HL-LHC Physics

May 26th 2022

LHC Paperfest

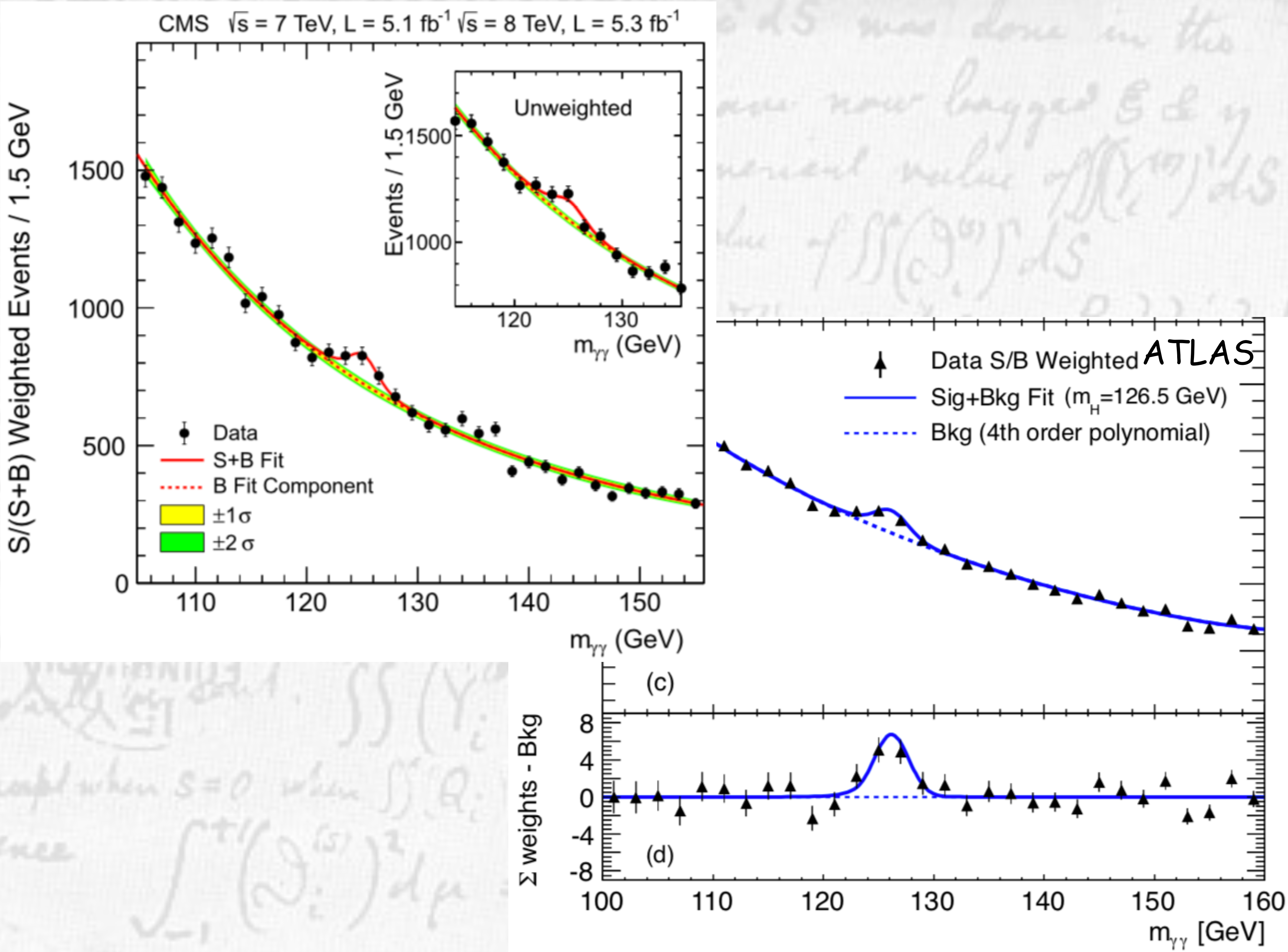
Institute of Physics

Matthew McCullough

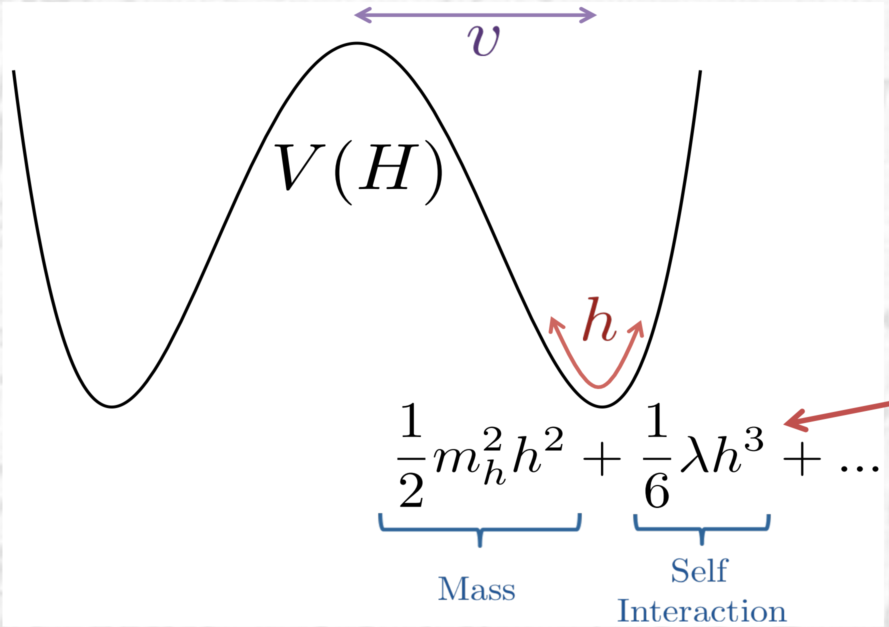
CERN

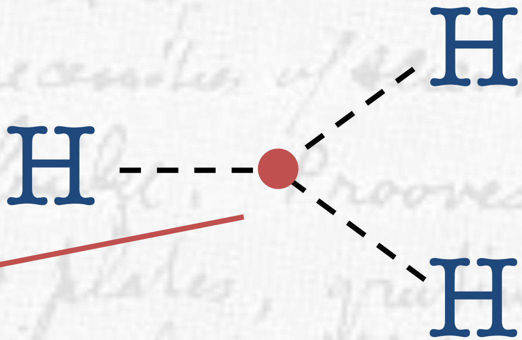
What's on the horizon?

...some examples, handpicked by theorists...


CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
S/(S+B) Weighted Events / 1.5 GeV
Unweighted
Events / 1.5 GeV
Data
S+B Fit
B Fit Component
±1σ
±2 σ
mγγ (GeV)
Data S/B Weighted
ATLAS
Sig+Bkg Fit (mH=126.5 GeV)
Bkg (4th order polynomial)
(c)
(d)
Σ weights - Bkg
mγγ [GeV]

What is the Higgs Field Potential?

