

# *The Large Hadron Collider: In Search of New Physics*

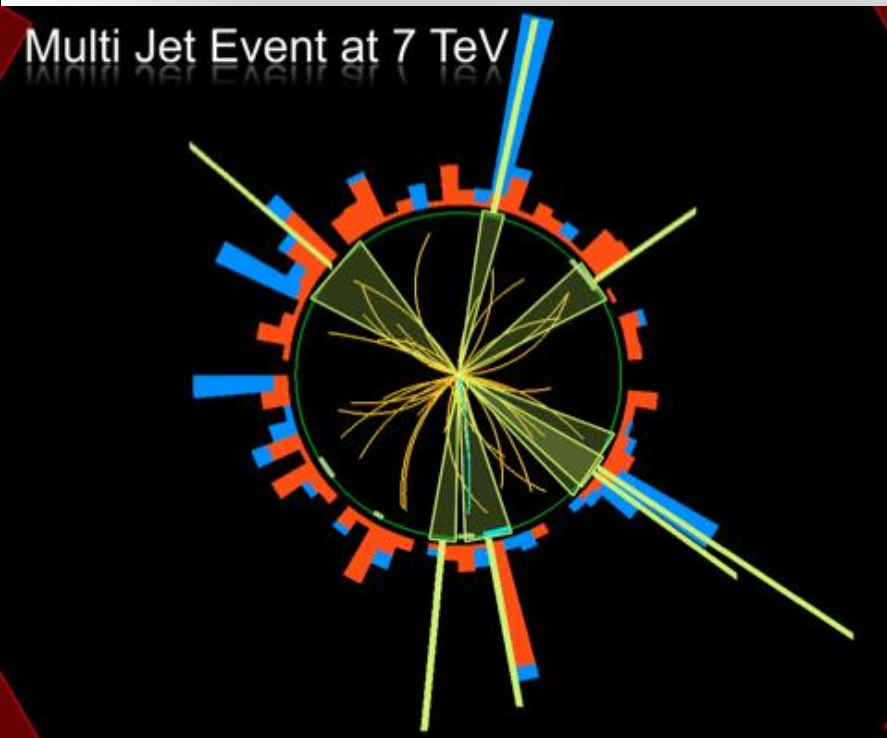
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CERN, Geneva, Switzerland  
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UC-Davis California USA  
BU, Cairo, Egypt  
NTU, Singapore

CERN 3 July 2018



African School of Fundamental  
Physics and Applications





# Outline

- Introduction: LHC & Higgs
- New Physics Searches @ the Large Hadron Collider
  - Dark Matter?
  - Supersymmetry?
  - Extra space dimensions?
  - Black Holes?
  - Matter Substructure?
- Summary

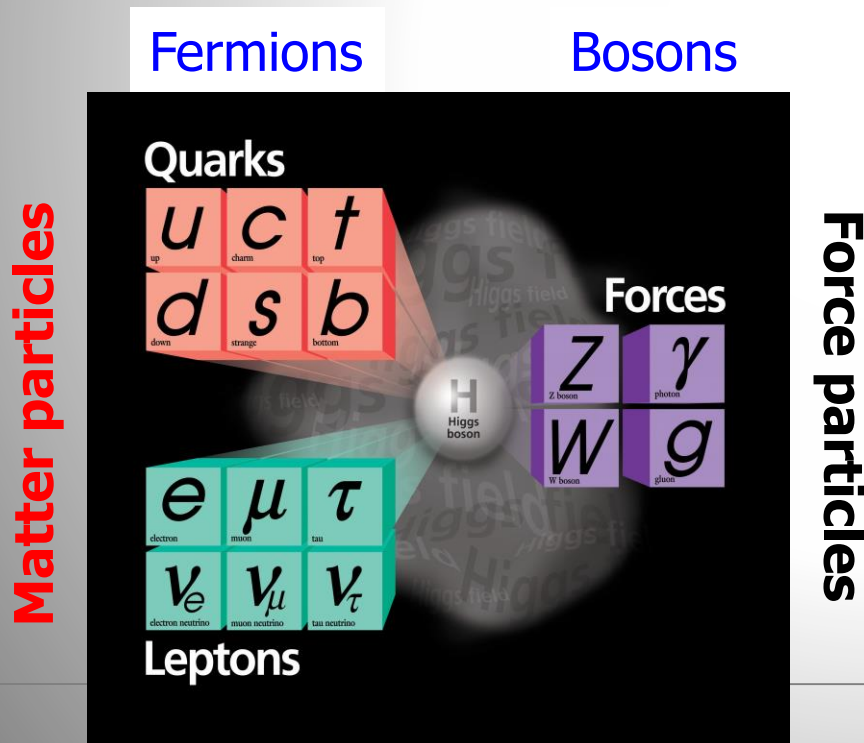
What is the world made of?  
What holds the world together?  
Where did we come from?



# The “Standard Model”

Over the last 100 years: combination of **Quantum Mechanics and Special Theory of relativity** along with all new particles discovered has led to the **Standard Model of Particle Physics.**

**The new (final?) “Periodic Table” of fundamental elements:**



The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time

**A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!**

Fermions: particles with spin  $\frac{1}{2}$   
Bosons: particles with integer spin

# The Hunt for the Higgs

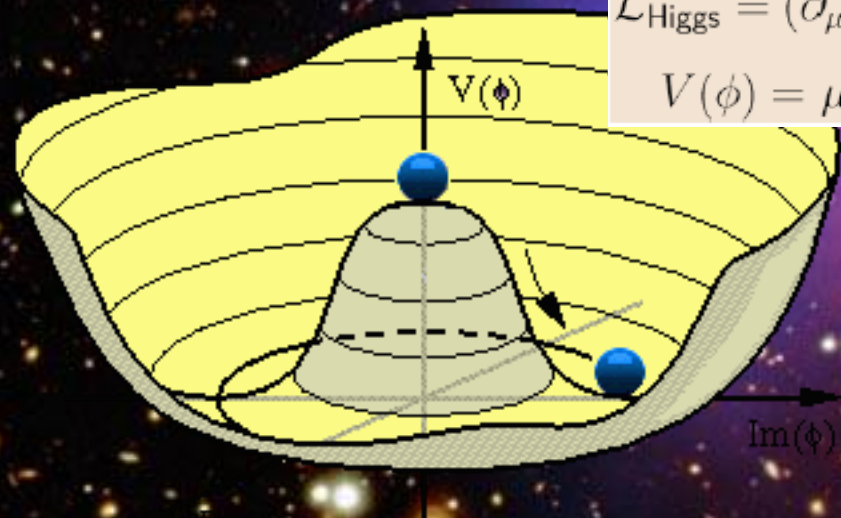
Where do the masses of elementary particles come from?

The key question (pre-2012):  
Does the Higgs particle exist?  
If so, 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

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$
$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



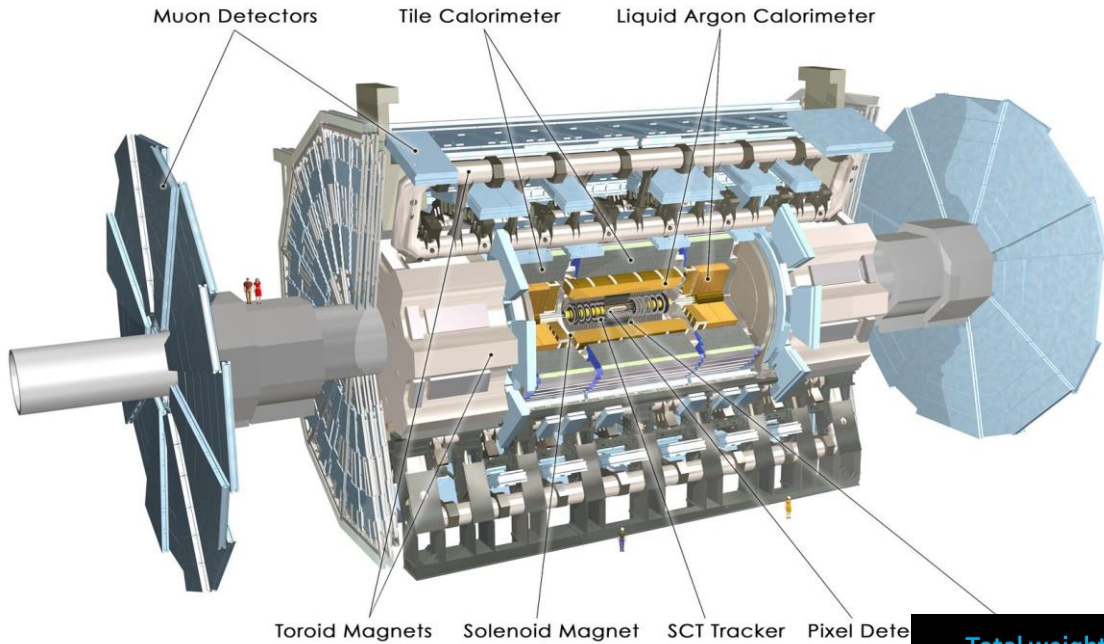
Scalar field with at least one scalar particle

Note: NOT the mass of protons and neutrons

It could be anywhere from 114 to ~700 GeV



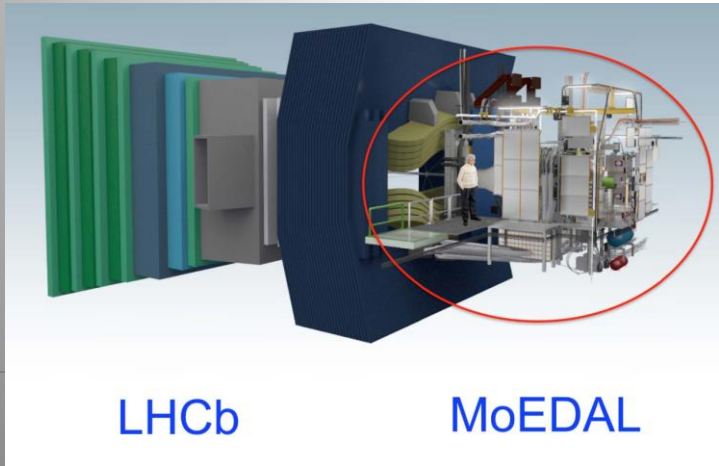
# New Physics Hunters @ the LHC



The ATLAS experiment

The CMS experiment

...And also LHCb and MoEDAL



**CMS**

Total weight 14000 t  
 Overall diameter 15 m  
 Overall length 28.7 m

**ECAL** 76k scintillating PbWO<sub>4</sub> crystals  
**HCAL** Scintillator/brass Interleaved ~7k ch  
**3.8T Solenoid**  
**IRON YOKE**  
**MUON ENDCAPS** 473 Cathode Strip Chambers (CSC) 432 Resistive Plate Chambers (RPC)  
**Preshower** Si Strips ~16 m<sup>2</sup> ~137k ch  
**Forward Cal** Steel + quartz Fibers 2~k ch  
**MUON BARREL** 250 Drift Tubes (DT) and 480 Resistive Plate Chambers (RPC)

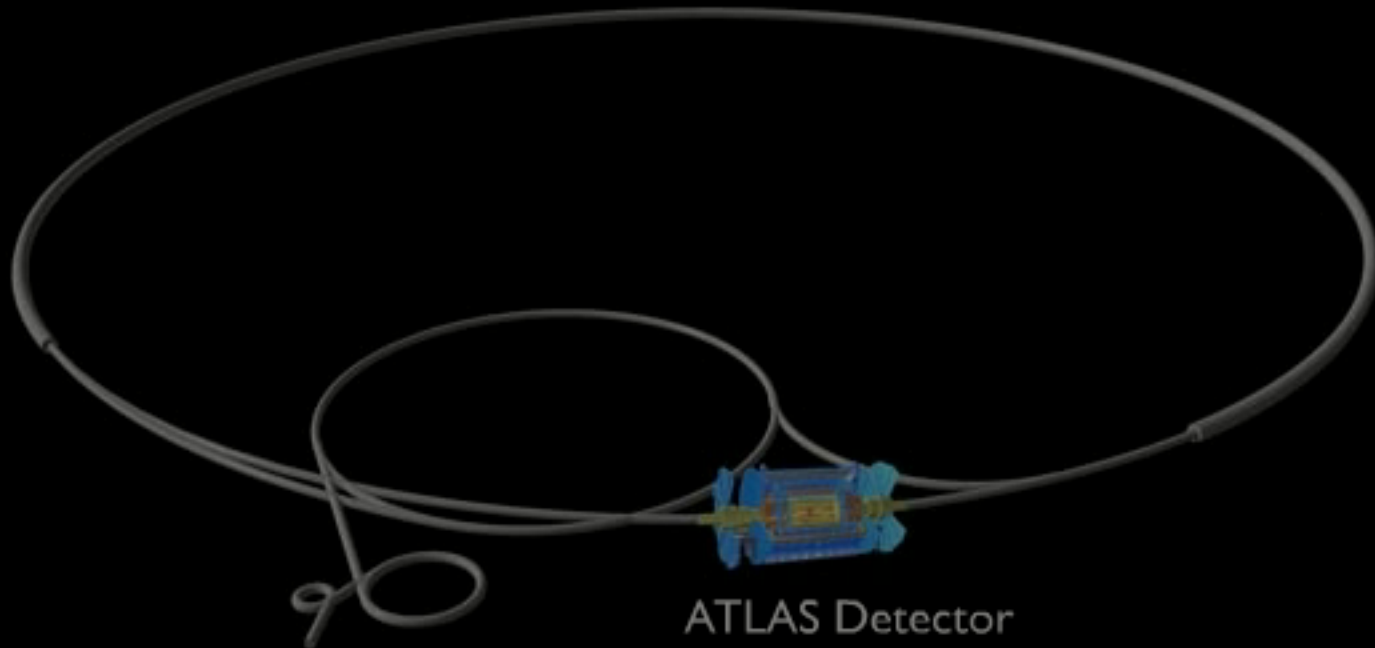
**Pixel Tracker**  
**ECAL**  
**HCAL**  
**Muons**  
**Solenoid coil**

