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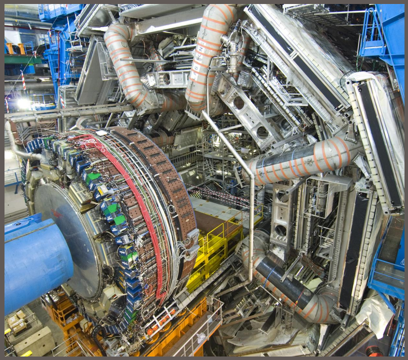
Canada’s national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

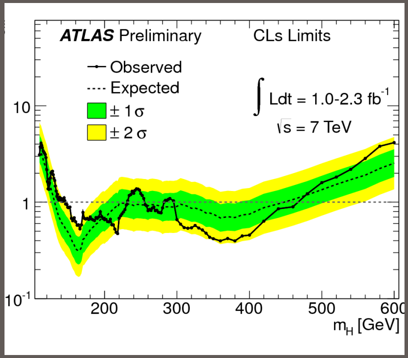
Making or Breaking the Standard Model

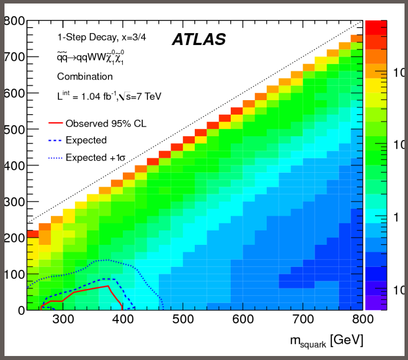
Looking for the Higgs boson and dark matter with ATLAS at the LHC

And not finding them yet… should we worry?

Isabel Trigger | TRIUMF

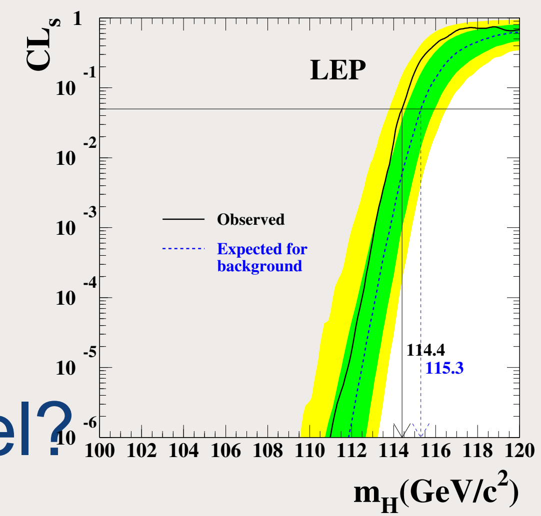






Outline

- What is the Standard Model?
  - Mass and elementary particles
  - The case for the Higgs Mechanism
  - The case for the Higgs Boson
- Why try to break the Standard Model?
  - … and the case for Dark Matter
- The Large Hadron Collider and ATLAS detector
- The hunting of the Higgs
- Searches for Dark Matter & other Smoking Guns
- Summary



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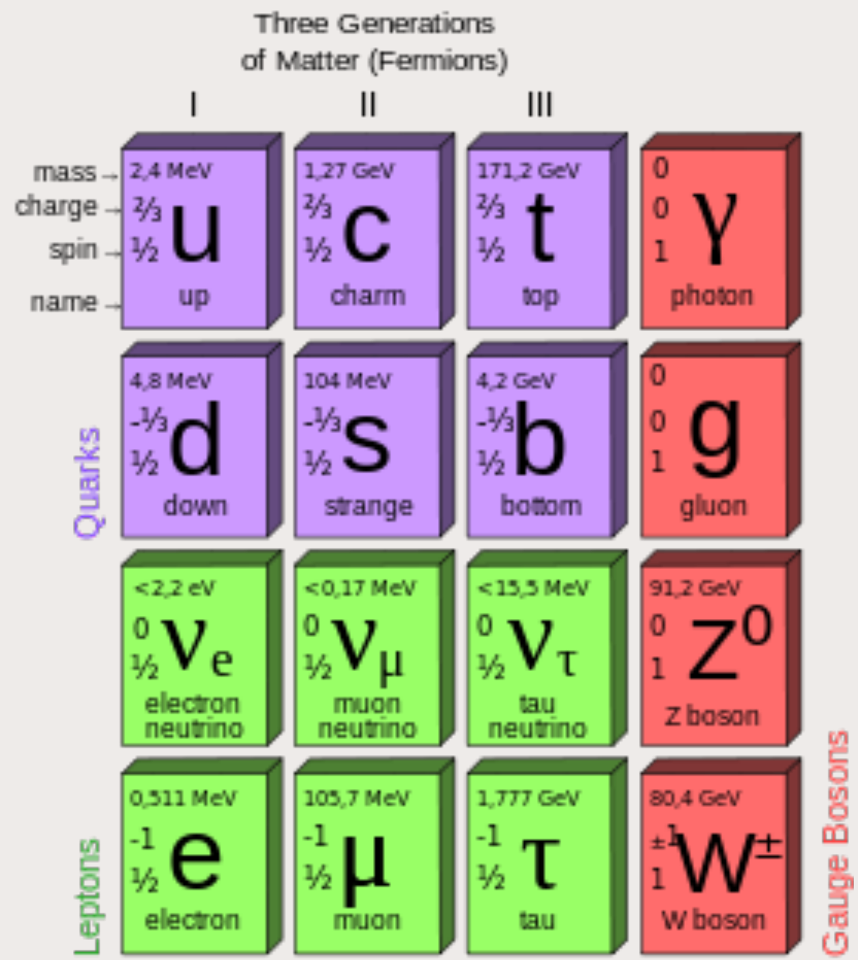
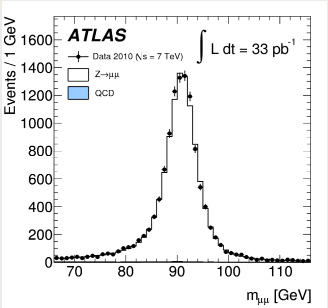
What is the Standard Model of Particle Physics?

- Matter:
  - 2 kinds of quark (u, d)
  - 2 kinds of lepton (e, ν_e)
  - × 3 “copies” (e, μ, τ)
- Forces:
  - Electromagnetic
  - Strong nuclear
  - Weak nuclear
  - (gravity - not in SM)

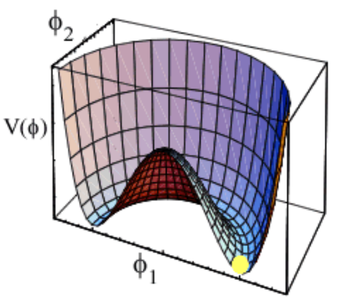


What is the matter with mass?

- The fundamental "matter" particles (quarks, leptons) all have masses
  - Masses do not follow obvious pattern, not quantized
  - Not origin of most of the visible mass in universe (quark mass ~1% of nucleon mass)
- The Weak Force bosons ($W^{\pm}$, Z^0) are massive
  - Unlike the photon (and gluons), which are strictly massless
- A "QED-like" quantum field theory for the Weak Nuclear Force is not gauge invariant if we insert mass terms for either the gauge bosons or the matter particles



The case for the Higgs Mechanism



- Higgs **Mechanism** is clever trick
- Insert just 1 extra ingredient:
  - Scalar field φ
  - Multiplet: at least complex doublet (+4 parameters)
  - Potential associated with field has *minimum which is not at zero*
- Adds gauge-invariant terms to SM Lagrangian involving new scalar and gauge fields
- Choose a gauge where photon mass is zero
  - W and Z have masses (**predicted**, correctly, using one experimental measurement, the Weak mixing angle)
  - Matter fermions can now have Yukawa masses without destroying gauge invariance
- **Very, very strong case for the Higgs *Mechanism*!**

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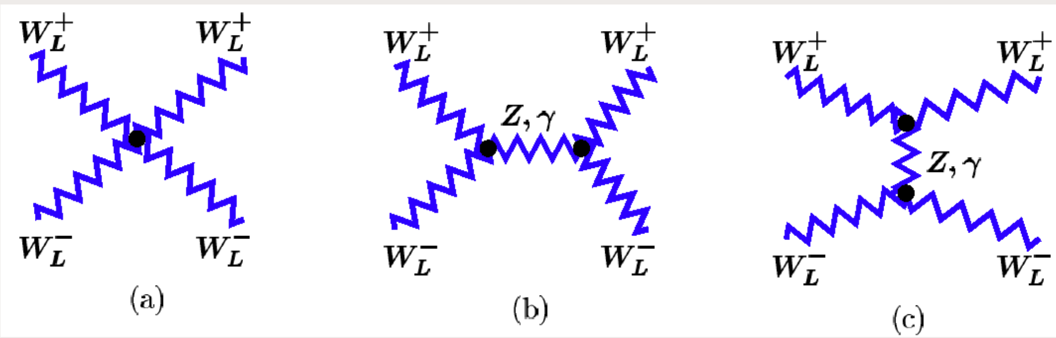
Does that mean there must be a Higgs Boson?

