Title: Introduction to Particle Physics

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Abstract:

Intro to Particle Physics

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google -> particle physics.

Thank you and good night.

Outline:

1. A broad overview of what particle physics is about.
2. What is going on in particle physics now.
3. What is going on in particle physics in the near future.

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1. A broad overview of what particle physics is about.
2. What is going on in particle physics now.
3. What is going on in particle physics in the near future.

sadly LHC moved from ↓

It is probably true that you:

a) know all of the stuff i am about to say,
and/or
b) are not really that interested as you choose a diff. Ph.D,
and/or
c) you are jet lagged.

So i will mostly try to amuse you.

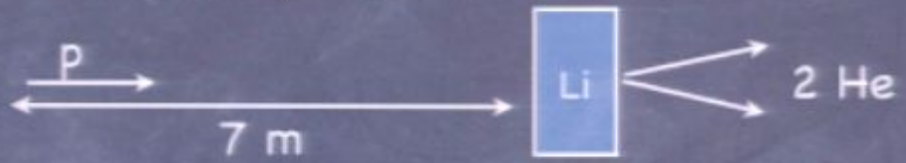
To appreciate where we are in particle physics.... consider where we came from.

People noticed a while ago when you smash things together very interesting things happen.

800 KeV

Cool 1930 tech !

Crockcroft and Walton in 1930-1932 used a large potential difference to smash a proton into lithium



So far so good 4p + 4n -> 4p + 4n easy to understand.

People/Things born in 1930

Increasing coolness.

Buffett

Eastwood

Connery

Particle Physics (arguably)

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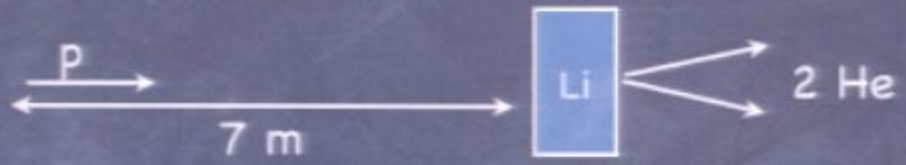


So far so good 4p + 4n -> 4p + 4n easy to understand.

4.5 inch, 80 000 eV

COOLER 1931 tech !

Around the same time Lawrence/Livingston cyclotron was developed

grad student who did the work

"Dr Livingston has asked me to advise you that he has obtained 1,100,000 volt protons. He also suggested that I add 'Whoopee'!"

—Telegram to Lawrence, 3 August 1931

11 inch, 1 MeV

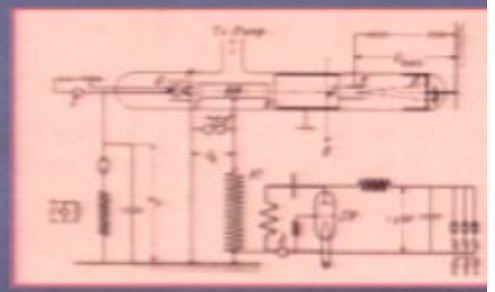
COOLEST 1931 tech !

see http://www.aip.org/history/lawrence/epa.htm

A broad overview of particle

 Crockcroft and Walton 1951

 Lawrence 1939



Interestingly for PI's philosophy/structure Lawrence was reading an electrical engineering journal (cross pollination!) when he saw an article by Rolf Wideroe that gave him the idea for the cyclotron.

What have we learned so far?

In particle physics, Grad students do the work, advisors get the  (exceptions exist).

New energies are reached very quickly:

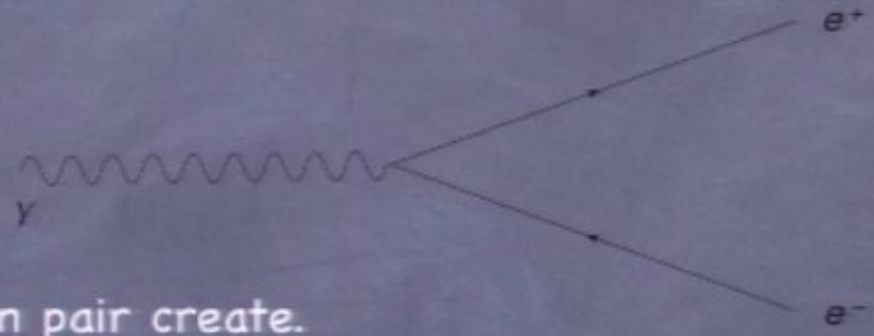
1930 800 KeV
1931 1 MeV
1946 100 MeV
(184 inch cyclotron)

things slowed down, particle physicists were busy with other things

The field rapidly advances, more energy is packed in a small space.....

A broad overview of particle

You start to convert E -> mass
then things get truly entertaining:



Photons with energy 1.022 MeV can pair create.
No sensible single particle, consistent relativistic quantum theory is possible.
Reminder of the necessity of the quantum field viewpont:

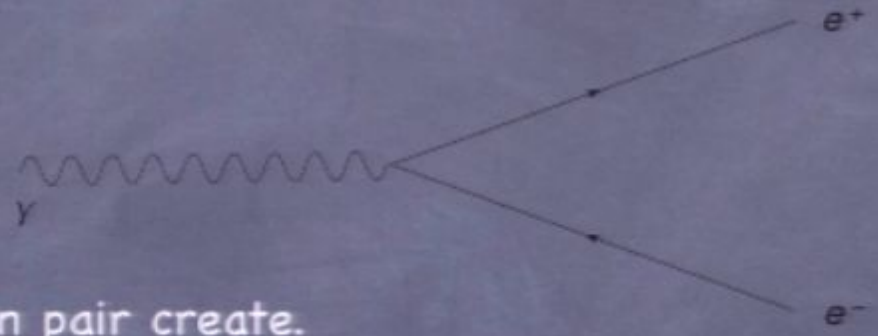
For L smaller than compton wavelength of electron, pair creation occurs.

Lesson: The Vacuum is a very EXCITING place!
The Vacuum is a party! (physics party but still jumping)

Other people in the building want: THEORY OF EVERYTHING.
Particle physicists want a sensible: THEORY OF NOTHING.

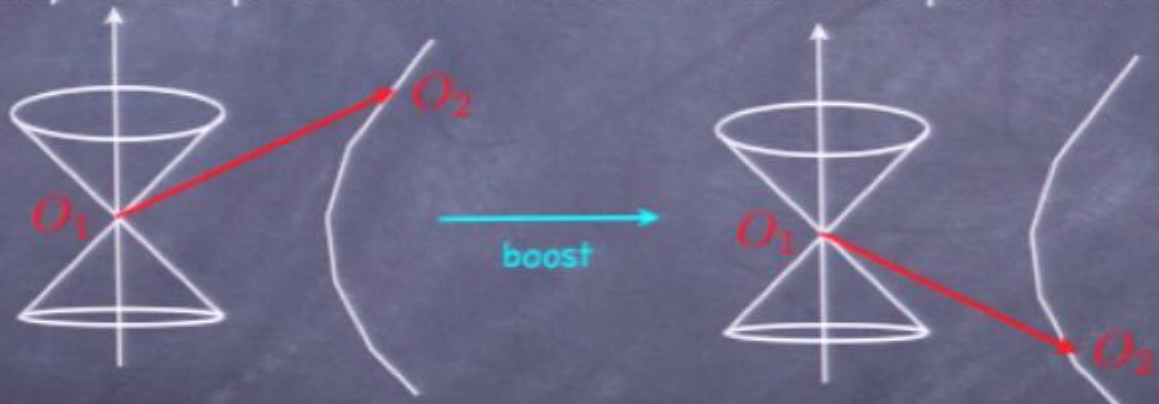
A broad overview of particle

You start to convert E -> mass
then things get truly entertaining:



Photons with energy 1.022 MeV can pair create.
No sensible single particle, consistent relativistic quantum theory is possible.

