CMS Physics Overview

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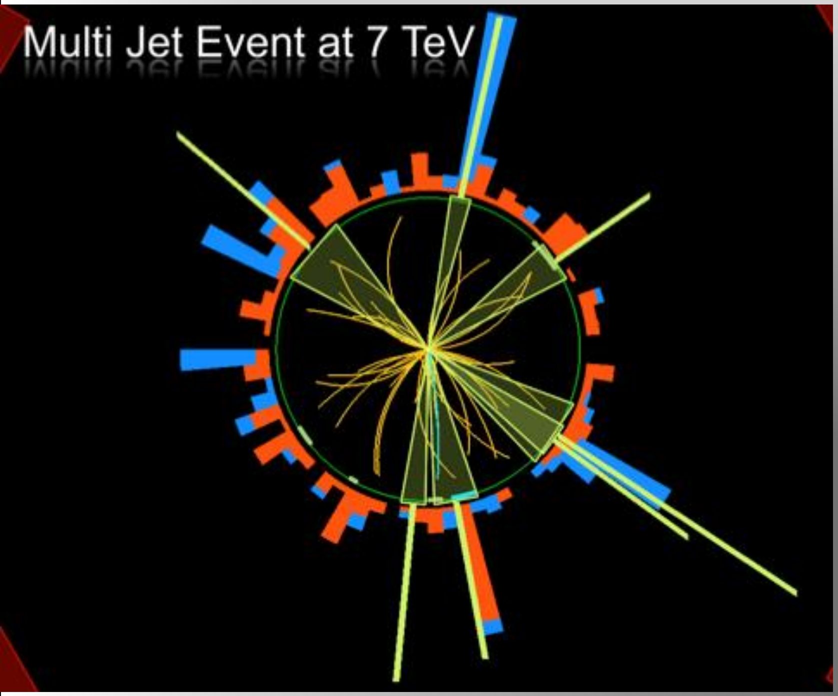
CMSDASia - CMS Data Analysis School in Taipei, Taiwan



Outline Lecture I

- Introduction: The Large Hadron Collider and CMS
- Basics of experimental pp collisions
- Standard Model measurements
- The Higgs Particle

Searches will be discussed in the next lecture

The "Standard Model"

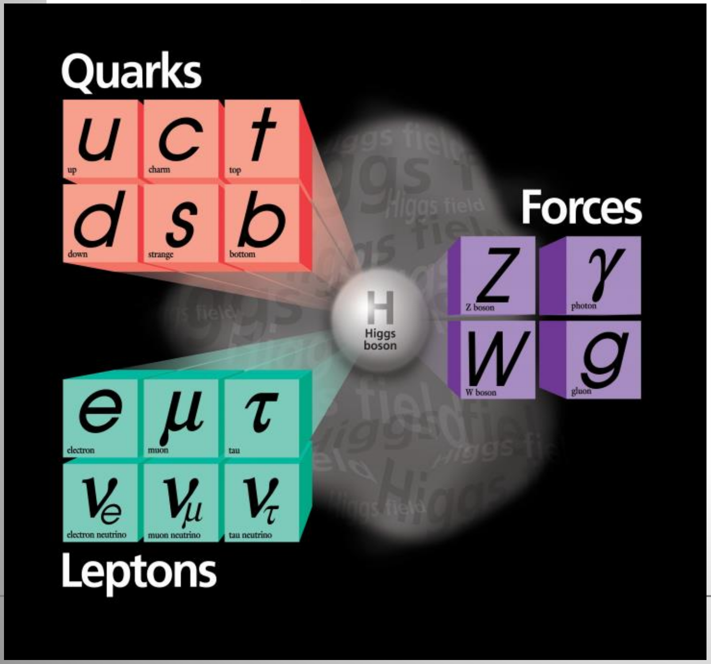
Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

Fermions

Bosons

Matter particles



Force particles

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 ½
Bosons: particles with integer spin

The Hunt for the Higgs

Where do the masses of elementary particles come from?

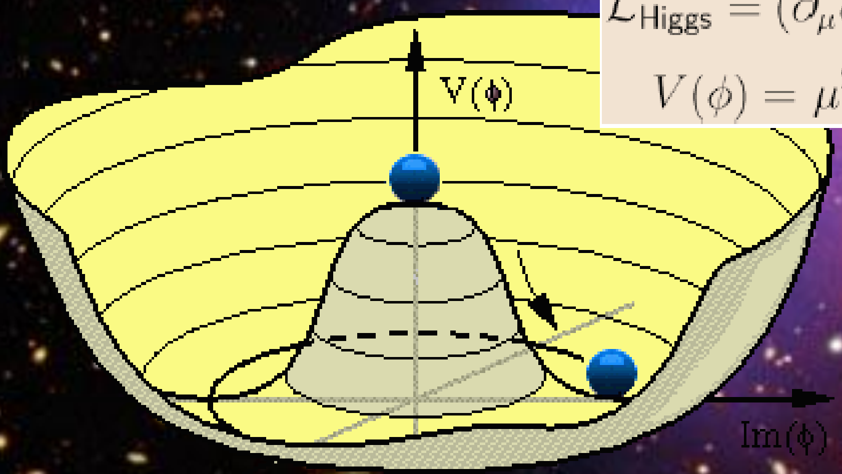
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

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

We do not know the mass of the Higgs Boson

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

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

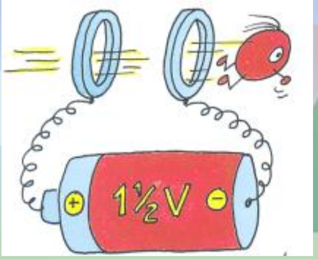


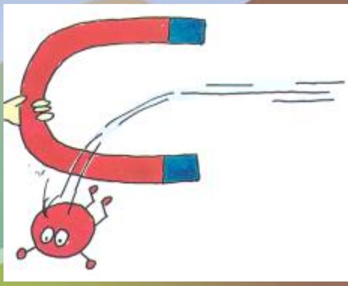
Scalar field with at least one scalar particle

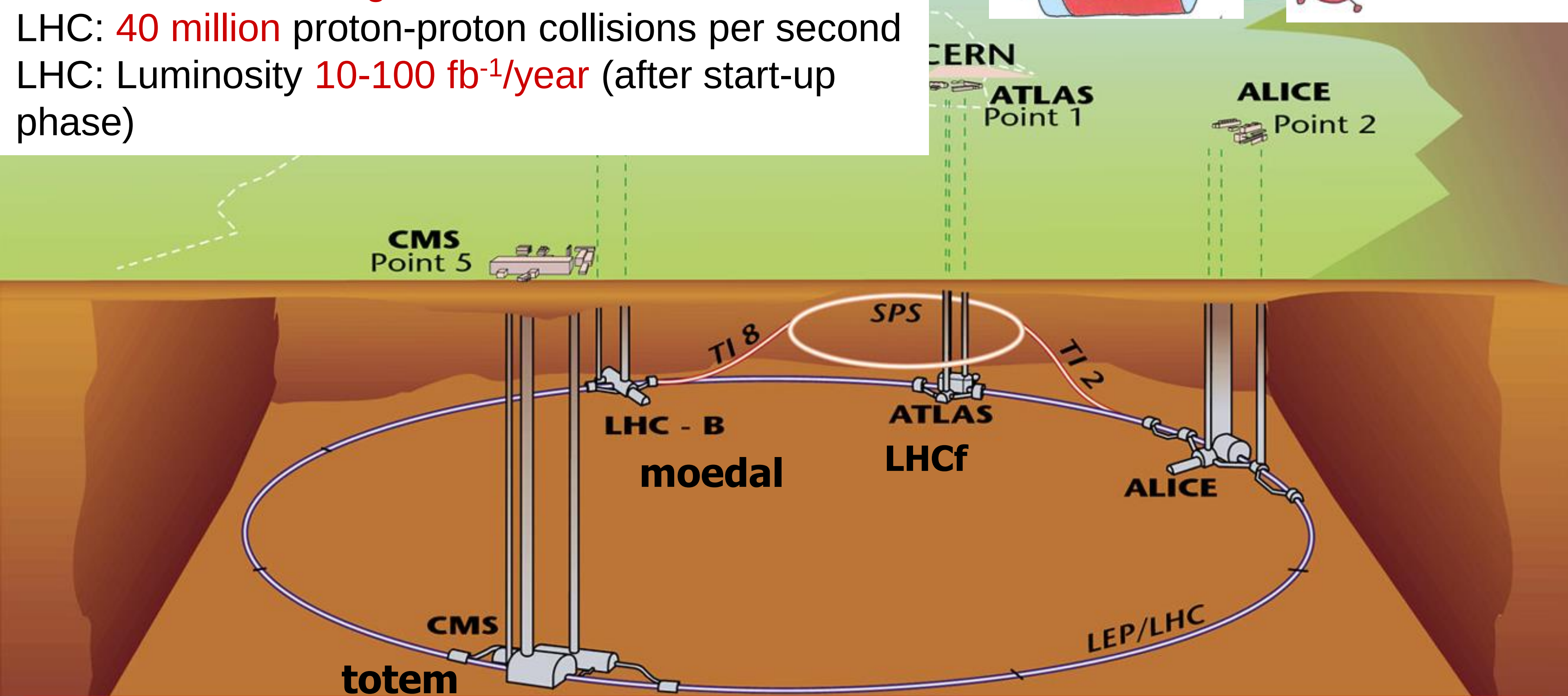
Before 2012: anywhere from 114 to ~700 GeV

The LHC Machine and Experiments

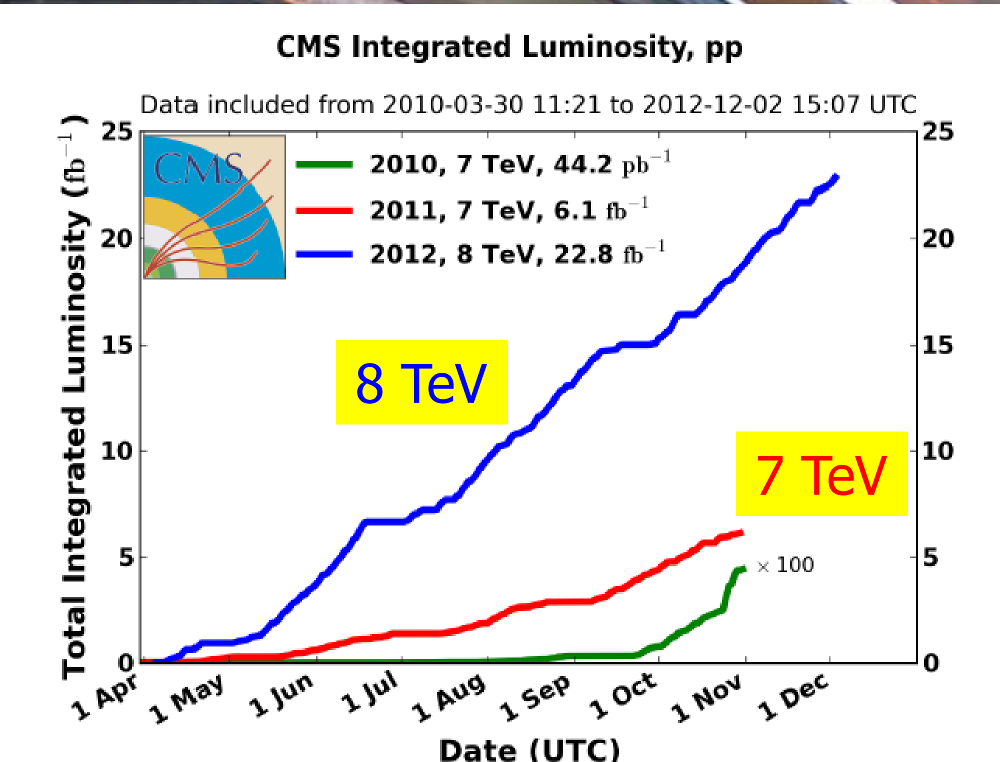
LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)







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



Run-I: LHC did very well in 2011/2012

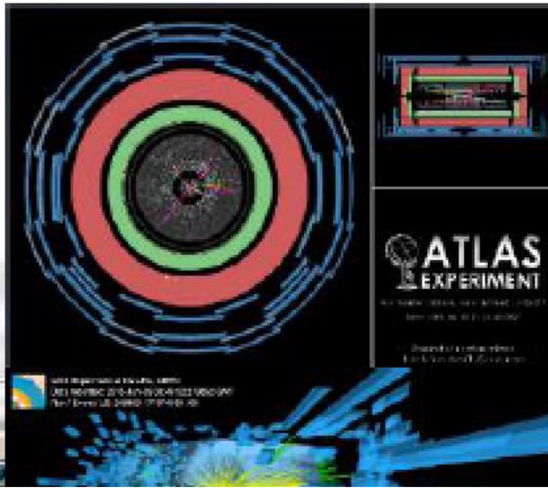
2011: luminosity 3 . 10^{33} cm^{-2} s^{-1} $\Rightarrow$ 5 fb^{-1} collected in total

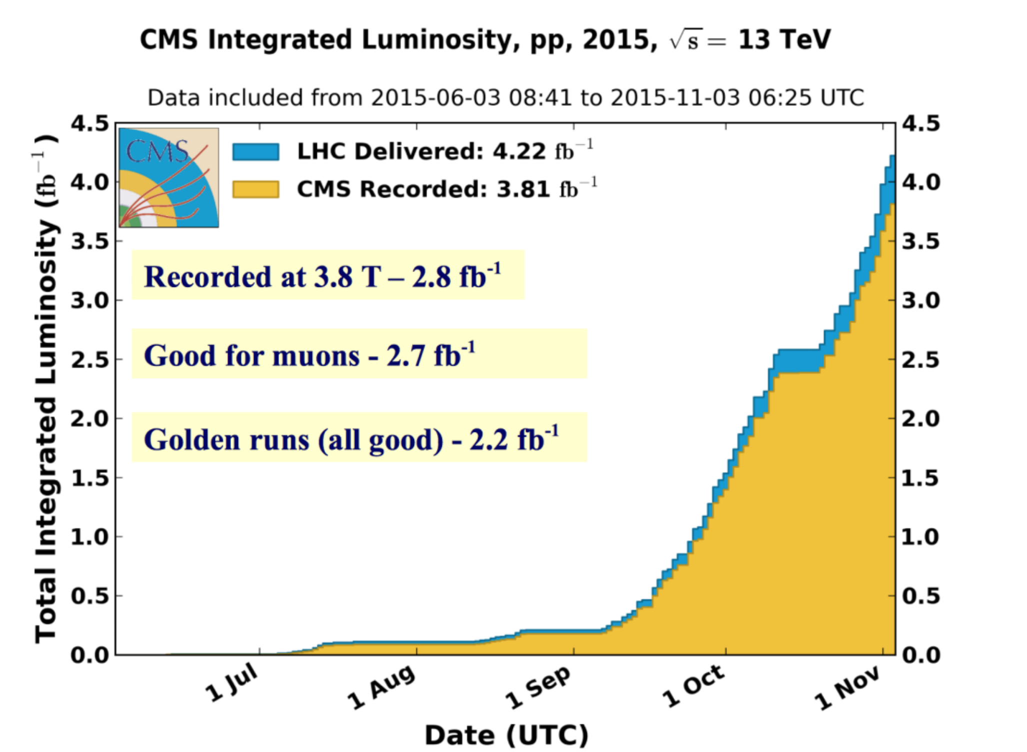
2012: luminosity 7.8 . 10^{33} cm^{-2} s^{-1} $\Rightarrow$ 20 fb^{-1} collected in total

LHC was shut down in 2013-2014 for 'upgrade' to 13/14 TeV

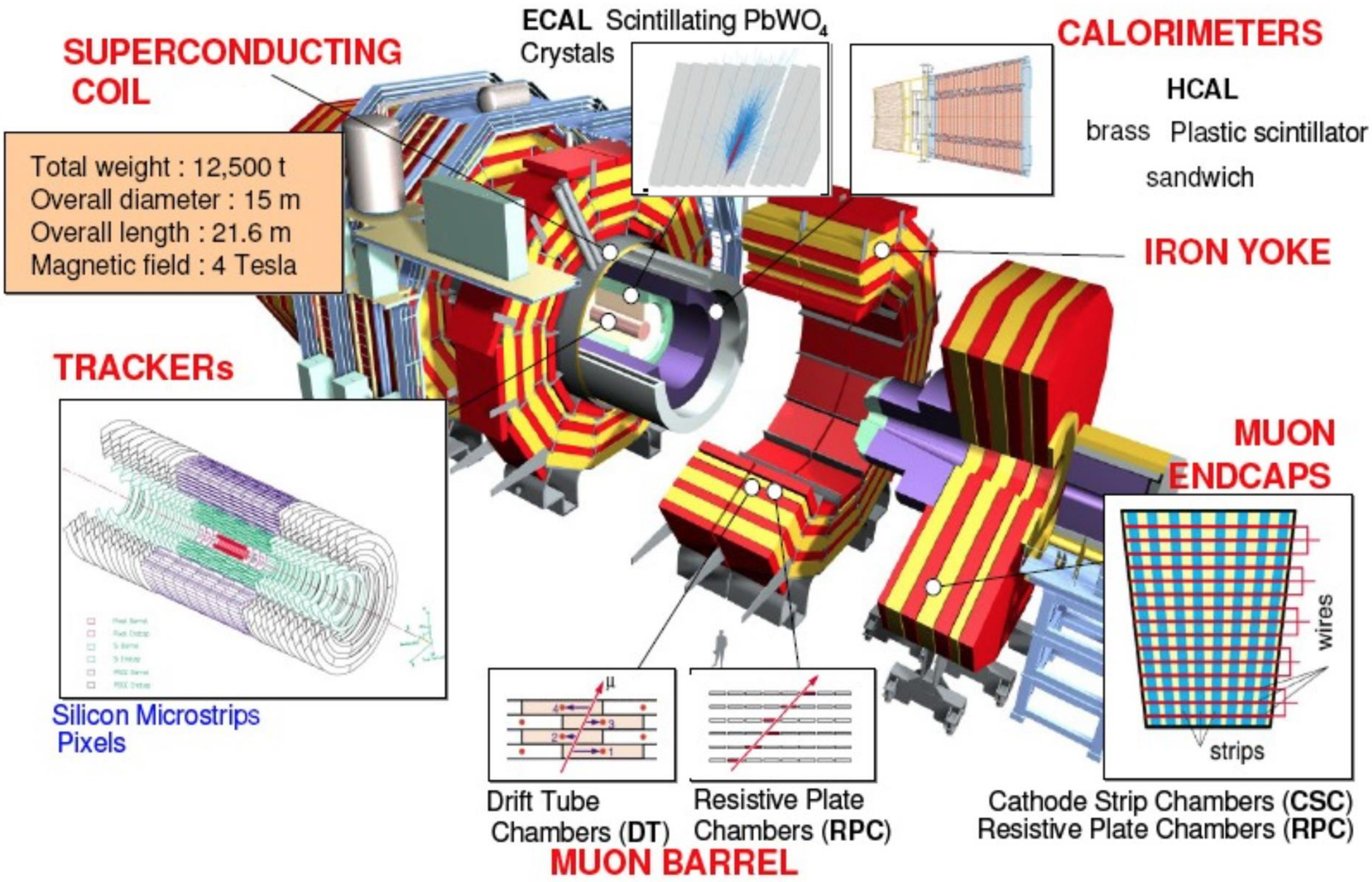
LHC experiments are back in business at a new record energy 13 TeV

