Title: Collider Experiments 4

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Abstract:

Colliders Four

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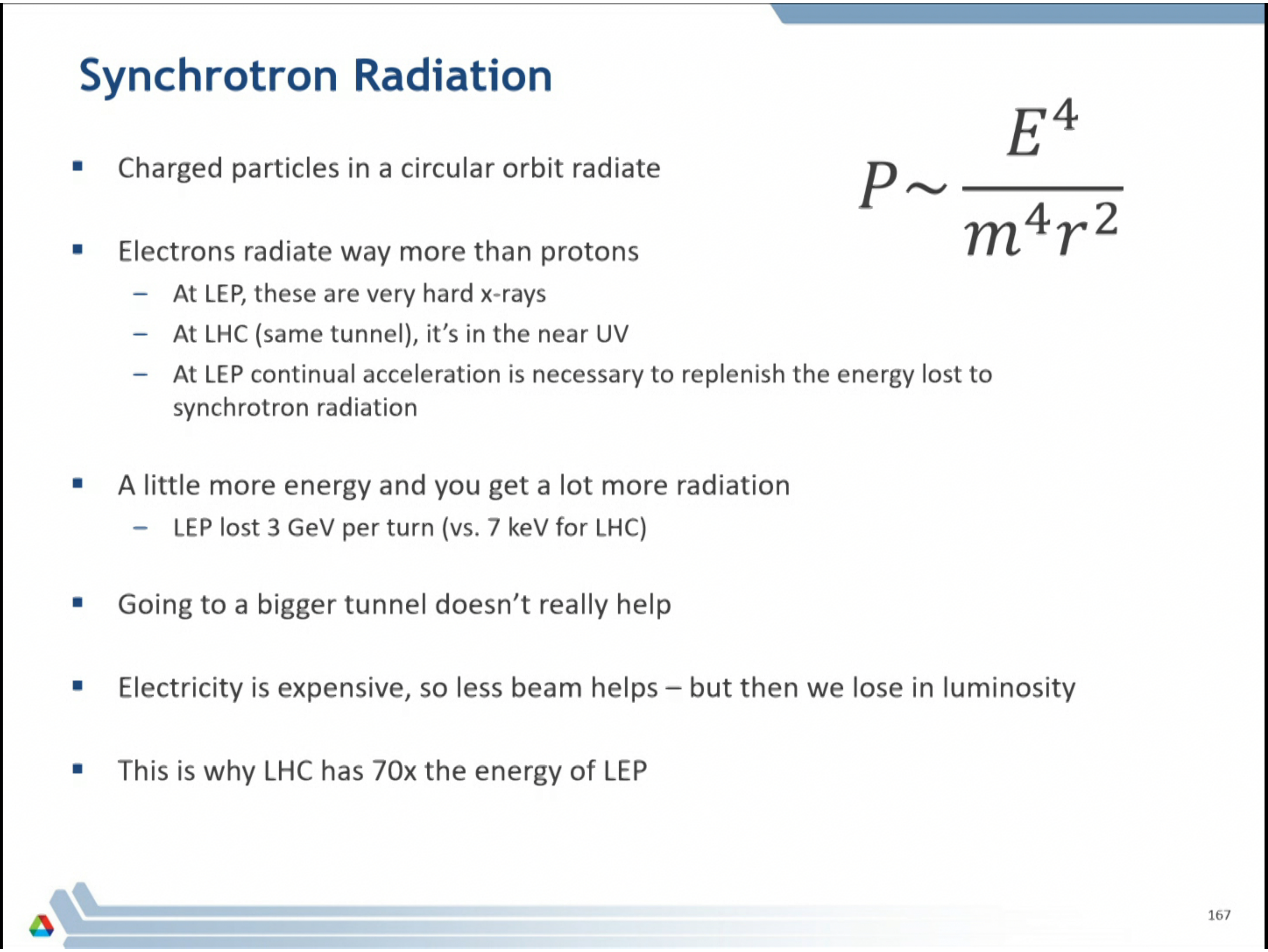


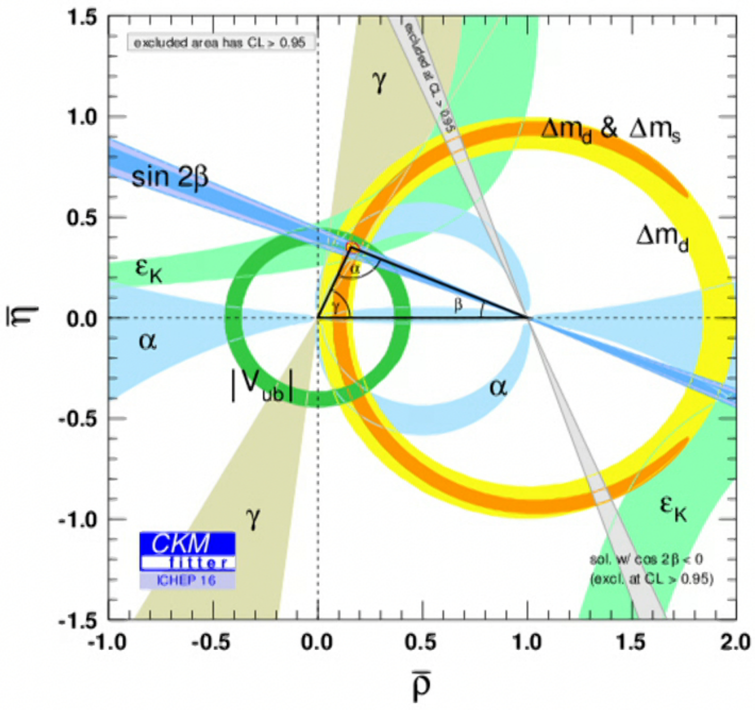
Synchrotron Radiation

$$P \sim \frac{E^4}{m^4 r^2}$$

- Charged particles in a circular orbit radiate
- Electrons radiate way more than protons
  - At LEP, these are very hard x-rays
  - At LHC (same tunnel), it's in the near UV
  - At LEP continual acceleration is necessary to replenish the energy lost to synchrotron radiation
- A little more energy and you get a lot more radiation
  - LEP lost 3 GeV per turn (vs. 7 keV for LHC)
- Going to a bigger tunnel doesn't really help
- Electricity is expensive, so less beam helps – but then we lose in luminosity
- This is why LHC has 70x the energy of LEP

A Great Place for e+e-: B Factories

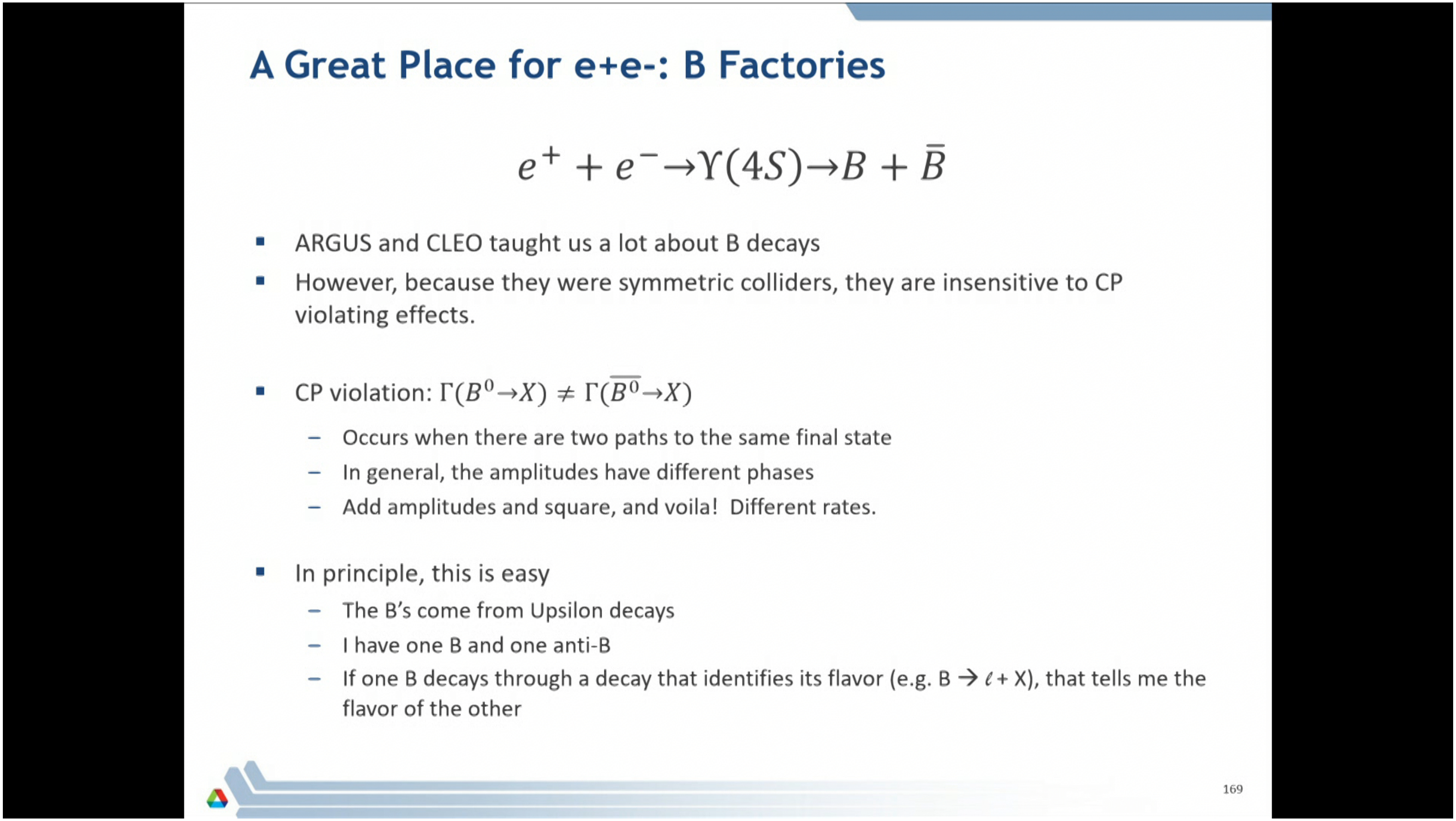
$$e^+ + e^- \rightarrow \Upsilon(4S) \rightarrow B + \bar{B}$$



The triangle is one of the CKM matrix unitarity triangles; the colored bands are ensembles of measurements.

B-decays are sensitive to processes with partial widths of order a ueV. (To compare, t, W and Z decays are all around 2 GeV)

This corresponds to a scale of new phenomena of a few TeV.



A Great Place for e+e-: B Factories

$$e^{+} + e^{-} \rightarrow \Upsilon(4S) \rightarrow B + \bar{B}$$

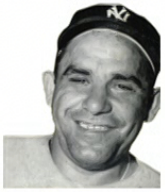
- ARGUS and CLEO taught us a lot about B decays
- However, because they were symmetric colliders, they are insensitive to CP violating effects.

- CP violation: $\Gamma(B^{0} \rightarrow X) \neq \Gamma(\overline{B^{0}} \rightarrow X)$
  - Occurs when there are two paths to the same final state
  - In general, the amplitudes have different phases
  - Add amplitudes and square, and voila! Different rates.

- In principle, this is easy
  - The B's come from Upsilon decays
  - I have one B and one anti-B
  - If one B decays through a decay that identifies its flavor (e.g. B → ℓ + X), that tells me the flavor of the other

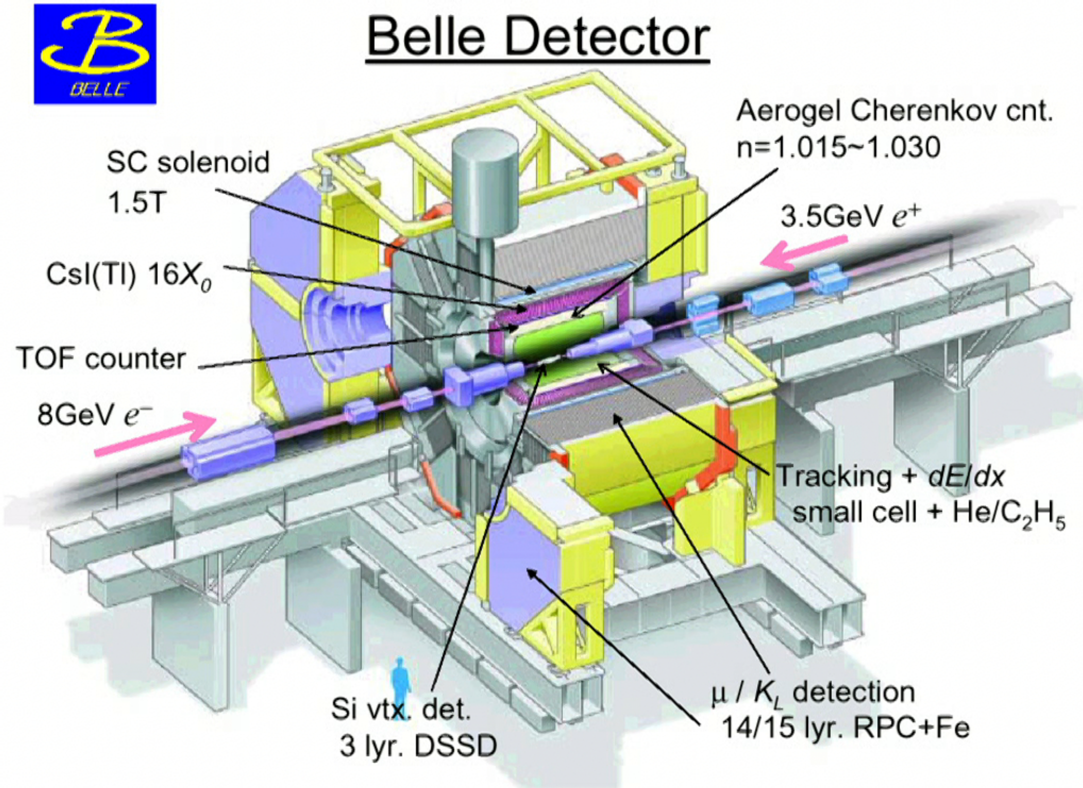
Why Asymmetric?

"In theory there is no difference between theory and practice; in practice there is."