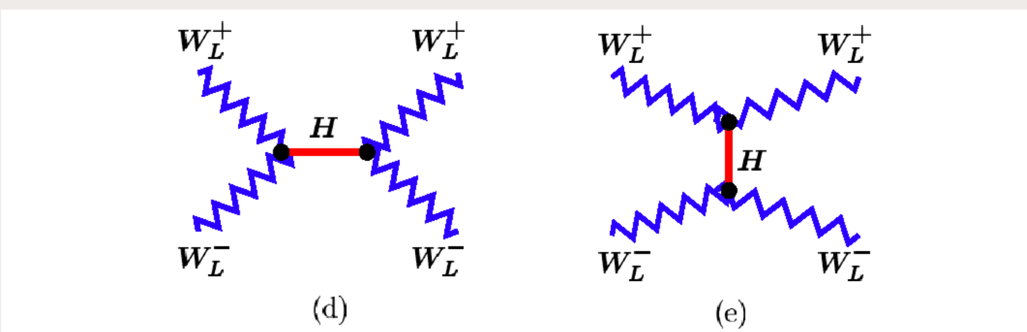
- There is always *at least one* “leftover” degree of freedom from the Higgs field, which shows up as a massive scalar (spin-0) boson: **Higgs boson**
  - We have never detected an elementary scalar…
- Could have **more complicated** Higgs sector:
  - Two complex scalar doublets instead of one gives five Higgs bosons (2 SM-like, 2 charged, 1 pseudoscalar)
- Could have either SM Higgs boson or more complicated Higgs sector, in model with additional particles
  - Modifies decay possibilities, dilutes (or enhances) exclusions
- “Higgs” might be composite (“pion” of some new force which becomes strong at TeV scale) or could arise from breaking global symmetry at TeV scale (Little Higgs)
  - SM as low-energy effective theory…
- BUT no way found to get Higgs Mechanism without some particle that looks, smells, acts like Higgs boson!

Other reasons for needing the Higgs boson

- Regularizing WW scattering amplitude



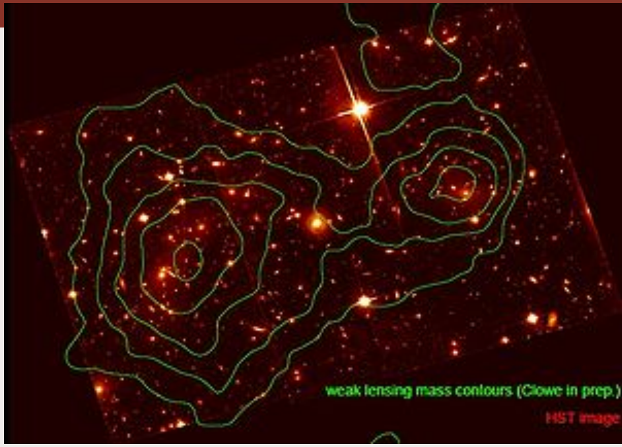
With only these 3 processes, cross section diverges (becomes infinite) at high W energy



… but if we add these two, unitarity is preserved – as long as m_H<1.2 TeV (approx.)

… but need 100s of fb^{-1} of data to test

Deficiencies of the Standard Model



- Matter / Antimatter asymmetry
  - Why is there so little antimatter?
- Gravity?
  - SM is all about mass
  - Gravity couples to mass
  - Yet SM has nothing to say about gravity
  - Hierarchy of force strengths: weak force $10^{32}\times$ stronger than gravity
- Dark Matter
  - If our understanding of gravity is correct, there is far more matter in galaxies than we can see – distributed differently from luminous stars
- Also: requires fine tuning to avoid unitarity violations

Extend the Standard Model

- Keep basics of SM and Higgs mechanism
- Assume SM is low-mass effective theory of something which explains more
- Add extra symmetries, extra particles, extra dimensions, extra forces… but with goal of *simplifying*
- Try to fix as many “deficiencies” as possible

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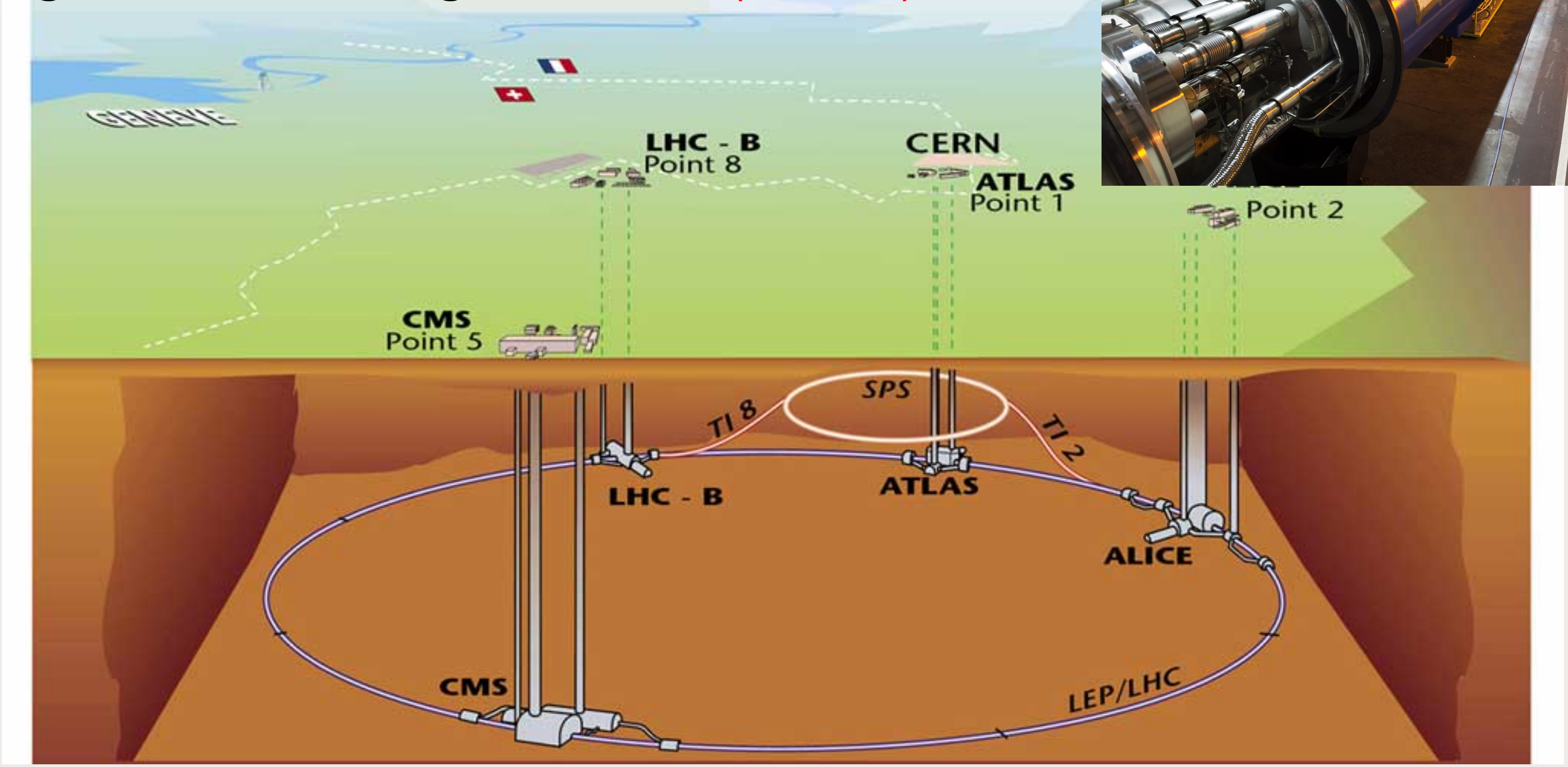
Plausible extensions to the SM

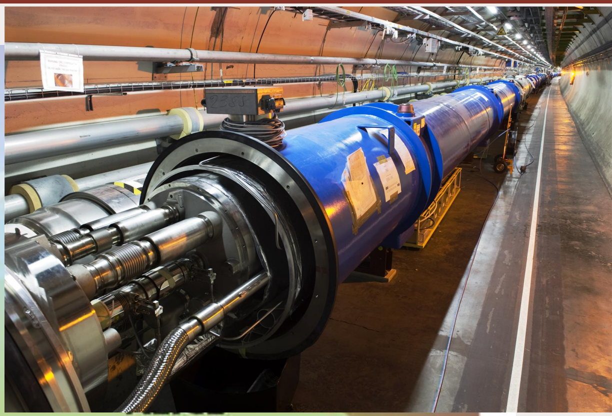
- Expanded Higgs sectors (e.g. Supersymmetry)
  - *Minimal* Supersymmetric SM
    - 2 complex Higgs doublets = 5 physical Higgs bosons
  - Can have more Higgs… but still *elementary* scalars
- Alternative Higgs(ish) Models (new strong dynamics)
  - Composite Higgs
    - genuine Higgs (or Higgs-like) particle exists: bound state of strongly-coupled theory
  - Technicolour (Higgsless)
    - Goldstone bosons eaten by W, Z are bound states "pions" of strongly-coupled dynamics
  - Little Higgs
    - Higgs kept light by an extra layer of global symmetries; allows strong-coupling scale to be pushed higher

(Thanks to H.Logan, Carleton, for classification)

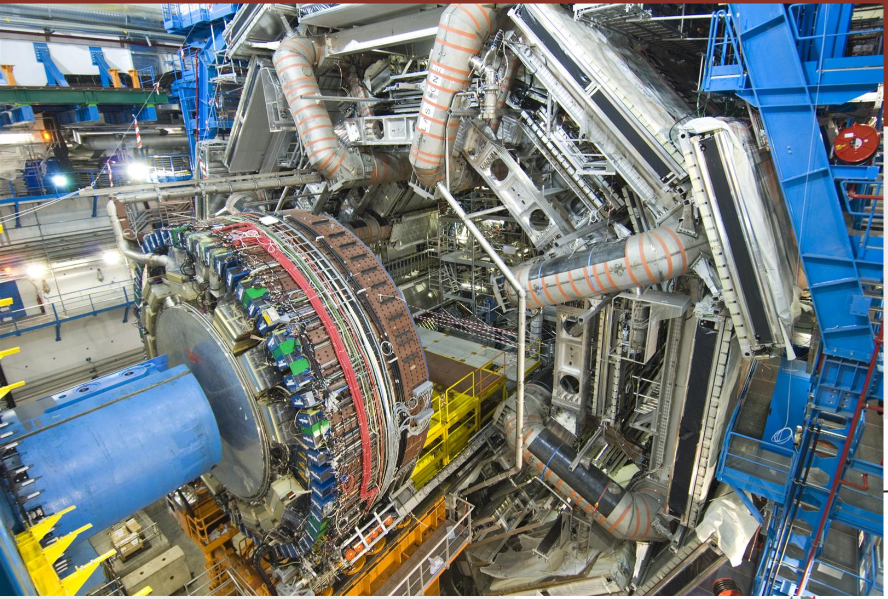
Large Hadron Collider: one ring to find them

