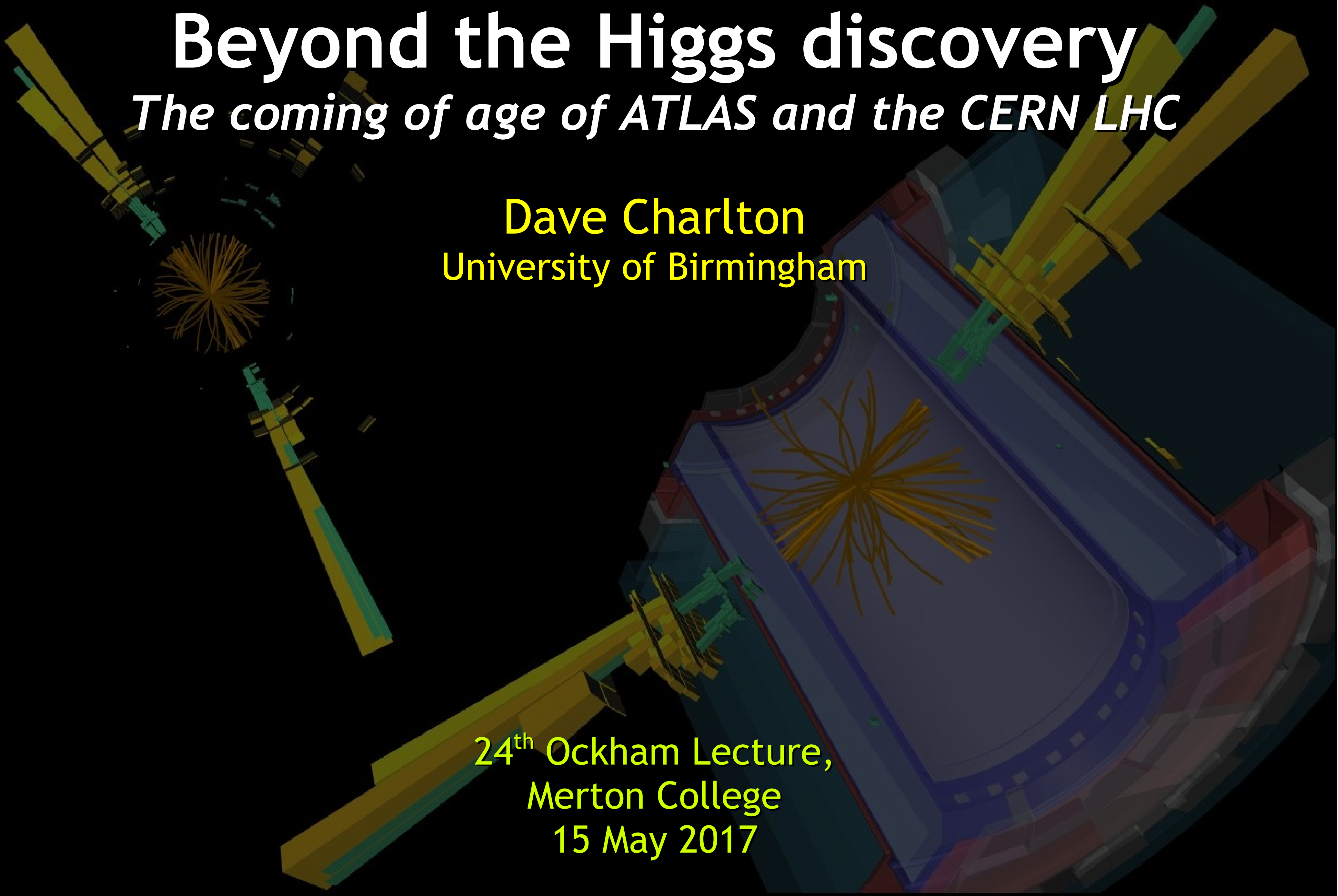


Beyond the Higgs discovery

The coming of age of ATLAS and the CERN LHC

Dave Charlton
University of Birmingham

24th Ockham Lecture,
Merton College
15 May 2017

Beyond the Higgs discovery

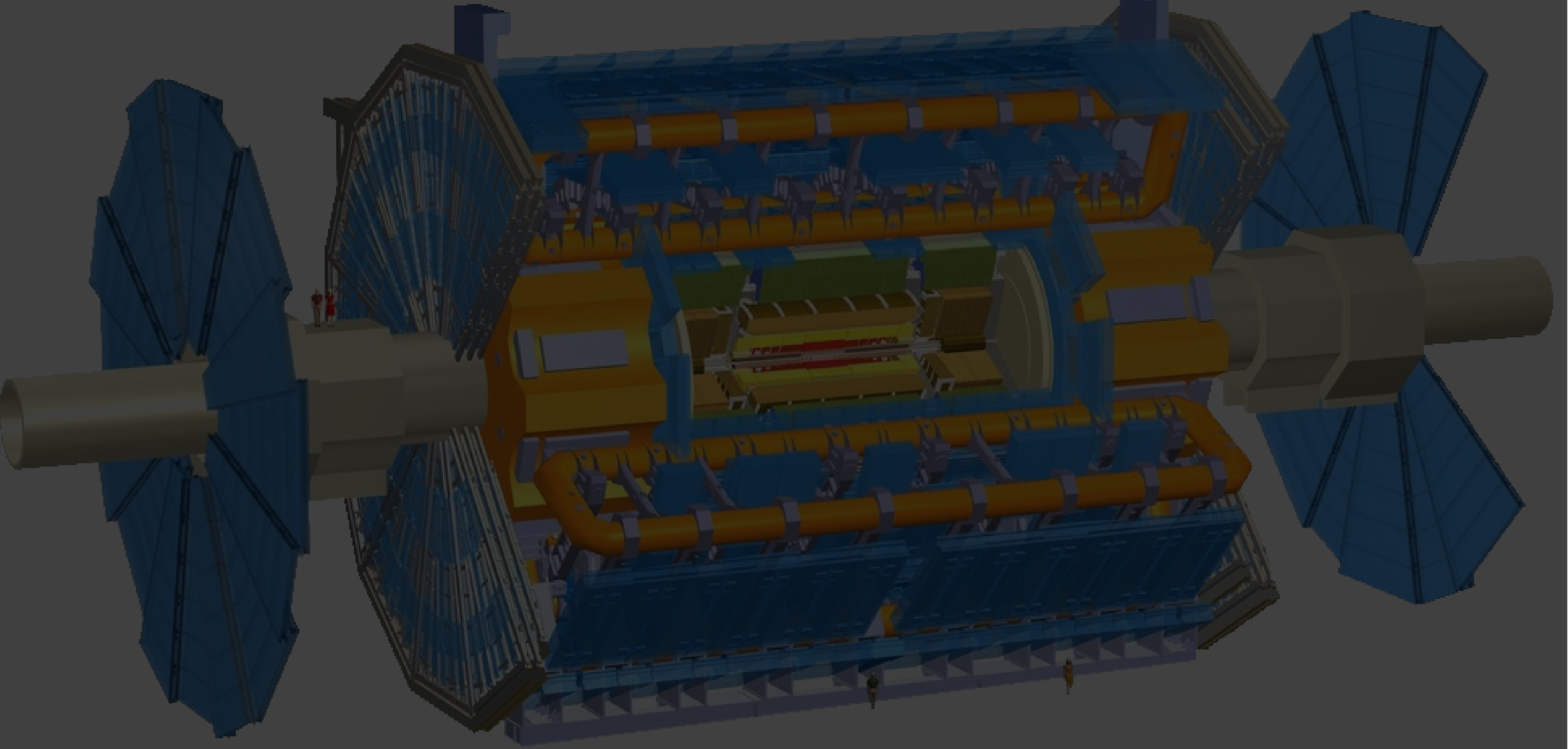
The coming of age of ATLAS and the CERN LHC