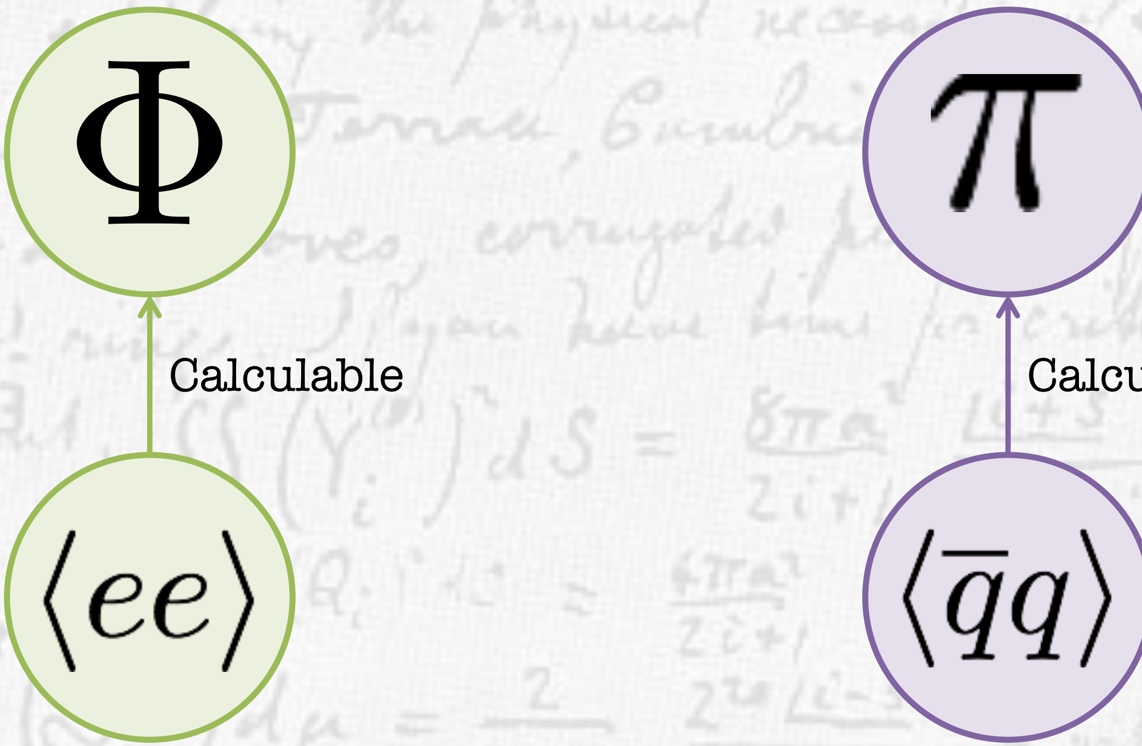




Why should I care?

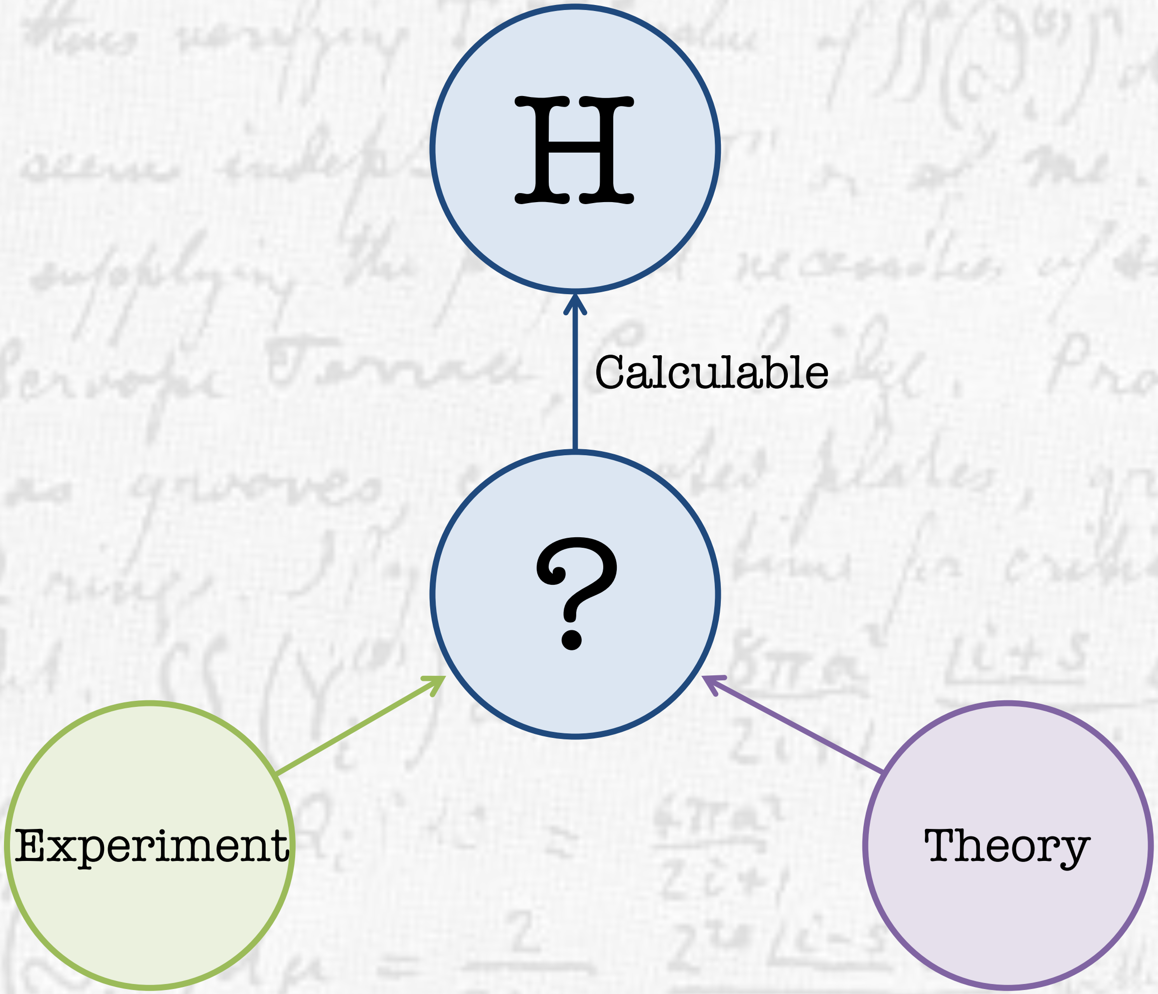
What's up with the Higgs Boson?

Every scalar we encountered until now has properties (mass, vev, etc) that are calculable within some more fundamental theory:



What's up with the Higgs Boson?

What about the Higgs?



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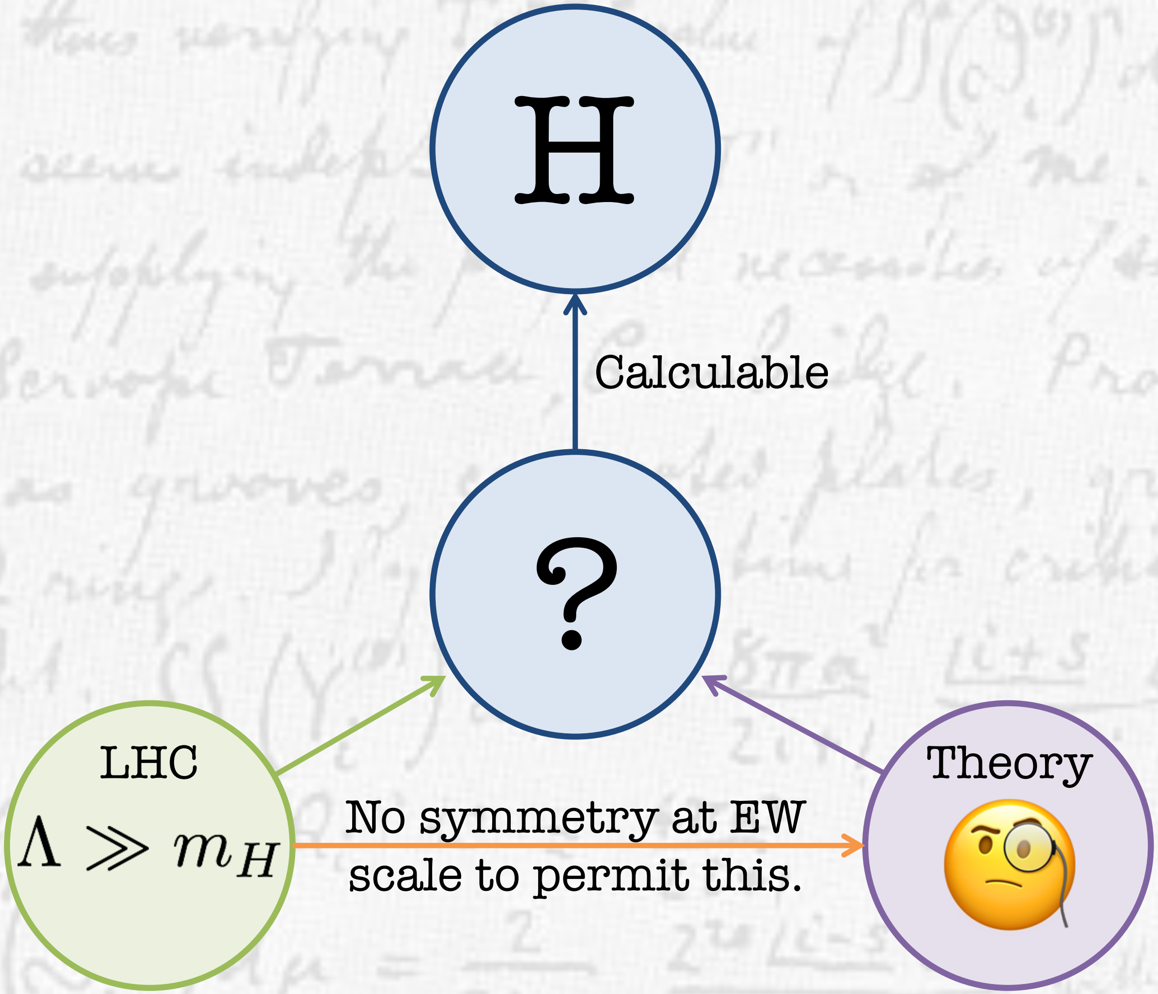
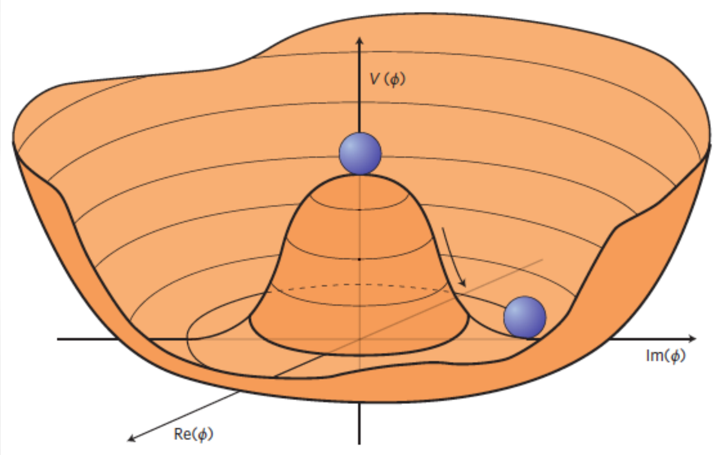