For causality to be preserved one must have the positron.



$$(\Delta t) - |\Delta \vec{x}|^2 = cst$$

Of course (a few) theorists already knew positrons had to be there. When one combines relativity and QM consistently one writes down $i\not{\partial}\Psi - m\Psi = 0$

DIRAC Eqn: Two solutions, one positron, one electron.

A broad overview of particle

This type of thinking is really the core of particle physics.
I mean this in two senses:

1. Our language is quantum fields, ie op valued functions of space-time whose dynamics are purely local.

2. Basic physical concepts like Lorentz invariance and required symmetries get expressed directly in the Lagrangian and are connected to the particle content observed. (We are symmetry addicts.)

We have been smashing stuff together for years and we have a model that explains everything we see coming out so far, its Lagrangian is in part

$$\mathcal{L} = \bar{\Psi}_i (i \not{D}) \Psi_i + (D^\mu H)^\dagger (D_\mu H) - V(H^\dagger H) - \frac{1}{4} G^A_{\mu\nu} G_A^{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \frac{1}{4} W^a_{\mu\nu} W_a^{\mu\nu}$$

The D^μ is a covariant derivative that is required by gauge invariance to introduce gauge fields (connections)

Field strengths of the gauge fields.

Gauge field quanta γ, W, Z, g^A

The standard model

The standard model has $SU(3) \times SU(2) \times U(1)$ gauge symmetry

EW theory:
radoactivity,EM
has a scale $v \sim 246\,\mathrm{GeV}$

QCD:
has a scale $\Lambda_{QCD} \sim 200\,\mathrm{MeV}$

We are symmetry addicts and we are interested in the scales in the problem. Scales set the masses of things and also the differences between masses are interesting.

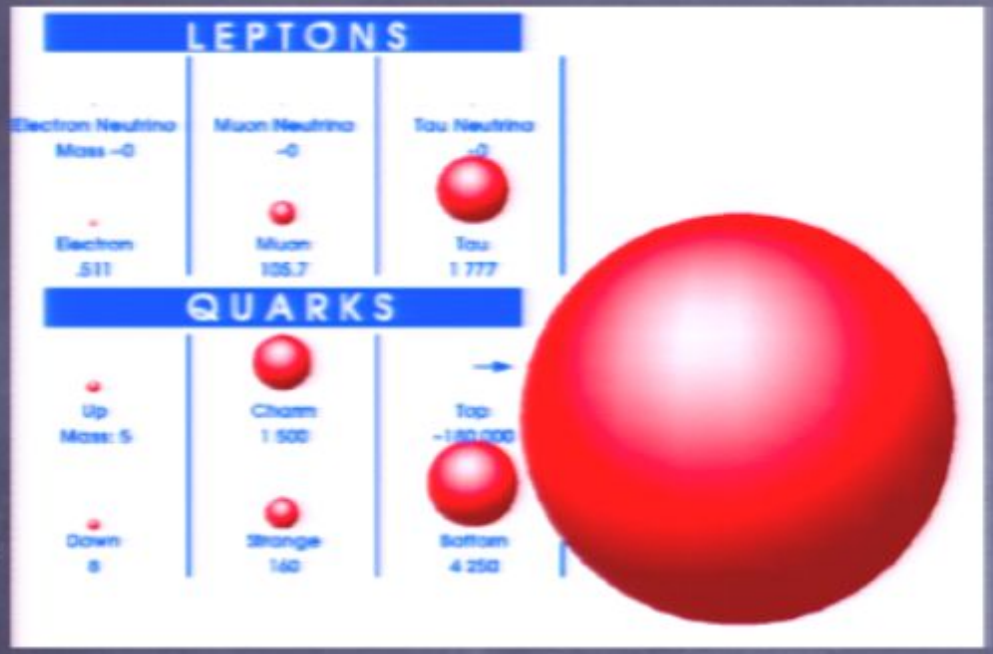
$v \sim 246\,\mathrm{GeV}$ Sets the masses of elementary particles

$\Lambda_{QCD} \sim 200\,\mathrm{MeV}$ Sets the scale of Hadronic muck.

We have quite a pattern of masses in the SM!

Boy o Boy have we found different masses

...and Girl o Girl.....



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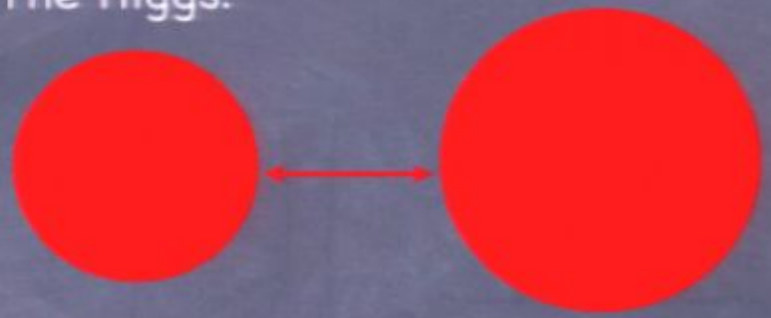
http://www-d0.fnal.gov/Run2Physics/WWW/results/final/TOP/T05D/T05D_files/aq_particle_mass_small.gif

The Higgs:



We better have a very good explanation for all these masses right?

I just said we have 2 scales $v \sim 246\,\mathrm{GeV}$ $\Lambda_{QCD} \sim 200\,\mathrm{MeV}$

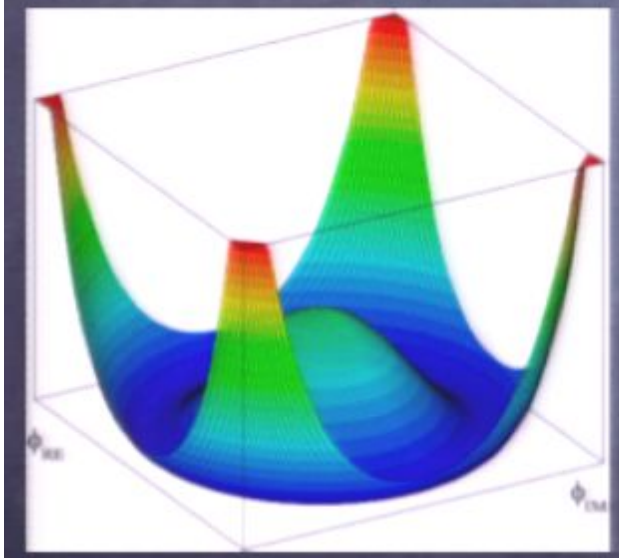
What is going on to give all the different masses?

We don't KNOW.

But we have a pretty good idea that has a lot of evidence to support it.

You do not just write masses down in the Lagrangian, that violates $SU(3) \times SU(2) \times U(1)$ gauge invariance.

We give masses to things by taking the Higgs and giving it a vacuum expectation value (by hand) with a potential



$$V(H^\dagger H) = \frac{\lambda}{4}(H^\dagger H - v^2/2)^2$$

So when you expand around the minimum of the potential the Higgs gets a vev $\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$

and through Yukawa couplings of the form

$$\mathcal{L}_Y = g_u^{ij}\, \bar{u}^i_R H^T \epsilon Q^j_L - g_d^{ij}\, \bar{d}^i_R H^\dagger Q^j_L - g_e^{ij}\, \bar{e}^i_R H^\dagger L^j_L + h.c.$$

The masses of the quarks and leptons get their masses from particular yukawa couplings times the scale $v \sim 246\,\mathrm{GeV}$

The Higgs and its consequences

So for the quarks and leptons we say a particular mass is $m_i = \frac{y_i v}{\sqrt{2}}$

Huge range in masses due to a huge range in couplings, easy right?

