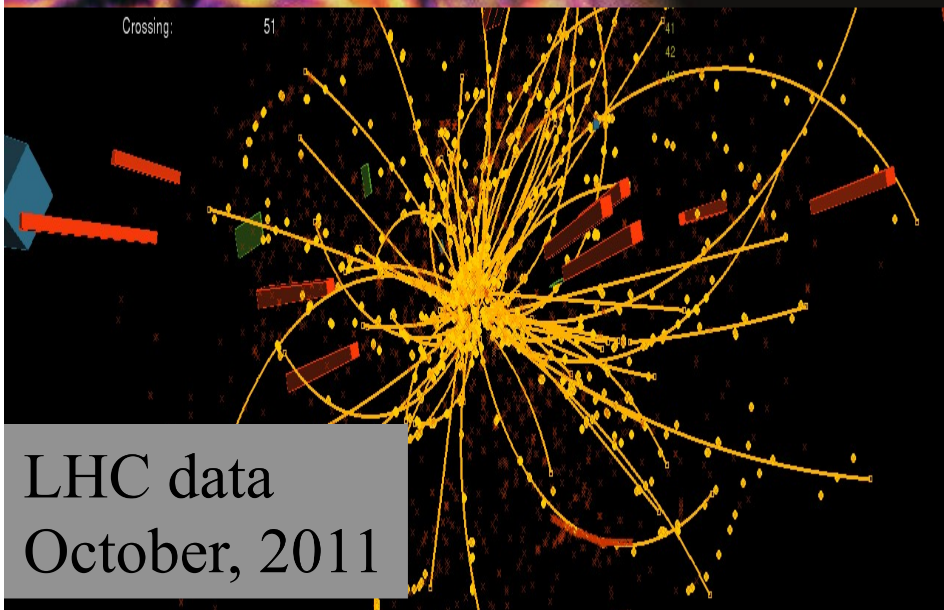
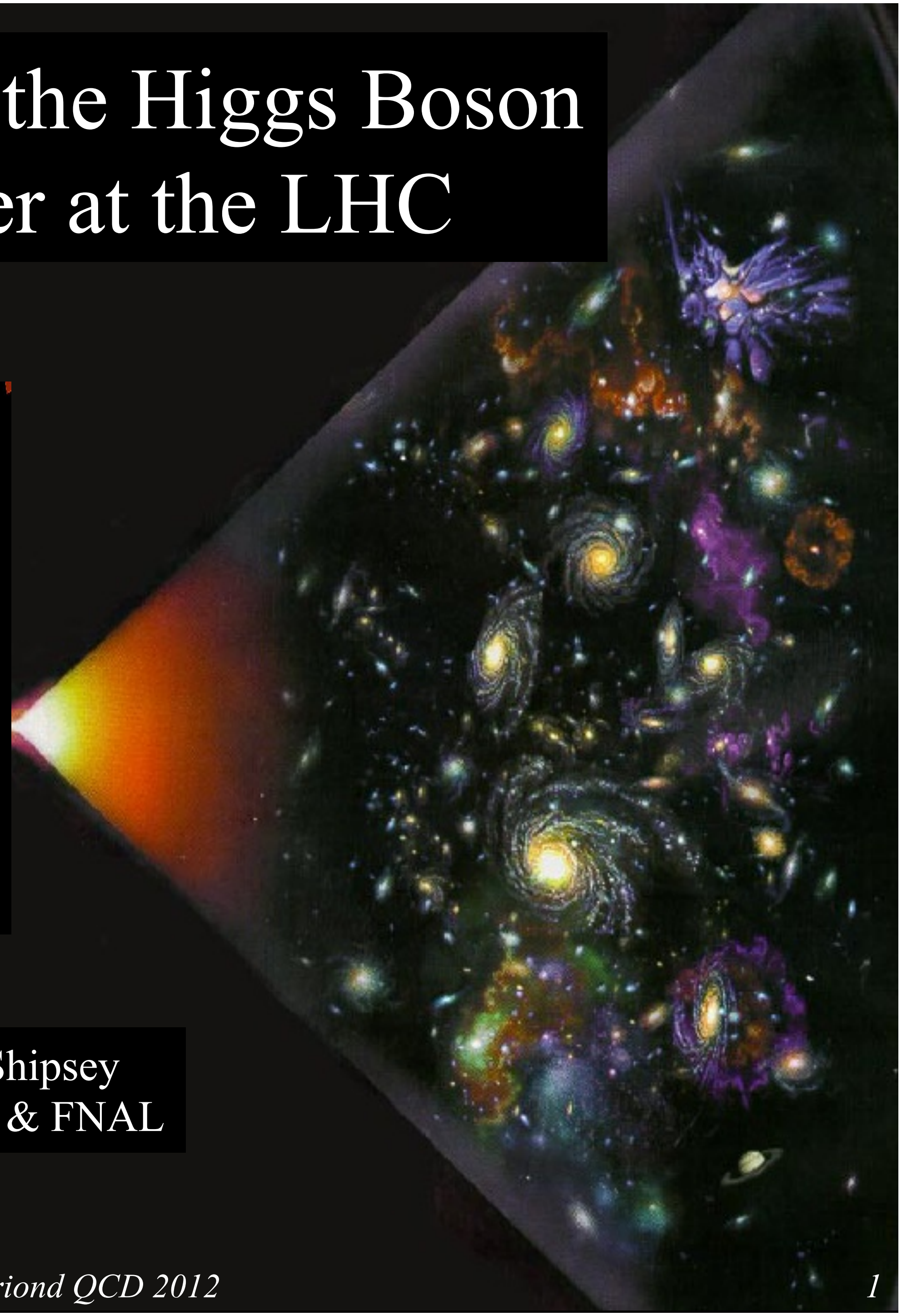
The Search for the Higgs Boson and Dark Matter at the LHC



LHC data
October, 2011



Ian Shipsey
Purdue & FNAL

The LHC has long been anticipated:

30-mile 'donut' to spin out atomic secrets

World's mightiest atomic accelerator, so huge it will span the border between two European countries, may unlock deep mysteries of the universe—and unleash virtually unlimited supplies of vital electric power.

by Hans Fantel

It will be so big you can see it in its entirety only by looking down from a mountaintop or airplane. A circular tube with a mind-boggling circumference of 30 miles, it's the largest machine ever conceived. It's still in the planning stage, but represents the most ambitious concept yet for building an atomic particle accelerator—popularly known as an atom smasher.

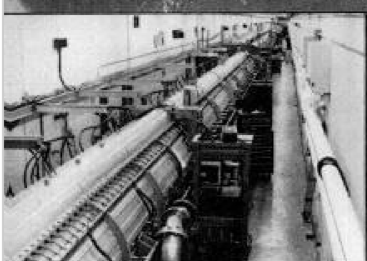
Why the incredible size? Such devices need a long path to accelerate their subatomic particle "bullets" up to the tremendous velocities required to penetrate and break down matter at the atomic level—just as a jumbo jet needs a long runway to get up to flying speed. The longer the path, the greater the acceleration that can be achieved.

Is such a giant merely a paper dream? By no means. The technology for building it exists—the final design, financing, location of construction site, and certain political considerations must still be worked out. But atom smashers have been getting bigger and more powerful all the time—a sign of even more ambitious projects to come. The famed Brookhaven accelerator, half a mile in circumference, is already dwarfed by a similar one with a four-mile girth at Fermilab in Batavia, Ill., currently the biggest atom smasher in the world. And now being planned is another, more modern installation for Brookhaven that will outpower them all—at least until that 30-mile monster goes into operation.

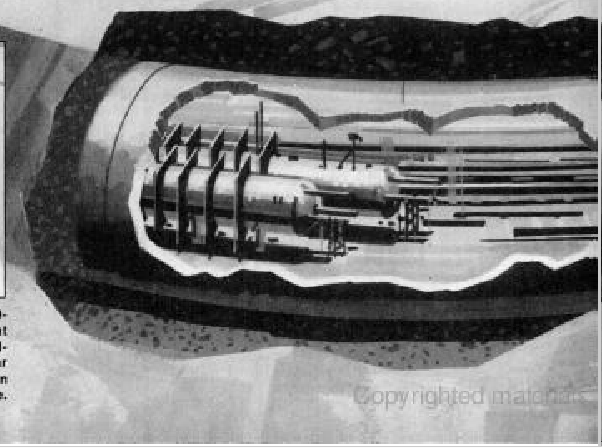
The newly proposed superaccelerator still has no official name. It's just called the VBA—short for Very Big Accelerator, which is an understatement if there ever was one. While the primary objective of the VBA will be to explore the properties of the atom and physical laws governing the universe, its findings may also lead to new ways of mass-producing nuclear energy in safe, economical, commercially usable quantities. If so, such discoveries might well provide virtually unlimited supplies of urgently needed electric power.

Since the VBA will be such a gigantic and costly undertaking, it is unlikely that any one nation could afford to foot the bill by itself. Thus the United States, the Soviet Union and several European countries are expected to chip in, making the project a truly international effort.

While a site has not been definitely



Like an entry ramp to a superhighway, this 500-foot-long linear (straight-line) accelerator at Fermilab pushes protons up to velocities needed to enter high-speed lanes in main circular accelerator. Such "preboosters" will be used in proposed 30-mile atom smasher shown above.

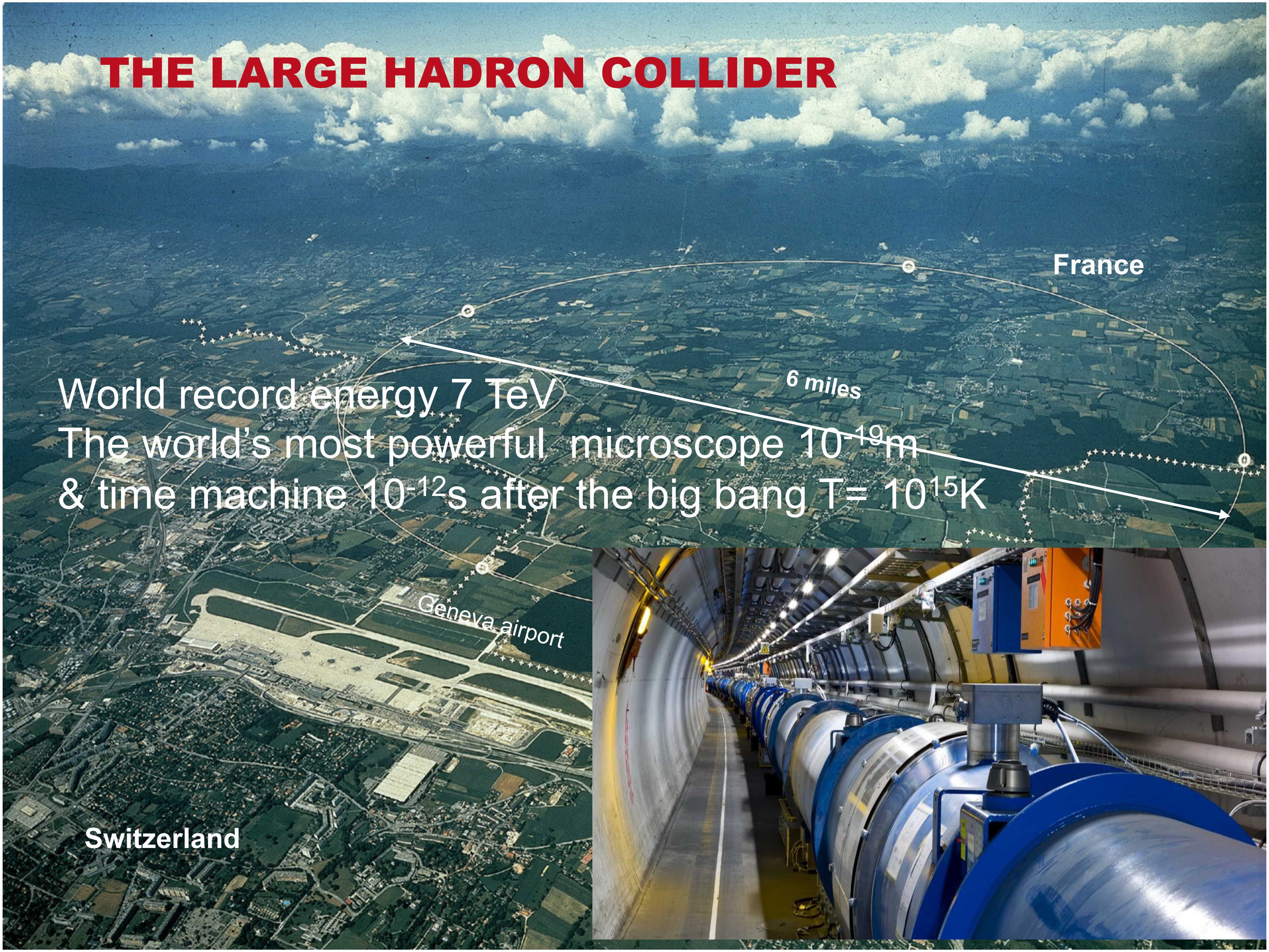


Map below shows one possible site for proposed new 30-mile-long atomic accelerator. If plan is adopted, the mammoth ring would span the boundary between France and Switzerland near Lake Geneva. It would be a joint international venture, built and operated by several countries.

Plan for new Brookhaven accelerator has twin tubes whirling counterrotating proton beams. Future 30-mile atom smasher depicted at left may use same arrangement.

***Popular Science*, April 1978**

- **TeV-scale proton collider**
- **international collaboration**
- **helium-cooled super-conducting magnets**
- **"electronic bubble chambers"**


THE LARGE HADRON COLLIDER
France
6 miles
World record energy 7 TeV
The world's most powerful microscope 10^{-19}m
& time machine 10^{-12}s after the big bang T= 10^{15}K
Geneva airport
Switzerland

The LHC is a global enterprise

Building the LHC brought together more than 10,000 people from 60 countries.

Spectacular Performance from the LHC

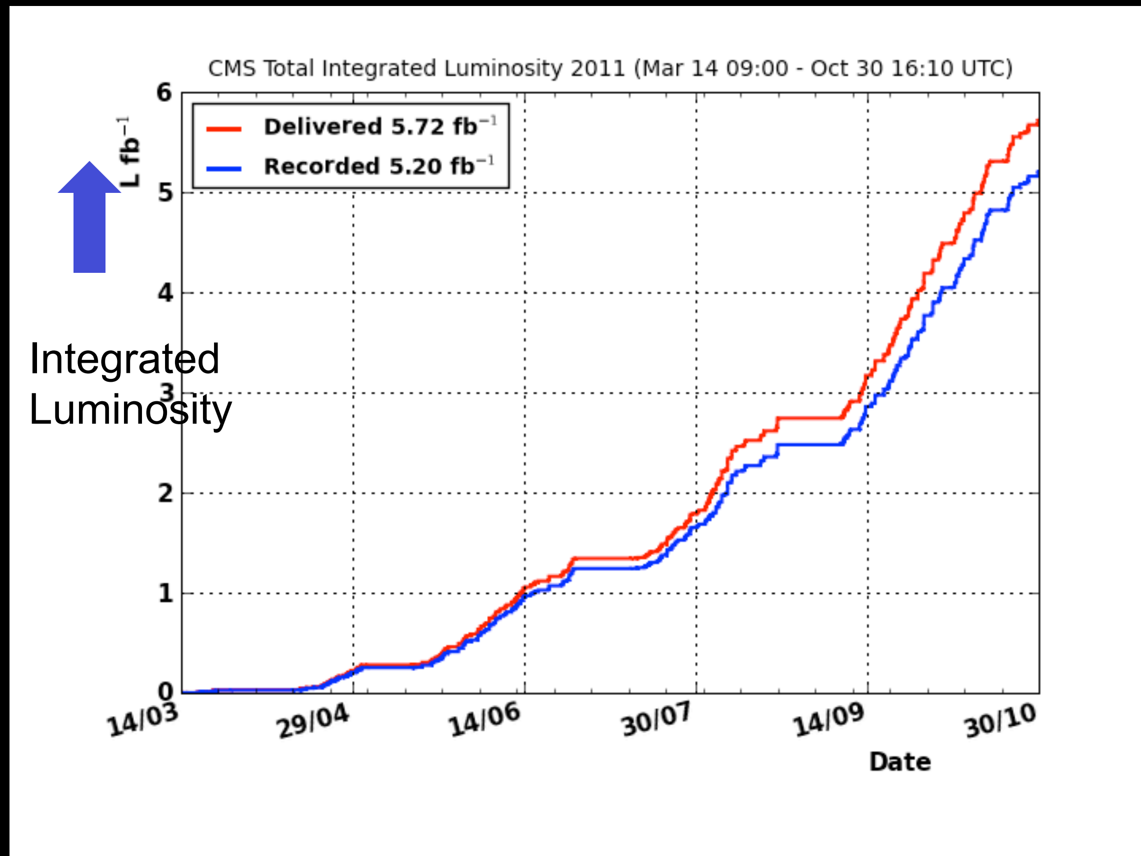
The number of interactions produced =
Luminosity x cross section (cm^2) x running time(s)

World Record Instantaneous Luminosity

$3.5 \times 10^{33}\ cm^{-2}\ s^{-1}$
~4 Z ➔ μμ
per second

Integrated Luminosity

5.2/fb recorded in 2011
~X100 2010 data
~ 350 trillion pp collisions
~ 100,000 Higgs produced



Great Optimism for imminent discovery

Unification

One of the guiding principles of physics

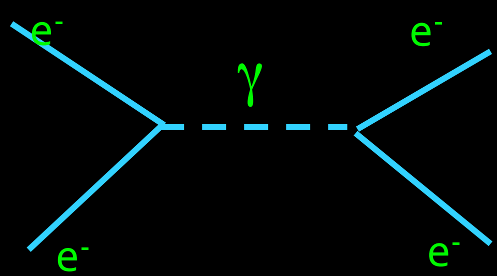
Newton unified all mechanical phenomena into a simple set of governing principles using a new mathematics

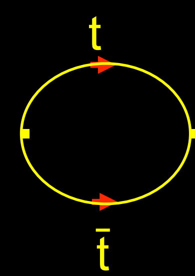
Maxwell unified electric and magnetic phenomena into a complete theory of electromagnetism

These unified theories led to Relativity, Quantum Mechanics and Relativistic Quantum Field Theory

Quantum Field Theory

- Energy and matter are equivalent ($E = mc^2$)
  - Repulsion of 2 electrons by the exchange of a photon





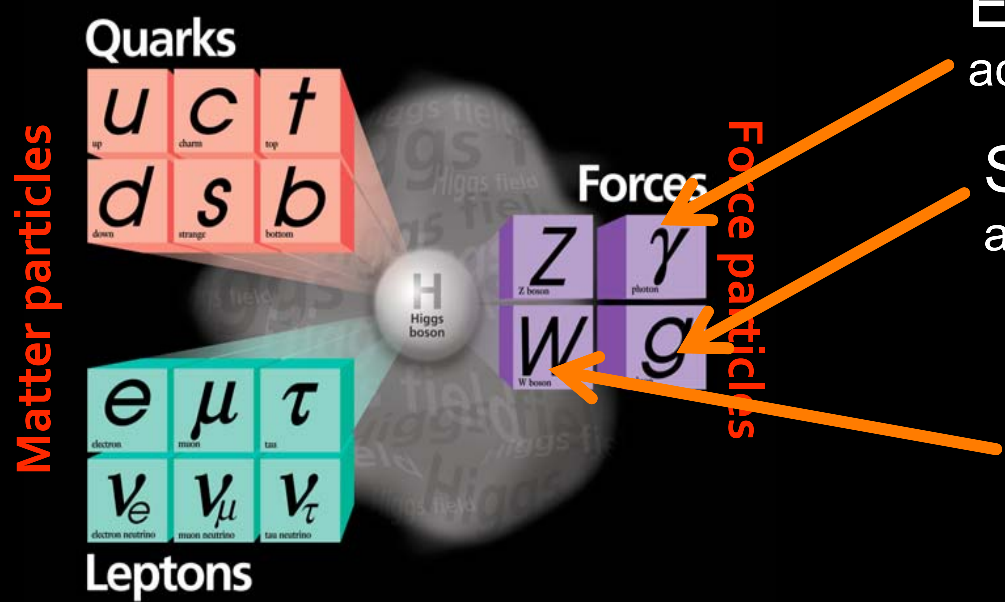
A Vacuum Fluctuation Involving top quarks

$$\Delta E \Delta t \geq \hbar$$

  - A particle-antiparticle pair can pop out of "the vacuum" even if the particles are very massive - but only for a short time.
  - These are *virtual particles.* Many of them existed in a real sense when the Universe was hotter.

The Standard Model

Last 100 years: the combination of Quantum Field Theory (Gauge Theory in particular) along with the many new particles discovered has led to the Standard Model



Electromagnetism
acts on all charged particles

Strong force
acts on all quarks

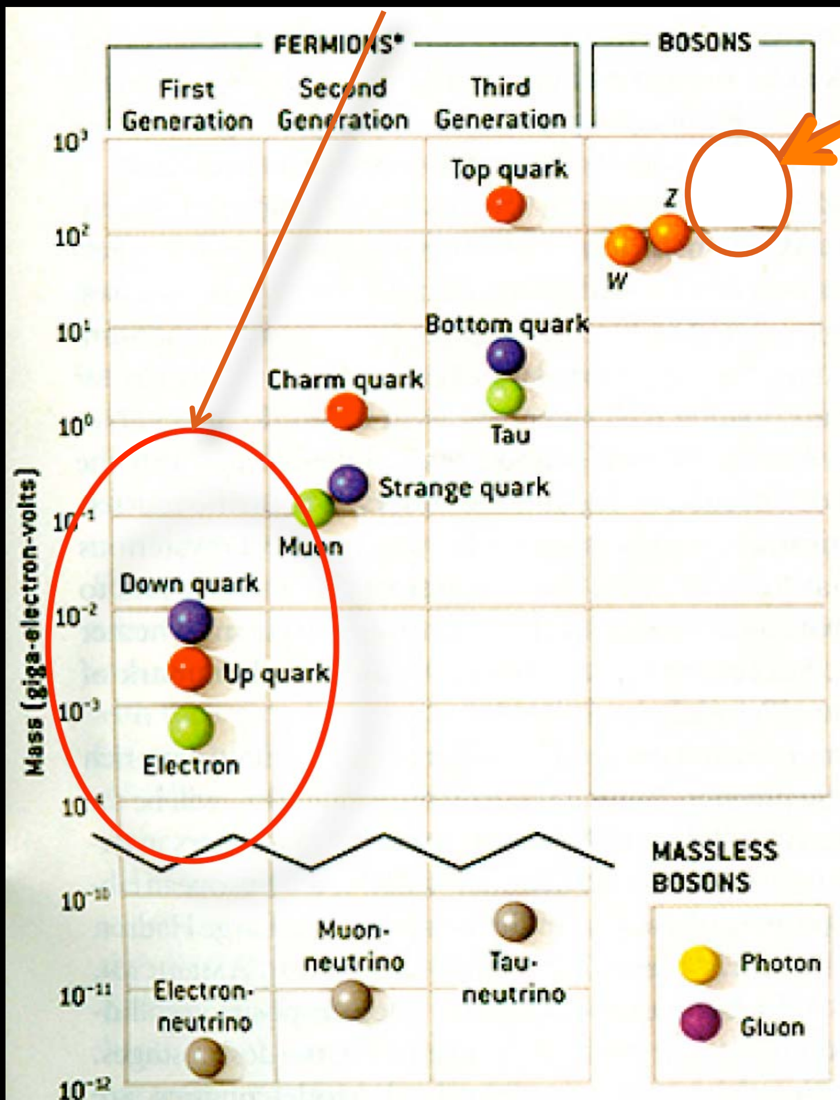
Weak force
acts on all particles

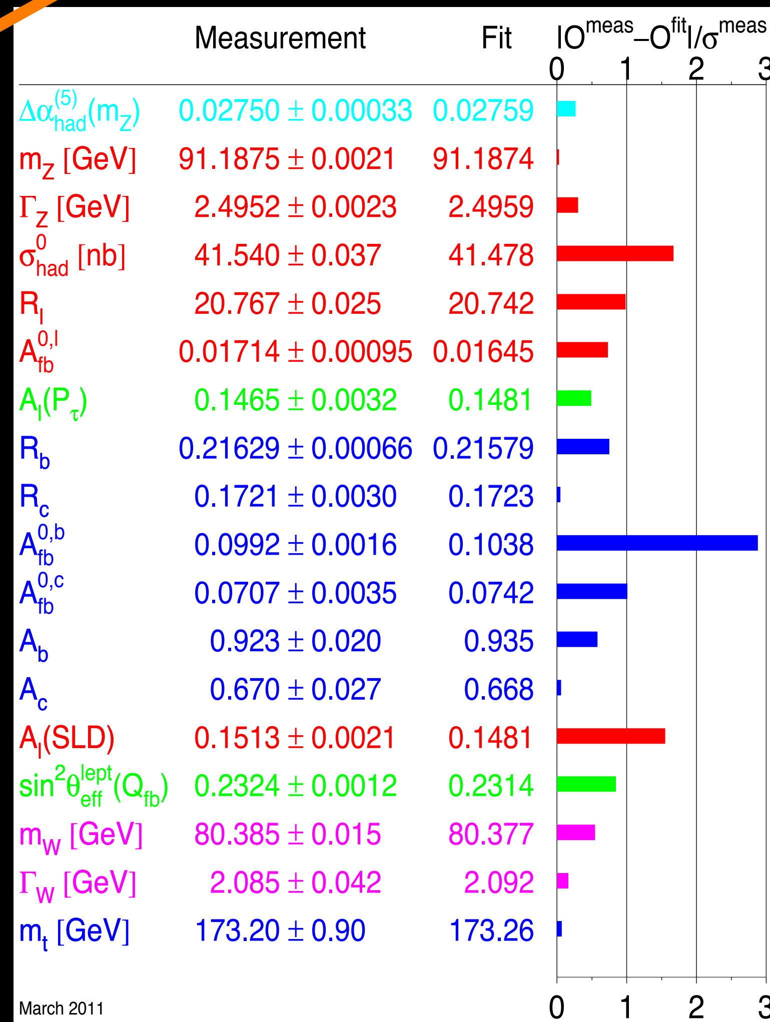
Great achievement of 20th century science

The Standard Model

These are what we are made of but the other particles are crucial to defining what we are

1 missing piece: Higgs





Confirmed at sub per cent level

Beyond the Standard Model

The main open questions in physics we hope to address with ATLAS & CMS data

What is the **origin of mass** of the fundamental particles in the SM?

Long favored answer is Higgs mechanism, but then we must find a SM higgs boson, or something like it

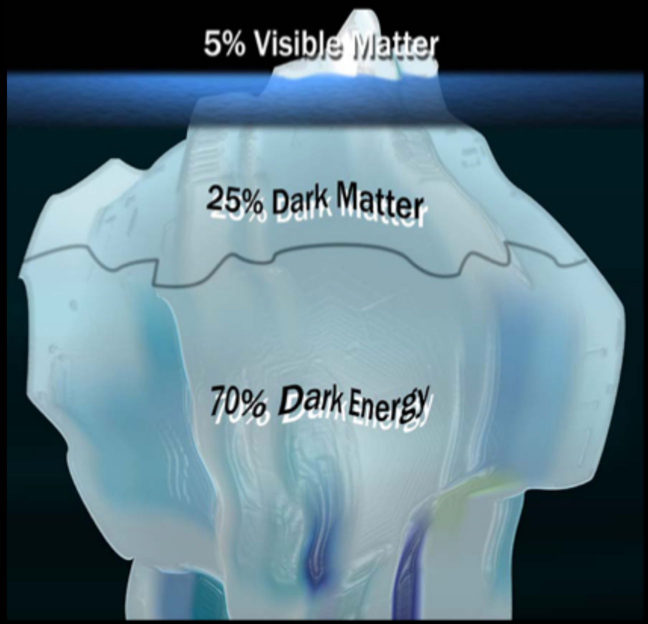
Why do the quarks and leptons come in three copies of increasing mass**? Why is the mass range so large?**

Are the fundamental particles of the SM really fundamental?

What about the forces? Only 4? **Can they be unified?**

What about gravity (absent in the SM)?

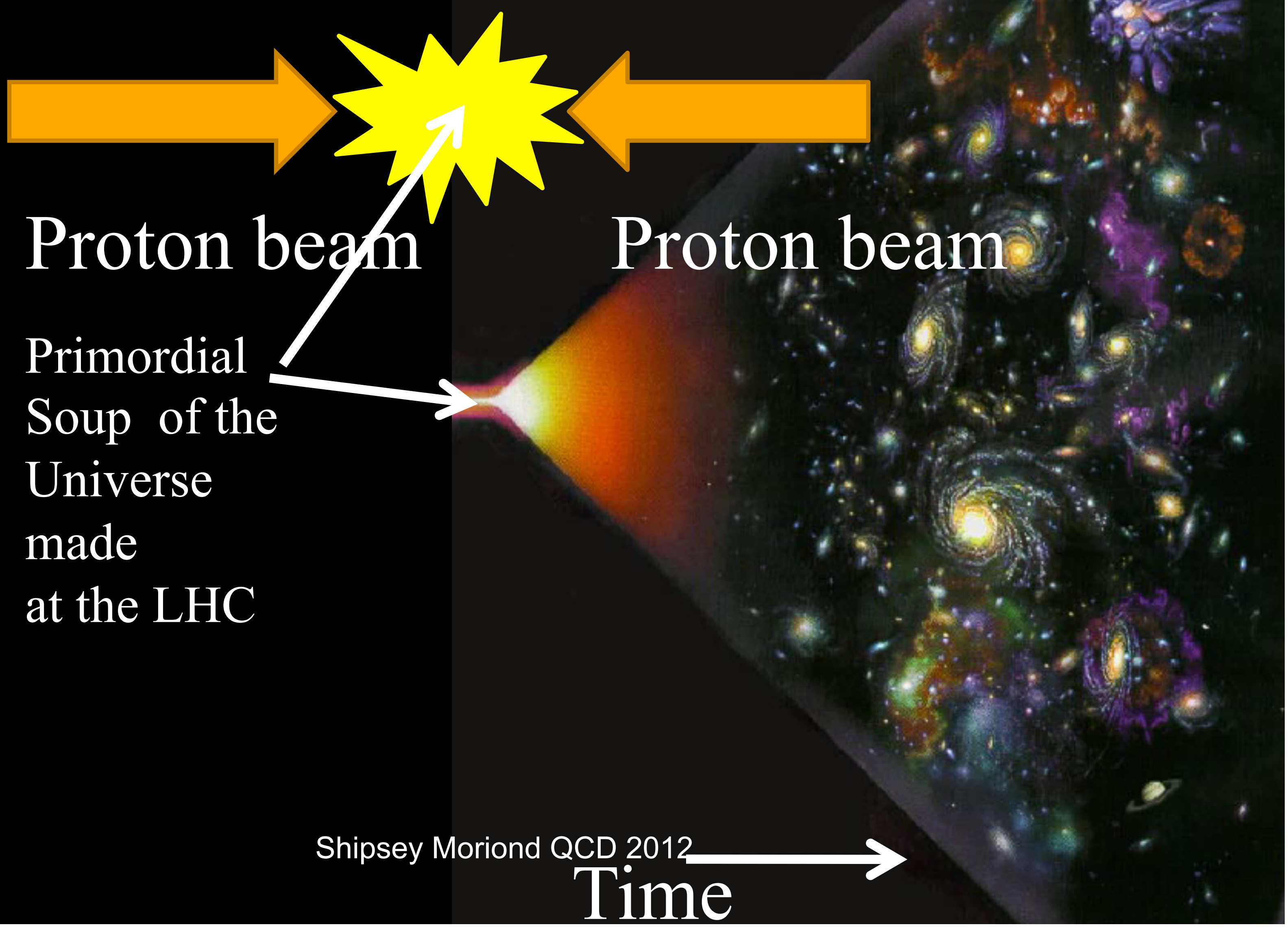
What about Dark Matter?

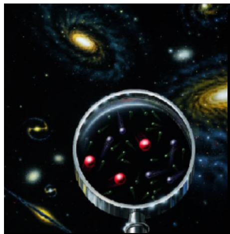


What we know: just the tip of the iceberg.

The sense of mystery has never been more acute or more evident in our field

Quarks to the Cosmos





Proton beam Proton beam

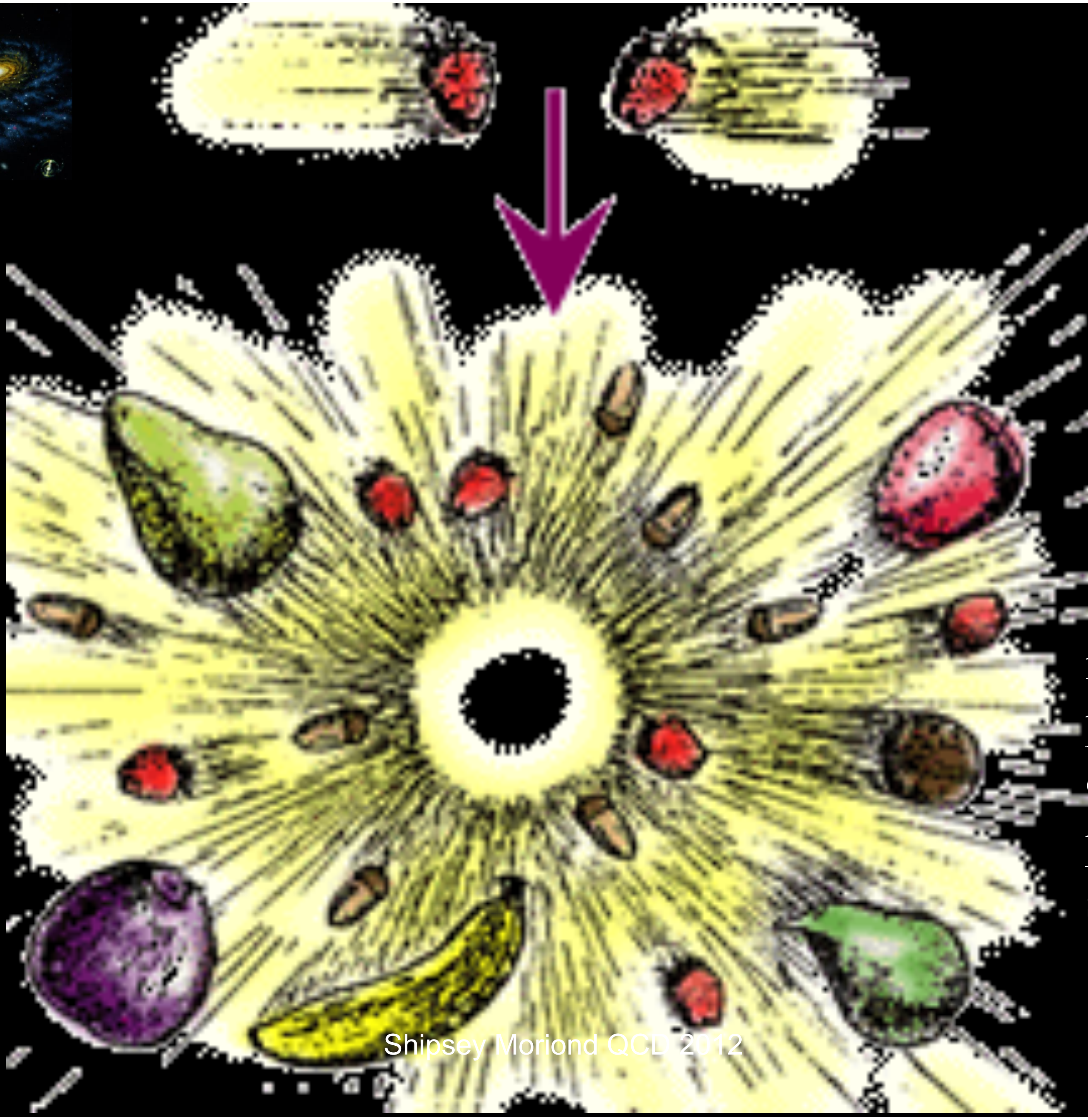
$$E = mc^2$$

new particles
of the primordial
soup

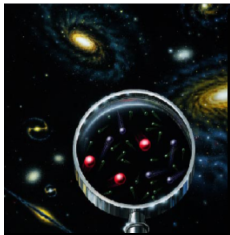
Energy of the beams

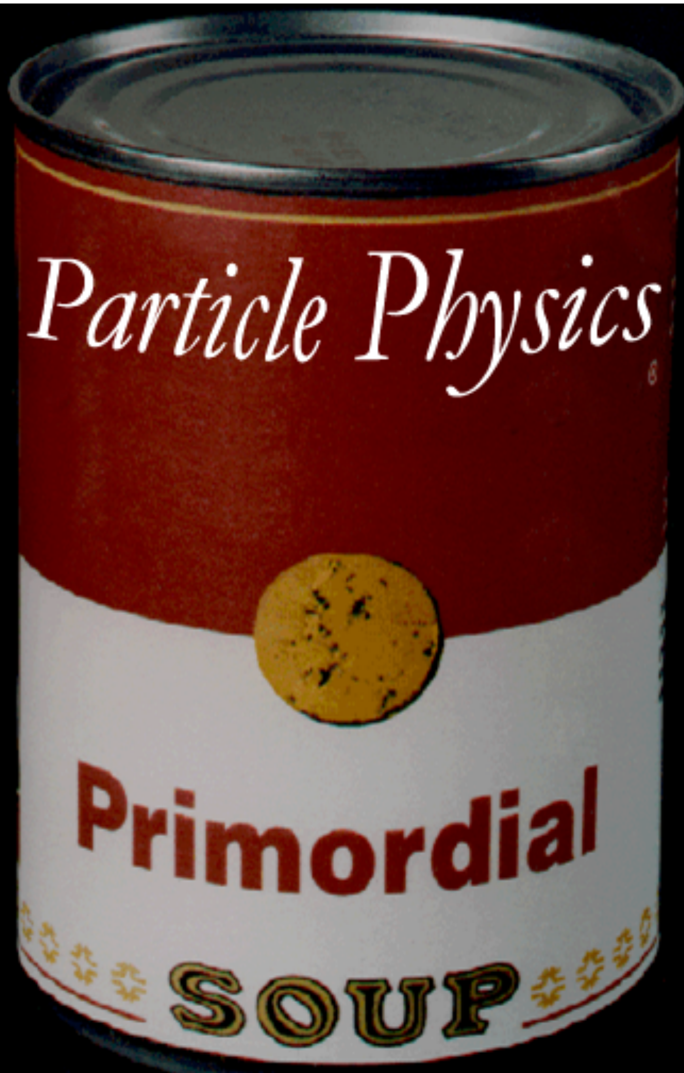
Larger E, larger m
& further back in
time we probe

The collisions are
remarkable…….