3rd June 2015

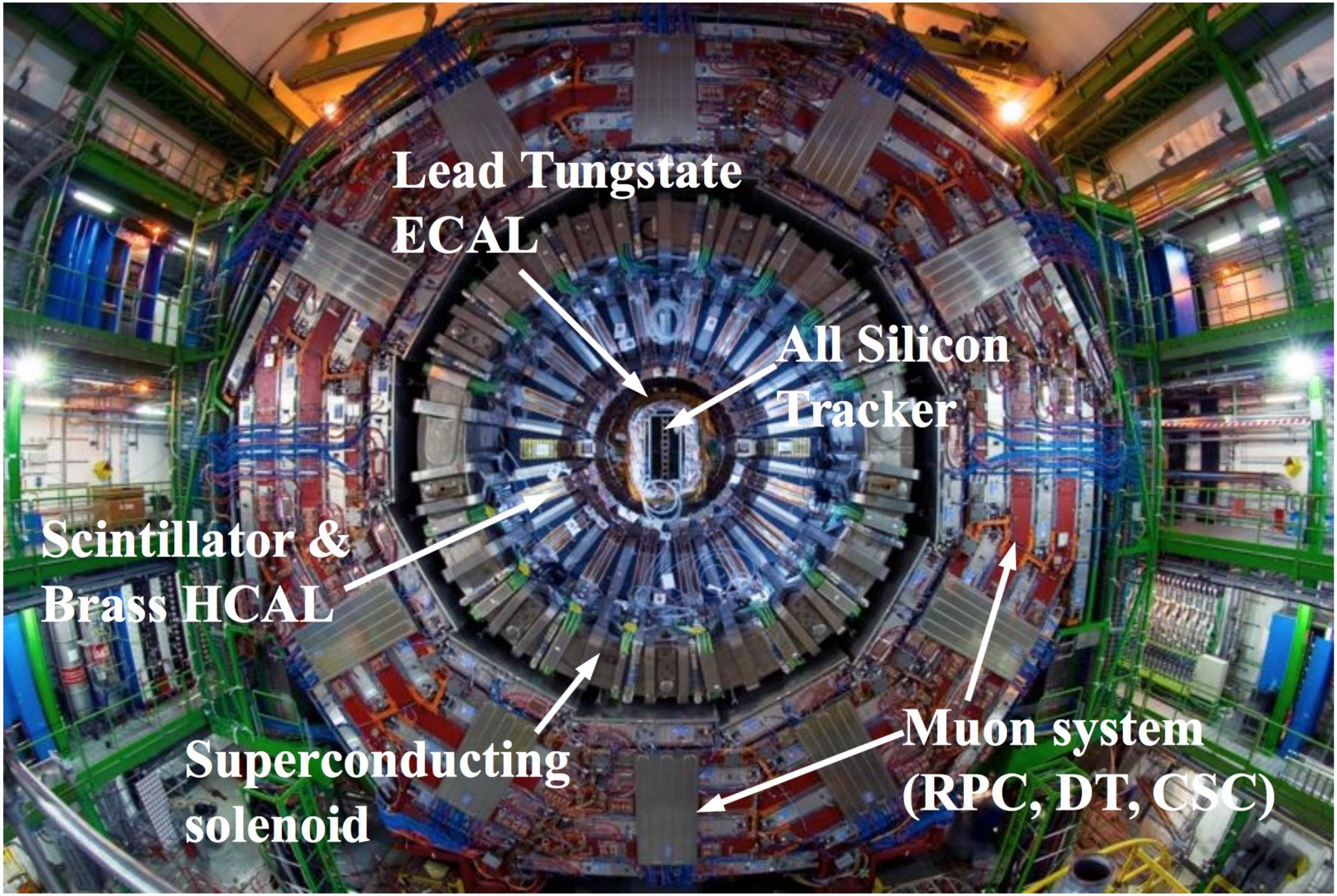




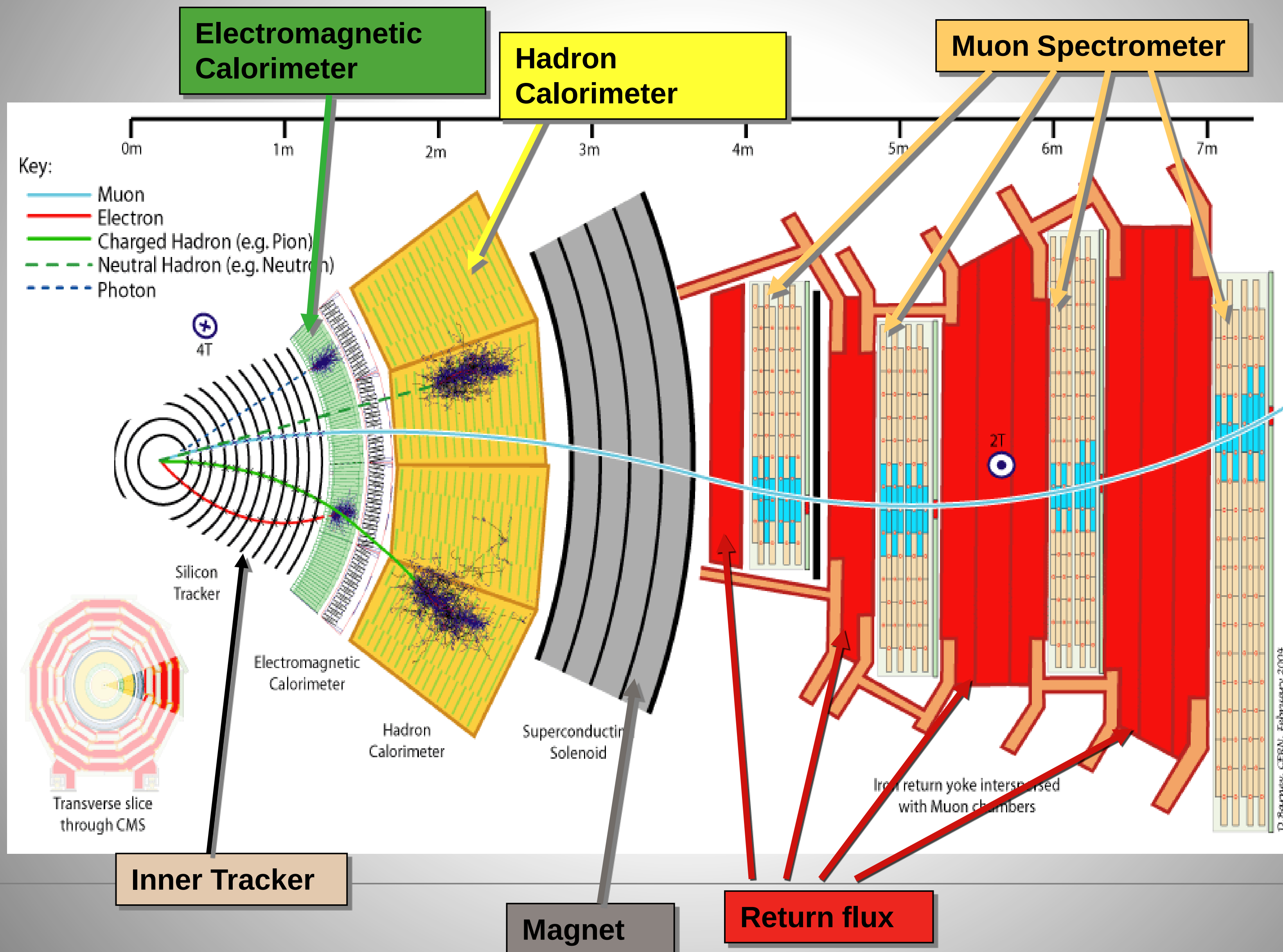
The CMS Experiment



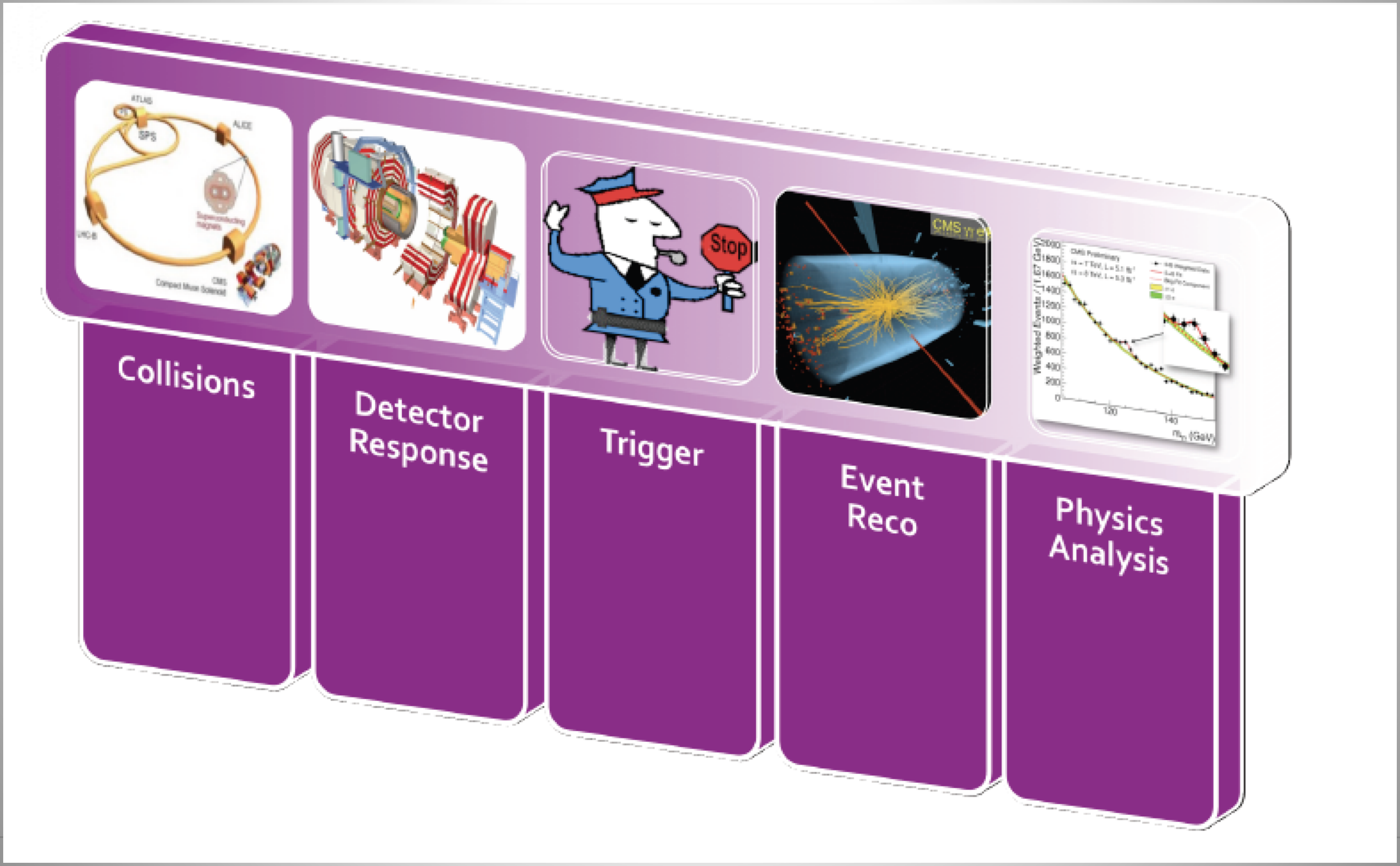
The CMS Experiment



Particles in Detectors

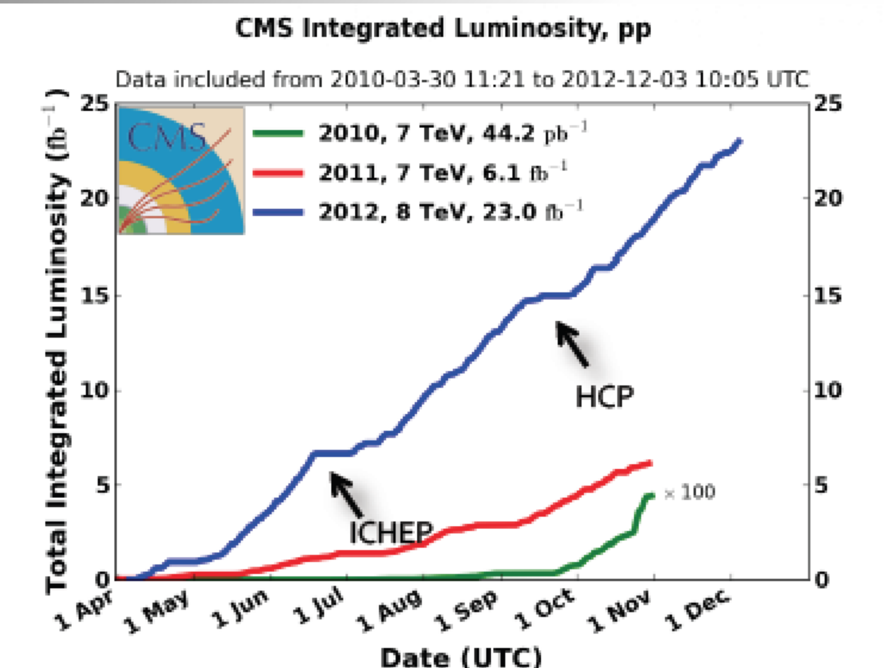


From Collisions to Papers…

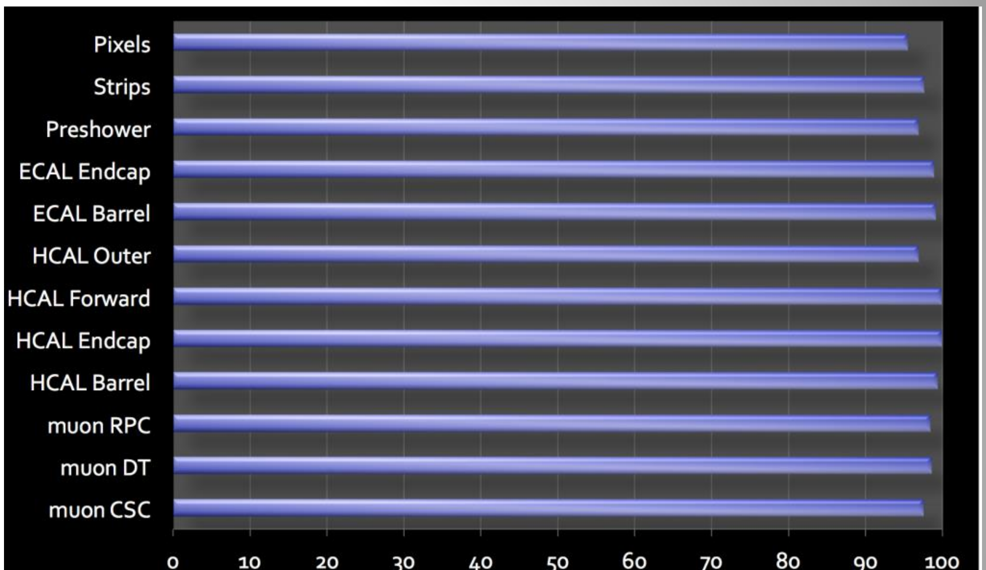


Operation of the Experiment

pp collisions luminosity for analysis:
5 fb^{-1} @ 7 TeV
20 fb^{-1} @ 8 TeV



CMS: sub-detector operation

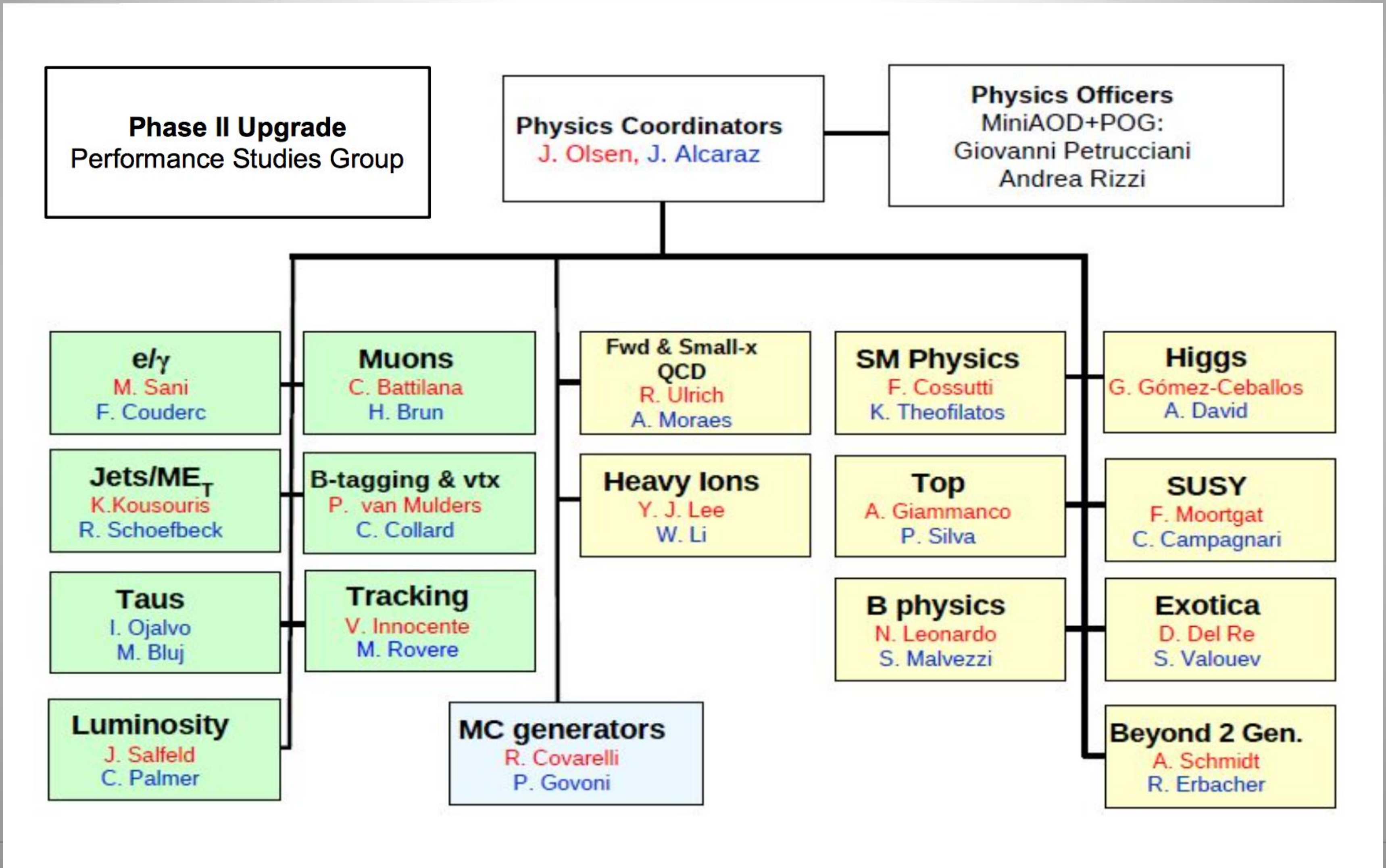


CMS Subsystem	muon CSC	muon DT	muon RPC	HCAL Barrel	HCAL Endcap	HCAL Forward	HCAL Outer	ECAL Barrel	ECAL Endcap	Preshower	Strips	Pixels
%Operational	97.6	98.6	97.7	99.4	99.96	99.9	96.9	99.11	98.4	96.8	97.5	95.9

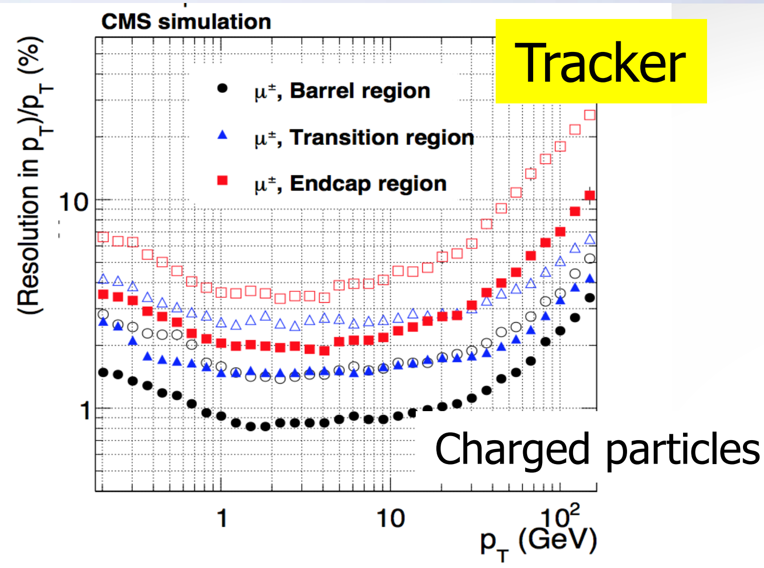
CMS: sub-detector operation efficiency in 2012

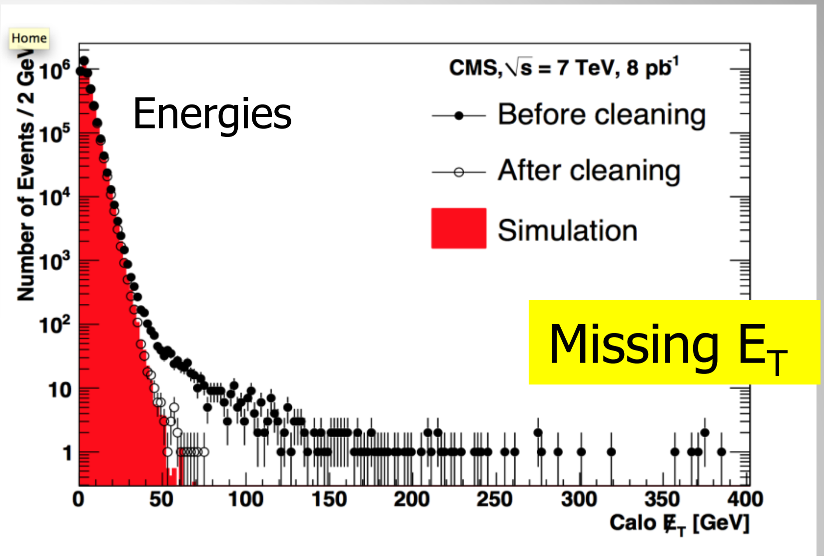
Period	Delivered* fb^{-1}	Recorded* fb^{-1}	Efficiency	Downtime	Dead-time
April - June	6.78	6.26	92.3%	5.9%	1.8%
July - 21Aug**	4.97	4.73	95.1%	3.8%	1%
22Aug - 16 Sep	2.99	2.74	94.4%	4.1%	1.5%
26 Sept – 7 Oct	1.44	1.37	95.1%	3.4%	1.5%
9 Oct – 3 Dec	6.9	6.5	94.8%	3.7%	1.5%

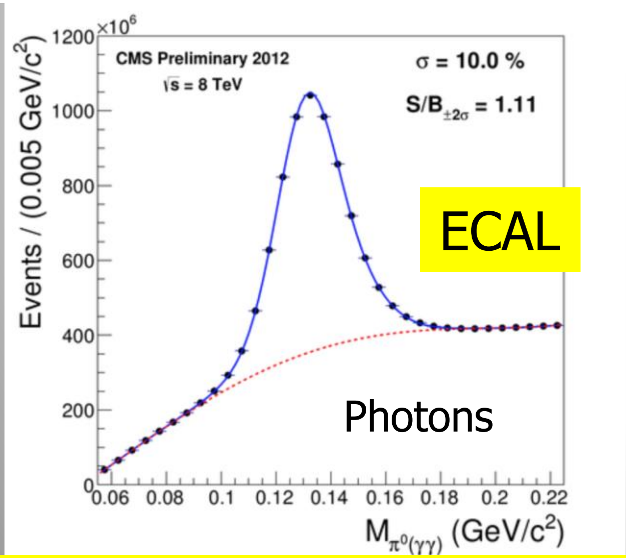
CMS Physics Organization Panorama

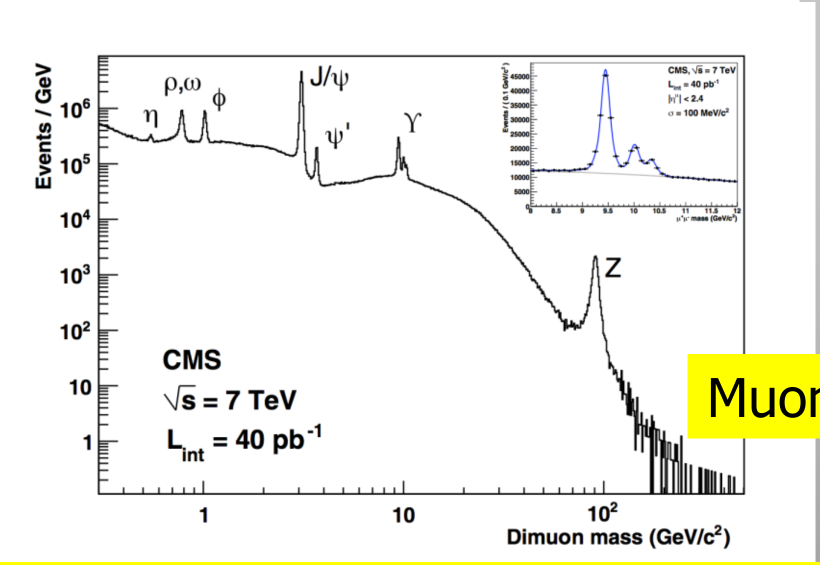


Object Reconstruction: Examples





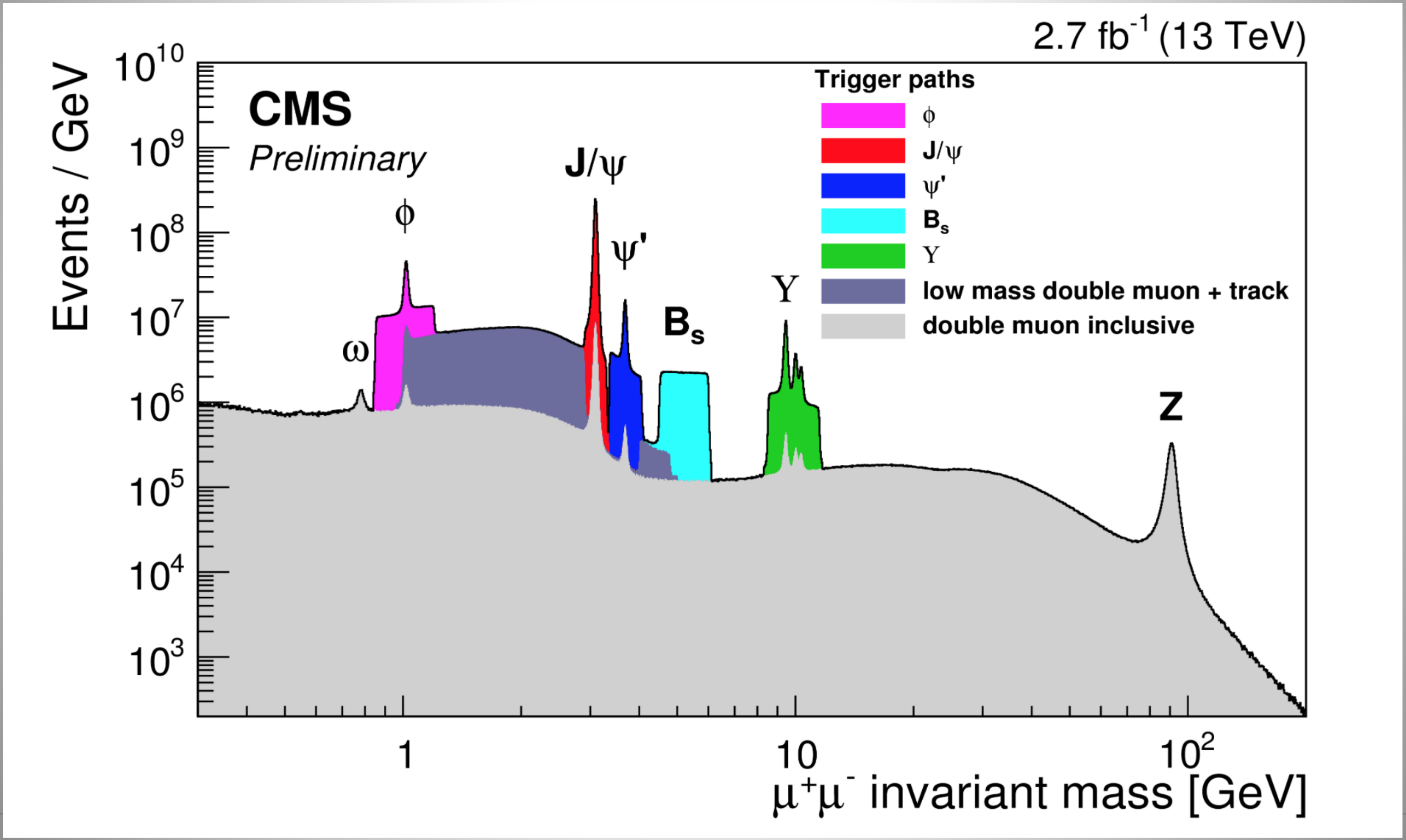




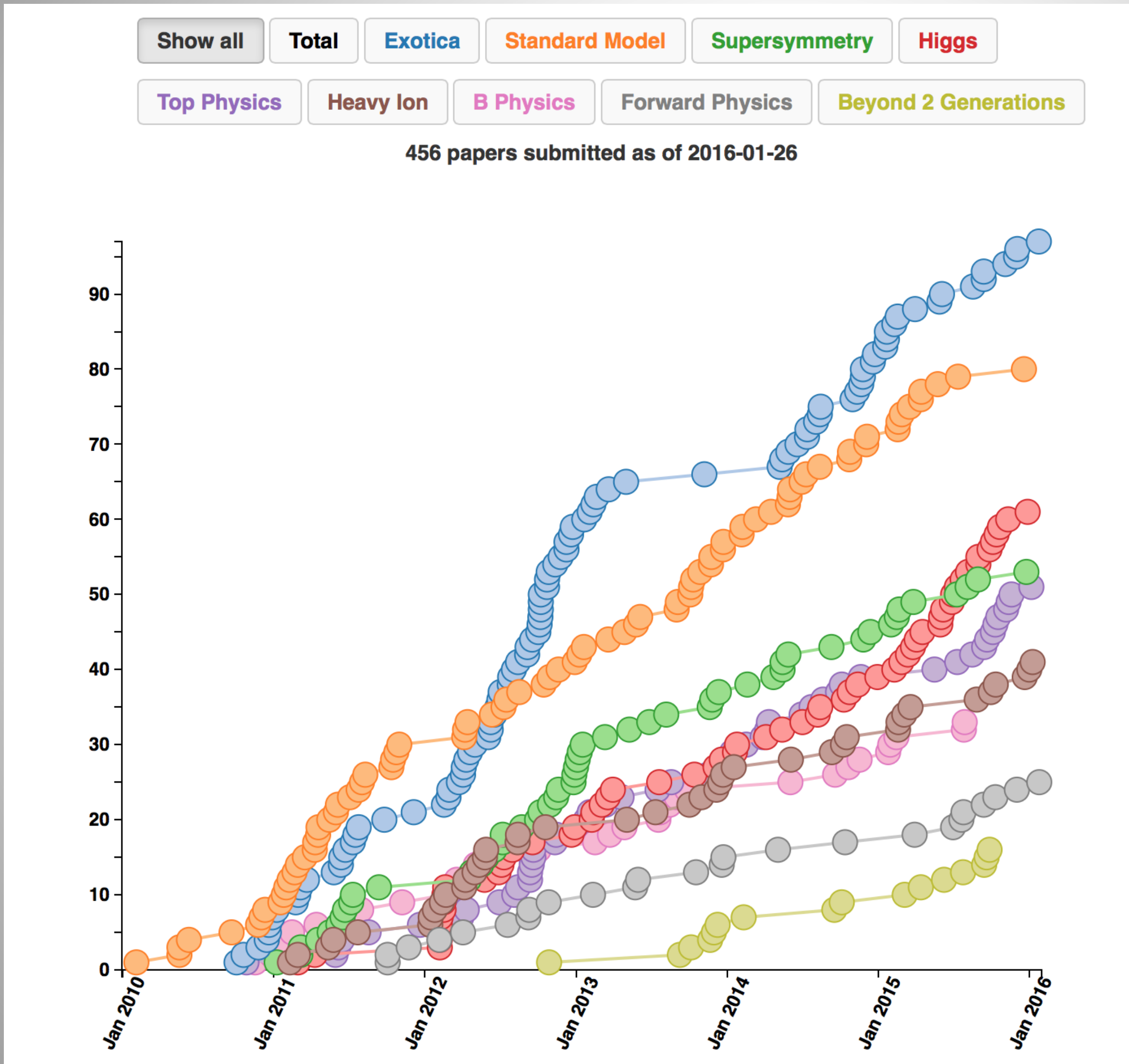
Important! Experiments are not like Monte Carlo Generators: often no unique assignment of particle type/fakes/backgrounds!!

