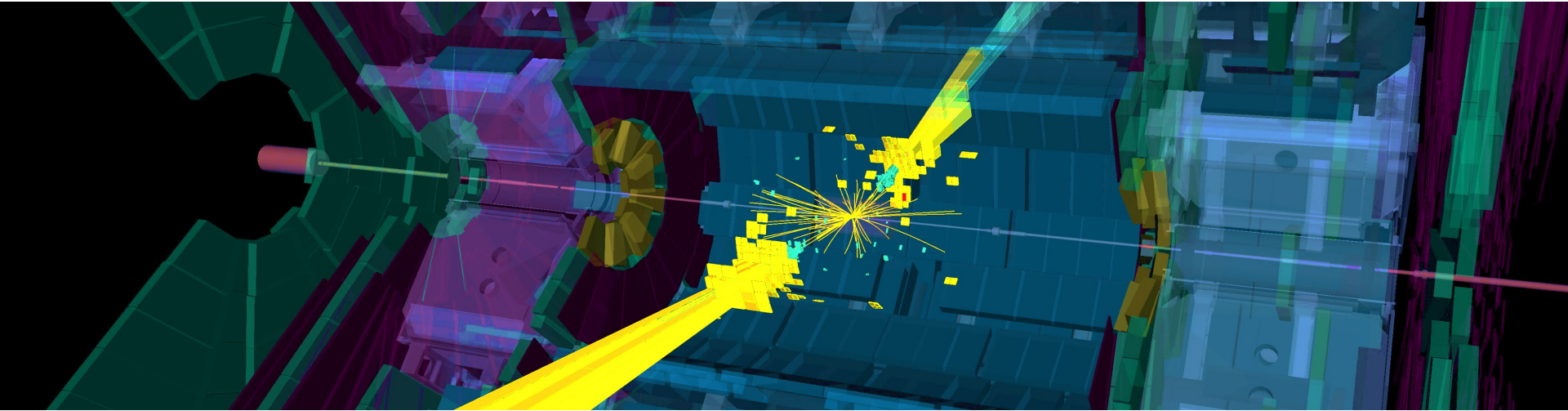


Particle Physics at the dawn of a new high-energy frontier

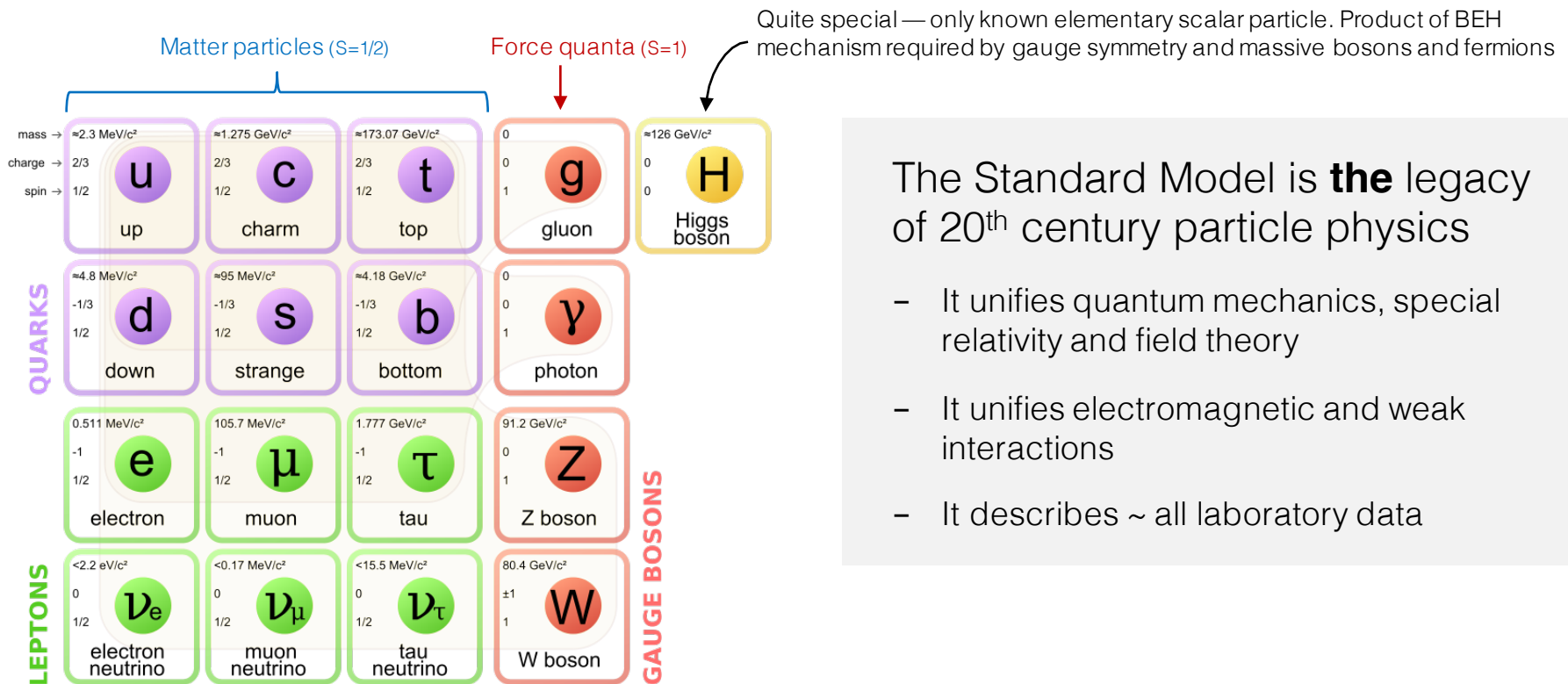


Andreas Hoecker (CERN)

Physikalisches Kolloquium

Max Planck Institut für Physik, München, Dec 6th 2016

The LHC at CERN probes nature at the smallest distances ever explored on Earth to study and improve our current knowledge of matter and force as it is encoded in the SM of particle physics.

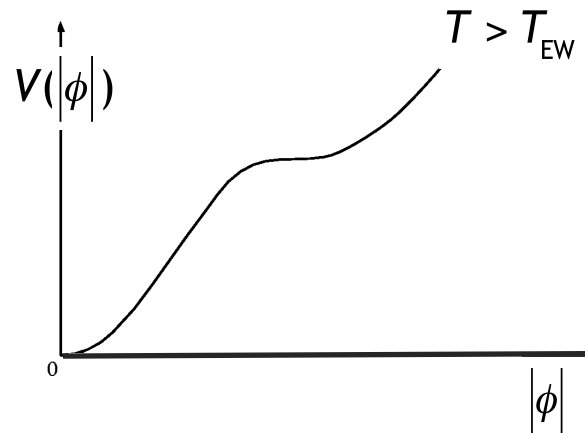


The Standard Model is **the** legacy of 20th century particle physics

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

BEH Potential

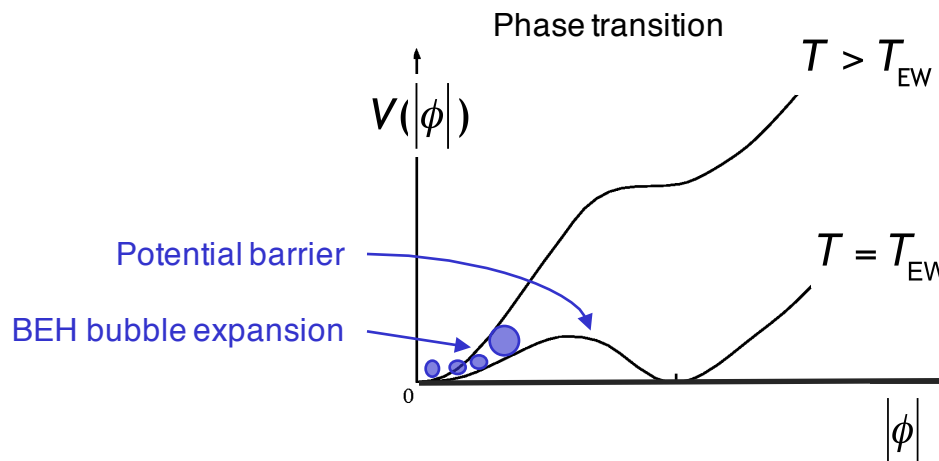
The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)



$V(T)$ dependence mainly governed by top loop, adding a cubic ϕ^3 term

BEH Potential

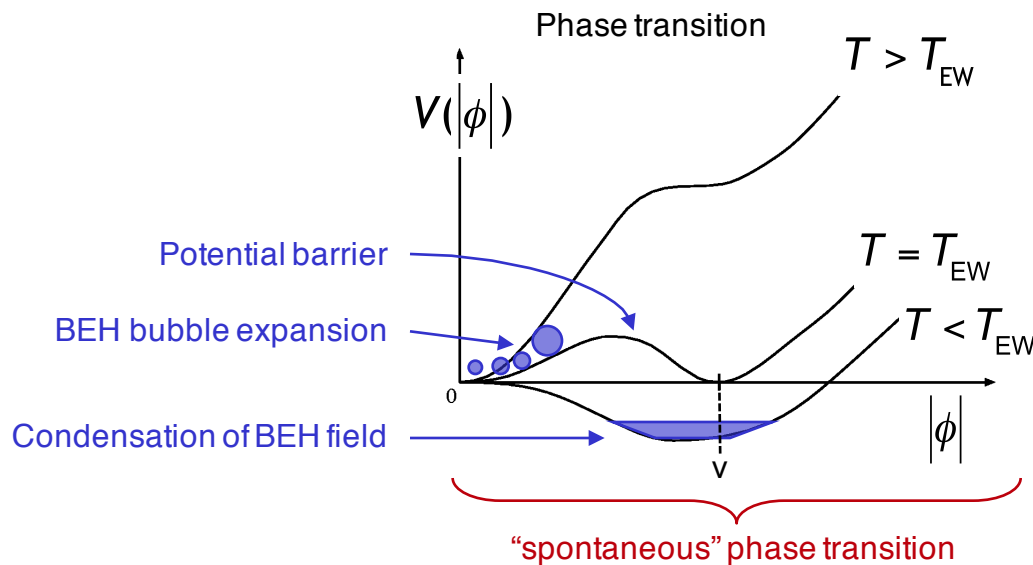
The early universe, at temperature $T > T_{EW}$, was in a symmetric phase ($|\phi_{min}| = 0$)
A phase transition at $\sim T_{EW}$ ($\sim$ several 10^{-11} s after big bang, causal domain of few cm) led to $|\phi_{min}| > 0$



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

BEH Potential

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 $|\phi_{min}| > 0$



The condensed field fills all space and time but without orientation as it has no spin. (One might view it as a Lorentz-invariant ether creating a vacuum viscosity)

Tree-level BEH potential at $T=0$:

$$V(\phi) = \mu_{<0}^2 |\phi|^2 + \lambda |\phi|^4 + Y^{ij} \psi_L^i \psi_R^j \phi$$

(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 Higgs boson

The SM predicts all its properties,
except for its mass

What was known about the Higgs before its discovery ?

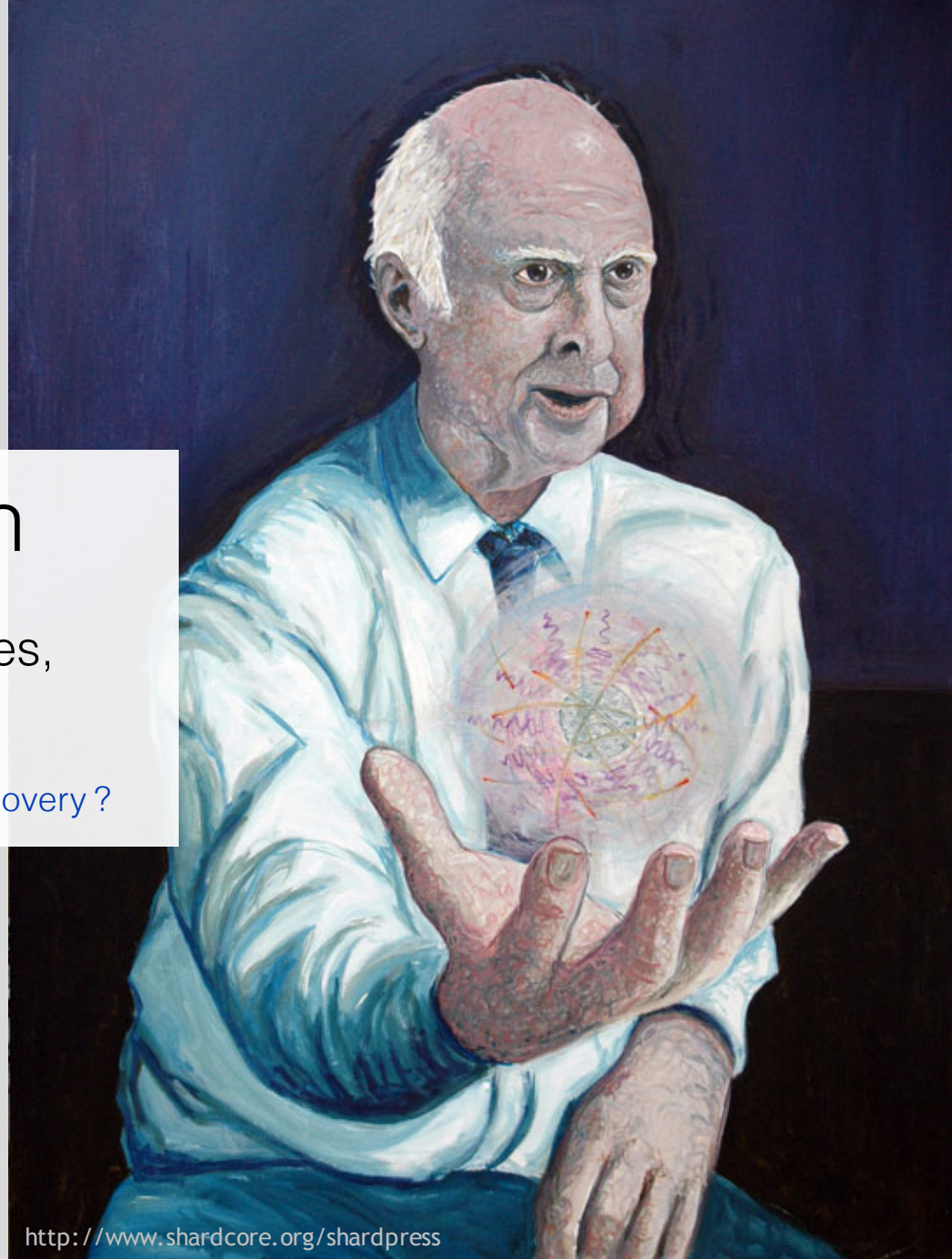
Full references for mechanism:

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.



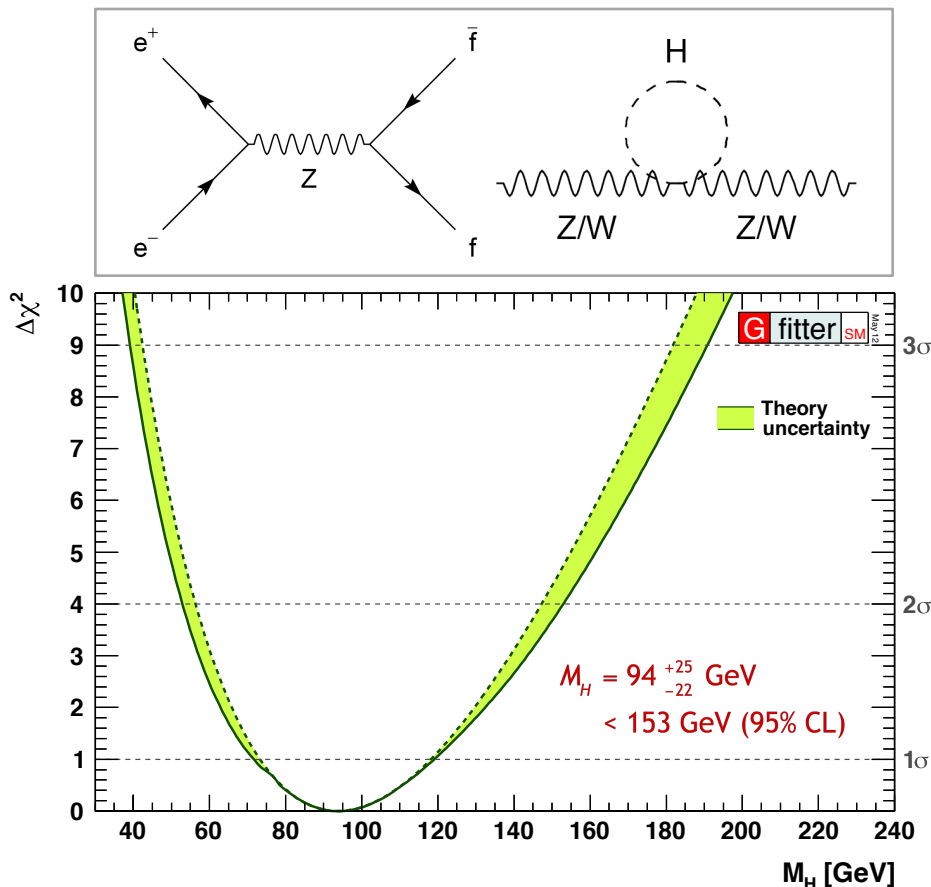
<http://www.shardcore.org/shardpress>

What was known about the Higgs (mass) before the LHC ?

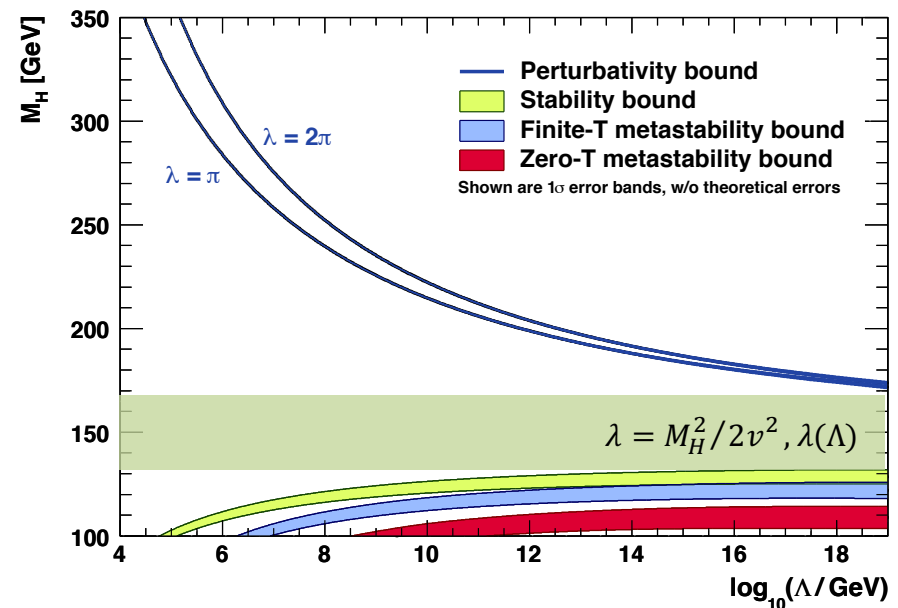
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Today's Tevatron exclusion (2013): $149 < m_H < 182$ GeV

Constraint from SM fit to EW precision data:



Perturbativity and stability bounds versus SM cut-off scale Λ :





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

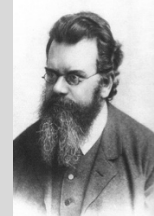


Lawrence
(First cyclotron provided 80 keV proton acceleration)

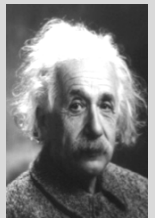
Particles accelerators:

- 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

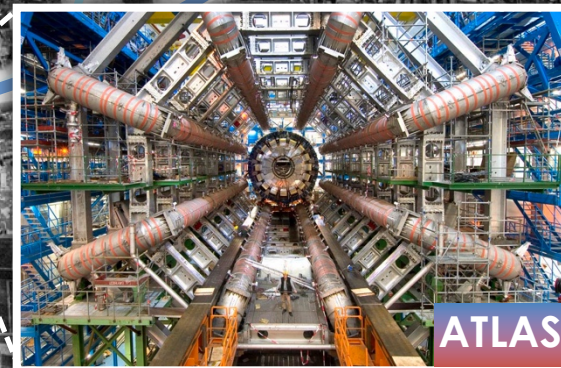
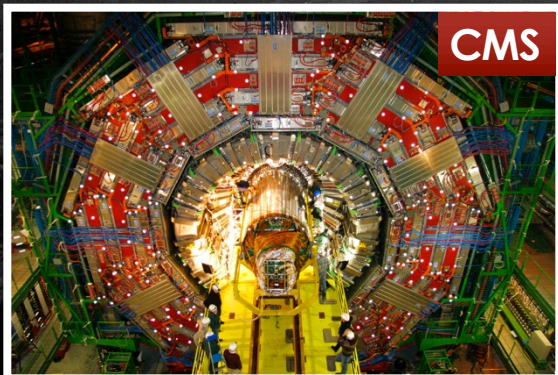
LHC
control
room

CERN (Prévessin site)

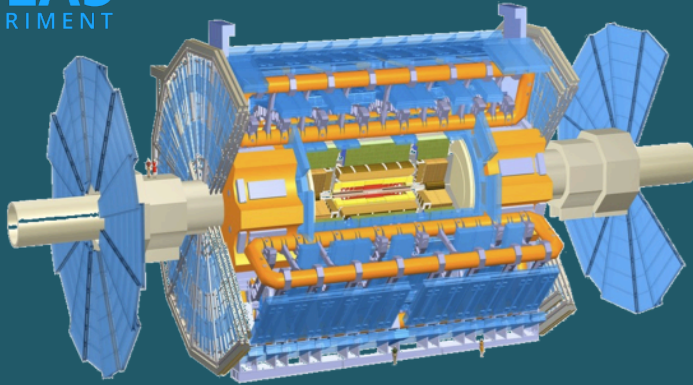
SPS ring:
7 km circumference

CERN (Meyrin site)

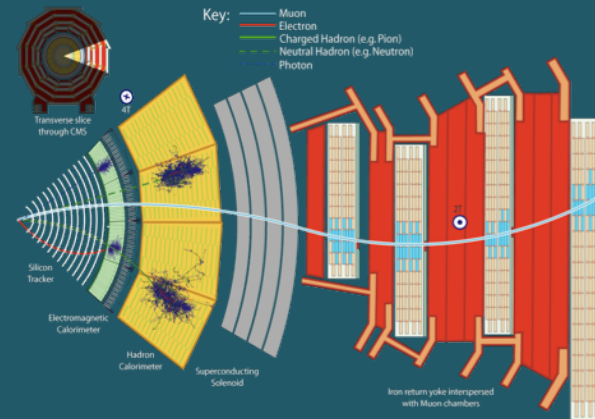
~20 minutes are required to accelerate the protons in the LHC from 450 GeV to 7 TeV



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

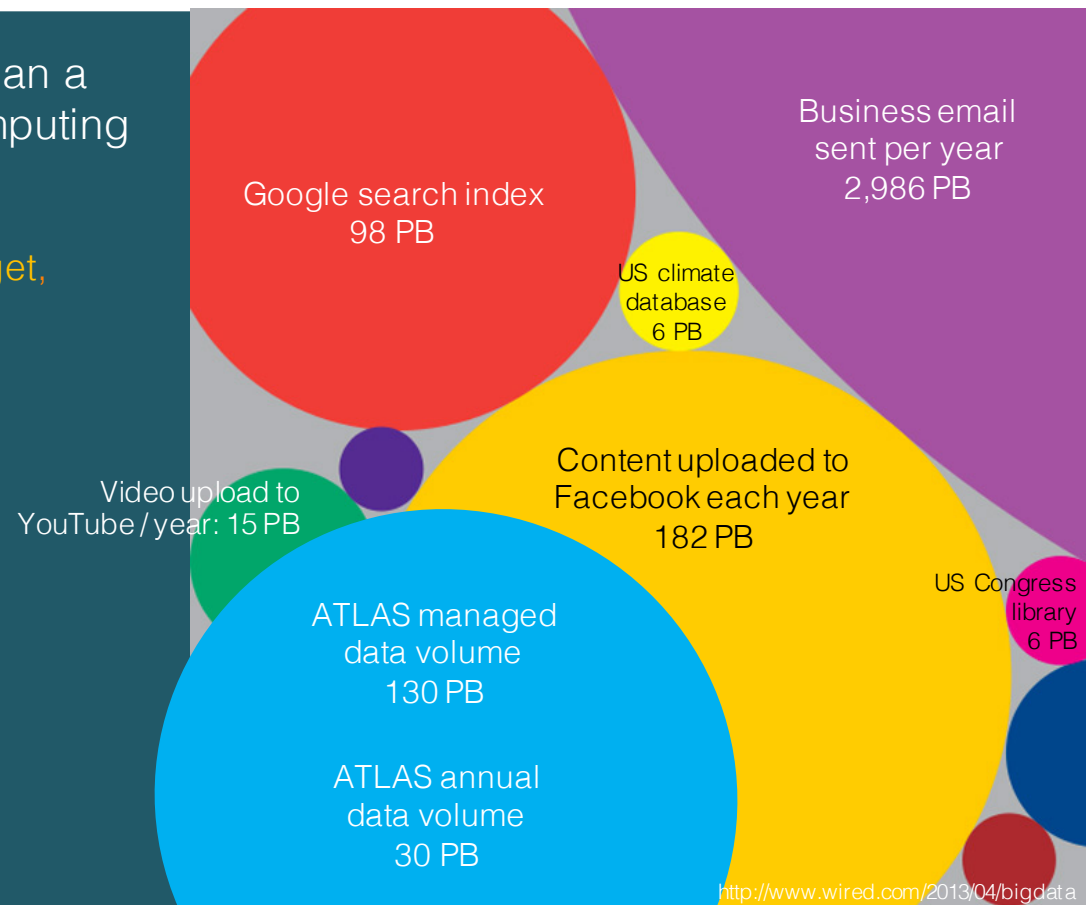
Both: excellent hermeticity – very few “cracks”

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 !



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

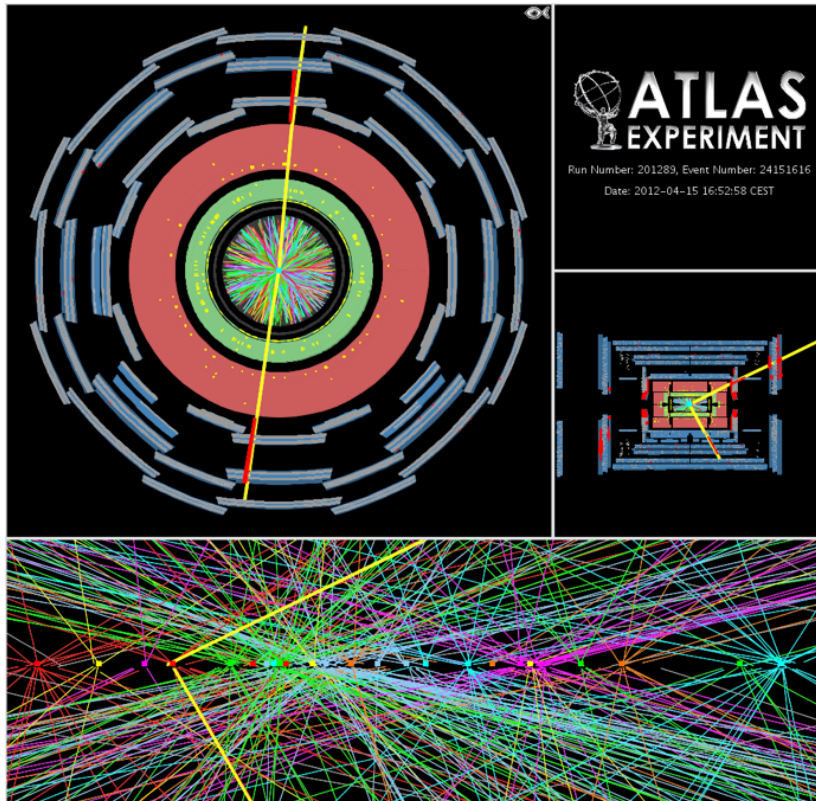
$$L = \frac{f_{\text{rev}} n_{\text{bunch}} N_p^2}{4\pi \sigma_x \sigma_y} \cdot R(\theta_c, \varepsilon, \beta^*, \sigma_z) = \frac{1}{4\pi} \cdot f_{\text{rev}} n_{\text{bunch}} N_p \cdot \frac{N_p}{\varepsilon_n} \cdot \frac{\gamma}{\beta^*} \cdot R(\theta_c, \varepsilon, \beta^*, \sigma_z)$$

Reduction factor

Crossing angle (0.3 mrad) and
“hourglass effect” ($\sigma_z \sim 4\text{--}6\text{ cm}$)



High luminosity comes at price of pileup interactions



Pileup interactions

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

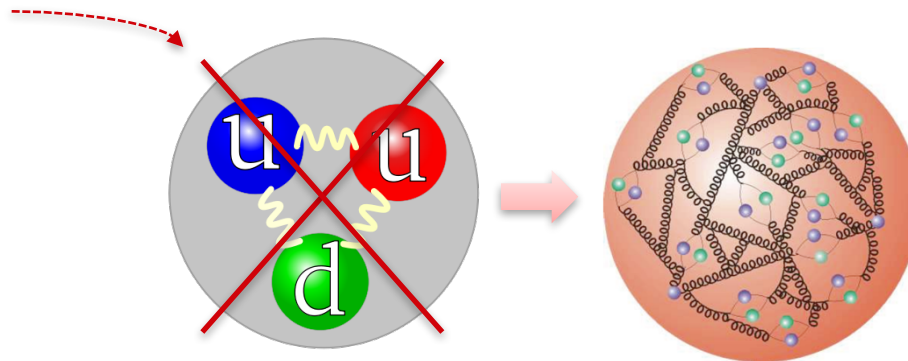
$$\mu = \frac{\sigma_{\text{inel}} \cdot L}{f_{\text{rev}} \cdot n_{\text{bunch}}} \approx \frac{80 \text{ mb} \cdot 10 \text{ nb}^{-1} \text{s}^{-1}}{11245 \text{ s}^{-1} \cdot 2808} = 25$$

- 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**

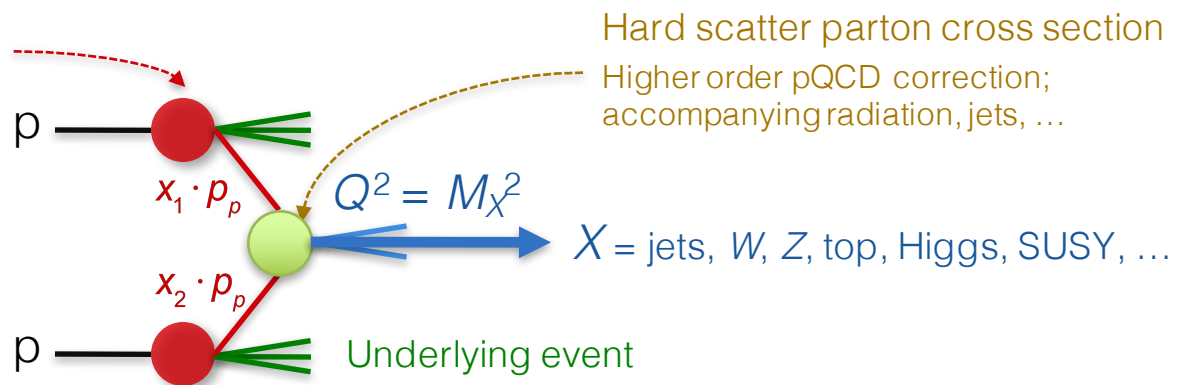
Parton distribution functions
Representing structure of proton,
extracted using experimental
data and QCD properties



Proton–Proton Collisions

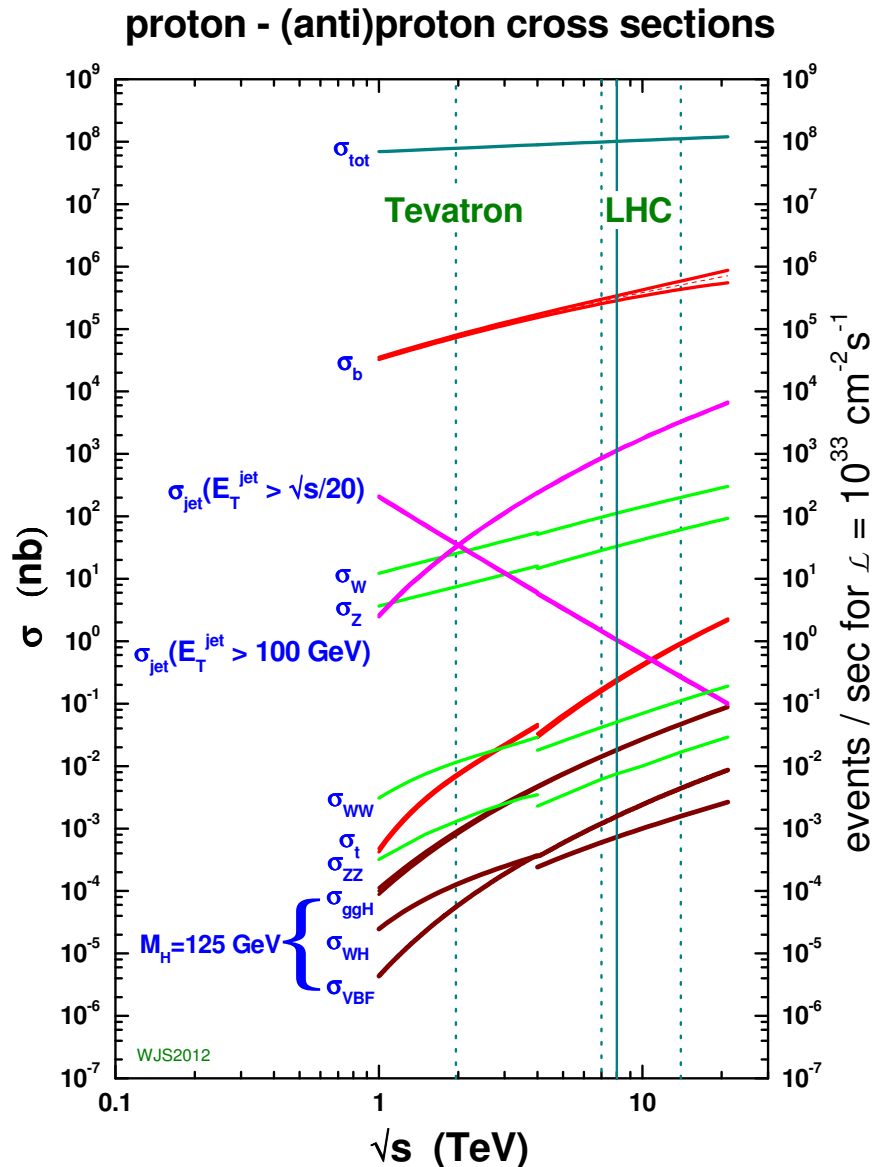
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Parton distribution functions
Representing structure of proton,
extracted using experimental
data and QCD properties



- 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



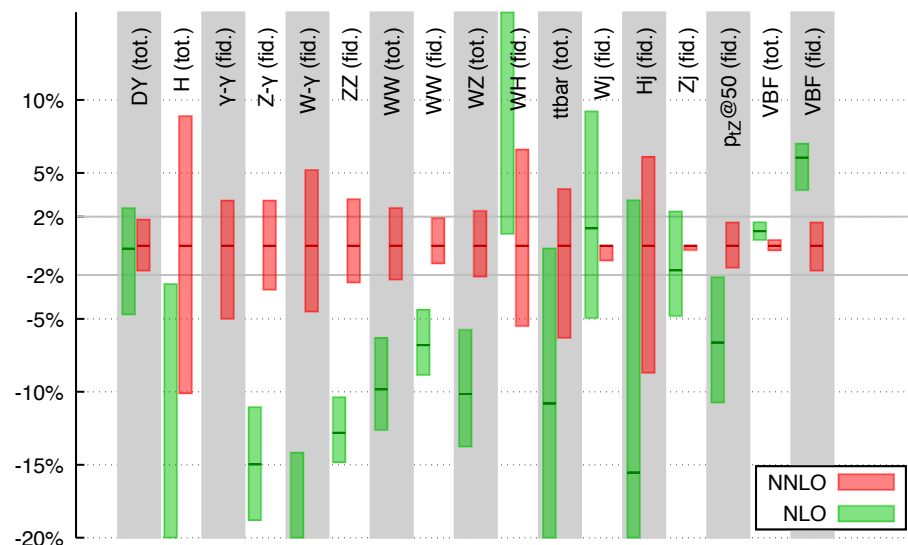
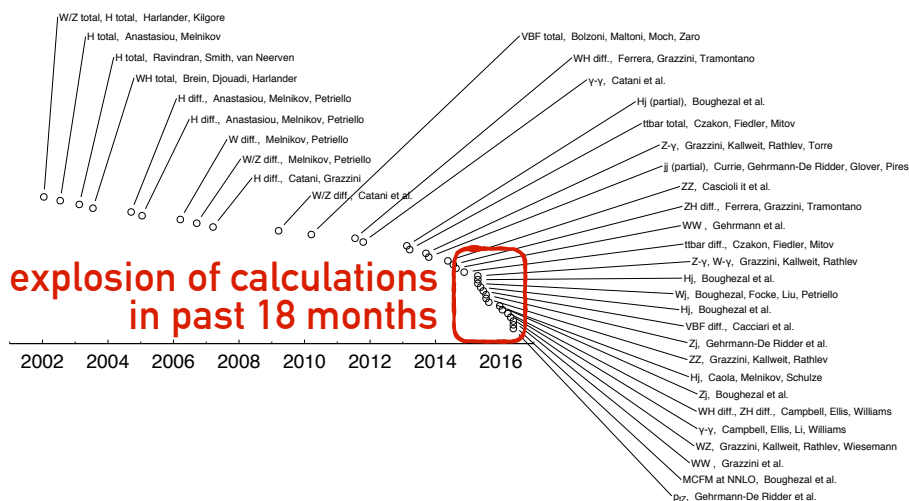
- Cross-section fully dominated by inelastic strong interaction
“minimum bias” events
- Detectors cannot record 40 MHz event rate* (each event $\sim 2 \text{ MB}$ size $\rightarrow 80 \text{ TB / second}$)
- Online custom hardware and software “triggers” reduce rate to filter out events with a million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

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

Theoretical cross-sections and uncertainties

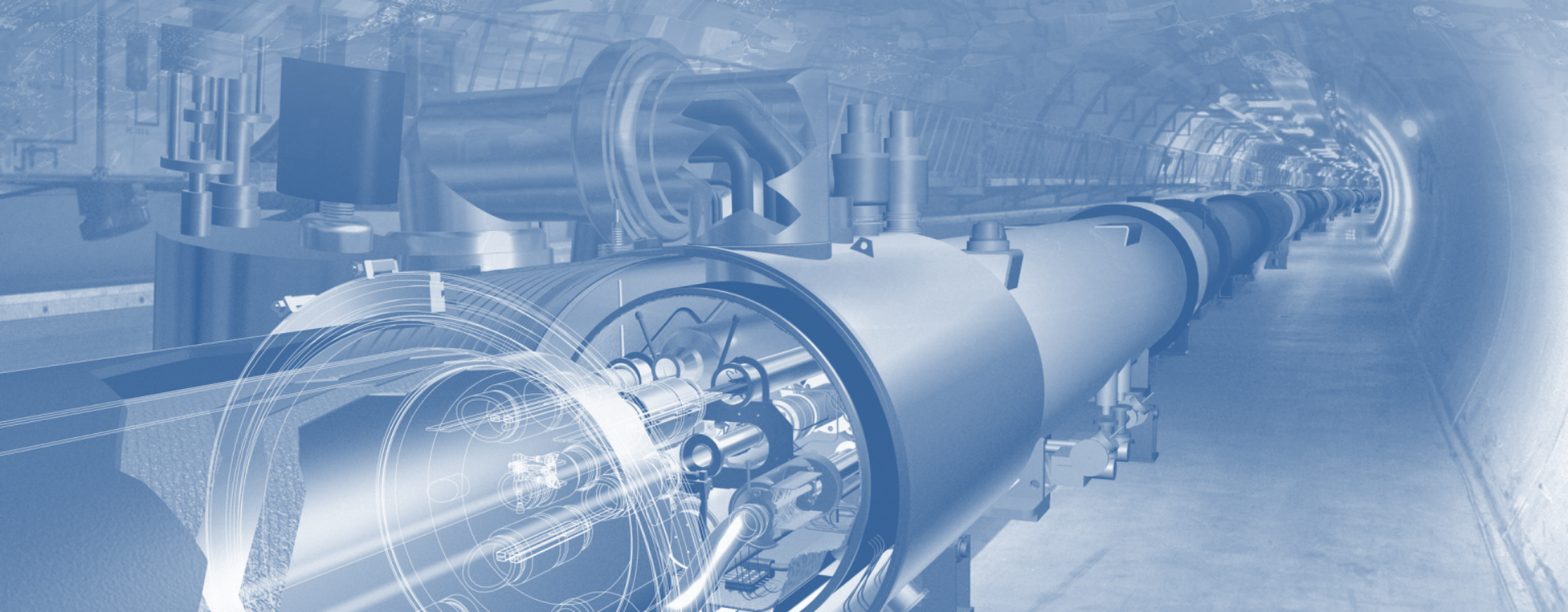
Progress in theoretical calculations*

NNLO revolution



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 !