Dave Charlton
University of Birmingham

Outline

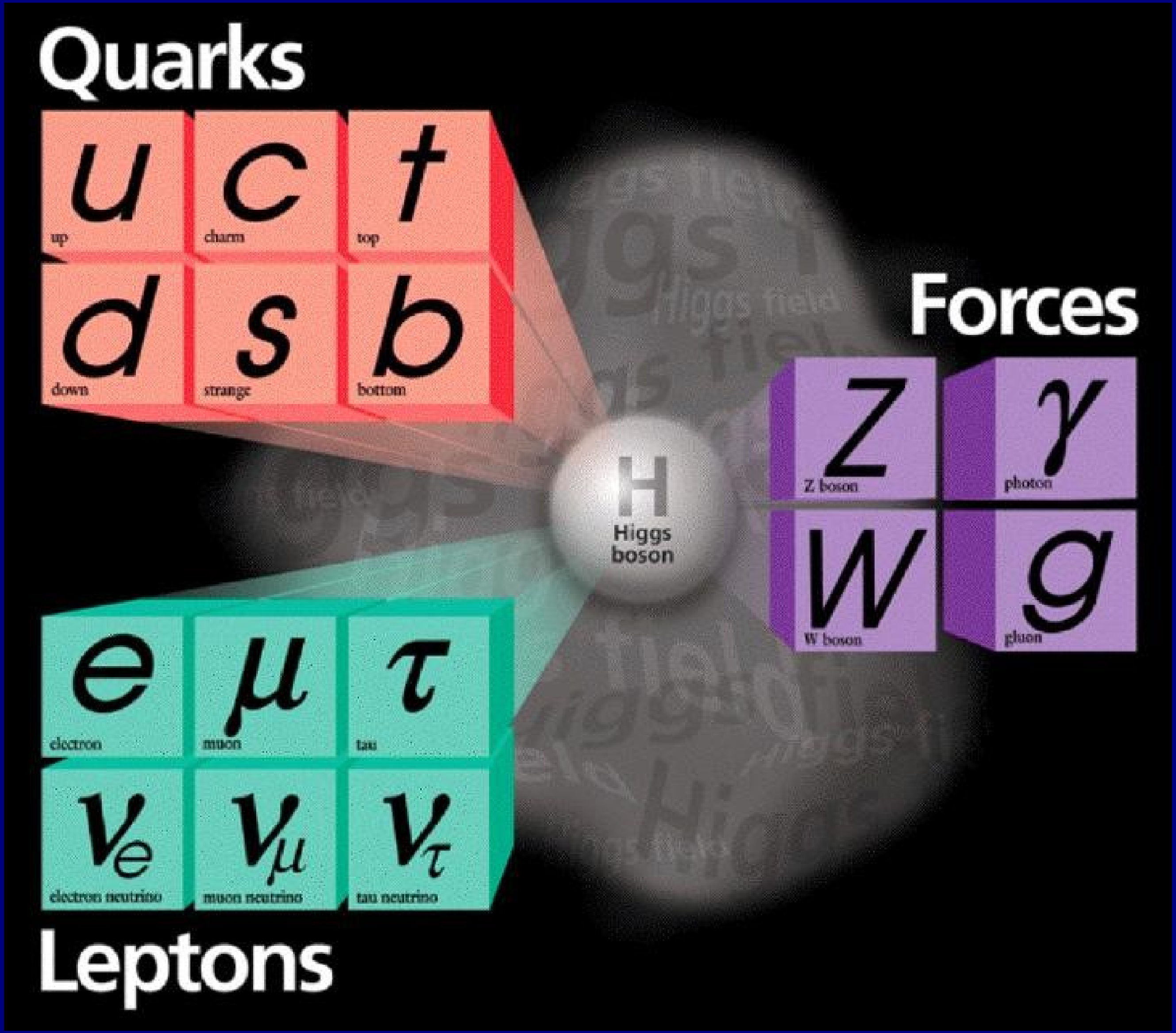
Where we start: the Higgs discovery
The LHC and ATLAS - coming of age
The Higgs boson, beyond the discovery
Beyond the Higgs
A look to the future

Where we start:
the Standard Model



The Standard Model, SM

Matter Particles



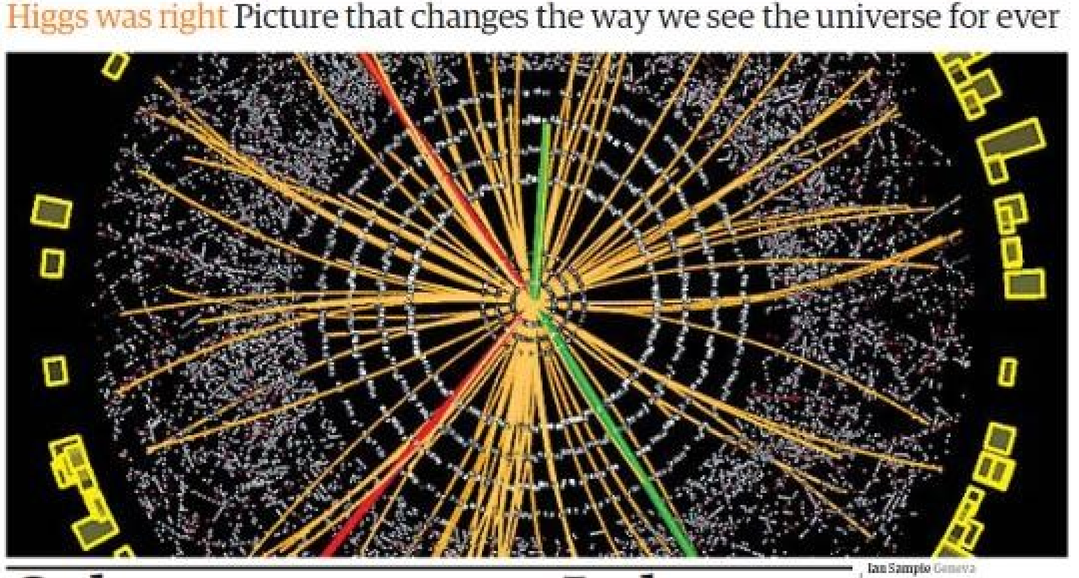
Force-carriers

Fermions

Bosons

Higgs Discovery (ATLAS and CMS)

July 4th 2012 (CERN and Melbourne)



