Physics at

Matthew McCullough

Where are we now?

After decades of combined effort...

Experiment.

Accelerator.

Theory.

We now have the correct effective theory (symmetries and particles) to describe all of the known fundamental particles.

This is a remarkable scientific achievement!

Where are we now?

After decades of combined effort...

Experiment.

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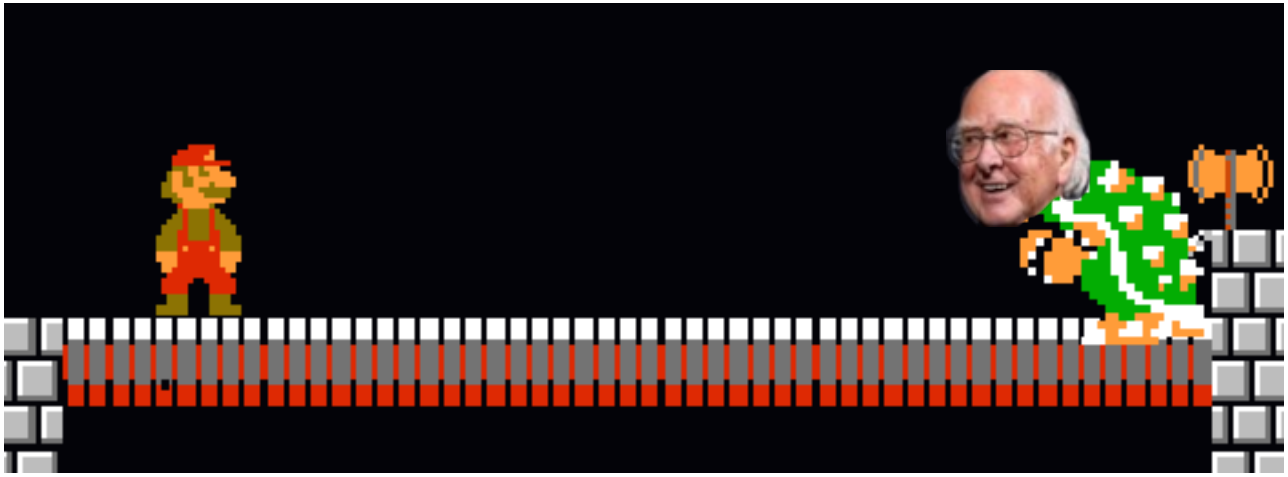
Theory.

The Higgs was the keystone,



bringing us to a new era of fundamental physics.

Where are we now?

The Higgs is the end of the first chapter...

and the beginning of the next, but LHC cannot address new frontier of fundamental questions.

How can we get there?

How we answer the next fundamental questions will boil down to the uncertainty principle:

Energy Frontier

To probe nature at the smallest distance scales, we must push to the highest momentum scales:

$$\Delta x \geq \frac{\hbar}{2\Delta p}$$

If new particles exist with a tiny Compton wavelength, high energy is the only way to observe them directly.

Intensity Frontier

Alternatively, we may gain indirect access to physics at the highest energies with high precision measurements:

$$\Delta E \geq \frac{\hbar}{2\Delta t}$$

If new interactions exist, beyond the Standard Model, the first cracks could show up in high precision.

FCC-ee, he, ee, fit both categories.

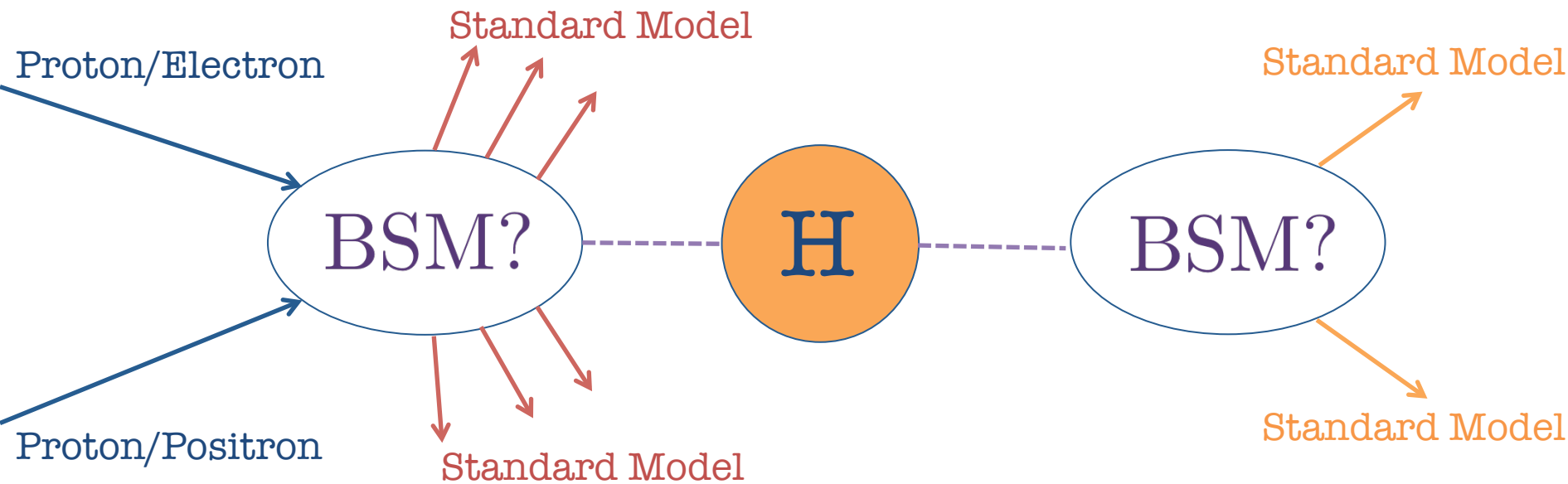
Where do we need to go?

Higgs! Higgs! Higgs!

- The Higgs is completely unique. We must strive to understand every aspect of it.

The question defines the machine...

The physics of the Higgs boson dictates some very clear physics targets.



Every measurement of the Higgs boson probes new physics. What <u>precision</u> should we aim for?

The question defines the machine...

The Higgs boson is uncharged and carries no spin, so can interact readily with unknown particles

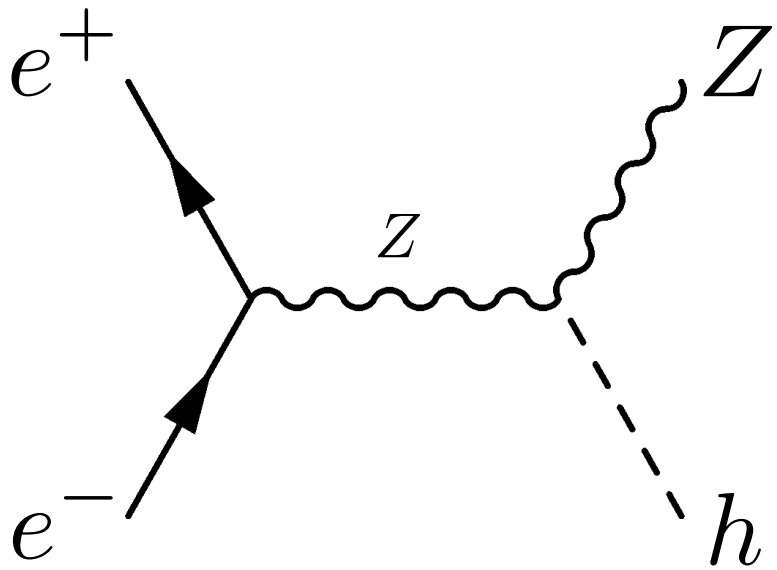
Even if we cannot "see" new particles, they affect the Higgs quantum mechanically, and we can search for these effects.

We can peek through the Higgs portal, by peering into the Higgs boson itself.

The measurements...

An e^+e^- collider is the surgeon's scalpel of particle physics.

- Dominant Higgs production at lower energies is associated production:



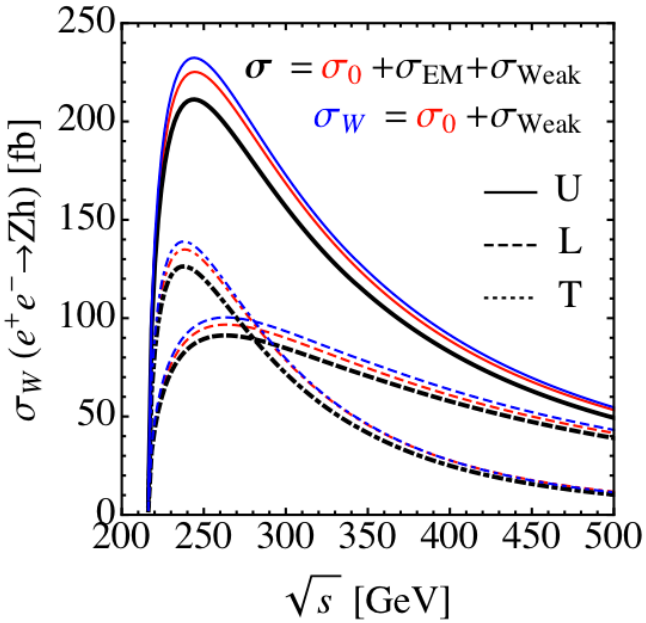
Can measure Z-recoils alone

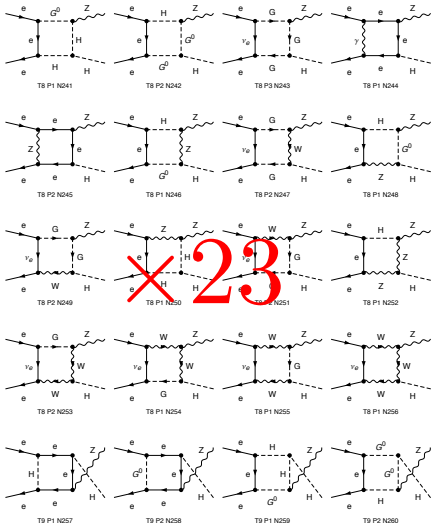
- Total cross section independent of Higgs decays, unique to e^+e^-! Clear determination of width!

The measurements...

- SM dictates we must exceed an accuracy of few % to truly measure the quantum mechanics of the Higgs boson.

SM 1-loop electroweak quantum corrections to cross section are a few %.

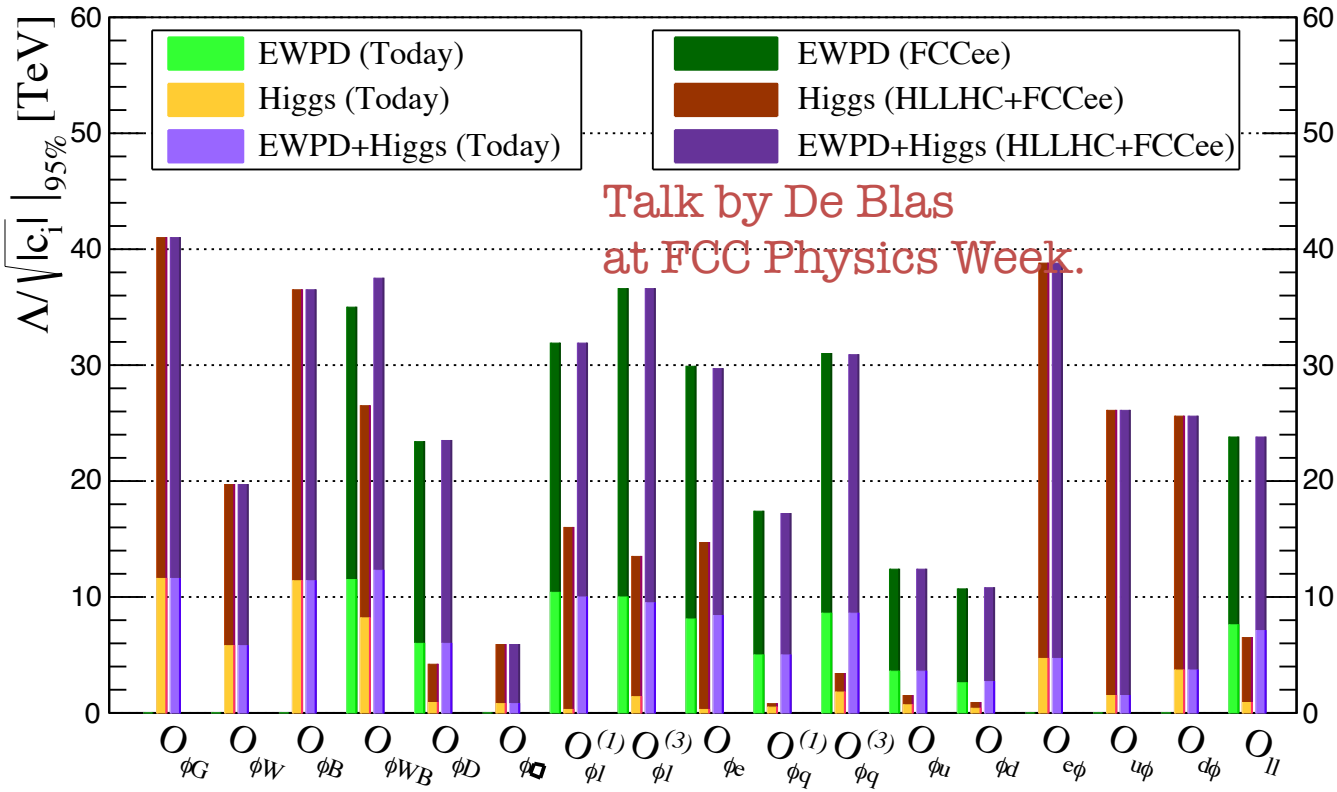




- FCC-ee would delve deep into this regime, with a measurement of 0.4% accuracy!

The size of the Higgs boson...

- Probing deep into the quantum nature (substructure) of the Higgs boson.



Would know about Higgs sub-structure, down to scales two orders of magnitude below Higgs Compton wavelength!

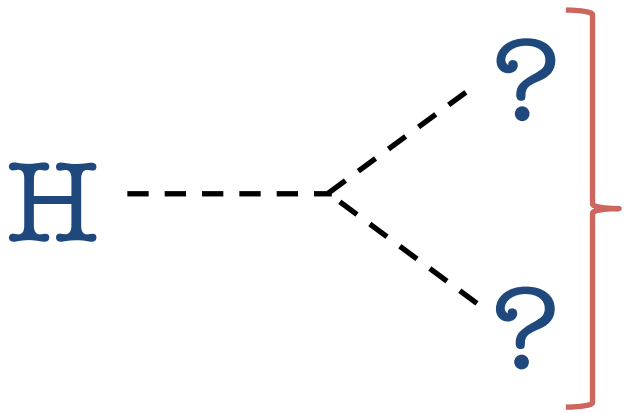
$$\lambda_h \approx 10^{-17}\ \mathrm{m}$$

$$\lambda_{10\ \mathrm{TeV}} \approx 10^{-19}\ \mathrm{m}$$

A Portal to Hidden Worlds...

Dark matter is uncharged, suggesting there are other hidden sectors beyond the Standard Model...

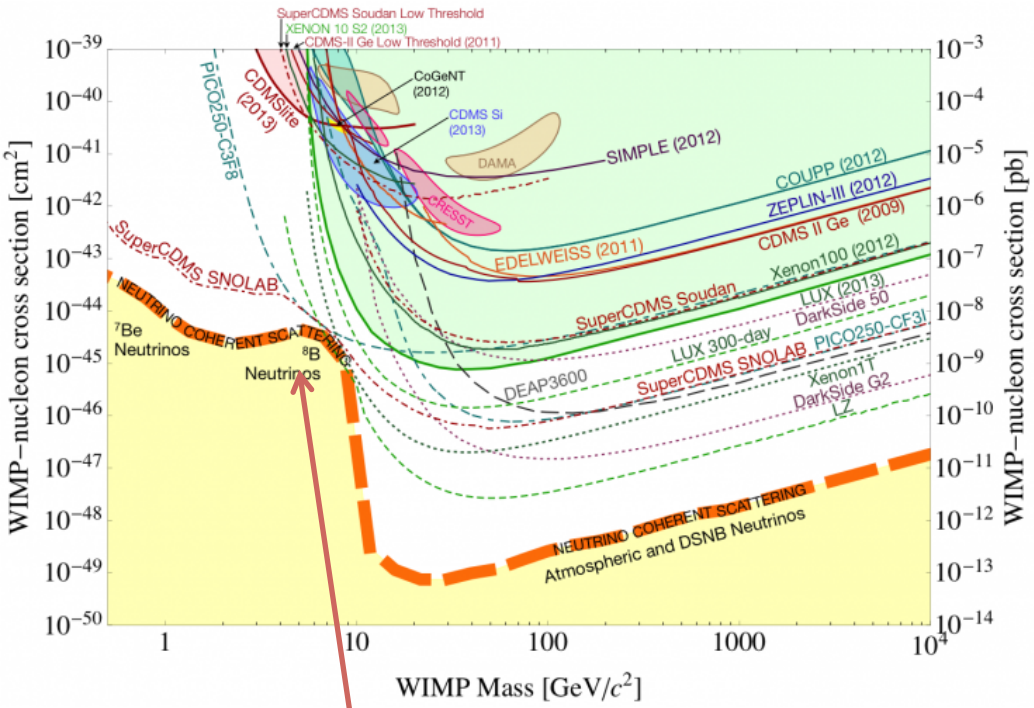
The Higgs boson is uncharged and carries no spin, so can interact readily with such hidden sectors



We don't know what's out there, but there is something, and the Higgs is a great place to look.

