Particle Physics

Dr Victoria Martin, Spring Semester 2012

Lecture 19: Higgs & Beyond the Standard Model

- ★Higgs searches at LHC
- ★Problems of the Standard Model
- ★Extended Higgs
- ★Supersymmetry
- ★Grand Unified Theories
- ★Extra Dimensions

Notes & Queries

- **Last lecture today**
- **Revision Tutorial**: *when?*
- **Past exam papers**: 2012 is first time I've taught the course. This year we didn't cover some topics in so much detail as for past years.
  - Past exam papers still representative of the level of format and level of questions.
  - Problems sheet are fairly representative of exam questions.
  - In problems sheets sometimes you have to consult notes to look up somethings, these would be provided in exam questions.
- Problem Sheet solutions will appear.
- Notes being uploaded: I will email when they are complete.

From Friday: Higgs Summary

- An extra field, ϕ, is introduced to the Standard Model with a potential:

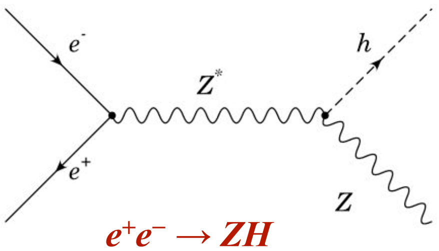
$$V(\phi) = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

- This symmetry of the system is spontaneously broken by minimising V
- The breaking of the symmetry gives terms which can be used to give mass to the W and Z boson.
- The symmetry breaking also gives rise to a spin-0 particle: the Higgs boson, H.
- The Higgs boson couples (in order of strength to): W-bosons, Z-bosons, fermions (in order of mass).
- Indirect evidence suggests $m_H \sim O(100\ \mathrm{GeV})$
- Direct searches have not found any conclusive evidence.
- At $m_H \sim 125\ \mathrm{GeV}$, hint of something using $H \to b\bar{b}$, $H \to W^+W^-$, $H \to \tau^+\tau^-$ $H \to ZZ$ and $H \to \gamma\gamma$

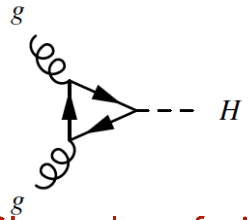
Direct Searches for the Higgs Boson

- We haven't detected the Higgs boson, we are still searching for it.
- It is heavy $m_H \sim O(100\ \mathrm{GeV})$, need a collider to make it.
- LEP (e^+e^- at CERN); TeVatron ($p\bar{p}$ at Fermilab); LHC(pp at CERN)

Main production modes:

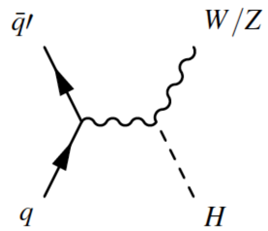


$e^+e^- \to ZH$



Gluon-gluon fusion: $gg \to H$ (Dominant mechanism at LHC)