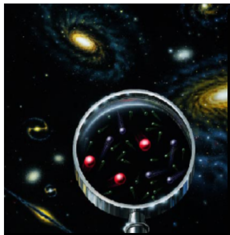


new
particles
of the
primordial
soup



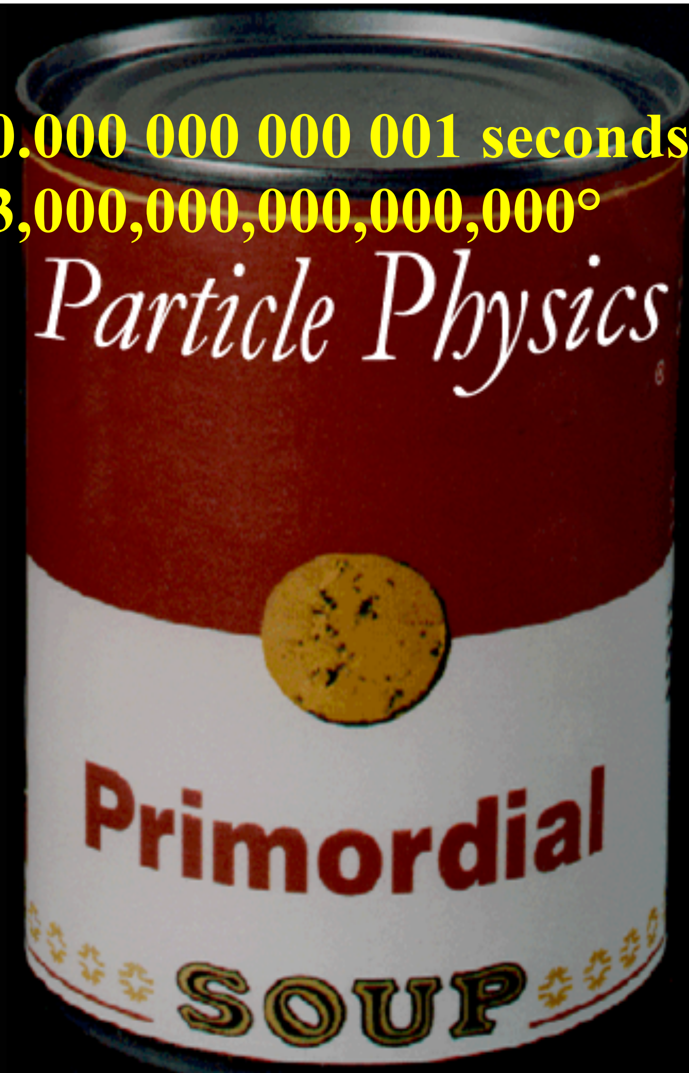


The energy concentration of the LHC collisions is large

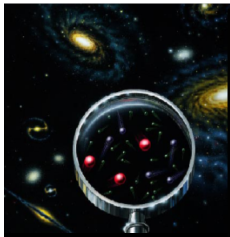


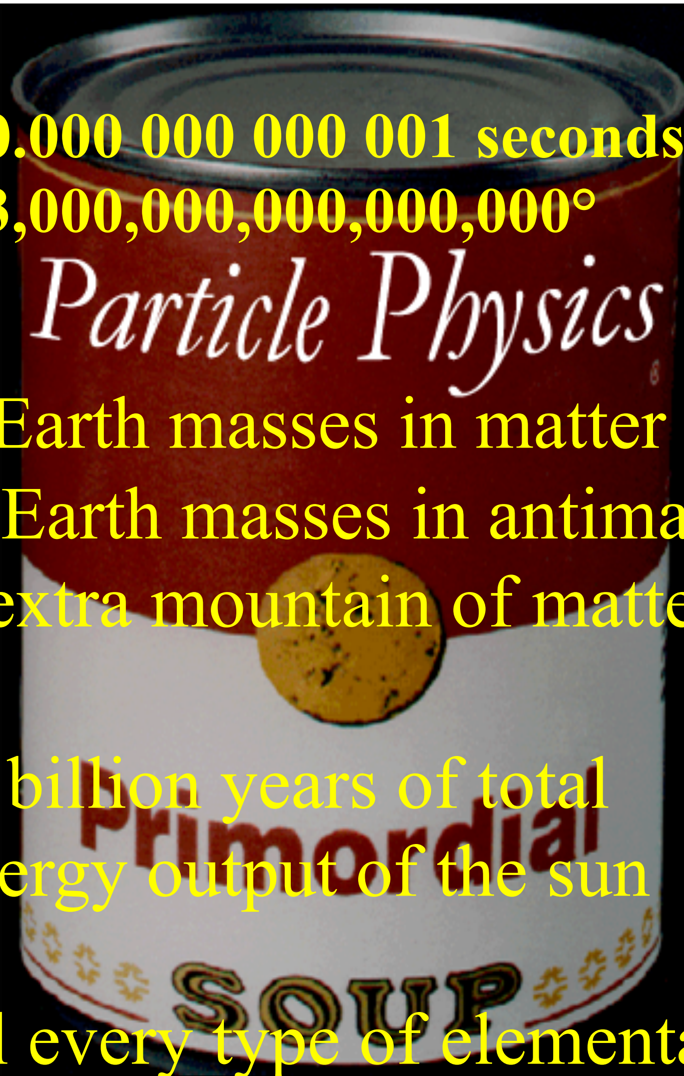
0.000 000 000 001 seconds AB

3,000,000,000,000,000°



The energy concentration of the LHC collisions is large





0.000 000 000 001 seconds AB
3,000,000,000,000,000°

CONDENSED

in 50 Earth masses in matter
one 50 Earth masses in antimatter
can + extra mountain of matter

HOT

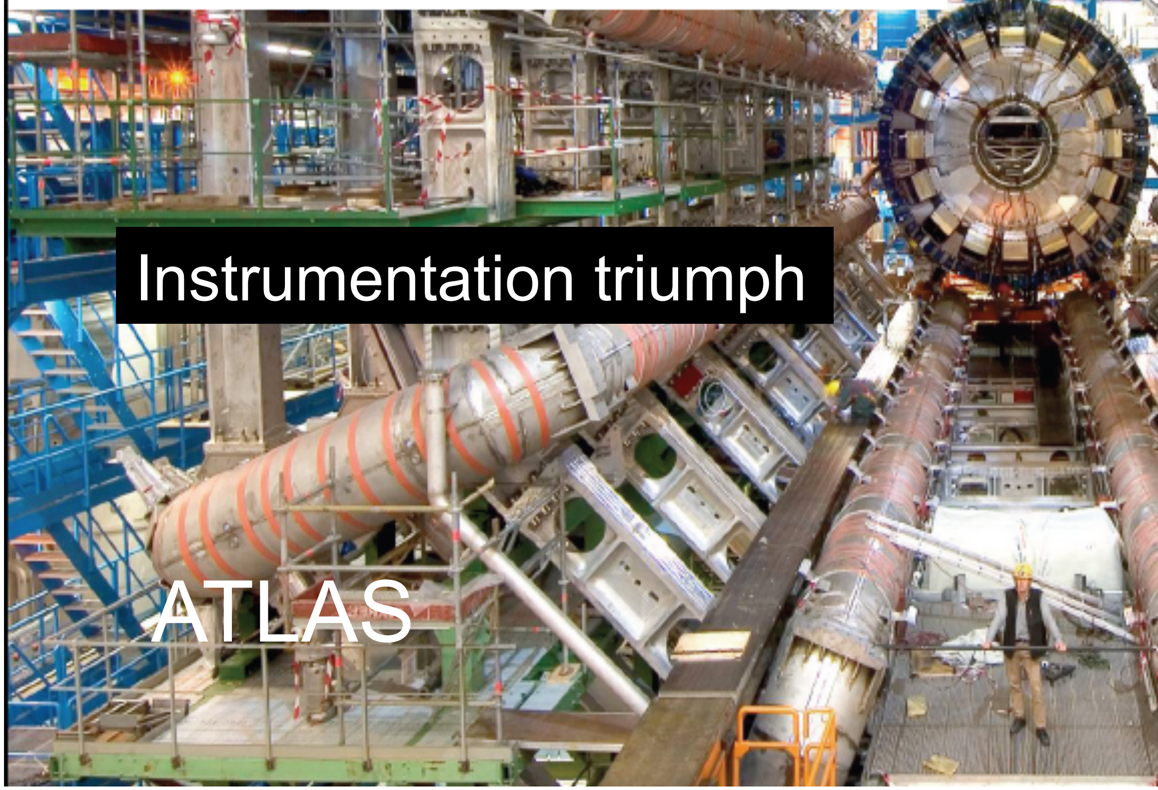
per 10 billion years of total
serving energy output of the sun

INGREDIENTS

In every spoonful every type of elementary particle
Both the known: quarks and electrons and photons
and we expect a sprinkling of the unknown:
Higgs, dark matter, and new spatial dimensions

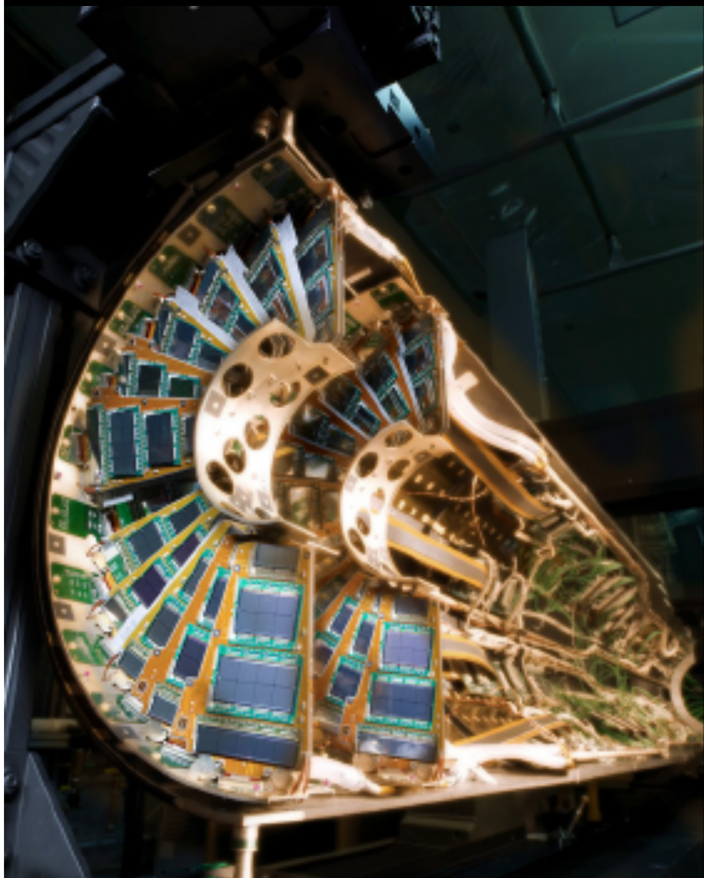
The energy concentration of the LHC collisions is large

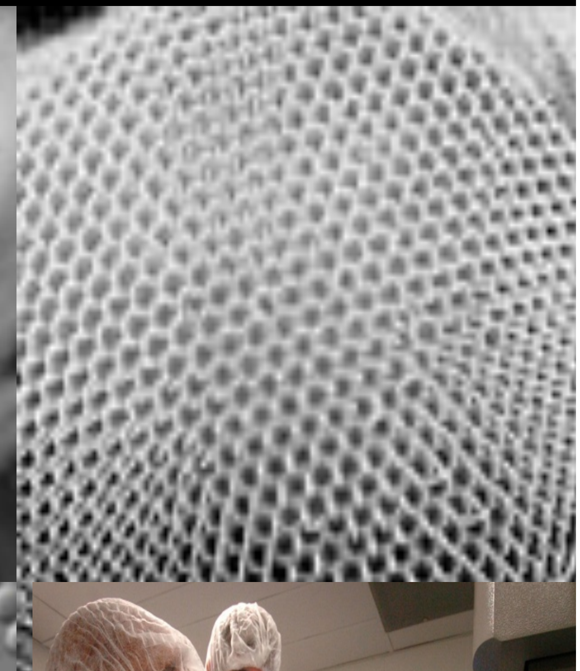
Object	Weight (tons)
Boeing 747 [fully loaded]	200
Endeavor space shuttle	368
ATLAS	7,000
Eiffel Tower	7,300
USS John McCain	8,300
CMS	12,500

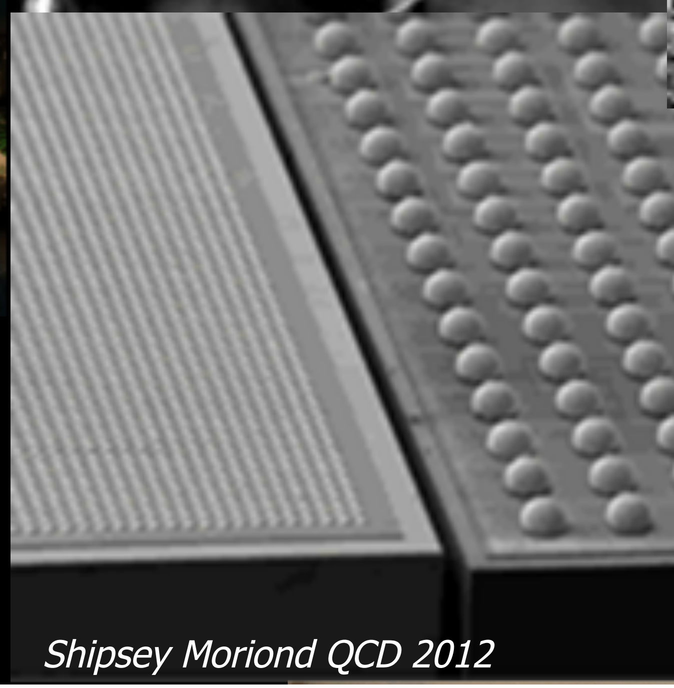


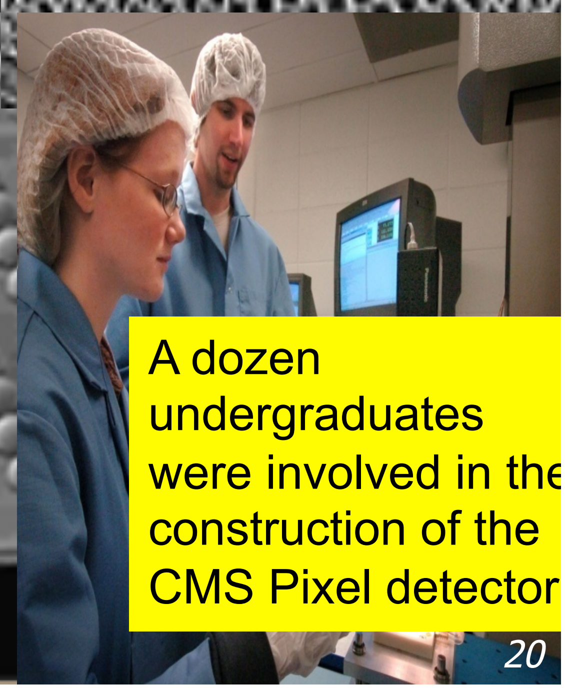
DIGITAL CAMERAS THE SIZE OF CATHEDRALS

AS INTRICATE AS A FLY'S EYE





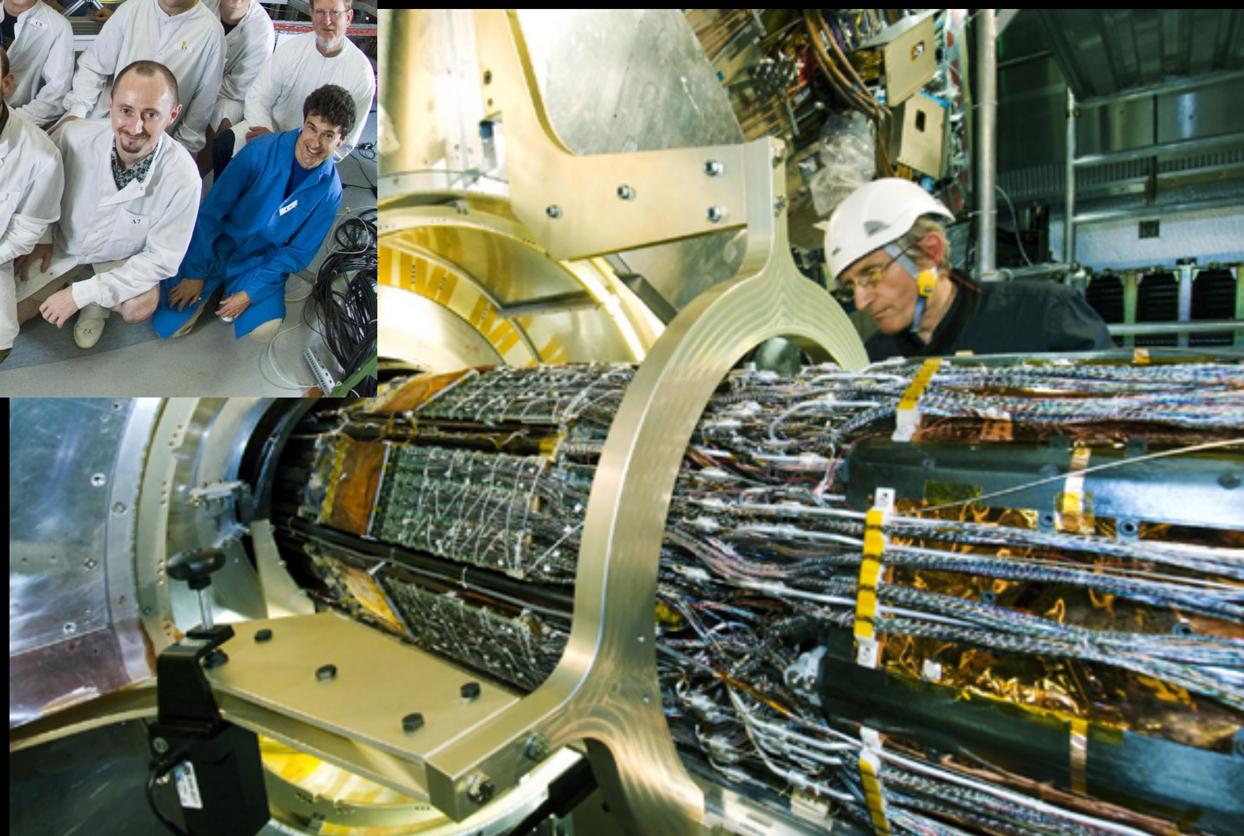




At the heart of CMS & ATLAS are silicon digital cameras

A dozen undergraduates were involved in the construction of the CMS Pixel detector

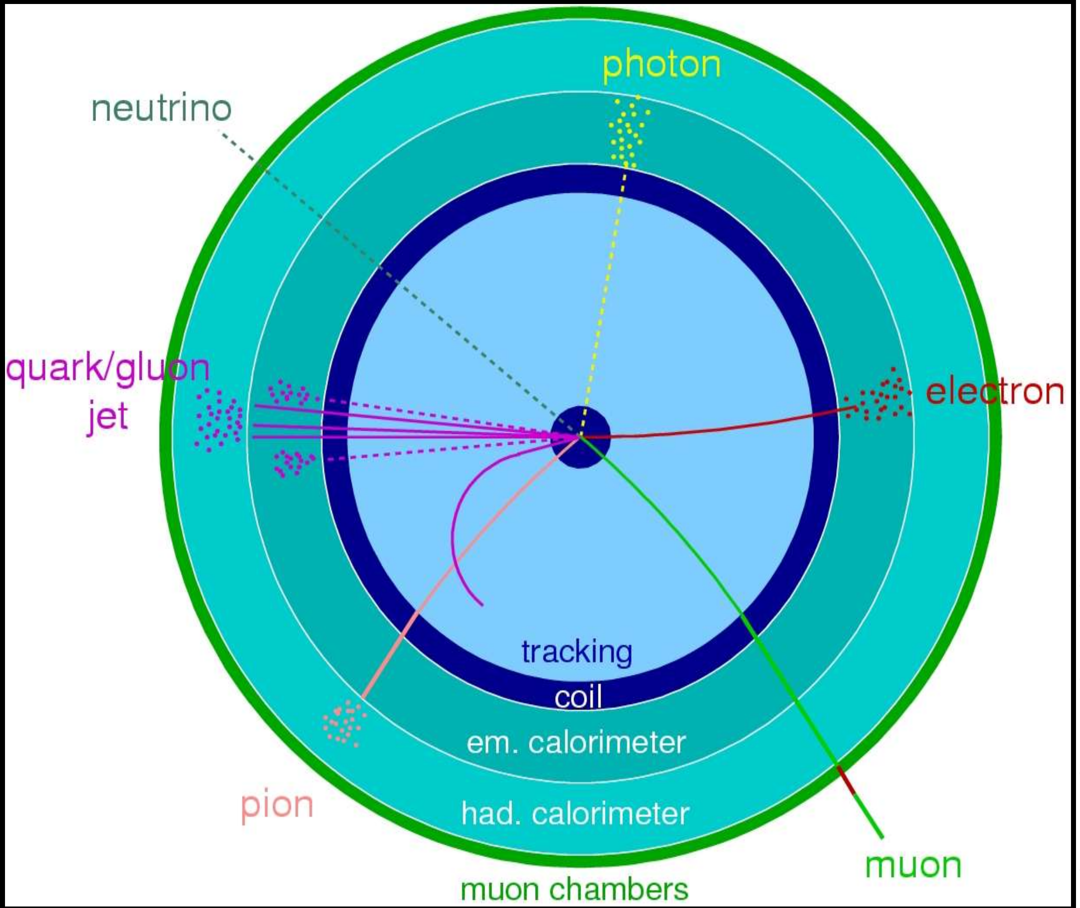
& PRECISION OF A SWISS WATCH



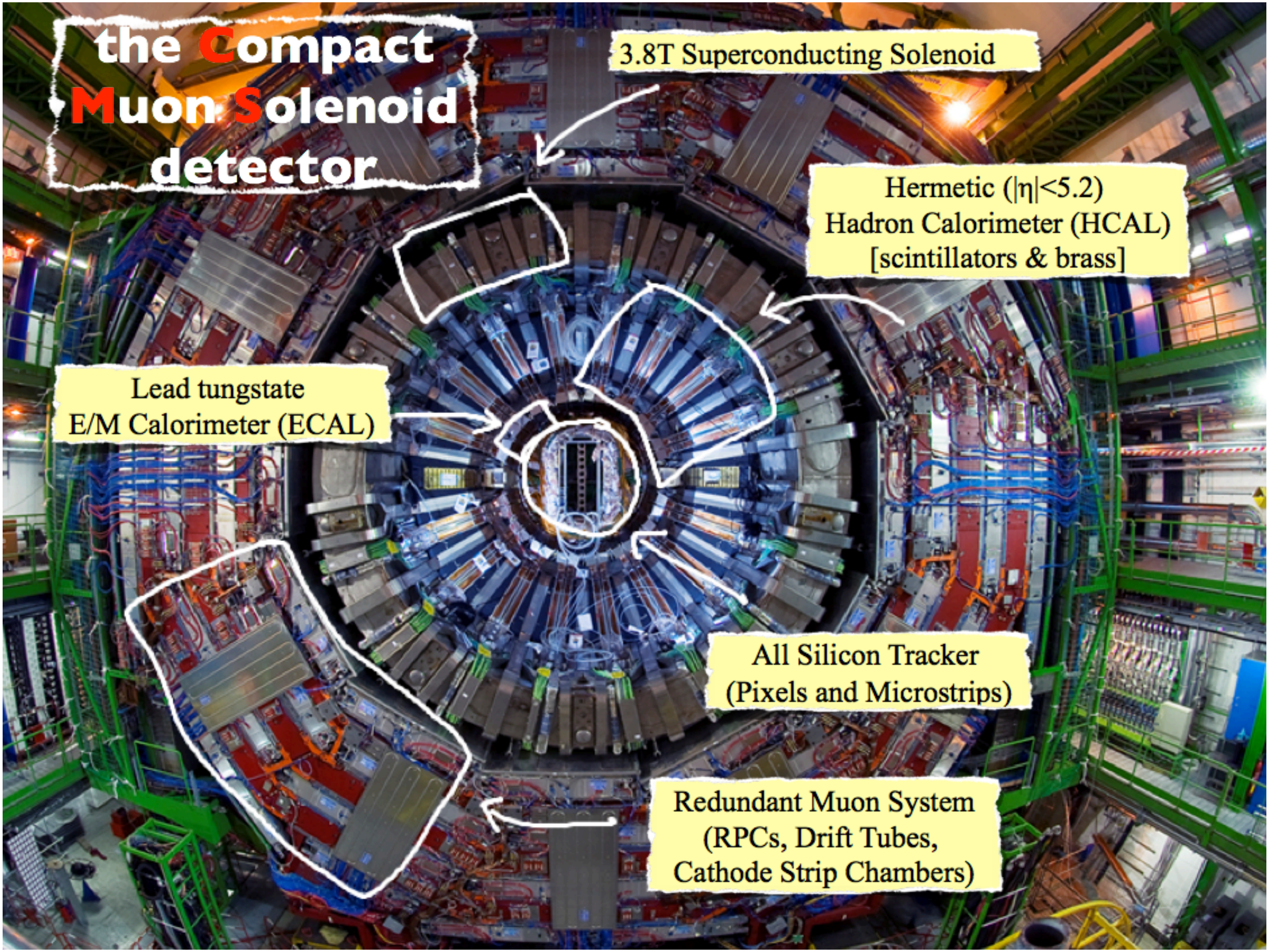
ATLAS silicon
camera sector

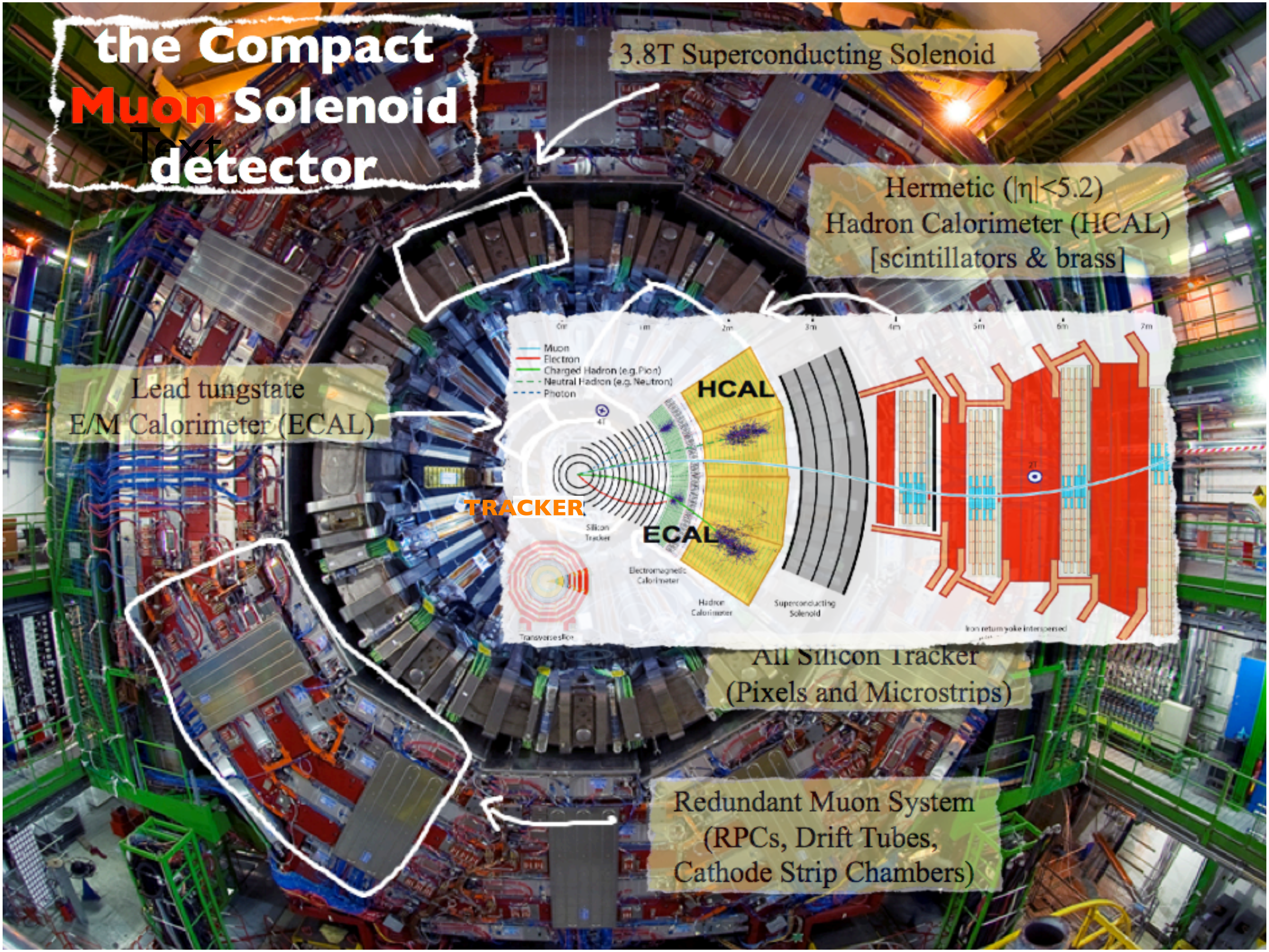
General Design of CMS and ATLAS

Collider detectors are like a set of nested Russian dolls, each of which tells us something useful.



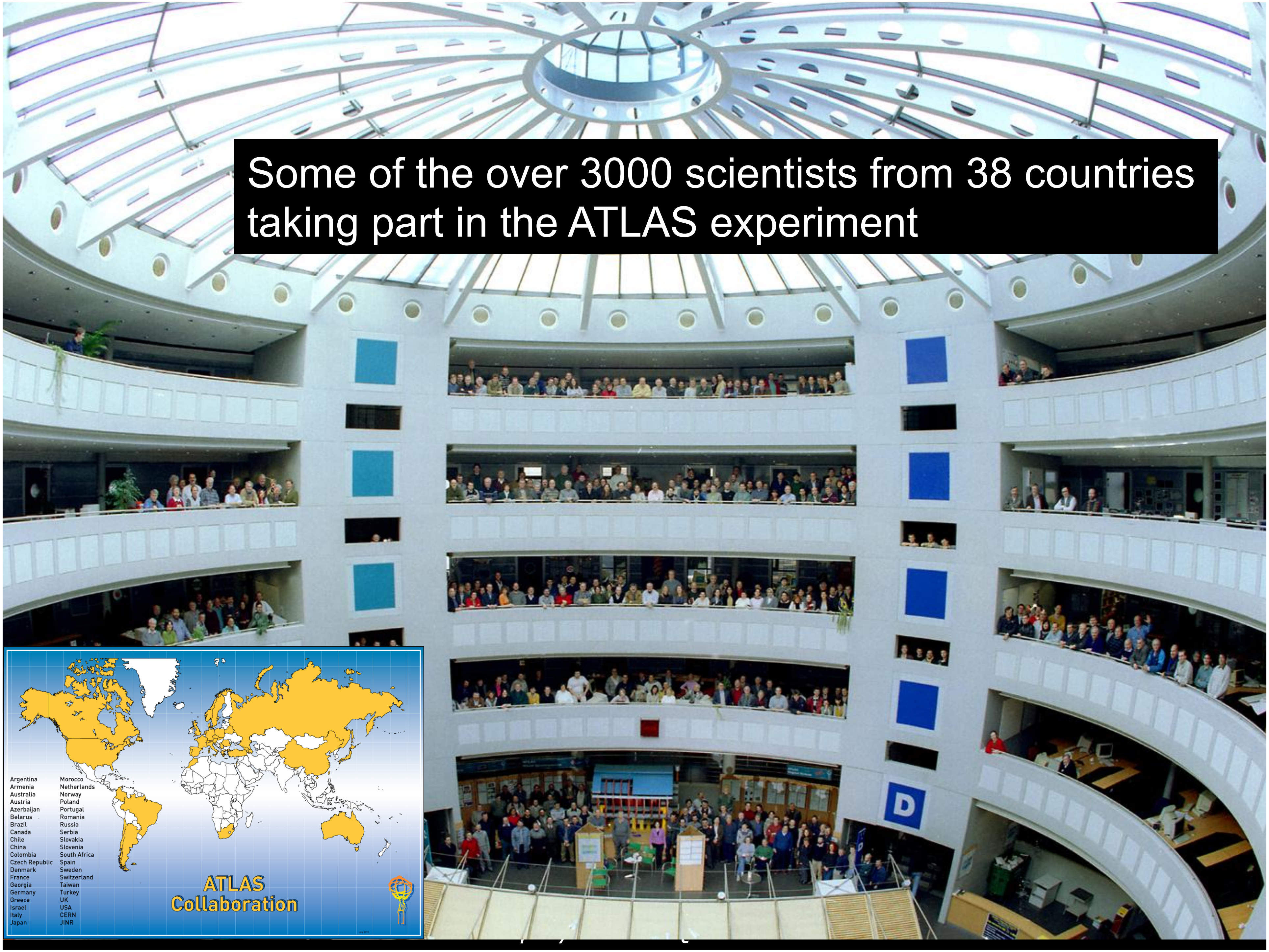
- charged particles leave tracks
- curvature (B-field) tells us p_T
- e & γ shower in the EM-CAL
- hadrons shower in the H-CAL
- μ don't shower and reach μ-det
- ν (and LSP's) are undetected


the Compact Muon Solenoid detector
3.8T Superconducting Solenoid
Hermetic (|η|<5.2) Hadron Calorimeter (HCAL) [scintillators & brass]
Lead tungstate E/M Calorimeter (ECAL)
All Silicon Tracker (Pixels and Microstrips)
Redundant Muon System (RPCs, Drift Tubes, Cathode Strip Chambers)

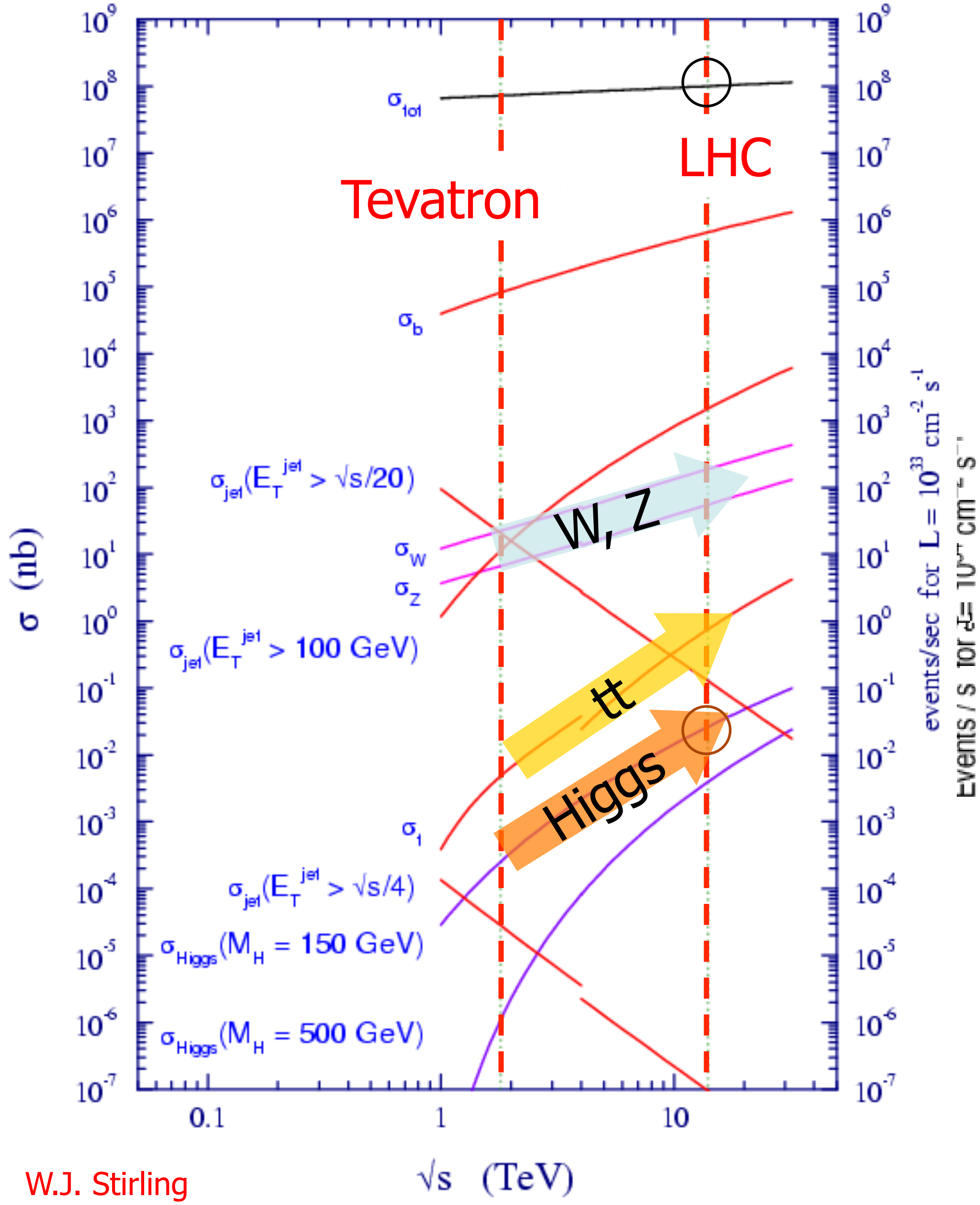


the Compact
Muon Solenoid
Text
detector
3.8T Superconducting Solenoid
Hermetic (|η|<5.2)
Hadron Calorimeter (HCAL)
[scintillators & brass]
Lead tungstate
E/M Calorimeter (ECAL)
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
HCAL
ECAL
TRACKER
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Transverse slice
Iron return yoke interspersed
All Silicon Tracker
(Pixels and Microstrips)
Redundant Muon System
(RPCs, Drift Tubes,
Cathode Strip Chambers)

Some of the over 3000 scientists from 38 countries taking part in the ATLAS experiment



Evolution of the Cross-Sections



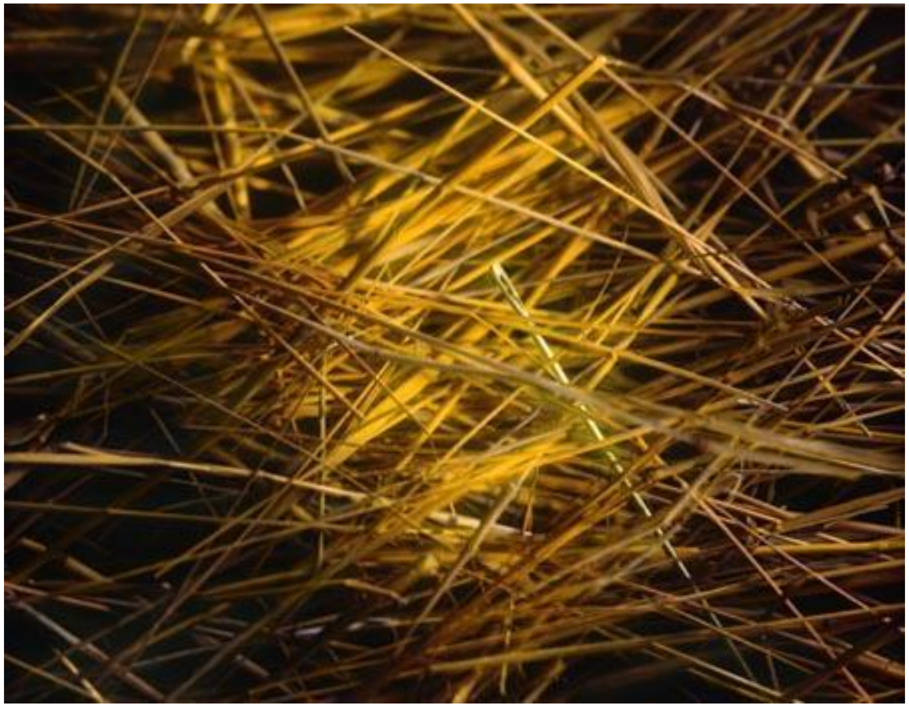
W.J. Stirling

$$\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

Process	σ (nb)	Production rates (Hz)
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W\to\ell\nu$	15	150
$Z\to\ell\ell$	2	20
$t\bar{t}$	1	10
$H(100\ \mathrm{GeV})$	0.05	0.5
$Z'\ (1\ \mathrm{TeV})$	0.05	0.5
$\tilde{g}\tilde{g}\ (1\ \mathrm{TeV})$	0.05	0.5
$H(500\ \mathrm{GeV})$	10^{-3}	10^{-2}

Cross sections are larger at the LHC than at the Tevatron

New Physics: precious and extremely rare



- 10^{-7} selection problem
- Selection process determines 99.99999% of your analysis

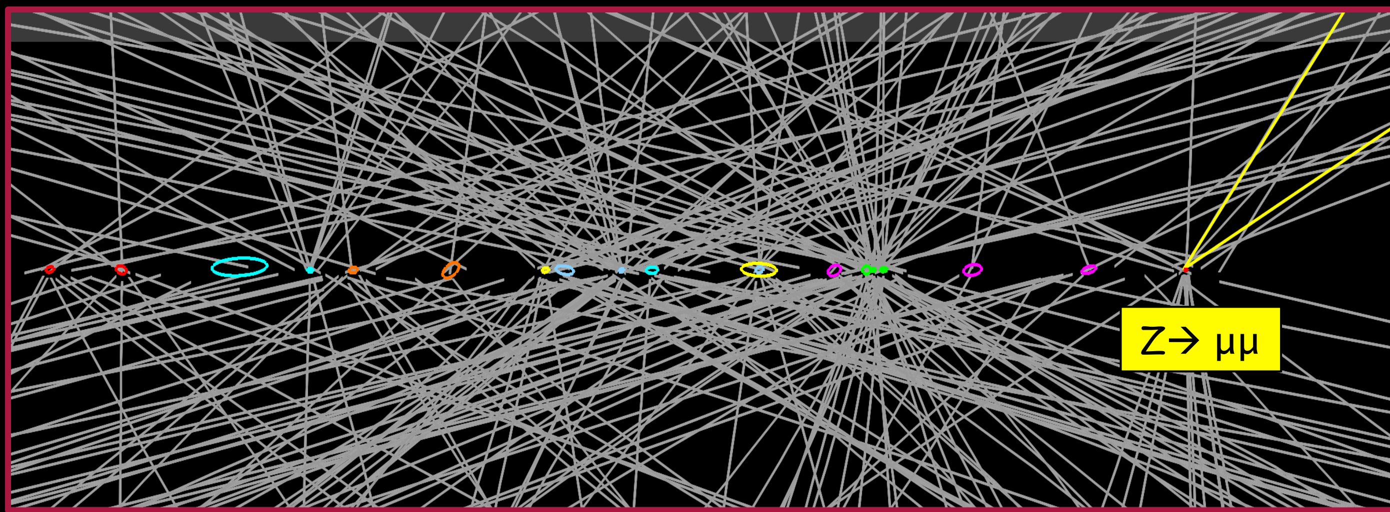
$$\mathcal{L} = 10^{34}\ \mathrm{cm^{-2}s^{-1}}$$

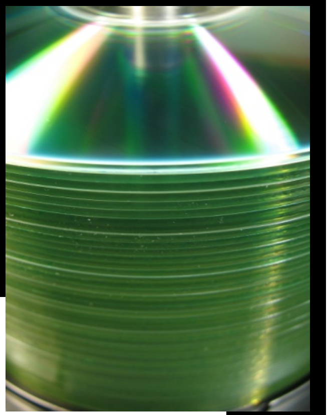
Process	σ (nb)	Production rates (Hz)
Inelastic	10^8	10^9
$b\bar{b}$	5×10^5	5×10^6
$W\to\ell\nu$	15	150
$Z\to\ell\ell$	2	20
$t\bar{t}$	1	10
H(100 GeV)	0.05	0.5
Z' (1 TeV)	0.05	0.5
$\tilde{g}\tilde{g}$ (1 TeV)	0.05	0.5
H(500 GeV)	10^{-3}	10^{-2}

Permanently stored: ~400 Hz

Collisions
produce prodigious quantities of data

ATLAS





…..15 million CDs, 15 petabytes per year,
a stack of CDs 10 miles high (X1.5 mount Everest)

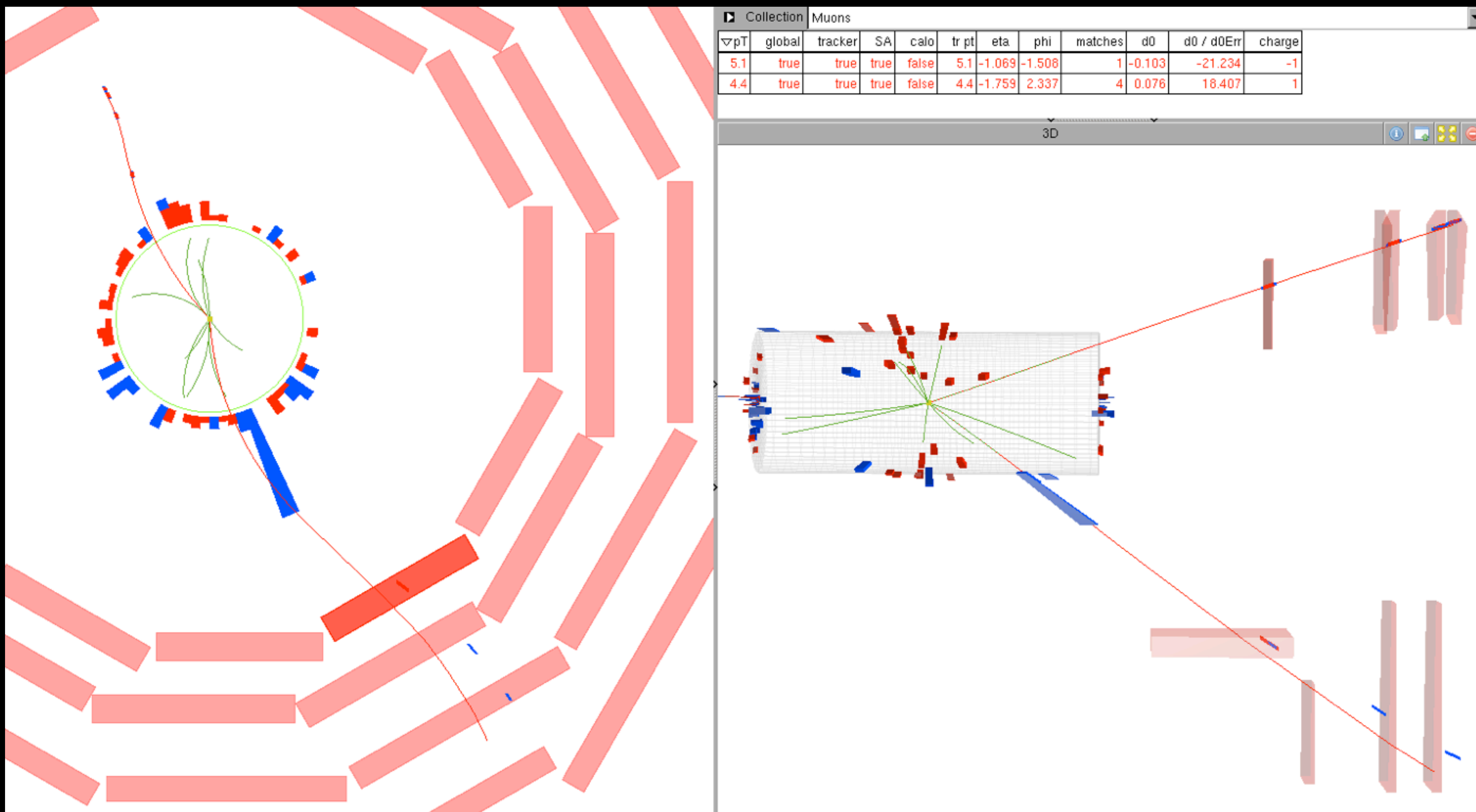
Data Analysis: Worldwide LHC Computing GRID

To analyze the LHC data is an enormous task – beyond the means of CERN alone.
Need to send these data to the computers and storage systems of the collaborating institutes around the world – in real time without stopping!
This is the World Wide LHC Computing GRID. Why not offer YOUR computer at http://lhcathome.cern.ch/ ?!

