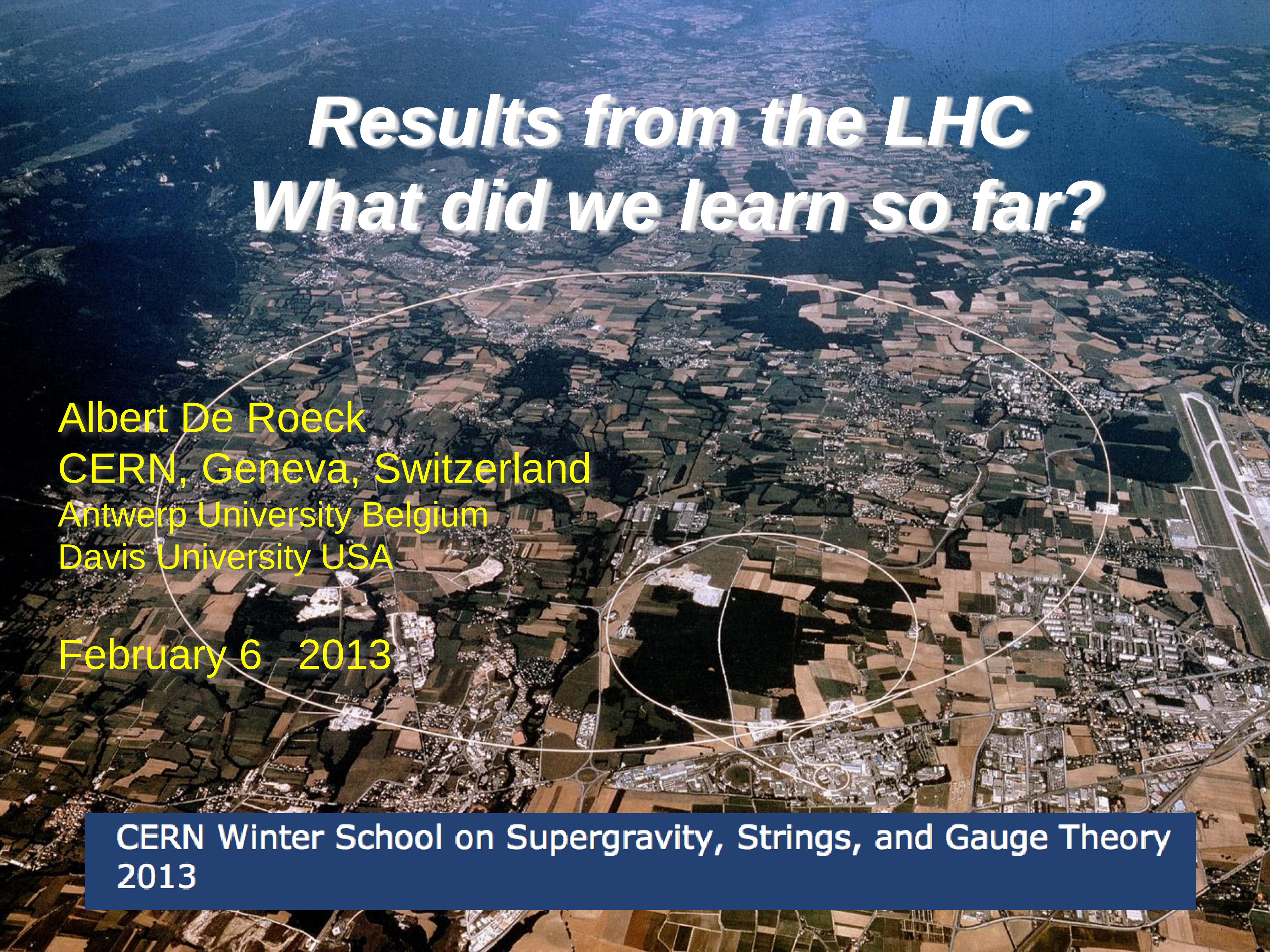
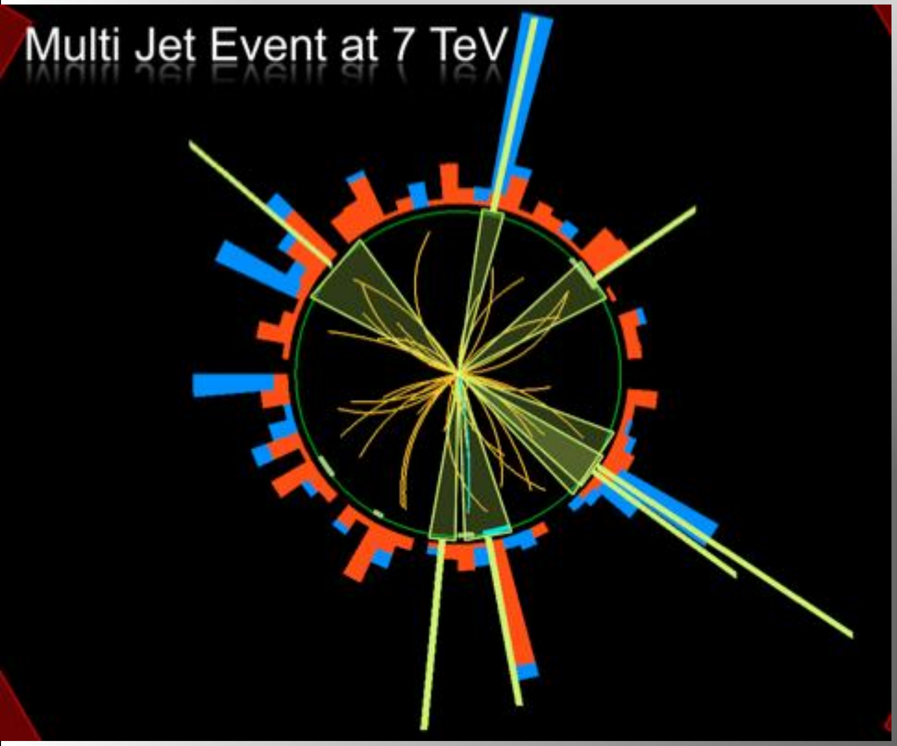


Results from the LHC
What did we learn so far?

Albert De Roeck
CERN, Geneva, Switzerland
Antwerp University Belgium
Davis University USA

February 6 2013

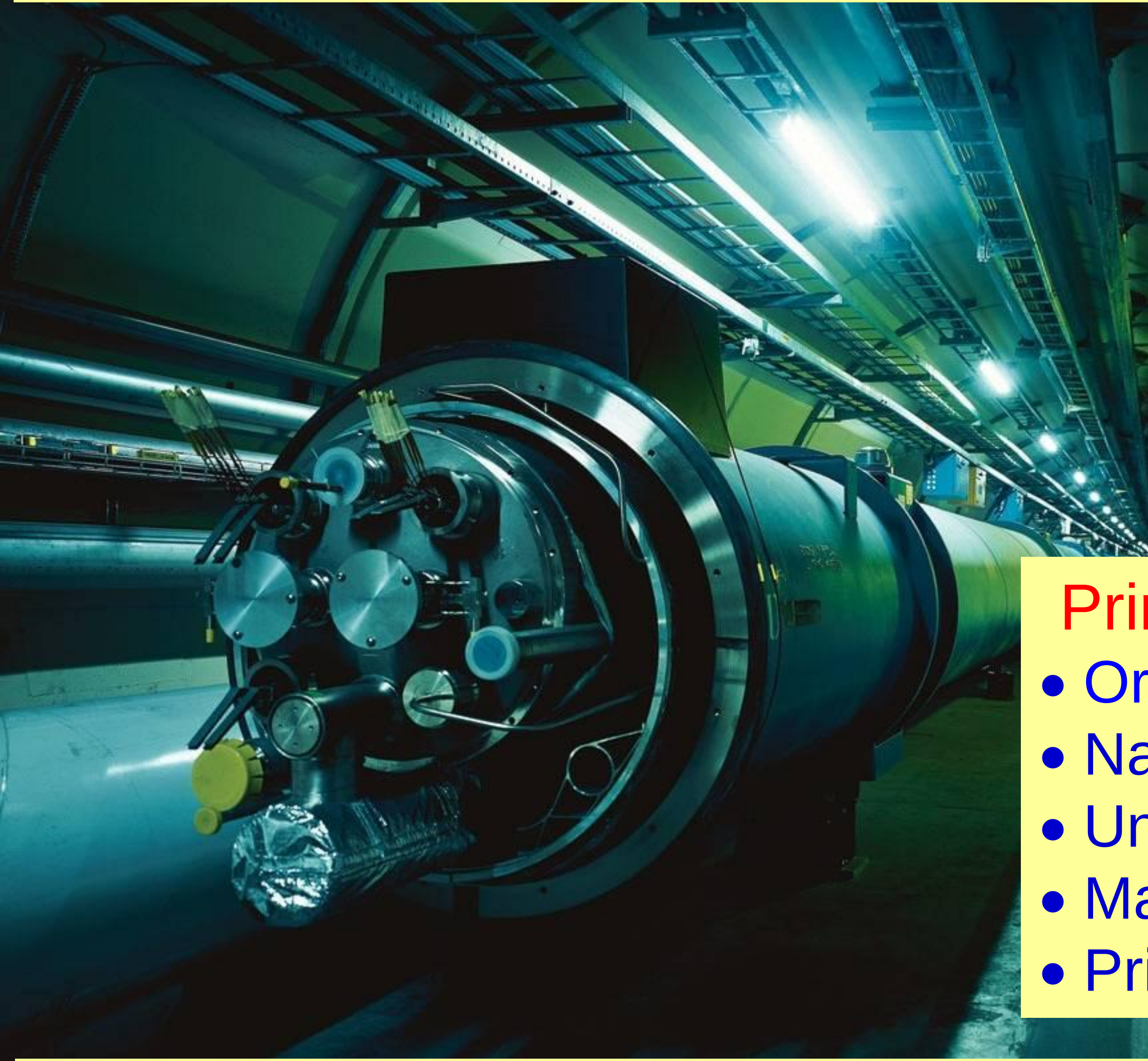
CERN Winter School on Supergravity, Strings, and Gauge Theory 2013



Outline

- Short Introduction
- The LHC and Experiments
- Standard Model Physics at 7/8 TeV
- The Higgs Boson
- Searches for Physics Beyond the Standard Model

The Large Hadron Collider = a proton proton collider



7 TeV + 7 TeV
(3.5-4 TeV + 3.5-4 TeV)

1 TeV = 1 Tera electron volt
= 10^{12} electron volt

Primary physics targets

- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

The LHC is a Discovery Machine

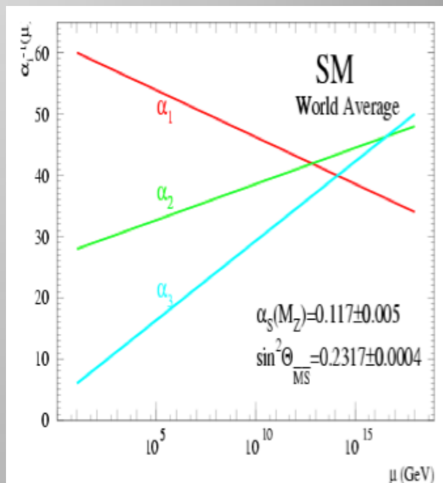
The LHC will determine the Future course of High Energy Physics

Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

Discover physics beyond the Standard Model

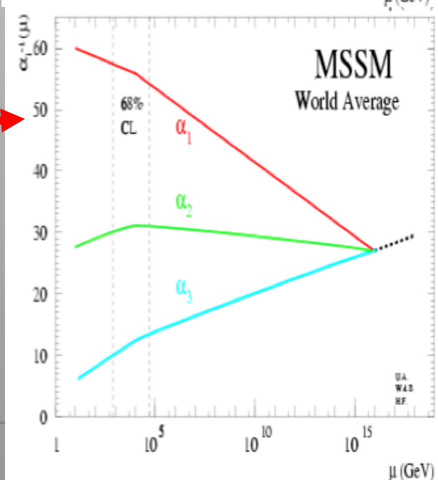
Reminder: The Standard Model
- tells us how but not why
  3 flavour families? Mass spectra? Hierarchy?
- needs fine tuning of parameters to level of 10^{-30} !
- has no connection with gravity
- no unification of the forces at high energy



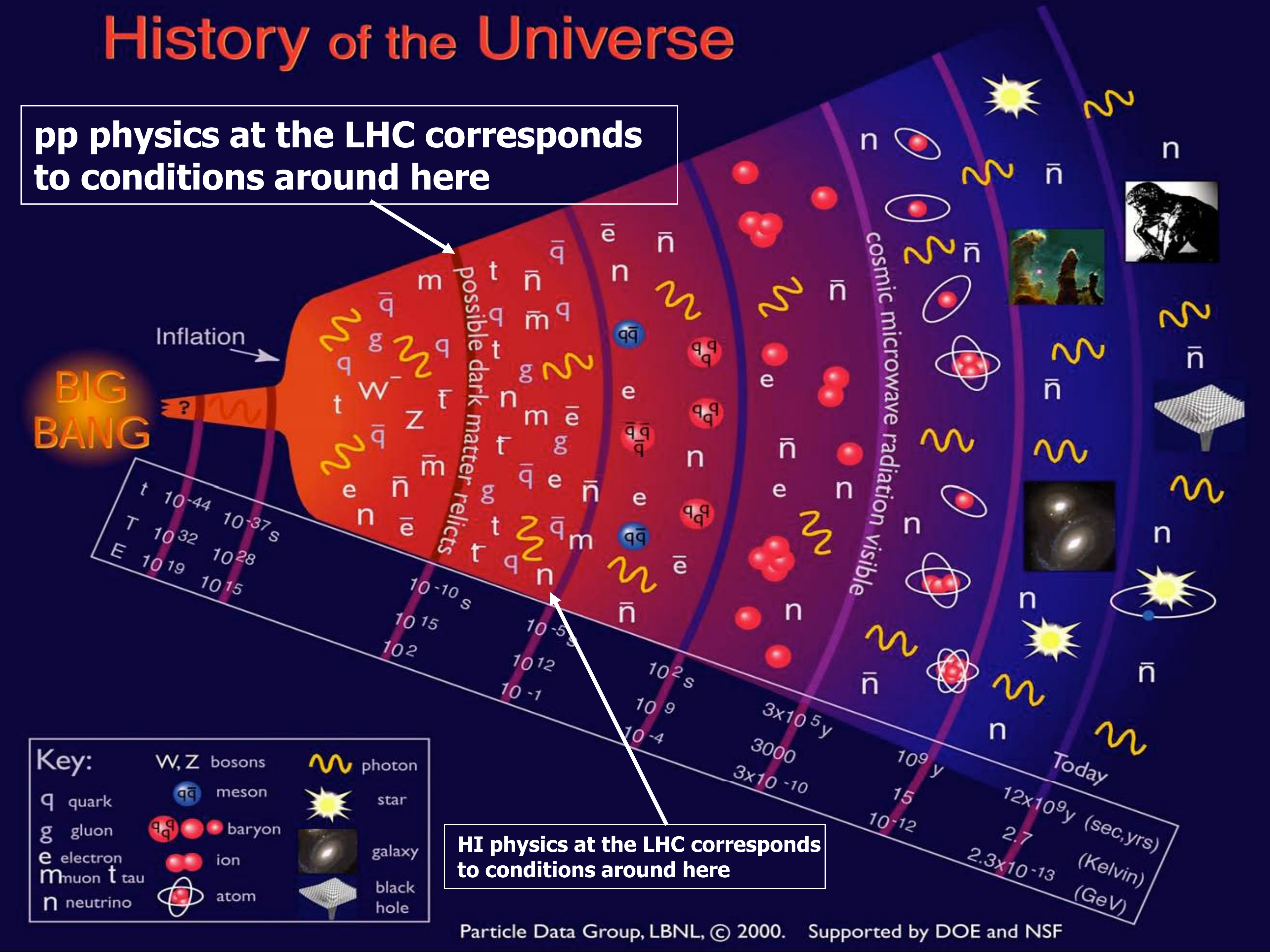
Most popular extensions these days

If a Higgs field exists:
- Supersymmetry
- Extra space dimensions

If there would be no Higgs below ~ 700 GeV
- Strong electroweak symmetry breaking around 1 TeV



Other ideas: more symmetry & gauge bosons, L-R symmetry, quark & lepton substructure, Little Higgs models, Technicolor, Hidden Valleys…

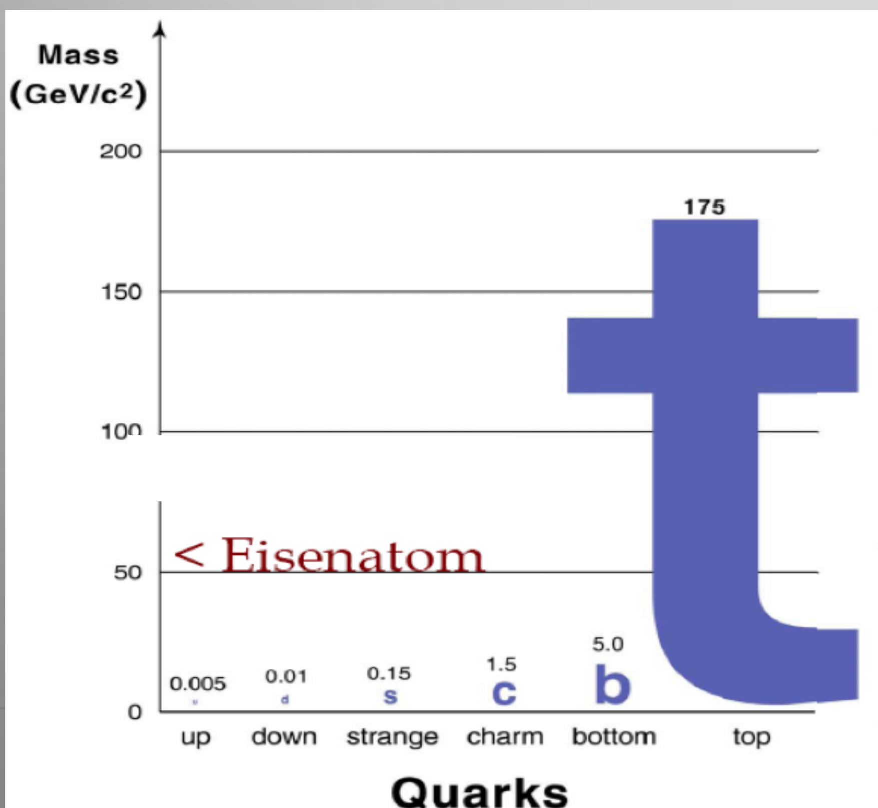

History of the Universe
pp physics at the LHC corresponds to conditions around here
HI physics at the LHC corresponds to conditions around here
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

The Origin of Particle Masses

A most basic question is why elementary particles have masses (and so different masses)

The mass mystery could be solved with the ‘Higgs mechanism’ which predicts the existence of a new elementary particle, the ‘Higgs’ particle (theory 1964, P. Higgs, R. Brout and F. Englert)

Peter Higgs



The Higgs (H) particle has been searched for since decades at accelerators…

The LHC will have sufficient energy to produce it for sure, if it exists

Francois Englert

Supersymmetry

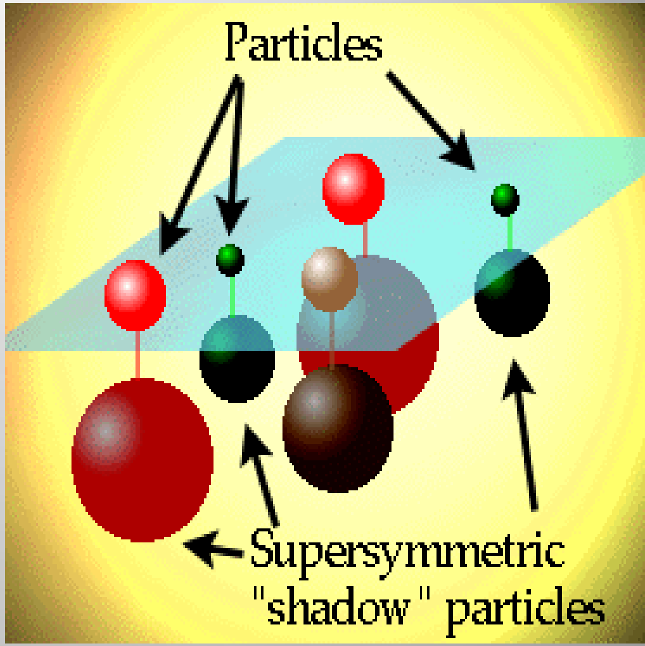
(Julius Wess and Bruno Zumino, 1974)

Establishes a symmetry between fermions (matter) and bosons (forces):

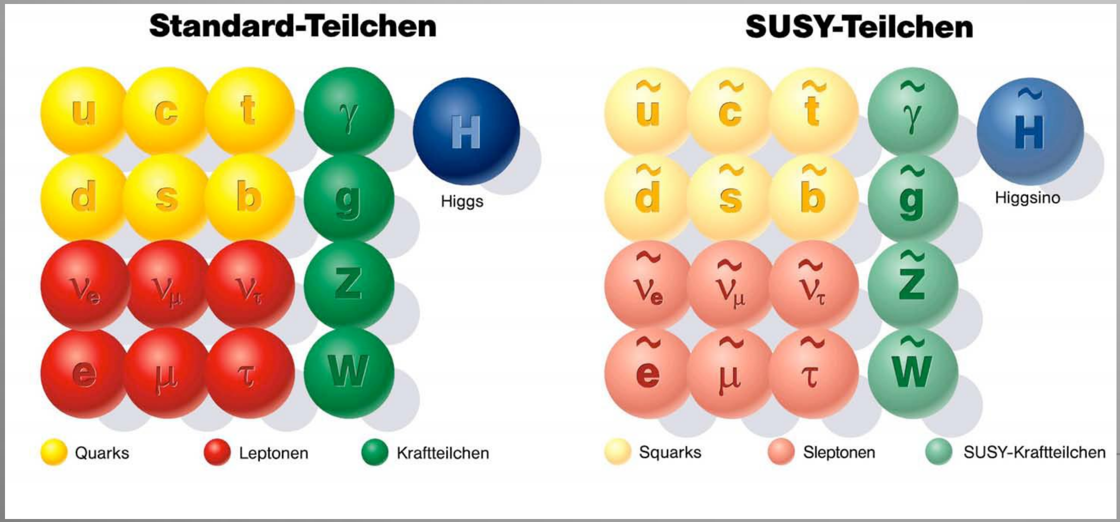
- Each particle p with spin s has a SUSY partner $\tilde{p}$ with spin s -1/2

- Examples q (s=1/2) → $\tilde{q}$ (s=0) squark

g (s=1) → $\tilde{g}$ (s=1/2) gluino



Our known world **Maybe a new world?**



Motivation:
- Unification (fermions-bosons, matter-forces)
- Solves some deep problems of the Standard Model

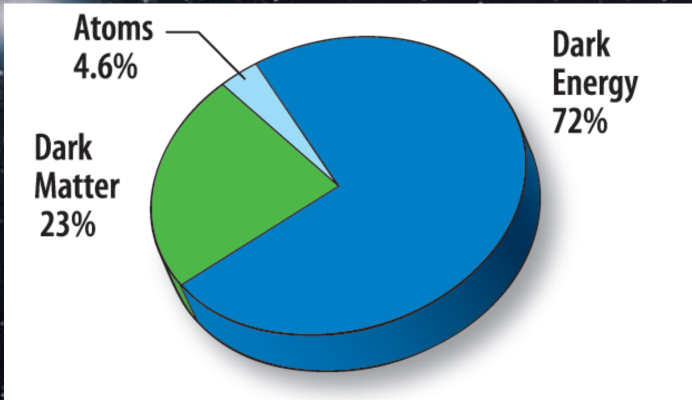
Dark Matter in the Universe

Astronomers found that most of the matter in the Universe must be invisible Dark Matter


Vera Rubin ~ 1970

'Supersymmetric' particles ?


F. Zwicky 1898-1974



This Study Requires…….

1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

2. Detectors : gigantic instruments that record the resulting particles as they "stream" out from the point of collision.

3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

4. Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".

The LHC Machine and Experiments

LHC is 100m underground

LHC is 27 km long

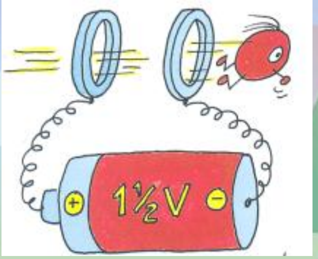
Magnet Temperature is 1.9 Kelvin = -271 Celsius

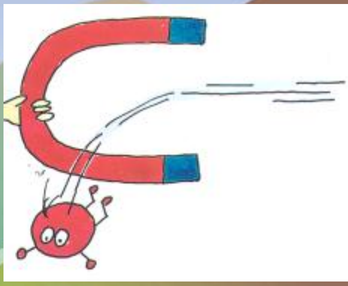
LHC has ~ 9000 magnets

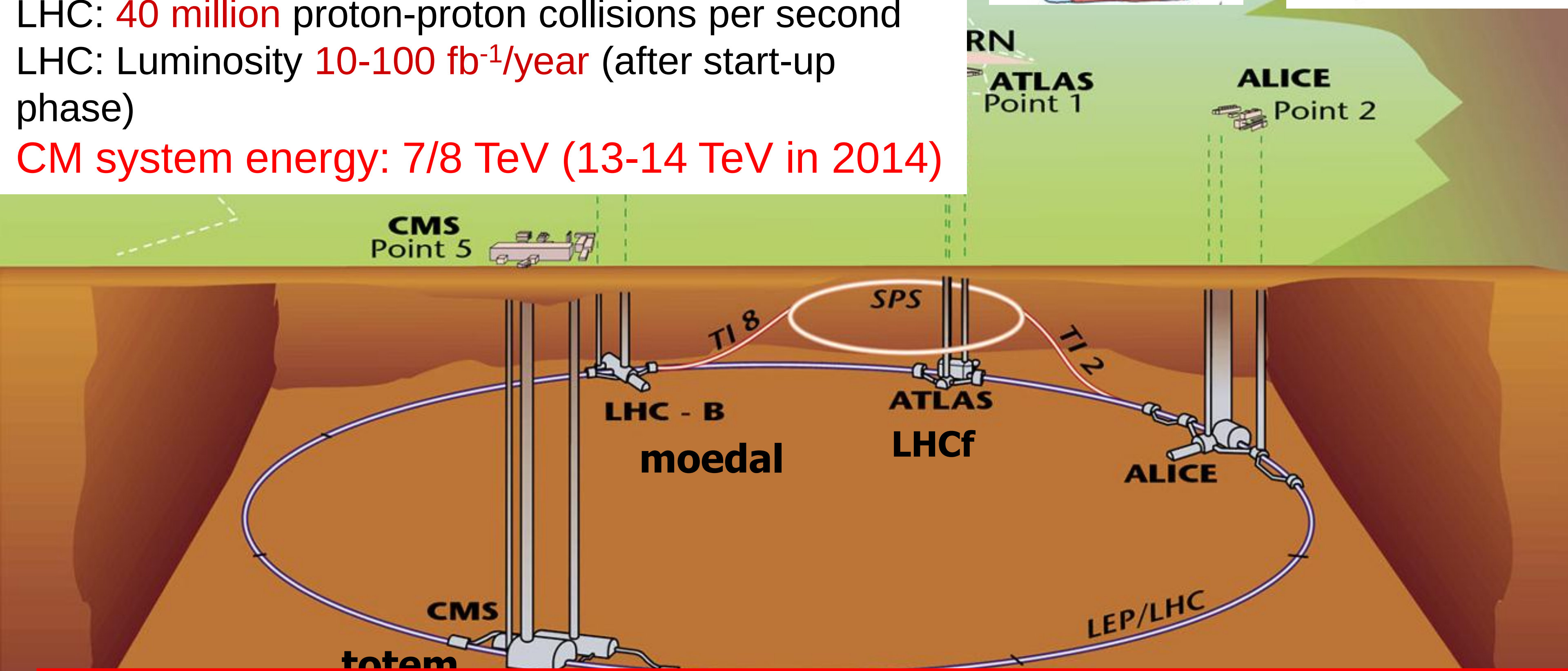
LHC: 40 million proton-proton collisions per second

LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)

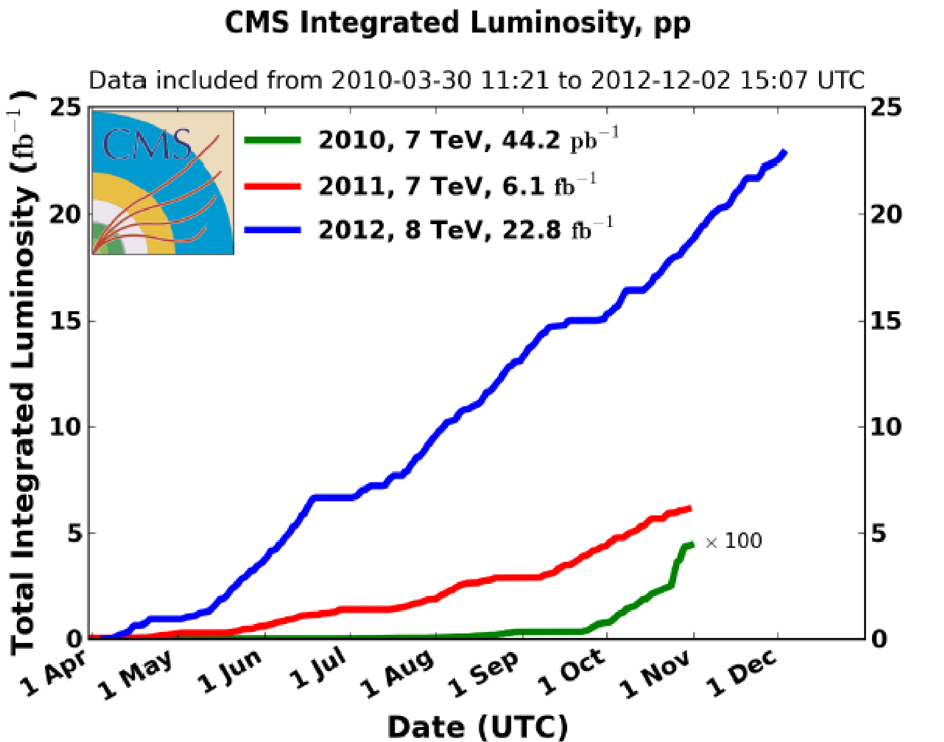
CM system energy: 7/8 TeV (13-14 TeV in 2014)







- High Energy ⇒ factor 3.5-7 increase w.r.t. present accelerators
- High Luminosity (# events/cross section/time) ⇒ factor 100 increase



Main changes in 2012:

- *Beam energy: **4 TeV**.*
- ***Reduction of β**** ↔ *tighter collimator settings.*

Parameter	2010	2011	2012	Nominal	Constrained by
N (10^{11} p/bunch)	1.2	1.5	1.6-1.7	1.15	
k (no. bunches)	368	1380	1380/1374	2808	Bunch spacing
Bunch spacing (ns)	150	75 / 50	50	25	
ε (μm rad)	2.4-4	1.9-2.4	2.2-2.5	3.75	Injectors
β* (m)	3.5	1.5 → 1	0.6	0.55	Aperture/ tolerance
L ($cm^{-2}s^{-1}$)	2×10^{32}	3.5×10^{33}	7.6×10^{33}	10^{34}	
Pile-up	3	19	35	23	

8

LHC did very well

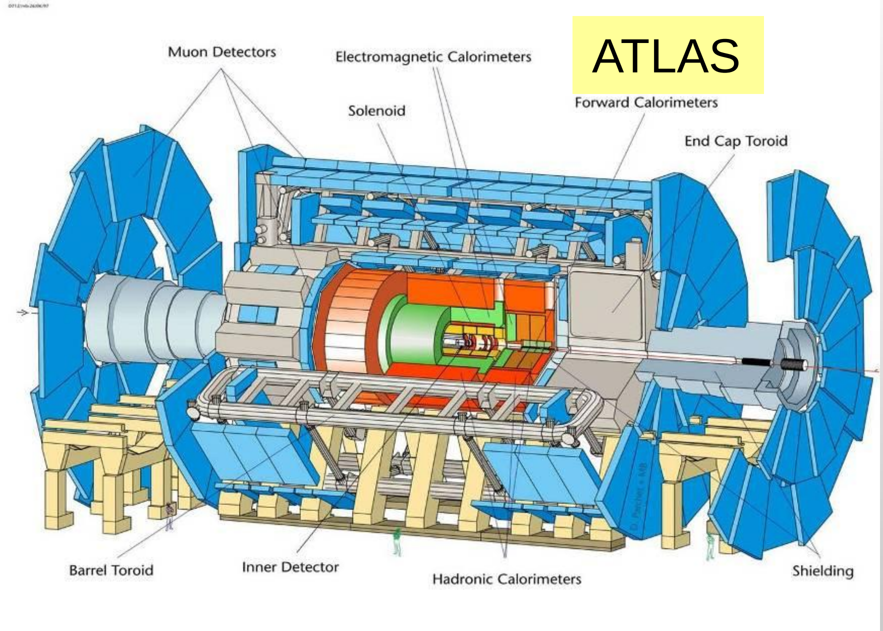
2011: luminosity 3.5 . 10^{33} cm^{-2} s^{-1} ⇒ >5 fb^{-1} collected in total

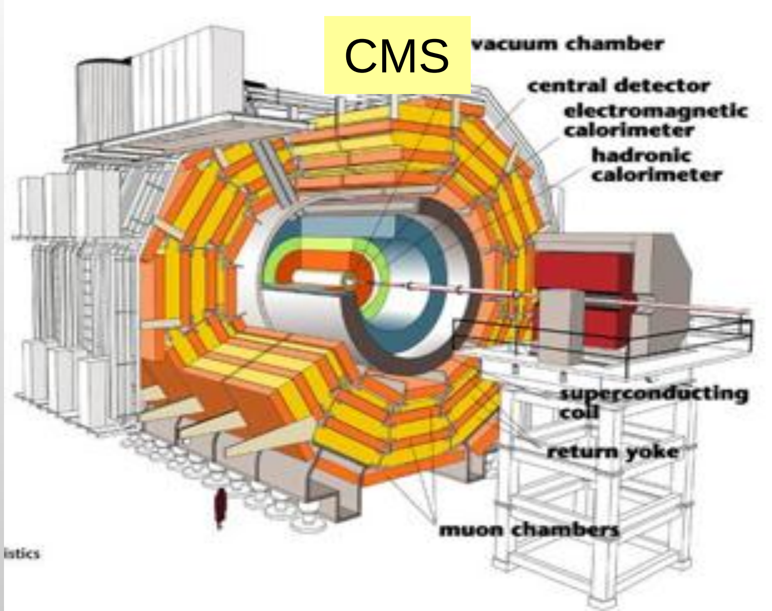
2012: luminosity 7.6 . 10^{33} cm^{-2} s^{-1} ⇒ >20 fb^{-1} collected in total

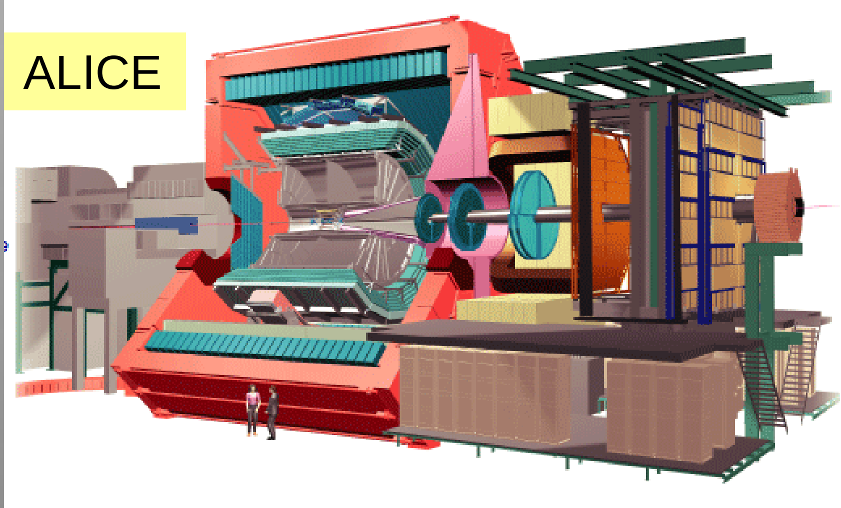
Next pp collisions in 2015. Shutdown for ‘energy upgrade’

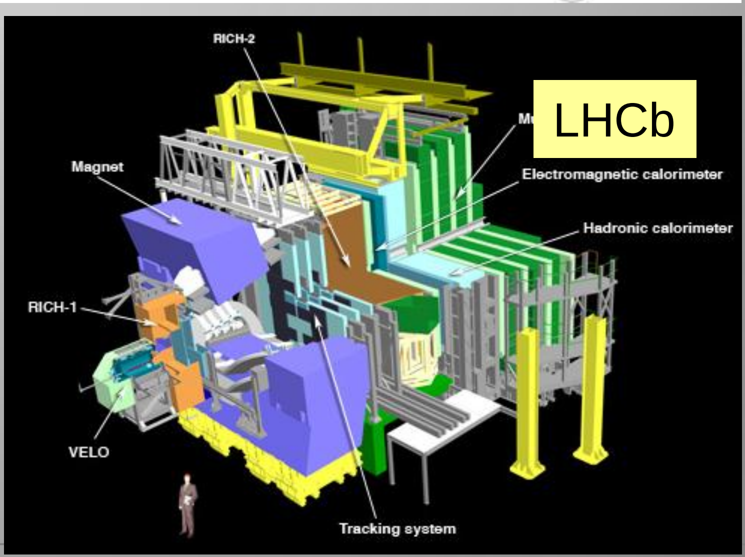
Experiments at the LHC

The Four Central Experiments

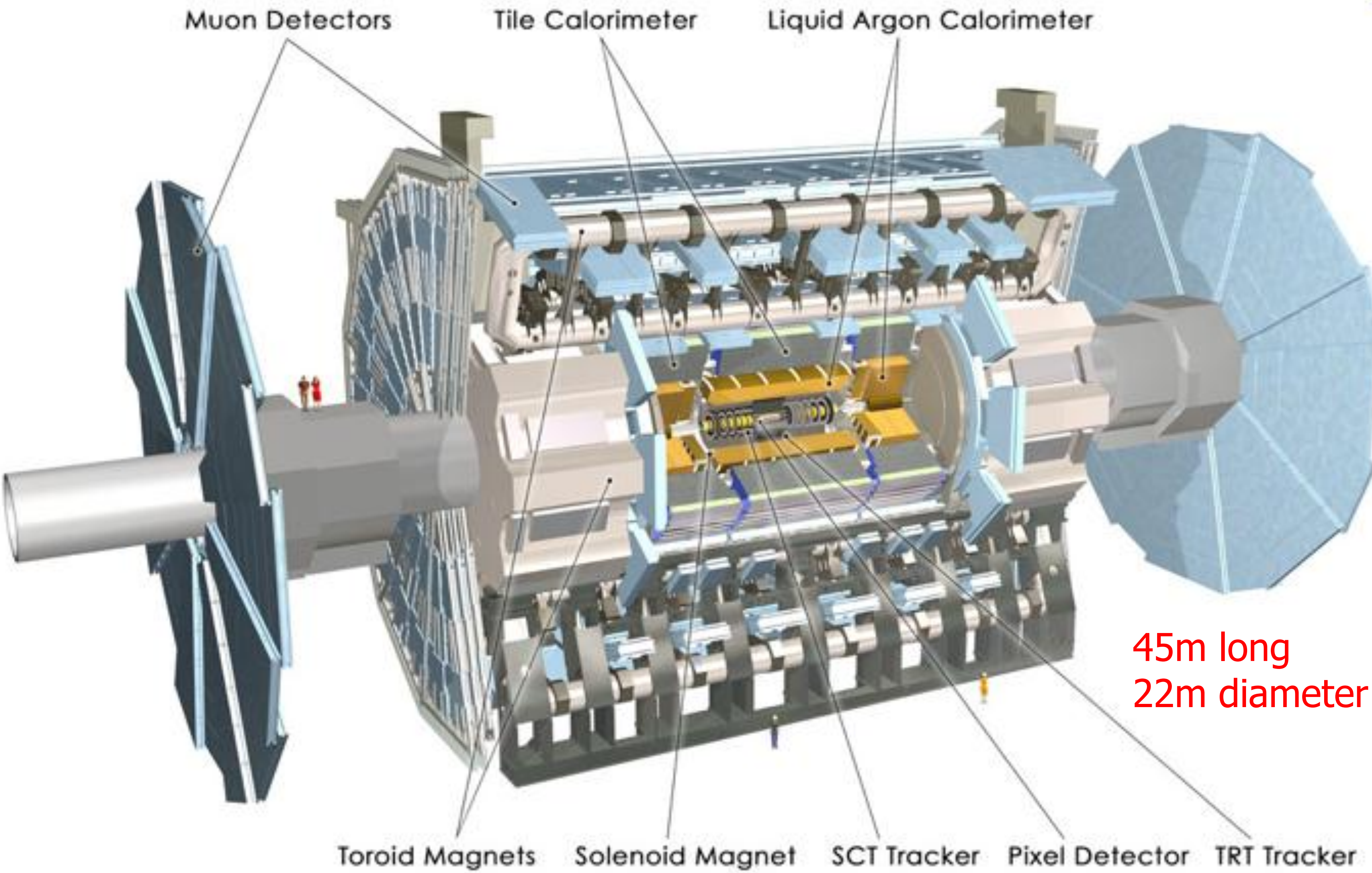








Example: The ATLAS Experiment



45m long
22m diameter

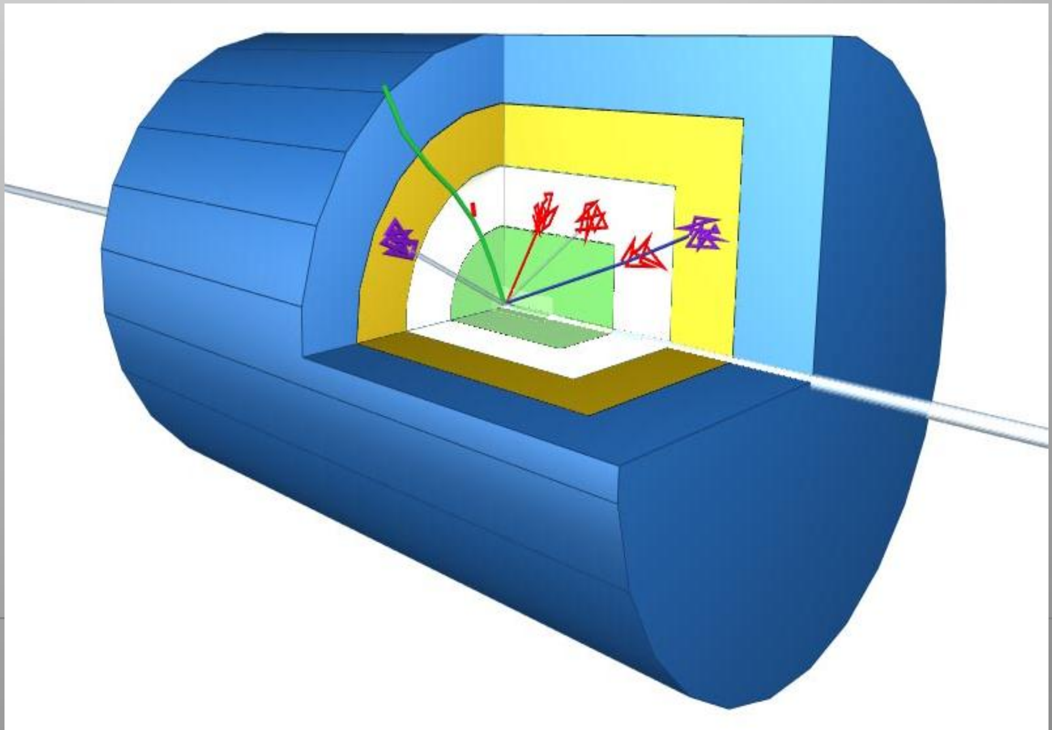
Schematic of a LHC Detector

Physics requirements drive the design!

