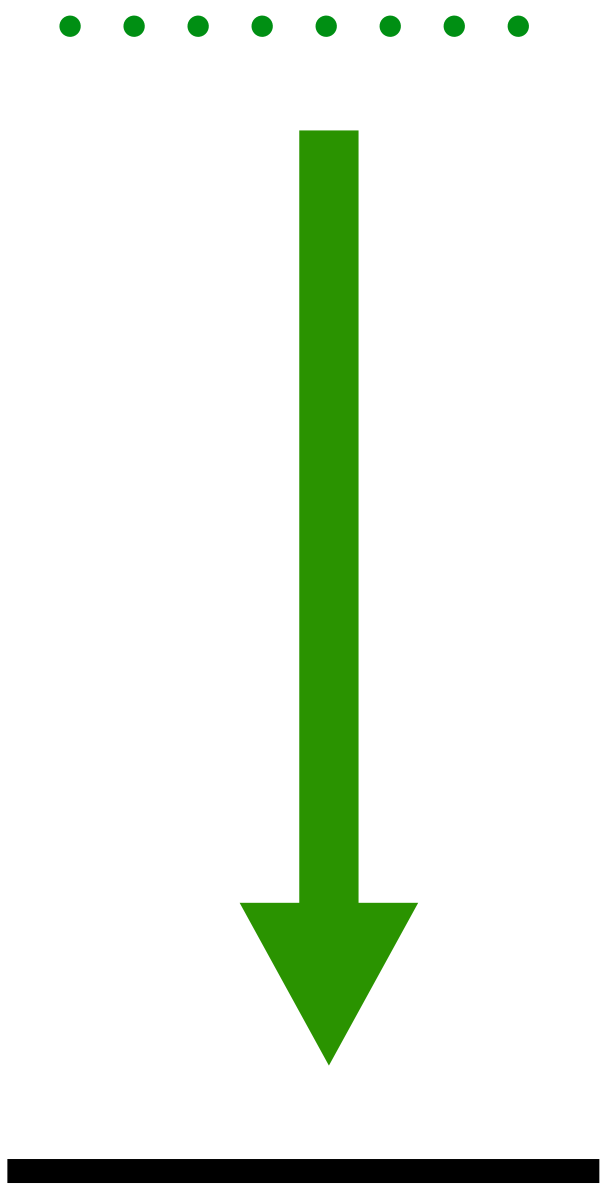
How to predict Higgs mass?



The energy scale of new physics
responsible for EWSB

Electroweak scale, 100 GeV.
m_h , m_W …

How to predict Higgs mass?



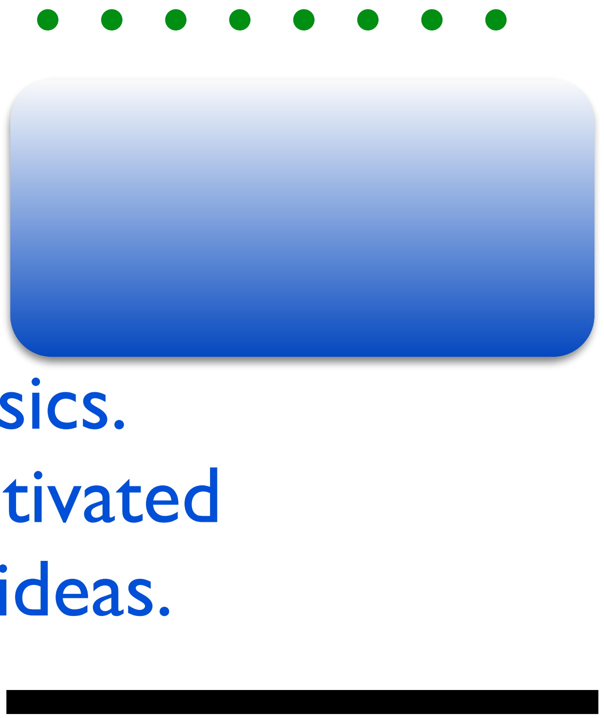
The energy scale of new physics
responsible for EWSB

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



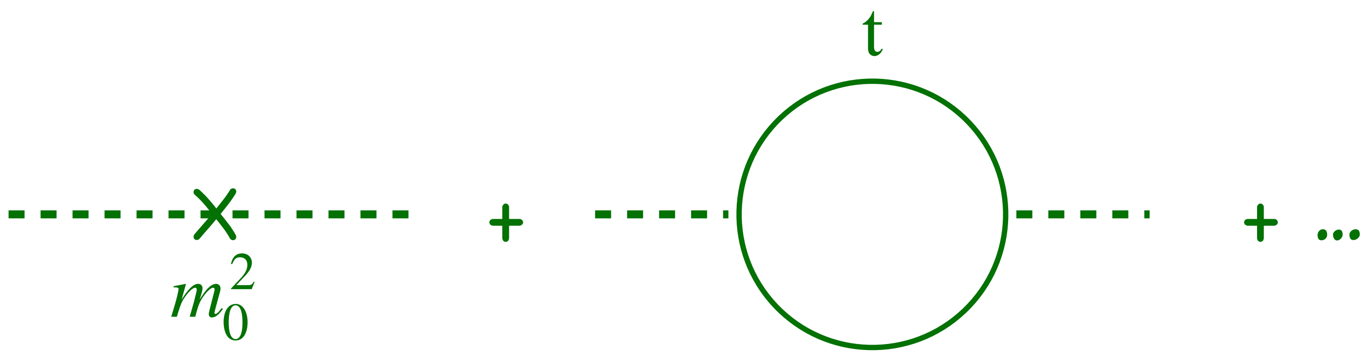
The energy scale of new physics
responsible for EWSB

TeV new physics.
Naturalness motivated
Many models, ideas.

Electroweak scale, 100 GeV.
m_h , m_W …

How to generate the electroweak scale?

- The Higgs mass is not calculable in the Standard Model. It is a parameter.



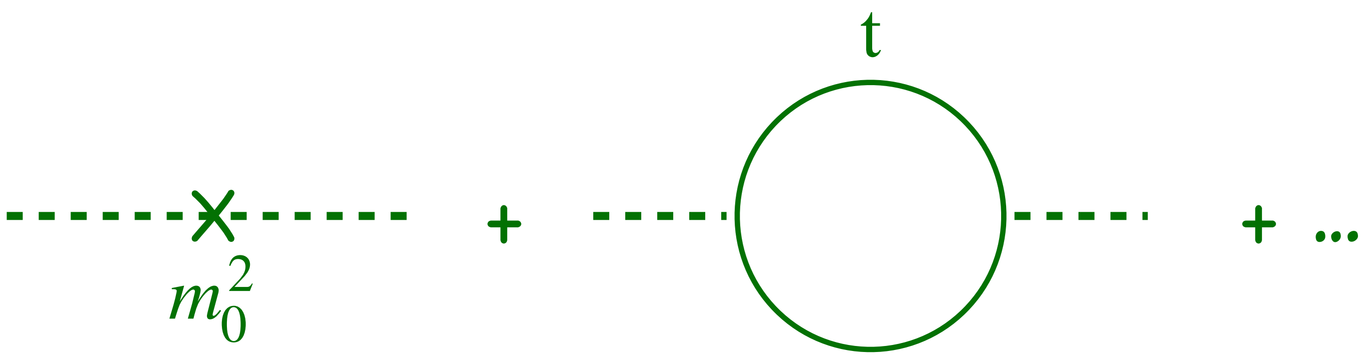
$$m_h^2 = m_0^2 - \frac{6y_t^2}{16\pi^2}\Lambda^2 + \ldots$$

Λ: mass scale of UV (more fundamental) physics

M_0^2 : bare mass term

We can use m_h^2 to calculate other observables. However, SM can't predict m_h^2 itself.

How to generate the electroweak scale?



$$m_h^2 = m_0^2 - \frac{6y_t^2}{16\pi^2}\Lambda^2 + \ldots$$

- A more fundamental theory to predict Higgs mass
  - With its own scale M.
  - No dependence on arbitrary (unknown) UV scale Λ, or a fudge bare mass term m_0.
  - Instead:

$$m_h^2 = cM^2$$

c: couplings, loops...

Toy model of scale generation

Scalar ϕ coupling to fermions

$$\mathscr{L} \supset M_\Psi(\bar{\Psi}_1\Psi_1 + \bar{\Psi}_2\Psi_2) + y\phi\bar{\Psi}_1\Psi_2 + \text{ h.c.}$$

Generating scalar potential:

$$V^\Psi(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_\Psi^4 + \underset{\text{mass}}{\underline{bM_\Psi^2 y^2\phi^2}} + \underset{\text{quartic}}{\underline{cy^4\phi^4}}\right) \times \left(\log\frac{M_\Psi^2}{\mu^2} - \dots\right)$$

$a,\ b,\ c \sim \mathcal{O}(1)$, calculable

Coupling to another scalar, similar story

$$\mathscr{L} \supset \frac{M_\Phi^2}{2}\Phi^2 + \frac{\kappa}{2}\phi^2\Phi^2$$

$$V^\Phi(\phi) \simeq \frac{1}{16\pi^2}\left(a' M_\Phi^4 + \underbrace{b'\kappa^2 M_\Phi^2\phi^2}_{\text{mass}} + \underbrace{c'\kappa^4\phi^4)}_{\text{quartic}}\right.\left(\log\frac{M_\Phi^2}{\mu^2} + \ldots\right)$$

Producing a viable potential for ϕ

$$V^{\Psi}(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_\Psi^4 + \boxed{by^2 M_\Psi^2 \phi^2} + cy^4\phi^4\right) \times \left(\log\frac{M_\Psi^2}{\mu^2} - \dots\right)$$

⇓

$$V_{\text{eff}}(\phi) = \frac{1}{2}m_\phi^2\phi^2 + \frac{\lambda}{4}\phi^4, \qquad m_\phi^2 = -\frac{b}{16\pi^2}M_\Psi^2$$