During one second of ATLAS /CMS operations, a data volume equivalent to 10,000 copies of Encyclopedia Britannica is recorded

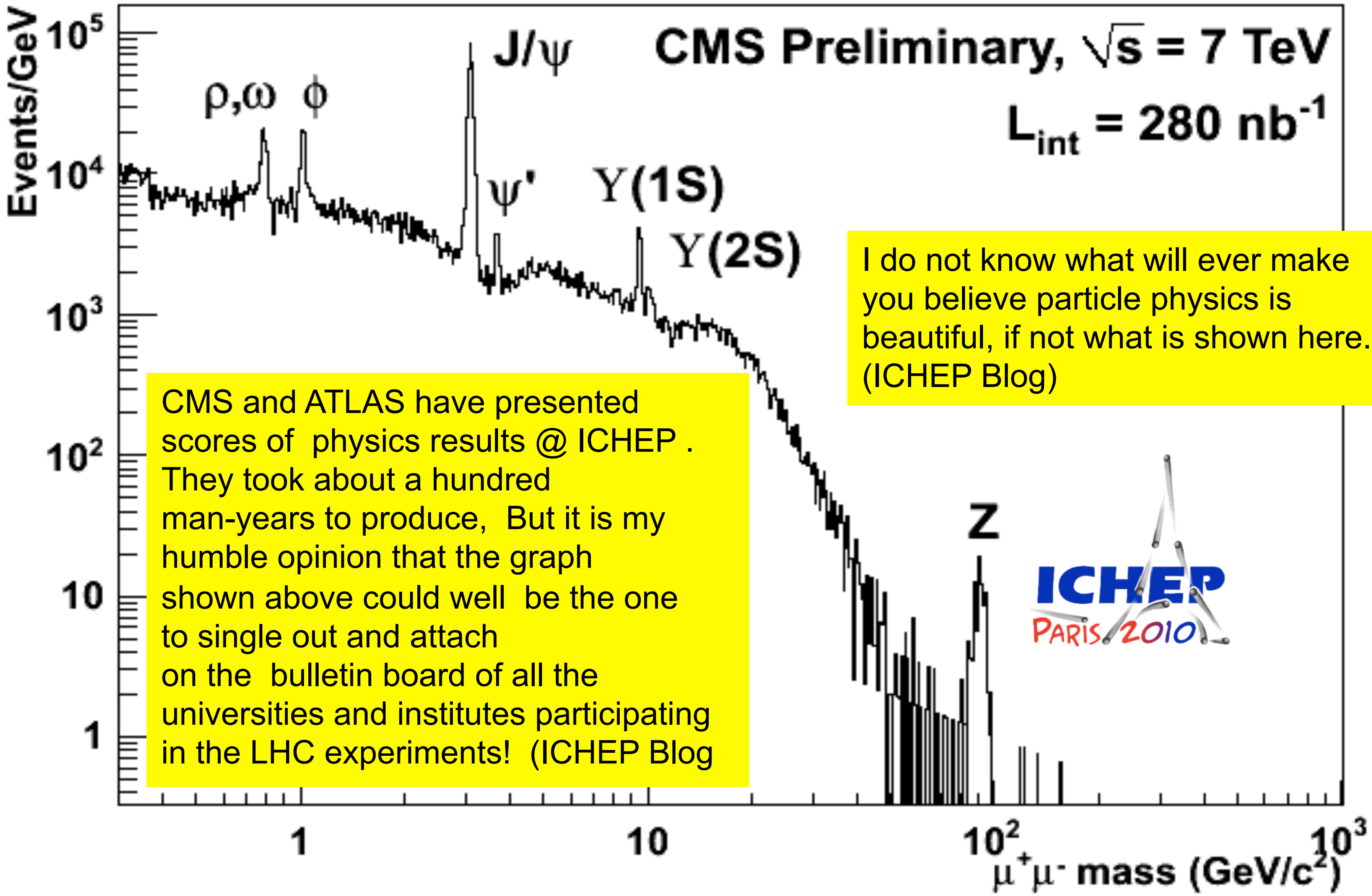
a dimuon candidate: $X \rightarrow \mu^+\mu^-$

event display



▽pT	global	tracker	SA	calo	tr pt	eta	phi	matches	d0	d0 / d0Err	charge
5.1	true	true	true	false	5.1	-1.069	-1.508	1	-0.103	-21.234	-1
4.4	true	true	true	false	4.4	-1.759	2.337	4	0.076	18.407	1

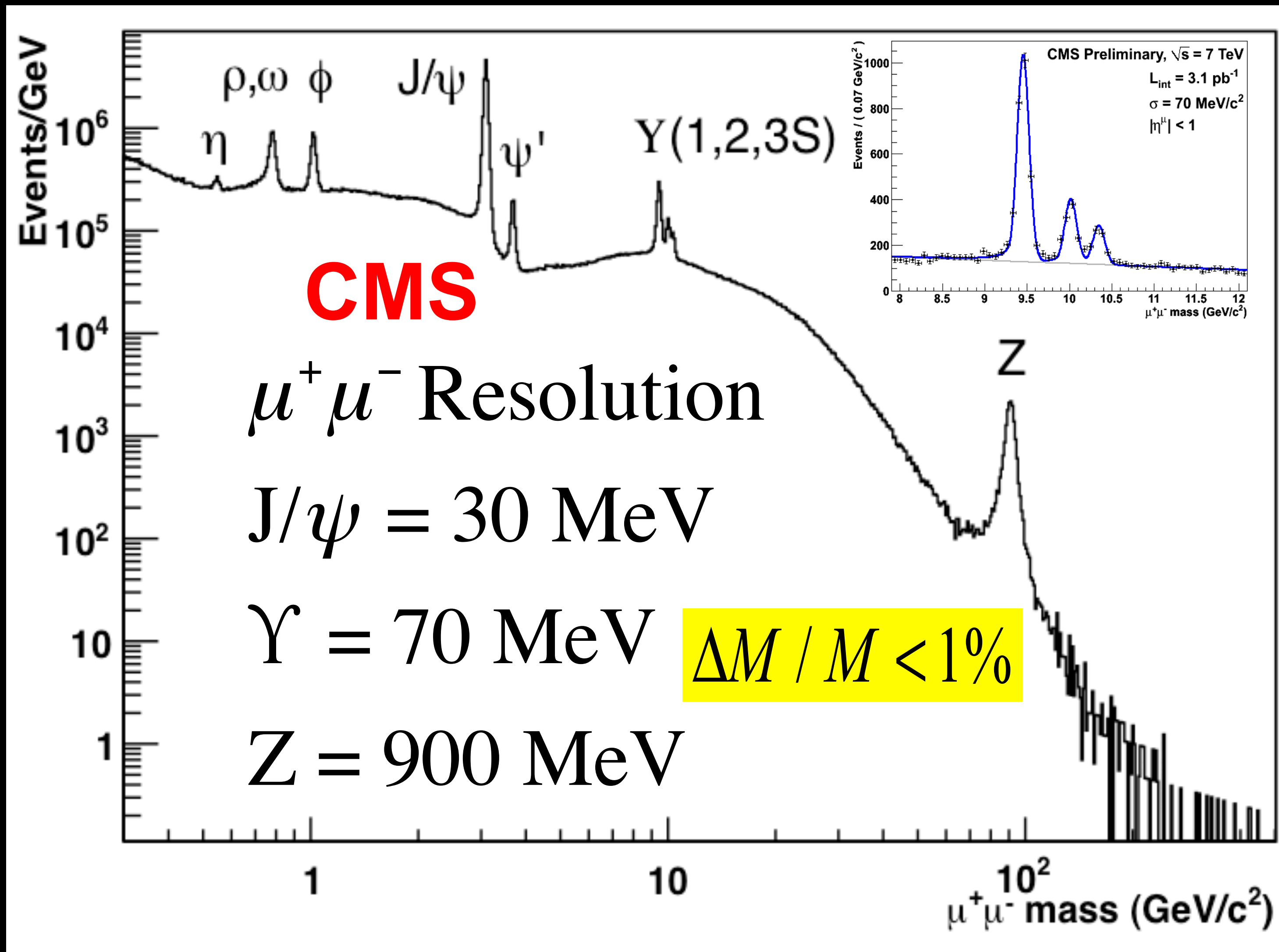
A spectroscopists delight
rediscovering the Benchmarks of the Standard Model



I do not know what will ever make you believe particle physics is beautiful, if not what is shown here. (ICHEP Blog)

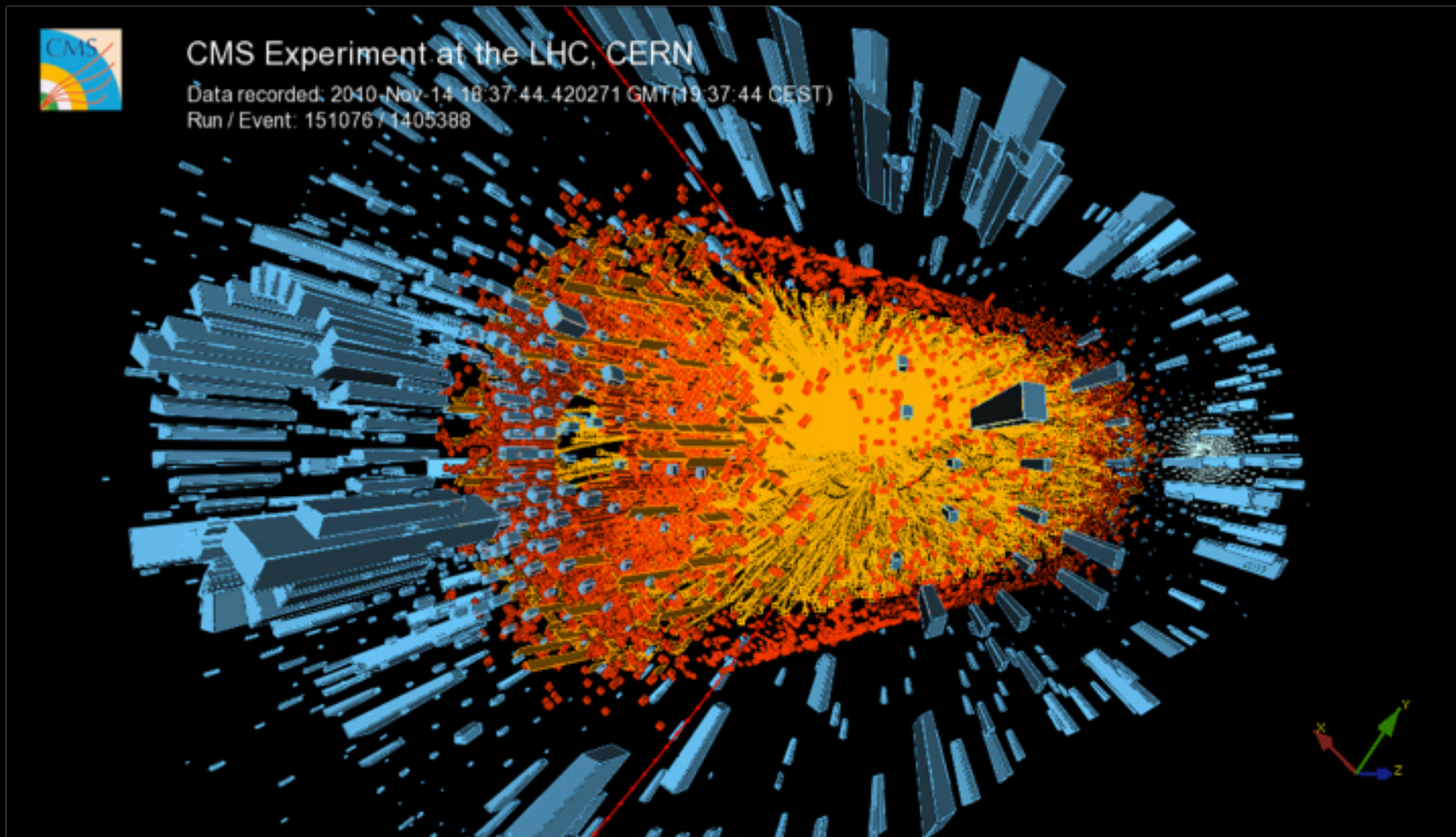
CMS and ATLAS have presented scores of physics results @ ICHEP . They took about a hundred man-years to produce, But it is my humble opinion that the graph shown above could well be the one to single out and attach on the bulletin board of all the universities and institutes participating in the LHC experiments! (ICHEP Blog

A spectroscopists delight
rediscovering the Benchmarks of the Standard Model

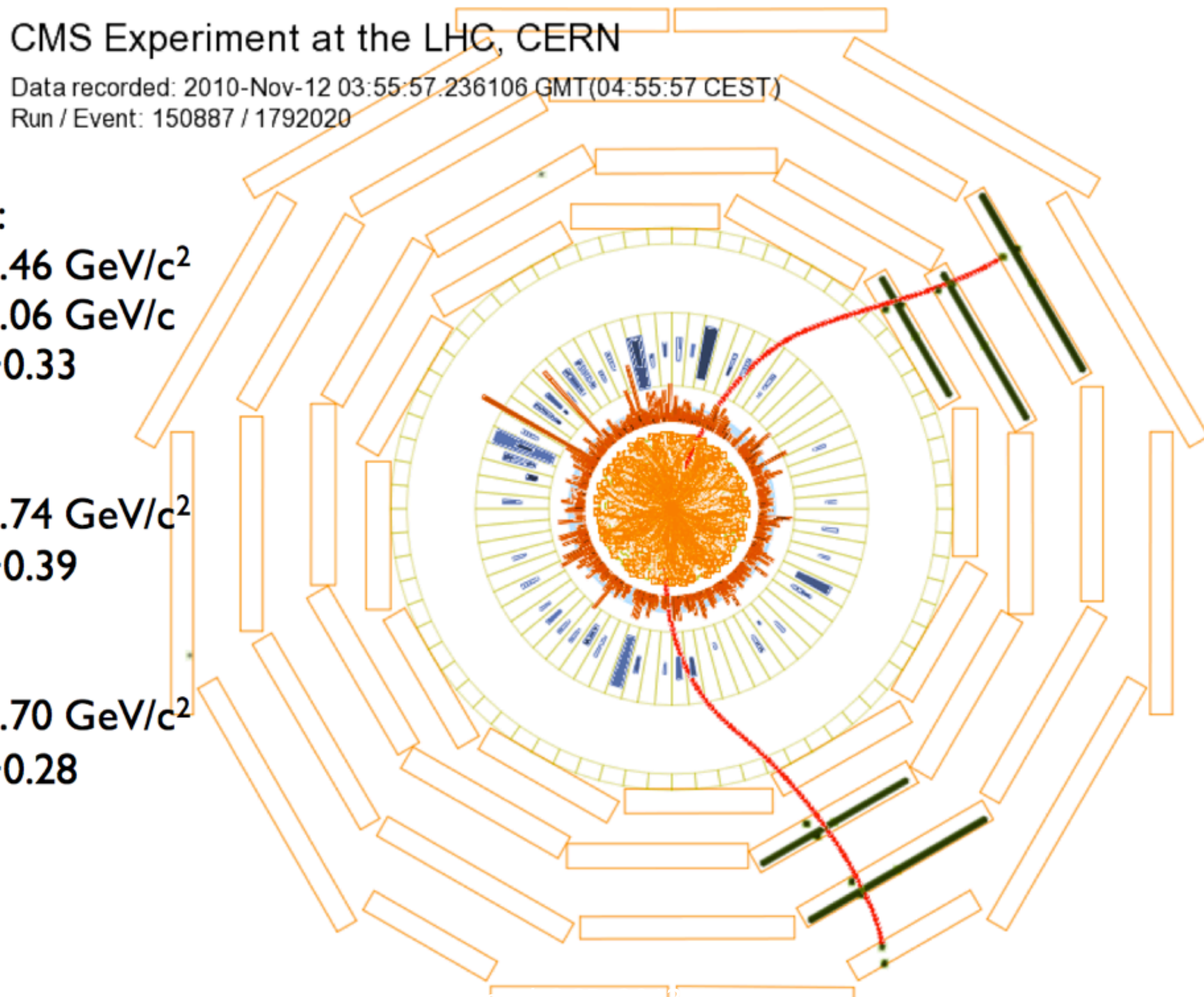


The granularity of the cameras combined with their speed enable them to cope with very large numbers of tracks in a single event

PbPb collisions (@ 2.76 TeV/nucleon (574 TeV per nucleus)



Υ candidate in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV



$\mu^+\mu^-$ pair:

mass: 9.46 GeV/c^2

p_T: 0.06 GeV/c

rapidity: −0.33

μ^+:

p_T = 4.74 GeV/c^2

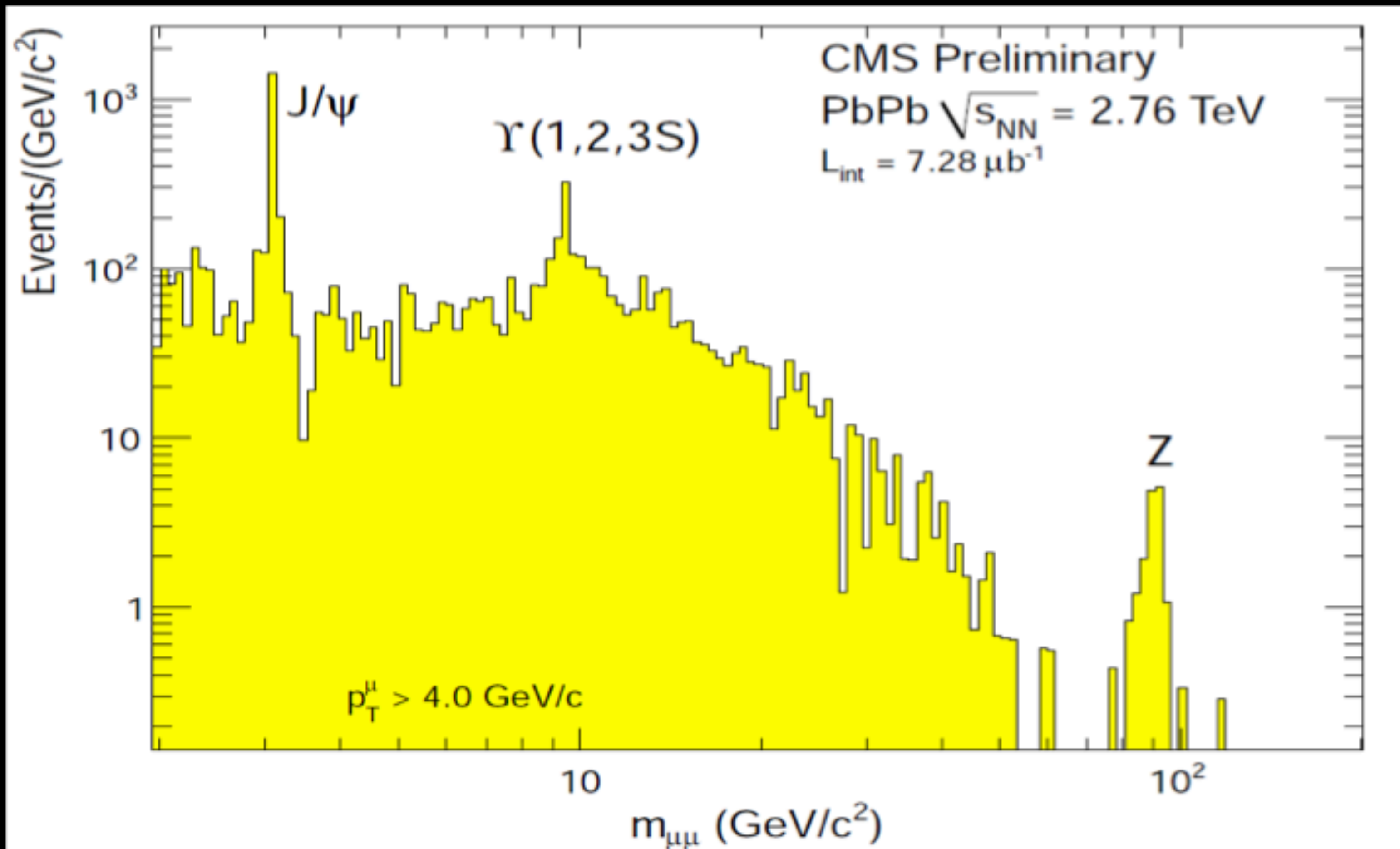
η = −0.39

μ^-:

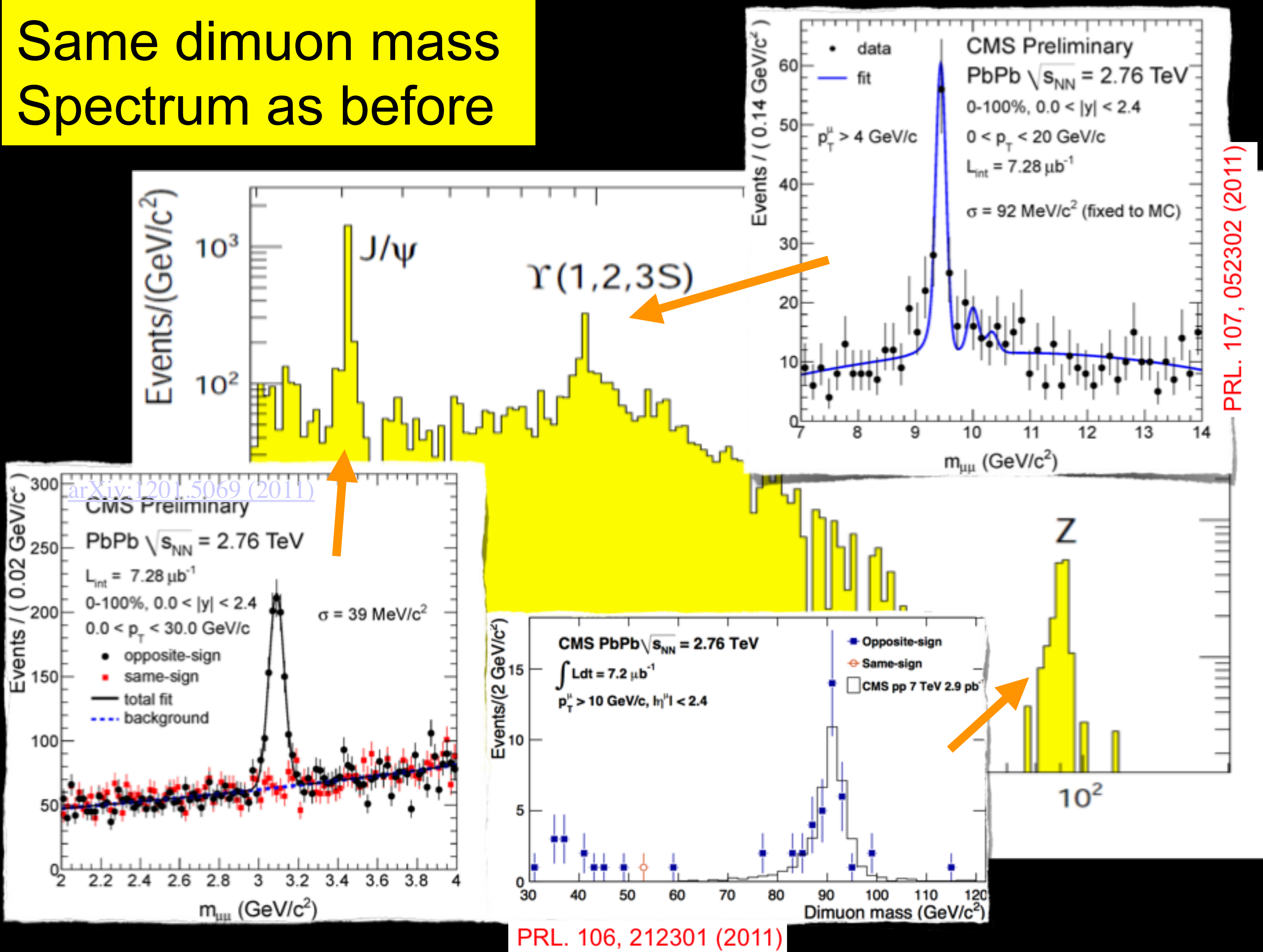
p_T = 4.70 GeV/c^2

η = −0.28

Same dimuon mass Spectrum as before

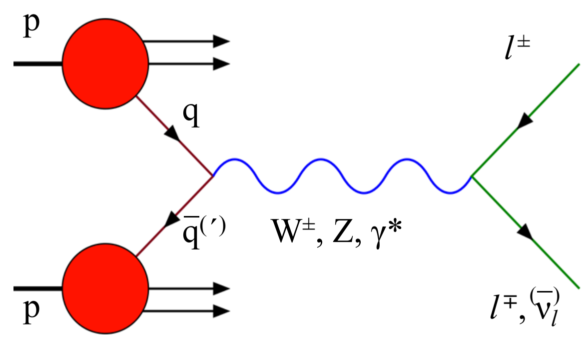


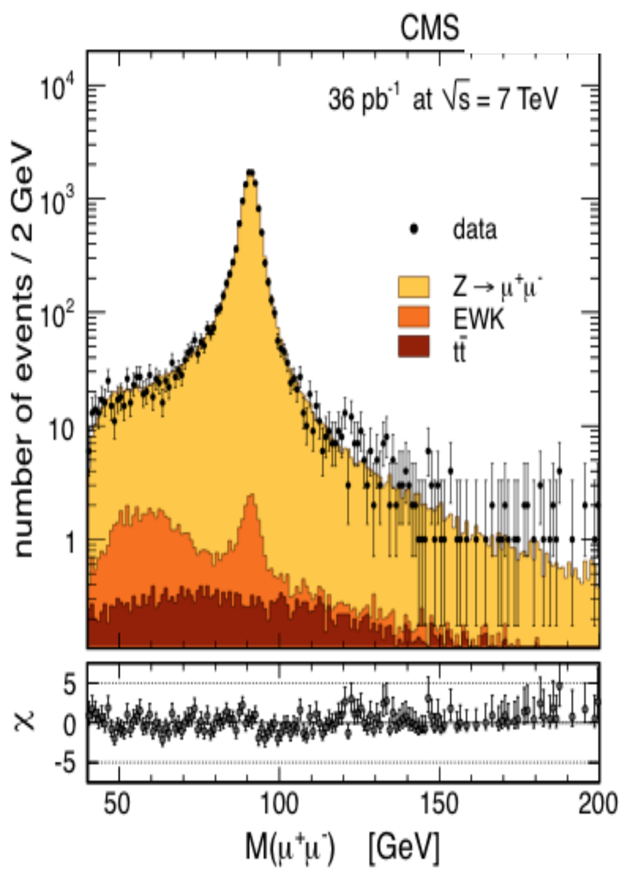
Same dimuon mass Spectrum as before

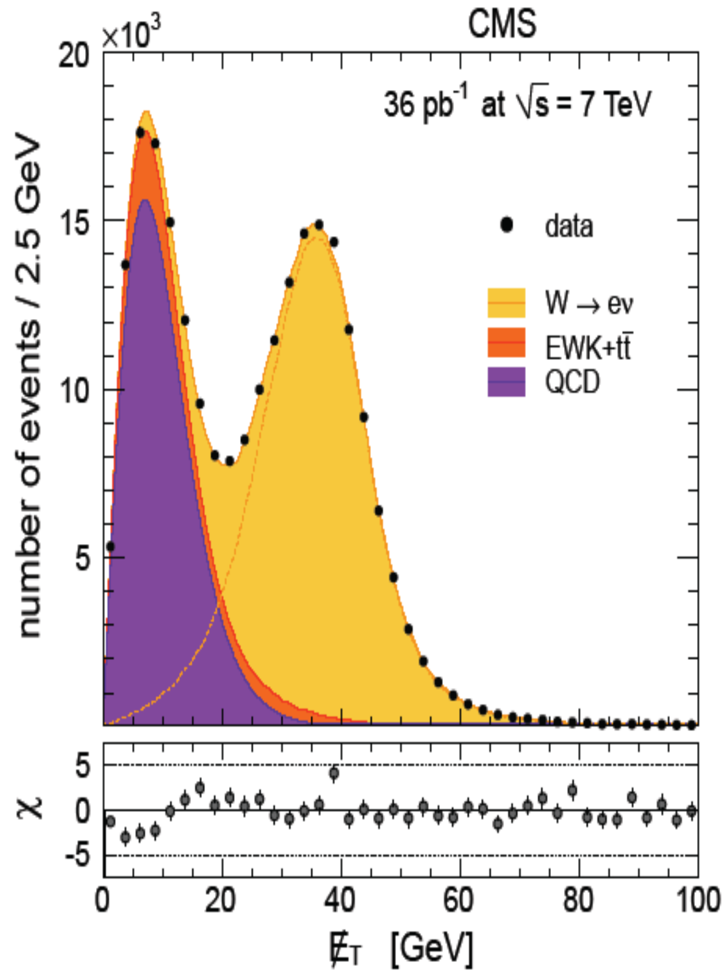


W & Z Production

X80 & ~x90 the mass of a proton
Cross sections about 10 nb)

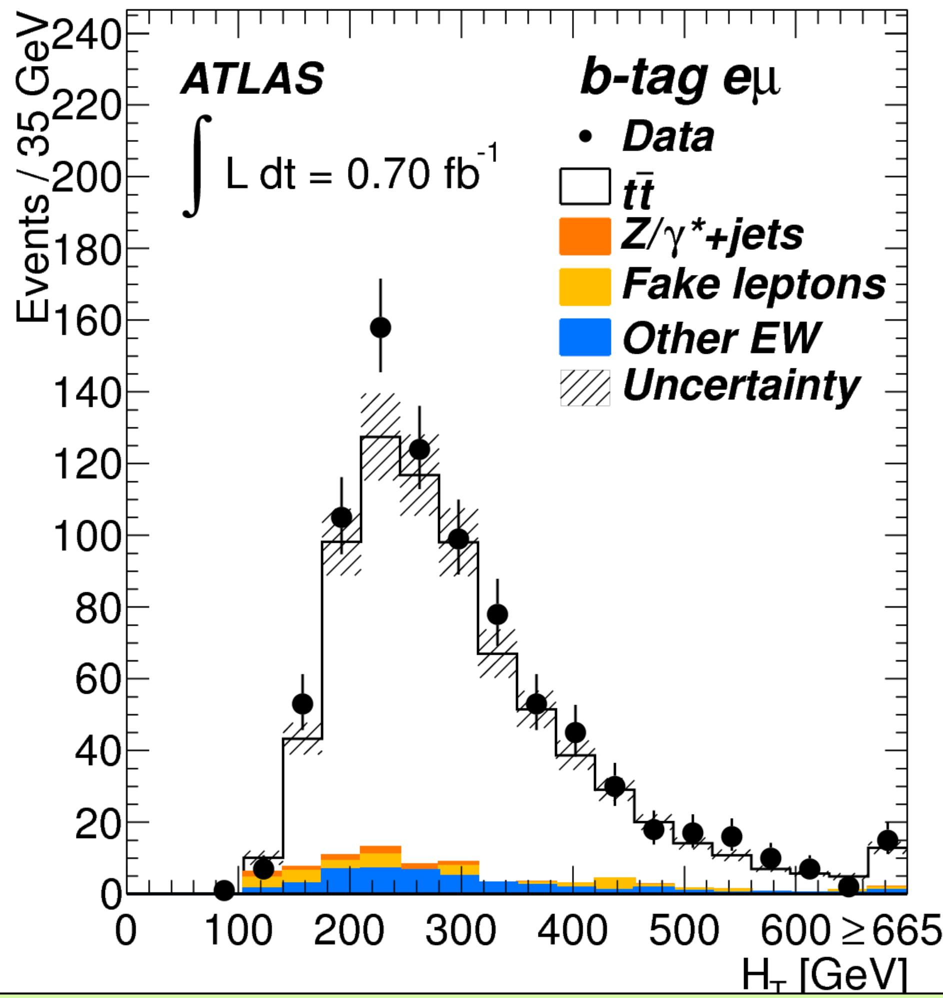




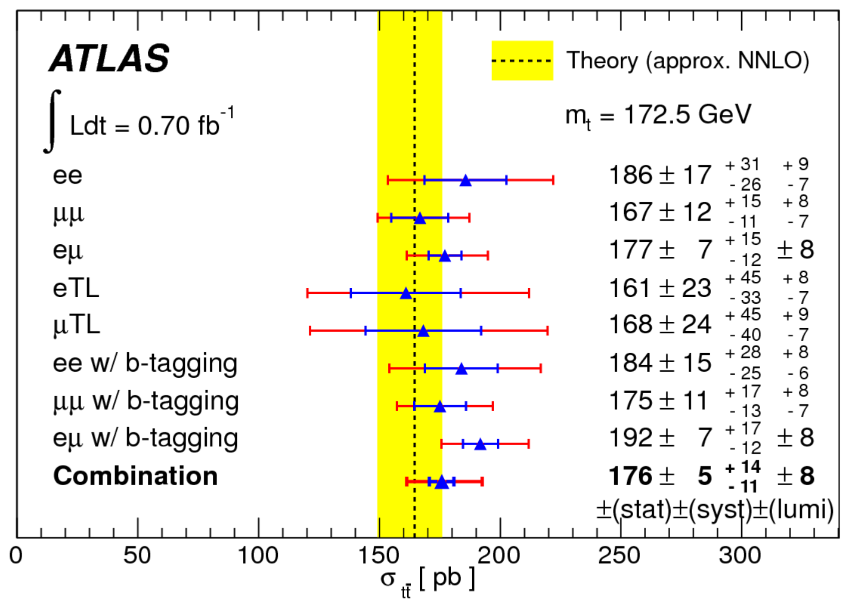


Top anti-top Production

$t \to b\mu\nu,\ t \to be\nu$



arXiv:1202.4892



ATLAS in 2011 data:

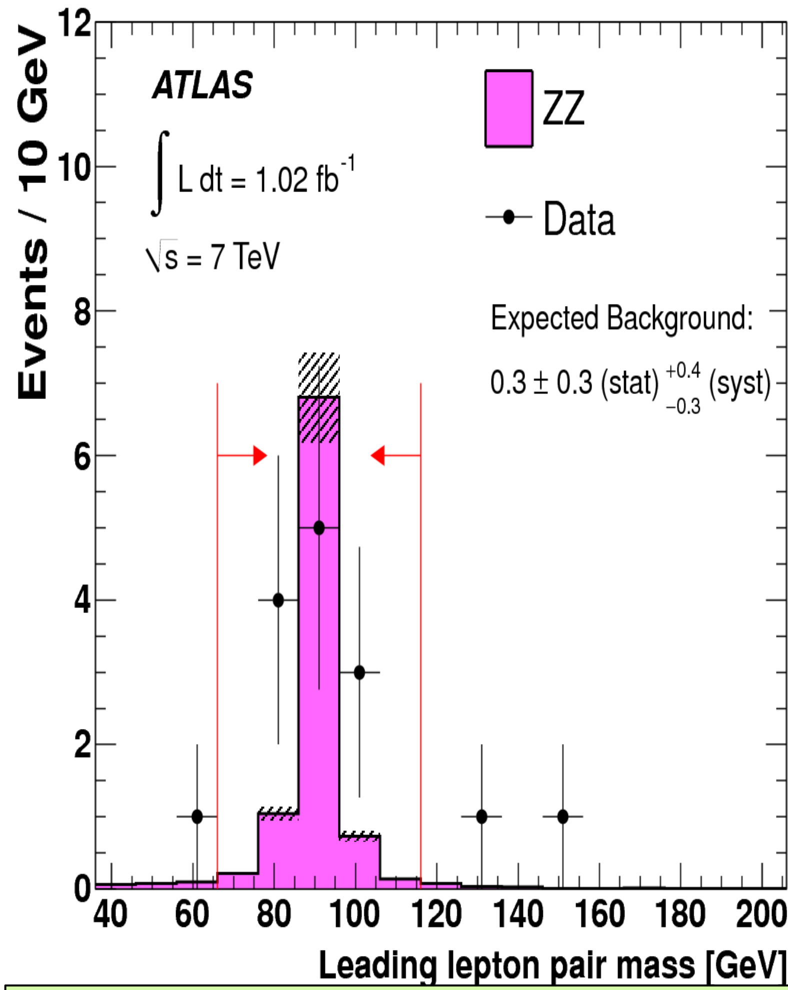
~ 60000 top-pair events

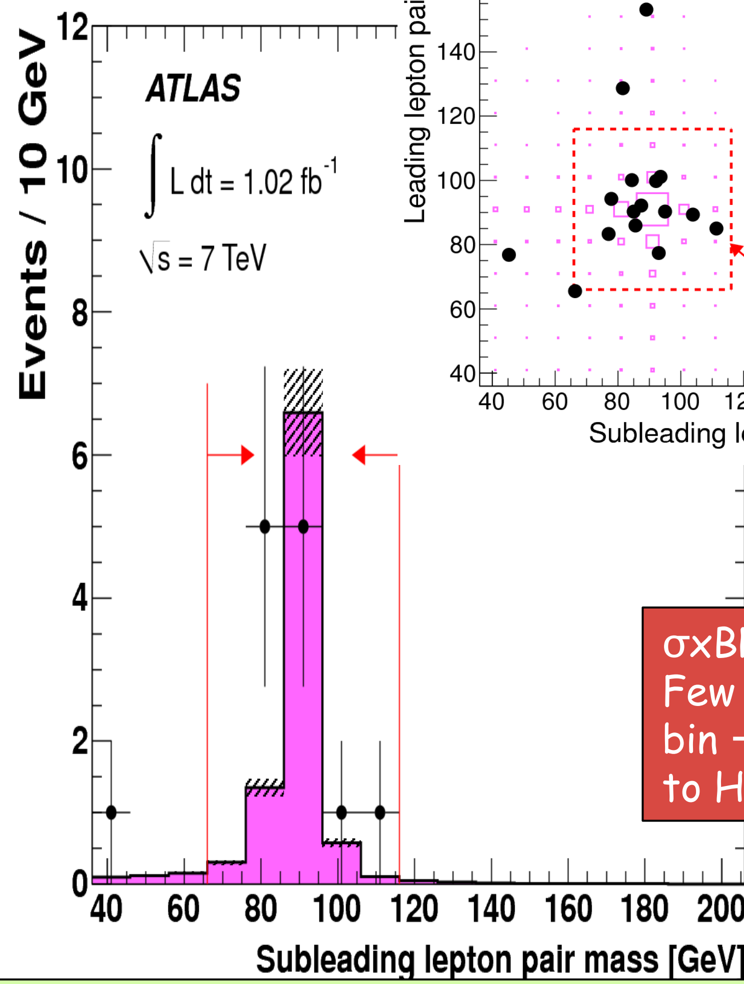
→ Factor ~ 10 more than total CDF and D0 datasets

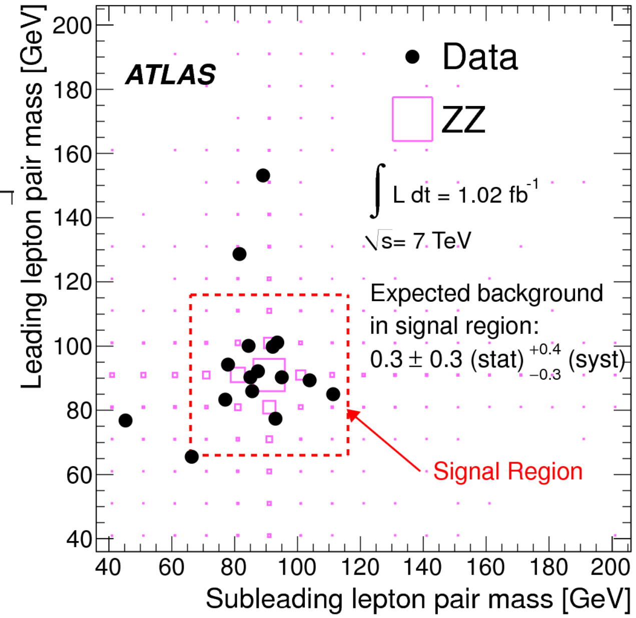
→ will allow more and more precise studies of a larger number of (exclusive) processes

ZZ Production

arXiv:1110.5016



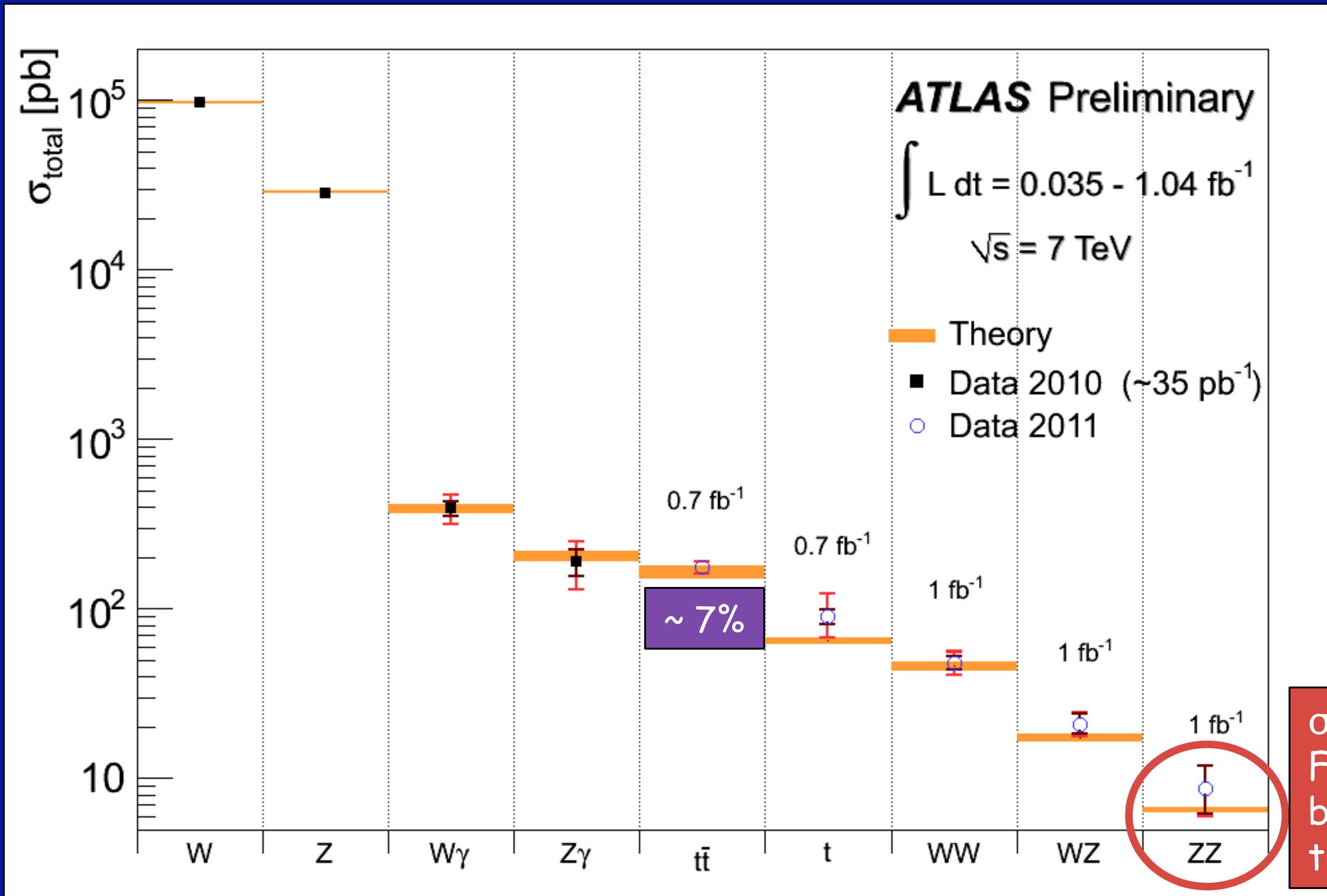




σxBR(ZZ→ 4l) ~ 40 fb
Few fb in narrow mass bin → comparable to H→ZZ(*)→ 4l

ATLAS in 2011 data:
~ 30 M W→ μν, eν events
~ 3 M Z → μμ, ee events
→ factor ~ 2 (W, Z) more than total CDF and D0 dataset, allows ZZ to be well-measured

Summary of main electroweak and top cross-section measurements



Inner error: statistical
Outer error: total

σxBR(ZZ→ 4l) ~ 40 fb
Few fb in narrow mass bin → comparable to H→ZZ$^{(*)}$→ 4l

Good agreement with SM expectations (within present uncertainties)

Experimental precision starts to challenge theory for e.g. tt (background to most H searches)

Measuring cross-sections down to few pb (~ 40 fb including leptonic branching ratios)

The Higgs

Searching for the mechanism of electroweak symmetry breaking, we seek to understand

why the world is the way it is.