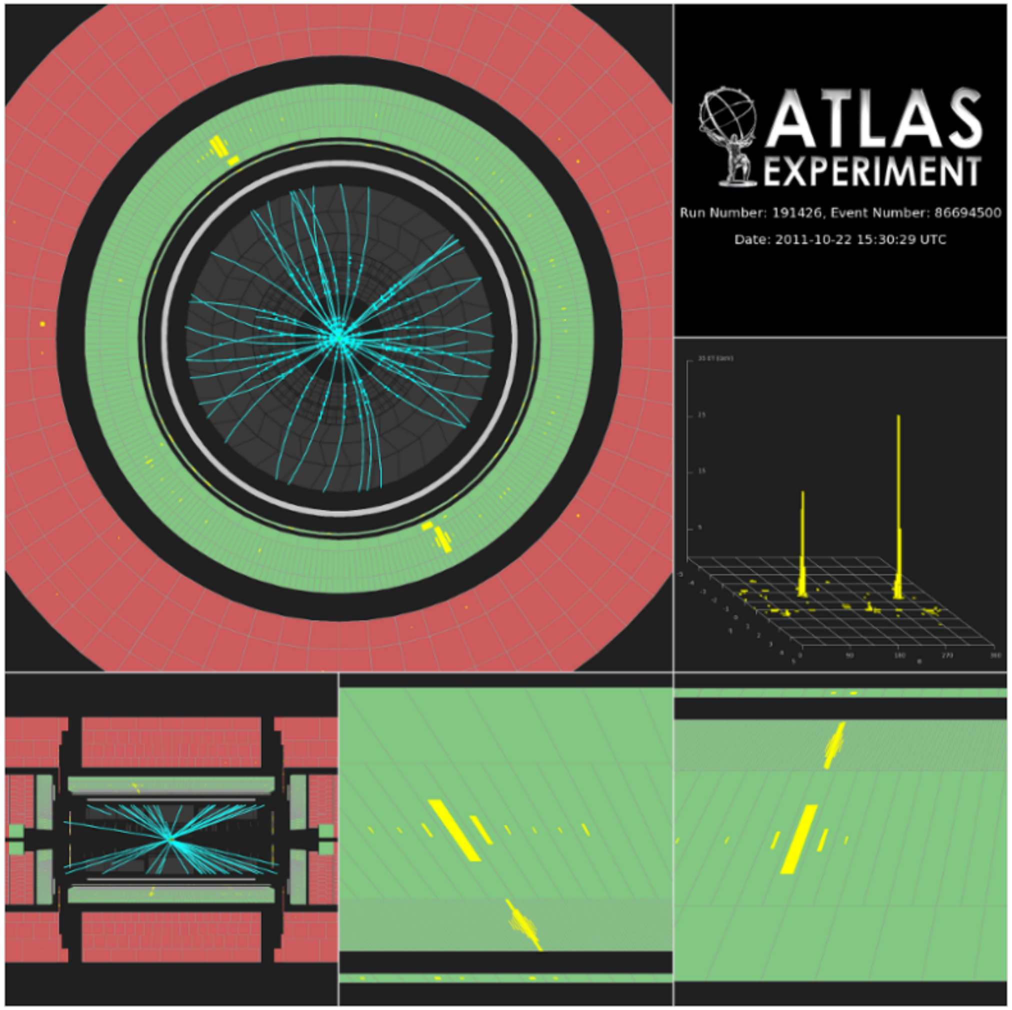
Higgs was right Picture that changes the way we see the universe for ever