THIS COULD DEEPLY OFFEND YOU.

But we actually think this is what is happening! Many tests work.

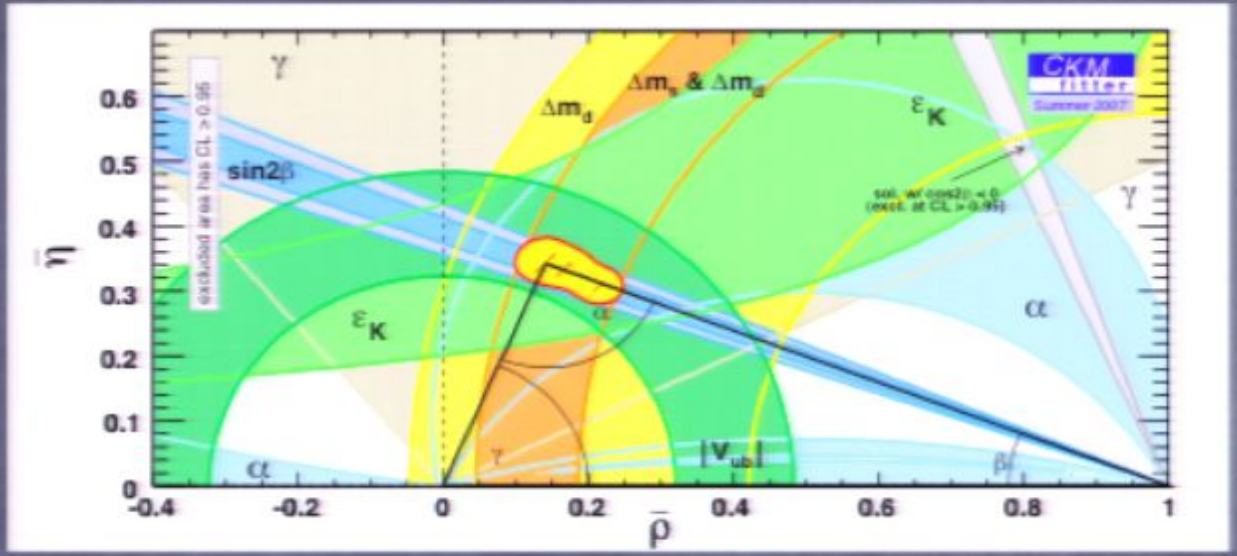
What you actually get out of $\mathcal{L}_Y = g_u^{ij}\,\bar{u}_R^i H^T \epsilon\, Q_L^j - g_d^{ij}\,\bar{d}_R^i H^\dagger\, Q_L^j - g_e^{ij}\,\bar{e}_R^i H^\dagger\, L_L^j + h.c.$

are mass matricies. They need to be rotated to go to mass eigenstates. The different mass matricies of the up and down type quarks are rotated differently.

This gives something known as the CKM matrix $V = \mathcal{U}(U,L)^\dagger\,\mathcal{U}(d,L)$

3x3 unitary matrix

What is going on in Particle now/recently:
1 The CKM matrix



from ckmfitter

Another Noble 2008
Kobayashi/Maskawa

Unitarity constraint $\sum_k V_{ik} V_{jk}^* = \delta_{ij}$ $\qquad V_{ud} V_{ub}^* + V_{cd} V_{cb}^* + V_{td} V_{tb}^* = 0$

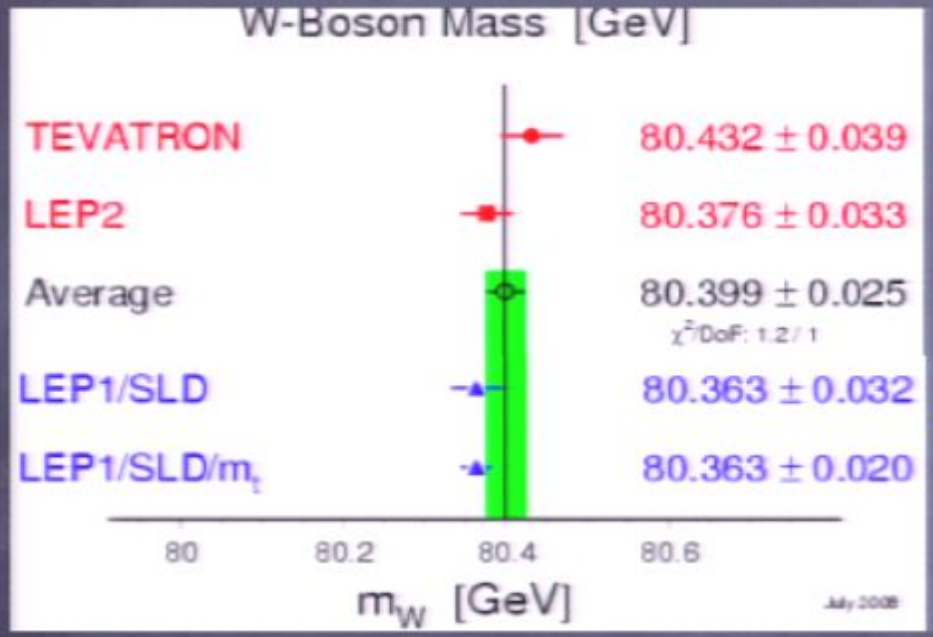
This matrix is just a representation of a basis change, it should be unitary!

Many, many different tests of this in the 1990'2 -> today.
THIS THING WORKS.

This cost a lot of money, and is very non trivial information that the CKM is consistent with this picture. Not really a pure test of the Higgs but many other schemes can have trouble doing this.

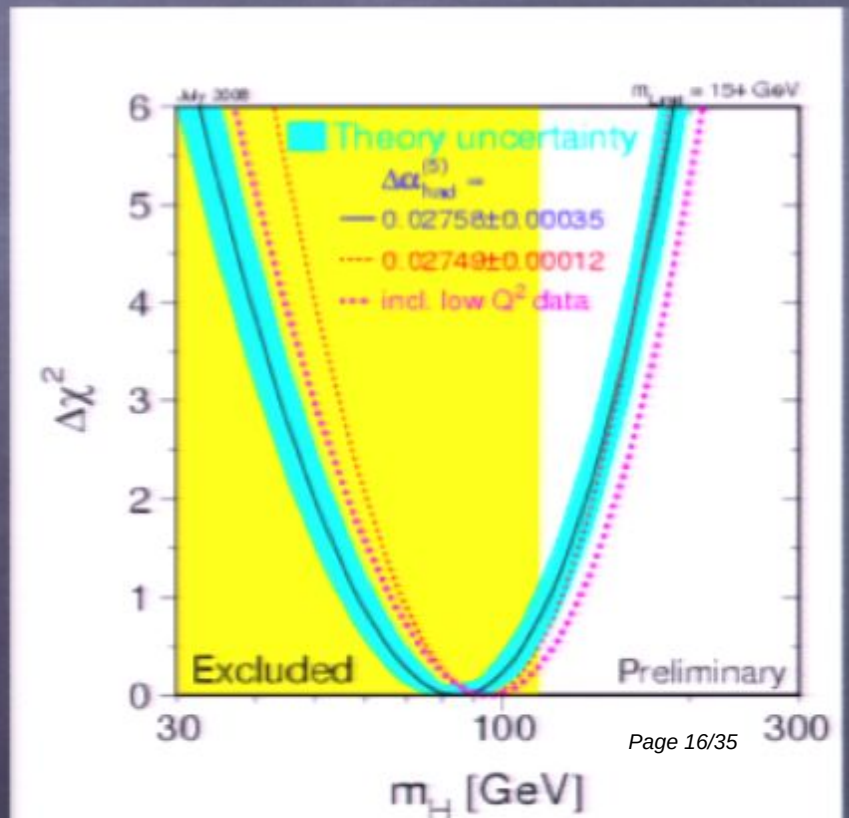
What is going on in Particle now/recently: 2 EW precision

Even though we haven't seen the Higgs directly we see its footprint.