Analogy with a cylindrical onion:

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

Such an experiment has ~ 100 Million read-out channels!!



The CMS Experiment (B40)

The CMS Collaboration: >3200 scientists and engineers, >800 students from ~190 Institutions in 39 countries .

The experiments are in good shape!

ATLAS

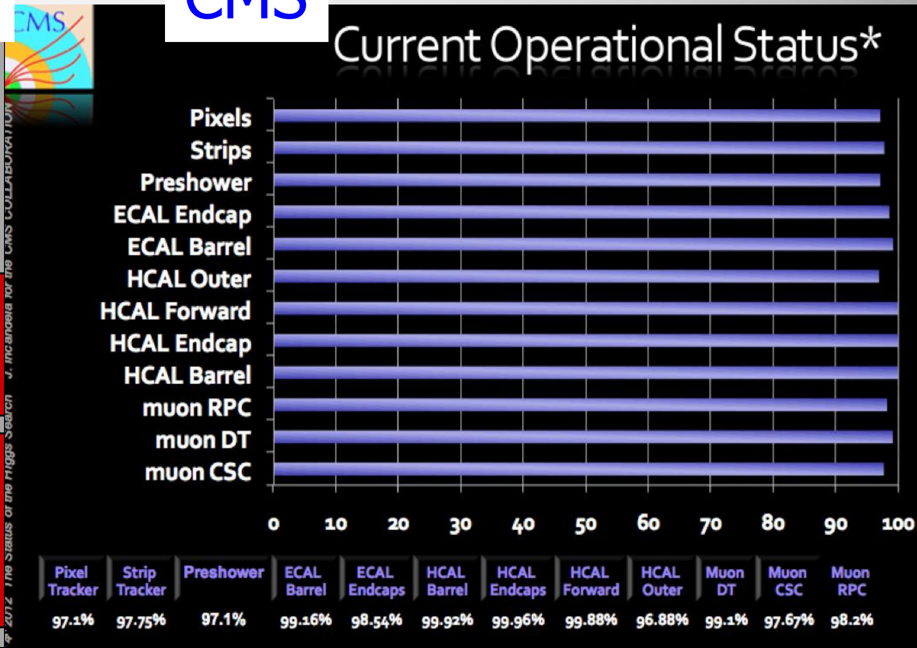
CMS

Fraction of non-operational detector channels: (depends on the sub-detector)

Few permil (most cases) to 4%

Data-taking efficiency = (recorded lumi)/(delivered lumi):~ 94.6%

Good-quality data fraction, used for analysis : ~ 93.6%
(will increase further with data reprocessing)



Pile-Up 2012!!

Z→ μμ event from 2012 data with 25 reconstructed vertices

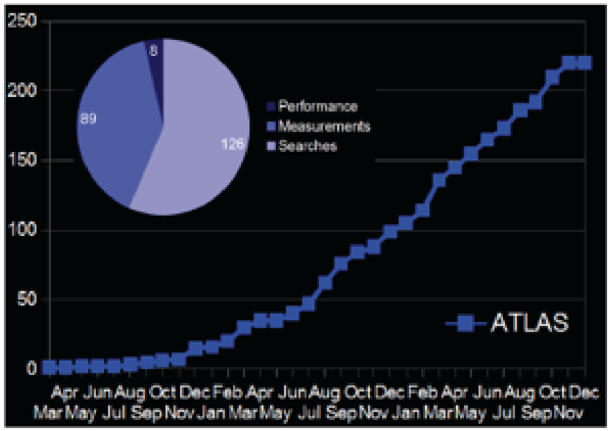
Z→ μμ

An issue for jet measurements

Data Taking Challenges

- Collider: 20M bunch crossings per second
- ~ 30 events per bunch crossing: pile-up
- Trigger on 400 events/sec (+ another 400-600 Hz of parked data in CMS): keep the interesting (incl. unknown) physics
- Total data volume in eg ATLAS: 5 billion detector events, 120 PB of data (simulation and data). Several billion Monte Carlo events (produce ~ 10^9 events/2
- ATLAS+CMS > 450 papers in 3 years

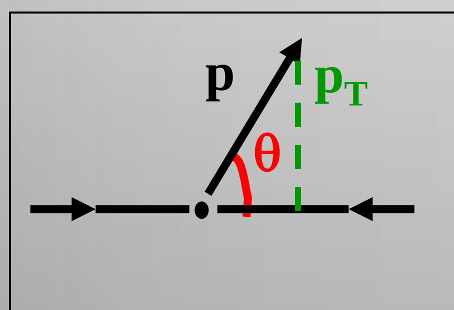
  > 550 papers for all experiments



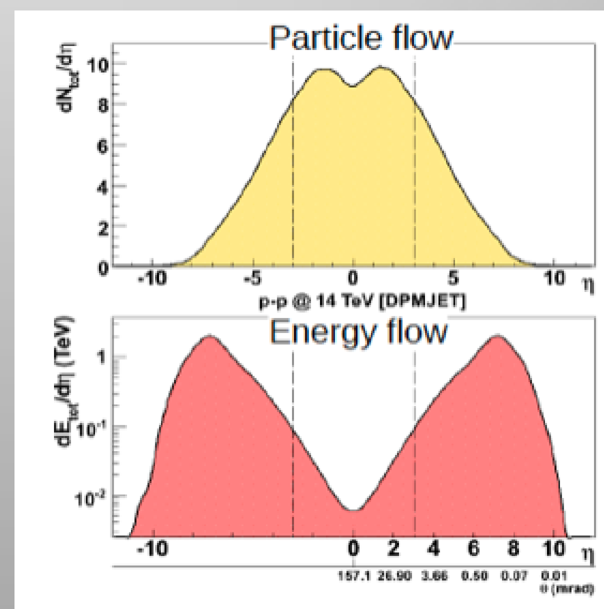
No attempt to cover everything ☺ but examples to illustrate the LHC

Most examples from CMS/ATLAS

Very Forward Measurements

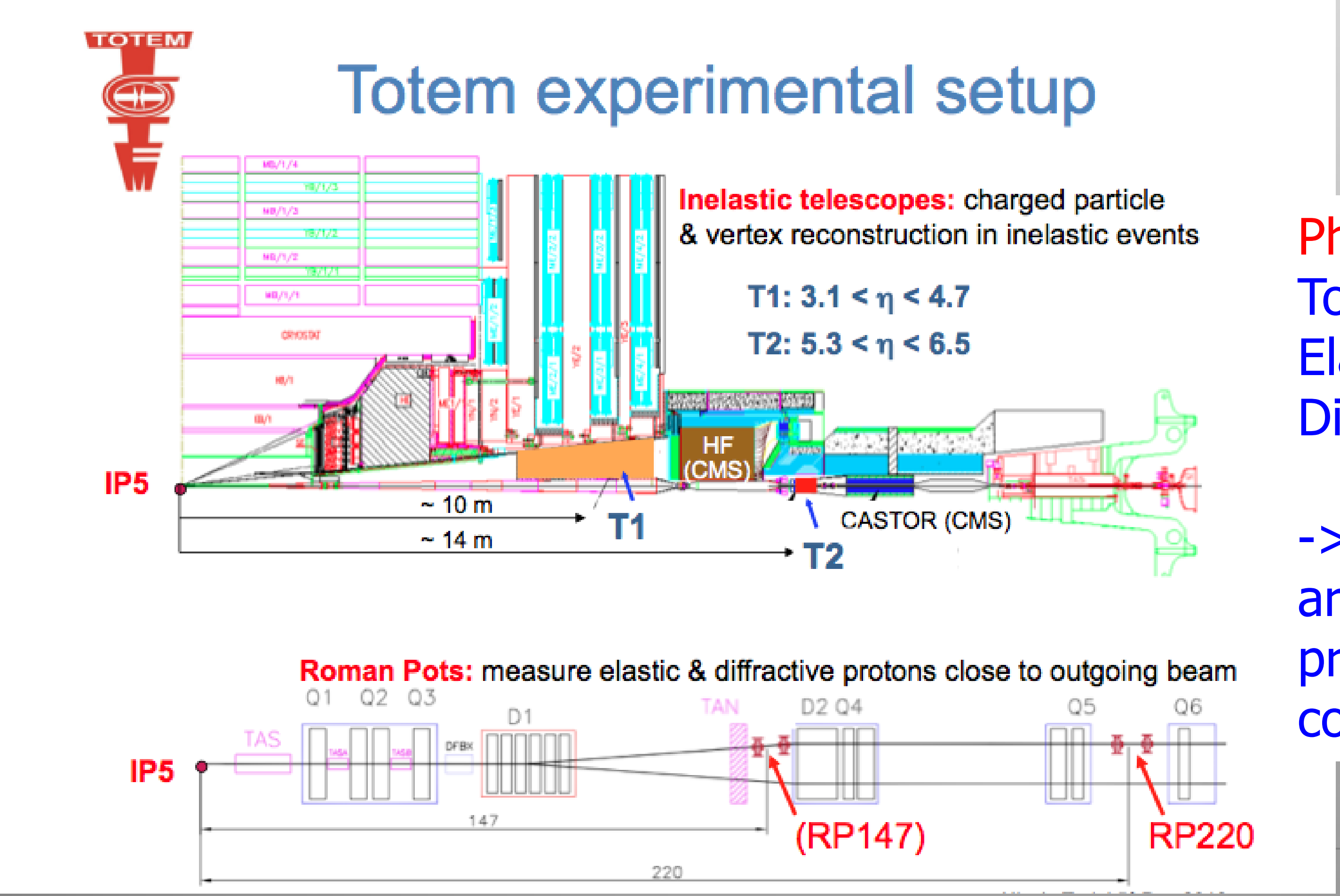


$$y = \eta = -\ln(\tan\frac{\theta}{2})$$



Total pp Cross Section: TOTEM

TOTEM uses the same Interaction Point as CMS (IP5)
TOTEM has forward detectors and Roman Pot Near Beam Detectors (150m-220m away from the IP)



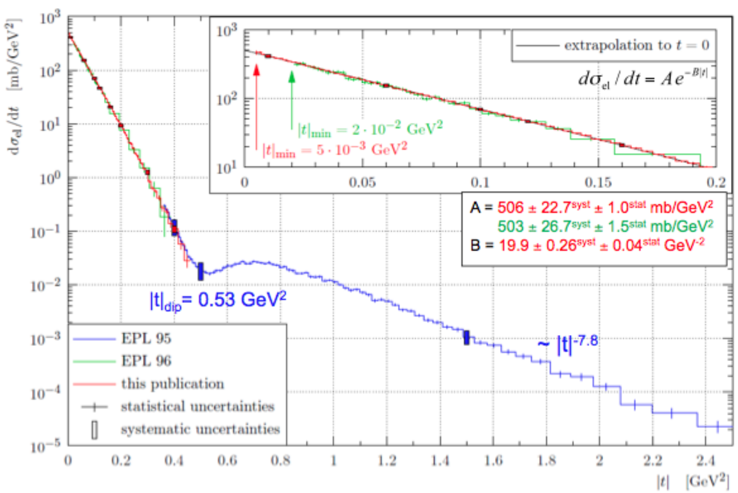
Physics Goals
Total cross section
Elastic cross section
Diffractive studies

-> Most collisions are soft peripheral proton proton collisions

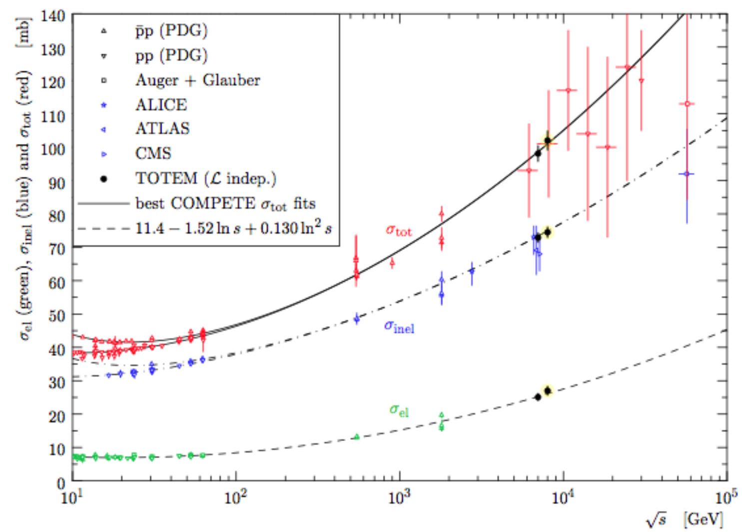
Elastic/Total pp cross section

Example Results

7 TeV elastic differential cross section



8TeV cross sections



$$\sigma_{tot} = \frac{16\pi}{1+\rho^2} \frac{dN_{el}/dt|_0}{N_{el} + N_{inel}}$$

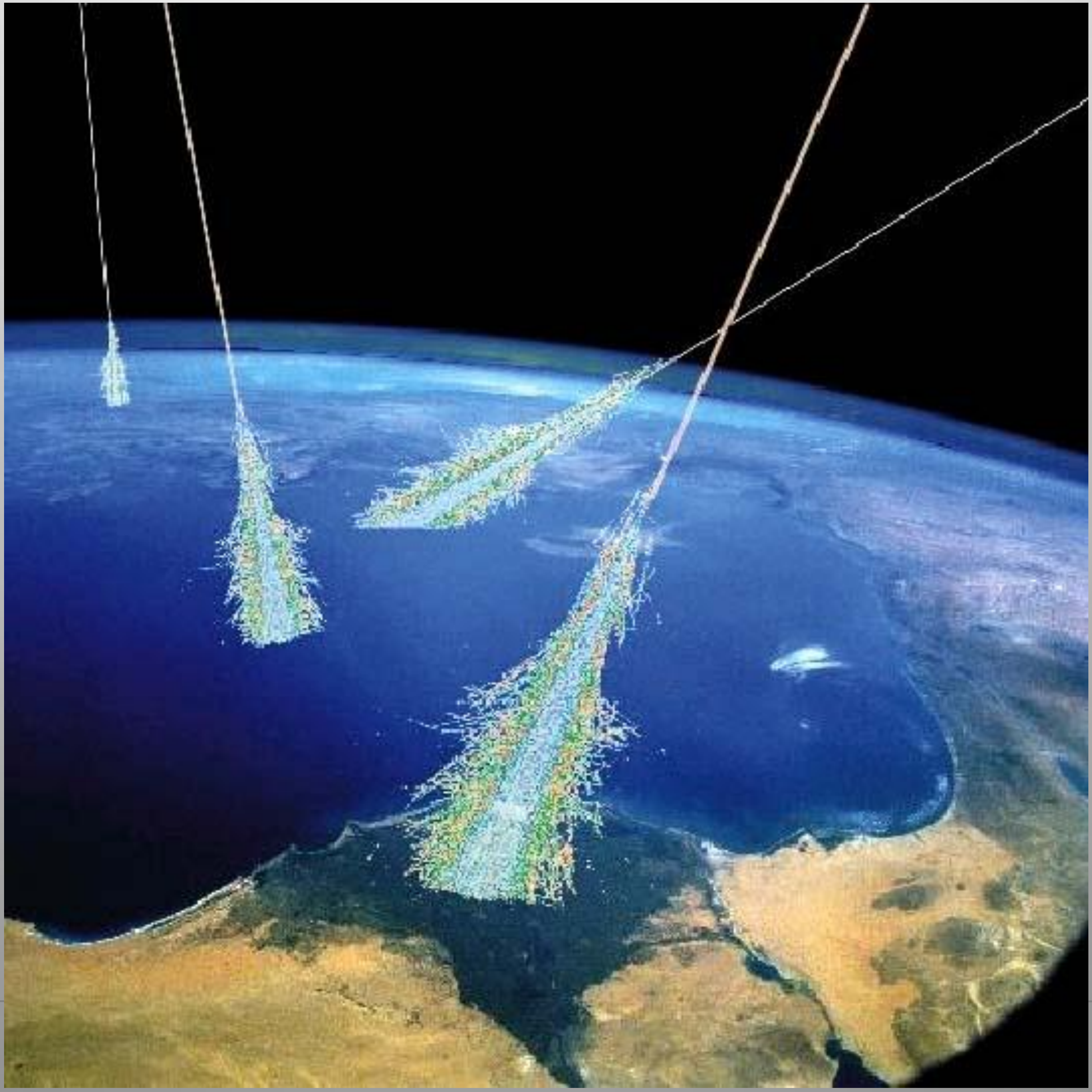
$$\sigma_{tot} = (101.7 \pm 2.9)mb$$

$$\sigma_{inel} = (74.7 \pm 1.7)mb$$

$$\sigma_{el} = (27.1 \pm 1.4)mb$$

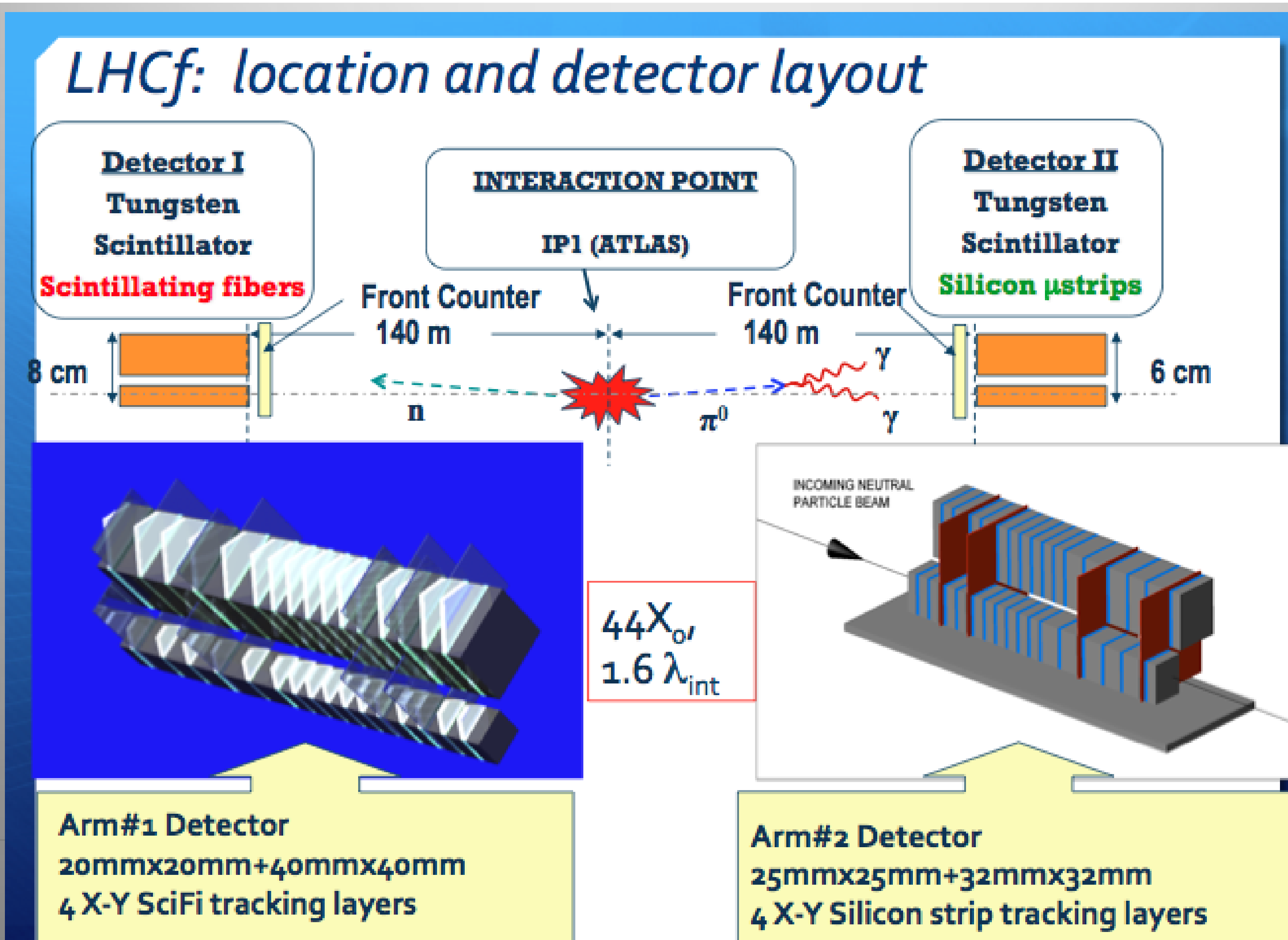
Future:
- High beta measurements for Coulomb-Nuclear interference
- Common data with CMS?

LHC Results for Cosmic Rays



Forward gammas: LHCf Experiment

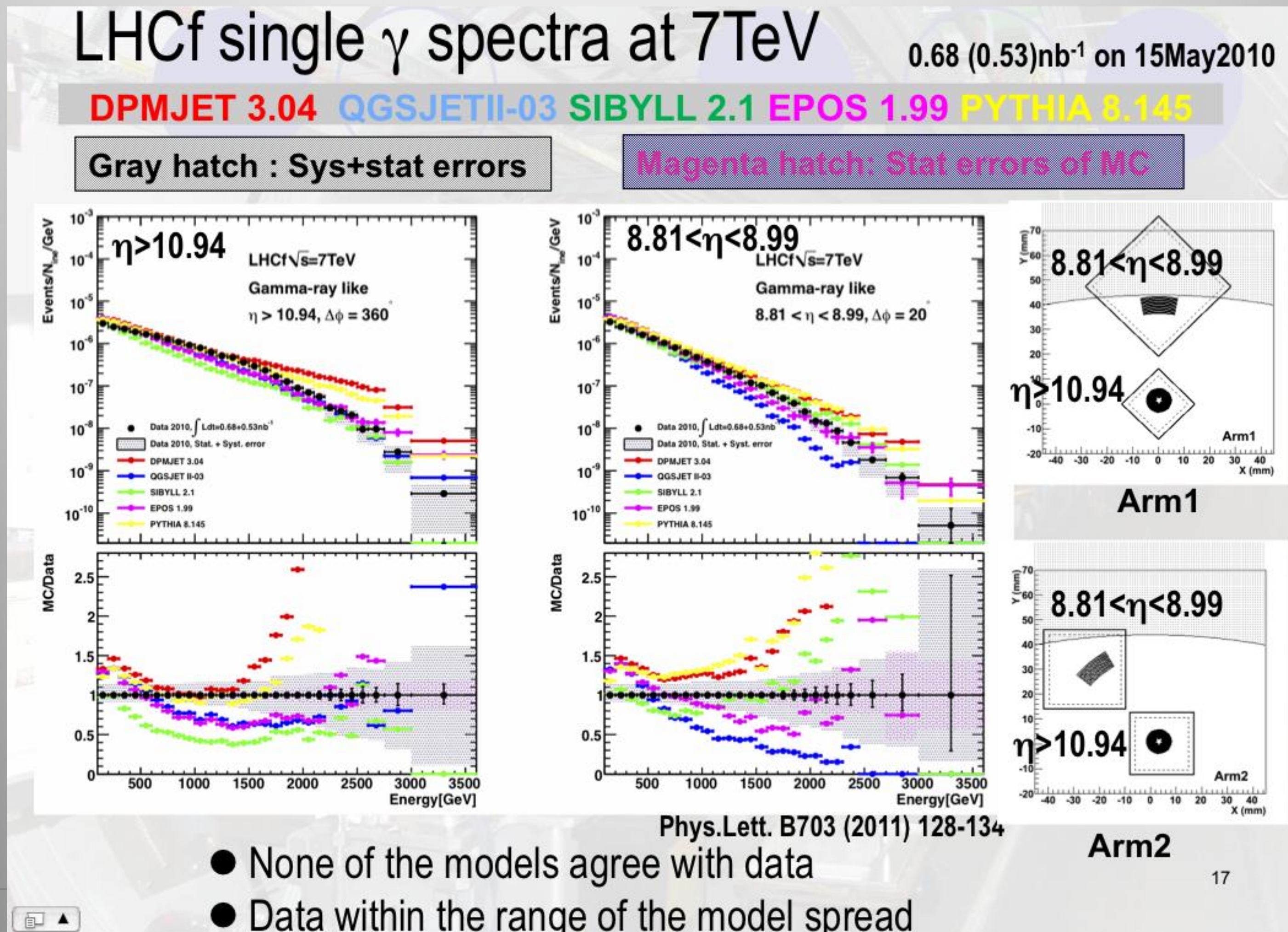
LHCf uses the same Interaction Point as ATLAS (IP1)
LHCf has forward detectors at zero degrees seen from the IP (140 away from the IP)



LHCf: Forward Photons @ 7 TeV

Y. Itow
ISVHECRI 2012

Forward gamma measurement compared to Monte Carlos
No model reproduces the data !!



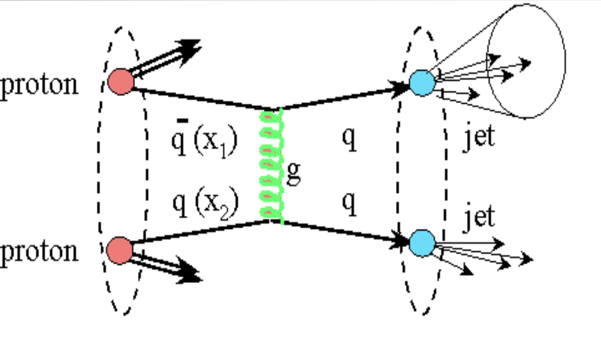
The Standard Model

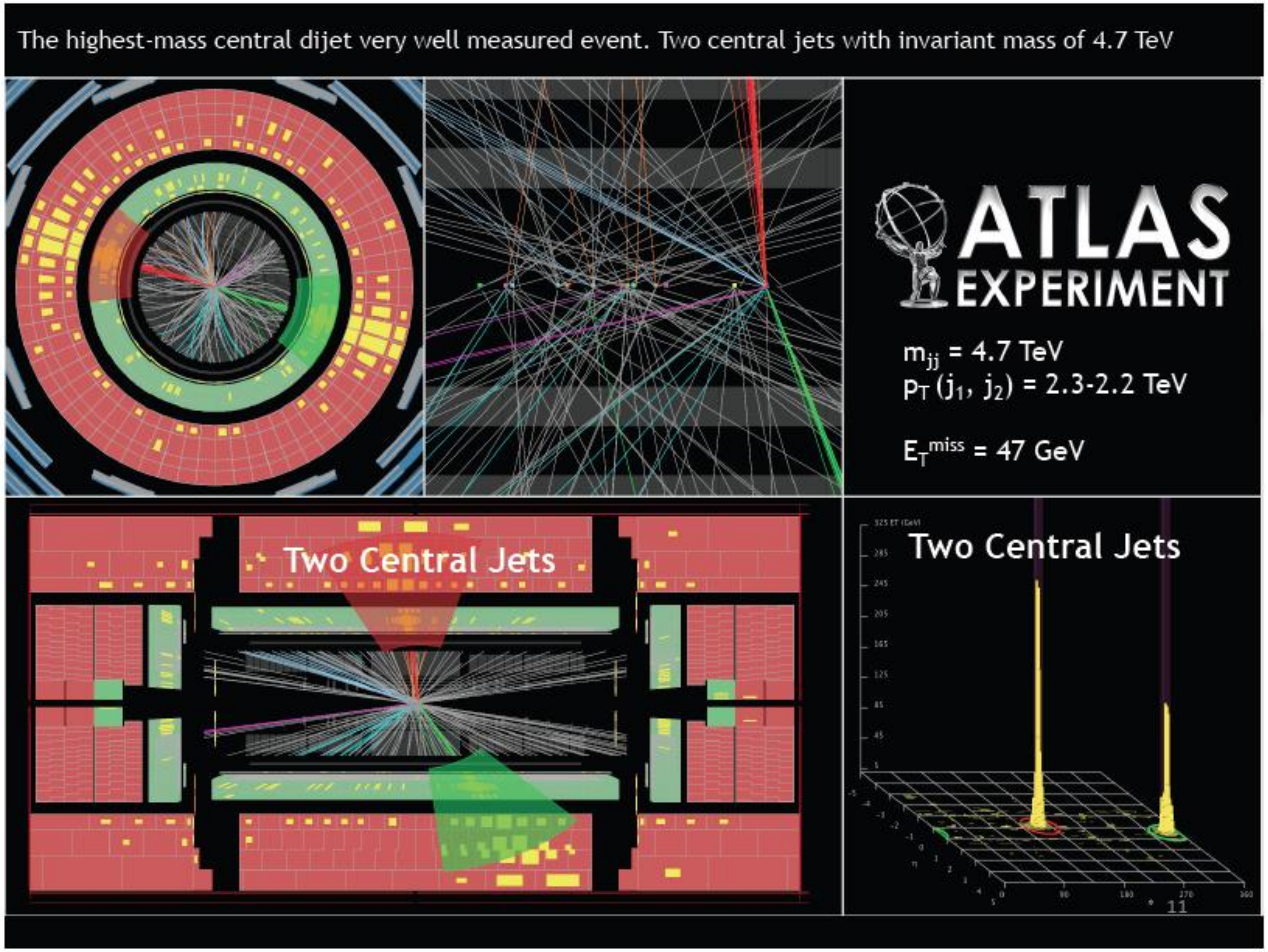
$SU(3) \times SU(2) \times U(1)$

Strong and Electroweak force

Strong Interaction: Jets!

Study the strong force via jet production



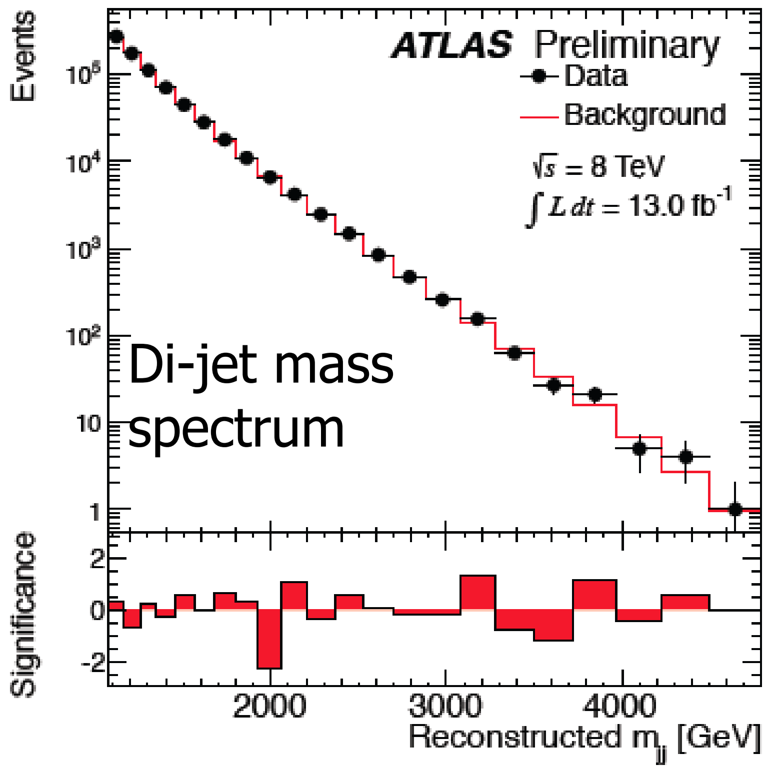


Jets of particles emerge after a high energy parton-parton scattering

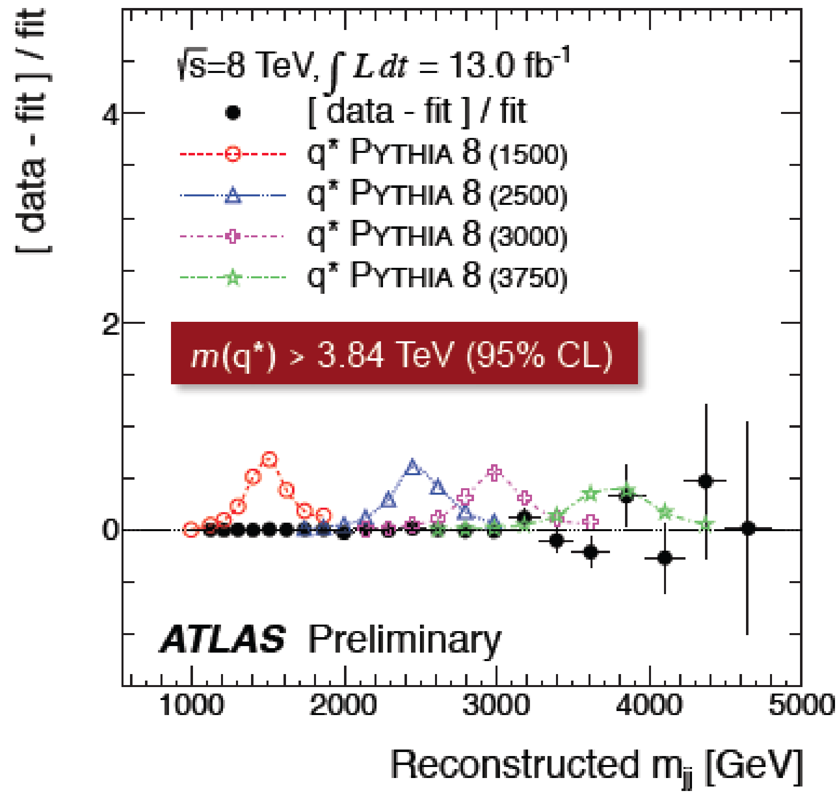
In this event more than 50% of the proton-proton energy ends up in jets

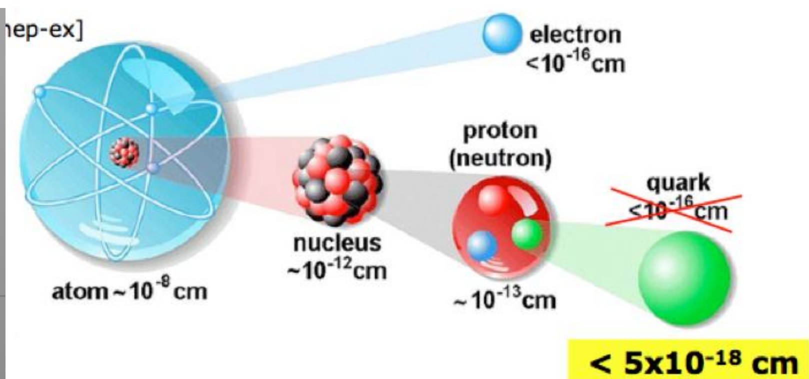
Strong Interactions QCD

Observed and fitted **dijet mass**



Data / fit ratio, compared to four q* models





Rutherford scattering:
-> gives limits on quark substructure

Dense Matter Interactions

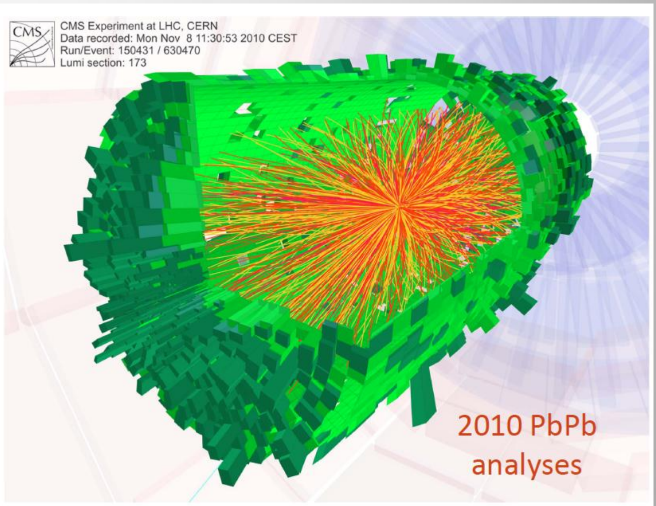
Heavy Ion Collisions

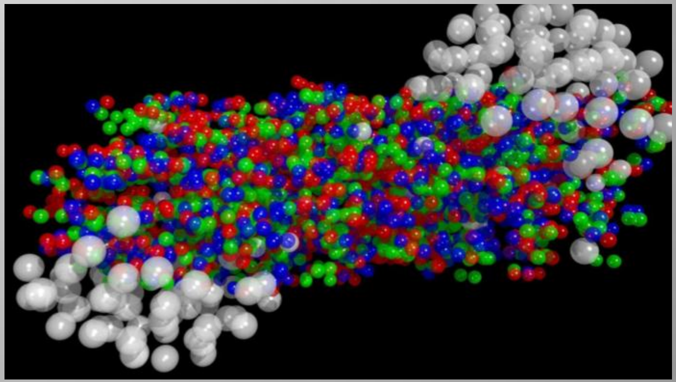
Hard Probes of Heavy Ion Physics

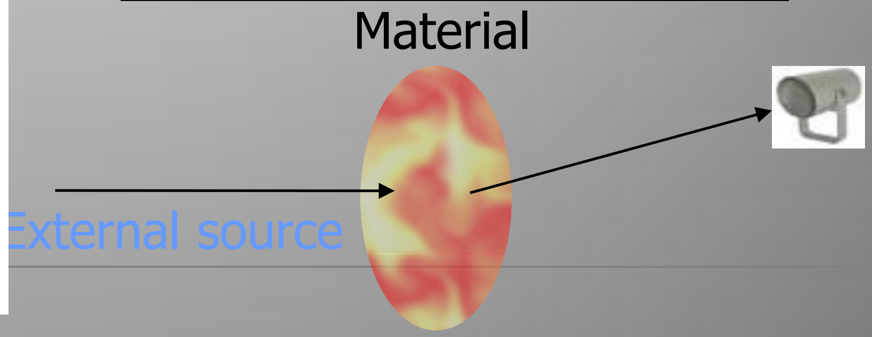
Goal:

Understand the properties of Quark Gluon Plasma: a new state of matter

- Problem: the lifetime of QGP is so short (O(fm/c)) such that it is not feasible to probe it with an external source.
- Solution: take the advantage of the large cross-sections of high p_T jets, γ/W/Z, quarkonia at the LHC energy, use hard probes produced in the collision.
- About 150 μbarn of PbPb collision data







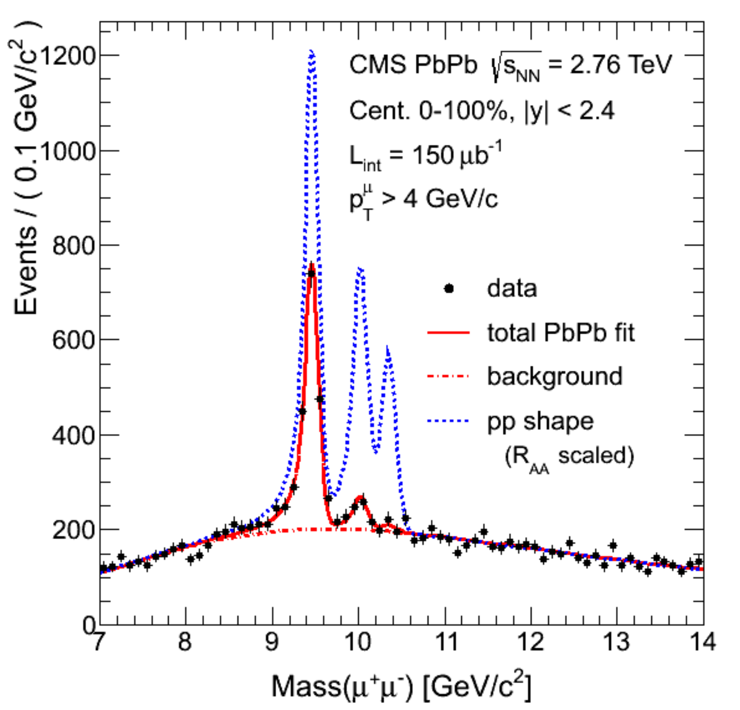
Theoretical Concepts in HIN Physics

- Relativistic fluid dynamics (space-time evolution of final state)
- Low-x, saturation, color-glass condensate (initial state effects, correlations inherited by the final state)
- pQCD (high-p_T jets, particles, energy loss)
- AdS/CFT, connection with string theory (shear viscosity over entropy density, heavy quark energy loss, QGP-black hole duality)
  - Velocity-dependent screening in the plasma for heavy quarks: can be calculated in the AdS/CFT framework
  - Energy loss of charm and bottom can be calculated in AdS/CFT and tested in experiments
  - η/s can also be calculated by AdS/CFT and also in various viscous hydrodynamical models, and results compared to experimental data

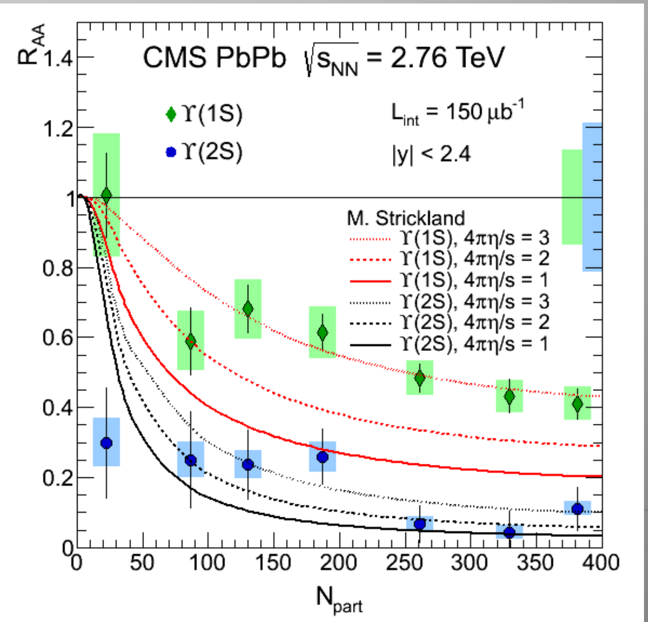
Measuring Shear Viscosity/s

- Azimuthal anisotropy of final state particles (unlike incoherent sum of NN collisions)
- Data provide typically an upper bound on η/s
- Policastro, Son, and Starinets (2003): at finite T in the strong coupling limit, the shear viscosity/entropy density (N=4 super-YM) is $1/4\pi$.
- Y suppression (measured by CMS) sensitive to η/s

arXiv:1207.5327v2

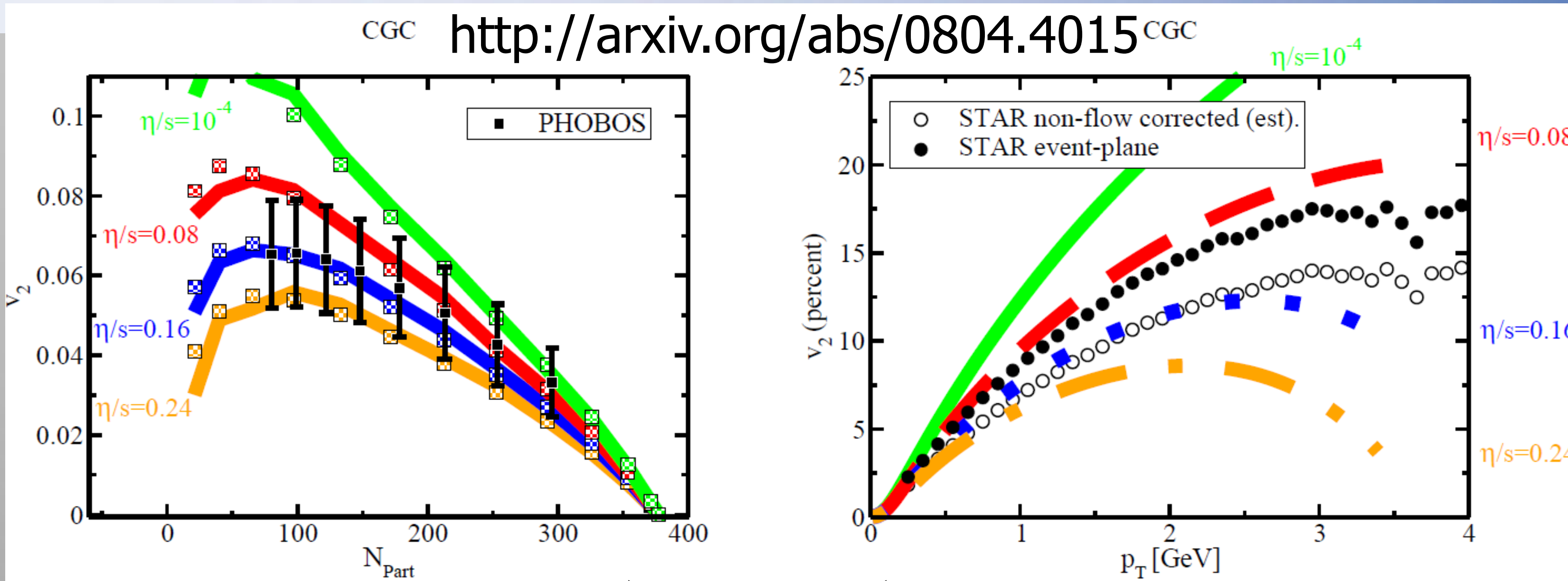


PRL 109 (2012) 222301

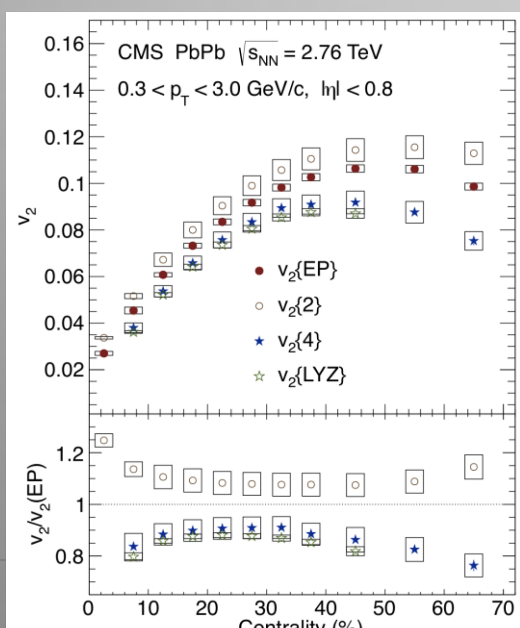


Viscosity from v_2 vs. centrality and transverse momentum

http://arxiv.org/abs/0804.4015

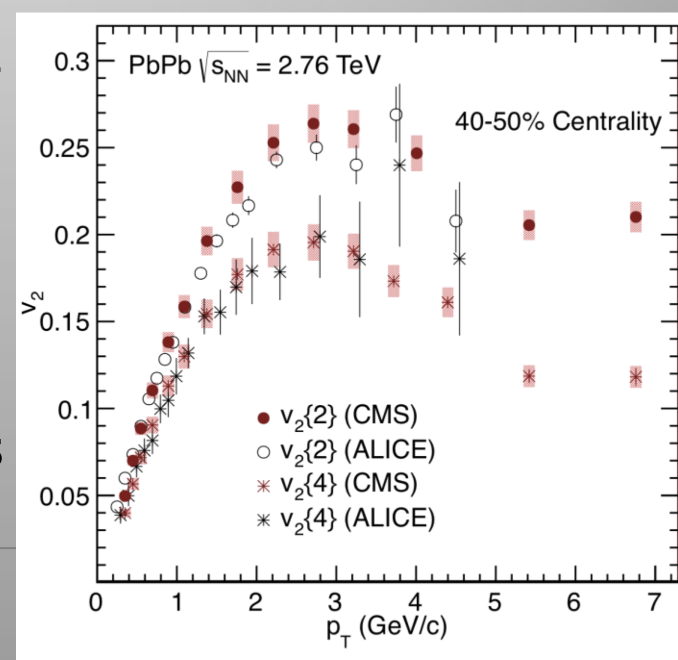


Analysis of RHIC data



PRC 87(2013) 014902

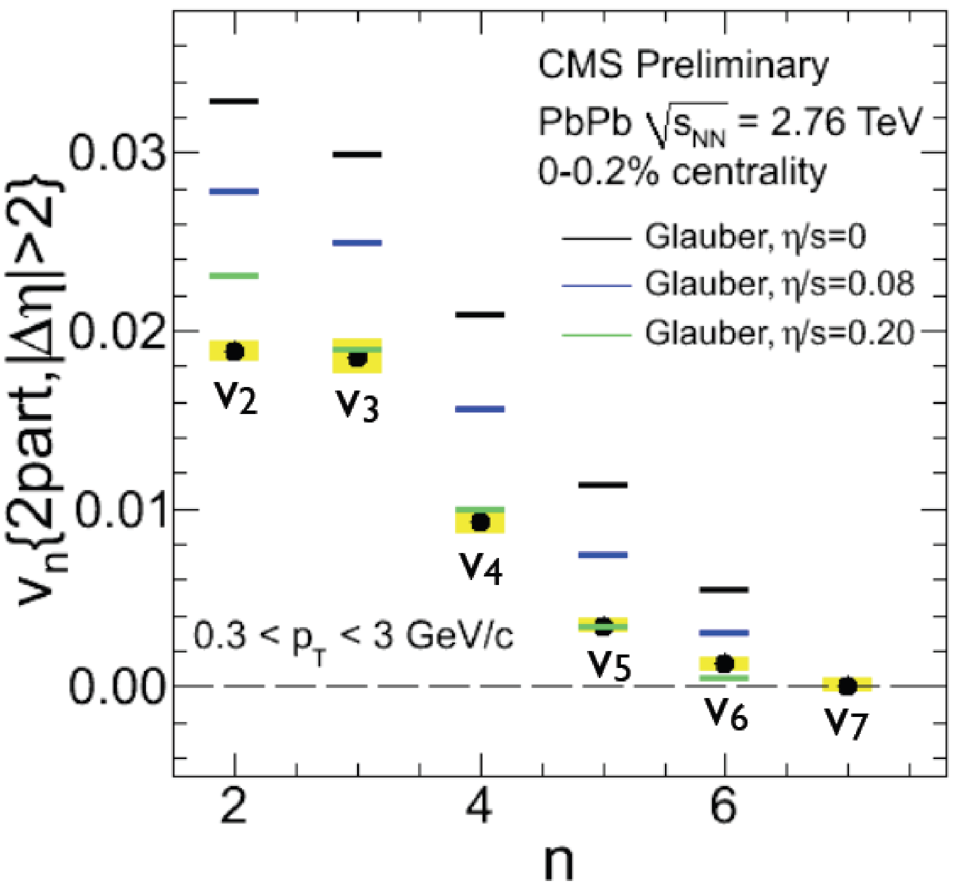
New results from LHC



Measurements of Asymmetries

Higher flow components in Ultra-central PbPb events sensitive to η/s

M. Luzum and J. Ollitrault.

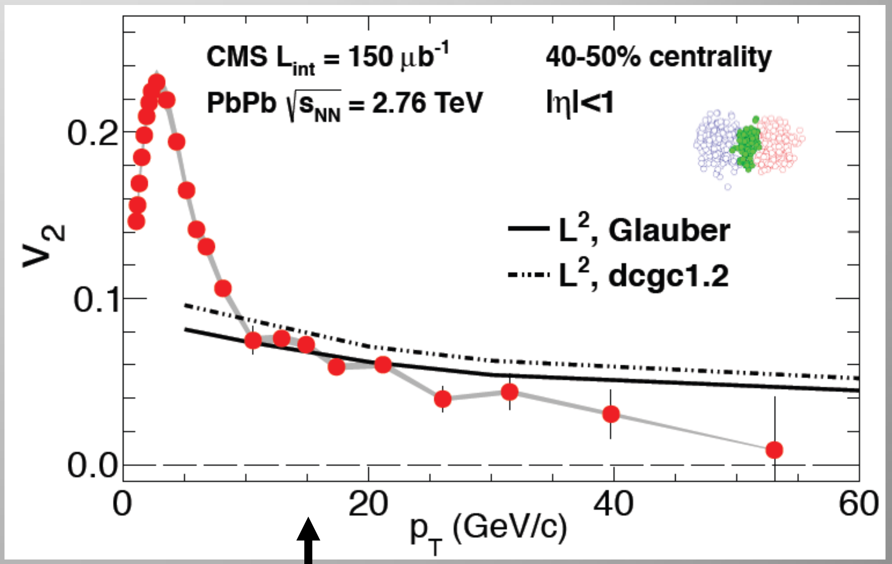


CMS PAS HIN-12-011

At high p_T, path length dependence of energy loss: AdS/CFT predicts stronger effect than pQCD

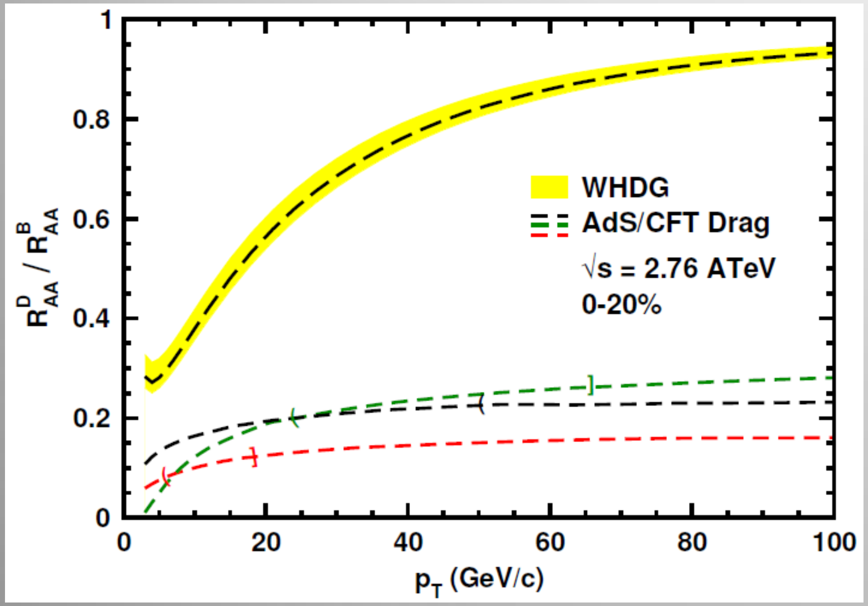
PRL 109 (2012) 022301

arXiv:1201.0281

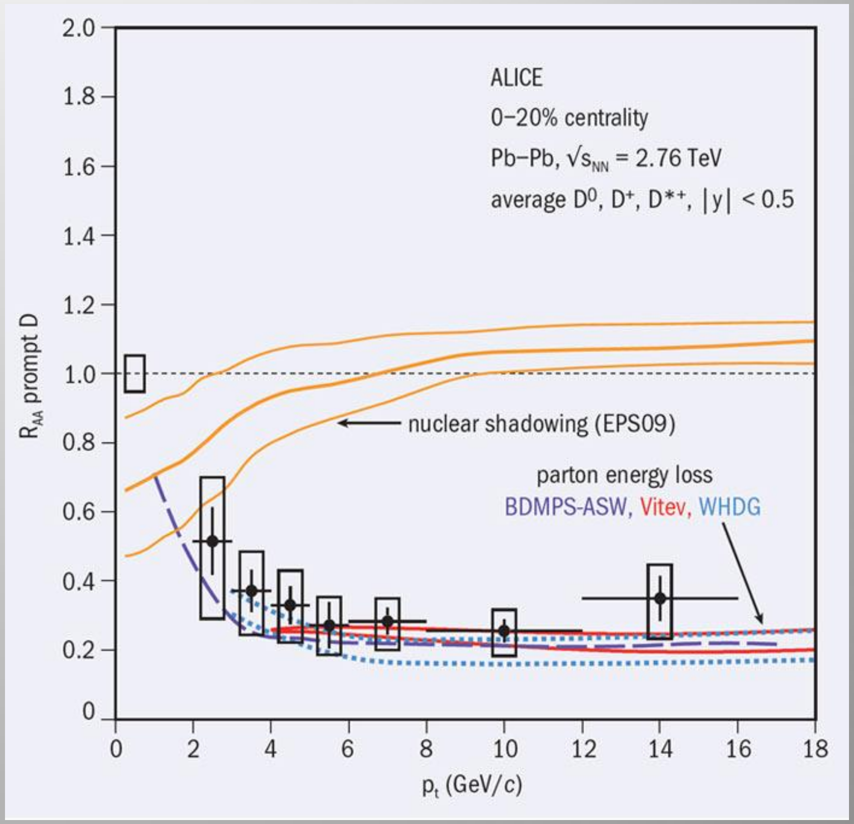


$$\Delta E \propto \begin{cases} L & \text{pQCD, collisional} \\ L^2 & \text{pQCD, radiative} \\ L^3 & \text{AdS/CFT} \end{cases}$$

Energy Loss of Heavy Quarks in Hot Plasma



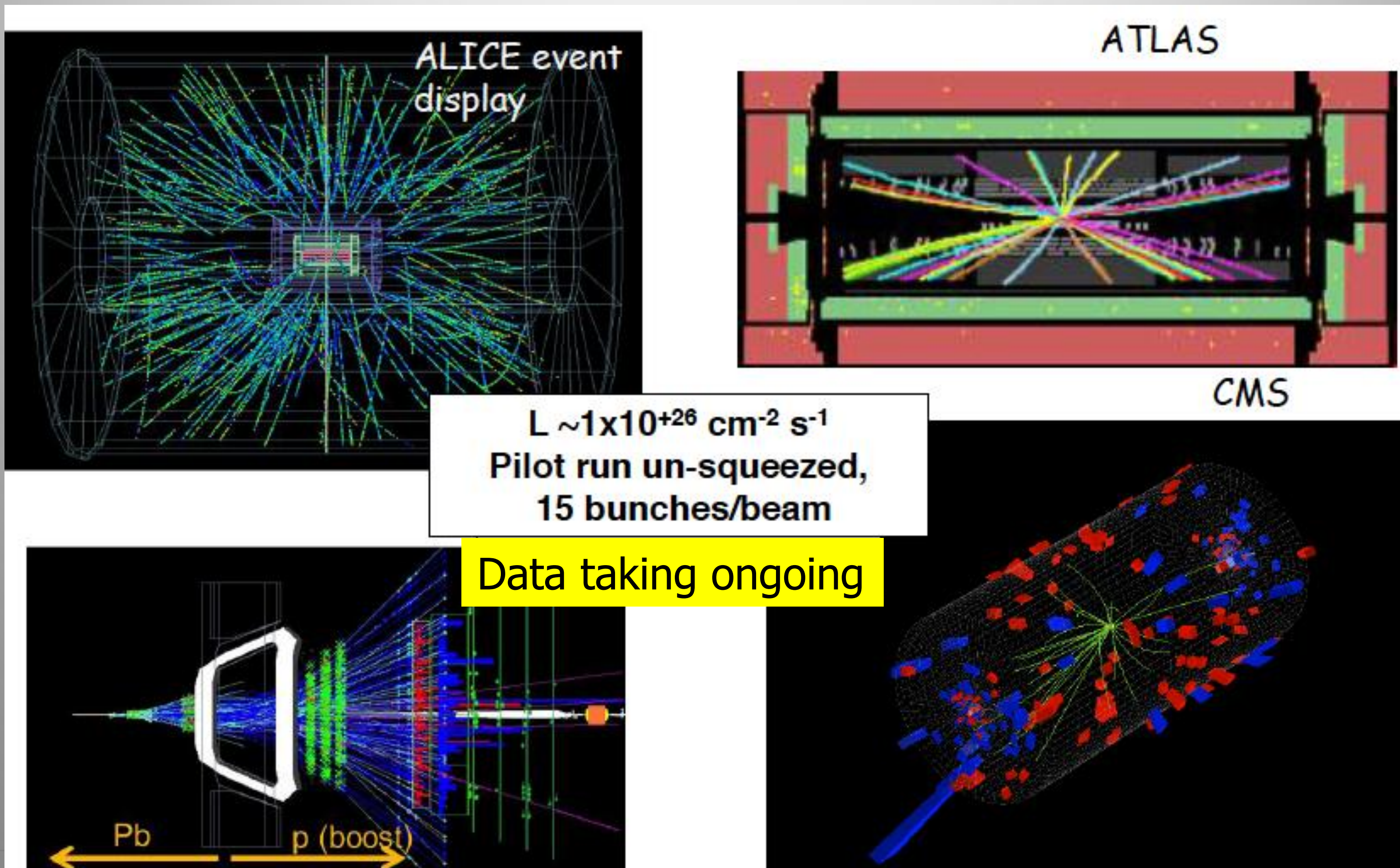
Horowitz, W.A. *et al.* J.Phys. G35 (2008)



AdS/CFT predicts much larger charm suppression than bottom suppression

ALICE results address open charm suppression

New: pPb Collisions



$L \sim 1\times10^{+26}$ cm^{-2} s^{-1}
Pilot run un-squeezed,
15 bunches/beam

Data taking ongoing

The Standard Model (Part II)

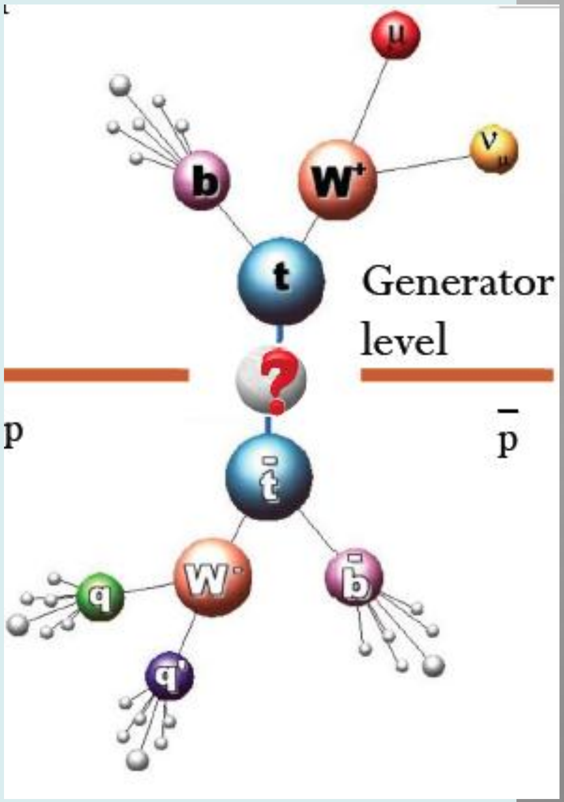
$SU(3) \times SU(2) \times U(1)$

Strong and Electroweak force

Studies of the TOP Quark

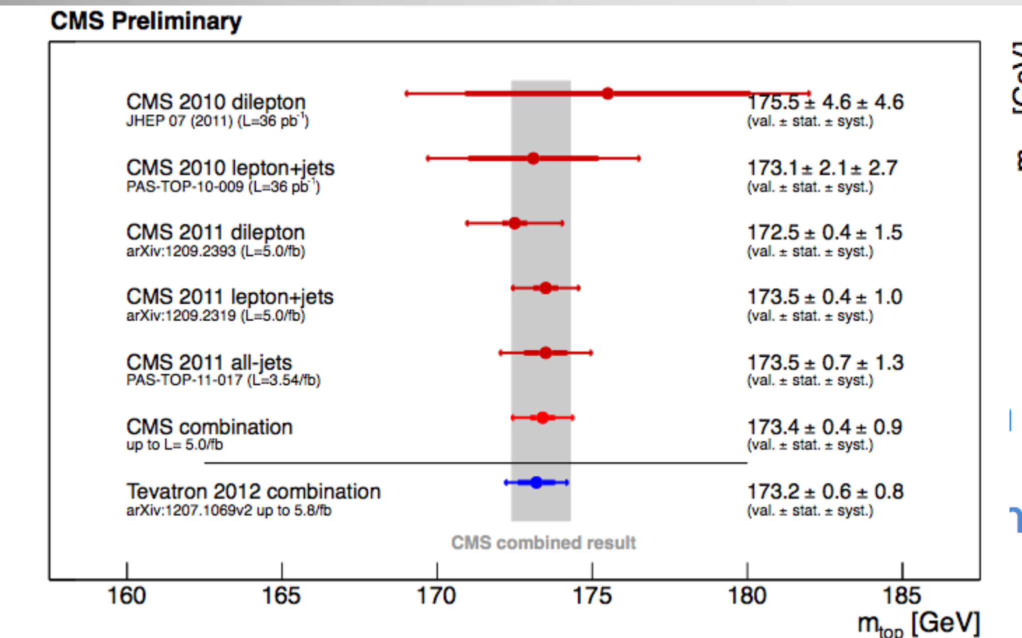
- The TOP quark is the heaviest elementary partcile we know. We produced ~ 5 10^6 pairs at the LHC so far
  It could play a special in electroweak symmetry breaking or physics Beyond the Standard Model.

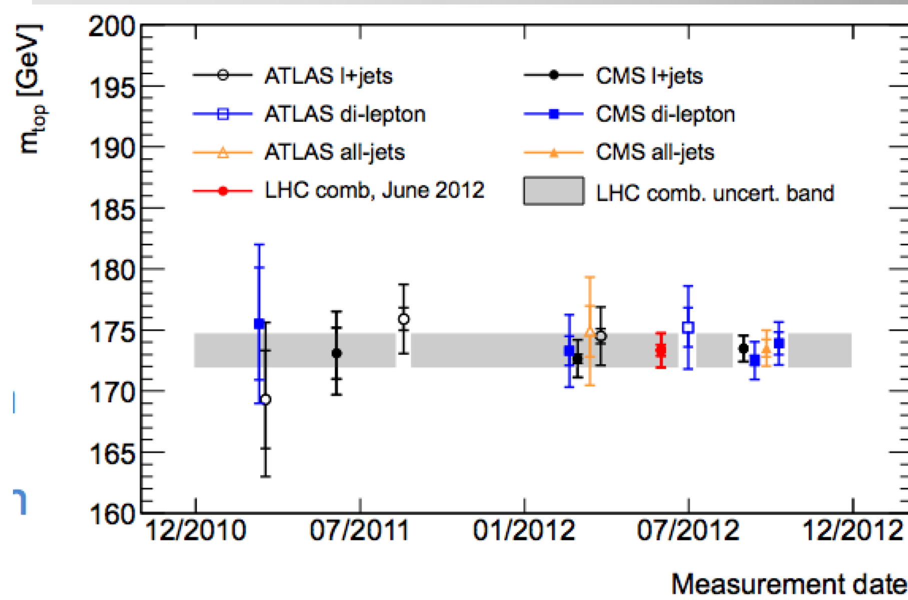
- Assume all tops decay to Wb: event topology then depends on the W decays:
  - one lepton (e or μ), E_T^{miss}, jjbb (37.9%)
  - di-lepton (ee, $\mu\mu$ or eμ), E_T^{miss}, bb (6.46%)
  - All hadronic channel



Top Quark: Top Mass Measurement

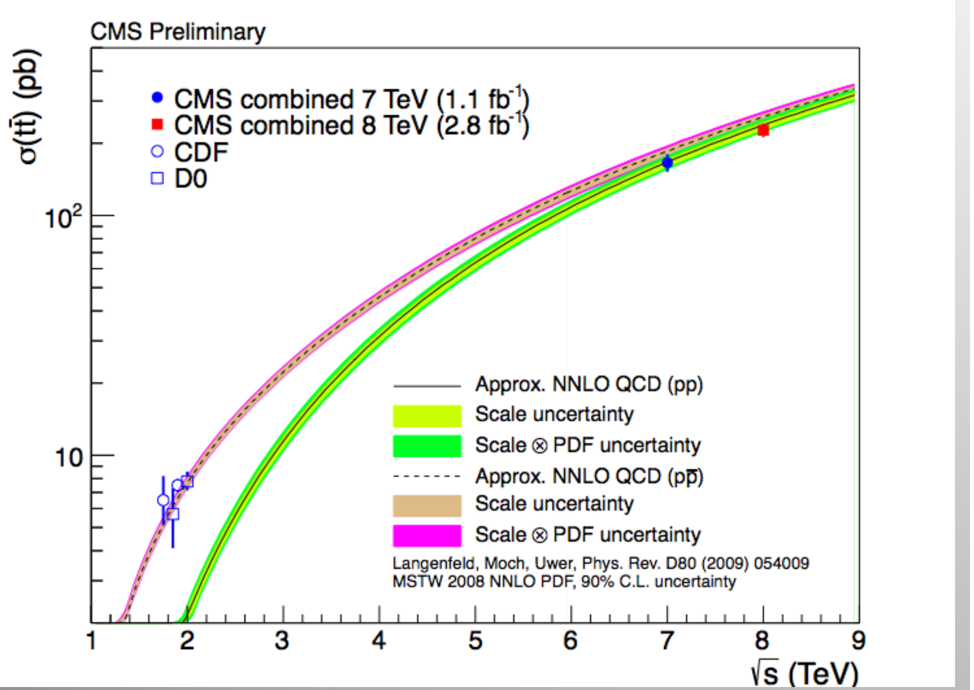
Very significant progress over the last 12 months
LHC Experiments now as precise as those of the Tevatron (16 year effort)

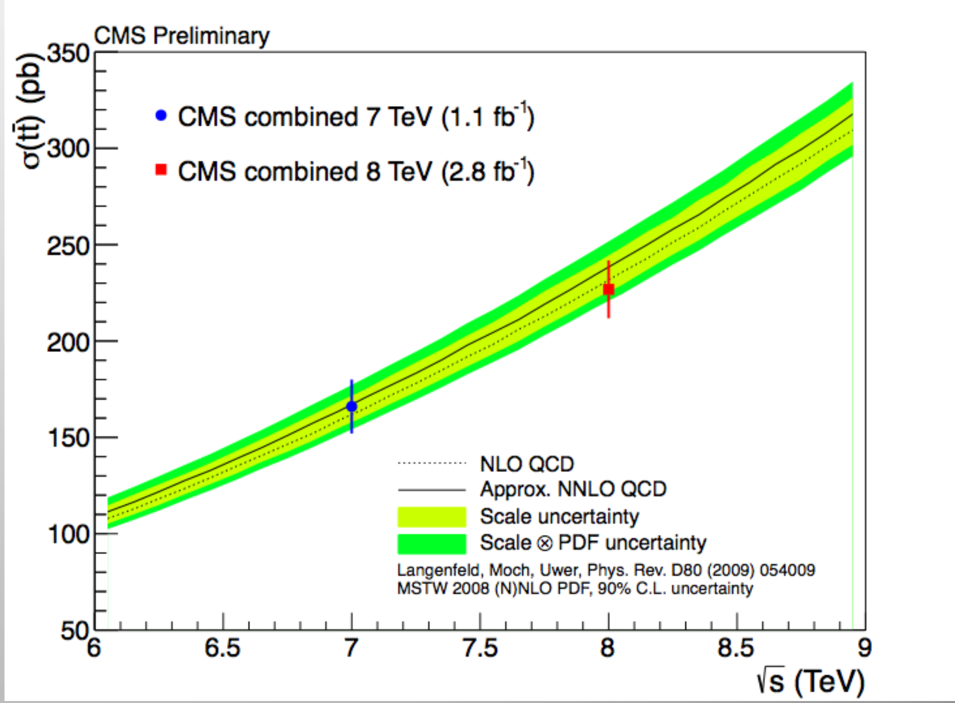




Precision on the mass now better than 1%
Important for EWK studies, Higgs, see later…

Top Quark: Top Cross Section



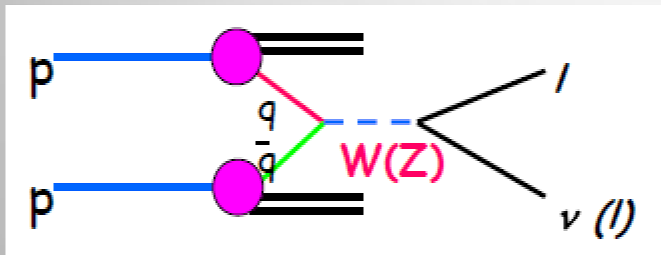


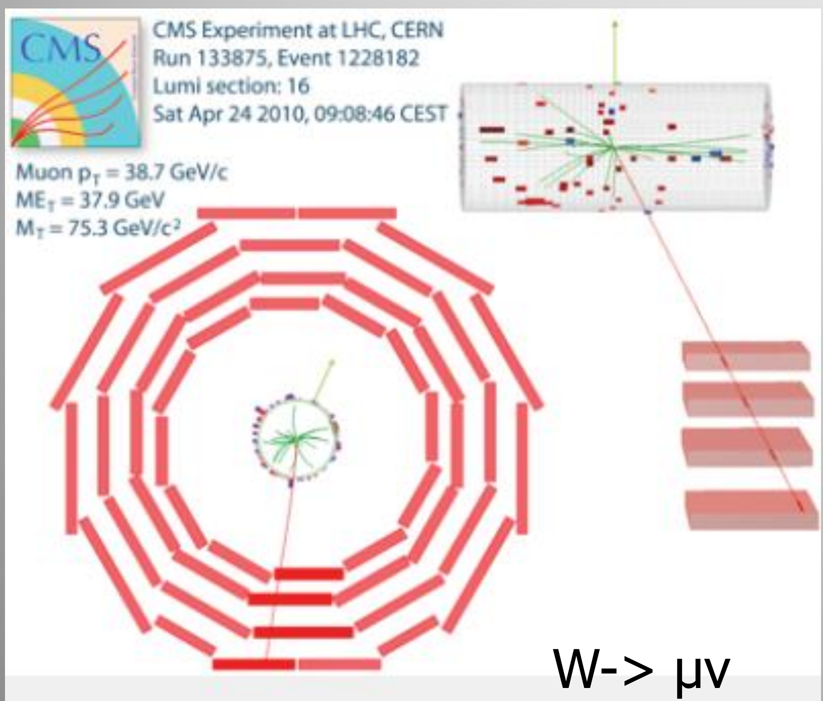
Precision of the cross section measurement ~ 5%

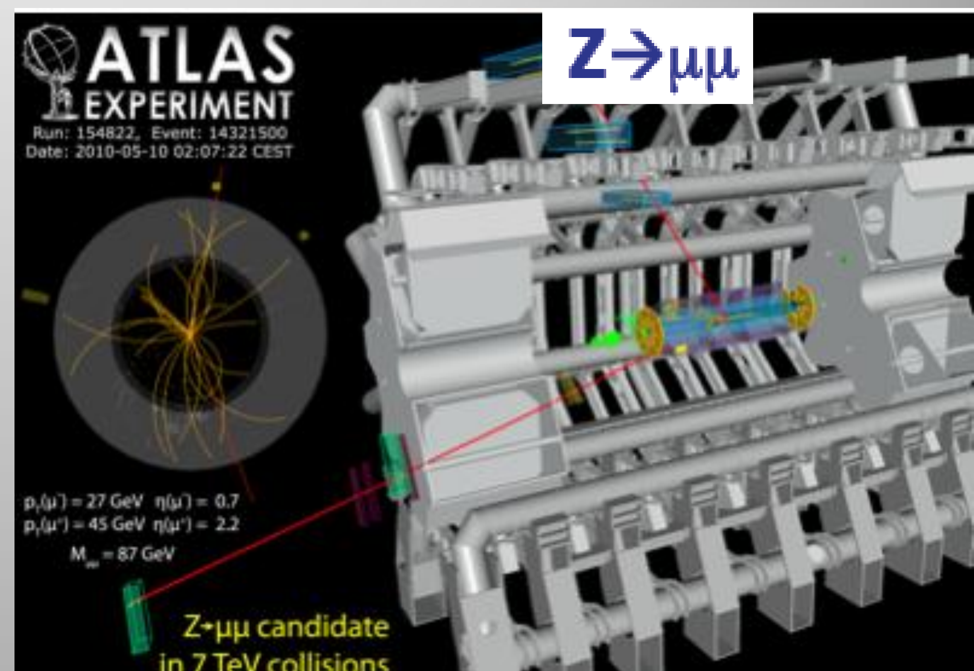
The measurements agree well with approximate NNLO calculations

7 TeV -> arXiv:1208.2671

Heavy Boson Production



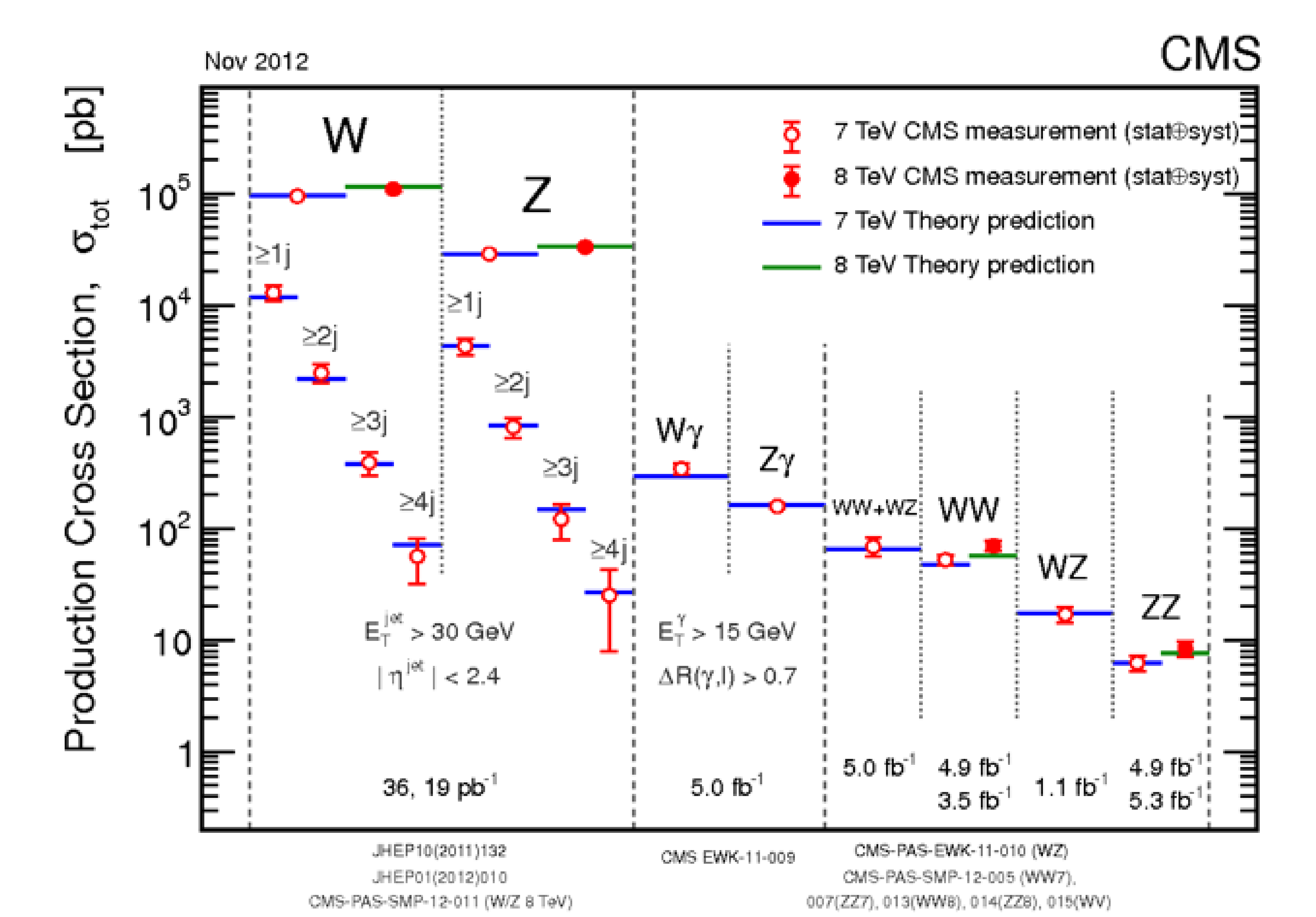




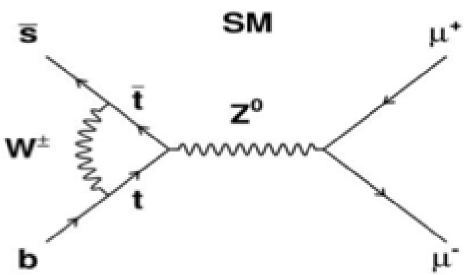
The first W & Z bosons showed up in May 2010 in the experiments