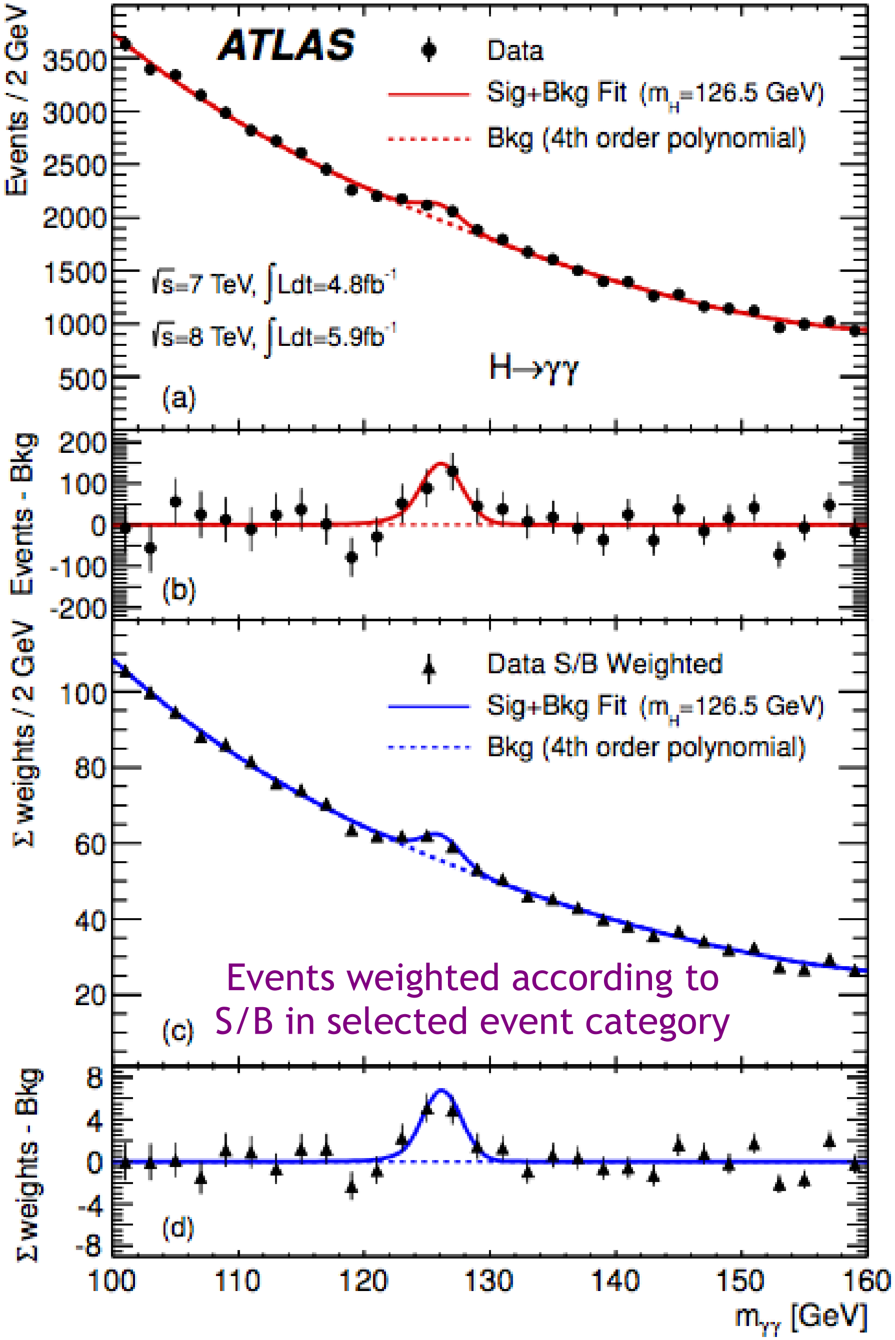
Ian Sample Geneva

July 2012 - the new boson

Fully reconstruct H→γγ final state

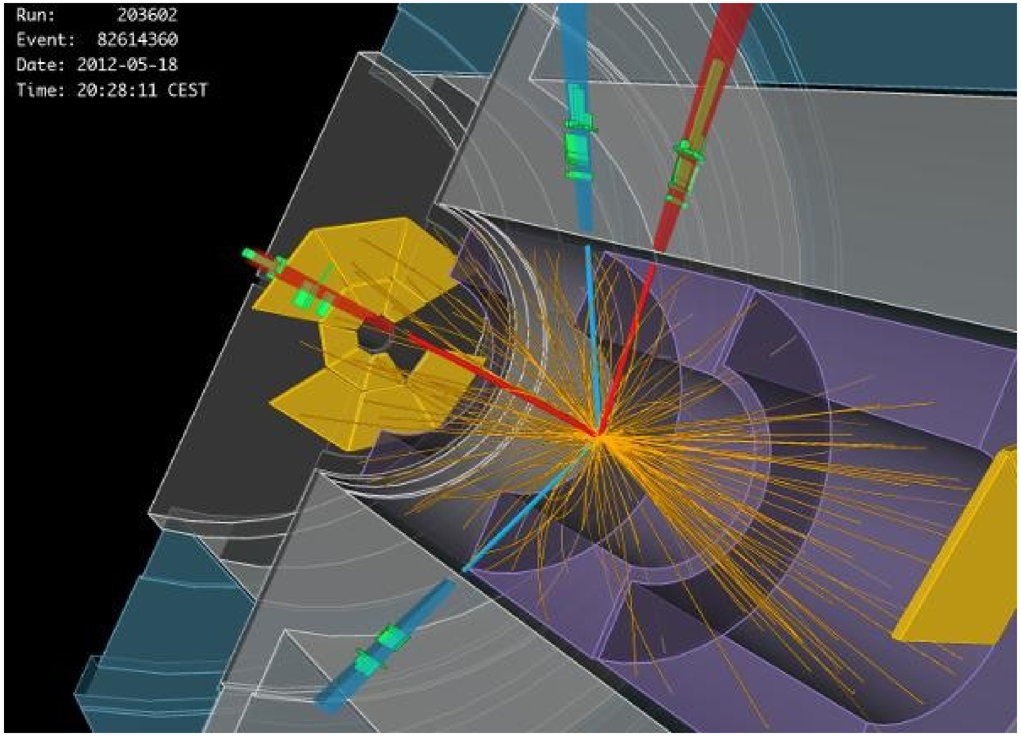
Excellent γγ mass resolution crucial, as well as γ-ID to reject jet/π^0 background