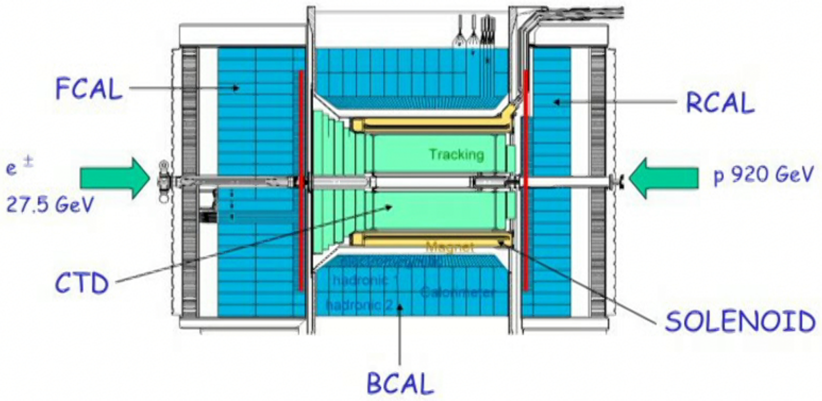


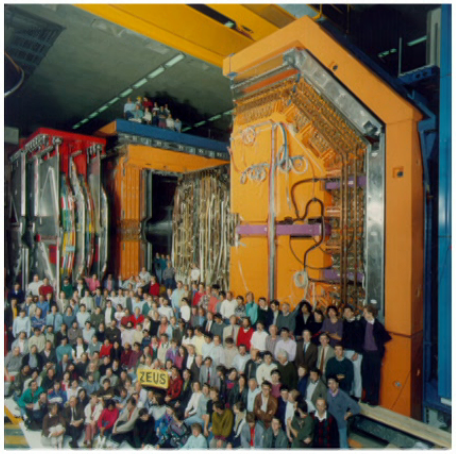
- In principle, this is easy
  - The B's come from Upsilon decays
  - I have one B and one anti-B
  - If one B decays through a decay that identifies its flavor (e.g. $B \rightarrow \ell + X$), that tells me the flavor of the other
- The problem with this argument is that the B's are entangled
  - A real-life version of the Einstein-Podolsky-Rosen paradox
  - Neither B knows its flavor until one decays into a flavor-determining mode
    - That "starts the clock" on the other one
    - Asymmetry is an odd function of t_1-t_2
    - If we don't know which B decays first, the asymmetry integrates to zero
- Solution: measure t_1-t_2
  - Boost the Upsilon so I can measure both B's decay vertices
  - That means I can't work in the center of mass frame: one beam needs more energy
    - E.g. 8 GeV on 3.5 GeV

A Detector Optimized for B Physics



Electron-Proton Collider


The ZEUS detector

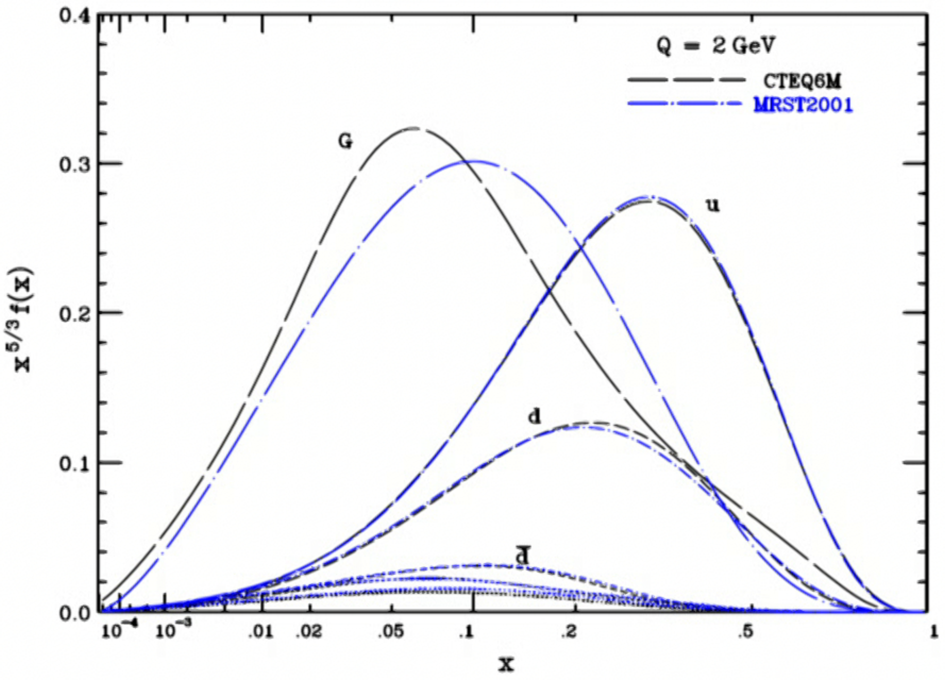


- HERA was an electron-proton collider at DESY in Hamburg, Germany, intended to study the structure of the proton

- Two experimemnts, Zeus and H1
- Proton structure probed by Deeply Inelastic Scattering (DIS):
  - What looks like an inelastic scattering between the proton and the electron is actually elastic scattering between the electron and quark (blackboard, anyone?)

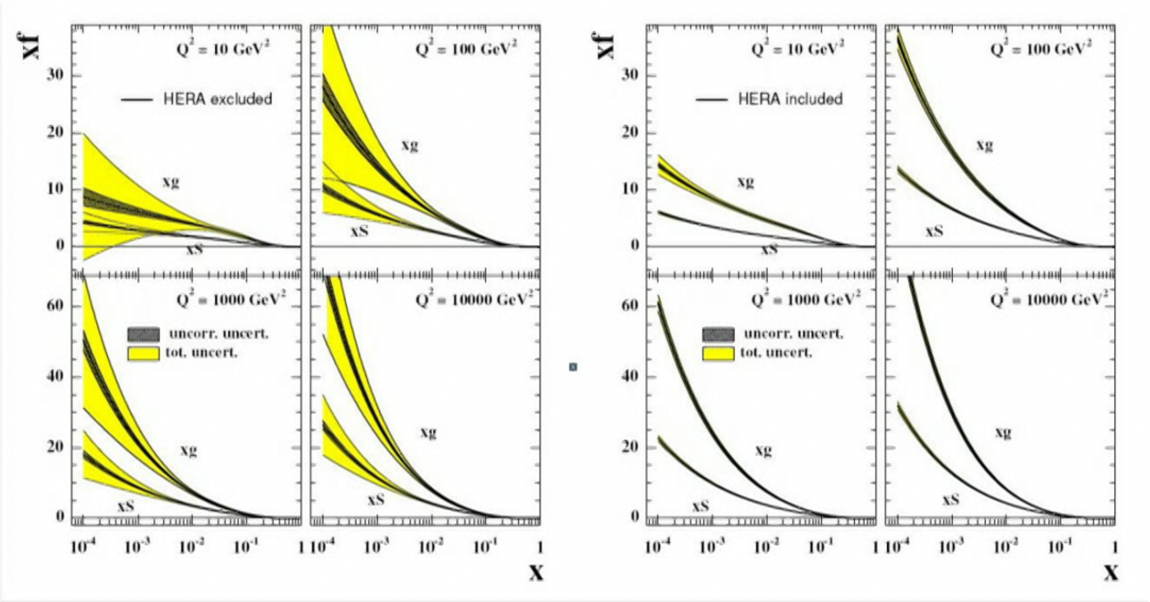
Proton Structure (Parton Density Functions) Today

- One fit from CTEQ and one from MRS is shown
  - These are global fits from all the data
- Despite differences in procedure, the conclusions are remarkably similar
  - Lends confidence to the process
- The gluon distribution is enormous:
  - The proton is mostly glue, not mostly quarks



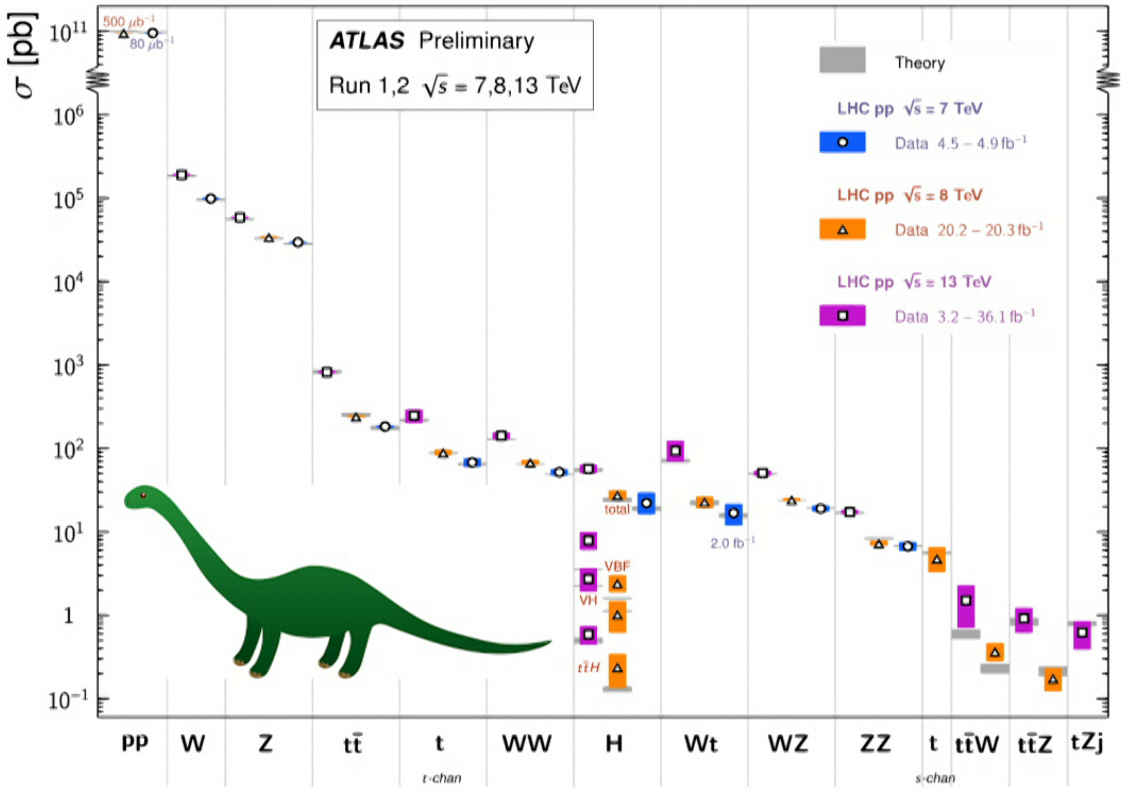
Want to know the uncertainties?
Use the Durham pdf plotter:
http://durpdg.dur.ac.uk/hepdata/pdf3.html

HERA: Before and After



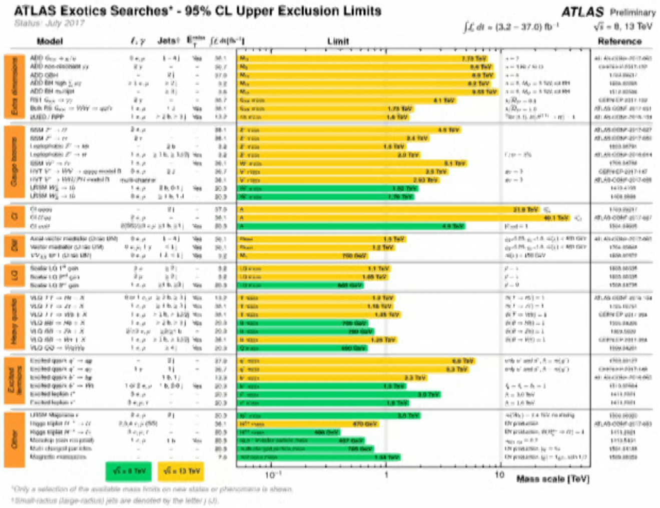
- HERA ***revolutionized*** our knowledge of parton densities
  - If you don't believe me, look at papers pre-HERA and post-HERA
  - It's even more dramatic than it looks, as the shapes in the left plots are still informed by the HERA data. Otherwise, the shapes would be more a function of imagination than of physics.
- There is still a need to explore for the LHC, where higher Q^2 matters.

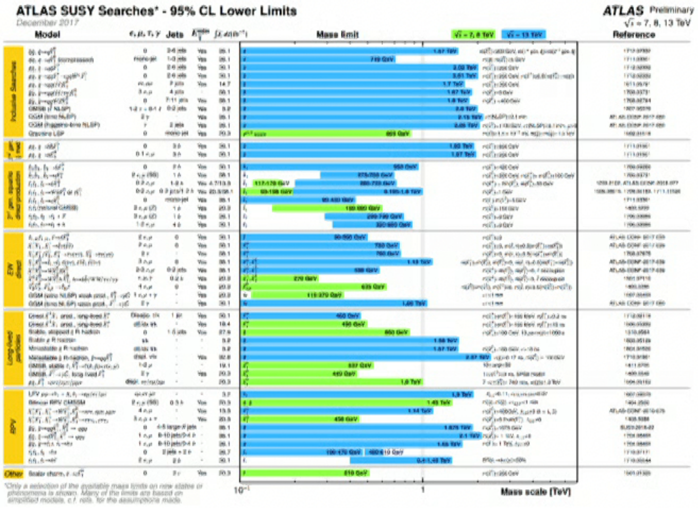
A Bevy of Standard Model Measurements



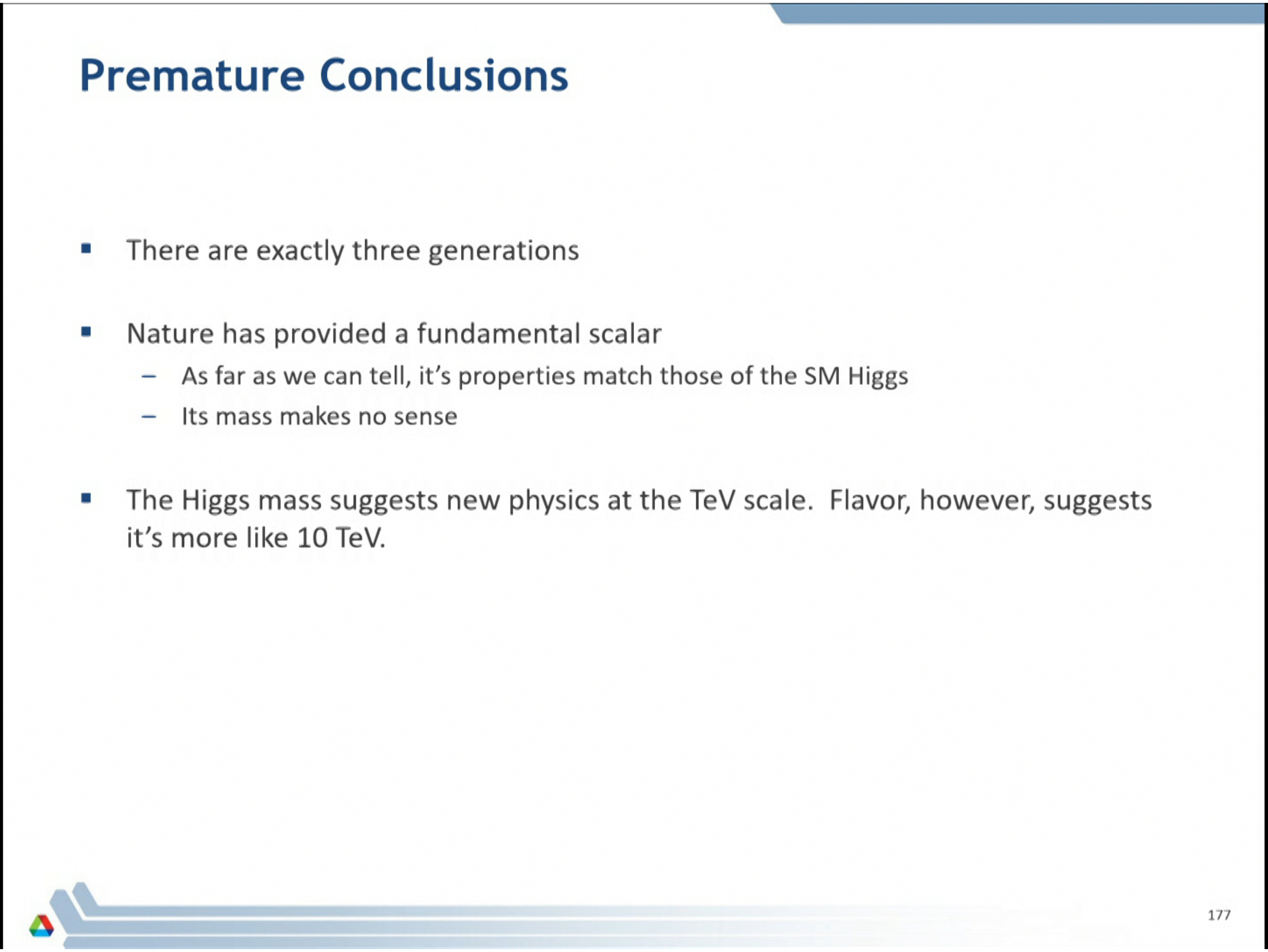
Standard Model Total Production Cross Section Measurements *Status: March 2018*