This is one of the deepest questions humans have ever pursued, and

it is coming within the reach of particle physics.

Slide adapted from talk by Chris Quigg

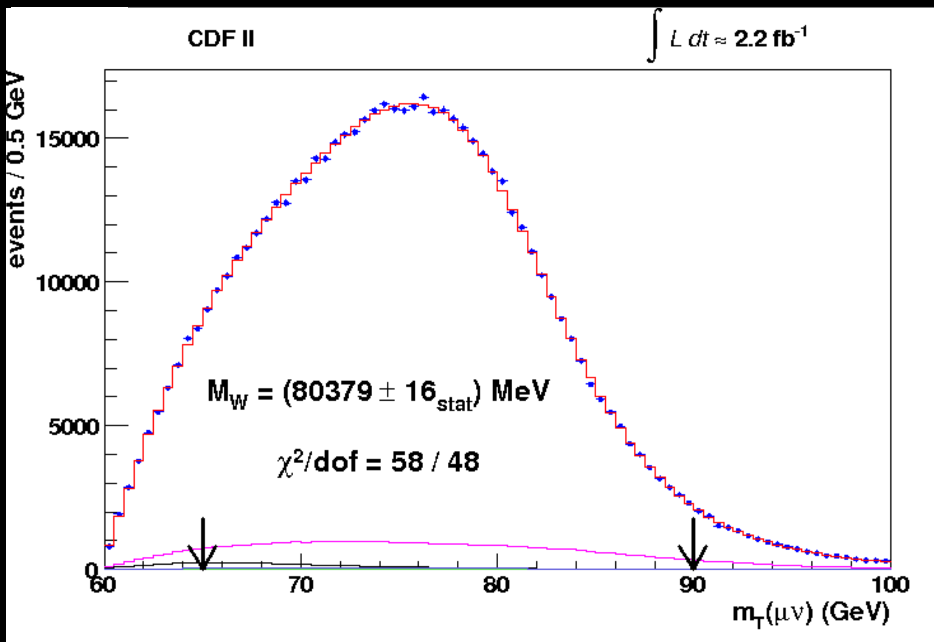
The Higgs

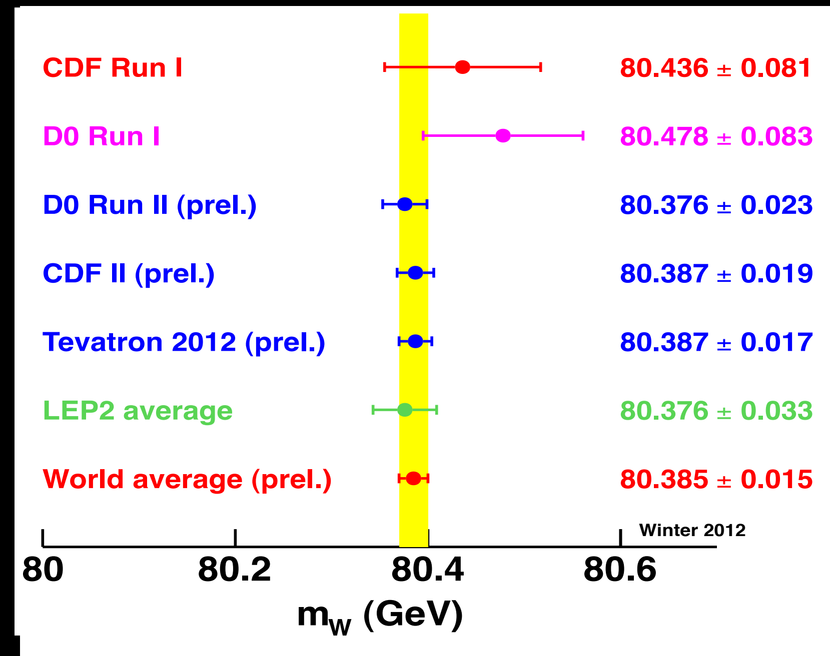
- Massless force carriers ⇒ infinite range:
  - photon,
- Massive force carriers ⇒ short range:
  - Weak nuclear force is short range
- Quantum field theory doesn't like massive force carriers!
  - A loophole: If the universe is filled with a field that attenuates the weak force, that would make it short-ranged.
- This is the *Higgs* field.

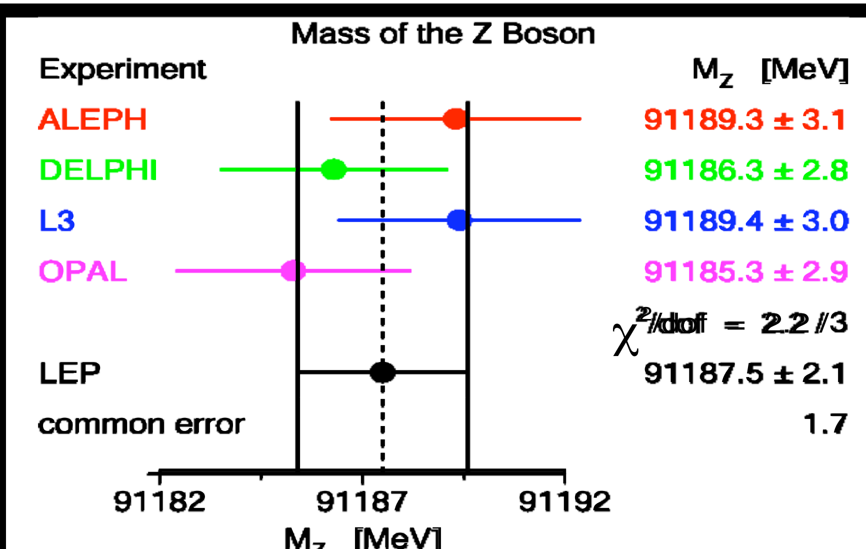
1970's: Theorists used Higgs mechanism to predict the existence of $W^{\pm}$ & Z particles with masses of 80 & 91 times that of the proton.

1983-84: They were found at CERN

W&Z - right where they should be…







New precise Tevatron

W mass at EWK Moriond 2012

$$\Delta M / M \sim 2 \times 10^{-4}$$

http://lepewwg.web.cern.ch/LEPEWWG/

properties of the standard model Higgs boson

- spin 0
- coupling to the Higgs gives particles mass
- Higgs couples to pairs of all massive particles and their antiparticles

$H \rightarrow \mu^+\mu^-$ if 210MeV<mH <270MeV

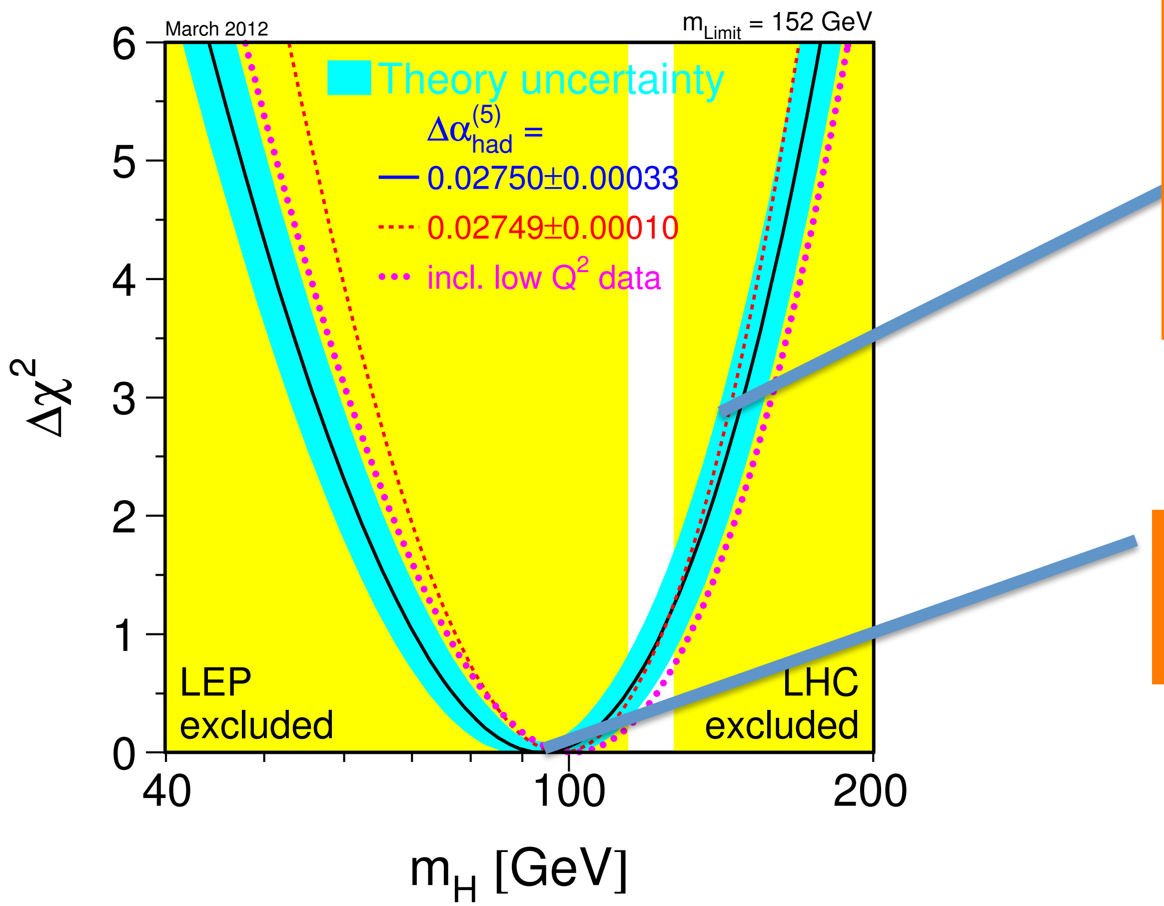
$H \rightarrow bb$ if 9GeV<mH <135GeV

$H \rightarrow WW$ if 135 GeV < mH

- coupling is proportional to particle mass

- decays preferentially to most massive particles with 2m<mH

The mass of the Higgs boson
Not yet measured by experiment
but constrained by experiment



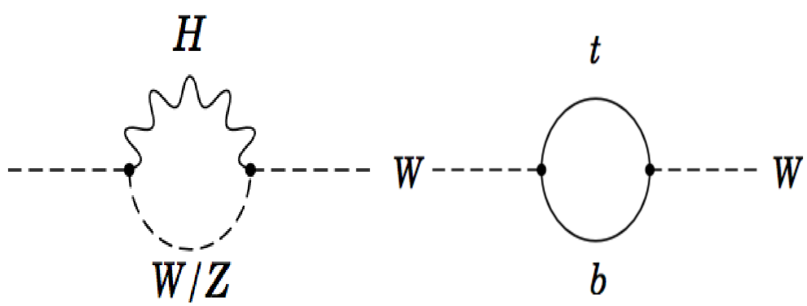
Global ewk fit consistency test of all measured parameters with Standard model

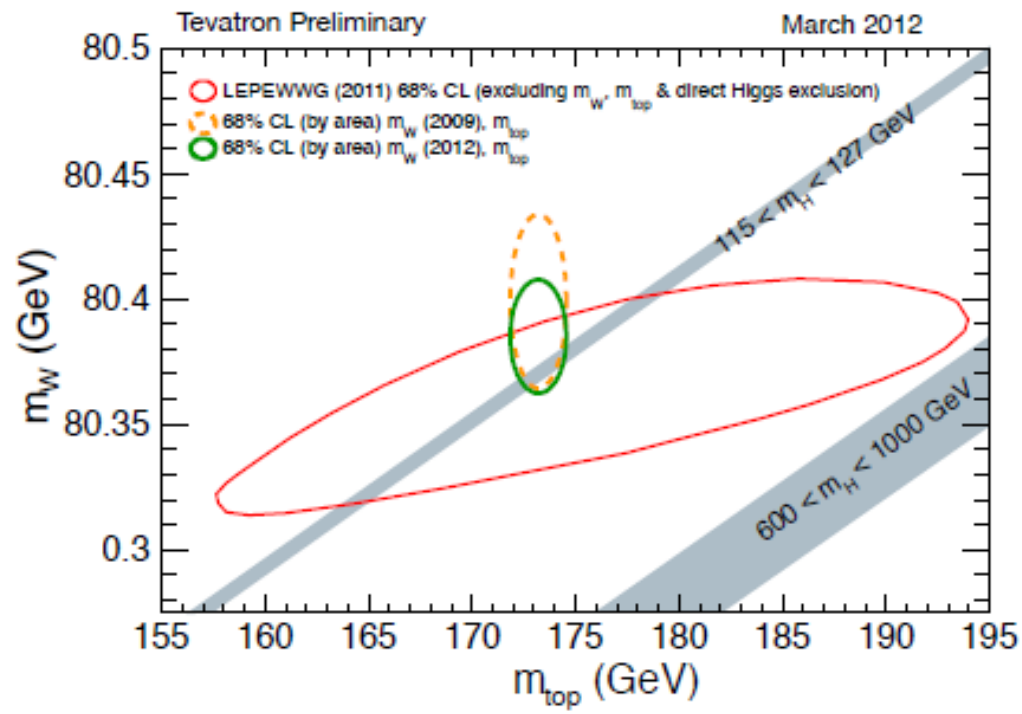
Preferred mass 94^{+29}_{-24} GeV

With M_W = 80385±15 MeV

$M_H = 94^{+29}_{-24}$ GeV
M_H < 152 GeV @95% CL

LEPEWWG/ZFitter





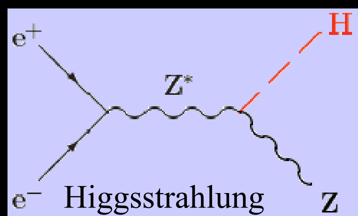
- W/Z mass ratio sensitive to radiative corrections
- Fix Higgs mass M(W) depends only on M(top) (gray bands).
  Note only drawn for Higgs mass regions not excluded by LHC

Evolution of the Higgs Search 1965 to Spring 2011

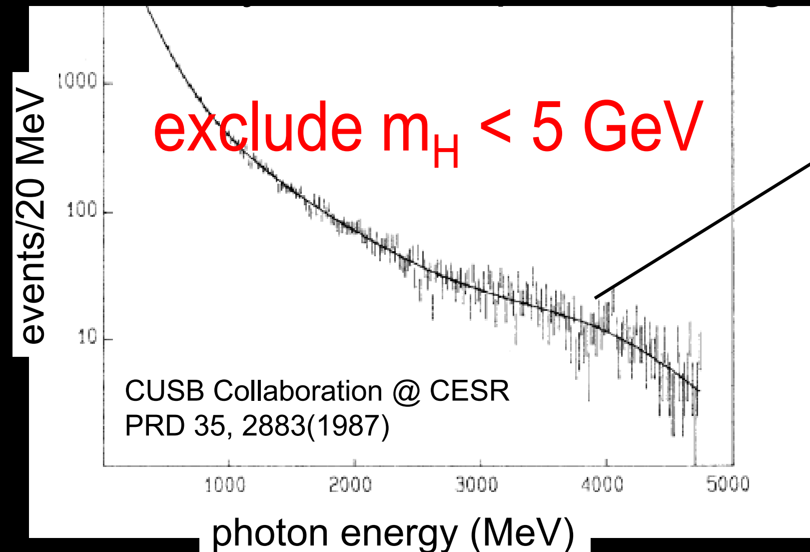
46 years of searches,

Early example: Y→ Hγ

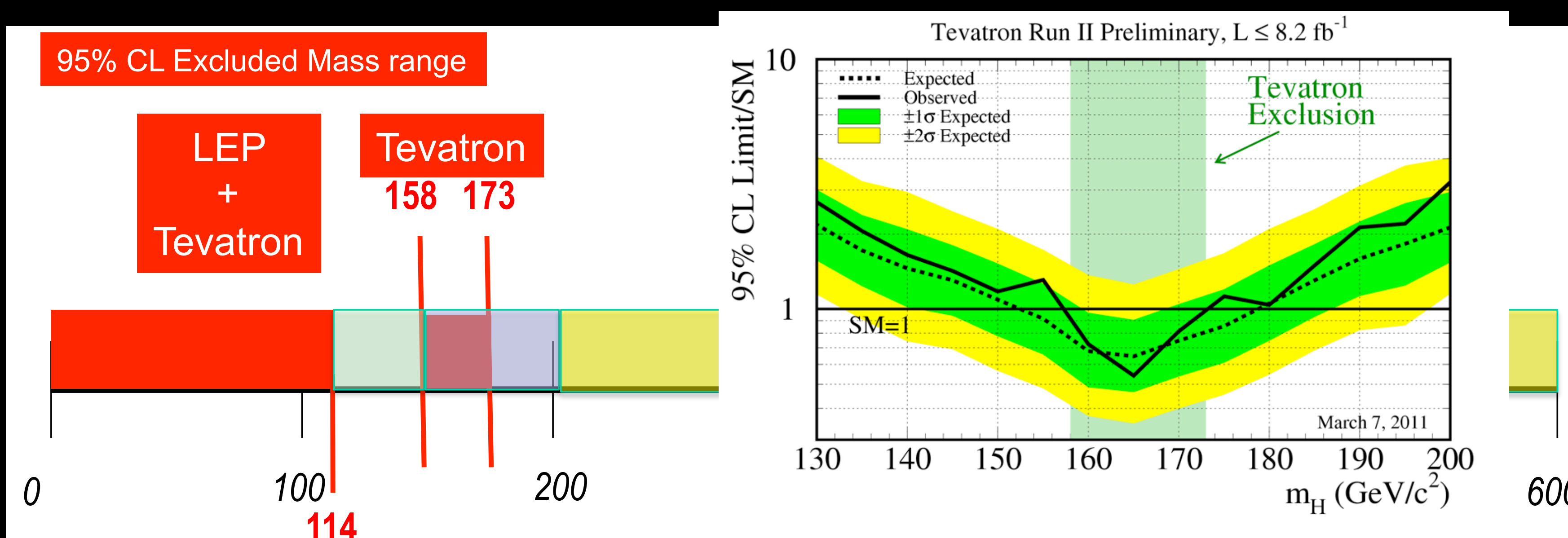
LEP



Tevatron



should see monochromatic line in photon energy spectrum



Dec 13 2011

Results of Searches in following Slides updated to March 2012

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13 December 2011 Last updated at 12:20 ET

15K Share

LHC: Higgs boson 'may have been glimpsed'

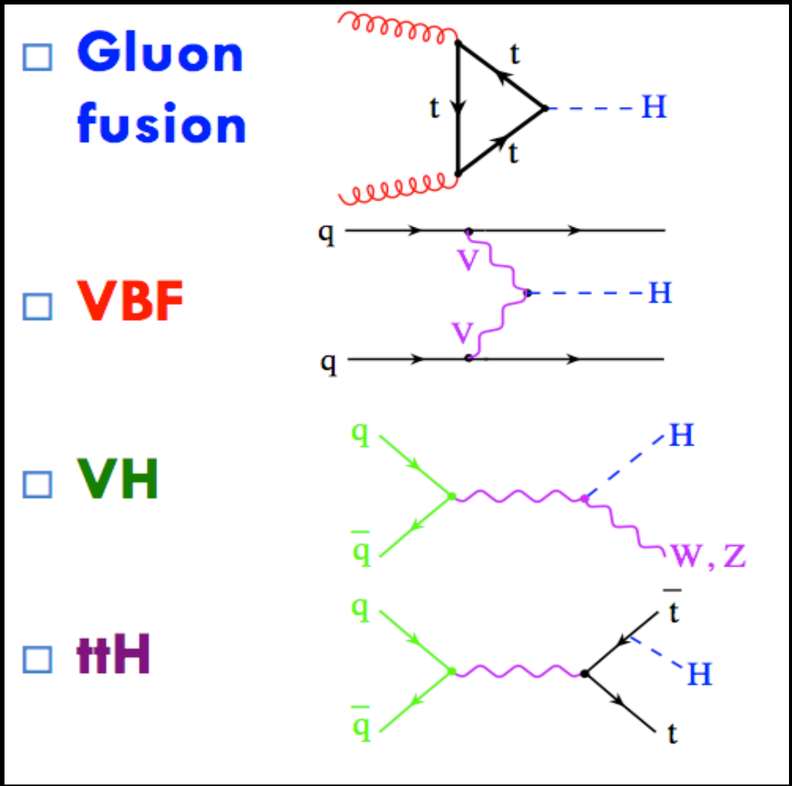
By Paul Rincon
Science editor, BBC News website, Geneva

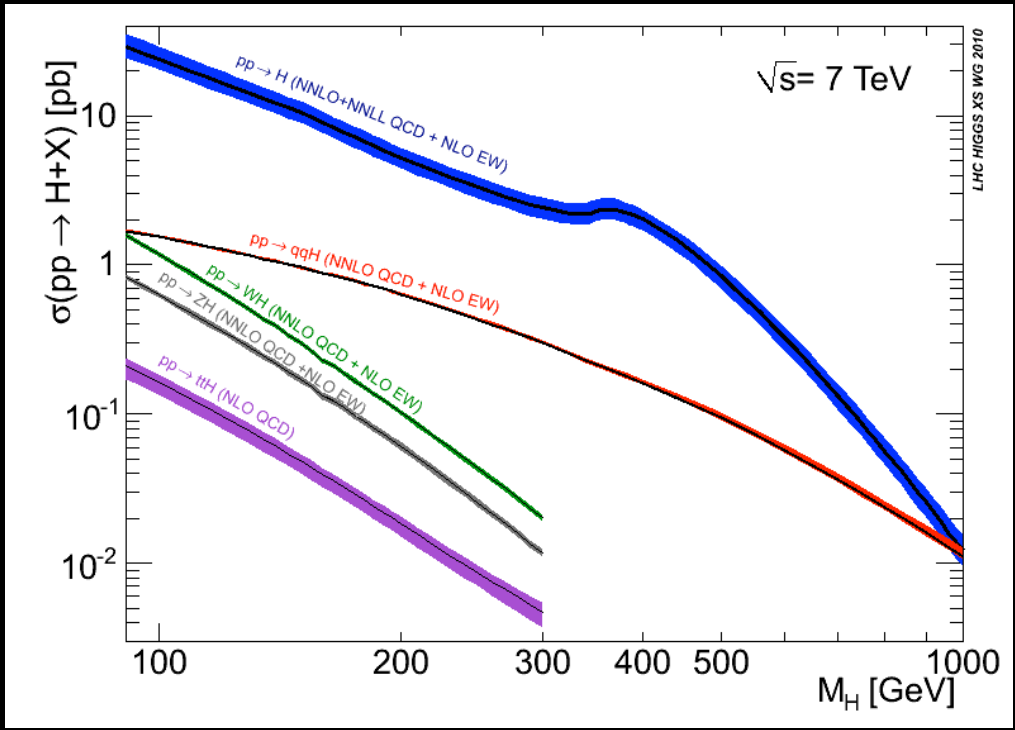
Two teams at the LHC have seen hints of what may well prove to be the Higgs

The most coveted prize in particle physics - the Higgs boson - may have been glimpsed, say researchers reporting at the Large Hadron Collider (LHC) in Geneva.

Related Stories

Standard Model Higgs Production at the LHC





Gluon fusion (gg → H) is the dominant production mechanism at LHC.
S/B better than at Tevatron except in VH
VBF & VH also very useful at LHC
ttH is probably for the 14 TeV run

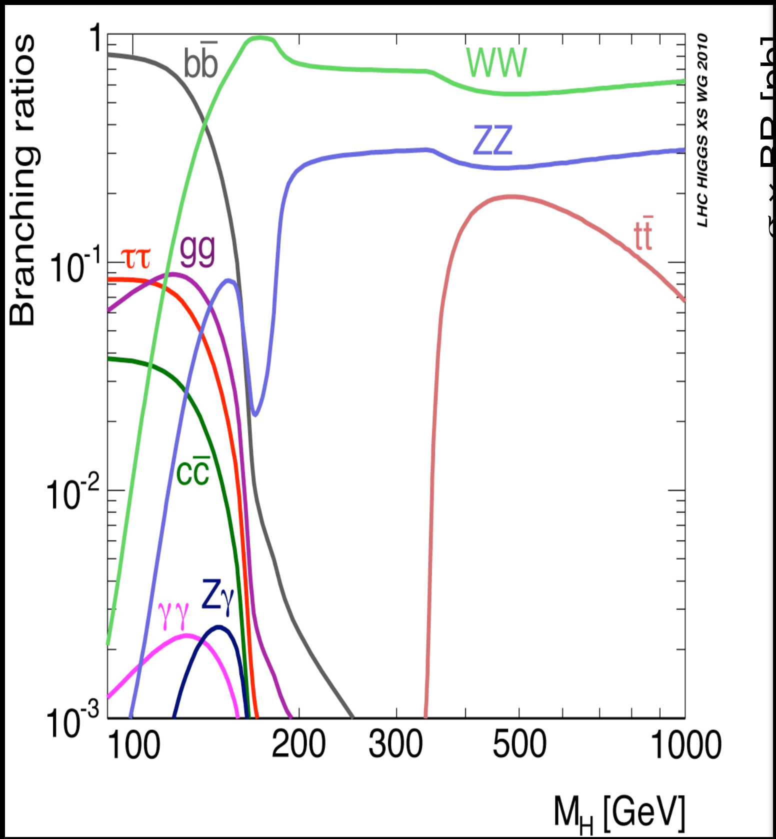
Standard Model Higgs Decays/Search Strategy ATLAS/CMS

Higgs couples to mass so decays to the heaviest states it can

"High Mass"
Above 2 x $M_{W/Z}$ WW, ZZ dominate
ZZ to 4l fully measurable
W→ lν, Wlν (neutrinos prevent measurement of mass peak)

"Low Mass"
bb is dominant, b→ jets, has large QCD backgrounds
Consequently, rarer but cleaner τ τ, gamgam modes are important
gamgam is most sensitive despite tiny BR
W*W, Z*Z still contribute (*=virtual)

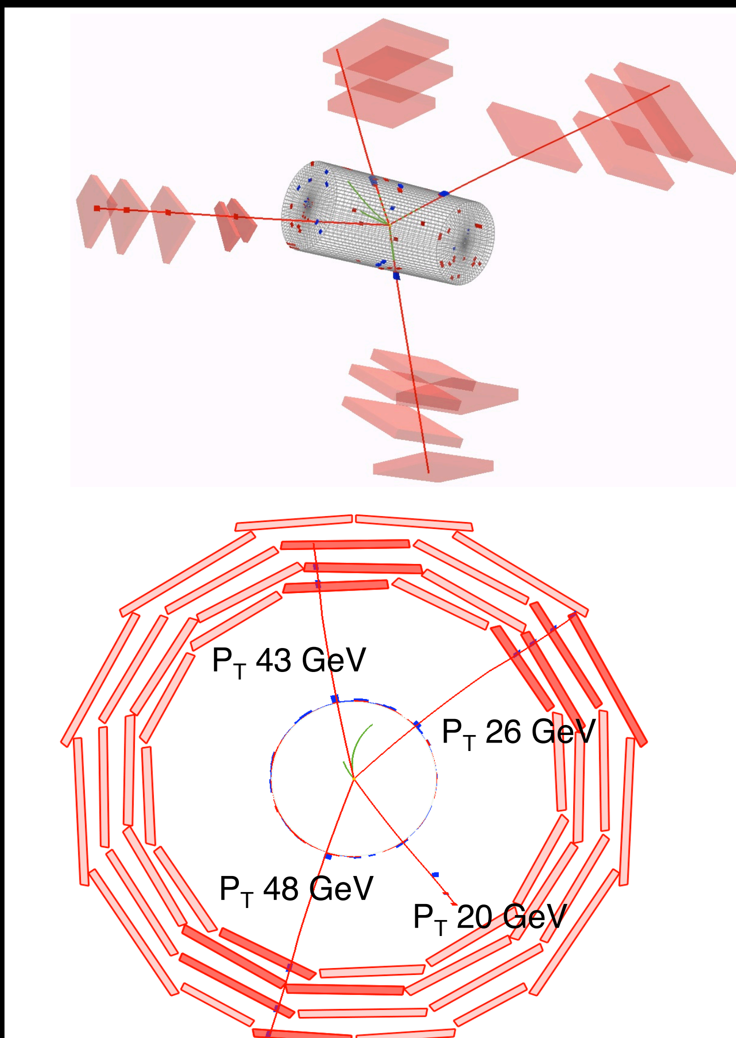
With the current dataset, ATLAS & CMS can't exclude the entire low mass region, due to an excess in the data -- hence the excitement



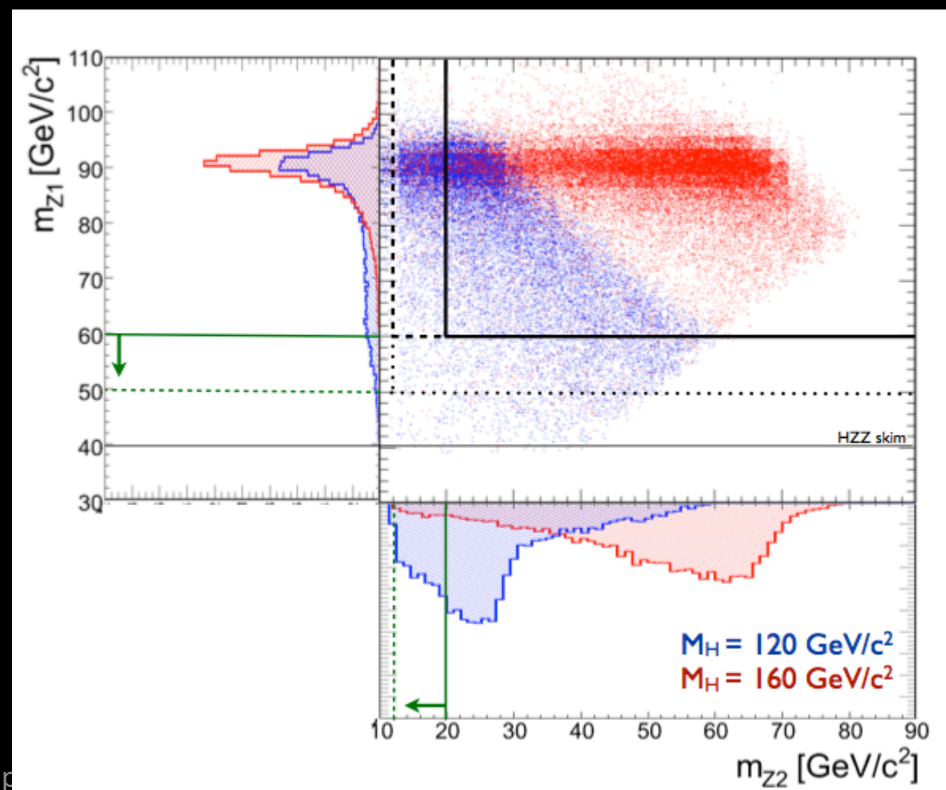
Look at ZZ and gamgam as examples

H→ZZ→4l (The Golden Mode)

Golden: 4 leptons, clean, fully reconstructable, excellent mass resolution (1%)
Challenge: small branching fraction H→> ZZ few % Z → μμ: 3%,
σB ~few fb low pT leptons



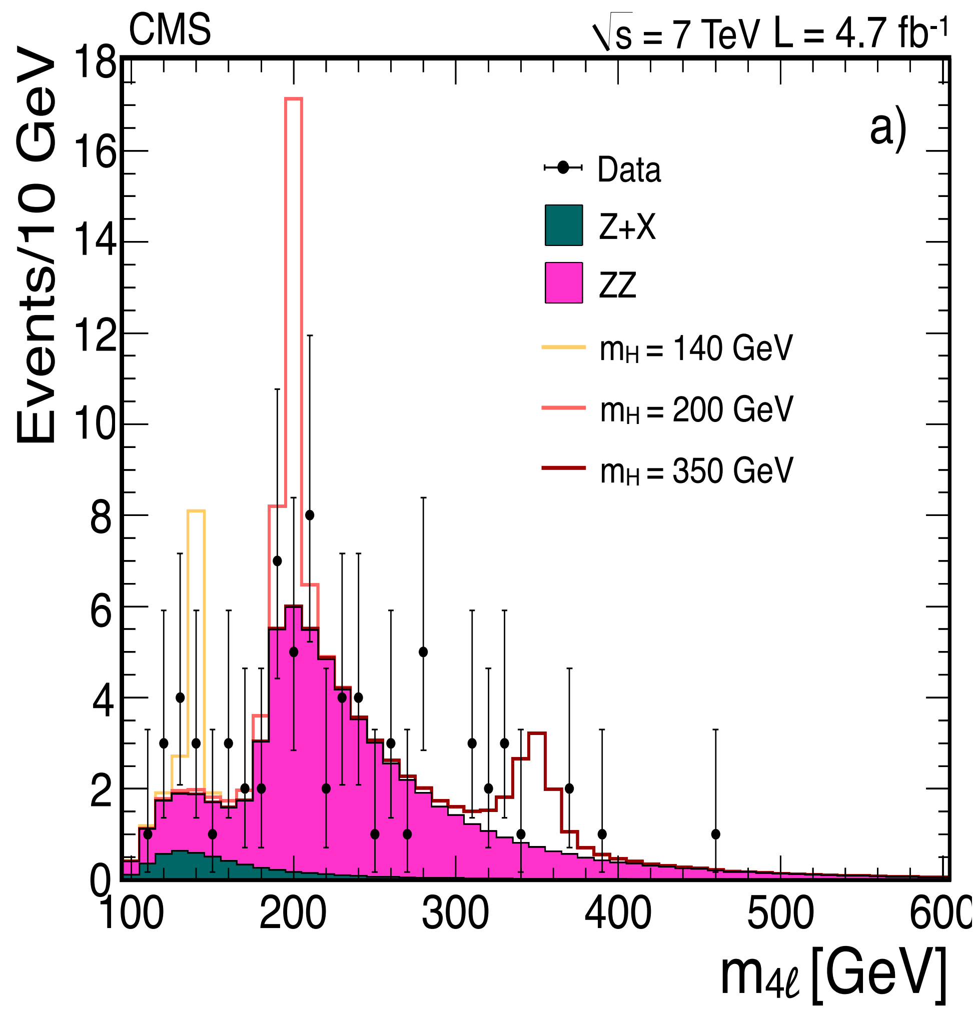
- Improved sensitivity at low Higgs masses in successive analysis iterations in 2011



H→ZZ→4l (4μ, 4e, 2μ2e)

Background: instrumental: real Z + fake lepton(s),
Physics: Z bbar ttbar WZ → 4l can be reduced to negligible level
Direct ZZ* production cannot be reduced, can be isolated & measured and found to be in agreement with standard model prediction

m_{4l} >100 GeV/c²
Observed events: 72
Expected events: 67.1 ± 6.0

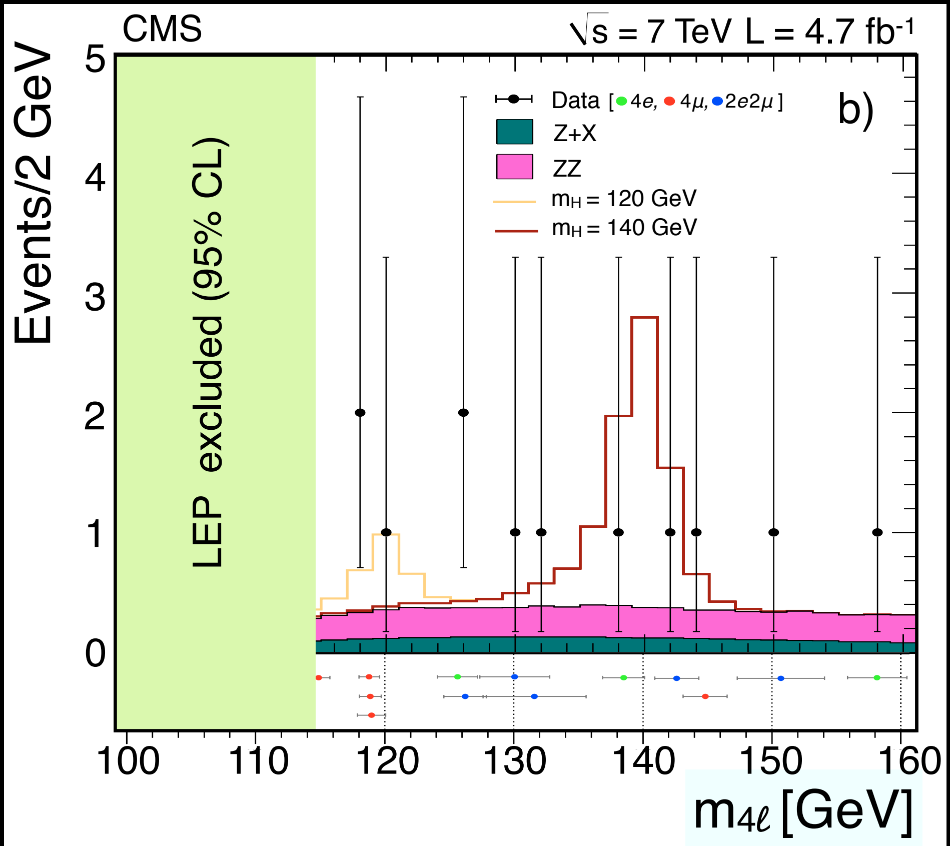


H➔ZZ➔4l (Zoom to low mass)

•Background is irreducible ZZ* continuum

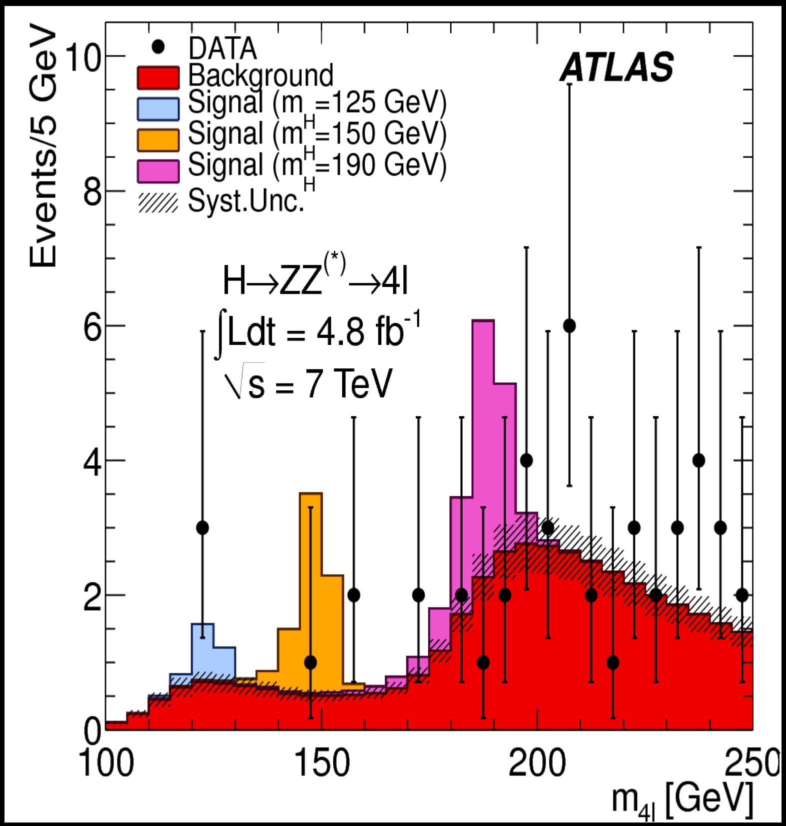
100 < M(ZZ*) < 160
13 observed
9.5 ± 1.3 expected