Eh?

A sample of how theory understanding is evolving and the role of HL-LHC…

A Pion-like Higgs?

Consider pions – particles we know and understand well. The reason they are so much lighter than their microscopic scale (QCD) is they come from spontaneous symmetry breaking (Goldstone's Theorem):



Their mass comes from interactions that explicitly break the global symmetry, notably quark masses.

Can we generalise this to the Higgs?

A Pion-like Higgs?

Durieux, MM, Salvioni 2021

To generate a pion-like Higgs potential assume some small explicit global symmetry-breaking "spurion" in a symmetric irrep with "n" indices:

Some equations, to show the words are backed up with maths.

$$V_\epsilon = \ldots \frac{\ldots}{f^n} \ldots \phi^{a_1} \phi^{a_2} \ldots \phi^{a_n}$$

We find:

$$V = \epsilon m_\rho^2 f^2 \, G_n^{(N-1)/2}(\cos \Pi / f)$$

This is a Gegenbauer polynomial!

A Pion-like Higgs?

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$$V_\epsilon = \frac{\lambda}{f^{n-4}} \epsilon_{a_1, a_2, \ldots, a_n} \phi^{a_1} \phi^{a_2} \ldots \phi^{a_n}$$

We find:

$$V = \epsilon m_\rho^2 f^2 \, G_n^{(N-1)/2}(\cos \Pi / f)$$

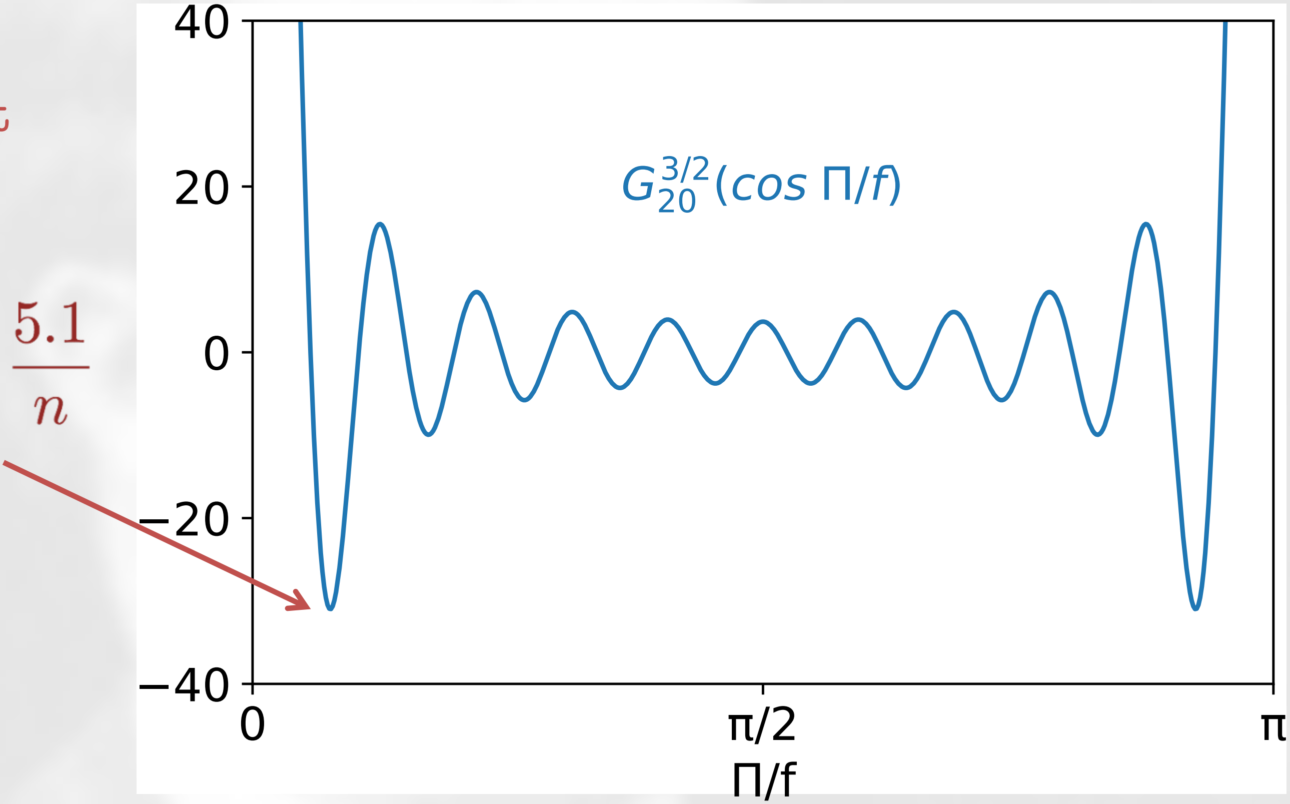
This is a Gegenbauer polynomial!