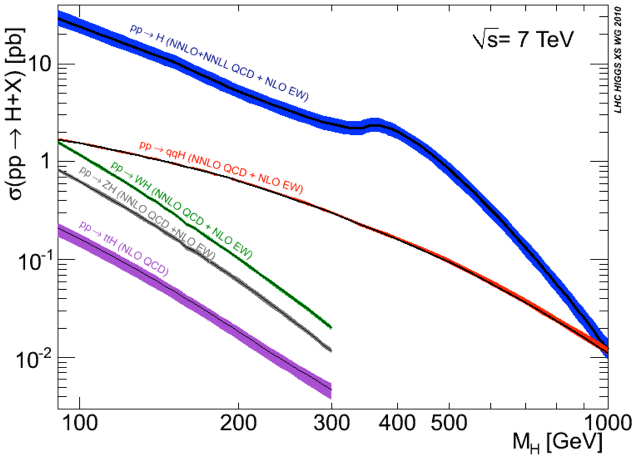
Top quark most likely in loop

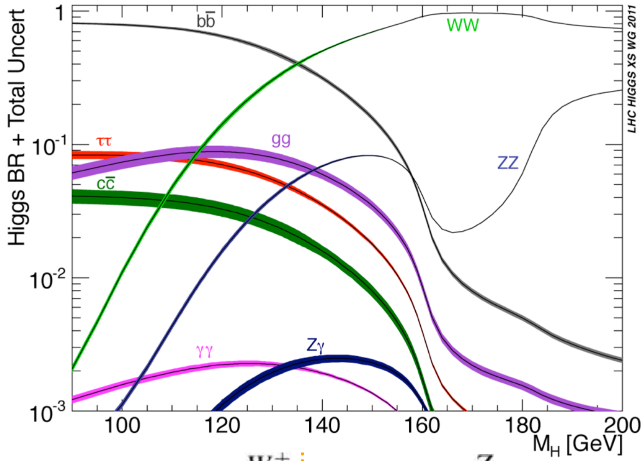


Associated production with a W or Z boson, e.g. $q\bar{q}' \to WH$

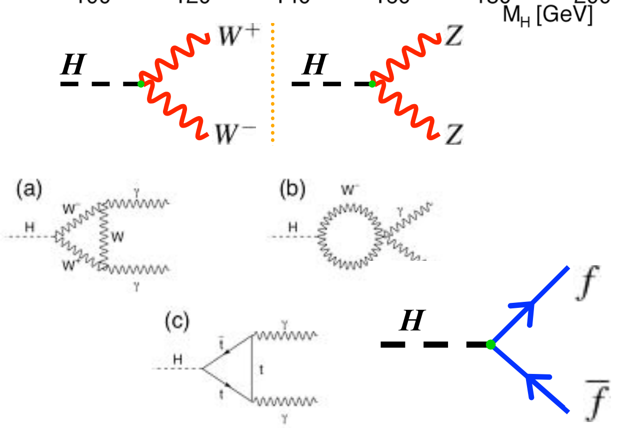
- LEP result: $m_H > 114.4\ \mathrm{GeV}$
- TeVatron ruled out: $100 < m_H < 106\ \mathrm{GeV}$, $147 < m_H < 179\ \mathrm{GeV}$

Higgs: Decay and Production at LHC

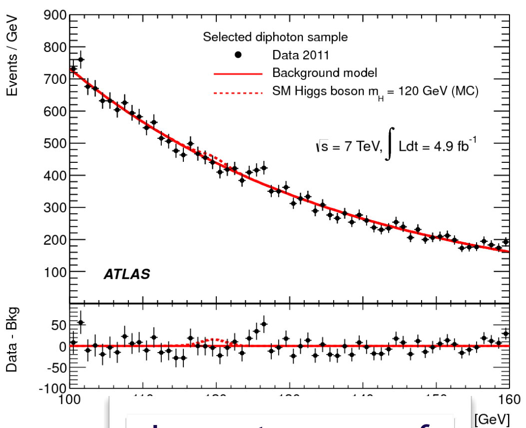




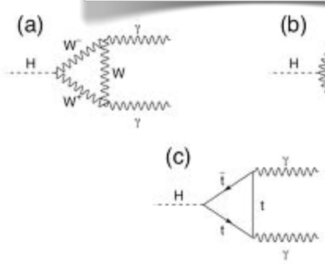
- Higgs cross section (**σ**) and branching ratios (**BR**) for the Higgs boson depend on m_H.
- Most interesting mass range is around $m_H \sim$ **120 GeV**
- Main decays are: $H \to b\bar{b}$, $H \to W^+W^-$, $H \to \tau^+\tau^-$
- $H \to ZZ$ and $H \to \gamma\gamma$ also useful
- On the following slides, a few results from the ATLAS and CMS experiments at LHC.