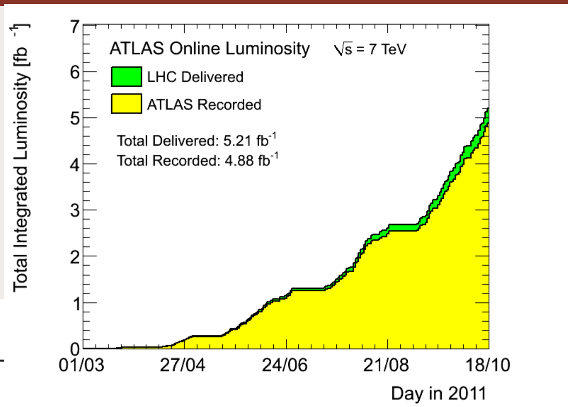
Design beam energy: 7 TeV (3.5 TeV now)
Design luminosity: 10^{34} p/cm^2/s (3.5×10^{33} now)
Design bunch crossing rate: 25 ns (50 now)

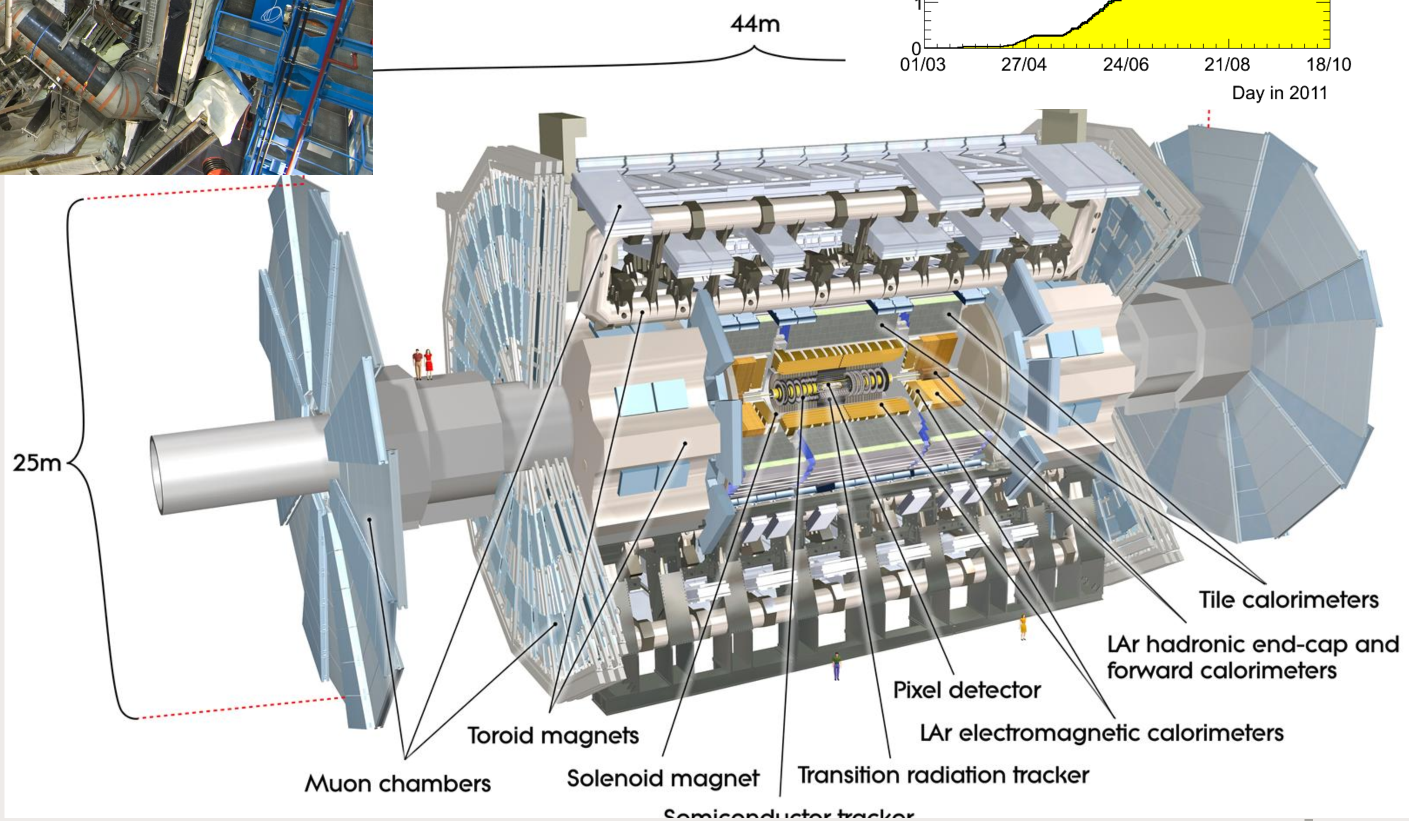




The ATLAS Detector

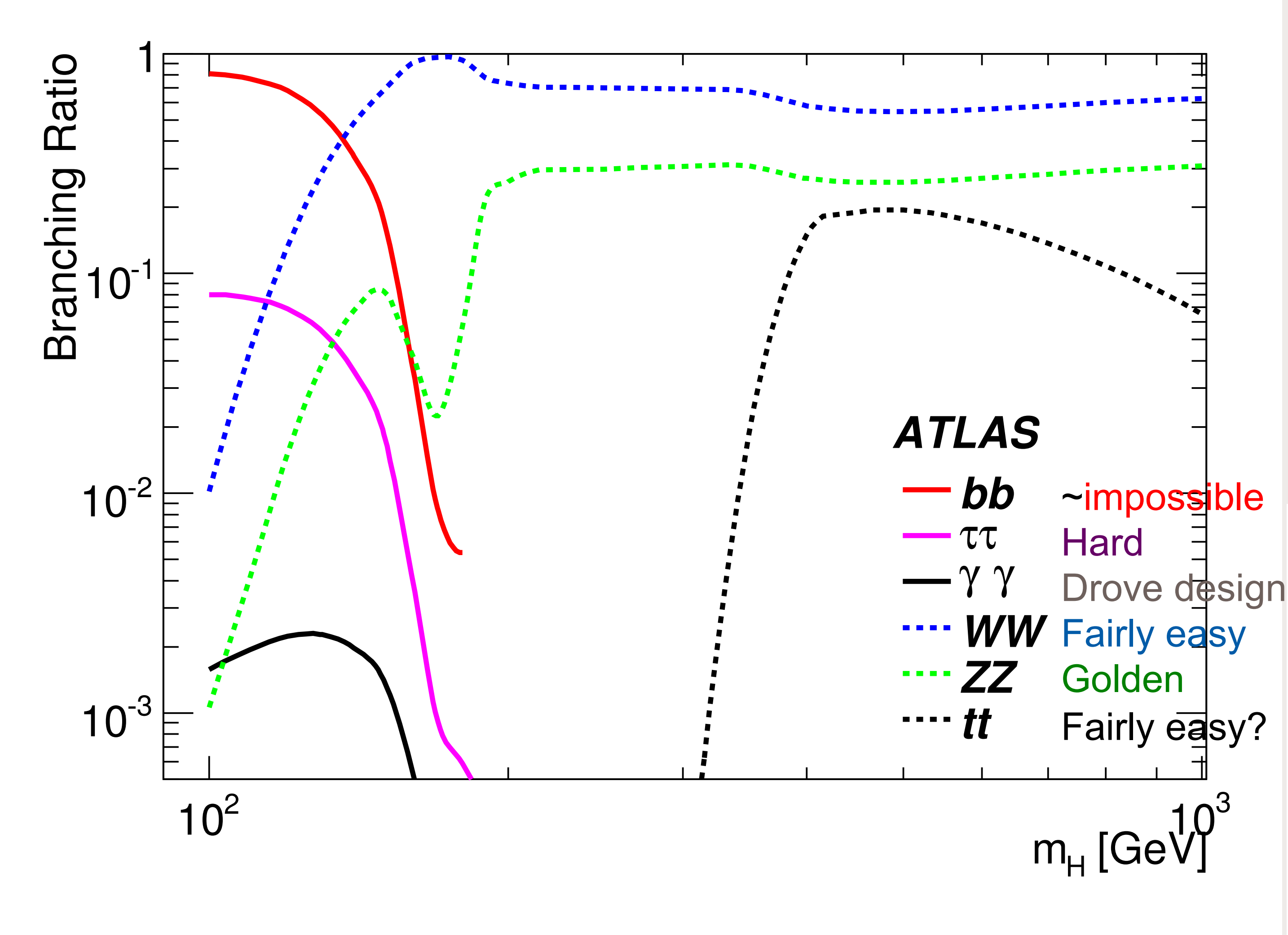




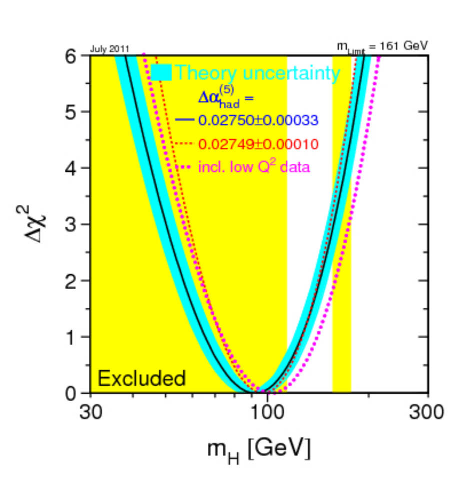


Amazing performance from detectors and accelerator means already have vastly expanded view of what is still possible compared to last year…