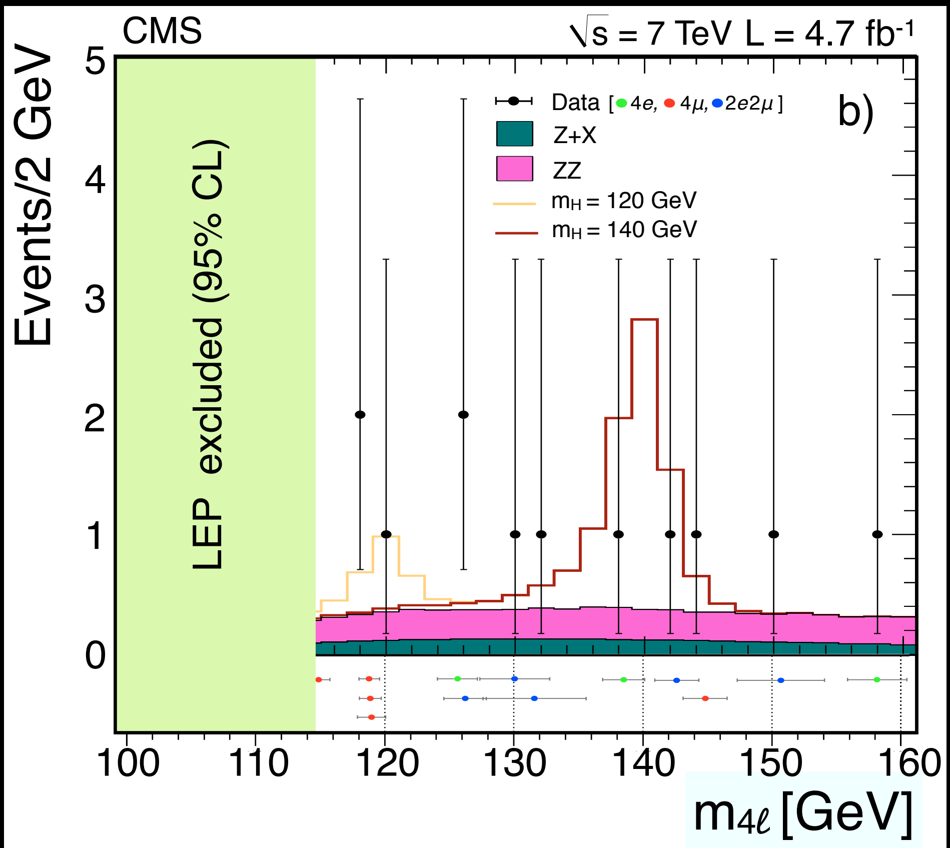
Final state:	4e	4μ	2e2μ
Obs. events:	3	5	5
Exp. events:	1.7	3.3	4.5



3 events: 118.3 118.9 119.0
2 events: 125.7 126.2

H➔ZZ➔4l (Zoom to low mass)



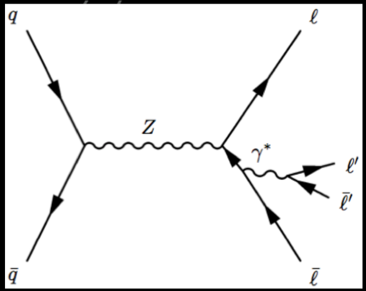


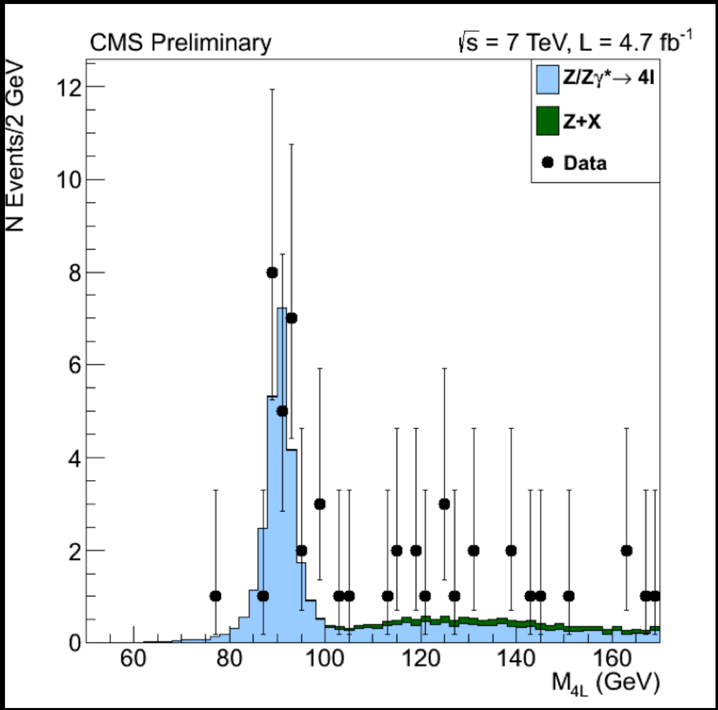
ATLAS below 140
4 expected from SM 3 observed
3 events 123.6 124.3 124.6

CMS below 140
6 expected from SM 9 observed
3 events: 118.3 118.9 119.0 2 events 125.7 126.2

Cross check – 1st observation of pp → Z → 4l

NEW
March 14 2012





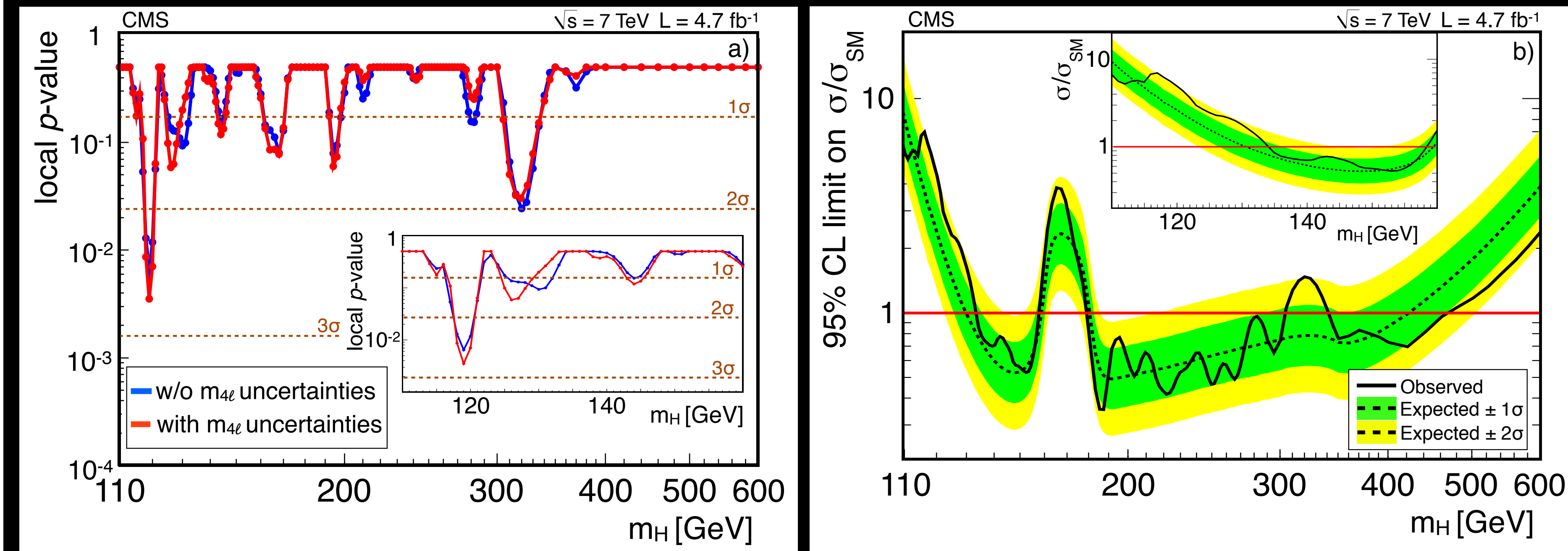
Same final state but at 90 GeV

$$\sigma \times BR(Z \to 4\ell) = 125^{+26}_{-23}(\mathrm{stat})^{+9}_{-6}(\mathrm{syst})^{+7}_{-5}(\mathrm{lumi})\ \mathrm{fb},$$

$$BR(Z \to 4\ell) = 4.4^{+1.0}_{-0.8}(\mathrm{stat}) \pm 0.2(\mathrm{syst}) \times 10^{-6}.$$

Mass @ known Z mass
Mass & mass resolution measured in data agree with simulation

H→ZZ→4l (limits)

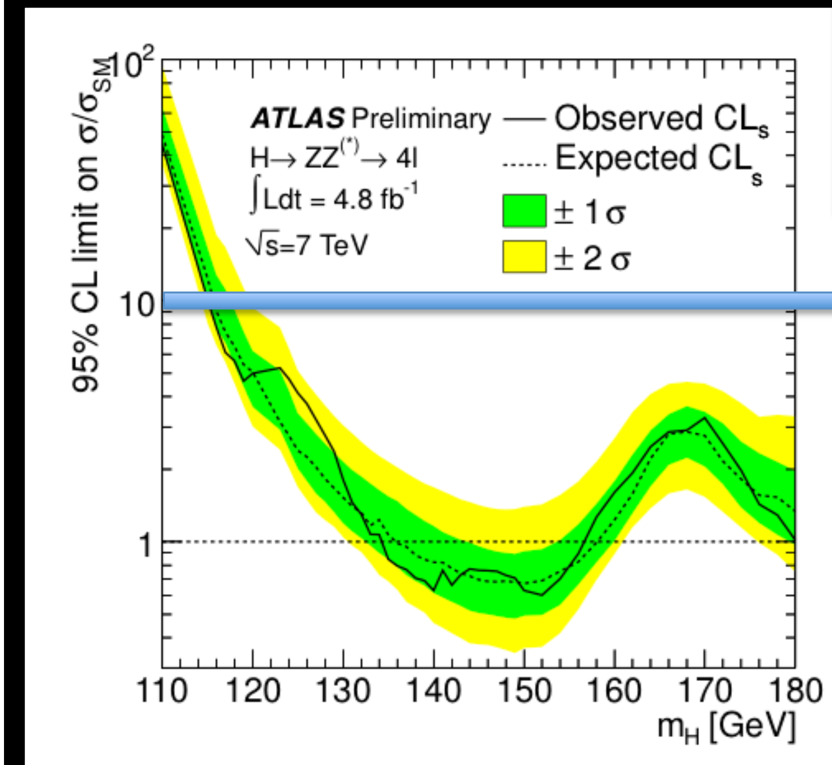


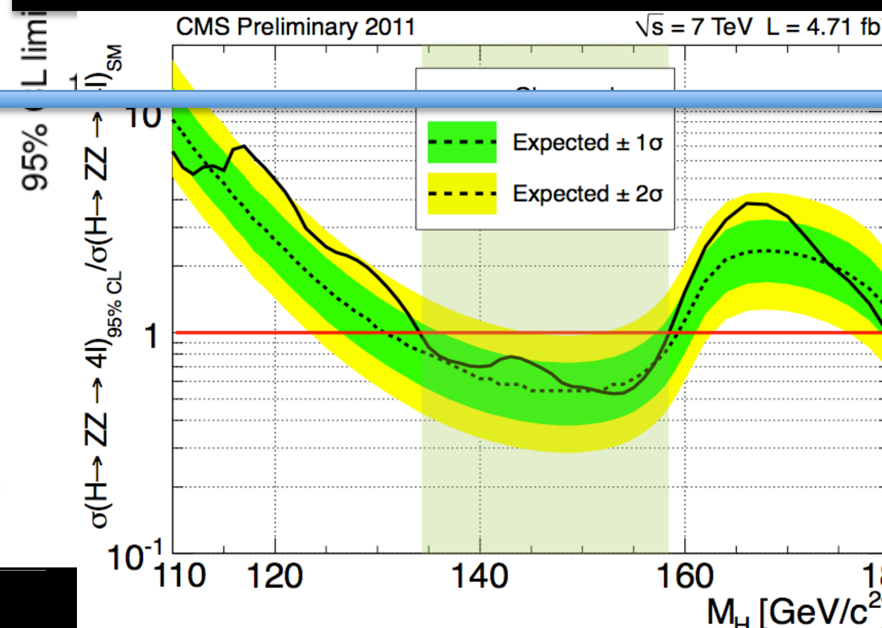
	m	local	full	110:160
p-value	119	2.5 (2.7)	1.0	1.6
	126	<1 (1.5)		
	320	2.0		

Expected range: $130 < M_H < 160$ GeV; $182 < M_H < 420$ GeV
Observed range: $134 < M_H < 158$ GeV; $180 < M_H < 305$ GeV; $340 < M_H < 460$ GeV

H→ZZ→4l (limits)

Excluded (95% CL): 135 < m_H < 156 GeV and 181 < m_H < 415 GeV (except 234-255 GeV)
Expected (95% CL): 137 < m_H < 158 GeV and 185 < m_H < 400 GeV

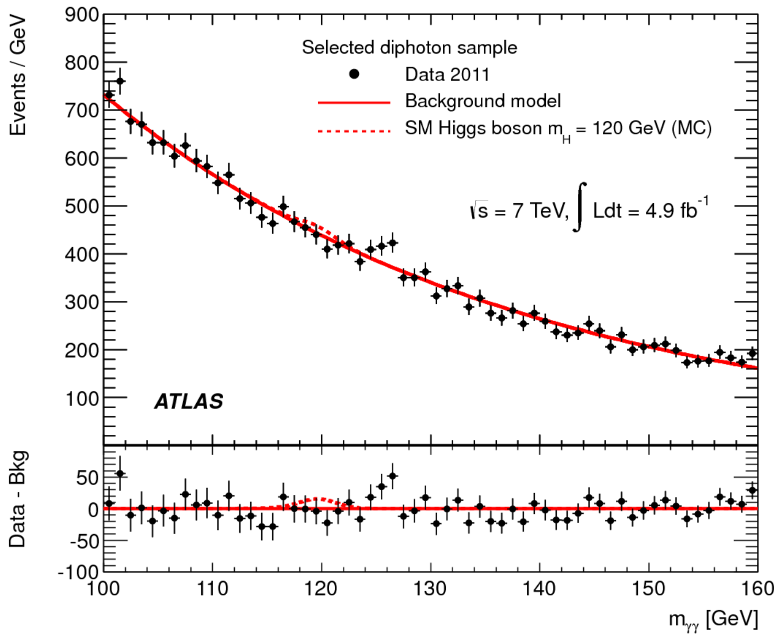




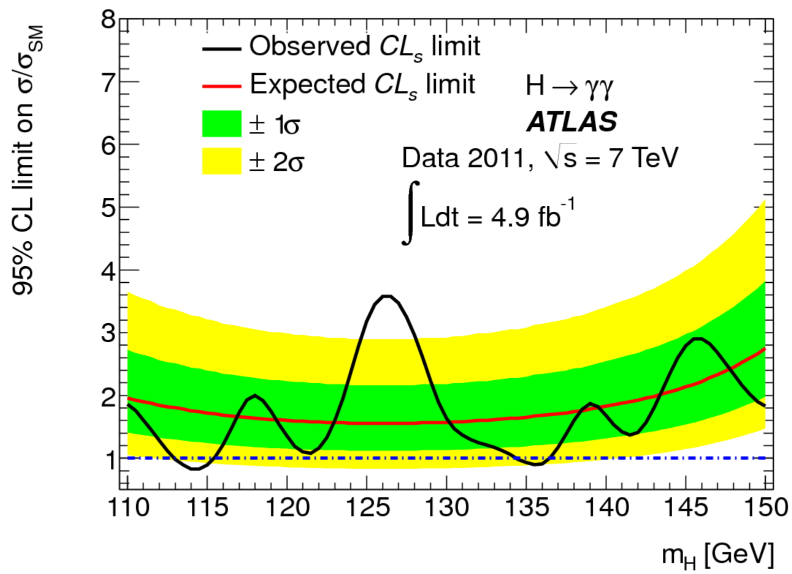
Expected range: 130 < M_H < 160 GeV; 182 < M_H < 420 GeV
Observed range: 134 < M_H < 158 GeV; 180 < M_H < 305 GeV; 340 < M_H < 460 GeV

Invariant $m_{\gamma\gamma}$ distribution,

summed over all categories:



Exclusion limit:



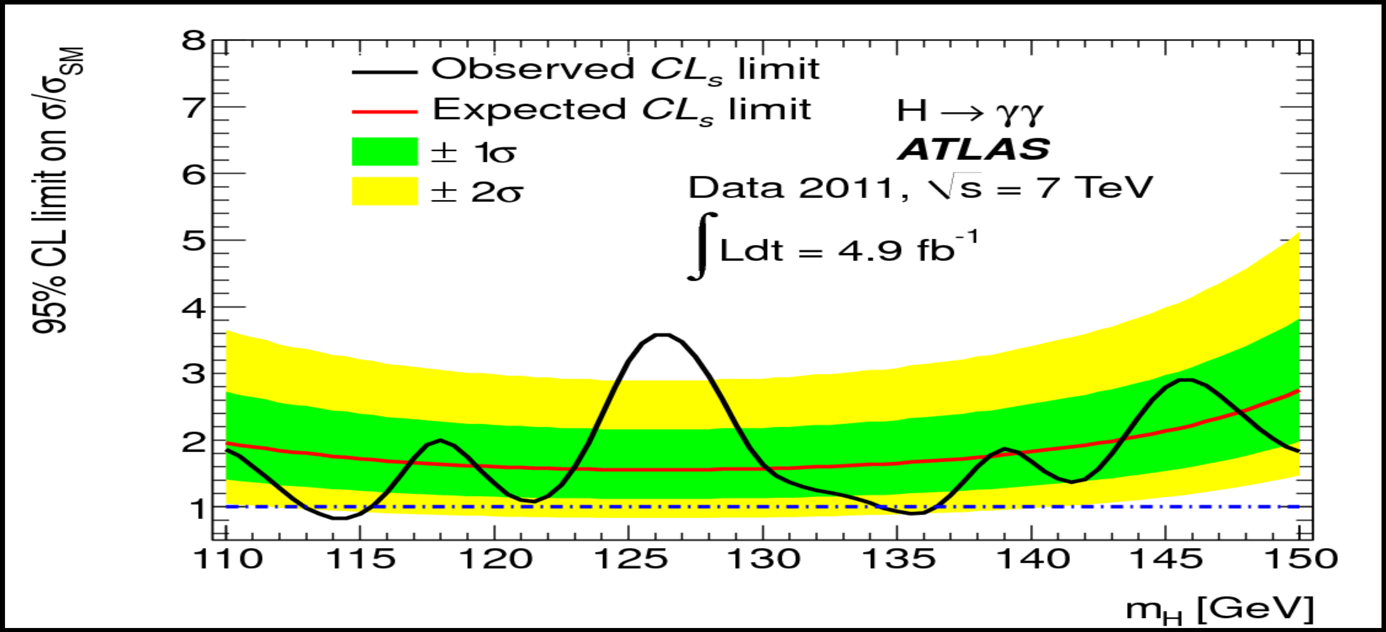
- Observed exclusion:

  113-115 GeV, 134.5-136 GeV.

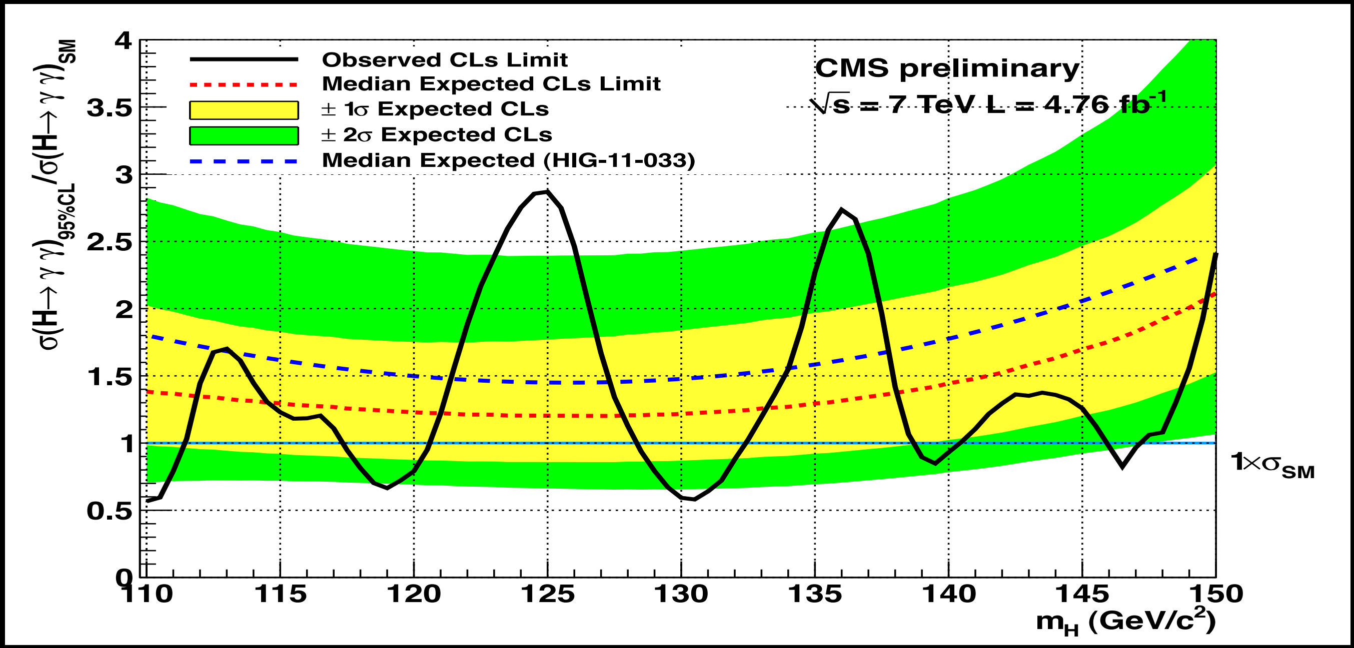
Largest excess of events observed at 126.5 GeV.

- Local significance: 2.8σ (Global: 1.5σ for m_H =110-150 GeV).

CMS and ATLAS diphoton limits

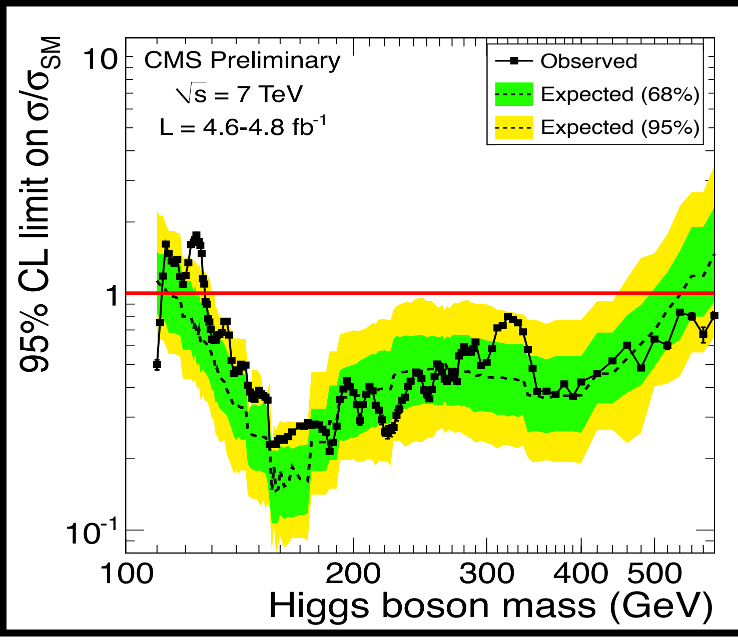


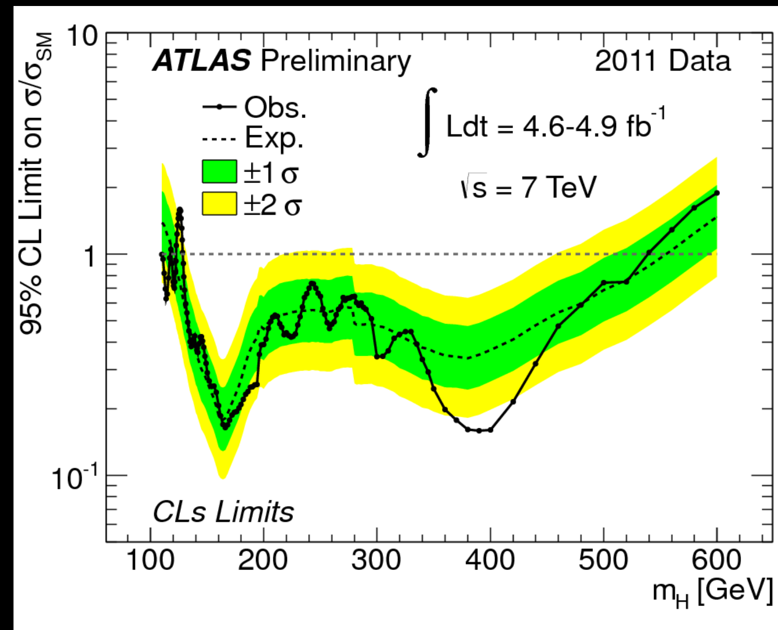
ATLAS largest excess 126.5 GeV

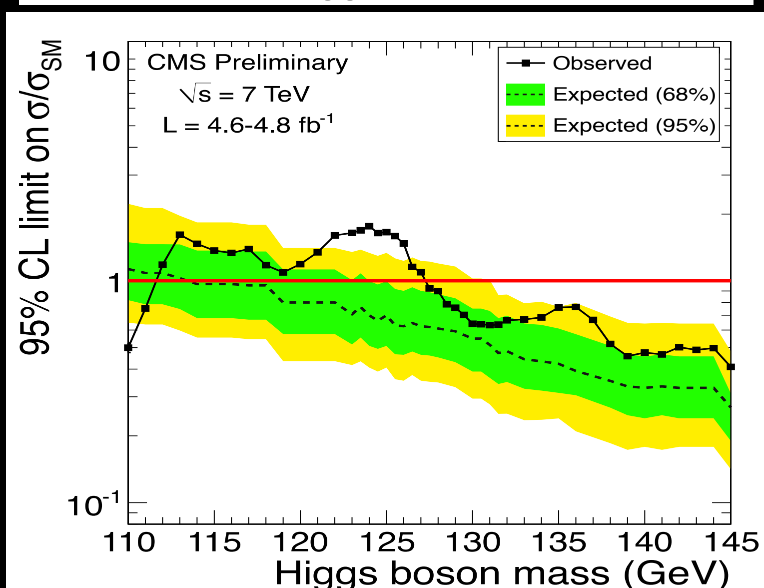


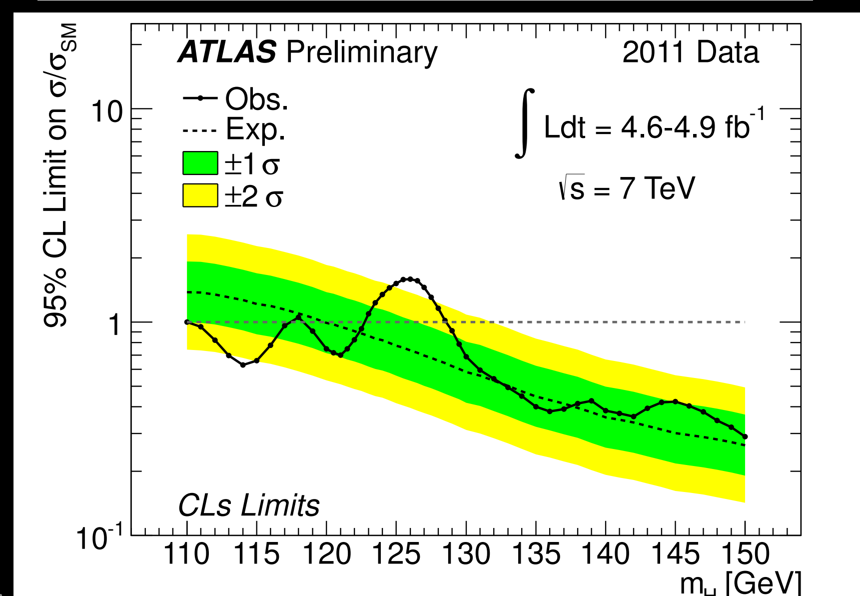
CMS largest excess 125 GeV

LHC Results with 2011 Data all modes combined

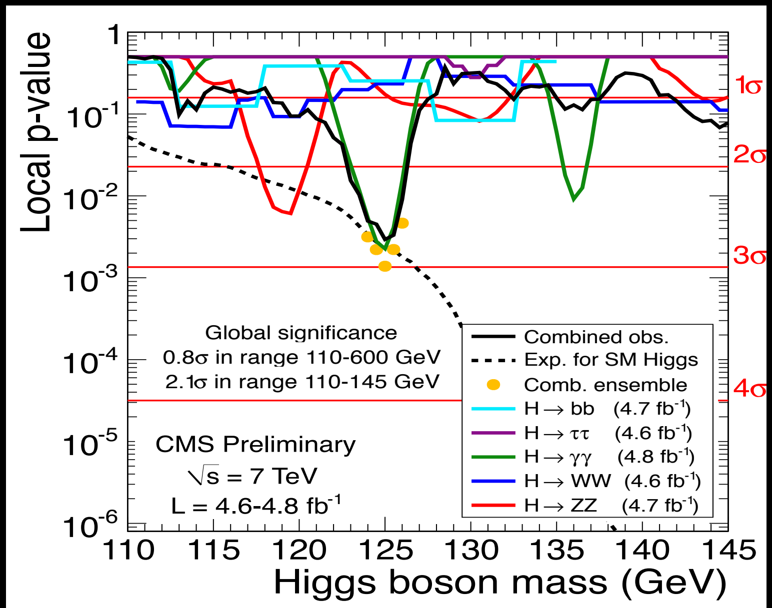


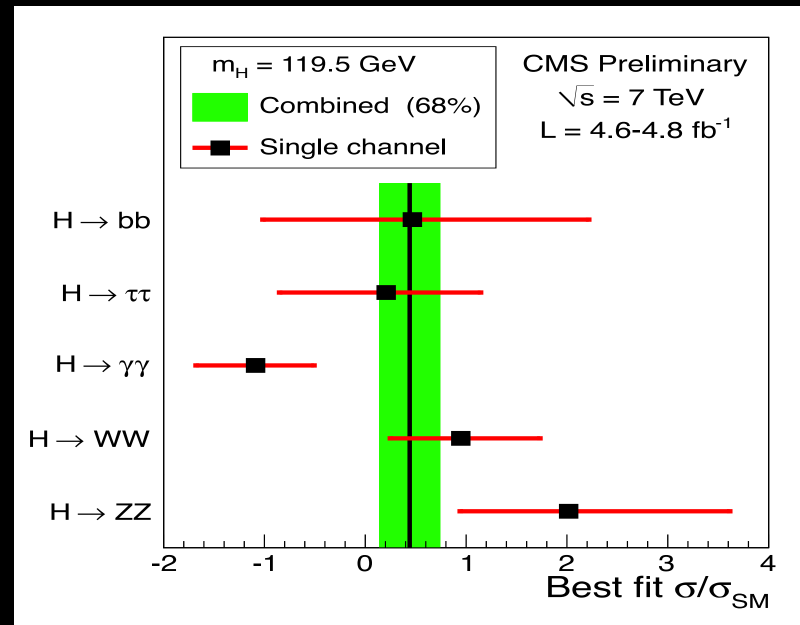


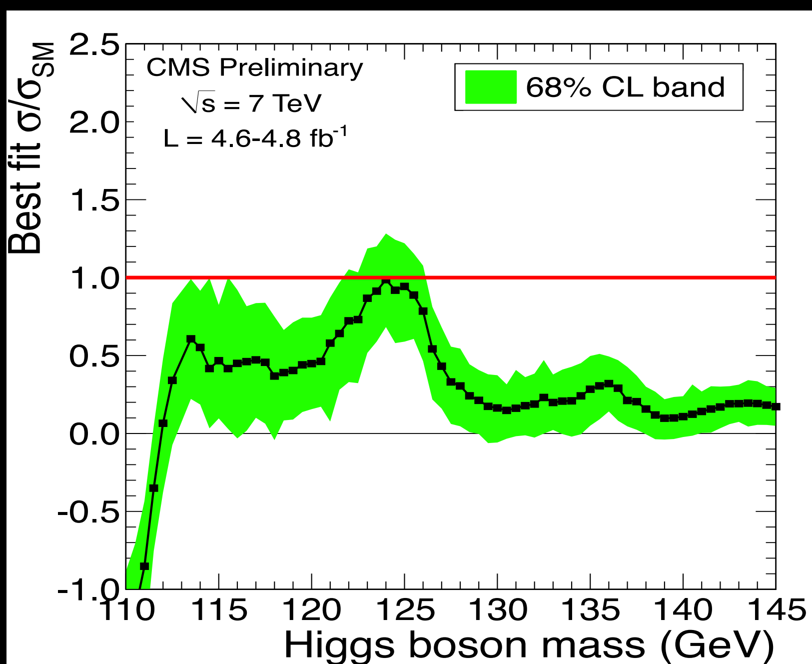


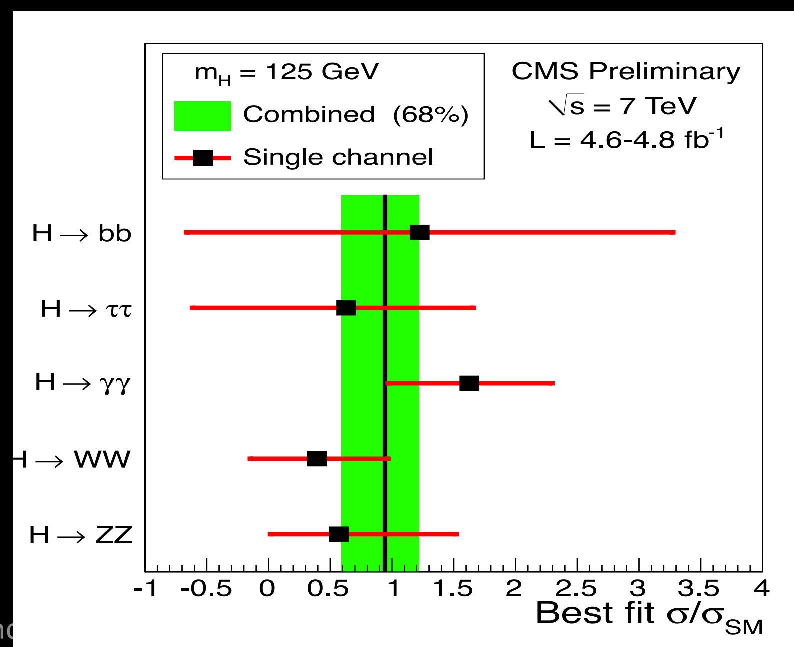


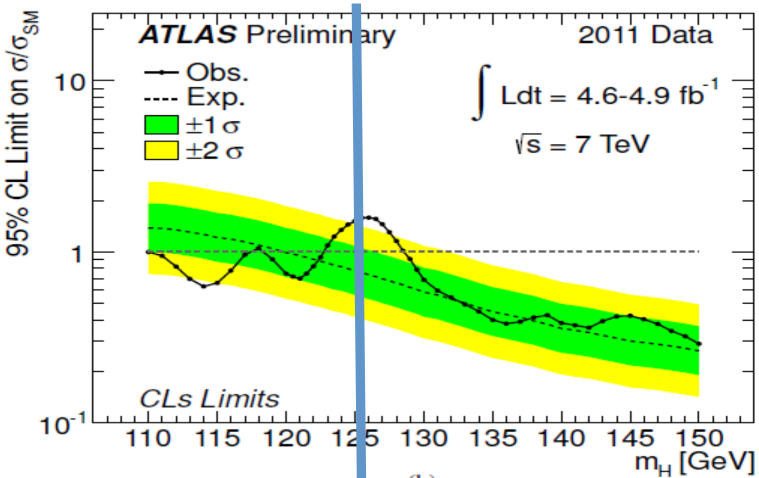
CMS Results by Decay Mode

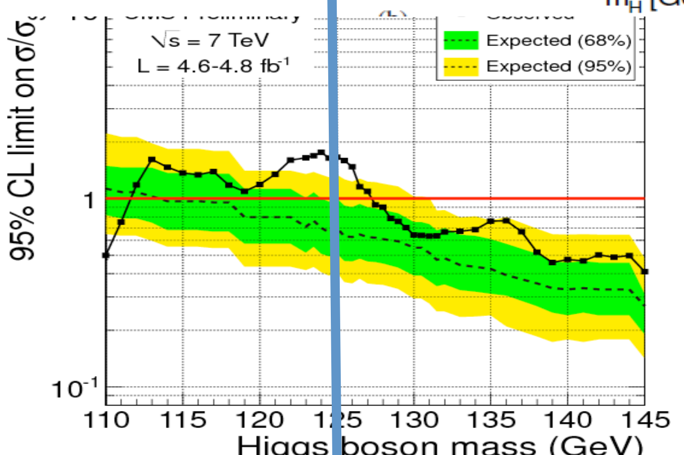


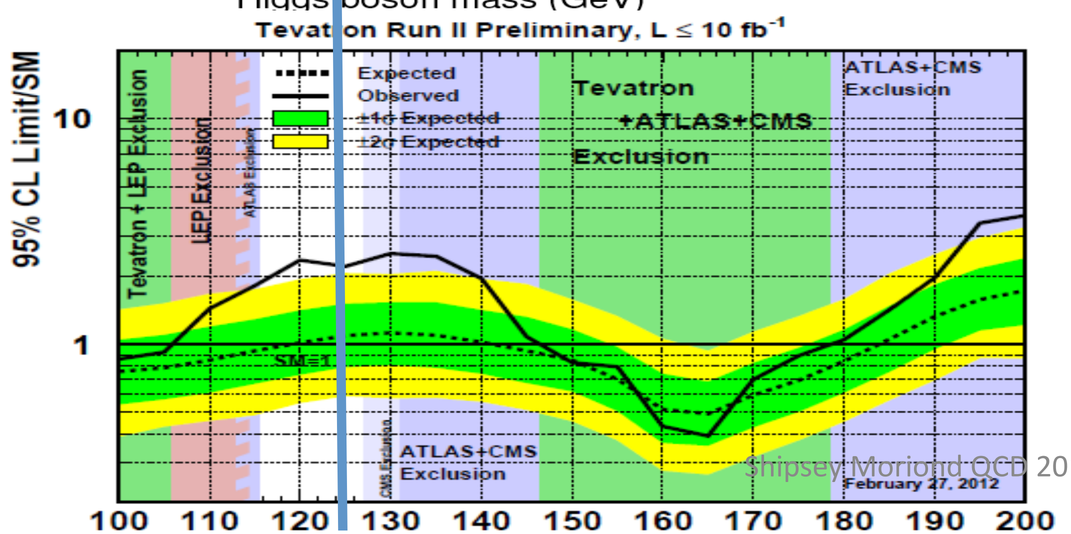










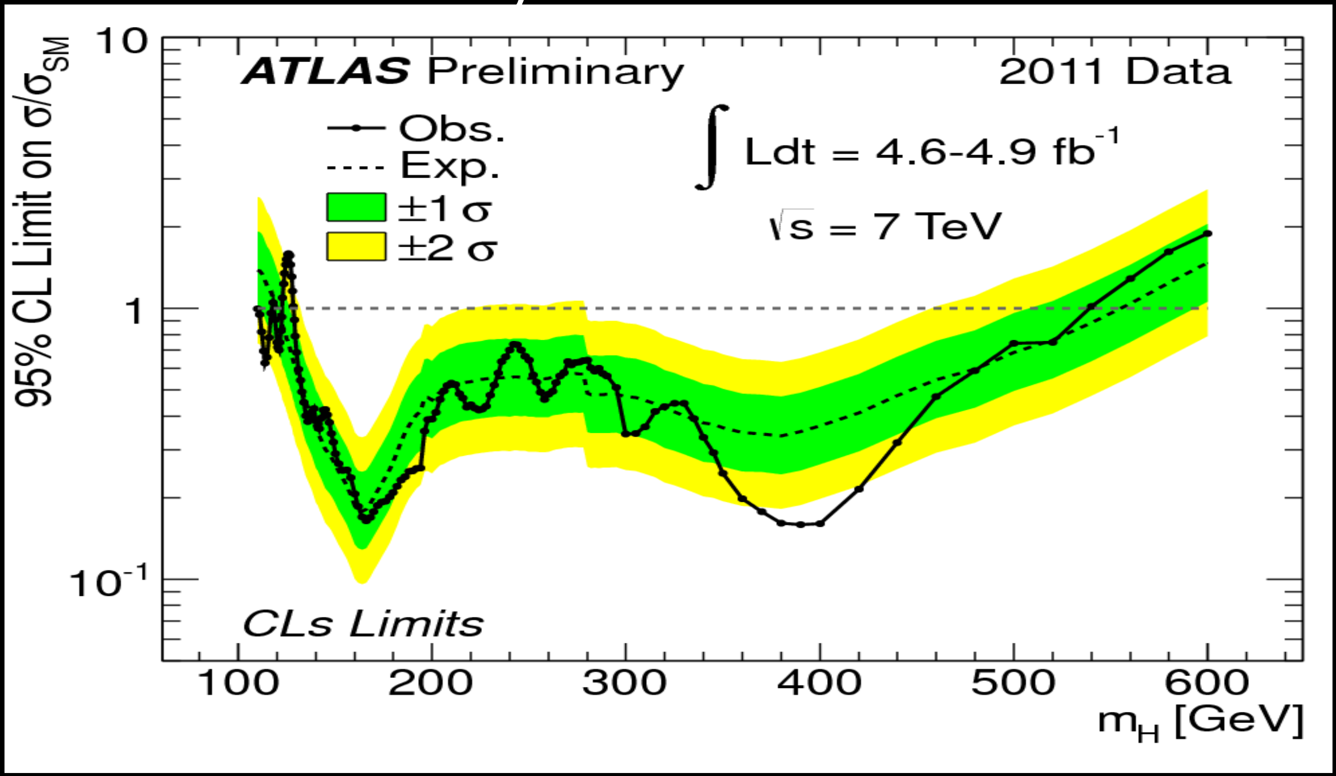


The effect at 125-126 GeV:

A broad excess seen by CDF and D0 in this mass range

CDF+ D0 mostly bb & WW

Summary



Remarkable Progress by ATLAS and CMS In just 9 months and consistency

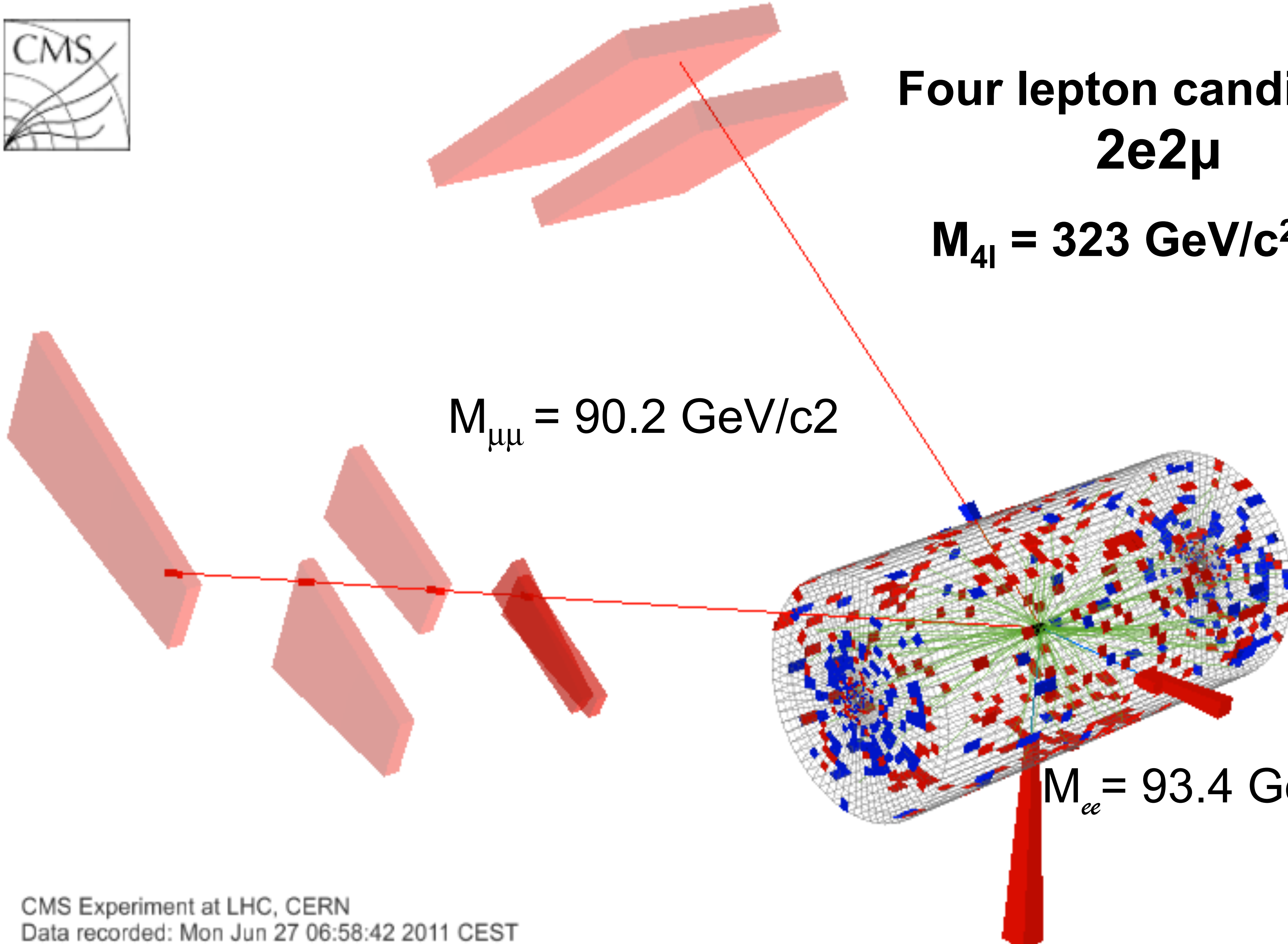
"the results of the experiment were inconclusive so we had to use statistics…"

from Louis Lyon's book "statistics for nuclear and particle physicists"

the Standard Model Higgs boson, if it exists, is most likely to have a mass constrained to the range 115 to 127.5 (CMS) 117.5-118.5 and 122.5-129 (ATLAS) Only with the data we shall collect this year, will we definitely be able to confirm or rule out a Standard Model Higgs.

