

*Will show mostly ATLAS results — CMS usually similar

The LHC at the Dawn of a New High-Energy Frontier

Andreas Hoecker (CERN)

Colloquium Pittsburgh University
Dec 7, 2015

What is particle physics ?

Jiro Taniguchi, Furari, © Casterman (2012)



*It's all made of a handful
of particles and forces*

*Through its relation with
cosmology the study of
particles and forces is also
a journey back in time*

Jiro Taniguchi, Furari, © Casterman (2012)



Mankind's search for the **smallest unit of matter, its different forms, and the forces acting** is much, much older than particle physics

Particle physics is a term naming the search for the **ultimate laws of Nature**

*Everyday life, and
particle physics, are
described by the
Standard Model (SM)*

Jiro Taniguchi, Furari, © Casterman (2012)



The SM is **the** legacy of 20th century particle physics

- It unifies quantum mechanics, special relativity and field theory
- It describes ~ all laboratory data

Is the SM the theory of everything?
Or rather of almost everything? **Or ...**

*Year
when
energy
reached
in labs*

~ 2010

~ 1970

~ 1900

$L_{\text{gravitation}} \sim 10^{-35} \text{ m}$

$L_{\text{weak}} \sim 10^{-18} \text{ m}$

$L_{\text{strong}} \sim 10^{-15} \text{ m}$

$L_{\text{atomic}} \sim 10^{-10} \text{ m}$

10^{19} GeV

10^{16} GeV

10^{14} GeV

100 GeV

10 GeV

1 GeV

100 MeV

10 MeV

1 MeV

100 keV

10 keV

1 keV

100 eV

10 eV

1 eV

100 meV

10 meV

0

Planck scale (M_{Pl})

GUT ?

ν_R ?

t, Z, W, H, EWSB

ψ, b, Y, B

$\tau, c, n, p, \rho, \phi$

μ, s, π, QCD

$u, d, \text{nuclear binding } E$

e

core of Sun

atomic binding E

ν 's

$\downarrow$?

γ, g

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10^{19} GeV

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10^{14} GeV

10 TeV

1 TeV

100 GeV

10 GeV

1 GeV

100 MeV

10 MeV

1 MeV

100 keV

10 keV

1 keV

100 eV

10 eV

1 eV

100 meV

10 meV

0

Planck scale (M_{Pl})

GUT ?

ν_R ?

LHC reach

New Physics ?

t, Z, W, H, EWSB

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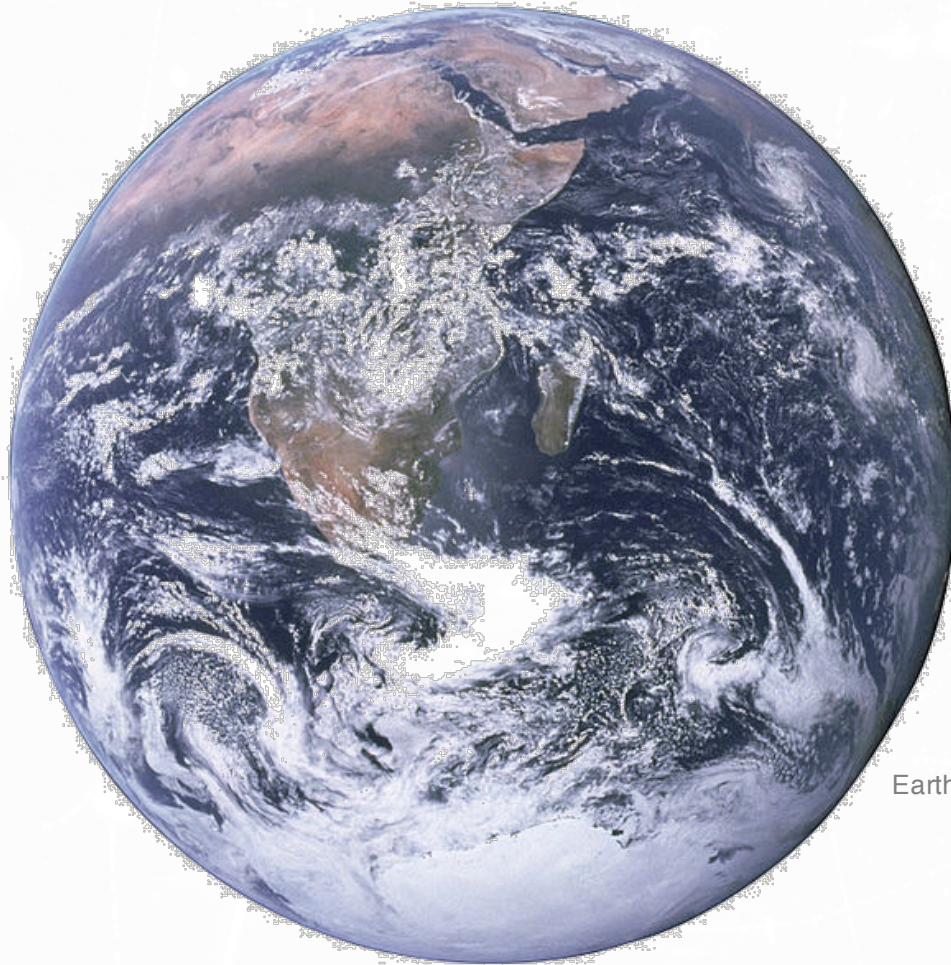
↓ ?

γ, g

...probing
attometer
scales

A 1 TeV-frequency microscope looks at really, really tiny objects...

Nanoscience



Earth

Particle physics today (TeV scale)



Siphonaptera (flea)

The Standard Model

The SM consists of 24 elementary matter particles and 3 forces with total of 26 parameters

Fermions

Matter particles

Organised in 3 families

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \quad \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \quad \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix}$$

6 Leptons

$$\ell$$

6 Quarks

$$q$$

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

Bosons

Force quanta

Distinguishing 3 forces

Photon

$$\gamma$$

3 weak bosons

$$W^\pm$$

$$Z^0$$

8 Gluons

$$8 \times g$$

Electro-magnetic force

Weak force

Strong force

Higgs boson

$$H^0$$

Degree of freedom belonging to field that breaks electroweak symmetry and generates boson and fermion masses

The Standard Model

Elementary particle physics is successfully described by **local gauge theories**

A problem: local gauge symmetry requires **massless spin-1 “gauge” (=force) boson**

This has been well verified for QED, with a massless photon (= infinite range)

However, the **W, Z bosons are massive** ($\rightarrow$ finite range $\sim 10^{-15}$ cm of weak interaction)

Only way to break gauge symmetry consistently is to **spontaneously break the symmetry of the vacuum** in the ground state:

$$M_{Z,W} \neq 0 \quad \Leftrightarrow \quad \langle 0 | \phi | 0 \rangle = v \neq 0 \quad [\text{non-zero vacuum expectation value}]$$

ϕ is a complex doublet field with non-zero vacuum expectation value.

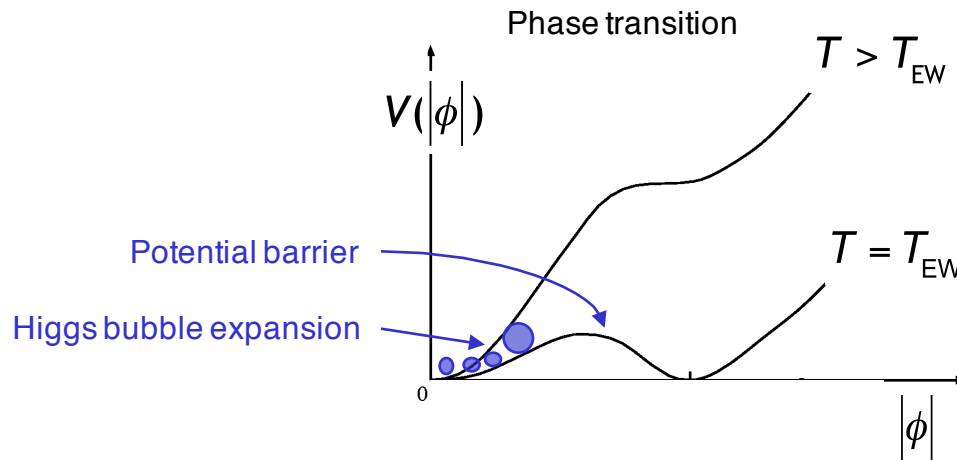
three d.o.fs become Z, $W^\pm$ masses, fourths d.o.f is **massive scalar Higgs boson**

This is known as the **“Englert-Brout-Higgs-Guralnik-Hagen-Kibble Mechanism”**

The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

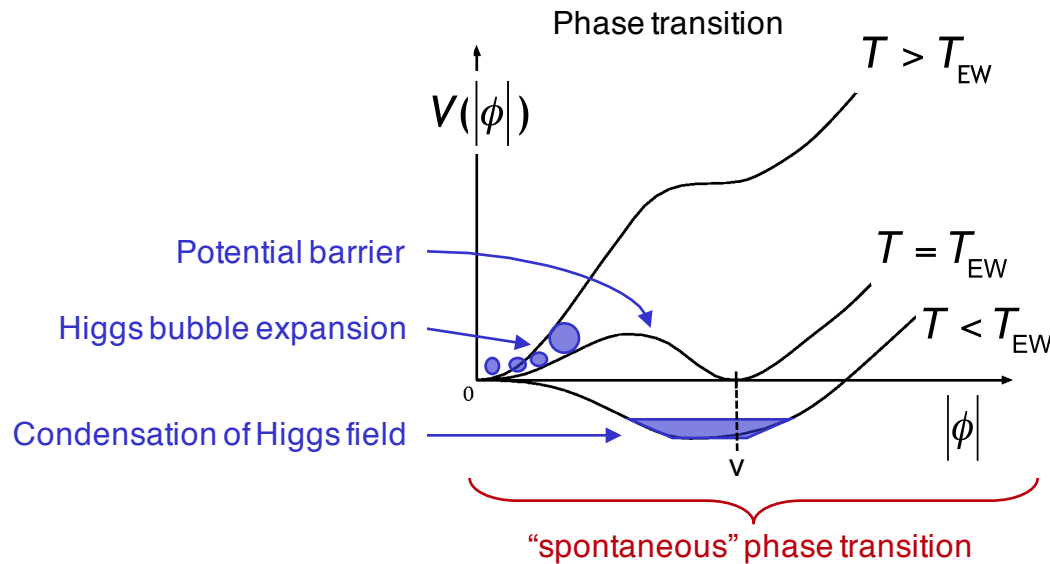
The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
A phase transition at $\sim T_{EW}$ ($\sim 10^{-10}$ s after big bang) led to $|\phi_{min}| > 0$



The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

The early universe, at $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
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Higgs potential: $V(\phi) = \mu_{<0}^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$

(μ, λ determined once Higgs mass known)

Simplest scalar potential that breaks ground state symmetry. Does what we need, but bears fundamental problems.

Carries the seeds of new physics ...

The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

Symmetric phase – early universe

Gravity 

Photon 

Weak boson 

Neutrinos 

Electrons 

Top quark 

H. Murayama

The Standard Model

Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

Early universe: symmetric phase,
fundamental particles are massless
→ gauge symmetry is respected

A Higgs field displaces ground state
breaking gauge symmetry

It fills all space time (but without
orientation as it has no spin)

Particles interact with Higgs field and
effectively reduce their velocity.
Acquired mass proportional to
interaction strength

→ Action of the Higgs field
creates “vacuum viscosity”

Higgs quantum liquid in broken phase

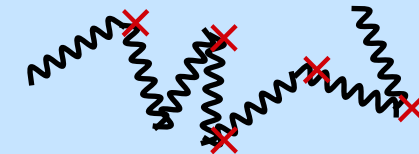
Gravity



Photon



Weak boson



Neutrinos



Electrons



Top quark



H. Murayama

Massive particles
interacting with the
condensed Higgs field

*... like fireflies in the
night sky of Ochiai*



The Higgs boson – last of the particles ?

The SM predicts all its properties, except
for its mass. What was known about it ?

Full references for mechanism:

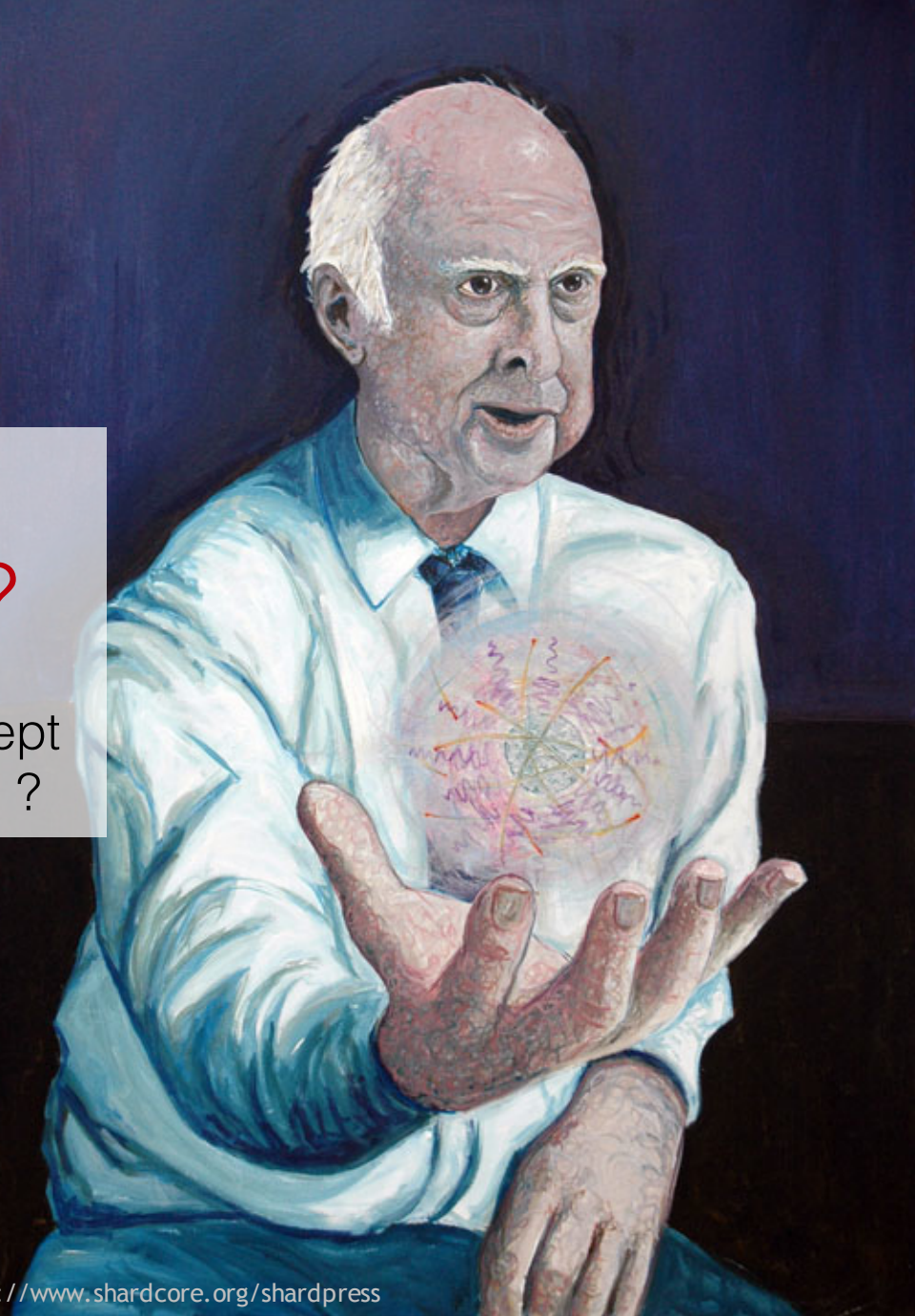
F. Englert and R. Brout, PRL 13 (1964) 321.

P.W. Higgs, PRL 13 (1964) 508.

G. Guralnik, C. Hagen, and T.W.B. Kibble, PRL 13 (1964) 585.

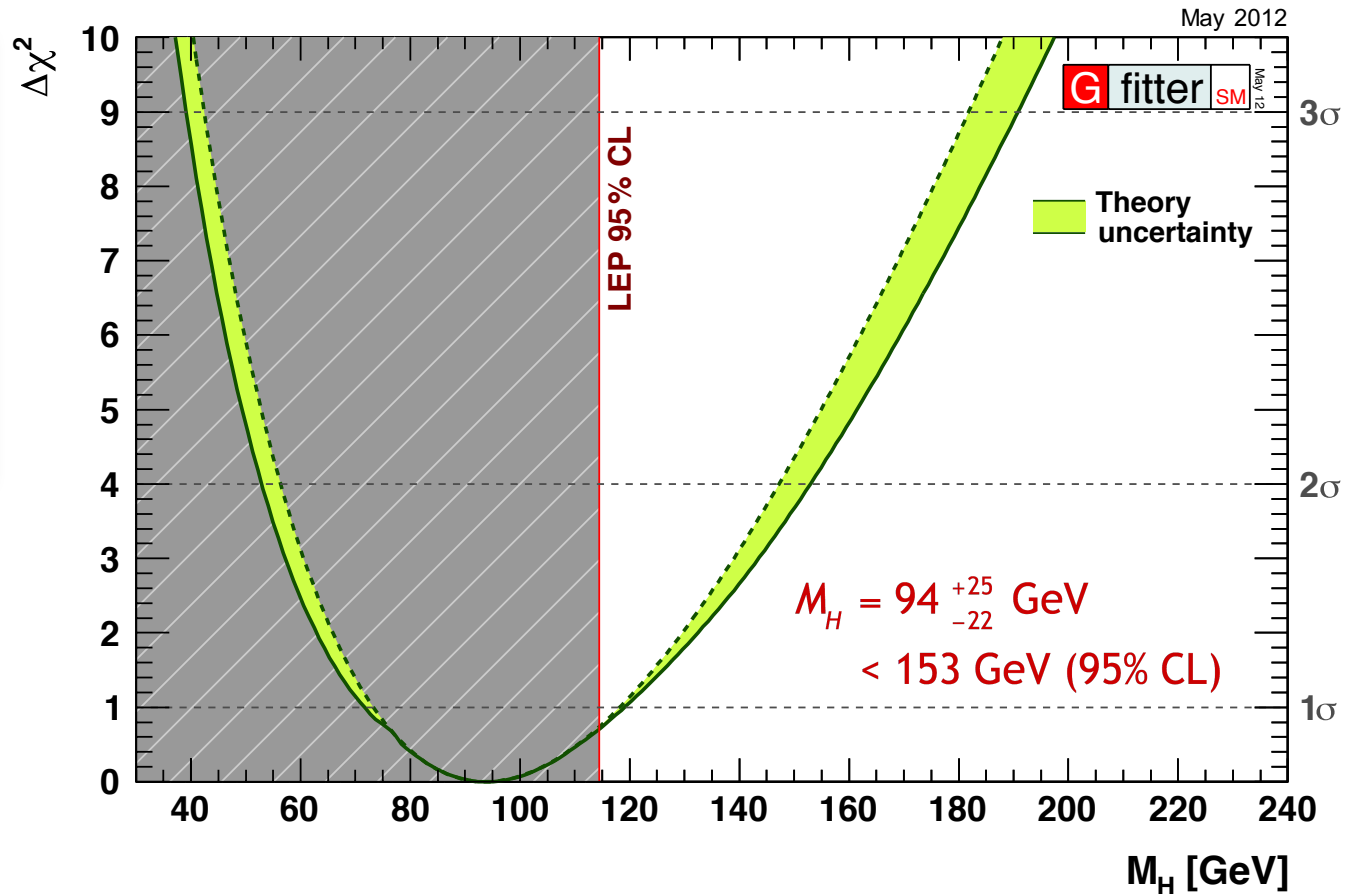
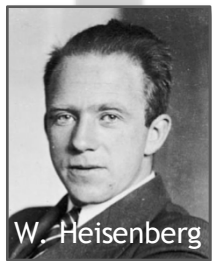
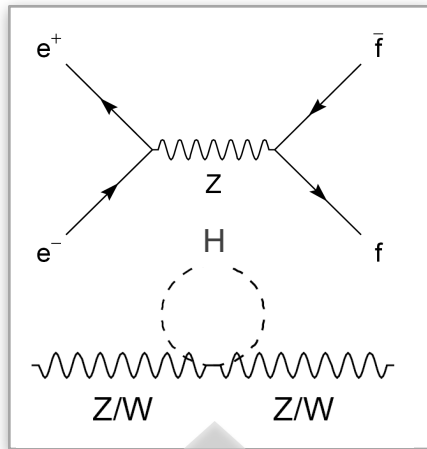
It should be noted that Landau and Ginzburg had proposed a field giving the photon a mass in a superconductor, the mathematics of which is identical to the “Higgs mechanism” and predates it by several years.

<http://www.shardcore.org/shardpress>



Constraints from global electroweak fit

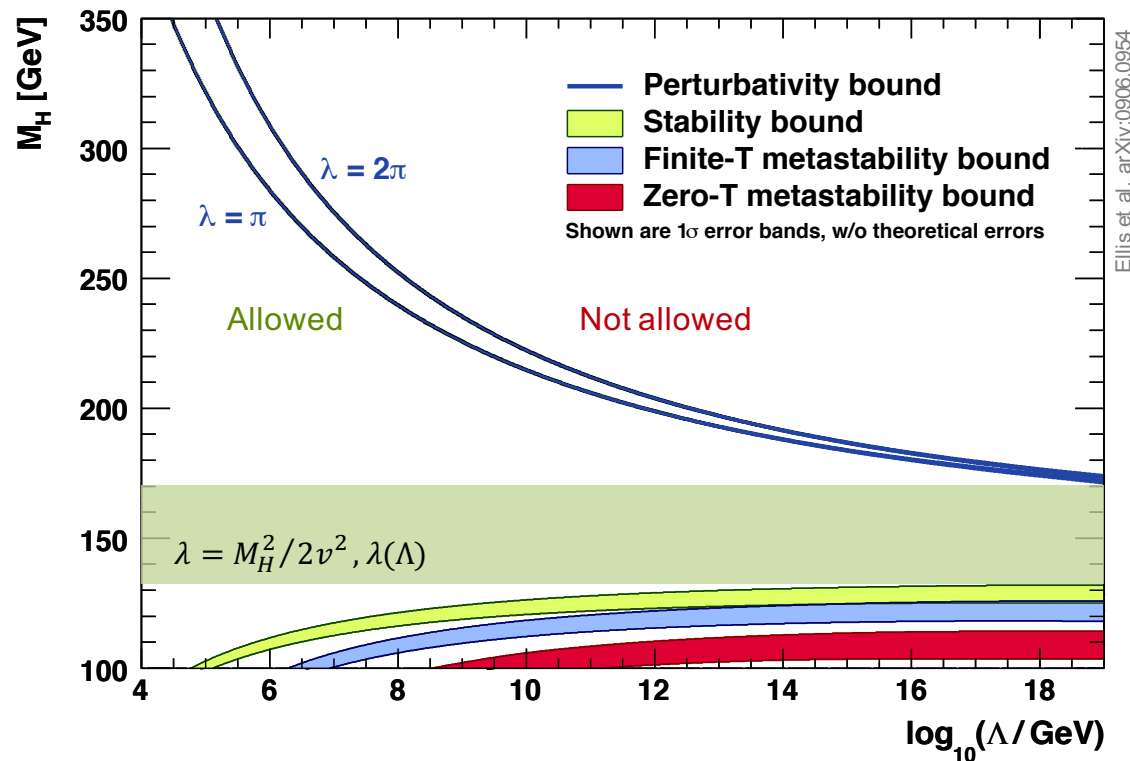
Global fit of all EW precision measurements to SM prediction constrains M_H



<http://gfitter.desy.de>

The Higgs boson should not be too light, and not too heavy...

Perturbativity and (meta)stability bounds versus the SM cut-off scale Λ



The SM Higgs must steer a narrow course between two disastrous situations if the SM is to survive up to the Planck scale $M_P \sim 2 \times 10^{18} \text{ GeV}$

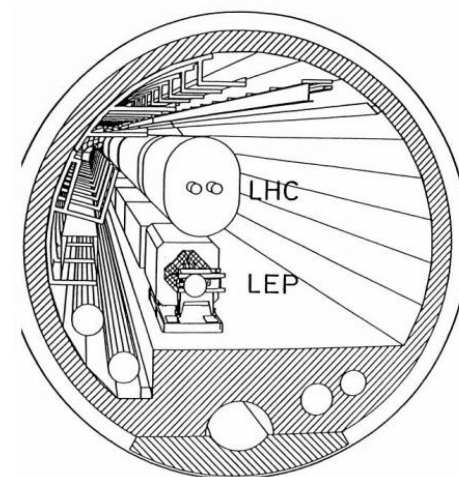
Global Effort → Global Success

Results today only possible due to
extraordinary performance of
accelerators – experiments – Grid computing

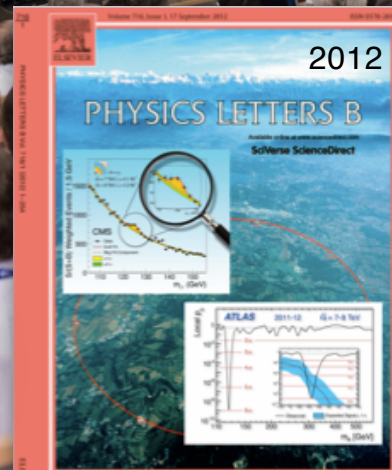
Observation of a new particle consistent with
a Higgs Boson (but which one...?)

Historic Milestone but only the beginning

Global Implications for the future



Duration of projects / planning stability:
1st LHC workshop 1984 (CERN & ECFA)
ATLAS & CMS Letter of Intents: 1992



**PRESS
COVERAGE**
after July 4th seminars at CERN

Global Effort → Global Success

Results today only possible due to
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Observation of a new particle consistent with
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Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine

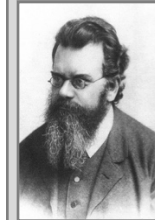


Lawrence

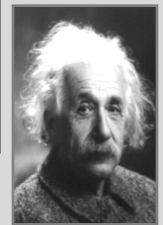
Particles accelerators:

- Look deeper into matter (size $\sim 1/E$)
("powerful microscopes")
- Discover new heavier particles ($E = mc^2$)
- Probe conditions of the early universe ($E = kT$)

de Broglie



Boltzmann



Einstein

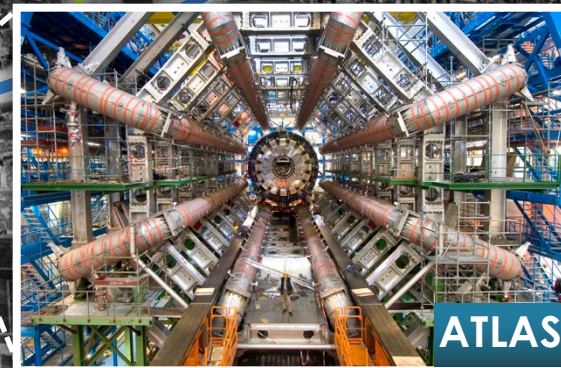
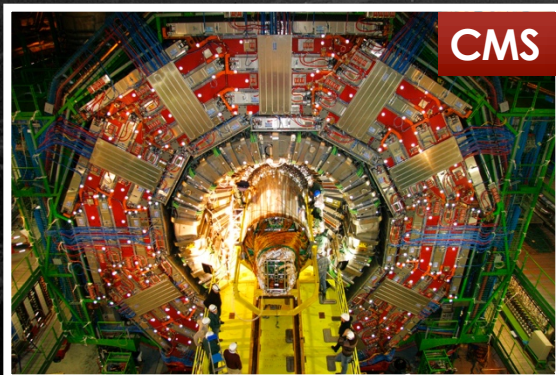
LHC ring at CERN:
27 km circumference

So far:
0.9 / 2.8 / 5 / 7 / 8 / 13 TeV proton–proton collisions
2.8 / 5 TeV Pb–Pb collisions
5 TeV p–Pb collisions

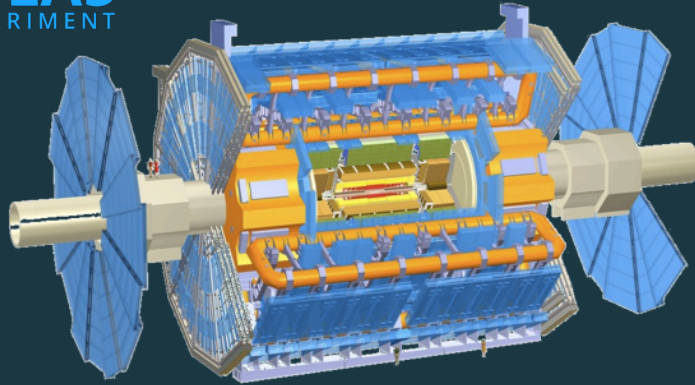
SPS ring:
7 km circumference

CERN (Meyrin site)

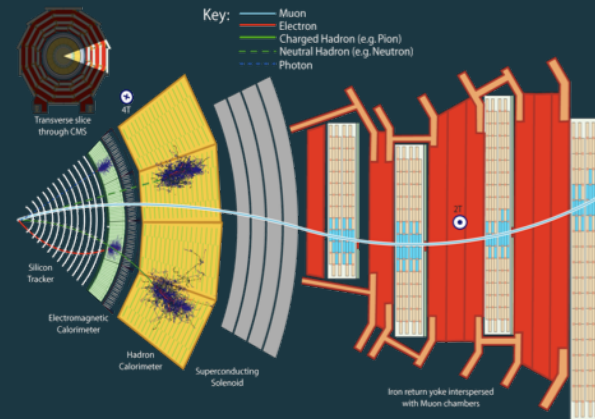




ATLAS & CMS: giant, ultra sophisticated particle detectors



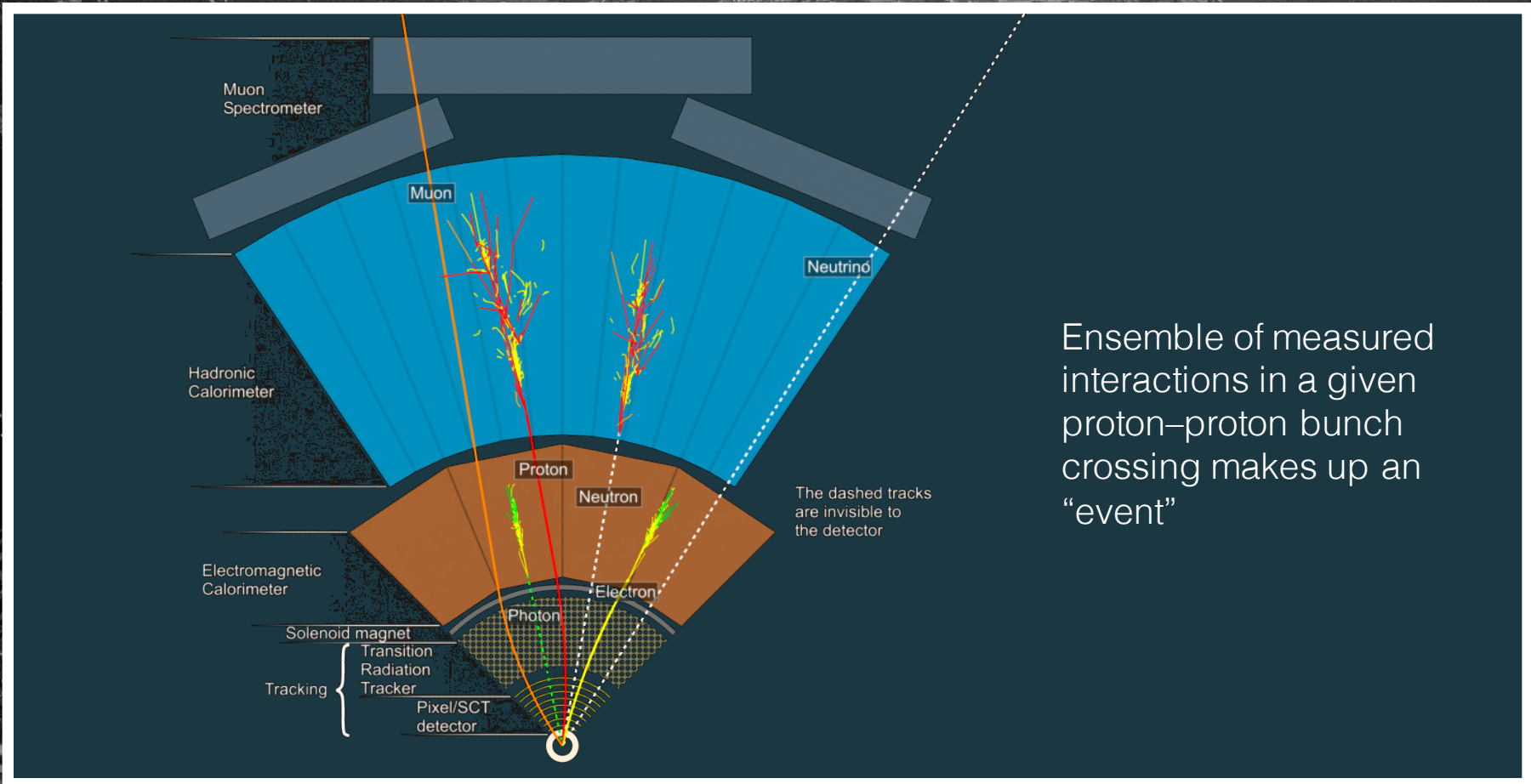
ATLAS: emphasis on excellent jet and missing- E_T resolution, particle identification, flavour tagging, and standalone muon measurement



CMS: emphasis on excellent electron/photon energy & track (muon) momentum resolution, and flavour tagging

Both: excellent hermeticity – very few “cracks”

The detectors measure interaction of particles with active material



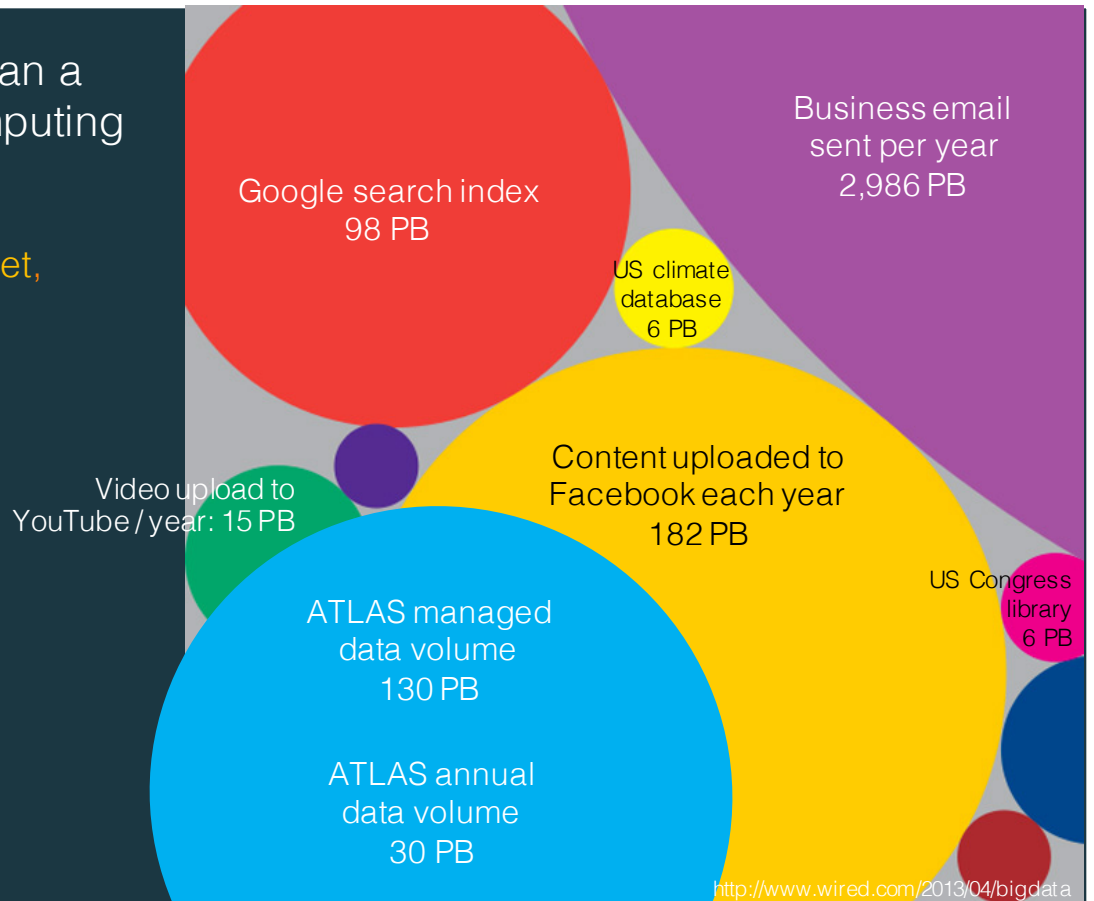
Ensemble of measured interactions in a given proton-proton bunch crossing makes up an "event"

LHC computing is big data

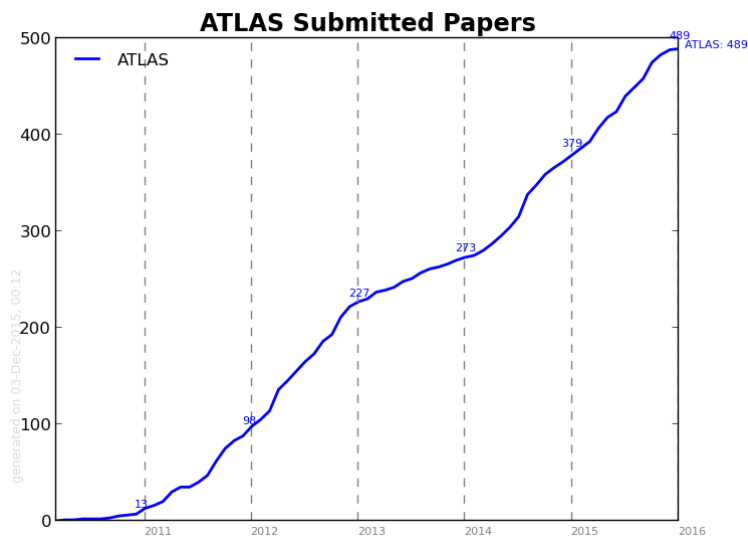
LHC experiments started more than a decade ago with large scale computing — now big data is everywhere

Note: LHC has a **public science budget**, unlike Google or Facebook

Largest data volume from simulated events, not from real collision data !



LHC Highlights from Run-1



ATLAS publications

<http://atlasresults.web.cern.ch/atlasresults>

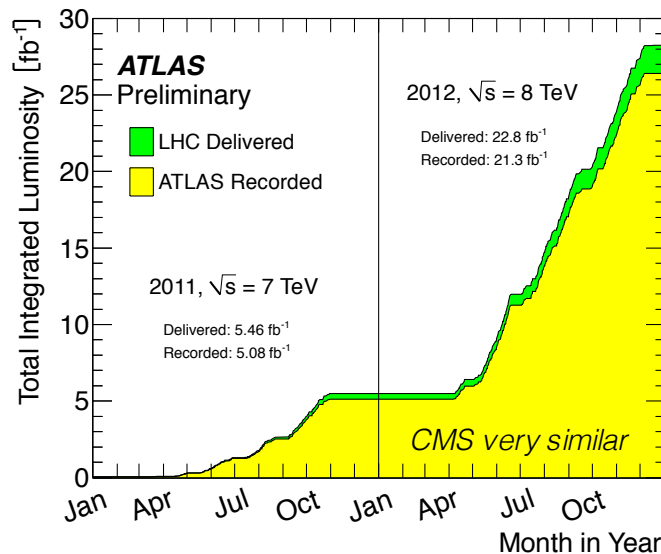
On Dec 7, 2015:

- ATLAS produced 489 papers on collision data (~half on measurements, ~half on searches)
- 666 preliminary conference notes

CMS very similar

LHC Highlights from Run-1

Luminosity is key quantity:
rate = cross section $\times$ efficiency $\times$ luminosity

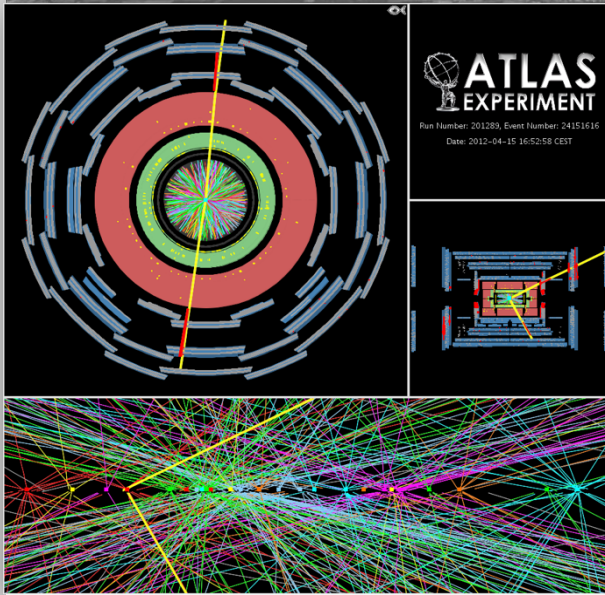


Run-1 luminosity profile

Total production:

- $L_{\text{int,recorded}} = 21 \text{ fb}^{-1}$ at 8 TeV
- $L_{\text{peak}} = 7.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$
- Max colliding bunches: 1380 with 50 ns bunch distance
- Max L_{int} / day: 286 pb^{-1}
- At L_{peak} every 45 min. 1 $H \rightarrow \gamma\gamma$, need ~ 2 typical 160 pb^{-1} fills to produced one $H \rightarrow 4l$

LHC Highlights from Run-1



High luminosity comes at price of pileup interactions

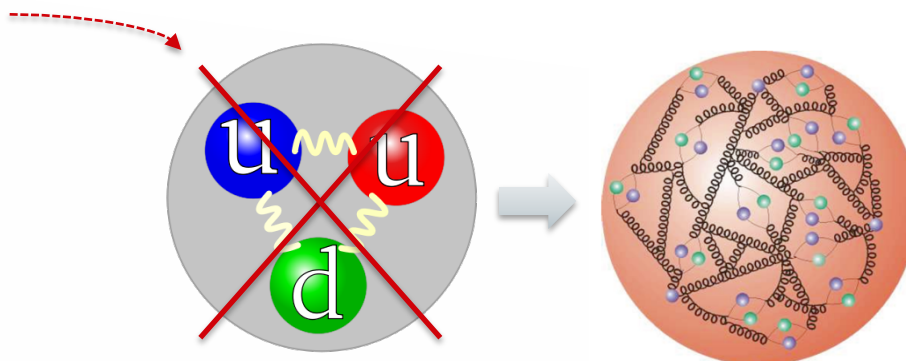
- Average of 21 (peak: 40) collisions per crossing in 2012
- Most analyses quite insensitive to pileup at this rate, several mitigation methods used
- Another price to pay: higher trigger thresholds → low- p_T physics suffers

Proton—Proton Collisions

- For proton–proton collisions, cross section is **convolution of Parton Density Functions (PDF) with parton scattering Matrix Element**

Parton distribution functions

Representing structure of proton,
extracted using experimental
data and QCD properties

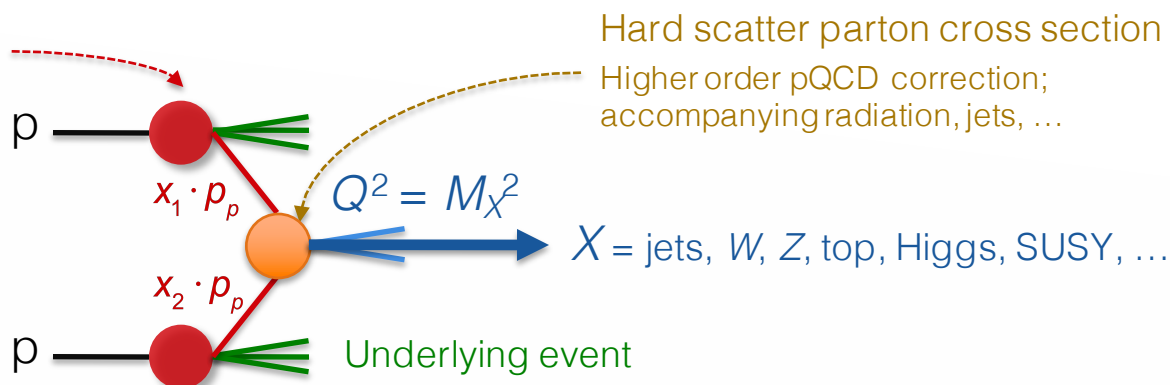


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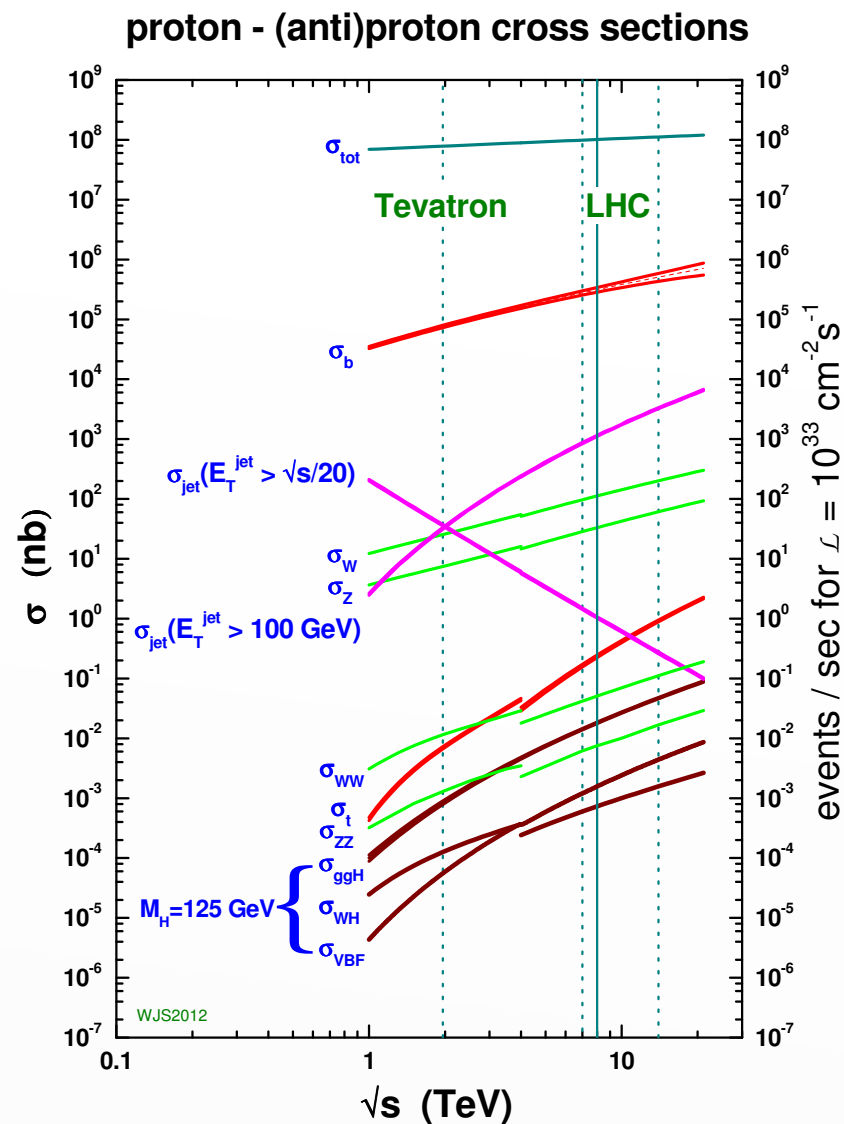
Representing structure of proton, extracted using experimental data and QCD properties



- CM energy-squared of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$
- The parton density functions rise dramatically towards low x :
 - Higher cross section at higher proton–proton collision energy
 - More luminosity also achieves higher achievable energy
 - Low- x regime (eg, Higgs production) dominated by gluon–gluon collisions: “gluon collider”

Proton—Proton Collisions

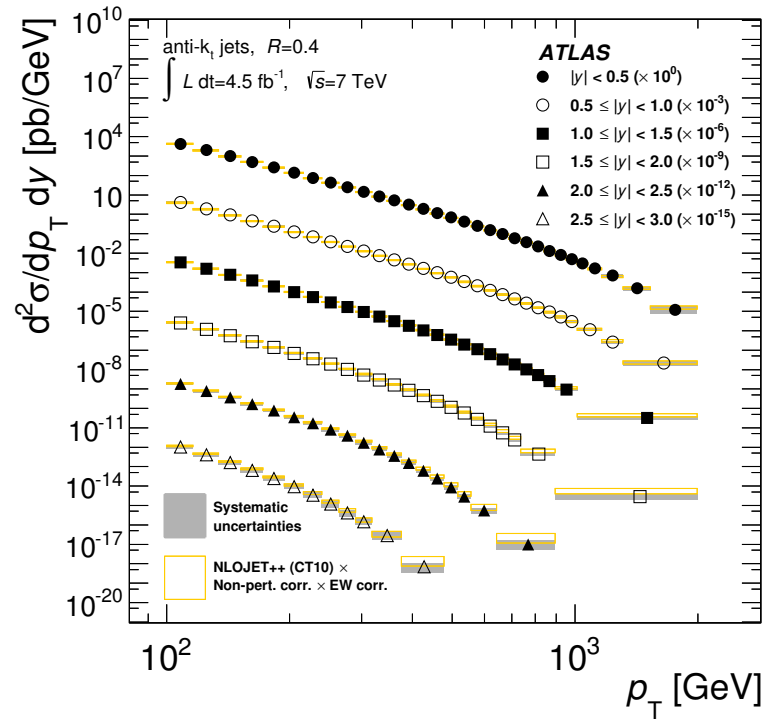
- Cross-section fully dominated by inelastic strong interaction “minimum bias” events
- Detectors cannot record 40 MHz event rate (each event ~ 2 MB size $\rightarrow 80$ TB / second)
- Online custom hardware and software “triggers” reduce rate to filter out events with a million & more times smaller cross-sections than minimum bias events
- Save ~ 1 kHz rate to disk (~ 2 GB / second)



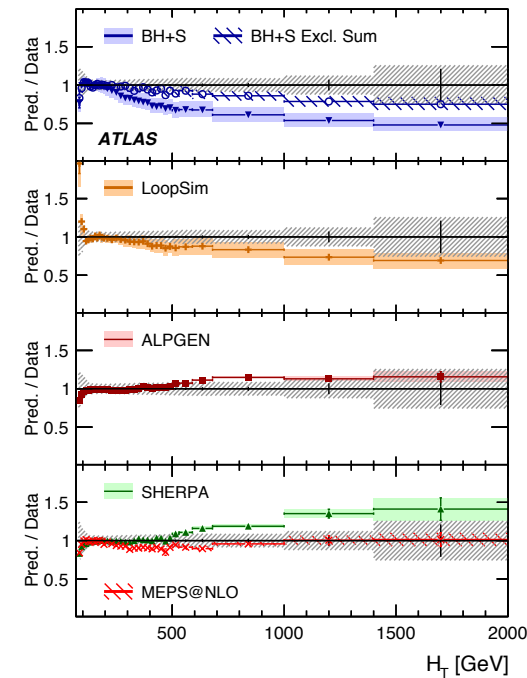
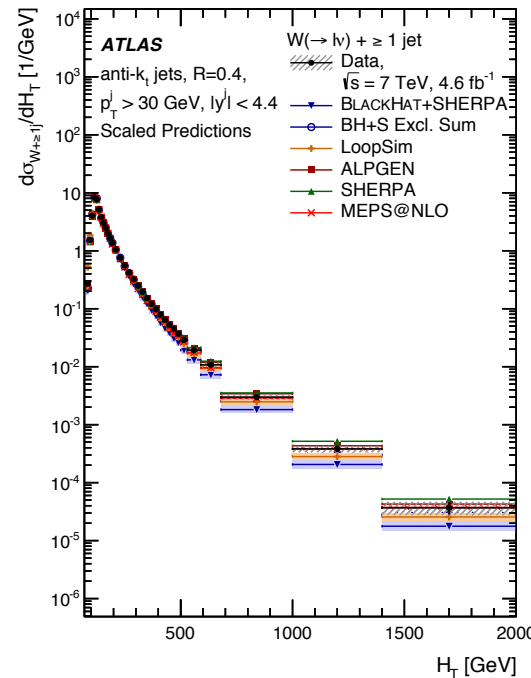
The theoretical approach to computing proton–proton interactions works very well in practice

ATLAS 1410.8857, 1409.8639

Double differential jet cross section vs. jet p_T and η



Cross-section of W + jets production versus scalar p_T sum (H_T)
Precise tests of NLO matrix element calculations matched to parton shower models



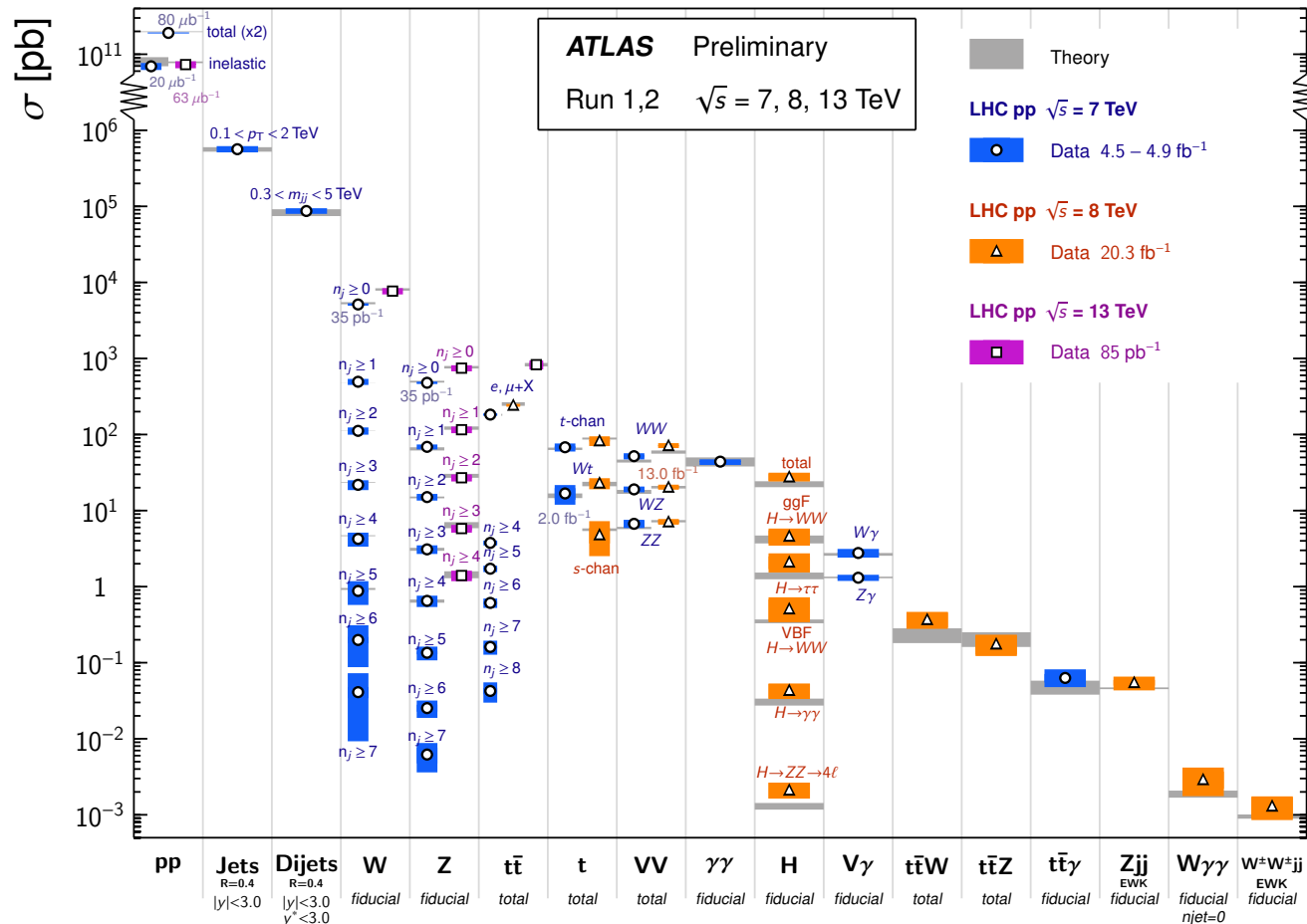
Precision measurements & theory developments $\rightarrow$ new quality of QCD tests at hadron colliders

Theory so far agrees with all measured cross-sections

Across widely different processes

Standard Model Production Cross Section Measurements

Status: Nov 2015



Harvest of cross-section measurements from LHC experiments confirmed the predictive power of the Standard Model

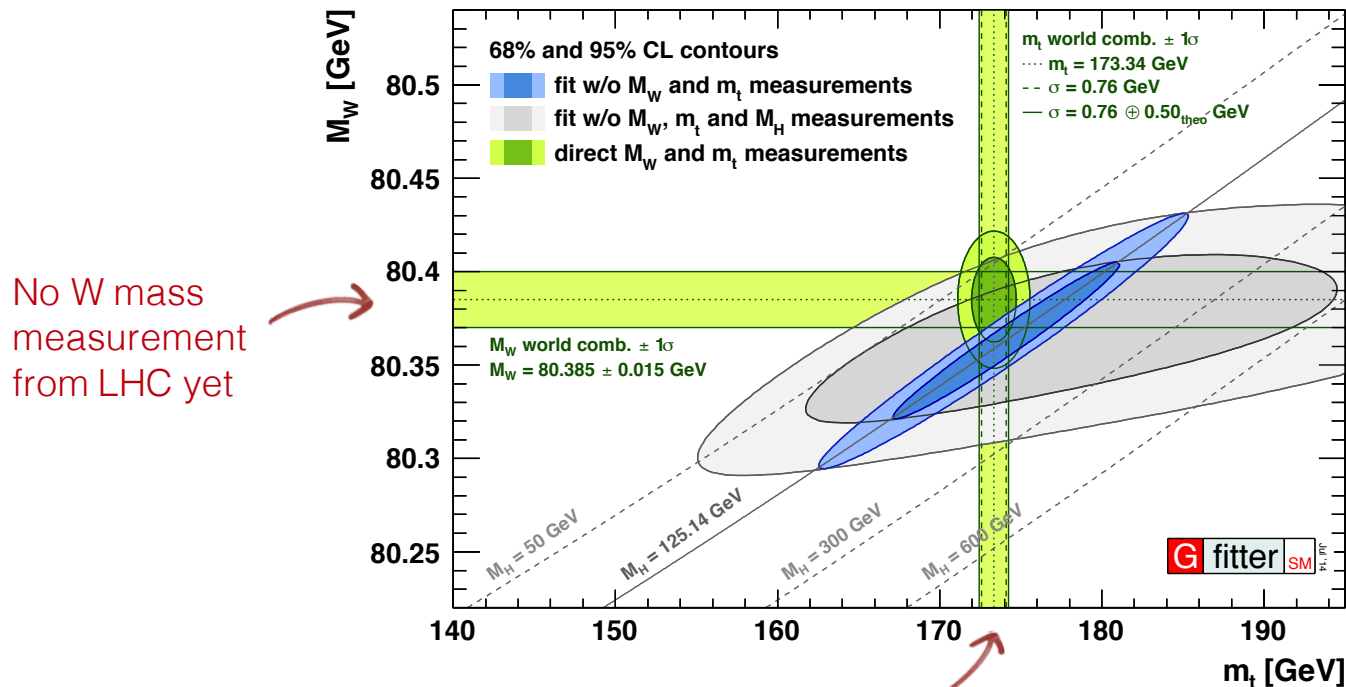
The LHC is also a precision machine

Electroweak sector requires precise measurements of m_{top} , M_W and the weak coupling strength

ATLAS 1405.6241

First forward-backward measurements in $Z \rightarrow \ell\ell$ events by ATLAS, CMS and LHCb are interesting feasibility tests, but yet an order of magnitude below the LEP/SLD precision

Best current M_W measurement from Tevatron ($\sigma_{\text{WA}} = 15 \text{ MeV}$), no result from LHC yet



The LHC is also a precision machine

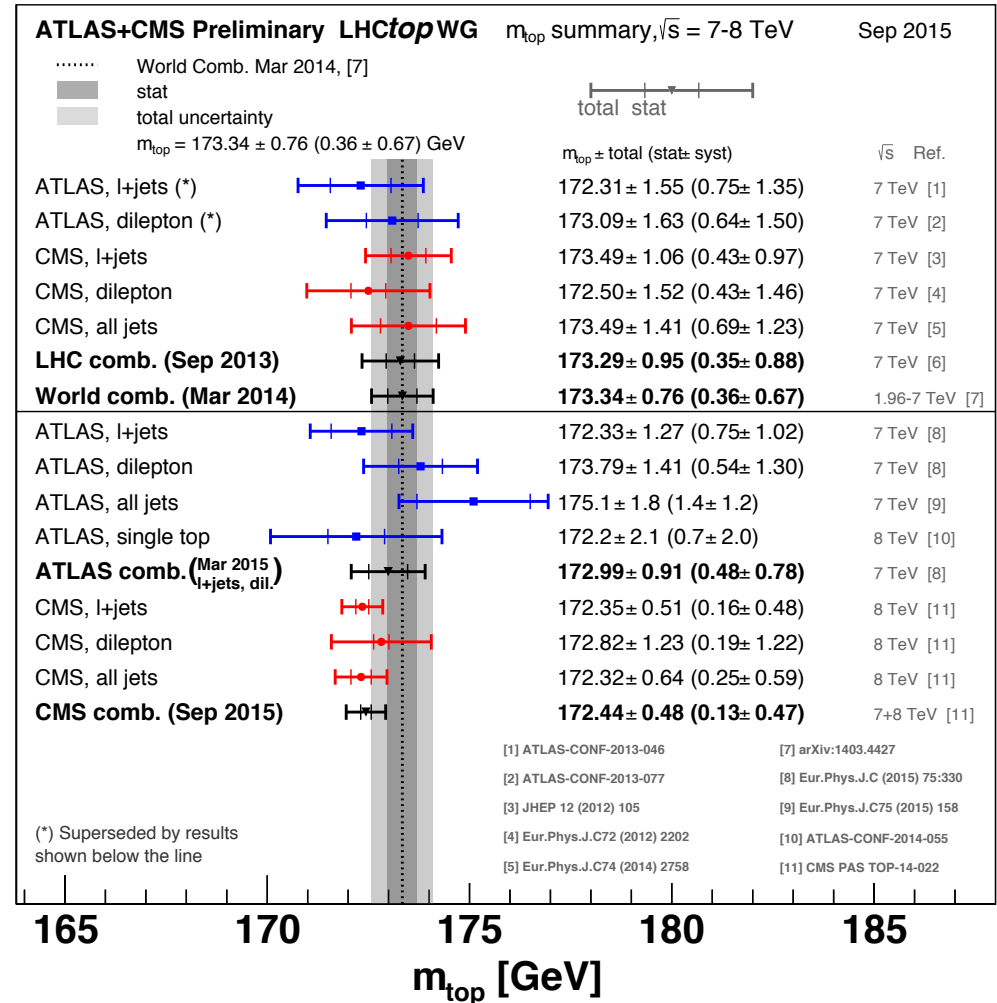
Electroweak sector requires precise measurements of m_{top} , M_W and the weak coupling strength

Newest top mass combination from CMS features total uncertainty of 480 MeV

640 MeV for Tevatron combination, ATLAS has no 8 TeV result yet

Important theoretical discussion on non-perturbative uncertainties

Alternative m_{top} determination via cross-section measurements

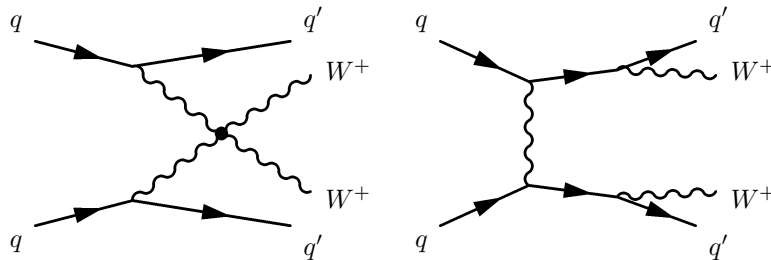


Run-1 allowed critical first electroweak studies

Higgs boson acts as “moderator” to unitarise high-energy longitudinal vector boson scattering

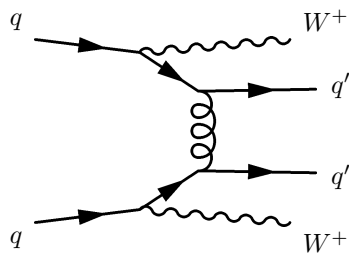
ATLAS 1405.6241

$W^\pm W^\pm$ + two jets production:



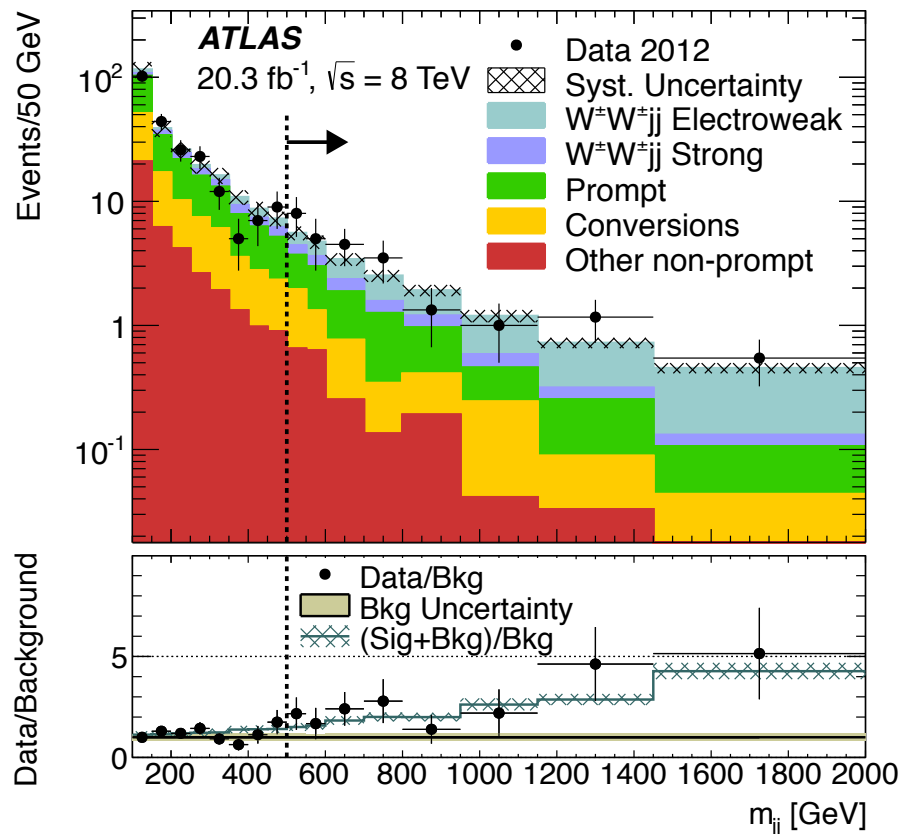
EW VBS production

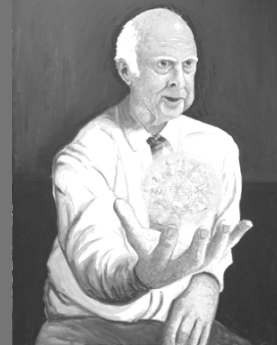
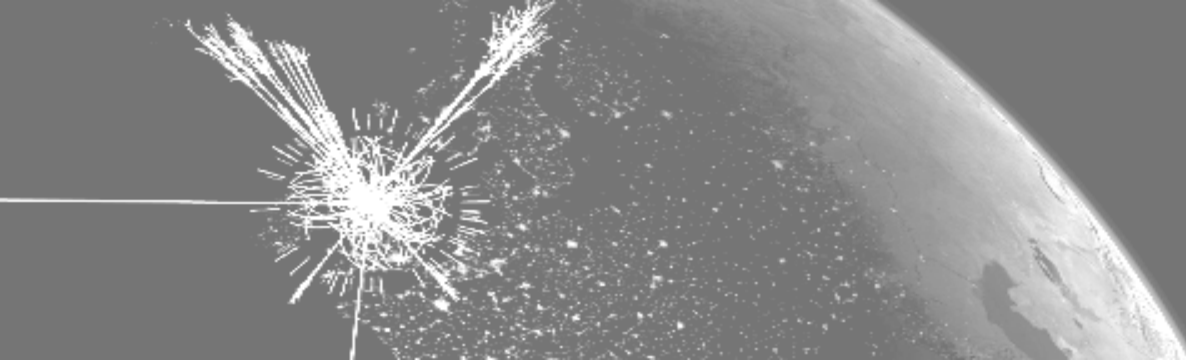
Non-VBS production



Strong production

Analysis provided first 3.6σ evidence for electroweak VBS production, ie, for VVVV scattering





Higgs Boson — Run-1 Masterpiece

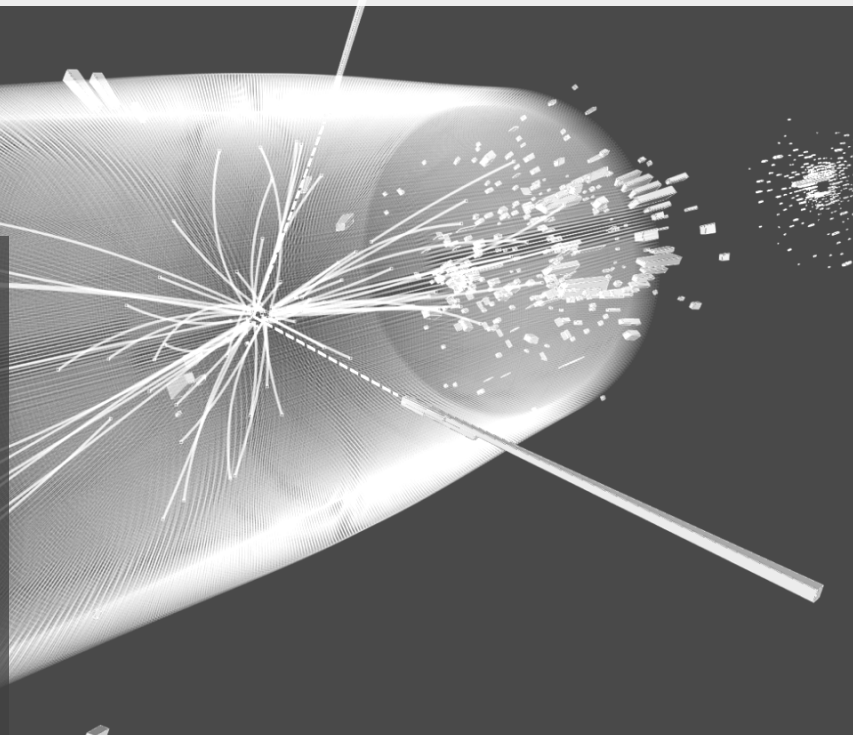
The Higgs boson had been vainly searched for at many accelerators

Best non-LHC 95% CL limits from LEP (CERN, 1989—2000) and Tevatron (Fermilab, 1990—2011):

$$m_H > 114 \text{ GeV}$$

$$147 \text{ GeV} < m_H < 179 \text{ GeV}$$

$$\text{EW fit: } m_H < 153 \text{ GeV}$$

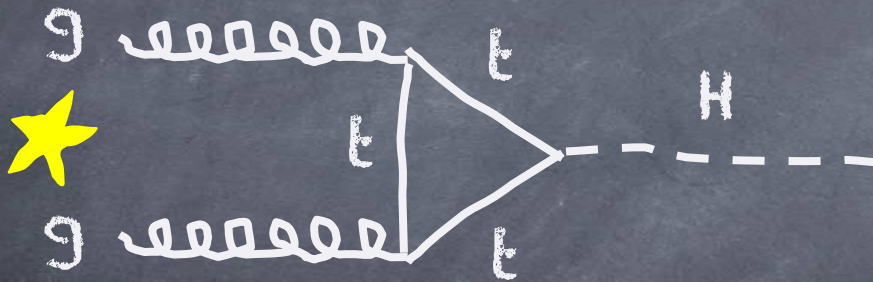


Higgs boson production at the LHC

Higgs production and decay probabilities predicted vs. Higgs mass by SM

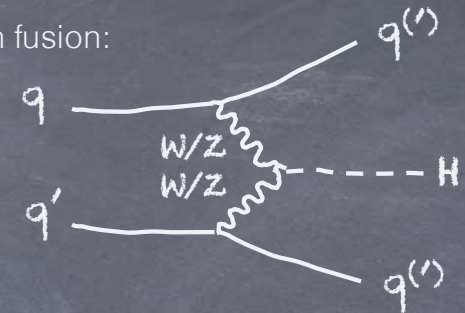
At the LHC, the Higgs boson is produced dominantly via gluon fusion $\sigma_{H,\text{total}} \sim 22 \text{ pb}$ at 8 TeV for $m_H = 125 \text{ GeV}$

Cross section steeply falling with Higgs mass



Total production of ~470 thousand SM Higgs bosons of 125 GeV in 2012 in each ATLAS and CMS

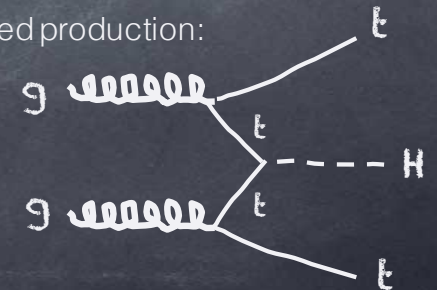
Vector boson fusion:



Higgs-strahlung:



"ttH" associated production:



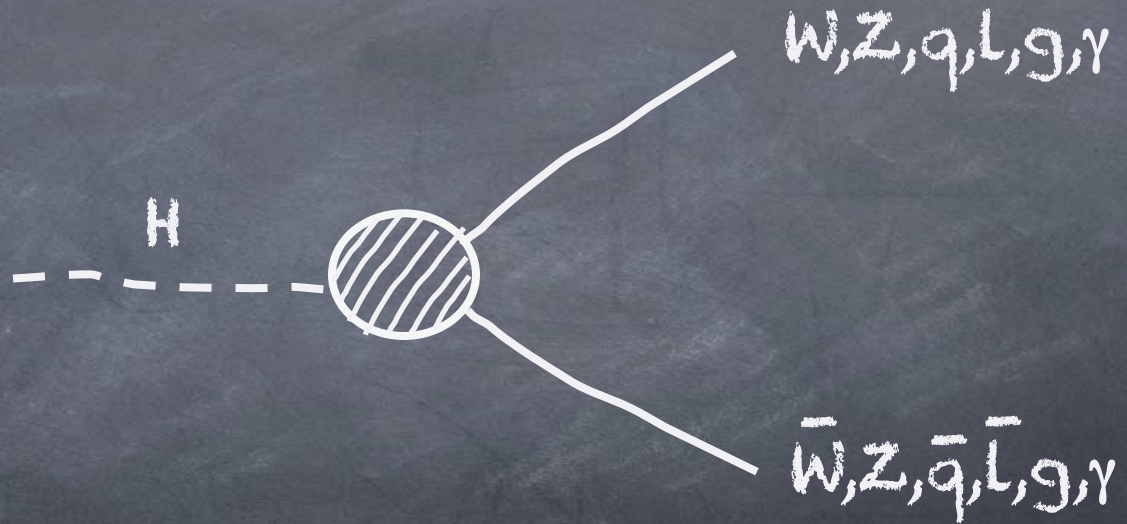
Higgs boson production at the LHC

Higgs production and decay probabilities predicted vs. Higgs mass by SM

Because of the coupling to the mass of the decay particles:

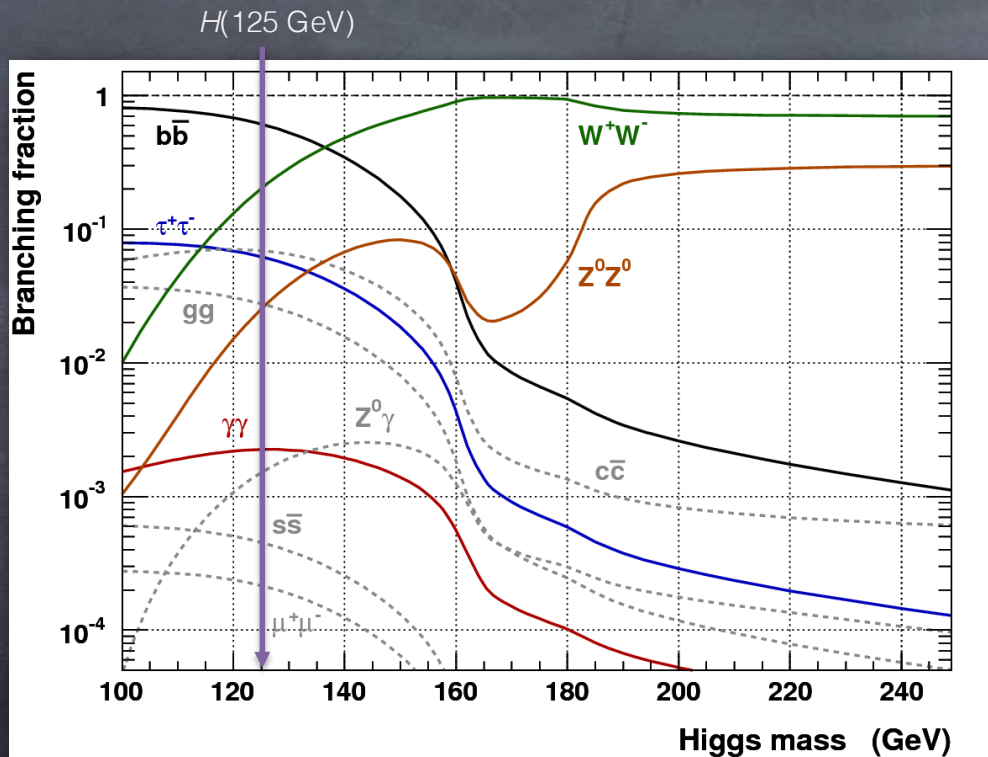
... the Higgs will decay with preference to the heaviest particles allowed

... the Higgs does not couple directly to photons and gluons, but only via “loops” involving heavy particles (e.g., top, W)



Higgs boson production at the LHC

Higgs production and decay probabilities predicted vs. Higgs mass by SM



For medium to heavy Higgs:

- Lepton final states via $WW^{(*)}$, $ZZ^{(*)}$

For light Higgs:

- Lepton final states via WW^* , ZZ^*
- Di-photon final state
- Di-tau final state

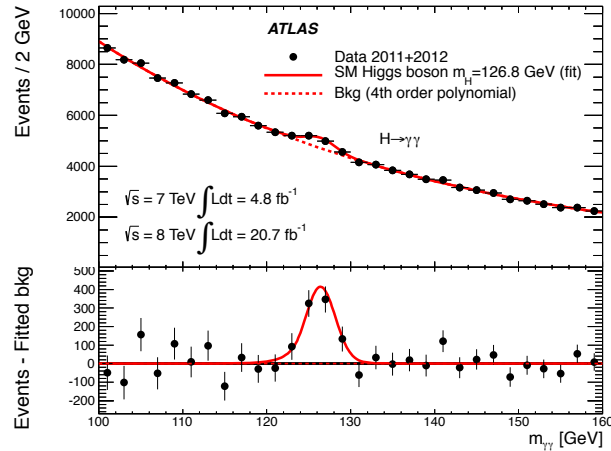
The dominant $H \rightarrow b\bar{b}$ mode is only exploitable in association with W/Z or $t\bar{t}$, also with strong Higgs boost

Associated leptons provide trigger signal as they help to reduce huge QCD background, $\sigma(b\bar{b}) \sim \mathcal{O}(100 \mu\text{b})$

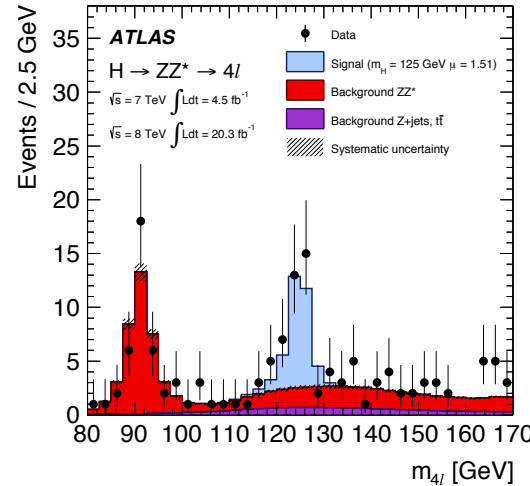
No doubt on H_{125} discovery in the bosonic channels

Much extended and improved Higgs analyses by both ATLAS & CMS since July 2012 discovery

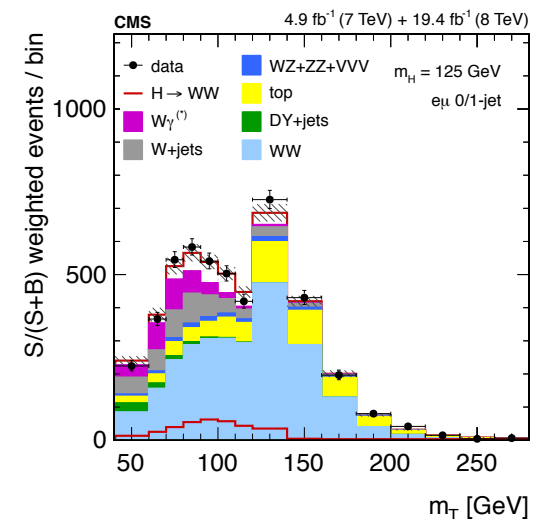
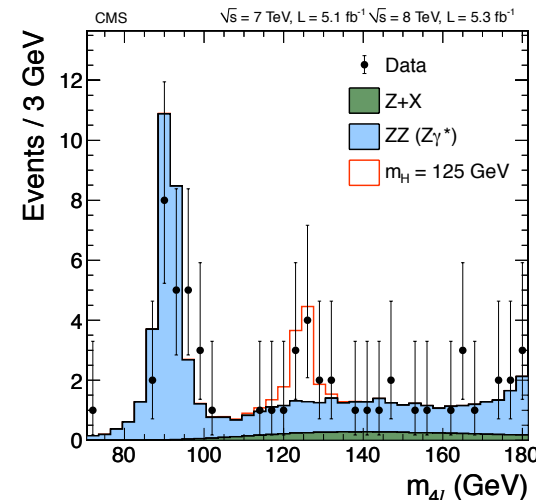
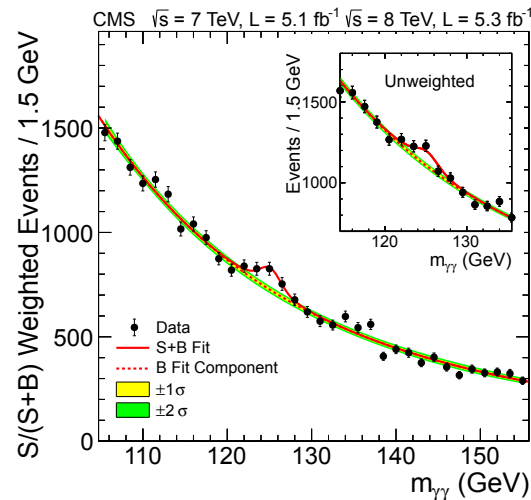
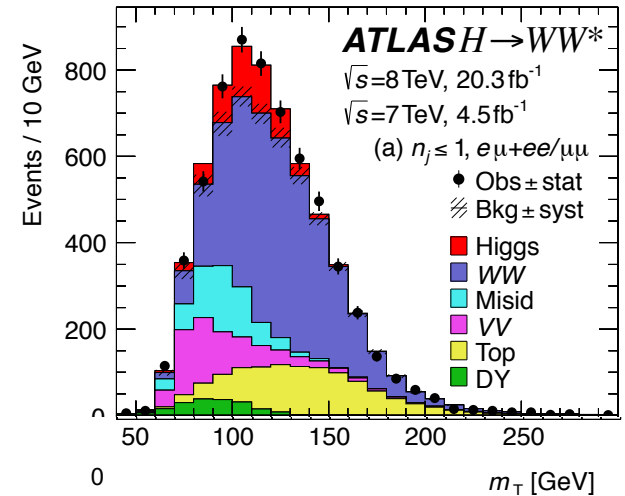
$H \rightarrow \gamma\gamma$



$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$

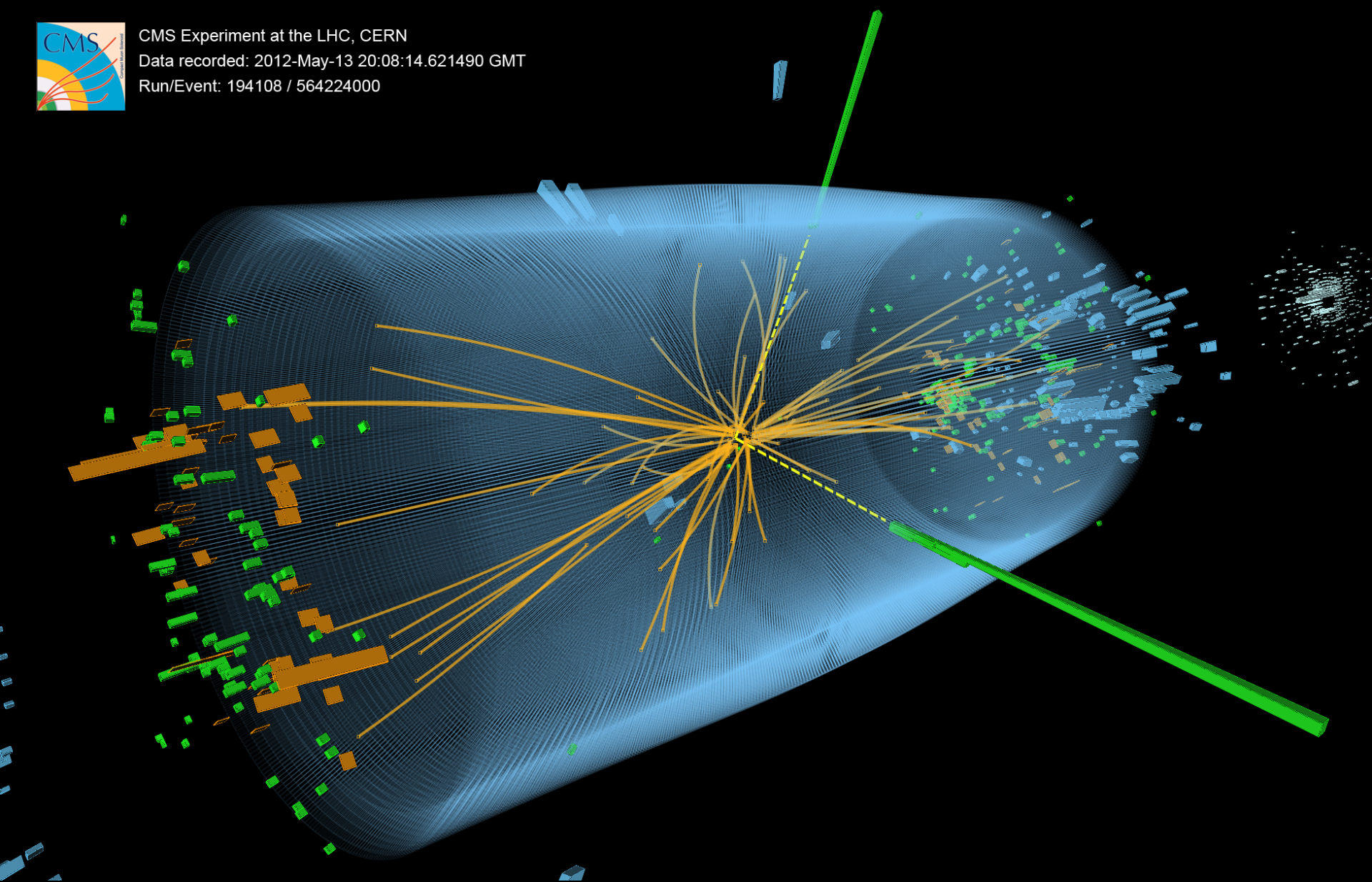


$H \rightarrow WW^{(*)} \rightarrow 2\ell 2\nu$

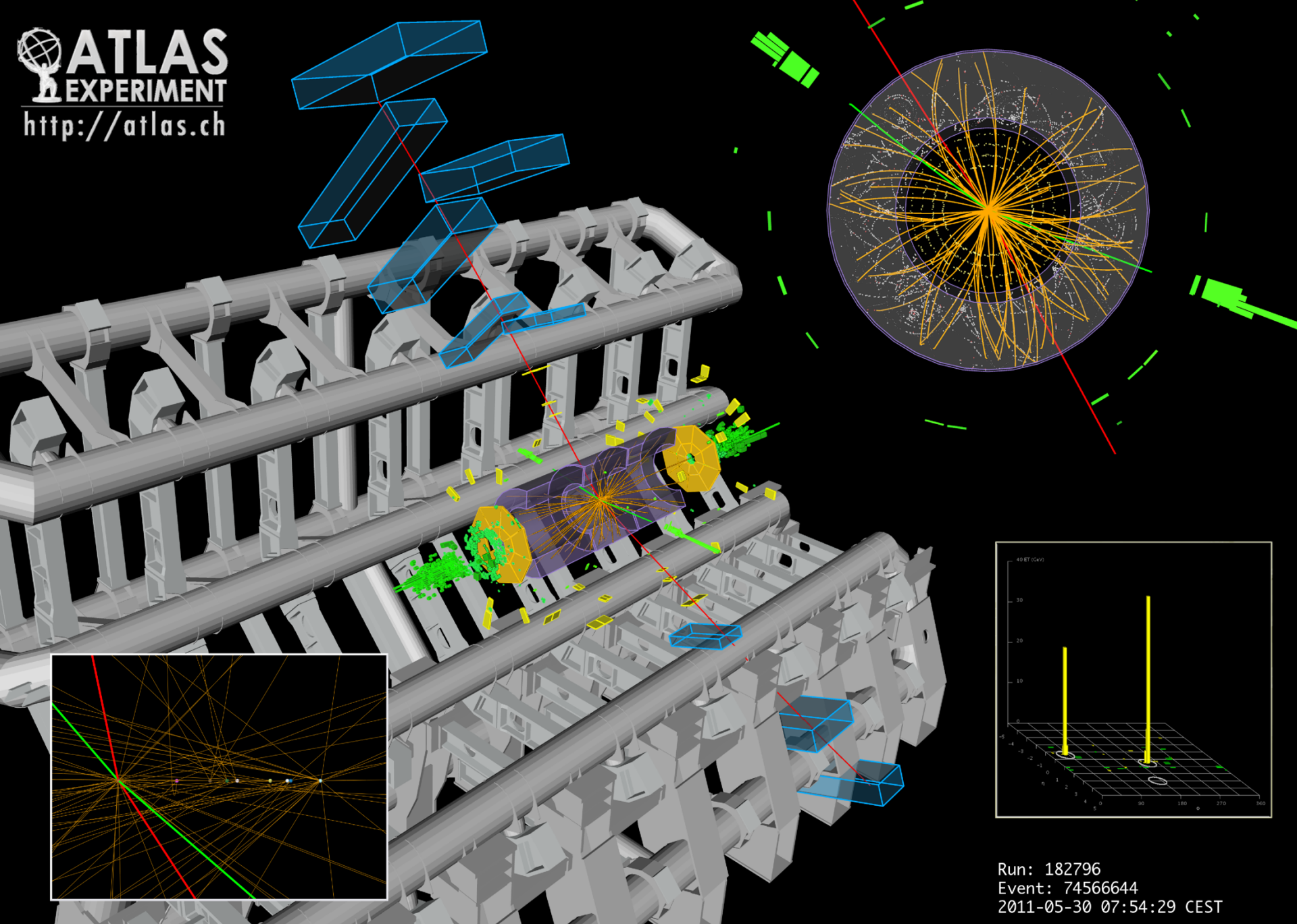




CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000



$H \rightarrow \gamma\gamma$ candidate event (CMS) — note: background dominated sample



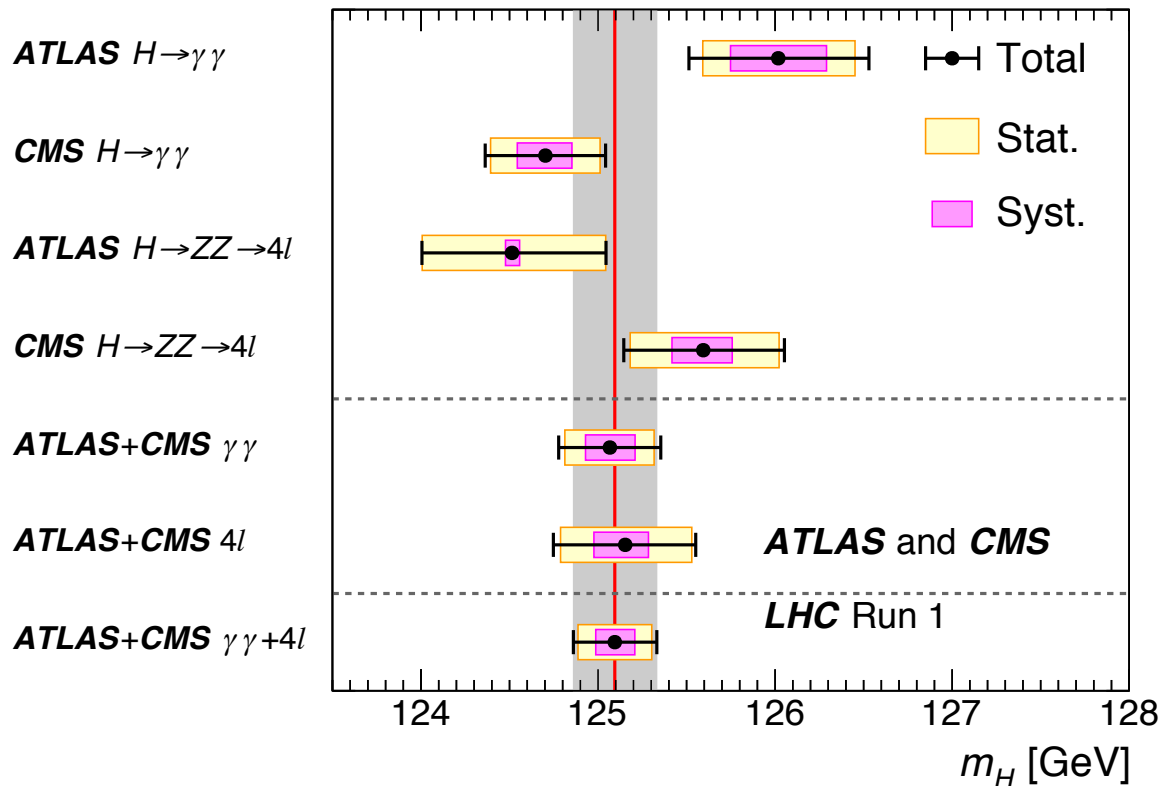
$H \rightarrow 2e2\mu$ candidate event (ATLAS)

ATLAS & CMS have joined forces

Combined mass and coupling measurements

ATLAS & CMS 1503.07589

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



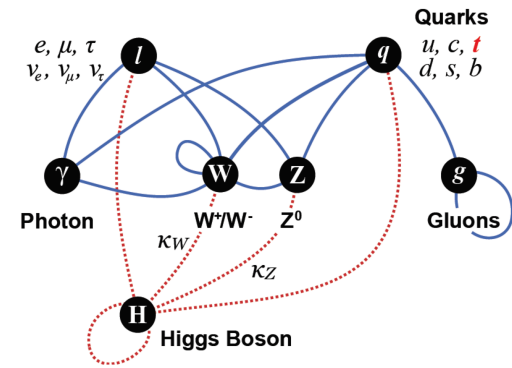
0.3% combined precision already!

Mass in agreement with EW fit

Knowledge of Higgs mass has huge impact on EW fit: SM prediction of m_W with 8 MeV precision

ATLAS & CMS have joined forces

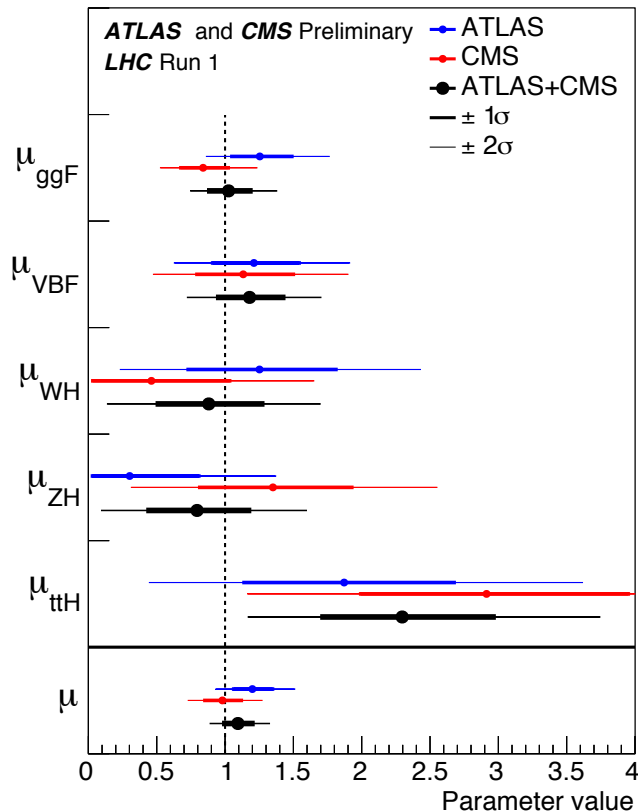
Combined mass and coupling measurements



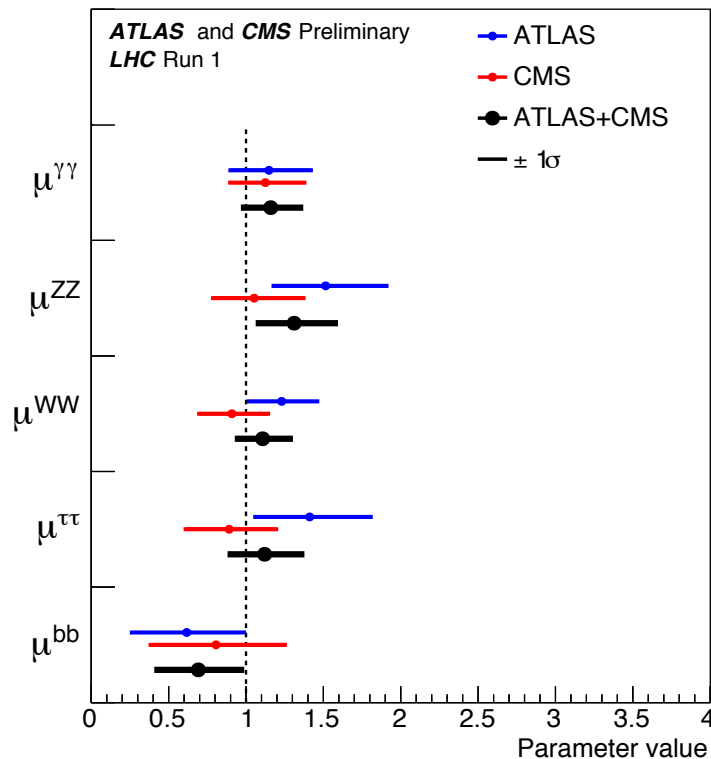
ATLAS-CONF-2015-044, CMS-PAS-HIG-15-002

Highly complex combination of couplings, simplified pictures of combined signal strength wrt. SM shown below. Overall: $\mu_H = 1.09 \pm 0.11$

Higgs **production** signal strengths



Higgs **decay** signal strengths



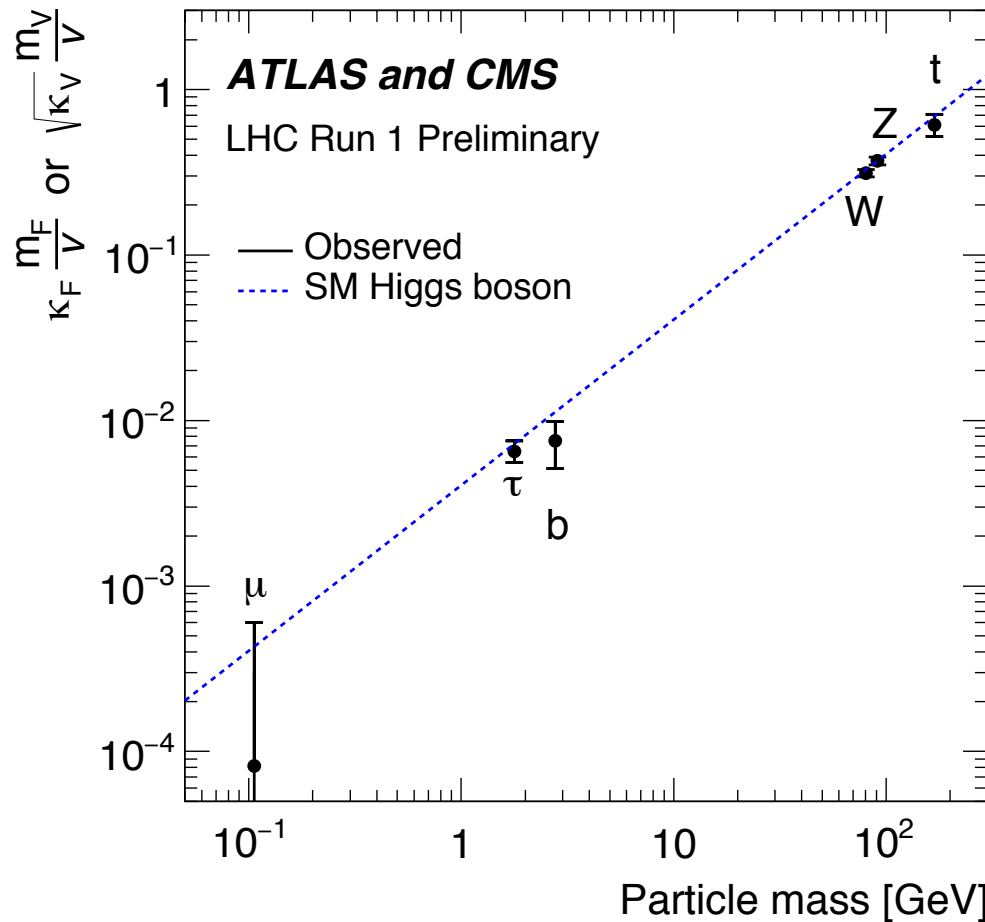
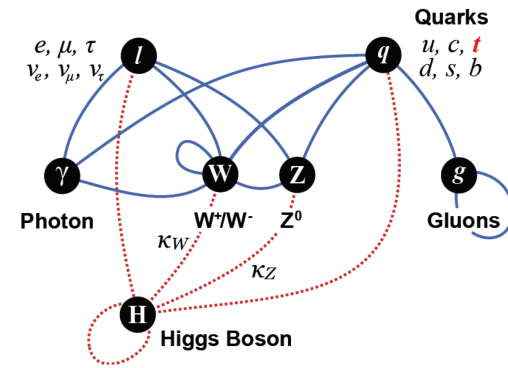
Excellent agreement among experiments

Combined observation of $H \rightarrow \tau\tau$ channel and VBF production

ttH channel a bit large:
4.4 σ significance (2.0 exp),
 $\mu = 2.3^{+0.7}_{-0.6}$

ATLAS & CMS have joined forces

Combined mass and coupling measurements



Higgs boson couples to matter particles (fermions) with a strength proportional to the particle's mass, and to force particles (bosons) with a strength proportional to the the particle's mass-squared

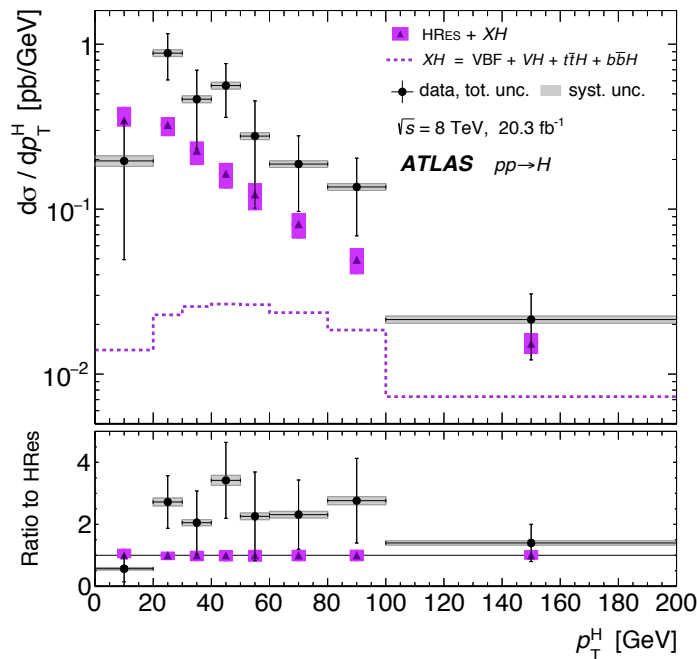
The Higgs boson appears SM-like

Large amount of additional experimental information

ATLAS 1504.05833, 1509.00672

Spin-parity measurements from angular distributions in $ZZ^{(*)}$, $\gamma\gamma$, $WW^{(*)}$ exclude other than 0^{+}

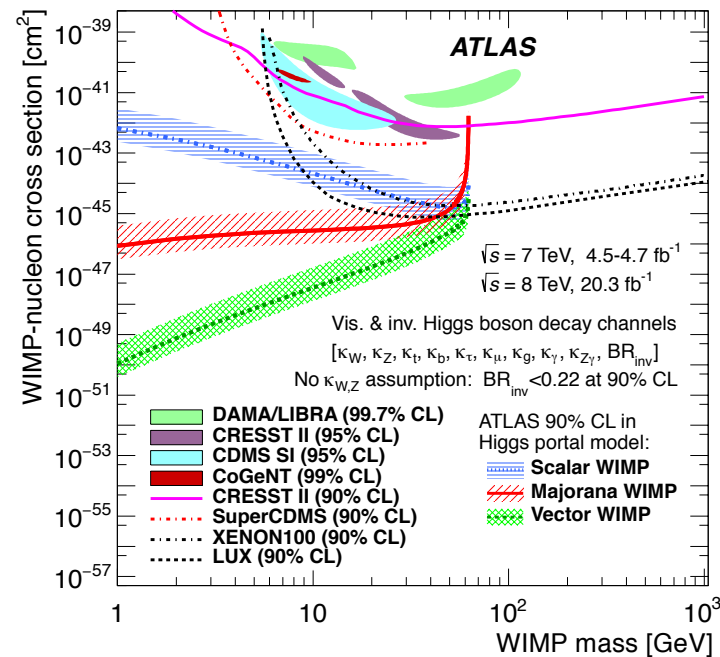
Differential cross-section measurements to increase sensitivity to new physics
(long-term project, needs much more data)



Invisible Higgs branching fraction constrained to $< 25\%$ (ATLAS)
→ dark matter constraint (model-dependent)

Also constraints on:

- spin/CP,
- anomalous off-shell couplings,
- forbidden decays (eg: FCNC)

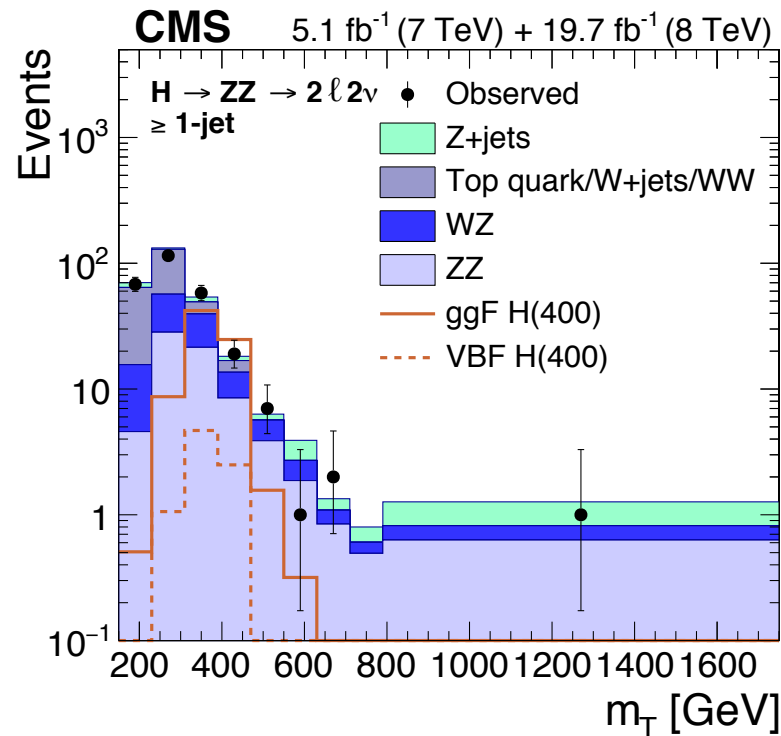


Does the Higgs boson have sisters or brothers?

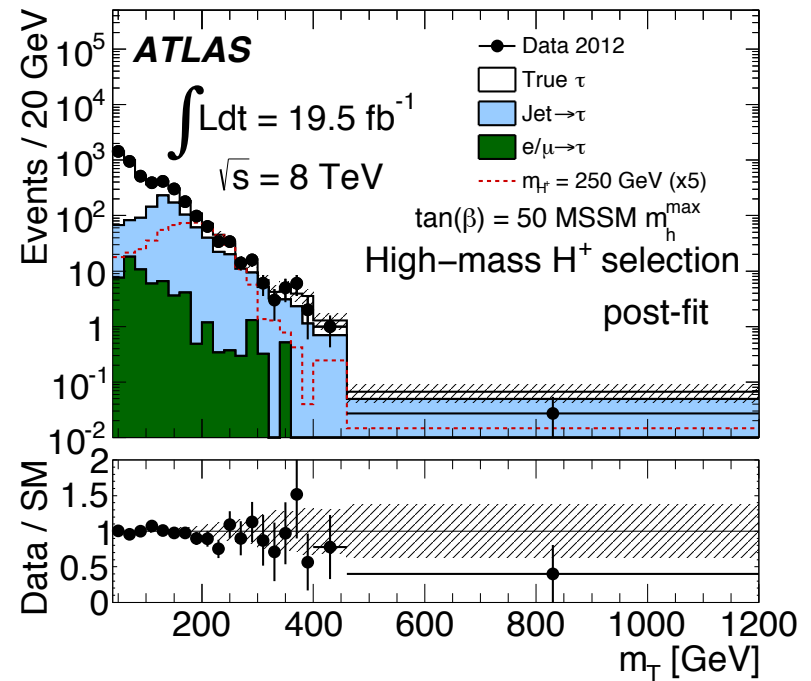
Many models predict more than one scalar doublet, eg, 2 doublets lead to 5 states: h , H , A , $H^\pm$

CMS 1504.00936, ATLAS 1412.6663

ATLAS and CMS performed numerous searches for other Higgs states — so far vain



Search for heavy $H \rightarrow ZZ$ (or WW)



Search for charged $H^\pm \rightarrow \tau\nu$
(also many indirect constraints on $H^\pm$)

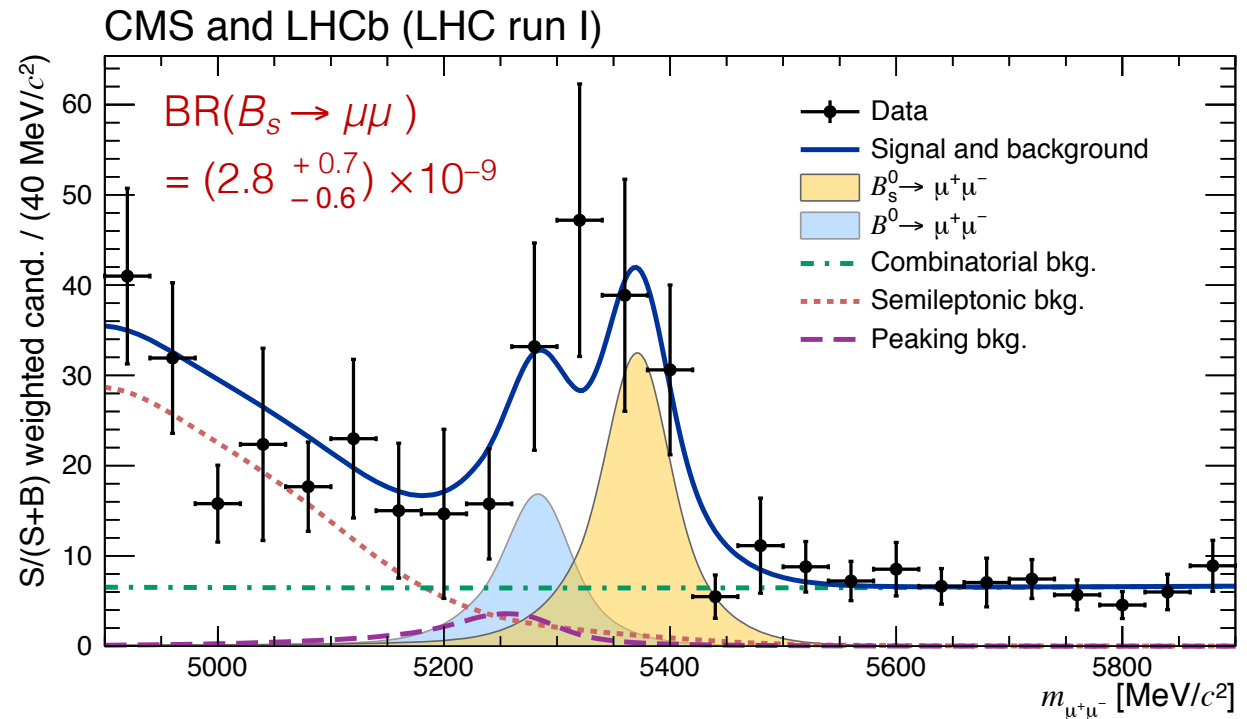
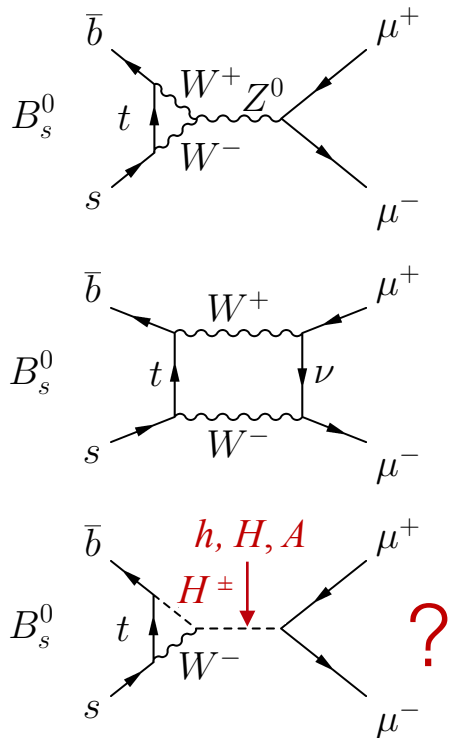
Does the Higgs boson have sisters or brothers?

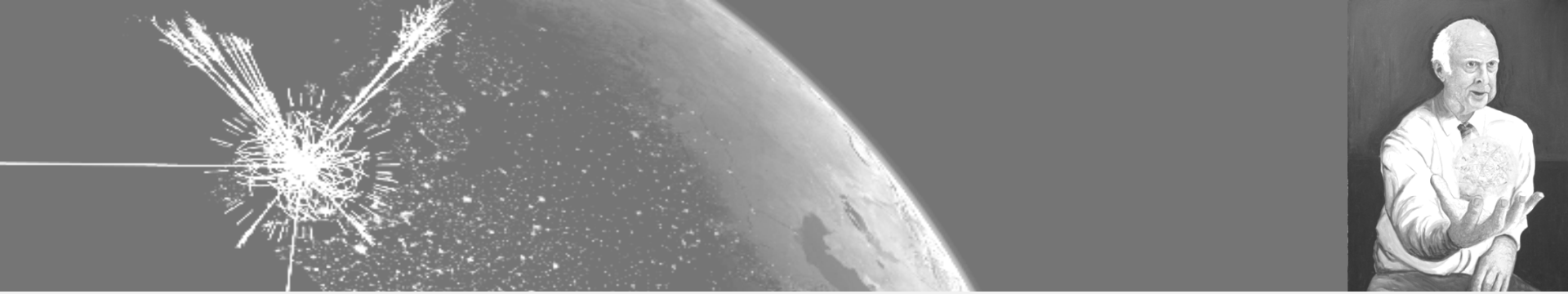
Many models predict more than one scalar doublet, eg, 2 doublets lead to 5 states: $h, H, A, H^\pm$

CMS & LHCb 1411.4413

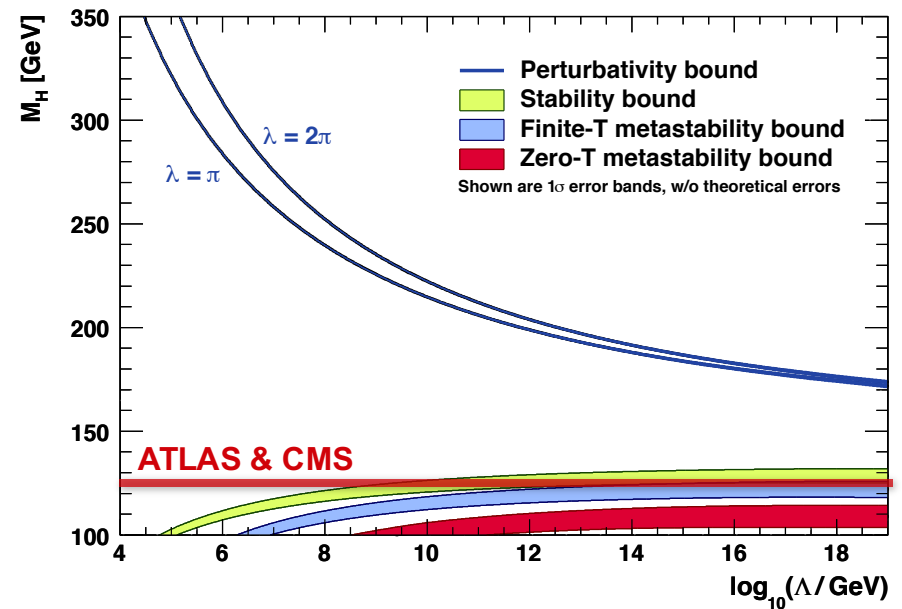
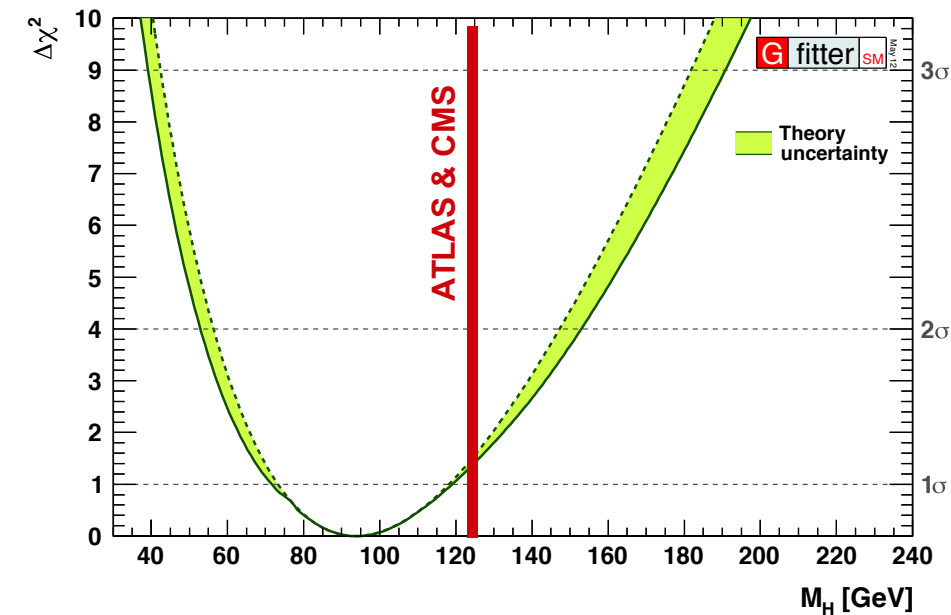
Higgs sector also tested via precision and rare low-energy processes, eg, $B_s \rightarrow \mu\mu$

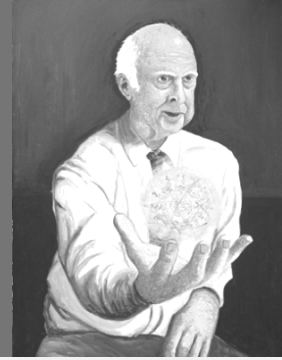
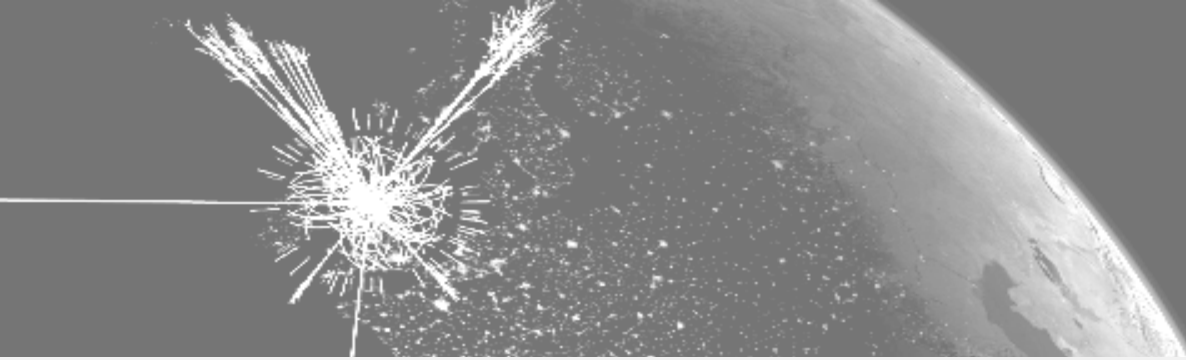
$B_s \rightarrow \mu\mu$ is loop process (no tree-level FCNC) that is in addition CKM & helicity suppressed: $\text{BR}(\text{SM}) = (9.7 \pm 0.7) \times 10^{-11}$





The Standard Model is complete





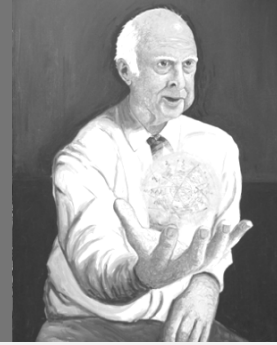
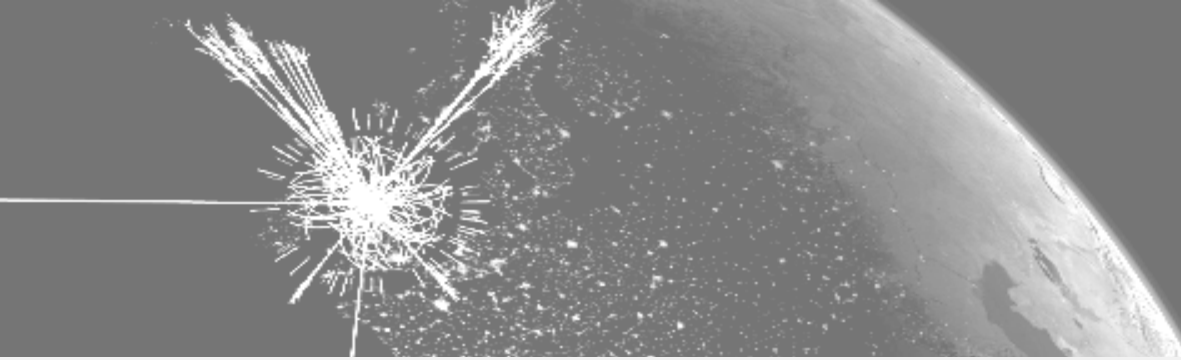
The Standard Model is complete

*It is a triumph for the
imagination and rigour
of the human mind*

*It is a triumph for the
greatest experimental
undertaking ever:*

*Frontier of accelerator &
detector technologies*

*Global data sharing,
analysis & collaboration*



Can we conclude that the Standard Model is *the* theory of matter and force ? No !

Higgs is only
fundamental
scalar

neither matter, nor force, -
all known scalars are
composite states

Huge mass
hierarchy
between matter
particles

Gauge hierarchy
/ Scalar SM
sector is
unstable

Causally
connected
observable
universe

Dark matter and
dark energy

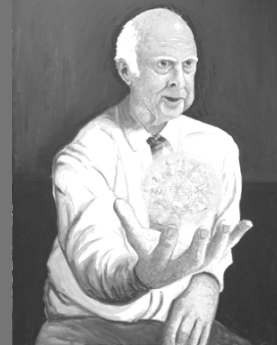
Matter-antimatter
asymmetry in
universe

Grand
unification of
the forces

strong CP
problem

Massive
neutrinos

Gravitation



The Higgs potential ($\mu < 0$, $\lambda \gtrsim 0$: physics or just mathematics ?) exemplifies our success with description but lack of understanding

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

Is this the right potential?

If the Higgs field fills all space-time, is it related to inflation and dark energy?

Higgs boson mass term

$$\delta m_H^2 \sim |\delta \mu_H^2| \propto \Lambda_{\text{cut-off}}^2$$

“Hierarchy problem”
→ new physics at $\sim \text{TeV}$

Higgs self coupling

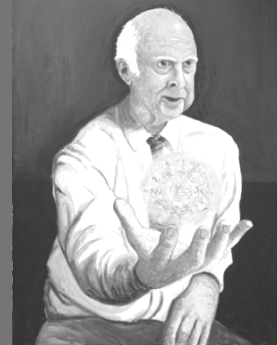
$$\lambda_{\text{SM}} = G_F m_H^2 / \sqrt{2} \sim 0.13$$

EW vacuum may be meta-stable

Higgs—fermion couplings

“SM flavour problem”: large mass hierarchy between fermion families

G. Isidori 2012



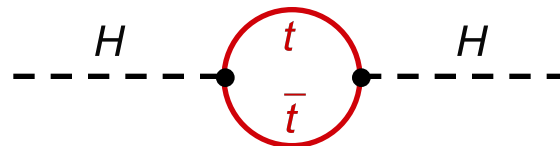
The Higgs potential ($\mu < 0$, $\lambda \gtrsim 0$: physics or just mathematics ?) exemplifies our success with description but lack of understanding

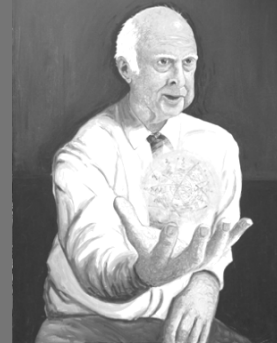
$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

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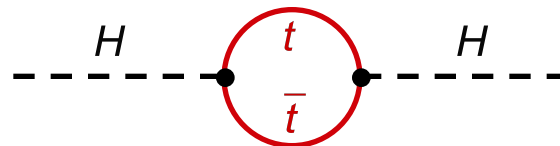
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$$\delta m_H^2 \sim |\delta \mu_H^2| \propto \Lambda_{\text{cut-off}}^2$$

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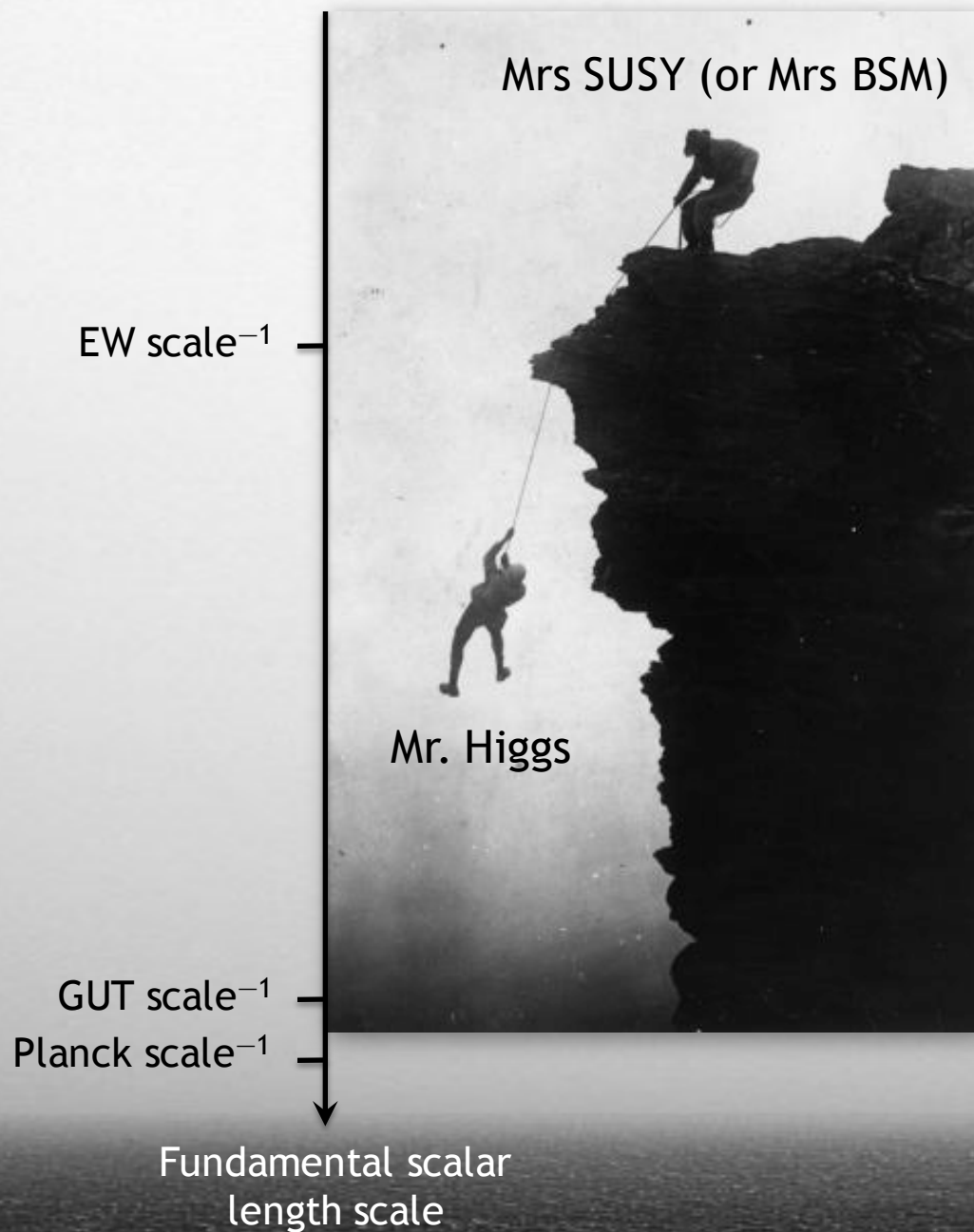


Proposed solutions to hierarchy problem

- Weakly coupled: Supersymmetry, ...
- Strongly coupled: Little Higgs, Composite Higgs, ...
- Dynamical (relax(ion)ation)

Different manifestations of similar scenarios. Many models also provide dark matter candidates. Most models propose new particles at the TeV scale

The scalar precipice



Theory-agnostic, signature based searches, as well as highly targeted model-dependent ones

Leptoquarks

- $LQ1(e\bar{l})\chi_2$
- $LQ1(e\bar{l})\chi_1(v\bar{l})$
- $LQ2(\mu\bar{l})\chi_2$
- $LQ2(\mu\bar{l})\chi_1(v\bar{l})$
- $LQ3(v\bar{l})\chi_2$
- $LQ3(v\bar{l})\chi_1(v\bar{l})$
- $LQ3(t\bar{l})\chi_2$
- $LQ3(v\bar{l})\chi_2$
- $LQ3(v\bar{l})\chi_1(v\bar{l})$
- Single $LQ1\ (\lambda=1)$
- Single $LQ2\ (\lambda=1)$

RS Gravitons

- $RS1(v\gamma), k=0.1$
- $RS1(e\bar{e},\mu\bar{\mu}), k=0.1$
- $RS1(j\bar{j}), k=0.1$
- $RS1(WW\rightarrow 4j), k=0.1$

Heavy Gauge Bosons

- $SSM\ Z'(\tau\bar{\tau})$
- $SSM\ Z'(\mu\bar{\mu})$
- $SSM\ Z'(\nu\bar{\nu})$
- $SSM\ Z'(\ell\bar{\ell})\chi_2$
- $SSM\ W'(\bar{j}j)$
- $SSM\ W'(\nu\bar{\nu})$
- $SSM\ W(WZ\rightarrow l\bar{l}l)$
- $SSM\ W(WZ\rightarrow 4j)$

Excited Fermions

- $e^* (M=A)$
- $\mu^* (M=A)$
- $q^* (qg)$
- $q^* (q\bar{q})$
- b^*

Multijet Resonances

- coloron($j\bar{j})\chi_2$
- coloron($j\bar{j})\chi_1$
- gluino($3j\bar{j})\chi_2$
- gluino($j\bar{j})\chi_2$

Long-Lived Particles

- stopped gluino (cloud)
- stopped stop (cloud)
- HSCP gluino (cloud)
- HSCP stop (cloud)
- $q=2/3e$ HSCP
- $q=3e$ HSCP
- chargino, $\tau\text{tau}=100\text{ns}$, AMSB
- neutralino, $\tau\text{tau}=25\text{cm}$, EGAL time

Dark Matter

- $j+\text{MET}$, vector $DM=100\text{ GeV}, \Lambda$
- $j+\text{MET}$, axial-vector $DM=100\text{ GeV}, \Lambda$
- $j+\text{MET}$, scalar $DM=100\text{ GeV}, \Lambda$
- $\gamma+\text{MET}$, vector $DM=100\text{ GeV}, \Lambda$
- $\gamma+\text{MET}$, axial-vector $DM=100\text{ GeV}, \Lambda$
- $l+\text{MET}$, $\xi=+1$, Si/SD $DM=100\text{ GeV}, \Lambda$
- $l+\text{MET}$, $\xi=-1$, Si/SD $DM=100\text{ GeV}, \Lambda$
- $l+\text{MET}$, $\xi=0$, Si/SD $DM=100\text{ GeV}, \Lambda$

Large Extra Dimensions

- ADD ($\gamma+\text{MET}$), $nED=4$, MD
- ADD ($j+\text{MET}$), $nED=4$, MD
- ADD ($e\bar{e},\mu\bar{\mu}$), $nED=4$, MS
- ADD ($\nu\bar{\nu}$), $nED=4$, MS
- ADD ($j\bar{j}$), $nED=4$, MS
- QBH, $nED=4$, MD=4 TeV
- NR BH, $nED=4$, MD=4 TeV
- QBH ($j\bar{j}$), $nED=4$, MD=4 TeV
- Jet Extinction Scale
- String Scale ($j\bar{j}$)

Compositeness

- dijets, $\Lambda+LL/RR$
- dijets, $\Lambda-LL/RR$
- dimuons, $\Lambda+LLIM$
- dimuons, $\Lambda-LLIM$
- dilelectrons, $\Lambda+LLIM$
- dilelectrons, $\Lambda-LLIM$
- single e, Λ HnCM
- single μ, Λ HnCM
- inclusive jets, $\Lambda+$
- inclusive jets, $\Lambda-$



Status: July 2015

Model

$\epsilon, \mu, \tau, \gamma$

Jets

E_{miss}^{max}

$\mathcal{L}_{int}(\text{fb}^{-1})$

Mass limit

$\sqrt{s} = 7 \text{ TeV}$

$\sqrt{s} = 8 \text{ TeV}$

Reference

Inclusive Searches

MSUGRA/CASSM

$0.3, \mu, 1/2 \rightarrow 2$

$1-10$

Jets 3 b

Yes

20.3

4.8

100-440 GeV

850 GeV

1.8 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1507.05525

$\tilde{q}\tilde{q} \rightarrow \tilde{q}\tilde{q}^*$

0

2-6

Jets

Yes

20.3

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1408.7875

$\tilde{q}\tilde{q} \rightarrow \tilde{q}\tilde{q}^*$ (compressed)

2

μ (off-Z)

2 jets

Yes

20.3

100-440 GeV

$m_{\tilde{g}}=m_{\tilde{t}_1} \pm 10 \text{ GeV}$

1507.05525

$\tilde{q}\tilde{q} \rightarrow \tilde{q}\tilde{q}^*$ ($\tilde{q}\tilde{q} \rightarrow \tilde{q}\tilde{q}^*$)

2

μ (off-Z)

2 jets

Yes

20.3

780 GeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1503.03290

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

0

2-6

Jets

Yes

20.3

1.35 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1408.7875

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$ ($\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$)

0.1 μ , 2

2-6

Jets

Yes

20

1.26 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1} \pm 10 \text{ GeV}$

1507.05525

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$ ($\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$)

2 μ

0-3

Jets

Yes

20.3

1.32 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1} \pm 10 \text{ GeV}$

1501.05555

GMSB (r NLSIP)

1-2 $\mu \rightarrow 0+1$

0-2

Jets

Yes

20.3

1.6 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1407.5603

GGM (bino NLSIP)

2 γ

-

Yes

20.3

1.29 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1507.05493

GGM (higgsino-bino NLSIP)

2 γ

1

Yes

20.3

1.3 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1507.05493

GGM (higgsino-bino NLSIP)

2 γ

7

Jets

Yes

20.3

1.25 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1507.05493

GGM (higgsino NLSIP)

2 μ (L)

2

Jets

Yes

20.3

850 GeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1507.05493

GMSB (r NLSIP)

0

mono-jet

2 jets

Yes

20.3

μ (L) scale

885 GeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1502.01518

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

0

3 b

Yes

20.1

1.25 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1407.56000

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

0

7-10

Jets

Yes

20.3

1.1 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1308.1841

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

0.1 μ , 3 b

3 b

Yes

20.1

1.34 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1308.1841

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

0.1 μ , 3 b

3 b

Yes

20.1

1.5 TeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1407.56000

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

0

2 b

Yes

20.1

100-630 GeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1306.231

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

2 μ (SS)

0-3 b

Yes

20.1

275-440 GeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1404.2500

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

1-2 μ

1-2 b

Yes

4.720.3

230-460 GeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1209.2102

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$ ($\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$) or $\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

0.1 μ

0-2

Jets 2 b

Yes

20.3

90-240 GeV

210-700 GeV

$m_{\tilde{g}}=m_{\tilde{t}_1}$

1507.05493

$\tilde{t}\tilde{t} \rightarrow \tilde{t}\tilde{t}^*$

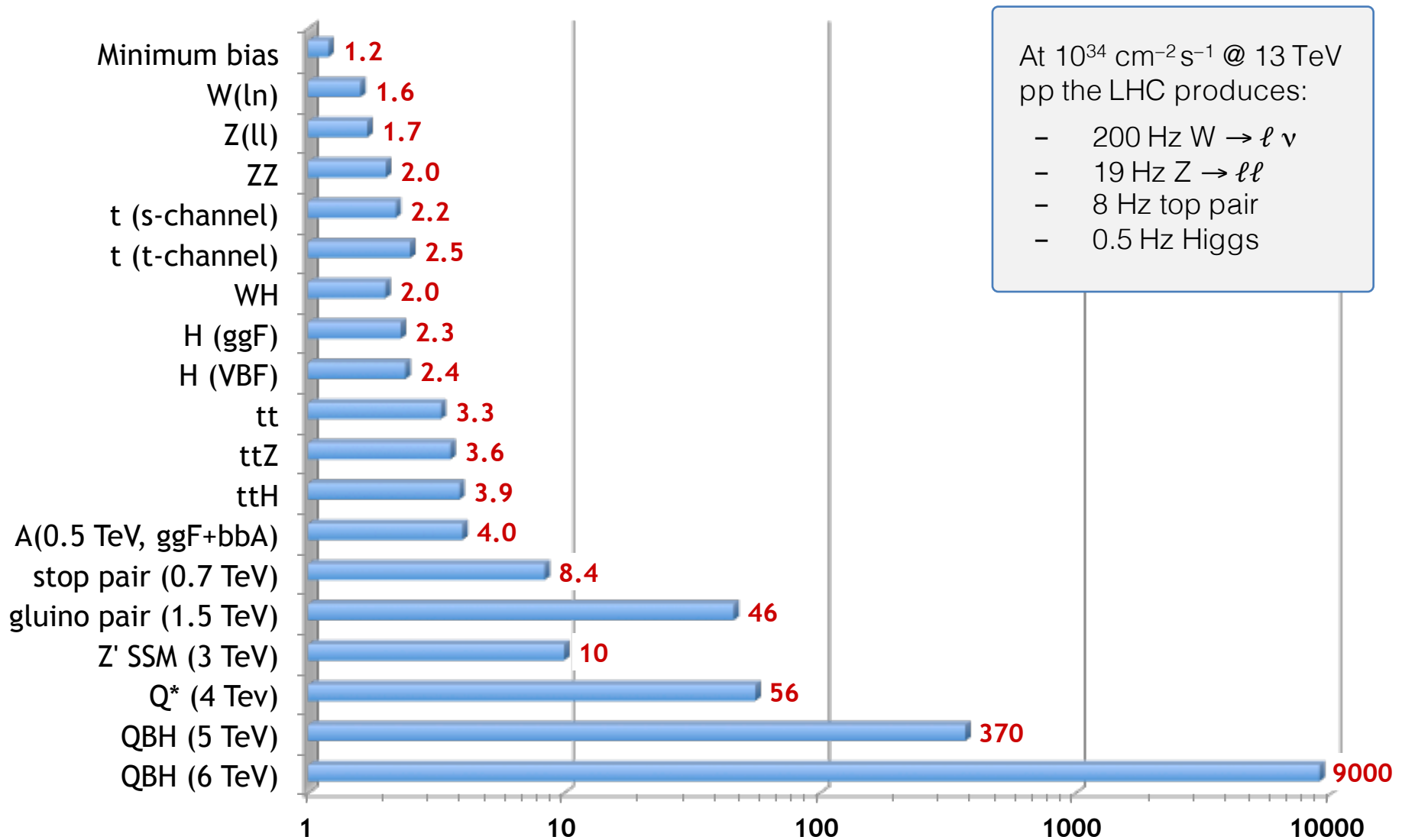
0

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

The LHC Run-2

Higher collision energy, more luminosity

The LHC Run-2: 13 TeV / 8 TeV inclusive pp cross-section ratio



Shown by Mike Lamont at Lepton-Photon 2015

Fitzcarraldo moving a steamer over a muddy hill ... (on his quest for money to build an opera house in the peruvian jungle)

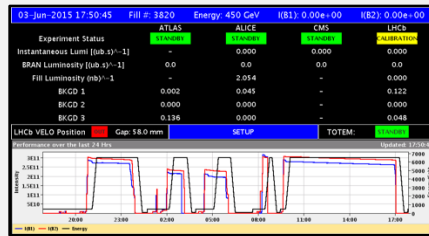


Long-Shutdown 1
Preparing Run-2

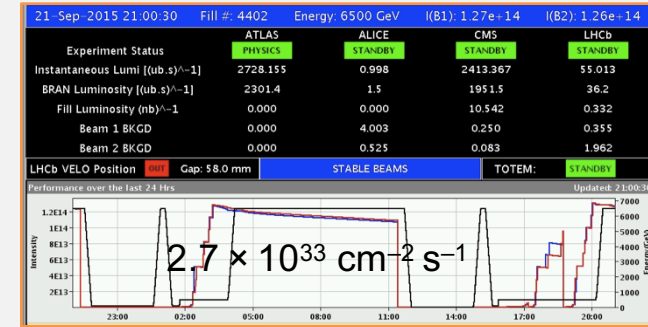
2015 LHC operation at a glance

From: Matteo Solfaroli, LHCC open session, Sep 23, 2015

3rd June First STABLE BEAMS!



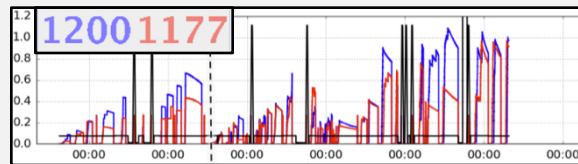
21st Sep 25 ns STABLE BEAMS with 1177 bunches/beam



5th Apr First circulating beam



30th June end of scrubbing for 50 ns



Intense beam
commissioning phase

TS-1

MD-1

MD-2 + TS-2

April

June

July

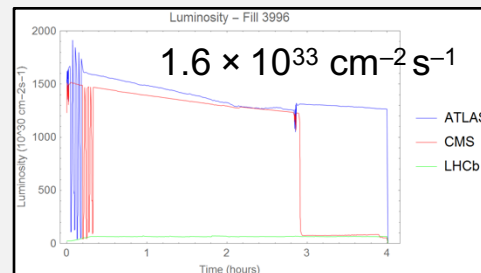
August

September

10th Apr 6.5 TeV for the first time (ever!)



14th July 476b (50 ns)



7th Aug end scrubbing for 25 ns



Since then, Oct/Nov:

- 2232 colliding bunches in ATLAS/CMS
- L_{max} of $5.2 \cdot 10^{33}$
- Nov 4: MD/TS-3
- Nov 20: Ions



Run: 286665
Event: 419161
2015-11-25 11:12:50 CEST

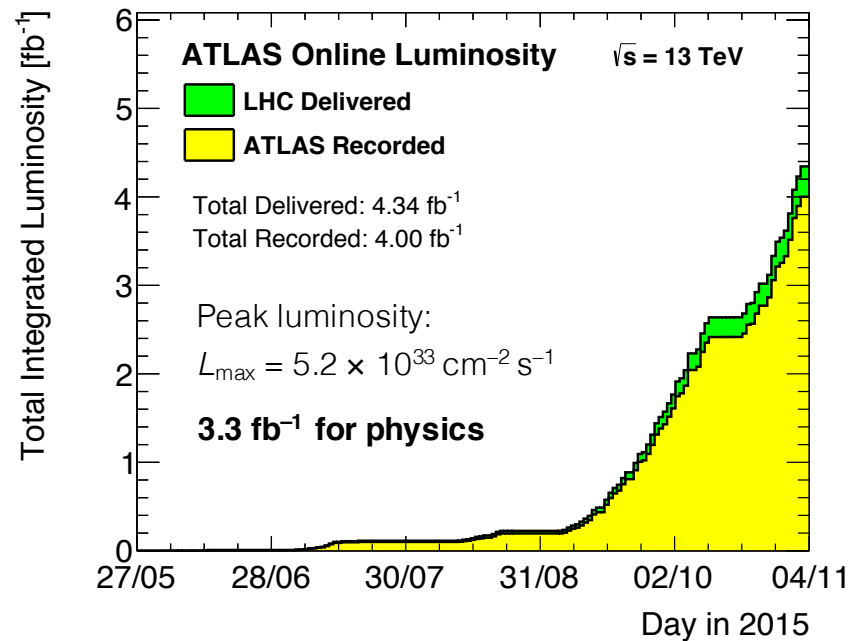
first stable beams heavy-ion collisions

2015 luminosity profile per experiment

Interesting data sample: almost 4 fb⁻¹ recorded luminosity per experiment (Run-1 8 TeV: 20 fb⁻¹)

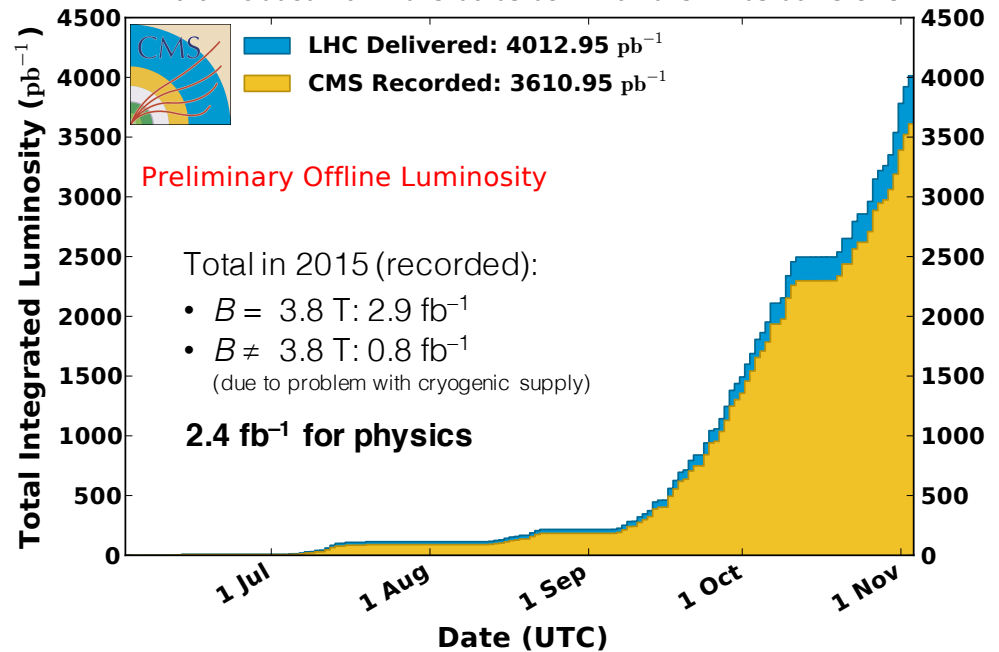
Luminosity calibrated with beam separation scans. Current uncertainty 5–12%, will improve in future.
Differences in amount of delivered luminosity between ATLAS and CMS under scrutiny by experiments

Pileup profile overall a bit lower than during 8 TeV Run-1
→ non-critical



CMS Integrated Luminosity, pp, 2015, $\sqrt{s} = 13$ TeV

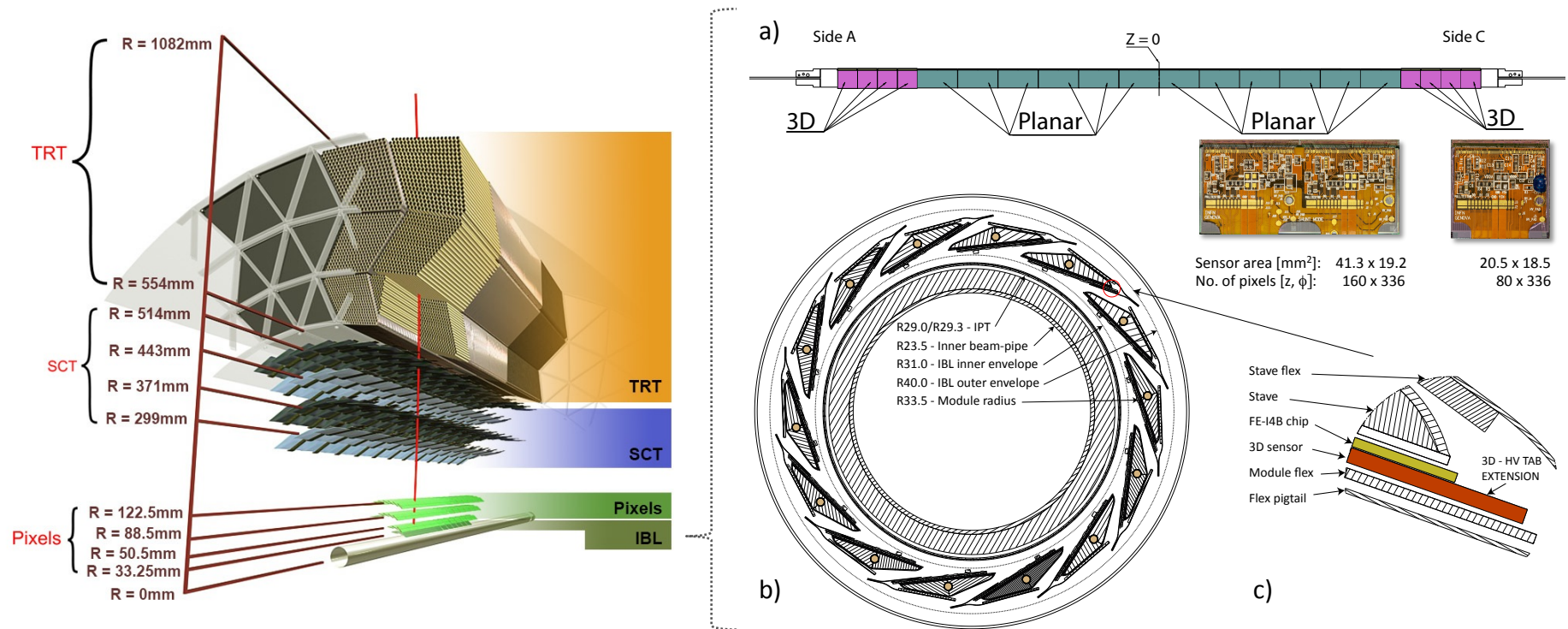
Data included from 2015-06-03 08:41 to 2015-11-03 06:25 UTC

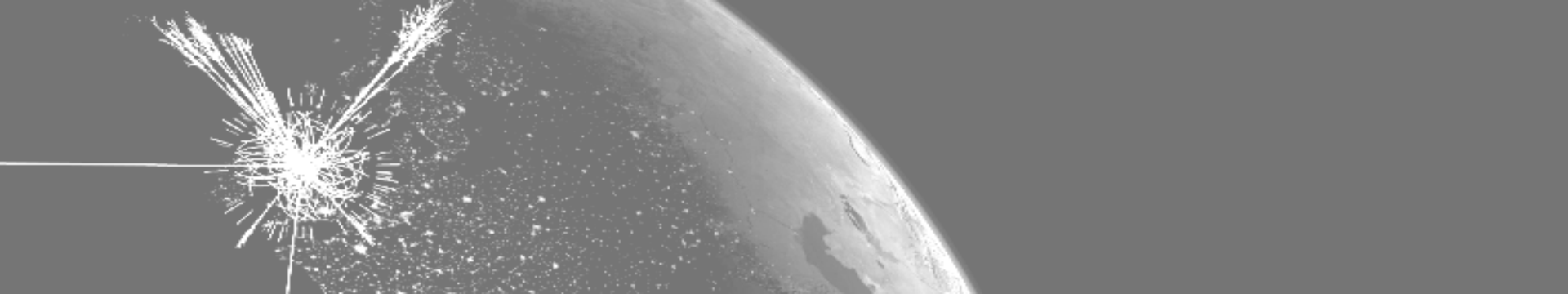


Intense activities during 2 years Long Shutdown 1 (LS1)

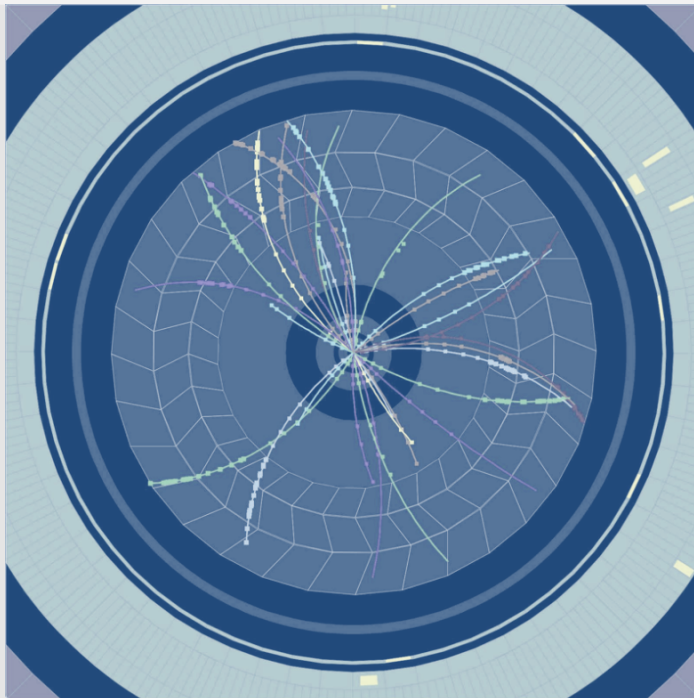
Huge consolidation & improvement programme for detector, online, offline, computing

Most important upgrade for ATLAS is new innermost Pixel layer ("IBL"), at 3.3 cm from beam
→ significant improvement of track position resolution (lifetime measurement, b-tagging)





Physics at unprecedented collision energy: 13 TeV



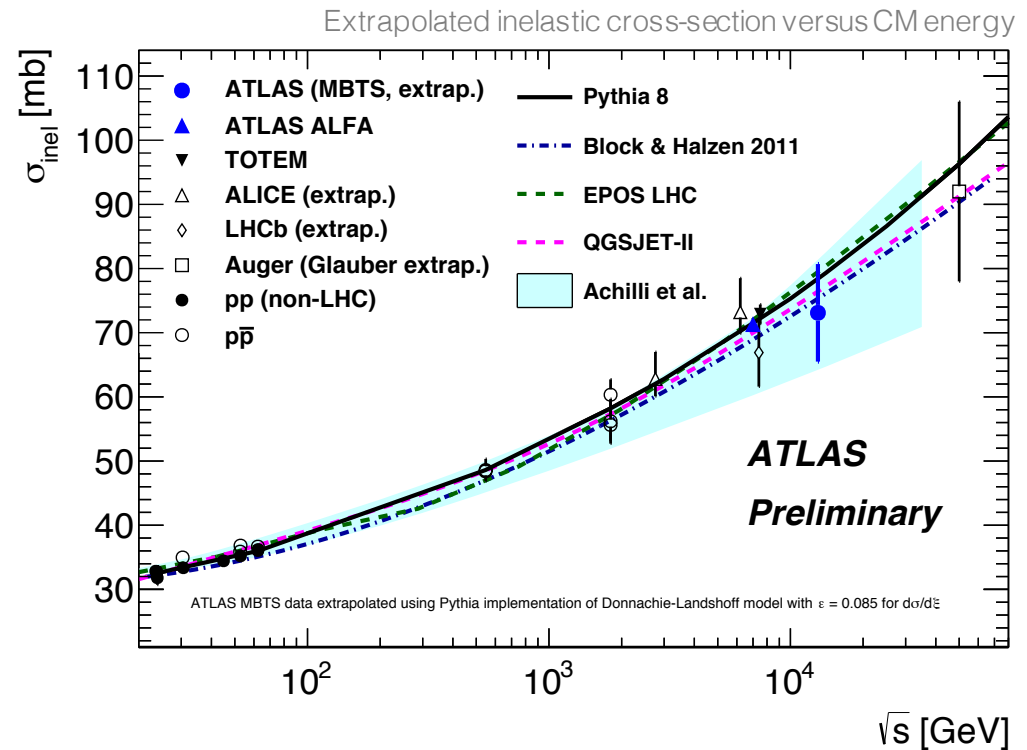
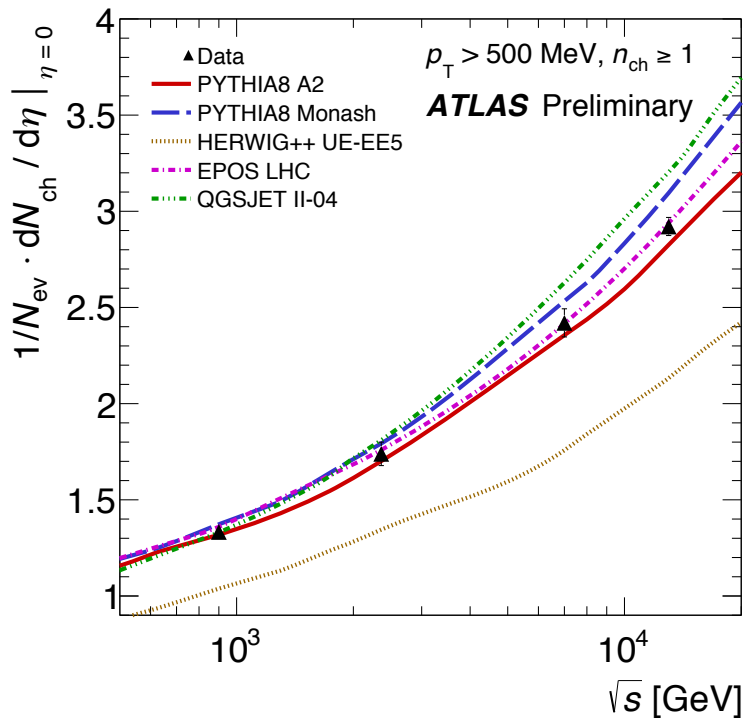
One of the very first proton–proton collisions recorded by ATLAS in “quiet beam” conditions in May 2015

Initial very low-luminosity data used for soft physics

Measurements of charged particle spectra, proton underlying event, correlations, cross-sections

CMS PLB 751, 143 (2015) , ATLAS-CONF-2015-028, ATLAS-CONF-2015-038

Collision energy-dependent evolution of charged particle multiplicity and total inelastic proton-proton cross section measured

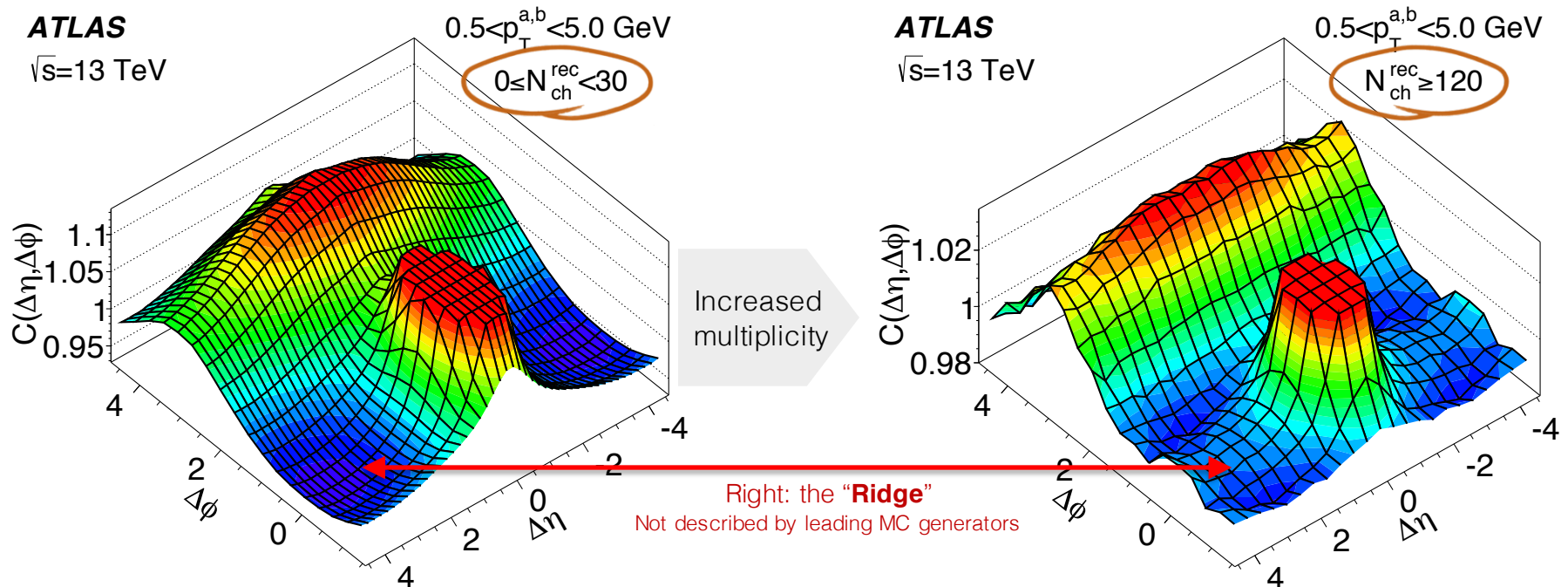


Initial very low-luminosity data used for soft physics

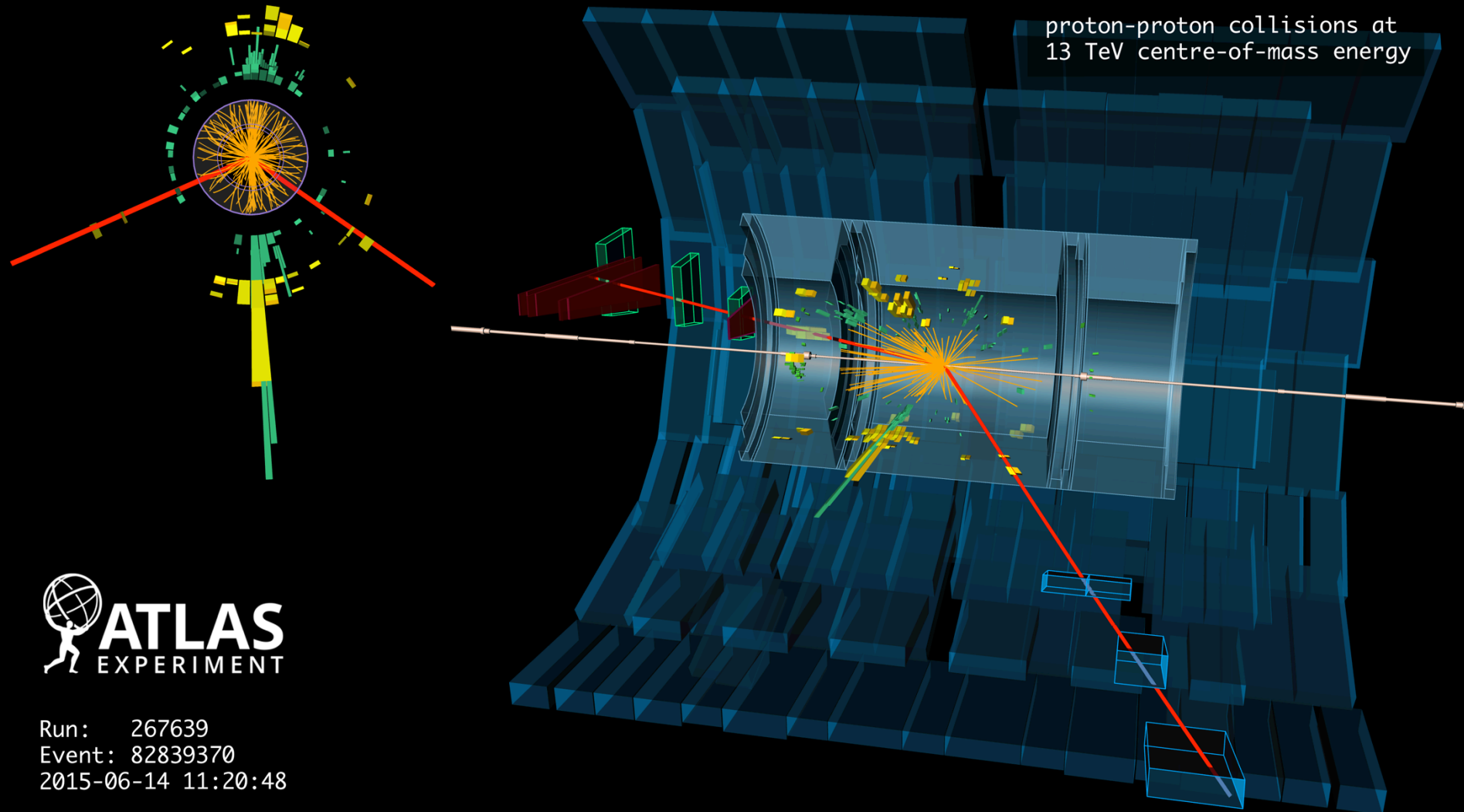
Measurements of charged particle spectra, proton underlying event, correlations, cross-sections

ATLAS 1509.04776, CMS 1510.03068

A peculiar phenomenon of long-range correlations (“Ridge”) in pp collisions, known from heavy ions, was reobserved → Understood to be per-event, single particle $\cos(2\Delta\phi)$ modulation whose amplitude is independent of multiplicity and CM energy; p_T dependence similar to pPb and PbPb



W, Z boson and top-quark production at 13 TeV



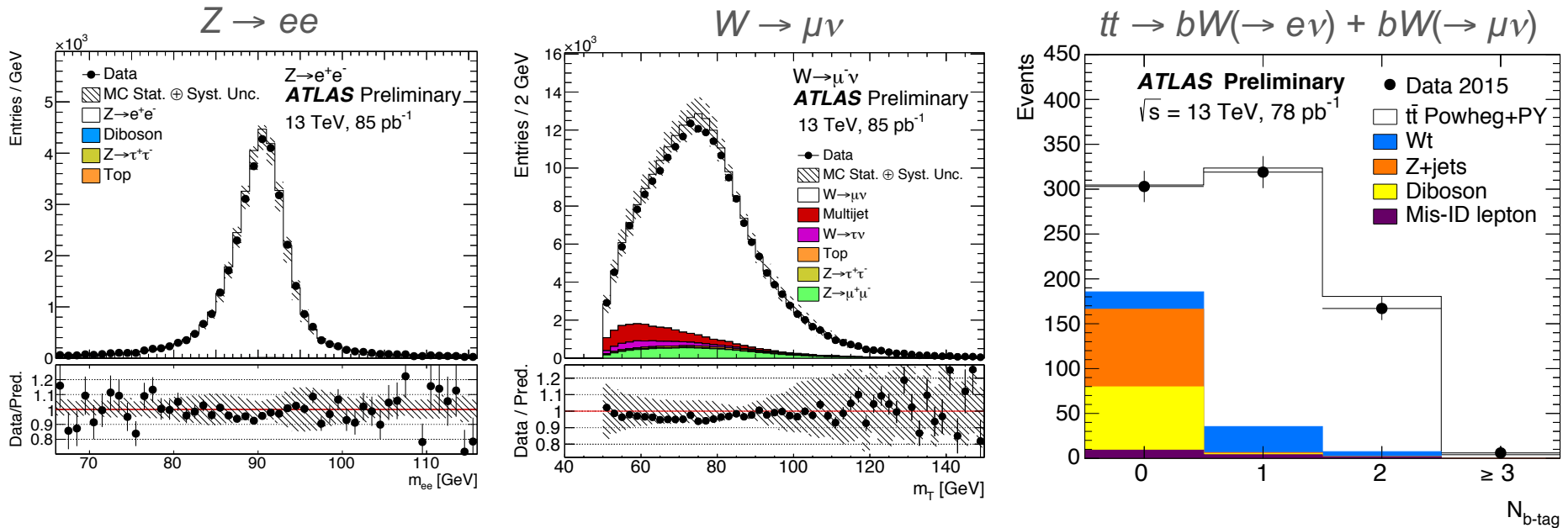
Displays of one $Z(\rightarrow \mu\mu) + \text{jets}$ candidate event

Standard probes: W , Z and top-quark production

At 13 TeV collision energy, cross-sections for W , Z , top-pair production increase

ATLAS-CONF-2015-039, CMS-PAS-SMP-15-004, ATLAS-CONF-2015-033, ATLAS-CONF-2015-049

Use leptonic decays to trigger and reconstruct objects



$$\text{Cross-section: } \sigma = \frac{N_{\text{selected}} - N_{\text{background}}}{\varepsilon \cdot A \cdot L}$$

Requires good understanding of reconstructed objects and background modelling in simulation

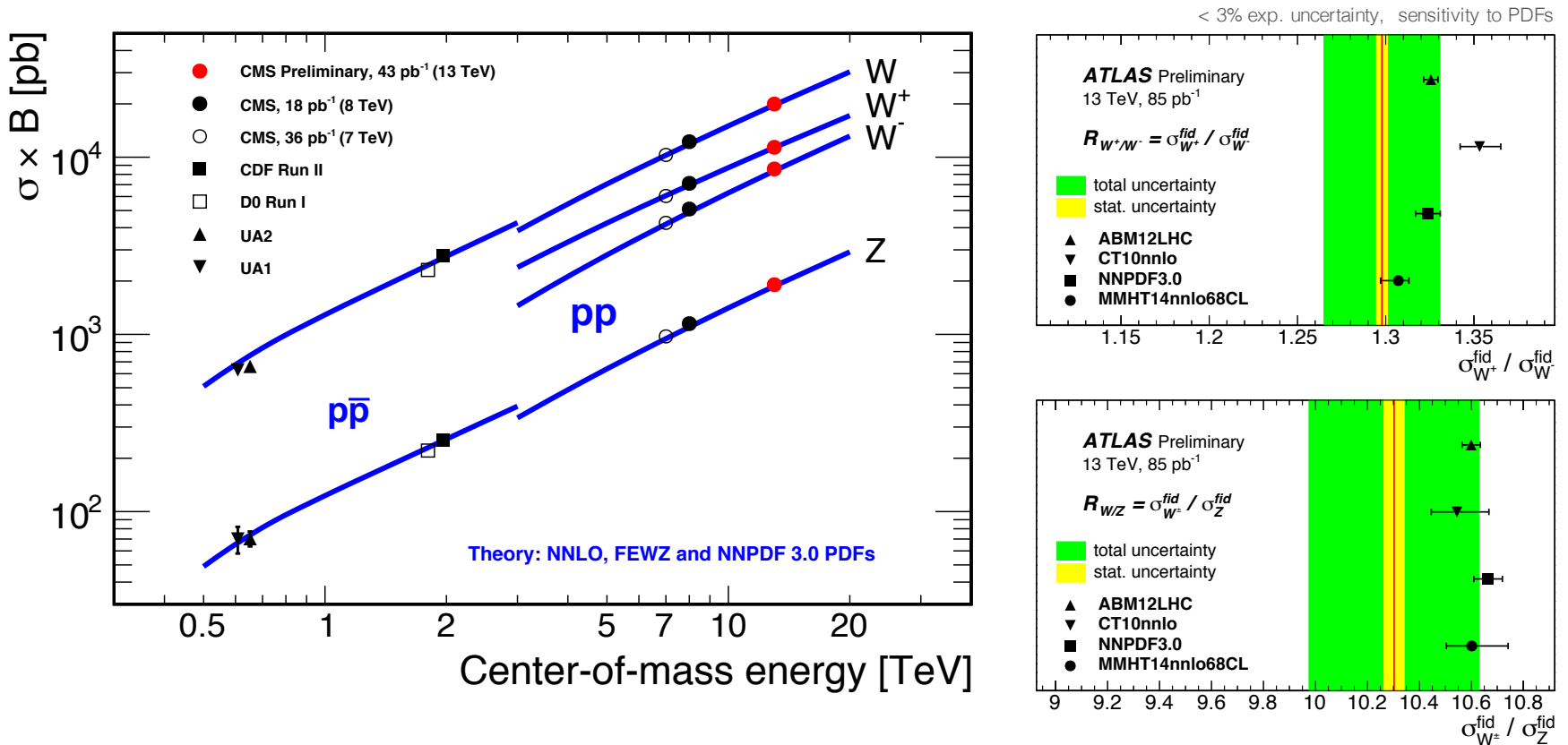
Largest uncertainty at this stage: $\sigma(L) \sim 5\text{--}12\%$

Standard probes: W , Z and top-quark production

At 13 TeV collision energy, cross-sections for W , Z , top-pair production increase

ATLAS-CONF-2015-039, CMS-PAS-SMP-15-004, ATLAS-CONF-2015-033, ATLAS-CONF-2015-049

Resulting cross-sections for W , Z inclusive (left) and ratios (right)

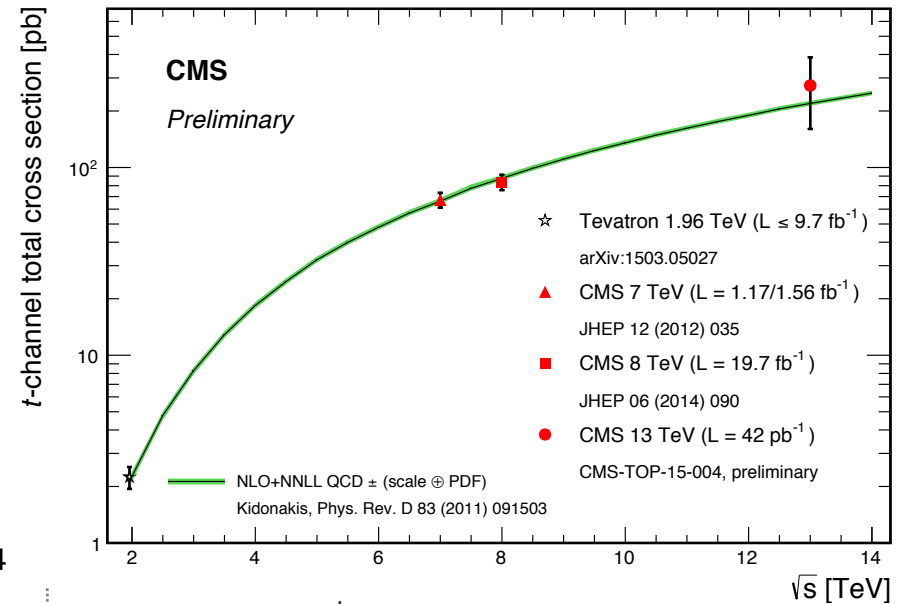
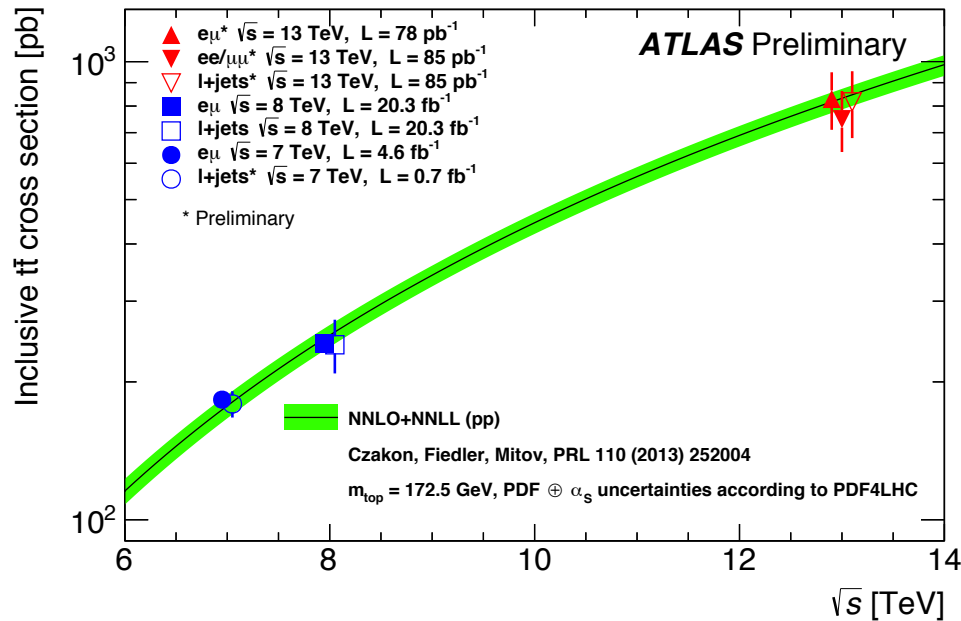


Standard probes: W , Z and top-quark production

At 13 TeV collision energy, cross-sections for W , Z , top-pair production increase

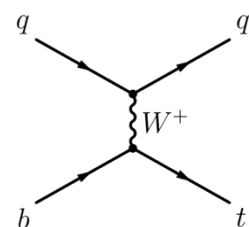
ATLAS-CONF-2015-039, CMS-PAS-SMP-15-004, ATLAS-CONF-2015-033, ATLAS-CONF-2015-049, CMS-PAS-TOP-15-013, CMS-PAS-TOP-15-004

Resulting cross-sections for **top-pair** (left) and **single-top (t-channel)** production (right)



All measurements compatible with SM-predicted cross-section factors (1.6_{W} , 1.7_Z , $3.3_{t\bar{t}}$, 2.2_t)

Also measured fiducial & differential cross-sections

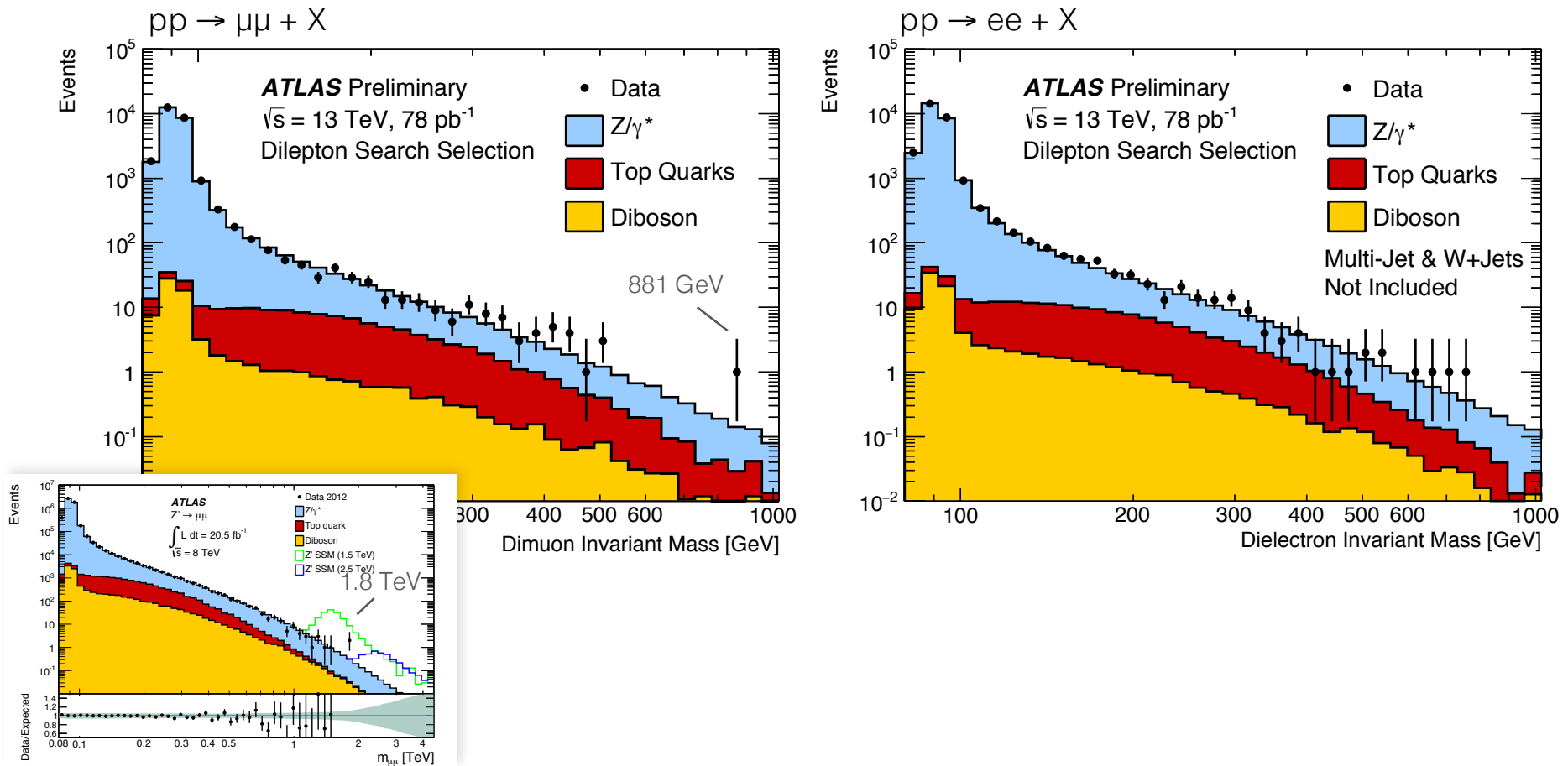


Hard to observe single-top at Tevatron, amazing result with only 42 pb $^{-1}$ of 13 TeV LHC data

High-mass dilepton production

Insufficient luminosity yet to challenge Run-1 sensitivity to new physics

ATLAS EXOT-2015-001, EXOT-2015-004

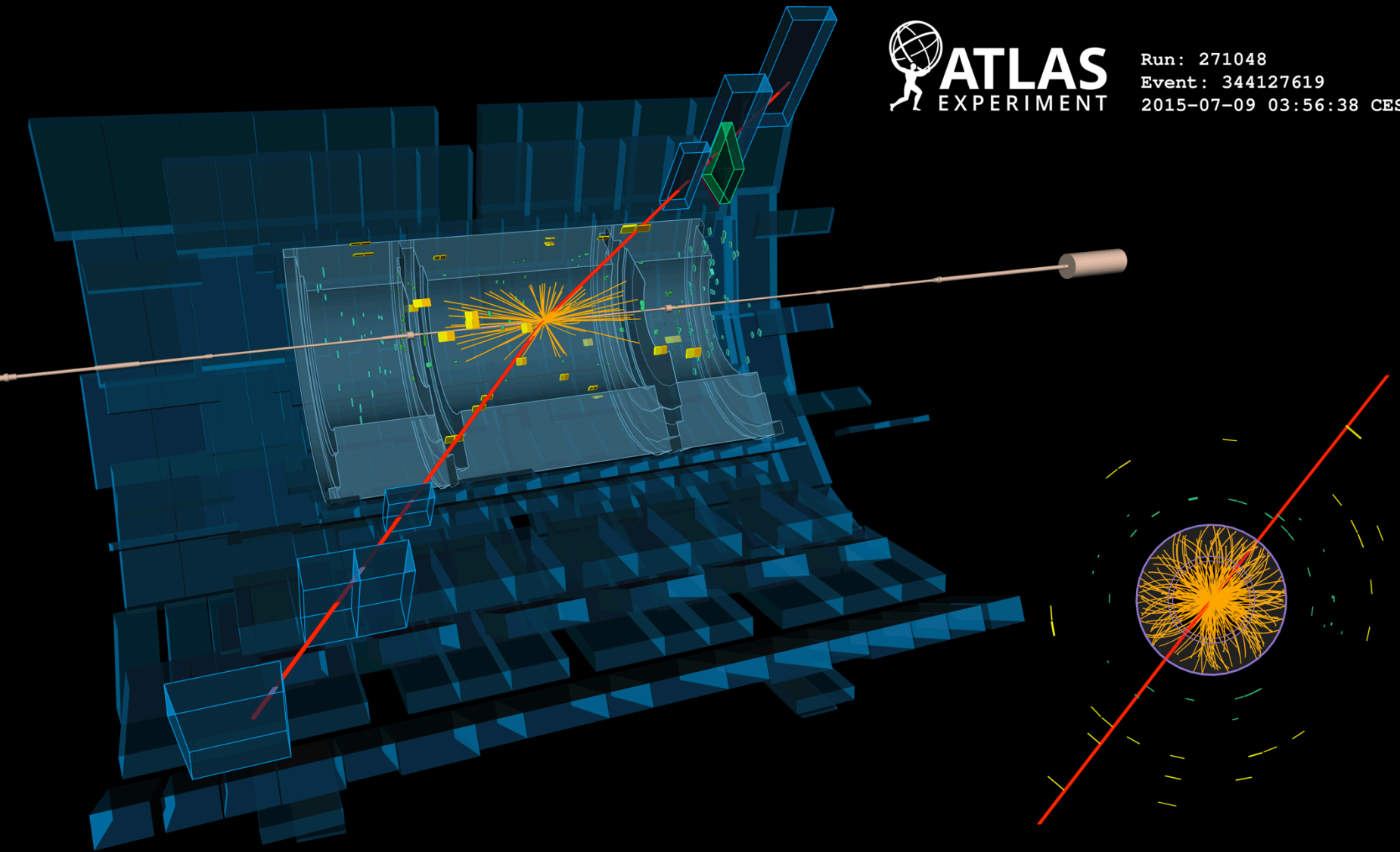


[20.3 fb⁻¹, 8 TeV, arXiv:1405.4123]

Display of $\mu^+\mu^-$ event with 881 GeV invariant mass



Run: 271048
Event: 344127619
2015-07-09 03:56:38 CEST

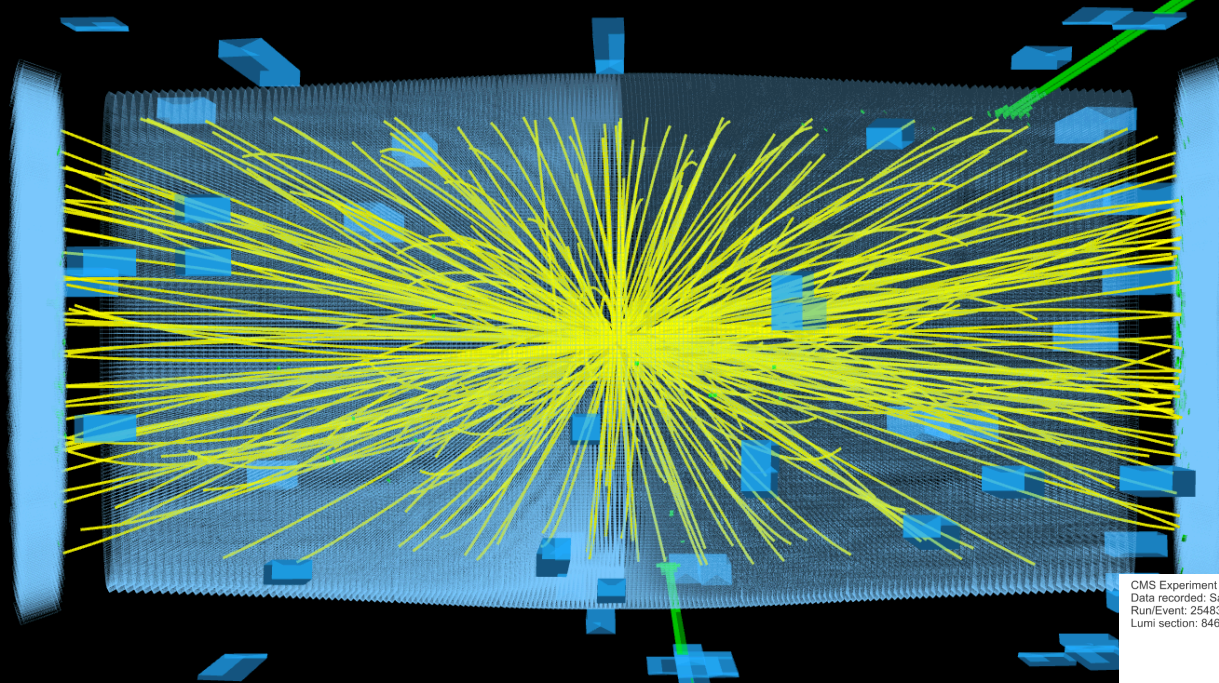




CMS Experiment at the LHC, CERN

Data recorded: 2015-Aug-22 02:13:48.861952 GMT

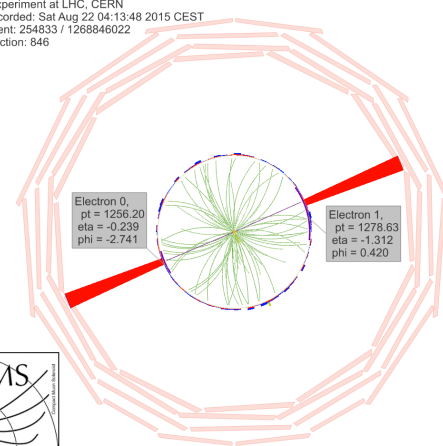
Run / Event / LS: 254833 / 1268846022 / 846



- Display of rare *colossal* e^+e^- candidate event with 2.9 TeV invariant mass
- Each electron candidate has 1.3 TeV E_T
- Back-to-back in ϕ

Highest-mass Run-1 events: 1.8 TeV (ee), 1.9 TeV ($\mu\mu$)

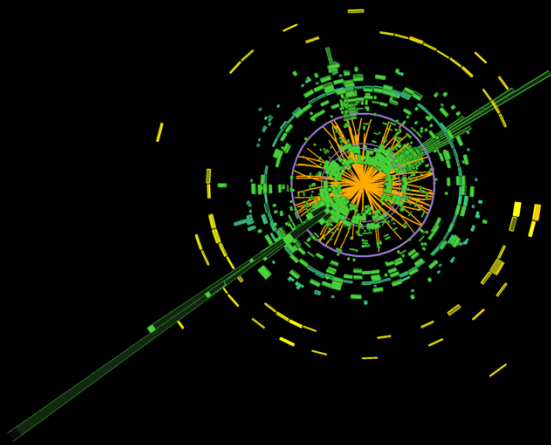
CMS Experiment at LHC, CERN
Data recorded: Sat Aug 22 04:13:48 2015 CEST
Run/Event: 254833 / 1268846022
Lumi section: 846



New physics in events with jets ?



Run: 279685
Event: 690925592
2015-09-18 02:47:06 CEST

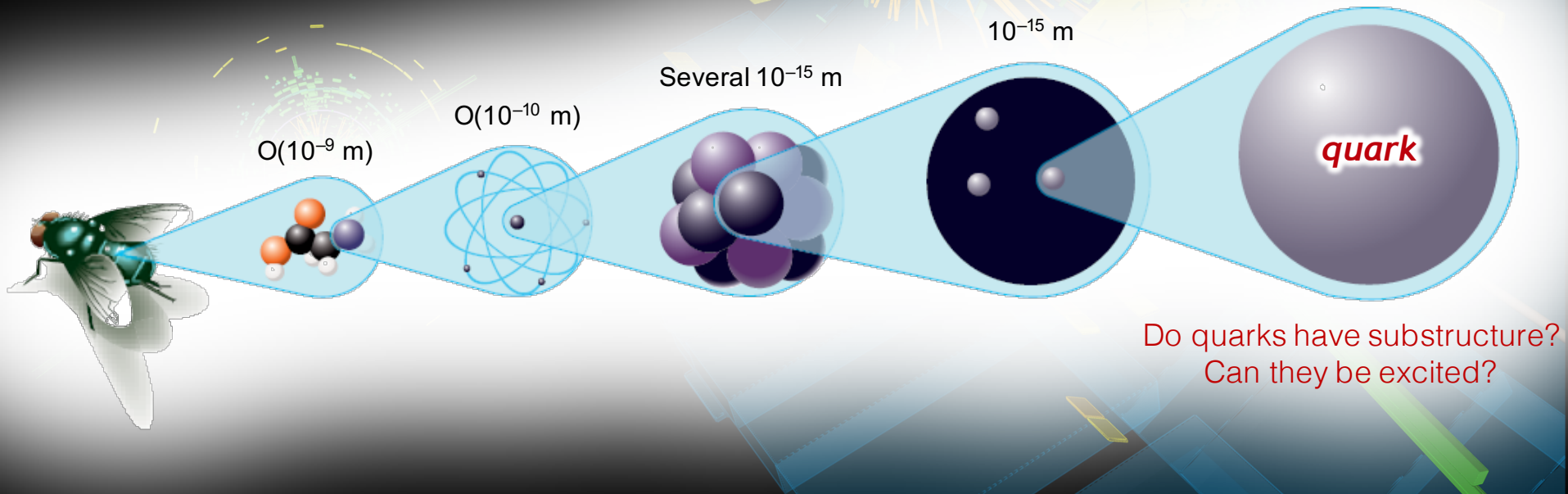


8.8 TeV mass dijet event collected by ATLAS in September 2015

New physics in events with jets ?



Run: 279685
Event: 690925592
2015-09-18 02:47:06 CEST

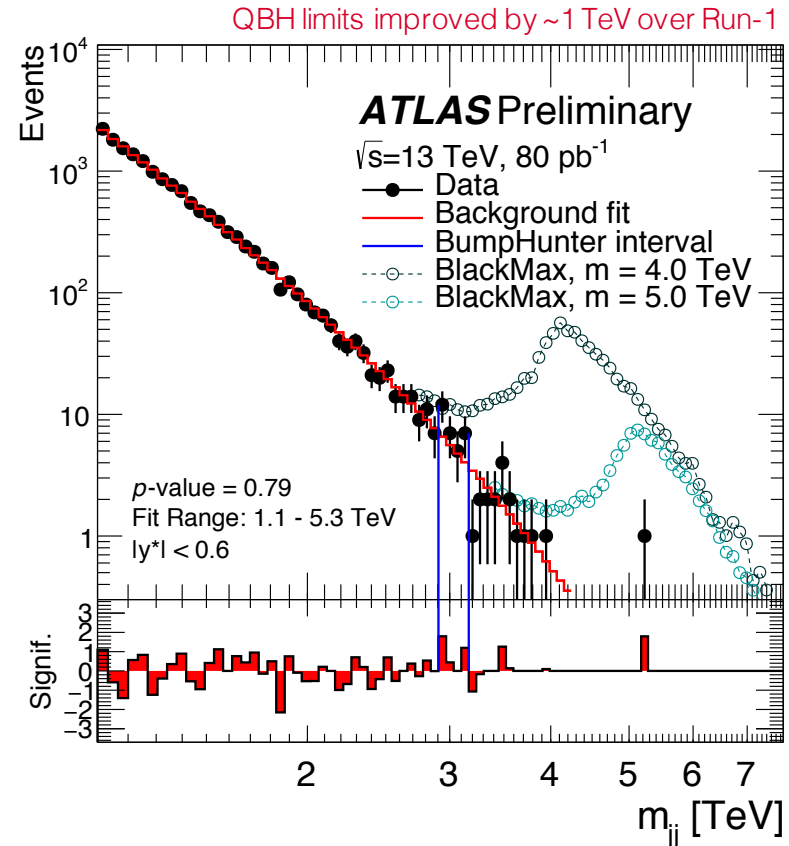
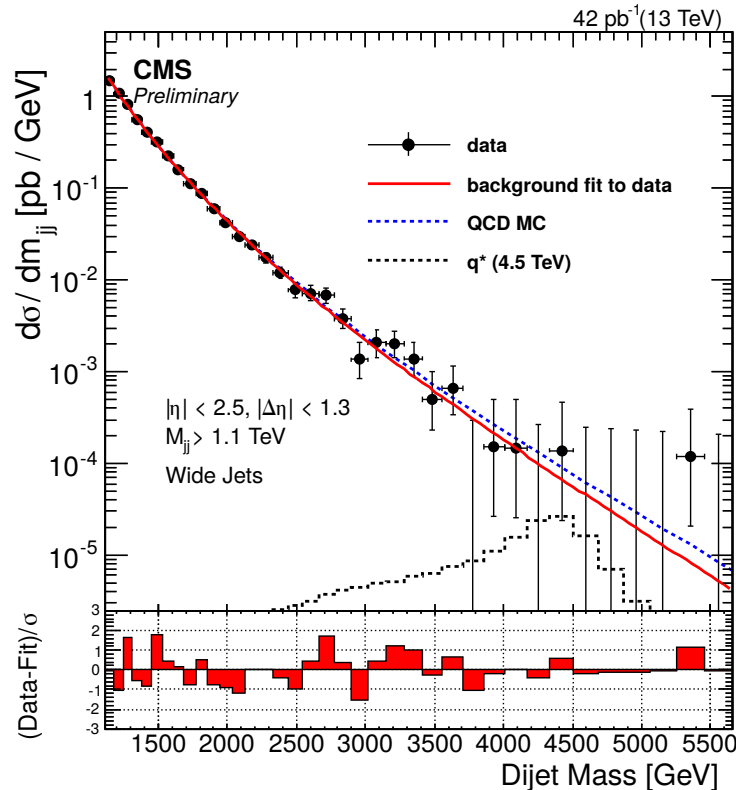


New physics searches with di-jets

Early 13 TeV data already sensitive to very high-mass & cross section physics (eg, QBH)

ATLAS-CONF-2015-034, CMS-PAS-EXO-15-001

Look for deviation in dijet invariant mass spectrum from smoothly falling function

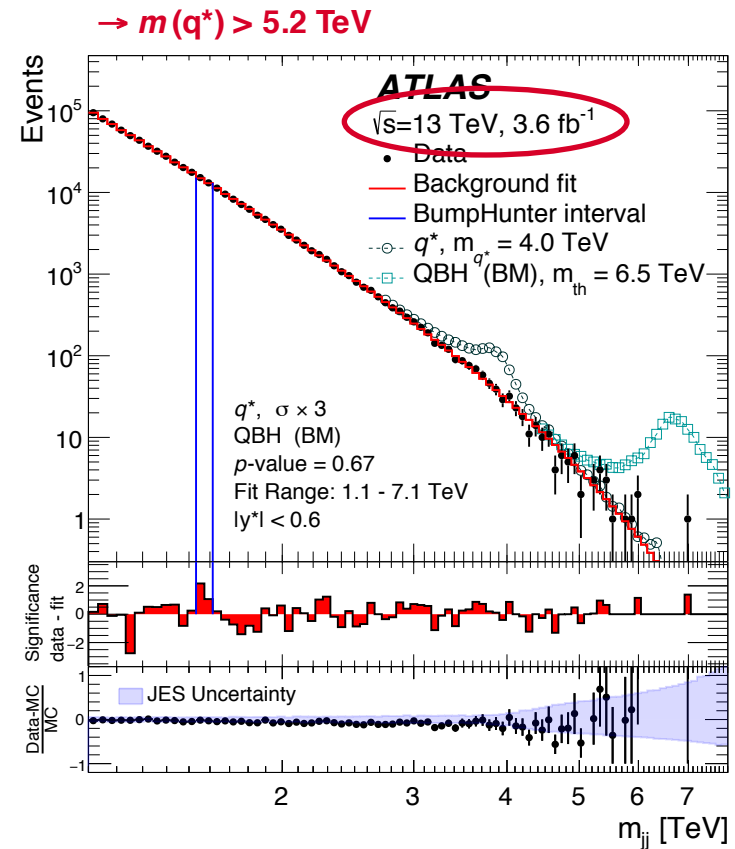
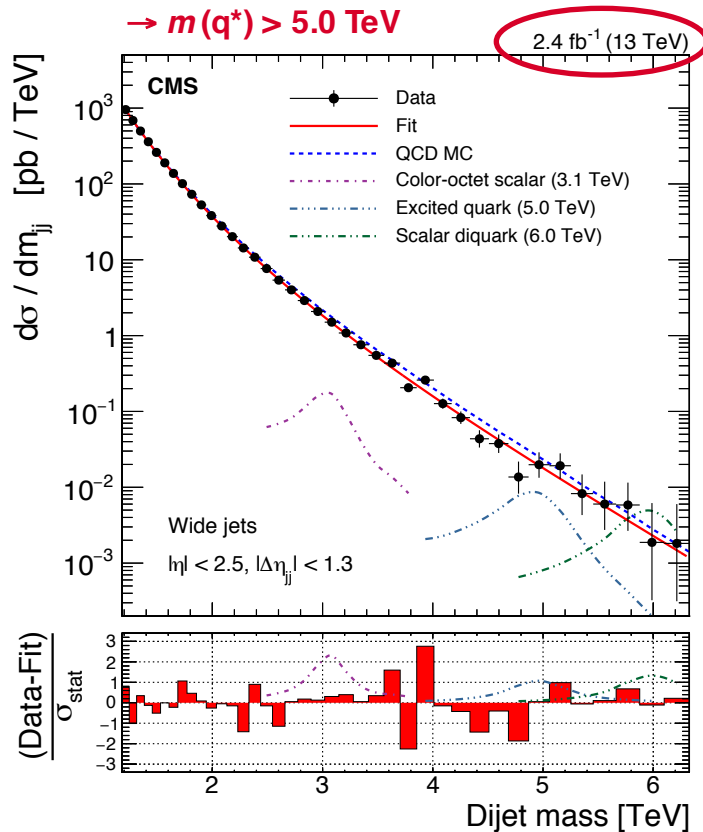


New physics searches with di-jets

Early 13 TeV data already sensitive to very high-mass & cross section physics (eg, QBH)

ATLAS 1512.01530, CMS 1512.01224

Brand new results from ATLAS & CMS — first 13 TeV results with full 2015 dataset



New physics searches with di-jets

Early 13 TeV data already sensitive to very high-mass & cross section physics (eg, QBH)

ATLAS 1512.01530

ATLAS also looked into angular distribution

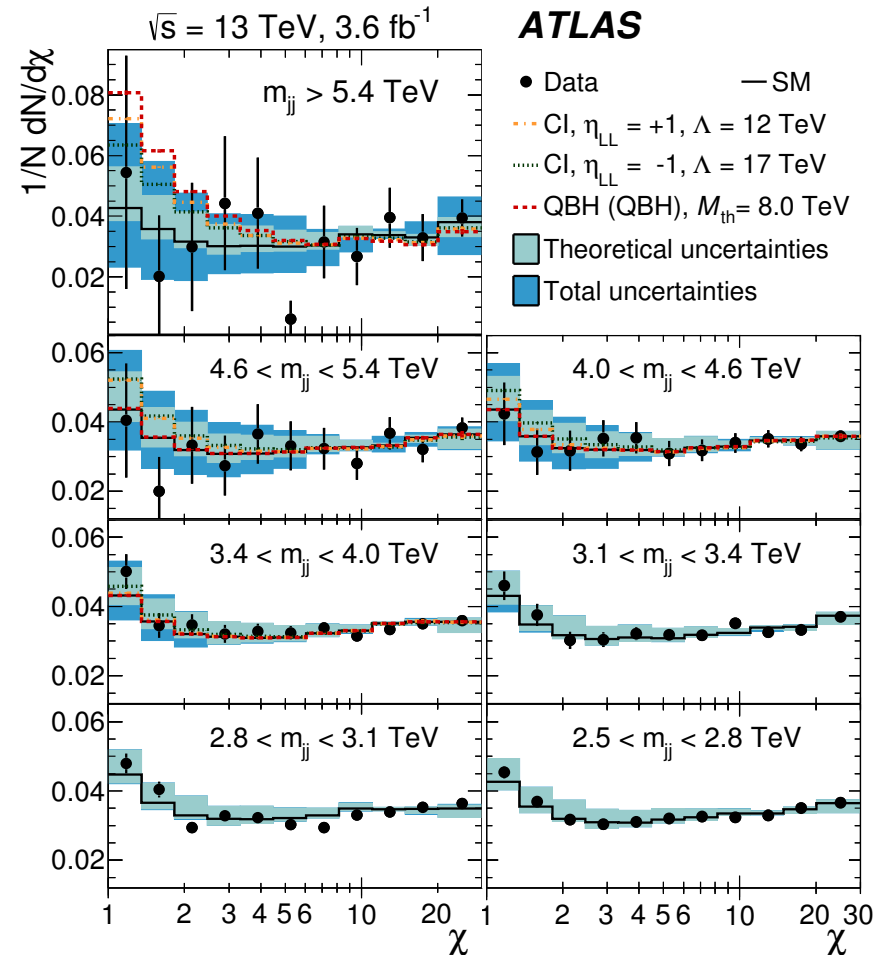
- Define for jets 1 & 2:

$$\chi = \exp |y_1 - y_2|$$

which is $\sim$ independent of m_{12} for t -channel LO QCD at parton level

Restrict analysis to $|y_1 + y_2| < 2.2$,
and to $m_{12} > 2.5$ TeV

- Prediction from NLOJET++ and including electroweak effects
- Systematic uncertainty dominated by QCD prediction and jet energy scale

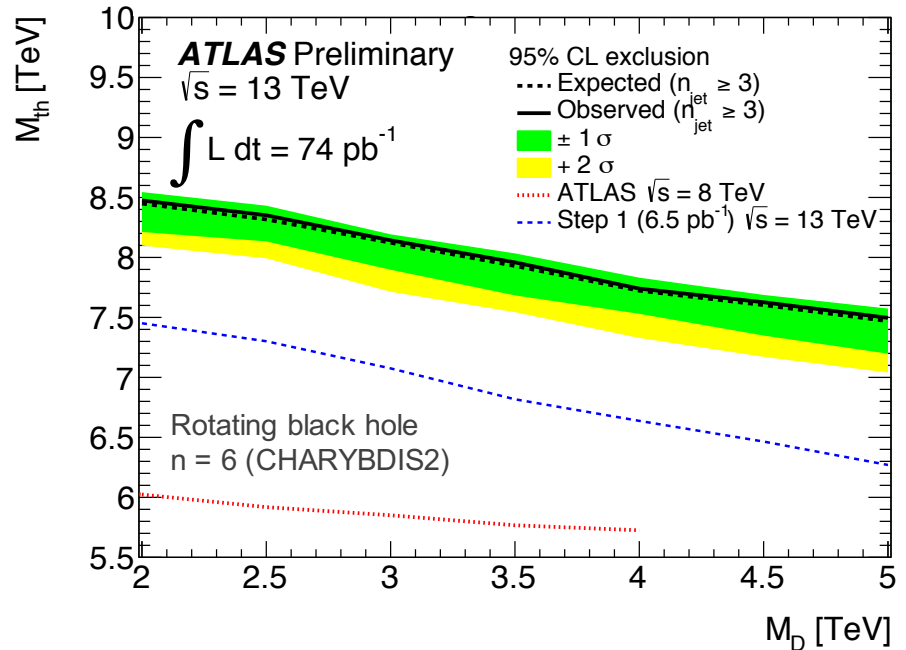
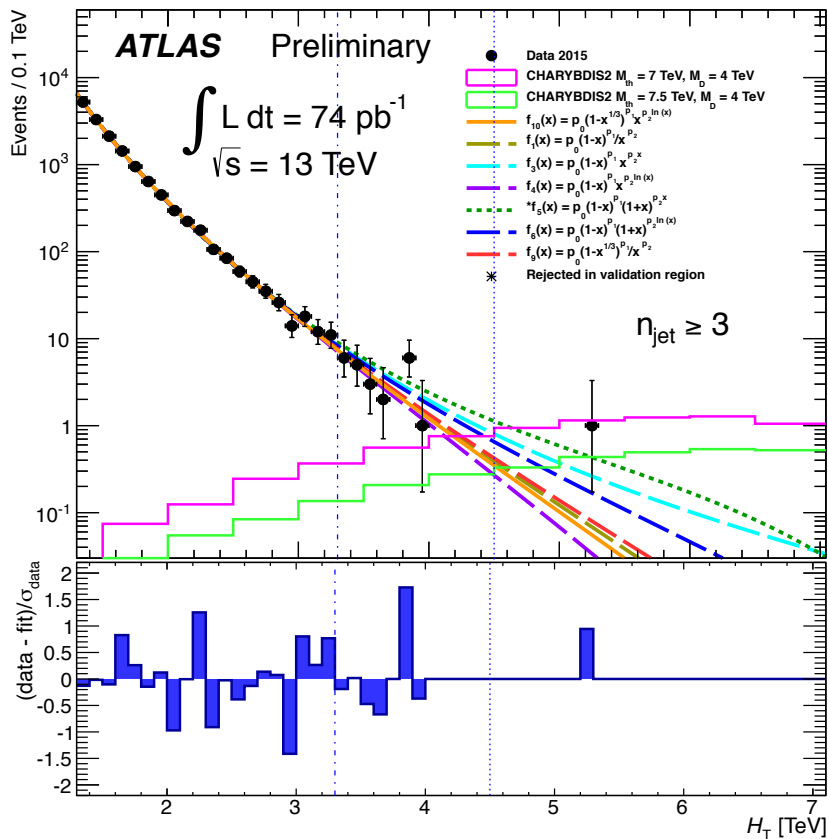


New physics searches with multi-jets

Early 13 TeV data already sensitive to very high-mass & cross section physics (eg, QBH)

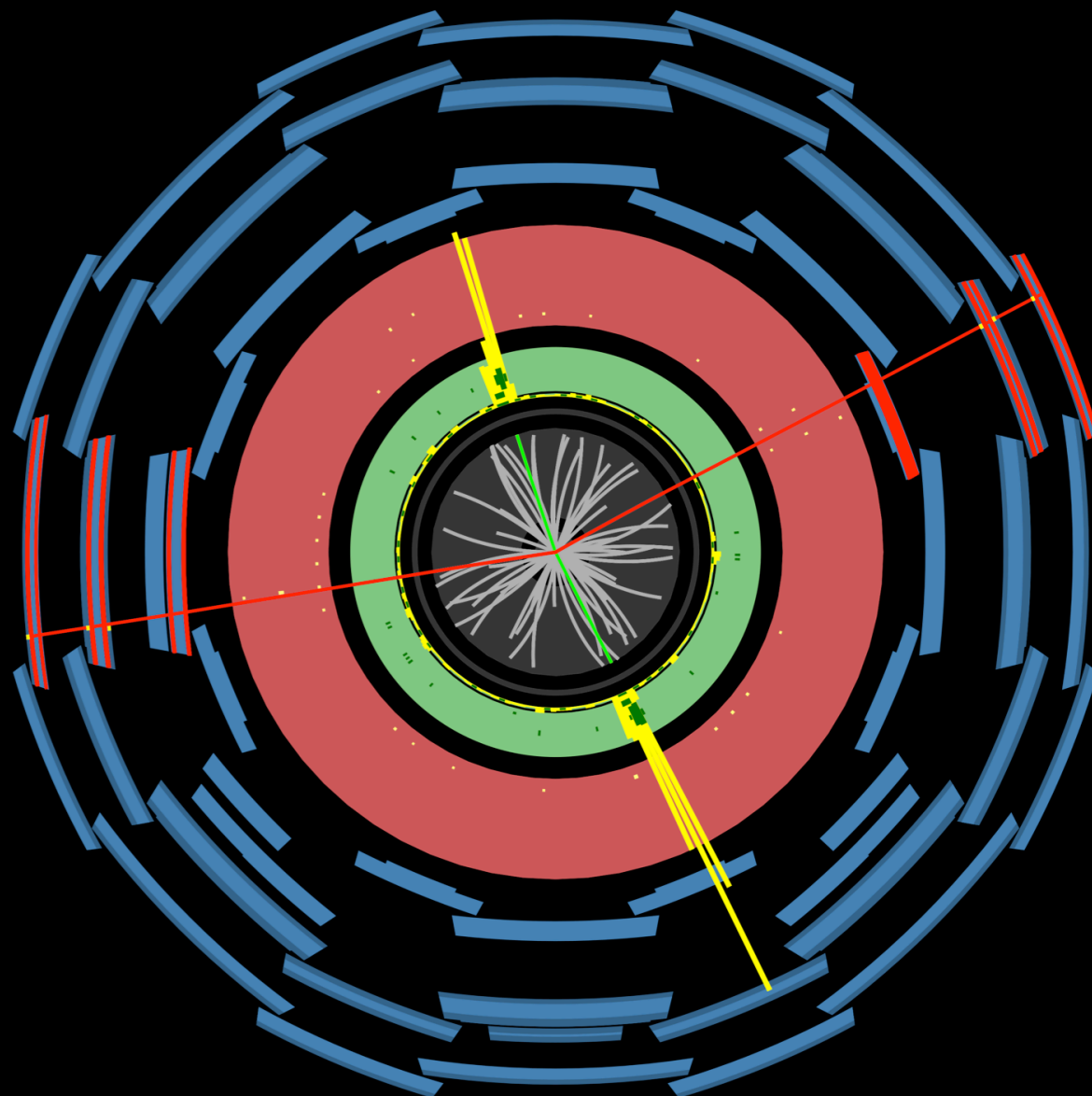
ATLAS-CONF-2015-043

Similarly, look for structure in $H_T = \sum_{\text{jets}} p_T$ in events with $\geq 3-8$ jets with $p_T > 50$ GeV



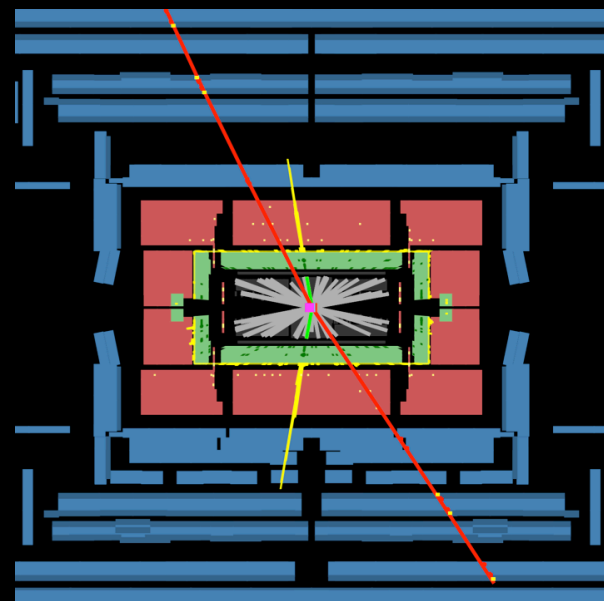
Limit increased over Run-1 by more than 2 TeV in threshold mass for $M_D < 4 \text{ TeV}$

Display of $ZZ \rightarrow \mu^+\mu^- + e^+e^-$ candidate event ($m_{\mu\mu/ee} = 94 / 86 \text{ GeV}$, $m_{\mu\mu ee} = 191 \text{ GeV}$)

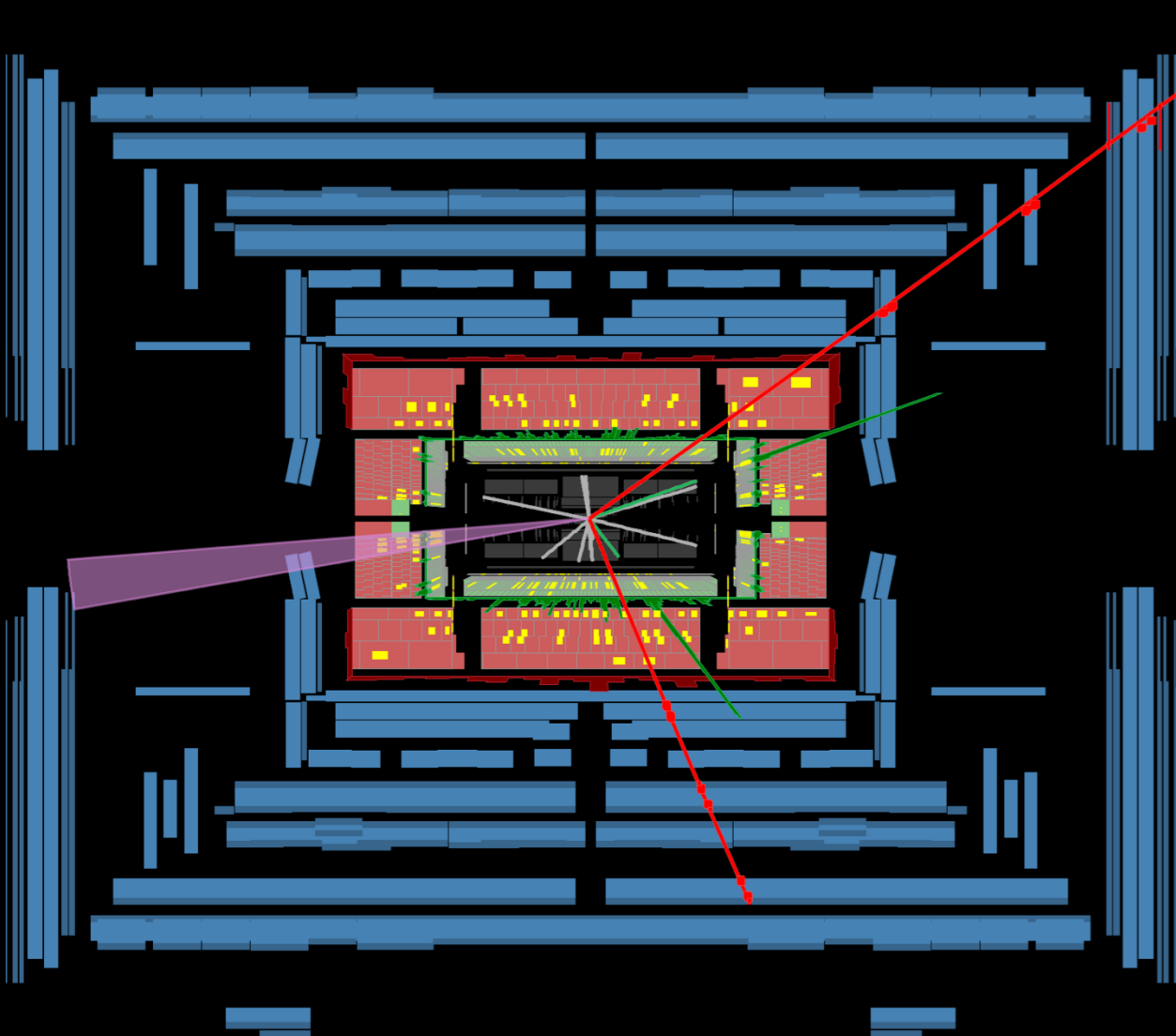


Run Number: 271298, Event Number: 78224729

Date: 2015-07-10 20:50:34 CEST

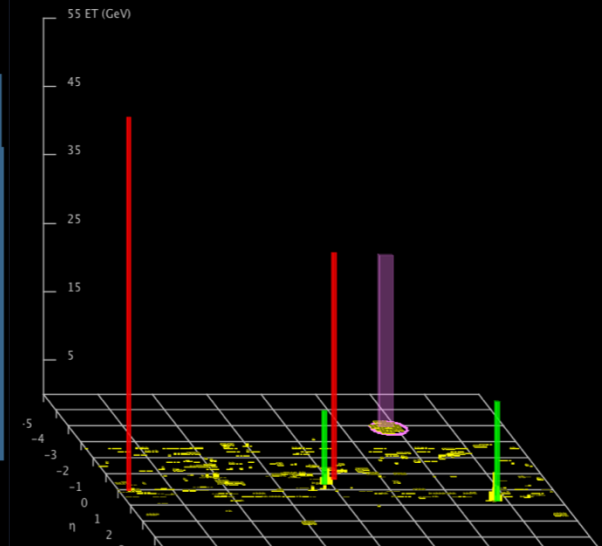


Display of $H \rightarrow \mu\mu ee$ candidate from 13 TeV pp collisions. The measured momenta are: $p_T(\mu) = 55, 33$ GeV, $p_T(e) = 14, 11$ GeV. The measured masses are: **$m(\mu\mu ee) = 123$ GeV**, $m(\mu\mu) = 91$ GeV, $m(ee) = 27$ GeV



Run Number: 280464, Event Number: 517140616

Date: 2015-09-28 04:21:57 CEST



Successful restart by LHC and detectors at 13 TeV

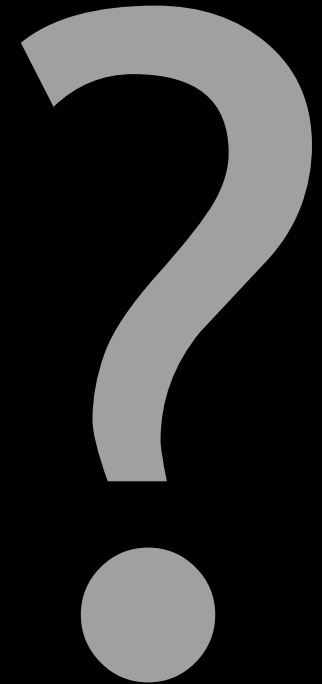
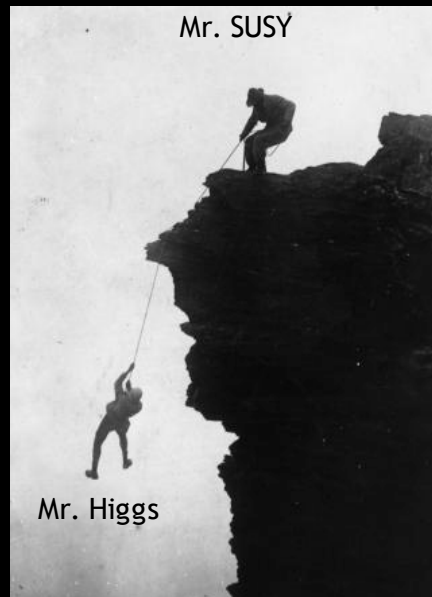
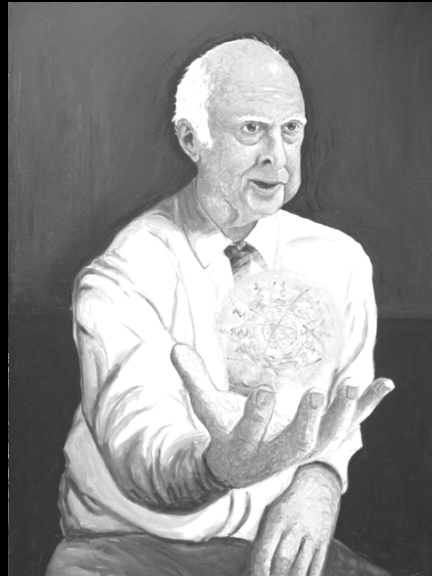
Experiments were well prepared – lots of interesting physics results already

Questions remain

Is the new boson the SM Higgs ?

If so, what protects it ?

And what makes the dark matter ?



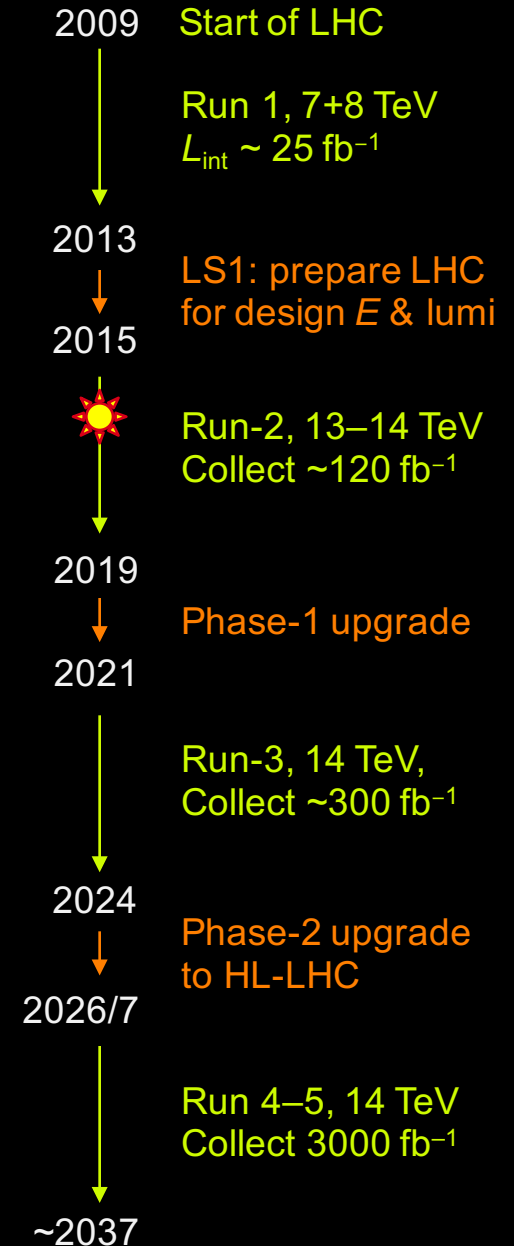
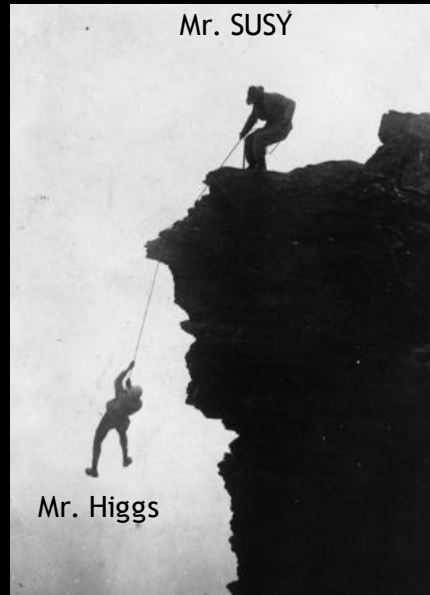
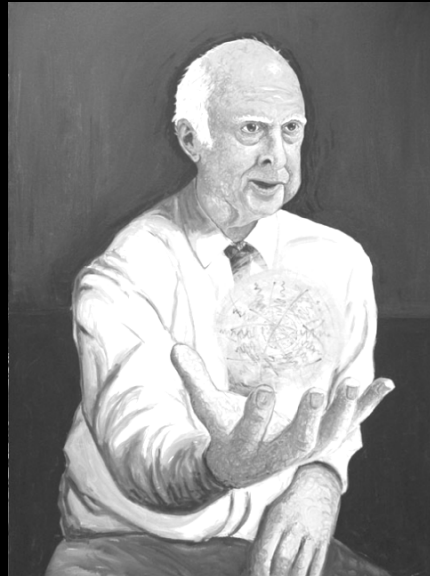
Only data can tell us !

LHC timeline

Is the new boson the SM Higgs ?

If so, what protects it ?

And what makes the dark matter ?





Next updates:

Watch the archive and the end-of-year seminars, 15 Dec 2015 at CERN

[<http://indico.cern.ch/event/442432>]



Thank you