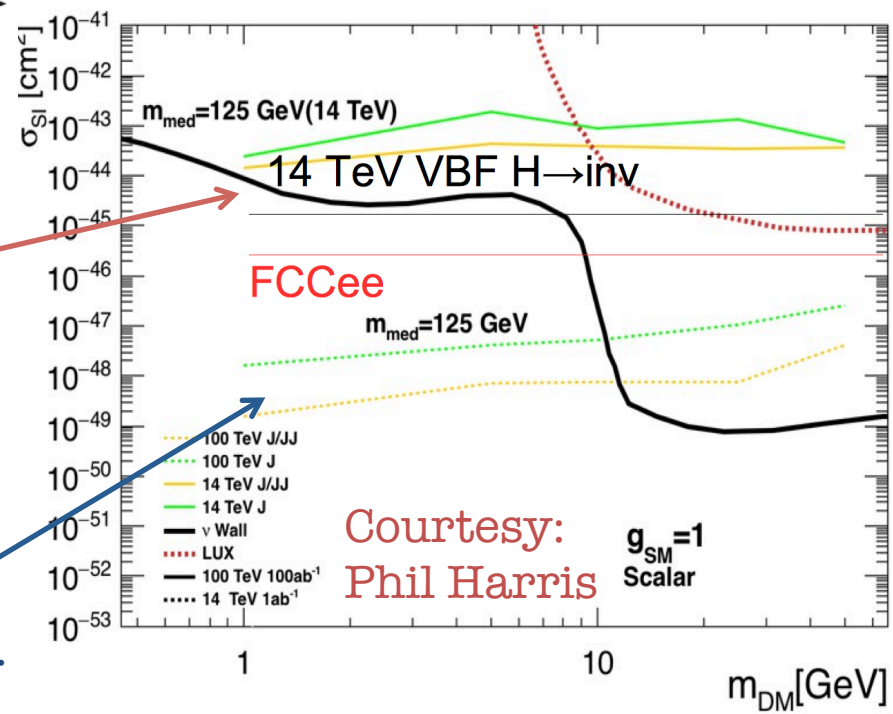
Even if generated at high energies, interactions remain relevant. Hence the term "Higgs Portal".

A Portal to Hidden Worlds...



FCC-hh Missing Energy searches, for example for decays of the Higgs to dark sector states, will hit the per-mille branching ratio level!

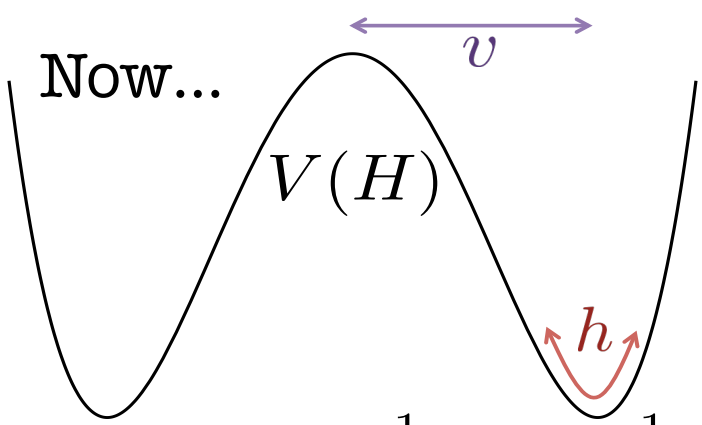
The laboratory search for dark matter will hit a difficult background, called the "neutrino floor".



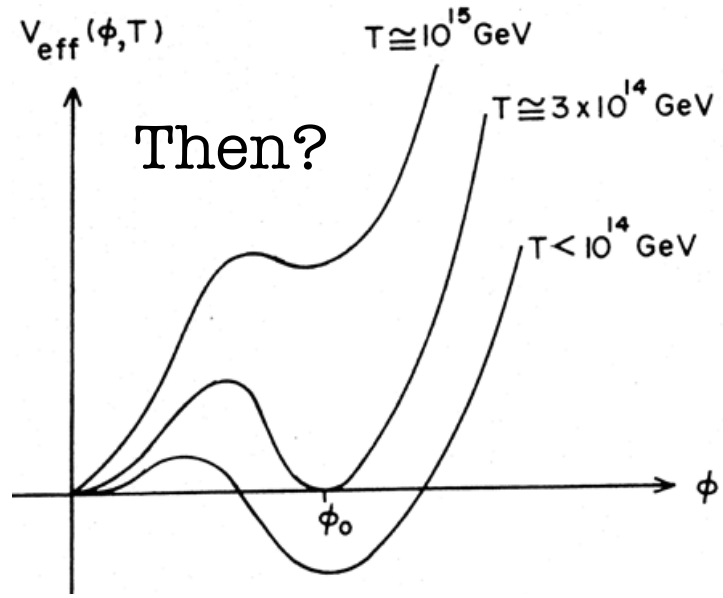
May not be a good thermal DM candidate...

The Dynamics of EWSB

How did the electroweak phase transition occur in the primordial Universe?



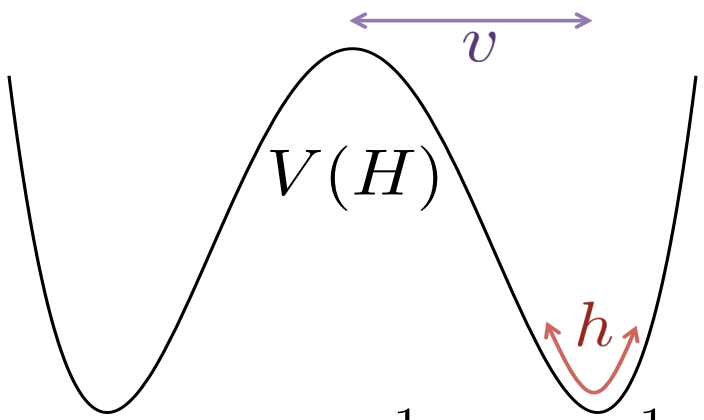
$$\underbrace{\frac{1}{2}m_h^2 h^2}_{\text{Mass}} + \underbrace{\frac{1}{6}\lambda h^3}_{\text{Self Interaction}} + \ldots$$

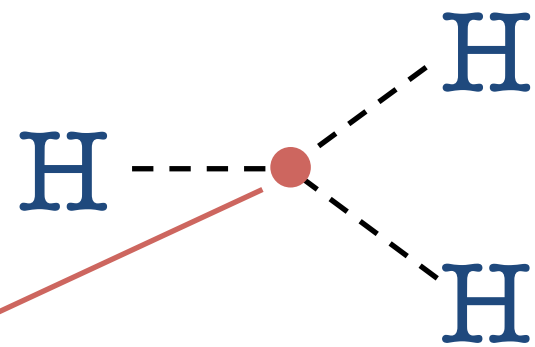


This answer has important consequences...

The Higgs Potential...

Measuring the Higgs self-coupling is the only way to measure the structure of the Higgs potential.



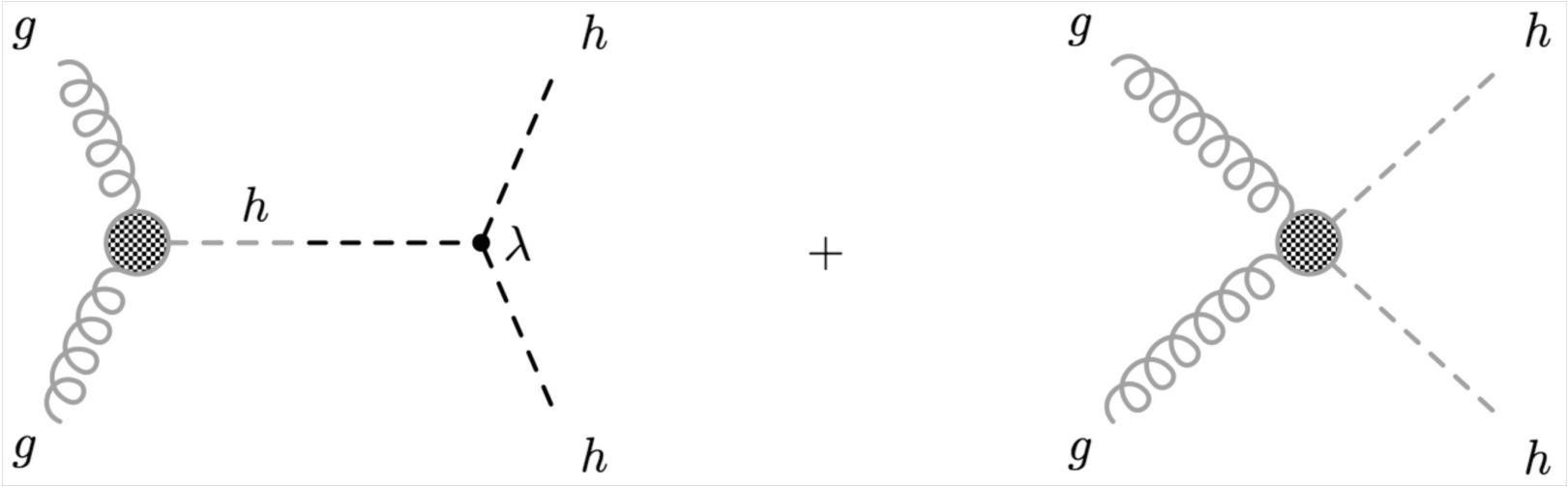


$$\underbrace{\frac{1}{2}m_h^2 h^2}_{\text{Mass}} + \underbrace{\frac{1}{6}\lambda h^3}_{\text{Self Interaction}} + \ldots$$

Discovering the Higgs was difficult enough, now we want to know how it behaves in private...

The Higgs Potential...

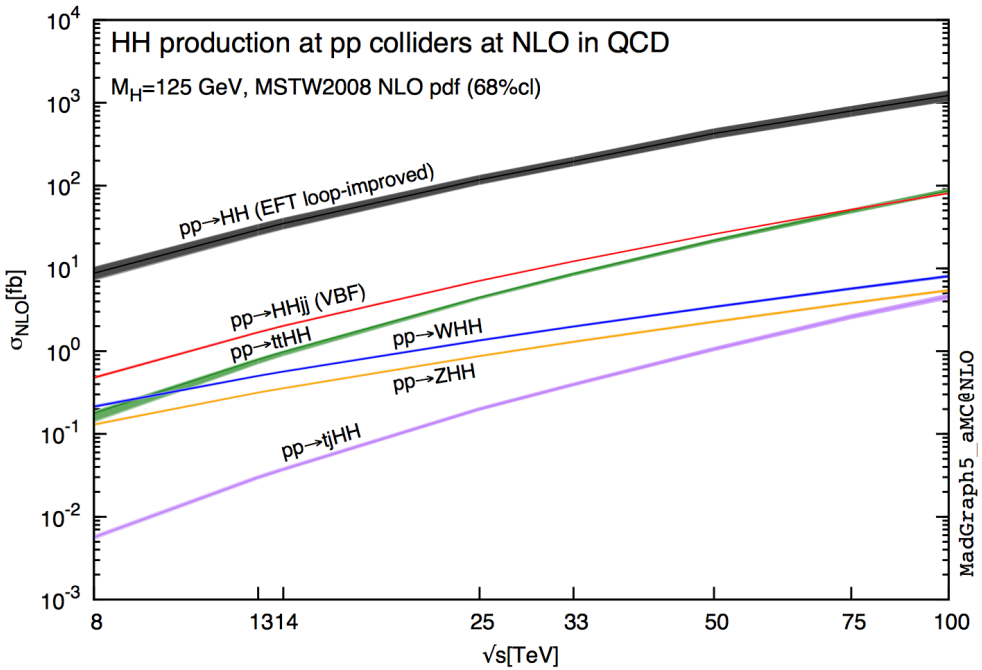
At FCC-hh gain sensitivity to self-interactions by searching for pair production:



There are many decay channels to consider, however most promising is:

$$hh \to b\bar{b}\gamma\gamma$$

The Higgs Potential...



Compared to the LHC, pair production cross section grows by a factor of 40. Note that this is a much greater increase than in CM energy...

From FCC Report

process	precision on σ_{SM}	68% CL interval on Higgs self-couplings
$HH \to b\bar{b}\gamma\gamma$	3%	$\lambda_3 \in [0.97, 1.03]$
$HH \to b\bar{b}b\bar{b}$	5%	$\lambda_3 \in [0.9, 1.5]$
$HH \to b\bar{b}4\ell$	$O(25\%)$	$\lambda_3 \in [0.6, 1.4]$
$HH \to b\bar{b}\ell^+\ell^-$	$O(15\%)$	$\lambda_3 \in [0.8, 1.2]$
$HH \to b\bar{b}\ell^+\ell^-\gamma$	–	–
$HHH \to b\bar{b}b\bar{b}\gamma\gamma$	$O(100\%)$	$\lambda_4 \in [-4, +16]$

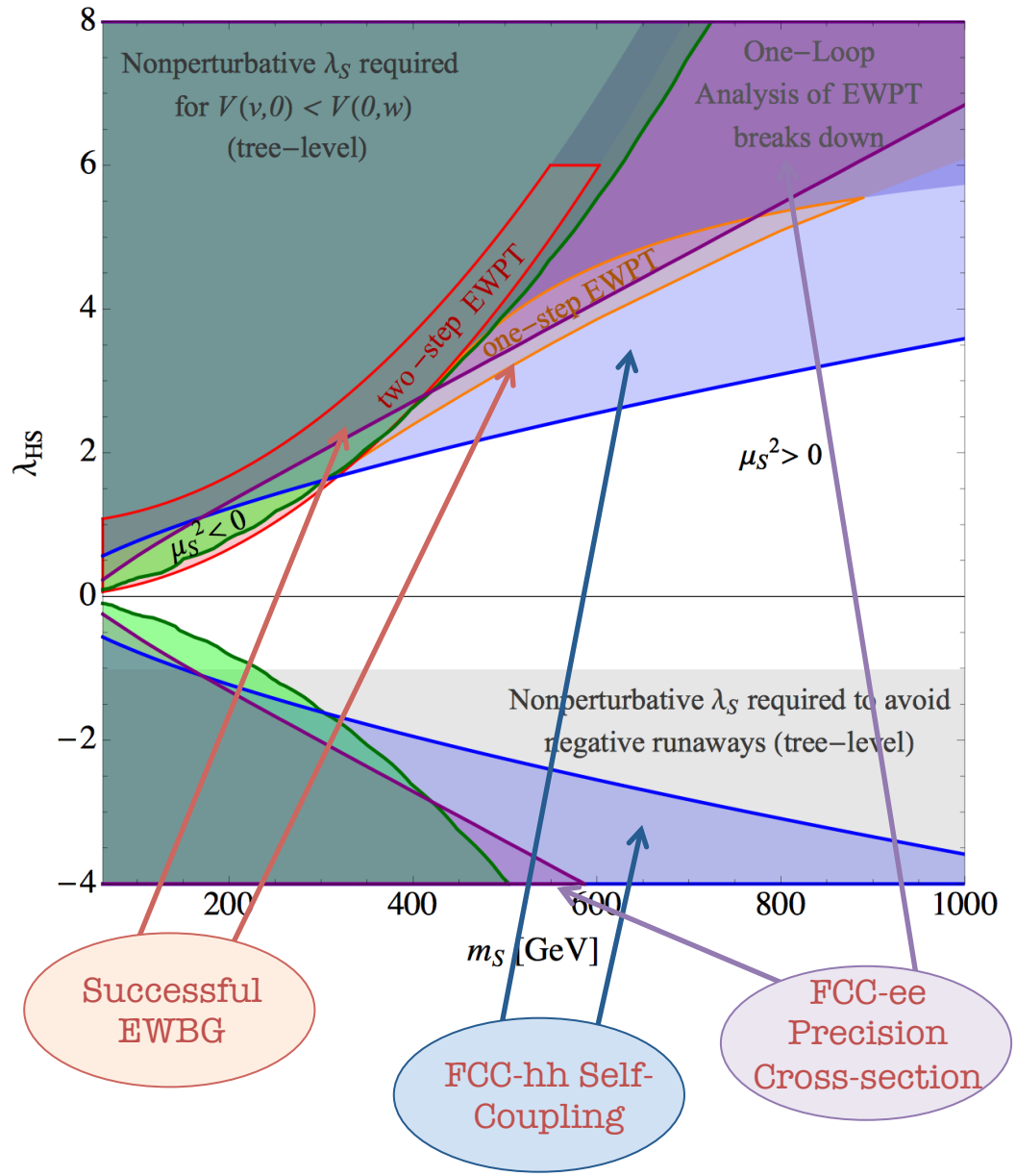
Huge increase in event numbers translates directly to a precise measurement of the nature of the Higgs potential!

The origins of matter...

The matter-antimatter imbalance can be generated during the primordial electroweak phase-transition.

This needs to be strongly first-order. SM does not work, however scenarios modifying the Higgs potential, through the influence of new particles, can.

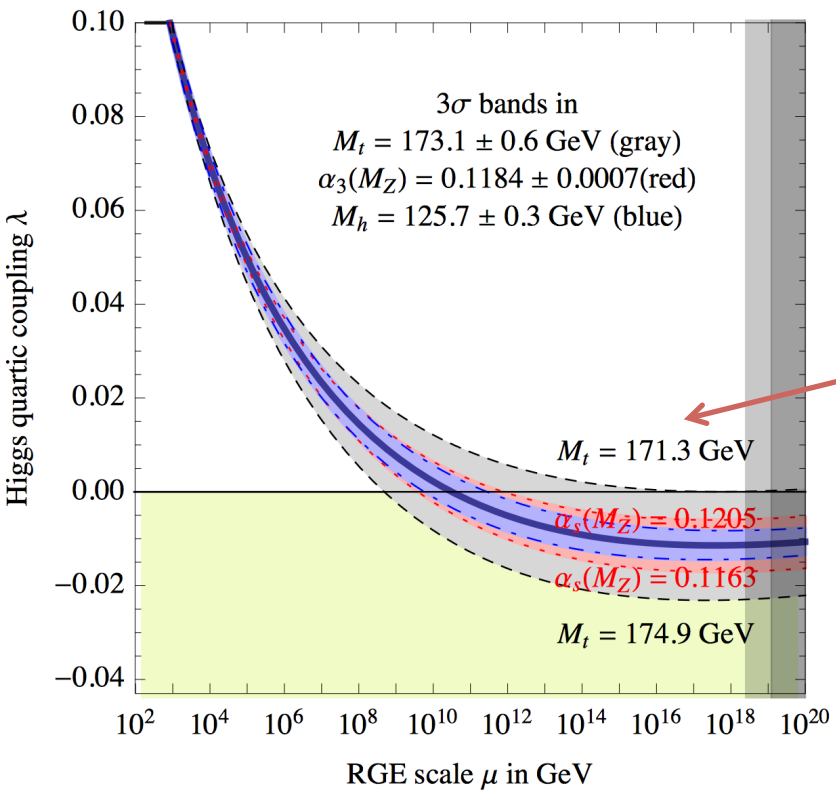
The "Nightmare scenario": A gauge singlet scalar, is the most difficult to discover.

