LHC Experiments: Status and plans

A Look at Recent Results and into the Future

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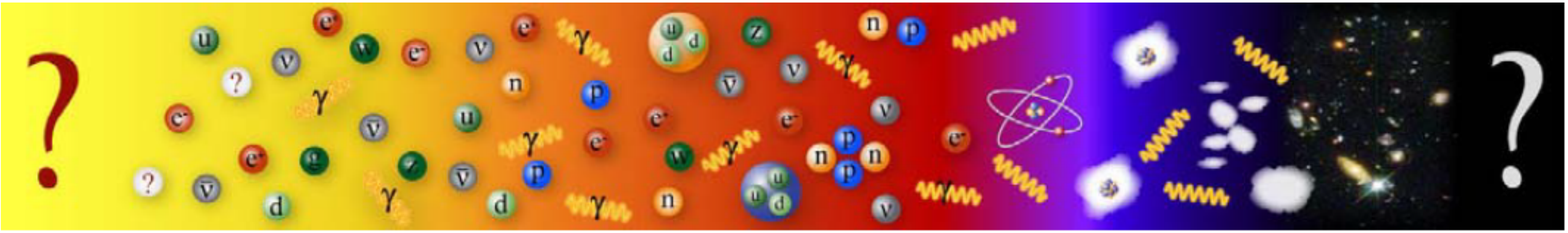
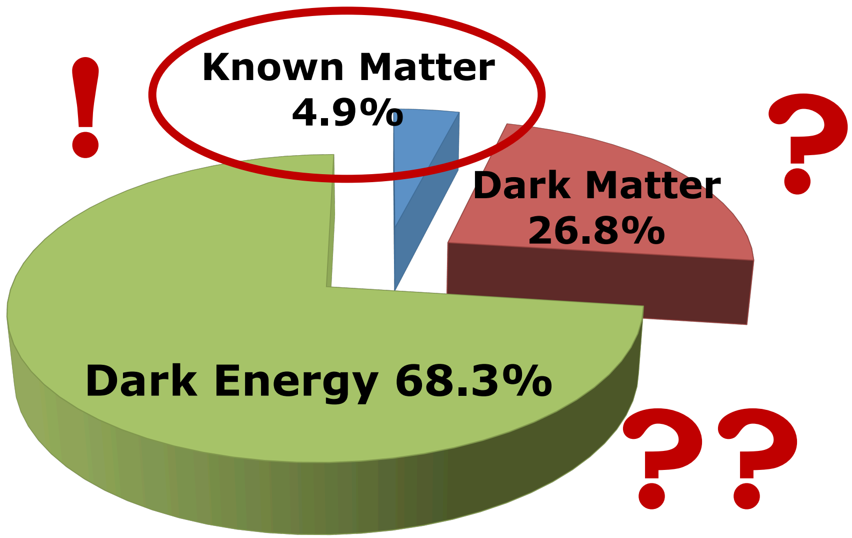
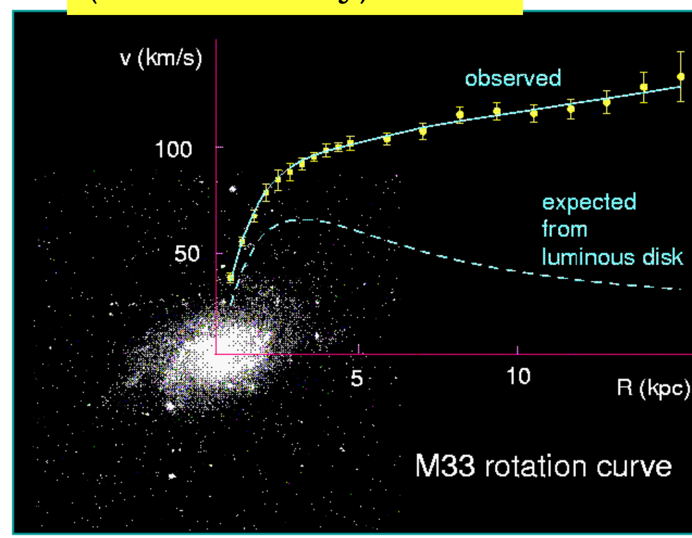
What is our Universe made of ?



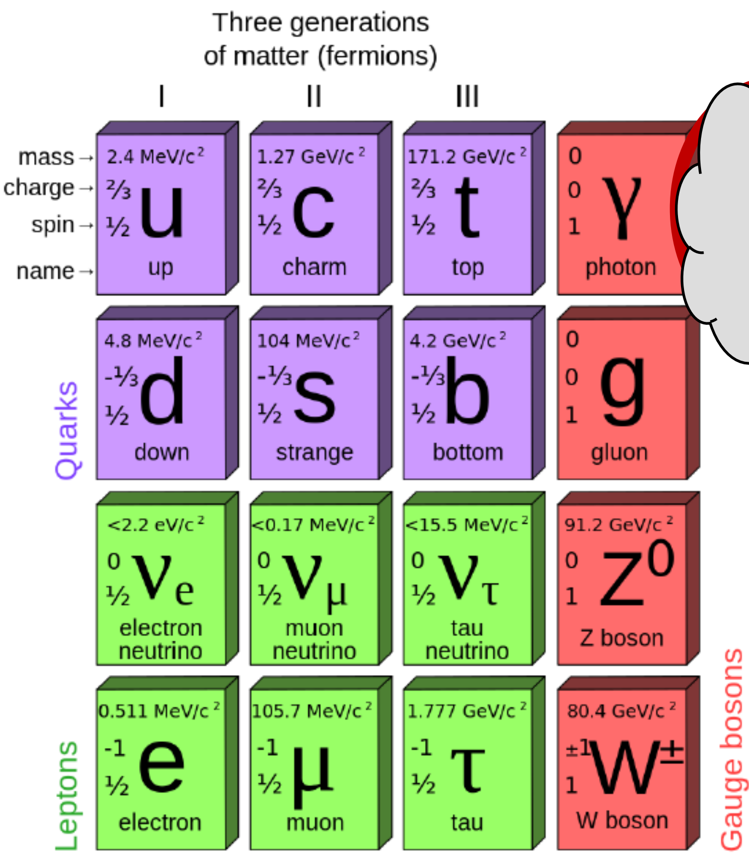


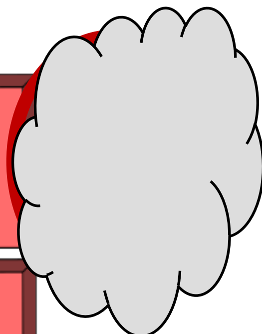
Galaxy rotation curves
(1933 – Zwicky)



Can we conclude from the familiar to the unknown ?
Are there deviations from predictions ?
Need highest precision to be able to find out!

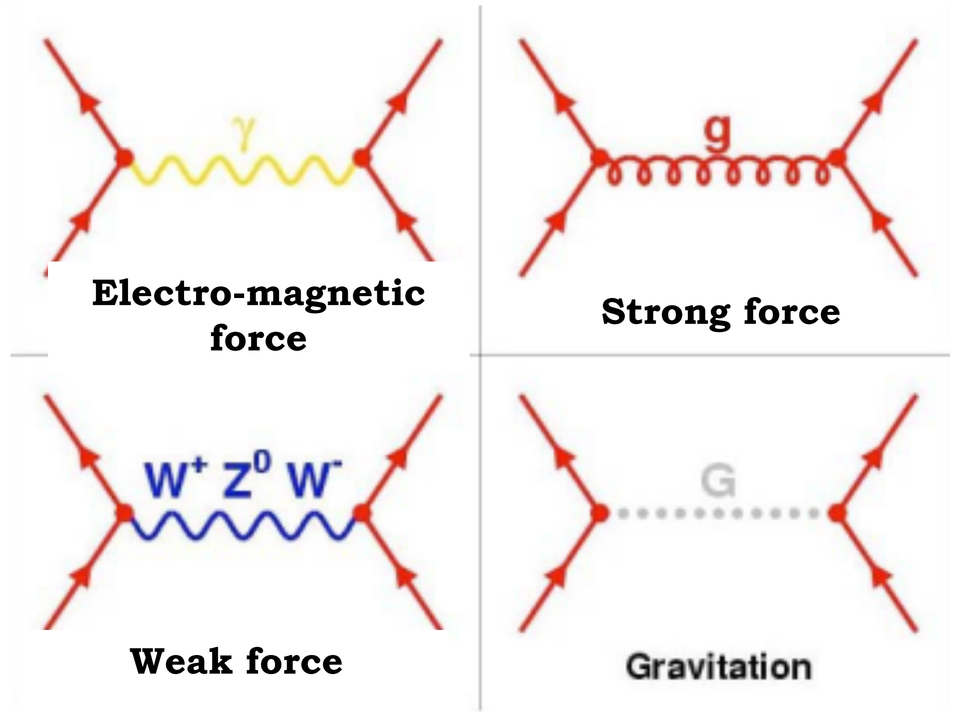
The Standard Model

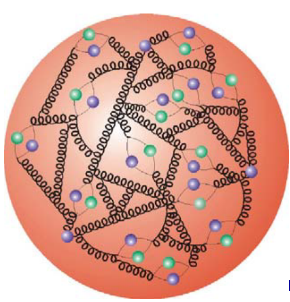




Four fundamental forces:

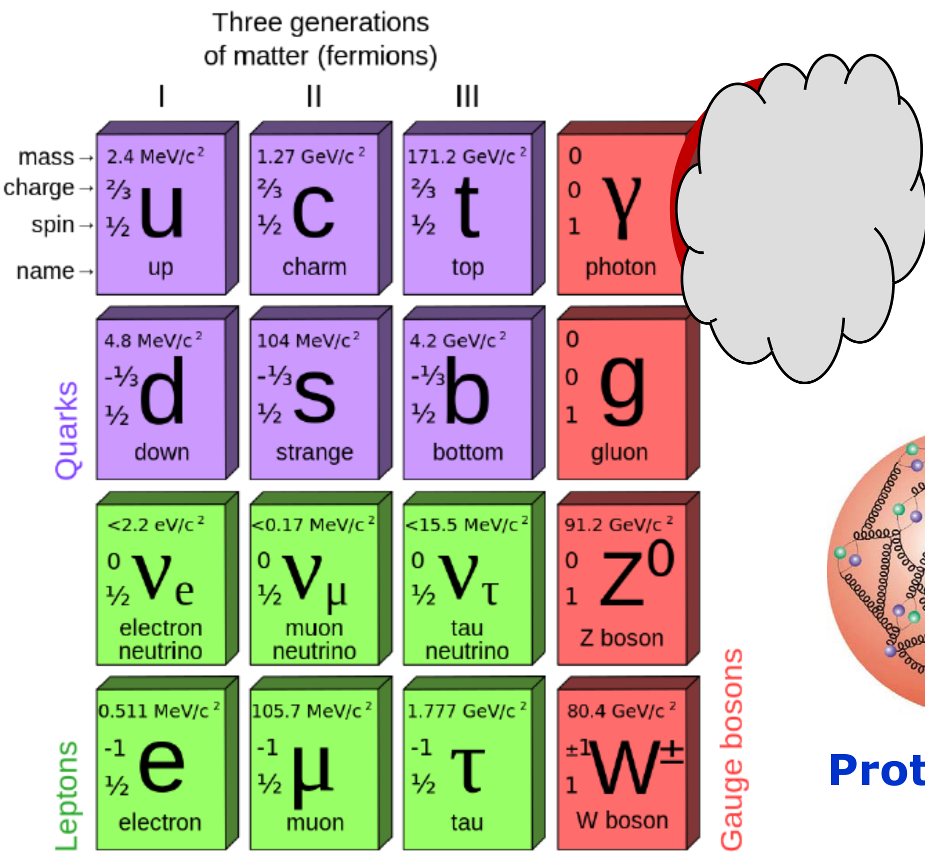
- Electro-magnetic force
- Strong force
- Weak force
- Gravitation





Proton

The Standard Model



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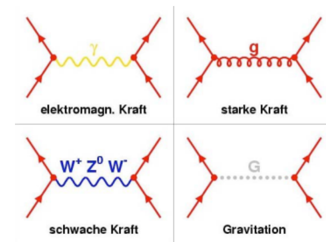
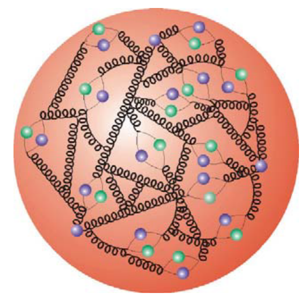
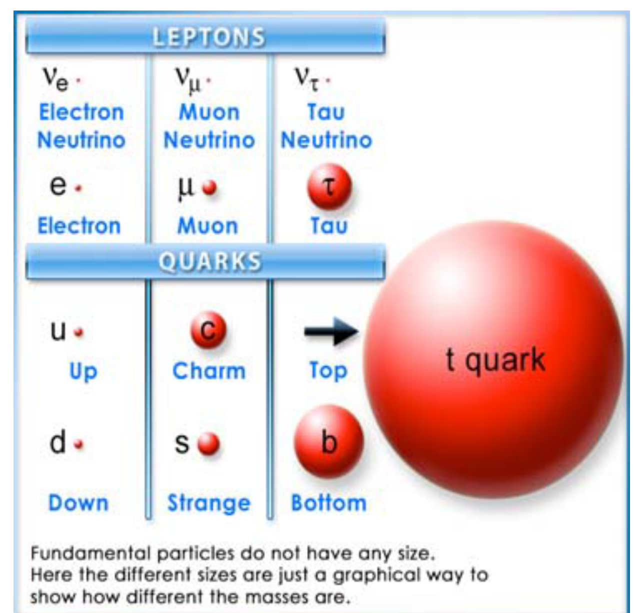




Proton



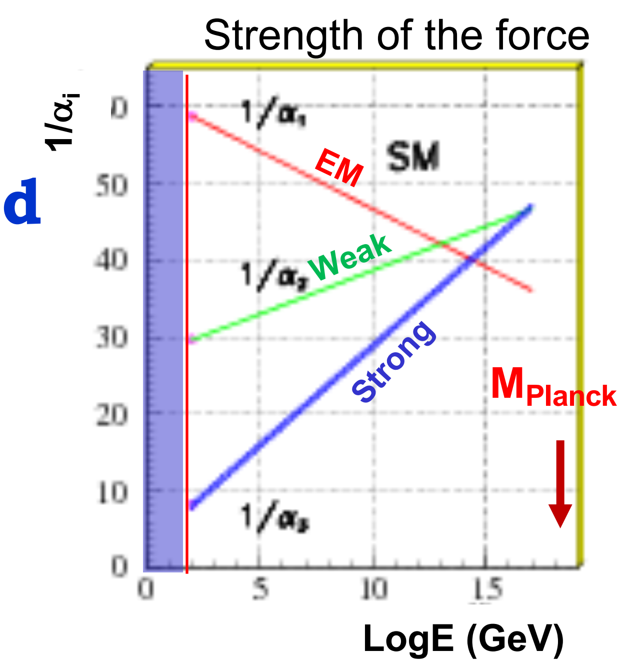
In the standard model all particles are mass-less.

Only through the interaction with the Higgs field they obtain their masses.

Is the Standard Model the ultimate solution ?

Important open questions:

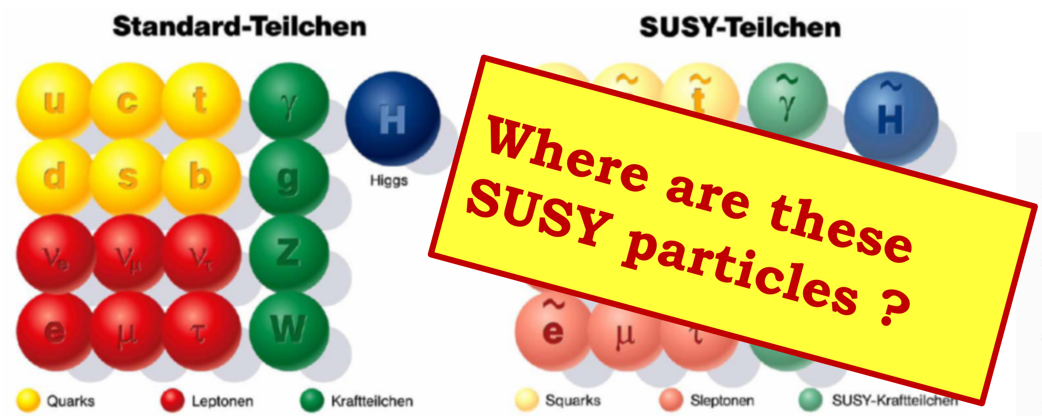
- Why do the masses differ by more than 13 orders of magnitudes ?
- Why is there more matter than anti-matter ?
- Do the fundamental forces unify in a single field theory ?
- What about gravity? Does a unified “World Equation – The Theory of Everything” exist?
- What is dark matter ?
- What is dark energy ?