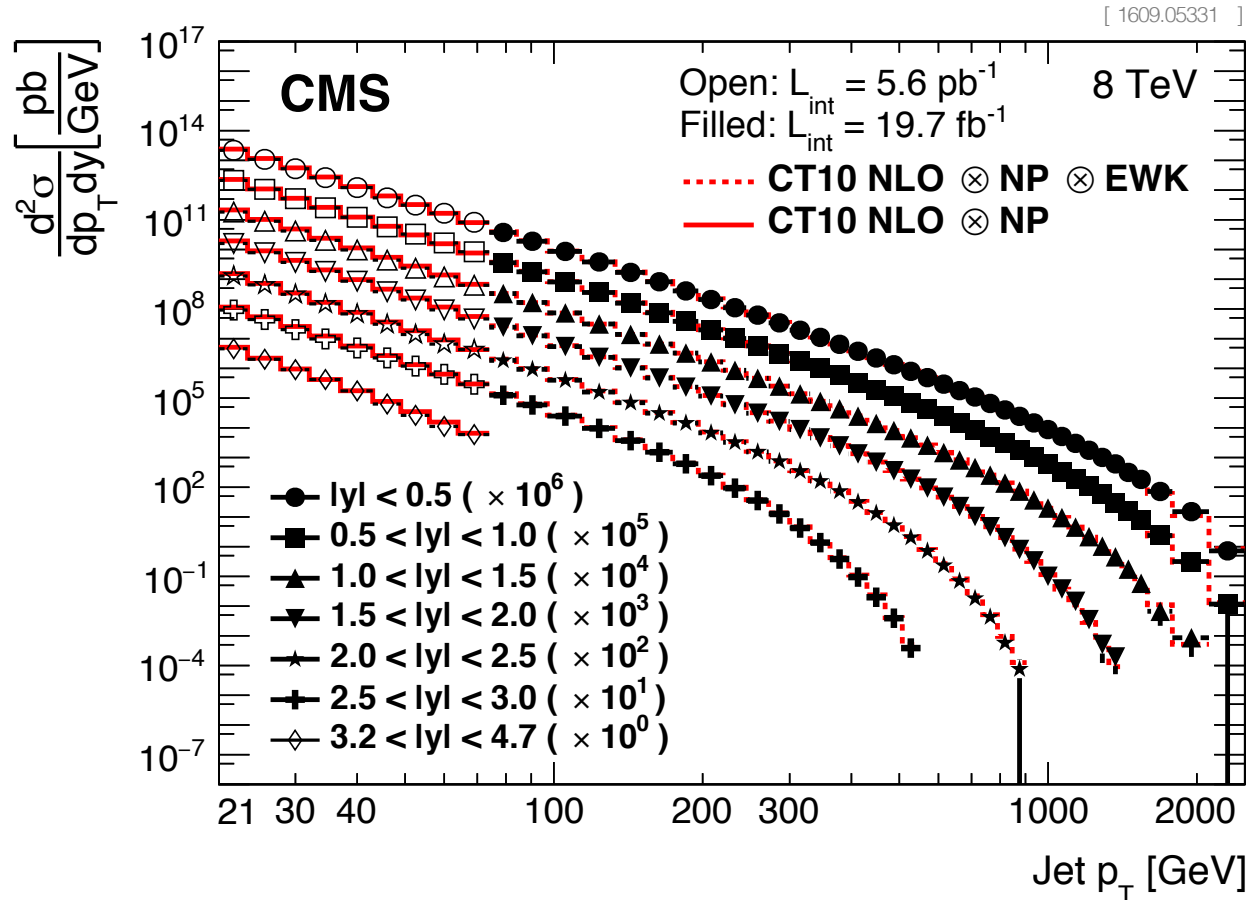


The LHC Run-1: 7 & 8 TeV pp, 5 & 20 fb⁻¹

A brief history of selected highlights

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

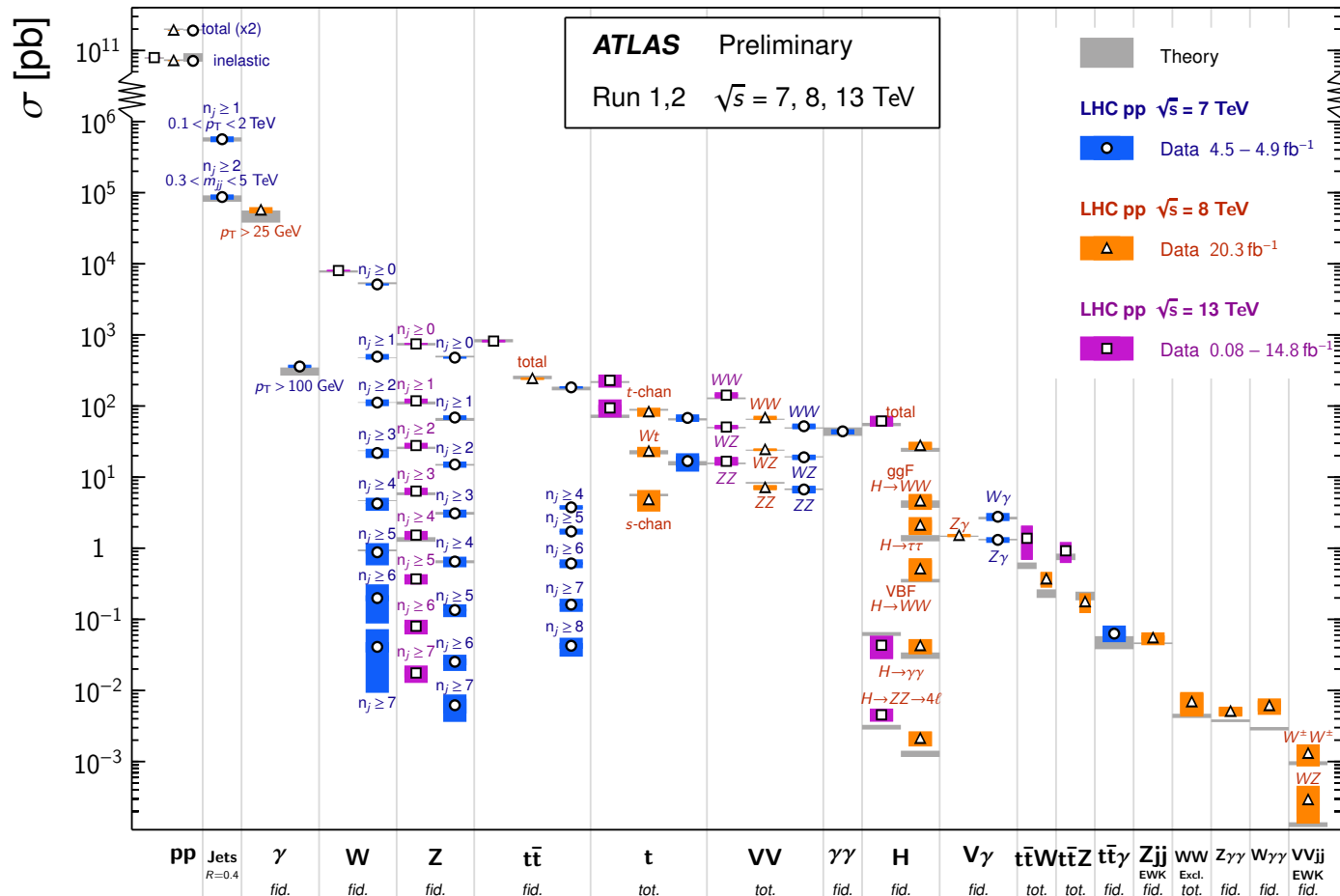
Agreement with theory over many orders of magnitude



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

Across widely different processes

Standard Model cross-section measurements



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

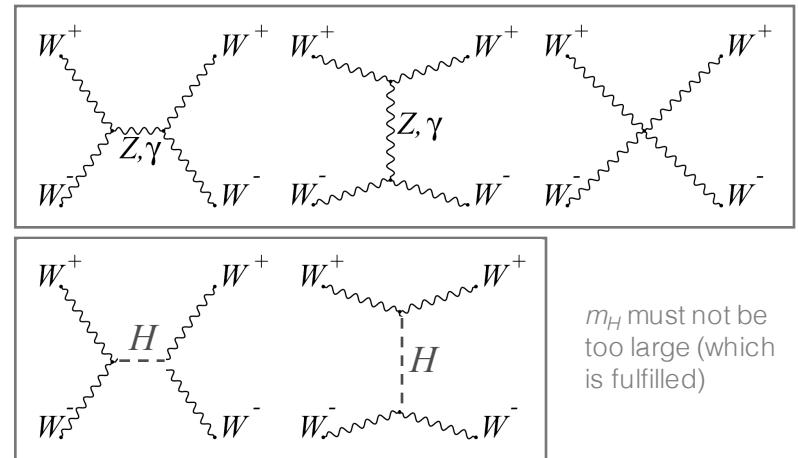
Higgs boson acts as “moderator” to unitarise high-energy longitudinal vector boson scattering

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

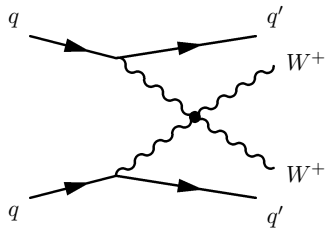
$$A_{Z,\gamma}(W^+W^- \rightarrow W^+W^-) \propto \frac{1}{v^2}(s+t)$$

Higgs boson restores unitarity of total amplitude:

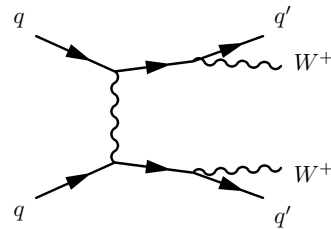
$$A_H(W^+W^- \rightarrow W^+W^-) \propto -\frac{m_H^2}{v^2} \left(\frac{s}{s-m_H^2} + \frac{t}{t-m_H^2} \right)$$



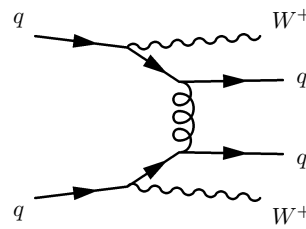
Same-sign WW selection greatly reduces strong production.
Removes s-channel Higgs process:



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

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

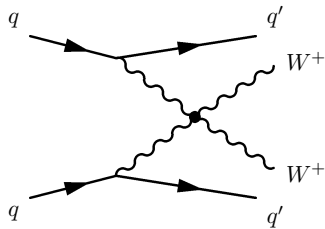
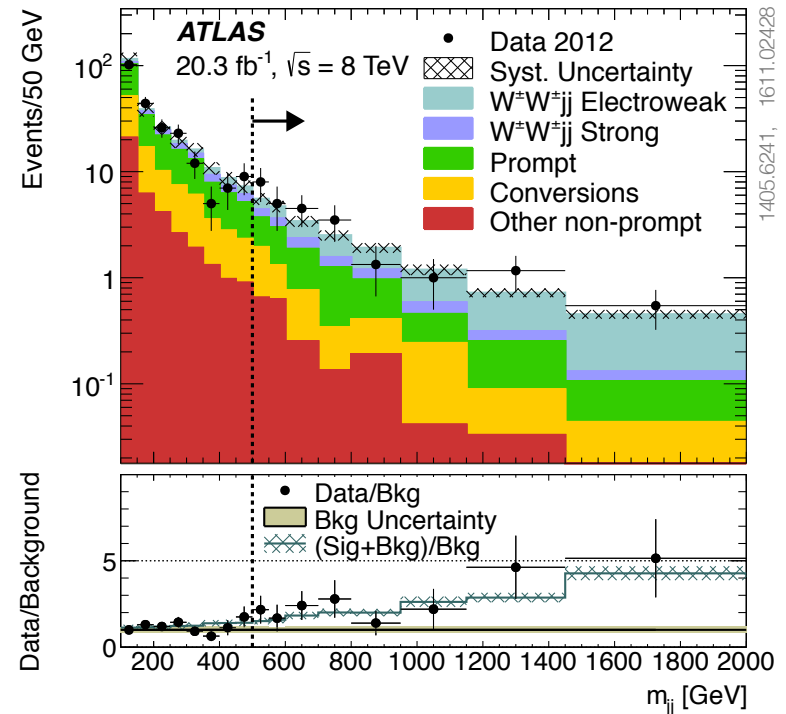
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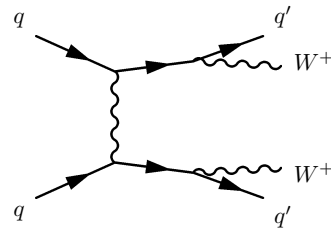
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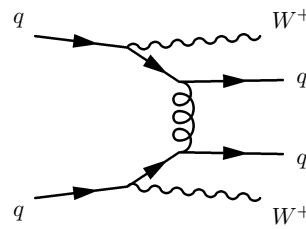
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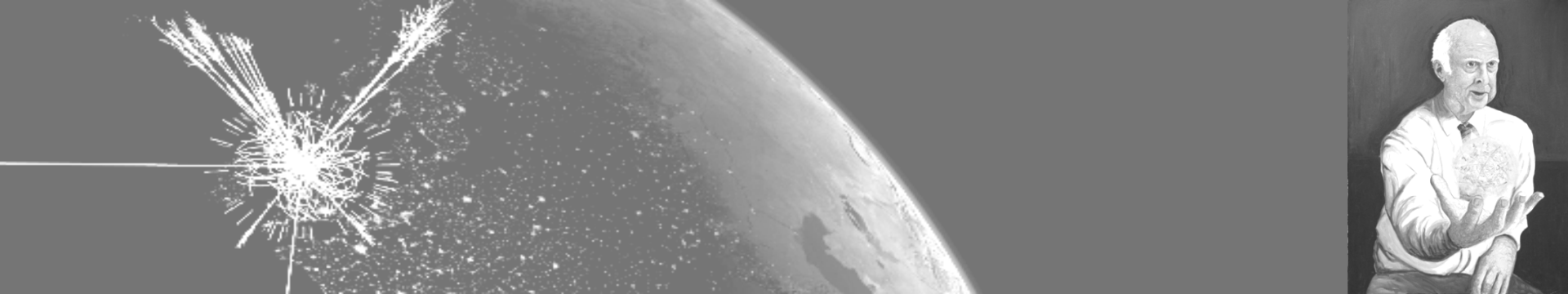
Non-VBS production



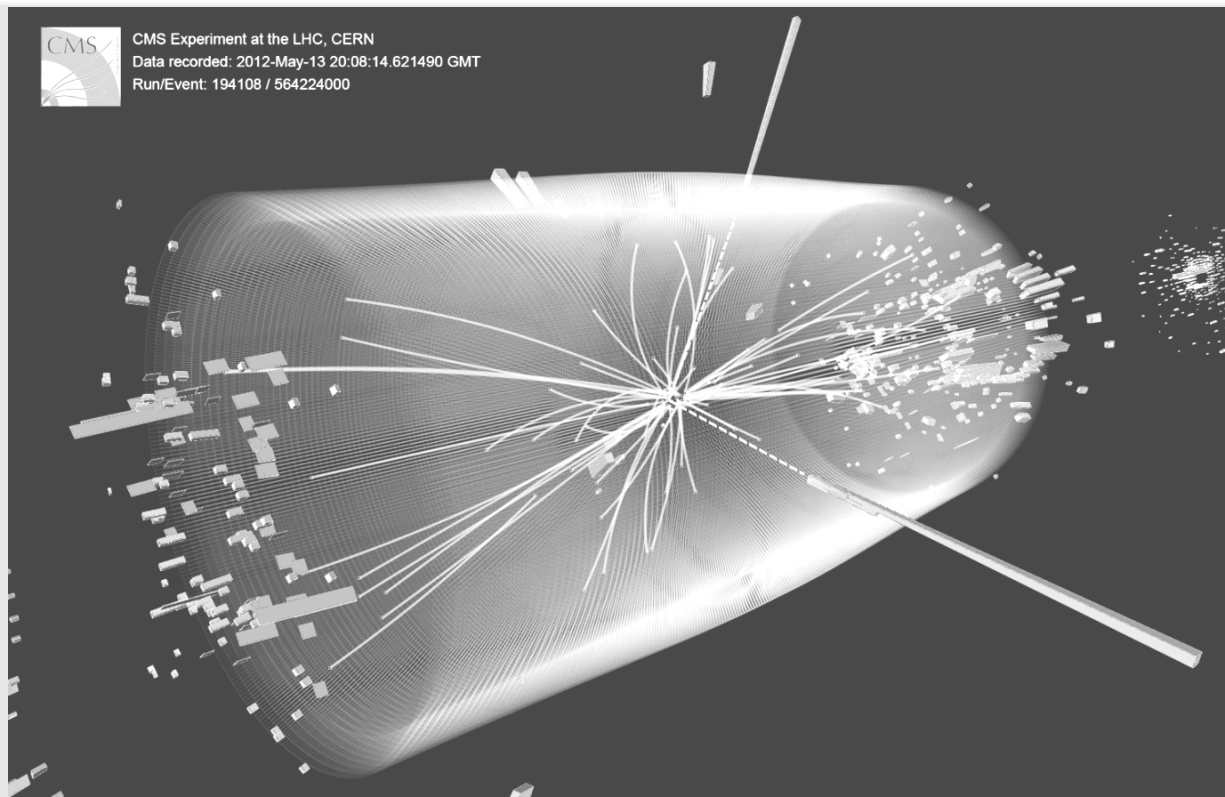
Strong production

Look for VBS scattering in high dijet invariant mass distributions

ATLAS finds 3.6σ evidence for EW production (2.3σ expected)



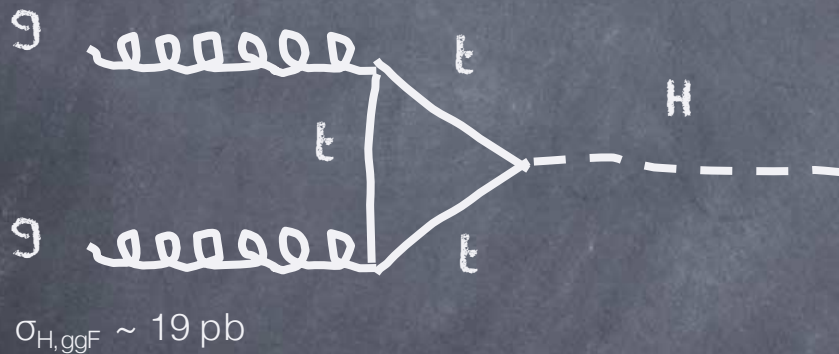
Higgs Boson — Run-1 magnum opus



Higgs boson production at the LHC

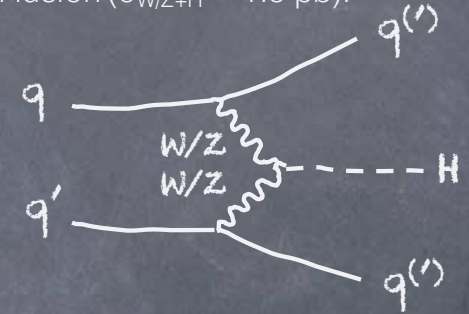
At the LHC, the Higgs boson is dominantly produced via gluon fusion for $\sigma_{H,\text{total}} \sim 22 \text{ pb}$ at 8 TeV for $m_H = 125 \text{ GeV}$

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

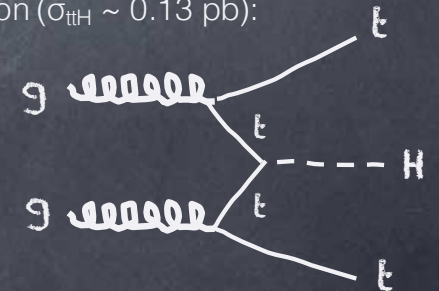
Vector boson fusion ($\sigma_{W/Z+H} \sim 1.6 \text{ pb}$):



Higgs-strahlung ($\sigma_{W/Z+H} \sim 0.7/0.4 \text{ pb}$):



“ttH” production ($\sigma_{ttH} \sim 0.13 \text{ pb}$):

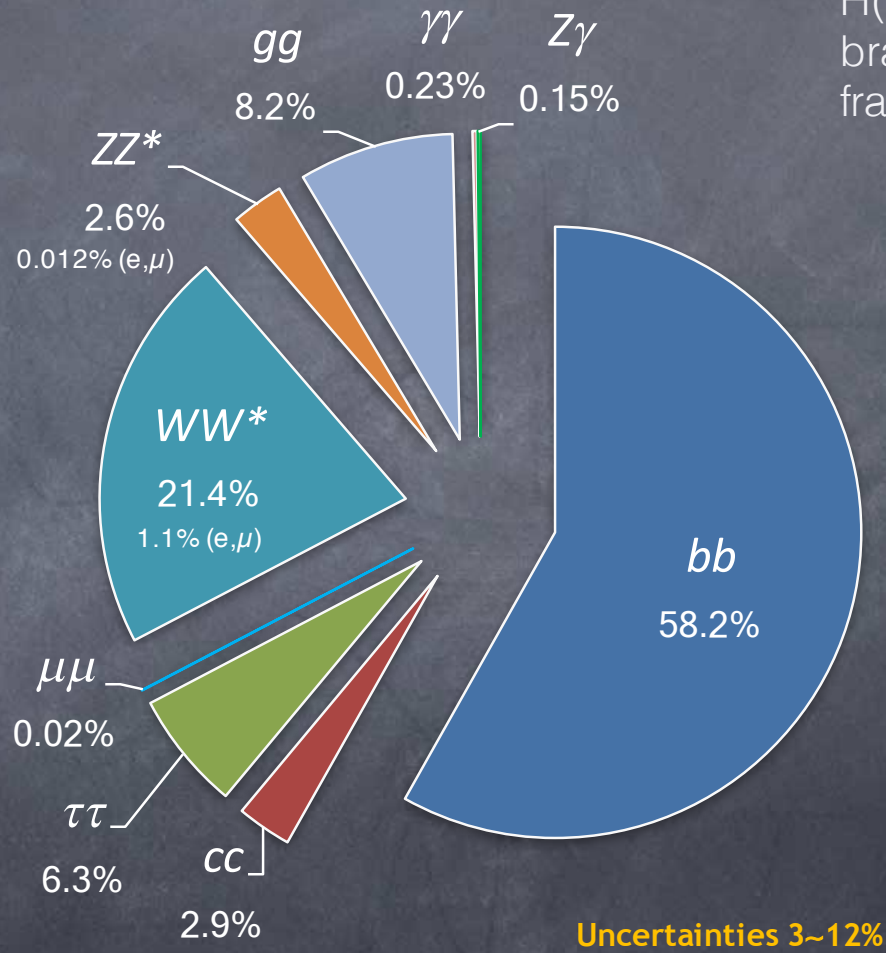


Higgs boson production at the LHC

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

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

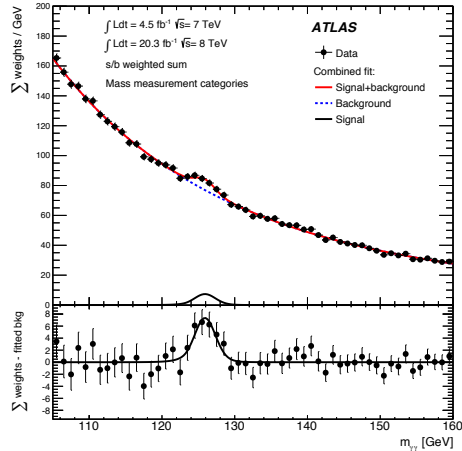
... the Higgs does not couple directly to photons and gluons, but only via “loops” involving preferentially heavy particles (e.g., top, W)



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

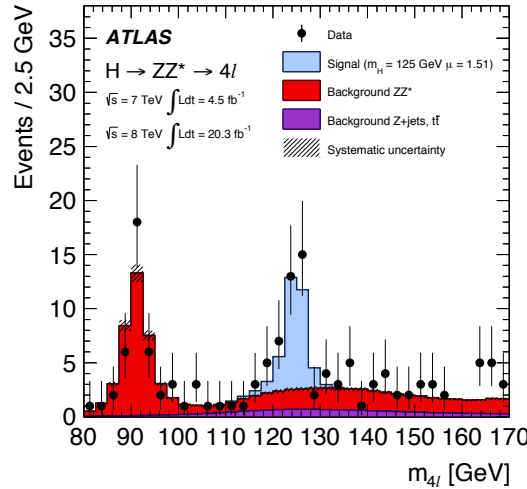
$$H \rightarrow \gamma\gamma$$

$$\sigma(m) \sim 1-2\%$$



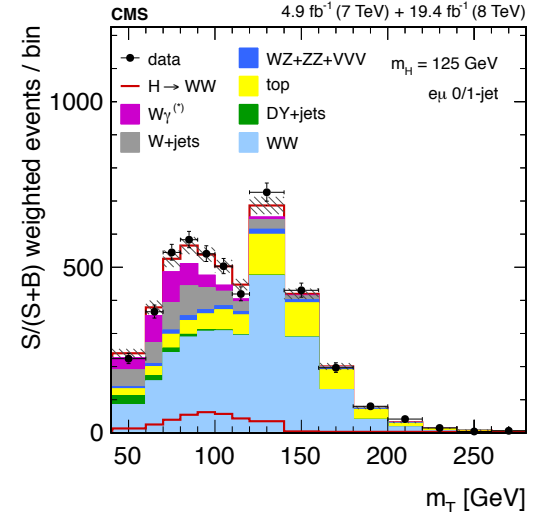
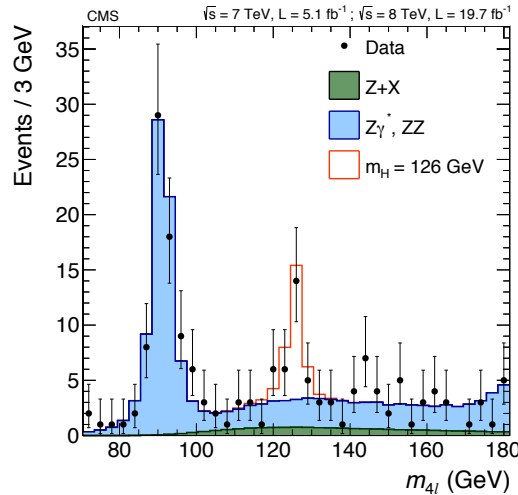
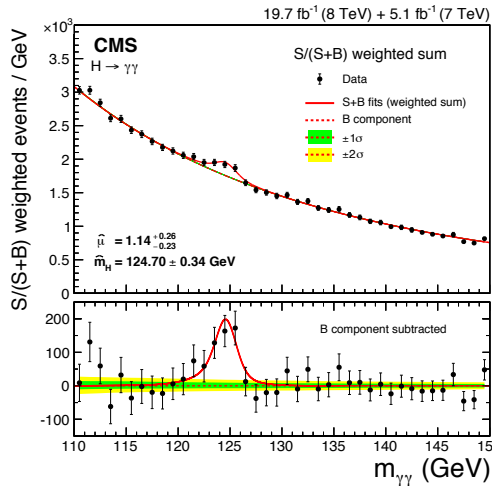
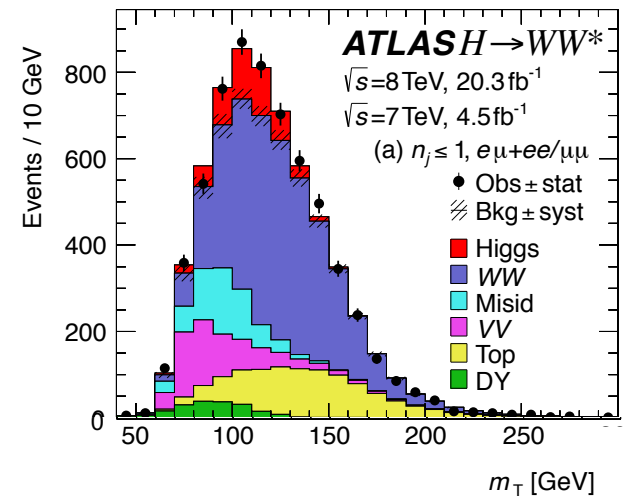
$$H \rightarrow ZZ^{(*)} \rightarrow 4\ell$$

$$\sigma(m) \sim 1-2\%$$



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

$$\sigma(m) \sim 20\%$$



Very different experimental challenges in each of these discovery channels.
All analyses significantly improved since July 2012. Resulting yields agree with SM predictions

Combined ATLAS & CMS Higgs analysis and flurry of Higgs property measurements

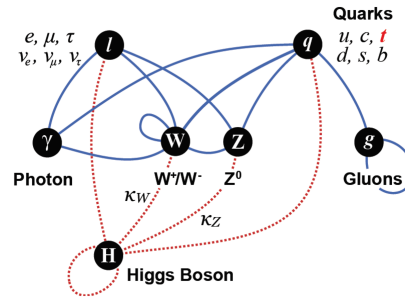
ATLAS & CMS Combinations of Higgs mass and coupling measurements

[1503.07589, 1606.02266]

Precise mass combination (0.2%):

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

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



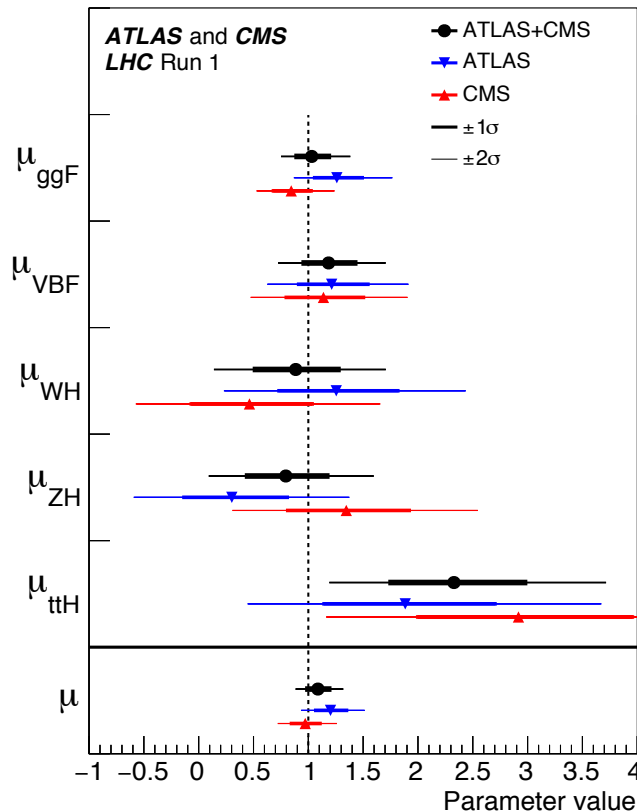
Agreement among experiments

Overall comparison: $\mu = 1.09 \pm 0.11$

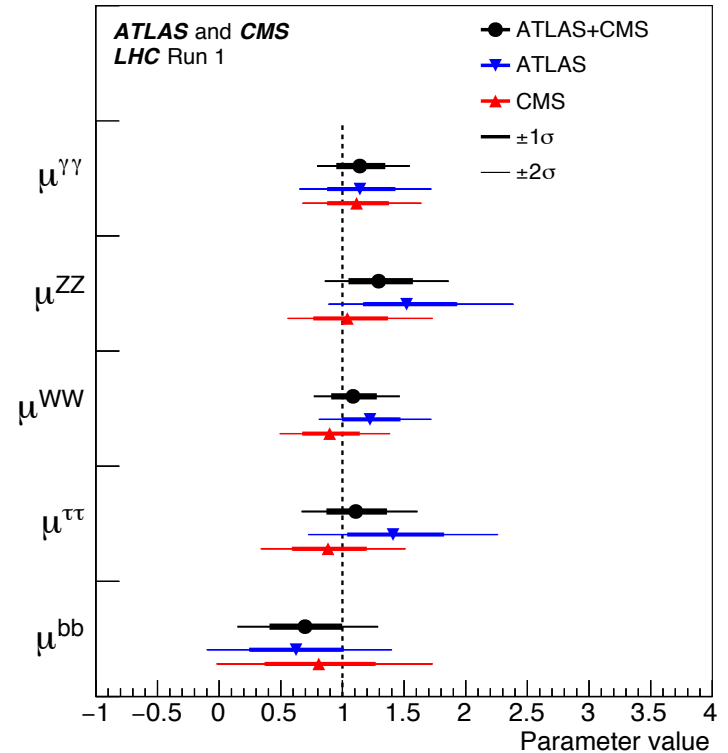
Combined **observation of $H \rightarrow \tau\tau$ channel & VBF production**

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

Higgs production processes



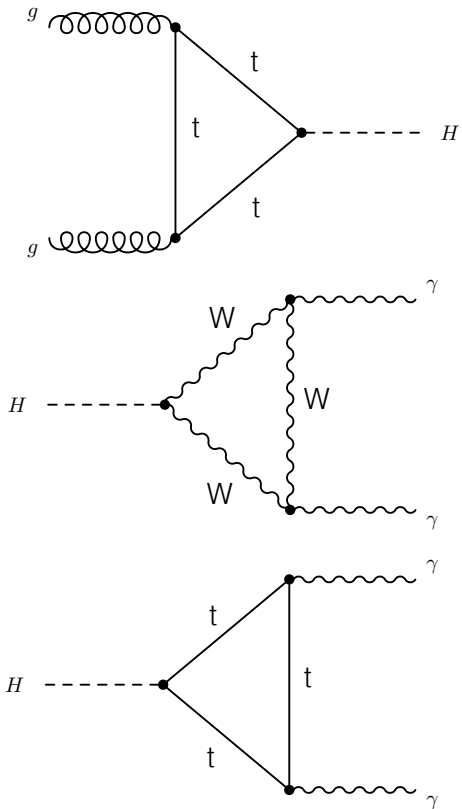
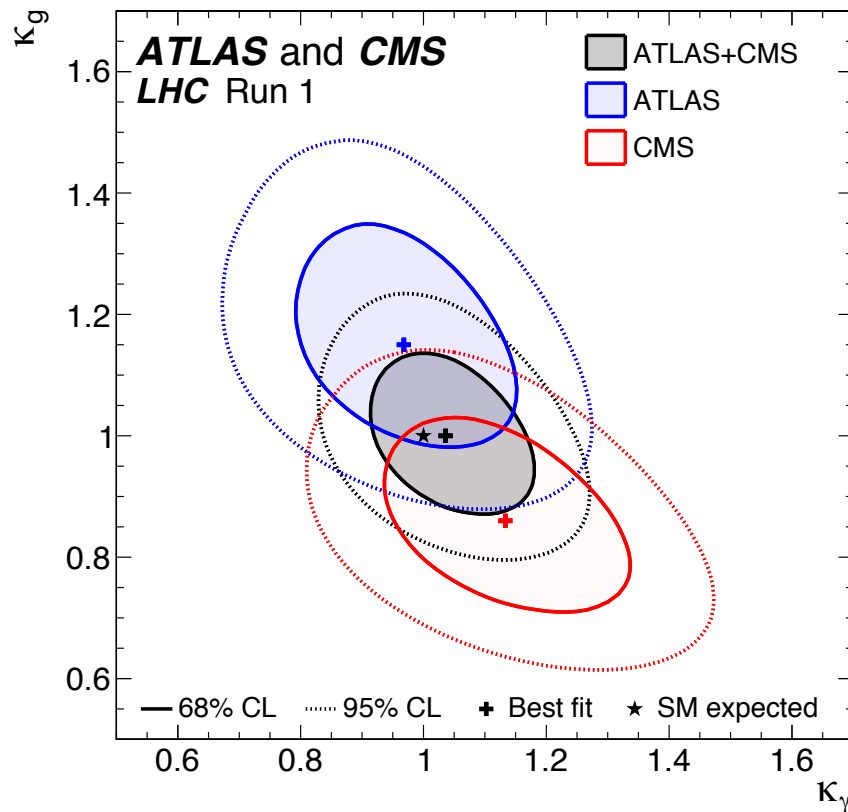
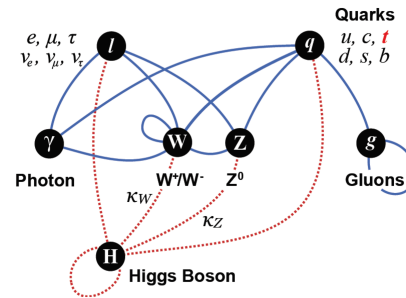
Higgs decay processes



Combined ATLAS & CMS Higgs analysis and flurry of Higgs 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

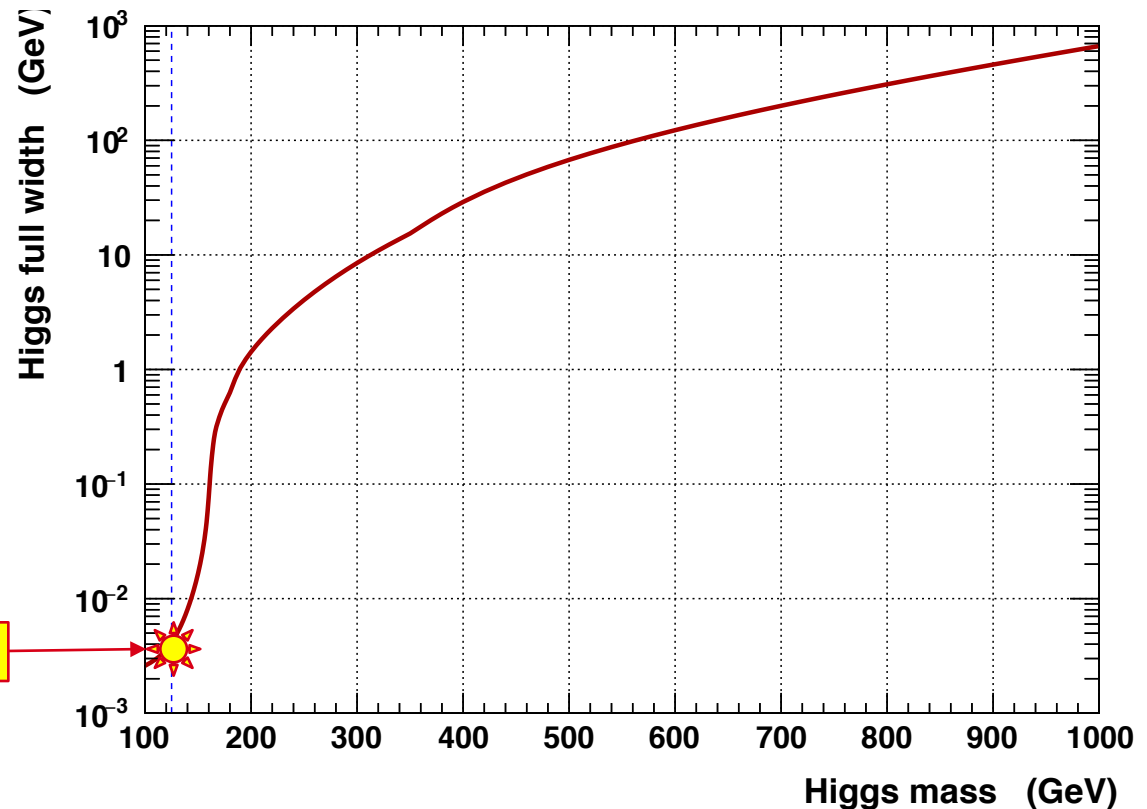
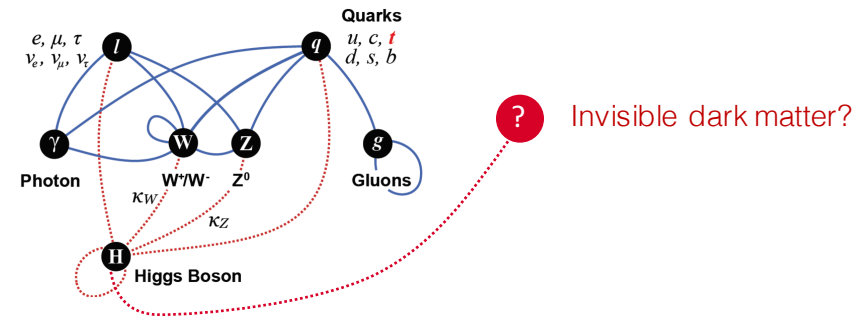
For comparison:

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

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

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

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

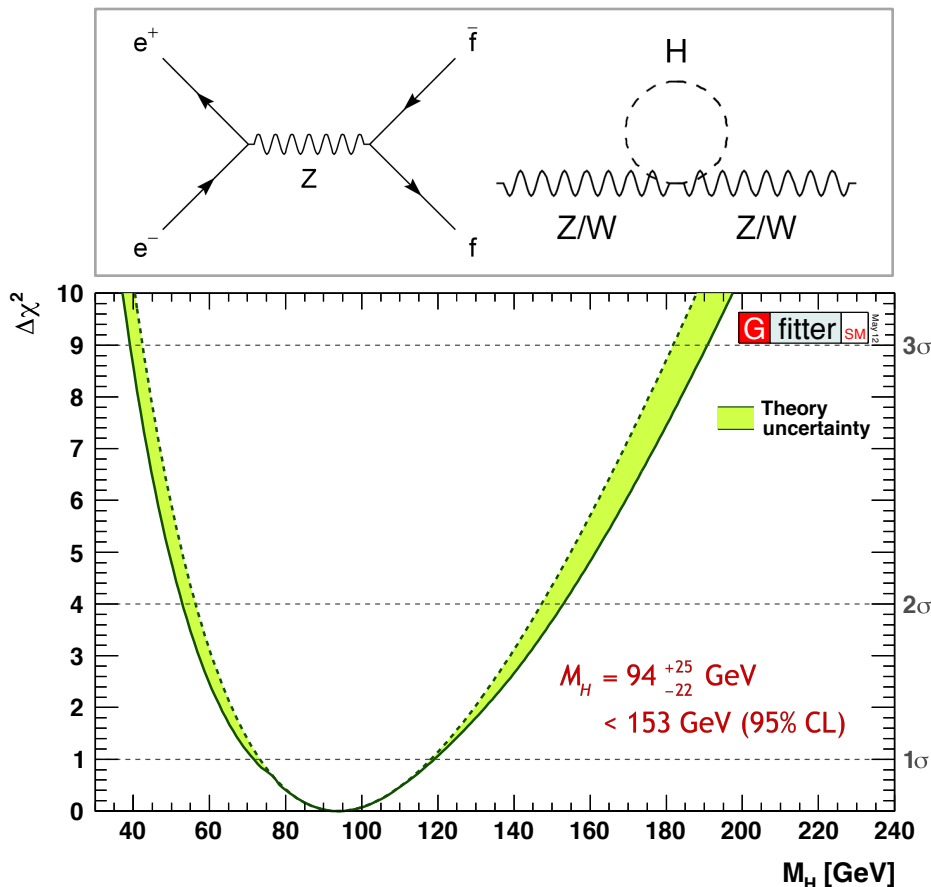


What was known about the Higgs (mass) before the LHC ?