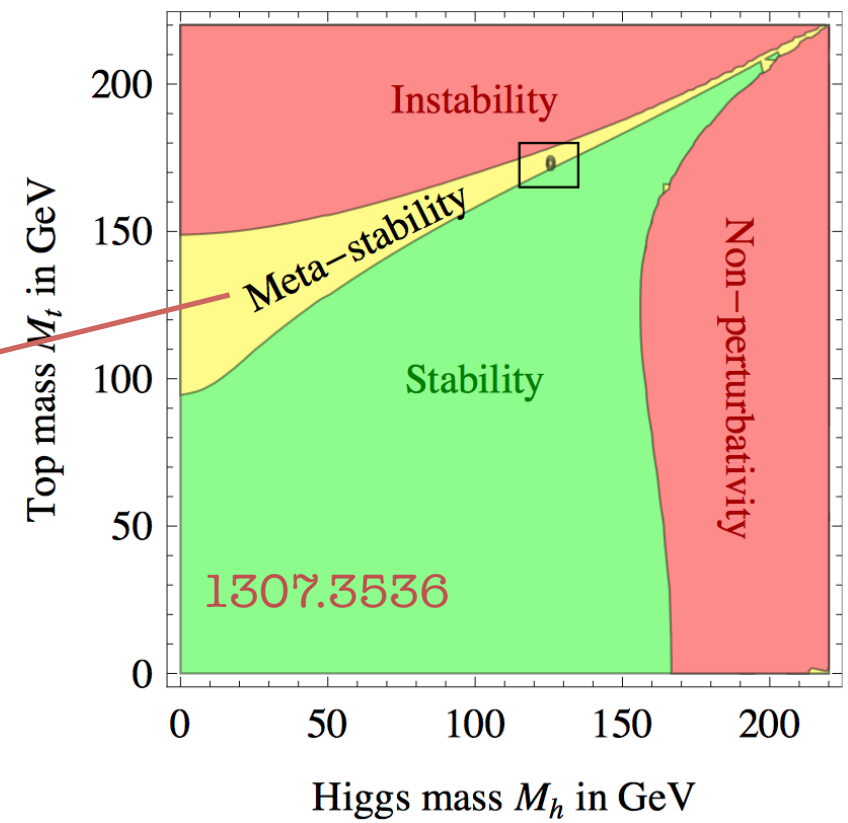


This plot assumes 10% accuracy.

The fate of the Universe...

The Higgs potential has another minimum...





If any evidence emerges for modifications of Higgs sector, huge consequences for our future...

Comment...

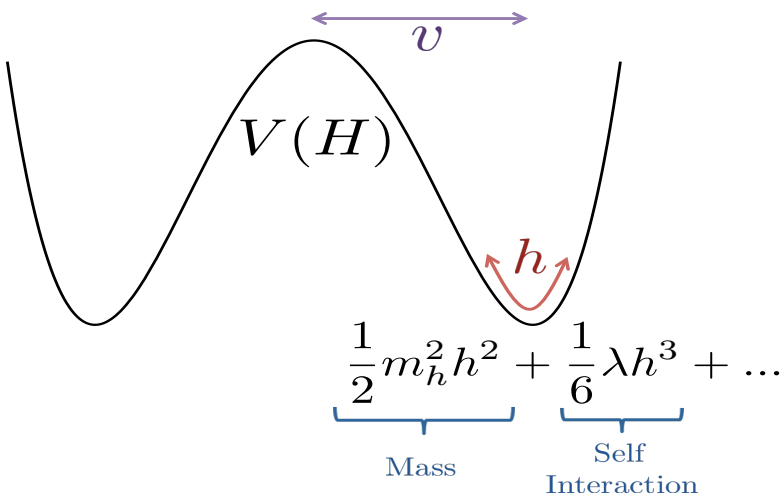
We got the symmetries: LEP.

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_{\mathrm{EM}}$$

Then we got the mechanism: LHC.

$$\langle H \rangle = v + h$$

Now it's time to get the dynamics: FCC.

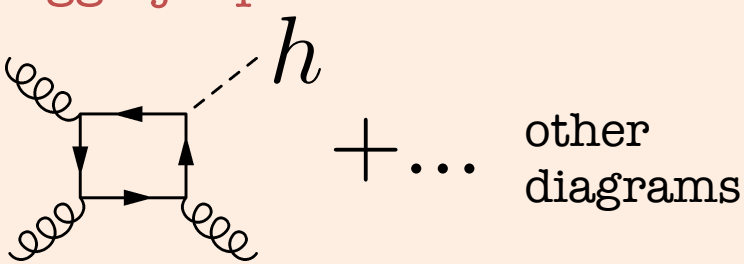


FCC-hh at Higgs Intensity frontier.

At FCC-hh TEN BILLION Higgs bosons produced. Allowing to study extremely rare behaviour.

Higgs Production

Higgs+jet production

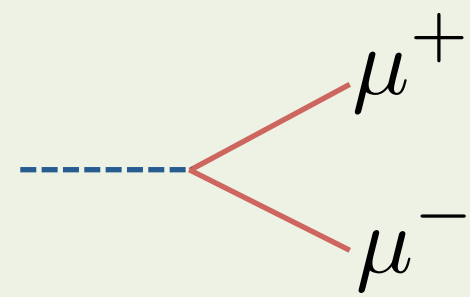


Would occur at Higgs p_T's as large as 7 TeV!

This is 56 times the mass, in other words, speed of 0.9998c.

Higgs Decays

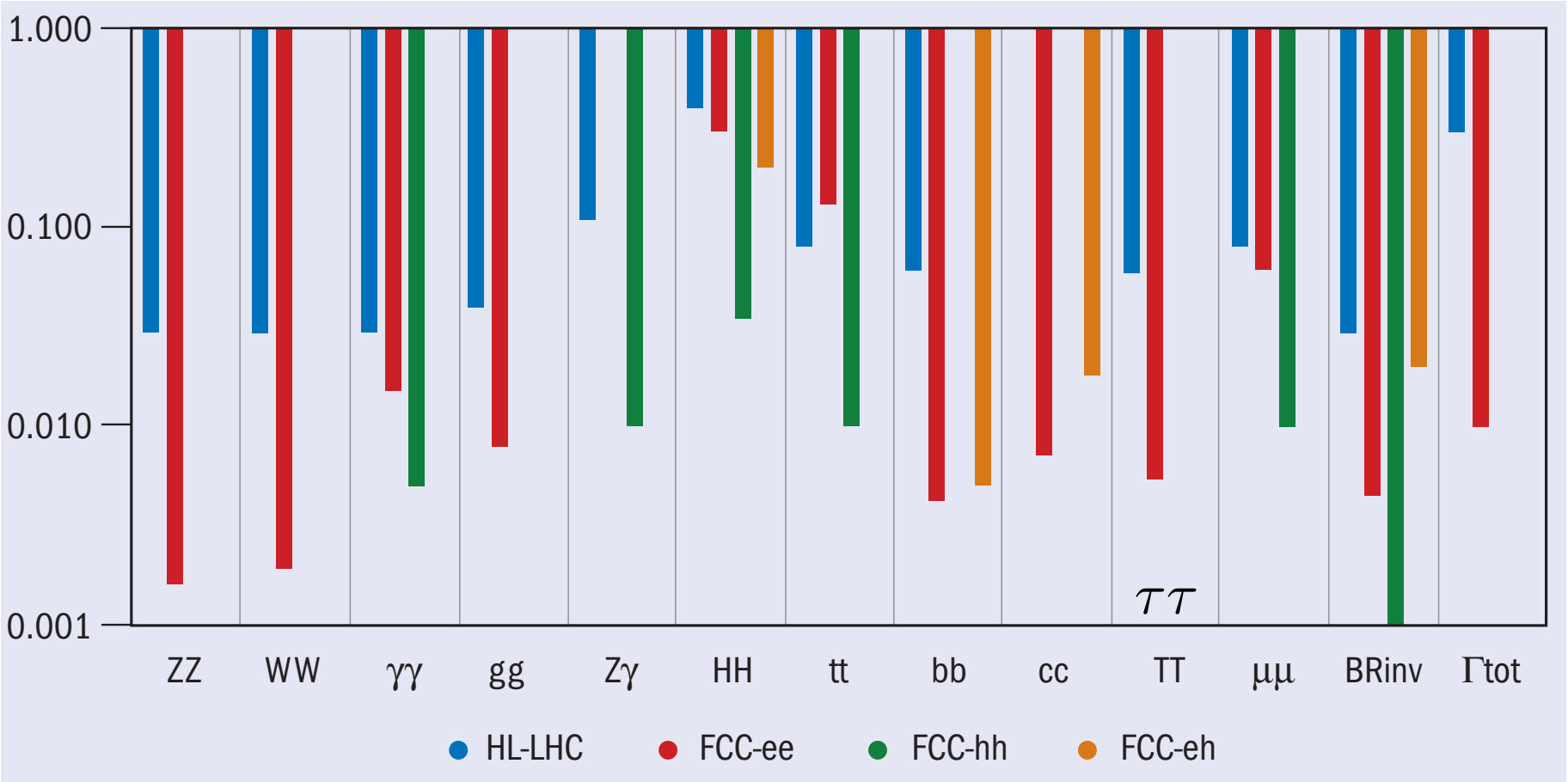
Higgs coupling to <u>muons</u>



Would be measured to 1%. The interaction strength to Higgs is $\lambda_\mu \approx 6 \times 10^{-4}$

Higgs at FCC.

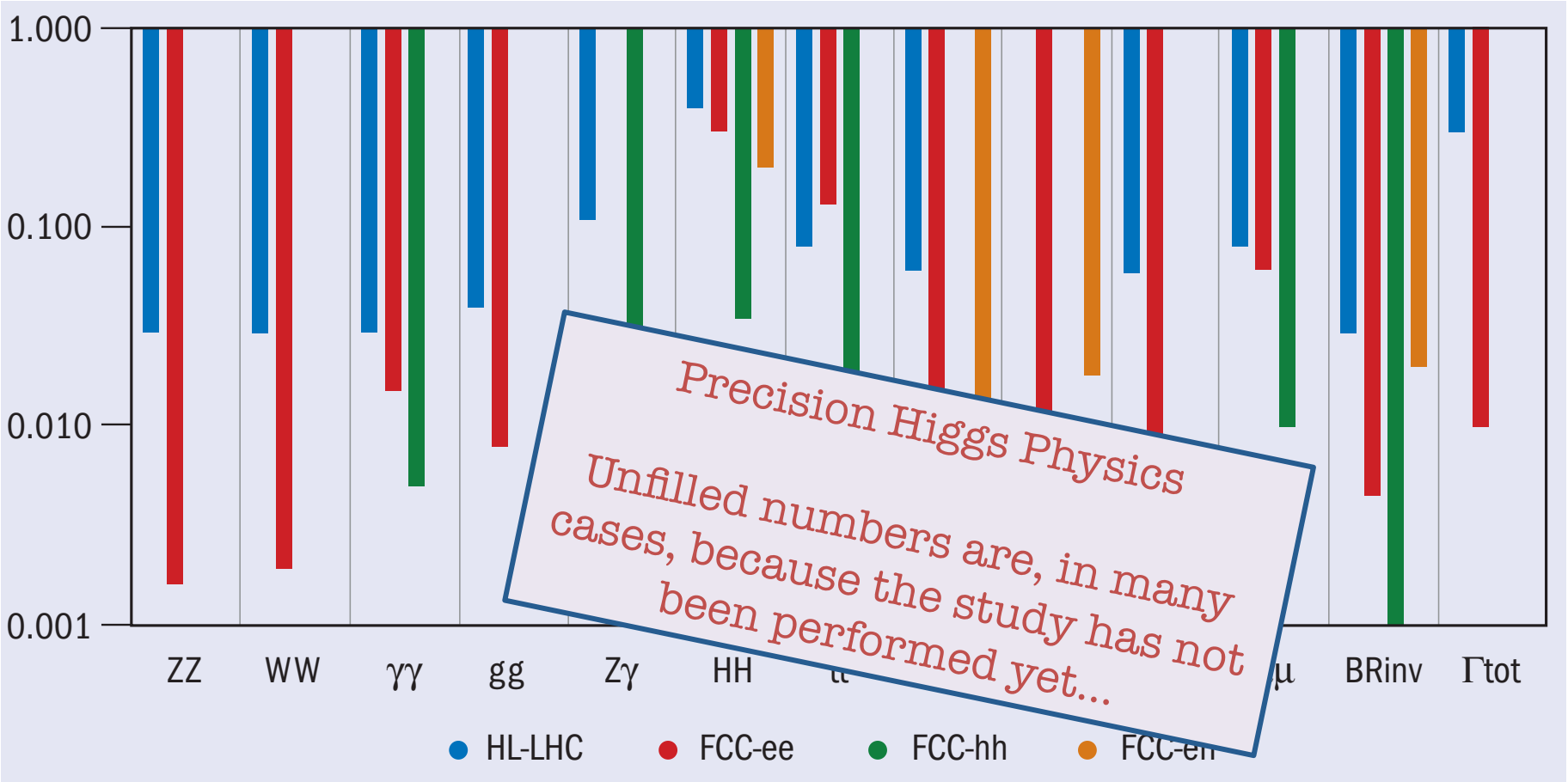
To summarise the Higgs programme...



Note that y-axis is logarithmic!

Higgs at FCC.

To summarise the Higgs programme...



Precision Higgs Physics

Unfilled numbers are, in many cases, because the study has not been performed yet...

Note that y-axis is logarithmic!

Where do we need to go?

Higgs! Higgs! Higgs!

- The Higgs is completely unique. We must strive to understand every aspect of it.

Dark Matter!

- We <u>have no idea</u> what 80% of the matter in nature is. We have to change this.

Dark Matters

Evidence for dark matter is now overwhelming

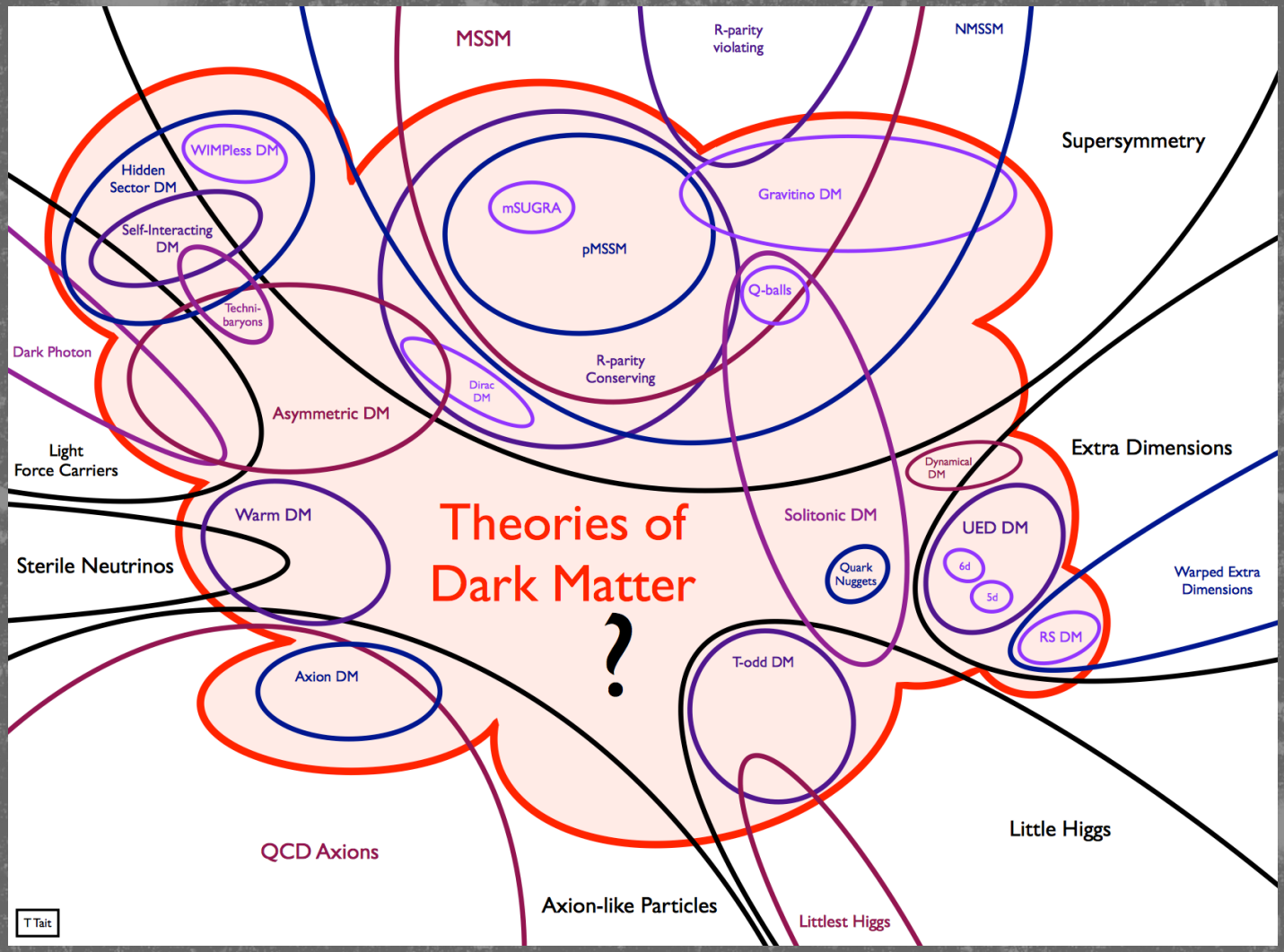
- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

Yet we have no clue what it is at the particle level!

?

