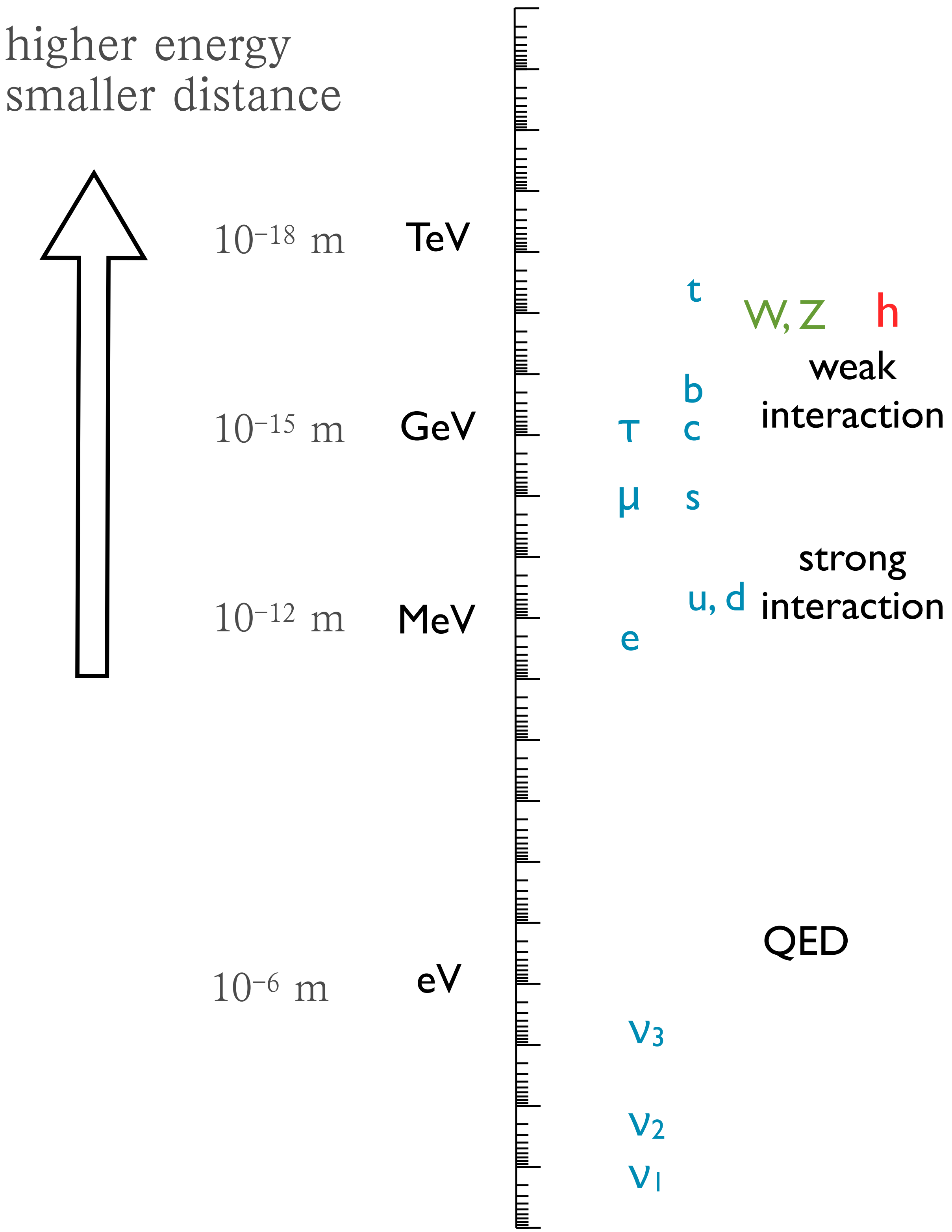
# Future of High energy physics
# LHC and beyond

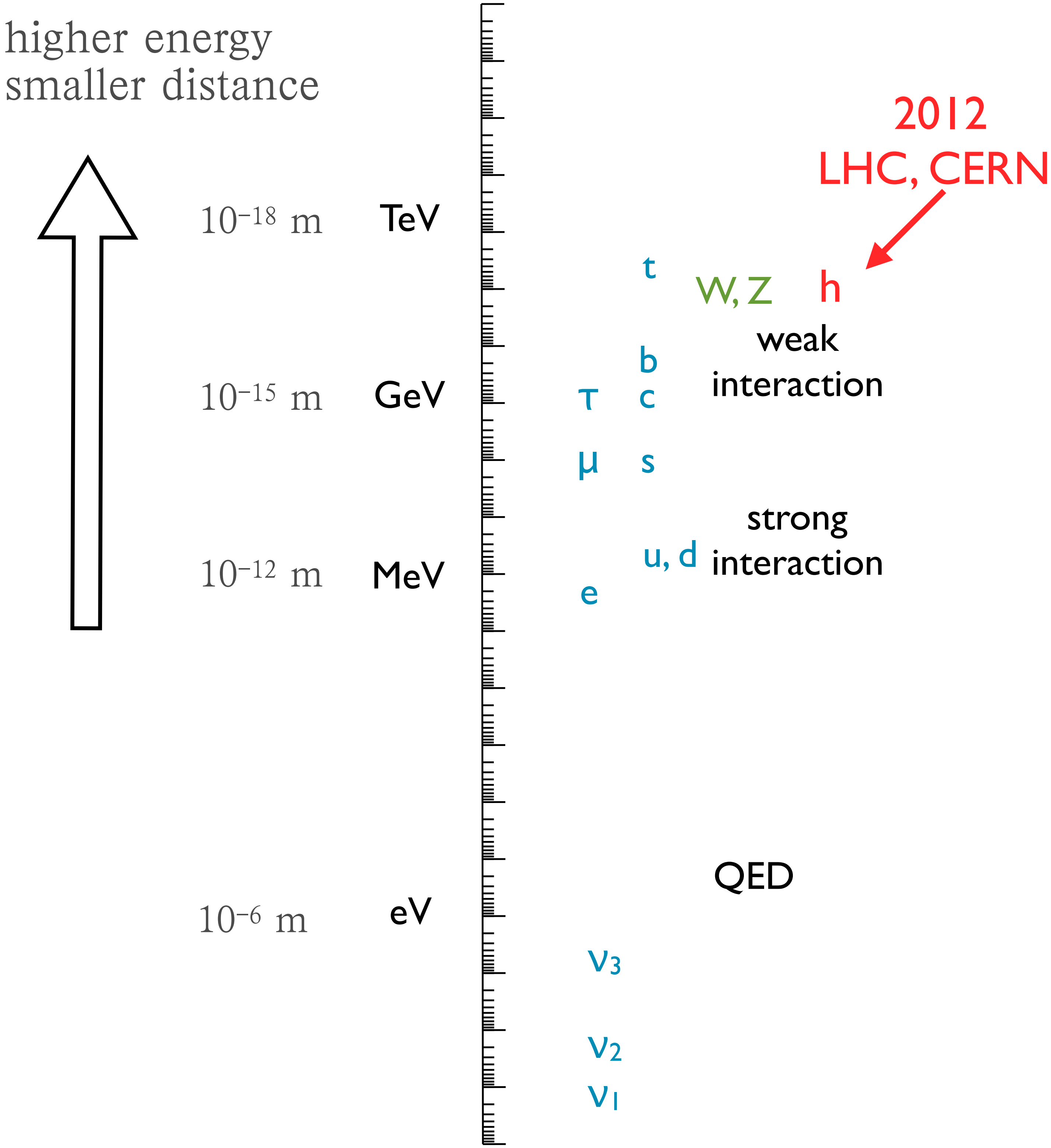
Lian-Tao Wang
University of Chicago

USTC. Nov 19, 2018

# The Standard Model



# The discovery of the Higgs boson

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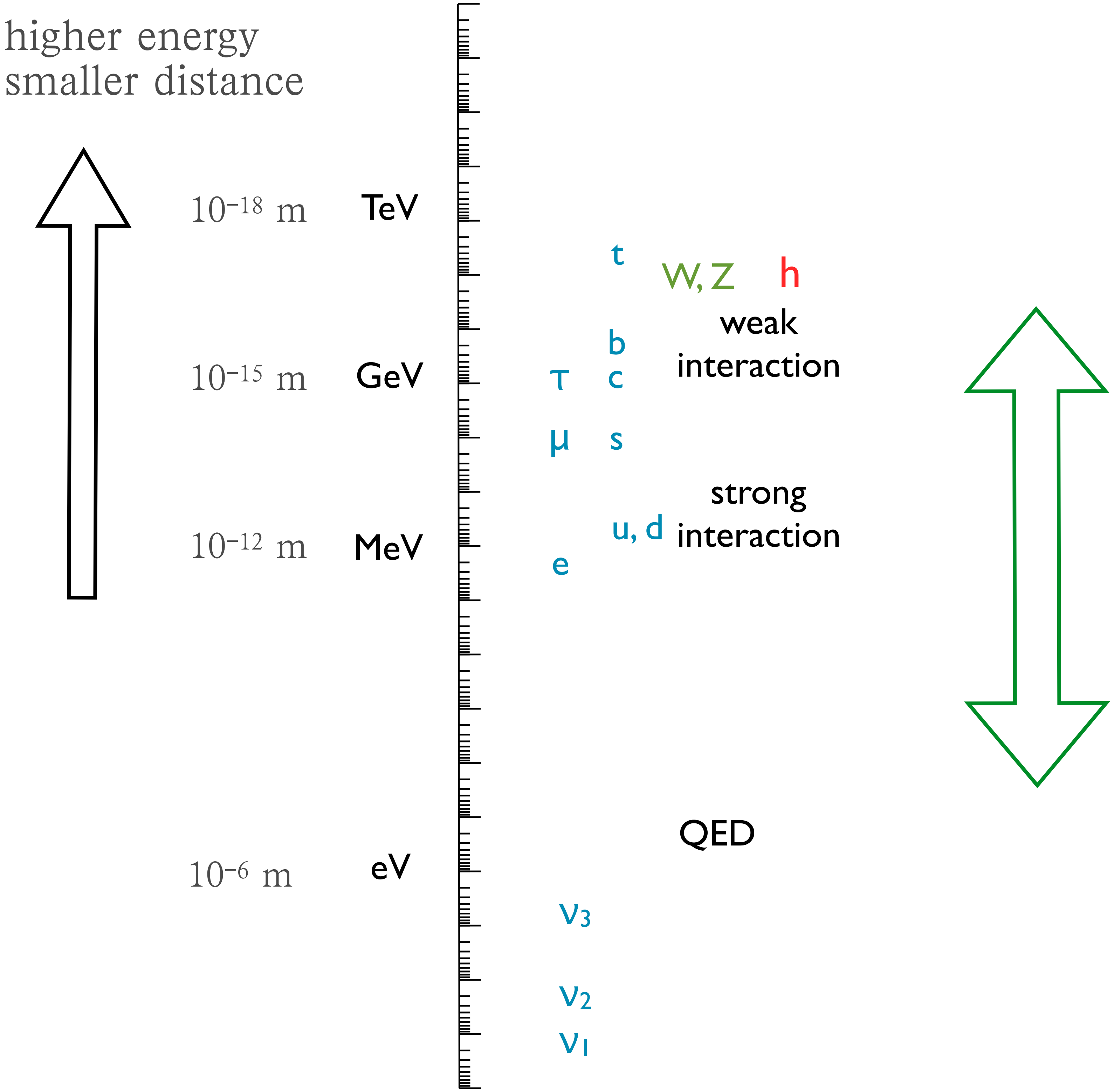
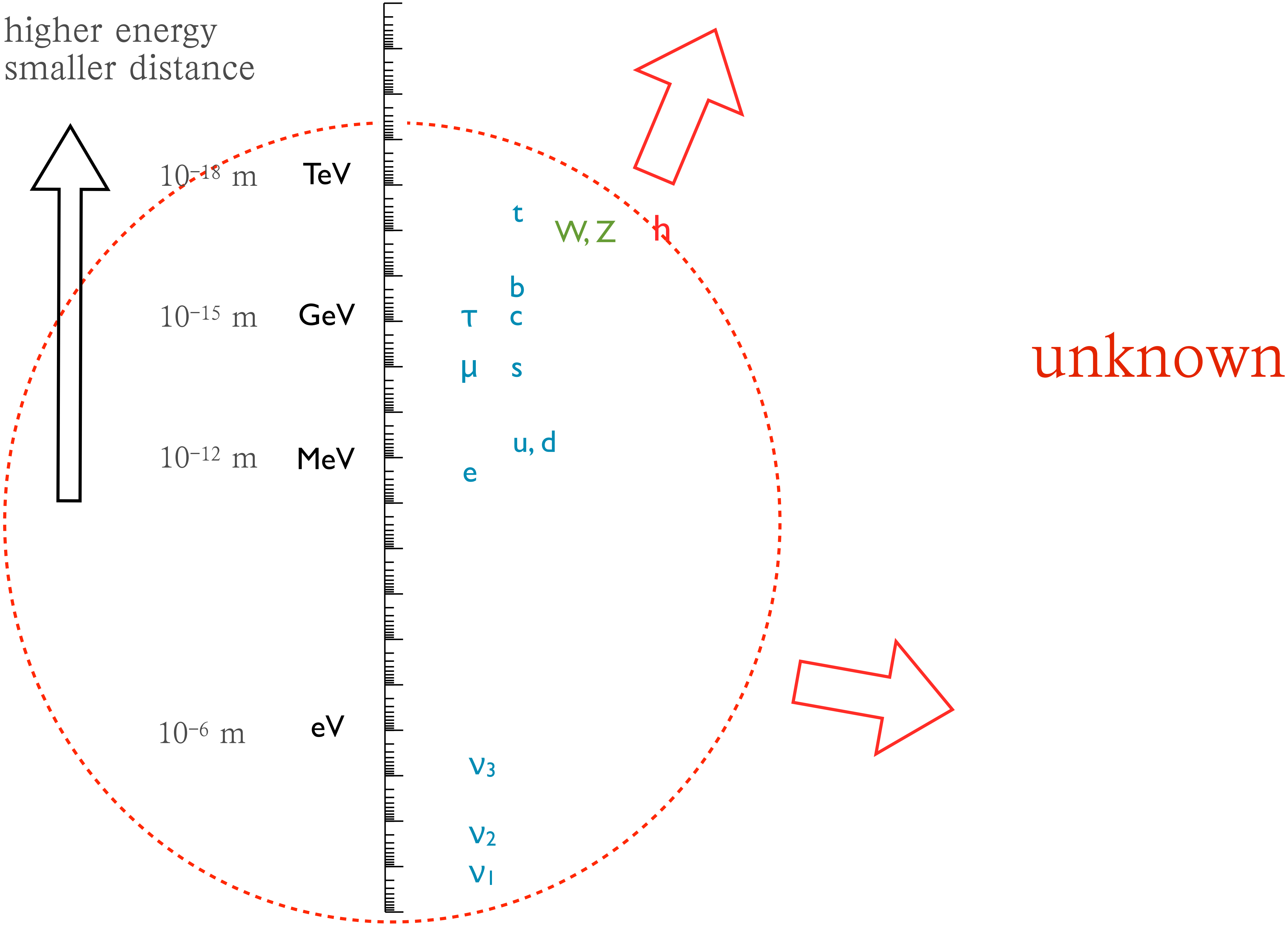


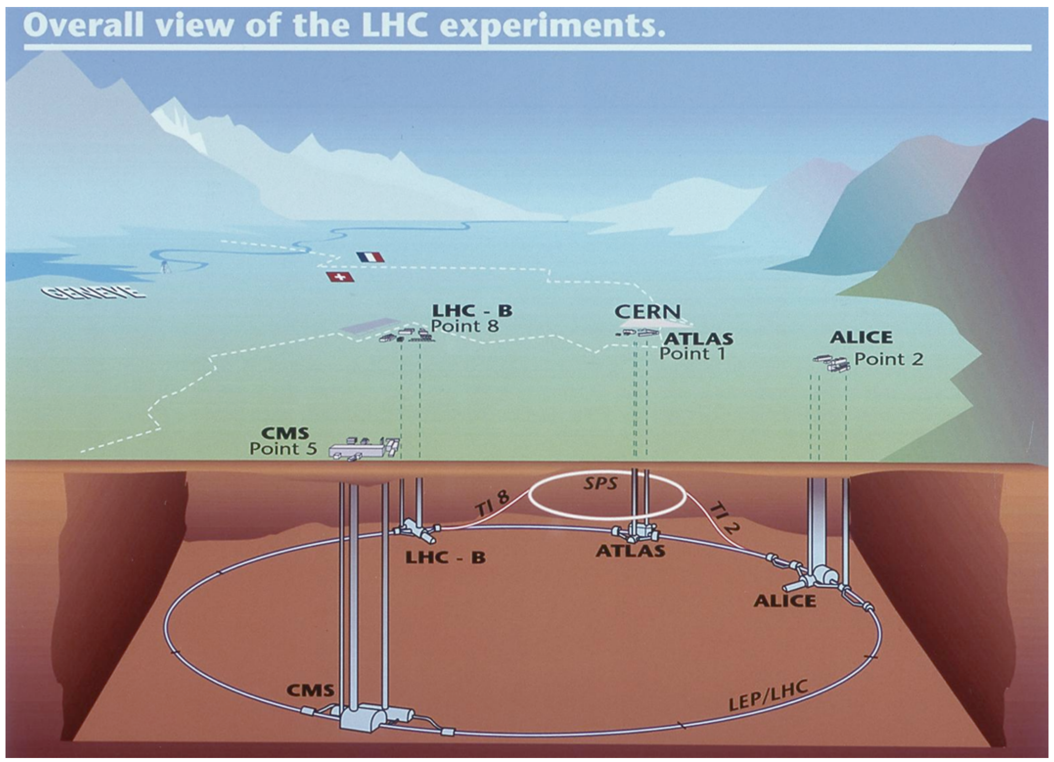

A milestone after
a century of amazing
progress

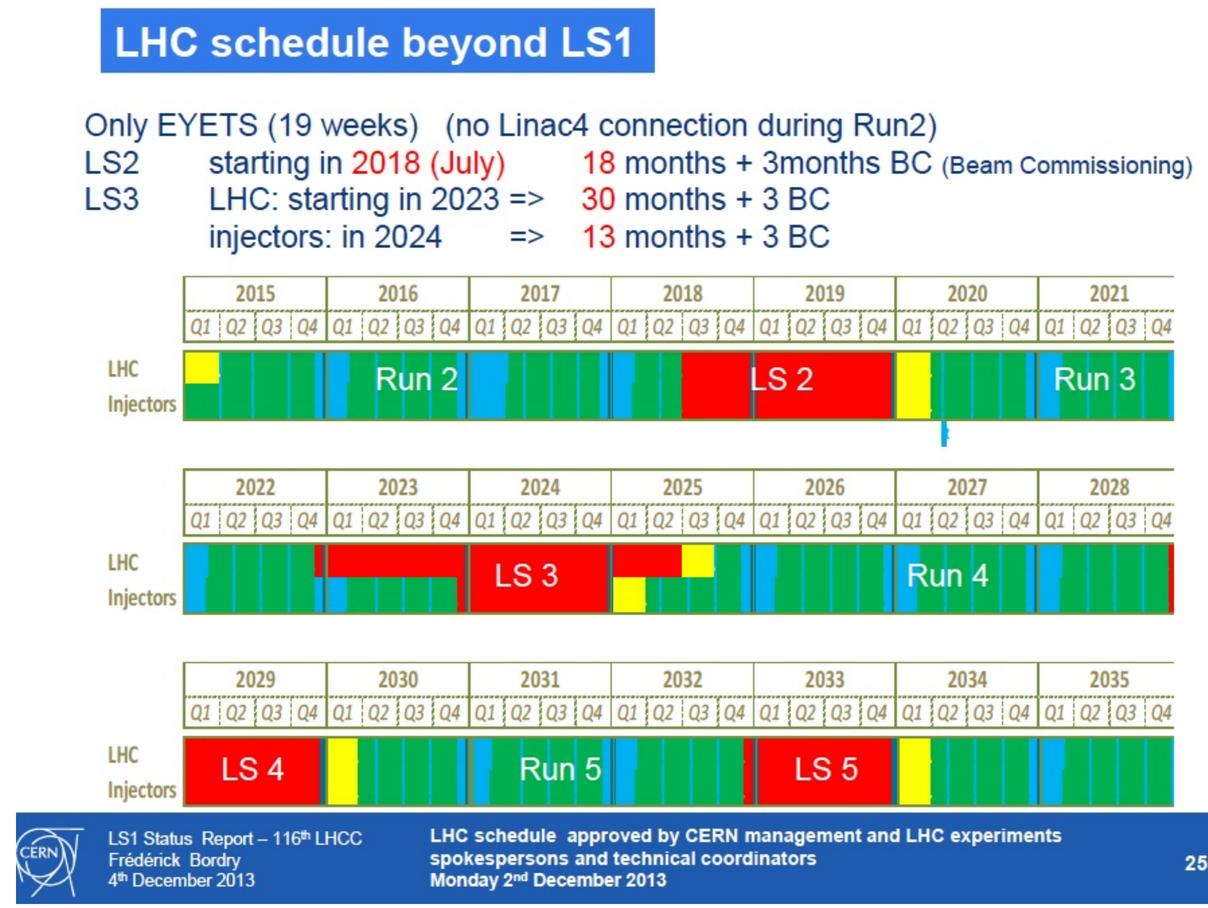
# Beginning of an new era



# LHC will soldier on

– 95+% data still to come in the coming 15-20 years.

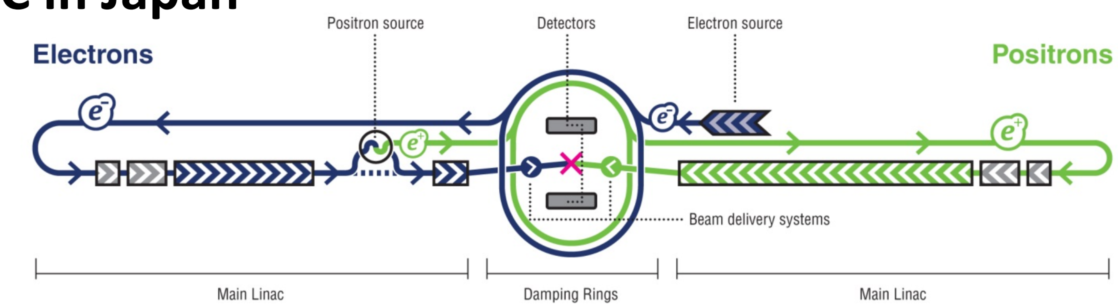


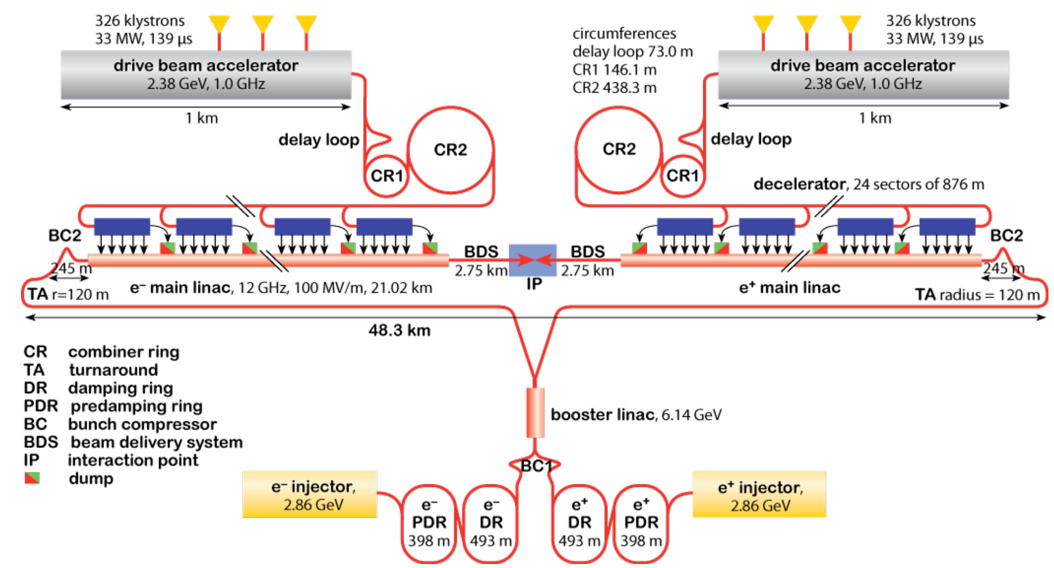



# Further down the road, proposals

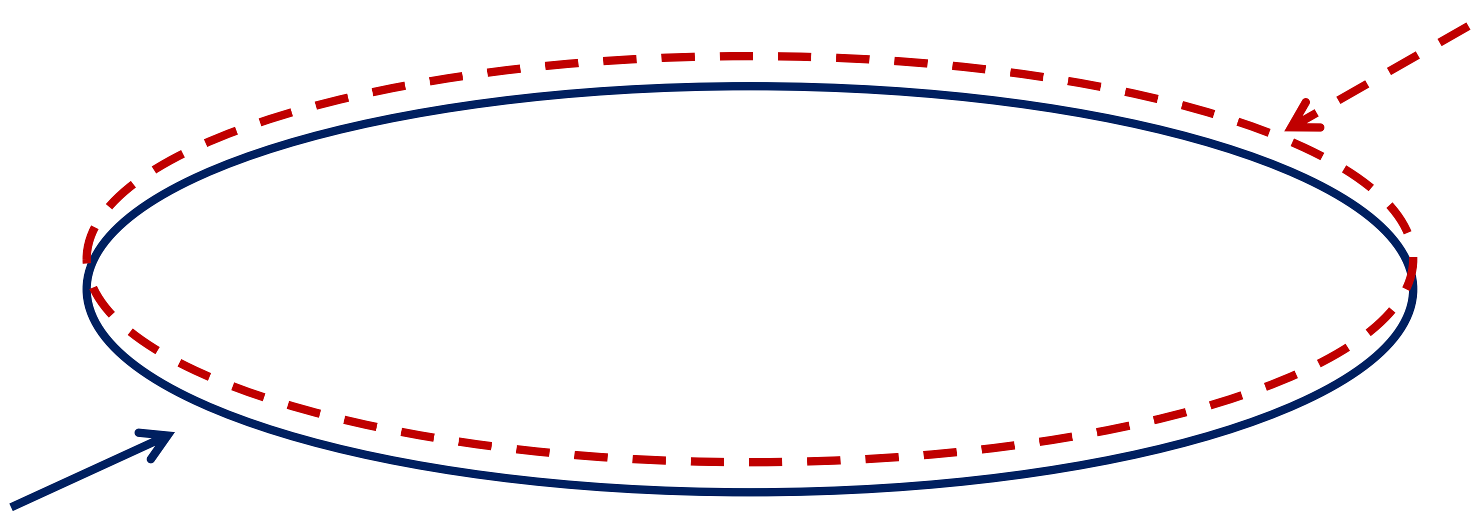
– Future colliders.

