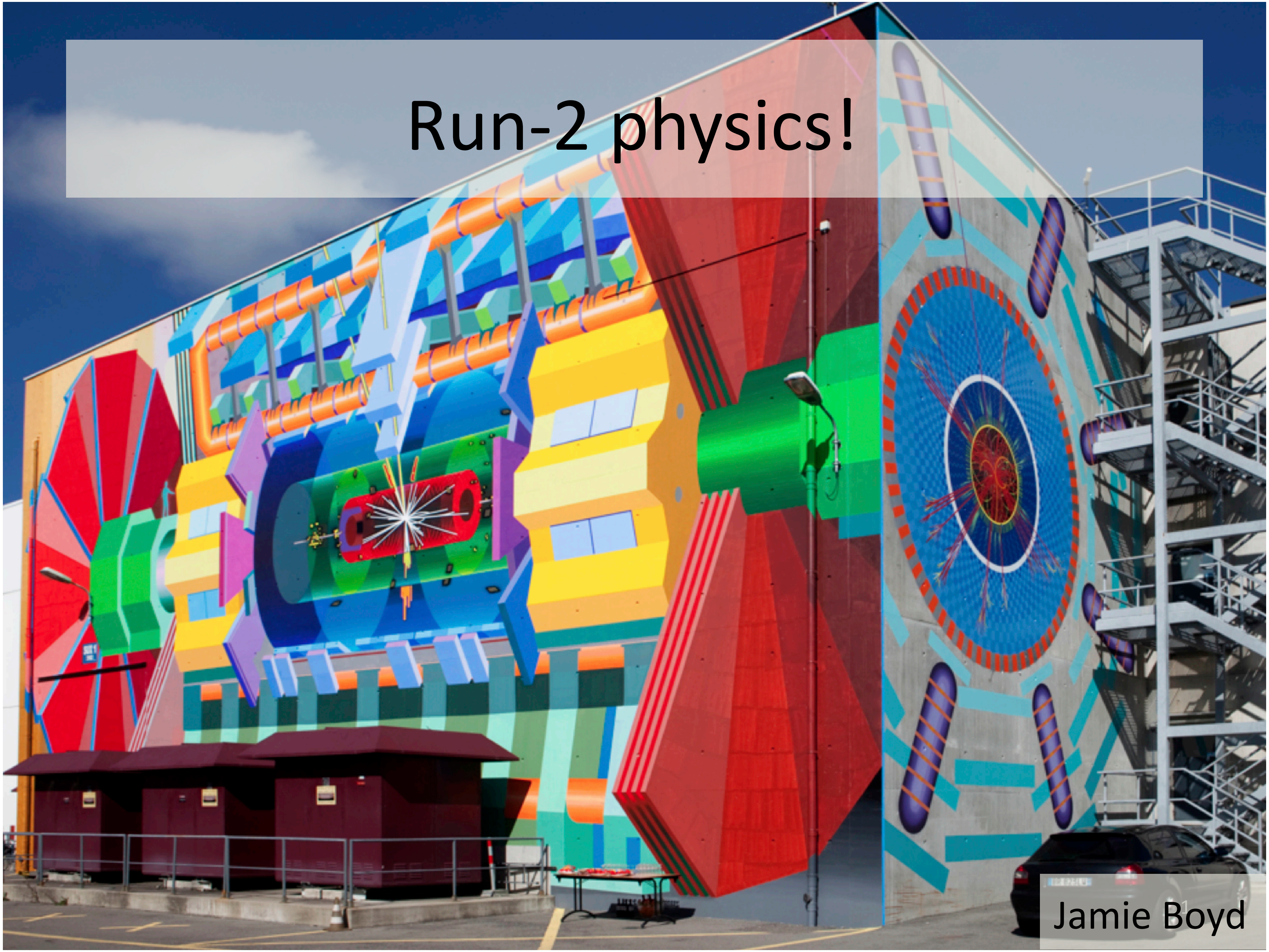
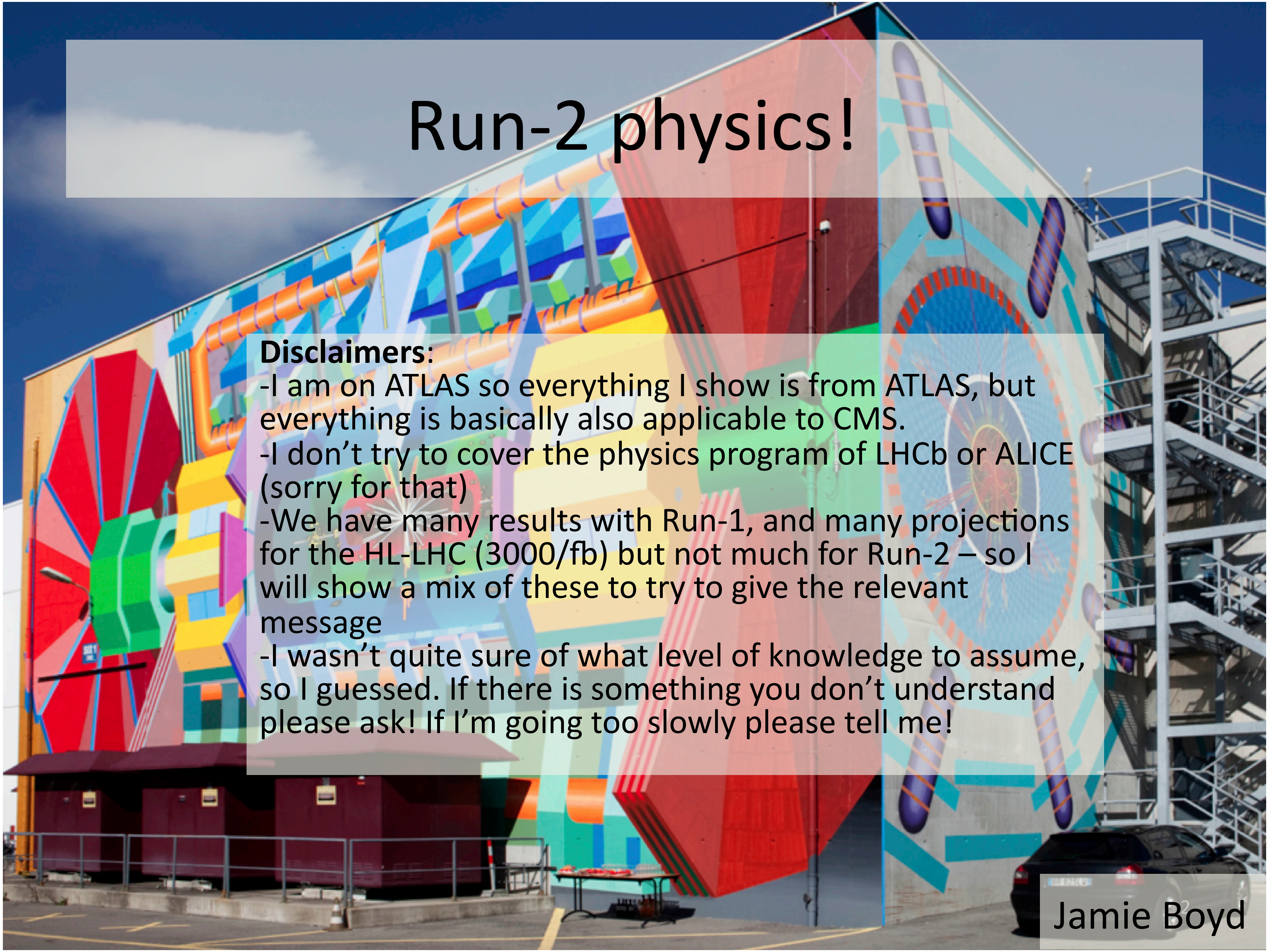


Run-2 physics!

Jamie Boyd



Run-2 physics!

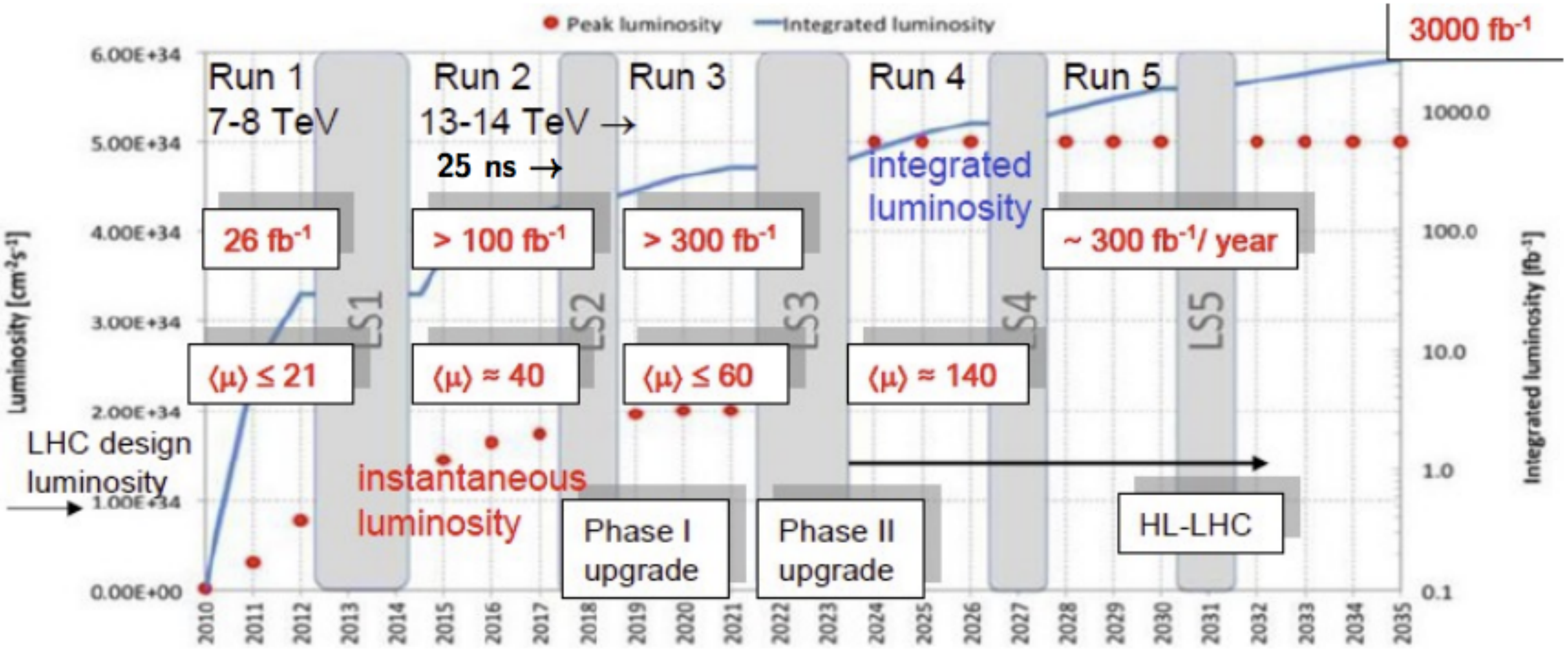
Disclaimers:
-I am on ATLAS so everything I show is from ATLAS, but everything is basically also applicable to CMS.
-I don't try to cover the physics program of LHCb or ALICE (sorry for that)
-We have many results with Run-1, and many projections for the HL-LHC (3000/fb) but not much for Run-2 – so I will show a mix of these to try to give the relevant message
-I wasn't quite sure of what level of knowledge to assume, so I guessed. If there is something you don't understand please ask! If I'm going too slowly please tell me!

Jamie Boyd

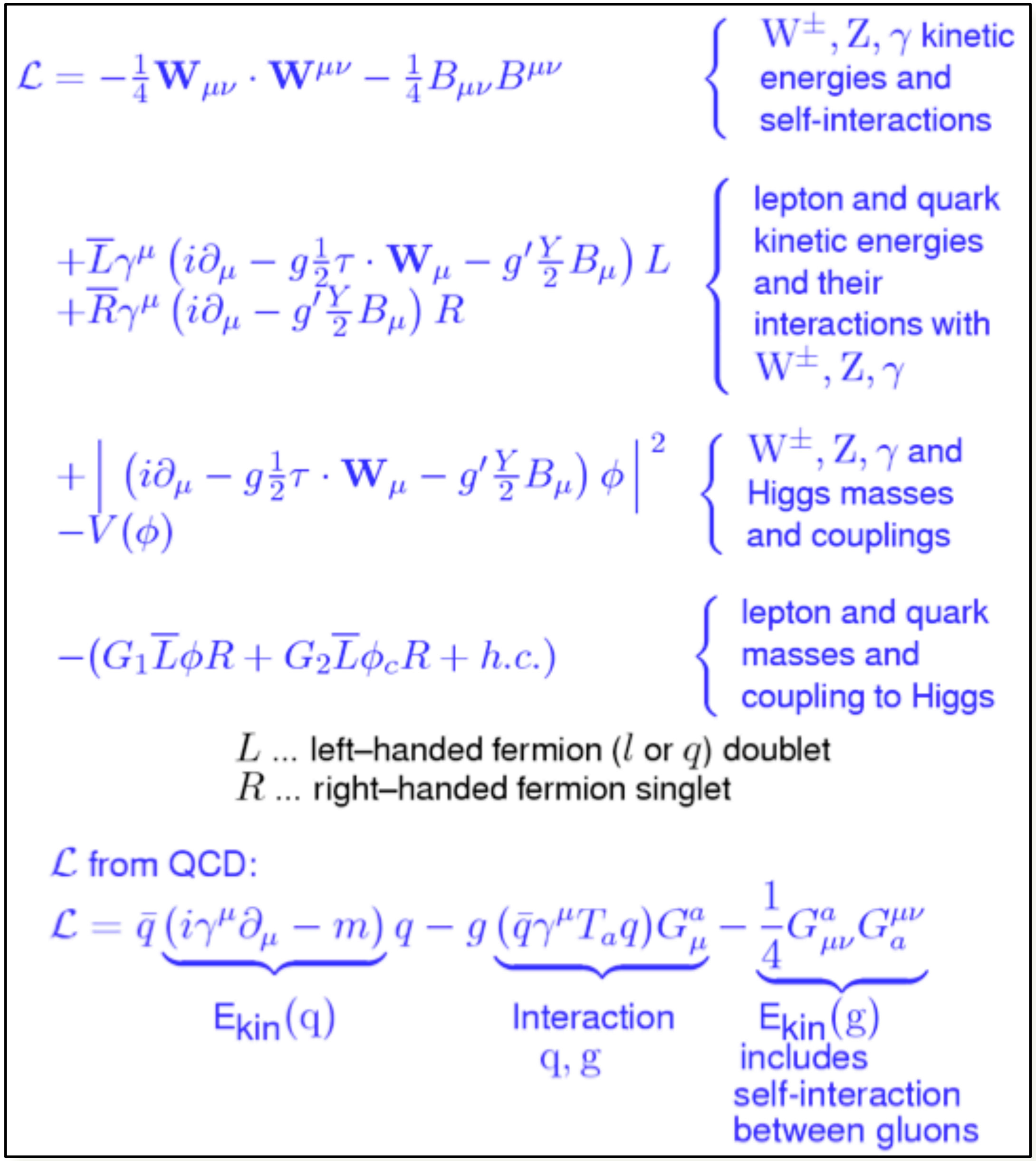
Introduction

- Goals of the LHC
  - In Run-1
    - discover the Higgs
    - search for ‘new physics’
  - In Run-2
    - study the Higgs
    - search for ‘new physics’
  - In Run-3 (hopefully)
    - study ‘new physics’

Introduction



The Standard Model



$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} \quad \left\{ \text{W}^{\pm}, \text{Z}, \gamma \text{ kinetic energies and self-interactions} \right.$$

$$\begin{aligned} &+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)L \\ &+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)R \end{aligned} \quad \left\{ \text{lepton and quark kinetic energies and their interactions with W}^{\pm}, \text{Z}, \gamma \right.$$

$$\begin{aligned} &+\left|\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)\phi\right|^{2} \\ &-V(\phi) \end{aligned} \quad \left\{ \text{W}^{\pm}, \text{Z}, \gamma \text{ and Higgs masses and couplings} \right.$$

$$-(G_{1}\bar{L}\phi R + G_{2}\bar{L}\phi_{c}R + h.c.) \quad \left\{ \text{lepton and quark masses and coupling to Higgs} \right.$$

L ... left–handed fermion (l or q) doublet
R ... right–handed fermion singlet

$\mathcal{L}$ from QCD:

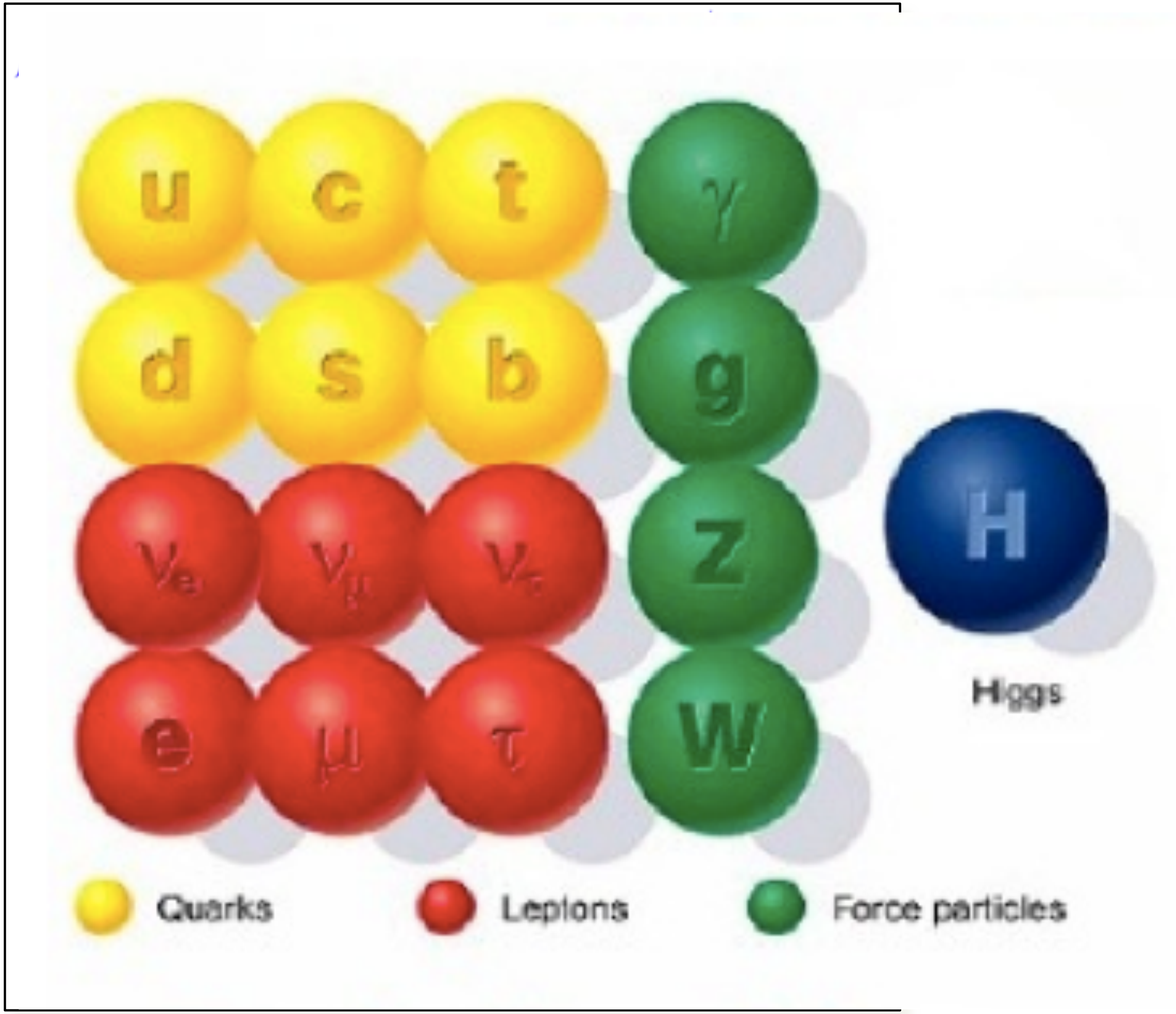
$$\mathcal{L} = \bar{q}\underbrace{(i\gamma^{\mu}\partial_{\mu} - m)}_{\text{E}_{\text{kin}}(\text{q})}q - g\underbrace{(\bar{q}\gamma^{\mu}T_{a}q)G^{a}_{\mu}}_{\substack{\text{Interaction} \\ \text{q, g}}} - \underbrace{\frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}}_{\substack{\text{E}_{\text{kin}}(\text{g}) \\ \text{includes} \\ \text{self-interaction} \\ \text{between gluons}}}$$

Theory that seems to explain the results in all of our particle physics experiments.

Extremely well tested and accurately describes very precise experimental results.

With the discovery of the Higgs boson the Standard Model is complete all SM particles have been observed and studied.