Dark Matters

But there are some ideas...



Stolen from slides of Tim Tait

Dark Matter at 100 TeV

Despite overwhelming evidence for its existence, the particle nature of dark matter is unknown.

Cosmology provides a strong motivation for direct and collider searches...

- Thermal freeze-out predicts observed abundance for:

$$M_{DM} \sim \mathcal{O}(\text{few GeV}) \rightarrow \mathcal{O}(10\text{'s TeV})$$

Cosmological constraints

Unitarity bounds

Motivates dark matter searches in ballpark of 100 TeV collider <u>independent</u> of hierarchy problem.

Simplified Dark Matter Models

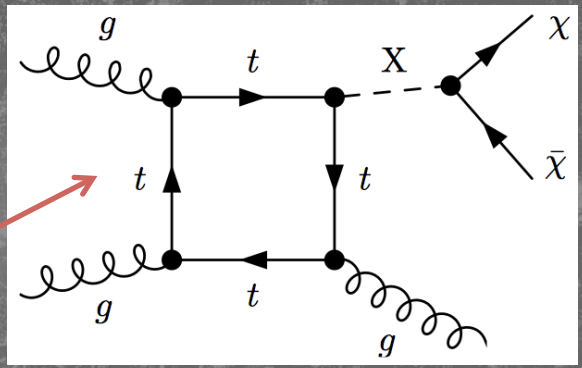
Write down simple scenarios to model production of dark matter at colliders:

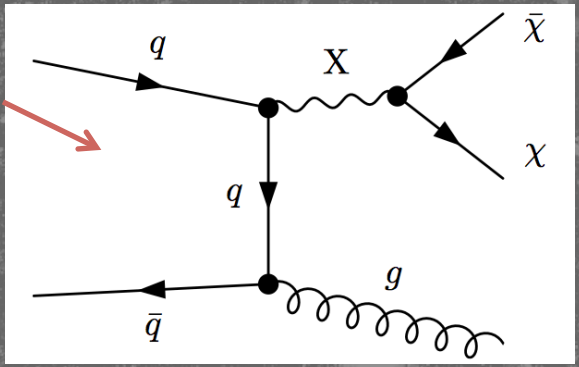
$$\mathcal{L}_{\mathrm{S}} \supset -\sum_q c_S \lambda_{h,q} S\, \bar{q}q - \frac{1}{2} m_{\mathrm{MED}}^2 S^2 + \mathcal{L}(S, \bar{\chi}, \chi)\,,$$

$$\mathcal{L}_{\mathrm{P}} \supset -\sum_q i c_P \lambda_{h,q} P\, \bar{q}\gamma^5 q - \frac{1}{2} m_{\mathrm{MED}}^2 P^2 + \mathcal{L}(P, \bar{\chi}, \chi)\,,$$

$$\mathcal{L}_{\mathrm{V}} \supset -\sum_q c_V V_\mu \bar{q}\gamma^\mu q - \frac{1}{2} m_{\mathrm{MED}}^2 V_\mu V^\mu + \mathcal{L}(V, \bar{\chi}, \chi)\,,$$

$$\mathcal{L}_{\mathrm{A}} \supset -\sum_q c_A A_\mu \bar{q}\gamma^\mu\gamma^5 q - \frac{1}{2} m_{\mathrm{MED}}^2 A_\mu A^\mu + \mathcal{L}(A, \bar{\chi}, \chi)\,,$$



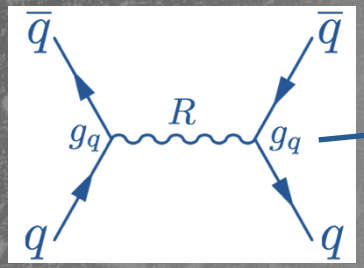


100 TeV Study: Harris, Khoze, Spannowsky, Williams, 2015.

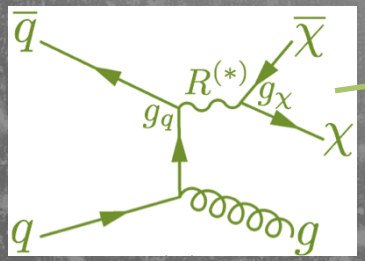
FCC-hh: Resonances and Dark Matter

Consider a scenario where dark matter interacts via a new Z' boson:

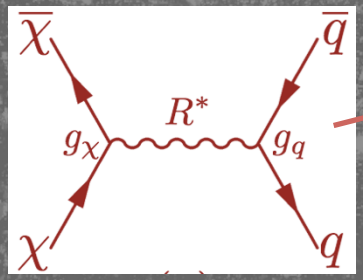
Dijet Resonances

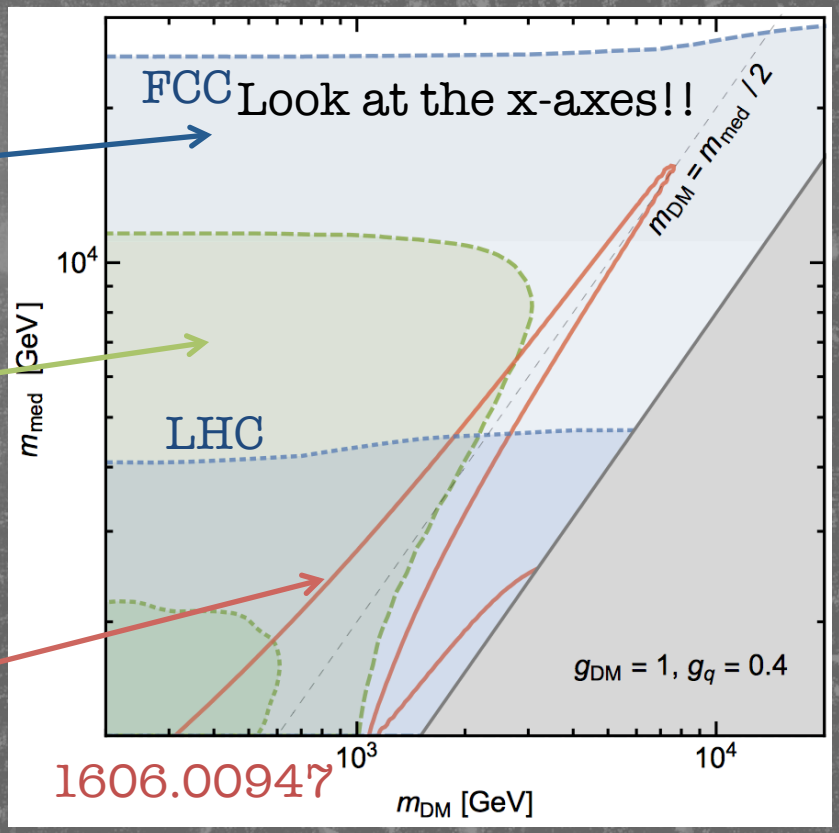


Missing Energy



Relic Density





1606.00947

Where do we need to go?

Higgs! Higgs! Higgs!

- The Higgs is completely unique. We must strive to understand every aspect of it.

Dark Matter!

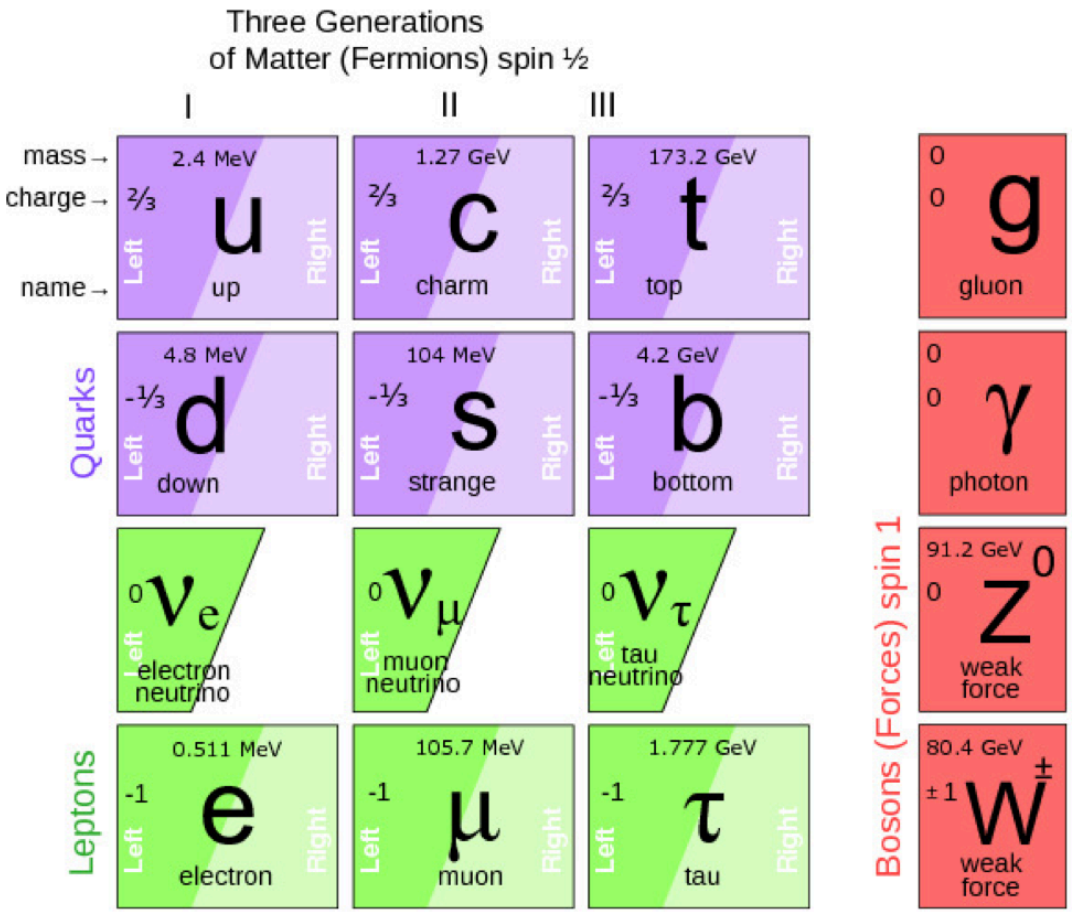
- We <u>have no idea</u> what 80% of the matter in nature is. We have to change this.

Neutrino Masses!

- The renormalisable Standard Model cannot explain this, so what is their origin?

Neutrino Masses!

Someone didn't show up to the party...



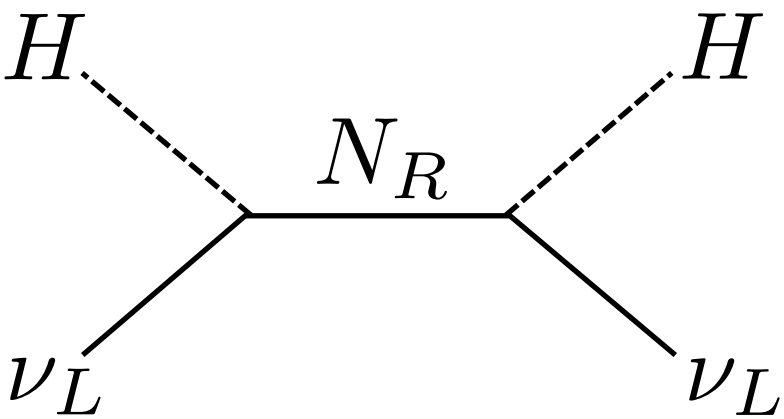
Shaposhnikov et al.

Neutrino masses might be Dirac, but then why such a small interaction with the Higgs? They are all below the eV range...

Or Majorana, but then where is the right-handed neutrino?

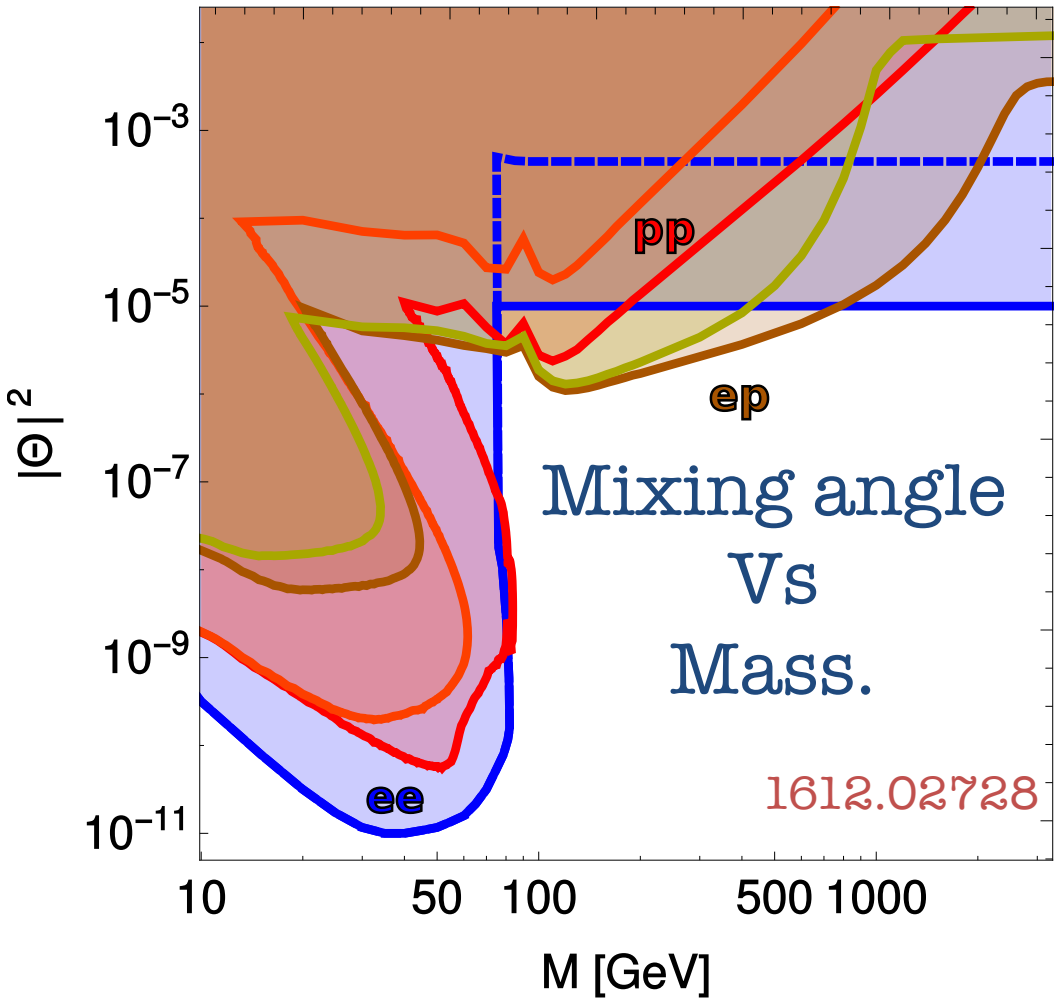
Neutrino Masses!

Neutrino masses: Long-standing puzzle in fundamental physics.



New heavy right-handed neutrinos can generate mass. Can be at collider energy scales.

FCC-eh can probe TeV frontier, FCC-ee weak-scale.



Neutrino Masses!

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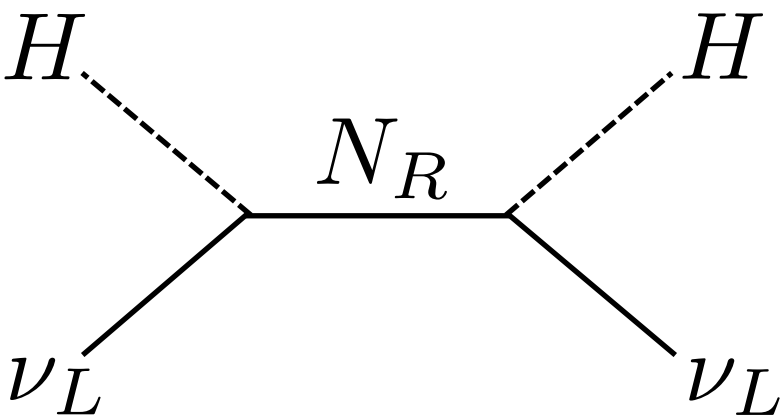
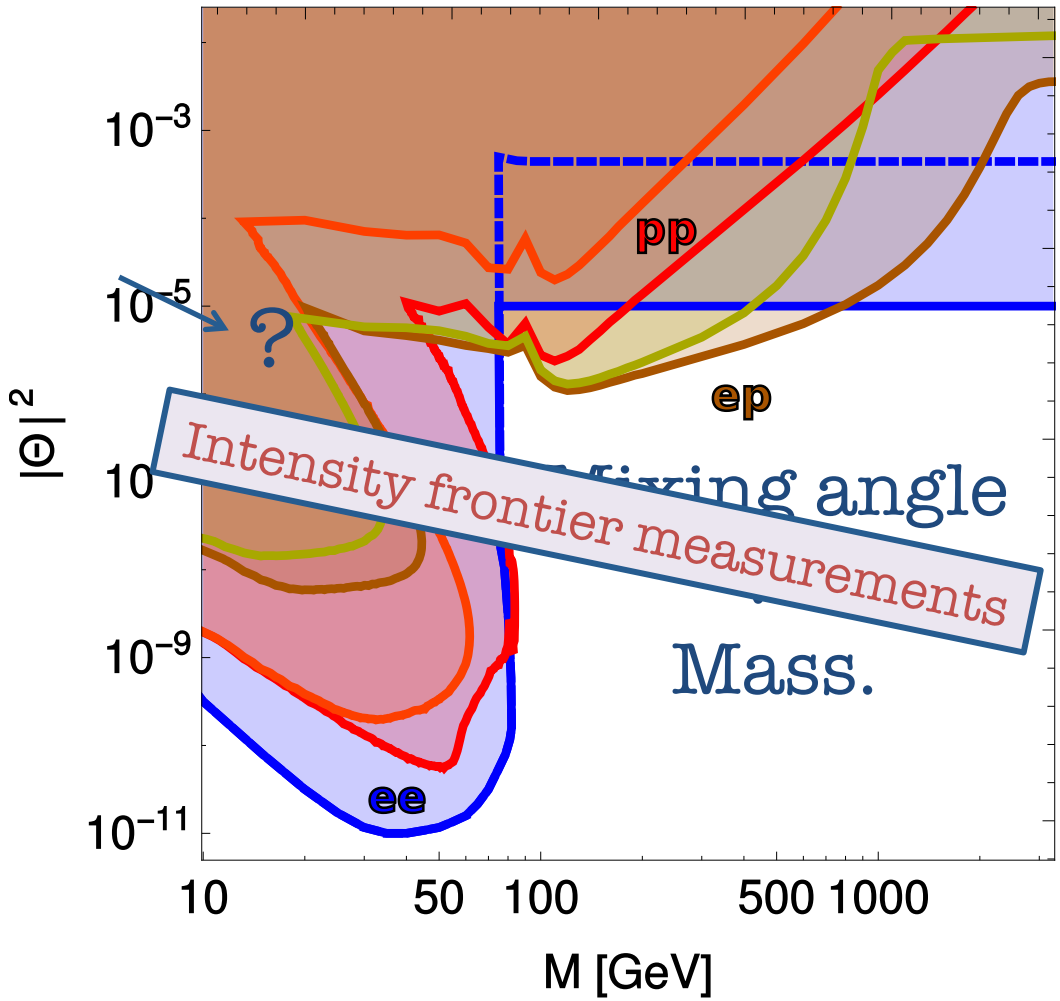




New heavy right-handed neutrinos can generate mass. Can be at collider energy scales.