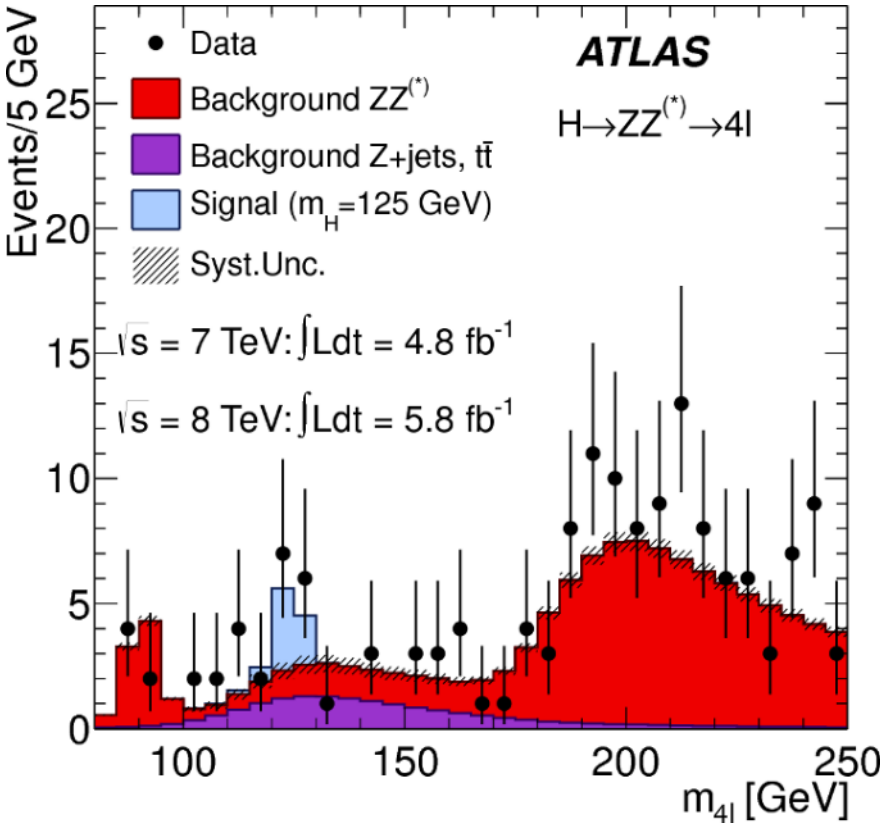




Events weighted according to S/B in selected event category

July 2012 - the new boson

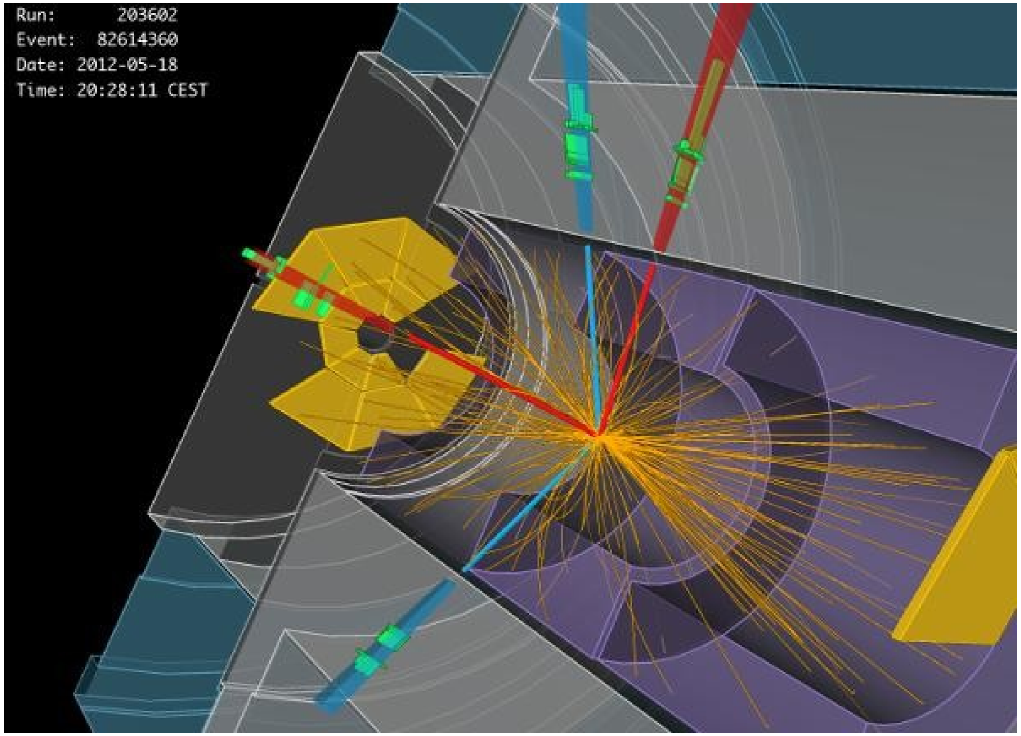


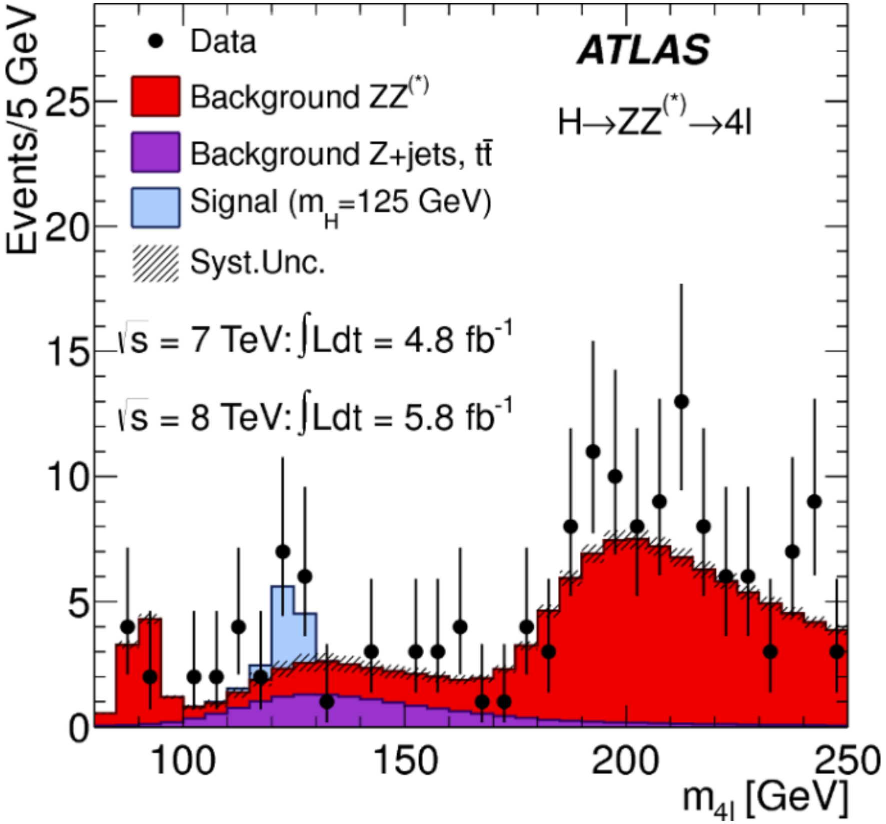


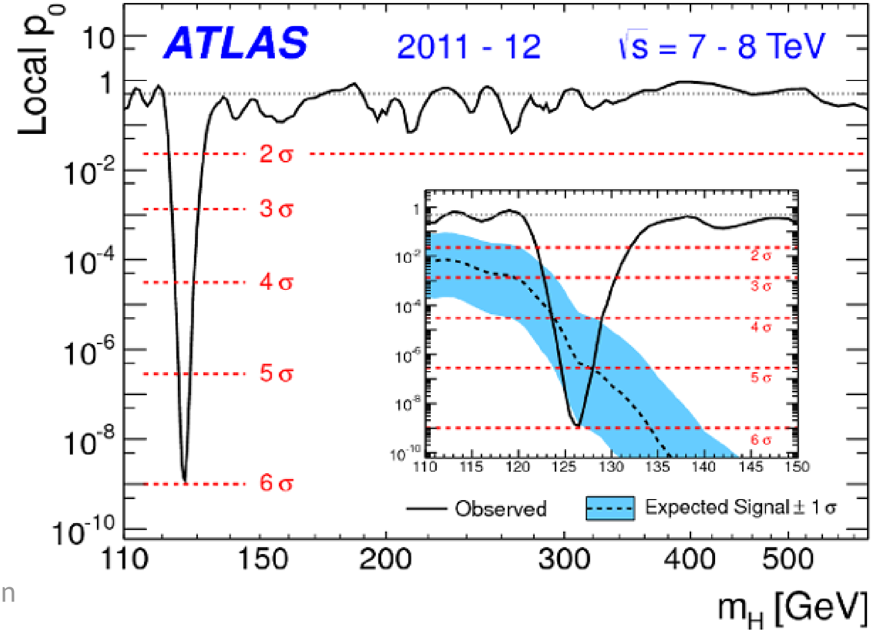
Fully reconstruct H→ZZ*→4ℓ final state