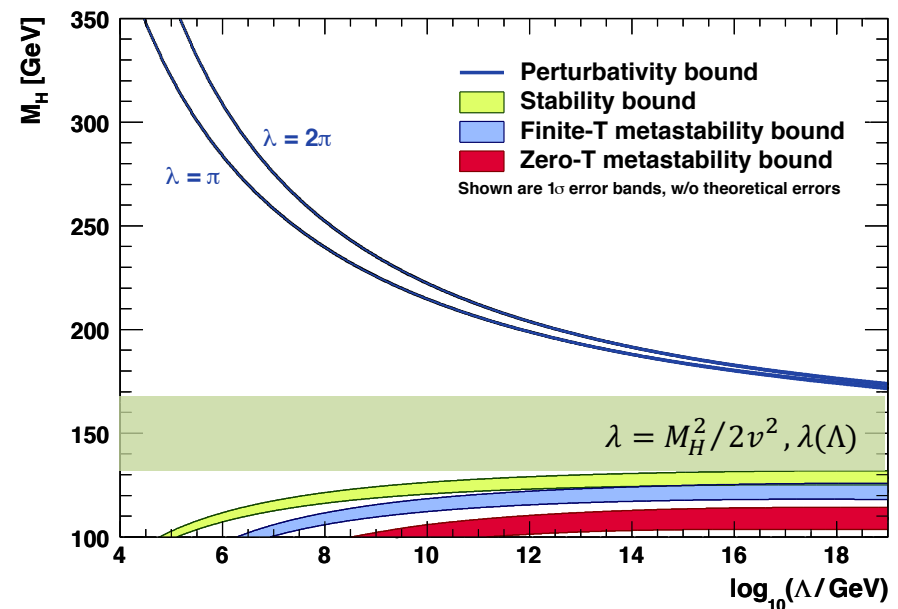
Direct searches at LEP excluded: $m_H < 114.4$ GeV | Tevatron: excluded $m_H \sim 160$ GeV

Today's Tevatron exclusion (2013): $149 < m_H < 182$ GeV

Constraint from SM fit to EW precision data:



Perturbativity and stability bounds for high SM cut-off scale Λ :

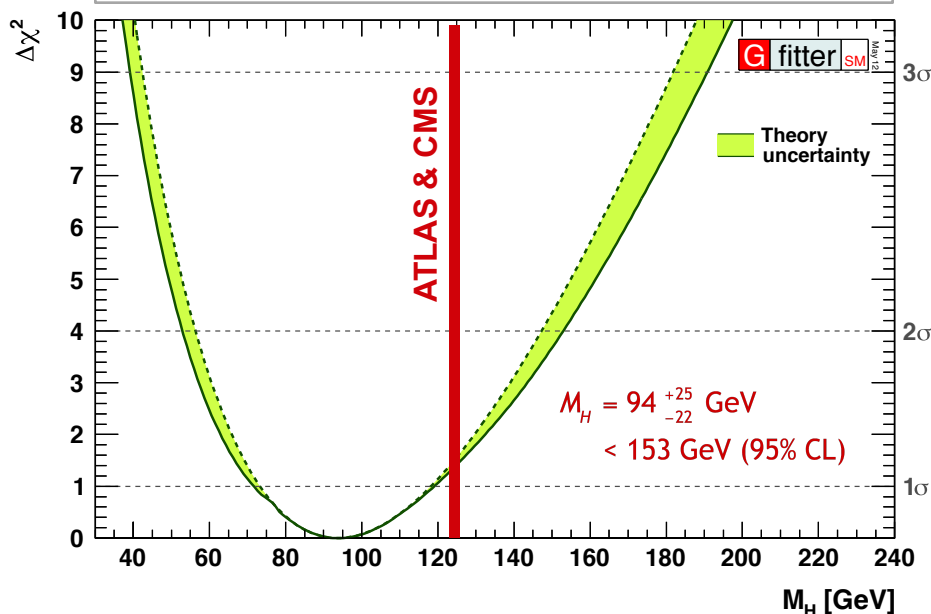
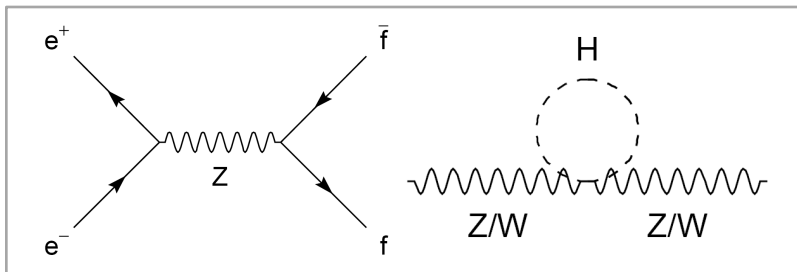


Agreement of observation with prior constraints

Direct searches at LEP excluded: $m_H < 114.4$ GeV | Tevatron: excluded $m_H \sim 160$ GeV

Today's Tevatron exclusion (2013): $149 < m_H < 182$ GeV

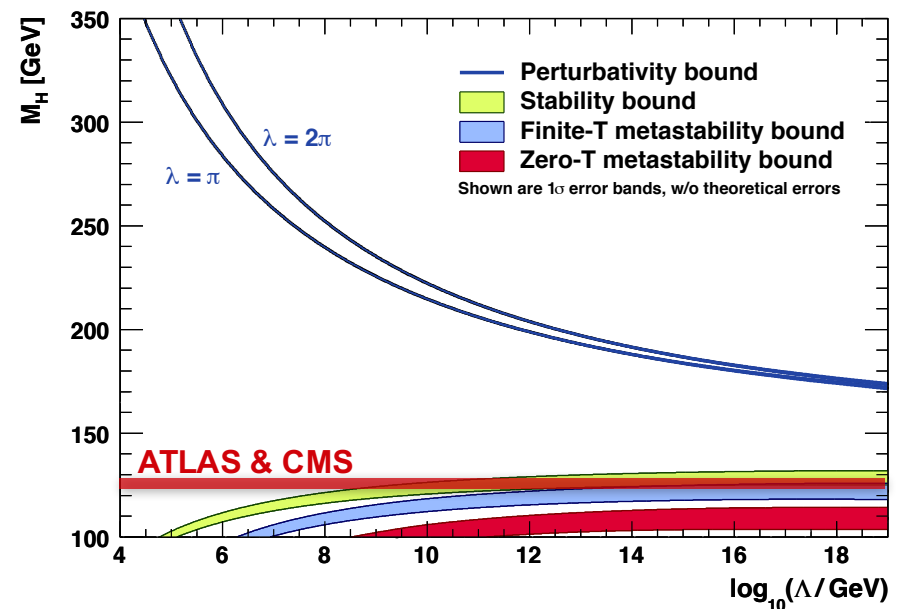
Constraint from SM fit to EW precision data:



ATLAS & CMS:

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

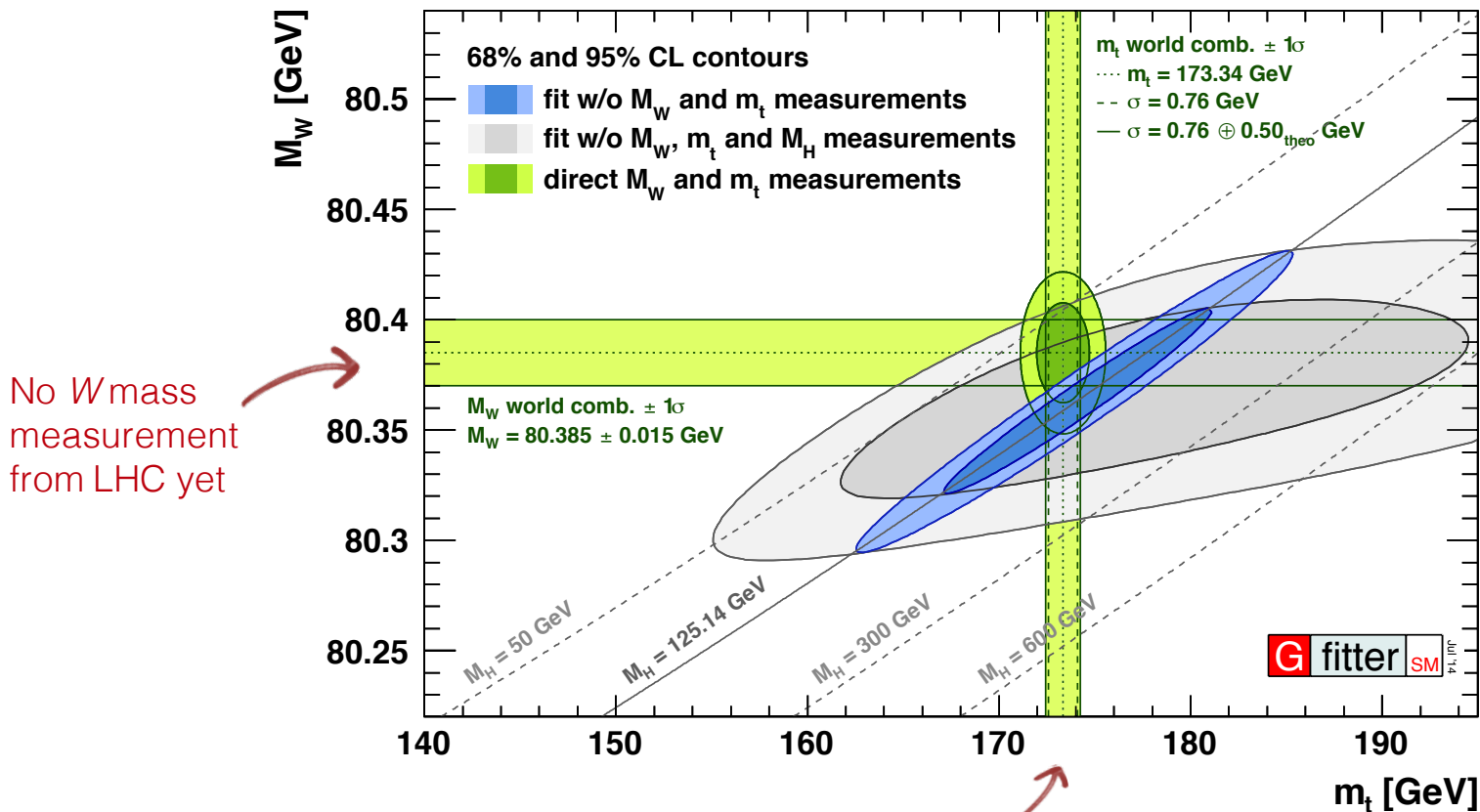
Perturbativity and stability bounds for high SM cut-off scale Λ :



Global fit to electroweak precision data

Global electroweak fit was masterpiece of LEP/SLD era.

Discovery of Higgs over-constrains the fit and dramatically improves predictability

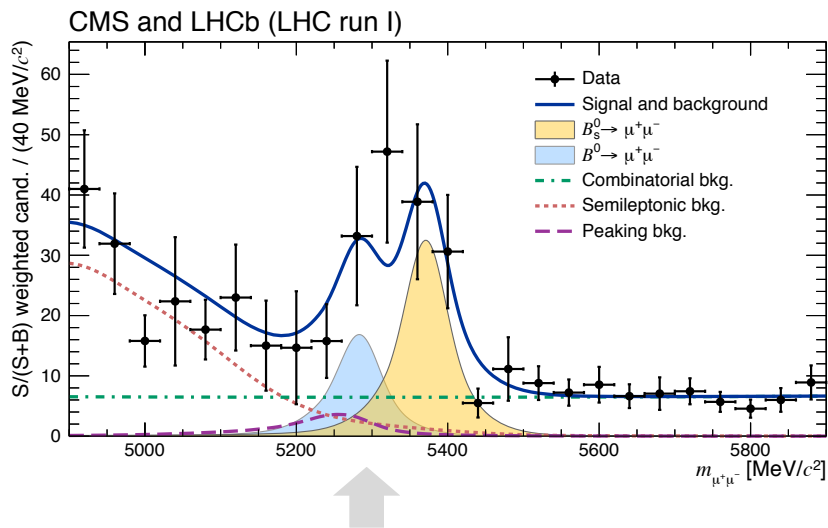


Competitive top mass results from the LHC

Best current results: $172.44 \pm 0.13 \pm 0.47$ GeV (CMS, 1509.04044),
 $172.84 \pm 0.34 \pm 0.61$ GeV (ATLAS, 1606.02179, not yet all 8 TeV)

Highly important flavour measurements

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



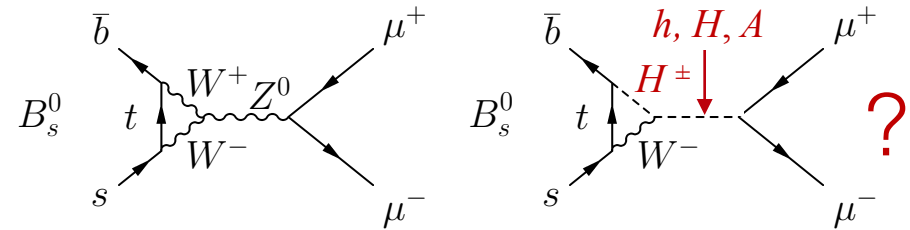
CMS & LHCb: observation of $B_s \rightarrow \mu\mu$

[Nat. 522 (2015) 68]

Lower ATLAS Run-1 result

[1604.04263, consistency with SM at 2 σ]

Does the Higgs boson has brothers and sisters?

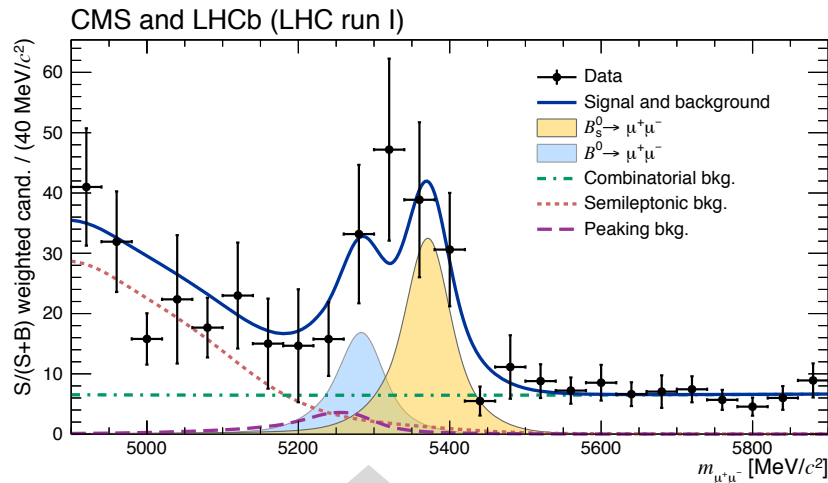


$B_s \rightarrow \mu\mu$ is loop process (no tree-level FCNC)
that is in addition CKM & helicity suppressed

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

Highly important flavour measurements

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



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

[Nat. 522 (2015) 68]

Lower ATLAS Run-1 result

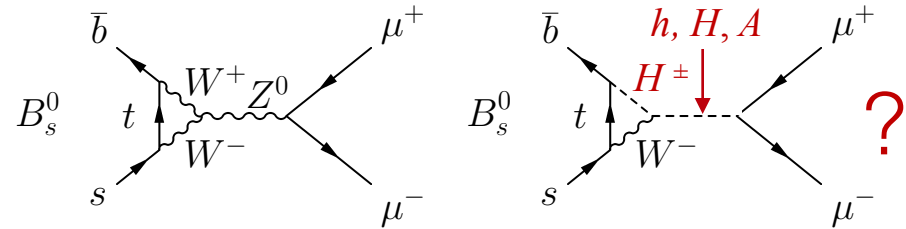
[1604.04263, consistency with SM at 2σ]

Precision measurement of ϕ_s

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

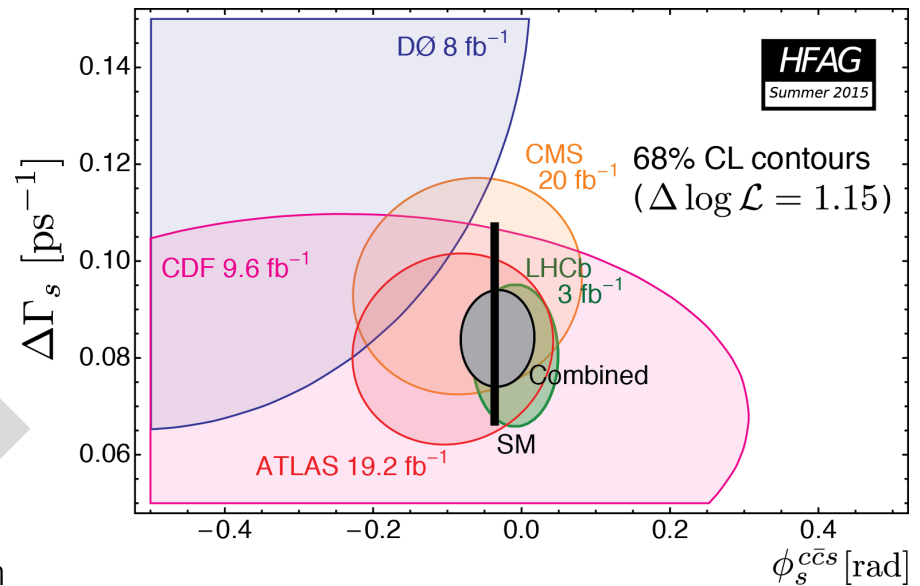
A few anomalies in $b \rightarrow s$ and lepton universality in semileptonic B decays are to be followed up

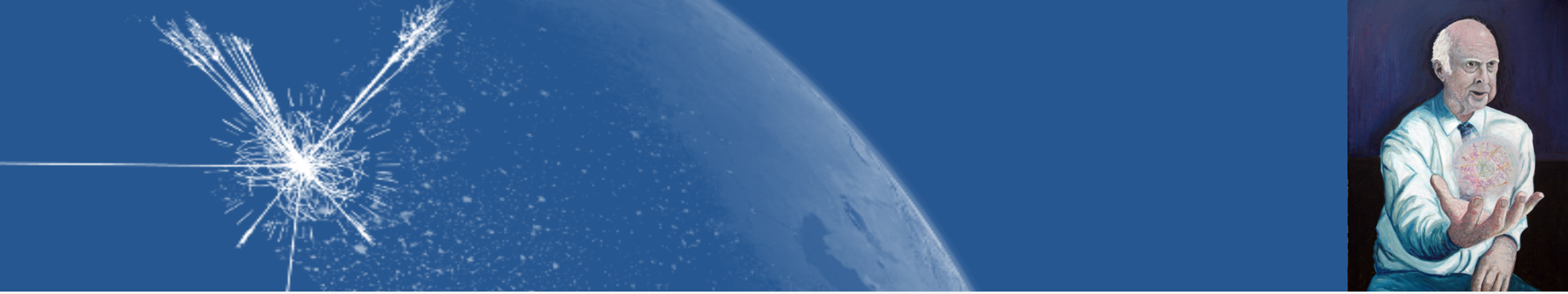
Does the Higgs boson has brothers and sisters?



$B_s \rightarrow \mu\mu$ is loop process (no tree-level FCNC)
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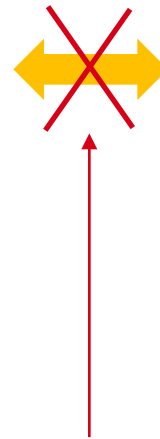
Two beautiful, extremely precise theories

The Standard Model of EW and strong interactions

Predicting, e.g., the anomalous magnetic moment of the electron to a relative precision of better than 10^{-9} in agreement with experiment

General relativity — theory of gravitation

Tested up to an accuracy of order 10^{-5} (Cassini probe [B Bertotti et al., Nature 425, 2003])



Unfortunately, the SM and general relativity don't work in regimes when both are important (ie, at very small scales)

A background image showing particle tracks in a detector, with a bright central point and several tracks extending outwards, set against a dark blue background.

Many open questions remain...

Scalar sector

- Single doublet or more
- Elementary or composite
- Form of potential
- Origin of Yukawa couplings

Dark matter

- Composition: WIMP, axions, sterile neutrinos, hidden sector particles, gravitational effect only
- Single or multiple sources

Expansion of Universe

- Primordial expansion via inflation; which fields, role of quantum gravity?
- Accelerated expansion today: cosmological constant problem

Strong CP problem

Quarks and leptons

- Origin of families, mass, mixing, CPV
- Matter–antimatter asymmetry
- Baryon and lepton number conservation (proton decay)

Neutrinos

- Origin and values of neutrino masses
- Nature: Majorana or Dirac
- CP violation
- Sterile neutrinos

High-scale physics

- Hierarchy problem and new physics at TeV scale
- Grand unification of forces
- Unification with gravity
- Quantum gravity, string theory



ATLAS SUSY

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

CMS Preliminary

Leptoquarks

$LQ1(l\bar{u}) \times 2$
 $LQ1(e\bar{u})+LQ1(\bar{\nu}_\mu)$
 $LQ2(u\bar{u}) \times 2$
 $LQ2(u\bar{u})+LQ2(\bar{\nu}_\mu)$
 $LQ3(\bar{u}b) \times 2$
 $LQ3(b\bar{u}) \times 2$
 $LQ3(t\bar{u}) \times 2$
 $LQ3(\bar{\nu}_\tau) \times 2$
 Single $LQ1$ ($\lambda=1$)
 Single $LQ2$ ($\lambda=1$)

RS Gravitons

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

Heavy Gauge Bosons

$SSM Z'(\tau\bar{\tau})$
 $SSM Z'(\bar{j}j)$
 $SSM Z'(\bar{b}b)$
 $SSM Z'(e\bar{e})+Z'(\bar{\mu}\mu)$
 $SSM W'(\bar{j}j)$
 $SSM W'(\bar{l}l)$
 $SSM W'(WZ \rightarrow \bar{l}l\bar{\nu})$
 $SSM W'(WZ \rightarrow 4j)$

Excited Fermions

$e^*(M=\Lambda)$
 $\mu^*(M=\Lambda)$
 $q^*(q\bar{q})$
 $q^*(q\bar{q})$
 b^*

Multijet Resonances

$coloron(j\bar{j}) \times 2$
 $coloron(4j) \times 2$
 $gluino(3j) \times 2$
 $gluino(j\bar{j}) \times 2$

Long-Lived Particles

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

Dark Matter

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

Large Extra Dimensions

ADD ($\gamma+\text{MET}$), $n\text{ED}=4$, MD
 ADD ($\gamma+\text{MET}$), $n\text{ED}=4$, MD
 ADD ($e\bar{e}, \mu\bar{\mu}$), $n\text{ED}=4$, MS
 ADD ($\gamma\gamma$), $n\text{ED}=4$, MS
 ADD ($j\bar{j}$), $n\text{ED}=4$, MS
 QBH, $n\text{ED}=4$, MD=4 TeV
 NR BH, $n\text{ED}=4$, MD=4 TeV
 QBH ($j\bar{j}$), $n\text{ED}=4$, 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
 dilectrons, $\Lambda+$ LLIM
 dilectrons, $\Lambda-$ LLIM
 single e , Λ HnCM
 single μ , Λ HnCM
 inclusive jets, $\Lambda+$
 inclusive jets, $\Lambda-$

No significant anomaly seen so far

Particle physics at the dawn of the LHC Run-2

No new physics in direct searches or study of quantum fluctuations

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 $g-2$)

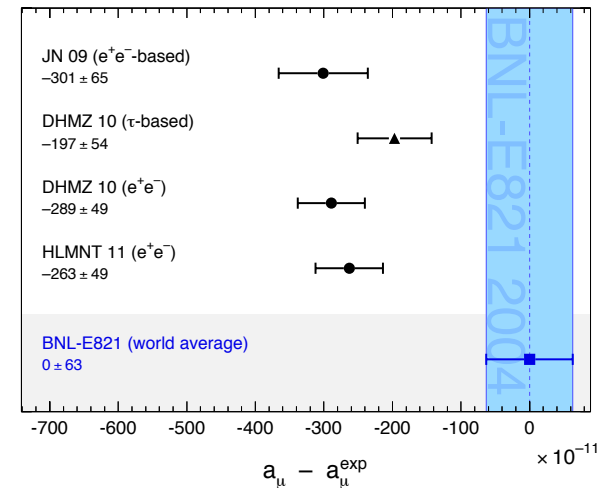
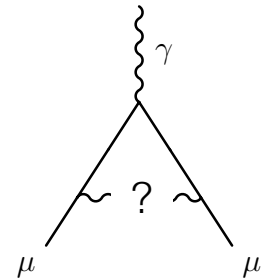
Asymptotic freedom in strong interactions verified at % level

Electroweak unification tested to high precision

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

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

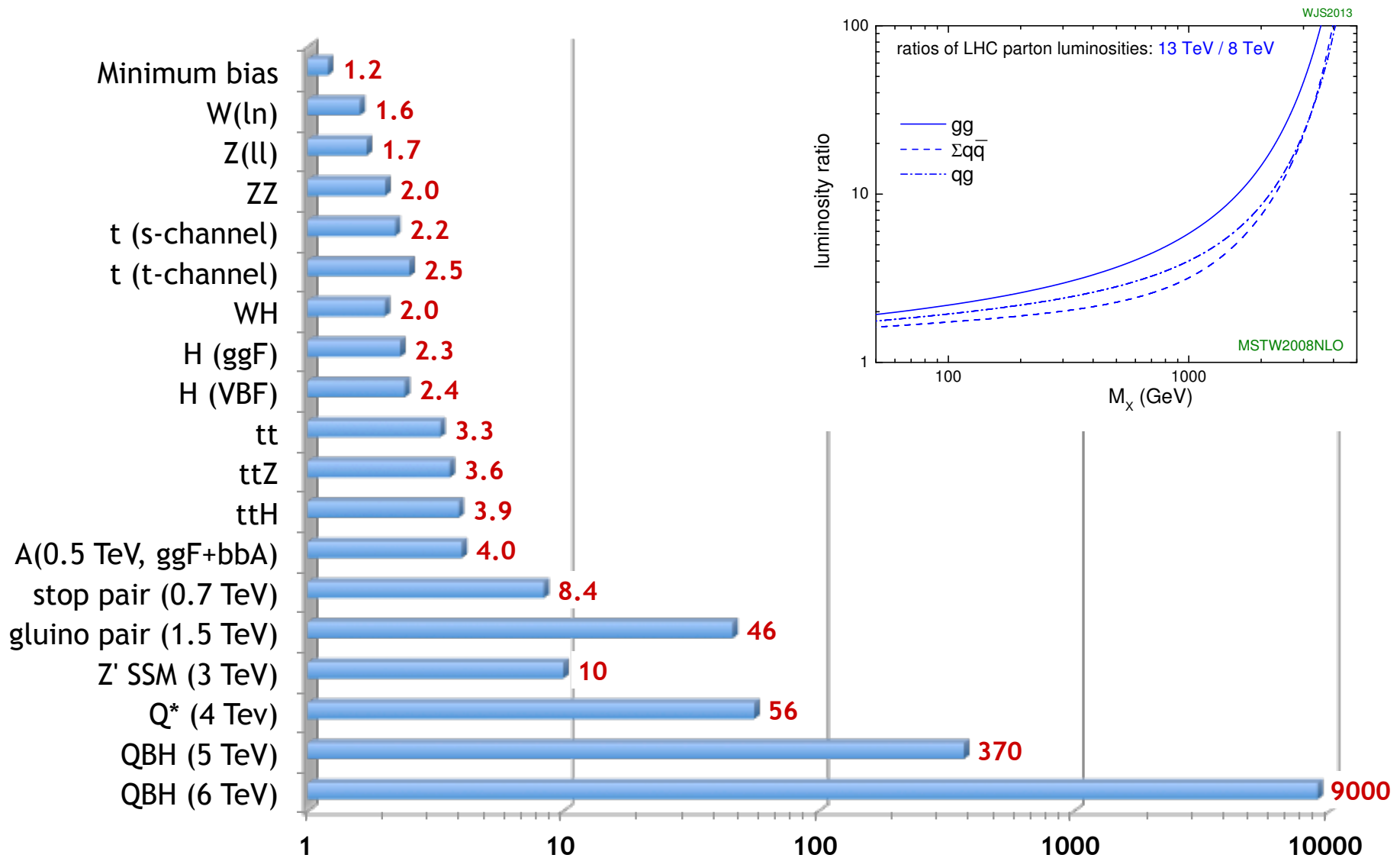
No compelling sign of new physics found at high mass scales, or anywhere else, eg: no electric dipole moments (EDM), no dark matter particles (gravitational hints only), no axions, no proton decay



The LHC Run-2 at 13 TeV — terra incognita —

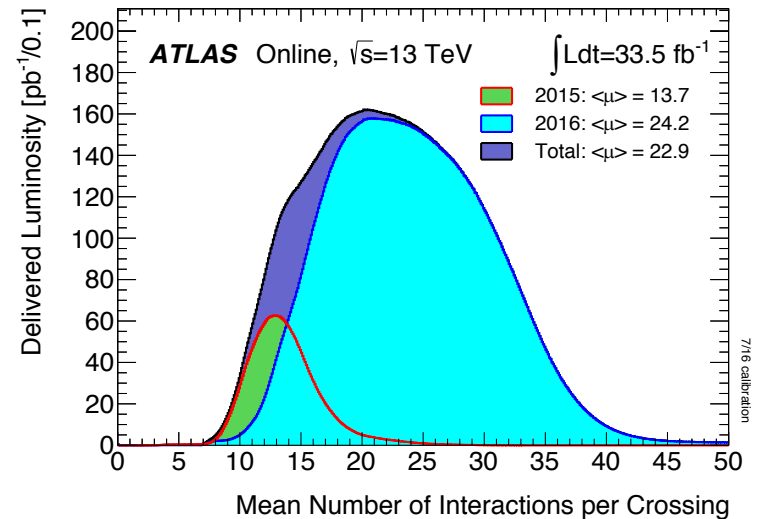
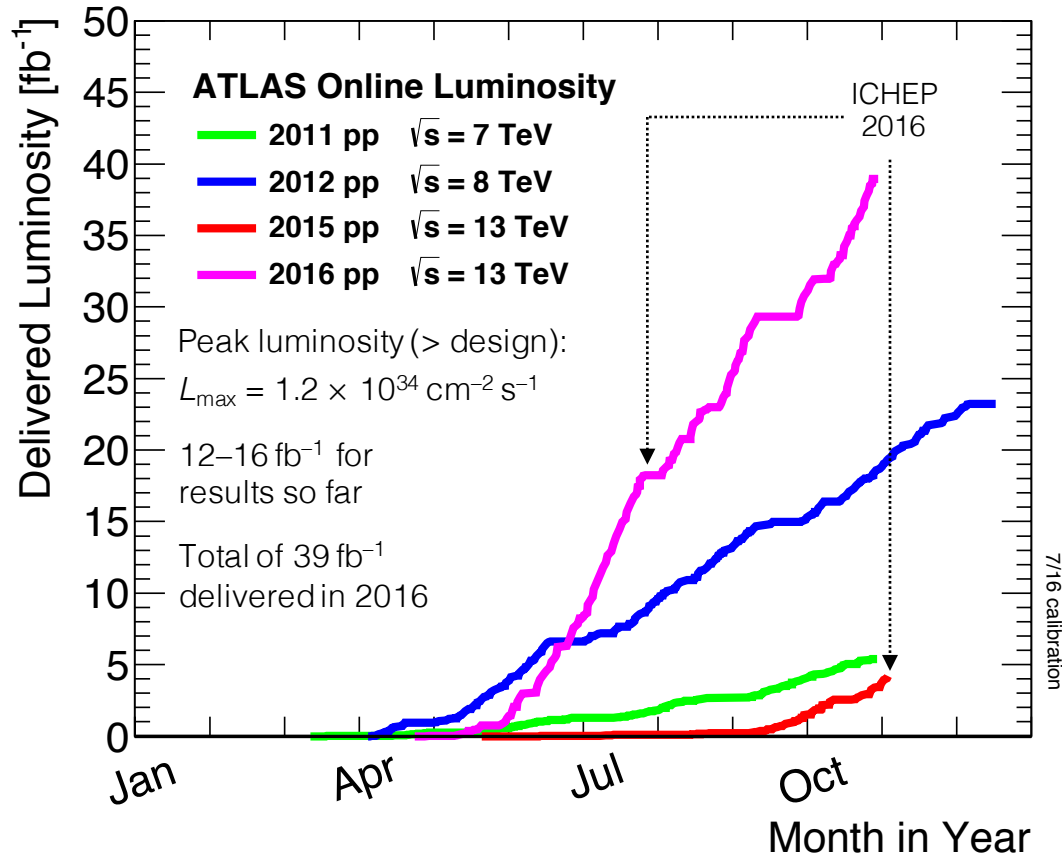


The LHC Run-2: 13 TeV / 8 TeV inclusive pp cross-section ratio



2015 LHC proton-proton luminosities

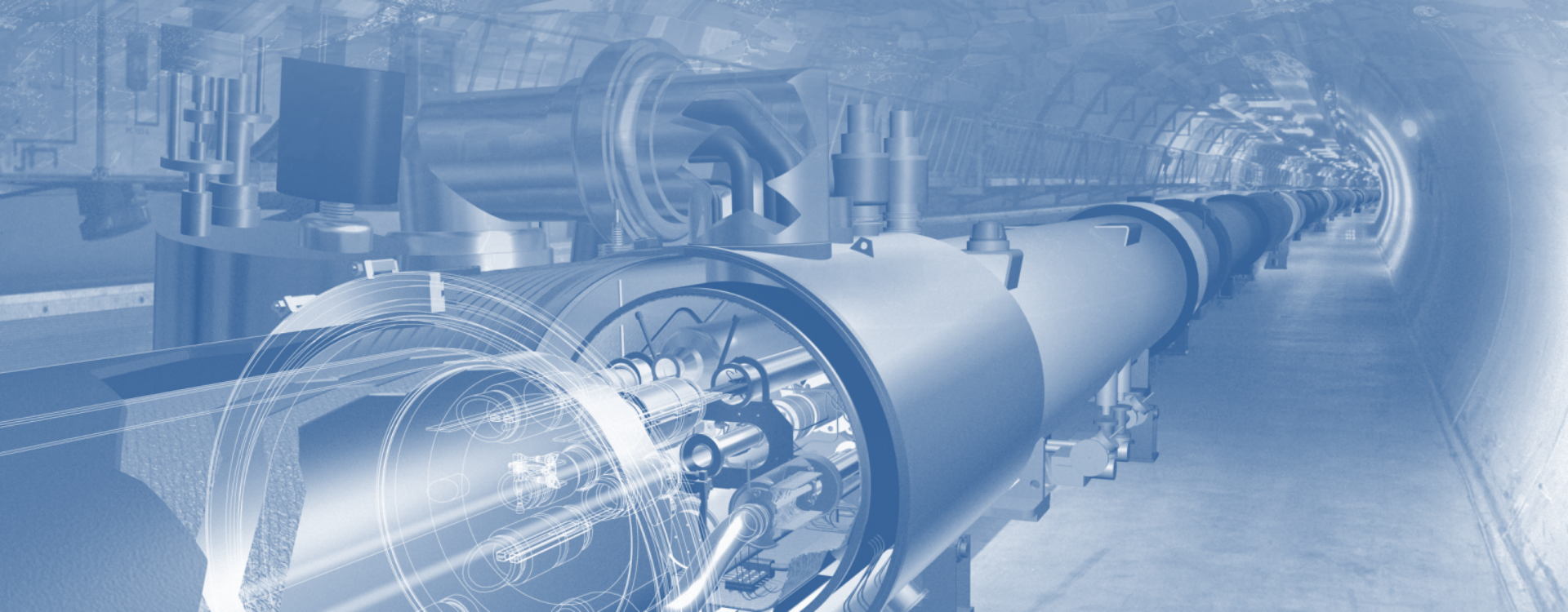
Most results reported by ATLAS & CMS use total 2015 and summer 2016 dataset



2015 and 2016 pileup profile in ATLAS & CMS
(LHCb mean pileup of ~ 1.7 due to levelling)

LHCb after luminosity levelling: 1.7 (1.9) fb^{-1} recorded (delivered)

Current luminosity precision from van-der Meer scans: 2.9% (ATLAS), 6.2% (CMS 2016), 3.8% (LHCb)



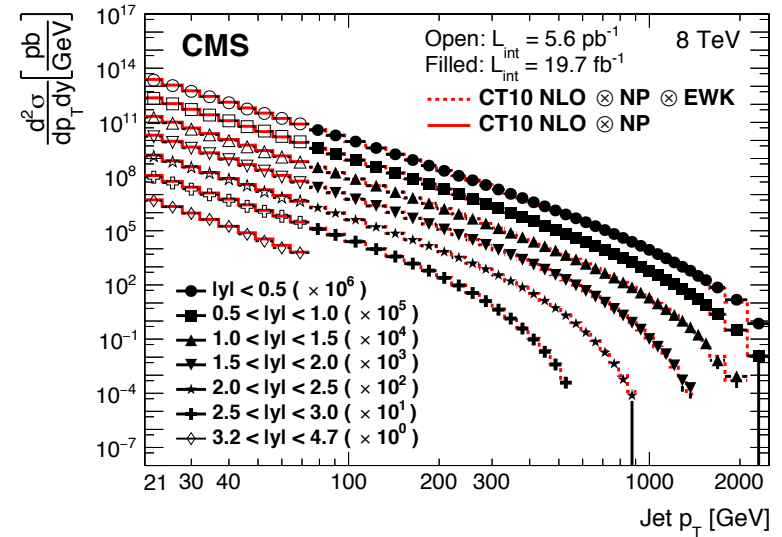
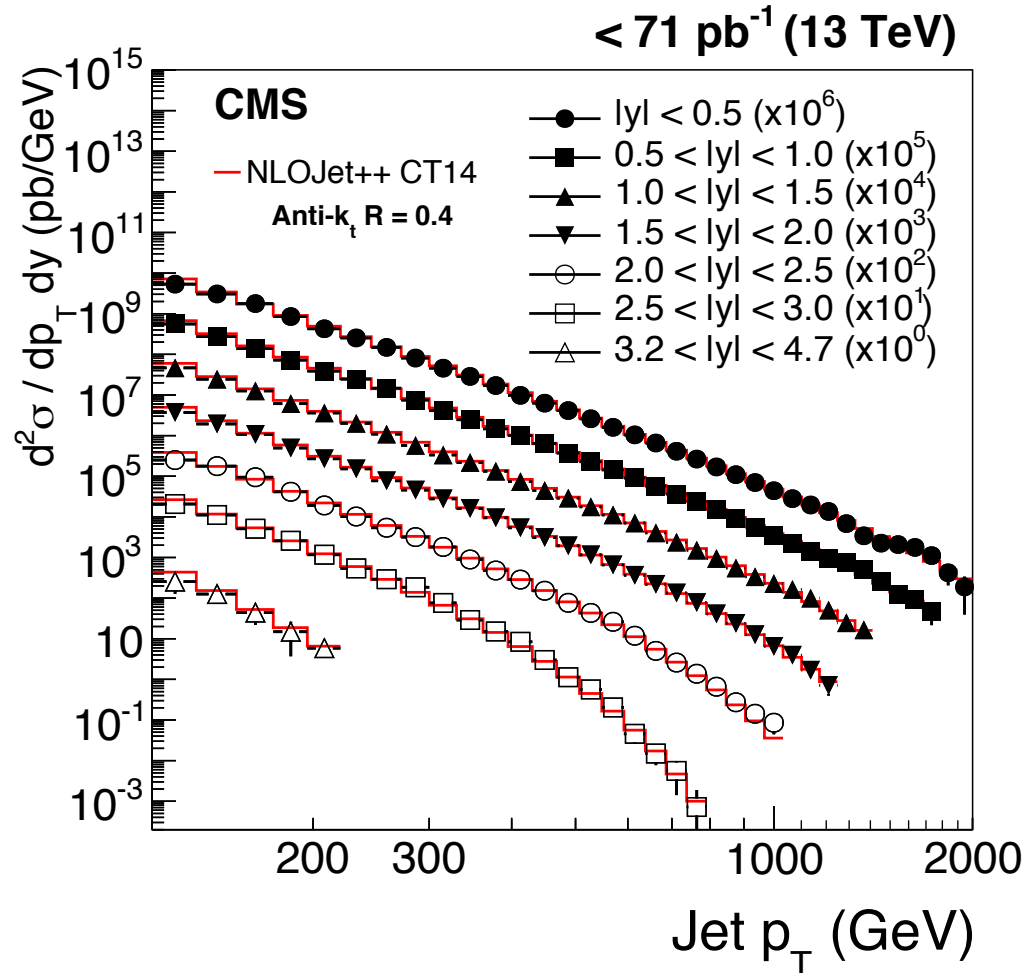
Selected physics at 13 TeV proton–proton collisions

Measurement of jet cross section at 13 TeV

Primary test of QCD at highest collision energy

CMS 1605.04436, 1609.05331

Double differential cross section measured by CMS



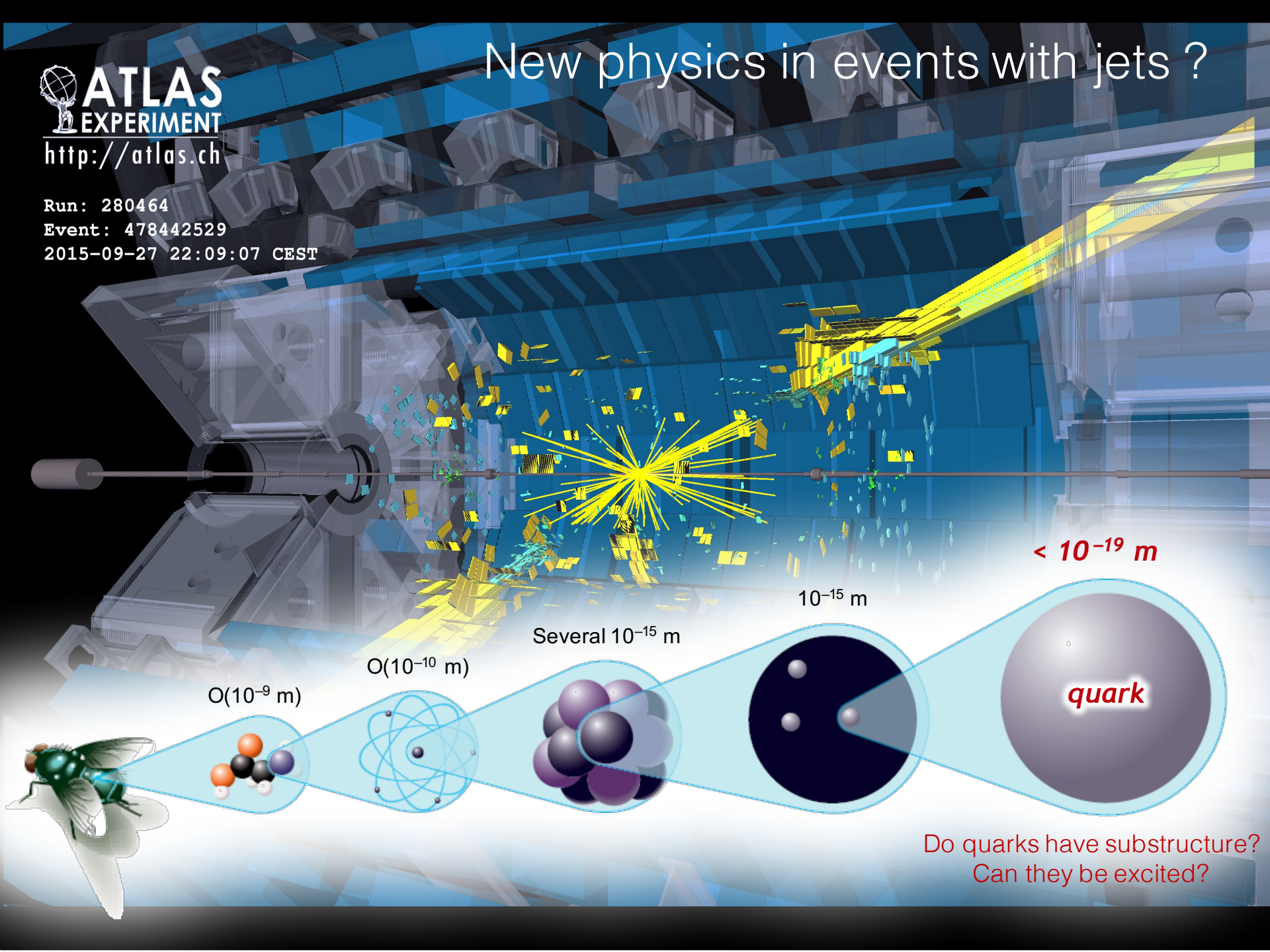
Comparison with 8 TeV plot (right) shows effect of increased parton luminosities at high jet p_T

Run: 280464

Event: 478442529

2015-09-27 22:09:07 CEST

New physics in events with jets ?