Now: about 6M W and 600K Z events/fb^{-1} for analysis (e+μ final states)

Vector Boson Production Overview



Rare Decays: B_s to μμ



Mode	SM prediction
$B_s \to \mu^+\mu^-$	$(3.54 \pm 0.30) \times 10^{-9}$
$B^0 \to \mu^+\mu^-$	$(0.11 \pm 0.01) \times 10^{-9}$

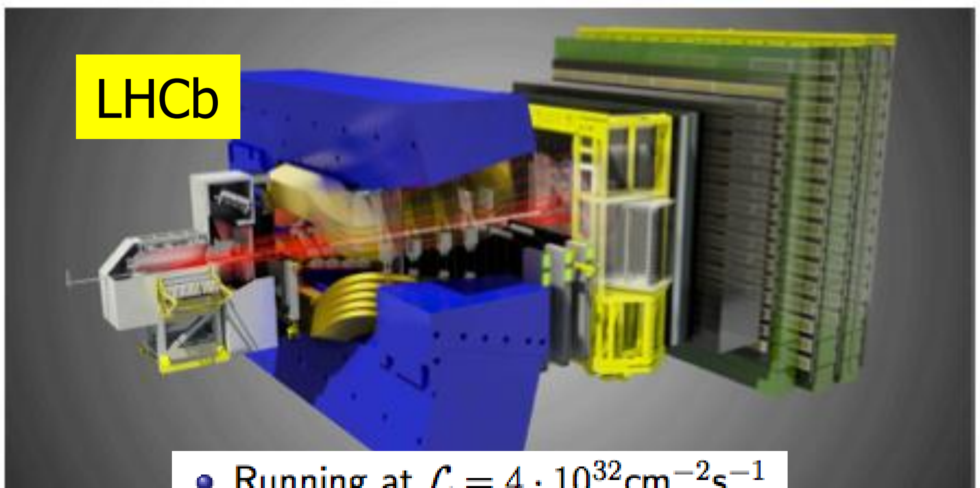
A. Buras et al., arXiv:1208.0934

DeBruyn et al., arXiv:1204.1737

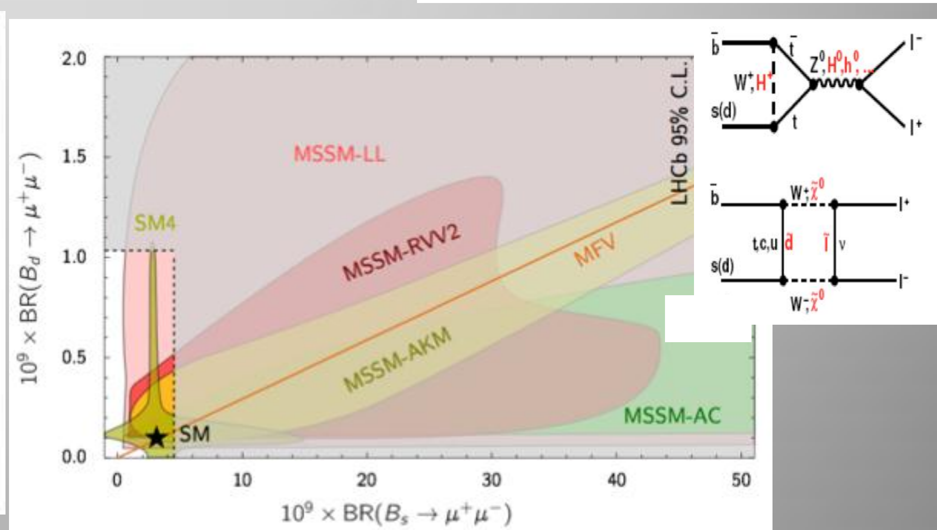
C. Davies, arXiv:1203.3862 (and ref. therein)

Since many years this decay has been chased CDF, D0, CMS, ATLAS and LHCb

New (pseudo) scalars can modify the SM predictions

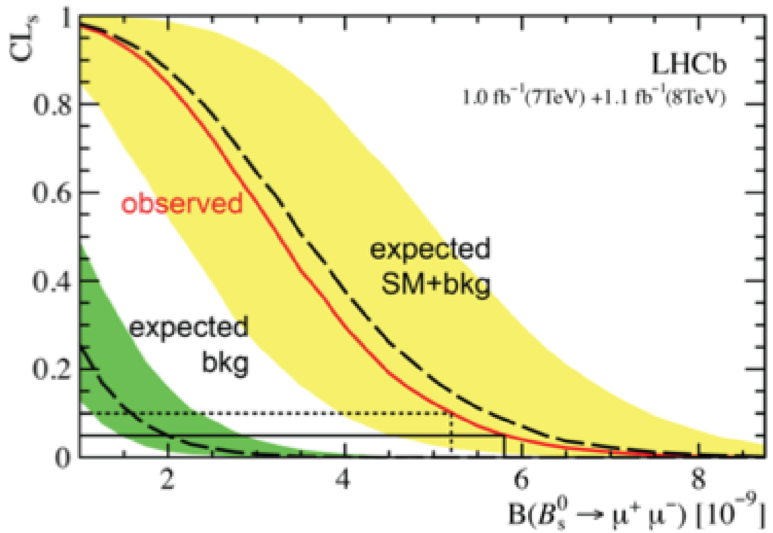


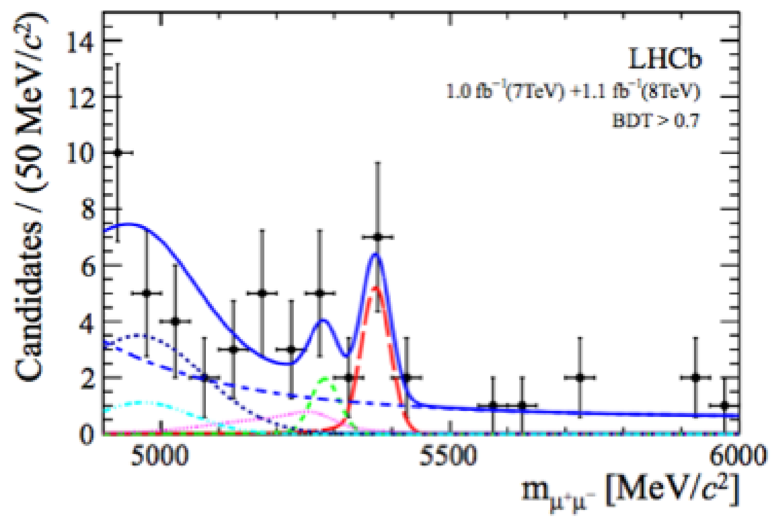
- Running at $\mathcal{L} = 4 \cdot 10^{32} \text{cm}^{-2}\text{s}^{-1}$



LHCb: Plethora of flavor measurements: D0 oscillations, observation of new B meson decays, CP asymmetry studies, CKM angle measurements,..

Rare Decays: B_s to μμ





- Combining 2011+2012 data
- Bkg only hypothesis p-value is 5×10^{-4} corresponding to 3.5 σ
- $\mathcal{B}(B_s \to \mu^+\mu^-) = 3.2^{+1.4}_{-1.2}(stat)^{+0.5}_{-0.3}(syst) \times 10^{-9}$
- First evidence of the decay $B_s \to \mu^+\mu^-$
- Consistent with the SM!
- Submitted to PRL arXiv:1211.2674

The Hunt for the Higgs

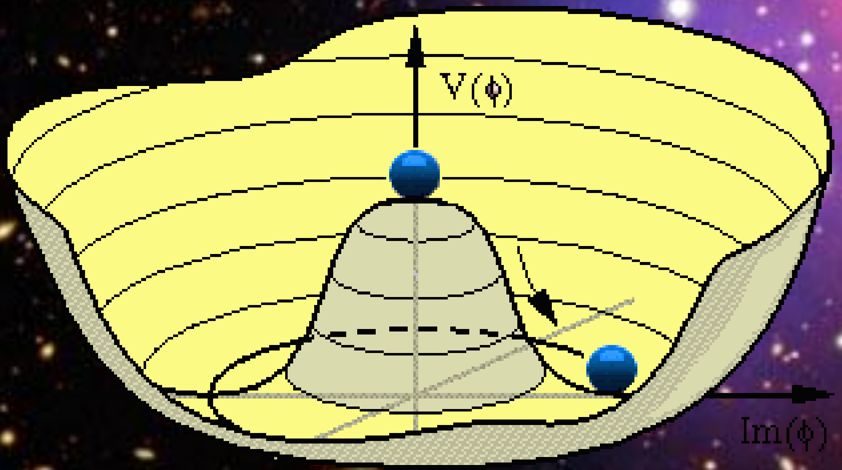
The Hunt for the Higgs

Where do the masses of elementary particles come from?

The key question: Where is the Higgs?

Massless particles move at the speed of light -> no atom formation!!

We do not know the mass of the Higgs Boson

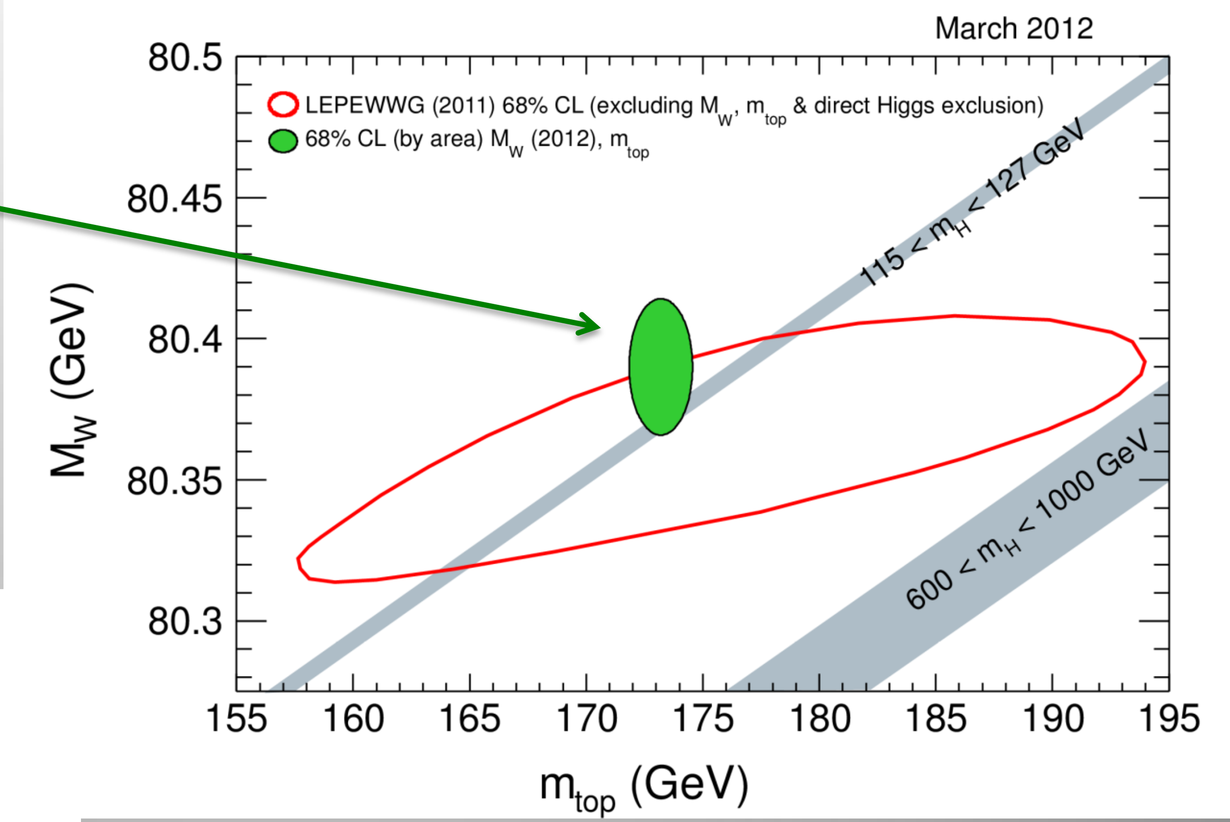


Scalar field with at least one scalar particle

It could be anywhere from 114 to 700 GeV

Higgs Situation in Early 2012

Exquisitely precise measurement of M_W driven mainly by the Tevatron.



Much of the SM Higgs range has been ruled out by 2011 LHC running.

Exclusions of M_H:

- LEP < 114.4 GeV (arXiv:0602042v1)
- Tevatron [156,177] GeV (arXiv:1107.5518)
- LHC [~127, 600] GeV arXiv:1202.1408 (ATLAS); arXiv:1202.1488 (CMS)

Higgs Hunters

Higgs Hunting Basics

Needle-in-the-hay-stack problem

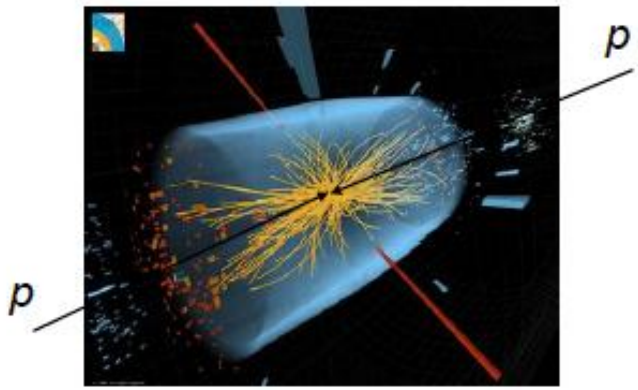
- need high energy:

  $E = mc^2$

- need lots of data

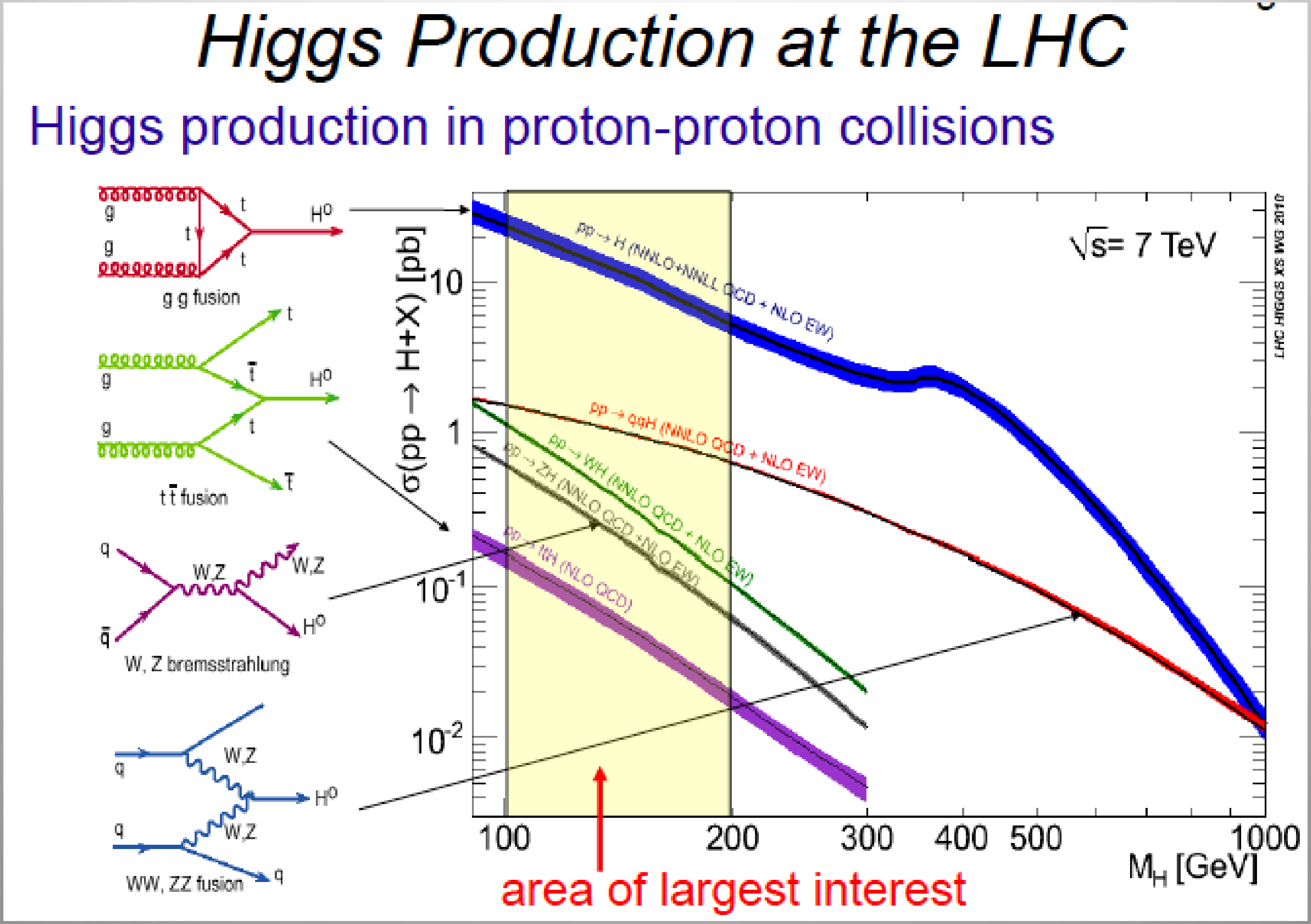
non-deterministic and very rare

order 1 in 10^{11}

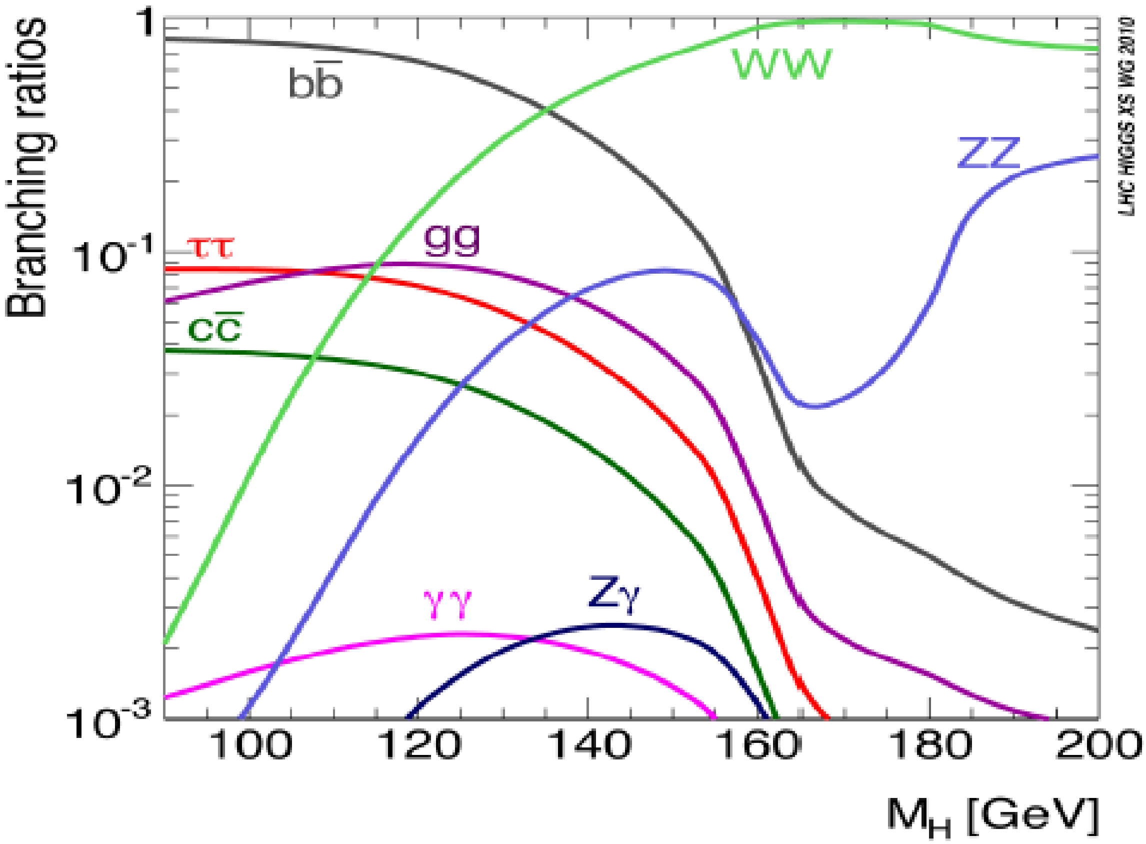


* for us finding the Higgs it was
48 years = 1,513,728,000 sec

Higgs Production Channels vs Mass



Higgs Decay Channel vs. Mass



Higgs boson couples to mass

$\Gamma_{Hff} \sim m_f^2$

Messy: many channels, many subsequent decays *etc. etc.*

- common: leptons/photons essential for any search
- 5 channels are most promissing

Higgs Hunting at the LHC

Overview – The big five

Channel	m_H range [GeV/c^2]	data set [fb^{-1}]	Data used CMS [fb^{-1}]	m_H resolution
1) $H \rightarrow \gamma\gamma$	110-150	5+5/fb	2011+12	1-2%
2) $H \rightarrow$ tau tau	110-145	5+12/fb	2011+12	15%
3) $H \rightarrow bb$	110-135	5+12/fb	2011+12	10%
4) $H \rightarrow WW \rightarrow l\nu l\nu$	110-600	5+12/fb	2011+12	20%
5) $H \rightarrow ZZ \rightarrow 4l$	110-1000	5+12/fb	2011+12	1-2%

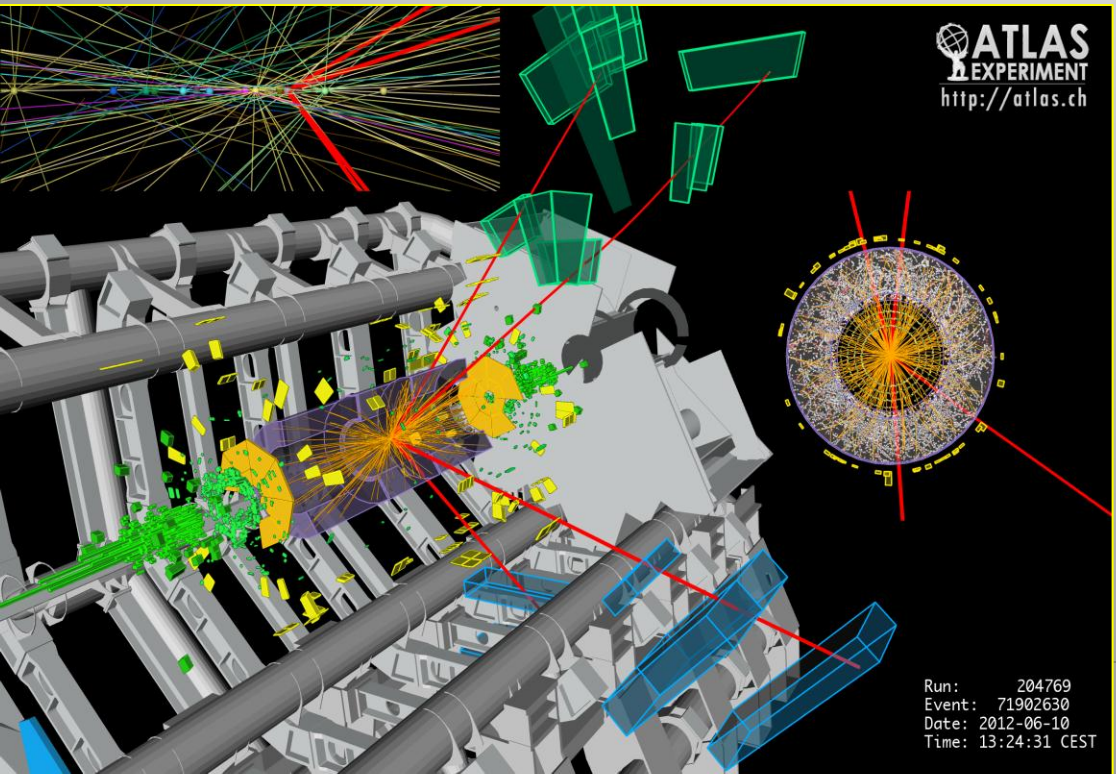
Searches for the Higgs Particle

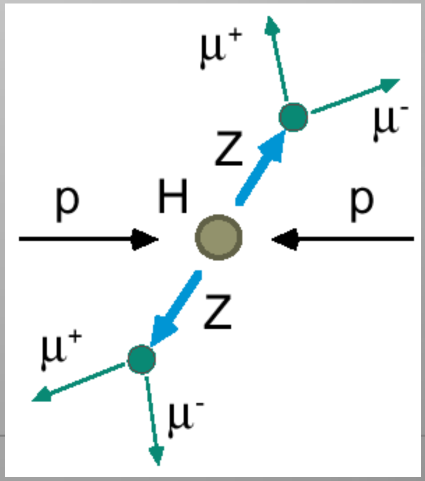
A Higgs particle will decay immediately, eg in two heavy quarks or two heavy (W,Z) bosons

Example: Higgs(?) decays into ZZ and each Z boson decays into μμ

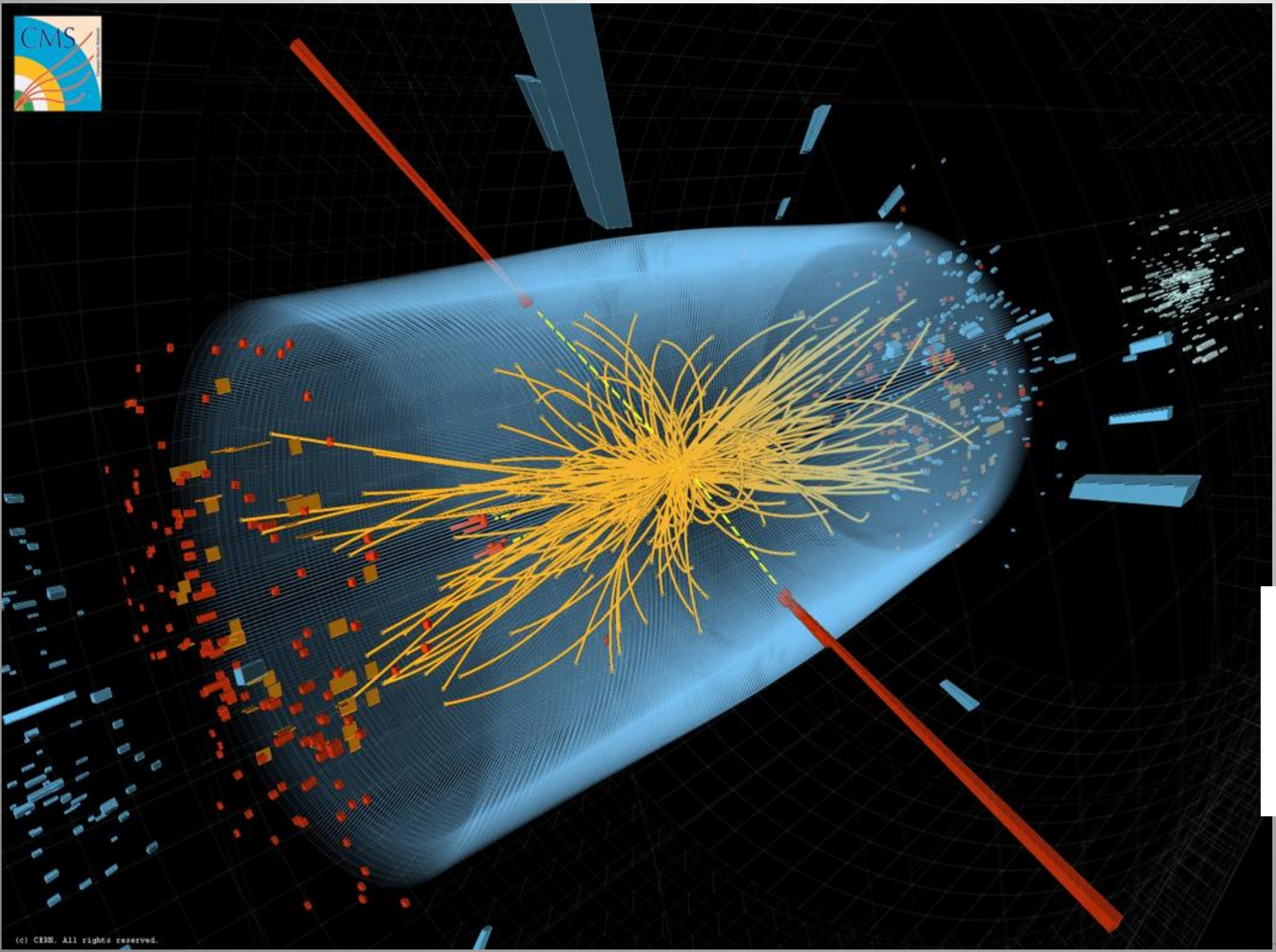
So we look for 4 muons in the detector

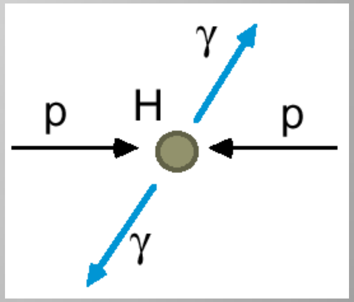
But two Z bosons can also be produced in LHC collisions, without involving a Higgs!
We cannot say for on event by event (we can reconstruct the total mass with the 4 muons)





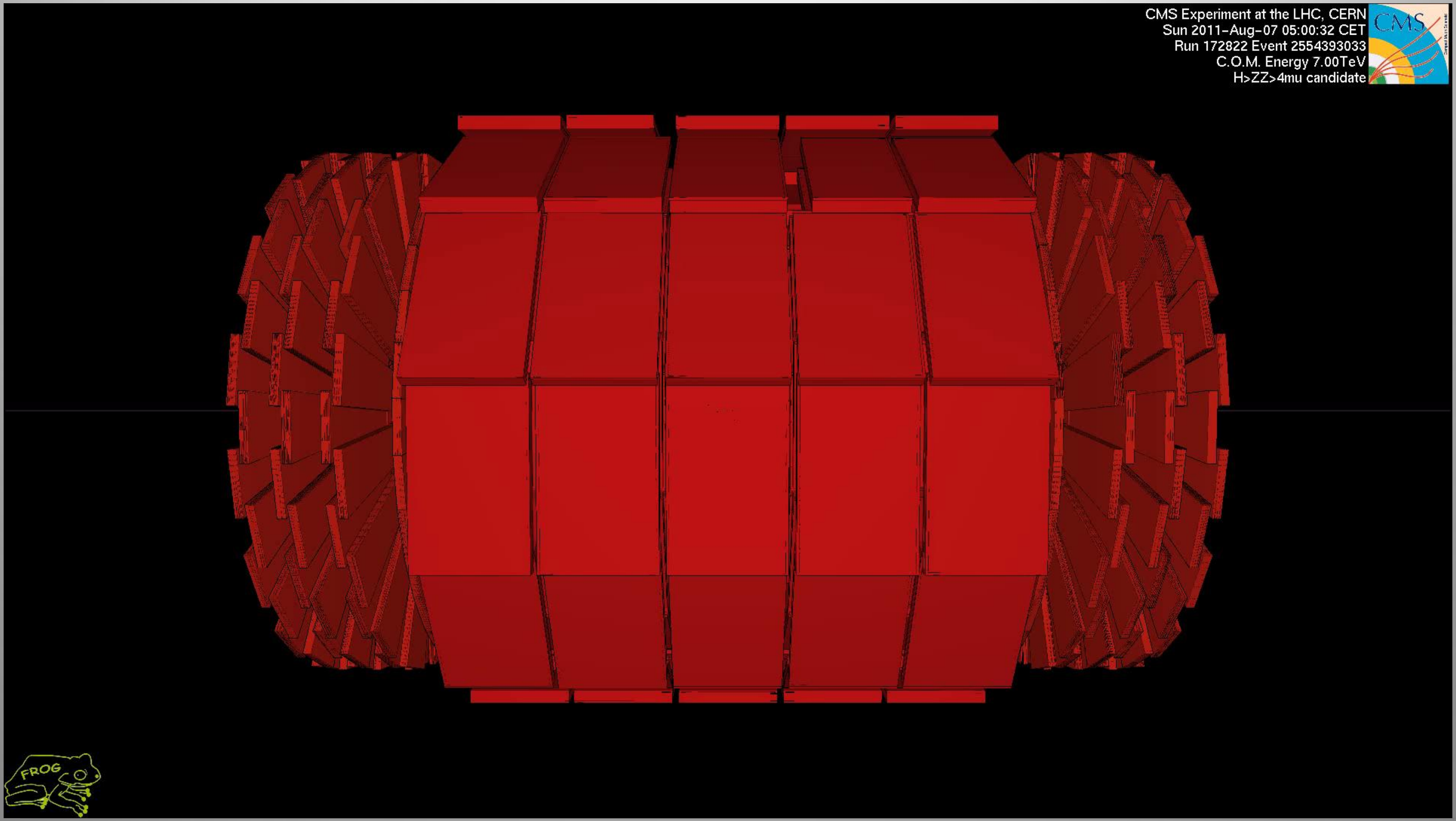
A Collision with two Photons





A Higgs or
a 'background'
process without
a Higgs?

A real collisions: ZZ-> 4 muons



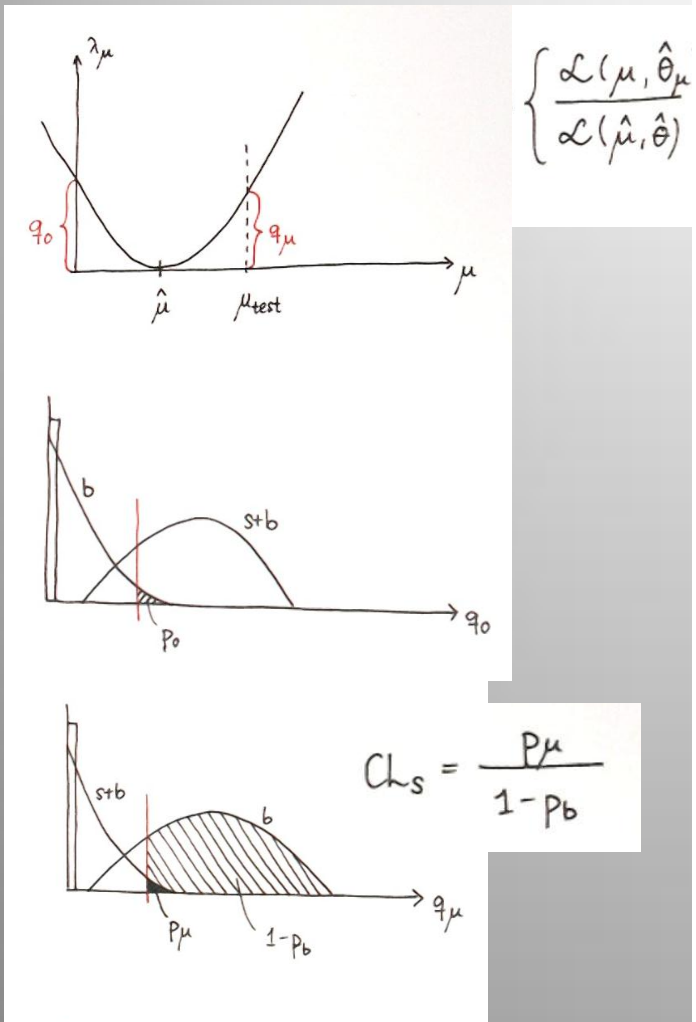
July 4th 2012

- Official announcement of the discovery of a Higgs-like particle with mass of 125-126 GeV by CMS and ATLAS.
- Historic seminar at CERN with simultaneous transmission and live link at the large particle physics conference of 2012 in Melbourne, Australia

CERN

Melbourne

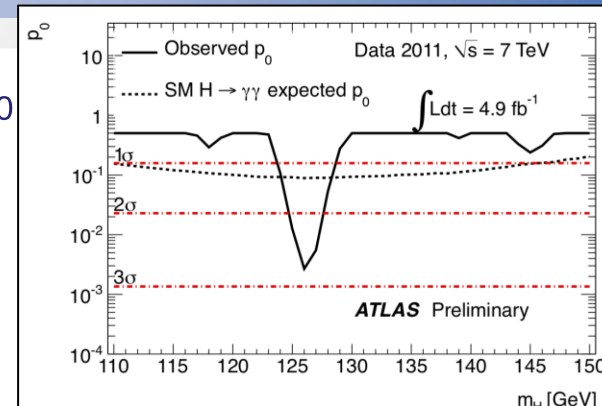
Profile likelihood Ratio, p_0 and CL_s

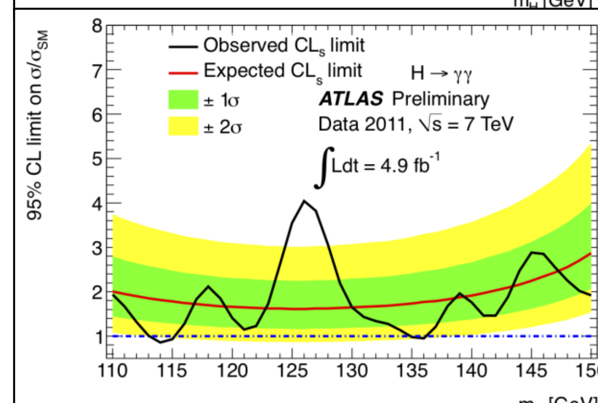


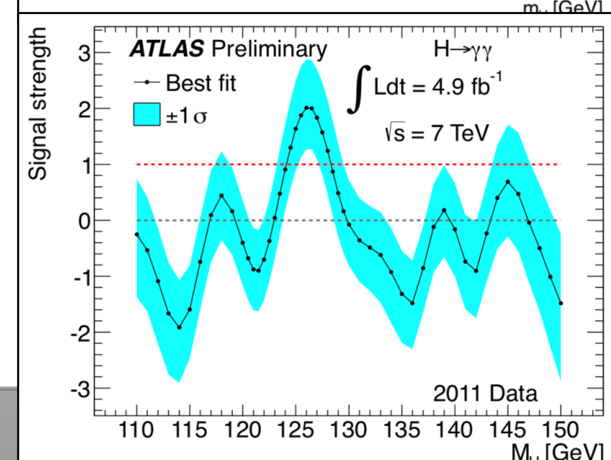
- Local significance p_0 to test background hypothesis

- $CL_s = CL_{s+b}/CL_b$ (log-likelihood ratio) to test signal hypothesis

- $\hat{m}$ to estimate signal strength (relative to expectation)



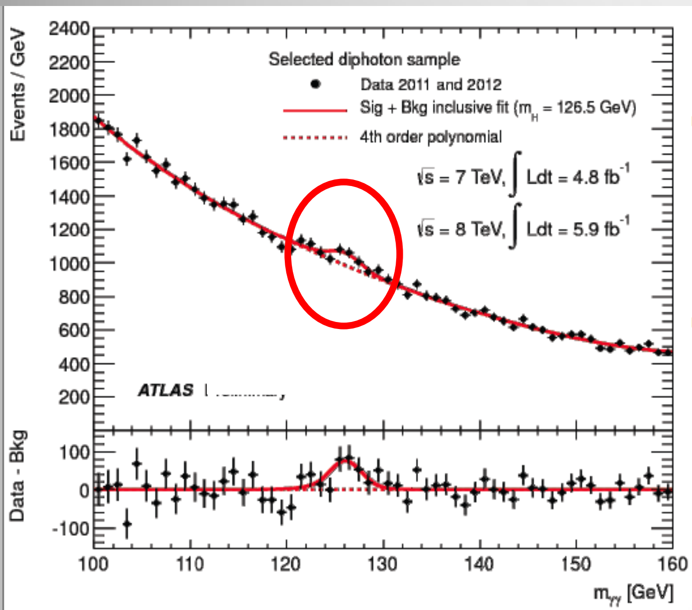


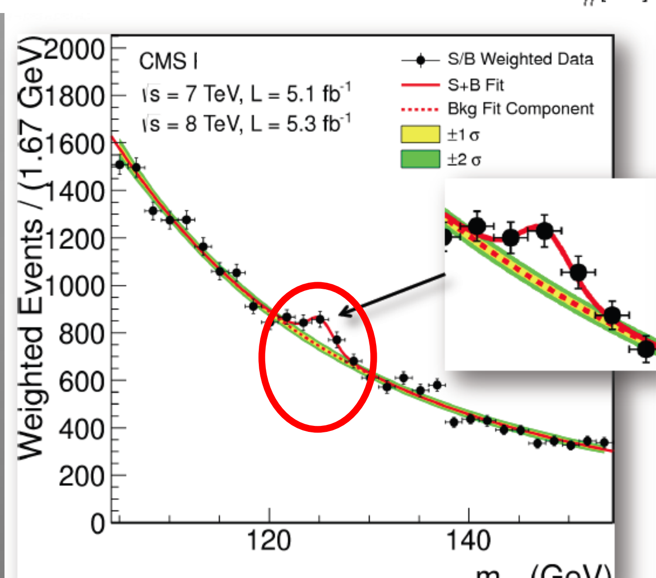


Follow LHCHCG Combination Procedures

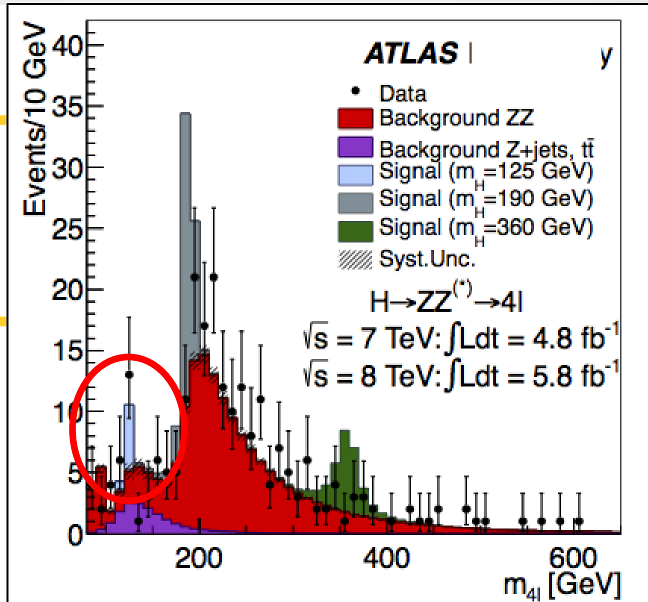
Summer 2012: Results

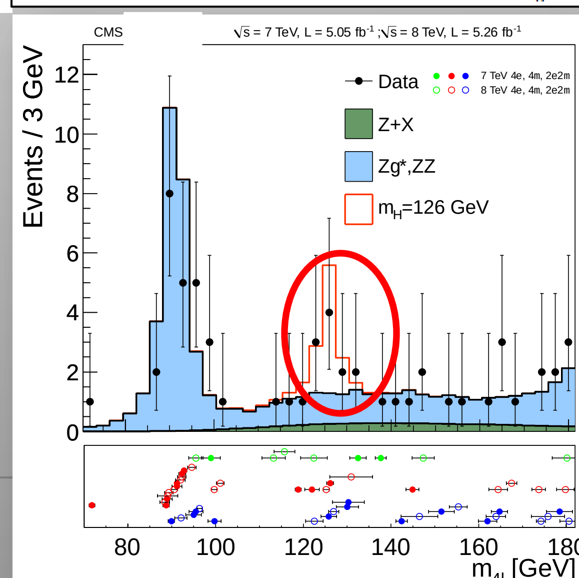
Higgs → 2 photons!!