Getting to know Gegenbauer

What a Gegenbauer potential looks like:

Global minimum at naturally small field values:

$$\frac{\langle \Pi \rangle}{f} \approx \frac{j_{\lambda+1/2,1}}{n+\lambda} \approx \frac{5.1}{n}$$

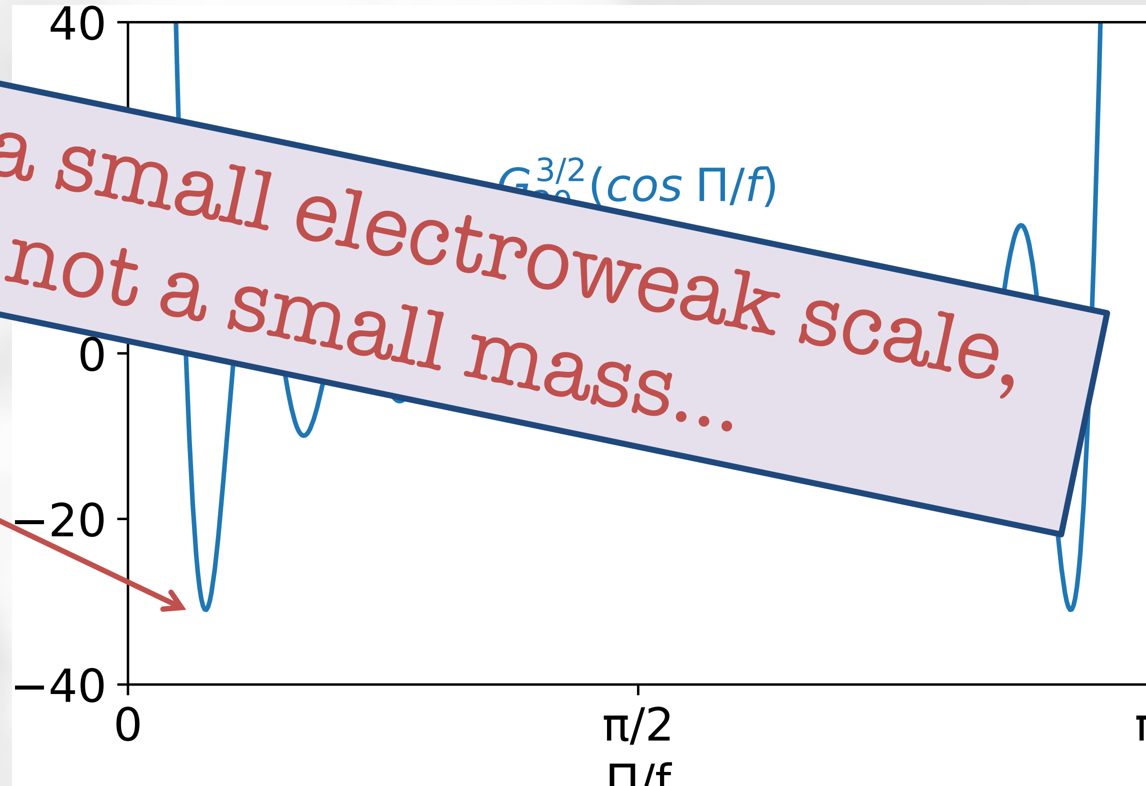


Getting to know Gegenbauer

What a Gegenbauer potential looks like:

Glo…
n…
field…

$$\frac{\langle \Pi \rangle}{f} \approx \frac{j_{\lambda+1/2,1}}{n+\lambda} \approx \frac{5.1}{n}$$



Explains a small electroweak scale,
but not a small mass…

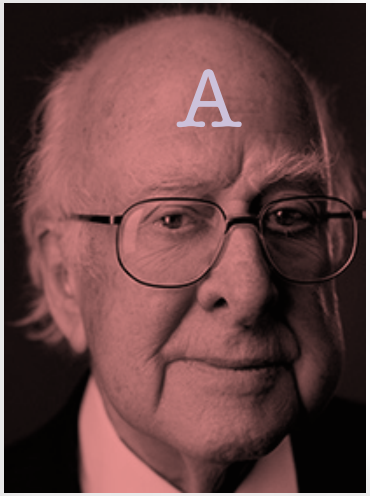
Twin Higgs

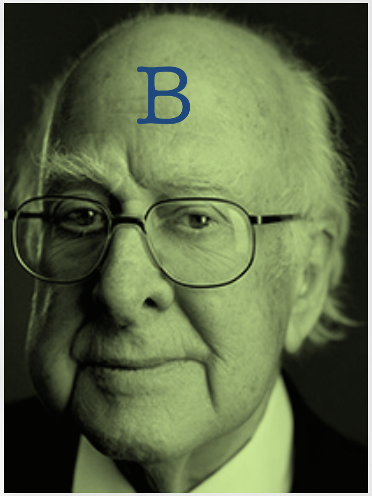
Chacko, Goh, Harnik 2005

Take two identical copies of the Standard Model:

SM_A $\xleftrightarrow{A \leftrightarrow B}$ SM_B

Everything twinned.





Twin Higgs

Chacko, Goh, Harnik 2005

Take two identical copies of the Standard Model:

$$\mathrm{SM}_A \xleftrightarrow{\;A \leftrightarrow B\;} \mathrm{SM}_B$$

Enhance symmetry structure to global symmetry:

Interaction dictated by accidental symmetry:

$$V_{\mathrm{Higgs}} = \lambda\left(|H_A|^2 + |H_B|^2\right)^2 - \Lambda^2\left(|H_A|^2 + |H_B|^2\right)$$

Exchange enforces equal quadratic corrections for each Higgs. Thus masses still respect underlying symmetry.

Twin Higgs

Chacko, Goh, Harnik 2005

Take two identical copies of the Standard Model:

SM_A $\quad A \leftrightarrow B \quad$ SM_B

Explains a small mass, but not a small electroweak scale...

Enhance sym... metry:

Interaction dictated by accidental sym...

$$V_{\text{Higgs}} = \lambda \left(|H_A|^2 + |H_B|^2\right)^2 - \Lambda^2 \left(|H_A|^2 + |H_B|^2\right)$$

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Gegenbauer's Twin

Durieux, MM, Salvioni 2022

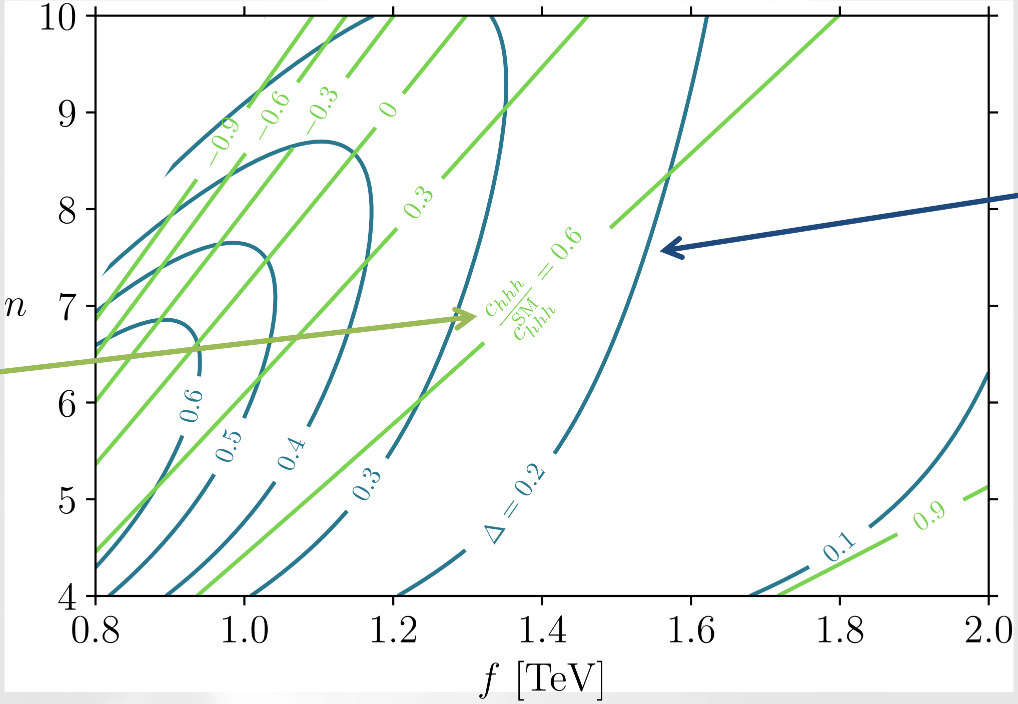
Gegenbauer structure allows to have a small weak scale...

Twin Higgs models, however, allow for a small mass...

Gegenbauer's Twin

Durieux, MM, Salvioni 2022

While the single-Higgs coupling corrections are small, Higgs self-interaction receives large corrections:



Tuning contours.

