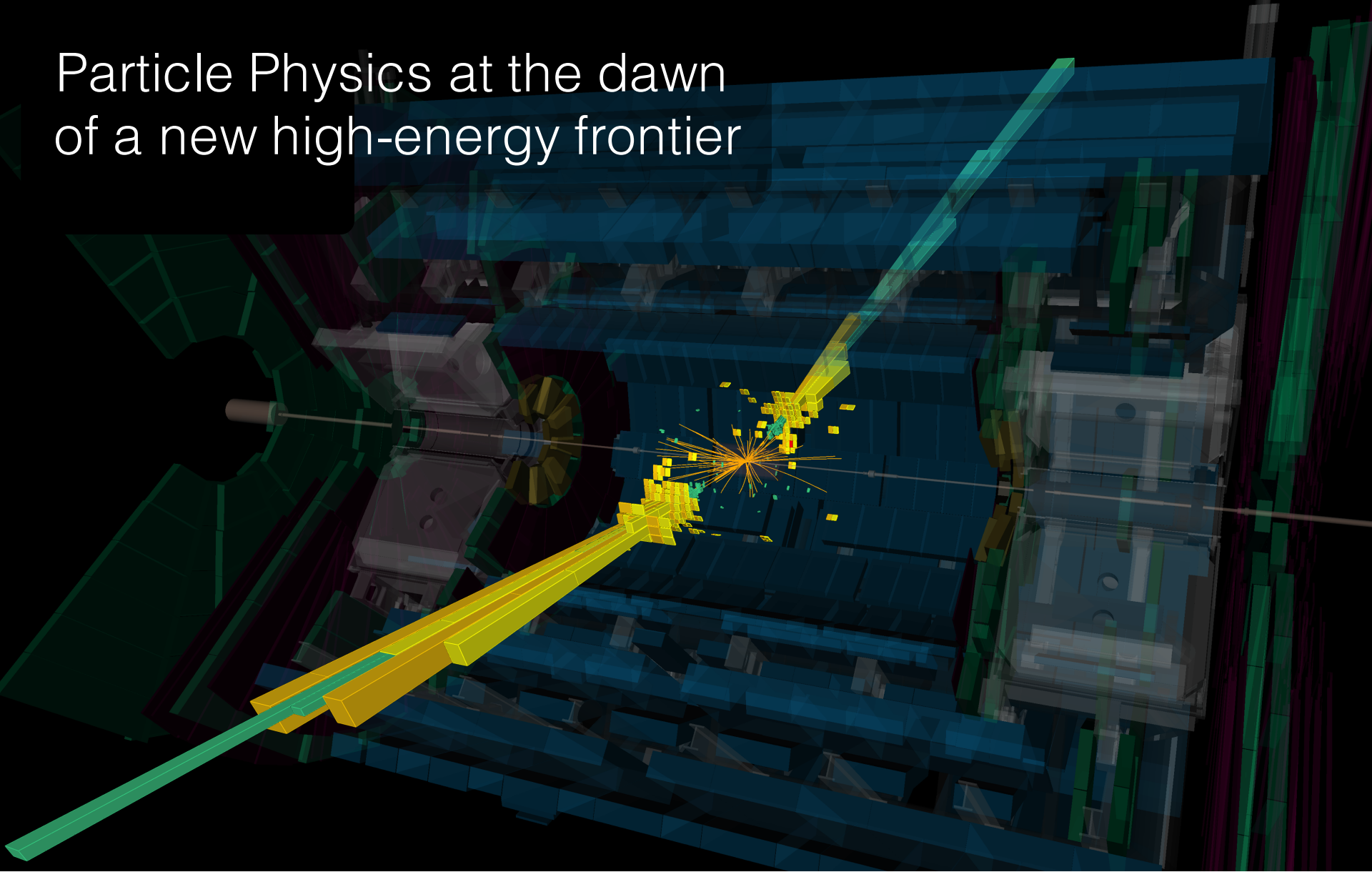


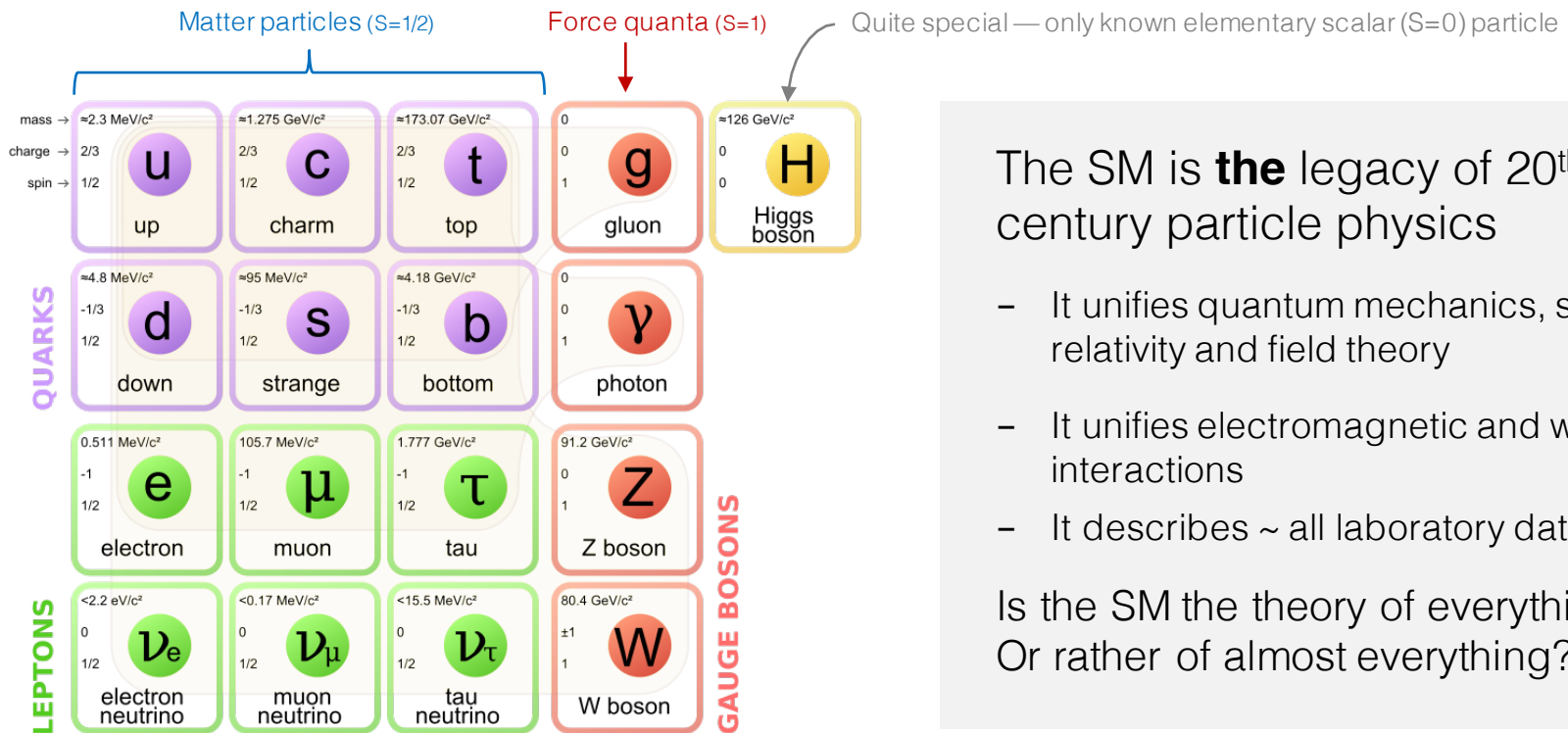
Particle Physics at the dawn of a new high-energy frontier



Andreas Hoecker (CERN)

Physikalisches Kolloquium, Universität Freiburg, July 4th 2016

Everyday life, and particle physics, are described by the Standard Model relying on gauge symmetry



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

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

Is the SM the theory of everything?
Or rather of almost everything? **No!**

+ gravitation (general relativity)

Scales in particle physics

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



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

0

Scales in particle physics

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10^{19} GeV

10^{16} GeV

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

Planck scale (M_{Pl})

GUT ?

ν_R ?

LHC reach

New Physics ?

t, Z, W, H, EWSB

ψ, b, Y, B

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

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

e

core of Sun

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ν 's

$\downarrow ?$

$\downarrow$

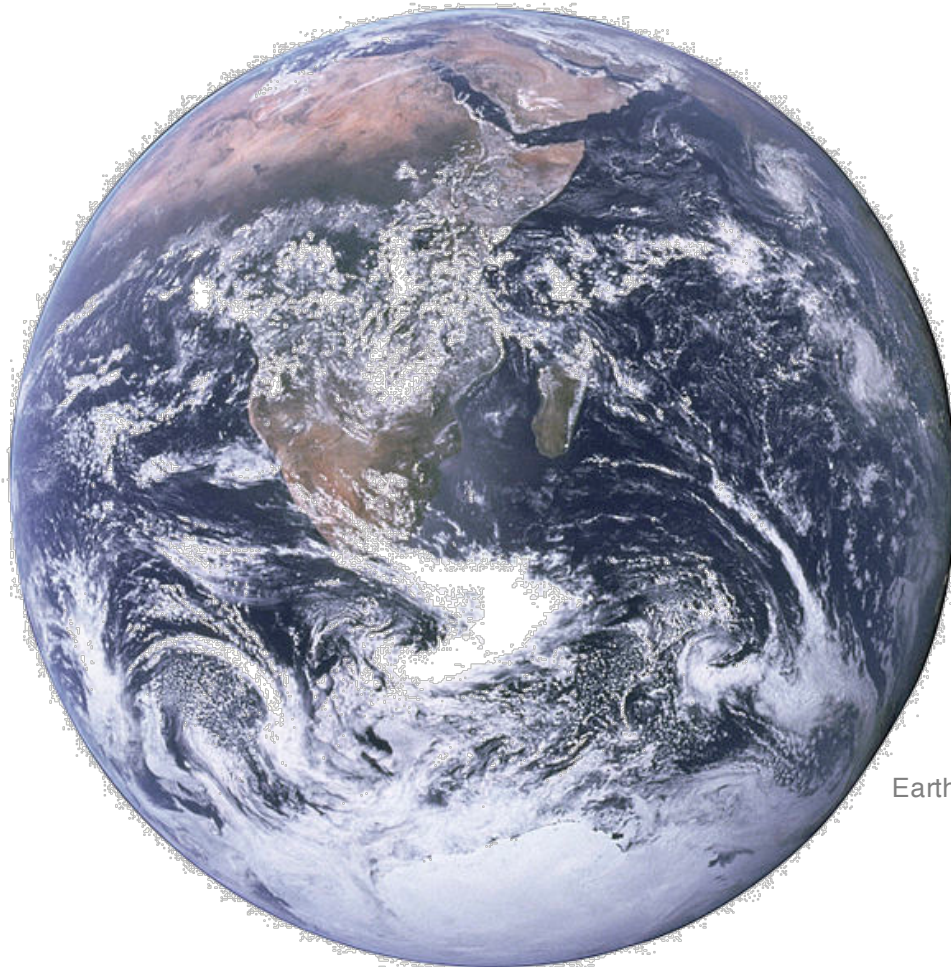
γ, g

...probing
attometre
scales

Scales in particle physics

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

Nanoscience



Earth

Particle physics today (TeV scale)



Siphonaptera (flea)

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 of a potential:

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

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

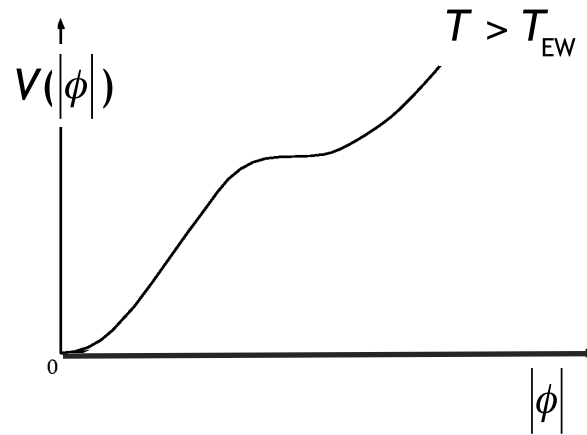
Three d.o.fs become Z, $W^\pm$ masses, fourth d.o.f is **massive scalar Higgs boson**

This is known as the “**Brout-Englert-Higgs (BEH) mechanism**”

The Standard Model

BEH mechanism

The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)

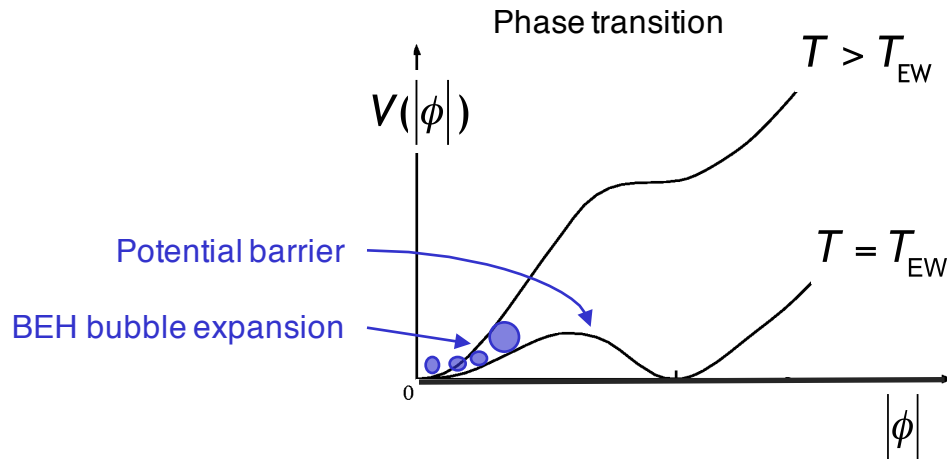


The Standard Model

BEH mechanism

The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)

A phase transition at $\sim T_{EW}$ ($\sim$ several 10^{-11} s after big bang, causal domain of few cm) led to $|\phi_{min}| > 0$



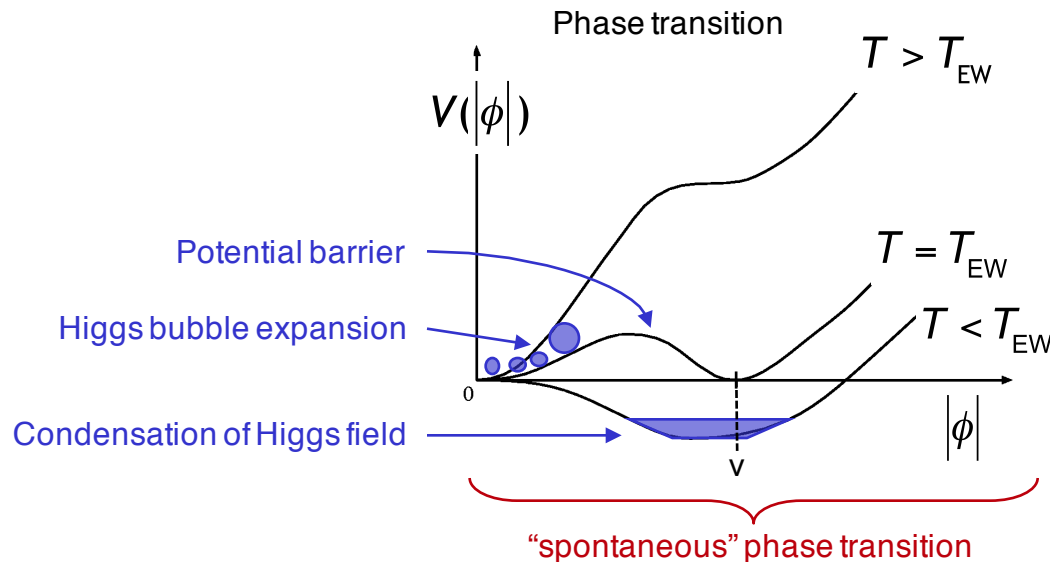
Picture describes a 1st order phase transition that would require light Higgs, or new physics $\rightarrow$ currently disfavoured

The Standard Model

BEH mechanism

The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)

A phase transition at $\sim T_{EW}$ ($\sim$ several 10^{-11} s after big bang, causal domain of few cm) led to $|\phi_{min}| > 0$



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

BEH 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 

The Standard Model

BEH 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

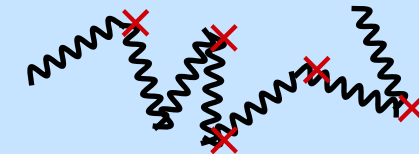
Gravity



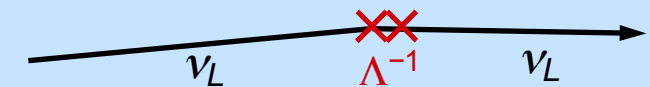
Photon



Weak boson



Neutrinos



Electrons



Top quark



Interaction with Higgs
field alters chirality of
massive Dirac fermion



Producing the Higgs Boson and Searching for New Physics at the TeV Scale Requires a Huge Machine

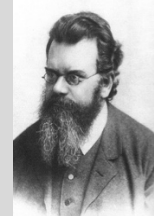


Lawrence
(First cyclotron provided 80 keV proton acceleration)

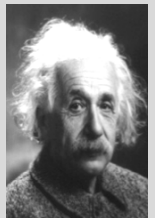
Particles accelerators:

- 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

Superconducting proton/ion accelerator and collider installed in a 27 km circumference underground tunnel (4 m tunnel cross-section diameter)

LHC ring at CERN:
27 km circumference

70 – 140 m depth

LHC
control
room

CERN (Prévessin site)

CERN (Meyrin site)

7 TeV



LHC

450 GeV



SPS

26 GeV



PS

1.4 GeV



BOO-
STER

50 MeV



LIN-
AC2



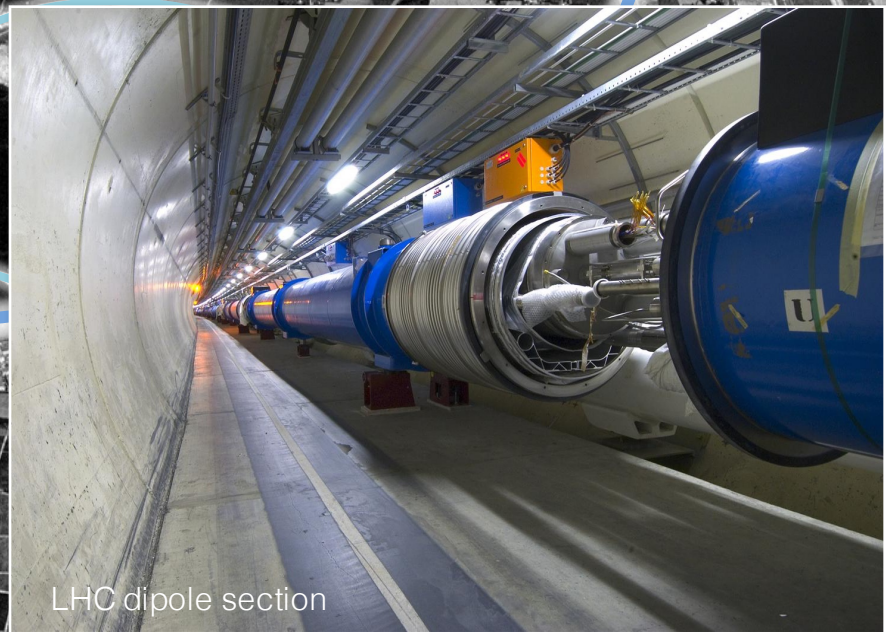
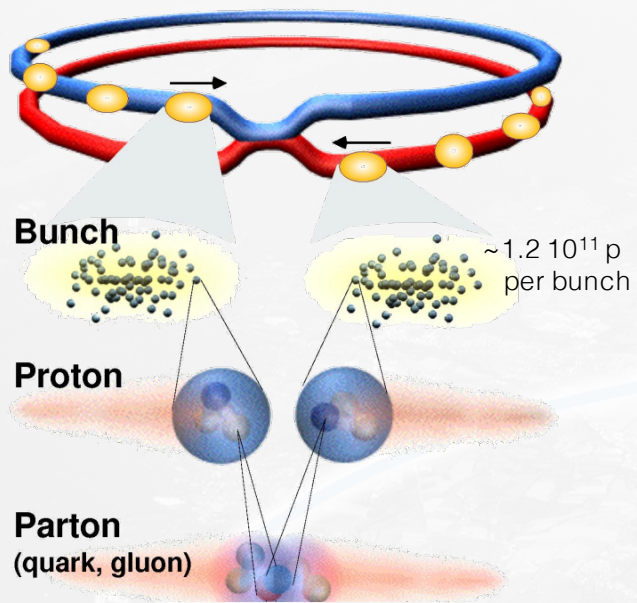
LHC ring at CERN:
27 km circumference

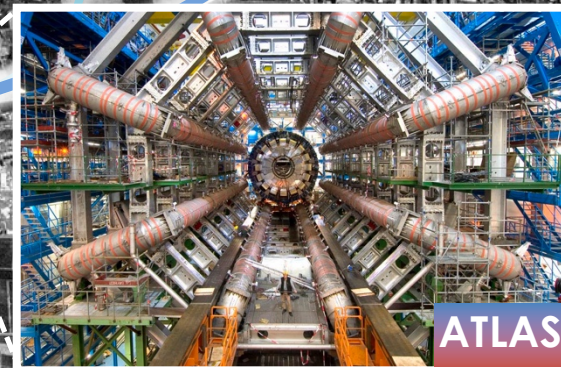
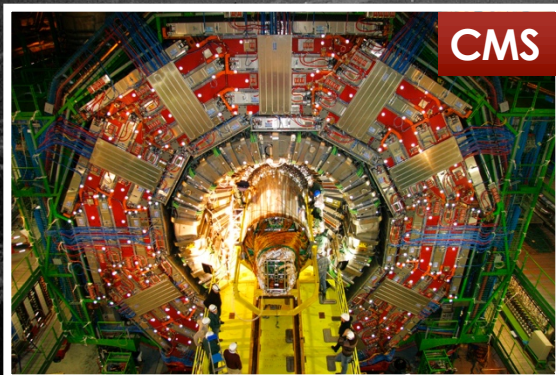
So far:
0.9 / 2.8 / 5 / 7 / 8 / 13 TeV proton–proton collisions
2.8 / 5 TeV Pb–Pb collisions
5 (soon 8) TeV p–Pb collisions

SPS ring:
7 km circumference

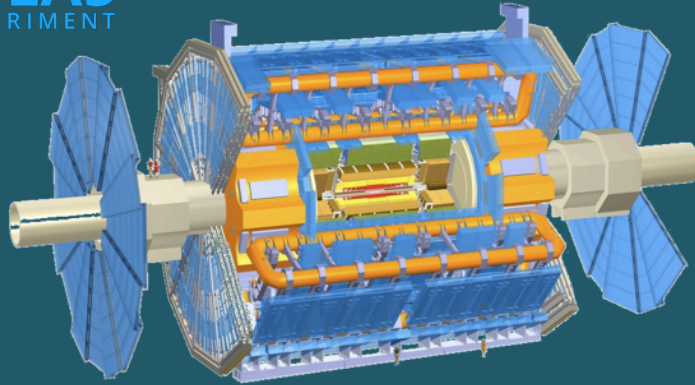
CERN (Meyrin site)

~20 minutes are required to accelerate the protons in the LHC from 450 GeV to 7 TeV

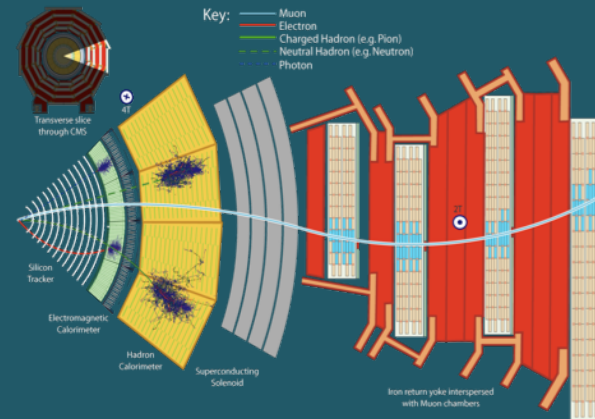




ATLAS & CMS: giant, ultra sophisticated particle detectors



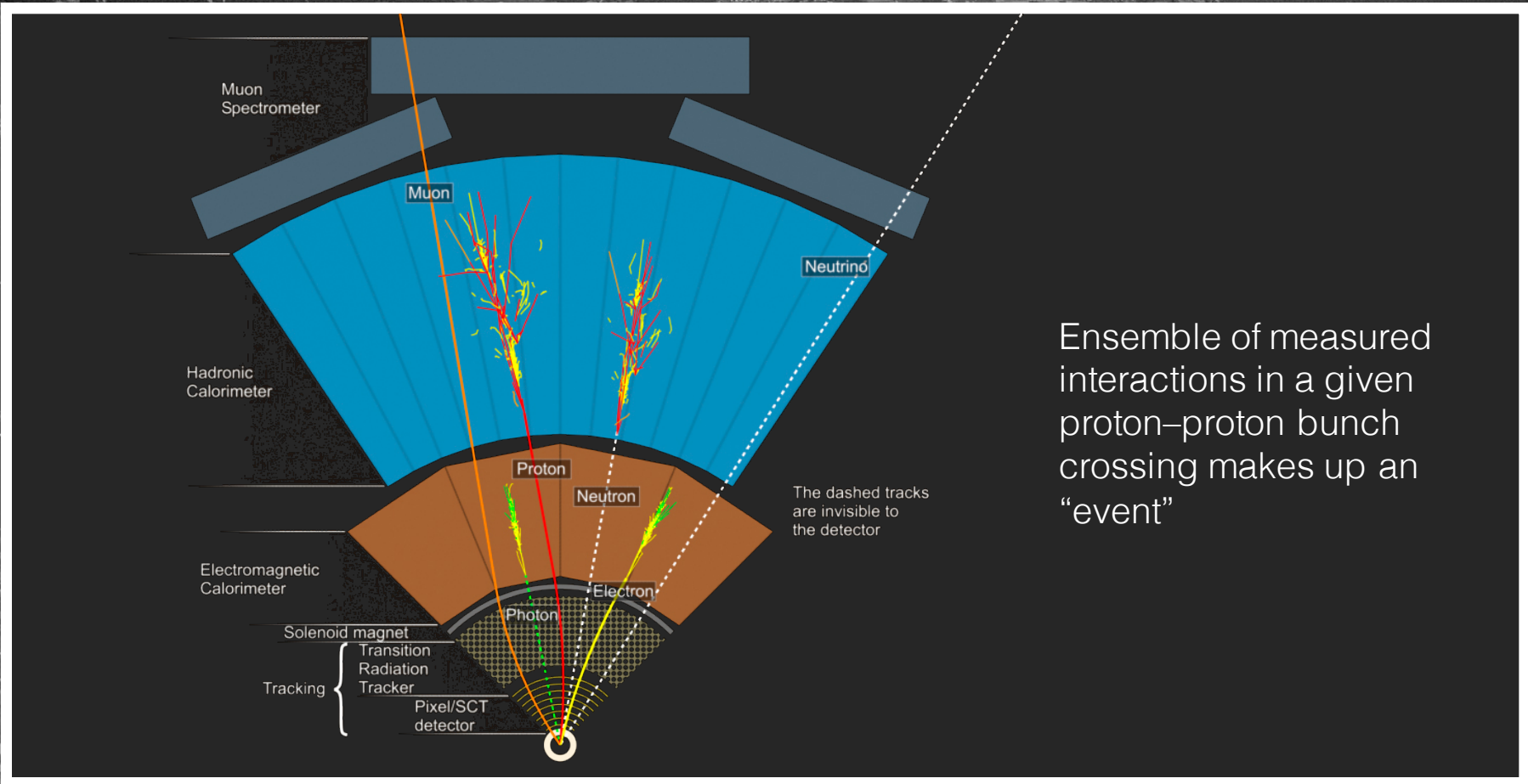
ATLAS: emphasis on excellent jet and missing- E_T resolution, particle identification, flavour tagging, and standalone muon measurement



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"



Luminosity — single most important quantity

- Luminosity drives our ability to detect low cross-section processes

$$N_{\text{events}}^{\text{obs}} = \text{cross section} \times \text{efficiency} \times \int L \cdot dt$$

“Cross section” given by Nature

“Efficiency” of detection optimised by experimentalist

Integrated luminosity delivered by LHC

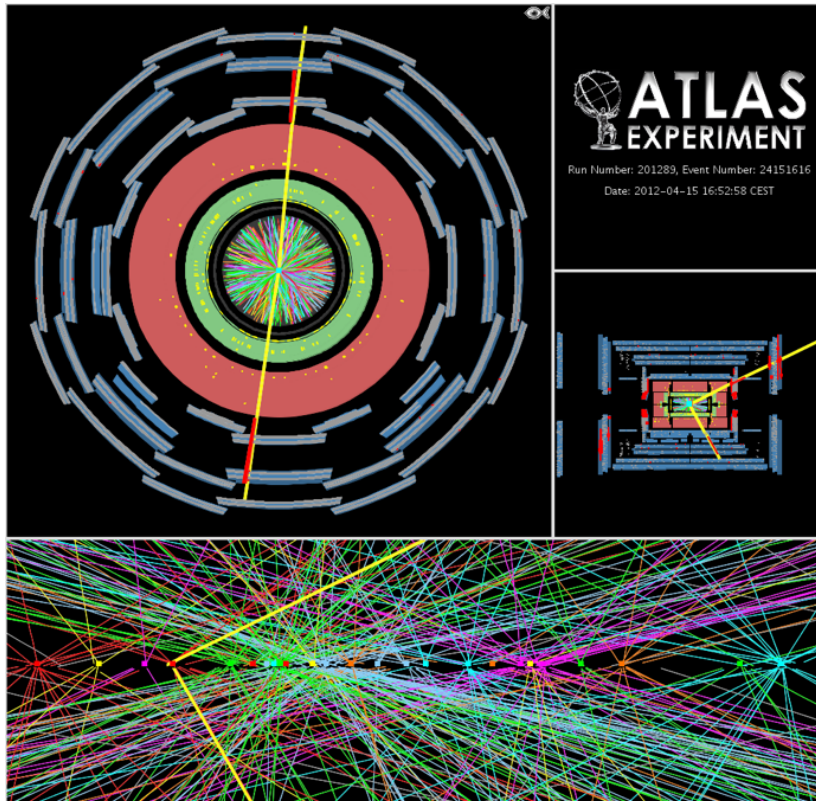
- Luminosity is a function of the LHC beam parameters

$$L \sim \frac{f_{\text{rev}} n_{\text{bunch}} N_p^2}{4\pi\sigma_x\sigma_y} \quad [L] = \frac{1}{\text{s} \cdot \text{cm}^2}$$

$$\begin{aligned} L_{\text{max}} &\sim 1.6 \times 10^{34} \text{ s}^{-1} \text{cm}^{-2} \\ 10 \text{ nb}^{-1} \text{s}^{-1} &= 10^{34} \text{ s}^{-1} \text{cm}^{-2} \\ &\sim 1 \text{ GHz interaction rate} \end{aligned}$$

- f_{rev} = 11245.5 Hz is the bunch revolution frequency
- n_{bunch} = 1...2808 is the number of bunches in the machine
- N_p = 1.1×10^{11} is the number of protons per bunch (“bunch intensity”)
- $\sigma_{x/y}$ = 12...50 μm is the transverse beam width characterising beam optics, $\sigma_{x/y}^2 = \varepsilon_{x/y} \beta_{x/y}^*$

High luminosity comes at price of pileup interactions



CMS very similar

Pileup interactions

- Average of 21 (peak: 40) interactions per crossing in 2012. Similar in 2016.
LHC design value:

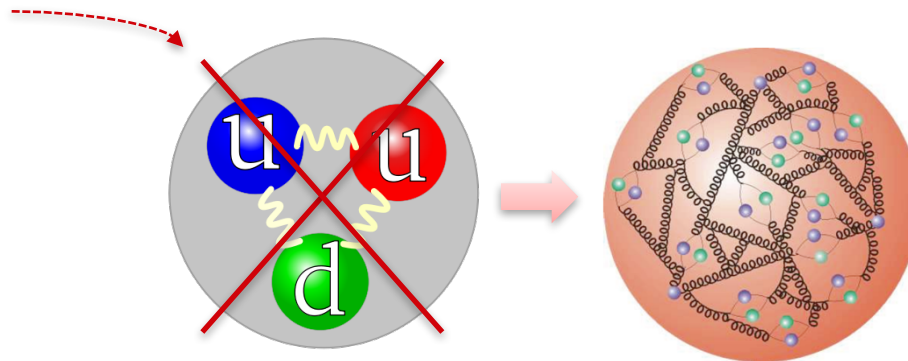
$$\mu = \frac{\sigma_{\text{inel}} \cdot L}{f_{\text{rev}} \cdot n_{\text{bunch}}} \approx \frac{80 \text{ mb} \cdot 10 \text{ nb}^{-1} \text{ s}^{-1}}{11245 \text{ s}^{-1} \cdot 2808} = 25$$

- Most analyses quite insensitive to pileup at this rate, several mitigation methods used
- However: 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**

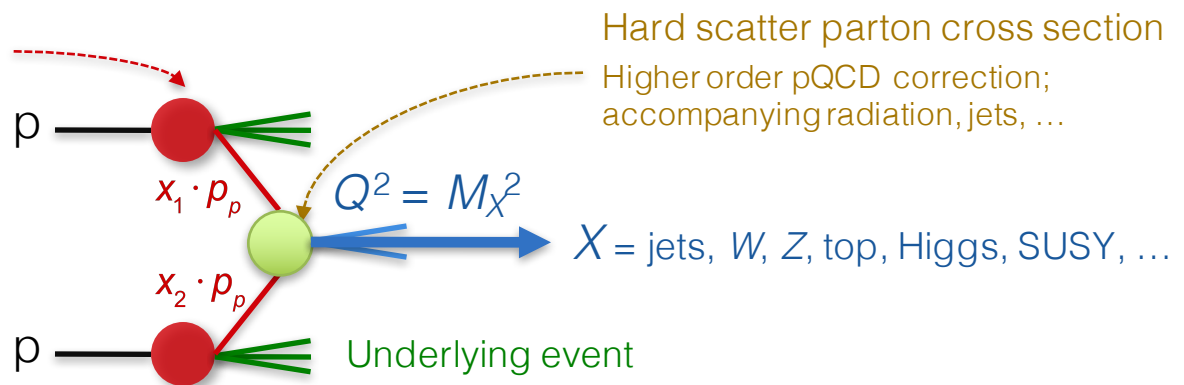
Parton distribution functions
Representing structure of proton,
extracted using experimental
data and QCD properties



Proton–Proton Collisions

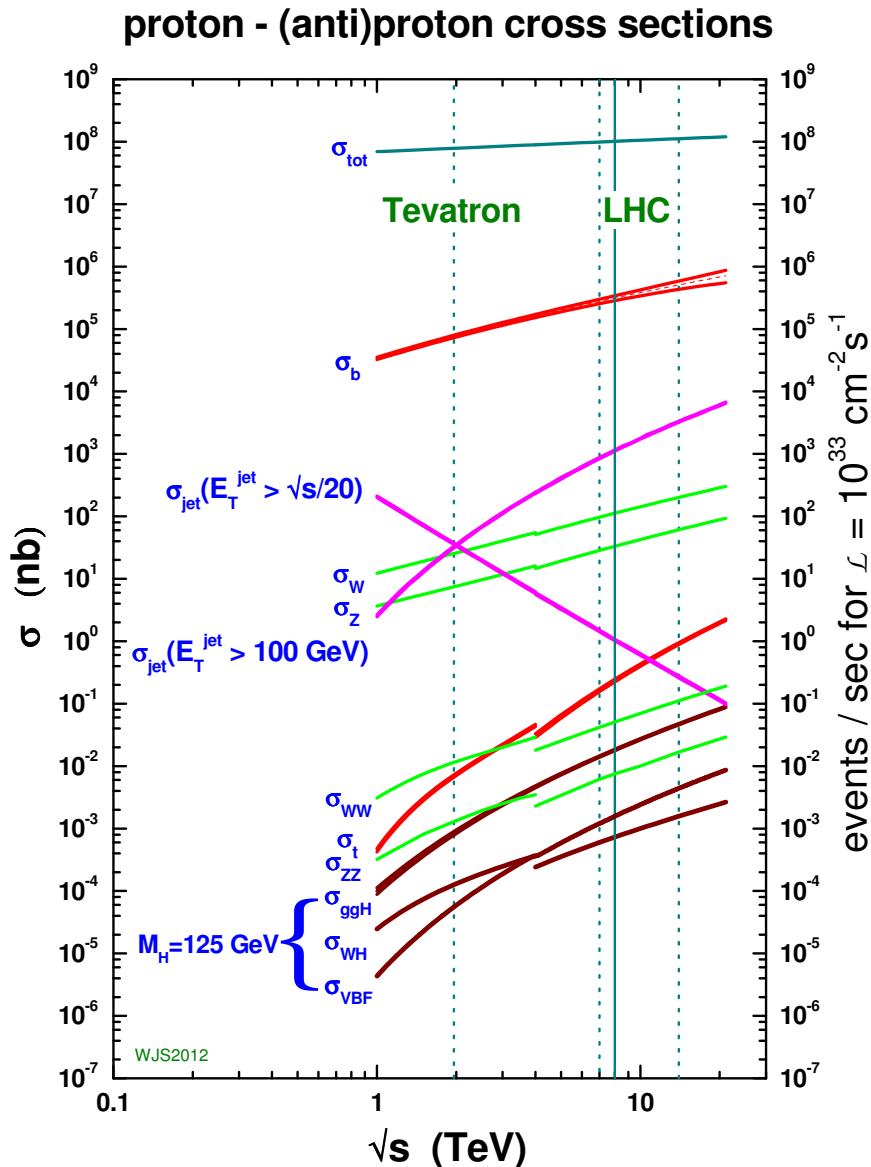
- For proton–proton collisions, cross section is **convolution of Parton Density Functions (PDF) with parton scattering Matrix Element**

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



- CM energy-squared of parton collision: $\hat{s} = M_X^2 = x_1 \cdot x_2 \cdot s_{\text{LHC}}$
- The PDFs 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

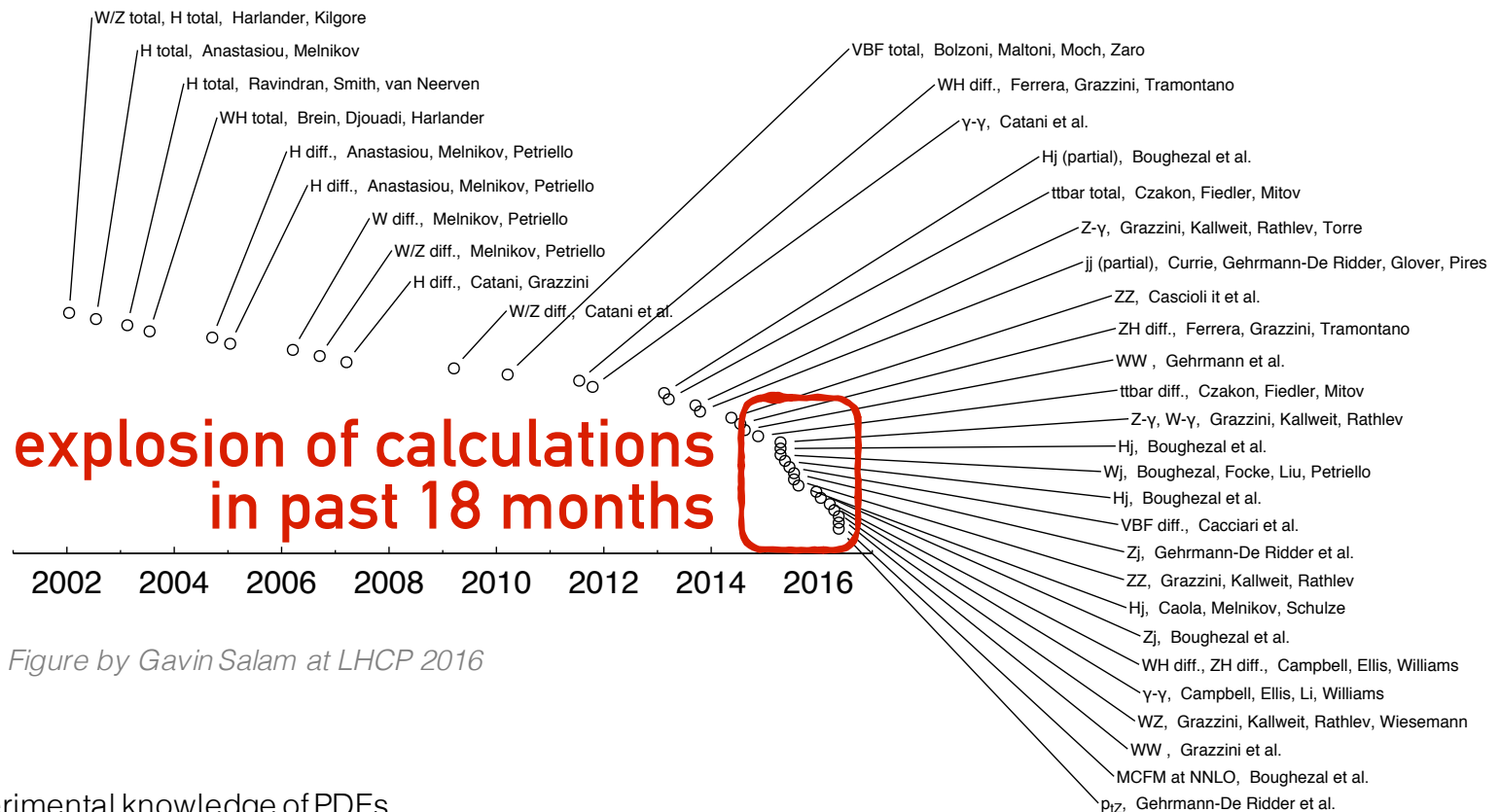


- Cross-section fully dominated by inelastic strong interaction
“minimum bias” events
- Detectors cannot record 40 MHz event rate* (each event ~ 2 MB size $\rightarrow 80$ TB / second)
- Online custom hardware and software “triggers” reduce rate to filter out events with a million & more times smaller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

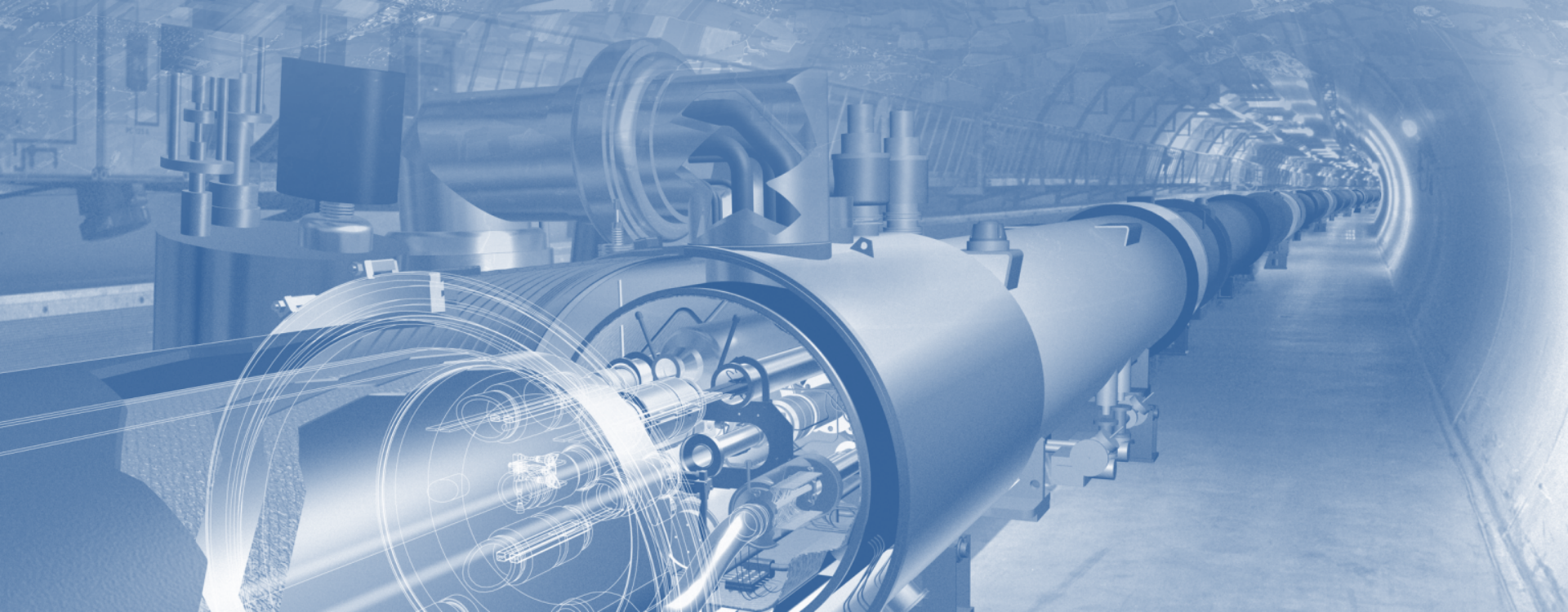
*The LHCb phase-1 upgrade is preparing for exactly that!