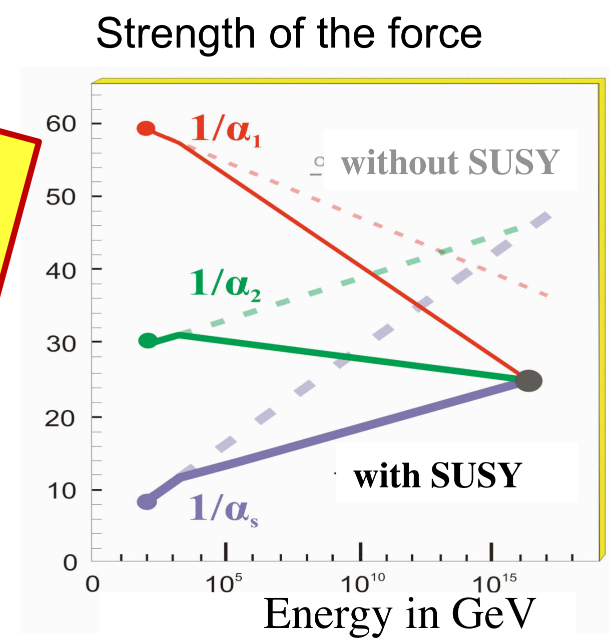


One potential solution: SUSY

Supersymmetry:

- Each elementary particle obtains a SUSY partner

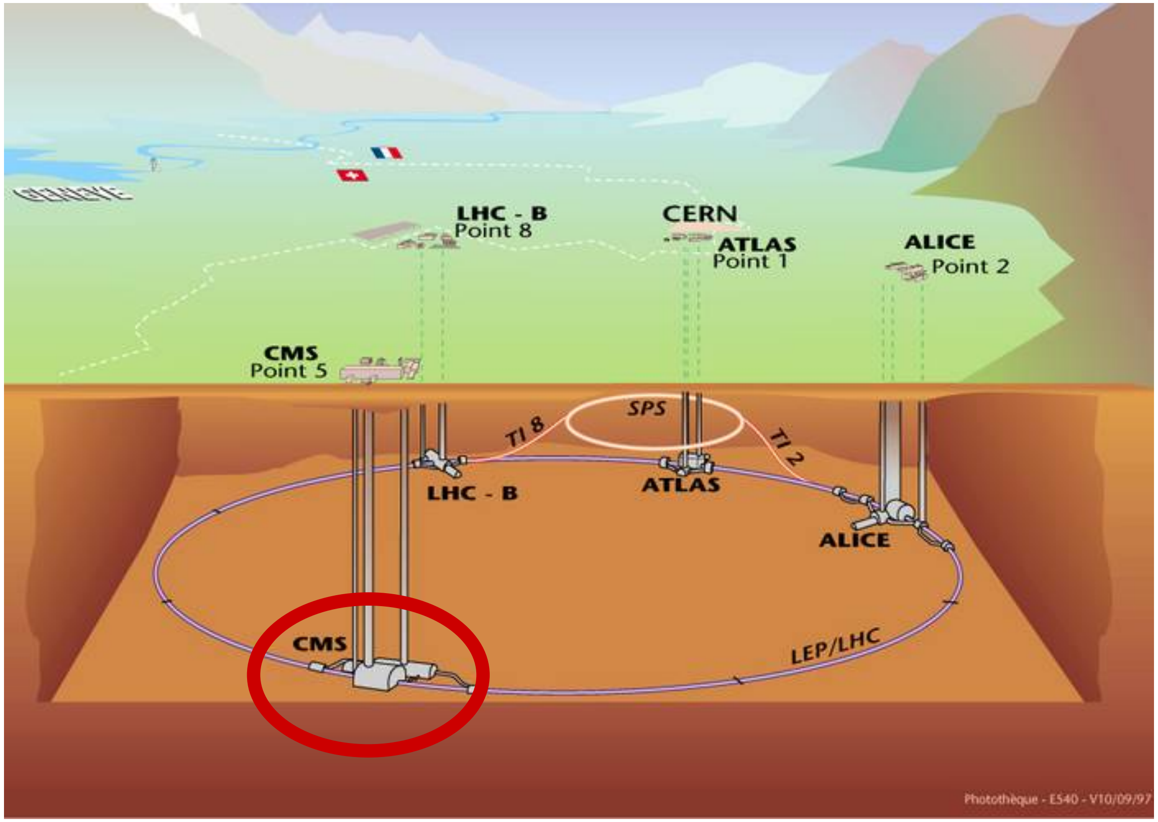




  - There are different flavors of the basic idea, which include a different number of new parameters

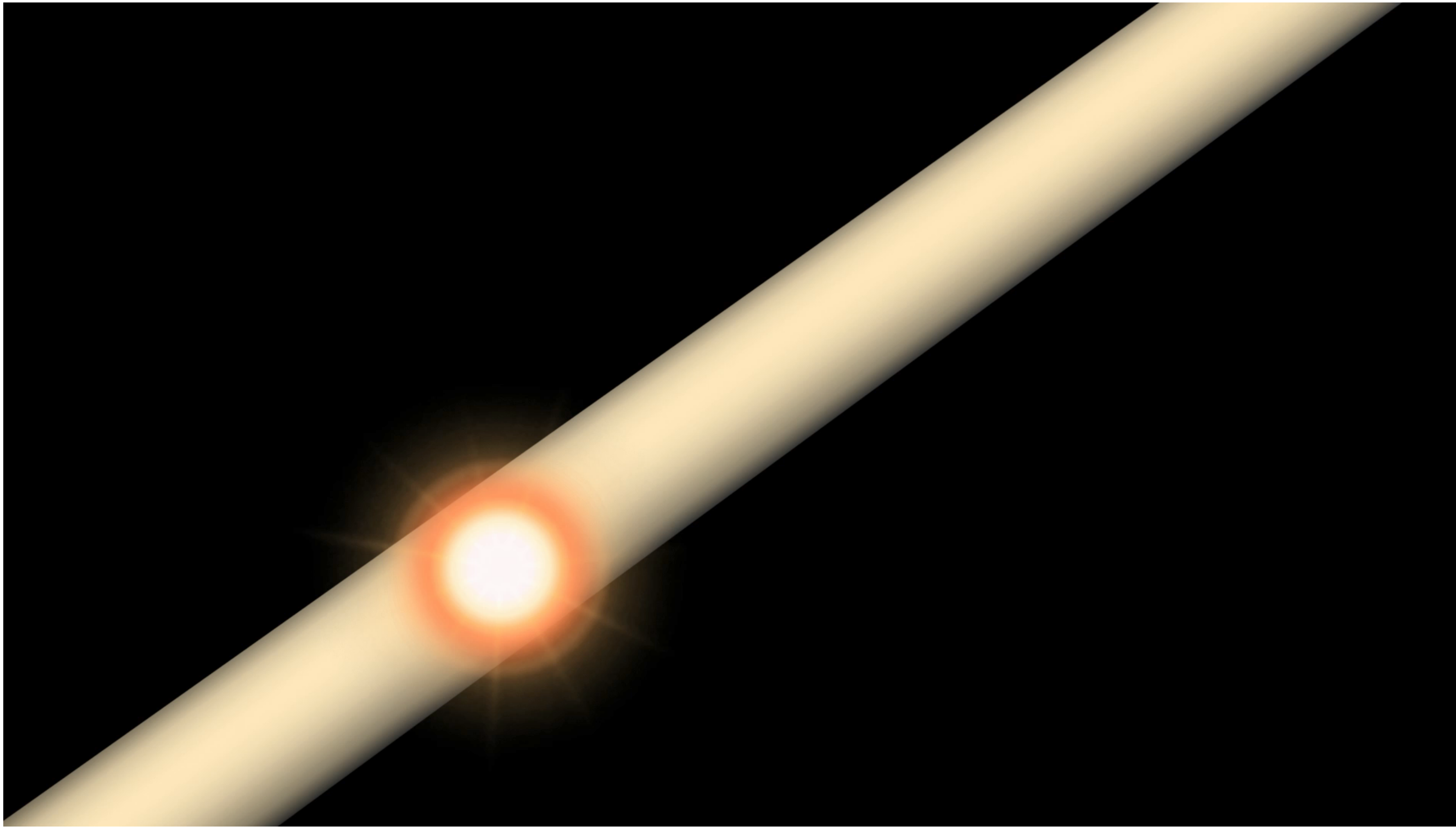
- ✓ Neutrinos have mass
- ✓ Unification of forces
- ✓ Gravitation is included
- ✓ Lightest SUSY particle → candidate for dark matter

High-Tech in Global Collaboration



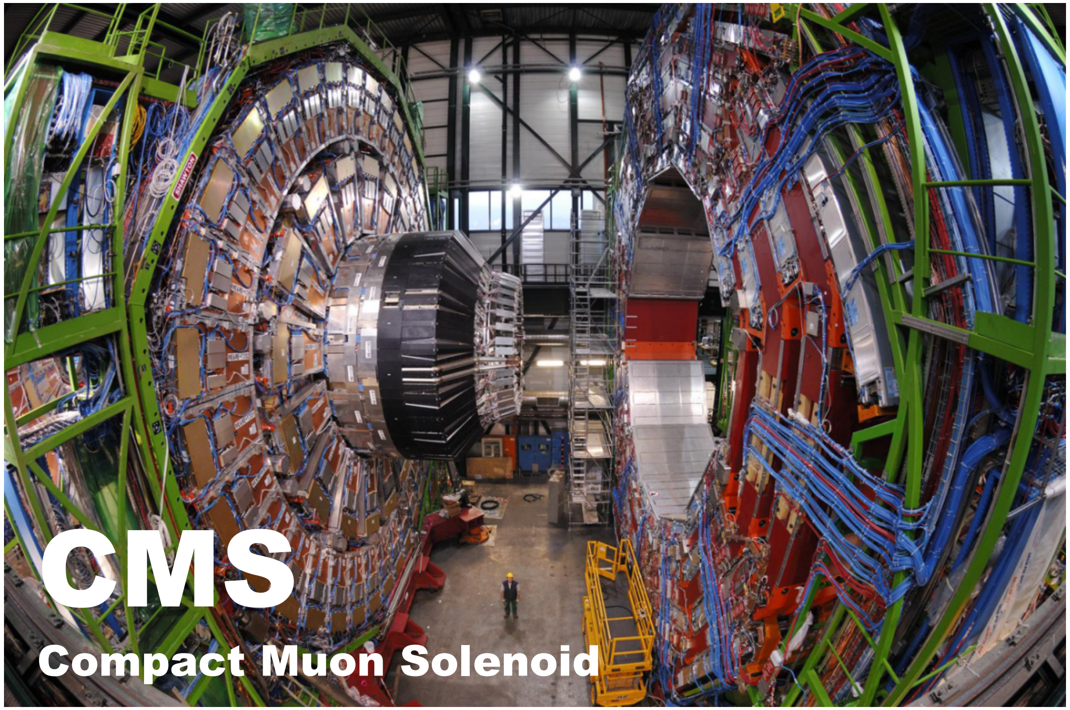
- 27 km long
- 9000 magnets, 2000 super-conducting
- colder than outer space
- proton-proton collisions with 8 → 13 TeV world record
- Lead-Lead, as well as proton-Lead collisions

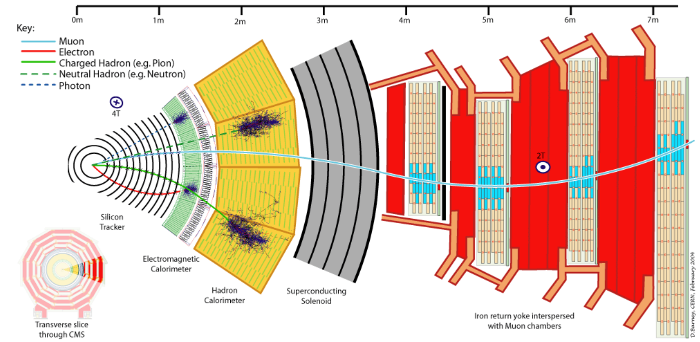
Collisions @ LHC



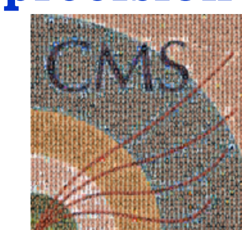
Copyright CERN

High-Tech in Global Collaboration



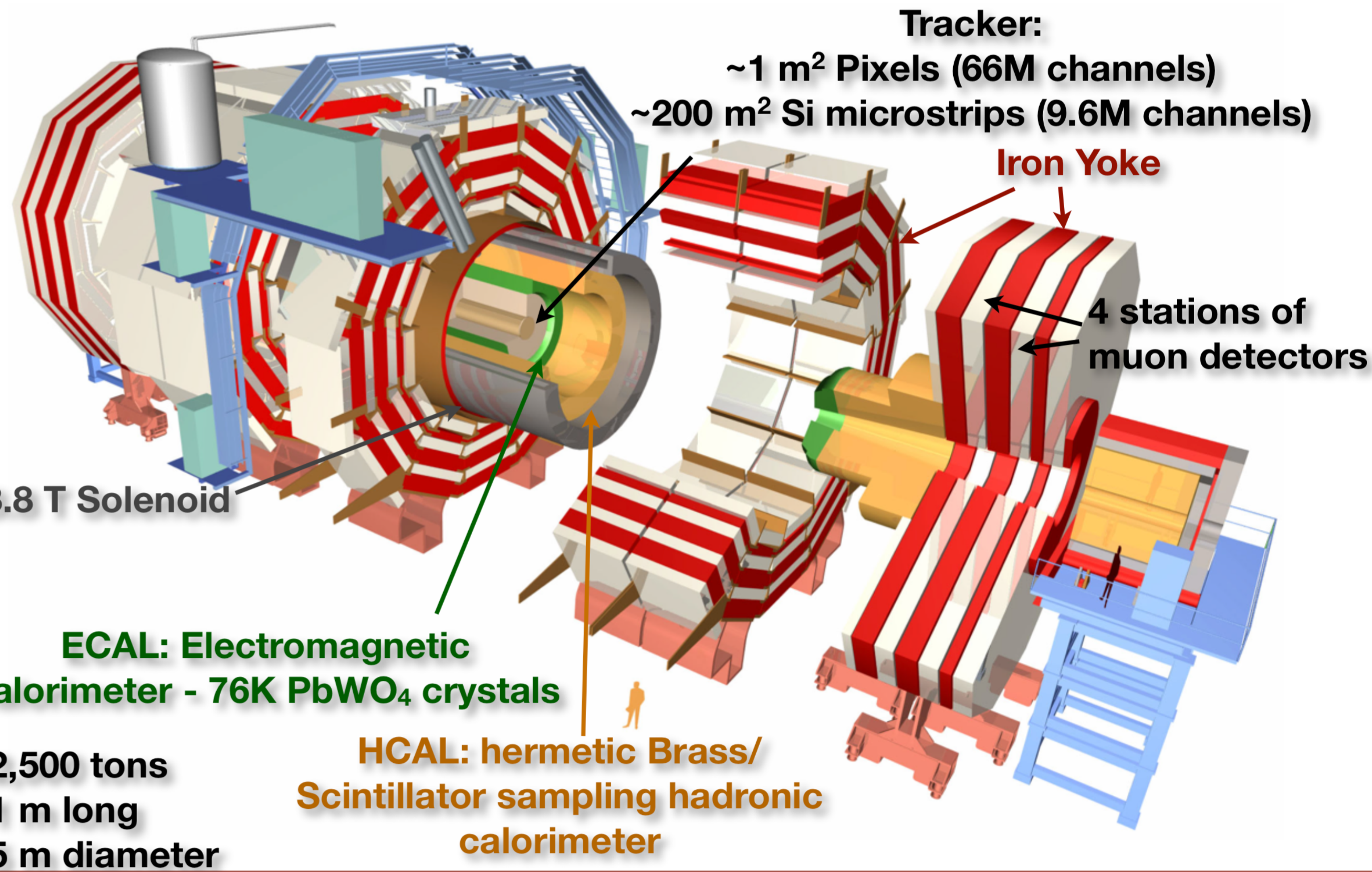


- **Large:** 21 m long, 15 m ∅, 14 000 t (> Eiffel Tower!)
- **Micro:** Tracking with hair-fine Si-strips and pixels with a precision of 20 micro-m
- **Many:** >5200 members, 1900 physicists, 1800 students, 950 engineers and technicians
- **Global:** 193 institutes from 43 countries



- **One Goal: Find out what our Universe is made of !**

The CMS Experiment



12,500 tons
21 m long
15 m diameter

LHC: Fascinating Science

Google at the LHC start in 2008

Higgs Discovery in Juli 2012

Discovery 2012, Nobel Prize in Physics 2013

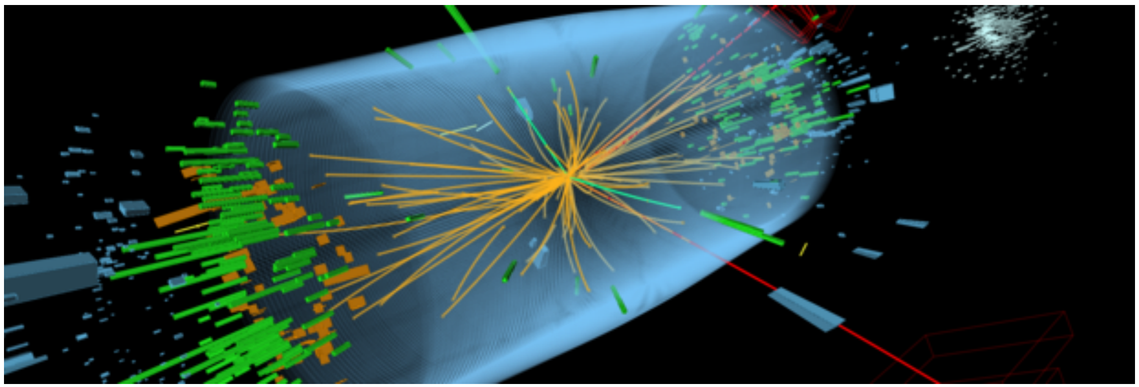
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

The long way to the Higgs Boson

Proposed in 1964 by Peter Higgs and other colleagues.

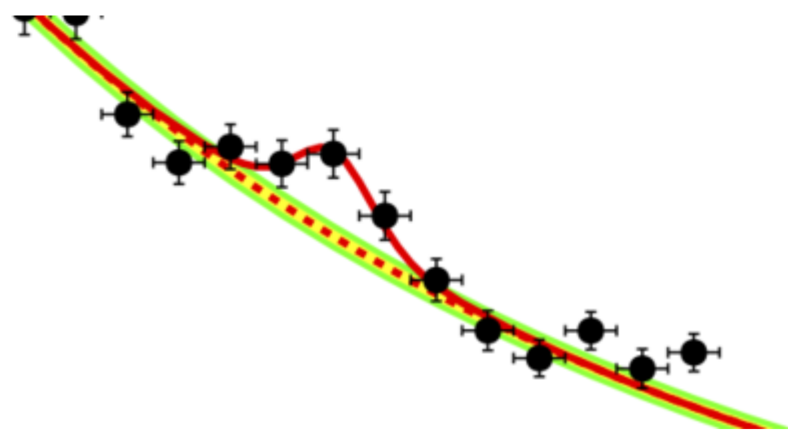
Almost 50 years searches at many colliders with higher and higher energies.