**YBO**  
**YB1-2**  
**YET-3**

**Pixels & Tracker**  
 • Pixels (100x150 μm<sup>2</sup>) ~ 1 m<sup>2</sup> ~66M ch  
 • Si Strips (80-180 μm) ~200 m<sup>2</sup> ~9.6M ch

PLAY ▶

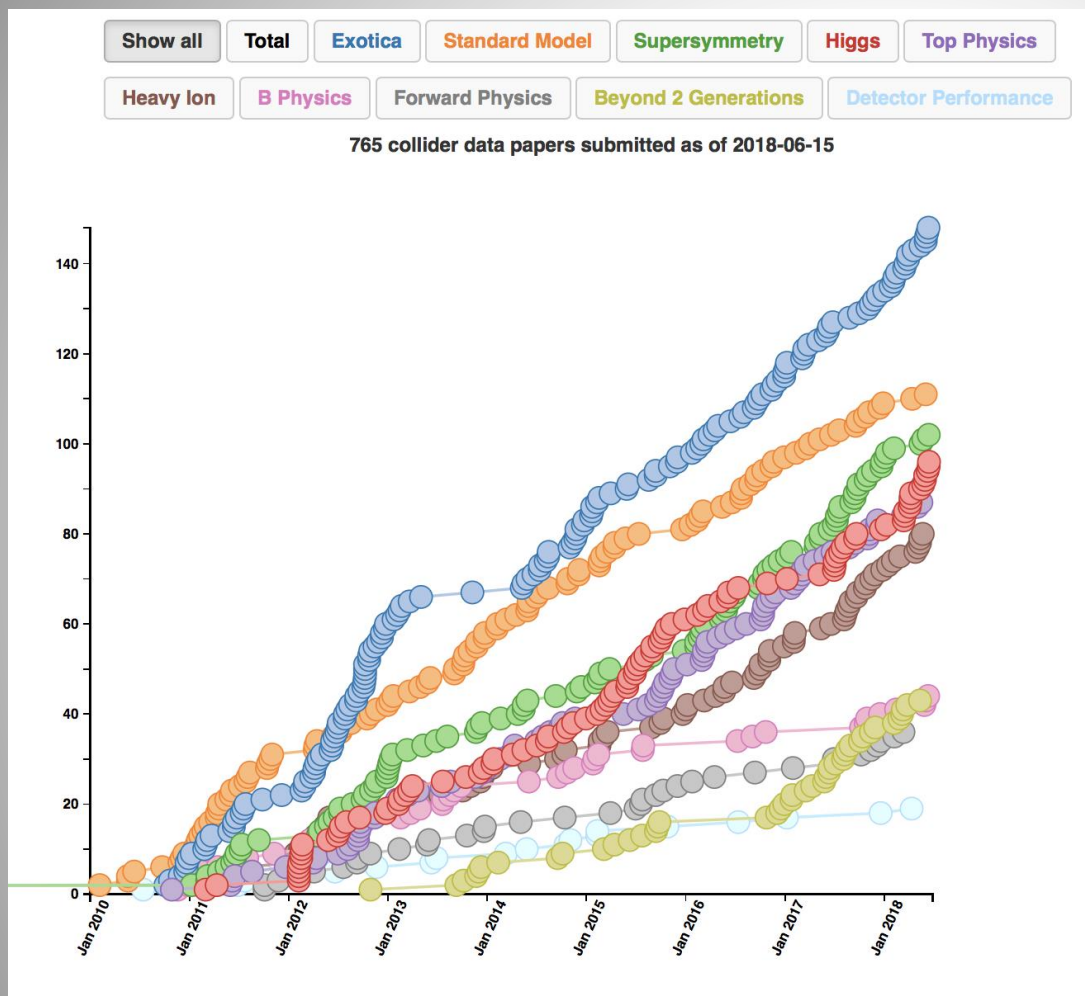
Large Hadron Collider



ATLAS Detector



# LHC Publications: Example CMS

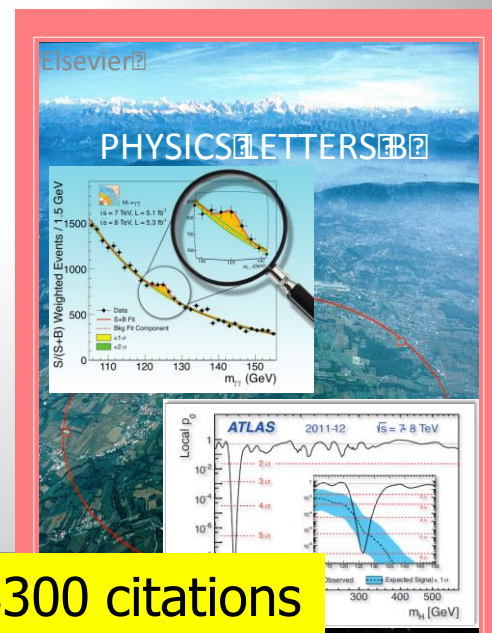


<http://cms-results.web.cern.ch/cms-results/public-results/publications-vs-time/>

Similar for ATLAS

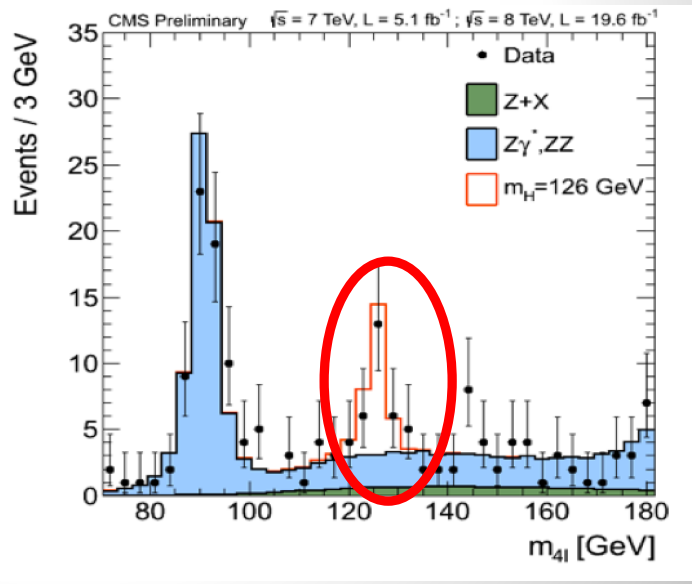
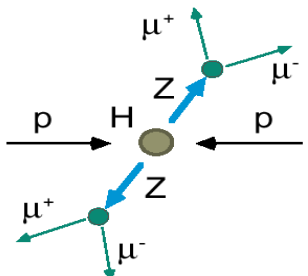
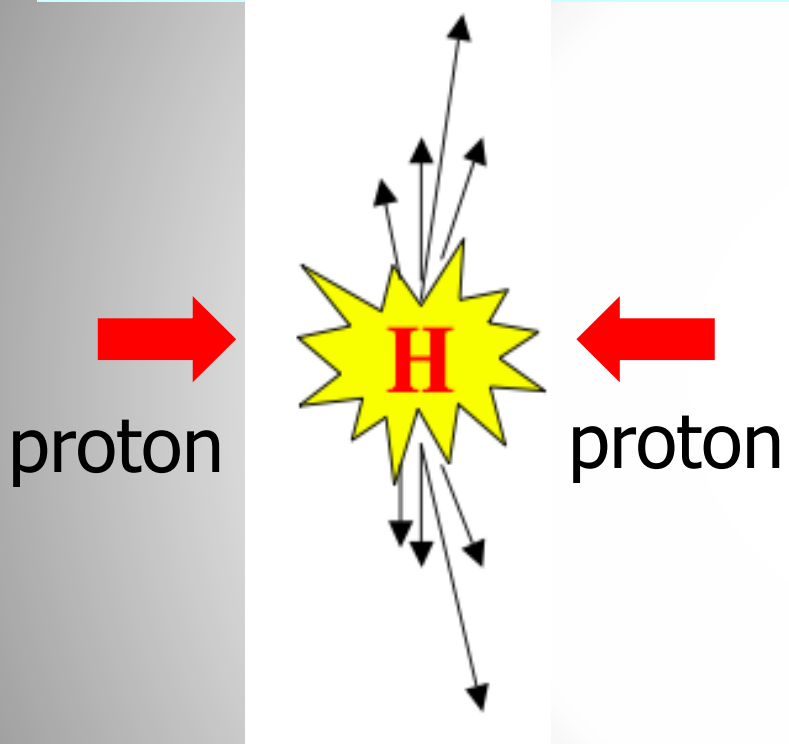
~ 765 publications on pp (and pPb/PbPb) physics since 1/2010

About 90 papers on Higgs studies!!  
Paper 16 was the discovery paper!



# 2012: A Milestone in Particle Physics

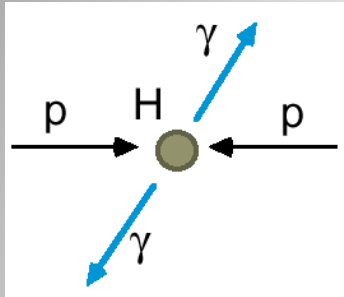
Observation of a **Higgs** Particle at the LHC, after about 40 years of experimental searches to find it



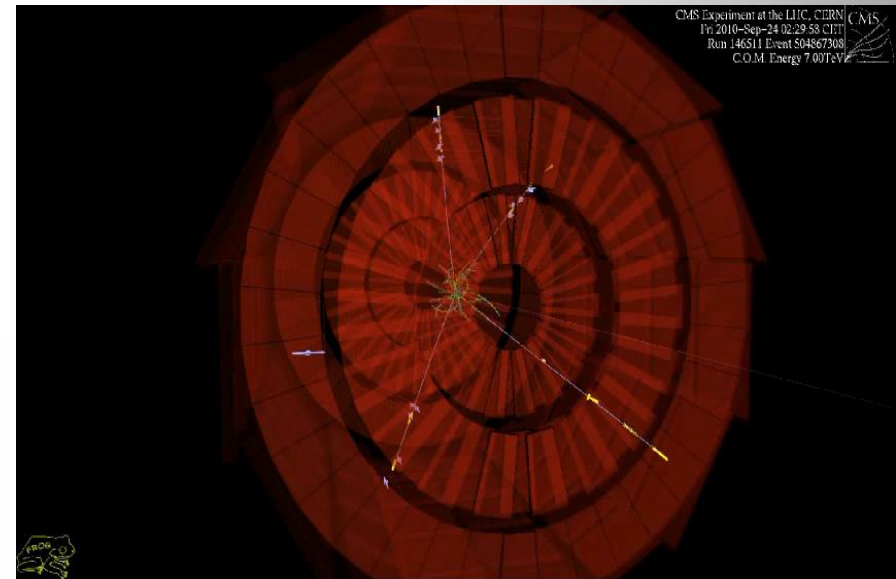
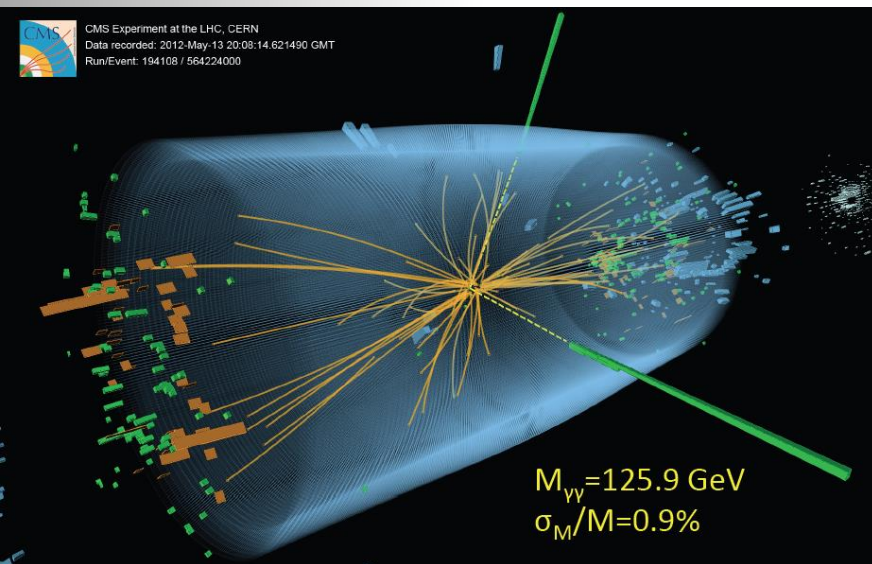
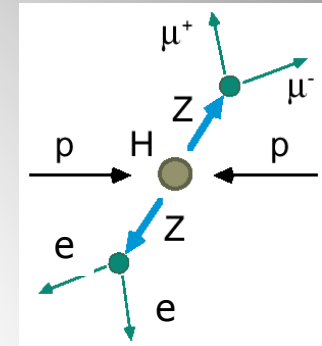
2013

The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

# Collisions with a Higgs Candidate

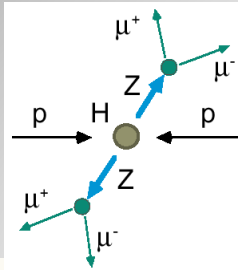


A Higgs or a 'background' process without a Higgs?