Higgs → 2 Z →4 leptons!!





A clear "excess" of events seen in both experiments around 125-126 GeV

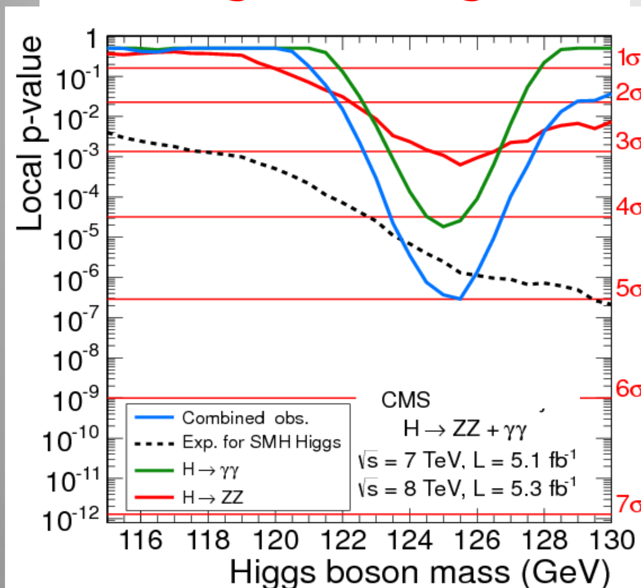
It became very significant in 2012

Sophisticated Statistical Methods have used to fully analyse this.

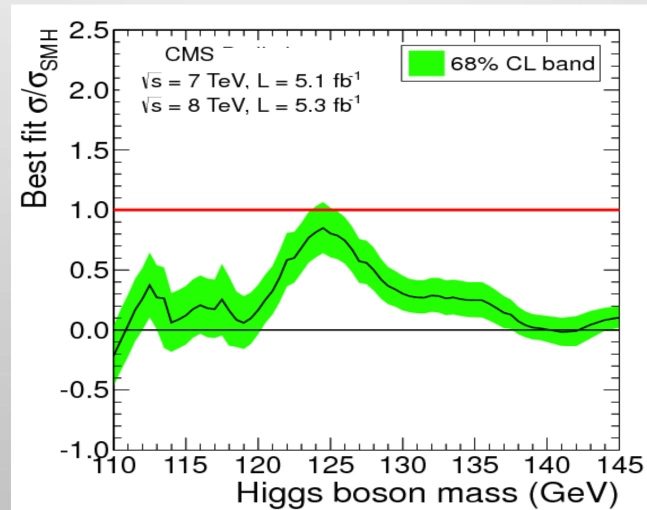
And the result is…→

Results from the Experiments

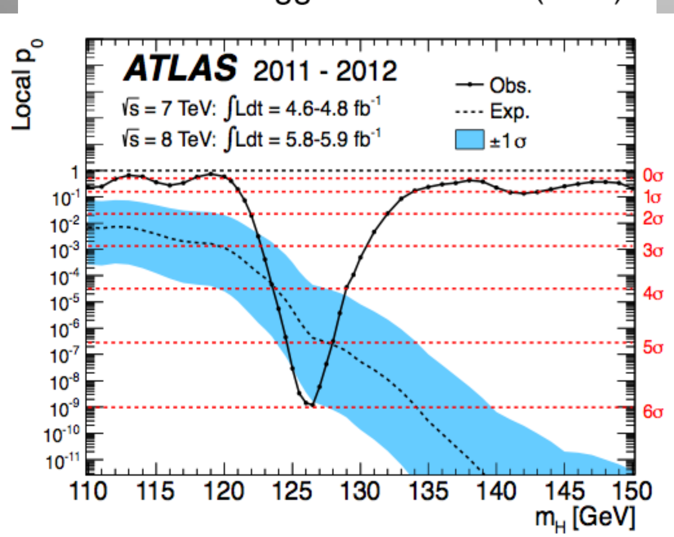
Statistical combination:
Total signal strength

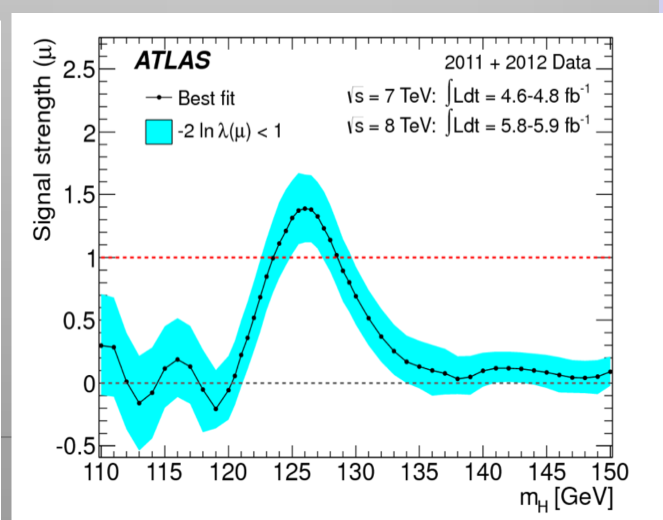


Compatibility with
a SM Higgs



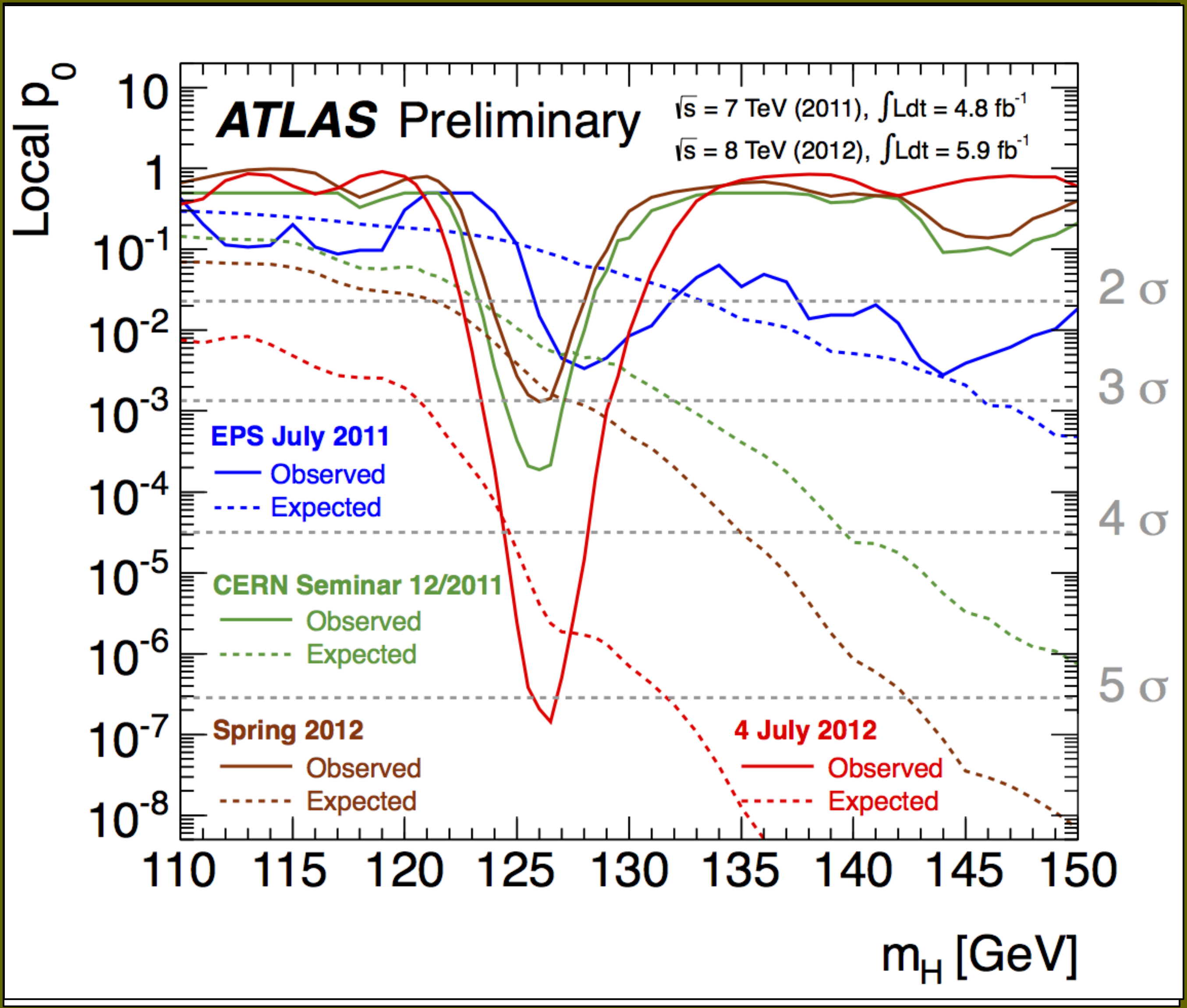
CMS and ATLAS observe a new boson with a significance of 5 sigma or more





The particle is consistent with a Higgs-like boson

Evolution of the excess with time

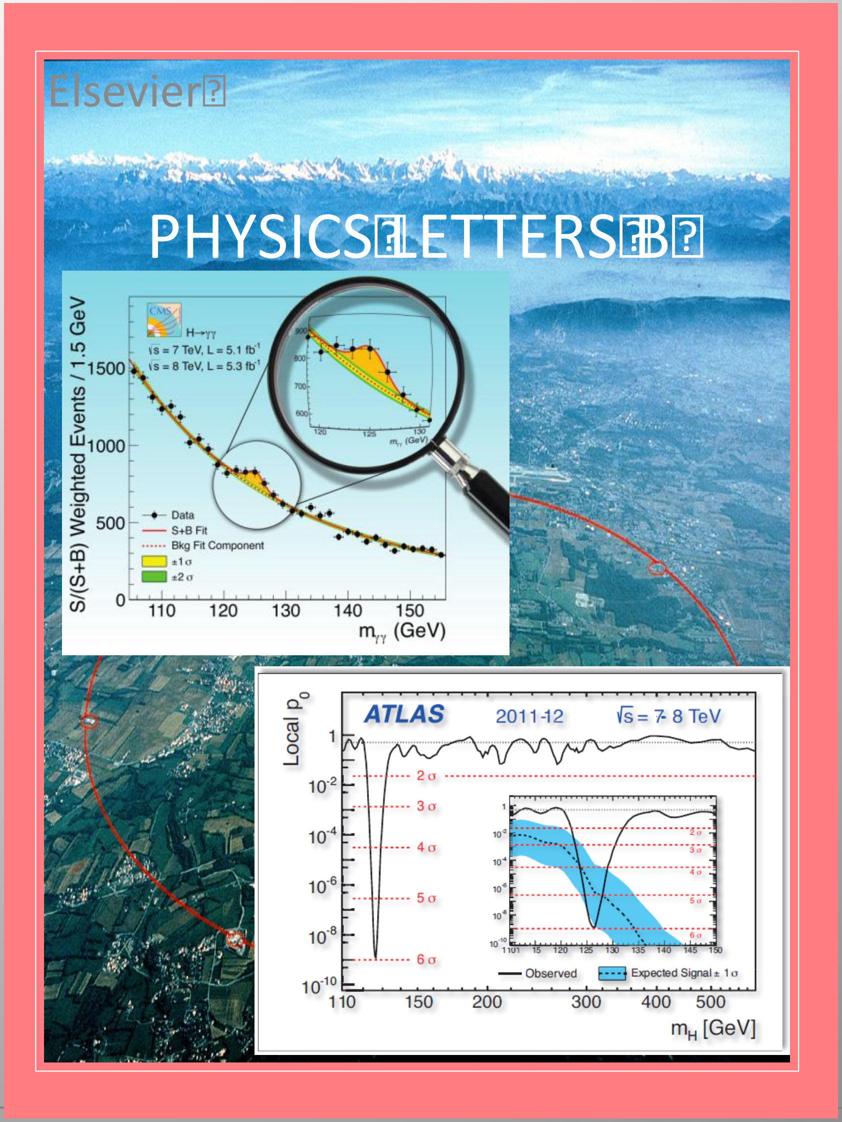


Energy-scale systematics not included

Higgs Publication

Two papers are published side by side in the same issue of PLB

Special booklet edition with the two papers and an art cover



The Press…

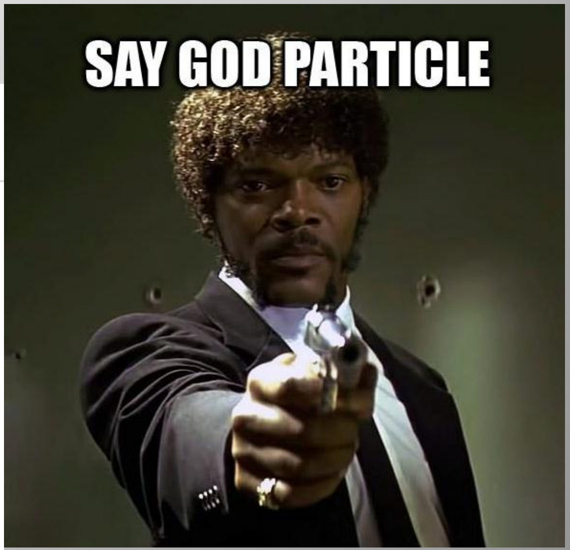
The discovery of the Higgs made the headlines worldwide

Hawking lost $100 bet over Higgs boson

What Comes After Higgs Boson?

the Atlantic wire — what matters now

'God Particle' 'Discovered': European Researchers Claim Discovery of Higgs Boson-Like Particle



HOW THE HIGGS COULD BECOME ANNOYING

Yes, the discovery of the Higgs boson is thrilling and game-changing. But it could also introduce some aggravating situations.

Хиггс увидит бозон

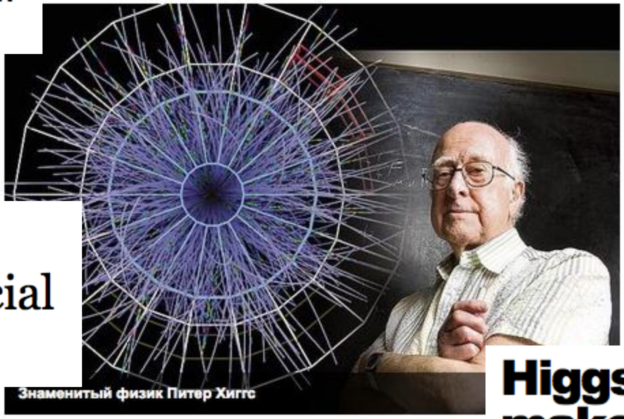
В CERN открыли бозон Хиггса

Текст

— 3.07.12 15:13 —

ТЕКСТ: АЛЕКСАНДРА БОРИСОВА
: SCIENCEUNSEEN.COM

Discovery of Higgs Boson Bittersweet News in Texas



Scientists Set The Higgs Boson To Music

3 Ways the Higgs Boson Discovery Will Impact Financial Services

Higgs boson discovery could make science fiction a reality

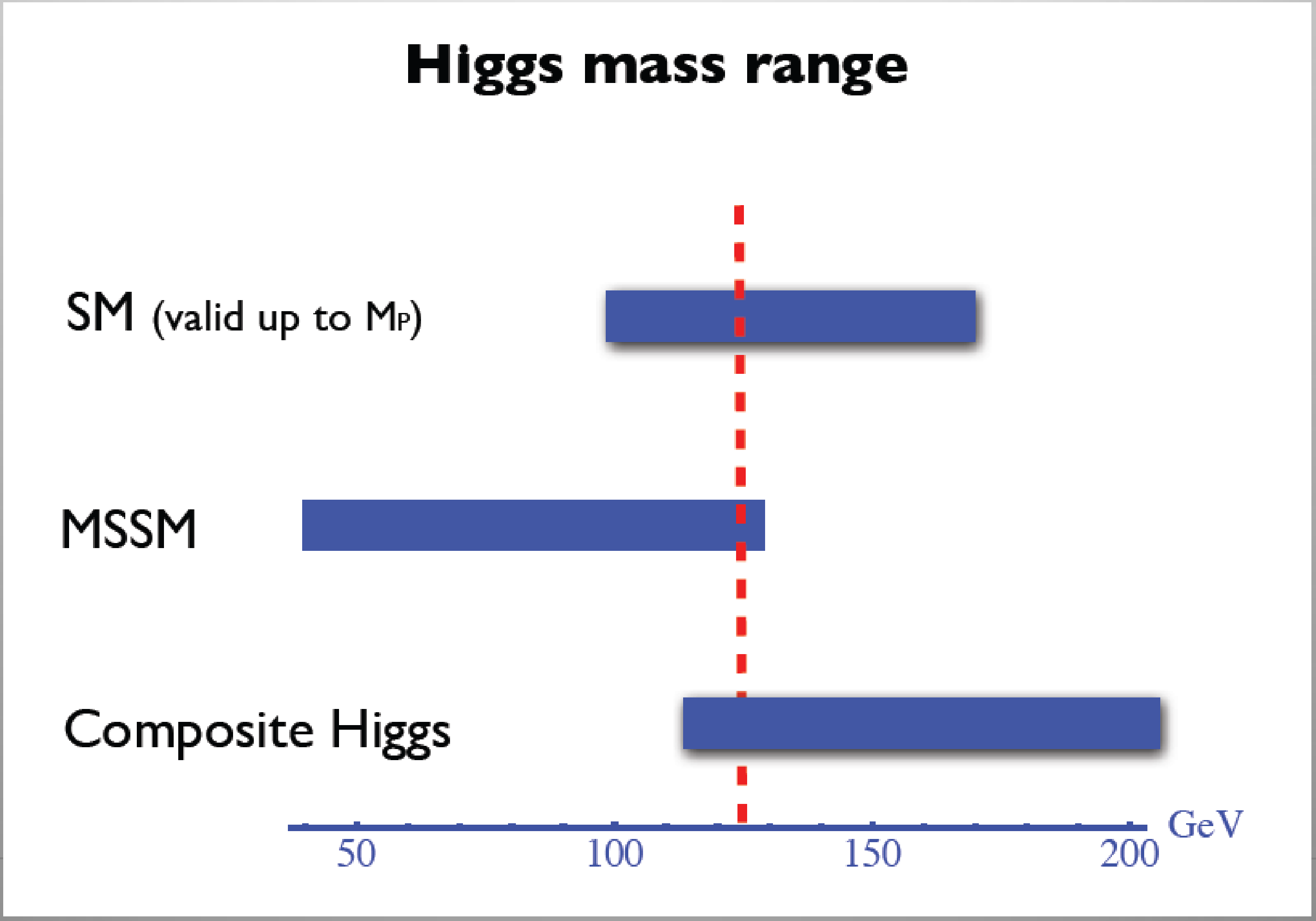
Discovery of the 'God particle' could make science fiction a reality, and answer one of the most basic questions of our universe: How did light become matter — and us?

Higgs boson researchers consider move to Cloud computing

"Within another decade the Cloud will be where grid computing is now"

The Theories

"125 GeV is a mass of maximum agony" N. Arkani Hamed May 2012
But excellent for the experiments & property measurements



The Theories?

But not so excellent for all theorists:

Specially for fans of **Higgsless models:**

Is it really the Higgs Boson?

We, experimentalists, call it a "Higgs-like" particle

- Does this new particle have all the properties that we expect a Higgs Boson to have?
  - So far it seems to couple as expected to photons, heavy Z and W bosons, but the evidence that it also couples to quarks or leptons is much weaker so far.
- What are the quantum numbers of this new particle?
  - EG Spin and Parity: for the SM Higgs we expect it to have spin = 0 and parity = +.
- Is there more than one Higgs-like particle? Some theories beyond the Standard Model predict these…
- Does it have 'exotic' properties?

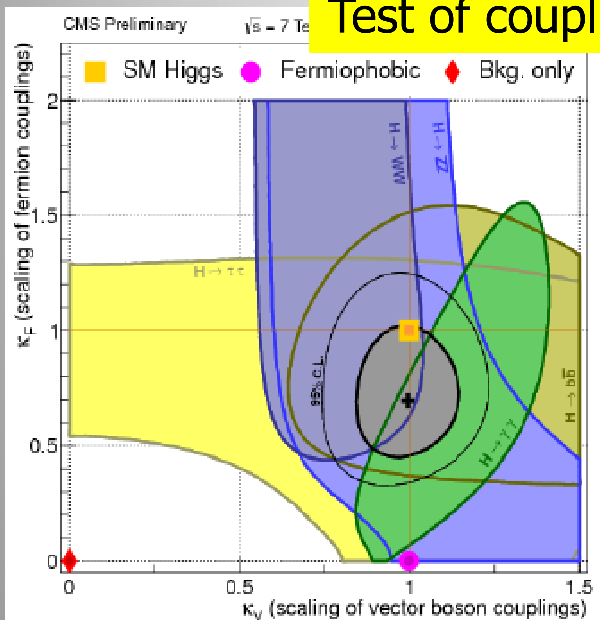
There is a lot to do for us in the next years!!

The News since July 4th

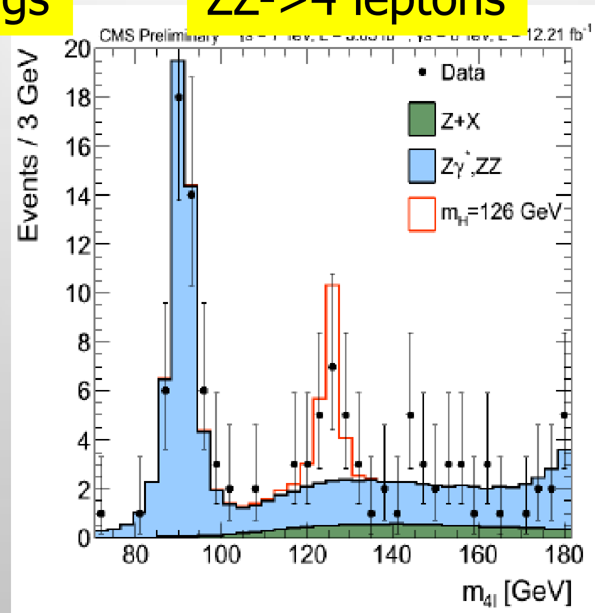
- The discovery of the new particle has been confirmed with more added collisions
- We got a first glimpse of the spin: it is a more likely a parity state 0+ as compared to a 0- (as should be if it is really a Higgs)
- Also seems to favour more spin 0 compare to spin 2 (but not conclusive yet)
- The mass is getting measured better with time, a and in the range125-126 GeV
- The couplings to Bosons and Fermions are consistent with the SM expectations (but these are not very precise/definite yet)

News after summer 2012 (CMS)

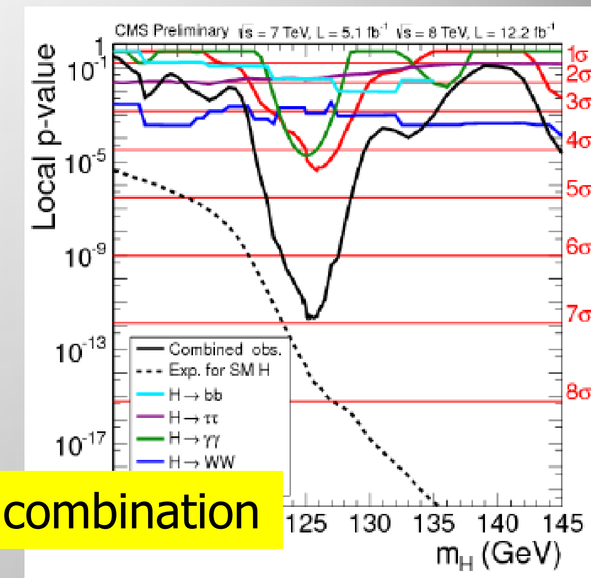
Test of couplings



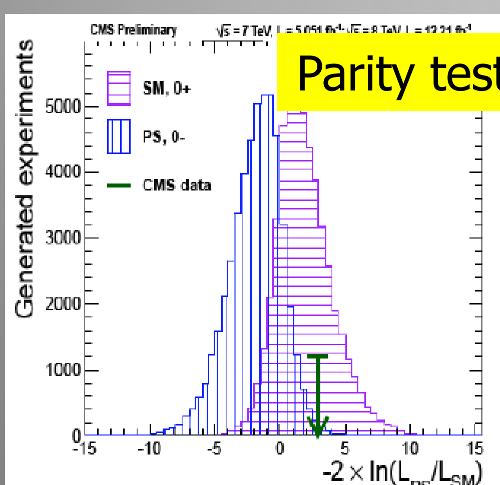
ZZ->4 leptons

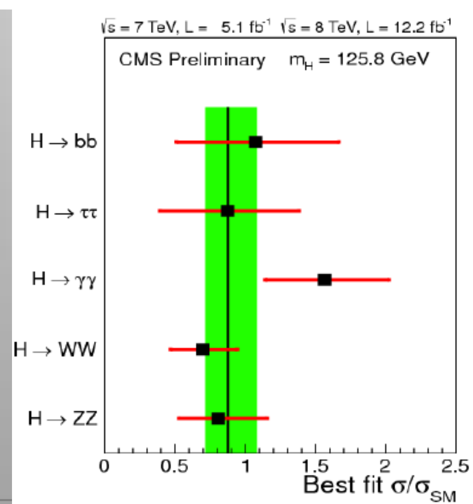


combination

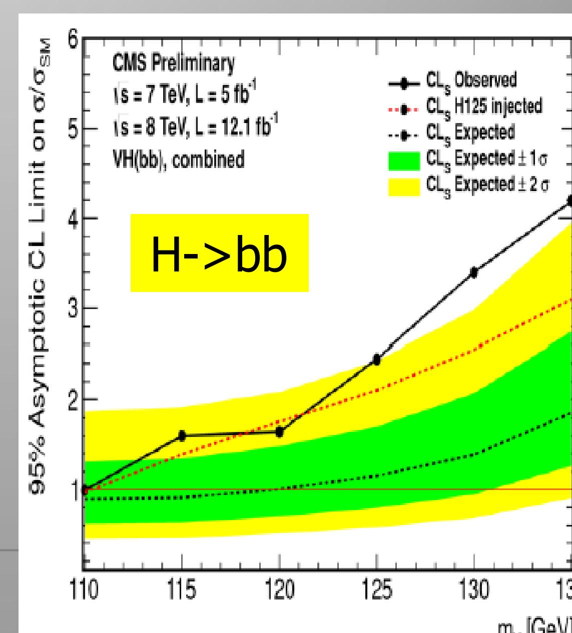


Parity test





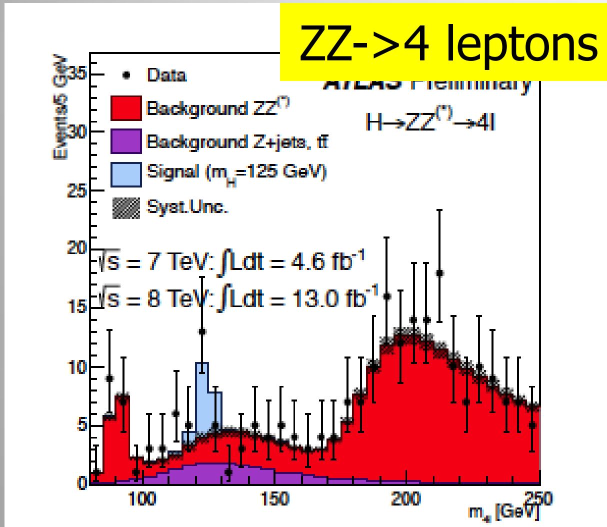
H->bb



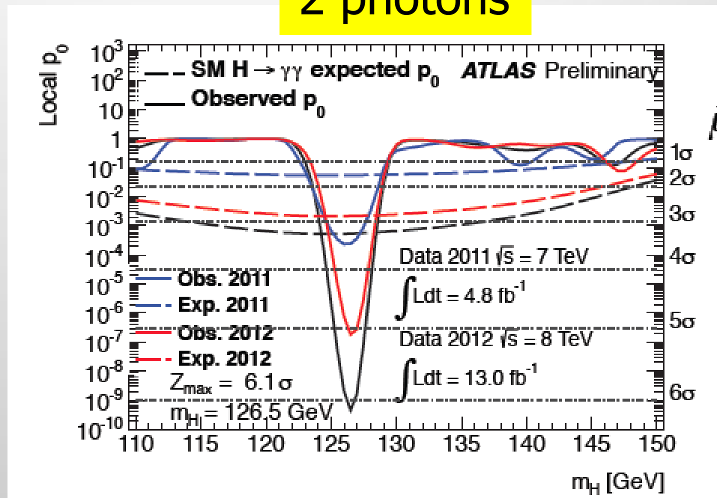
m_χ = 125.8 ± 0.4(stat) ± 0.4 (syst) GeV

News after summer 2102 (ATLAS)

ZZ->4 leptons

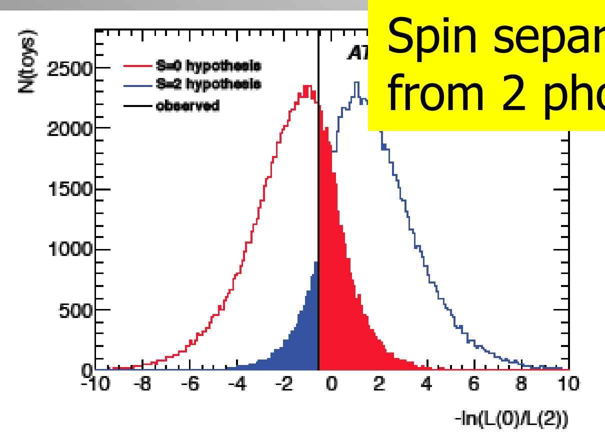


2 photons

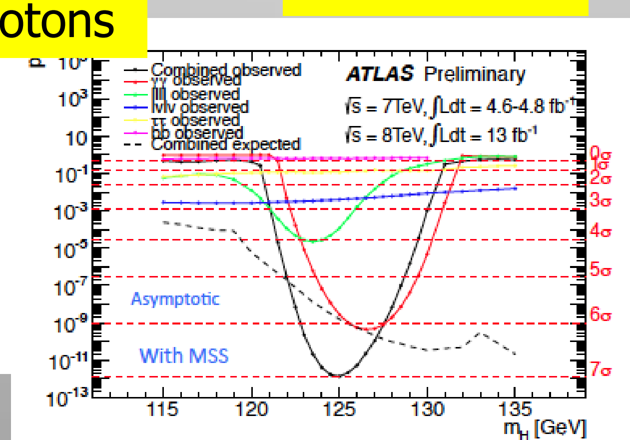


$$\hat{\mu} = 1.8 \pm 0.3\ (stat)^{+0.29}_{-0.21}\ (syst)$$

Spin separation from 2 photons

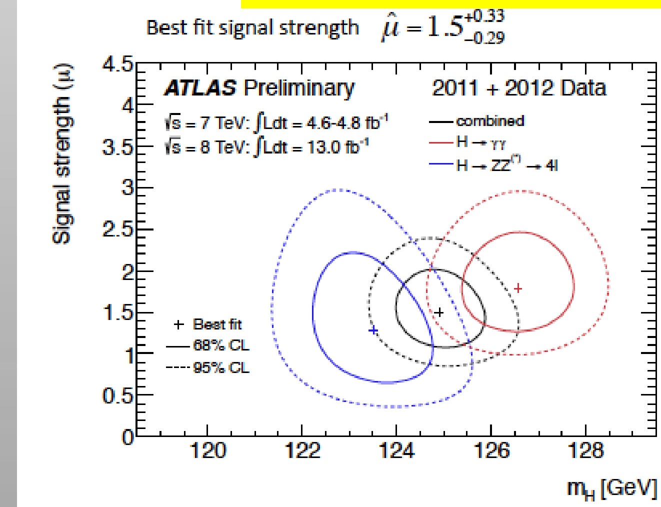


Combination



Mass and strength

Best fit signal strength $\hat{\mu} = 1.5^{+0.33}_{-0.29}$

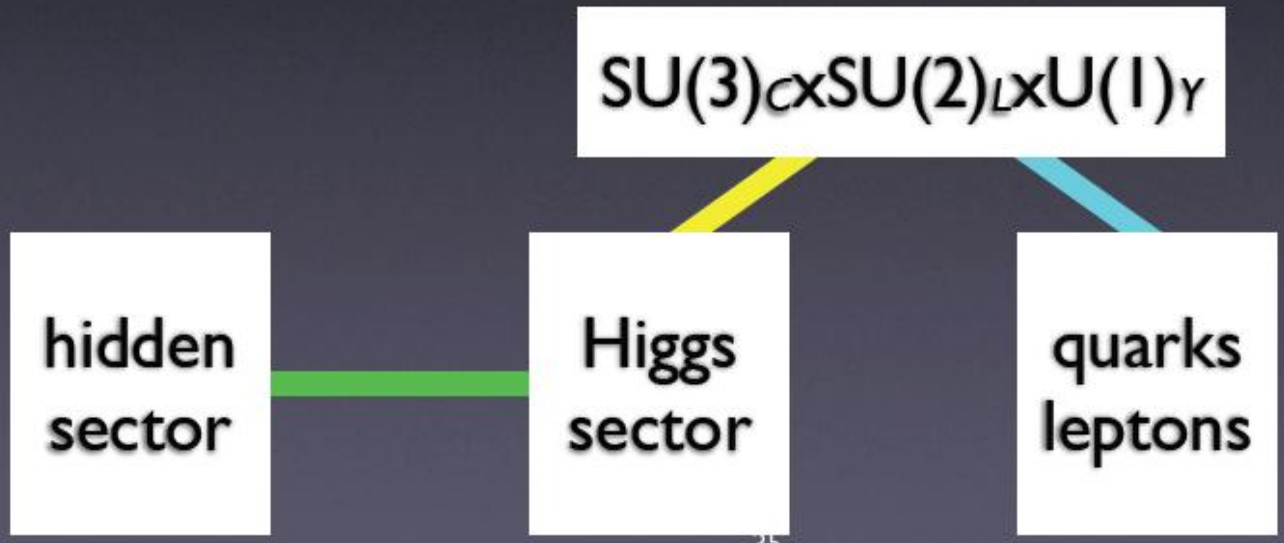


$$m_H = 125.2 \pm 0.3\ (stat)\ \pm\ 0.6\ (syst)\ \text{GeV}$$

The Higgs

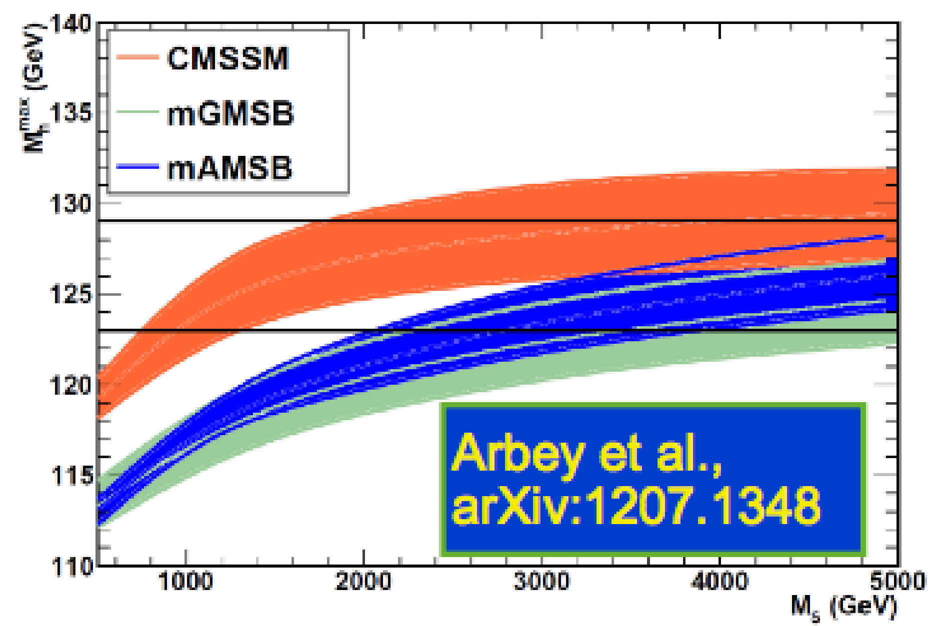
Higgs as a portal

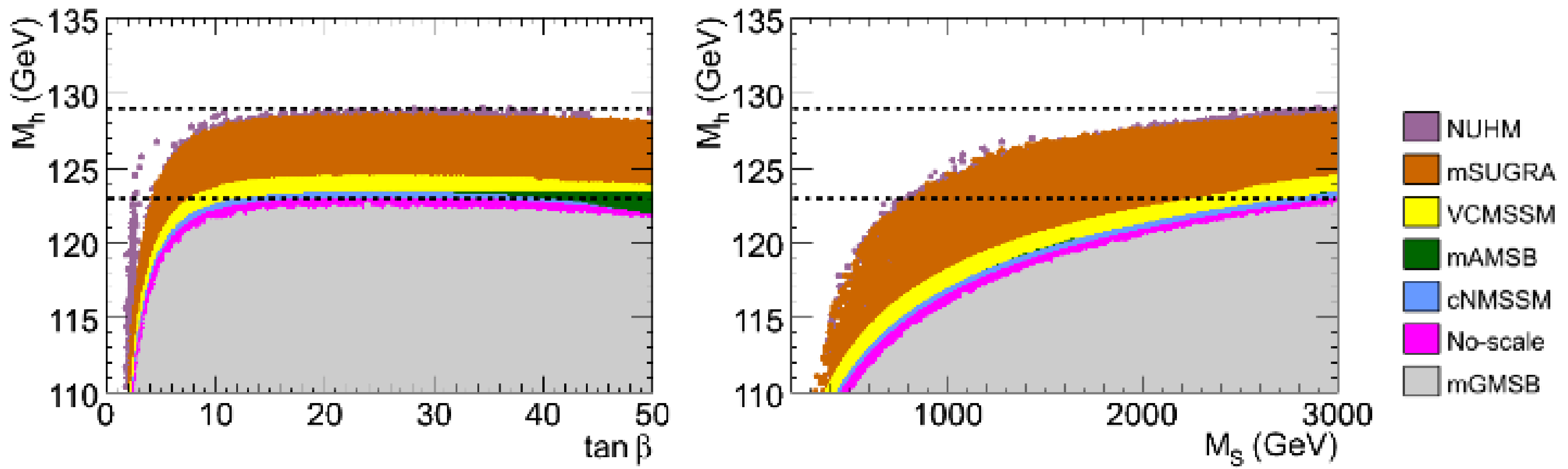
- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors"



Higgs @ 125 GeV has Consequences

- A 125 GeV Higgs is challenging to accommodate in constrained versions of SUSY particularly for natural superpartner masses
- Starts to constrain some of the simpler models-> High SUSY masses
- If SUSY exists, is it really natural?