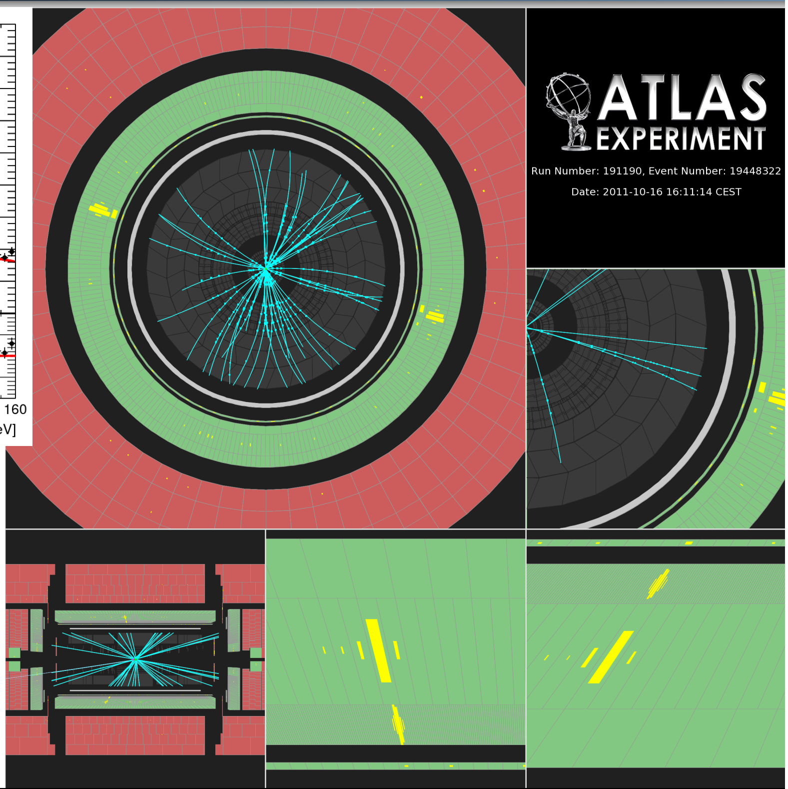


$H \to \gamma\gamma$: The Beautiful



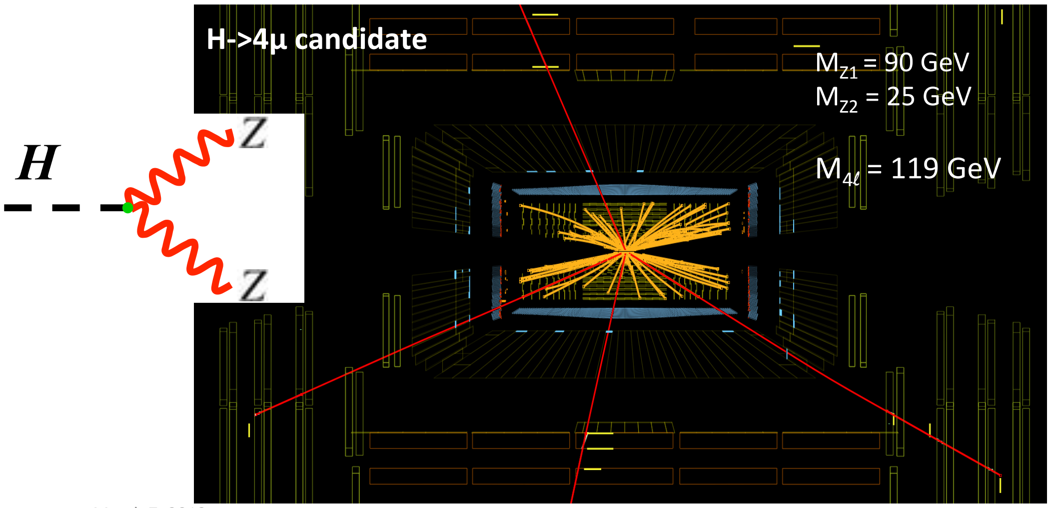
Largest excess of events observed at **m(γγ) = 126.5 GeV**





Full mass range: H → ZZ → 4l (4μ, 4e, 2e2μ)

- Clean channel: 2 high mass pairs of isolated electrons or muons
- **Narrow mass peak**
  - Very good mass resolution 1-2 %
- Small BR ~1E-3 at high mass
- Background
  - irreducible: ZZ, Reducible: Z+jets, Zbb, tt, WZ
- Most important aspect:
  - highest possible lepton id efficiency down to very low P_t

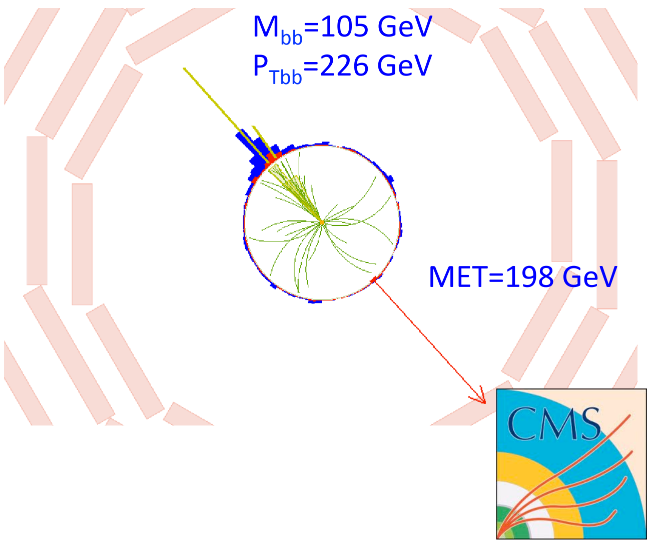


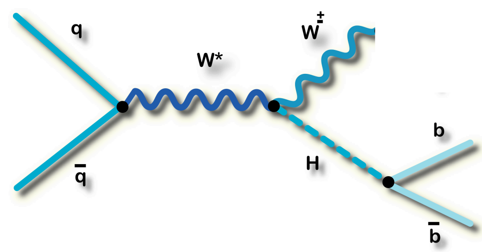
March 7, 2012 20

Marco Pieri, UCSD, Moriond EWK, 7th March 2012

Search for $H \to b\bar{b}$

- Signature of $H \to b\bar{b}$ production is two jets with $m(j_1 j_2) \sim m_H$.
- The cross section of Higgs production at the LHC is ~10 pb.
- Enormous background from other two jet processes (~10^8pb): Very hard to identify $H \to b\bar{b}$ above background processes.

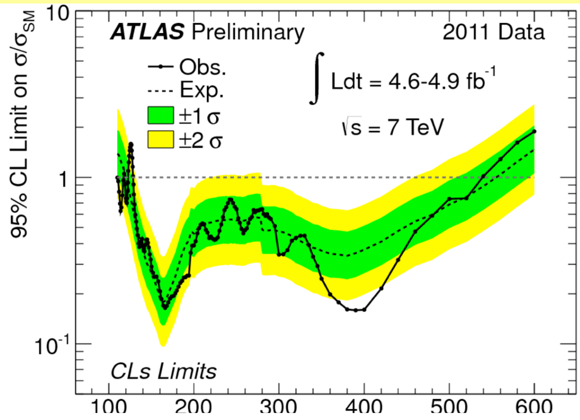




- Look for Higgs production in association with a W or Z boson: e.g. $p\bar{p} \to WH \to bb\ell\nu$. Reduces background level.
- The Higgs often has high momentum to balance the energy of the W or Z. Therefore two jets are close together in detector.

ATLAS Limits on Higgs Boson

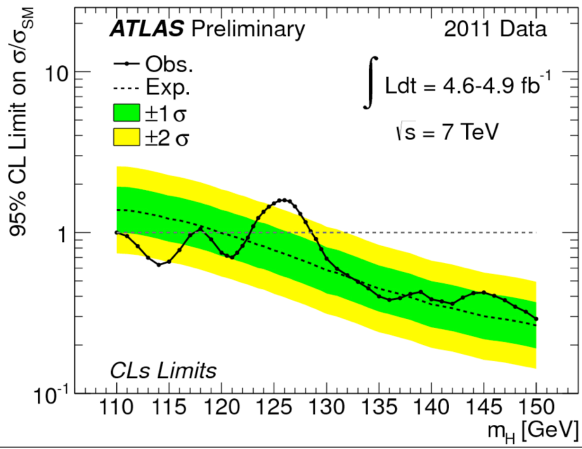
- Plots show results of experimental searches for Higgs boson
- Higgs boson of given mass ruled out when black line < 1
- Green and yellow band shows the predicted shape for the no Higgs boson scenario.



- No conclusive evidence for the Higgs boson observed.

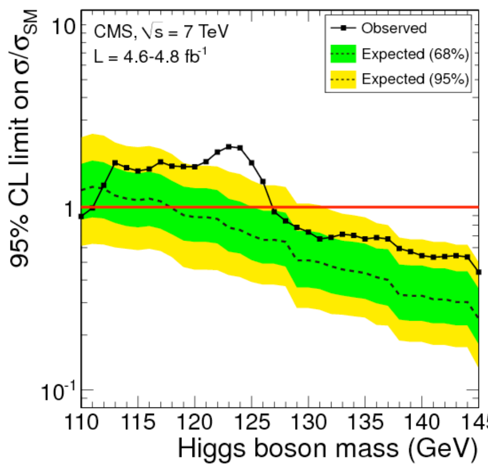
- Higgs boson ruled out for many values of m_H: otherwise we would have seen it already!

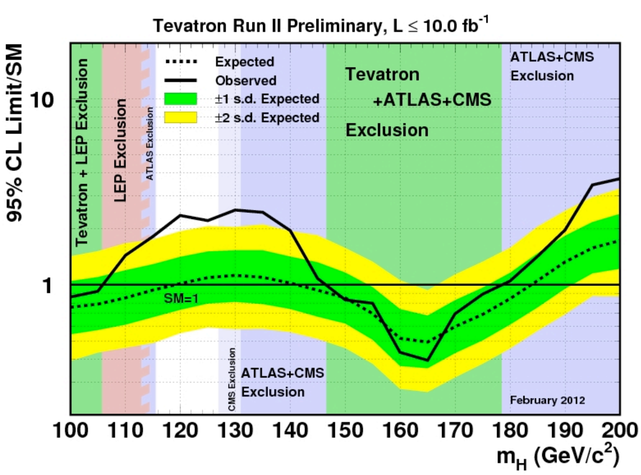
- Hint of a Higgs signal around $m_H \sim$ **125 GeV**

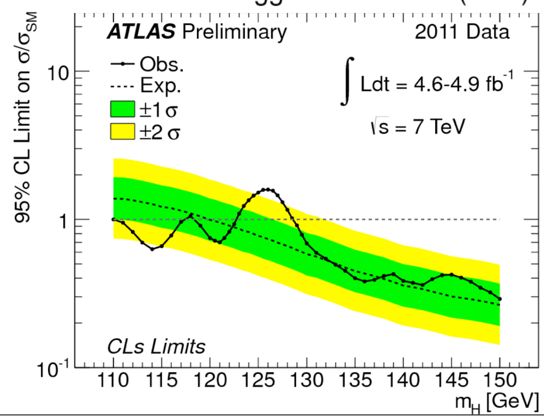


LHC/TeVatron Limits on Higgs Boson

- Both ATLAS and CMS experiments at the LHC and the Tevatron Collider see a disagreement with the no-Higgs scenario for $m_H \sim$ **125 GeV**
- Need LHC experiments to collect and analyse more data to decide if this is just a statistical fluctuation or not...

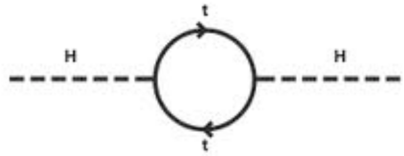






Limitations of the Standard Model

- **Neutrinos** have mass; only left-handed neutrinos are observed.
- The Higgs mechanism only gives mass to particles with both left- and right-handed components: how can we describe the **mass of neutrinos**?
- Neutrinos oscillations suggest the electron, muon and tau quantum numbers are not fully conserved.
- *CP* violation exists, but very small effect in quarks only. Not large enough to explain matter anti-matter asymmetry of universe.
- **Higgs boson mass**: Renormalisation of the mass suggest that the mass should be naturally very high.



- Standard Model does not explain dark matter or include gravity. On following slides examine a few models proposed to address some of these problems

From Lecture 1: The Dark Side

- Only 4.6% of the current universe is normal matter (baryons + electrons = atoms)
- To account for rotation curves of galaxies, gravitational lensing and large scale structure need:

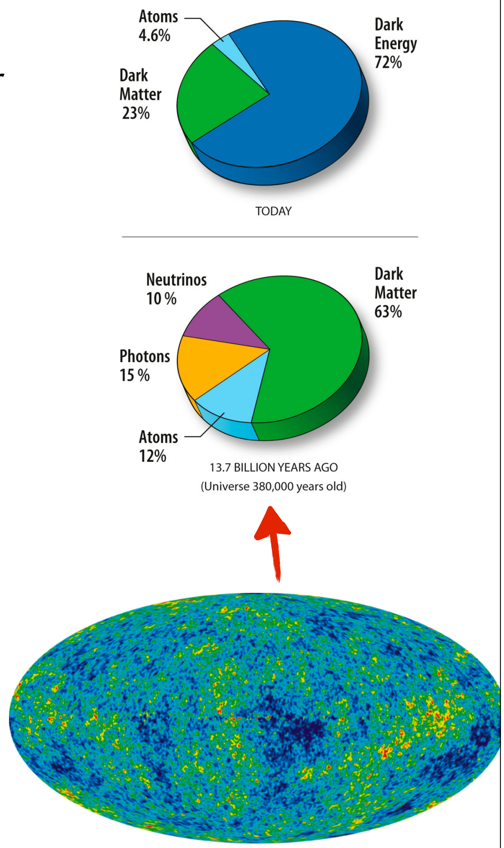
  23.3% "Dark Matter"

  Must be weakly interactive massive particles (not yet discovered)
- To account for acceleration of expansion of the universe need:

  72.1% "Dark Energy"

  May be described by a cosmological constant Λ

Could particle physics describe either dark matter or dark energy?

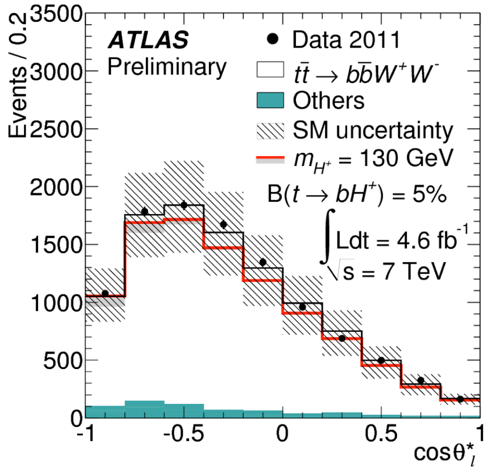


Two Higgs Doublets

- The Standard Model (SM) assumes the simplest possible Higgs mechanism with one Higgs field doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

- Can introduce further Higgs doublets.
- ***e.g.*** Two doublets: 8 degrees of freedom. Two charged and one neutral used to give mass to $W^{\pm}$ and Z^0.
  - Leaves five free parameters: five Higgs bosons: $\mathbf{h^0, H^0, A^0, H^+, H^-}$
  - Searches at LHC made for charged Higgs bosons, e.g. $\mathbf{t \rightarrow H^+ b}$, nothing observed (as yet)

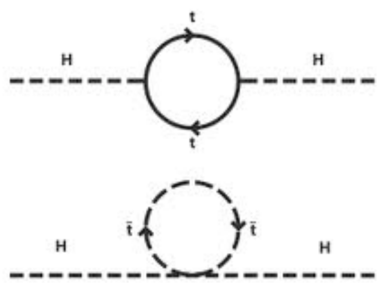


Supersymmetry (SUSY)

★ Corrections to the Higgs boson mass suggest that naturally it should be very high.

★ Low Higgs mass would be more natural if these contributions would be cancelled.

★ **Supersymmetry** introduce a new symmetry between fermions (half-integer spin) and boson (integer spin).



New supersymmetry particles cancel with SM particle contributions.

★ Supersymmetry is the only unobserved symmetry that commutes with Lorentz group.

★ SU(3) SU(2) U(1) symmetries also commute, already observed.

QCD (SU(3)) Electroweak (SU(2) U(1))

SUSY Particles

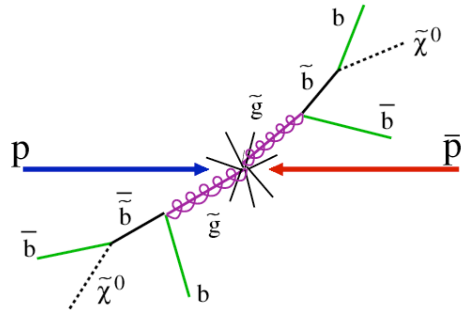
- ★ Every SM particle has a supersymmetry partner, different by $\Delta S = \frac{1}{2}$
- ★ SUSY requires two Higgs boson doublets: 5 Higgs bosons, $\mathbf{h^0, H^0, A^0, H^\pm}$
  - ➡ $S=0$ partners for fermions: squarks ($\tilde{q}$), sleptons ($\tilde{\ell}$), sneutrinos ($\tilde{\nu}$)
  - ➡ $S=\frac{1}{2}$ partners for W, Z, γ: photino, Wino, Bino
  - ➡ $S=\frac{1}{2}$ partners for Higgs: Higgsinos
  - ➡ $S=\frac{1}{2}$ partners for gluon: gluinos

} mix to give "charginos" & "neutralinos"

$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$

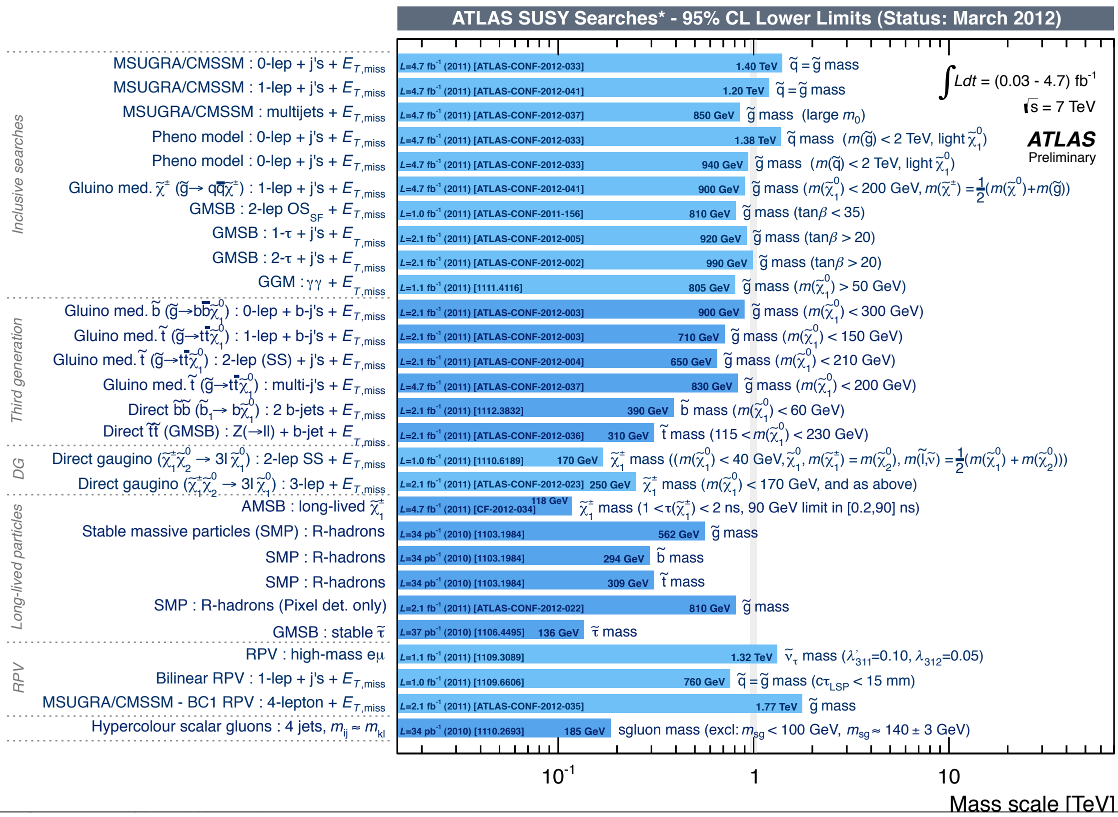
$\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$

- ★ Lightest SUSY particle could be stable (neutralino, squark?)
- ★ If one of the neutralinos is stable it would provide a candidate for dark matter.
- ★ Searches are underway at LHC for these particles … no evidence yet.