LEP electroweak working group arXiV:0712.0929
and see http://lepewwg.web.cern.ch/LEPEWWG/

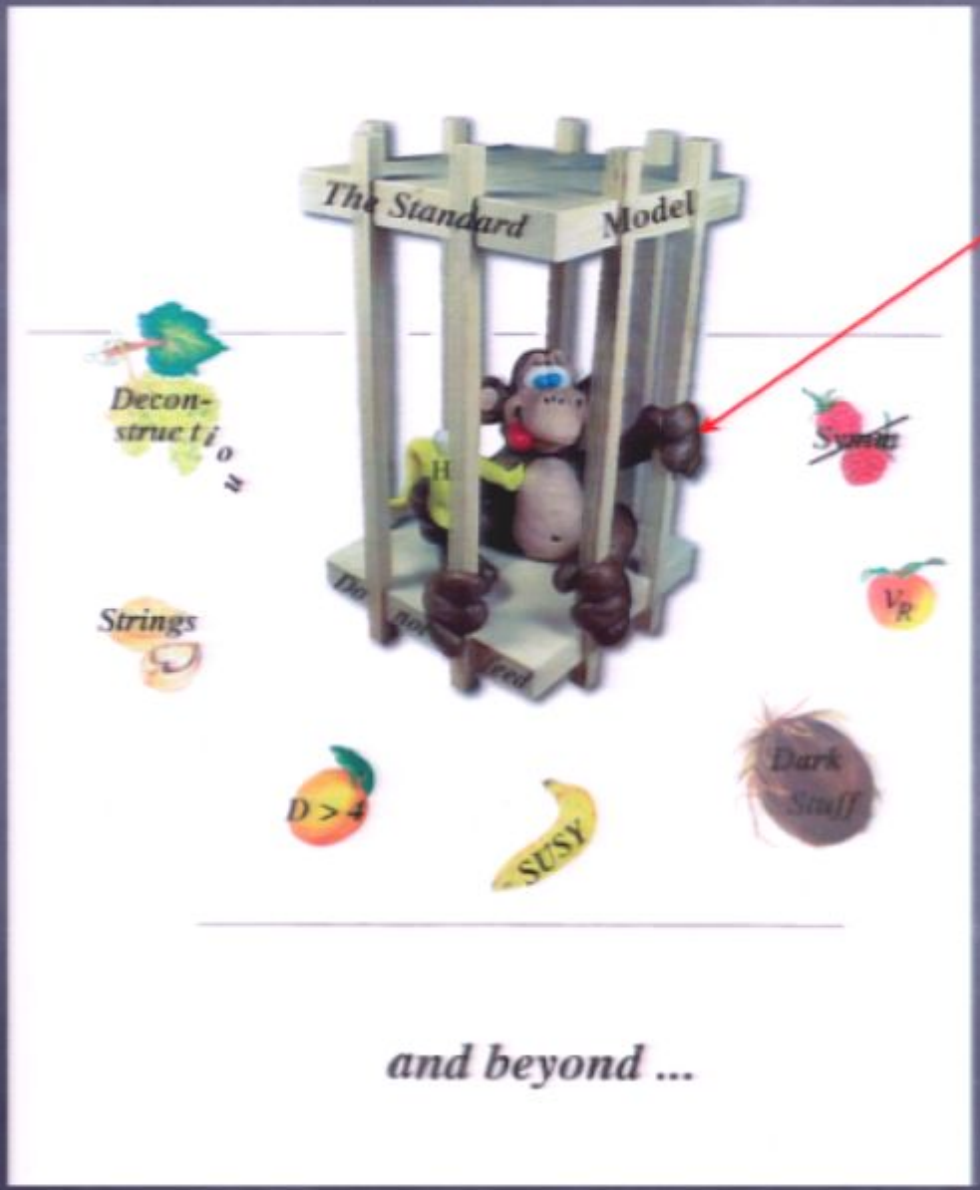
Here is an example of indirect evidence for a mass and then the direct measurements. This approach works!



Measuring many properties of the Z pole at LEP a best fit indicates that the Higgs exists and that it will be found at LHC.

The Higgs is unsatisfying but it seems to work.

The intellectual cage of the SM



Lange/Trott Tasi2002 t-shirt suggestion

Take heart, there are many good reasons to think that the Higgs isn't the end of particle physics, but the start of a new age of discovery.

What is going on in Particle now/recently: 3 The need for new physics beyond SM

We need new particle content beyond the standard model to explain DM

galaxy cluster 1E 0657-56

See papers
http://arxiv.org/abs/astro-ph/0608407
http://arxiv.org/abs/astro-ph/0608408

DM is real, deal with it. And there is 5X more of it than standard ordinary baryonic matter of the SM. The SM does not explain DM.

Also the standard model alone (with no higher scale physics) cannot explain the observed baryon asymmetry of the universe.

What is going on in Particle now/recently: 4 DM speculation

DM arguably has something to do with the Higgs and EW sym breaking

One can derive from astrophysics alone that for a WIMP the typical cross section is about the size of an electroweak cross section: $\langle \sigma v \rangle = 1\,p$

see 0810.4995

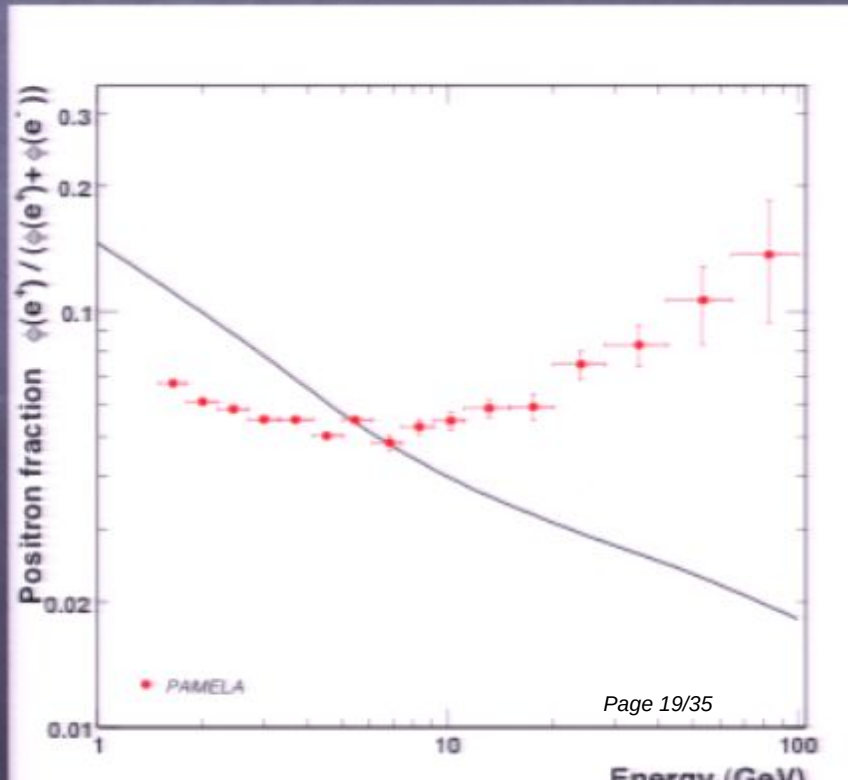
Typical mass: $100\,\mathrm{GeV} - 1\,\mathrm{TeV}$

This is suspiciously close to EW cross sections and masses.