"Golden channel" - excellent mass resolution and signal/background~1

July 2012 - the new boson



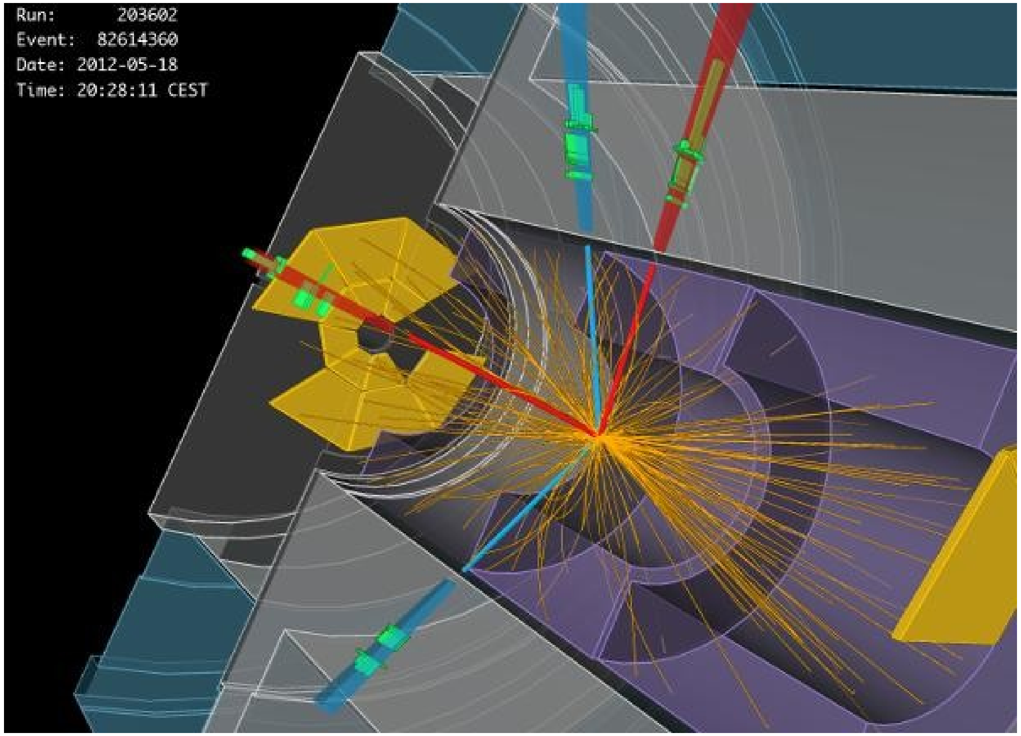


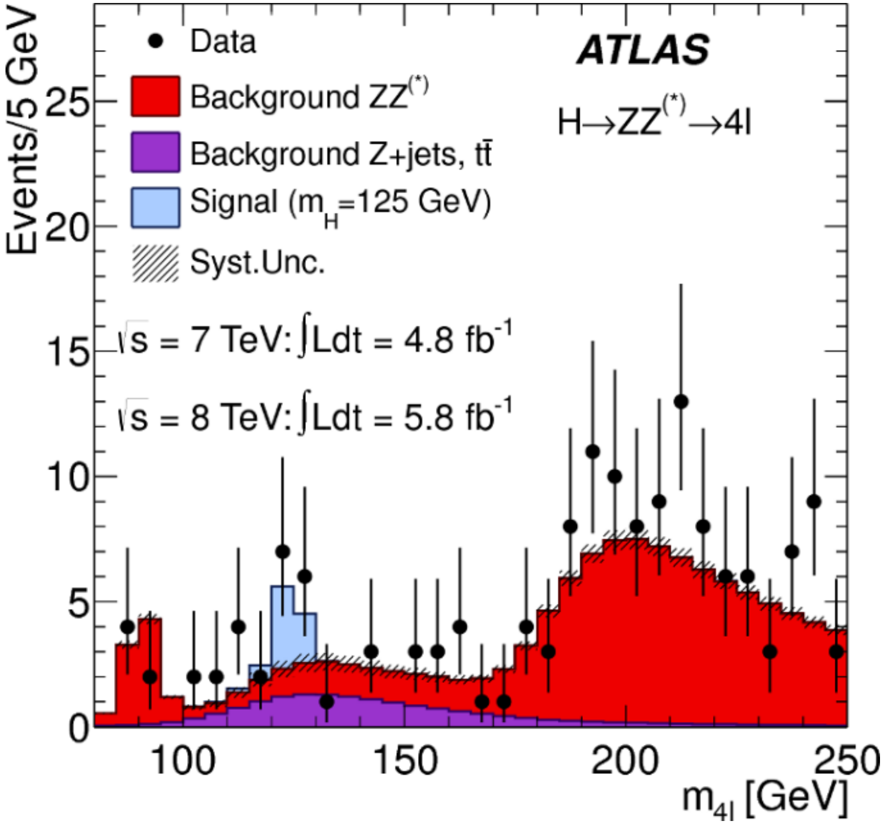


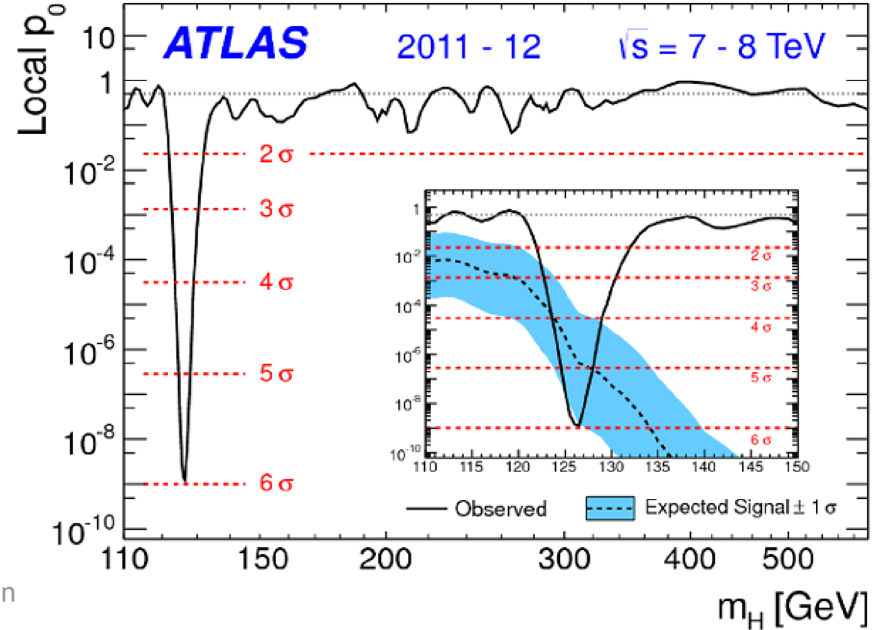
Combining γγ, 4ℓ and WW* channels

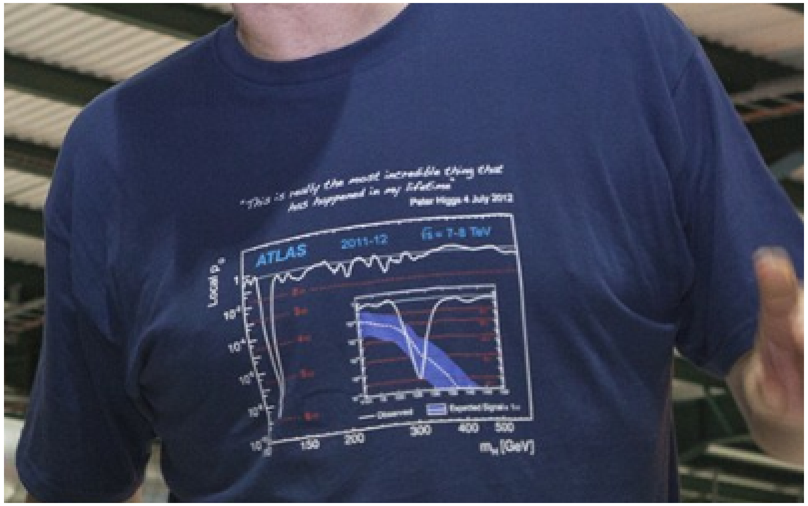
Overall significance (end July 2012) 5.9σ