**ILC in Japan**




Circular. “Scale up” LEP+LHC



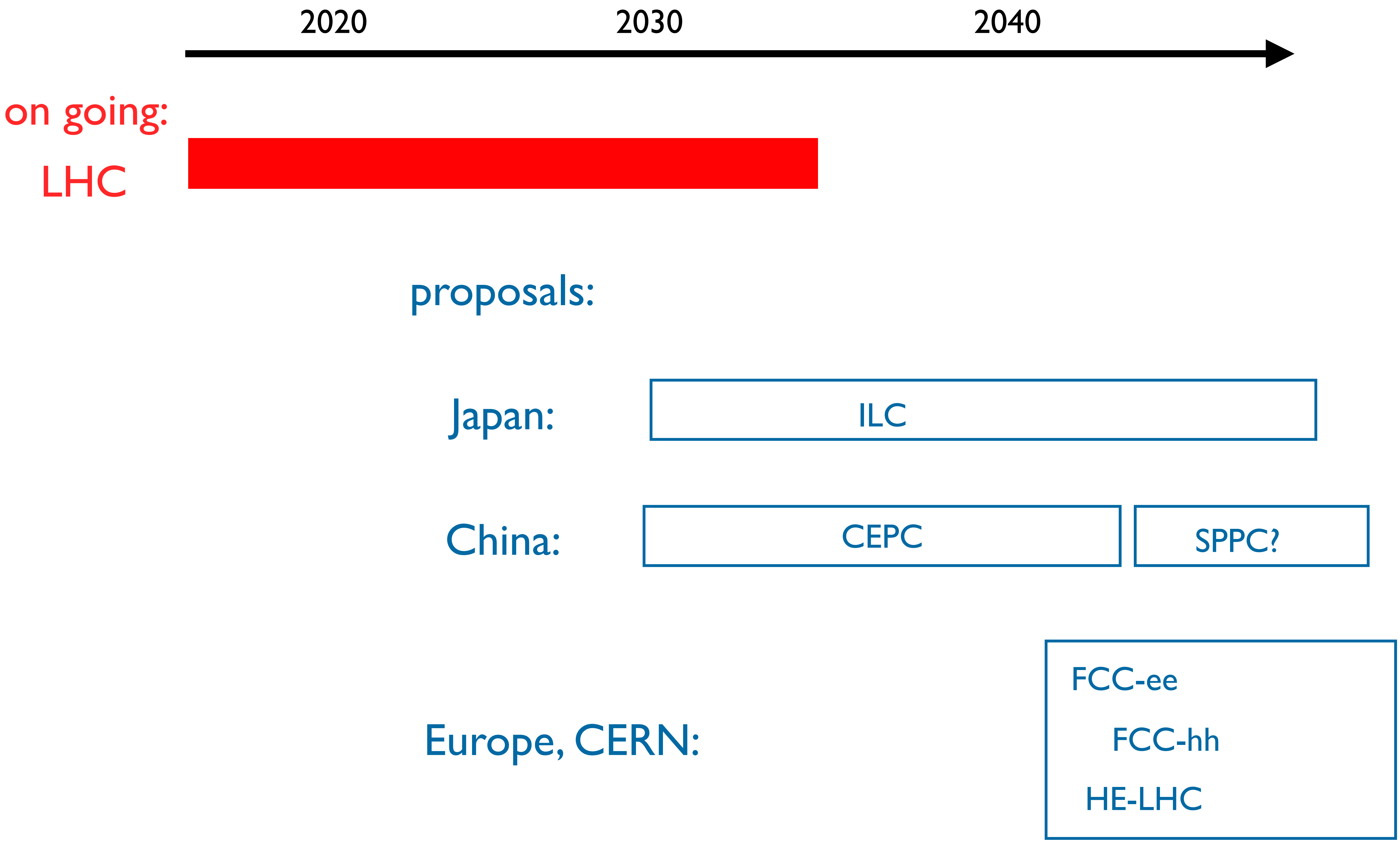
**pp collider**

FCC-hh, SPPC

**e⁻e⁺ Higgs Factory**

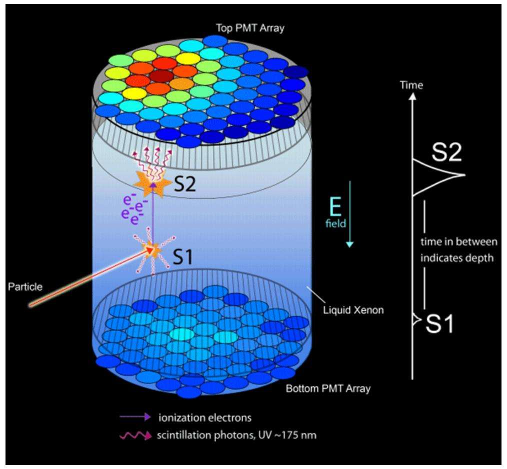
FCC-ee, CEPC

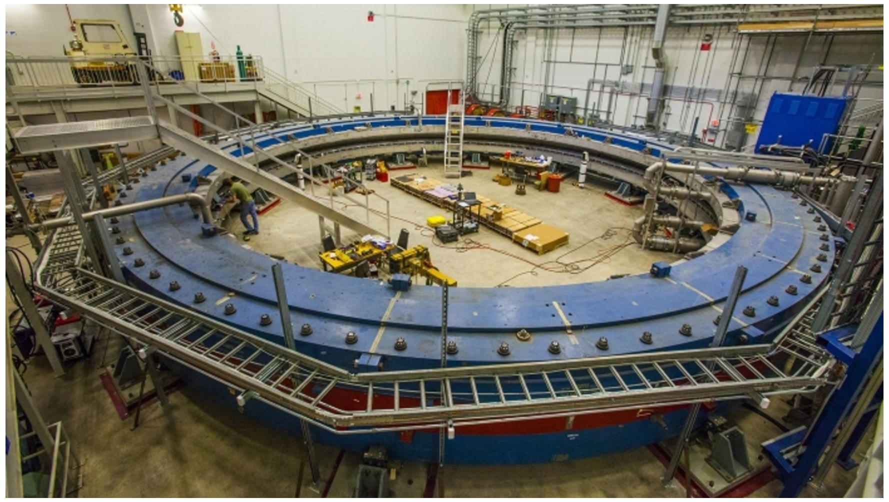
# Timeline of high energy colliders

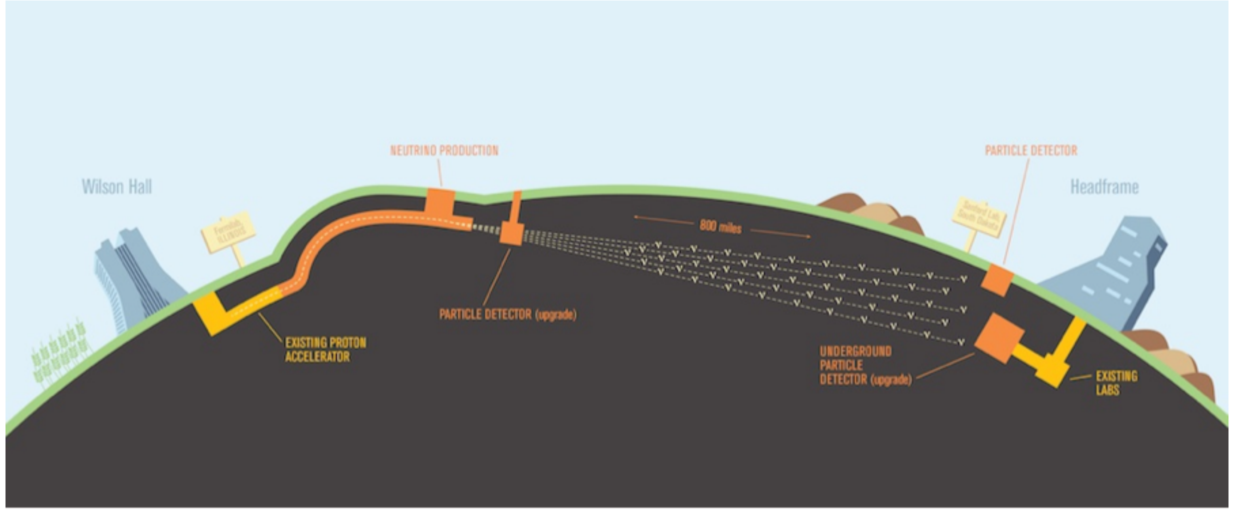


# Many other probes:

- Dark matter detection, cosmological observations, gravitational wave, low energy high intensity, etc.

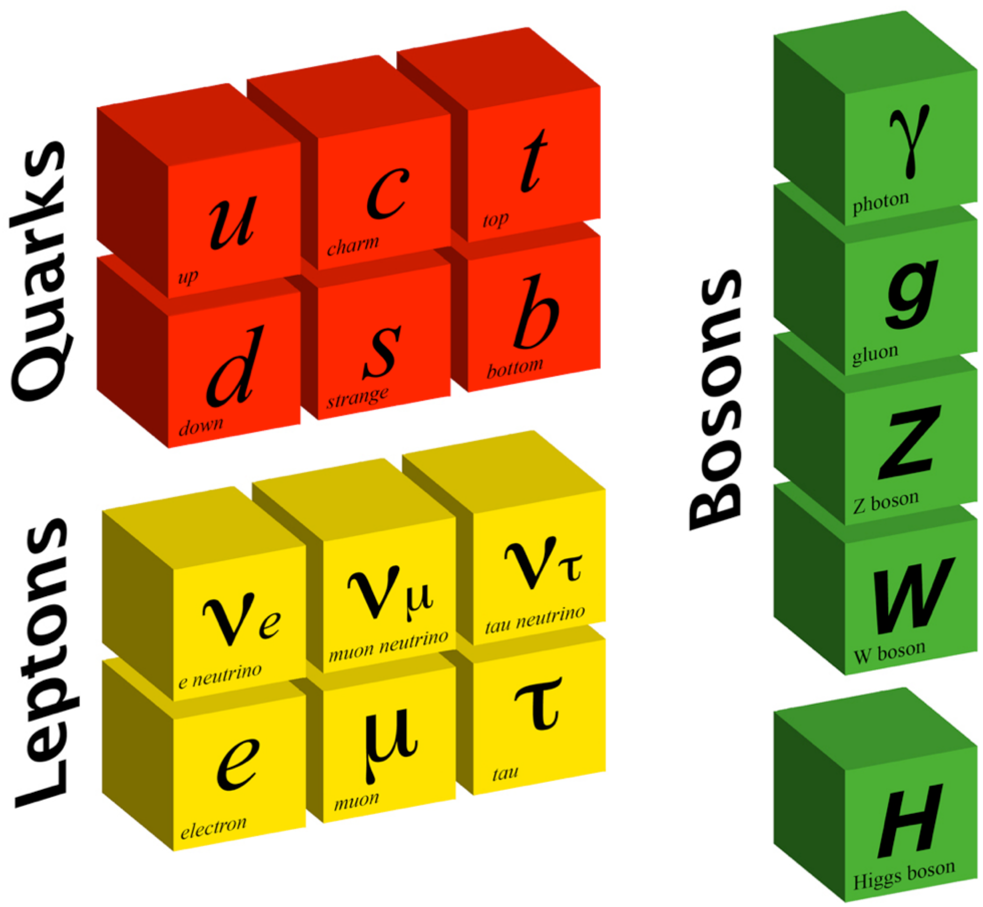




## What are we looking for?

# The Standard Model does not have all the answers.




We know *what* they are,
*how* they behave.

We don't know *why*.

We know it is *incomplete*.

# Open questions in particle physics

- Electroweak symmetry breaking.
- Dark matter.
- Matter anti-matter asymmetry of the universe
- Origin of flavor structure
- CP violation
- Dark energy
- Quantum gravity
- ....

# Open questions in particle physics

- Electroweak symmetry breaking.

Focus of this talk

- Dark matter.
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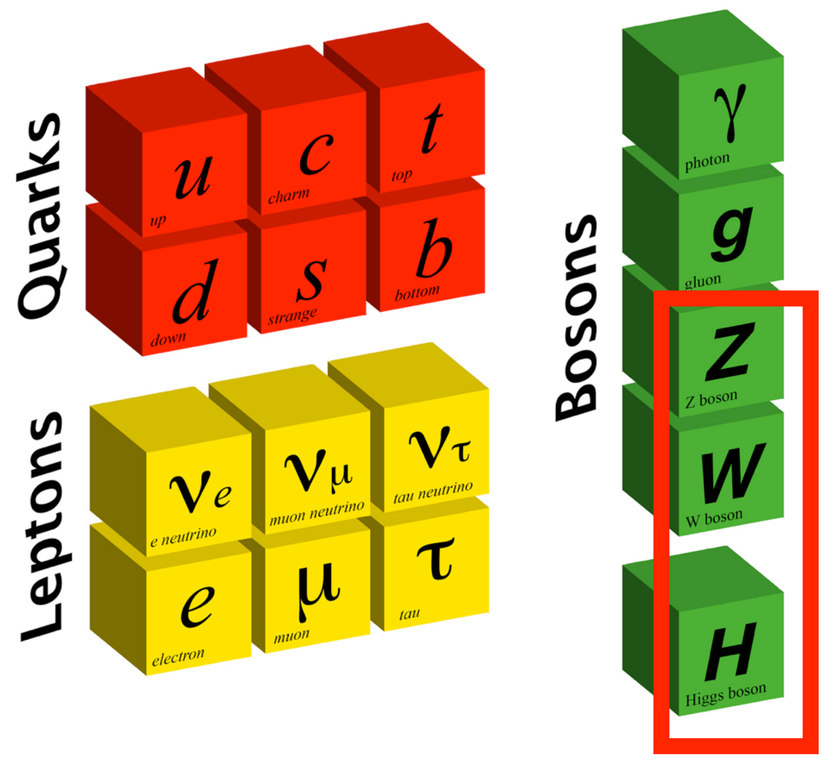
# Electroweak symmetry breaking

Urgent question, after the discovery of the Higgs boson

And, we are ready to make progress here!

# Electroweak interaction




$$m_{\rm W,Z} \simeq 10^2 \ \rm GeV$$

- Electroweak symmetry breaking (EWSB).
  - Weak interaction has finite range

$$V_{\rm weak}(r) \approx \frac{e^{-r/r_{\rm W}}}{r}, \ r_{\rm W} \approx m_{\rm W,Z}^{-1} \approx 10^{-17} \ \rm m$$

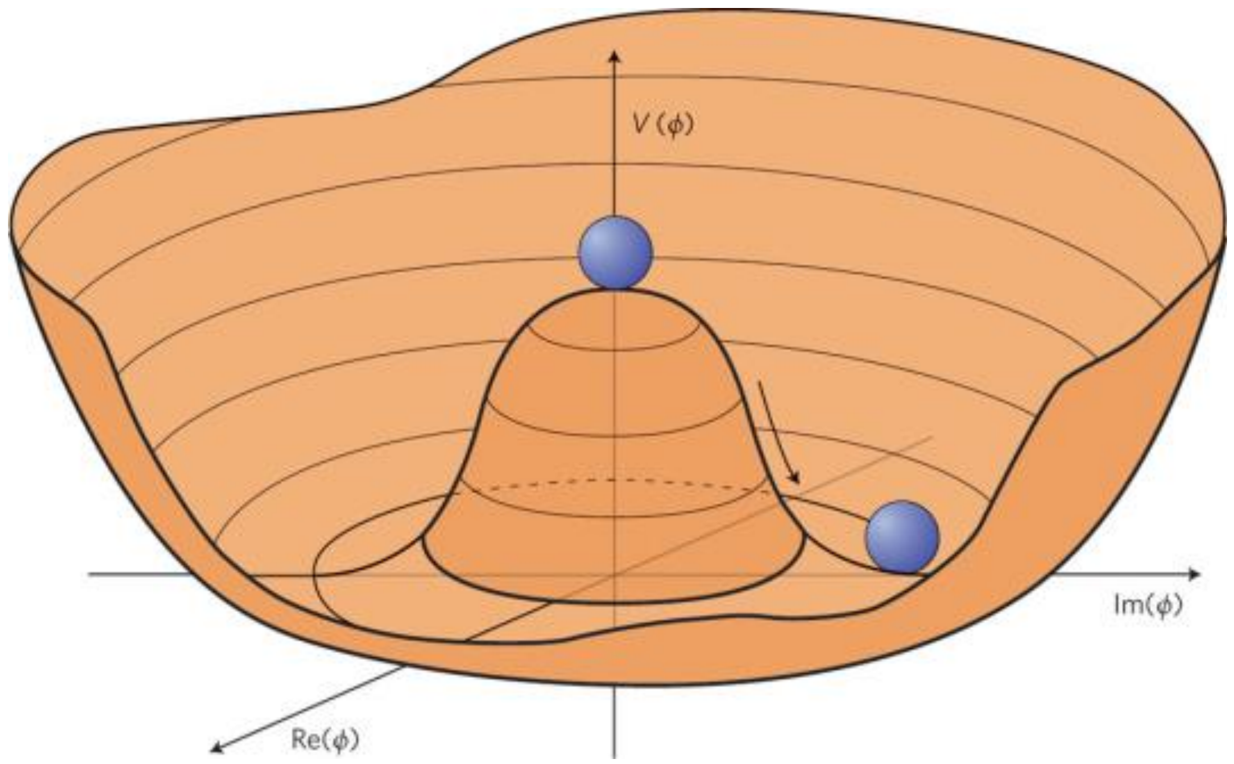
Fermi, 1934

# Why is Higgs special?

| 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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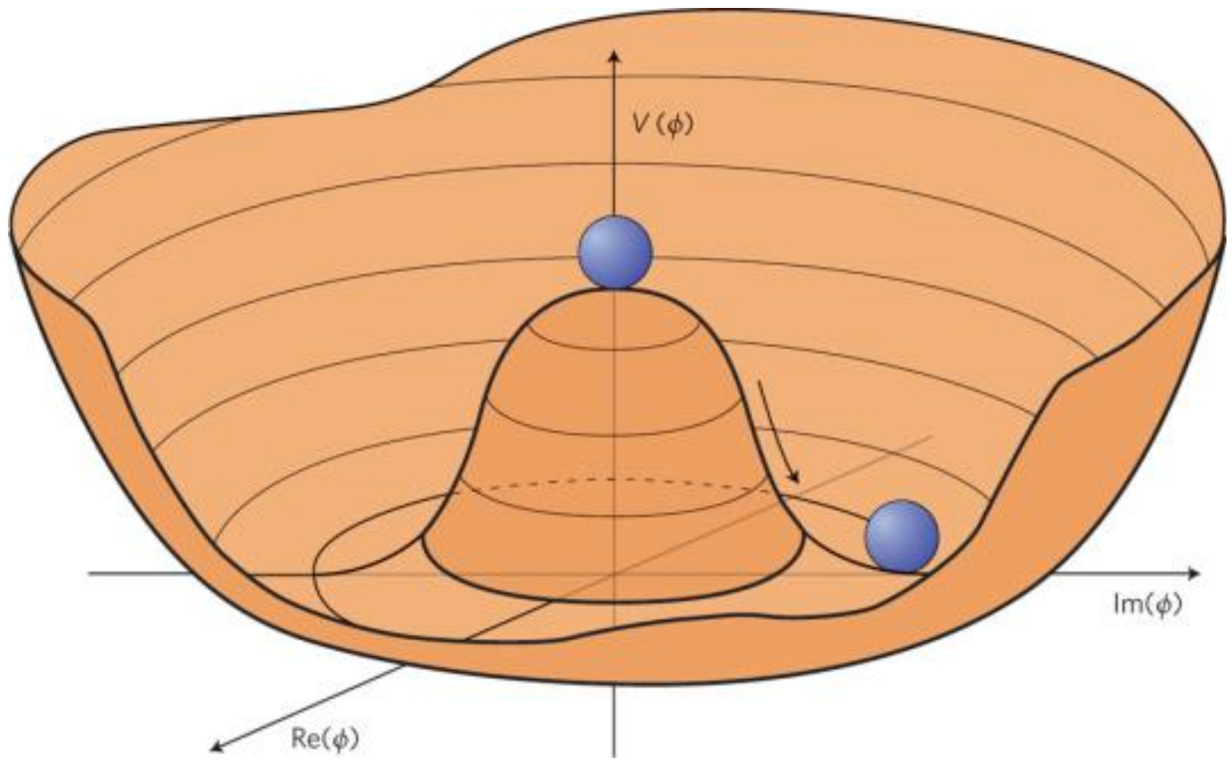


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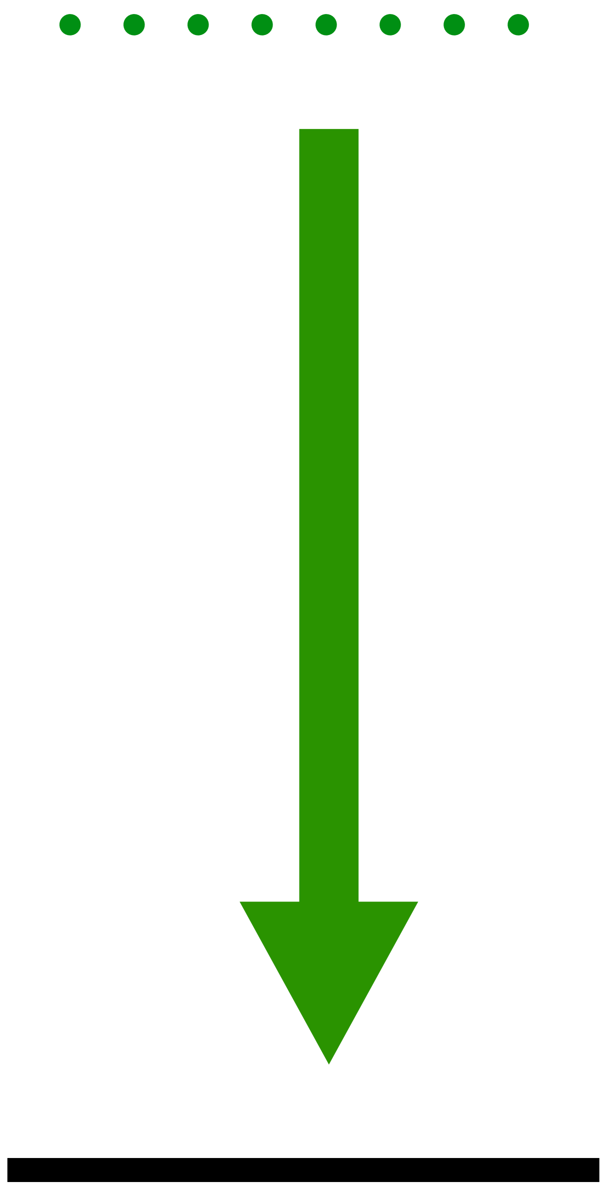
Similar to, and motivated by Landau-Ginzburg theory of superconductivity.