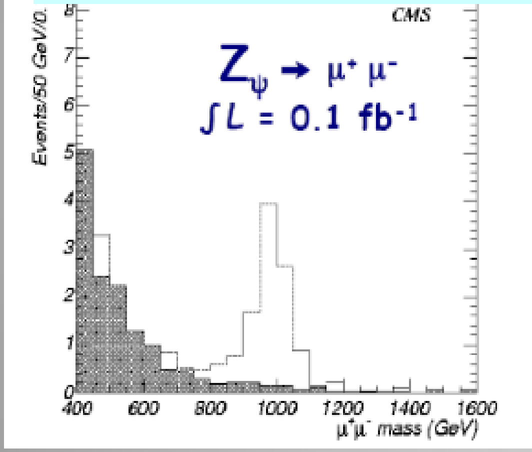


Mahmoudi, ICHEP 2012

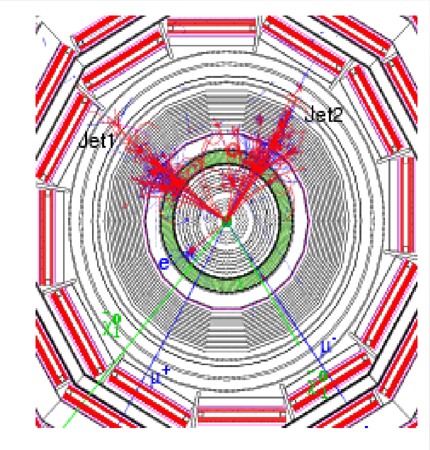
Searches for New Physics

New Physics at High Energies?

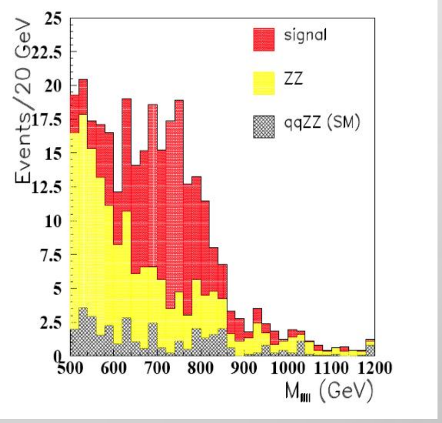
New Gauge Bosons?



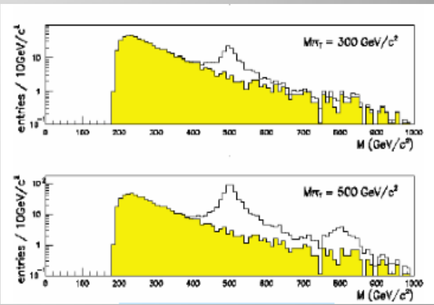
Supersymmetry



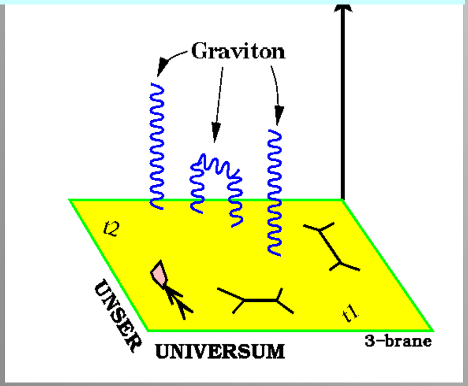
ZZ/WW resonances?



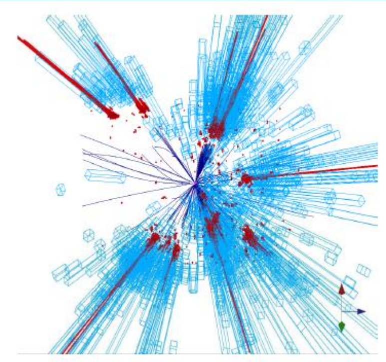
Technicolor?



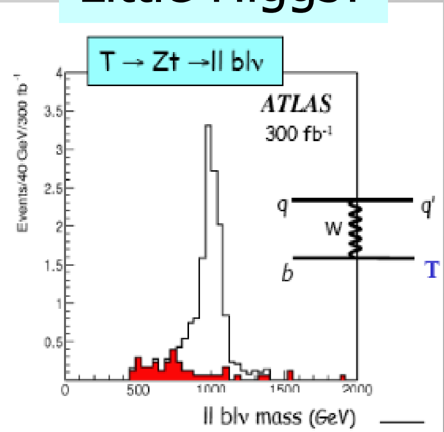
Extra Dimensions?



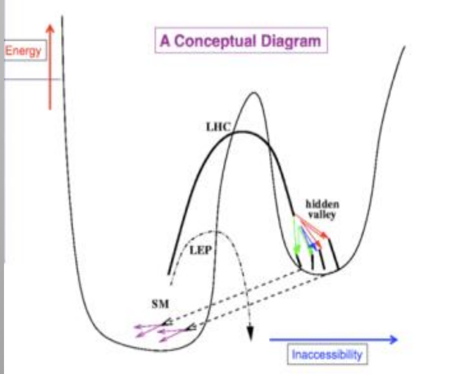
Black Holes???



Little Higgs?



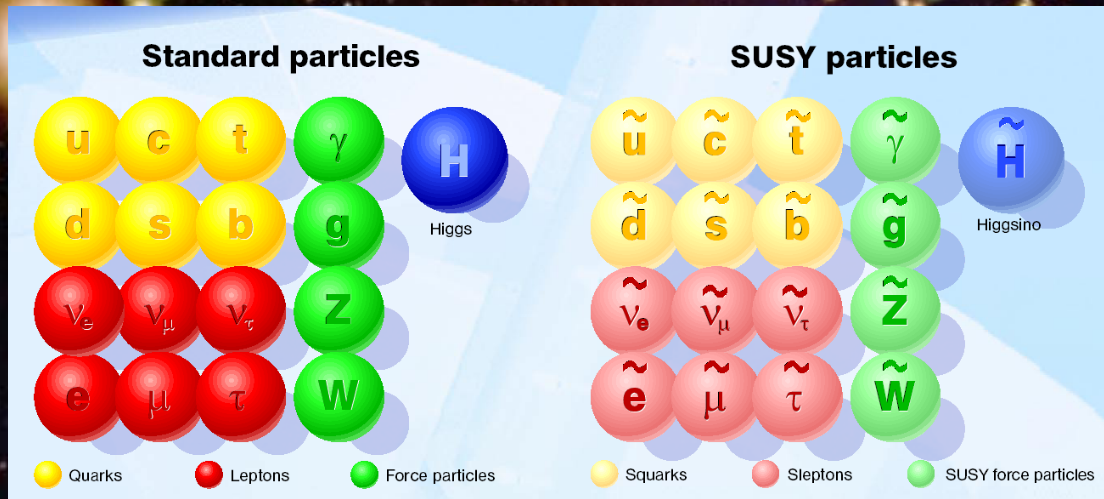
Hidden Valleys?



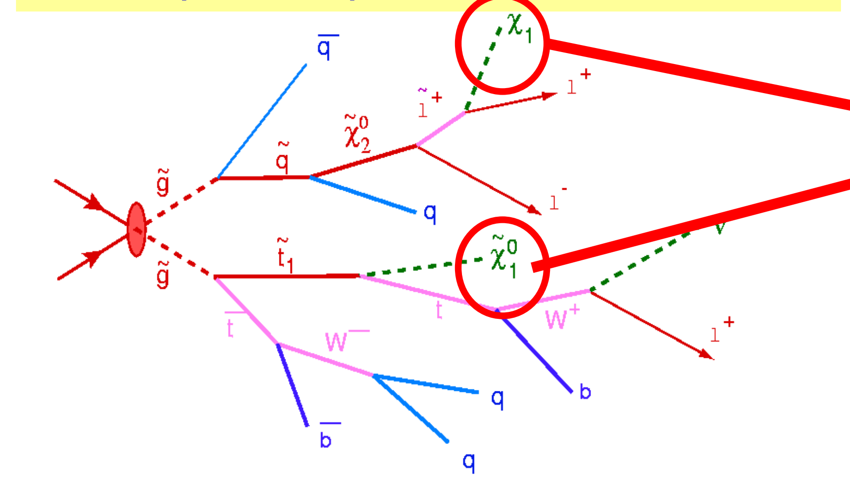
We do not know what is out there for us…

A large variety of possible signals. We have to be ready for that

Searches for Supersymmetry



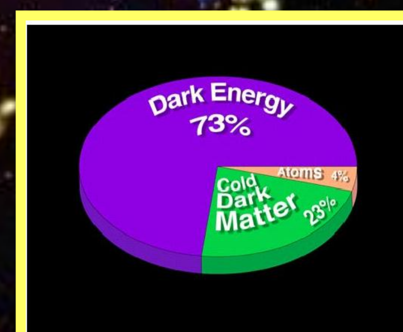
SUSY particle production at the LHC



Assume “R-Parity” Conservation

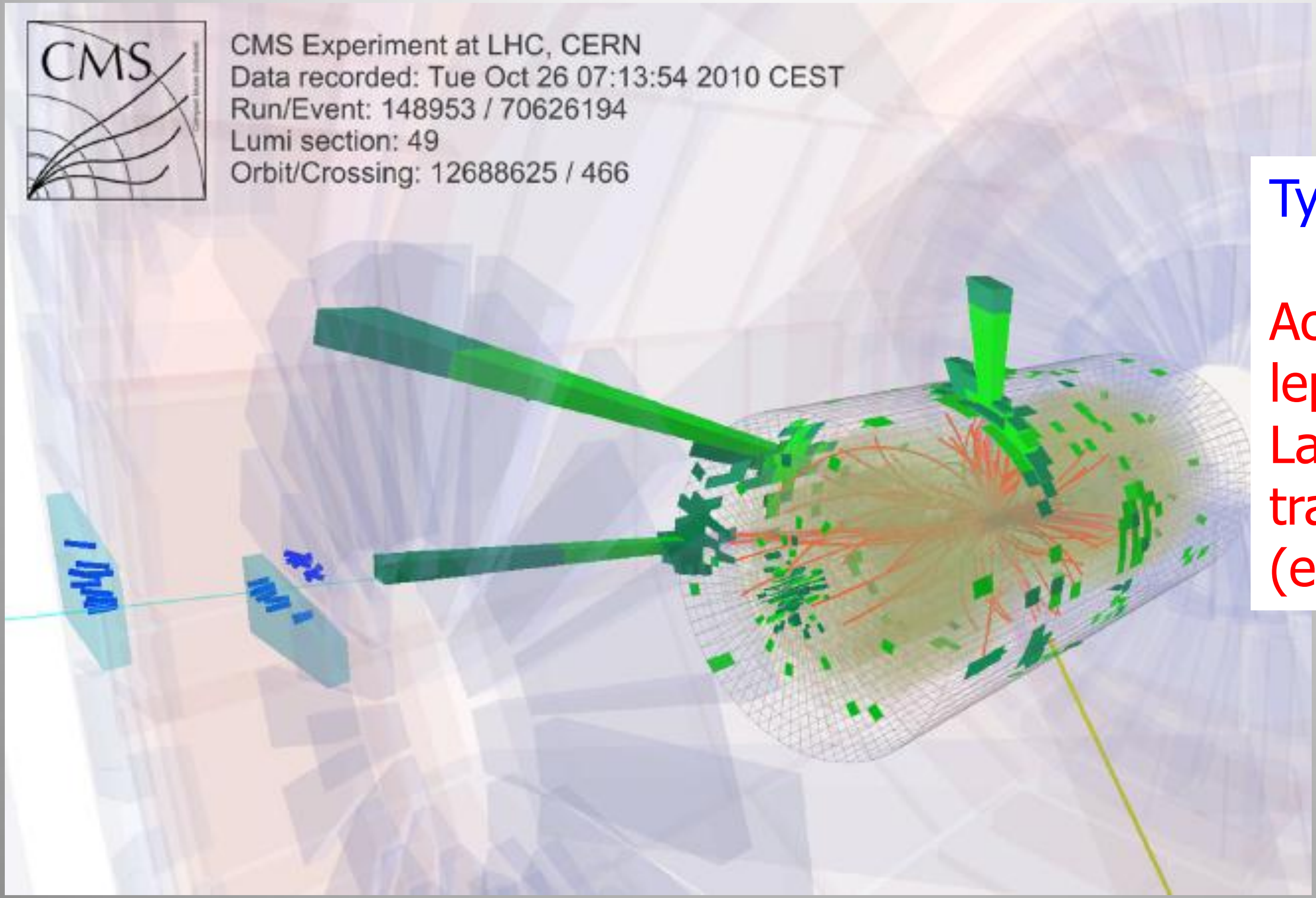
Candidate particles for Dark Matter

⇒ Produce Dark Matter in the lab



ac

…Interesting Events…



Typical search:

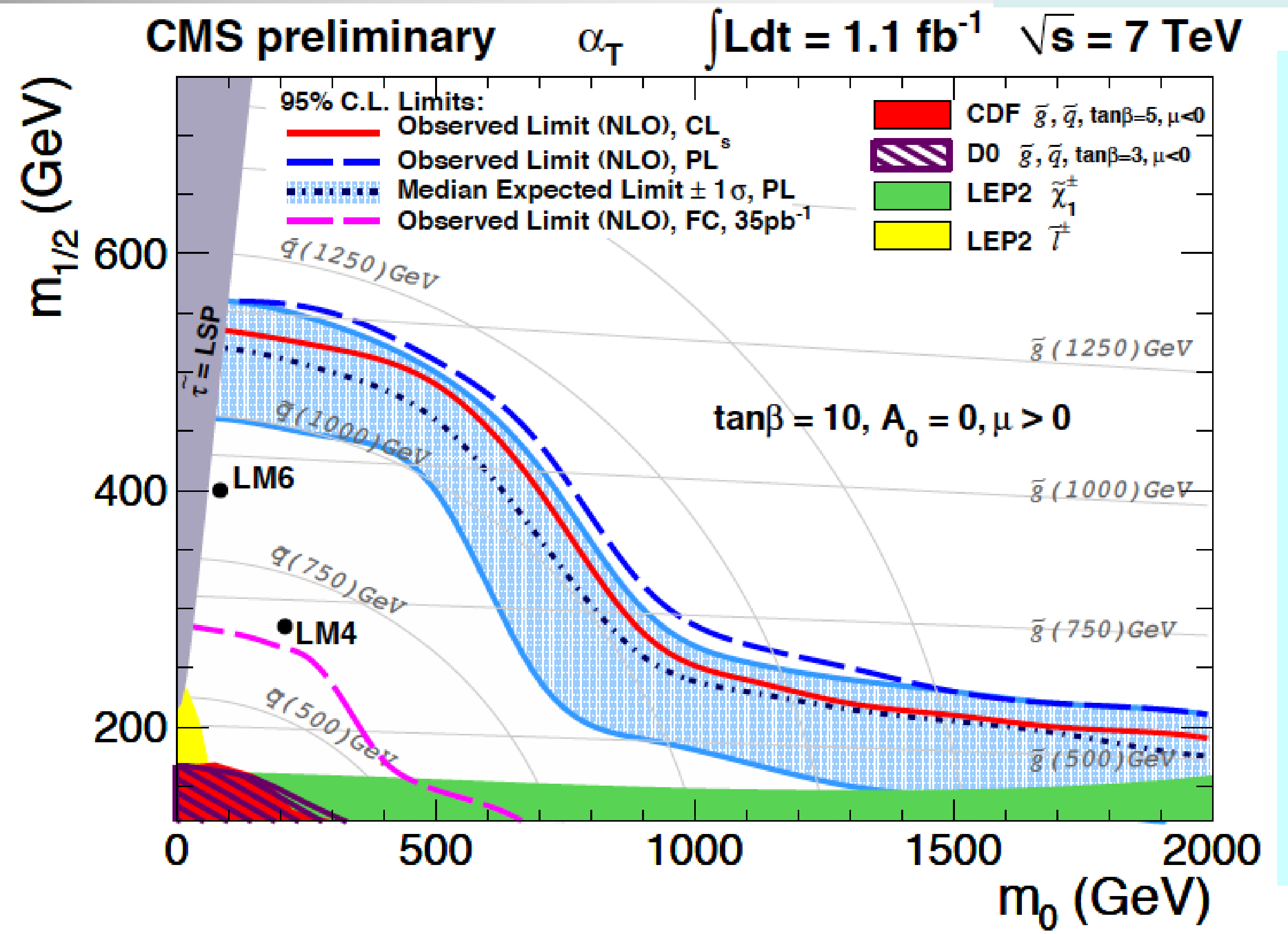
Activity: (jets, leptons, photons)+ Large missing transverse energy (escaping neutralinos)

- Event with five jets and large missing transverse energy
- Total sum of transverse momentum H_T= 1132 GeV and missing transverse energy H_{TMiss} = 693 GeV

Jets + Missing E_T Channel (2011)

CMS-SUS-11-003

Using 1 fb^{-1}



So far Constrained Minimal Supersymmetric Standard Model CMSSM is often used as a benchmark model for presenting the search results…

The CMSSM has 4 parameters

-$m_{1/2}$: universal gaugino mass at GUT scale

- m_0: universal scalar mass at GUT scale

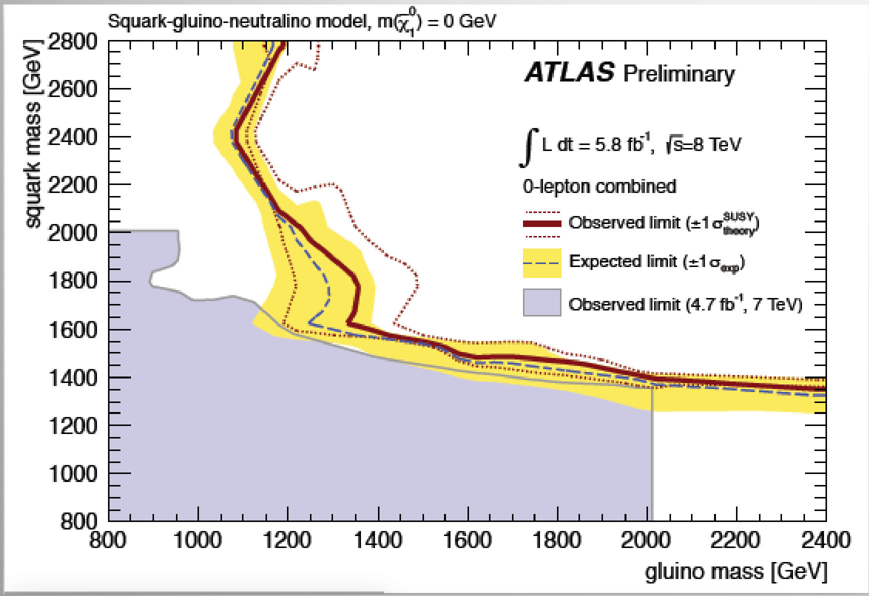
-tanβ: vev ratio for 2 Higgs doublets

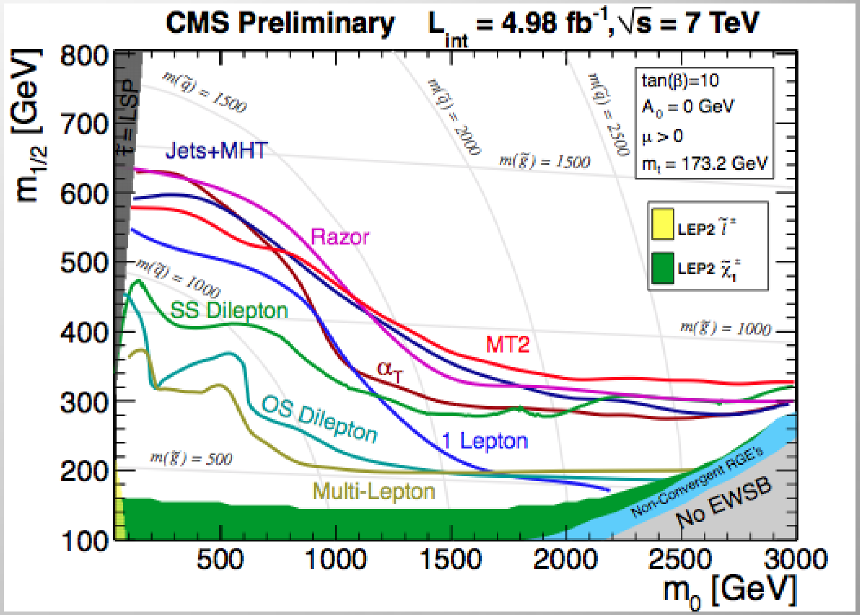
-A_0: trilinear coupling

and the sign of Higgs mixing parameterμ

Within the Constrained MSSM model we are crossing the border of excluding gluinos up to 1TeV and squarks up to 1.25TeV

Generic SUSY Searches (2012)





Limits from this model:

$$m(\tilde{q}) \approx m(\tilde{g}) < 1.5 \text{ TeV}$$

$$m(\tilde{q}) < 1.4 \text{ TeV } (\forall\ m(\tilde{g}) < 2 \text{ TeV})$$

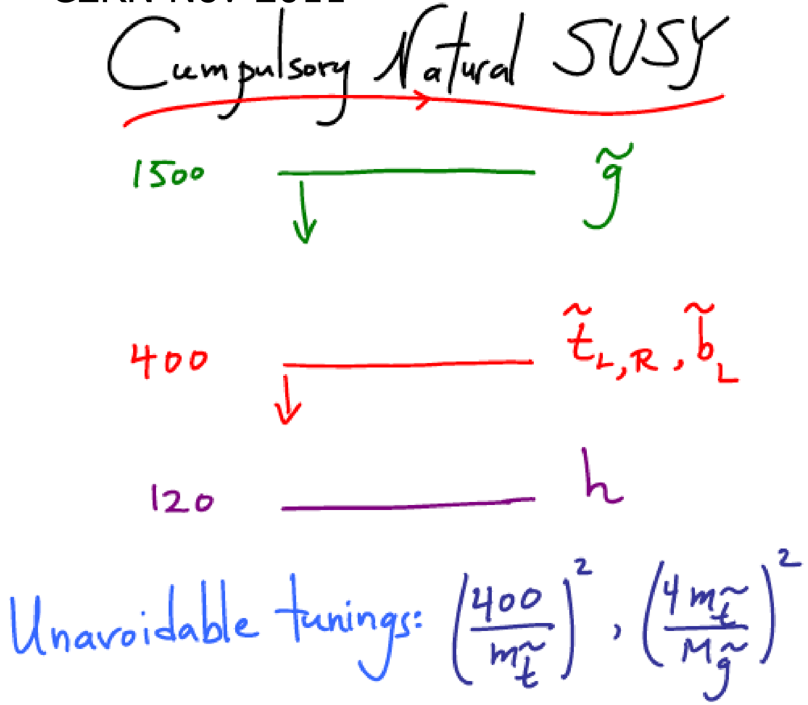
$$m(\tilde{g}) < 1 \text{ TeV } (\forall\ m(\tilde{q}) < 2 \text{ TeV})$$

Still no sign of SUSY
in generic searches…

->Design more specific searches

Supersymmetry: Natural SUSY

N. Arkani-Hamed
CERN Nov 2011

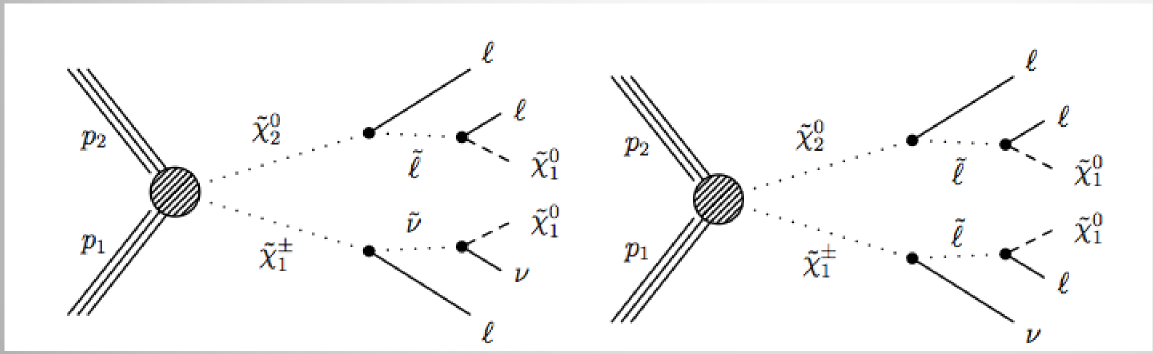


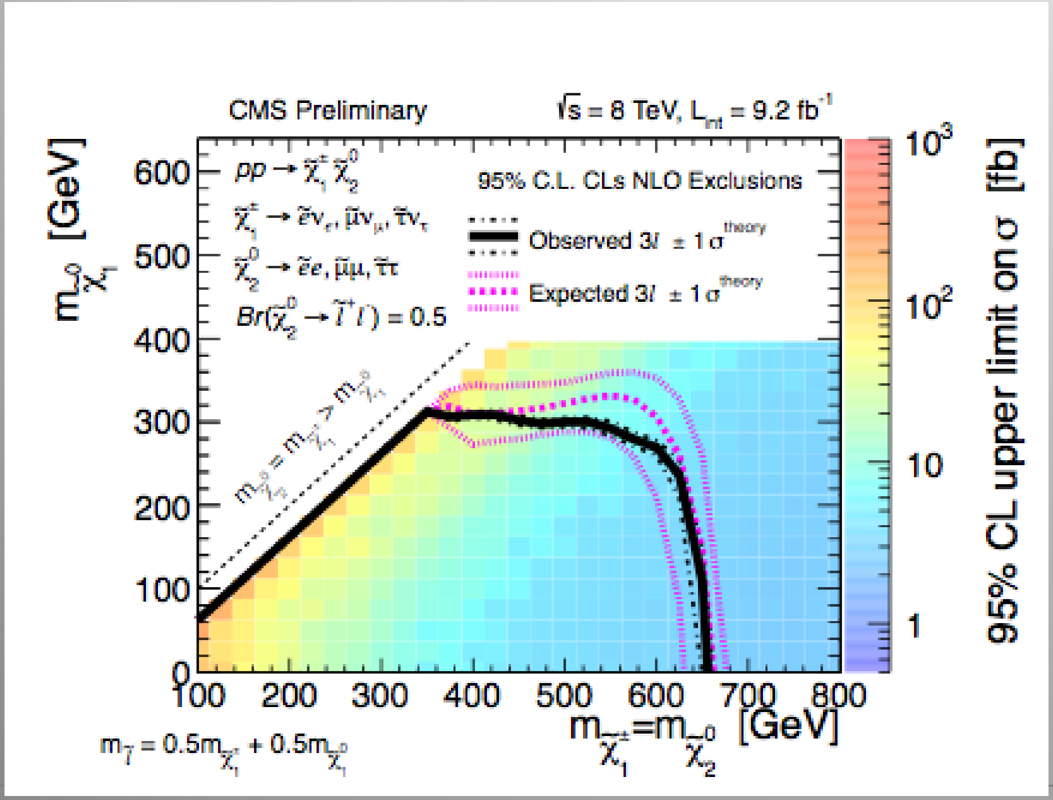
- Squarks, sleptons can be mult-TeV
- Gluino should not be too high, typically below 1.5 TeV
- Stop and Bottom_left well below a TeV
- Gauginos can be 'light' (O(500 GeV)

Look for 3rd generation squarks
Look for EWK production of gauginos

Importance of the partners of the third generation: stops and bottoms
…Other scenarios, such as compressed spectra, multi-top production…

Search for Gauginos





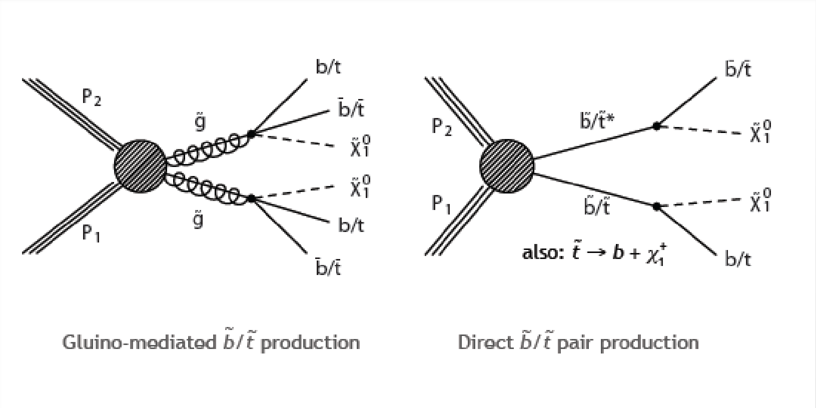
Direct Electroweak production of gauginos

Signal:
Trilepton + MET search

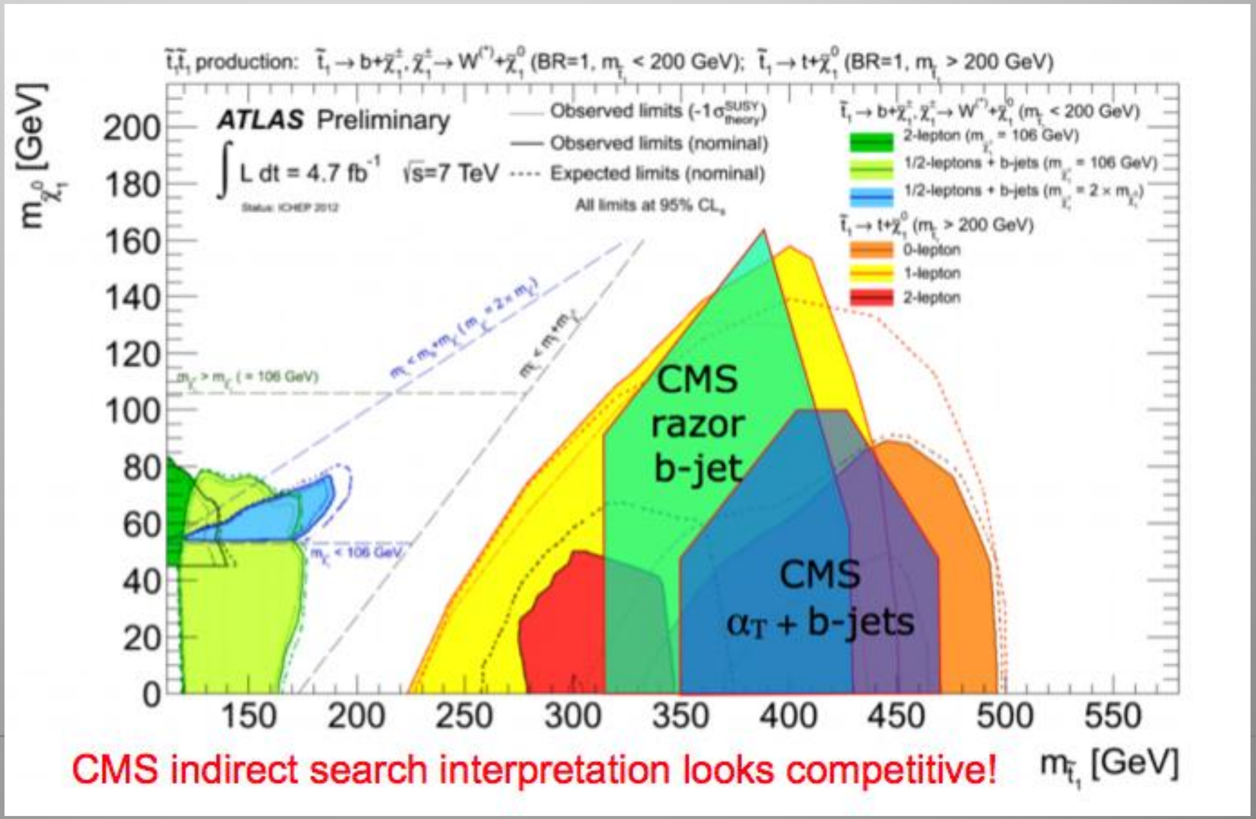
Excluded phase space depends on the kinematics assumptions

Exclusion ~ M> 600 GeV

Search for Stop Quarks

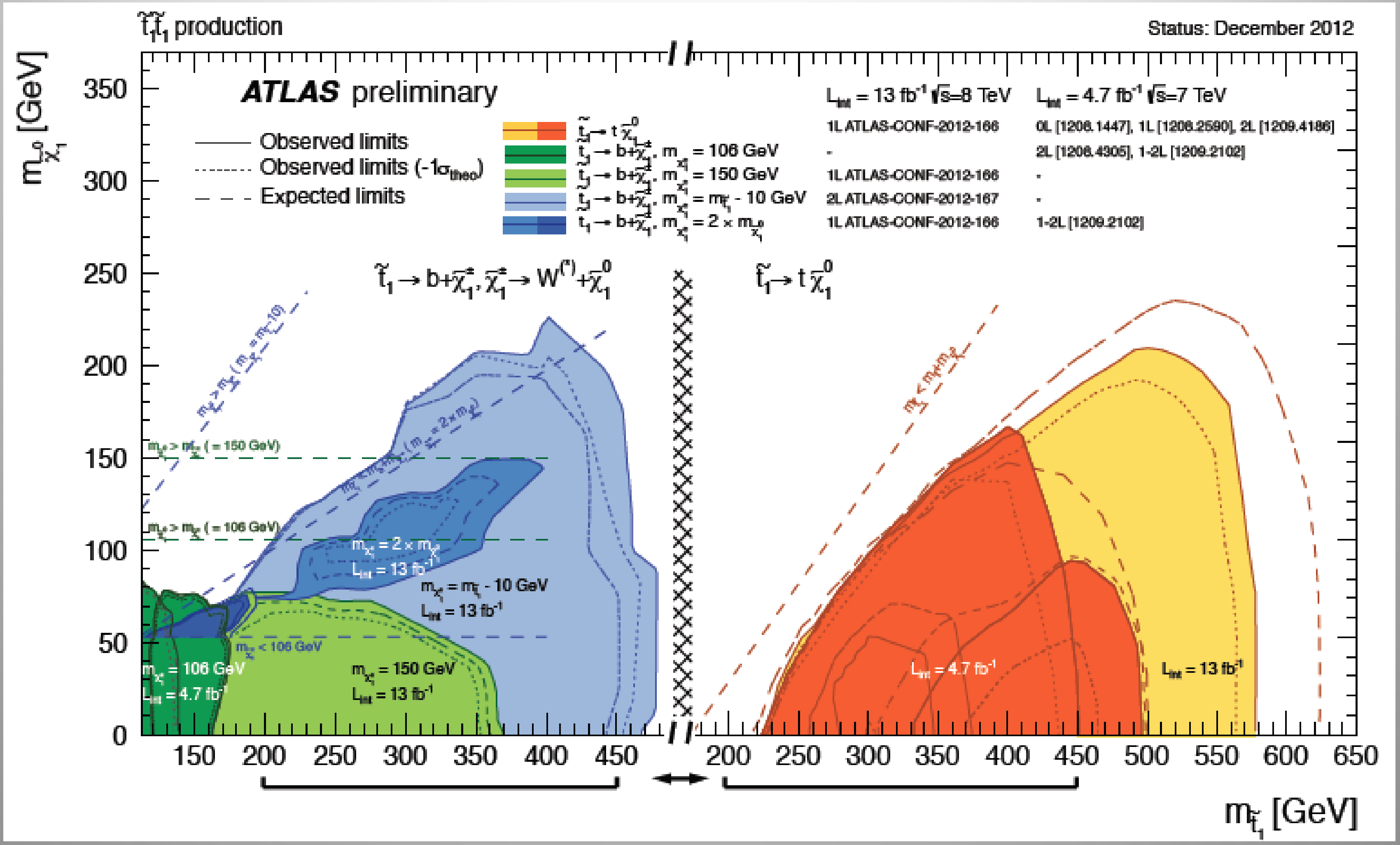


Summer 2012



To date:
No light stop squarks found…

Search for Stop Quarks



Latest results

Limits reaching 500-550 GeV in stop mass

-> Natural SUSY gets under pressure…

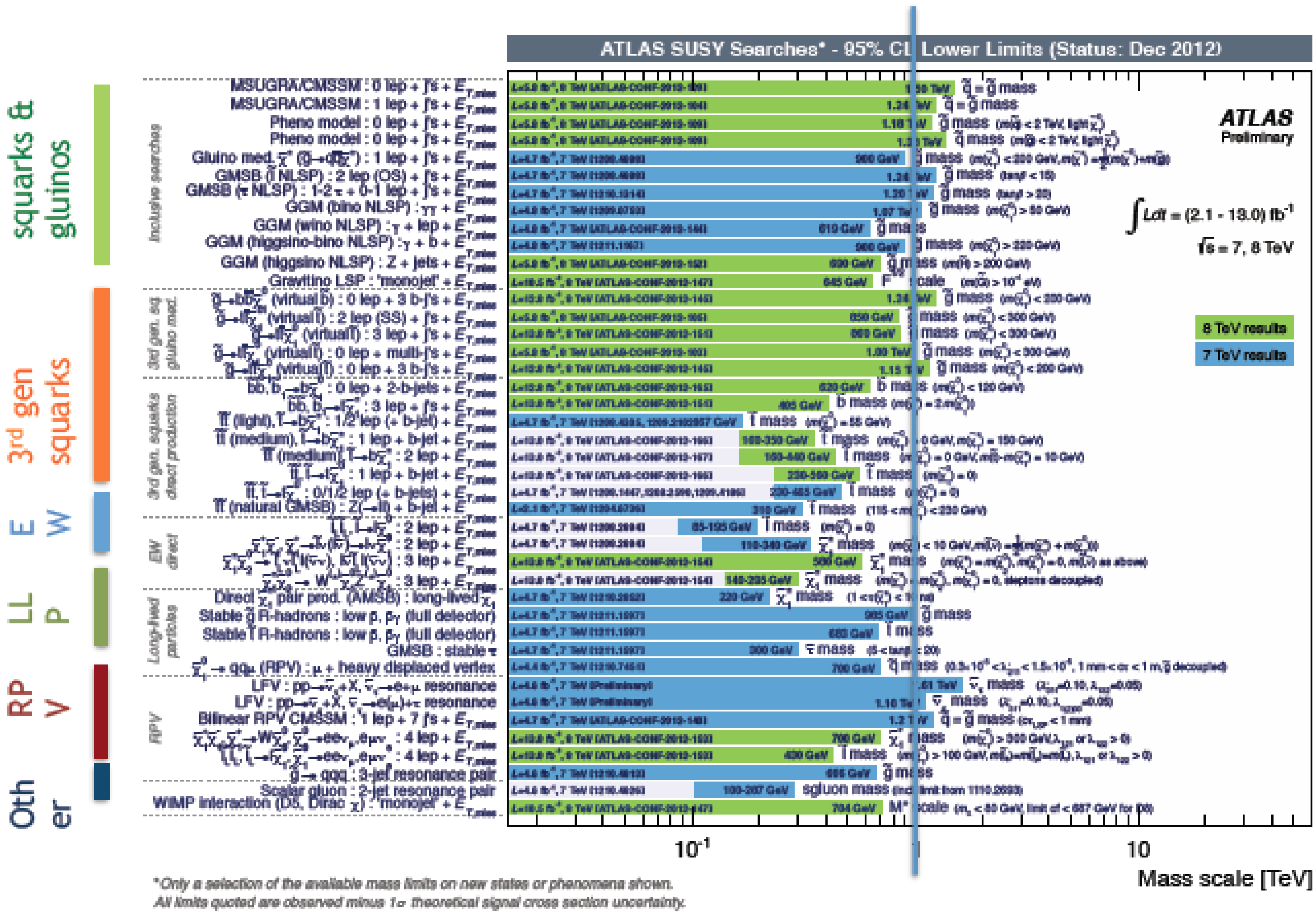
Overview of SUSY Searches

Example ATLAS

Vast number of SUSY models studied… Concentrating on the most « Natural » scenarios