Theoretical cross-sections and uncertainties

Progress in theoretical calculations — NNLO revolution



Also experimental knowledge of PDFs
limits precision in many LHC analyses !

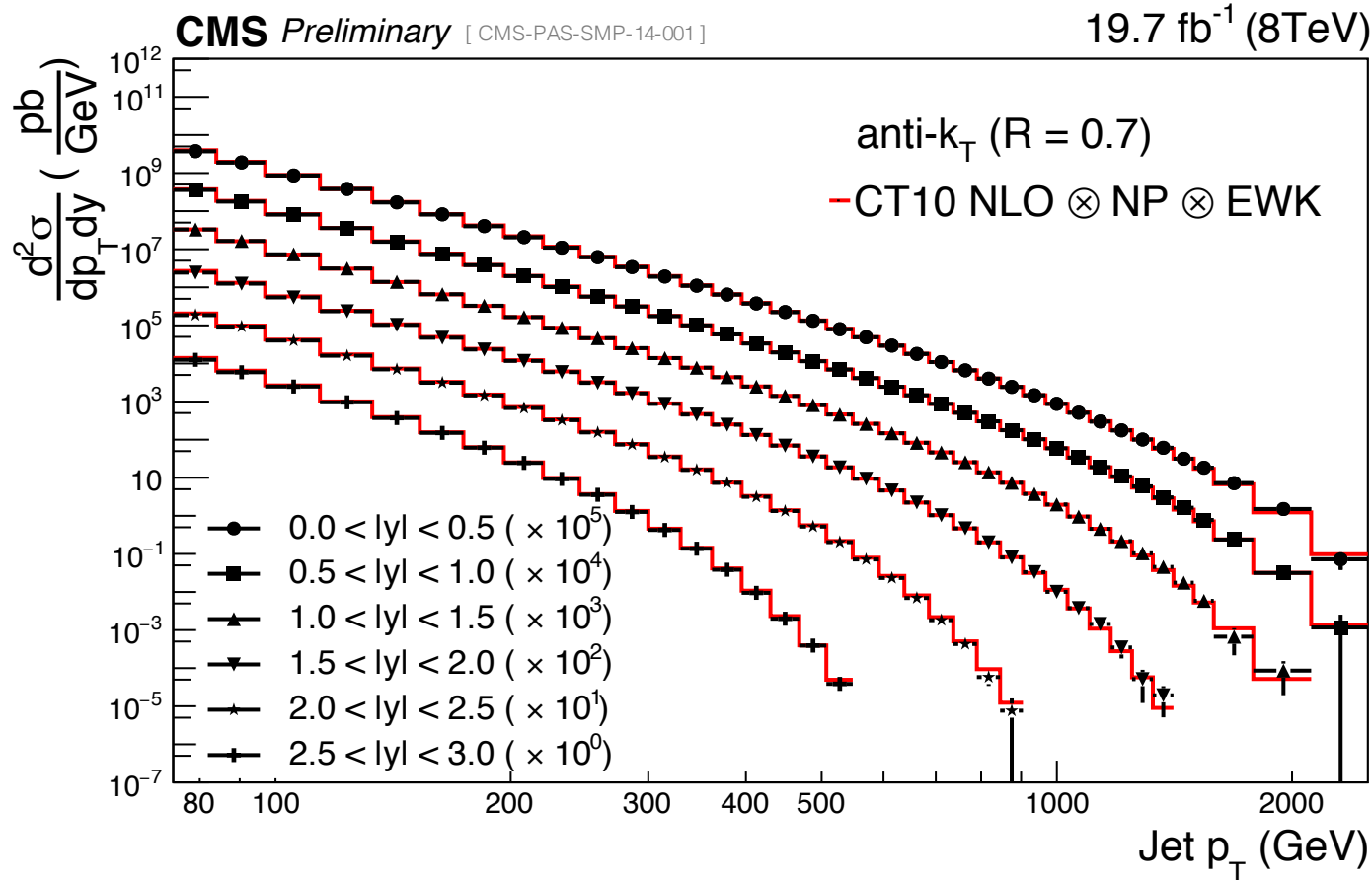


The LHC Run-1: 7 & 8 TeV pp, 5 & 20 fb⁻¹

A brief history of selected highlights

Inclusive and differential jet cross section vs. jet p_T and rapidity

Agreement with theory over many orders of magnitude



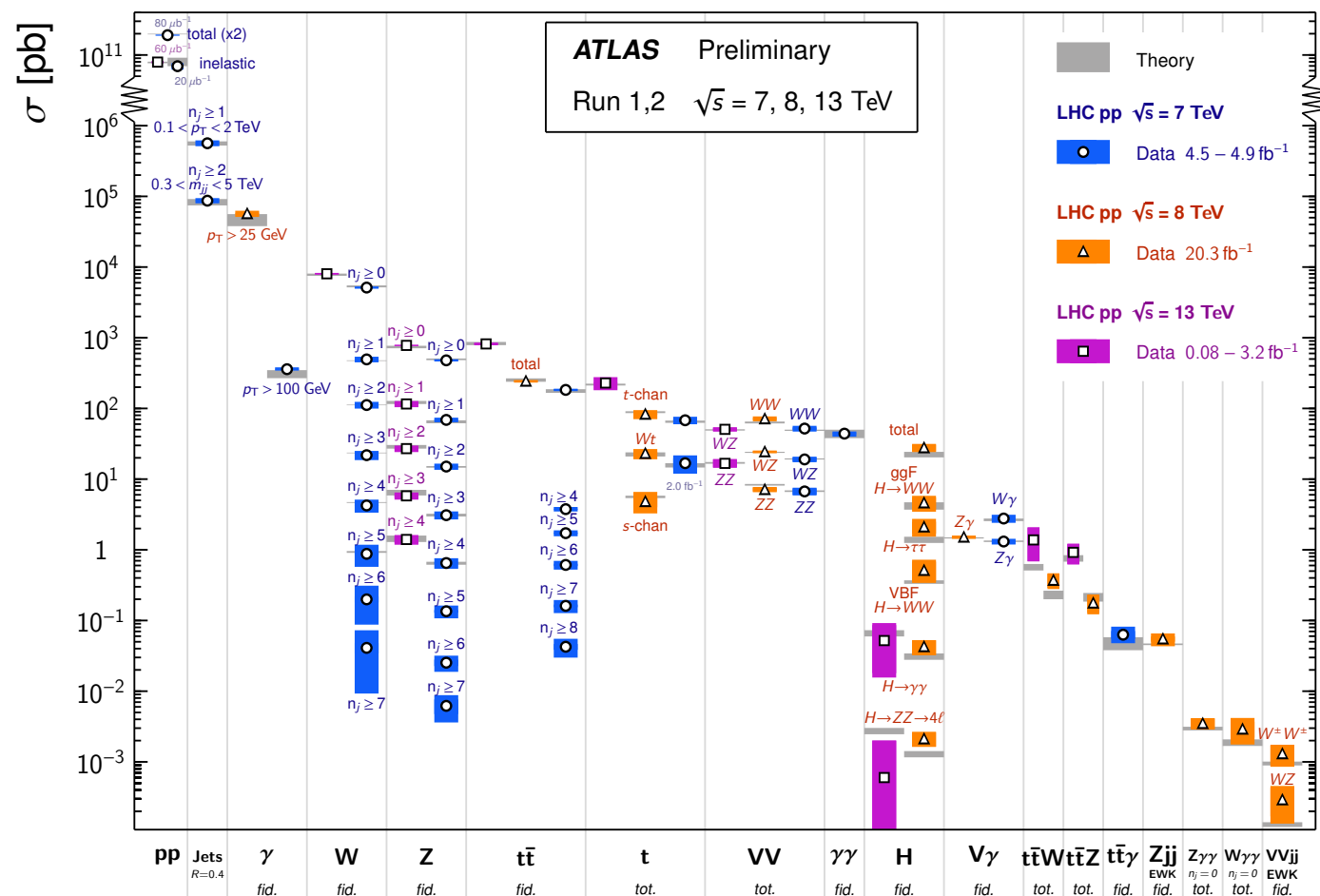
Precision measurements
& theory developments
(includes non-perturbative and
electroweak corrections)
→ new quality of QCD
tests at hadron colliders

Theory so far agrees with all measured cross-sections

Across widely different processes

Standard Model cross-section measurements

Status: June 2016



Harvest of cross-section measurements from LHC experiments (> 500 papers / exp) confirmed the predictive power of the Standard Model

Run-1 is not over yet: high-quality, extremely well understood data sample for precision measurements

Run-1 allowed critical first electroweak studies

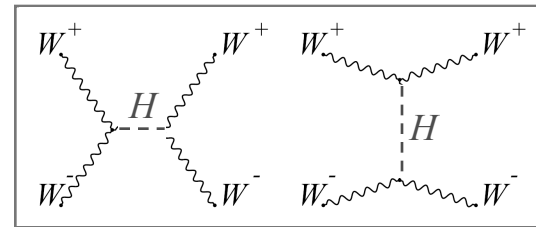
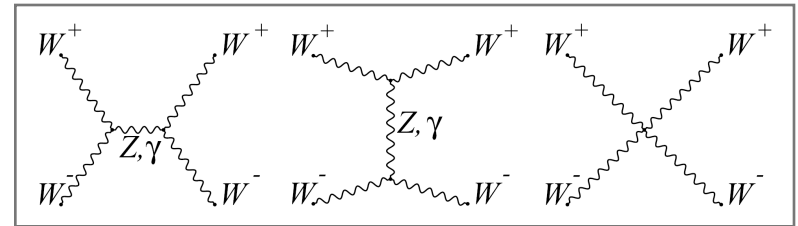
Higgs boson acts as “moderator” to unitarise high-energy longitudinal vector boson scattering

Unitarity: if only Z and W are exchanged, the amplitude of (longitudinal) $W_L W_L$ scattering violates unitarity

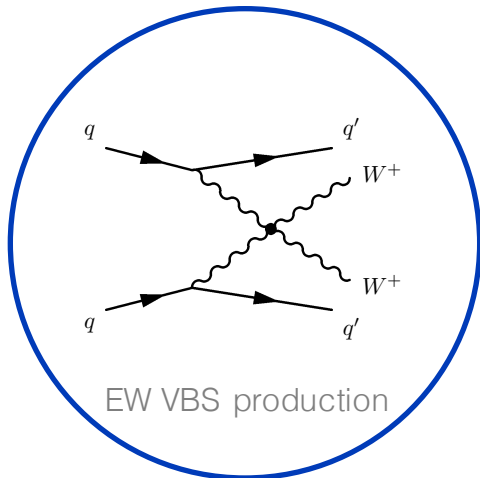
$$A_{Z,\gamma}(W^+W^- \rightarrow W^+W^-) \propto \frac{1}{v^2}(s+t)$$

Higgs boson restores unitarity of total amplitude:

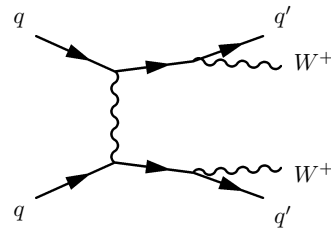
$$A_H(W^+W^- \rightarrow W^+W^-) \propto -\frac{m_H^2}{v^2} \left(\frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} \right)$$



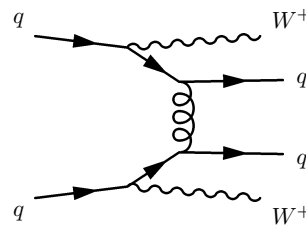
m_H must not be too large (which is fulfilled)



EW VBS production



Non-VBS production



Strong production

Look for VBS scattering in high dijet invariant mass distributions

Run-1 allowed critical first electroweak studies

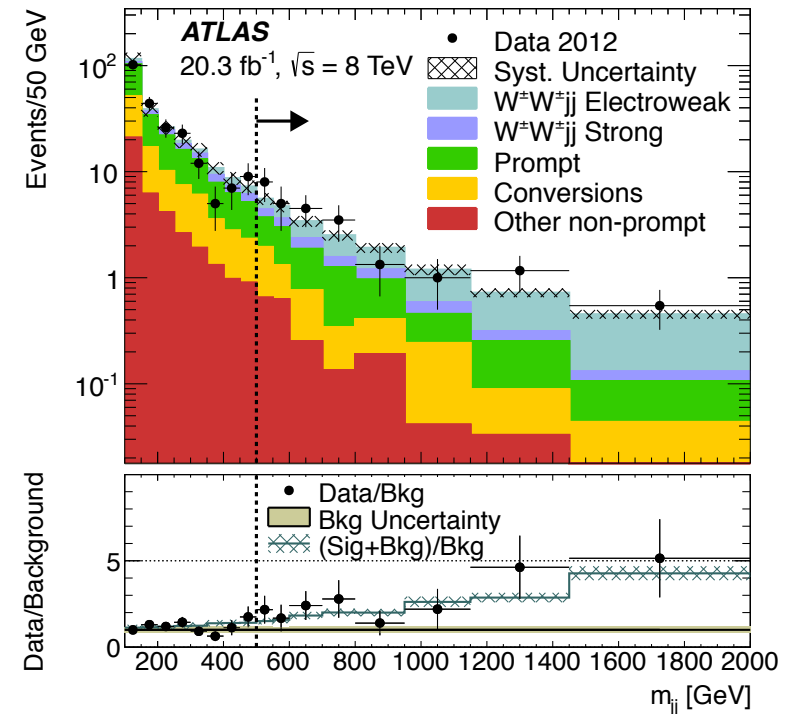
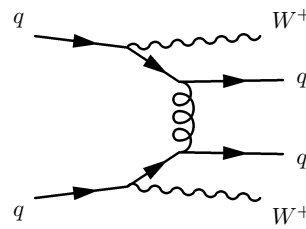
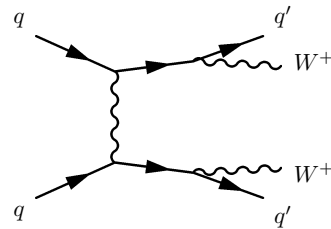
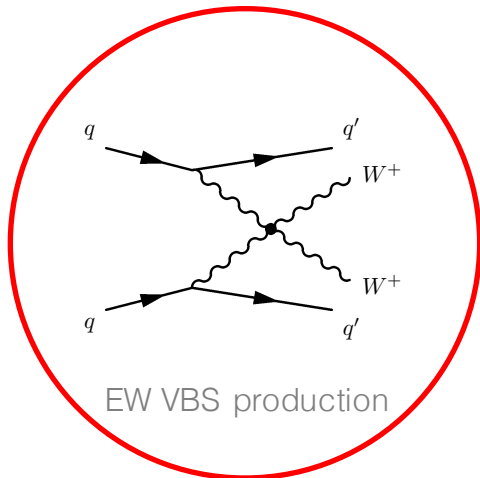
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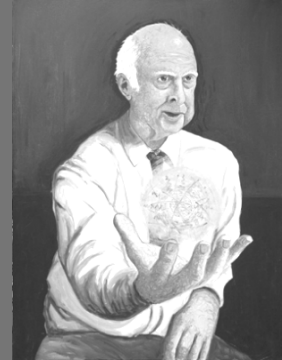
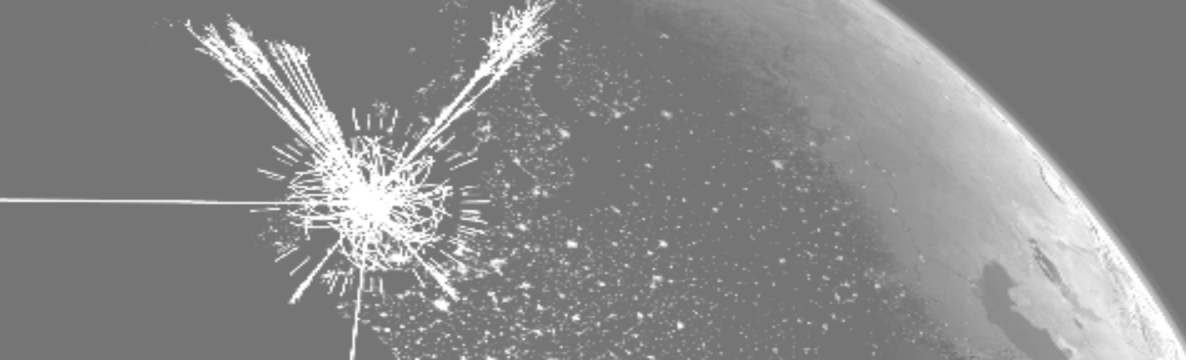
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Look for VBS scattering in high dijet invariant mass distributions



Higgs Boson—Run-1 Masterpiece

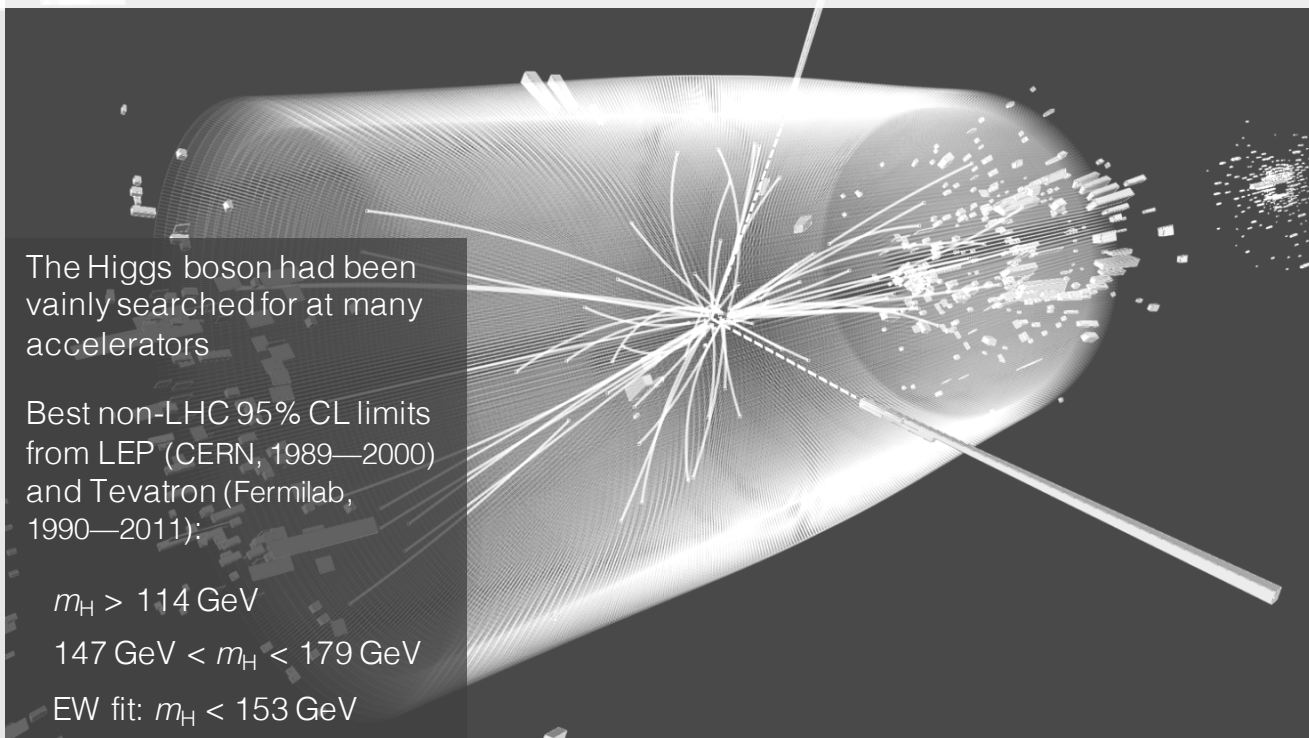
The Higgs boson had been vainly searched for at many accelerators

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

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

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

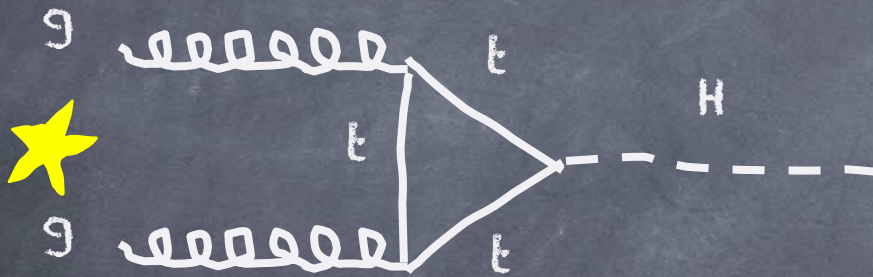
$$\text{EW fit: } m_H < 153 \text{ GeV}$$



Higgs boson production at the LHC

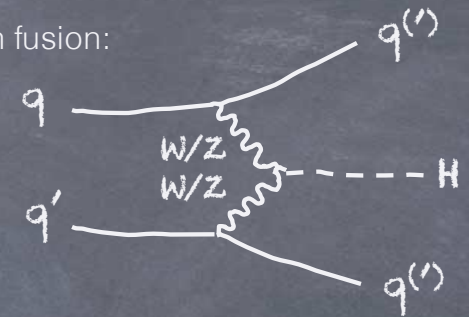
At the LHC, the Higgs boson is dominantly produced via gluon fusion $\sigma_{H,\text{total}} \sim 22 \text{ pb}$ at 8 TeV for $m_H = 125 \text{ GeV}$

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

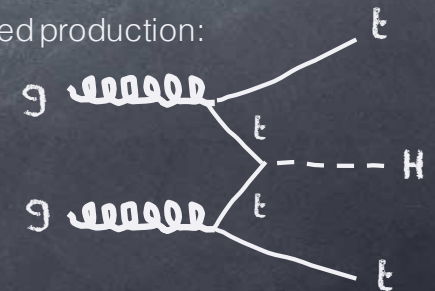
Vector boson fusion:



Higgs-strahlung:



"ttH" associated production:



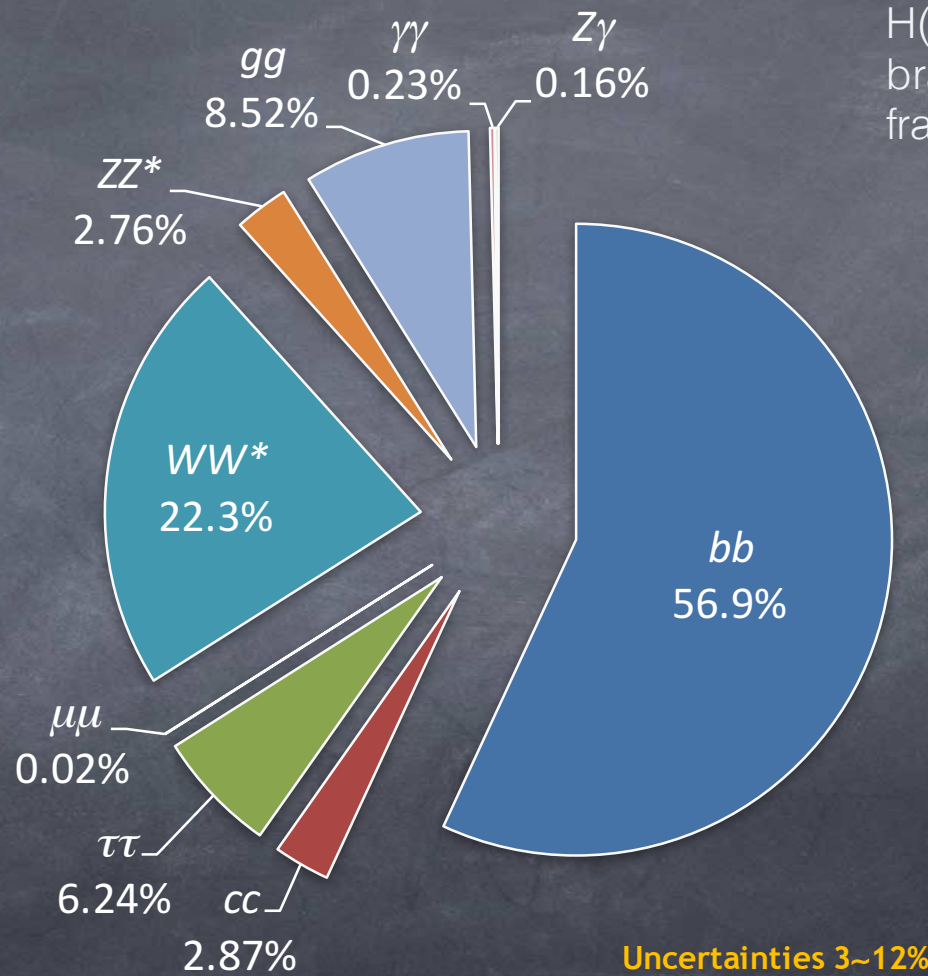
Higgs boson production at the LHC

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

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

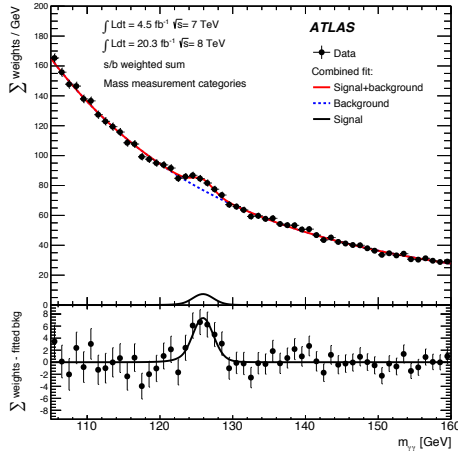
... the Higgs does not couple directly to photons and gluons, but only via “loops” involving preferentially heavy particles (e.g., top, W)

H(125 GeV)
branching
fractions:

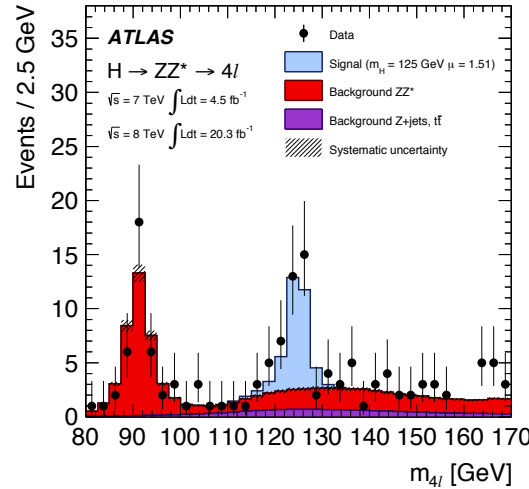


No doubt on H_{125} discovery in the bosonic channels

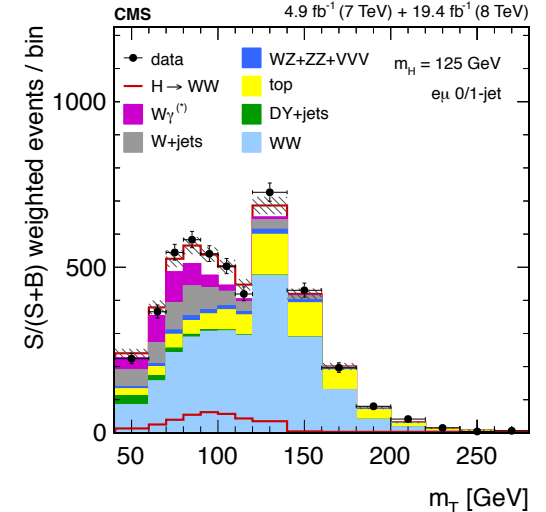
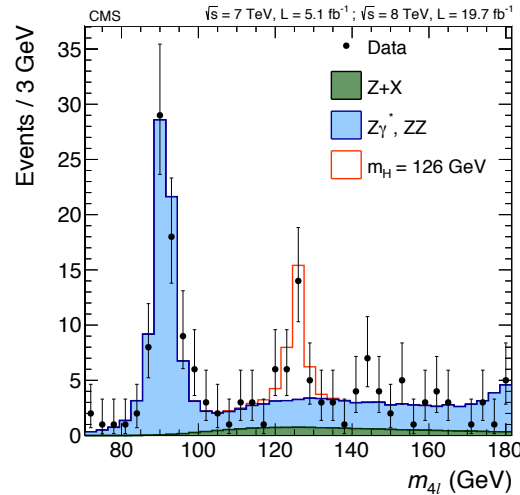
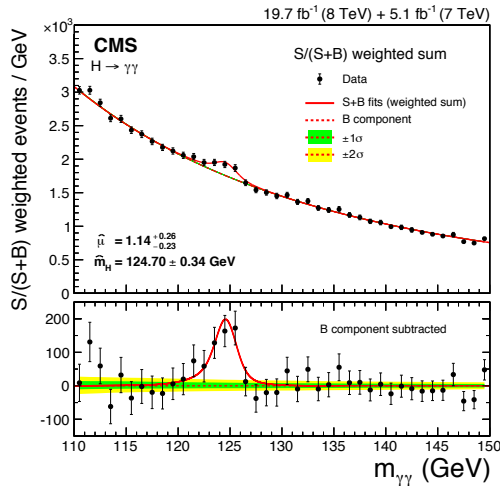
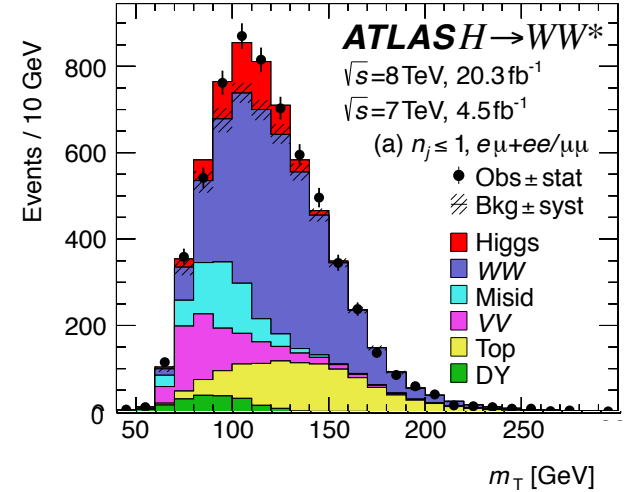
$$H \rightarrow \gamma\gamma$$



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



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



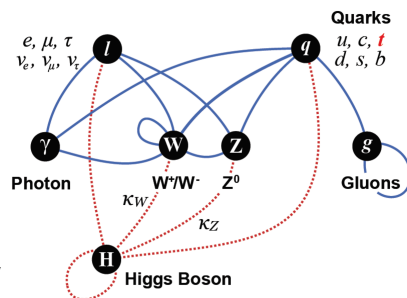
Very different experimental challenges in each of these discovery channels.
 All analyses significantly improved since July 2012

Combined Higgs analysis and a flurry of property measurements

ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]

$$m_H = 125.09 \pm 0.21_{\text{stat}} \pm 0.11_{\text{syst}} \text{ GeV}$$



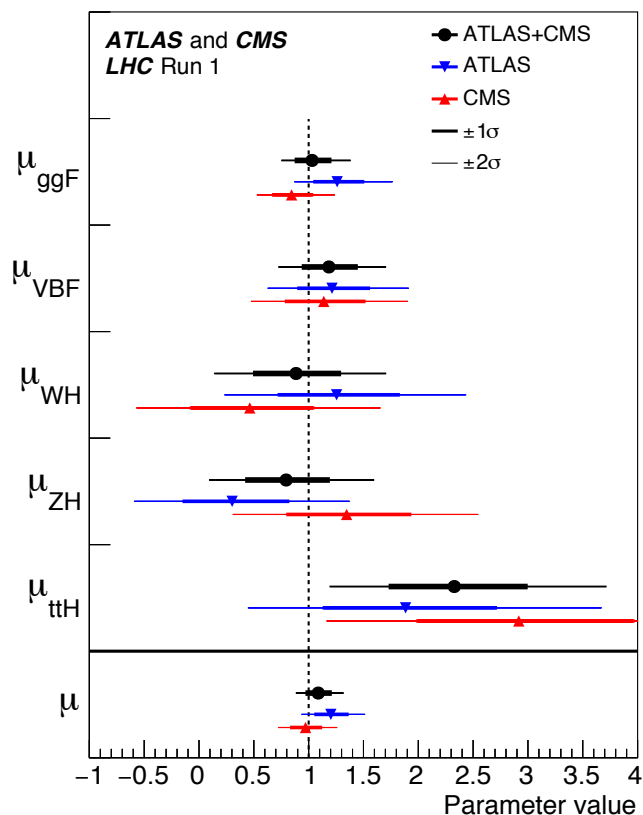
Agreement among experiments

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

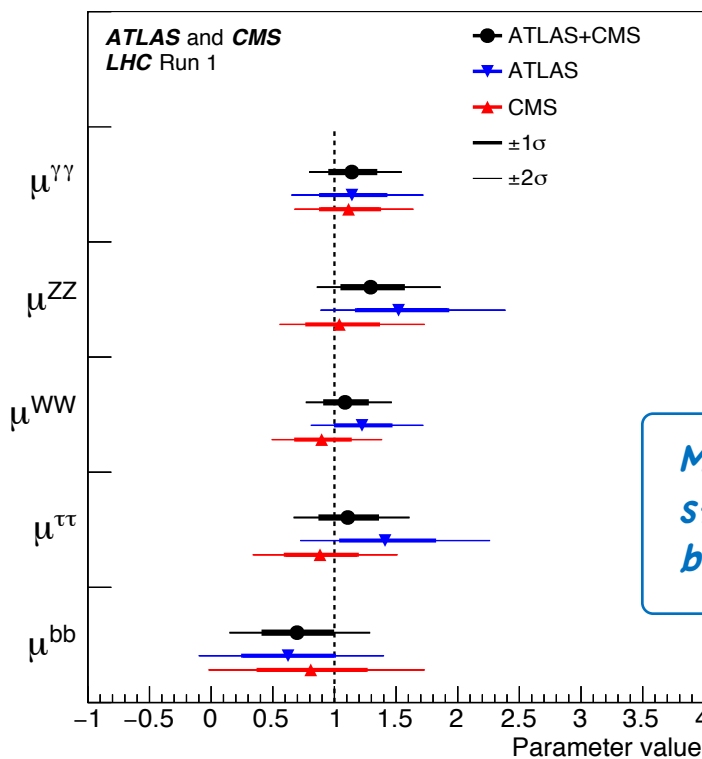
$t\bar{t}H$ channel a bit large: 4.4σ (2.0 exp), $\mu = 2.3$

Note that the least model-dependent observables at the LHC are **ratios of couplings**

Higgs production processes



Higgs decay processes

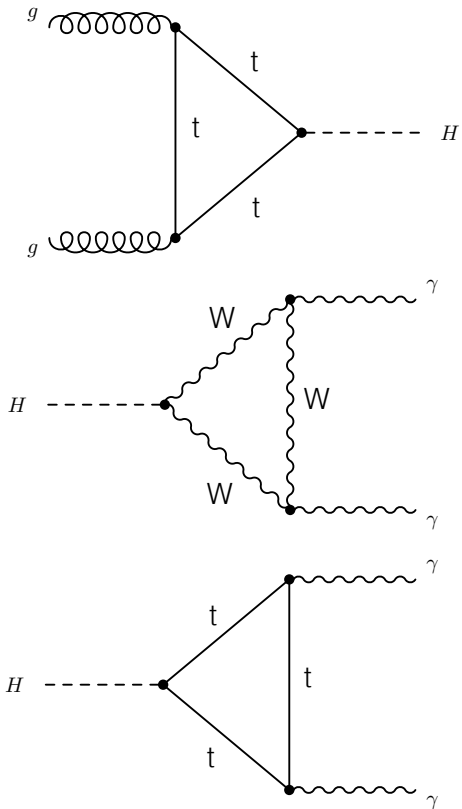
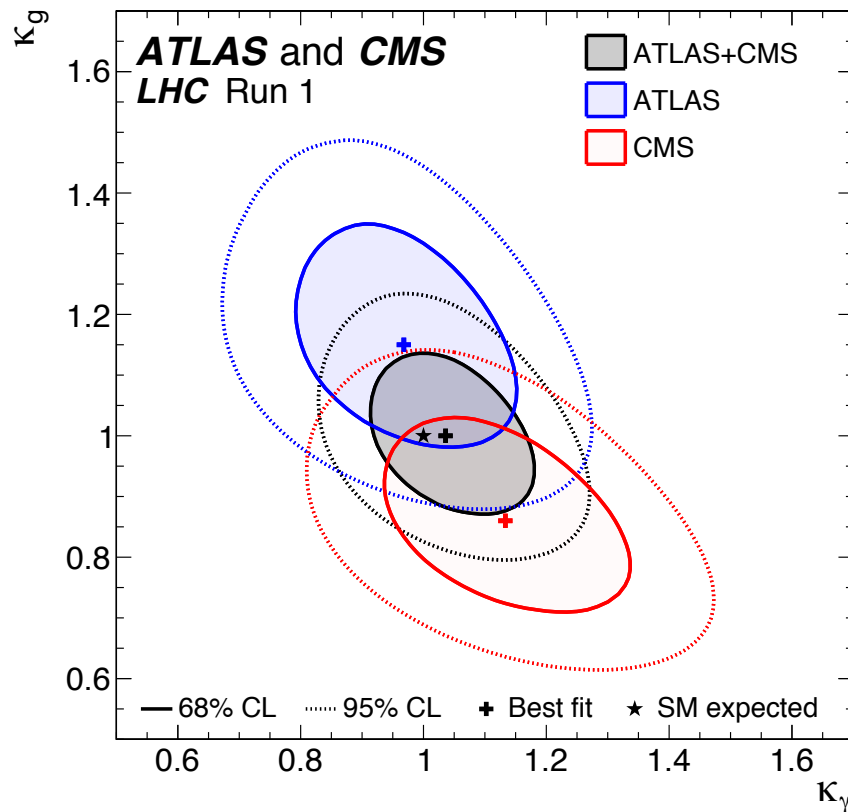
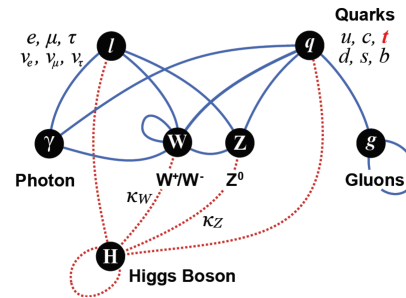