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.
$m_h$ , $m_W$ …

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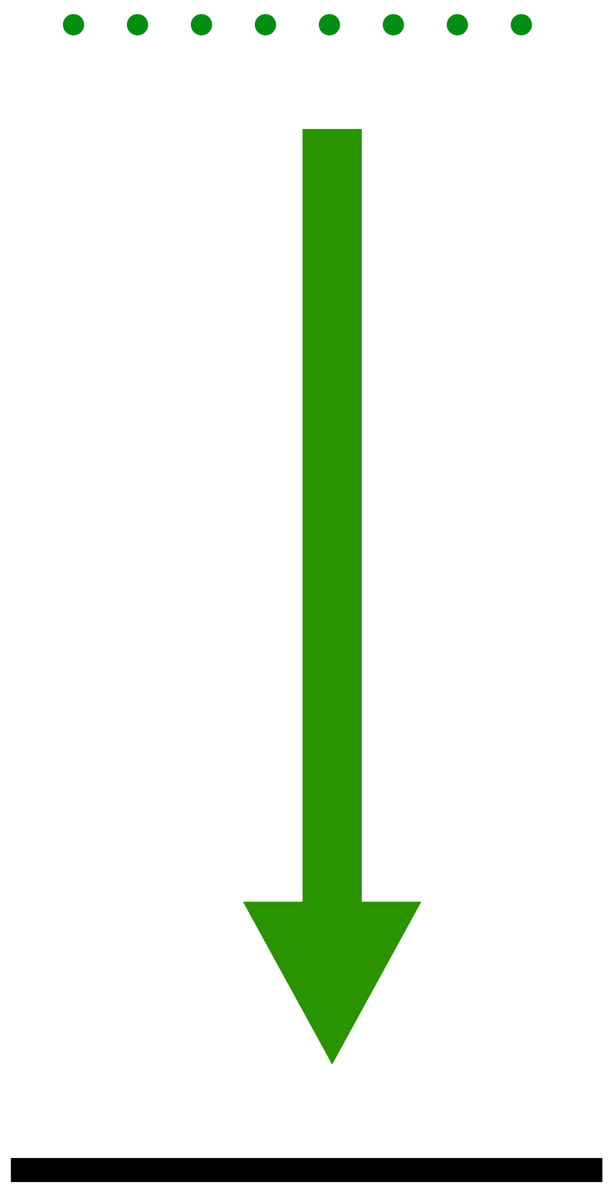


The energy scale of new physics responsible for EWSB

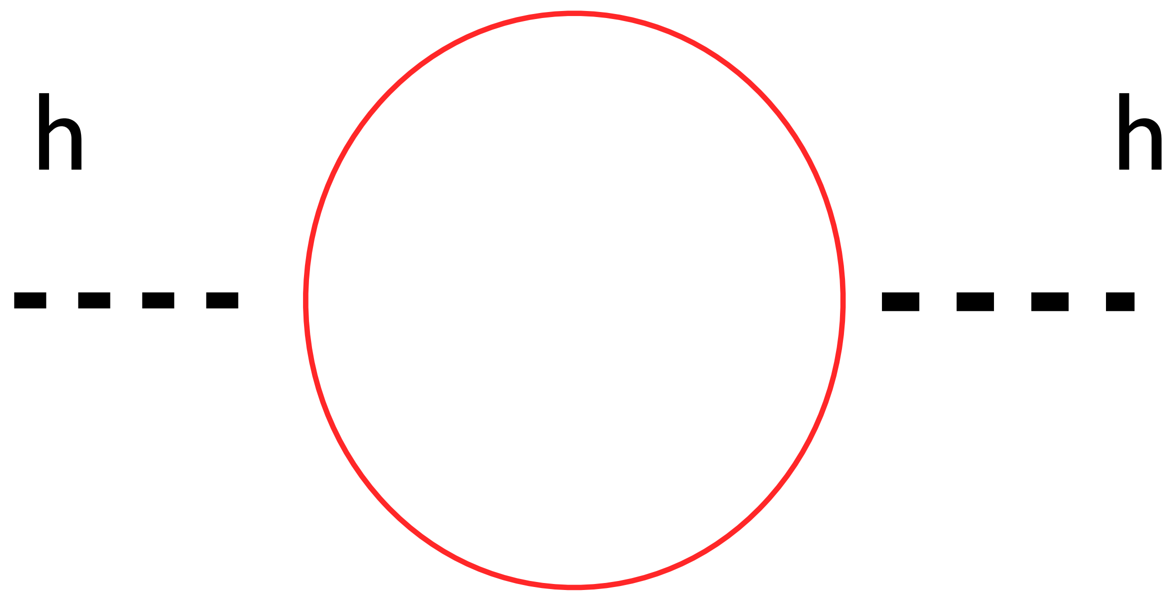
What is this energy scale?
$M_{Planck}$ = $10^{19}$ GeV, …?

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

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

# Higgs mass in quantum theory.

Quantum fluctuation:
virtual particles in the vacuum




Quantum fluctuations know about
new physics at high energy scale Λ

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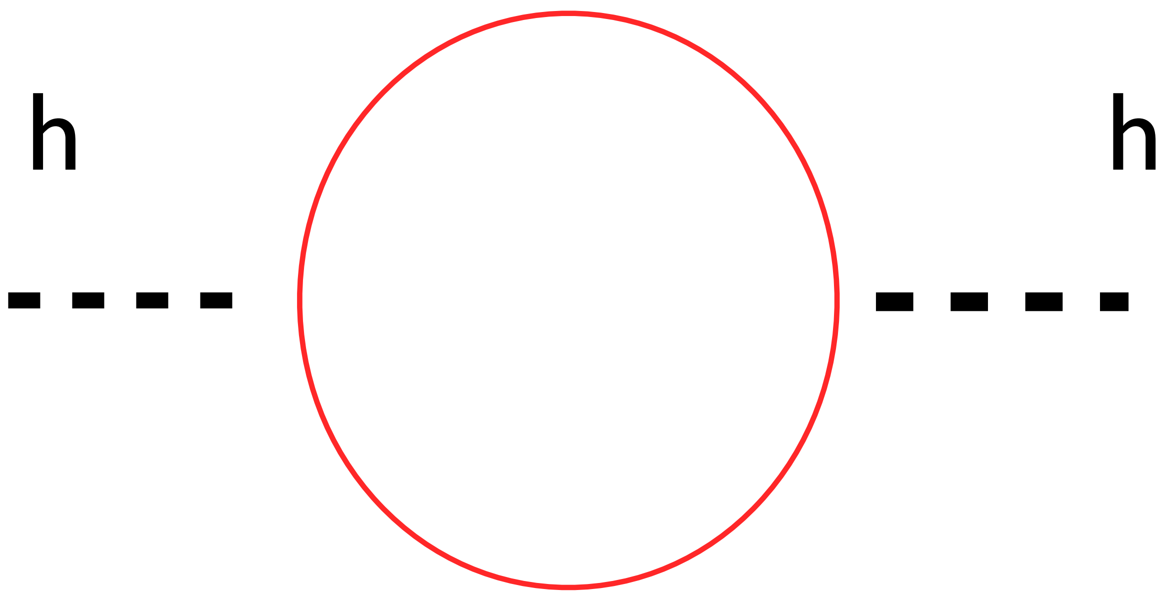


Quantum fluctuations know about
new physics at high energy scale Λ

- $m_h^2$(physical) = $m_0^2 + c\,\Lambda^2$
  - $m_0^2$ can always be adjusted to give correct $m_h^2$(physical).

# Naturalness problem.

- $m_h^2$ (physical) = $m_0^2 + c\,\Lambda^2$ , $c \approx O(0.01)$

- What is $\Lambda$? Or where is new physics?
  - Some fundamental scale beyond the Standard Model. $\Lambda \approx M_{Pl} = 10^{19}$ GeV, $M_{unification} = 10^{16}$ GeV...?

- $\Lambda^2 \approx M_{Pl}^2$ , $m_0^2$ must be very close to $M_{Pl}^2$ . Must cancel to the precision of $10^{-32}$ to have $m_h^2$ (physical) $\approx (100\ \mathrm{GeV})^2$, fine-tuning.

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- $1/M_{Pl}^2 \approx$ strength of gravitational interaction.

- $1/(100\ \text{GeV})^2 \approx$ strength of weak interaction.

Naturalness problem:
Why is gravity so much weaker than the weak interaction?

# Is fine-tuning ok?

- Mathematically, yes.
  Can always solve $m_h^2$(physical) = $m_0^2 + c\,\Lambda^2$. But...

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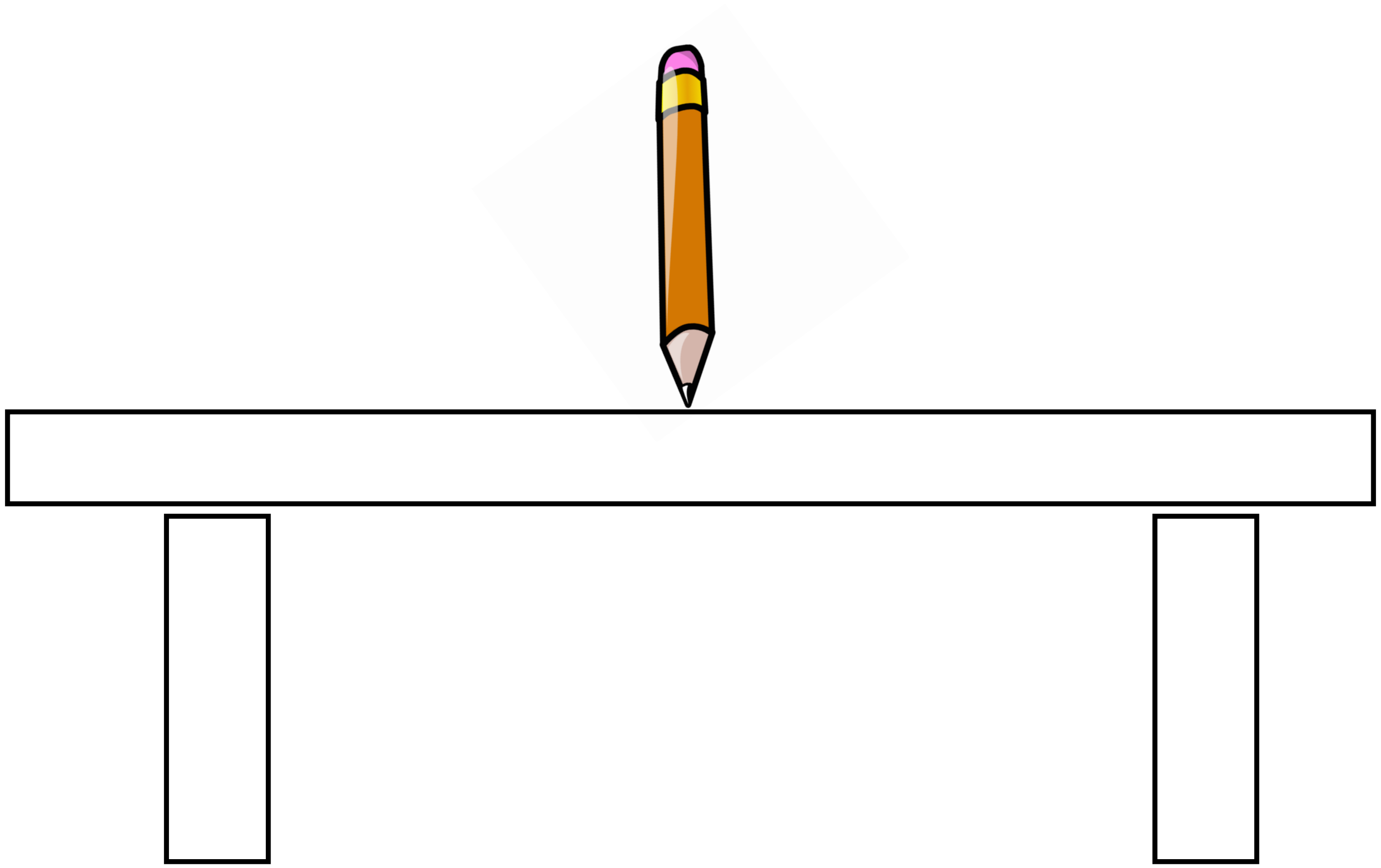

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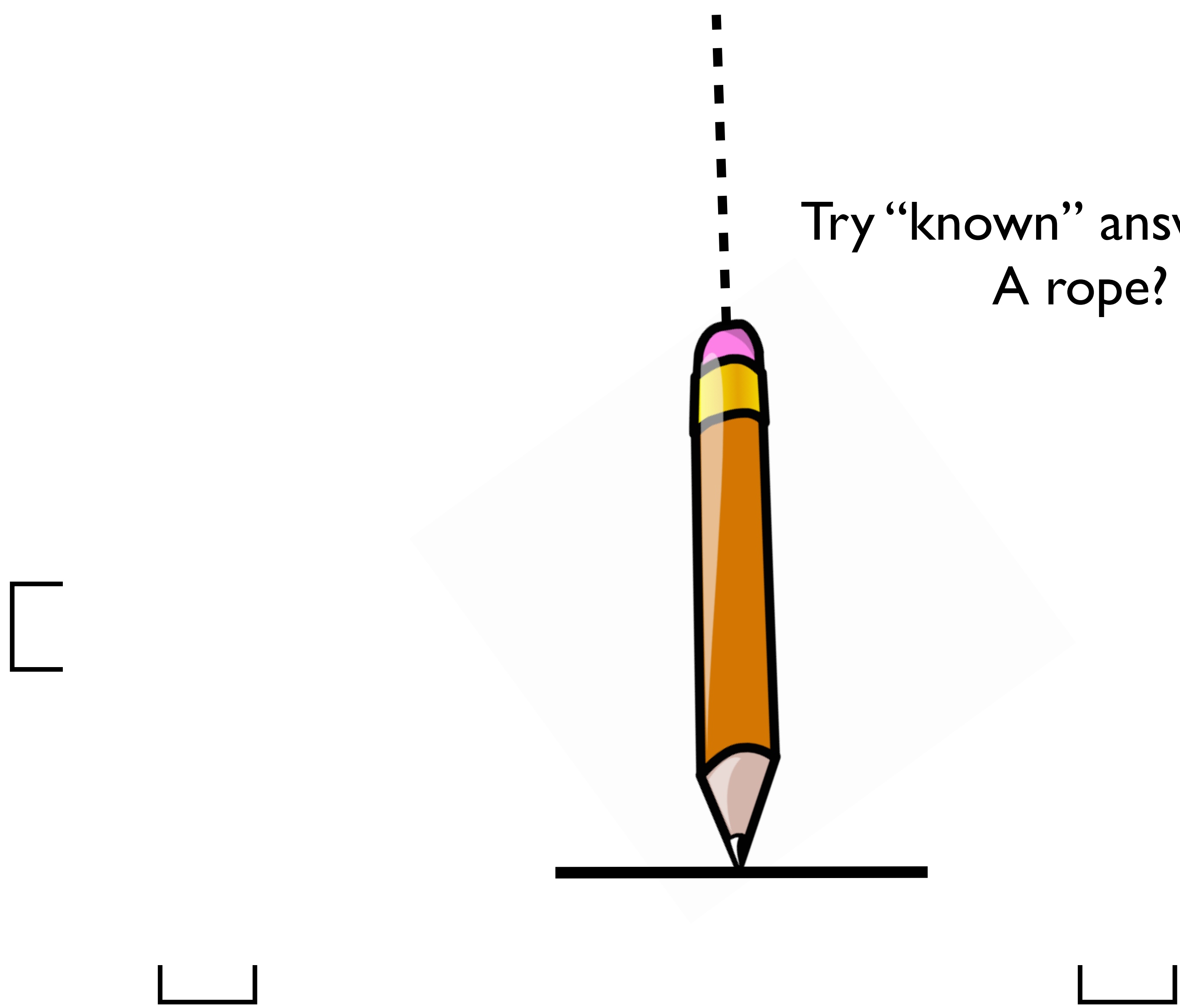


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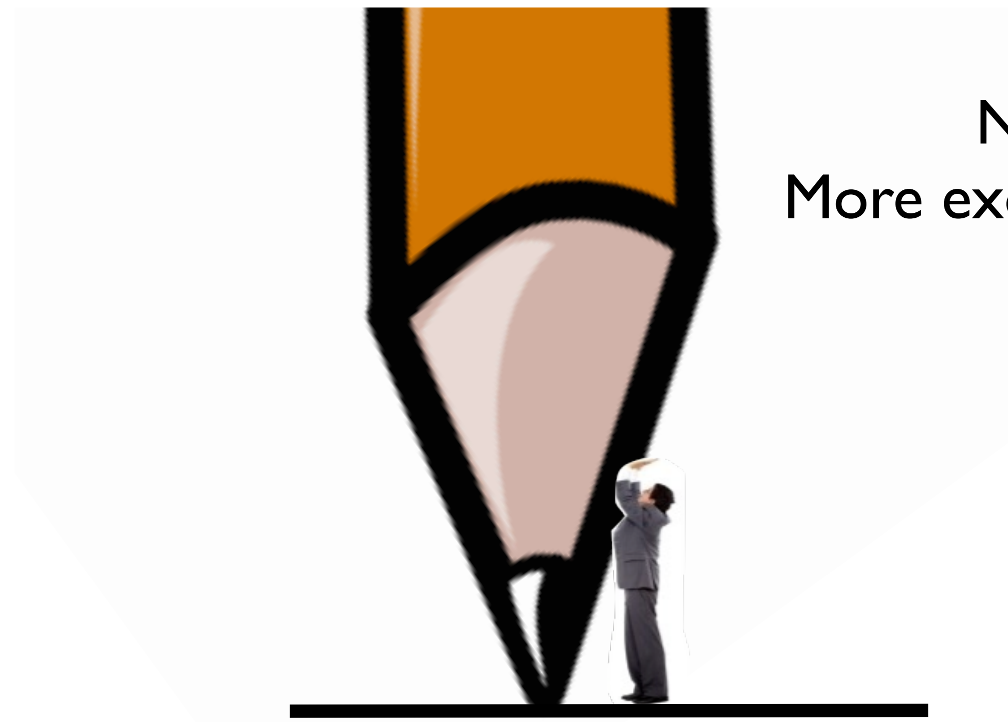

No rope?
More exotic possibilities

Another fine-tuning problem

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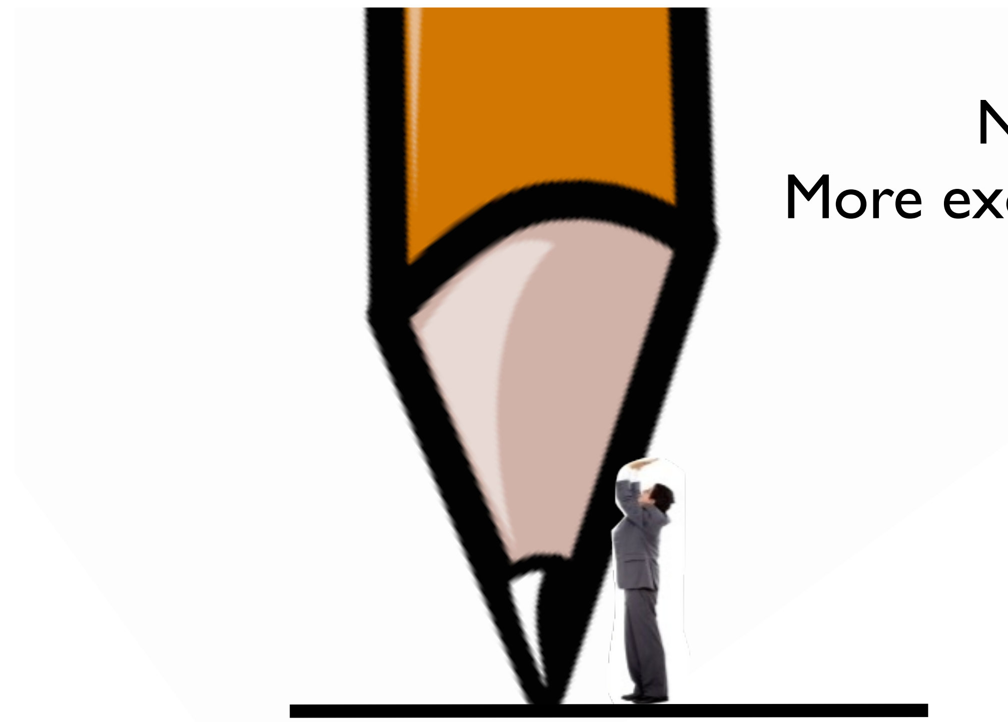

No rope?
More exotic possibilities

Similarly, we have been searching for an explanation for the fine-tuning of Higgs mass $O(10^{-32})$

Another fine-tuning problem

# Naturalness problem.

- $m_h^2$ (physical) = $m_0^2 + c\ \Lambda^2$ , $c \approx O(0.01)$
- No large cancellation $\Rightarrow$ $m_h^2$ (physical) $\approx c\Lambda^2$
  - $\Lambda \approx$ TeV, new physics at TeV scale!

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  - $\Lambda \approx$ TeV,  new physics at TeV scale!

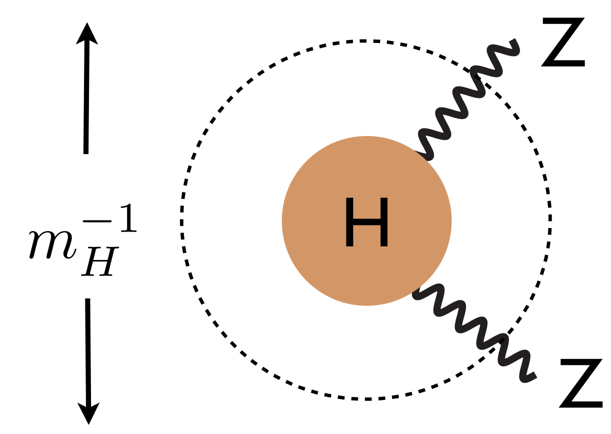
Naturalness criterion leads to a prediction of the mass scale of new physics!!

# Finding the solution to naturalness problem

# A simple idea to start

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

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




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

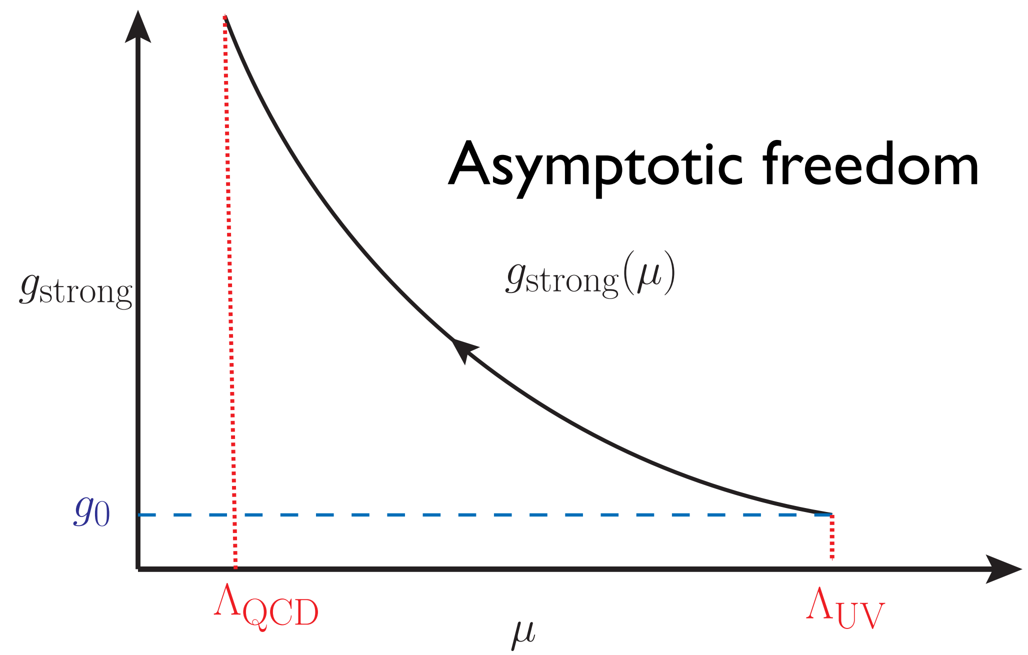
# An example: BCS Superconductivity

- Another known example of the Higgs mechanism.
- Described by the same effective theory, with Mexican hat potential.
- Yet, if we look closer, there are inner structure
  - The Cooper pairs of electrons!
- Can Higgs be the same?