4.July 2012: Announcement of the discovery of a particle that resembles

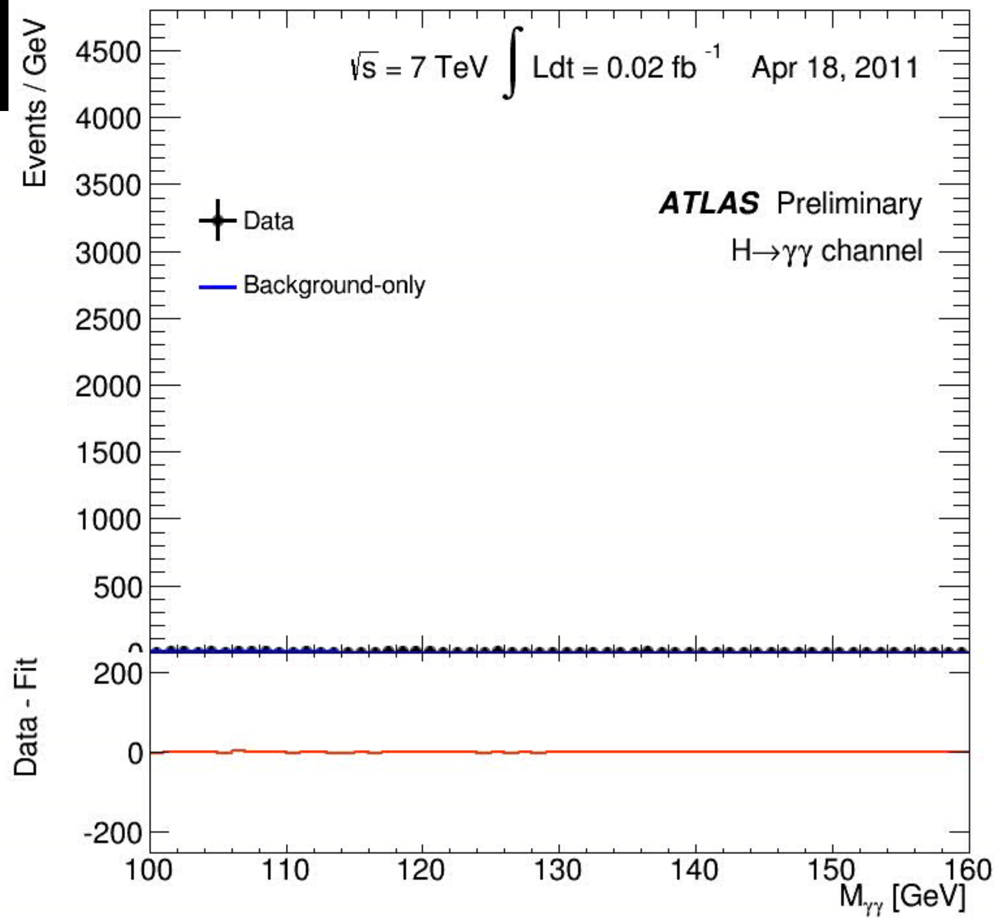


the Higgs Boson at the

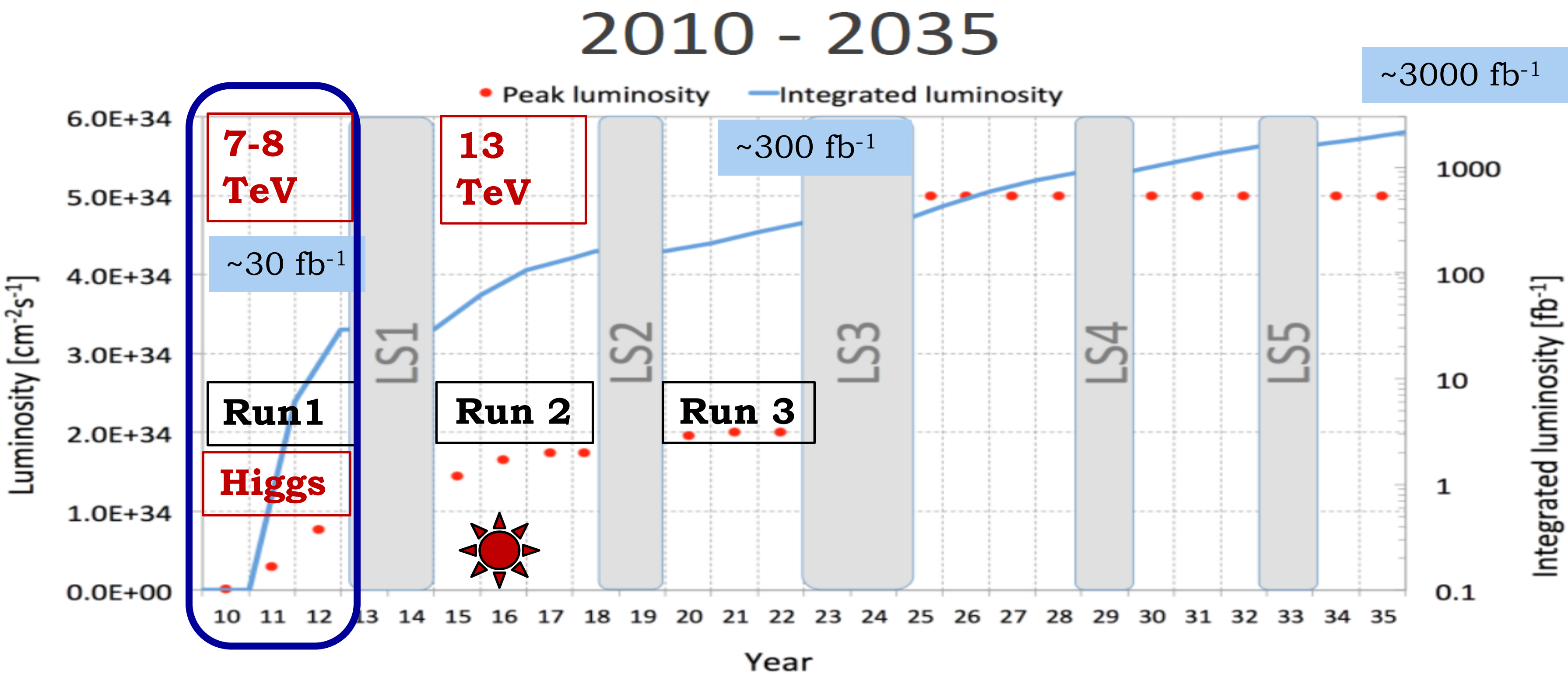
Large Hadron Collider



Discoveries need many data!



The Harvest of Run 1



Major Achievement: Higgs discovery and characterization

→ **Mass, spin, coupling, …**

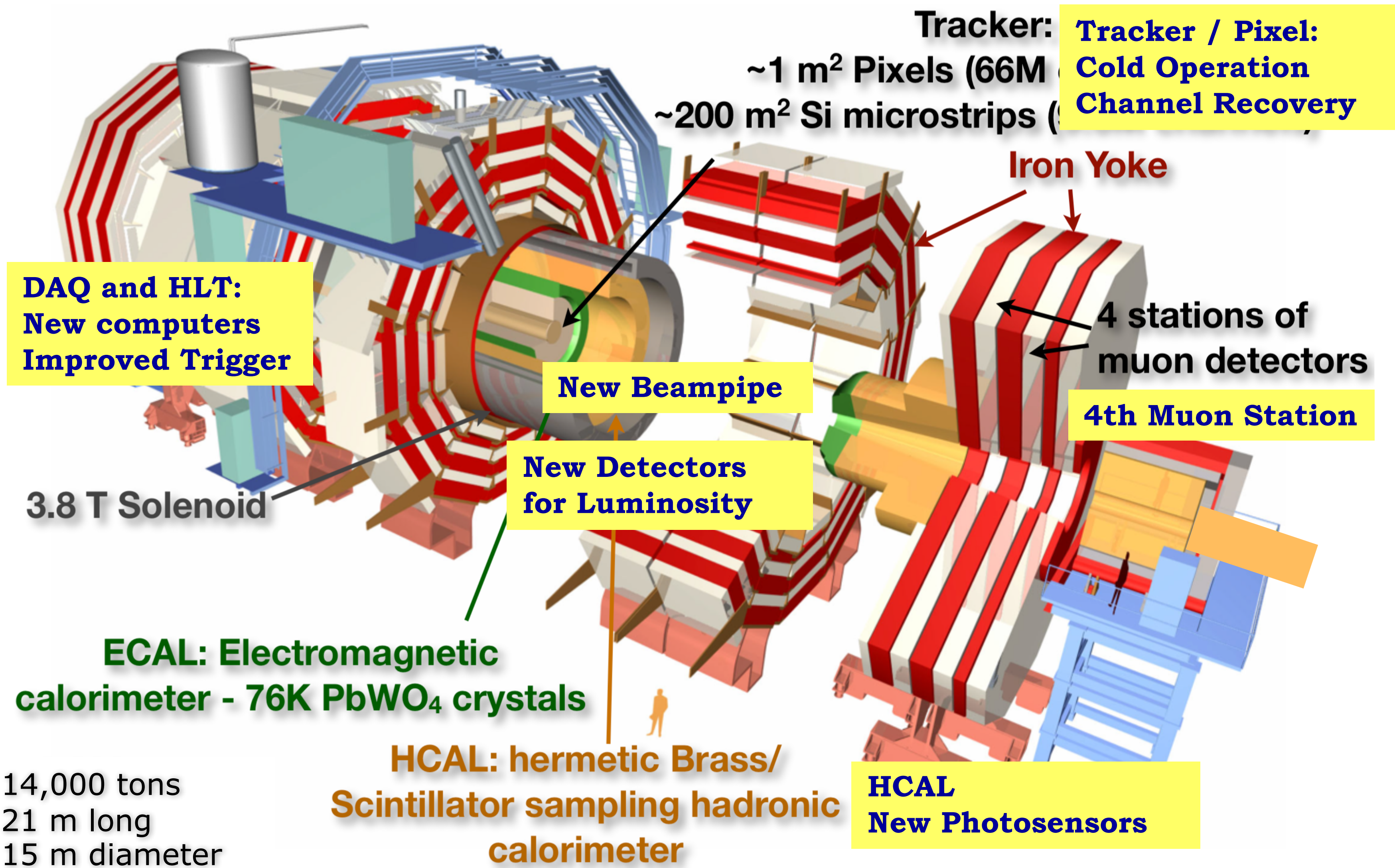
Top Quark: LHC is a top quark factory

→ **High precision measurements: mass, decays, spin…**

Searches for SUSY and other exotic particles beyond the SM

→ **Many limits for masses and couplings set.**

CMS after Long Shutdown 1



Start on 3rd of June 2015

Science & Environment

Large Hadron Collider turns on 'data tap'

By Paul Rincon
Science editor, BBC News website

3 June 2015 | Science & Environment

BBC NEWS

Sciences

L'accélérateur de particul… CERN : quatre questions s… d'un géant

Par David Larousserie

Le Monde

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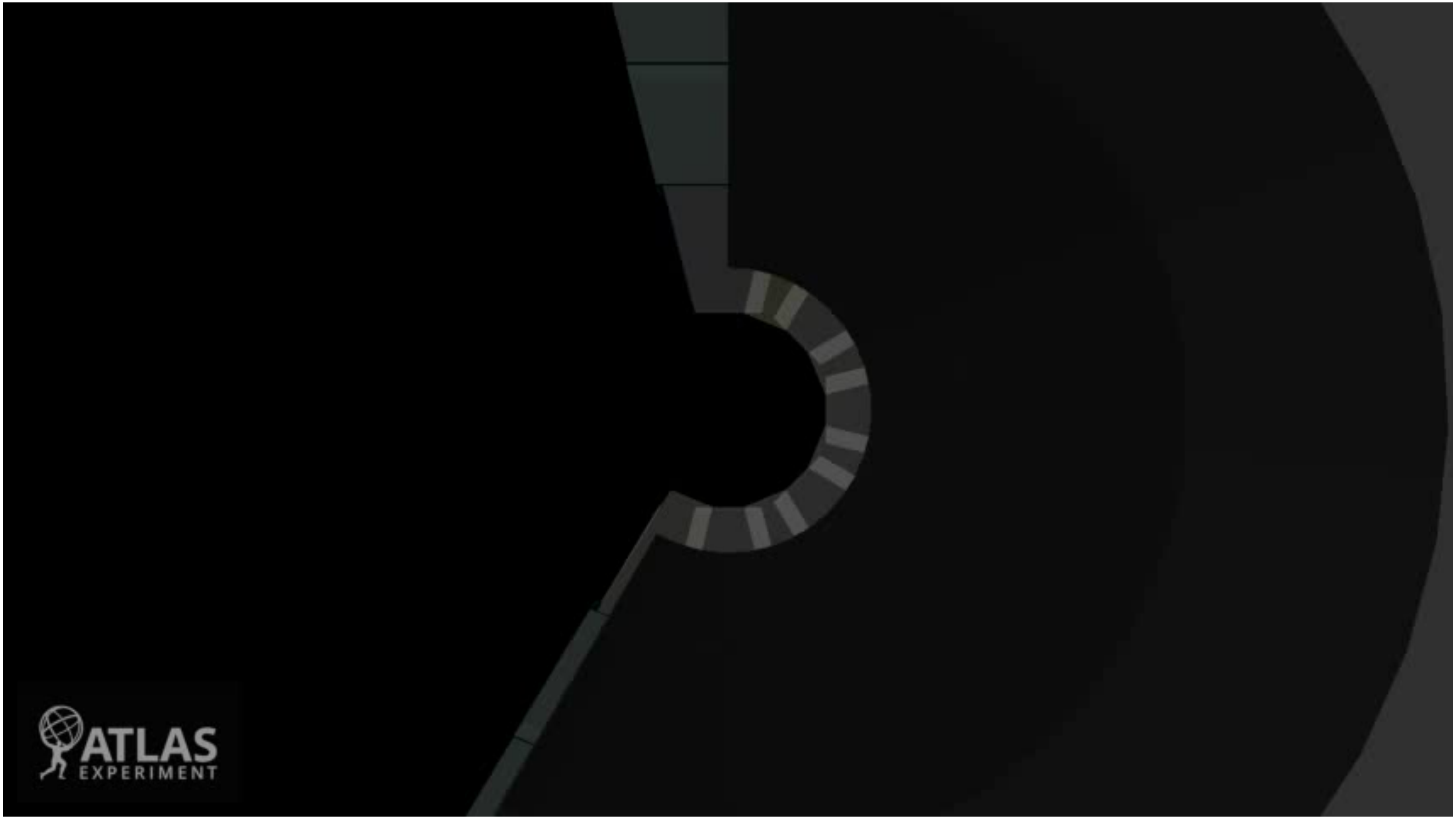
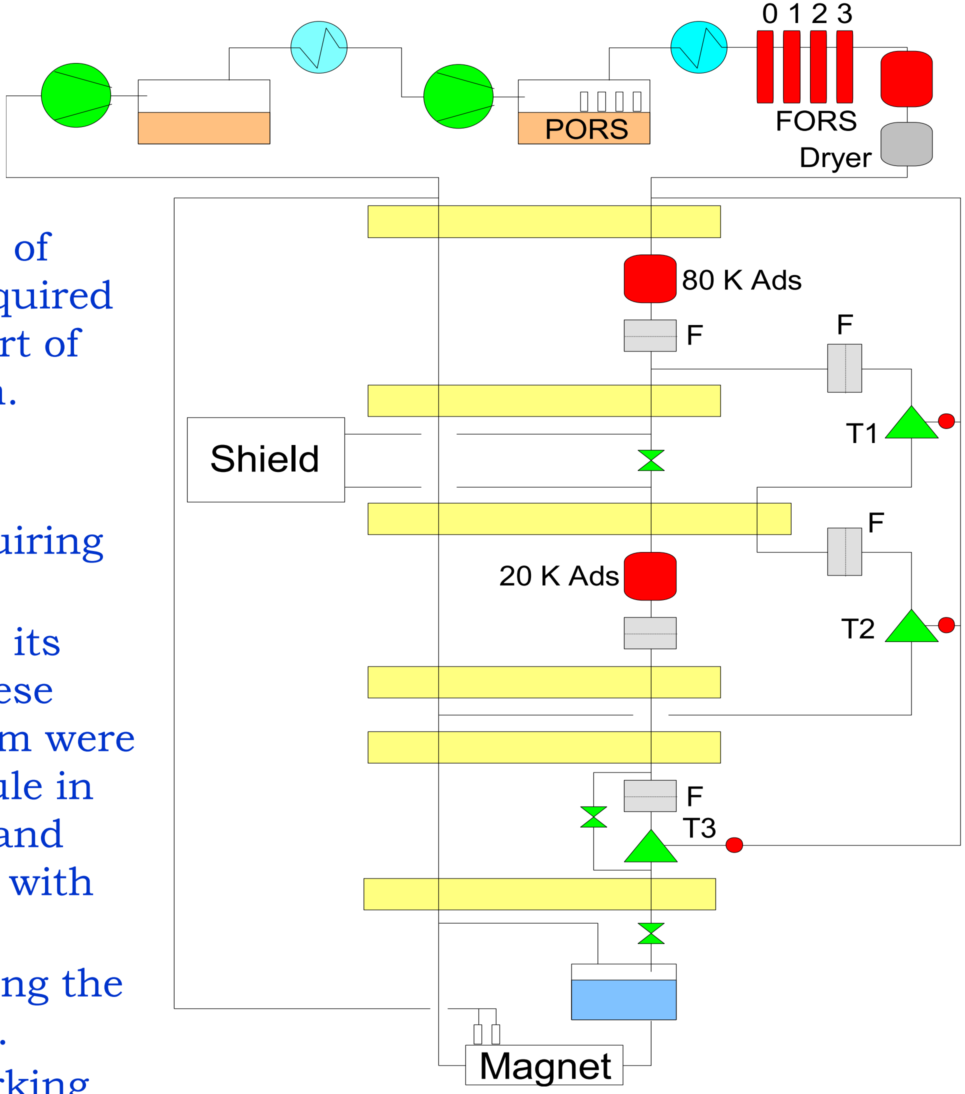
The Future has started