Difficult to generate: $m_\phi \ll M_\Psi$

Expectation: new physics scale close to scalar mass

Producing a viable potential for ϕ

$$V^{\Psi}(\phi) \simeq \frac{-1}{16\pi^2}\left(aM_\Psi^4 + \boxed{by^2M_\Psi^2\phi^2} + cy^4\phi^4\right) \times \left(\log\frac{M_\Psi^2}{\mu^2} - \ldots\right)$$

$$V^{\Phi}(\phi) \simeq \frac{1}{16\pi^2}\left(a'M_\Phi^4 + \boxed{b'\kappa^2M_\Phi^2\phi^2} + c'\kappa^4\phi^4\right)\left(\log\frac{M_\Phi^2}{\mu^2} + \ldots\right)$$

$$\boxed{} + \boxed{} \quad \Rightarrow \quad m_\phi^2 = \frac{1}{16\pi^2}(-aM_\Psi^2 + bM_\Phi^2)$$

Producing a viable potential for ϕ

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$$\square + \square \Rightarrow \quad m_{\phi}^2 = \frac{1}{16\pi^2}(-aM_{\Psi}^2 + bM_{\Phi}^2)$$

Possible to have $m_{\phi} \ll M_{\Psi,\Phi}$ However,

need cancellation : $\sim \mathcal{O}\left(16\pi^2\frac{m_{\phi}^2}{M_{\Psi,\Phi}^2}\right)$ fine-tuning

tuning $\propto M_{\mathrm{NP}}^{-2}$ is bad if $m_{\phi} \ll M_{\mathrm{NP}}$

Back to the Higgs mass

$$m_h^2 = cM^2 \qquad c \sim \frac{(\text{coupling})^2}{16\pi^2}$$

- Coupling is about O(0.1–1).
- Without large cancellation: M $\lesssim$ TeV.
  - New physics near weak scale!
- In particular:
  - Since top quark gives largest contribution to Higgs mass, we expect some "top-partner" to be around TeV scale.

TeV Supersymmetry (SUSY)

- Supersymmetry, $|\,\text{boson}\rangle \Leftrightarrow |\,\text{fermion}\rangle$
- An extension of spacetime symmetry.
- New states: "Partners"

	spin			spin
gluon, g	1	gluino	$\tilde{g}$	1/2
$W^{\pm}$, Z	1	gaugino	$\tilde{W}^{\pm}, \tilde{Z}$	1/2
quark	1/2	squark	$\tilde{q}$	0
....		....		
Standard Model particles		superpartners		

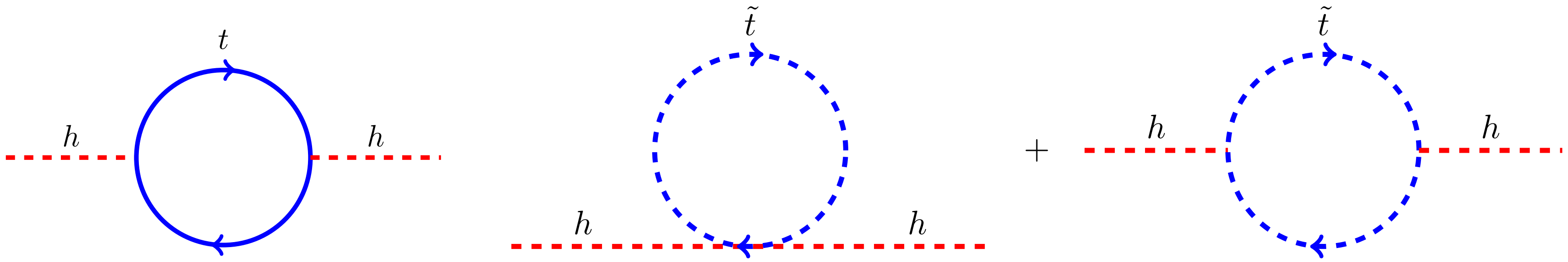
- Mass of superpartners ∼TeV.

Electroweak scale in Supersymmetry

A unique property of supersymmetry:

No Λ^2 dependence.

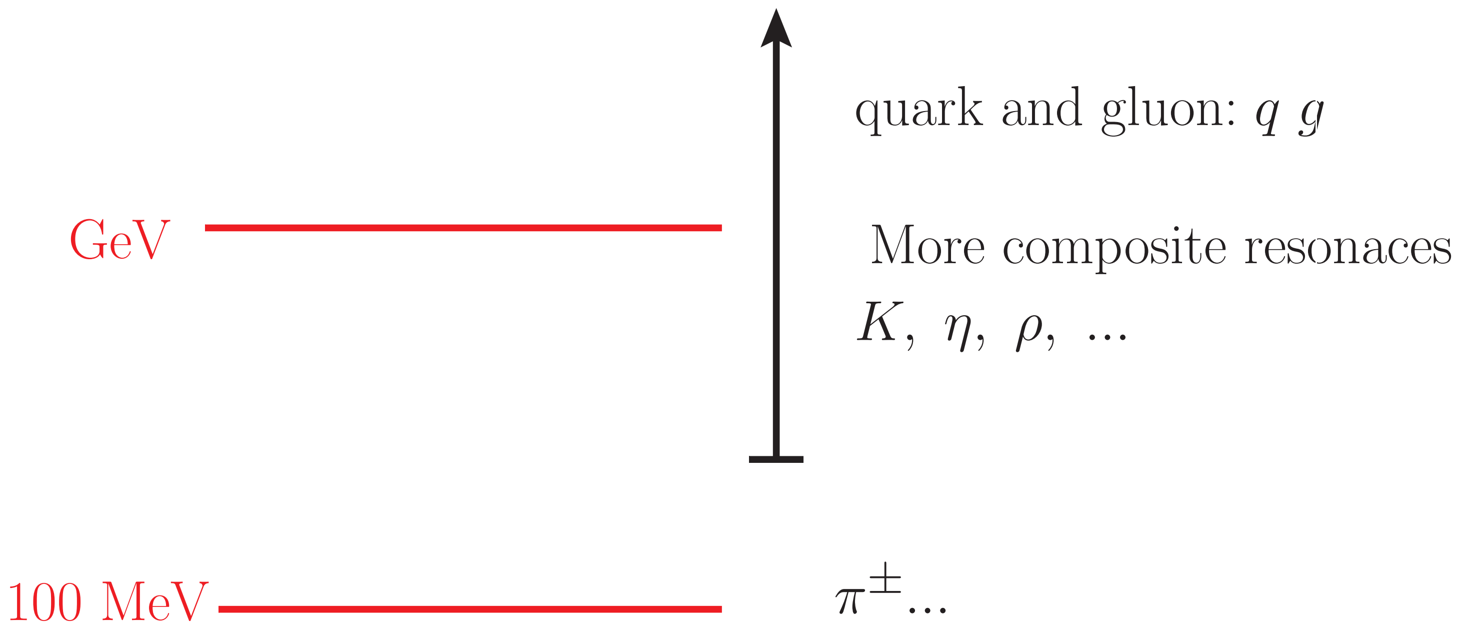
Mass parameters evolves slowly, generating large scale separation.



$$\delta m_{H_u}^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2 \right) \log \frac{\Lambda}{\text{TeV}}.$$