# Theory of strong interactions (QCD)

$$\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm UV}} = e^{-\frac{8\pi^2}{g_0^2 b}}, \ \Lambda_{\rm QCD} \leq \ \text{GeV}$$

$$b = 7$$



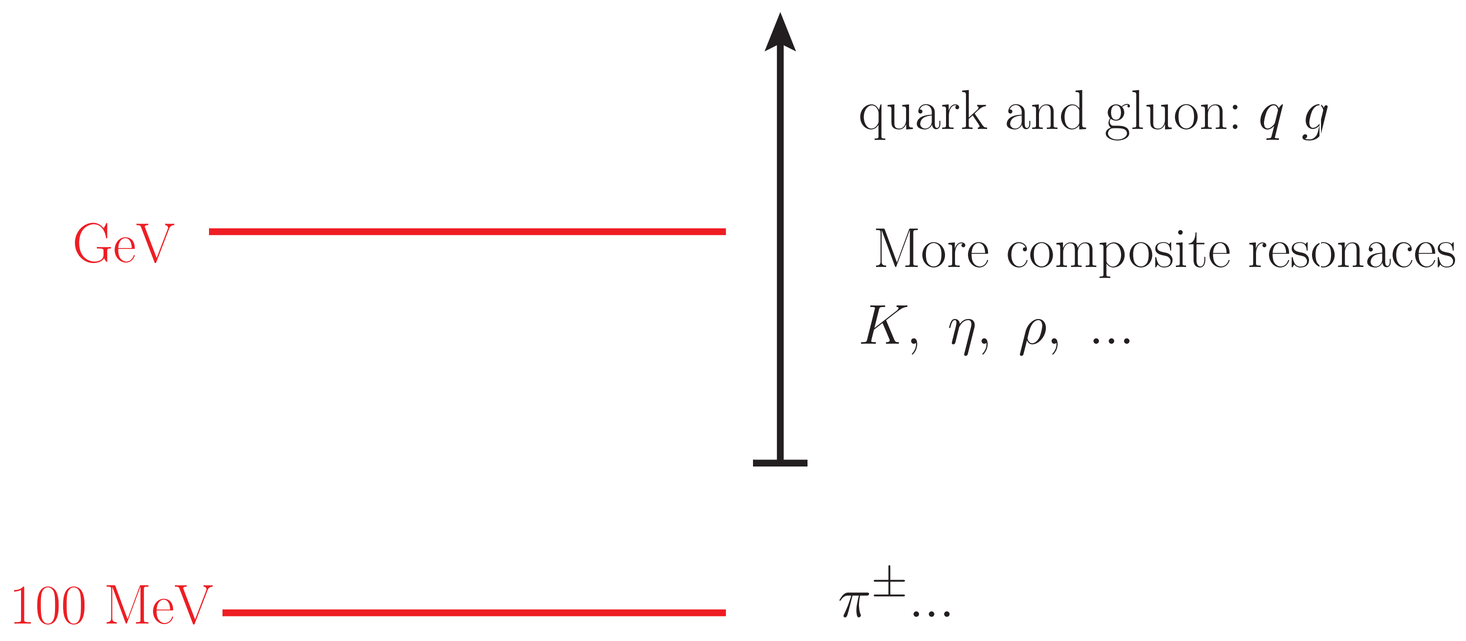

- Coupling evolves slowly. Exponentially separated scales from the choice of an order one number $g_0$.

- A strong coupling results in bound (composite) states.

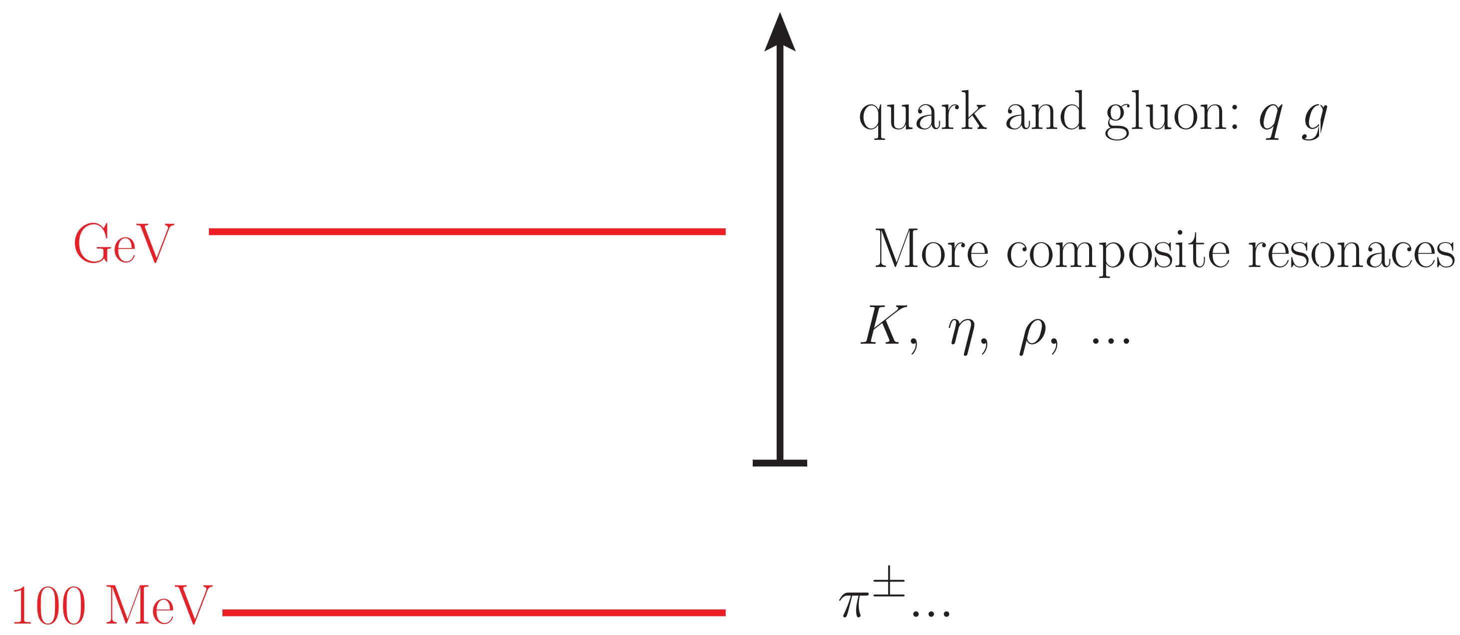
Composite scalar mass calculable:

$$m_\pi^2 \simeq m_q \Lambda_{\rm QCD}$$

# "Learning" from QCD



# "Learning" from QCD



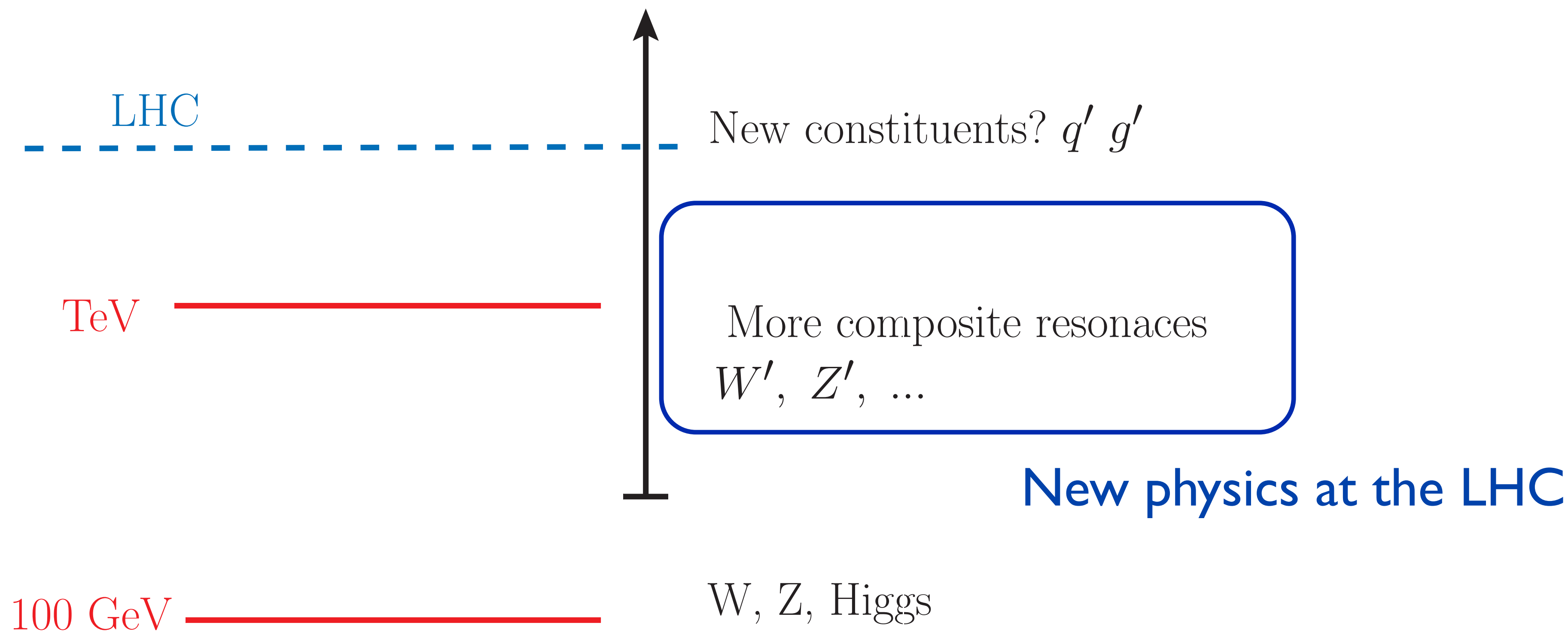

⇒ new strong dynamics, symmetry breaking

⇒ 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

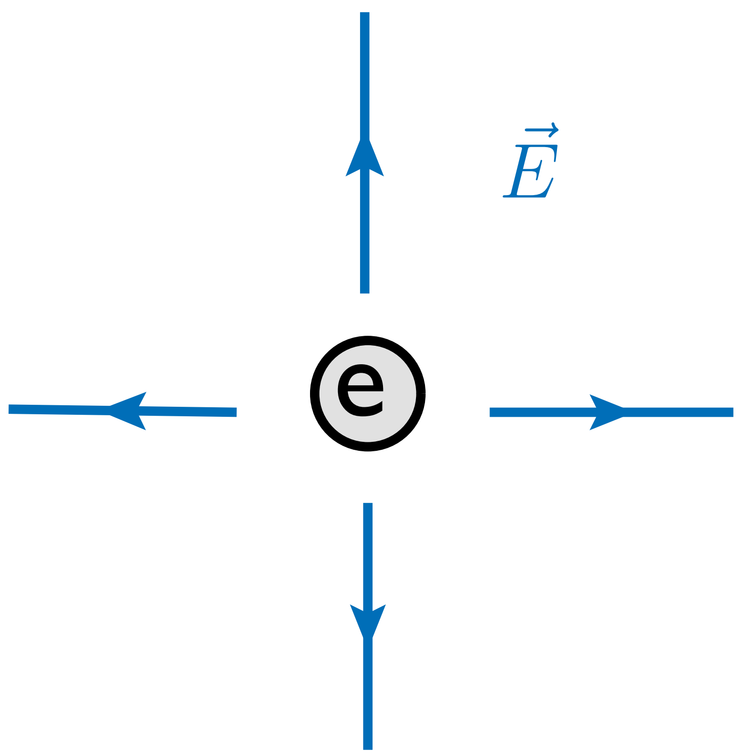



- Many many scenarios, models in this class.
- Little, fat, twin, holographic .... Higgs

– Similar scenarios: Randall-Sundrum, UED...

- Theories with Higgs + resonances.

# Naturalness in nature: electron mass



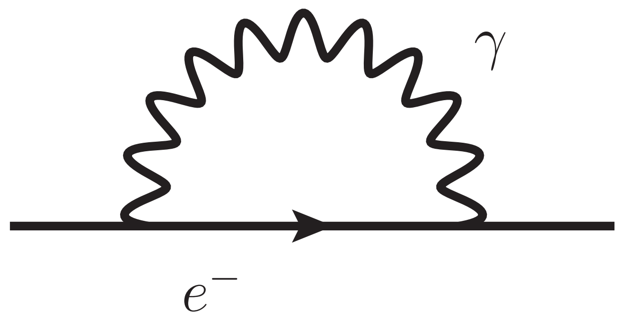

Classically:

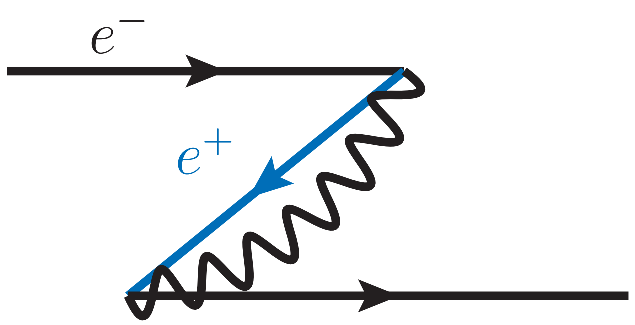
$$\delta m_e = \int_{r=\Lambda^{-1}} d^3 r \vec{E}^2 \simeq \alpha\Lambda$$

Weisskopf 1939

- Linearly dependent on new physics scale $\Lambda$.
- If we require $m_e \approx \delta m_e$, i.e., no fine tuning, we need new physics ($\Lambda$) below $\sim \alpha^{-1} m_e$

# New physics: the positron




$$\delta m_e \simeq \frac{\alpha}{\pi} m_e \log\left(\frac{\Lambda}{m_e}\right)$$

- From extension of spacetime symmetry:
  - Lorentz symmetry + quantum mechanics $\Rightarrow$ positron.
- Log divergence (very mild). Proportional to $m_e$, "natural".

# Learning from electron

- Fermion, spin-1/2 , mass is natural. No fine-tuning needed.
- Higgs, spin-0, mass requires fine-tuning.
- A possible way out
  - Could be solved if the theory has a symmetry

$$\text{spin } 0 \leftrightarrow \text{spin } \frac{1}{2}$$

# 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 |
| Higgs, h | 0 | Higgsino | | 1/2 |
| Standard Model particles | | superpartners | | |

- Mass of superpartners $\sim$TeV.

# Electroweak scale in Supersymmetry

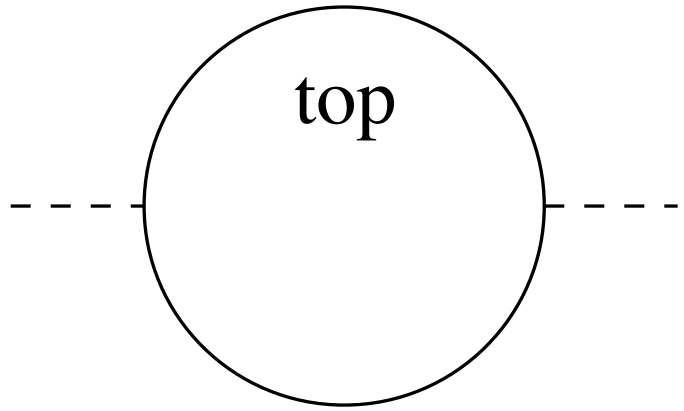
A unique property of supersymmetry:
Mass parameters evolves slowly, generating large scale separation.

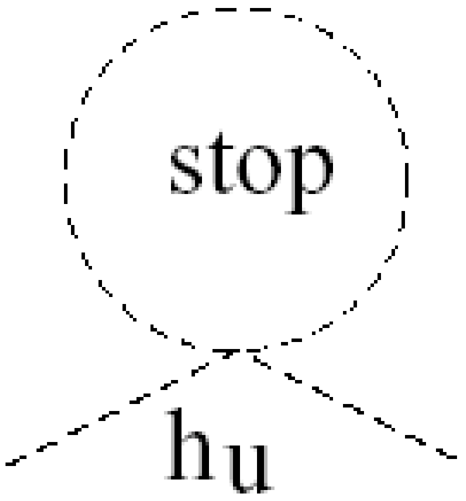
$$m_h^2 \simeq m_{\rm SUSY}^2 \left( 1 - \frac{y_{\rm top}^2}{16\pi^2} \log\left[ \frac{\Lambda^2}{m_{\rm W,Z}^2} \right] + \cdots \right) \qquad y_{\rm top} \simeq 1$$

Natural, large hierarchy: $\frac{m_{\rm h,W,Z}^2}{\Lambda^2} \simeq e^{-\frac{16\pi^2}{y_{\rm top}^2}}$

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

# A prediction of Naturalness

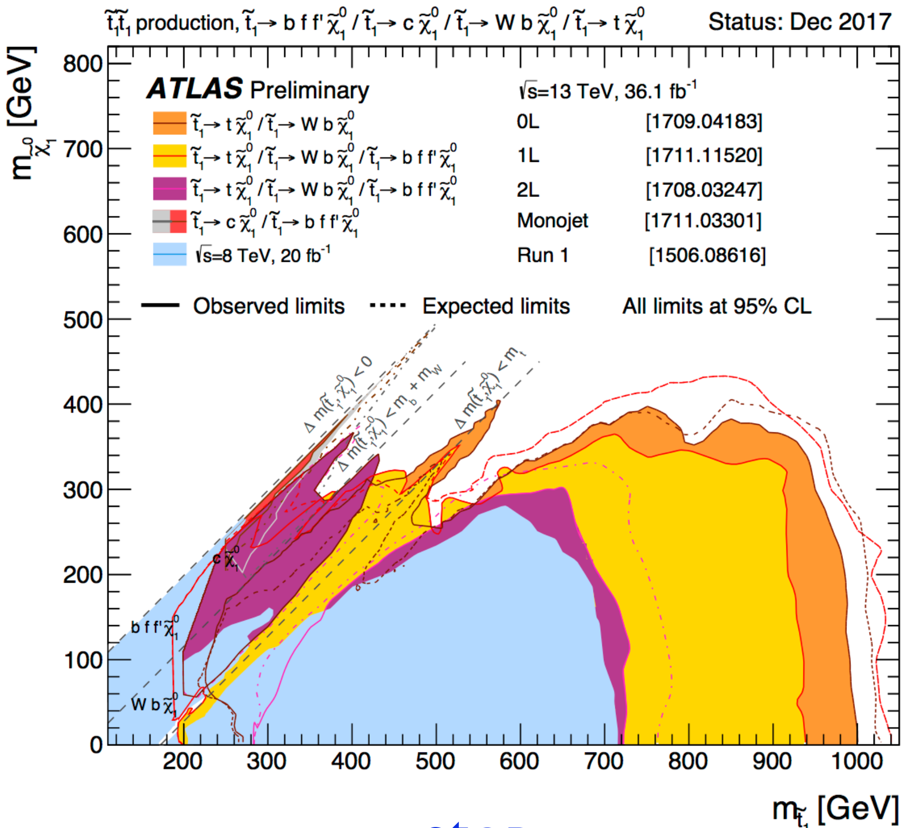



- Tuning, comparing: $m_h^2 \text{ vs } \frac{3}{8\pi^2} m_{\tilde{t}}^2$
- Needs light stops (SUSY), top partner (composite Higgs).

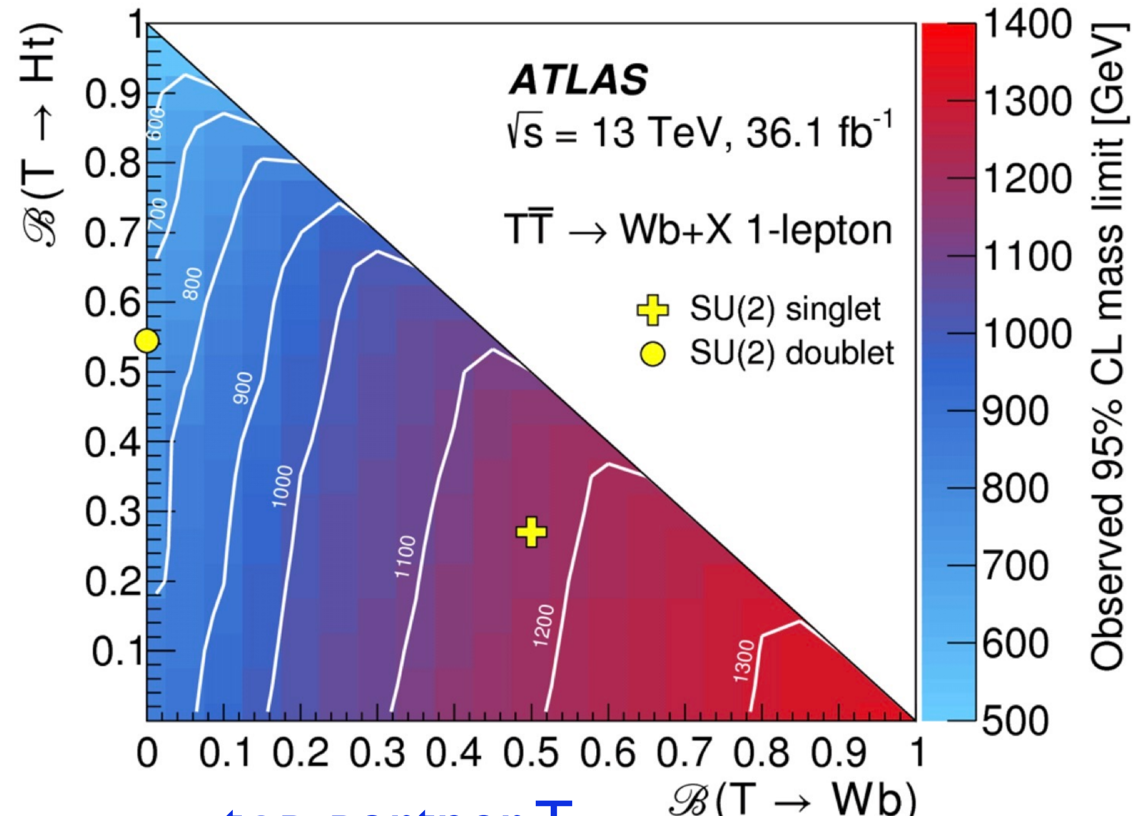
# All eyes on these searches

Supersymmetry




stop

Composite Higgs



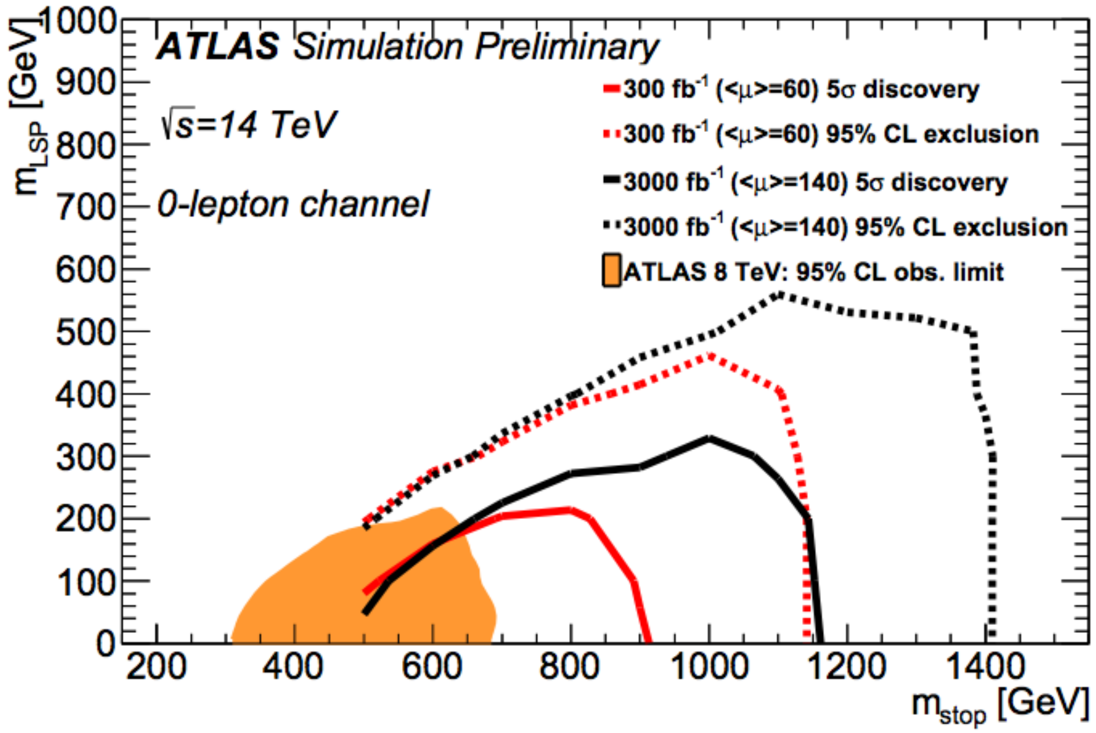

top partner, T

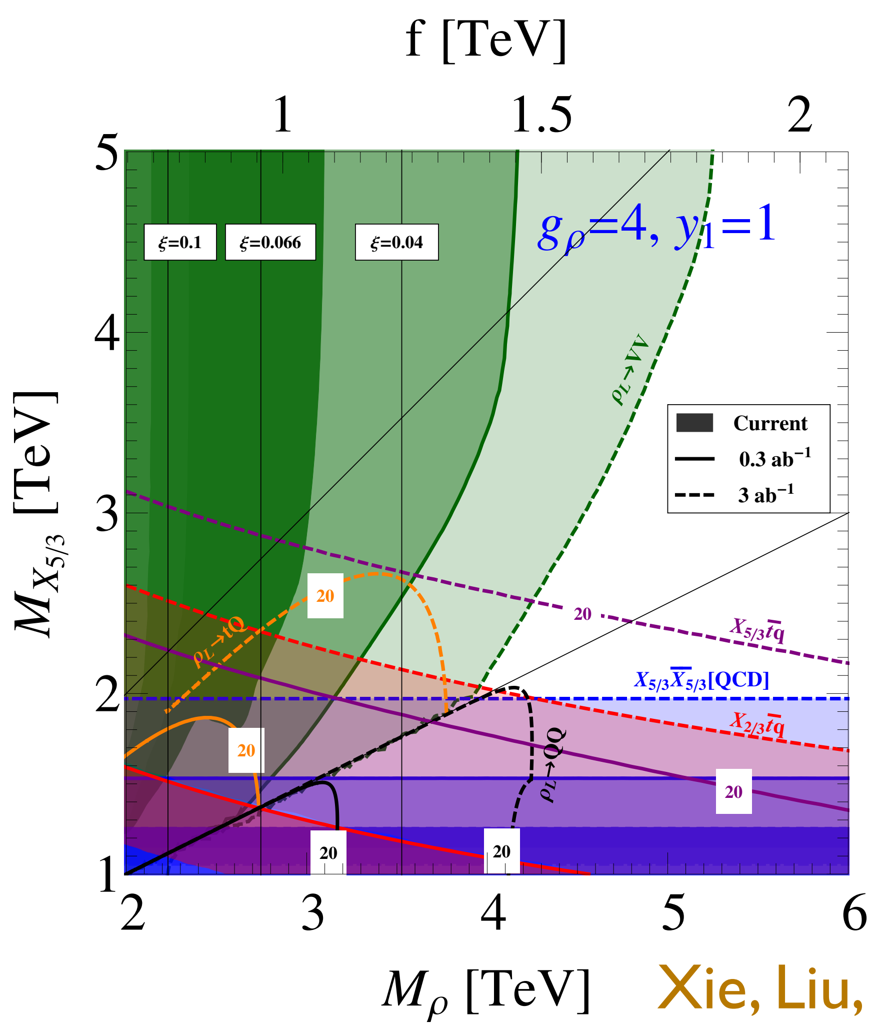
fine-tuning = comparison: $\frac{1}{16\pi^2} m_{\mathrm{T}}^2 \quad vs \quad m_h^2 = (125\ \mathrm{GeV})^2$

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

My view: not a big problem yet.