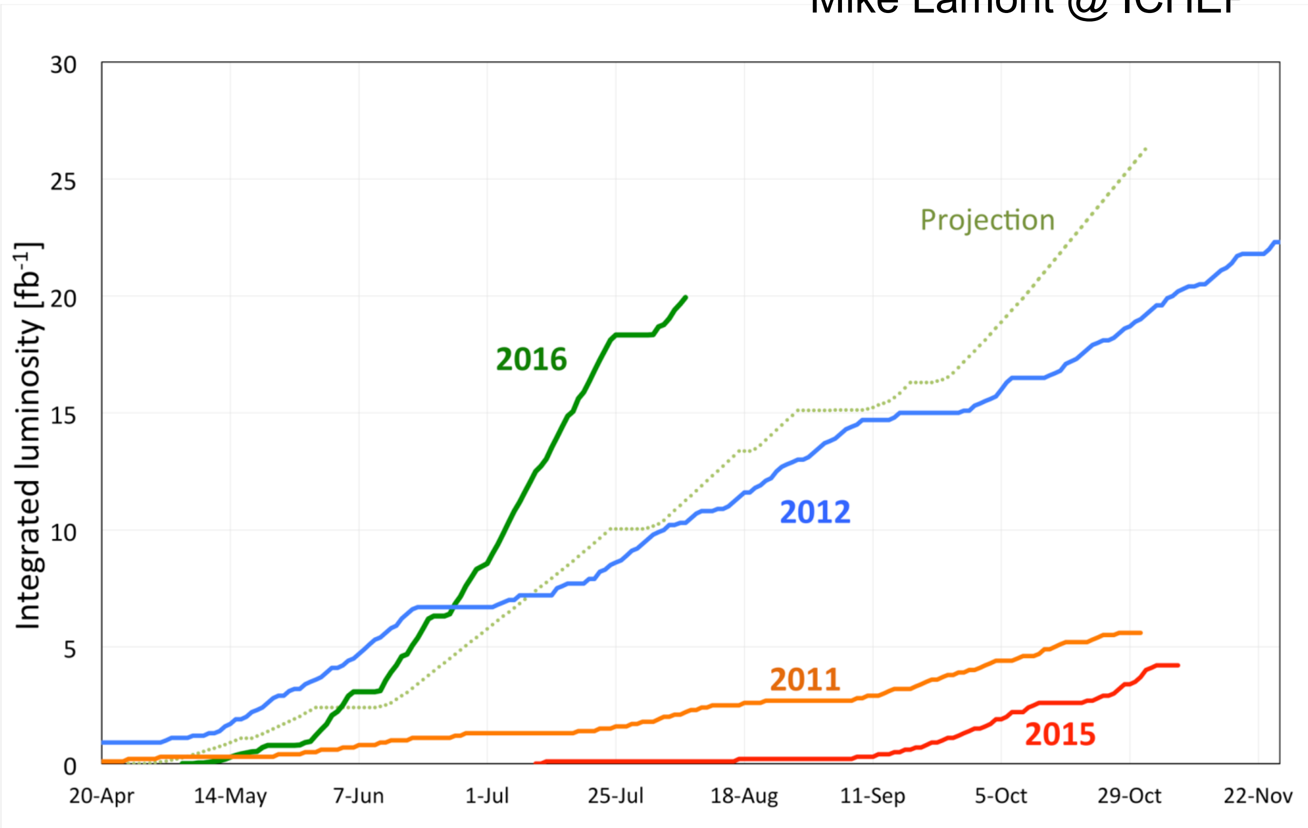
Cryogenics Plant for CMS Magnet

- The restart of the CMS magnet after LS1 was difficult due to problems with the cryogenic system in providing liquid Helium.
- Inefficiencies of the oil separation system of the compressors for the warm Helium required several interventions and delayed the start of routine operation of the cryogenic system.
- The magnet could be operated, but the continuous up-time was limited by the performance of the cryogenic system requiring more frequent maintenance than usual.
- A comprehensive program to re-establish its nominal performance was performed. These recovery activities for the cryogenic system were synchronized with the accelerator schedule in order to run for adequately long periods and enabled CMS to take ¾ of the luminosity with magnet on.
- A thorough cleaning was performed during the long the technical stop at end of the year.
- All went very well and the cold box is working flawlessly



LHC Status and Outlook

Mike Lamont @ ICHEP

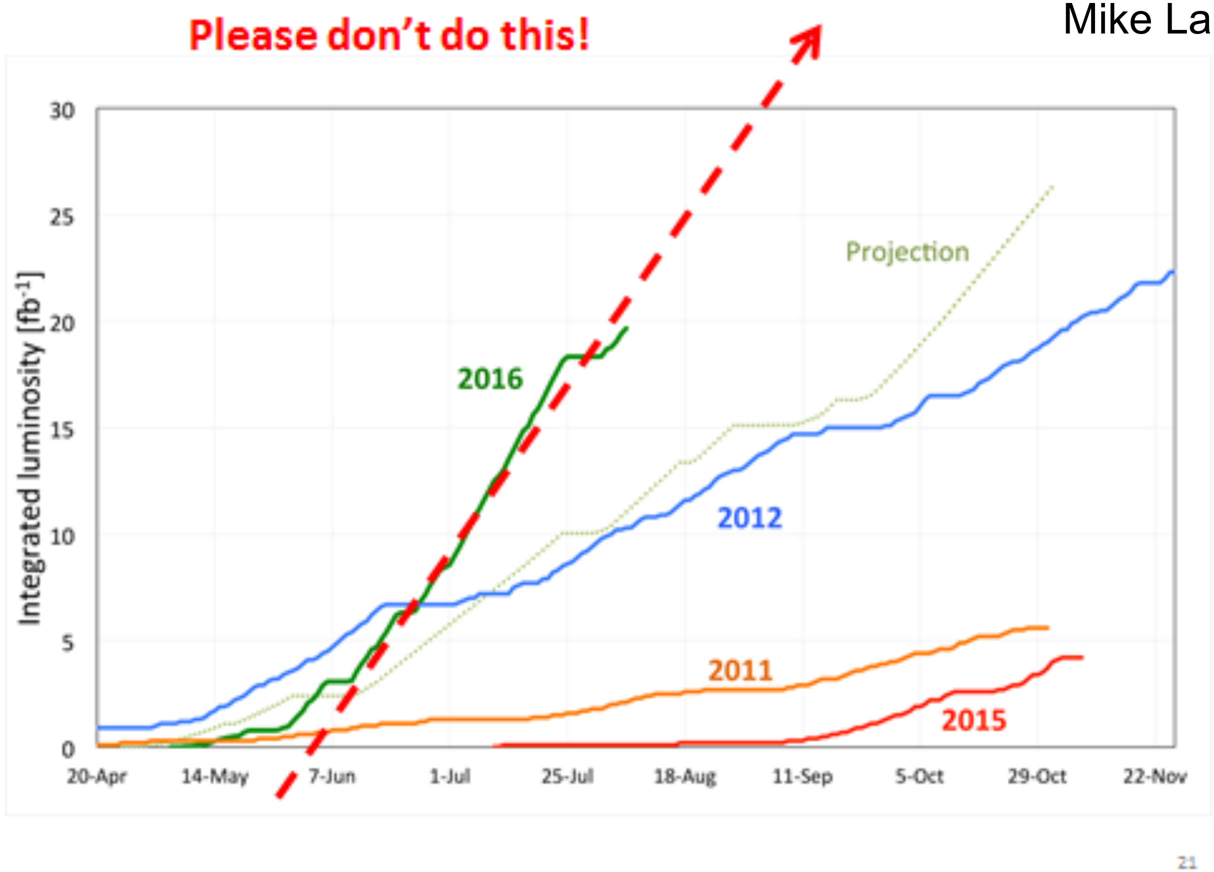


- Outstanding performance
- Record fills with up to 0.7/fb

- Luminosity monitors calibrated with beam-separation scans: Current precisions for 2015: 2%-2.7 %, 2016: 5%-8% Needs hard and detailed work to reach desired accuracy.

LHC Status and Outlook

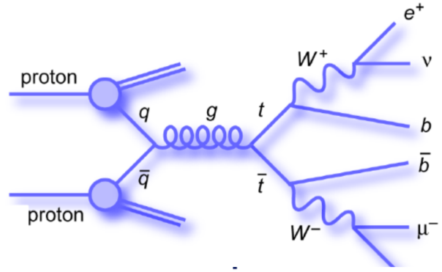
Mike Lamont @ ICHEP



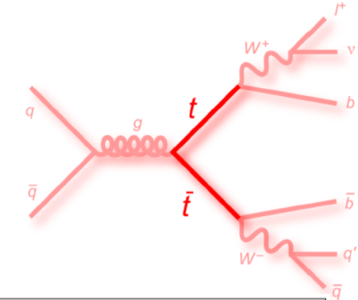
- **A bit of a rocky startup after the Machine Development end of July, issues with kicker magnet, dipole magnet, …**
- **Also several tests for optimizations are planned.**

Impressive Precision for Top Quark

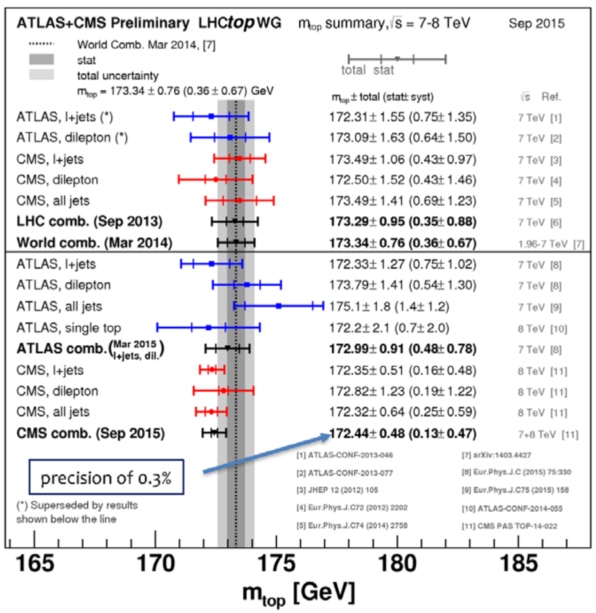
Top pair to di-leptons



Top pair to lepton+jets



LHCTOPWG



Analysis combined using BLUE, accounts for correlations between all uncertainties.

CMS combination :

m_{top} = 172.44 ± 0.48 GeV

ATLAS combination :

(OLD) m_{top} = 172.99 ± 0.91 GeV

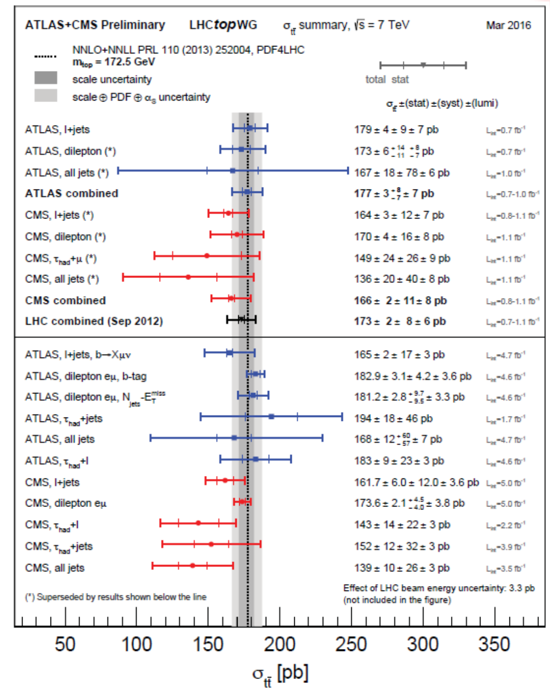
(NEW) m_{top} = 172.84 ± 0.70 GeV

(not in the combination plot)

World combination:

m_{top} = 174.34 ± 0.76 GeV

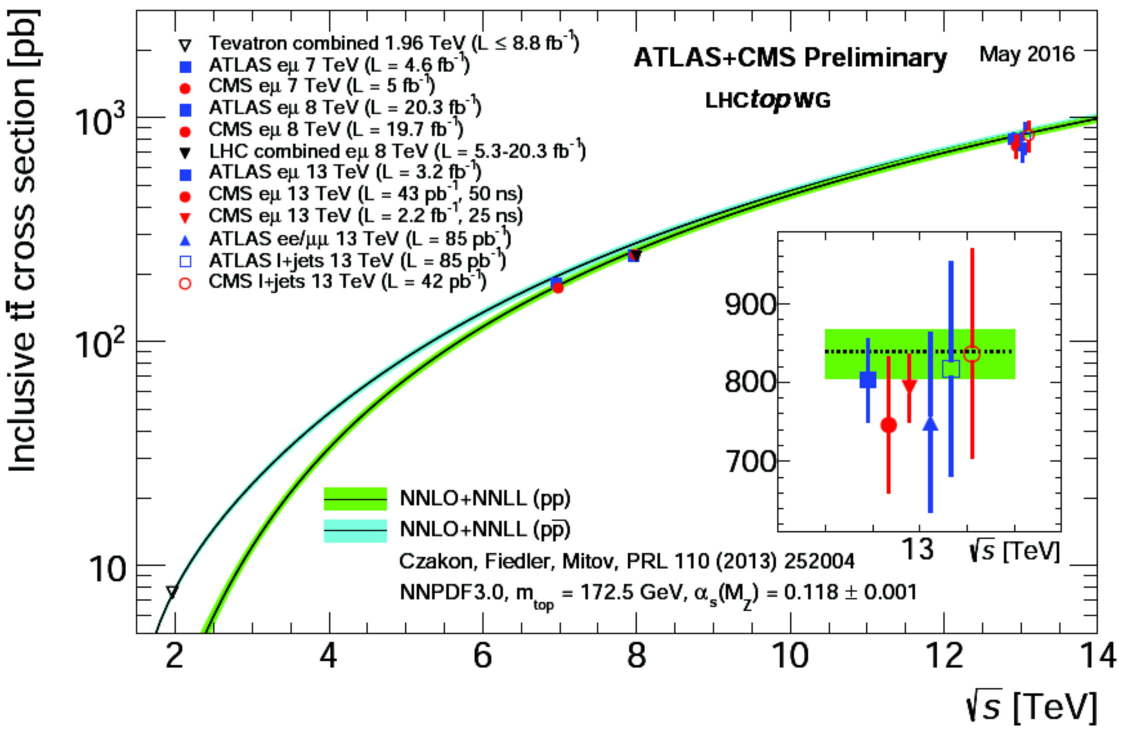
Total uncertainty is now well below 1 GeV



- **High precision for top quark measurements with preliminary Run 1 combinations produced**

Precision for Top Quark

- **ATLAS & CMS: several modes at 13 TeV analyzed**
  → very prompt analyses turn around

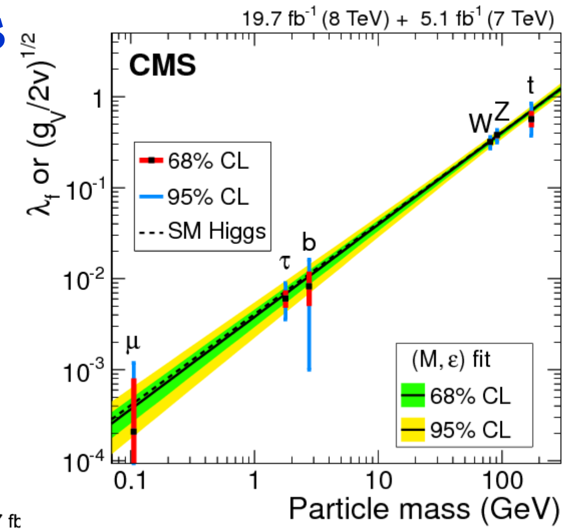


- **Robust eμ final state gives most precise inclusive results at all center of mass energies.**
- **Differential cross-section measurements at 13 TeV show reasonable modelling, though some deviations at large jet multiplicity.**

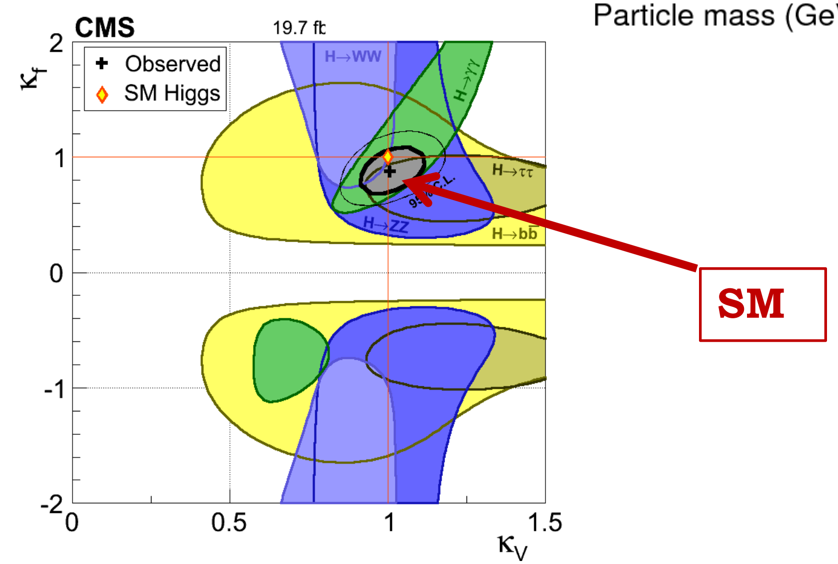
CMS Higgs Combination (Run 1)

- **Five main decay channels all published**
- **All results consistent with SM Higgs**

$$m_H = 125.02 \; {}^{+0.26}_{-0.27} \,(stat.)\; {}^{+0.14}_{-0.15}\,(syst.)\,GeV$$

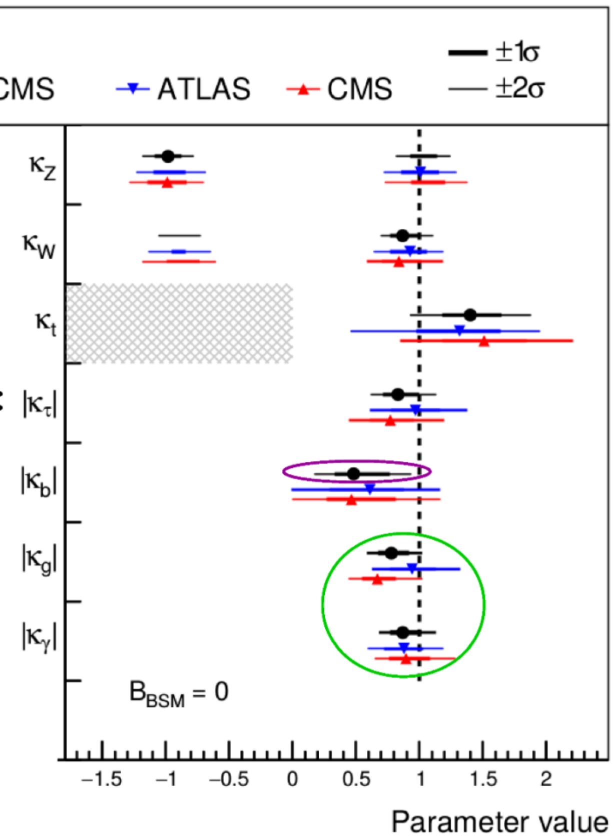


Channel	Obs (σ)	Exp (σ)
$H \to ZZ$	6.5	6.3
$H \to \gamma\gamma$	5.6	5.3
$H \to WW$	4.7	5.4
$H \to \tau\tau$	3.8	3.9
$H \to bb$	2.0	2.6
$H \to \mu\mu$	< 0.1	0.4