Still many analyses to be completed with 8 TeV data, surprises might be waiting in the present data, and/or data to come at higher energy in 2015

1 TeV



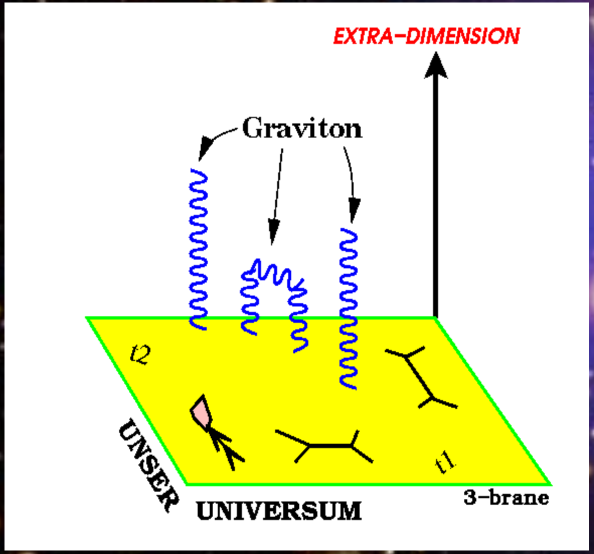
Search for Non-SUSY BSM

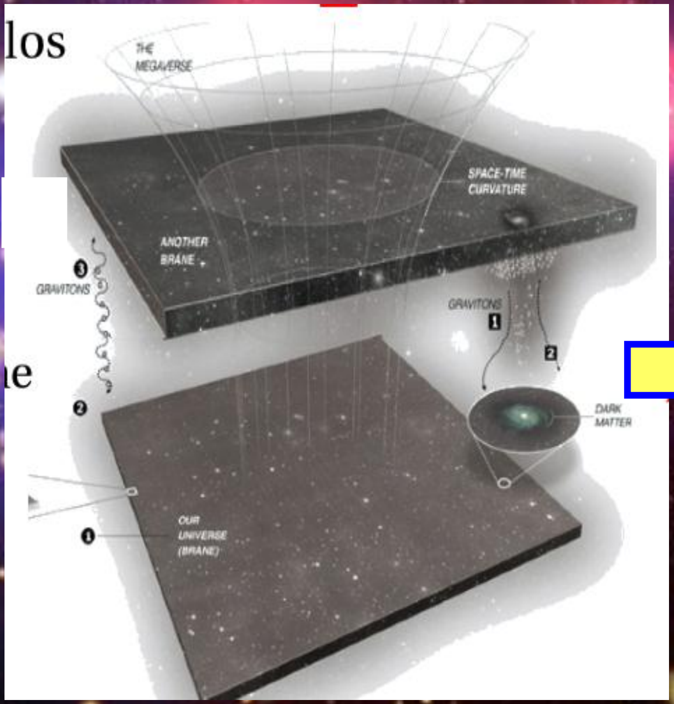
Extra Space Dimensions

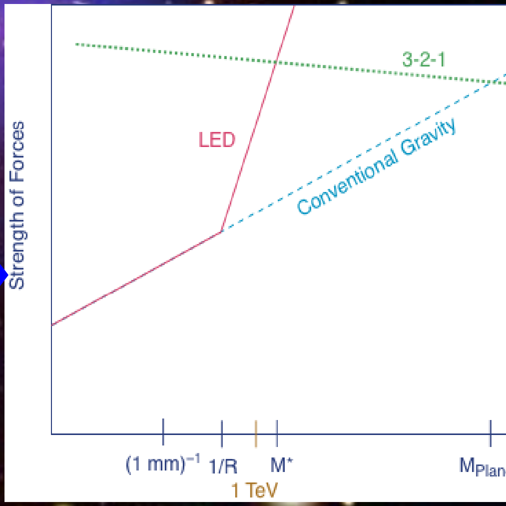
Problem:

$$m_{EW} = \frac{1}{(G_F \cdot \sqrt{2})^{\frac{1}{2}}} = 246 \text{ GeV}$$

$$M_{Pl} = \frac{1}{\sqrt{G_N}} = 1.2 \cdot 10^{19} \text{ GeV}$$

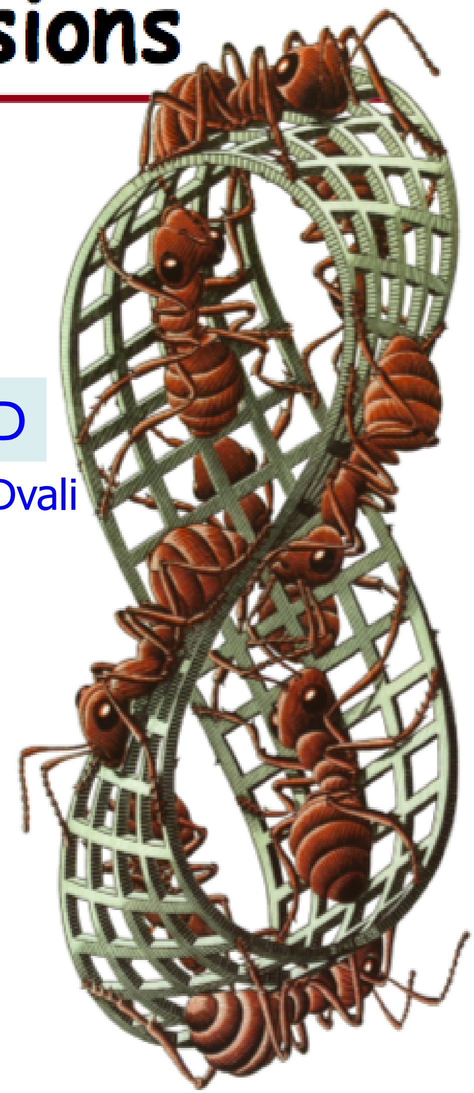






Gravity becomes strong!

Models with Extra Dimensions



Large Extra Dimensions

Planck scale (M_D) ~ TeV

Size: » TeV^{-1}; SM-particles on brane; gravity in bulk

KK-towers (small spacing); KK-exchange; graviton prod.

Signature: e.g. x-section deviations; jet+$E_{T,miss}$ ....

ADD

Arkani-Hamed Dimopoulos Dvali

Warped Extra Dimensions

RS

Randall Sundrum

5-dimensional spacetime with warped geometry

Graviton KK-modes (large spacing); graviton resonances

Signature: e.g. resonance in ee, μμ, γγ-mass distributions ...

TeV-Scale Extra Dimensions

look-like SUSY

SM particles allowed to propagate in ED of size TeV^{-1}

[scenarios: gauge fields only (nUED) or all SM particles (UED)]

UED

Universal Extra Dimensions

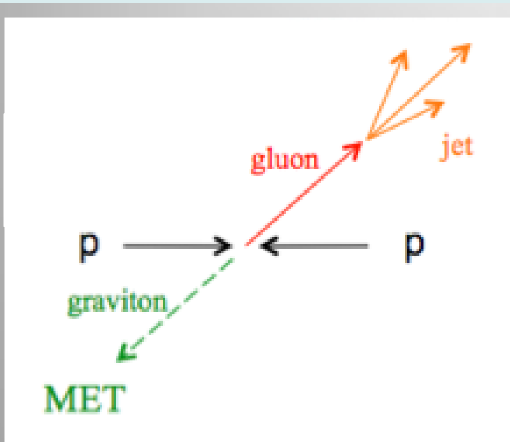
nUED : KK excitations of gauge bosons

UED : KK number conservation; KK states pair produced (at tree-level) ...

Signature: e.g. Z'/W' resonances, dijets+$E_{T,miss}$, heavy stable quarks/gluons...

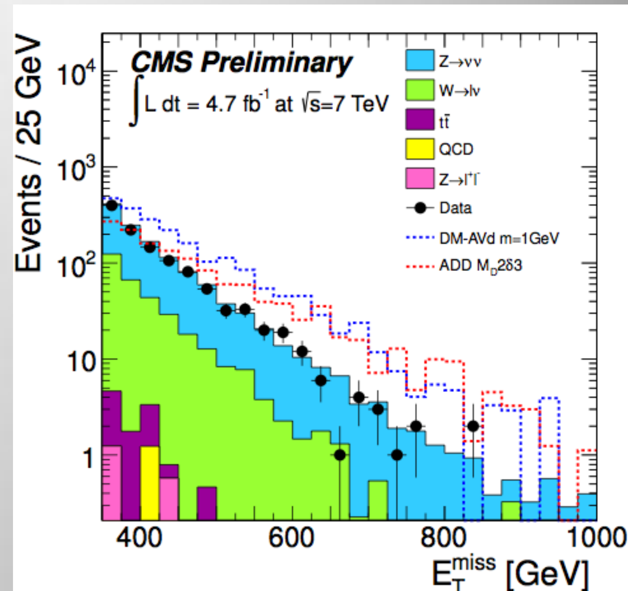
Search for Large Extra Dimensions

Mono-jet final state +Missing E_T (ADD)



p_T jet > 110 GeV
MET > 200 GeV

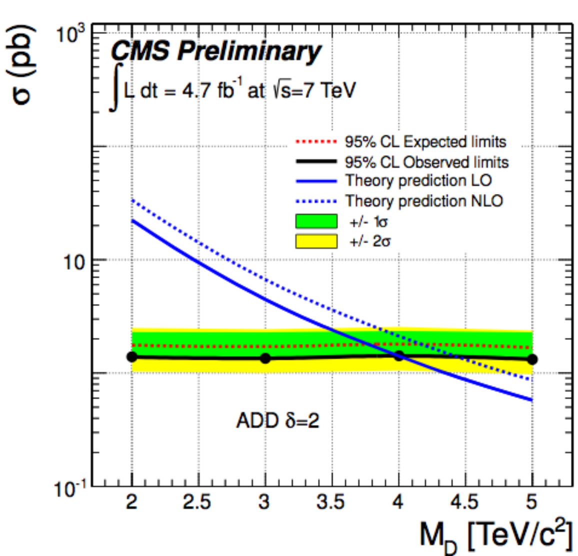
Limits on M_D between 2.5 and 4.5 TeV

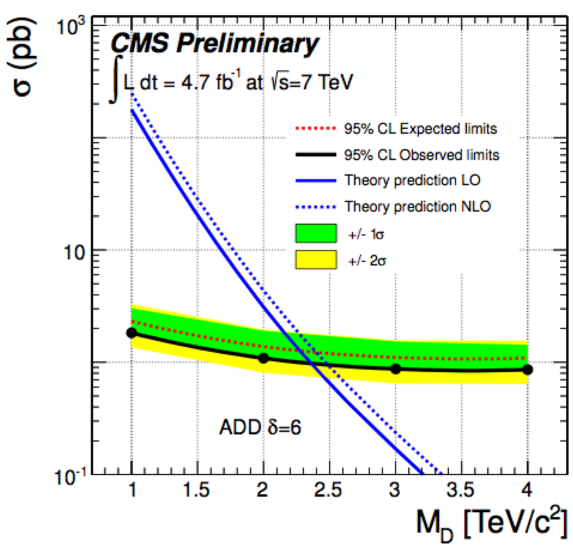


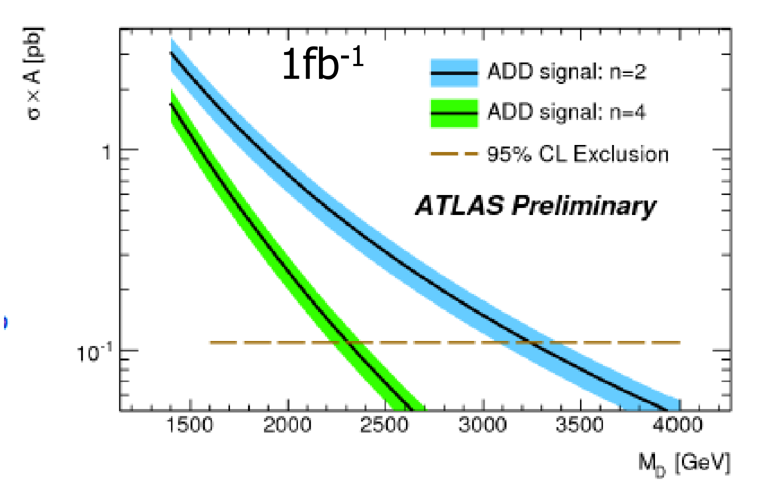
CMS-EXO-11-059

Lower limit on the Planck Scale versus number of extra dimensions

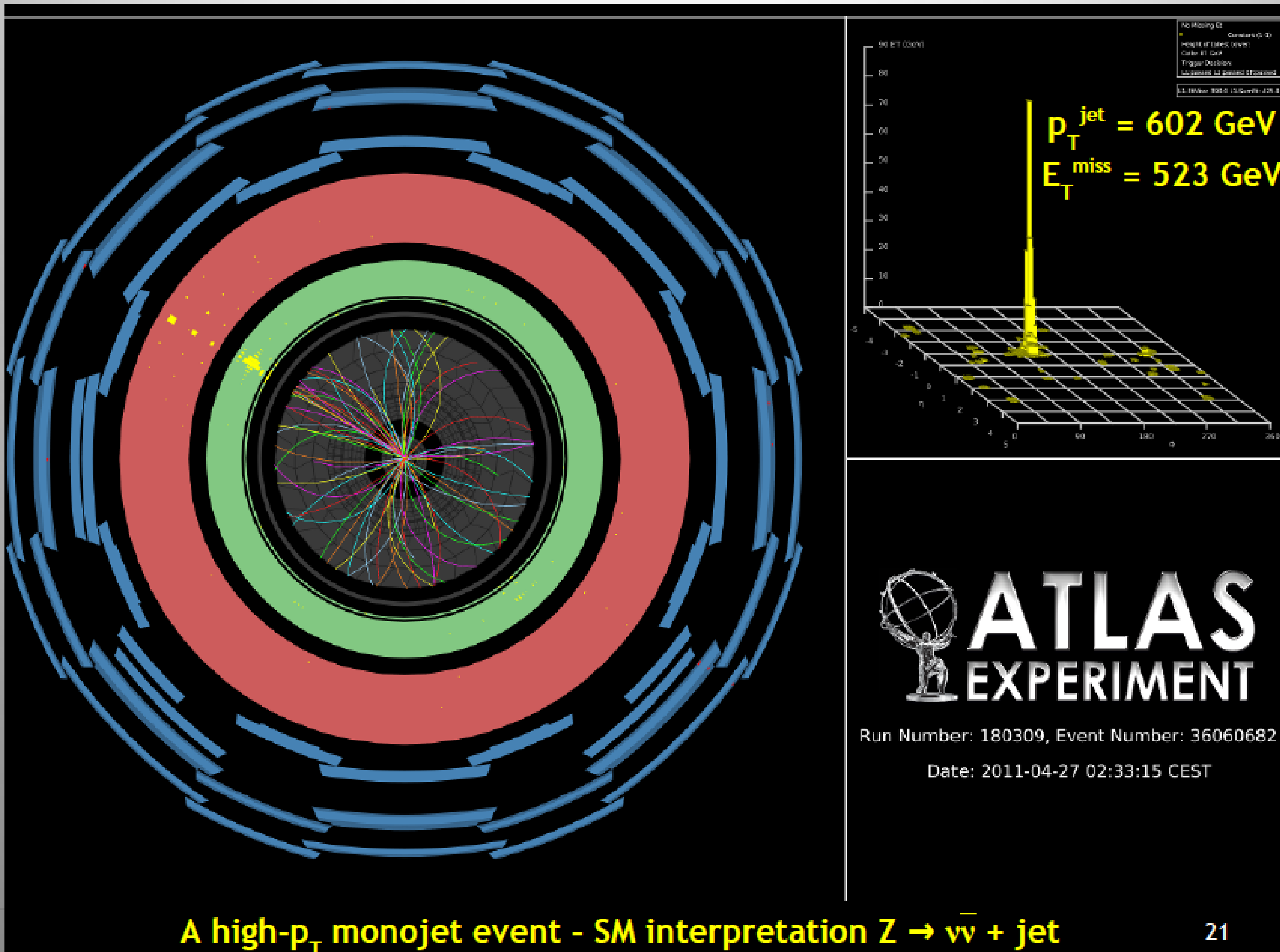
ATLAS-CONF-2011-096





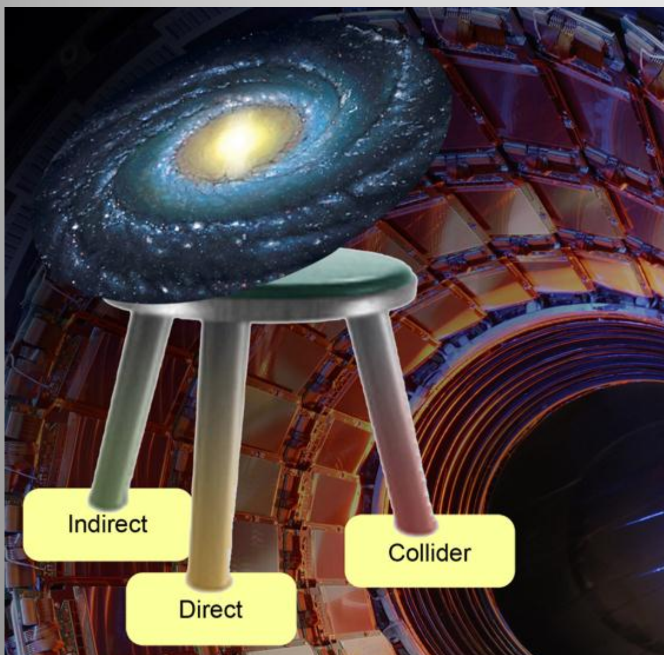


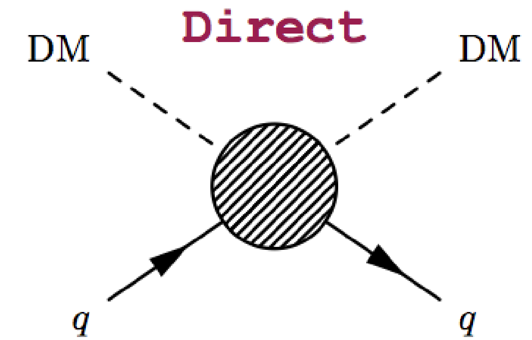
A High p_T Mono-jet event

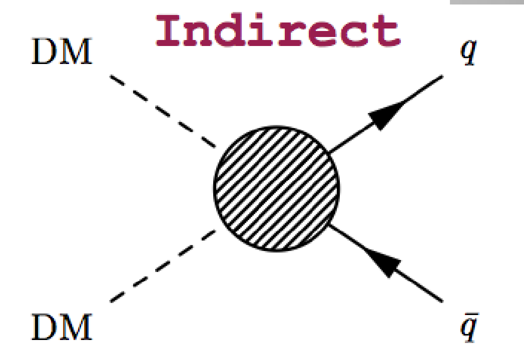


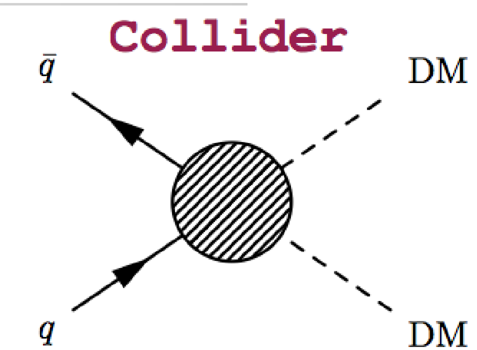
The Dark Matter Connection

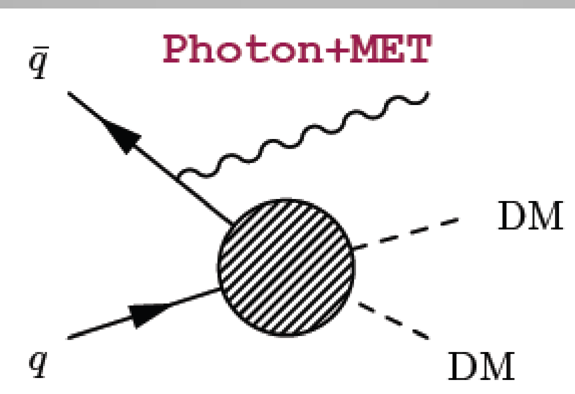
Searches for mono-jets and mono-photons can be used to search for Dark Matter (DM)

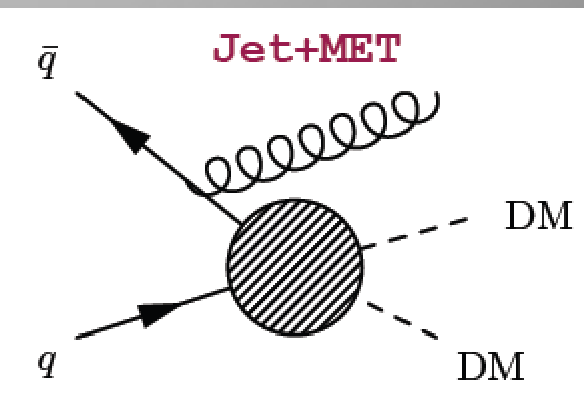








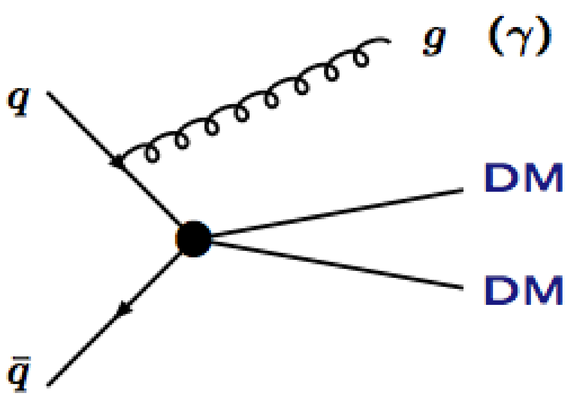


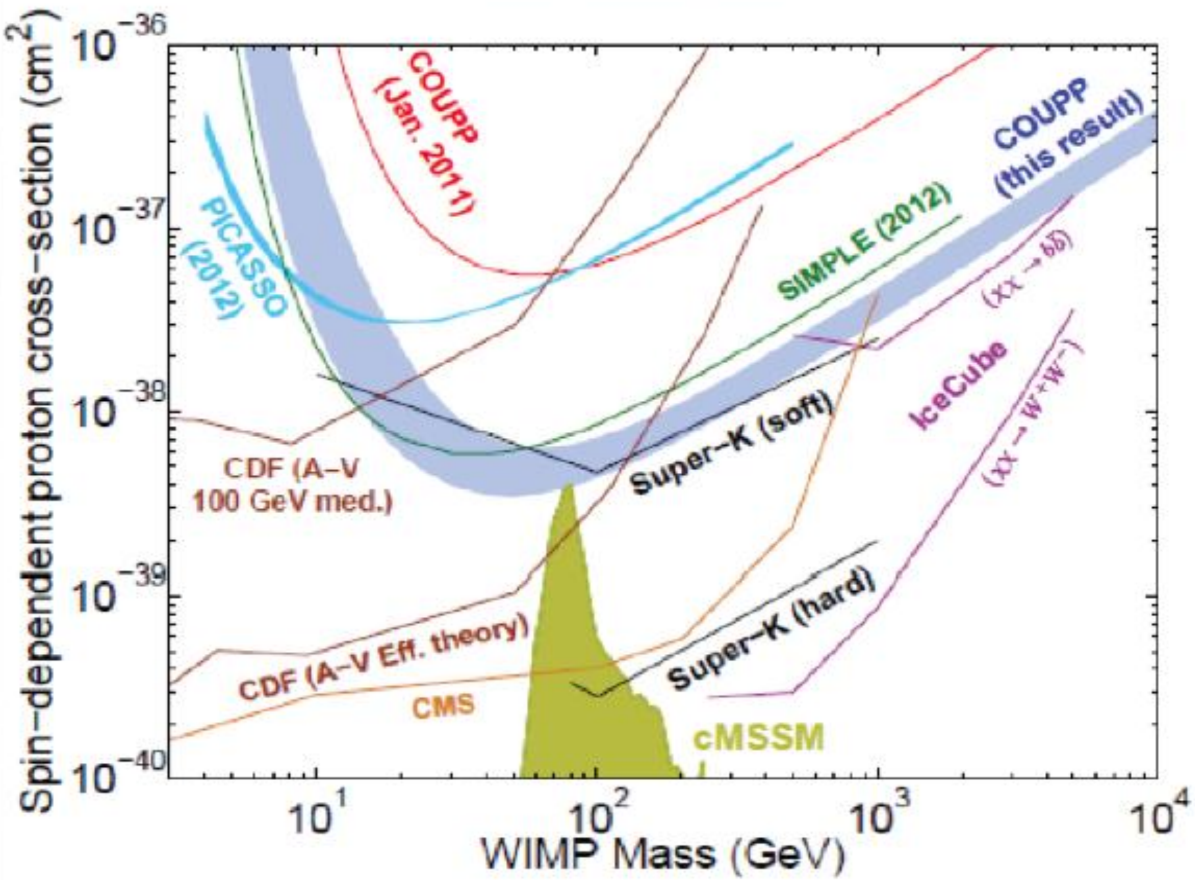


The Dark Matter Connection

Results for direct searches and collider searches for Dark Matter

-> Spin dependent and spin independent cross sections of Dark Matter with ordinary matter





Effective contact interaction approach

$$\mathcal{O}_V = \frac{(\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu q)}{\Lambda^2}$$

$$\mathcal{O}_{AV} = \frac{(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)}{\Lambda^2}$$

Collider searches are very competitive!!

Quantum Black Holes

- Schwarzschild radius

Landsberg, Dimopoulos, Giddings, Thomas, Rizzo

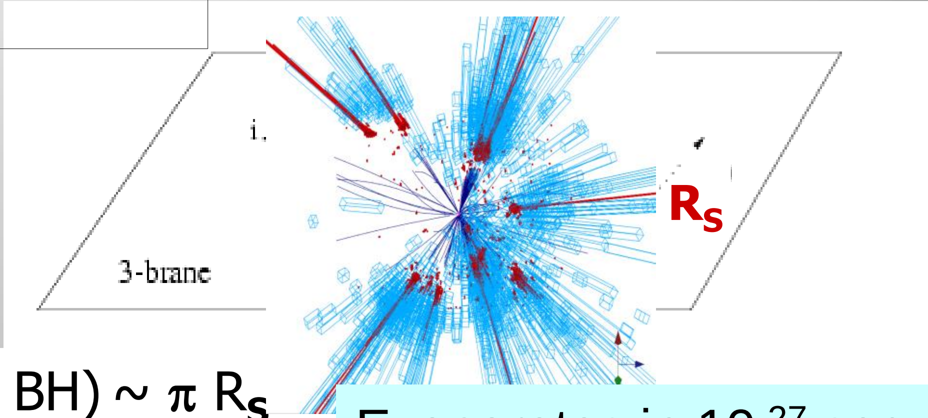
4-dim., $M_{gravity} = M_{Planck}$:

$R_s \rightarrow << 10^{-35}$ m

4 + n-dim., $M_{gravity} = M_D$ ~TeV:

$R_s \rightarrow \sim 10^{-19}$ m

Since M_D is low, tiny black holes of M_{BH} ~ TeV can be produced if partons ij with $\sqrt{s_{ij}} = M_{BH}$ pass at a distance smaller than R_S



Evaporates in 10^{-27} sec

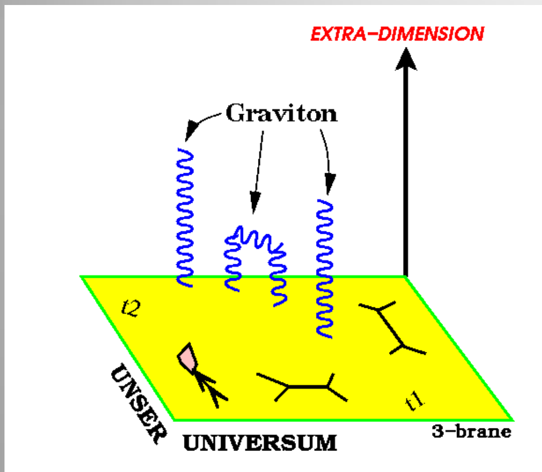
- Large partonic cross-section : $\sigma(ij \rightarrow BH) \sim \pi R_S^2$
- $\sigma(pp \rightarrow BH)$ is in the range of 1 nb – 1 fb

  e.g. For M_D ~1 TeV and n=3, produce 1 event/second at the LHC

- Black holes decay immediately by Hawking radiation (democratic evaporation)
  - -- large multiplicity
  - -- small missing E
  - -- jets/leptons ~ 5

  expected signature (quite spectacular …)

Search for Micro Black Holes

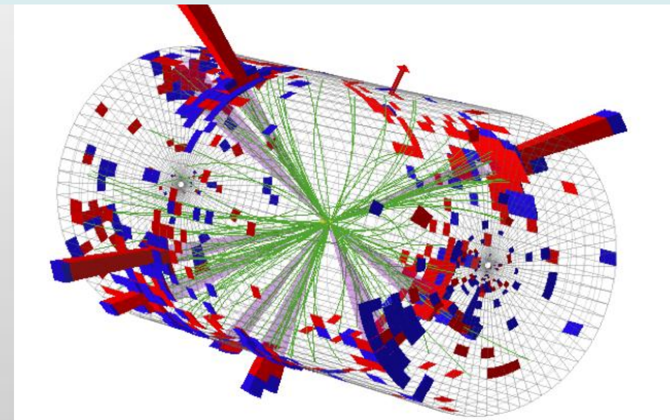


arXiv:1202.6396

Extra Dimensions!

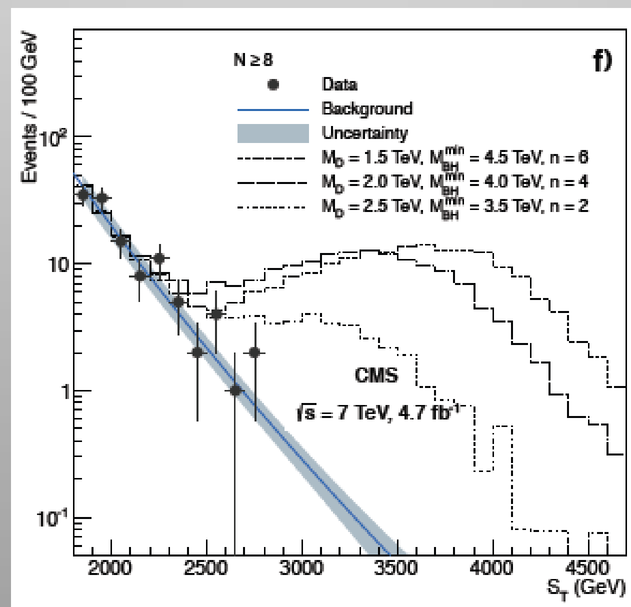
Planck scale
a few TeV?

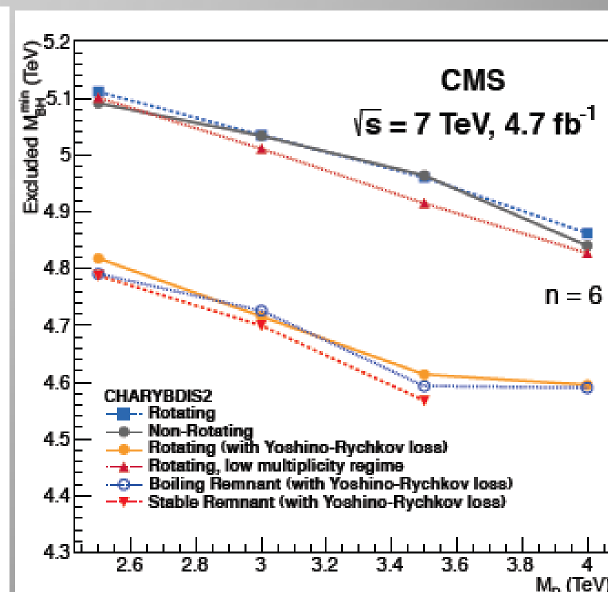
Nice events, eg a 10 jet event



Look for the decay producs of an evaporating black hole

- Define S_T to be the scalar sum of all high p_T objects found in the event
- Look for deviations at high S_T





Black hole masses excluded in range ~5 TeV depending on assumptions

Search for Resonances

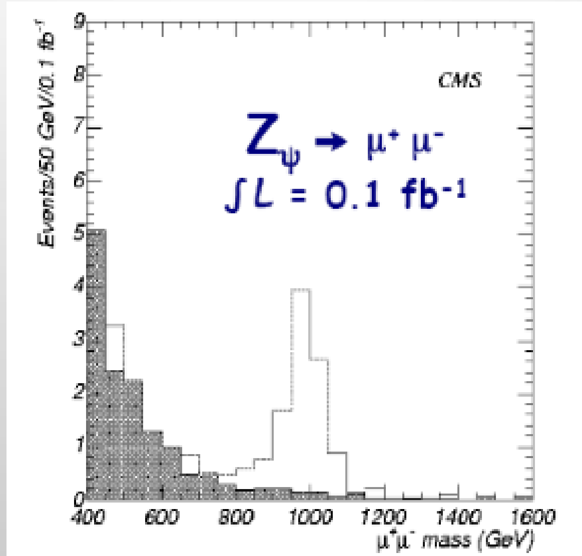
E.g. Di-lepton Resonance

Plot the di-lepton invariant mass

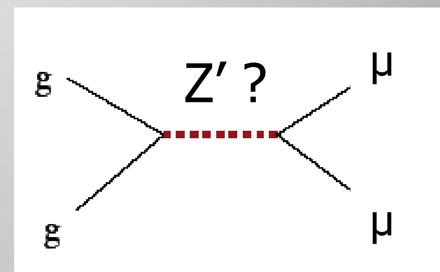
A peak!!

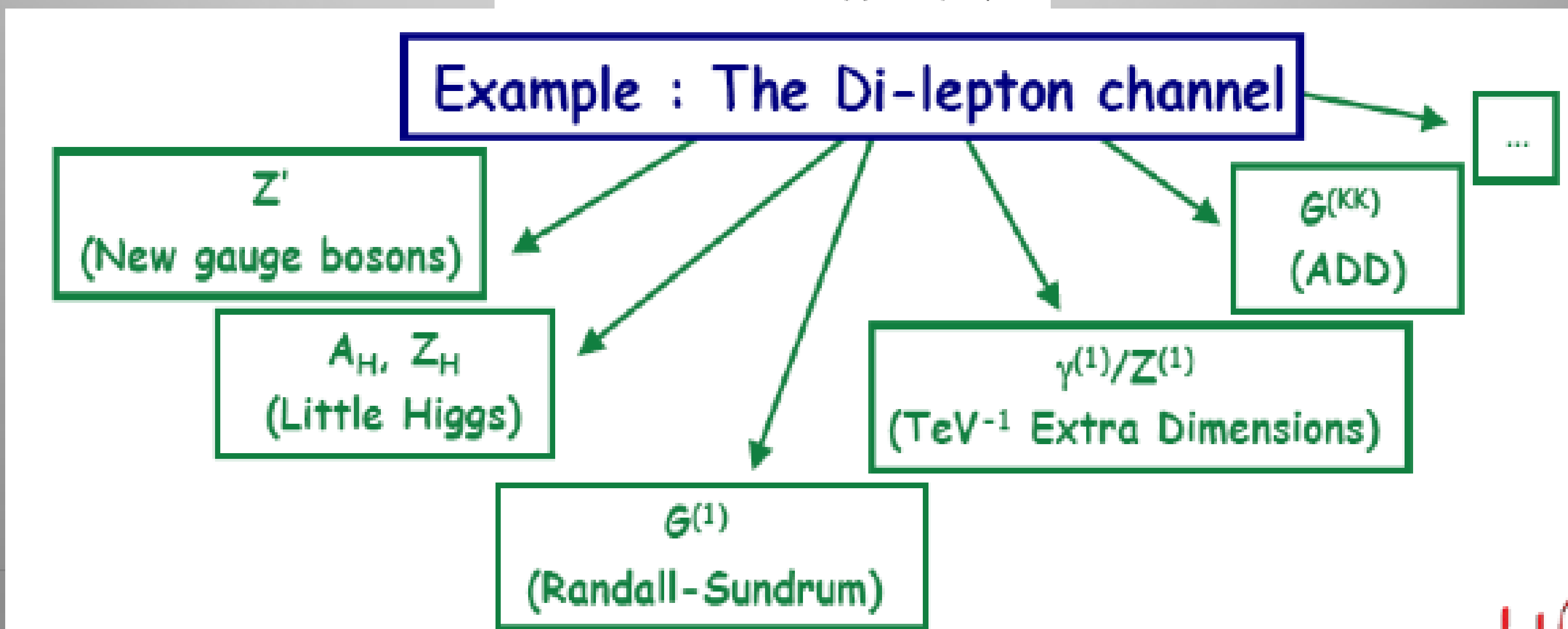
A new particle!!

A discovery!!