Many more Higgs studies, SM and beyond

Combined Higgs analysis and a flurry of property measurements

ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]



Couplings to massless particles mediated by loops involving heavy particles

Powerful test for new physics (eg, excludes SM-like heavy 4th fermion generation)

The Higgs boson as a *portal* to beyond the SM physics

Higgs is narrow: 4.1 MeV

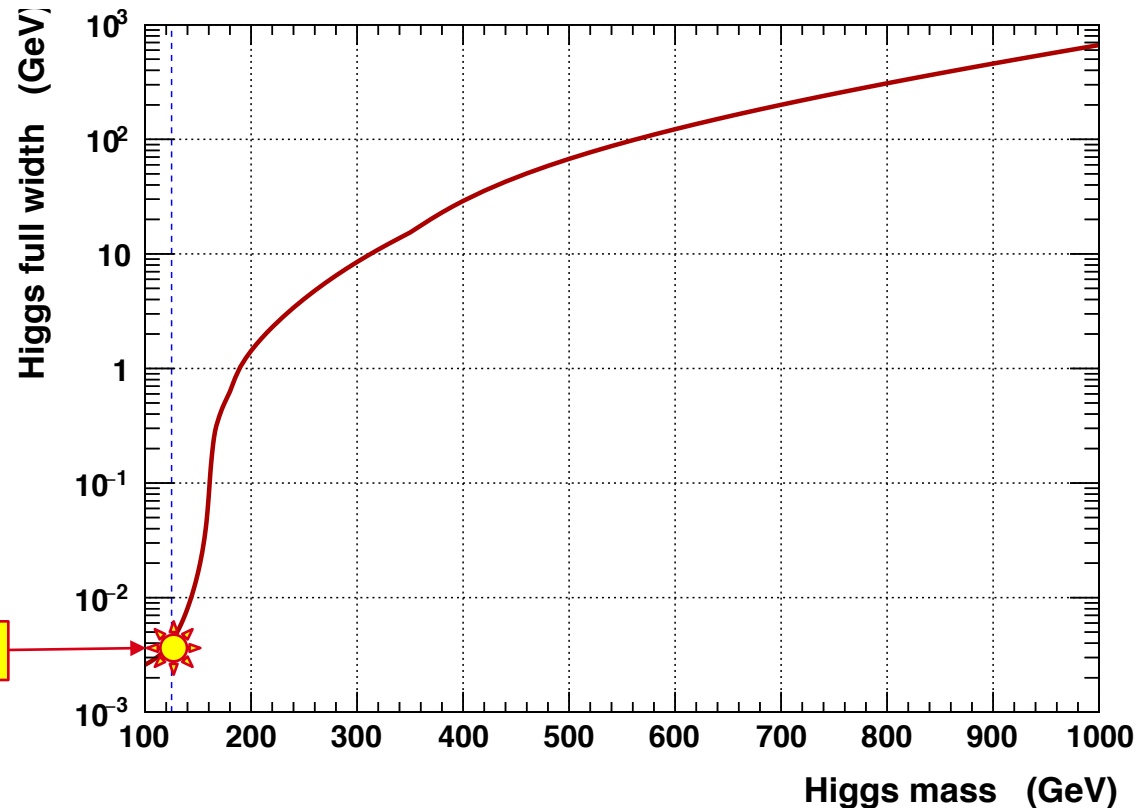
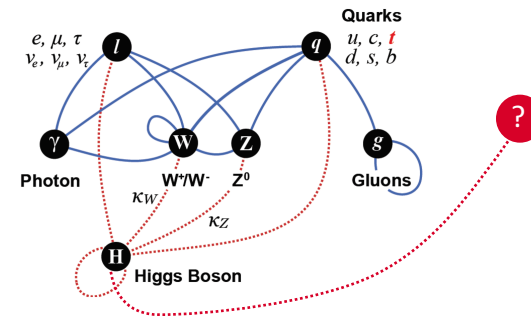
For comparison:

$$\Gamma_W = 2.1 \text{ GeV}$$

$$\Gamma_Z = 2.5 \text{ GeV}$$

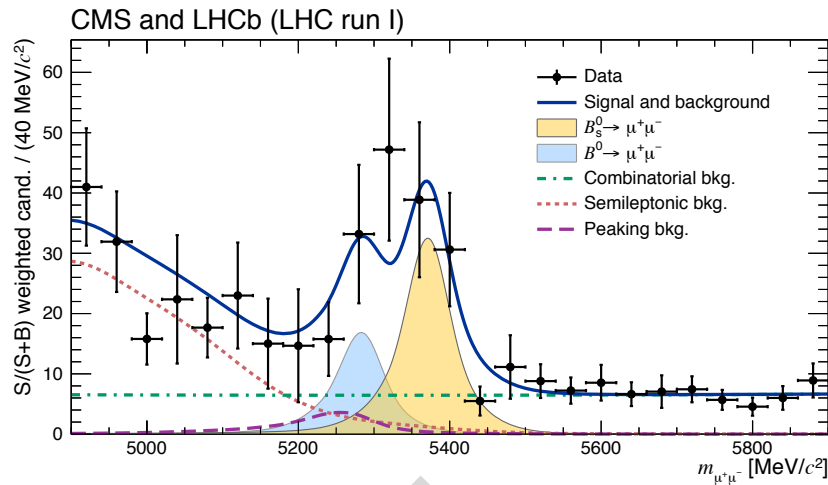
$$\Gamma_{\text{top}} = 1.3 \text{ GeV}$$

Even small couplings
to new light states can
measurably distort
branching fractions



Beautiful flavour and low- p_T physics measurements

Flurry of results from LHCb [~300 papers to date]



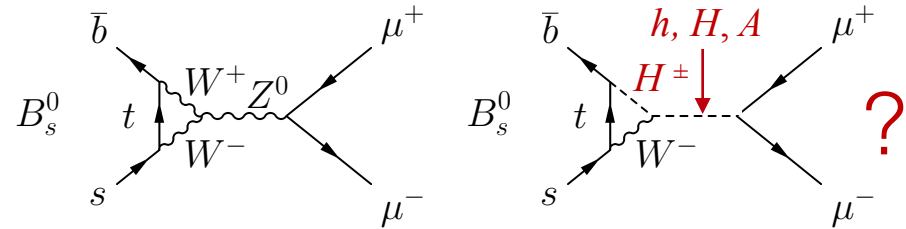
CMS & LHCb: observation of $B_s \rightarrow \mu\mu$

[Nat. 522 (2015) 68]

ATLAS Run-1 result

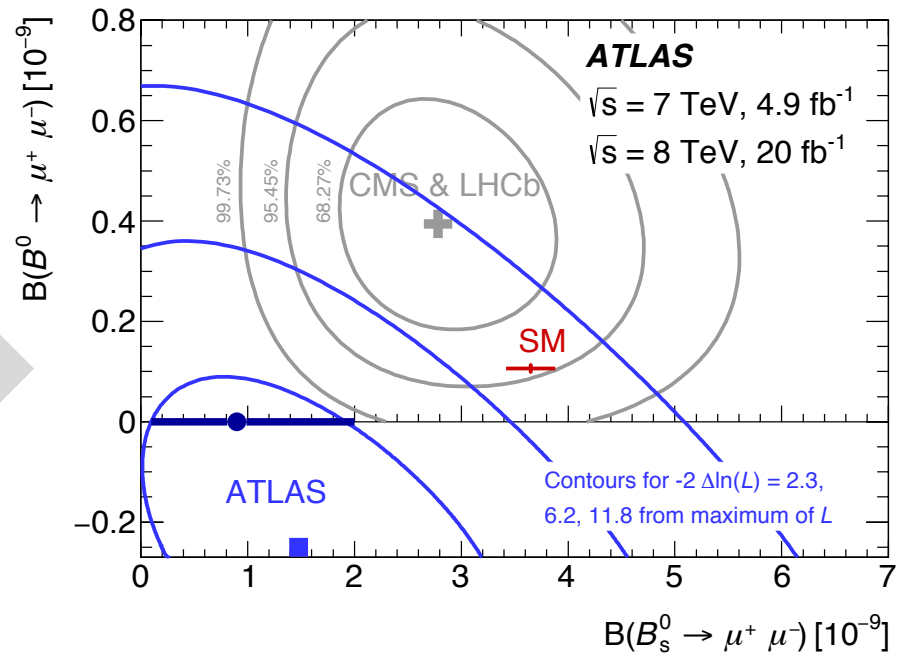
[1604.04263, consistency with SM at 2σ]

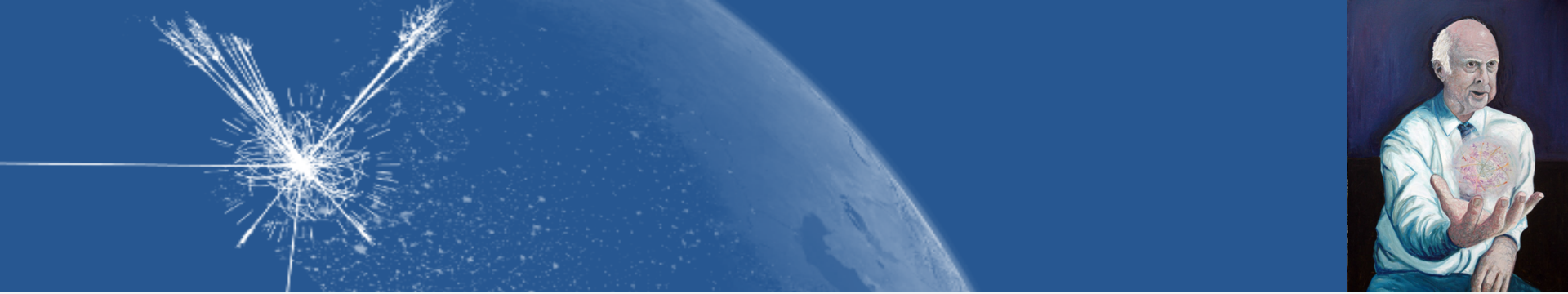
Does the Higgs boson has brothers and sisters?



$B_s \rightarrow \mu\mu$ is loop process (no tree-level FCNC)
that is in addition CKM & helicity suppressed

SM: $3.7 \pm 0.2 \times 10^{-9}$





Since the LHC Run-1 the Standard Model is complete

It is a triumph for the imagination and rigour of the scientific endeavour

It is a triumph for the greatest experimental undertaking ever:

Frontier of accelerator & detector technologies

Global data sharing, analysis & collaboration



It seems, however, that
the SM isn't all there is

Higgs is only
fundamental
scalar

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

Huge mass
hierarchy
between matter
particles

Gauge hierarchy
/ apparent lack
of naturalness
No separation of scales

Dark matter

Grand
unification of
the forces

Massive
neutrinos

Inflation

Matter-antimatter
asymmetry in
universe

Strong CP
problem

Quantum
gravity

Dark energy (1)

It seems, however, that the SM isn't all there is

ATLAS SUSY Searches* - 95% CL Lower Limits

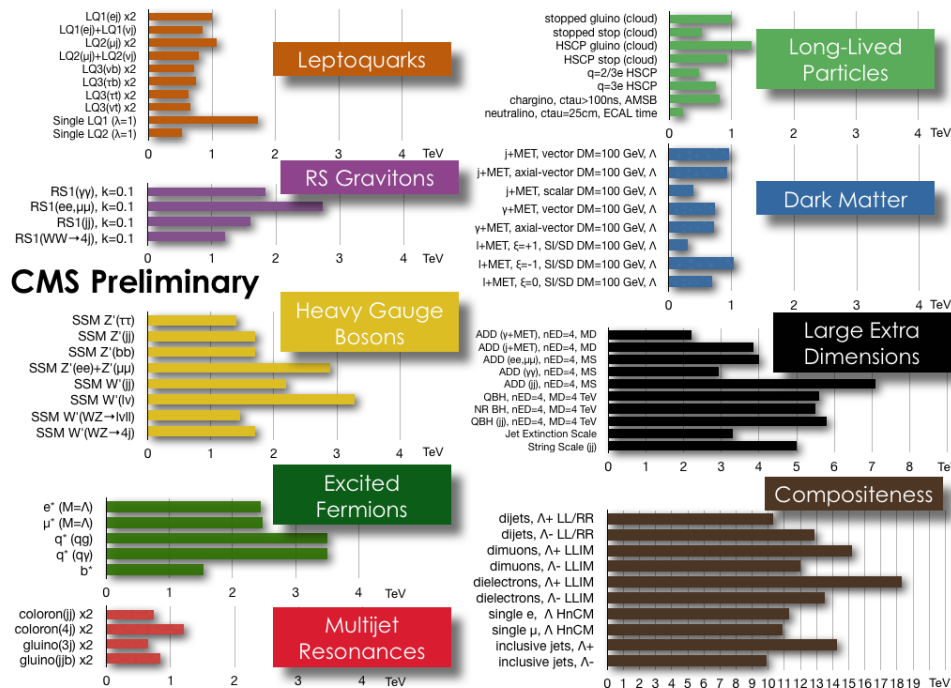
Status: July 2015

ATLAS Preliminary
 $\sqrt{s} = 7, 8 \text{ TeV}$

Model	e, μ, τ, γ	Jets	E_{miss}^T	$[L dt[\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7 \text{ TeV}$	$\sqrt{s} = 8 \text{ TeV}$	Reference
MSUGRA/CMSSM	0-3 e, μ 1-2 τ	2-10 jets/3 b	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1507.05525
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0	2-6 jets	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1405.7875
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$ (compressed)	0	mono-jet	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1507.05525
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$ (compressed)	0	2 e, μ (off- Z)	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1503.03290
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0	2-6 jets	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1405.7875
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0	0-1 e, μ 2-6 jets	Yes	20	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1507.05525
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0	2 e, μ 0-3 jets	Yes	20	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1501.05555
GMSB (f NLSP)	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1407.0603
GGM (higgsino-bino NLSP)	2 γ	1 b	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1507.05493
GGM (higgsino-bino NLSP)	2 γ	2 jets	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1507.05493
GGM (higgsino NLSP)	2 e, μ (Z)	mono-jet	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1503.03290
Gravitino LSP	0	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1502.01518
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0	3 b	Yes	20.1	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1407.0600
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0	7-10 jets	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1308.1841
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1407.0600
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1407.0600
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0	2 b	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1308.2631
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1404.2500
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	1-2 e, μ	1-2 b	Yes	4.7/20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1209.2102, 1407.0563
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0-2 e, μ	0-2 jets 1-2 b	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1506.08616
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	0	mono-jet 1-tag	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1407.0608
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1403.5222
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	3 e, μ (Z)	1 b	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1403.5222
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1403.5294
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1403.5294
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1407.0550
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1402.7029
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1403.5294, 1402.7029
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1501.07110
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1405.5086
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1507.05493
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1310.3675
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1506.05332
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1310.5584
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1411.6795
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1411.6795
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1409.5542
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1504.05162
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1504.05162
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1503.04430
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1404.2500
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1405.5086
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1502.05686
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1502.05686
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1404.2500
$\tilde{g}, \tilde{u}, \tilde{d} \rightarrow q\bar{q}$	2 e, μ	0	Yes	20.3	$\tilde{g}, \tilde{u}, \tilde{d}$	100-440 GeV	850 GeV	1501.01325

Vast amount of BSM searches

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



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

No significant anomaly seen so far

Particle physics at the dawn of the LHC Run-2

Confirmation of mass generation through spontaneous symmetry breaking in BEH potential. Scalar sector SM-like so far (but lacking precision)

QED tested to parts per million accuracy (slight anomaly in muon $g-2$)

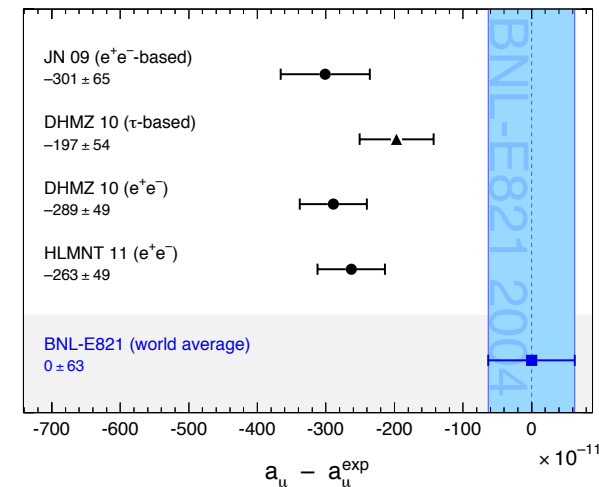
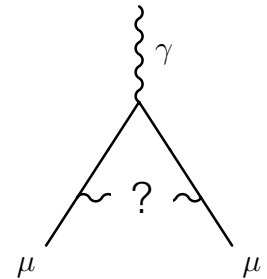
Asymptotic freedom in strong interactions verified at % level

Electroweak unification tested to high precision

Quark sector: CKM picture for quark mixing & CP violation confirmed

Lepton sector: massive neutrinos, unknown masses, nature, CP violation, sterile ν 's ? No flavour violation in charged lepton sector. Lepton universality tested to per-mil level

No compelling sign of new physics found at high mass scales, or anywhere else, eg:
no electric dipole moments (EDM), no dark matter particles (only gravitational hints),
no axions (strong CP problem), no proton decay (GUT)



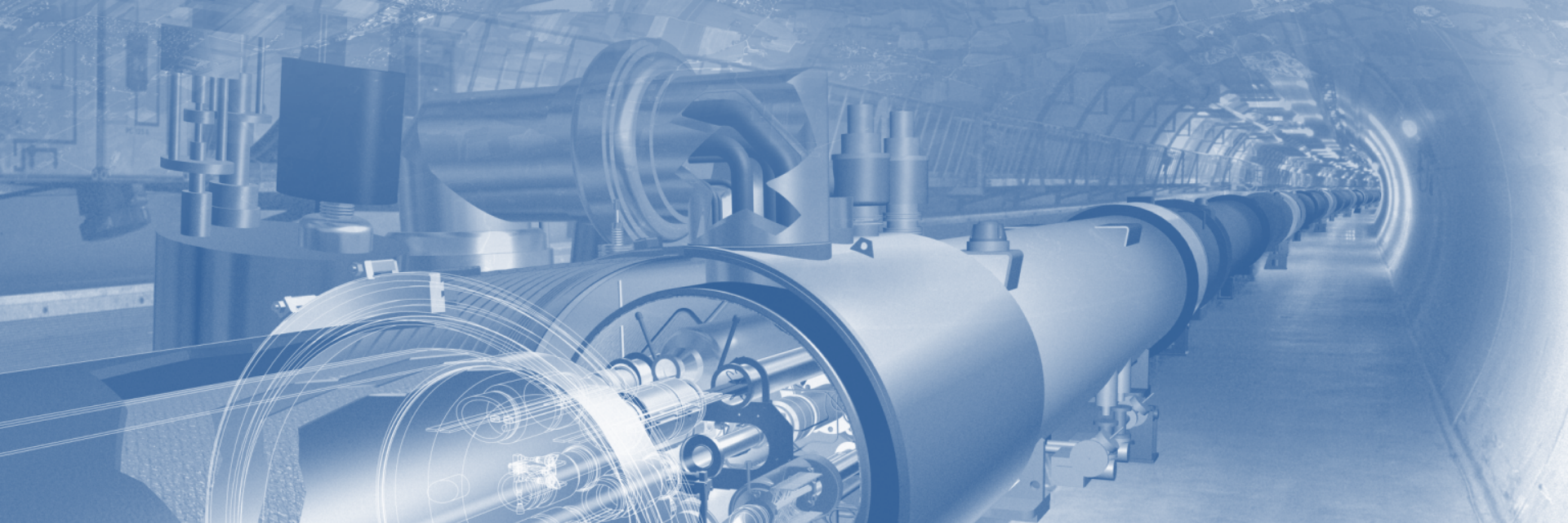
The LHC Run-2: terra incognita

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



The LHC Run-2 at 13 TeV

Following a two-year shutdown with consolidation and upgrade work for LHC and experiments

Huge milestone achieved in 2015 with record proton-proton collision energy of 13 TeV

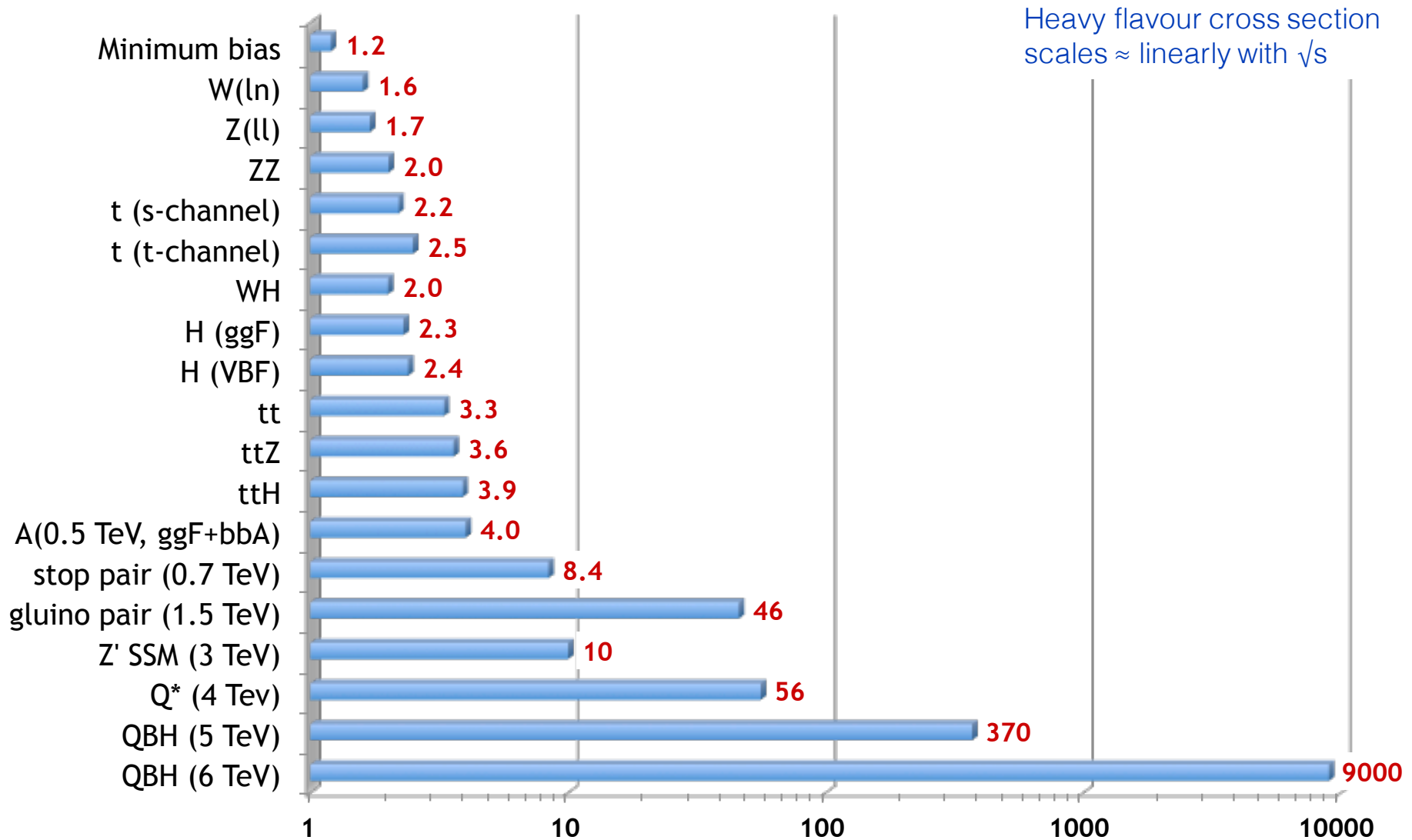
After a rocky start, the LHC delivered $L_{\text{int}} = 4.2 \text{ fb}^{-1}$

That luminosity already increases the new physics reach for many searches

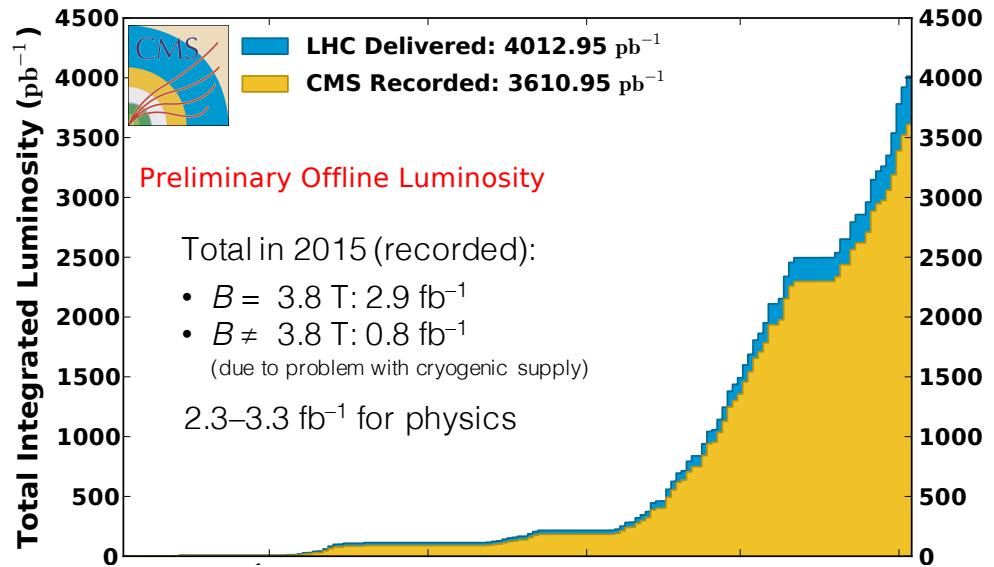
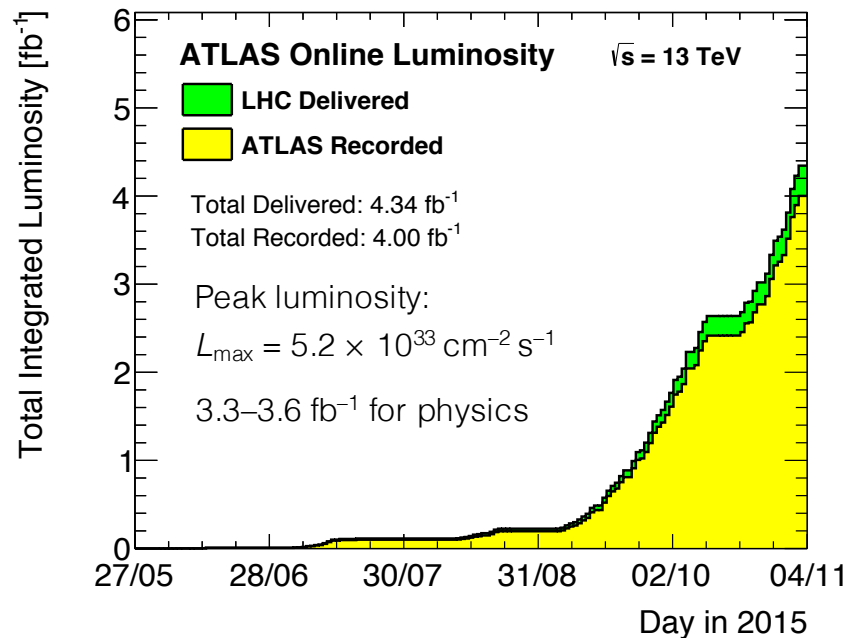
Expect $\sim 1.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and $\sim 25 \text{ fb}^{-1}$ in 2016



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



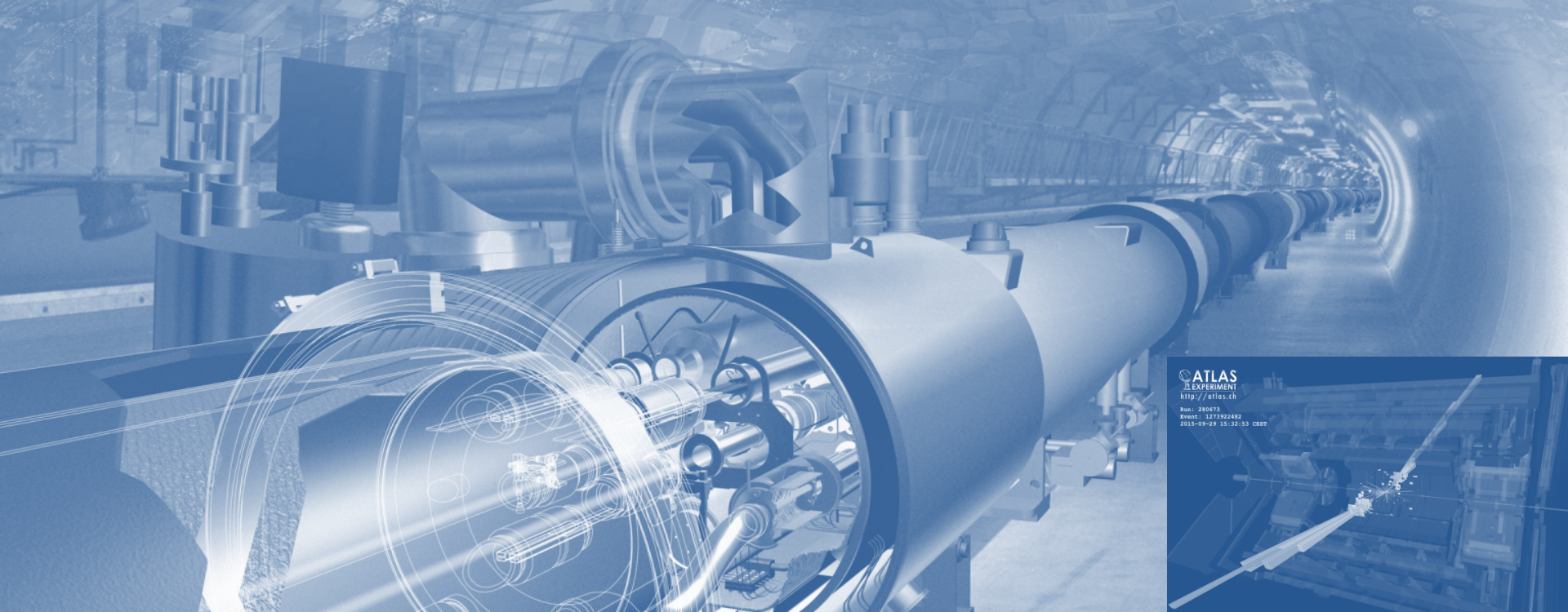
2015 LHC proton–proton luminosities (no 2016 data results released yet)



LHCb after luminosity levelling: $0.32 \text{ (} 0.36 \text{) fb}^{-1}$ recorded (delivered)

Current luminosity precision from van-der Meer scans: 2.1% (ATLAS), 2.7% (CMS), 3.8% (LHCb)

Pileup profiles: ATLAS/CMS: $\langle \mu \rangle_{50 \text{ ns}} = 20$, $\langle \mu \rangle_{25 \text{ ns}} = 13$ ($\langle \mu \rangle_{8 \text{ TeV}} = 21$), LHCb: $\langle \mu \rangle \sim 1.7$



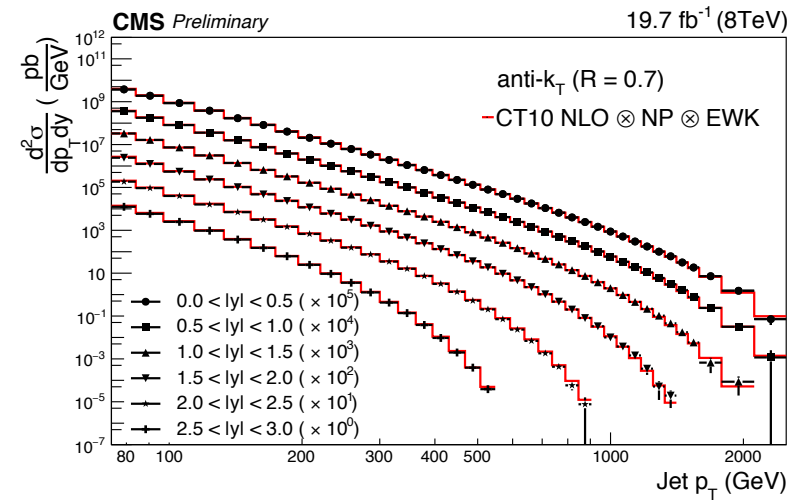
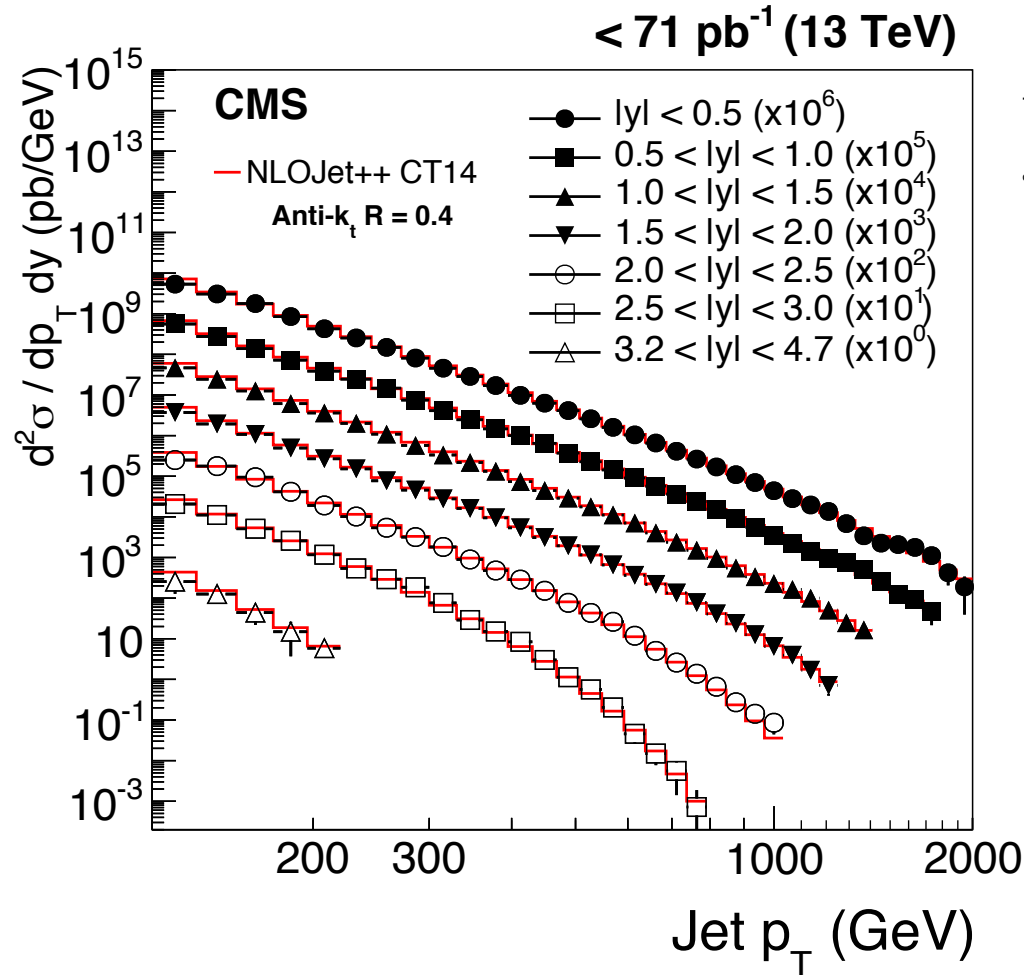
(First) physics at 13 TeV proton–proton collisions

Measurement of jet cross section at 13 TeV

Primary test of QCD at highest collision energy

CMS 1605.04436

Double differential cross section measured by CMS



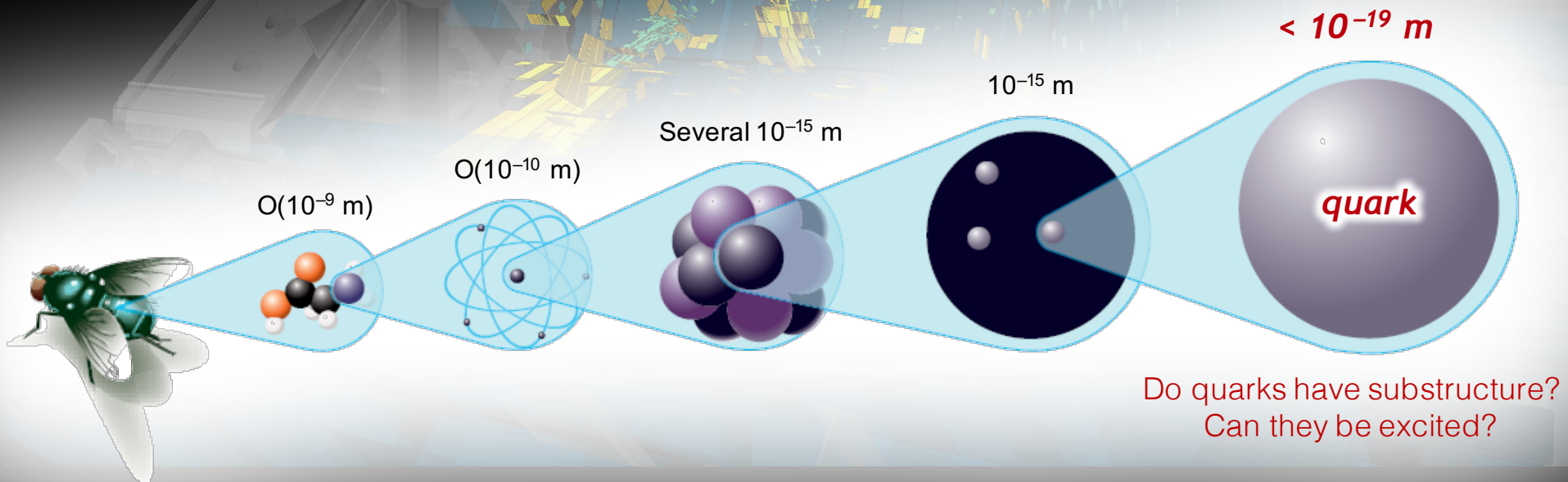
Comparison with 8 TeV plot (right) shows effect of increased parton luminosities at high jet p_T

New physics in events with jets ?