What we know about SM Higgs boson decays

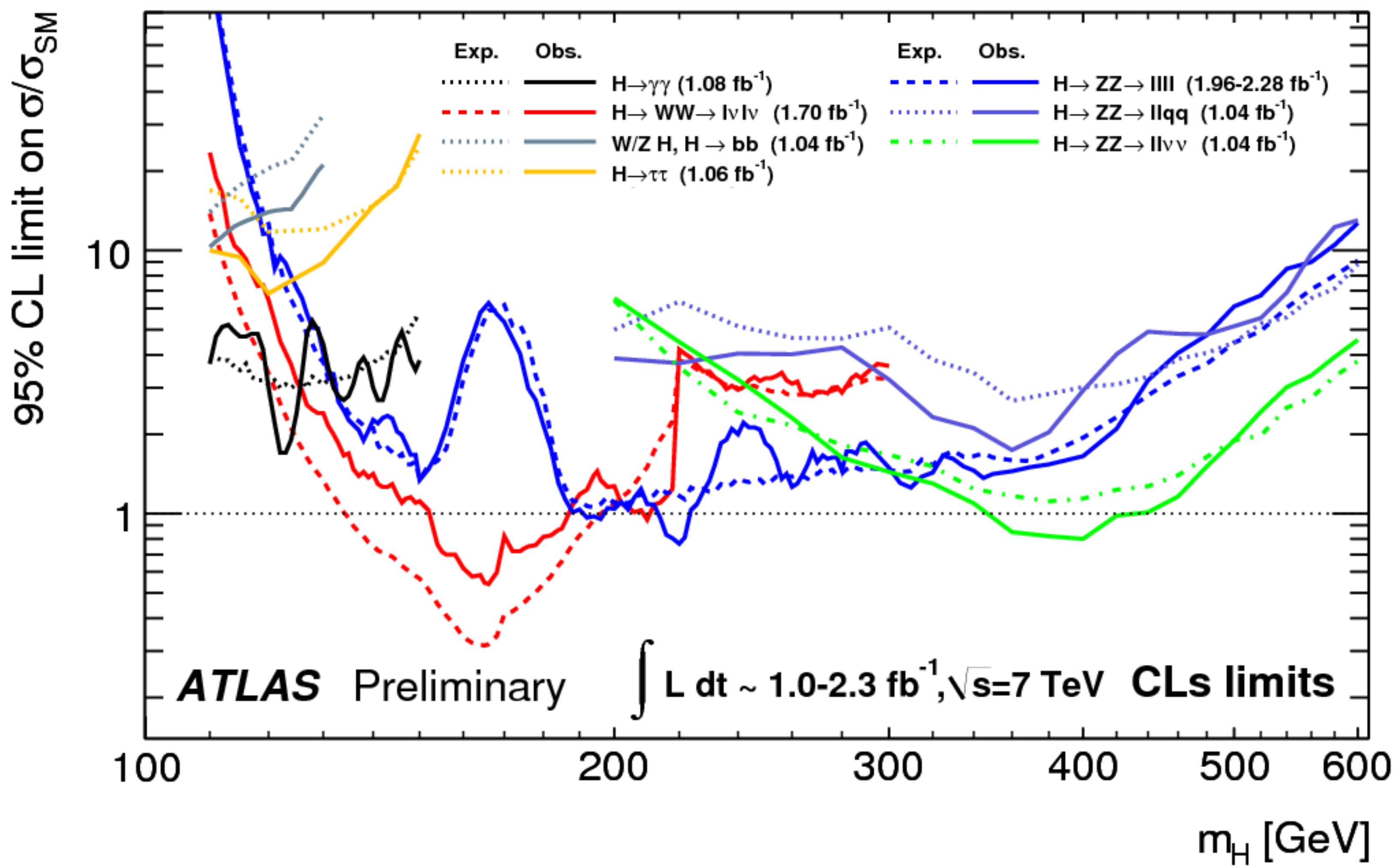


Some are easier to see than others, especially at a proton collider…

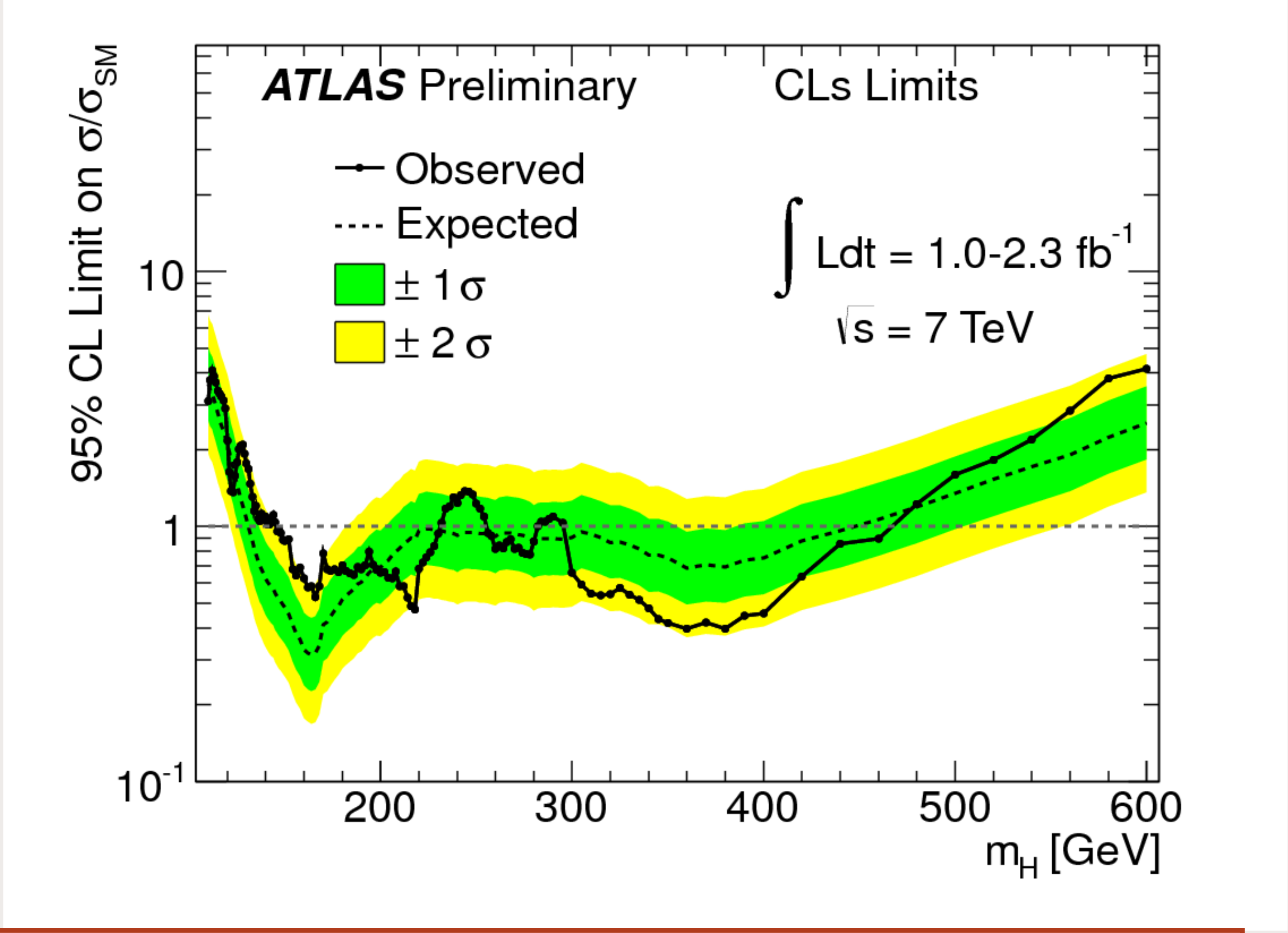


Searches for the Standard Model Higgs Boson

Many searches are combined to get the final limit…



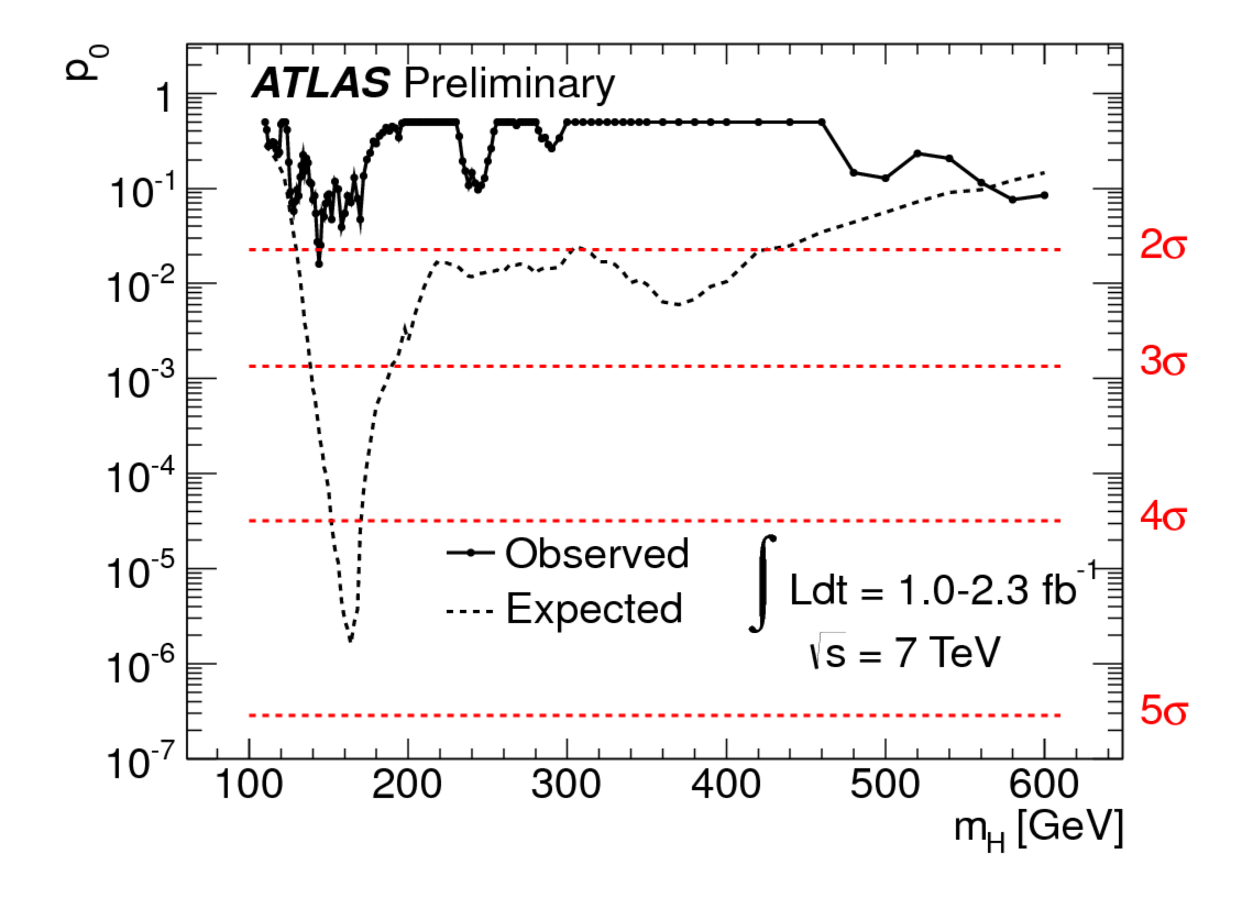
Searches for the Standard Model Higgs Boson



When we do combine them, we can exclude several mass ranges

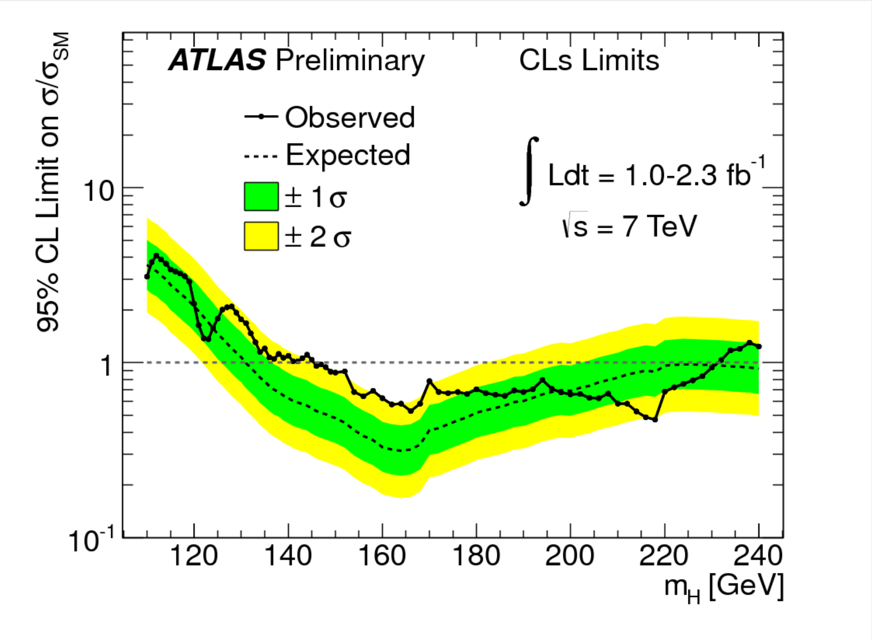
All masses where the black line is <1 are excluded at 95% CL

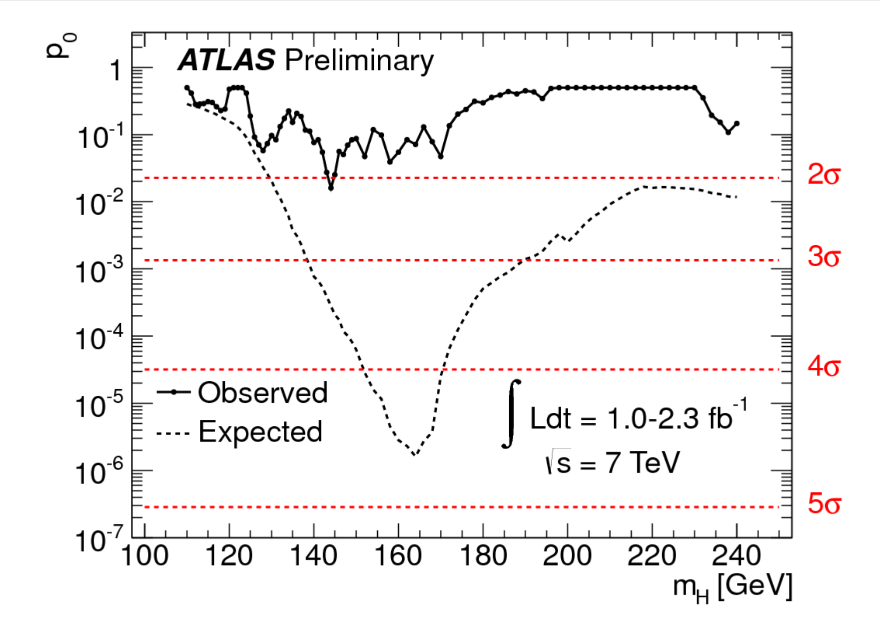