Prefer light superpartners $m_{\text{SUSY}} \sim 1 \text{ TeV}$

“Learning” from QCD



quark and gluon: q g

GeV

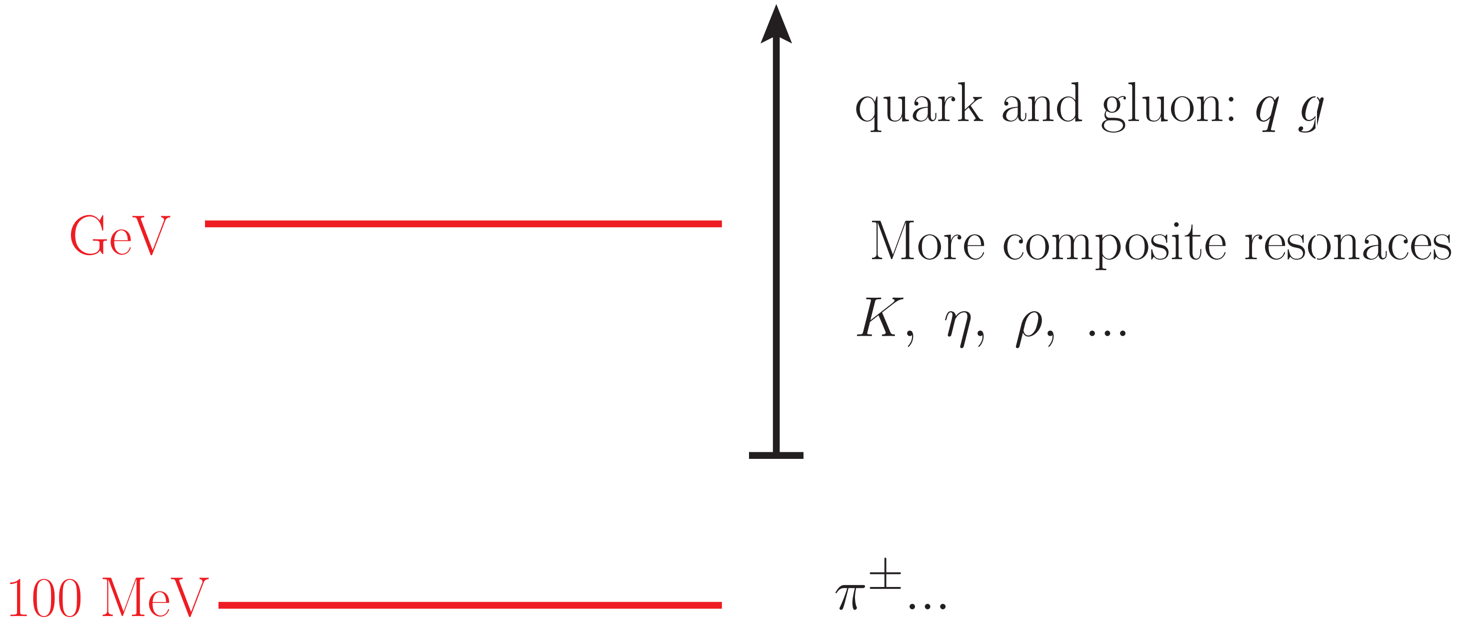
More composite resonaces

$K, \ \eta, \ \rho, \ \ldots$

100 MeV

$\pi^{\pm}\ldots$

“Learning” from QCD



quark and gluon: $q\ g$

GeV

More composite resonaces

$K,\ \eta,\ \rho,\ \ldots$

100 MeV

$\pi^{\pm}\ldots$

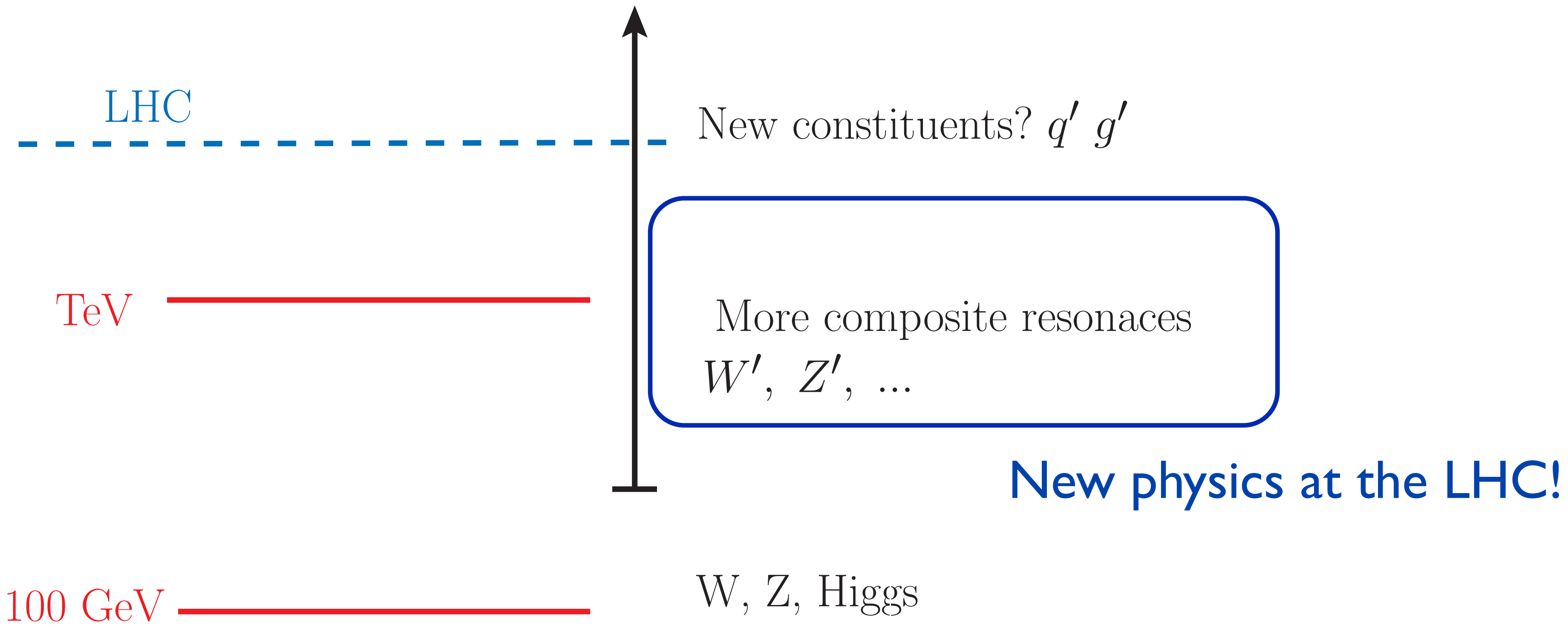
⇒ new strong dynamics,
symmetry breaking

⇒ SM Higgs

- Construct a new strong dynamics in which the low lying states will be the SM Higgs.

- Composite Higgs models. Still a natural theory.

Composite Higgs



LHC

New constituents? q' g'

TeV

More composite resonaces

W', Z', ...

New physics at the LHC!

100 GeV

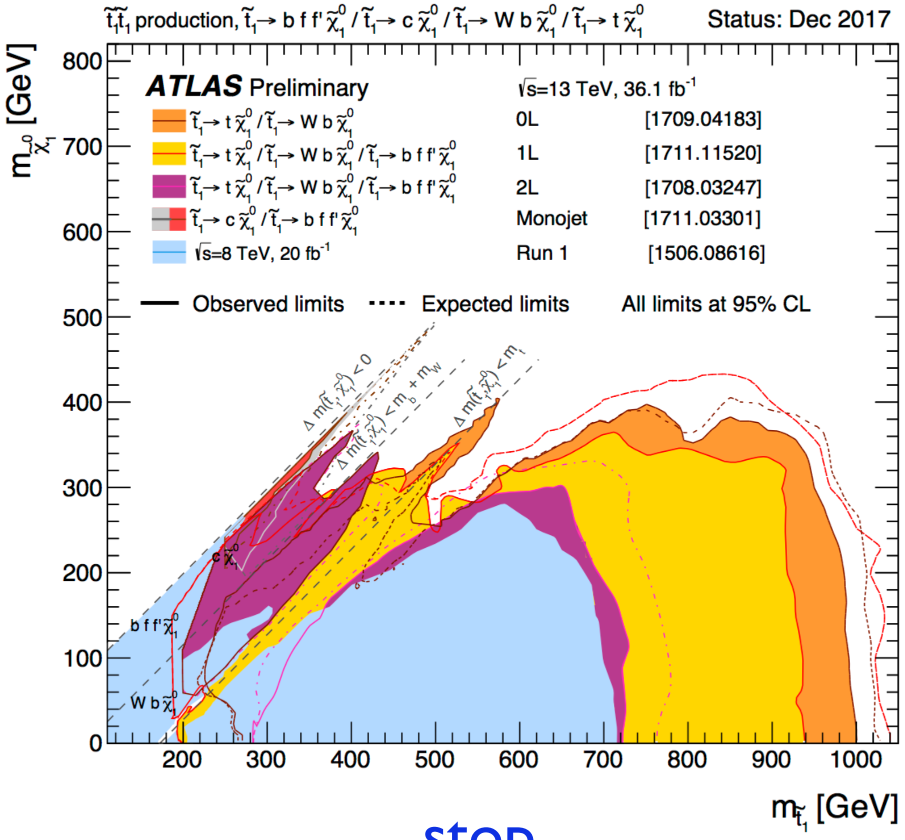
W, Z, Higgs

- Many many scenarios, models in this class.
- Little, fat, twin, holographic .... Higgs

- Similar scenarios: Randall-Sundrum, UED...
  - Theories with Higgs + resonances.

All eyes on these searches

Supersymmetry



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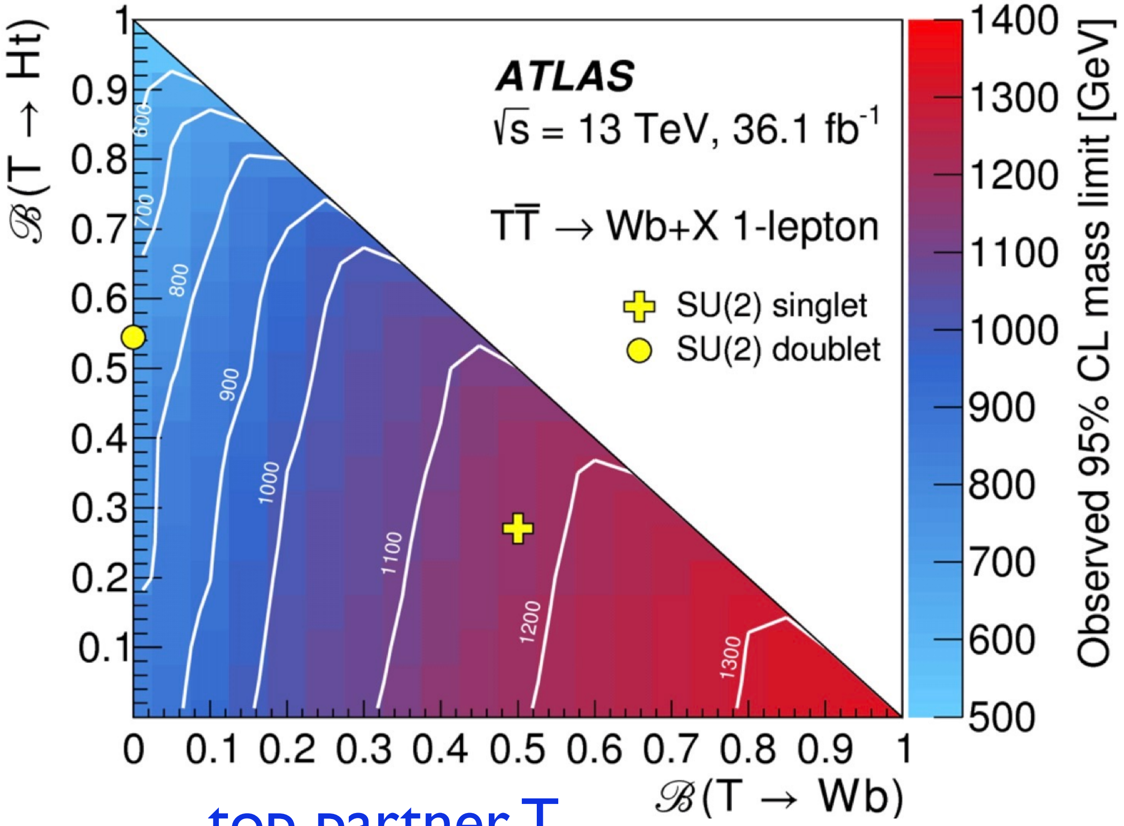
Composite Higgs