Example
pp→μμ +X



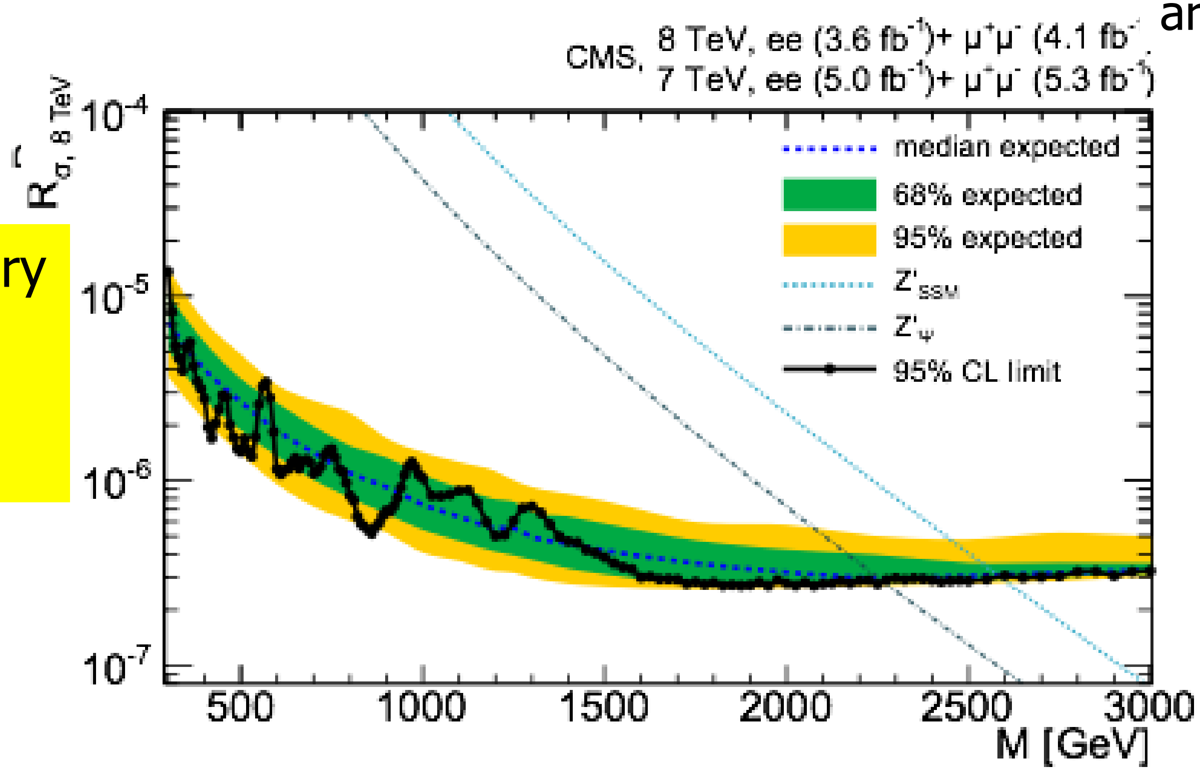


Z' Combination of 7 & 8 TeV Data

arXiv:1212.6175

But no discovery so far ☹

Limits…



- Short time between data-taking and result

$$R_\sigma = \frac{\sigma(\mathrm{pp} \to Z' + X \to \ell\ell + X)}{\sigma(\mathrm{pp} \to Z + X \to \ell\ell + X)}$$

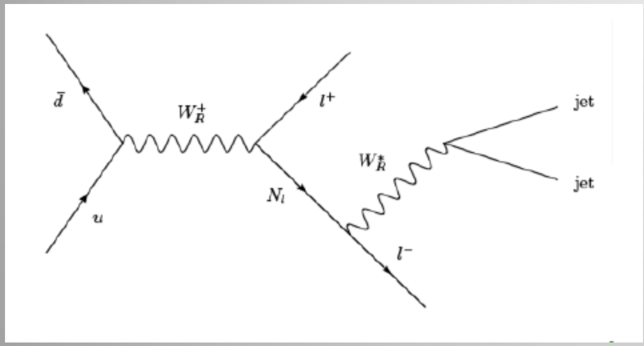
- Limits on the combined 7 TeV and 8 TeV data from 2011+2012
  - $M(Z'_{SSM}) > 2590$ GeV at 95% C.L.
  - $M(Z'_{\psi}) > 2260$ GeV at 95% C.L.

Excess just below 1 TeV all but gone in CMS data

Search for Heavy Neutrinos

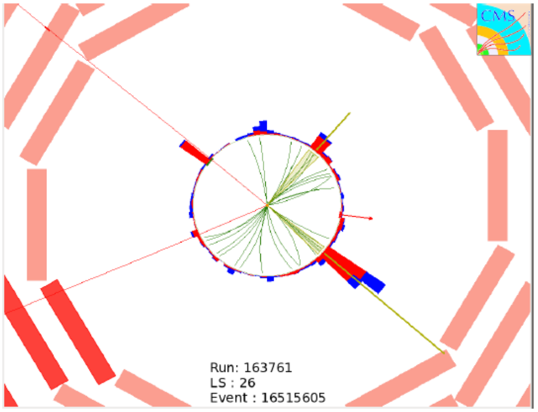
Heavy Neutrinos in W_R Decays

Left-right symmetric extension of the Standard Model

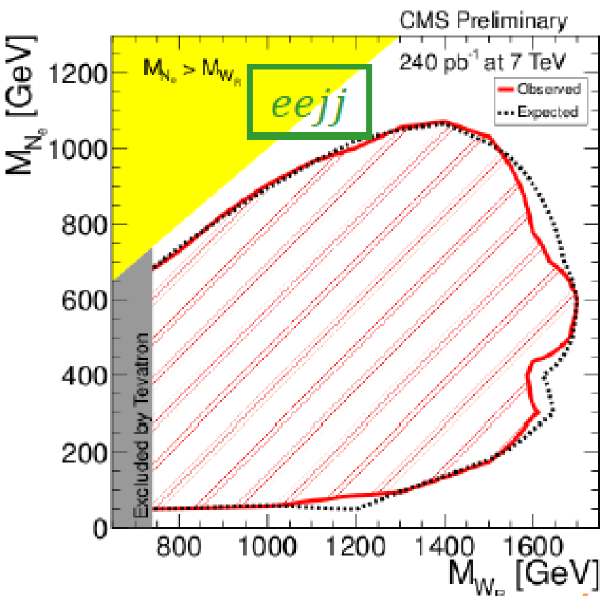


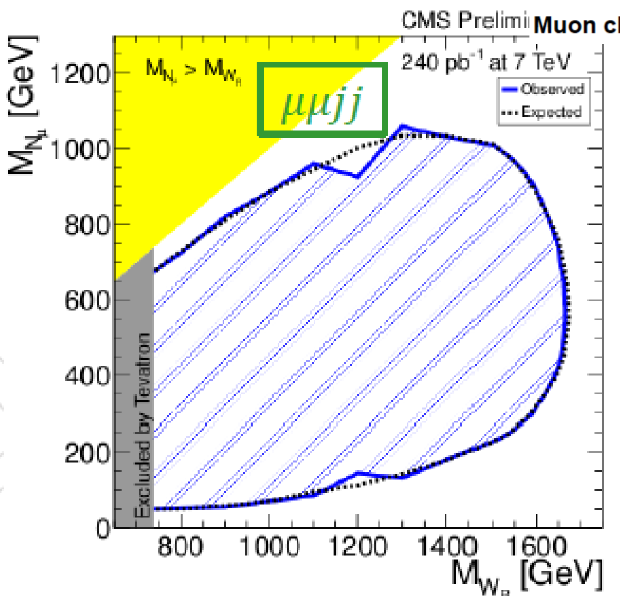
CMS-EXO-11-002

Select events with
2 leptons and 2 jets



Muon channel: Event with $M_{\mu\mu}$ = 331 GeV, $M_{\mu\mu jj}$ = 881 GeV





Large exclusion range in mass of the W_R and heavy neutrino

Tevatron excludes W_R~ 780 GeV

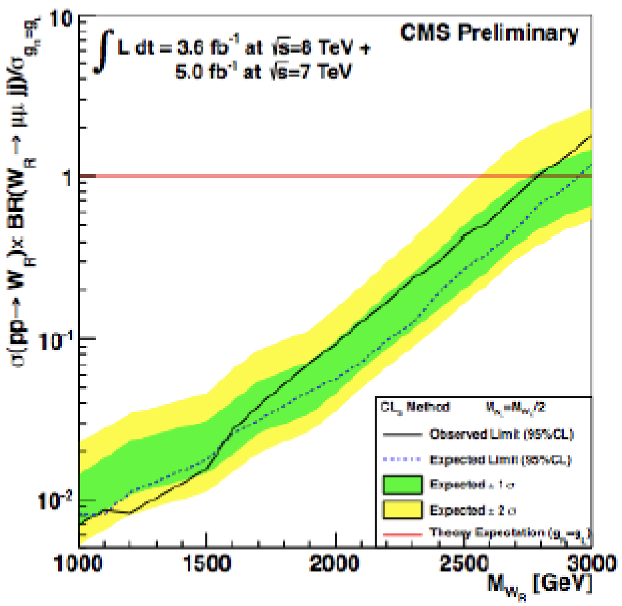
Limits ~ 1 year ago

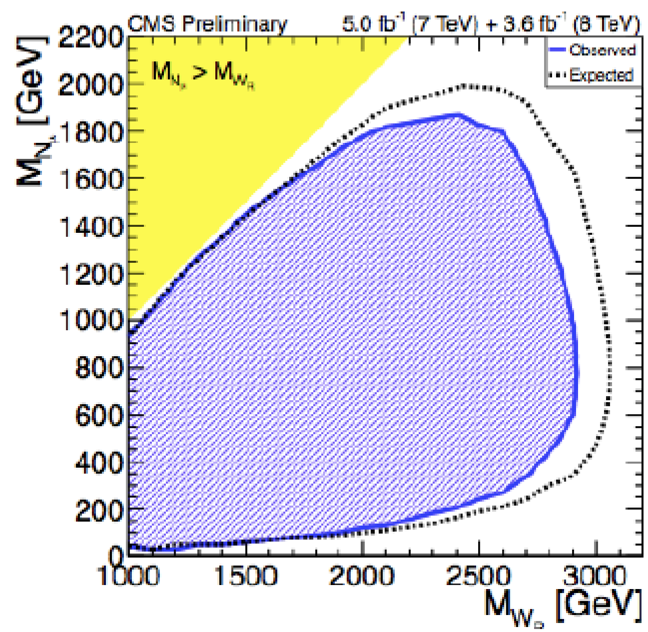
Heavy Neutrinos in W_R Decays

[CMS PAS EXO-12-017]

- Search assumes small W_R–W_L and N_l–$N_{l'}$ mixing angles, only one lepton channel kinematically accessible
- Primary Systematic Uncertainties
  - Signal Eff.: 6-10% from lepton
  - Background: ~50% from DY+jets shape, ~16% from top shape

For $M(N)=M(W_R)/2$; $M(W_R) > 2.8$ TeV



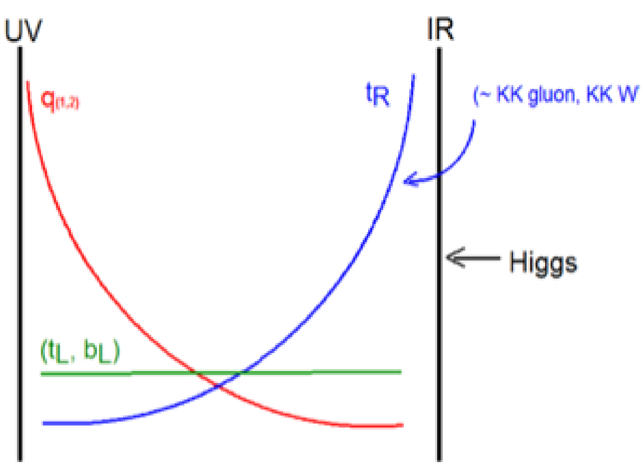


Searches with Top Quark

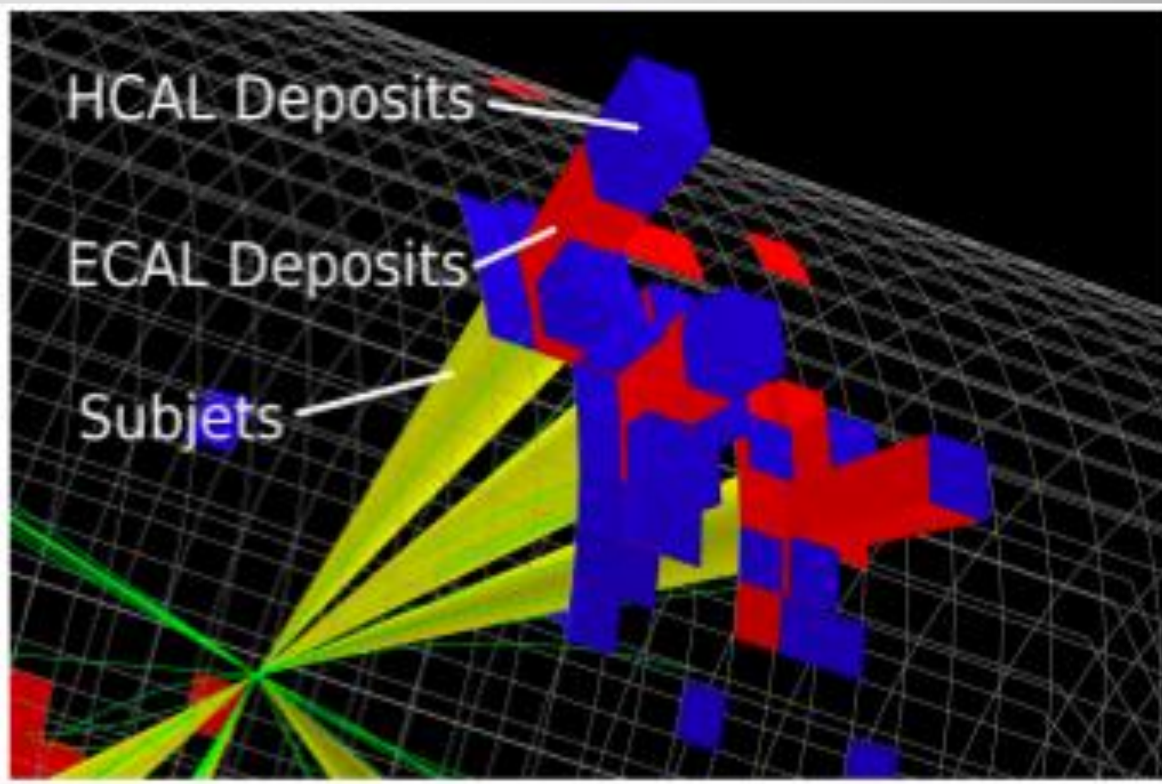
TeV Resonances into Top Quark Pairs

Recent developments in models: a prominent role of top production
-light SM fermions live near Planck brane, heavy (top) near TeV brane
-decay of Randall Sundrum gravitons into top pairs!!

- Eg RS → t tbar

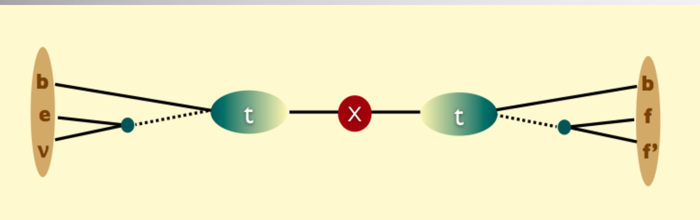


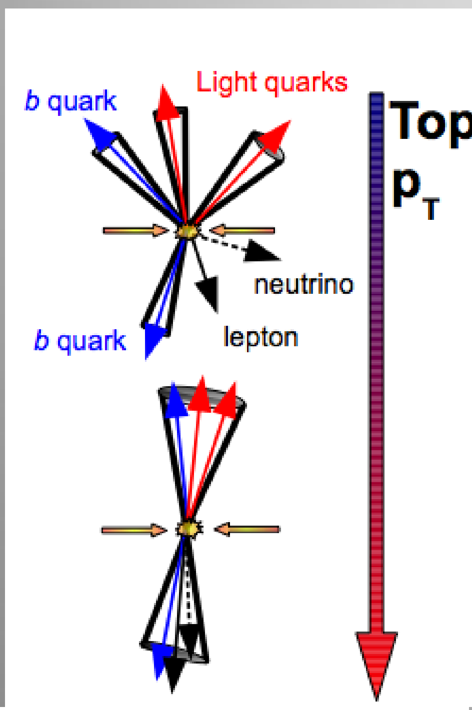
⇒High P_T tops



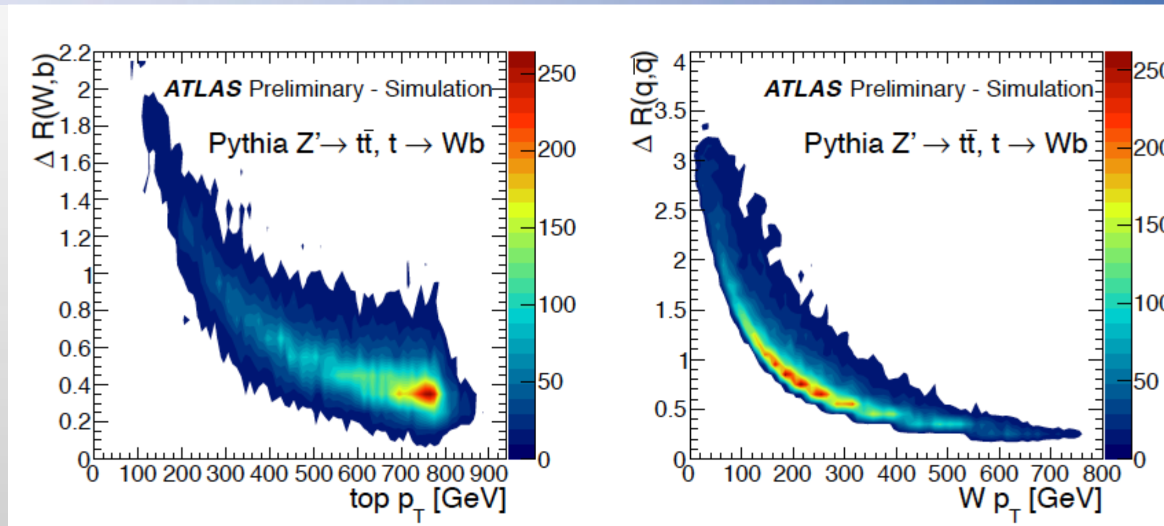
Top quark decay products merged in one ‘fat’ jet

New Physics with Boosted Objects





ATLAS-CONF-2012-065



W,Z and top decays from heavy, typically multi-TeV objects are of special interest at the LHC

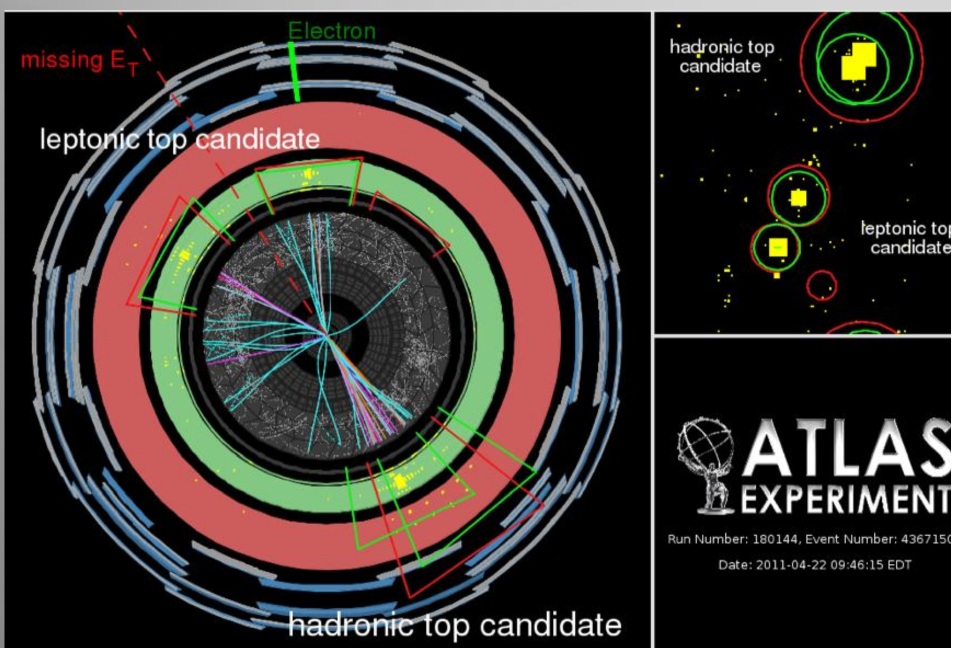
- $\Delta R \sim 2m/p_T$: decay product merge at large p_T
- New techniques developed – and discussed in a series of topical Workshops- for leptonic and hadronic decays of W,Z, top…
  Eg.: Jet substructure, grooming: mass drop filtering, trimming, pruning…

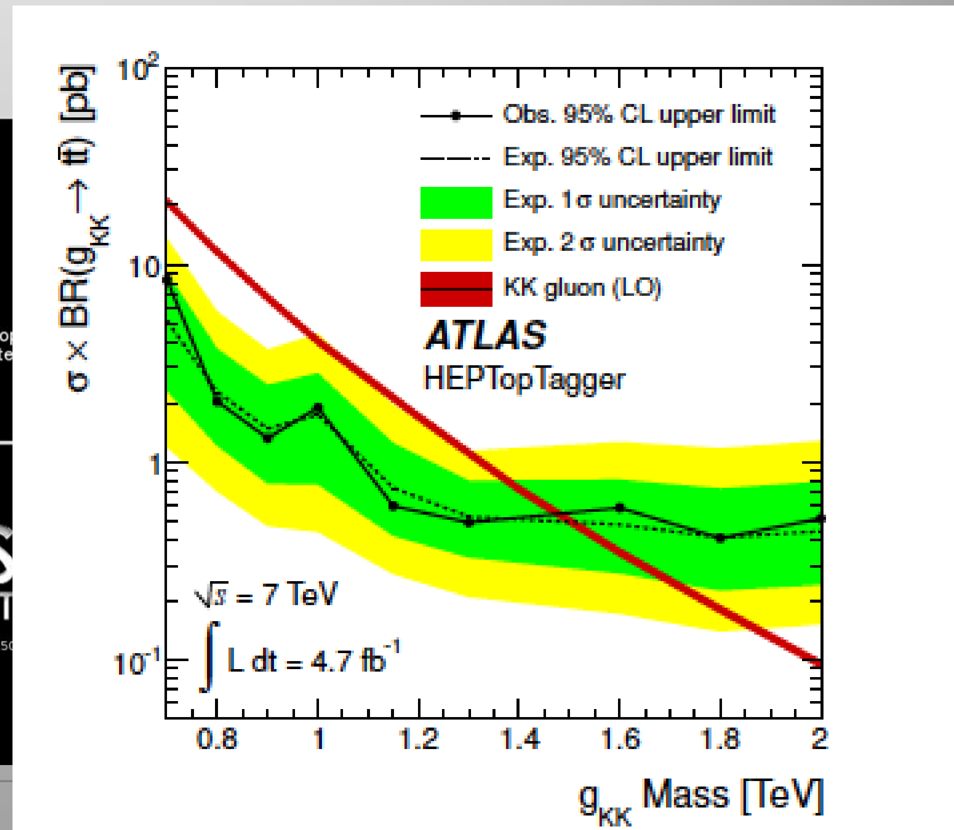
Top resonance study

arXiv:1207.2409

- Boosted objects are reconstructed as one fat jet R=1.0, p_T> 250 GeV. Analyse the jet substructure
- Modified isolation for the leptonic decay side

$$pp \to t\bar{t} \to b\bar{b}q\bar{q}'\ell\nu_\ell,$$





Searches for Unusual Particles

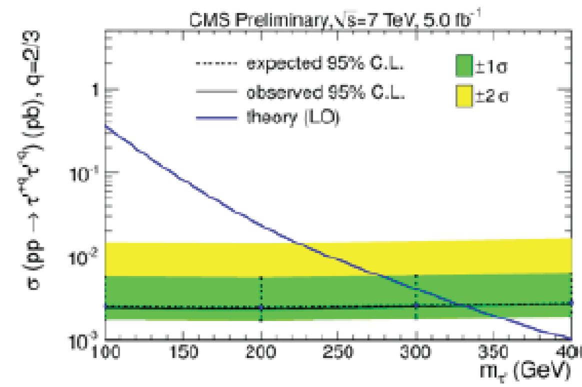
- Heavy stable charged particles with unit charge traversing the detector
- Heavy stable charged particles with multiple charge traversing the detectors
- Heavy stable charge particles with fractional charge traversing the detector
- Heavy new particles decaying in the detector
- Heavy new particles stuck in the material in or before the detector

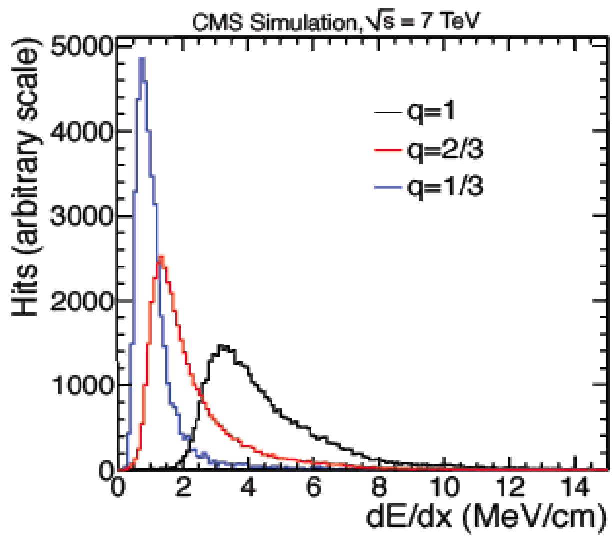
Particles with Fractional Charge

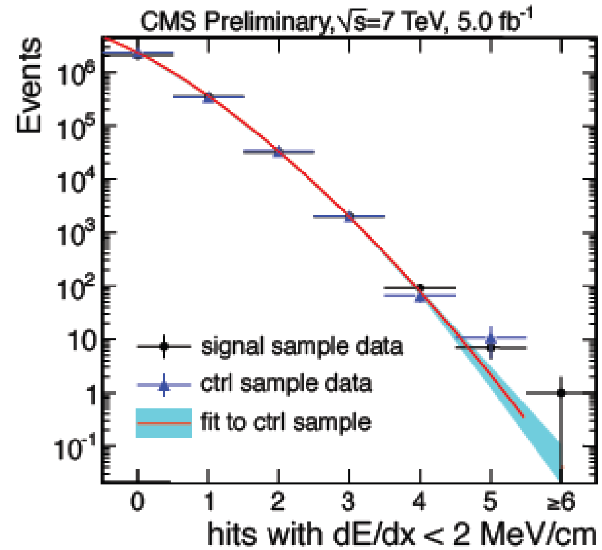
[CMS PAS EXO-11-074]

- Search for long-lived particles with fractional charge
- Backgrounds
  - Cosmics: estimate from d_{xy} sidebands
  - Collisions: using $Z \rightarrow \mu\mu$ data, fit N_{hits} with low dE/dx
- Assume lepton-like spin=1/2 particle masses

Exclude: Q= e/3: m > 210
Q=2e/3: m > 330



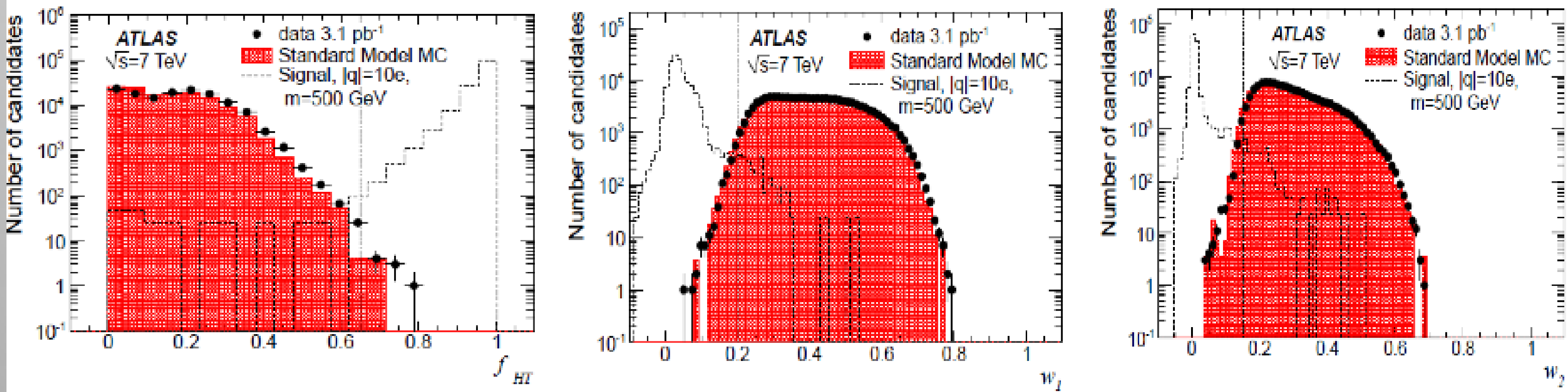




Highly Ionising Particles

ATLAS

Search for Massive Long-Lived Highly Ionising Particles



- Search for massive long-lived HIP: concentrate on large mass (>100GeV), non-relativistic speed, charges 6-17e (Q-balls, stable micro black holes)
- Signal has high ionization in tracker, narrow calorimeter deposits
- No events pass selection shown above (96% efficient for signal)

Cross-section limits @ 95% CL in pb for any model

m [GeV]	$\lvert q\rvert = 6e$	$\lvert q\rvert = 10e$	$\lvert q\rvert = 17e$
200	1.4	1.2	2.1
500	1.2	1.2	1.6
1000	2.2	1.2	1.5

Cross-section limits at 95% CL in pb assuming Drell-Yan-like production mechanism

m [GeV]	$\lvert q\rvert = 6e$	$\lvert q\rvert = 10e$	$\lvert q\rvert = 17e$
200	11.5	5.9	9.1
500	7.2	4.3	5.3
1000	9.3	3.4	4.3

Search for Monopoles

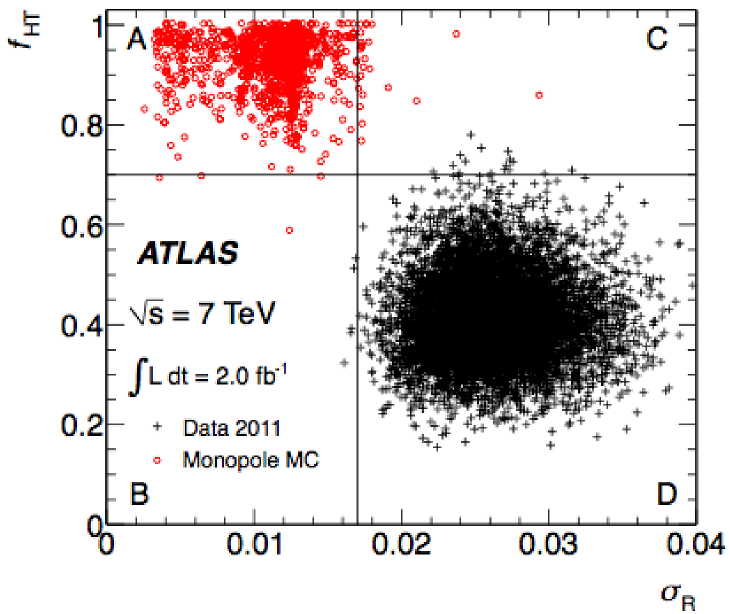
arXiv:1207.6411

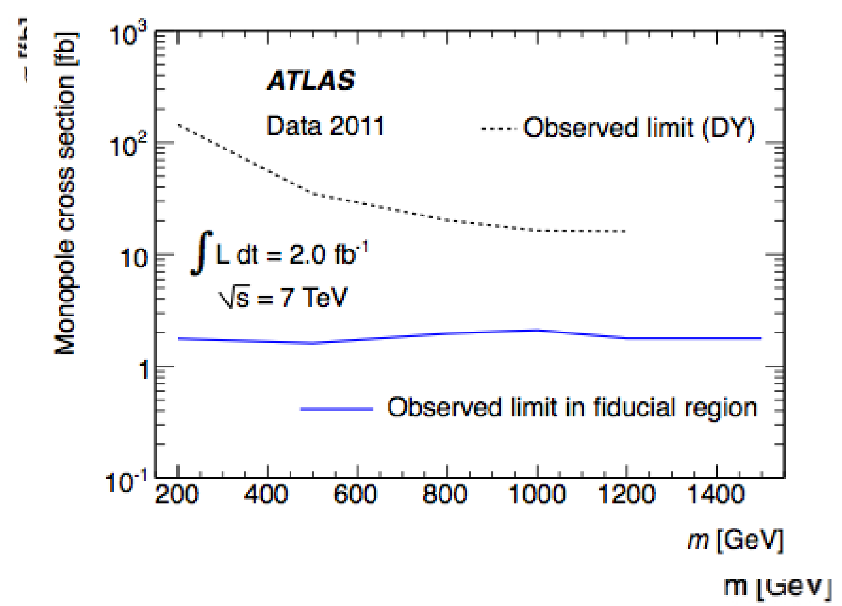
- Magnetic charge g yields strong coupling α_m and very high ionisation

$$\frac{ge}{\hbar c} = \frac{1}{2} \Rightarrow \frac{g}{e} = \frac{1}{2\alpha_e} \approx 68.5 \qquad \alpha_m = \frac{(g\beta)^2}{\hbar c} = \frac{1}{4\alpha_e}\beta^2$$

- Look for high ionisation in Transition Radiation Tracker and high hit fraction (f_{HT}) and also deposition in the Liquid Argon Electromagnetic Calorimeter
- Pair-produced (Drell-Yan) production

Cross Section limits set for m(M) = 0.2–1.2 TeV

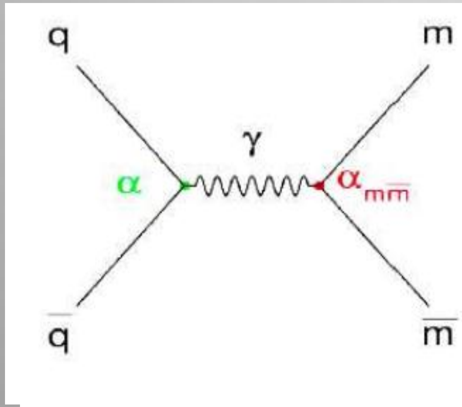




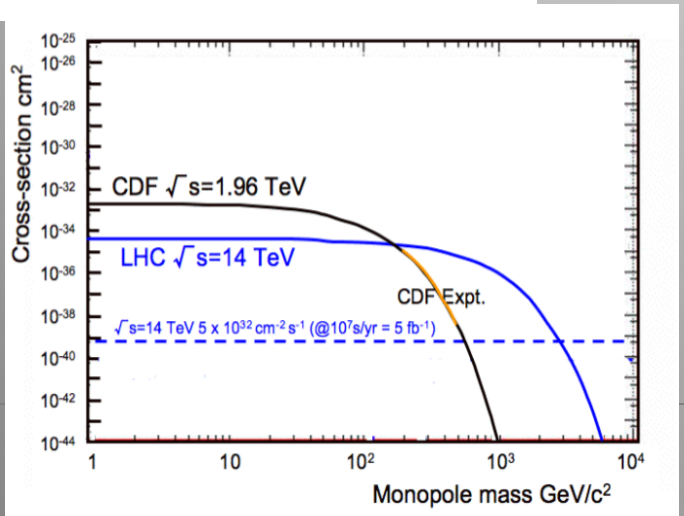
MoEDAL: Monopole and Exotics Detector at the LHC

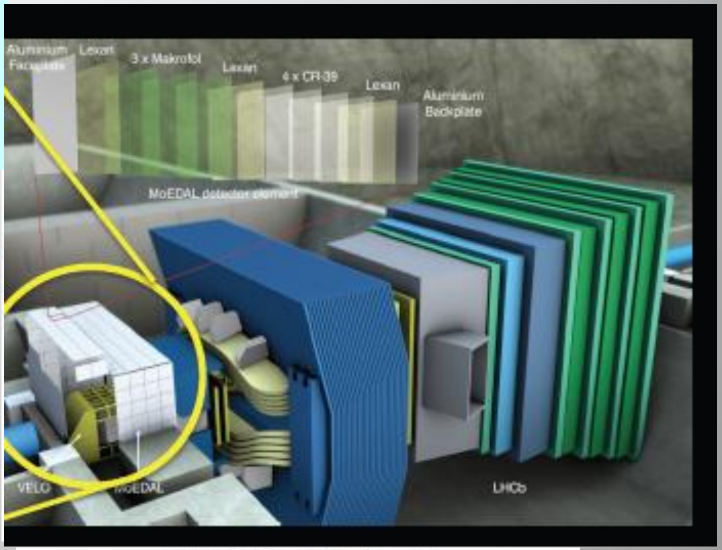
Heavy particles which carry “magnetic charge”
Could eg explain why particles have “integer electric charge”

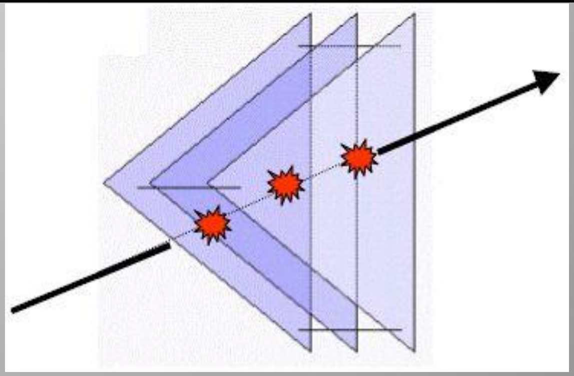
First Data Results in 2015



Direct Monopole production

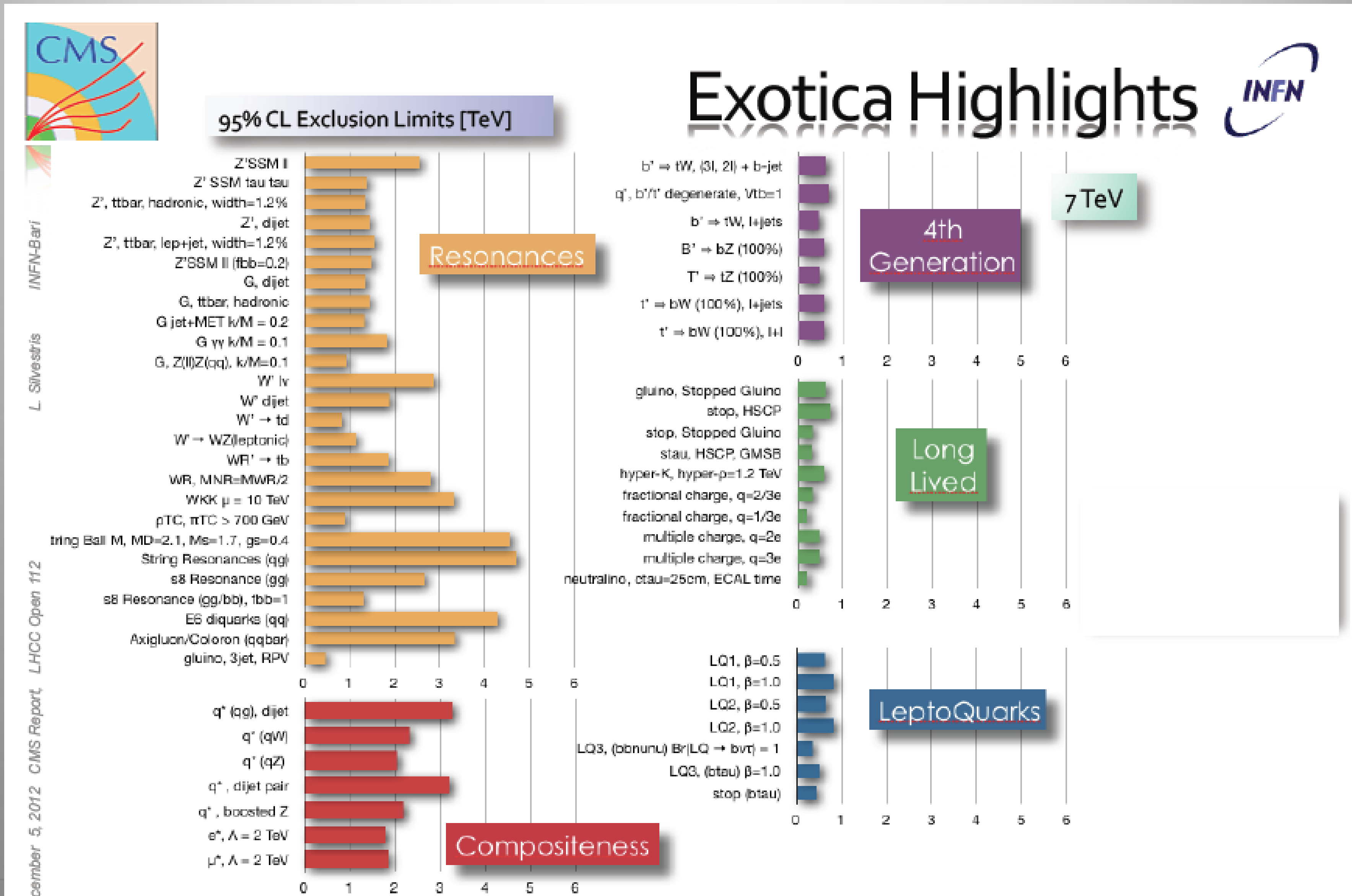






Remove the sheets after some running time and inspect for ‘holes’

Summary of Searches



Summary: What did we learn so far?

- The LHC has entered new territory. A new particle was detected @ mass ~ 125 GeV. Mounting evidence that this is a Higgs boson, but cannot be completely sure yet.
- The ATLAS and CMS experiments make important Standard Model measurements and are heavily engaged in searches for New Physics. The most popular example is SUSY, but many other New Physics model searches are covered.
- No sign of new physics yet in the 7/8 TeV with the analyses reported in this lecture. Cut into the 'preferred regions' for a number of models Still many new channels l
- In 2015 the energy will be (>)13 TeV, exceller for New Physics so maybe what awaits us
- And who knows, maybe soon….