We could see it at LHC!

Direct evidence this October? ⟶

$$\chi\chi \to e^+ e^-$$



What is going on in Particle now/recently: 5 Utter agony over the Hierarchy problem

We have all these non trivial tests telling us the Higgs exists.

1 It is consistent with CKM/flavour sector.
2 EW precision data, etc etc

The Higgs probably exists and will be found soon (once we fix LHC).

Dirty little fact. The Higgs doen't make any sense (alone) in QFT.

Symmetry is important remember. No Symmetry in the SM makes the Higgs have a mass $\geq 114.4\,\mathrm{GeV}$ $\leq 150\,\mathrm{GeV}$.

What mass should the Higgs have in the SM?

- The divergence of the Higgs mass is a big problem

$$\left(\frac{m_t^2}{v^2}\right)\frac{3\mathcal{M}^2}{8\pi^2}$$

$10^{15}\,\mathrm{GeV}$ ← cut off of theory

This is a serious discrepancy of size 10^13!!!!!!!

What is going on in Particle now/recently:
5 Utter agony over the Hierarchy problem

But wait! Remember that parameters are renormalized in the SM due to the party in the vacuum. Everything is divergent until you renormalize.

$$m_H^{measured} = M_{bare} + \lambda_1 v^2 + (\frac{m_t^2}{v^2}) \frac{3\mathcal{M}}{8\pi^2} + \cdots$$

Could be that this happens to be
- 5,123,515,871,592,025 GeV

Could be that this happens to be
5,123,515,871,592,140 GeV

Then $m_H^{measured} = 5,123,515,871,592,140 - 5,123,515,871,592,025$
$= 115\,\mathrm{GeV}$

This could be the answer. If it is, I am retiring in disgust and becoming a hermit.

Generally, we don't think this is the answer.
We think that New Physics has to come in and fix this.

What is going on in Particle now/recently: 5 Utter agony over the Hierarchy problem

History gives us hope. We have had very similar problems in the past.

Classical electron self energy was infinite as $r_e \to 0$!

$$m_e = \int_{r_e}^{\infty} dr(4\pi r^2)\frac{1}{2}\left(\frac{q^2}{4\pi r^2}\right)^2$$

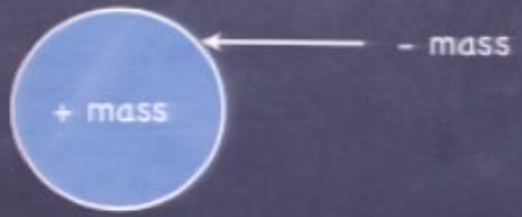
$$m_e = \frac{q^2}{8\,\pi\, r_e}$$

Classical electron radius re about 10^(-15)

$$r_e = \frac{1}{137}\frac{\hbar}{m_e c}$$

Positron came in at exactly the right energies/scale to solve this problem.

Before the positron people were thinking of fine tuning too, Lorentz and Abraham gave the mass shell of the electron a negative mass to fix the problem, same spooky cancelation idea.



What is going on in Particle now/recently:
5 Utter agony over the Hierarchy problem

How can New Physics fix this?

Many particle physicists spend lots of time building models that fix this.

To forbid a mass term correction in loops you need a symmetry.

What is going on in Particle now/recently: 5 Utter agony over the Hierarchy problem

How can New Physics fix this?

Many particle physicists spend lots of time building models that fix this.

To forbid a mass term correction in loops you need a symmetry.

The good models have a simple symmetry built in that forbids $\mu^2 H^\dagger H$

$$H \to H + \delta H$$

Use a shift symmetry on H,
Pseudo-Goldstone Higgs Models

Relate the Higgs to a Gauge field and forbid the mass term by Gauge symmetry
Extra Dimension Models

Relate the Higgs to a fermion field and use chiral symemtry to forbid its mass: SUSY

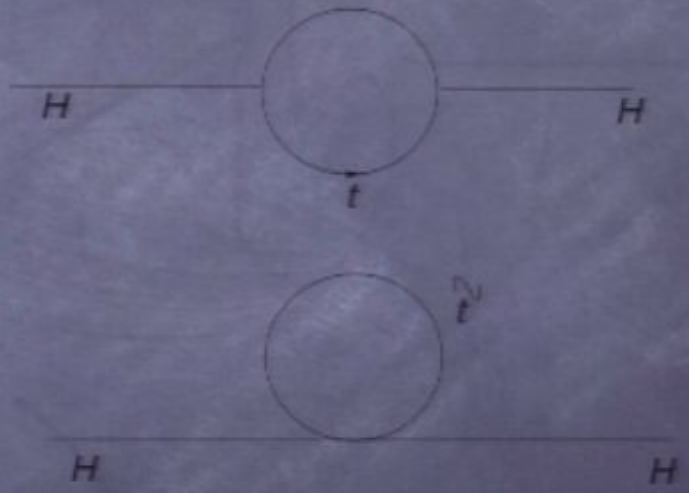
Or lower the cut off scale of the theory, Strong EW sym breaking (techni-theories), extra dimension models again.

What is going on in Particle now/recently:
5 Utter agony over the Hierarchy problem

SUSY is by far the prettiest way to get it done.

It is mathematically beautiful, elegant and particle physics is full of people convinced reality is Supersymmetric.

How does it work? Every SM particle
has a Super partner that is degenerate
in mass but different by spin 1/2.
Then the loops cancel out.
(just like for antiparticles a beautiful soln!)



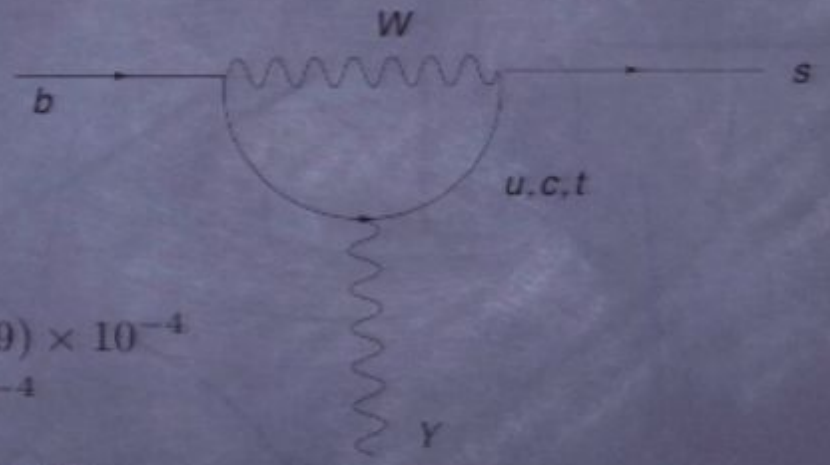
This has got to be right!
Except, the only reason to believe the Higgs is it explains the data.
What does data say about SUSY?

What is going on in Particle now/recently: 5 Utter agony over the Hierarchy problem

SUSY has one problem, but it is a big one. DATA.
It was believed (by many) that it should effect flavour physics (that CKM)

We find no direct evidence for its existence in reality (yet) and we have been looking pretty hard for it.

One Loop process, SUSY could directly effect this at one loop



DATA $B(\bar{B} \to X_s \gamma) = (3.52 \pm 0.23 \pm 0.09) \times 10^{-4}$

SM no SUSY $B(\bar{B} \to X_s \gamma) = (3.15 \pm 0.23) \times 10^{-4}$

serious work here 20000 loops at 4th order calculated!!!!!!!!! see [hep-ph/0612329

Options: 1) Build SUSY models that avoid this problem, it can be done.
2) Think about alternate models and have SUSY at a higher scale.