Do quarks have substructure?
Can they be excited?

Searches in high- p_T multijet final states at 13 TeV

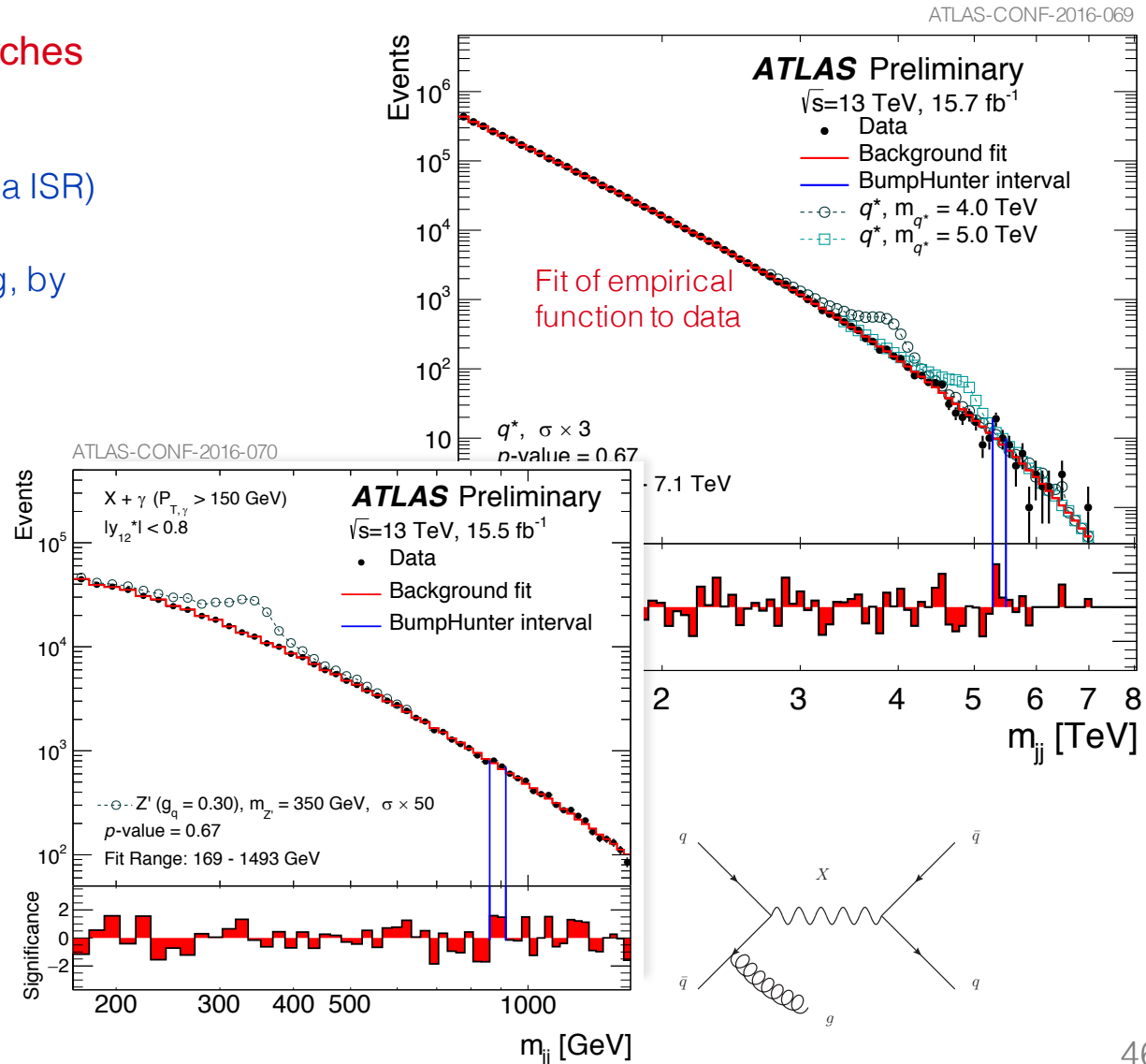
Processes with large cross-sections, sensitivity to highest new physics scales

High priority early 13 TeV searches

- Dijet resonance and angular distribution (incl. lower mass via ISR)
- High- p_T multijets produced, eg, by strong gravity
- High- p_T lepton + jets (strong gravity)
- Second generation scalar lepto-quark pair production (μq - μq final state, excl. < 1.2 TeV)

None of these searches showed an anomaly so far

Limits on excited quarks (for example) at 5.6 TeV



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

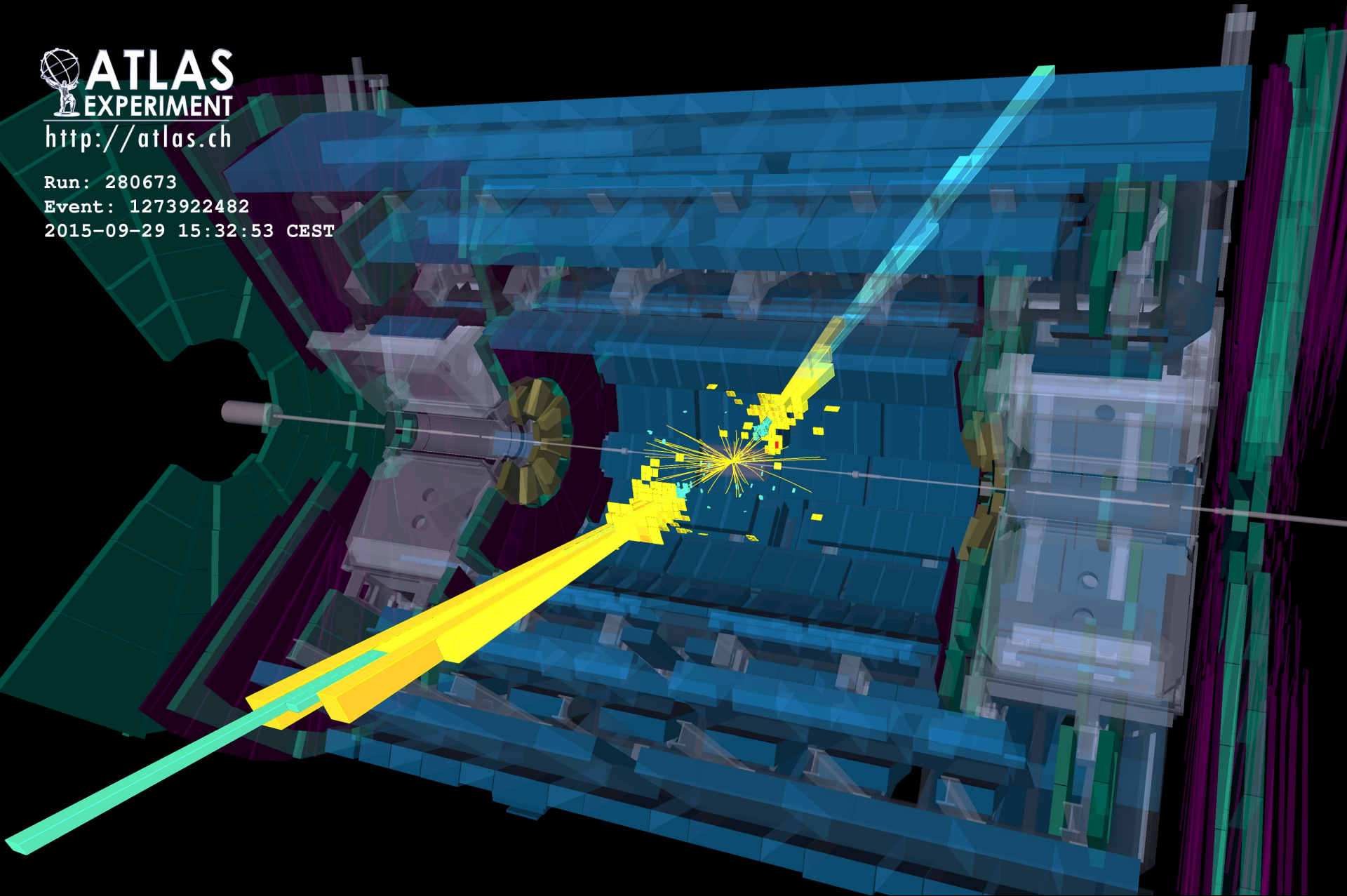


<http://atlas.ch>

Run: 280673

Event: 1273922482

2015-09-29 15:32:53 CEST

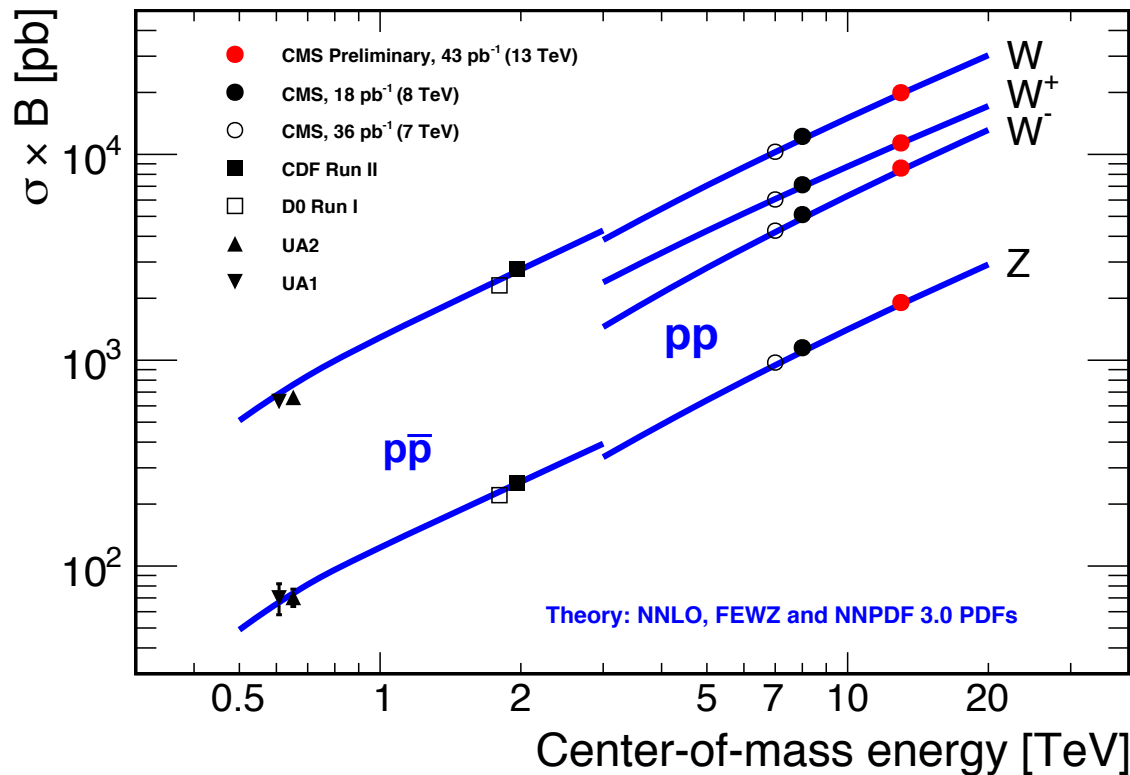


Z and W production at 13 TeV

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



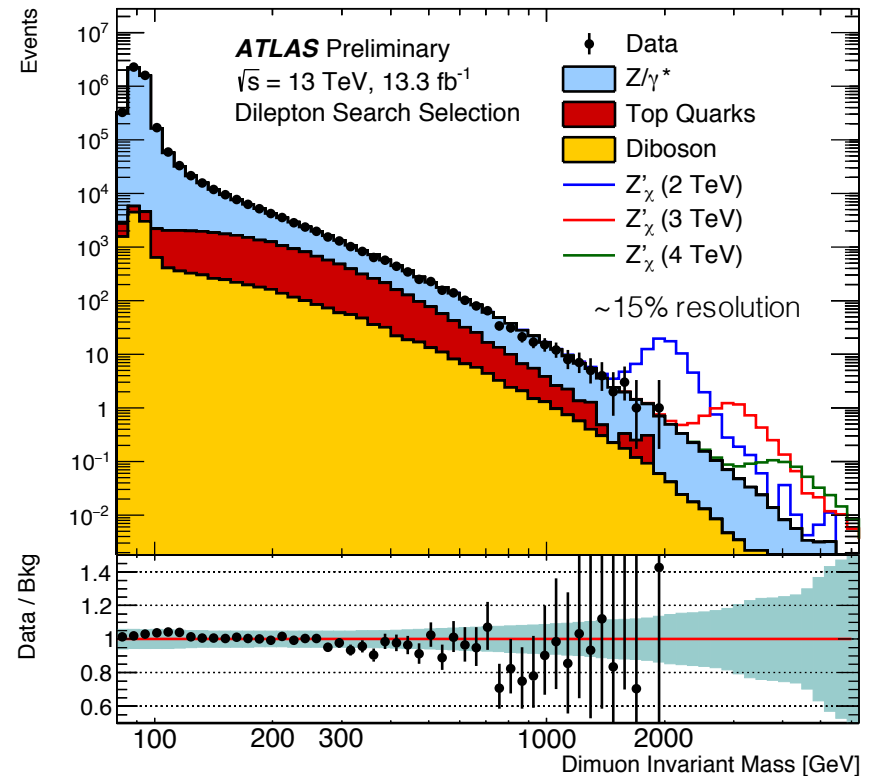
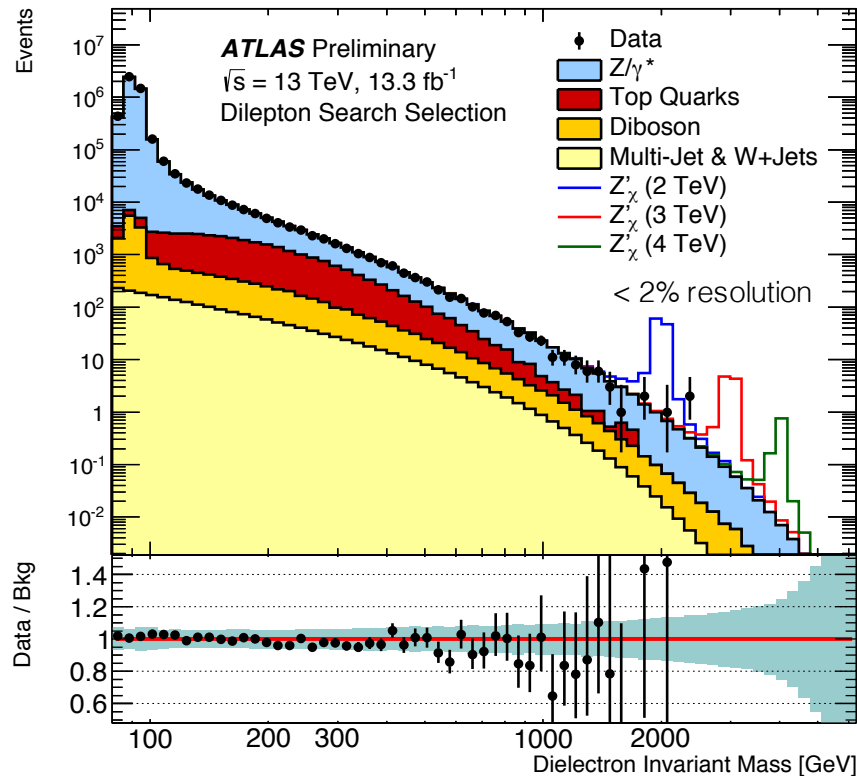
Also: LHCb σ_Z ($2.0 < \eta < 4.5$)
in agreement with SM

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 4.0 / 4.7 TeV (2.9 / 3.3 TeV at 8 TeV)



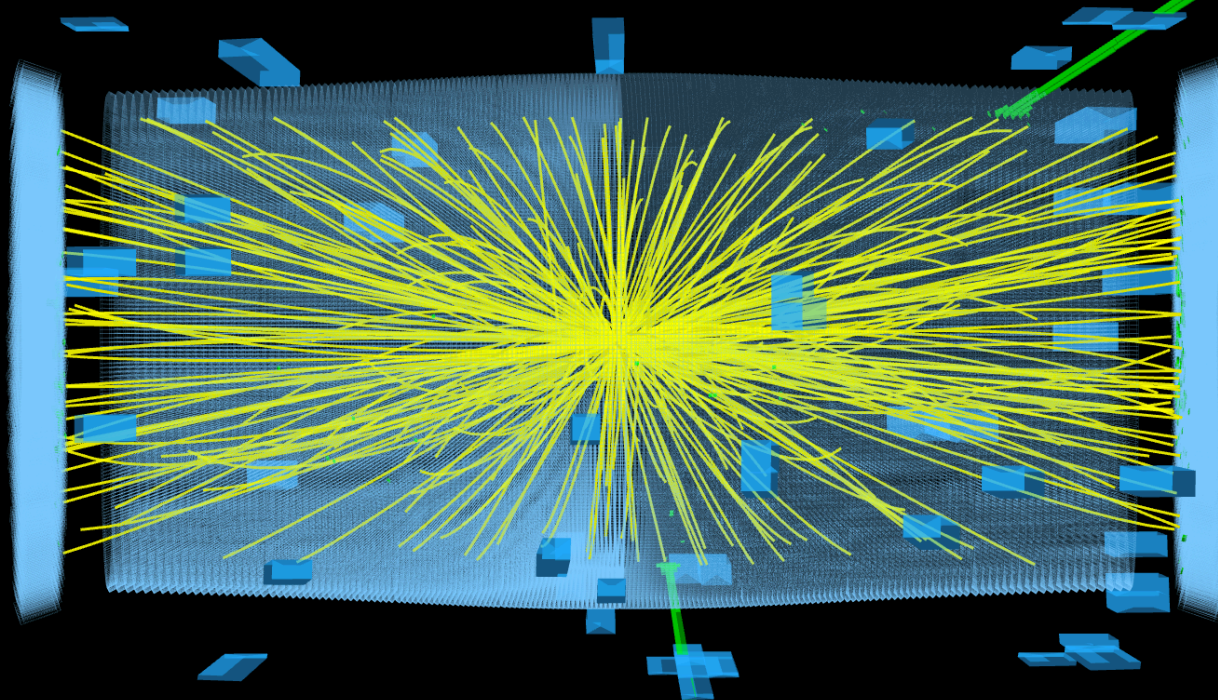
ATLAS & CMS also looked into high-mass $e\mu$ (LFV) production. Main background here: top-antitop.



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

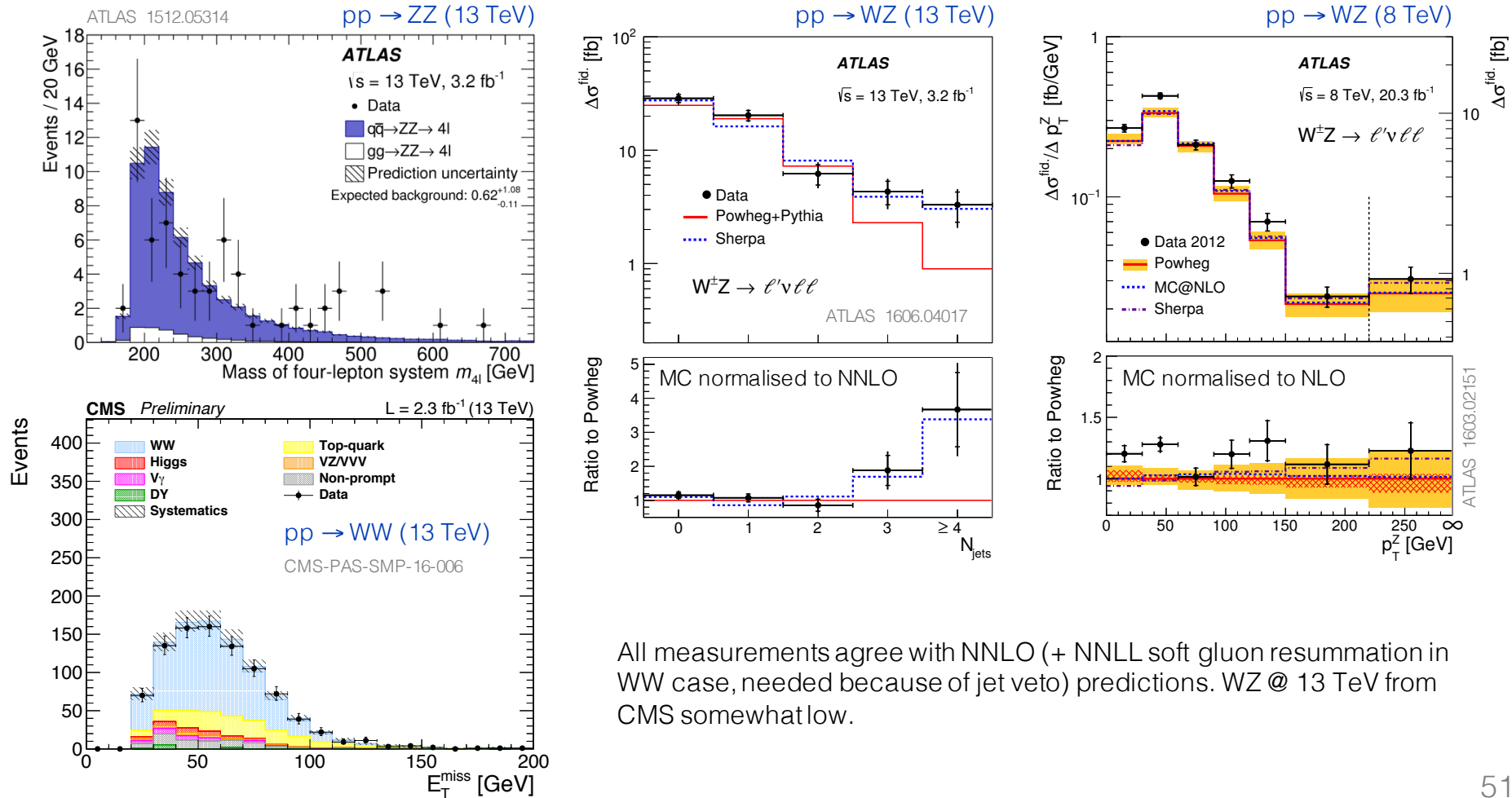
Highest-mass Run-1 events: 1.8 TeV (ee), 1.9 TeV ($\mu\mu$)

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.**



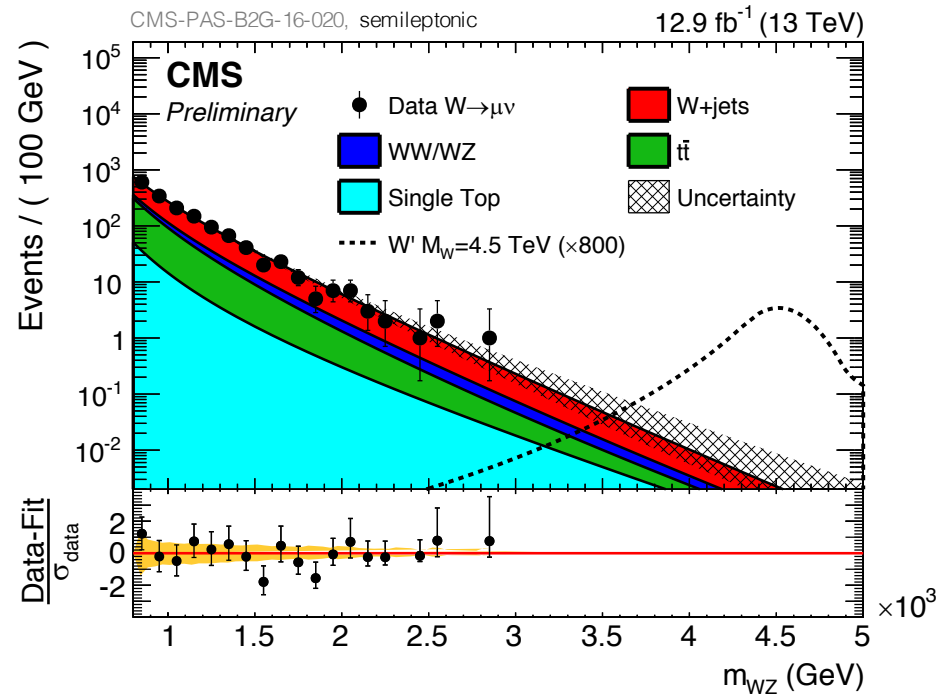
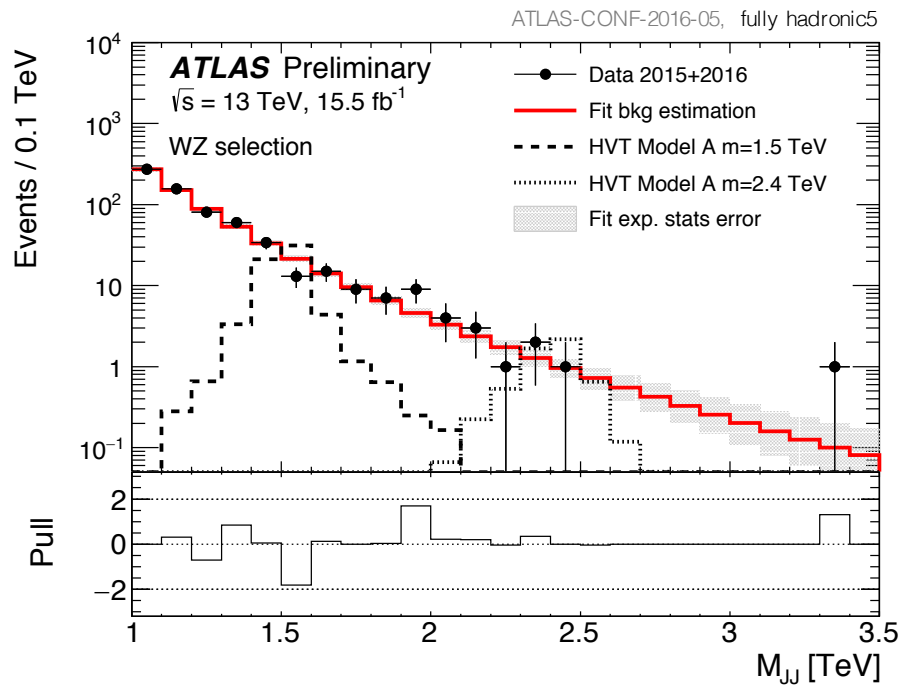
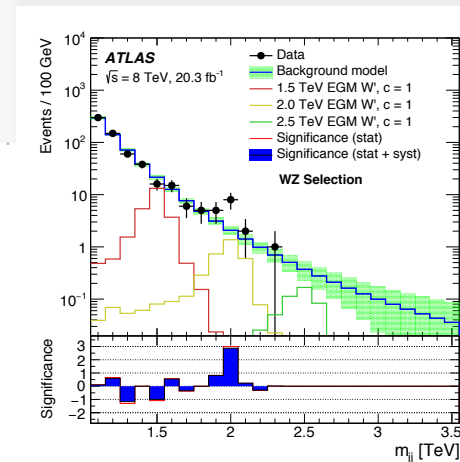
All measurements agree with NNLO (+ NNLL soft gluon resummation in WW case, needed because of jet veto) predictions. WZ @ 13 TeV from CMS somewhat low.

Searches for diboson resonances (hh, Vh, VV)

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

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

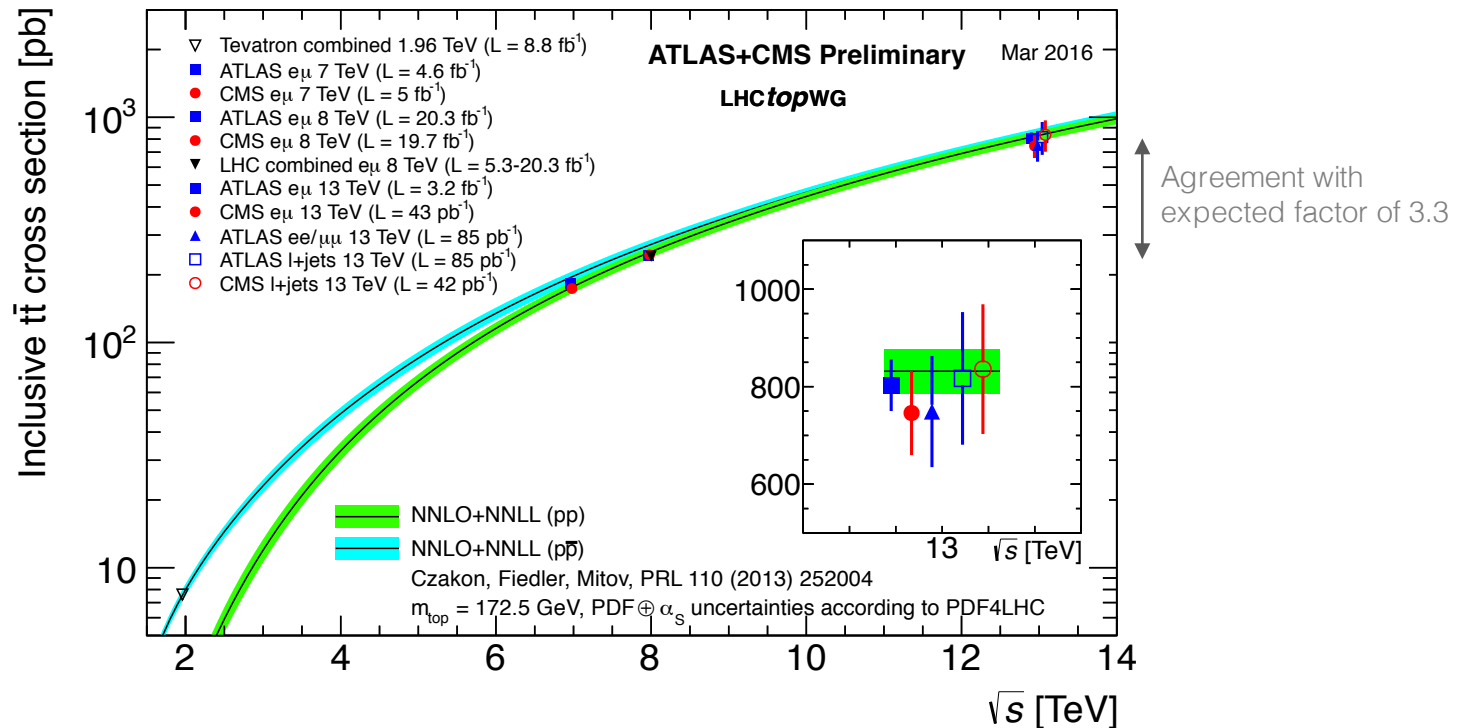
Some excess of events around 2 TeV (globally 2.5σ for ATLAS) seen at 8 TeV in VV in fully hadronic channel, not seen in the other decay channels (eg, $\nu\bar{\nu}q\bar{q}$)



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



Differential cross-section measurements at 13 TeV show reasonable modelling, though some deviations at large jet multiplicity. Known modelling problems from Run-1 not all solved!

Also first results on t-channel single top production — found in agreement with SM

Higgs reobservation at 13 TeV

13/8 TeV cross section ratios of 2~2.4 for VH, ggH, VBF, and 3.9 for ttH

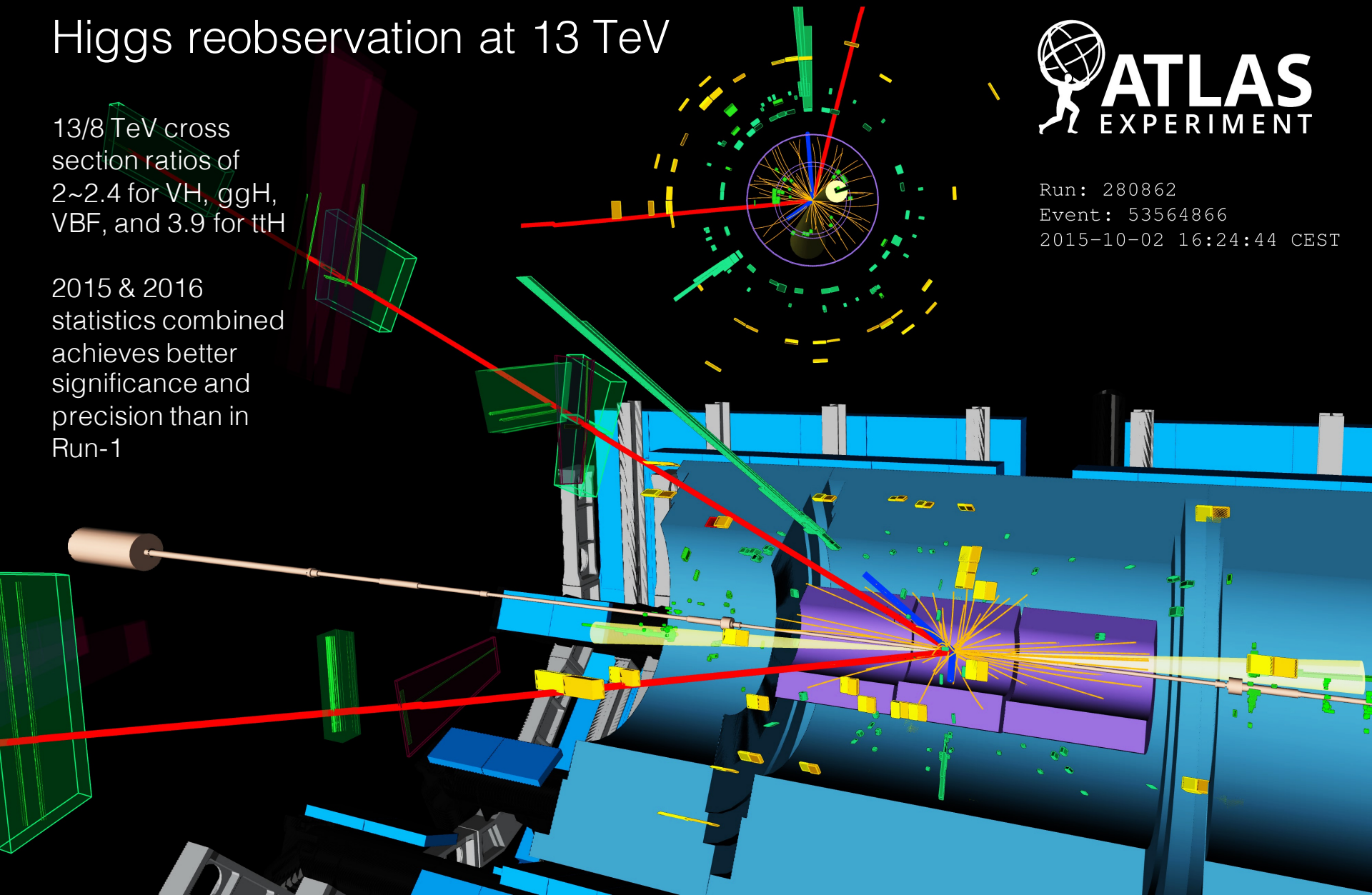
2015 & 2016 statistics combined achieves better significance and precision than in Run-1



Run: 280862

Event: 53564866

2015-10-02 16:24:44 CEST

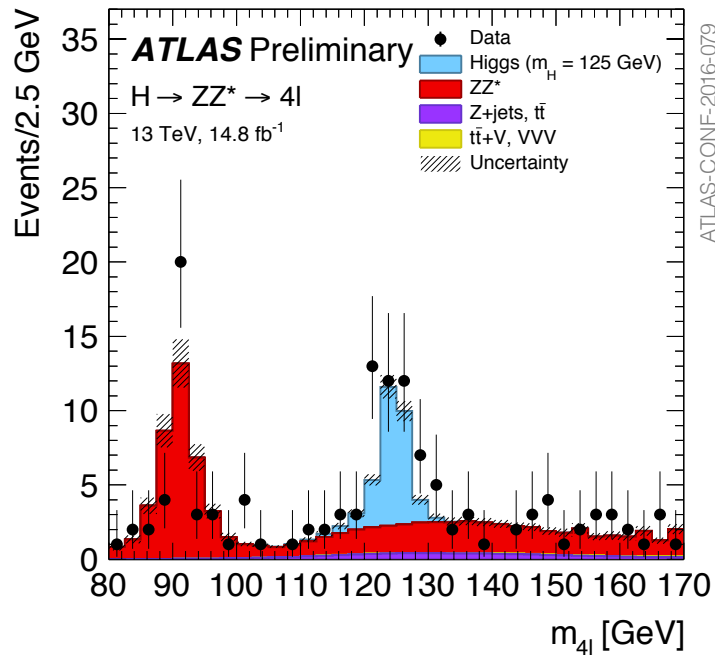


Display of VBF $H \rightarrow e\bar{e}\mu\mu + 2\text{jets}$ candidate from 13 TeV pp collisions. The electrons have a transverse momentum of 111 and 16 GeV, the muons 18 and 17 GeV, and the jets 118 and 54 GeV. The invariant mass of the four lepton system is 129 GeV, the dielectron (dimuon) invariant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

ATLAS and CMS studied H_{125} in bosonic channels

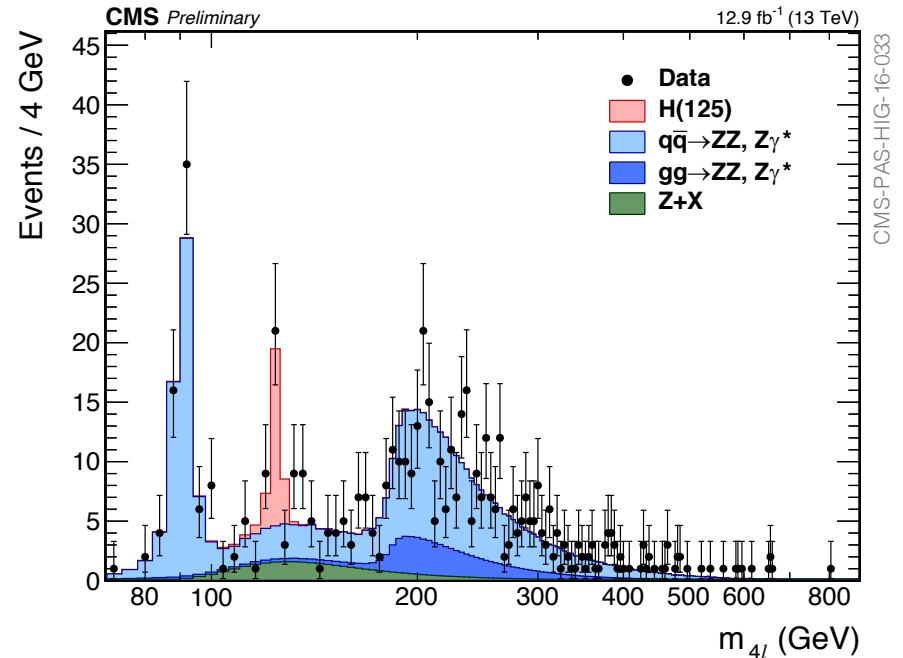
Preliminary fiducial and total cross-section and coupling measurements (ggF and VBF significant)

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



$$\sigma_{\text{tot,data}} = 81^{+18}_{-16} \text{ pb}$$

$$\sigma_{\text{tot,SM}} = 55 \pm 4 \text{ pb}$$



$$\mu = \sigma_{\text{data}} / \sigma_{\text{SM}} = 0.99^{+0.33}_{-0.26}$$

Expected significance (SM): 6.5 σ

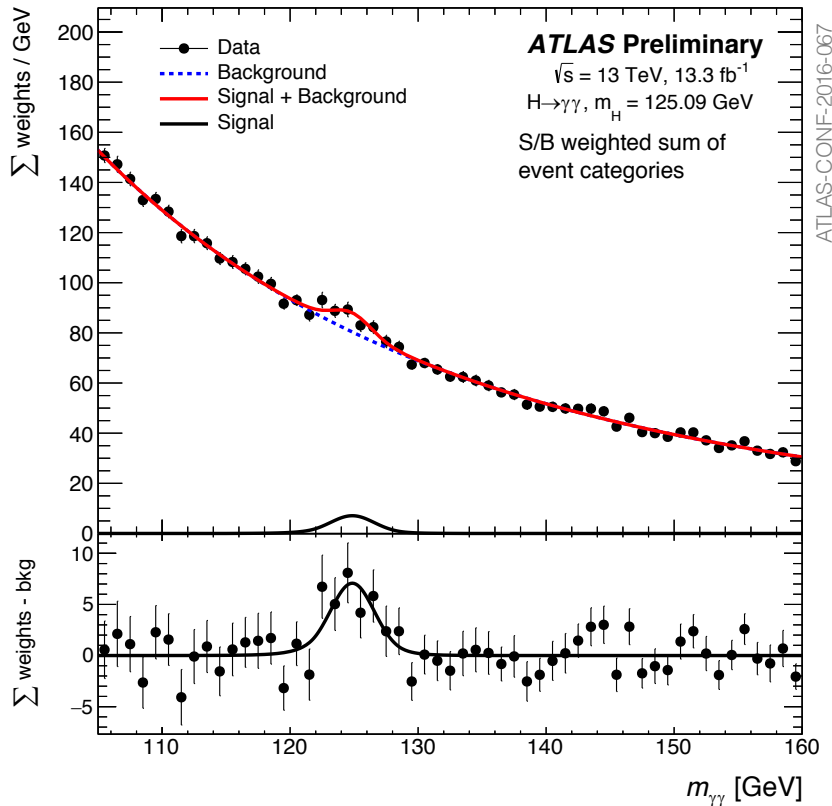
CMS also measured: $m_H = 124.50^{+0.48}_{-0.44} \text{ GeV}$