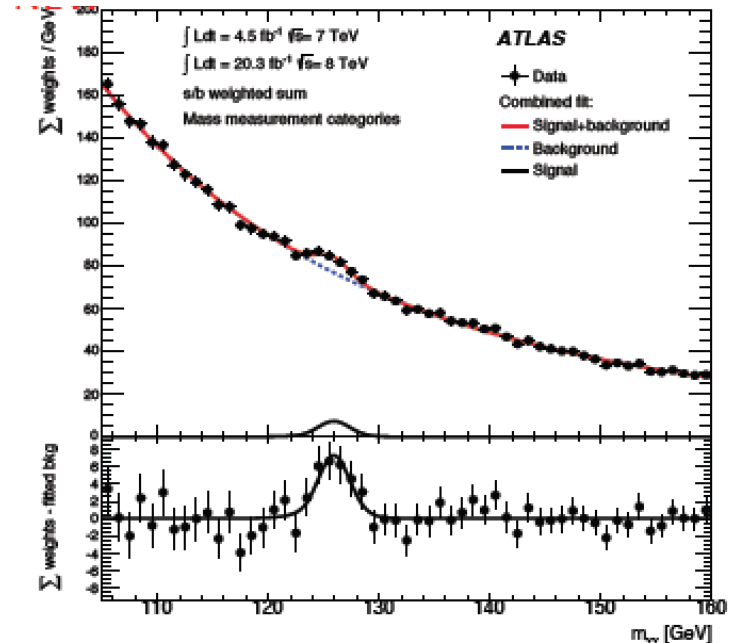
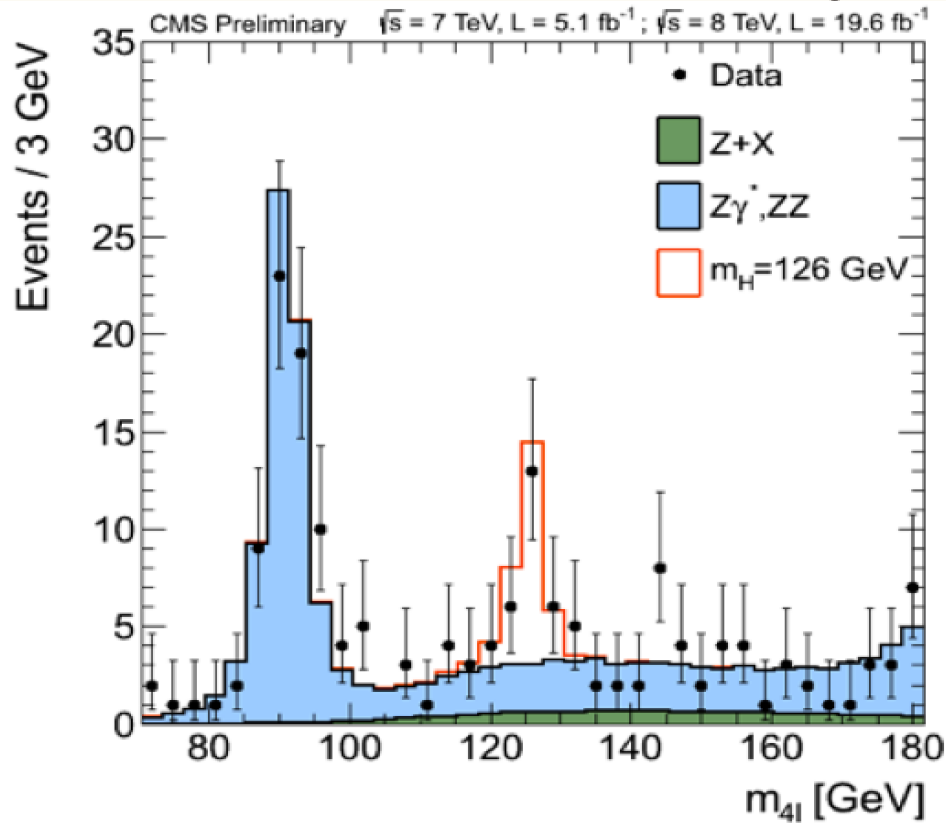
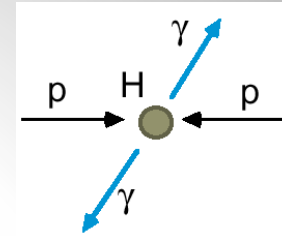


The Higgs is the new playground: **Room for new experimental/theoretical ideas!!**  
We have ~1 Million Higgses produced at the LHC, but use less than 1 per mille

# Higgs $\rightarrow$ ZZ and $\gamma\gamma$



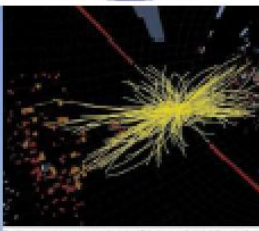
Discovery Channels!





Discovery upends world of physics

3000 years of physics... discovery upends world of physics



July 4<sup>th</sup> 2012
The discovery of a new particle

Physicists Find Elusive Particle Seen as Key to Universe
Discovery upends world of physics



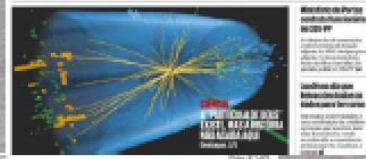
The Economist
A giant leap for science
Finding the Higgs boson



新発見粒子検出 年内に結論
ビッグス粒子発見か

ビッグス粒子発見か
年内に結論

Milhares de moradores de bairros sociais em risco de perderem RSI
Science: la matière dévoilée



MK
ПОСЛЕДНИЙ КИРПИЧ В СТЕНУ МИРОЗДАНИЯ
КРЕМЛЕВСКИЕ САМОЛЕТЫ ПРИШЛОСЬ МЕНЯТЬ НА ПЕРЕПРАВЕ
МЕТРО СПУСКАЕТ НА ВОДУ

AD ALGEMEEN DAGBLAD
EENDELIJK GELIJK NA 48 JAAR

Frankfurter Allgemeine
Major world's...
Große Mehrheit...

The Gazette
EL PAIS
EL PERIÓDICO GLOBAL EN ESPAÑOL

CHINADAILY
THE TIMES OF INDIA
Big bang moment: Scientists may have found 'God particle'

THE HINDU
Elusive particle found, looks like Higgs boson
Discovery upends world of physics

CORRIERE DELLA SERA
La particella che può svelare i segreti dell'universo
Nomine Rai bloccate Scontro Fini Schifani

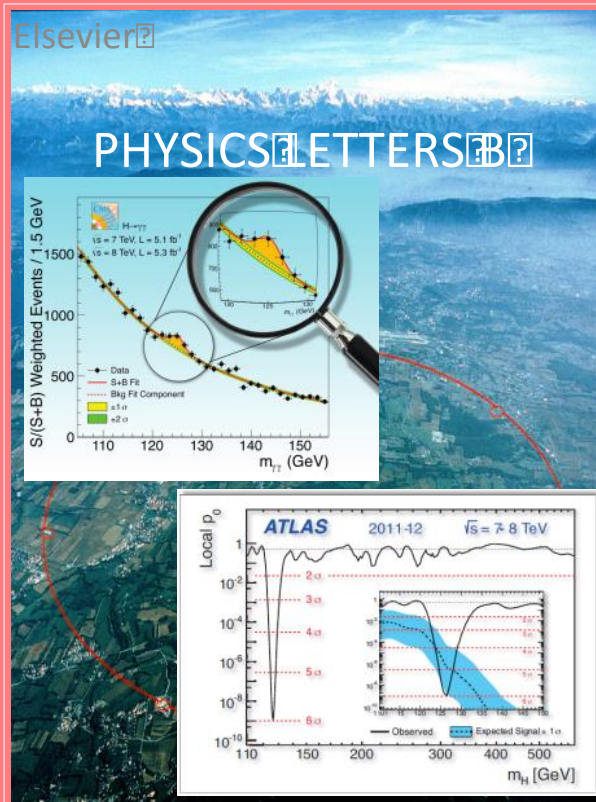
gazeta
BOSKA MASA
Człowiek Higgsa może napisać wypracunki, zanim skończy 40 lat

বিশ্বজ্ঞানের 'ঈশ্বর' দর্শন
আনন্দবাজার পত্রিকা
সত্যোন্মেষণ বিনয় প্রণা

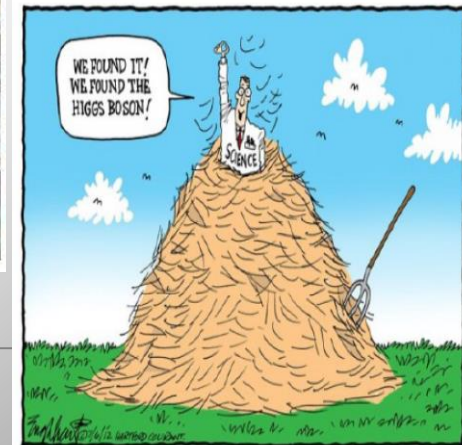
# Most cited paper so far...

Special Physics Letters B edition  
with the ATLAS and CMS  
papers on the **Higgs Discovery**

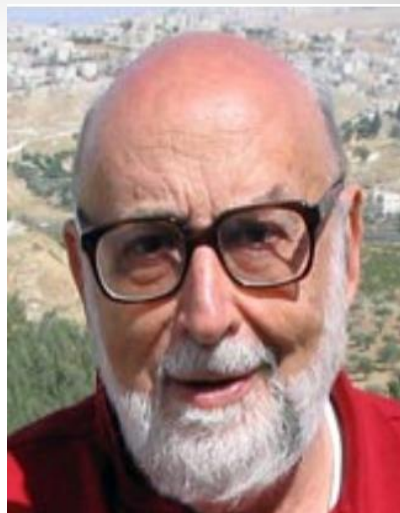
Also...



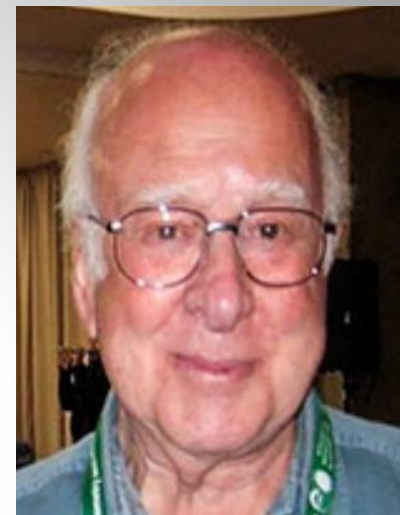
Cited about 8400 times  
so far...