Run: 280464

Event: 478442529

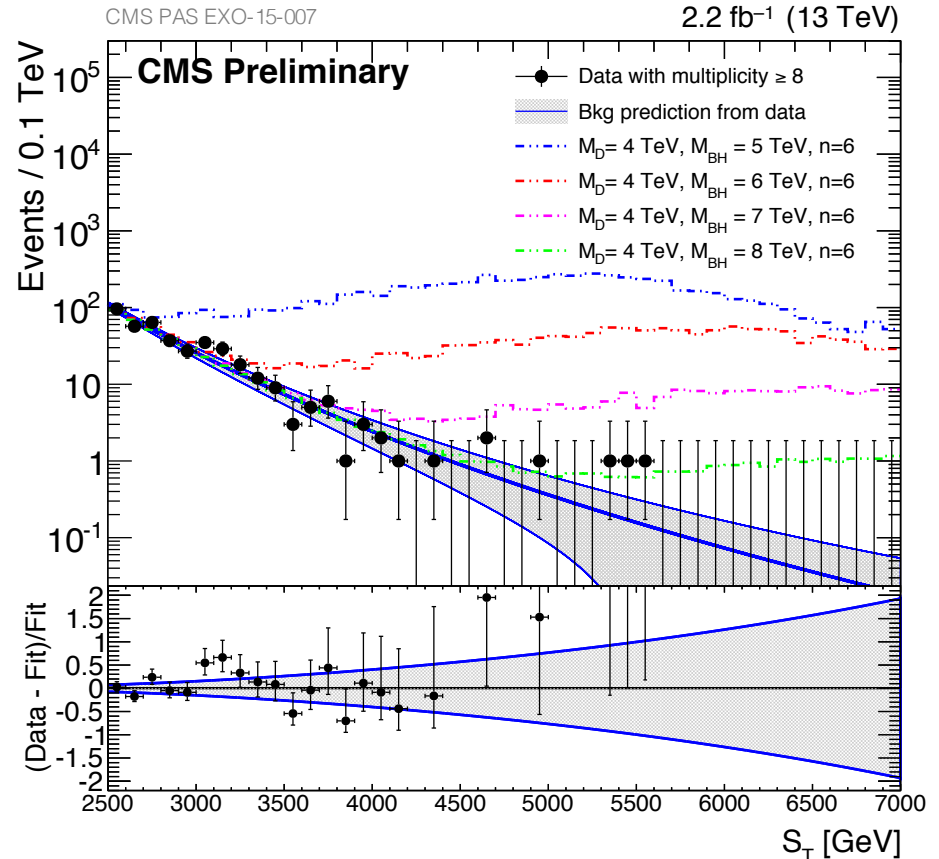
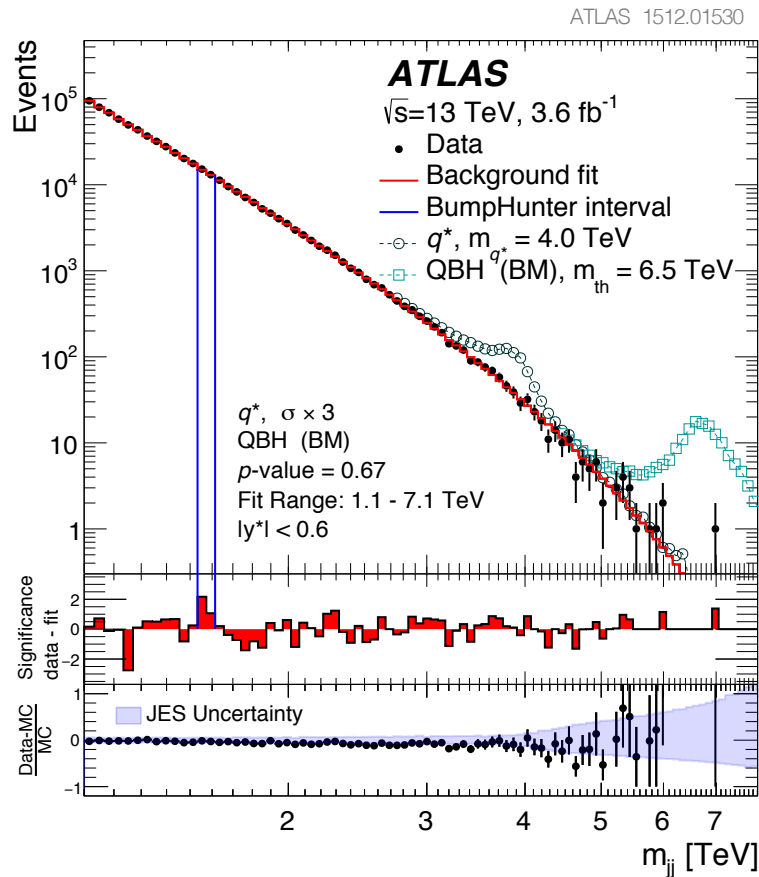
2015-09-27 22:09:07 CEST



Searches in high- p_T multijet final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

Look for deviation in mass or S_T spectrum from smoothly falling function



Sensitivity to excited quarks, strong gravity, etc. Also looked for lepton-jet resonances (lepto-quarks)

No anomaly seen in these searches

Highest mass *central* dijet event measured by ATLAS in 2015 ($\sqrt{s} = 13$ TeV): $m_{jj} = 6.9$ TeV

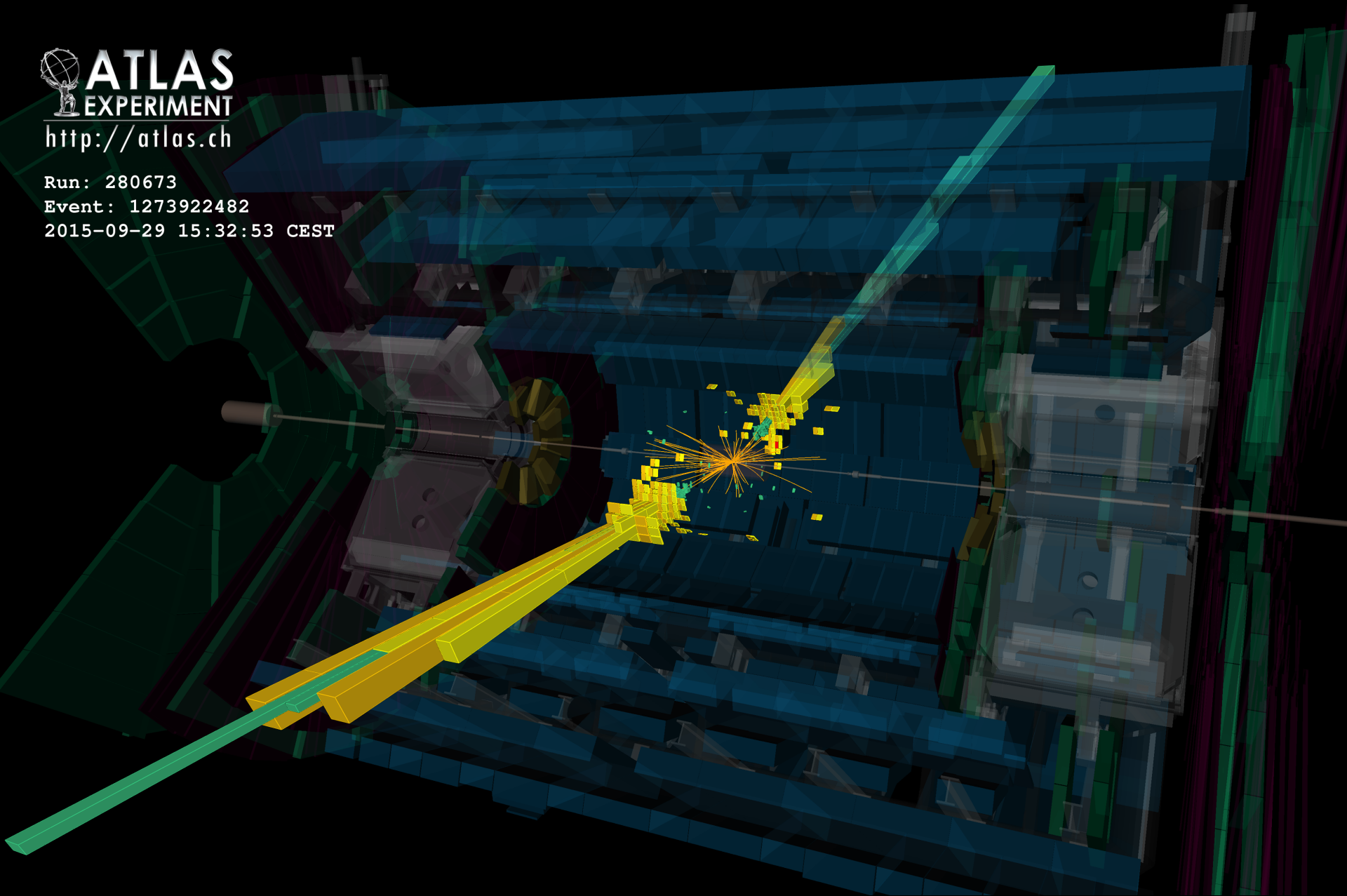


<http://atlas.ch>

Run: 280673

Event: 1273922482

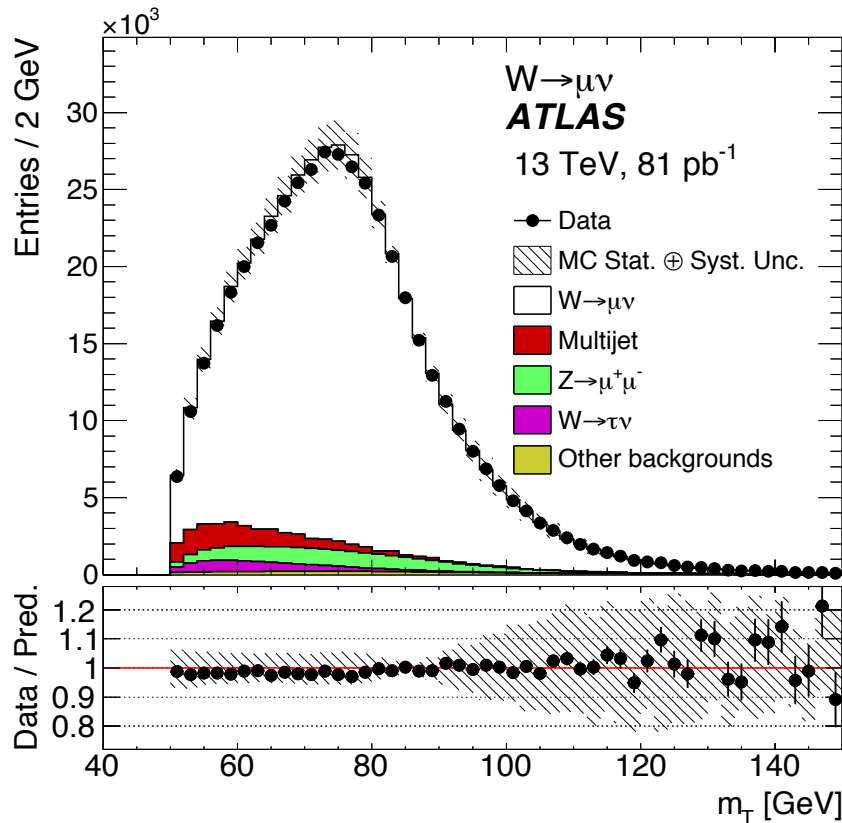
2015-09-29 15:32:53 CEST



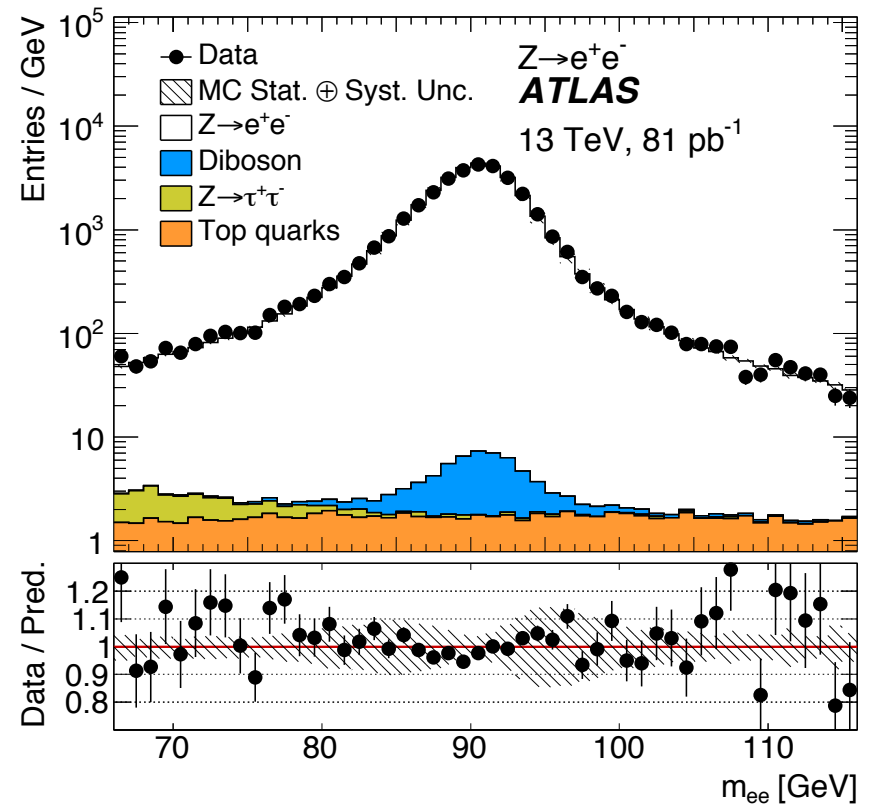
Z and W production at 13 TeV — examples: $\sigma_{Z \rightarrow \mu\mu}$ (13 TeV) ~ 1.9 nb, $\sigma_{W \pm \rightarrow \mu\nu}$ (13 TeV) ~ 19.7 nb

Expect increase of cross section by **factors of 1.7 and 1.6**, respectively

Pure channels. Leptonic decays of Z & W are also standard candles to calibrate e/ μ performance



$$m_T = \sqrt{2p_{T,\ell}E_T^{\text{miss}}(1 - \cos\Delta\phi_{\ell\nu})}$$



$$m_{e_1e_2} = \sqrt{2p_{T,1}p_{T,2}(\cosh\Delta\eta_{12} - \cos\Delta\phi_{12})}$$

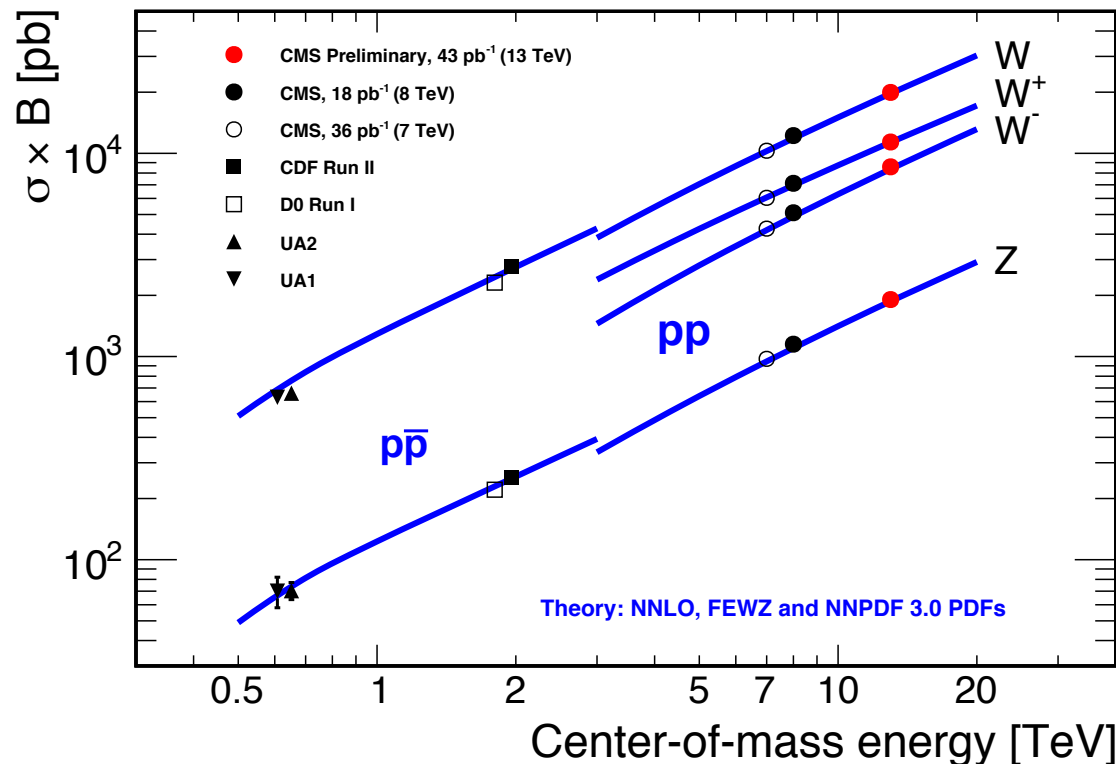
Z and W production at 13 TeV

Expect increase of cross section by **factors of 1.7 and 1.6**, respectively

Inclusive cross sections shown, also **fiducial cross sections** measured

Comparison of measured cross-sections with NNLO QCD & NLO EW Drell-Yan predictions (FEWZ 3.1):
good agreement found within uncertainties

Ratios are powerful tools to constrain PDFs: W^+ / W^- sensitive to low- x u & d valence, W / Z constrains s

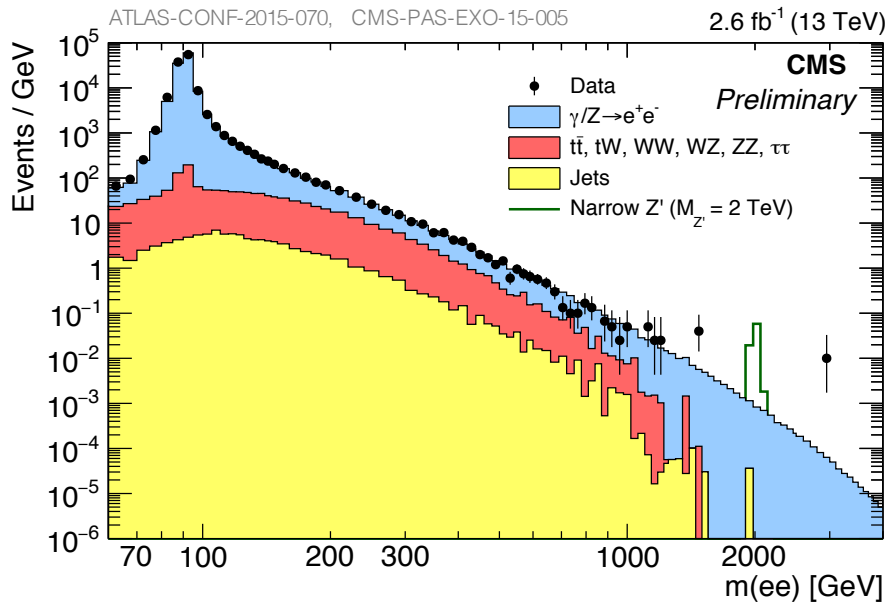


Searches in leptonic final states

Canonical searches for new physics in high-mass Drell-Yan production (Z' , W')

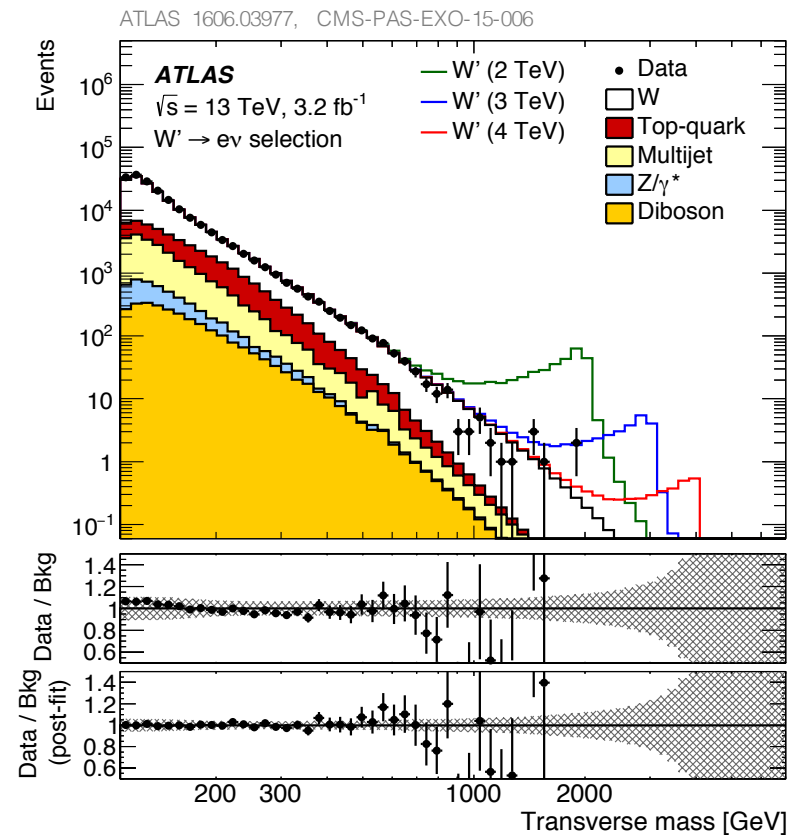
Measured mass spectra are compared with SM prediction

No anomaly found. SSM Z' / W' benchmark limits set at 3.4 / 4.4 TeV (2.9 / 3.3 TeV at 8 TeV)



ATLAS & CMS also looked into high-mass $e\mu$ (LFV) production. Main background top-antitop.

No anomaly seen

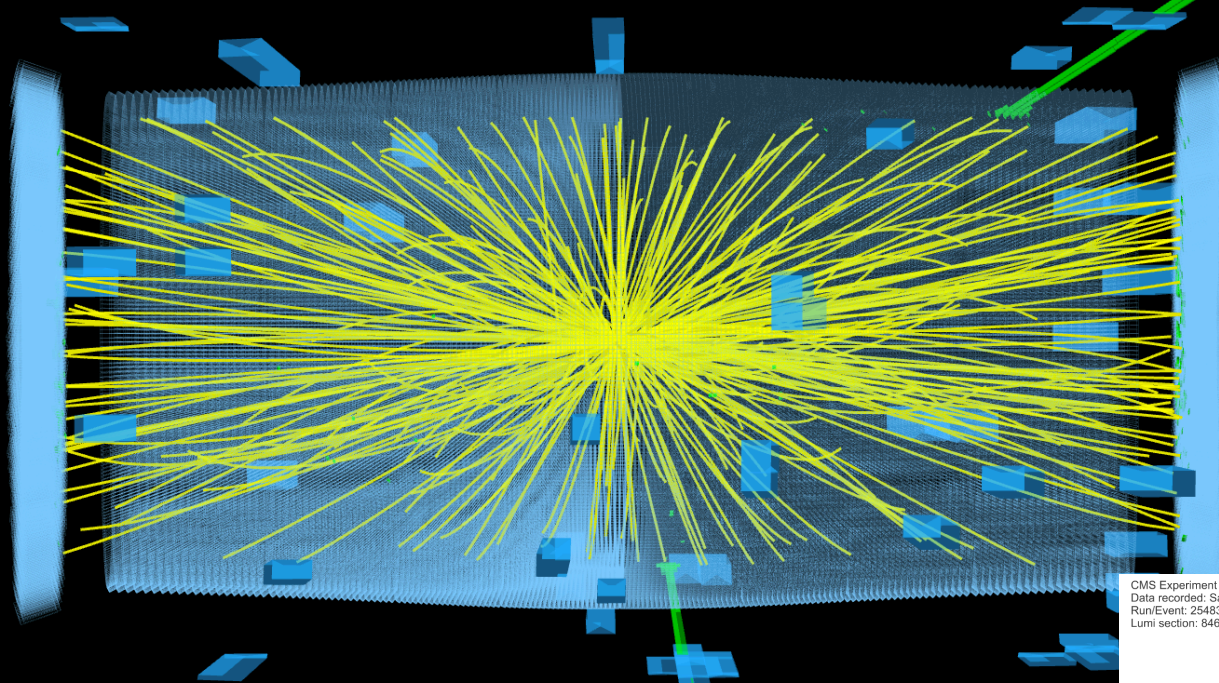




CMS Experiment at the LHC, CERN

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

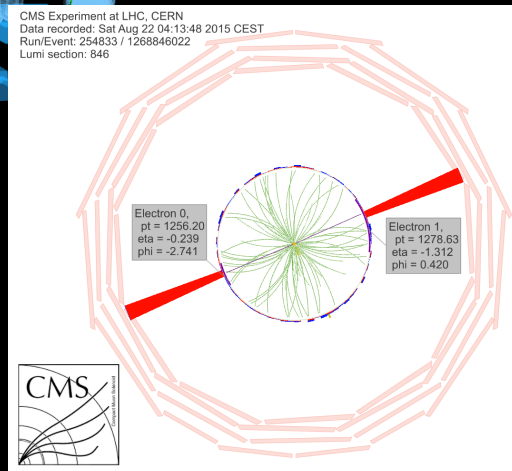
Run / Event / LS: 254833 / 1268846022 / 846



- 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

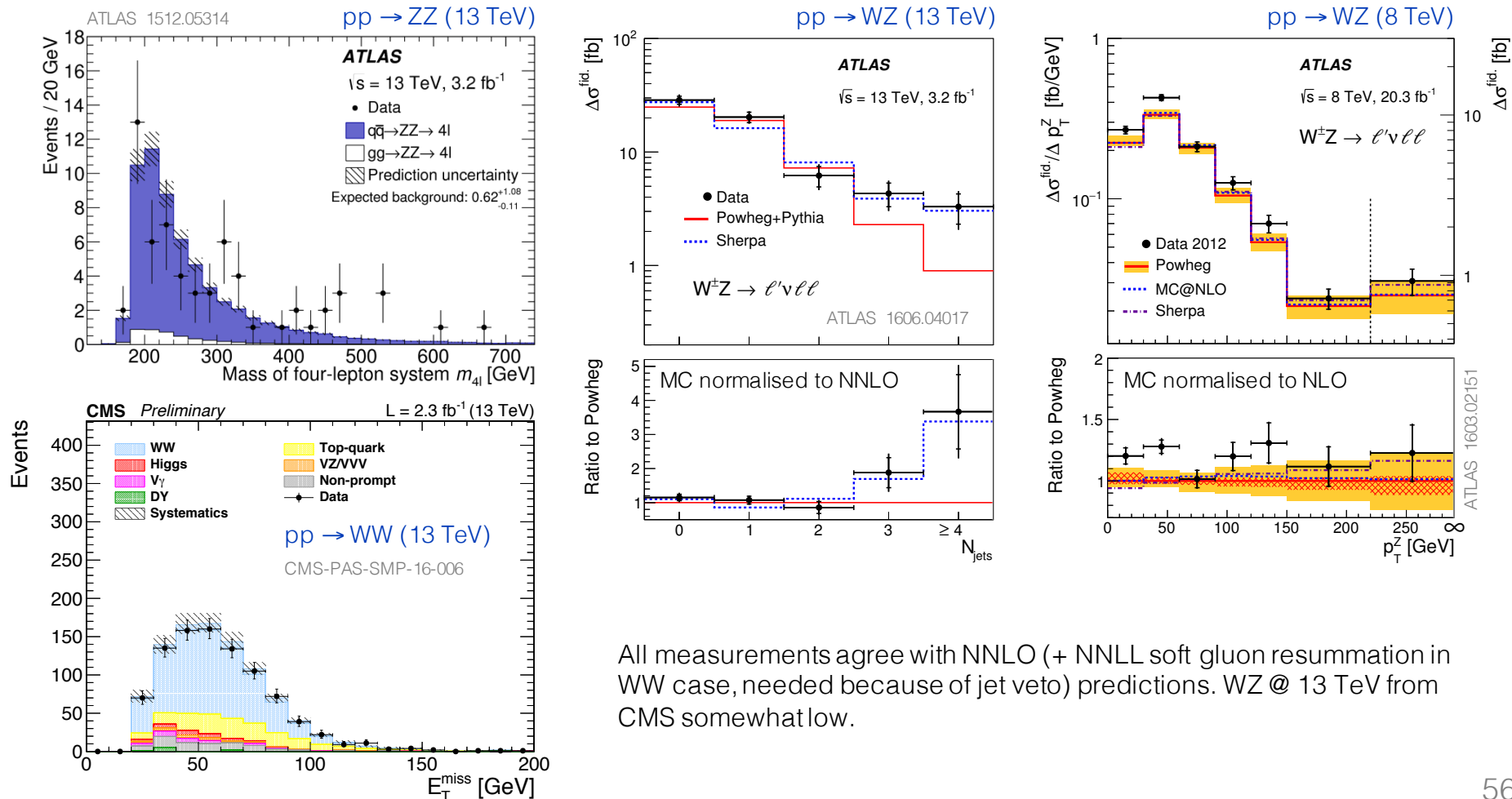


Diboson production — example: $\sigma_{WW, \text{ no Higgs}}(13 \text{ TeV}) \sim 120 \text{ pb}$

Highly important sector of LHC physics, intimately related to electroweak symmetry breaking

ATLAS & CMS performed inclusive, fiducial and differential cross-section analyses at 8 TeV.

First 13 TeV results. **Theoretical predictions at NNLO needed to match data.**

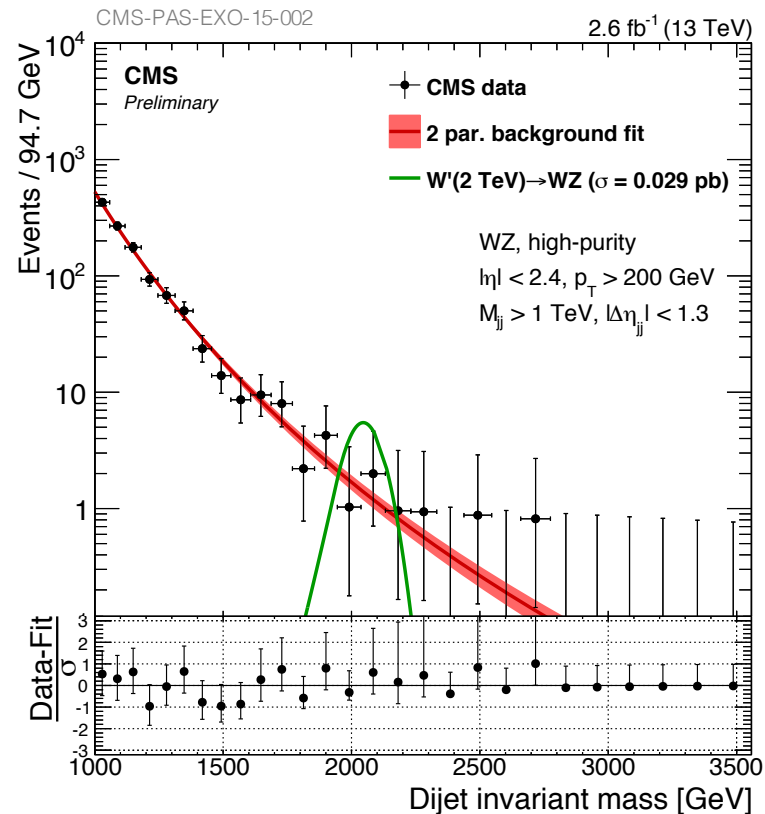
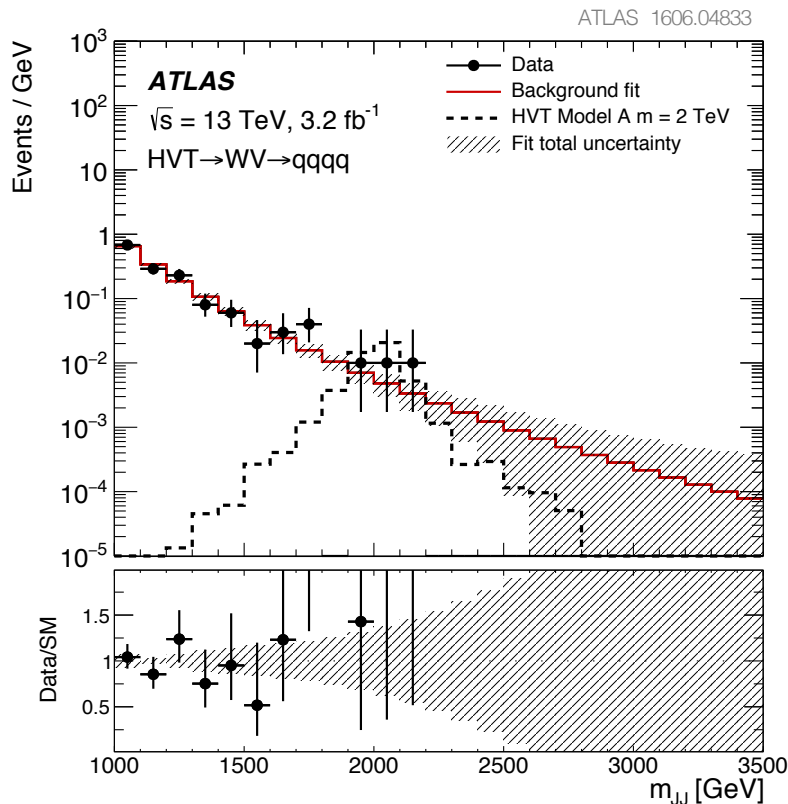
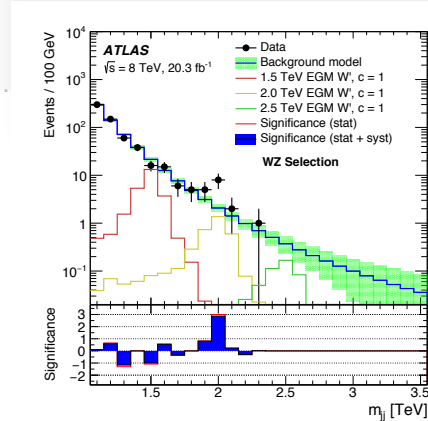


Searches for diboson resonances ($X \rightarrow VV, VH, HH, V=W/Z$)

High- p_T of bosons boosts hadronic decay products giving merged jets

Hadronic decay modes use jet substructure analysis to reconstruct bosons.
Important strong interaction backgrounds

Some excess of events around 2 TeV (globally 2.5σ for ATLAS) seen at 8 TeV in VV in fully hadronic channel, not seen in the other decay channels (eg, $lvqq$)



So far no excess in 13 TeV data around 2 TeV, also other diboson searches do not show anomaly

Diphoton resonance searches: **ATLAS**

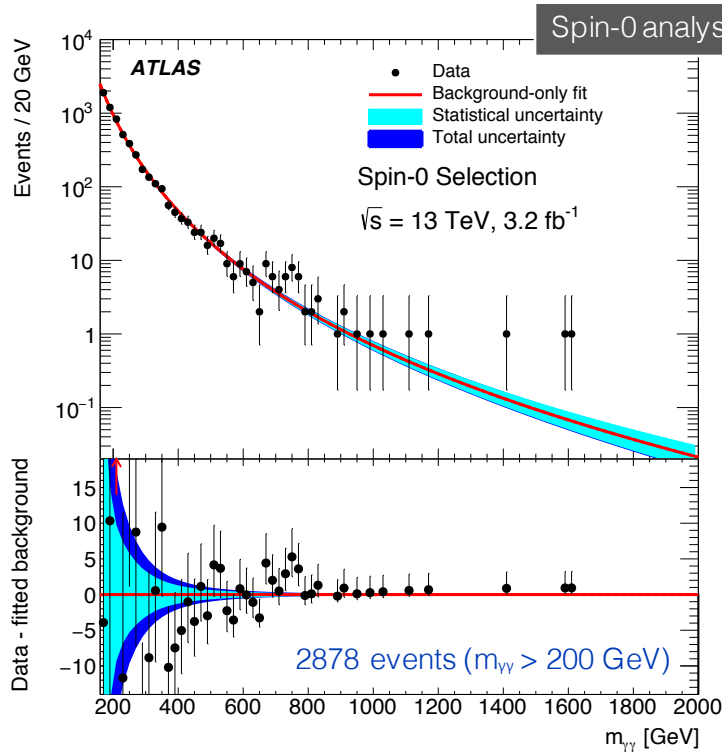
Dedicated searches for a spin-0 and a spin-2 diphoton resonance.

ATLAS 1606.03833

Main difference is acceptance: spin-0: $E_T(\gamma_1) > 0.4 \cdot m_{\gamma\gamma}$, $E_T(\gamma_2) > 0.3 \cdot m_{\gamma\gamma}$, spin-2: $E_T(\gamma_{1/2}) > 55 \text{ GeV}$

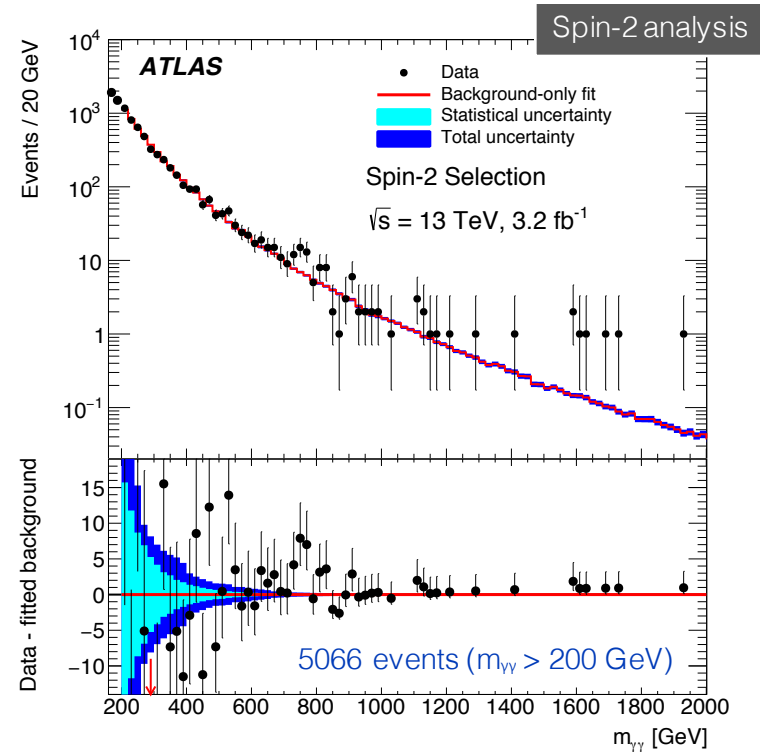
Photons are tightly identified and isolated. Typical purity $\sim 94\%$

Background modelling empirical in spin-0, and (mainly) theoretical in spin-2 case (for high-mass search)



Lowest p-value at $\sim 750 \text{ GeV}$, $\Gamma \sim 45 \text{ GeV}$ (6%)

Local / **global** $Z = 3.9 / 2.1\sigma$



Lowest p-value at $\sim 750 \text{ GeV}$, $\Gamma \sim 7\%$ of mass

Local / **global** $Z = 3.8 / 2.1\sigma$

Diphoton resonance searches: CMS

Agnostic search for spin 0 and 2 bosons

CMS 1606.04093

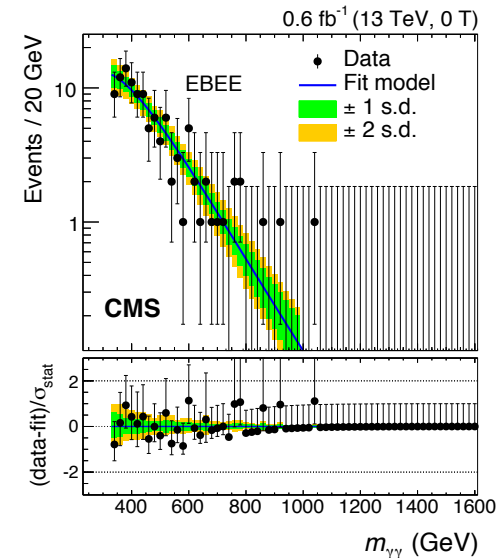
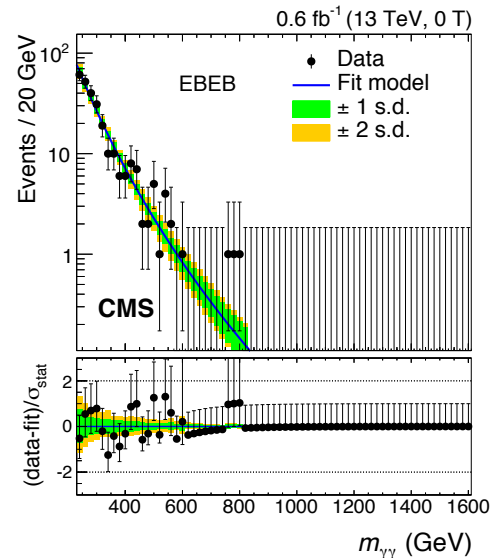
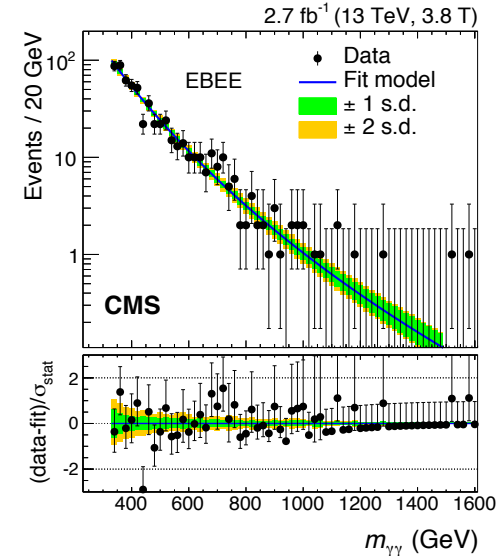
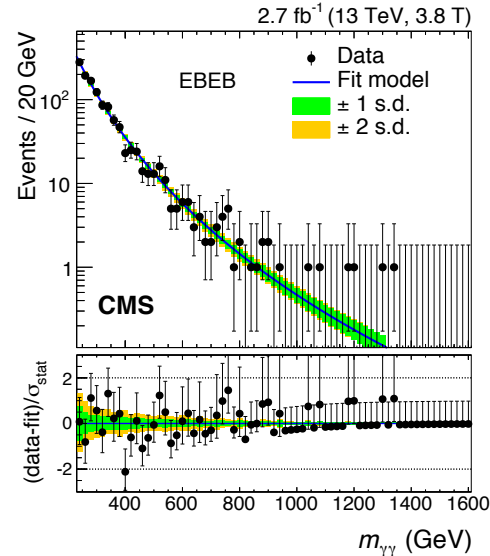
New 13 TeV analysis with improved ECAL calibration ($\sim 30\%$ improved resolution above $m_{\gamma\gamma} \sim 500$ GeV), and including 0.6 fb^{-1} of B-field off data

- Acceptance: $E_T(\gamma_{1/2}) > 75$ GeV, at least one γ with $|\eta| < 1.44$ (barrel), split EB-EB, EB-EE
- Dedicated calibration of B-field-off data, slightly lower γ -ID efficiency, better resolution, harder PV finding
- Empirical background modelling
- Combination of 13 & 8 TeV data (model-dependent, good compatibility)

Lowest p-value at ~ 750 GeV
(760 for 13 TeV data only), narrow width

Local / **global Z** = 3.4σ / **1.6σ**
(2.9σ / < 1 for 13 TeV data only)