And Searches Galore



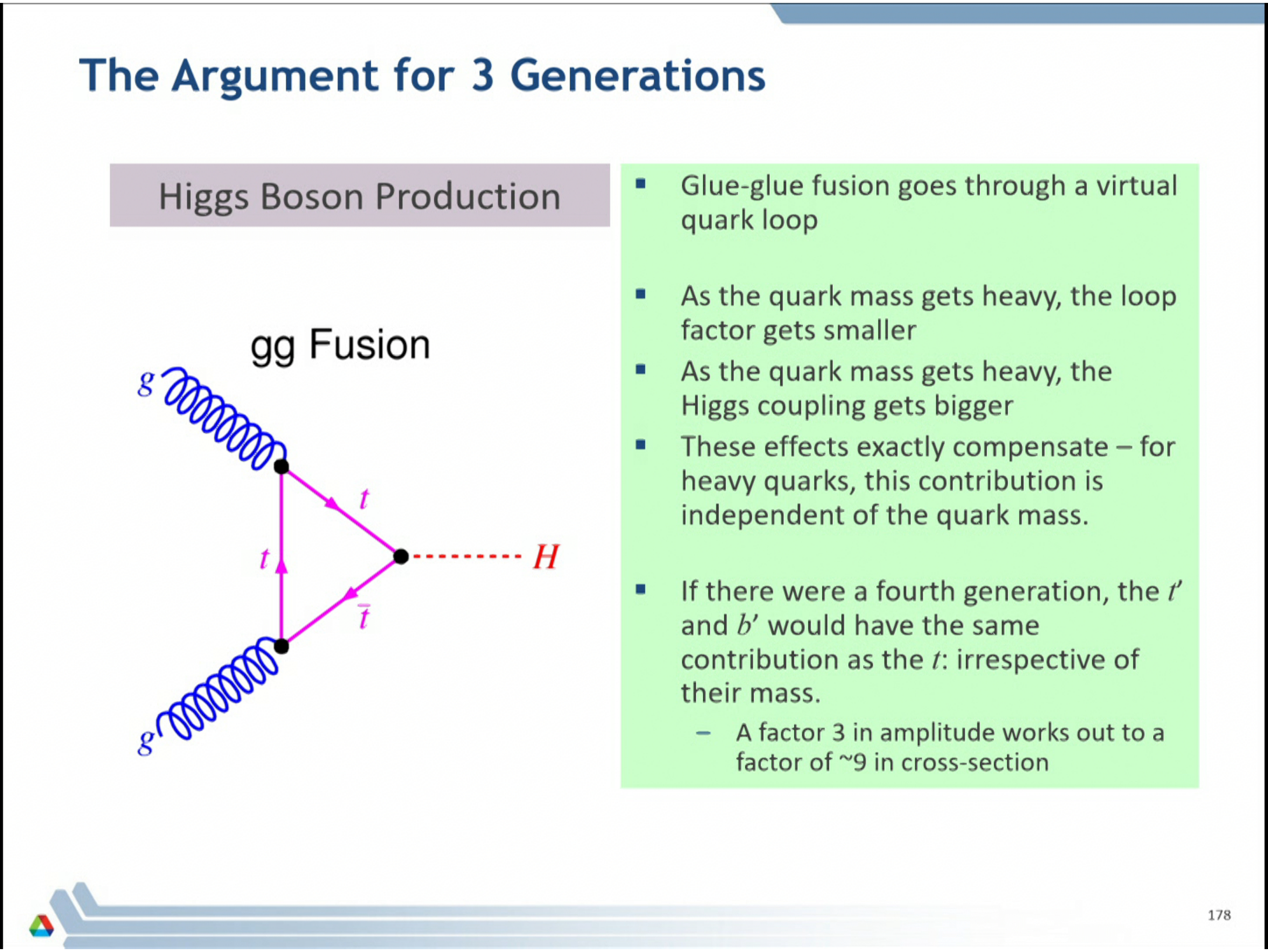


- As of last month, 349 separate search papers published on searches
  - No surprises
- In most cases, we're ~10x as sensitive as pre-LHC experiments, sometimes more, sometimes much more.



Premature Conclusions

- There are exactly three generations
- Nature has provided a fundamental scalar
  - As far as we can tell, it's properties match those of the SM Higgs
  - Its mass makes no sense
- The Higgs mass suggests new physics at the TeV scale. Flavor, however, suggests it's more like 10 TeV.



The Argument for 3 Generations

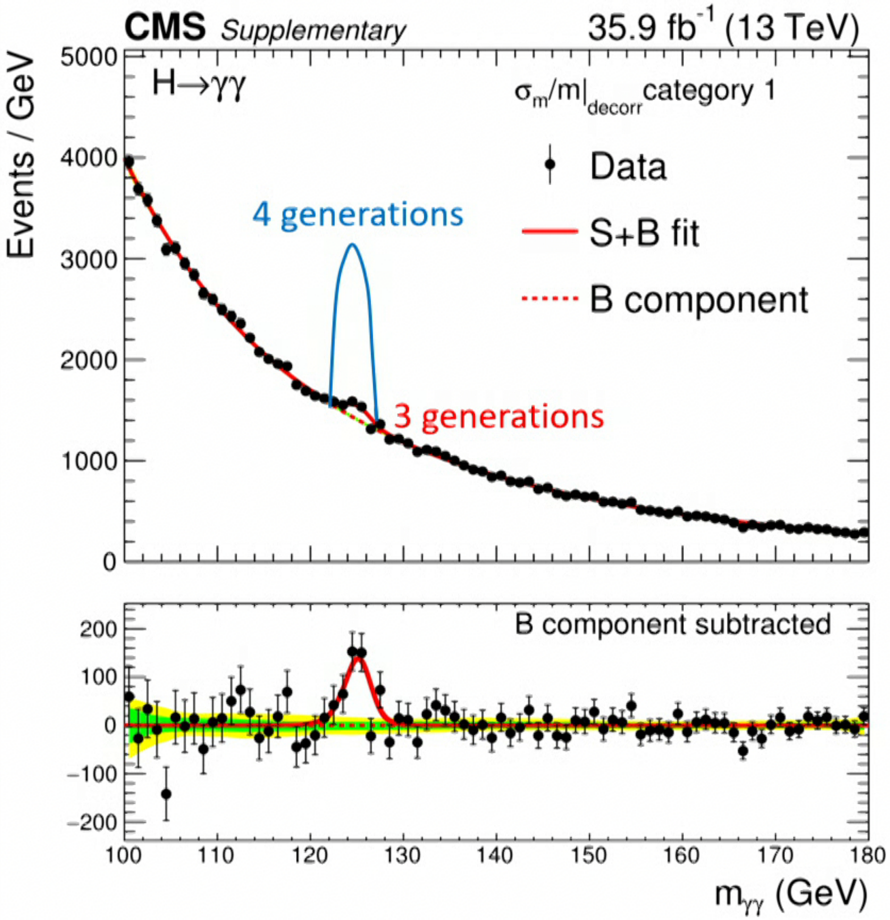
Higgs Boson Production

gg Fusion

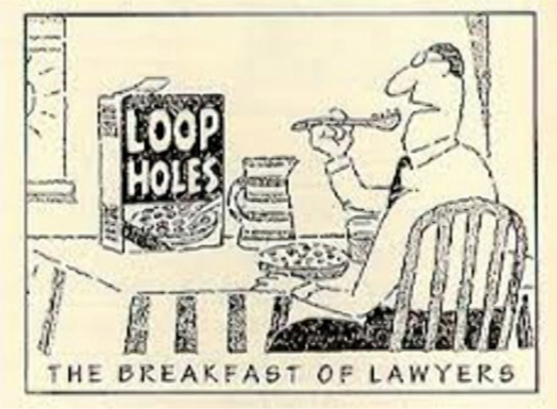
- Glue-glue fusion goes through a virtual quark loop
- As the quark mass gets heavy, the loop factor gets smaller
- As the quark mass gets heavy, the Higgs coupling gets bigger
- These effects exactly compensate – for heavy quarks, this contribution is independent of the quark mass.
- If there were a fourth generation, the t' and b' would have the same contribution as the t: irrespective of their mass.
  - A factor 3 in amplitude works out to a factor of ~9 in cross-section

Exactly 3 Generations II

- This is not a tiny or subtle effect.
- One (admittedly silly) way to look at this is that there are 3.00 ± 0.04 generations.
- Another is that we are actually more confident that there are 3 generations and not 4 than we are that the Higgs exists.



Loopholes



- This argument is for a truly sequential fourth generation
  - It's chiral
  - It gets its mass by a Higgs Yukawa from the same Higgs

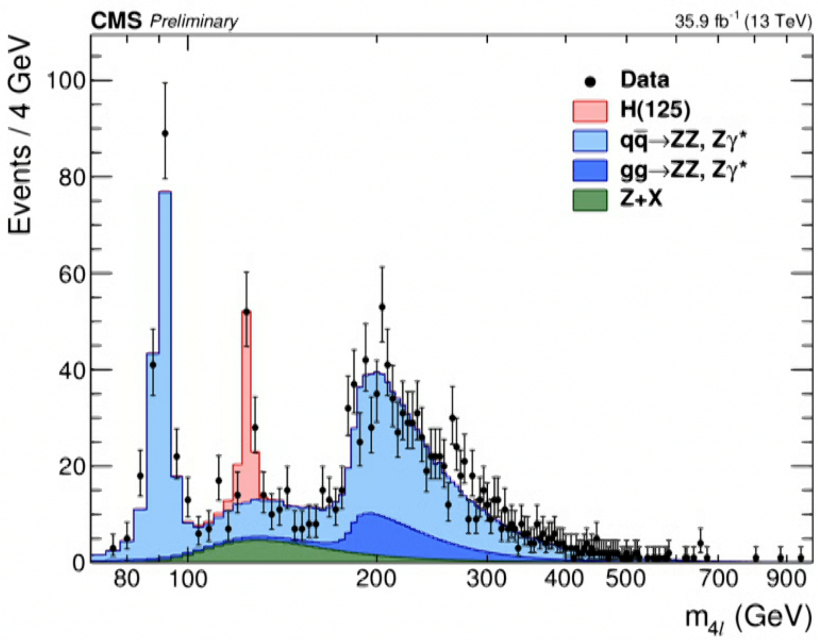
- Ways around this
  - There are vector-like families
  - There are multiple Higgs bosons, and these new particles get their mass from another Higgs
    - Strictly speaking, they get their masses from a different Higgs field, and this field has a different boson.
  - A miraculous cancellation
    - i.e. two kinds of new physics conspire to hide each other

The data tells us that there are **three and only three** sequential standard model families of fermions. **This is huge!**

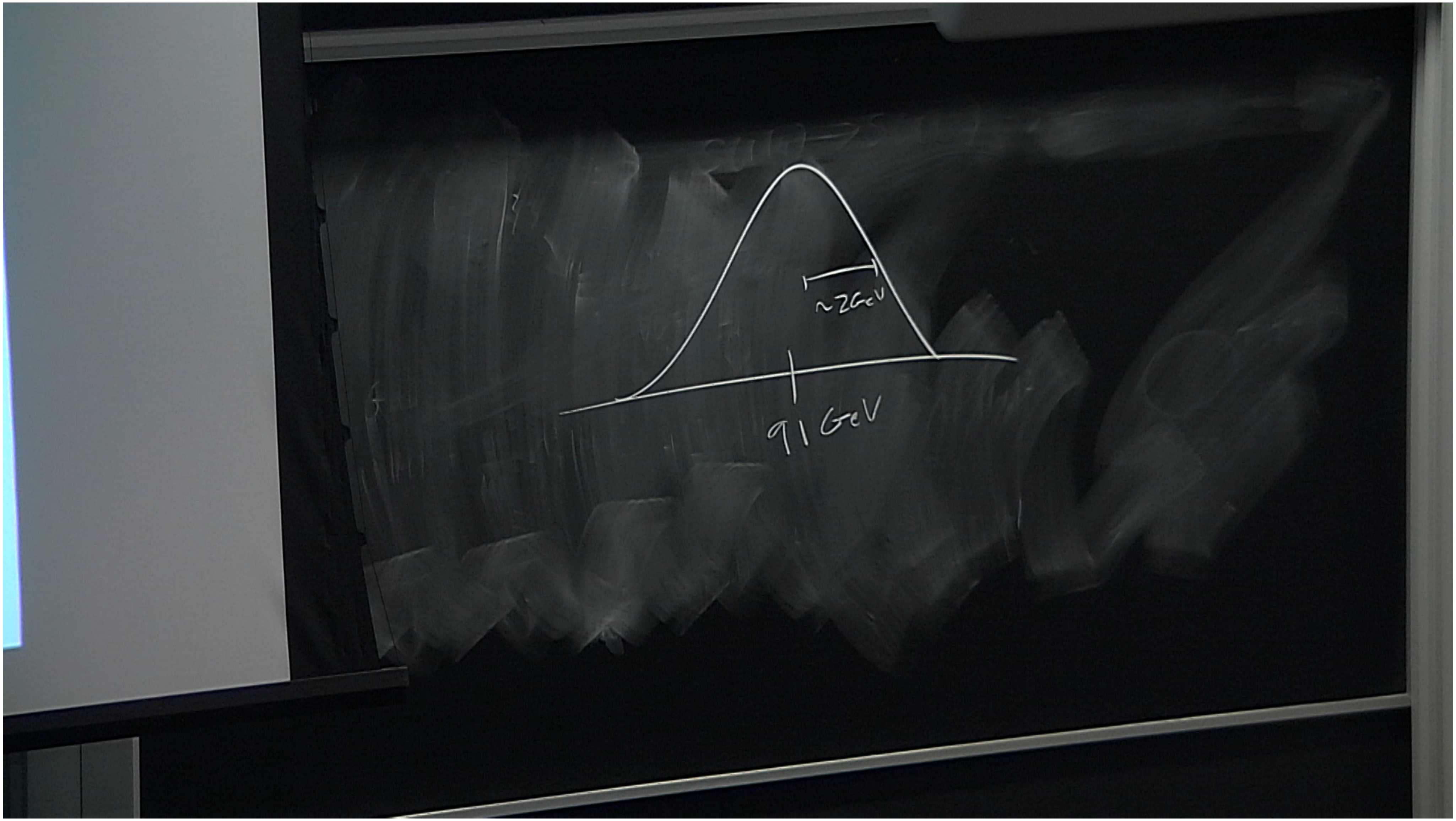
If there is a fourth, it either is vector-like, or the child of another Higgs.