FCC-eh can probe TeV frontier, FCC-ee weak-scale.

Where do we need to go?

New Particles!

- There is strong motivation for the existence of new particles in the multi-TeV range.

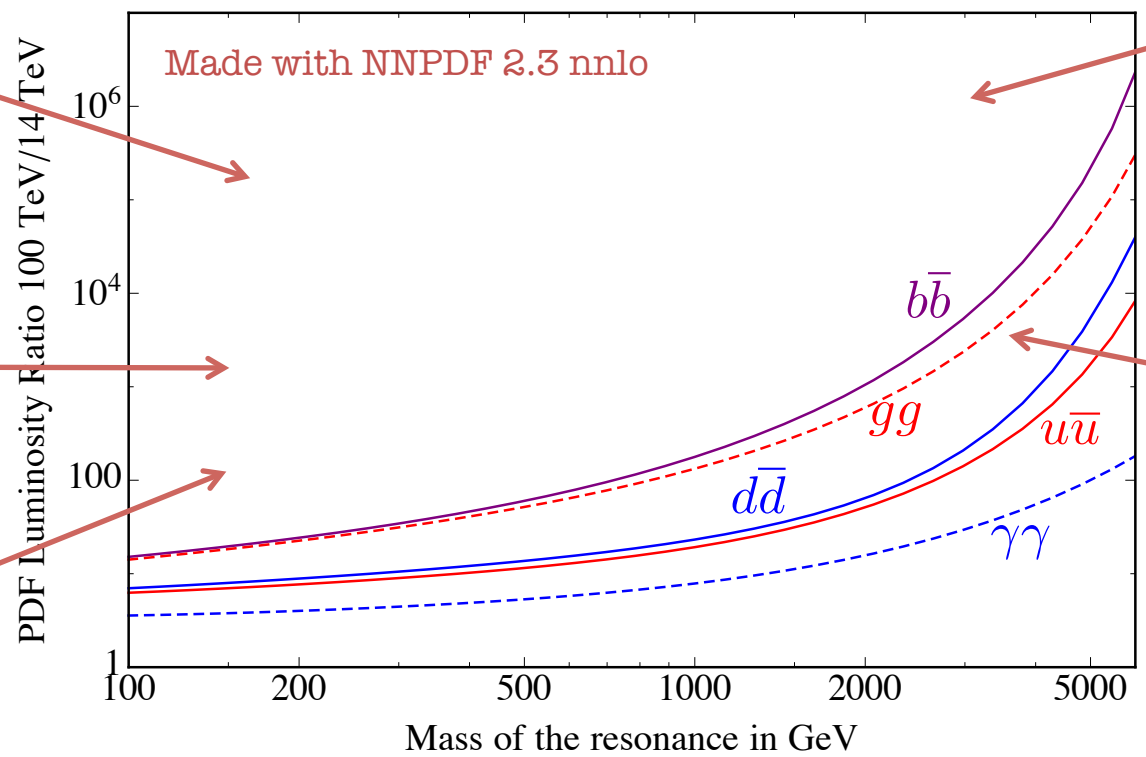
FCC-hh: General Comments

It is a very good idea to consider luminosity ratio plots. They tell us about a vast physics program if e.g. a heavy resonance is discovered...

High precision in dominant production modes.

Differential distributions.

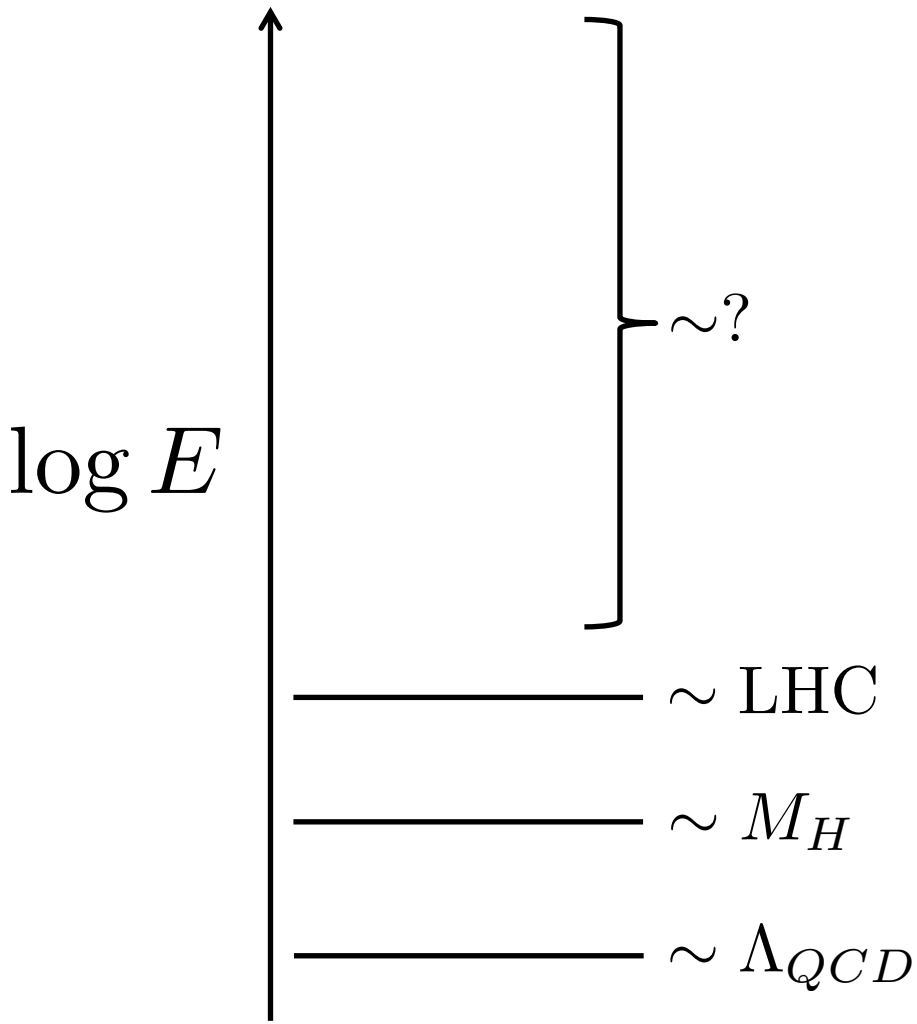
Rare/ associated production modes



Rare/ exotic decays.

For exotic signatures can take full advantage of cross section if background is small. E.g. displaced vertices.

Looking to the sky.

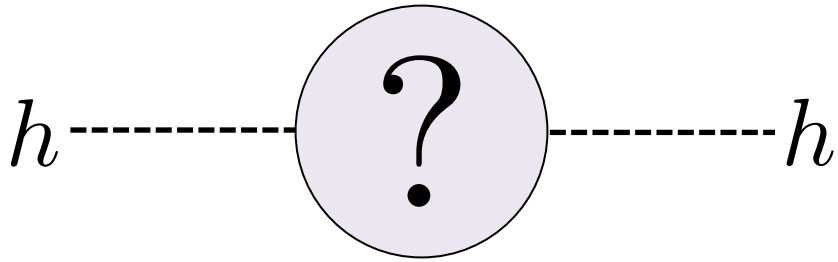


We do not know what new physics lies above, but we have hints...

- Neutrino masses?
  $$M_N \gtrsim 10^{10}\ \text{GeV}$$
- Strong CP?
  $$M_{\text{PQ}} \gtrsim 10^{10}\ \text{GeV}$$
- Unification?
  $$M_{\text{GUT}} \sim 10^{15}\ \text{GeV}$$
- Quantum gravity?
  $$M_P = 2 \times 10^{18}\ \text{GeV}$$
- Hypercharge Landau pole?
  $$M_{\Lambda_Y} \gg M_P$$

The Naturalness Paradox

This has implications at the weak scale...



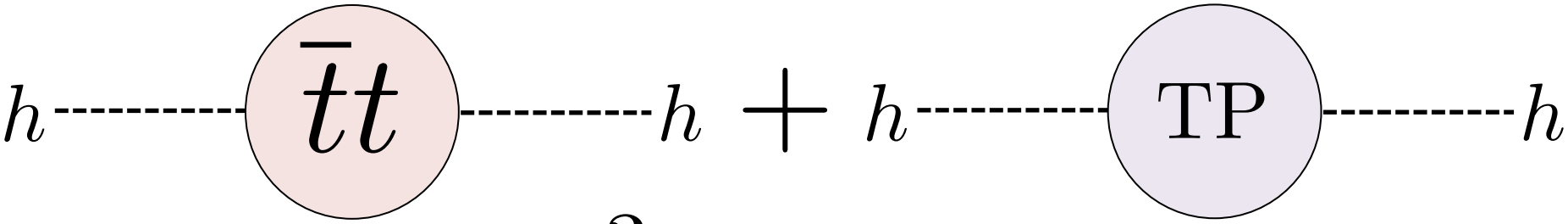
At quantum level, new physics will correct Higgs mass, pulling it up to $m_h \sim \Lambda$.

Should expect $m_H \sim \Lambda$. But I just argued $\Lambda \gg M_W$ so how can we reconcile with

$$m_h = 125 \text{ GeV } ?$$

The Naturalness Paradox

Hierarchy problem solutions typically involve a "Top Partner":



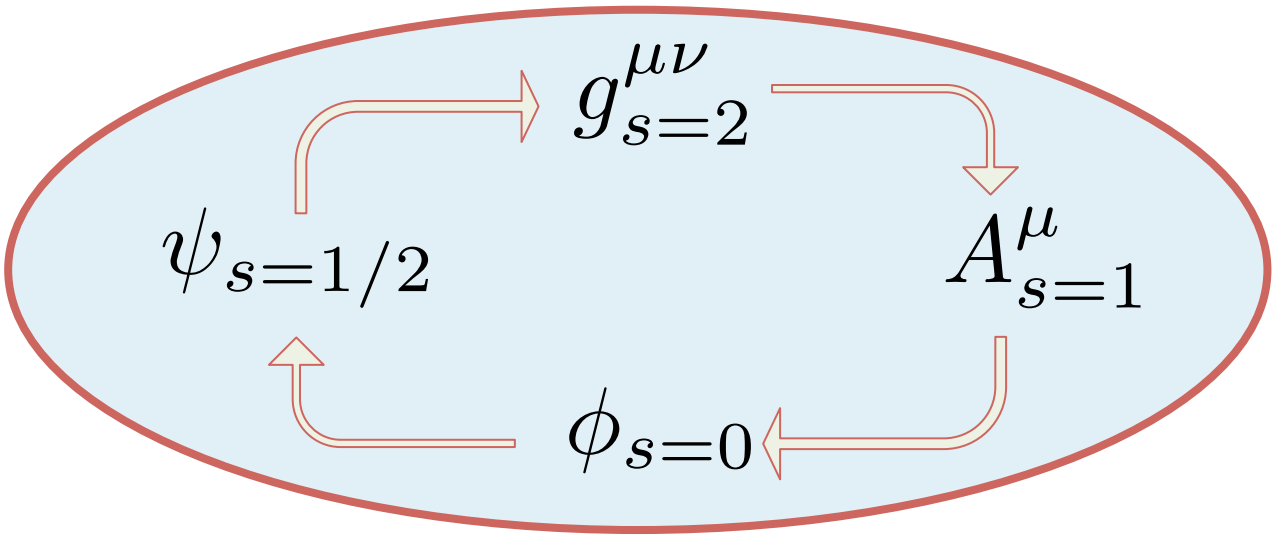
$$\approx \frac{3}{8\pi^2} m_{TP}^2 \log \Lambda$$

If top partner is near the weak scale, Higgs mass corrections logarithmically sensitive to new physics scales, hence naturally light Higgs.

For naturalness expect $m_{TP} \lesssim 400 \text{ GeV}$.

Supersymmetry

What is supersymmetry?



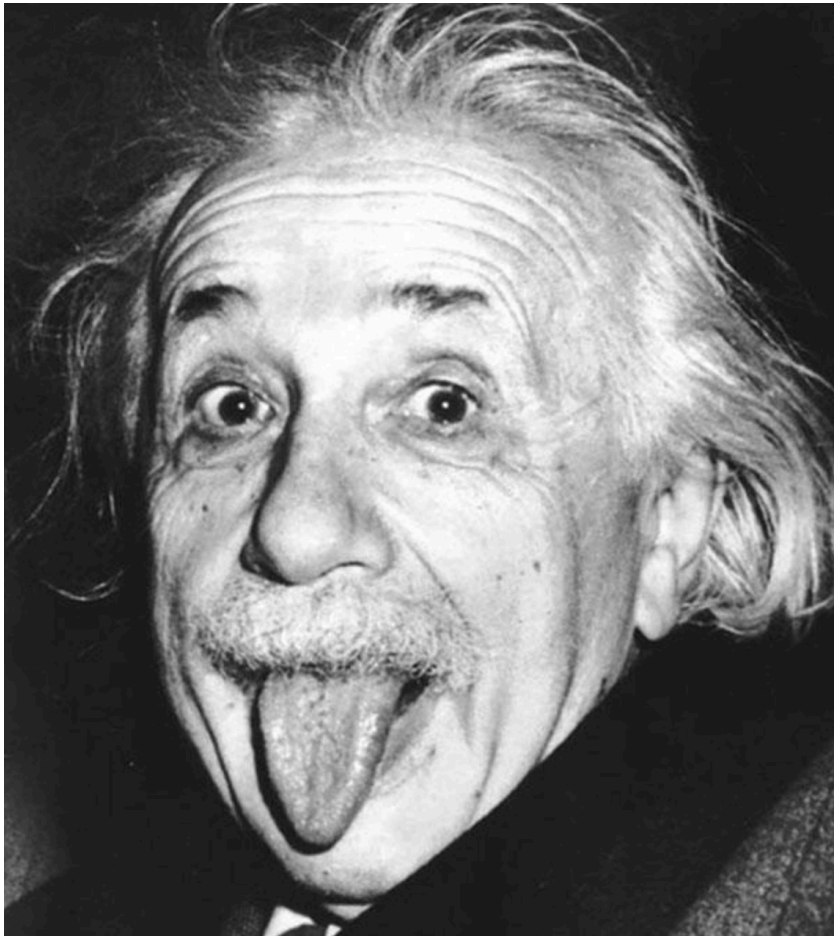
Entirely new spacetime symmetry!

Unifies fields into superfields, transforming into one another!

Also predicts... $\tilde{g}_{s=3/2}$

Supersymmetry

The last time a spacetime symmetry was discovered...

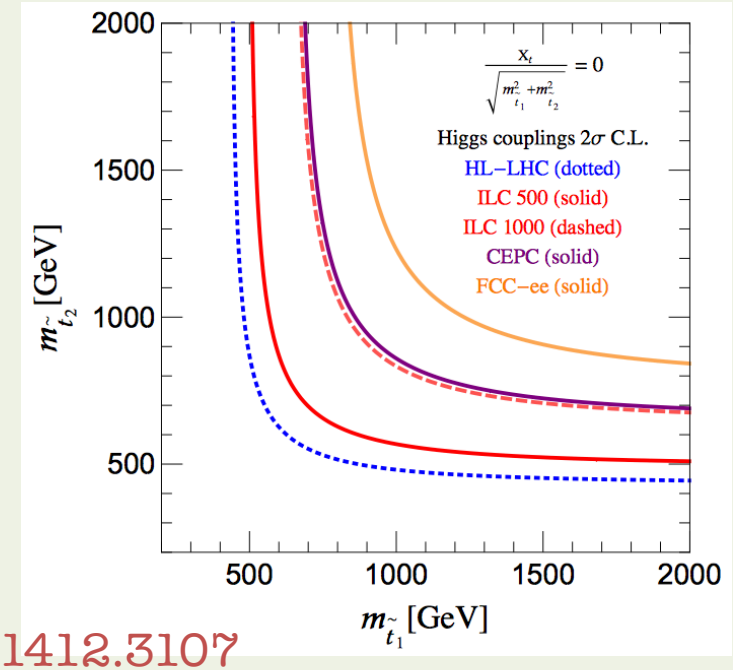


Supersymmetry

In supersymmetry top partner is “stop squark”.