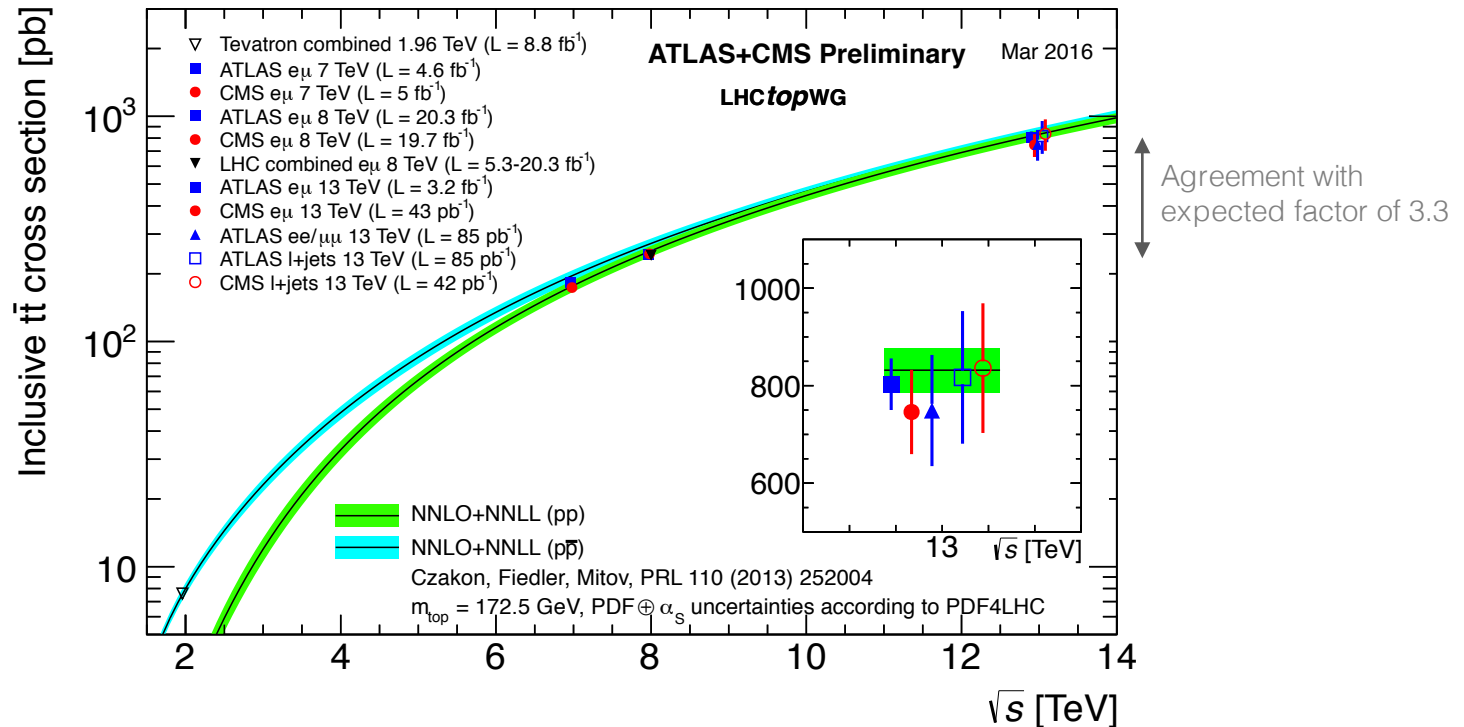
*No compelling evidence for signal.
More data needed.*



Top-antitop production at 13 TeV

Extraction of top-pair cross section (expect: 13 TeV / 8 TeV $\sim$ 3.3)

ATLAS & CMS studied top production in many ways at 13 TeV $\rightarrow$ very prompt analyses turn around



Robust $e\mu$ final state gives most precise inclusive results at all CM energies

Also differential cross-section measurements at 13 TeV: reasonable modelling, though some deviations at large jet multiplicity. Known problems from Run-1 not fully solved

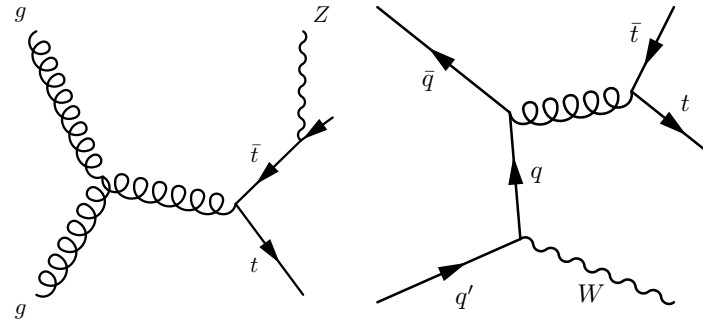
Top-antitop production and a vector boson at 13 TeV

First results on important $t\bar{t}V$ process, in it's own right, and as background to $t\bar{t}H$ and searches

ATLAS & CMS have preliminary 13 TeV results

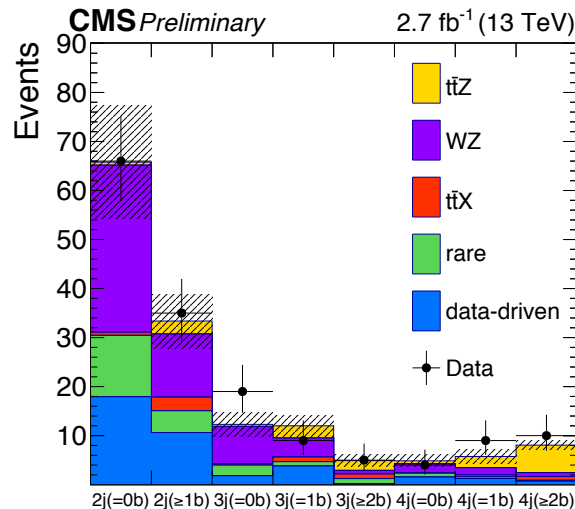
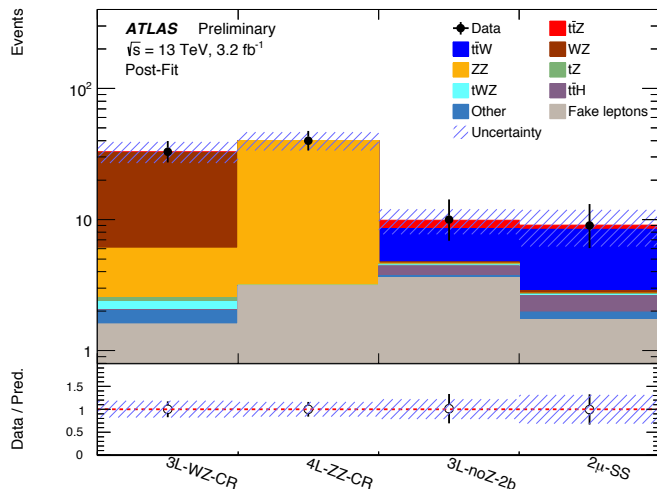
Analyses combine several multilepton final states, difficult mis-ID background

At 8 TeV, both processes observed, and found to agree with SM prediction ($t\bar{t}W \sim 1\sigma$ up in both ATLAS & CMS)



Different production processes and thus 13/8 TeV cross-section ratios for $t\bar{t}Z$ & $t\bar{t}W$: 3.6 & 2.4

Preliminary $t\bar{t}+W/Z$ results from ATLAS, $t\bar{t}+Z$ from CMS:



ATLAS:

$t\bar{t}W: 1.38 \pm 0.70 \pm 0.33 \text{ pb}$

$t\bar{t}Z: 0.92 \pm 0.30 \pm 0.11 \text{ pb}$

CMS:

$t\bar{t}Z: 1.07^{+0.35}_{-0.31} {}^{+0.17}_{-0.14} \text{ pb}$

SM (NLO):

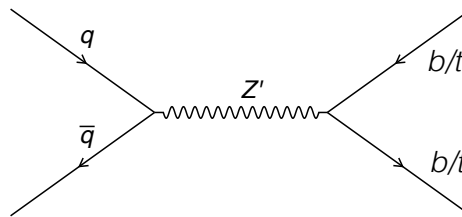
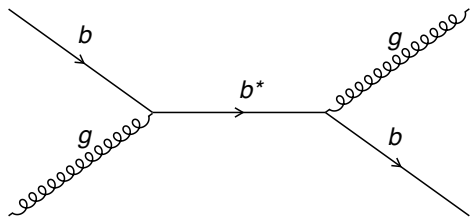
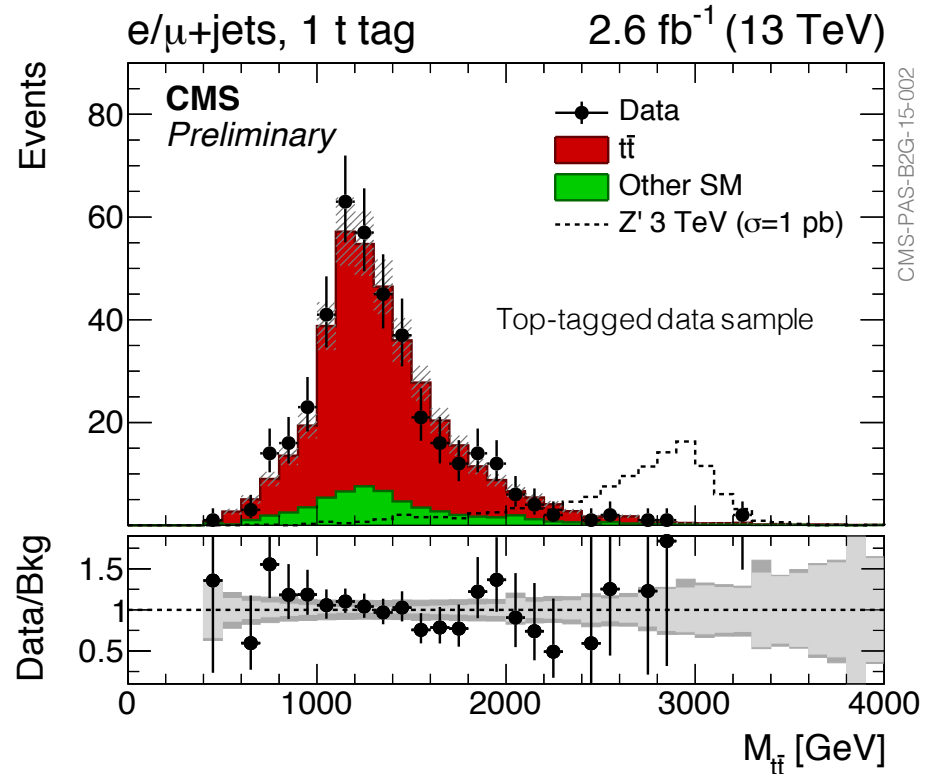
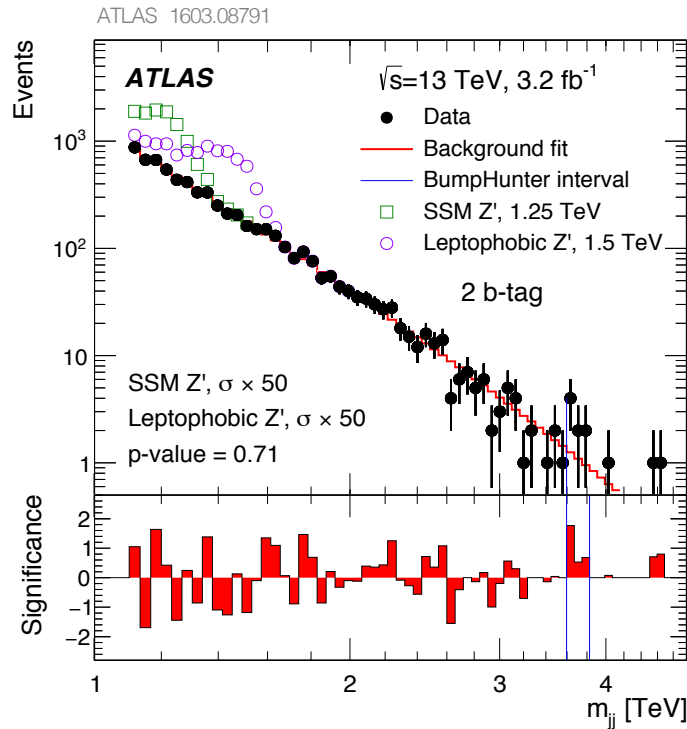
$t\bar{t}W: 0.57 \pm 0.06 \text{ pb}$

$t\bar{t}Z: 0.76 \pm 0.08 \text{ pb}$

Searches in high- p_T heavy-flavour final states at 13 TeV

Processes with large cross-sections, sensitivity to highest new physics scales

Also searches for a b-anti-b and top-antitop resonance



(Very) first Higgs boson results

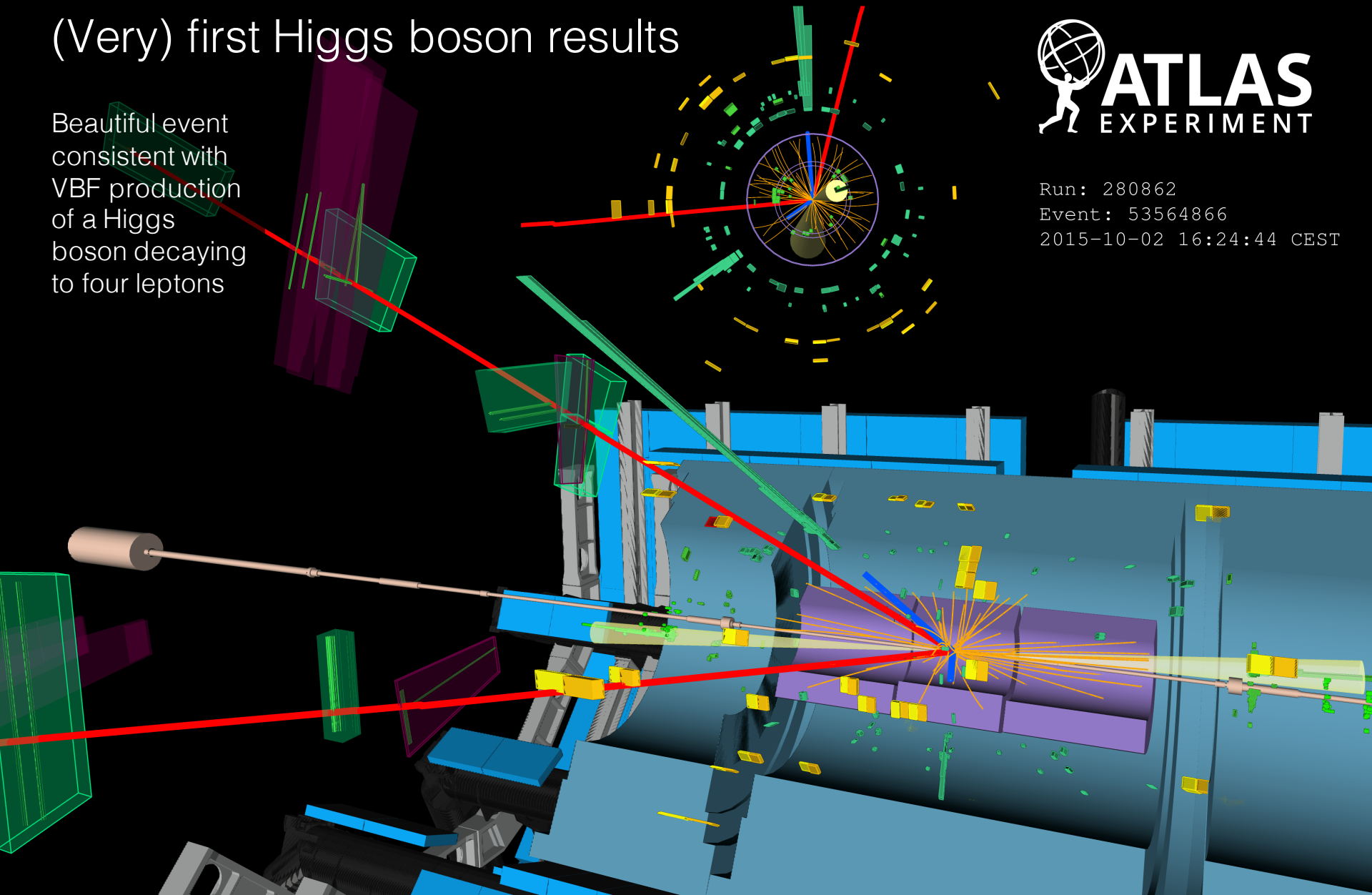
Beautiful event
consistent with
VBF production
of a Higgs
boson decaying
to four leptons



Run: 280862

Event: 53564866

2015-10-02 16:24:44 CEST



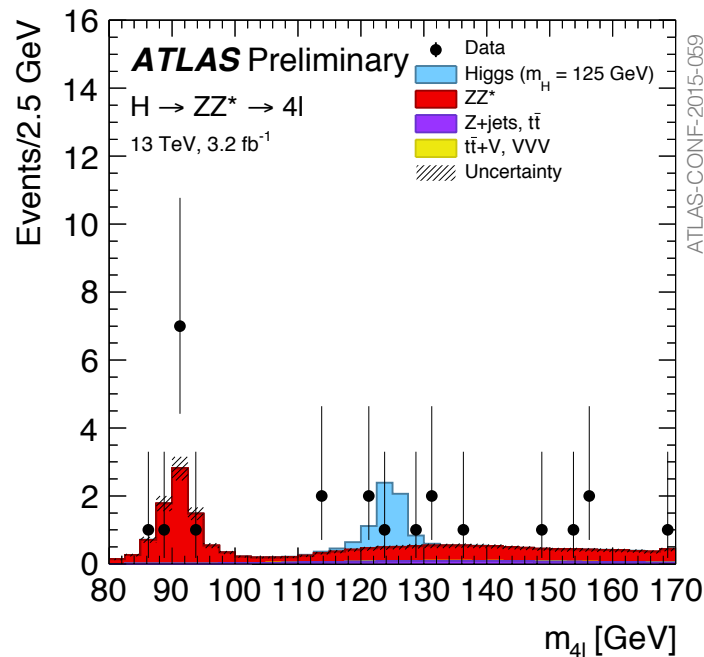
Display of $H \rightarrow ee\mu\mu$ candidate from 13 TeV pp collisions. The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, and the jets 118 and 54 GeV. The invariant mass of the four lepton system is 129 GeV, the dielectron (dimuon) invariant mass is 91 (29) GeV, the pseudorapidity difference between the two jets is 6.4 and the dijet invariant mass is 2 TeV.

Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

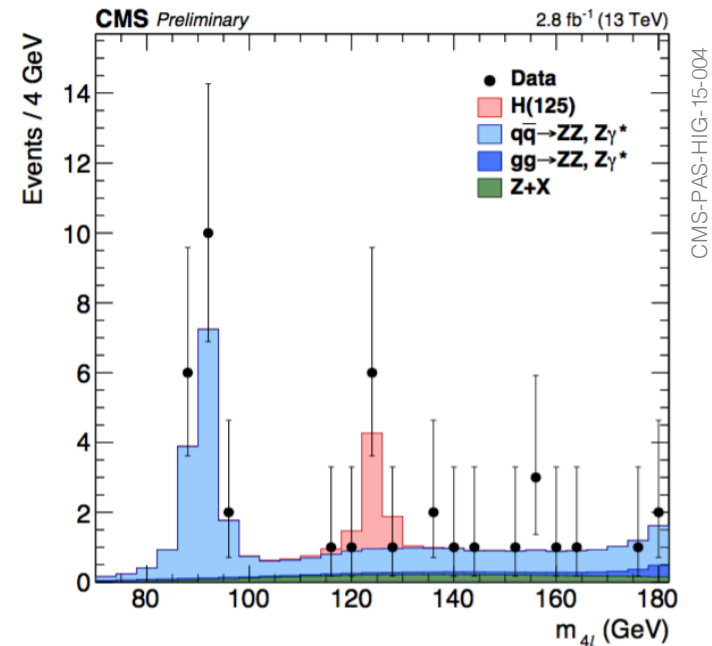
$H \rightarrow ZZ^* \rightarrow 4\ell$



$$\sigma_{\text{tot,data}} = 12^{+25}_{-16} \text{ pb}$$

$$\sigma_{\text{tot,SM}} = 51 \pm 5 \text{ pb}$$

Expected significance (SM): 2.8 σ



$$\mu = \sigma_{\text{data}} / \sigma_{\text{SM}} = 0.82^{+0.57}_{-0.43}$$

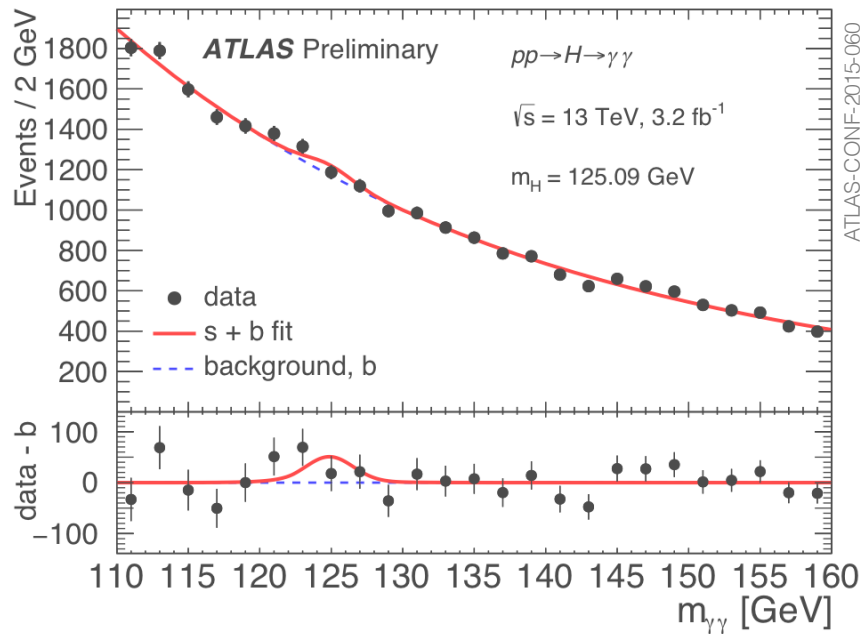
Expected significance (SM): 3.4 σ

Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

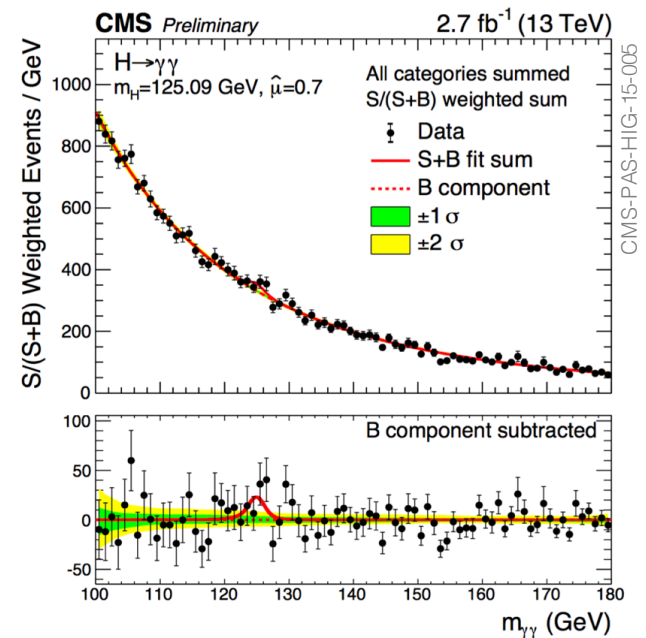
$H \rightarrow \gamma\gamma$



$$\sigma_{\text{tot,data}} = 40 \pm 26^{+16}_{-10} \pm 2_{\text{lumi}} \text{ pb}$$

$$\sigma_{\text{tot,SM}} = 51 \pm 5 \text{ pb}$$

Expected significance (SM): 1.9σ



$$\mu = 0.69^{+0.47}_{-0.42}$$

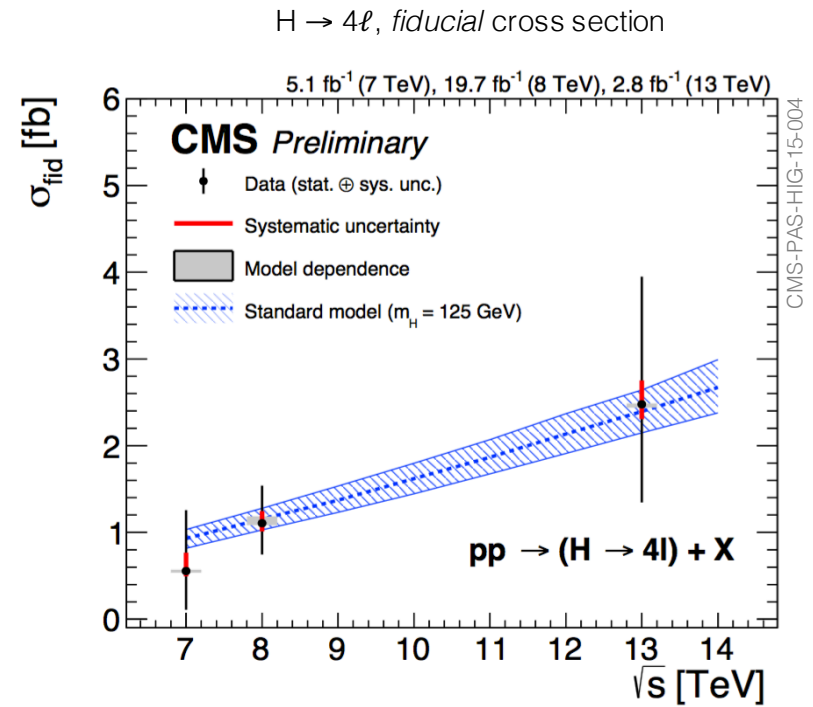
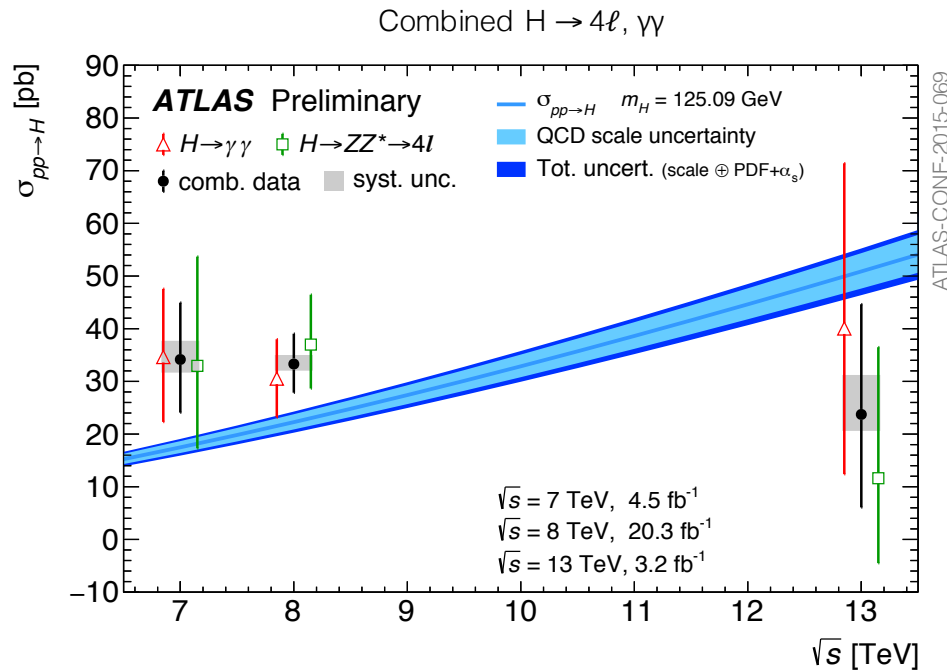
Expected significance (SM): 2.7σ

Current 13 TeV data sample still marginal for H_{125}

But important to look for the signal in an agnostic way at new CM energy

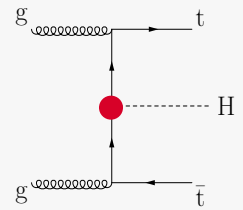
ATLAS & CMS looked for Higgs decays to bosonic and fermionic channels

Extracted cross sections vs CM energy



First search for ttH production at 13 TeV by CMS

Most interesting of the SM Higgs channels at current luminosity



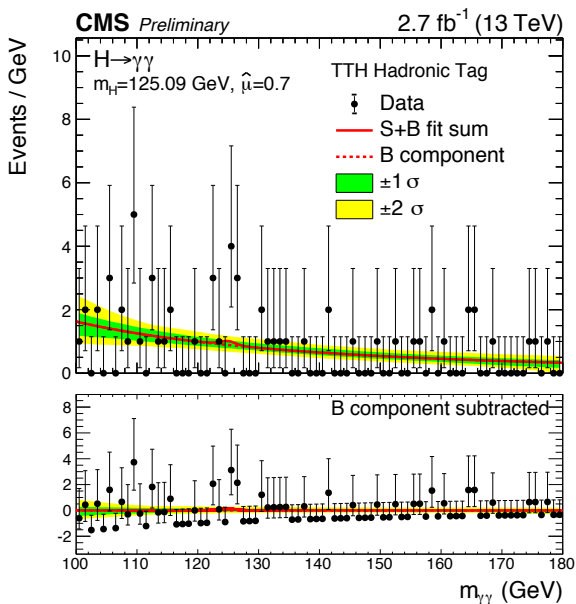
CMS showed preliminary results for ttH in all major Higgs decay channels: **H** → **γγ**, **multi-leptons**, **bb**

Highly complex analyses, huge effort to get these done so quickly after data taking

H → **γγ**,
tt → 0 & 1 leptons

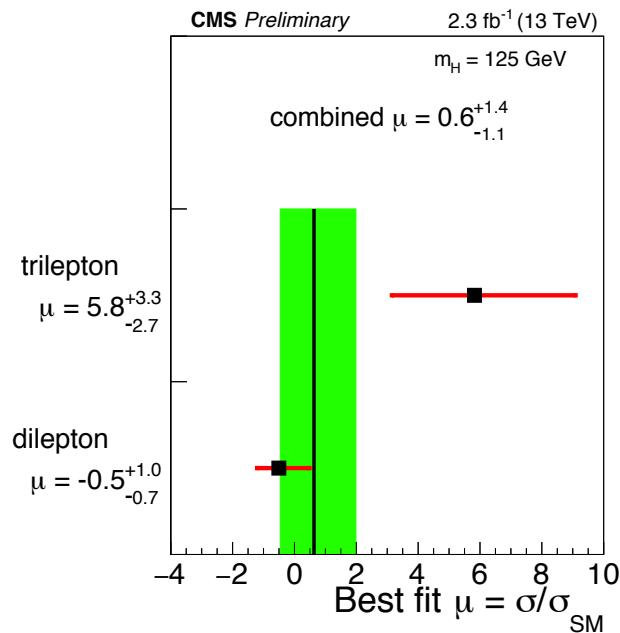
ttH → **multi-leptons**
2 same charge / 3 leptons

H → **bb**
tt → 1 & 2 leptons



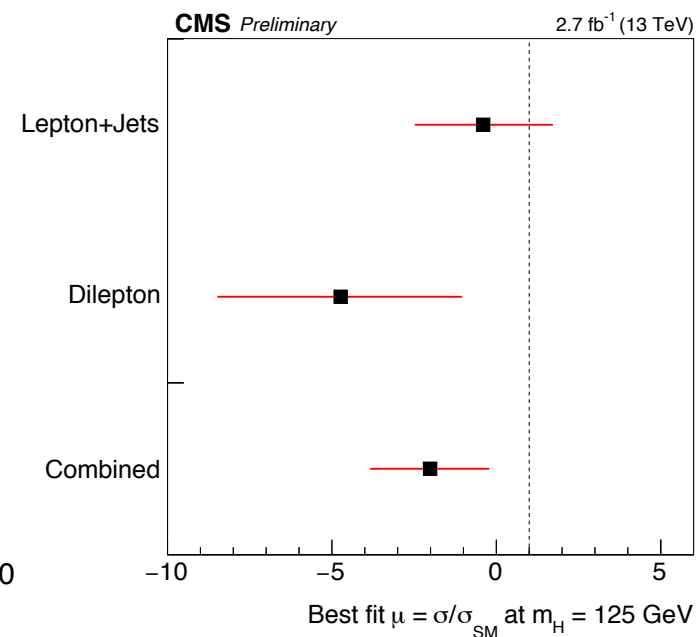
$$\mu = 3.8^{+4.5}_{-3.6}$$

CMS-PAS-HIG-15-005



$$\mu = 0.6^{+1.4}_{-1.1}$$

CMS-PAS-HIG-15-008



$$\mu = -2.0 \pm 1.8 < 2.6 \text{ (95\% CL)}$$

CMS-PAS-HIG-16-004

BSM Higgs boson searches

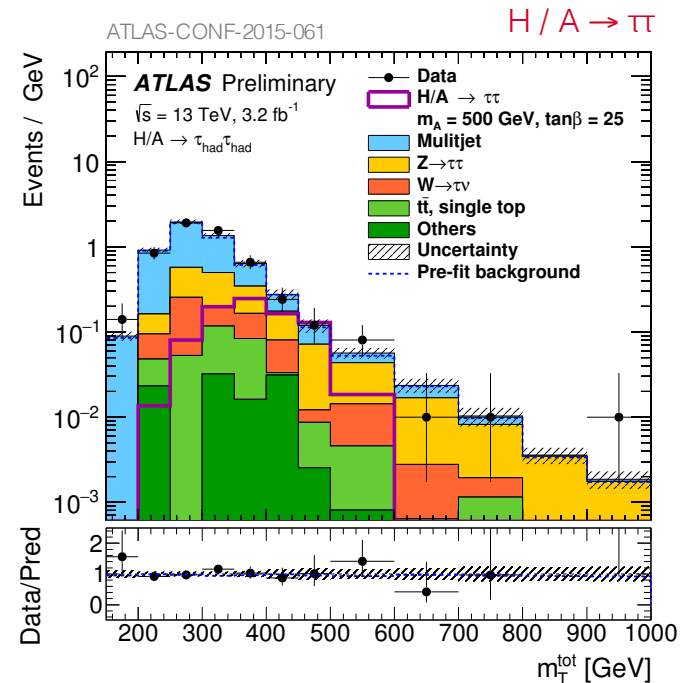
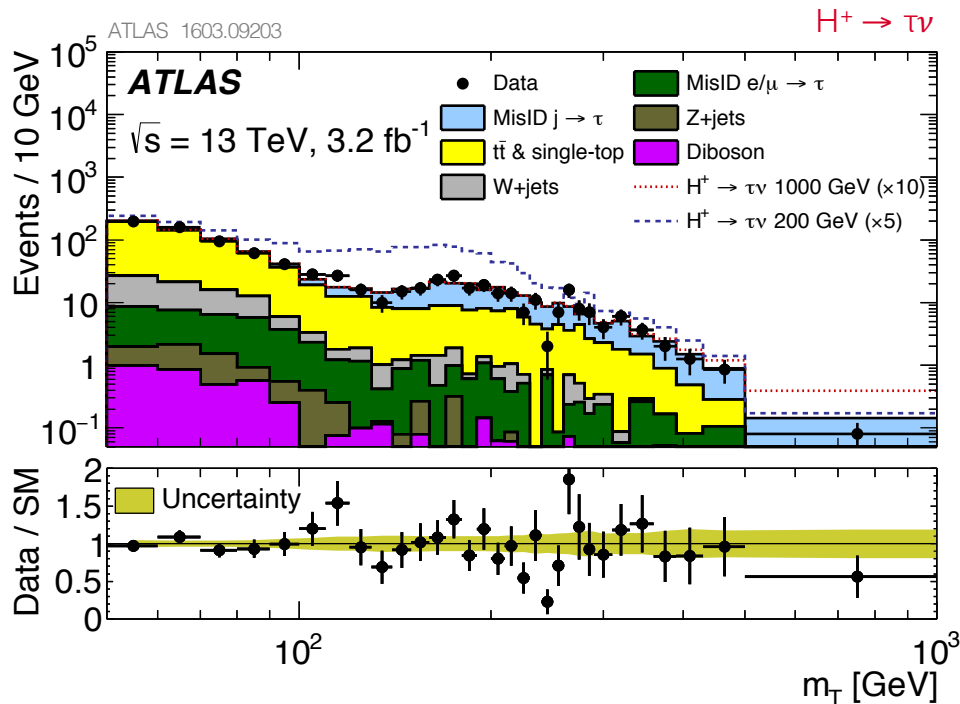
Single BEH doublet and form of potential simple but Nature may be more complex (eg, SUSY)

Beyond the SM “Higgs zoo”

[Will Davey, LHCP 2014]



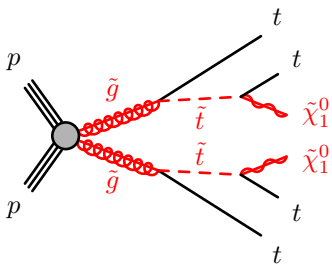
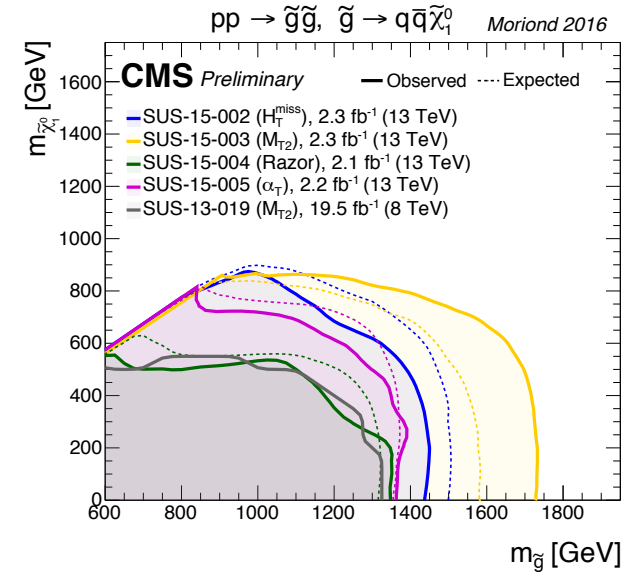
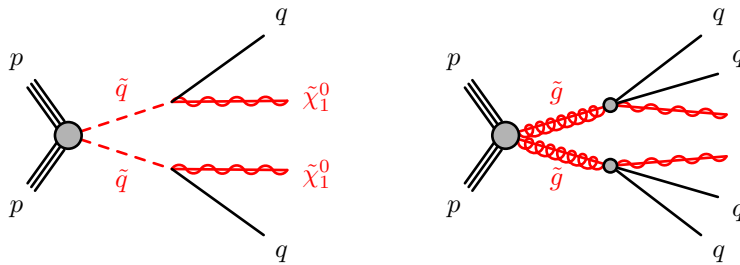
Higgs coupling to mass, look for decays to tau leptons or weak bosons, for example:



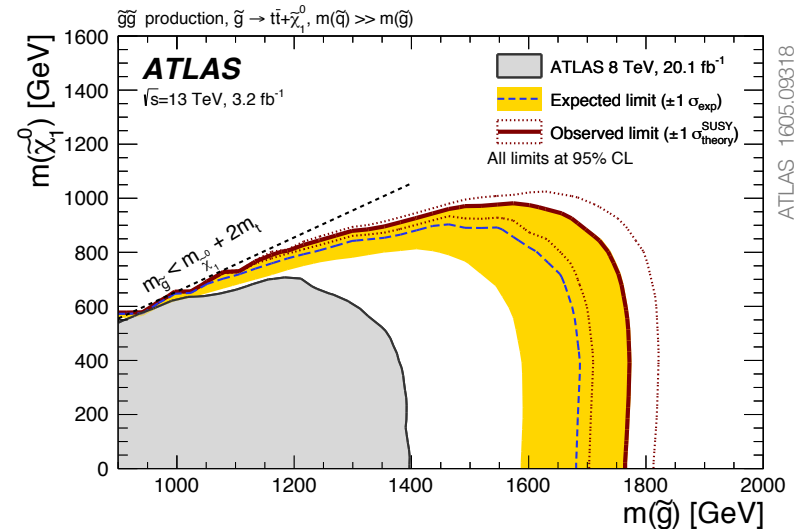
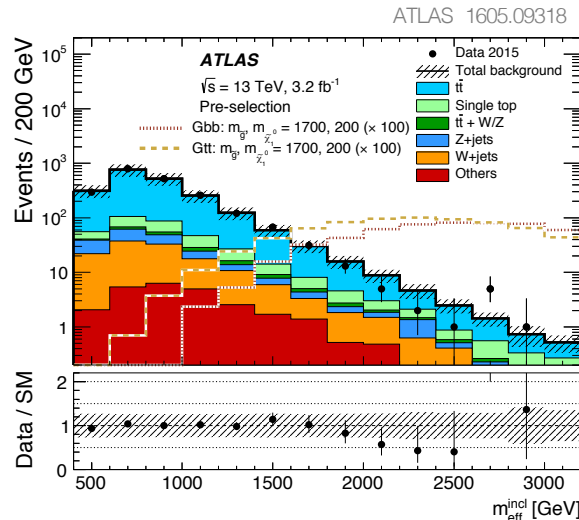
Supersymmetry

Still among the most popular SM extensions as elegant solution of hierarchy problem

Very diverse signatures. Highest cross-section events produce gluino / squark pairs with decays to jets and missing transverse momentum



No significant anomaly seen in many different analyses



Searches for dark matter production at the LHC

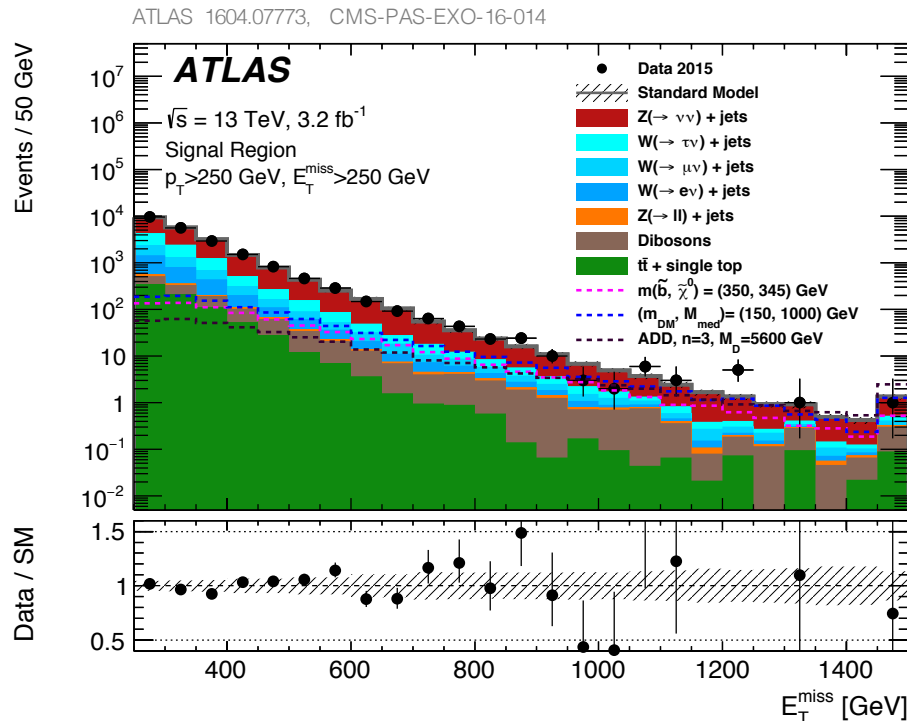
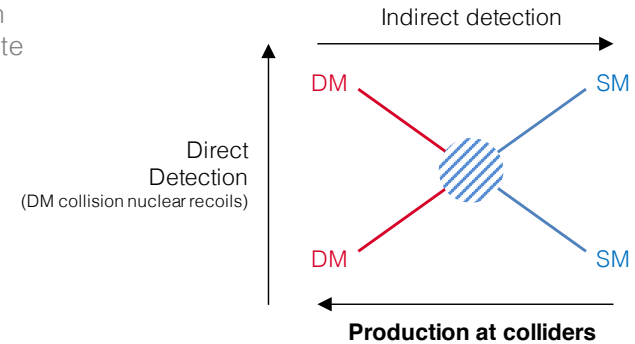
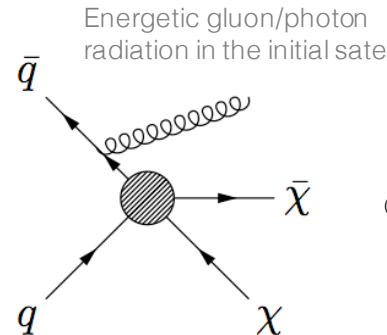
Canonical signature is 'X+MET' with large variety of 'X'

May not be able to prove at LHC that it is dark matter

Direct dark matter production at the LHC

Requires boost for triggering. Depending on coupling it can be made by different objects.