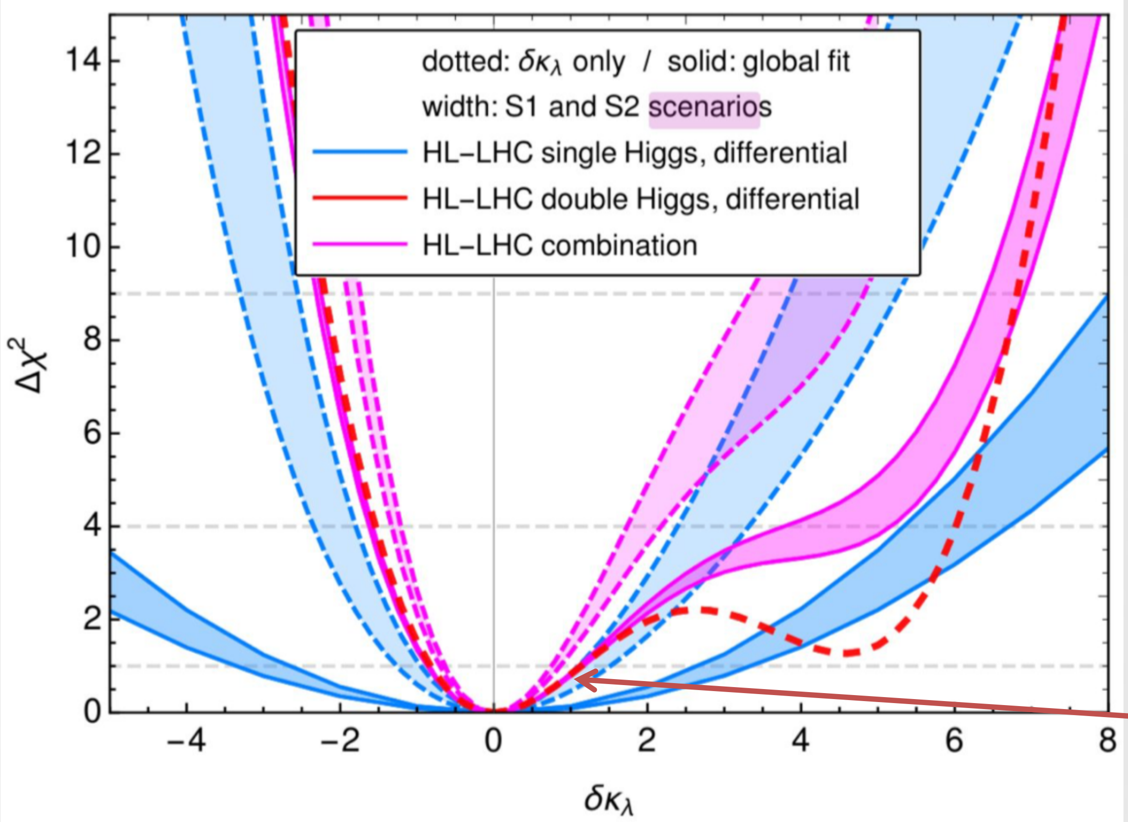
Contours of self-interaction relative to SM prediction.

The smoking-gun signal of Gegenbauer's Twin models.

But at HL-LHC…

Combination of various single and di-Higgs measurements:

CERN Yellow report Vol. 7 (2019)



Ultimately 50% or better sensitivity!

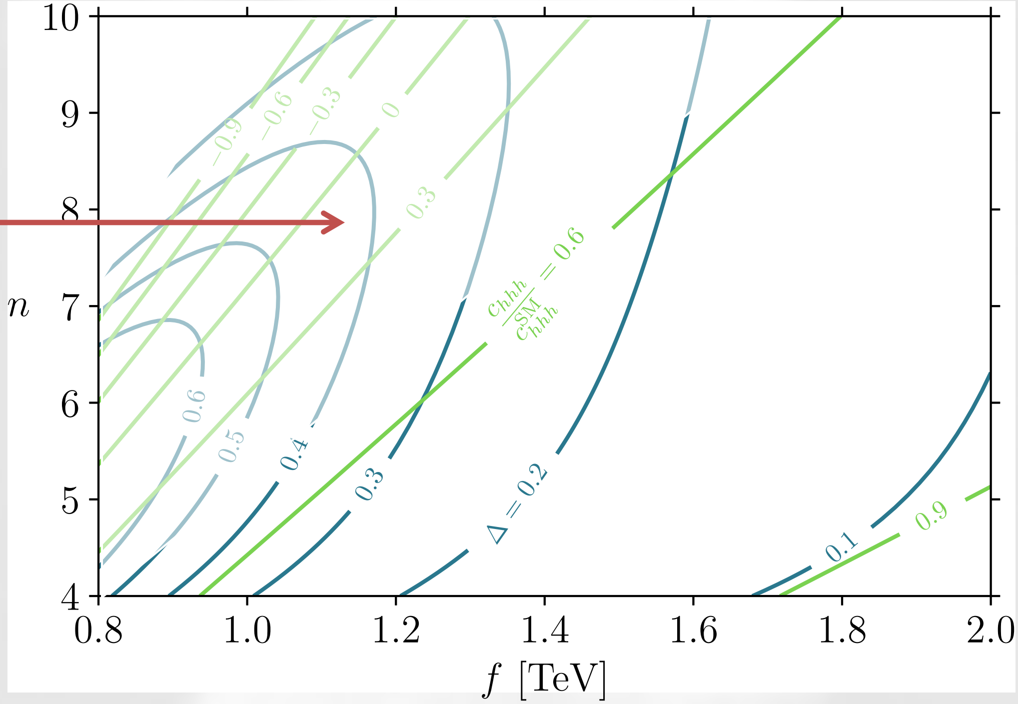
Will provide a crucial probe of self-interaction!

Gegenbauer's Twin

Durieux, MM, Salvioni 2022

While the single-Higgs coupling corrections are small, Higgs trilinear receives big corrections:

Generic parameter space explored by HL-LHC!



This is a smoking-gun signal of Gegenbauer's Twin and could be detected at the HL-LHC.

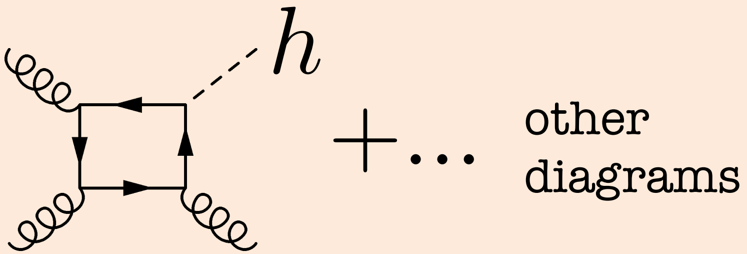
What else will we explore?

Deep Exploration of the Higgs

HL-LHC would perform many measurements in signal space inaccessible to 300 fb^{-1} LHC.

Higgs Production

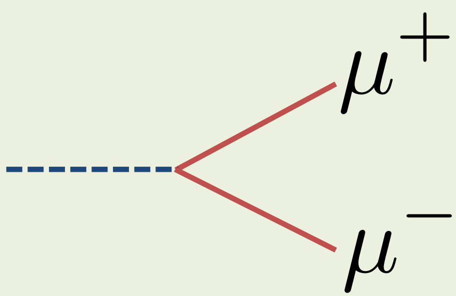
Higgs+jet production



Would occur at Higgs p_T's as large as 2 TeV!

Higgs Decays

Higgs coupling to muons



Would be measured to 4.5%.

Totally unexplored territory, who knows what to expect?

News from the dark side?