FCC-ee

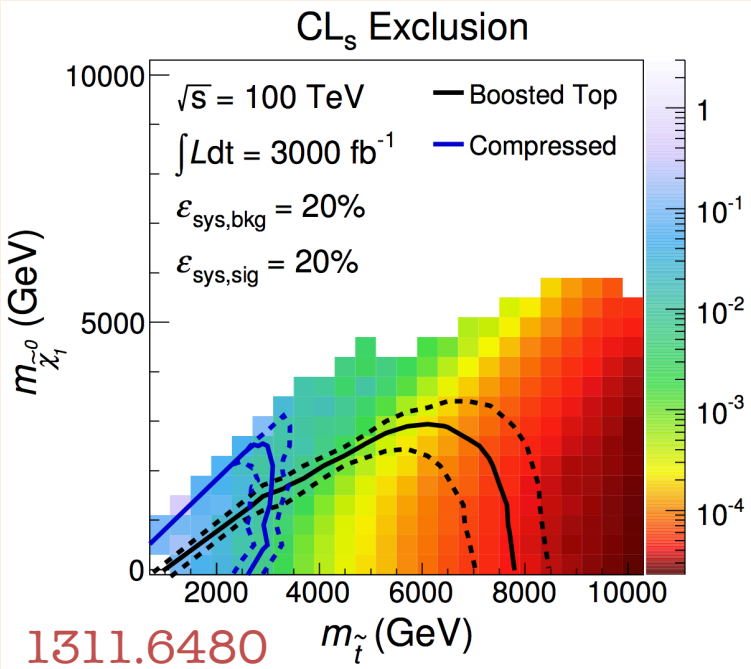
Coloured and charged, stops modify Higgs couplings:



1412.3107

FCC-hh

And show up directly at hadron colliders:

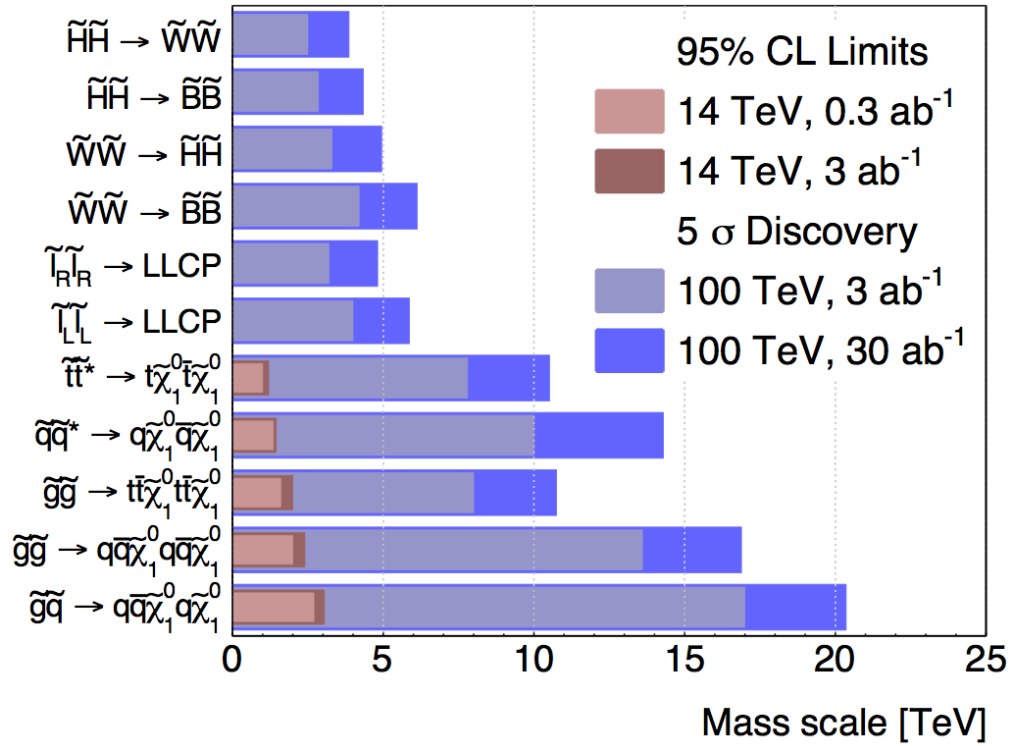


1311.6480

FCC-ee: Indirect, but more “spectrum independent”, for a model.
FCC-hh: Direct confirmation, but direct might be hidden.

Supersymmetry

Summary from FCC Report:



The paradigm of low energy supersymmetry has dominated ideas in physics beyond the Standard Model for decades. FCC-hh would provide the final word, by pushing far beyond the naturalness paradigm.

Composite Higgs Models

If the Higgs is made up of constituents

$$H = \bar{f} f \sim f$$

$$\xi \sim \frac{v^2}{f^2}$$

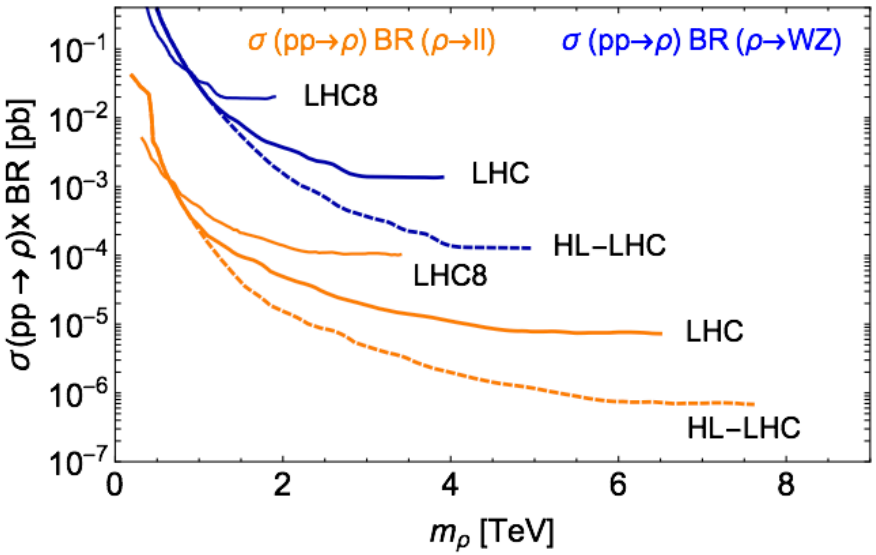
Then no hierarchy problem, since no fundamental scalar!

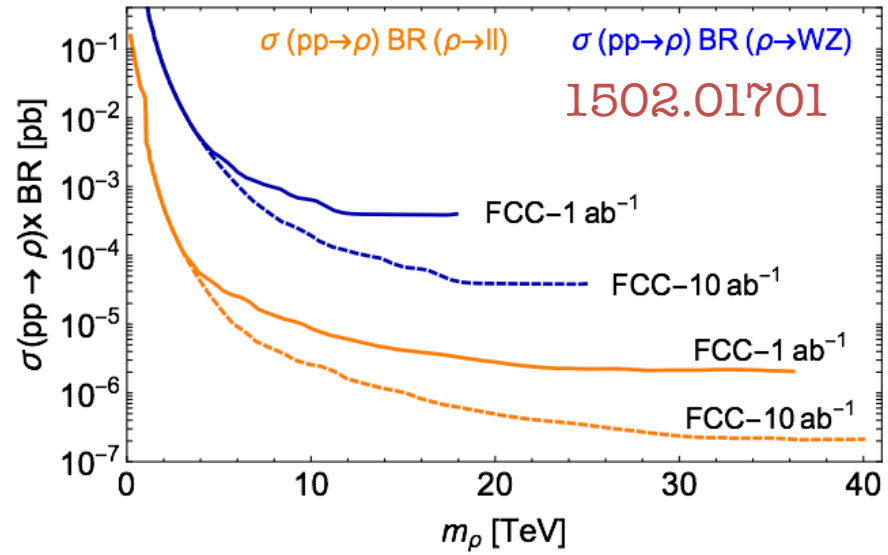
These models can be thought of as realising the Higgs boson analogously to the pion in QCD.

$$\rho = \bar{f} f \sim \Lambda$$

Should also get other heavy resonances then!

Composite Higgs Models





These models can be thought of as realising the Higgs boson analogously to the pion in QCD.

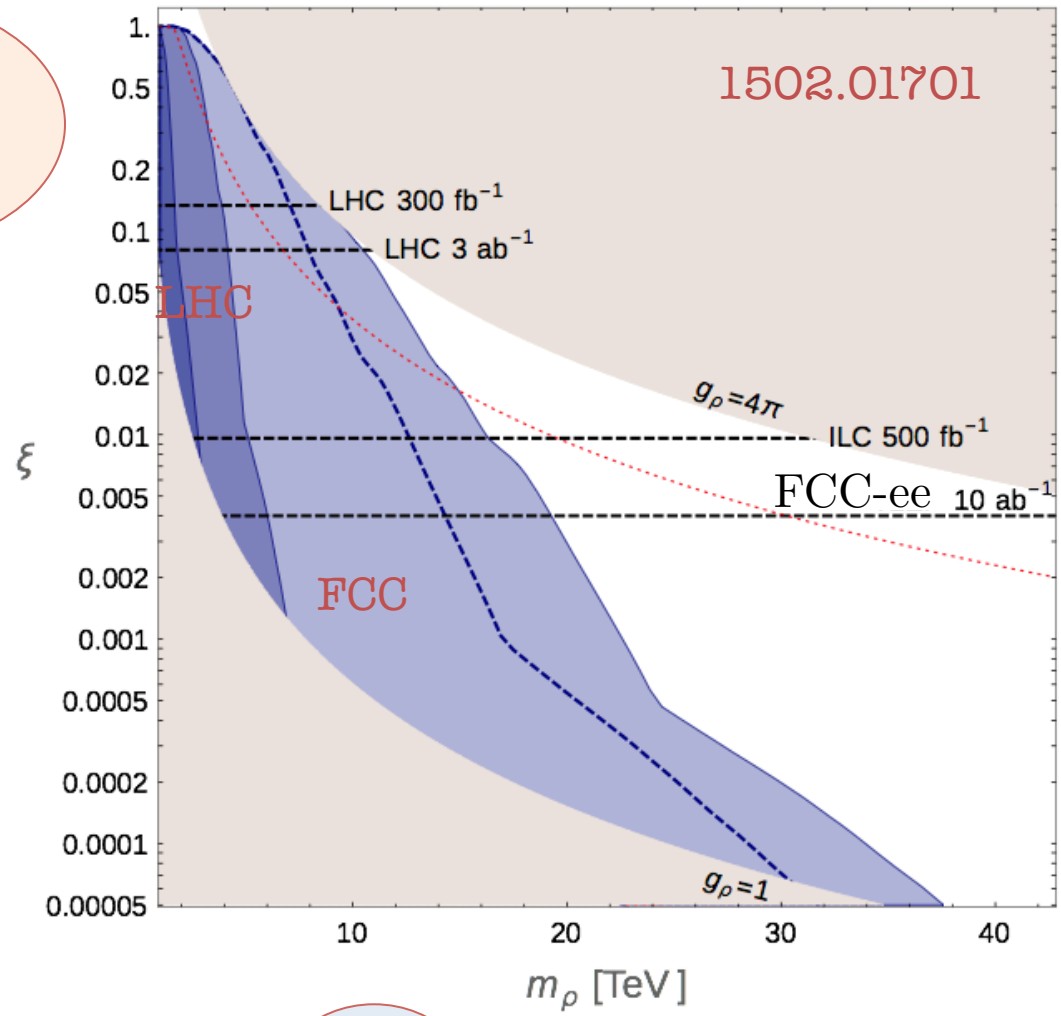
$$\rho = \bar{f} f \quad \updownarrow \quad \sim \Lambda$$

Should also get other heavy resonances then!

Composite Higgs Models

$$\xi \sim \frac{v^2}{f^2}$$

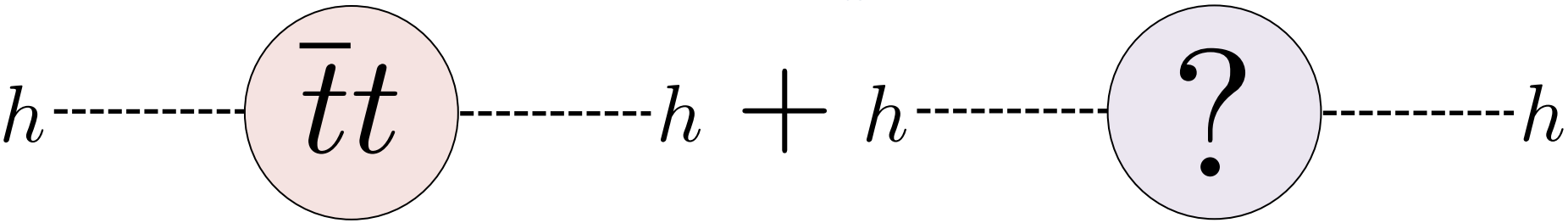
Combining precision measurements with high mass resonance searches, can fully answer the question of Higgs compositeness.



$$\rho = \overline{f} f$$

Neutral Naturalness

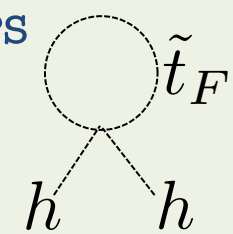
Could there be a hidden "Top Partner"?



Much attention now to alternative ideas:

Folded SUSY hep-ph/0609152

Theory where EW-charged uncoloured scalars are top partners

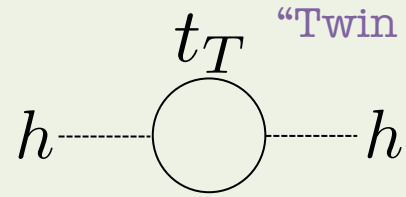


"Folded Stops"

...but they must be charged under new hidden QCD'.

Twin Higgs hep-ph/0506256

Theory where top partners are SM gauge neutral fermions



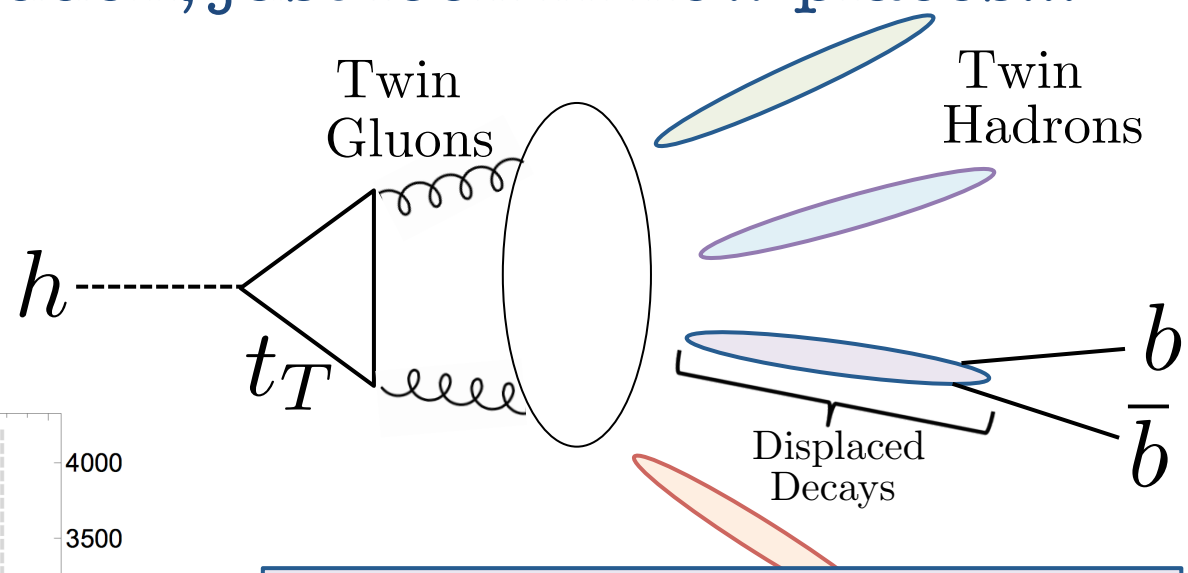
"Twin Tops"

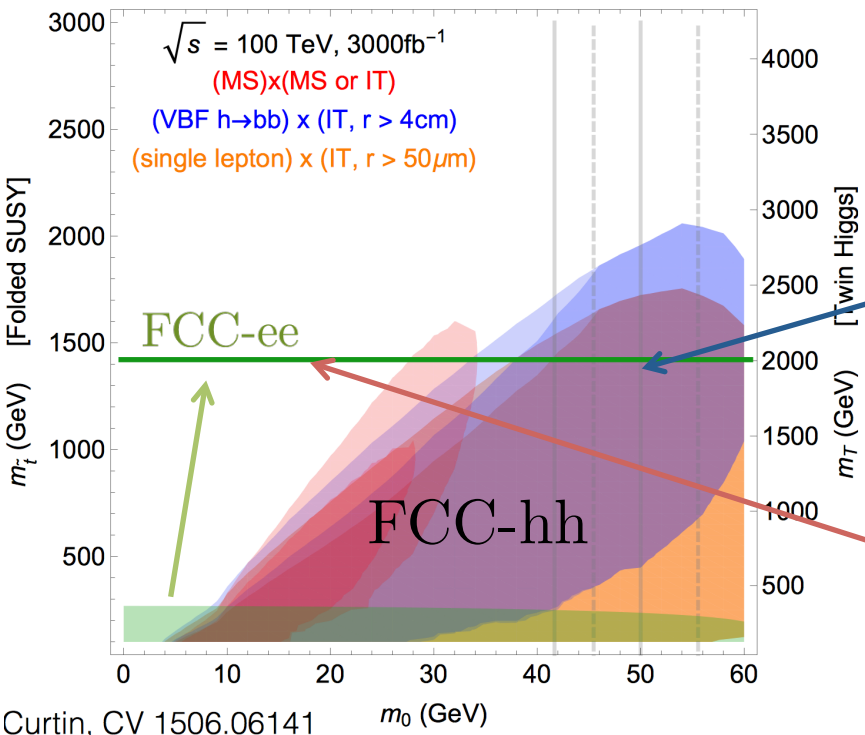
...but they must be charged under new hidden QCD'.

Neutral Naturalness

Naturalness not hidden, just look in new places...