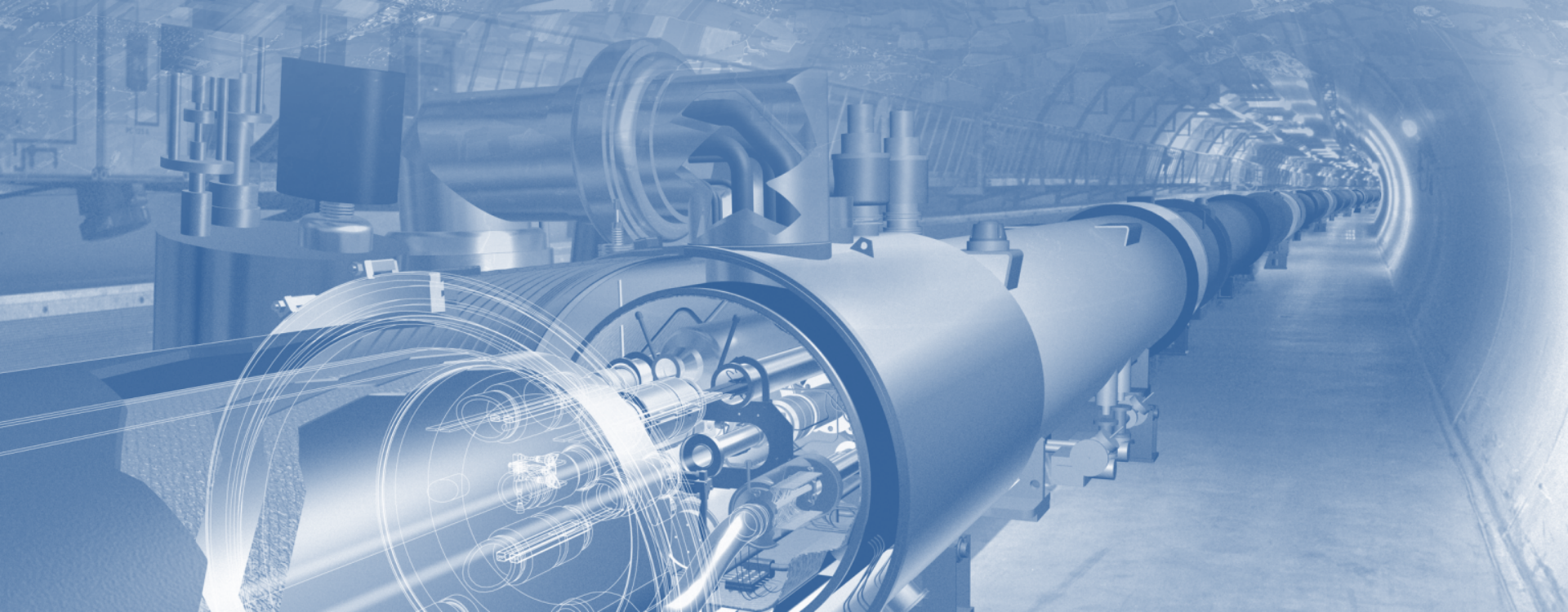
Experimentally challenging to control Z/W+jet background. Theory input needed.



Several 13 TeV results already available:

- jets + MET
- γ + MET
- V + MET
- bb/tt + MET

No anomaly seen

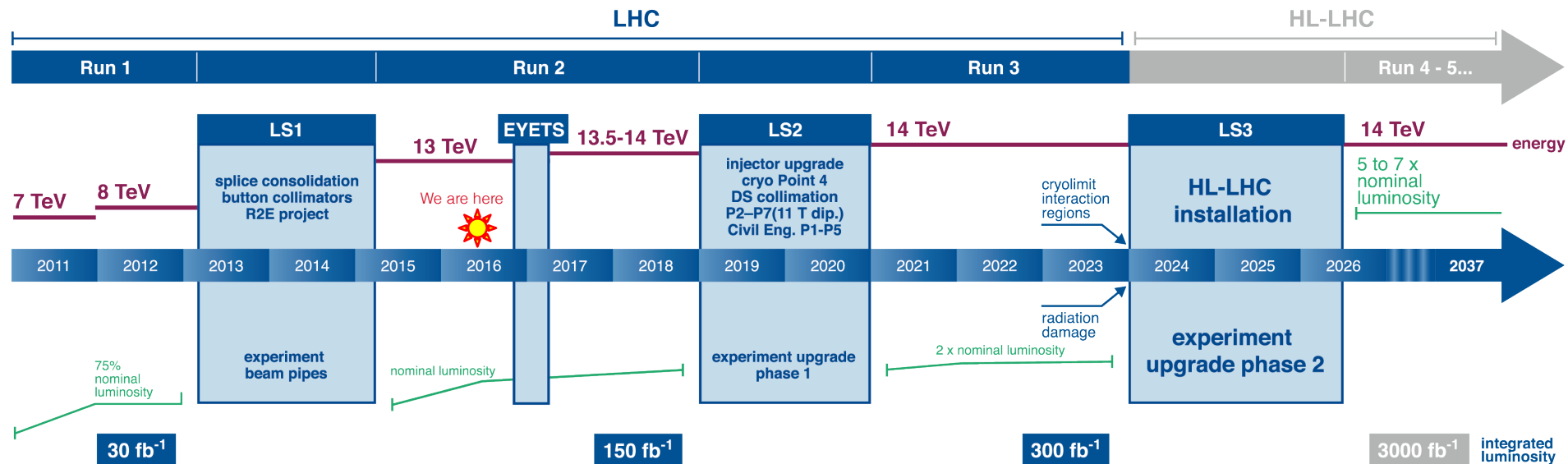


The next steps

The road to the future

The LHC Run-2 and beyond

LHC / HL-LHC Plan



The main proton–proton physics goals in a nutshell

Run-1 (up to 8 TeV, 25 fb⁻¹)

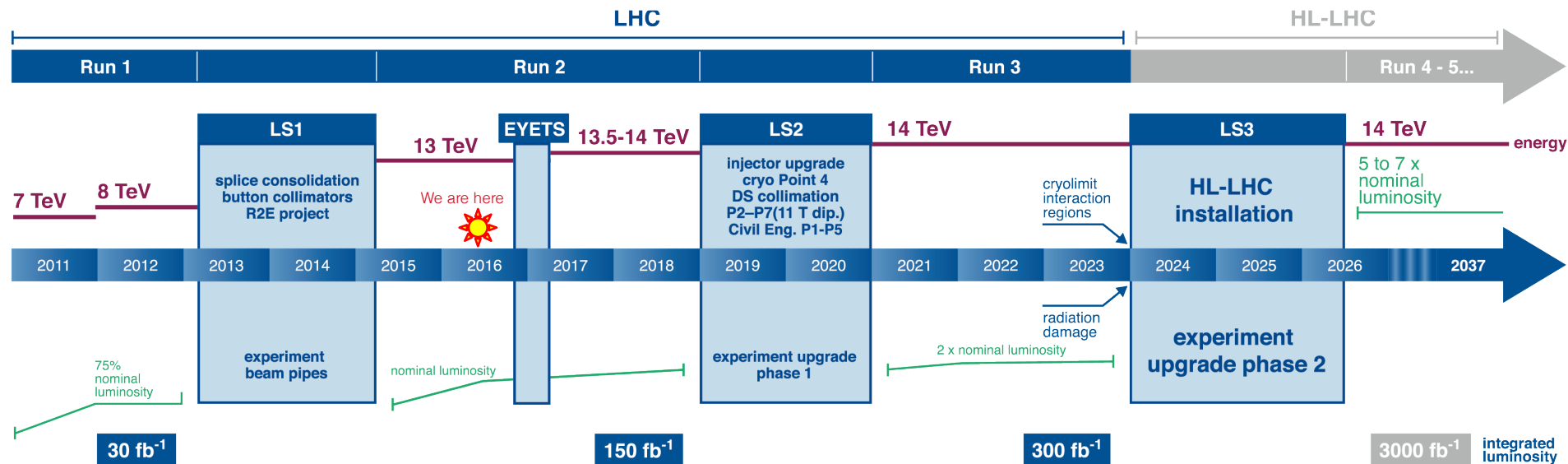
- Discovery of Higgs boson
- Searches for additional new physics (negative)
- Observation of rare processes, such as $B_s \rightarrow \mu\mu$
- Precision measurements of Standard Model processes
- Study of CP asymmetries in B_s sector

Run 2 & 3 (13–14 TeV, 300 fb⁻¹)

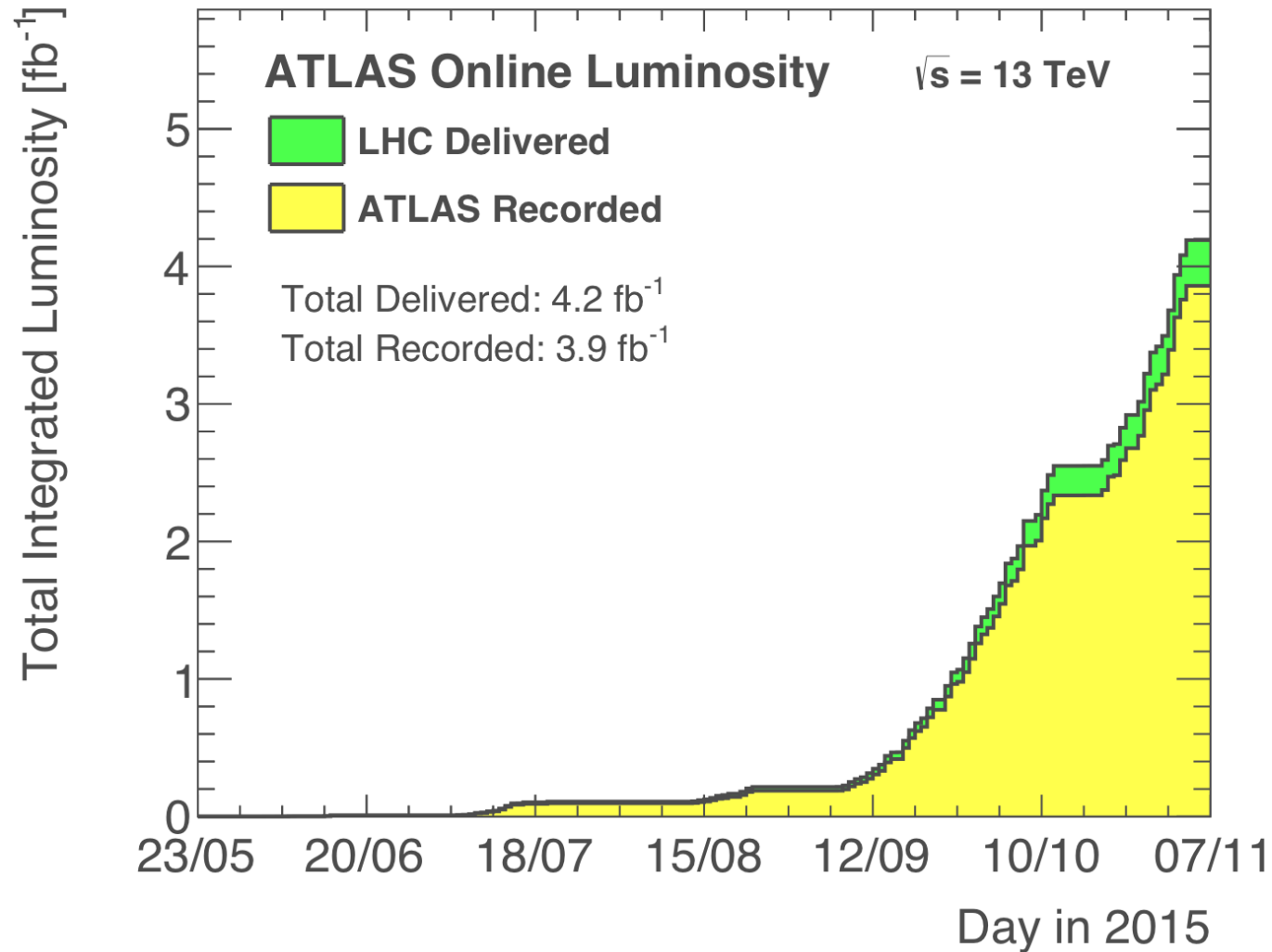
- Searches for new physics
- Improved measurements of Higgs couplings in main channels
- Consolidation / observation of Higgs channels ($\tau\tau$, bb , $t\bar{t}H$, VH , VBF)
- Measurement of rare Standard Model processes & more precision
- Improved measurements of rare B decays and CP asymmetries

HL-LHC (14 TeV, 3000 fb⁻¹)

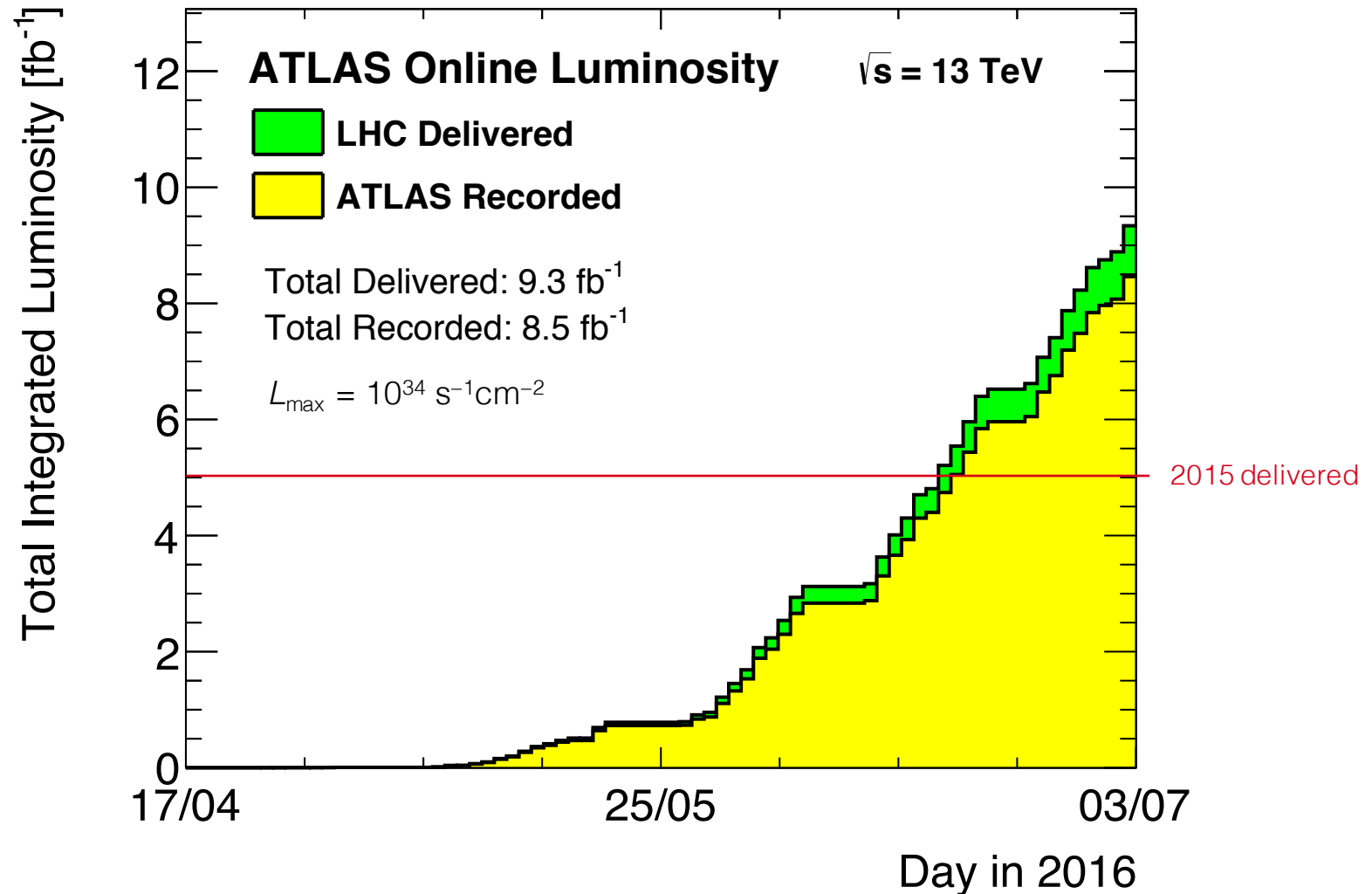
- Precision measurements of Higgs couplings
- Observation of very rare Higgs modes ($\mu\mu$, $Z\gamma$, HH)
- Ultimate new physics search reach (on mass & forbidden decays, eg, FCNC)
- Ultimate SM & HF physics precision for rare processes



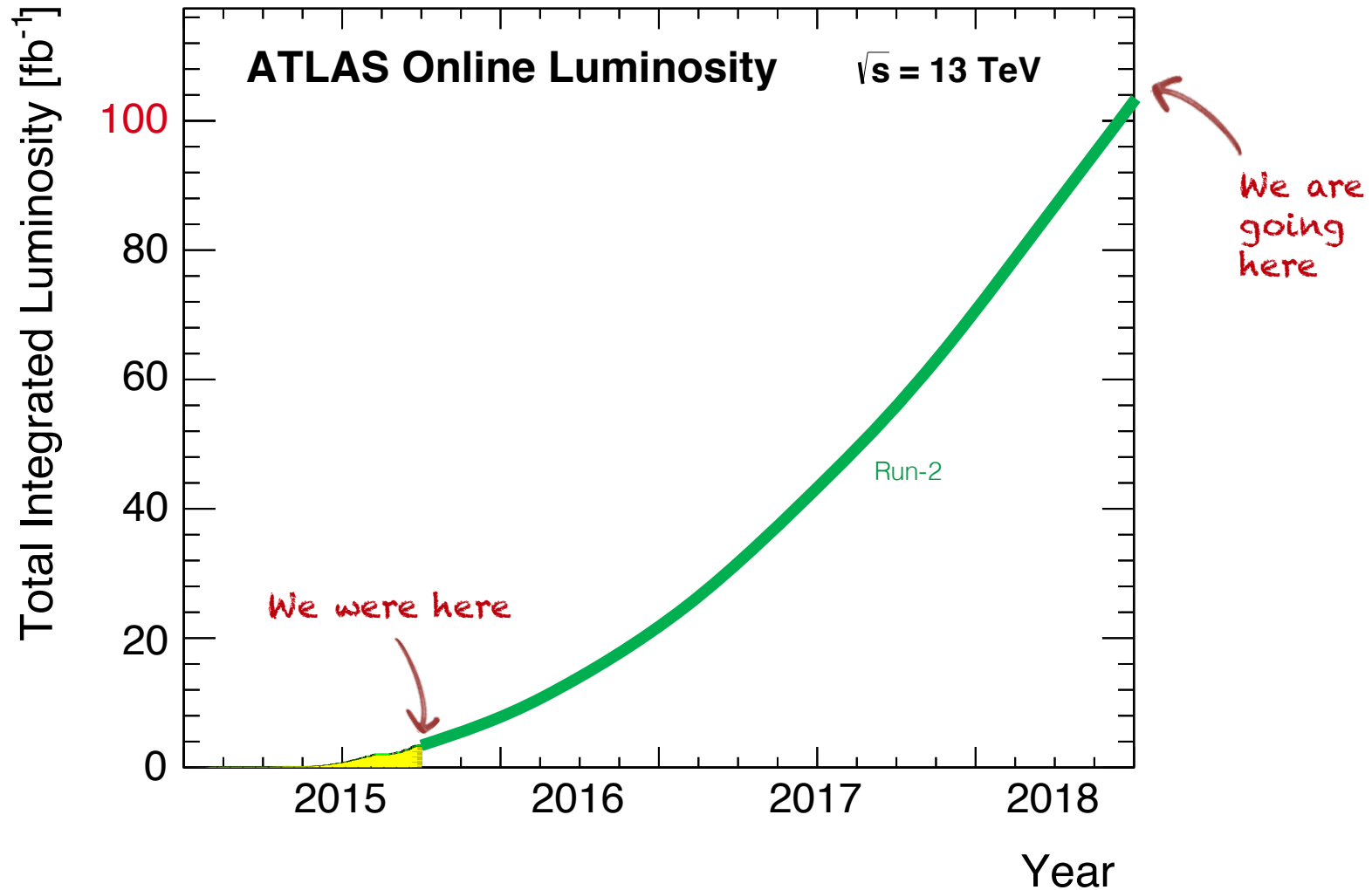
Status of Run-2 (2015)



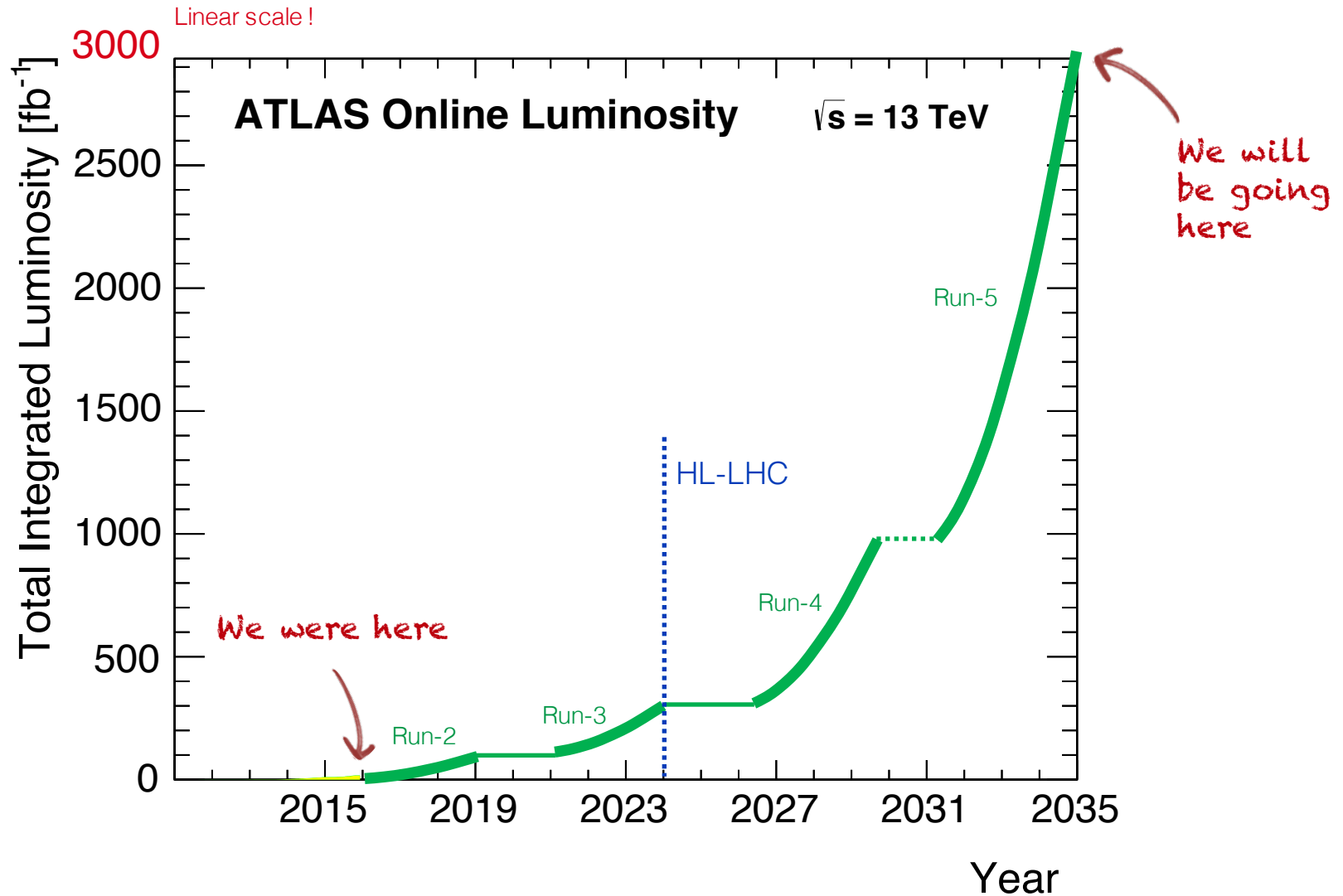
Status of Run-2 (2016)



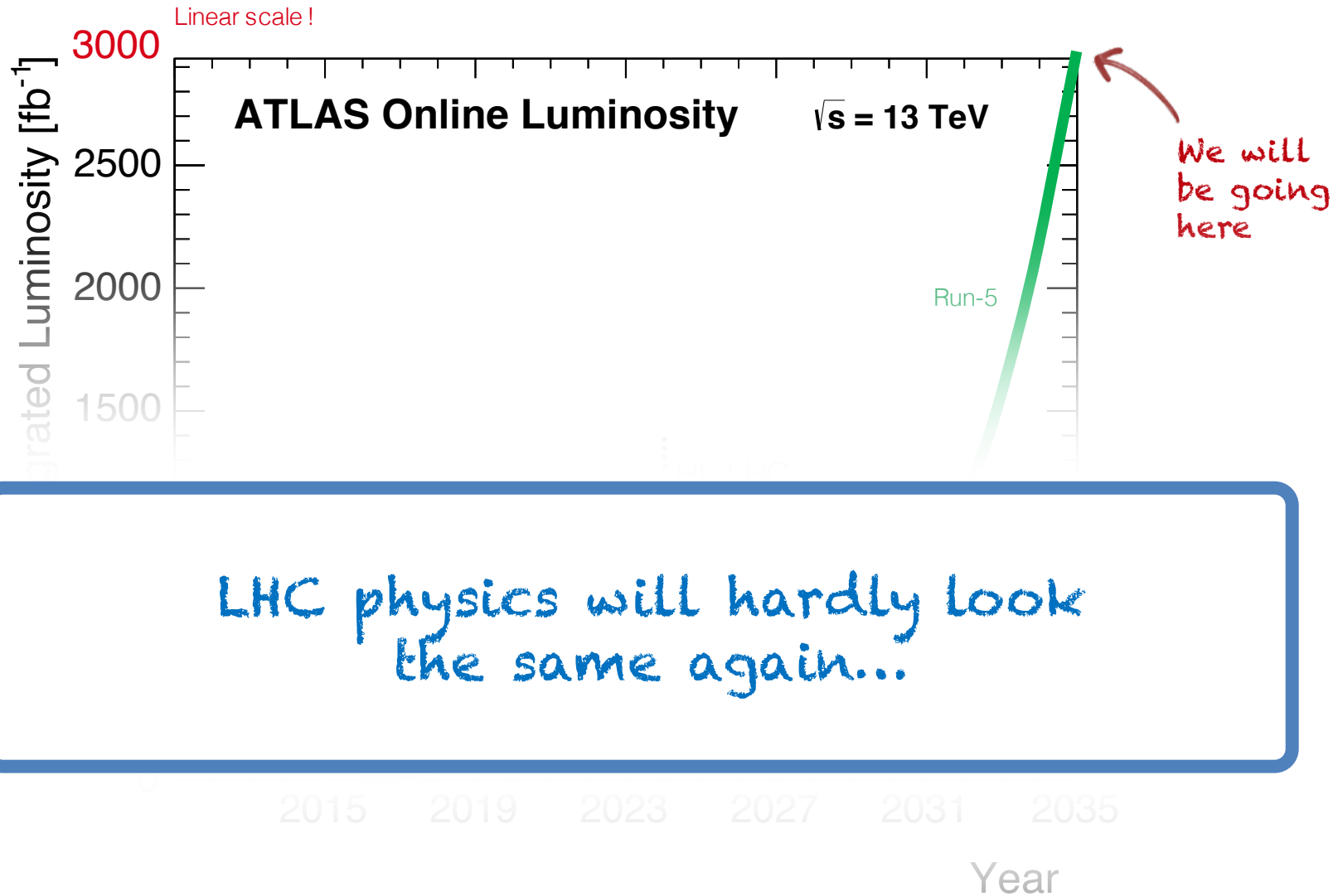
Expected integrated luminosity of **Run-2 until end of 2018**



Expected integrated luminosity of the **LHC & HL-LHC** until ... 2035



Expected integrated luminosity of the **LHC & HL-LHC** until ... 2035



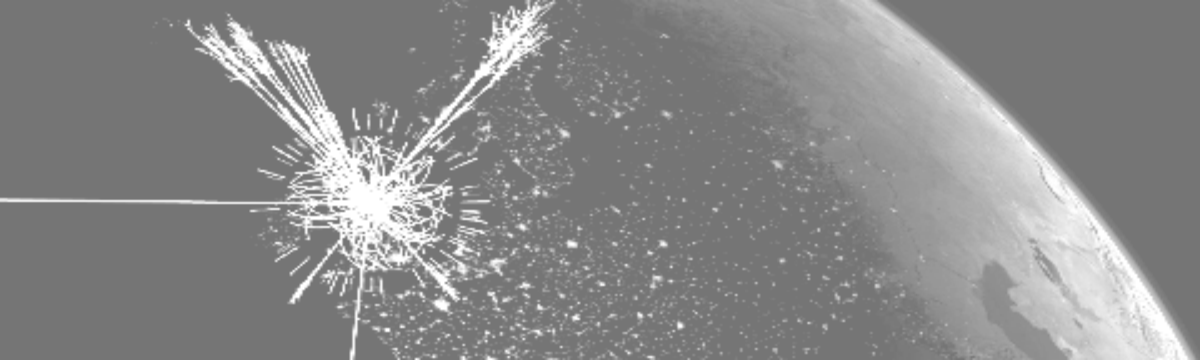


Next updates:
International Conference on High-Energy Physics (ICHEP 2016),
3–10 August 2016, Chicago, USA

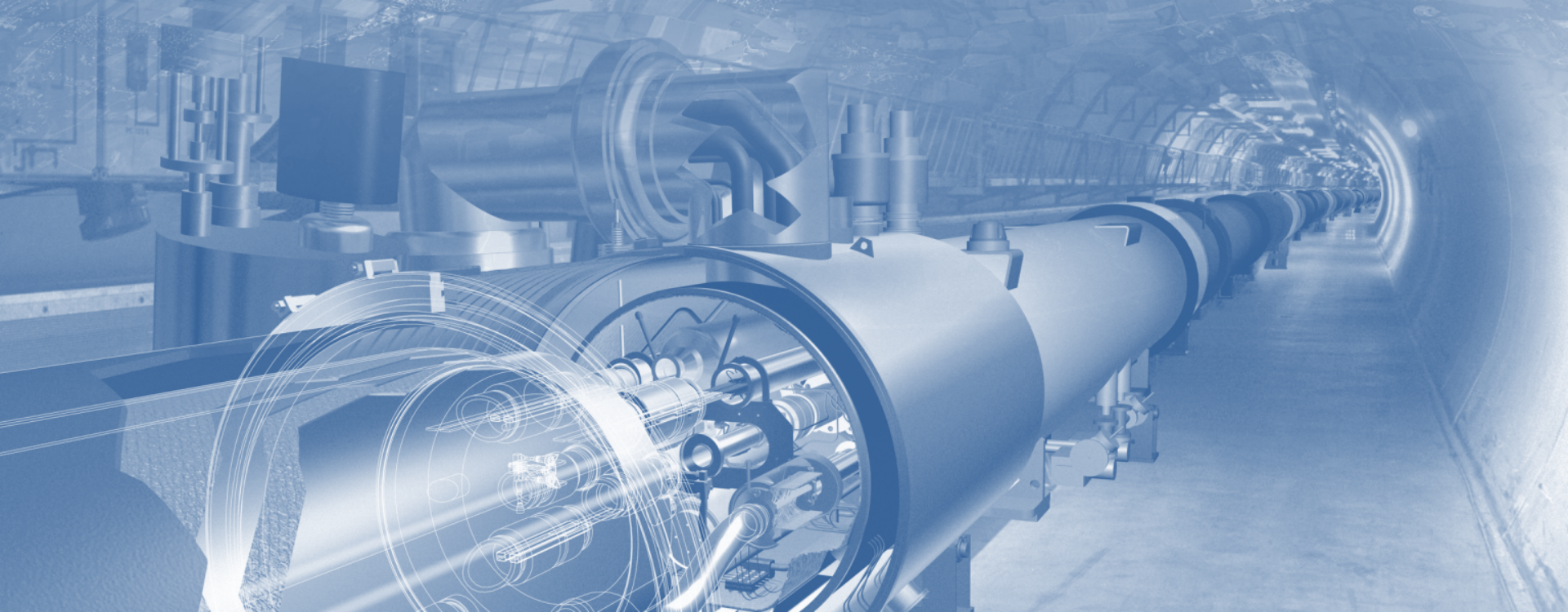
[<https://www.ichep2016.org>]



Thank you



Extra slides



Conclusions in more words

A visualization of a particle collision, likely from the LHC, showing a central bright point with numerous tracks radiating outwards, set against a dark blue background with a curved horizon line.

Conclusions

The Higgs-boson discovery proved the BEH mechanism to break gauge symmetry, but many profound questions remain unanswered. Among these:

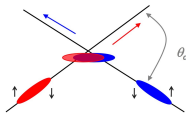
- Naturalness requires the separation of scales, but in the SM what happens at the electroweak scale seems to depend on much larger scales
- There are only gravitational proofs of dark matter, no massive WIMPs seen (axion?)
- The SM flavour sector with its 22 parameters has no dynamical explanation
- Lepto- and baryogenesis require new physics

The currently ongoing LHC Run-2 is a key period for particle physics

- High CM energy and first 100 fb^{-1} are critical for searches for new physics in all signatures
- Further consolidation of Higgs sector with observation and measurement of $H \rightarrow \tau\tau$ & bb , and ttH , as well as precise coupling and fiducial & differential cross section measurements
- The luminosity of Run-2 will hugely increase the amount of interesting Standard Model and flavour physics measurements

How can these LHC luminosity improvements be achieved ?