# Tuesday 8 October 2013

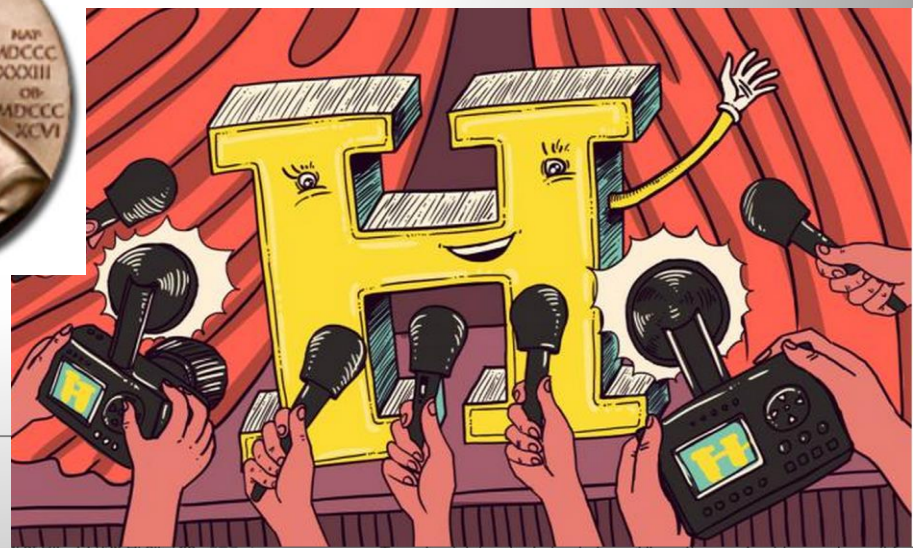


Francois Englert



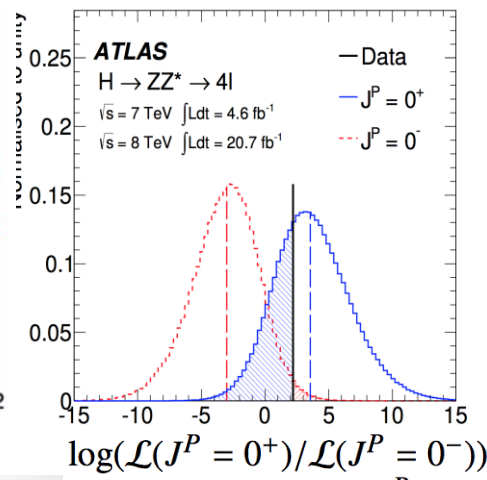
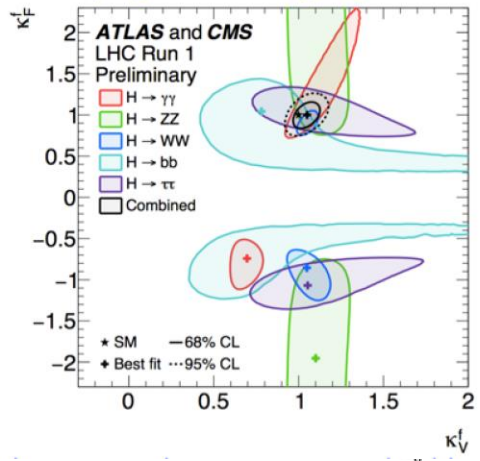
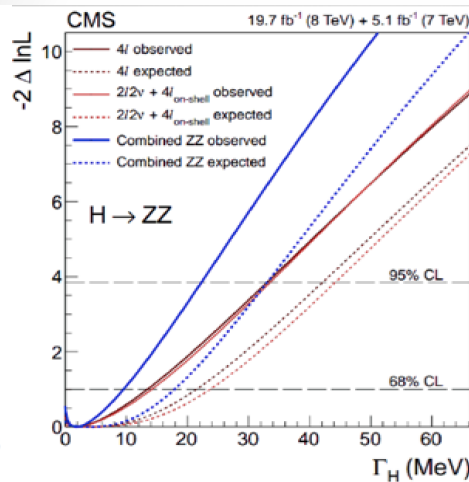
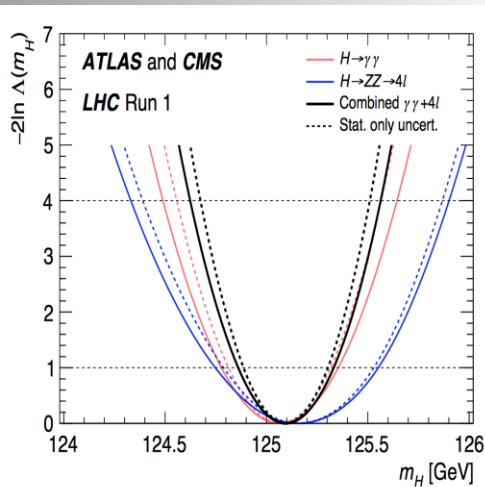
Peter Higgs

**Congratulations!!!!**



# Brief Higgs Summary

We know already a lot on this Brand New Higgs Particle!!



**Mass = CMS+ATLAS**  
125.09 ± 0.21(stat)  
± 0.11(syst) GeV

**Width**  
< 24 MeV  
(95%CL)

**Couplings are**  
within ~20% of  
the SM values

**Spin =**  
0<sup>+(+)</sup> preferred  
over 0<sup>-</sup>, 1, 2

SM-like behaviour for most properties, but continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production...



# Physics Beyond the Standard Model?

Important SM parameter → stability of EW vacuum

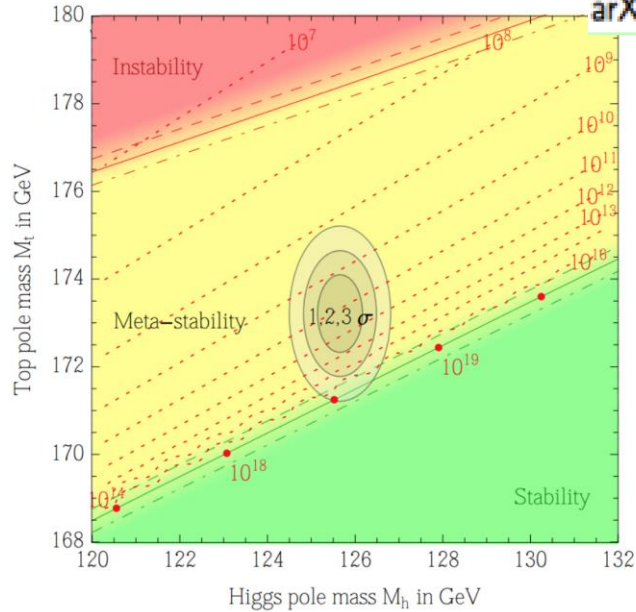
arXiv:1205.6497



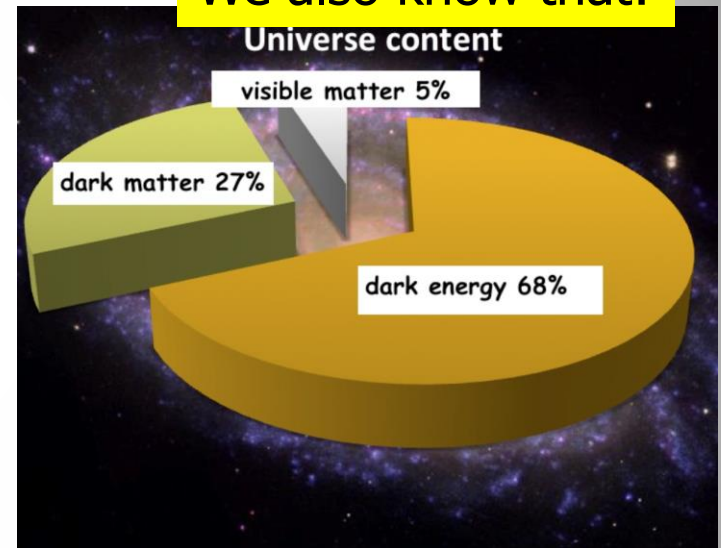
A Higgs at 125 GeV

Precise measurements of the top quark and the Higgs mass

arXiv:1403.6535

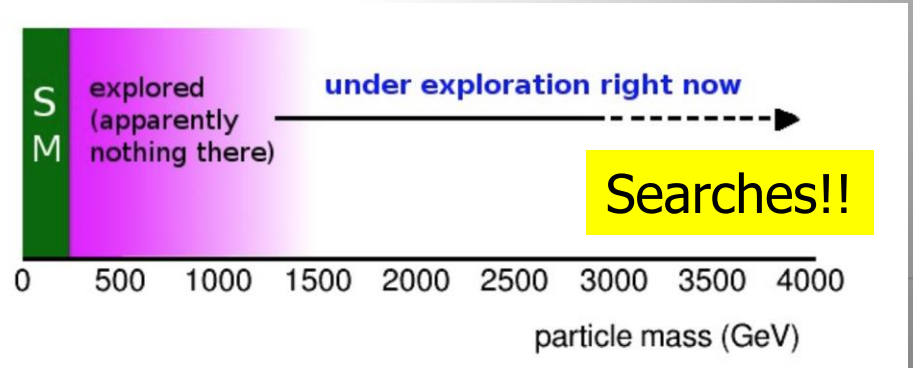


We also know that:



New Physics inevitable?  
 But at which scale/energy?

But Where Is Everybody?  
 N. Arkani-Hamed



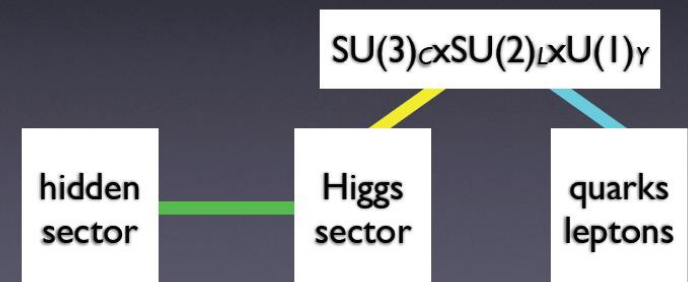
# The Future: Studying the Higgs...



- More LHC Data 2015-2023
- LHC upgrade ! 2026-2036
- Experiment upgrades!!
- (Other/new machines?)

## Higgs as a portal

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

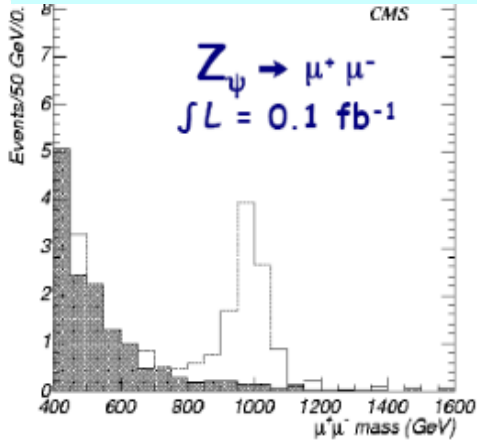


Many questions are still unanswered:

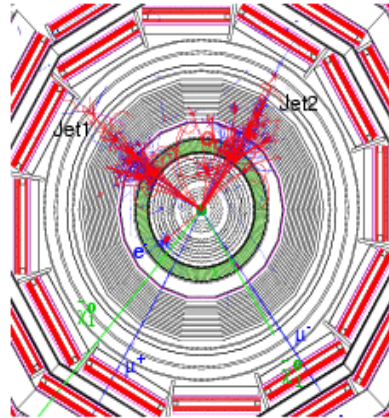
- What explain a Higgs mass  $\sim 125$  GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤

# New Physics?

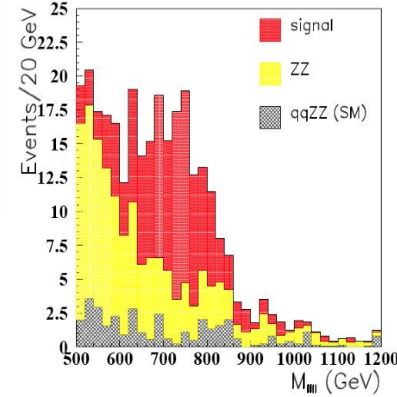
## New Gauge Bosons?



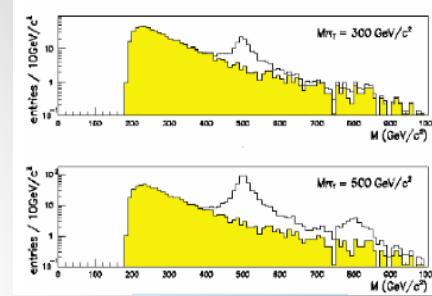
## Supersymmetry



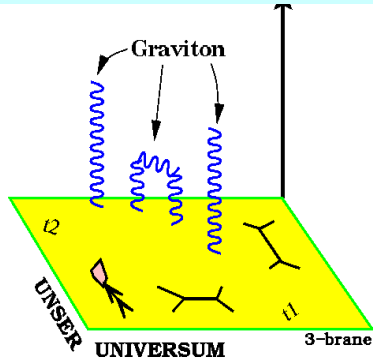
## ZZ/WW resonances?



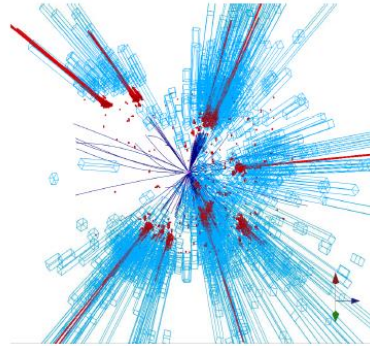
## Technicolor?



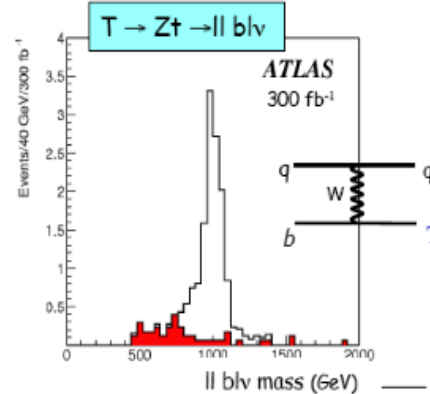
## Extra Dimensions?



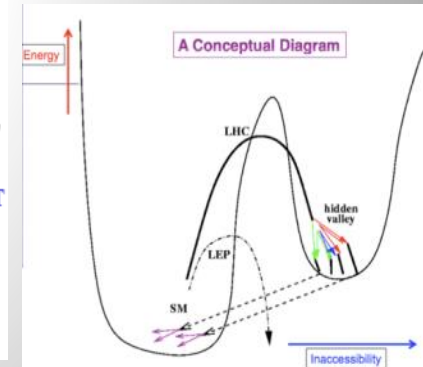
## Black Holes???