The Standard Model



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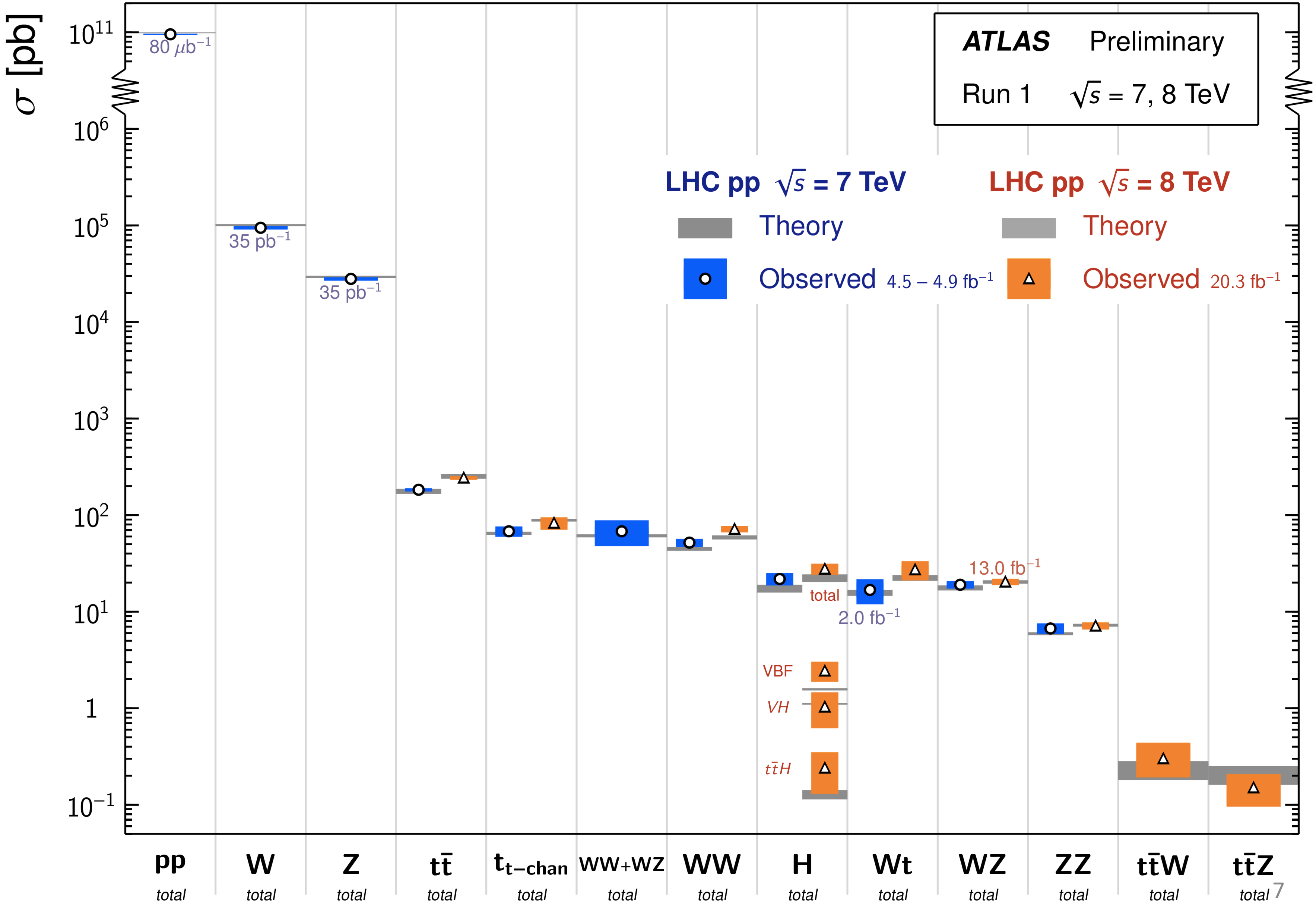
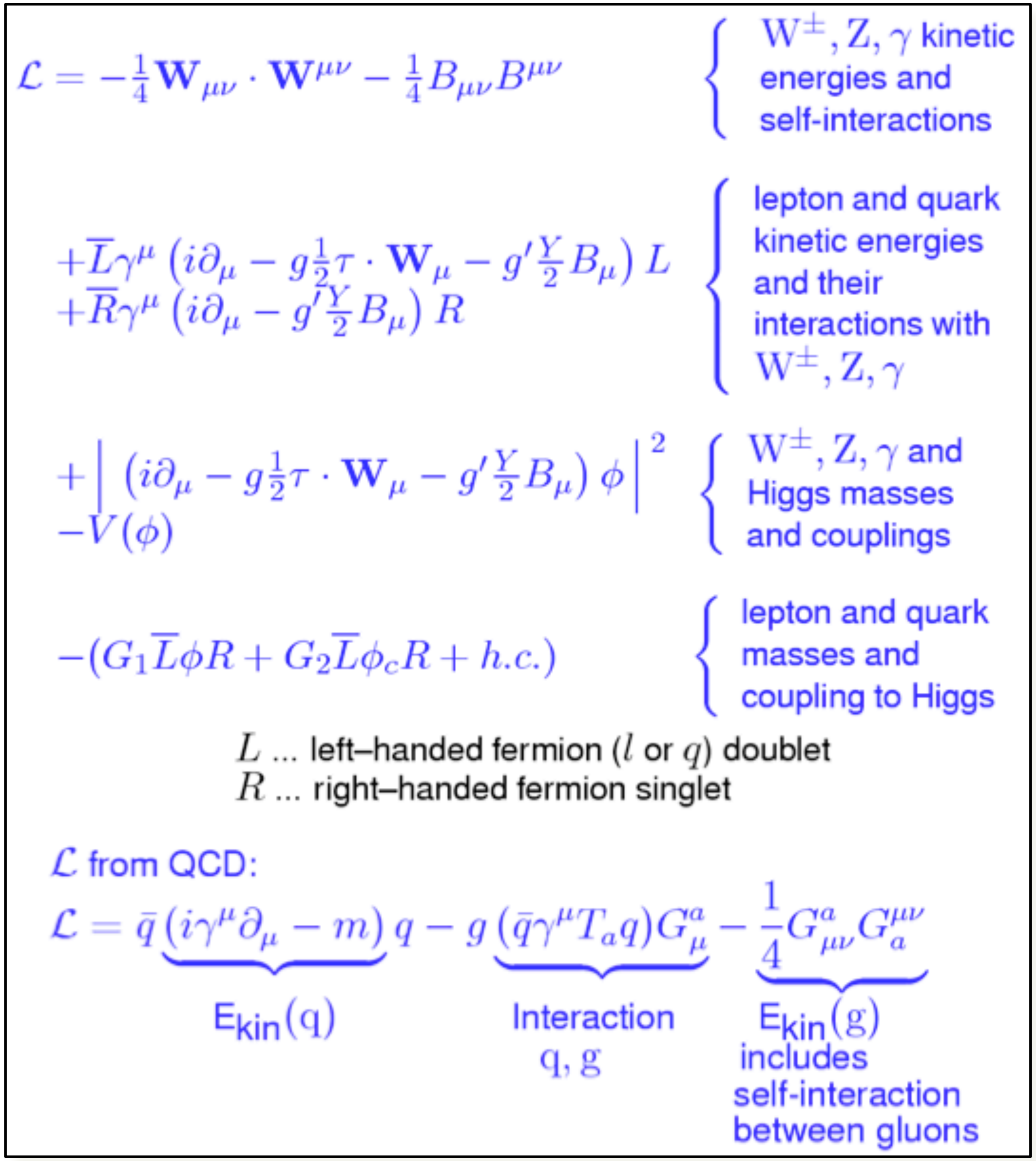
Standard Model Total Production Cross Section Measurements

Status: March 2015



The Standard Model



$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$W^{\pm}, Z, \gamma$ kinetic energies and self-interactions

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)L$$
$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)R$$

lepton and quark kinetic energies and their interactions with $W^{\pm}, Z, \gamma$

$$+\left|\left(i\partial_{\mu} - g\tfrac{1}{2}\tau\cdot\mathbf{W}_{\mu} - g'\tfrac{Y}{2}B_{\mu}\right)\phi\right|^{2}$$
$$-V(\phi)$$

$W^{\pm}, Z, \gamma$ and Higgs masses and couplings

$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + h.c.)$$

lepton and quark masses and coupling to Higgs

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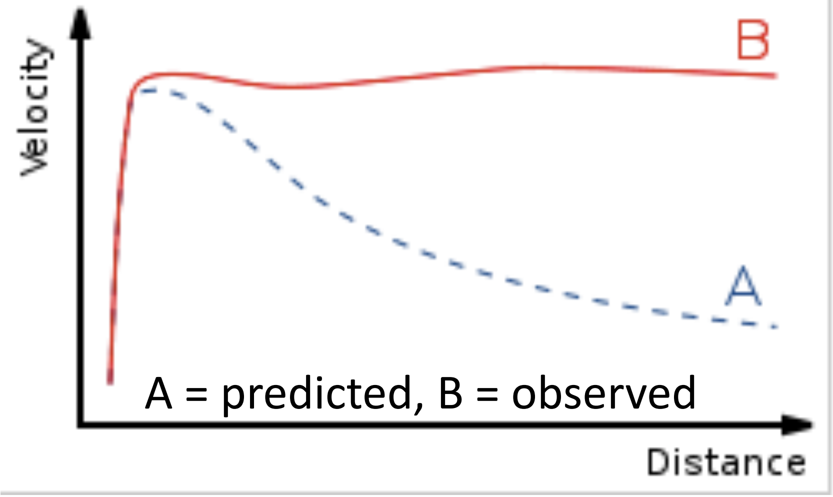
Ekin(g) includes self-interaction between gluons

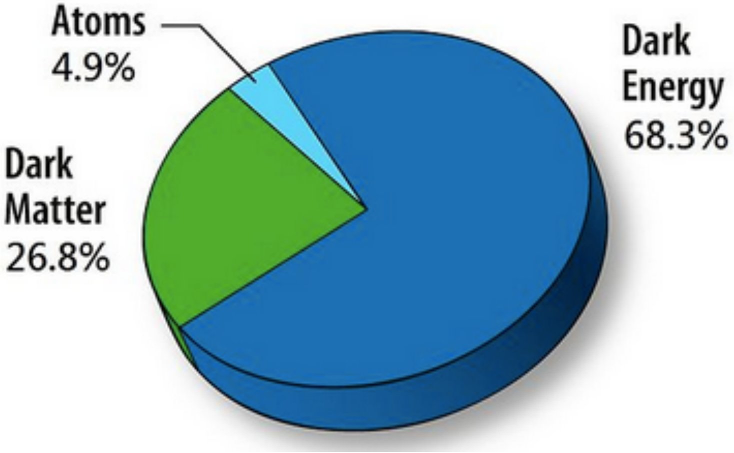
Theory that seems to explain the results in all of our particle physics experiments.
Extremely well tested and accurately describes very precise experimental results.
With the discovery of the Higgs boson the Standard Model is complete all SM particles have been observed and studied.

But there are a number of reasons why we think the SM is not the full storey
-doesn't include gravity
-doesn't include dark matter
-unnatural/ fine-tuned
-matter/anti-matter asymmetry
We *think* it is a low energy effective theory, we want to understand the 'real' theory!

Dark Matter



A = predicted, B = observed



Dark matter postulated to explain measurements of galaxy rotation speeds. Not enough observable matter to explain the results.

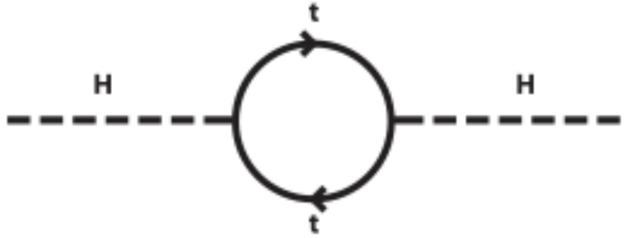
Now part of the cosmological Standard Model, which predicts ~25% of the mass of the universe is dark matter.

Most popular explanation is the WIMP which would be a new particle which interacts weakly and has a mass of ~1 TeV (in reach of the LHC!)

Many other searches for Dark Matter ongoing e.g. direct detection experiments under ground, and indirect detection experiments in space.

Naturalness

- In the SM the Higgs boson mass is sensitive to quantum corrections that would naturally make it very massive



- It is possible to get a physical mass of ~125 GeV (which we measure) but this requires a HUGE level of fine tuning something a bit like

$$m^2(h) = 149058072860157071229512437042397658961 - 149058072860157071229512437042397643336 = 15625\,\mathrm{GeV}^2$$

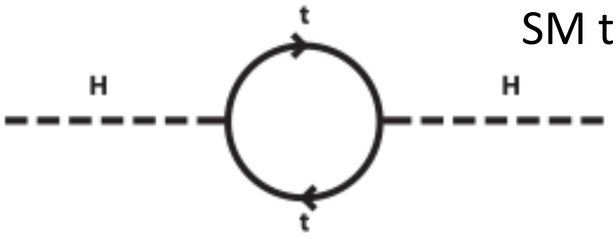
- This is very unnatural
- Two possible solutions
  - There is a physical reason (a symmetry) why this doesn't happen (e.g. supersymmetry)
  - There are a huge number of possible universes, and only in the one where this works are we here to ask questions about it (multiverse / athropic)

Beyond the Standard Model

- Theorists have come up with many ideas to try to fix some of these problems with the SM
  - Supersymmetry
  - Extra dimensions
  - WIMP dark matter
  - String theory
  - Black holes
  - BSM Higgs
- Many of these theories predict new particles that could be observable at the LHC

Supersymmetry (SUSY)

- SUSY is the most popular of the Beyond Standard Model theories
- In SUSY there is a new particle for every SM particle with different spin
  - (boson <-> fermion)
- This naturally solves the fine-tuning problem as the boson and fermion loops contribute to the Higgs mass correction with opposite sign



SM top quark

SUSY stop squark

these contributions would cancel!

SUSY can also provide a dark-matter particle candidate – as the Lightest SUSY Particle is (in many models) stable, and would act as a DM particle.

SUSY is needed as the basis of string theory which could lead to a quantum description of gravity.

SUSY can allow the unification of the force couplings

Supersymmetry (SUSY)

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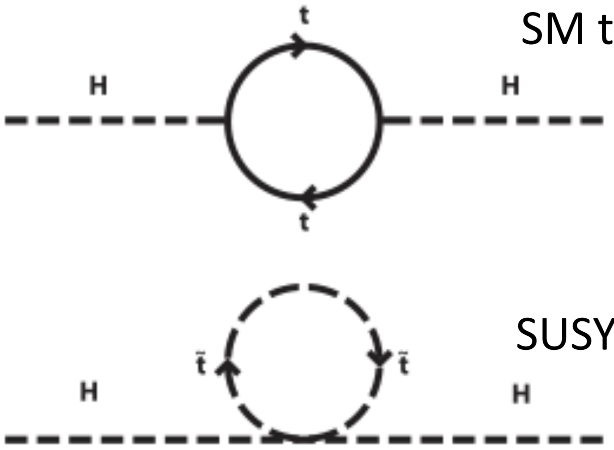

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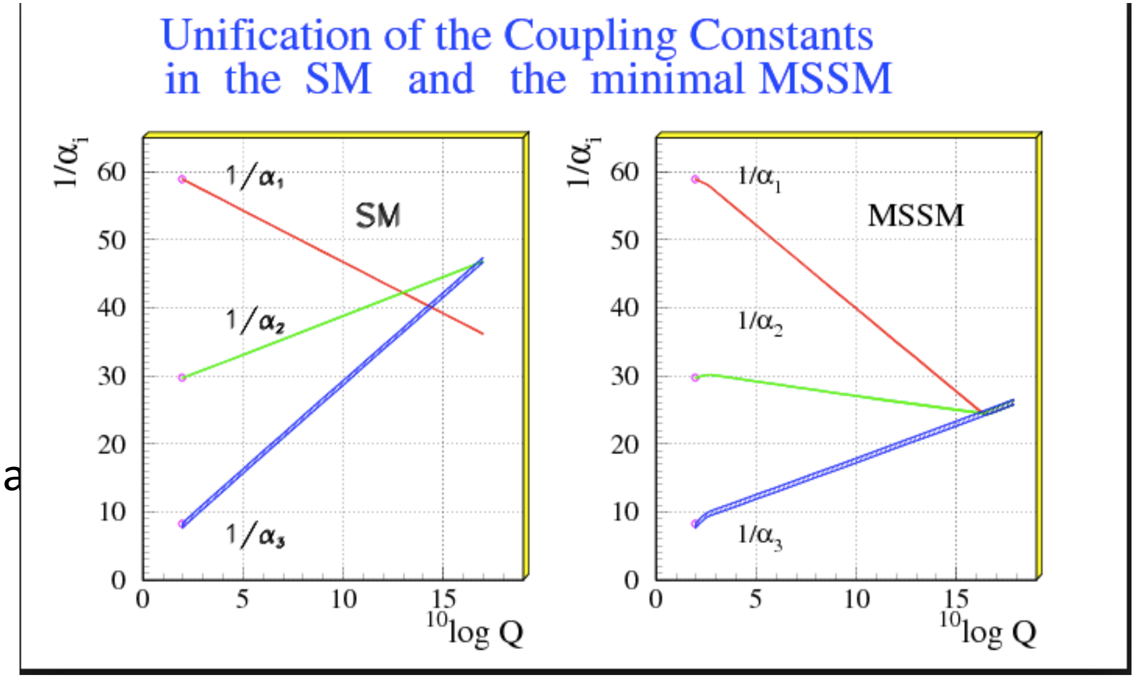
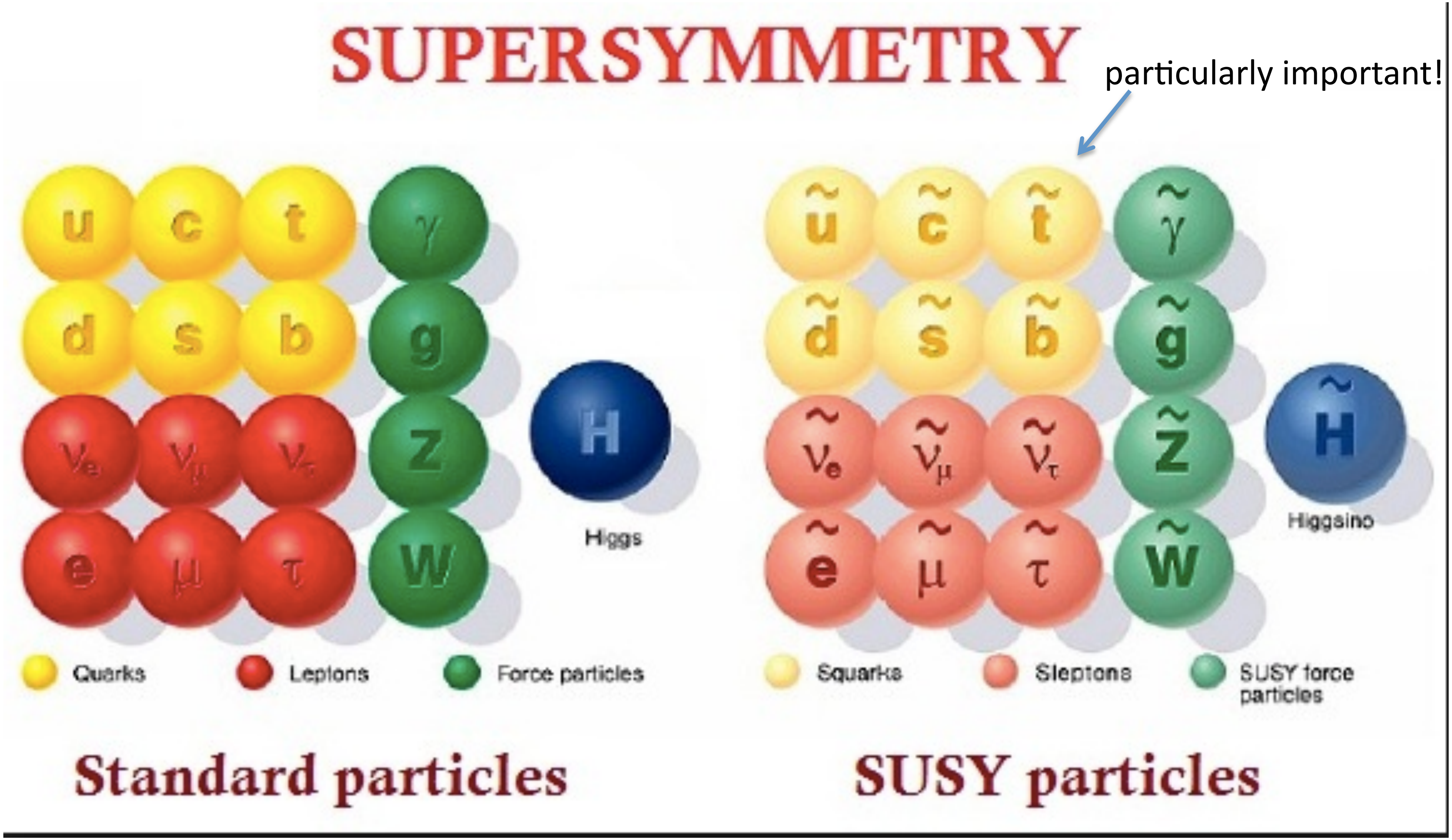
SUSY stop squa



these contributions would cancel!

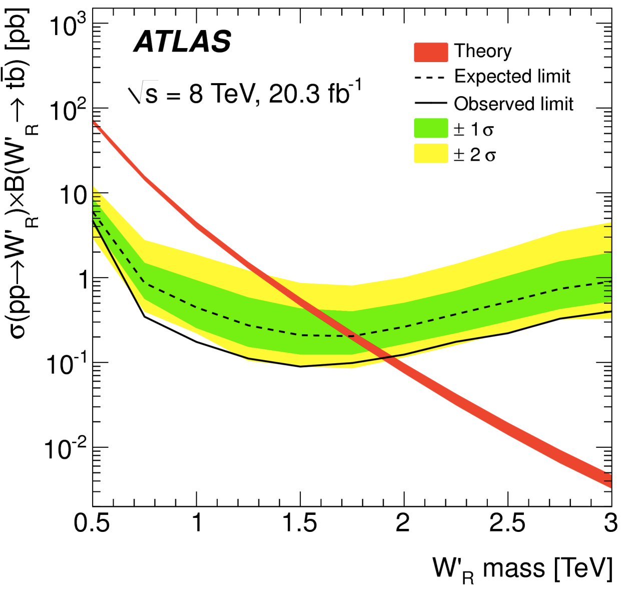


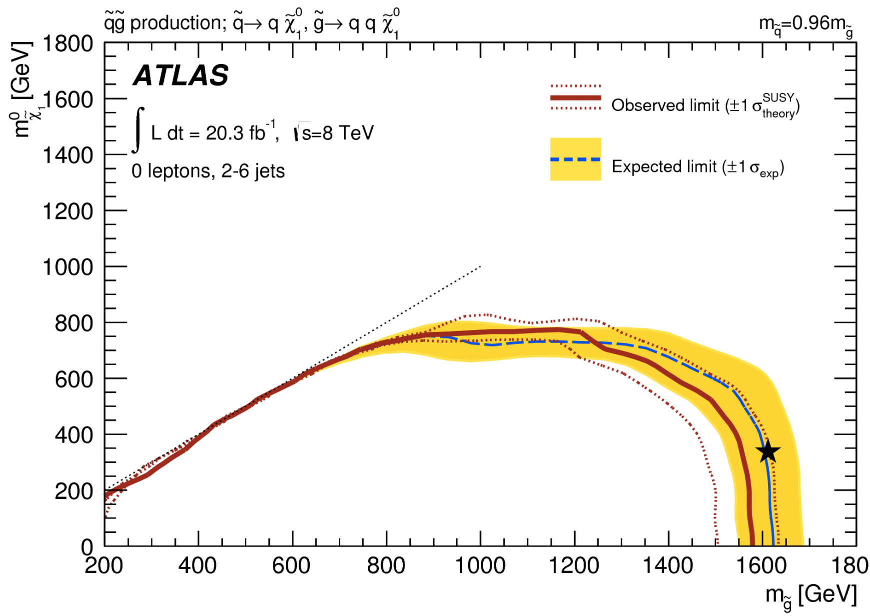
particularly important!

If SUSY were a unbroken symmetry the SUSY particles would have the same mass as their SM partners. Since we havent seen them in experiment we know that this is not the case.
SUSY is a broken symmetry, the SUSY particles are heavier than their SM partners,
how heavy is a ‘free parameter’, but if too heavy SUSY doesn’t solve the fine-tuning problem!

Run-1 Searches

- In Run-1 we had many searches for BSM models (new particles, predicted in SUSY, extra-dimensions and many other models)
- No evidence of new physics was seen
- Limits are set on the masses of new particles
  - e.g. in this model the gluino (SUSY particle) must be heavier than ~1.6 TeV otherwise we would have seen it in Run-1
- In some models we can predict the signal cross section (the number of new particles of a given mass we would expect to produce) and so set limits on the mass, in other models we can set limits on the mass as a function of the cross section

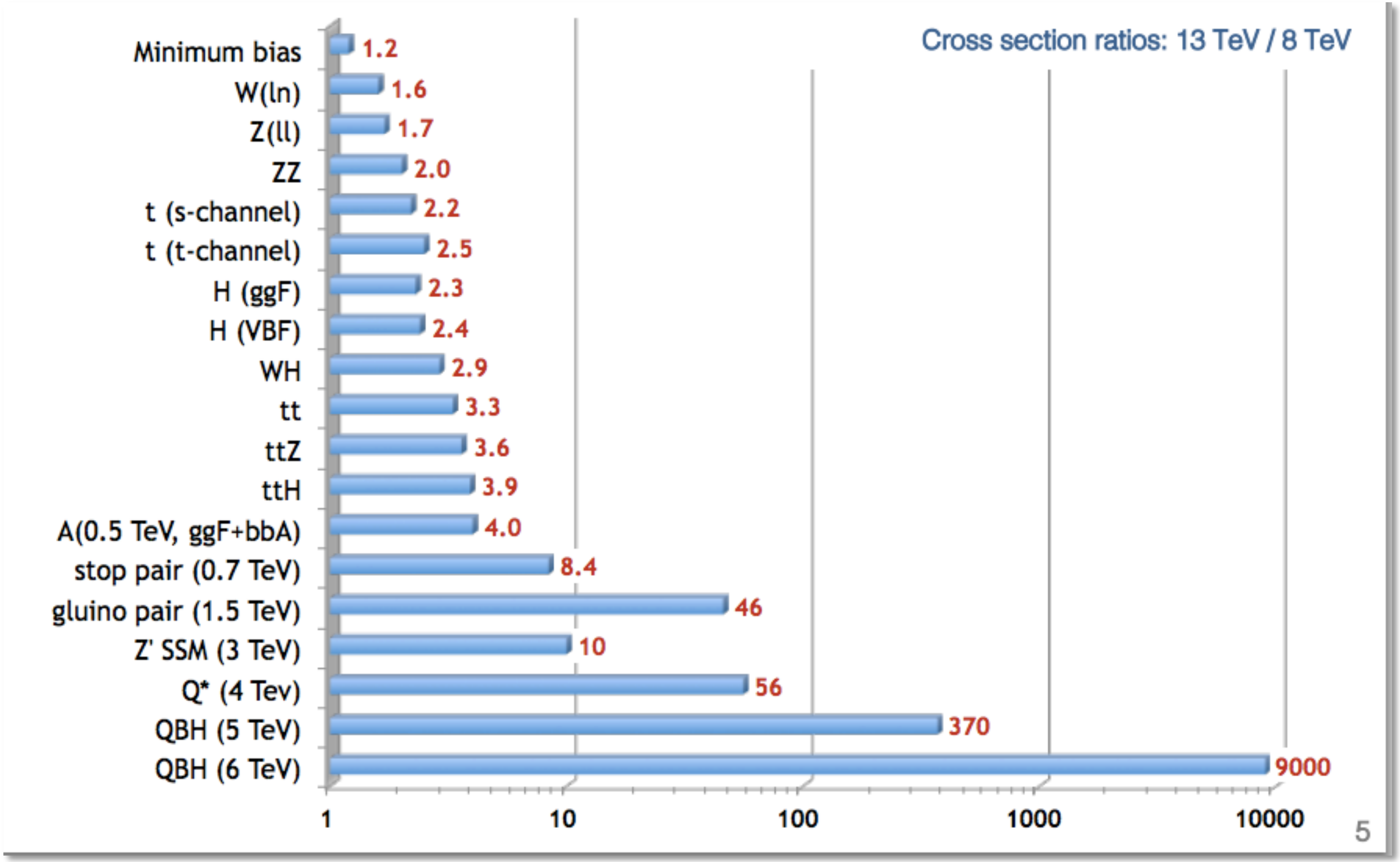




Effect of increasing the collision energy

- In Run-1 we ran with a collison energy of 7 TeV (in 2011) and 8 TeV (in 2012) for Run-2 we will run at 13 TeV
- Due to $E=mc^2$ the higher energy the collisions the higher mass particles can be produced
- We collide protons at the LHC, but what actually physically interact are the gluons or quarks in the proton
  - The amount of the protons energy carried by the colliding g/q is not fixed but is a function (PDF)
  - Colliding protons together at 8 TeV there is a tiny probability to have a g/q interaction with an energy close to 8 TeV. (8 TeV is the kinematic limit in this case)
- The probability of producing a heavy particle in 13 TeV collisions is MUCH higher than in 8 TeV collisions
  - the exact increase depends on the mass of the particle and which partons interact to produce it

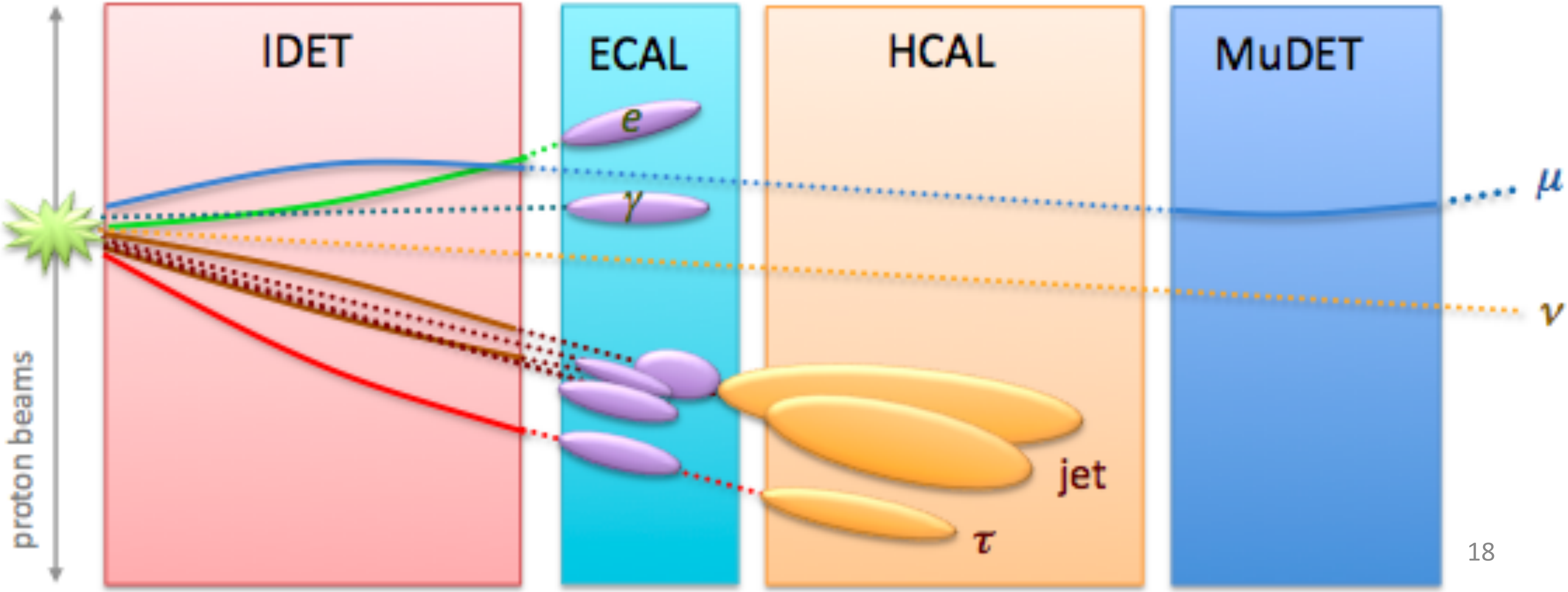
Effect of increasing the collision energy



Brief intro to experimental collider physics

In our detectors we generally see the following particles:

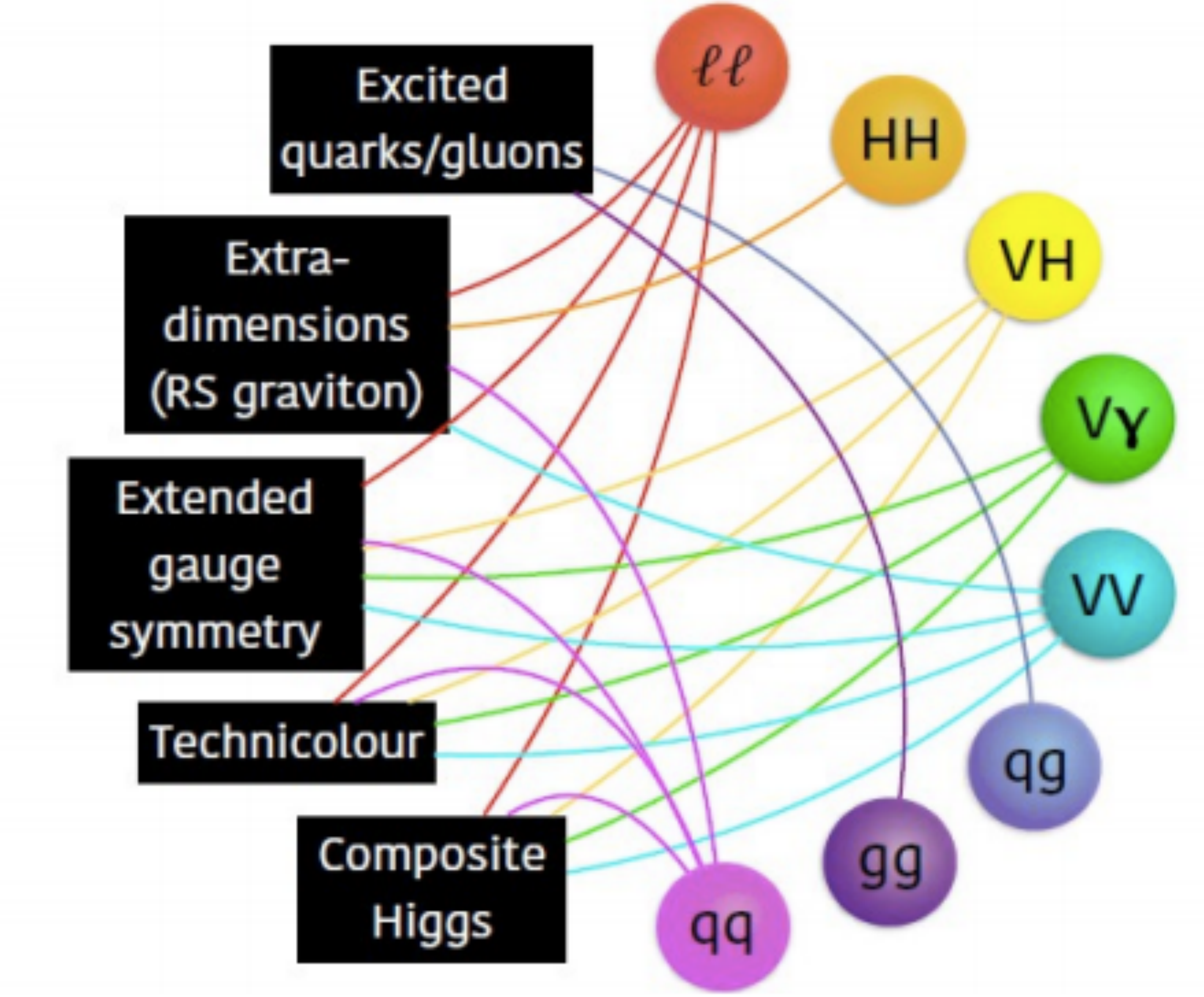
- electrons, muons, photons
- hadrons (such as pions, kaons, protons, neutrons) – these originate from quark/gluons that very quickly 'hadronize' into streams (jets) of these particles - we never 'see' a quark or gluon
    - -jets originating from b-quarks can be tagged as they come can contain slightly displaced vertices inside them coming from the 'long' lifetime of the b-quark!
- -neutrinos that are undetected can be inferred by their missing energy signature



Resonance searches

- In the past many new particles have been discovered by seeing a bump (resonance) in the mass spectrum of 2 reconstructed particles
  - e.g. the mass of a positive and negative muon
  - mass can de calculated from the momentum 4-vector (energy, direction) of the reconstructed particles
- This is the signature of a Z’ particle which is predicted by extra-dimension theories
  - And is one of the main searches at the LHC
- But there are also jet-jet resonances, photon-photon resonances that are searched for

Resonance searches



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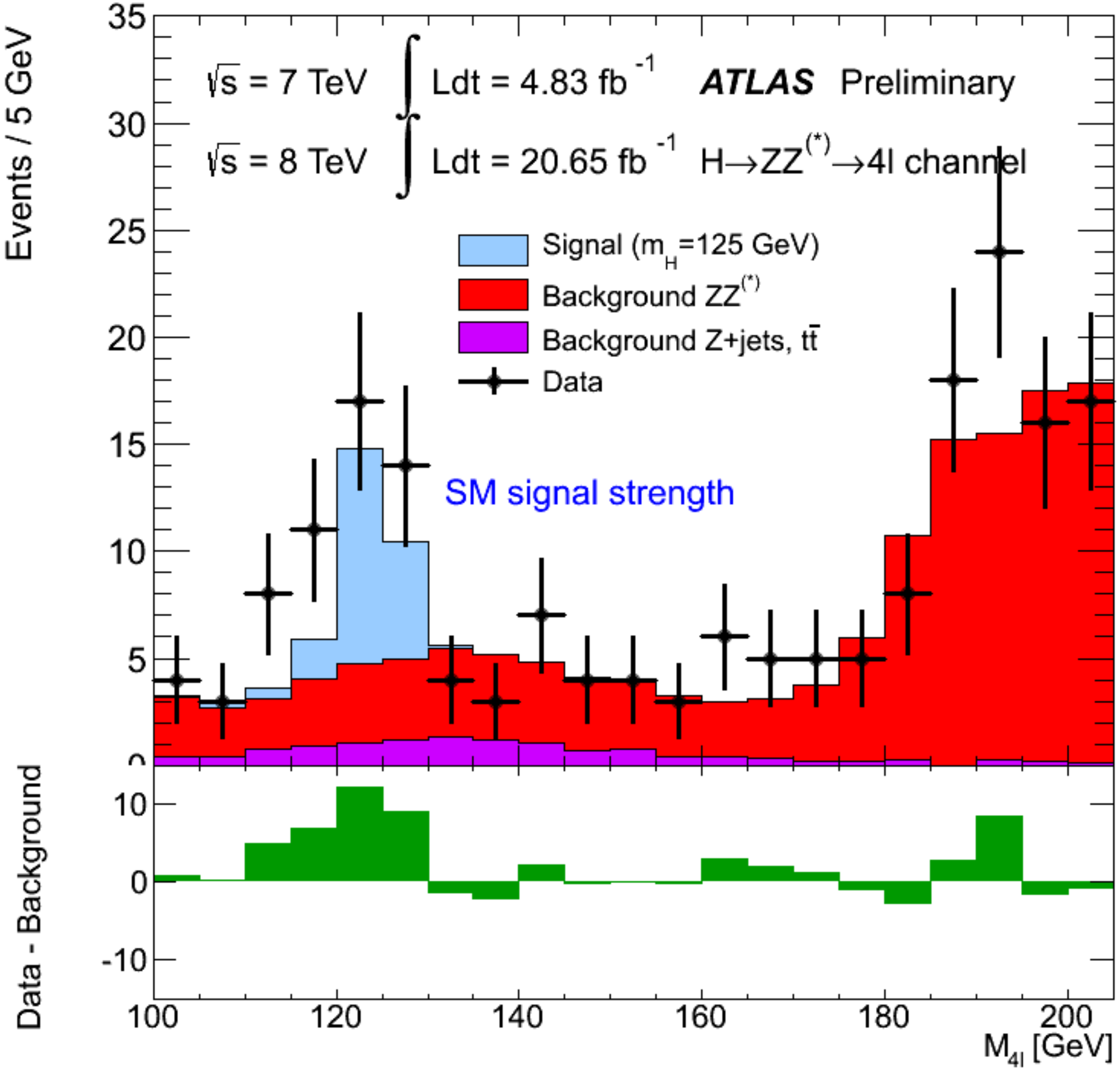
$\sqrt{s}$ = 7 TeV $\int$Ldt = 4.83 fb^{-1}
$\sqrt{s}$ = 8 TeV $\int$Ldt = 20.65 fb^{-1}
ATLAS Preliminary
$H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel
Signal (m_H=125 GeV)
Background $ZZ^{(*)}$
Background Z+jets, $t\bar{t}$
Data
SM signal strength
Events / 5 GeV
35
30
25
20
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5
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Data - Background
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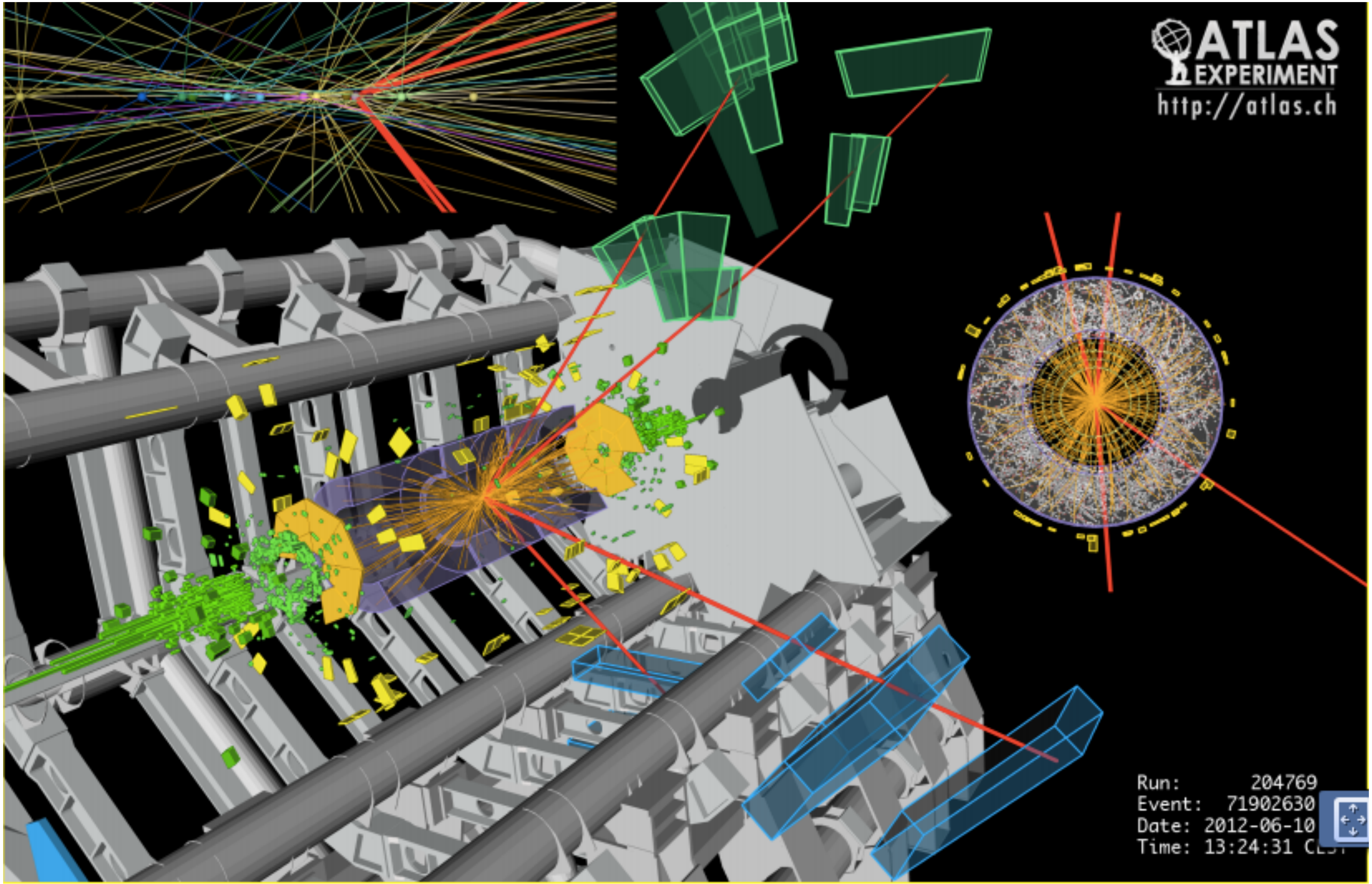
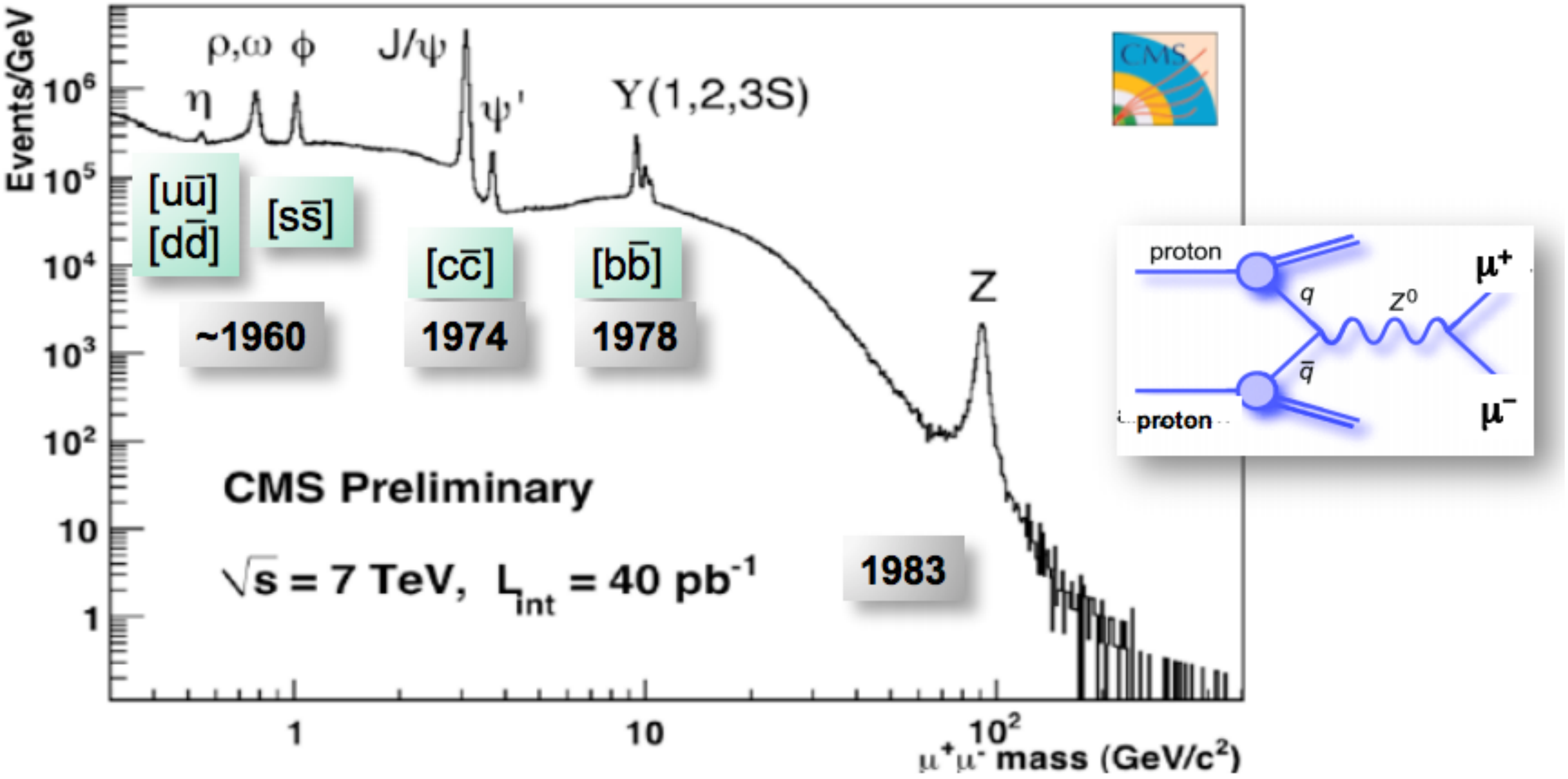
0
-10
100
120
140
160
180
200
M_{4l} [GeV]


ATLAS EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 C

Example – search for a new heavy Z’

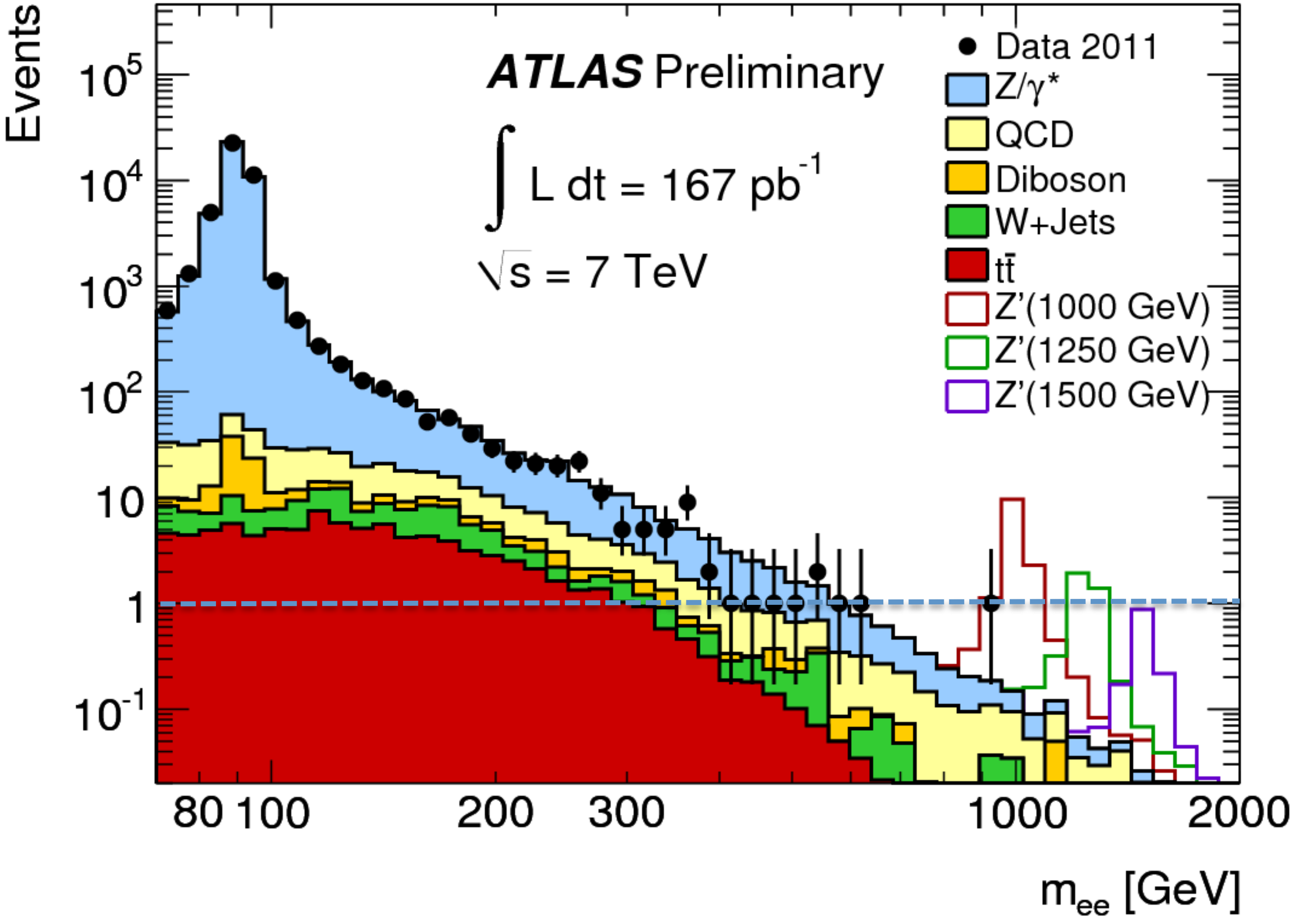
Many new physics models have a new heavy gauge boson which can decay to leptons.
Like a Z but heavier - called Z’.
Important to search for such new particles at the LHC.



Historically many important discoveries (Nobel prizes) in di-lepton mass spectrum

Example – search for a new heavy Z’

Like Z->ee but at higher mass.



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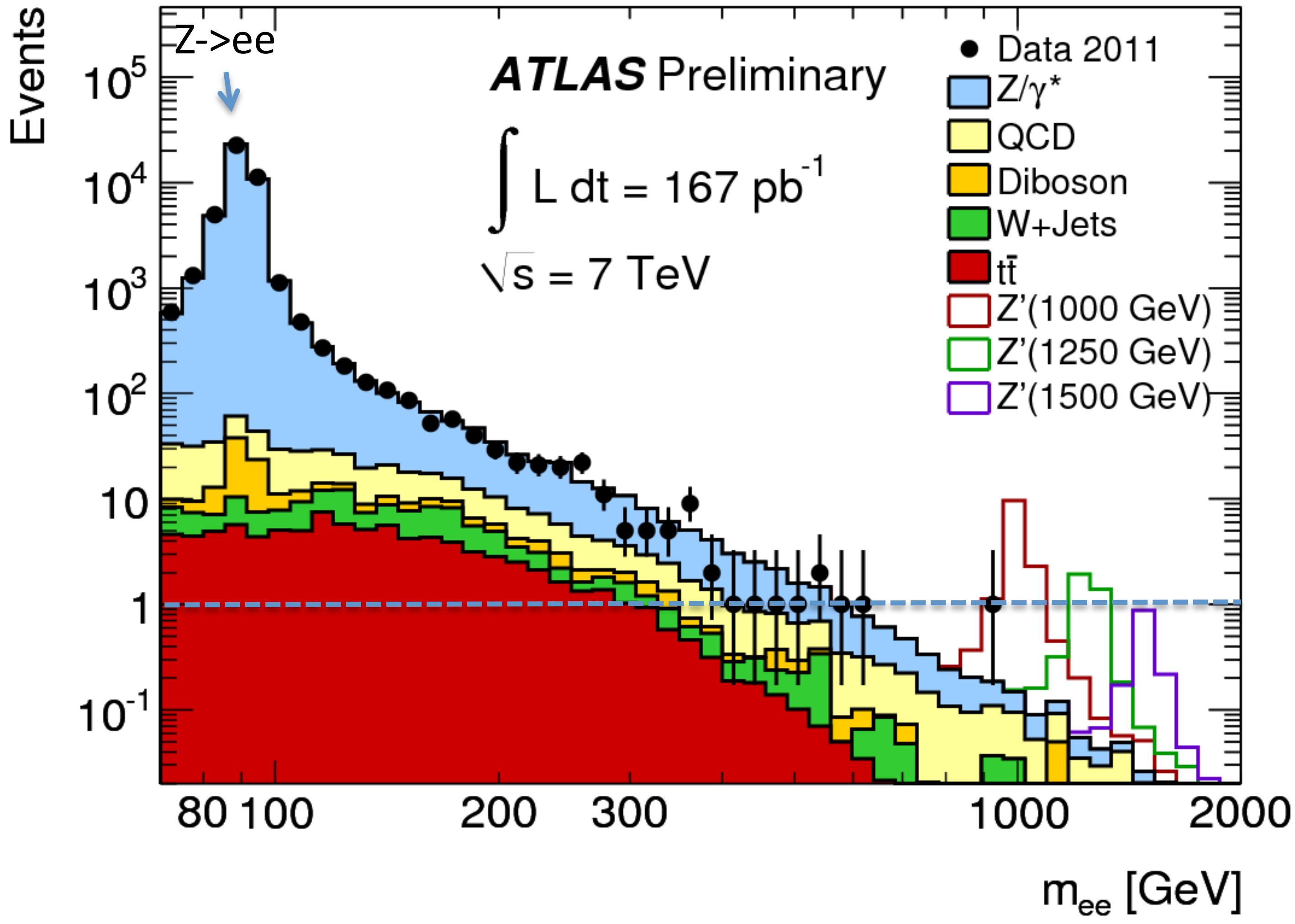

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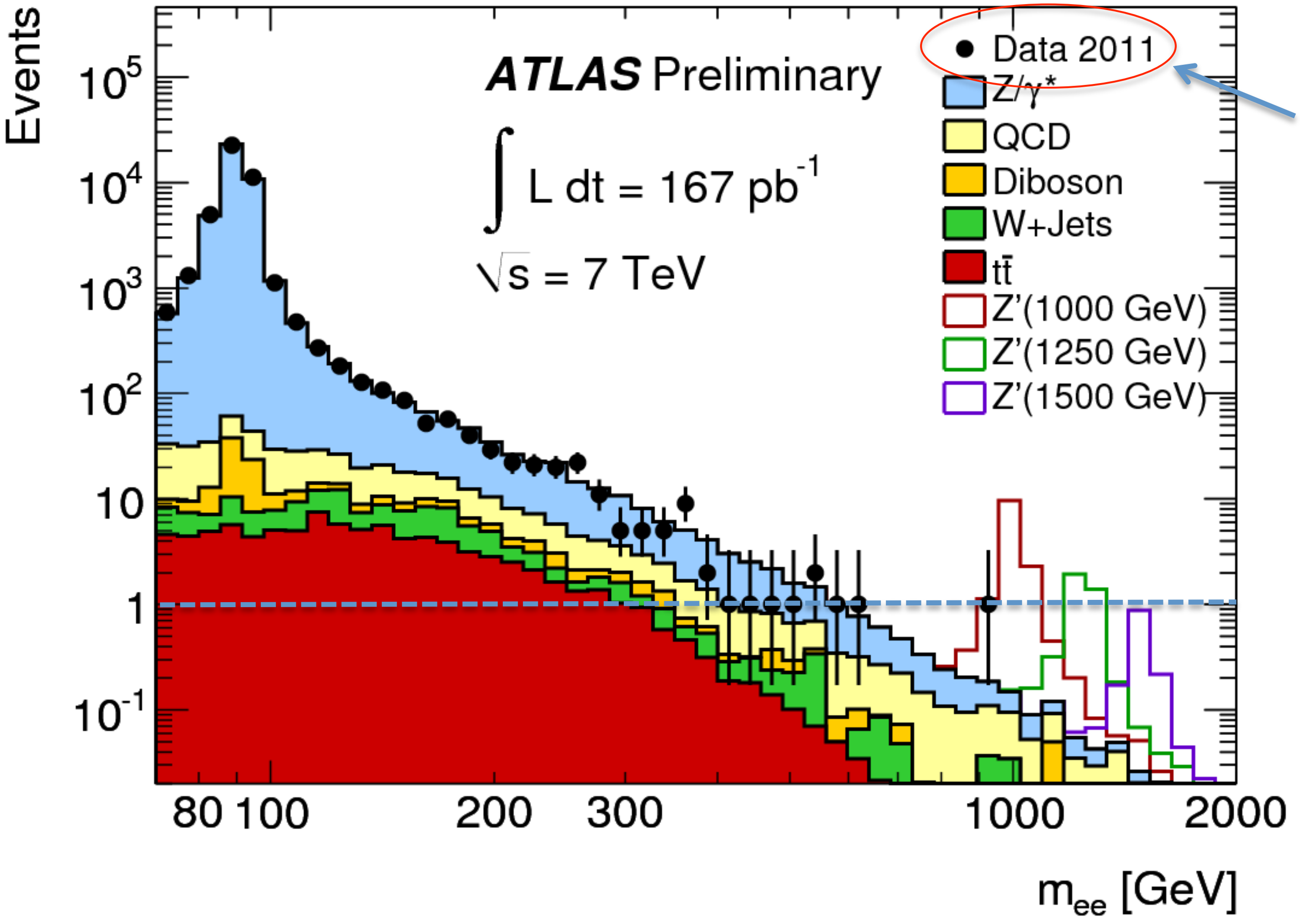
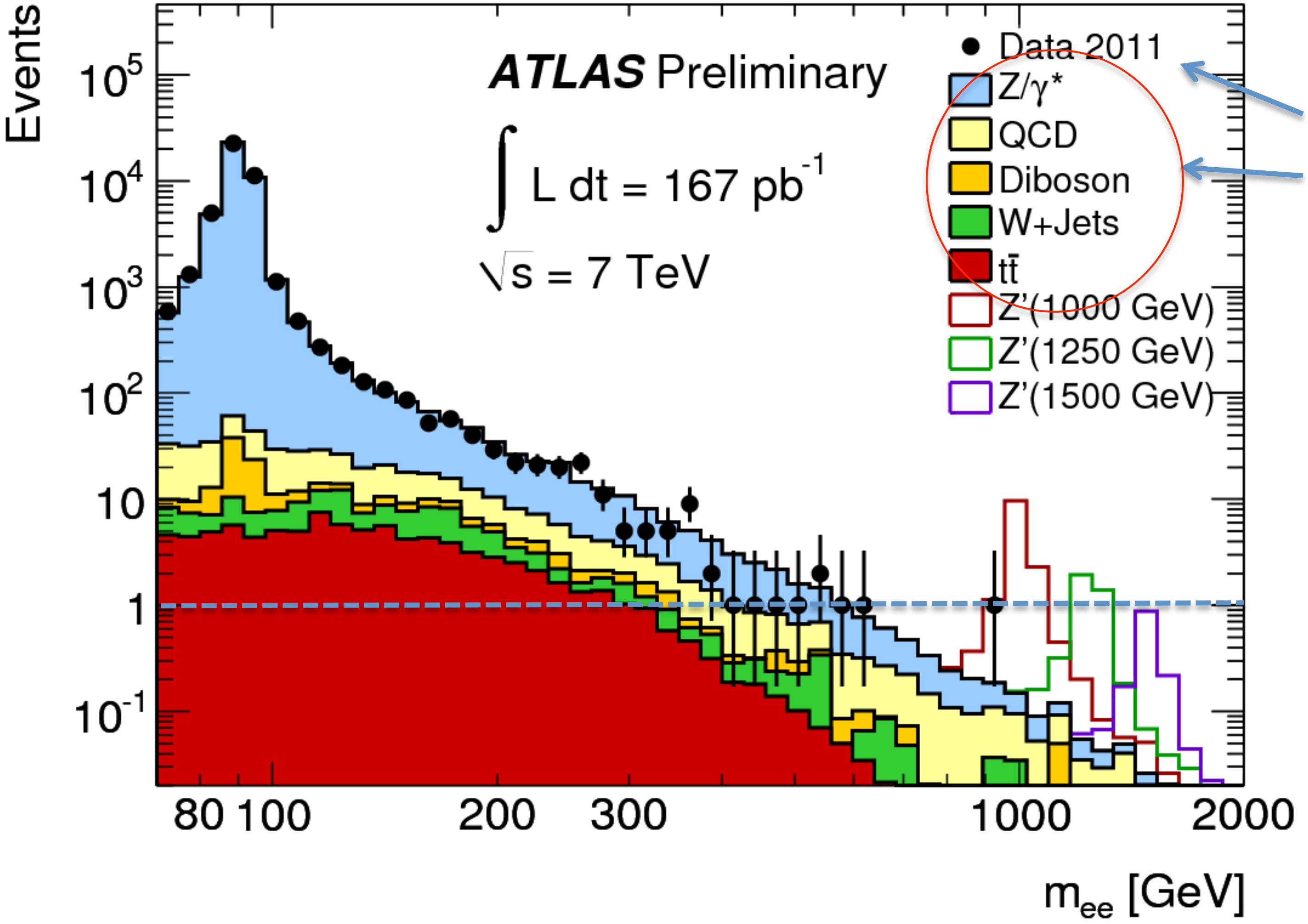


Select 2 electron candidates and plot their invariant mass for

1. **Data**

Example – search for a new heavy Z'

Like Z->ee but at higher mass.

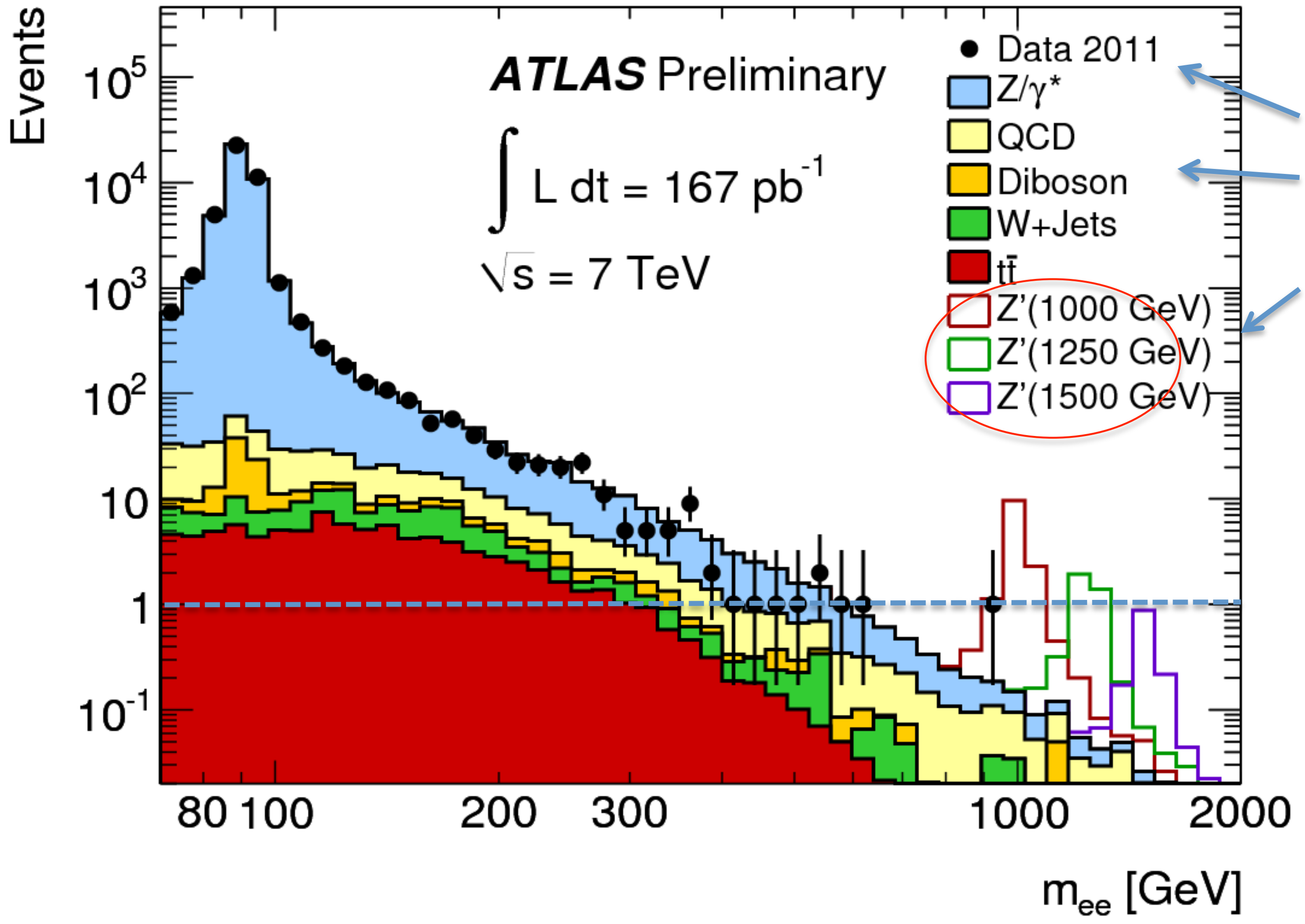


Select 2 electron candidates and plot their invariant mass for

1. Data
2. **Simulated backgrounds events**

Example – search for a new heavy Z’

Like Z->ee but at higher mass.

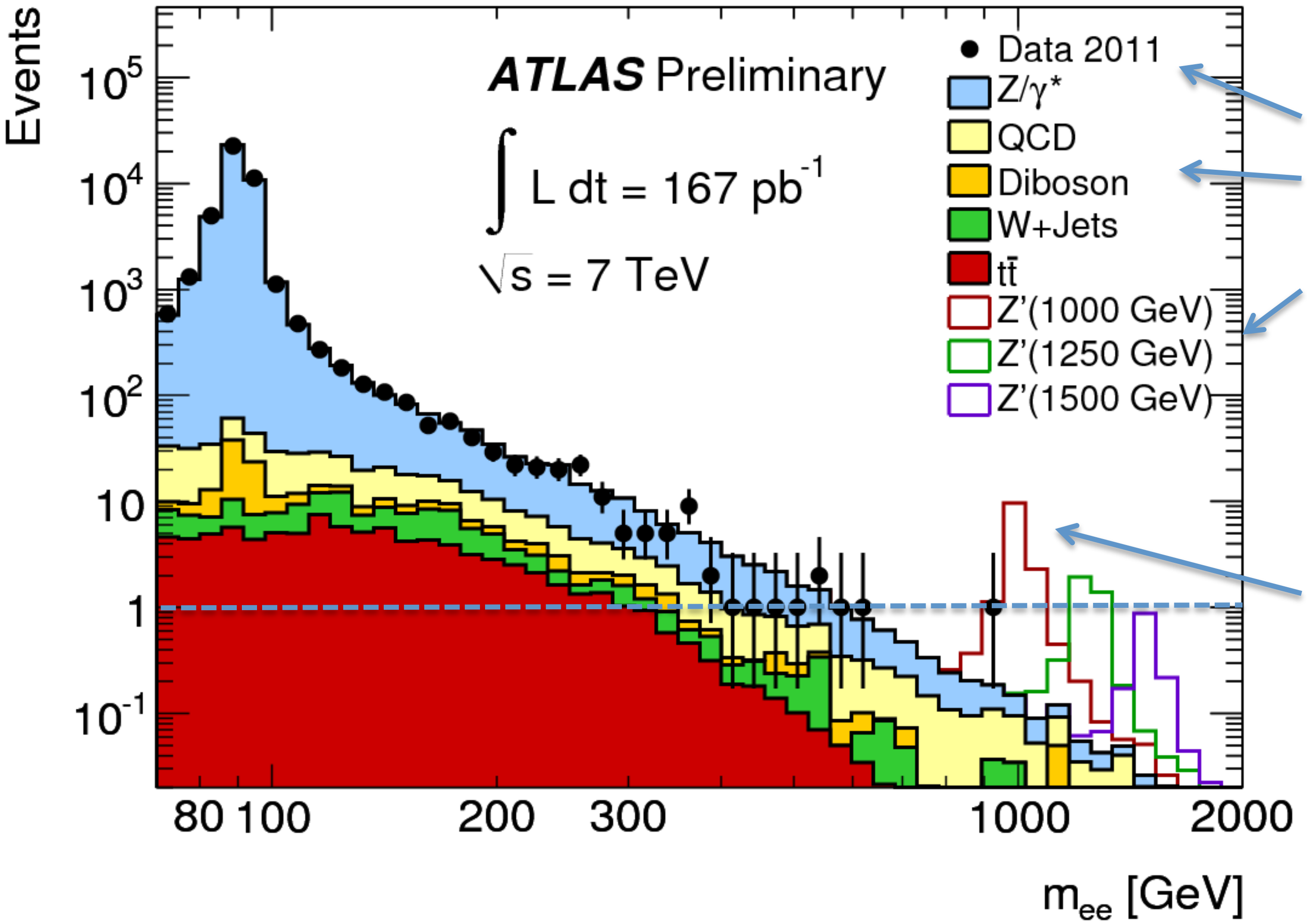


Select 2 electron candidates and plot their invariant mass for

1. Data
2. Simulated backgrounds events
3. **Simulated signal (Z’) with different masses**

Example – search for a new heavy Z'

Like Z->ee but at higher mass.



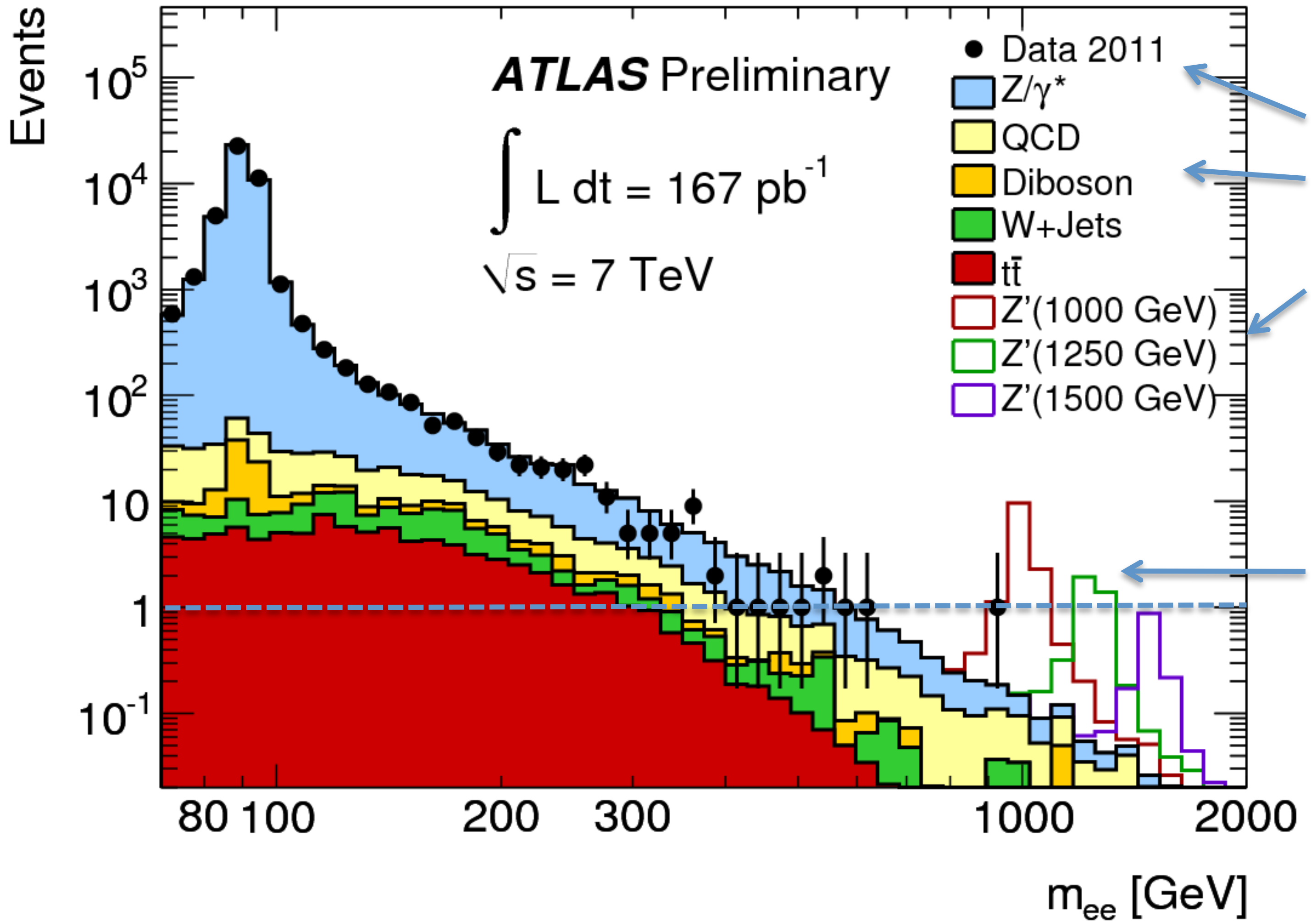
Select 2 electron candidates and plot their invariant mass for

1. Data
2. Simulated backgrounds events
3. Simulated signal (Z') with different masses

Data inconsistent with a 1TeV Z'

Example – search for a new heavy Z'

Like Z->ee but at higher mass.



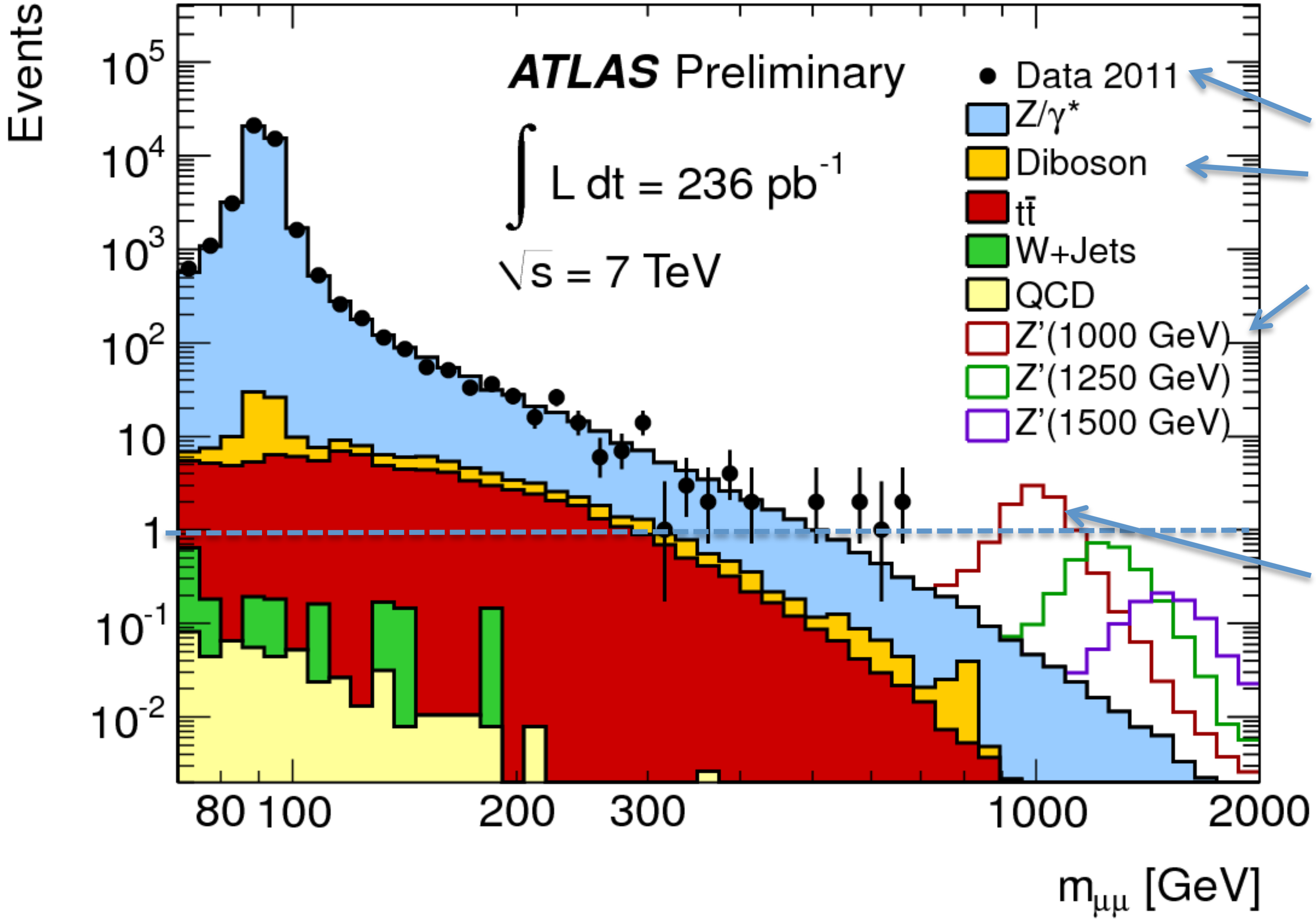
Select 2 electron candidates and plot their invariant mass for

1. Data
2. Simulated backgrounds events
3. Simulated signal (Z') with different masses

Cross-section decreases with mass (higher the mass of the Z', the more data needed to discover it)

Example – search for a new heavy Z’

Now for **muons**!



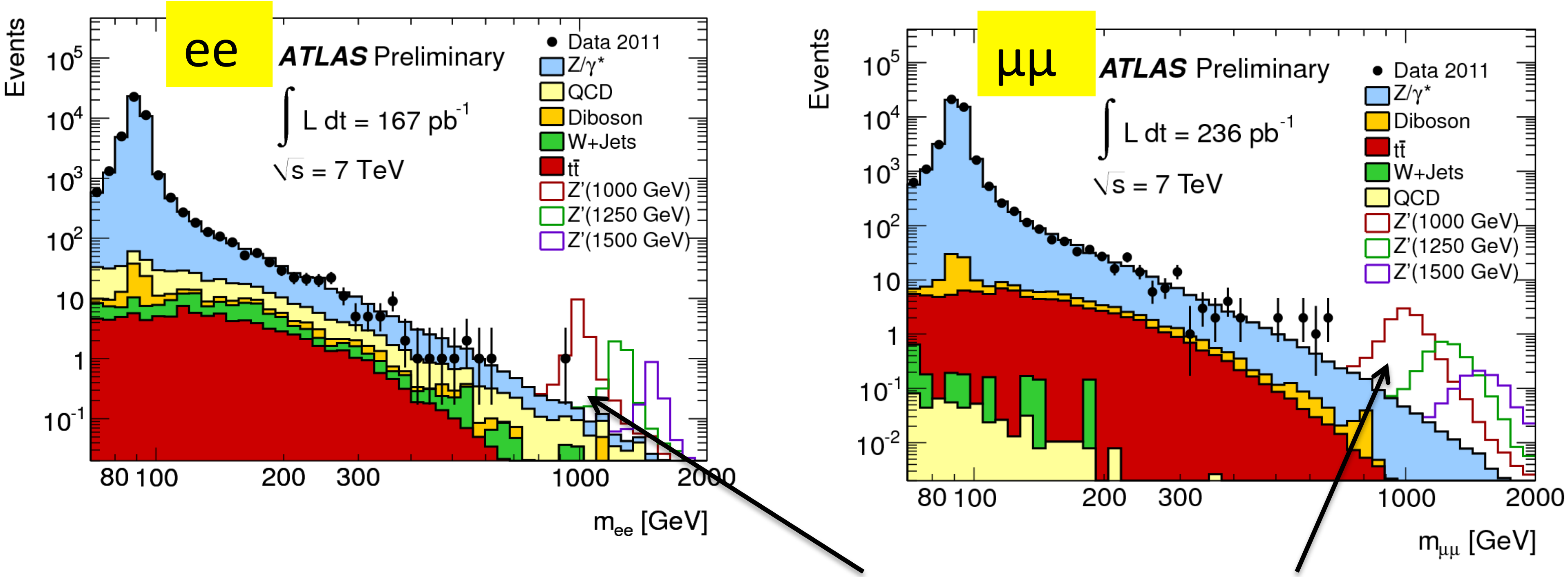
Select 2 muon candidates and plot their invariant mass for

1. Data
2. Simulated backgrounds events
3. Simulated signal (Z’) with different masses

Data inconsistent with a 1TeV Z’

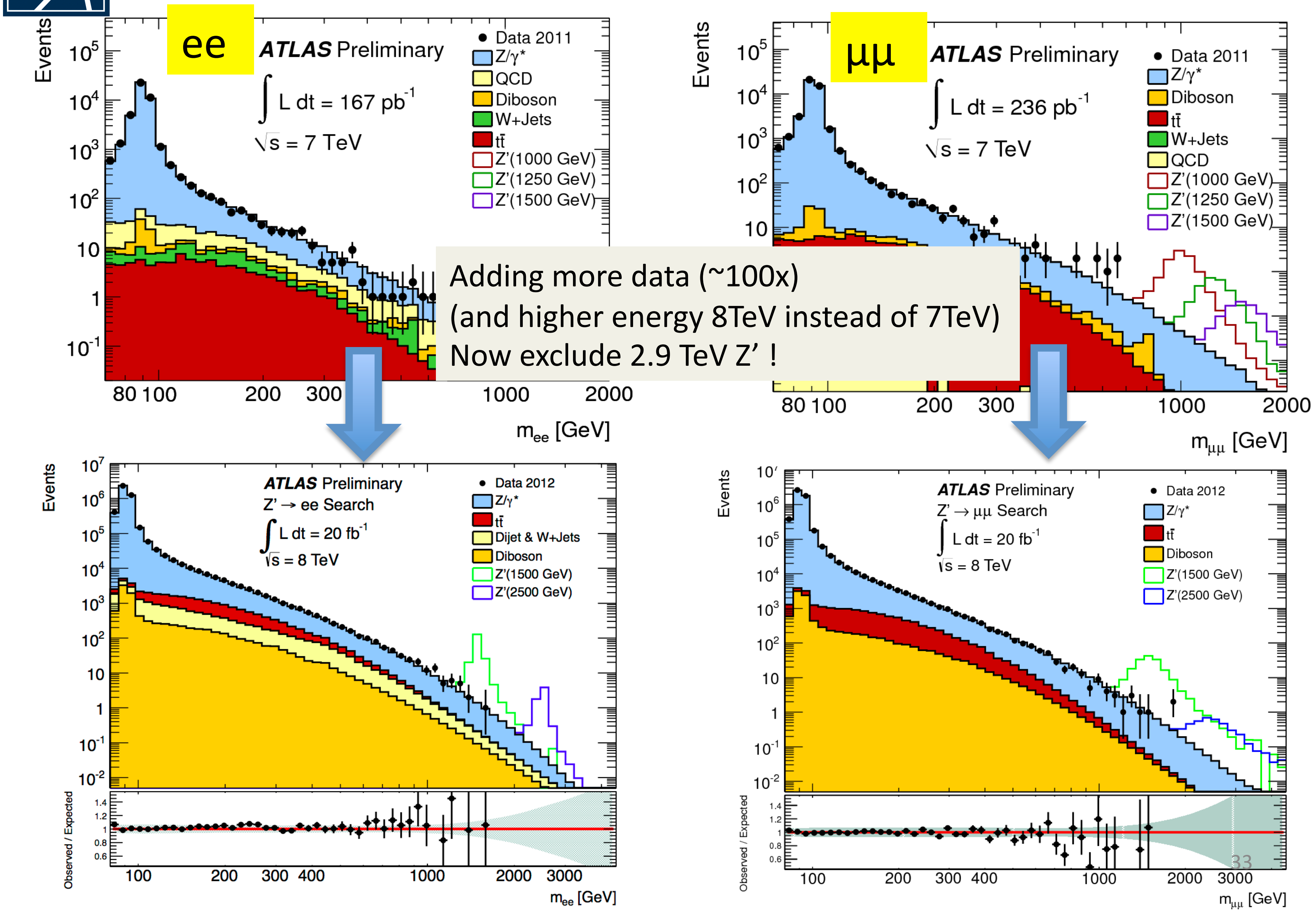
Z’ analysis (Run-1)

Combining the electron and muon channel the data exclude Z’ upto mass of 1.4 TeV
Need to take into account the statistical and systematic uncertainties!

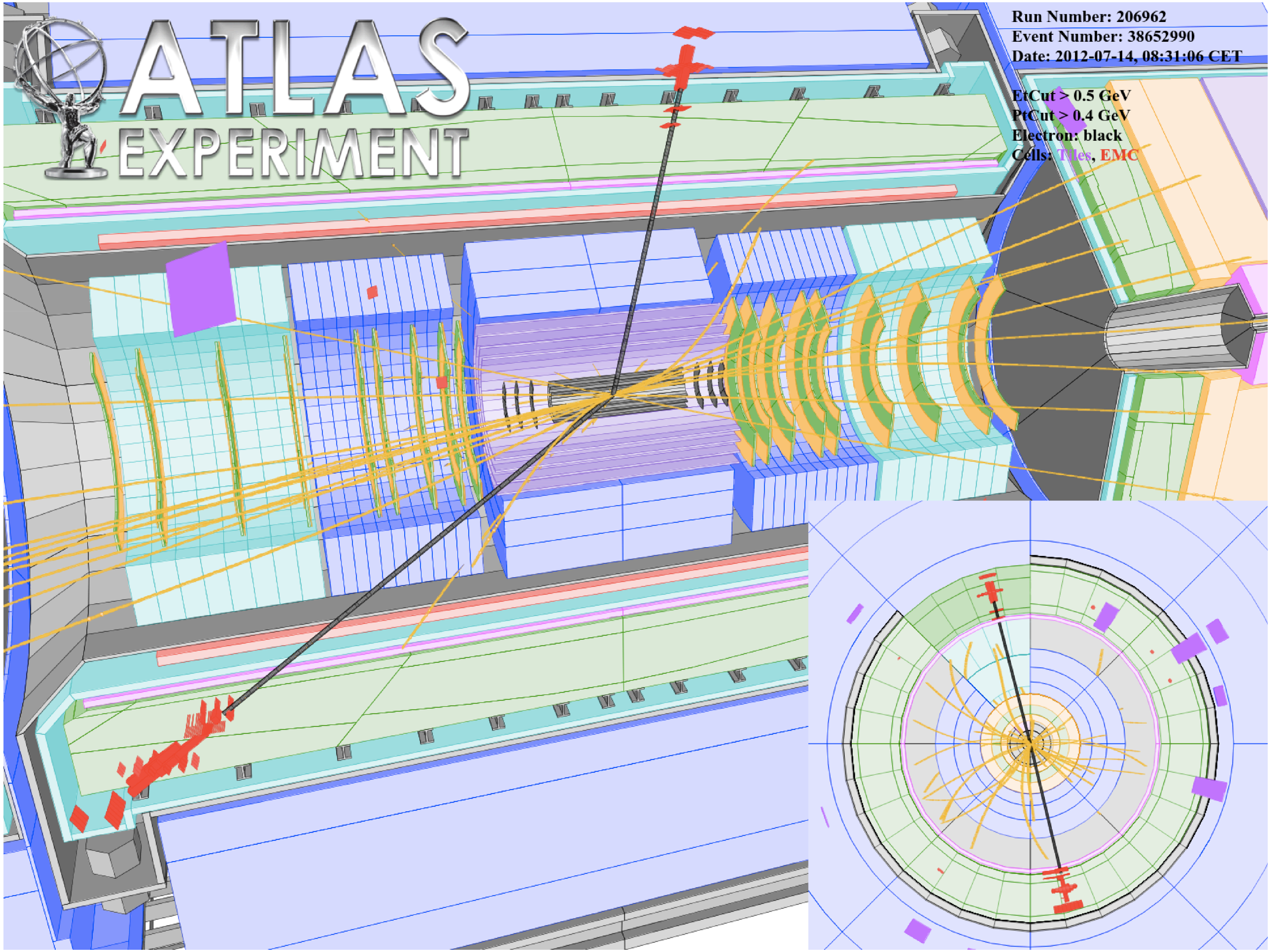


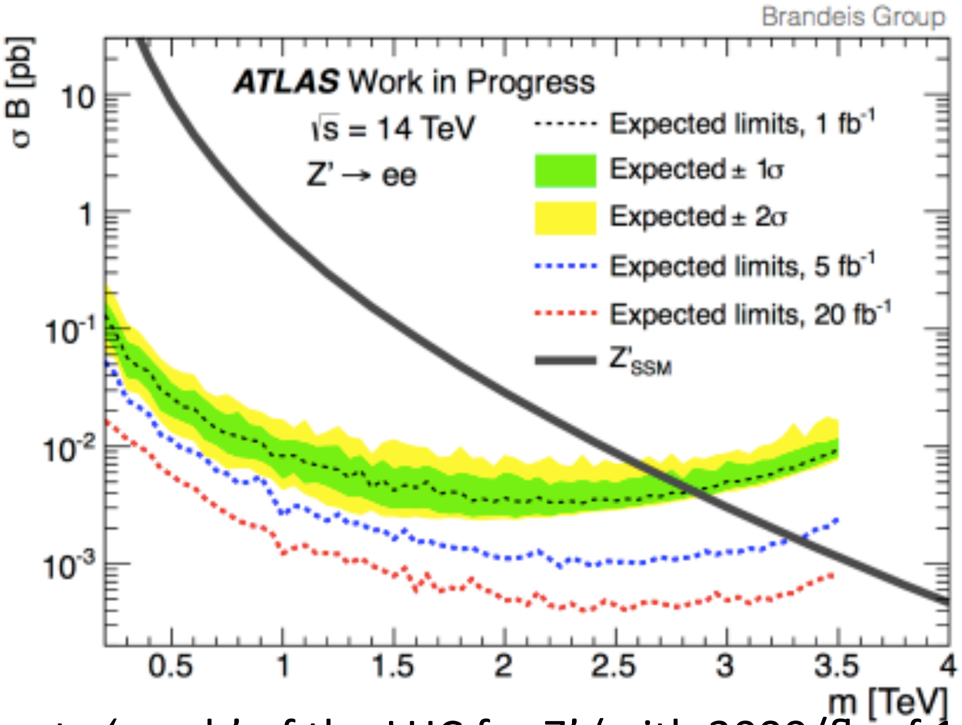
Simulation tells us that the 1TeV Z’ is narrower in electron decay mode than muon decay mode
(Electron momentum resolution better at high energy)
Background composition different in the electron and muon channels.

Z’ analysis (Run-1)



Adding more data (~100x)
(and higher energy 8TeV instead of 7TeV)
Now exclude 2.9 TeV Z’ !

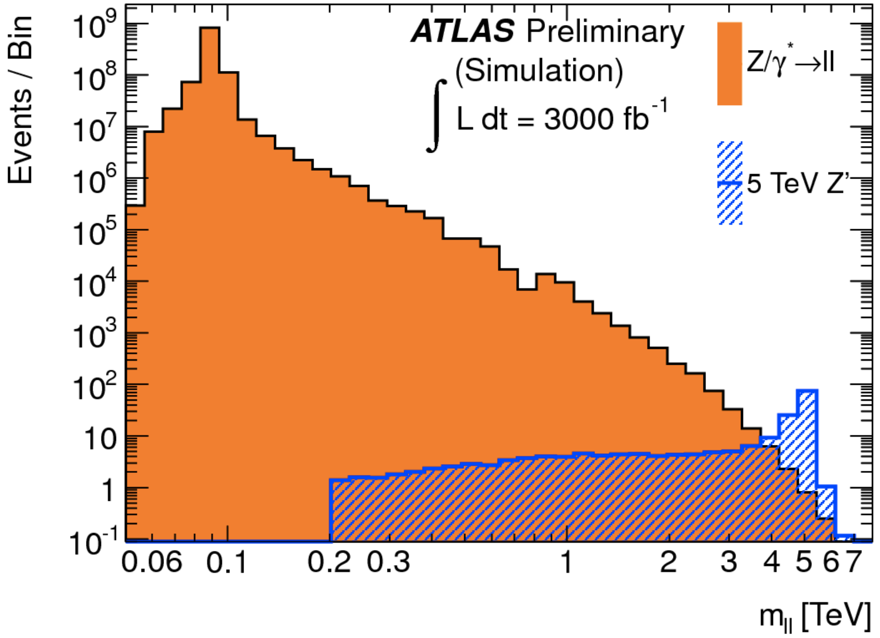

ATLAS EXPERIMENT
Run Number: 206962
Event Number: 38652990
Date: 2012-07-14, 08:31:06 CET
EtCut > 0.5 GeV
PtCut > 0.4 GeV
Electron: black
Cells: Tiles, EMC

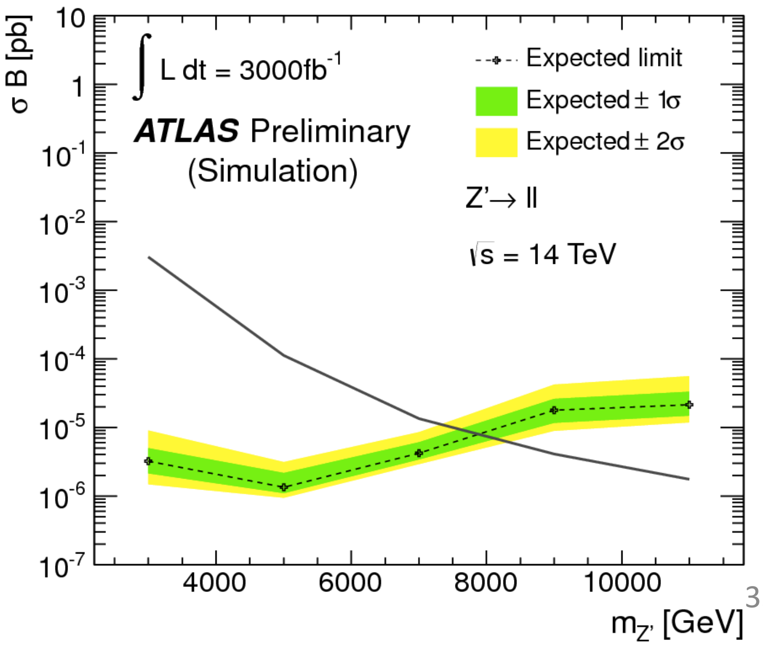


first (non-public!) studies suggest we will be sensitive to Z' masses above the Run-1 limits with ~3/fb of Run-2 data (expected by the end of August).

The good things about these searches is they are quite simple so can expect reliable results fast!

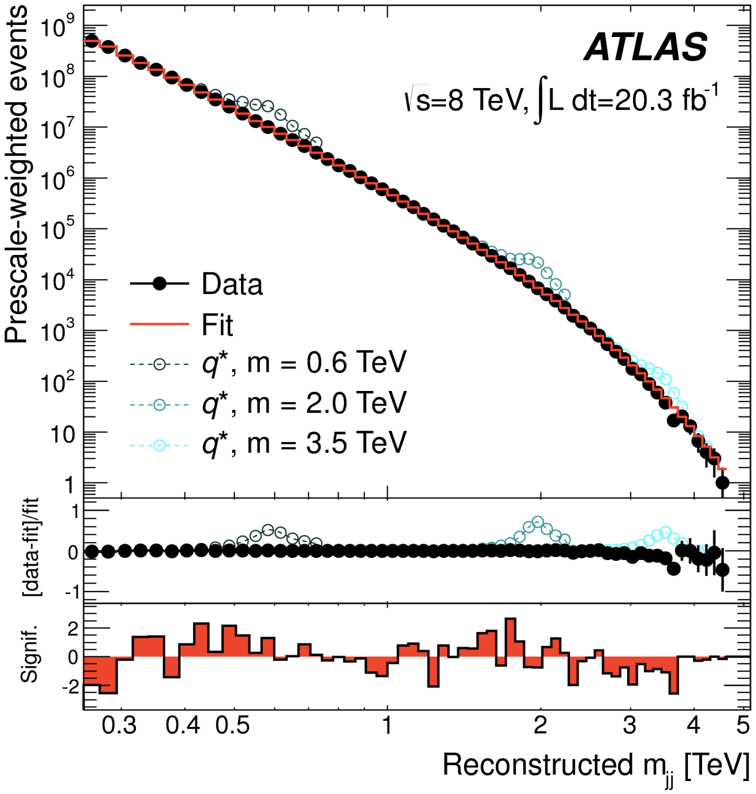
The ultimate 'reach' of the LHC for Z' (with 3000/fb of 14 TeV data) is to be able to exclude Z' of masses of ~8TeV

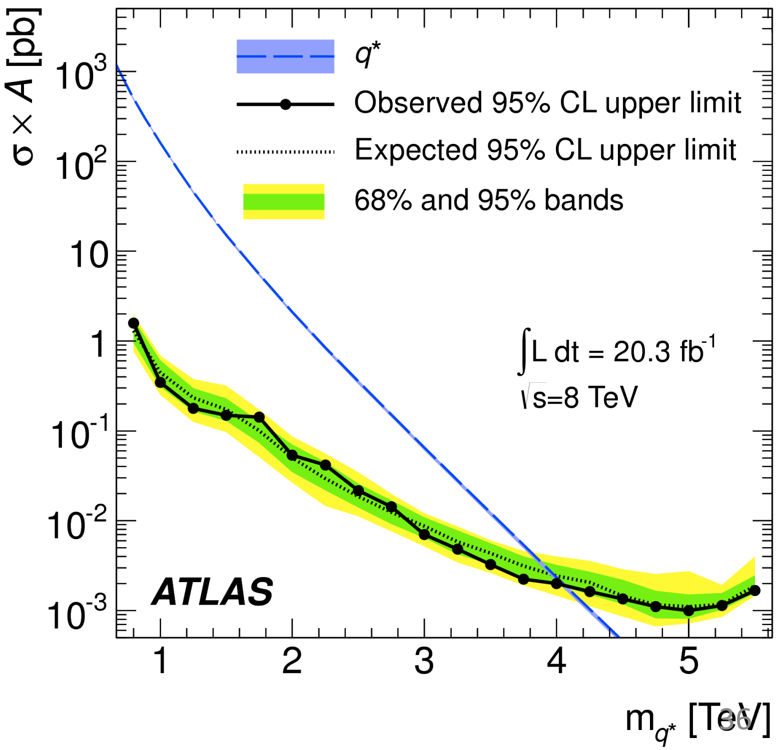




di-jet resonances

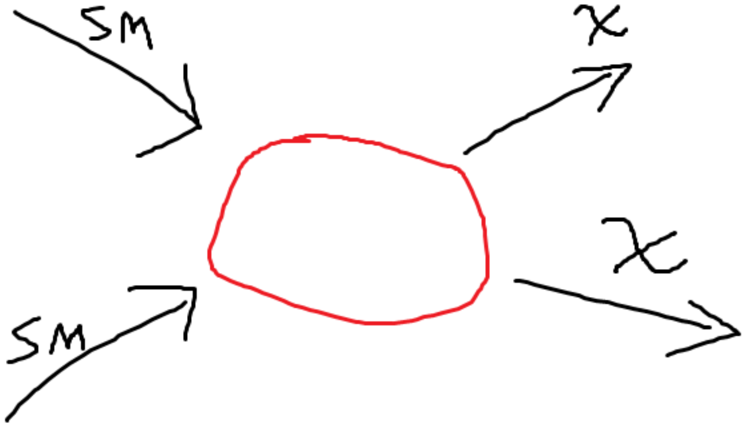
- In theories where the quarks are not fundamental particles but made up of constituent particles we can expect a resonance in the mass of the jet-jet system
- Run-1 limit of ~4 TeV could be passed with a few days of Run-2 data!

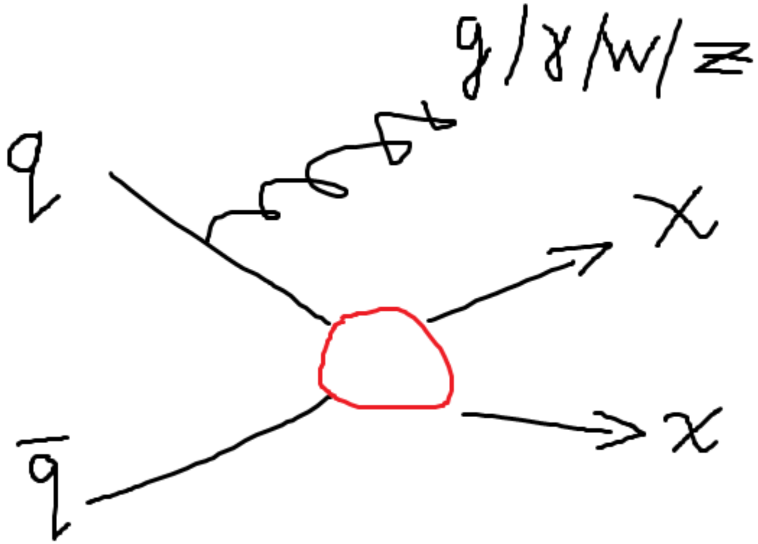




Dark Matter searches

- Dark Matter doesn’t interact with the detector so if you produce DM particles in the collisions they will not be ‘seen’
- However can use ‘initial state radiation’ where a gluon (or other particle) is radiated off the before the collision where the DM particle is produced





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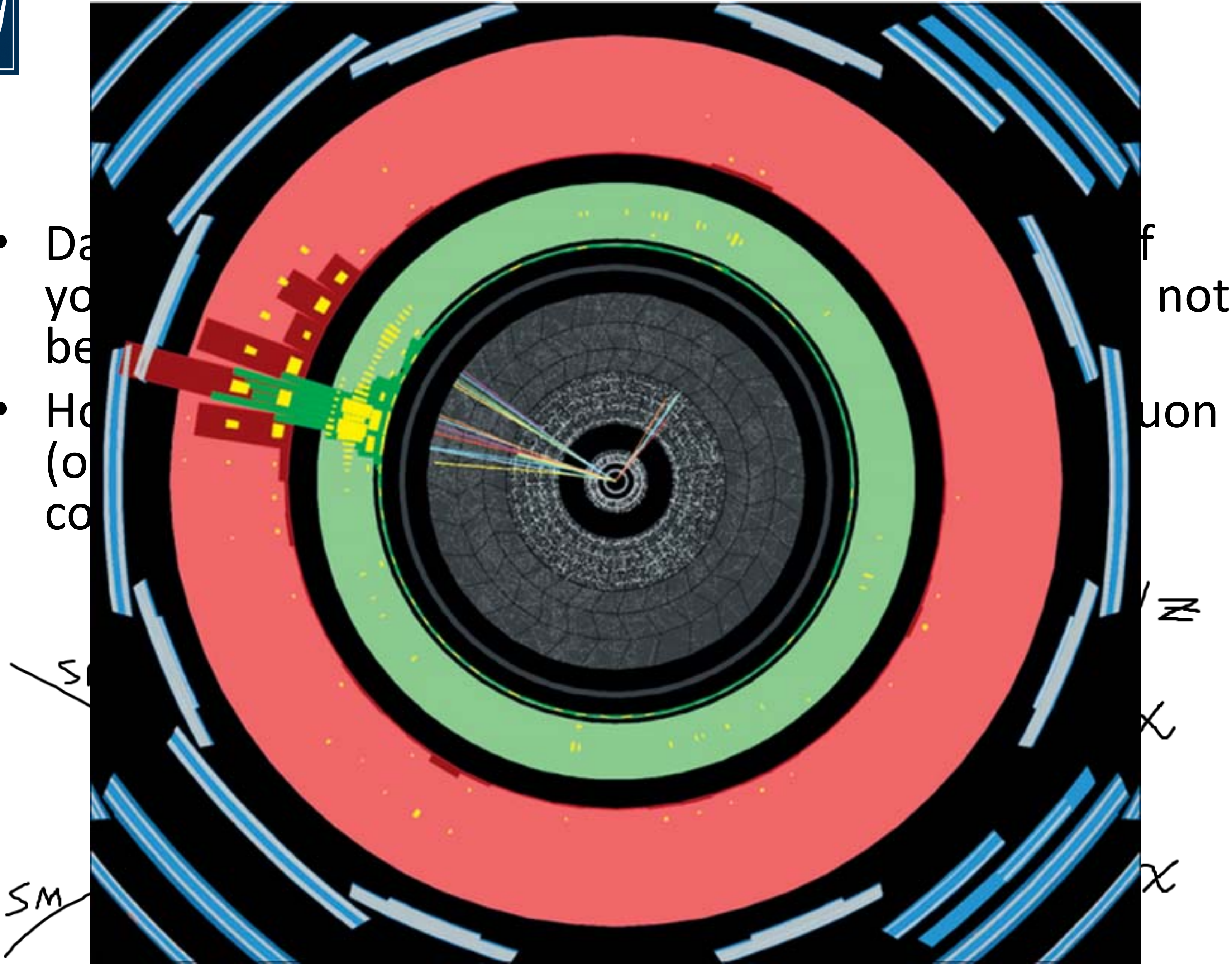
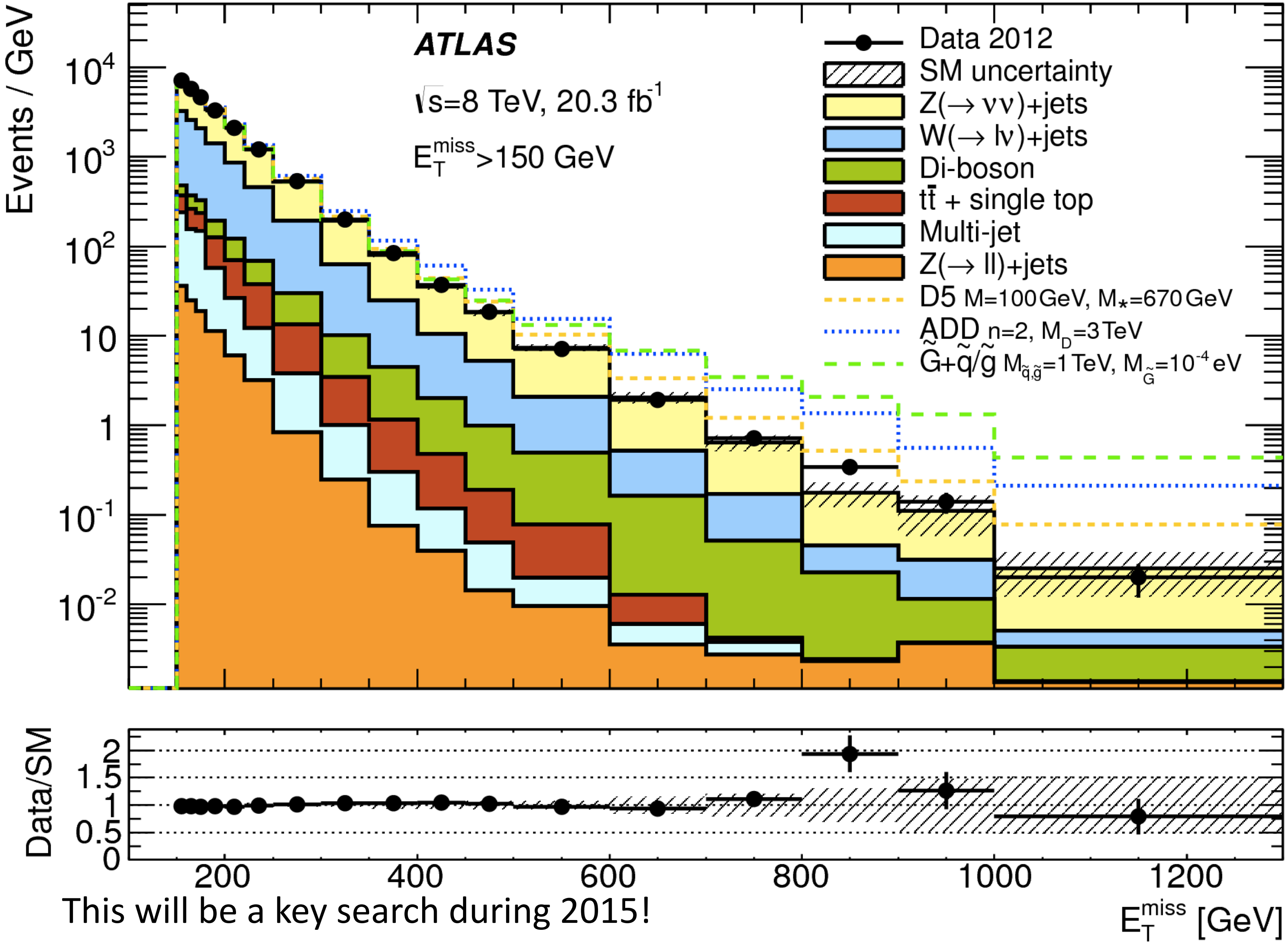


This will be a key search during 2015!

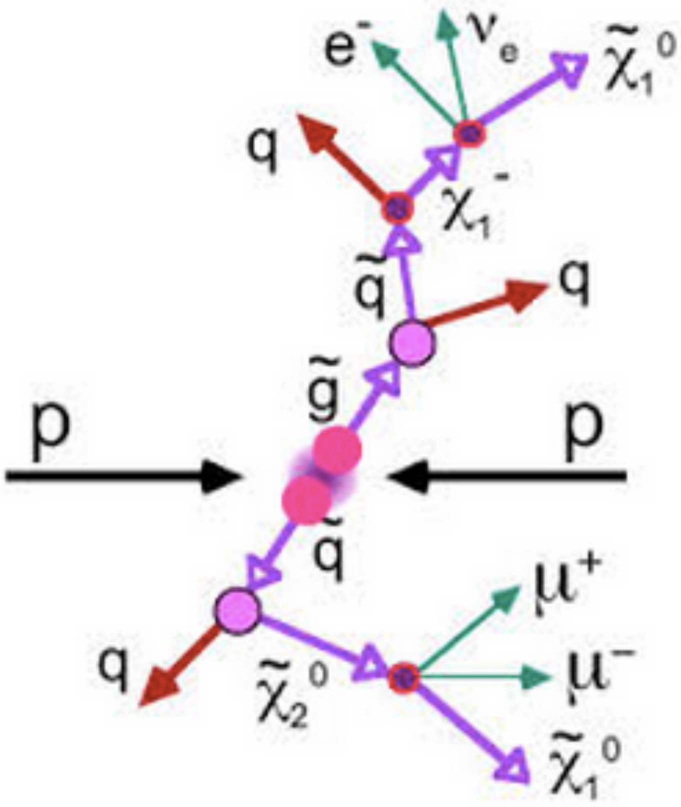
Dark Matter searches

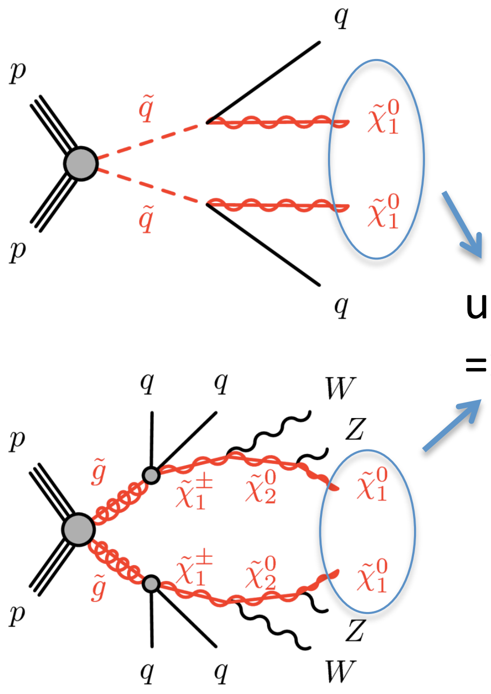


This will be a key search during 2015!

SUSY Searches

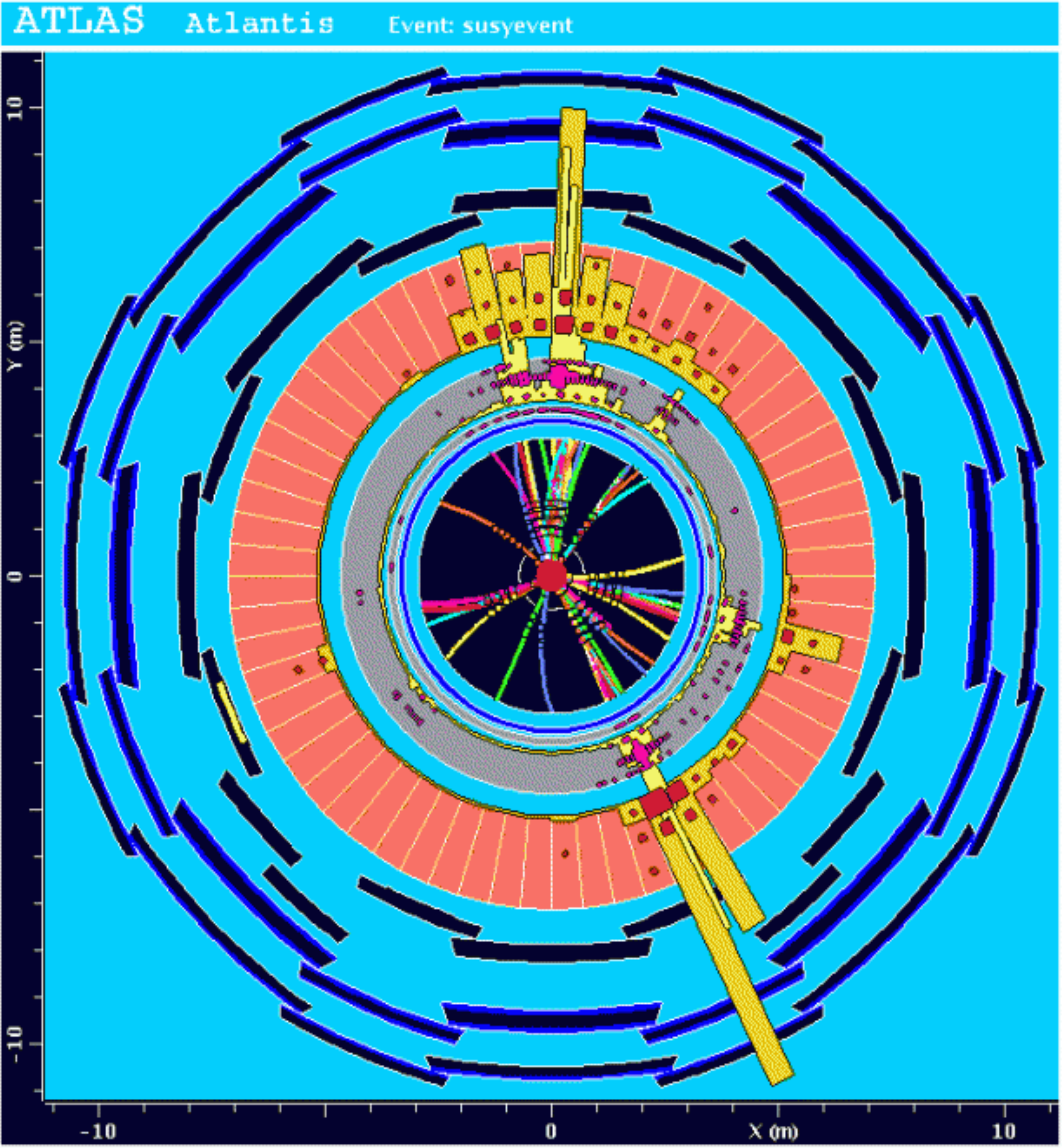
- SUSY particles are generally produced in pairs and decay via a decay cascade through (el,mu,ph) + jets + missing energy
- missing energy comes from the 2 lightest SUSY particles which are undetected





undetected

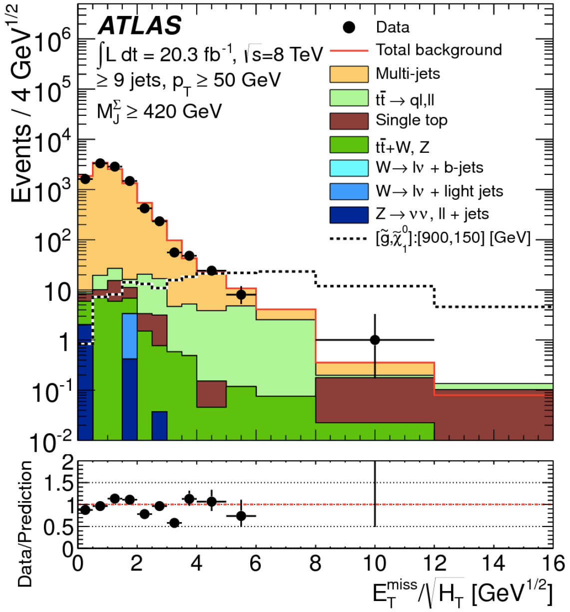
=> missing energy!

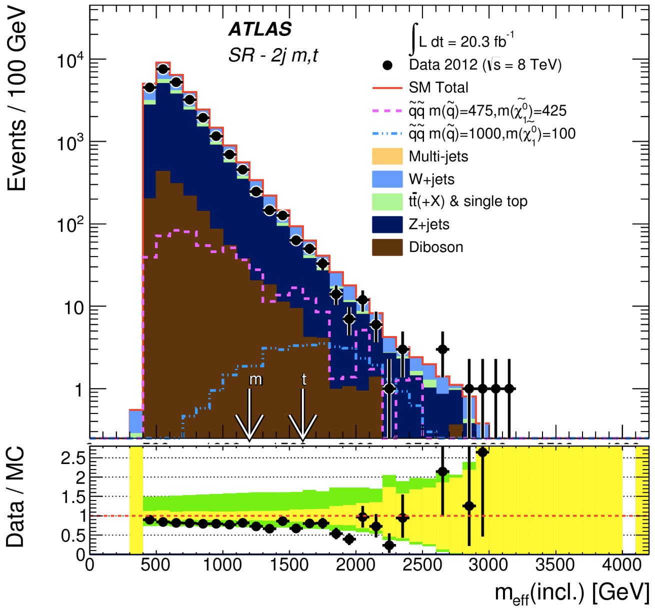


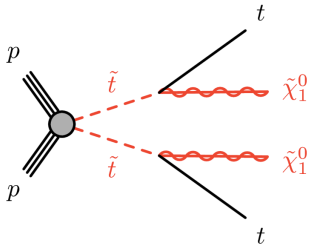
An event display of a simulated SUSY event.

SUSY searches in Run-2

- There will be many SUSY searches in early Run-2
  - jets + missing energy
  - jets + electron/muon + missing energy
  - b-jet(s) + missing energy etc…
- Most should start to become sensitive to SUSY particle with mass above the masses excluded in Run-1 with ~3/fb of data (expected by end of Aug)
- With the full LHC program it is expected that the 'most favoured' region of SUSY parameter space can be excluded (e.g. stop's <1 TeV)
  - But it will not be possible to completely rule out SUSY with the LHC
- There are many potential difficult versions of SUSY such as
  - long lived SUSY particles
  - compressed SUSY spectrum which give little missing energy
- Clever ideas are needed to try to constrain these…

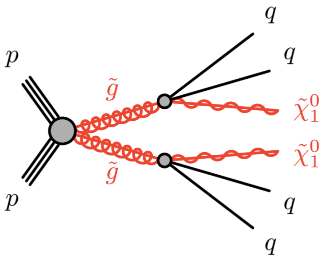


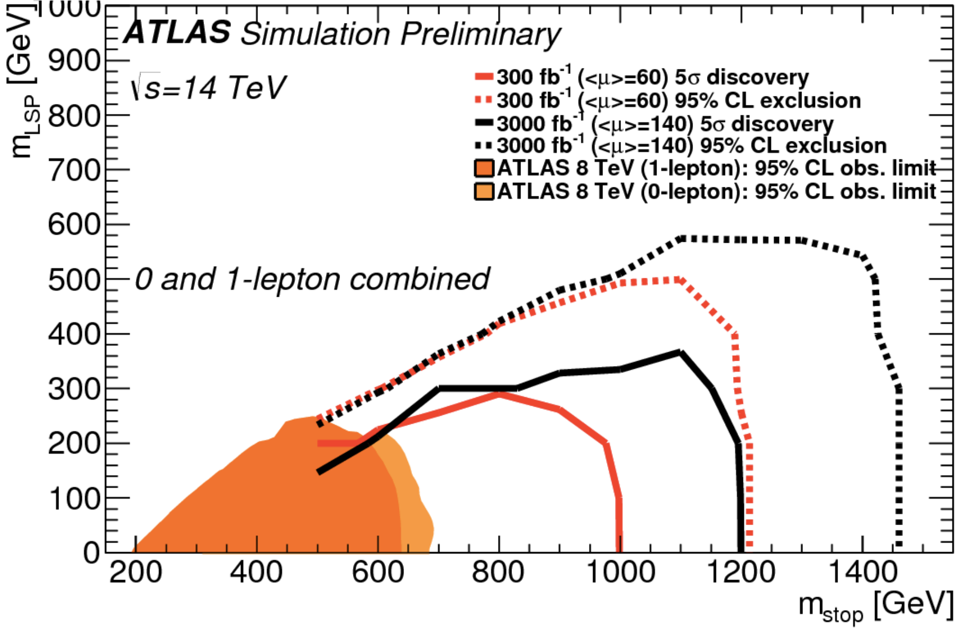


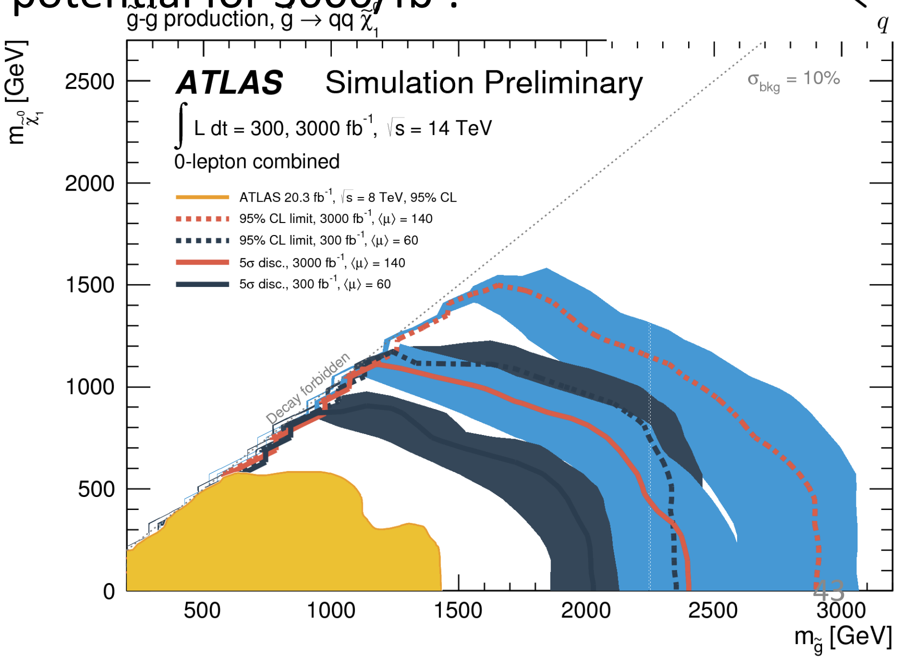


SUSY searches look for excess of events in the ‘tails’ of the missing energy distribution. In these searches the background estimation is the key!

Bottom plots show discovery potential for 3000/fb !

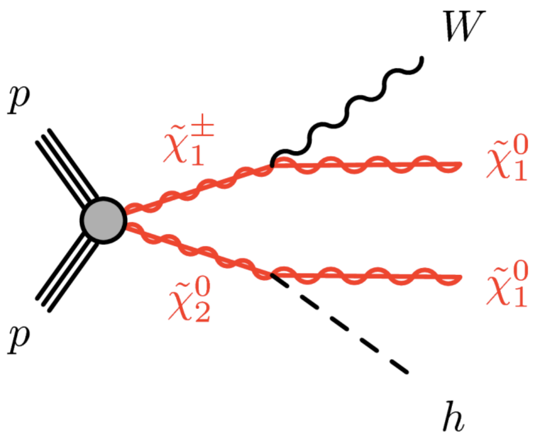


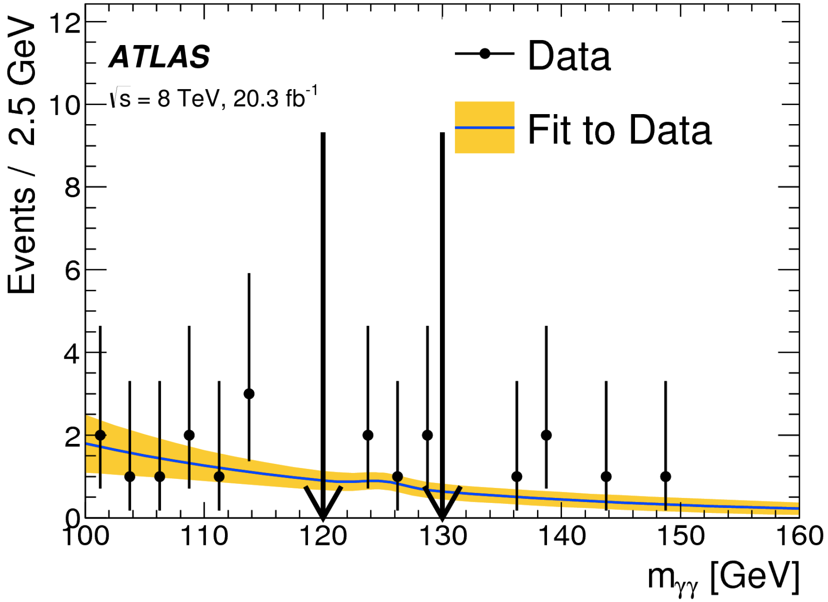




Using Higgs in decay of new physics

- One exciting new thing we can do now that the Higgs has been discovered is to look for new physics with the Higgs in the decay of the new particles
- e.g. in SUSY we can look for:

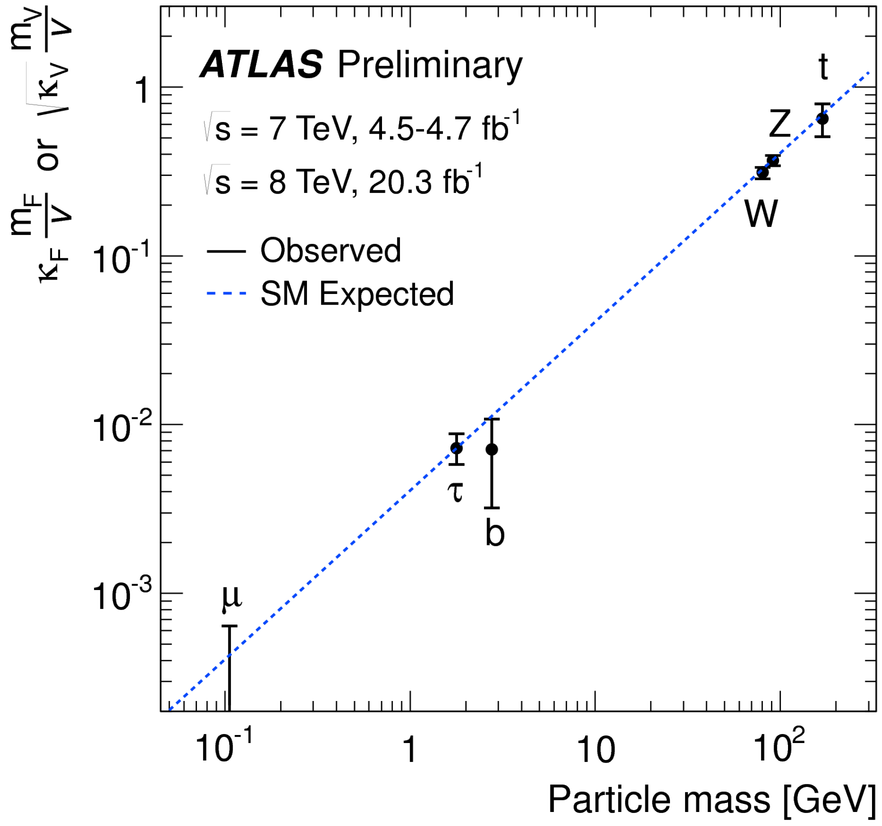


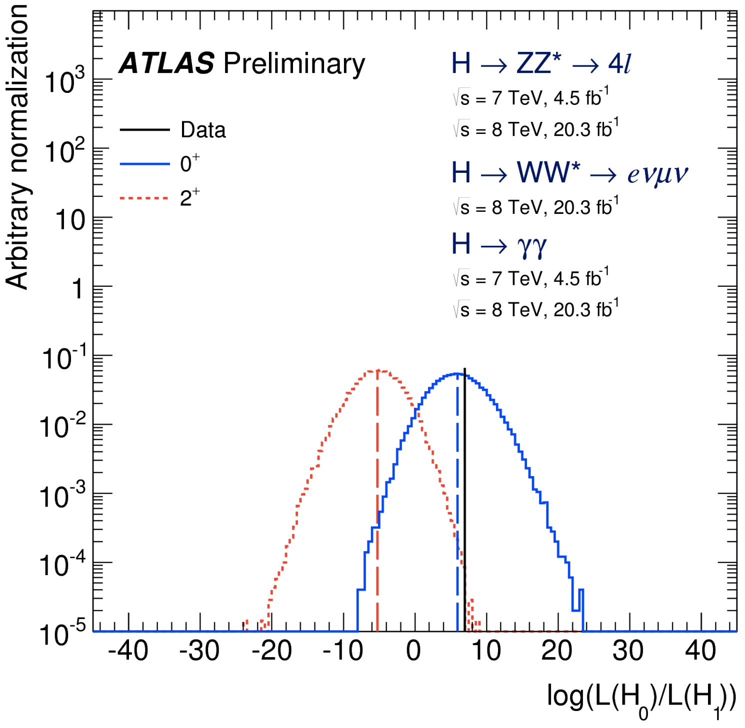


- Another relevant point is that Higgs production can become a background for some of our searches!

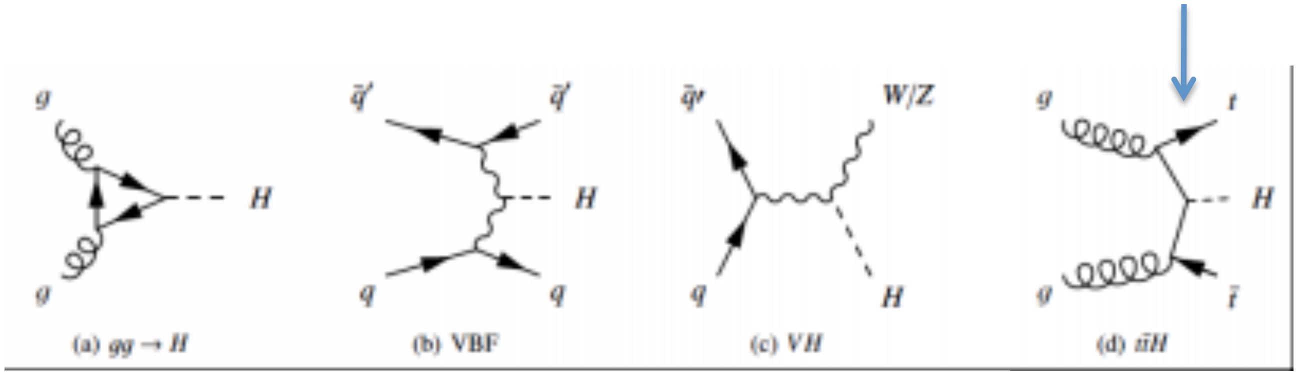
Higgs physics

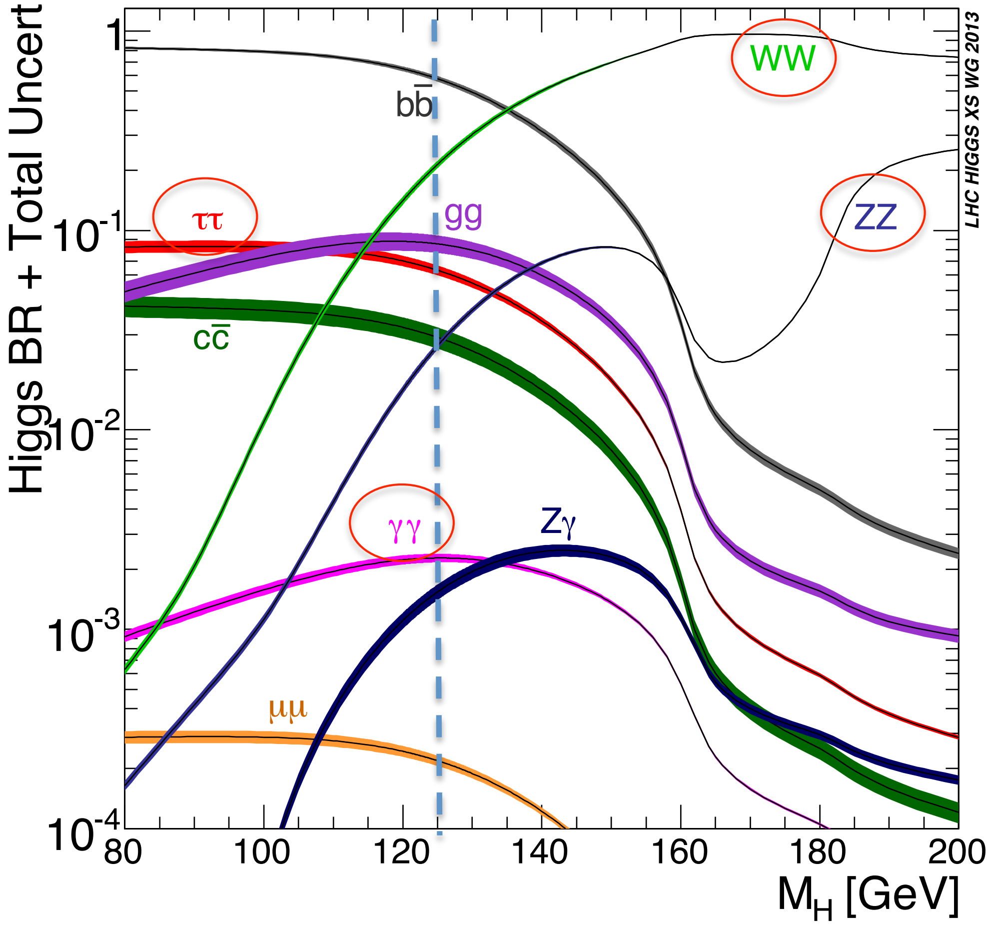
- Since the Higgs discovery we have tried to measure its decays to different particles
- So far everything looks as expected, but with large uncertainties in some cases
- Also measuring the spin and CP of the Higgs is very important. Run-1 results indicate it is very likely spin 0 but further studies will be needed for full confirmation.





different Higgs production/decay modes at LHC: not yet observed

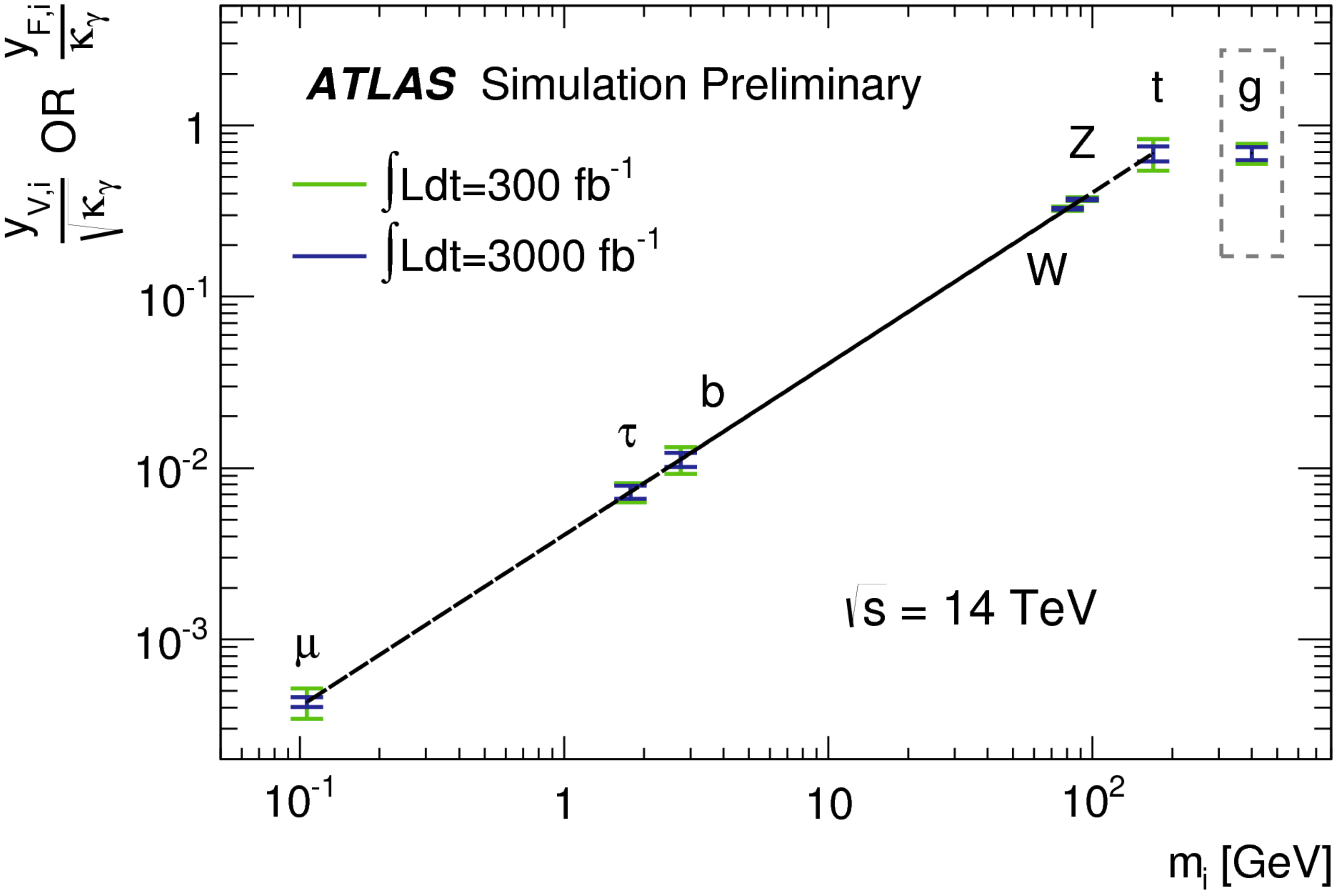




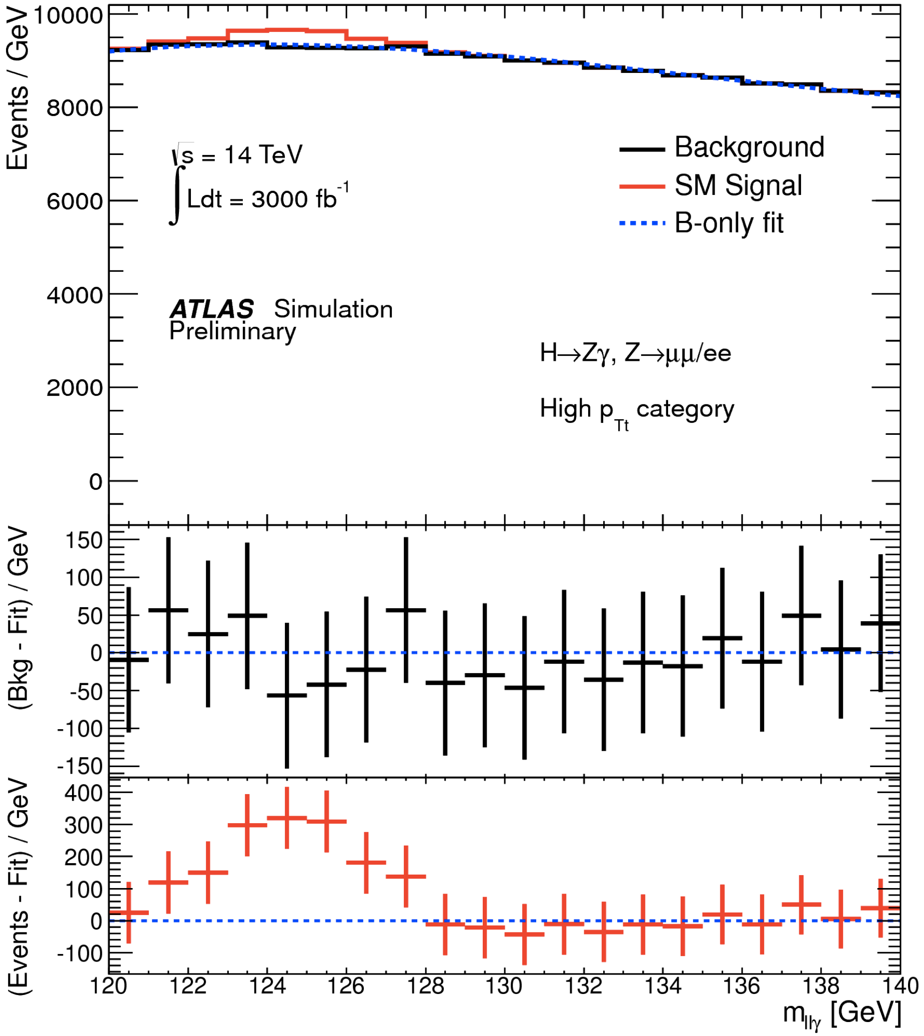
only channels in red circle have been observed.
In Run-2 hope to observe bb (the highest rate decay).
With the full HL-LHC hope to see Zγ and μμ (but these are very difficult!)

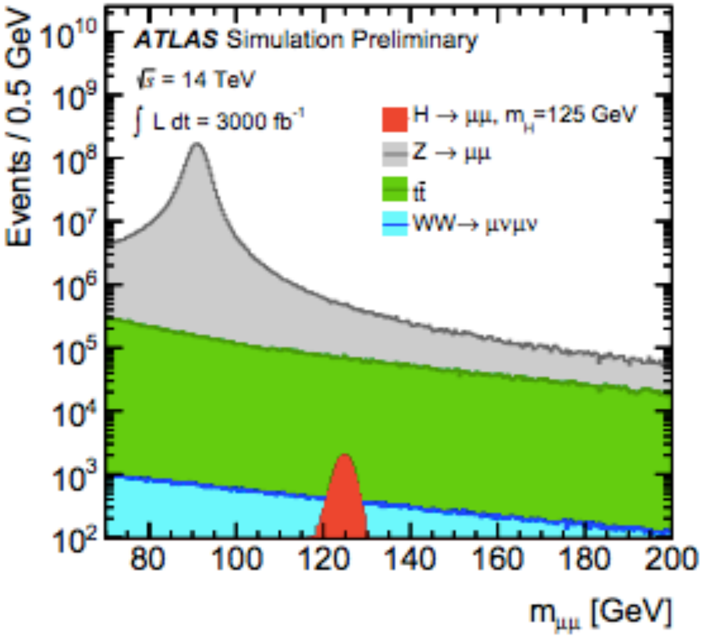
H->bb and ttH production will be very important goals for Run-2.

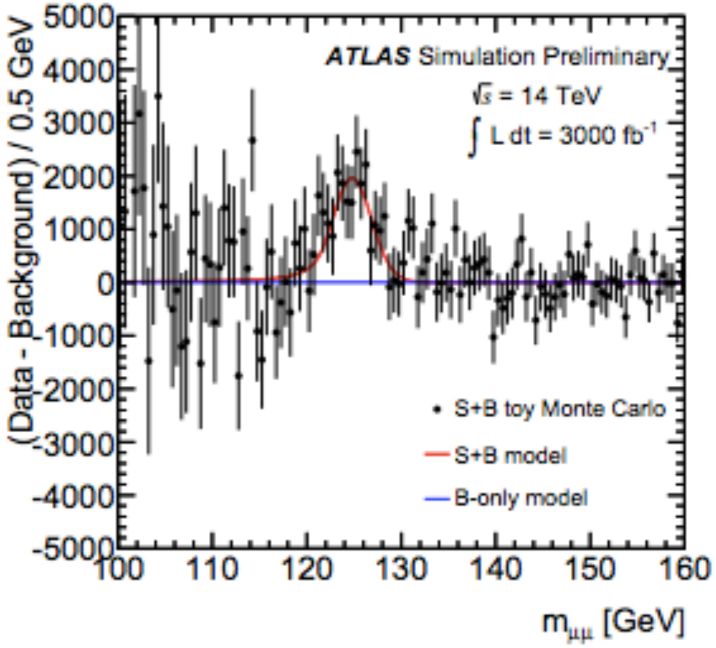
projection for the end of Run-3 and after the HL-LHC



an example of a *very* rare Higgs decay in the SM, but one which can be significantly enhanced in BSM theories is H->Z gamma, and H-> mu mu is another example

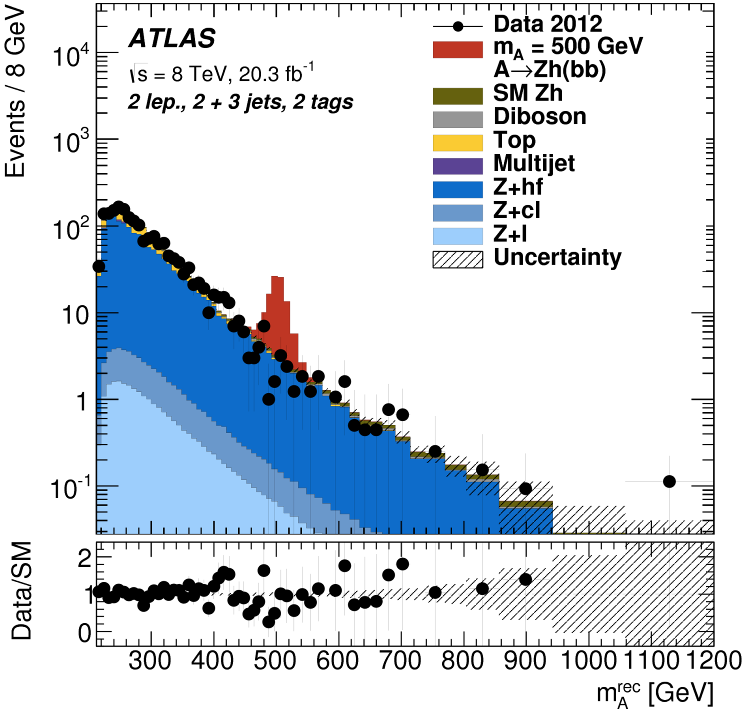


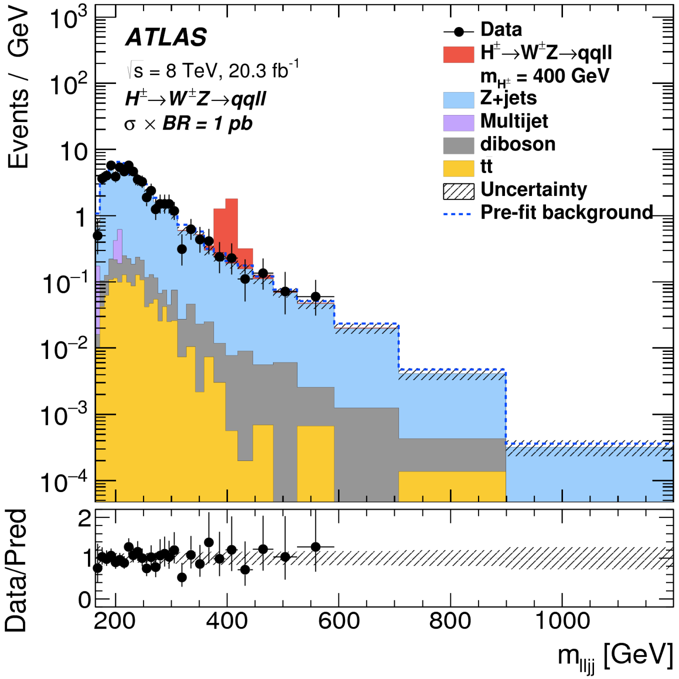


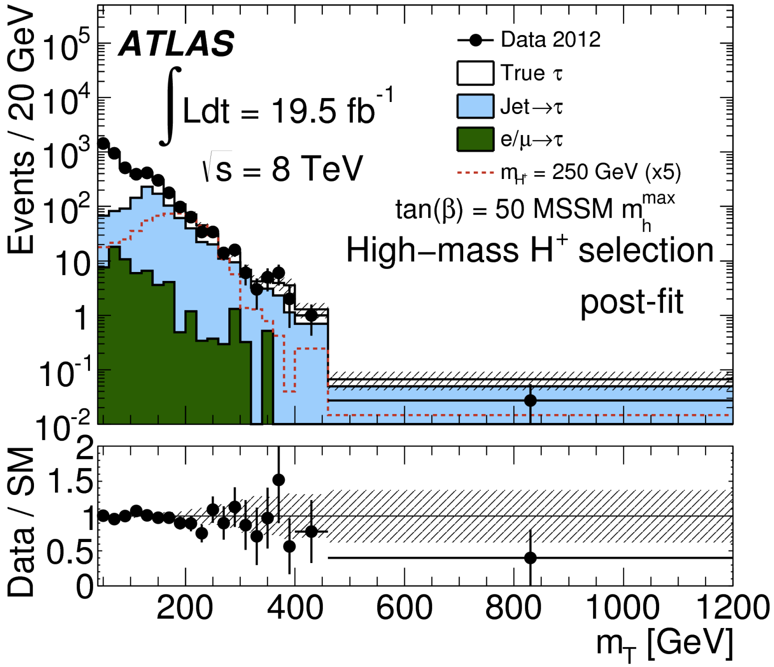


BSM Higgs

- The SM Higgs is the simplest version of the Higgs mechanism
- There are more complex ways in which more than 1 Higgs boson appear
  - Actually in SUSY you have 5 Higgs bosons, but the lightest can be SM-like
- Searching for Heavy Higgs is therefore an important way to look for BSM effects
- There are many channels to search in for example resonances in tau tau, bb, WW, ZZ, gamma gamma
  - Similar to the searches for the Higgs but at higher mass



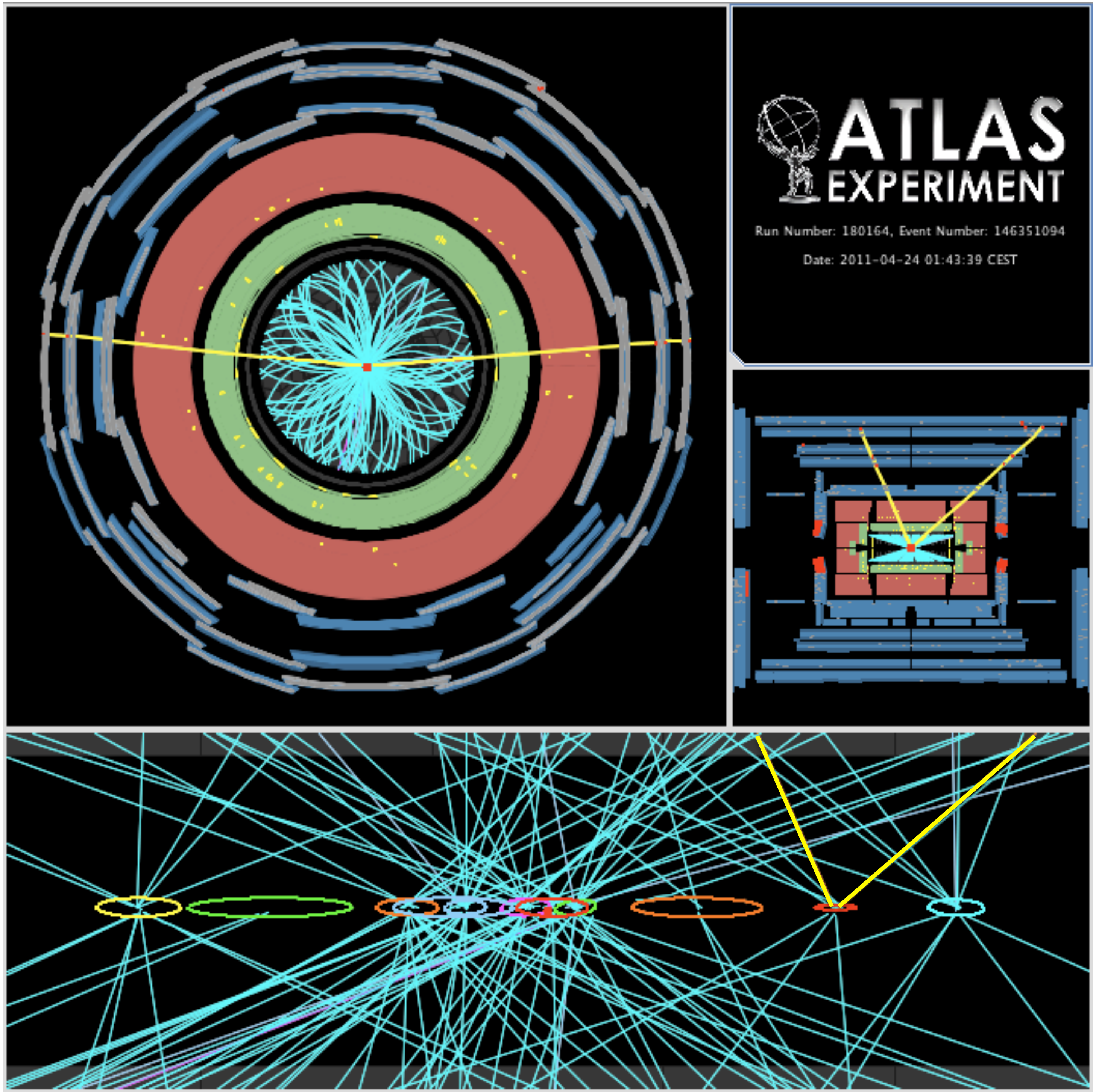




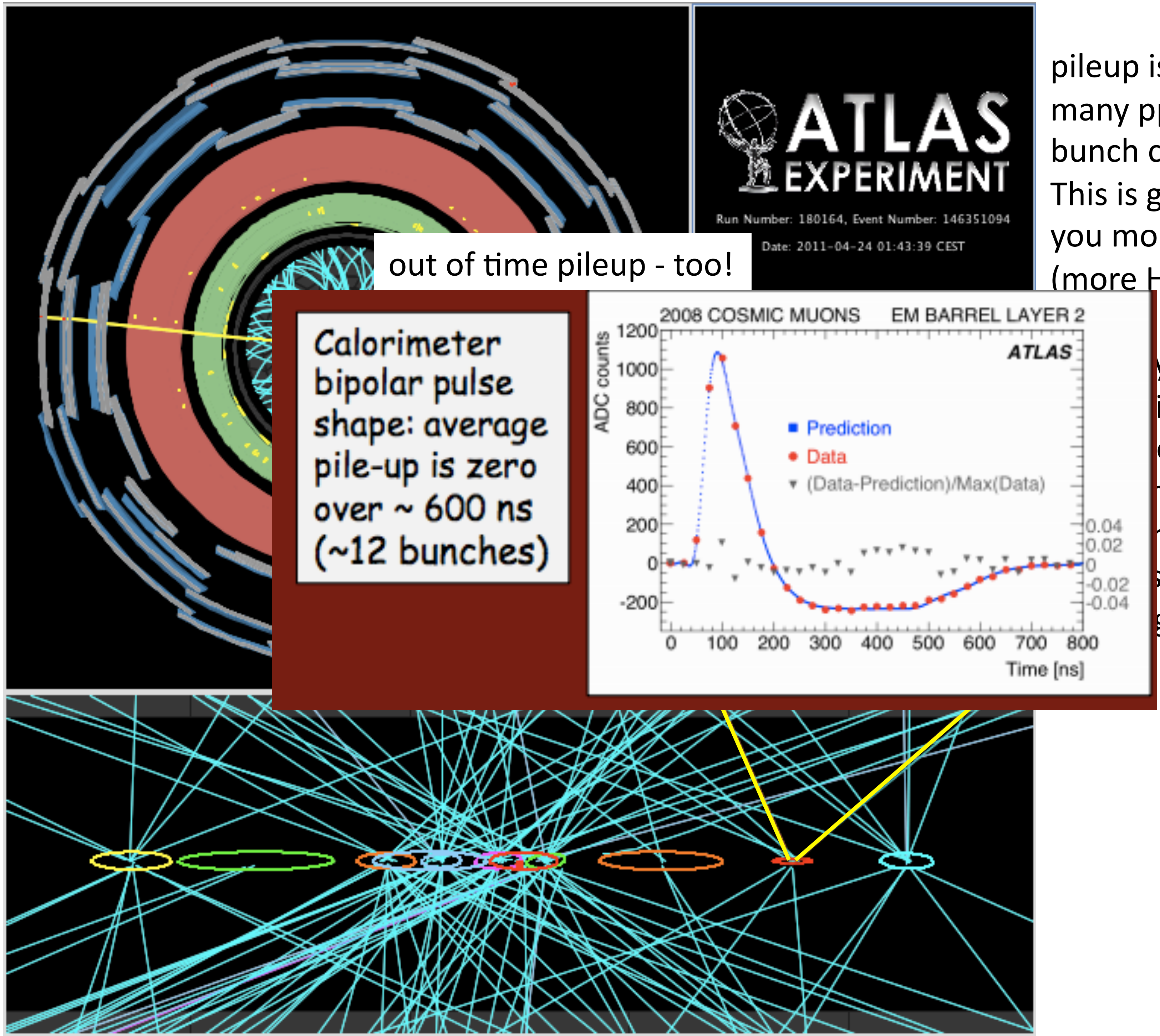
Many, many different BSM Higgs searches….

Experimental challenges

- 25 ns bunch spacing –> more out of time pileup
- higher luminosity -> more in-time pileup
- higher luminosity + energy -> higher rates for SM particles -> higher trigger rates, need more stringent triggers, careful not to throw away interesting physics!
- Some detector components performance will start to deteriorate from ageing/radiation
- Upgraded parts of the detectors to help deal with these issues



pileup is when you have many pp collisions per bunch crossing.
This is good as it gives you more luminosity (more Higgs bosons etc..), but bad because it means your detector is full of signals from the many non-interesting collisions that can make doing the physics analysis more challenging.



out of time pileup - too!

Calorimeter bipolar pulse shape: average pile-up is zero over ~ 600 ns (~12 bunches)

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Conclusions

- There is a huge physics program for Run-2 and beyond
- Searching for ‘new physics’ is the most relevant thing (especially early on)
  - The huge increase in cross section for heavy new particles means we could have a discovery in 2015 (if we are lucky!)
  - Many possible models: SUSY, extra dimensions dark matter
- Precision Higgs physics is another way to probe the Standard Model
  - measuring H->bb, ttH production as well as precise measurements of the spin
- If we find new particles there is a huge amount of work ahead to study them and to try to map out the underlying theory
- Beyond Run-2 there is an important physics program for the HL-LHC (3000/fb)
  - e.g. for studying very rare Higgs decays
- Throughout this there are many experimental challenges ahead
  - Including many related to computing!

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QUESTIONS?