(dominated by statistical uncertainty, compare to $125.09 \pm 0.24 \text{ GeV}$ from ATLAS & CMS Run-1 combination)

ATLAS and CMS studied H_{125} in bosonic channels

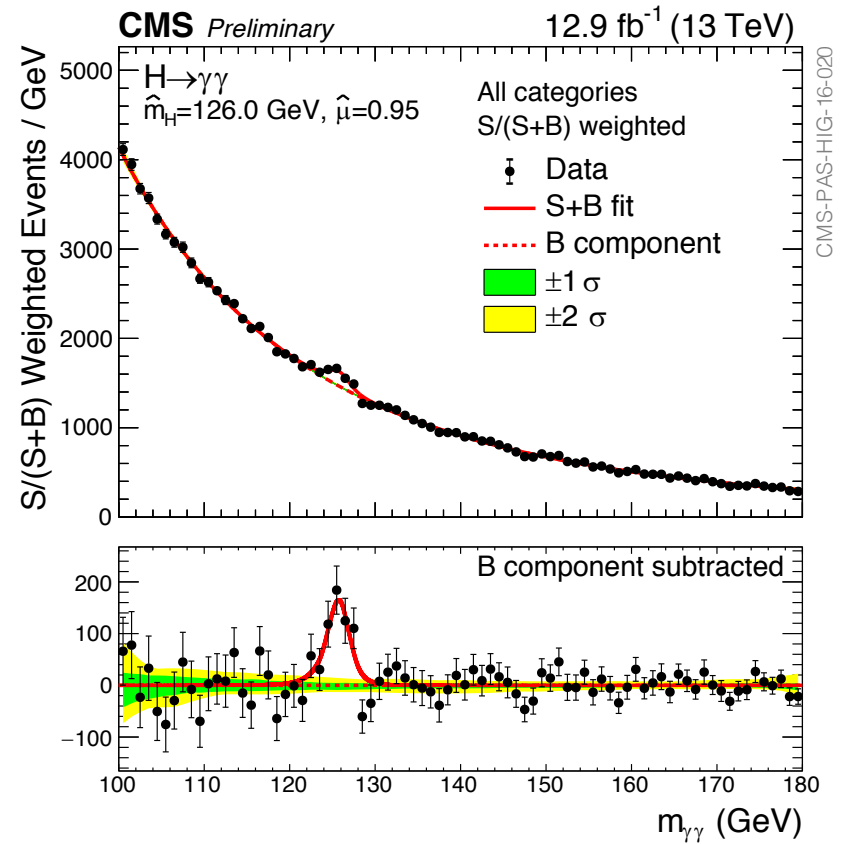
Preliminary fiducial and total cross-section and coupling measurements (ggF and VBF significant)

$H \rightarrow \gamma\gamma$



$$\mu = 0.85^{+0.22}_{-0.20}$$

Expected significance (SM): 5.4σ



$$\mu = 0.91 \pm 0.20$$

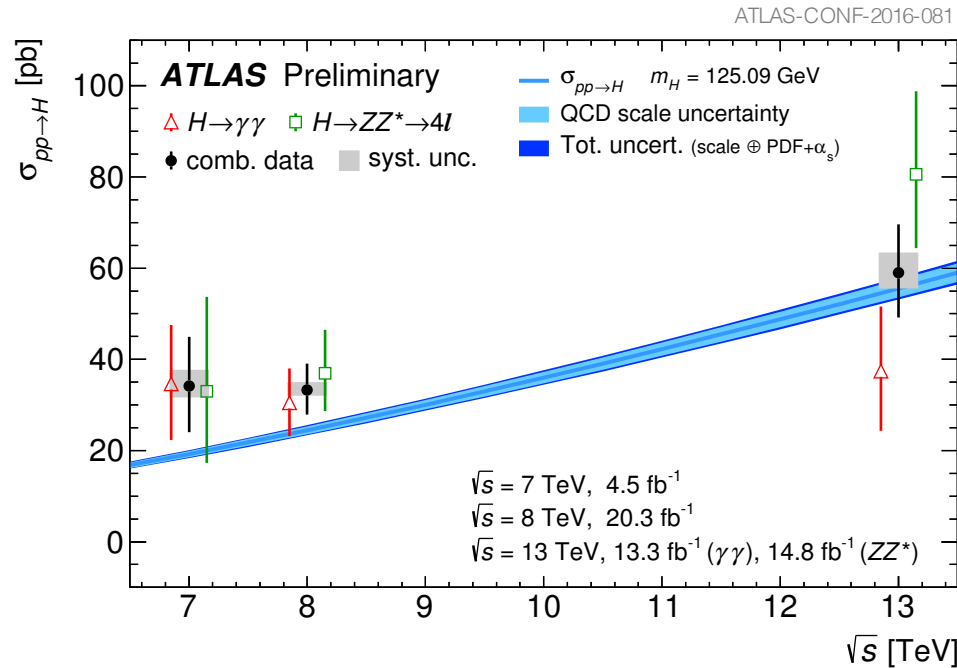
Expected significance (SM): 6.2σ

ATLAS and CMS studied H_{125} in bosonic channels

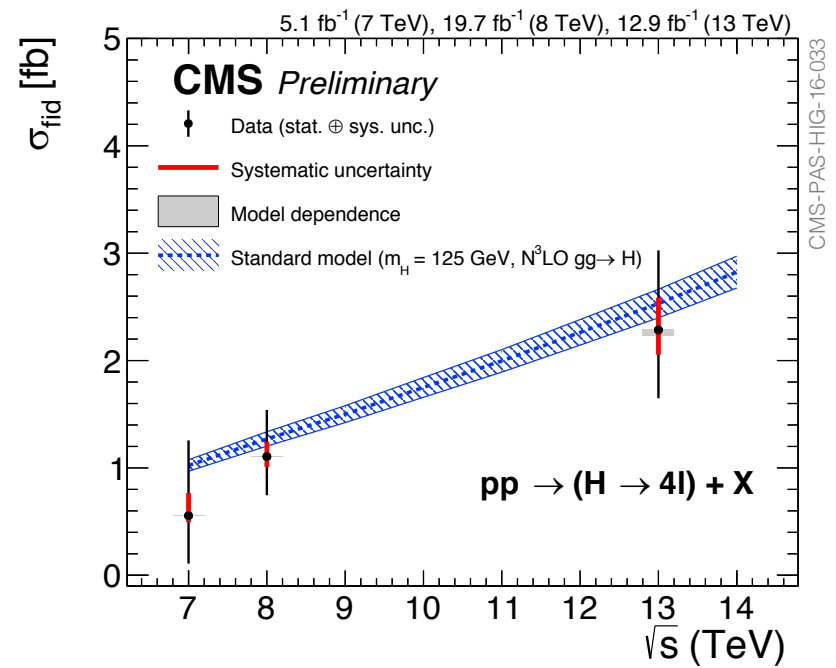
Cross section versus centre-of-mass energy

$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ combined (left)

Combined $H \rightarrow 4\ell, \gamma\gamma$



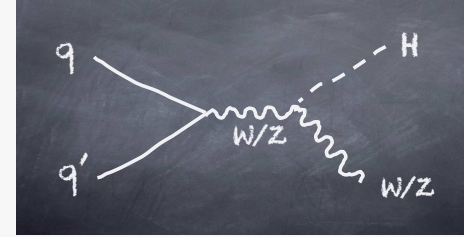
$H \rightarrow 4\ell$, *fiducial* cross section



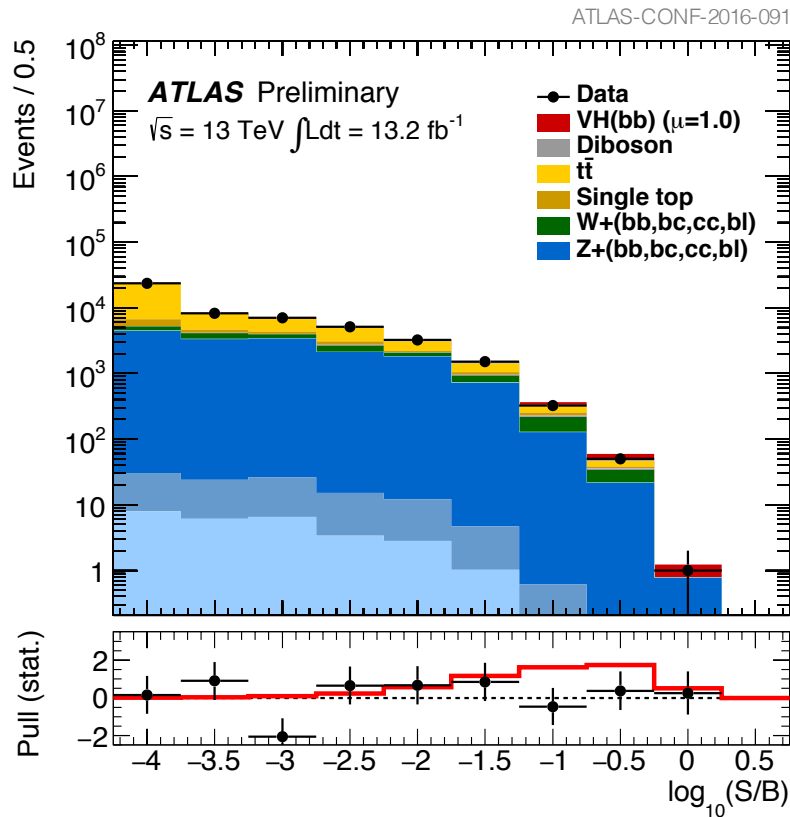
Expected rise of cross-section observed in data

ATLAS studied H_{125} in bb decay channel

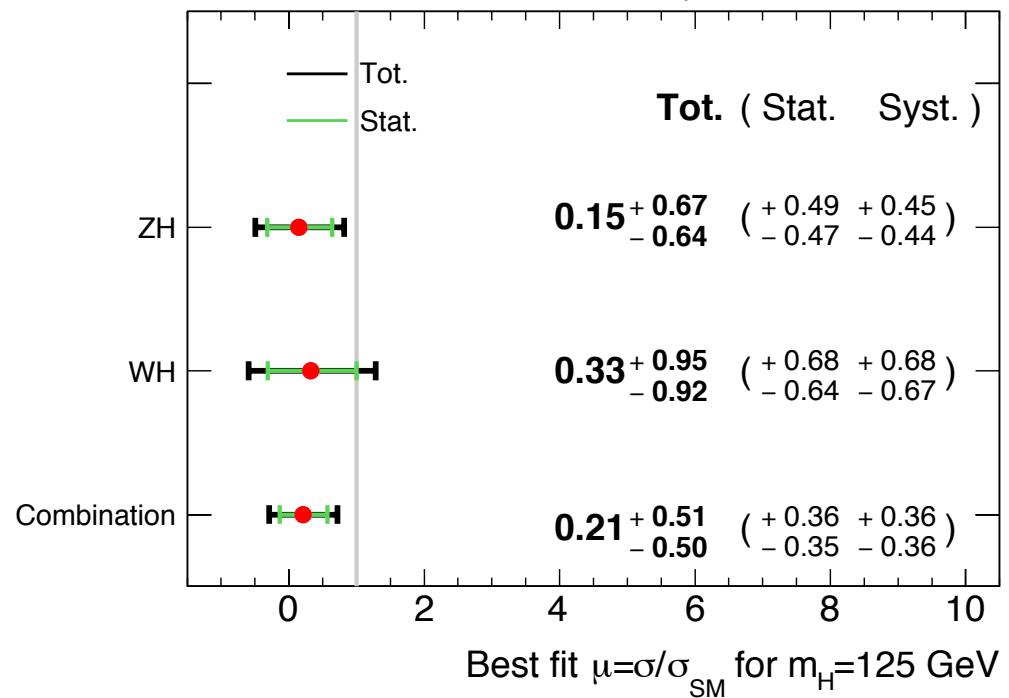
Associated production, challenging final states



$H \rightarrow W/Z + H \rightarrow \ell\nu / \ell^+\ell^-, \nu\nu + bb$



ATLAS Preliminary $\sqrt{s}=13 \text{ TeV}$, $\int \mathcal{L} dt = 13.2 \text{ fb}^{-1}$



Slightly lower yield than SM, similar for Run-1

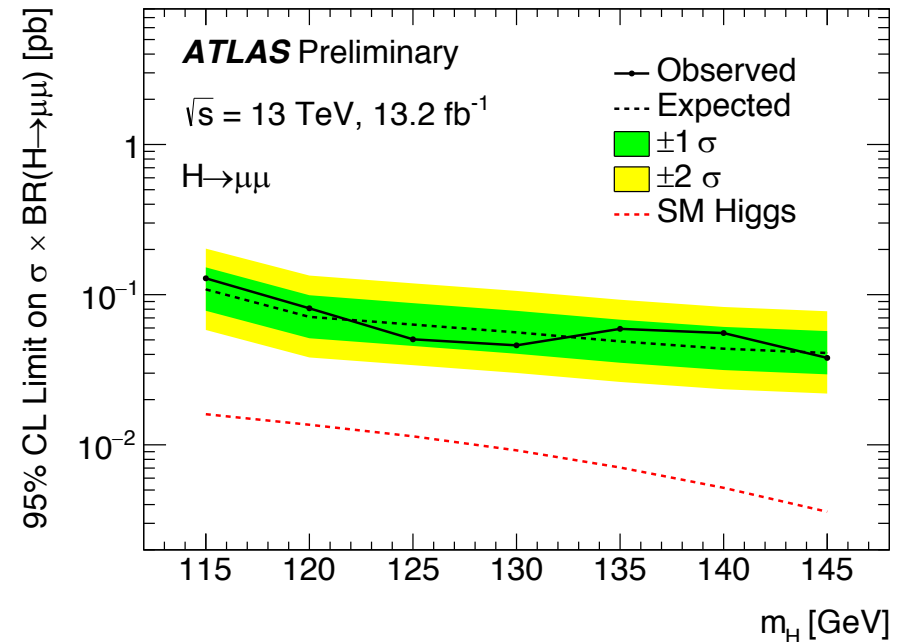
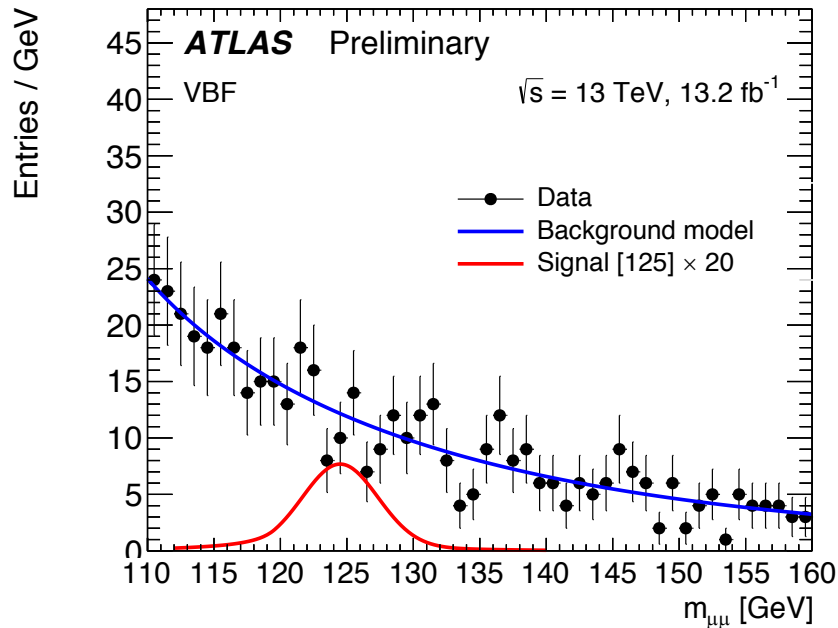
($\mu = 0.7 \pm 0.3$ for ATLAS & CMS, $\mu = 0.5 \pm 0.4$ for ATLAS)

Searches for rare Higgs decays

Beyond SM reach at present, but could have new physics contributions ?

$H \rightarrow \mu\mu$ [expected branching fraction: 0.02%]

Strongly resolution dependent, improve sensitivity by categorising events (low/high p_T , central/forward, VBF)



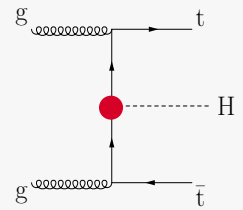
Observed limit 4.4 times SM (3.5 combined with Run-1). Need about 300 fb^{-1} of data to reach SM

Can already exclude universal Higgs coupling to fermions !

(Would have observed $H \rightarrow \mu\mu$, if same BR as $H \rightarrow \tau\tau$)

First search for ttH production at 13 TeV by CMS

Direct measurement of Higgs–top coupling



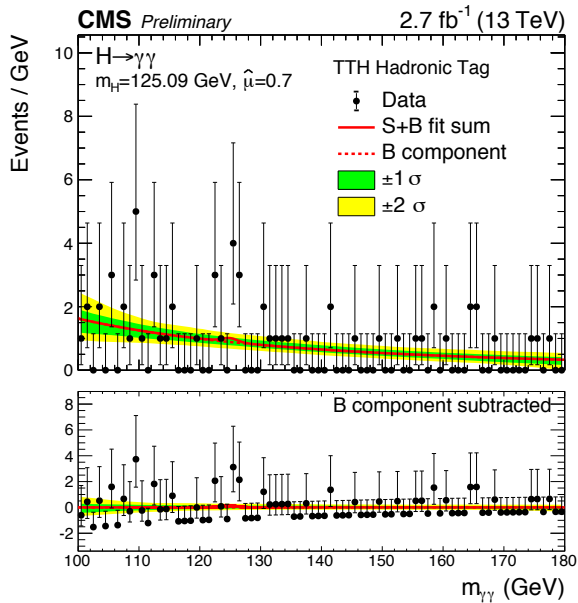
CMS showed preliminary results for ttH in all major Higgs decay channels: **H → γγ, multi-leptons, bb**

Highly complex analyses, huge effort to get these done so quickly after data taking (already by Moriond 2016)

H → γγ,
tt → 0 & 1 leptons

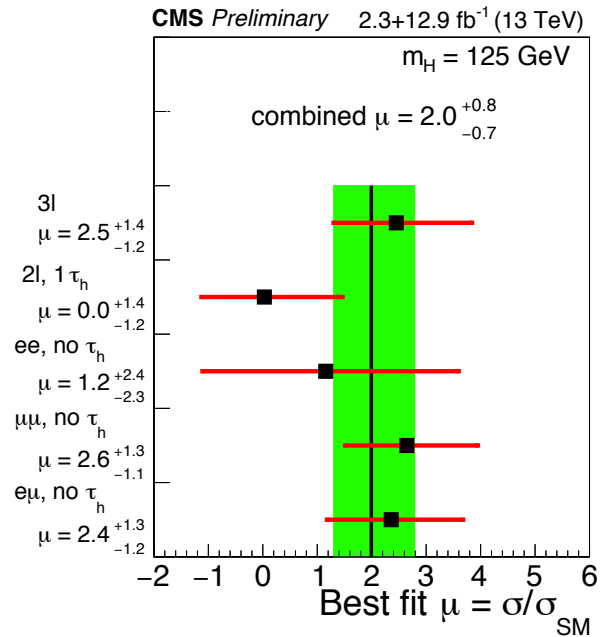
ttH → multi-leptons
2 same charge (+ τ) / 3 leptons

H → bb
tt → 1 & 2 leptons



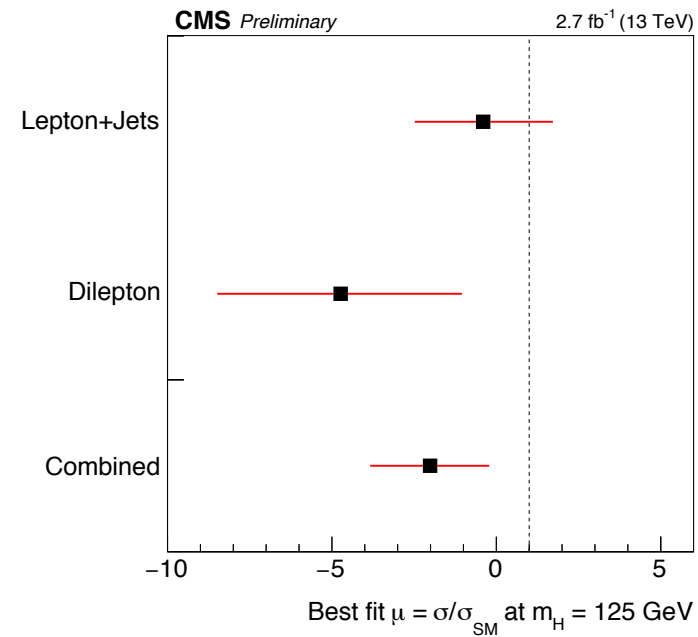
$$\mu = 3.8^{+4.5}_{-3.6}$$

CMS-PAS-HIG-15-005



$$\mu = 2.0^{+0.8}_{-0.7}$$

CMS-PAS-HIG-16-022

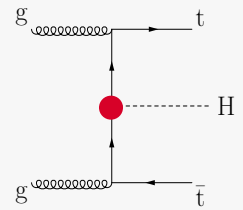


$$\mu = -2.0 \pm 1.8 < 2.6 \text{ (95\% CL)}$$

CMS-PAS-HIG-16-004

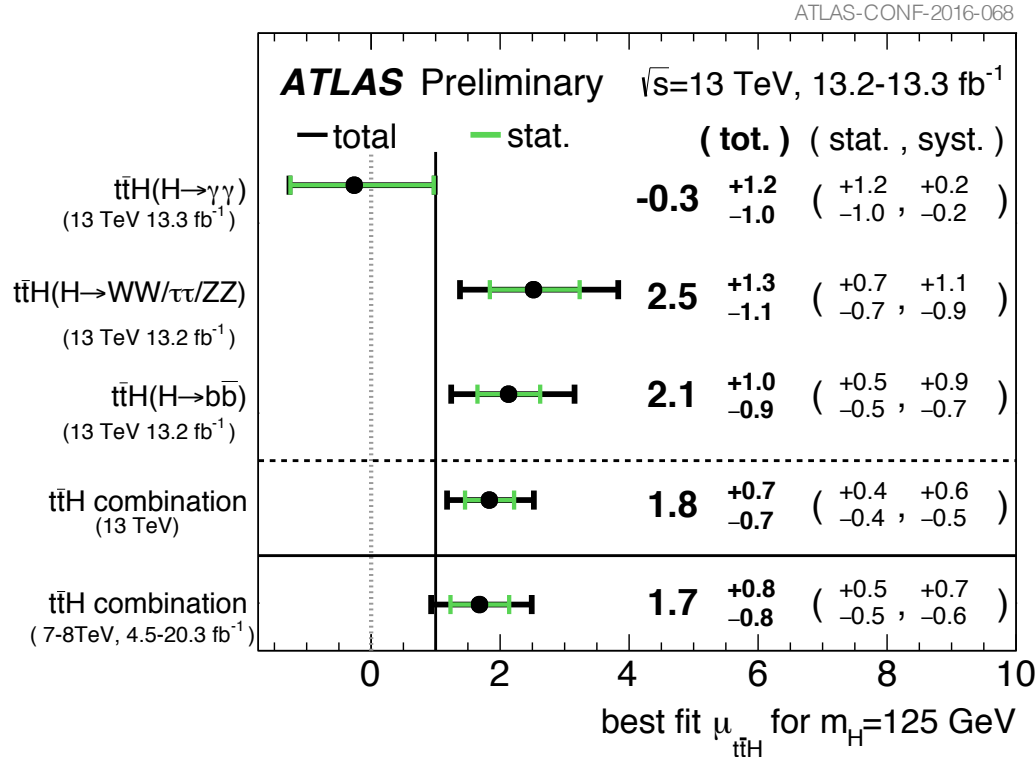
First search for ttH production at 13 TeV by ATLAS

Direct measurement of Higgs-top coupling



ATLAS showed preliminary results for ttH in **all major channels** and their combination at ICHEP 2016

Individual channels and combination

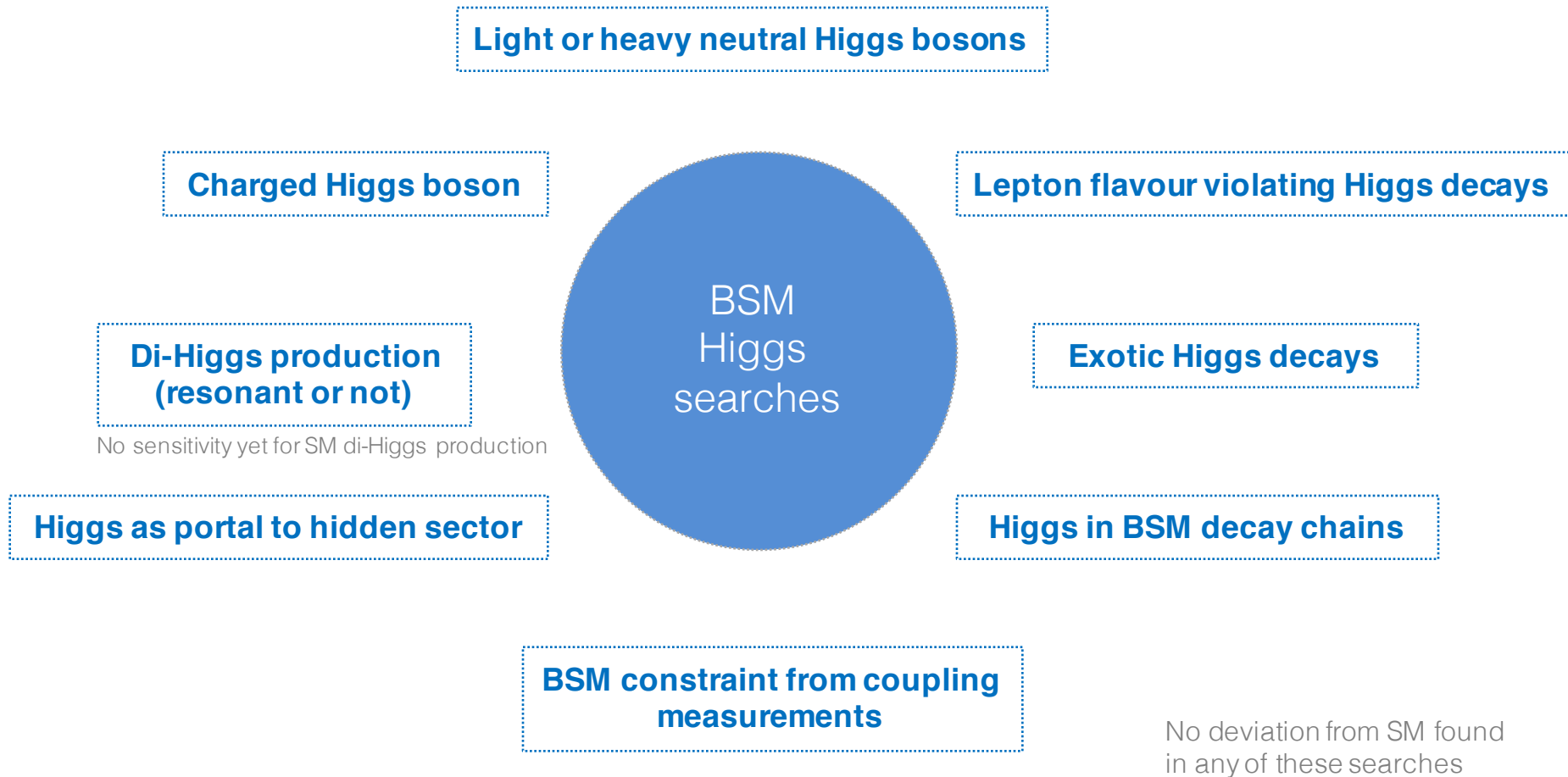


Improved sensitivity
over Run-1

Beyond the Standard Model Higgs physics

Higgs sector may be non-minimal and/or Higgs boson may couple to new physics

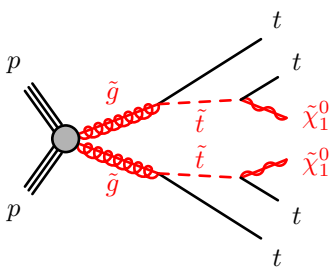
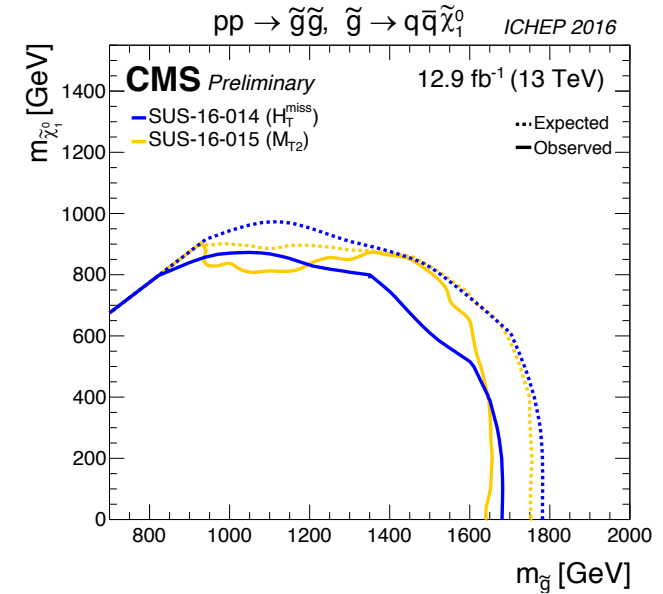
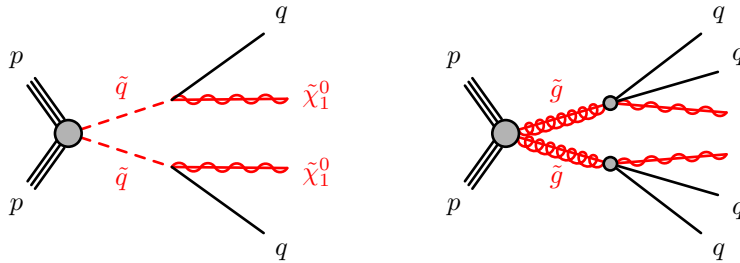
Diverse search programme:



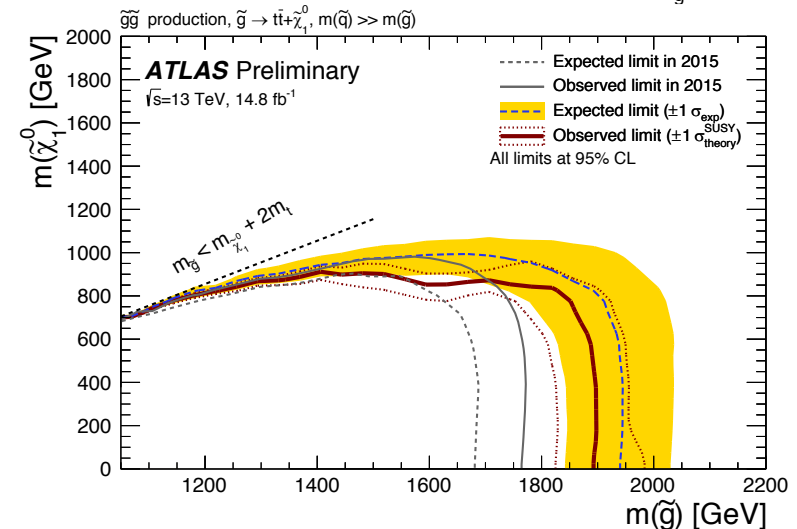
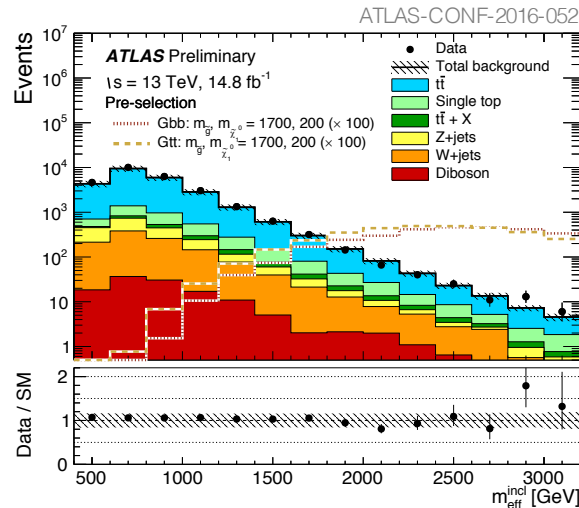
Supersymmetry

Offers elegant solution to: naturalness problem, unification, dark matter

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

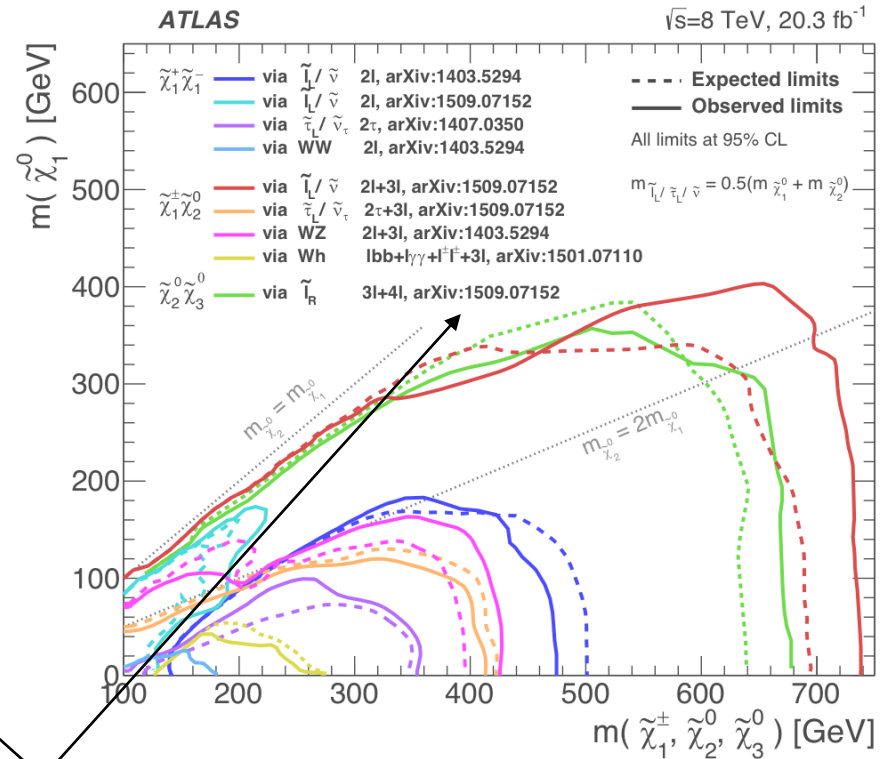
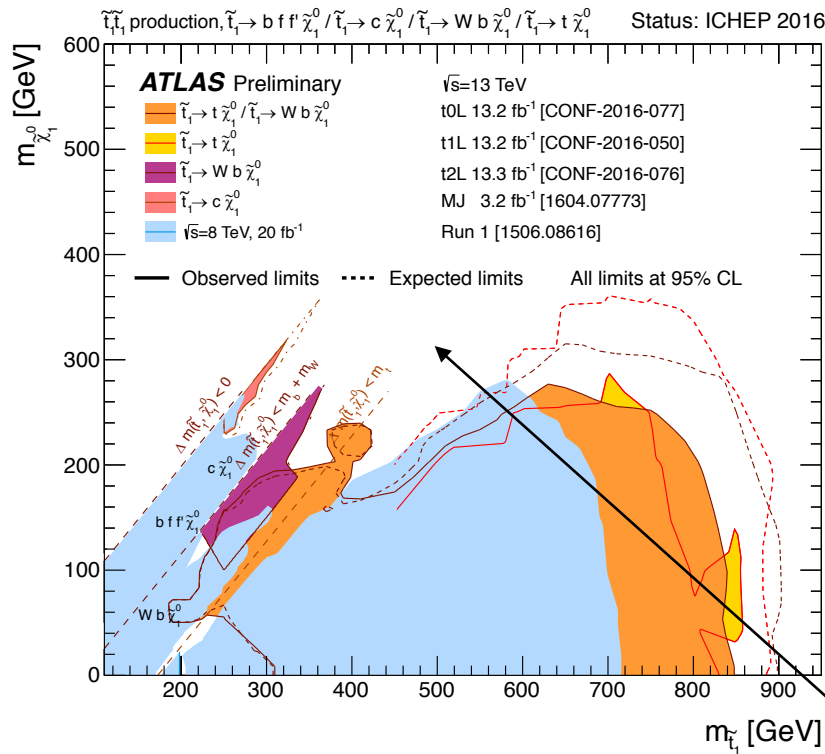
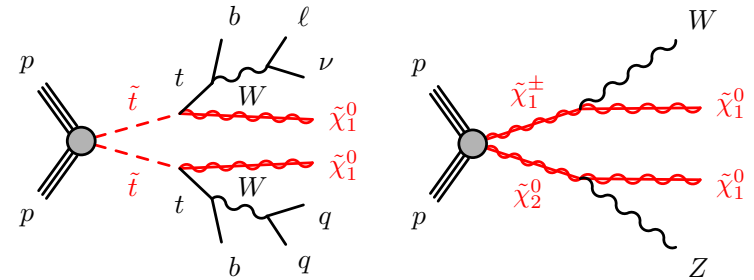


Naturalness driven SUSY searches

Searches for direct production of stop/sbottom & charginos/neutralinos

SUSY stop and sbottom, or “Electroweak-inos”

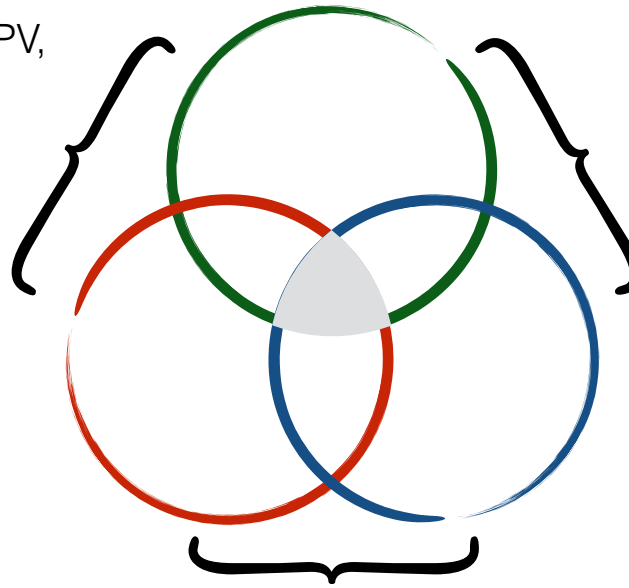
may be the lightest SUSY particles. Low-cross section searches requiring dedicated optimisation. Long-term search effort



“Compressed” regions

Naturalness & Unification

- Light-flavor UDD RPV, LQD w/ taus
- RPV Higgsino
- Higgs properties
- <Your idea here>



Naturalness & Dark Matter

- Additional states near weak scale (sgluon, KK resonances, ...)
- Higgs properties
- <Your idea here>

Unification & Dark Matter

- Conventional split SUSY searches
- Pure wino, higgsino LSP
- Extended Higgs sector?
- <Your idea here>

Good idea ?

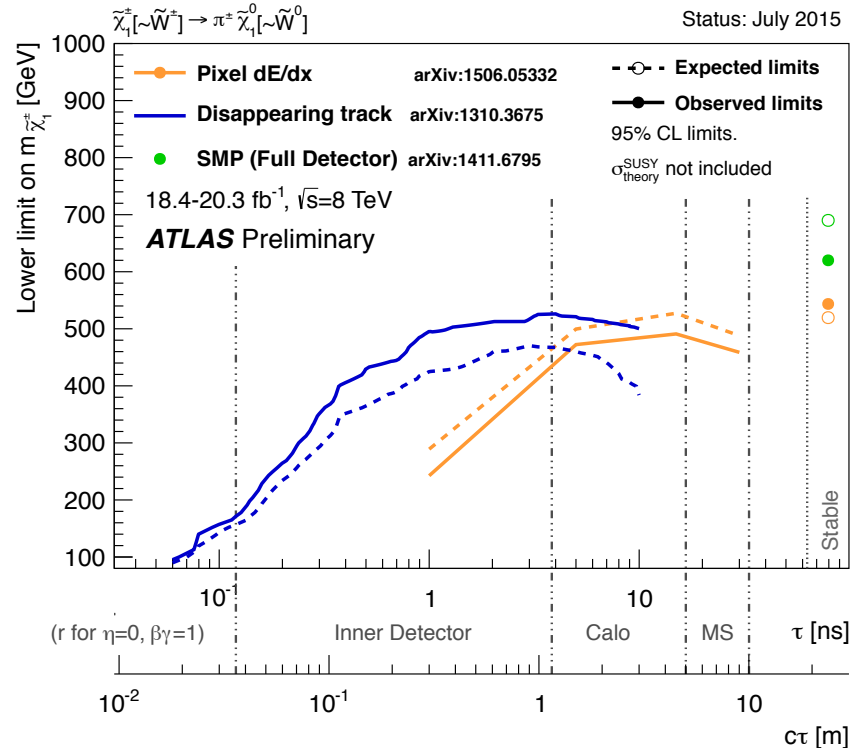
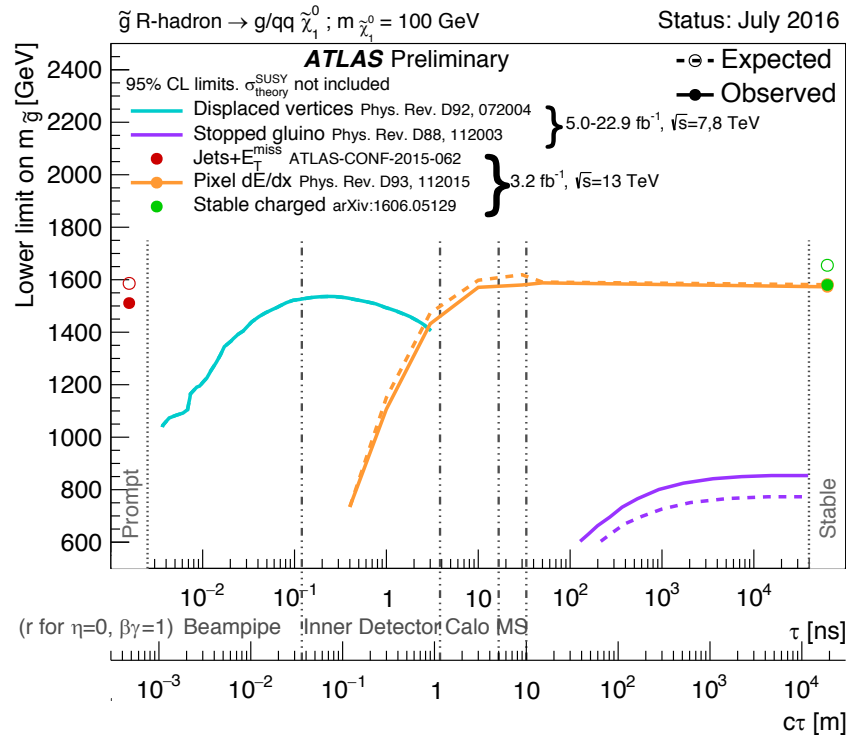
Long-lived particles predicted in many new physics models

Reason: large virtuality in decay, low coupling, or mass degeneracy

Multitude of signatures depending on lifetime, charge, decay: highly ionising, slow, out-of-time decay, displaced vertex, kinked or disappearing track, lepton-jets, ...