## Little Higgs?



## Hidden Valleys?



What stabilizes the Higgs Mass? Many ideas, not all viable any more  
 A large variety of possible signals. We have to be ready for that

# Next Questions...

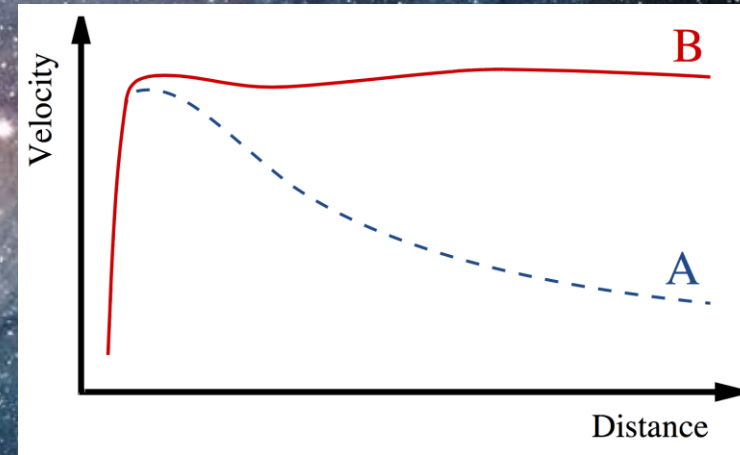
**Dark Matter at the LHC?**

**Are we Supersymmetric?**

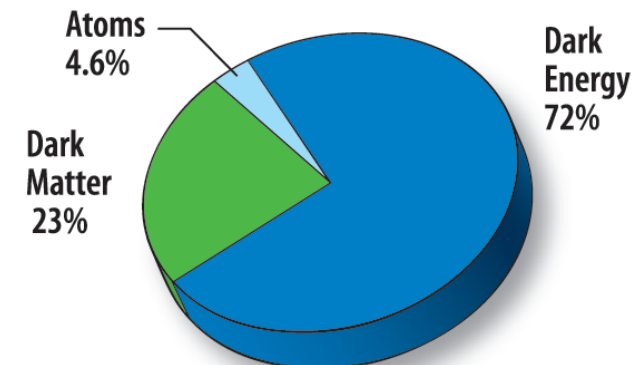
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# Dark Matter in the Universe

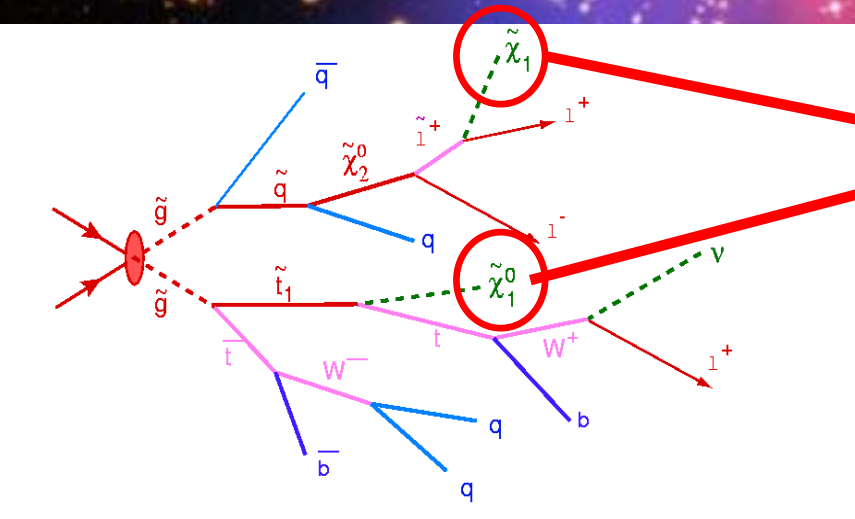
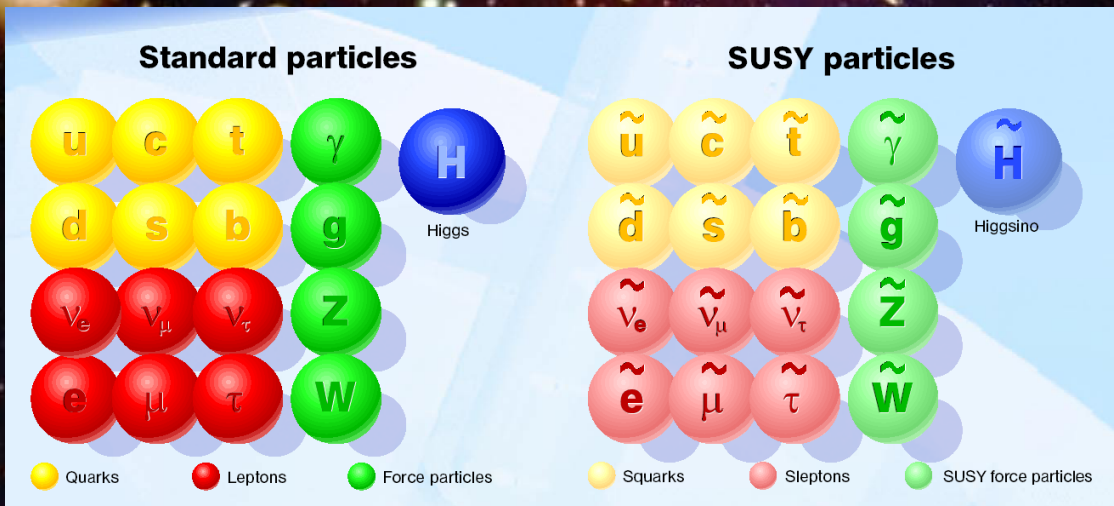
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



**'Supersymmetric' particles ?**



# Supersymmetry: a new symmetry in Nature?



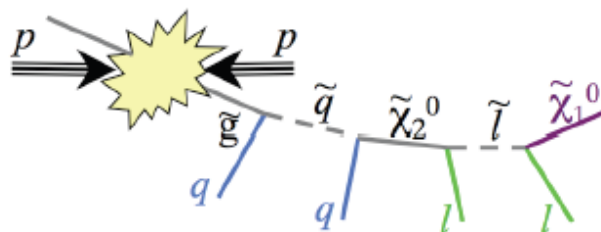
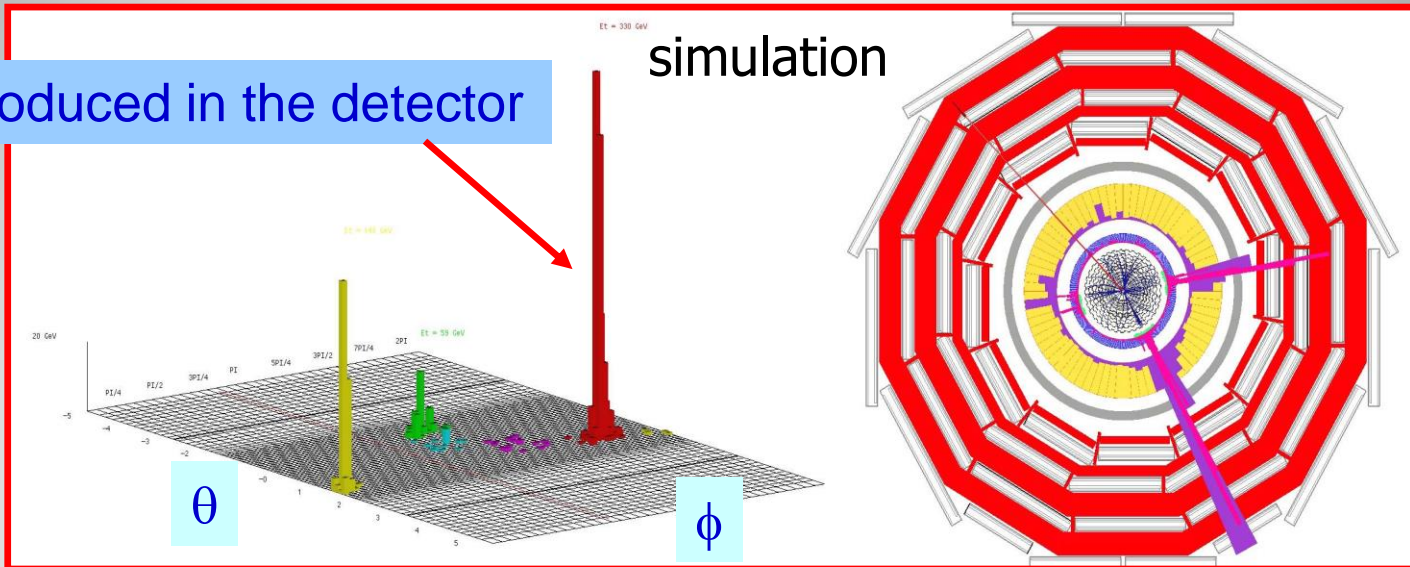
Candidate particles for Dark Matter  
 $\Rightarrow$  Produce Dark Matter in the lab

SUSY particle production at the LHC

Picture from Marusa Bradac

# Detecting Supersymmetric Particles

Energy produced in the detector

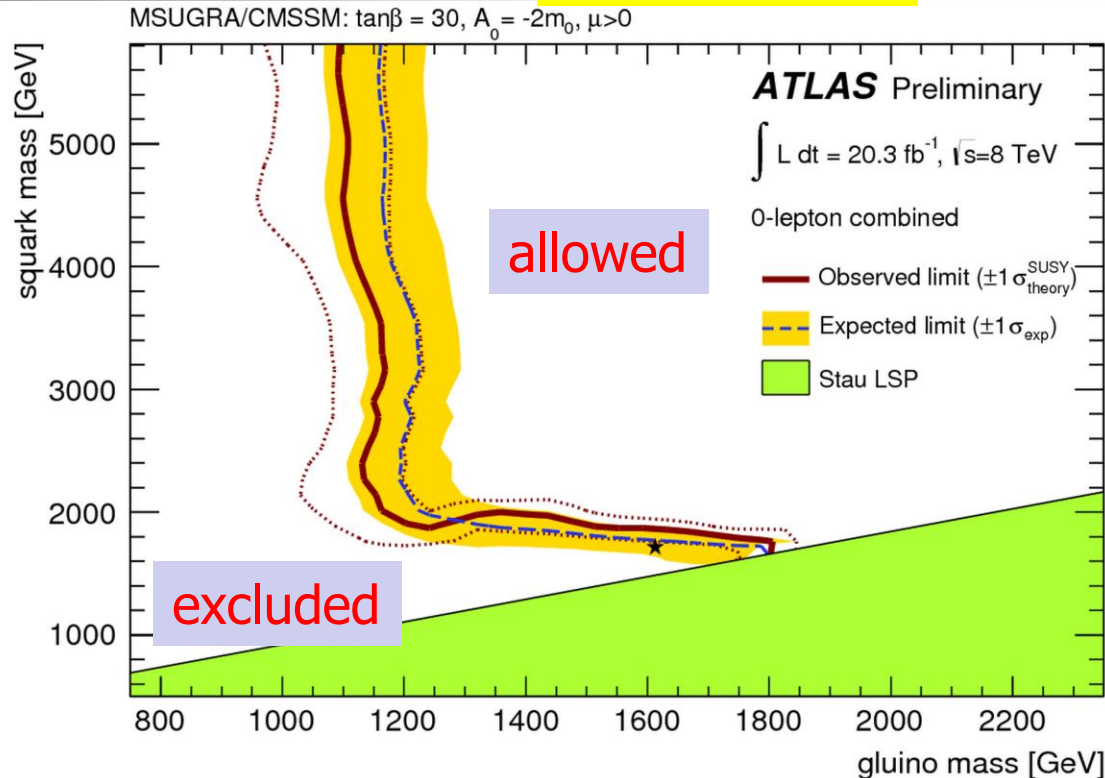


Supersymmetric particles decay and produce a cascade of jets, leptons and missing transverse energy (MET) due to escaping 'dark matter' particle candidates

 Very prominent signatures in CMS and ATLAS

# SUSY Searches: No signal yet to date...

## Status in 2013



- So far **NO** clear signal of supersymmetric particles has been found

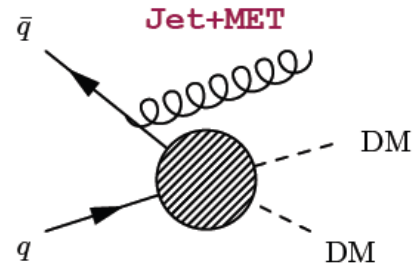
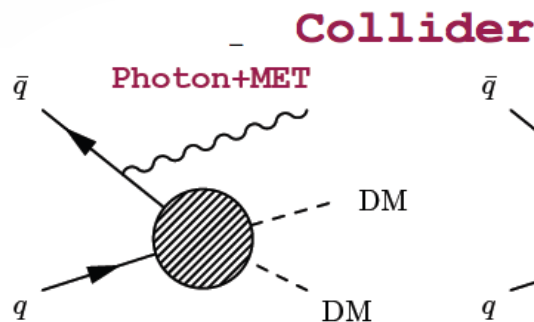
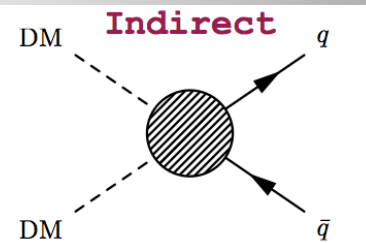
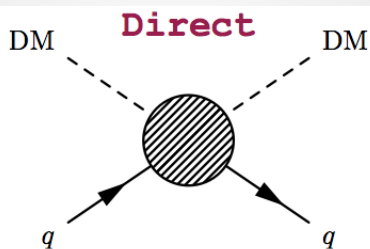
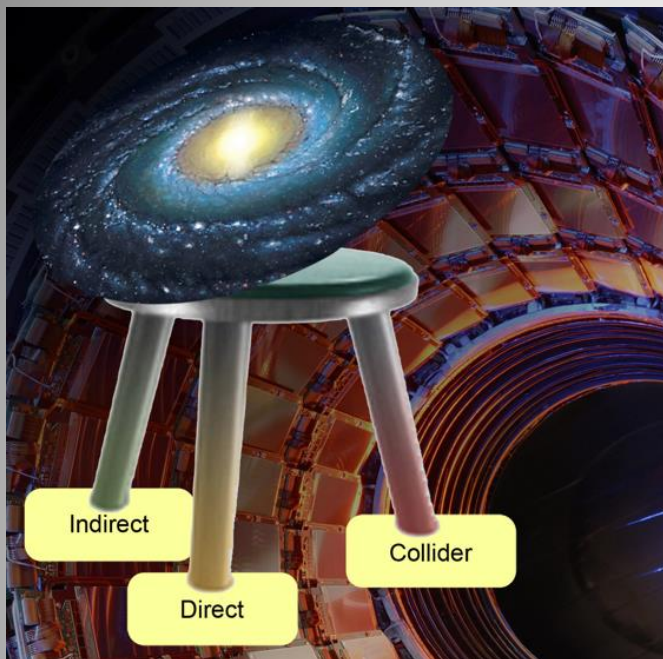
- We can exclude regions where the new particles could exist.