Could there be a Higgs in here?



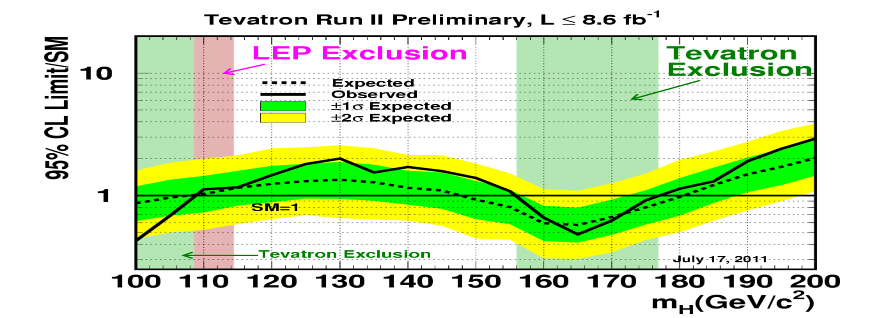
Does it look more like the Higgs? Or more like everything but?
Dotted line is what we would expect at Higgs mass, if there is a SM Higgs.

Zoom on low mass region: Tevatron interesting here





Only in challenging mass region below ~120 GeV do results really still look perfectly consistent with what we expect for a Higgs of that mass… but that is exactly where electroweak fits prefer.



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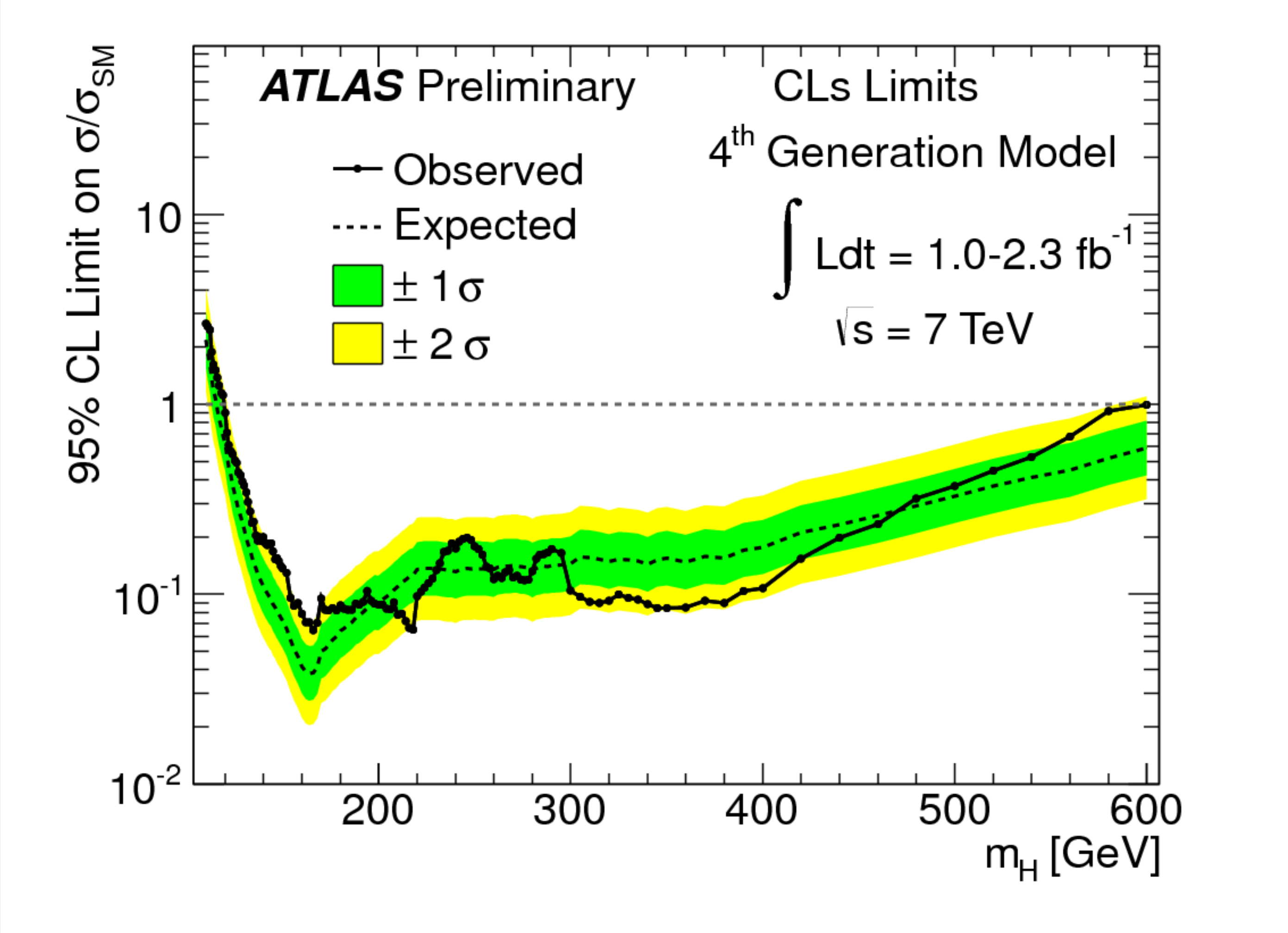
And what if it is a little more complicated?