New hidden sector introduces exotic Higgs decays:





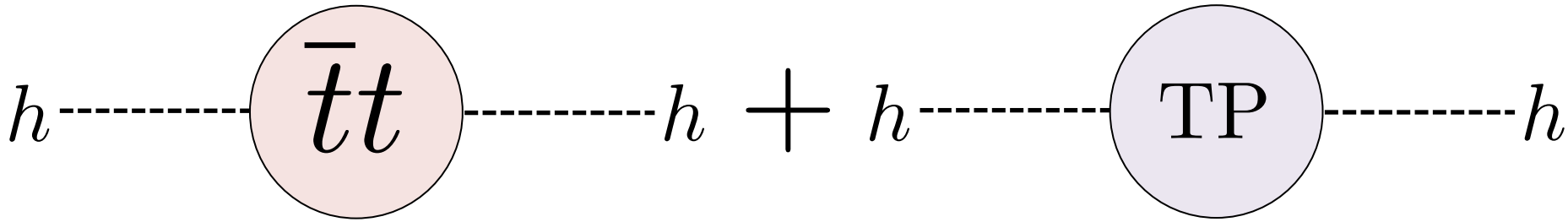
Curtin, CV 1506.06141

FCC-hh can thoroughly probe larger Twin scales through displaced searches.

FCC-ee has access for light top partners, including for well-motivated low confinement scales.

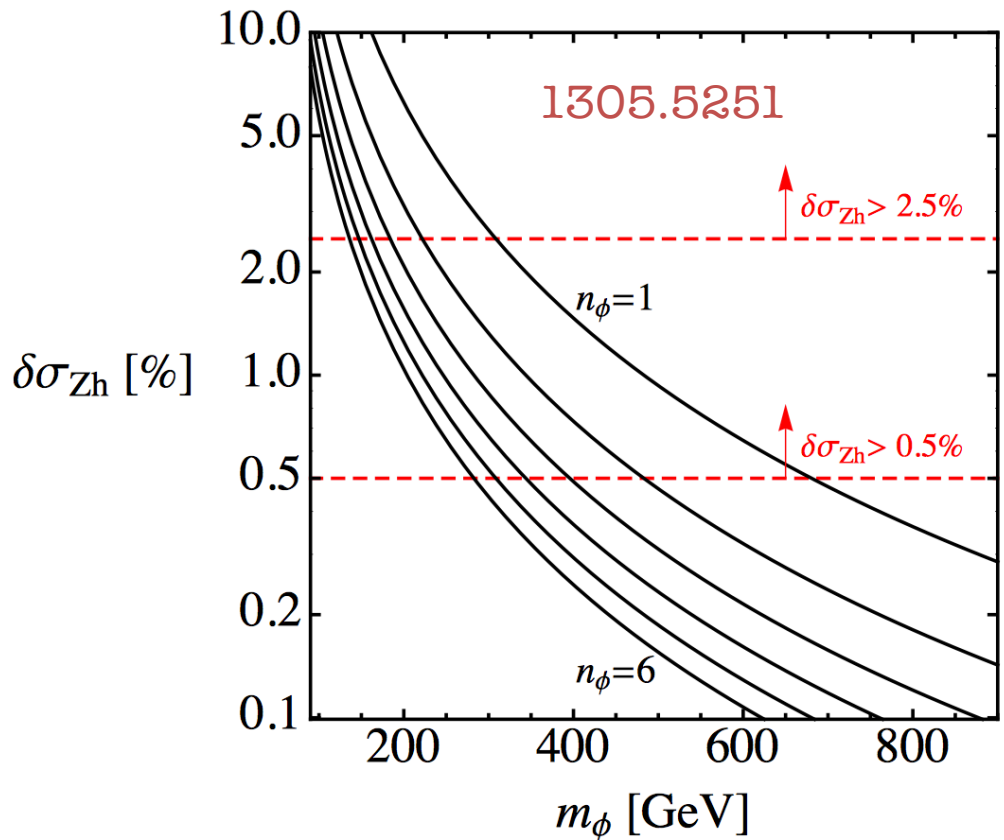
Neutral Naturalness

- What if the top partners are completely neutral and inert?



Even in this nightmare scenario at FCC-ee can probe the existence of hidden new particles through miniscule quantum mechanical shifts in Higgs couplings.

Note that no one has yet constructed such a theory yet...



The Naturalness Paradox

FCC can comprehensively test even the most contorted theoretical constructions.

Effective Field Theory has been a successful guide for decades, in high energy physics and elsewhere.

It's failure at the weak scale would point to entirely new principles of nature.

Where do we need to go?

New Particles!

- There is strong motivation for the existence of new particles in the multi-TeV range.

New Weak Forces!

- Sometimes we overlook the role of future high energy colliders as intensity frontier machines.

Intensity Frontier

There are models in which there is no preferred mass scale for new particles.

An "Axion-like particle" (ALP) is a canonical example:

$$a$$

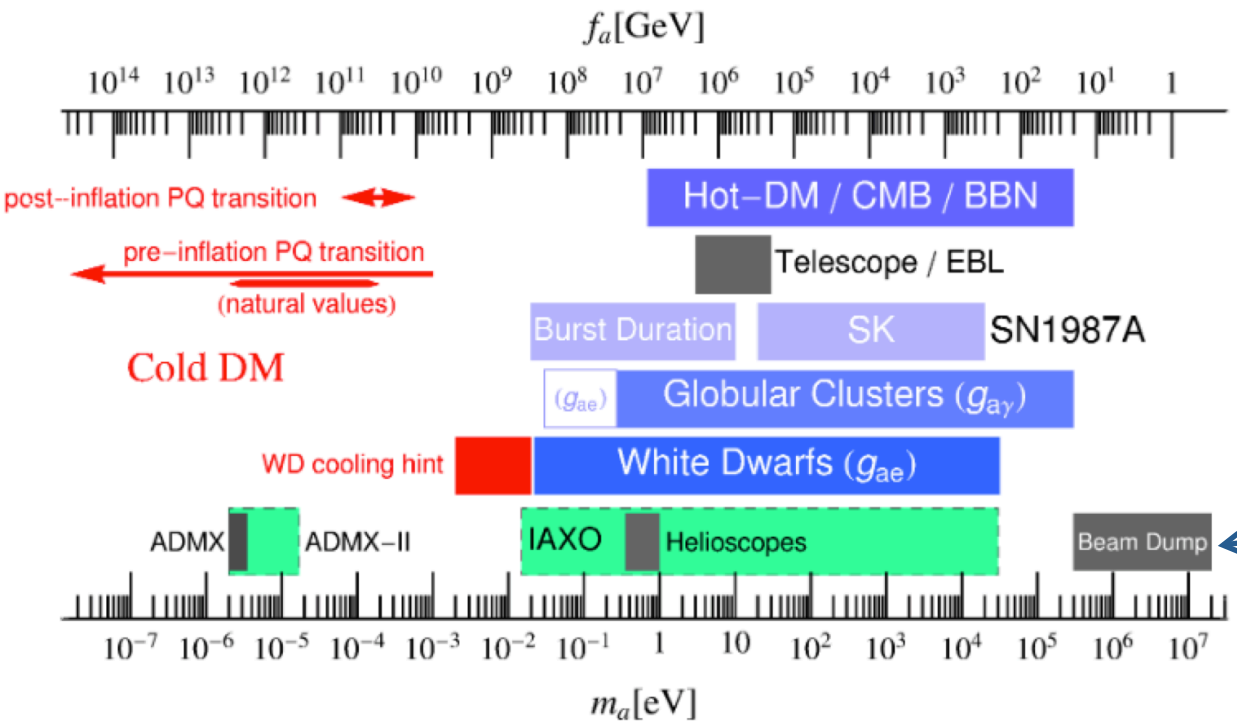
ALPs emerge as pseudo-Goldstone bosons of spontaneously broken global symmetries.

Since the parameter that gives mass breaks a symmetry, it can be naturally small.

Intensity Frontier

ALPs can also couple to photons, gluons etc,

$$\mathcal{L} \supset \frac{a}{f} B^{\mu\nu} \widetilde{B}_{\mu\nu}$$

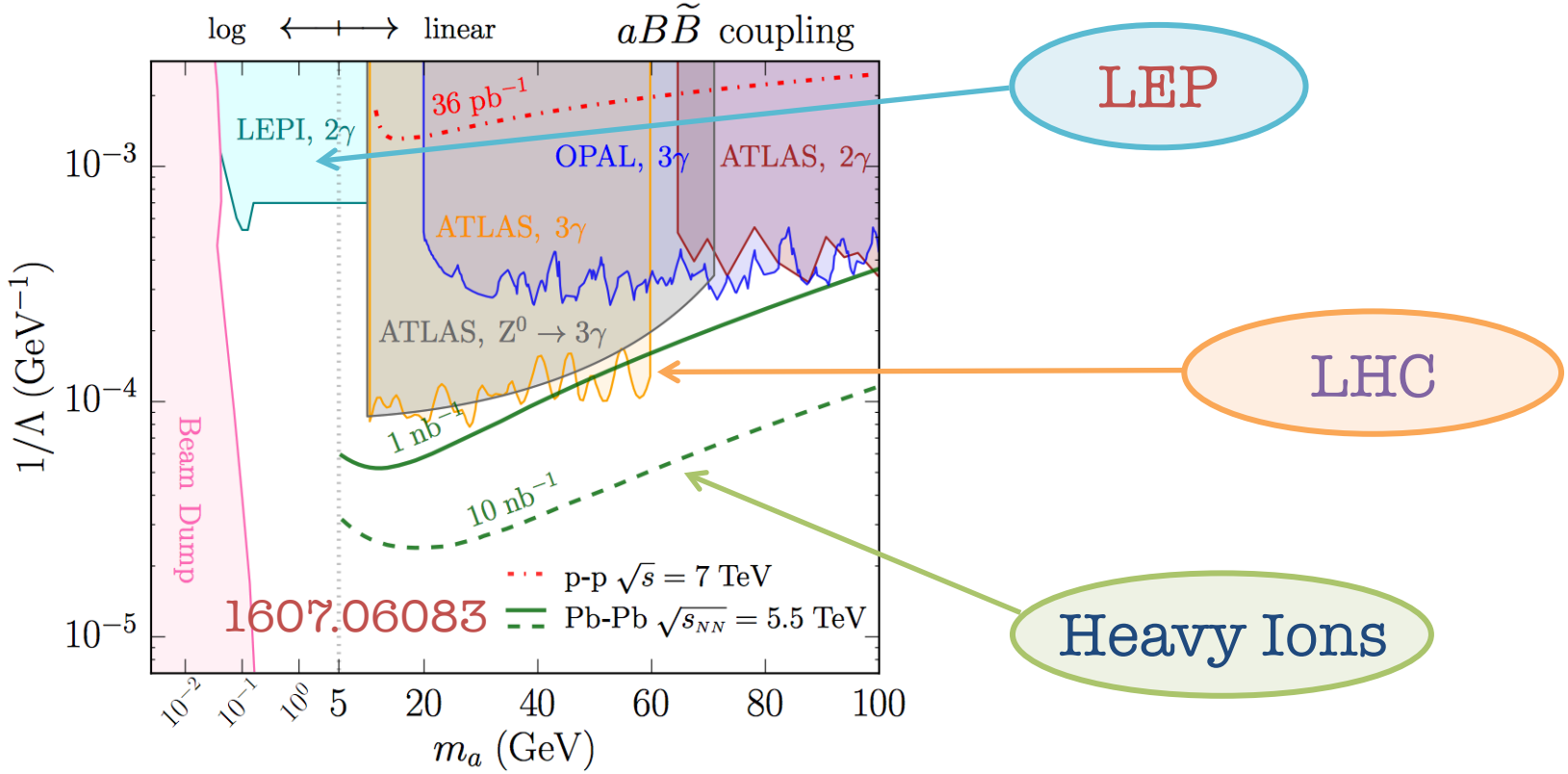


This is why we consider ALPs searches over many orders of magnitude...

But why do so many plots end here?

Intensity Frontier

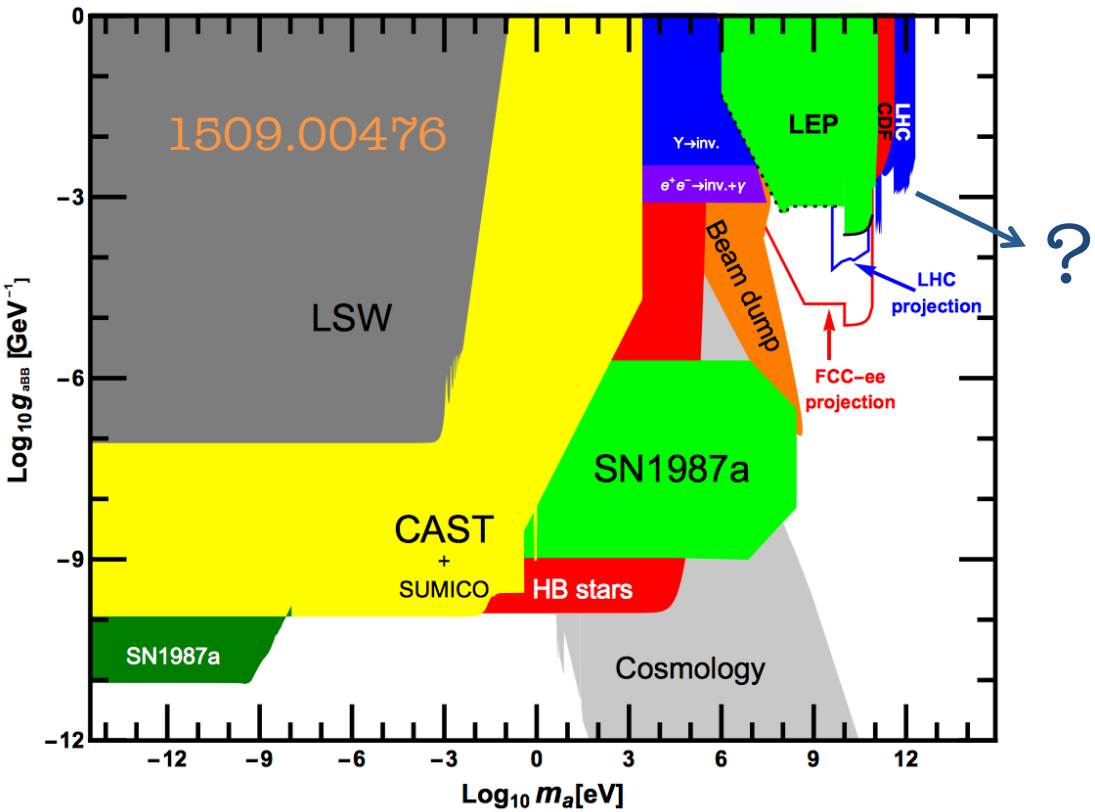
LEP+LHC already proven effective



Together they fill the gap from beam dumps to weak scale, but not at "intensity frontier"-level cross sections...

Intensity Frontier

The extra two orders of magnitude luminosity at FCC-ee would push this further, to "intensity frontier level"!



Where should FCC-hh go on this plot?

Due to:

a) CM energy
b) Huge PDFs
c) Large L_{int}

FCC-hh would perform as "intensity frontier": Lower couplings than LHC, and higher masses than FCC-ee.

Where do we need to go?

New Particles!

- There is strong motivation for the existence of new particles in the multi-TeV range.

New Weak Forces!

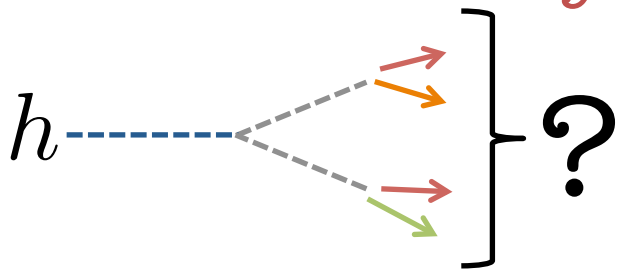
- Sometimes we overlook the role of future high energy colliders as intensity frontier machines.

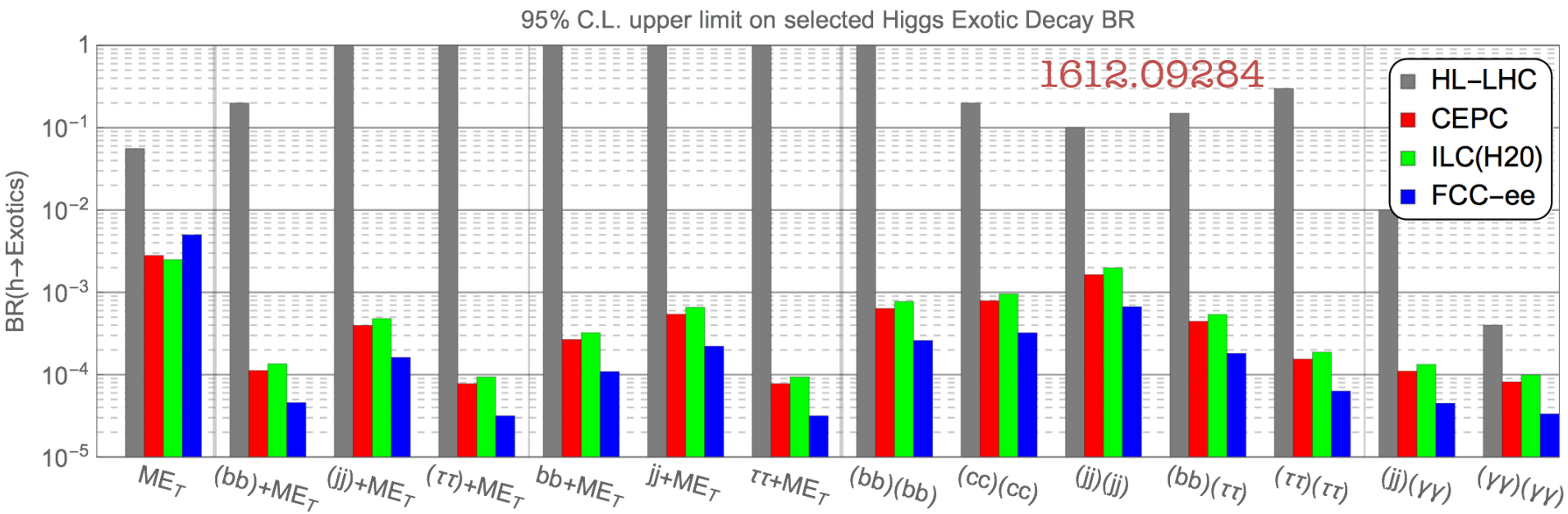
The Unexpected!