- Searches will continue for the **higher energy in 2016**

Plenty of searches ongoing: with jets, leptons, photons, W/Z, top, Higgs, with and without large missing transverse energy  
Also special searches for contrived model regions



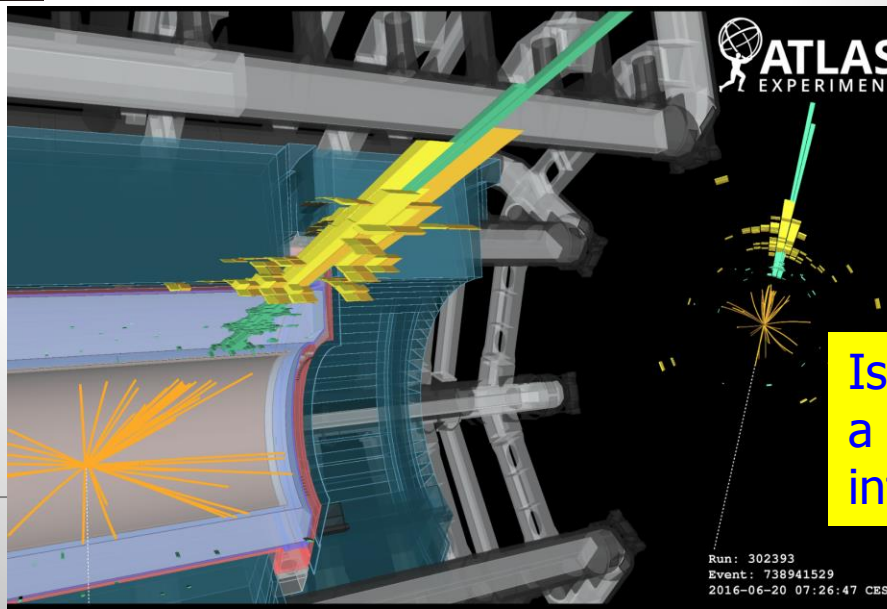
# Dark Matter Searches at the LHC



• Identifying Dark Matter is one of the most important questions in physics today!

• It is likely a new as yet undetected particle

• Can it be produced at the LHC?



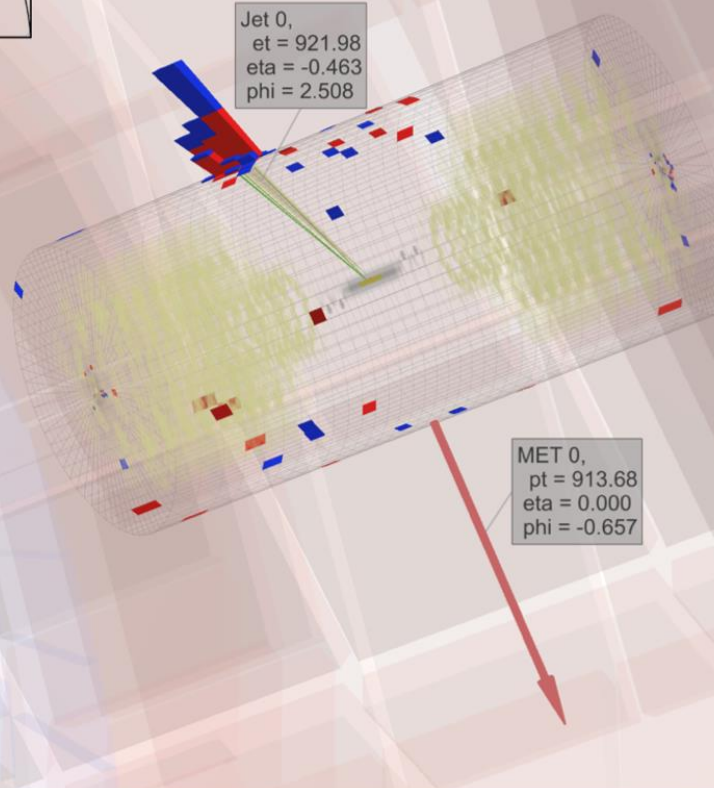
Mono-photon and mono-jet searches

Is Dark Matter a new weakly interacting particle?

# Mono-Jet Event



CMS Experiment at LHC, CERN  
Data recorded: Fri Oct 5 20:41:32 2012 CEST  
Run/Event: 204553 / 26729384  
Lumi section: 31

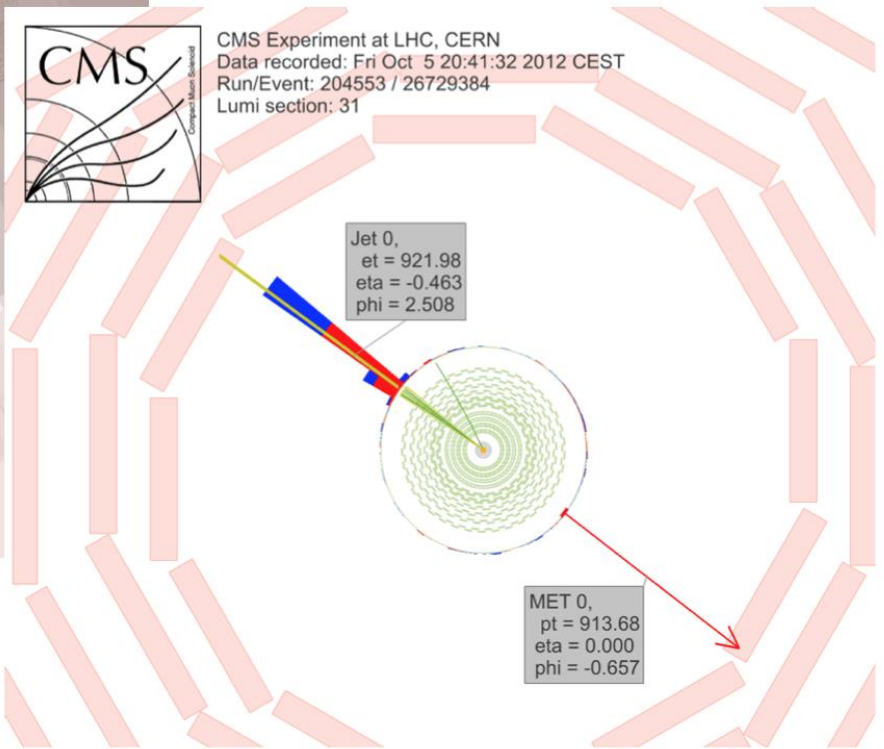


Jet 0,  
et = 921.98  
eta = -0.463  
phi = 2.508

MET 0,  
pt = 913.68  
eta = 0.000  
phi = -0.657



CMS Experiment at LHC, CERN  
Data recorded: Fri Oct 5 20:41:32 2012 CEST  
Run/Event: 204553 / 26729384  
Lumi section: 31



Jet 0,  
et = 921.98  
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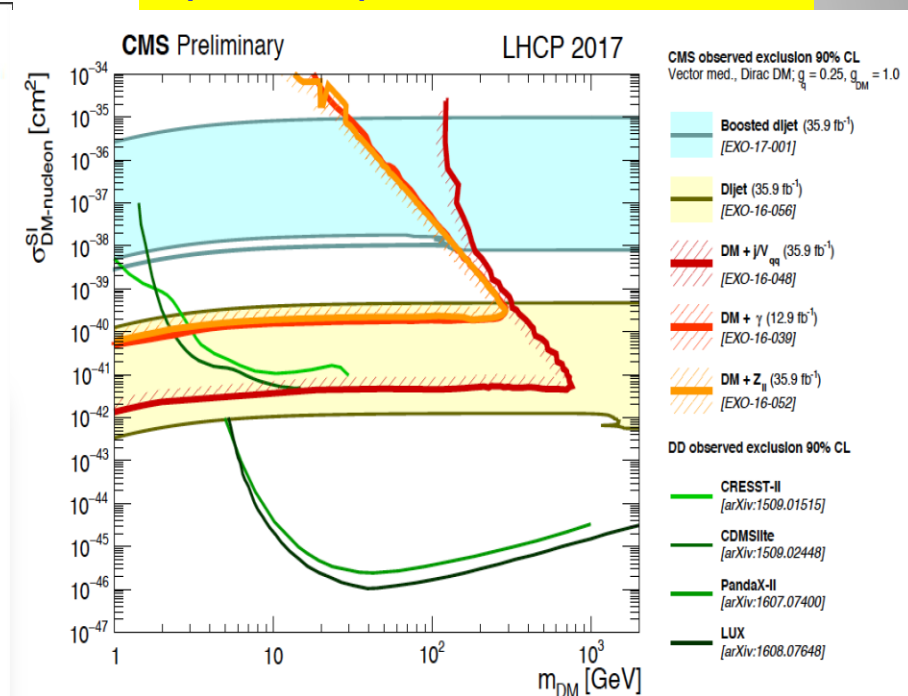
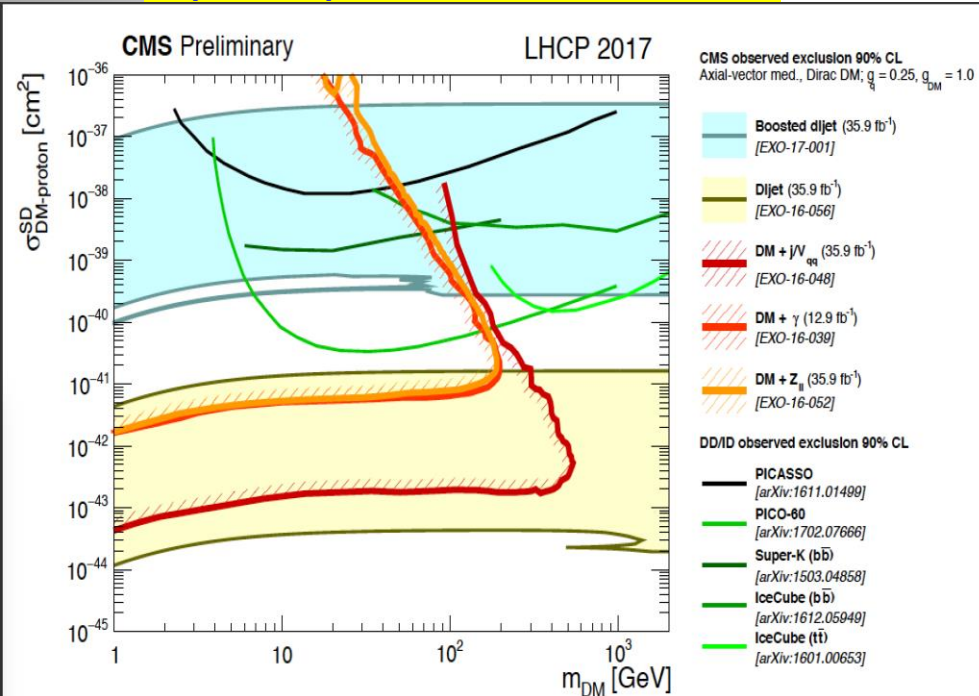
Mono-jet events observed  
But also Standard Model  
can produce these with  
escaping neutrinos

# Comparison with Direct Detection

No signal seen in any of the "mono"-signals so far -> limits  
 Comparison with direct detection (underground) experiments

Axial-vector mediator and  
 Spin-dependent direct limits

Vector mediator and  
 Spin-independent direct limits

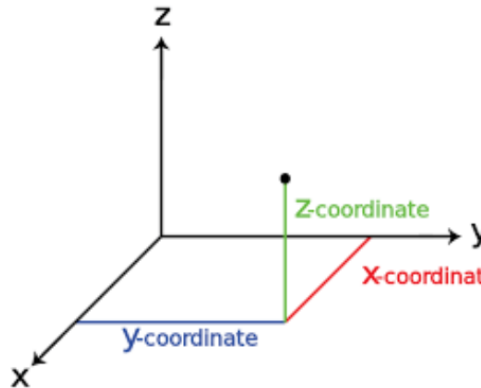


Mono-jet/V searches are typically the most sensitive ones

90% CL limits

# New Questions...

**Does space have more than 3 space dimensions?**



**Do Micro Black Holes exist?**

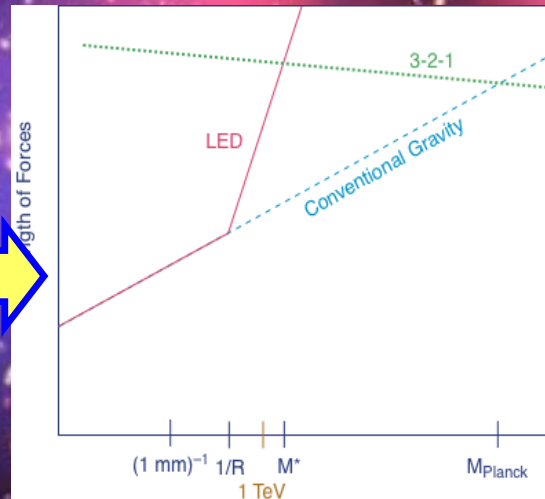
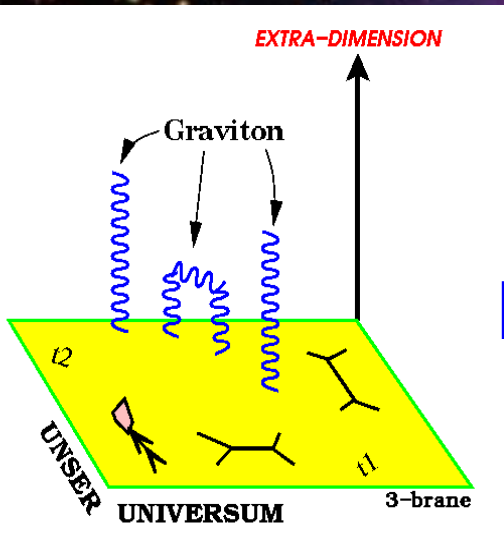
# Extra Space Dimensions

Problem:

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



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



The Gravitational force becomes strong!