- All models have at least one particle that looks something like a Higgs boson
  - But in models with more than one Higgs, couplings and decays can be different… (esp.YY)
  - In models with weakly interacting massive particles, Higgs can decay “invisibly”, or not couple to fermions…
  - In models with additional scalar fields, other scalars can mix with the Higgs boson
- In these cases limits typically less stringent

(In some models, limits are *stronger* than SM!)



This is for a model with 4 generations of quarks & leptons

What else can we look for?

- Resonances
- Excited states
- Kinks and end-points in spectra
- Dark matter
  - Limited time: focus on dark matter

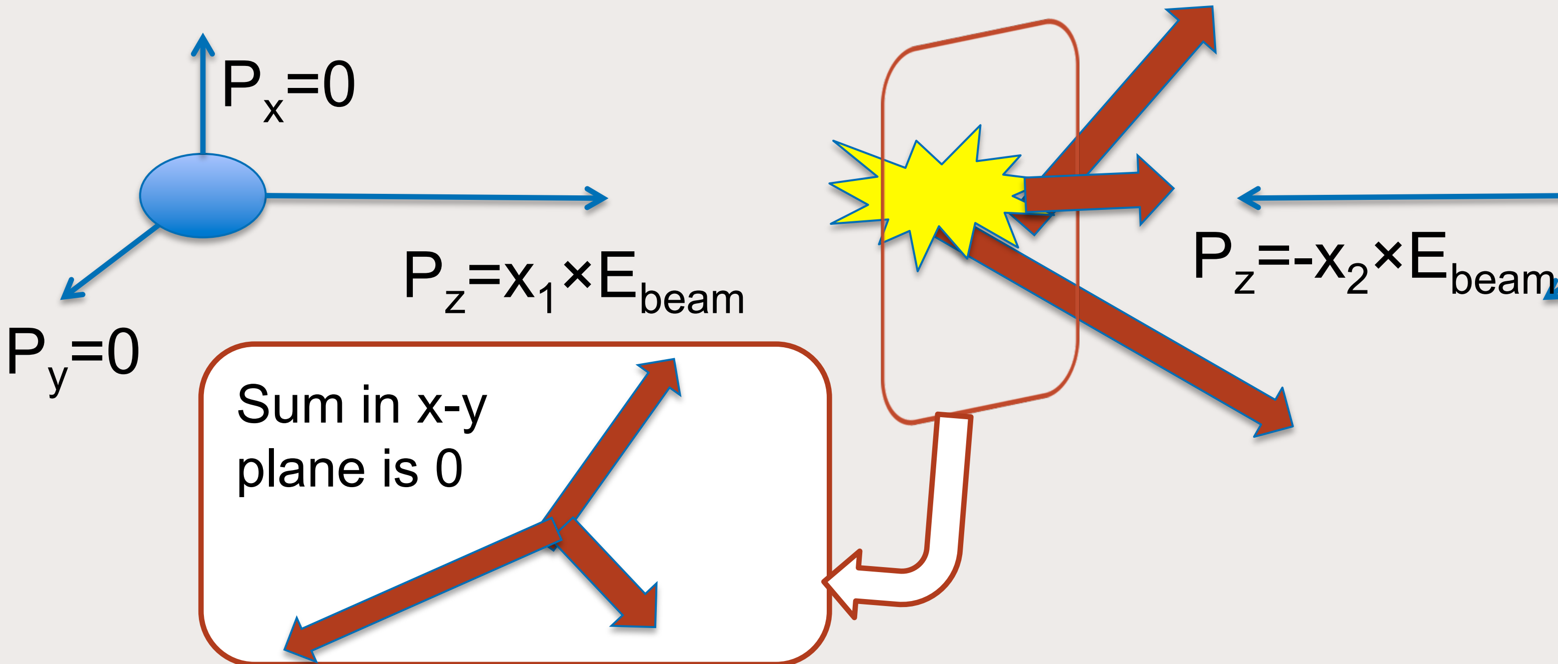
- Most models predict more than "just" a Higgs boson at TeV scale…
- Lots of things we can discover if they are there!
- BUT higher energy will help a lot for most other searches – only SM Higgs can really be definitively ruled out with 3.5 TeV beams at LHC

Searches for dark matter: general idea of "missing transverse energy"

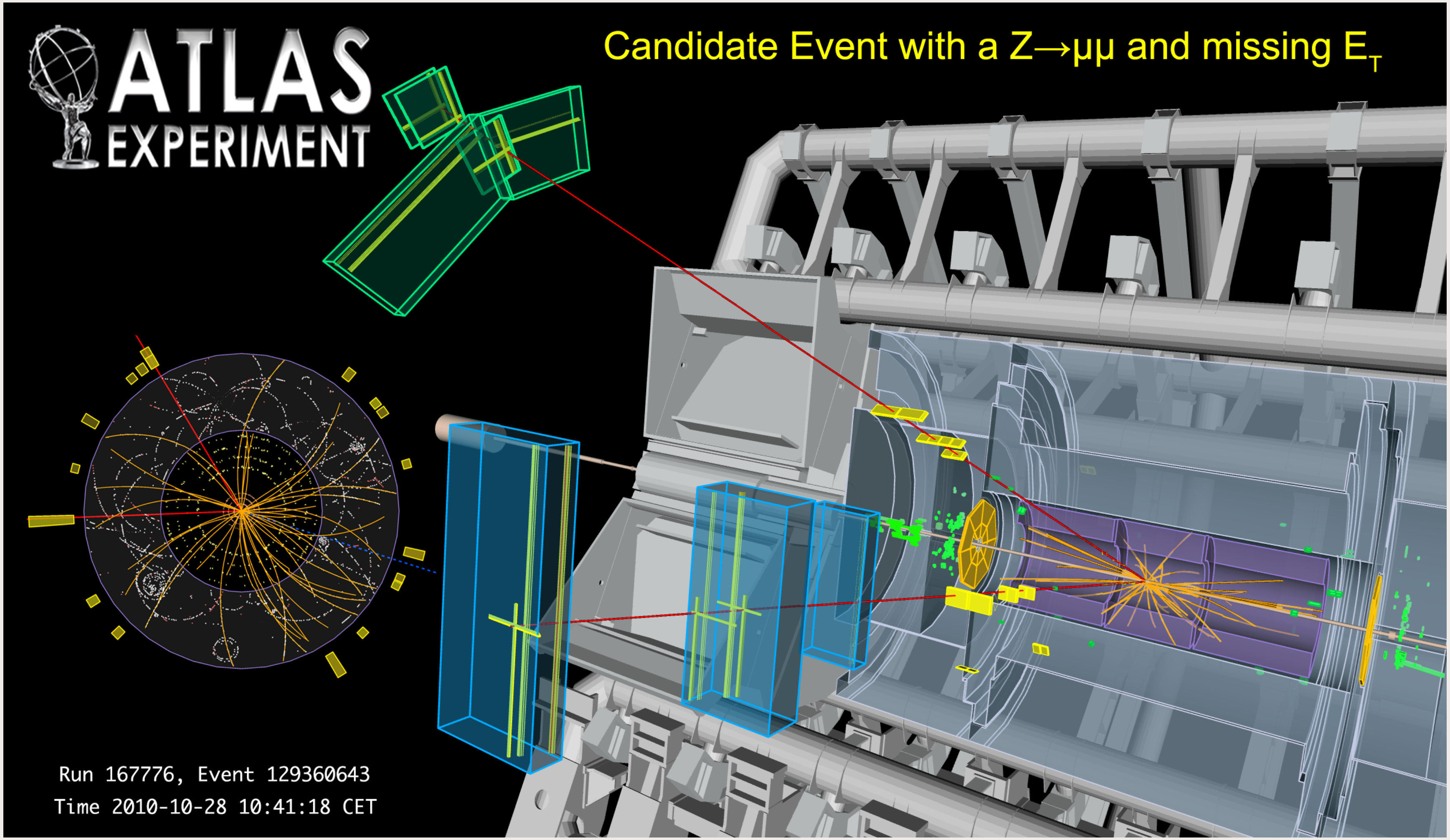
- Most models of new physics "beyond the SM" introduce many new particles…
  - … *none* of which we have ever seen
- Can avoid embarrassment this should cause
  - By having most new particles very massive
  - And rest "invisible" (colourless, chargeless, weakly interacting…)
  - Or by letting new particles slip away into extra dimensions in which SM forces do not propagate (though gravity might)
- In all these scenarios, "invisible" particles leave "missing energy" signature, as energy & momentum conserved
- Initial beams have *no momentum transverse to beam* direction:
  - Transverse momentum in final state **must sum to zero**

Transverse energy

- Initial z-momentum of partons (quarks and gluons) involved in collision is unknown
- Initial x- and y-momentum of partons is zero
- Transverse momenta of final state particles must sum to zero!