Some signatures require dedicated triggers, most requiring dedicated analysis strategies.

Standard searches sometimes sensitive to signatures with long-lived particles as well



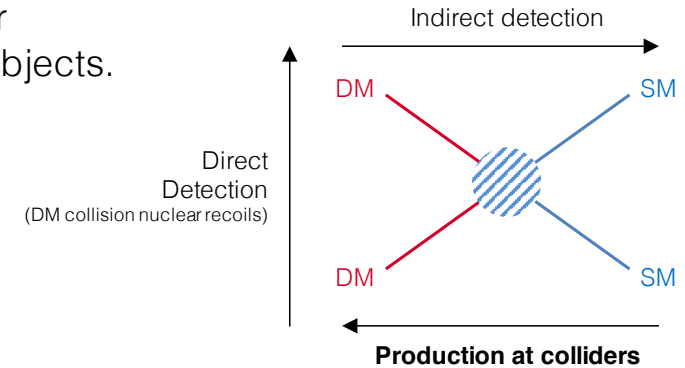
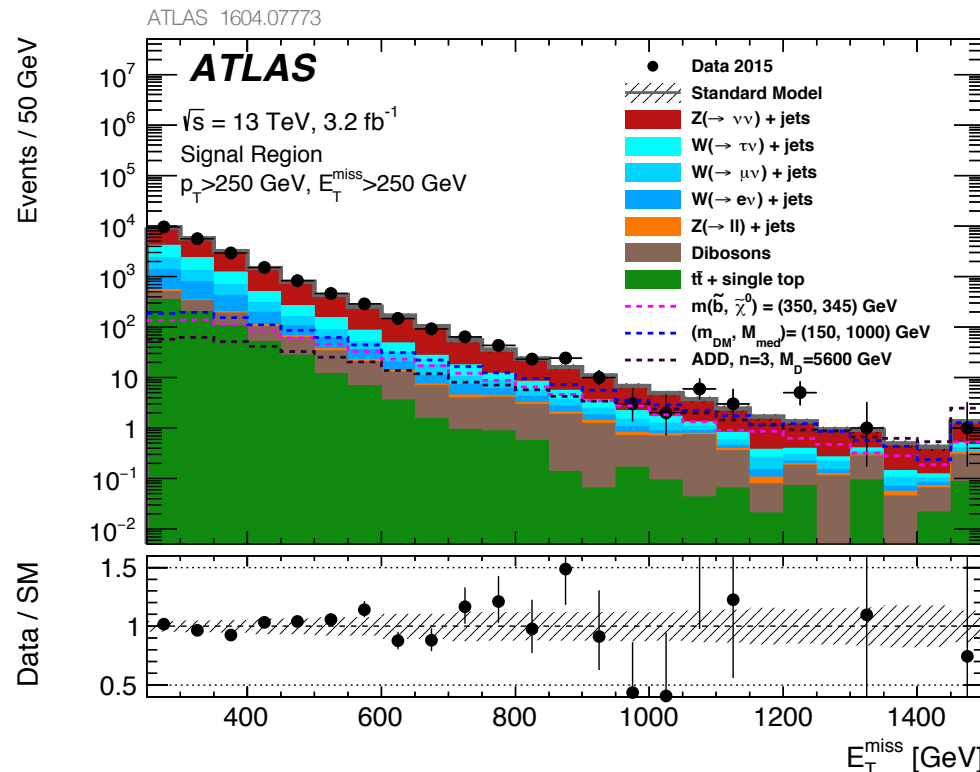
Searches for dark matter production at the LHC

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

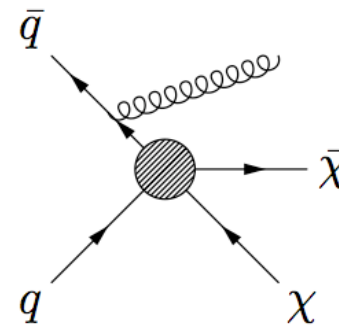
May not be able to prove at LHC that a signal is dark matter

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+jets background. Theory input needed.



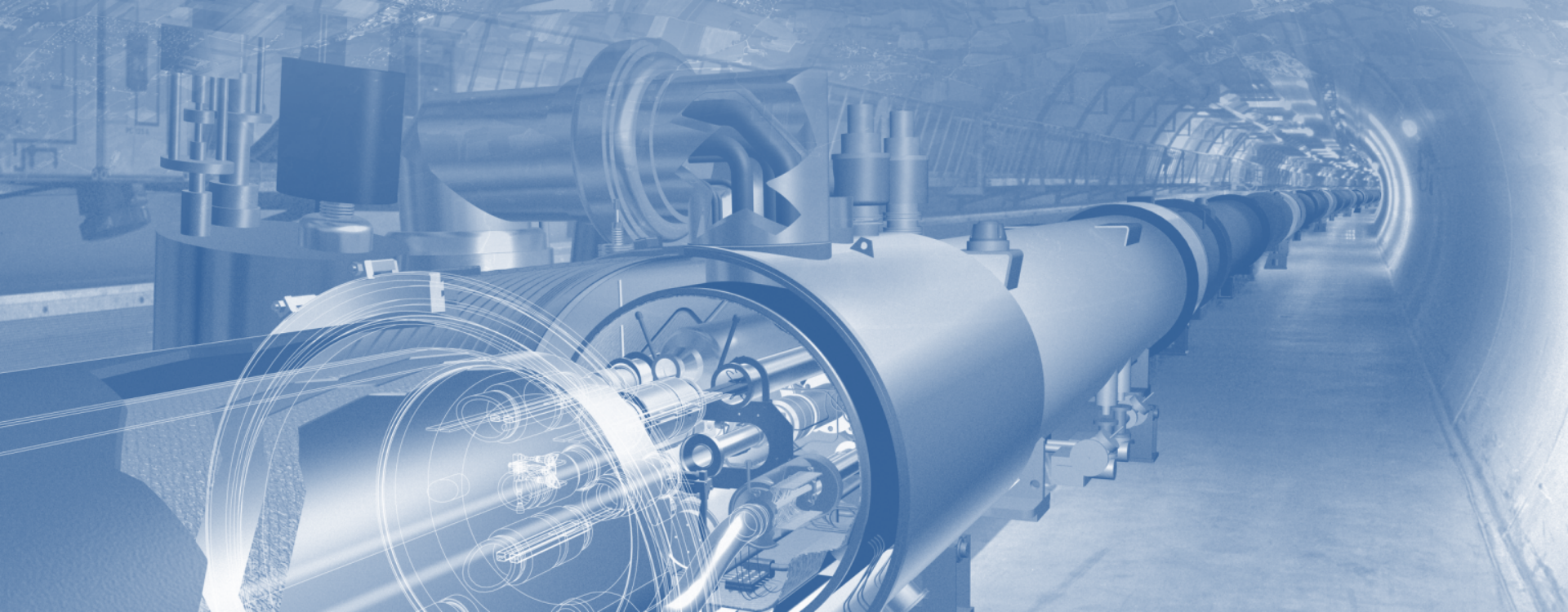
Energetic gluon/photon radiation in the initial state



Many other 13 TeV results available:

- jets + MET
- γ + MET
- V + MET
- H + MET
- $t\bar{t}$ + MET

No anomaly seen so far

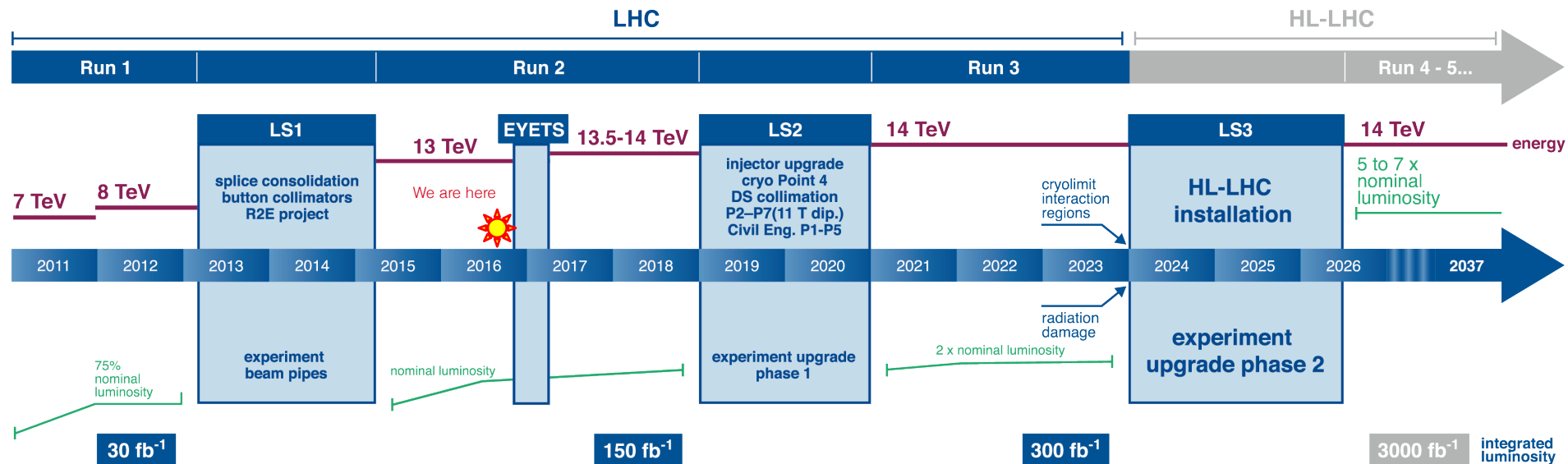


The next steps

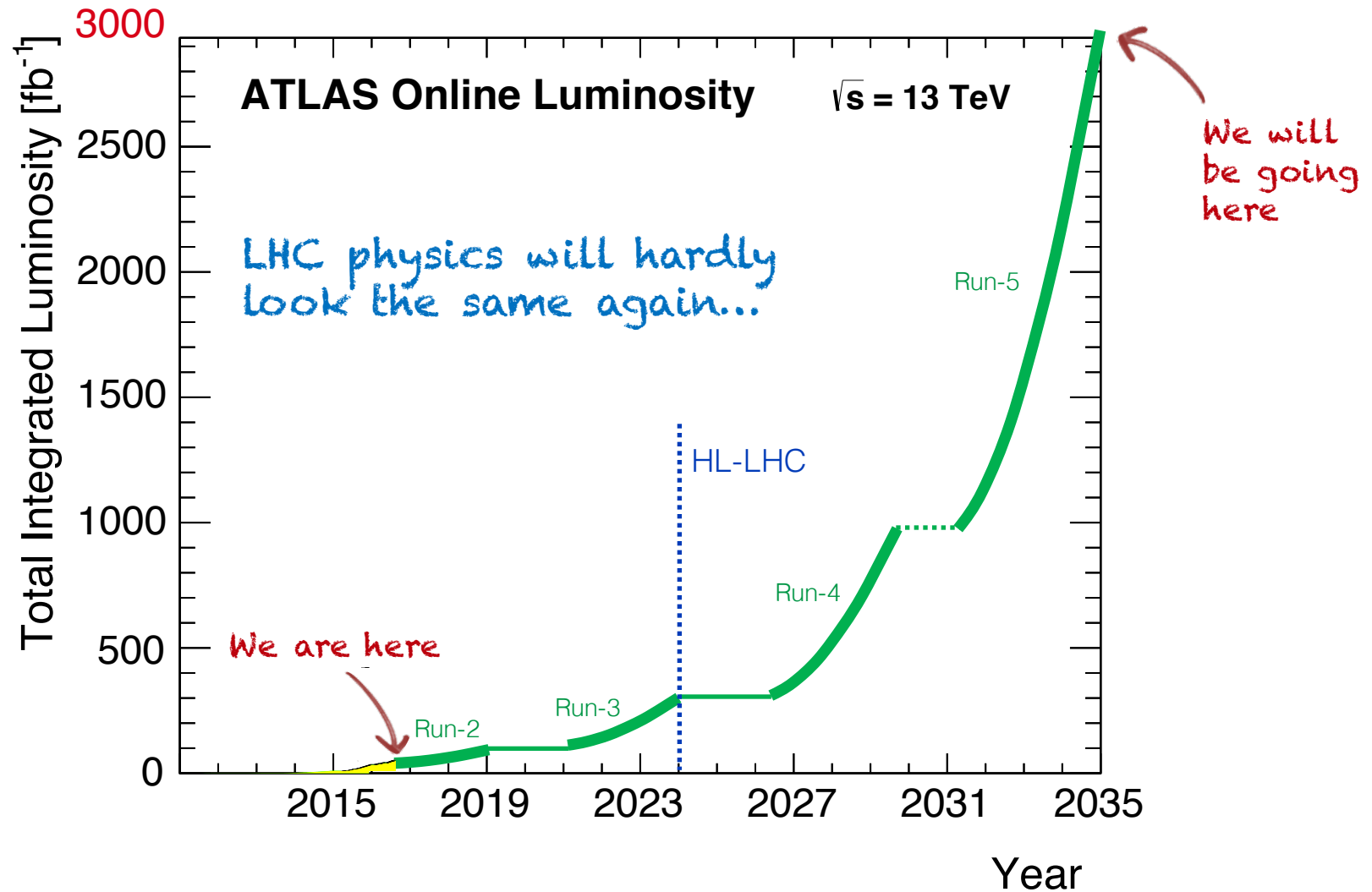
The road to the future

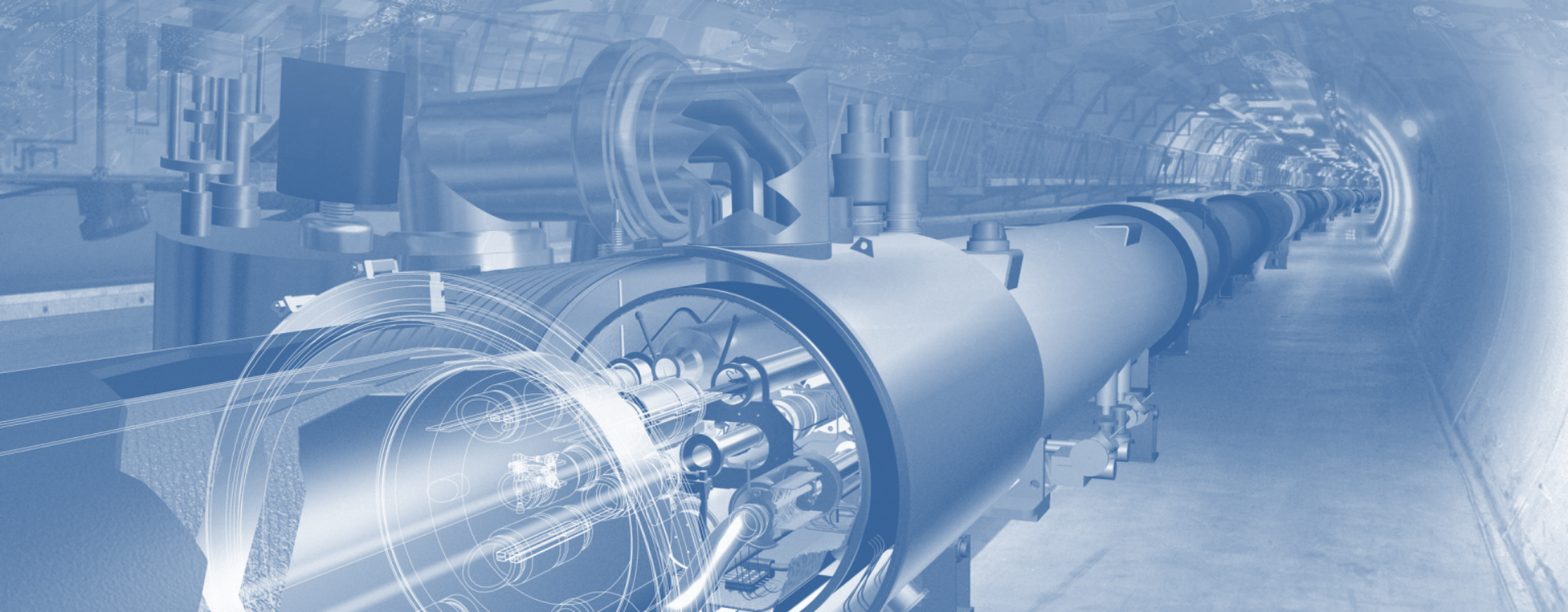
The LHC Run-2 and beyond

LHC / HL-LHC Plan



Expected integrated luminosity of LHC & HL-LHC





Prospects for the LHC Run-2/3 and beyond (HL-LHC)

Three examples only !

Of course: any detection of new physics till then would likely be a game changer !

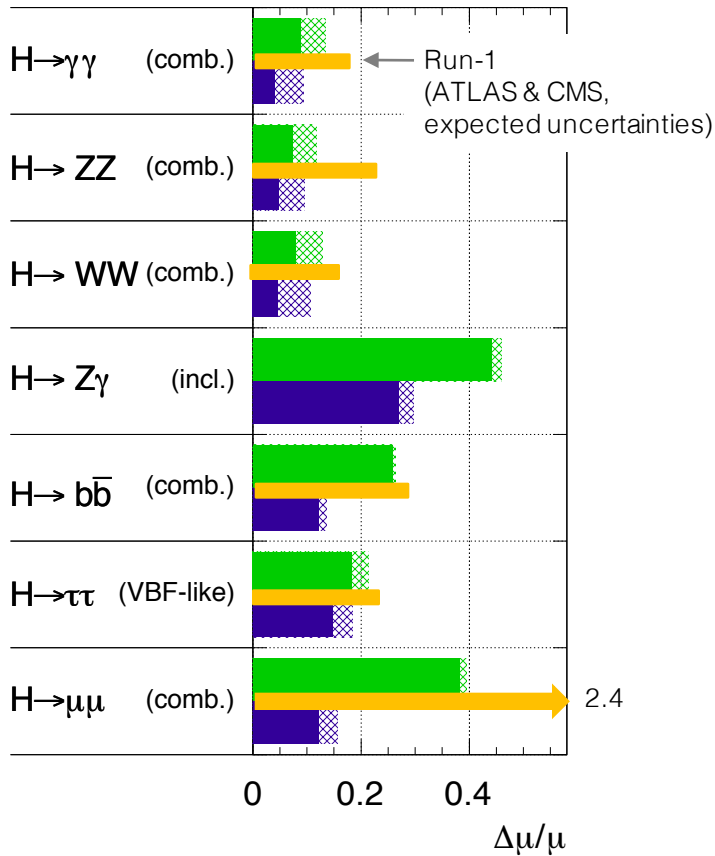
Higgs boson physics

(Conservative) extrapolation of Higgs coupling measurements

Higgs signal strengths (left) and ratios of coupling modifiers (right), compared to current precision (orange)

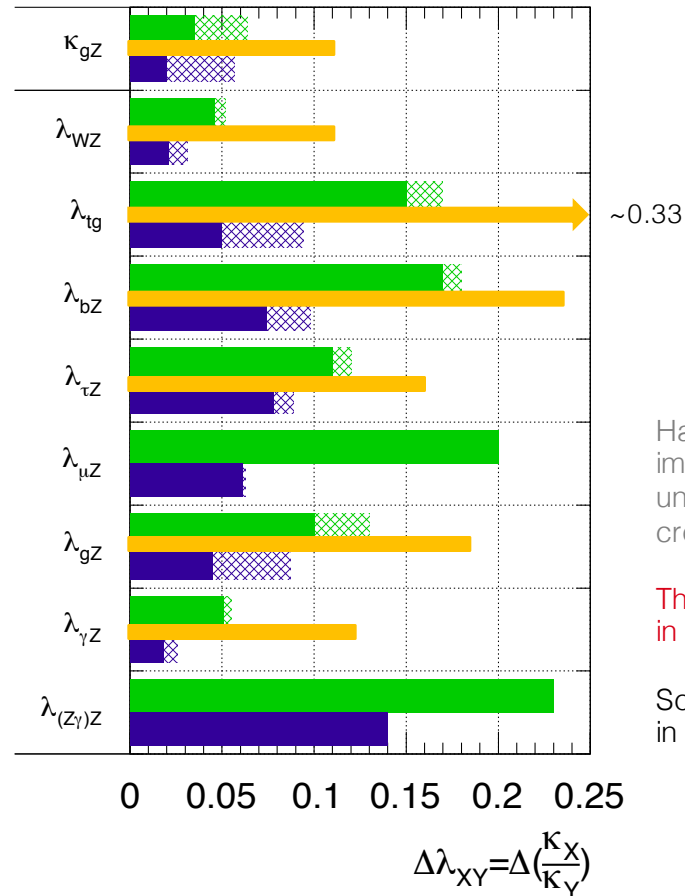
ATLAS Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



ATLAS Simulation Preliminary

$\sqrt{s} = 14$ TeV: $\int \mathcal{L} dt = 300 \text{ fb}^{-1}$; $\int \mathcal{L} dt = 3000 \text{ fb}^{-1}$



$$\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\lambda_{ij} = \frac{\kappa_i}{\kappa_j}$$

Hatched areas indicate impact of theoretical uncertainties on expected cross-sections

Theory uncertainty limiting in several cases

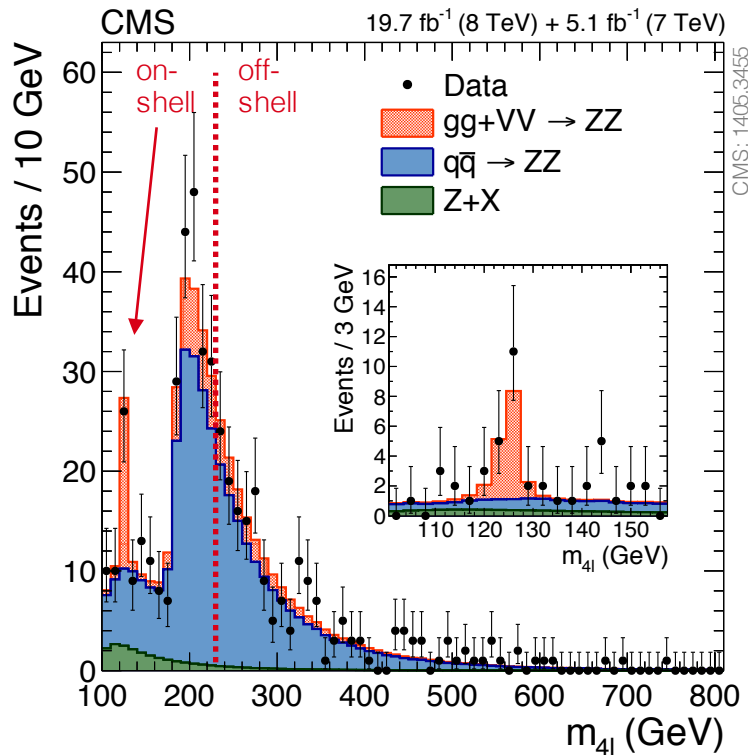
Some uncertainties cancel in ratios

Higgs boson physics

Constraining the Higgs off-shell coupling

Both CMS and ATLAS have measured the Higgs off-shell coupling and through this constrained Γ_H

Method uses the independence of off-shell cross section on Γ_H and relies on identical on-shell and off-shell Higgs couplings. One can then determine Γ_H ($=4.1$ MeV in SM) from the measurements of $\mu_{\text{off-shell}}$ and $\mu_{\text{on-shell}}$



$$\mu_{\text{off-shell}}(\hat{s}) \equiv \frac{\sigma_{\text{off-shell}}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})}{\sigma_{\text{off-shell, SM}}^{gg \rightarrow H^* \rightarrow VV}(\hat{s})} = \kappa_{g, \text{off-shell}}^2(\hat{s}) \cdot \kappa_{V, \text{off-shell}}^2(\hat{s})$$

$$\mu_{\text{on-shell}} = \frac{\sigma_{\text{on-shell}}^{gg \rightarrow H \rightarrow ZZ}}{\sigma_{\text{on-shell, SM}}^{gg \rightarrow H \rightarrow ZZ}} = \frac{\kappa_{g, \text{on-shell}}^2 \cdot \kappa_{Z, \text{on-shell}}^2}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

With Run-1, limits of the order of $5 \times \Gamma_H^{\text{SM}}$ obtained

With $L_2 = 3000 \text{ fb}^{-1}$ expect:

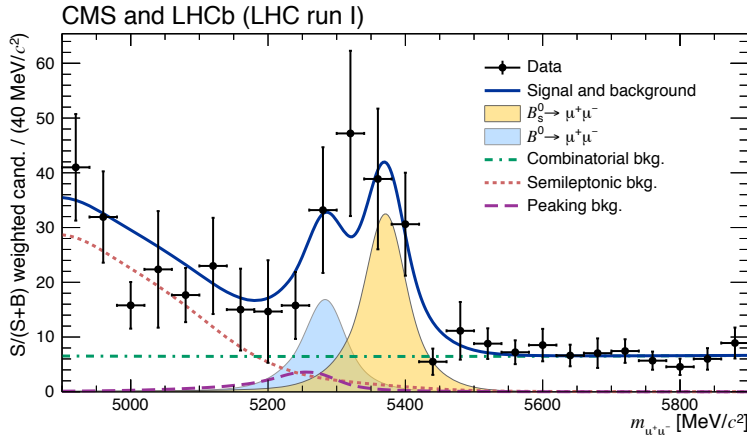
$$\mu_{\text{off-shell}}^{(L2)} = 1.00^{+0.43}_{-0.50} \text{ (stat+sys)}$$

$$\Rightarrow \Gamma_H^{(L2)} = 4.2^{+1.5}_{-2.1} \text{ MeV (stat+sys)}$$

ATLAS: ATL-PHYS-PUB-2015-024

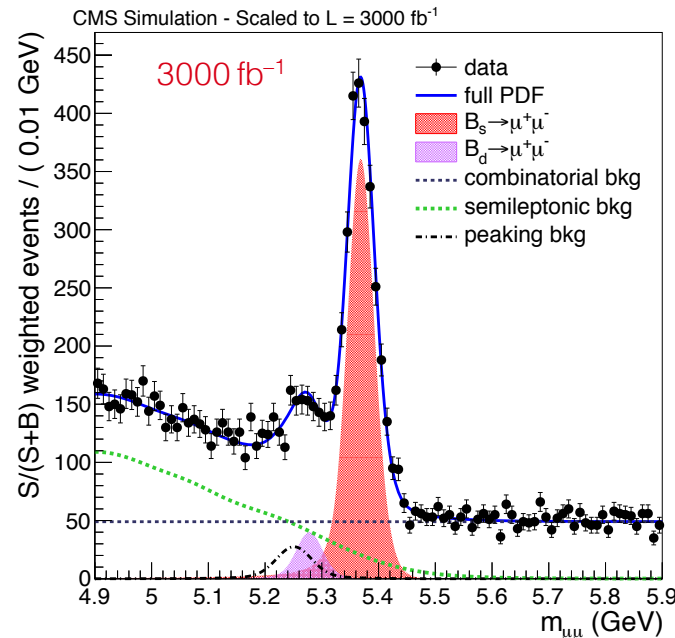
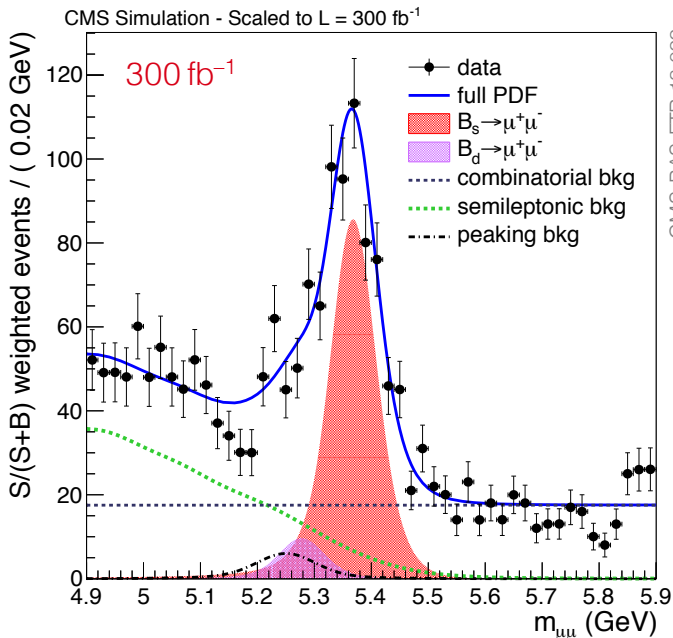
Great potential for rare SM and flavour physics processes

Example: $B_{(s)} \rightarrow \mu\mu$

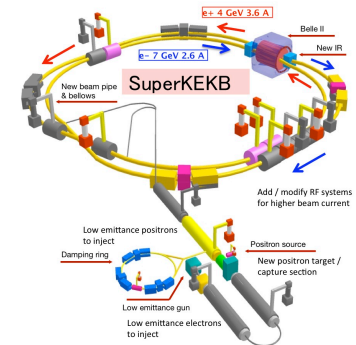


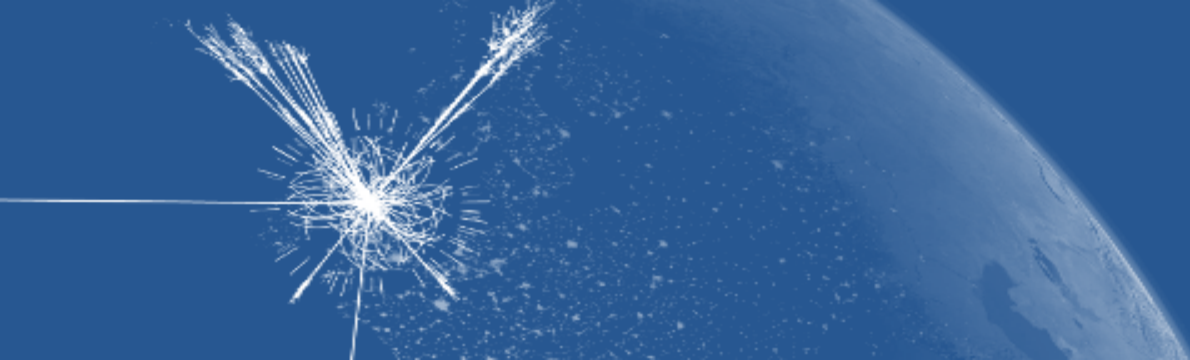
Remember: Run-1 observation of $B_{(s)} \rightarrow \mu\mu$ by CMS and LHCb (ATLAS finds lower value)

Prospective study by CMS for LHC Phase 1 & Phase 2



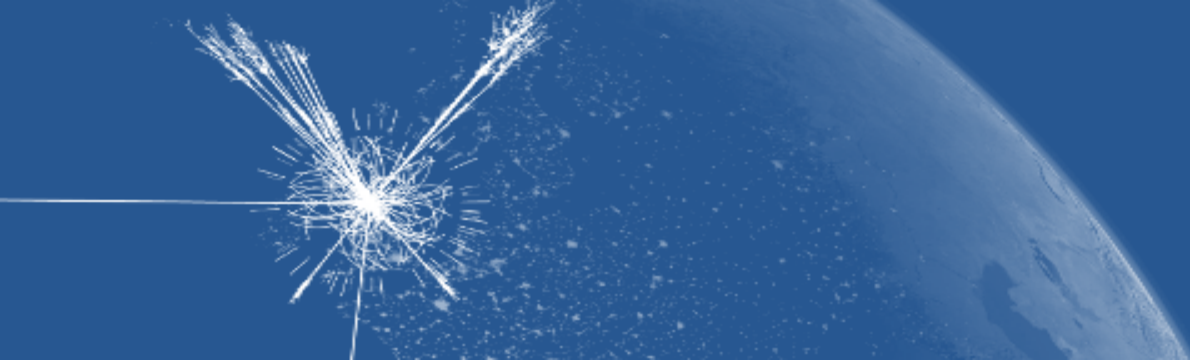
Complementary to SuperKEKB/Belle-II physics programme !



A composite image showing a particle detector's view of particle tracks (a starburst pattern of lines) overlaid on a view of the Earth's horizon from space, set against a dark blue background.

Challenges and opportunities

Particle physics has entered an era of uncertainty: we have a beautiful theory, and many indications that it is incomplete, possibly the SM is only the tip of the iceberg. Contrary to Fermi, who knew the TeV scale, we do not know the next new physics scale. Naturalness suggests it should be $O(\text{TeV})$, but we do not know how much Nature cares about naturalness.

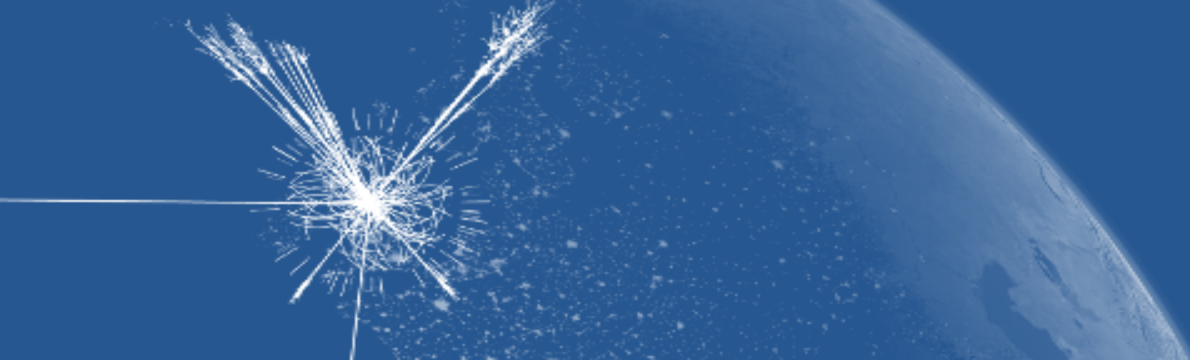
A visualization of a particle collision, showing a central bright point with numerous tracks radiating outwards, set against a dark blue background with a curved horizon line.

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We live in **data-driven times**, experiment must guide us to the next stage.
That means we need a very broad research programme (“no stone unturned”).

- We need a flagship collider programme at the energy frontier (LHC, HL-LHC, HE-LHC, FCC, ...)
- We need a lepton collider for precision Higgs, electroweak and top physics
- We need to develop high-field magnets and compact high-gradient accelerators for the long-term future
- We need to continue and further extend the intensity and precision programme: rare B and kaon physics, $g-2$, lepton flavour violation, $n/p/e/\mu$ EDM, neutrino physics with all that belongs to it, proton decay
- We need to search for dark matter particles/WIMPs, direct DM experiments, indirect searches in space, fixed target searches, axion searches

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

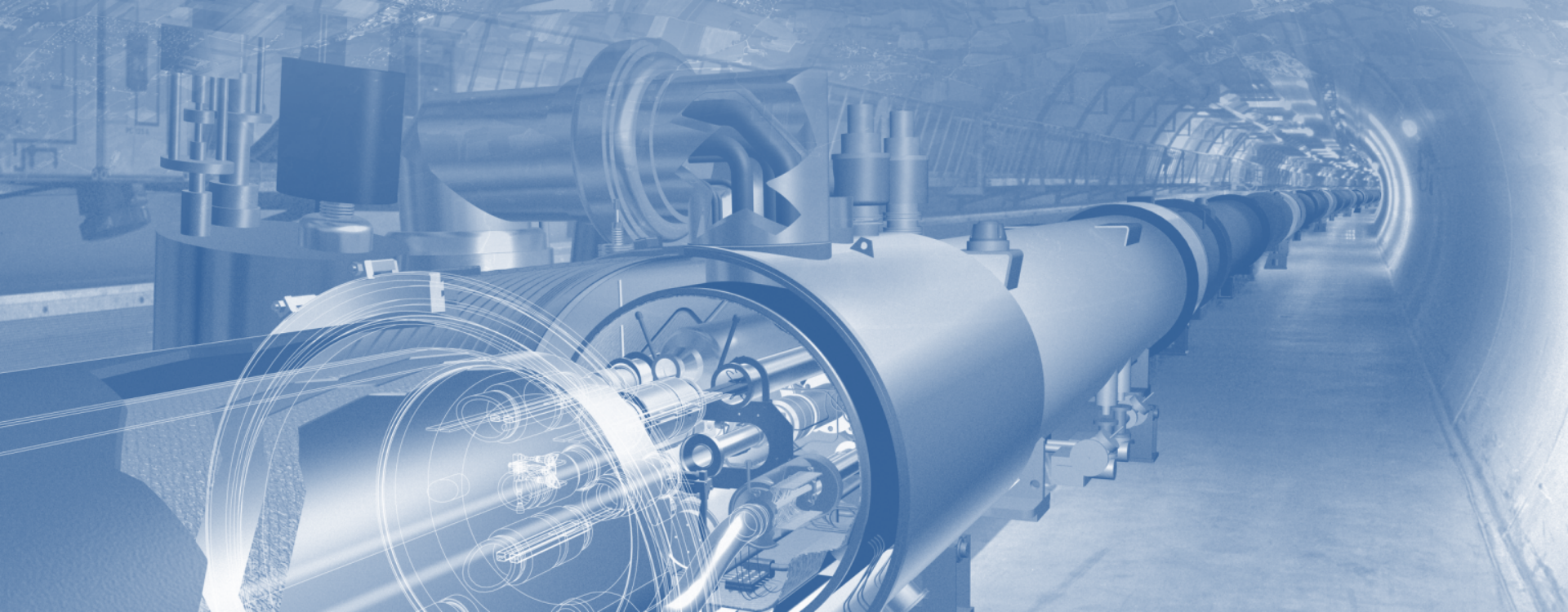
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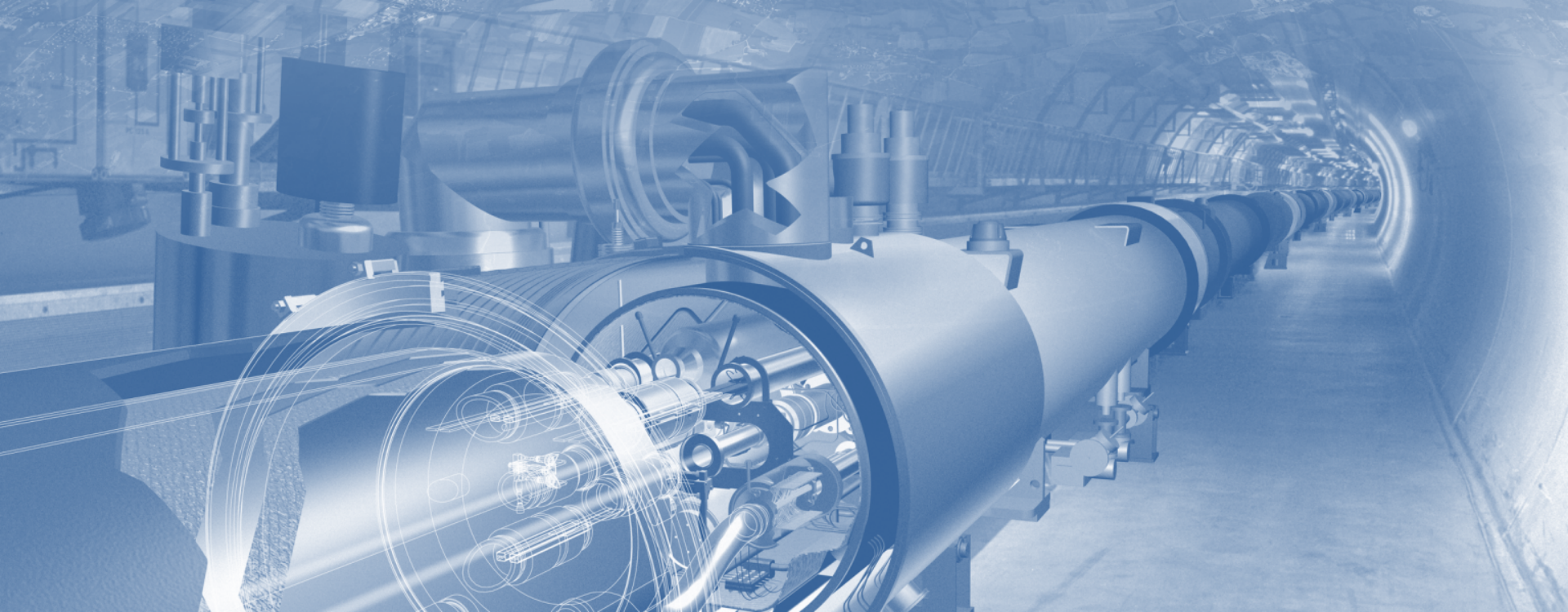
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This institute is well positioned to play creative and leading roles in this endeavour !