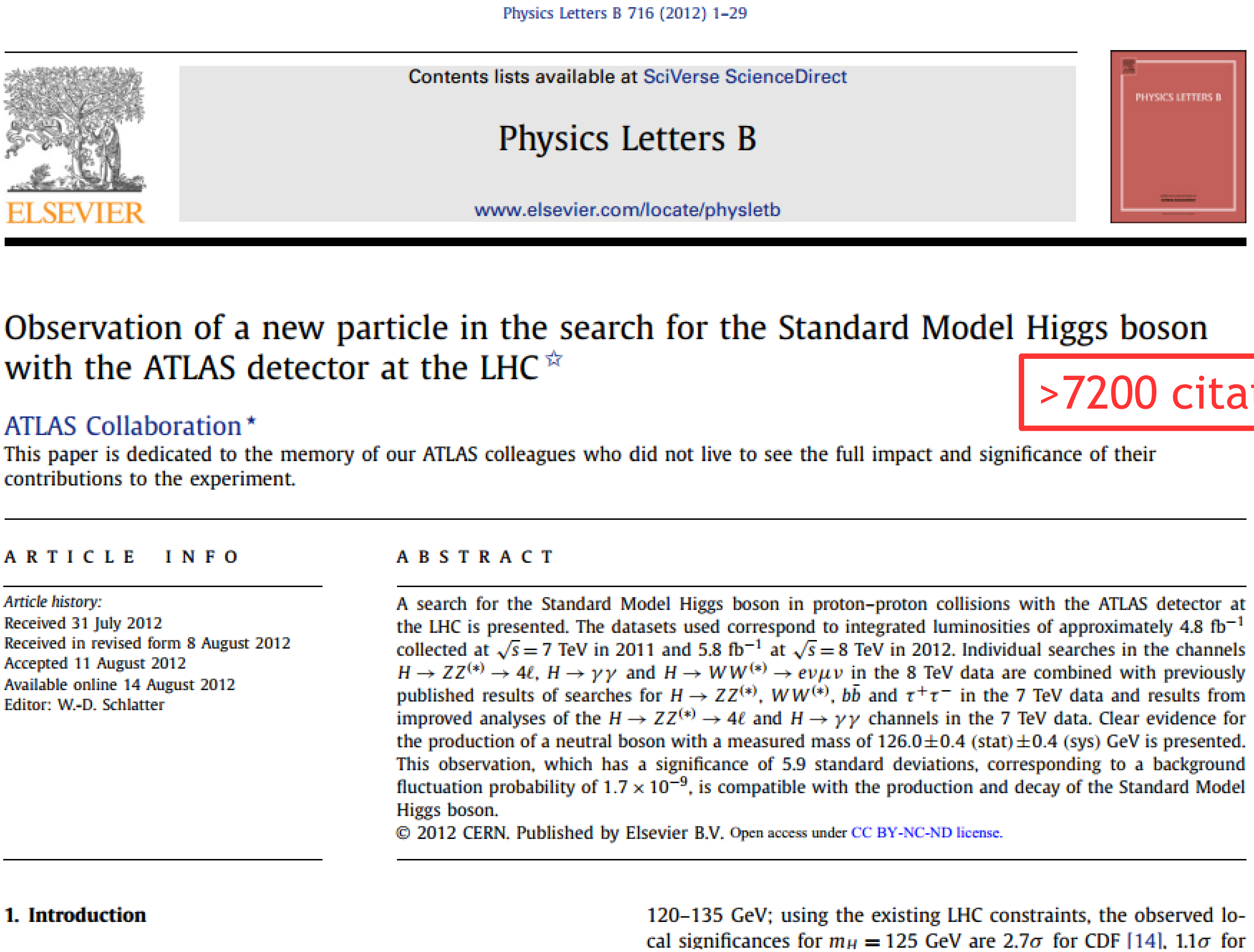
July 2012 - the new boson











Physics Letters B 716 (2012) 1–29

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Physics Letters B

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Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

>7200 citations

ARTICLE INFO

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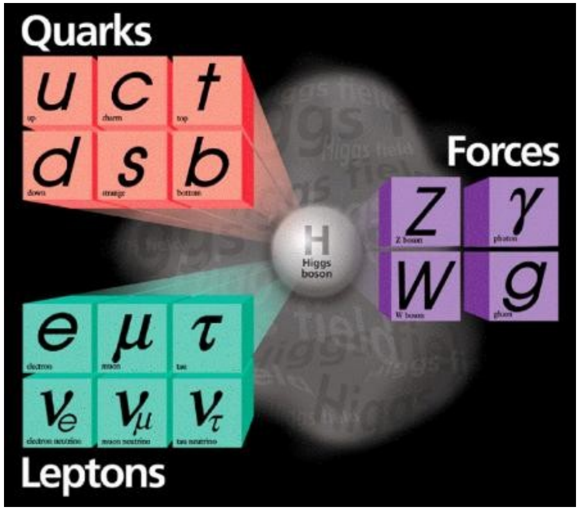
ABSTRACT

A search for the Standard Model Higgs boson in proton–proton collisions with the ATLAS detector at the LHC is presented. The datasets used correspond to integrated luminosities of approximately 4.8 fb^{-1} collected at $\sqrt{s} = 7$ TeV in 2011 and 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV in 2012. Individual searches in the channels $H \to ZZ^{(*)} \to 4\ell$, $H \to \gamma\gamma$ and $H \to WW^{(*)} \to e\nu\mu\nu$ in the 8 TeV data are combined with previously published results of searches for $H \to ZZ^{(*)}$, $WW^{(*)}$, $b\bar{b}$ and $\tau^+\tau^-$ in the 7 TeV data and results from improved analyses of the $H \to ZZ^{(*)} \to 4\ell$ and $H \to \gamma\gamma$ channels in the 7 TeV data. Clear evidence for the production of a neutral boson with a measured mass of $126.0 \pm 0.4\,(\text{stat}) \pm 0.4\,(\text{sys})$ GeV is presented. This observation, which has a significance of 5.9 standard deviations, corresponding to a background fluctuation probability of 1.7×10^{-9}, is compatible with the production and decay of the Standard Model Higgs boson.

1. Introduction

120–135 GeV; using the existing LHC constraints, the observed local significances for $m_H = 125$ GeV are 2.7σ for CDF [14], 1.1σ for

Questions crystallise...



About the identity of the H(125) particle

- Is it a Higgs boson?
- Is it unique?
- Does it couple to the vector bosons with the right coupling strength and structure?
- Is it also responsible for giving mass to the fermions?
- Is the H(125) the only mechanism for electroweak symmetry-breaking?

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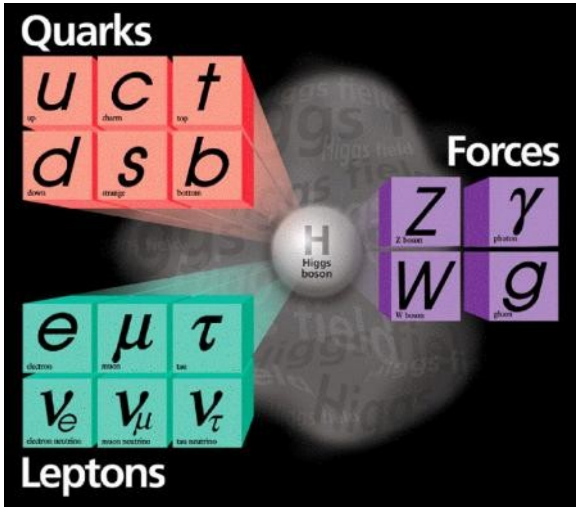
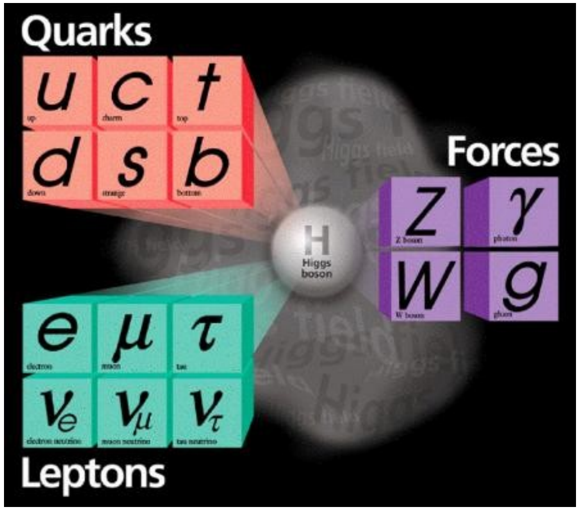


We can now study these questions via precision measurements of the Higgs sector, and of EWSB in general

Questions crystallise...