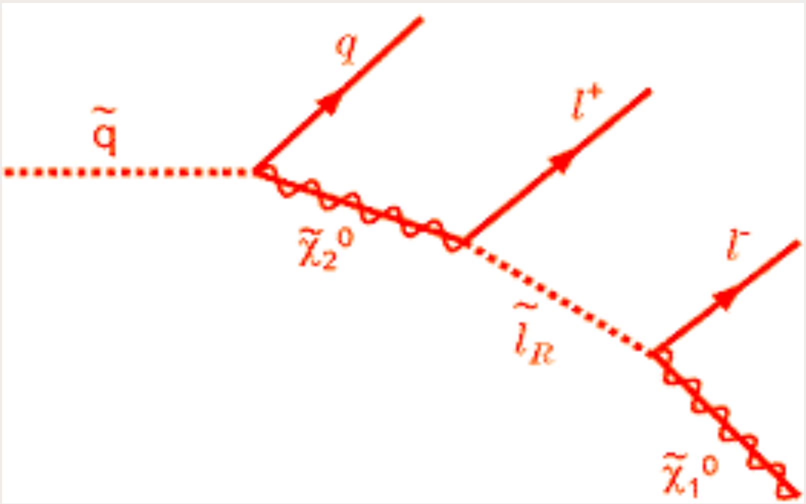
Event with missing transverse energy

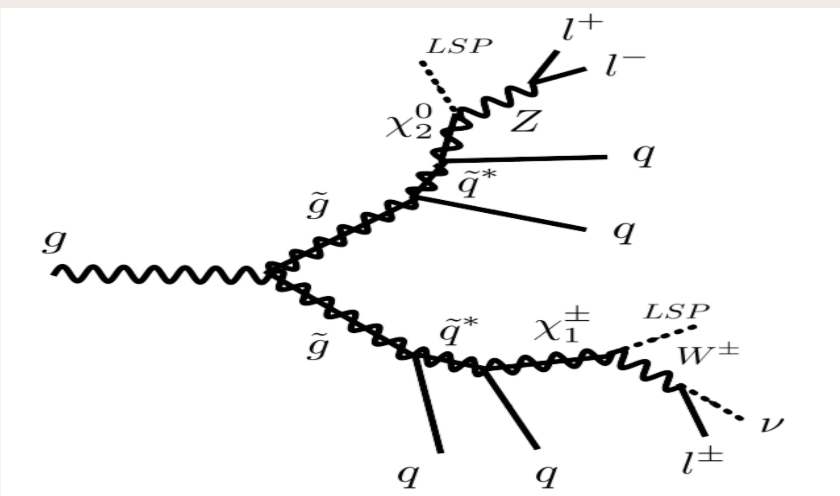


Candidate Theory: Supersymmetry

- Add a new fermion-boson symmetry (SUSY)
- **Double** the number of elementary particles
  - Must be **broken** symmetry or SUSY particles would have same masses as normal partners and we would have discovered them already
  - SUSY *breaking* mechanism may be “natural” way to involve **gravity**…
- Assume SUSY particles must be pair-produced
  - “R-parity” – define R=1 for “ordinary” Standard Model particles, R=-1 for super-partners, require R-conservation
  - Has (useful!) implications for allowed decays…

Searches for dark matter: supersymmetry

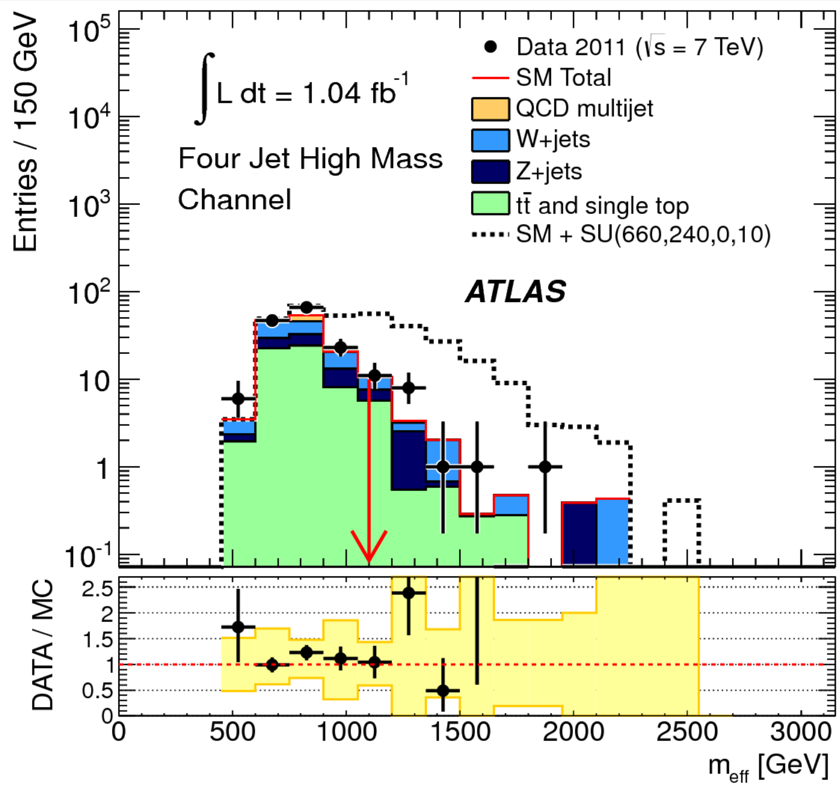


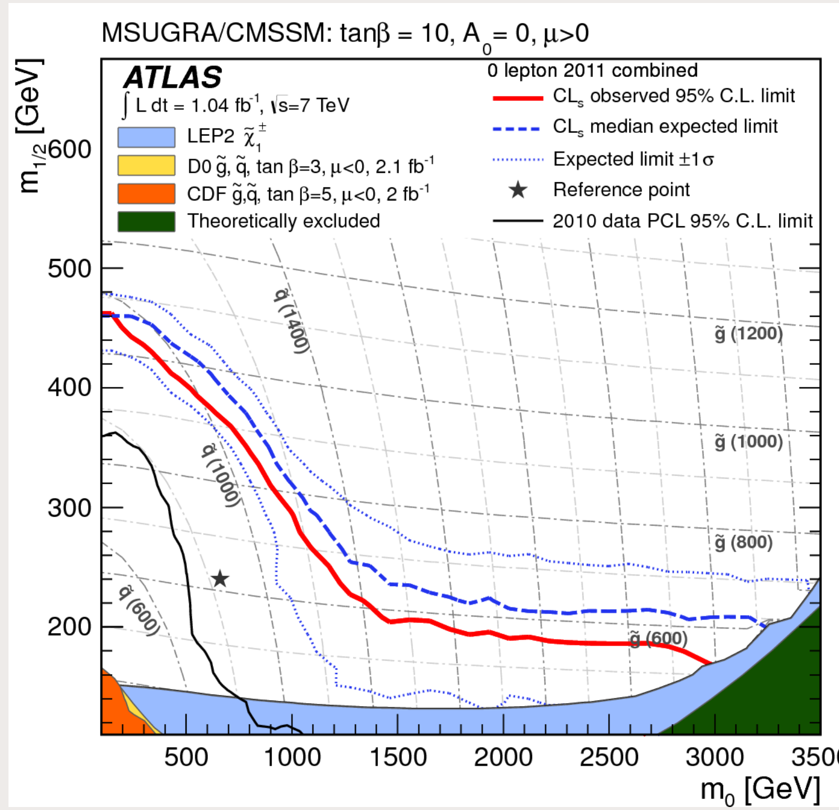


- If SUSY particles conserve "R parity" all decay chains must end with **stable "lightest SUSY particle"** (LSP)
- Typically LSP is lightest neutralino
  - (or other neutral particle)
- Neutral, stable, weakly interacting: perfect **cold dark matter** candidate…
  - No interaction in detector = missing transverse energy

SUSY: Jets +E_T^{miss}

One channel among many, non-overlapping by construction

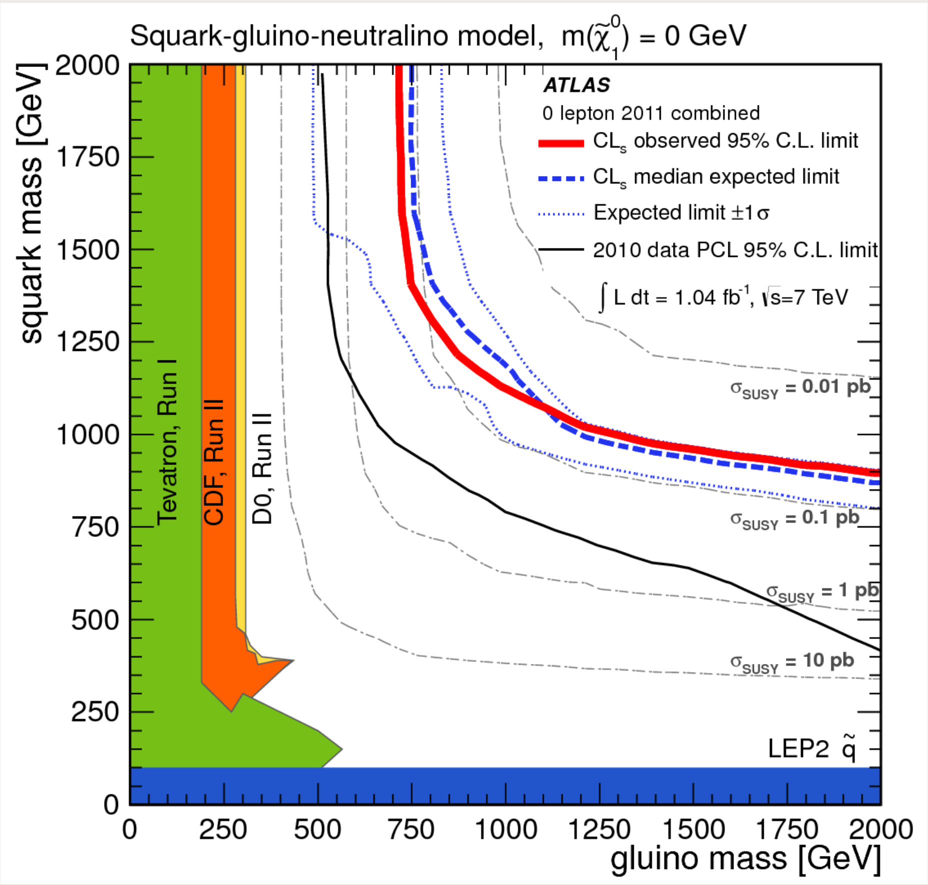




Analysis further subdivided by number of jets and variable ranges, one example

Limits set in benchmark model (* = --- LH plot)