Extra slides



Beyond the HL-LHC

Only a very brief enumeration of projects

Future hadron collider projects in a nutshell

The next discovery machine

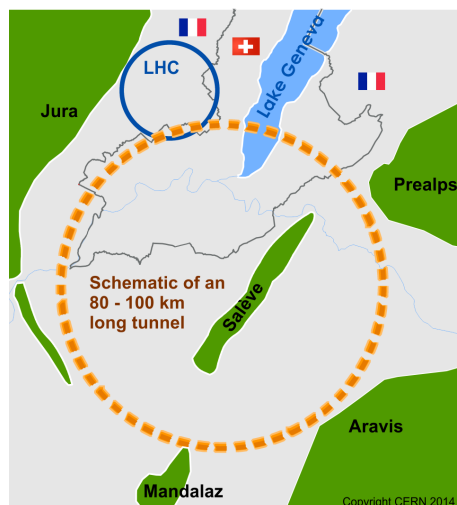
HL-LHC: $E_{\text{CM}} = 14 \text{ TeV}$, 3 ab^{-1} , 2026~2035... (formally approved as *project* by CERN council last week)

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 needed 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

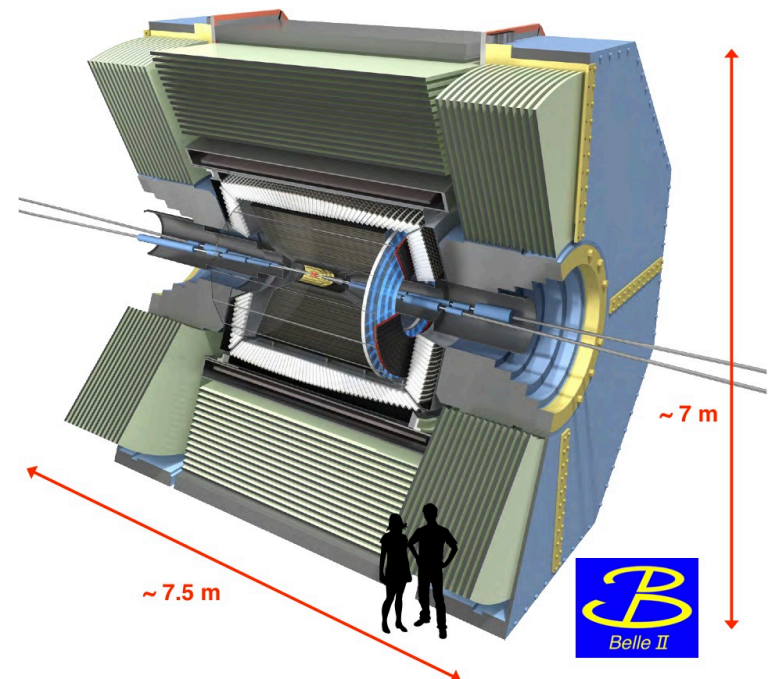
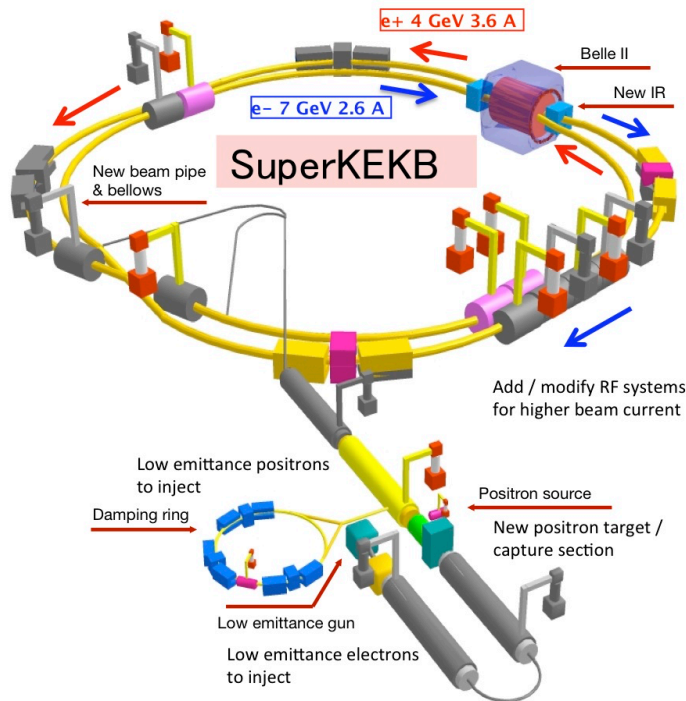
More Standard Model and Flavour physics

Complementary to SuperKEKB / Belle II programme !

Expect ~40 times luminosity of 1st generation asymmetric B-factories: up to 50 ab^{-1}

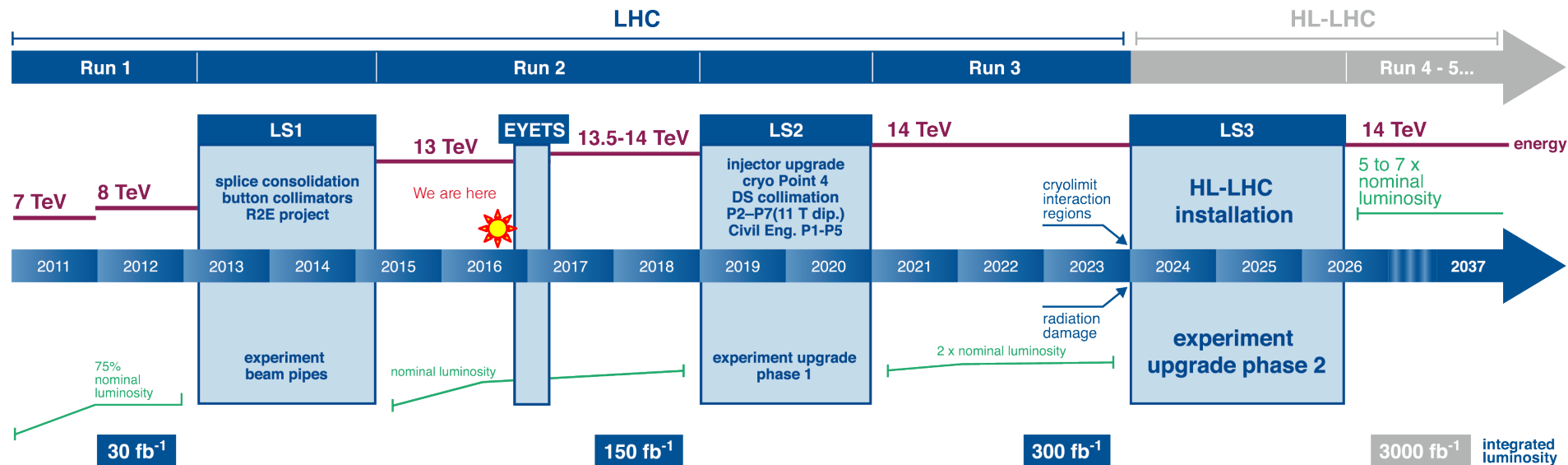
Among the physics highlights:

- Rare decays: $B \rightarrow \tau \nu$ ($< 5\%$), R_D , detailed $b \rightarrow s$ studies (incl. $B \rightarrow K^{(*)} \nu \nu$ penguin+box to ~20%)
- Lepton flavour violation, universality tests
- CP violation in bottom and charm systems



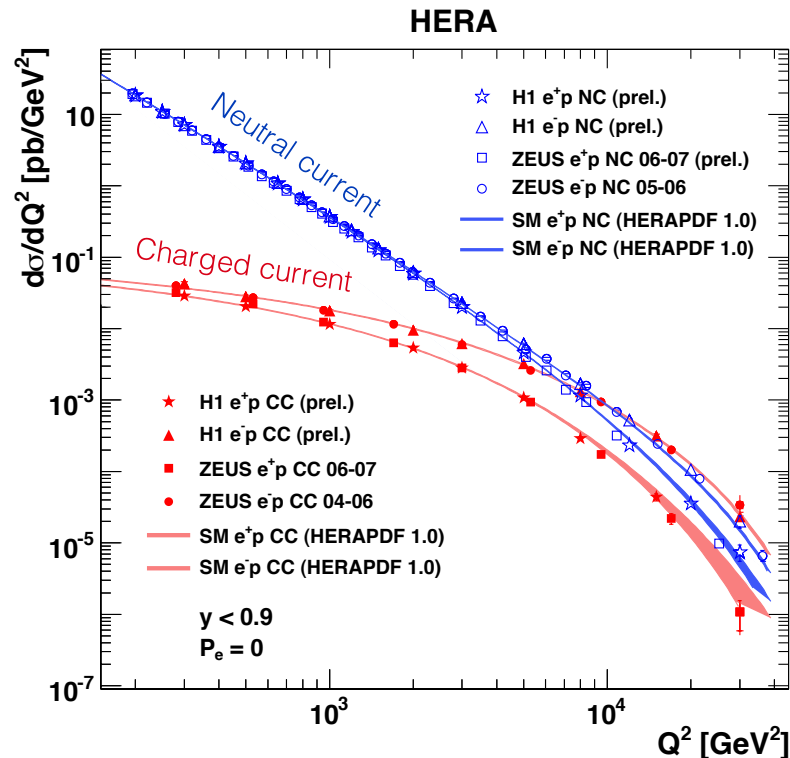
How can these LHC luminosity improvements be achieved?

Parameter	LHC Run-1	LHC Run-2 & 3	HL-LHC
Beam energy [TeV]	0.45–4	6.5–7	7
Peak inst. luminosity [$\text{cm}^{-2} \text{s}^{-1}$]	$0.8 \cdot 10^{34}$	$(0.7\text{--}2) \cdot 10^{34}$	$5 \cdot 10^{34}$ (levelled)
Bunch distance [ns]	50	25	25
Max. number of bunches	1380	2028~2748	2748
β^* [cm]	60	40	15
ε_n [μm]	2.3	2.5–3.5 (2.3 with BCMS)	2.5
Max. num. protons per bunch	$1.7 \cdot 10^{11}$	$1.2 \cdot 10^{11}$	$2.2 \cdot 10^{11}$
Average pileup $\langle\mu\rangle$	21	21~50	140



The LHC at CERN probes nature at the smallest distances ever explored on Earth to study and improve our current knowledge of space and time, matter and force as it is encoded in the SM of particle physics.

HERA data from electron-quark scattering into $e+q$
(NC = γ, Z) or $\nu+q$ (CC = $W^\pm$)



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

EW unification reduces 20 SM parameters to 19 (if $\nu = 0$)

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

$>10^{10} \text{ GeV}$

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 ?

$\nu_R, f_a ?$

t, Z, W, H, EWSB

ψ, b, Y, B

τ, c, n, ρ, ϕ

μ, s, π, QCD

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

e

core of Sun

atomic binding E

ν 's

$\downarrow ?$

$\downarrow$

γ, g

0

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

$>10^{10} \text{ GeV}$

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, f_a ?

LHC reach

New Physics ?

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

$\downarrow ?$

$\downarrow$

γ, g

...probing
attometre
scales

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

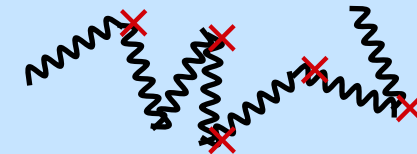
Gravity



Photon



Weak boson



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Electrons



Top quark

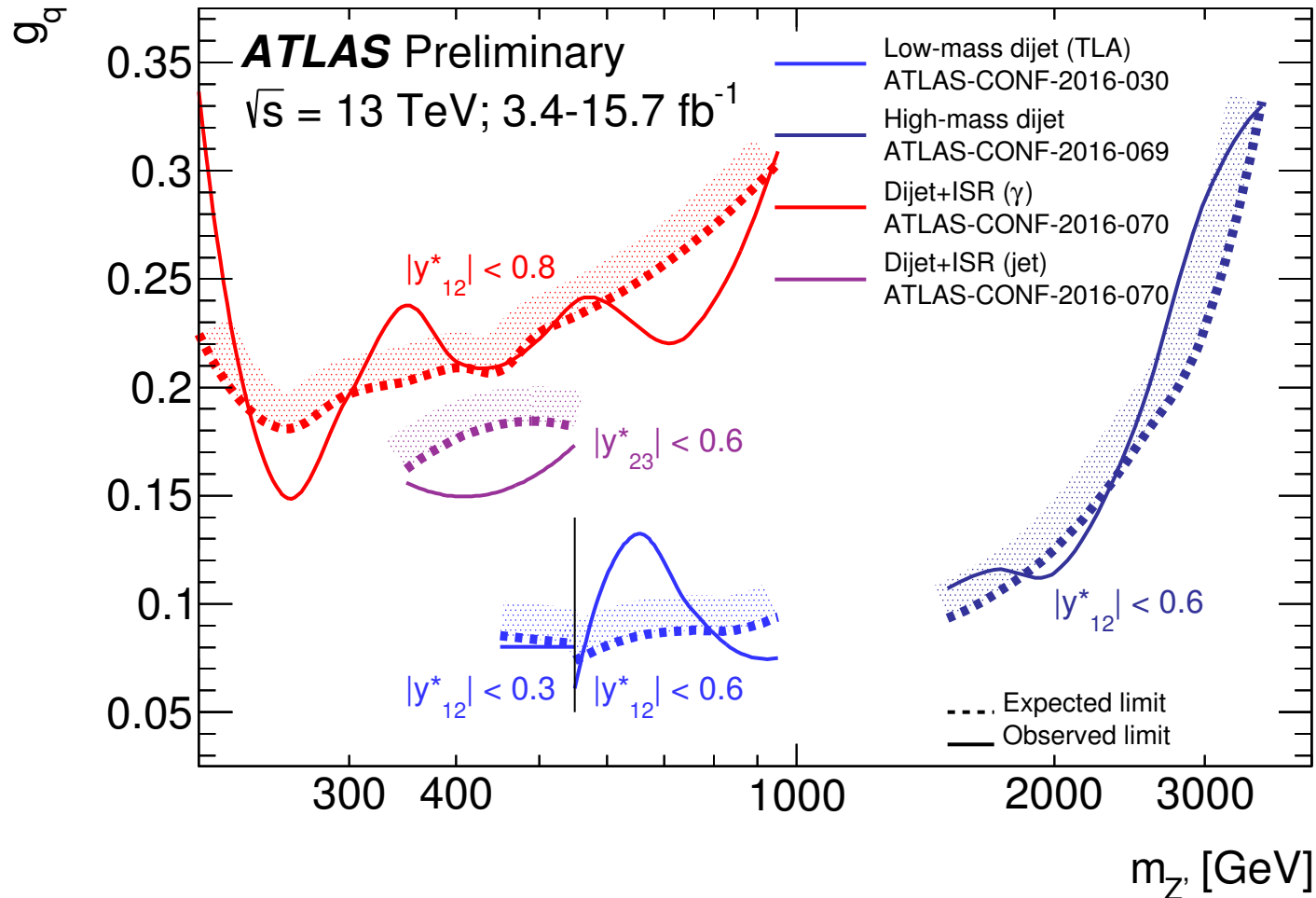


Interaction with Higgs
field alters chirality of
massive Dirac fermion

Searches in high- p_T multijet final states at 13 TeV

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

ATLAS bounds in the coupling-vs-mass plane for leptophobic Z' model from dijet searches



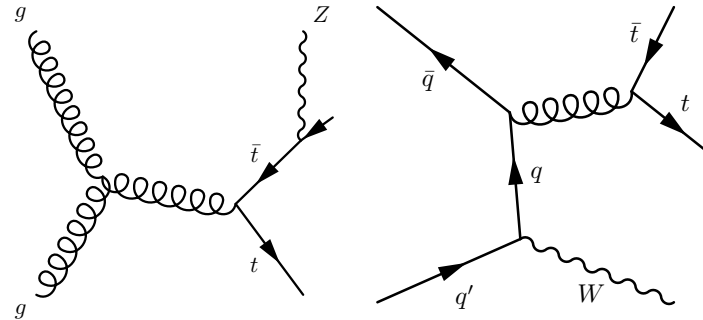
Top-antitop production and a vector boson at 13 TeV

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

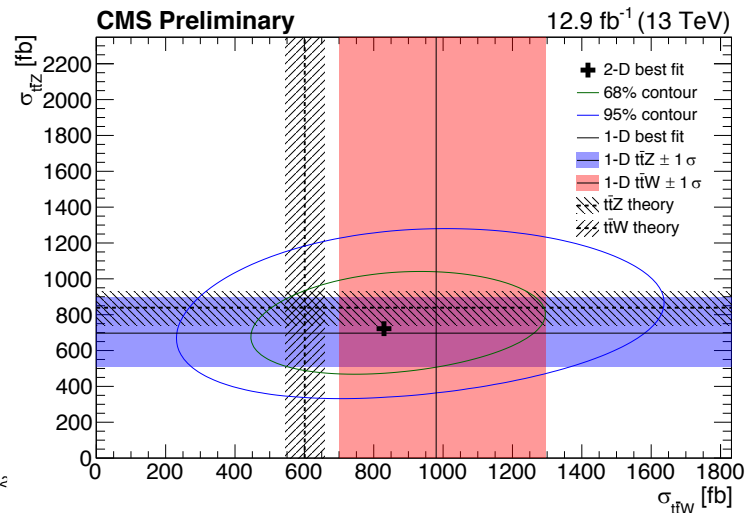
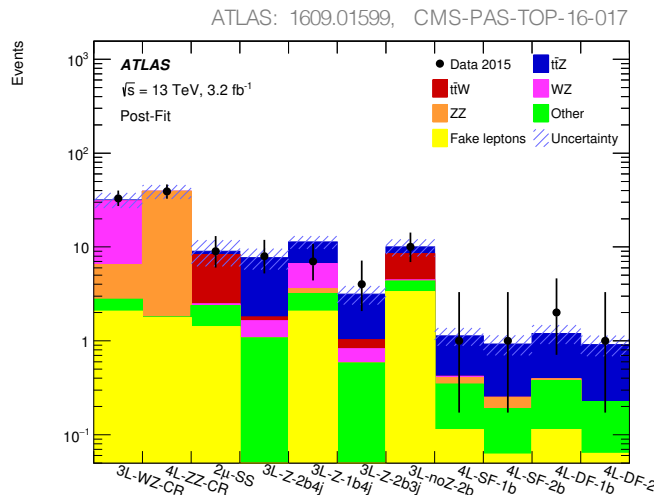
Analyses combine several multilepton final states, difficult mis-ID background

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

13 TeV $t\bar{t}+W/Z$ results from ATLAS and CMS in agreement with SM:



ATLAS (3.2 fb^{-1} , 2015):
 $t\bar{t}W$: $1.5 \pm 0.8 \text{ pb}$
 $t\bar{t}Z$: $0.9 \pm 0.3 \text{ pb}$

CMS (12.9 fb^{-1} , 2016):
 $t\bar{t}W$: $0.98^{+0.23}_{-0.22} {}^{+0.22}_{-0.18} \text{ pb}$
 $t\bar{t}Z$: $0.70^{+0.16}_{-0.15} {}^{+0.14}_{-0.12} \text{ pb}$

SM (NLO):
 $t\bar{t}W$: $0.60 \pm 0.08 \text{ pb}$
 $t\bar{t}Z$: $0.84 \pm 0.09 \text{ pb}$

BSM Higgs boson searches

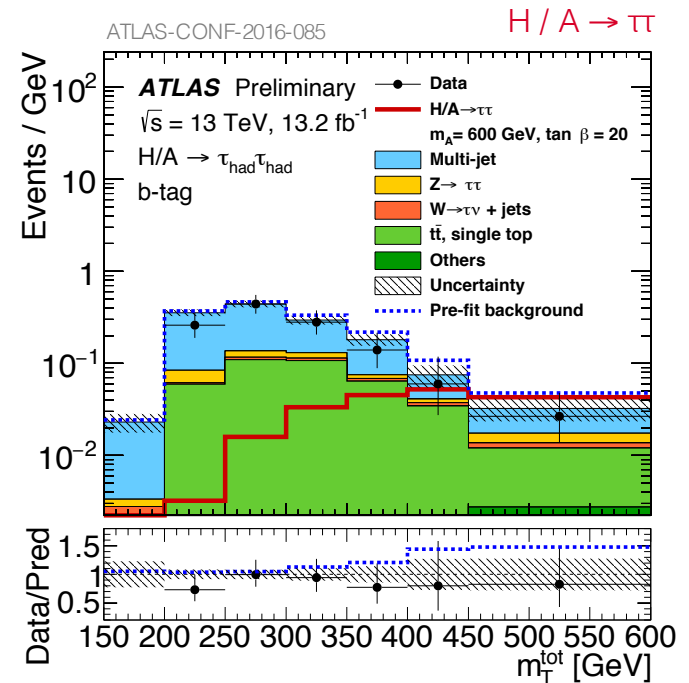
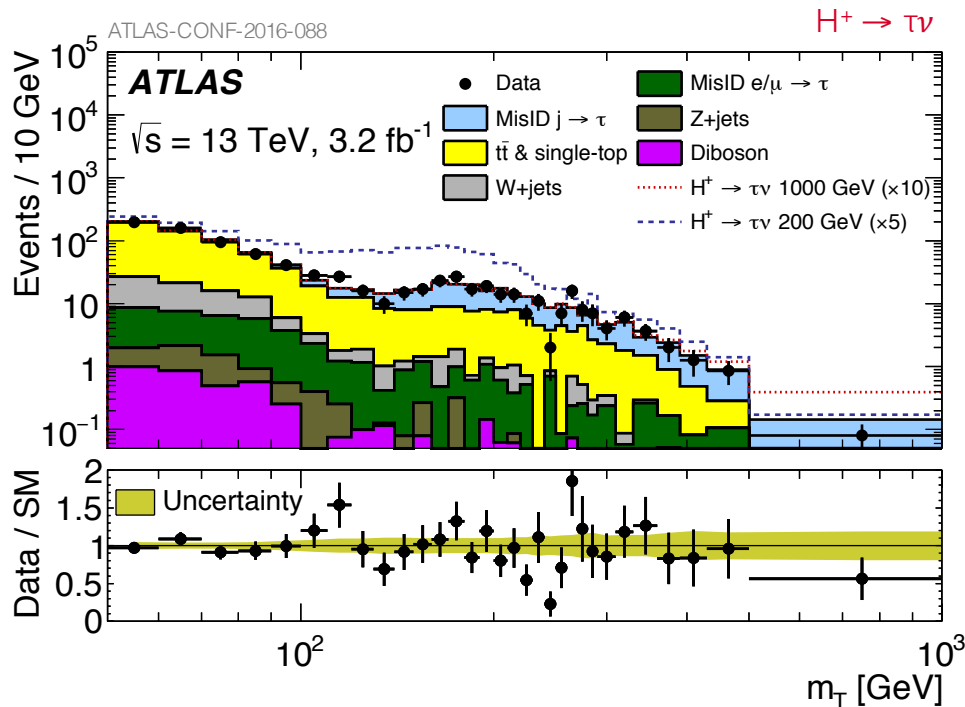
Single BEH doublet and form of potential simple but Nature may be more complex (eg, SUSY)

Beyond the SM “Higgs zoo”

[Will Davey, LHCP 2014]



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



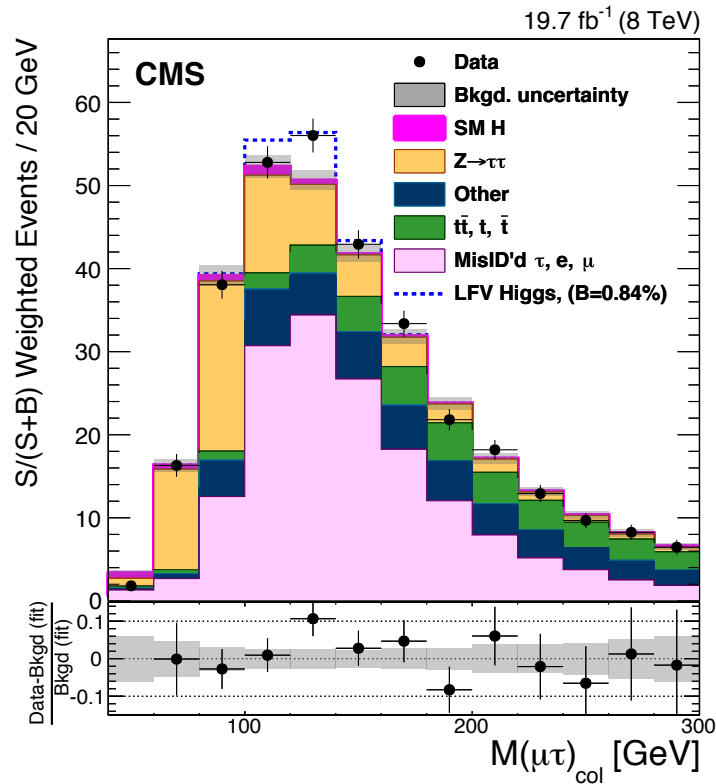
One word on lepton flavour violation in Higgs decays

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

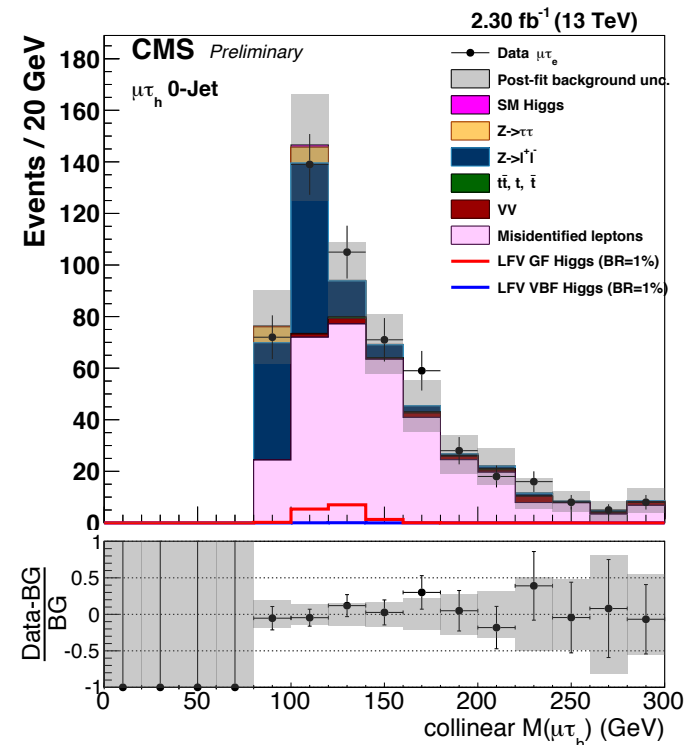
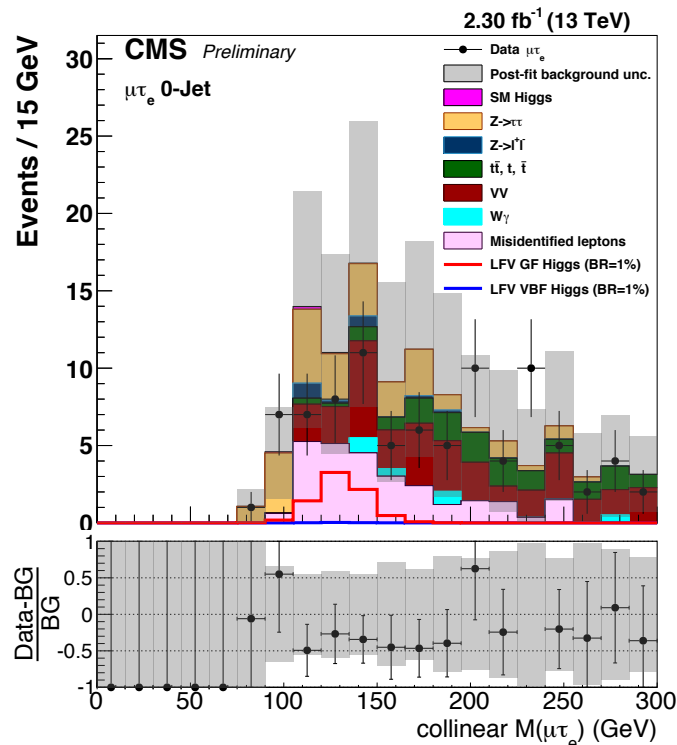
Both experiments have finalised their Run-1 LFV analyses

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: $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \times 10^{-3}$

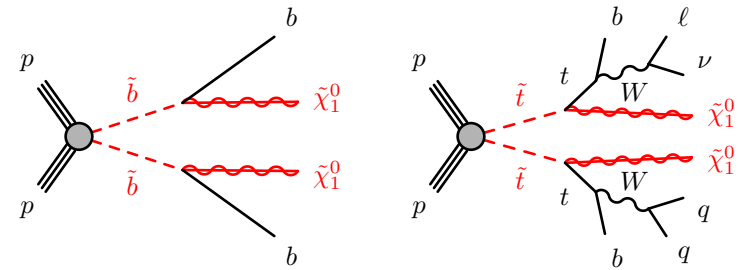


Naturalness driven searches

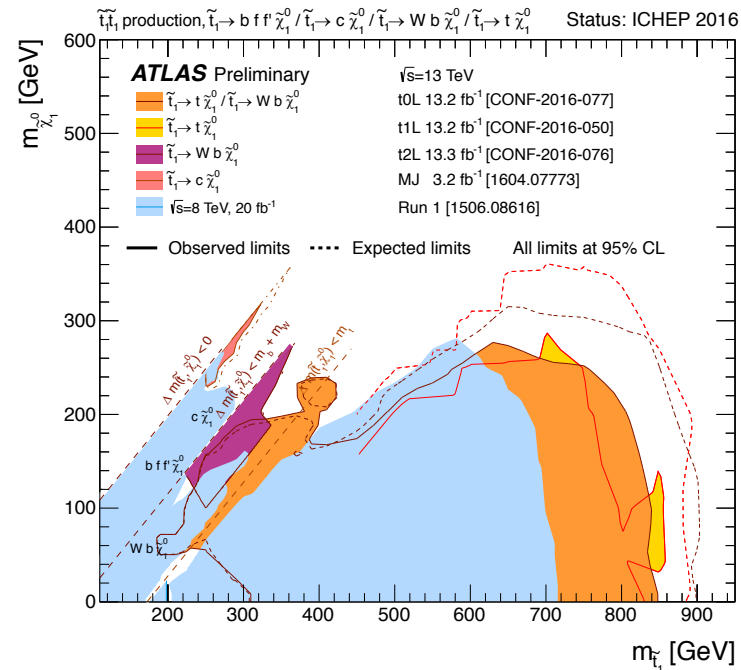
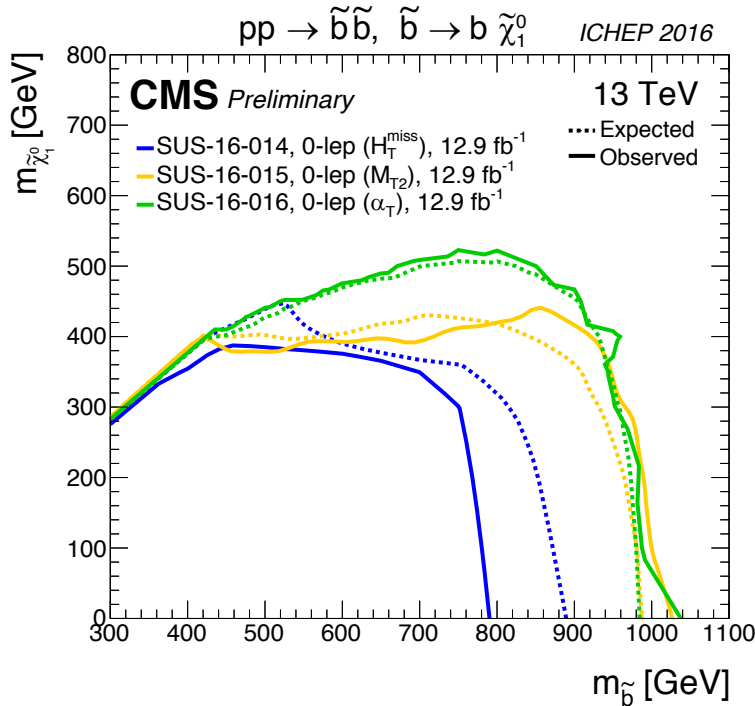
Searches for direct production of stop/sbottom and charginos/neutralinos

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



No anomaly seen

Sensitivity improved over Run-1

Similar for VLQ searches

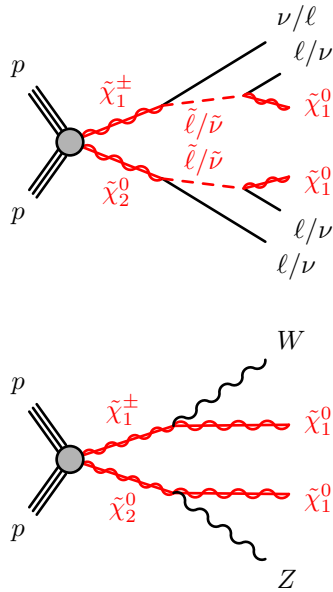
*Hypothetical fermions that transform as triplets under colour and who have left- and right-handed components with same colour and EW quantum numbers

Electroweak supersymmetry production

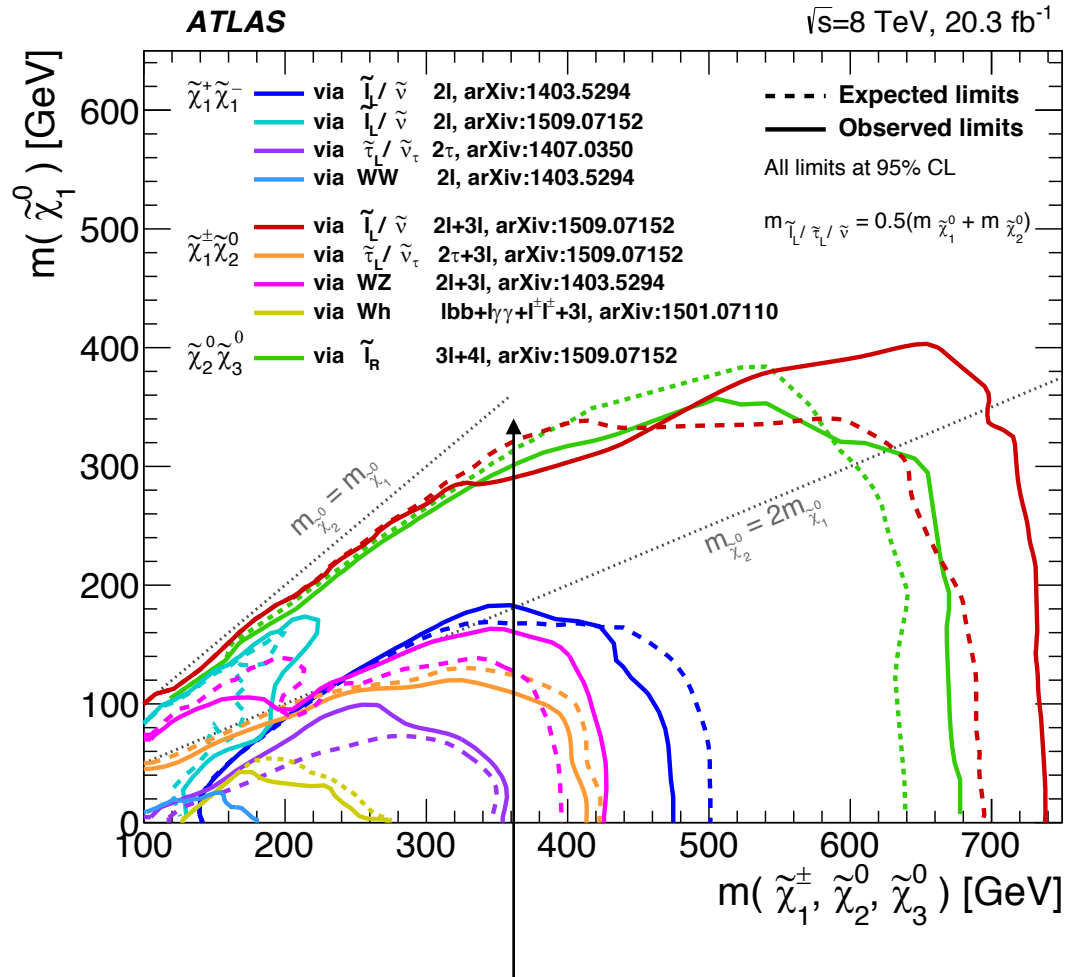
Searches for direct production

“**Electroweak-inos**” may be the lightest fermions. They also have low cross-sections, so Run-2 luminosity just enough to increase sensitivity

Signatures are leptons, few or no jets, MET

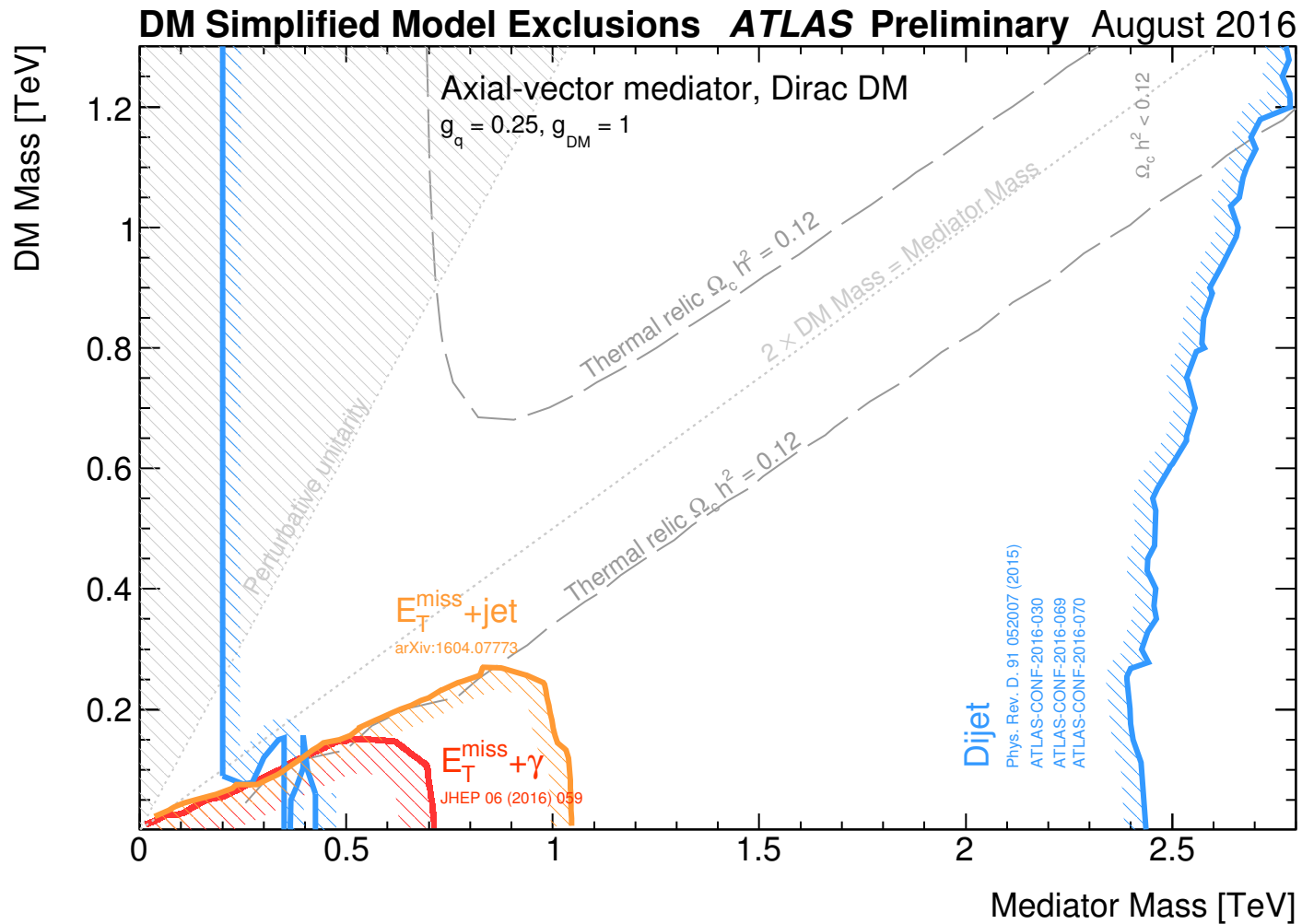


Example diagrams



Compressed region (“higgsino” case)

Exclusion regions for simplified models with heavy particle mediating interaction between initial state quarks and final state WIMPs



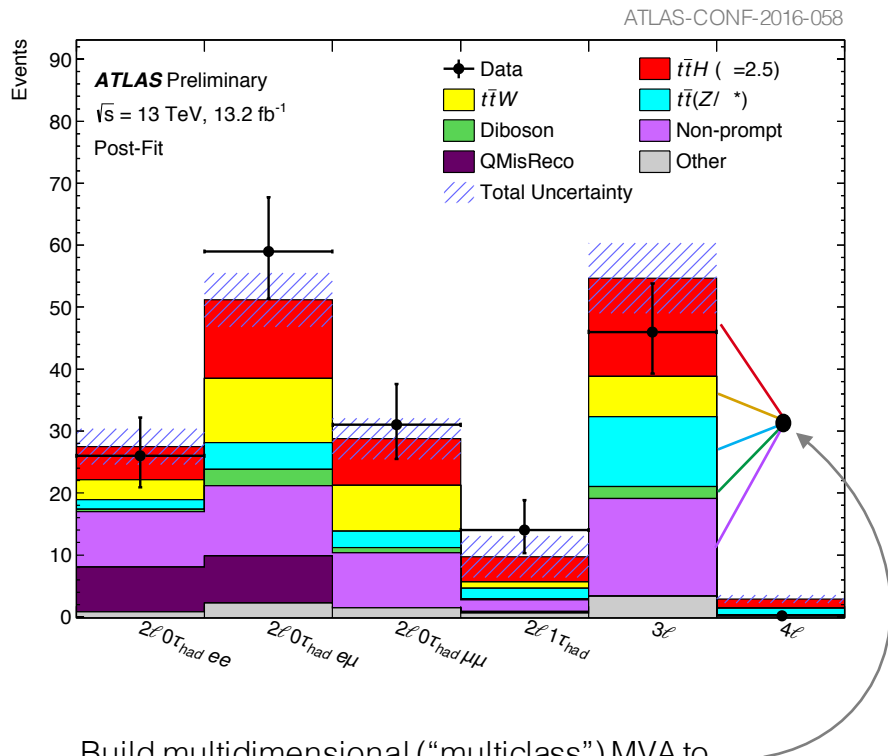
Since the mediator is produced via quark annihilation (g_q), it can also decay to quarks

Digression: machine learning in high-energy physics

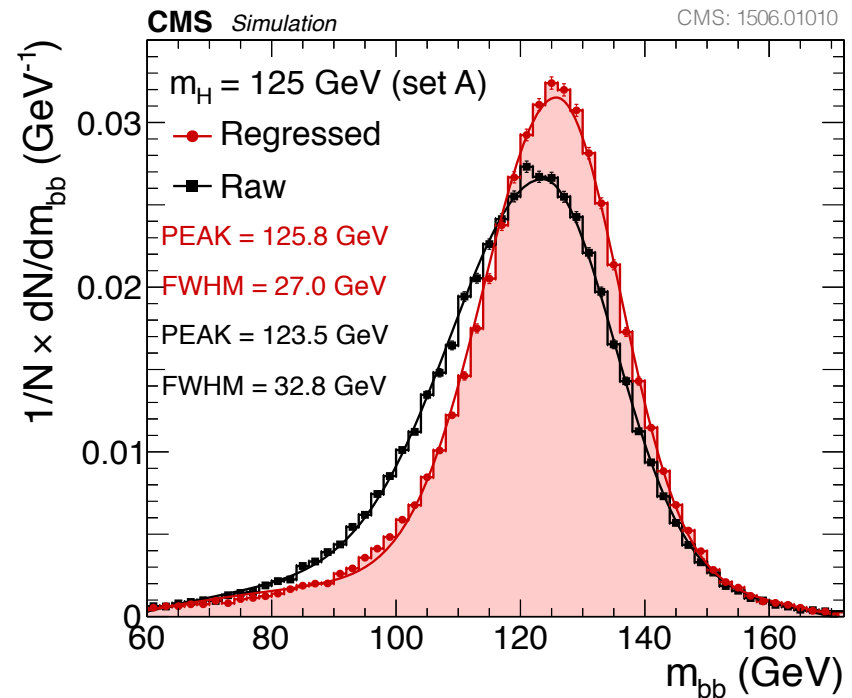
Rare background-heavy channels like $t\bar{t}H$ need MVA support. But ML offers much more.