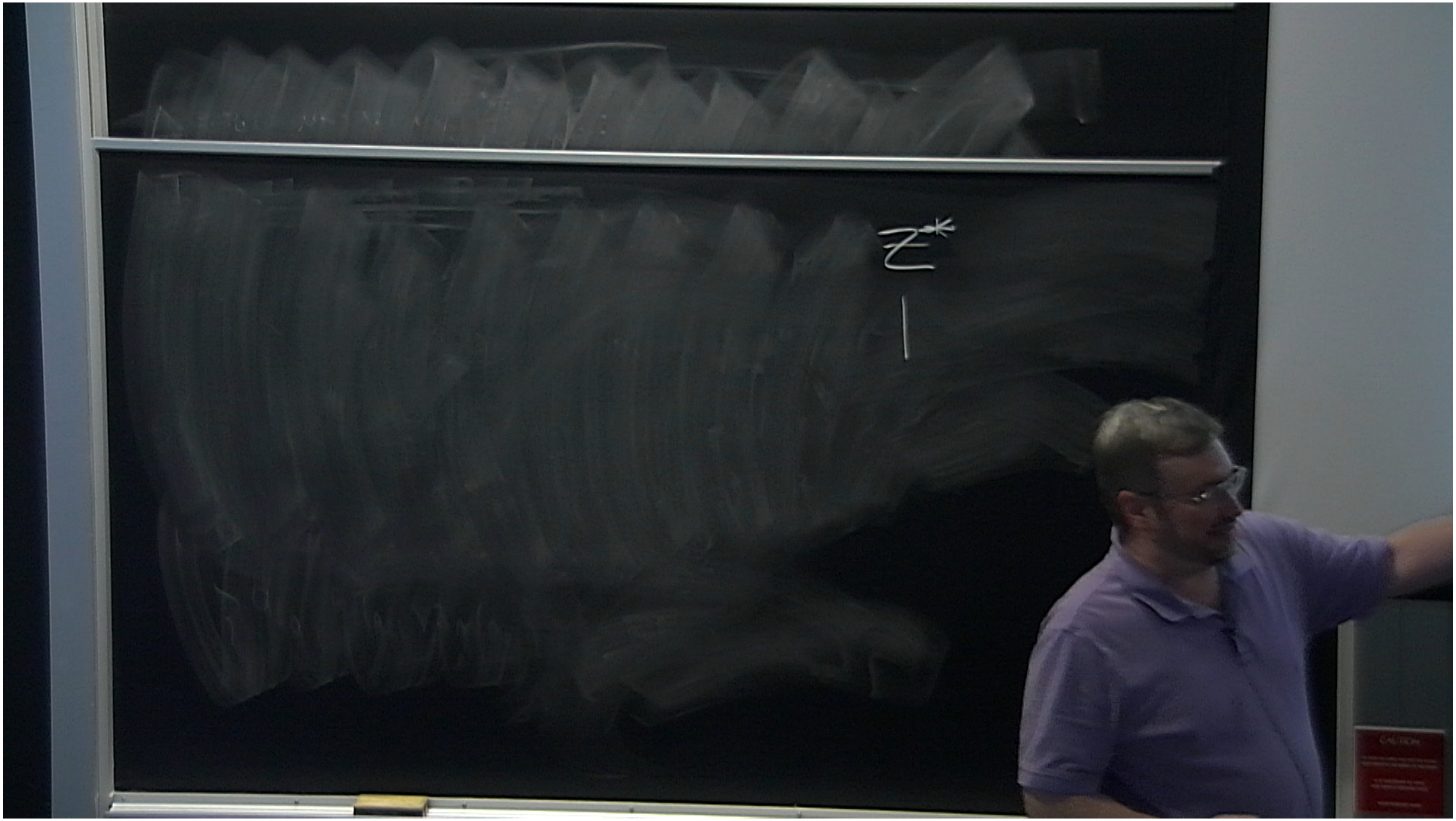
How Do You Know This Is The Higgs, Anyway?

- This particle couples very strongly to ZZ*
  - Despite being > 20Γ away from the pole
- It also couples very strongly to WW*
  - Again, despite being far from the pole
  - The equivalent figure does not make this easy to see.
- No matter what, one cannot write down a theory of EWSB without including the 125 GeV particle



Additionally, the spin-parity appears to be 0^+, the production rate matches theory, and the mass is consistent with precision EWK measurements.


~2GeV
91 GeV

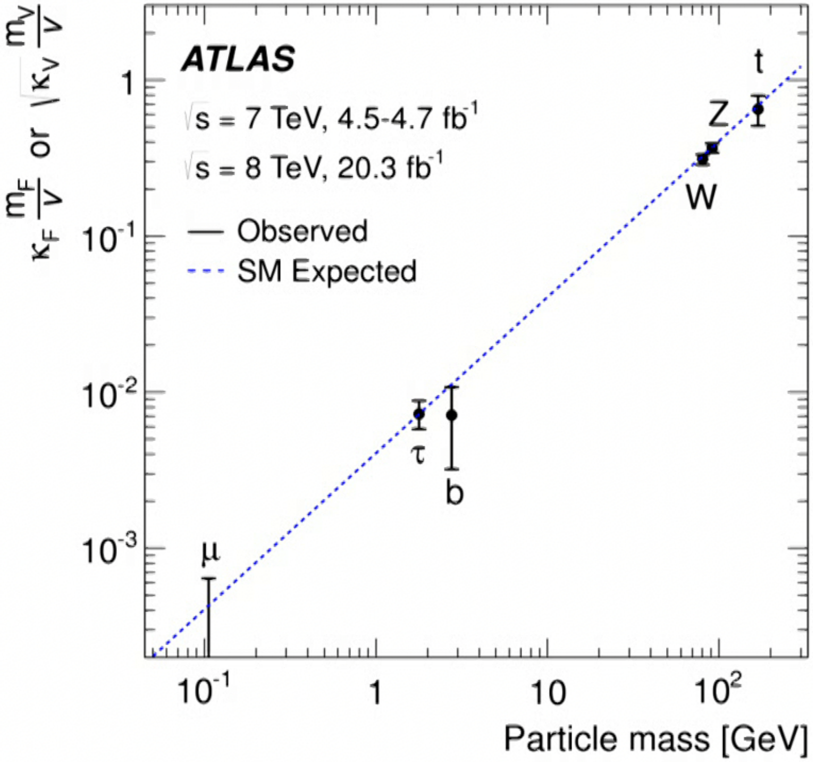


z^*

Higgs Couplings

As far as we can tell, the Higgs couplings match what the SM expects.

Good news, right?



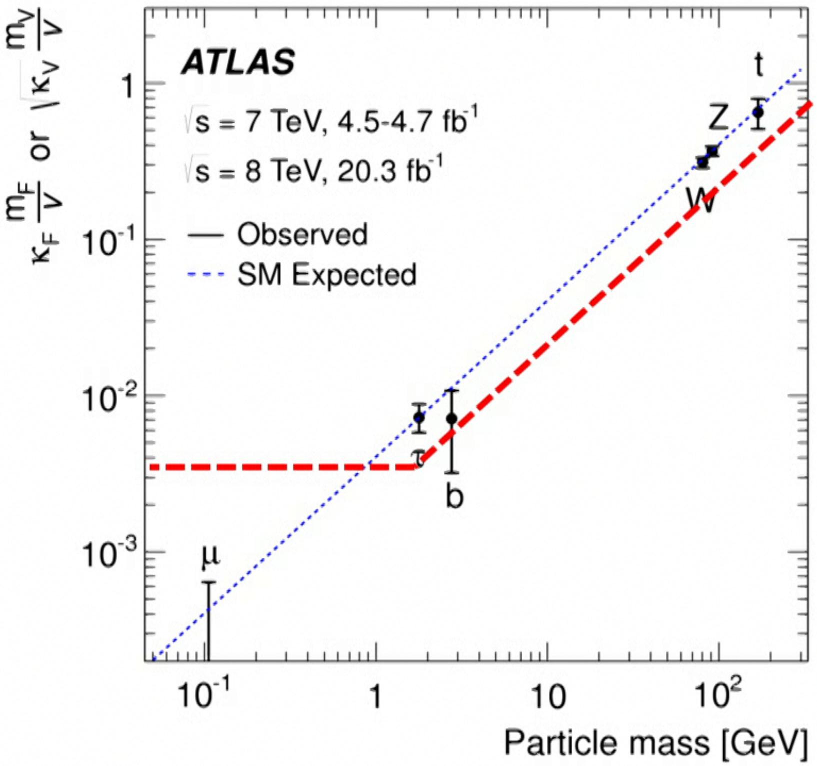
Higgs Couplings II

As far as we can tell, the Higgs couplings match what the SM expects.

Good news, right?

Well, maybe.

The experimental sensitivity is (very roughly) given by the red dashed line – if the couplings were much smaller, the LHC can't see the Higgs, and if they were much bigger, the Tevatron would have seen it first.



Everything We Know About The Higgs Coupling to the 1st and 2nd Generations:

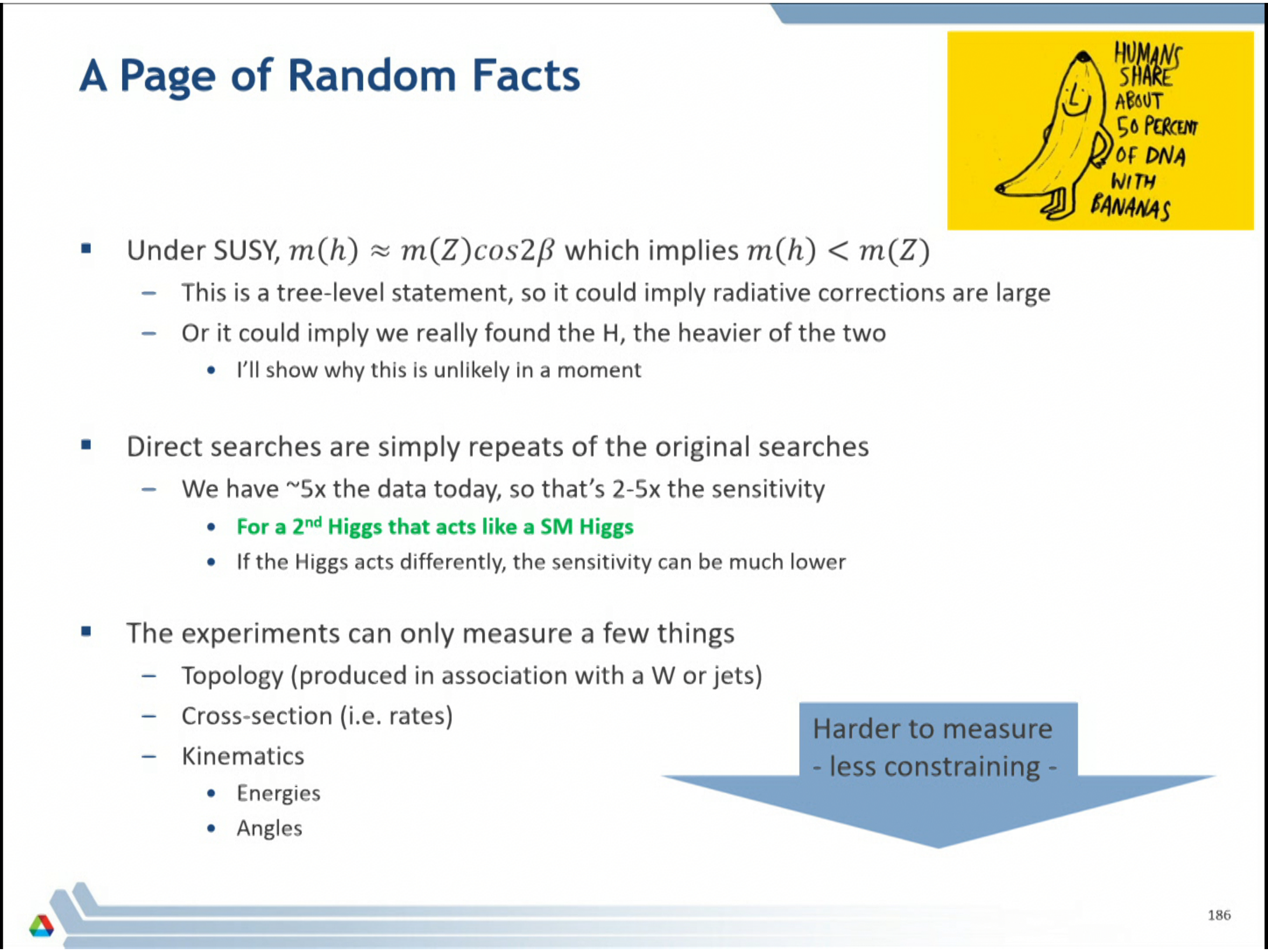
Another Higgs?

- If nature permits one, why not two? Or ten?

- A useful framework is the Two Higgs Doublet Model (2HDM)
  - Four types: fermions vs. bosons, up-type vs. down-type, leptons vs. quarks, “flipped”
    - SUSY requires up-type and down-type fermions to get their masses from
  - Five physical particles: h, H, A^0, $H^\pm$

- In Type-II (SUSY like) models, there are two parameters:
  - α: mixing (how much ϕ_1 and ϕ_2 are in the h; the H is the orthogonal combination)
  - β: (arctangent of) ratio of the u-type vev to the d-type vev
  - People explain why this must be so with words like “superpotential” and “holomorphic”

- Two possible signatures
  - Direct observation
  - The h-125 has properties that differ from the SM Higgs
  - These are coupled



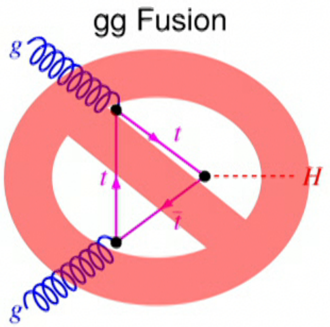
A Page of Random Facts

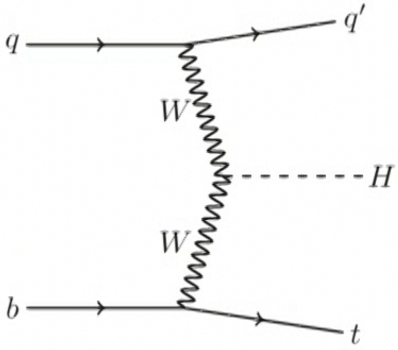
- Under SUSY, $m(h) \approx m(Z)cos2\beta$ which implies $m(h) < m(Z)$
  - This is a tree-level statement, so it could imply radiative corrections are large
  - Or it could imply we really found the H, the heavier of the two
    - I'll show why this is unlikely in a moment
- Direct searches are simply repeats of the original searches
  - We have ~5x the data today, so that's 2-5x the sensitivity
    - **For a 2nd Higgs that acts like a SM Higgs**
    - If the Higgs acts differently, the sensitivity can be much lower
- The experiments can only measure a few things
  - Topology (produced in association with a W or jets)
  - Cross-section (i.e. rates)
  - Kinematics
    - Energies
    - Angles

Harder to measure
- less constraining -

A Fermiphobic Higgs?

- Suppose we have a Higgs that couples only to bosons. What would happen?
- The branching fractions to WW, ZZ and $\gamma\gamma$ all go up by ~10
- The normal production shuts off and VBF dominates





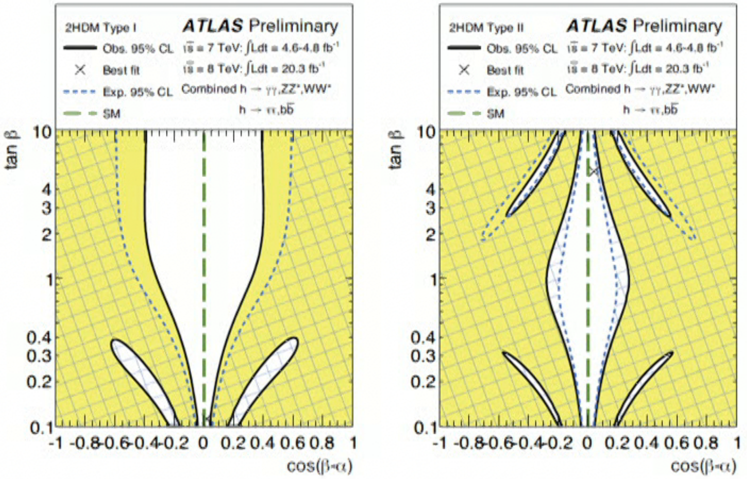
- The cross-sections go down by a factor of ~10: **the rate is almost unchanged!**

Not As Easy As It Looks

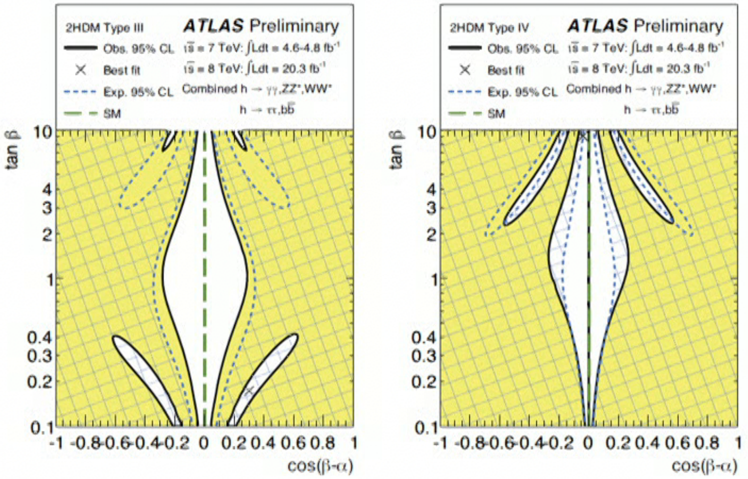
- Not as hopeless as it looks either
- While some observables (e.g. total rates) are less sensitive, others are still OK:
  - In this case, the number of associated jets and the p_T distributions
- What do we really have?
  - Rates, kinematics and associated particles for the channels
    - Two photons
    - WW
    - ZZ
    - Taus
    - b's (associated with W or Z)

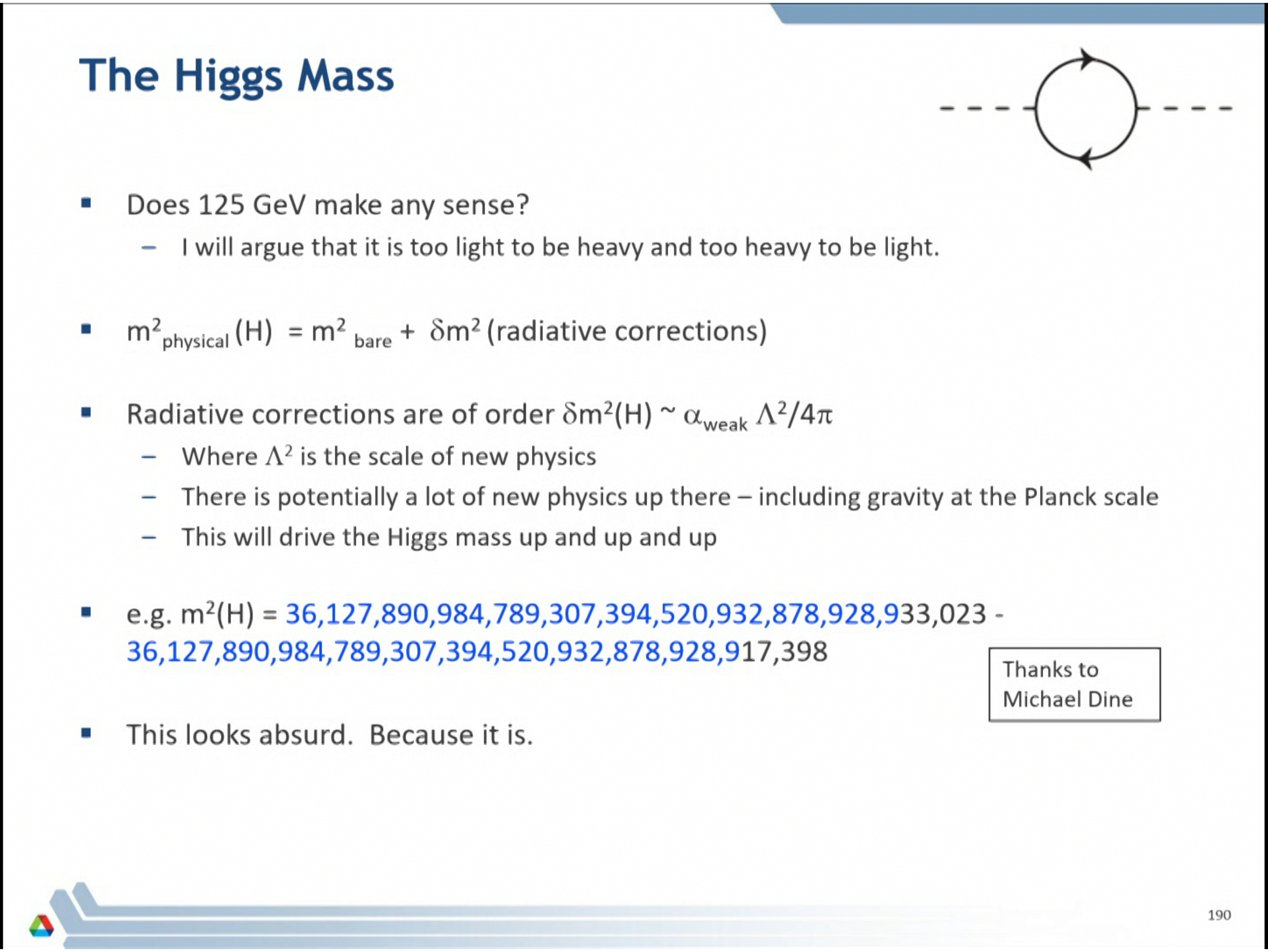
Higgs & the 2HDM

- The allowed region includes the SM Higgs
- The allowed region is centered around the SM Higgs: i.e. we have found the more/most SM-like of the Higgs bosons
- This tends to drive the other Higgs boson(s) into regions of parameter space where they are hard to see.
  - Could there be another Higgs out there? The ~10-30% measurements of the h-125 properties suggest more luminosity would be helpful in the direct searches.



(a) Type I (b) Type II

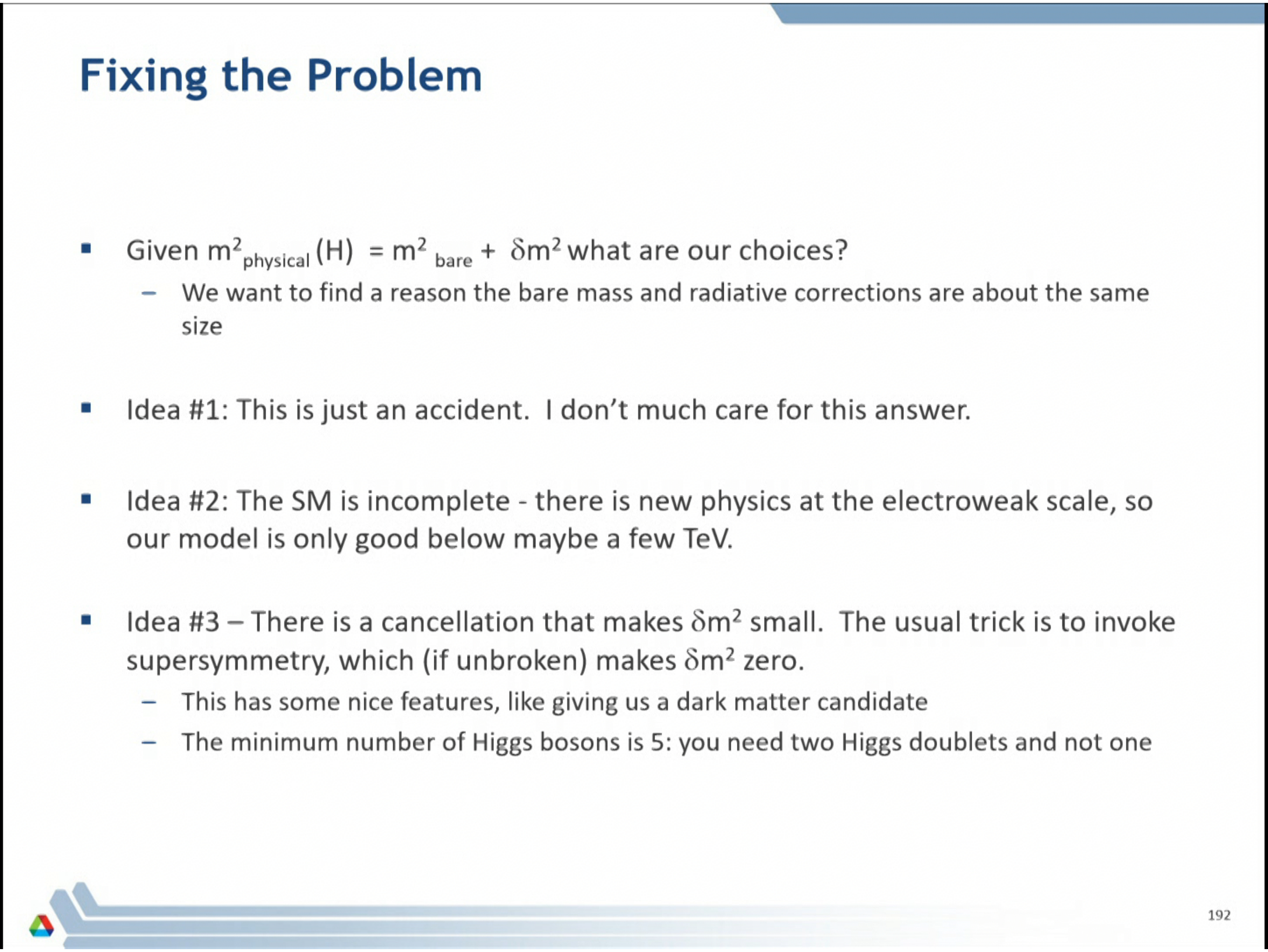




The Higgs Mass

- Does 125 GeV make any sense?
  - I will argue that it is too light to be heavy and too heavy to be light.
- $m^2_{\text{physical}}(H) = m^2_{\text{bare}} + \delta m^2$ (radiative corrections)
- Radiative corrections are of order $\delta m^2(H) \sim \alpha_{\text{weak}} \Lambda^2/4\pi$
  - Where Λ^2 is the scale of new physics
  - There is potentially a lot of new physics up there – including gravity at the Planck scale
  - This will drive the Higgs mass up and up and up
- e.g. $m^2(H)$ = 36,127,890,984,789,307,394,520,932,878,928,933,023 - 36,127,890,984,789,307,394,520,932,878,928,917,398
- This looks absurd. Because it is.

Thanks to
Michael Dine



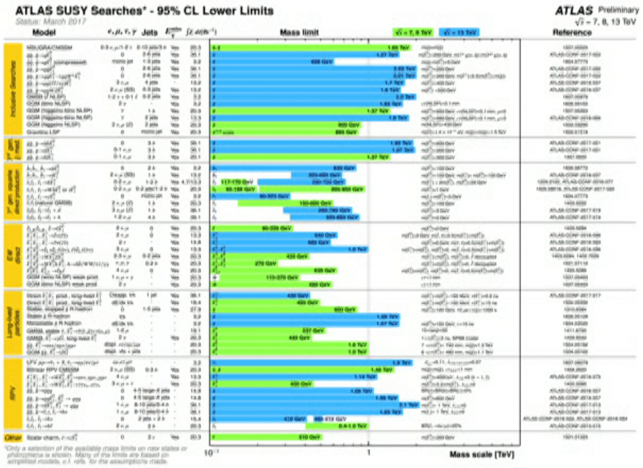
Fixing the Problem

- Given $m^2_{physical}(H) = m^2_{bare} + \delta m^2$ what are our choices?
  - We want to find a reason the bare mass and radiative corrections are about the same size
- Idea #1: This is just an accident. I don't much care for this answer.
- Idea #2: The SM is incomplete - there is new physics at the electroweak scale, so our model is only good below maybe a few TeV.
- Idea #3 – There is a cancellation that makes δm^2 small. The usual trick is to invoke supersymmetry, which (if unbroken) makes δm^2 zero.
  - This has some nice features, like giving us a dark matter candidate
  - The minimum number of Higgs bosons is 5: you need two Higgs doublets and not one

Is Supersymmetry The Answer?

See F. Alonso's talk

- It does provide this cancellation, and if it is broken in the right way, can naturally give a Higgs of the right mass:
  - Favors a light top squark (how light depends on your definition of "naturally")
  - Gives a Dark Matter candidate for free



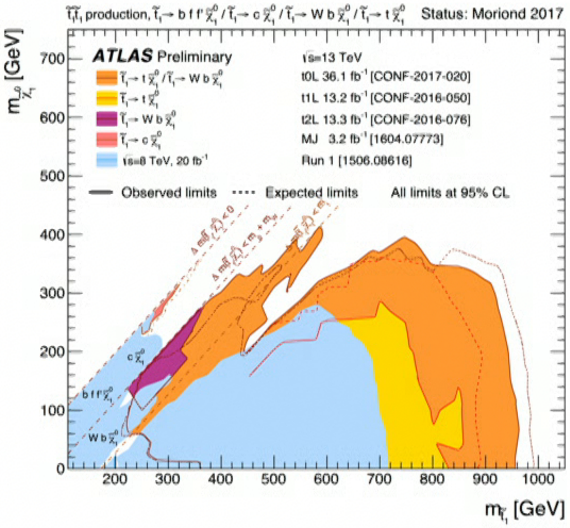
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2017

ATLAS Preliminary $\sqrt{s}$ = 7, 8, 13 TeV

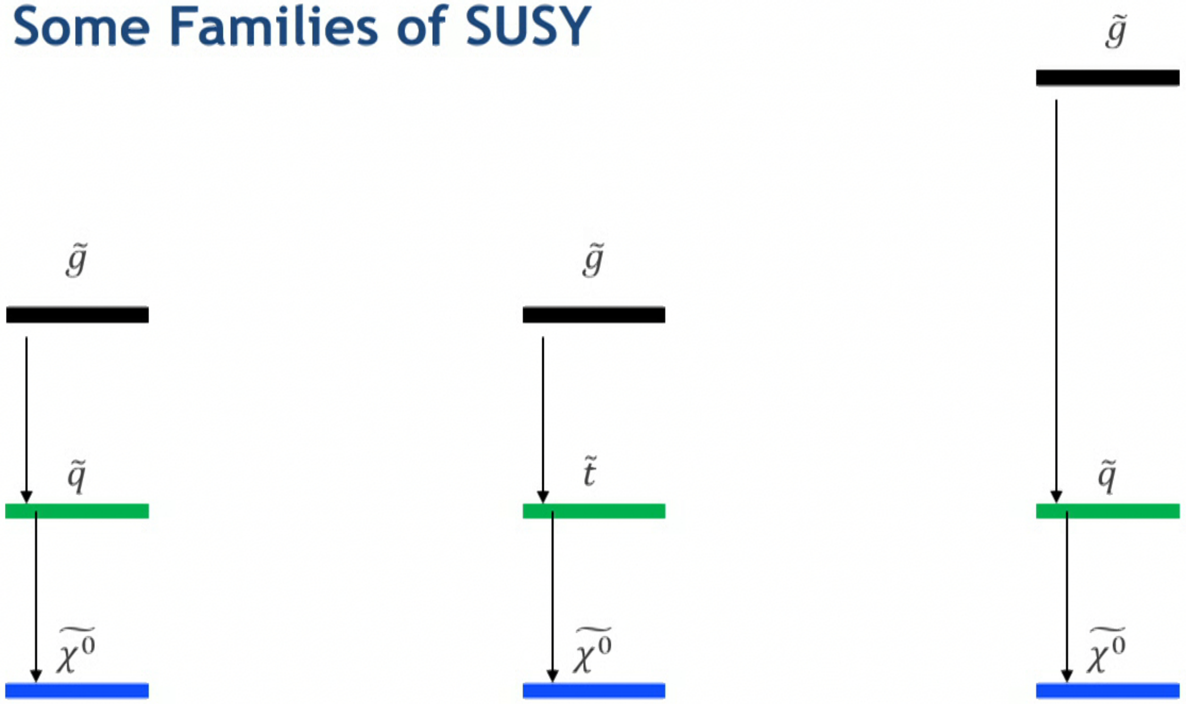
Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\,dt\,[fb^{-1}]$	Mass limit	Reference

Mass scale [TeV]



- Thus far, there is no sign of it anywhere
  - Limits are starting to be in tension with this idea (how "natural" is "natural"?)

Some Families of SUSY

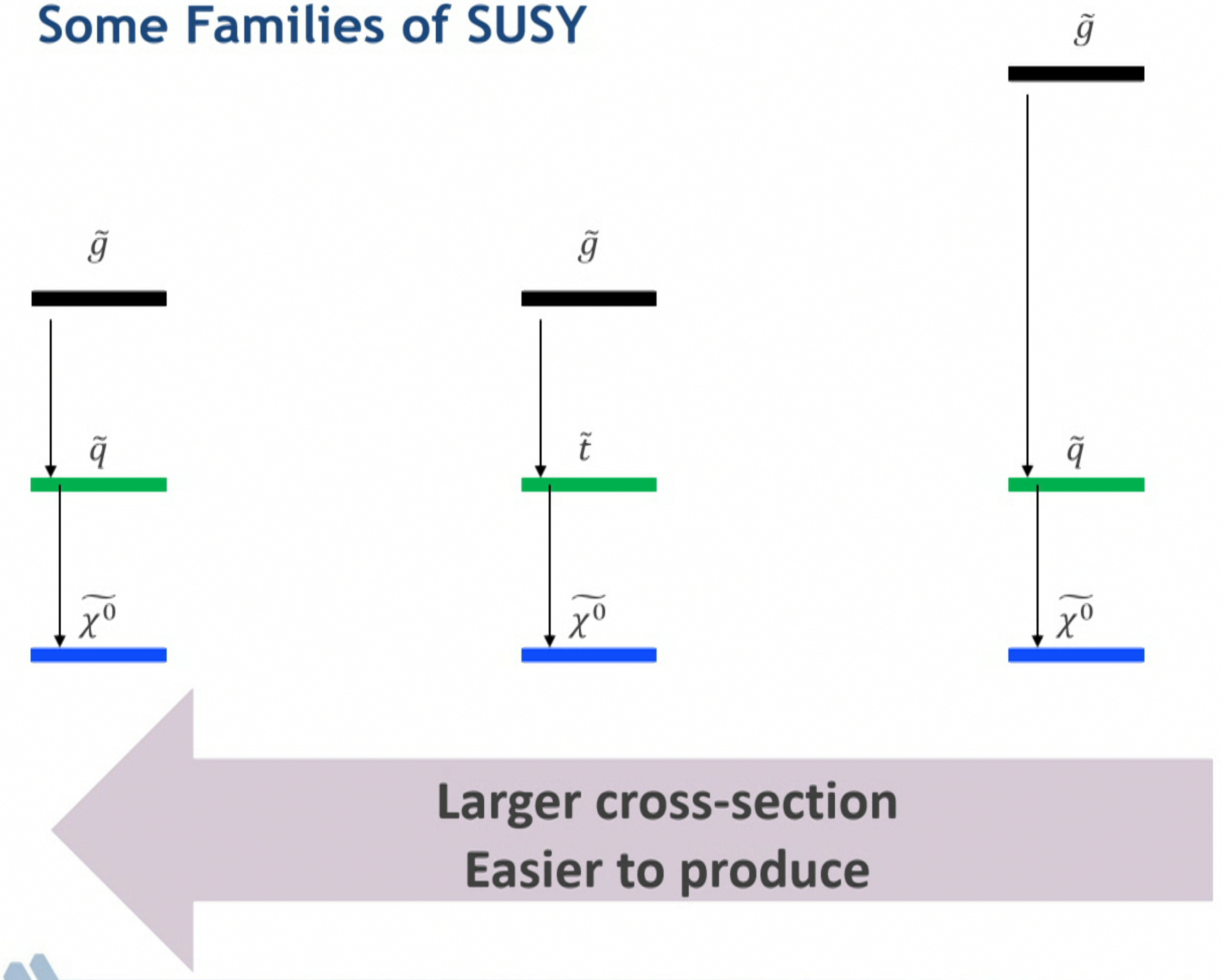


Conventional
Three degenerate squarks.

“Natural”
Only the stop squark is light.

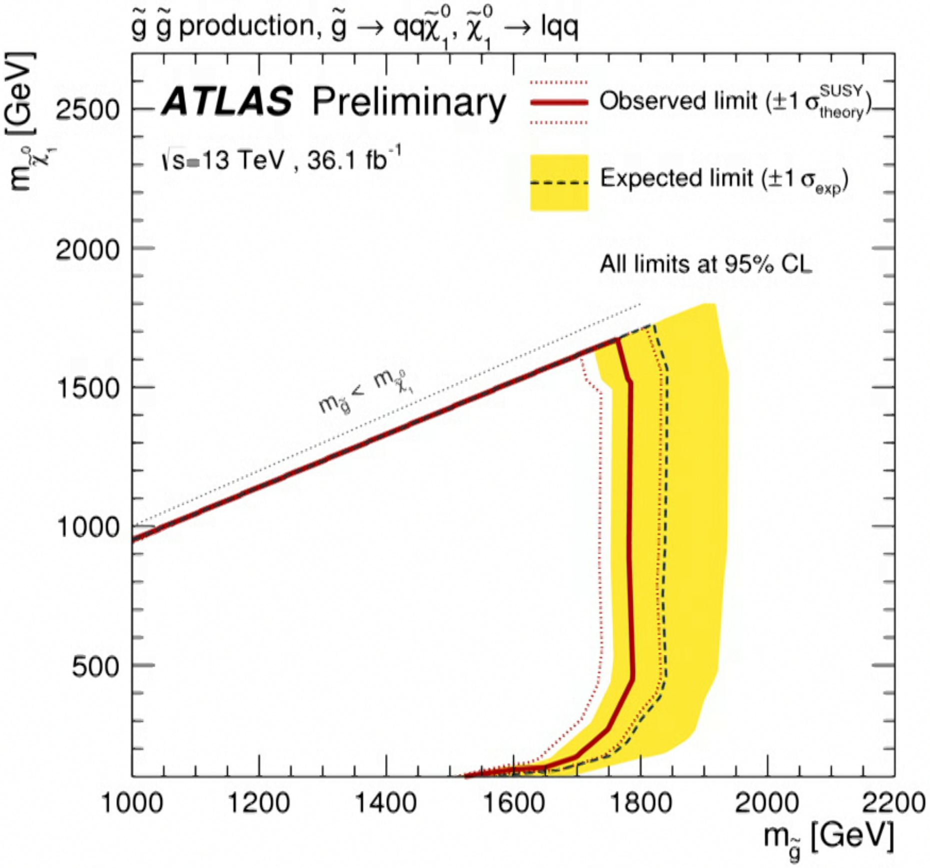
“Electroweak”
Gluino is too heavy for strong production.

Some Families of SUSY



Larger cross-section
Easier to produce

How To Read A Limit Plot



Limitations of Limit Plots

- All of these plots have some model dependence built in
- Typically, they assume that the only SUSY particles that matter are the ones being searched for (and their daughters)
  - A consequence of this is that the branching fractions are (usually) 100% which means the limits are at their maximum.
    - The worst assumption you can make, except for all the others

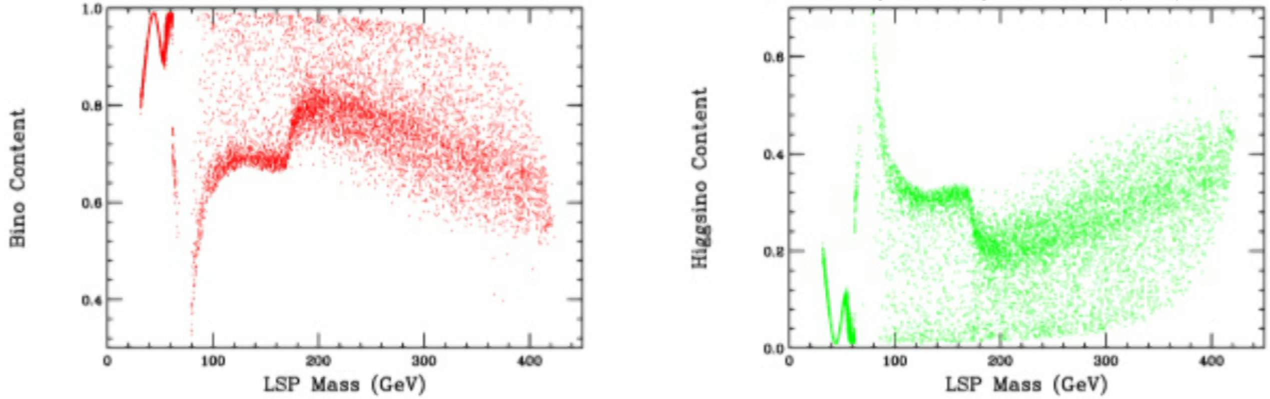
If you have this, $\tilde{t} \rightarrow \chi^0 + t$

You may also have this, $\tilde{t} \rightarrow \chi^+ + b$

- While many plots seem to exclude SUSY below around 1 TeV this is absolutely not iron-clad.

Another Way To Look At the Data

- Take an N-dimensional SUSY parameterization (N=19 is popular)
- Look at the entire ensemble of measurements: LHC, cosmology, etc.
- Plot those points that have not been excluded



M. Cahill-Rowley et al. Phys.Rev. D90 (2014) no.9, 095017

- Only when these plots are empty is SUSY excluded
  - e.g. for LSPs lighter than ~30 GeV

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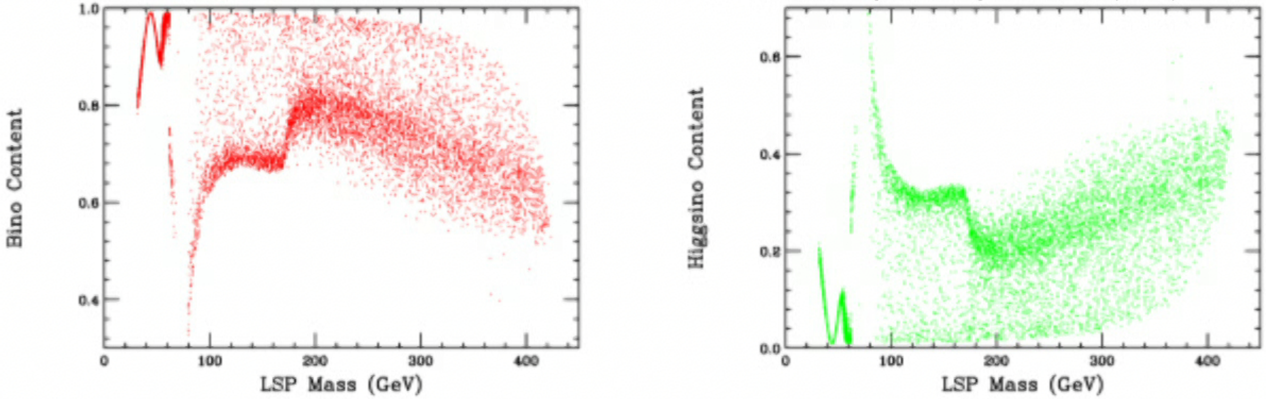