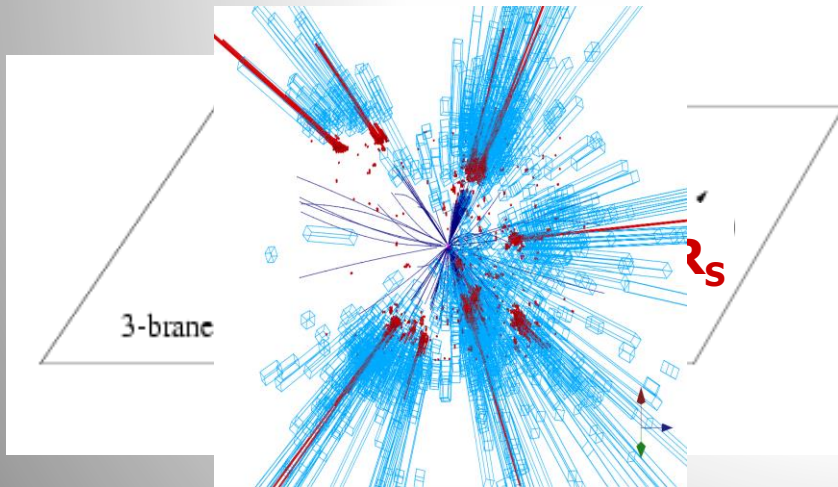
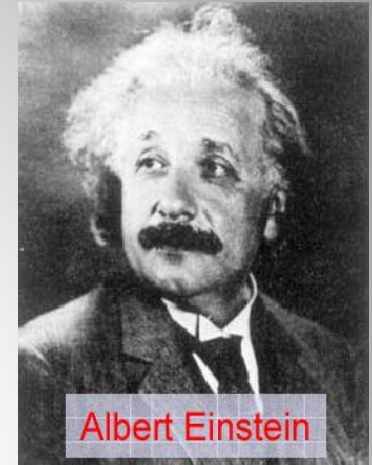
New Planck scale is larger than 3 TeV

# Quantum Black Holes at the LHC?

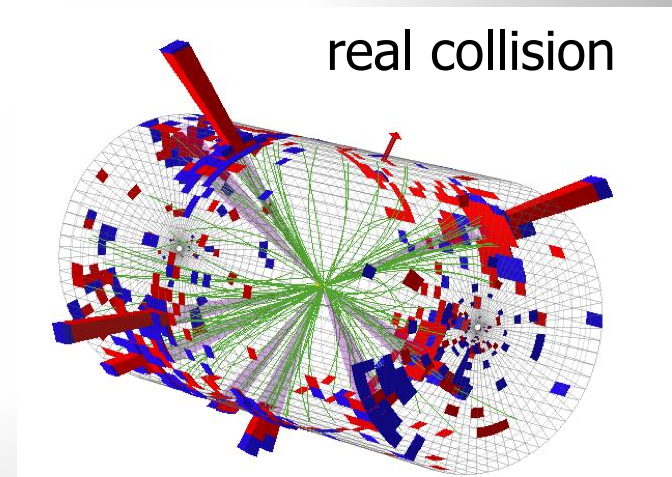
Black Holes are a direct prediction of Einstein's general theory on relativity

If the Planck scale is in  $\sim$ TeV region:  
can expect Quantum Black Hole production

Quantum Black Holes are harmless for the environment: they will decay within less than  $10^{-27}$  seconds  $\Rightarrow$  SAFE!



Simulation of a Quantum Black Hole event

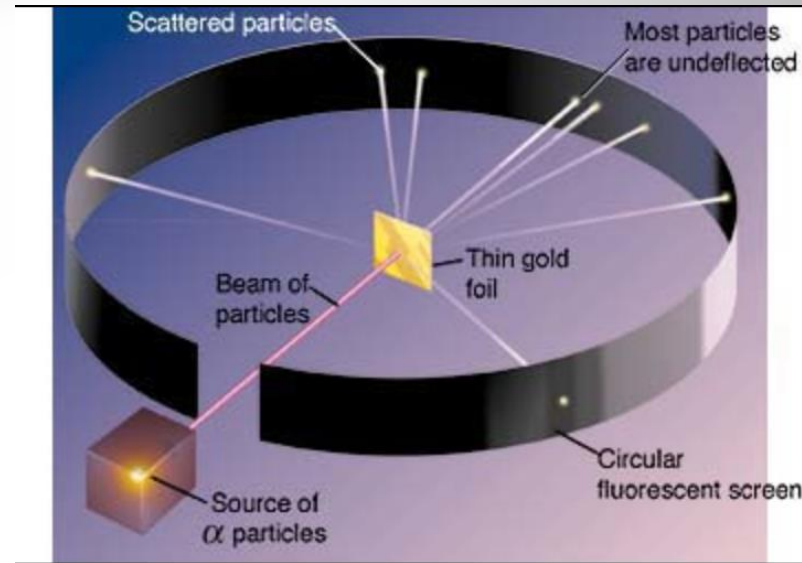


Black holes with mass  
Below 10 TeV are excluded

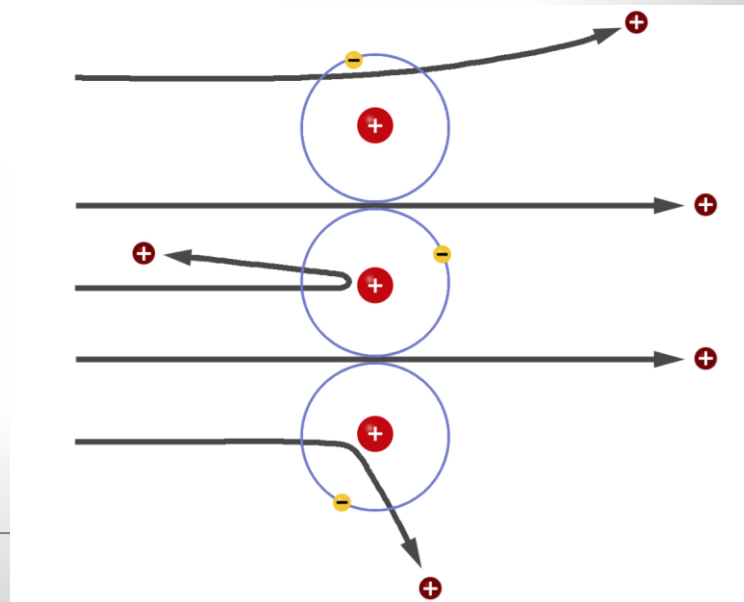
# Black Holes Hunters at the LHC...



# Are Quarks Elementary Particles?

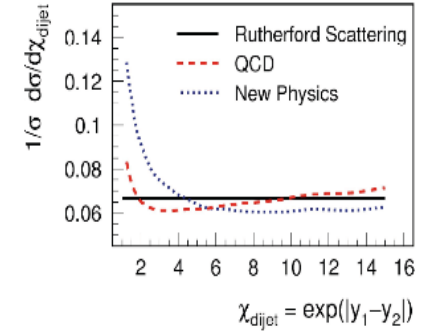
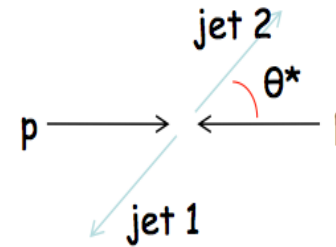
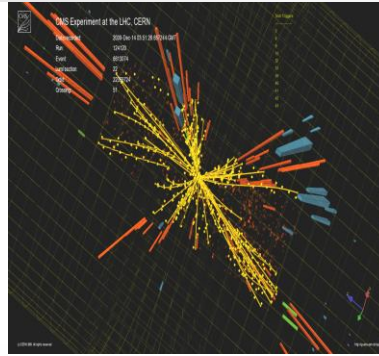
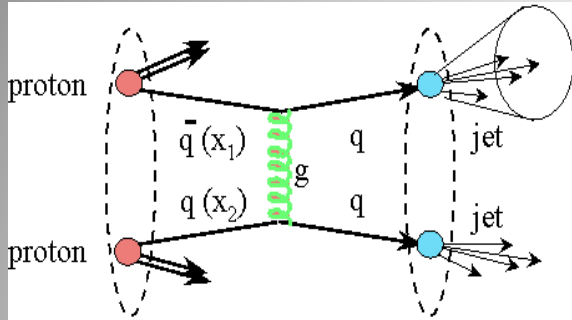


Rutherford experiment:  
Unexpected backscattering  
of  $\alpha$ -particles:  
Evidence for the structure  
of atoms !! (1911)

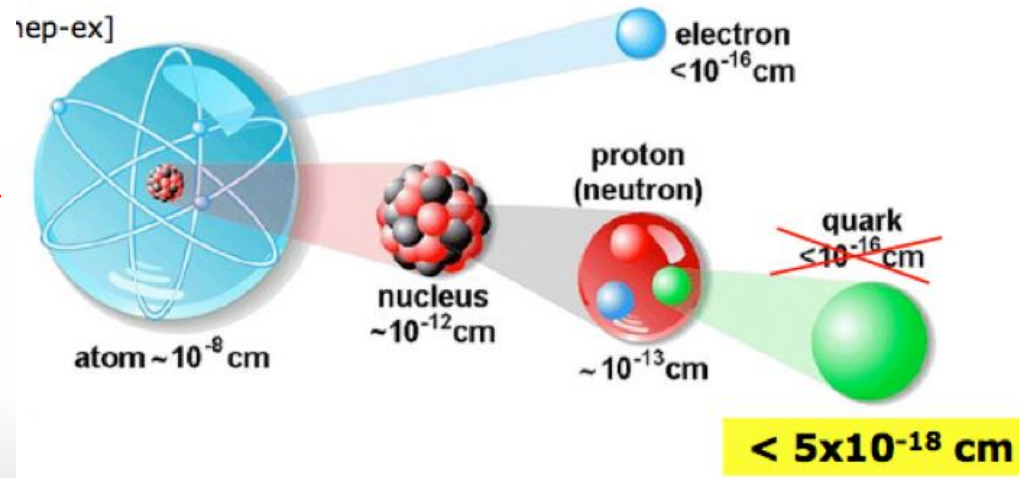
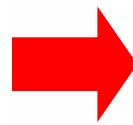
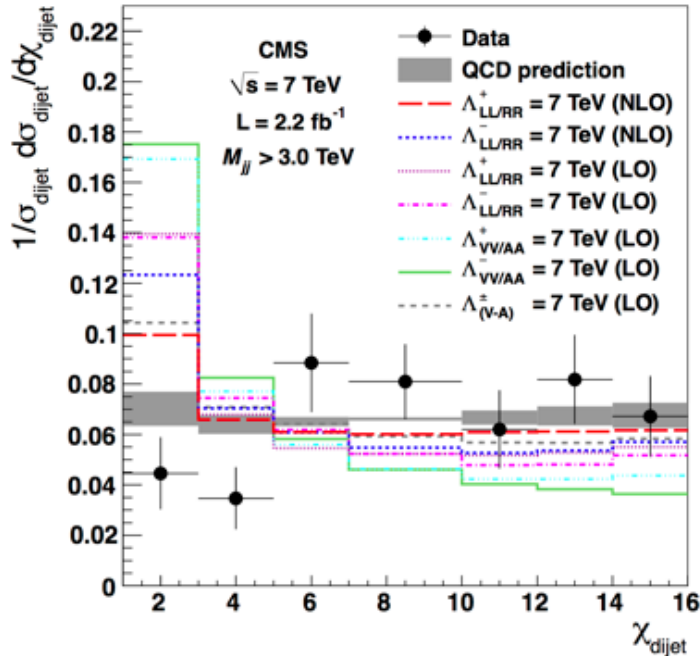




# Are Quarks Elementary Particles?



Measurement of the production angle of the jet with respect to the beam  
 -> High Energy Rutherford Experiment