What is going on in Particle in the Near Future

Particle physicists fight about this but on balance people believe in SUSY. Other models do compete with SUSY, but it is the 800 lb gorilla.

Soon the fights will end as DATA in the form of LHC is coming.

I promised you the LHC WOW moment. Here it is.

Remember that Crockcroft guy?

He went on to found a little place called CERN that is soon to have the newest biggest particle physics collider working.

Proton-Proton Collider they move at .99999999 c

27 km, (17 mi) circumference, (remember we started at 7m)

14 TeV energy (factor of 10^9 increase in energy)

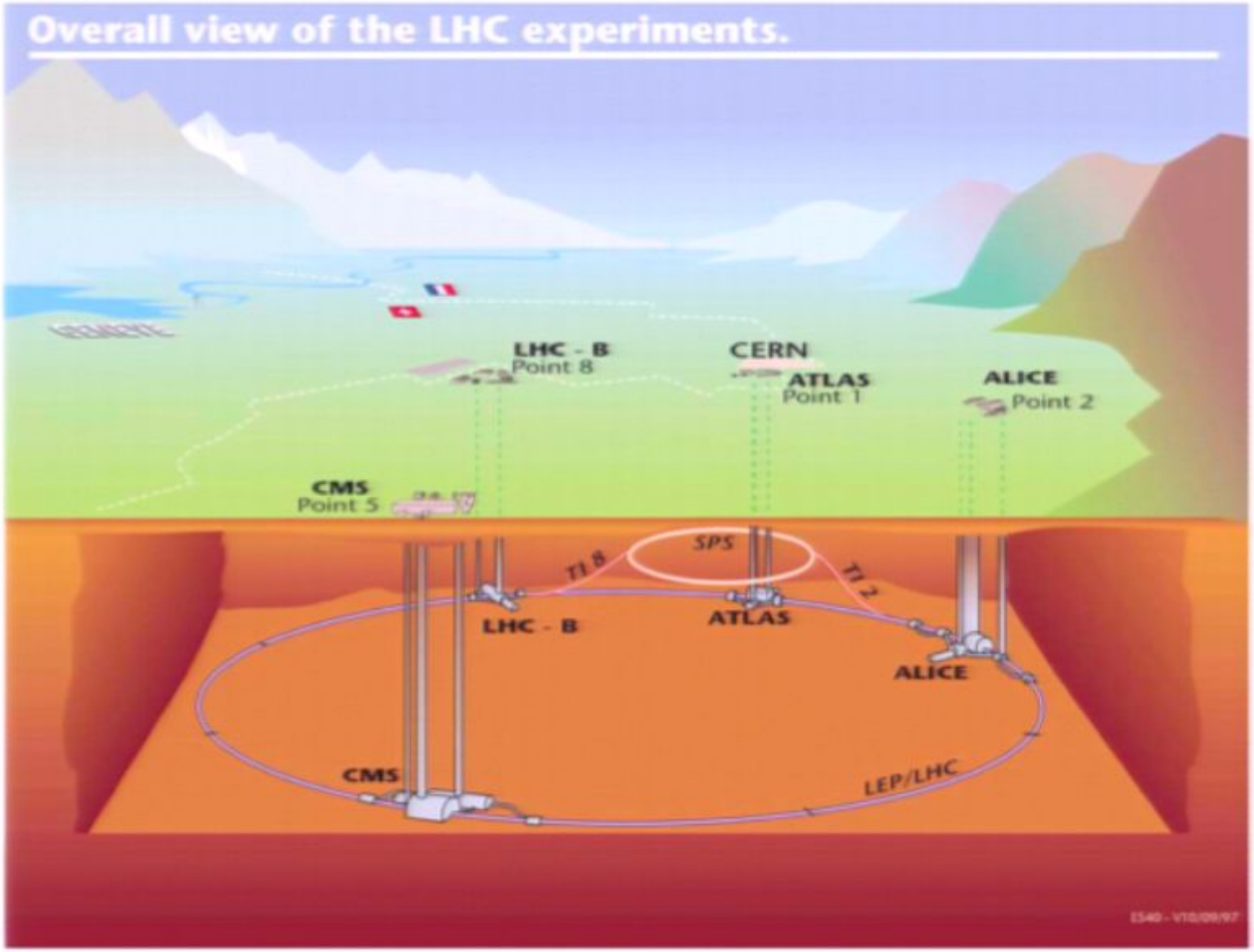
> 3.2 - 6.4 Billion cost (this went up a lot too!)

Largest exp ever in physical size, about 6000 physicists working on it, it is 300ft down, 16 miles of superconducting magnets

What is going on in Particle in the Near Future

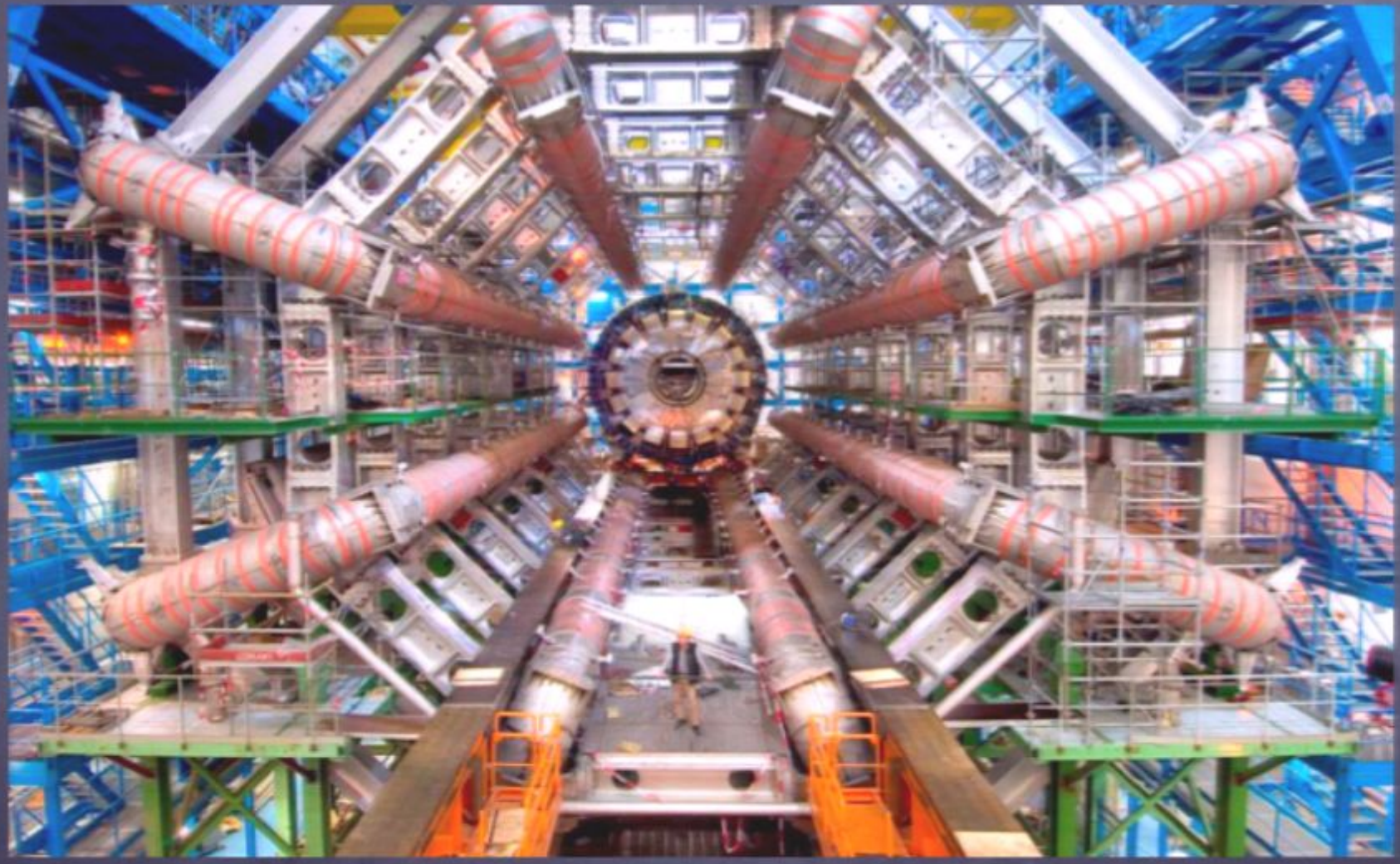
LHC is magnificent.