High Quality Data in 2015!

Di-muon mass spectrum



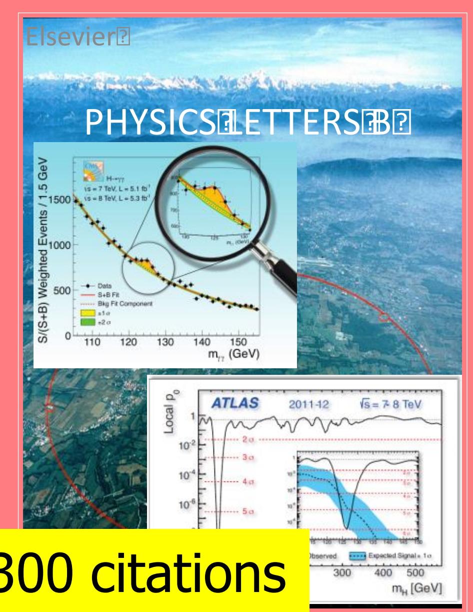
CMS Publications



~456 publications on pp (and pPb/PbPb) physics since 1/2010 (1/2/2016)

About 50 papers on Higgs studies!!

Paper 16 was the discovery paper!

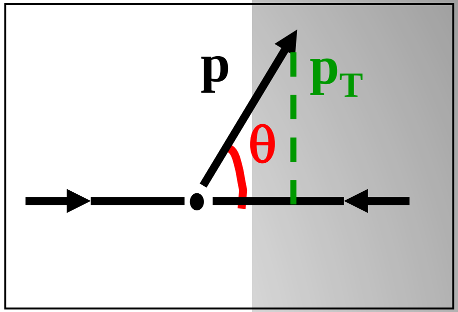


https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG

~5300 citations

Kinematic Variables for pp Scattering

- Transverse momentum, p_T and E_T=E sinθ
  - Particles that escape detection (0) have p_T=0
  - Visible transverse momentum =0
    - Very useful variable!



- Longitudinal momentum and energy, p_z and E
  - Particles that escape detection have large p_z
  - Visible p_z is not conserved
    - Not so useful variable
- Angle:
  - Polar angle θ is not Lorentz invariant
  - Rapidity: y
  - Pseudorapidity: η

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

For M=0

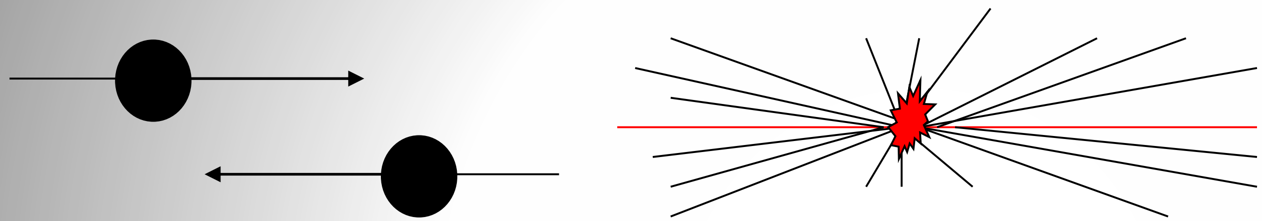
$$y = \eta = -\ln(\tan\frac{\theta}{2})$$

- Missing E_T and P_T: : Vectorial sum of all transverse momenta

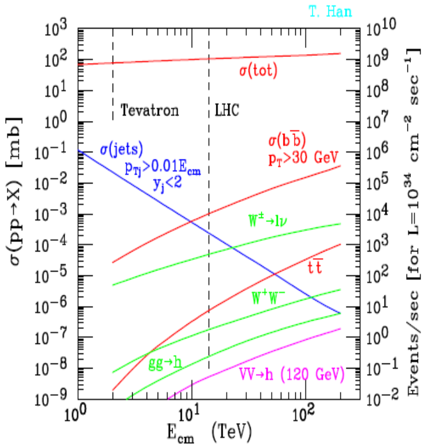
Soft Scattering
Non-Perturbative QCD

Understanding Soft Collisions

Most collisions at the LHC do not involve a hard scattering scale: these are so called soft collisions. They make up most of a “minimum bias” event sample



Scattering cross sections for various SM processes:



- Detailed studies of multi-particle production in pp
- Monte Carlos tunes, eg for describing the pile-up

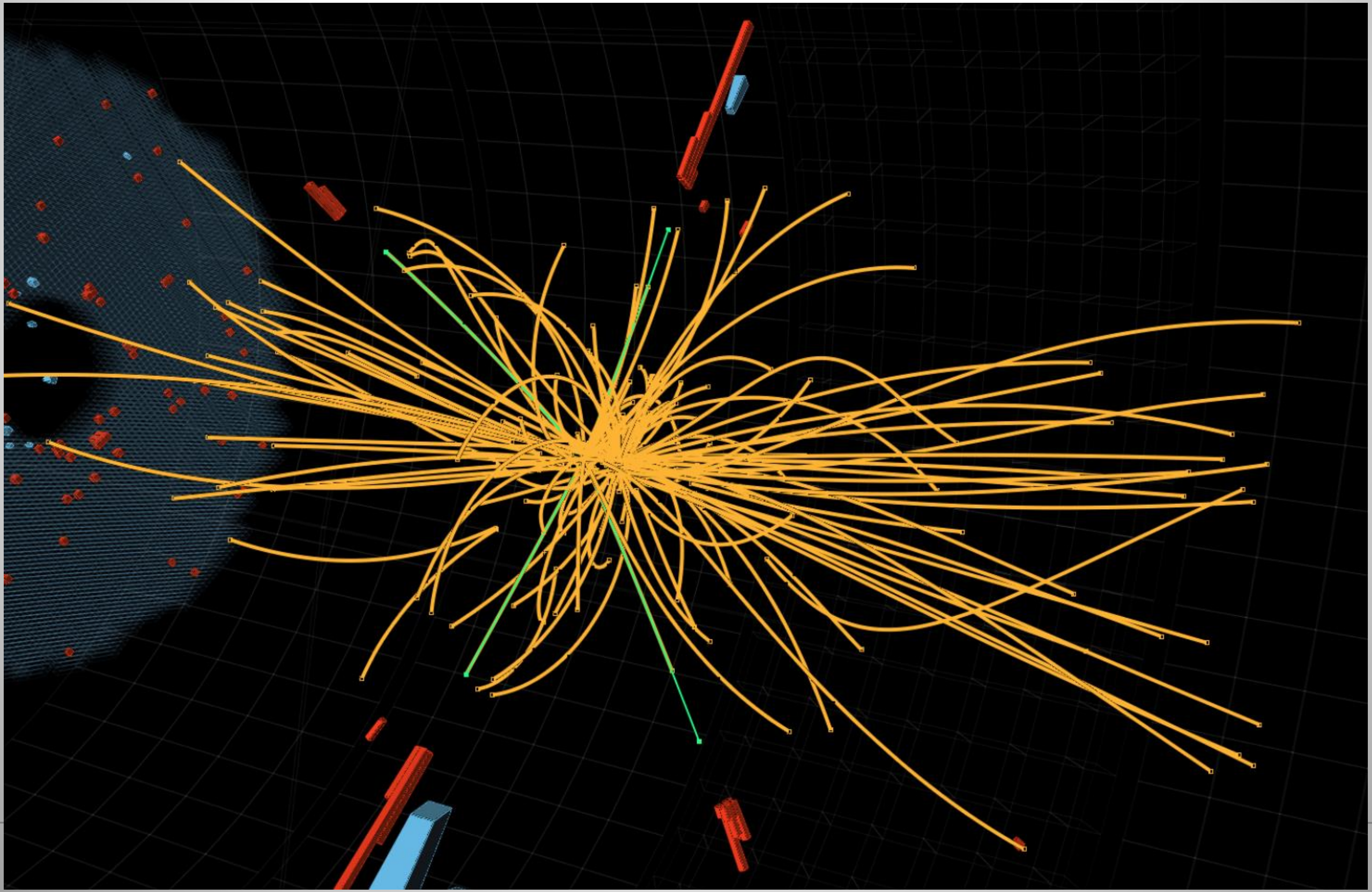
Z→ μμ event from 2012 data with 25 reconstructed vertices

Pile-up 2012!!
Much more in 2015+

Understanding Particle Production

Proton-Proton Collisions:

What particles are produced and with what energies and angles?

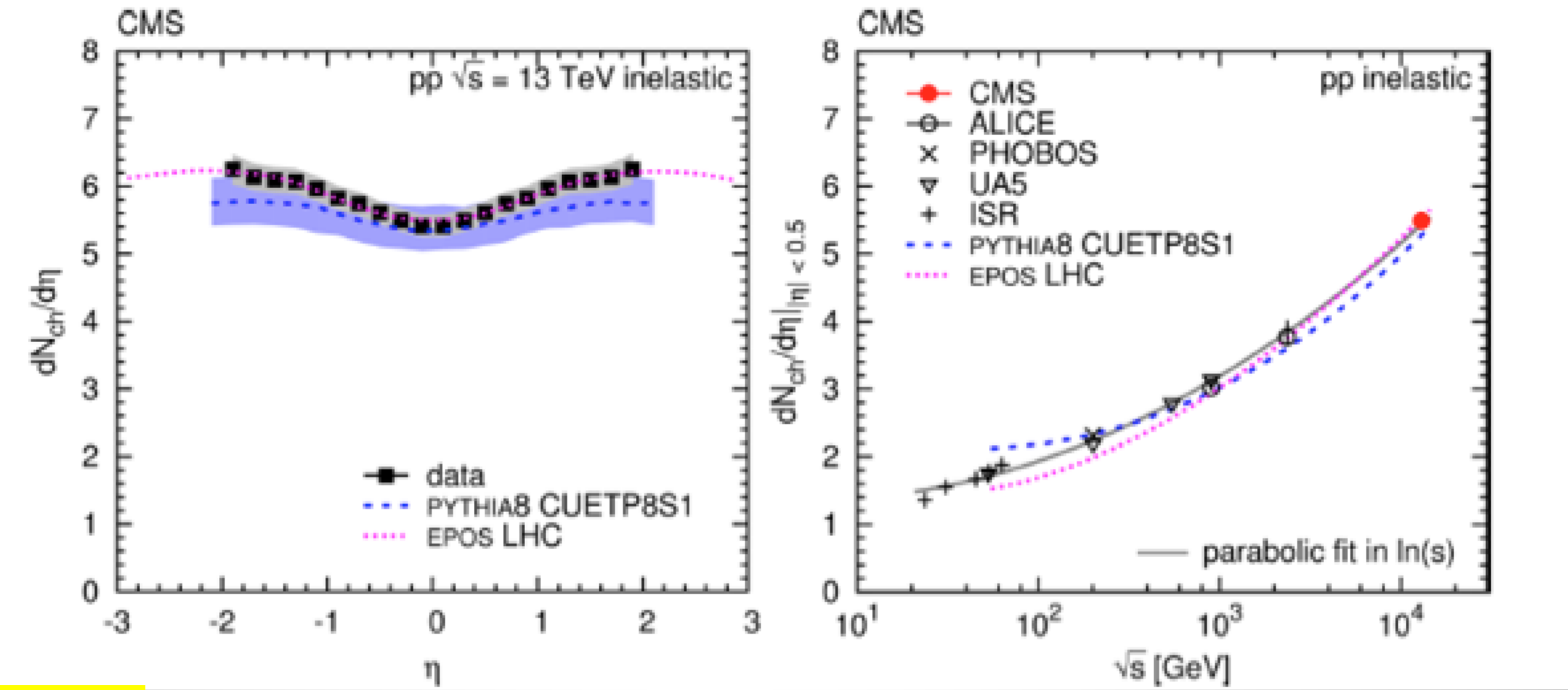


First Publication with 13 TeV Data!

B=0

Pseudorapidity distribution of charged hadrons in proton-proton collisions at $\sqrt{s}$ = 13 TeV

http://arxiv.org/abs/1507.05915

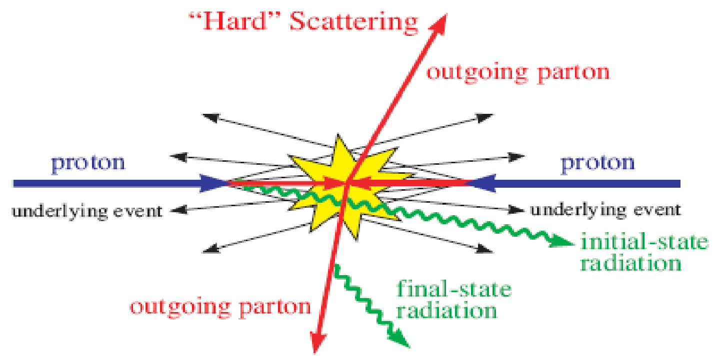


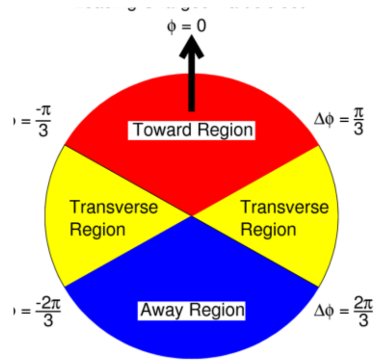
Using the pixel detector

$dn_{ch}/d\eta|_{|\eta| < 0.5}$
= 5.49±0.01 (stat)±0.17 (syst)

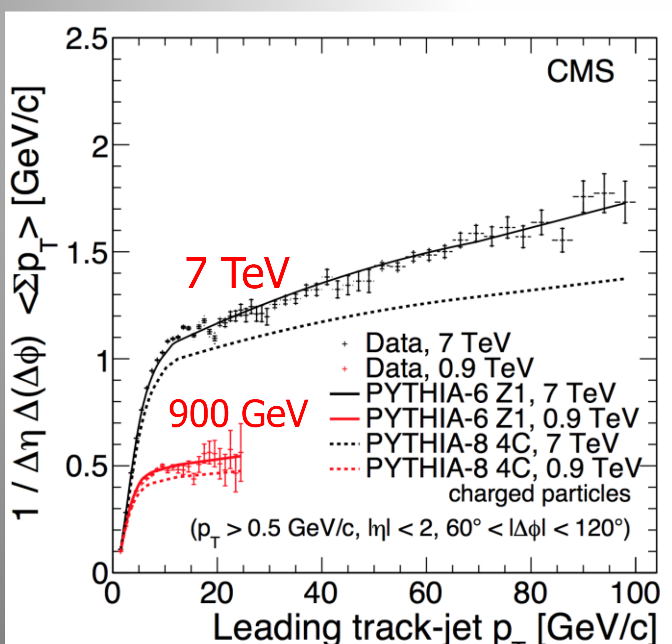
Underlying Event Studies

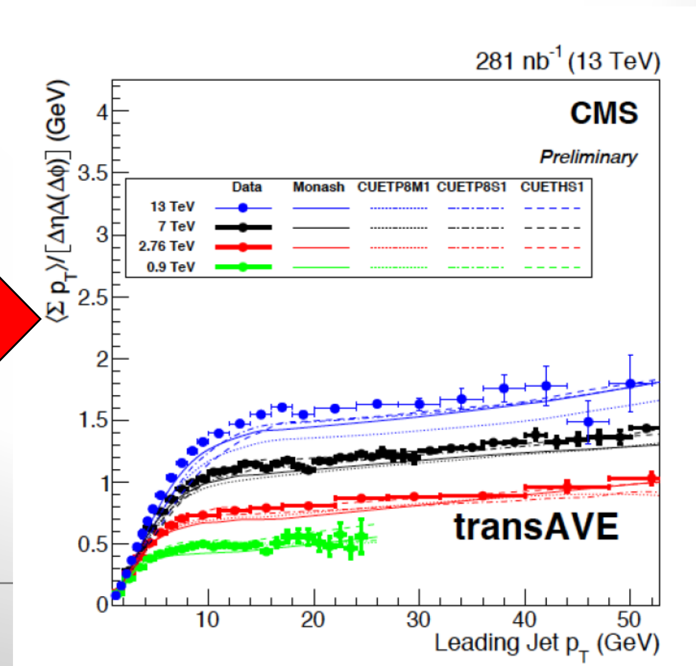
Underlying event = all minus the hard scattering and related radiation
An important systematic effect for precision measurements, eg top mass
All central detectors have made measurements in the 'transverse' region:





Measure the particle flow in transverse region as function of the hard scale



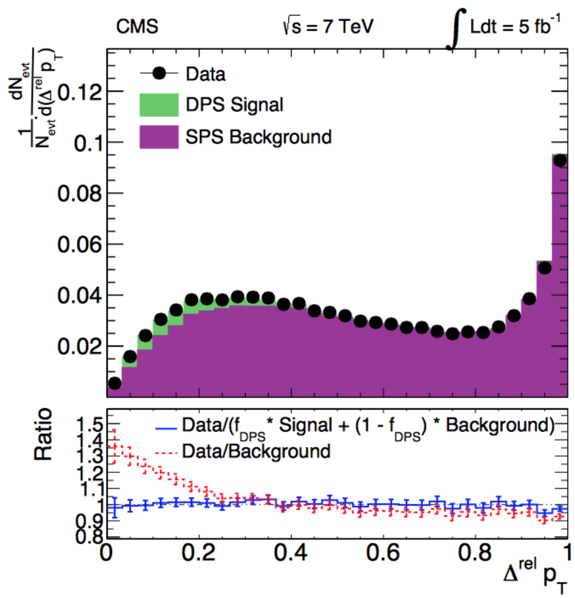


TransAVE is the average of the sum p_T in both transverse regions

Double Parton Scattering

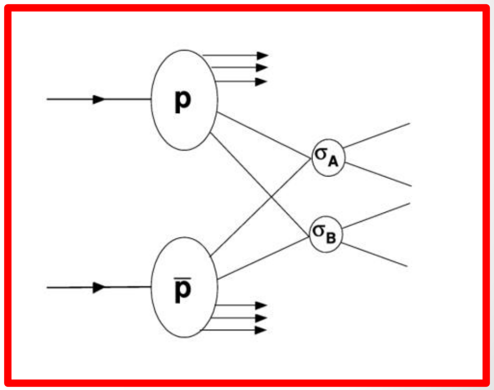
Two independent parton collisions within one proton collision!!

Example: angular correlations study of W+ 2jet events: The fraction of the cross section attributed to DPS= 0.055 ± 0.002 (stat.) ± 0.014 (sys.)

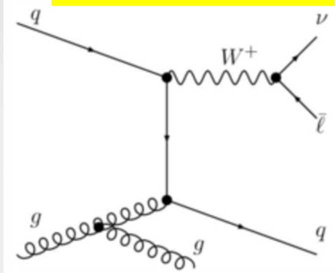


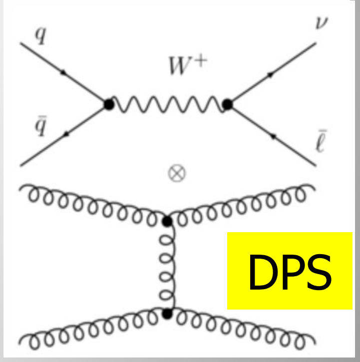
Difference between the transverse momenta of the two jets (p_T > 20 GeV)

arXiv:1312.5729



Basic process



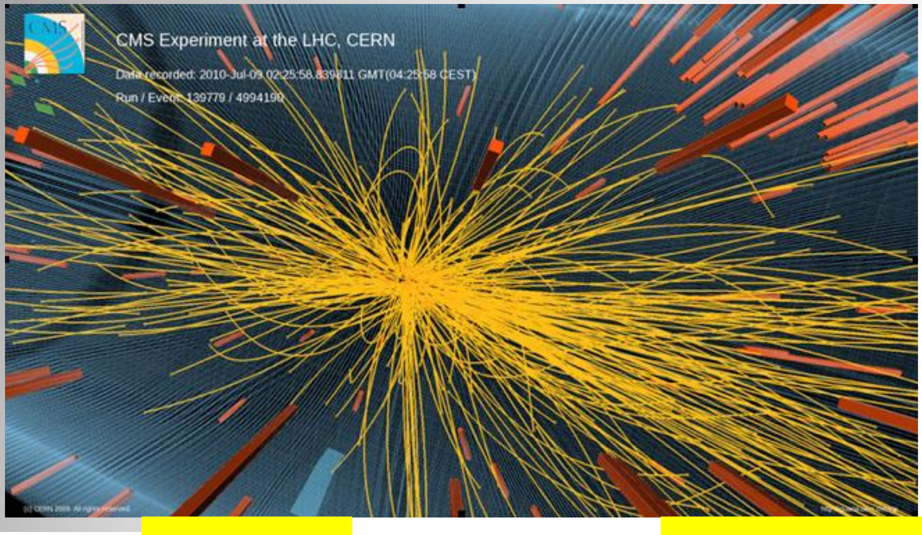


DPS

DPS can be important for searches where after cuts only a few events remain…

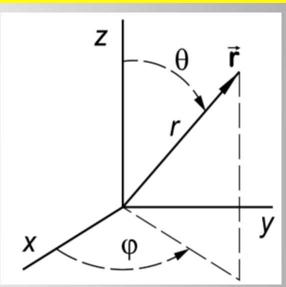
- How well do we control DPS at the LHC energies?
- Expect increase of DPS for pp collisions at 13 TeV

Correlations Between Produced Particles



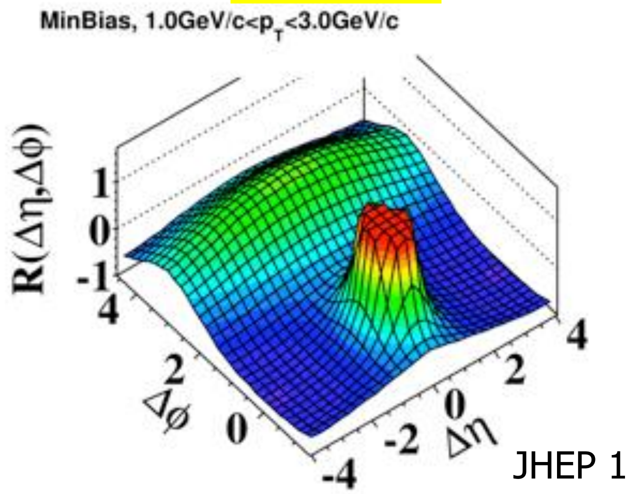
- Select high multiplicity events
- Study the correlation between two charged particles in the angles φ (transverse): Δφ and θ (longitudinal): Δθ

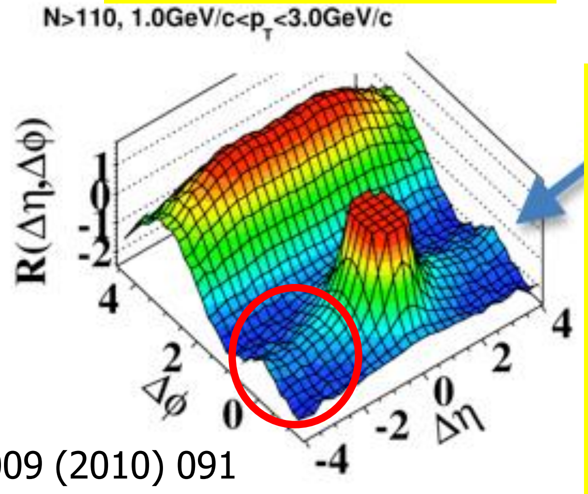
η= -ln tanθ/2



All events

High multiplicity events





JHEP 1009 (2010) 091

A new phenomenon in the 'stronge force'?
- Multiple interactions?
- Glass condensates?
- Hydrodynamic models?

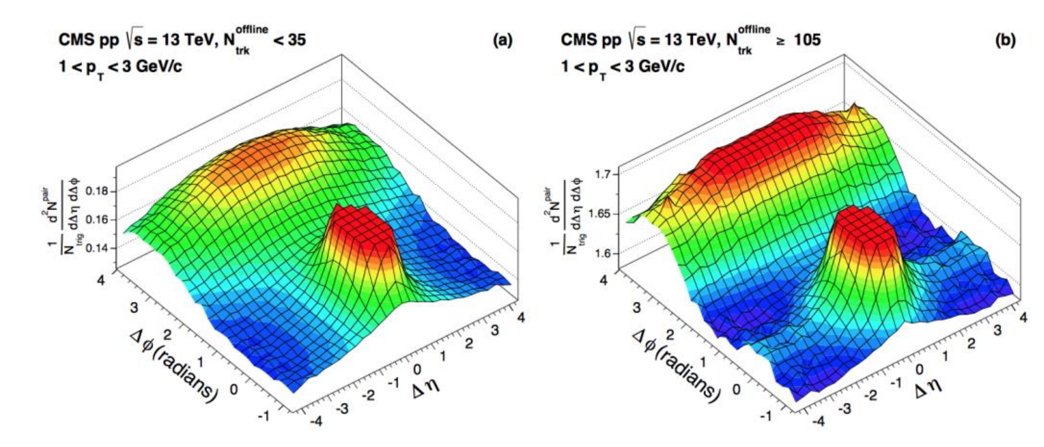
…

- Understanding the "Ridge" in pp collisions? New measurements at 13 TeV!
- Was first seen in AA, then pp (unexpected) and now also pA (~unexpected)

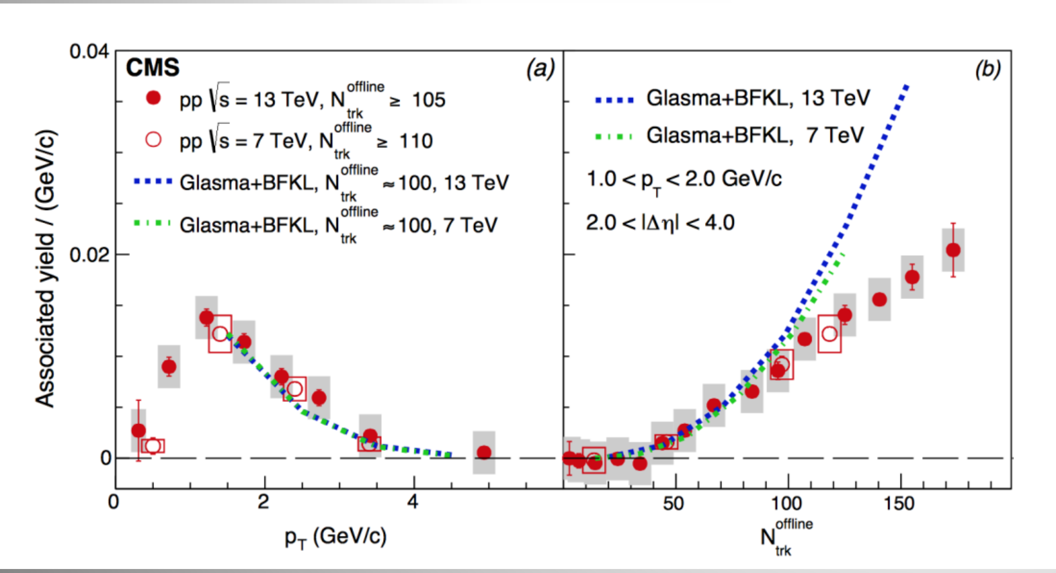
The Ridge at 13 TeV

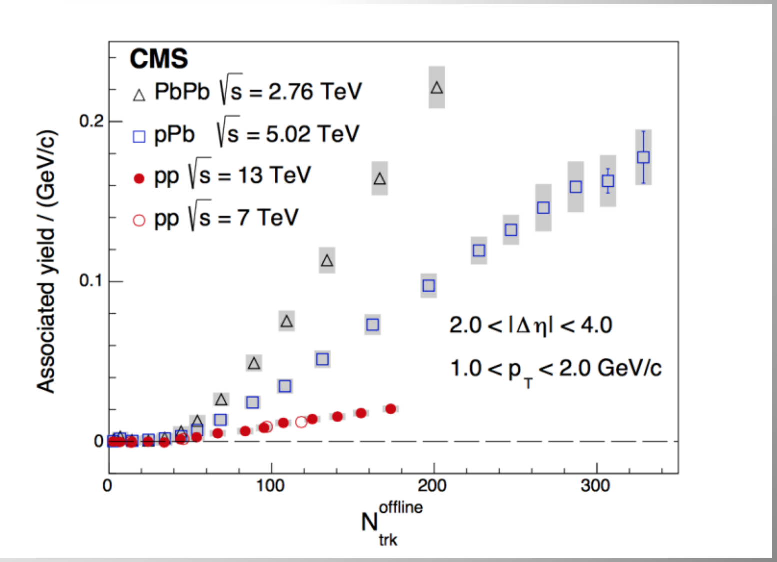
arXiv:1510.03068

Analysis with the first 13 TeV data

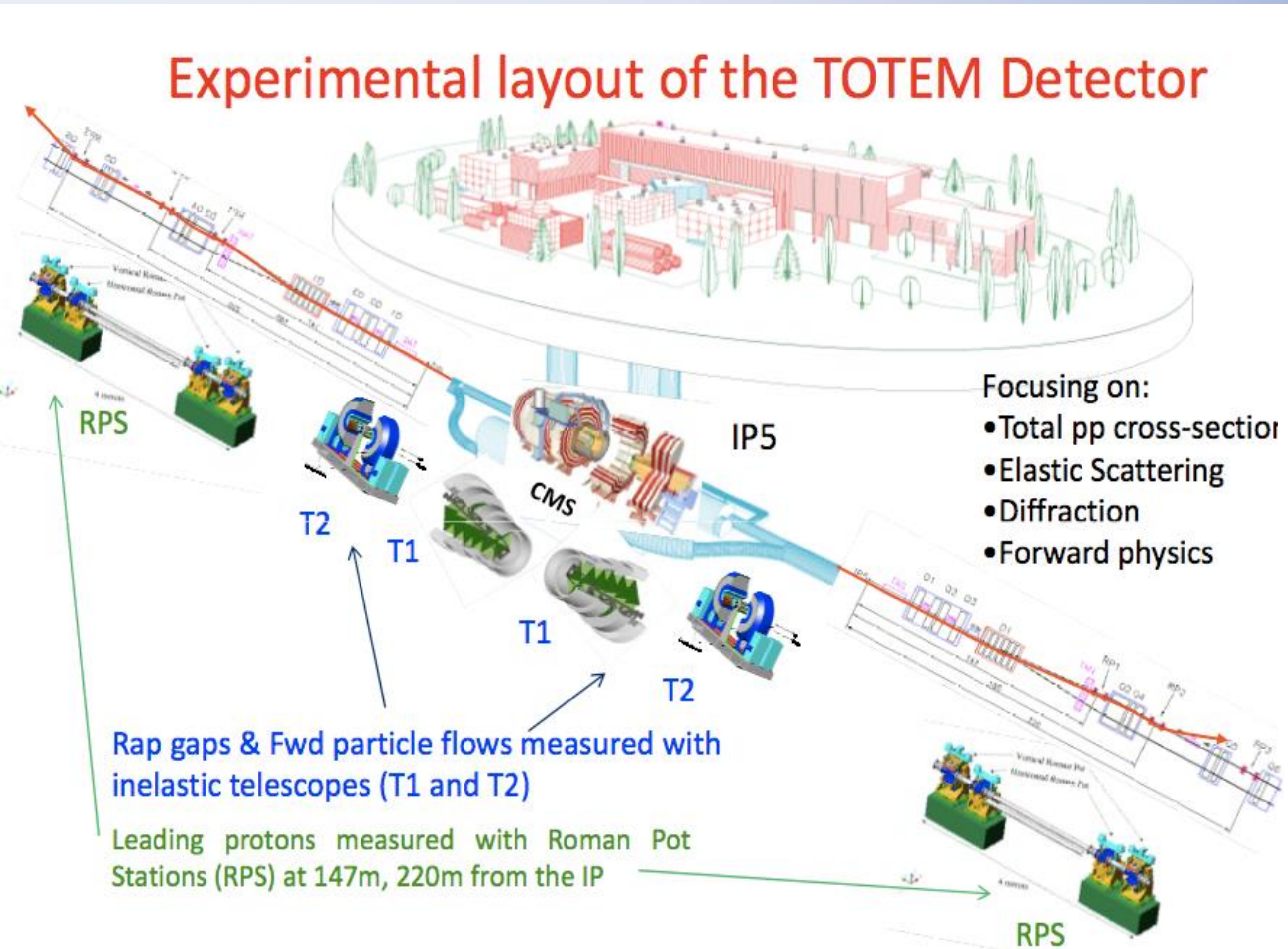


The ridge is still there at 13 TeV!
It does not get stronger at 13 TeV!
It is much weaker than in pPb and PbPb!
We still do not know what it means

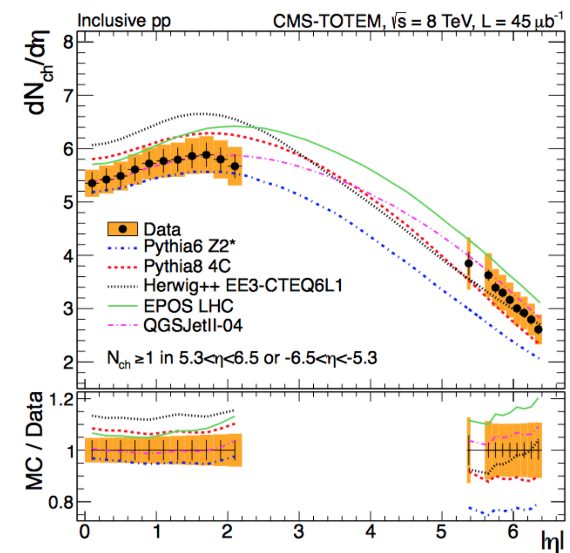




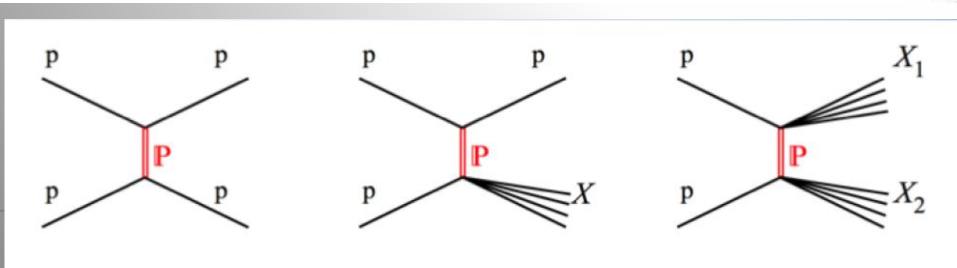
CMS + TOTEM Common Analyses



arXiv:1405.0722



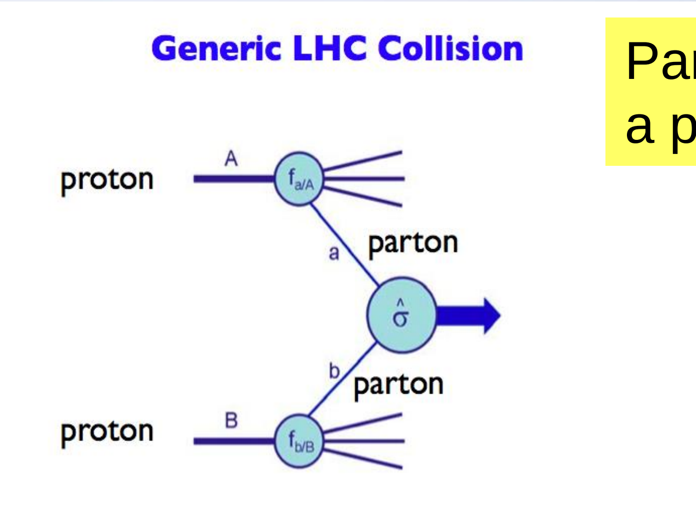
TOTEM+CMS common study on particle production



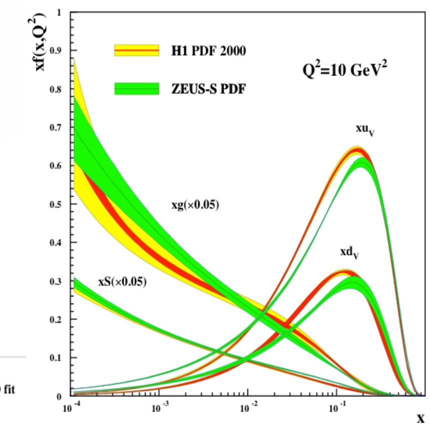
Leads to exciting opportunities for a common diffractive physics program !!

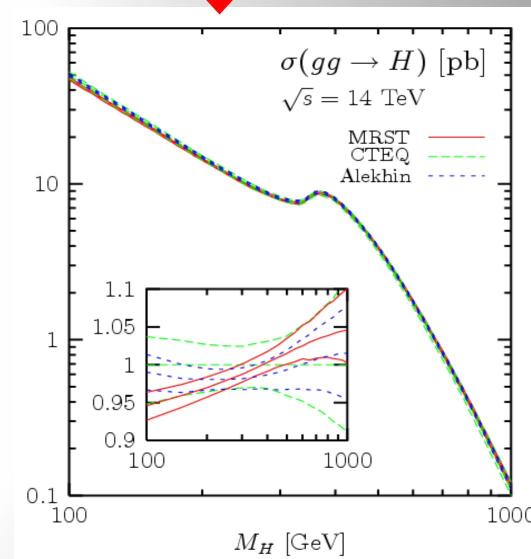
Hard Scattering
Perturbative QCD

Proton-proton collisions and PDFs

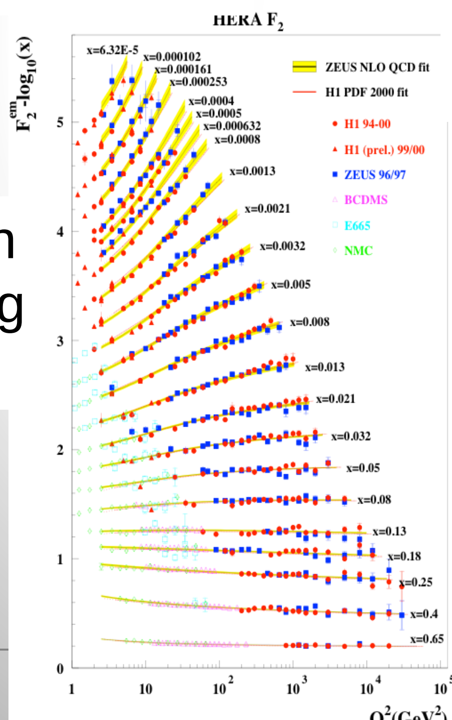


Parton Distribution Functions: the probability of finding a parton with momentum fraction x in the proton





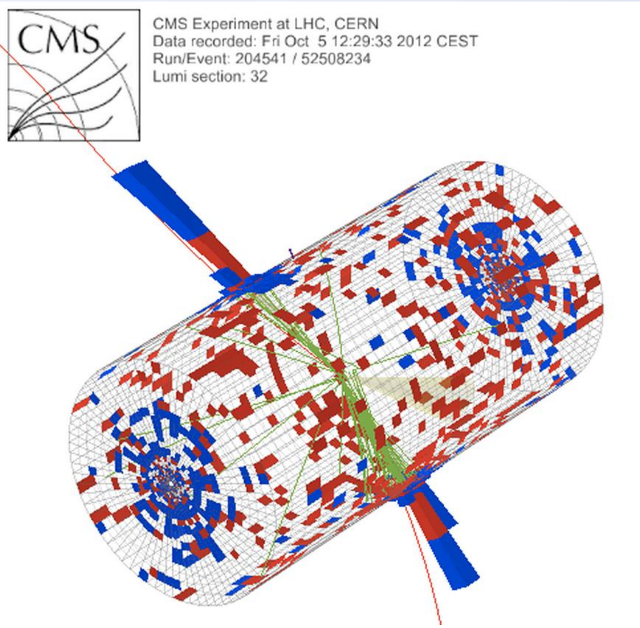
Structure function measurements eg from HERA

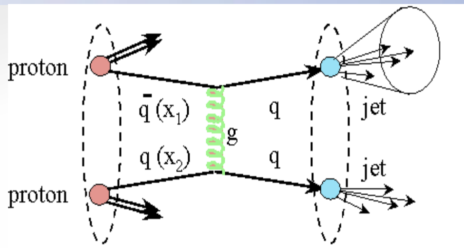


Simple spread of existing PDFs gives up to 10% uncertainty on Higgs cross section. News: factor of 2 improvement with data & PDF studies (PDF4LHC)

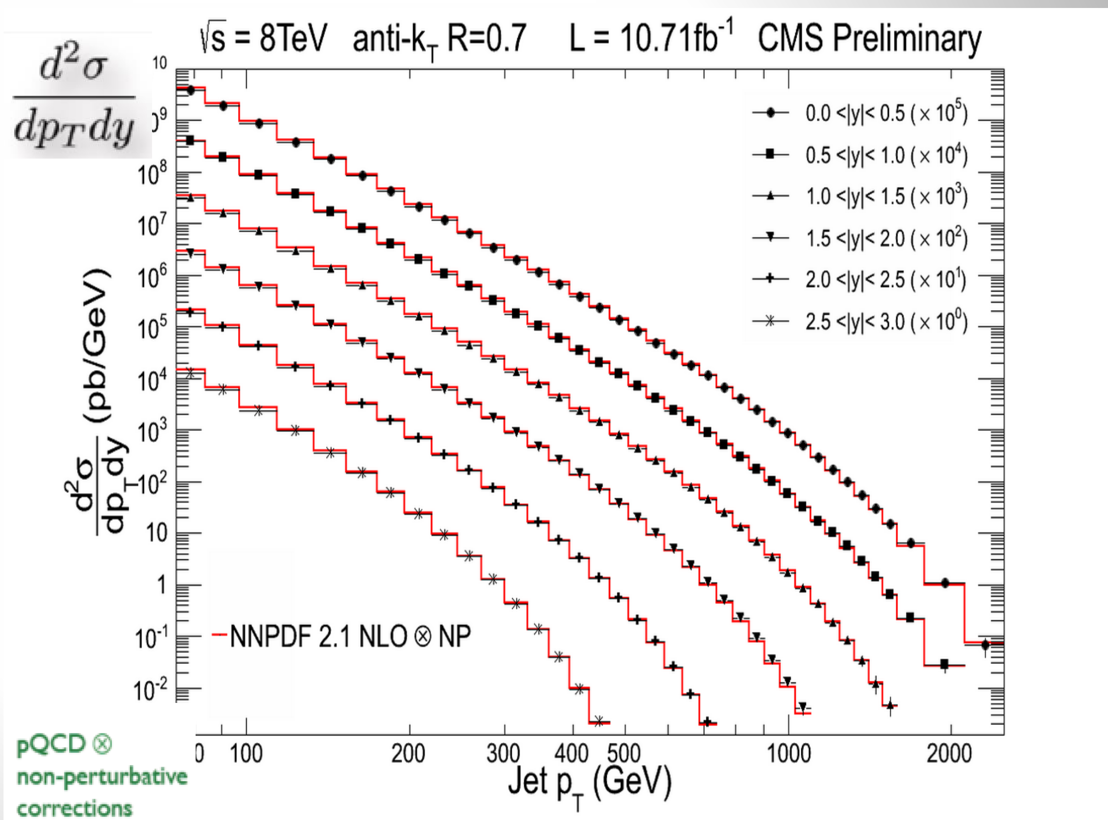
Inclusive Jet Production (8 TeV)

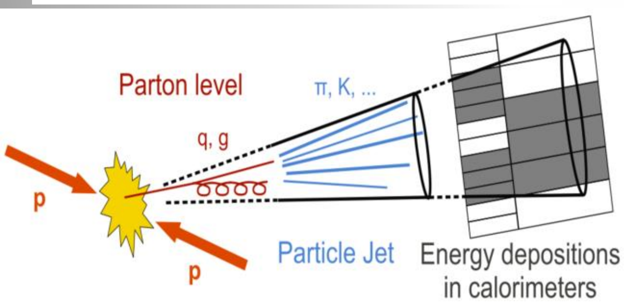
CMS-PAS-SMP-12-012





Di-jet invariant mass =
5.15 TeV (R=1.1 jets)



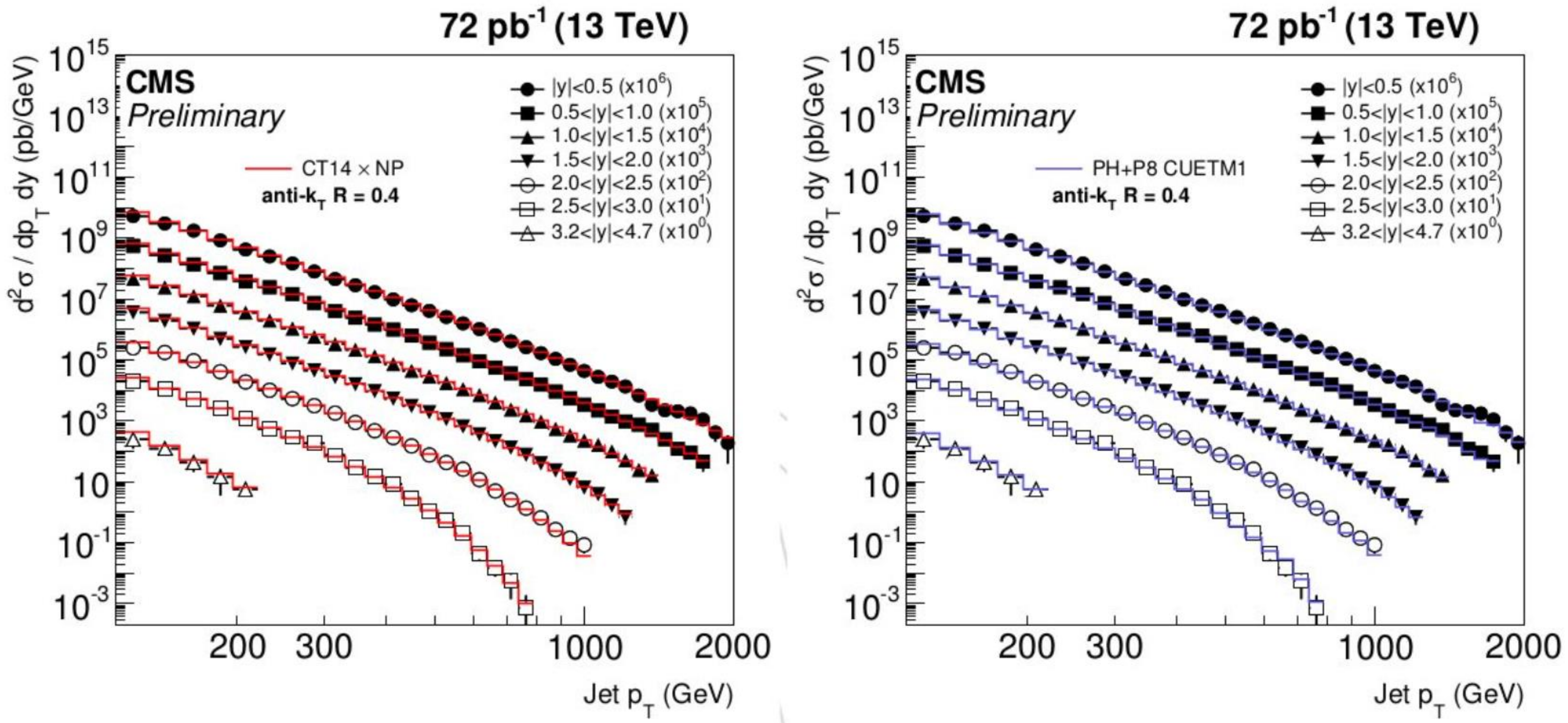


Agreement with NLO calculations over the full range, up to and beyond 2 TeV p_T jets… Hard scattering via the strong force works well…

First Measurements at 13 TeV

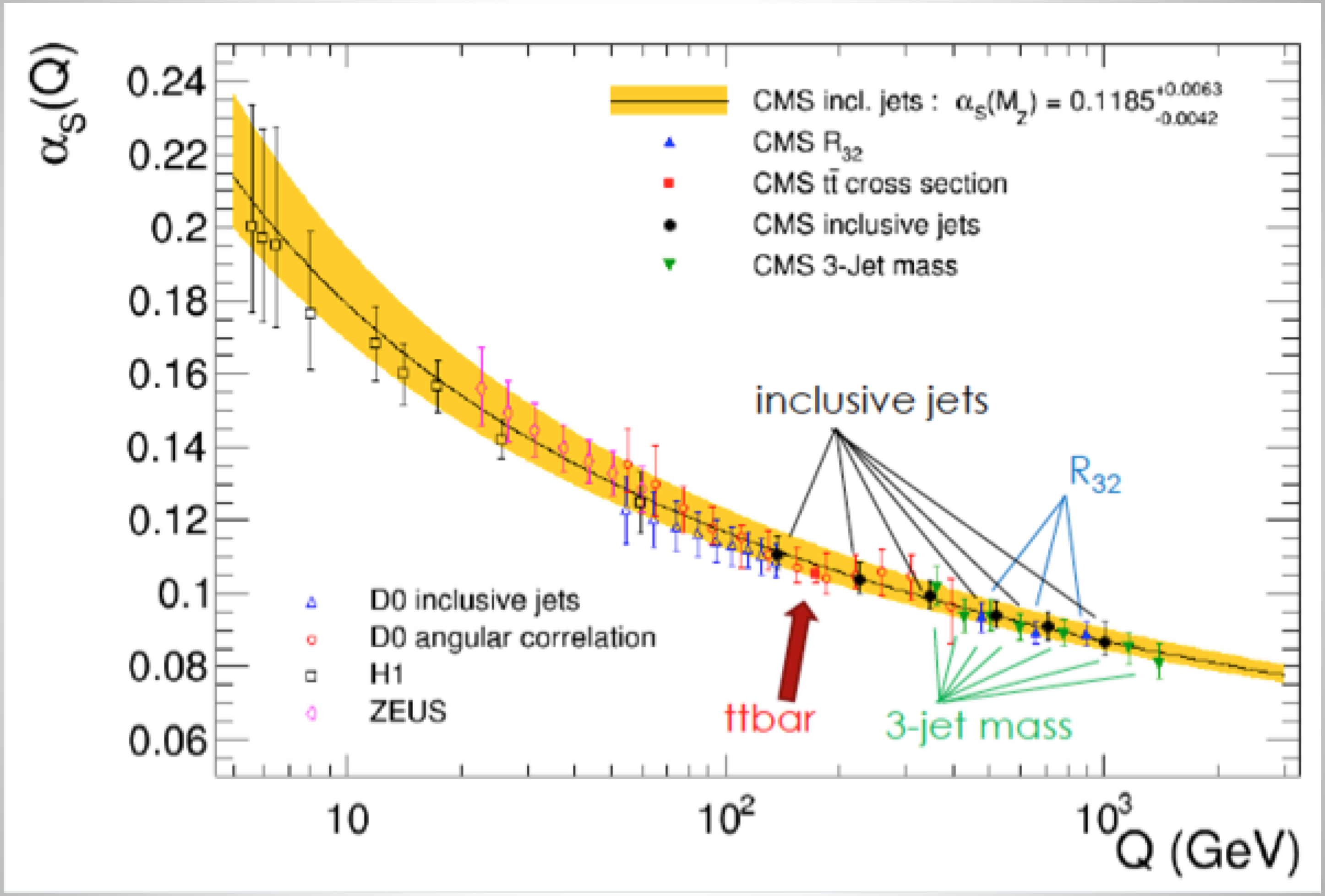
SMP-15-007

Jet are among the first hard scatters we can observe



- Double differential jet cross sections as a function of p_T and rapidity; R=0.4 and 0.7
- Comparisons with NLOJet++ analytical predictions (+non-pert. corrections) and POWHEG (+CUETM1 tune).
- Publishing the 50 ns analysis without further modifications

QCD Studies: Extracting α_s



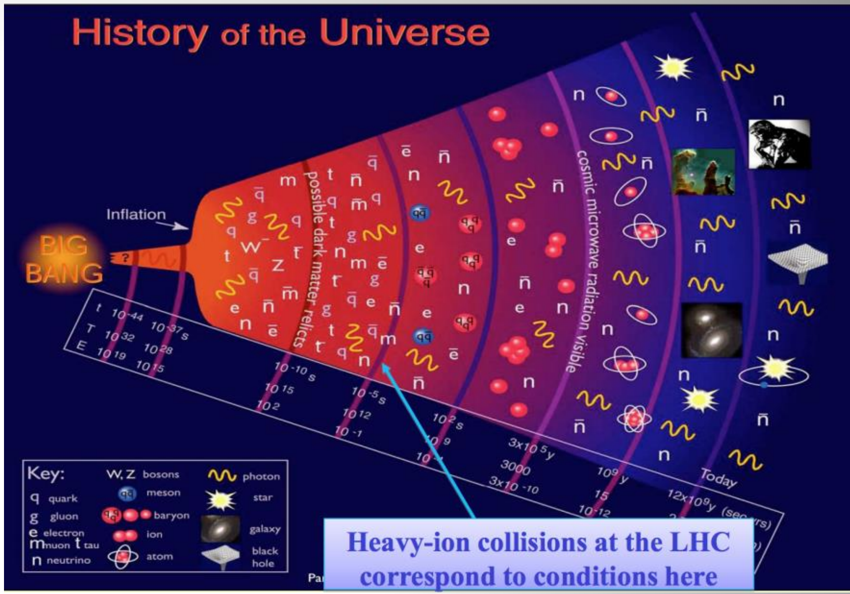
Several new studies: 3-jet mass, top cross section… Many Opportunities!