- We might not always be looking in the right places.

The Unexpected

Maybe the Higgs has some totally unexpected, weird decays





At FCC-ee, reach for exotic decays is remarkable!

The Unexpected

Long-lived particles come up in many models.

Many exciting and creative ideas on the theoretical front...

...

Hidden Valleys

Baryogenesis

Mini-Split

Neutrino Masses

Neutral Naturalness

RPV

RHD Neutrinos

FCC?

Conclusions.

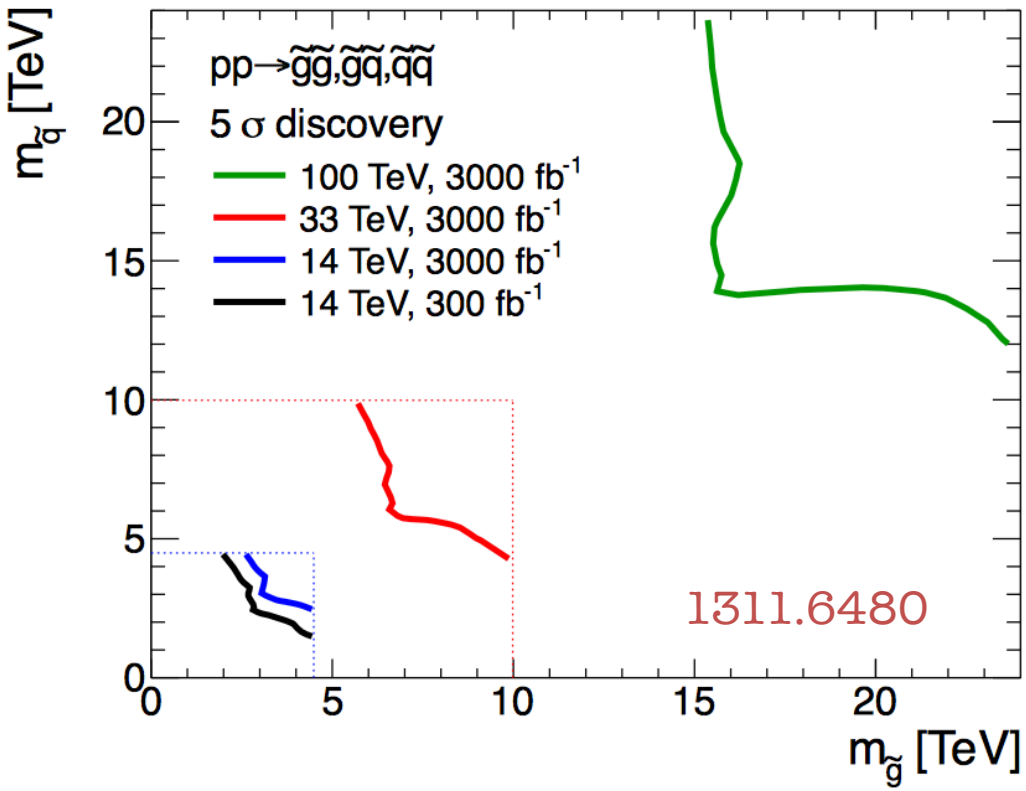
This talk had a lot of plots. Things are qualitatively changing, as we see the physics possibilities come into focus.

With FCC we can examine the dynamics of electroweak symmetry breaking, and test the fundamental principles that have guided progress for decades.

Backup Slides.

Supersymmetry

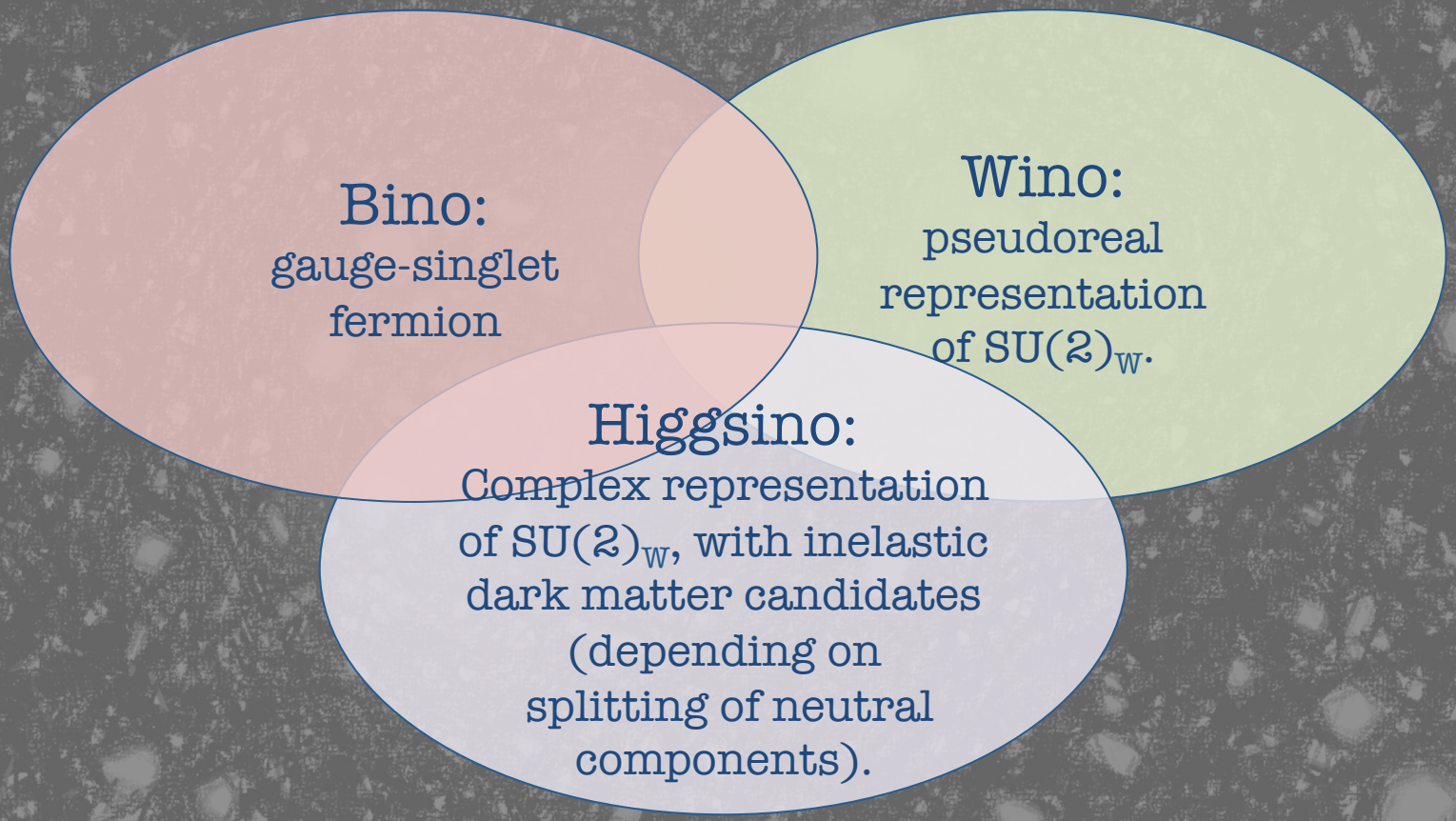
Combining gluino and squark limits onto one plane:



Reach in combination stronger than individual reach to due enhanced production rates with all states present.

Supersymmetry

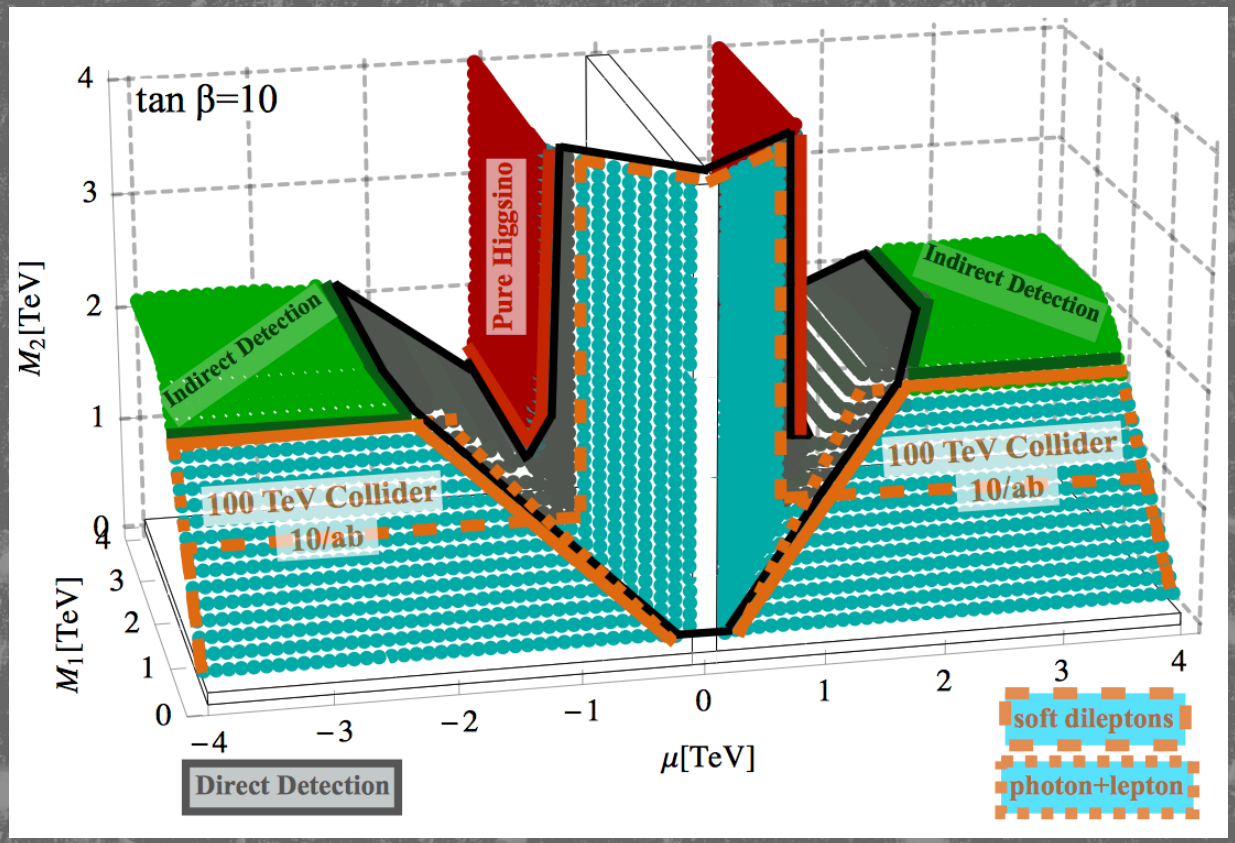
Dark Matter: Neutralino is a compelling ingredient of the SUSY setup:



Relic density points towards no more than few TeV!

Relic Neutralino Surface

Collider signatures considered: MET + Jet and either soft dileptons or lepton+photon



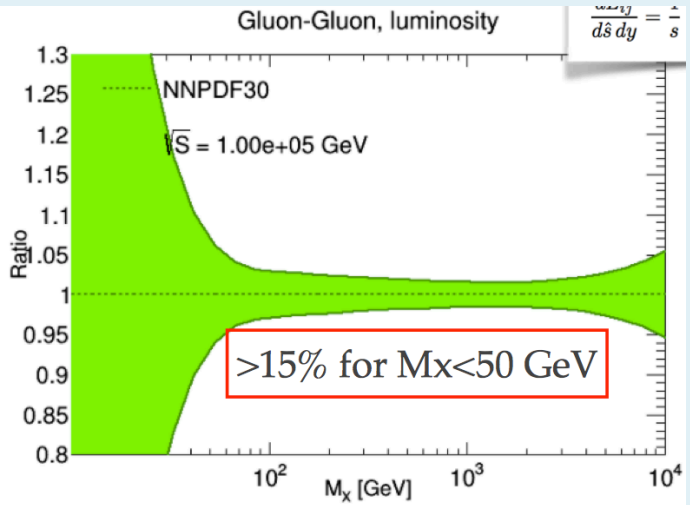
100 TeV Study: Bramante, Desai, Fox, Martin, Ostdiek, Plehn. 2015.

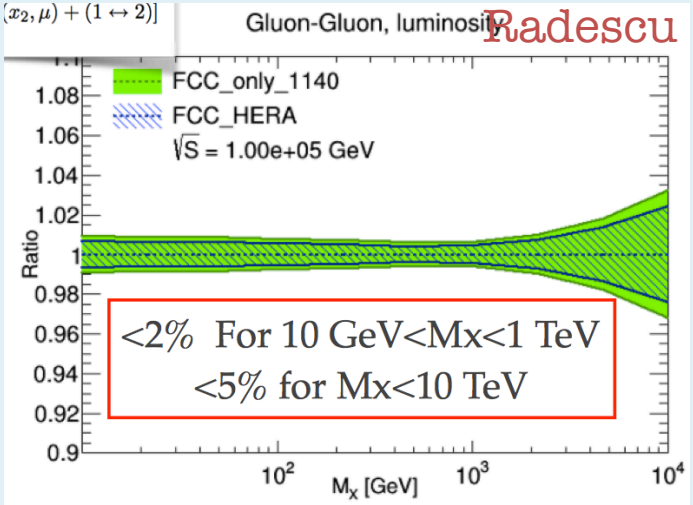
Complementarity

There are important aspects in which colliders would be complementary. E.g.

PDFs precisely determined at FCC-eh

Camarda
Radescu

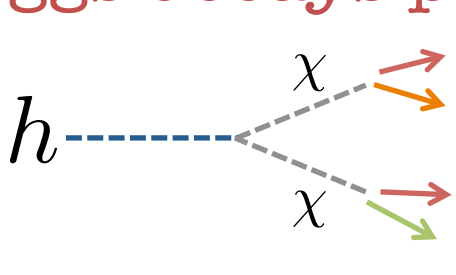




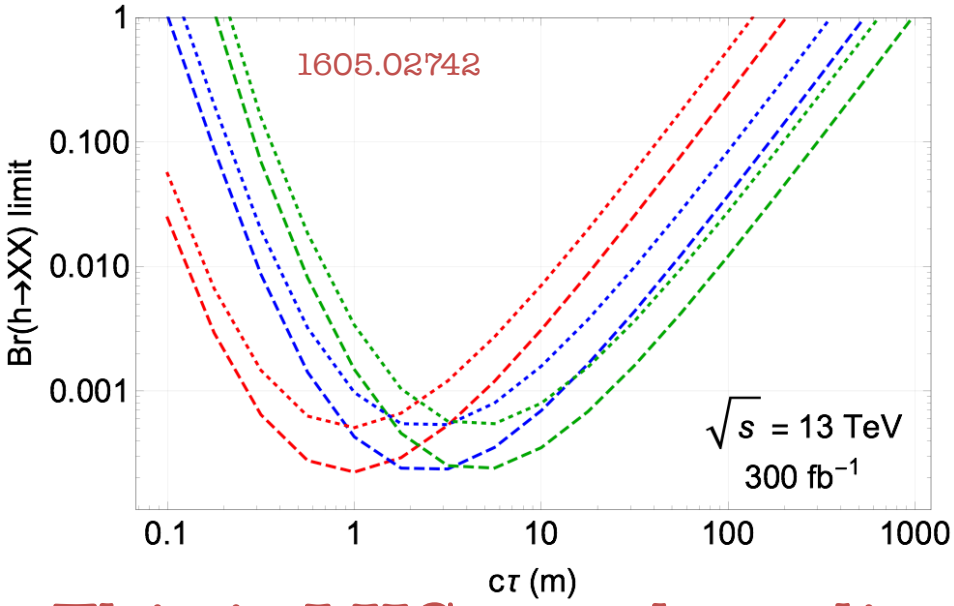
Improvement in low-x predictions for FCC-hh.

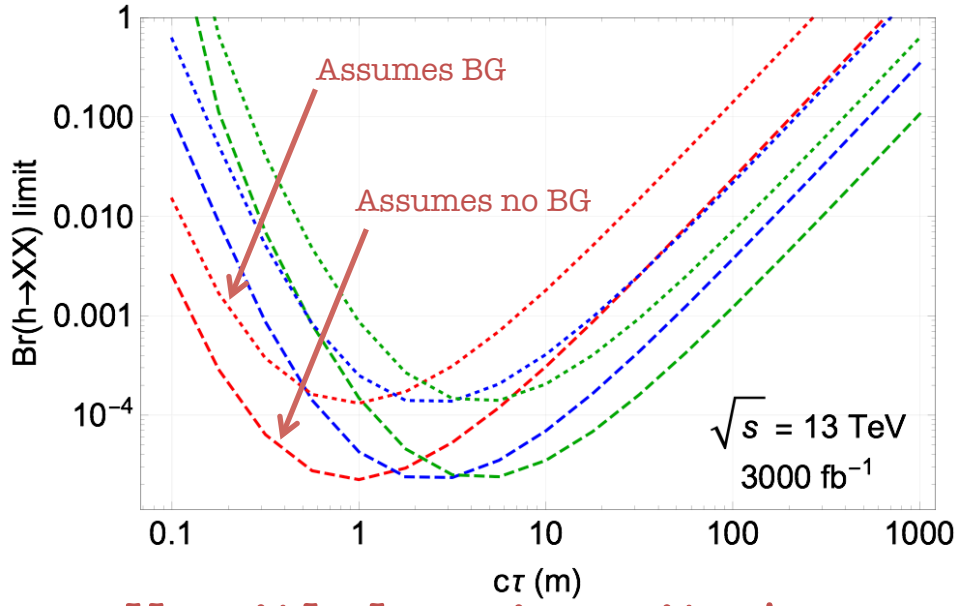
The Unexpected

Exotic Higgs decays provide a signature "standard candle"



$$m_\chi = 10, 25, 40. \text{GeV}$$





This is LHC, reach scaling well with luminosity!

FCC-hh? Two orders of magnitude more H's!