# LHC will keep make another big step



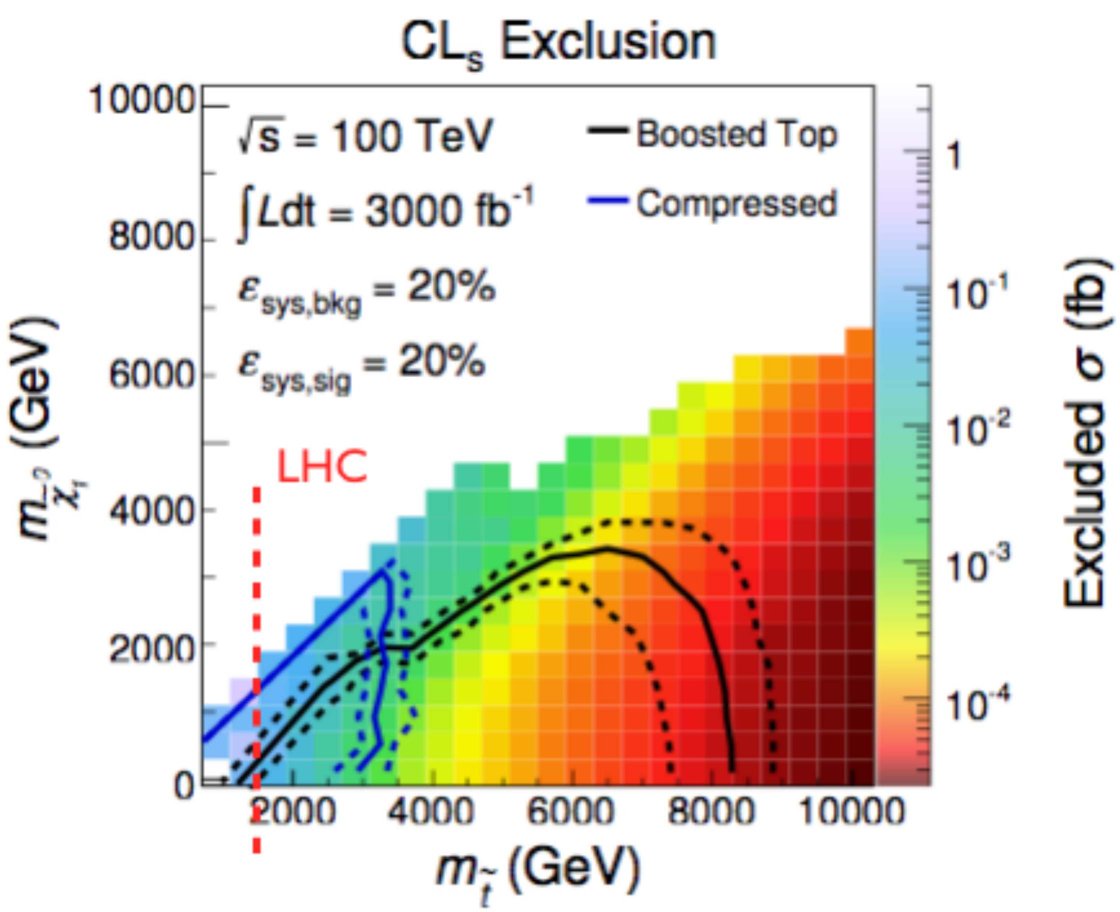




Xie, Liu, LTW

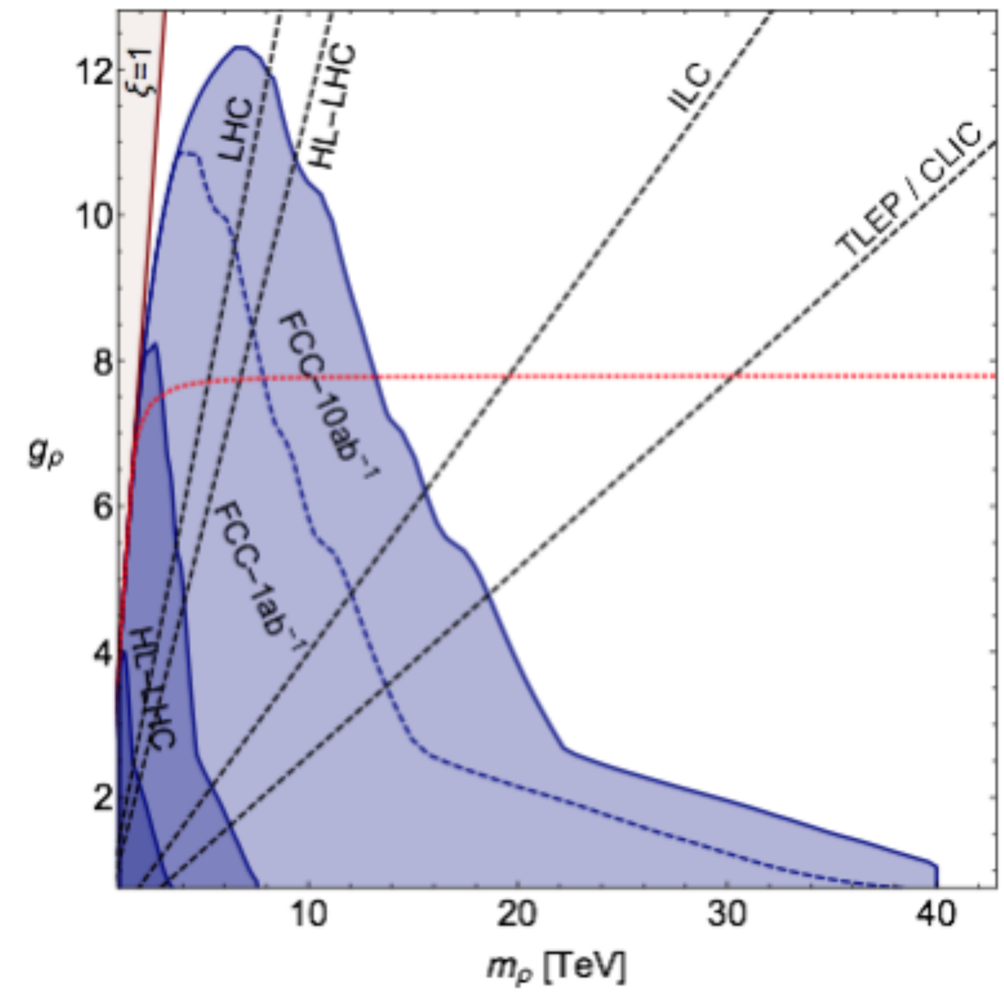
– Improve a factor of 1.5-2 beyond current reach.

# Testing naturalness at 100 TeV pp collider

Cohen et. al., 2014




Pappadopulo, Thamm, Torre, Wulzer, 2014

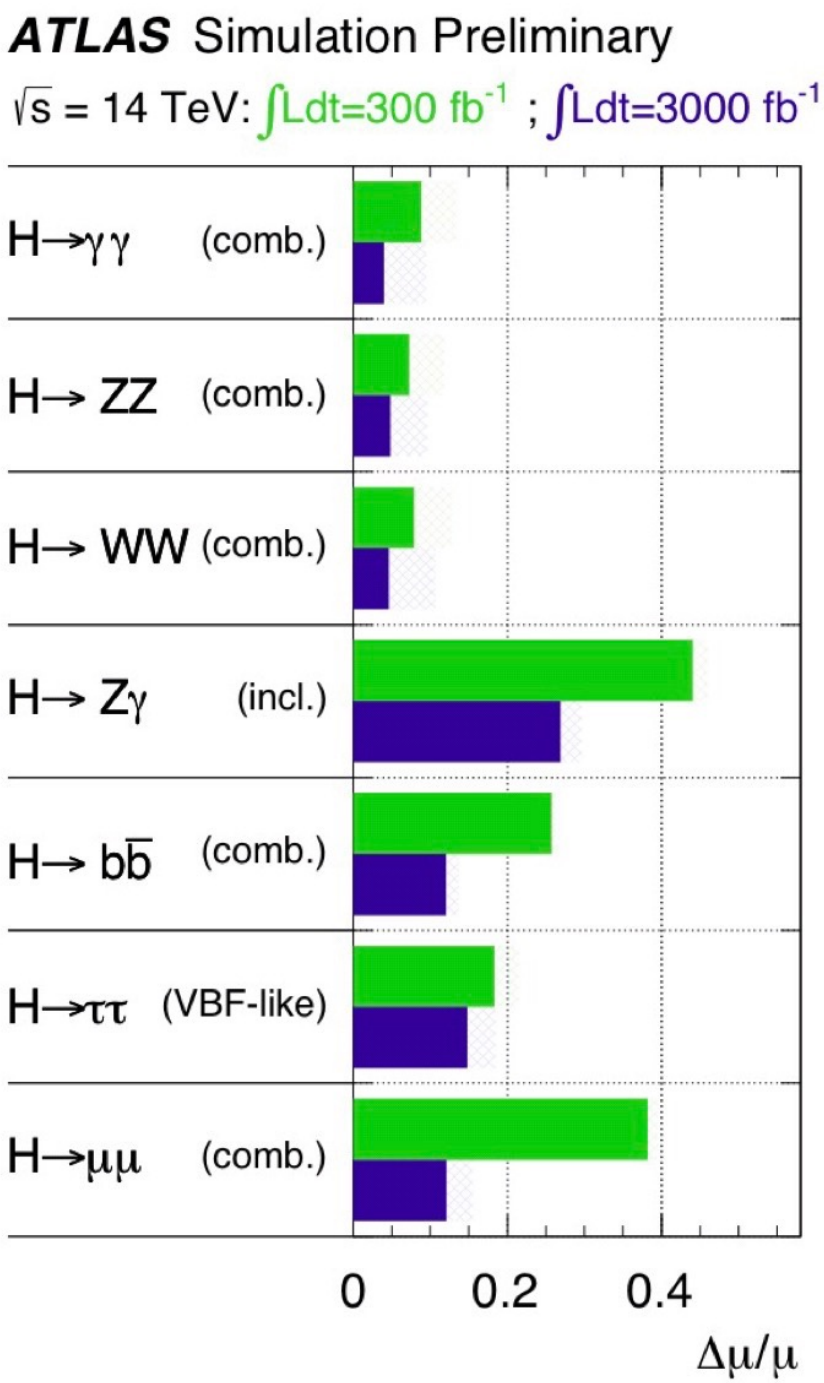


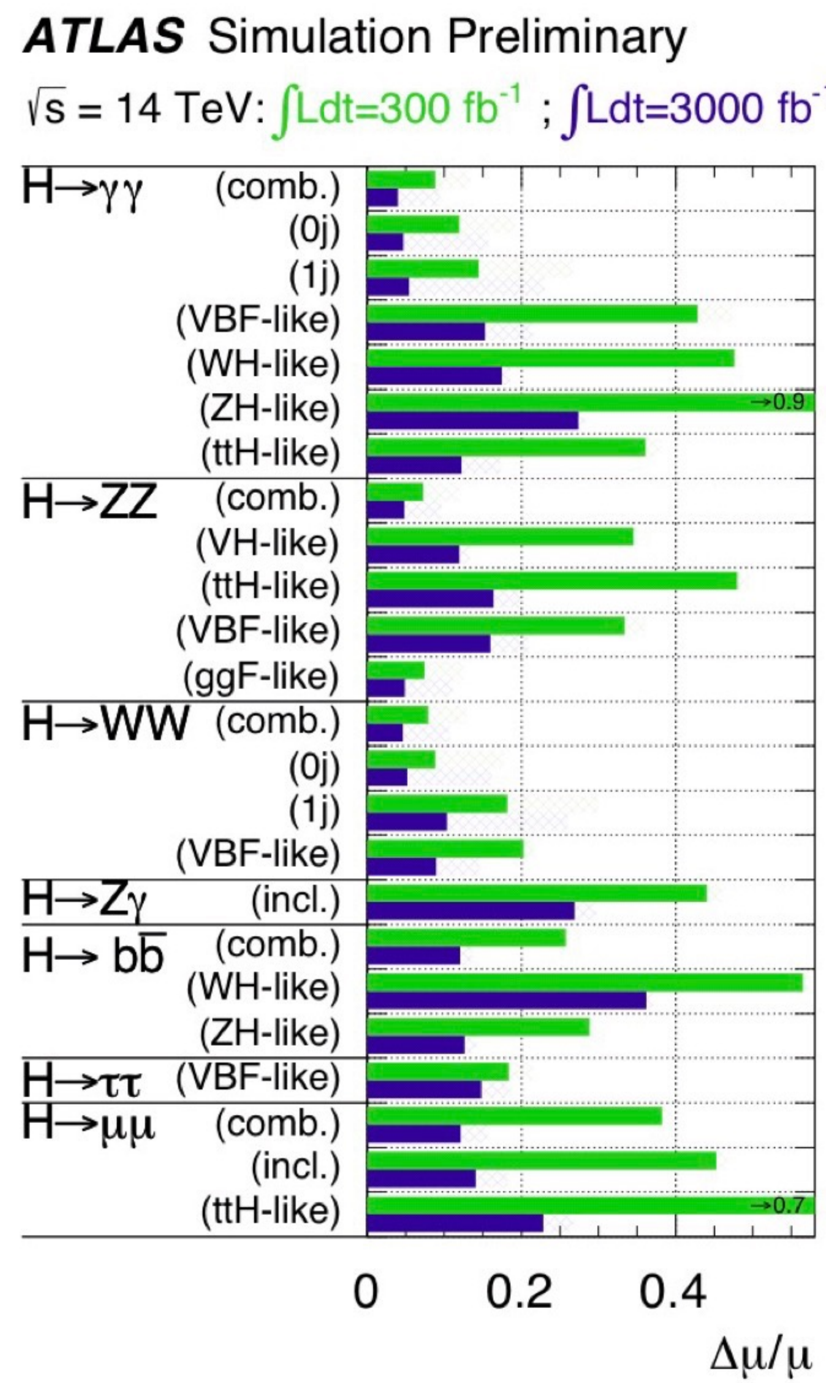

Future colliders, FCC-hh/SPPC, can continue the quest.

# Rethinking naturalness

- LHC has not confirmed any of our ideas yet.
- We may not have the right idea. No confirmation of any of the proposed models.
- More creative ("crazy") ideas. Some examples below.
- Crucially, need experiment!
- Fortunately, with Higgs, we know where to look.
- The clue to any possible way to address naturalness problem must show up in Higgs coupling measurement.

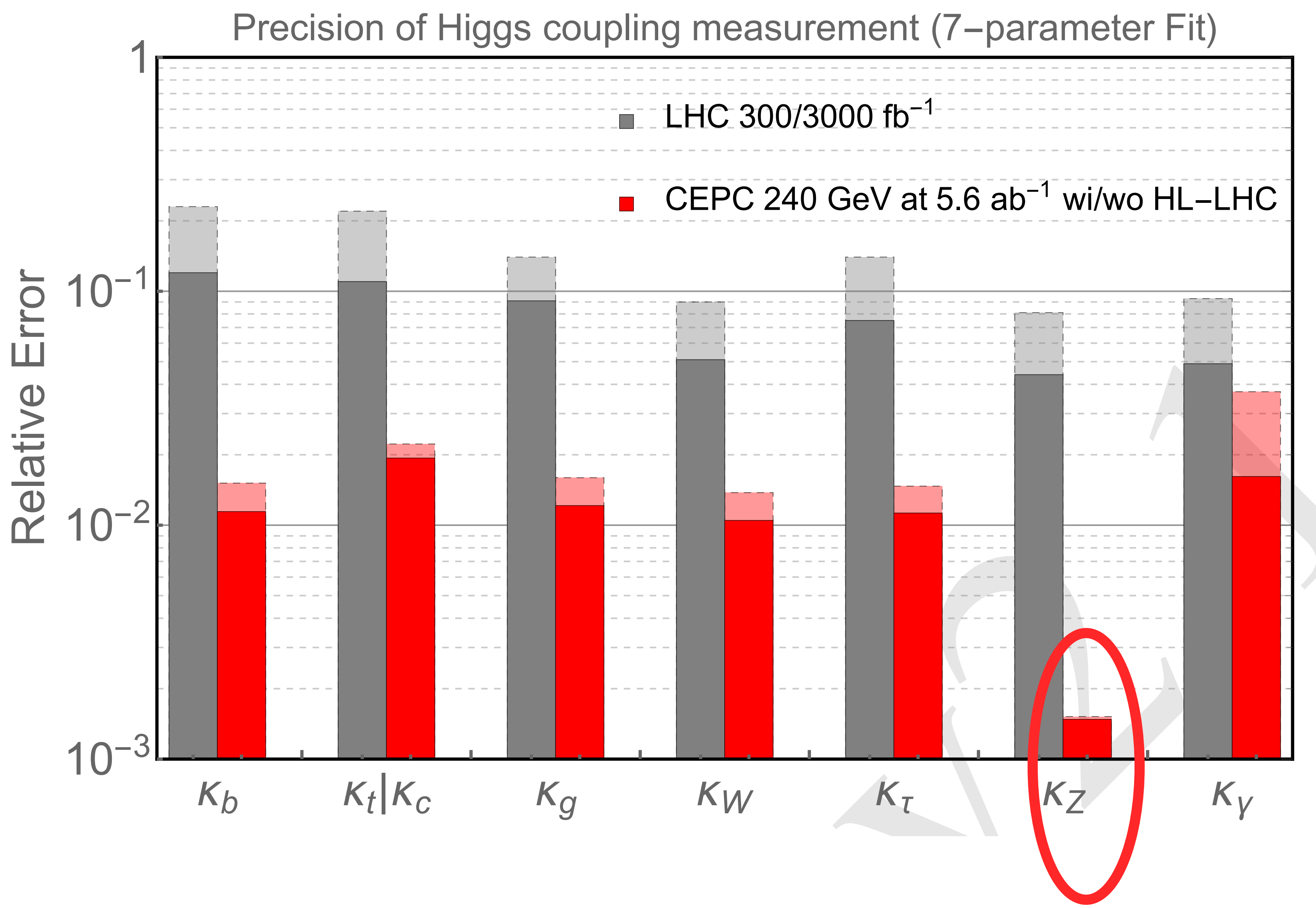
# LHC



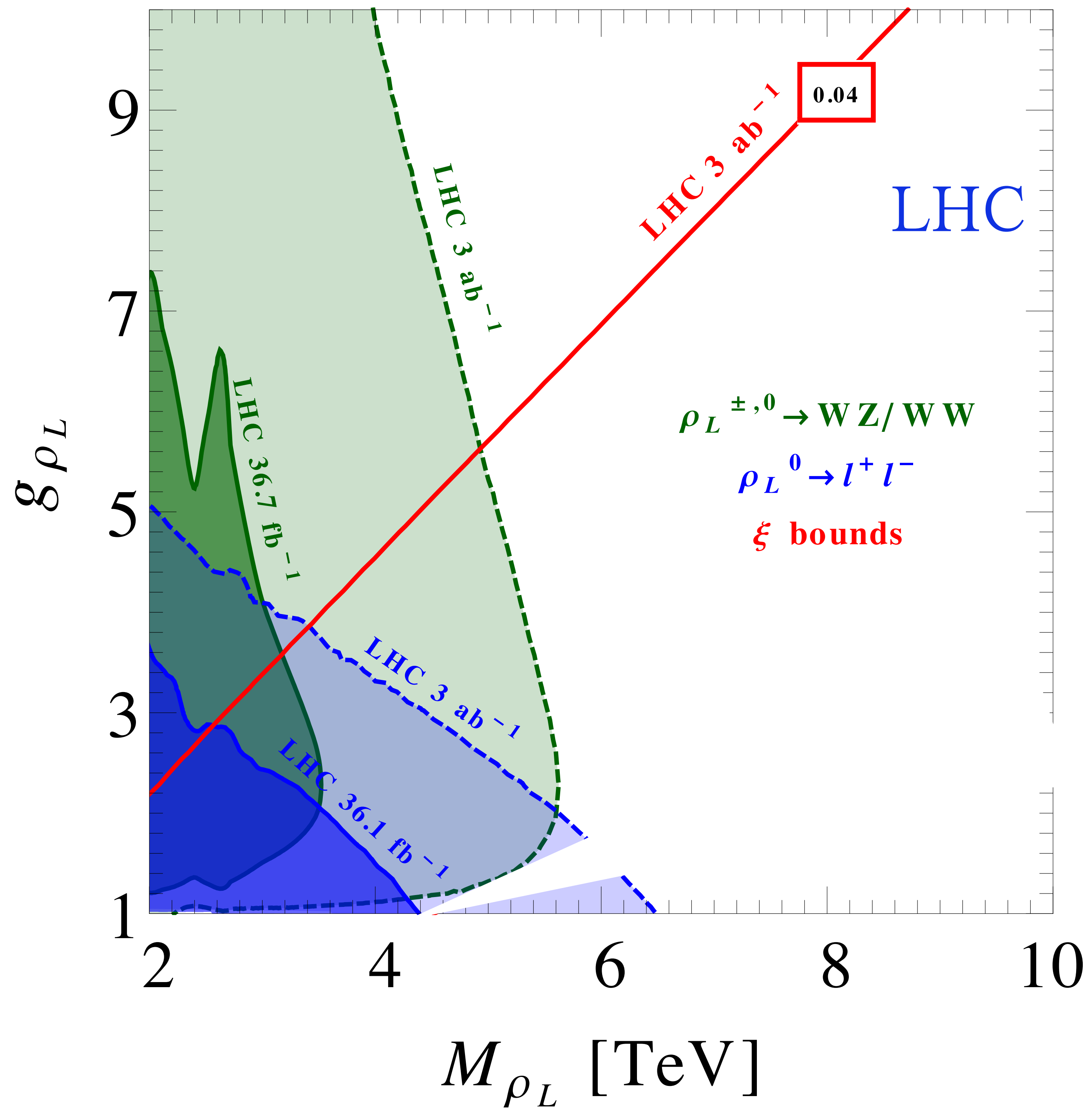

4-5% on Higgs coupling, reach TeV new physics

# Electron positron collider: CEPC

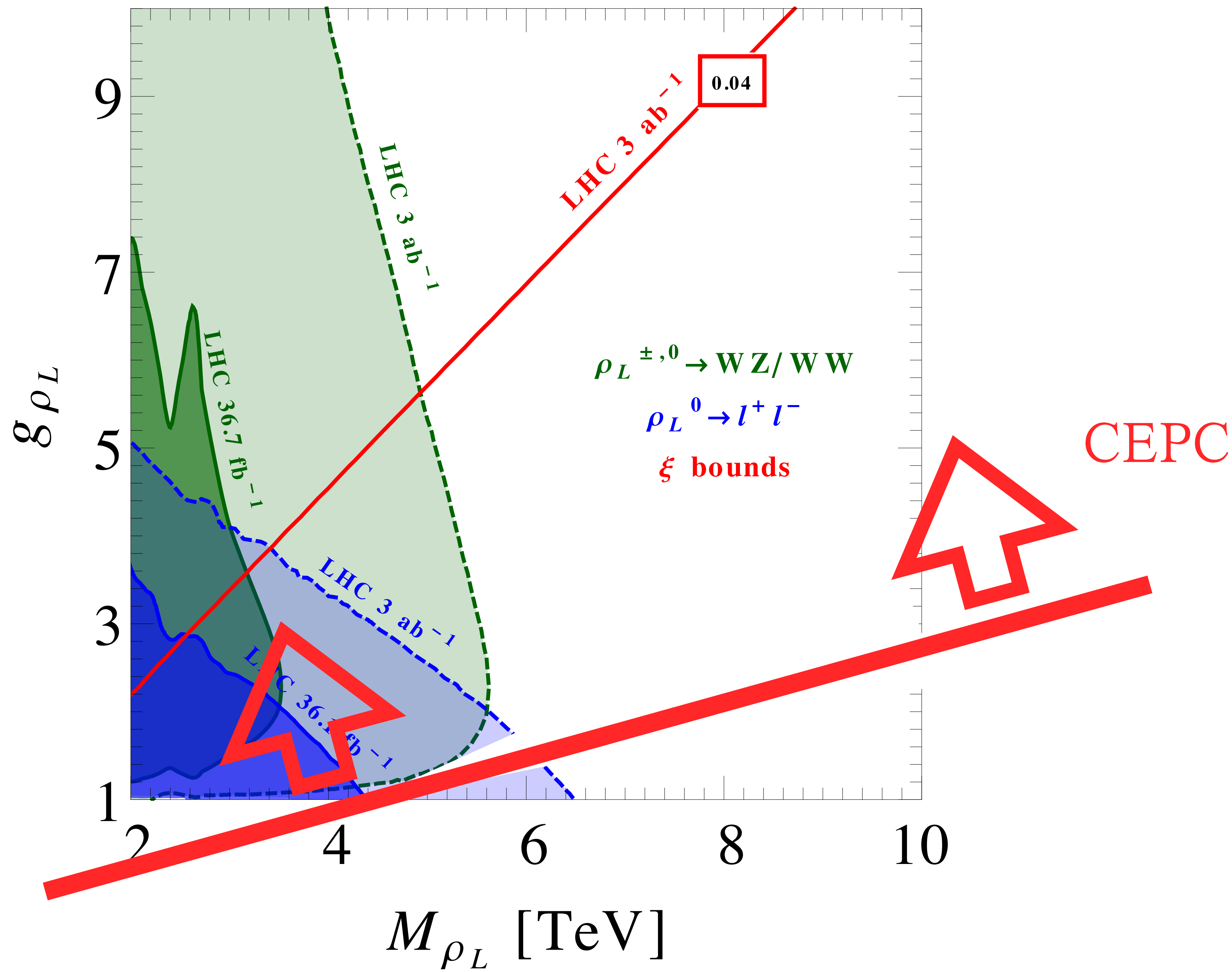



Up to sub percent precision, reach to new physics at multi-TeV scale.
Far beyond the reach of LHC.

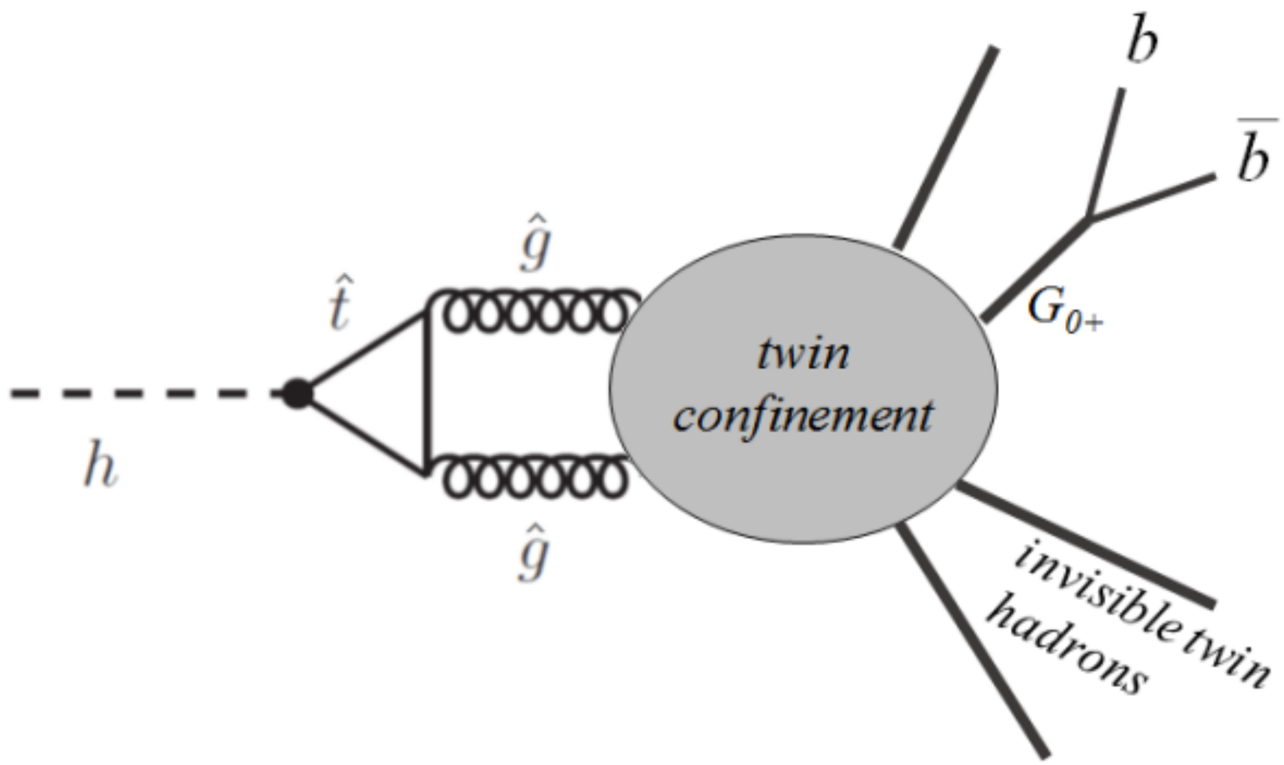
# Testing naturalness: composite Higgs



# Testing naturalness: composite Higgs



# Stealthy top partner.

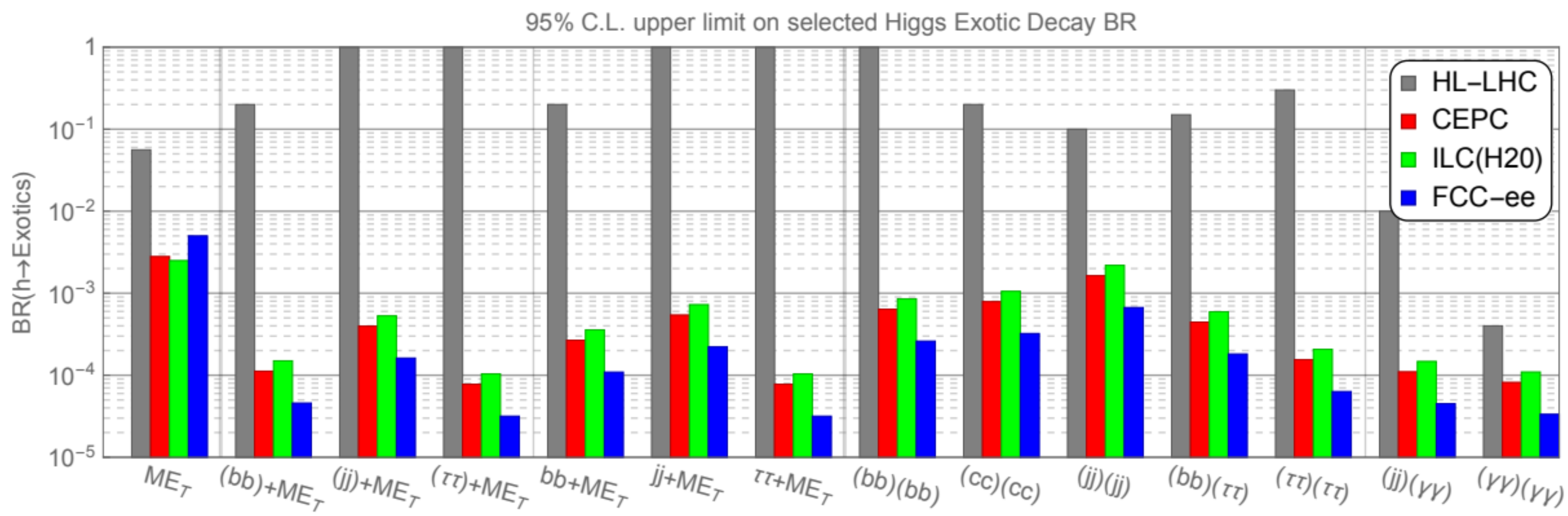



Top partner T not colored.

Higgs decay through hidden world.

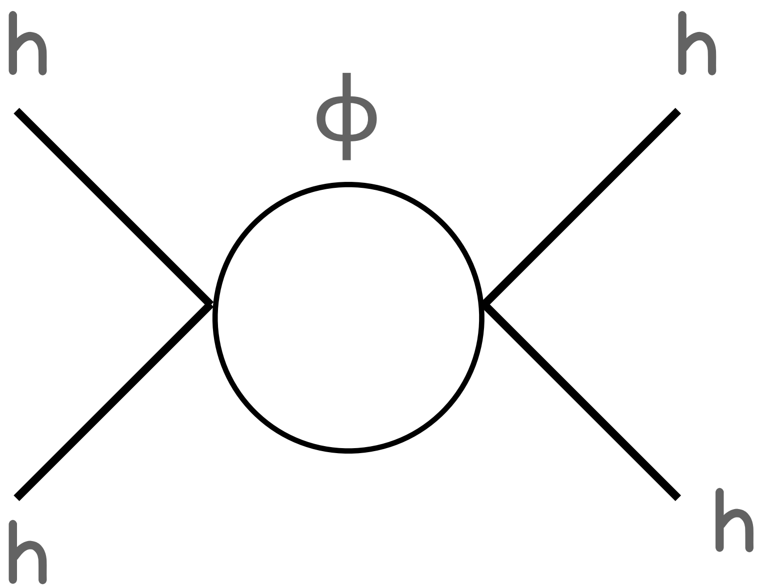
# Stealthy top partner.

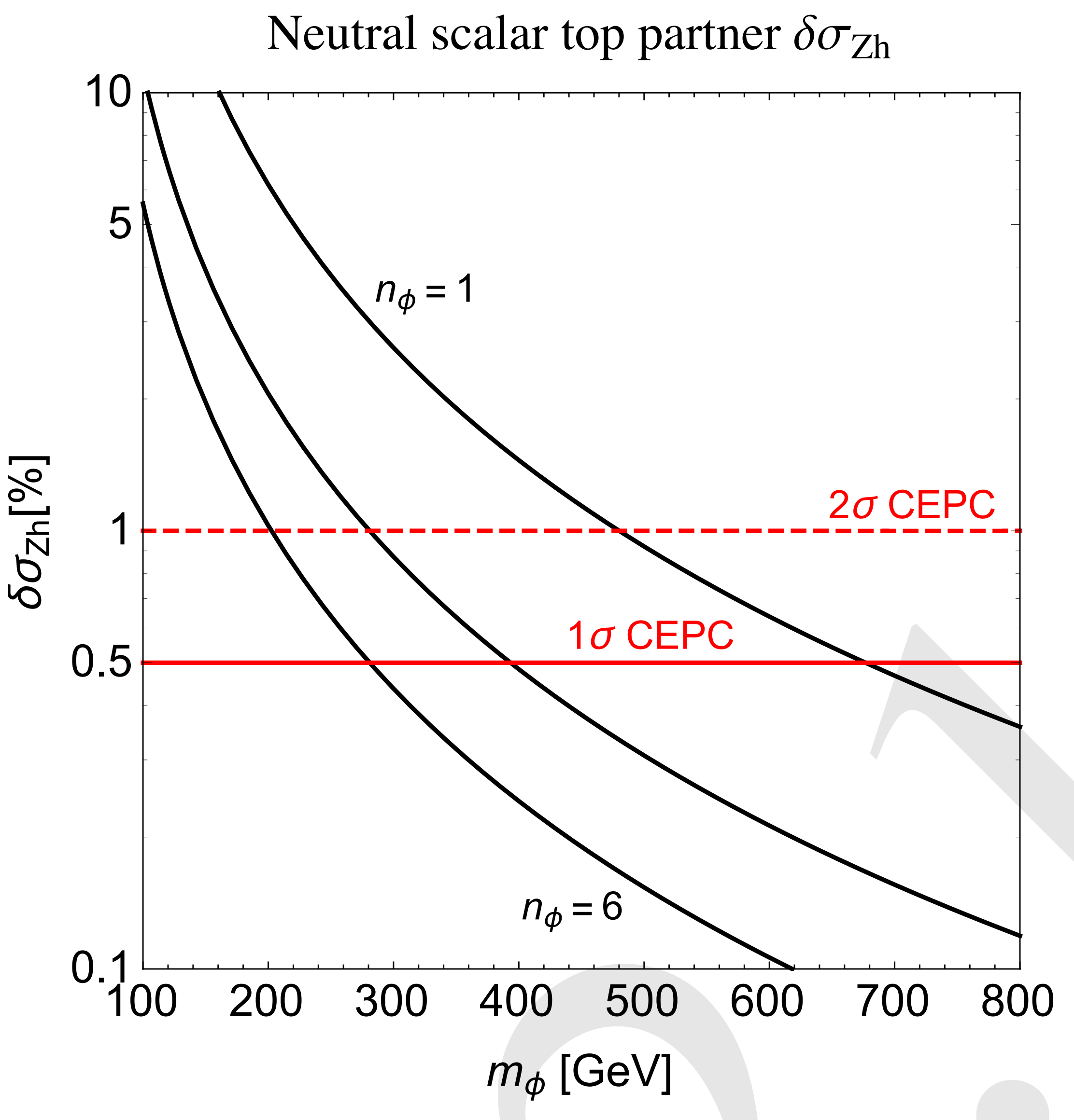
# Stealthy top partner.




- New Higgs decays or "exotic" decays.
- Can be tested at LHC and Higgs factories.

# A quantum probe

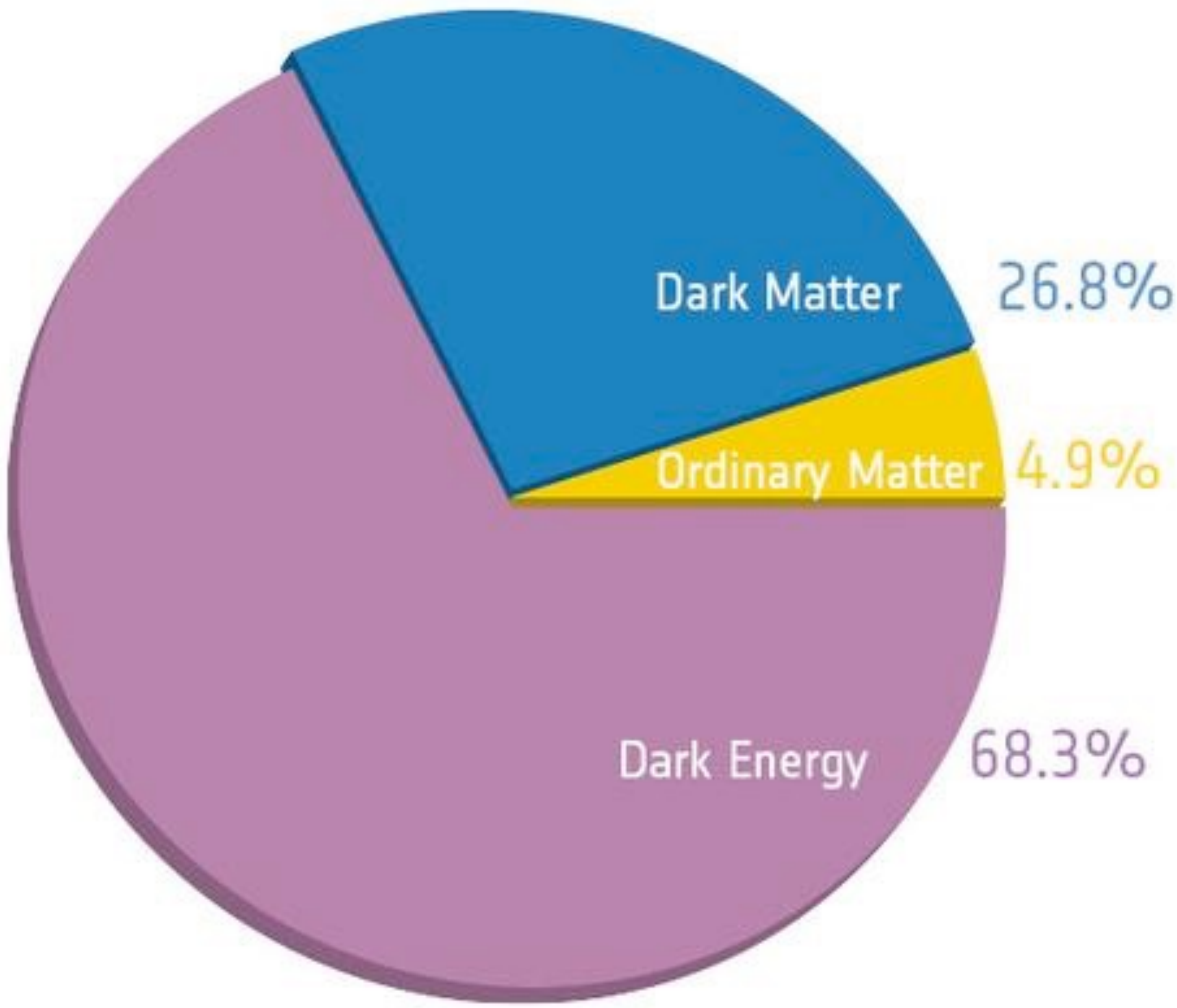



Signals of quantum fluctuations of new physics.

Direct test of naturalness.

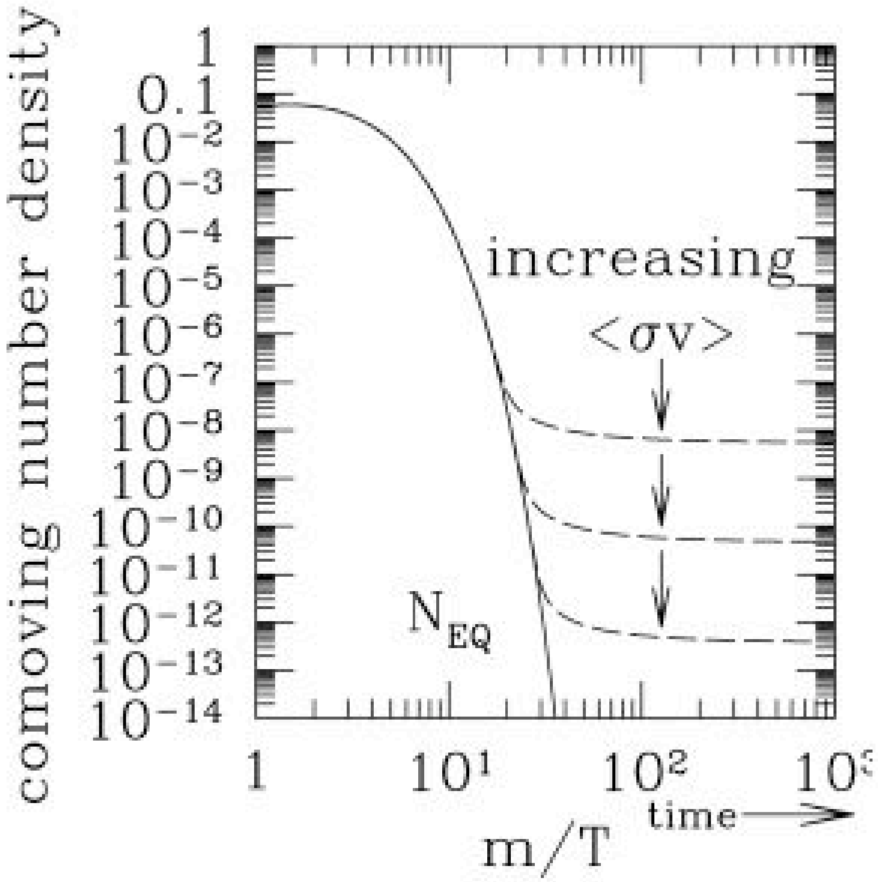
# Dark side of the Universe

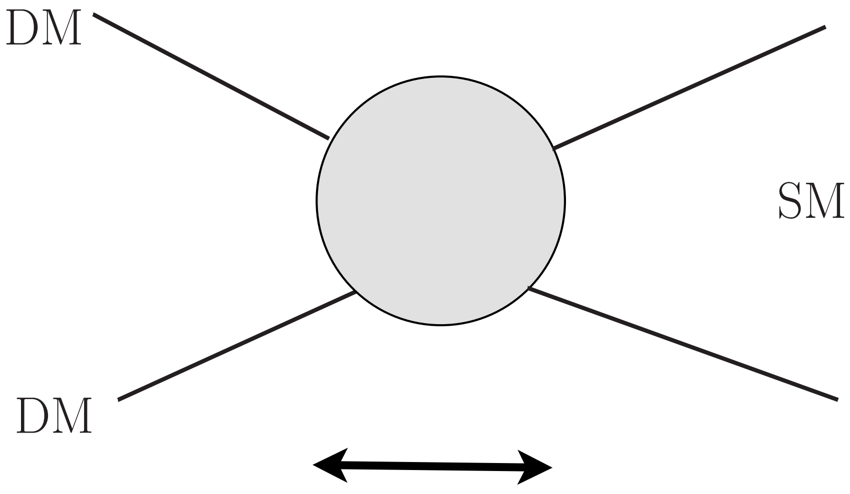


# Dark matter

- Vast possibilities, from blackholes to Bose-Einstein condensate.
  - Possible mass range: 80 order of magnitude.
- Could it be close to weak scale?
  - Compelling WIMP story.