Quarks remain elementary particles after these first results

# The Physics Program at LHC

**Data taking started in 2010**

**Now we have about 750 reviewed scientific papers per experiment!**

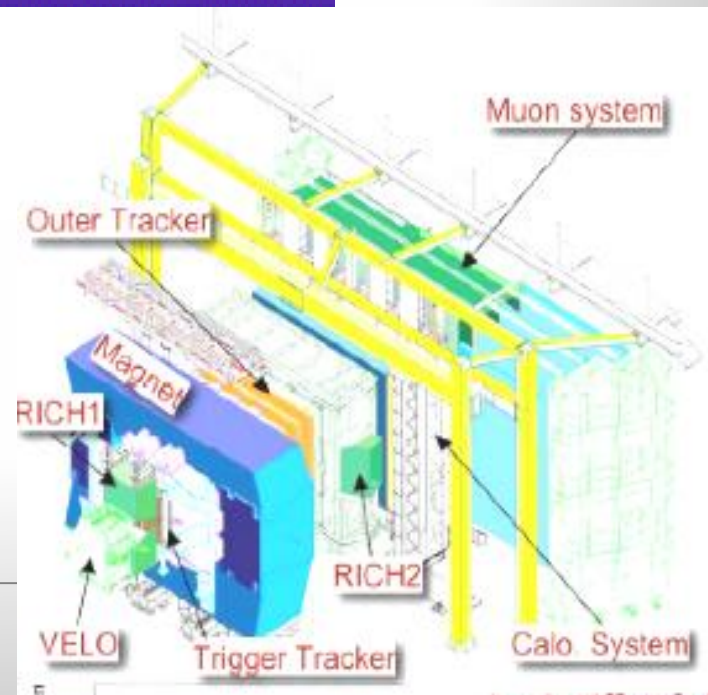
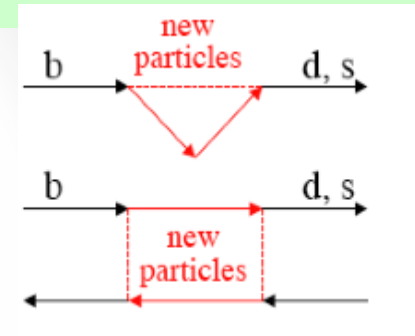
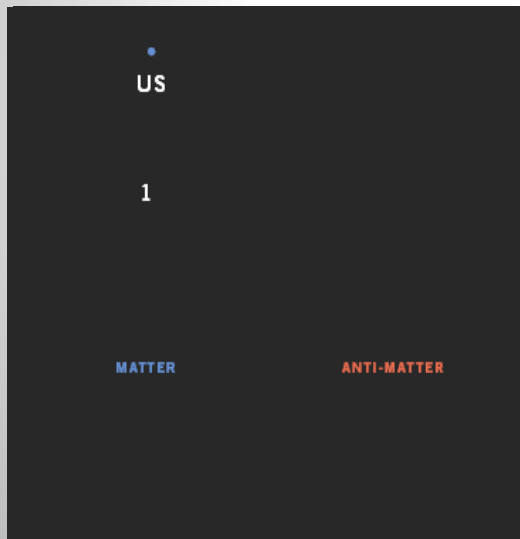
**Mostly measurements of the strong and electroweak force at 7/8/13 TeV and Searches**

- |  |                   |
|--|-------------------|
| <b>-Are quarks the elementary particles?</b> | <b>So far yes</b> |
| <b>-Do we see supersymmetric particles?</b>  | <b>Not yet</b>    |
| <b>-Do we see extra space dimensions?</b>    | <b>Not Yet</b>    |
| <b>-Do we see micro-black holes?</b>         | <b>No</b>         |

**->The Discovery of a Higgs-like particle!!**

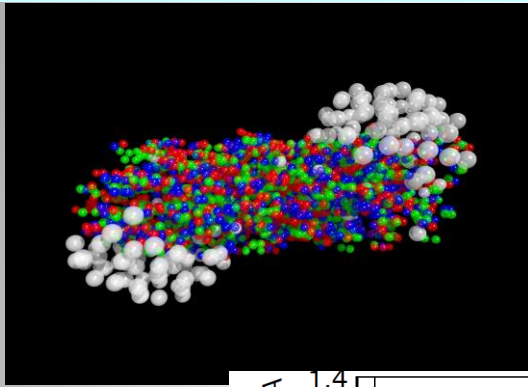
# Matter-Antimatter

The properties and subtle differences of matter and anti-matter using mesons containing the beauty quark, will be studied further in the **LHCb experiment**



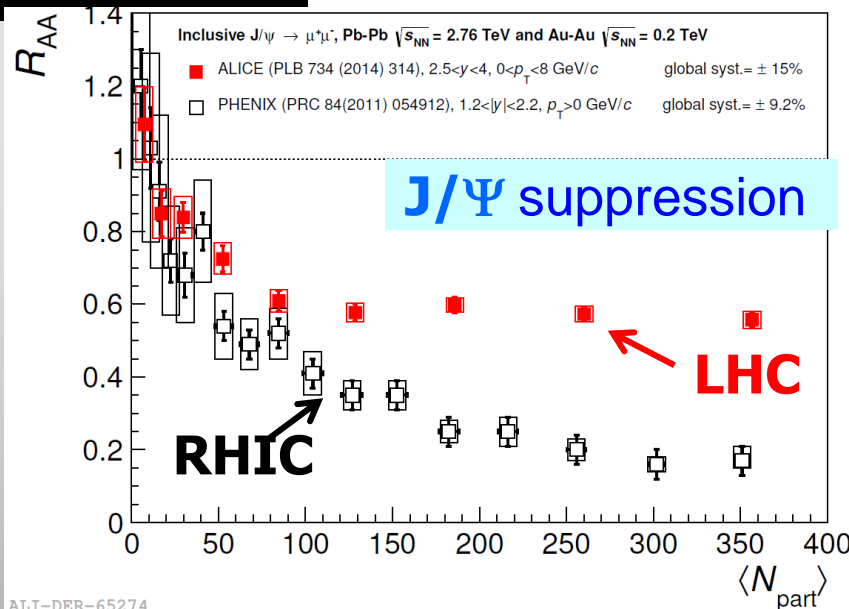
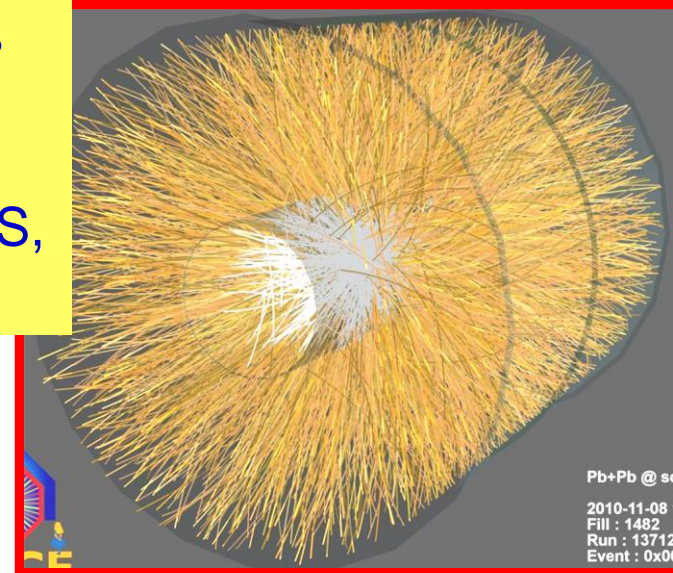
# Heavy Ions in the Alice Experiment

Lead-lead collisions at the LHC to study the primordial plasma, a state of matter in the early moments of the Universe



Hundreds of particles  
in the detector

Also studies with CMS,  
ATLAS and LHCb

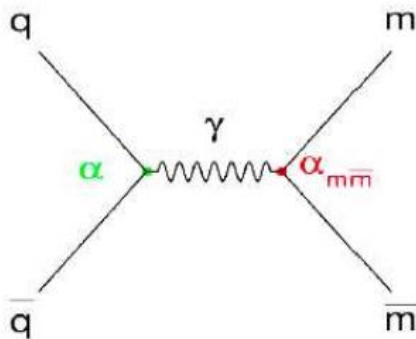


ALI-DER-65274

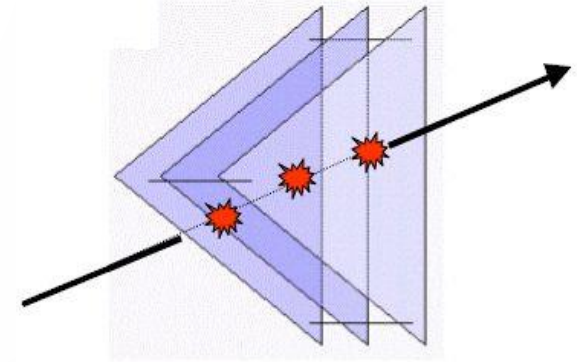
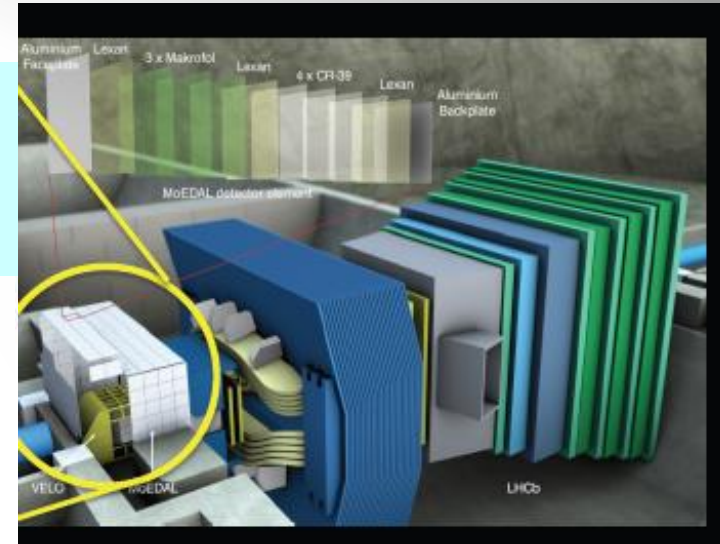
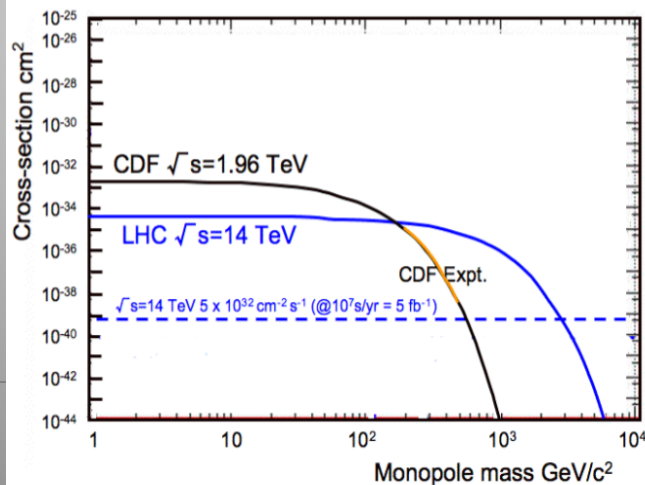
Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today

# MoEDAL: Monopole and Exotics Detector at the LHC

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



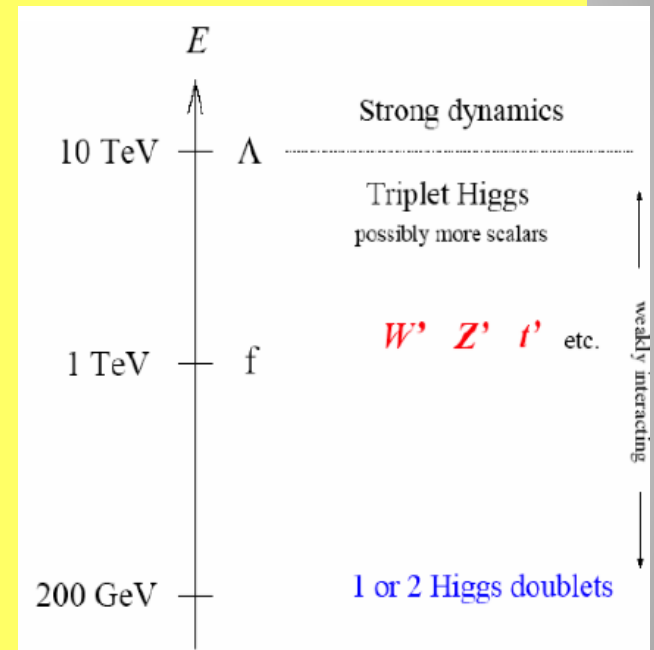
Direct Monopole production



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

# Many Other New Physics Ideas...

- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - Long lived particles
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Unparticles
  - Classicalons
  - Dark/Hidden sectors
  - Colored resonances
  - And more....



Have to keep our eyes open for all possibilities:  
Food for many PhD theses!! And Discoveries!!!

# Summary: The Searches at the LHC!

- The LHC has entered a new territory. The ATLAS and CMS experiments are heavily engaged in searches for New Physics. The most popular example is Supersymmetry, but many other New Physics model searches are covered.
- Physics Beyond the Standard Model has to be there. So far we exclude regions for a large number of models. New searches are starting with much more data at 13 TeV, that will be collected in the coming years (more than factor 10)
- More exotic channels are now being covered: Many as yet unexplored channels left to explore. Still a lot of opportunities for the discovery of new physics (and PhD theses)
- The LHC did its part so far with a great run in 2012. We found the Higgs!! LHC machine now is breaking records

And maybe one day soon:

