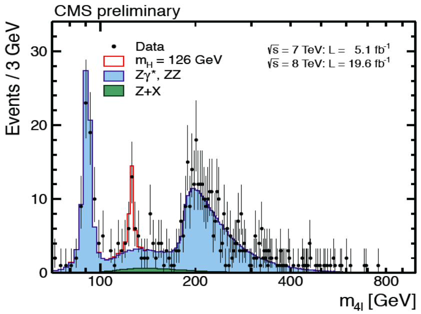
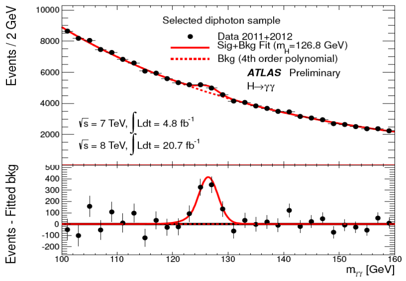
Imperial College
London

Highlights from LHC Physics

European School of Physics
Parafurdo, Hungary
June 2013

Sergio da Vittorio Veneto



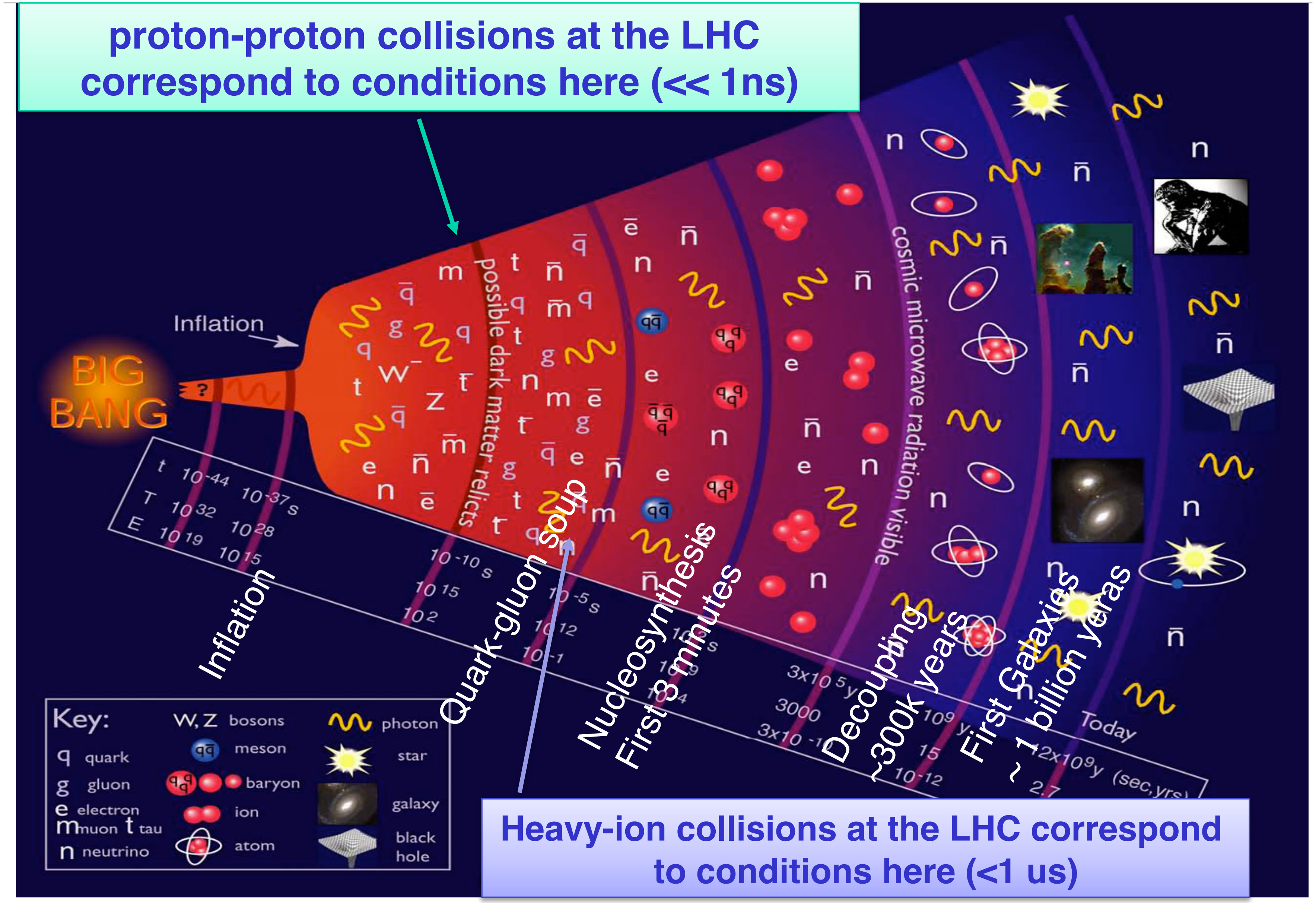


Acknowledgements
Talks at LHCP 2013
Many LHC Colleagues
P. Sphicas, G. Dissertori

Tejinder S. Virdee, Imperial College

Brief History of Our Universe

proton-proton collisions at the LHC correspond to conditions here (<< 1ns)

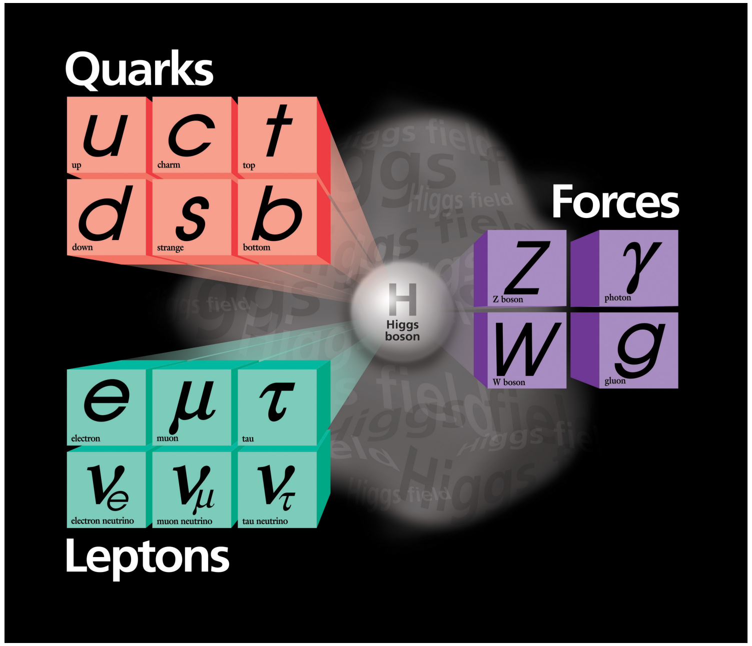


Heavy-ion collisions at the LHC correspond to conditions here (<1 us)

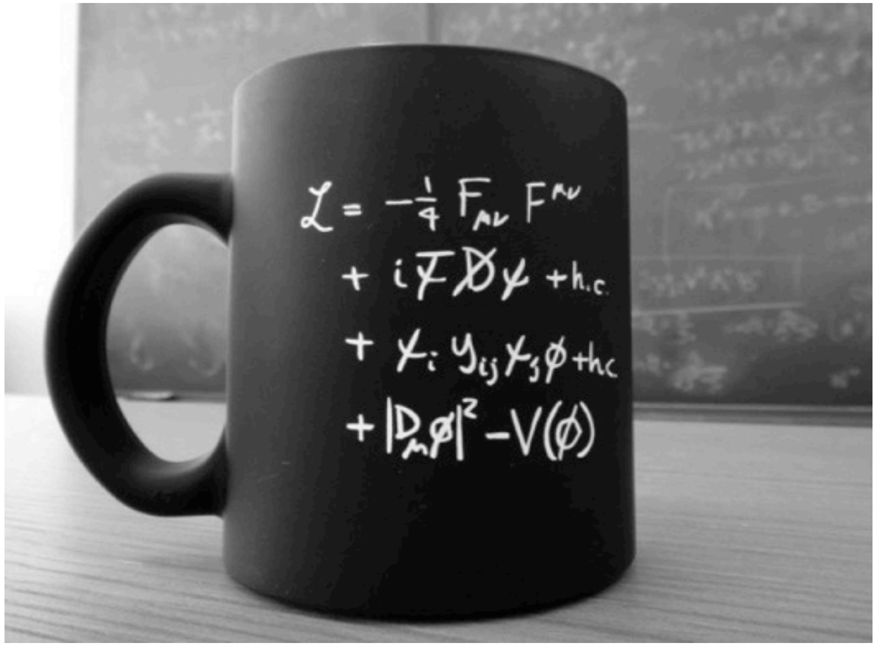
The Standard Model of Particle Physics

A crowning achievement of 20th Century Science

Matter particles



Force particles



The SM has been tested thousands of times, to excellent precision.
its most basic mechanism, that of granting mass to particles,
needed elucidation, => the Higgs boson?

Physics Outlook: Questions for the LHC

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

2. Clarify the e-w symmetry breaking sector
SM has an unproven element: the generation of mass
Higgs mechanism ->? or other physics ?
Answer will be found at **LHC energies**

e.g. why $M_\gamma = 0$
M_W, $M_Z \sim 100{,}000$ MeV!

Transparency from the early 90's

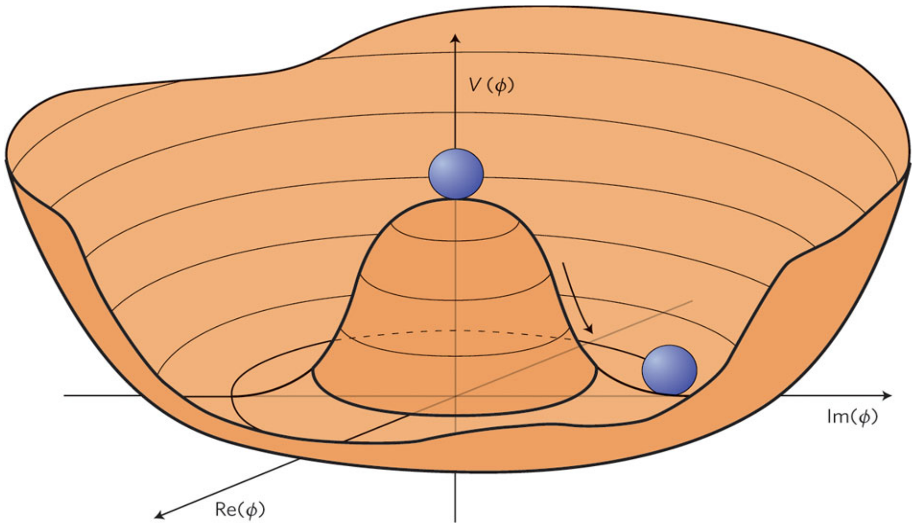
3. SM gives nonsense at LHC energies
Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!
Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter
Even if the Higgs exists all is not completely well with SM alone:
next question is "Why is (Higgs boson) mass so low"?
*If a new symmetry (Supersymmetry) is the answer, it must show up at O(***1TeV)**

5. Search for new physics at the TeV scale
SM is logically incomplete – does not incorporate gravity
Superstring theory ⇨dramatic concepts: supersymmetry , extra space-time dimensions ?

Spontaneous Symmetry Breaking

$$V(\Phi) = \mu^2\Phi^\dagger\Phi + \lambda^2\left(\Phi^\dagger\Phi\right)^2$$



Unbroken Gauge Theory
Massless Gauge Bosons

→ SSB →

EW Theory
Massive W±, Z
Massless γ
New boson, H

Brief History of the Electroweak Theory
Almost 50 years ago – the seminal papers

Higgs

An Intellectual Conjecture: The 1st references in ATLAS/CMS Discovery papers

[1] F. Englert and R. Brout, "Broken symmetry and the mass of gauge vector mesons", *Phys. Rev. Lett.* **13** (1964) 321, doi:10.1103/PhysRevLett.13.321.

[2] P. W. Higgs, "Broken symmetries, massless particles and gauge fields", *Phys. Lett.* **12** (1964) 132, doi:10.1016/0031-9163(64)91136-9.

[3] P. W. Higgs, "Broken symmetries and the masses of gauge bosons", *Phys. Rev. Lett.* **13** (1964) 508, doi:10.1103/PhysRevLett.13.508.

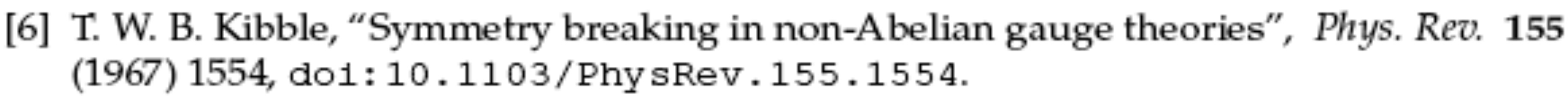
[4] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, "Global conservation laws and massless particles", *Phys. Rev. Lett.* **13** (1964) 585, doi:10.1103/PhysRevLett.13.585.

These papers on the *spontaneous symmetry breaking mechanism* attracted very little attention at the time.

The *boson* attracted even less interest (T. Kibble, 2011)

Brief History of the Electroweak Theory
Almost 50 years ago – the seminal papers

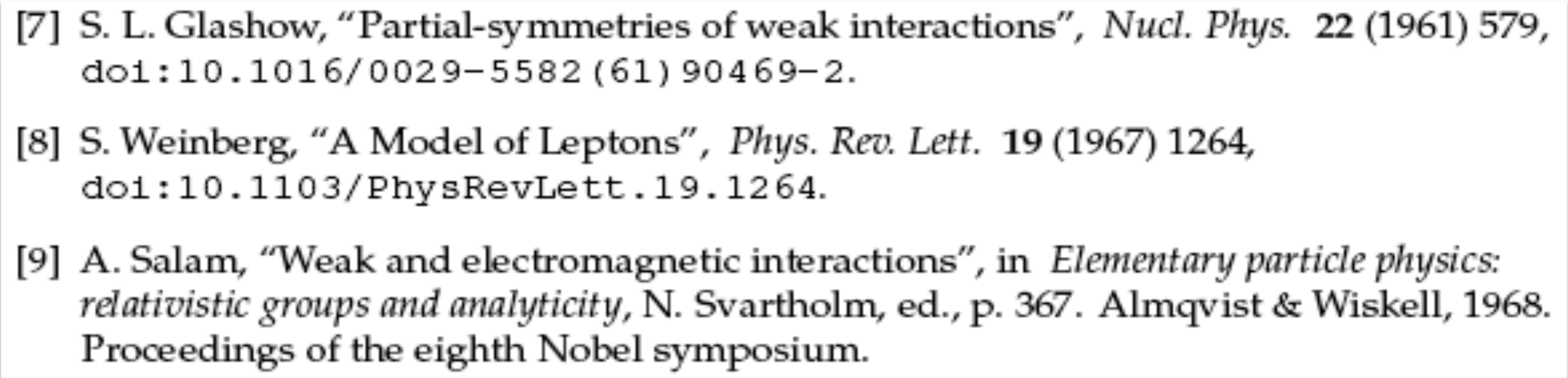
References in ATLAS/CMS Discovery papers



[6] T. W. B. Kibble, "Symmetry breaking in non-Abelian gauge theories", *Phys. Rev.* **155** (1967) 1554, `doi:10.1103/PhysRev.155.1554`.

Further work on the detailed application of the SSB mechanism to non-abelian theories. This work helped in getting to electroweak unification.

Describes the real world: photon massless, W/Z massive"
F. Close, "Infinity Puzzle"



[7] S. L. Glashow, "Partial-symmetries of weak interactions", *Nucl. Phys.* **22** (1961) 579, `doi:10.1016/0029-5582(61)90469-2`.

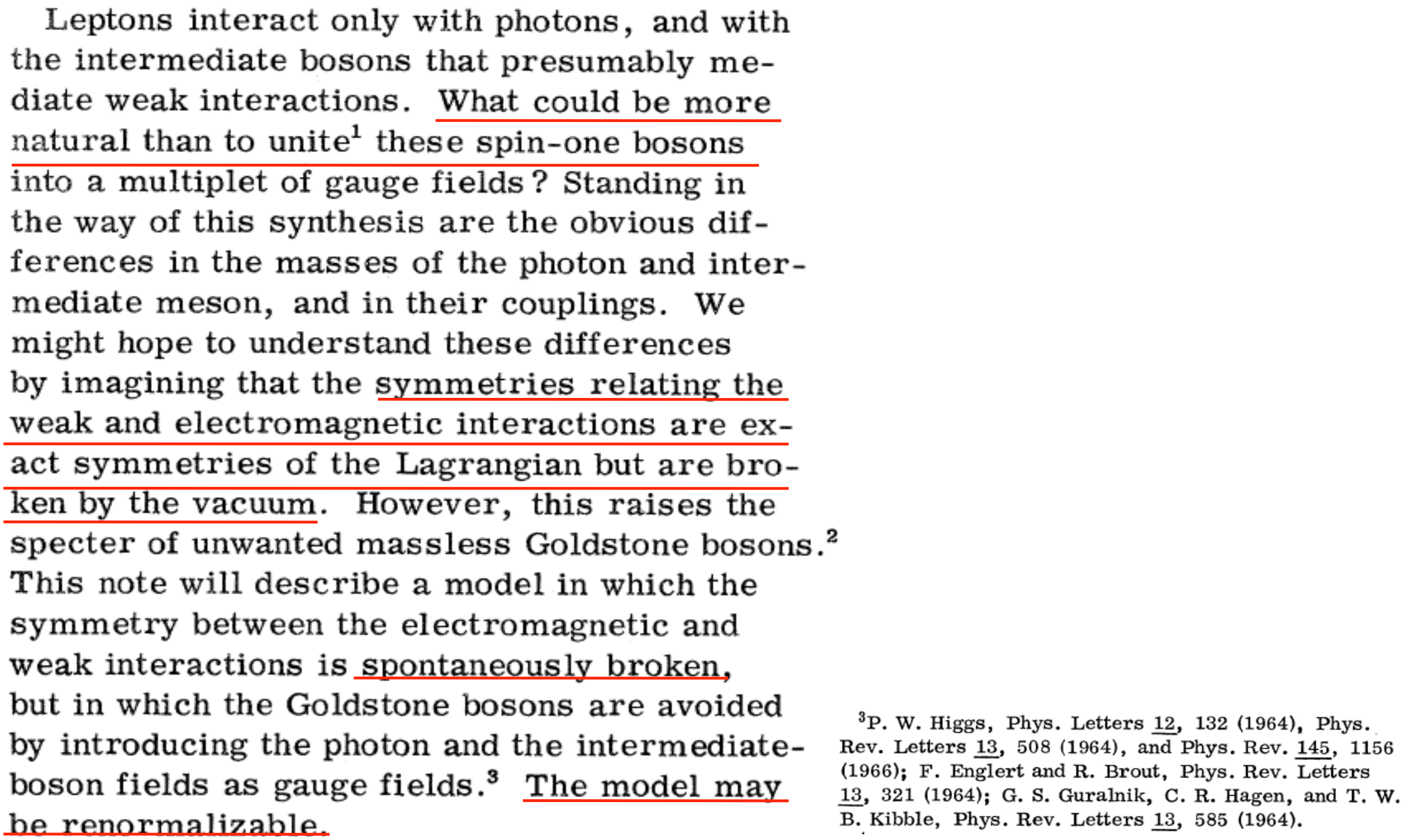
[8] S. Weinberg, "A Model of Leptons", *Phys. Rev. Lett.* **19** (1967) 1264, `doi:10.1103/PhysRevLett.19.1264`.

[9] A. Salam, "Weak and electromagnetic interactions", in *Elementary particle physics: relativistic groups and analyticity*, N. Svartholm, ed., p. 367. Almqvist & Wiskell, 1968. Proceedings of the eighth Nobel symposium.

SU(2)XU(1): Unified model of weak and electromagnetic interactions of leptons proposed by Weinberg (1967), and independently by Salam (1968).
Labeled electroweak theory by Salam

Electro-weak Unification: seminal papers

A Model of leptons (S. Weinberg, 1967)



Leptons interact only with photons, and with the intermediate bosons that presumably mediate weak interactions. What could be more natural than to unite[1] these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate meson, and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons.[2] This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and the intermediate-boson fields as gauge fields.[3] The model may be renormalizable.

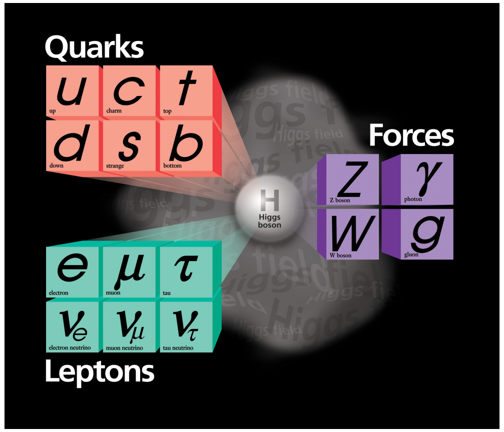
[3] P. W. Higgs, Phys. Letters 12, 132 (1964), Phys. Rev. Letters 13, 508 (1964), and Phys. Rev. 145, 1156 (1966); F. Englert and R. Brout, Phys. Rev. Letters 13, 321 (1964); G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble, Phys. Rev. Letters 13, 585 (1964).

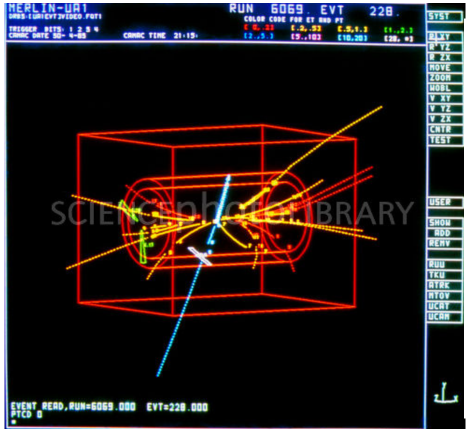
Further Theoretical and Experimental Developments

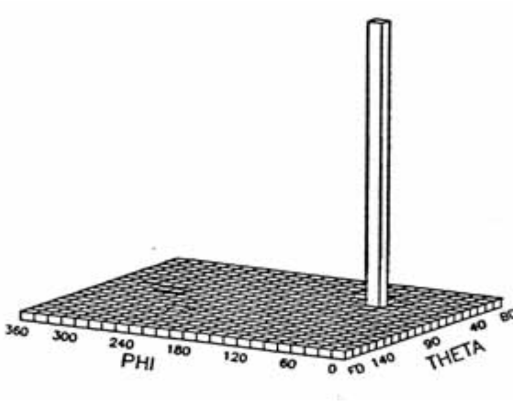
Salam and Weinberg speculated that their theory was renormalizable
This conjecture was proven in 1971 (by Gerard ’t Hooft & Tini Veltman)

In 1973 a key prediction of the e-w theory, the existence of neutral current interactions — those mediated by Z^0 — was confirmed at CERN.

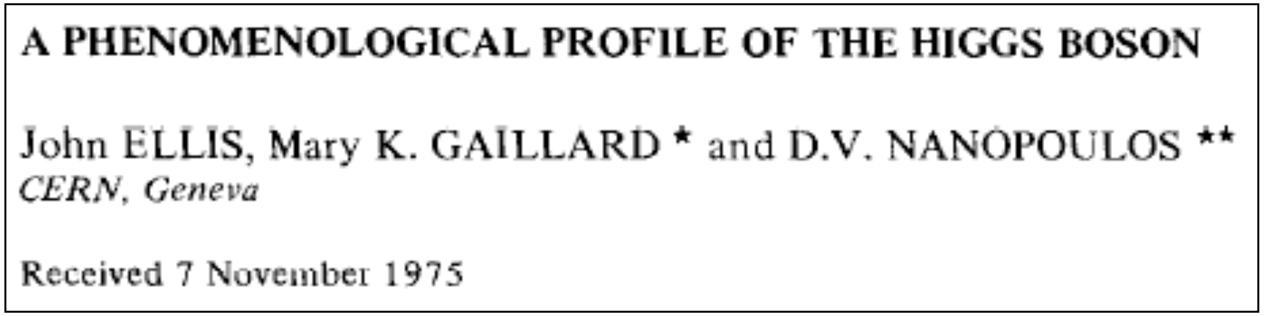
In 1983 the *W* and *Z* particles were discovered at CERN (UA1 and UA2)
***then* the Higgs boson became the last important missing piece of the SM!**







A Phenomenological Profile of the Higgs Boson

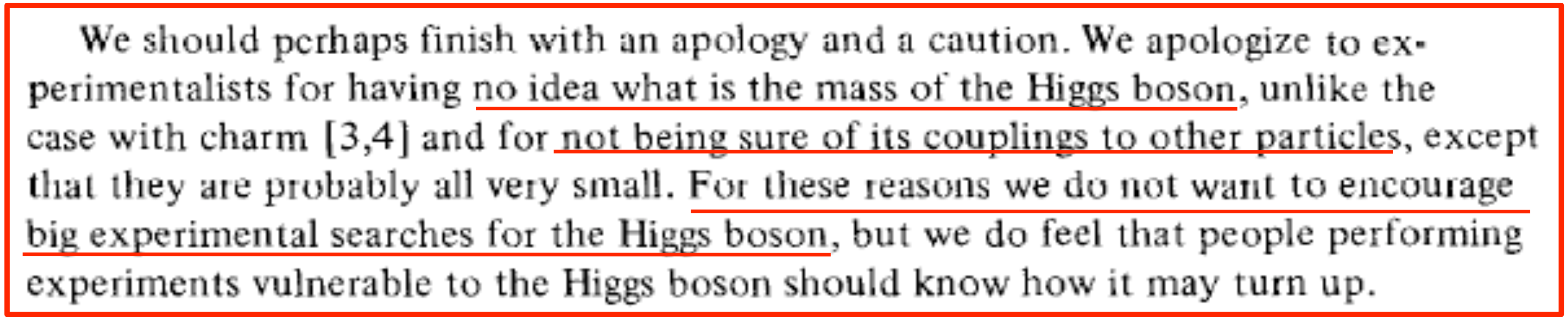


A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

Reviewed Higgs decay modes and status of the searches in 1975



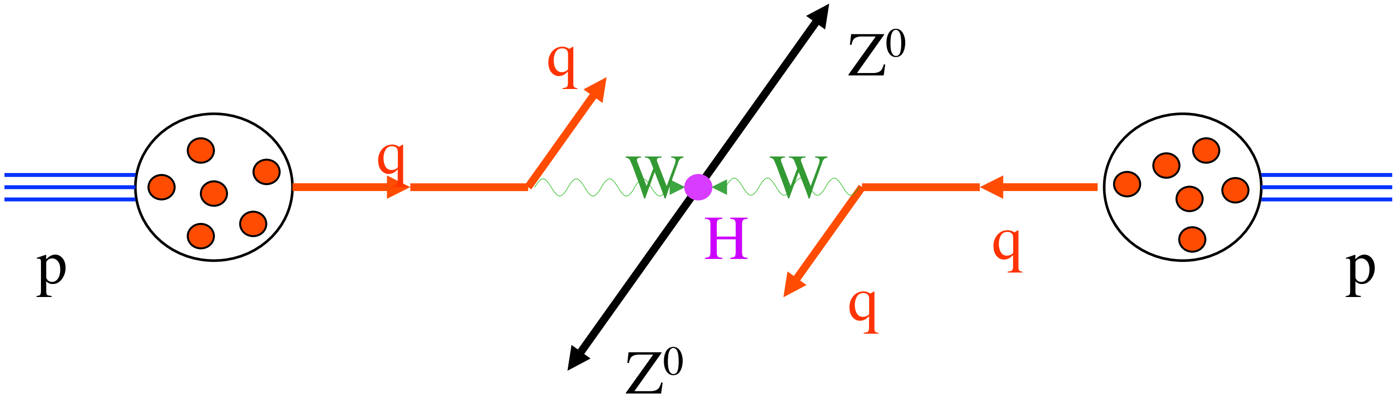
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

Timeline of the LHC Project

1984	Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne
1987	Rubbia “Long-Range Planning Committee” recommends Large Hadron Collider as the right choice for CERN’s future
1990	**ECFA LHC Workshop, Aachen**
1992	**General Meeting on LHC Physics and Detectors, Evian les Bains**
1993	**Letters of Intent (ATLAS and CMS selected by LHCC)**
1994	Technical Proposals Approved
1996	**Approval to move to Construction (materials cost of 475 MCHF)**
1998	Memorandum of Understanding for Construction Signed
1998	Construction Begins (after approval of Technical Design Reports)
2000	**ATLAS and CMS assembly begins above ground. LEP closes**
2008	**ATLAS & CMS ready for First LHC Beams**
2009	First proton-proton collisions
2012	A new heavy boson discovered with mass ~125 × mass of proton

The LHC: Design Energy and Luminosity

To study W_L-W_L scattering need a centre of mass energy of ~ 1 TeV (now a closure test of the SSB)



- ⇨ E_W ~ 500 GeV
- ⇨ E_{quark} ~ 1 TeV
- ⇨ E_{proton} ~ 6 TeV

⇨ LHC: pp collisions at **7 + 7 TeV**

Event Rate = Luminosity . Cross-section . Branching Ratio = L . σ .BR
e.g. H(1 TeV) → ZZ → 2e+2μ or 4e or 4μ
For 10 Evts/yr = $10^{34}\ 10^{-37}.10^{-3}.10^{7}$!! ⇨ **L ~$10^{34}$ cm^{-2} s^{-1}**

- **Luminosity**, measured in $cm^{-2}s^{-1}$, is indicative of the number of proton-proton collisions taking place per sec. Rate = 8.10^8/sec for L=$10^{34}cm^{-2}s^{-1}$ and σ=80mb
- **Integrated Luminosity** of 1fb^{-1} corresponds to examining 80 trillion pp collisions

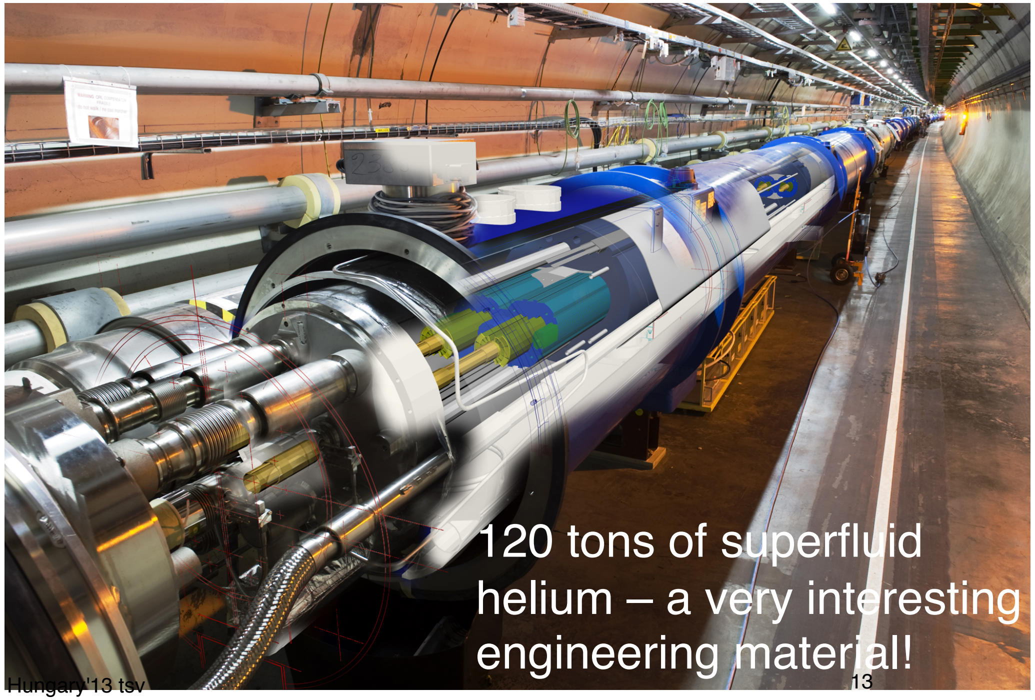
The LHC Accelerator

Protons are accelerated by powerful electric fields to very (very) close to the speed of light **(superconducting r.f. cavities)**

And are guided around their circular orbits by powerful **superconducting dipole magnets**.

The dipole magnets operate at 8.3 Tesla (200’000 x Earth’s magnetic field) & 1.9K (-271°C) in **superfluid helium**.

Protons travel in a tube which is under a better **vacuum**, and at a lower temperature, than that found in inter-planetary space.



120 tons of superfluid helium – a very interesting engineering material!

Run 1: The LHC has performed marvelously well!

Parameter	2010	2011	2012	Nominal
Energy (TeV)	3.5	3.5	**4.0**	7.0
N (10^{11} p/bunch)	1.2	1.45	1.6-1.7	1.15
k (no. bunches)	368	1380	1374	2808
Bunch spacing	150	75 / 50	**50**	25
Stored energy (MJ)	25	112	140	362
ε (μm rad)	2.4	2.4	2.5	3.75
β^* (m) (high lumi experiments)	3.5	1.5 → 1	0.6	0.55
L (cm^{-2}s^{-1})	2×10^{32}	3.5×10^{33}	7.7×10^{33}	10^{34}
Beam-beam parameter/IP	-0.0054	-0.0065	-0.0069	-0.0033
Average Pile-up @ beg. of fill	8	17	38	26

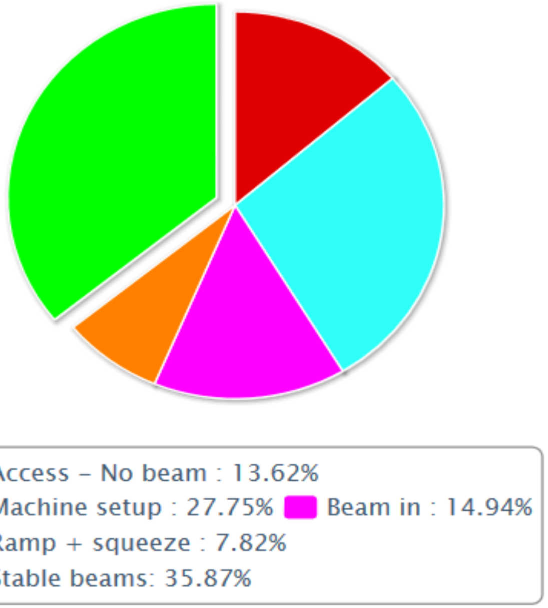
M. Pojer LHCP

Run 1: The LHC has performed marvelously well!

2012

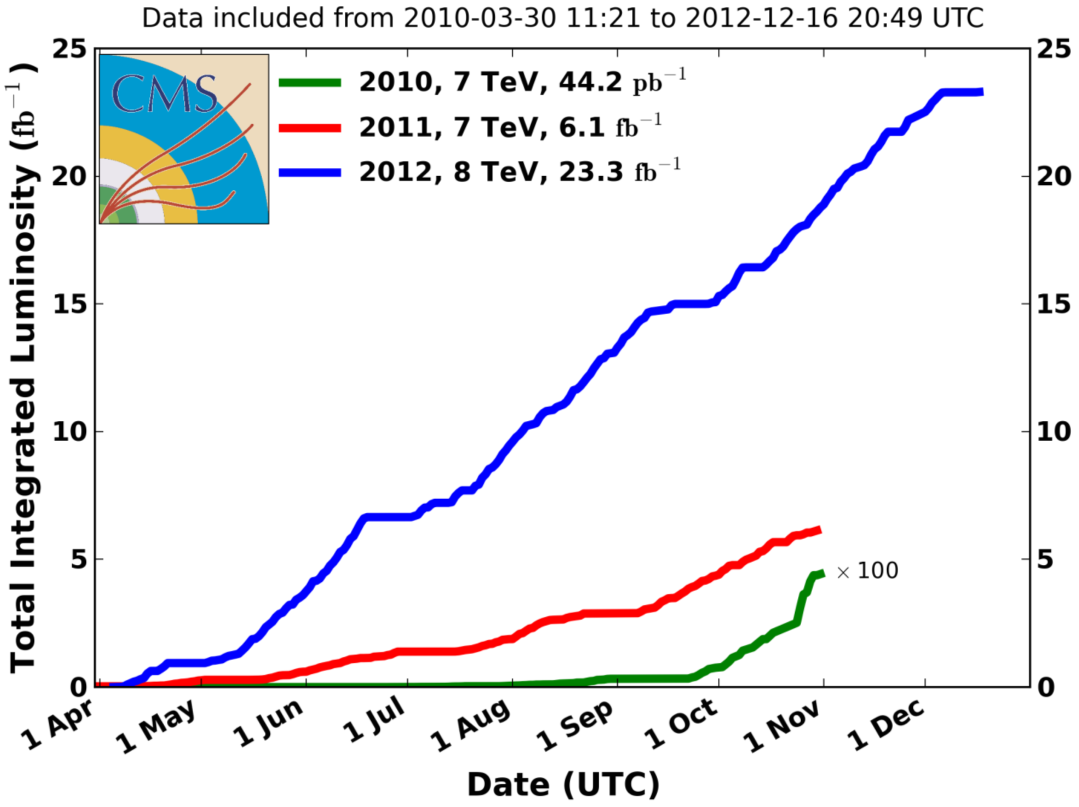
LHC Run Efficiency

Mode: Proton Physics
Fills: 2469 – 3457 [776 Fills]
SB Time: 73 days 17 hrs 45 mins

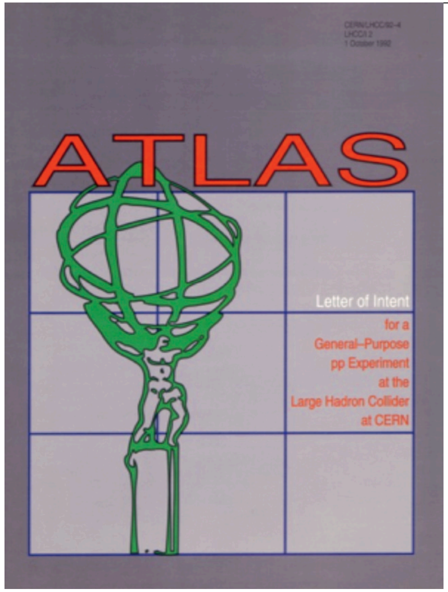


Stable beams 36%

CMS Integrated Luminosity, pp



20 Years Ago: Approval of ATLAS and CMS LoI

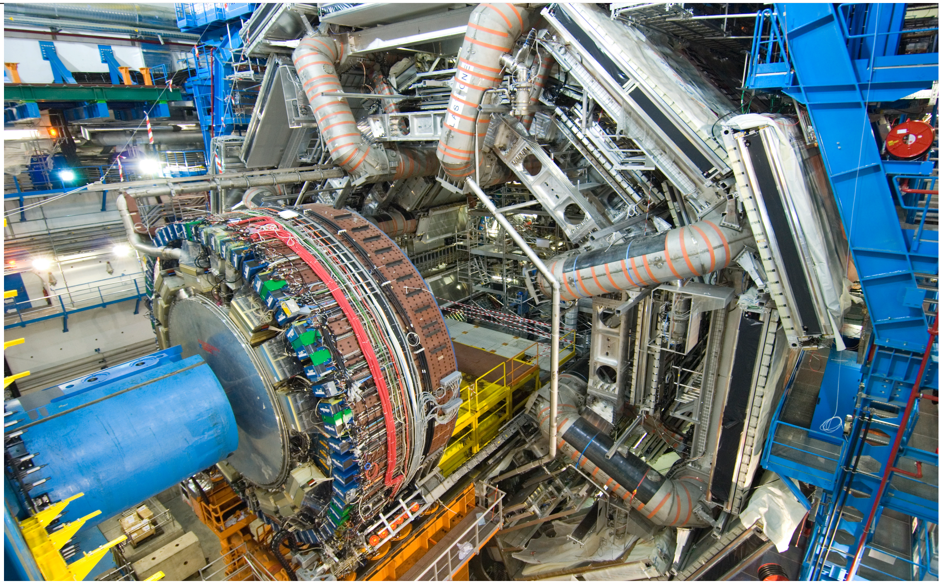


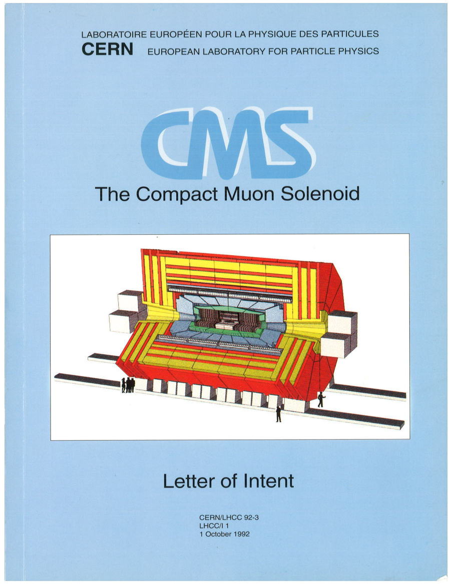
CERN/LHCC/92-4
LHCC/I 2
1 October 1992

ATLAS

Letter of Intent
for a
General-Purpose
pp Experiment
at the
Large Hadron Collider
at CERN

LHCC
June 1993





LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

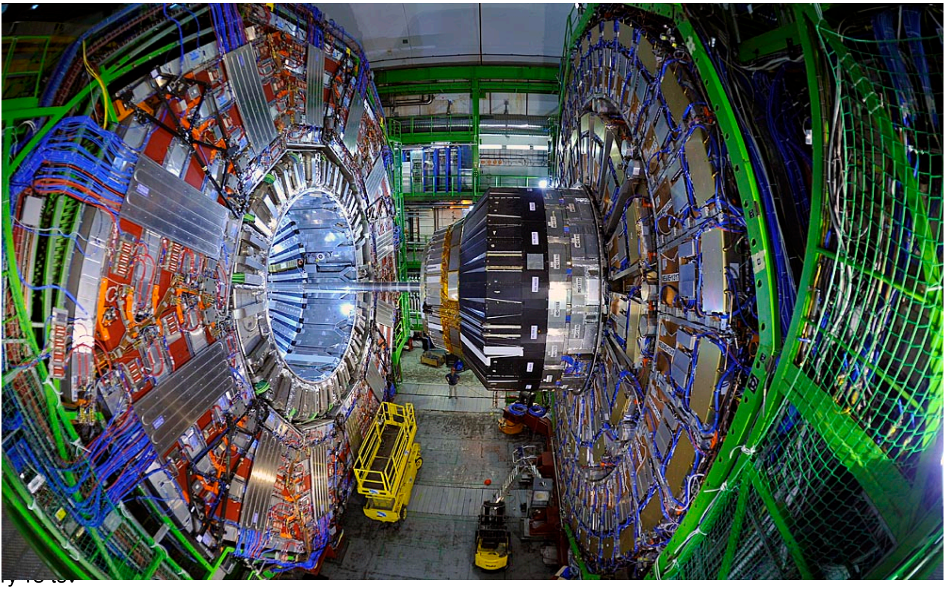
CMS

The Compact Muon Solenoid

Letter of Intent

CERN/LHCC 92-3
LHCC/I 1
1 October 1992

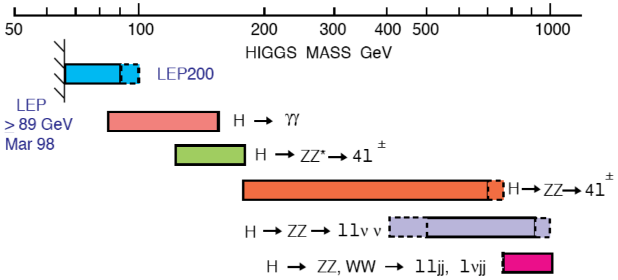
15 Years Later



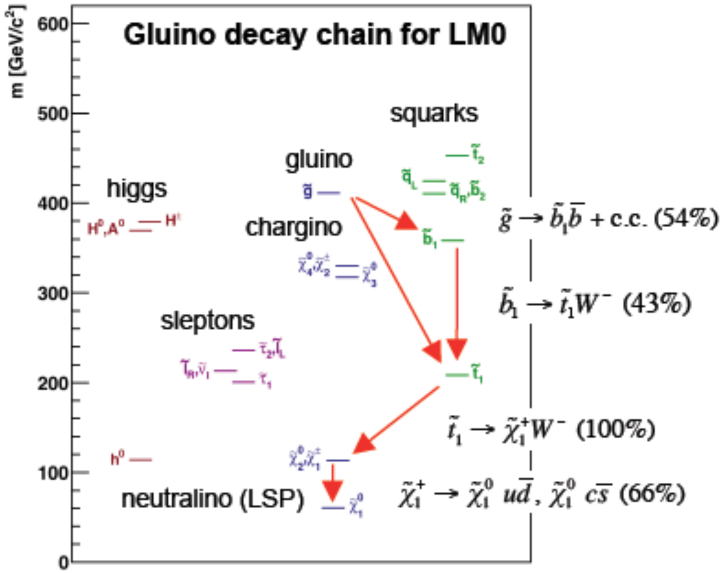
Physics that Drove LHC-GPD Experiment Design

SM Higgs boson

See next slide



Experimentally - early 1990's



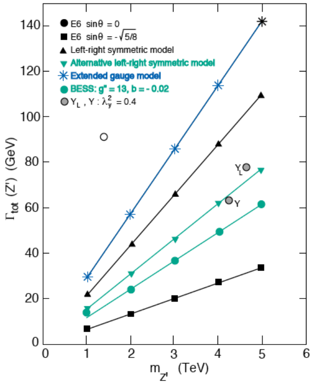
Supersymmetry

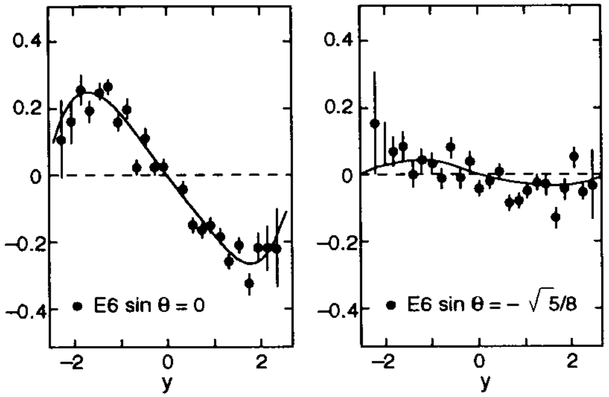
Several high-P_T jets and charged leptons

Large missing E_T (calo. coverage |η| < 5)

b-quarks (need for pixel detectors)

Heavy bosons (Z',…)



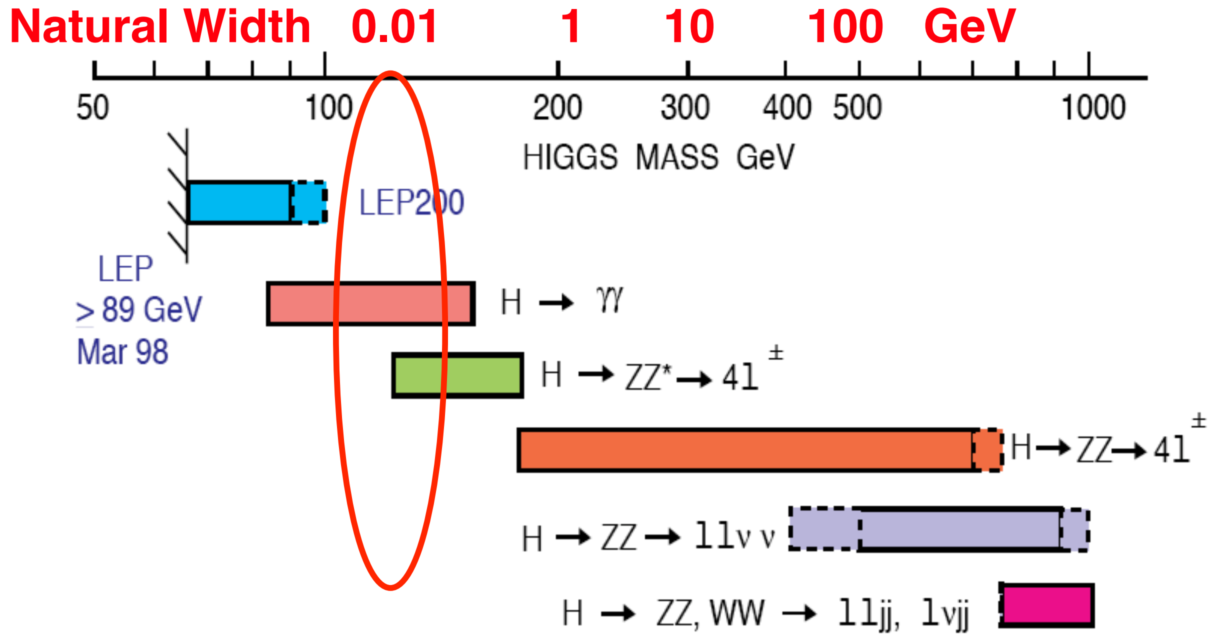


Measure the charge of TeV muons

dp/p ~ 10% at p_T=1 TeV/c

Search for the Standard Model Higgs Boson and LHC Experiment Design

The possibility of detection of the SM Higgs boson over the wide mass range, and its diverse manifestations, played a crucial role in the conceptual design of the ATLAS and CMS experiments



Search for a low mass Higgs boson (e.g. $H\to\gamma\gamma$, $H\to ZZ\to 4l$) **placed stringent performance requirements on ATLAS and CMS detectors** (Tracker momentum and ECAL energy resolution)**.**

Experimental Challenge in High Luminosity Hadron Colliders

In 1980's: "we think we know how to build a high energy, high luminosity hadron collider – we don't have the technology to build a detector for it"

1 billion proton-proton interactions per second

Bunches, each containing 100 billion protons, cross 40 million times a second in the centre of each experiment

Large Particle Fluxes

~ thousands of particles stream into the detector every 25 ns

⇨ **large number of channels (~ 100 M ch)**

⇨ ~ 1 MB/25ns i.e**. 40 TB generated per second !**

High Radiation Levels

⇨ radiation hard (tolerant) detectors and electronics

Extreme requirements in several domains

Looked at what existed, innovated and automated to drive costs down

N. Ellis, T.S. Virdee, Ann. Rev. Nucl. Part. Sci. 44 (1994) 609

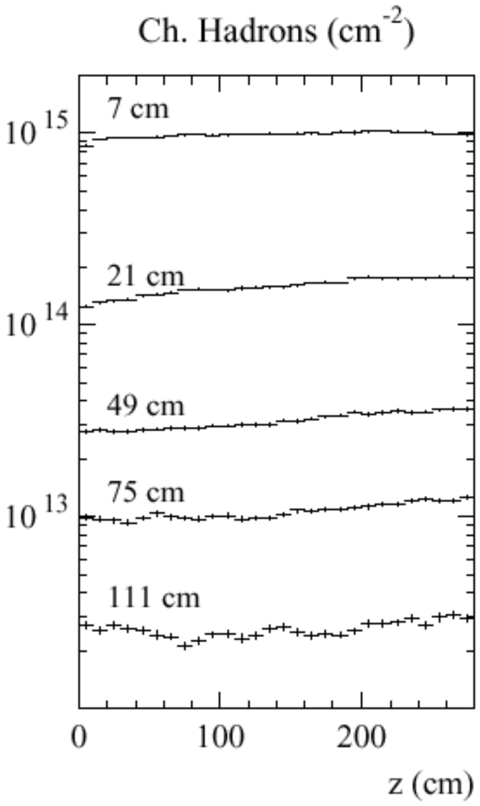
It was not at all evident that the desired performances could be achieved!

CMS-LOI/92-LF

ANSWERS TO PROFESSOR LORENZO FOA

QUESTION 0

General question that concerns all experiments: What can your e.m. calorimeter do in a "stand alone" mode, I mean if you have to switch off your inner tracking because of excessive rate?



$\leq 4.10^7$ h$^\pm$/cm^2/s
pixels ($\approx 10^4$ μm^2)
occupancy $\approx 10^{-4}$

$\leq 4.10^6$ h$^\pm$/cm^2/s
Si μ-strip det.
($\approx$10 mm^2)
occupancy $\approx$ 1%

$\leq 4.10^5$ h$^\pm$/cm^2/s
Si or Gas detectors.
($\approx$1 cm^2)
occupancy $\approx$ 1%

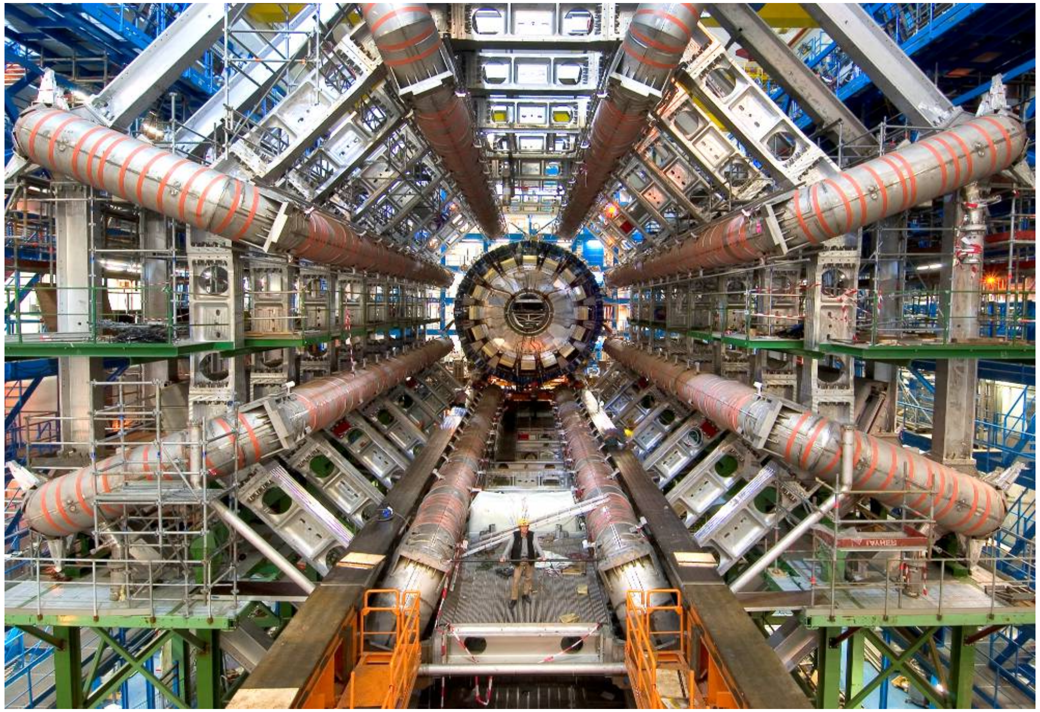
Both ATLAS and CMS have pixels detectors ~ 4cm from the beamline!

Designs of LHC-GPDs

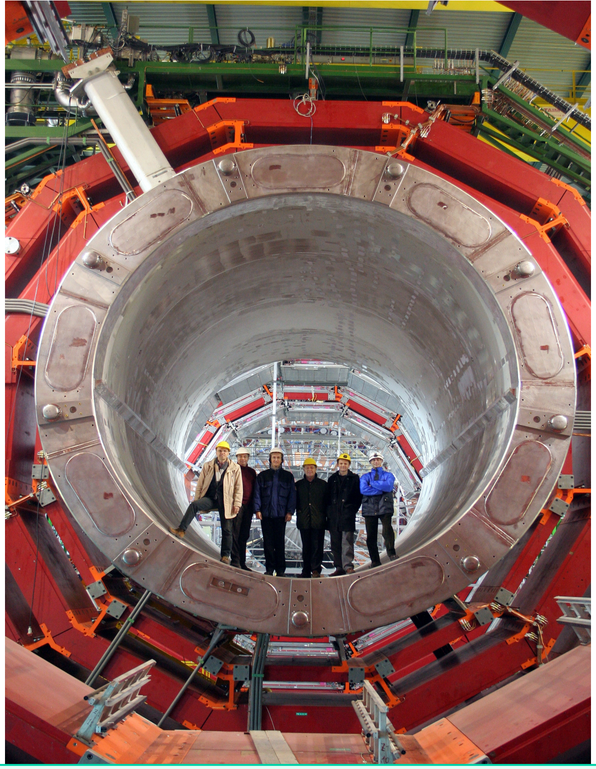
The conceptual design of ATLAS and CMS was largely determined by the choice of the magnetic field configuration for the measurement of muons.

Complementary detector designs

Rate from genuine muons is very high – must make a p_T cut in real-time

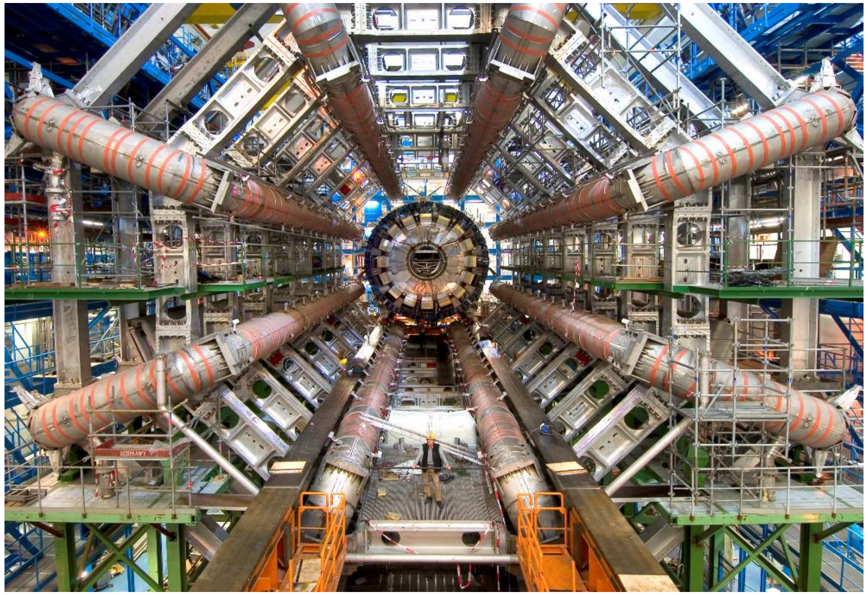


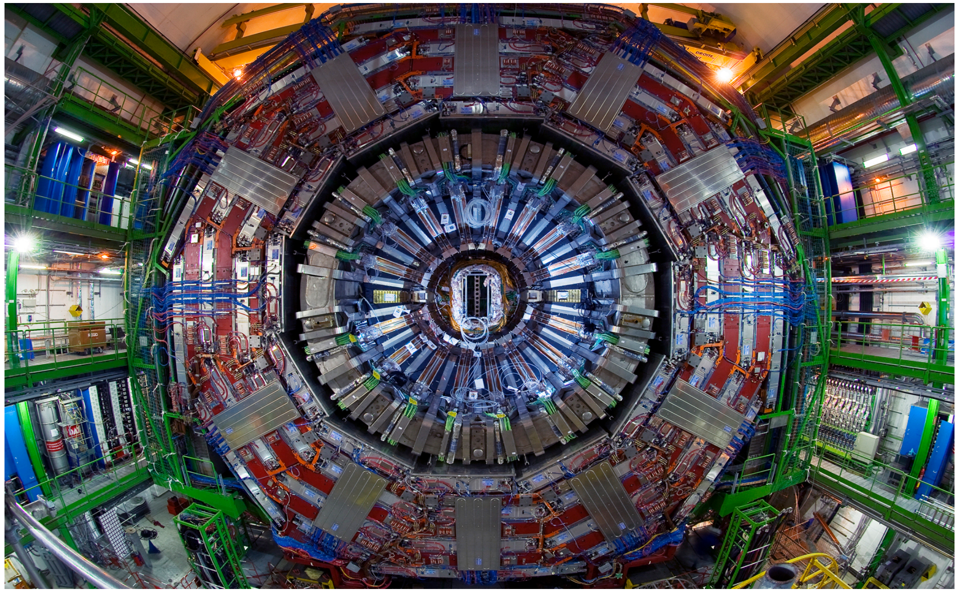
ATLAS Superconducting Air-core Toroid

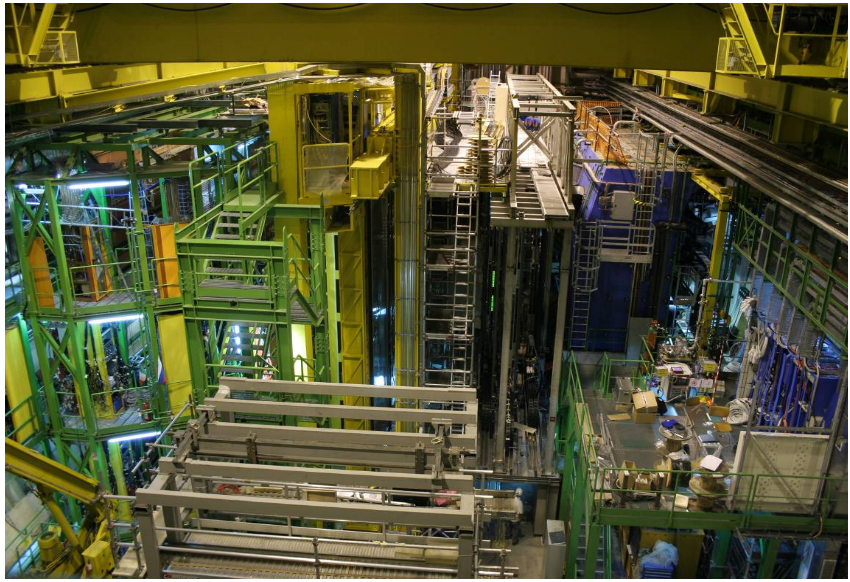


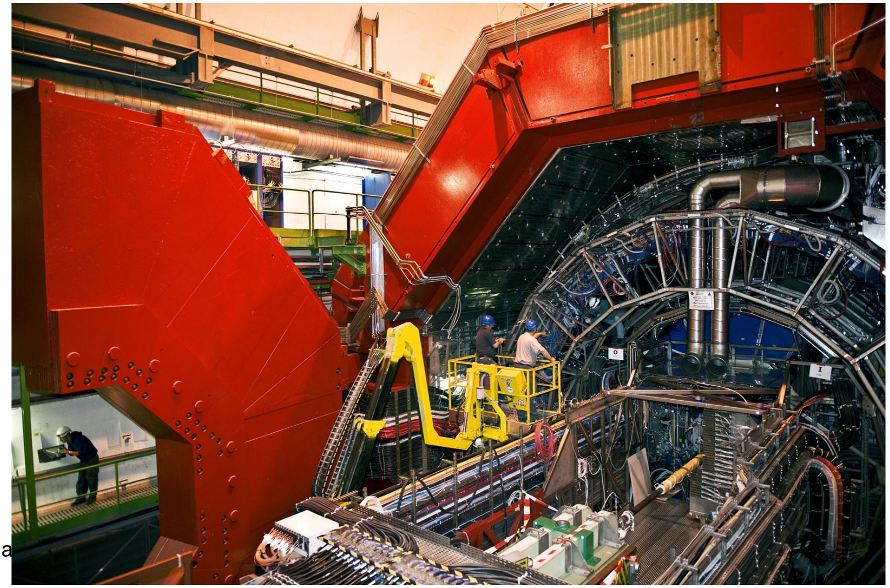
CMS Superconducting Solenoid

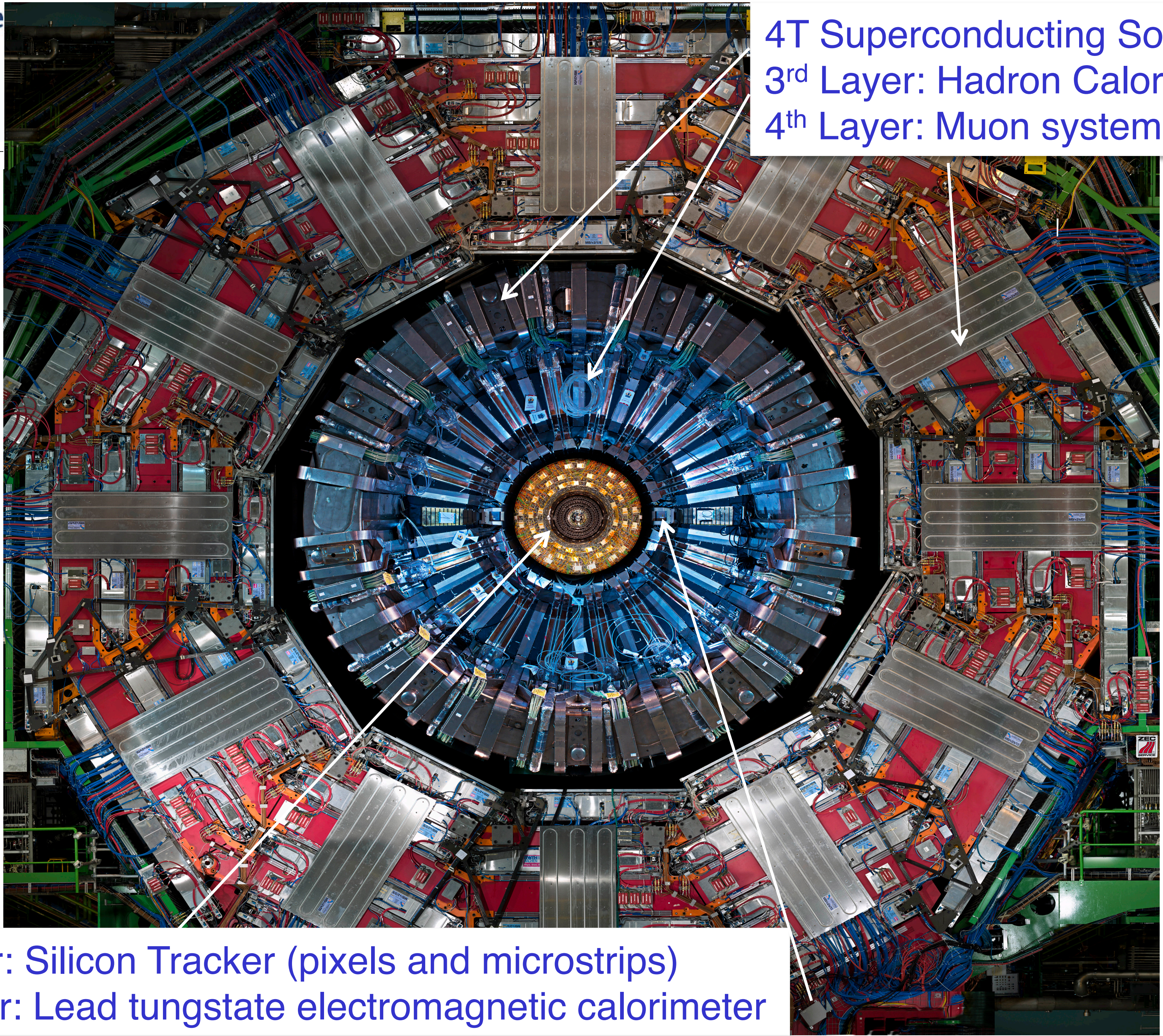
The LHC Four Experiments have also Performed Well











4T Superconducting Solenoid
3^{rd} Layer: Hadron Calorimeter
4^{th} Layer: Muon system

1^{st} Layer: Silicon Tracker (pixels and microstrips)
2^{nd} Layer: Lead tungstate electromagnetic calorimeter

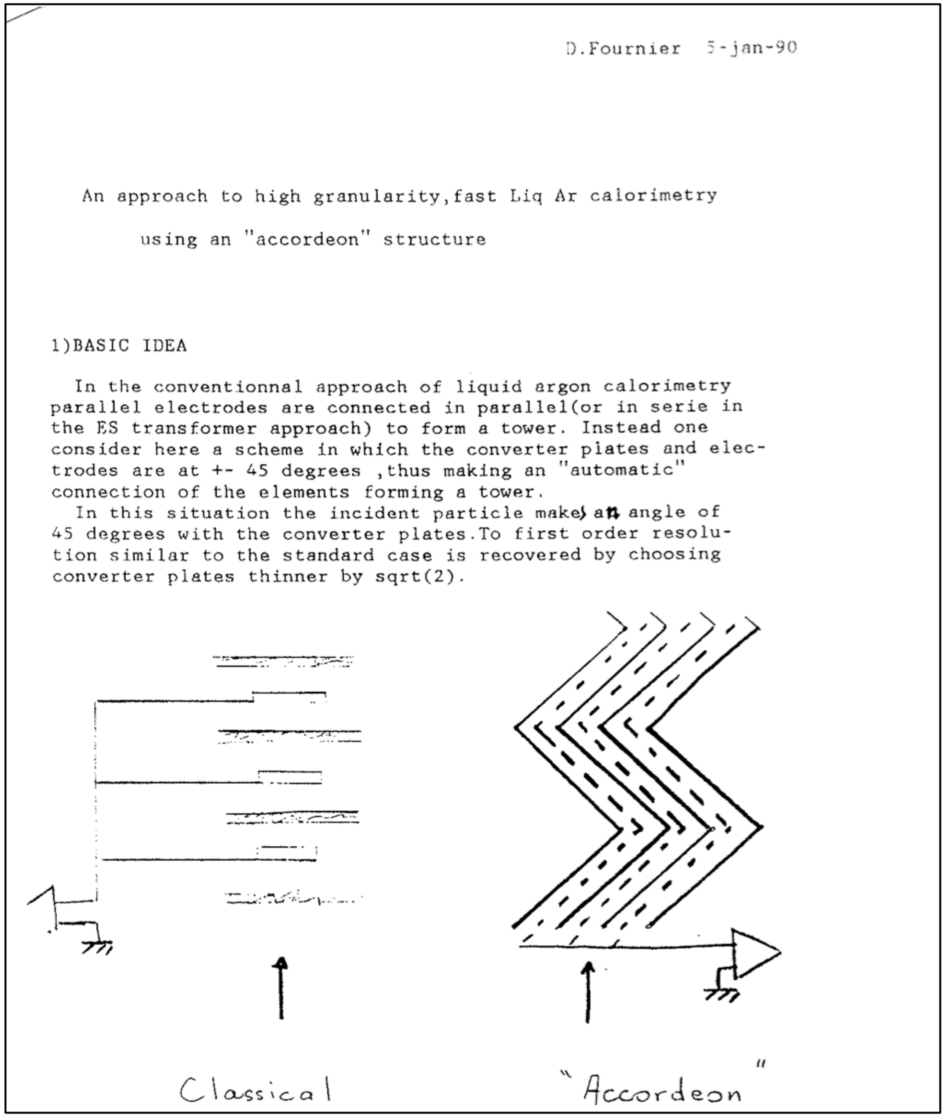
An Example from the Construction of ATLAS and CMS

The Electromagnetic Calorimeters

Physics Driving Detector Design
Measure the energies of photons from
a decay of the Higgs boson
to a precision of ~ 0.5%
and mass to a precision of < 1%.

ATLAS Electromagnetic Calorimeter

From Concept to Construction: the Liquid Argon Calorimeter



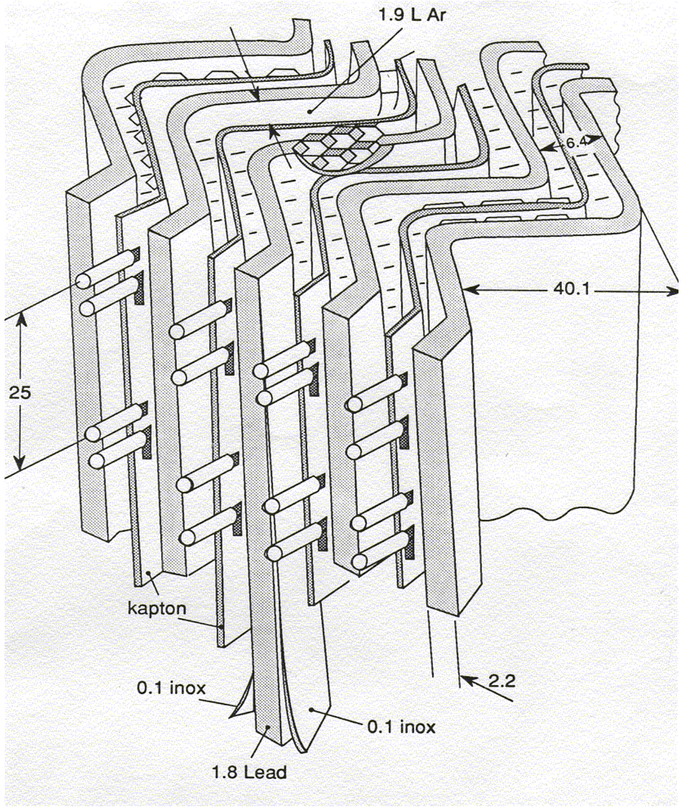
D.Fournier 5-jan-90

An approach to high granularity,fast Liq Ar calorimetry
using an "accordeon" structure

1)BASIC IDEA

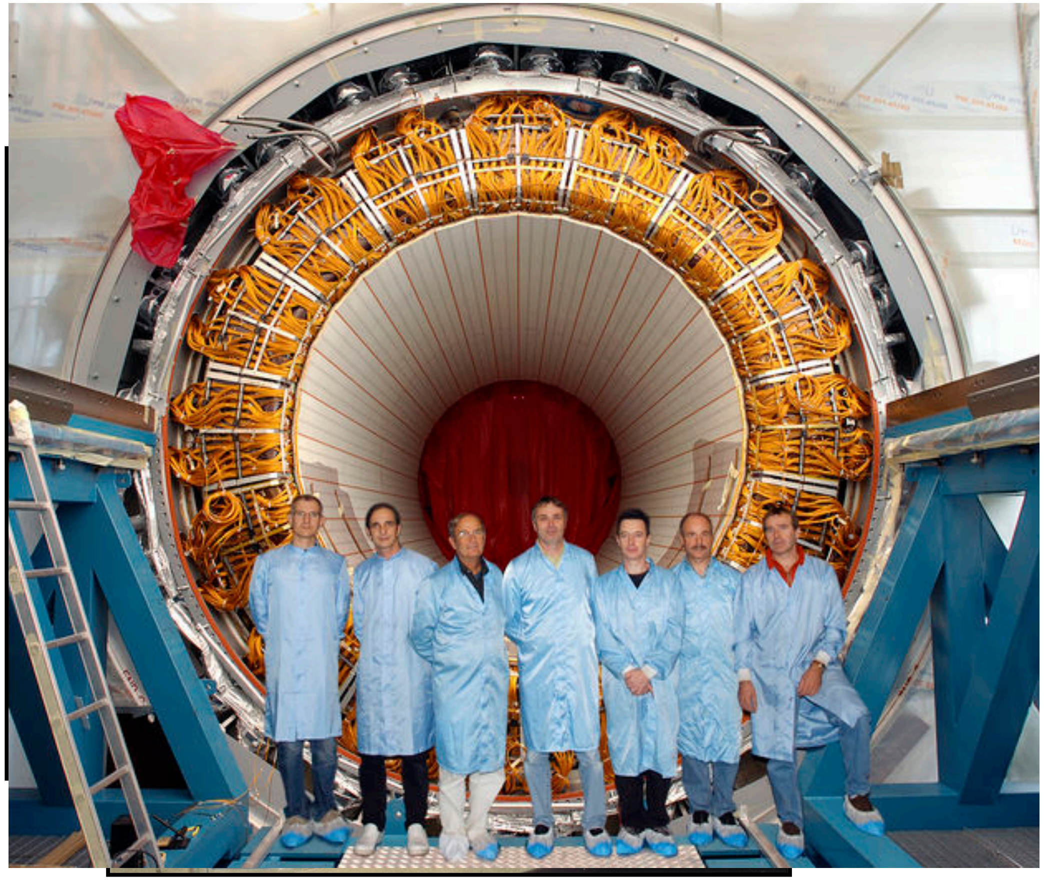
In the conventionnal approach of liquid argon calorimetry parallel electrodes are connected in parallel(or in serie in the ES transformer approach) to form a tower. Instead one consider here a scheme in which the converter plates and electrodes are at +- 45 degrees ,thus making an "automatic" connection of the elements forming a tower.
In this situation the incident particle makes an angle of 45 degrees with the converter plates.To first order resolution similar to the standard case is recovered by choosing converter plates thinner by sqrt(2).

- a very stable and radiation hard detector
- easy to calibrate
- a lot of freedom in spatial granularity
- difficult to construct… cryogenics



ATLAS Electromagnetic Calorimeter

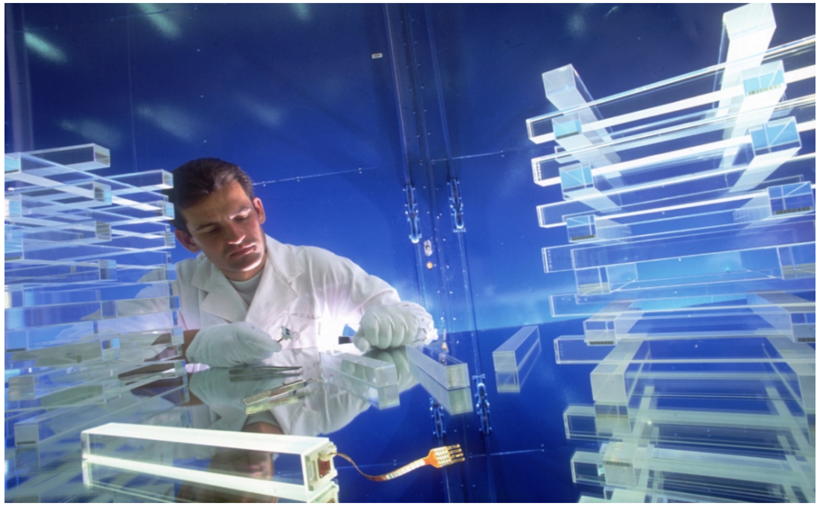
From Concept to Construction: the Liquid Argon Calorimeter



Installation 2004

Example of Challenging Technologies: ECAL: Lead Tungstate Crystals

Physics Driving the Design
Measure the energies of photons from
a decay of the Higgs boson
to a precision of ≤ 0.5%.



Idea (1993 – few yellowish cm^3 samples)

→ **R&D (1993-1998: improve rad. hardness: purity, stoechiometry, defects)**

→ **Prototyping (1994-2001: large matrices in test beams, monitoring)**

→ **Mass manufacture (1997-2008: increase production, QC)**

→ **Systems Integration (2001-2008: tooling, assembly)**

→ **Installation and Commissioning (2007-2008)**

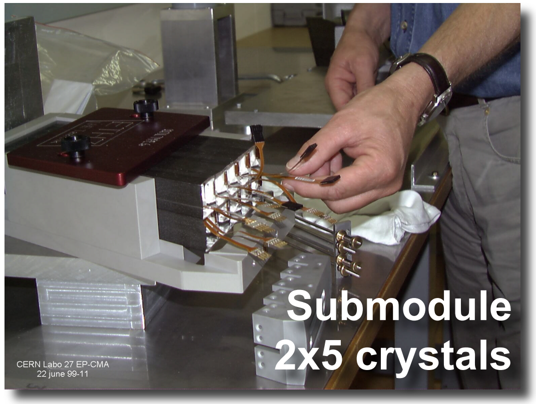
→ **Collision Data Taking (2009 onwards)**

→ **Discovery of a new heavy boson (2012)**

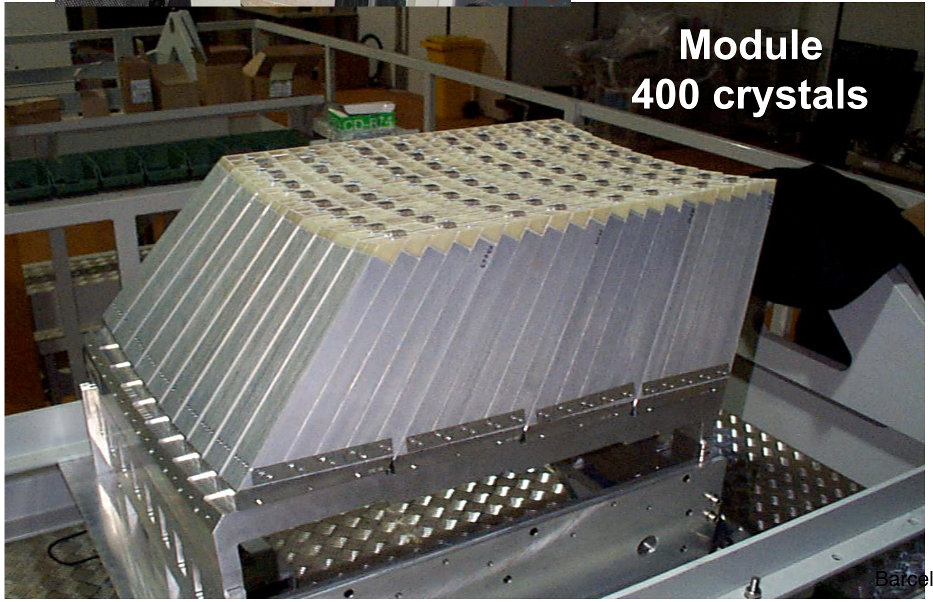
Δt ~ 20 years !!!

CMS Electromagnetic Calorimeter:

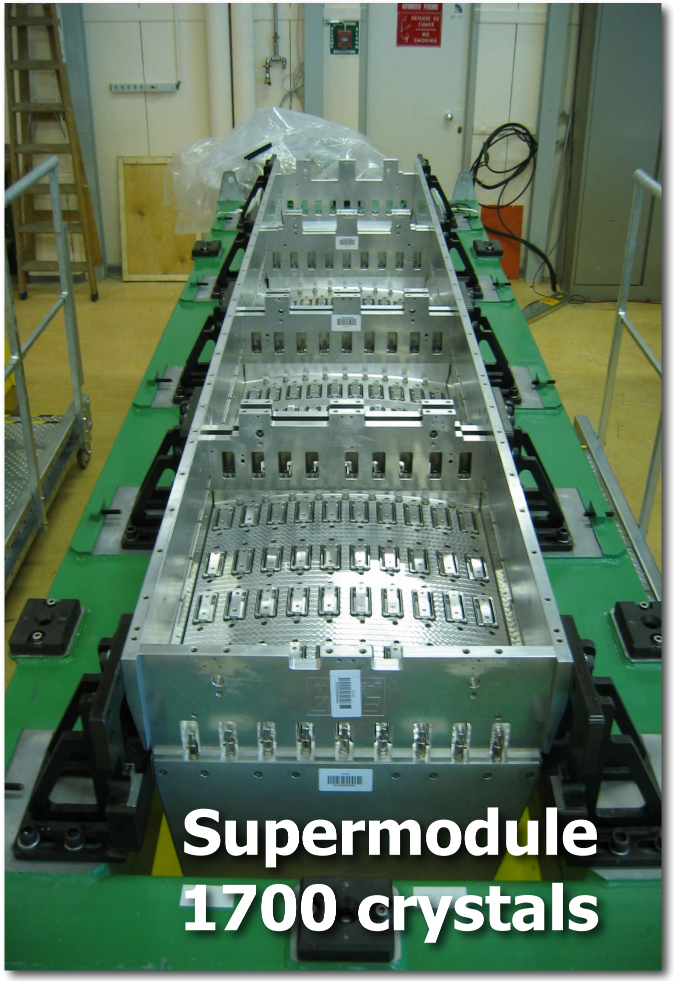
Lead Tungstate Scintillating Crystals



**Submodule
2x5 crystals**



**Module
400 crystals**

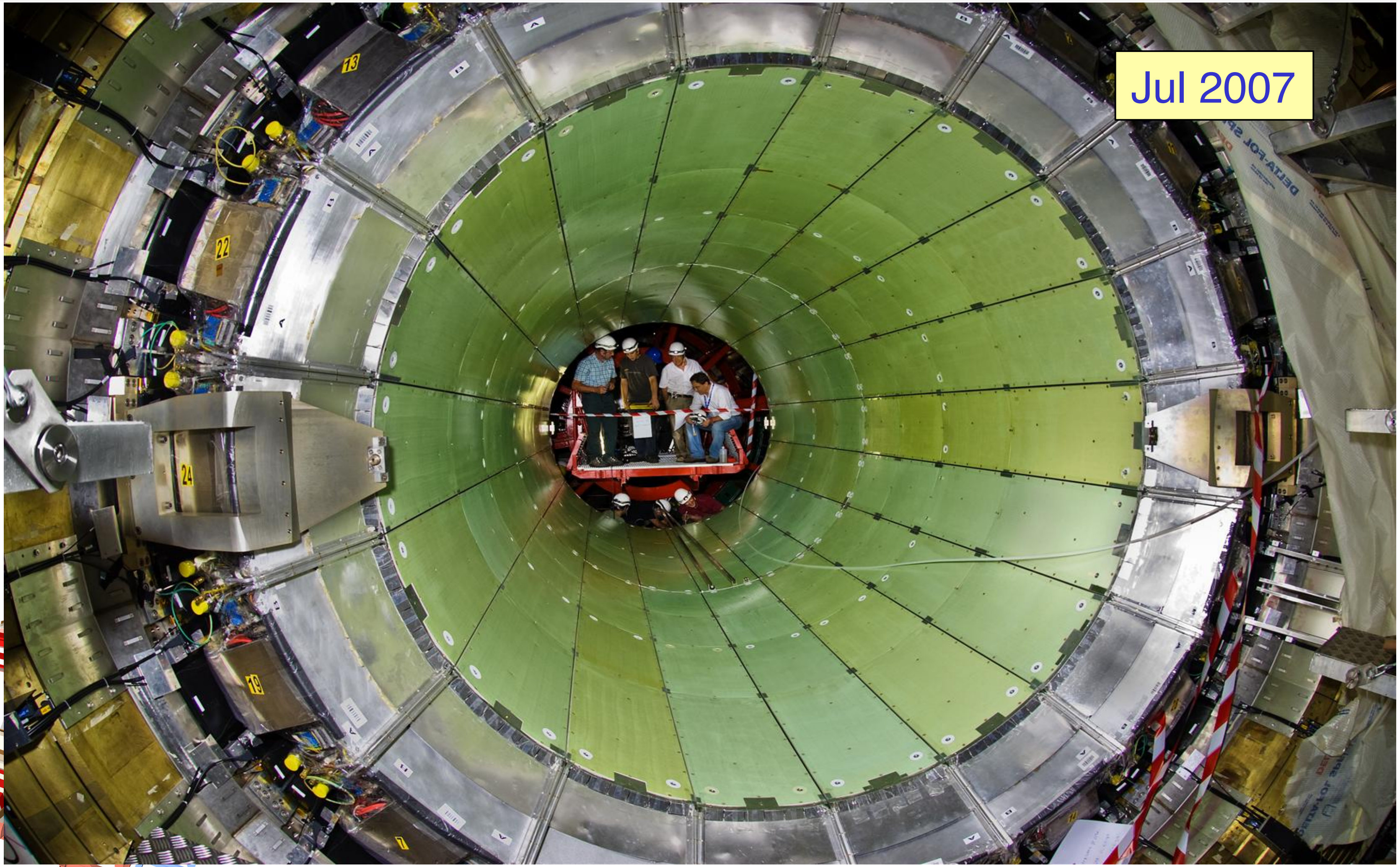


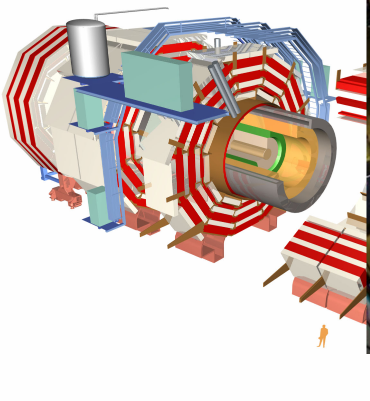
**Supermodule
1700 crystals**

Total 36 Supermodules

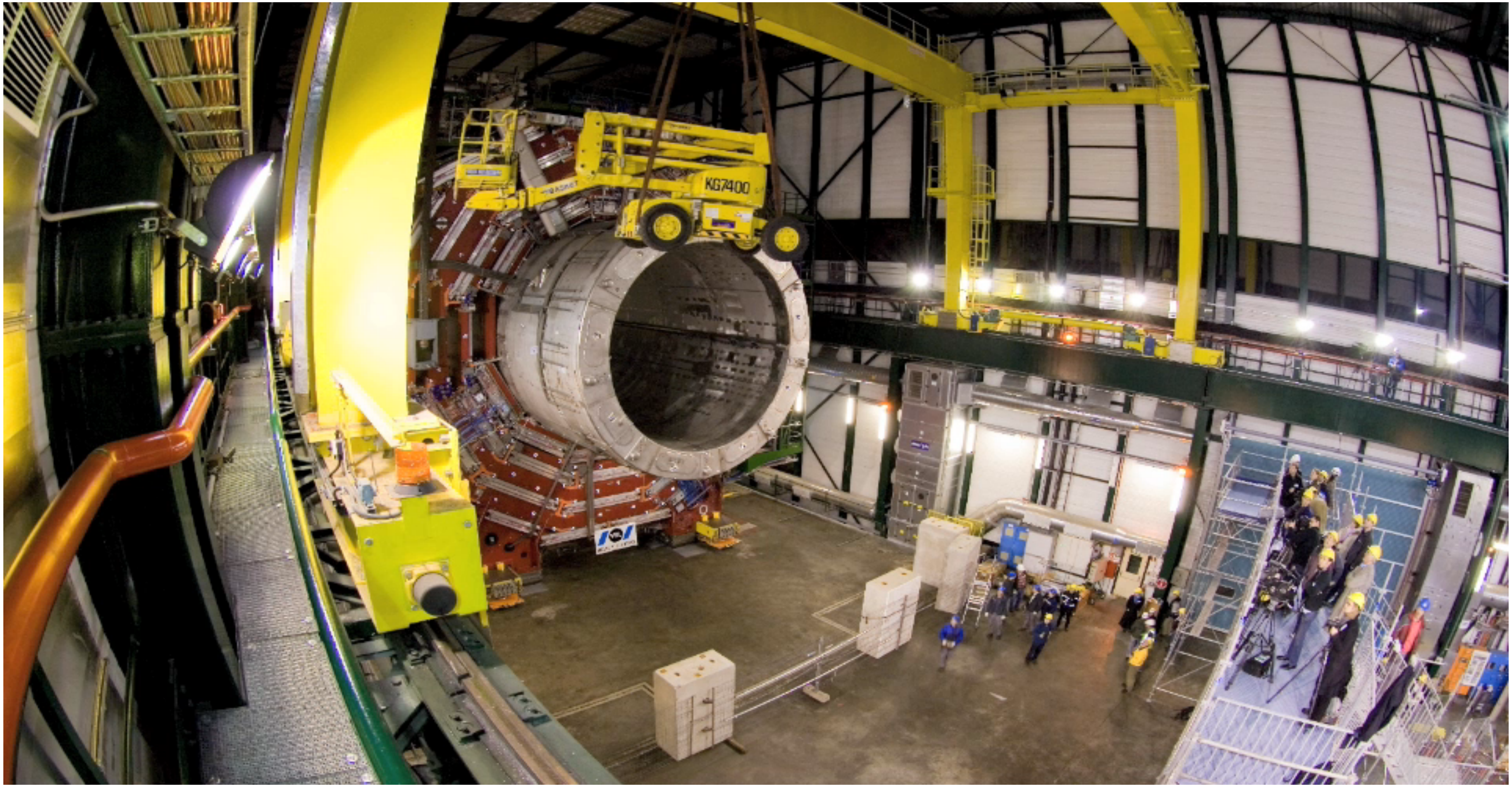
Installation of Barrel ECAL

CMS has more crystals (75000) than all previous HEP experiments put together


Jul 2007



Spectacular Engineering Operations (Feb. 2007)

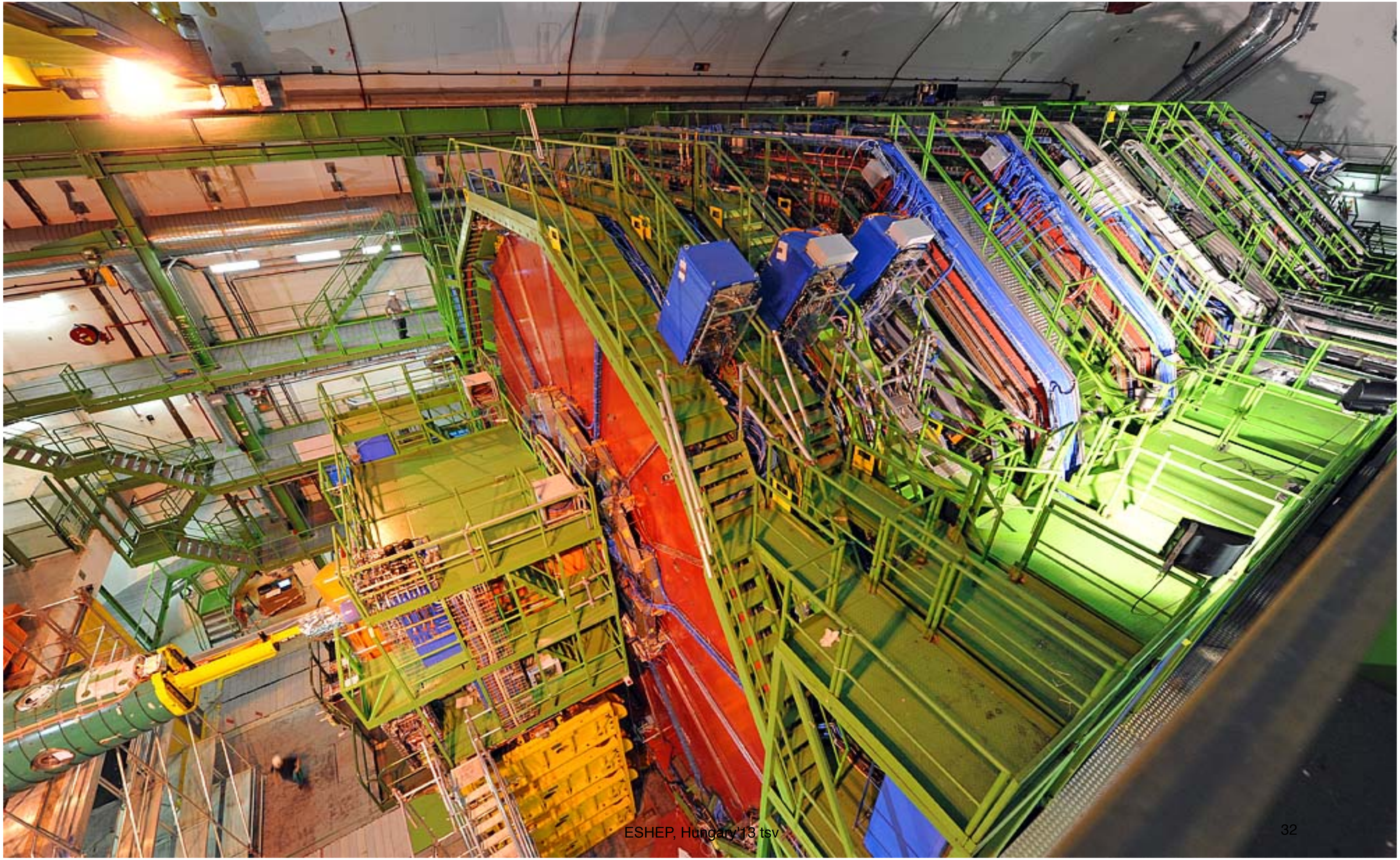


Cables, Pipes and Optical Fibres !

Nov 2007

Took 50’000 man hours

CMS Detector Closed (Aug. 2008)



Going to the Science

1. **Do the experiments perform as designed?**
2. **Is known physics correctly observed?**
3. **Then look for new physics**

We can only claim signals of new physics after having made measurements of already known physics that are consistent with the precise predictions of the Standard Model.

Performance of LHC Experiments I

ATLAS

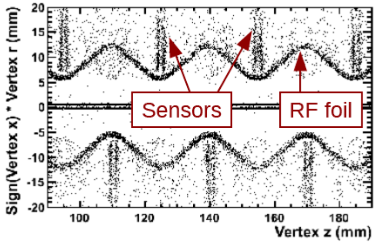
Inner Tracking Detectors			Calorimeters				Muon Detectors				Magnets	
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC	Solenoid	Toroid
99.8	99.6	99.2	97.5	99.2	99.5	99.2	99.4	98.8	99.4	99.1	99.8	99.3

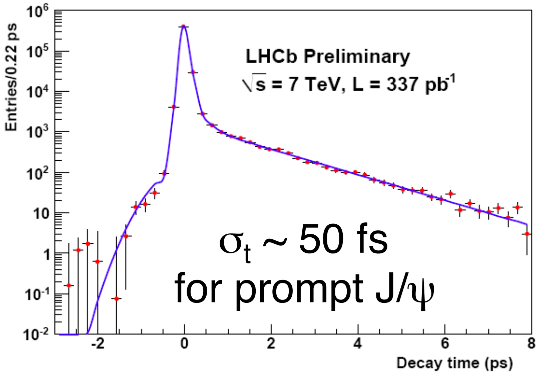
Luminosity weighted relative detector uptime. **Used for Physics > 90% of recorded data.**

LHC*b*

- Typical primary vertex resolution (with 30 tracks):
  - $\sigma_{x,y}$ = 12 μm,
  - σ_z = 65 μm.
- Decay time resolution: 40-50 fs

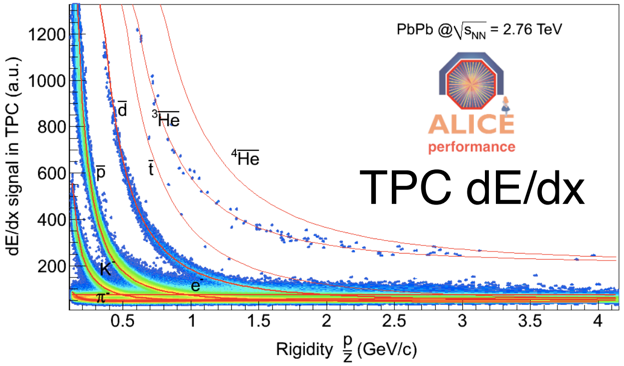
VELO

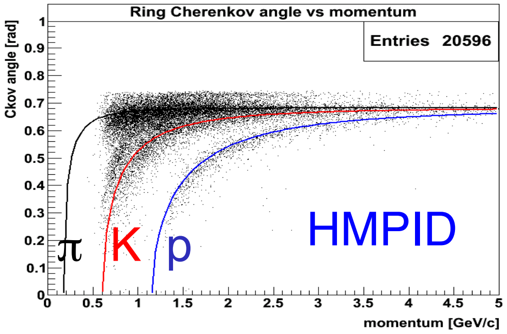




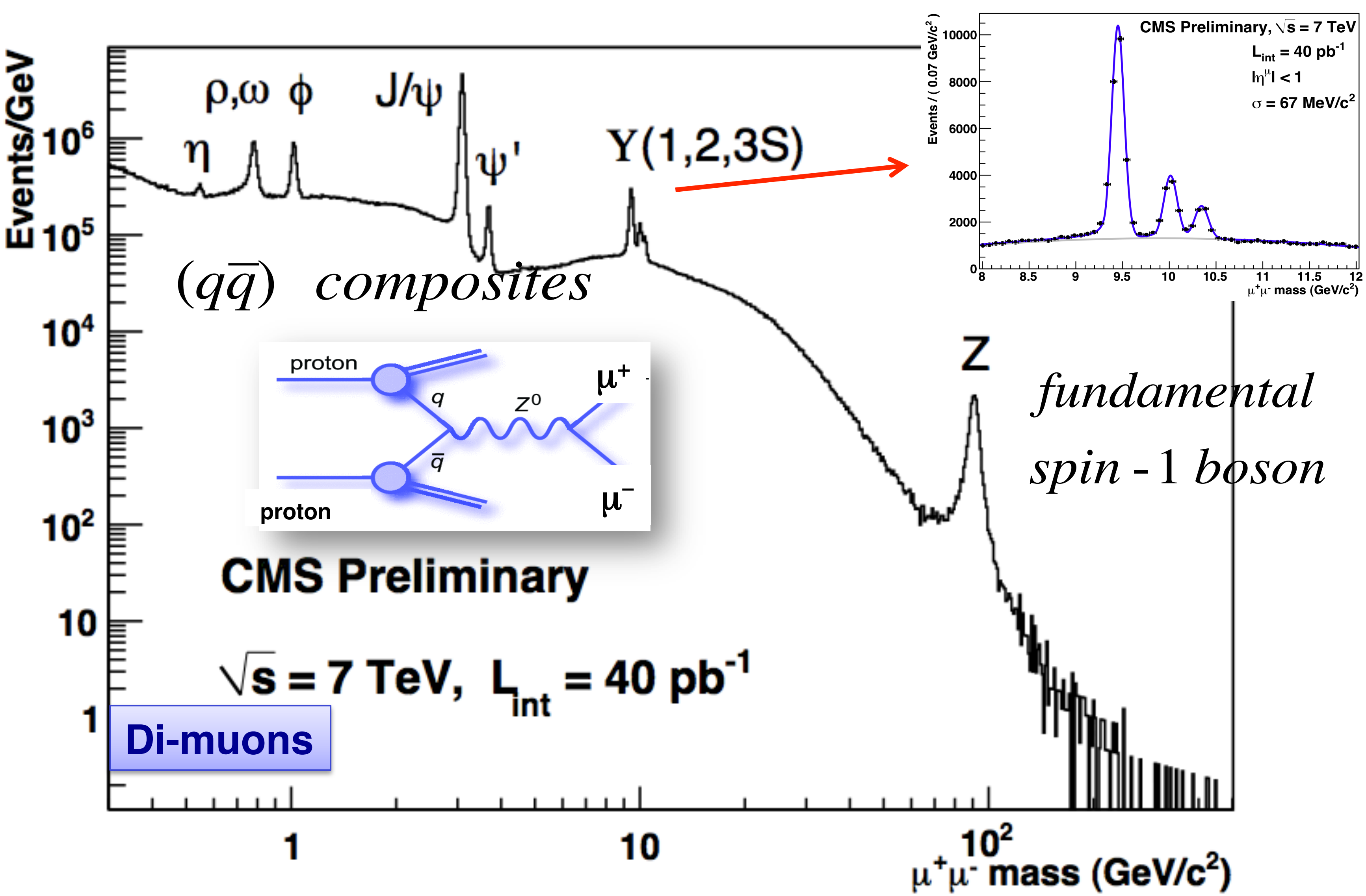
$\sigma_t \sim 50$ fs
for prompt J/ψ

ALICE Part id





Performance of the LHC Experiments II



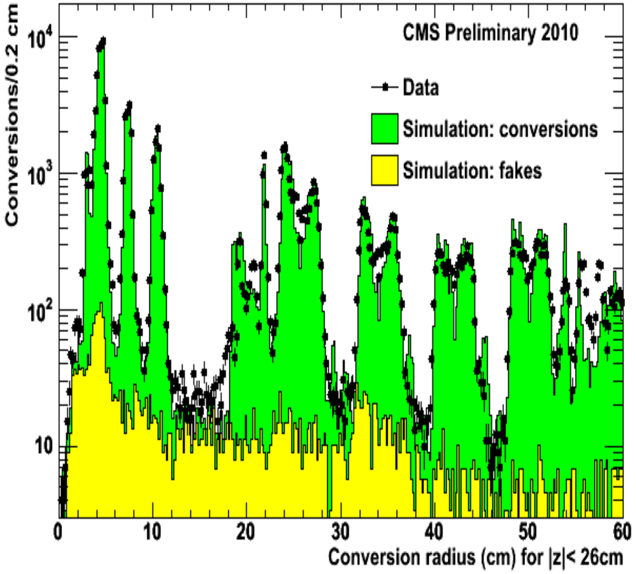
$(q\bar{q})$ composites

fundamental spin - 1 boson

Di-muons

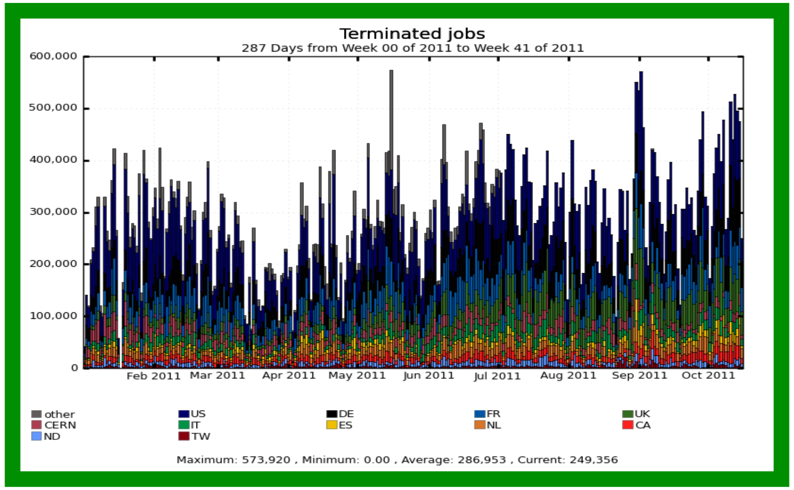
Performance of LHC Experiments III

The experiments are well described in simulation code

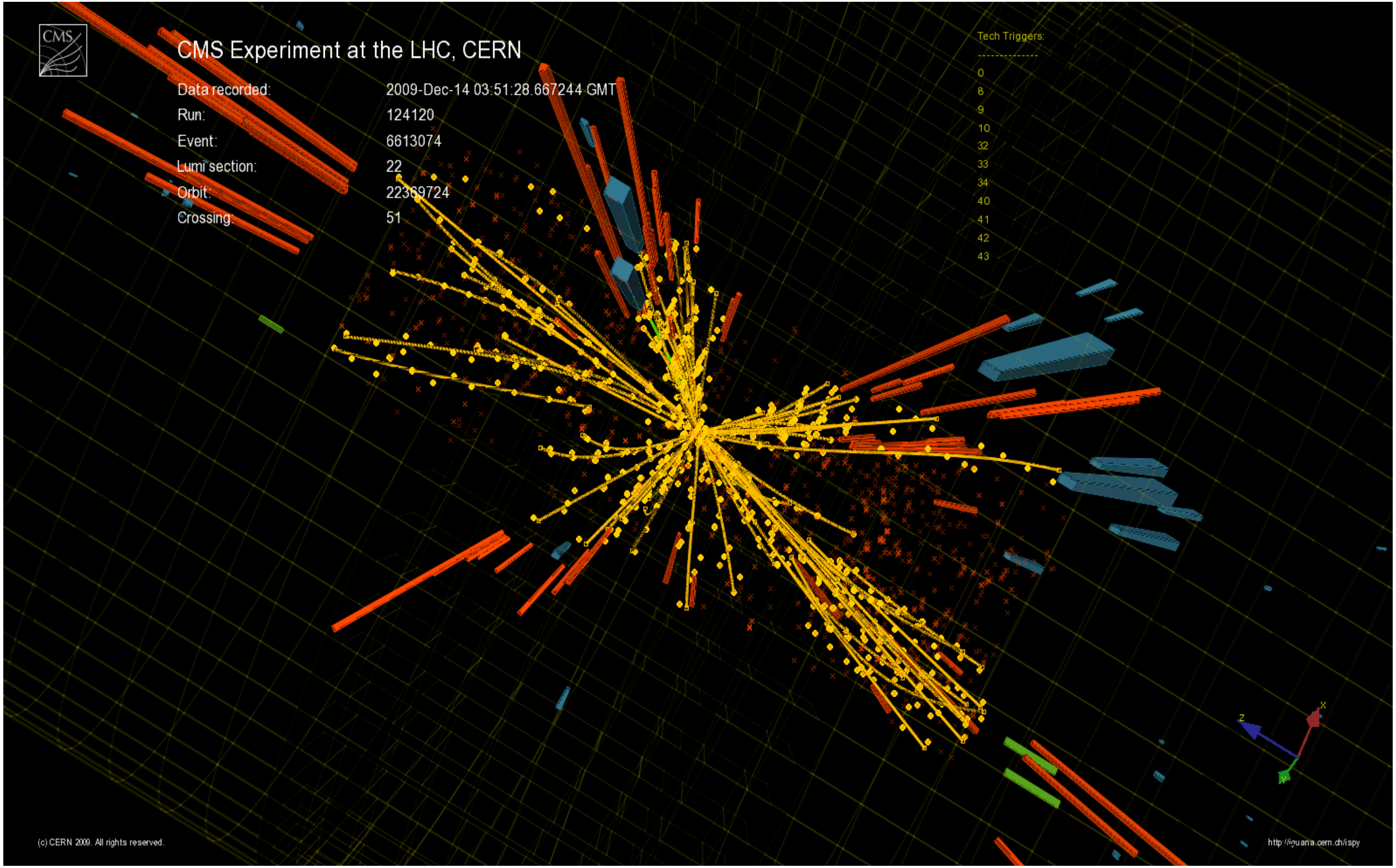


The Worldwide LHC Computing Grid (WLCG) is operating well

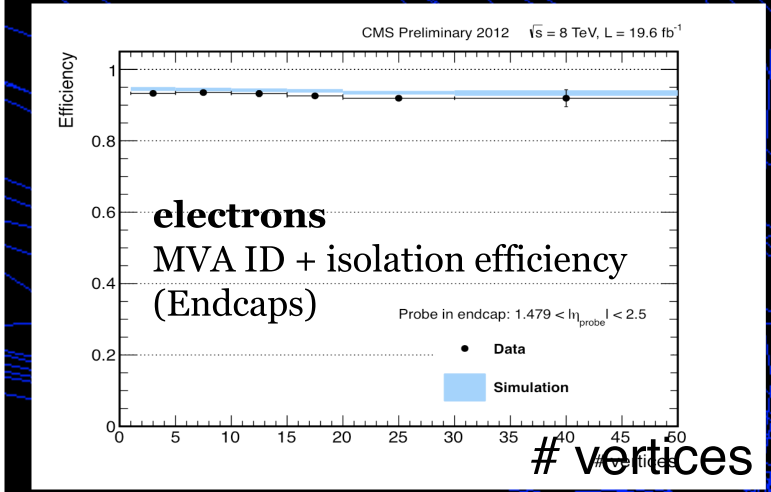
ATLAS
Average: ~287 000 jobs/day
(~ 15% of total available CPU time)



A proton-proton Collision at the LHC

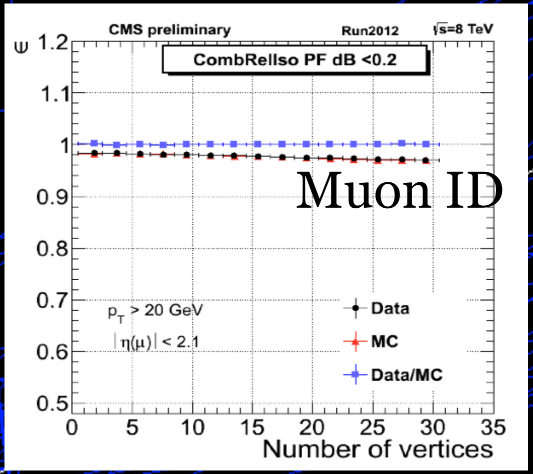


Performance under Pileup

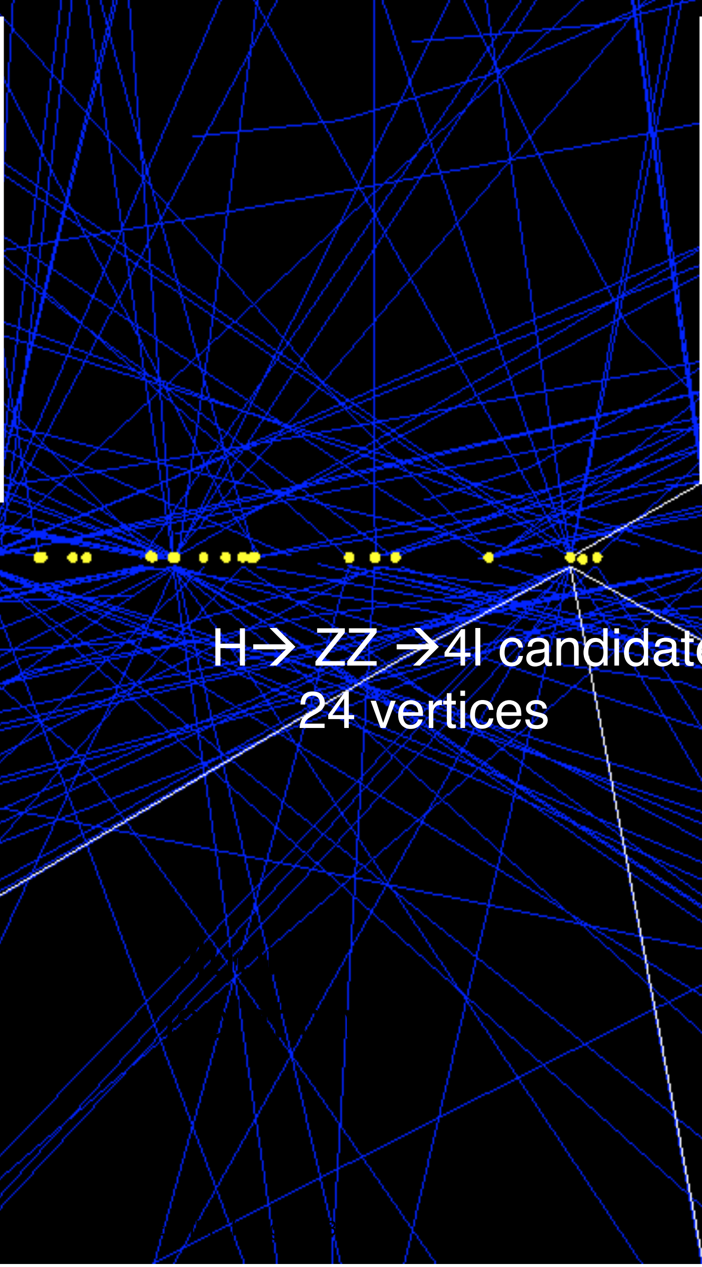


electrons
MVA ID + isolation efficiency
(Endcaps)

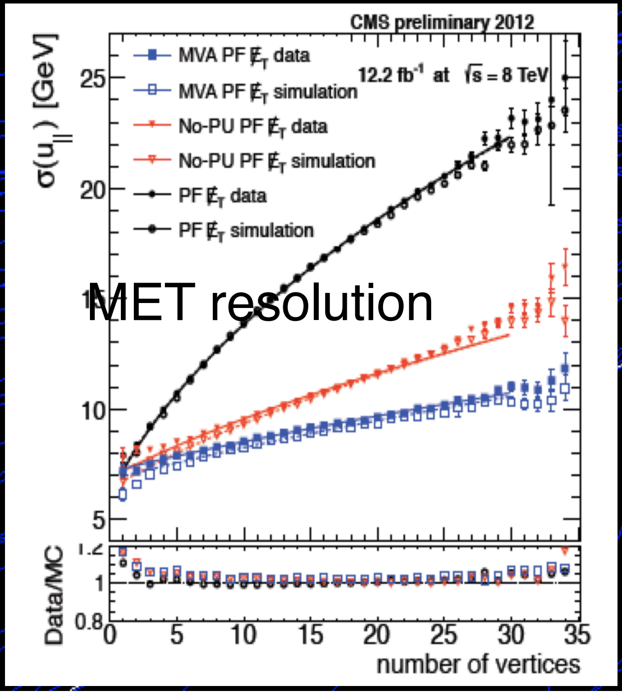
vertices



Muon ID



H→ ZZ →4l candidate
24 vertices

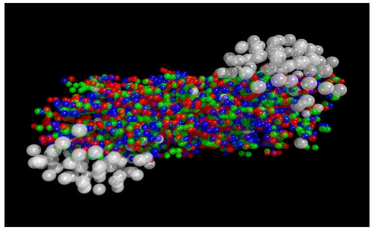


MET resolution

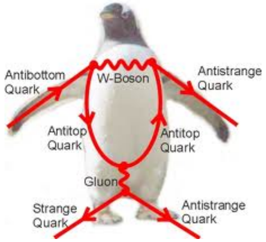
Leptons and MET
Almost insensitive
to pileup

The Menu for Physics Highlights

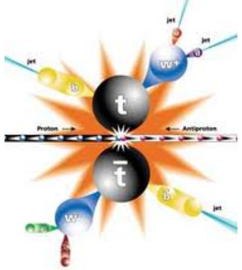
Heavy Ions

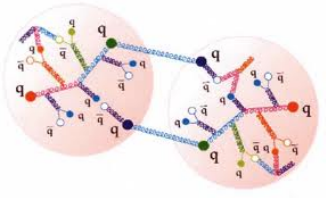


Heavy Flavours

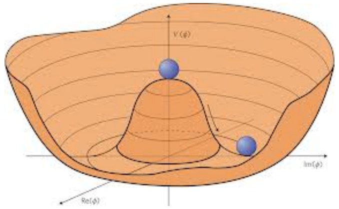


Standard Model
QCD, EWK, Top Physics

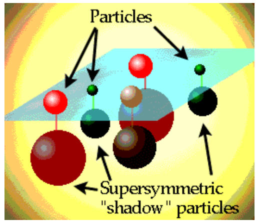


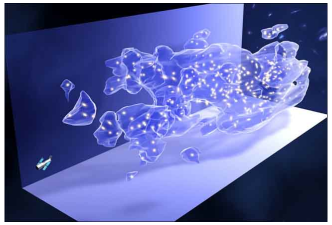


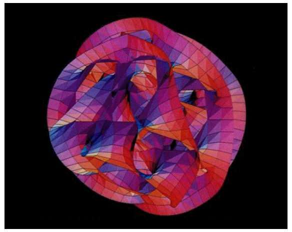
Higgs Boson Physics

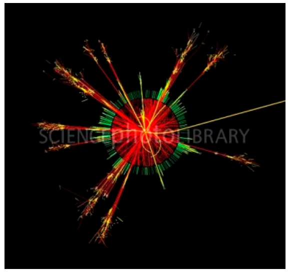


Beyond Standard Model



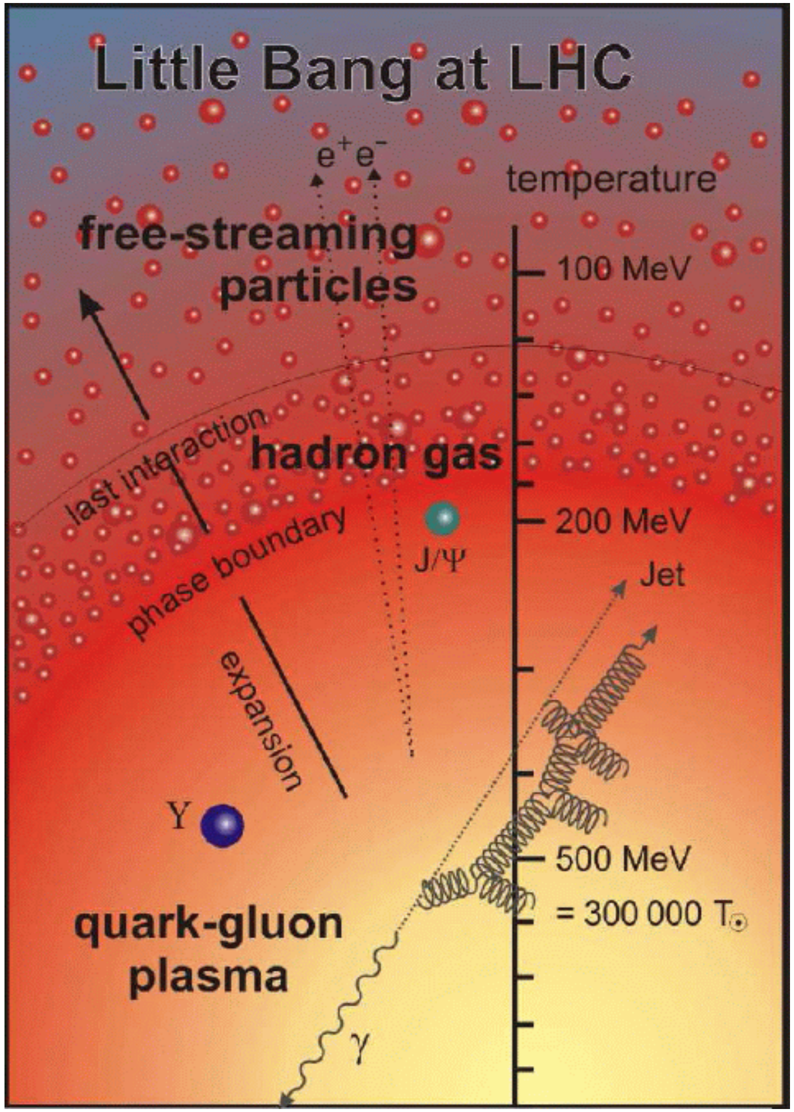






Many physics papers published:
ATLAS, CMS > 250 each
LHCb > 100, ALICE > 60
A personal (& severe) selection

Heavy Ion Collisions - Evolution of the Fireball

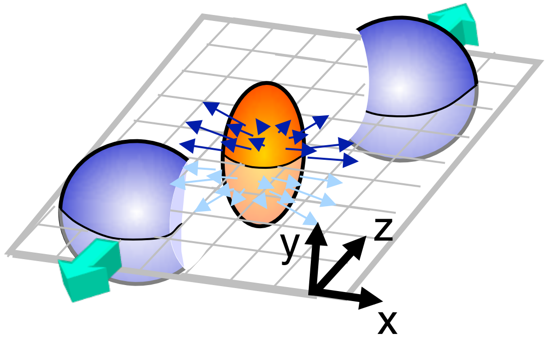


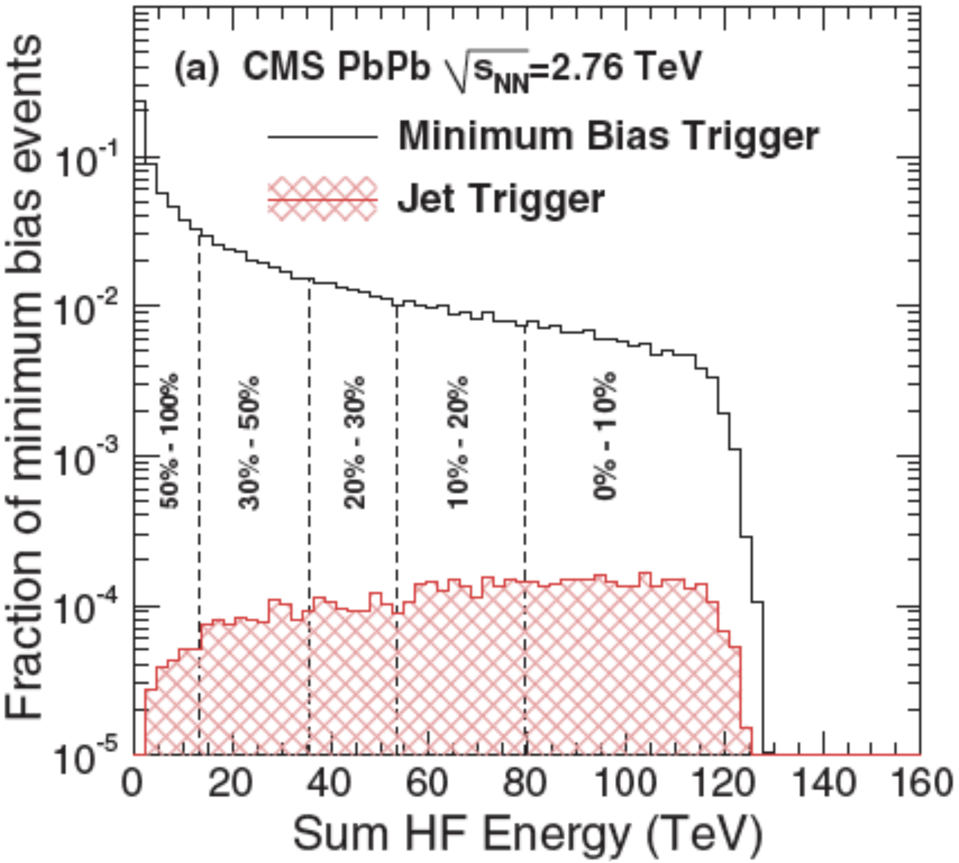
soft

hard probes

- **global observables:**
  multiplicities, rapidity distributions
- **geometry of the emitting source:**
  HBT, impact parameter via
  zero-degree energy flow
- **early state collective effects:**
  elliptic flow
- **chiral symmetry restoration:**
  neutral to charged ratios,
  resonance decays
- **fluctuation phenomena - critical behavior:**
  event-by-event particle composition and spectra
- **degrees of freedom as a function of T:**
  hadron ratios and spectra,
  leptons from W and Z, direct photons
- **deconfinement:**
  charmonium and **bottomium spectroscopy**
- **energy loss of partons in QG medium:**
  jet quenching, high p_t spectra,
  open charm and **open beauty**

Some Definitions: Centrality, N_{part} and N_{coll}





N_{part}: the total number of nucleons in the two lead (^{208}Pb) nuclei which experienced at least one inelastic collision,

N_{coll}: *the total number* of binary nucleon-nucleon collisions

T_{AA} – NN-equivalent integrated luminosity

Using Glauber model

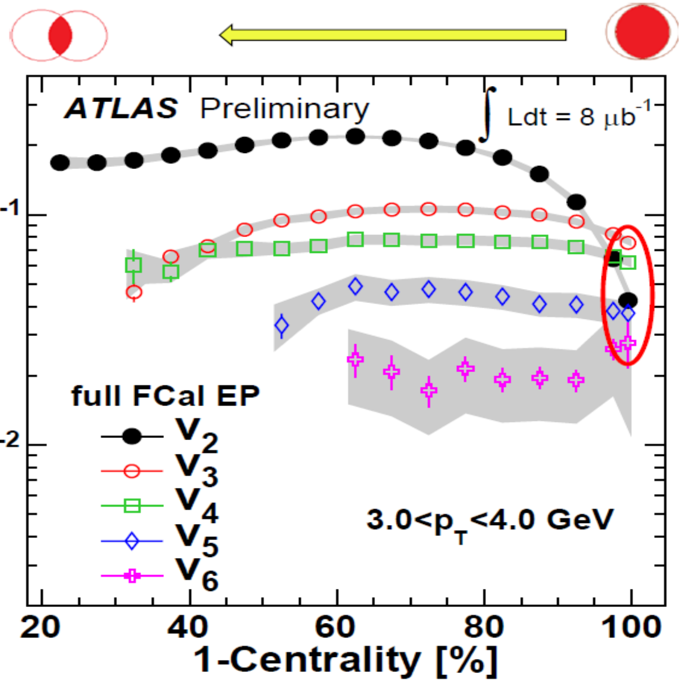
Centrality	N_{part}	N_{coll}	T_{AA}
0-10%	*365*	*1484*	*~25*
20-30%	*187*	*562*	*~12*
50-100%	*22*	*30*	*~1.5*

nuclear modification factor (R_{AA}) for isolated photon production in PbPb collisions,

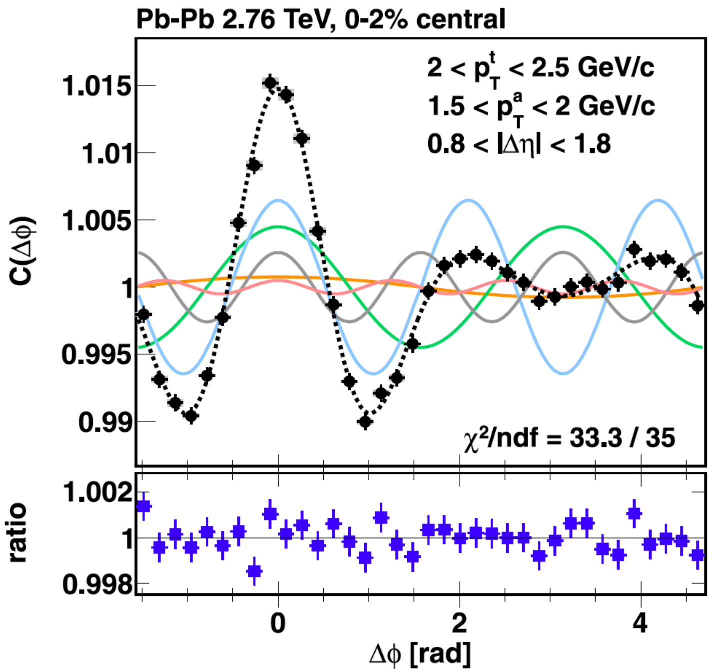
$$R_{AA} = dN^{\gamma}_{PbPb}/dE^{\gamma}_{T}/(T_{AA} \times d\sigma^{\gamma}_{pp}/dE_{T})$$

Collective Effects

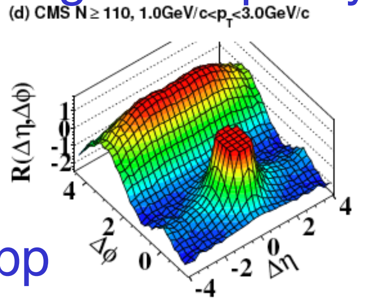
$$E\frac{d^3N}{d^3p}=\frac{d^2N}{2\pi p_T dp_T dy}\left(1+2v_1\cos[\varphi-\psi_{RP}]+2v_2\cos[2(\varphi-\psi_{RP})]+2v_3\cos[3(\varphi-\psi_{RP})]+\ldots\right.$$



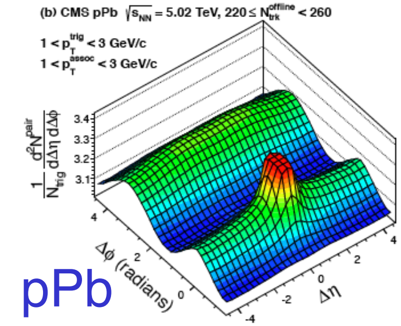
ALICE: Phys Lett B708 (2012) 249



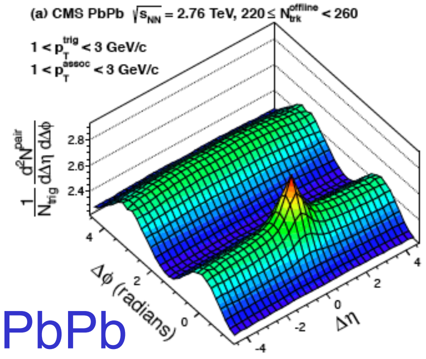
High Multiplicity



pp



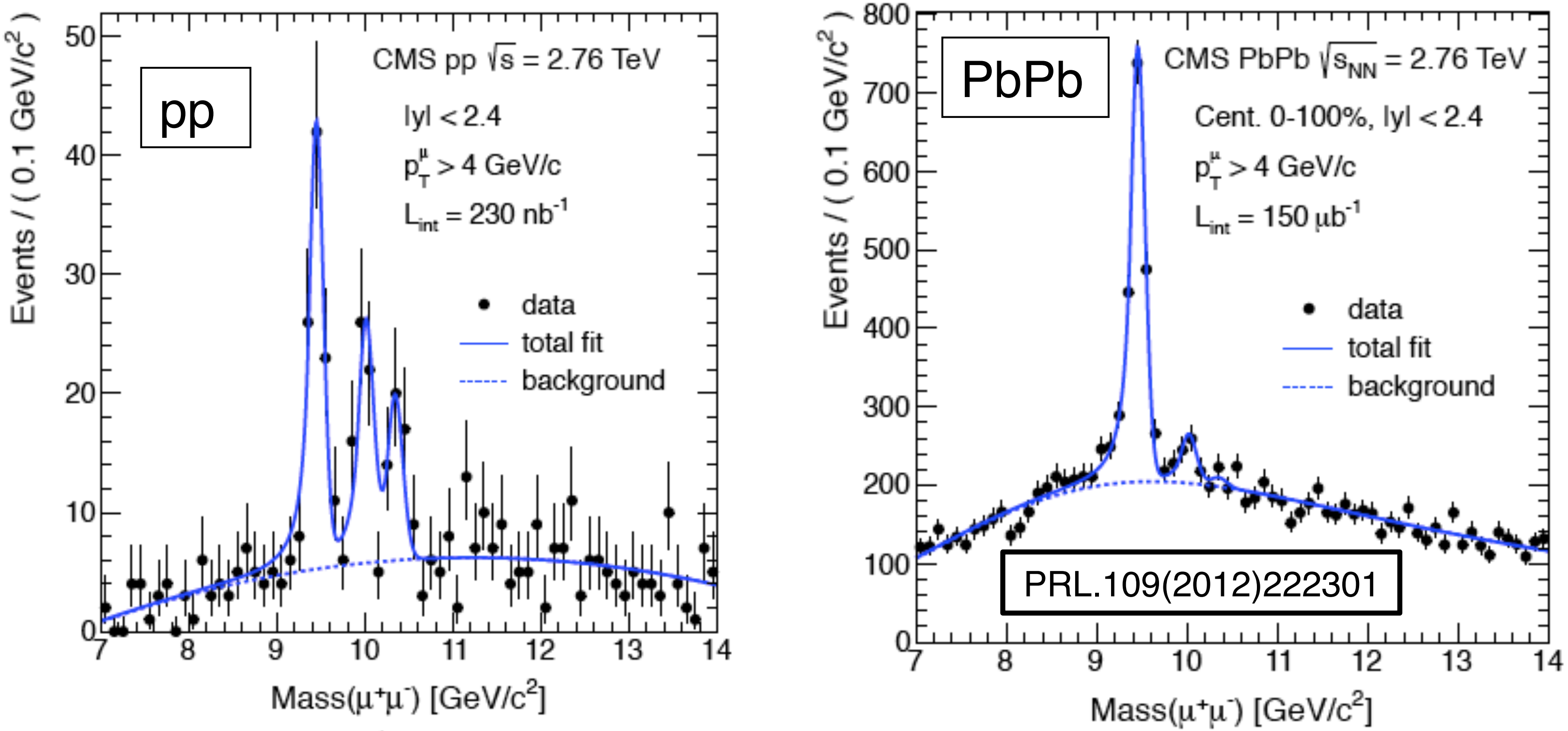
pPb



PbPb

- Higher Harmonics arise from fluctuations in the initial nucleon distribution.
- The existence of high moment – indication of perfect fluid being formed.
- Structures in the di-hadron distributions, aka “ridge” and “cone”, probably can be explained by v_2-v_6 plus a momentum conservation term v_1.

Deconfinement: Suppression in the Upsilon Family



PRL.109(2012)222301

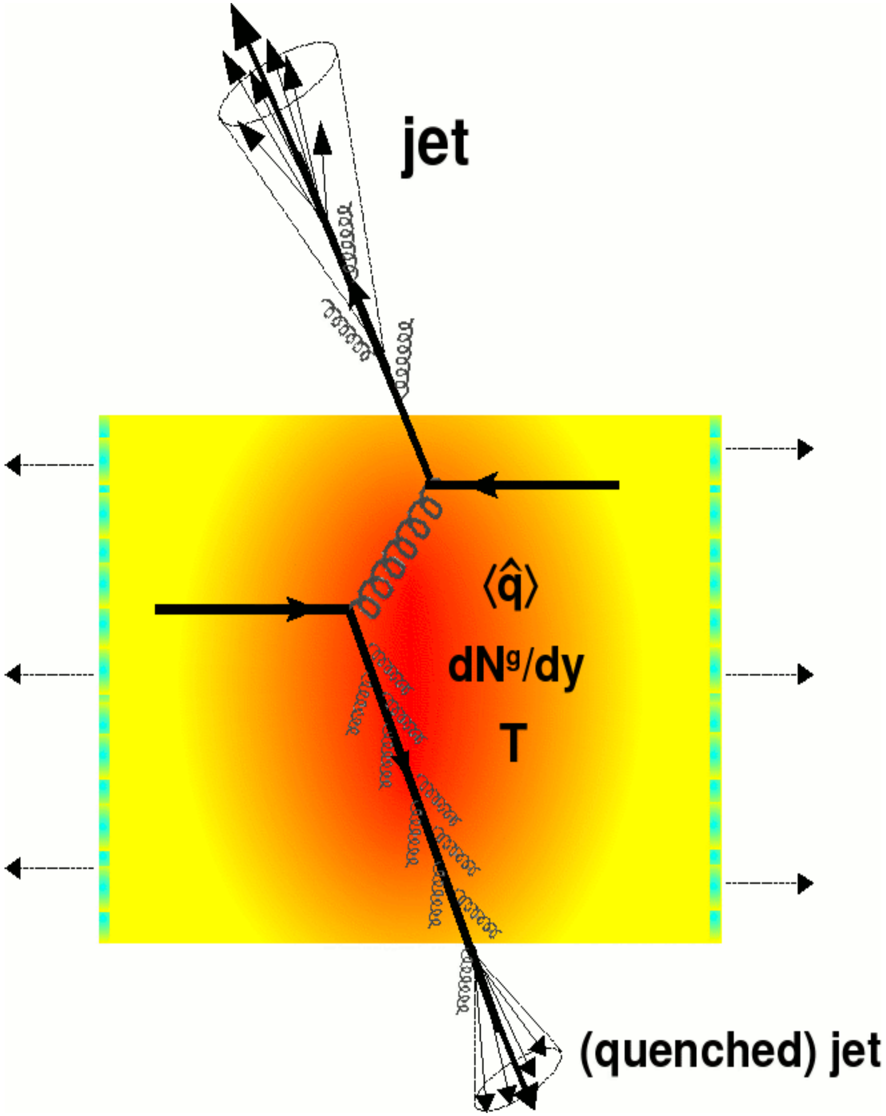
$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{\text{PbPb}}}{\Upsilon(2S)/\Upsilon(1S)|_{\text{pp}}} = 0.21 \pm 0.07\,(\text{stat.}) \pm 0.02\,(\text{syst.}),$$

$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{\text{PbPb}}}{\Upsilon(3S)/\Upsilon(1S)|_{\text{pp}}} = 0.06 \pm 0.06\,(\text{stat.}) \pm 0.06\,(\text{syst.}) \quad (< 0.17 \text{ at } 95\% \text{ CL})$$

T_c ~ 150 MeV

- R_{AA}(1S) = 0.56±0.11, R_{AA}(2S) = 0.12±0.04, R_{AA}(1S) = 0.03±0.04
- Excited states ϒ(2S,3S) relative to ϒ(1S) are suppressed.
- QCD predicts Y(nS) states melt at 1.2 T_c (3S), 1.6 T_c (2S), and above 4 T_c (1S).

Energy Loss by Partons in a Dense Medium

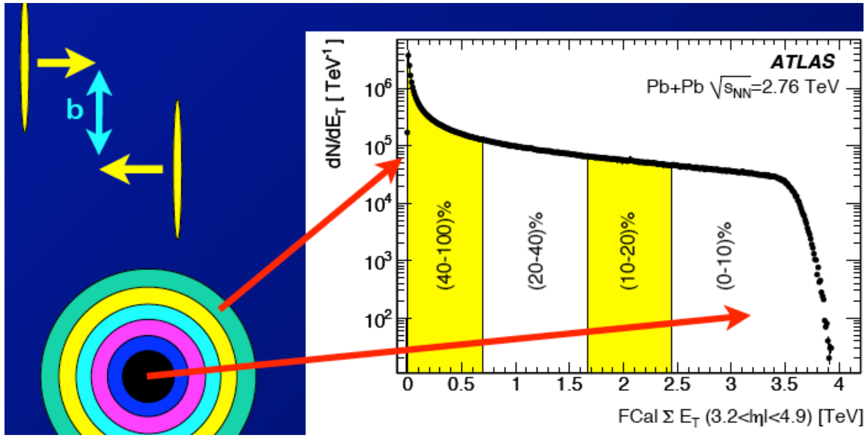


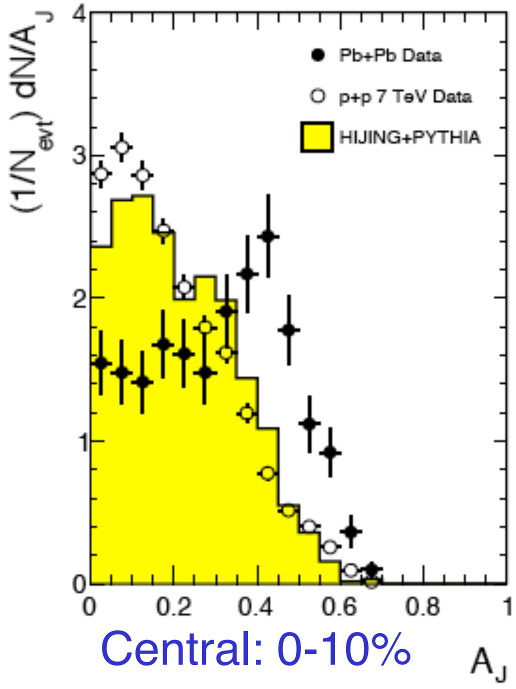
- Fragmentation of quarks and gluons into jets is strongly modified as they traverse the quark-gluon medium created in head-on (central) high energy Pb-Pb collisions - labeled **"jet quenching"**.

- Such effects were observed in at RHIC for single particle spectra and particle correlations.

- At the LHC one can fully reconstruct the jets!

“Jet Quenching”: ATLAS

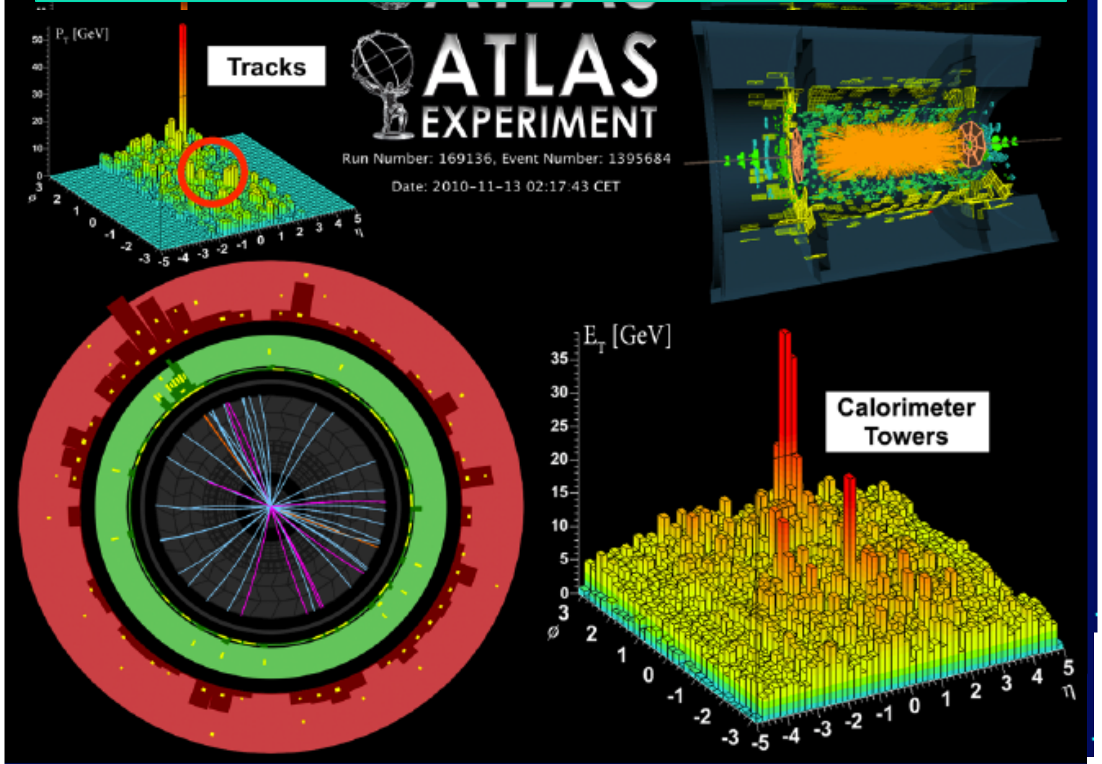




Central: 0-10%

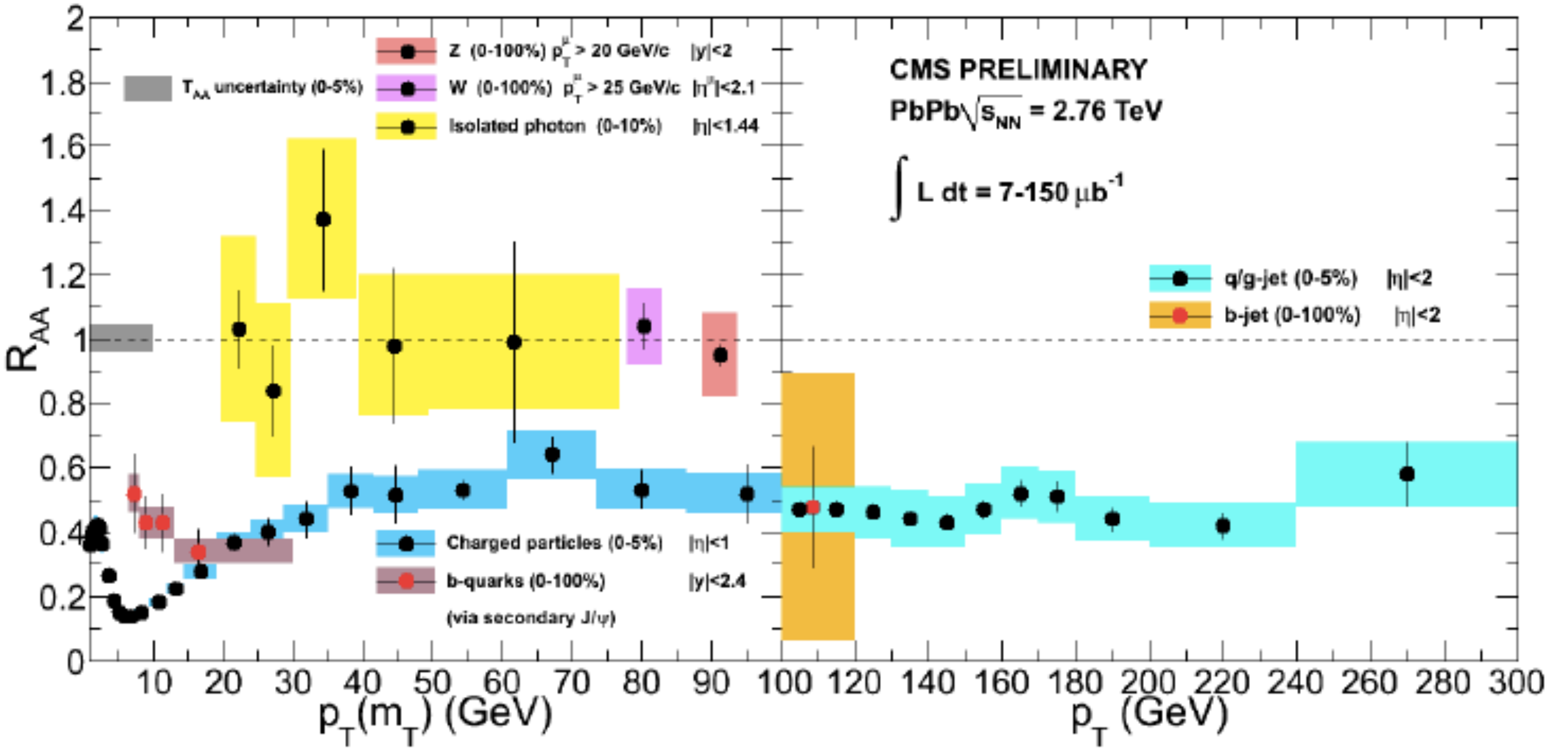
$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

- Fragmentation pattern independent of energy lost in medium
- Consistent with strong out of cone energy loss and fragmentation of the parton remnant as if in vacuum



Central event, with split dijet + additional activity

Summary of Heavy Ions Results on Modification



Strong suppression for hadrons and quarkonia, latter depending on strength of quarkonium binding
No suppression for photons, Z or W bosons

Unmodified probes (isolated photons, Z and W bosons) validate and confirm some of the tools used (Ncoll)
Detailed results on jet quenching, jet fragmentation, inclusive jet production, jet flavour dependence
… in PbPb and in pPb – good input for models.

The Proton-Proton Physics

General event properties
inelastic: 10^9 Hz
Heavy flavour physics

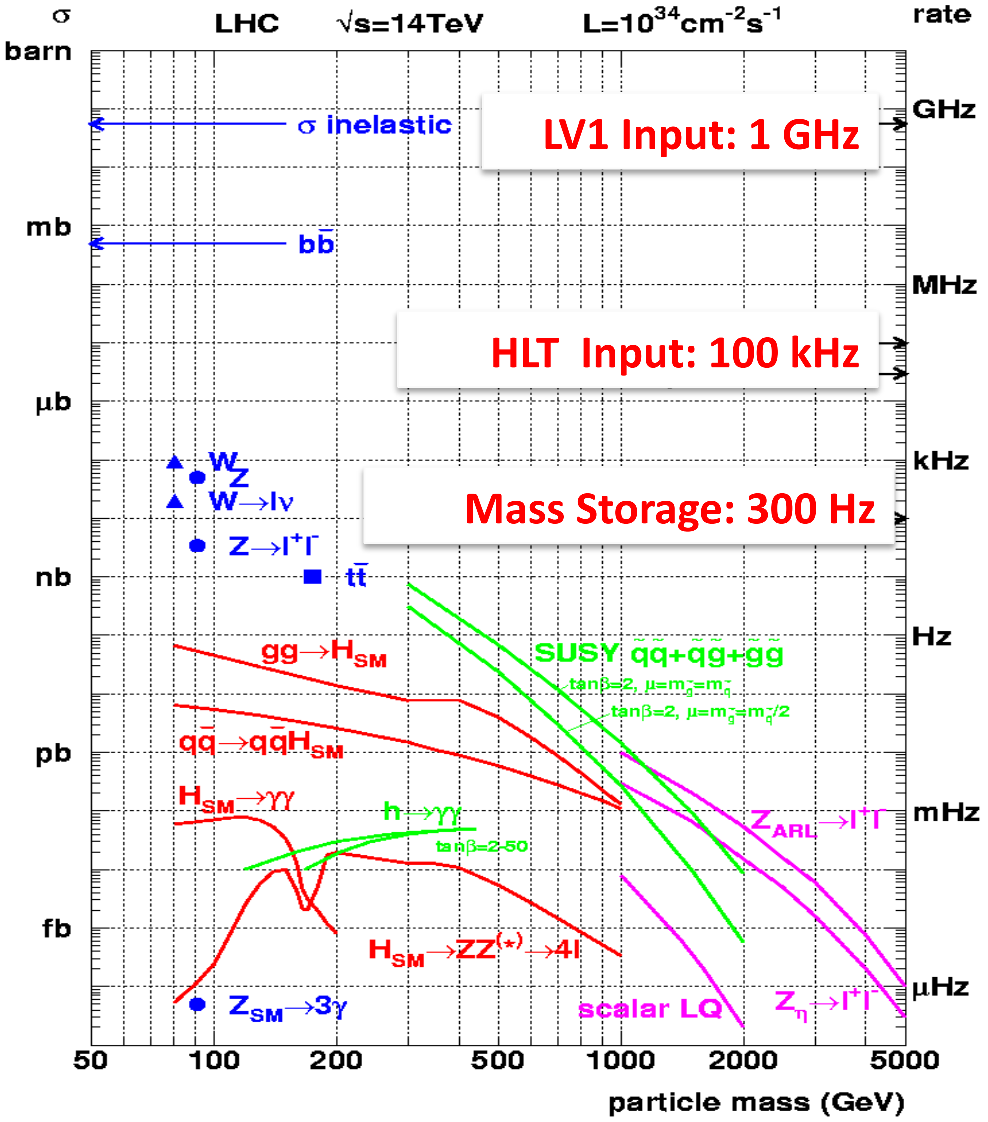
Standard Model physics
including QCD jets
W→ ℓ ν: 10^2 Hz @ 10^{34}
t tbar : 10 Hz @ 10^{34}

Searches for SUSY
Higgs searches

‘Exotic’ new physics

Increasing
Integrated Luminosity

Selection Required 1:10^{10}

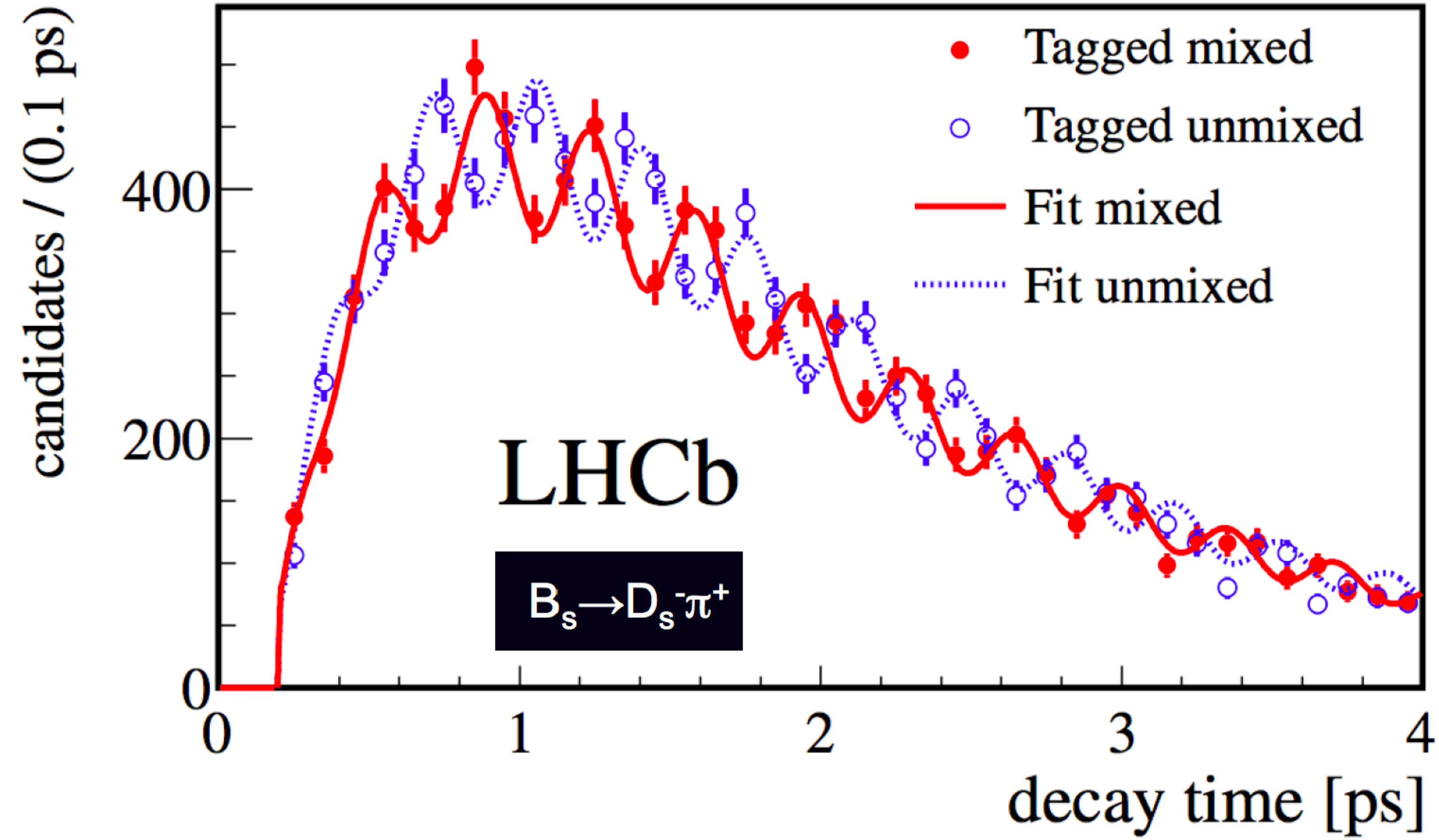


LV1 Input: 1 GHz

HLT Input: 100 kHz

Mass Storage: 300 Hz

Heavy Flavour Physics

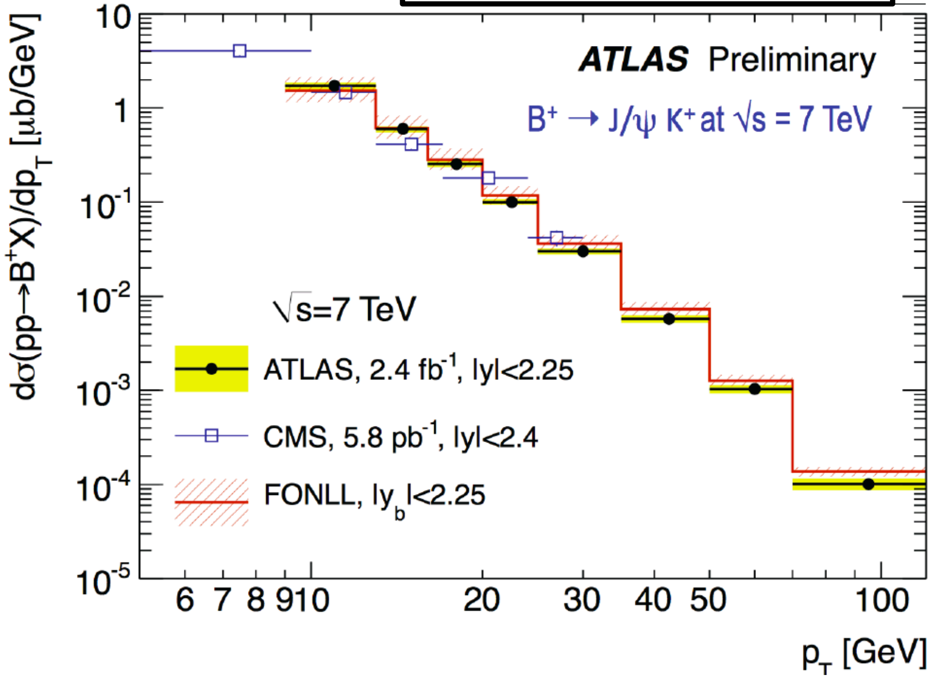


Δm_S = 17.768±0.023(stat)±0.006(syst) ps^{-1}

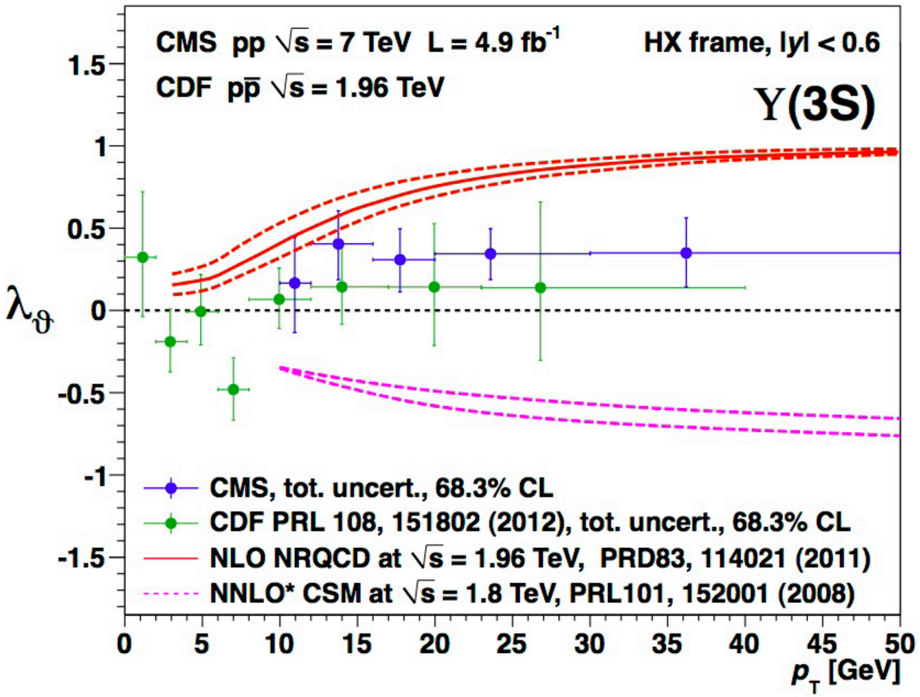
LHCb: NJP 15(2013)053021

Heavy Flavour Physics

ATLAS-CONF-2013-008



CMS: PRL 110 (2013) 081802

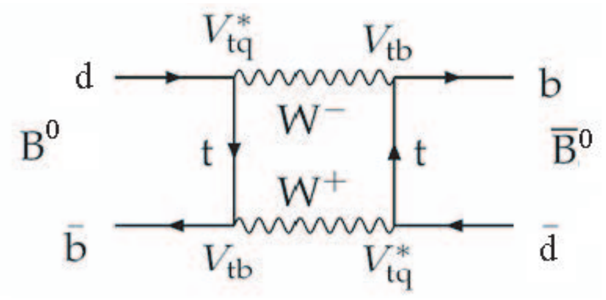


Successful description of open flavour production by pQCD

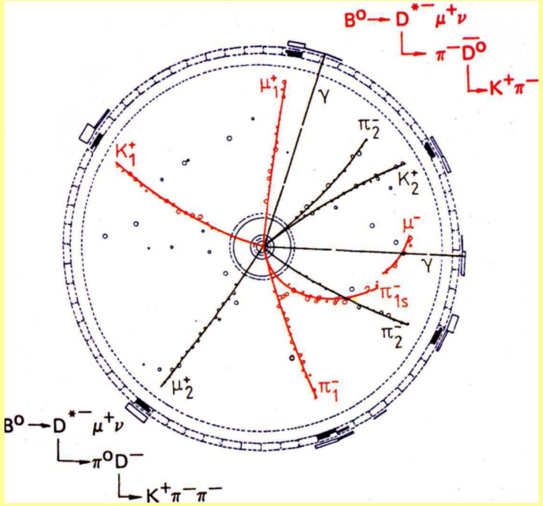
First measurement of Υ(1S), Υ(2S), Υ(3S) and J/Ψ polarization.
No significant polarization – significant discrepancy with predictions

LHC*b* Physics

- LHCb is designed to search for New Physics through *indirect* effects on **charm** and **beauty** decays via virtual production in loop diagrams:



$e^+e^- \to \Upsilon(4S) \to B^0B^0$



- Such an indirect approach can be very powerful:
  e.g. B^0–B^0 mixing discovered at ARGUS (1987)
  → top quark unexpectedly heavy: $m(t) > 50$ GeV/c^2

- *Key topics for LHCb include:* check whether **CP violation** is due to a single phase in the quark mixing (CKM) matrix, as in the Standard Model

  Study **rare decays**: FCNC decays (*e.g.* $B_s \to \mu^+\mu^-$) are strongly suppressed in SM, may be enhanced by Supersymmetry, or other new physics

Flavour Physics in LHCb

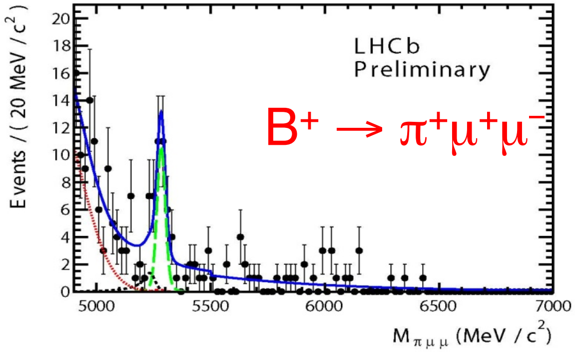
- ***High cross section for bb*-pairs production at LHC energy**
  - (σ_{bb} ~ 300-500 μb at 7-14 TeV: 10^{12} *bb* produced/year at $L = 2 \cdot 10^{32}$ cm^{-2}s^{-1})
- **All species of particles containing a b-quark are produced**
  - (B_u^+, B_u^-, B_d^0, B_d^0, B_c^+, B_c^-, B_s^0, B_s^0, Λ_b , etc.)
- ***bb*-pairs correlated and sharply peaked forward-backward**
  - detector with forward geometry with $2 < \eta < 6$ coverage
- **Large boost - B decays have long flight-distance ~1 cm** (distinguish B-decays from other background decays, and essential for ***time-dependent*** CP violation measurements)
- **Particle Identification**
- Complementary coverage for other physics (EW, QCD, exotics….)

The Challenge to select events of interest:

- σ_{bb} is less than 1% of total inelastic cross section
- B decays of interest typically have BR < 10^{-5}
- **Need high statistics and high selectivity!**

BR ($B^+ \to \pi^+\mu^+\mu^-$) = $(2.4 \pm 0.6) \times 10^{-8}$

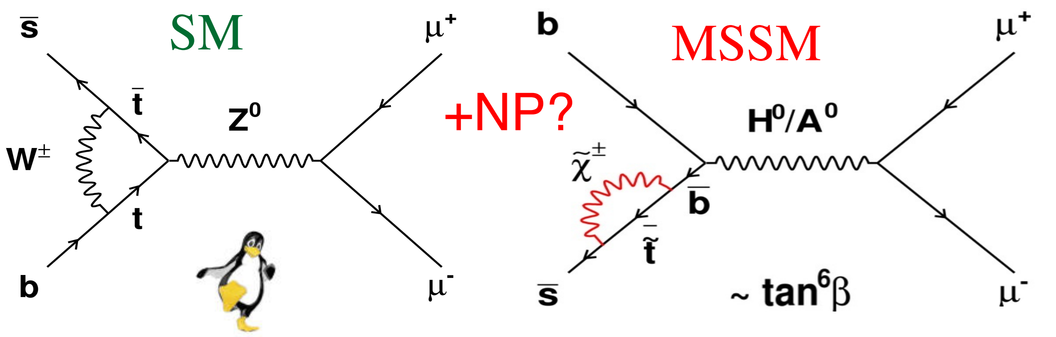
Rarest B decay ever observed!



[CONF-2012-006]

Very rare decays: $B_{d,s} \to \mu\,\mu$

$B_{d,s} \to \mu\mu$ the super-rare loop decay



In Standard Model:

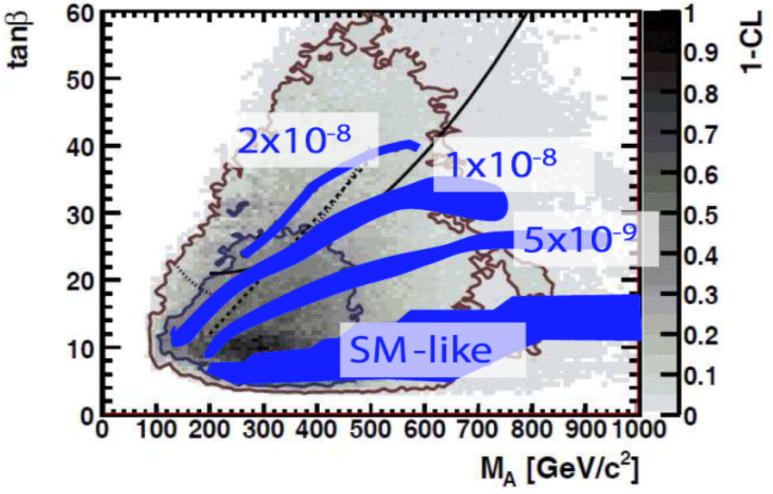
$\mathcal{B}(B_d \to \mu\,\mu) = (0.10 \pm 0.01)\times10^{-9}$

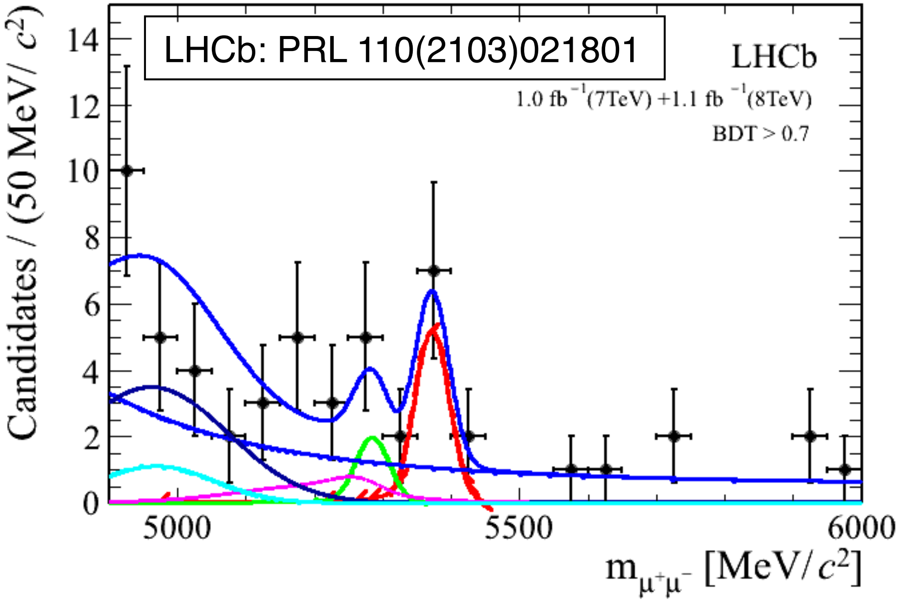
$\mathcal{B}(B_s \to \mu\,\mu) = (3.2 \pm 0.2)\times10^{-9}$

[A.J.Buras: arXiv:1012.1447]

Sensitive to New Physics, can be strongly enhanced in SUSY with scalar H exchange

Sensitive probe for MSSM with large tanβ: $\mathcal{B}(B_S \to \mu^+\mu^-) \sim \tan^6\beta / M_A^4$





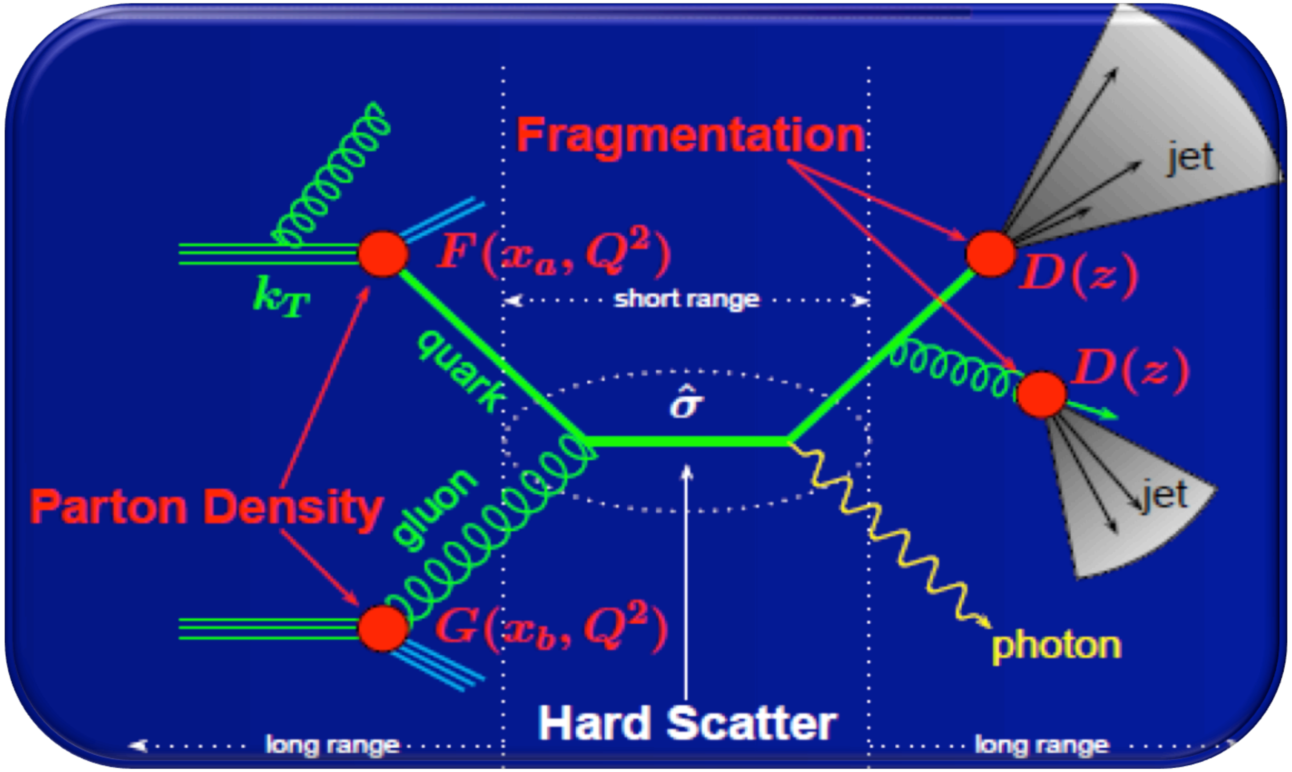
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.2\,^{+1.4}_{-1.2}(\text{stat})\,^{+0.5}_{-0.3}(\text{syst})) \times 10^{-9}$$

Physics Commissioning

Standard Model at 7, 8 TeV

Soft QCD (minimum bias, underlying event, “ridge”, ..)
Production of Jets, b’s, prompt photons, J/ψ, Y, ….
W, Z production,
Top production,
….

The Hard Scatter



Jet Algorithm
Anti-k_T, R=0.5

Typical of hard scatter
e, μ, γ : $E_T > 20$ GeV
Jets: $E_T > 20$ GeV

Isolation
$E_T, p_T <$ thresh in cone

$$\Delta R \equiv \sqrt{\Delta\eta + \Delta\phi}$$

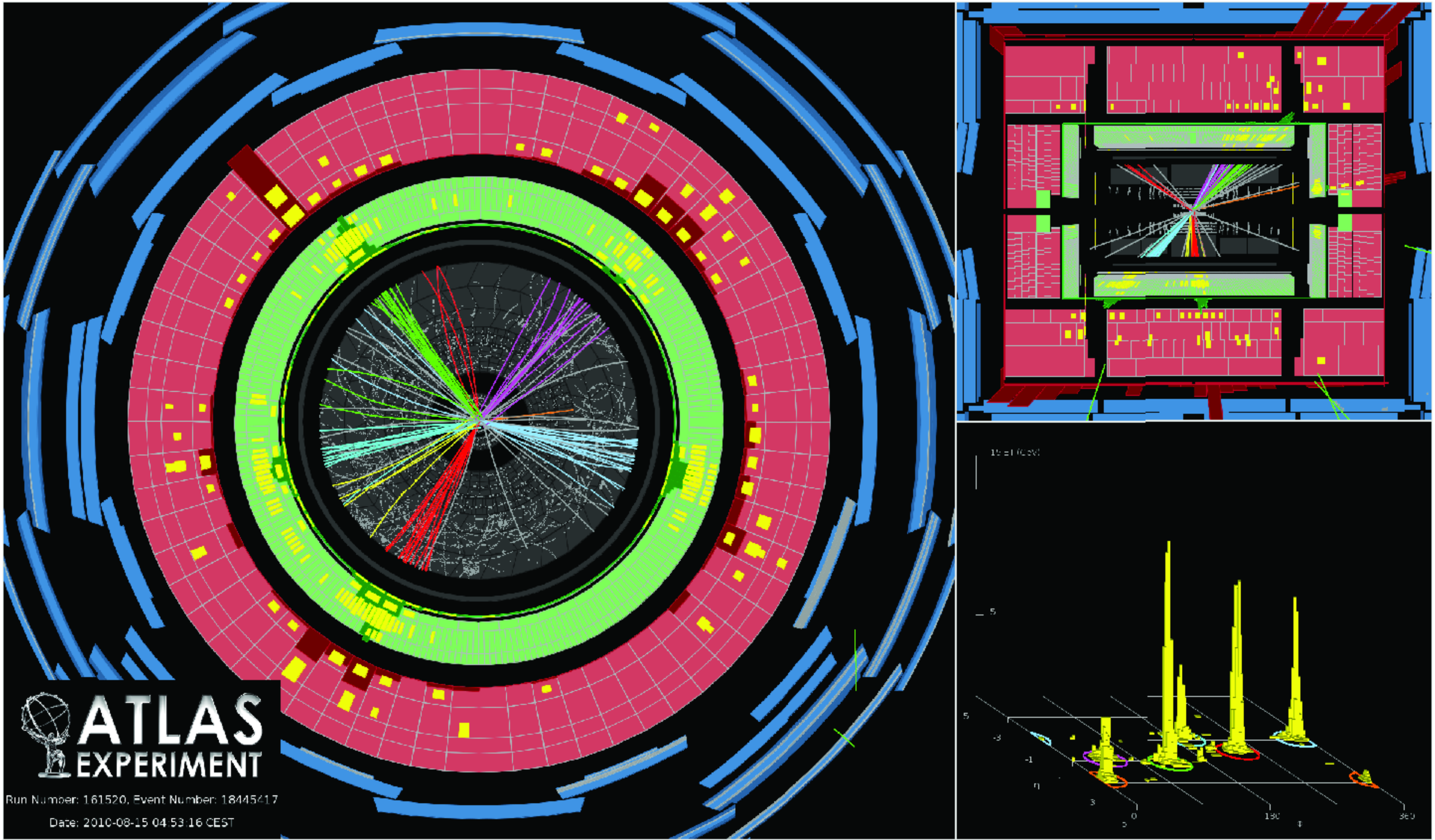
$\Delta R \sim 0.3$

H_T - scalar sum of E_T of all jets with e.g. $P_T > 30$ GeV/c
S_T - scalar sum of E_T of N individual objects (jets, e, μ, γ) with e.g. $E_T > 50$ GeV/c

Transverse Mass,

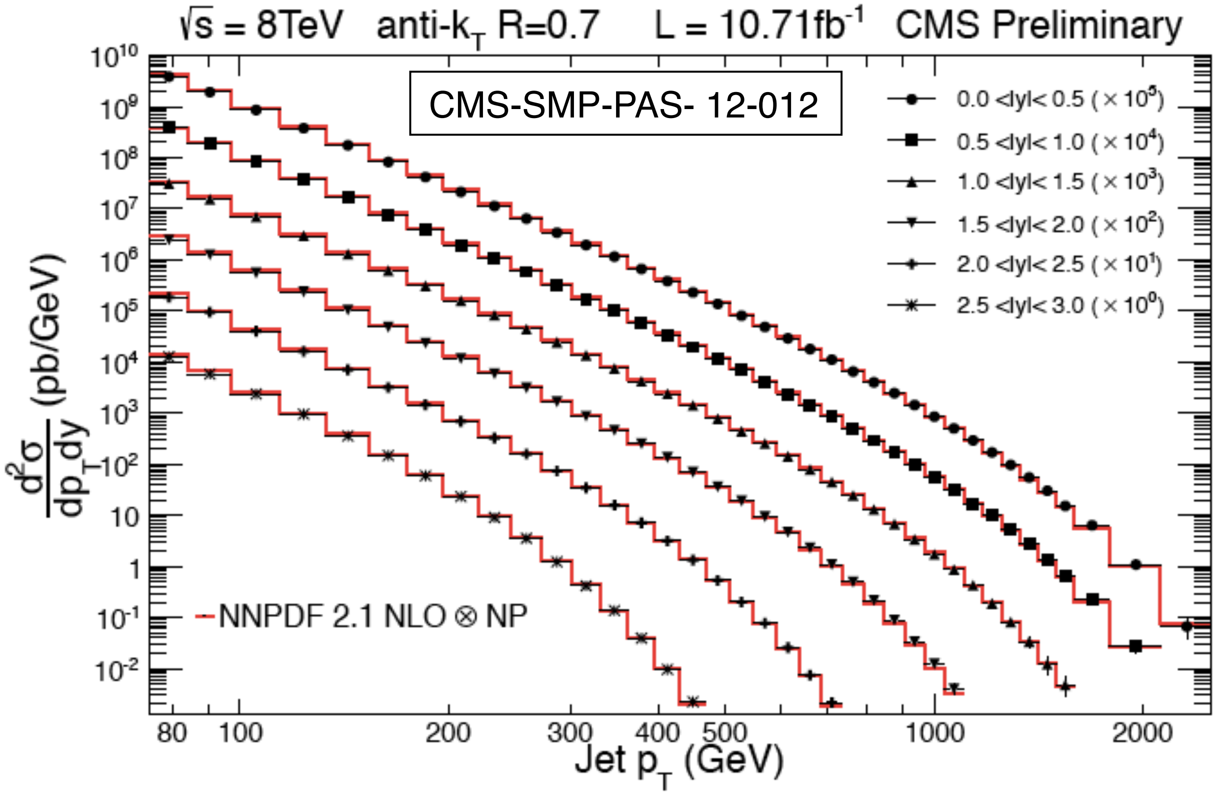
$$M_T = \sqrt{2E_T^{\mu} E_T^{miss} (1 - \cos\Delta\phi_{e,miss}}$$

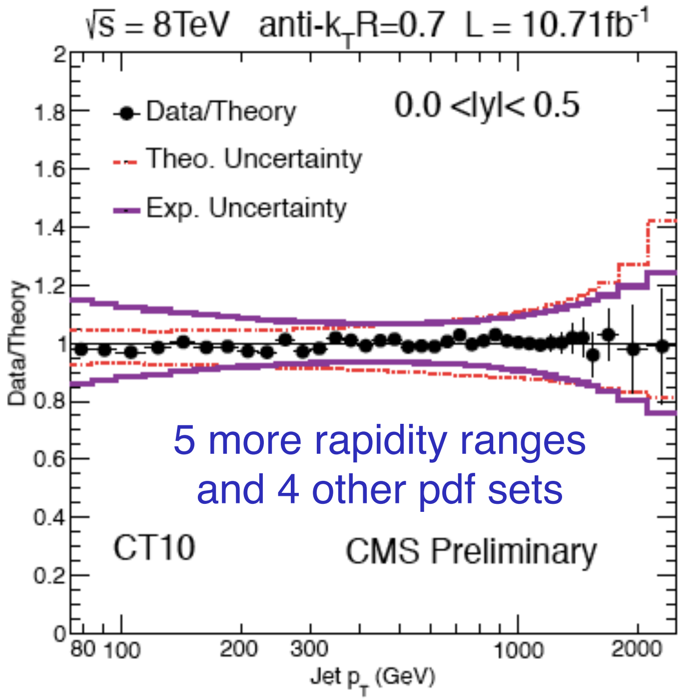
A Multi-Jet Event



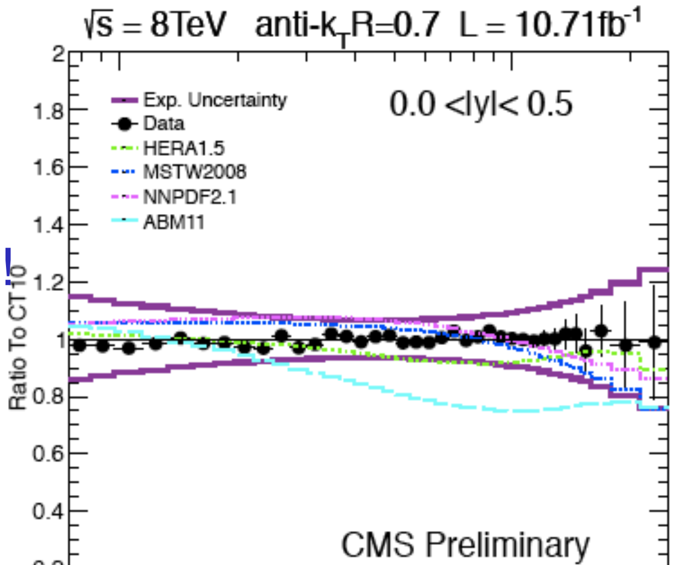
Checking the Predictions of the SM: QCD

Inclusive Jet Cross-section at LHC (√s=8 TeV)





5 more rapidity ranges
and 4 other pdf sets

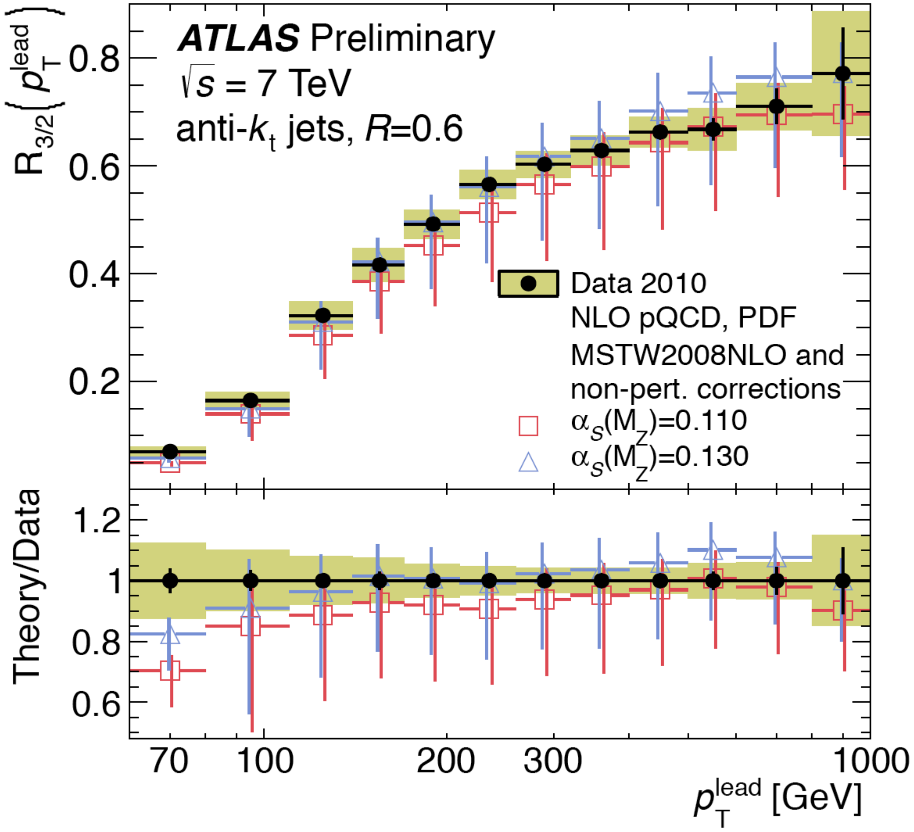


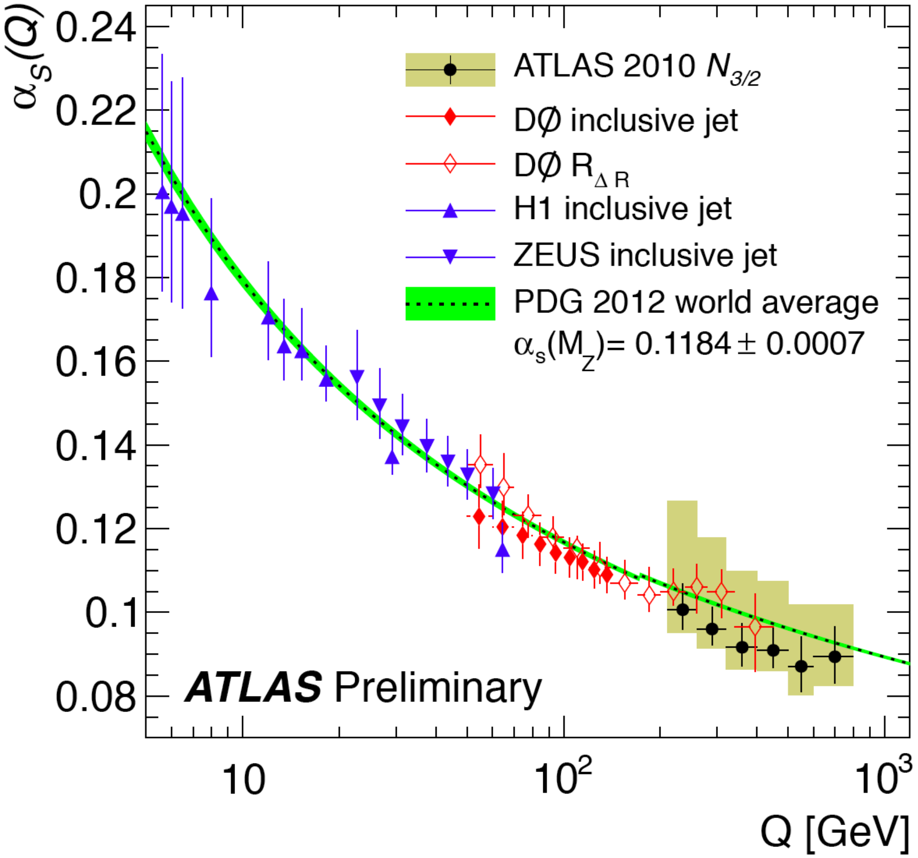
NLO QCD describes data over ~10 orders of magnitude!
Starting to constrain PDFs

Checking the Predictions of the SM: QCD Inclusive Jet Ratios and α_S

$$R_{3/2}(p_T^{\mathrm{lead}}) = \frac{d\sigma_{N_{\mathrm{jet}}\geq 3}/dp_T^{\mathrm{lead}}}{d\sigma_{N_{\mathrm{jet}}\geq 2}/dp_T^{\mathrm{lead}}}$$

$\alpha_S(M_Z)=0.111\pm0.006(\mathrm{exp})\ {}^{+0.016}_{-0.003}(\mathrm{th})$

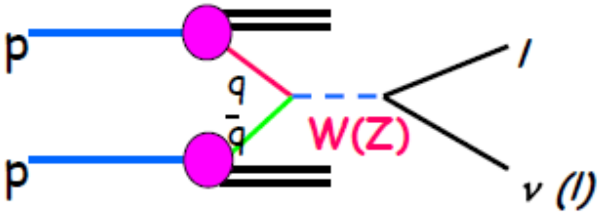




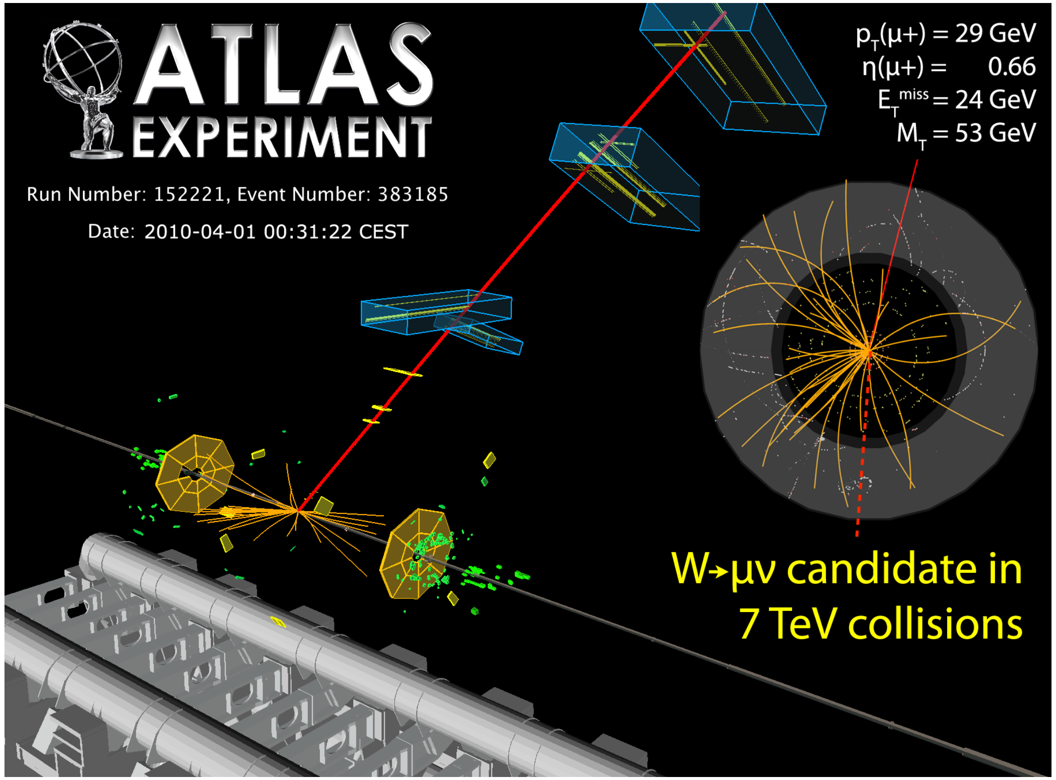
Good agreement except for $p_T^{\mathrm{lead}} < 140$ GeV

ATLAS-CONF-2013-041

Standard Model Physics: W/Z Production



ATLAS W → eν candidate

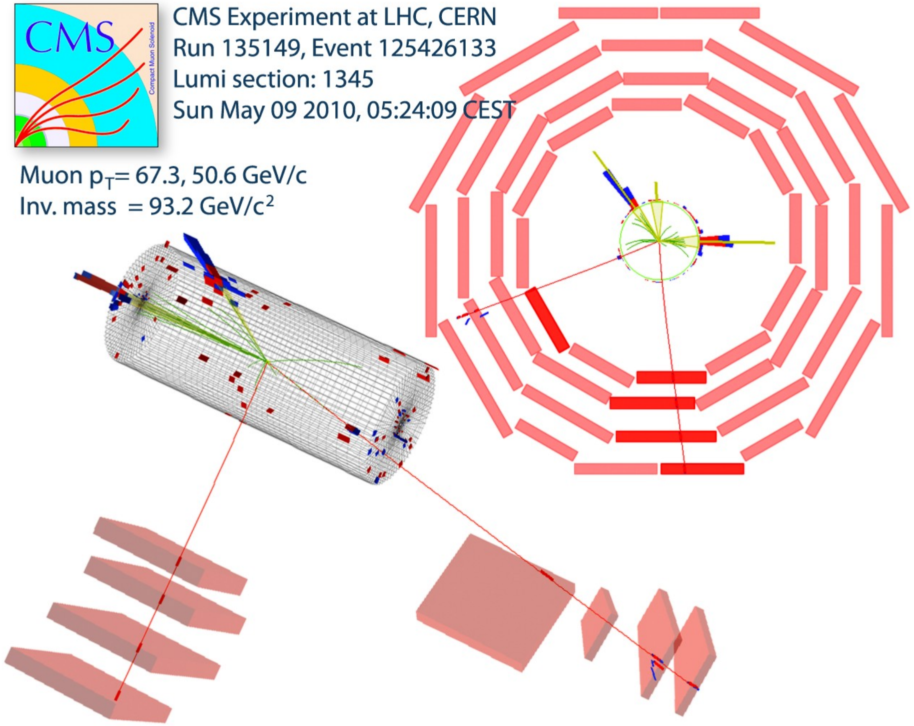


Run Number: 152221, Event Number: 383185

Date: 2010-04-01 00:31:22 CEST

$p_T(\mu+) = 29$ GeV
$\eta(\mu+) = 0.66$
$E_T^{miss} = 24$ GeV
$M_T = 53$ GeV

W→μν candidate in 7 TeV collisions

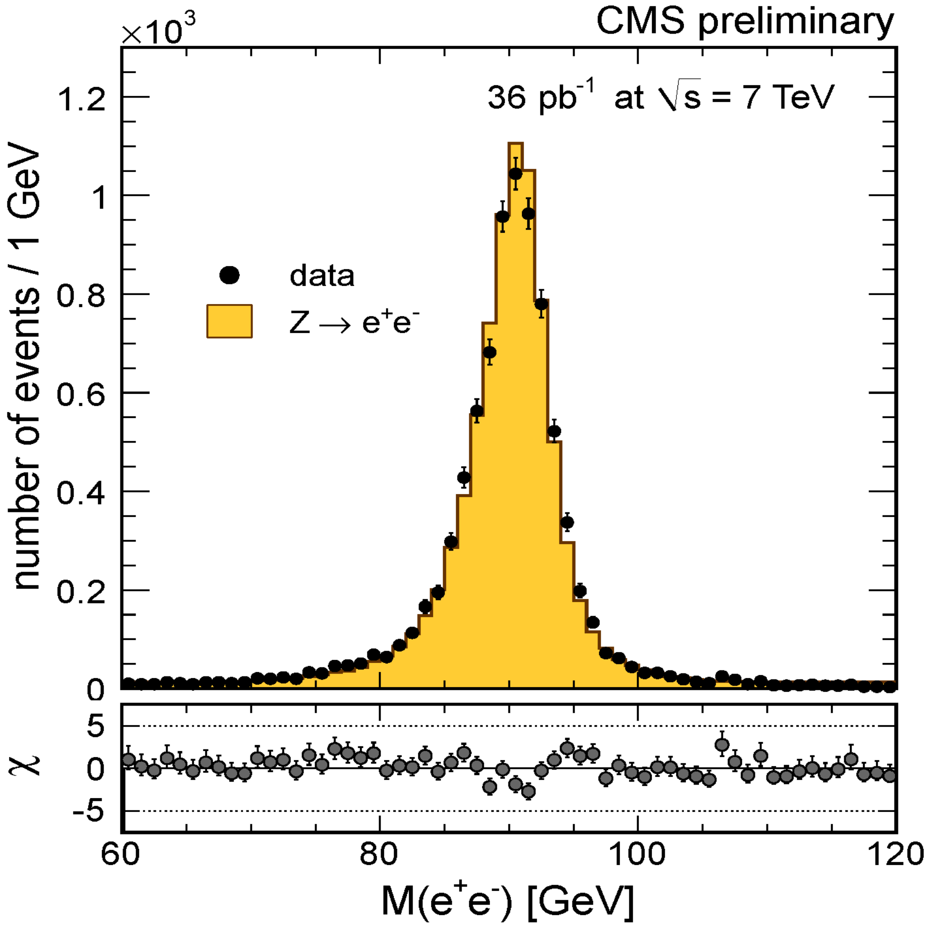


CMS Experiment at LHC, CERN
Run 135149, Event 125426133
Lumi section: 1345
Sun May 09 2010, 05:24:09 CEST

Muon p_T= 67.3, 50.6 GeV/c
Inv. mass = 93.2 GeV/c^2

CMS candidate Z → $\mu^+\mu^-$

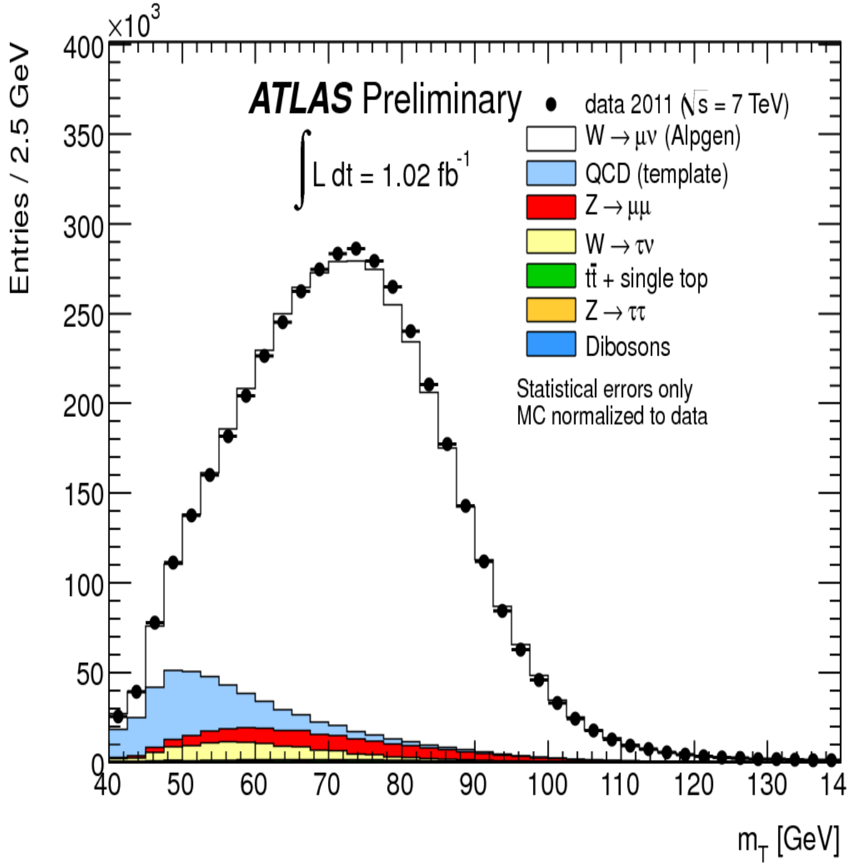
Z and W production



Z peak (di-lepton pair mass distributions)

$$m = \sqrt{(E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2}$$

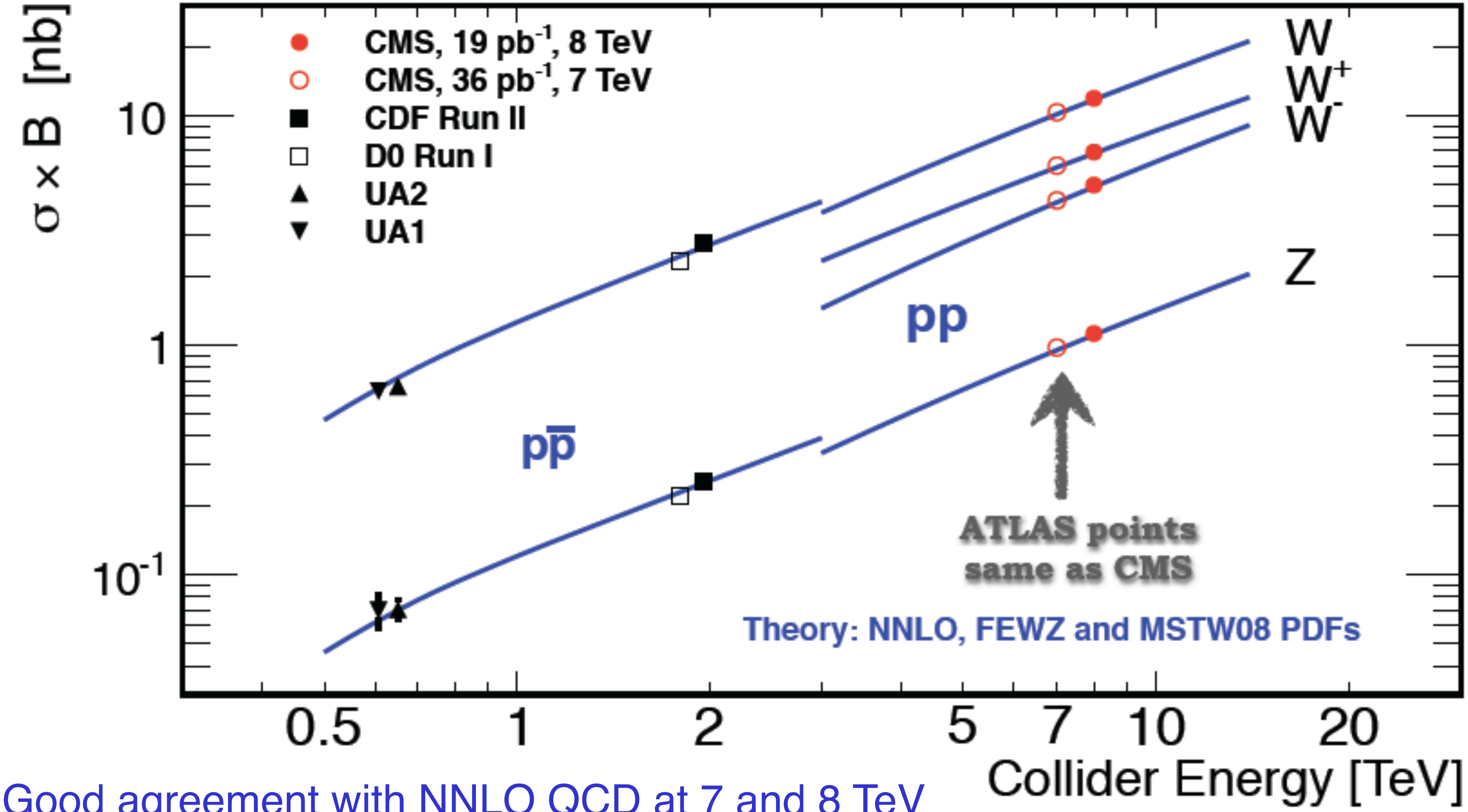
μ with p_T>20 GeV, E_T^{miss}>25 GeV



W transverse mass

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\nu} (1 - \cos(\phi^{\ell} - \phi^{\nu}))}$$

W/Z Cross-section Measurement



Good agreement with NNLO QCD at 7 and 8 TeV

Cross sections measured to ~ 2%*

(*luminosity excluded)

CMS: JHEP 1110(2011)132

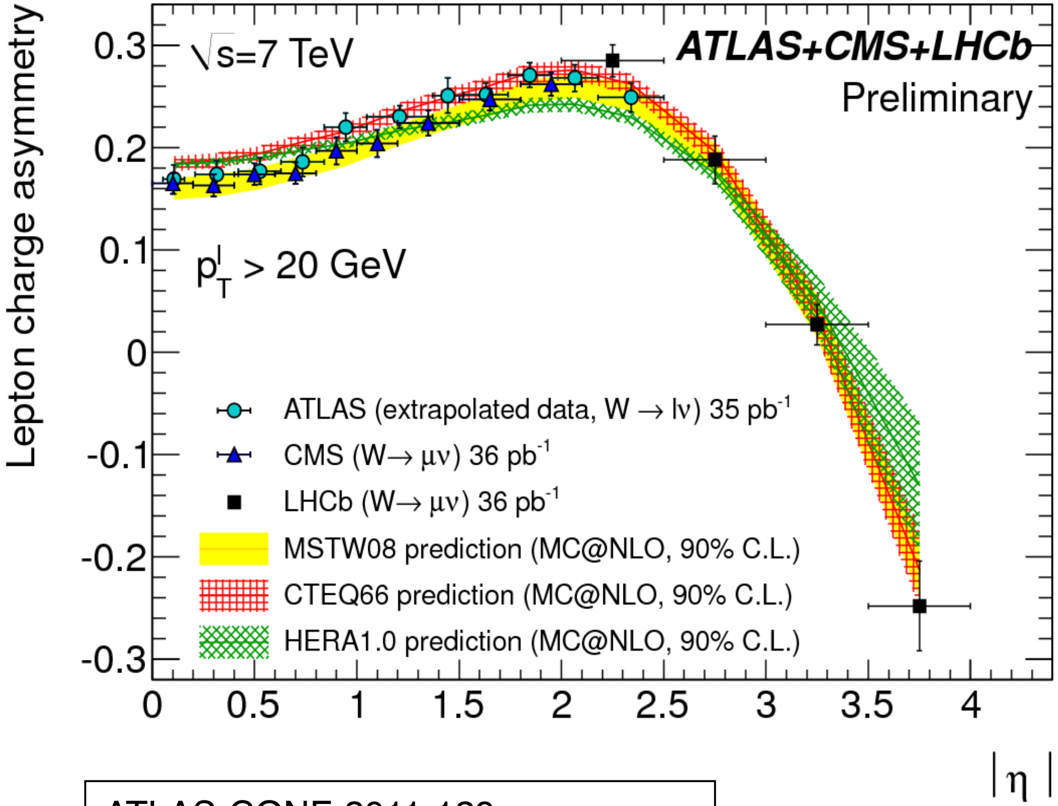
ATLAS: JHEP 1012(2010) 060

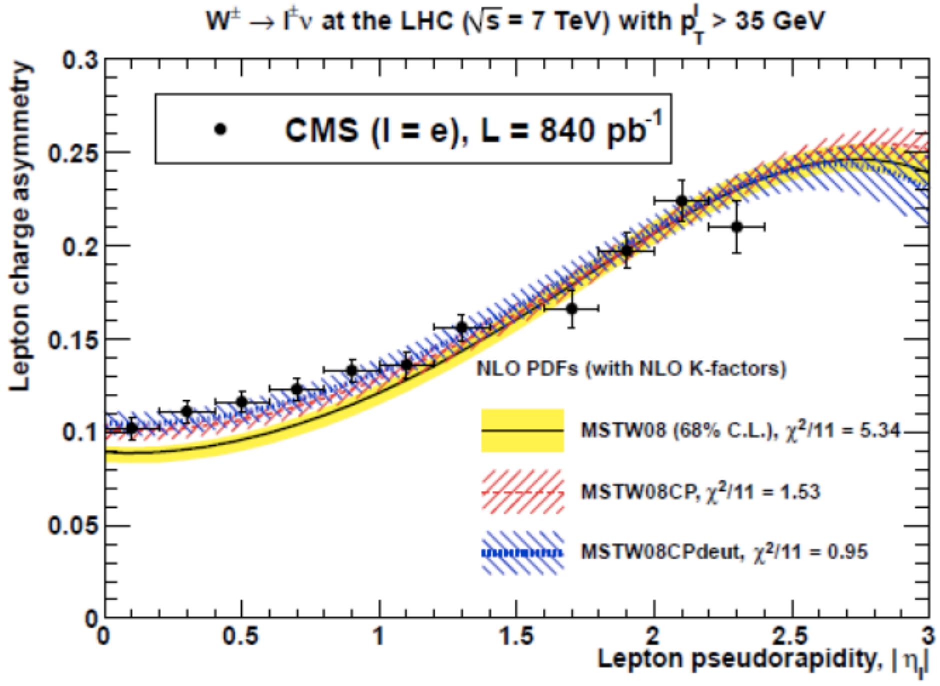
CMS-PAS-SMP-12-011

W → lν Charge Asymmetry Measurement

$$\mathcal{A}(\eta) = \frac{d\sigma/d\eta(W^+ \to \ell^+\nu) - d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}{d\sigma/d\eta(W^+ \to \ell^+\nu) + d\sigma/d\eta(W^- \to \ell^-\bar{\nu})}$$

Data are constraining PDFs



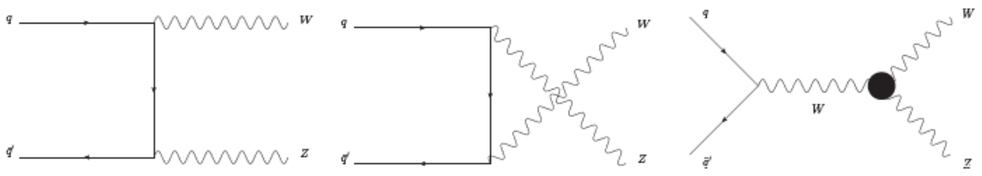


ATLAS-CONF-2011-129
LHCb-CONF-2011-039
CMS-EWK-10-006 (aXiv:1103.3407)

CMS: Phys Rev Lett 109(2012) 111806
A.D.Martin et al, Eur Phys J C73(2013)2318

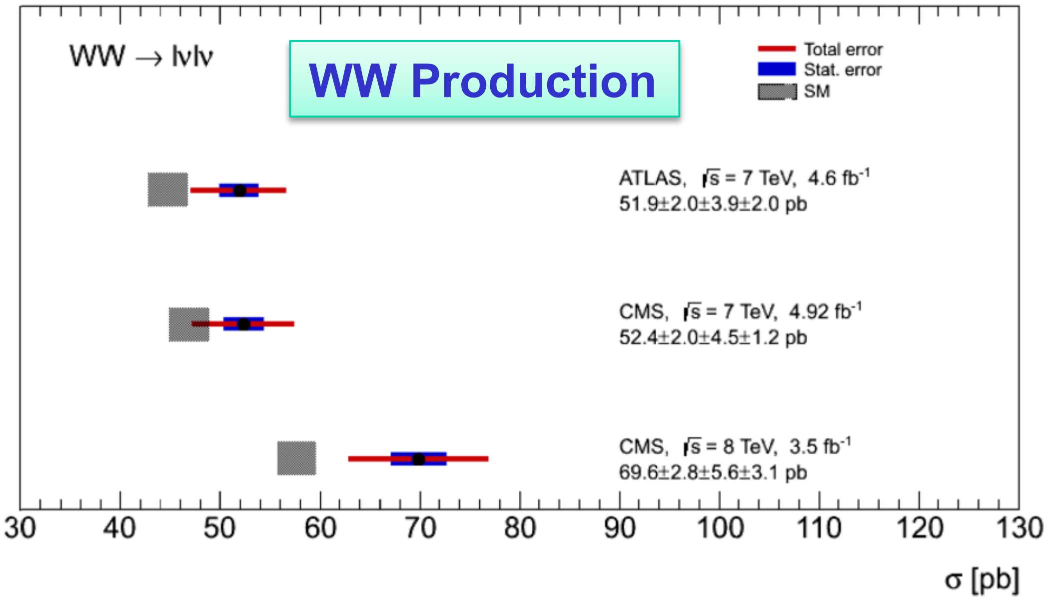
Imperial College London

Di-Boson Production

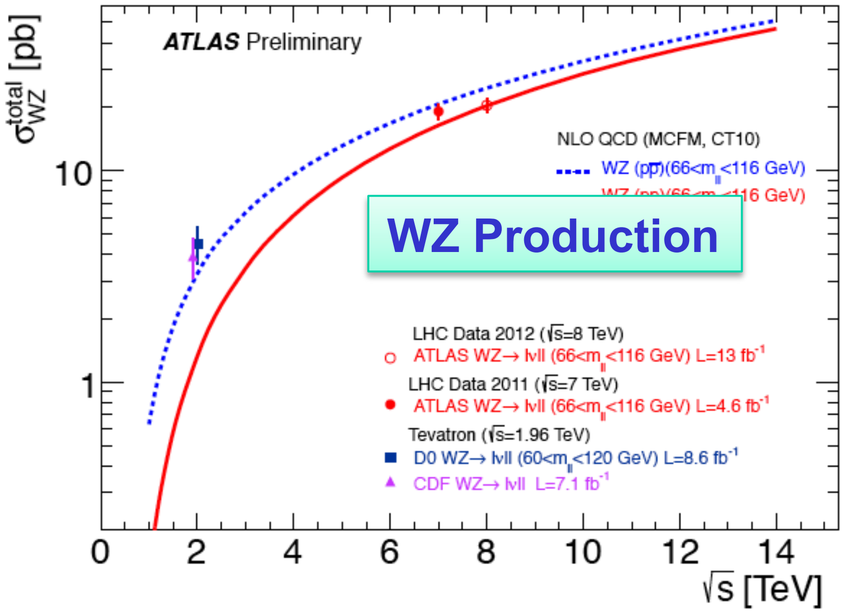


(a) t-channel (b) u-channel (c) s-channel

Ward, LHCP 2013

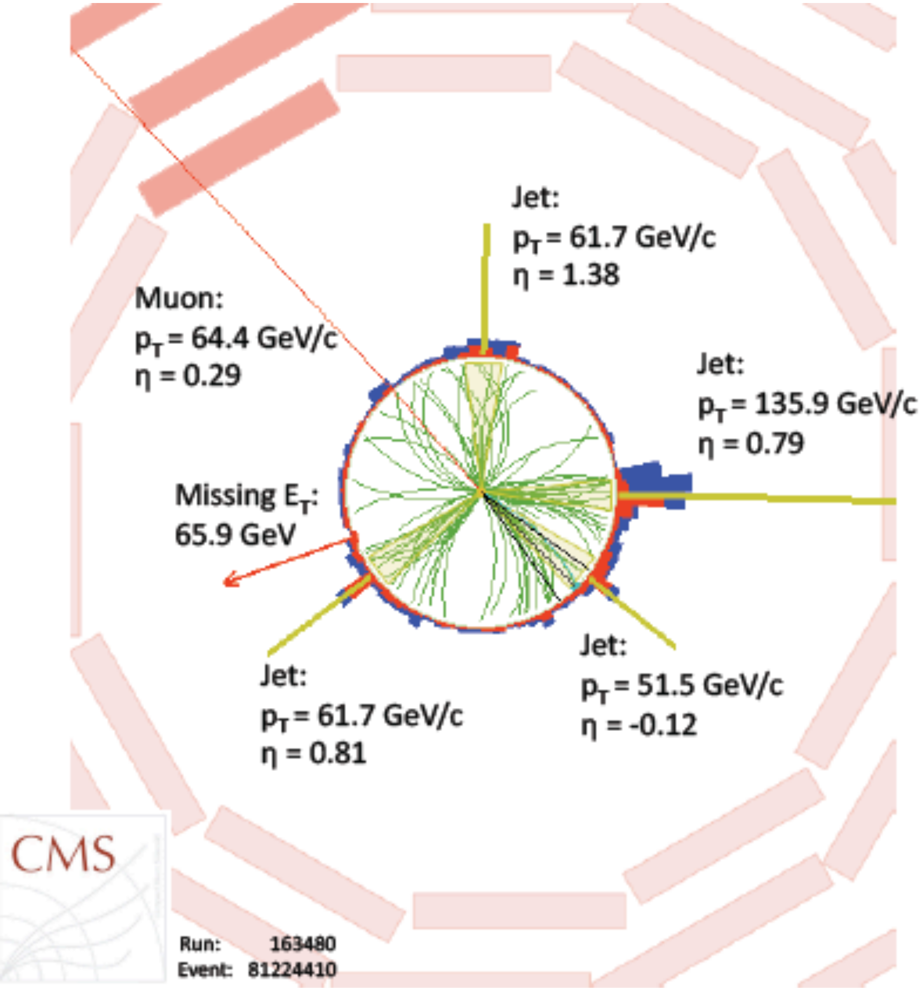

WW Production

ATLAS: CONF-2013-021

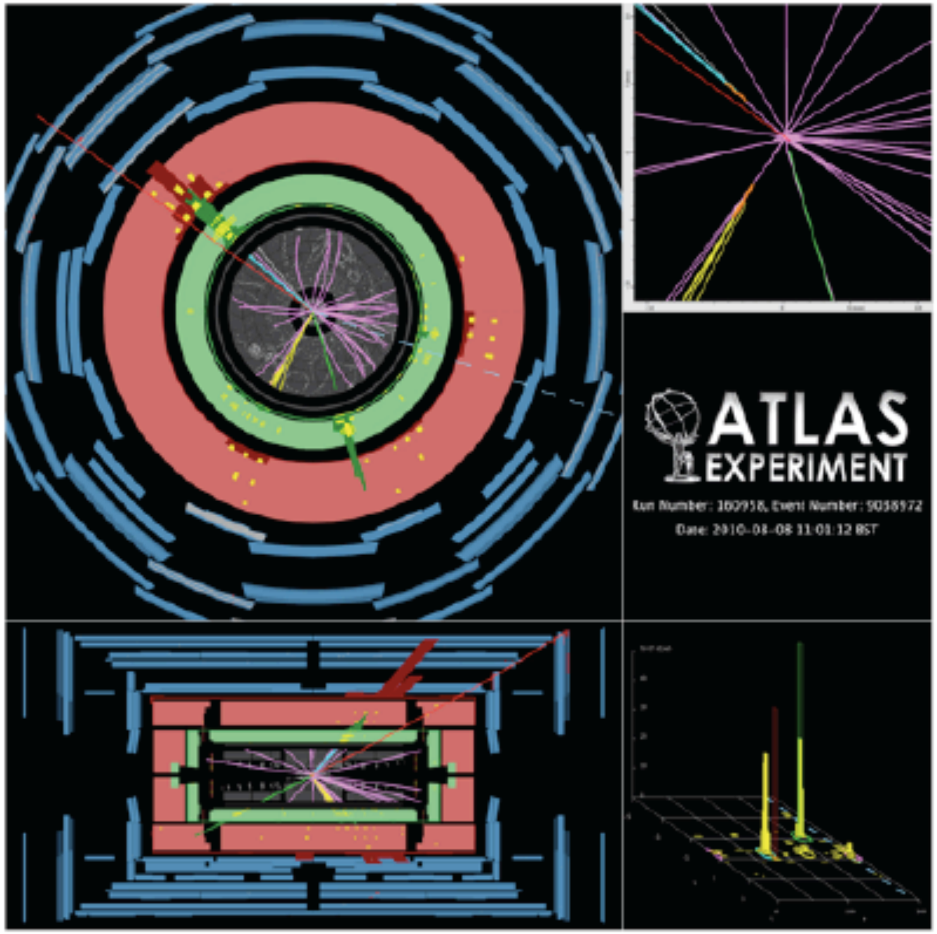

WZ Production

WW cross section 10-20% above the NLO predictions

Top Physics

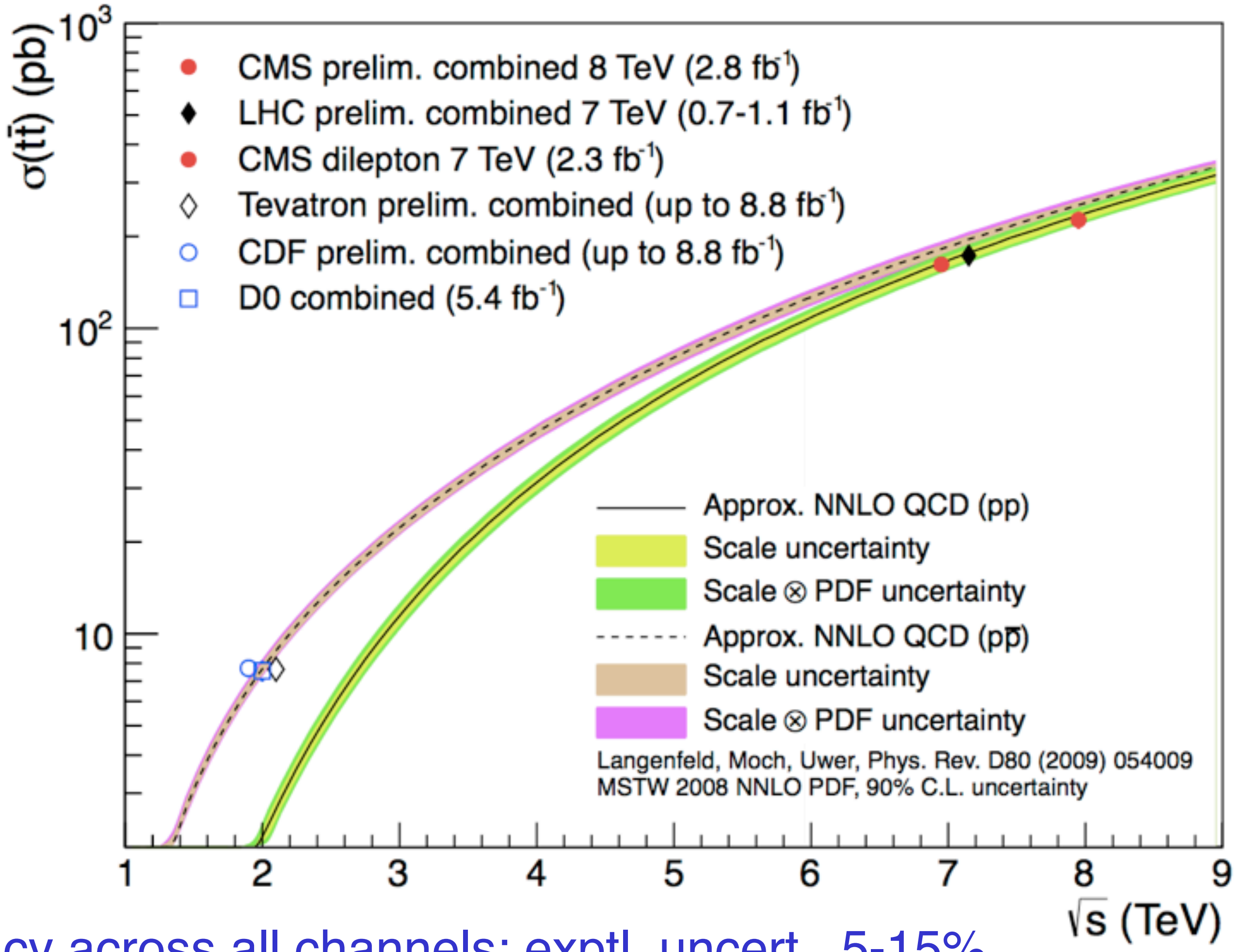


muon+jets event



electron+muon event

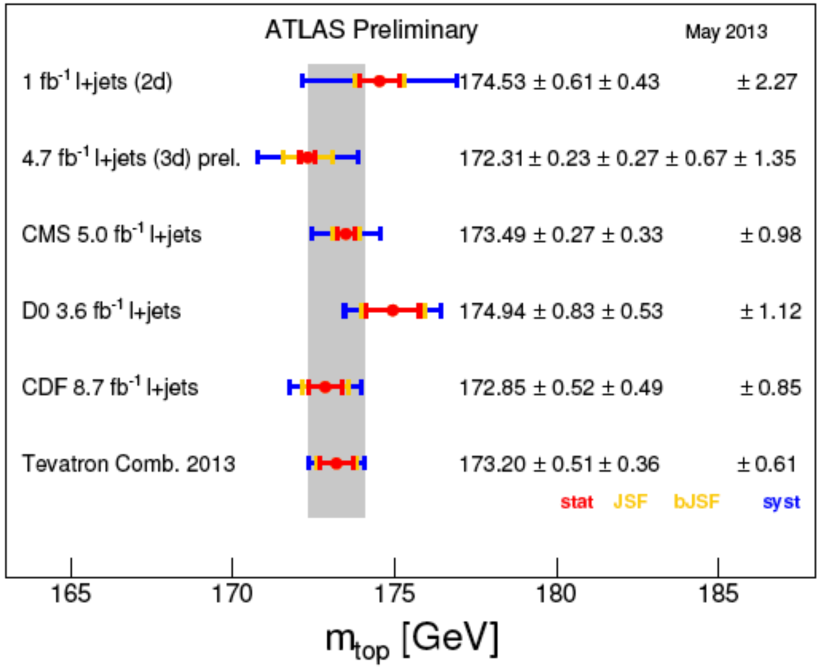
Top Quark Pair Production Cross Section



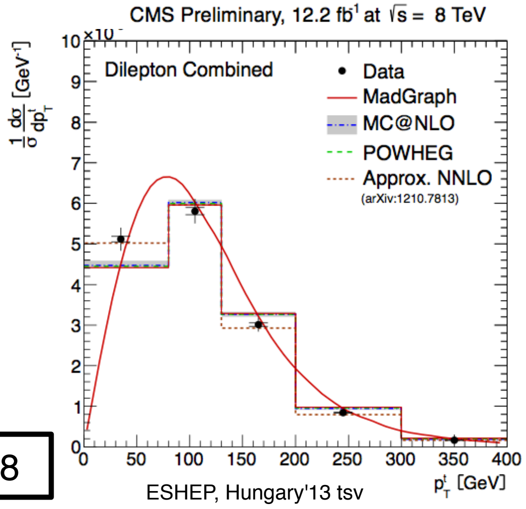
Consistency across all channels; exptl. uncert. 5-15%
Theoretical uncert. ~4%
Top production becoming a test of gluon PDFs

Top Quark: Mass and Kinematics

- Mass: combinations - sys. uncert. < 1 GeV
- Many kinematic properties of top final state measured. In general good description by MC and/or NNLO QCD

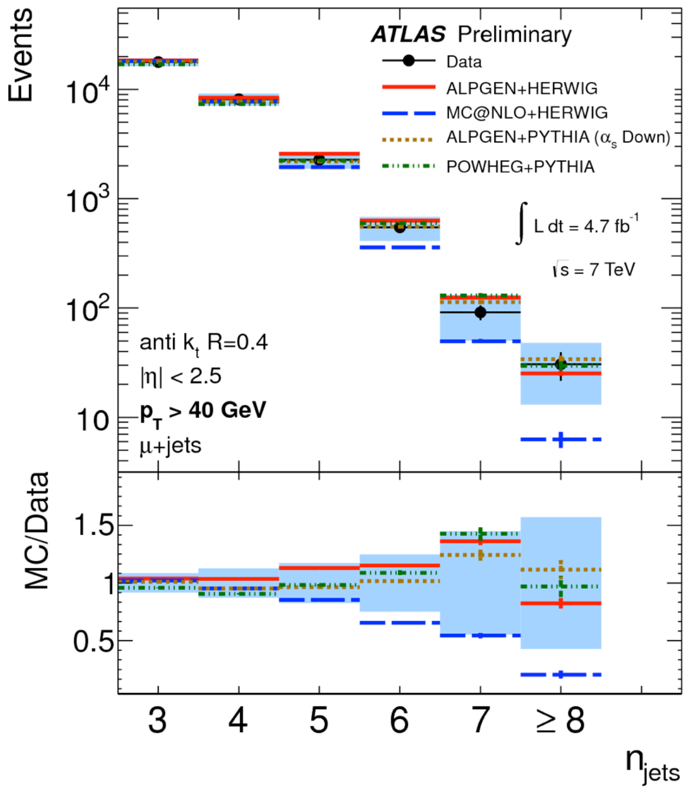


ATLAS CONF 2013-046



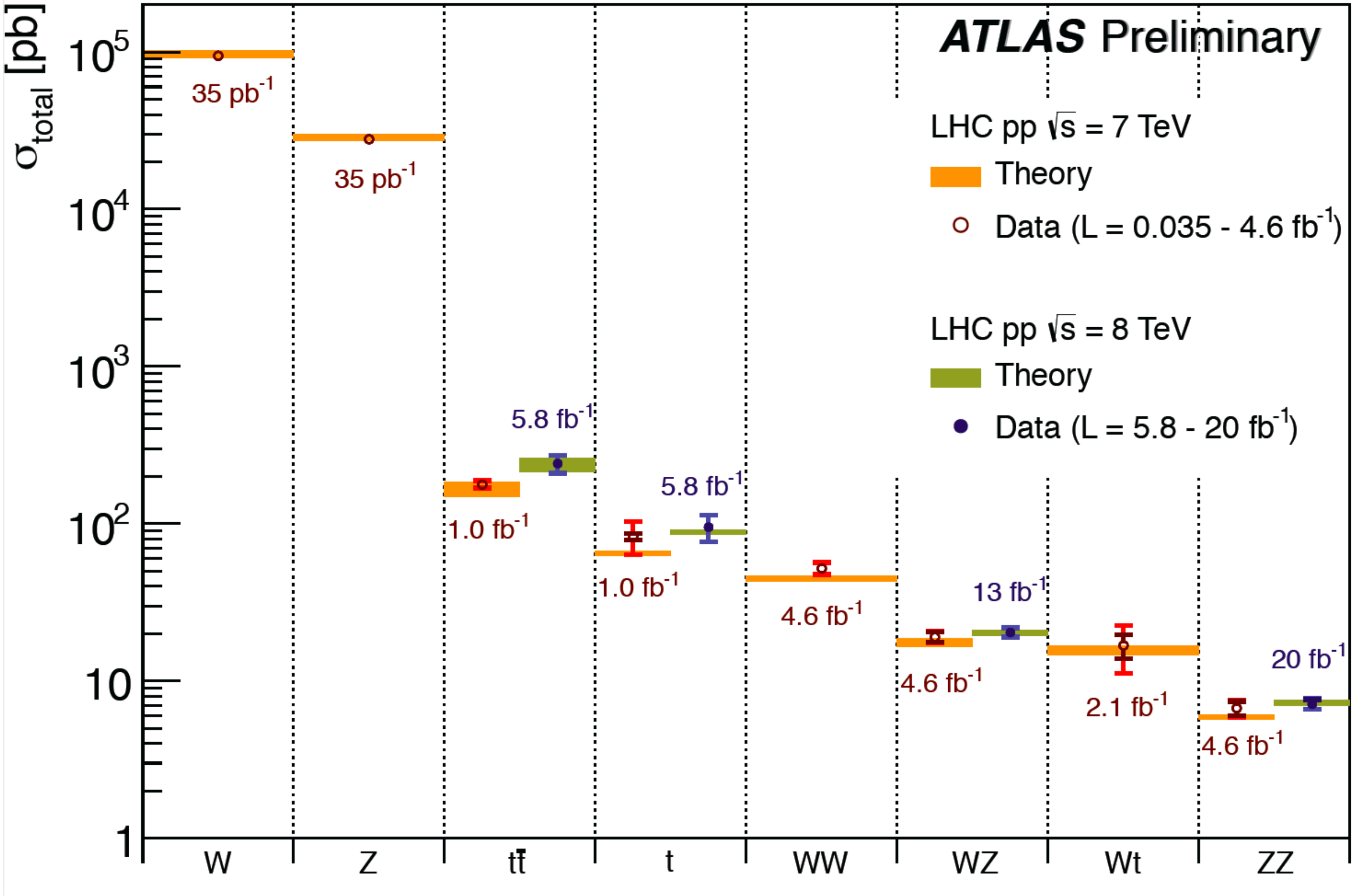
CMS PAS-TOP-12-028

ATLAS CONF 2012-155



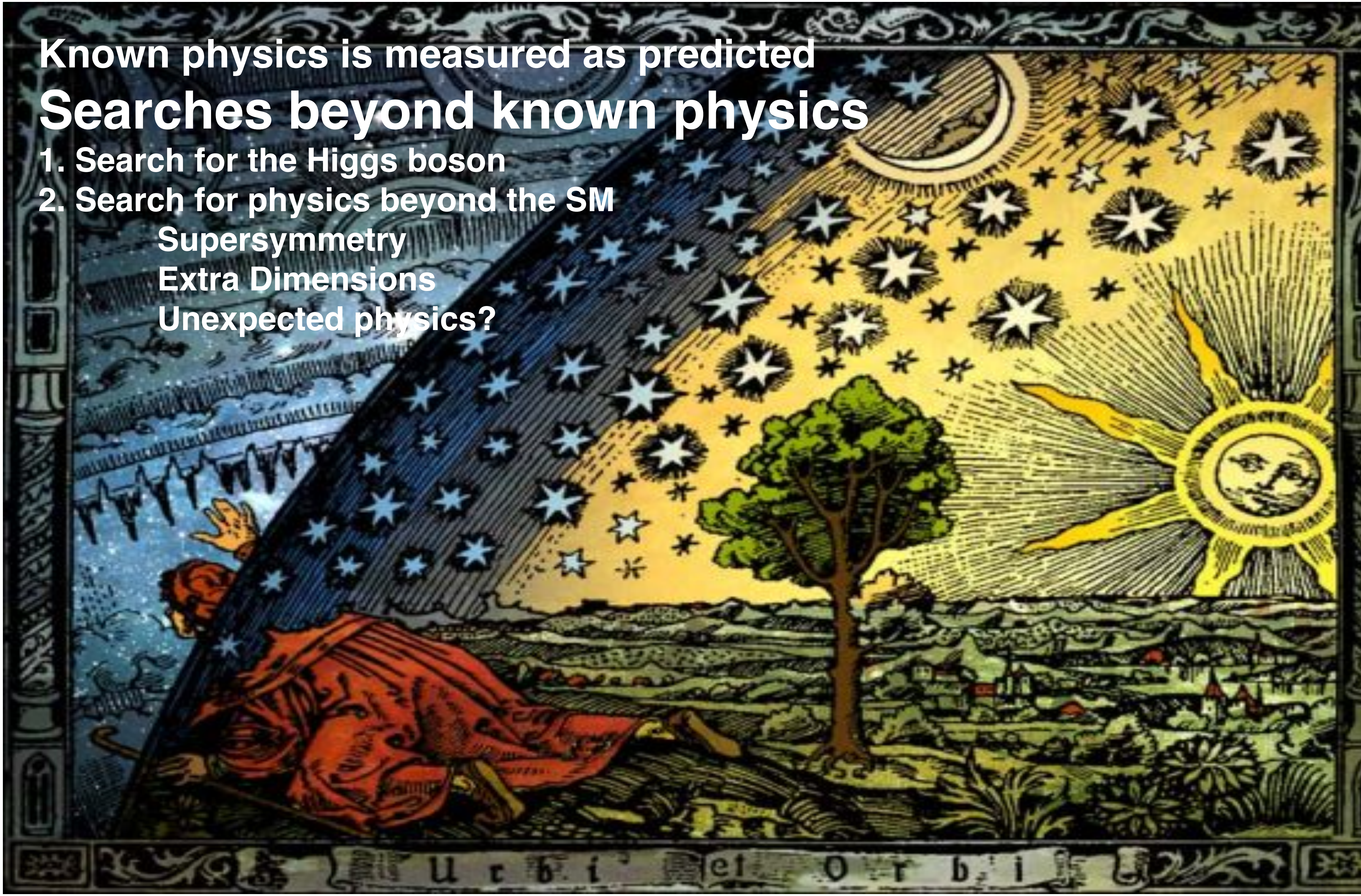
Summary: QCD, EWK and Top Physics

https://twiki.cern.ch/twiki/pub/AtlasPublic/CombinedSummaryPlots/SM_SummaryPlotMoriondEWK2013.pdf



Wide range of measurements have shown that **SM predictions for known physics have been essentially spot on.**

This is a tribute to a large amount of work done by our theory colleagues along with the results from the other collider experiments at LEP, Tevatron, HERA, b-factories etc.

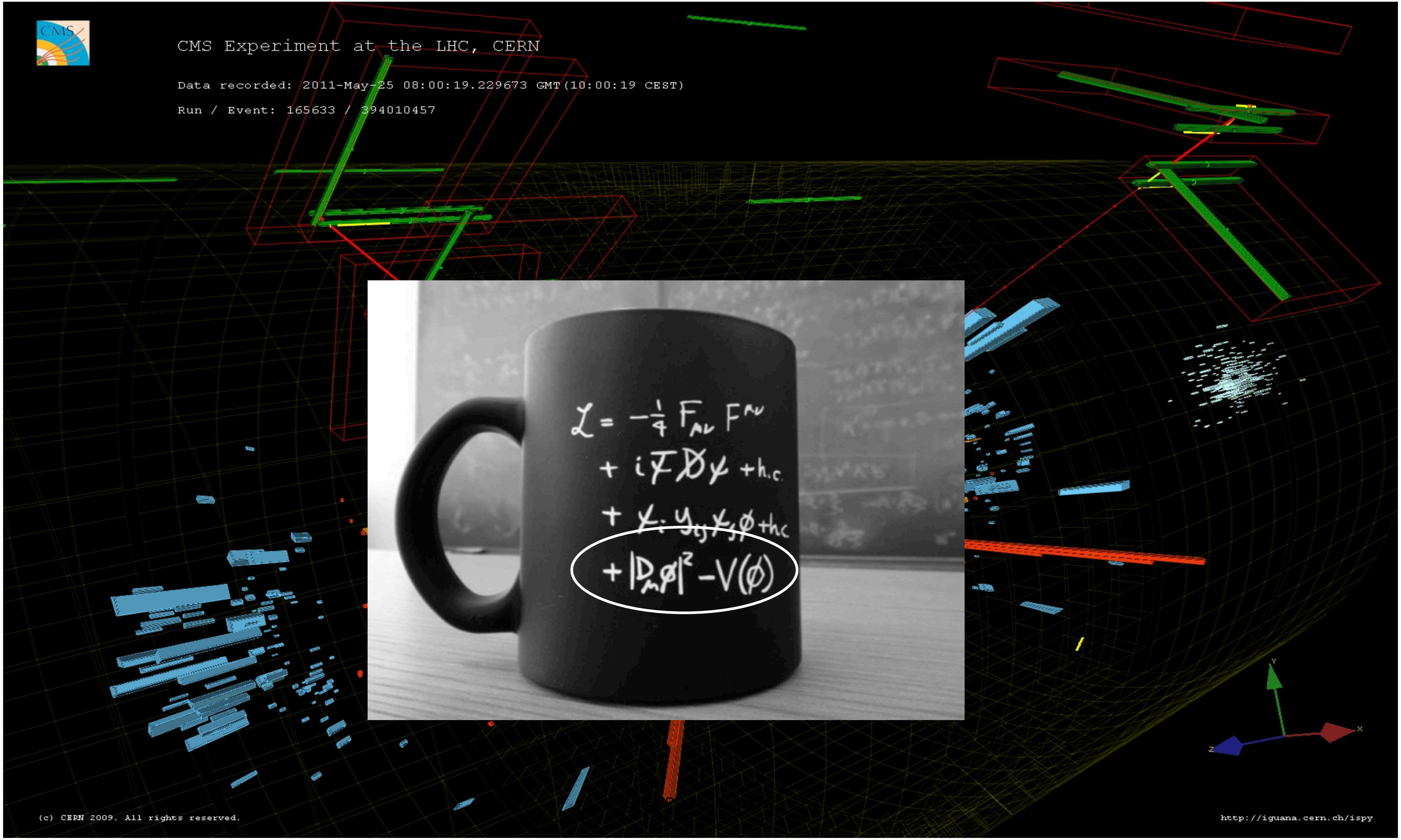


Known physics is measured as predicted

Searches beyond known physics

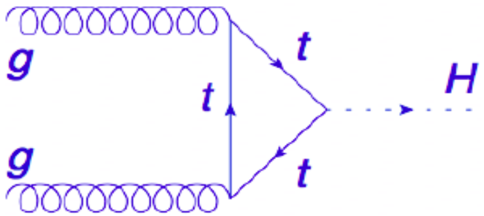
1. Search for the Higgs boson
2. Search for physics beyond the SM
    - Supersymmetry
    - Extra Dimensions
    - Unexpected physics?

Search for the Higgs Boson



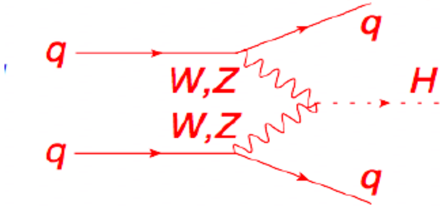
SM Higgs Boson: Production Cross-section

gluon fusion



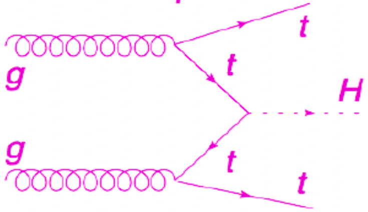
Main production via a quantum loop!

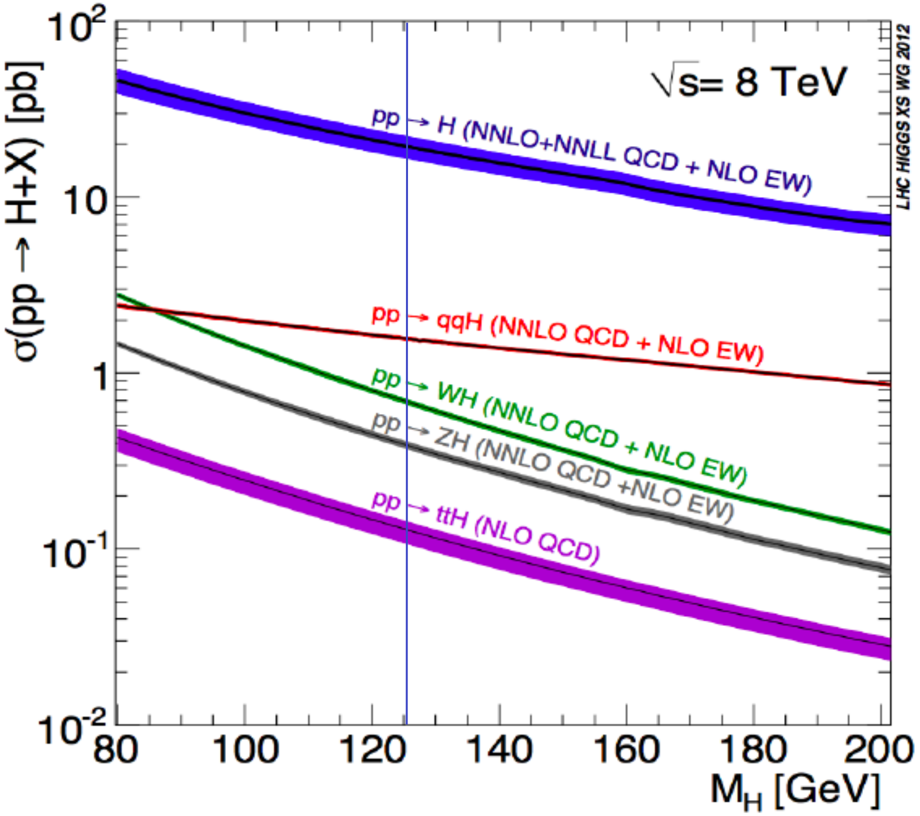
vector boson fusion (VBF)



associated prod. with W/Z

associated prod. with tt





Integrated Luminosity

~5 fb^{-1} at √s=7TeV and ~ 20fb^{-1} at √s=8TeV

2000 trillion pp collisions examined

And potentially produced

~ 700k SM Higgs bosons (m_H=125 GeV)

SM Higgs Boson: Decay Modes

- Natural Width: Γ_{H_125} ~ few MeV
- The best instrumental mass resolution achievable is ~1GeV
- Only two channels have such a resolution

$$H \rightarrow ZZ \rightarrow 4l,\ H \rightarrow \gamma\gamma$$

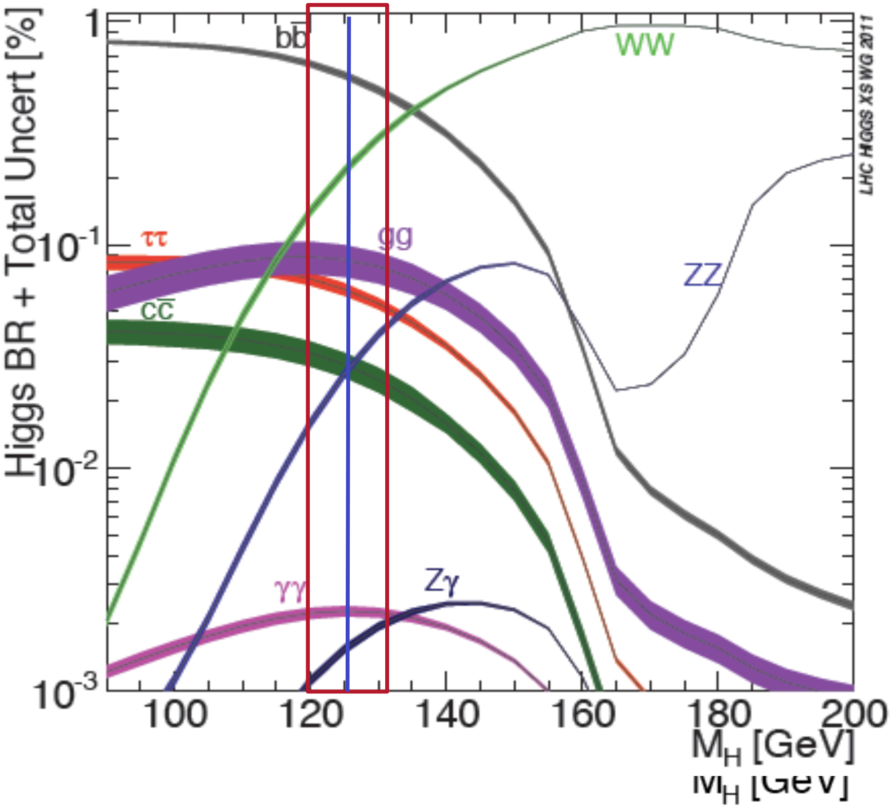
- with decay Branching Fractions:

  $\gamma\gamma$ is 2 per mille

  $ZZ \rightarrow 4l$ is ~10^{-4}

m_H= 125	BF(%)	Exp Sig	σ_M/M
bb	58	2.2σ	10%
$\tau\tau$	6.5	2.6σ	10%
WW	21.5	5.3σ	20%
ZZ	2.5	7.1σ	1-2%
$\gamma\gamma$	0.2	3.9σ	1-2%

decay branching fraction

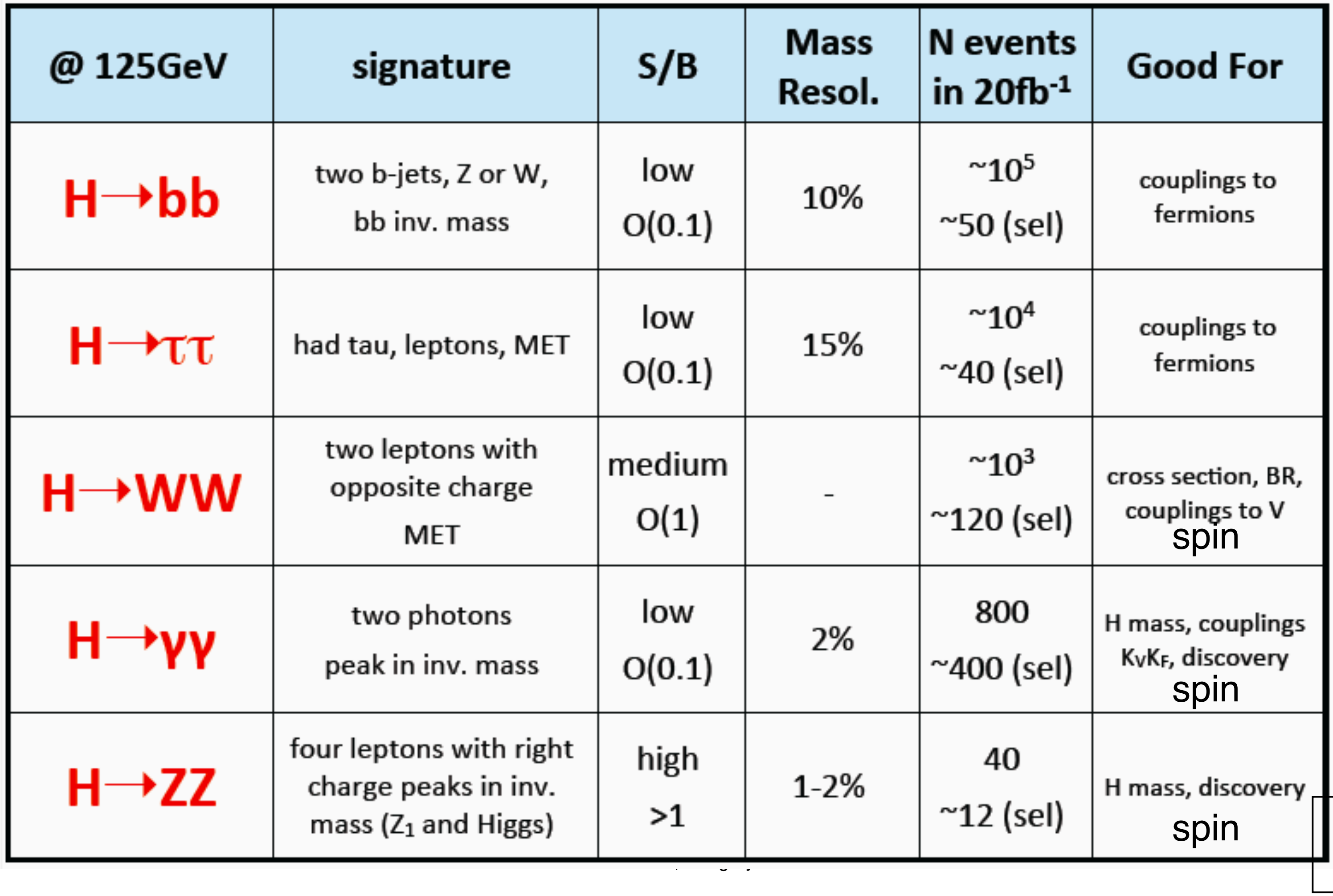


At m_H ~125 GeV many decay modes are detectable

Makes it easier to establish whether it is a SM Higgs boson or not

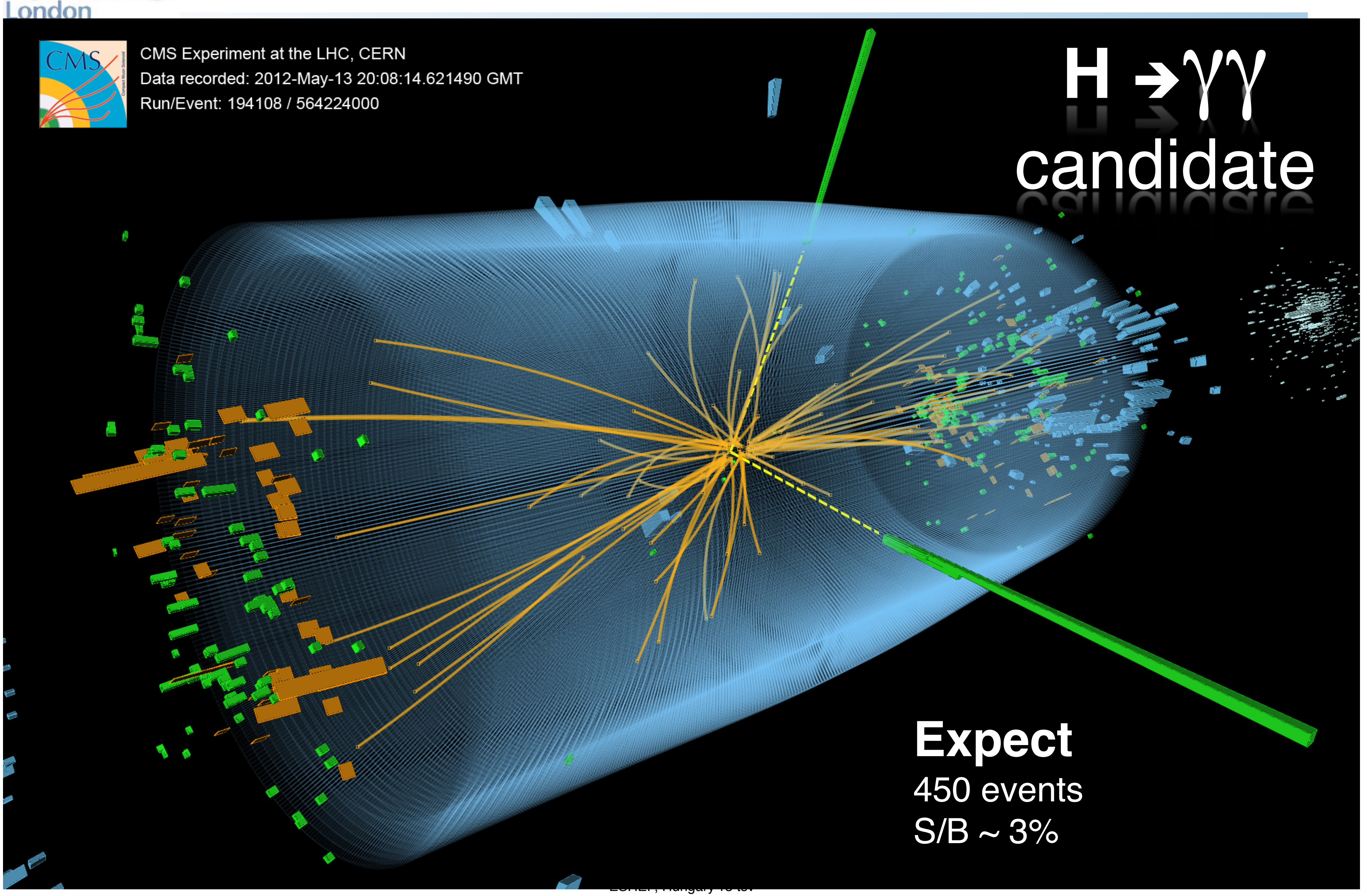
The Search for the Standard Model Higgs Boson

- **Analysis performed in many distinct channels**
- **Low-mass region: H→ γγ, H→ ZZ* → 4l, H→ WW* → lνlν, H → ττ, H → bb**
- **All results based on the full dataset recorded in 2011 and 2012**



@ 125GeV	signature	S/B	Mass Resol.	N events in 20fb^{-1}	Good For
H→bb	two b-jets, Z or W, bb inv. mass	low O(0.1)	10%	~10^5 ~50 (sel)	couplings to fermions
H→ττ	had tau, leptons, MET	low O(0.1)	15%	~10^4 ~40 (sel)	couplings to fermions
H→WW	two leptons with opposite charge MET	medium O(1)	-	~10^3 ~120 (sel)	cross section, BR, couplings to V spin
H→γγ	two photons peak in inv. mass	low O(0.1)	2%	800 ~400 (sel)	H mass, couplings $K_V K_F$, discovery spin
H→ZZ	four leptons with right charge peaks in inv. mass (Z_1 and Higgs)	high >1	1-2%	40 ~12 (sel)	H mass, discovery spin

H →γγ candidate



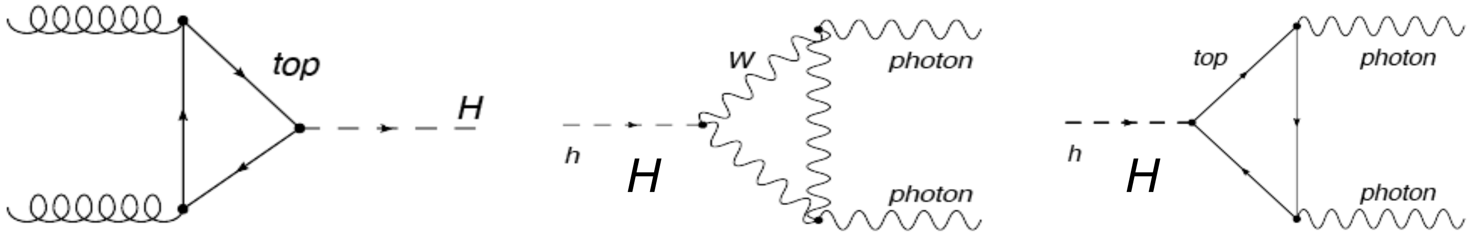
Expect

450 events

S/B ~ 3%

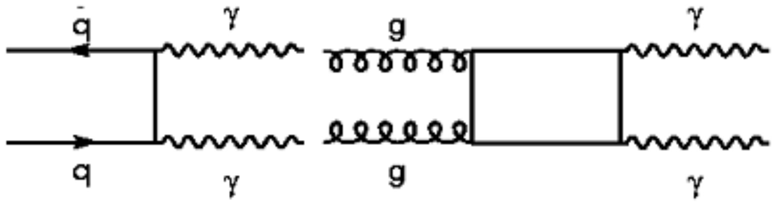
Search for the SM Higgs boson in the γγ channel

Signal:

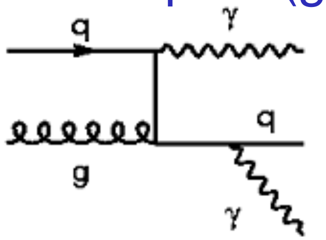


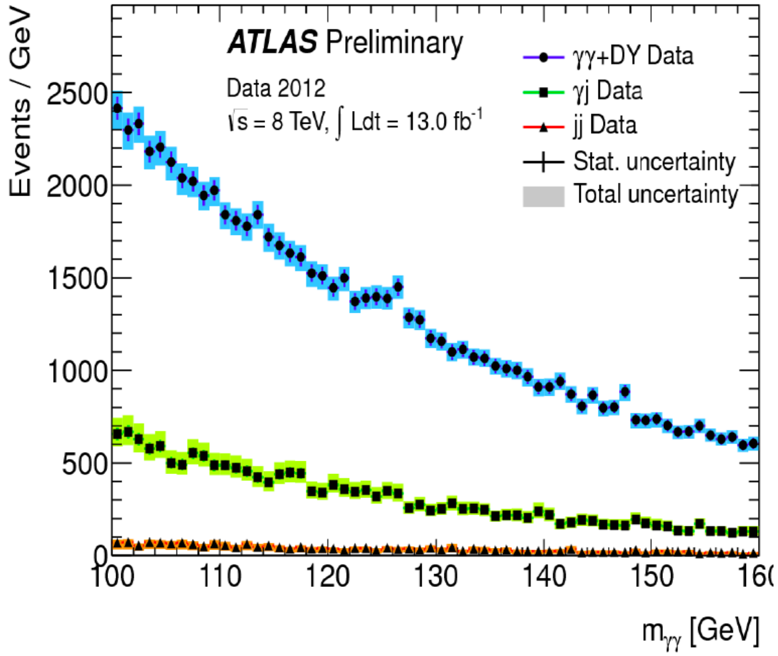
Background: essentially from QCD processes

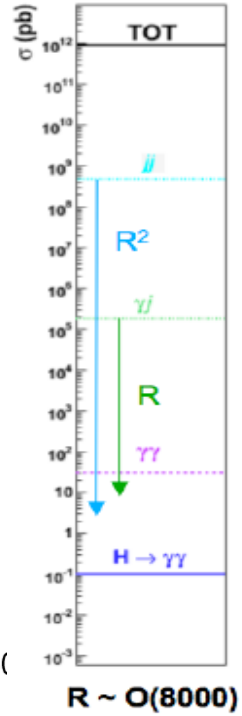
Irreducible: QCD processes



Reducible: Compton (gq→γq, q(jet)→γ)





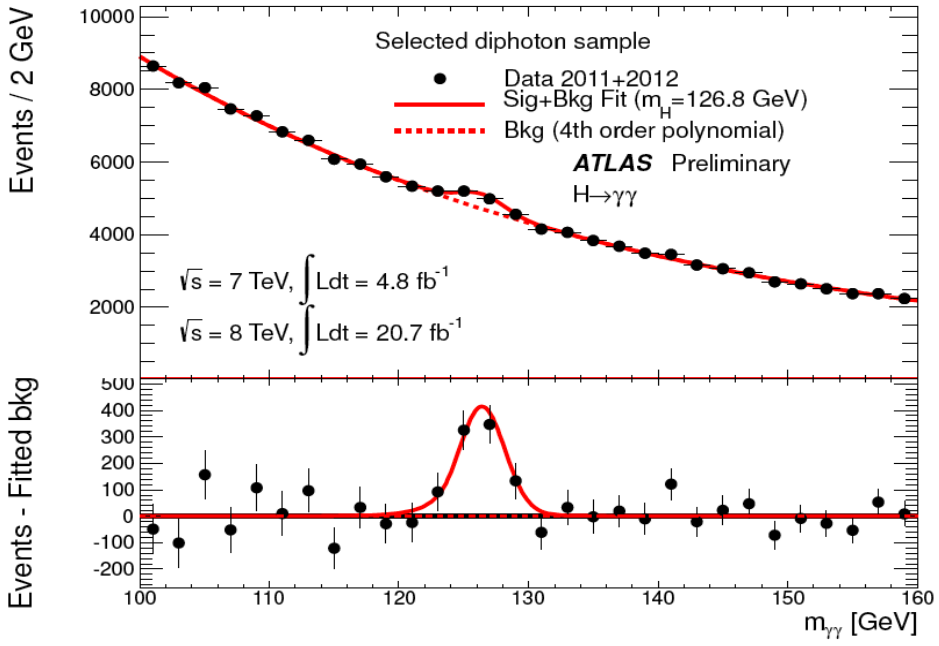


R ~ O(8000)

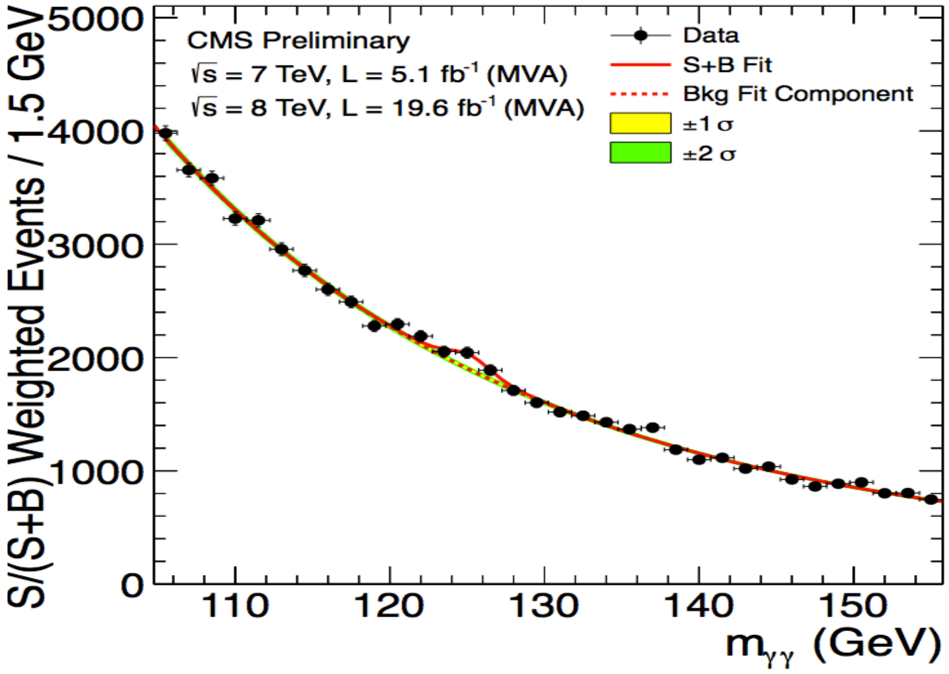
Preliminary Results from the Full Dataset

ATLAS: H→ 2γ Channel

CMS: H→ 2γ Channel



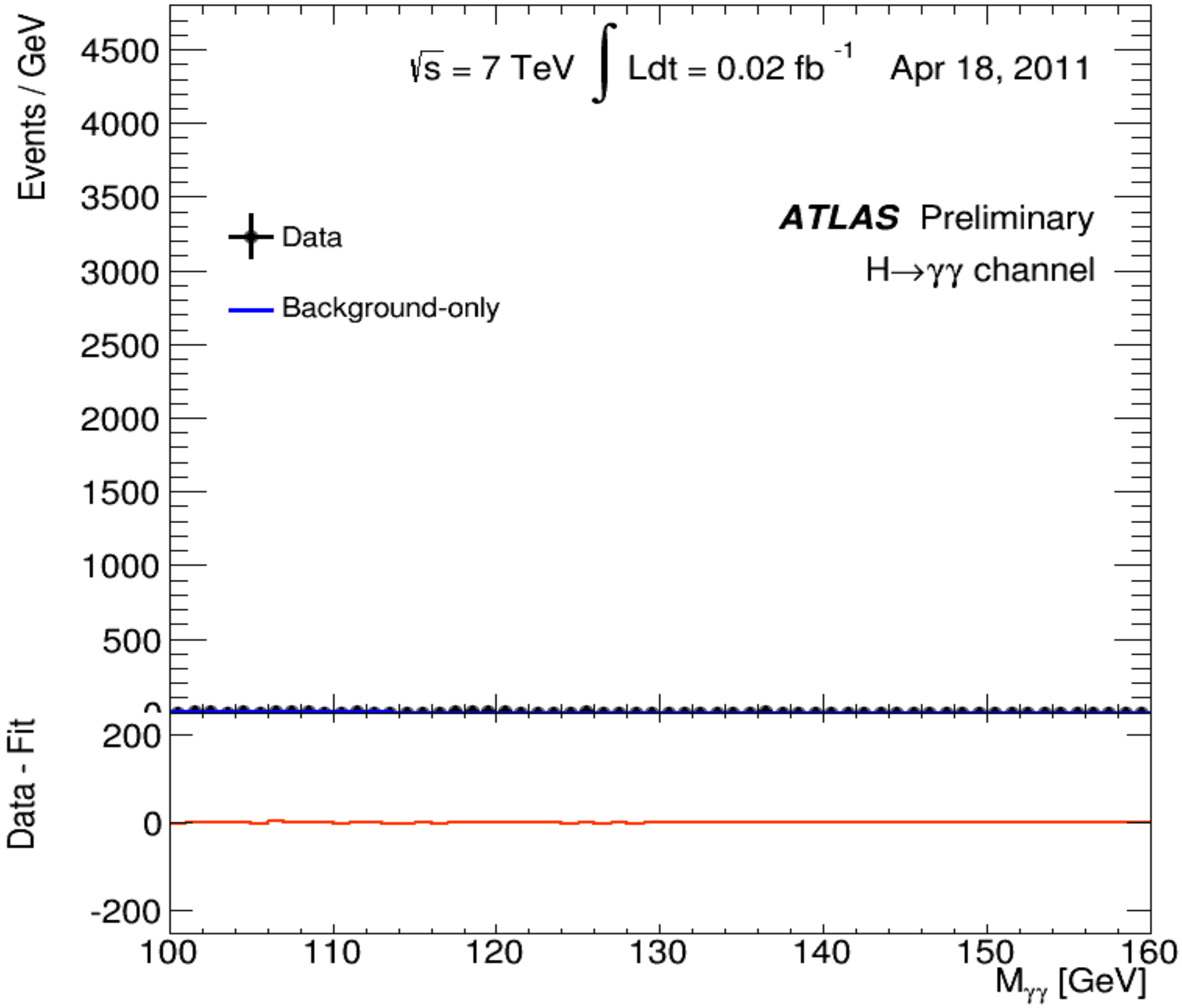
ATLAS CONF 2013-012



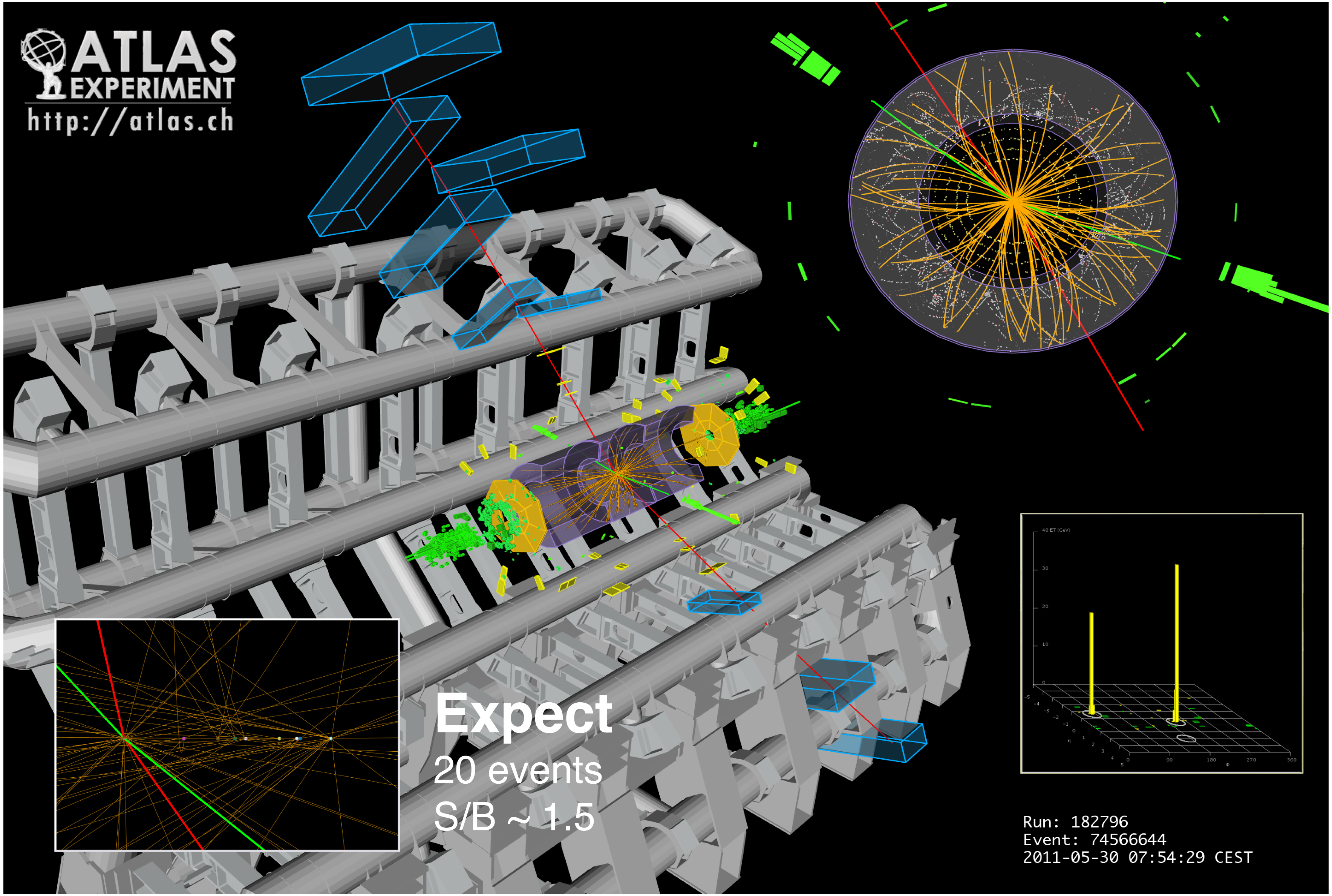
CMS PAS HIG-13-001

Sign/Exp	Exp	Obs
ATLAS	4.1 σ	7.1 σ
CMS	4.2 σ	3.2 σ

The Situation Now
ATLAS H→ 2γ Channel Full Dataset



$ZZ^{(*)} \rightarrow 2\mu 2e$ Channel



Expect

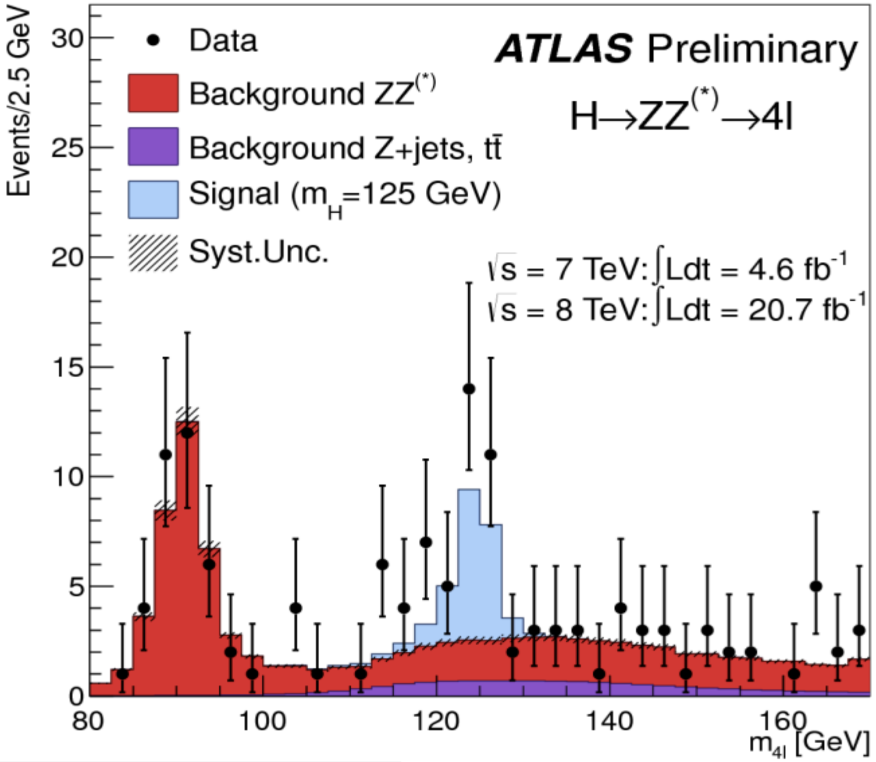
20 events

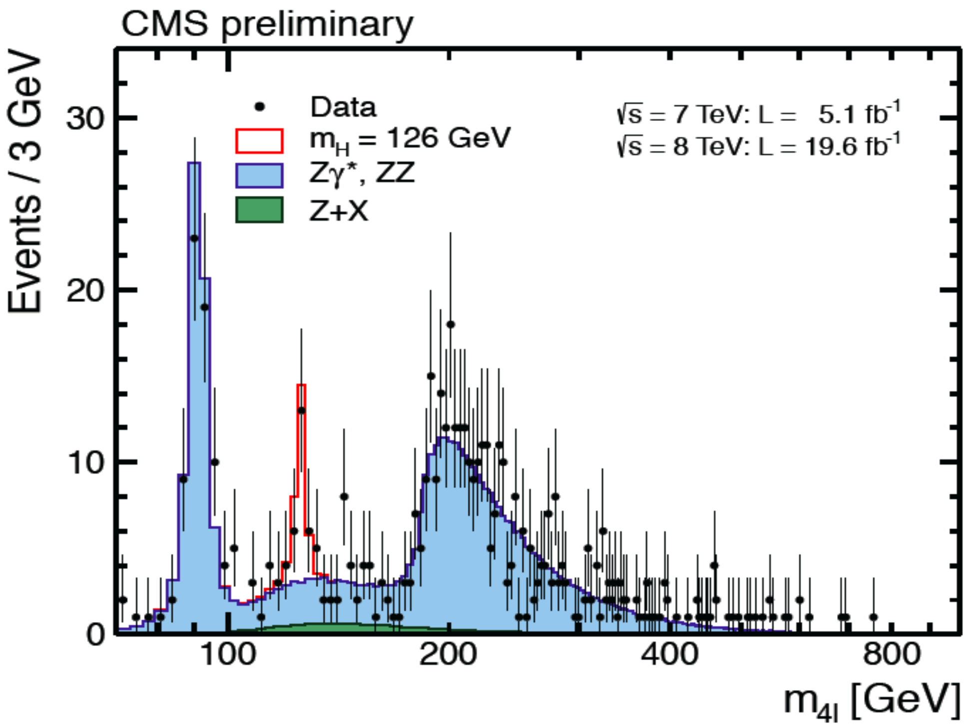
S/B ~ 1.5

Preliminary Results from the Full Dataset

ATLAS: H→ 4*l* Channel

CMS: H→ 4*l* Channel





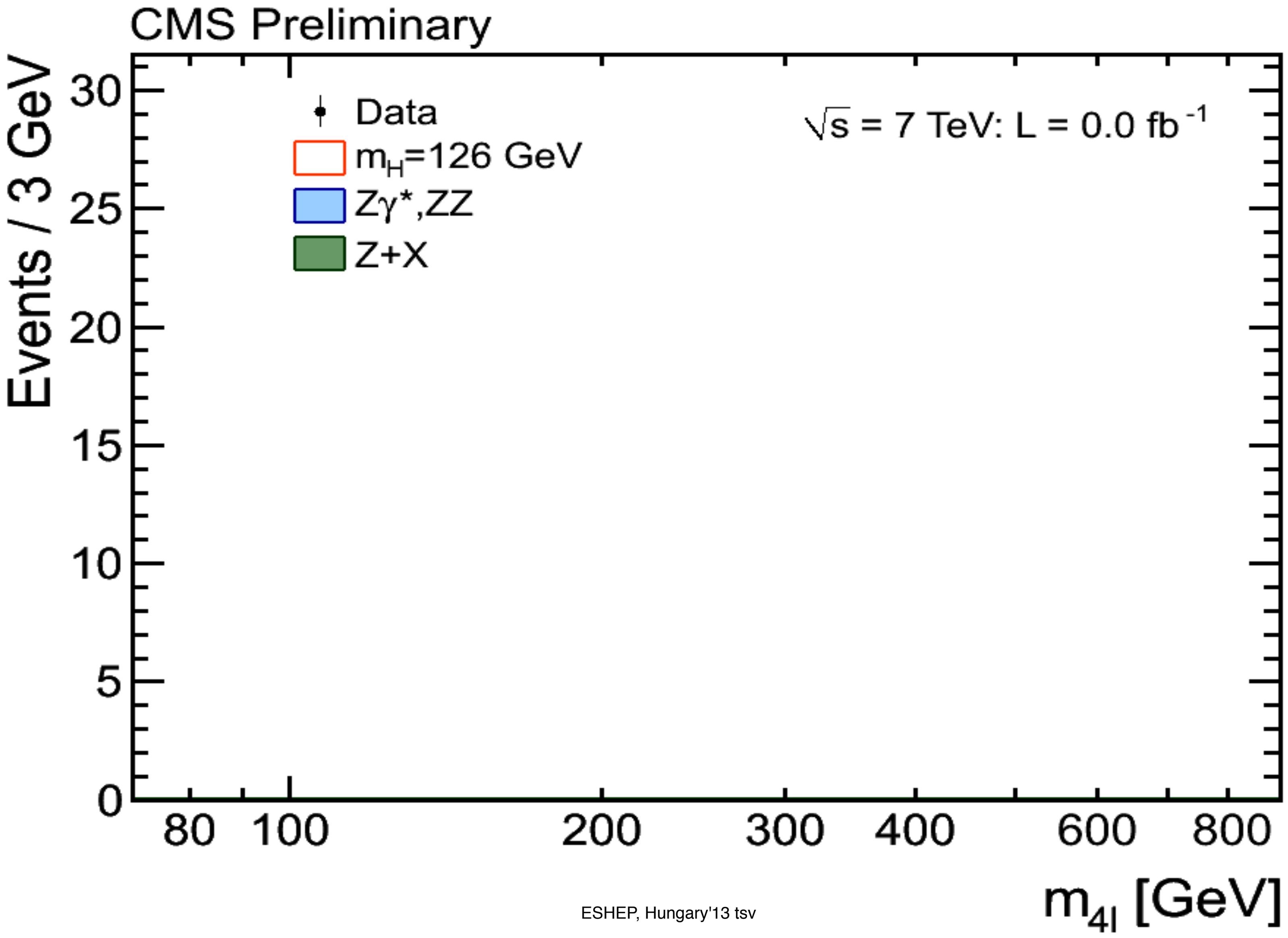
ATLAS CONF 2013-013

CMS PAS HIG-13-002

Significance	**Exp**	**Obs**
ATLAS	**4.4 σ**	**6.6 σ**
CMS	**6.7 σ**	**7.2 σ**

The Situation Now

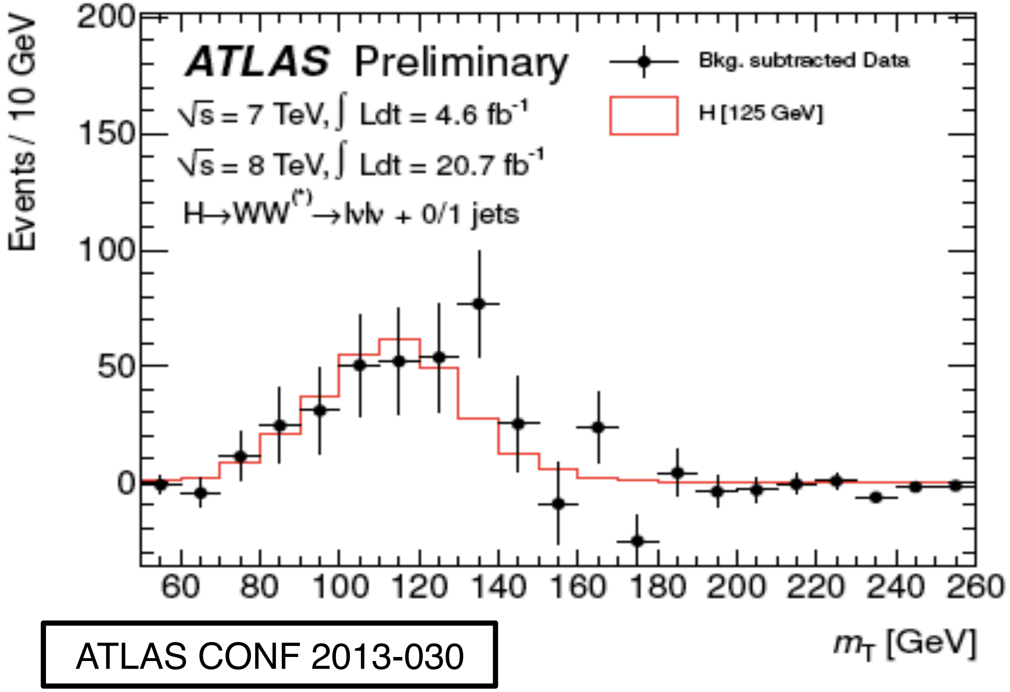
CMS H→ $ZZ^{(*)}$ → 4*l* Channel Full Dataset



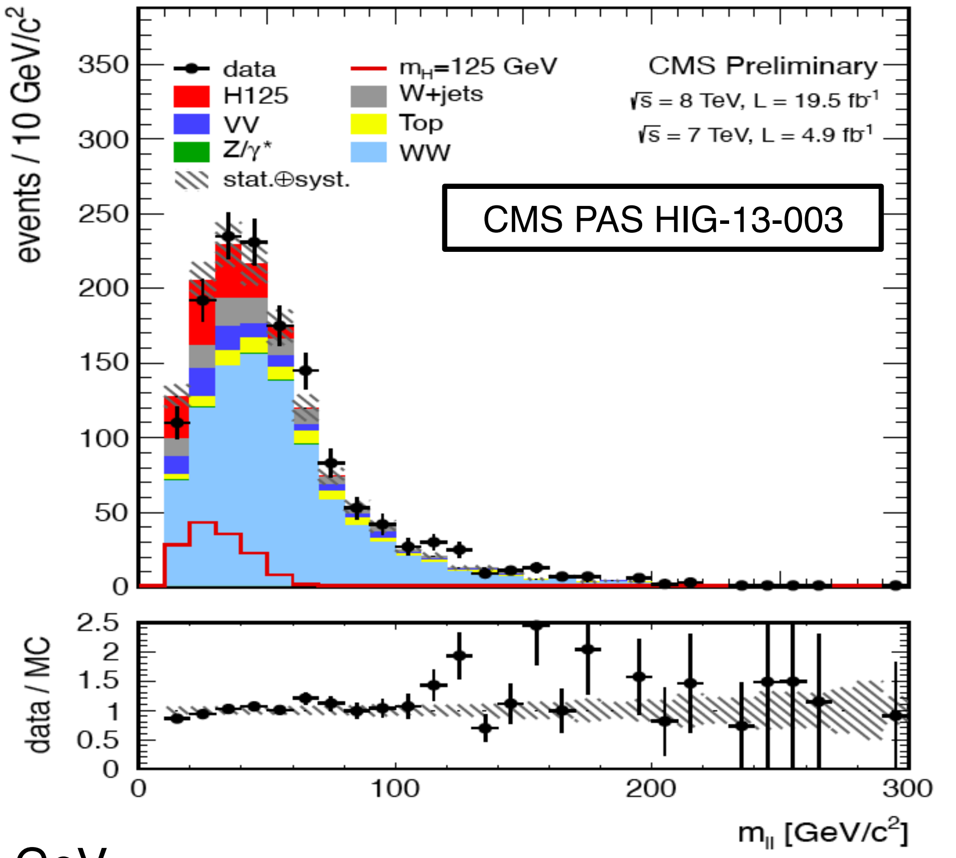
H → WW → 2l2ν channel

ATLAS: H→ WW→2*l* 2ν Channel Full Dataset

CMS: H→ WW→2*l* 2ν Channel Full Dataset



ATLAS CONF 2013-030

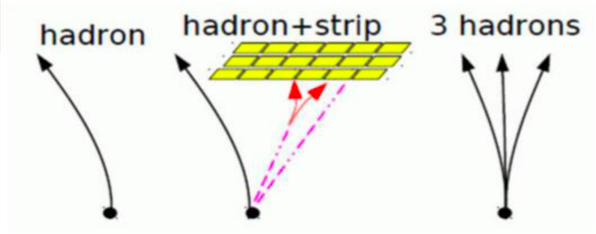


CMS PAS HIG-13-003

Sign/Exp	Exp	Obs
ATLAS$_{full}$	3.7 σ	3.8 σ
CMS$_{full}$	5.1 σ	4.0 σ

at 125 GeV

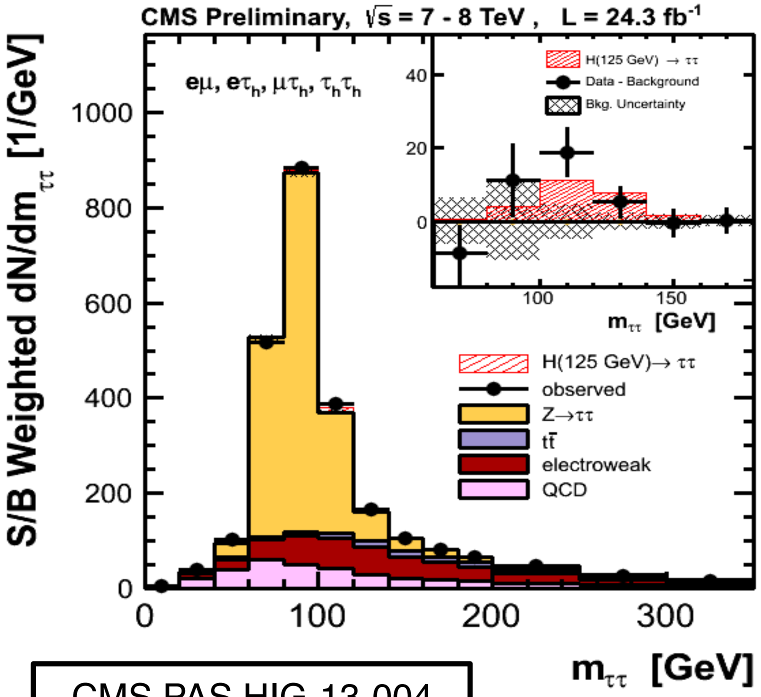
W/Z + H, H→$\tau\tau$
CMS Preliminary results from Full Dataset



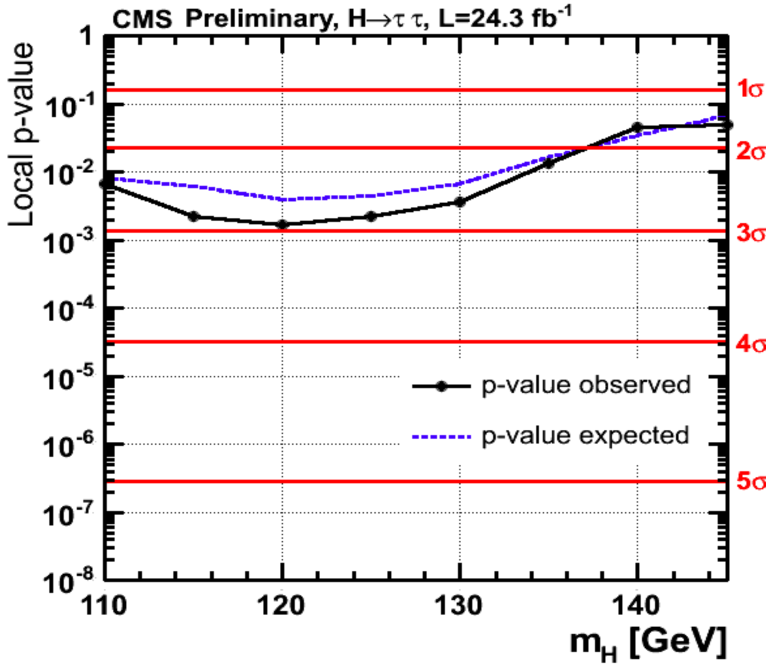
$e\tau_h$, $m\tau_h$, $e\mu$, $\tau_h\tau_h$

Signif.	Exp	Obs
CMS	2.6 σ	2.9 σ

at 125 GeV

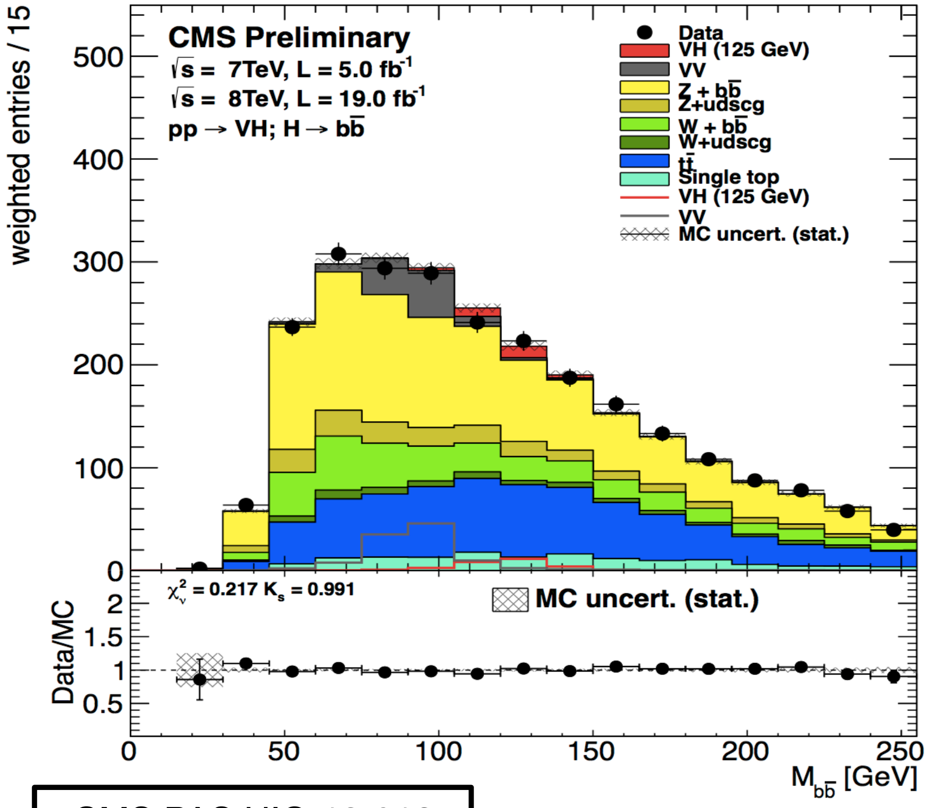


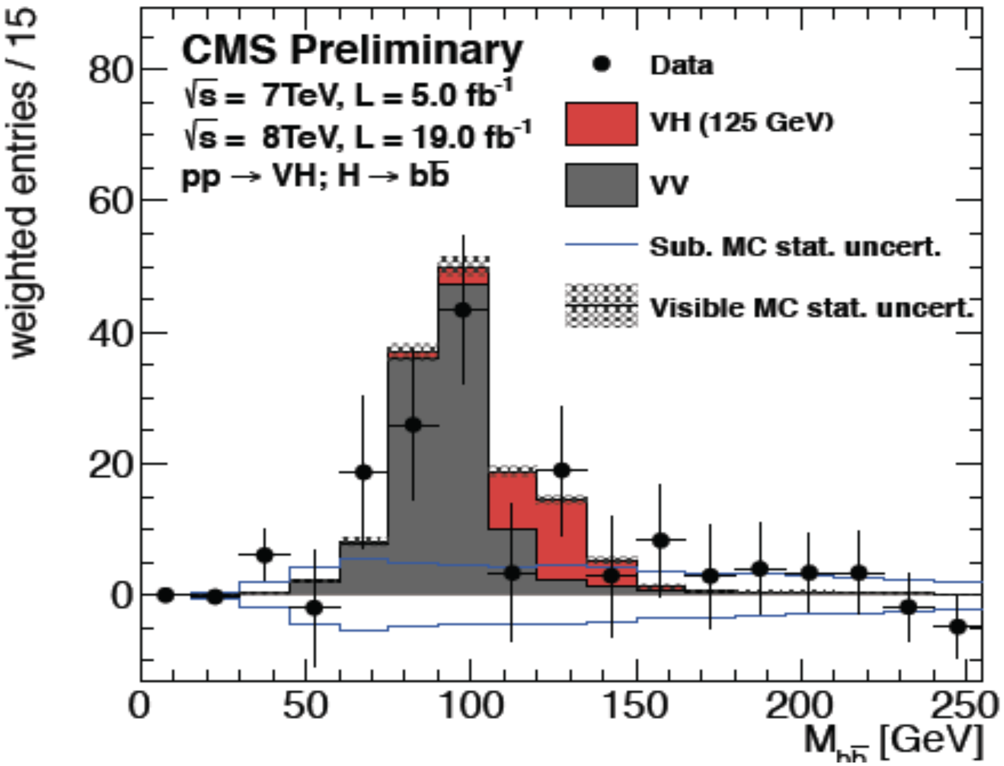
CMS PAS HIG-13-004



It decays to taus (and thus to fermions)

Search for SM VH (H → $b\bar{b}$): CMS Full Dataset





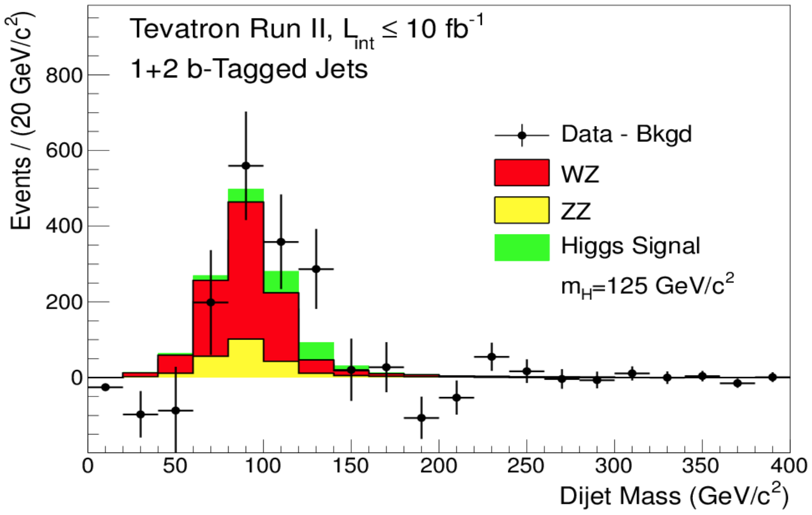
CMS PAS HIG-13-012

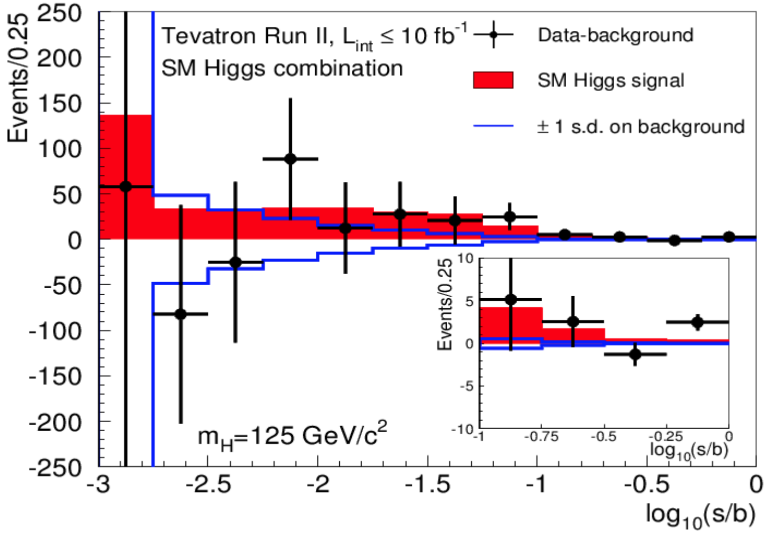
Significance	Exp	Obs
CMS	2.1 σ	2.1 σ

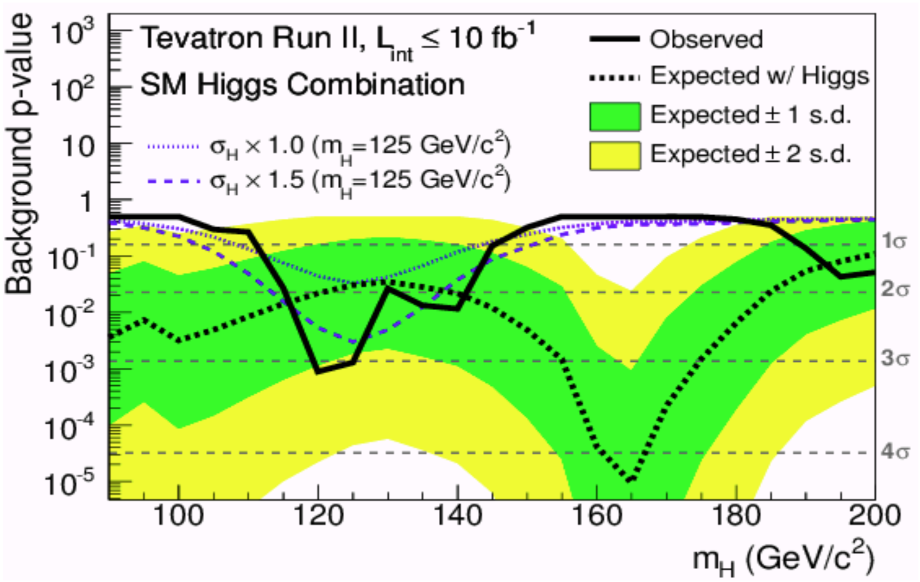
at 125 GeV

σ/σ_{SM} = 1.0±0.5

Search for SM VH ($H \rightarrow b\bar{b}$) (Tevatron)







Sign/Exp	Exp	Obs
Tevatron	2.1 σ	3.0 σ

at 125 GeV

$\sigma/\sigma_{SM} = 1.4 \pm 0.6$

Putting It All Together

Mass and Couplings

Signal strength and comparison to SM Higgs boson: $\mu = \sigma/\sigma_{SM}$

CMS : 0.80 ± 0.14

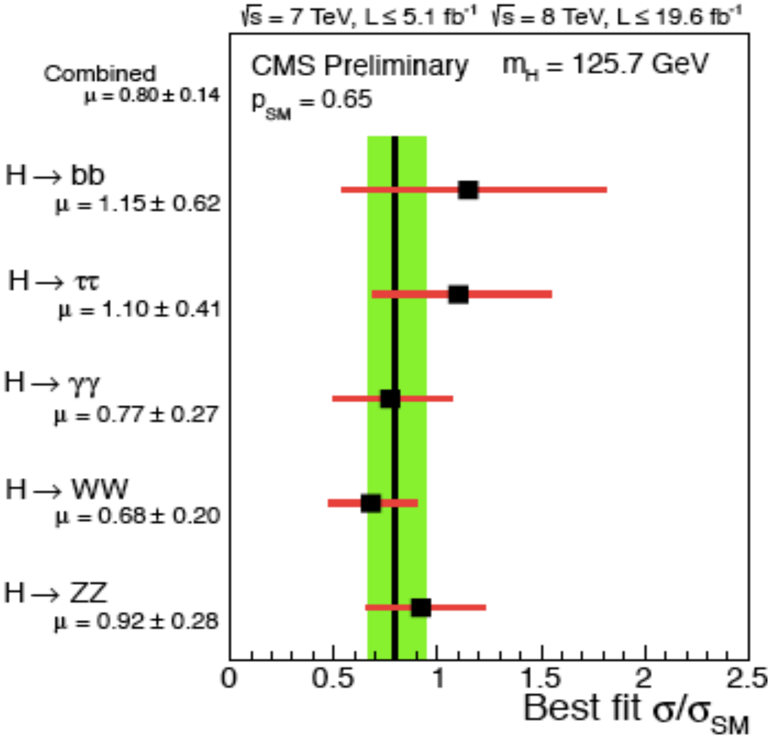
ATLAS: 1.30 ± 0.20

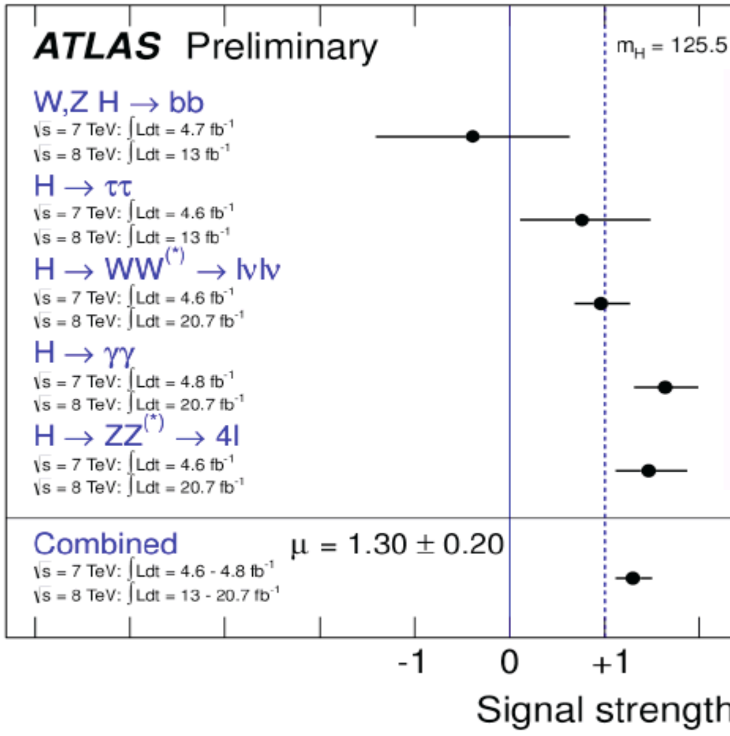
Tevatron
1.40 ± 0.60

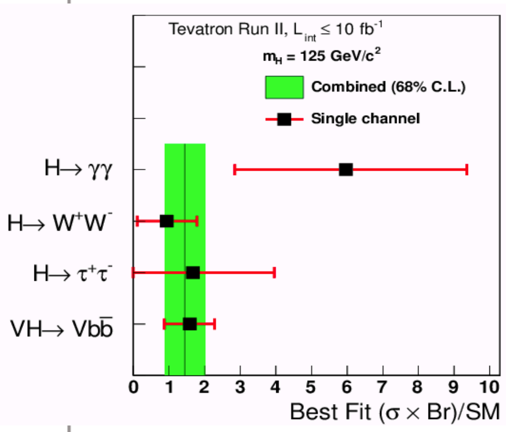
CMS PAS HIG-13-005

By Decay Mode

ATLAS-CONF-2013-014







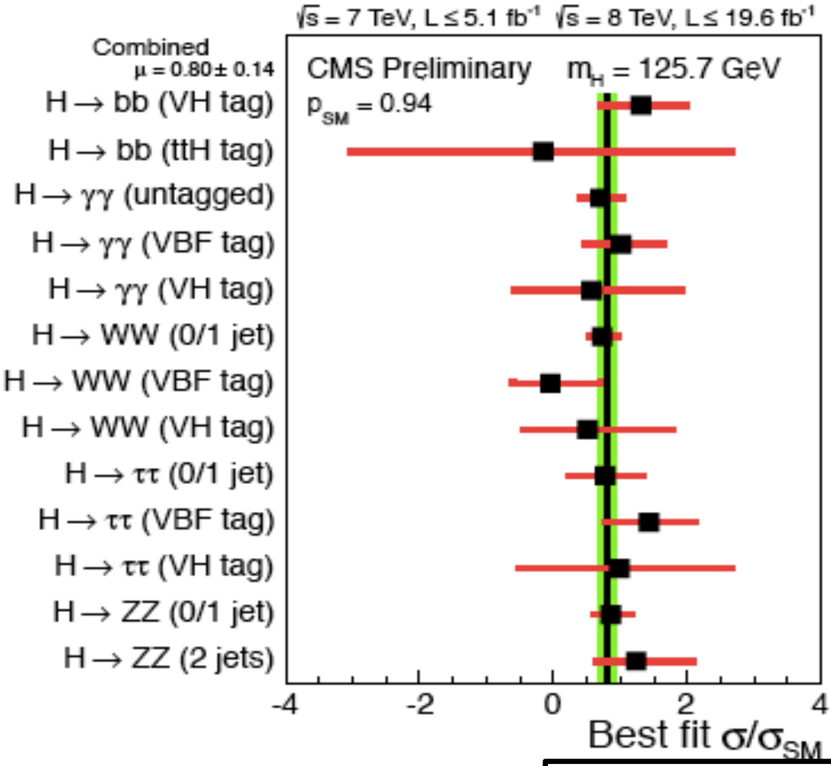
M_X = 125.7 ± 0.3 (stat)
± 0.3 (syst) GeV

M_X = 125.5 $^{+0.5}_{-0.6}$ (stat)
± 0.2 (syst) GeV

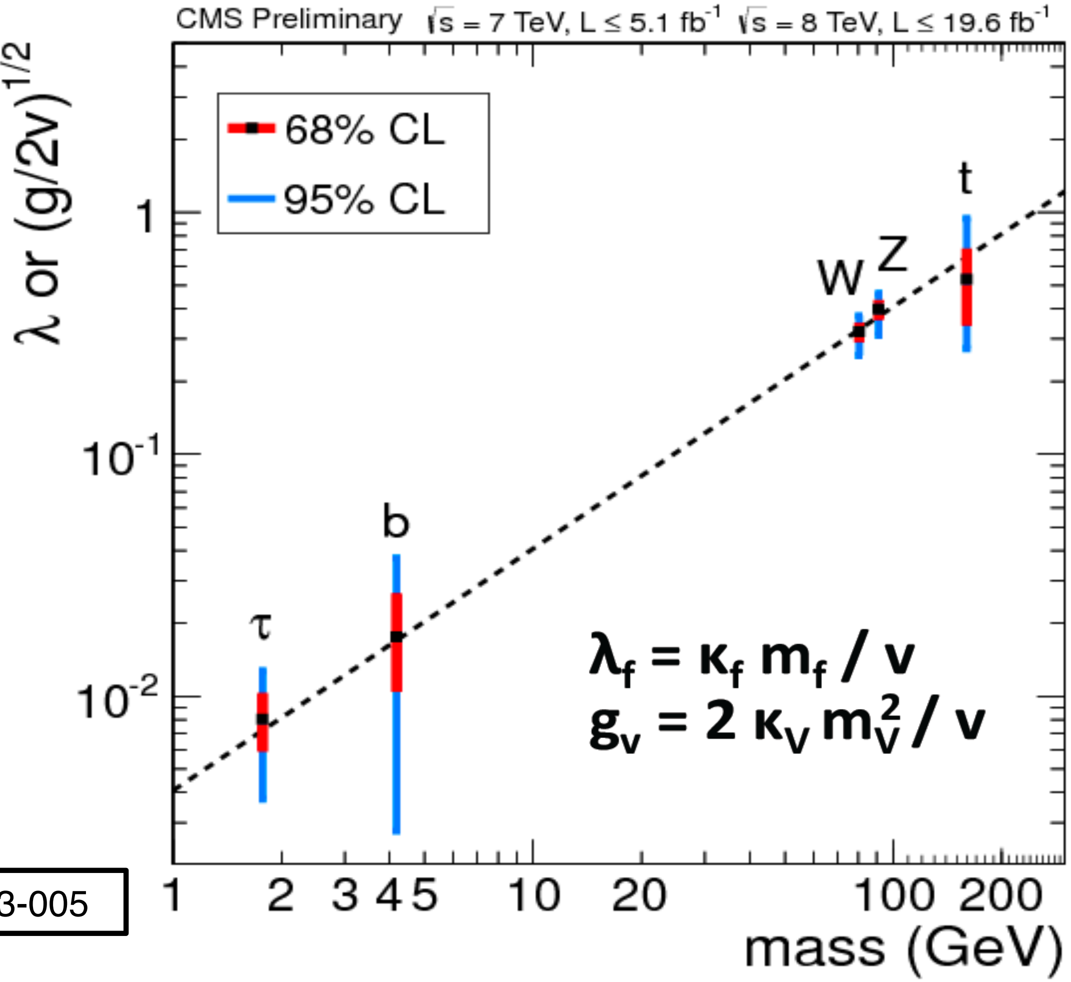
Imperial College London

Do Couplings Scale as Expected in the SM?

By Production and Decay Mode



CMS PAS HIG-13-005



$$\lambda_f = \kappa_f \, m_f / v$$

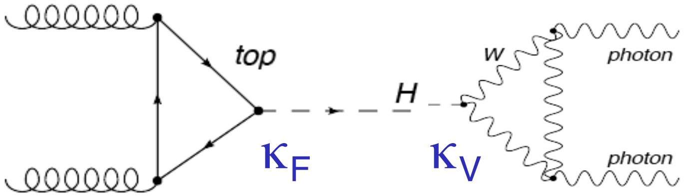
$$g_V = 2 \, \kappa_V \, m_V^2 / v$$

$\sigma.BR/(\sigma.BR)_{SM}$
is consistent with 1

Higgs couplings are proportional to masses

Properties of the New Boson: Couplings

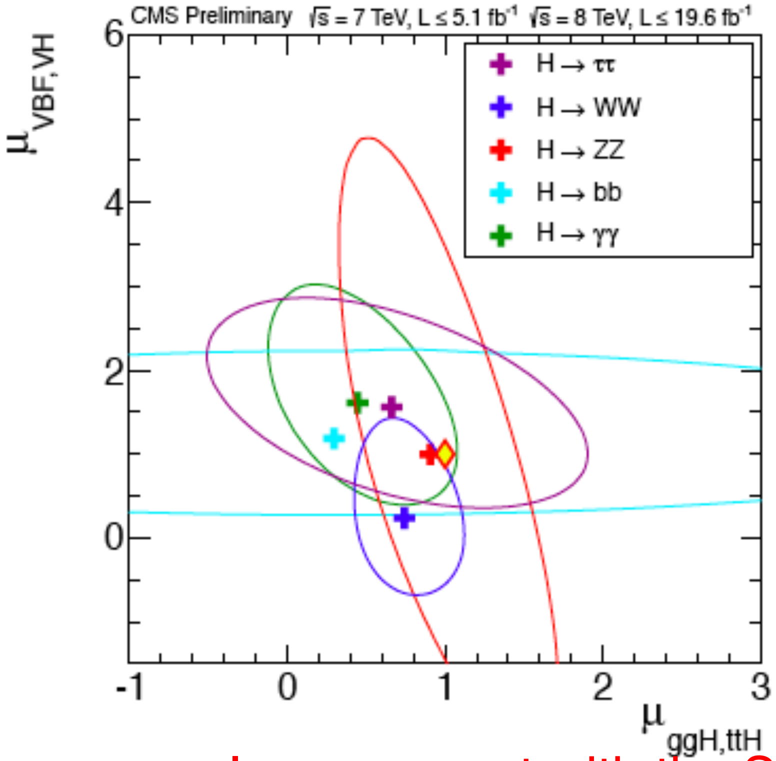
Group the Higgs couplings into "Vectorial" and "Fermionic" sets. Attach a modifier to the SM prediction to each of those (κ_V and κ_F): e.g.

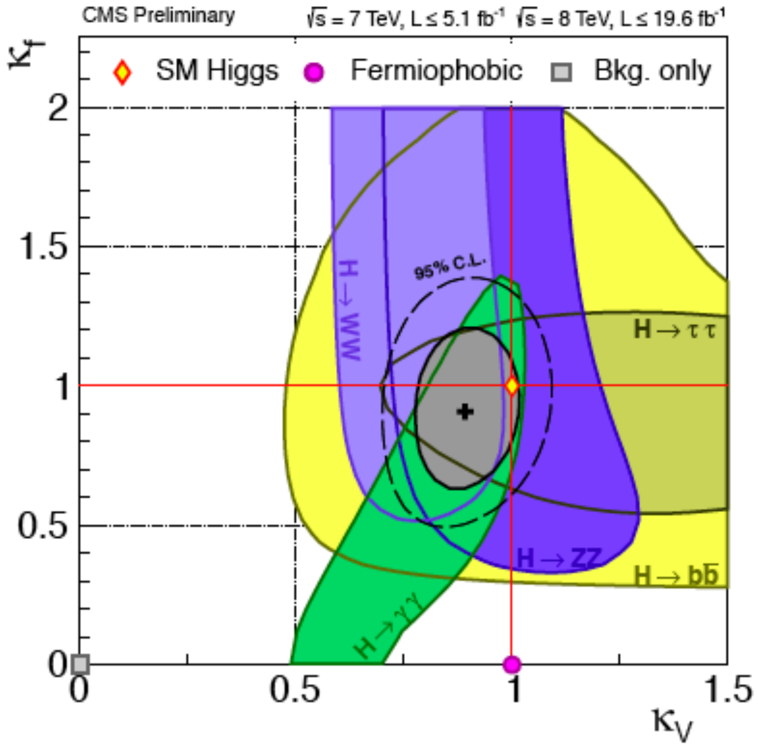


By production mechanism

CMS PAS HIG-13-005

By decay mode





In agreement with the SM within the 95% confidence range

Spin

Prediction for SM Higgs boson is $J^P = 0^+$

It decays into two photons so not spin-1 (Landau-Yang theorem)

Use angular distributions of the decay products in H rest frame
Construct BDT variables out of distinguishing information

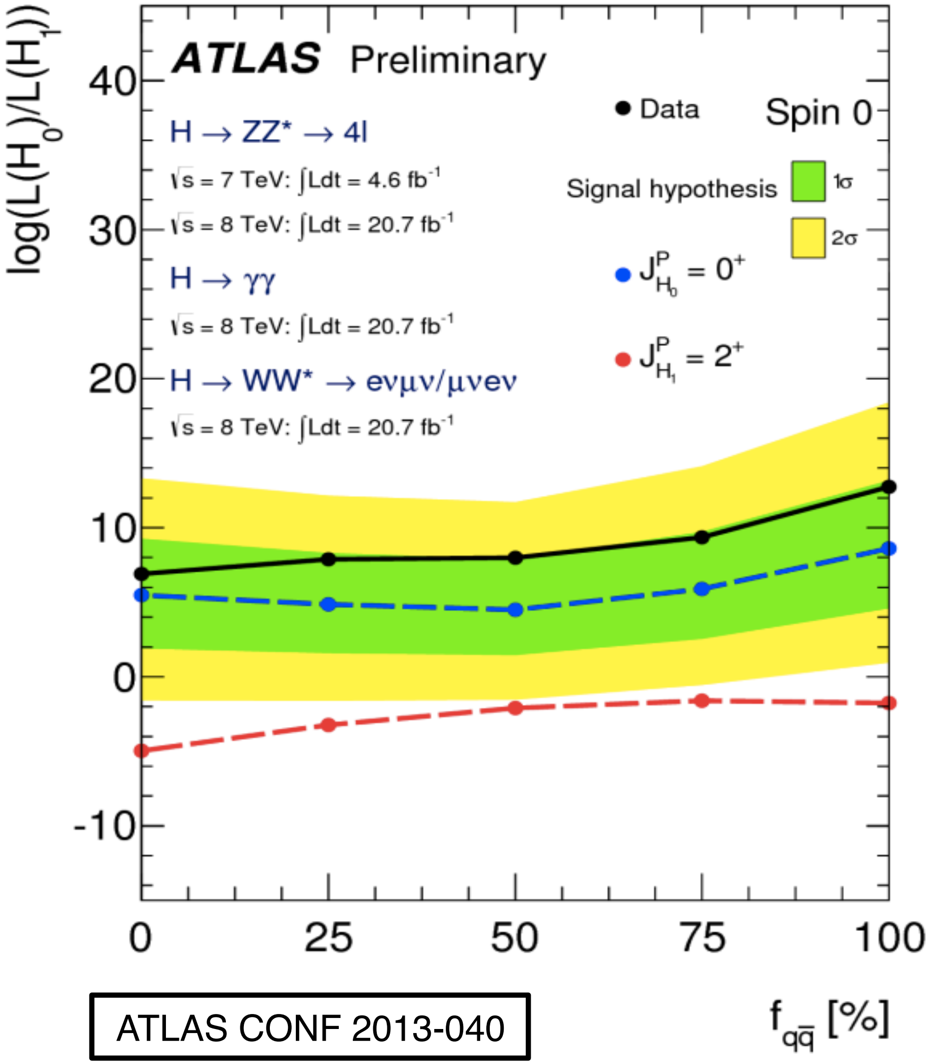
$H\rightarrow\gamma\gamma$, $H\rightarrow ZZ$ and $H\rightarrow WW$

$H\rightarrow ZZ$ used to test 0^- and 0^+ scenarios

Spin 2^+ hypothesis tested in all channels*

*Graviton inspired model - production mechanism is unknown so present results as fraction of qq to gg

ATLAS Summary: Spin



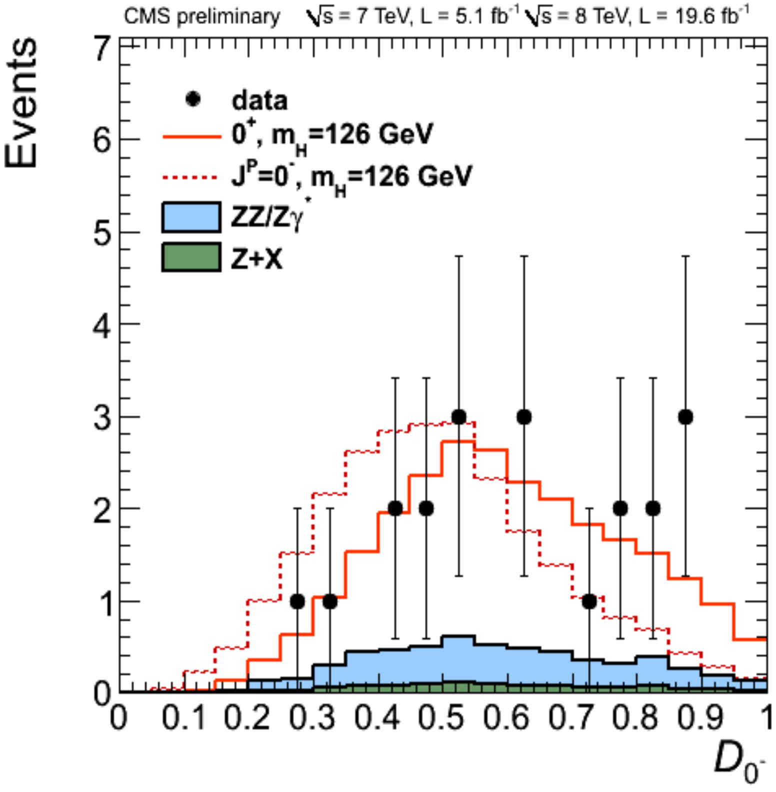
ATLAS CONF 2013-040

3 channels combined exclude 2_m^+ model at 99.9% CL, independent of production mode

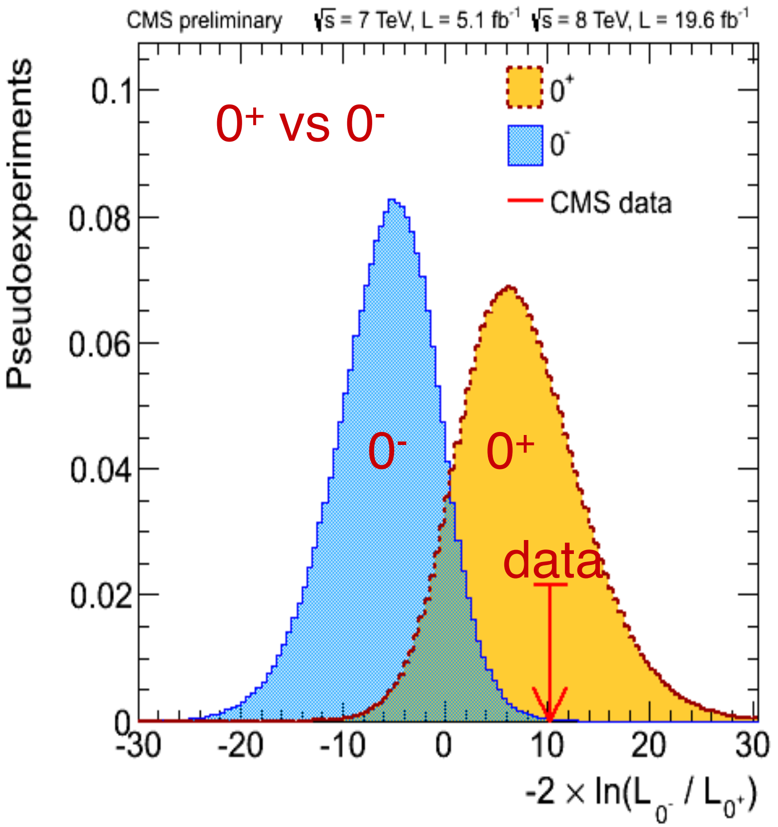
$H \rightarrow ZZ$ excludes 0^-, 1^+ and (1^-) at >95% (94%) CL.

CMS: H→ ZZ$^{(*)}$ → 4l: Spin 0$^+$ v/s 0$^-$

CMS data consistent with scalar (0$^+$)



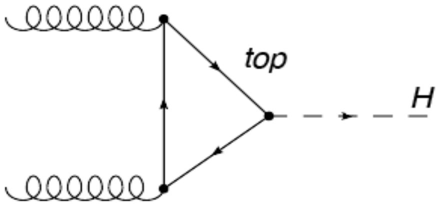
CMS PAS HIG-13-002



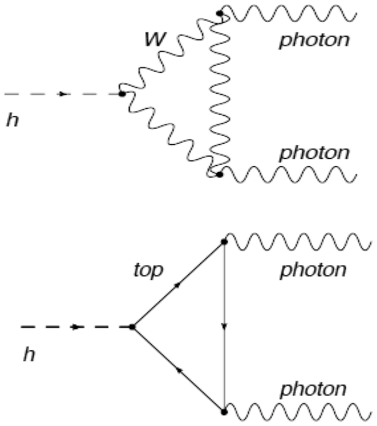
CL_s=0.16%

Influence of Undiscovered Heavy Charged Particles?

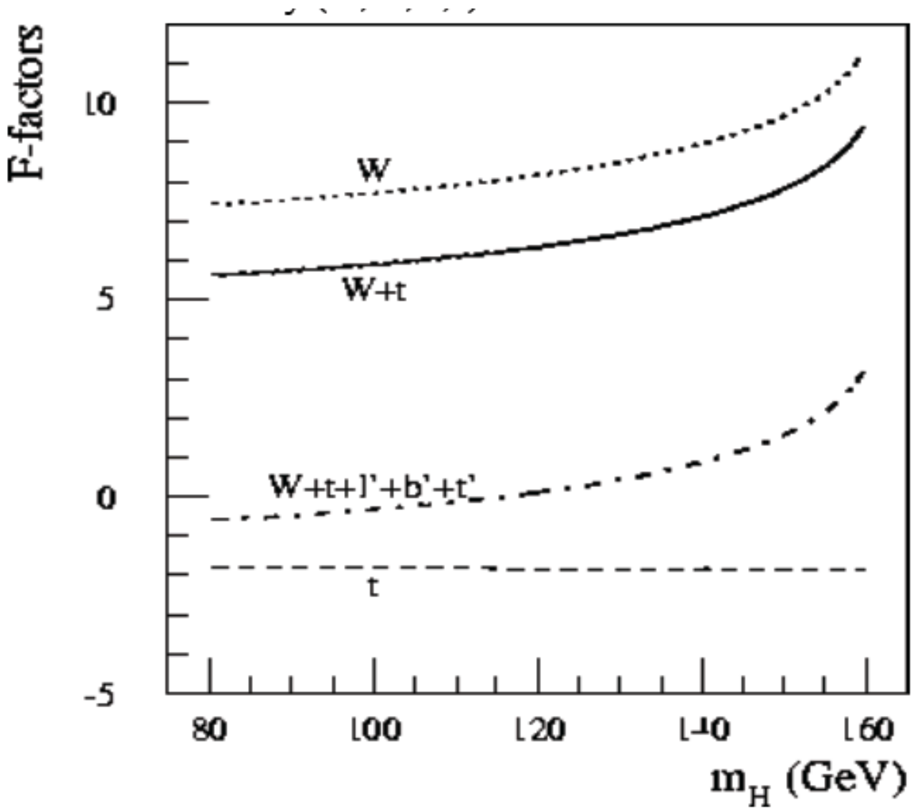
e.g. H → γγ



Dominant production mechanism



SM decay to 2γ



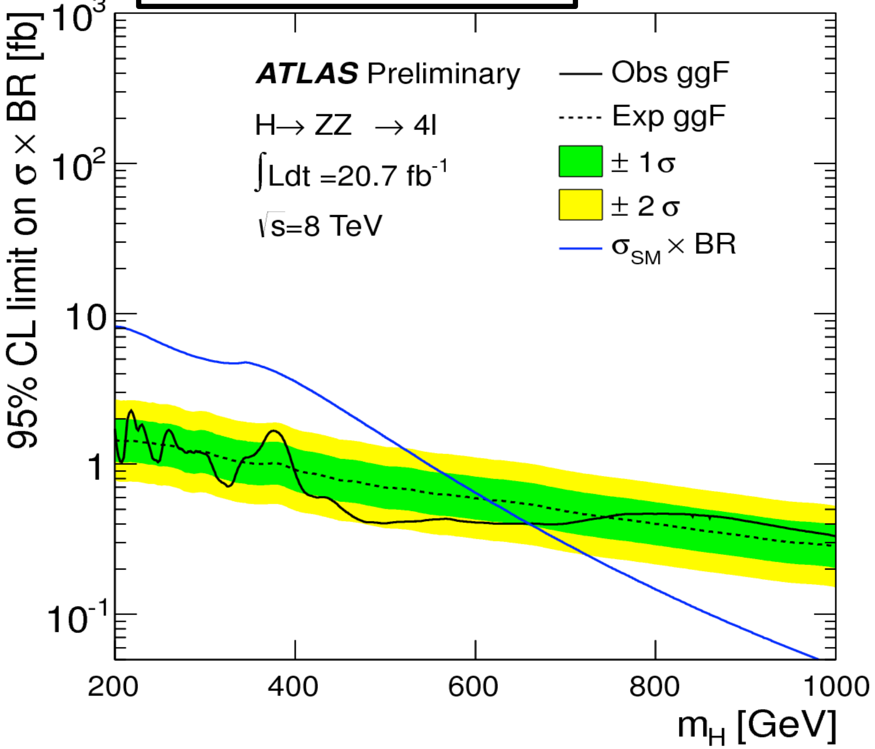
$$|M|^2 = \frac{g^2 m_H^4}{32\pi^2 m_W^2} \left| \sum_i \alpha N_c e_i^2 F_i \right|^2$$

Importance of H → γγ channel
A signal strength different from SM would indicate new physics

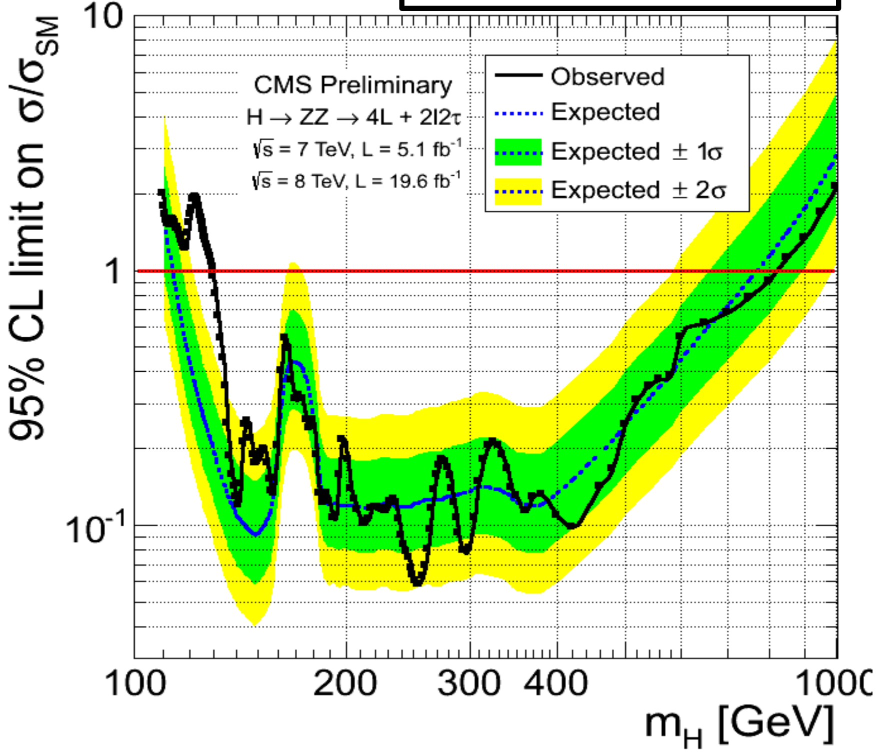
ATLAS: $\mu=1.65^{+0.34}_{-0.30}$ CMS: $\mu=0.78^{+0.28}_{-0.26}$

Any other Higgs bosons?

ATLAS-CONF-2013-013



CMS PAS HIG-12-034



σ × BR limit for an additional gluon-gluon fusion produced Higgs boson with SM-like width decaying to ZZ → 4l

H to ZZ → 4l
Exclude $M_H < 800$ GeV (95% CL)

What makes a SM Higgs boson?

Does it have spin 0 or 2? What is its parity (SM H → 0^+)

Data consistent with 0^+, excluding 0^- at >95% CL

Is it elementary or composite? (SM H is elementary)

No significant deviations from Standard Model

Couples to particle masses in proportion to their masses ($\sim M_f^2/v^2$, $\sim M_V^4/v^2$) ?

Clear evidence that it does

Couples to massless photon (gluons) trhrough loops of virtual charged/coloured particles (t, W,…)?

$\gamma\gamma$ coupling > Standard Model? Average appears consistent with SM.

What are its self-couplings? HL–LHC (>2025)

Is it alone? No evidence for another one but still looking

Is there any room for new physics?

We believe there must be new physics

Some real and some virtual reasons to believe in new physics

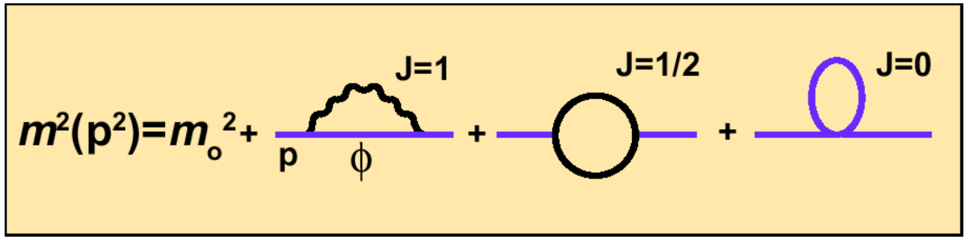
Real reasons: dark matter & ν masses
Virtual reasons: naturalness

P. Sphicas, Latsis Symposium 2013

How can the mass of Higgs boson be anything small?

It should “resist” itself (since it couples to mass, it should couple to itself as well)

Its mass should be almost infinite through quantum corrections.



$M_H^2 \rightarrow M_H^2$ (bare) + c Λ^2 (quadratic divergence in the mass!)

Λ is the scale of the underlying theory (could be $M_{GUT} \sim 10^{15}$ GeV !)

Requires incredibly unnatural fine tuning to keep M_H small !!

What can be done ?

L_{SSB} does not contain an elementary Higgs boson (now unlikely)

OR

Somehow cancel quadratic divergences

OR

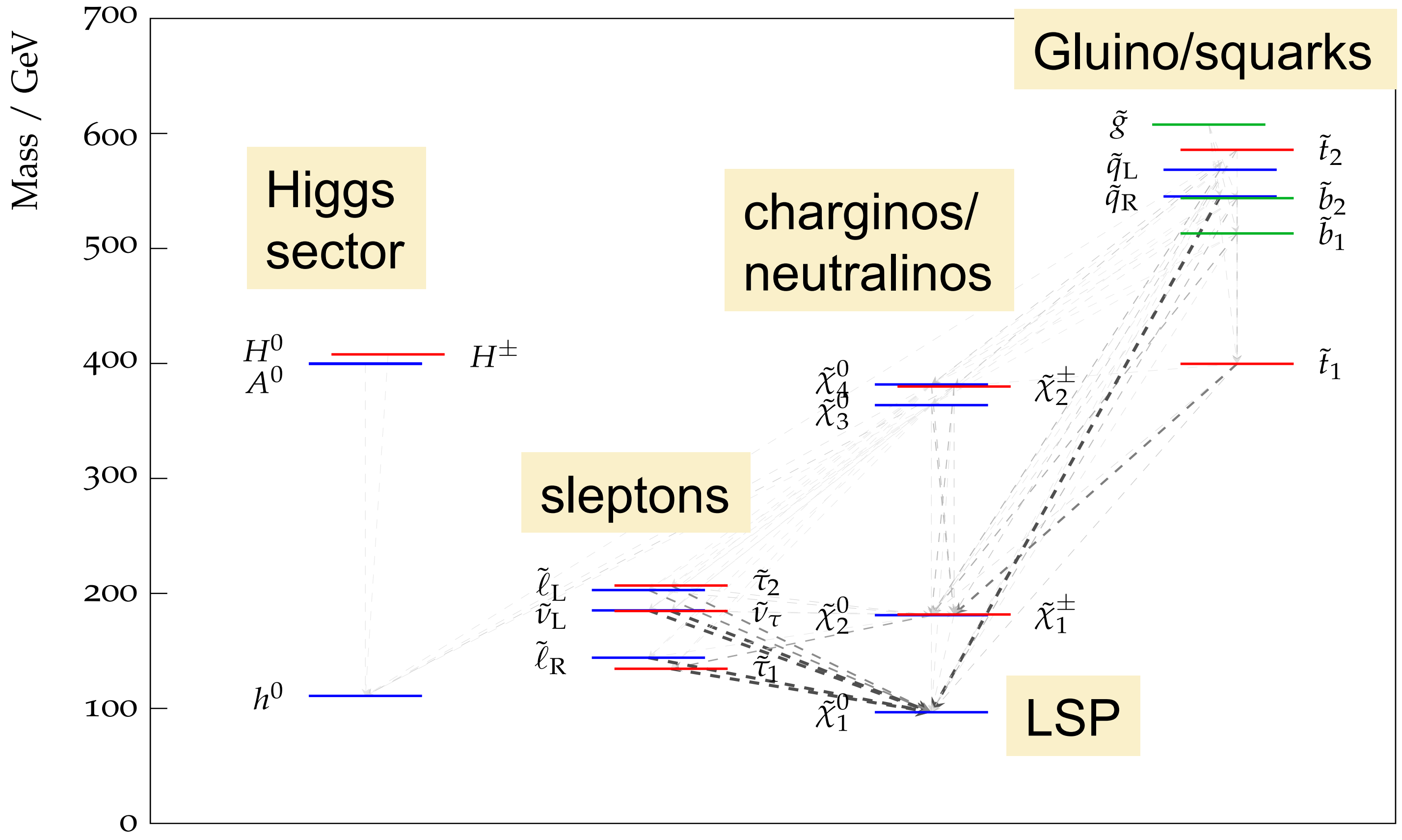
Accept fine tuning!

A “Typical” SUSY Spectrum

Use the famous SPS1a benchmark point for illustration
[m_0=100, m_{12}=250, tanβ=10, A_0=-100, μ>0]

CMSSM

$$m_0, m_{1/2}, \tan\beta, A_0, sign(\mu)$$



Advantages:

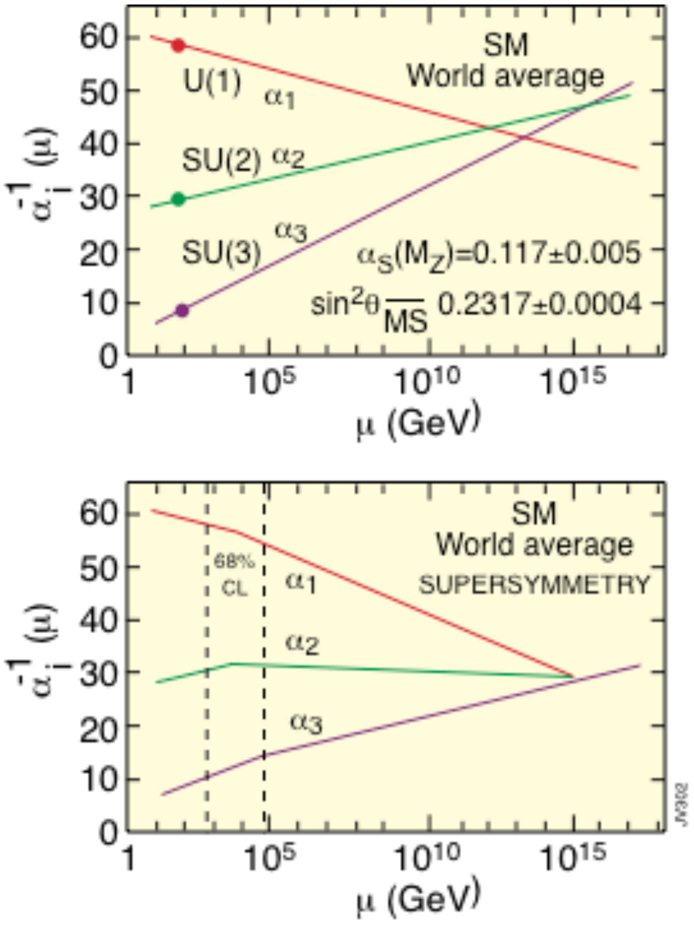
- Only four free parameters (when sign(μ) fixed)
- One of the most studied incarnations of the MSSM

Disadvantage:

- Not fully representative of SUSY (e.g. fixed mass relation between M_{gluion} and M_{LSP})

O. Buchmuller, CMS Physics Highlights, 2012

Features of Supersymmetry



$M_S=10^{3.7\pm0.8\pm0.4}$GeV $M_U=10^{15.9\pm0.2\pm0.1}$GeV

Supersymmetry can play an important role in:

Grand unification (strong + EW forces)

Proton decay

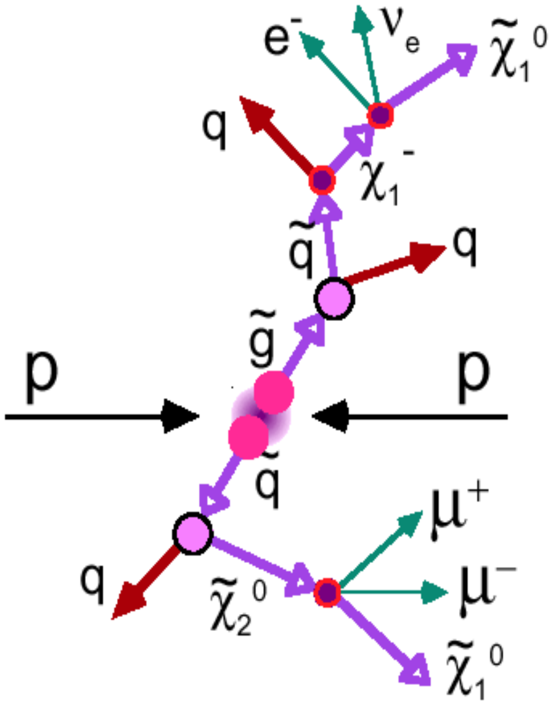
Heirarchy problem - why is the Higgs mass so low

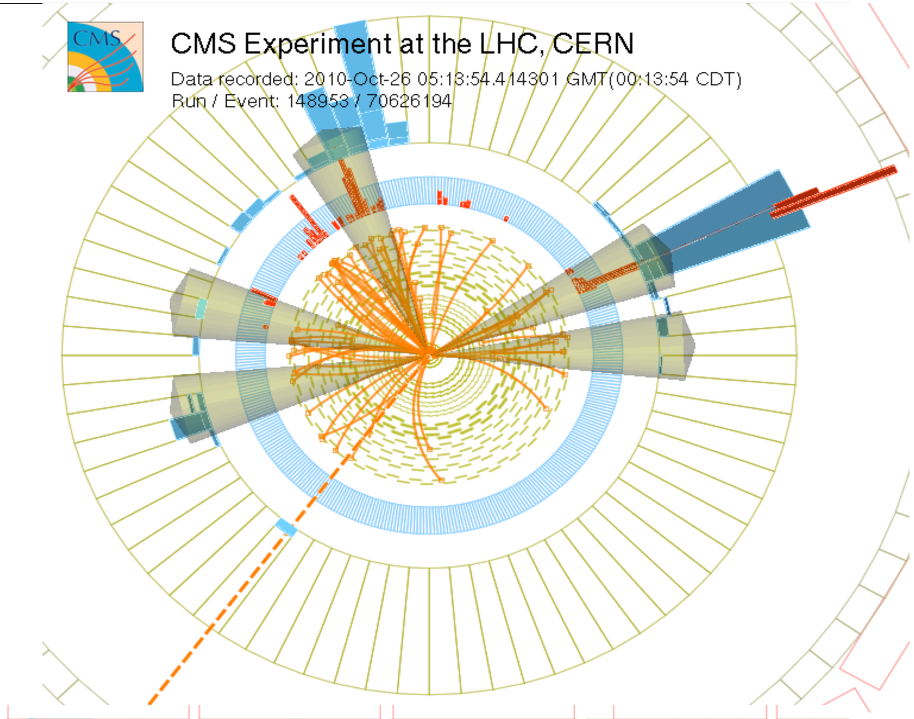
Candidate for dark matter - lightest neutral sparticle

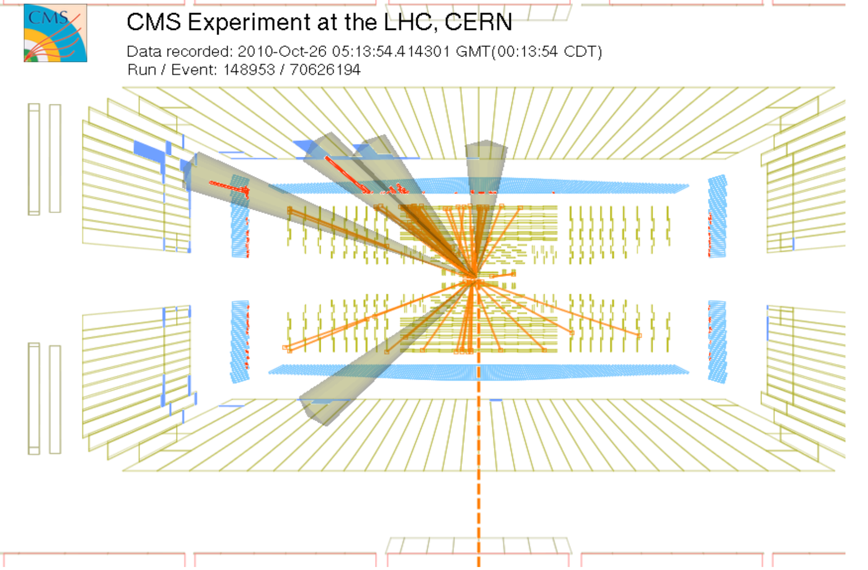
String theory requires supersymmetry (towards reconciling gravity and QM)

Is SUSY expected to do too much?

“SuperParticles”: a New Zoology of Particles?







Searches require (high-P_T) jets + (high) E_T^{miss} and charged leptons:

- 0ℓ (all-hadronic);
- 1ℓ
- 2ℓ (and breakdown into OS and SS)

Experimentally: signatures

- **R_P conservation:**
  - Stable LSP, weakly interacting, “missing transverse energy” (E_T^{miss})
  - Mostly strong production – rich cascades; many jets, a few leptons
  - When going after the stop: b-tagging
- **R_P violation:**
  - The dreaded possibility (harder, except in corners of possibility space)
  - Hadronic modes: to first order, no ME_T (veeery hard); Leptonic modes more promising
  - Strong production, but several interesting new EWK-ino production mechanisms; even more jets and leptons
- **Prompted by R_P violation, but still possible with R_P conservation: exotic SUSY particles**
  - Long-lived particles (some are even “stable”)

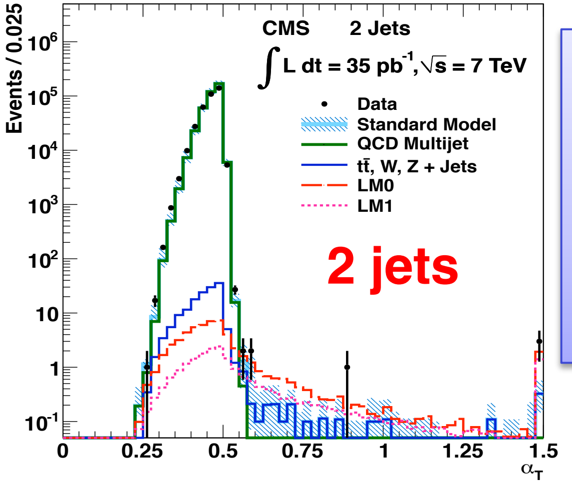
P. Sphicas, Latsis Symposium 2013

“Alpha_T” (α_T)

0ℓ (all-hadronic)

$$\alpha_T = \frac{E_T(j_2)}{M_T(j_1 j_2)} = \sqrt{\frac{E_T(j_2)}{E_T(j_1)}}\frac{1}{\sqrt{2(1-\cos\Delta\varphi)}} \le \frac{1}{2}$$

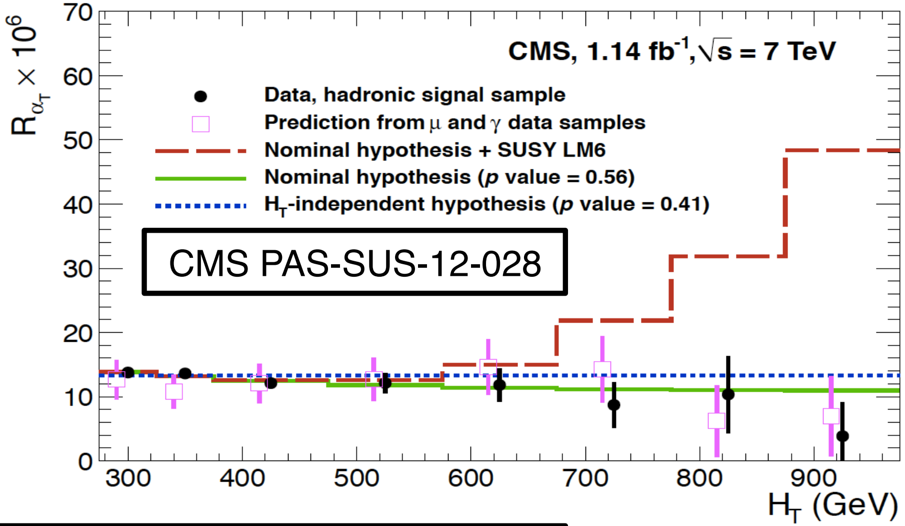
Well-measured QCD: $\alpha_T = 0.5$
Jet mismeasurements: $\alpha_T < 0.5$



For higher jet mutiplicities: merge jets: form two “superjets”

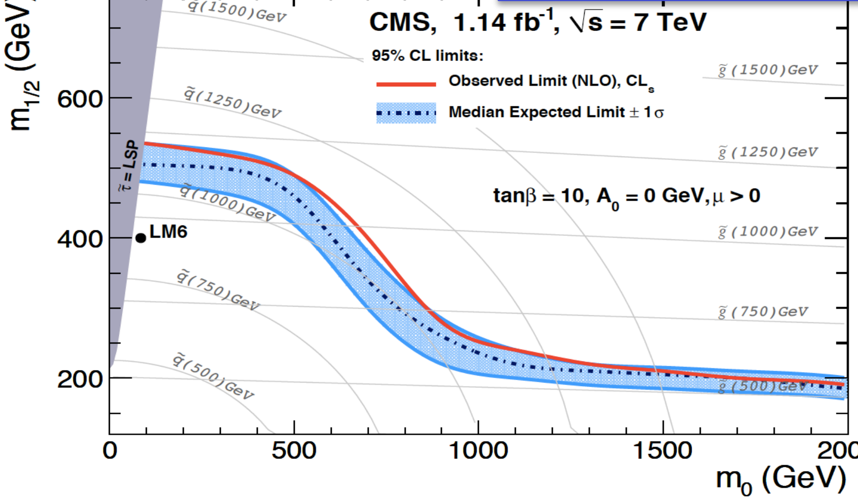
$$R(\alpha_T) = \frac{N(\alpha_T > 0.55)}{N(\alpha_T < 0.55)}$$

Evolution of $R(\alpha_T)$ with H_T



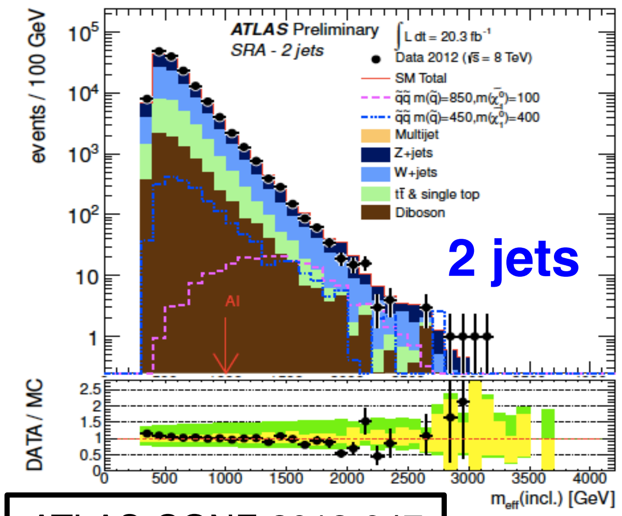
CMS PAS-SUS-12-028

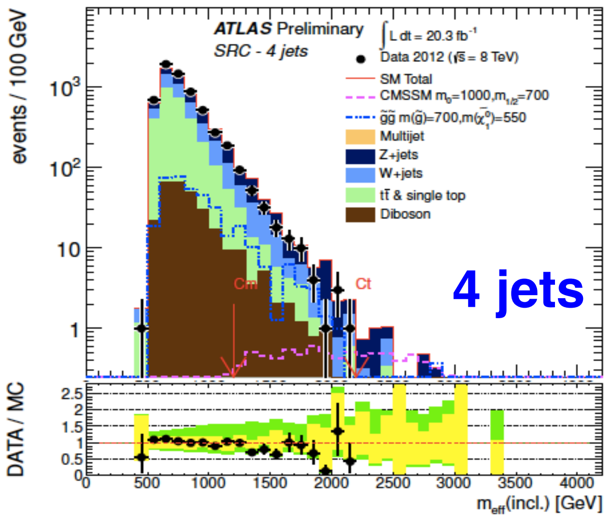
1st-gen results



P. Sphicas, Latsis Symposium 2013

And the full inclusive jets+MET spectrum



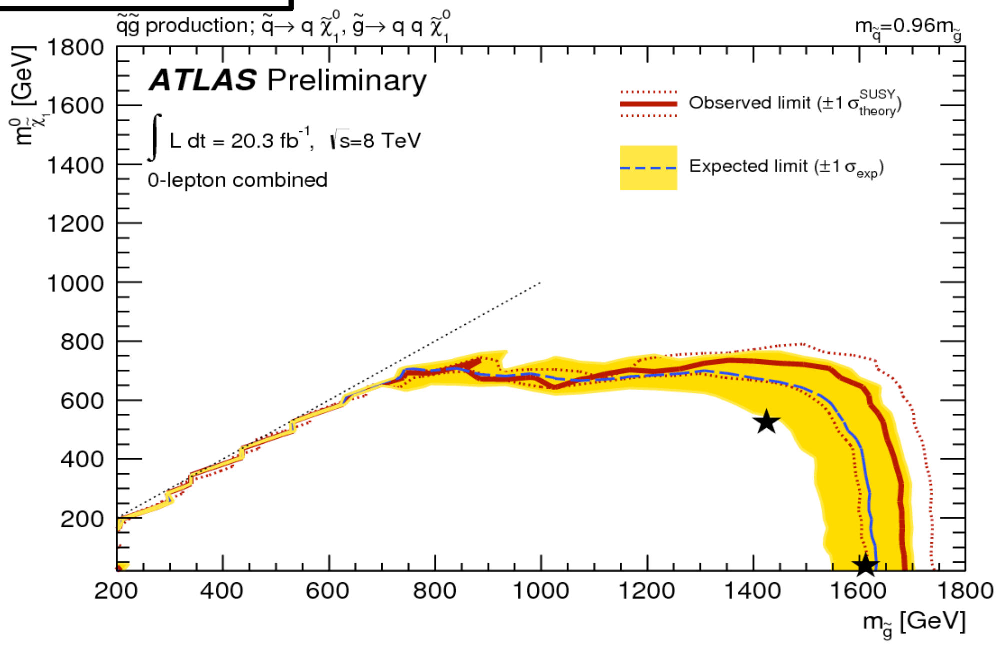


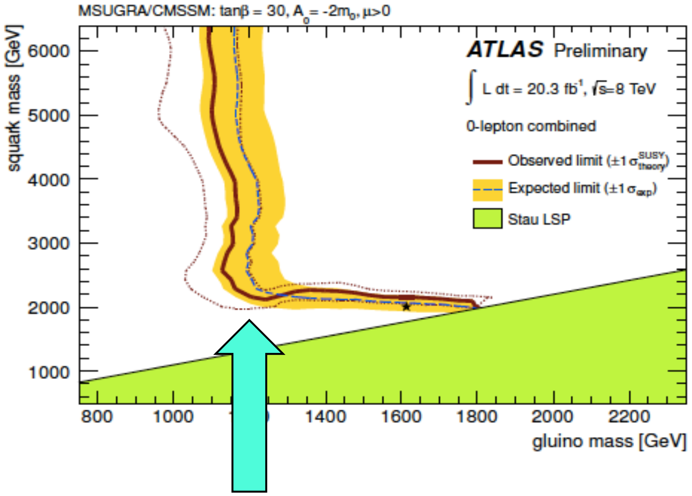
ATLAS-CONF-2013-047

- Effective mass:

$$M_{eff} = \sum p_T^{jets} + E_T^{miss}$$

- Analyze different jet multiplicities





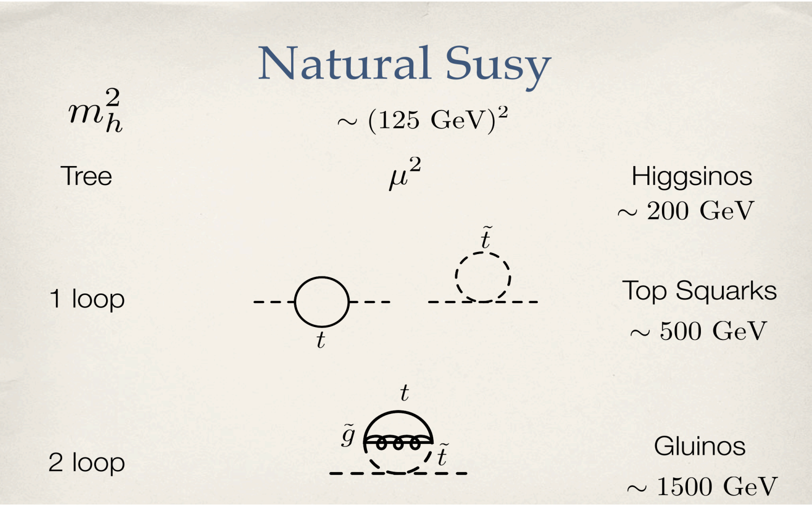
$$M(\tilde{g}) > 1.1 - 1.2 \ \text{TeV}$$

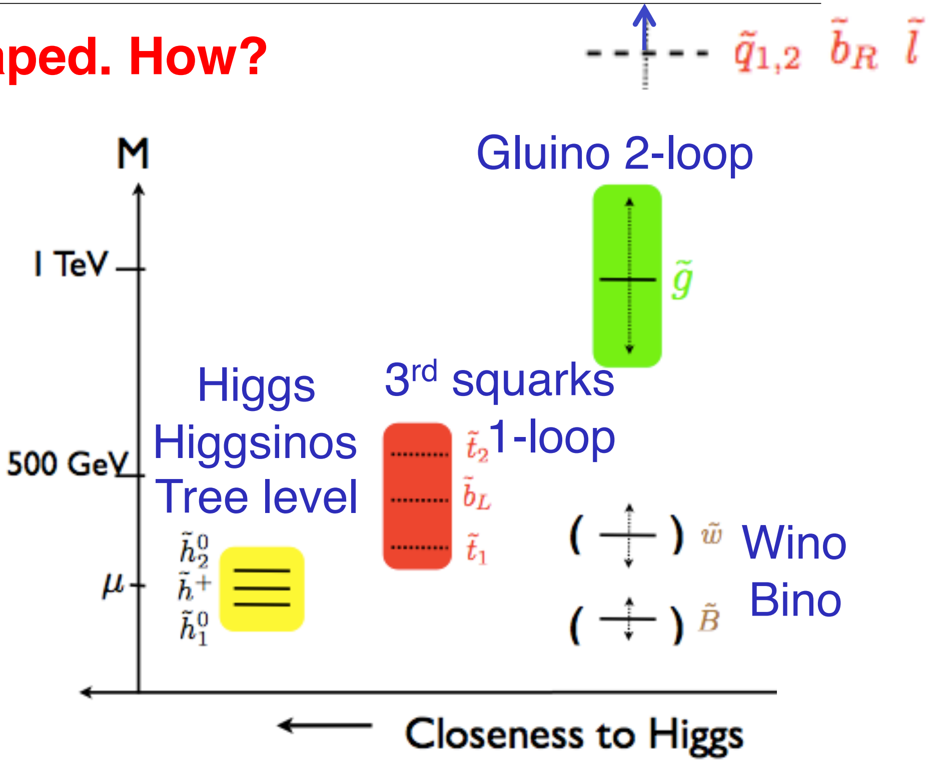
$$M(\tilde{q}) > 2 \ \text{TeV}$$

Natural relationship between Higgs & SUSY

Assuming SUSY is there, but it has escaped. How?

"We will always have the stop"





Previous limits not applicable, due to (expected) different decays of the stop

Previous limits not applicable when E_T^{miss} is small
(Compressed spectra; or even zero? R_P violation?!?)

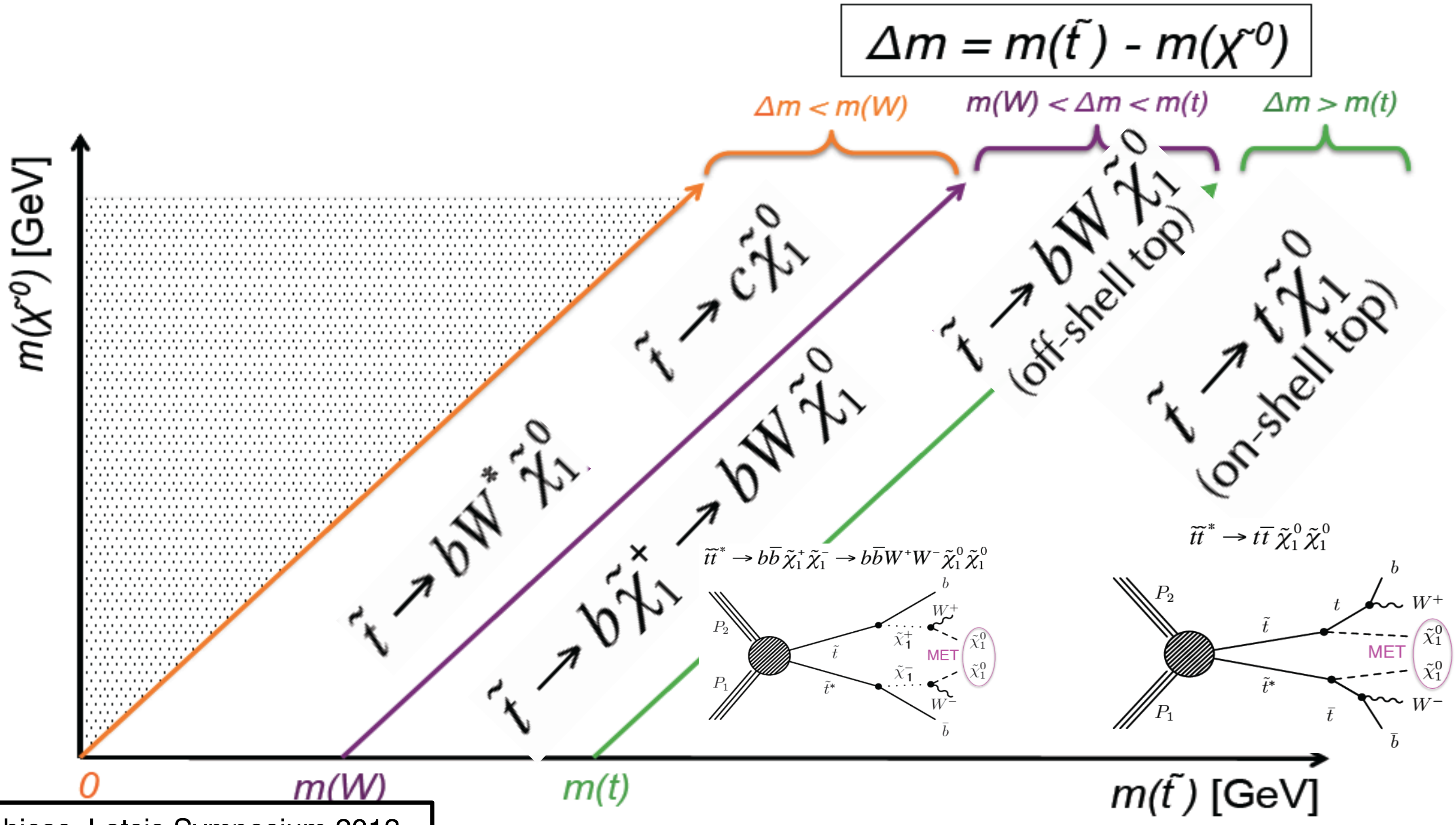
Other signatures that would have (easily!) escaped?

So focus on "natural" SUSY scenarios with light sbottom/stop

~ P. Sphicas, Latsis Symposium 2013

Direct stop search

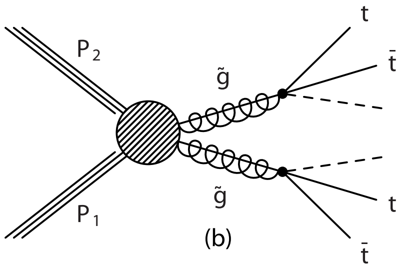
- Top squark decays: in large region, ~ "top+ME_T"

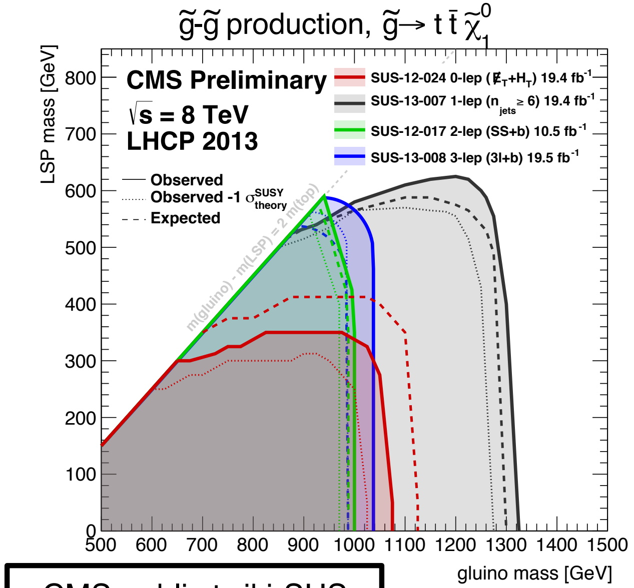


P. Sphicas, Latsis Symposium 2013

Focus on 3rd Generation and EWKino Production

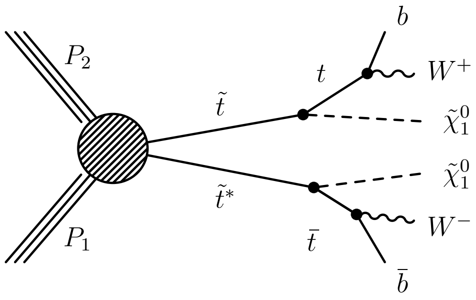
gluino-mediated

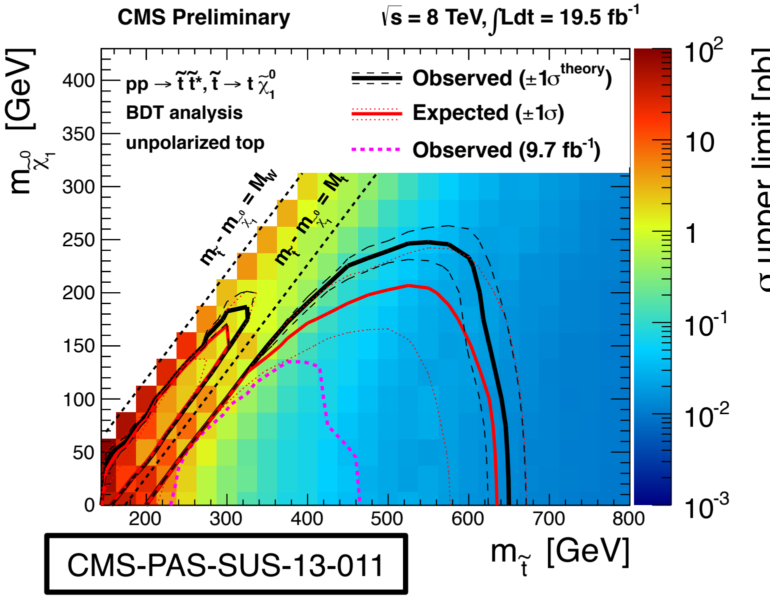




CMS-public twiki-SUS

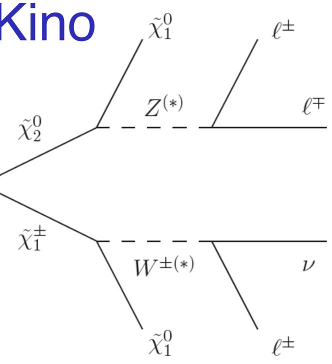
direct

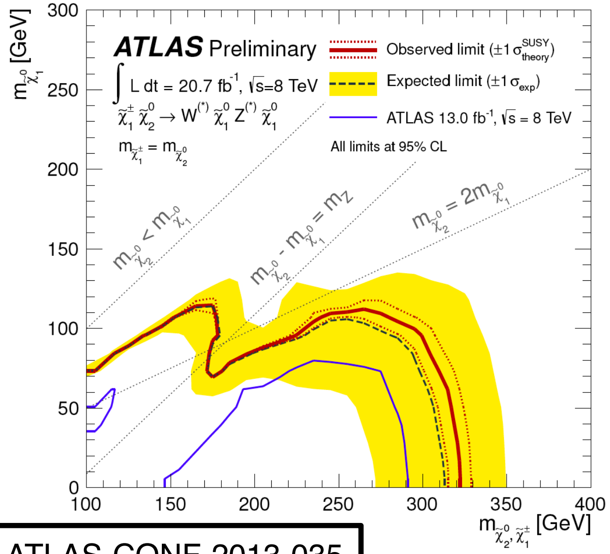




CMS-PAS-SUS-13-011

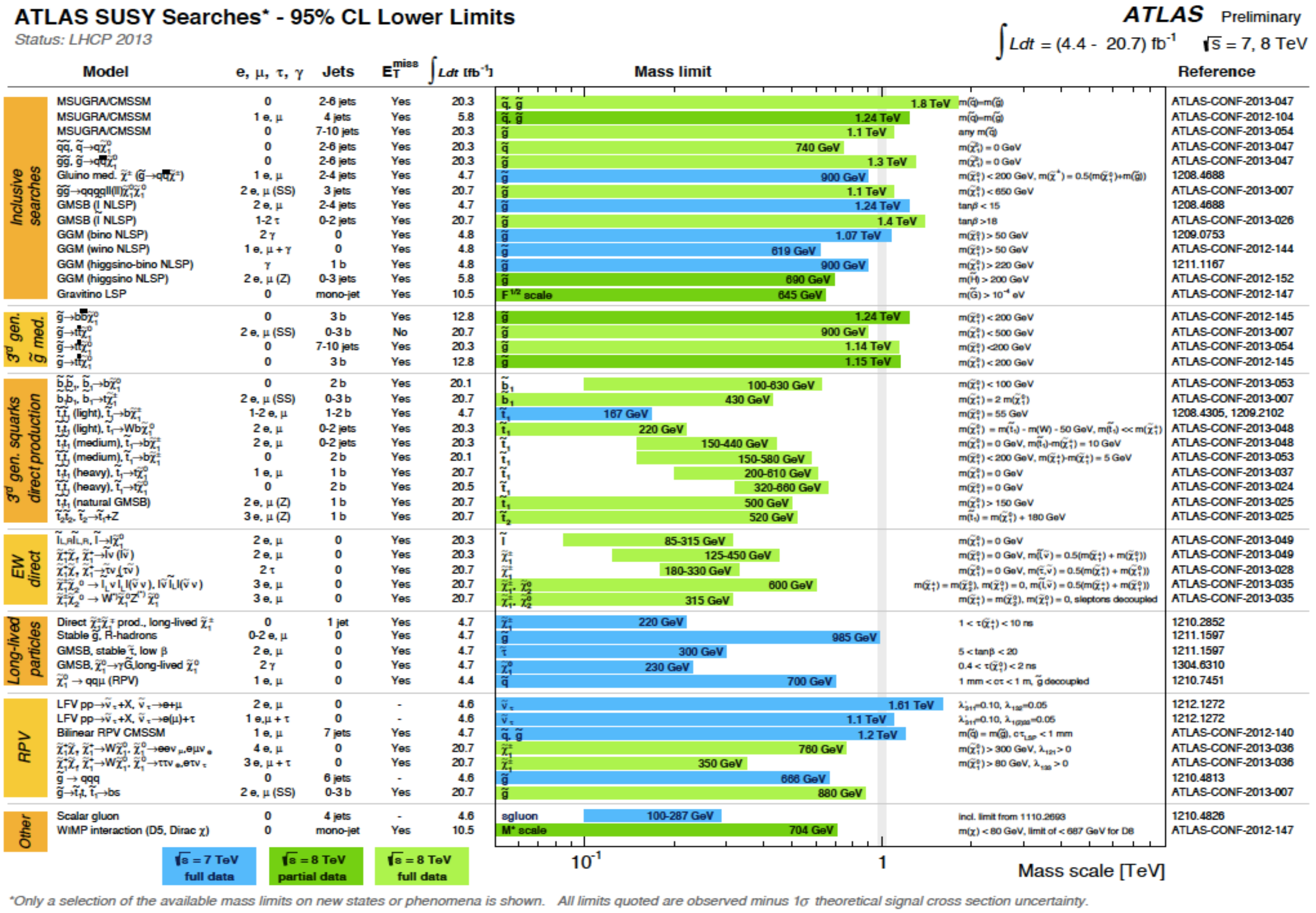
EWKino





ATLAS-CONF-2013-035

A dizzying exclusion map



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: LHCP 2013

ATLAS Preliminary

$\int L dt = (4.4 - 20.7)\ \mathrm{fb}^{-1}$ $\sqrt{s} = 7, 8$ TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int L dt\ [\mathrm{fb}^{-1}]$	Mass limit		Reference
Inclusive searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$ 1.8 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2013-047
	MSUGRA/CMSSM	1 e, μ	4 jets	Yes	5.8	$\tilde{q}, \tilde{g}$ 1.24 TeV	$m(\tilde{q})=m(\tilde{g})$	ATLAS-CONF-2012-104
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.1 TeV	any $m(\tilde{q})$	ATLAS-CONF-2013-054
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$ 740 GeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-047
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$ 1.3 TeV	$m(\tilde{\chi}_1^0)=0$ GeV	ATLAS-CONF-2013-047
	Gluino med. $\tilde{\chi}^{\pm}$ ($\tilde{g}\to q\bar{q}\tilde{\chi}^{\pm}$)	1 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}^{\pm}) = 0.5(m(\tilde{\chi}_1^0)+m(\tilde{g}))$	1208.4688
	$\tilde{g}\tilde{g}\to qqqqll(lll)\tilde{\chi}_1^0\tilde{\chi}_1^0$	2 e, μ (SS)	3 jets	Yes	20.7	$\tilde{g}$ 1.1 TeV	$m(\tilde{\chi}_1^0) < 650$ GeV	ATLAS-CONF-2013-007
	GMSB ($\tilde{l}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$ 1.24 TeV	$\tan\beta < 15$	1208.4688
	GMSB ($\tilde{\tau}$ NLSP)	1-2 τ	0-2 jets	Yes	20.7	$\tilde{g}$ 1.4 TeV	$\tan\beta > 18$	ATLAS-CONF-2013-026
	GGM (bino NLSP)	2 γ	0	Yes	4.8	$\tilde{g}$ 1.07 TeV	$m(\tilde{\chi}_1^0) > 50$ GeV	1209.0753
	GGM (wino NLSP)	1 $e, \mu + \gamma$	0	Yes	4.8	$\tilde{g}$ 619 GeV	$m(\tilde{\chi}_1^0) > 50$ GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0) > 220$ GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$ 690 GeV	$m(\tilde{H}) > 200$ GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale 645 GeV	$m(\tilde{G}) > 10^{-4}$ eV	ATLAS-CONF-2012-147
3rd gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	12.8	$\tilde{g}$ 1.24 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2012-145
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	2 e, μ (SS)	0-3 b	No	20.7	$\tilde{g}$ 900 GeV	$m(\tilde{\chi}_1^0) < 500$ GeV	ATLAS-CONF-2013-007
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$ 1.14 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2013-054
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	3 b	Yes	12.8	$\tilde{g}$ 1.15 TeV	$m(\tilde{\chi}_1^0) < 200$ GeV	ATLAS-CONF-2012-145
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$ 100-630 GeV	$m(\tilde{\chi}_1^0) < 100$ GeV	ATLAS-CONF-2013-053
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{b}_1$ 430 GeV	$m(\tilde{\chi}_1^{\pm}) = 2\,m(\tilde{\chi}_1^0)$	ATLAS-CONF-2013-007
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$ 167 GeV	$m(\tilde{\chi}_1^0) = 55$ GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$ (light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 220 GeV	$m(\tilde{\chi}_1^0) = m(\tilde{t}_1) - m(W) - 50$ GeV, $m(\tilde{t}_1) \ll m(\tilde{\chi}_1^{\pm})$	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$ 150-440 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{t}_1)-m(\tilde{\chi}_1^{\pm}) = 10$ GeV	ATLAS-CONF-2013-048
	$\tilde{t}_1\tilde{t}_1$ (medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$ 150-580 GeV	$m(\tilde{\chi}_1^0) < 200$ GeV, $m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_1^0) = 5$ GeV	ATLAS-CONF-2013-053
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20.7	$\tilde{t}_1$ 200-610 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2013-037
	$\tilde{t}_1\tilde{t}_1$ (heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.5	$\tilde{t}_1$ 320-660 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2013-024
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_1$ 500 GeV	$m(\tilde{\chi}_1^0) > 150$ GeV	ATLAS-CONF-2013-025
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1+Z$	3 e, μ (Z)	1 b	Yes	20.7	$\tilde{t}_2$ 520 GeV	$m(\tilde{t}_1) = m(\tilde{\chi}_1^0) + 180$ GeV	ATLAS-CONF-2013-025
EW direct	$\tilde{l}_{L,R}\tilde{l}_{L,R}$, $\tilde{l}\to l\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{l}$ 85-315 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{l}\nu(l\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$ 125-450 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{l},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-049
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 180-330 GeV	$m(\tilde{\chi}_1^0) = 0$ GeV, $m(\tilde{\tau},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-028
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \tilde{l}_L\nu\tilde{l}_L l(\tilde{\nu}\nu), l\tilde{\nu}\tilde{l}_L l(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 600 GeV	$m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 0$, $m(\tilde{l},\tilde{\nu}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	ATLAS-CONF-2013-035
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to W^{*}\tilde{\chi}_1^0 Z^{(*)}\tilde{\chi}_1^0$	3 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$ 315 GeV	$m(\tilde{\chi}_1^{\pm}) = m(\tilde{\chi}_2^0)$, $m(\tilde{\chi}_1^0) = 0$, sleptons decoupled	ATLAS-CONF-2013-035
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	0	1 jet	Yes	4.7	$\tilde{\chi}_1^{\pm}$ 220 GeV	$1 < \tau(\tilde{\chi}_1^{\pm}) < 10$ ns	1210.2852
	Stable $\tilde{g}$, R-hadrons	0-2 e, μ	0	Yes	4.7	$\tilde{g}$ 985 GeV		1211.1597
	GMSB, stable $\tilde{\tau}$, low β	2 e, μ	0	Yes	4.7	$\tilde{\tau}$ 300 GeV	$5 < \tan\beta < 20$	1211.1597
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	0	Yes	4.7	$\tilde{\chi}_1^0$ 230 GeV	$0.4 < \tau(\tilde{\chi}_1^0) < 2$ ns	1304.6310
	$\tilde{\chi}_1^0 \to qq\mu$ (RPV)	1 e, μ	0	Yes	4.4	$\tilde{q}$ 700 GeV	1 mm $< c\tau <$ 1 m, $\tilde{g}$ decoupled	1210.7451
RPV	LFV $pp\to\tilde{\nu}_{\tau}+X$, $\tilde{\nu}_{\tau}\to e+\mu$	2 e, μ	0	-	4.6	$\tilde{\nu}_{\tau}$ 1.61 TeV	$\lambda'_{311}=0.10$, $\lambda_{132}=0.05$	1212.1272
	LFV $pp\to\tilde{\nu}_{\tau}+X$, $\tilde{\nu}_{\tau}\to e(\mu)+\tau$	1 $e,\mu + \tau$	0	-	4.6	$\tilde{\nu}_{\tau}$ 1.1 TeV	$\lambda'_{311}=0.10$, $\lambda_{1(2)33}=0.05$	1212.1272
	Bilinear RPV CMSSM	1 e, μ	7 jets	Yes	4.7	$\tilde{q}, \tilde{g}$ 1.2 TeV	$m(\tilde{q}) = m(\tilde{g})$, $c\tau_{LSP} < 1$ mm	ATLAS-CONF-2012-140
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to ee\nu_{\mu}, e\mu\nu_e$	4 e, μ	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 760 GeV	$m(\tilde{\chi}_1^0) > 300$ GeV, $\lambda_{121} > 0$	ATLAS-CONF-2013-036
	$\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^+\to W\tilde{\chi}_1^0$, $\tilde{\chi}_1^0\to\tau\tau\nu_e, e\tau\nu_{\tau}$	3 $e, \mu + \tau$	0	Yes	20.7	$\tilde{\chi}_1^{\pm}$ 350 GeV	$m(\tilde{\chi}_1^0) > 80$ GeV, $\lambda_{133} > 0$	ATLAS-CONF-2013-036
	$\tilde{g}\to qqq$	0	6 jets	-	4.6	$\tilde{g}$ 666 GeV		1210.4813
	$\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.7	$\tilde{g}$ 880 GeV		ATLAS-CONF-2013-007
Other	Scalar gluon	0	4 jets	-	4.6	sgluon 100-287 GeV	incl. limit from 1110.2693	1210.4826
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale 704 GeV	$m(\chi) < 80$ GeV, limit of $<$ 687 GeV for D8	ATLAS-CONF-2012-147

**Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1σ theoretical signal cross section uncertainty.*

ATLAS LHCP 2013

Incorporating Gravity

How many space dimensions are there?

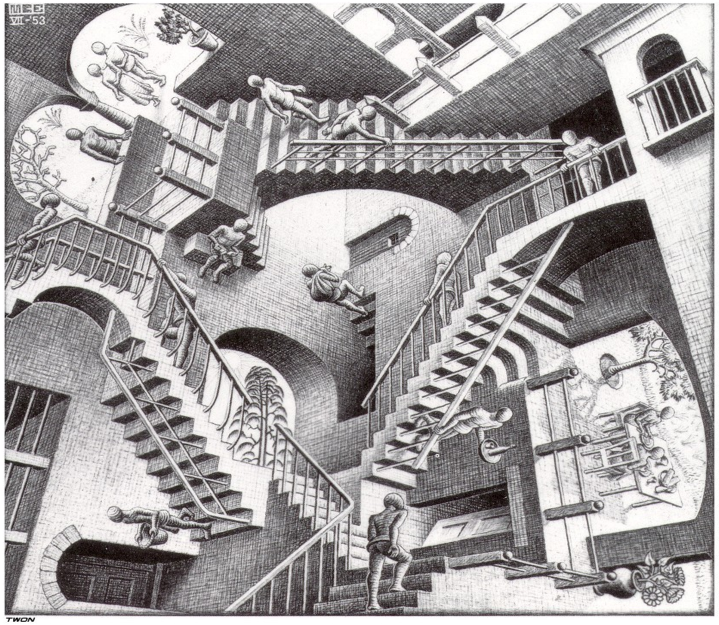
Law of Gravity
In 3-D(∞ large dim):

$$F = \frac{GMm}{r^2}$$

e.g. in 2-D (∞ large dim):

$$F \propto \frac{1}{r}$$

Number of space-time dimensions determines the observed form of a force



Gravity may propagate in 4+n dimensions, but we could see strong effects only at very small distances, perhaps reachable in pp collisions at the LHC

e.g. by finding new heavy Z-like particles

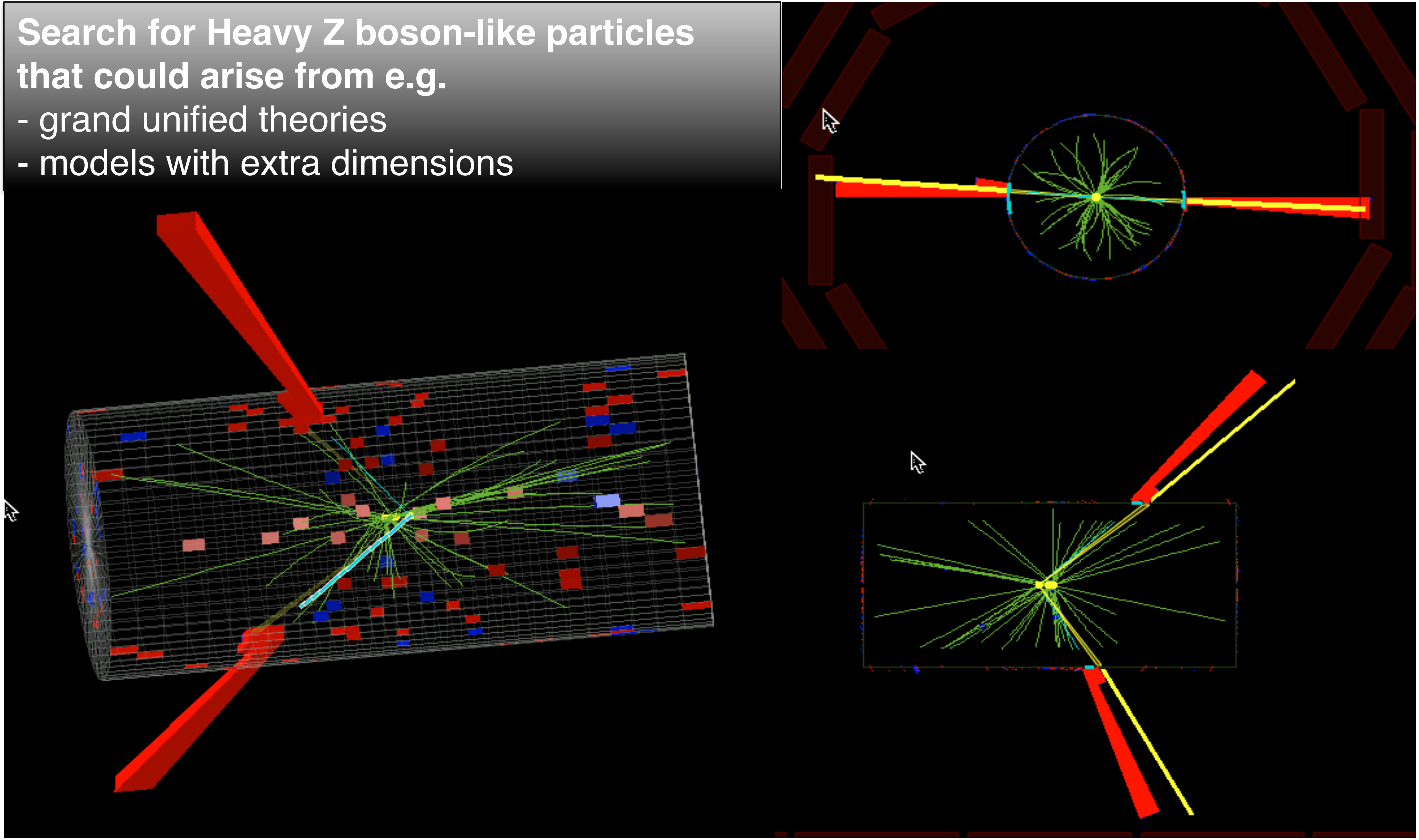
Path to combining gravity : Superstring theory ?

⇨dramatic concepts: supersymmetry, extra space-time dimensions ?

Searching for Extra Dimensions

Search for Heavy Z boson-like particles that could arise from e.g.

- grand unified theories
- models with extra dimensions



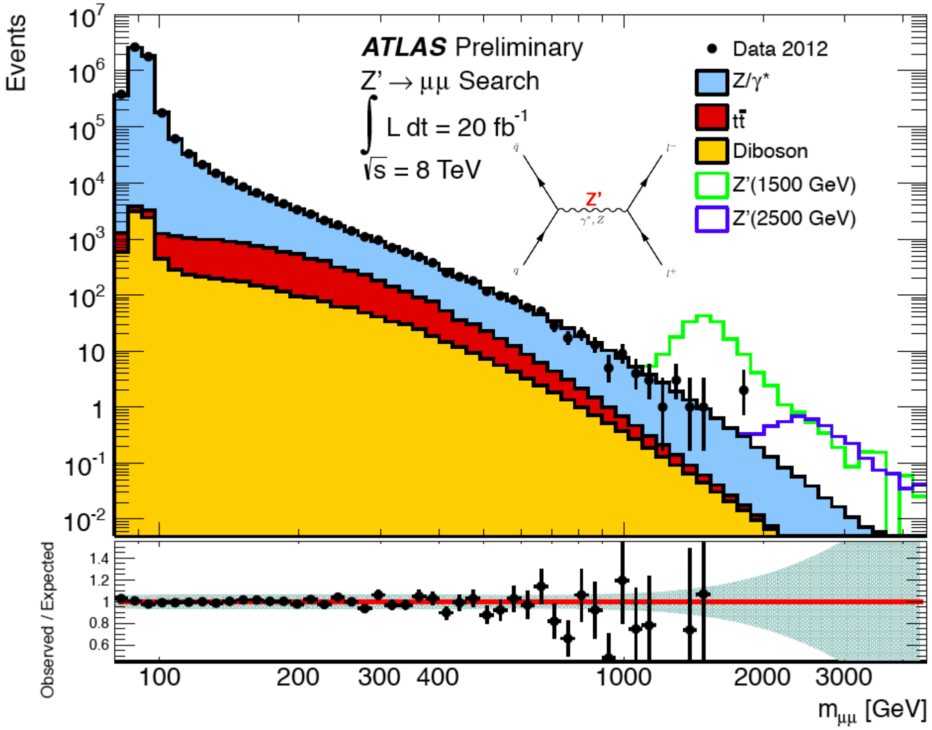
Imperial College London

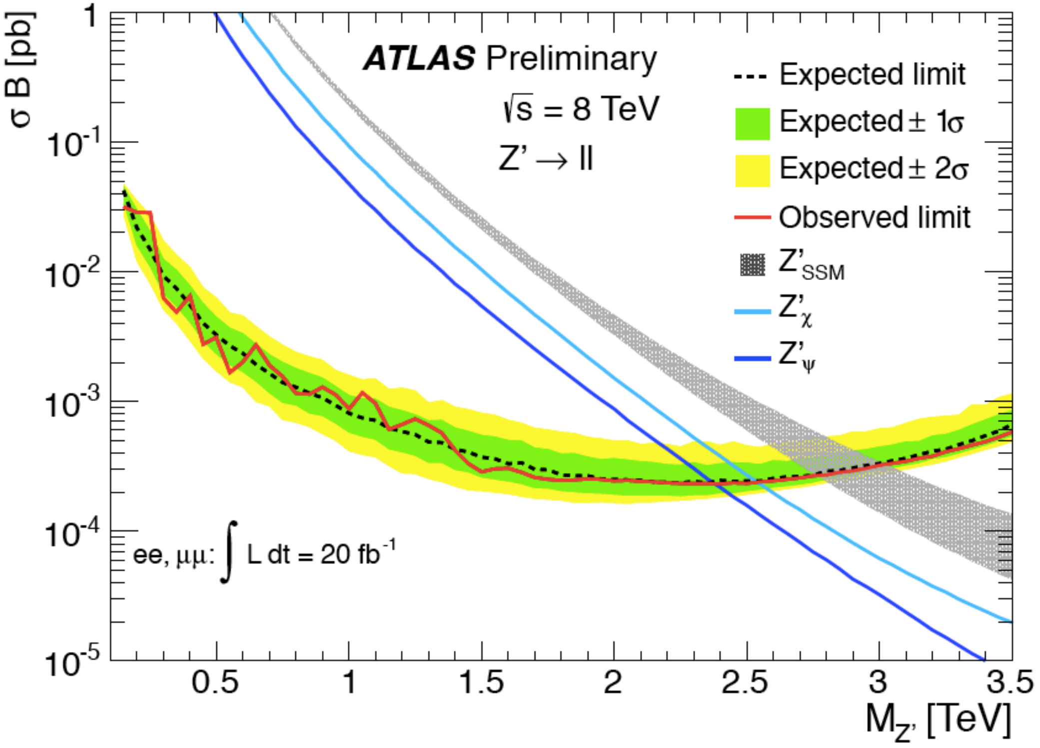
ATLAS: Search for Heavy Vector Bosons Z’

Di-muons

ee+μμ

Narrow intrinsic width (~3%):
E_6 models 0.5-1.3%





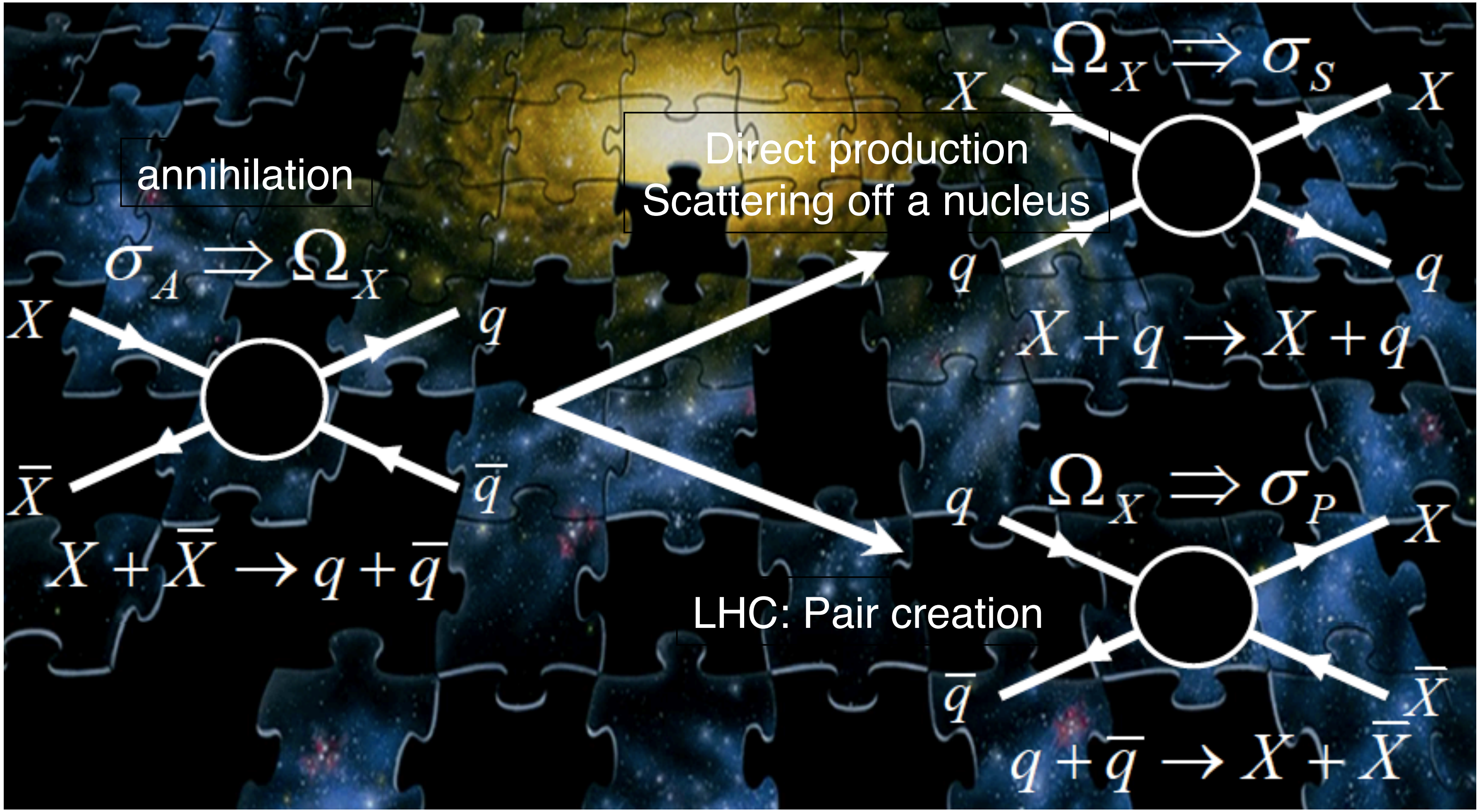
ATLAS-CONF-2013-017

ATLAS: ee and μμ at 95% CL

$M(Z'_{SSM})> 2.86$, $M(Z'_{E6})> 2.38-2.54$,

$M(Z'_{RS})> 1.1-2.47$ TeV

Search for Dark Matter



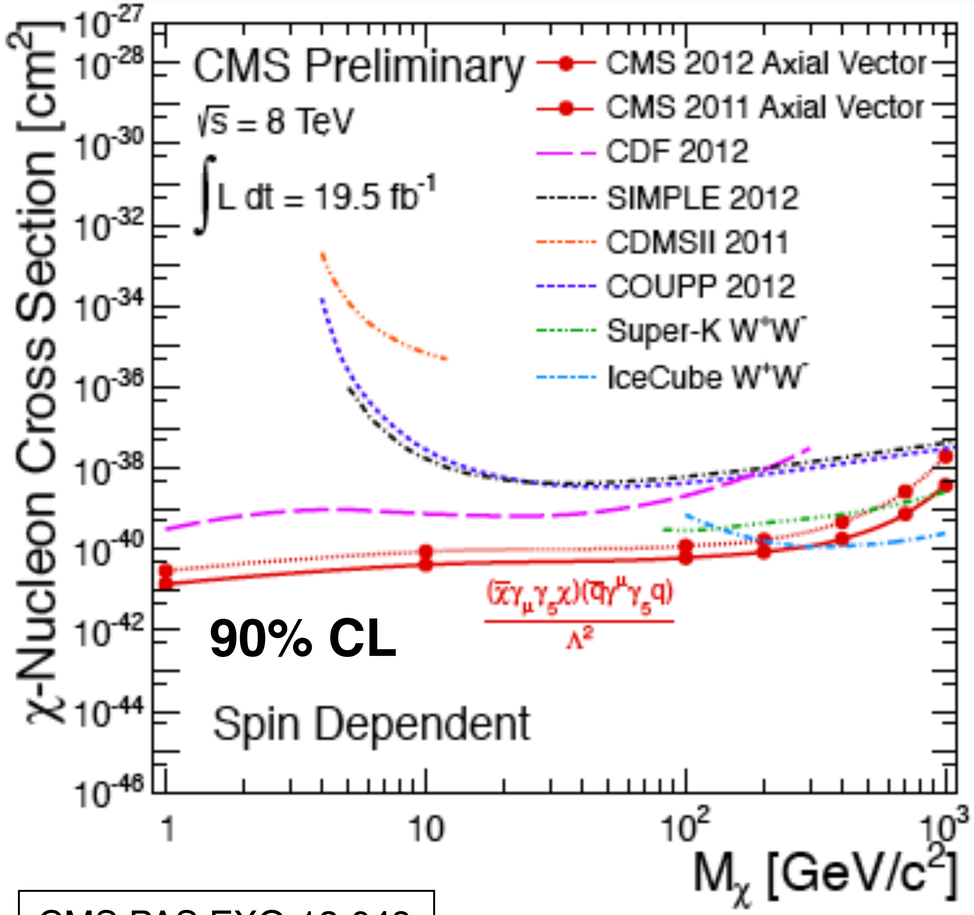
annihilation

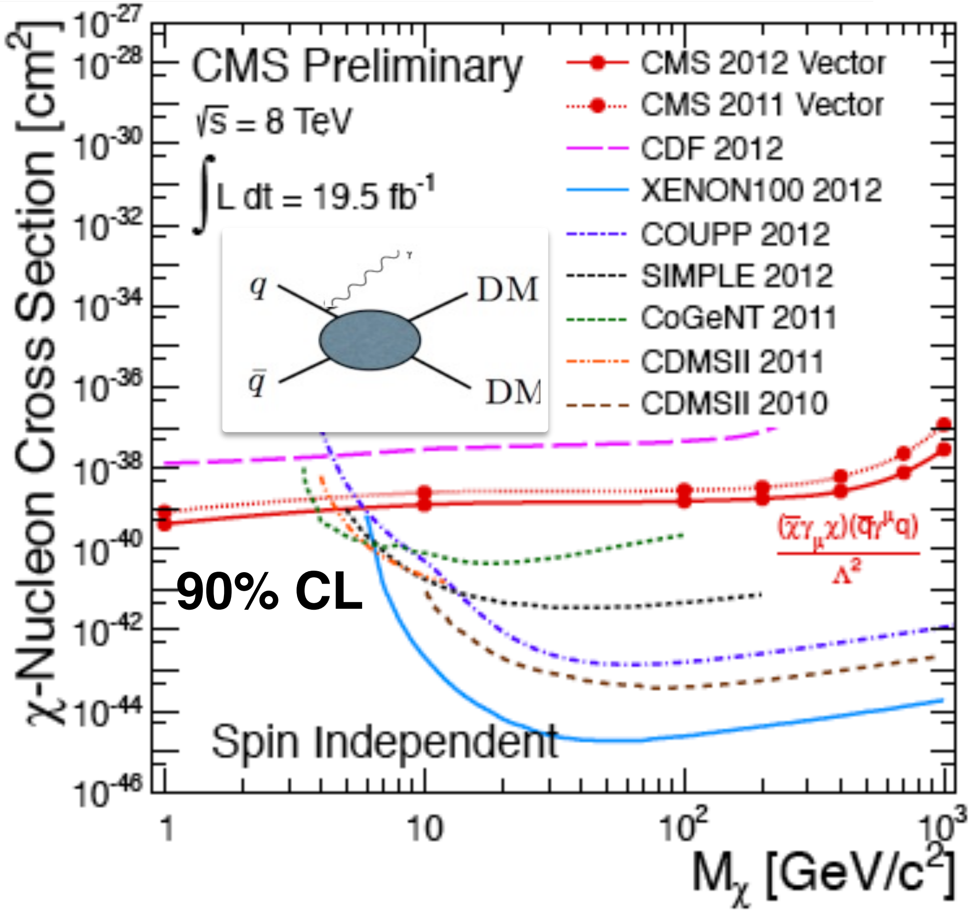
Direct production
Scattering off a nucleus

LHC: Pair creation

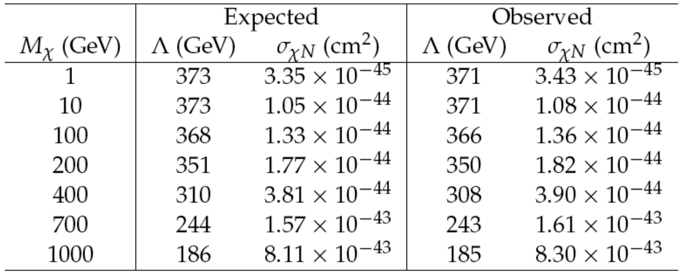
R. Kolb, CERN Academic Lectures 2012

CMS: Dark Matter and Mono-Jet Searches





CMS PAS EXO-12-048



	Expected		Observed	
M_χ (GeV)	Λ (GeV)	$\sigma_{\chi N}$ (cm^2)	Λ (GeV)	$\sigma_{\chi N}$ (cm^2)
1	373	3.35×10^{-45}	371	3.43×10^{-45}
10	373	1.05×10^{-44}	371	1.08×10^{-44}
100	368	1.33×10^{-44}	366	1.36×10^{-44}
200	351	1.77×10^{-44}	350	1.82×10^{-44}
400	310	3.81×10^{-44}	308	3.90×10^{-44}
700	244	1.57×10^{-43}	243	1.61×10^{-43}
1000	186	8.11×10^{-43}	185	8.30×10^{-43}

Interaction treated as a contact interaction with scale $\Lambda = M/\sqrt{g_\chi g_q}$ where M is the mass of the mediator

Outlook for the LHC

Increase the Energy (√s)
Increase the Rate of Useful Integrated Luminosity

14 TeV vs 8 TeV – Gain Factors

Use parton luminosties to illustrate the gain of 14 vs 8 TeV

Higgs:

pp → H, H→WW, ZZ and γγ
mainly gg: Factor **~2**

SUSY – 3rd Generation:

Mass scale ~ 500 GeV
qq and gg: Factor **~8**

SUSY – Squarks/Gluino:

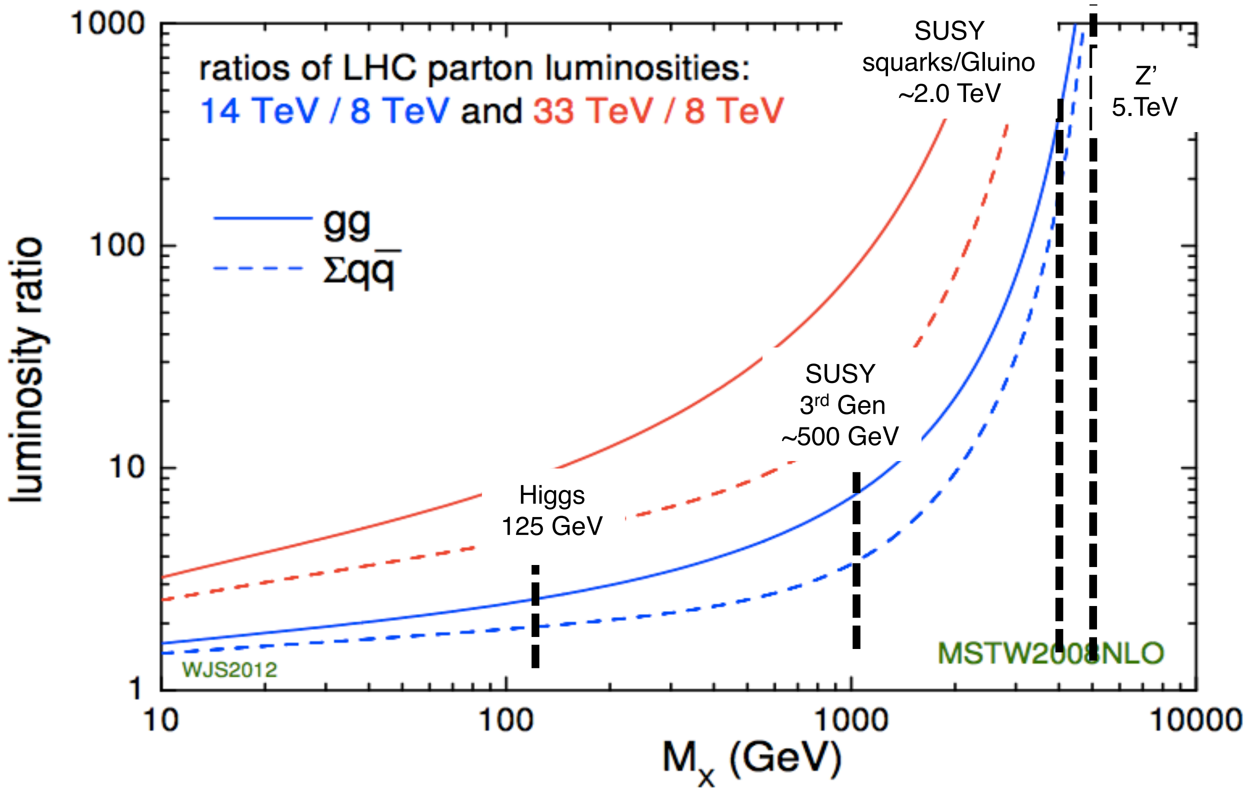
Mass scale ~ 2.0 TeV
qq,gg,qg: Factor **~300**

Z' :

Mass scale ~ 5 TeV
qq: Factor **~1000**

O. Buchmuller

J. Stirling



For the searches increase in energy will help a lot!

Short-term Outlook

2012-2013:

Measurement of the properties of the new boson

Final “legacy” results from the full dataset – 2nd half-2013

2015 and beyond ($\sqrt{s} > 13$ TeV)

Elucidate the detailed nature of the new boson

Does it really behave like the SM Higgs boson? Is it alone?

Search for Dark Matter (SUSY) (mass scale up to 3.0 TeV)

Search for conjectured new physics

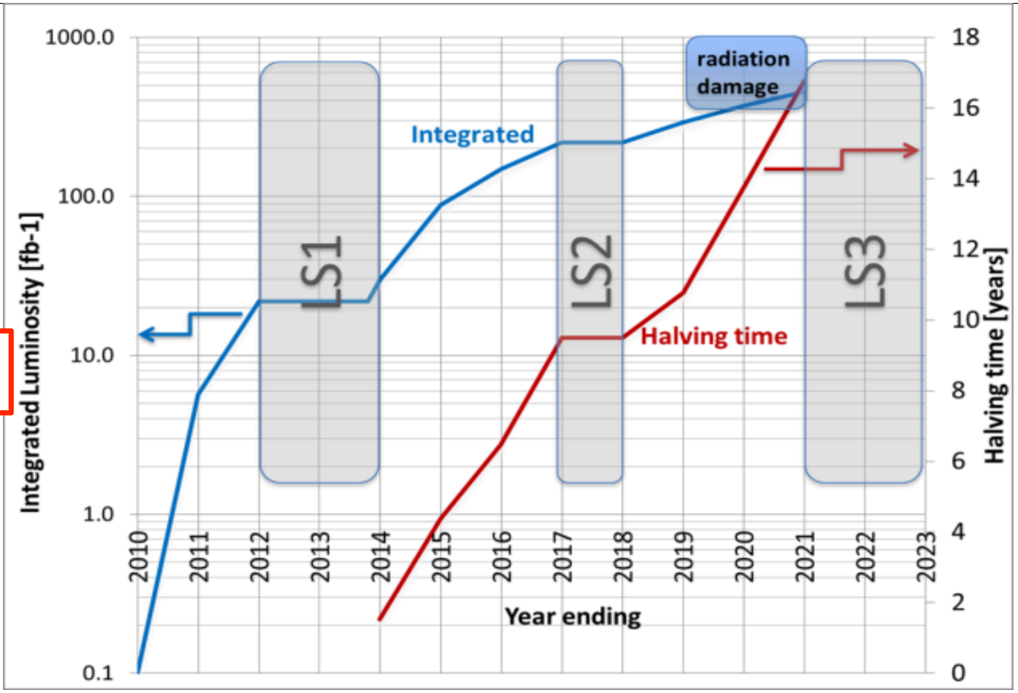
Why is m_H so low? Supersymmetry? Extra Dimensions?

Mass reach for objects with mass up to 4.0 TeV

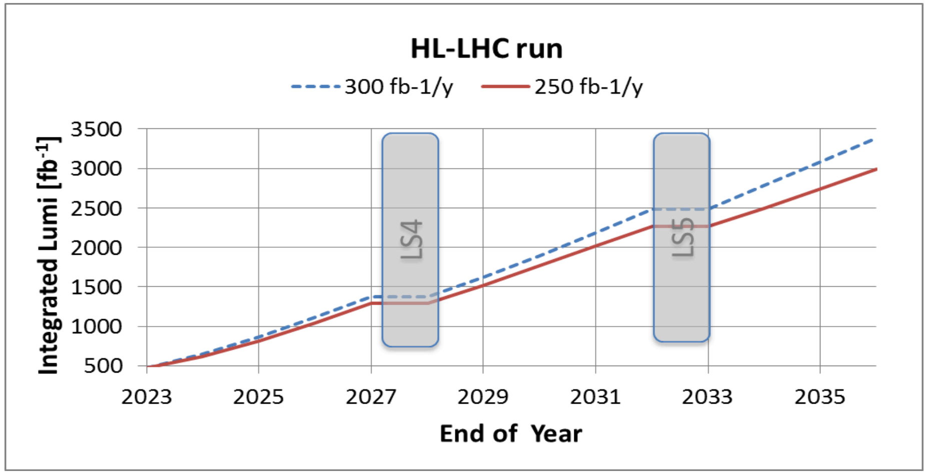
Look for the unexpected

Looking Further Ahead: LHC→HL-LHC

LHC



“Halving-time” for statistical errors becomes very long after LS3.



HL-LHC

Increase substantially the annual useful integrated luminosity

Need to upgrade LHC→ HL-LHC
Aim to integrate 3000fb^{-1},

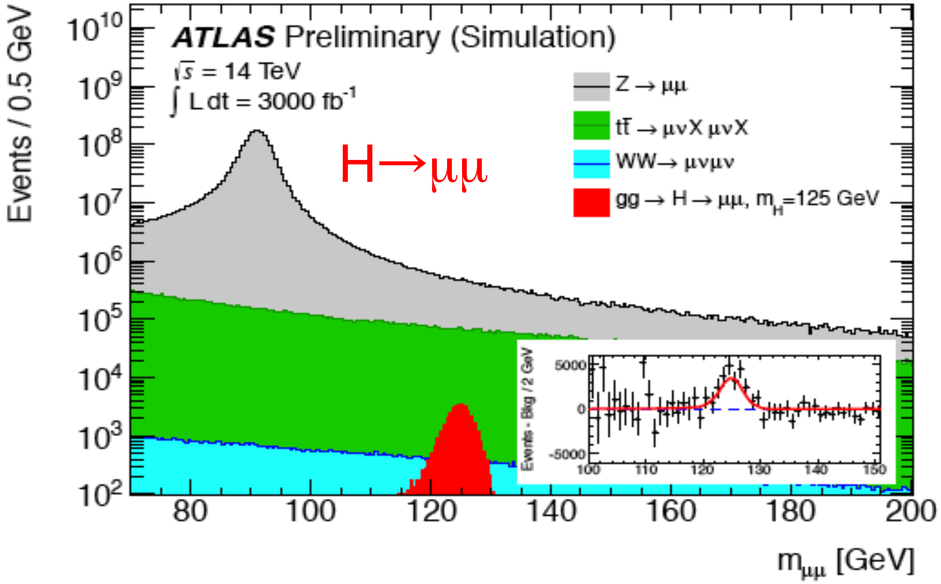
Long Term Outlook: The Physics with 3 ab^{-1}

A clear priority: In depth studies of the found Higgs boson
Improved measurements of: i) mass, spin, signal strengths and couplings

With increasing integrated luminosity search for rare decay modes and make increasingly precise measurements of the couplings, self-interaction,
Is it alone? Is it elementary or composite?
How much does it contribute to restoring unitarity in VBF?
LHC → HL-LHC (HL-LHC will be a Higgs factory! 100M produced 3ab^{-1})

Coupling	300 fb^{-1}		3000 fb^{-1}	
CMS	syst. (%)		syst. (%)	
	actual	scaled	actual	scaled
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

What accuracy is needed and why?



Long Term Outlook: The Physics with 3 ab^{-1}

Another clear priority

i) Search for new physics: resonances, supersymmetry, exotica, yet unknown.

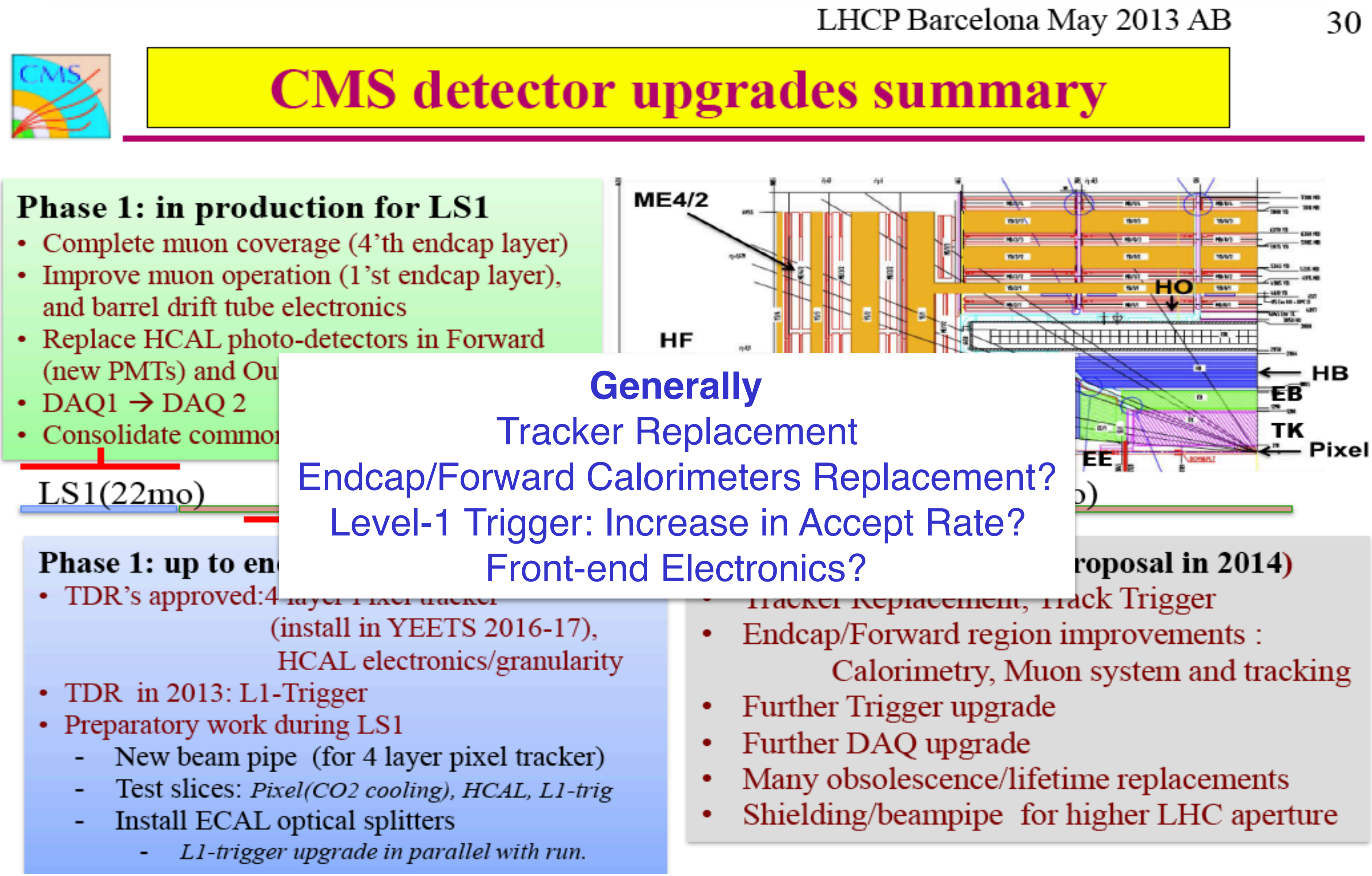
ii) Probe possible new physics through more precise SM measurements e.g.: - top physics → study rare decays & measure couplings (LHC as top factory)

iii) study of new physics via vector boson fusion

If new physics has been found, study it in detail

Detector Challenge: Must maintain/improve on detector performance as in Run I, in more hostile conditions

HL-LHC: What does it mean for the Detectors?



LHCP Barcelona May 2013 AB 30

CMS detector upgrades summary

Phase 1: in production for LS1

- Complete muon coverage (4'th endcap layer)
- Improve muon operation (1'st endcap layer), and barrel drift tube electronics
- Replace HCAL photo-detectors in Forward (new PMTs) and Ou
- DAQ1 → DAQ 2
- Consolidate commo

LS1(22mo)

o)

Phase 1: up to en

- TDR's approved:4 layer Pixel tracker (install in YEETS 2016-17), HCAL electronics/granularity
- TDR in 2013: L1-Trigger
- Preparatory work during LS1
  - New beam pipe (for 4 layer pixel tracker)
  - Test slices: *Pixel(CO2 cooling), HCAL, L1-trig*
  - Install ECAL optical splitters
    - *L1-trigger upgrade in parallel with run.*

roposal in 2014)

- Tracker Replacement, Track Trigger
- Endcap/Forward region improvements : Calorimetry, Muon system and tracking
- Further Trigger upgrade
- Further DAQ upgrade
- Many obsolescence/lifetime replacements
- Shielding/beampipe for higher LHC aperture

Generally

Tracker Replacement

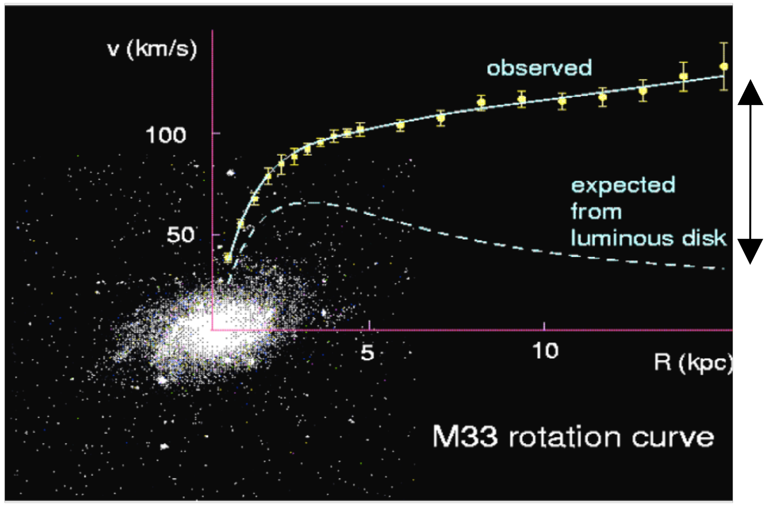
Endcap/Forward Calorimeters Replacement?

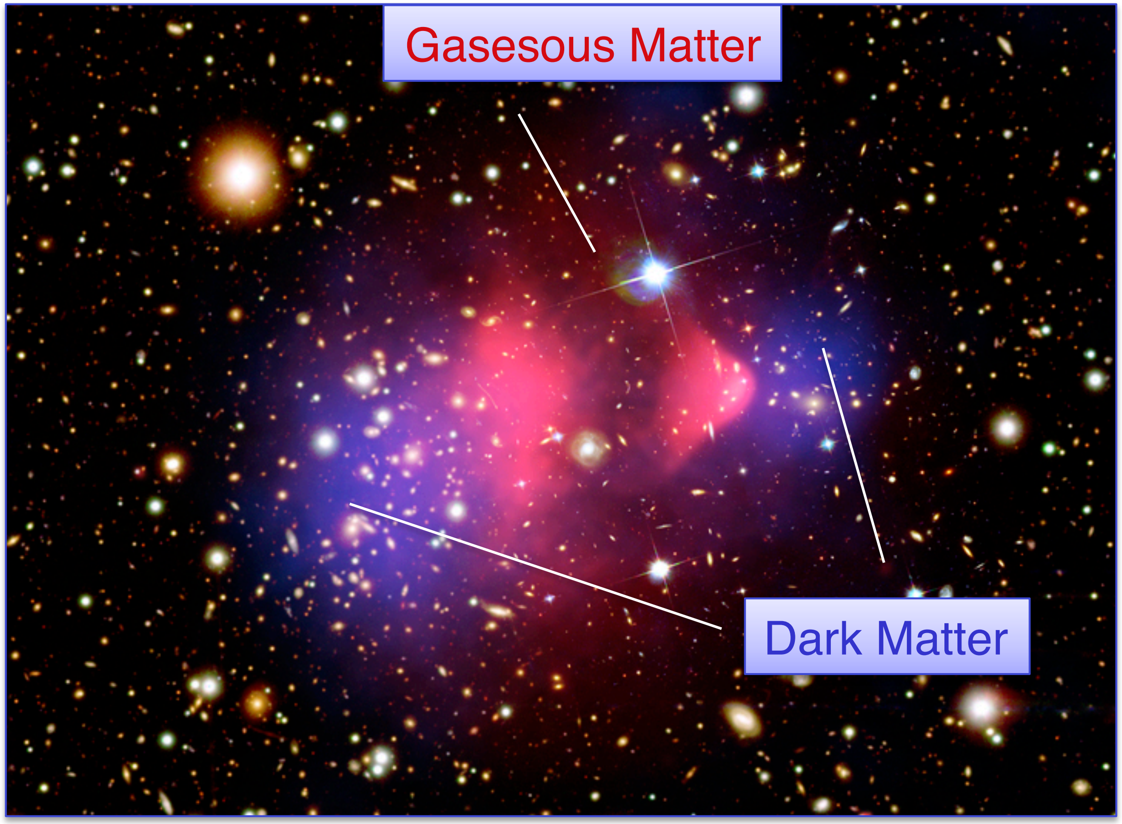
Level-1 Trigger: Increase in Accept Rate?

Front-end Electronics?

LHC and Dark Side of the Universe: Dark Matter

Dark (invisible) matter!



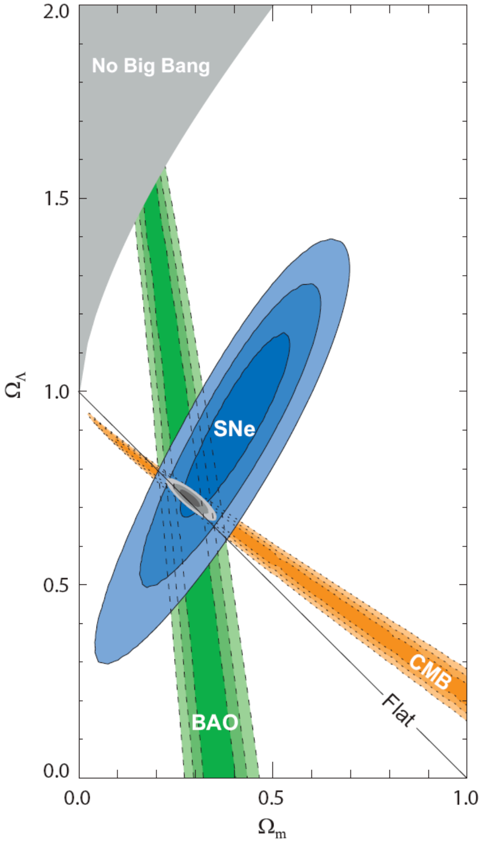


Dark Matter appears to be made of weakly interacting massive particles.

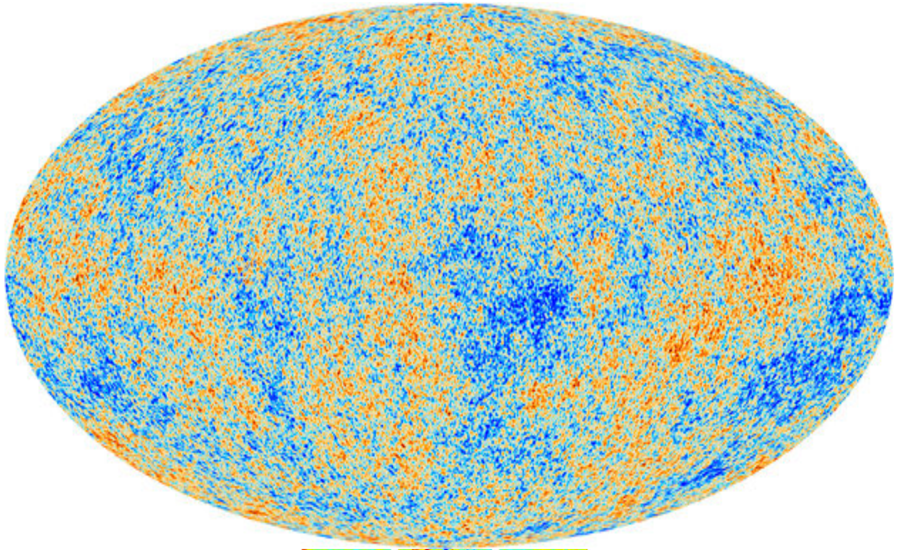
Lightest SUSY particle has these properties !

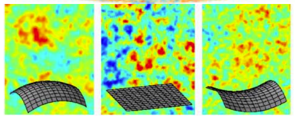
LHC and Dark Side of the Universe: Dark Energy

It appears that the rate of expansion of the universe is accelerating !!



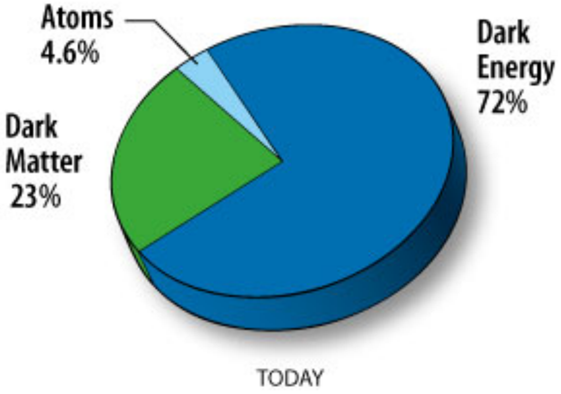
PLANCK





Simulated Closed Flat Open

"The Standard Model of Cosmology"



Dark Energy?

Remnant of some elementary scalar field analagous to the Higgs field?

Summary

- After twenty years of design, construction we are in the 2nd half of the journey - that of extraction of the science.

- The accelerator and the experiments have operated very well.
- The LHC experiments are physics producing engines!

- A "massive" discovery has been made – A Higgs boson.

The boson discovered appears just to be the one predicted by the SM.

- The Standard Model with a single "elementary" scalar doublet seems to work well (too well)
- No evidence found yet of physics BSM

- The discovery of Higgs boson is just the start of the exploration of the Terascale. Ahead is a major programme - in equal parts:
  - Precision measurements (not only of the new boson)
  - Searches for new particles and phenomena

Summary II

The discovery is a triumph for science and a tribute to

- **all the theorists** who built the SM, those who carried out detailed calculations of the many processes (including precise predictions for known physics),
- **all the accelerator builders and operations teams,**
- **all the technicians, engineers and the experimental physicists,**

who had the vision and tenacity to build and operate the superb accelerator and the experiments

We seem to have discovered a particle *sans precedent*

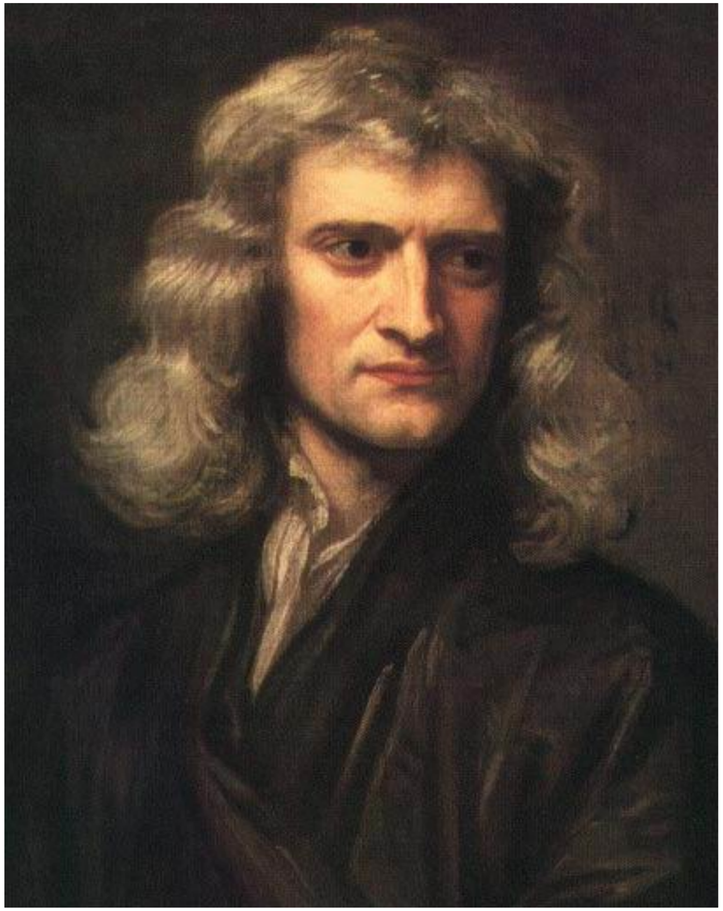
Likely to have far-reaching consequences on our thinking about Nature.

Must exploit the FULL potential of the LHC

“this includes the high luminosity upgrade of the accelerator and the experiments with a view to collecting ten times more data than in the initial design by around 2030”

European Strategy Group 2013

Epilogue



Sir Isaac Newton

I seem to have been only like a boy playing on the seashore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.

To me there has never been a higher source of earthly honour or distinction than that connected with advances in science.