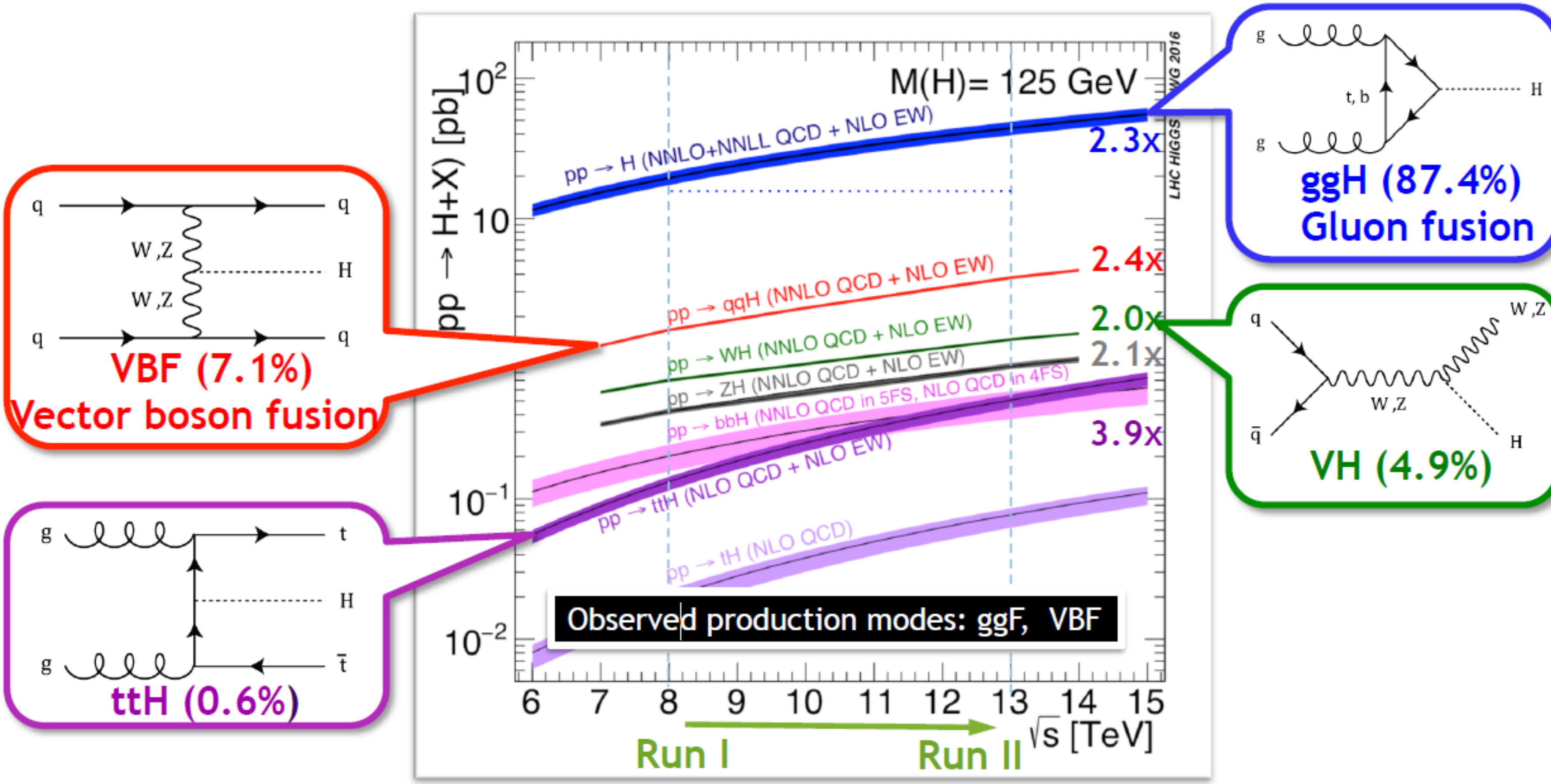
Higgs Coupling Combination (Run 1)

- **ALTAS + CMS:** monumental (71 pages) combined couplings paper is out (1606.02266) !
- Production signal strengths as expected (ttH somewhat high, but difficult !)



- All κ_i are compatible with the SM within 2σ, but $\kappa_b = 0.49^{+0.27}_{-0.15}$.
- $\kappa_{g/\gamma}$ compatible with SM:
  - $\kappa_g = 0.81^{+0.13}_{-0.10}$
  - $\kappa_\gamma = 0.90^{+0.10}_{-0.09}$
- **Global p-value compatibility with SM is 11%.**

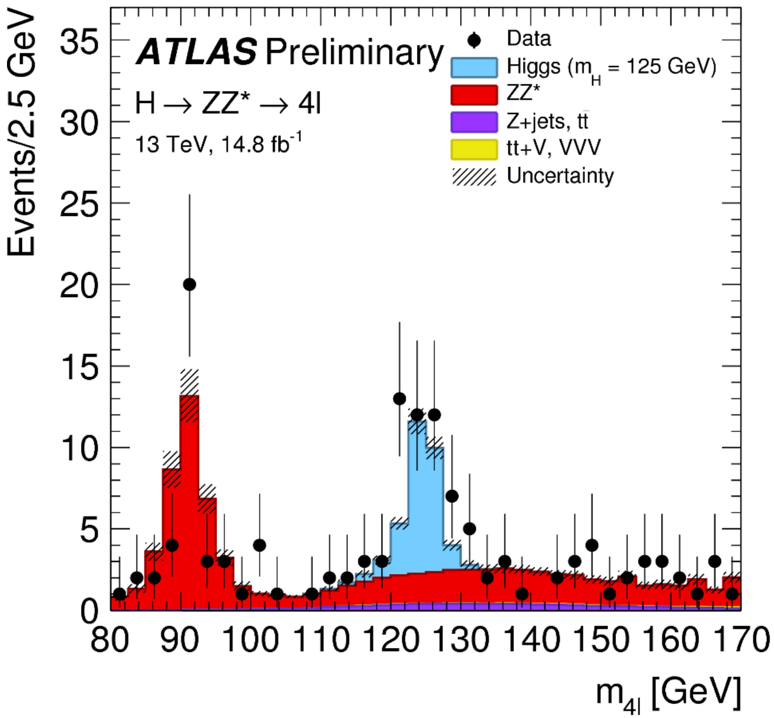
Higgs Boson Production



7/8 TeV (2011/2012) 13 TeV (>2015)

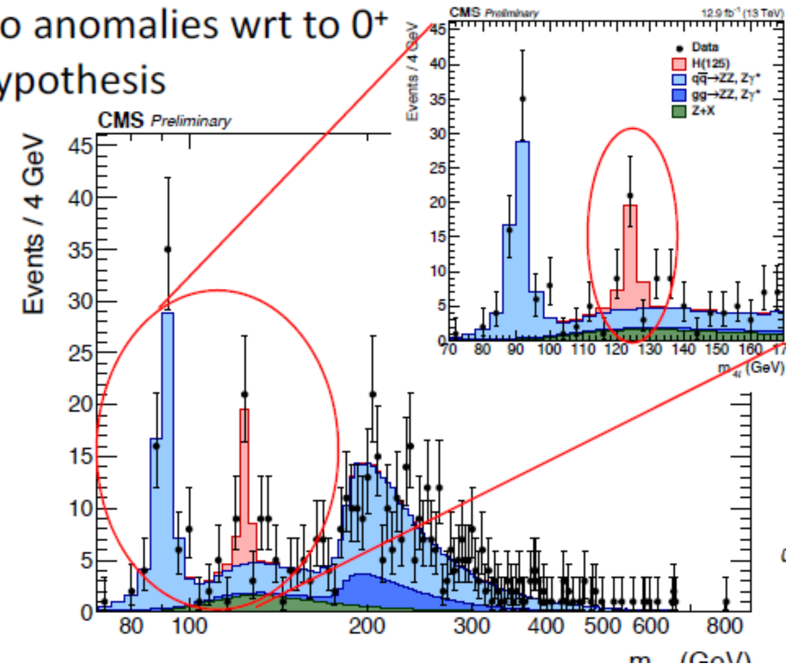
Higgs: H → ZZ* → 4l

ATLAS



CMS

No anomalies wrt to 0+ hypothesis



ATLAS: event categories used, clear re-observation, rate consistent with SM H expectation (1.6σ high), overall significance at 13TeV ~ 10σ

CMS: at m_H=125.09 GeV $\mu = \sigma/\sigma_{SM} = 0.99^{+0.33}_{-0.26}$

Profiling all nuisances and μ: $m_H = 124.50^{+0.48}_{-0.46}$ GeV $= 124.50^{+0.47}_{-0.45}(\text{stat.})^{+0.13}_{-0.11}(\text{sys.})$ GeV

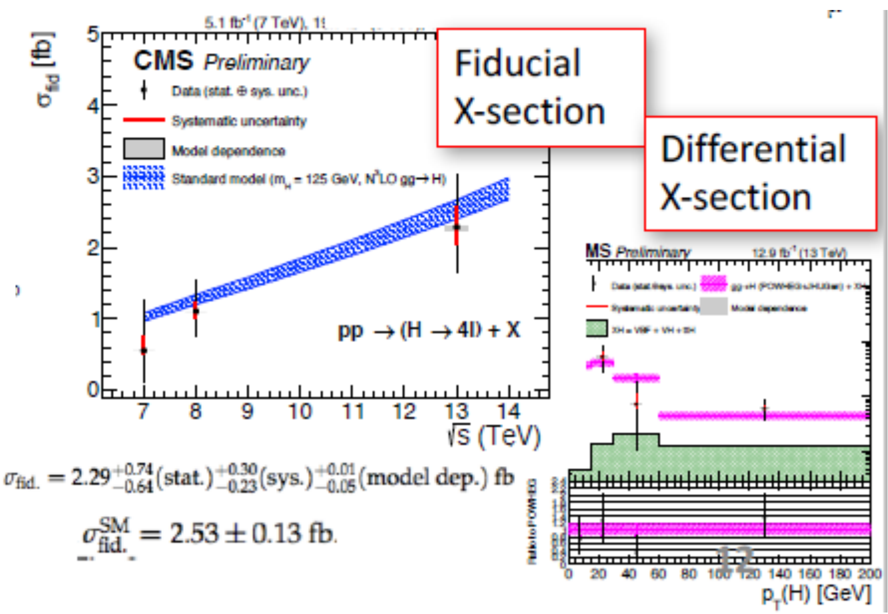
Γ_H<41 MeV (comparing off-shell and on-shell)

No anomalies wrt to 0+ hypothesis

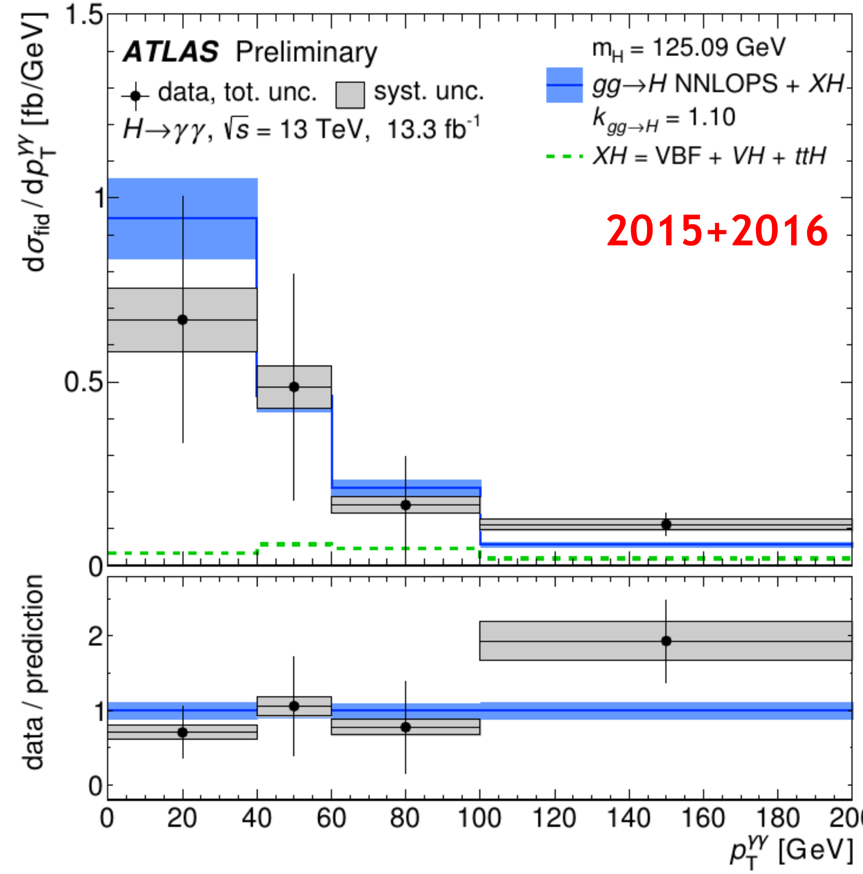
Higgs: Differential dependencies

ATLAS & CMS looked at different dependencies in these channels:

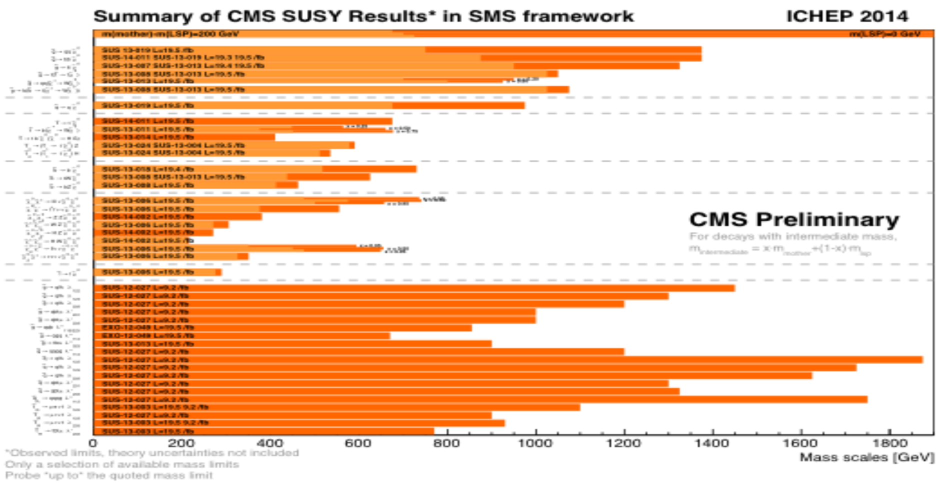
H → ZZ* → 4l

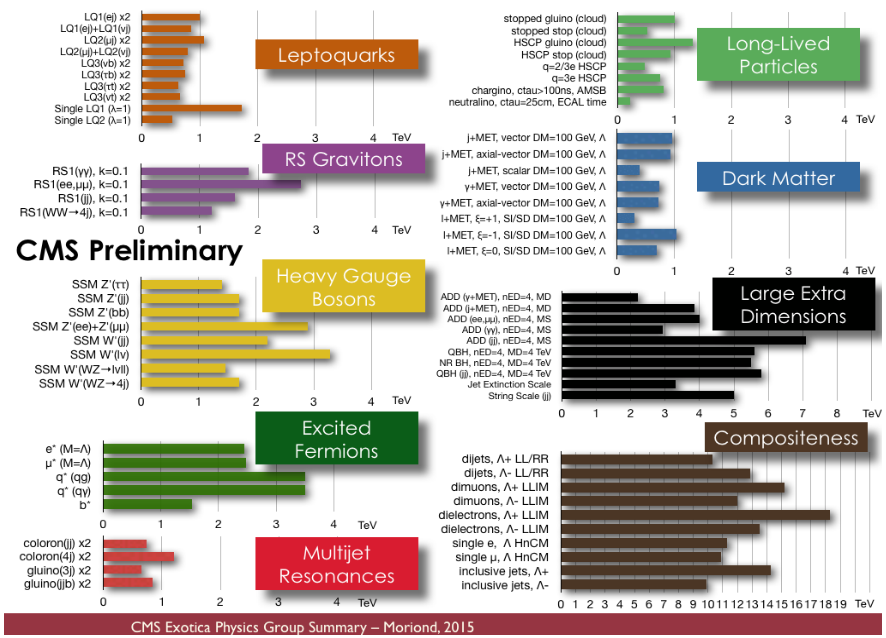


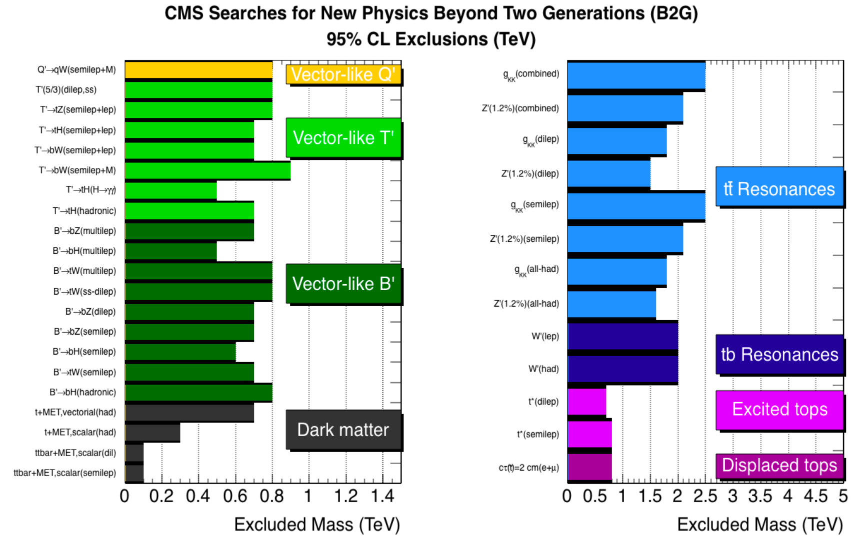
H → γγ



Searches for New Physics - Run 1





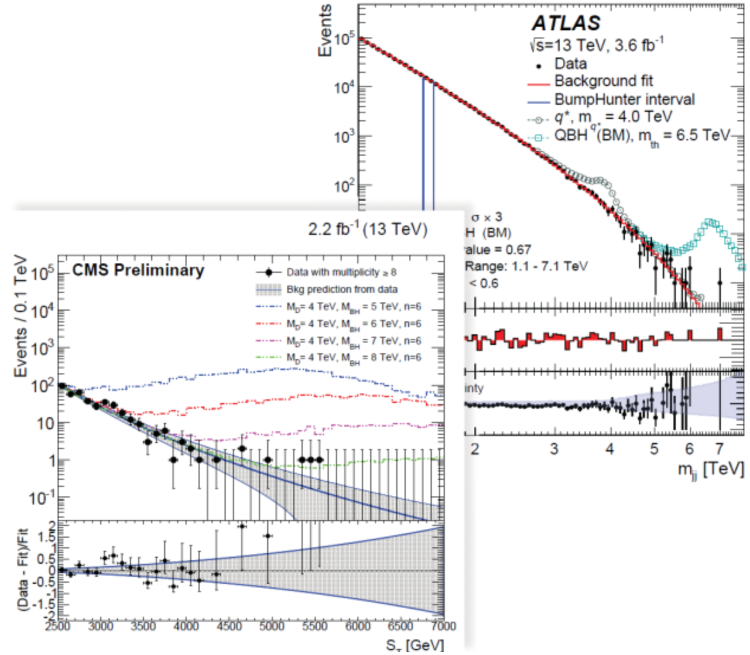


- **Many models and their predictions investigated**
- **Unfortunately nothing found**
- **CAVEAT: several assumptions behind these limits**