# WIMP



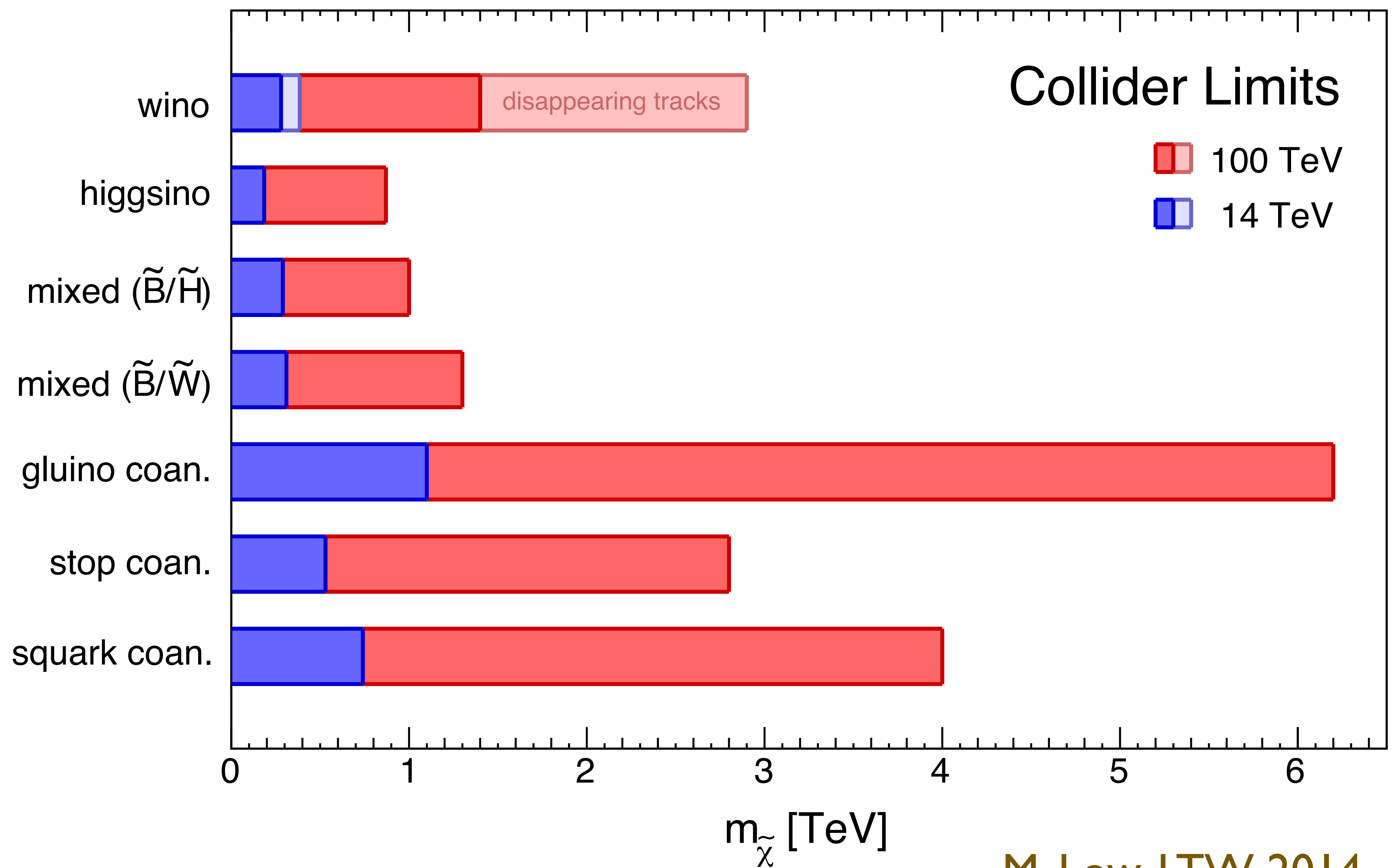

$$\langle \sigma v \rangle \sim \frac{g_D^4}{m_{DM}^2}$$

- 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!

# Dark matter

- If dark matter is close to the weak scale, it is closely related to the naturalness question.
  - Can be part of the solution!
- Can be tested at colliders, and DM experiments.

# Dark matter with Mono-jet

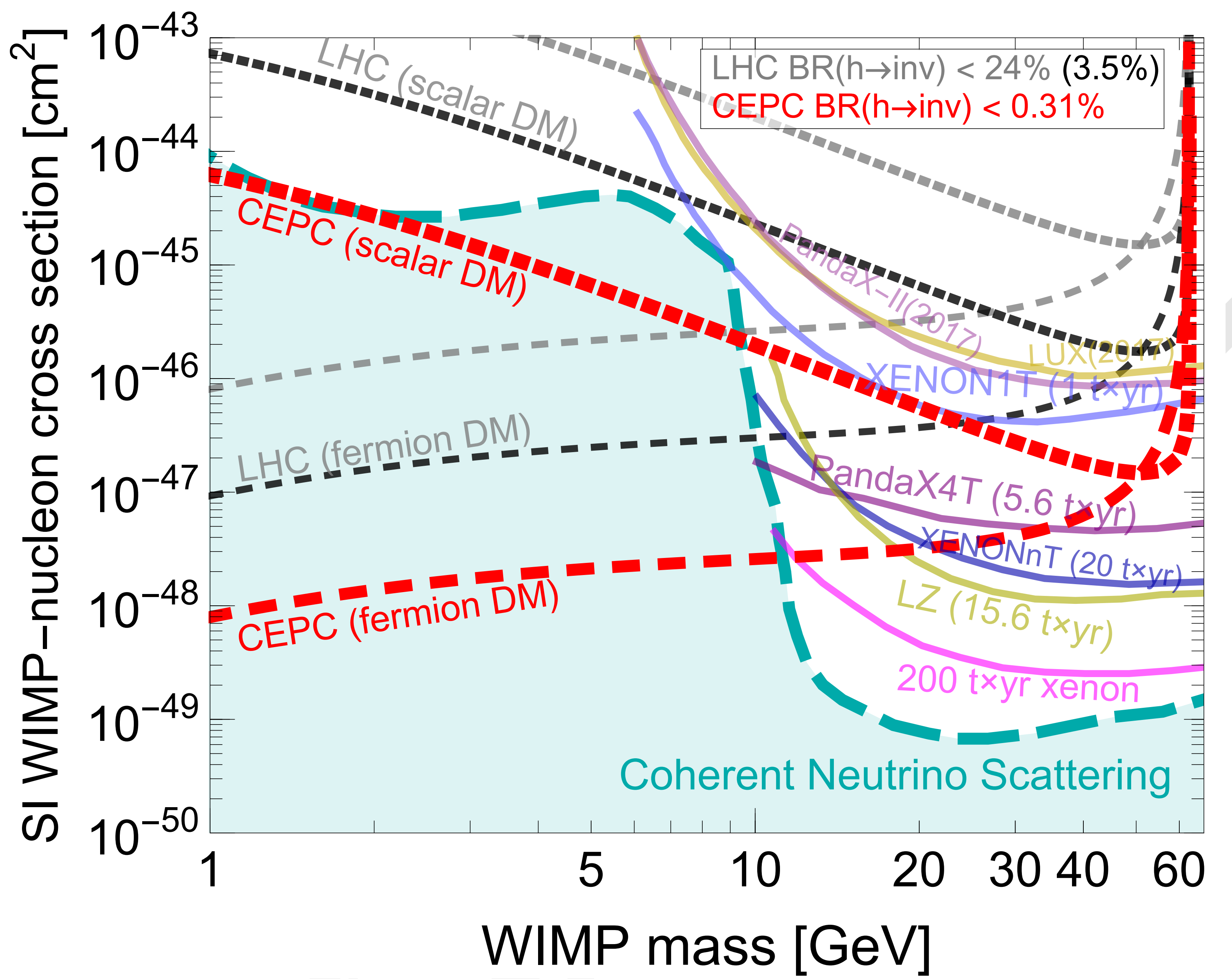



M. Low, LTW 2014

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

# Higgs portal dark matter

$H^\dagger H X X$




From Higgs invisible decay

# Dark energy

- The universe is big: $\approx 10^{25}$ meter
- The curvature $\Longleftrightarrow$ dark energy
  - Dark energy is very sensitive to the vacuum quantum fluctuations.
  - Naively, the size would be $(M_{Planck})^{-1} \approx 10^{-33}$ meter
- A very severe naturalness problem!
  - Similar to the Higgs mass, but much worse.

Why is the Universe so big?

# Dark energy

- $10^{25}$ meter vs $(M_{Planck})^{-1} \approx 10^{-33}$ meter
- Perhaps we don't understand gravity at the scale of the Universe?
  - Modified Einstein gravity. No workable theory yet.
- Perhaps there are many many universes?
  - We just lived in a livable large one.
  - Landscape, anthropics...
- Either way, some really deep ideas necessary.

# Where does this lead us ?

We searched for natural models
Not found yet. We will continue to look

Discover new physics.
Triumph (again) for
naturalness, and
Quantum Field Theory
as we know it.

No discovery. More motivation
for a big paradigm shift.
UV/IR, landscape....
No great idea yet.

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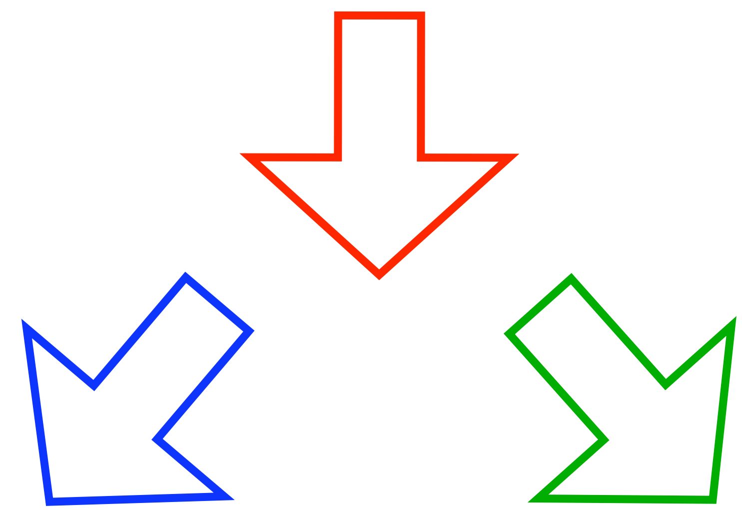
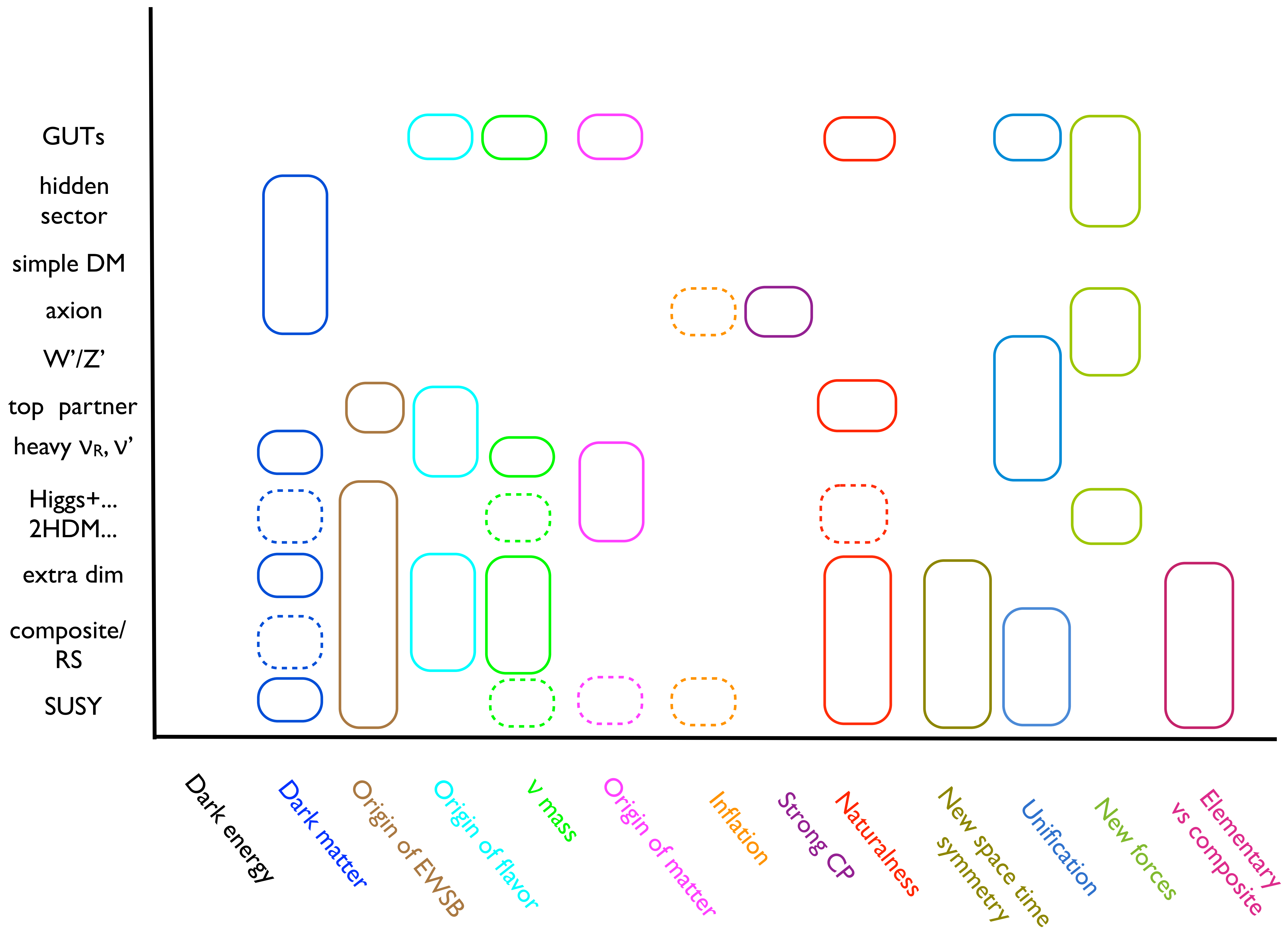


Discover new physics. Triumph (again) for naturalness, and Quantum Field Theory as we know it.

No discovery. More motivation for a big paradigm shift. UV/IR, landscape.... No great idea yet.

Greatest discovery can com from null experimental result.
(Example: Michelson-Morley)


GUTs
hidden sector
simple DM
axion
W'/Z'
top partner
heavy νR, ν'
Higgs+... 2HDM...
extra dim
composite/ RS
SUSY
Dark energy
Dark matter
Origin of EWSB
Origin of flavor
ν mass
Origin of matter
Inflation
Strong CP
Naturalness
New space time symmetry
Unification
New forces
Elementary vs composite

# Conclusion

- In the past 100 years, finding new particles lead to many discoveries, establishing the Standard model.

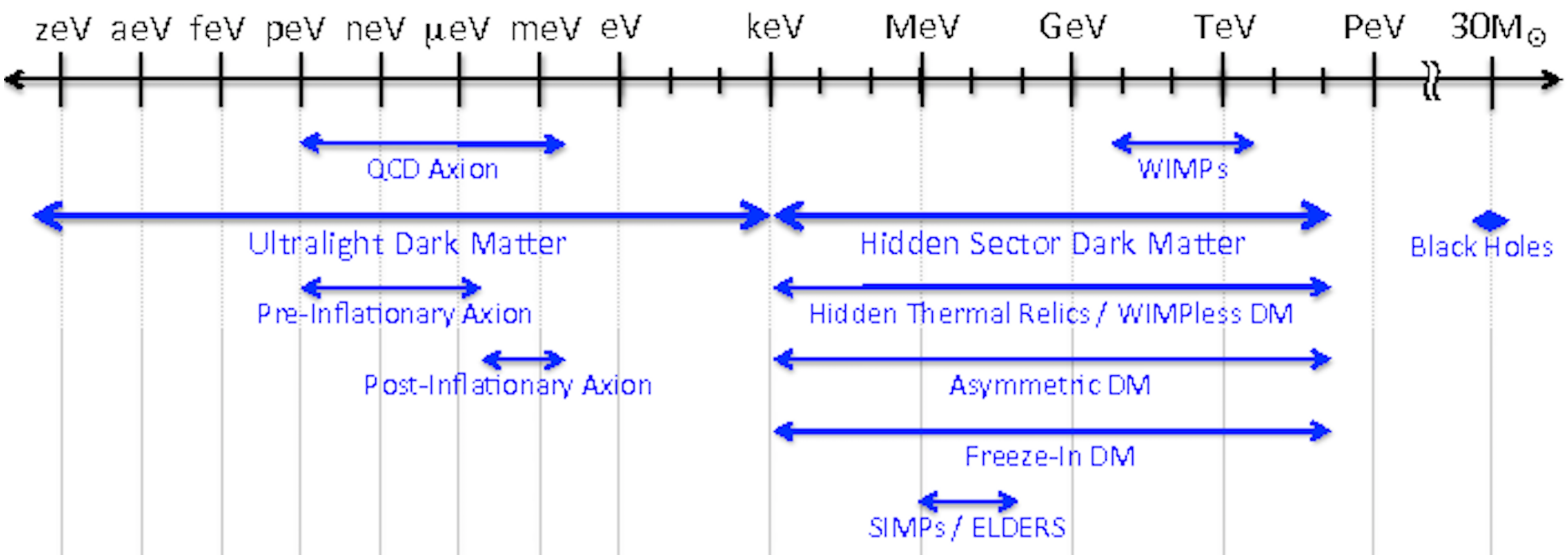
- The path in the future is uncertain. We don't know what's out there.

- Yet, we have exciting questions in front of us.
  - Naturalness seems to be the clue to deep questions, and big breakthroughs.
  - Similar to 100 years ago.

- Higgs provides a crucial window to make progress.

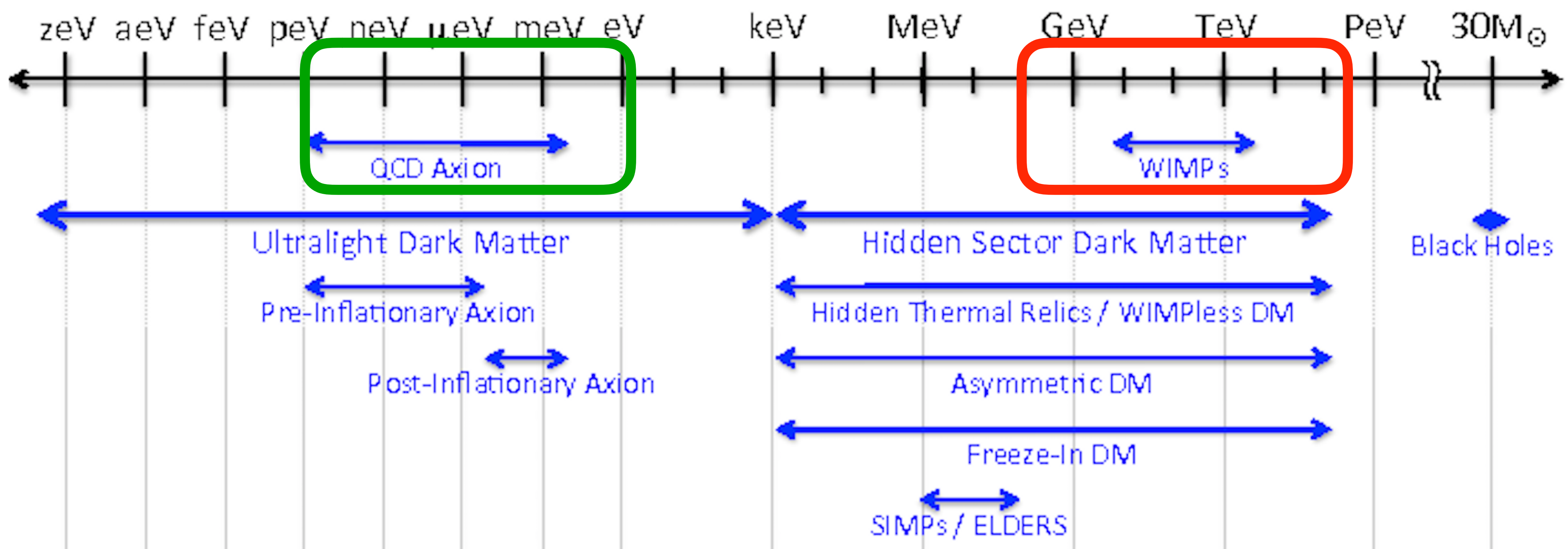

A lot to look forward to...

# Vast range of possibilities




- Possible mass range: over 100 orders of magnitude.
- Can have very different couplings.
- Only a few good stories.

# Vast range of possibilities




- Possible mass range: over 100 orders of magnitude.
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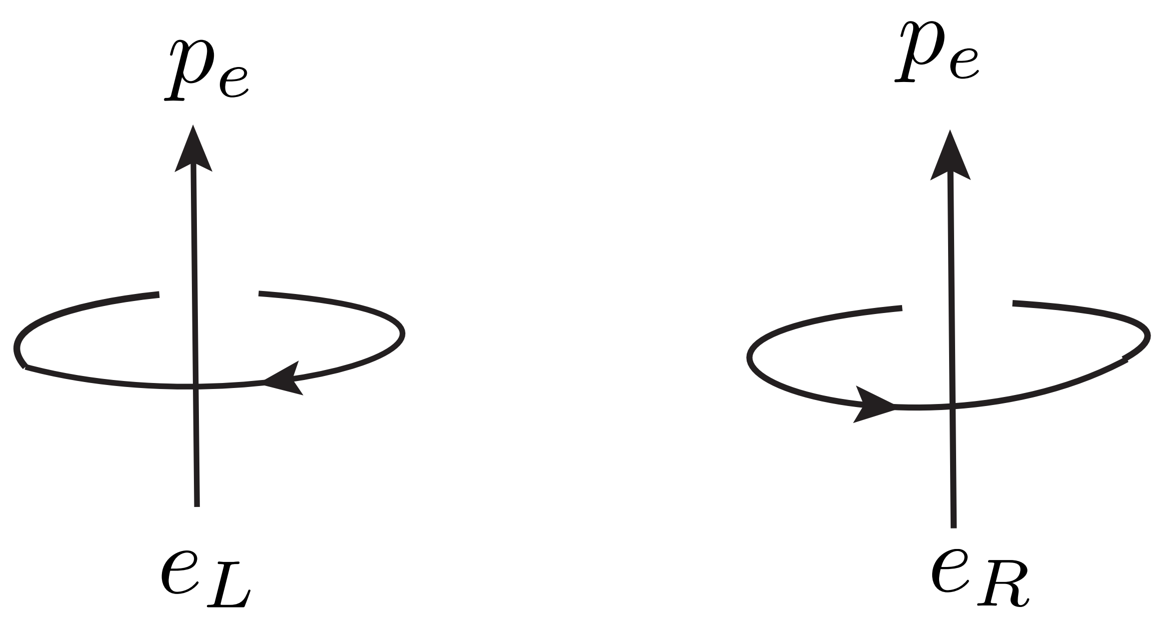
- Only a few good stories.