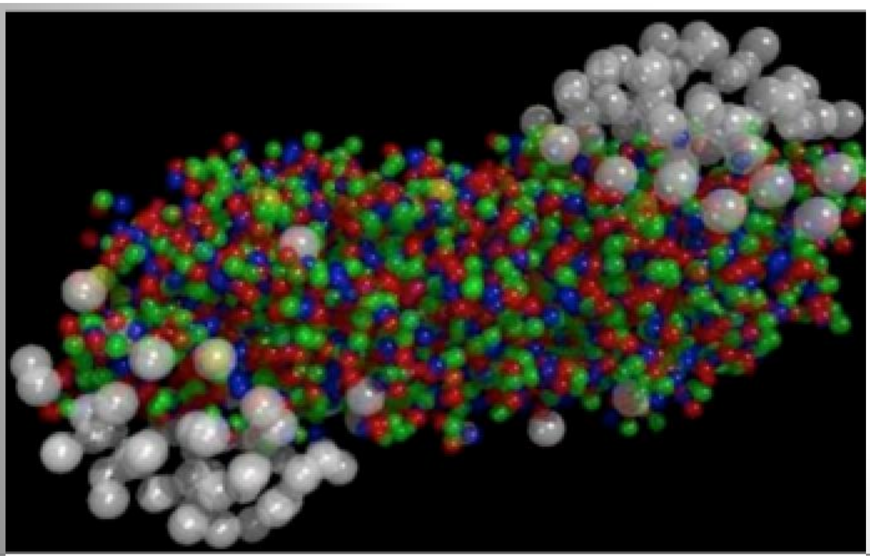
Theory uncertainties are main precision delimiter! Extended range @ 13 TeV!

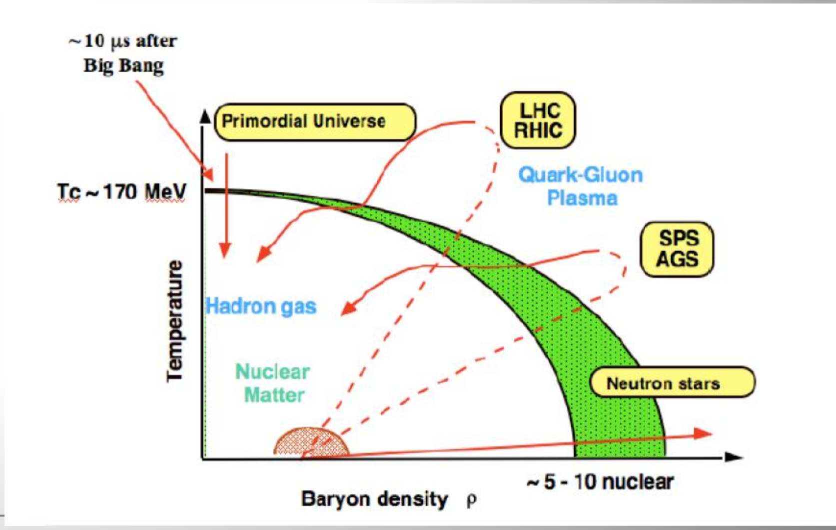
Heavy Ion Collisions

Heavy Ion Collisions

- A new state of matter: observed at SPS and RHIC
- Further studied at the LHC
  - larger temperature, volume, energy density and lifetime…
  - large cross section for hard probes
- ALICE especially designed for HIC
  CMS, ATLAS and LHCb take and analyse pPb & PbPb data too

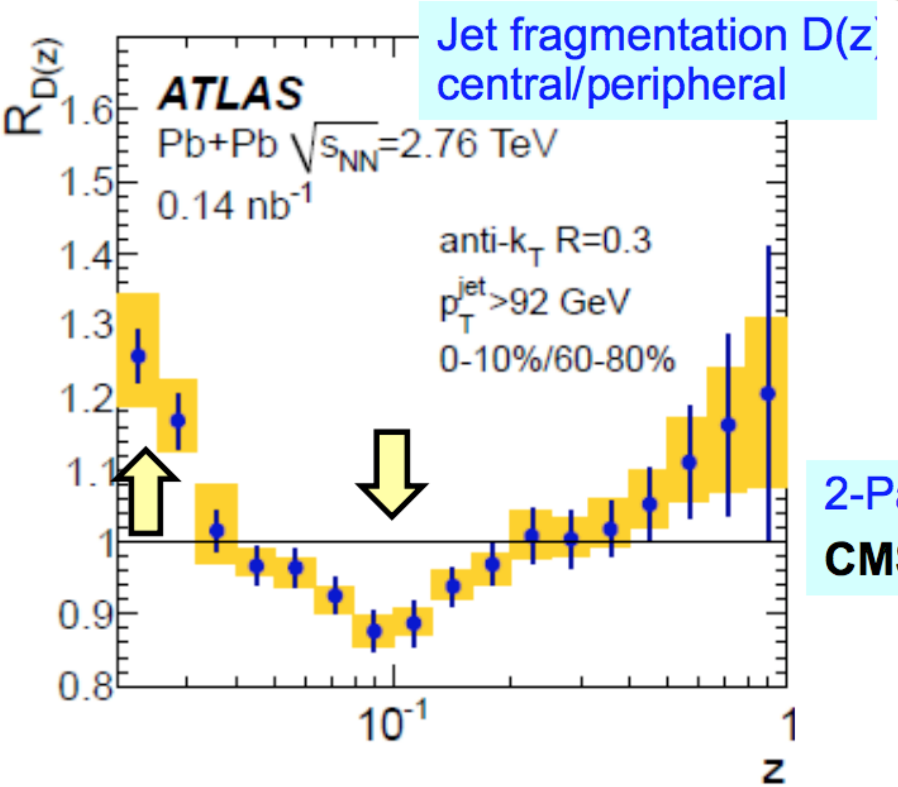




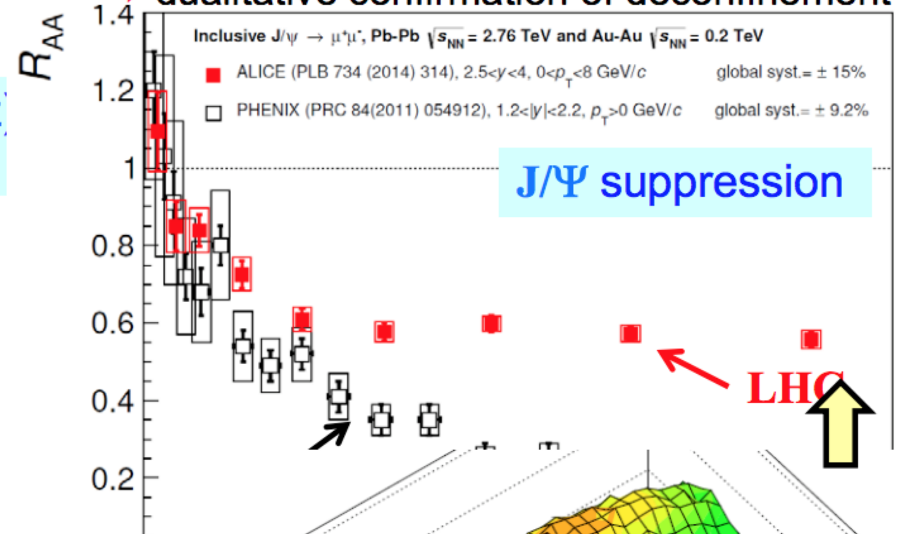


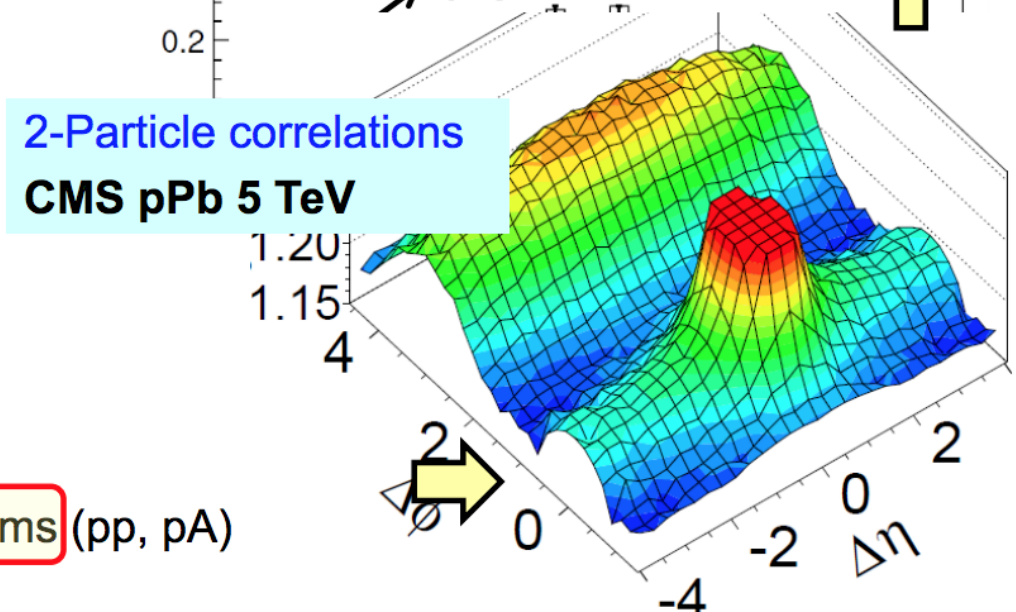
Highlights from the LHC

- in-medium jet fragmentation
  - ⇨ insight into dynamics of jet quenching
    - multiple soft gluon radiation at large angles (inverted angular and time ordering !!)



- J/Ψ coalescence & seq. Υ melting
  - ⇨ SPS/RHIC J/Ψ puzzle solved
  - ⇨ qualitative confirmation of deconfinement





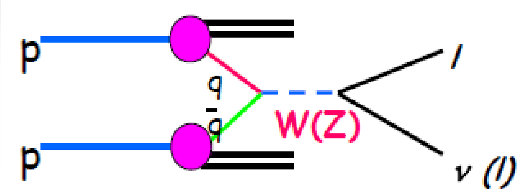
- the ever surprising ideal liquid
  - ⇨ collective hydro flow in small systems (pp, pA)

J. Schukraft, Kruger 2014

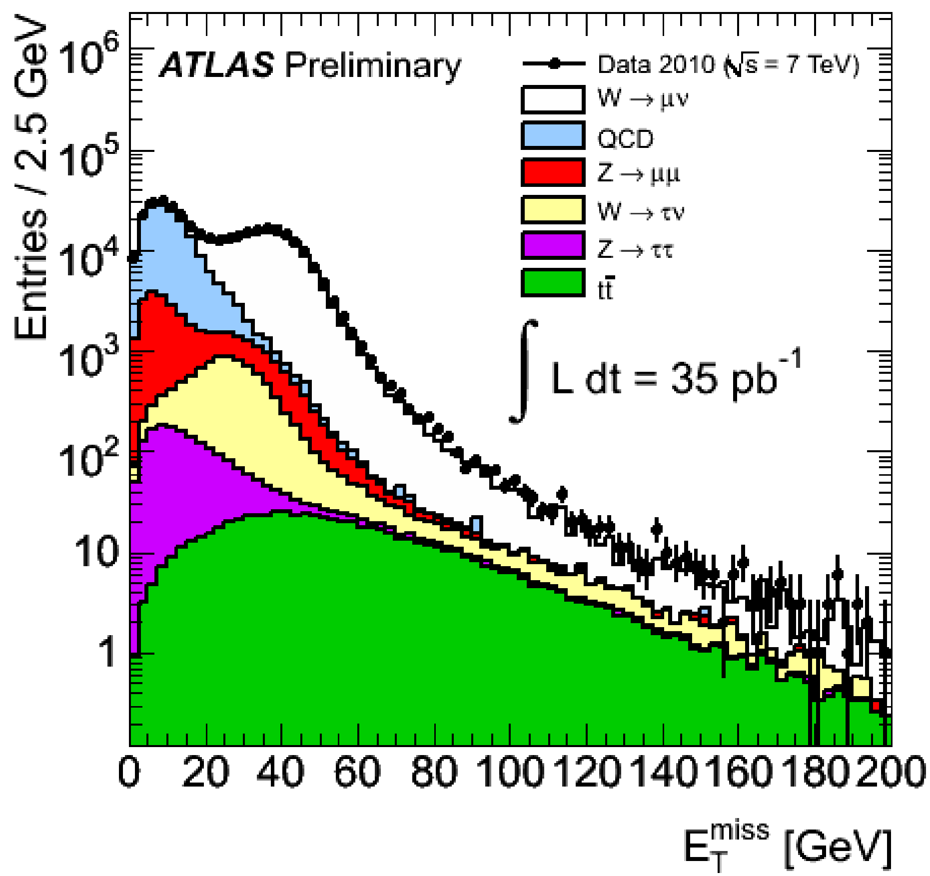
W and Z Boson Production

W and Z Boson Production

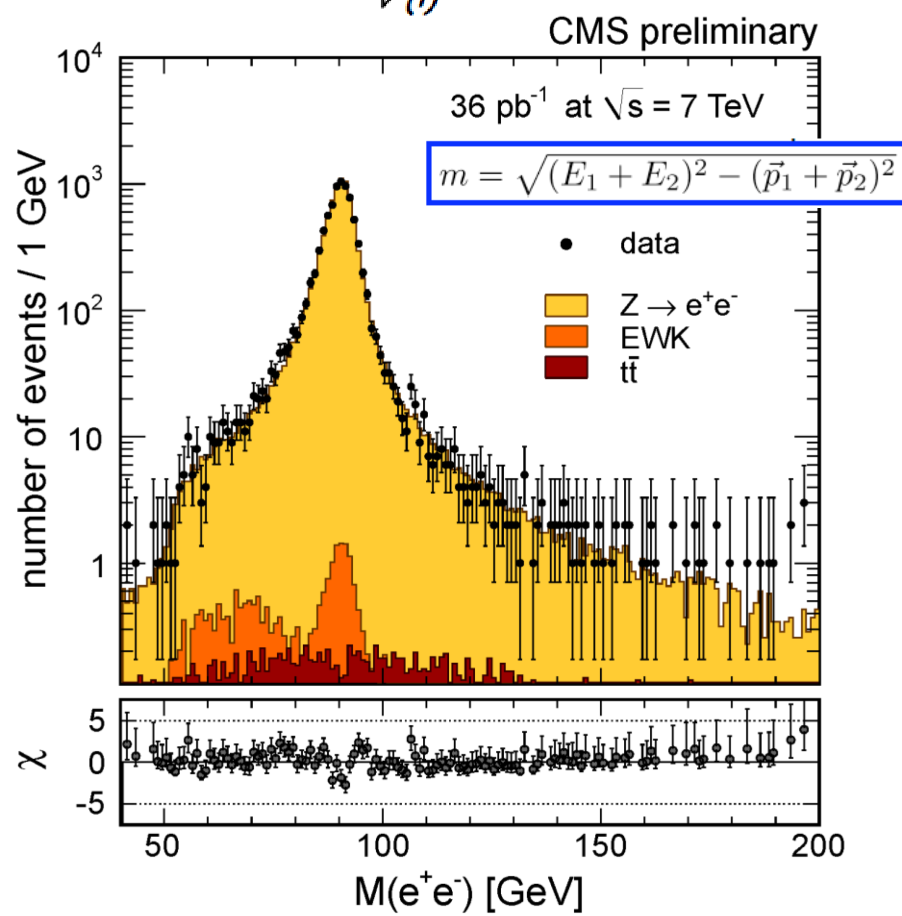
Select final states with leptons



arXiv:1109.5141



arXiv:1107.4789

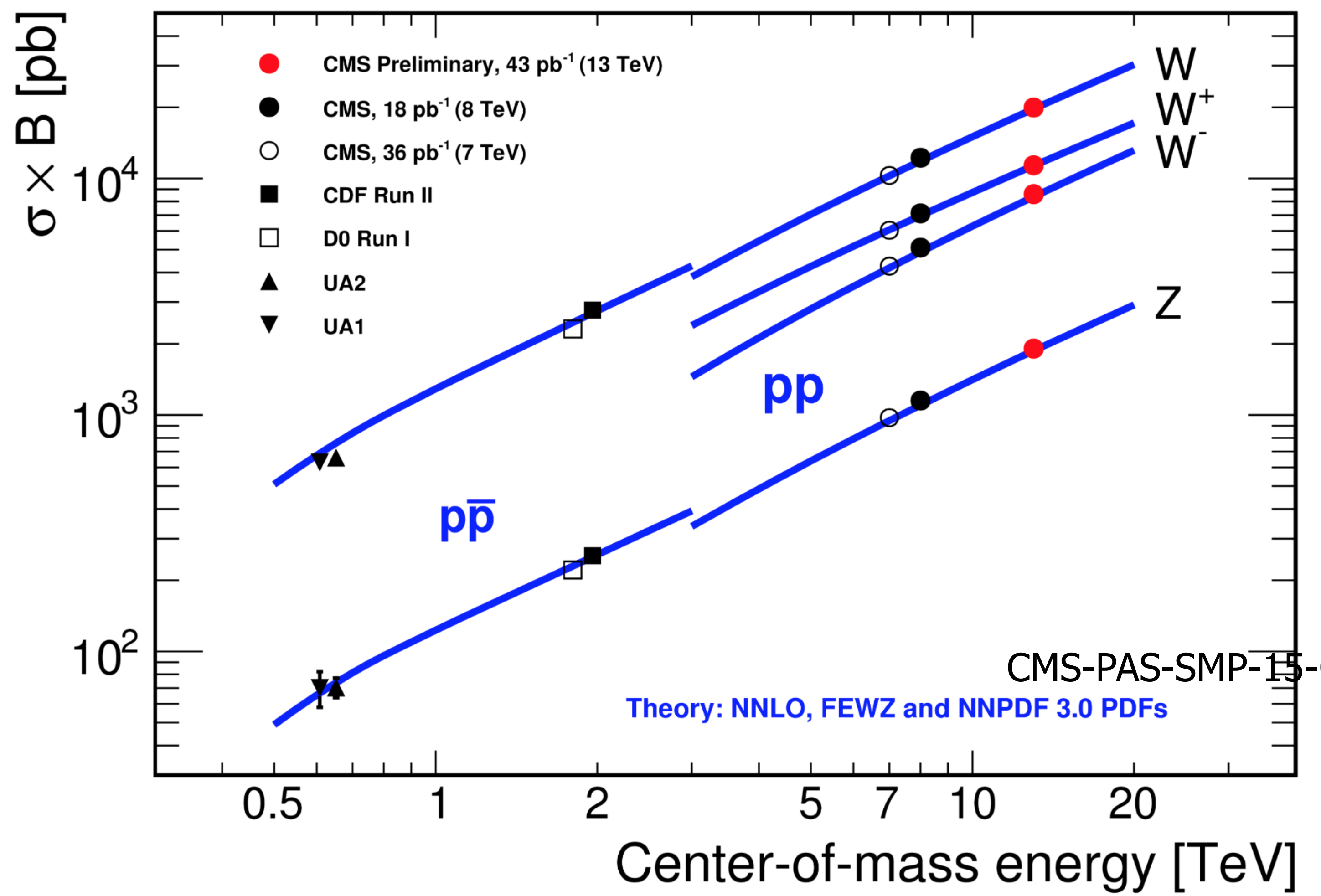


Missing transverse energy from the W → μ+ν decays

Z peak (di-lepton pair mass distributions)

W and Z Boson Production

Contains a new measurements at 13 TeV! with about 5% precision

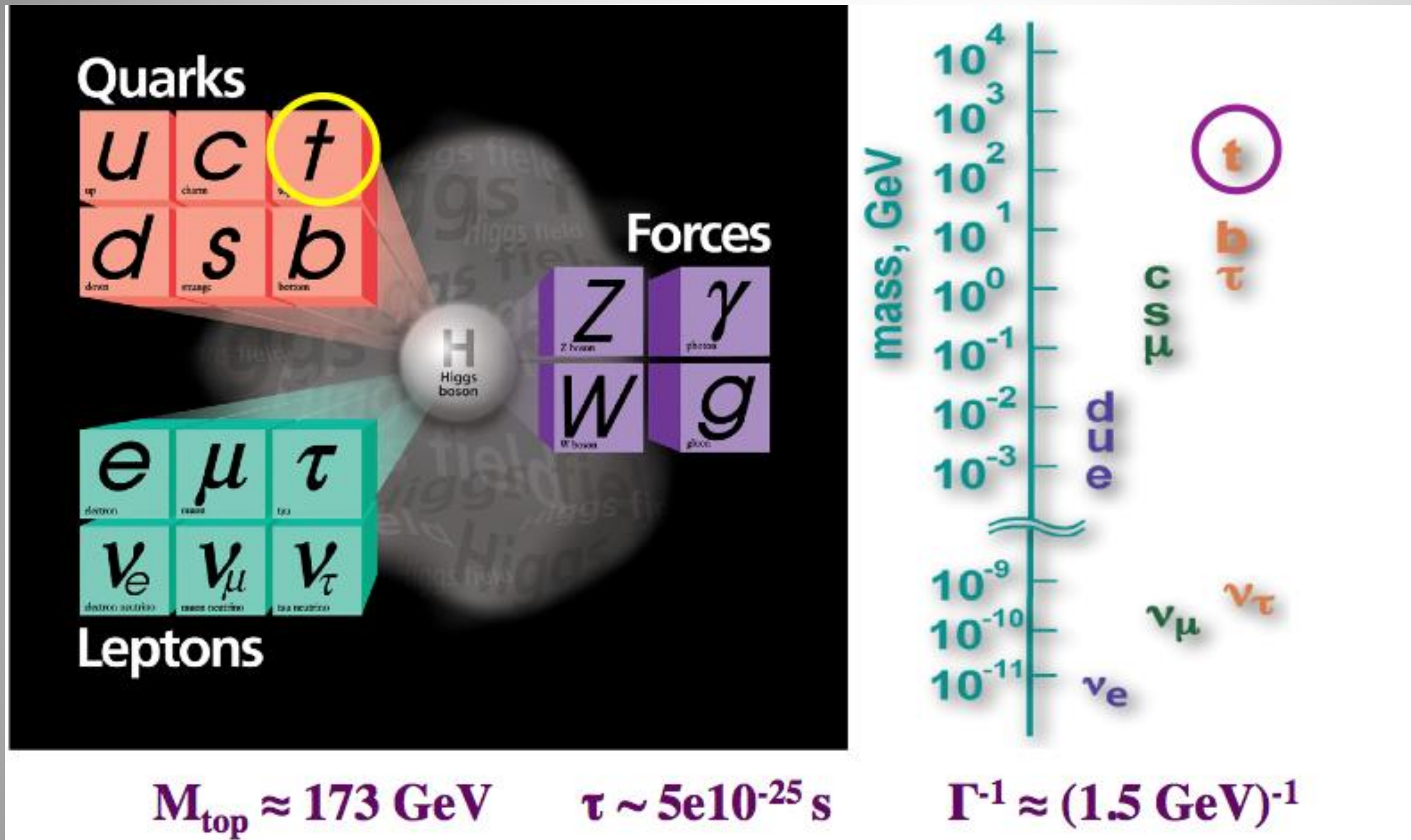


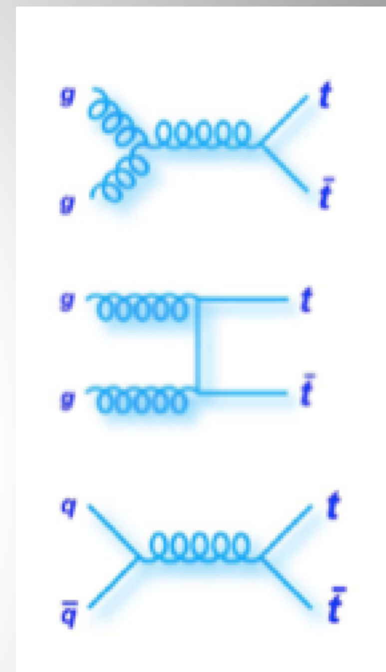
CMS-PAS-SMP-15-004

Many detailed EWK studies possible –and done-- with the large Z,W samples

Top Quark Production

Top Quark Physics

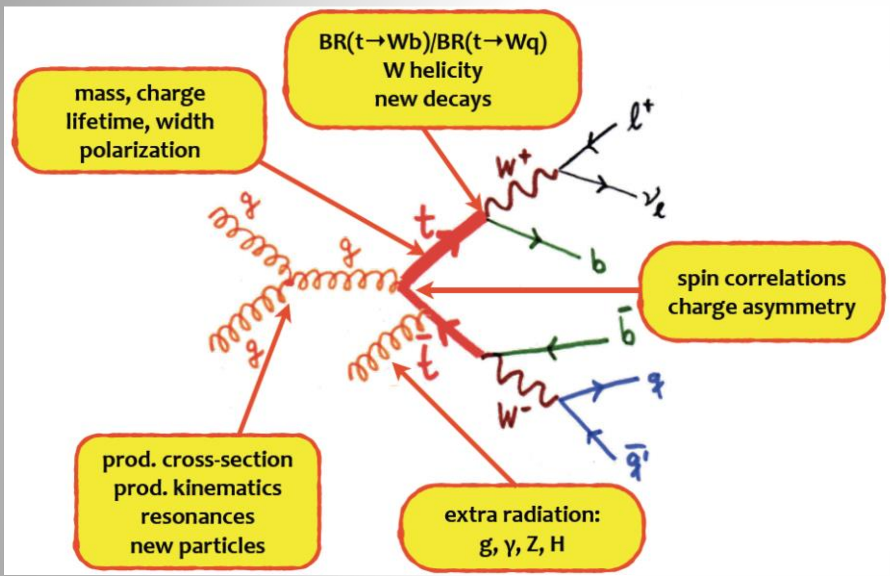




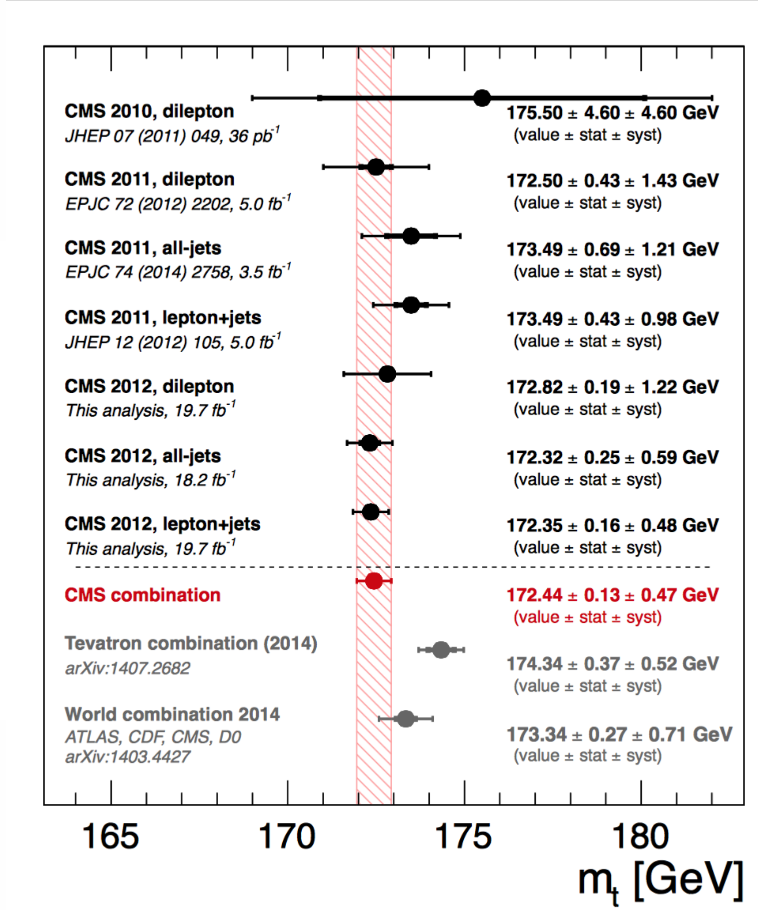
- The heaviest known elementary particle: ~173 GeV
- Coupling to the Higgs ~1 $\rightarrow$ Special role in EWK symmetry breaking?
- Special sector to searches for new physics