What is going on in Particle in the Near Future



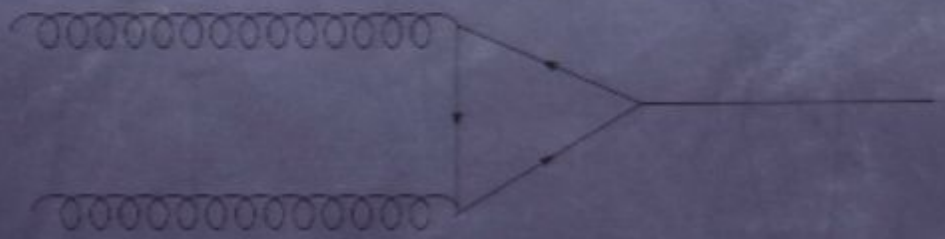
300 ft

What is going on in Particle in the Near Future



What is going on in Particle in the Near Future

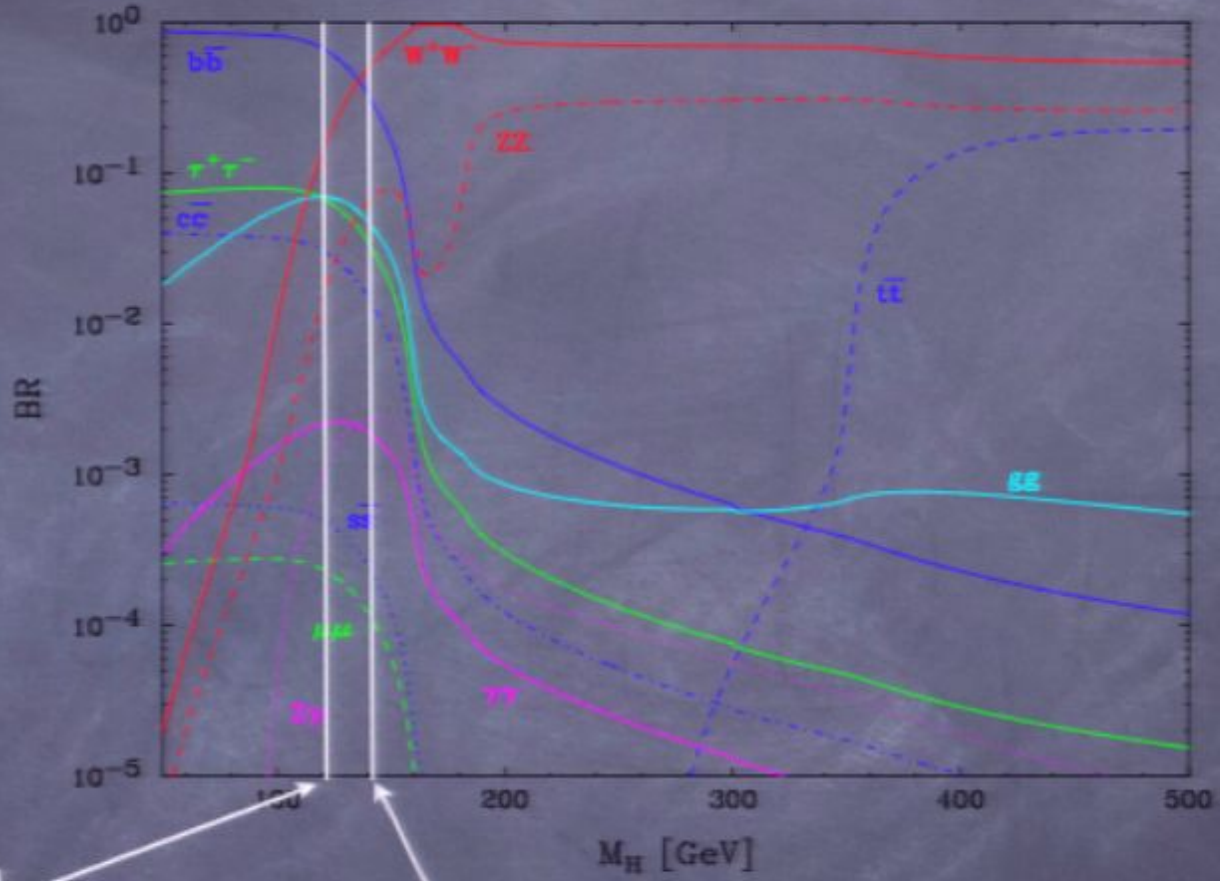
Really it is a gluon collider that should make a lot of Higgses.



This is how we make the Higgs, how will we detect it?

What is going on in Particle in the Near Future

Branching ratios of the Higgs in the SM, these will change in the context of NP.



Smart money is on a Higgs with mass about 120 GeV

Once the higgs mass gets up to 140 GeV it is really easy to see

What is going on in Particle in the Near Future

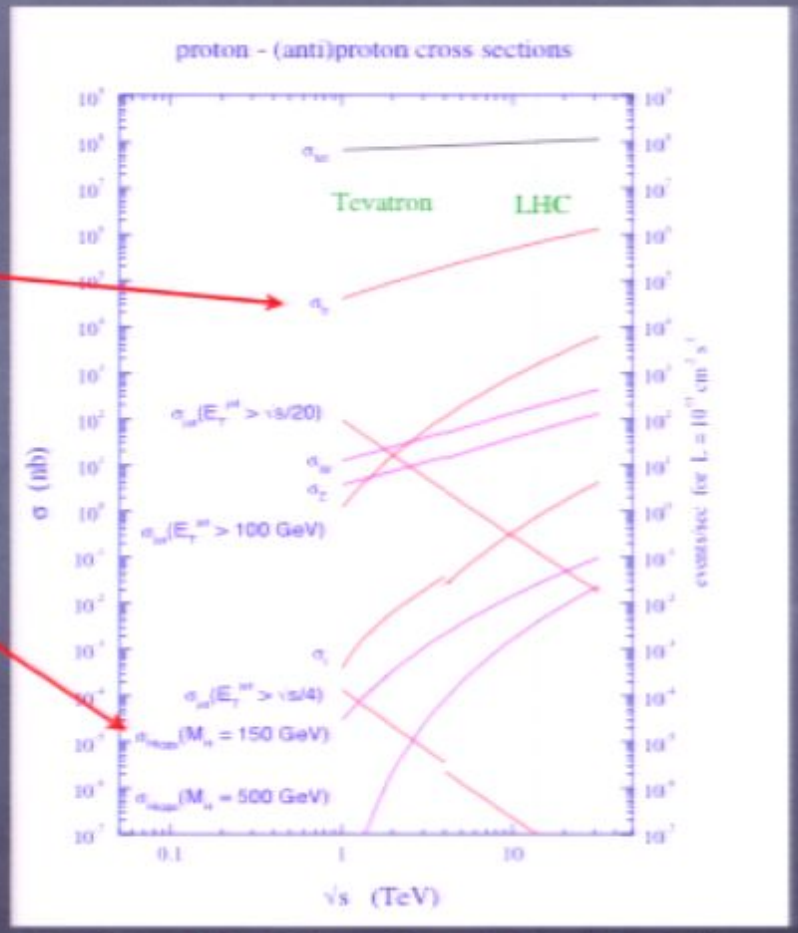
How will we find the Higgs?