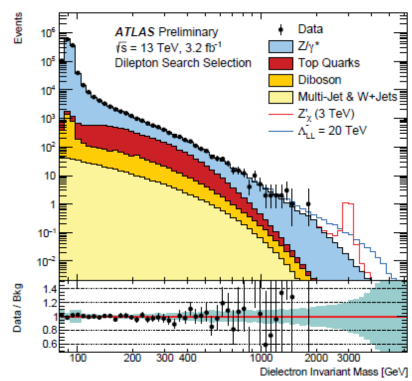
Searches Commenced in Run 2

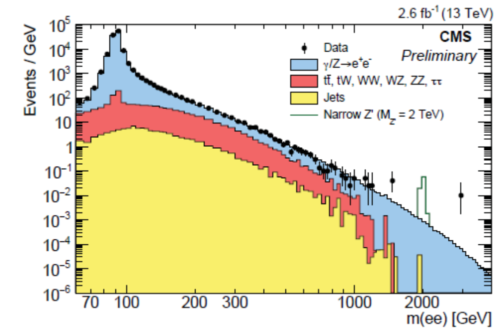
LHC at 13TeV: resonance factory at a novel energy scale:

- Di-jet and multi-jet mass spectra



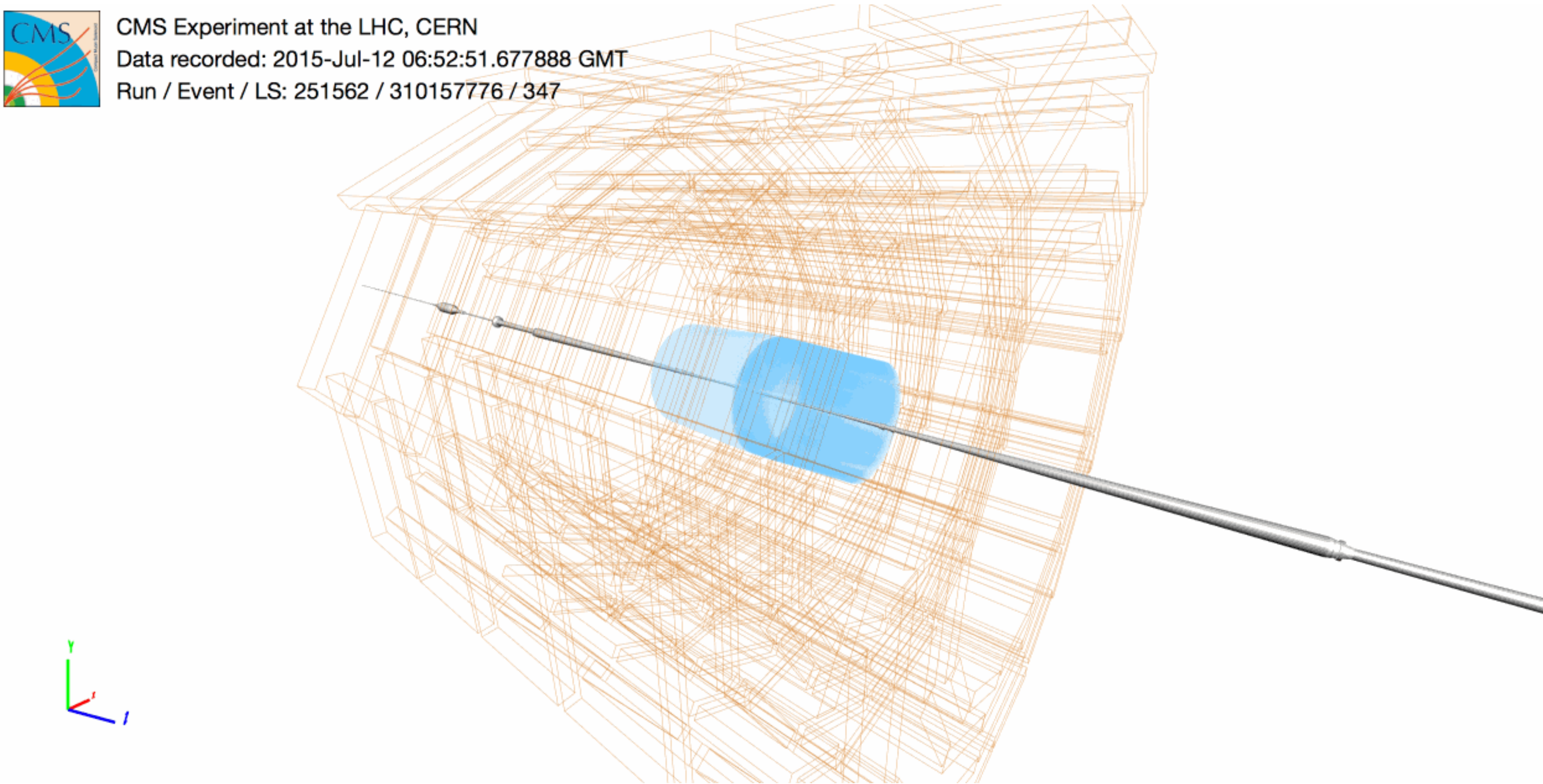
- Di-lepton (ee, μμ, ττ) mass spectra





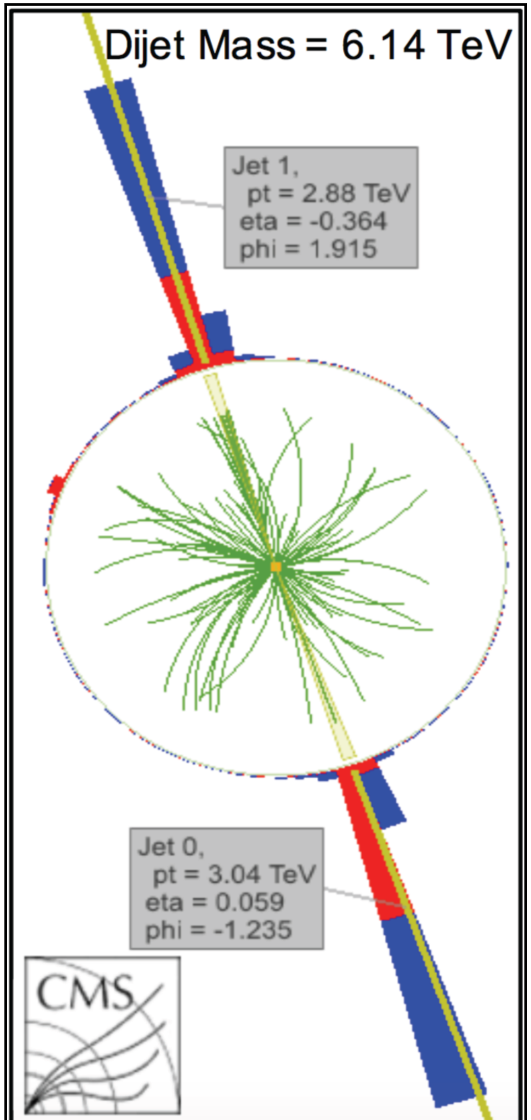
- Di-photon mass spectrum
- Lepton + MET final state
- Boosted Topologies

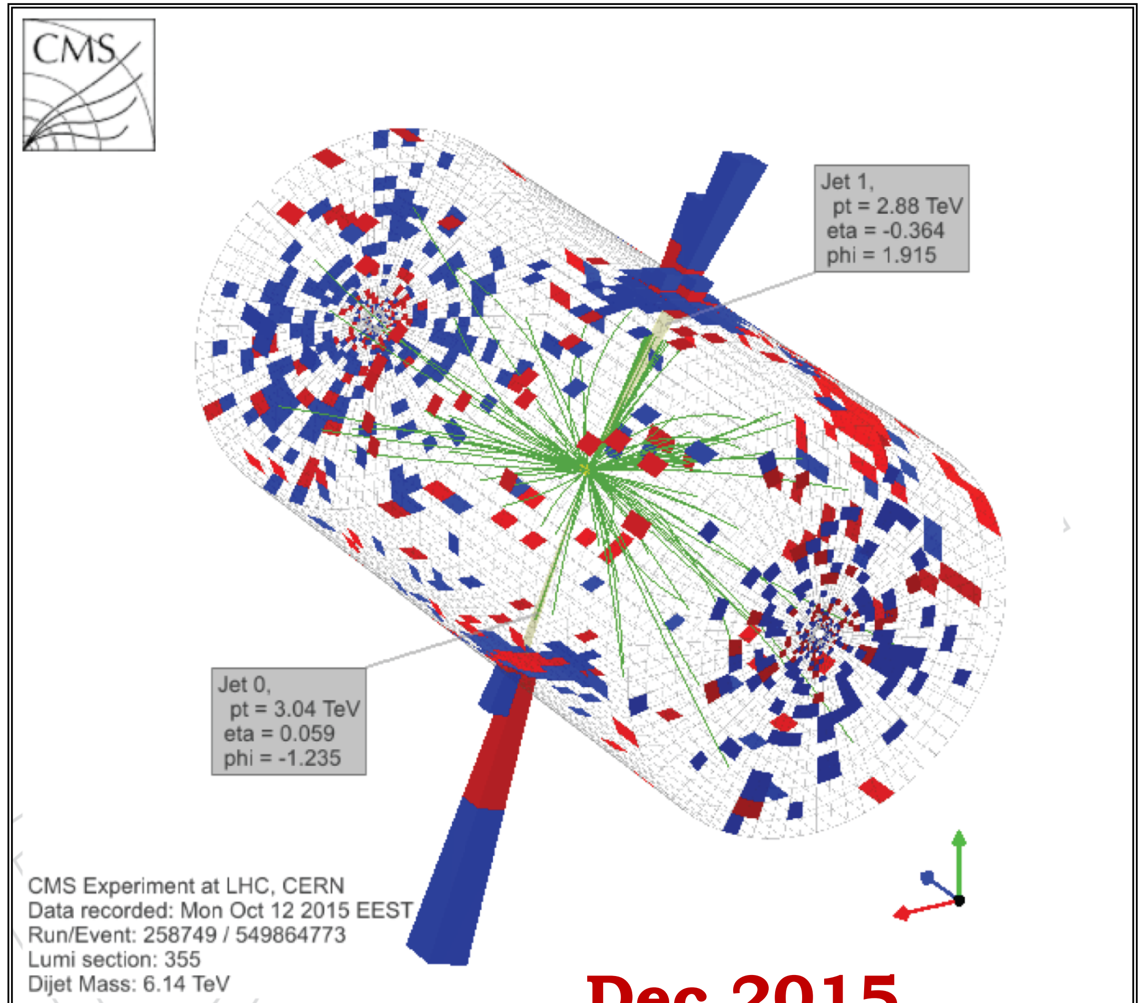
Highest mass dijet event: ~5 TeV



Summer 2015

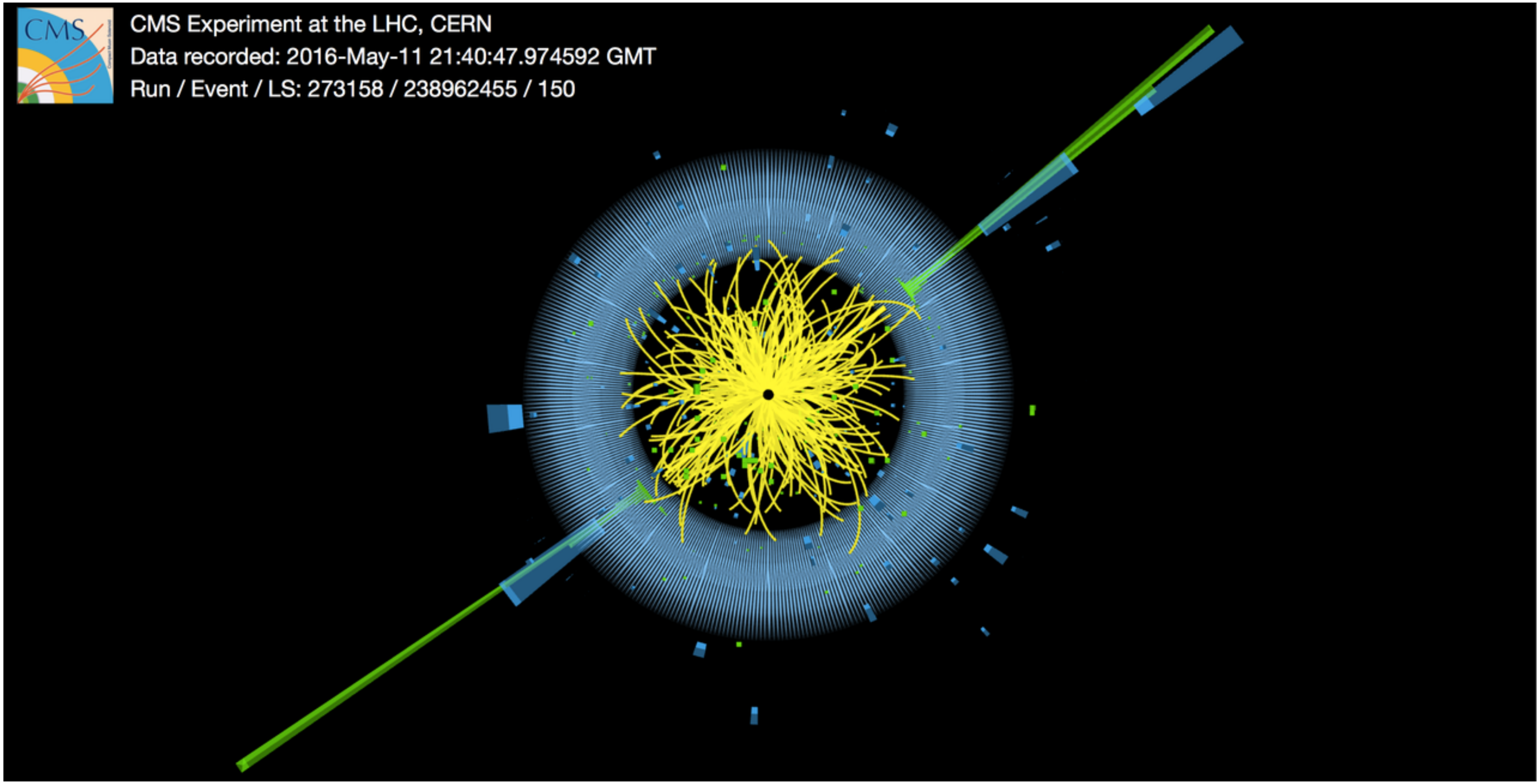
Highest mass dijet event: 6.14 TeV





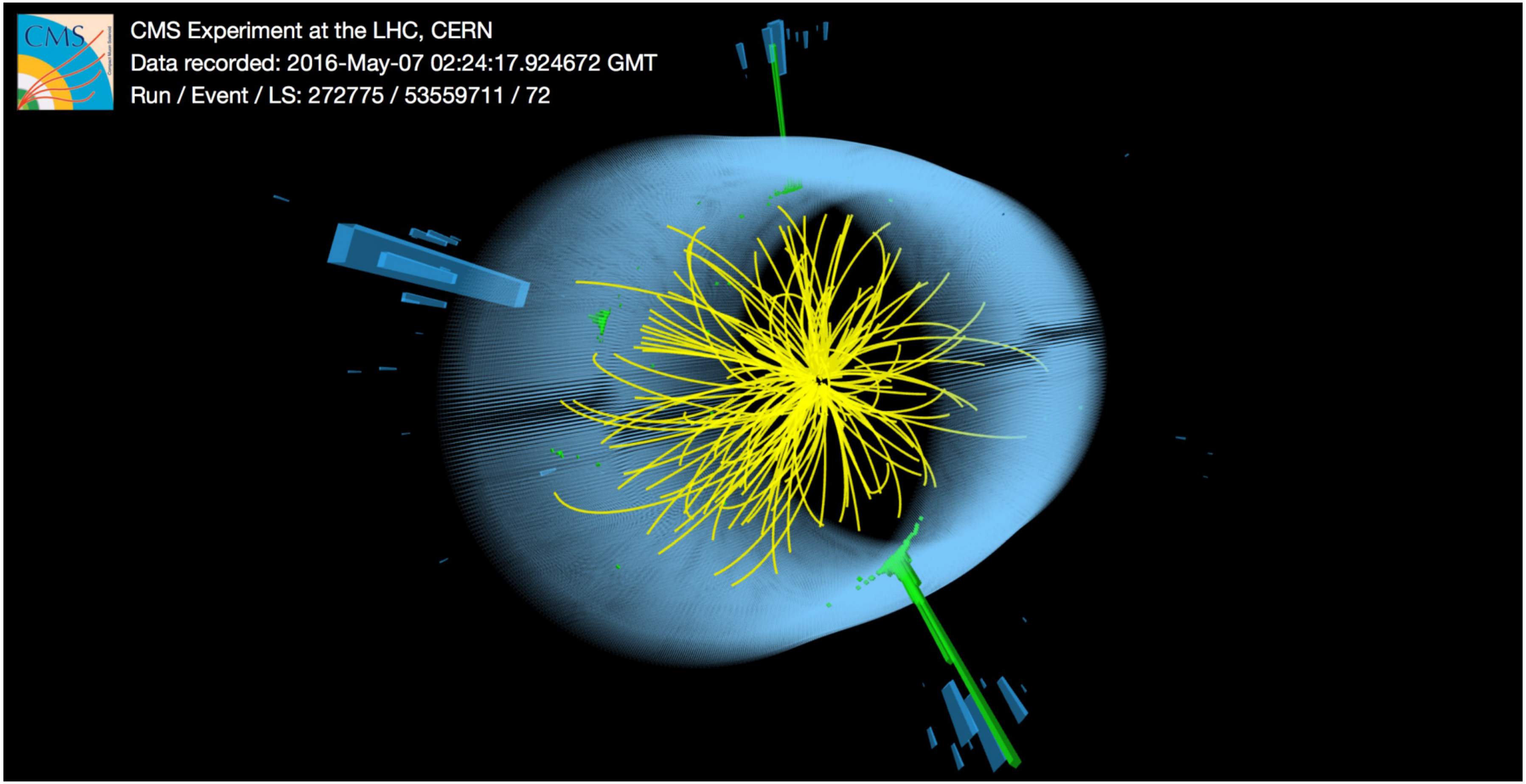
Dec 2015

Highest mass dijet event: 7.7 TeV



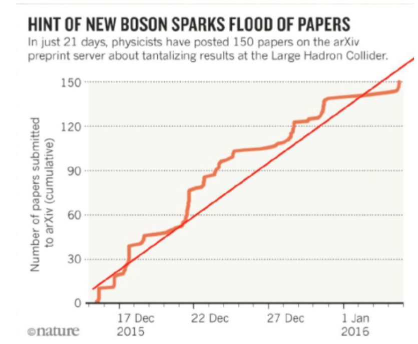
Summer 2016

A nice diphoton event



Searches for Diphoton Resonances

In December 2015 both ATLAS and CMS showed a small excess above background at around 750 GeV.