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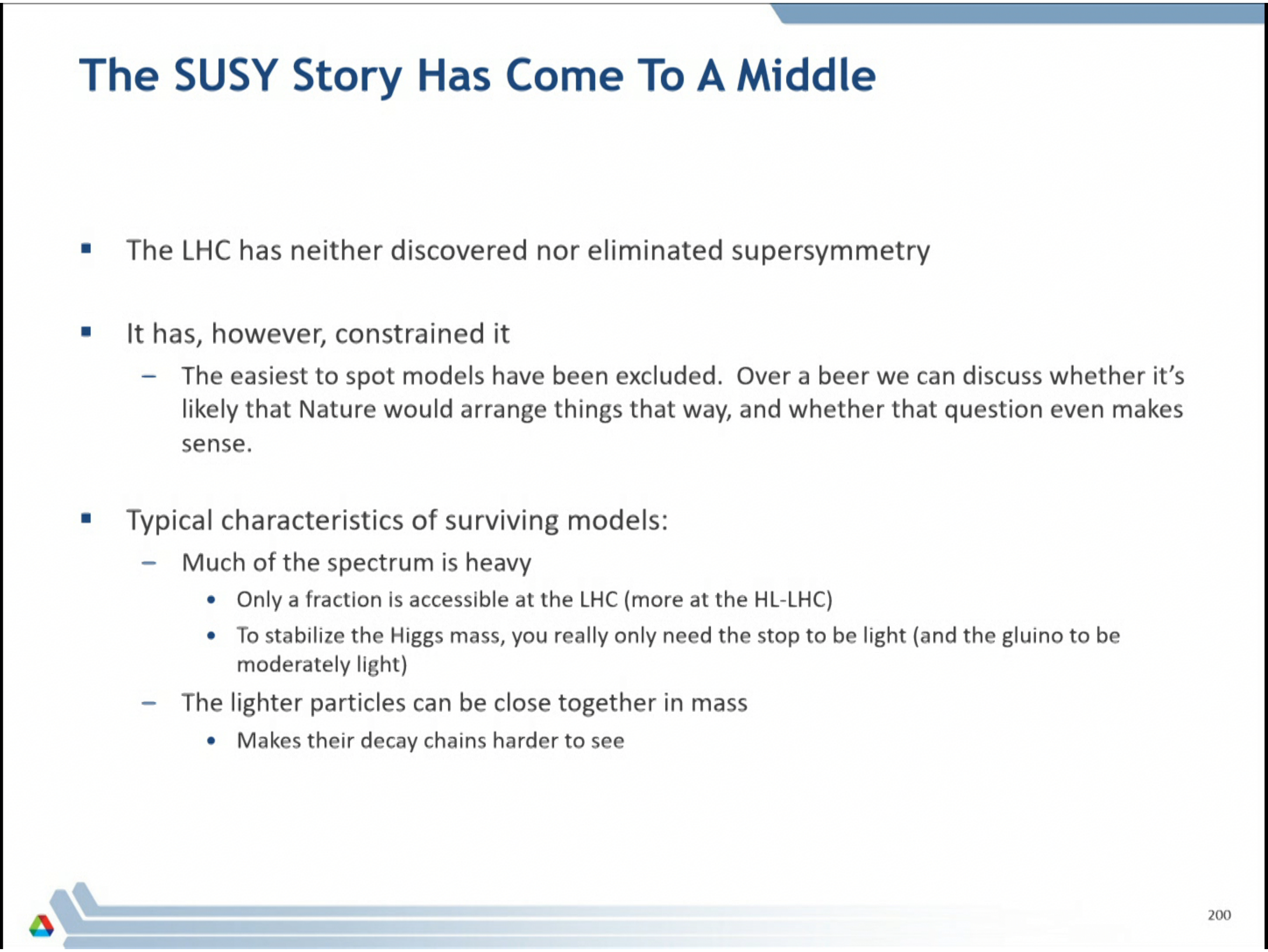
Quiz: What do these plots together tell us?



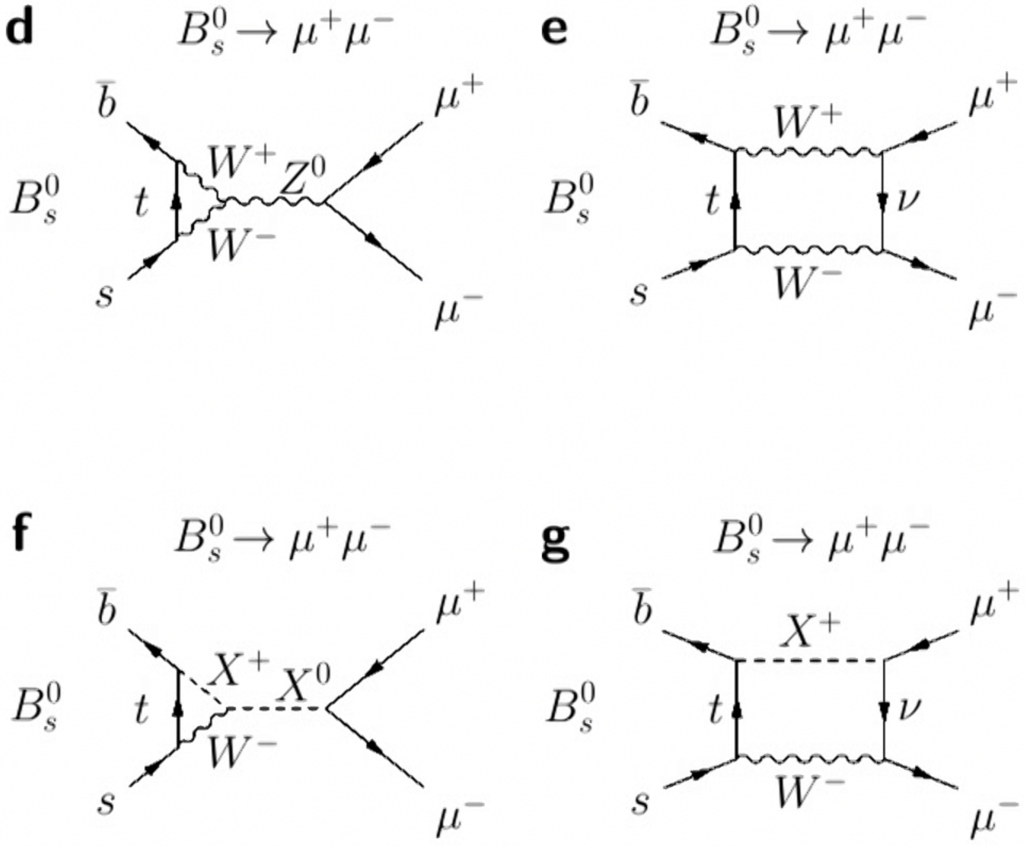
The SUSY Story Has Come To A Middle

- The LHC has neither discovered nor eliminated supersymmetry
- It has, however, constrained it
  - The easiest to spot models have been excluded. Over a beer we can discuss whether it’s likely that Nature would arrange things that way, and whether that question even makes sense.
- Typical characteristics of surviving models:
  - Much of the spectrum is heavy
    - Only a fraction is accessible at the LHC (more at the HL-LHC)
    - To stabilize the Higgs mass, you really only need the stop to be light (and the gluino to be moderately light)
  - The lighter particles can be close together in mass
    - Makes their decay chains harder to see

$B_s \rightarrow \mu\mu$

In the SM these decays are GIM suppressed and decay through loops.

Partial lifetimes would be measured in seconds.



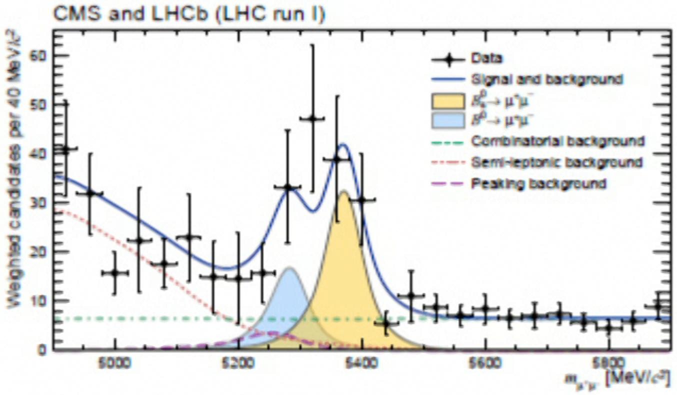
BSM amplitudes can compete with SM amplitudes and can even be enhanced.

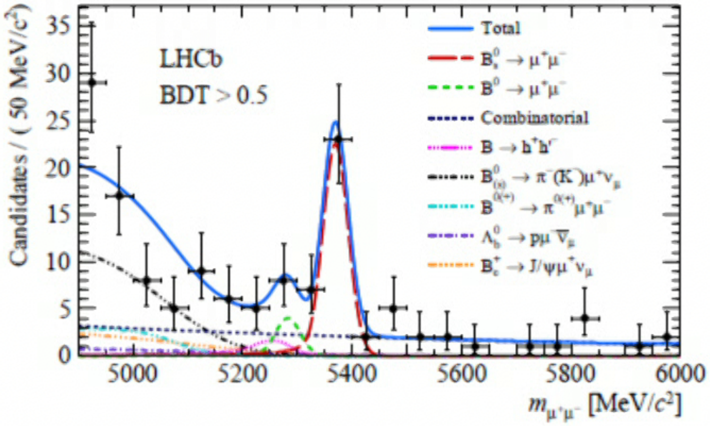
In SUSY, these decays are enhanced by $\tan^6\beta$.

What The Data Show

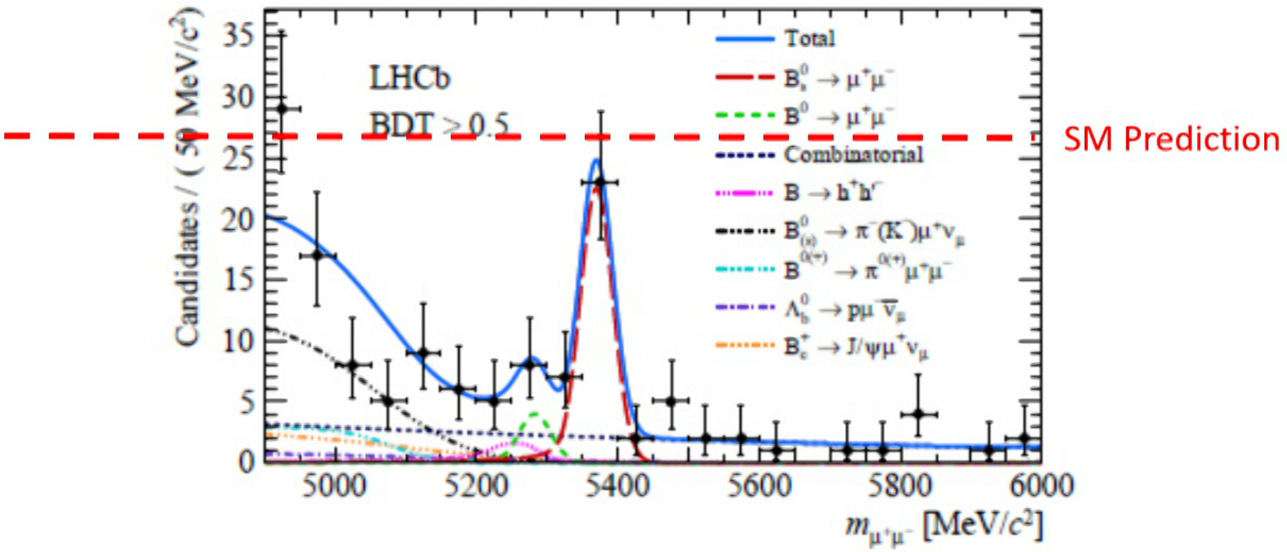
The signal is very weak - 3 decays per billion – so the first observation took the combination of two experiments, LHCb and CMS

Now that there is more data, single experiments are showing compelling signals





What Does This Mean?



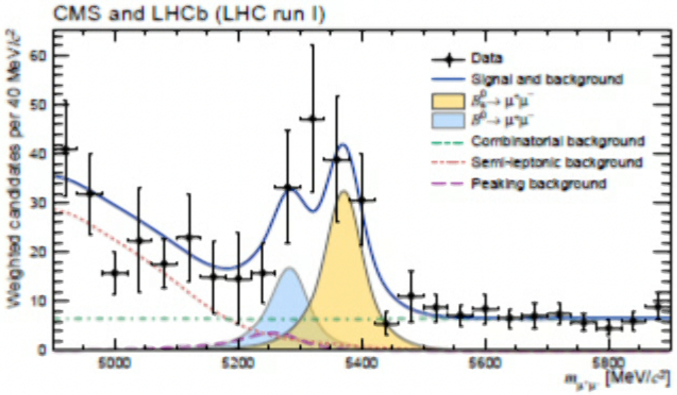
SM Prediction

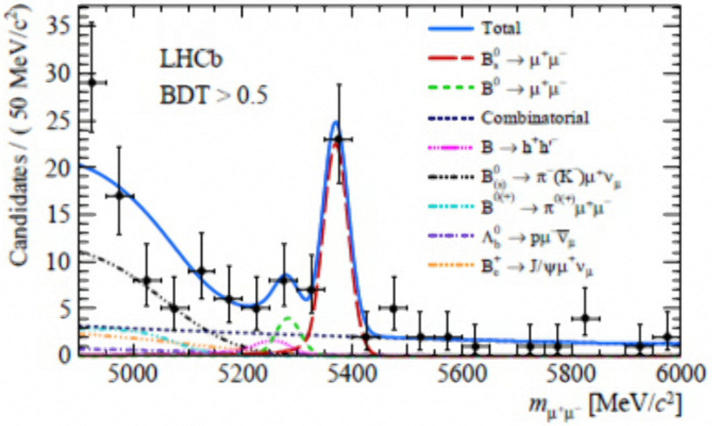
The data is bang on the SM prediction.

Any new physics is limited to having an amplitude less than about half of the SM.

A Quick Word on Anomalies

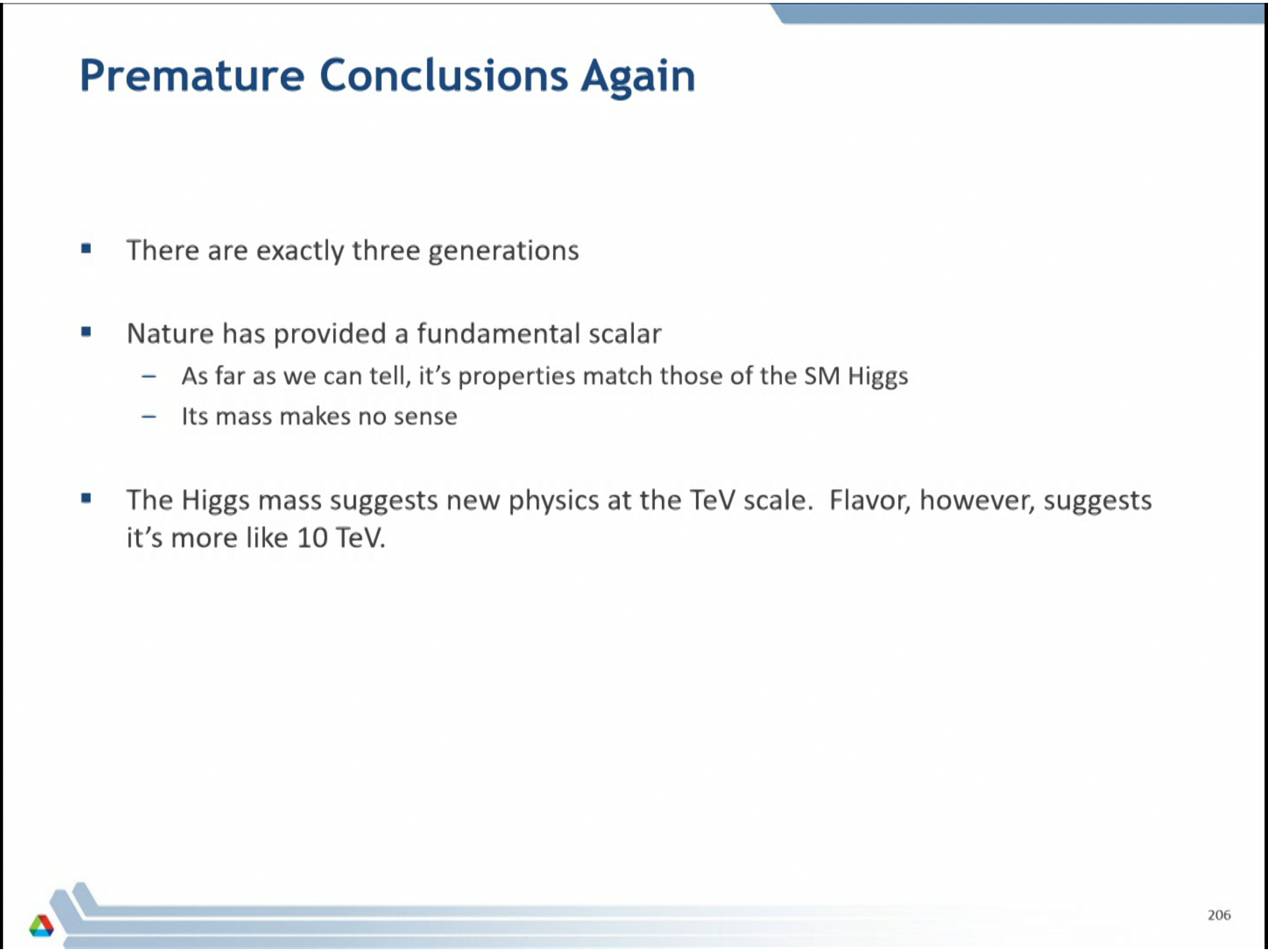
- People were very excited about the size of the B_d (left peak) signal as a sign of new physics
- Not only is it statistically marginal, you're practically guaranteed an upward fluctuation – if it fluctuated down, you don't see anything.
- With more data, it went away.