Huge experience with MVA in HEP since the 90's. Likelihood methods and fits still in heavy use. Classification and, more recently, regression methods used everywhere at the LHC and in HEP.

Most common methods: Boosted Decision Trees (very robust) and Neural Networks



Build multidimensional (“multiclass”) MVA to simultaneously discriminate against all backgrounds



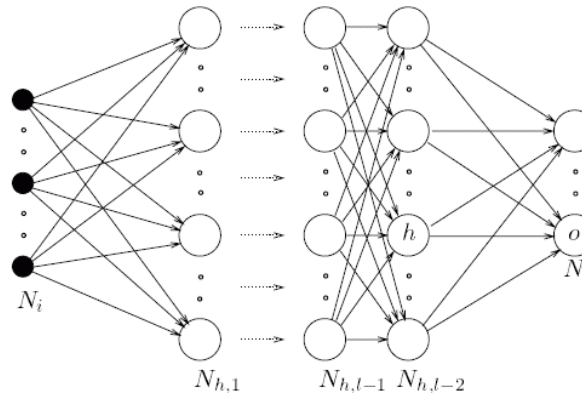
Multivariate (BDT) regression to improve $m(bb)$ resolution in $H \rightarrow bb$: better calibration and 18% improved resolution

Digression: multivariate analysis (MVA) & machine learning

Rare background-heavy channels like ttH need MVA support. But ML offers much more.

New opportunities with improved computers and algorithms allowing *Deep Learning*

Deep neural network = Artificial neural network with many hidden layers



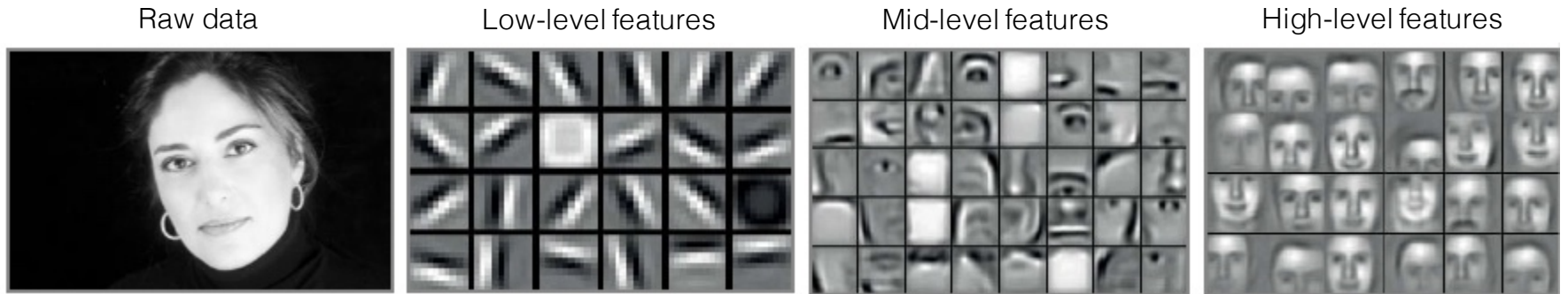
That's all it means, but it has important consequences

Digression: multivariate analysis (MVA) & machine learning

Rare background-heavy channels like ttH need MVA support. But ML offers much more.

New opportunities with improved computers and algorithms allowing *Deep Learning*

Many hidden layers (& usage of convolution kernels) allows NN to learn hierarchy of features



<https://developer.nvidia.com/deep-learning-course>

Getting rid of “hand-crafted features”, revolutionised:

- Image recognition, speech recognition, natural language processing
- Complex automation (eg, self-driving car)

And particle physics ?

- Track fitting (helix pattern recognition)? Event reconstruction from 4-vectors? Online (trigger, FTK)?
- Only starting to explore opportunities...

Digression: multivariate analysis (MVA) & machine learning

Rare background-heavy channels like ttH need MVA support. But ML offers much more.

New opportunities with improved computers and algorithms allowing *Deep Learning*

“Deep learning is the idea that an artificial intelligence system should learn abstract/high-level/hierarchical representations of the world”

Yann Lecun (head of FAIR, Facebook AI research), in a Quora session, July 2016

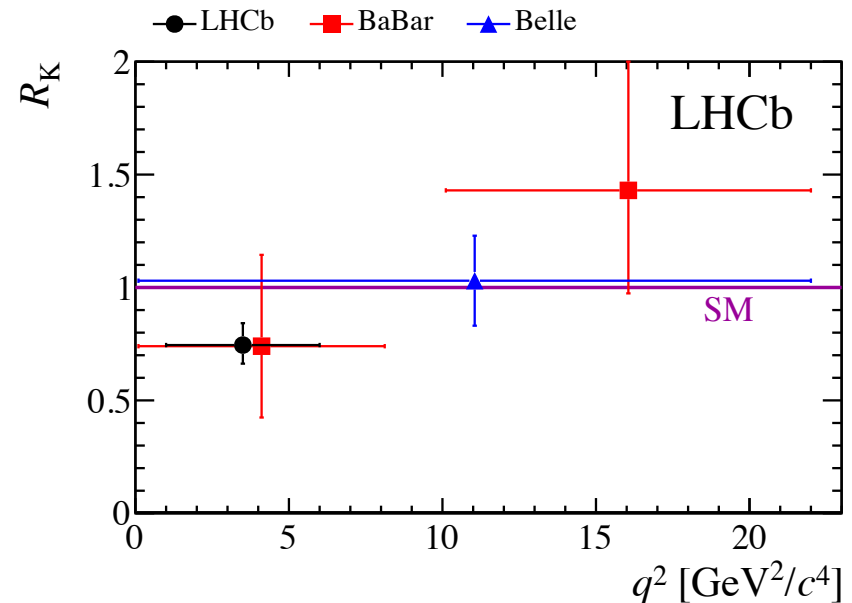
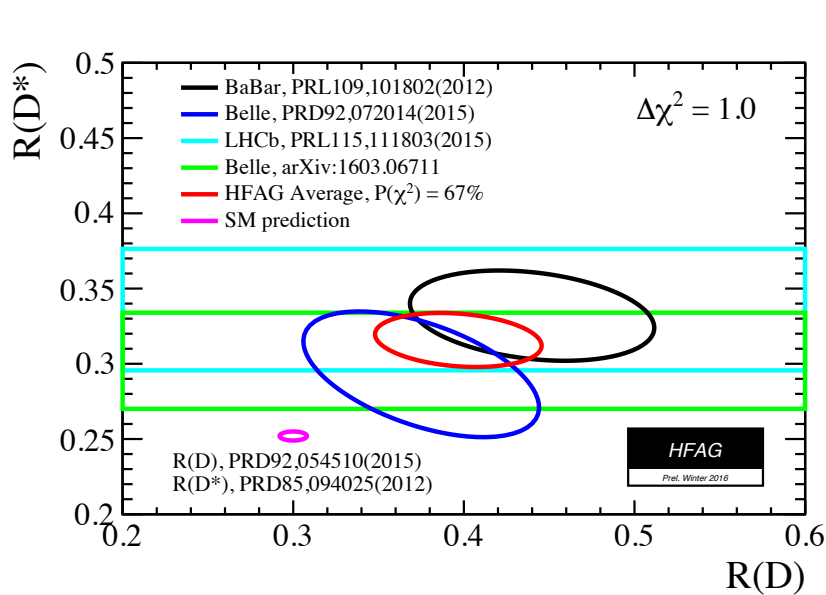
<https://www.quora.com/session/Yann-LeCun/1>

Flavour anomalies ?

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

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

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



World average HFAG: $R_{D^*} = 0.316 \pm 0.016 \pm 0.010$ (3.3 σ from SM 0.252 ± 0.003 , combined R_{D^*} & R_D is 4.0 σ)

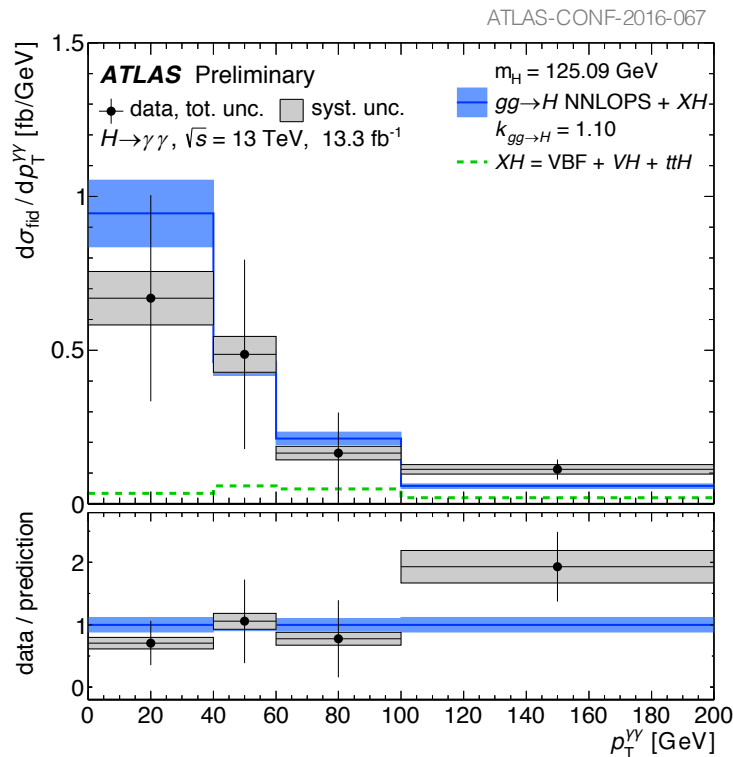
http://www.slac.stanford.edu/xorg/hfag/semi/winter16/winter16_dtaunu.html

New Belle measurement using hadronic t decays gives: $R_{D^*} = 0.276 \pm 0.034_{\text{stat}} \pm 0.028_{\text{syst}}$ [1608.06391]

ATLAS and CMS studied H_{125} in bosonic channels

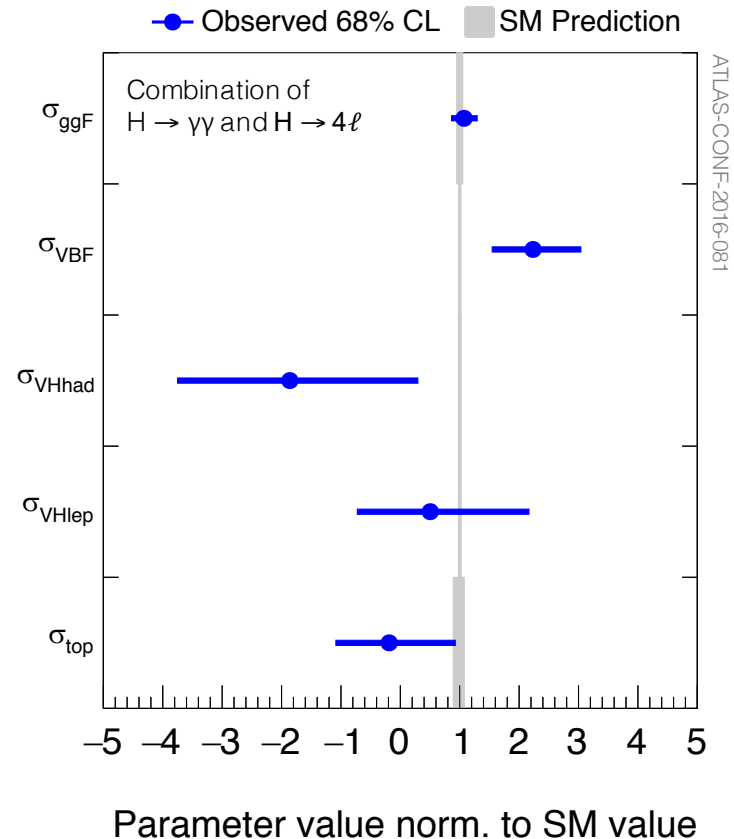
Preliminary fiducial and total cross-section and coupling measurements (ggF and VBF significant)

$H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ (right combined)



Differential fiducial cross-section measurement in $H \rightarrow 4\ell$ compared to NNLO+PS theoretical prediction

ATLAS Preliminary $m_H = 125.09$ GeV
 $\sqrt{s} = 13$ TeV, 13.3 fb $^{-1}$ ($\gamma\gamma$), 14.8 fb $^{-1}$ (ZZ)



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

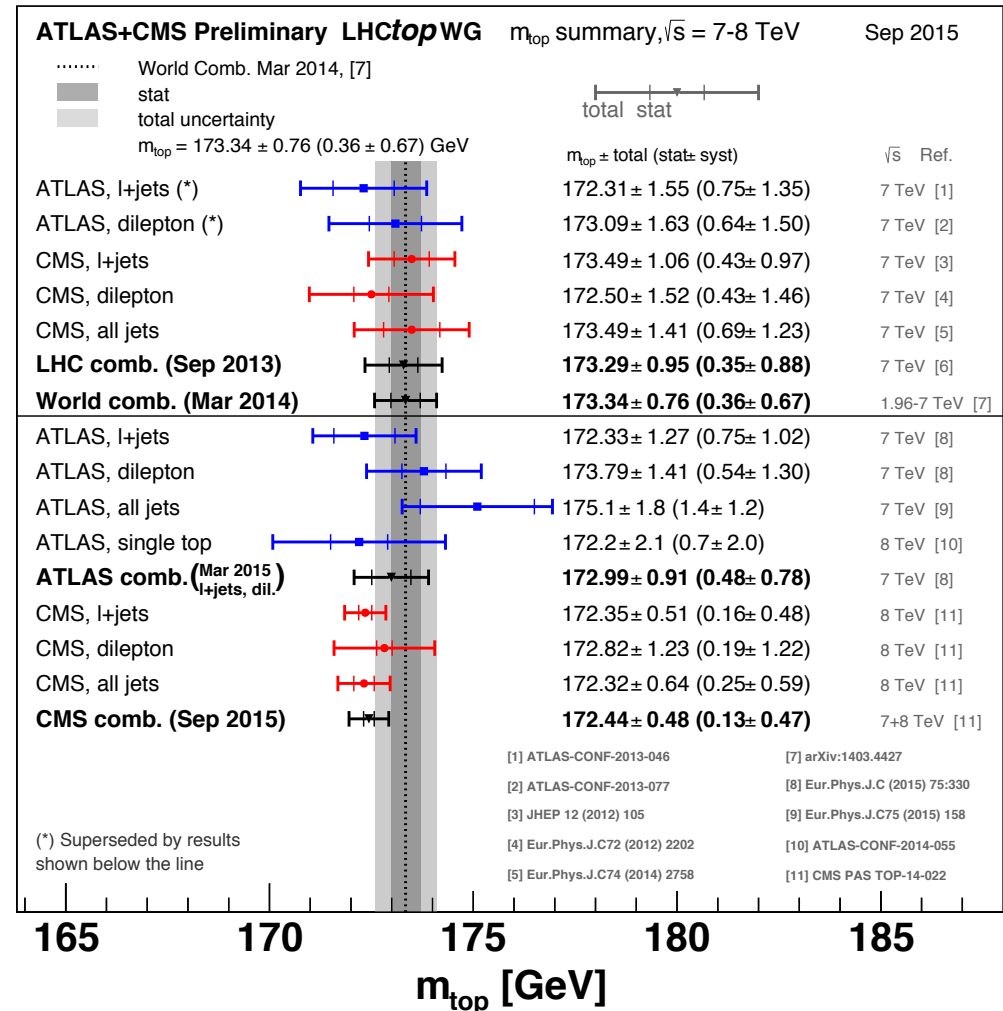
Best top mass from LHC:

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

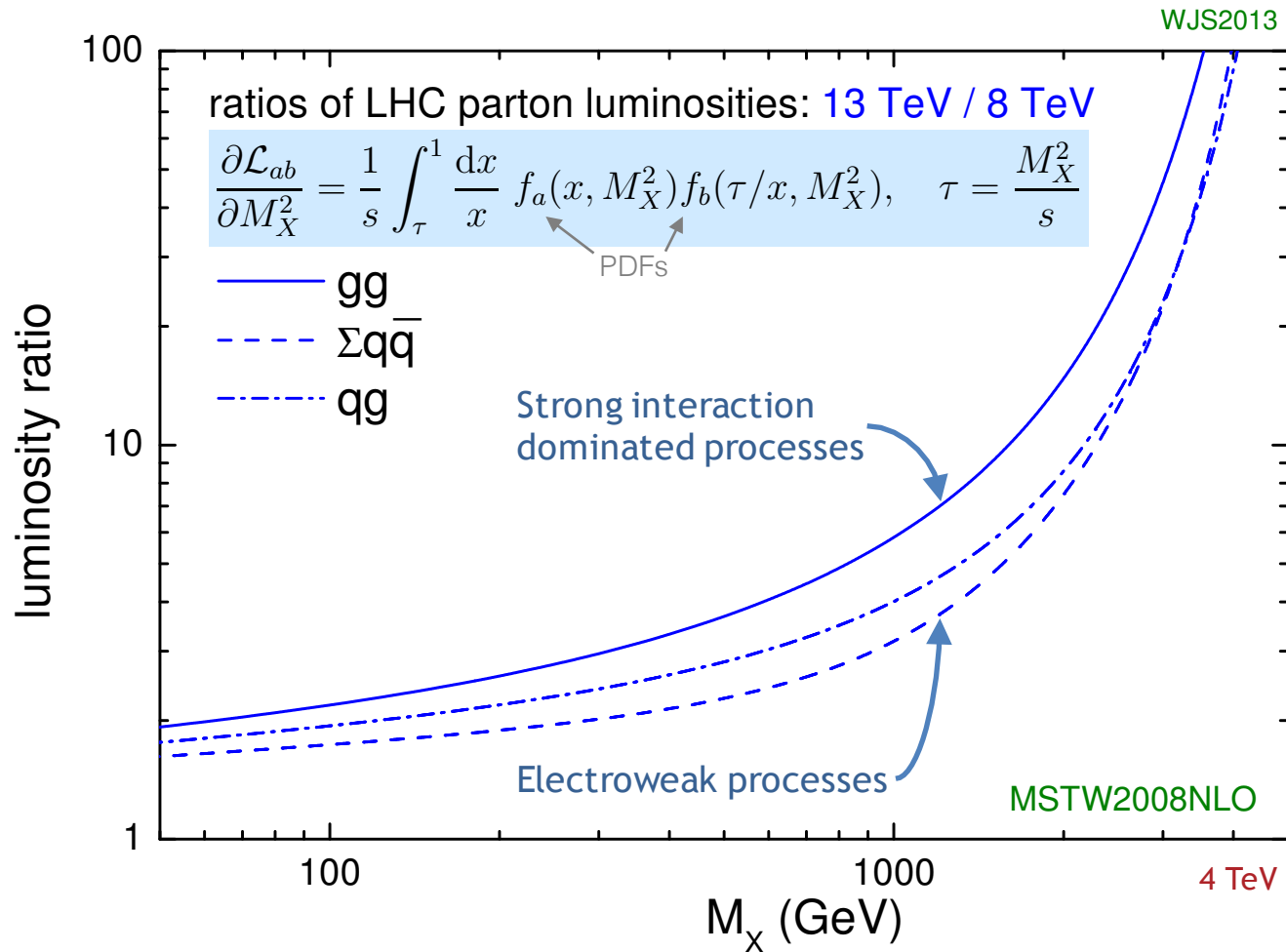
640 MeV for Tevatron combination

Reaching systematic limit from b-quark fragmentation

Alternative m_{top} determinations



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



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

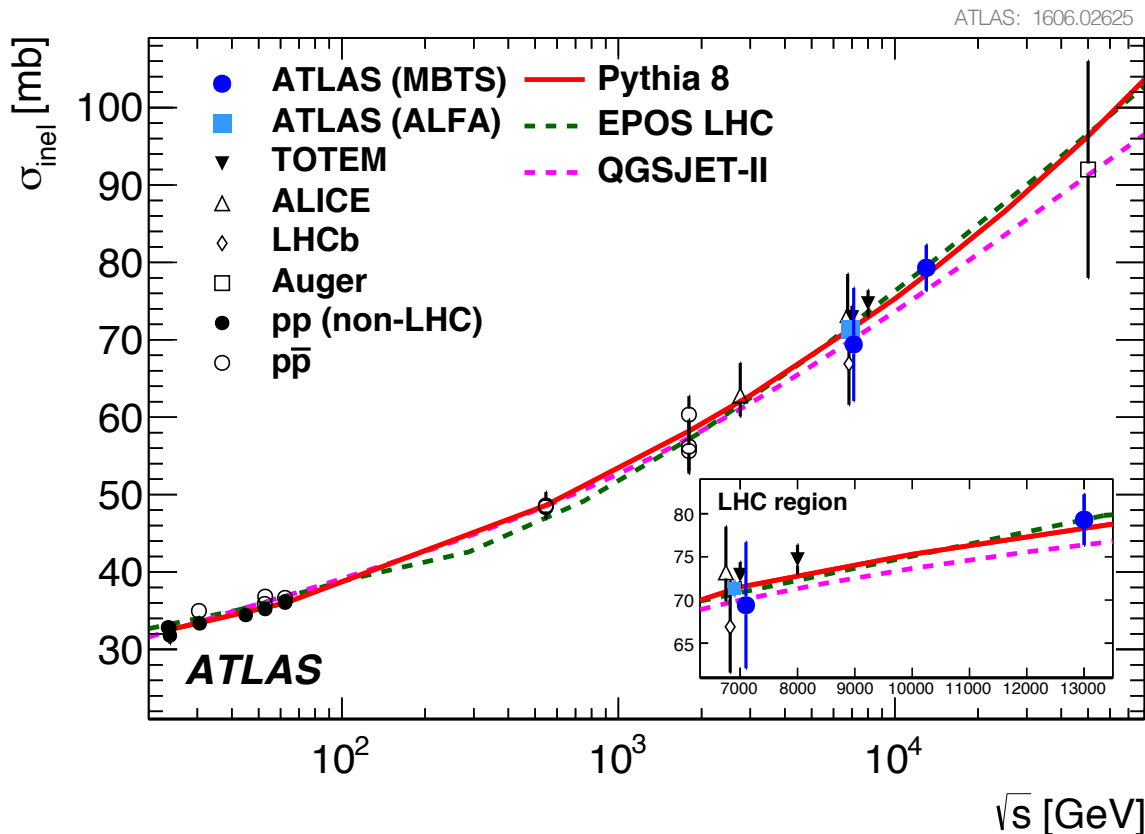
Early Run-2 puts emphasis on searches

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:

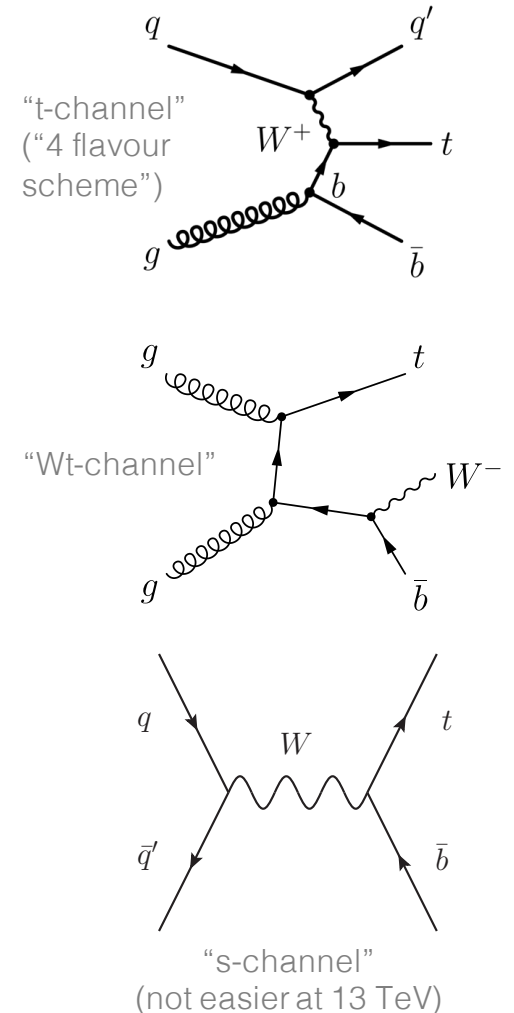
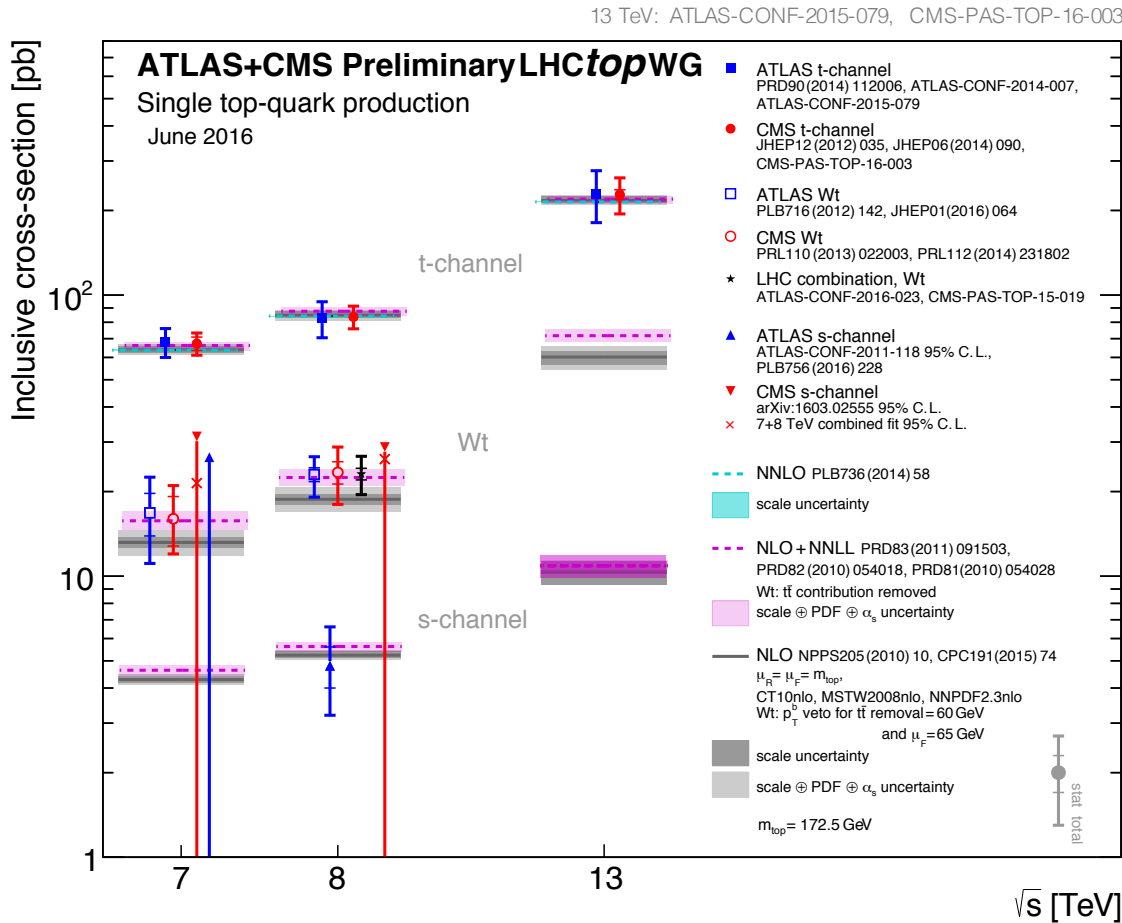
$$\sigma_{\text{tot}} \propto \text{Im } f_{\text{elastic}}(t \rightarrow 0)$$

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

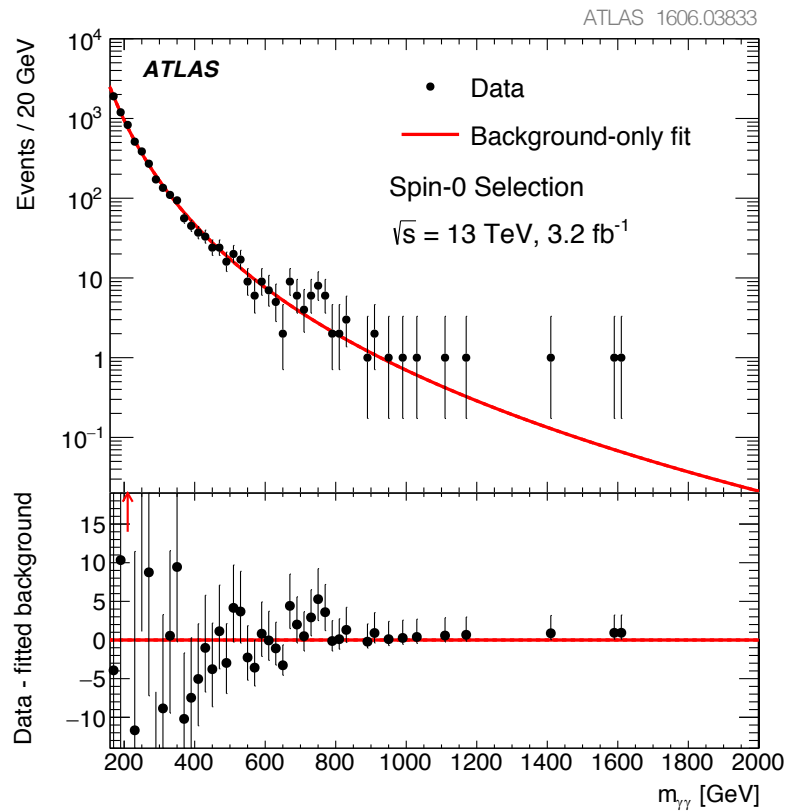


Tevatron: 6.3 σ , ATLAS Run-1: 3.2 σ

Diphoton resonance searches, the 2015 data

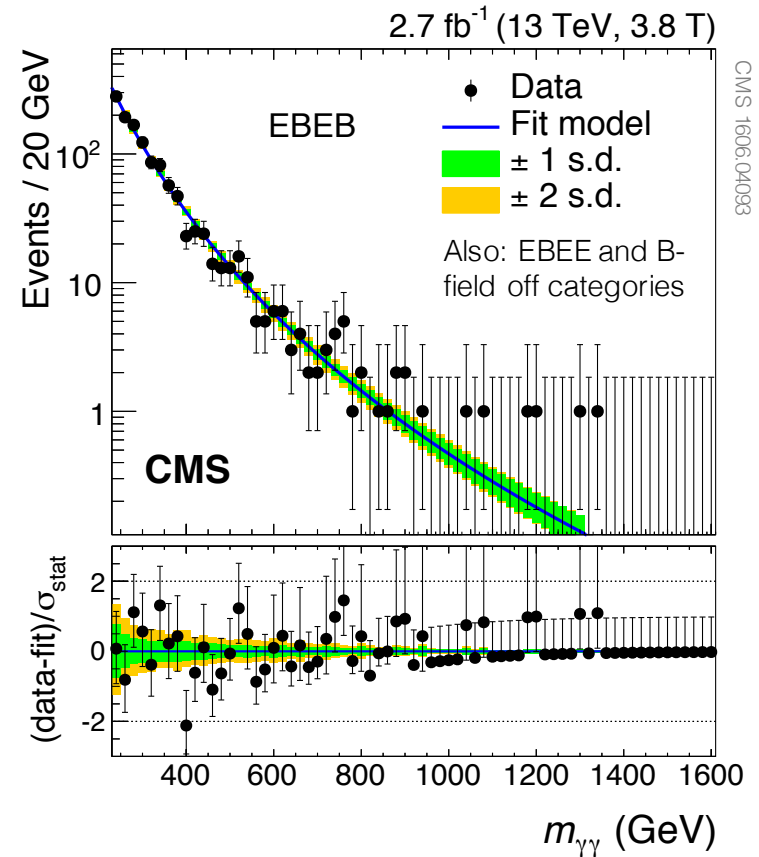
Dedicated searches for a spin-0 and a spin-2 diphoton resonance

- Photons are tightly identified and isolated. Typical purity $\sim 94\%$, background modelling empirical in spin-0 (theoretical in spin-2 case for ATLAS)



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

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



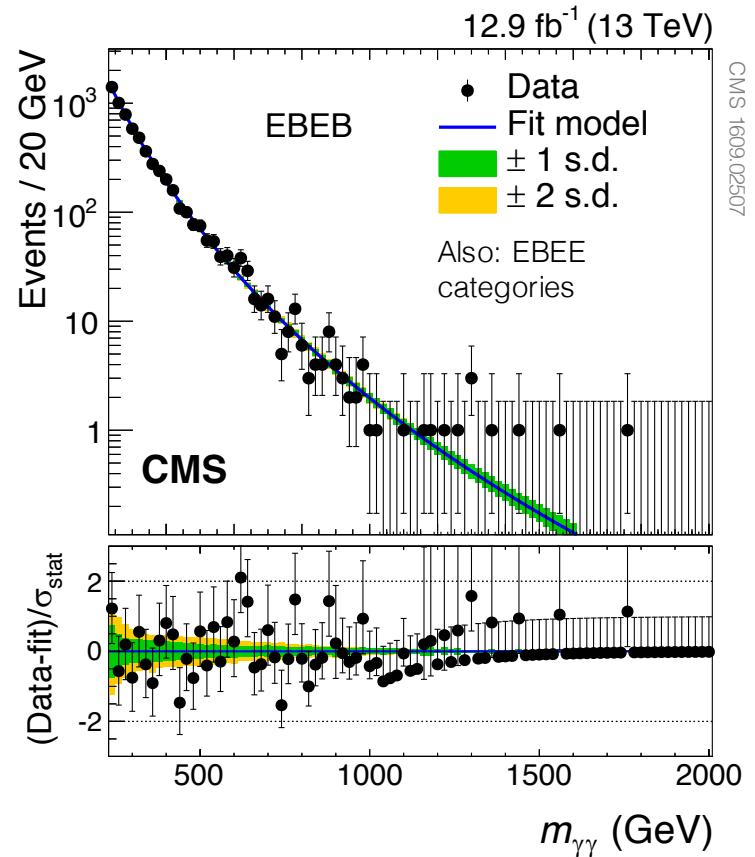
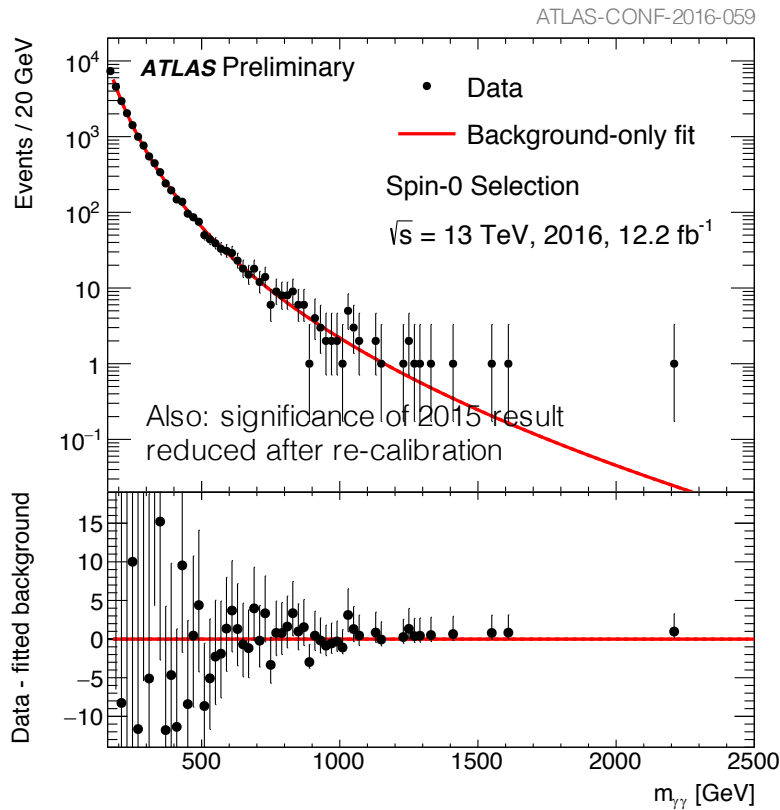
Lowest p-value at $\sim 750 \text{ GeV}$, narrow width

Local / **global** $Z = 3.4\sigma / 1.6\sigma$ (Run-1+2 combination)

Diphoton resonance searches, the 2016 results

Repeated ~unchanged analyses with 2016 data

- Photons are tightly identified and isolated. Typical purity ~94%, background modelling empirical in spin-0 (theoretical in spin-2 case for ATLAS)

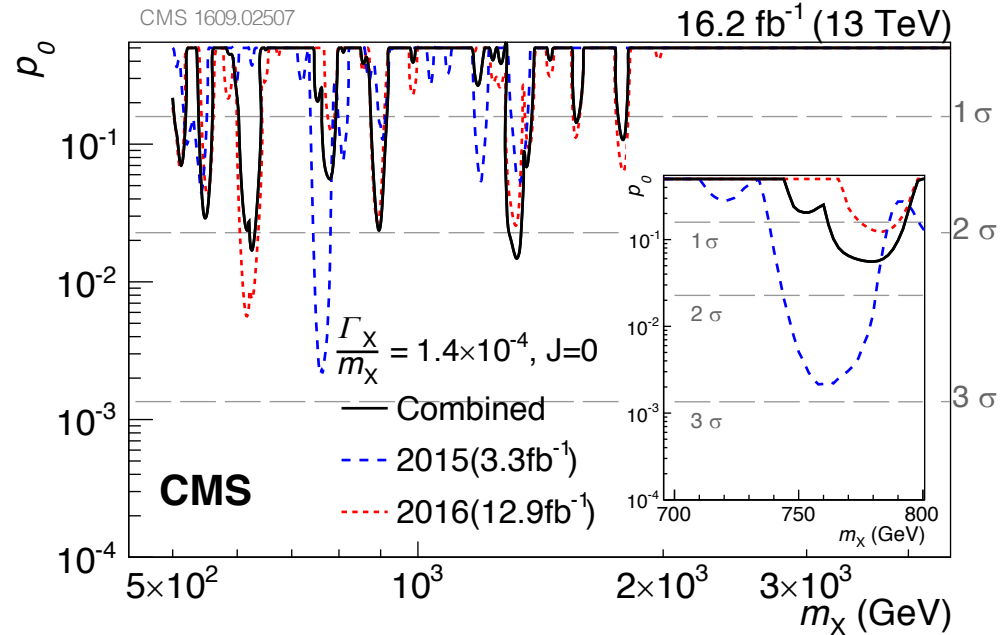
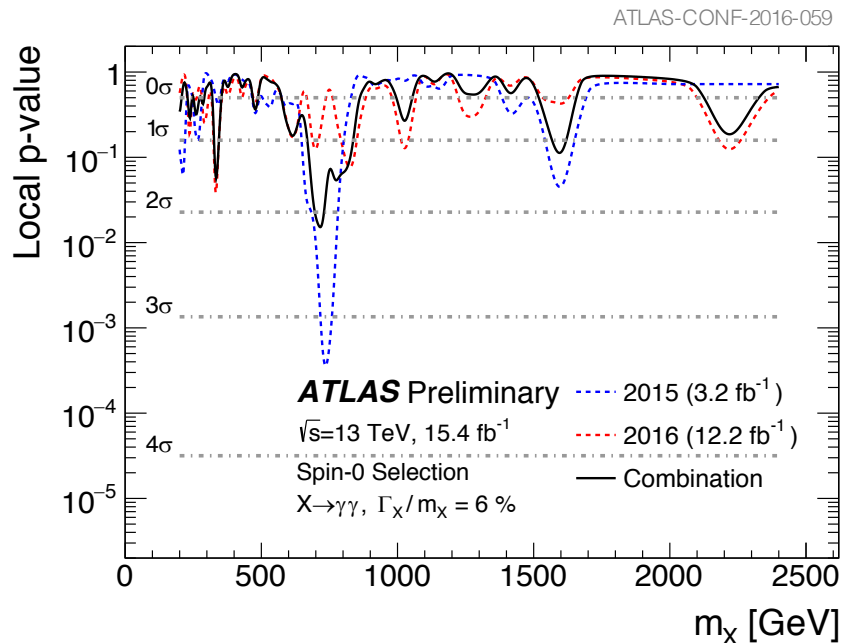


No noticeable excess in 2016 data

Diphoton resonance searches, the 2016 results

Comparison of 2015 and 2016 p-values

Resulting background-only p-values



Lesson? Statistical fluctuation. Can happen, nothing wrong.

Actual trials factor larger than global factor quoted, as very many signatures probed by experiments (hard to estimate, but keep in mind!). Having a second experiment with a similar non-significant excess does not remove trials factor if you keep both. Removing 2015 data, and looking at 750 GeV in 2016 does remove trials factor.

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