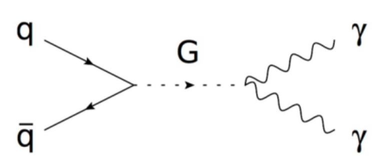


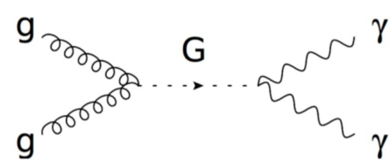
Nature, Paul Ginsparg

- Triggered a flood of theoretical papers: 263 papers on 1st of March

Two benchmark models:

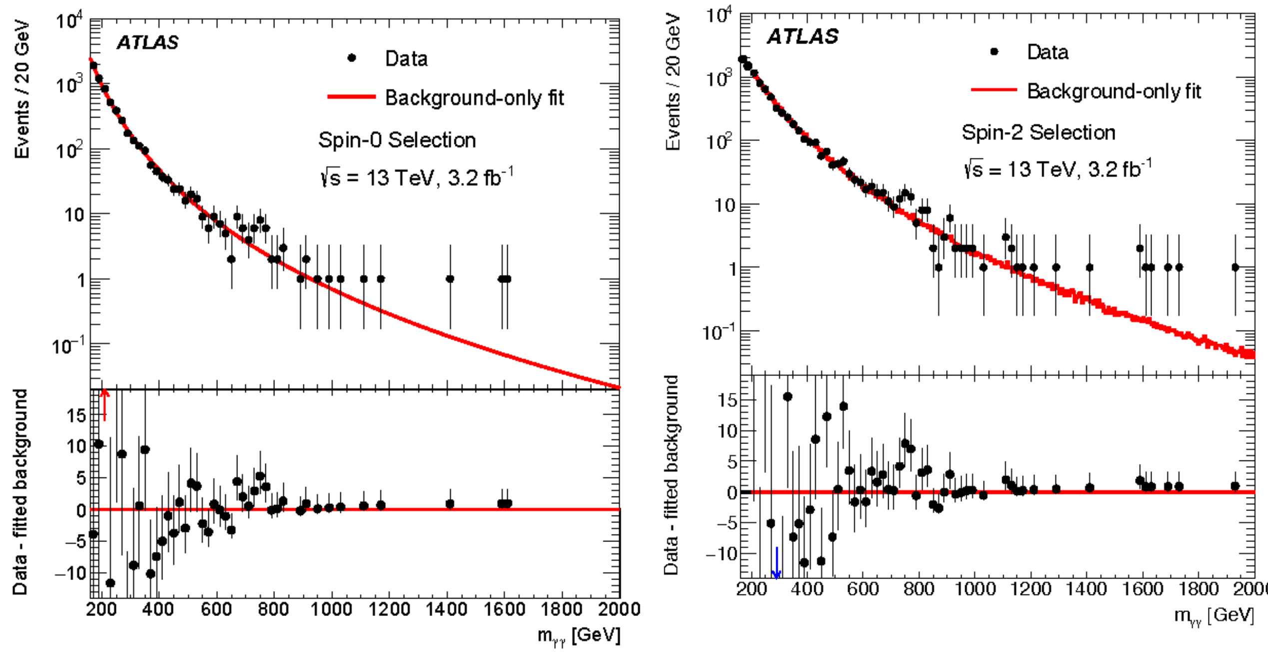
- **Spin-0 analyses (e.g. extended Higgs sector)**
  - 2HDM (Two-Higgs-Doublet-Model)
  - 5 physical states h^0, H^0, A^0, $H^\pm$
  - under certain conditions, scalar and/or pseudo-scalar states can have sizable branching ratio to diphoton
- **Spin-2 analyses (e.g. Randall-Sundrum graviton)**
  - Model predicts Kaluza-Klein graviton states with TeV mass scale
  - Phenomenology:
    - m_{G^*} = mass of lightest KK excitation
    - κ/M_{Pl} = dimensionless coupling to SM fields





ATLAS: Diphoton Result Run 2 -2015

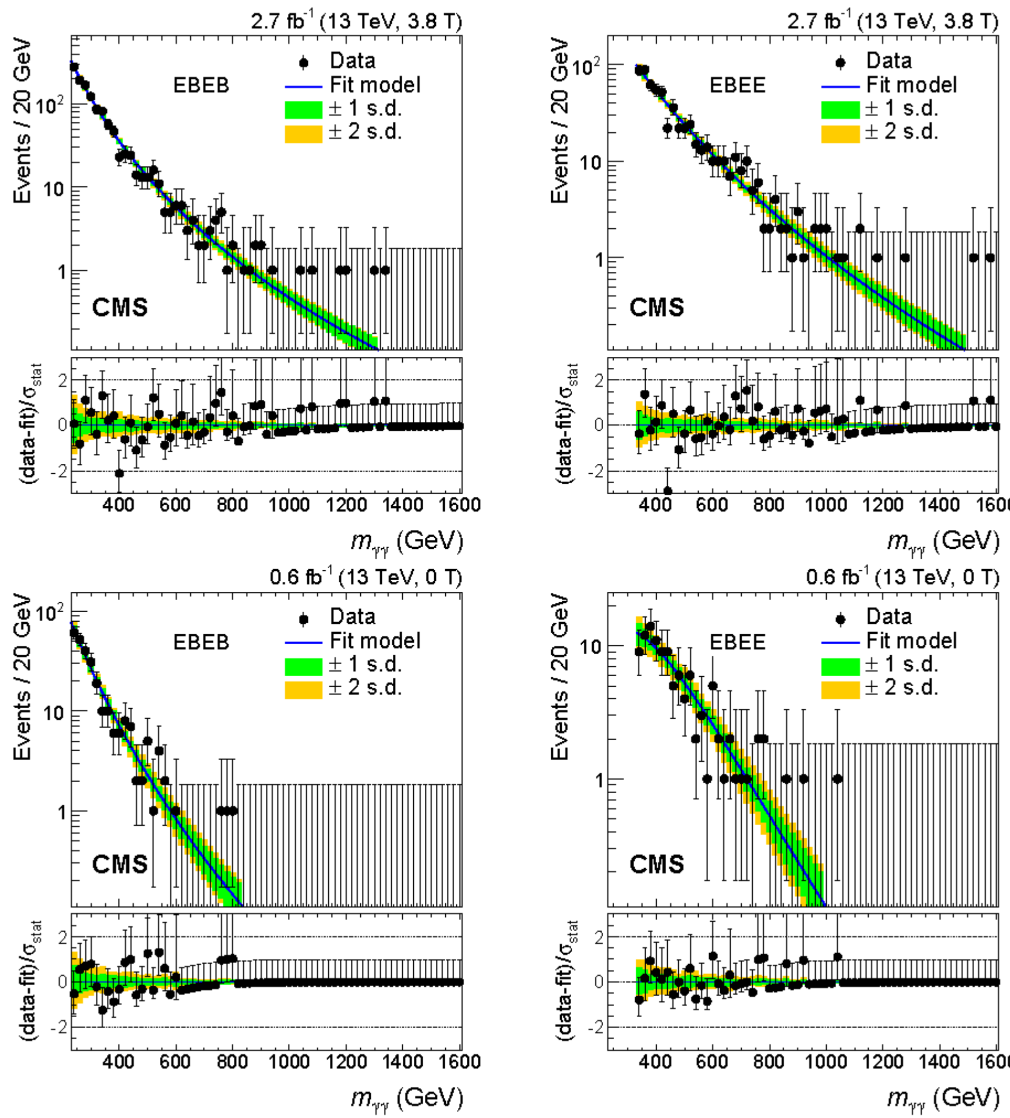
The ATLAS paper appeared on arXiv on Tue 14th June 2016: 1606.03833



- Spin-0 hypothesis analysis (left): ET1> 0.4mγγ, ET2> 0.3mγγ, m~750 GeV, significance: local 3.9σ, global 2.1σ
- Spin-2 hypothesis analysis (right): ET1> 55 GeV, ET2> 55 GeV, m~750 GeV, significance: local 3.8σ, global 2.1σ
- More data (~10 fb-1?) have certified ~5 fb-1in 2016) expected for ICHEP

CMS: Diphoton Results Run 2 - 2015

The CMS paper appeared on arXiv on Tue 14th June 2016: 1606.04093

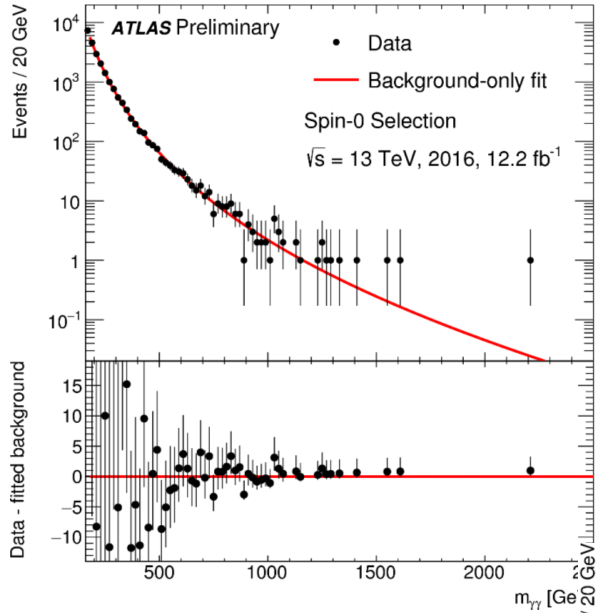


- **B=3.8T** data sample (top) and **B=0T** sample (bottom): ET1 > 75 GeV, ET2 > 75 GeV, m~750 GeV.
- **Combined 8 and 13 TeV** significance: local 3.4σ, global 1.6σ.

ATLAS: Diphoton Result Run 2

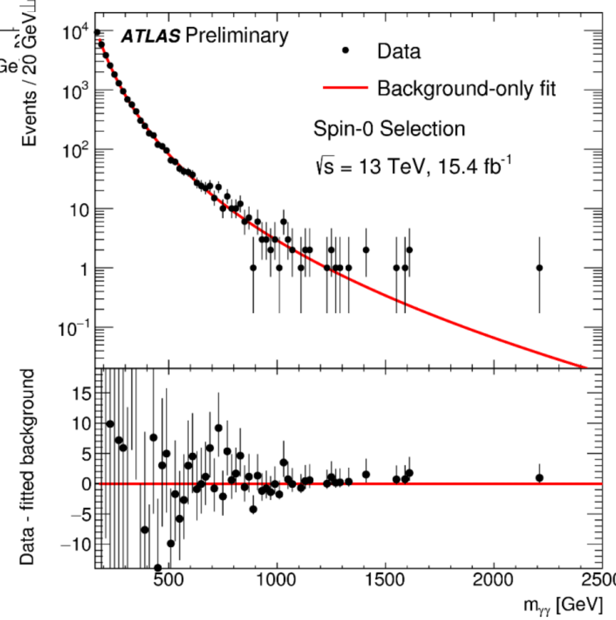
2016 Data:

- no clustering around 730-750 GeV, 3.8x more data
- 2016 data consistent with 2015 at the 2.7σ level
- Appears that the 2015 excess was a statistical fluctuation



2015+2016 Data:

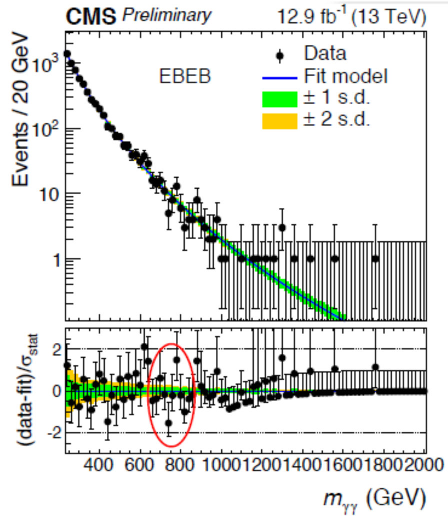
- With 2015+2016 data:
- Small excess at 710 GeV (Γ/m~10%)
- Local significance 1.4σ, global <1σ

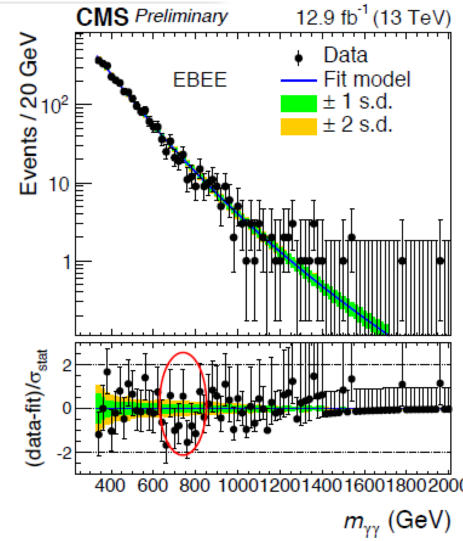


CMS: Diphoton Result Run 2

2016 Data:

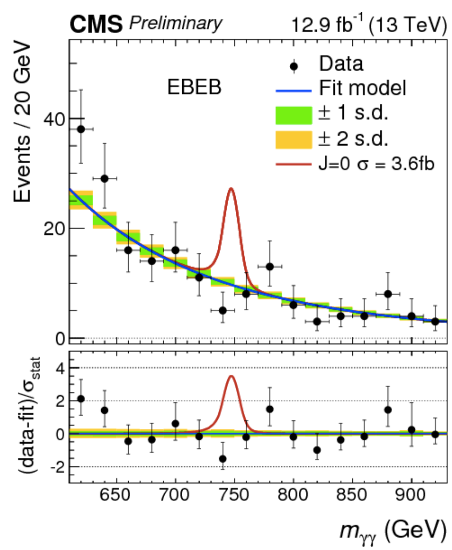
- straight reload of 2015 analysis
- no evidence of strengthening of this bump

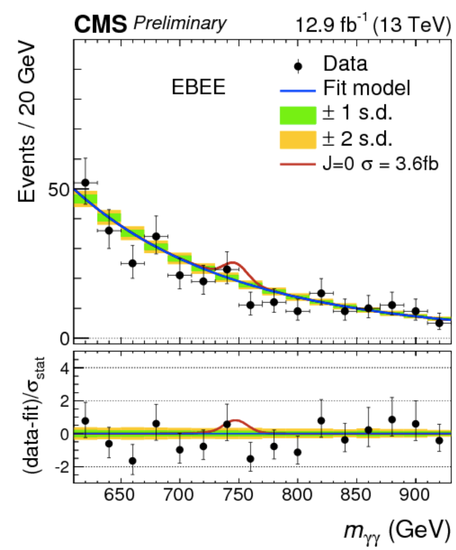




What we would have seen:

- Recall that global significance of CMS 13 TeV (2015)+8 TeV was 1.6 σ
- …not really seen !
- Searched also in Zγ → nothin!





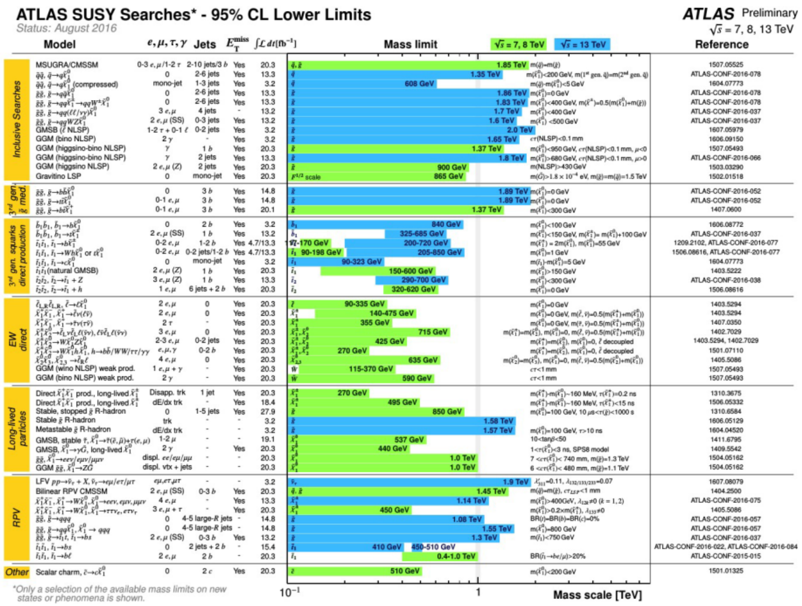
Lesson to be learned:

Stay careful with statistics

Even if two experiments seem to see the same thing, it can be a

FLUCTUATION !