Obviously this process ...

...is much more likely than this process

(multiply by BR(h->bb) = 0.179 for a 150 GeV h)

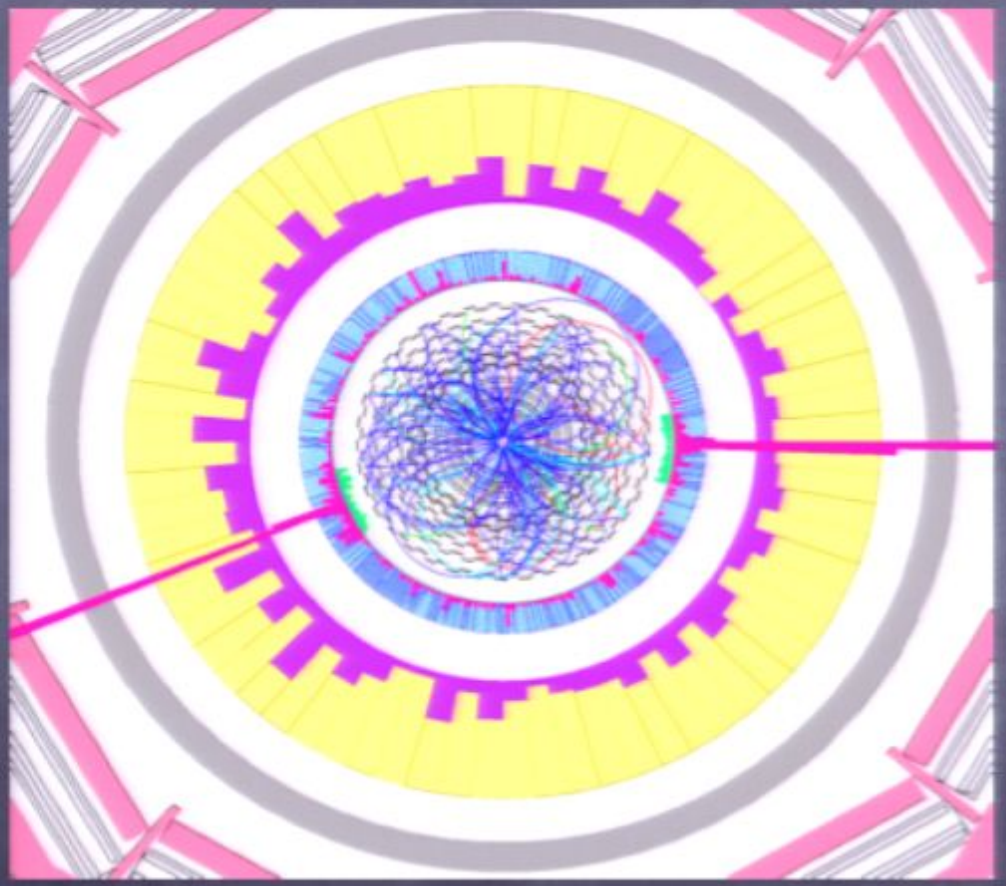
This is a log scale. Ouch.



F. Gianotti, Phys. Rep 403 (2004)

Even though h -> bb is the biggest decay, it is too hard to see.

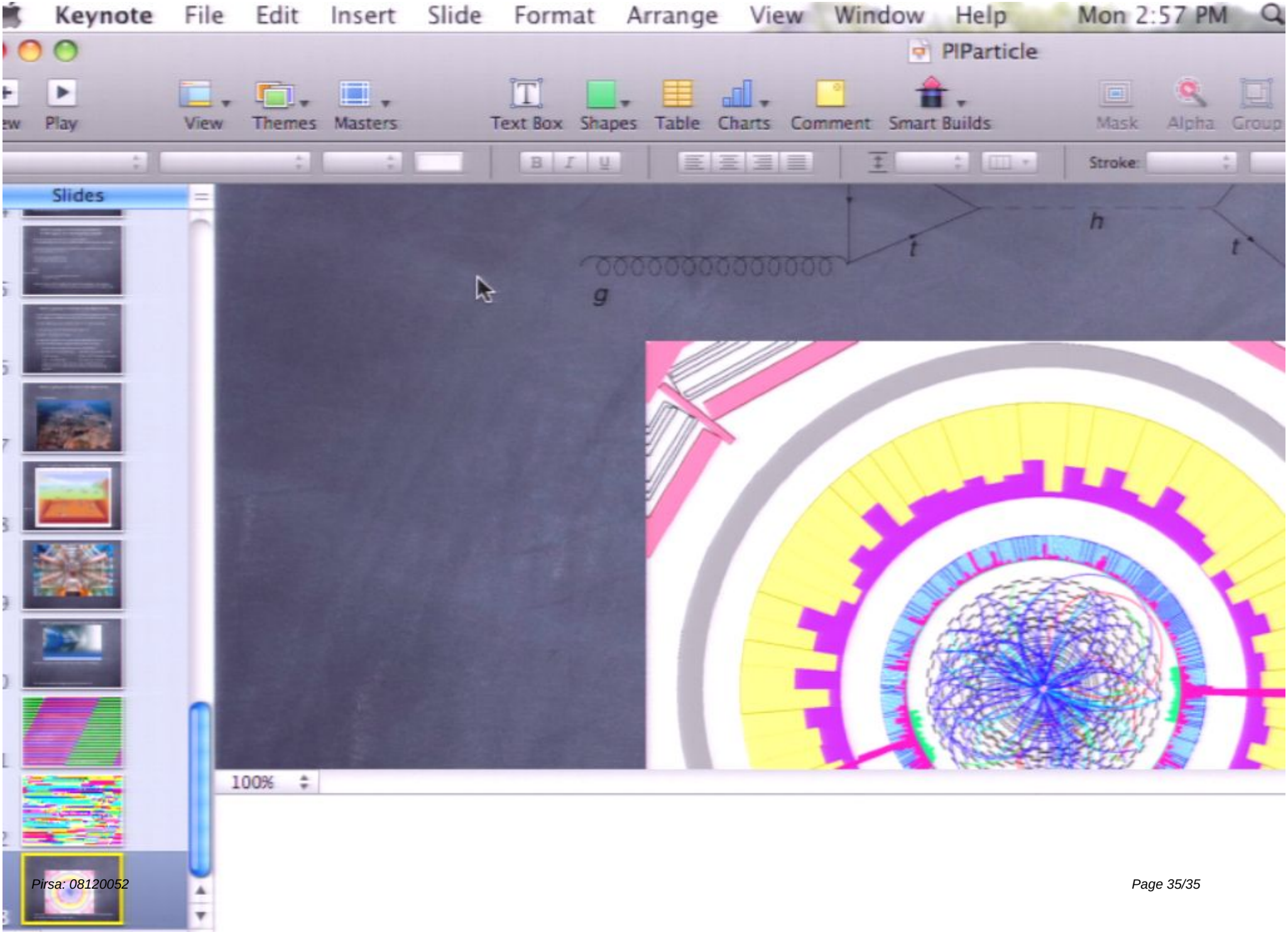
What is going on in Particle in the Near Future



CMS TDR

This is a h -> gamma gamma event simulated by CMS, this could be how we discover the origin of mass, soon.

Stay tuned!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