SUSY: Jets + E_t^{miss}

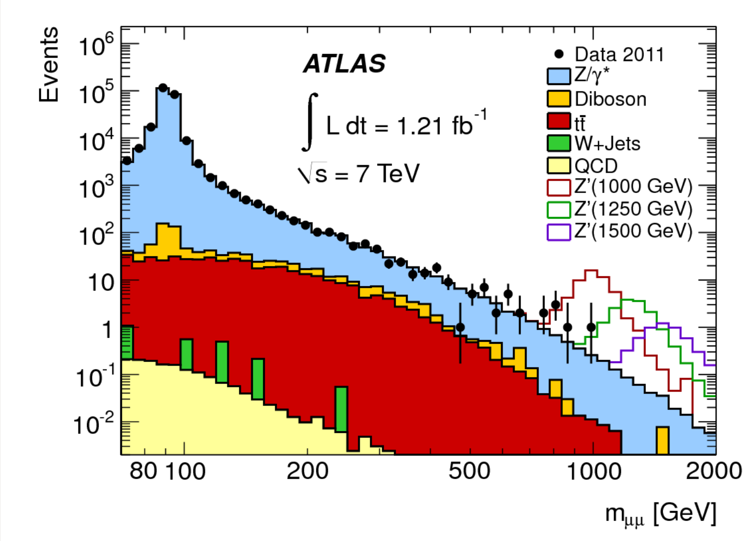


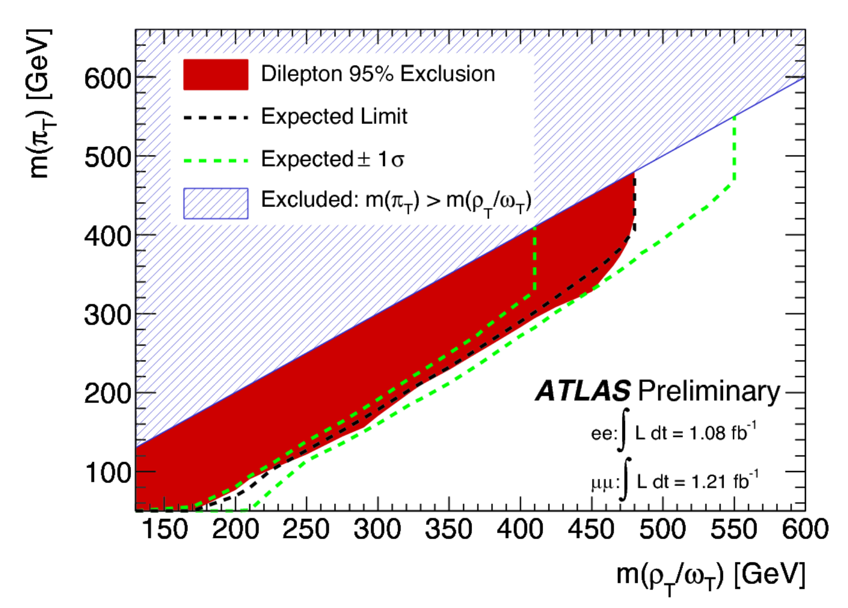
- Can set rather generic cross section limits in simplified SUSY models
- To notice:
  - LHC excludes a lot more phase space than LEP or Tevatron
    - Doubling energy post-2012 will help!
  - Excluded region from LHC is still growing fast as we collect more data

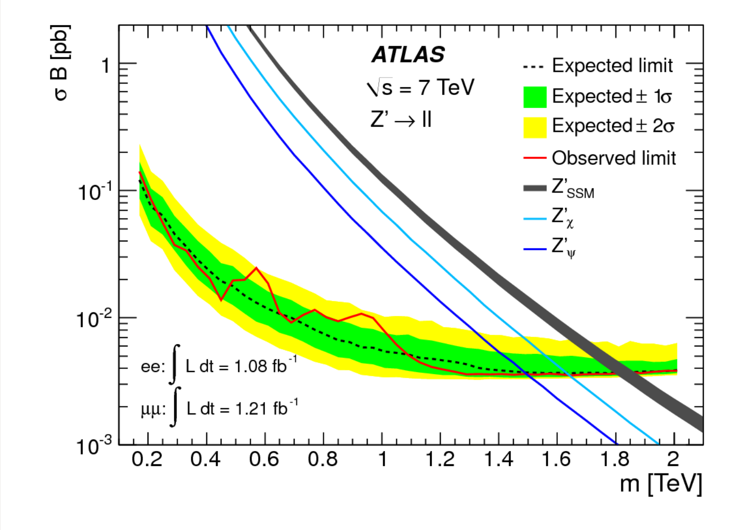
Supersymmetry

- SUSY is a very appealing theory…
  - … strong theoretical motivation (boson-fermion cancellation eliminates fine-tuning SM Higgs mass)
  - … great dark matter candidates
- But >100 free parameters and more than doubles the number of particles to find
  - …and we haven't found *any* of the SUSY partners
- Still, SUSY can **reproduce typical signatures of almost any other theory** you dream up to solve the same problems, so level of "belief" is irrelevant
  - Hunt to prove it doesn't exist? Not so useful…
  - Hunt to find anything like it?

Searches for new resonances and technicolour

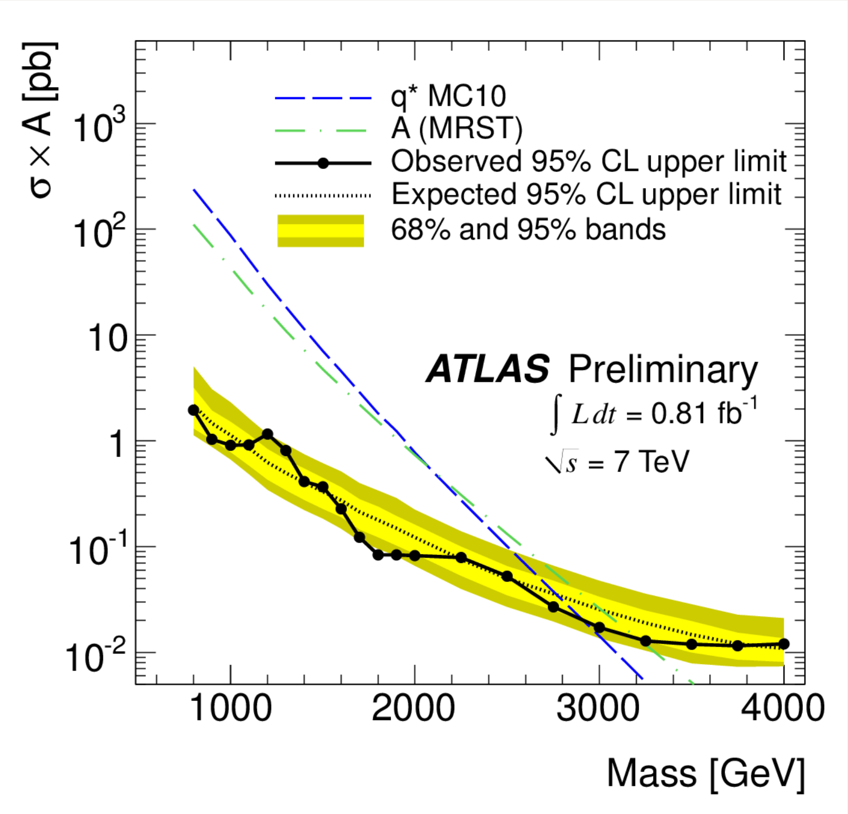






Search for dilepton resonances can be used for both Z' and technimesons – simple signature, lots of interpretations!

Covering all the bases: searches for compositeness



- Most mass of baryons is strong force binding energy – nothing to do with Higgs
- Maybe all mass is like that, and quarks, leptons are not elementary particles?
- No sign of excited quarks or leptons… but keep looking!

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Summary: have we fully appreciated the gravity of the situation?

- Every reason to believe in the **Higgs mechanism**
  - Implies Higgs-like particle **we must soon find at LHC**
  - **Still room for SM Higgs in most likely mass range**
- Finding *only* SM Higgs unsatisfying, what next?
  - Not finding anything Higgs-like would be (death?) blow to otherwise totally successful Standard Model
- Searches for “dark matter” (if successful) would solve many more problems
  - What is connection between mass (funny non-quantized form of energy) and gravity (funny non-quantized force)?
- LHC is just starting, and will give first answers **soon** – This is the future!