Crab crossing:
(deflects head and tail
in opposite direction)



Run-1 (up to 8 TeV, 25 fb⁻¹)

- $E_{\text{beam}} = 0.45\text{--}4\text{ TeV}$
- $L_{\text{max}} = 0.8 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$
- $\Delta t_{\text{bunch}} = 50\text{ ns}$
- $N_{\text{bunches,max}} = 1380$
- $\beta^* = 60\text{ cm}$
[recall: $L \propto (\sigma_x \sigma_y)^{-1} = (\varepsilon_n \beta^* \gamma)^{-1}$]
- Norm. emittance $\varepsilon_n \sim 2.3\text{ }\mu\text{m}$
- $N_{\text{protons / bunch}} \leq 1.7 \cdot 10^{11}$
- $\langle \mu \rangle \sim 21$
(note: μ_{peak} much larger)

Run 2 & 3 (13–14 TeV, 300 fb⁻¹)

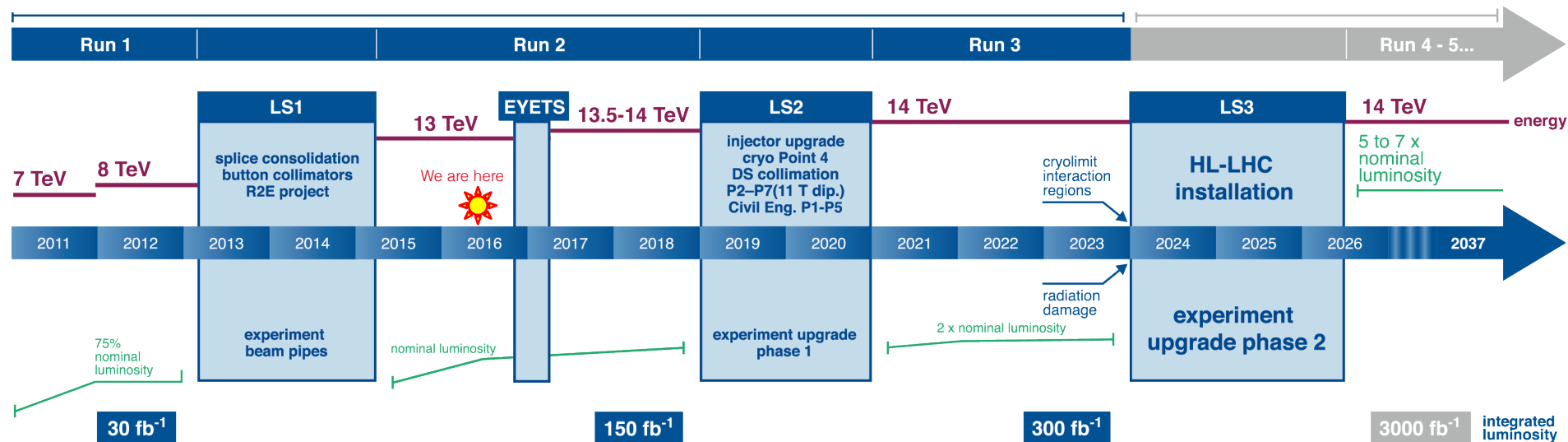
- $E_{\text{beam}} = 6.5\text{--}7\text{ TeV}$
- $L_{\text{max}} = 0.7\text{--}2 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$
- $\Delta t_{\text{bunch}} = 25\text{ ns}$
- $N_{\text{bunches,max}} = 2028\text{--}2748(?)$
- $\beta^* = 40\text{ cm}$
- $\varepsilon_n = 2.5\text{--}3.5\text{ }\mu\text{m}$ (2.3 μm with BCMS)
- $N_{\text{protons / bunch}} \sim 1.2 \cdot 10^{11}$
- $\langle \mu \rangle \sim 21\text{--}50$

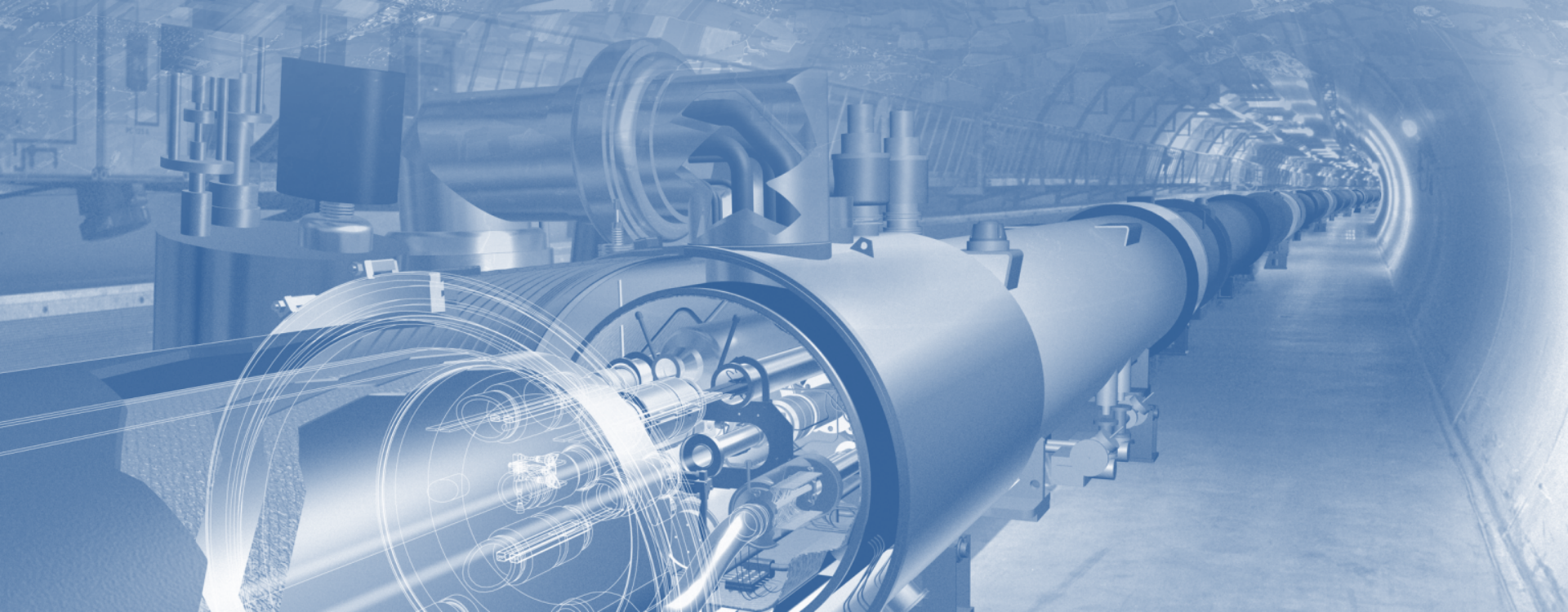
LS2: injector upgrade for increased beam brightness (batch compression in PS, new optics in SPS, collimator upgrades)

HL-LHC (14 TeV, 3000 fb⁻¹)

- $E_{\text{beam}} = 7\text{ TeV}$
- $L_{\text{max}} \sim 5 \times 10^{34}\text{ cm}^{-2}\text{s}^{-1}$
- $\Delta t_{\text{bunch}} = 25\text{ ns}$
- $N_{\text{bunches,max}} = 2748$
- $\beta^* = 15\text{ cm}$
- $\varepsilon_n = 2.5\text{ }\mu\text{m}$
- $N_{\text{protons / bunch}} = 2.2 \cdot 10^{11}$
- $\langle \mu \rangle \sim 140$

LS3: new triplet design (low- β^* quadrupoles, crab cavities), injector upgrades for luminosity levelling





Beyond the HL-LHC

Only a very brief enumeration of projects

Future hadron collider projects in a nutshell

The next discovery machine

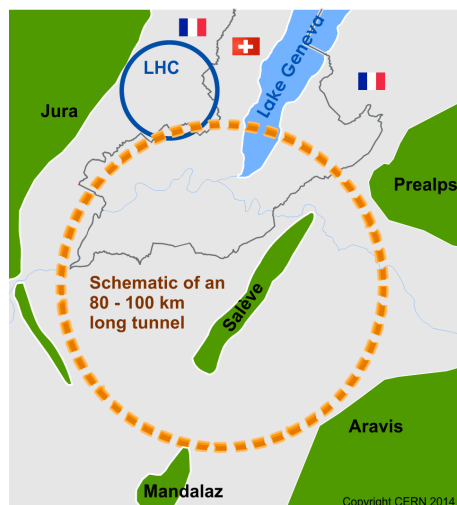
HL-LHC: $E_{\text{CM}} = 14 \text{ TeV}$, 3 ab^{-1} , 2026~2035... (formally approved as *project* by CERN council last week)

Future Circular Collider FCC-hh (CERN):

- $E_{\text{CM}} \sim 100 \text{ TeV}$ in 100 km ring, $L \sim 2 \times 10^{35} \text{ s}^{-1}\text{cm}^{-2}$
- $\sim 16 \text{ T}$ magnets, possibly HE-LHC ($E_{\text{CM}} \sim 28 \text{ TeV}$) as intermediate stage
- Huge detectors for muon p_T measurement
- Possible start of physics ~ 2035

SppC (China):

- $E_{\text{CM}} \sim 71 \text{ TeV}$ in 55 km ring, $L \sim 1 \times 10^{35} \text{ s}^{-1}\text{cm}^{-2}$
- Requires very high gradient dipole magnets $\sim 20 \text{ T}$
- Possible start of physics ~ 2042



Parameter	FCC-hh		SppC	LHC	HL LHC
collision energy cms [TeV]	100		71.2	14	
dipole field [T]	16		20	8.3	
# IP	2 main + 2		2	2 main + 2	
bunch intensity [10^{11}]	1	1 (0.2)	2	1.1	2.2
bunch spacing [ns]	25	25 (5)	25	25	25
luminosity/lp [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	5	~ 25	12	1	5
events/bunch crossing	170	~ 850 (170)	400	27	135
stored energy/beam [GJ]	8.4		6.6	0.36	0.7
E-loss/turn	5 MeV		2 MeV	7 keV	7 keV
synchrotron radiation/beam	3 MW		5.8 MW	5.4 kW	9.5 kW

Future e⁻e⁺ collider projects in a nutshell

Measure EW & EWSB sector to highest precision

International Linear Collider ILC (host candidate: Japan)

- 20 years of R&D, mature technology, ~32 MV/m accelerating gradient ~ xFEL at DESY (45 MV/m for 1 TeV)
- $E_{\text{CM}} \sim 500\text{--}1000$ GeV in 31–45 km total length, $L \sim 1.8 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$, only one interaction region
- nm beam size, possible start of physics ~ 2030

Compact Linear Collider CLIC (CERN)

- High-gradient 2-beam scheme*: 100 MV/m gradient
- $E_{\text{CM}} \sim 380\text{--}3000$ GeV, 11–50 km total length, $L \sim \text{a few} \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$, only one interaction region
- 0.5 ns bunch distance, nm beam size, large beamstrahlung, physics ~ 2035

*A low energy, high current, “drive” beam is decelerated in power extraction structures and the RF power is transferred to the cavities that accelerate the main beam

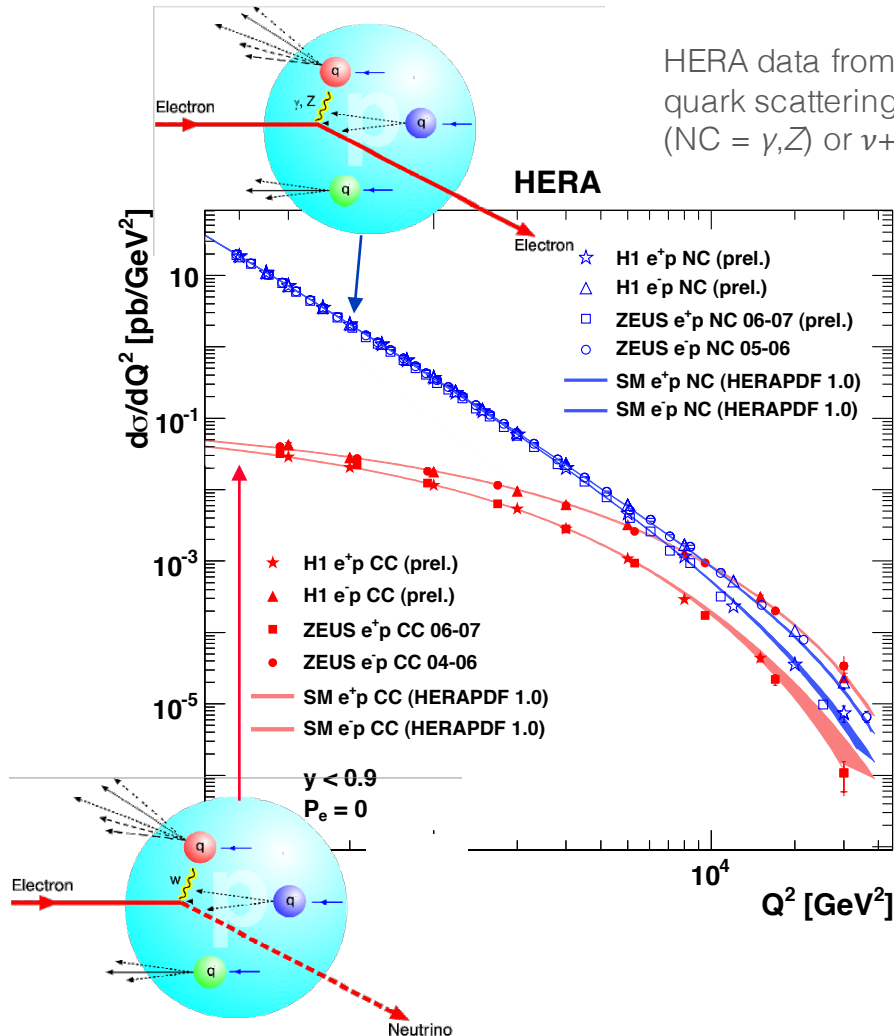
Future Circular Collider FCC-ee (CERN):

- $E_{\text{CM}} \sim 90\text{--}350$ GeV in 2 rings (90k bunches), $L \sim 70\text{--}1.3 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$
- Synchrotron power (E^4/R up to 7.5 GeV/turn): 100 MW (LEP-2: 22 MW)

Circular EP collider CEPC (China):

- $E_{\text{CM}} \sim 240$ GeV, $L \sim 2 \times 10^{34} \text{ s}^{-1}\text{cm}^{-2}$
- Single ring, 50 bunches
- Possible start of physics ~ 2028

parameter	FCC-ee			CepC	LEP2
energy/beam [GeV]	45	120	175	120	105
bunches/beam	90000	770	78	50	4
beam current [mA]	1450	30	6.6	16.6	3
luminosity/IP $\times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$	70	5	1.3	2.0	0.0012
energy loss/turn [GeV]	0.03	1.67	7.55	3.1	3.34
synchrotron power [MW]	100			103	22
RF voltage [GV]	0.08	3.0	10	6.9	3.5



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

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

Is the SM the theory of everything?
Or rather of almost everything? **No!**

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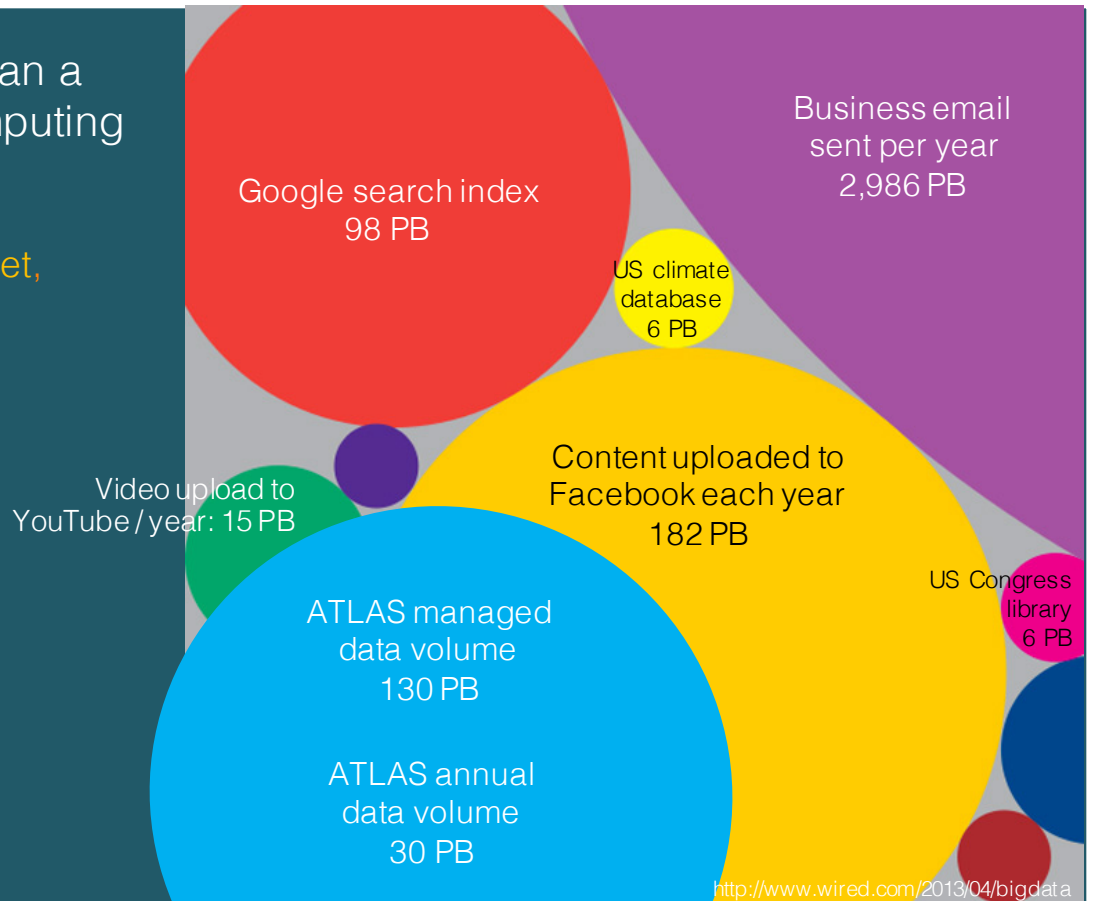
- Electroweak unification reduces 27 SM parameters by one

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

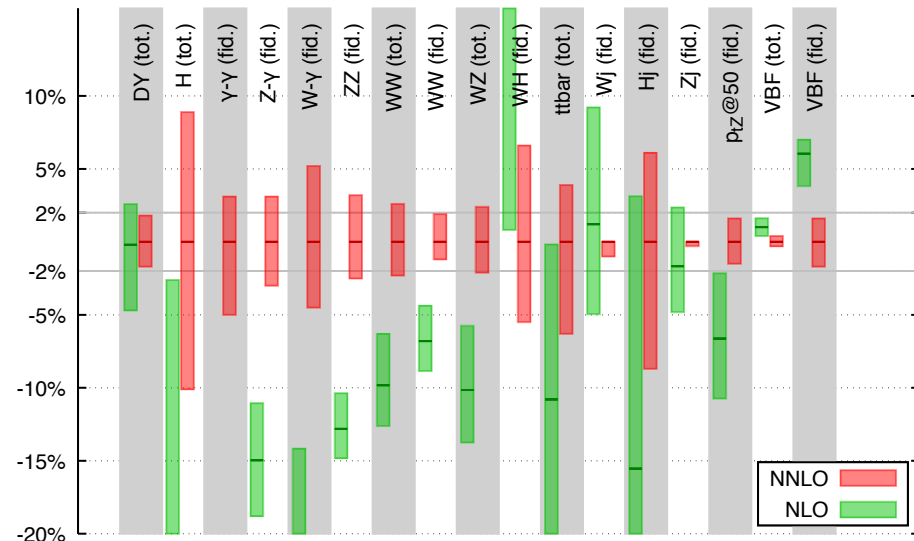
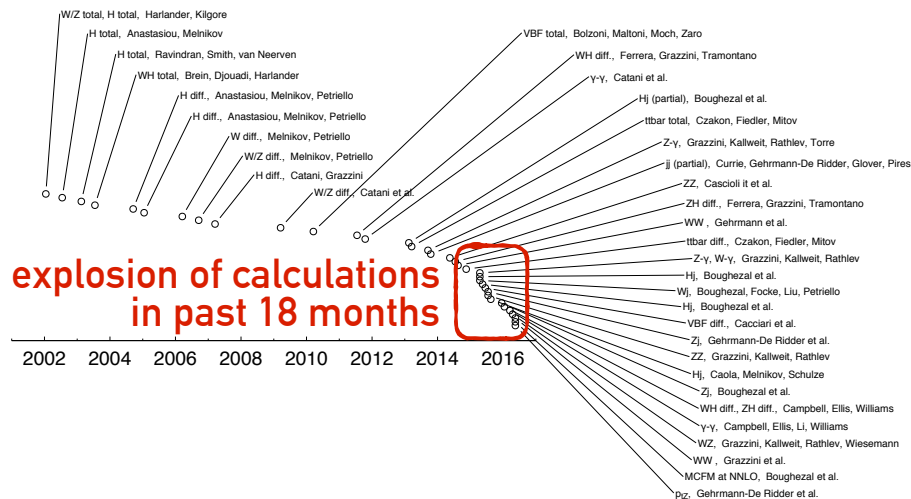
Largest data volume from simulated events, not from real collision data !



Theoretical cross-sections and uncertainties

Progress in theoretical calculations*

NNLO revolution



For many processes NNLO scale band is $\sim \pm 2\%$
But only in 3/17 cases is NNLO (central) within NLO scale band...

Also experimental knowledge of PDFs is limiting precision in many LHC analyses !

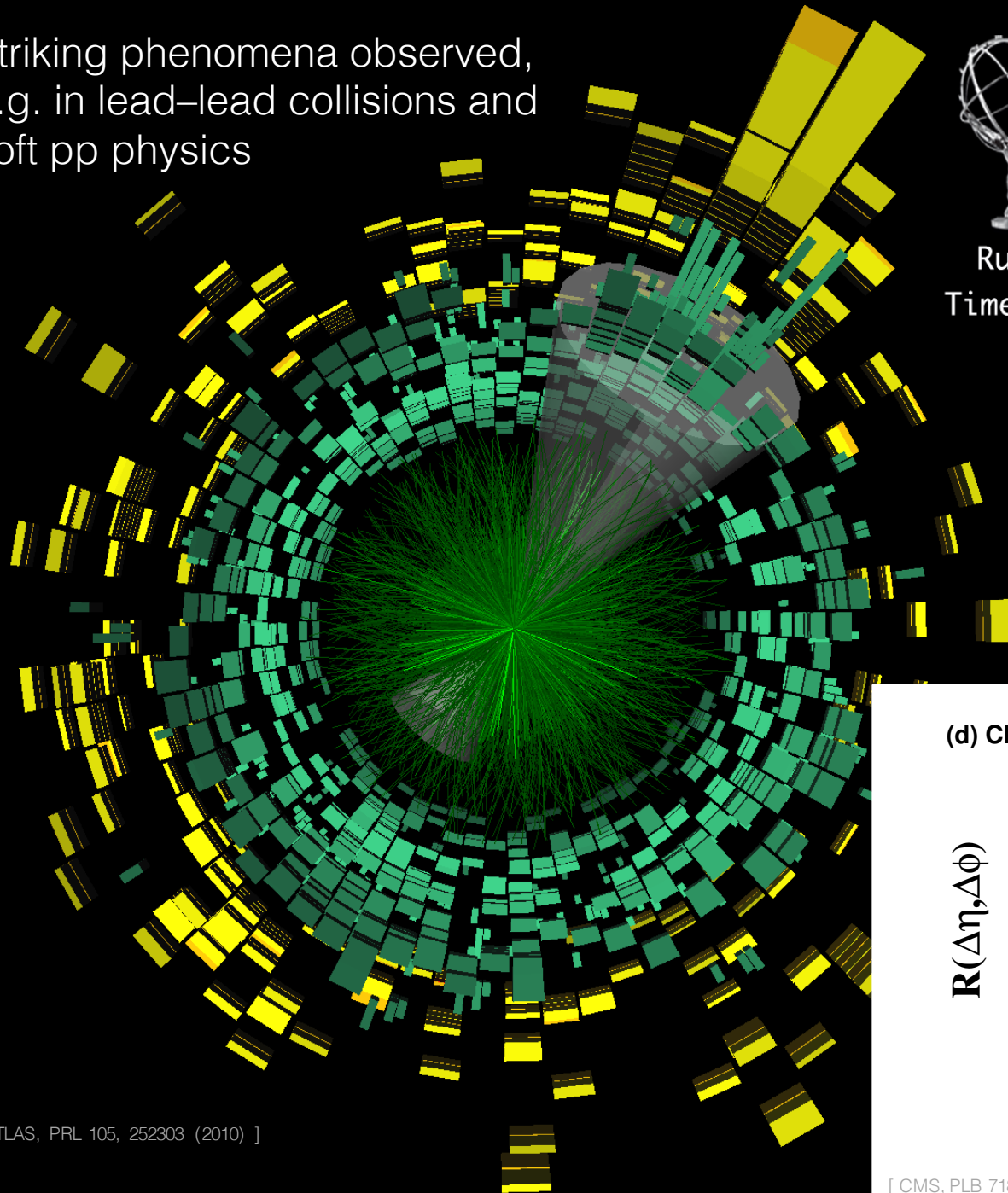
Striking phenomena observed,
e.g. in lead–lead collisions and
soft pp physics



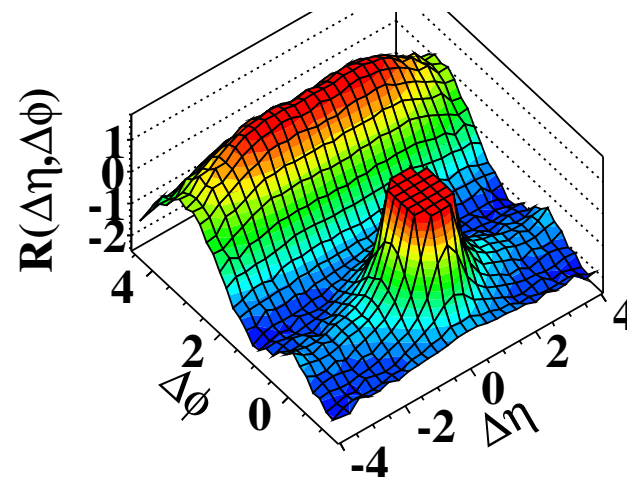
ATLAS EXPERIMENT

Run 168795, Event 7578342

Time 2010-11-09 08:55:48 CET



(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



[ATLAS, PRL 105, 252303 (2010)]

[CMS, PLB 718 (2013) 795]

The LHC is also a high-precision machine

Electroweak sector requires precise measurements of m_{top} , M_W , $\sin^2\theta_w$

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

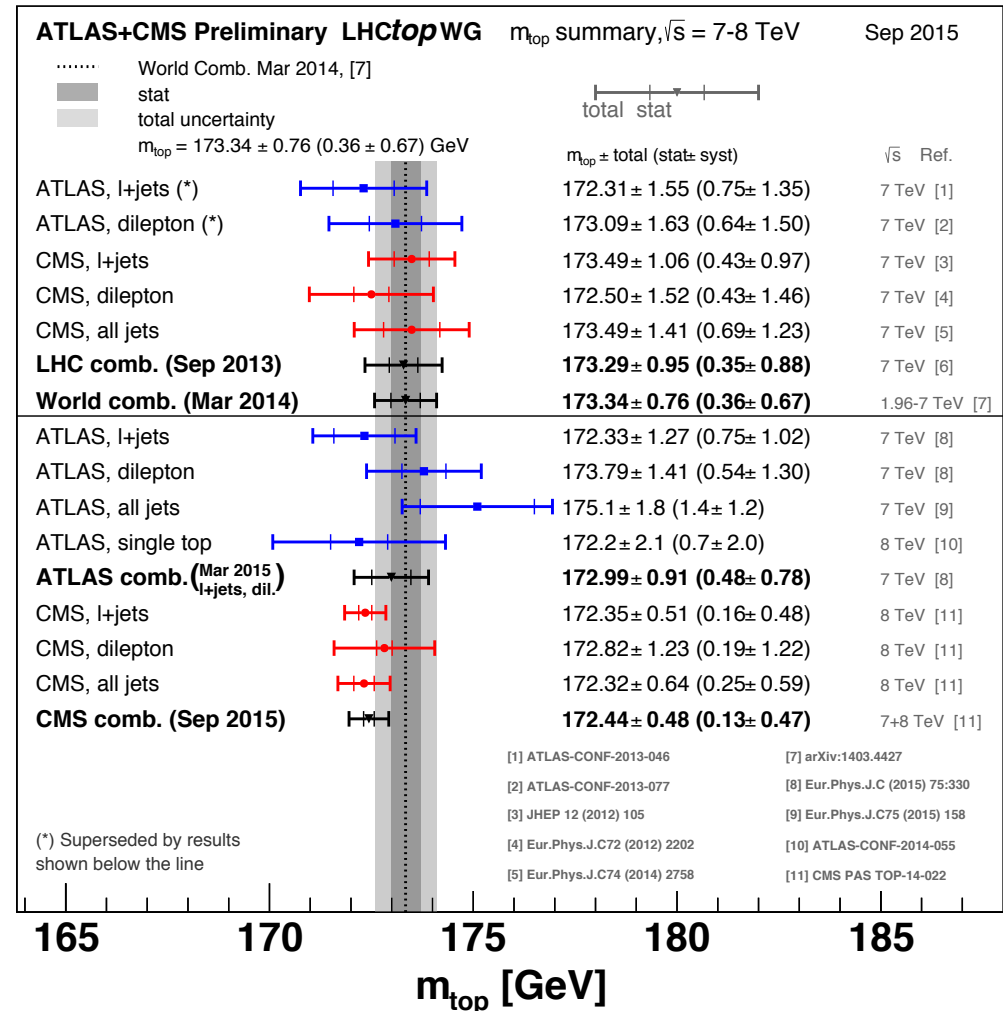
Best top mass from LHC:

- $172.44 \pm 0.13 \pm 0.47$ GeV (CMS)
- $172.84 \pm 0.34 \pm 0.61$ GeV (ATLAS, not yet all 8 TeV results available)

640 MeV for Tevatron combination

Reaching systematic limit from b-quark fragmentation

Alternative m_{top} determinations

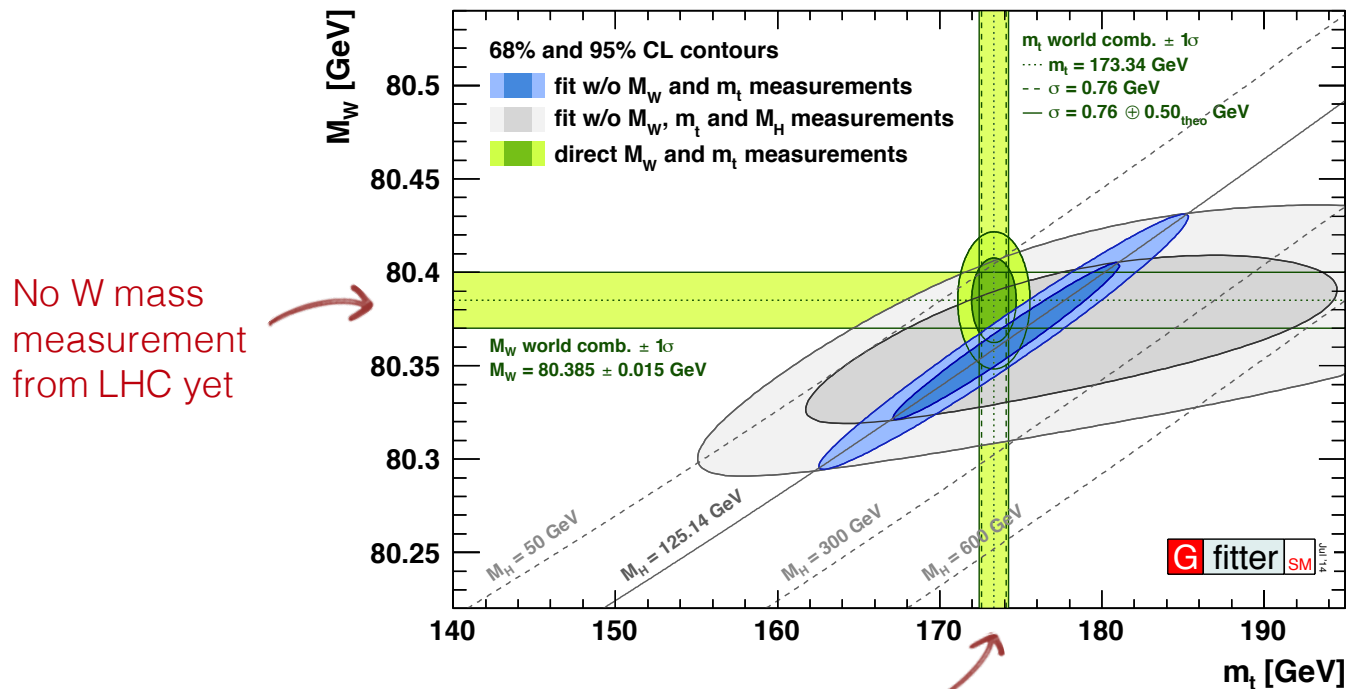


The LHC is also a precision machine

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

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 [CDF & D0, 1204.0042], $\sigma_{\text{WA}} = 15 \text{ MeV}$, no result from LHC yet

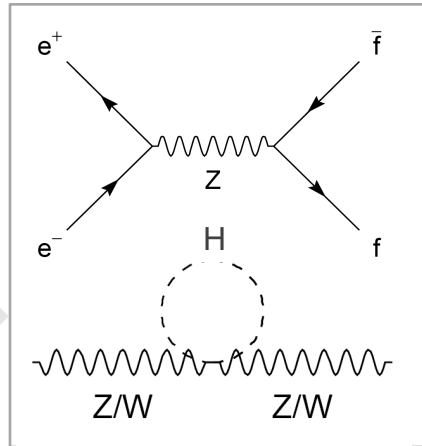
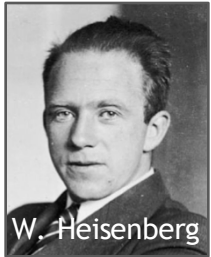


Competitive top mass results from the LHC

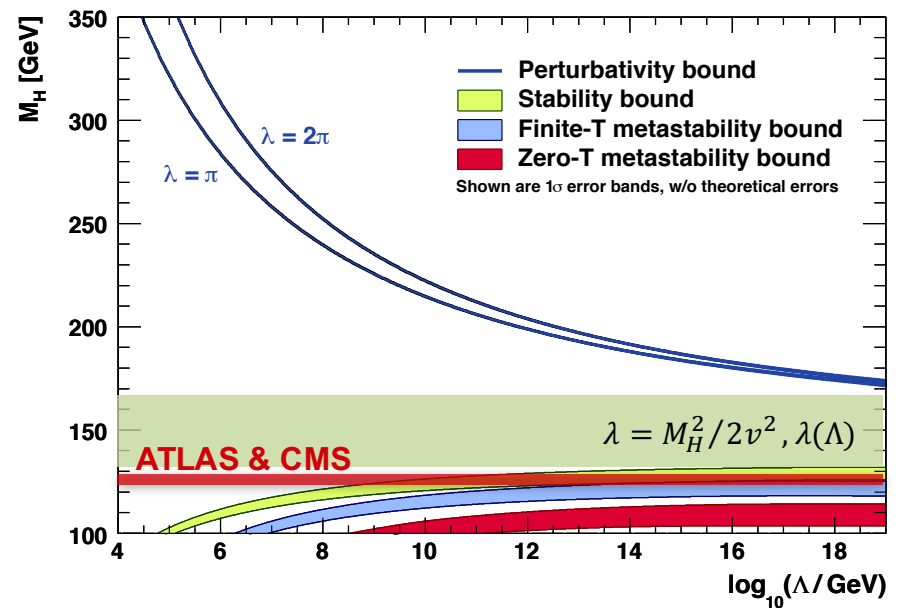
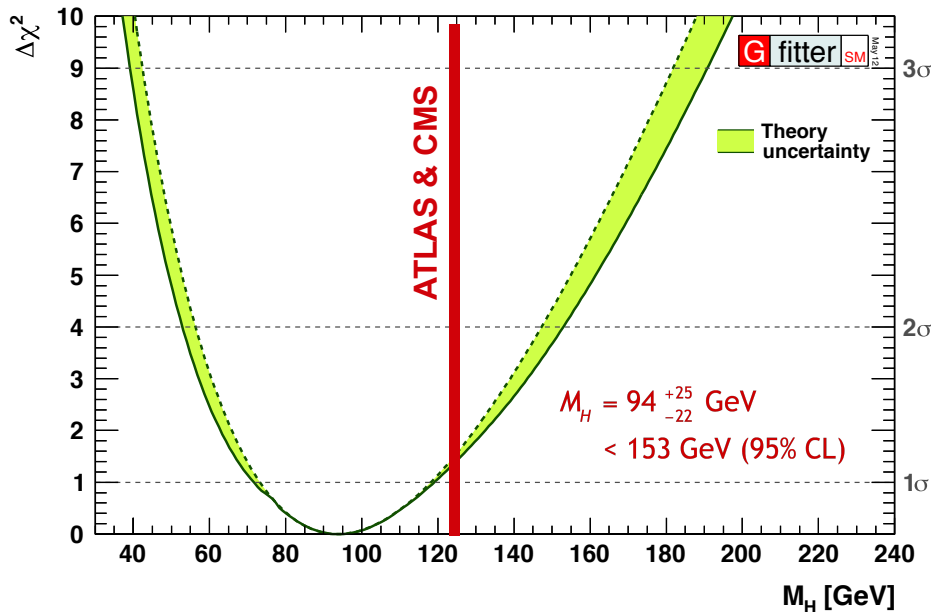
Best current top mass from LHC: $172.44 \pm 0.13 \pm 0.47 \text{ GeV}$ (CMS), $172.84 \pm 0.34 \pm 0.61 \text{ GeV}$ (ATLAS, not yet all 8 TeV)

The Higgs mass value has important implications

Agreement with
electroweak
precision data



~Agreement with perturbativity and
(meta)stability bounds for high SM
cut-off scale Λ



Beautiful flavour and low- p_T physics measurements

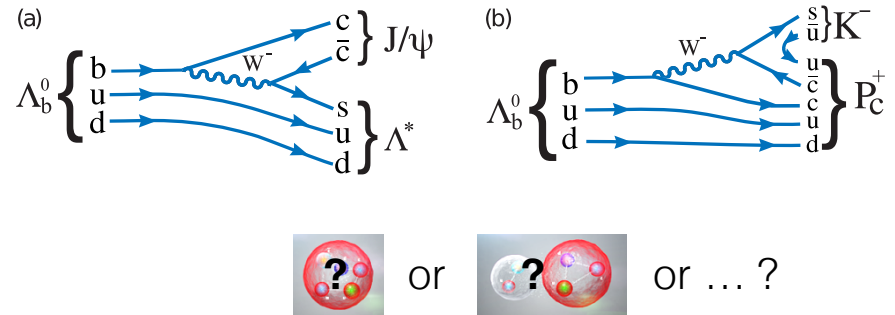
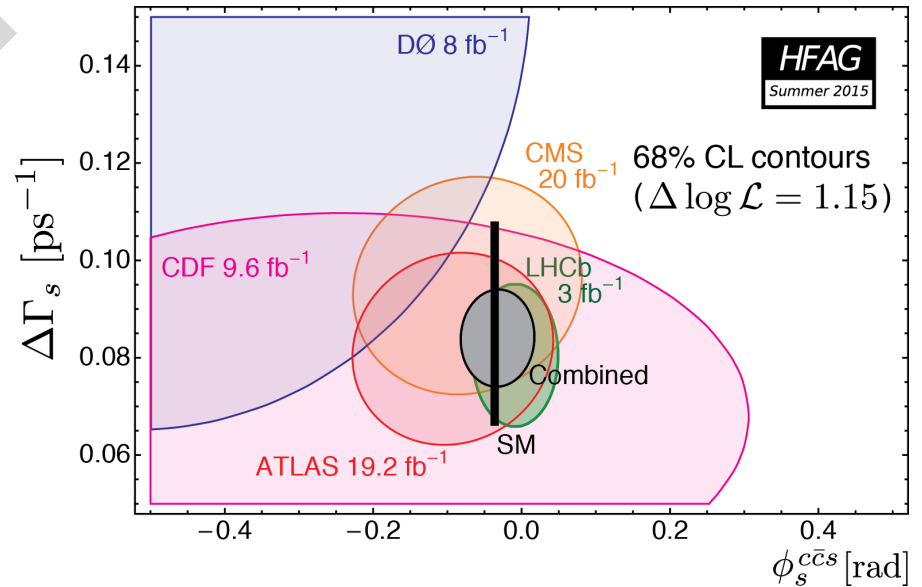
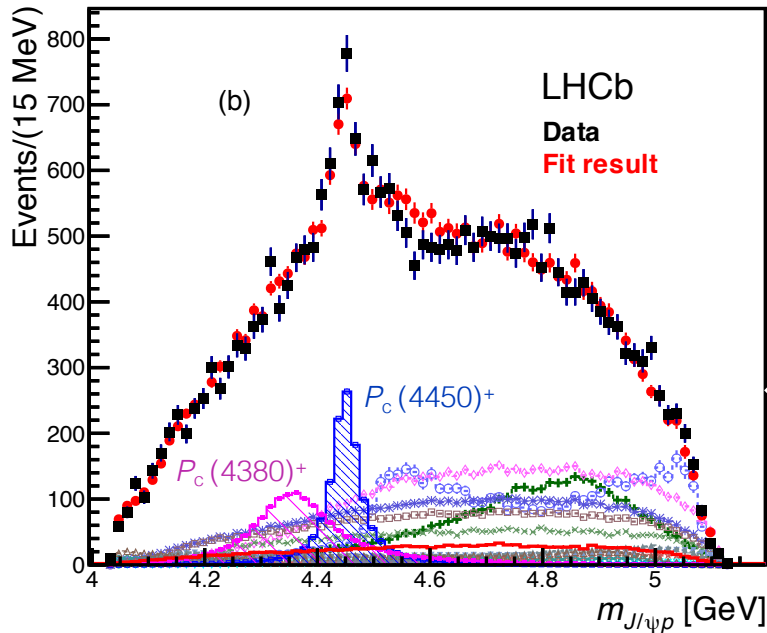
Flurry of results from LHCb [~300 papers to date]

Precision measurement of ϕ_s

[PRL 114, 041801 (2015): $\phi_s = -0.010 \pm 0.039$]

Observation of new states consistent with pentaquarks

[PRL 115, 072001 (2015)]

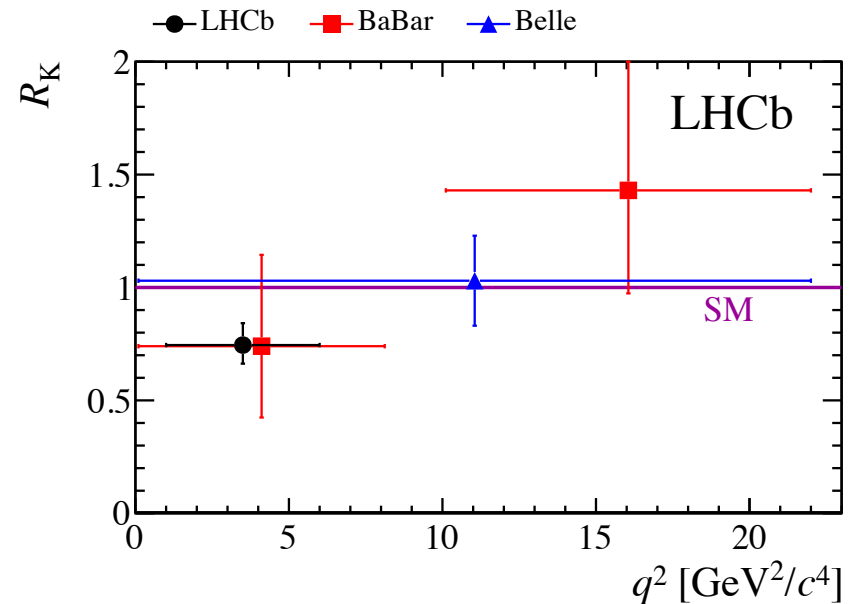
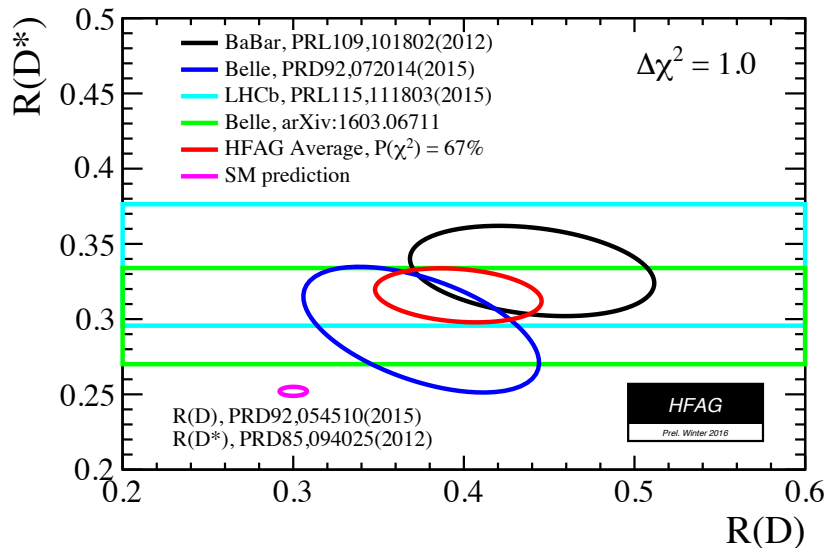


Flavour anomalies ?

B-factories and LHCb measure ratios of semileptonic B decays. Robust SM predictions

$$R_{D^{(*)}} = \frac{\text{BR}(B^0 \rightarrow D^{(*)} \tau \nu)}{\text{BR}(B^0 \rightarrow D^{(*)} \ell \nu)}$$

$$R_K = \frac{\text{BR}(B^+ \rightarrow K^+ \mu \mu)}{\text{BR}(B^+ \rightarrow K^+ e e)}$$



Latest measurement by Belle using semileptonic tagging of recoil B (Moriond EW):

$$R_{D^*} = 0.302 \pm 0.030_{\text{stat}} \pm 0.011_{\text{syst}} \quad [\text{SM: } 0.252 \pm 0.003, 1.6\sigma]$$

New world average by HFAG: $R_{D^*} = 0.316 \pm 0.016 \pm 0.010$ (3.3 σ from SM, combined R_{D^*} & R_D is 4.0 σ)

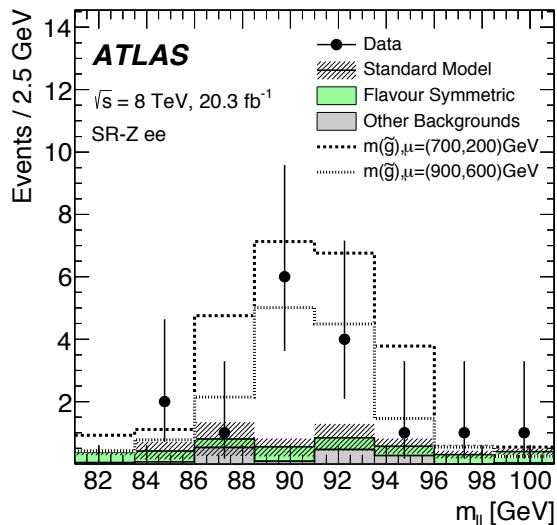
http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html

It seems, however, that the SM can't be all there is

Not unexpectedly*, a few of these searches ended up showing some anomaly, a legacy to be checked in Run-2

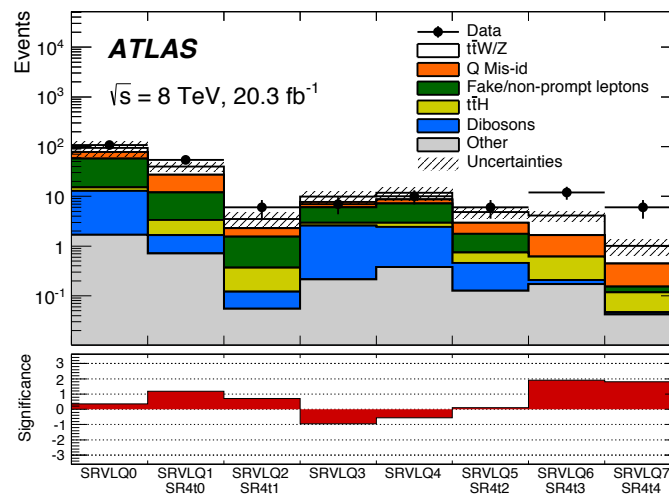
2L(Z) + MET

[ATLAS 1503.03290]



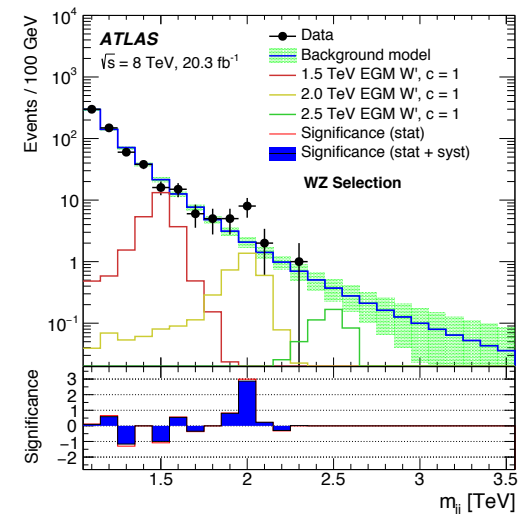
2L(SS) + b-jets + H_T + MET

[ATLAS 1504.04605]



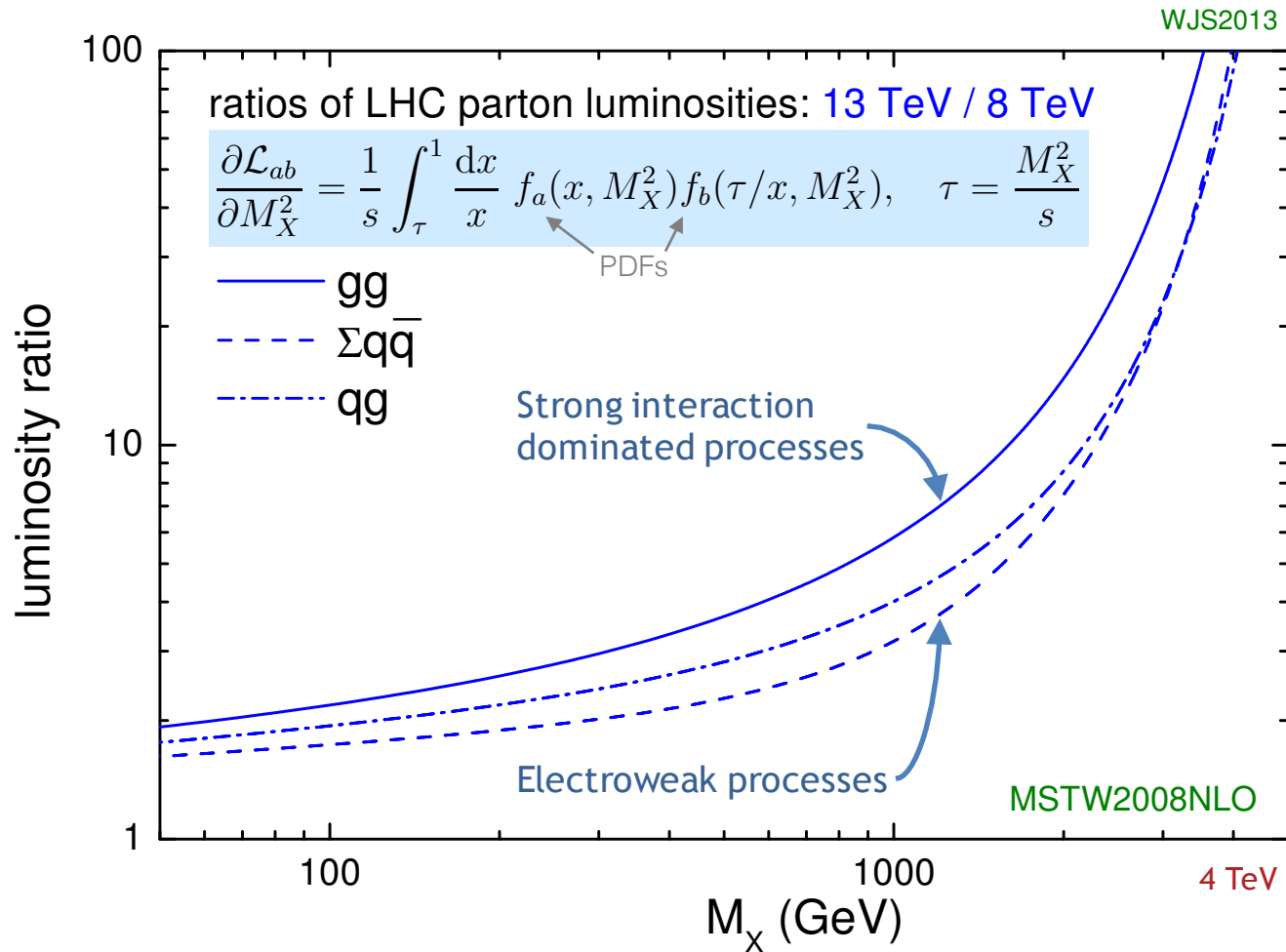
Diboson resonance ($VV' \rightarrow JJ$)

[ATLAS 1506.00962]



*There is a large “look elsewhere effect” (= statistical trials factor) in these searches, hard to quantify

The LHC Run-2: 13 TeV / 8 TeV inclusive “parton luminosity” ratio



Larger cross section increase for gluon induced than for quark induced processes

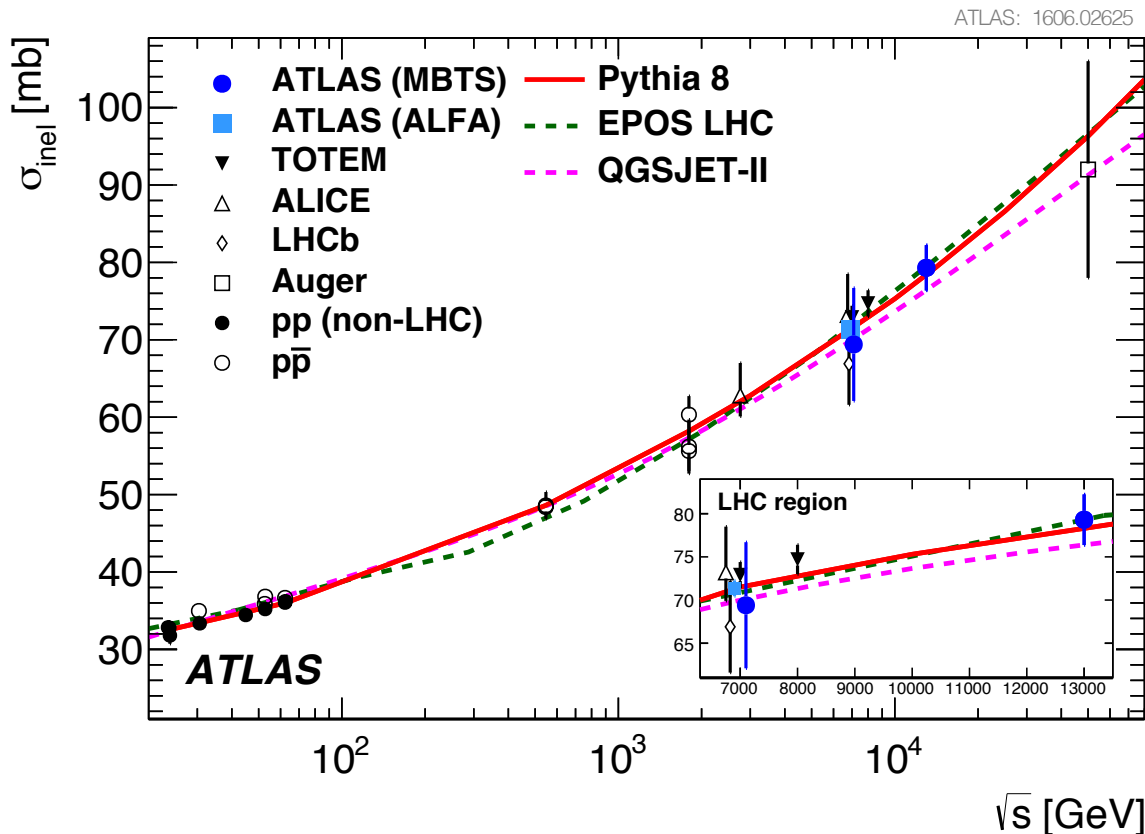
Early Run-2 puts emphasis on searches

Inclusive inelastic cross-section measurement at 13 TeV

Fundamental initial measurement, based on forward scintillators

Measurement in fiducial region $\xi = M_X^2 / s > 10^{-6}$ (M_X largest mass of two proton-dissociation systems)

- Use Minimum Bias Trigger Scintillators (MBTS) with acceptance $2.07 < |\eta| < 3.86$, 4.2M selected events
- Systematic uncertainty fully dominated by luminosity



Measured inclusive inelastic cross section:

$$\sigma_{13 \text{ TeV}} = 79.3 \pm 0.8 \pm 1.3 \text{ (lumi)} \\ \pm 2.5 \text{ (extr) mb}$$

Best measurement of total cross section via elastic scattering and optical theorem:

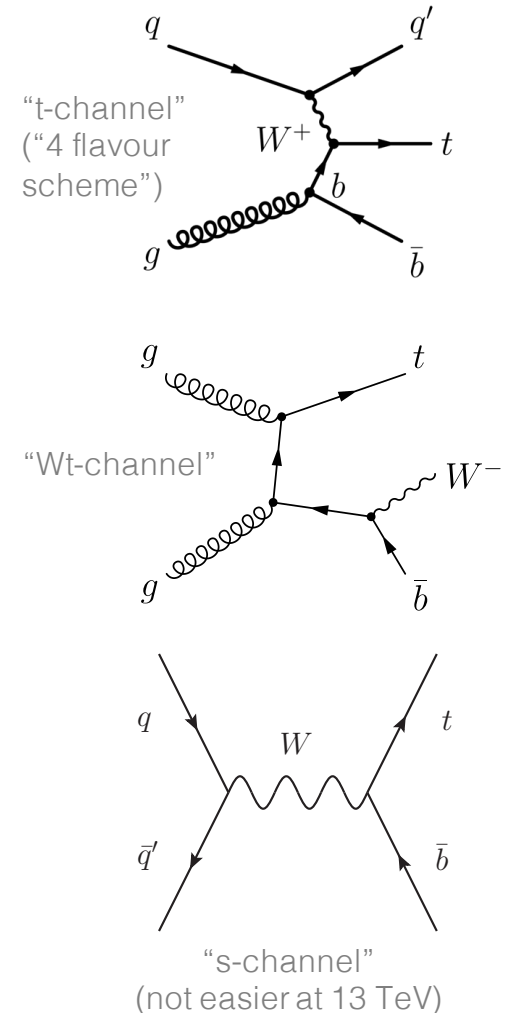
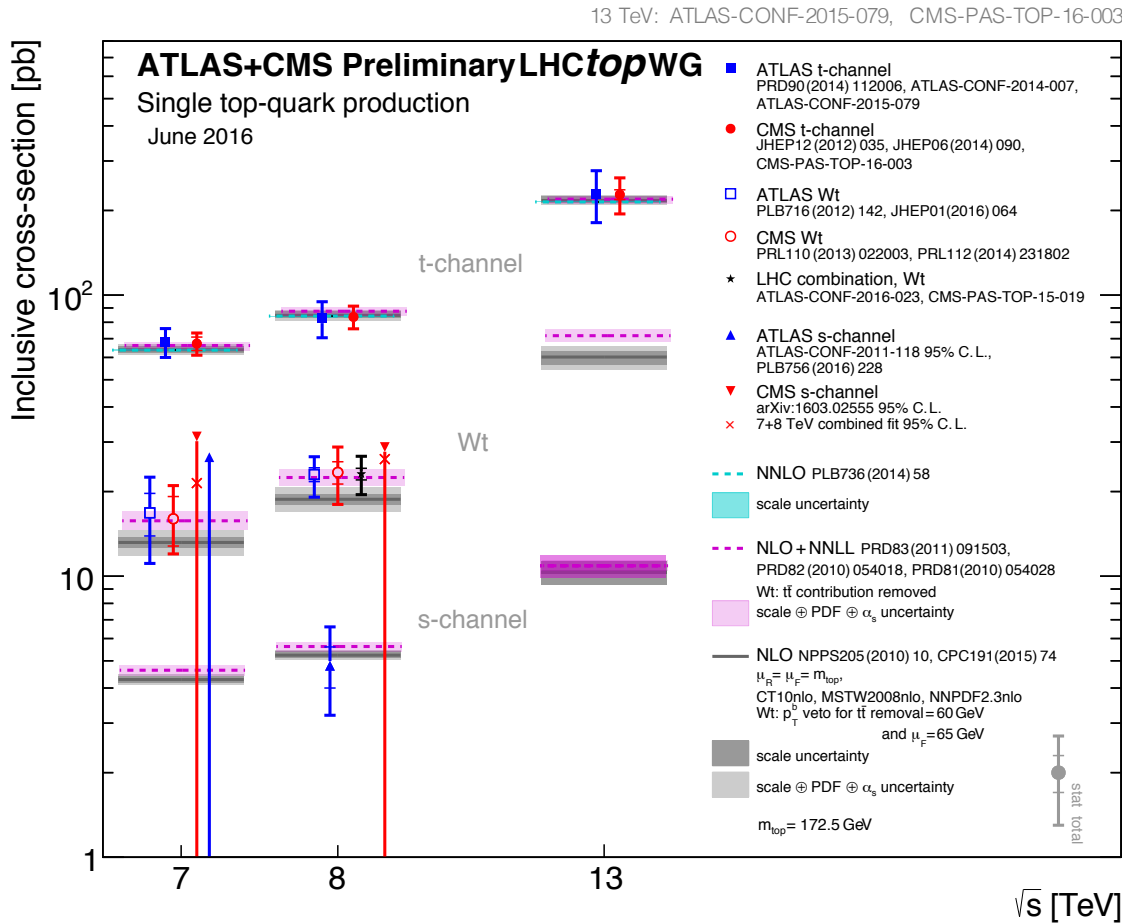
$$\sigma_{\text{tot}} \propto \text{Im } f_{\text{elastic}}(t \rightarrow 0)$$

using dedicated forward devices
(up to 1.4% precision in Run-1,
dominated by luminosity error)

Single top quark production

Increase of cross section by factor of 2.5 (t-channel) over 8 TeV, roughly 1/3rd of tt cross section

ATLAS & CMS have so far released preliminary t-channel measurements at 13 TeV



Tevatron: 6.3 σ , ATLAS Run-1: 3.2 σ

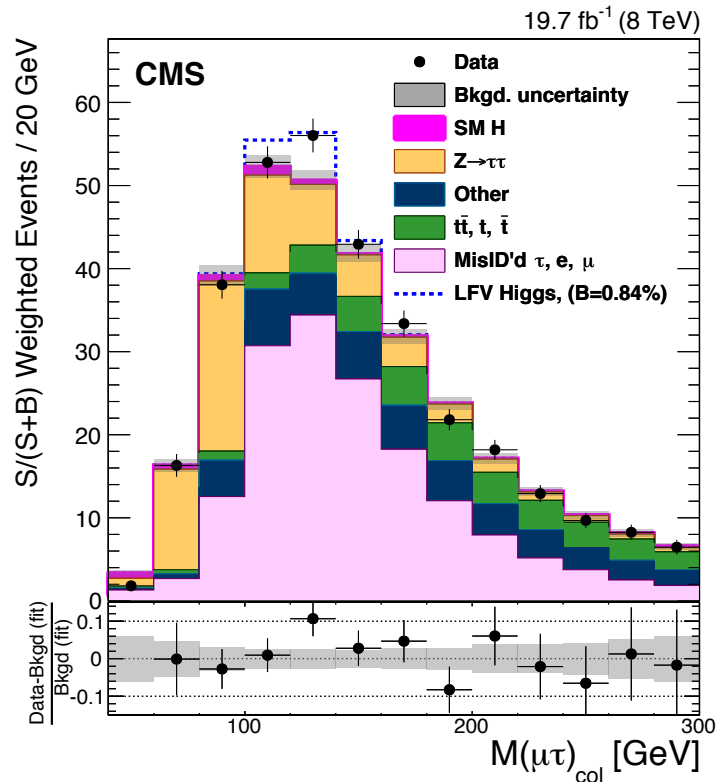
One word on lepton flavour violation in Higgs decays

Both experiments have finalised their Run-1 LFV analyses

While $H \rightarrow \mu e$ is severely constrained from flavour physics, $H \rightarrow \tau\mu$, τe are not ($\sim 10\%$ limits)

CMS released early 2015 a $H \rightarrow \tau\mu$ search finding a slight (2.4σ) excess

Not confirmed by ATLAS in the full Run-1 analysis



$H \rightarrow \tau\mu$:

ATLAS:

$$\text{BR} = 0.53 \pm 0.51\% < 1.43\% \text{ (95\% CL)}$$

CMS:

$$\text{BR} = 0.84^{+0.39}_{-0.37} \% < 1.51\% \text{ (95\% CL)}$$

$H \rightarrow \tau e$:

ATLAS:

$$\text{BR} = -0.3 \pm 0.6\% < 1.04\% \text{ (95\% CL)}$$

One word on lepton flavour violation in Higgs decays

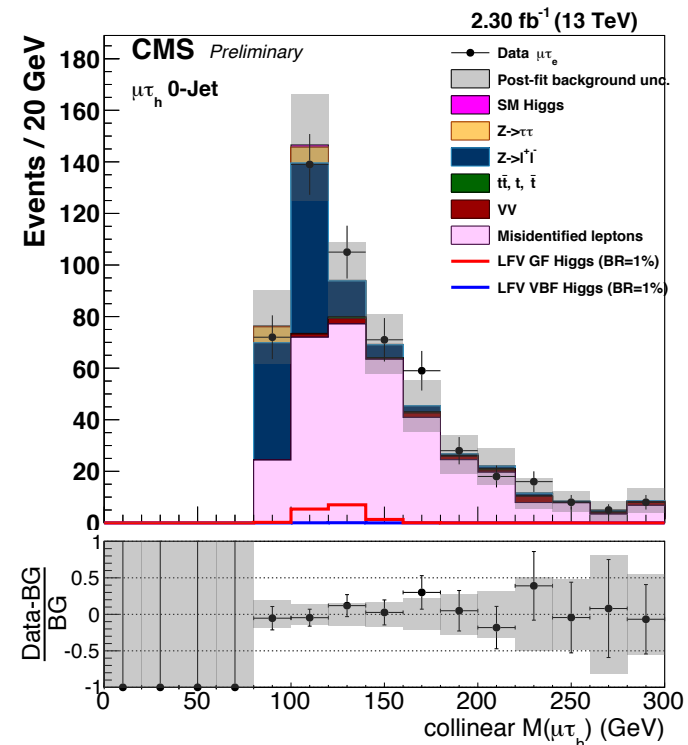
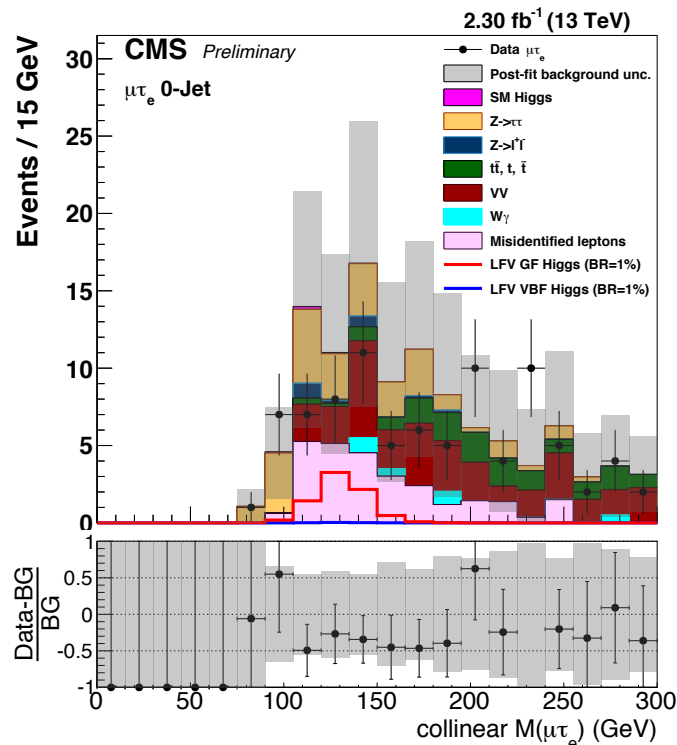
Both experiments have finalised their Run-1 LFV analyses

New preliminary result with 13 TeV from CMS [CMS-PAS-HIG-16-005]

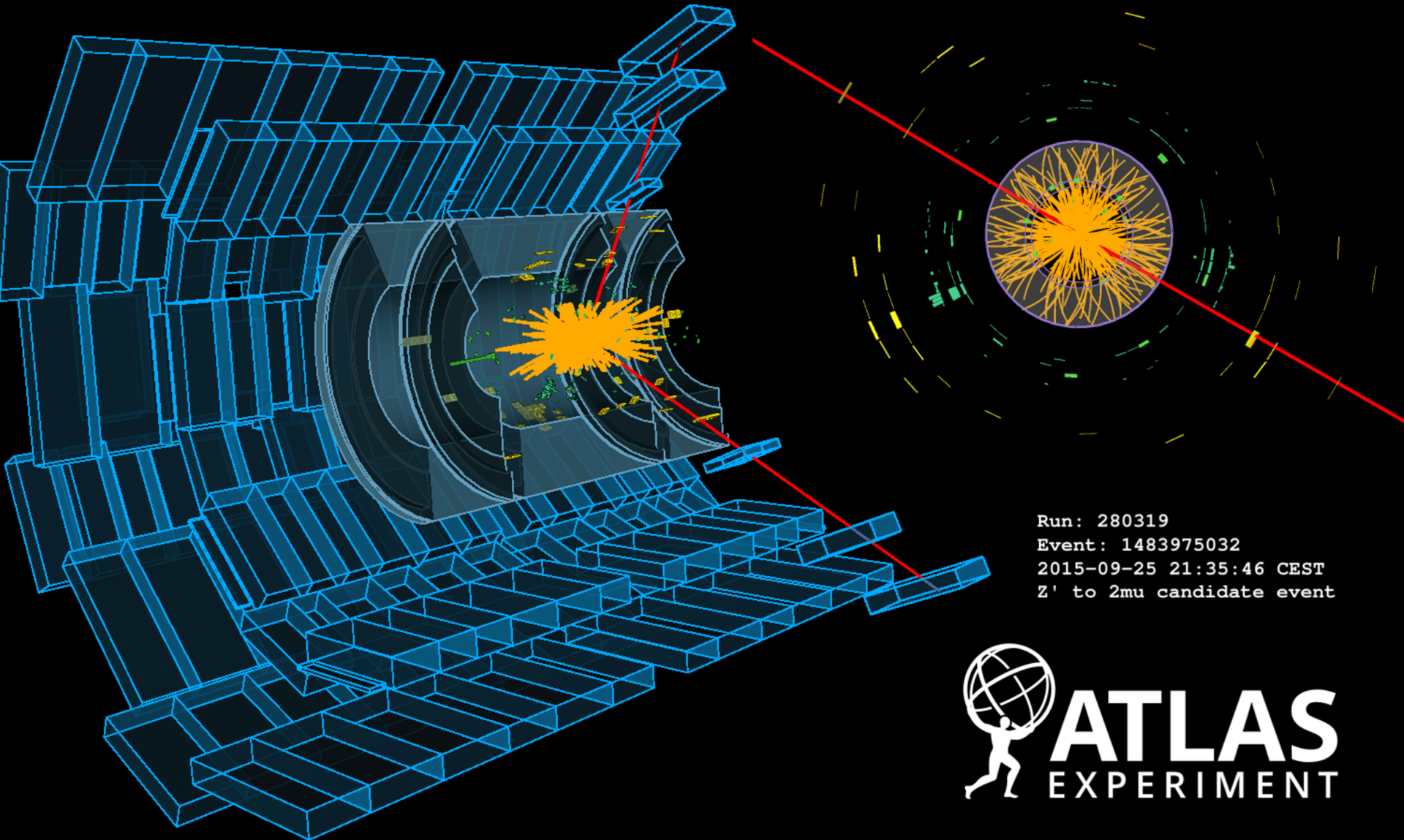
Six categories considered: $(\mu\tau_h, \mu\tau_e) \times (0, 1, 2 \text{ jets})$

No significant excess, combined limit: $BR = -0.8 \pm 0.8 \% (<1.2\% \text{ at } 95\%CL)$

Limit on non-diagonal Yukawa couplings: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \times 10^{-3}$



Highest mass dimuon event seen by ATLAS: $m_{\mu\mu} = 1.4 \text{ TeV}$

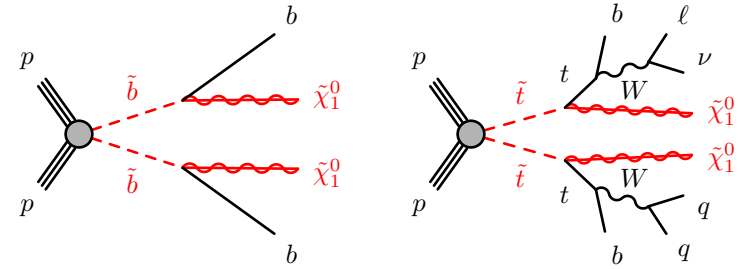


Third generation quark partners

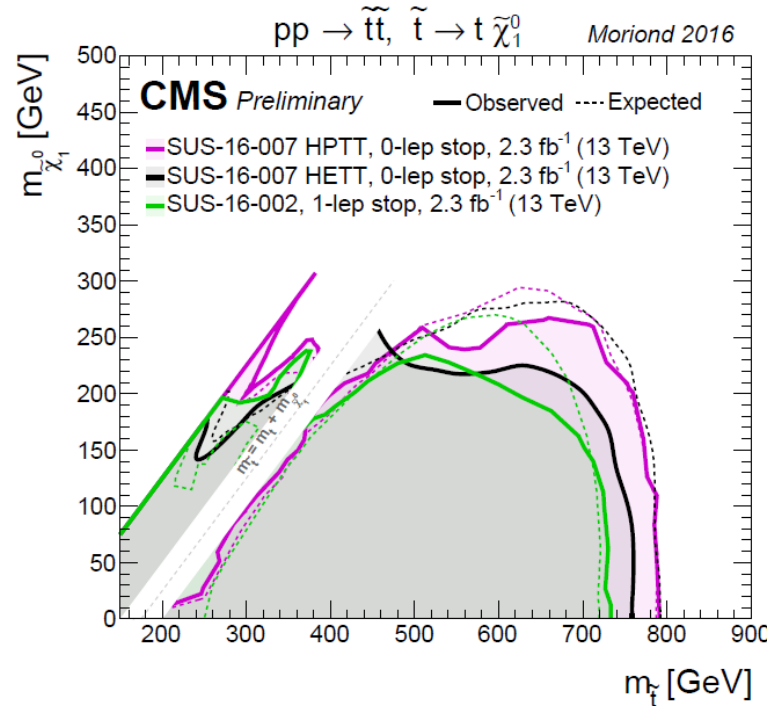
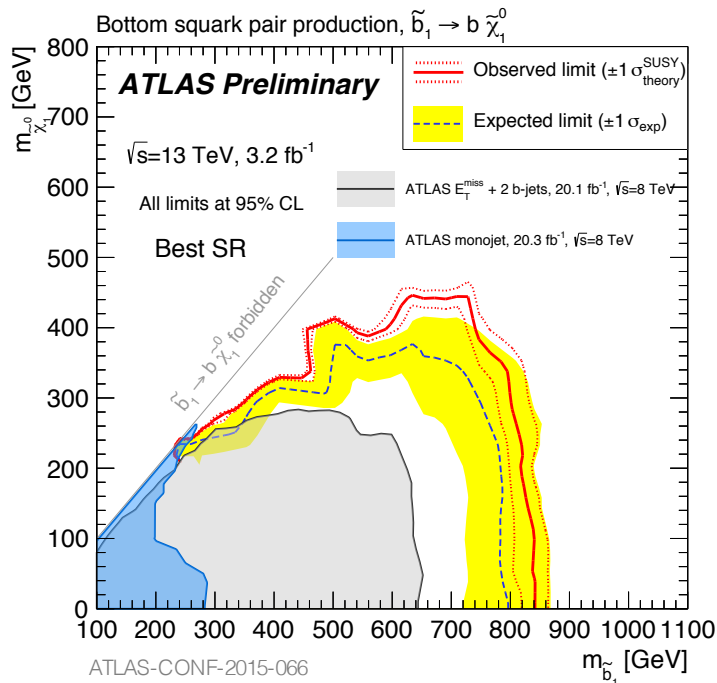
Top-quark largest contributor to Higgs corrections

SUSY stop and sbottom may be the lightest sfermions. They have low cross-sections, so run-2 luminosity just enough to increase sensitivity

Vector-like quarks* (VLQ) singly or pair produced decay to bW , tZ or tH . Also exotic $X_{5/3} \rightarrow tW$ possible



Signatures are b-jets, jets, possibly leptons and MET



Total of 10
Run-2 analyses

No anomaly
seen

Sensitivity
improved
over Run-1

Similar for
VLQ searches

*Hypothetical fermions that transform as triplets under colour and who have left- and right-handed components with same colour and EW quantum numbers

Searches in unconventional final states

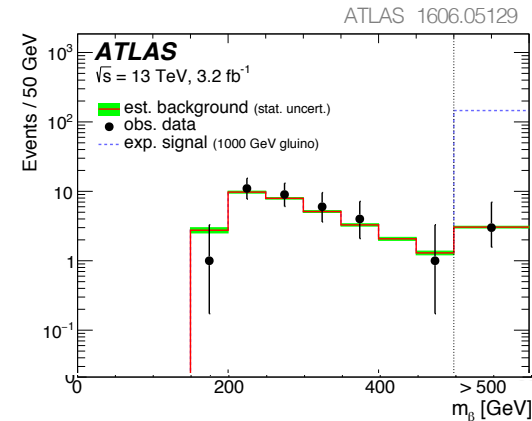
ATLAS & CMS also started to look for long-lived massive particle at 13 TeV

Long-lived particles in many new physics models

(due to: large virtuality, low coupling, mass degeneracy).

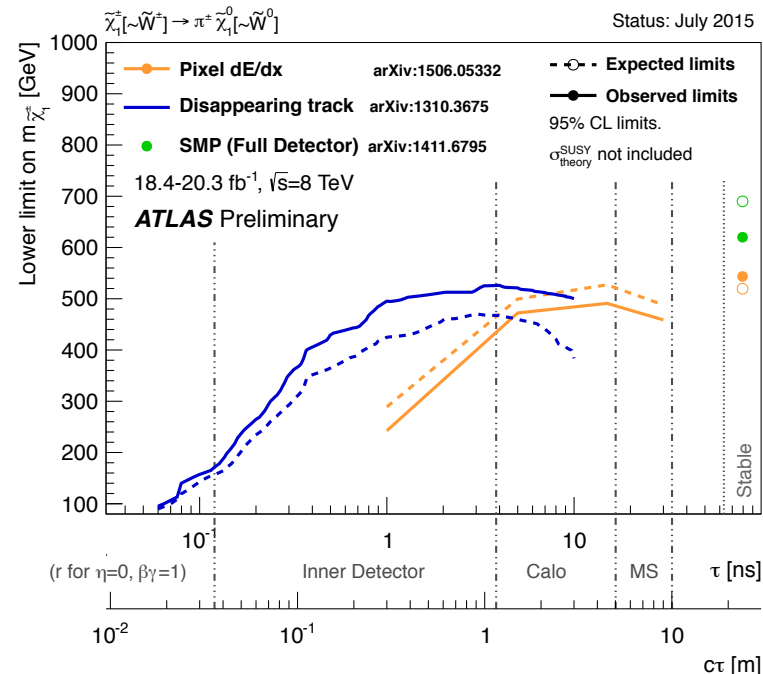
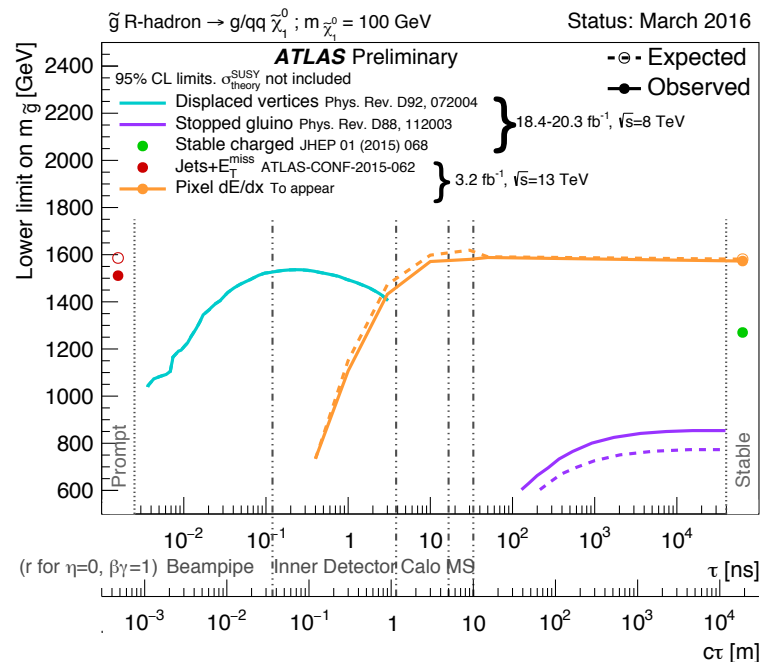
Multitude of signatures, some requiring dedicated triggers, most requiring dedicated analysis strategies.

ATLAS and CMS have so far looked into heavy long-lived SUSY particles at 13 TeV



Particle mass from velocity via time-of-flight measured in Tile calorimeter

Similar analysis from CMS uses tracker dE/dx and TOF from muon system



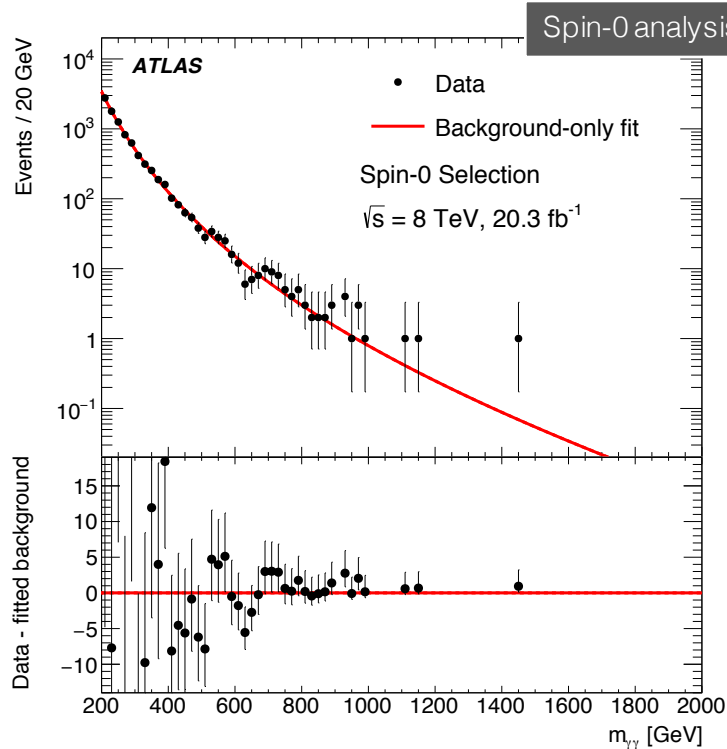
Summaries of mass limits versus lifetime of new particle

Diphoton resonance searches: **ATLAS**

Dedicated searches for a spin-0 and a spin-2 diphoton resonance

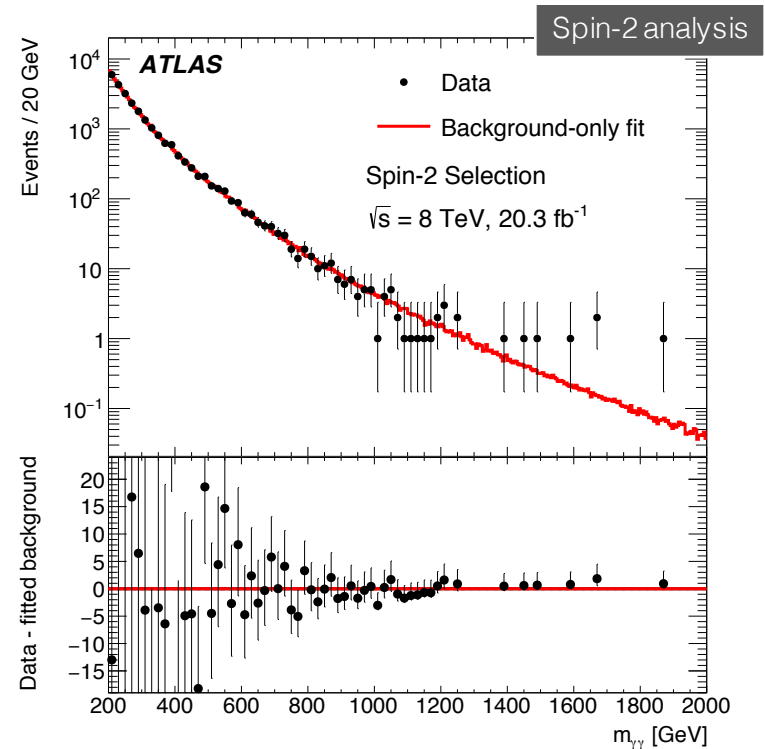
ATLAS 1606.03833

Compatibility with 8 TeV result (slight reanalysis: latest e/γ calibration, 13 TeV analysis method)



P-value at 750 GeV, $\Gamma \sim 6\%$ of mass: 1.9σ

Compatibility: gg = 4.7 / qq = 2.7 scaling: 1.2σ / 2.1σ



No excess at 750 GeV

Compatibility: gg / qq scaling: 2.7σ / 3.3σ