LHC as a Top Factory

Cross section ~ 250 pb (8 TeV)
->• ~5.10^6 produced tt-pairs (2012)
•a few 10^5 used in the analyses



Top mass determination



Spring 2014

Using Tevatron and LHC combination of the mass measurements

$m_t = 173.34 \pm 0.76$ GeV

Meanwhile: TOP-14-022

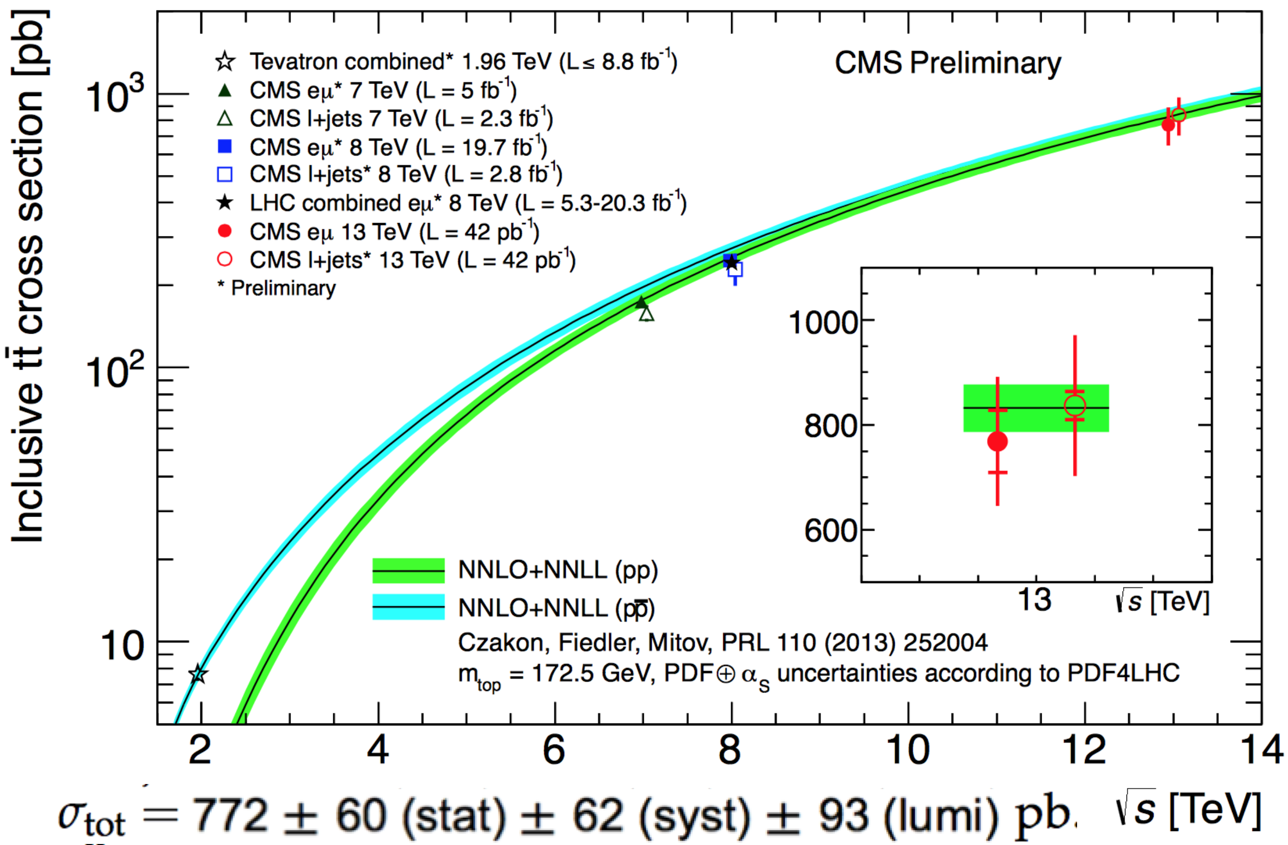
CMS update: 172.44±0.13 (stat)±0.47 (syst) GeV

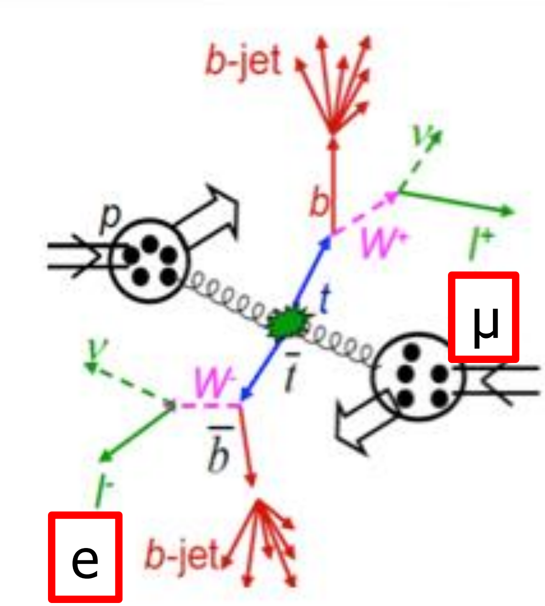
Tevatron update: 174.34 ± 0.64 GeV

Top Pair Cross Section

CMS-PAS-TOP-15-005
CMS-PAS-TOP-15-003

From dilepton eμ events and lepton+jet events





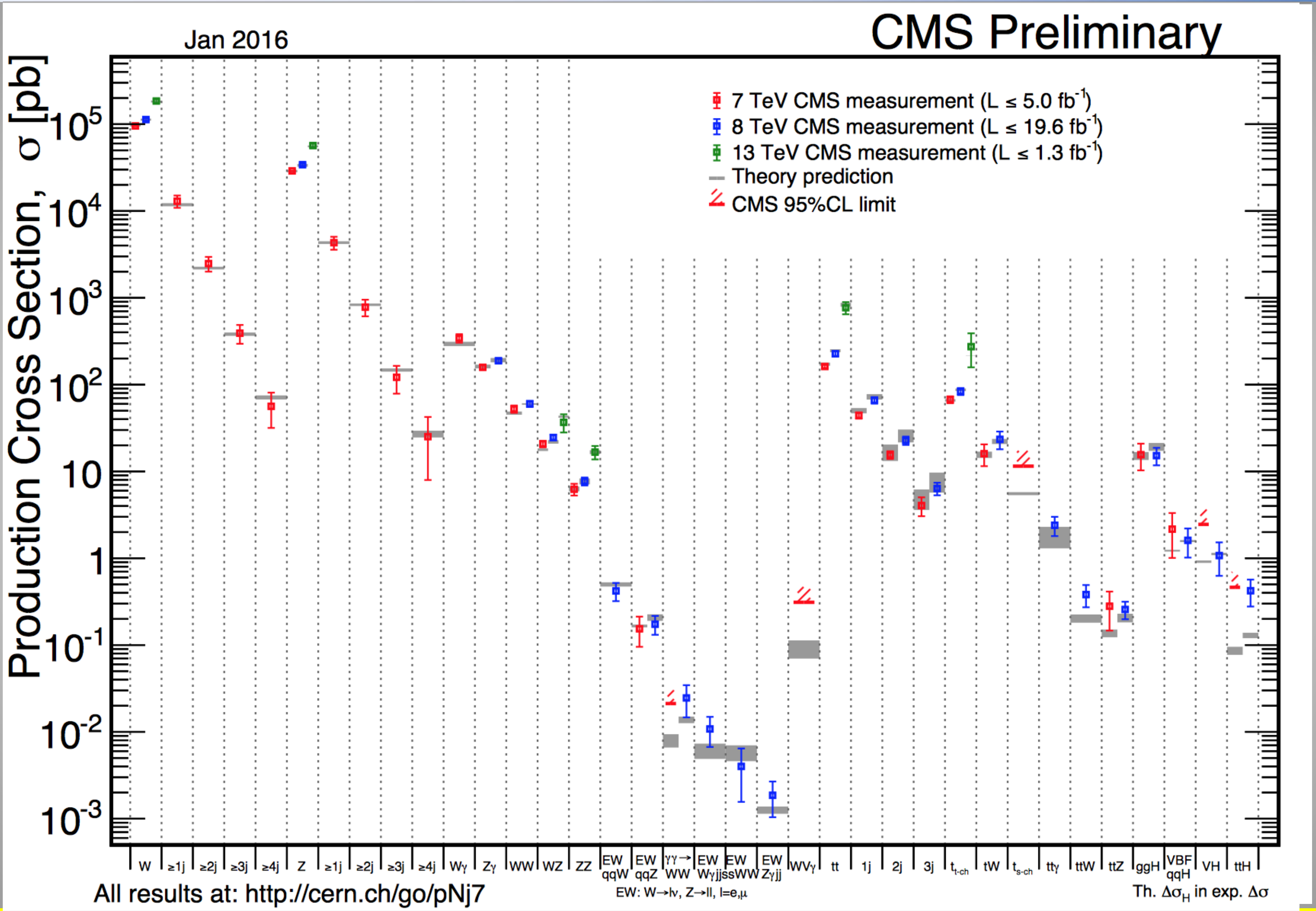
$$\sigma_{tot} = 772 \pm 60\,(\text{stat}) \pm 62\,(\text{syst}) \pm 93\,(\text{lumi})\ \text{pb}.$$

$$\sigma_{tot} = 836 \pm 27\,(\text{stat}) \pm 84\,(\text{sys}) \pm 100\,(\text{lumi})\ \text{pb}.$$

New: measurement at 13 TeV

ATLAS and CMS have made a first top anti-top pair cross-section measurements At 13 TeV. Present precision ~ 15% --driven by the preliminary lumi uncertainty

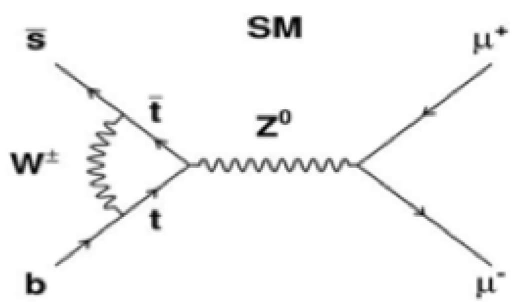
Summary: Cross Sections at 7/8 TeV



Measurements in good agreement with the Standard Model predictions!!

Precision Measurements: $B_{s(d)} \rightarrow \mu\mu$

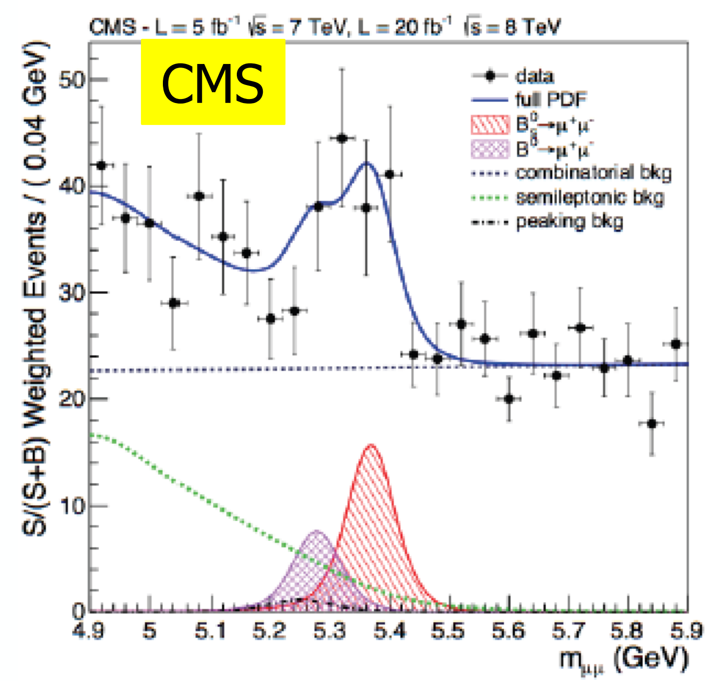
- A B_s particle is a particle consisting of a beauty-quark and strangeness-quark, with a mass of ~ 5.4 GeV
- Three B_s particles in a billion will decay into two muons. This decay has been chased since 30 years.
- New physics modifies these Standard Models predictions



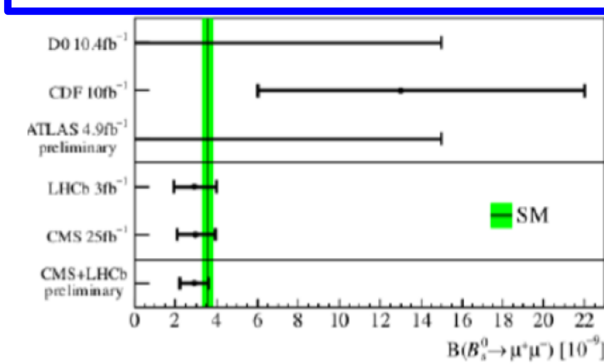
PRL 111 (2013) 101804

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-)_{\rm SM} = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-)_{\rm SM} = (1.06 \pm 0.09) \times 10^{-10}$$

$$\mathrm{BR}(B_s \to \mu\mu) = \left(3.0^{+0.9}_{-0.8}\ (\mathrm{stat})^{+0.6}_{-0.4}\ (\mathrm{syst})\right) \times 10^{-9}$$
$$\mathrm{BR}(B_d \to \mu\mu) = \left(3.5^{+2.1}_{-1.8}\ (\mathrm{stat+syst})\right) \times 10^{-10}$$



Significance:
$B_s \to \mu\mu$: 4.3 σ (exp. median 4.8 σ)
$B^0 \to \mu\mu$: 2.0 σ



Precision Measurements: $B_{s(d)} \rightarrow \mu\mu$

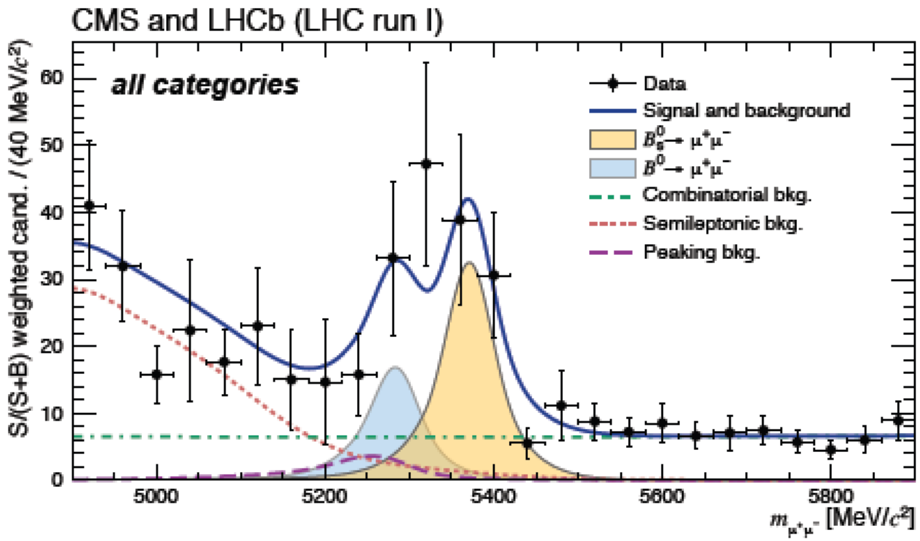
Combined CMS+LHCb analysis submitted to Nature Dec 2014

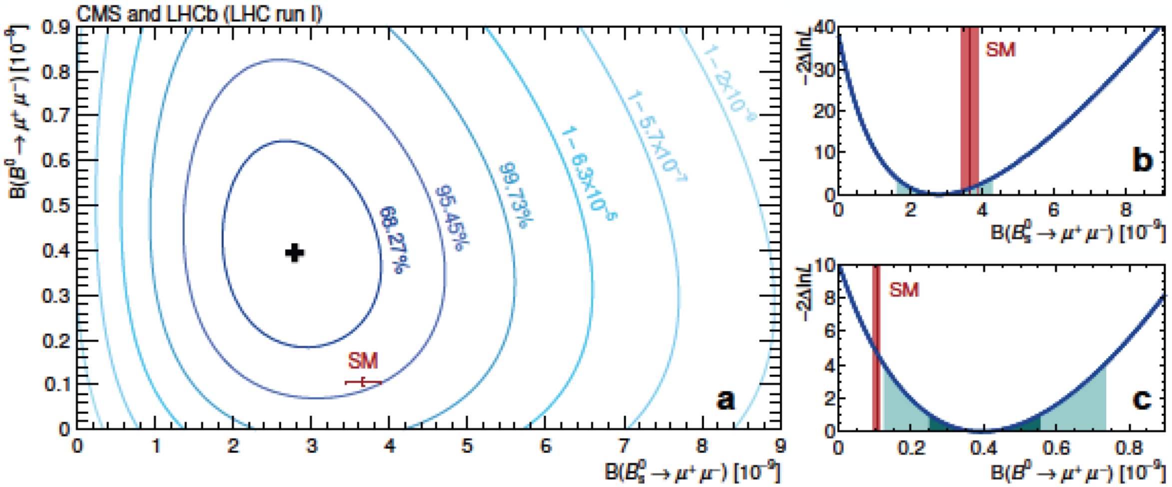
- Results:

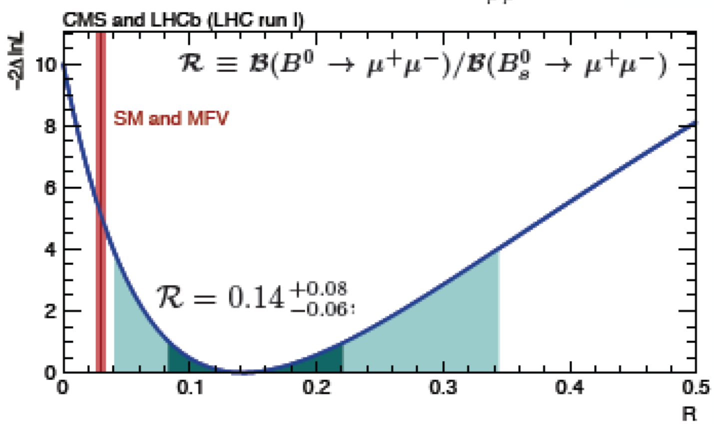
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

- Observed (Expected) significance
  - B_s: 6.2σ (7.4σ)
  - B^0: 3.2σ [WT], 3.0 [FC]σ (0.8σ)

V. Chiochia







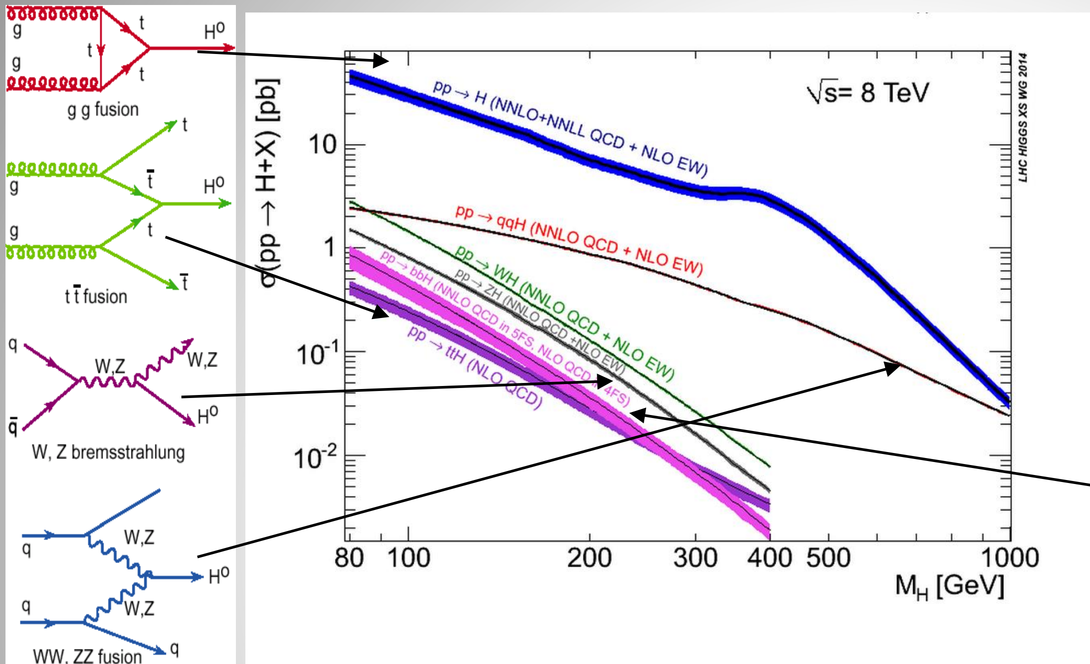
But no sign of New Physics …☹

"The combined analysis of data from CMS and LHCb, […] establishes conclusively the existence of the $B_s^0 \to \mu^+\mu^-$ decay and provides an improved measurement of its branching fraction."

Higgs!

We discovered a Higgs particle!

Higgs Production & Decay

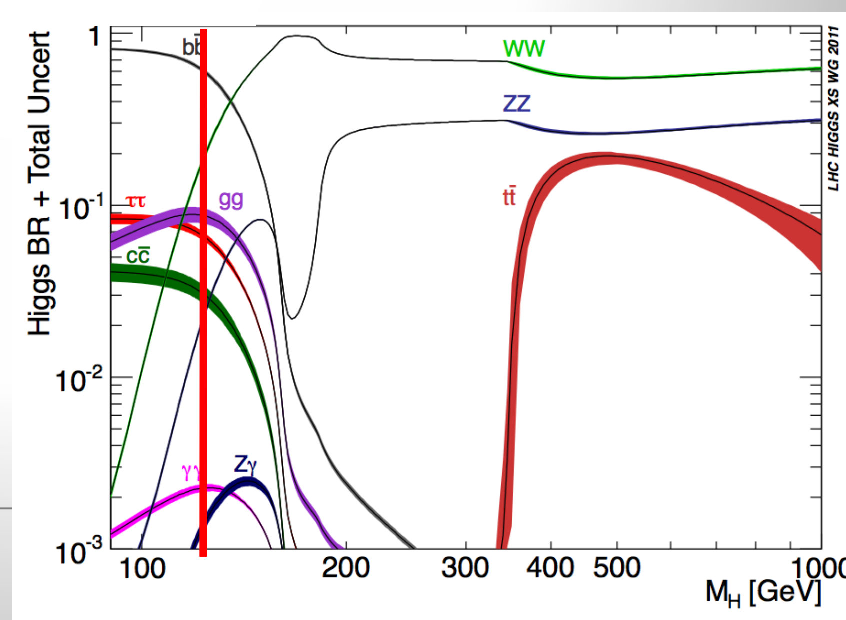


Processes

- Gluon fusion
- Vector Boson Fusion
- W/Z associated prod.
- Top associated prod
- B-quark associated prod?

Numbers taken from the
LHC Higgs Cross Section WG

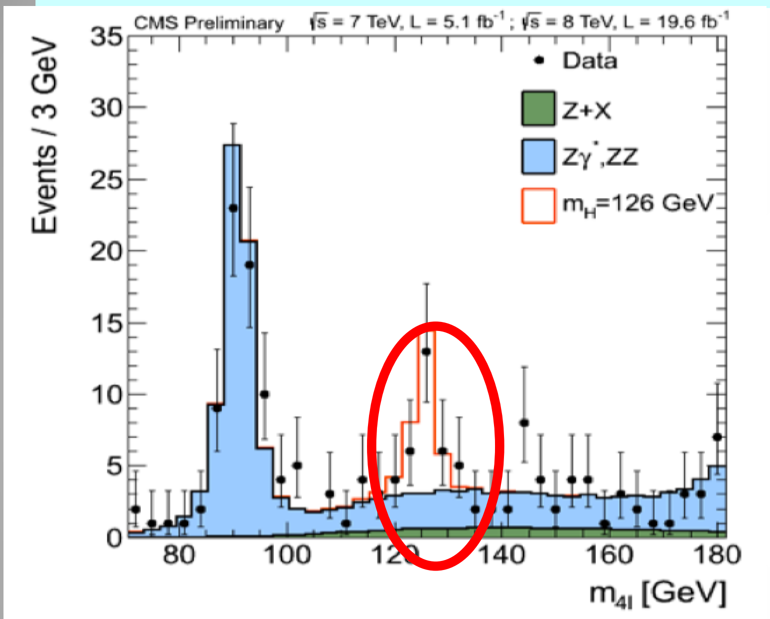
See yellow reports:
YR1: Inclusive cross sections
YR2: Differential cross sections
YR3: Properties

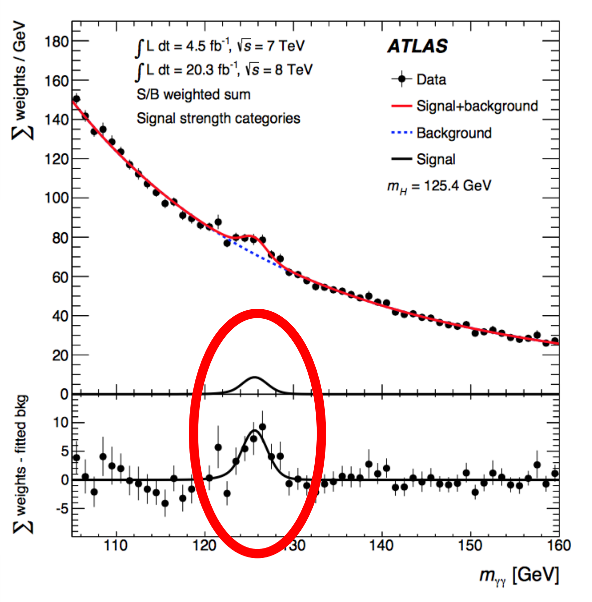


2012: A Milestone in Particle Physics

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

2013





2015: Higgs Boson well established.

All accessible channels studied

	untagged	VBF	VH	ttH
H-> gamgam				
H-> ZZ				
H->WW				
H-> bb				
H-> tau tau				
H-> Zgamma				
H-> mumu				
H-> invisible				

Results released

In progress

Higgs Analyses

- In summer 2012 we called it a "Higgs-like" particle
- In spring 2013 (with 3x more data) we called it a Higgs particle

Spin/parity 0^+ favored, couplings roughly as in SM for Bosons

What happened Next?

- More detailed analyses of the 125 GeV particle, in particular the search for direct decays into fermions, ttH channel, single top...
- More precise measurements of the "signal strength σ/σ_{SM}" and of the mass of the particle, and the spin, couplings
- Searches for Higgs like particles at higher masses
- Searches for exotic, non-SM decays (none found so far)
- Searches for di-Higgs events (in BSM scenarios, none found so far)
- Differential distributions + fiducial volume cross sections

→We have by now published all Run-I legacy papers

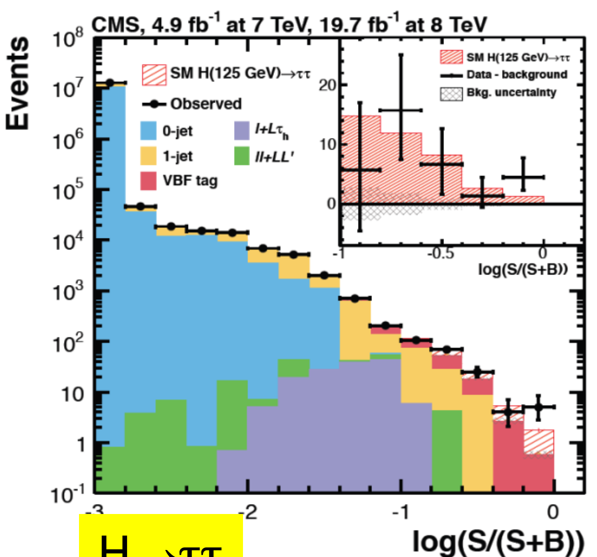
The Higgs is the new playground: Room for new experimental/theoretical ideas!!
Remember: we have already ~1 Million Higgses produced at the LHC

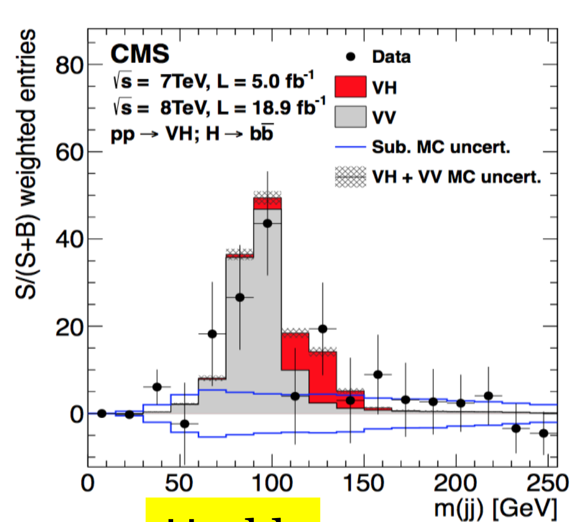
Results Summary @ 125 GeV

Run-I Legacy papers

Channel	ATLAS Lumi [fb-1]	CMS Lumi [fb-1]	Specialty	σ Obs. (exp.)	Mass [GeV]	Signal strength μ	$J^P = 0^+$
H→γγ	4.8+20.7	5.1+19.6	mass, discovery, couplings	5.2 (4.6)	126.	1.17±0.27	✓
				5.7 (5.3)	124.7	1.14+ 0.26- 0.23	✓
H→ZZ→4l	4.6+20.7	5.1+19.7	mass, discovery, couplings	8.1 (6.0)	124.7	1.44 ± 0.4	✓
				6.8 (6.7)	125.6	0.93 +0.29- 0.25	✓
H→WW→2l2ν	4.6+20.7	4.9+19.4	cross section, couplings	6.1 (5.8)	Compatible with 125GeV	1.09 +023-0.21	✓
				4.3 (5.8)	125.5+3.6–3.8 (μ = 1)	0.72 +0.20- 0.18	✓
H→bb	4.5+20.3	5.1+18.9	couplings to fermions	1.4 (2.6)	--	0.52 +0.40- 0.27	--
				2.1 (2.1)	Compatible with 125GeV	1.0 ± 0.5	--
H→ττ	20.3	4.9+19.4	couplings to fermions	4.5 (3.4)	Compatible with 125GeV	1.43 +0.43–0.37	--
				3.2 (3.7)	122 ±7 GeV	0.78 ± 0.27	--

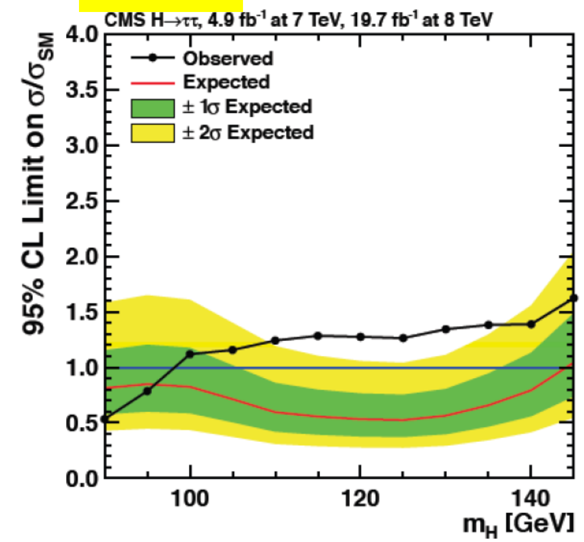
The Decay Higgs to Fermions

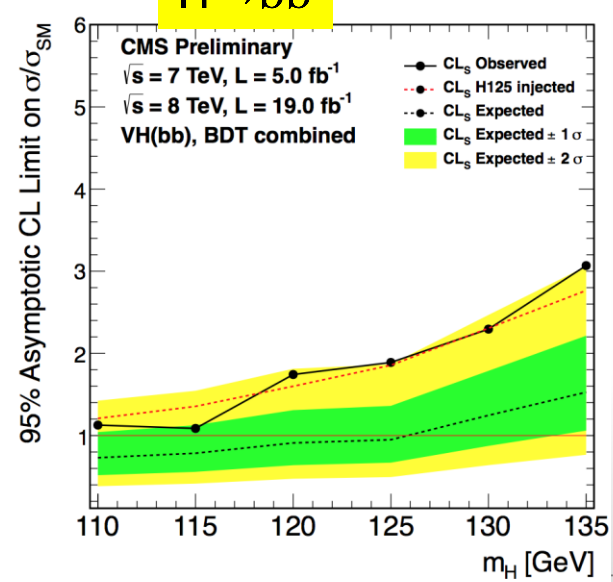




H→ττ

H→bb





H-> bb
Associated production channels: ZH and WH

H-> tau tau
Inclusive and with jets
All tau decay modes used

A (mild) excess seen in both channels
Poor mass resolution

arXiv1401.5041
arXiv1310.3687

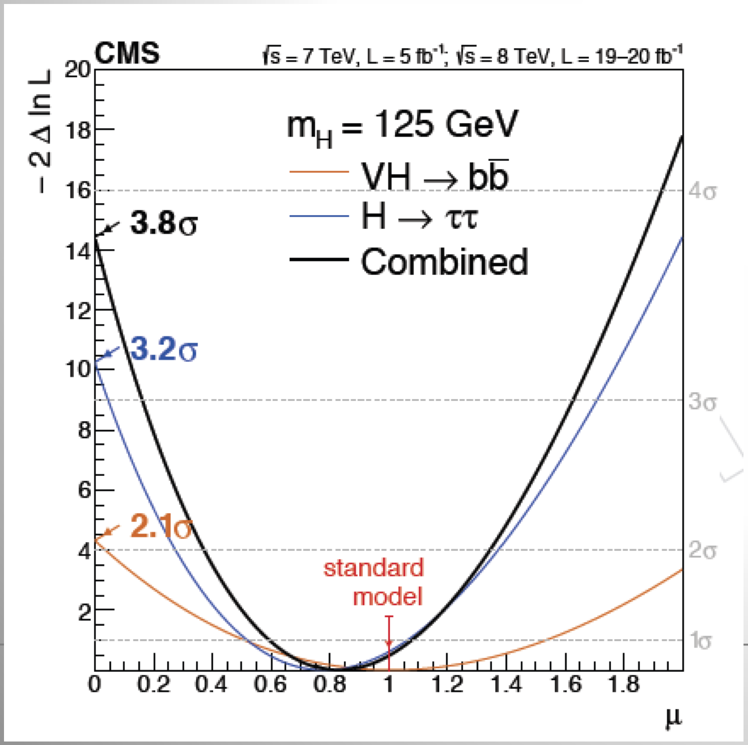
CMS @ 125 GeV
H→ττ 3.2σ (obs) 3.7σ (exp)
→ $\mu = 0.78^{+0.27}_{-0.27}$
H→bb 2.1σ (obs) 2.1σ (exp)
→ $\mu = 1.0 \pm 0.5$

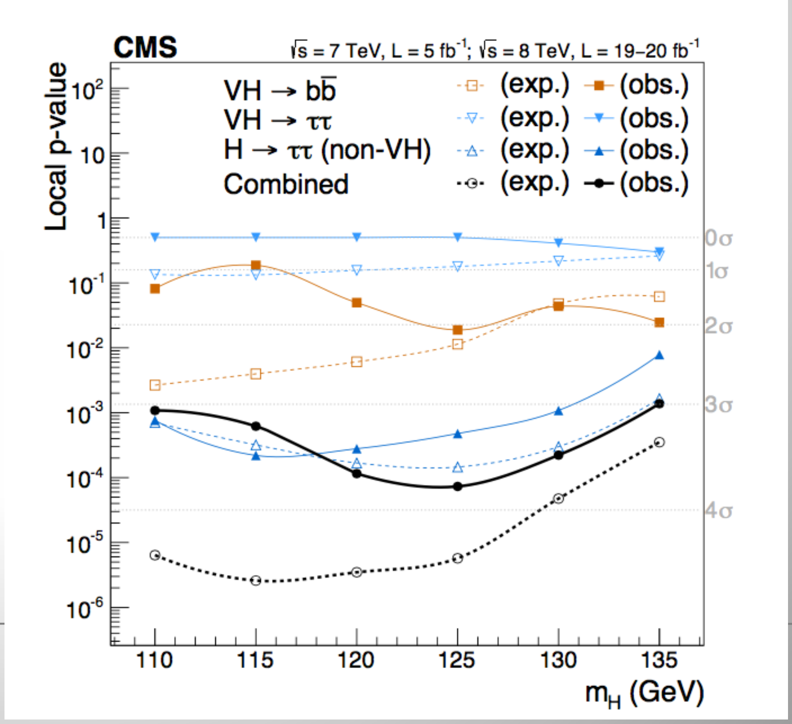
Higgs → Fermions Combination

- The combined H(ττ) and H(bb) result establishes a strong evidence for coupling of the Higgs boson to down-type third generation fermions
- Indirect and direct results on ttH coupling also evident for a coupling to up-type fermions

arXiv:1401.6527 and
Nature Physics 10 (2014)

Channel ($m_H = 125\,GeV$)	Significance (σ) Expected	Significance (σ) Observed	Best-fit μ
$VH \to b\bar{b}$	2.3	2.1	1.0 ± 0.5
$H \to \tau\tau$	3.7	3.2	0.78 ± 0.27
Combined	4.4	3.8	0.83 ± 0.24





Higgs → Fermions Combination

More blogging than for the discovery paper … Bizar

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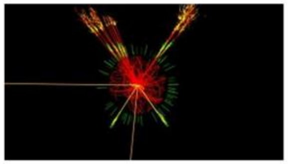
Home » Physics » General Physics » June 22, 2014

Evidence found for the Higgs boson direct decay into fermions

Jun 22, 2014



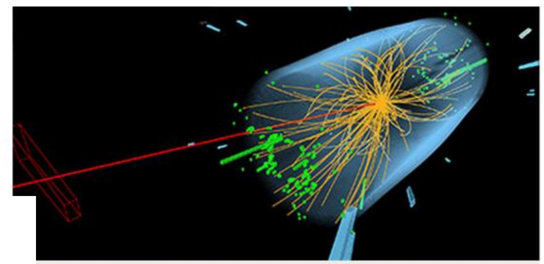
Simulated production of a Higgs event in ATLAS. Image credit: CERN.

For the first time, researchers at CERN have found evidence for the direct decay of the Higgs boson into fermions—another strong indication that the particle discovered in 2012 behaves in the way the standard model of particle physics predicts. Researchers

... differently

Decay into quarks and leptons supports the standard model of particle physics

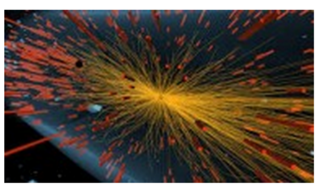
Confirmation for the Higgs: Physicists have for the first time demonstrated the second, postulated by the Standard Model decay of the Higgs boson. In data of the CMS experiment at the Large Hadron Collider (LHC), they discovered an excess of bottom quarks and tau leptons. This shows that the Higgs can not only decompose into other force particles, but also of matter, according to the researchers in the journal "Nature Physics".



...cay traces of a Higgs boson into a pair of tau leptons.
CMS Collaboration

23 giugno 2014

Nuove conferme per il bosone di Higgs



Cortesia Collaborazione CMS/CERN

La particella scoperta presso il Large Hadron Collider del CERN di Ginevra si comporta proprio come il bosone di Higgs previsto dal modello standard della fisica delle particelle. La conferma viene da una nuova analisi dei dati raccolti con l'esperimento CMS che ha mostrato che il bosone di Higgs può decadere anche in una coppia di fermioni, e non solo di bosoni (red)

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June 23, 2014

Nuevas medidas ... Higgs

El descubrimiento del bosón de Higgs e... portadores de fuerzas en la naturaleza. ... encontrado evidencias de la desintegració... materia, y con una tasa que se ajusta al mod...

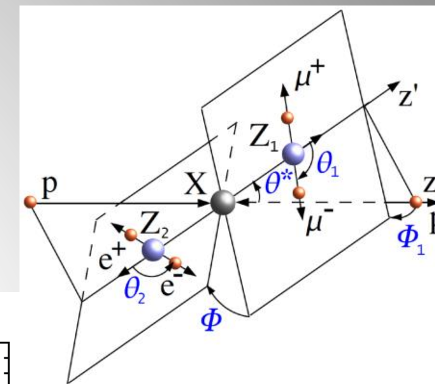
http://www.altmetric.com/details.php?citation_id=2456622

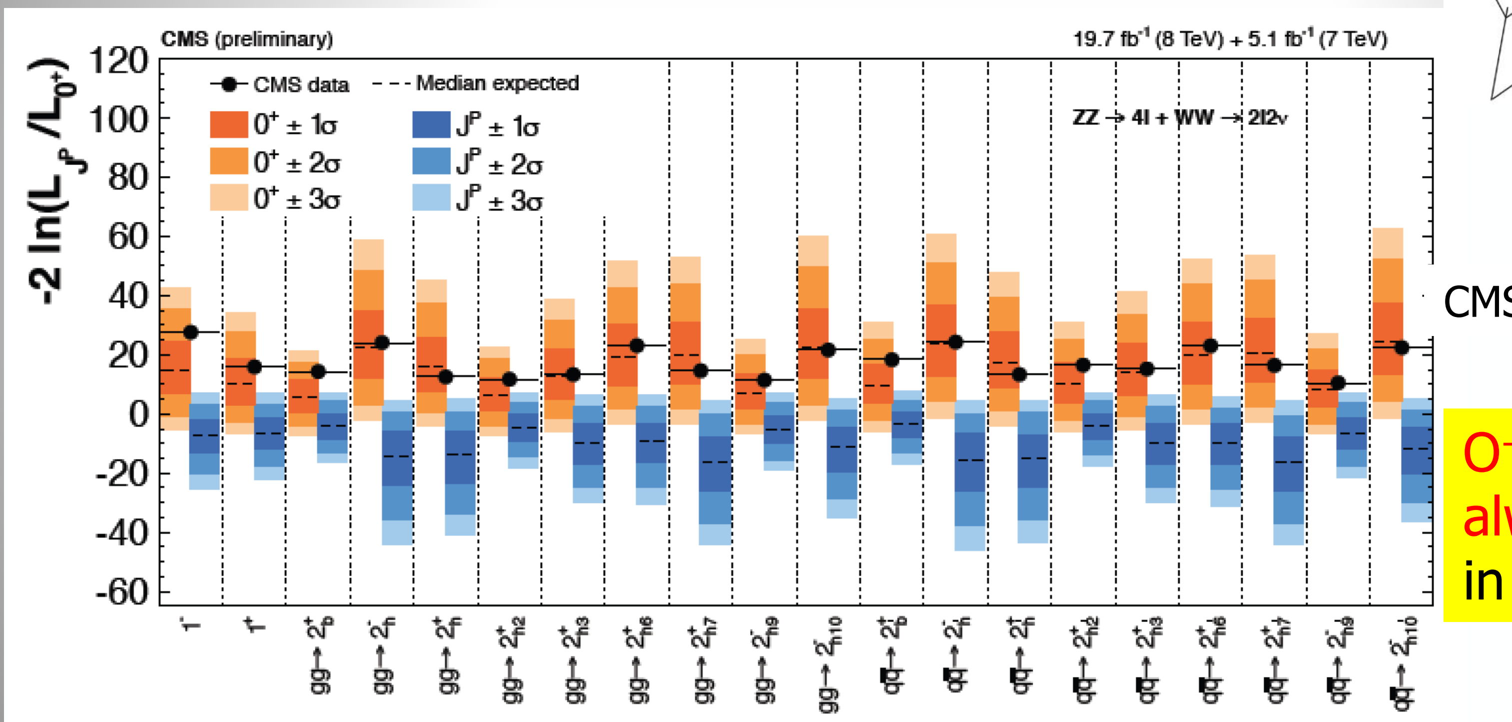
Altametric considers citations in blogs and social media.
The paper is actually the highest ranked Nature Physics paper.
It's actually the highest scoring article in this journal that we've seen so far.
It's in the top 5% of all articles (2,789,380) ever tracked by Altmetric

Spin/Parity Studies

Combined study of H→ZZ and H→WW

- Tested using all diboson channels
- Hypotheses comparison O⁺/other states





CMS-PAS-HIG-14-014

O⁺ hypothesis is always favoured in the comparison

All "exotic" scenarios excluded scenarios excluded with 99.9% CL

Also CP studies of J=0 state → Results consistent with SM

Higgs Combined analysis

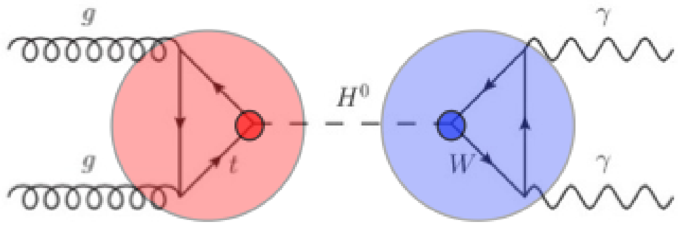
The Run-I Legacy!

Coupling Measurements

Assume the observed signal stems from one narrow resonance.

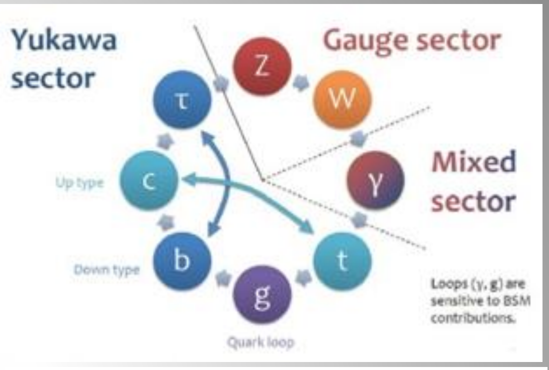
$$(\sigma \cdot \mathrm{BR})\,(ii \to \mathrm{H} \to ff) = \frac{\sigma_{ii} \cdot \Gamma_{ff}}{\Gamma_{\mathrm{H}}}$$

Parametrize deviations w.r.t. the SM in production and decay. This implies precise knowledge of the SM Higgs. Not considered are BSM acceptance effects.



$$(\sigma \cdot \mathrm{BR})\,(\mathrm{gg} \to \mathrm{H} \to \gamma\gamma) = \sigma_{\mathrm{SM}}(\mathrm{gg} \to \mathrm{H}) \cdot \mathrm{BR}_{\mathrm{SM}}(\mathrm{H} \to \gamma\gamma) \cdot \frac{\kappa_{\mathrm{g}}^2 \cdot \kappa_{\gamma}^2}{\kappa_{\mathrm{H}}^2}$$

$$\kappa_H^2 = \sum_X \kappa_X^2 \frac{\mathrm{BR}_{\mathrm{SM}}(H \to X)}{1 - \mathrm{BR}_{\mathrm{BSM}}}$$



- one common scale factor
- scale vector and fermion coupling
- custodial symmetry
- new physics in loops
- BSM Higgs decays
- ...

Decay tag	incl.(ggH)	VBF tag	VH tag	ttH tag
H→ZZ	✔	✔		
H→γγ	✔	✔	✔	✔
H→WW	✔	✔	✔	✔
H→ττ	✔	✔	✔	✔
H→bb		✓	✔	✔
H→Zγ	✓	✓		
H→μμ	✓	✓		
H→inv.		✓	✓	

✔ **Used in the NEW combination**

- Overall combinations from ATLAS and from CMS

CMS arXiv:1412.8662

ATLAS arXiv:1507.04548

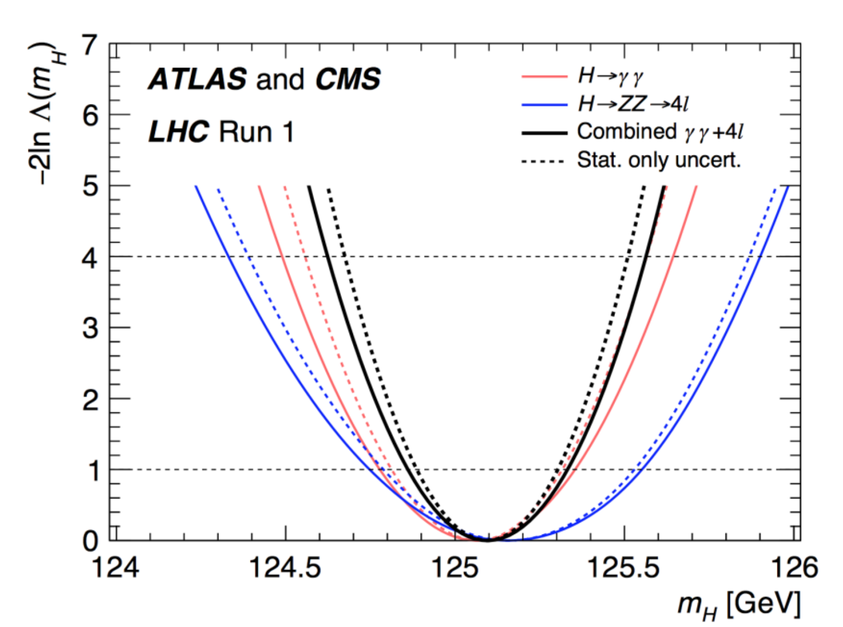
Combination of ATLAS & CMS
Released August 2015 at LHCP
Paper in CMS CWR since last week!!

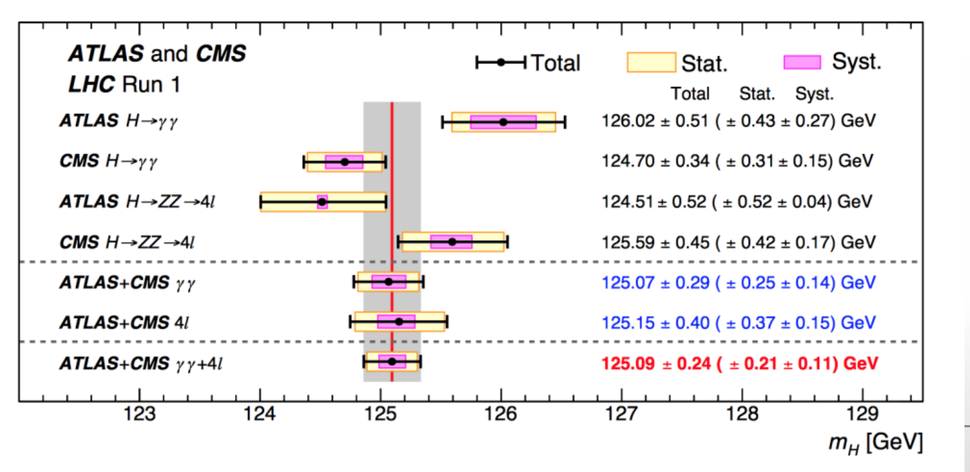
Mass of the Higgs

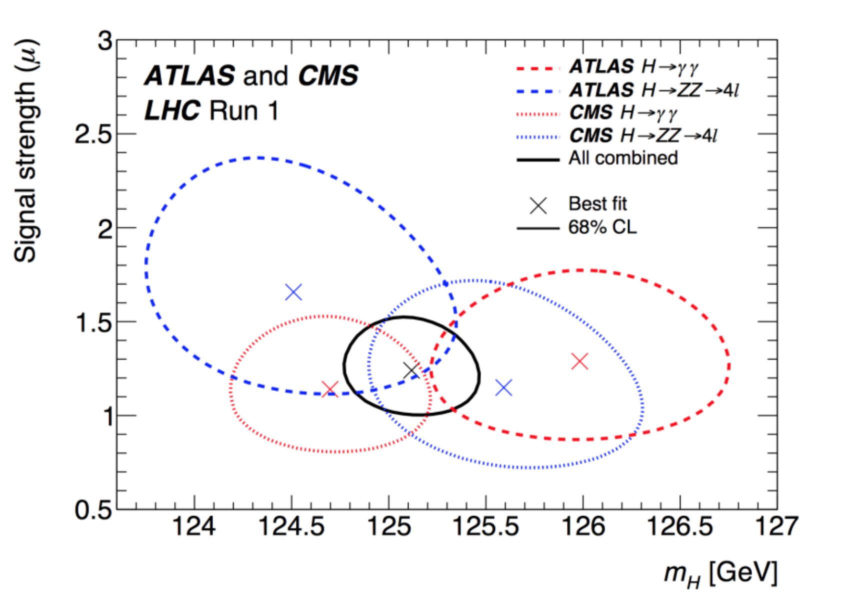
- The first combined result from CMS and ATLAS
- Combine the H->ZZ and H->γγ channels (most precise channels)
- Mass precision ~ 0.2%

$$m_H = 125.09 \pm 0.21\,(\text{stat.}) \pm 0.11\,(\text{syst.})\ \text{GeV}$$

arXiv:1503.07589







CMS+ATLAS Mass Paper

First common paper CMS+ATLAS!!

For the record

- 5153 authors.
  - One duplicate, 2×10^{-4} effect.
- Found that there are two:
  - Archana Sharma (both CMS)
  - **Andrea Bocci (one CMS, one ATLAS)**
  - Muhammad Ahmad (ditto)
  - F. M. Giorgi (ditto)

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Physics paper sets record with more than 5,000 authors

Detector teams at the Large Hadron Collider collaborated for a more precise estimate of the size of the Higgs boson.

Davide Castelvecchi

15 May 2015

CERN

Thousands of scientists and engineers have worked on the Large Hadron Collider at CERN.

A physics paper with 5,154 authors has — as far as anyone knows — broken the record for the largest number of

New: the ATLAS/CMS Combination

To appear soon

CMS PAS HIG-15-002
ATLAS-HIGG-2015-xx

DRAFT
CMS Physics Analysis Summary

The content of this note is intended for CMS internal use and distribution only

CMS-HIG-15-002

AN-2015/183

2015/08/22
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Measurements of the Higgs boson production and decay rates and constraints on its couplings from a combined ATLAS and CMS analysis of the LHC pp collision data at $\sqrt{s} = 7$ and 8 TeV

The ATLAS and CMS Collaborations

Abstract

Combined ATLAS and CMS measurements of the Higgs boson production and decay rates as well as constraints on its couplings to vector bosons and fermions are presented. The combination is based on the analysis of five production processes in several or all of the $H \to ZZ^*, WW^*, \gamma\gamma, \tau\tau$, and $\mu\mu$ decay modes. The results correspond to the LHC proton-proton collision datasets recorded by the ATLAS and CMS detectors in 2011 and 2012, corresponding to integrated luminosities per experiment of ~ 5 fb^{-1} at $\sqrt{s} = 7$ TeV and ~ 20 fb^{-1} at $\sqrt{s} = 8$ TeV. The total signal yield relative to the Standard Model expectation is measured to be 1.09 ± 0.11. The Higgs boson production and decay rates are combined between the two experiments within the context of two generic parameterisations: one based on ratios of cross sections and branching ratios and the other based on ratios of coupling modifiers, introduced within the context of a leading-order Higgs boson coupling framework. Several interpretations of the results with more model-dependent parameterisations, derived from the generic ones, are also given. All results are reported assuming the central value of the LHC Higgs-boson mass combination, = 125.09 GeV. The data are consistent with the Standard Model predictions for all parameterisations considered.

The CMS and ATLAS data on the Higgs have now been analysed in a combined analysis

The results were shown public for the first time at the LHCP conference August 2015

Here are a few highlights

	Best-fit value	Uncertainty Total	Stat	Expt	Thbgd	Thsig
ATLAS and CMS (obs)	1.09	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.07}_{-0.06}$
ATLAS and CMS (exp)	–	$^{+0.11}_{-0.10}$	$^{+0.07}_{-0.07}$	$^{+0.04}_{-0.04}$	$^{+0.03}_{-0.03}$	$^{+0.06}_{-0.06}$
ATLAS (obs)	1.20	$^{+0.15}_{-0.14}$	$^{+0.10}_{-0.10}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$
CMS (obs)	0.98	$^{+0.14}_{-0.13}$	$^{+0.10}_{-0.09}$	$^{+0.06}_{-0.05}$	$^{+0.04}_{-0.04}$	$^{+0.08}_{-0.07}$

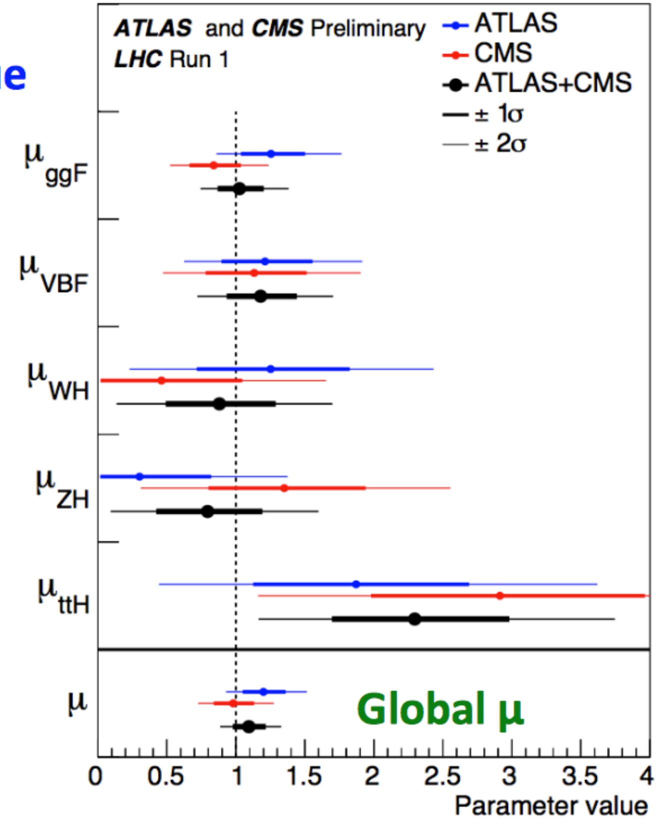
$$\mu = 1.09^{+0.11}_{-0.10}$$

Channel	References from individual publications ATLAS	CMS	Signal strength μ from results in this paper (Section 5.2) ATLAS	CMS	Signal significance [σ] ATLAS	CMS
$H \to \gamma\gamma$	[26]	[48]	$1.15^{+0.27}_{-0.26} \pm 0.27$	$1.12^{+0.25}_{-0.23}$	~5.2	5.6
			(±0.27)	(±0.25)	(4.6)	(5.1)
$H \to ZZ \to 4\ell$	[49]	[50]	$1.52^{+0.40}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	6.6	7.0
			(±0.29)	(±0.27)	(5.5)	(6.8)
$H \to WW$	[51,52]	[53]	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	6.8	4.8
			(±0.23)	(±0.30)	(5.8)	(5.6)
$H \to \tau\tau$	[54]	[55]	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	4.4	3.4
			(±0.40)	(±0.35)	(3.3)	(3.7)
$H \to b\bar{b}$	[35]	[36]	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	1.7	2.0
			(±0.45)	(±0.50)	(2.7)	(2.5)
$H \to \mu\mu$	[56]	[57]	-0.7 ± 3.6	0.8 ± 3.5		
			(±3.6)	(±3.5)		
ttH production	[58–60]	[62]	1.9 ± 0.8	$2.9^{+1.0}_{-0.9}$	2.7	3.6
			(±0.80)	(±0.80)	(1.6)	(1.3)

Signal Strength for Production & Decay

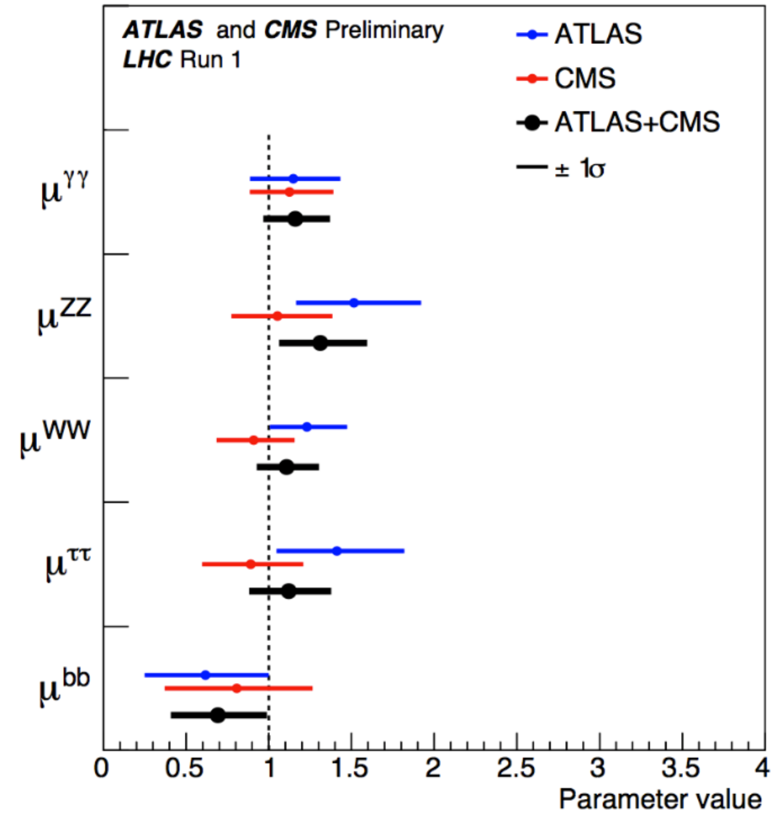
SM BRs assumed

SM p-value 25%



SM production σ assumed

SM p-value 60%



- Signal strengths in different channels are consistent with 1 (SM)
- Largest difference in ttH: 2.3σ excess with respect to SM

Significance in the Different Channels

- Comparing likelihood of the best-fit with $\mu_{prod}=0$ and $\mu^{decay}=0$ we obtain:

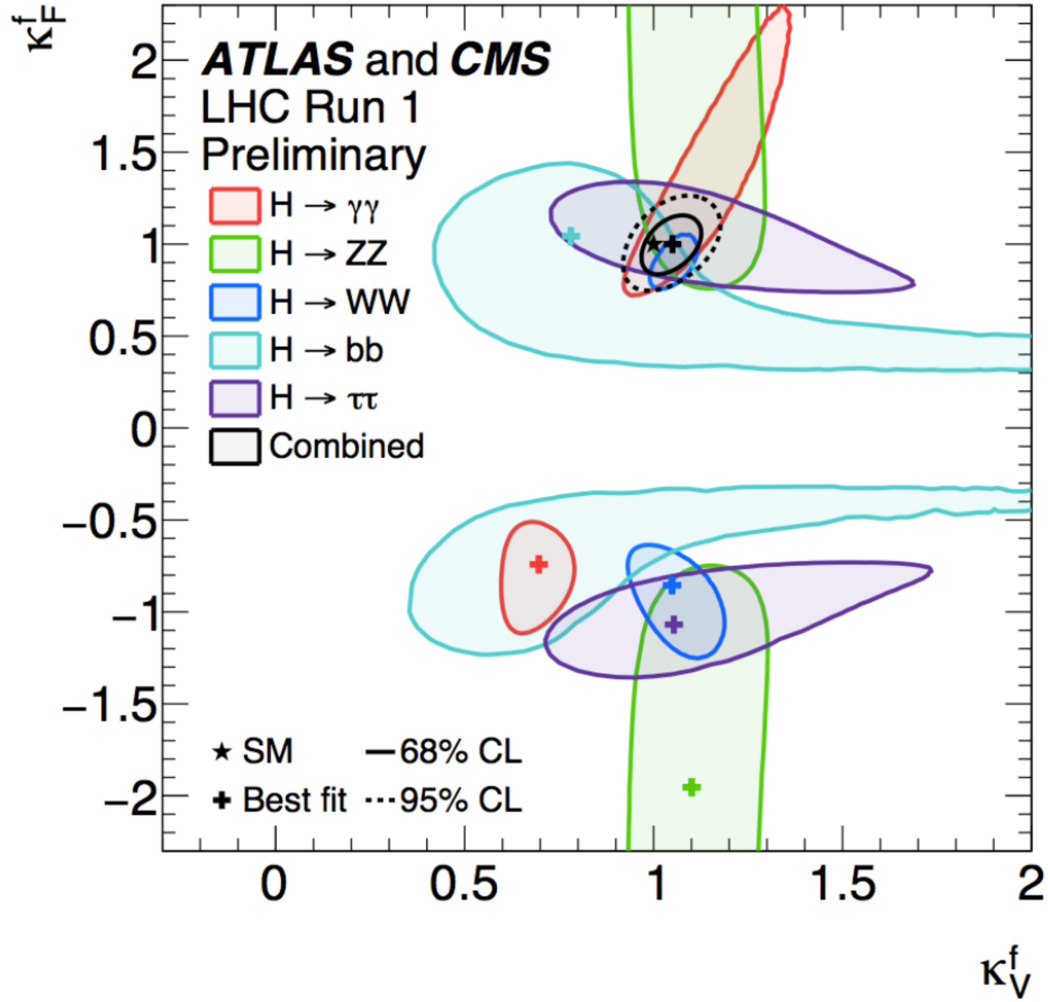
Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	**4.7**
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	**5.0**
H→bb	2.6	3.7

- Combination largely increases the sensitivity

VBF and H→ττ now established at over 5 σ. Same as ggF and H→ZZ, γγ, WW from single experiments

Coupling Modifiers

- Negative couplings would change sign of interference



Standard Model:
-> κ=1

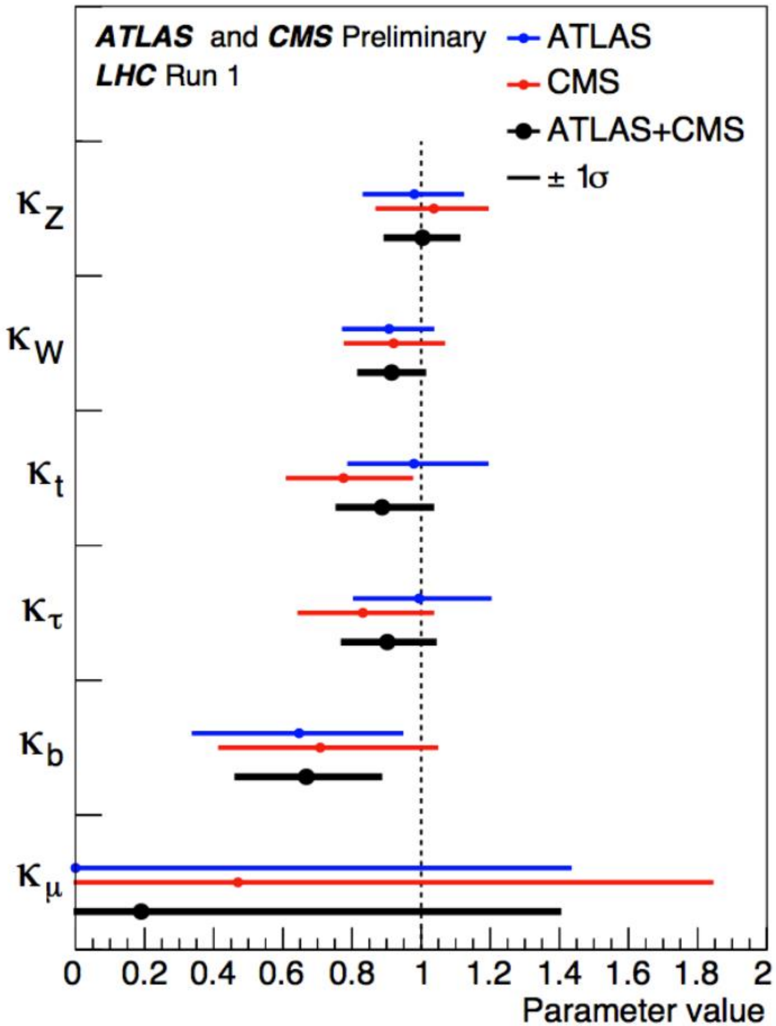
Almost 5σ exclusion of $\kappa_F<0$

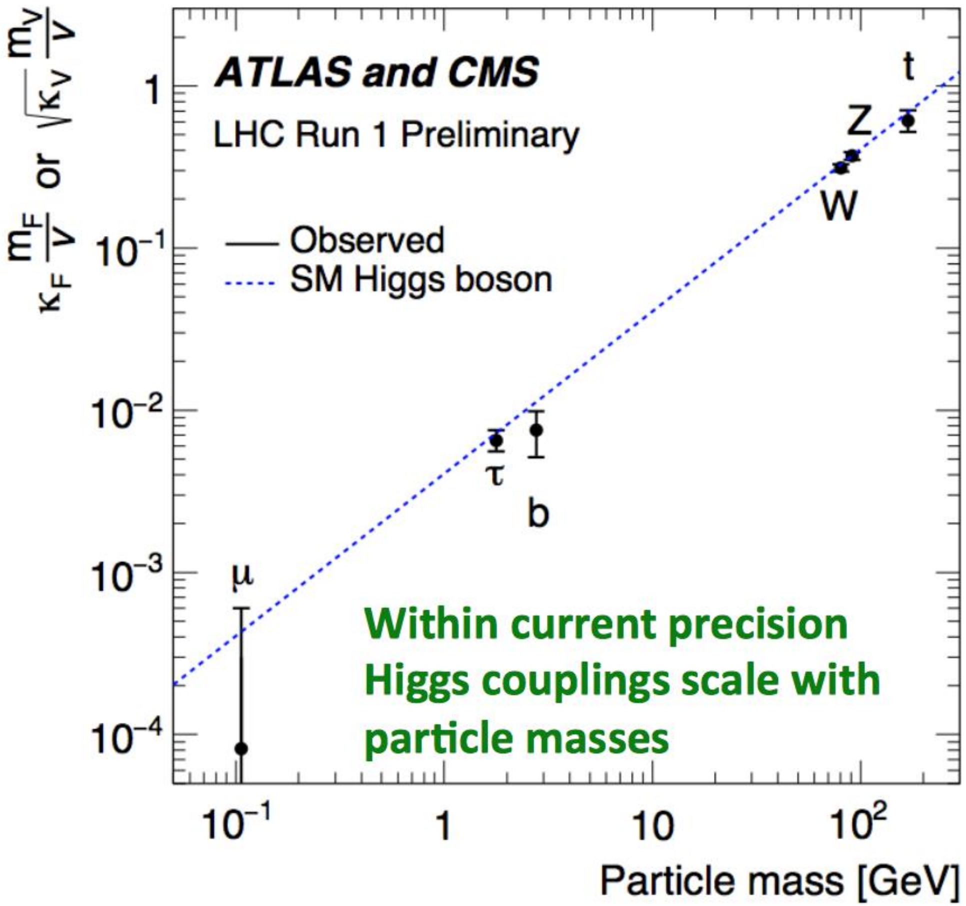
- The other two quadrants are symmetric with respect to (0,0), all physical quantities only depend on a product of two κ's

Fiting all Couplings

- Fitting the 5 main tree level coupling modifiers + κ_μ and resolving all the loops.

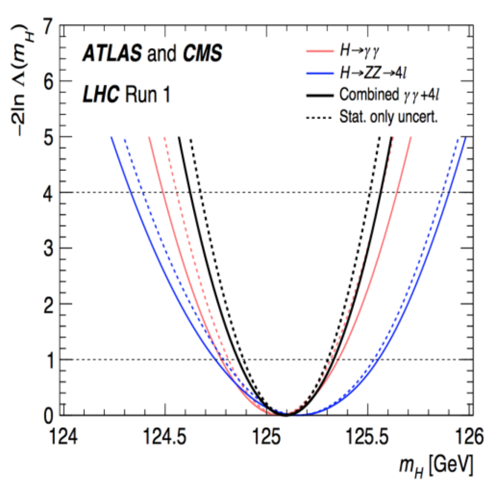
Assume no BSM contributions in the loops

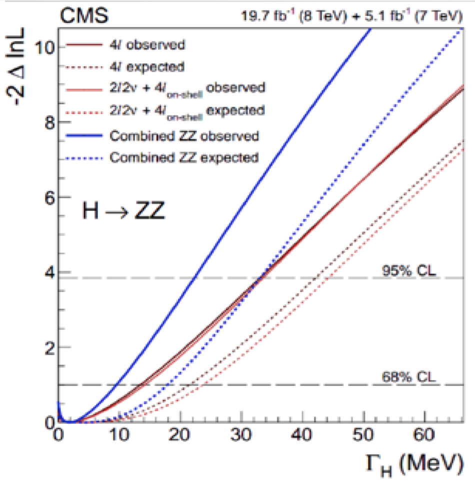


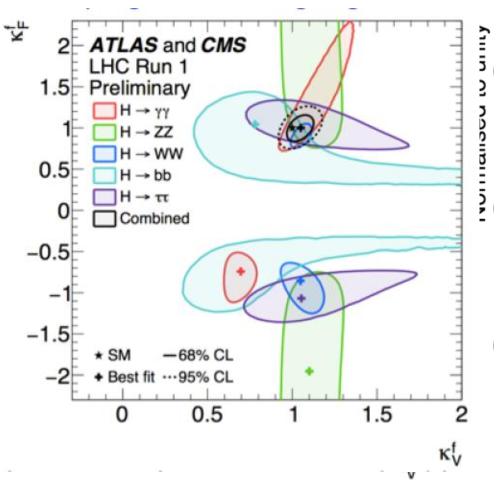


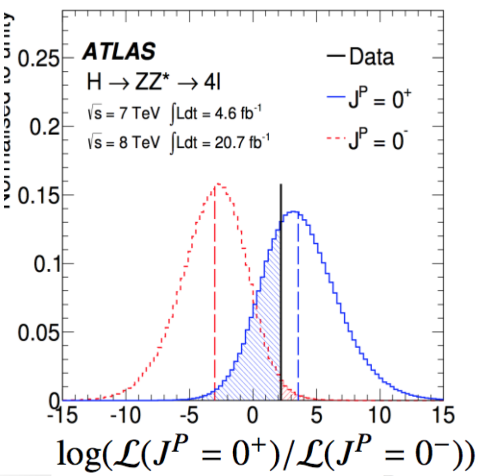
Brief Higgs Summary

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









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

Width =
A: < 24 MeV
C: < 22 MeV
(95%CL)

Couplings are within 15% of the SM values

Spin = $0^{+(+)}$ preferred over 0^{-},1,2

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

Summary

- Run-I delivered many measurements of Standard Model processes, eg on the top quark, EWK and in QCD. Some features of multi-particle production are not understood.
- Electroweak measurements show agreement with the data in general.
- The LHC is a top-factory. Very detailed study of the top quarks ongoing. No surprises yet!
- A prime target of the LHC was the discovery of “a” or “the” Higgs particle. Particle found/Mission accomplished! ☺
- The new particle has properties compatible with a Higgs, but surprises are still possible. This will be one of the topics for the coming run.

But where is the New Physics? → Lecture II