Four lepton candidate: 2e2μ

M_{4l} = 323 GeV/c^2



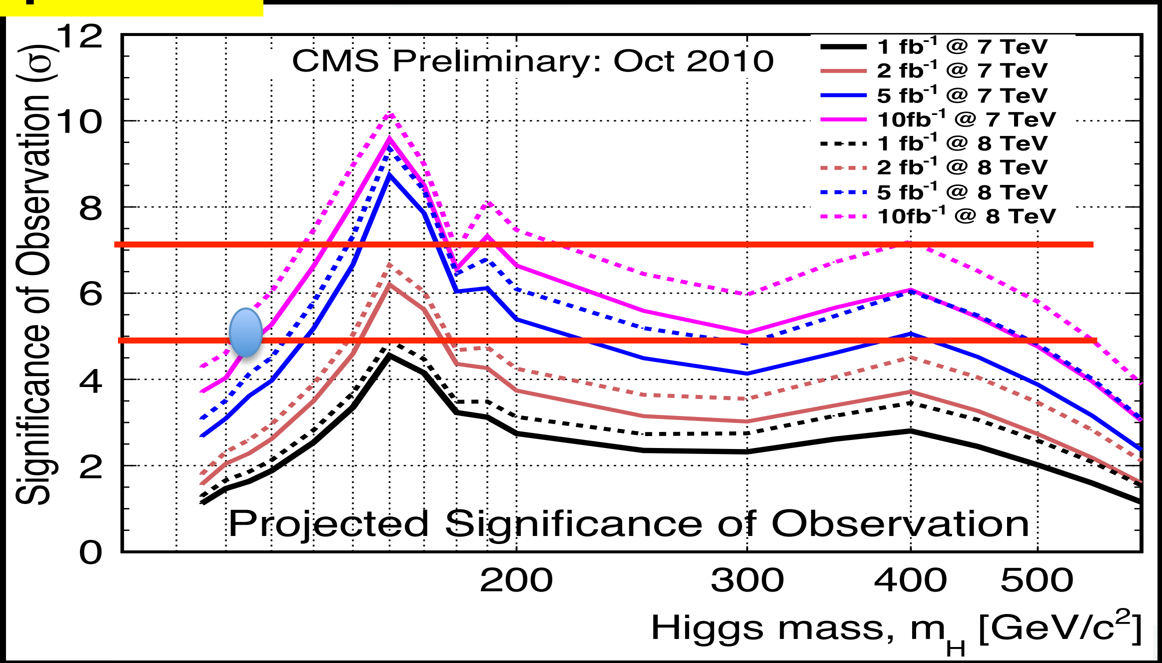
CMS Experiment at LHC, CERN
Data recorded: Mon Jun 27 06:58:42 2011 CEST
Run/Event: 167807 / 966824024
Lumi section: 750
Orbit/Crossing: 196361127 / 722

Higgs Search Prospects

We are tracking earlier projections well

We can therefore reasonably confidently extrapolate

Confirmation/refutation of low Mass Higgs hypothesis will Need > 10/fb @ 7 TeV

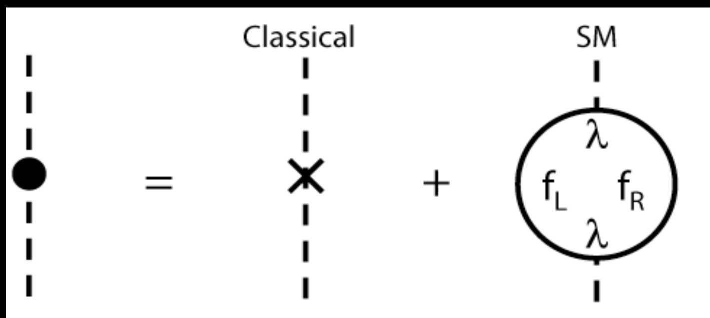


Increasing √s =8 TeV is significant

5σ (local significance) at 125 GeV, if excess due to a signal, in reach in 2012

If Higgs is found a major milestone final missing piece of SM. The end of the beginning of a ~45 year quest to understand electroweak symmetry breaking.
Next stage: Is it really the SM Higgs? Determine properties couplings, spin, width etc.
Is our simplest picture of the origin of mass correct or is electroweak symmetry breaking intertwined with beyond standard model physics?
Both LHC and future lepton colliders will contribute
If Higgs is not found: certain SM processes (WW scattering) have bad high energy behavior without a Higgs, so something must take its place

Problems with the Higgs particle

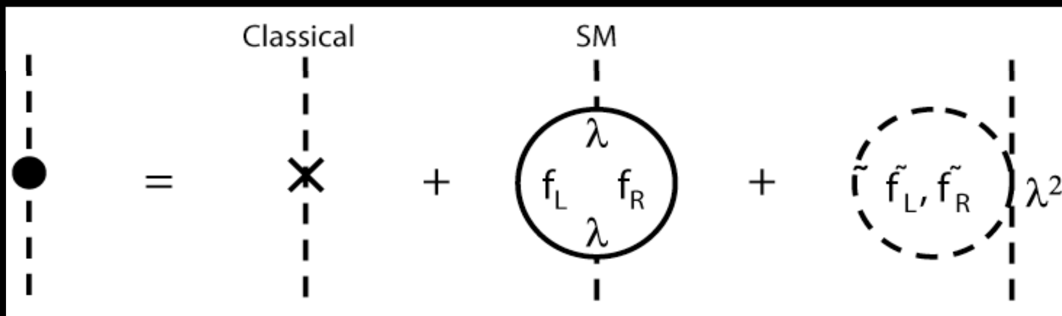


$$m_h^2 = (\, m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots ,$$

- Higgs mass:
  - Virtual particles contribute to the Higgs mass via “loop corrections” that diverge quadratically!
    - Λ is a huge quantity! Could be the Planck scale (10^{19} times the mass of the proton i.e. 10^{19} GeV)

This is an example of the hierarchy problem

The cure comes from partner particles



Cancellation

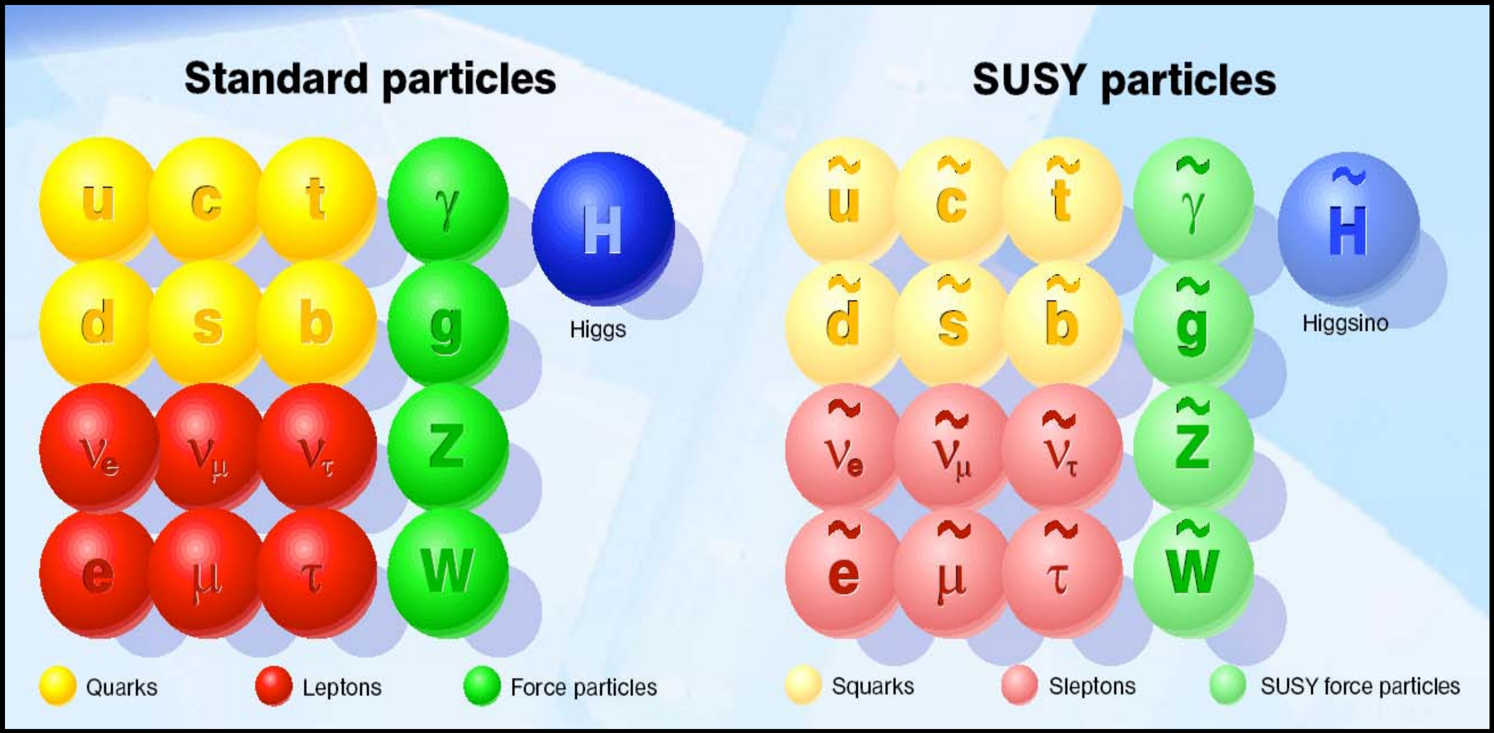
$$m_h^2 = (m_h^2)_0 - \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \frac{1}{16\pi^2}\lambda^2\Lambda^2 + \ldots$$
$$\approx (m_h^2)_0 + \frac{1}{16\pi^2}(m_{\tilde{f}}^2 - m_f^2)\ln(\Lambda/m_{\tilde{f}}),$$

- Partner particles fix this:
  - Need same coupling λ
  - Need partners to have roughly similar masses
    - Otherwise the logarithmic term becomes too large,

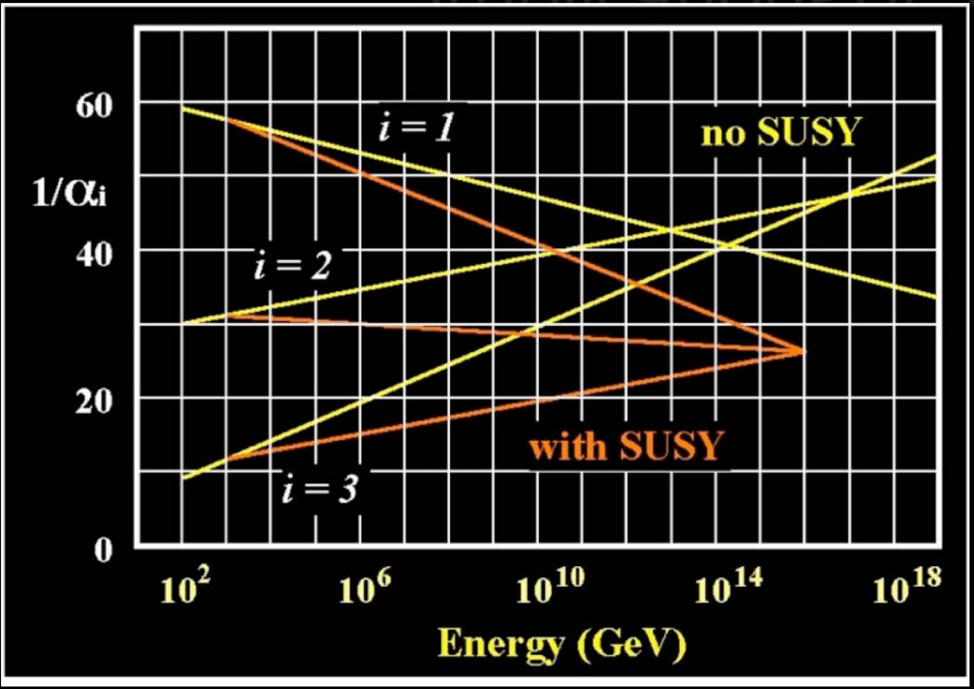
But where do the partner particles come from?

Super Symmetry (SUSY)

- The only unused Symmetry of the Poincare Group
  - For each ½ integer spin particle (Fermion) there is an integral spin (Boson) partner and vice versa
    - Complete spectrum of partners to standard model particles
    - They are heavier and their spins are different by ½ unit



Implications of SUSY



Unification: a mass scale (interaction energy) at which the electromagnetic weak and strong interaction have the same strength. This happens in SUSY but not in the SM

Solution to Higgs mass problem (as just described)

Provides a path to unification with gravity

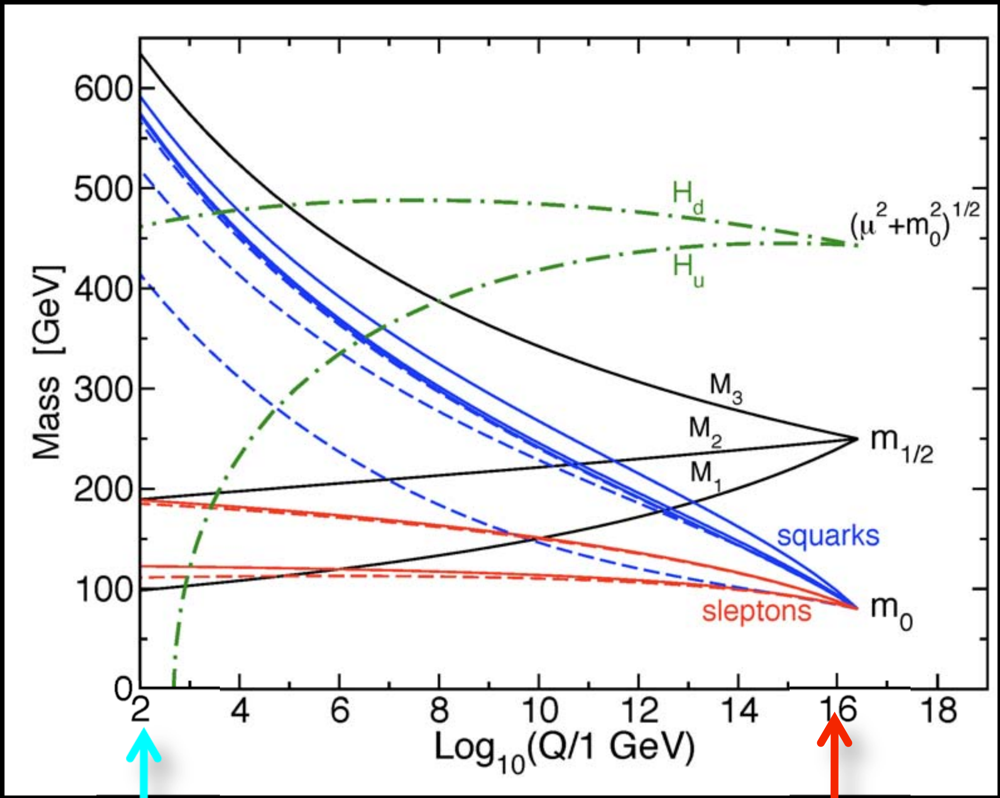
String theory requires supersymmetry

Predicts the existence of stable massive neutral particles (LSP) that are dark matter candidates ex: neutralino or gravitino

25% of the mass-energy of the universe is dark matter, SUSY can happily predict this amount

Example of a Supersymmetric Model: (CMSSM)

- SUSY has >100 free parameters
- We like simplicity and unification
- Derive all of them from minimal set at the unification scale.
  - Where you end up (now) depends on where you started (unification scale just after the Big Bang)

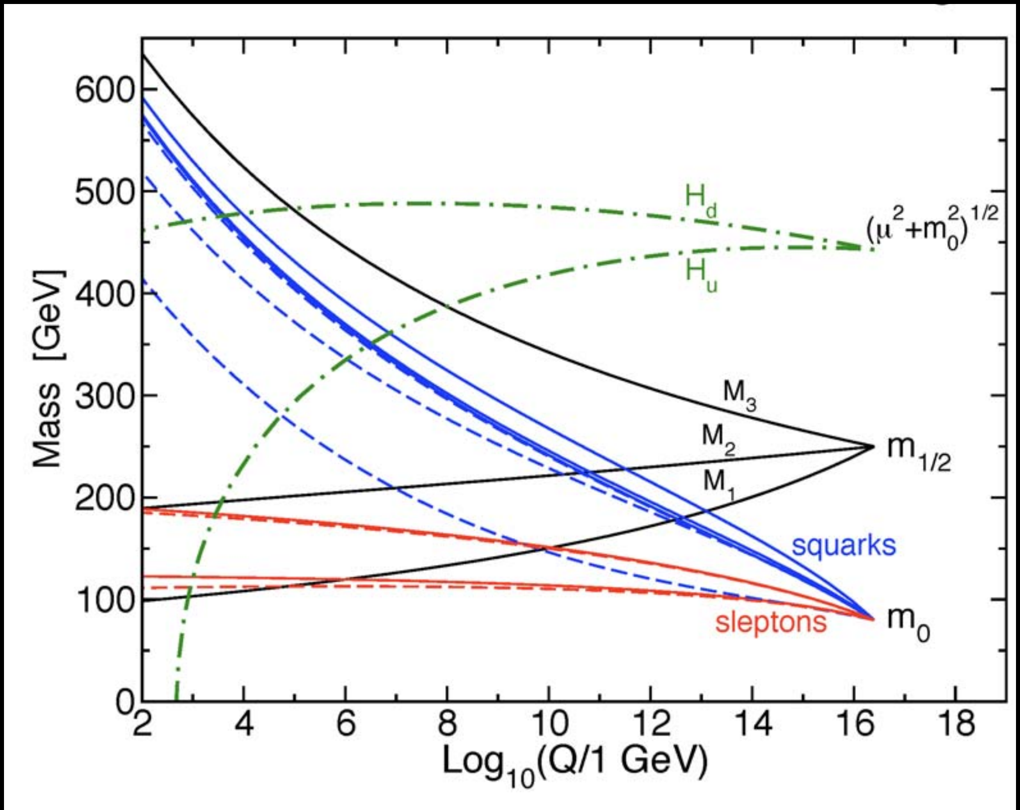


~Now

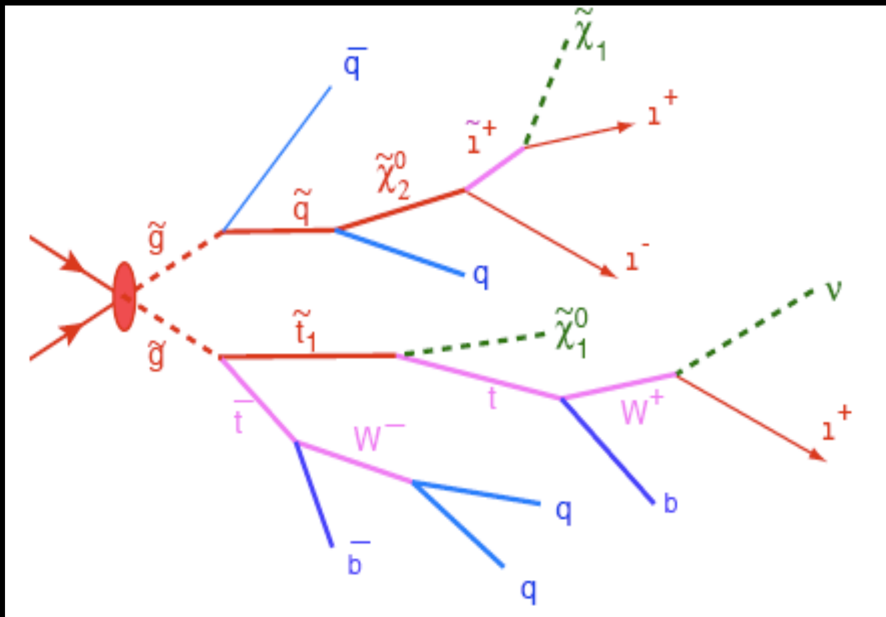
Just after the Big Bang

Example of a Supersymmetric Model: (CMSSM)

- 5 main parameters
  - m_o , $m_{1/2}$, A_o , $\tan(\beta)$, and $\text{sign}(\mu)$
- m_o and $m_{1/2}$ are "universal masses"
- We don't know what m_o and $m_{1/2}$ were at the start so we have to scan ...
  - More on this later…



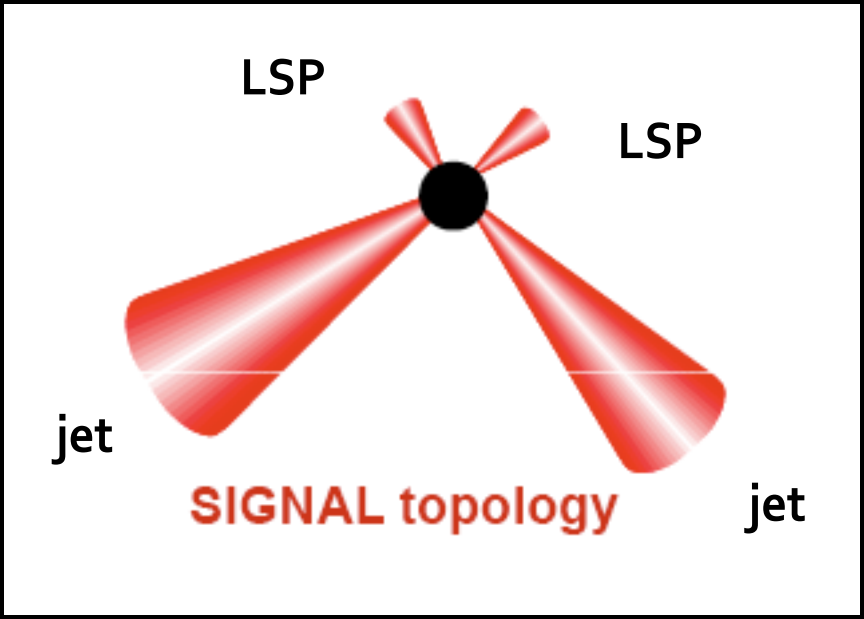
SUSY Search



Example of production of Gluino pairs at the LHC that decay to quarks and other SUSY particles.

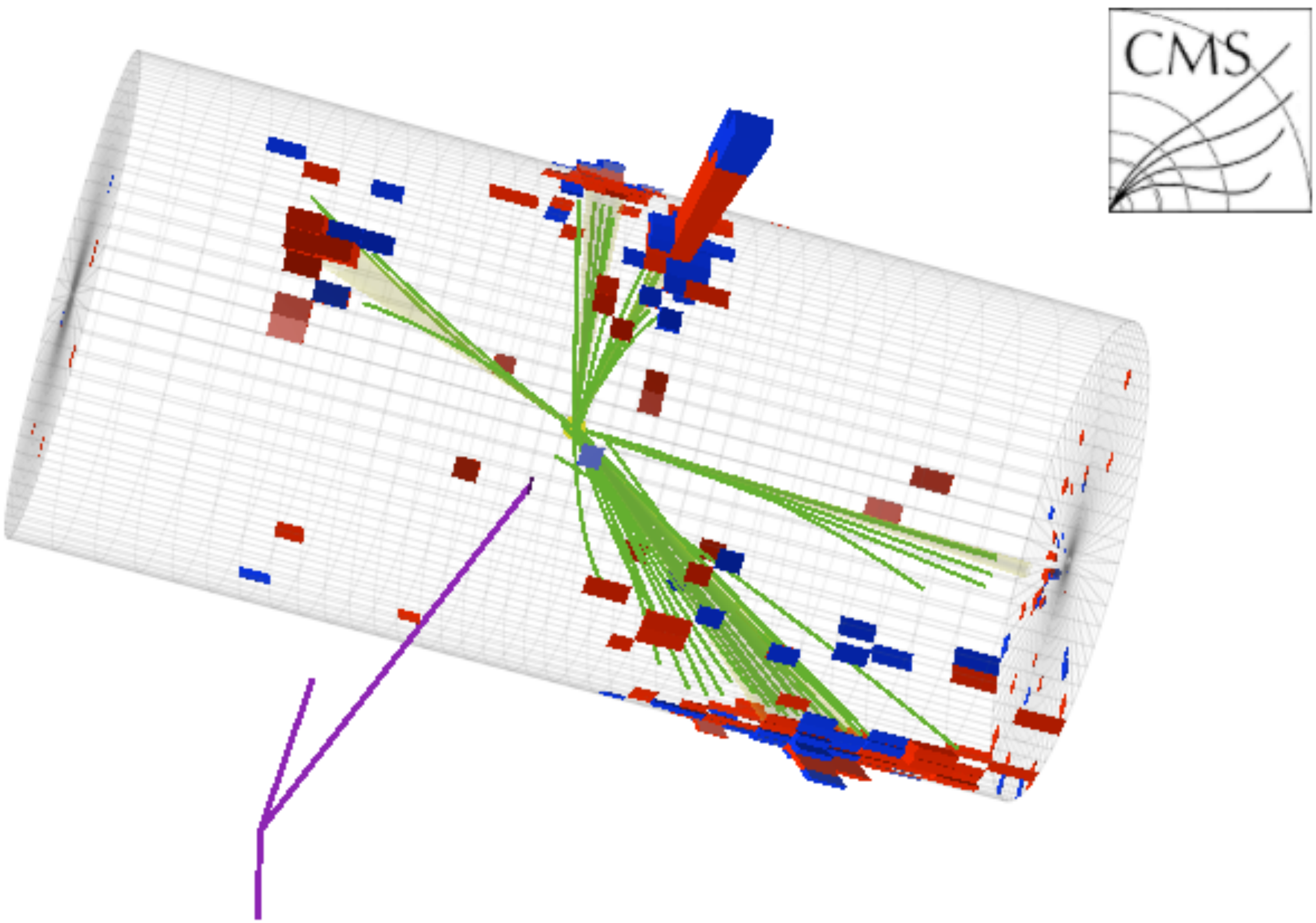
- Final States:
- Missing Energy from:
  - Neutralinos and Neutrinos
    - Dashed green lines
- Jets of particles:
  - Formed around final state quarks and gluons
    - Solid blue lines
- Leptons:
  - From decays of SUSY partners to the leptons and Weak force carriers
    - Solid red lines
  - From the weak force carriers themselves: $W^{\pm}$ and Z^o

Anatomy of a SUSY search using events with jets

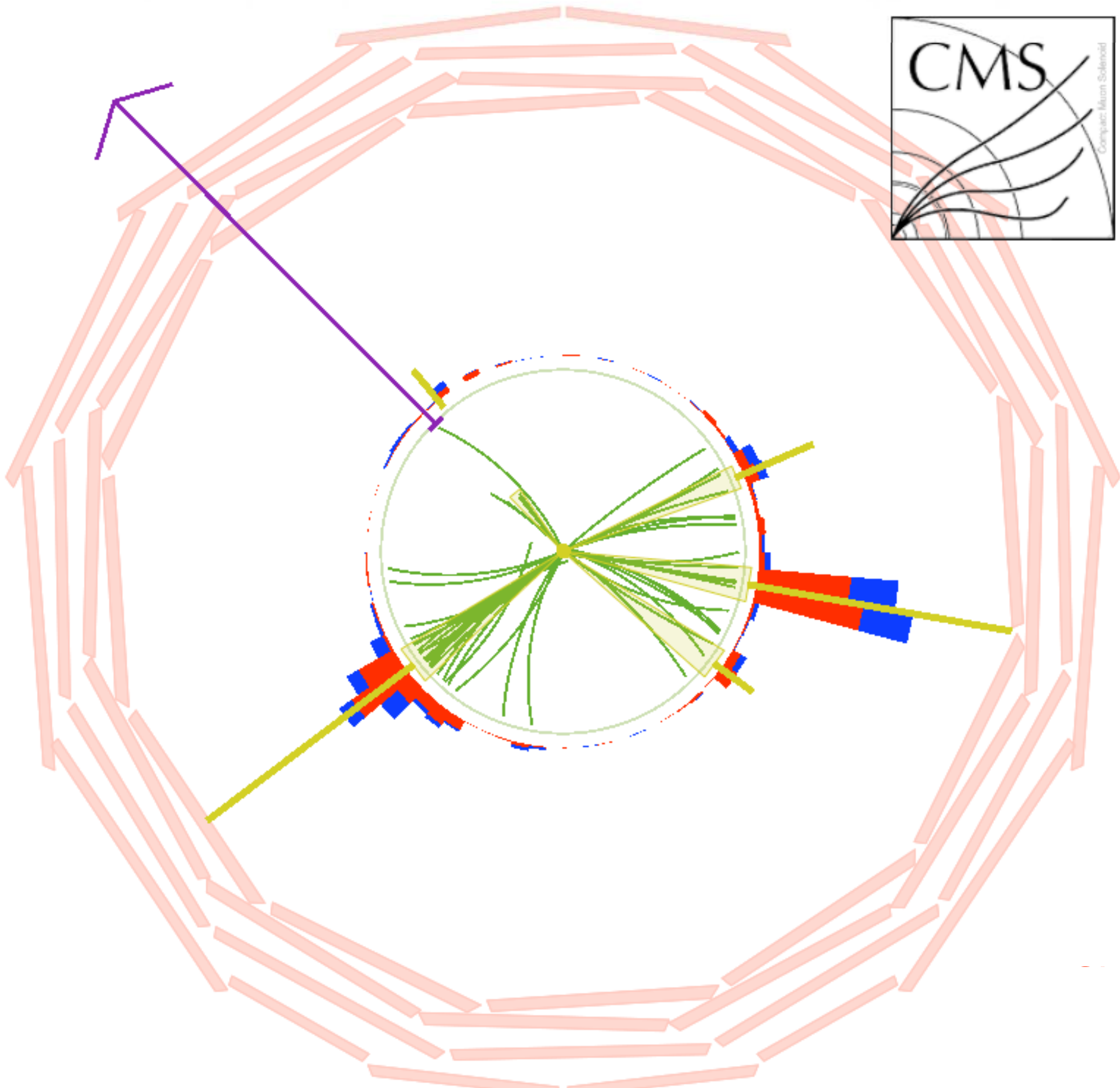


- Example LHC produces $Q\bar{Q}$ (Squark–antisquark pair)
- $\bar{Q}$,Q decay to quarks and Dark Matter (LSP):
  - $Q \rightarrow q$+LSP
  - $\bar{Q} \rightarrow \bar{q}$+LSP
    - Lightest SUSY Partner (LSP)
- Signature
  - 2 or more jets of particles
    - from q and $\bar{q}$
  - And missing energy
    - From the 2 LSP

Signal = Jets with missing energy



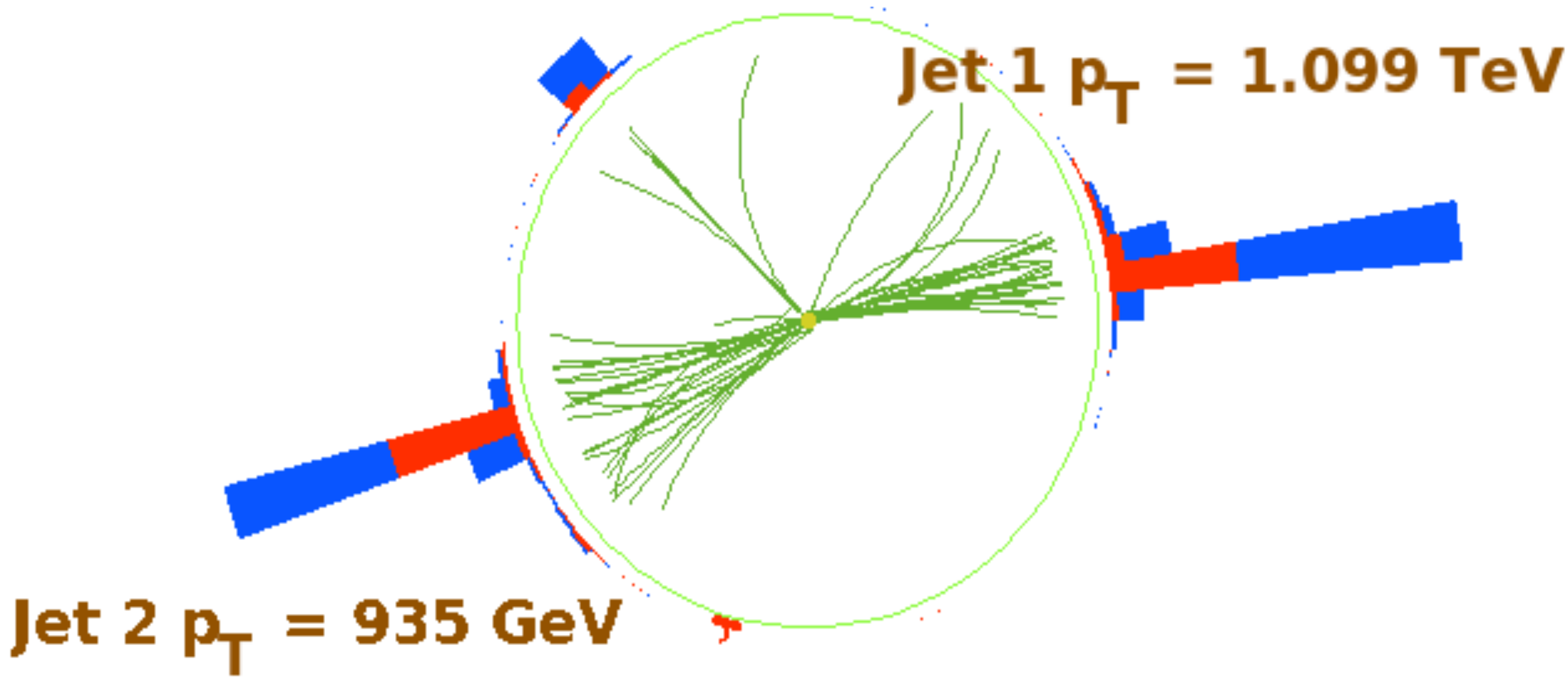
Energy imbalance perpendicular to beams



The backgrounds

- Main concern: jets from quarks and gluons
  - Showers of many particles in our detectors
  - Sometimes imbalanced because one or more is mismeasured
- Other backgrounds
  - W+jets (also from top quarks) and Z+jets

Jets that are not balanced

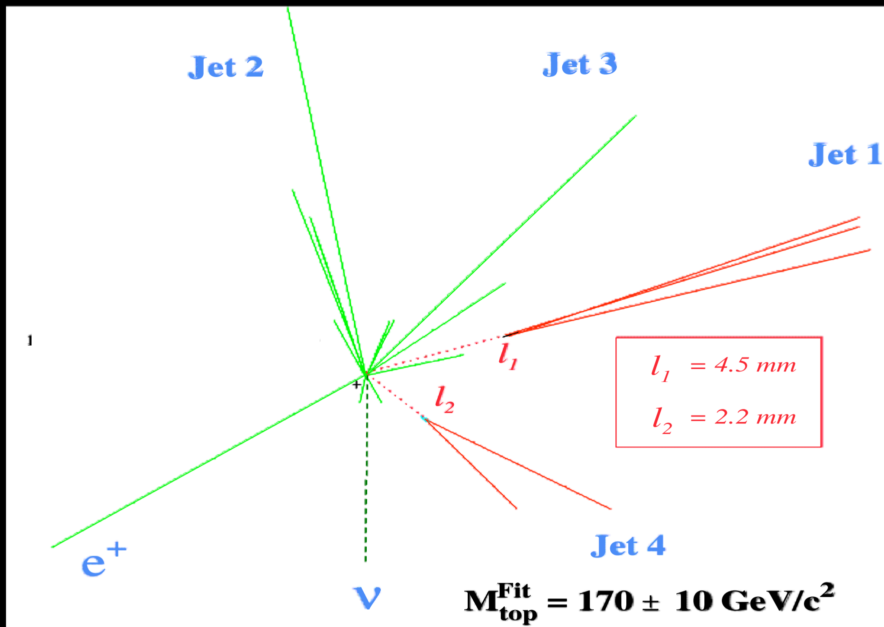


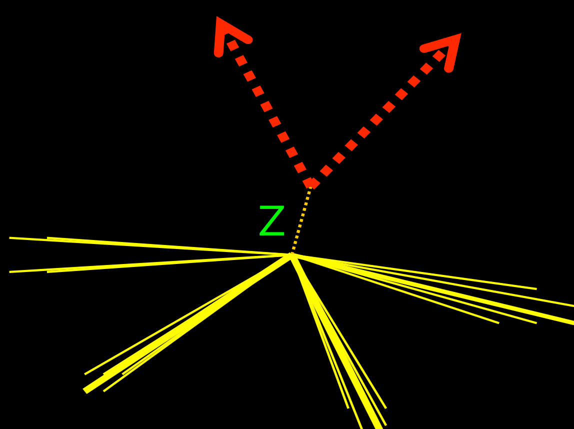
Imbalances can be due to instrumental effects (noise and dead channels), fluctuations in how jets are manifested, and even neutrinos in jets.