top partner, T

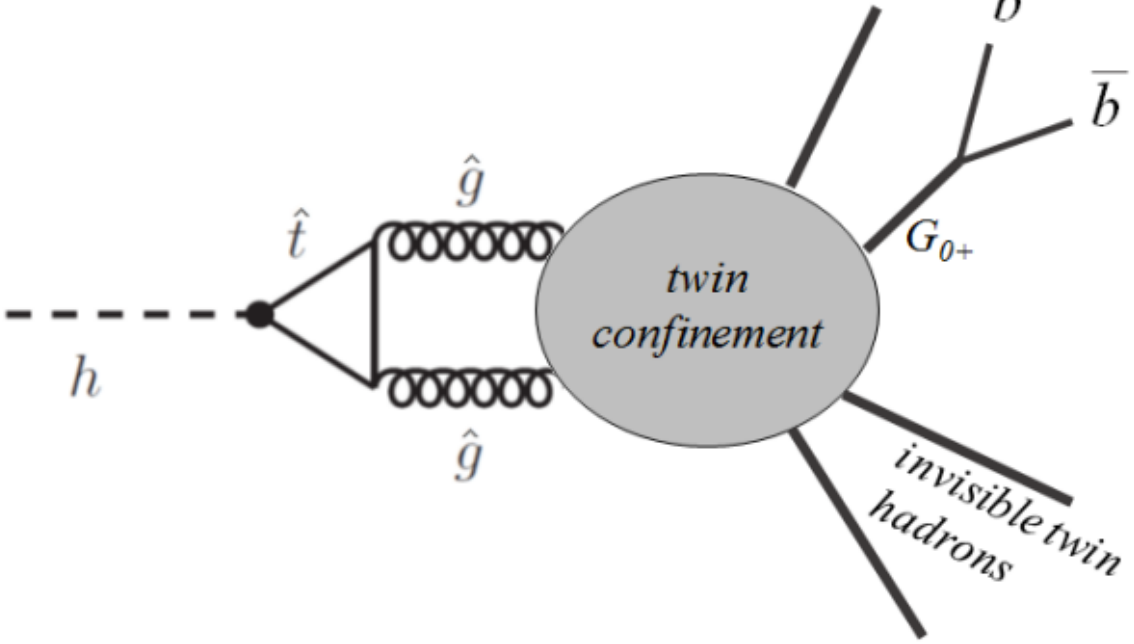
fine-tuning = comparison: $$\frac{1}{16\pi^2} m_{\mathrm{T}}^2 \quad vs \quad m_h^2 = (125\ \mathrm{GeV})^2$$

current limit: $$m_{\mathrm{T}} \sim 1\ \mathrm{TeV}$$

Stealthy top partner. “twin”

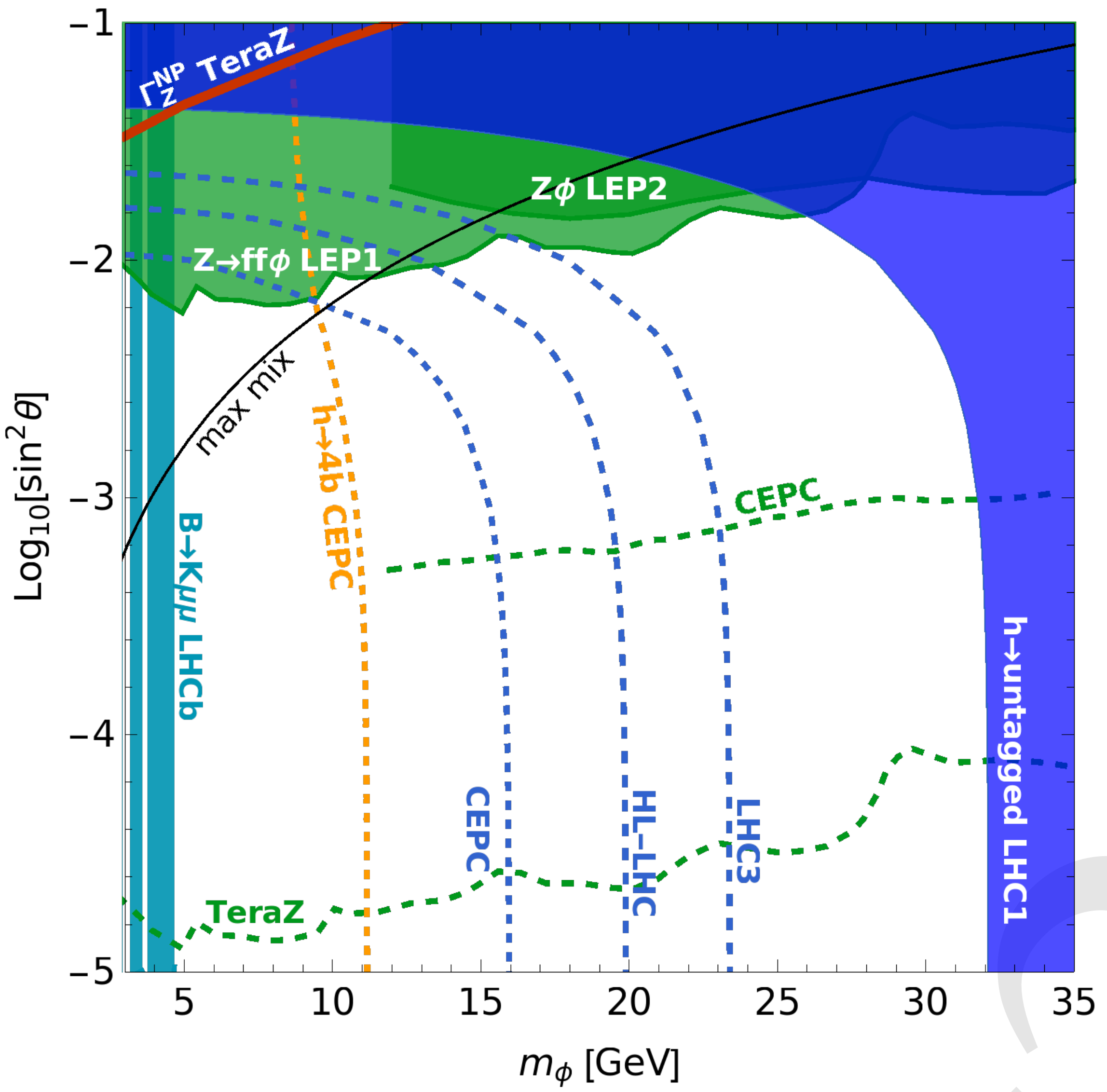
Chacko, Goh, Harnik

Craig, Katz, Strassler, Sundrum



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

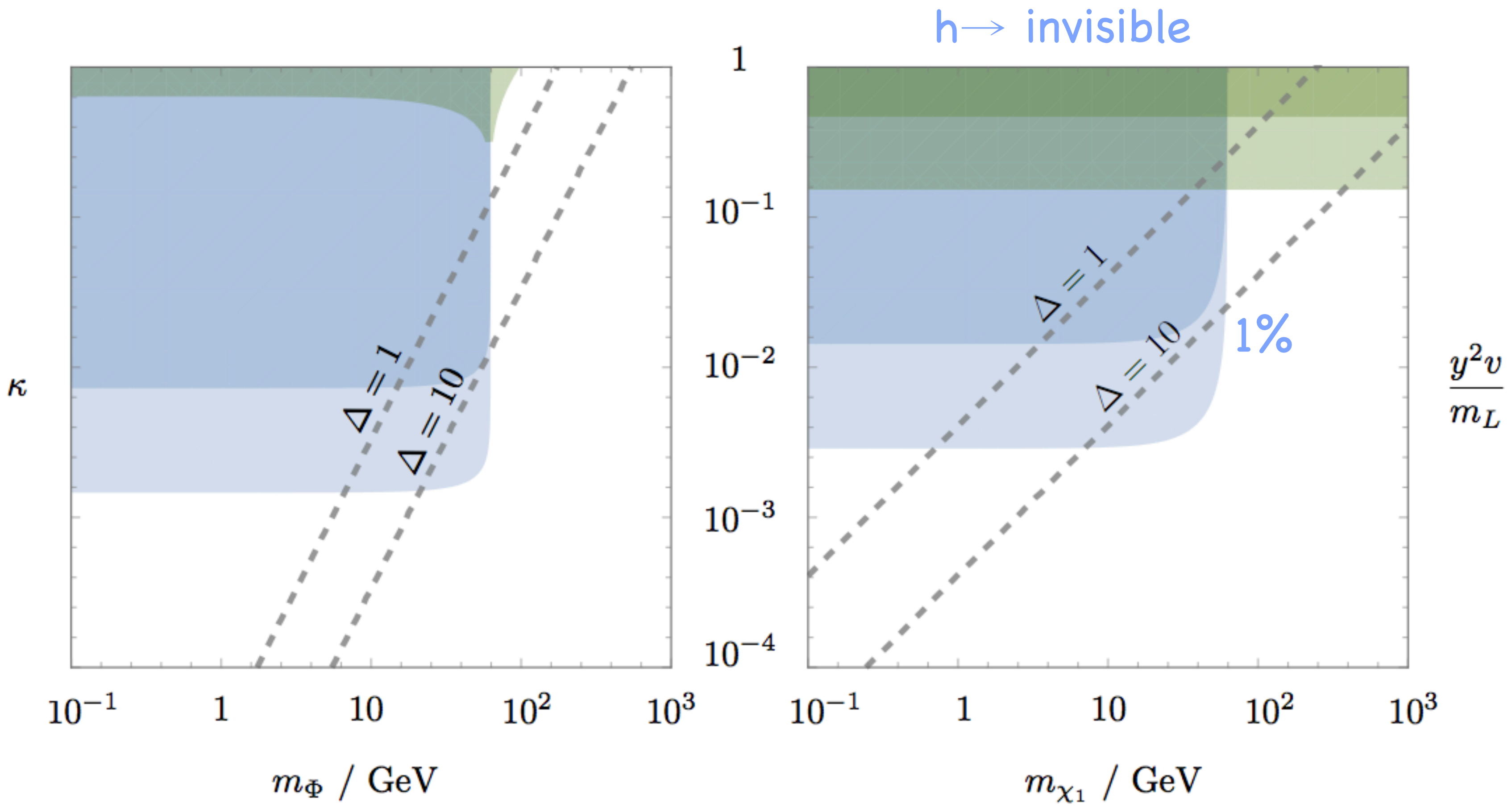
Relaxion



Cosmological evolution of a light scalar, the relaxion, sets the weak scale

Signal from relaxin-Higgs mixing,
and Higgs rare decay, $h \to \phi\phi \to 4b$ and rare Z decay

Weak gravity conjecture



h→ invisible

1%

- For a U(1) gauge theory, new physics at scale gM_{Pl}. If g<<1, responsible for weak scale?

Cheung

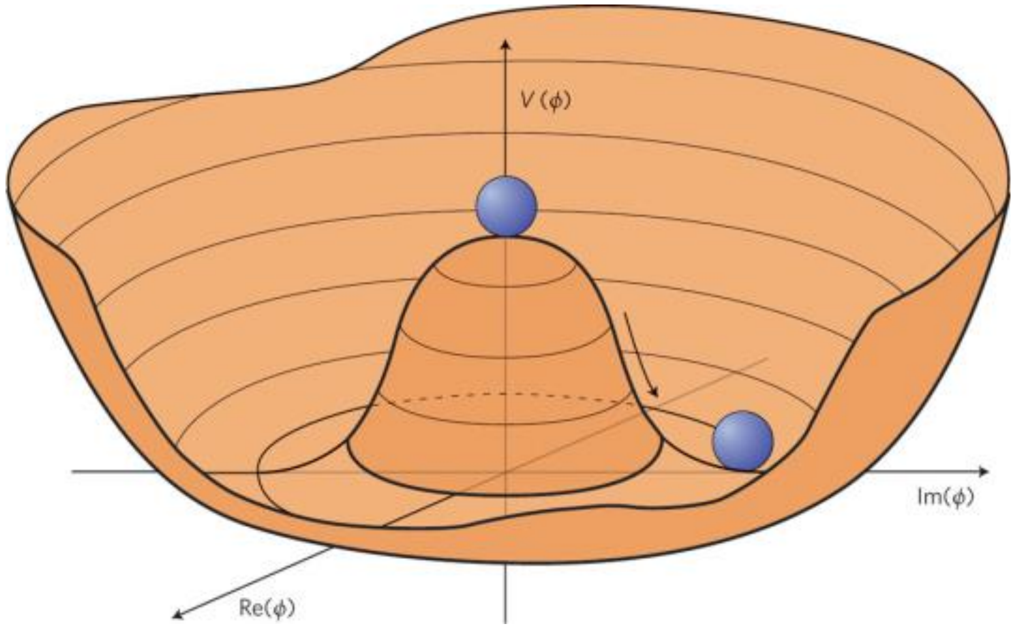
- This requires new physics close to weak scale couples to the Higgs boson.

Craig, Garcia, Koren

Why is Higgs measurement crucial?

- 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.

Mysteries of the electroweak scale.



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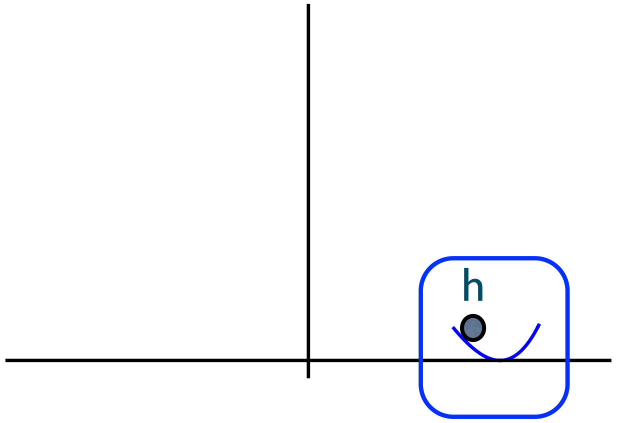
$$\langle h \rangle \equiv v \neq 0 \;\rightarrow\; m_W = g_W \frac{v}{2}$$

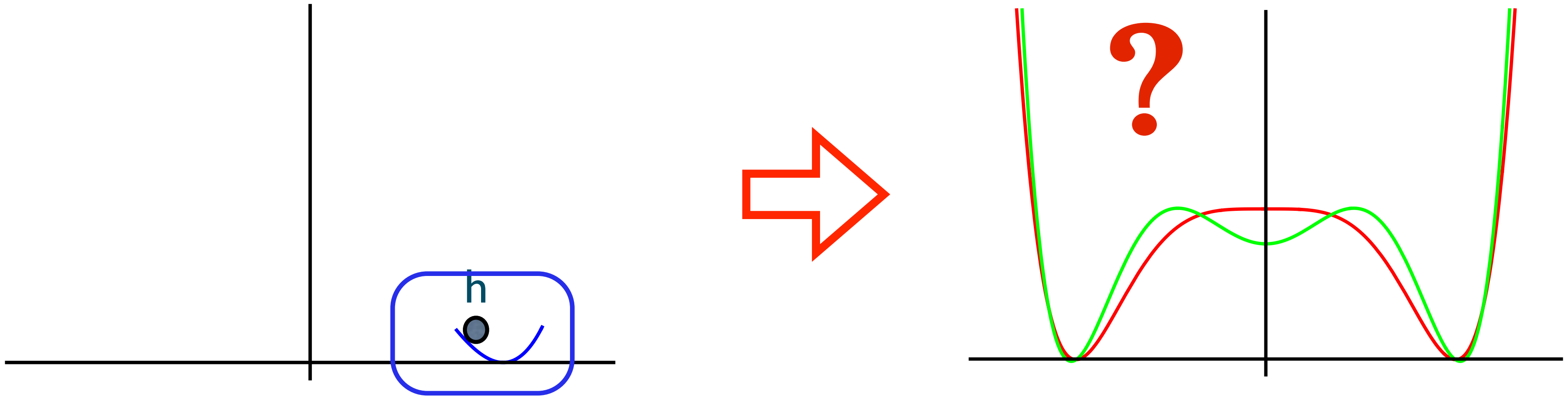
Mysteries of the electroweak scale.



What we know now

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

Nature of EW phase transition



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

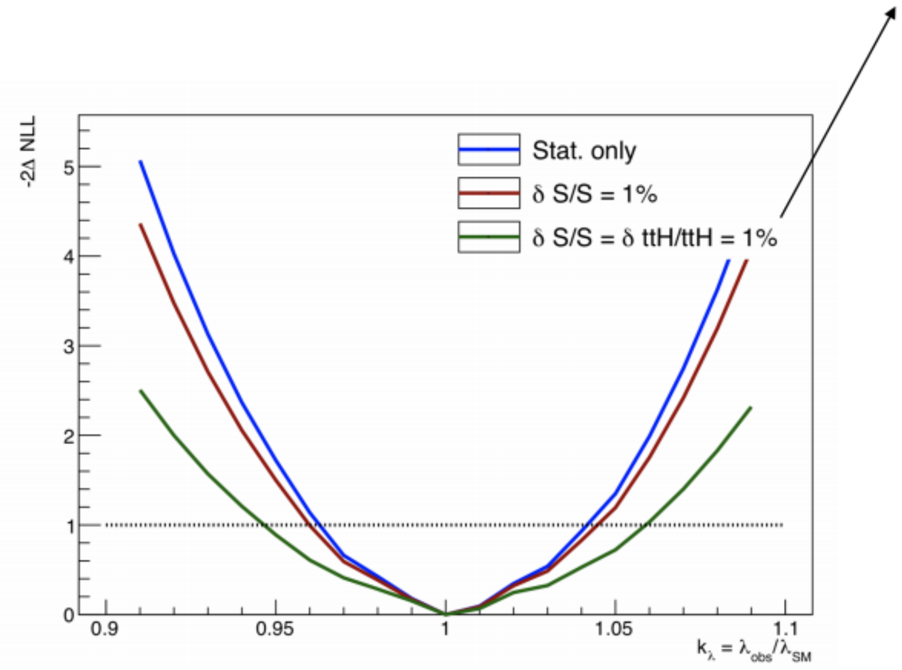
“wiggles” in Higgs potential

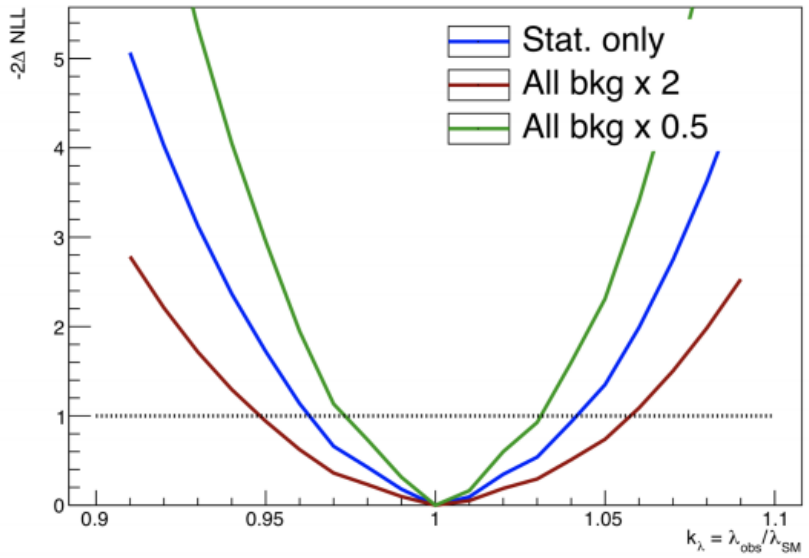
Big difference in triple Higgs coupling

Triple Higgs coupling at 100 TeV collider

Precision on the self-coupling

assuming QCD can be measured from sidebands





nominal background yields:

$\delta\kappa_\lambda(\text{stat}) \approx 3.5\ \%$
$\delta\kappa_\lambda(\text{stat + syst}) \approx 6\ \%$

varying (0.5x-2x) background yields:

$\delta\kappa_\lambda(\text{stat}) \approx 3 - 5\ \%$

Talk by Michele Selvaggi at 2nd FCC physics workshop

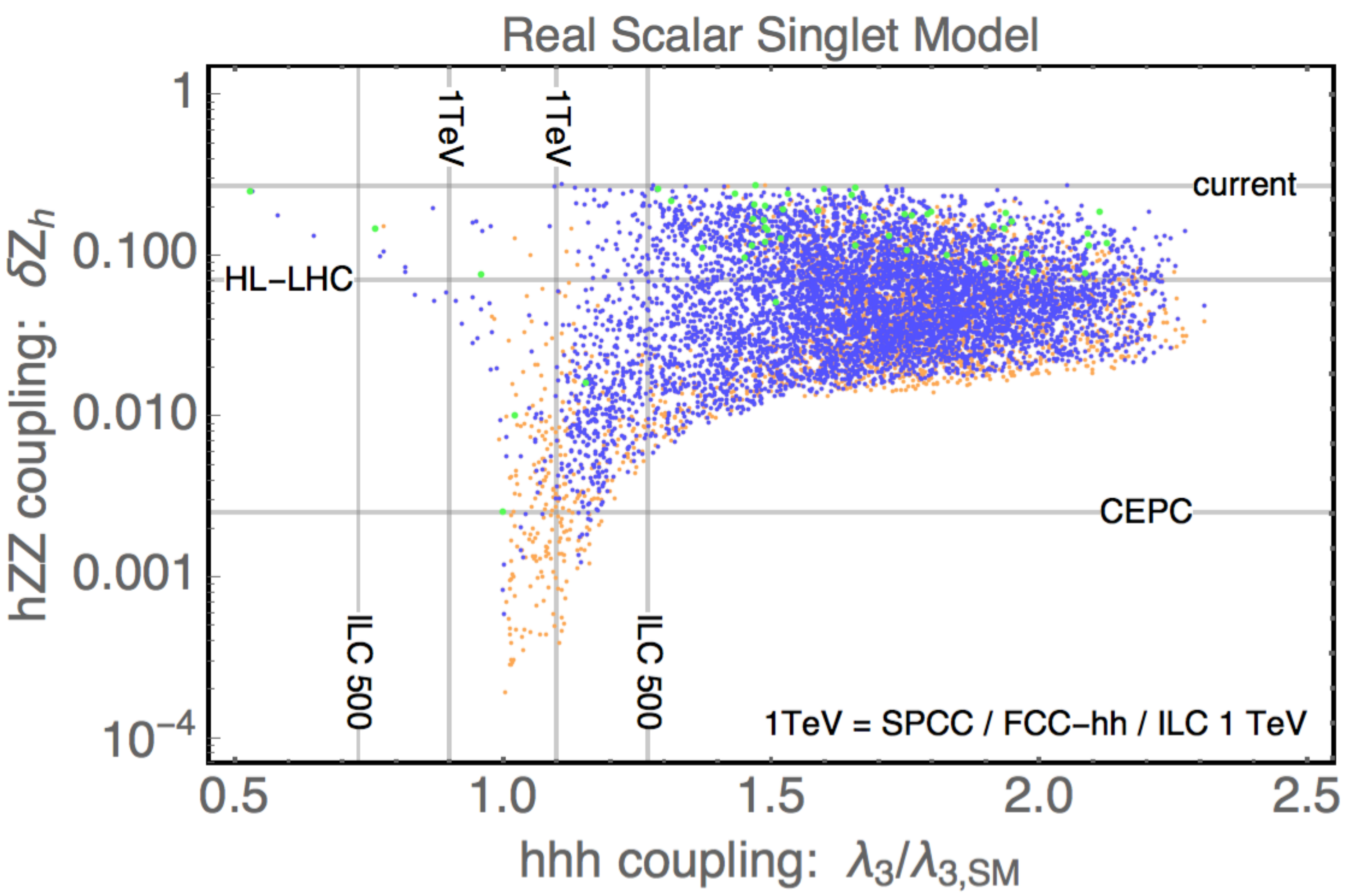
But, there should be more

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

- Large deviation in the Higgs potential means there is new physics close to the weak scale.
- Will leave more signature in Higgs coupling.

For example: $$\frac{[\partial(HH^\dagger)]^2}{\Lambda^2} \rightarrow \delta_{Zh} \sim \frac{v^2}{\Lambda^2}$$

Probing EWSB at higgs factories



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

Good coverage in model space

Higgs portal

- Dark sector
  - Does not carry SM quantum number.
- Dark sector coupling to the SM

$$O_{\mathrm{SM}} \cdot O_{\mathrm{dark}}$$

O_{SM}: gauge inv. SM operator O_{dark}: dark sector operator

- More relevant coupling ⇔ lowest dim operator
  - Lowest dimension $O_{\mathrm{SM}} = HH^{\dagger}$. Higgs portal.
  - A unique gateway to dark sector.

Higgs portal

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

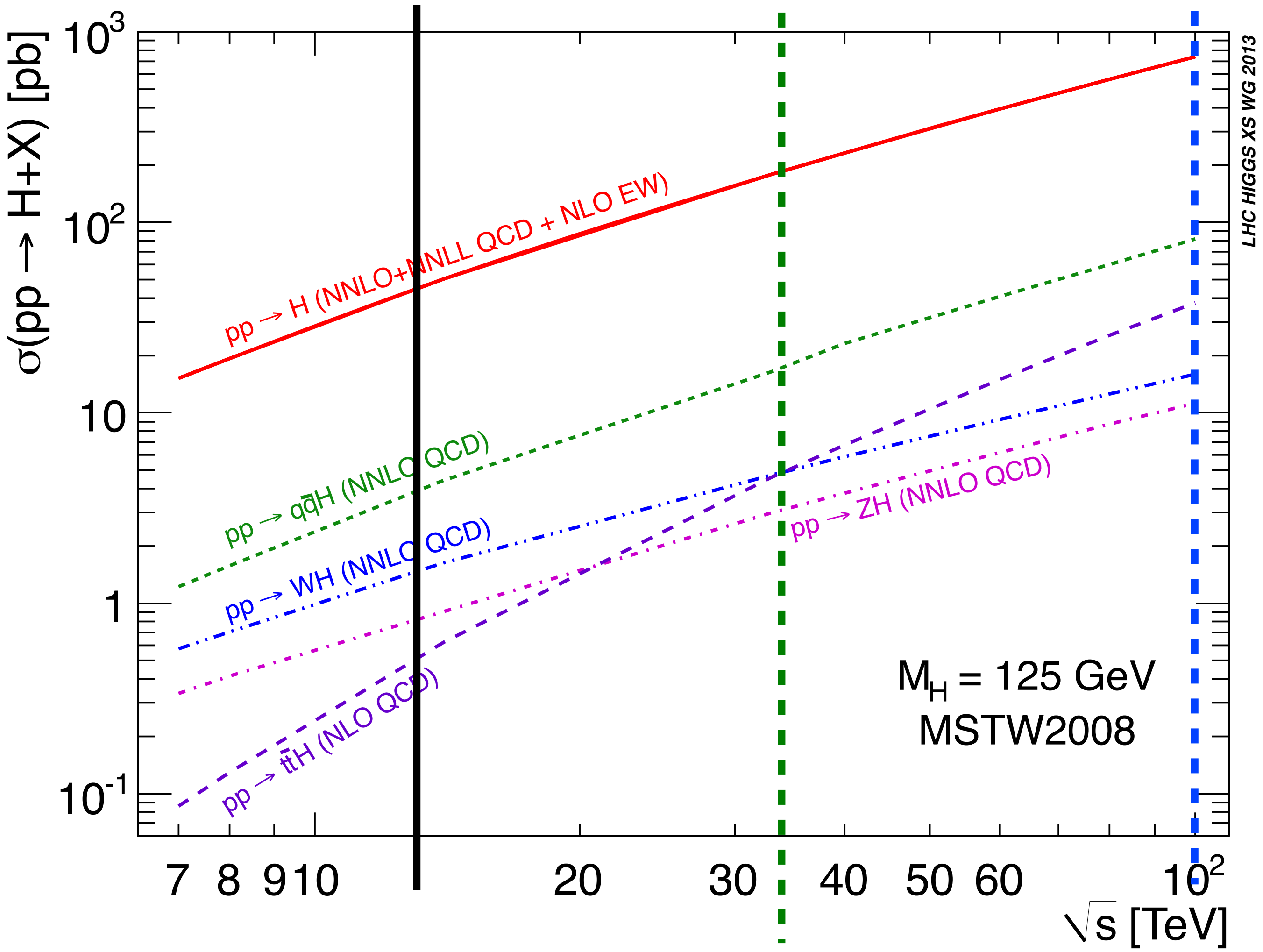
- Producing dark sector particles through the Higgs portal.
- Higgs rare decays:
  - Higgs → invisible at LHC can constrain down to a few percent.
  - A lot of room for exotic decay:

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

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

Hadron collider

- The “ultimate” Higgs factories



# of Higgses in 3 ab^{-1}

14 TeV > 150 million

33 TeV > 500 million

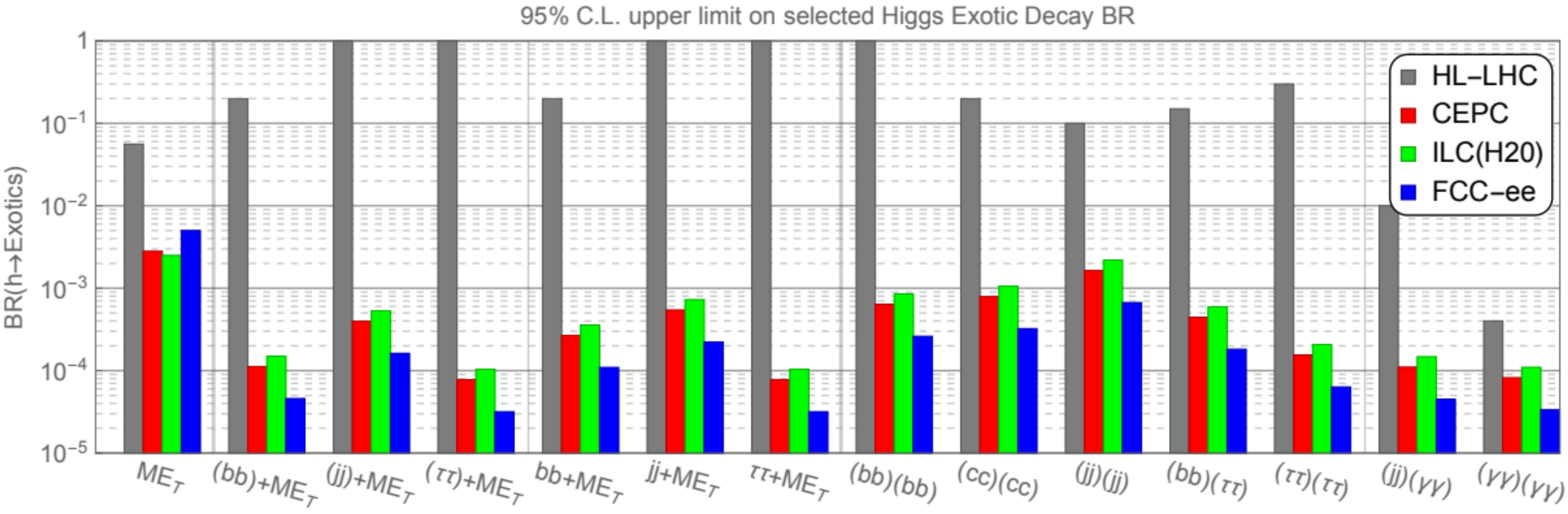
100 TeV > 2 billion

In comparison, O(million)
Higgs at ee Higgs factories

Hadron collider good for rare but clean signal

In principle, can be sensitive to BR ≈ 10^{-7}

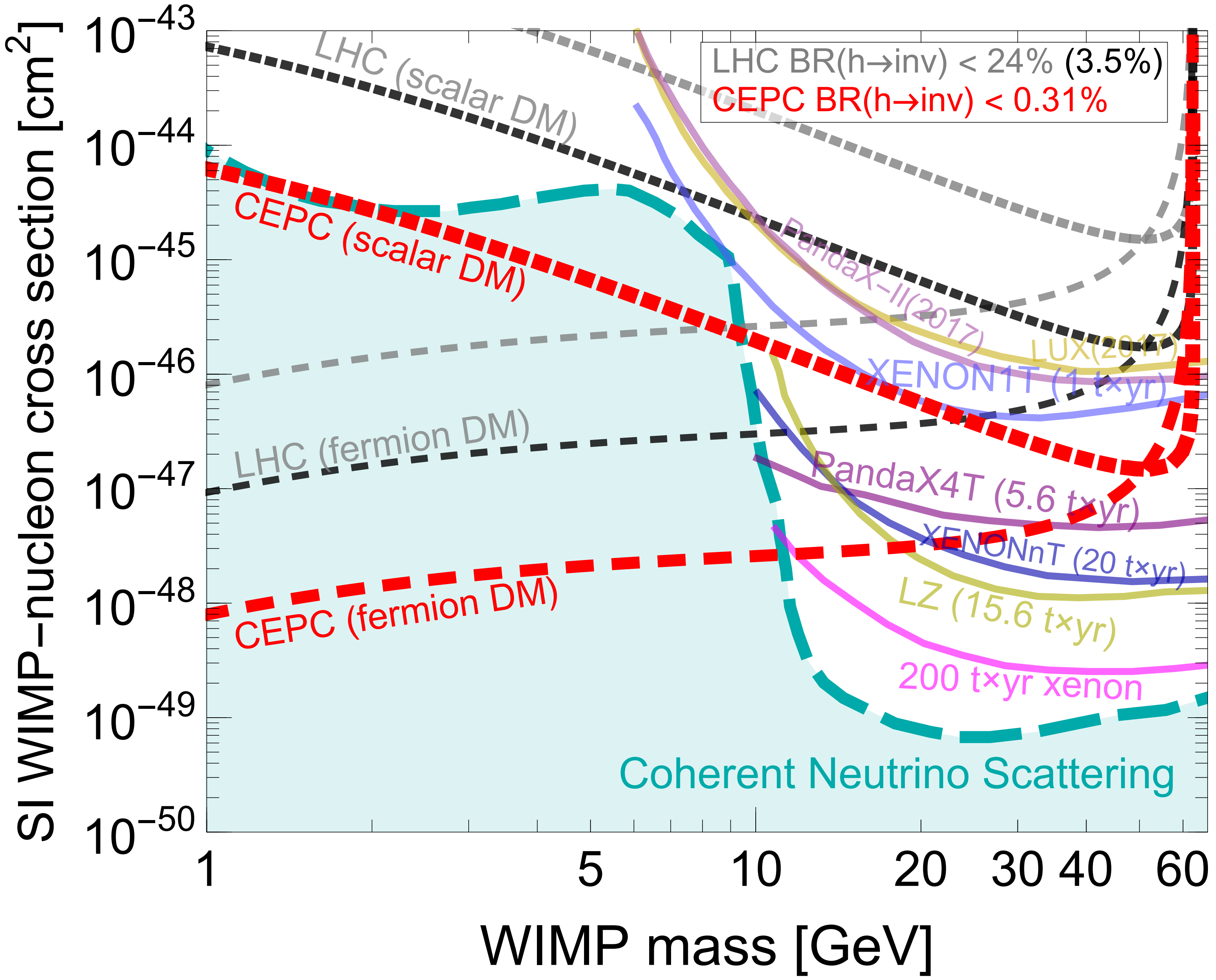
Higgs exotic decay



Complementary to hadron collider searches

Higgs portal dark matter

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



Higgs and EFT

Higgs and EFT

$$\mathscr{L} = \mathscr{L}^{\mathrm{SM}}_{\mathrm{renormalizable}} + \sum_{i,n} \frac{c_{i,n}}{\Lambda^n} \mathscr{O}_i^{(4+n)}$$

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  - Accidental symmetries of the renormalizable part (such as lepton, baryon number, custodial,...) can be broken.

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Higgs and EFT

$$\mathscr{L} = \mathscr{L}^{\text{SM}}_{\text{renormalizable}} + \boxed{\sum_{i,n} \frac{c_{i,n}}{\Lambda^n} \mathscr{O}_i^{(4+n)}}$$

rest of this school

- With all particles in the Standard Model, consistent with all gauge invariances.
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Precision from coupling measurement

- In new physics searches from precision measurement, we are going after deviations of the form

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

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

- Take the Higgs coupling.
  - LHC precision: ≈5% ⇒ sensitive to $M_{NP} \approx$ TeV
  - M_{NP} < TeV will also be covered by direct NP searches at the LHC. Precision measurements are complementary.
  - Beyond the LHC, 1% or less precision can be achieved.

Precision from high energies at LHC

Measurement limited by: $$\frac{\delta\sigma}{\sigma} < \delta_{\text{systematic}} \oplus \frac{1}{\sqrt{N}}$$

- Coupling measurement at low energy have significant systematic error.

$$\frac{\delta\sigma}{\sigma} \sim \frac{v^2}{\Lambda^2} \sim \delta_{\text{systematic}}$$

- Effect of new physics grow with energy.
  - Beneficial to measure at higher energy E > $m_{Z,W,h}$ if systematics does not grow as fast

$$\frac{\delta\sigma}{\sigma} \sim \frac{E^2}{\Lambda^2} \sim \delta_{\text{systematic}}$$

⇒ probing higher NP scales Λ

EFT $\neq$ everything

- EFT is a great tool, applying broadly to cases where heavy new physics can be integrated out.

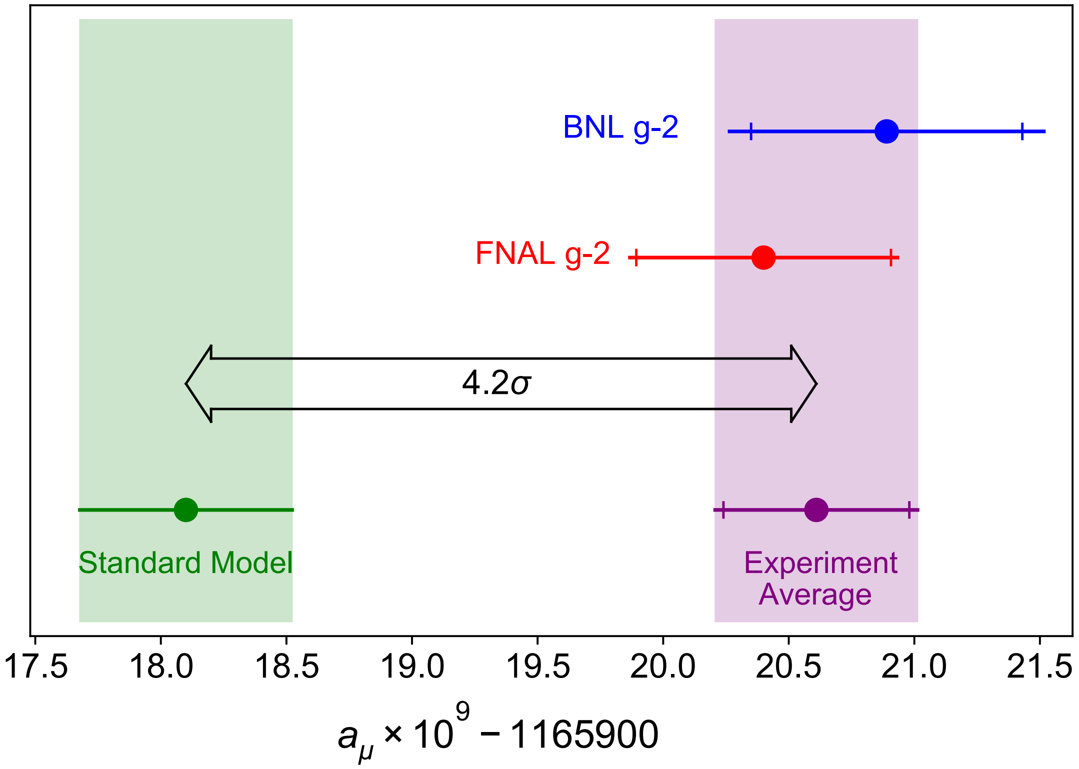
- However, it is important to keep in mind the there are cases where EFT does not cover.