Dark Sectors

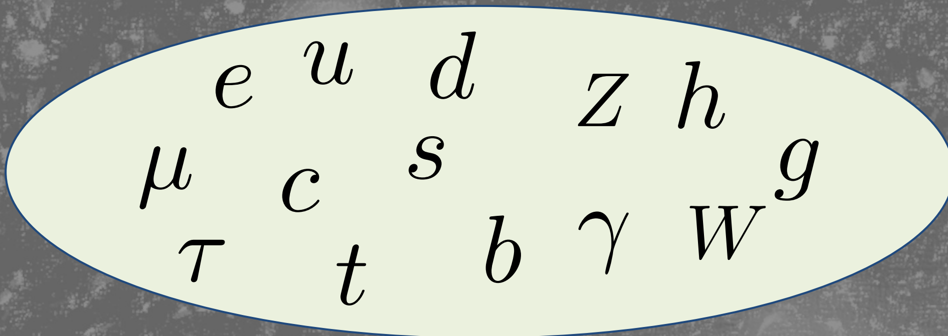
Evidence for dark matter is now overwhelming

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

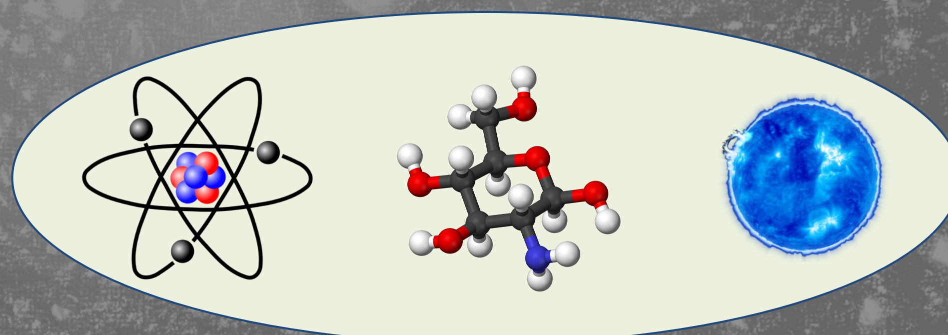
Yet we have no clue what it is at the particle level!

?

Only 18% of all matter in Universe is visible.



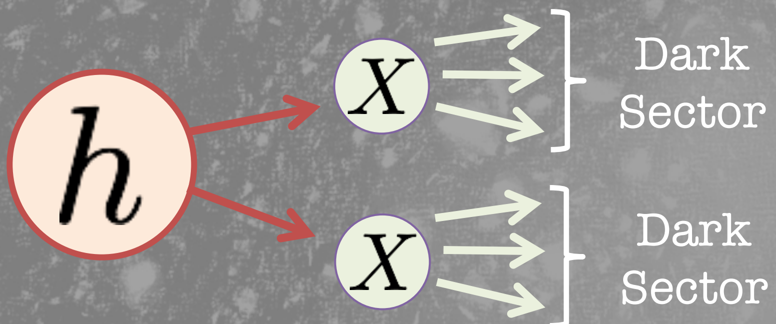
Within that 18% we observe extraordinary complexity.



Similarly, it may be the light mediators, or other states, that open the window to the dark sector.

Higgs Portal

The Higgs could be the window to the dark sector:



1905.03764

kappa-3 scenario	HL-LHC
$1 \geq \kappa_W > (68\%)$	0.985
$1 \geq \kappa_Z > (68\%)$	0.987
κ_g (%)	±2.
κ_γ (%)	±1.6
$\kappa_{Z\gamma}$ (%)	±10.
κ_c (%)	–
κ_t (%)	±3.2
κ_b (%)	±2.5
κ_μ (%)	±4.4
κ_τ (%)	±1.6
BR_{inv} (<%, 95% CL)	1.9

HL-LHC could ultimately probe Higgs to invisible dark sector branching ratios as small as 2%!

The Unexpected

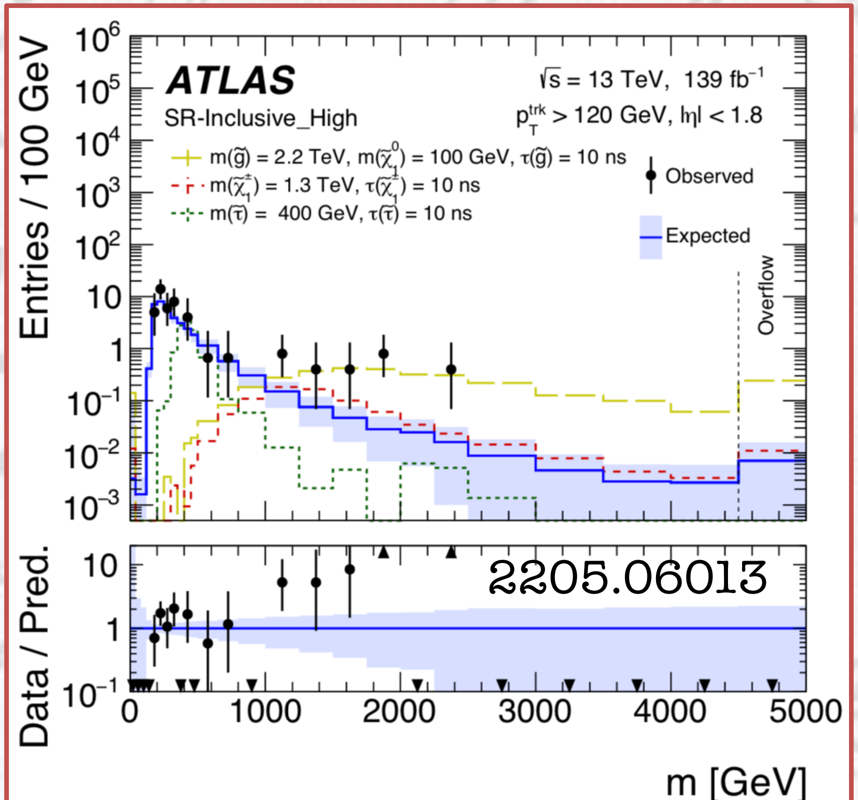
Sometimes nature is more creative than theorists…

FIG. 12. Pike's Peak, 7900 gauss. A disintegration produced by a nonionizing ray occurs at a point in the 0.35 cm lead plate, from which six particles are ejected. One of the particles (strongly ionizing) ejected nearly vertically upward has the range of a 1.5 MEV proton. Its energy (given by its range) corresponds to an $H\rho = 1.7 \times 10^5$, or a radius of 20 cm, which is three times the observed value. If the observed curvature were produced entirely by magnetic deflection it would be necessary to conclude that this track represents a massive particle with an e/m much greater than that of a proton or any other known nucleus.

Something to keep an eye on...

Bethe-Bloch formula allows us to correlate mass, charge, and energy-loss for long-lived particles:

$$\mathrm{MPV}_{\mathrm{d}E/\mathrm{d}x}(\beta\gamma) = \frac{1+(\beta\gamma)^2}{(\beta\gamma)^2}\left(c_0 + c_1 \log_{10}(\beta\gamma) + c_2\left[\log_{10}(\beta\gamma)\right]^2\right)$$



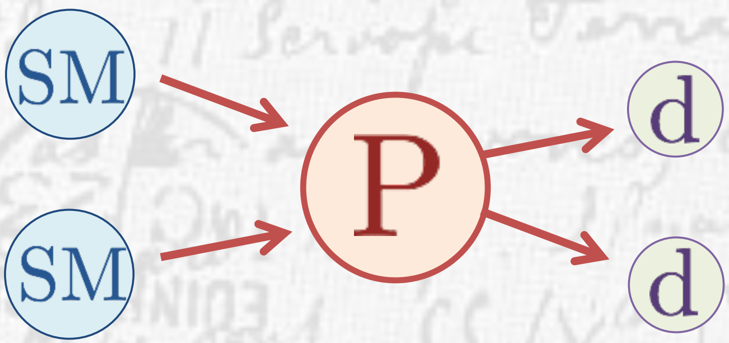
Recent ATLAS search based on this technique had 6 or 7 excess events.