Run 144112 Event 1189490855

M_{jj}~2.05 TeV

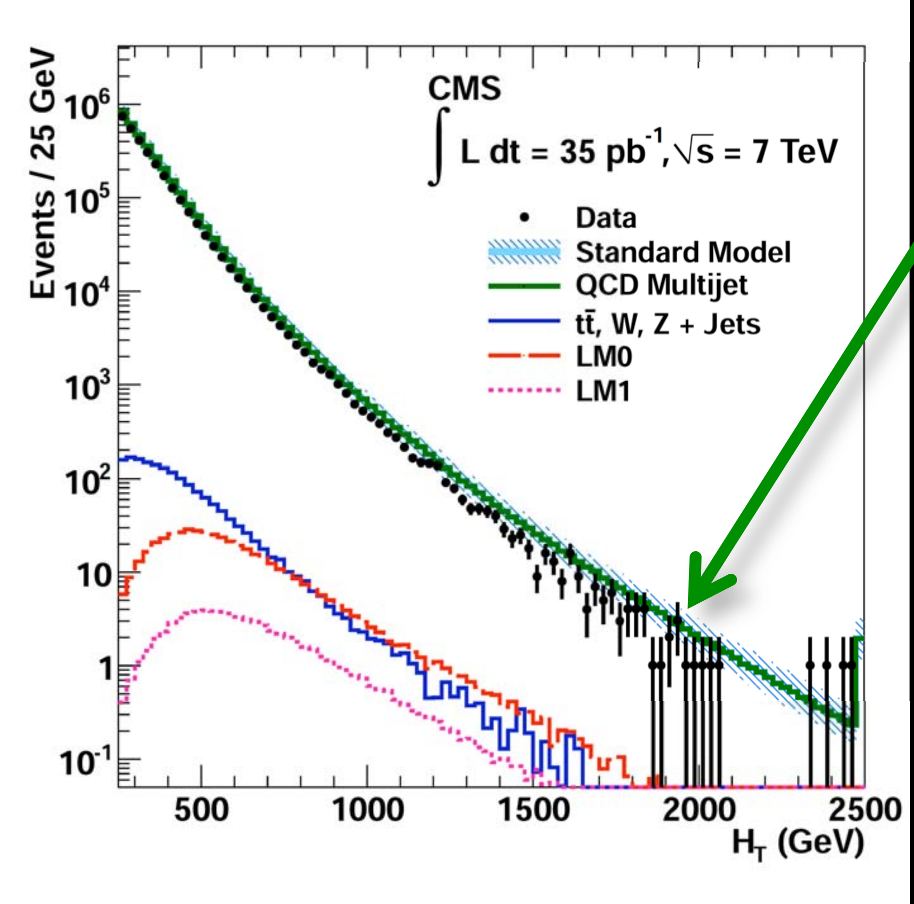
top, W+jets or Z +jets backgrounds





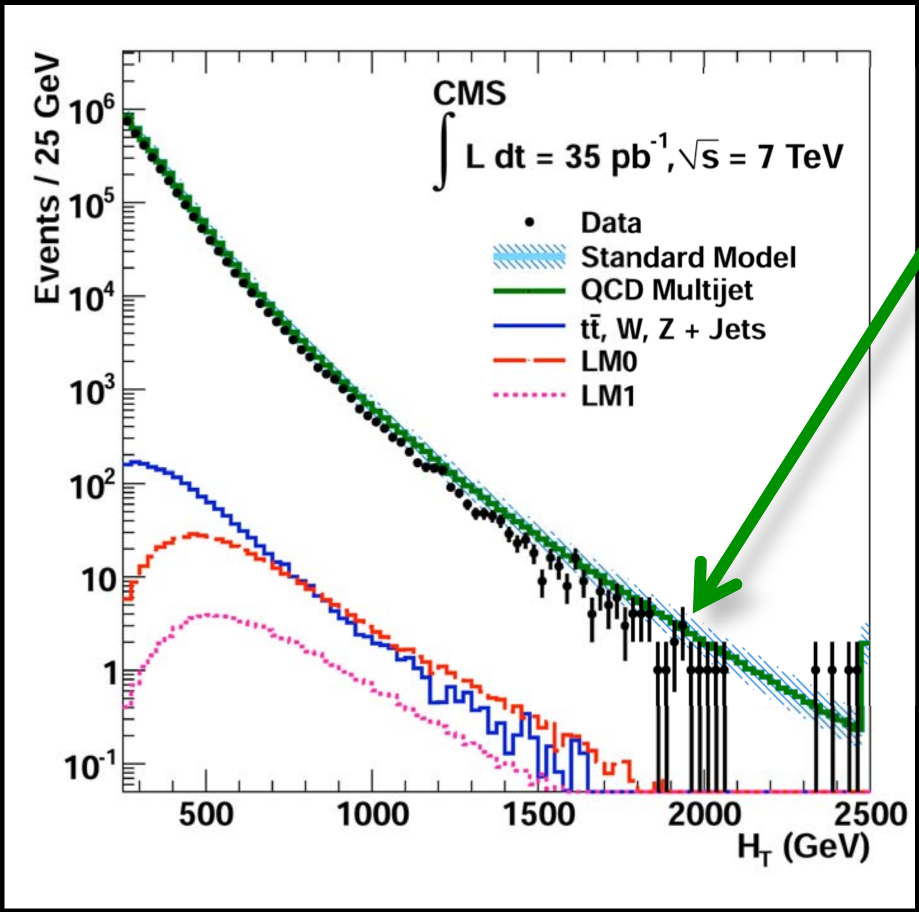
- We cannot detect neutrinos
- Top quarks decay to a W and a bottom quark
  - $t \rightarrow Wb$
- W's sometimes decay to a lepton and neutrino
  - $W \rightarrow e\nu$
- Z's sometimes decay to 2 neutrinos
  - $Z \rightarrow \nu\bar{\nu}$

The Data

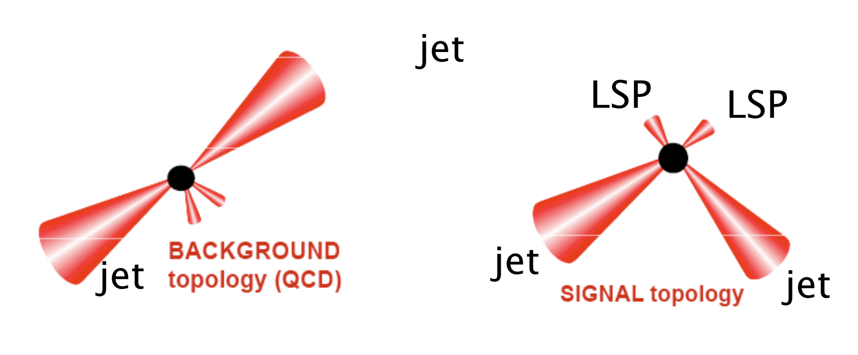


- This plot shows a distribution of measured numbers of events (black points with error bars) as a function of the sum of the energy of the jets in the event (H_T)
- The green curve is what we roughly expect to come from jets
- The blue curve is what we expect from W's, Top, Z's
- The red and magenta curves are what we expect from some possible SUSY points (different m_o, $m_{1/2}$)

The Data



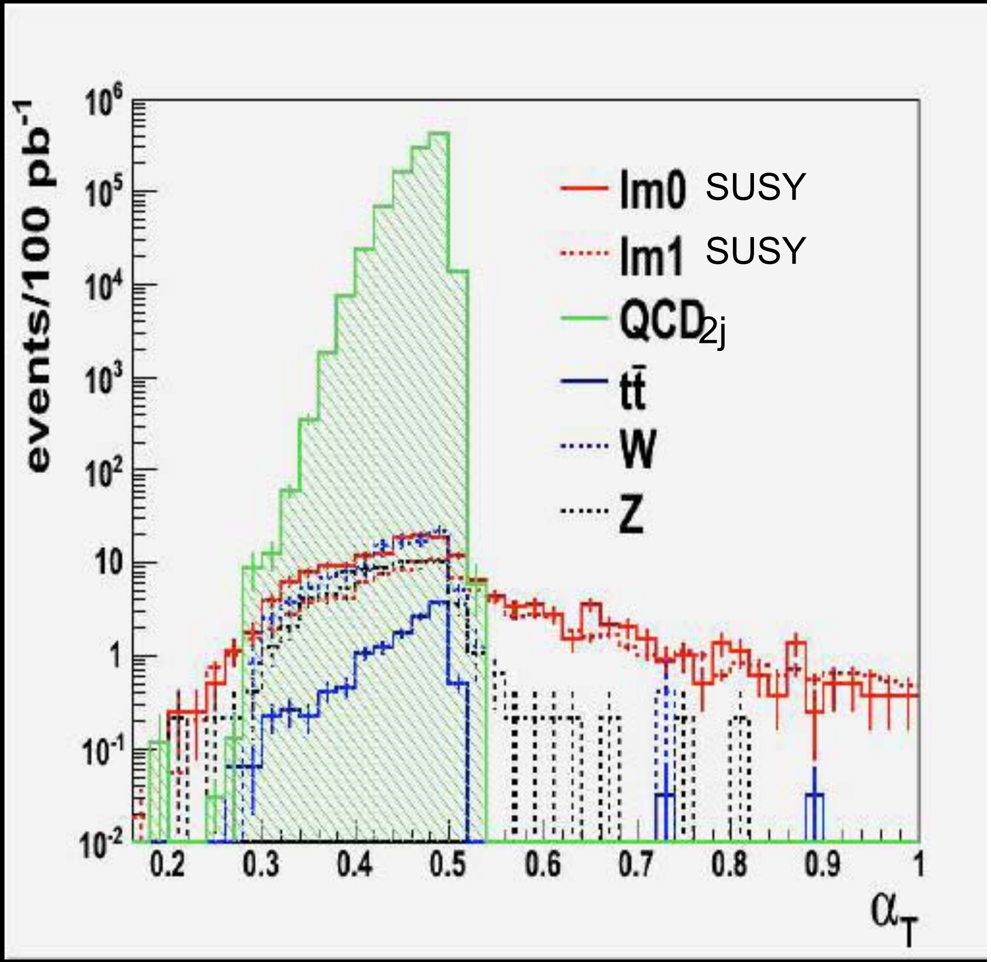
- How to deal with these jet events?
- We use a kinematic variable that can separate the signal from the background



$$\alpha_T = \frac{E_{T\ j2}}{M_{T\ j1j2}} = \frac{\sqrt{E_{T\ j2}/E_{T\ j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

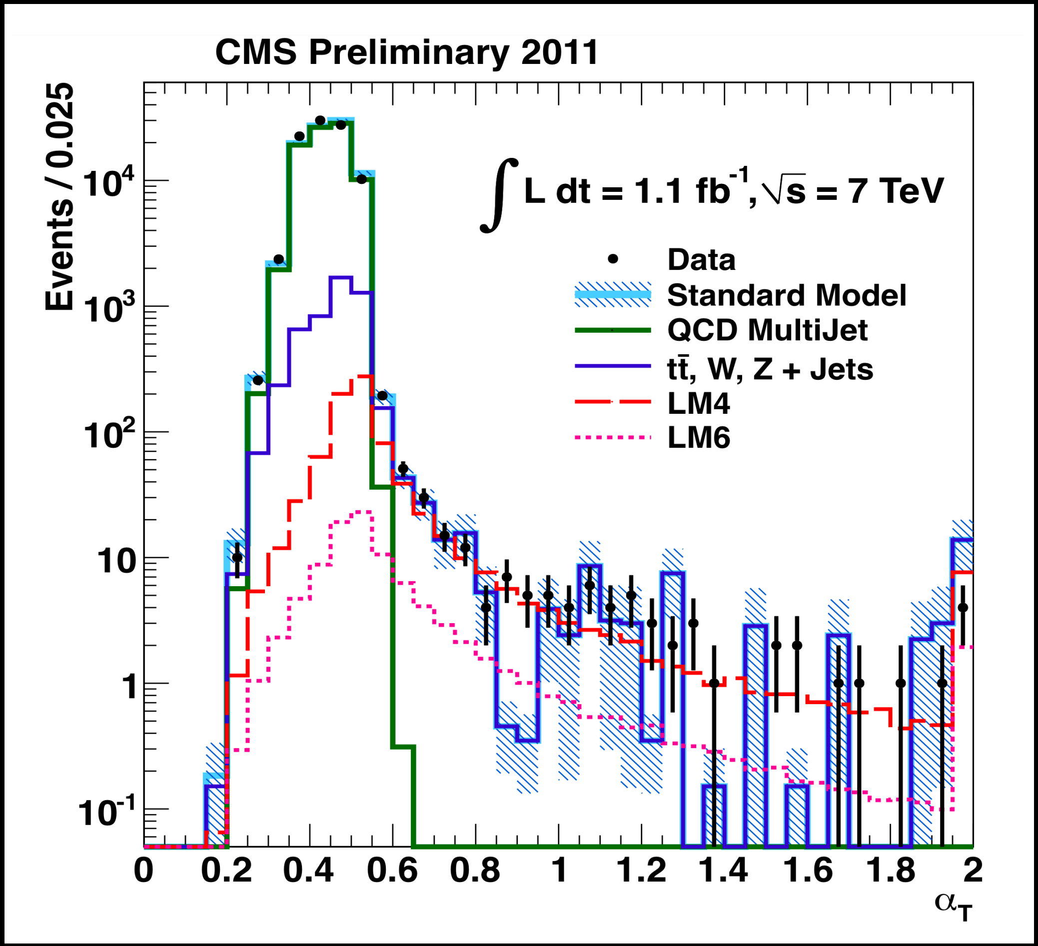
SUSY search with jet events using α_T

- Signature:
  - Typically ≥ 2 jets + Missing energy
- For $\alpha_T > 0.55$
  - Essentially no jet events
  - But there is SUSY and some top quarks, W, and Z events



Plot shows CMS Simulations

Application to the data



CMS Reference

Measure standard model top, W Z backgrounds in independent control Samples in data

Look for an excess above Background, none found

Calculate acceptance & efficiency for each value of m0, m1/2

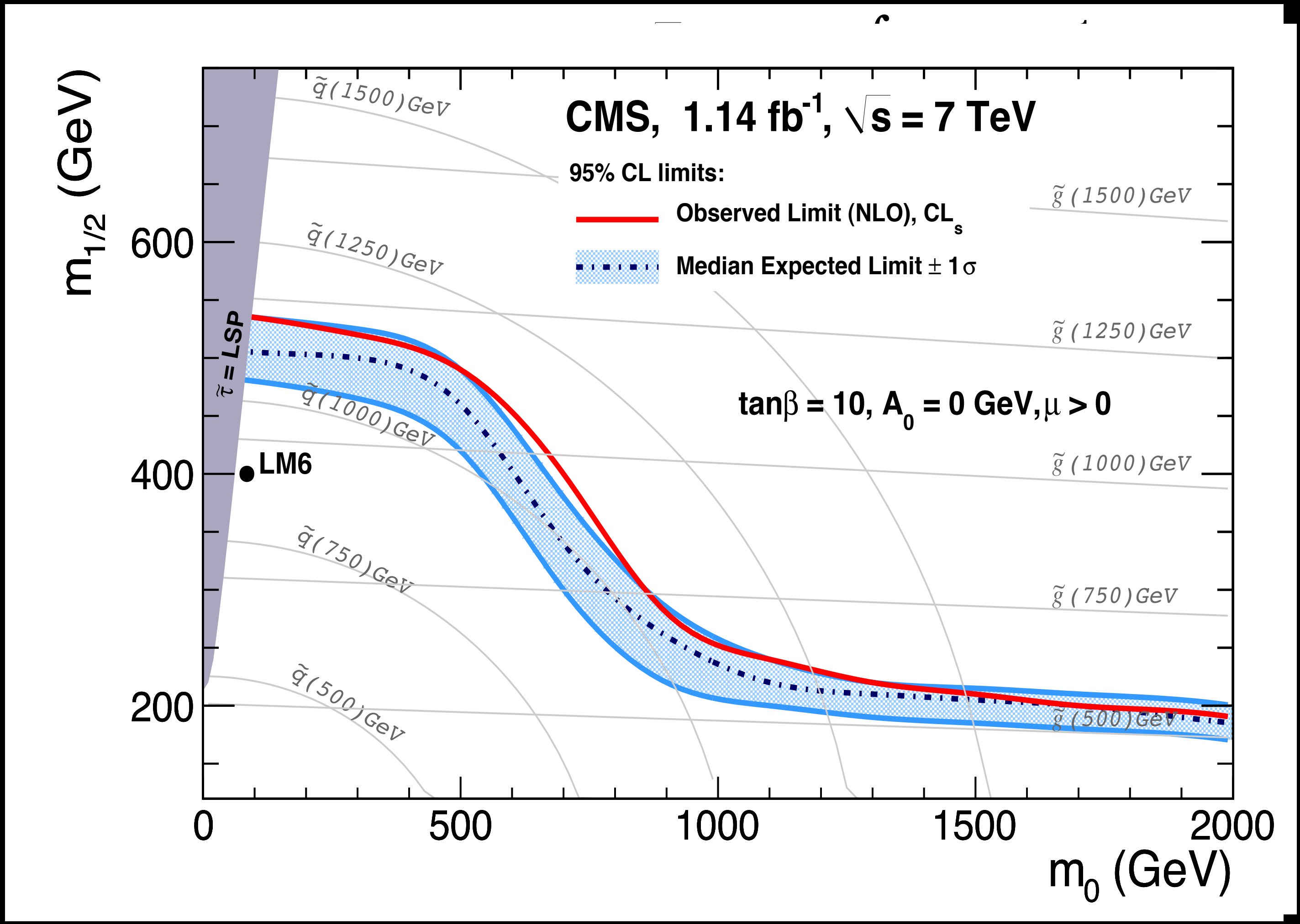
Obtain upper limits as a a function of m0, m1/2

Method works well

Method applicable to multiple jets too

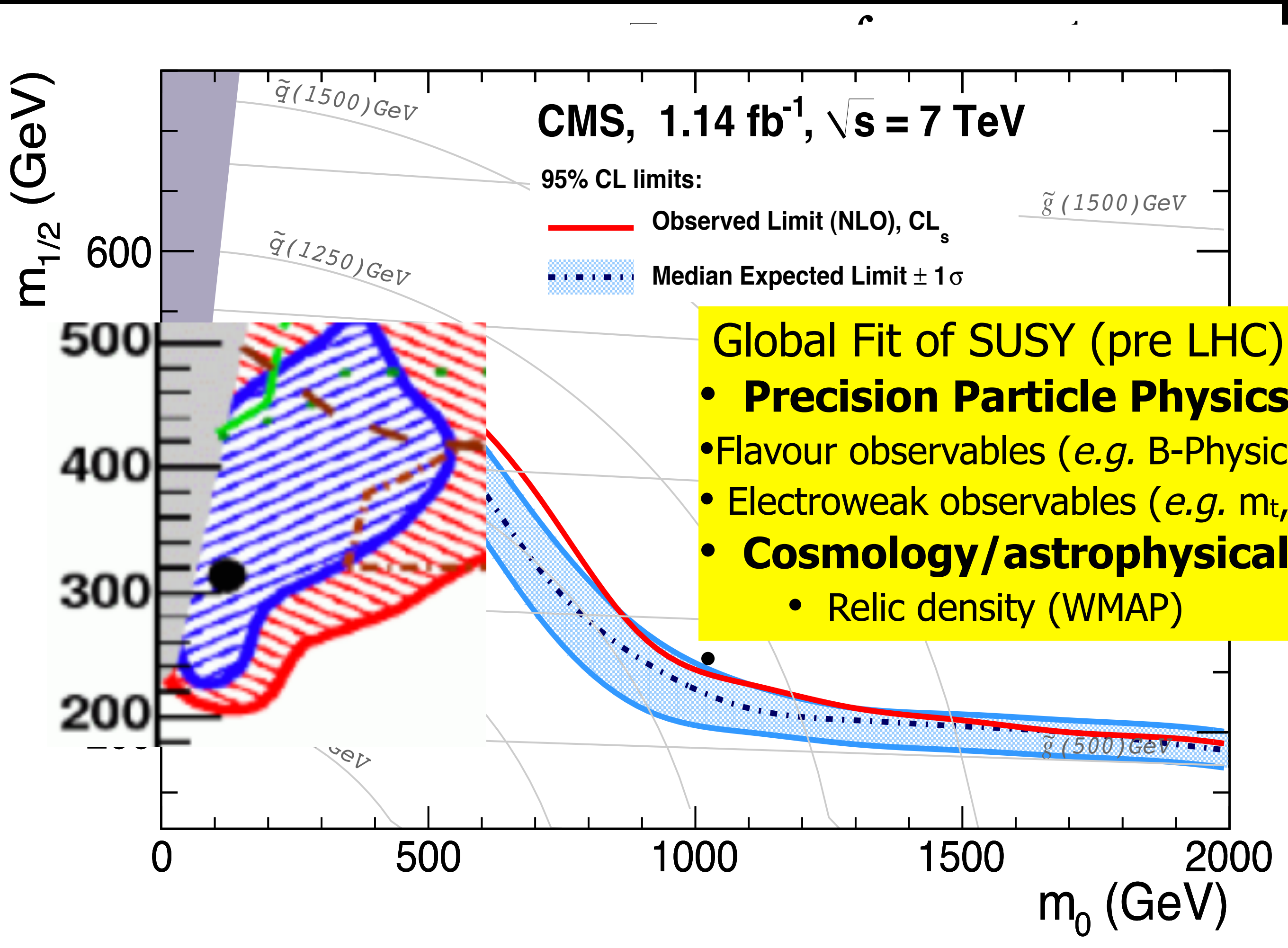
Summary of CMS α_T Search for SUSY

- Observed limits from the α_T SUSY search plotted in the CMSSM (m_0, $m_{1/2}$) plane



Summary of CMS α_T Search for SUSY

- Observed limits from the α_T SUSY search plotted in the CMSSM (m_0, $m_{1/2}$) plane

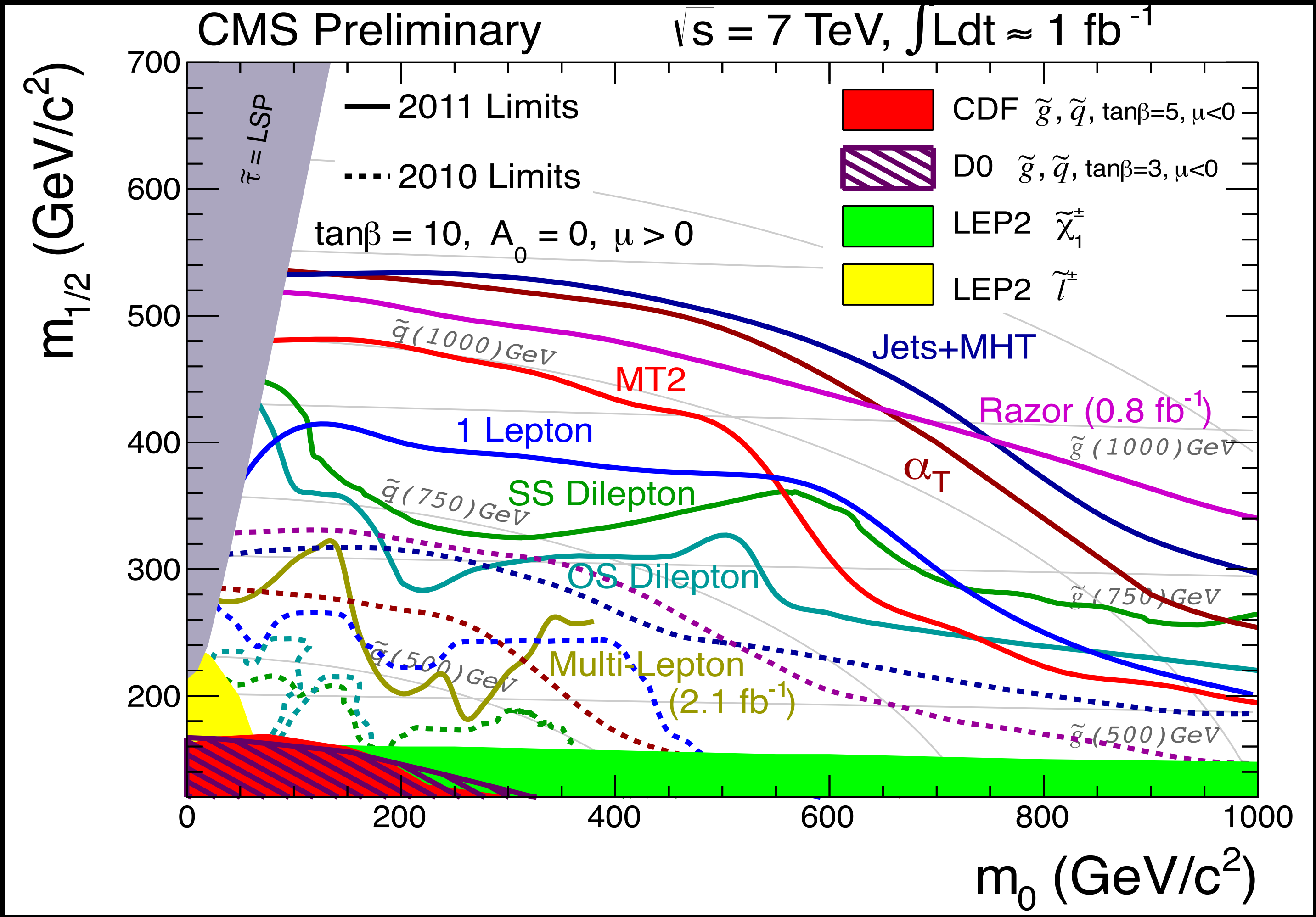


Global Fit of SUSY (pre LHC)

- **Precision Particle Physics data**
- Flavour observables (*e.g.* B-Physics, g-2
- Electroweak observables (*e.g.* m_t, m_W)
- **Cosmology/astrophysical data**
  - Relic density (WMAP)

Summary of *all* CMS Searches for SUSY

- Squarks < ~ 1 TeV are excluded in cMSSM, gluinos too for m_0<500 GeV
- Update to full data set (x5 this plot) is in process, some 5/fb searches shown at both Morionds (2012) from ATLAS and CMS



Summary of *all* CMS Searches for SUSY

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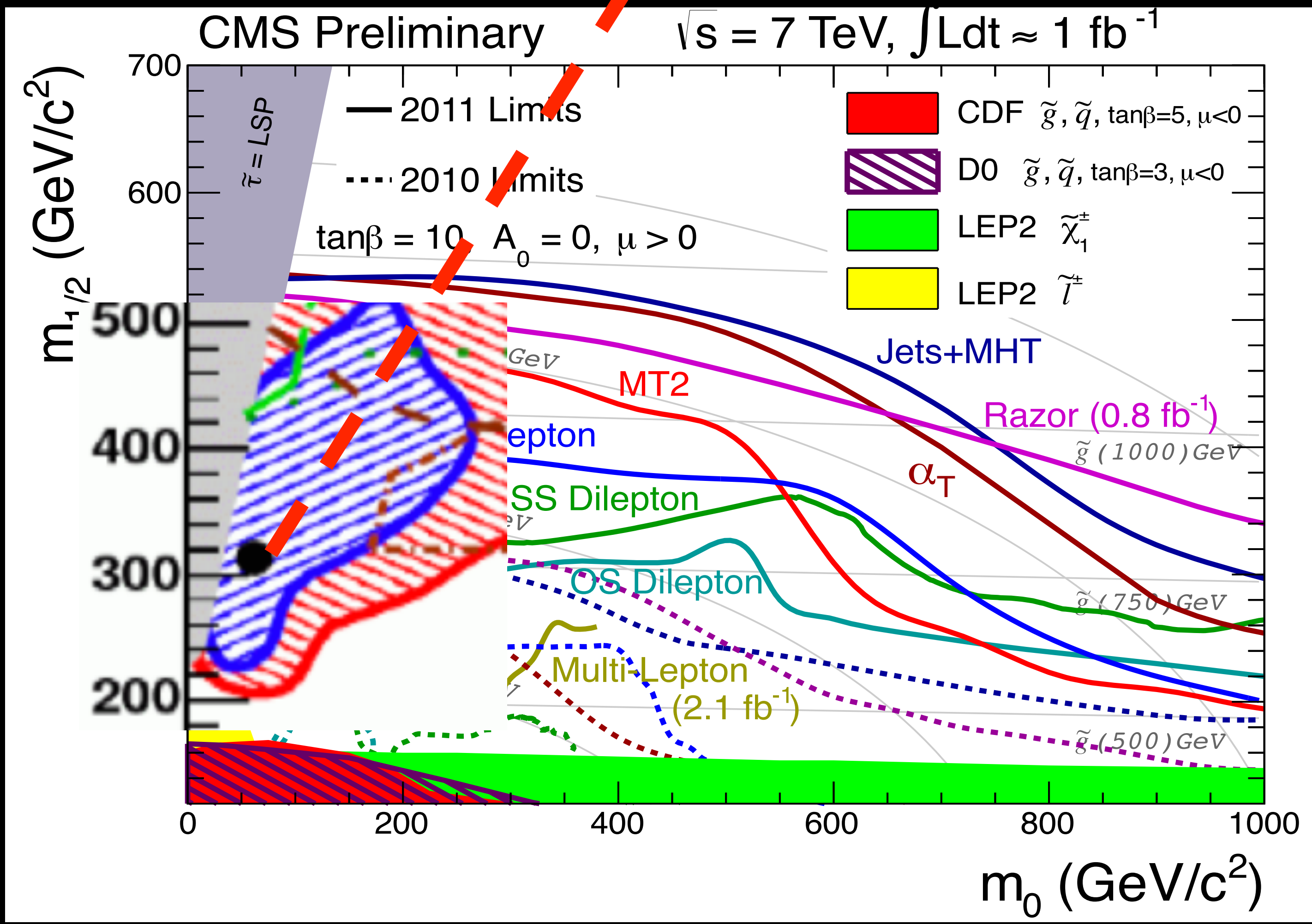
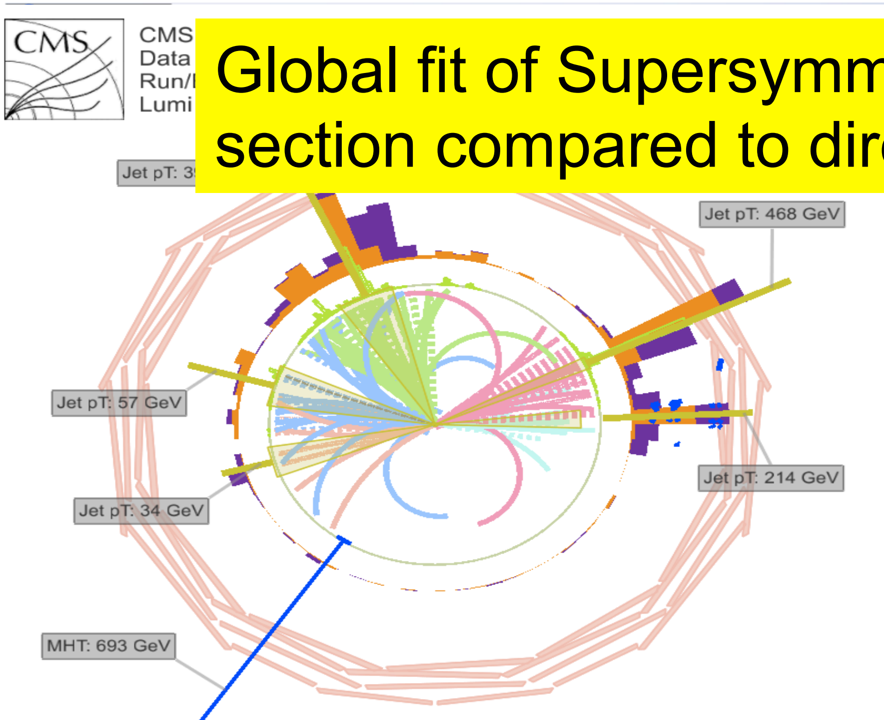
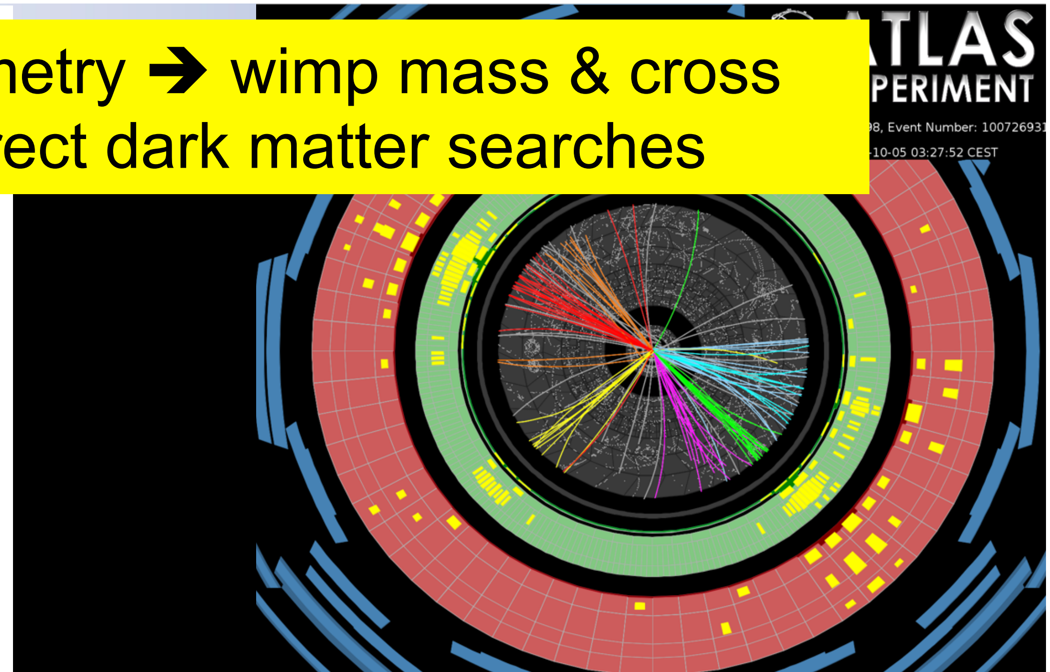


Global fit of Supersymmetry ➔ wimp mass & cross section compared to direct dark matter searches





Global Fit of SUSY :

- **Precision Particle Physics data**
- Flavour observables (*e.g.* B-Physics, g-2
- Electroweak observables (*e.g.* m_t, m_W)

Cosmology/astrophysical data

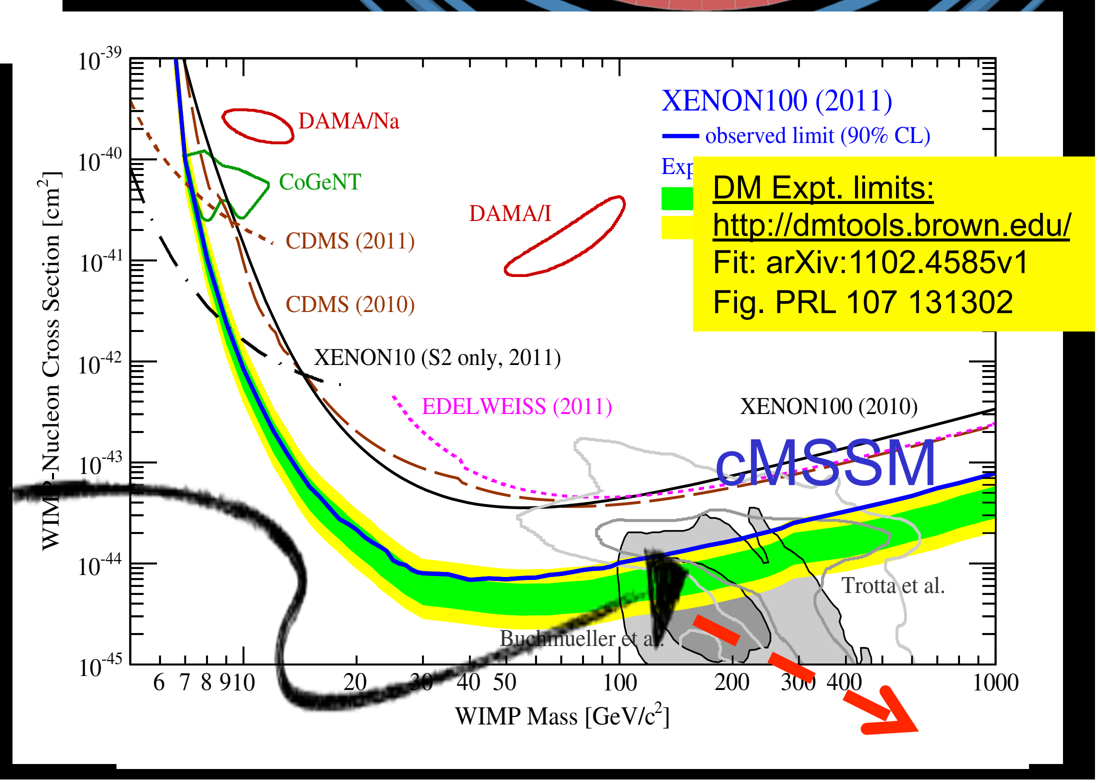
Relic density (WMAP)

ATLAS, CMS, LHCb data

Direct searches

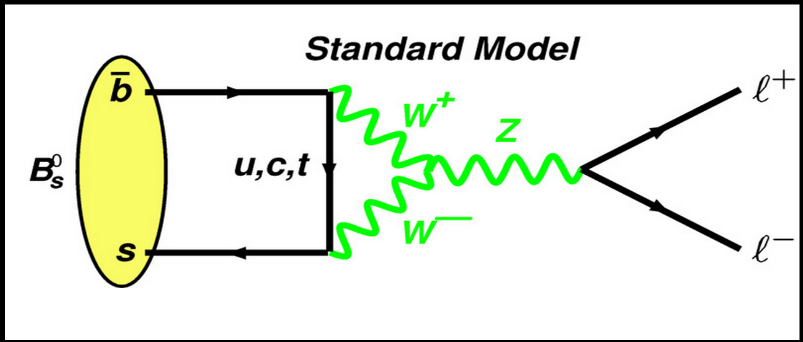
XENON100 direct Dark Matter search cut into allowed fit region 2010 LHC run

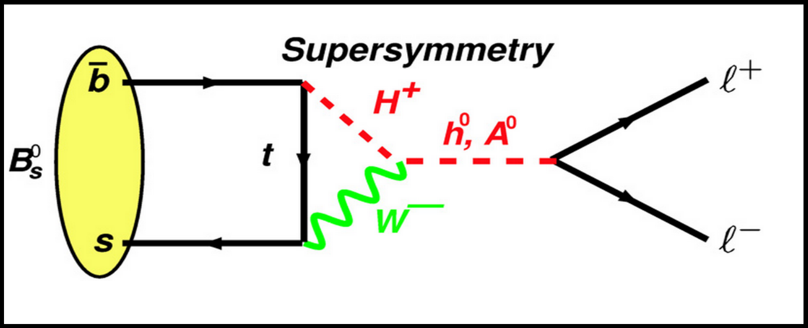
Allowed region has moved lower in 2011 LHC run (red dashed arrow)

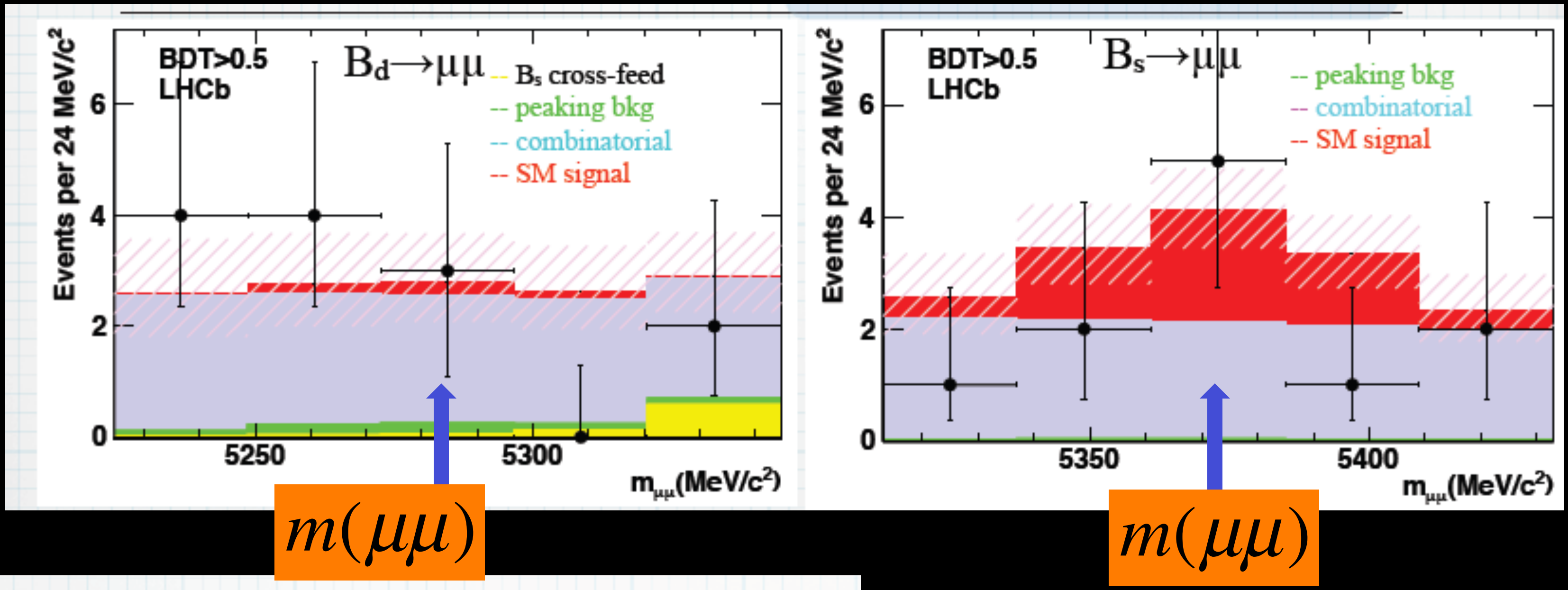


DM Expt. limits: http://dmtools.brown.edu/
Fit: arXiv:1102.4585v1
Fig. PRL 107 131302

LHCb is an intensity frontier experiment at LHC studying b & c quarks







- SM prediction (FCNC, helicity suppressed)
  - SM $B(Bs \to \mu\mu) = (3.2 \pm 0.2)\ 10^{-9}$
  - SM $B(B \to \mu\mu) = (0.1 \pm 0.01)\ 10^{-9}$

arXiv:1005.5310
arXiv:1012.1447

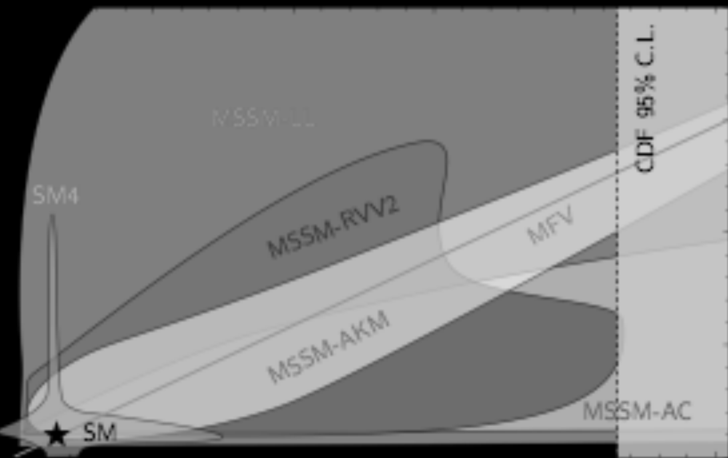
- Branching ratio very sensitive to NP

$B(B_s \to \mu\mu) < 4.5\ 10^{-9}$ at 95% CL

$B(B \to \mu\mu) < 10.3\ 10^{-10}$ at 95% CL

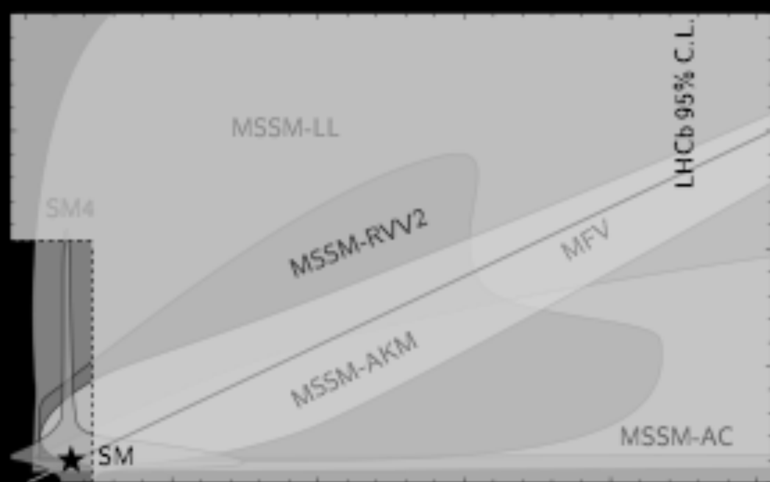
best limit!