# Weak interaction and parity

helicity:

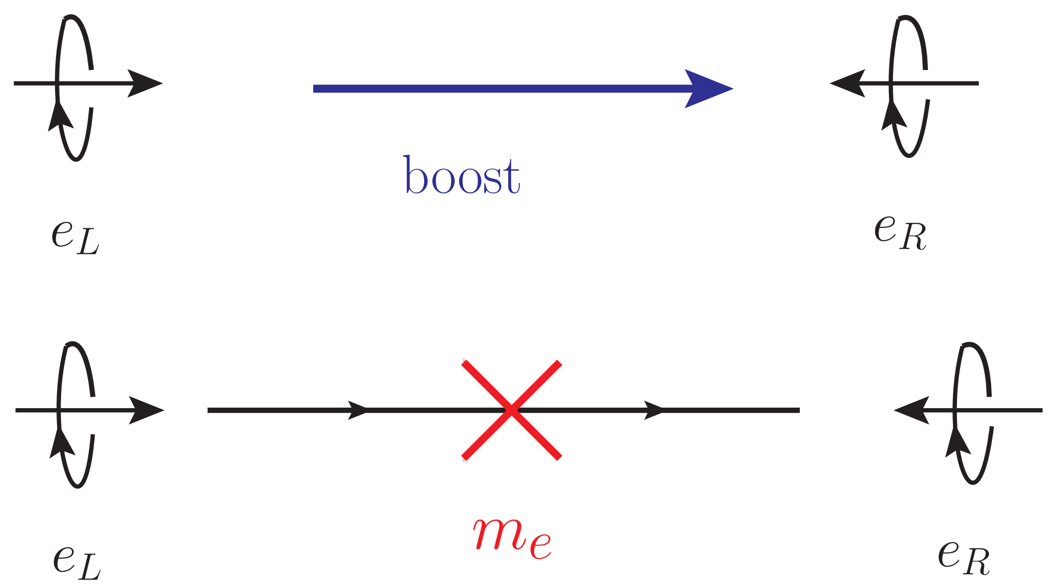
Left (right) handed




- Only left handed electron, $e_L$ , has weak interaction. (fixed by symmetry)
- Parity violation. Lee and Yang, 1956

# EWSB and origin of mass

Lorentz invariance:



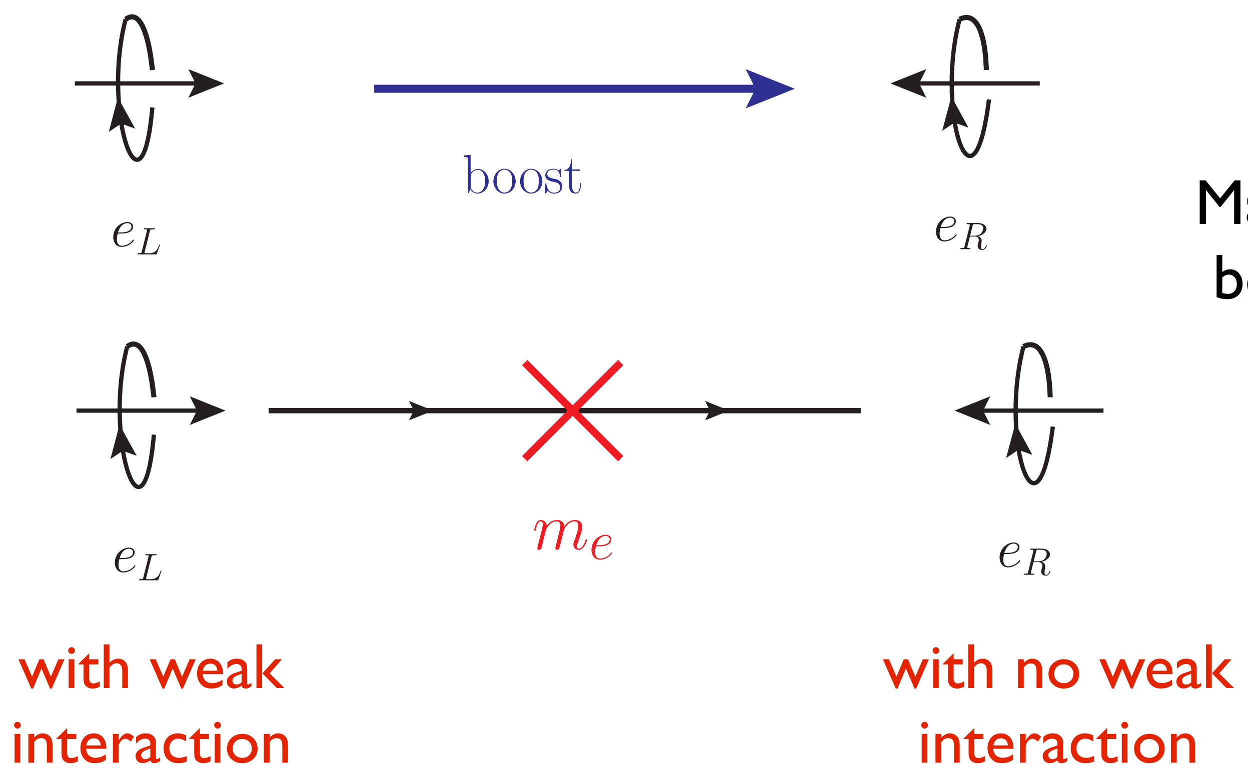

with weak interaction

with no weak interaction

Massive electron must have both $e_L$ and $e_R$

# EWSB and origin of mass

Lorentz invariance:

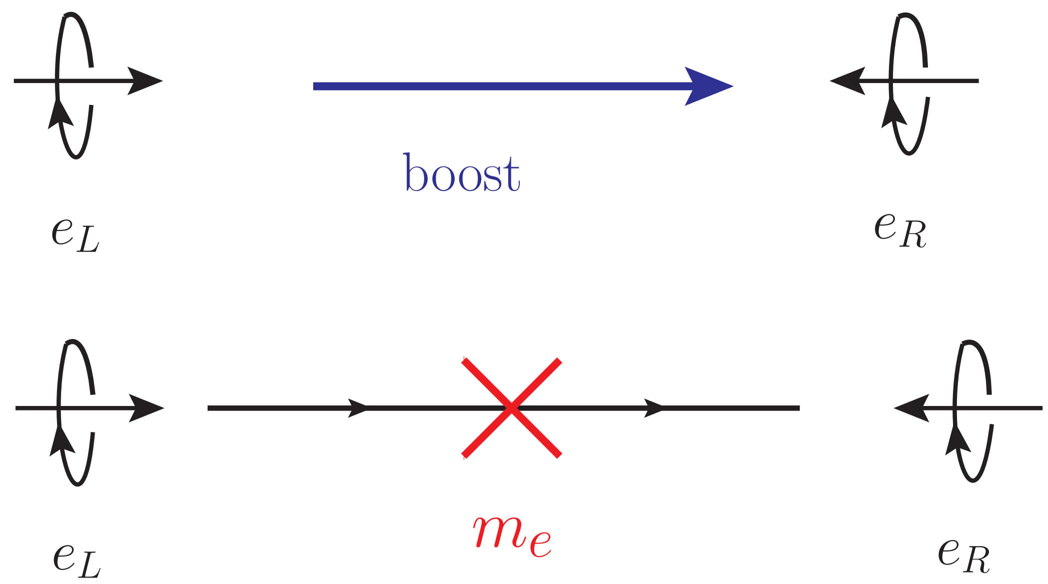



Massive electron must have both $e_L$ and $e_R$

- Whatever generates $m_e$ must break the symmetry of weak interaction.

# EWSB and origin of mass

Lorentz invariance:



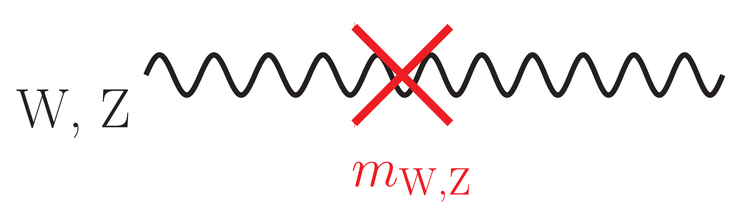

Massive electron must have both $e_L$ and $e_R$

with weak interaction

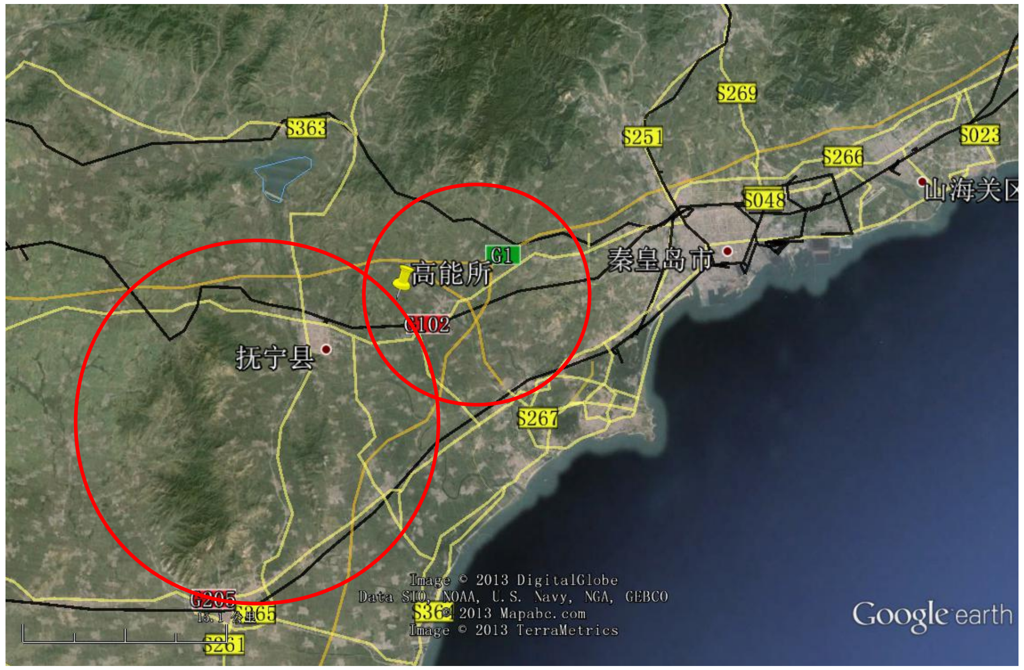
with no weak interaction

- Whatever generates $m_e$ must break the symmetry of weak interaction.

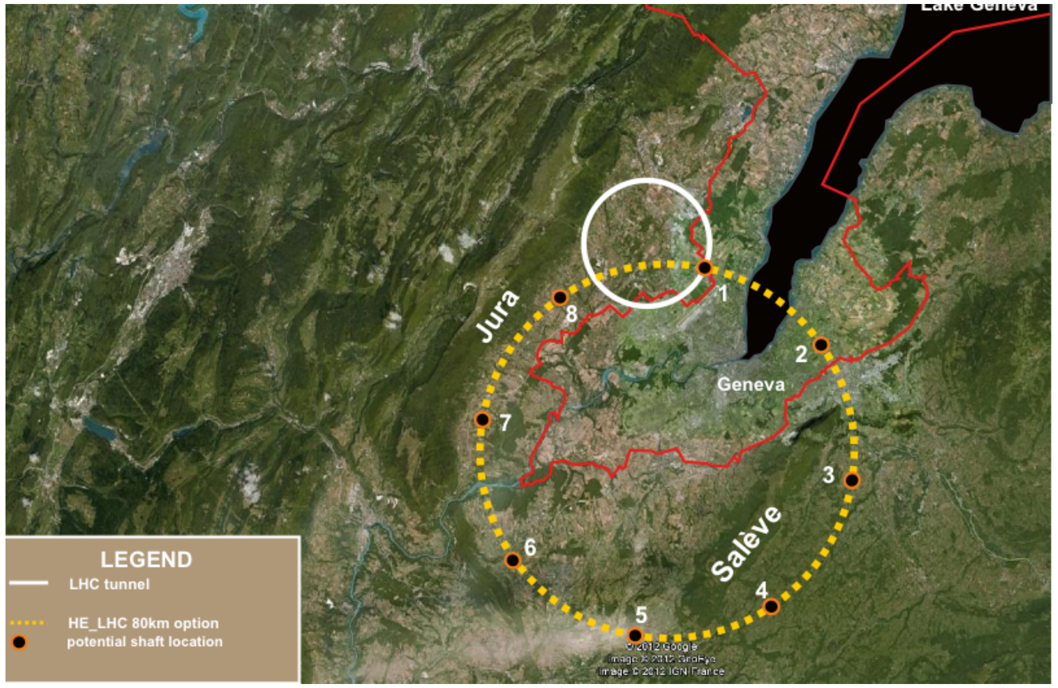
- As a result, it will give $W^{\pm}$, Z masses as well



# Future circular colliders

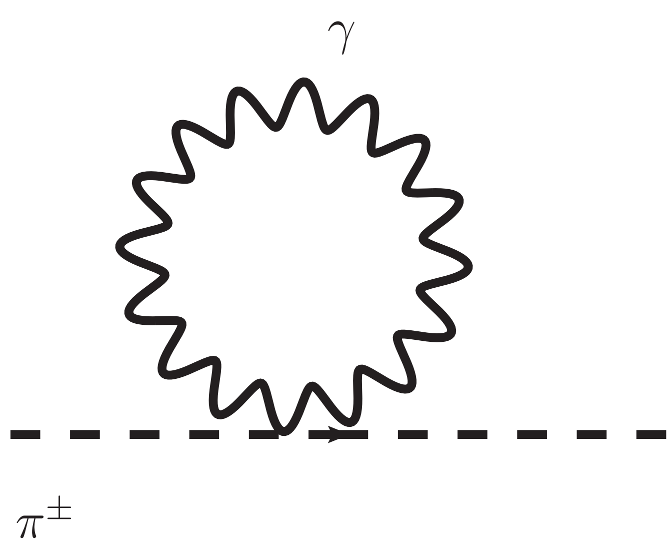


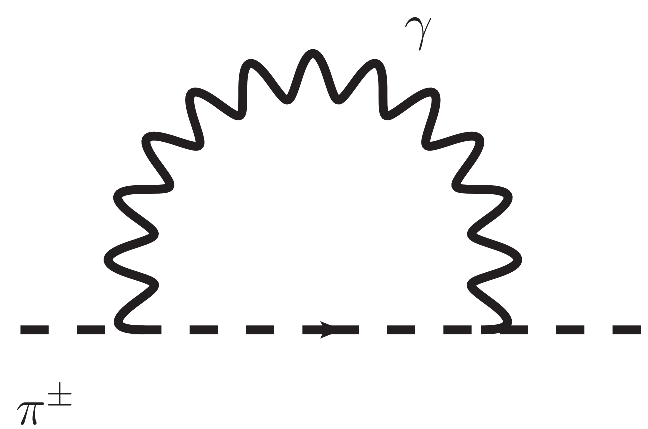

China.
Higgs factory: CEPC
pp Collider: SppC




CERN
Higgs factory: FCC-ee
pp Collider: FCC-hh

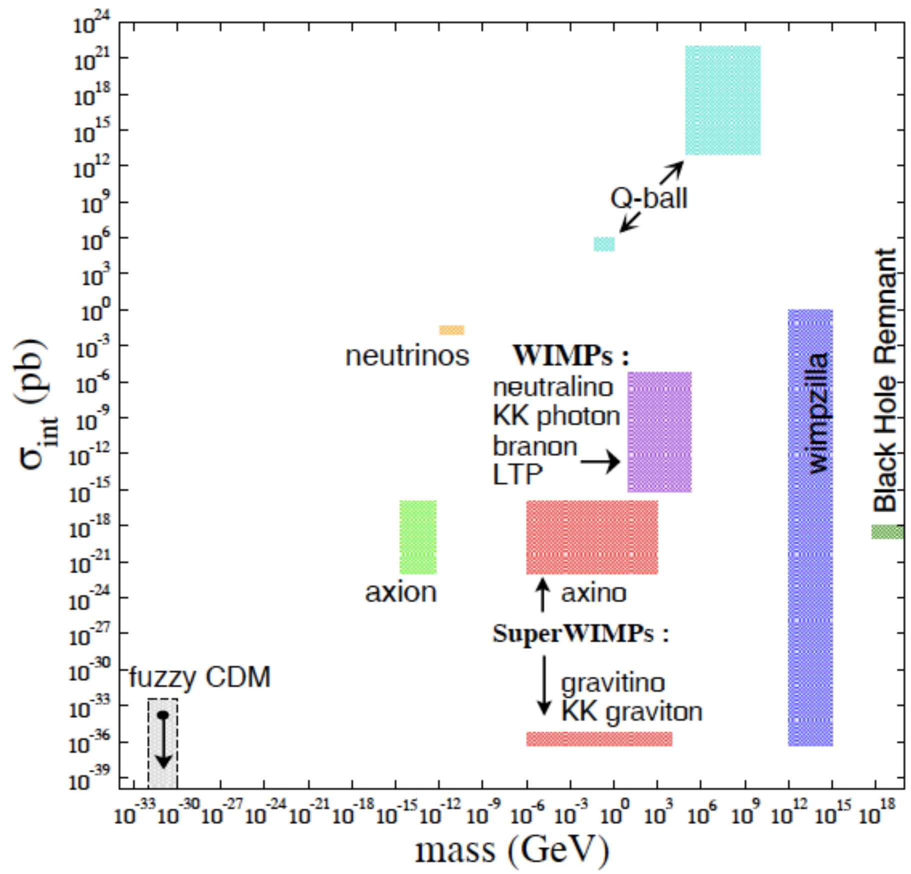
# Naturalness in nature?



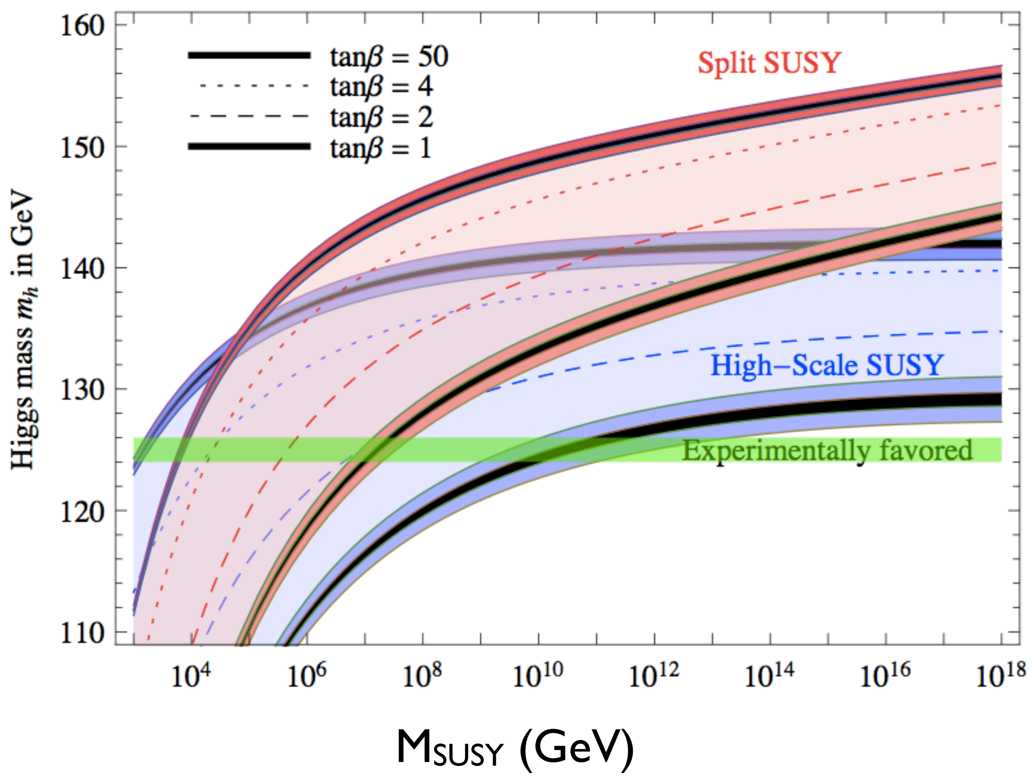

$$\delta m^2_{\pi^\pm} \simeq \frac{e^2}{16\pi^2}\Lambda^2$$

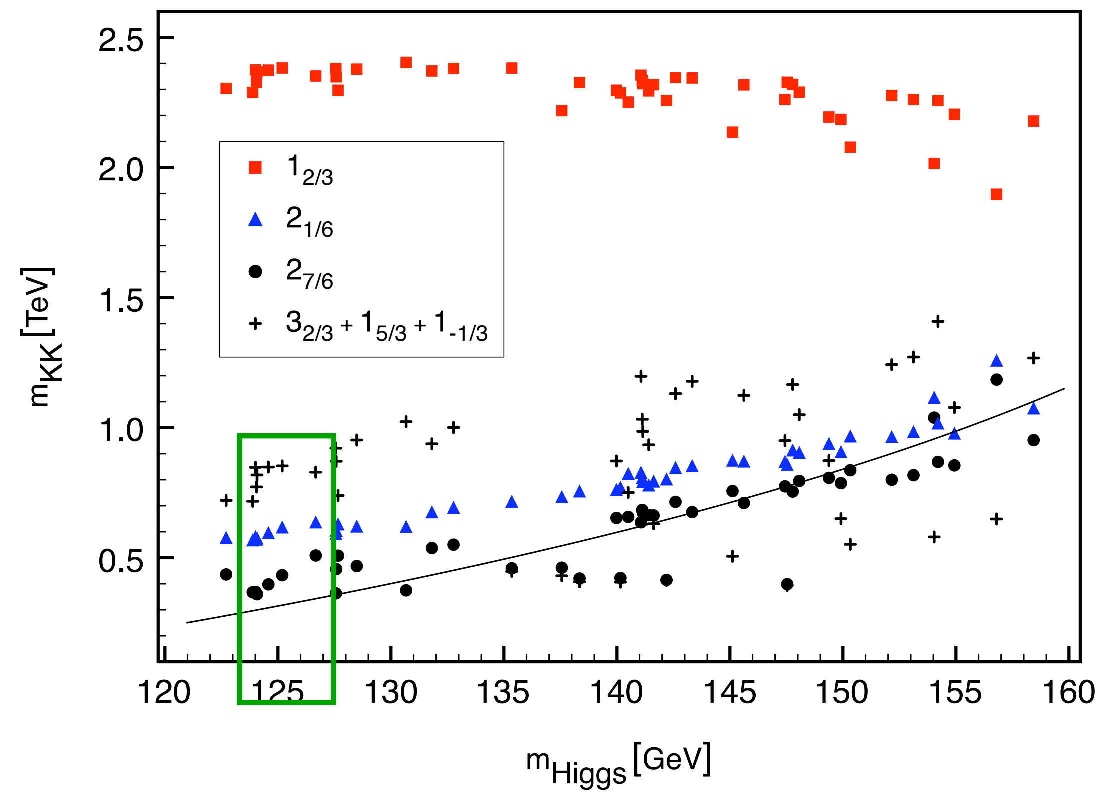
- Example: low energy QCD resonances: pion ....
- $m_\pi$ ~ 100 MeV.
- Naturalness requires $\Lambda$ ≈ GeV.
  - Indeed, at GeV, QCD ⇒ theory of quark and gluon



Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
wimpzilla
Black Hole Remnant
$\sigma_{int}$ (pb)
mass (GeV)

# A confusing picture for Higgs mass



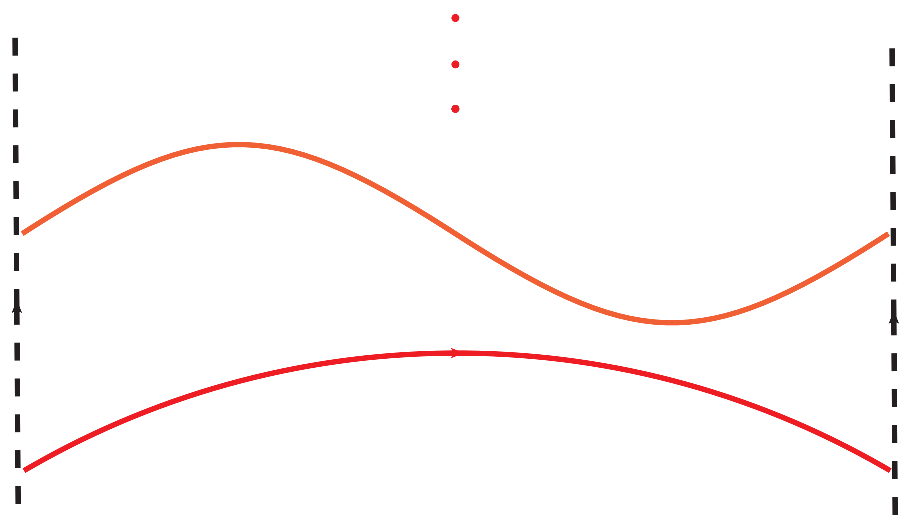




Supersymmetry
Stop too heavy to be natural

Composite top partner
too light, excluded

Such conclusions too simplistic, "work around" available.
A bit uncomfortable, yes. Not time to give up just yet.

# Higgs mass in quantum theory.
# Quantum fluctuation: Zero point energy



$$\mathcal{H}_{\text{quant}} = \sum_{\vec{p}} \frac{1}{2}\hbar\omega_{\vec{p}} \simeq \int^{|p|<\Lambda} \frac{d^3\vec{p}}{(2\pi)^3}\hbar\omega_{\vec{p}}$$

$$\omega_{\vec{p}} = \sqrt{\vec{p}^2 + m^2} \qquad (\hbar = 1)$$

$\Lambda$: a cut-off.
The energy scale of new physics.

Standard Model: include fluctuations of W boson, top quark, ....

$$m_{\text{W}} = g_2 h, \quad m_{\text{top}} = y_t h \qquad \mathcal{H}_{\text{quant}} \simeq \frac{9}{64\pi^2} g_2^2 \Lambda^2 h^2 - \frac{3}{8\pi^2} y_t^2 \Lambda^2 h^2 + \cdots$$

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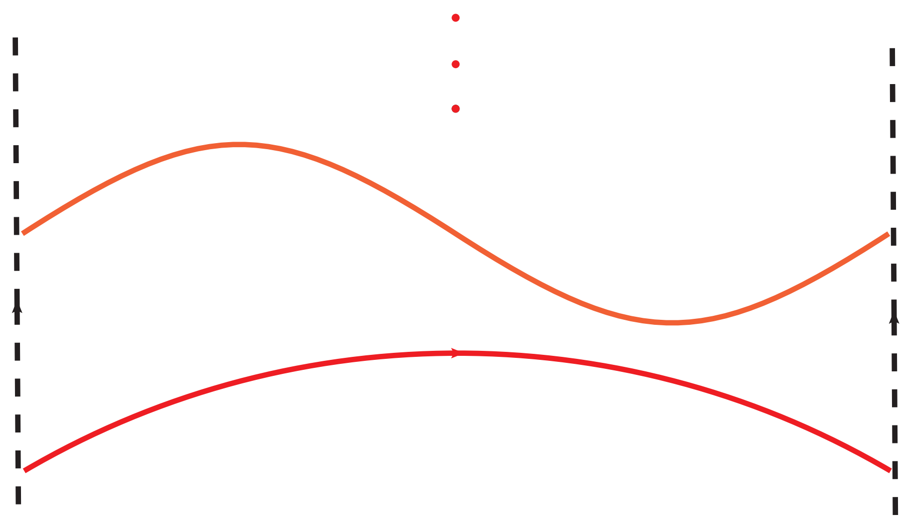

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- $m_h^2$(physical) = $m_0^2 + c\,\Lambda^2$
  - $m_0^2$ can always be adjusted to give correct $m_h^2$(physical).