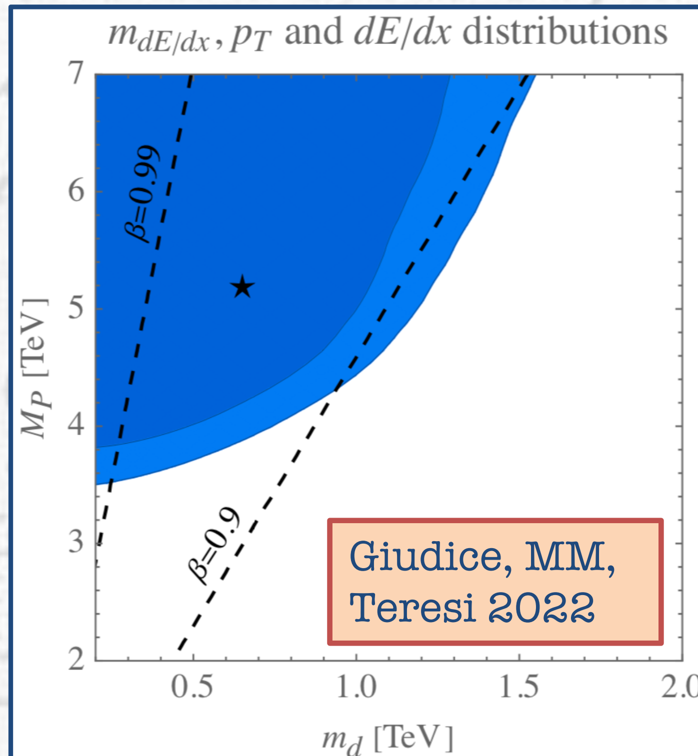
New-physics interpretation challenged by time-of-flight measurements, which are inconsistent with low-β for charge-1 in Bethe-Bloch.

Something to keep an eye on...

However, alternatively could have higher-charge, higher-β particles...

$$\mathrm{MPV}_{dE/dx}(\beta\gamma) = \frac{1+(\beta\gamma)^2}{(\beta\gamma)^2}\left(c_0 + c_1 \log_{10}(\beta\gamma) + c_2\left[\log_{10}(\beta\gamma)\right]^2\right) \times Q^2$$





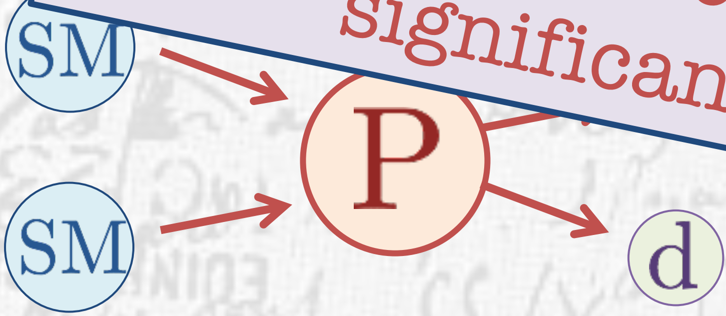
Allows a good fit to the data and consistency with time-of-flight.

Something to keep an eye on...

However, alternatively could have higher-charge, higher-β particles...

$$\text{MPV} \ldots (\beta\gamma)^2 \left(\ldots + c_1 \log_{10}(\beta\gamma) + c_2 \left[\log_{10}(\beta\gamma)\right]^2 \right) \times Q^2$$

If true, easily discoverable at LHC, with greater than discovery significance at HL-LHC!



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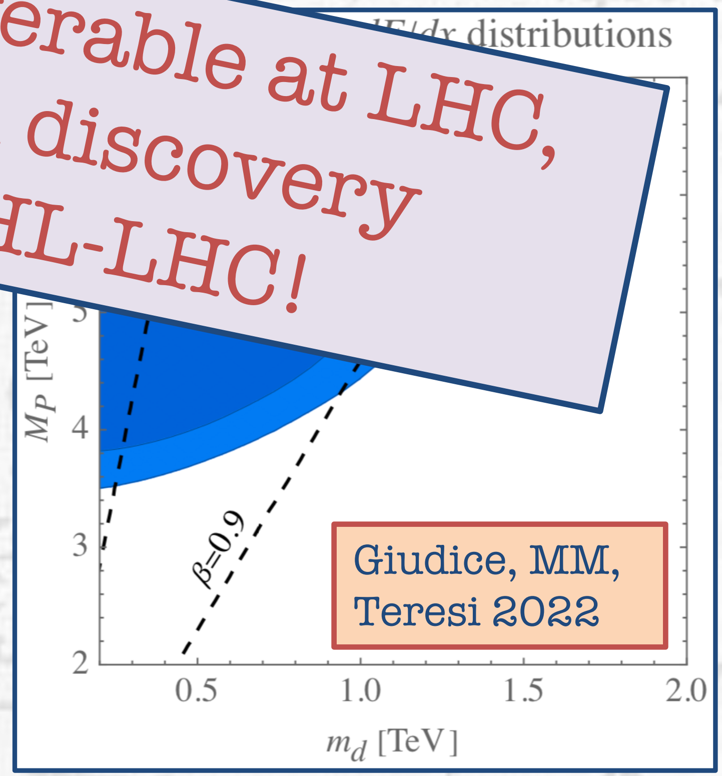
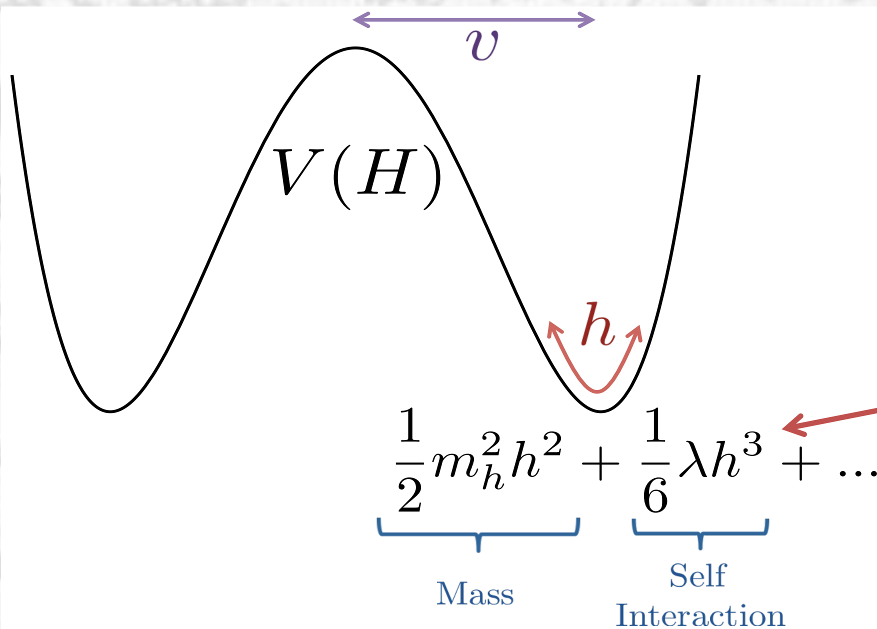
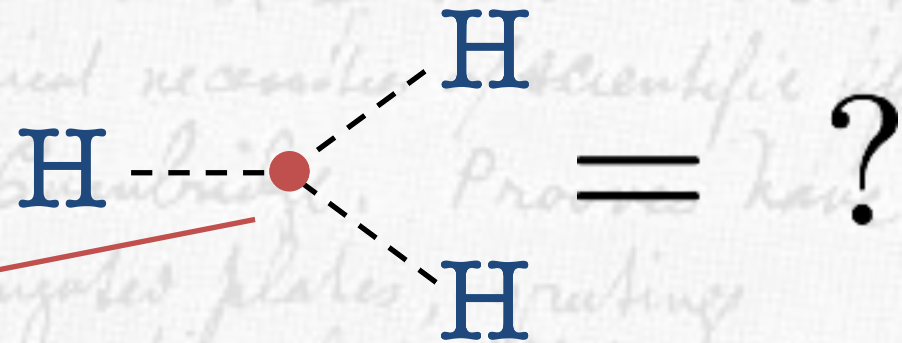


Summary

HL-LHC will open the door to one of the most important questions in fundamental physics:

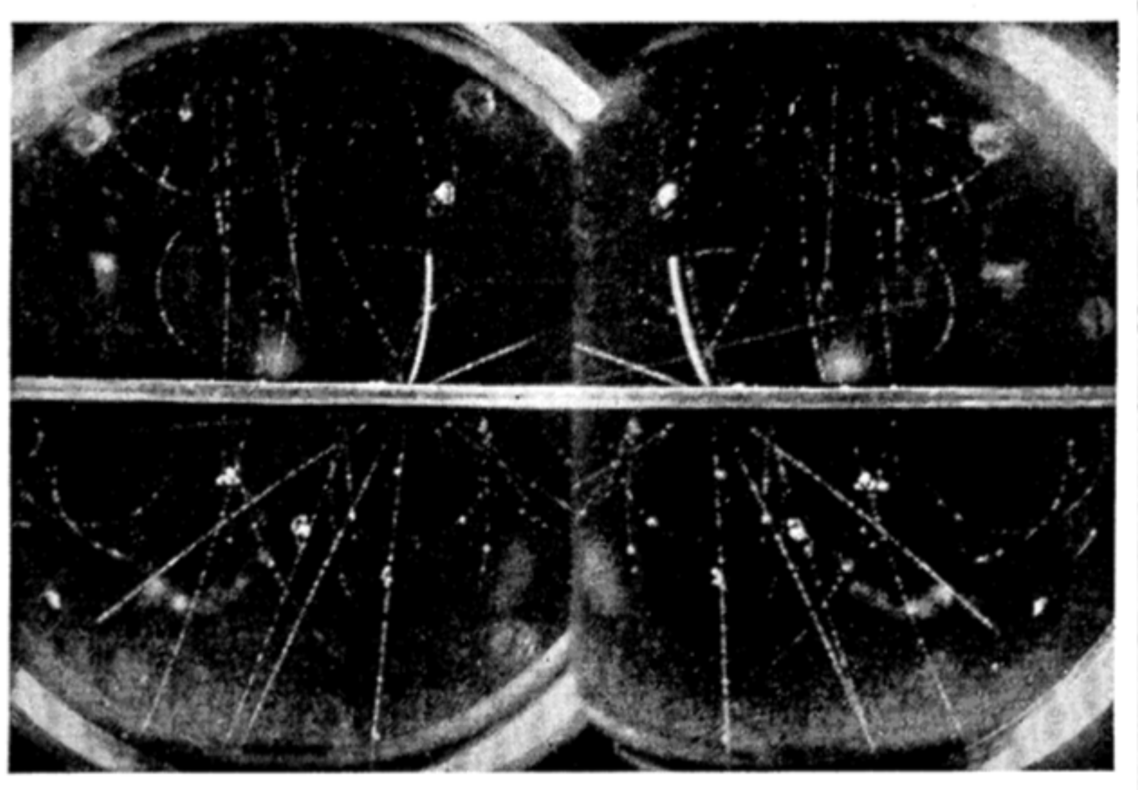




The Higgs self-interaction determined the dynamics of one of the most spectacular events to have occurred in our distant past: The moment fundamental particles got their mass!

Summary

For low-background signatures (like LLPs) the HL-LHC is a significant leap forward.



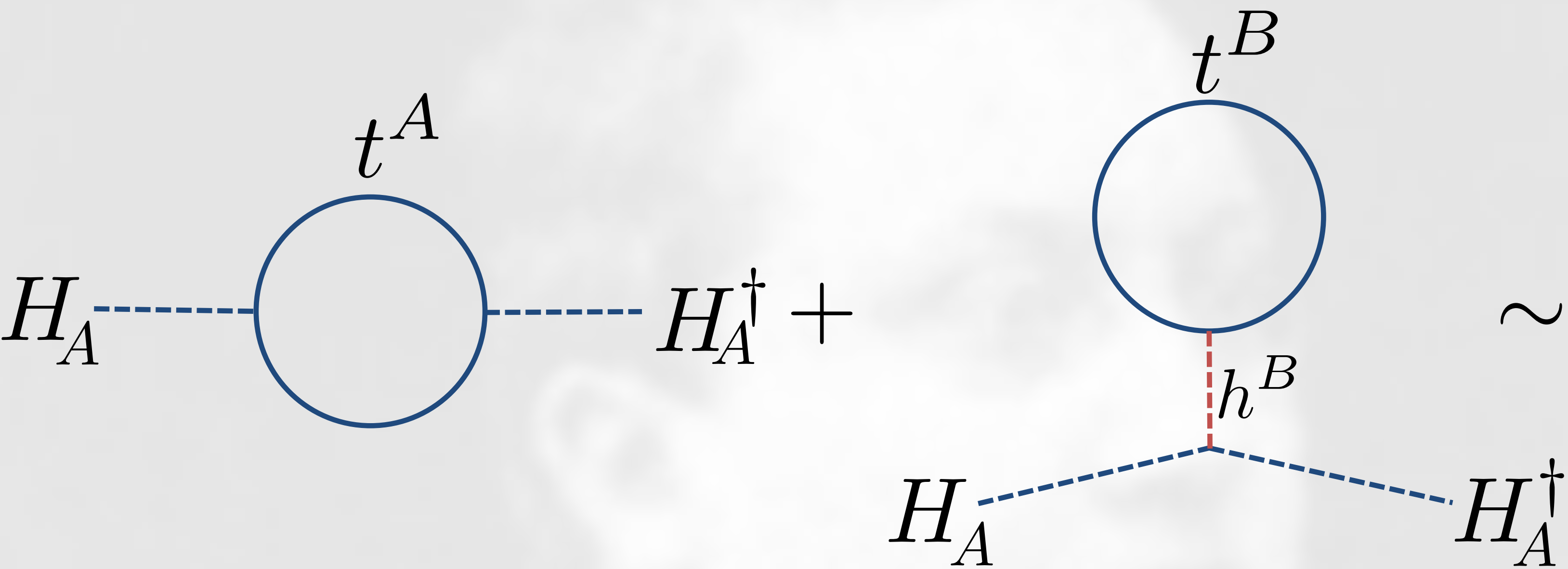
Heed lessons of past: "The farther back you can look, the farther forward you are likely to see."

A lot of great physics to look forward to at HL-LHC!

Twin Higgs

Chacko, Goh, Harnik 2005

In outdated “quadratic divergences” parlay:



$$\sim 0 \times \Lambda^2$$

Quadratic divergences from SM top quark loops cancelled by loops of “Twin” top quarks.

Cancellation persists for all Twin particles: Twin W-bosons, Twin gluons, etc.

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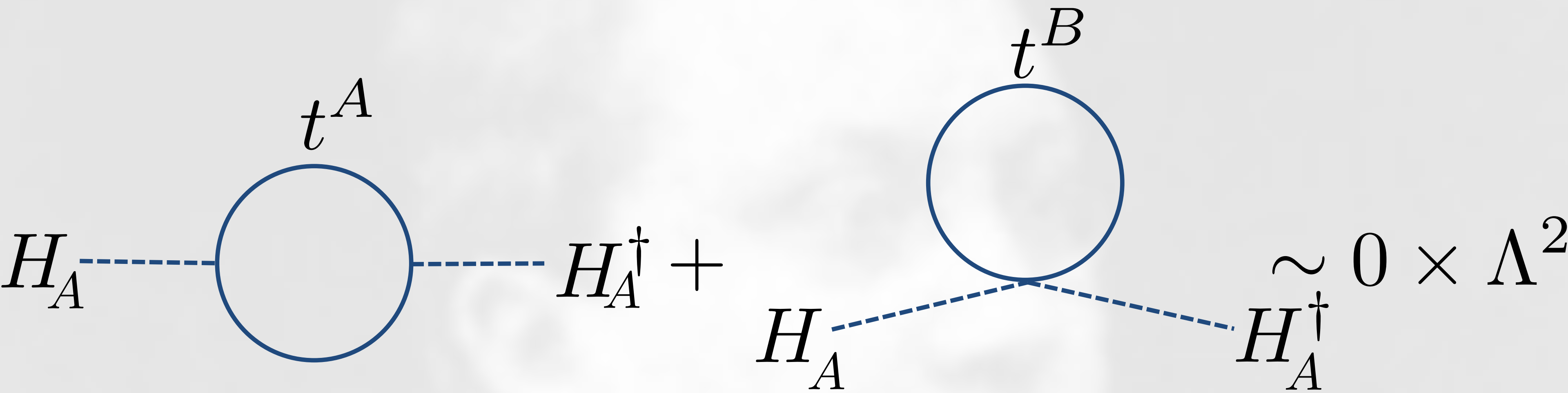

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