- Obviously, not applicable in direct production of new physics particles.

    - For example: Higgs exotic decay.

Or this

Muon g-2



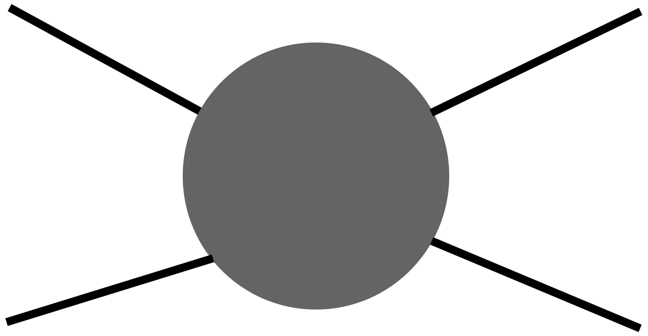
$$\mathscr{L} \supset \frac{e}{16\pi^2}\frac{m_\mu}{\Lambda^2} H\bar{L}\sigma_{\mu\nu}\mu_R F^{\mu\nu} \;\rightarrow\; \delta a_\mu \simeq \frac{e}{16\pi^2}\frac{m_\mu^2}{\Lambda^2}$$

Disagreement with SM ⇒ $\Lambda \sim$ 300 GeV, “light”!

LHC should be able to directly produce this new physics and discover it!

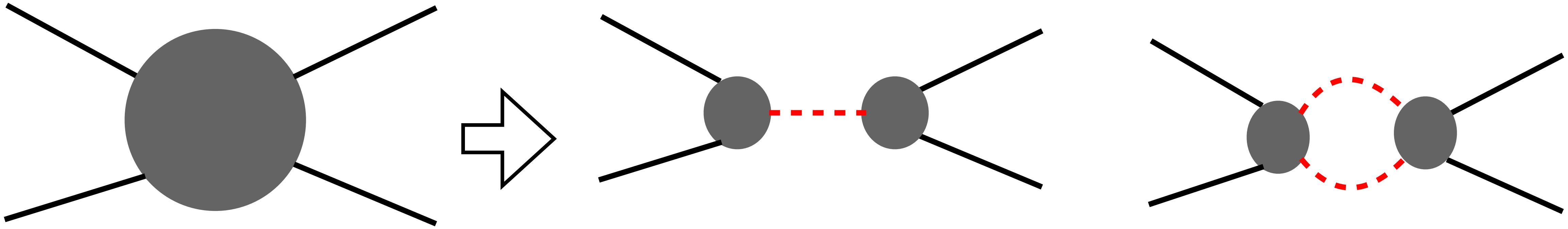
EFT ≠ everything

Focus on scattering with SM external states



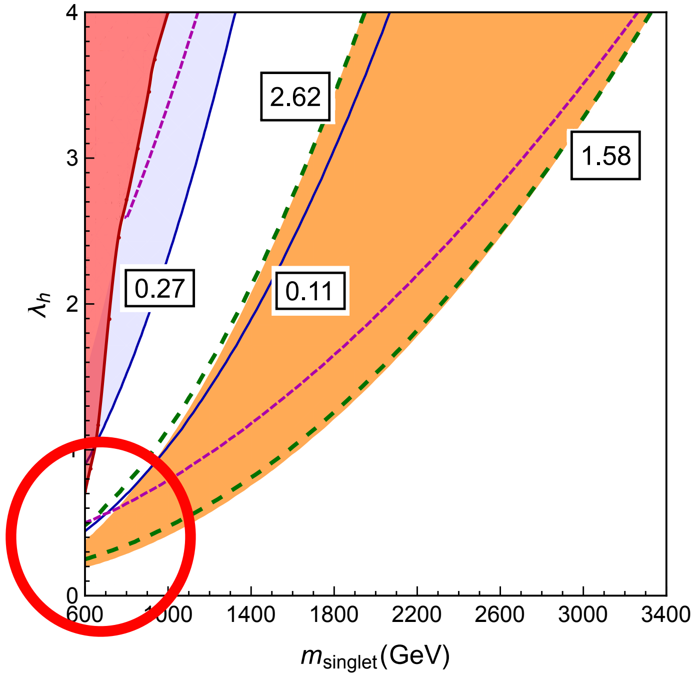
- Modeled with an EFT operator: amplitude $\propto E^n$, n=1, 2...
- However, there can be important exceptions.

EFT ≠ everything



- Light particle

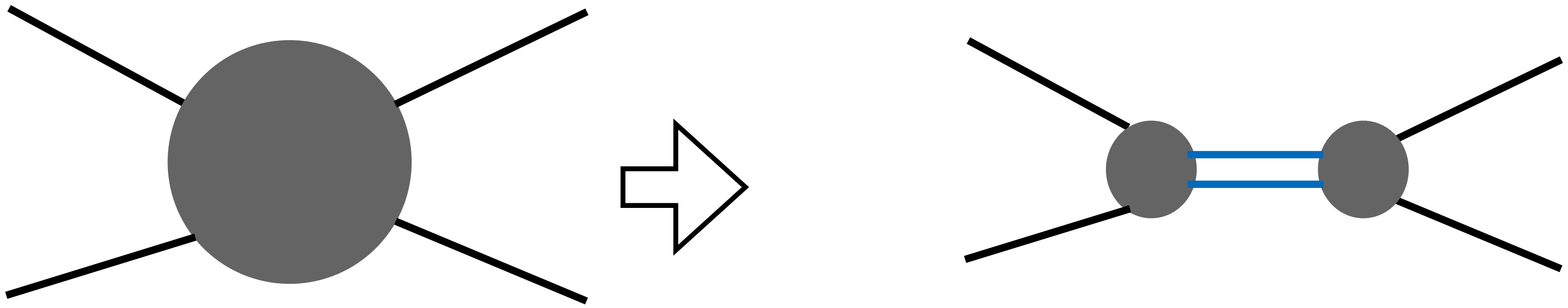
Amplitude will deviate (soften) from the prediction of the contact EFT operator.



For example: light singlet scalar for first order EW phase transition.

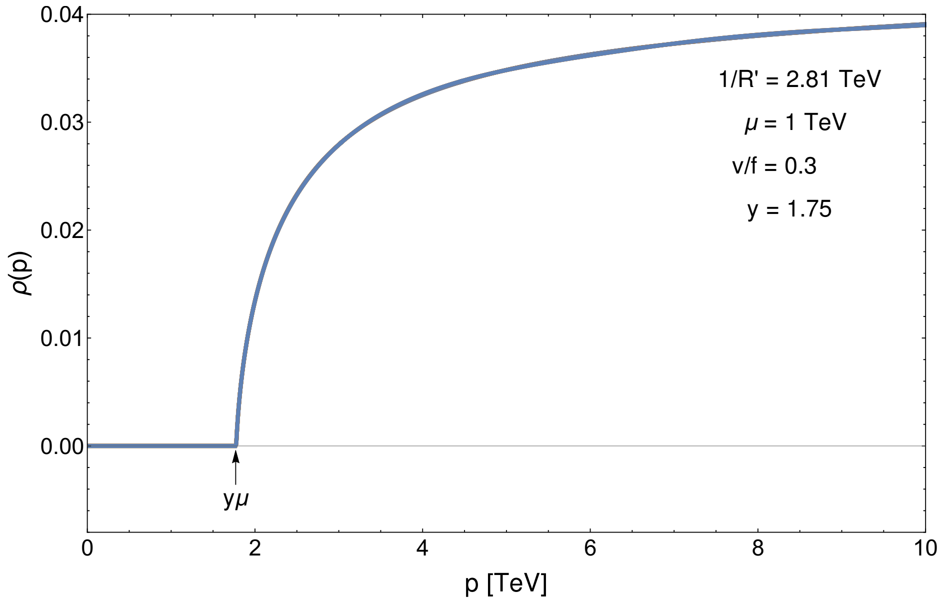
Huang, Joglekar, Li, Wagner, 1512.00068

EFT $\neq$ everything



- Strongly coupled, broad resonance, continuum, …

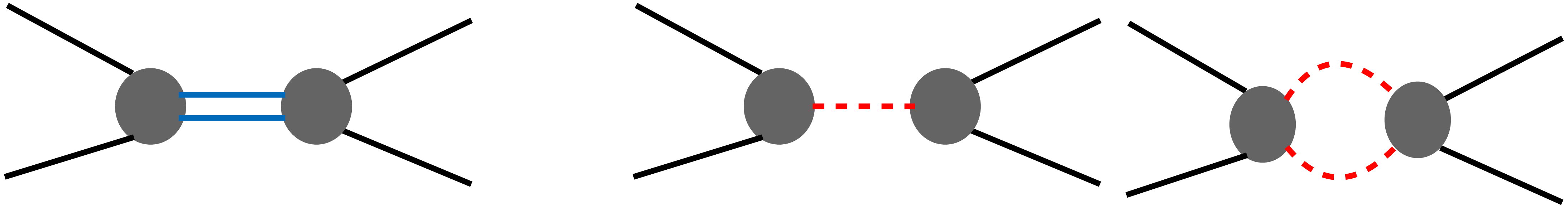
  In this case, the amplitude can be a general form factor: $f(q^2)$



e.g.: top partner as a continuum

Csaki, G. Lee, S. Lee, Lombardo, Telem, 1811.06019

Bottom line:



- These new physics may not be easy to discover directly. Precision measurement could be the main (only) window.

- In addition to energy dependence, we need to measure as a broad range of kinematical distribution as possible.

Enjoy this rest of the school!