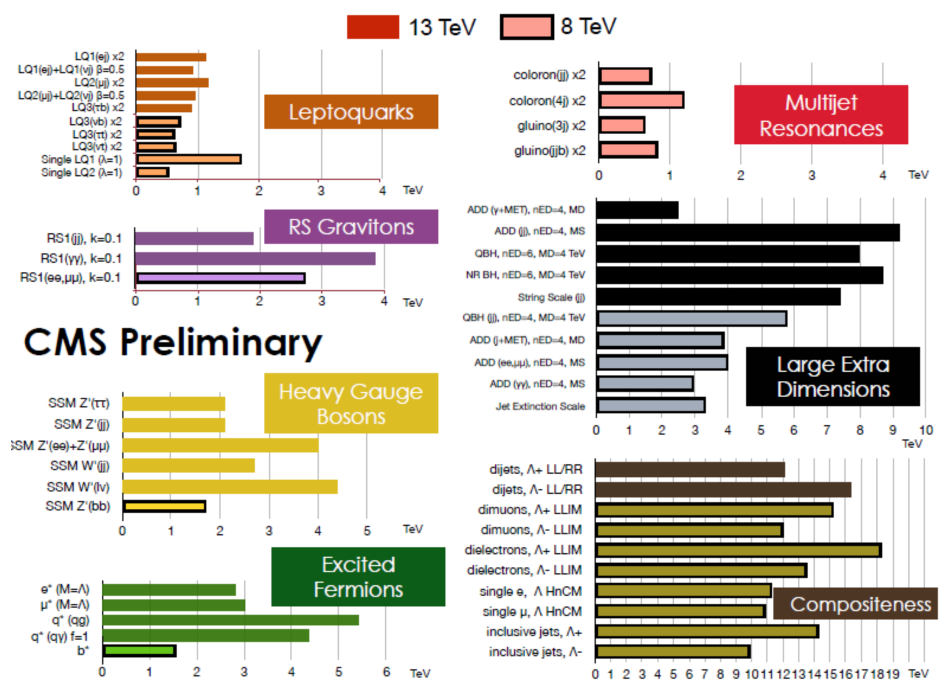
Searches for New Physics - Run 2



ATLAS SUSY Searches

CMS Exotica Searches

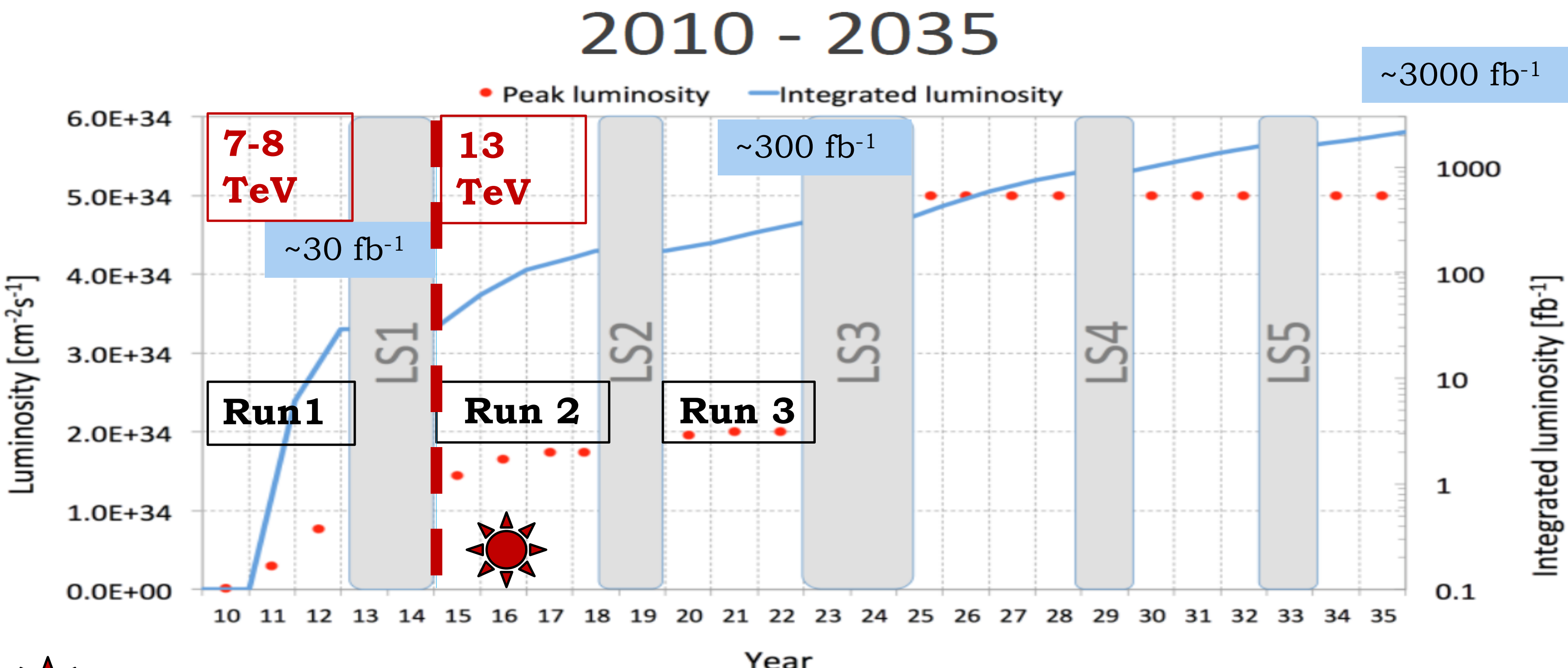
Excluding Dark Matter and Long Lived particles searches



Keep watching out !

Took only less than 10% of the data expected for Run 2 up to 2018 !

Future @ LHC



: new world-record energy and much more statistics

→ Opening the window to unexplored territories for much higher masses of unknown particles and forces

→ New Physics

→ Dark Matter ? SUSY ? Extra-Dimensions ?

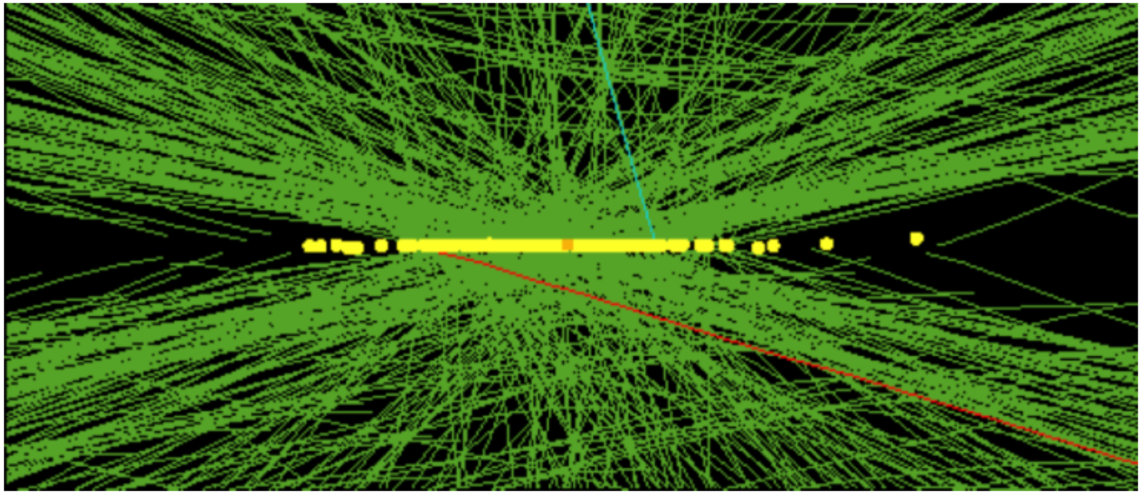
→ Precision measurements of the Higgs, top, …

Challenges @ LHC

- **Highest Energies**
- **Intense Beams**

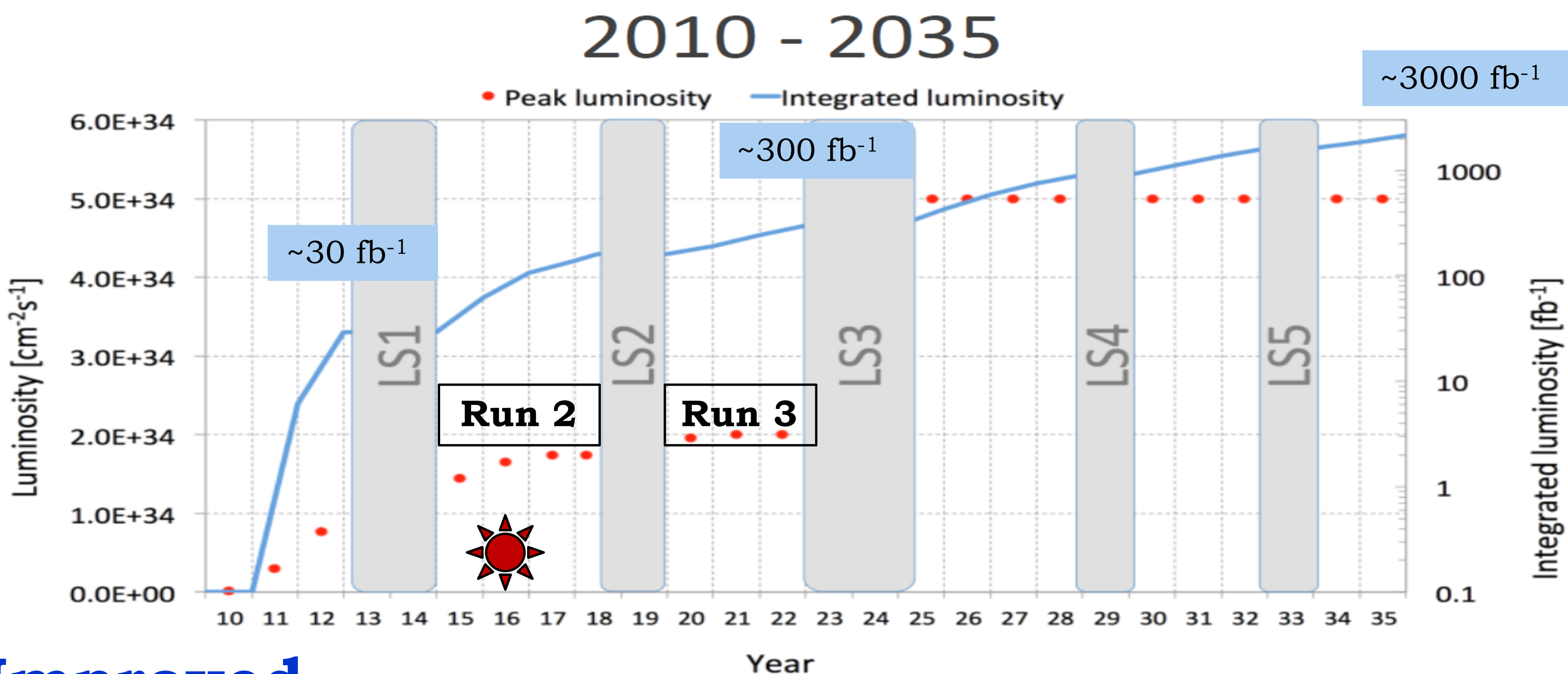
extreme particle flow

  - **Pile up 20 → 50 → 200 → complex analyses**
  - **Extreme radiation hardness of detectors**
  - **Extrems high readout rate (DAQ, Computing)**



- **Need new technologies and clever ideas: detectors, computing, analyses**

Future @ LHC



Improved detectors

Ready ☺ **Phase I Construction**

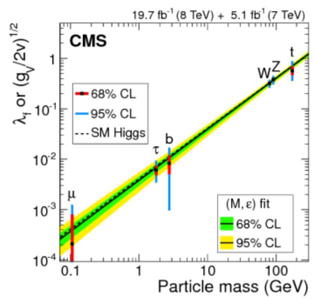
Phase II

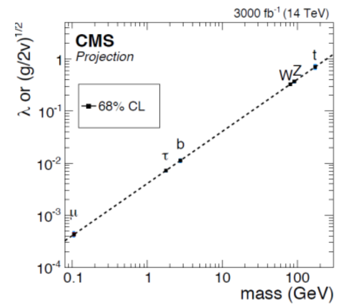
Physics studies, R&D application for funding

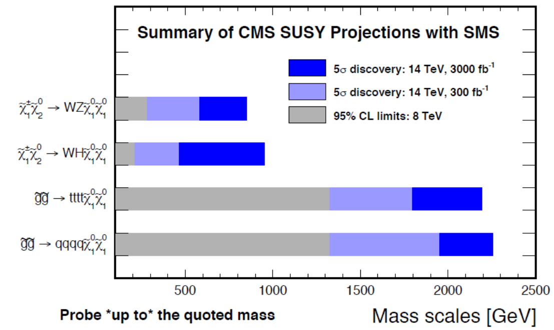
High Luminosity LHC

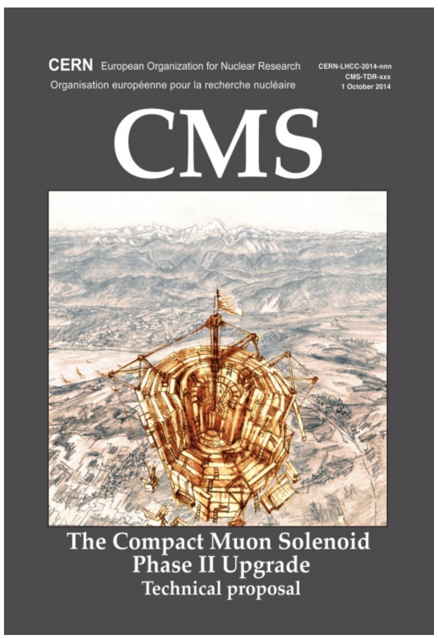
Physics Topics:

- Higgs Physics
- Searches
- VBF / VBS
- … many more









Technical Proposal for the CMS Phase II Upgrade:

- Physics motivation
- Detector Upgrades & Performance
- Physics Object Performance
- Physics Performnace
- Core Costs

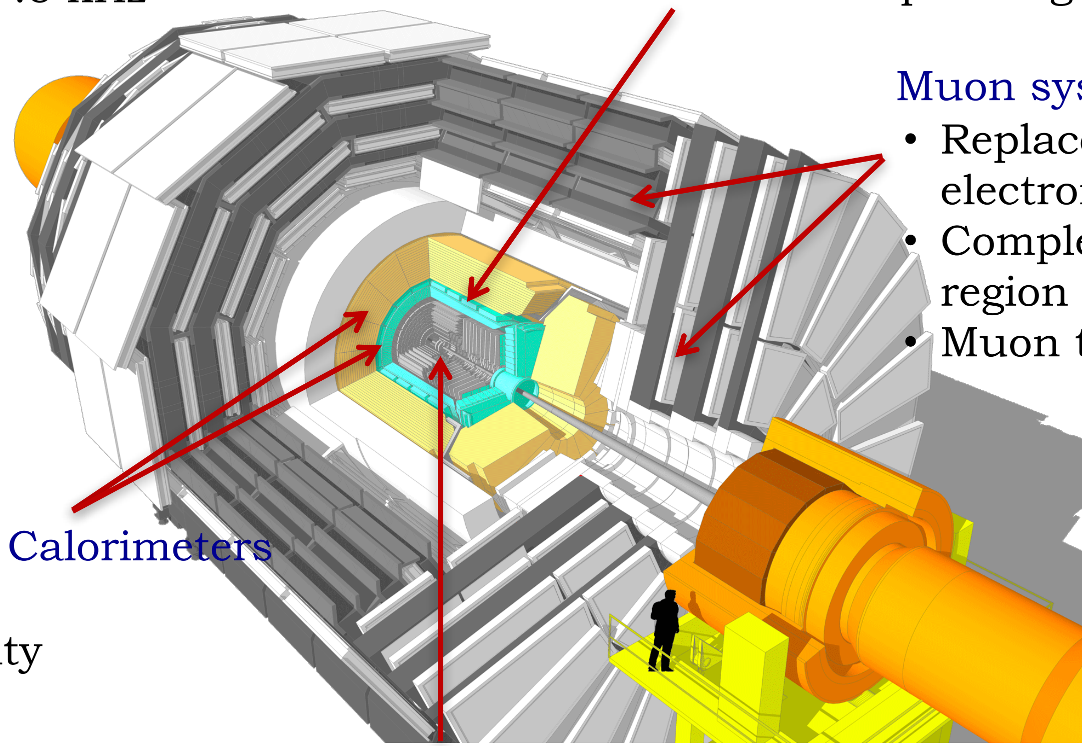
CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886

CMS Phase II Upgrades

Trigger/HLT/DAQ
- Track information at L1-Trigger
- L1-Trigger: 12.5 µs latency - output 750 kHz
- HLT output ≃7.5 kHz

Barrel EM calorimeter
- Replace FE/BE electronics
- Lower operating temperature (8∘C)

Muon systems
- Replace DT & CSC FE/BE electronics
- Complete RPC coverage in region $1.5 < \eta < 2.4$
- Muon tagging $2.4 < \eta < 3$



Replace Endcap Calorimeters
- rad. tolerant
- high granularity
- 3D capability

Replace Tracker
- Rad. tolerant - high granularity - significantly less material
- 40 MHz selective readout (Pt≥2 GeV) in Outer Tracker for L1-Trigger
- Extend coverage to $\eta = 3.8$

Summary

- **Overwhelming harvest from Run 1 Data**
- **Detector improvements in LS 1 paying off**
- **LHC with its Experiments return to discovery mode**
  - **improved detectors, trigger and reconstruction algorithms**
- **2015 data taking in Run 2 delivered novel results**
  - **high precision measurements**
  - **hot searches for New Physics**
- **2016 data taking has started with outstanding performance**
- **Road to the future paved**
  - **Phase I upgrades proceeding well**
  - **Phase II technical proposal submitted**

Full collection of newest results, more details and many pictures taken from:

LHCP 2016:	https://indico.cern.ch/event/442390/timetable/
Moriond EW 2016:	https://indico.in2p3.fr/event/12279/
Moriond QCD 2016:	http://moriond.in2p3.fr/QCD/2016/
ICHEP 2016:	http://indico.cern.ch/event/432527/timetable/#20160810

Any Questions ?

BACKUP