Then:
(prior to
June 2011)



Straub
Moriond
EWK
Parkinson
Moriond
QCD

Now:



SOON these decays will be measured providing complementary information to direct searches for SUSY particles

The road to SUSY
Minimal SUSY models severely constrained

………… many more SUSY possibilities pMSSM, NMSSM, low MET signatures, R-parity violating…

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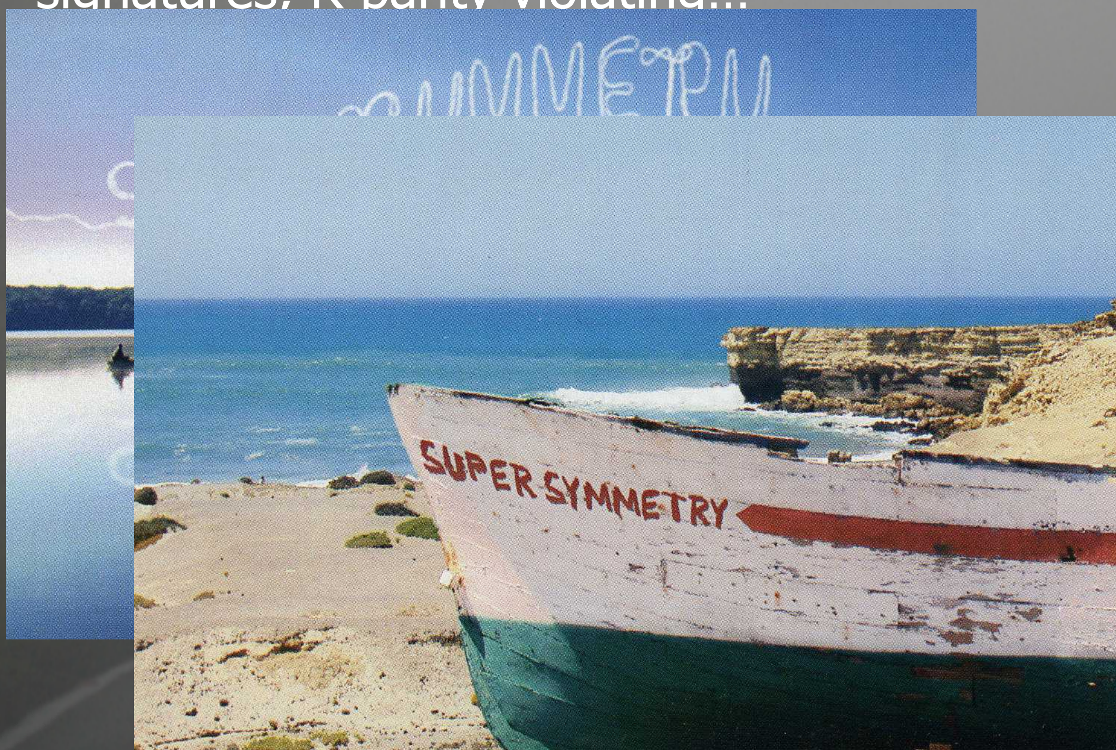
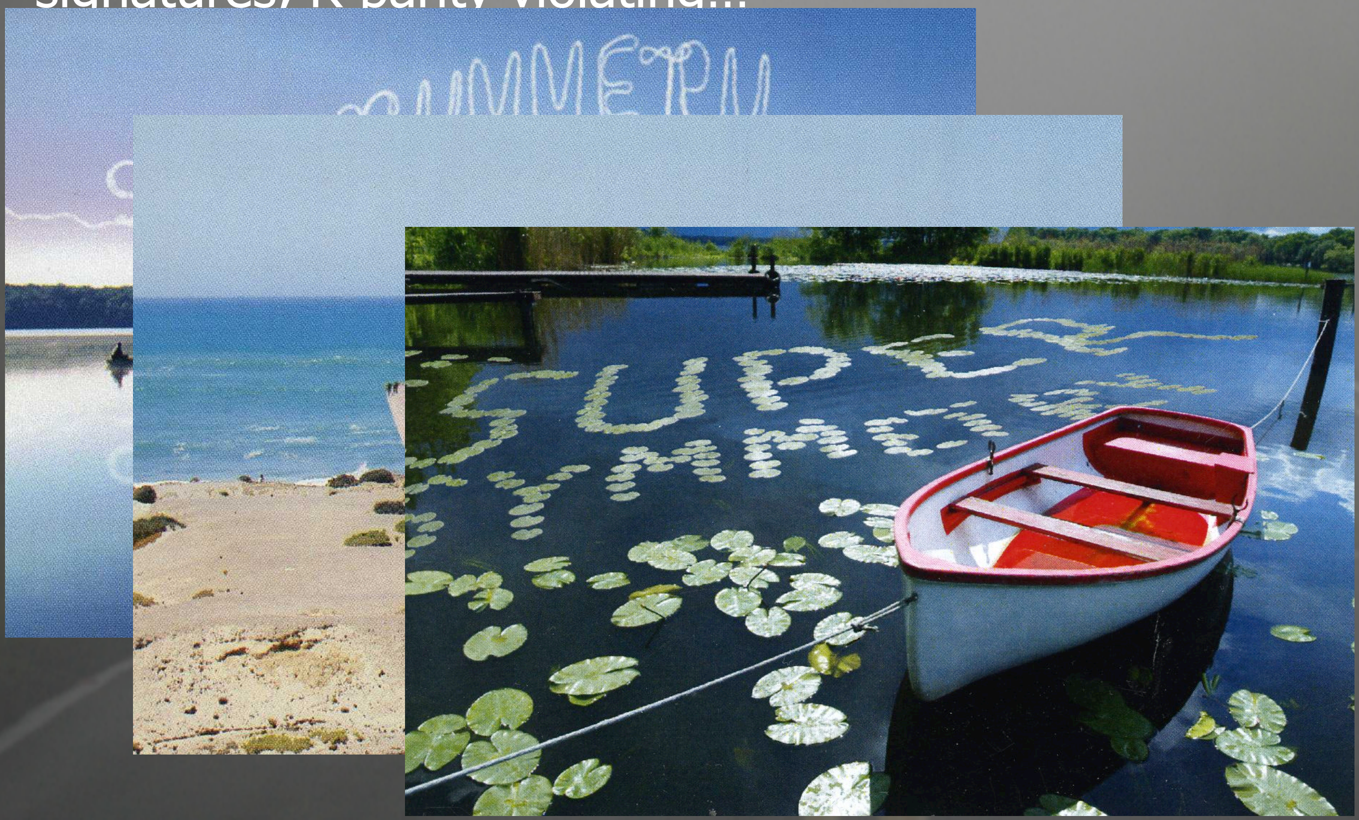


The road to SUSY
Minimal SUSY models severely constrained

………… many more SUSY possibilities pMSSM, NMSSM, low MET signatures, R-parity violating…

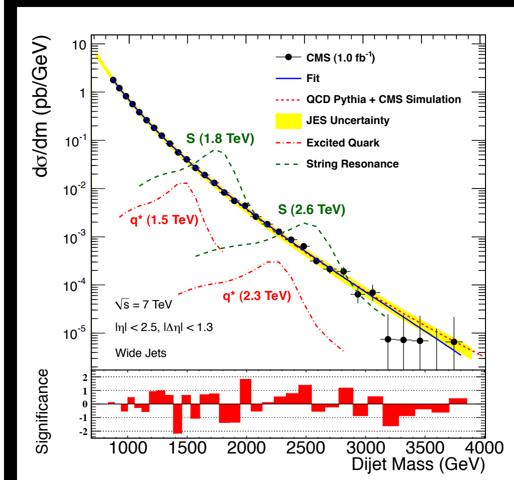


The road to SUSY
Minimal SUSY models severely constrained

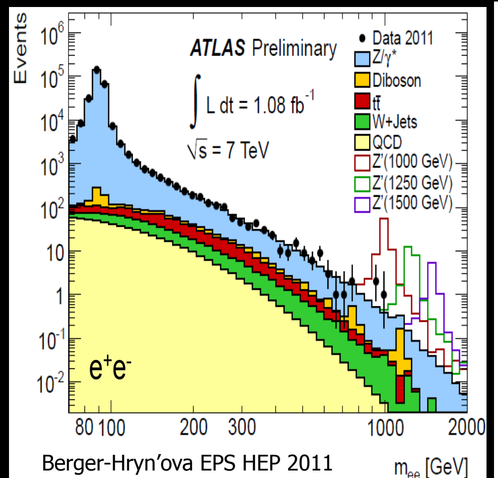
………… many more SUSY possibilities pMSSM, NMSSM, low MET signatures, R-parity violating…

Exotica: Off Road

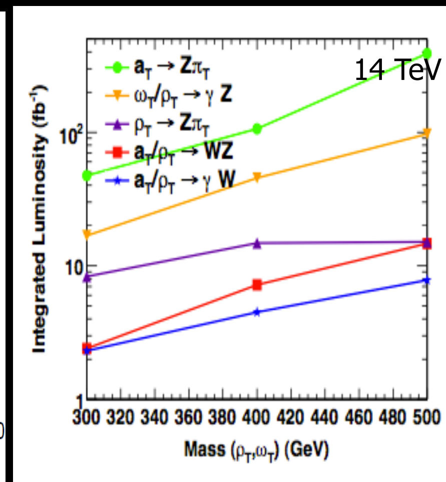
Contact Interactions ? Excited quarks ?



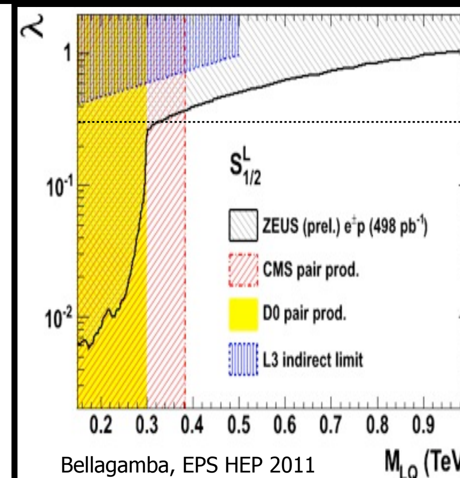
New Gauge Bosons ?



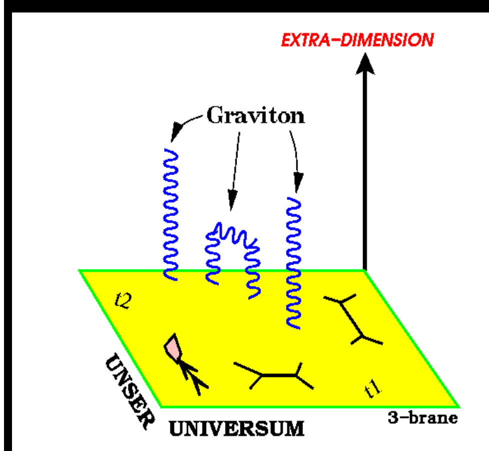
Technicolour ?



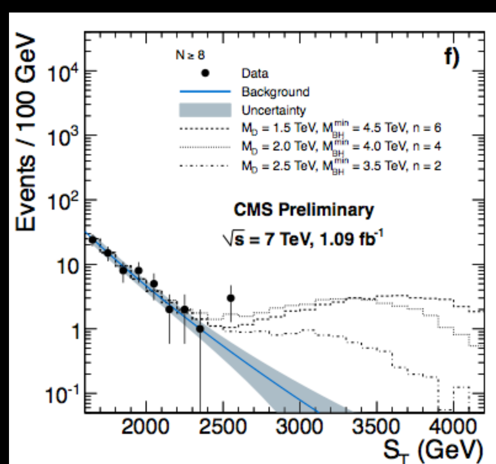
Leptoquarks ?



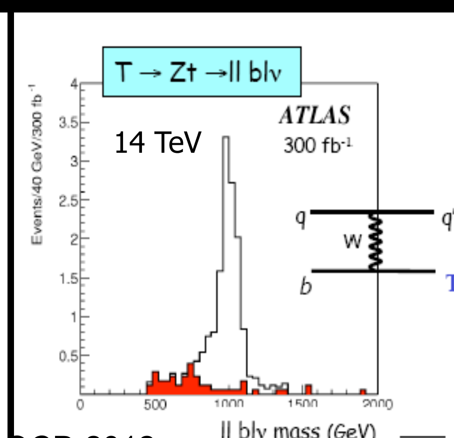
Extra Dimensions ?



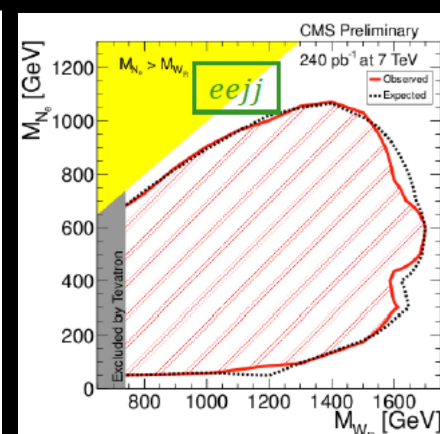
Black Holes ??



Little Higgs ?



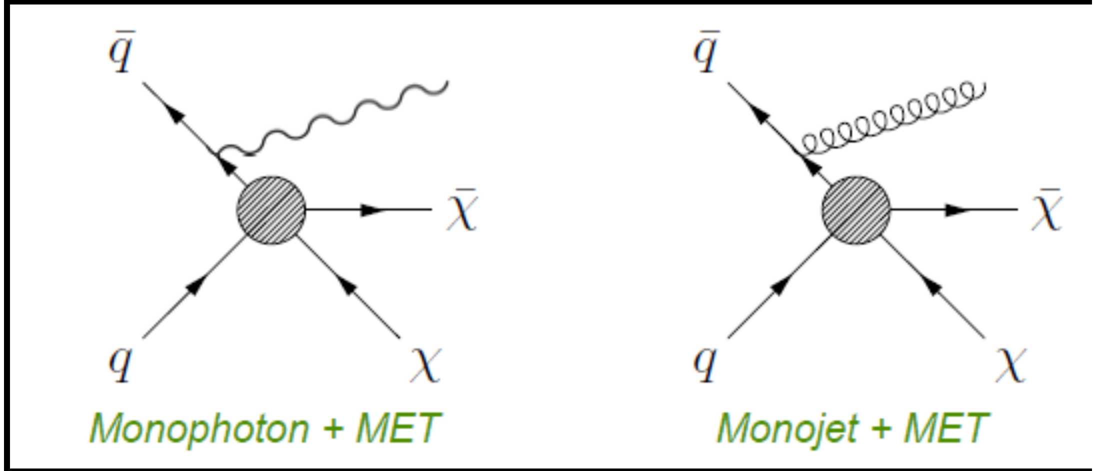
Heavy Neutrinos ?

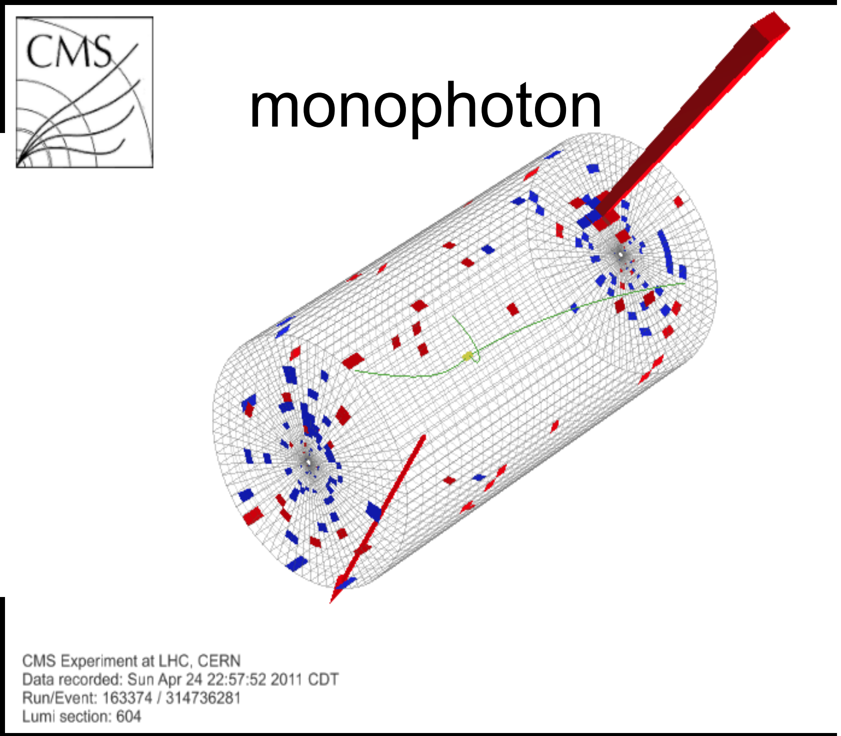


… Non exhaustive list (by far)

Collider Search for Dark Matter

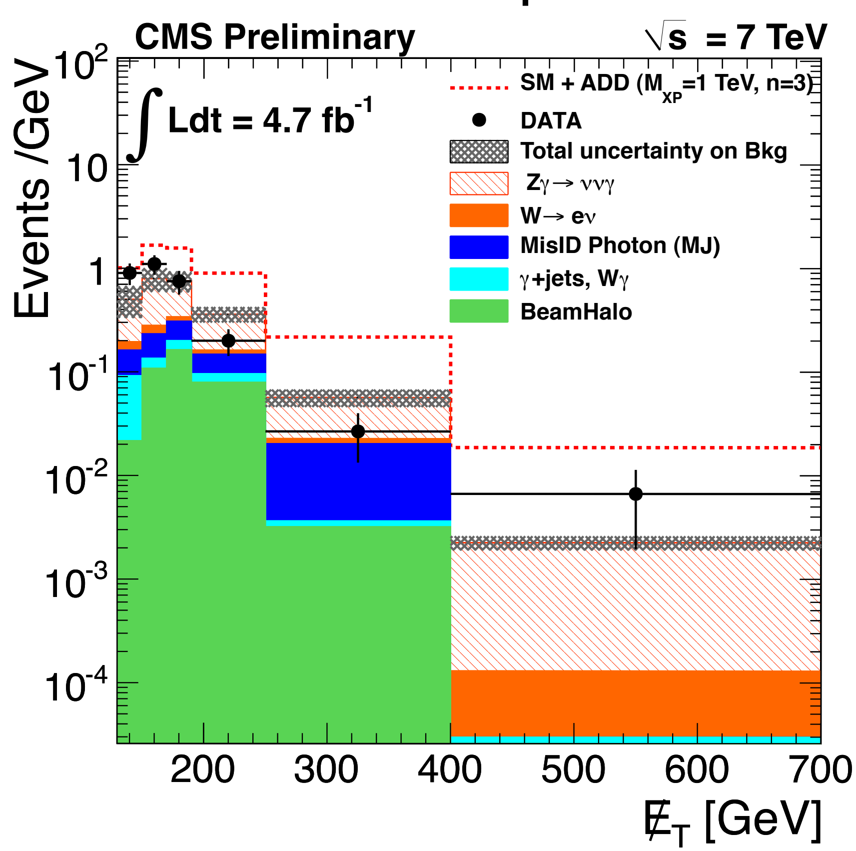
Isolated high Pt photon or jet + missing Transverse Energy (MET)



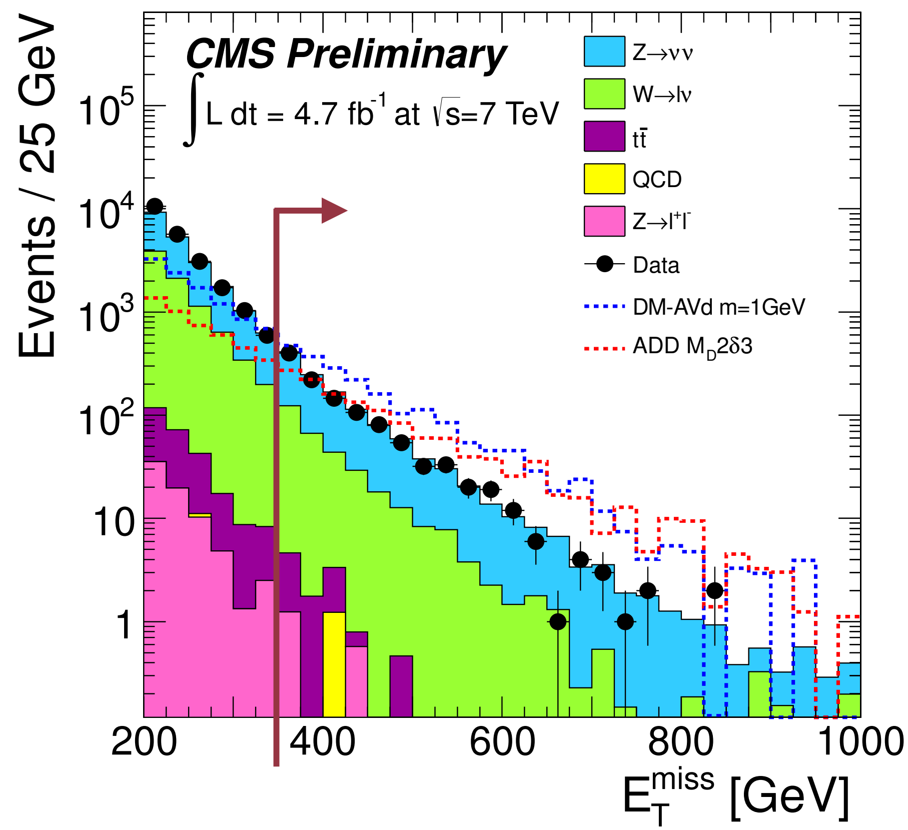


Collider Search for Dark Matter

photons



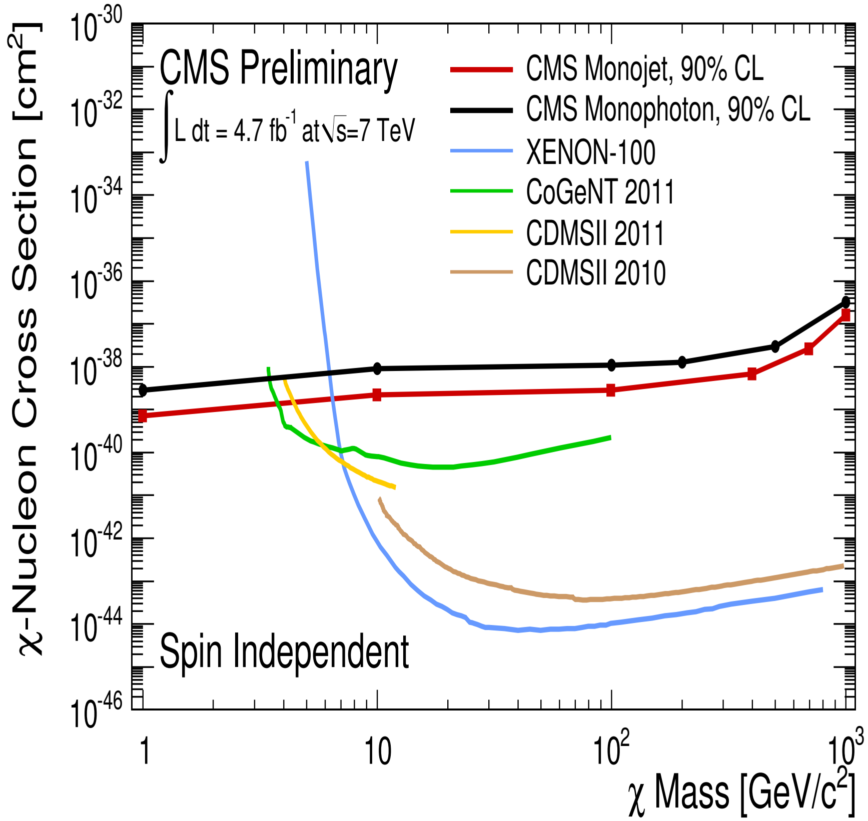
jets

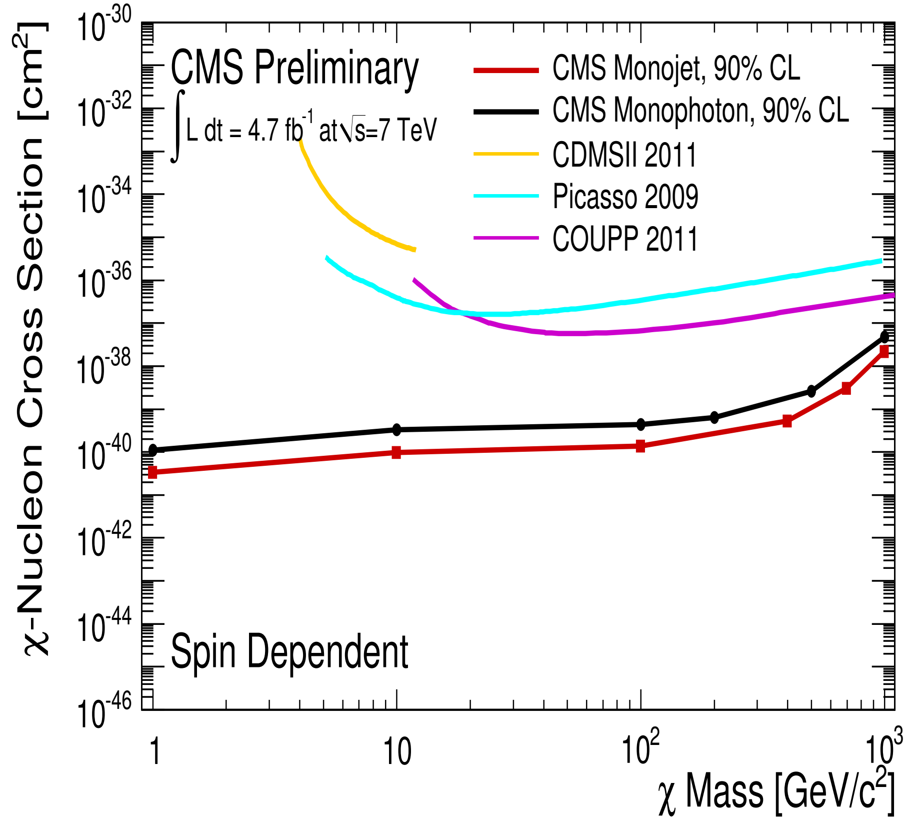


- *No excess observed – good agreement with Standard Model and background expectations*

EXO-11-059 (monojet) and EXO-11-096 (monophoton)

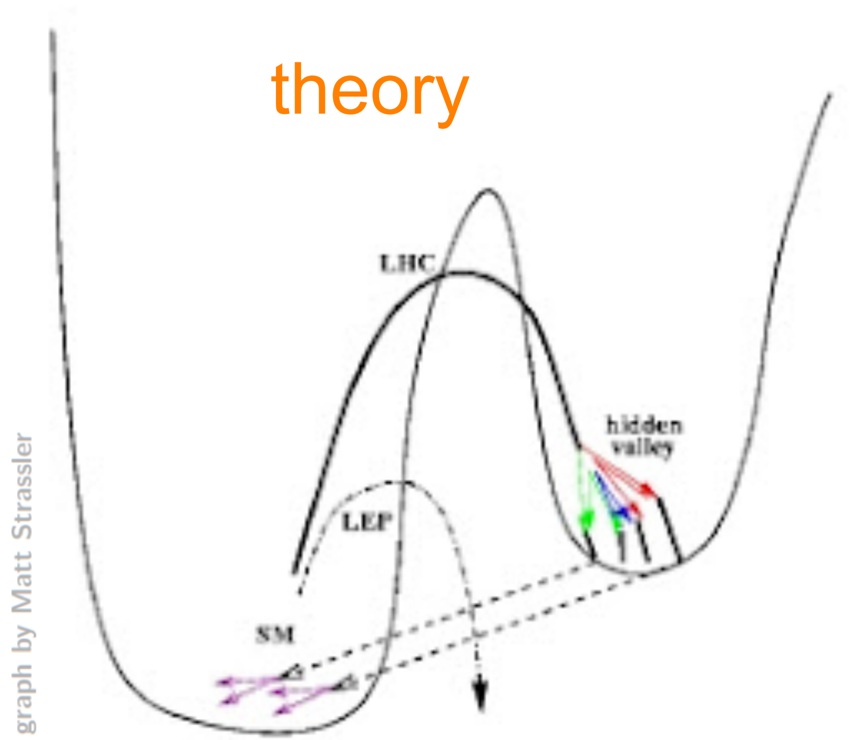
Presented at Moriond EWK





- *Best limits for low mass DM, below 3.5 GeV, a region as yet unexplored by direct detection experiments*
- *Limits represent the most stringent constraints by several orders of magnitude over entire 1-1000 GeV mass range*

Exotica: long lived particles



eg: hidden valley scenario

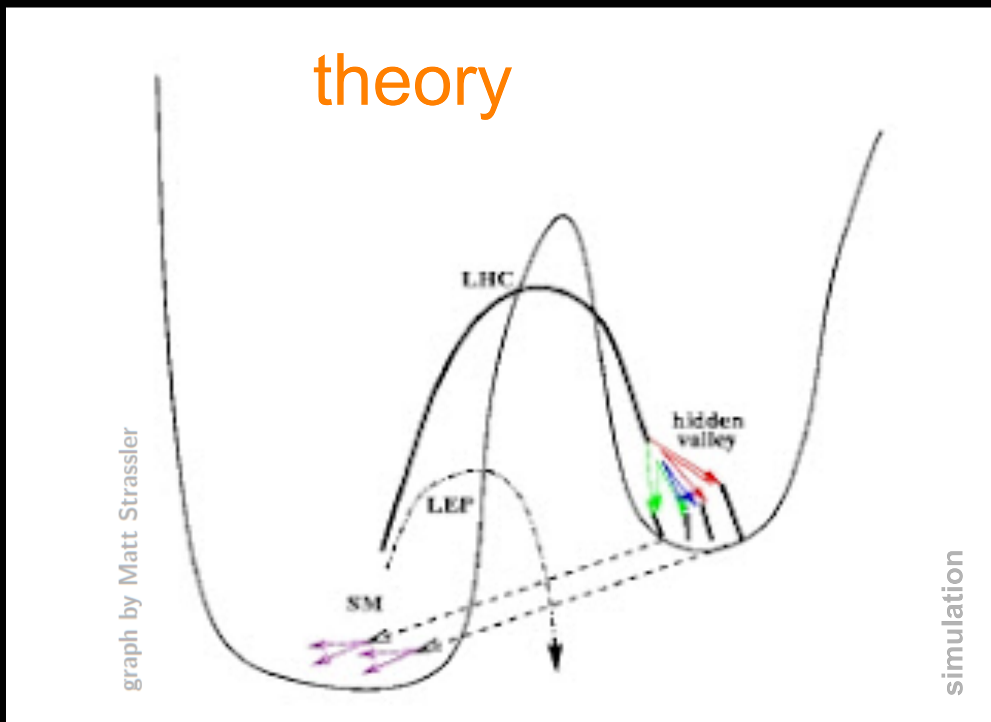
SM ~ HV weakly coupled

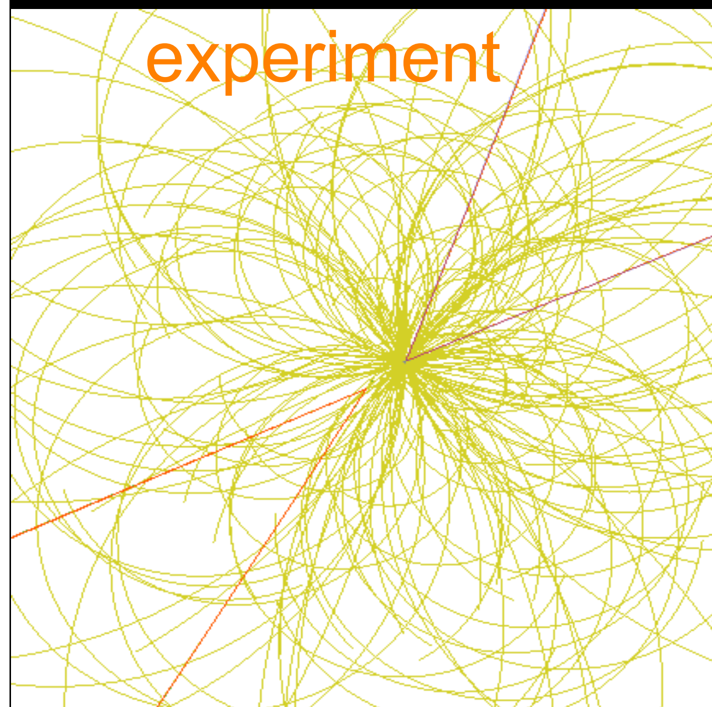
➻ hidden hadrons: long lifetime

also source of dark matter candidates

long lived particles

Probe beyond SM scenarios, experiment driven important to look because we can + 'hidden valley',SUSY, Z' with Dark Matter candidates.





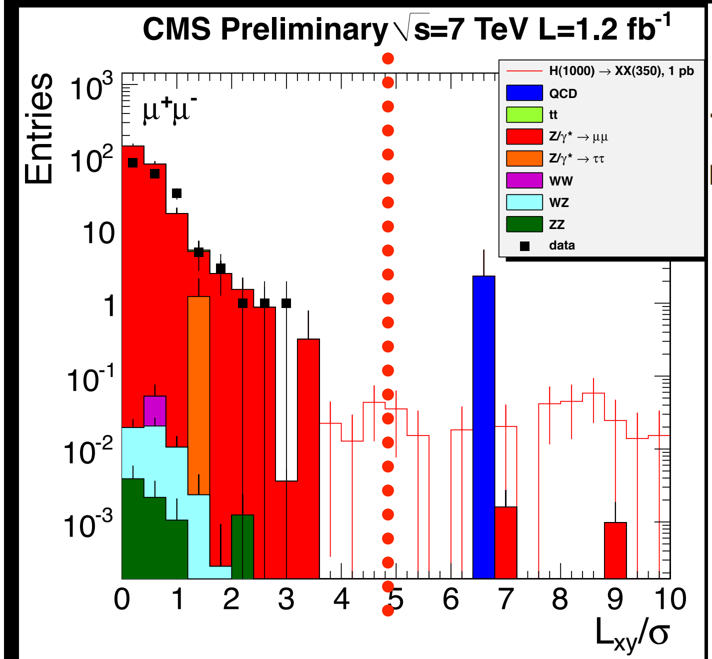
eg: **hidden valley** scenario
SM ~ HV weakly coupled
➳ hidden hadrons: long lifetime ➶

signature: highly
displaced vertices

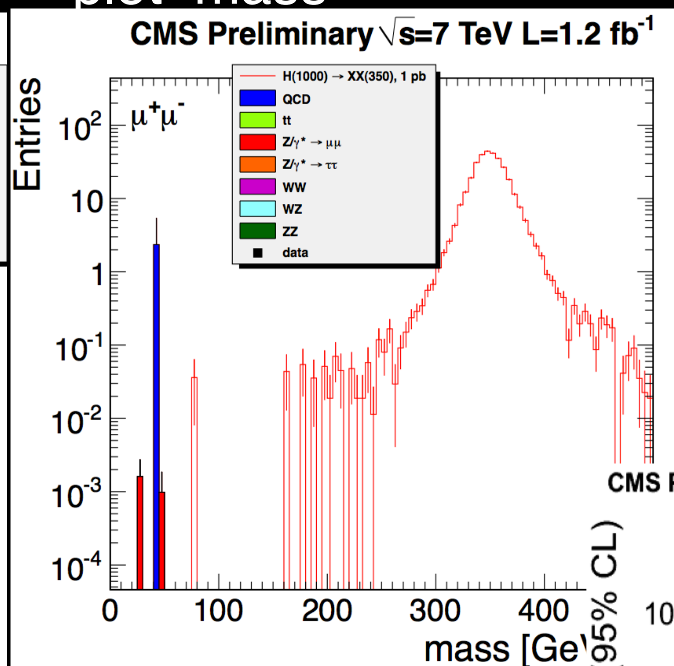
Long-lived particle search

$H \rightarrow XX$
$X \rightarrow \mu\mu$

Decay length significance

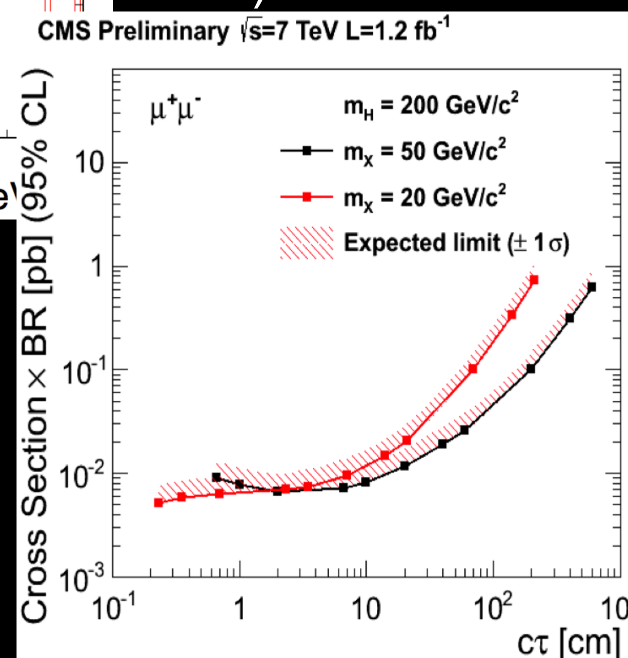


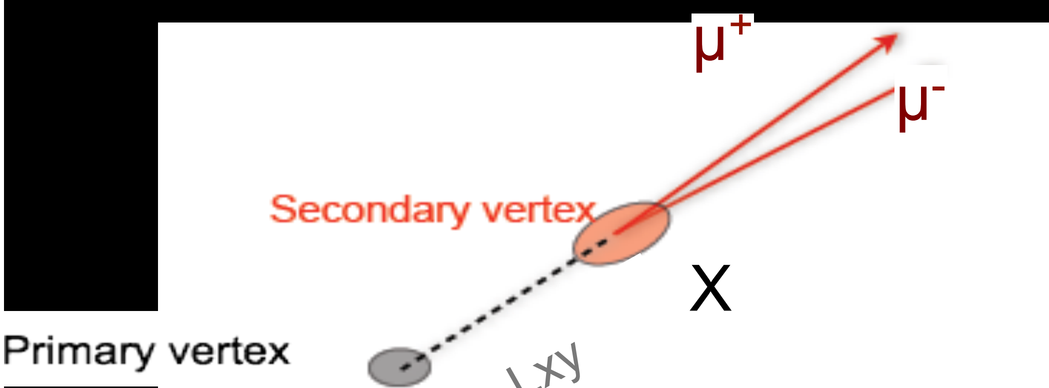
Require Lxy/σ>5
plot mass



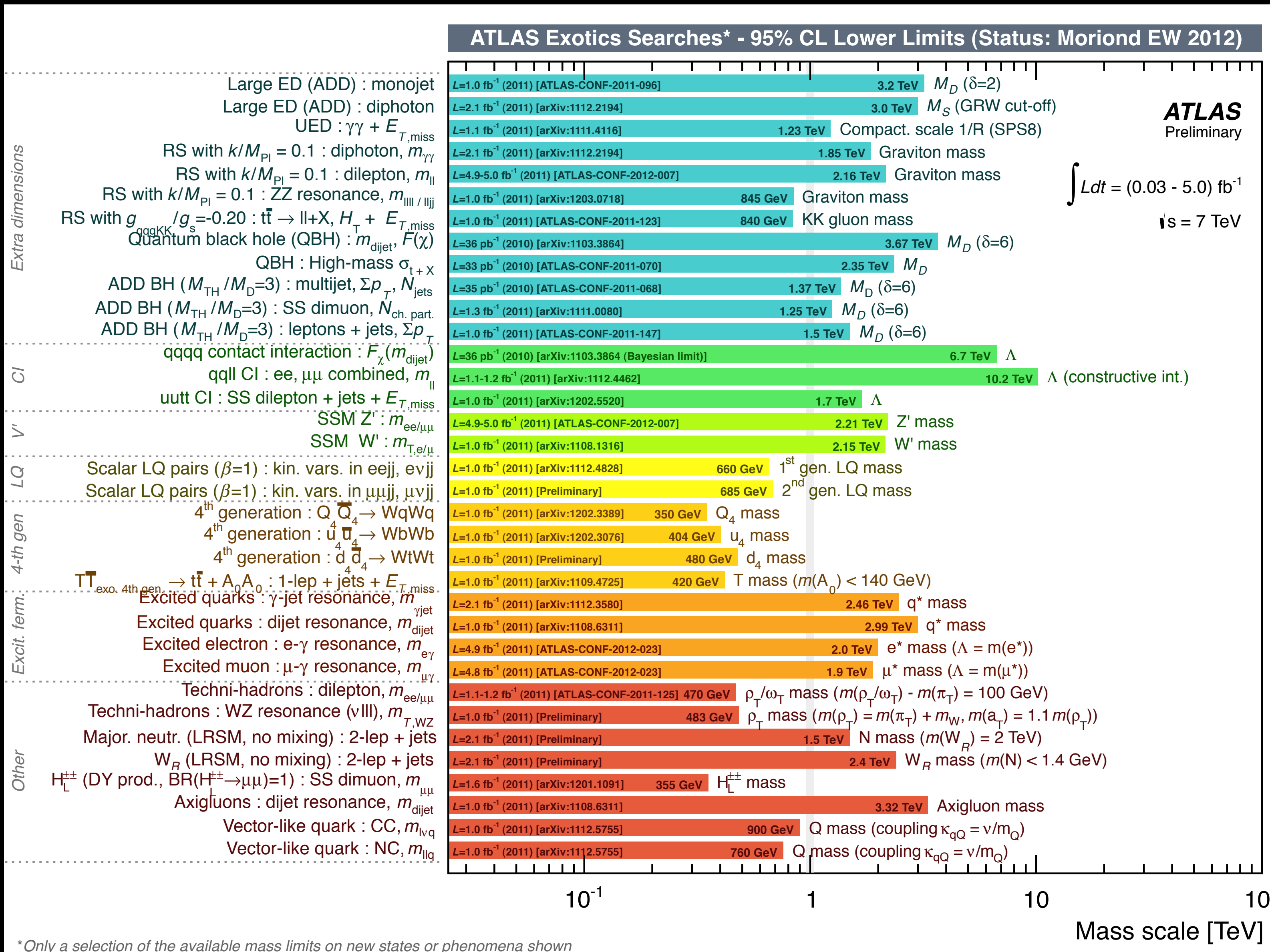
No events consistent with signal found

compute upper limits (most sensitive to date)





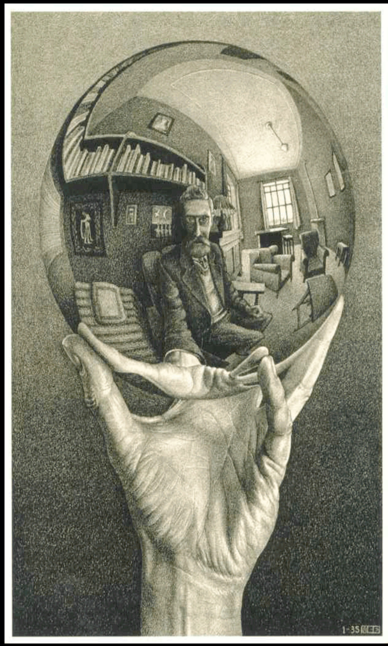
Summary of (selected) Exotica Searches (ATLAS)



Imminent Future

The 2010 and 2011 LHC runs have been very successful

•Restart running LHC at 8 TeV, 50 ns bunch spacing, after a careful risk analysis based on 2011 experience
• Gain 20% for Higgs production cross section & X3-4 for high mass objects
•Aim: 15/fb of data (x3 2011)



•Priority: discover the SM Higgs or exclude it in 2012
….and keep looking for new physics which might appear at any moment

The LHC program must be complemented by comprehensive programs at the intensity frontier: beauty Factories, Mu to electron conversion, g-2, Rare kaon, the study of Neutrinos, $0\nu\nu\beta\beta$ and cosmic frontier: direct detection of dark matter, dark energy with WL, BAO, Clusters and SN1a etc. with each technique taken to its astrophysical limits

Dedication

To the citizens of the world, through your labours it is possible for the international science community to participate in this great voyage of discovery. We do so on your behalf.

Acknowledgment

Sergio Bertolucci, Daniela Bortoletto, Joel Butler, Bill Brinkman, Rick Cavanaugh, Albert de Roeck, Jonathan Feng, Fabiola Gianotti, Saul Gonzalez, Howard Gordon, Al Goshaw, Nick Hadley, Chris Hill, Joe Incandela, Boaz Klima, Rocky Kolb, Nuno Leonardo, Christos Leonidopoulos, Dan Marlow, Felicitas Pauss, Moishe Pripstein, Chris Quigg, Gigi Rolandi, Michael Schmidt, Marjorie Shapiro, Yves Sirois, Mark Trodden, Tim Tait, Guido Tonelli, Mike Tutts.

The LHC.

The ATLAS, CMS and LHC-b Collaborations.

At Purdue: Kirk Arndt, Bo Xin

At Fermilab: Liz Clements, Judy Jackson.