Flavor Conclusions

- This is just a taste of flavor physics
  - There are other B decays, explored at the LHC and the B factories
  - There are K and D decays, explored elsewhere
  - There are (or rather, aren't) rare muon decays
  - There are precision measurements, like g-2 of the electron and muon
- The emerging picture is that flavor measurements match the SM to a high degree of accuracy
  - How high? Expressed as a scale of new physics, we're in the 10+ TeV ballpark
  - Alternatively, there is some reason that new physics at the TeV scale keeps its fingerprints out of the flavor sector

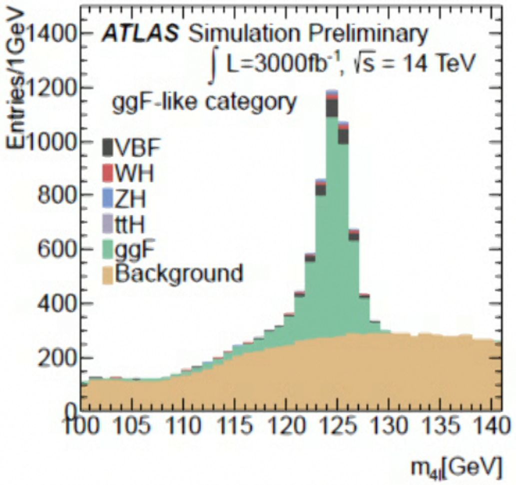


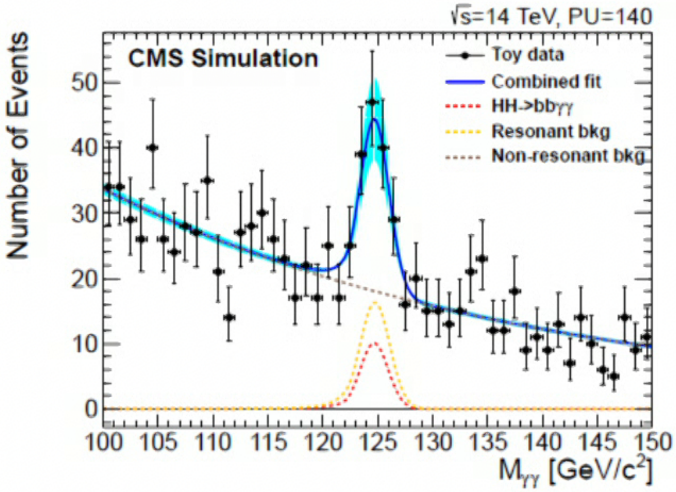
Premature Conclusions Again

- There are exactly three generations
- Nature has provided a fundamental scalar
  - As far as we can tell, it's properties match those of the SM Higgs
  - Its mass makes no sense
- The Higgs mass suggests new physics at the TeV scale. Flavor, however, suggests it's more like 10 TeV.

Step One: HL-LHC

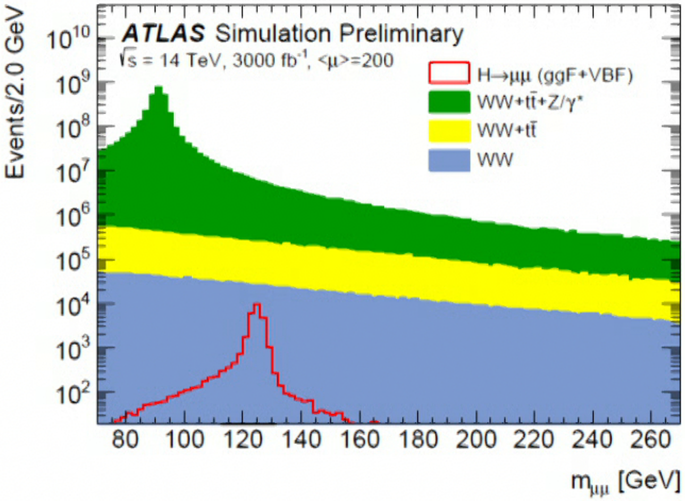
- An LHC with 50x the integrated luminosity we have today could let us probe the Higgs self-coupling (in the SM, uniquely determined by the mass, or the other way around) to a precision of 10-ish %.





Step One: HL-LHC

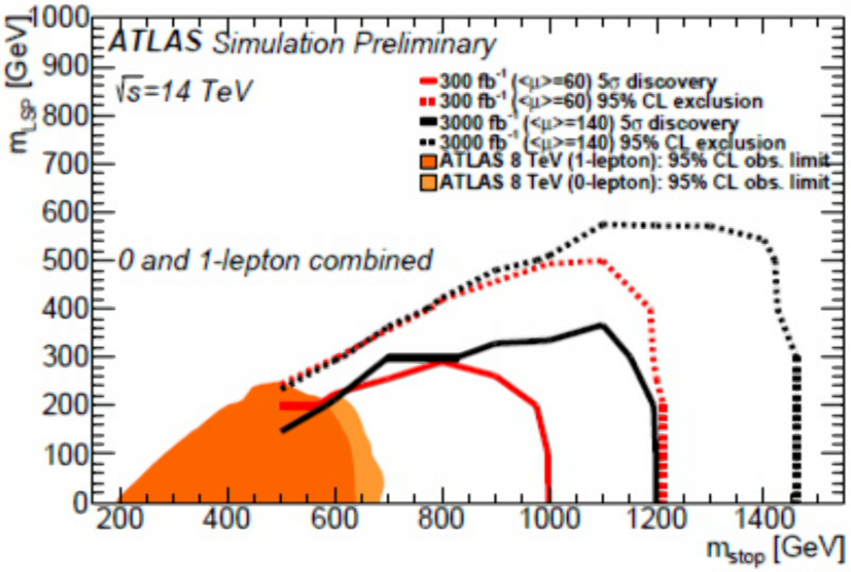
- An LHC with 50x the integrated luminosity we have today could let us measure the Higgs coupling to the 2nd generation



- Why do we need so much data? We need to see the signal over a large background, and the uncertainty in the background is proportional to √N.

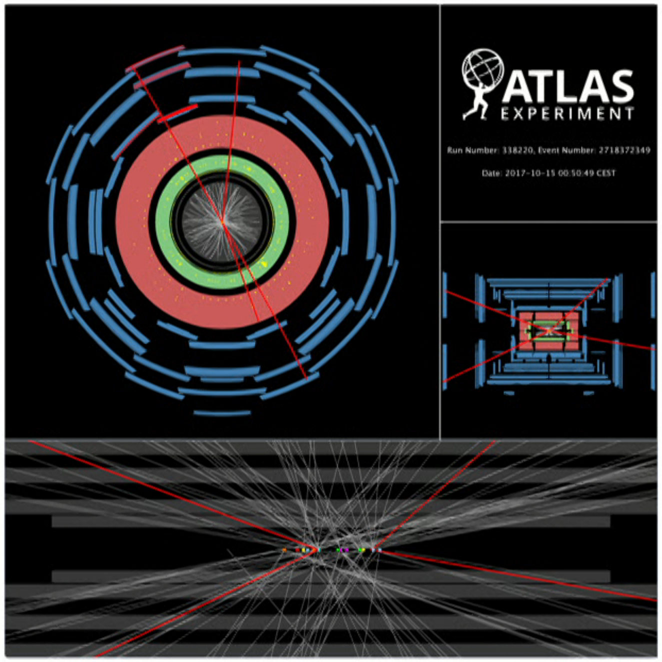
Step One: HL-LHC

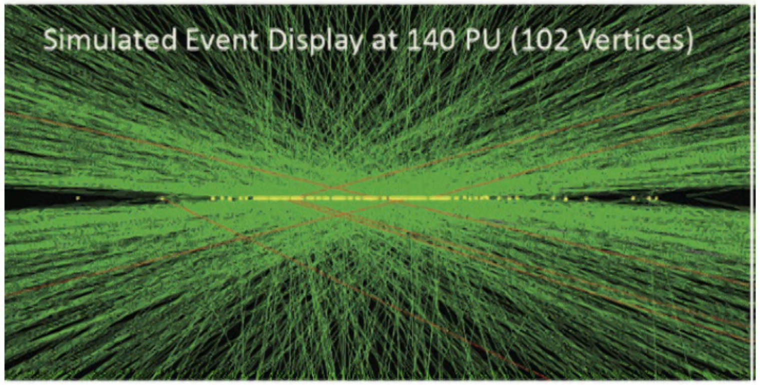
- An LHC with 50x the integrated luminosity we have today lets our searches push out in sensitivity: but we're in a region of diminishing returns – 10x the data gives us 15-20% in reach



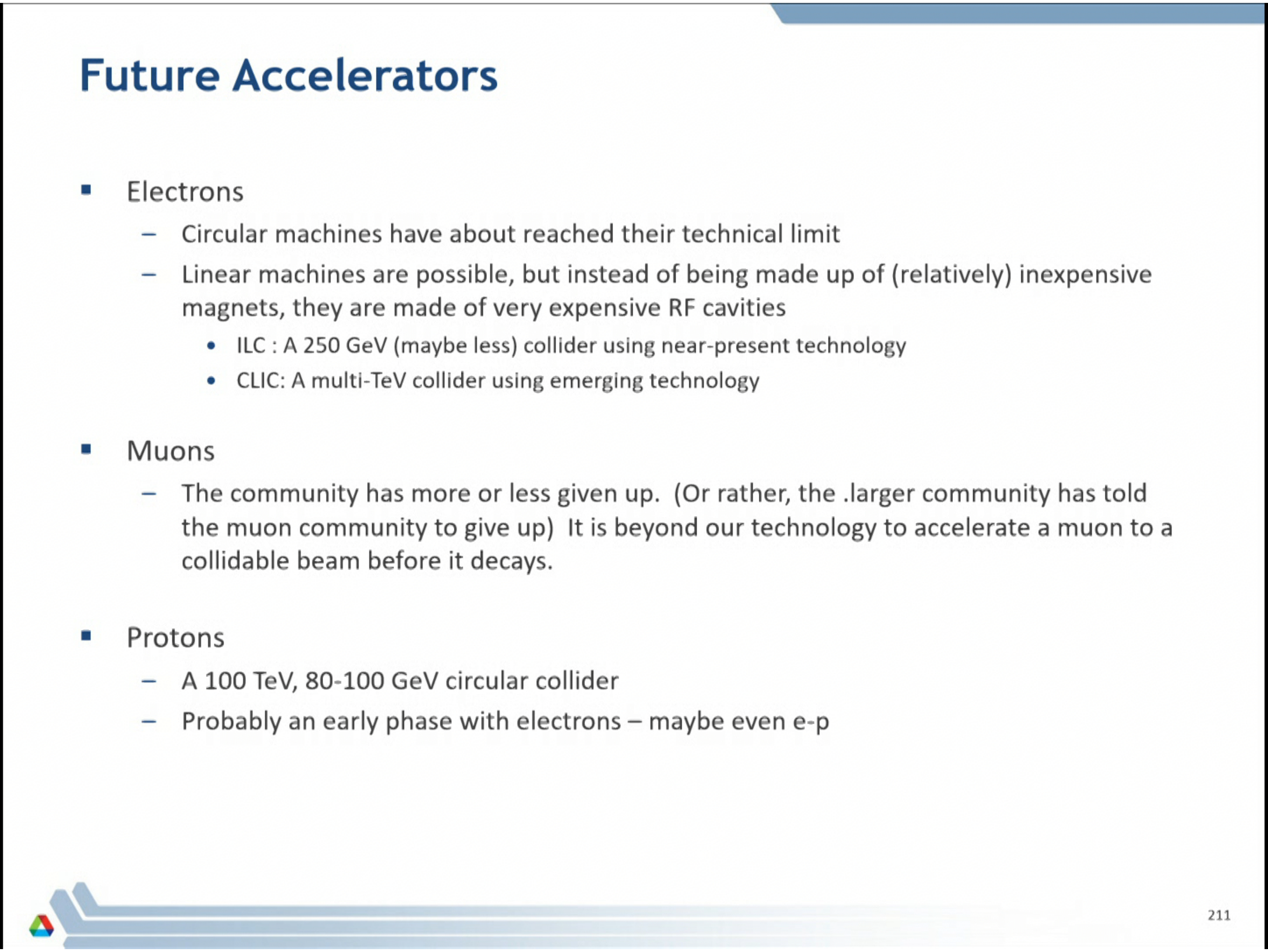
HL-LHC: The Challenge

- To collect 50x the data, we need to run at 3-5x the luminosity
- As many as 200 collisions per crossing





We need to be able to pick out the event of interest from ~200 others. Requires major detector upgrades to do this.



Future Accelerators

- Electrons
  - Circular machines have about reached their technical limit
  - Linear machines are possible, but instead of being made up of (relatively) inexpensive magnets, they are made of very expensive RF cavities
    - ILC : A 250 GeV (maybe less) collider using near-present technology
    - CLIC: A multi-TeV collider using emerging technology
- Muons
  - The community has more or less given up. (Or rather, the .larger community has told the muon community to give up) It is beyond our technology to accelerate a muon to a collidable beam before it decays.
- Protons
  - A 100 TeV, 80-100 GeV circular collider
  - Probably an early phase with electrons – maybe even e-p

That's all Folks!

- Quiz: is this from a Looney Tune or Merrie Melody?


ASK
QUESTIONS