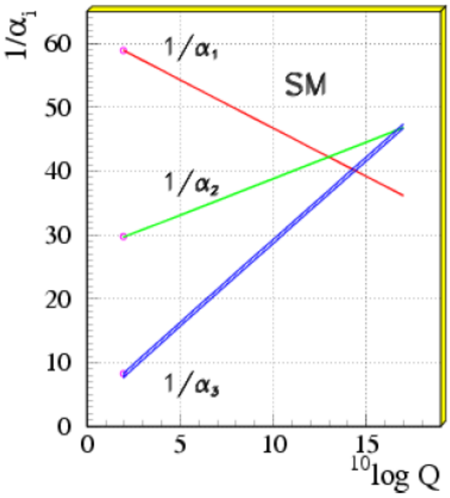


SUSY Searches at ATLAS

Summary of SUSY-things not found by ATLAS

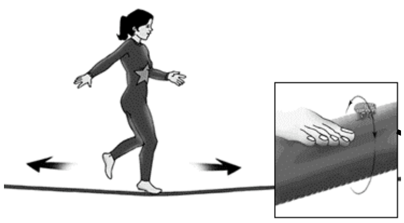


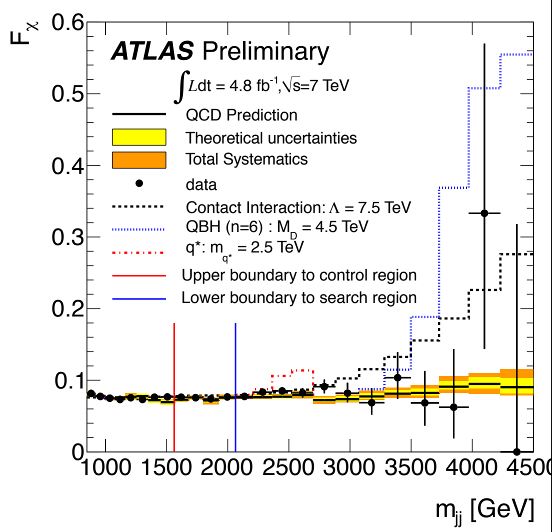
Grand Unified Theories (GUTs)



- The strong (α_S=α_3), electromagnetic (α=α_1) and weak ($g_W/4\pi = \alpha_2$) couplings depend on the energy scale of the interaction (Q)
- The coupling constants do not merge.
- Supersymmetric particles would modify the running at **Q~1 TeV**, allowing interactions to merge at **Q ~ 10^{16} GeV**

Extra Dimensions, Strings & Branes





- Extra dimensions (**D**>**4**) could incorporate gravity naturally
- "Compactified" into 1D strings or 2D branes with small radius, **1/*R* > a few TeV**
- Excitations within extra dimensions are known as Kaluza-Klein (**KK**) states
- **KK** resonances decay into dijet or dileptons
- Can also have "warped" extra dimensions (Randall-Sundrum) → Predicts massive **KK** graviton

- No excess jet-jet events found, limits the size of extra dimension **1/*R* > 3.96 TeV**

- Extra dimensions (and SUSY GUTs) are required by string theories
- These attempt to explain quantum gravity at the Planck scale

Summary

- The Standard Model of particle physics: electroweak and QCD is highly predictive, tested and verified to a high degree of precision.
- However in a few areas it leaves open questions… new models are developed to overcome these issues.
- Searches are underway at the LHC for new phenomena associated with the new models, but as yet, none found.

- The **Higgs boson** is ruled out for many possible masses, “hints” of a signal around $m_H \sim 125$ GeV.
- Main decay modes are: $H \to b\bar{b}$, $H \to W^+W^-$; $H \to ZZ$ and $H \to \gamma\gamma$ also useful

- **Additional neutral and charged Higgs bosons** are predicted by extensions to the Standard Model.
- **Supersymmetry** predicts a doubling of particles.
- **Grand Unified theories** predict all there forces merge at very high energies.
- **Extra dimensions** could incorporate gravity into particle physics.