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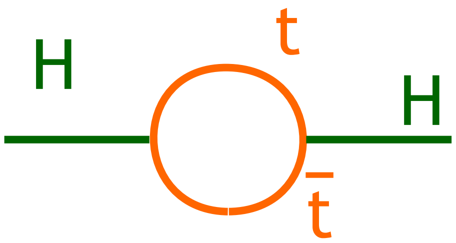
- Does it couple to the vector bosons with the right coupling strength and structure?
- Is it also responsible for giving mass to the fermions?
- Is the H(125) the only mechanism for electroweak symmetry-breaking?

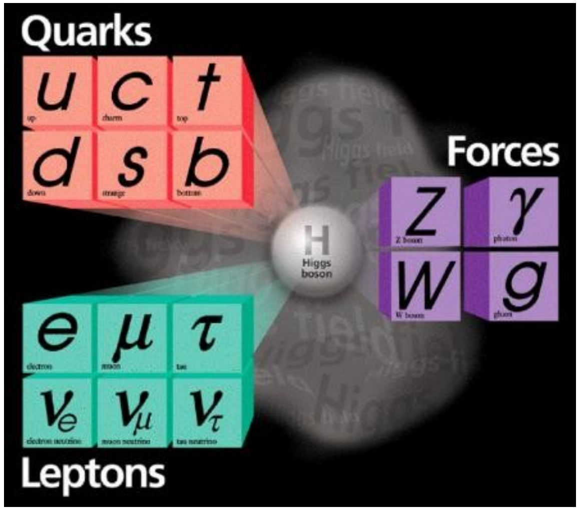
- **Why is the H so light?**



Divergent corrections to the H mass from loops, cut off only if new physics enters at a mass scale close to the electroweak scale

“Hierarchy problem” / fine-tuning

...others are not addressed



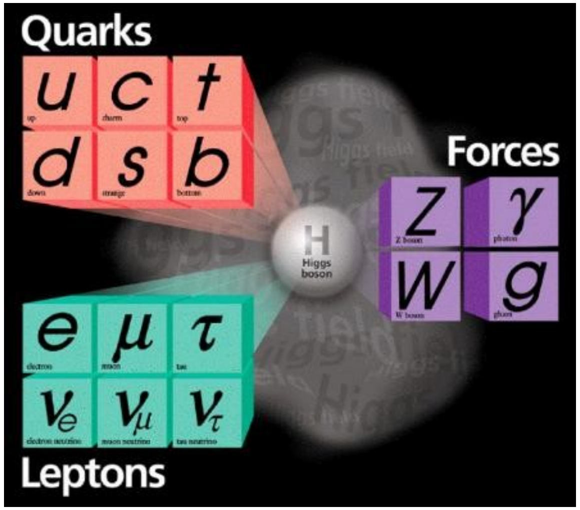
Hard questions that we often forget to ask

- Why 3 generations of (light) fermions?
- Why such *different* fermion masses?

- The gauge theory descriptions of the electroweak and strong (QCD) sectors of the Standard Model are so similar
  - Where is grand unification?
  - Extra dimensions of space-time? Branes …?

- Baryon asymmetry?
- Dark matter & energy?

…others are not addressed



Hard questions that we often forget to ask

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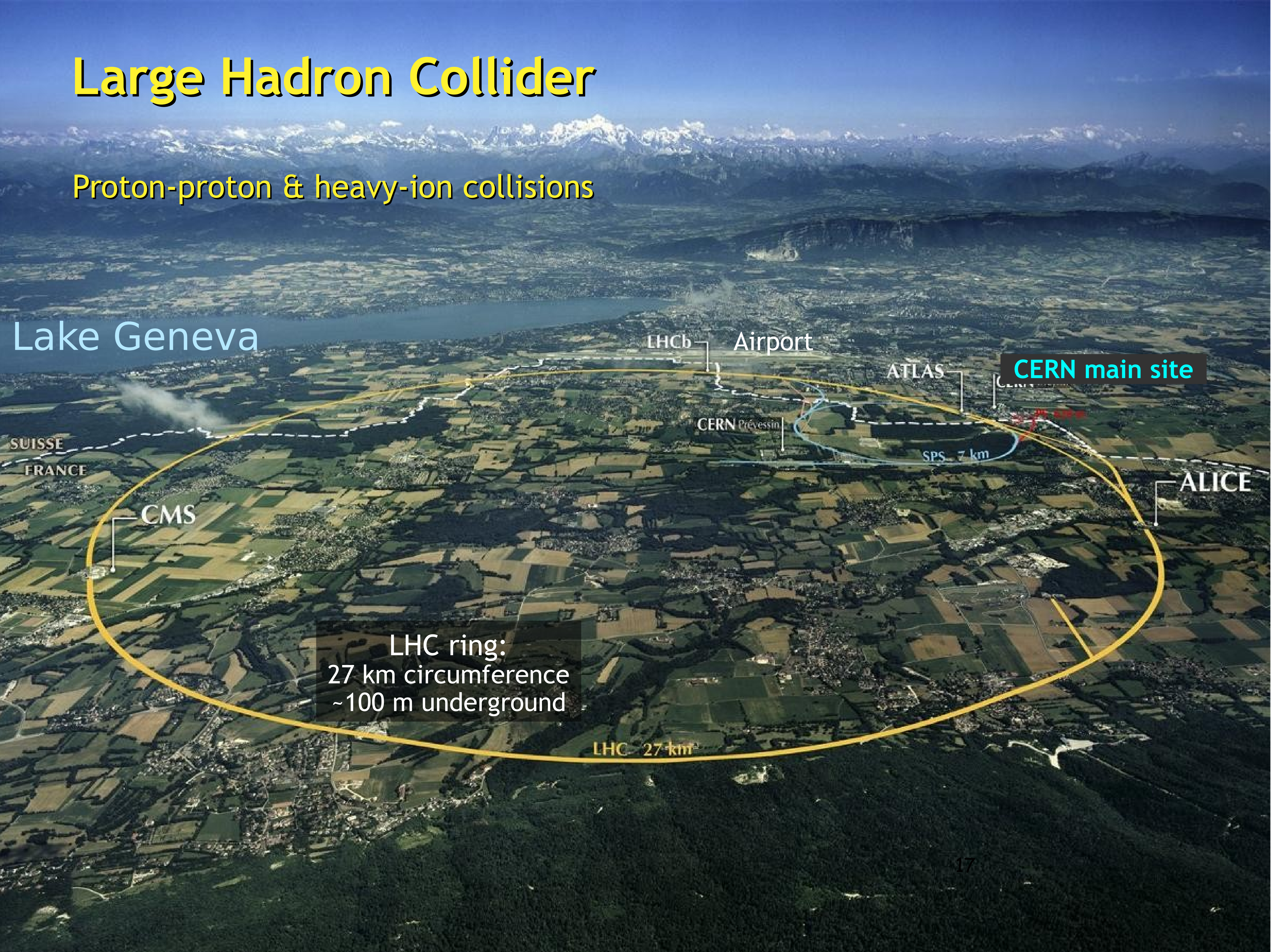
- Baryon asymmetry?
- Dark matter & energy?

Searching for new physics at the TeV scale may gain further insight to these questions - and to the hierarchy problem

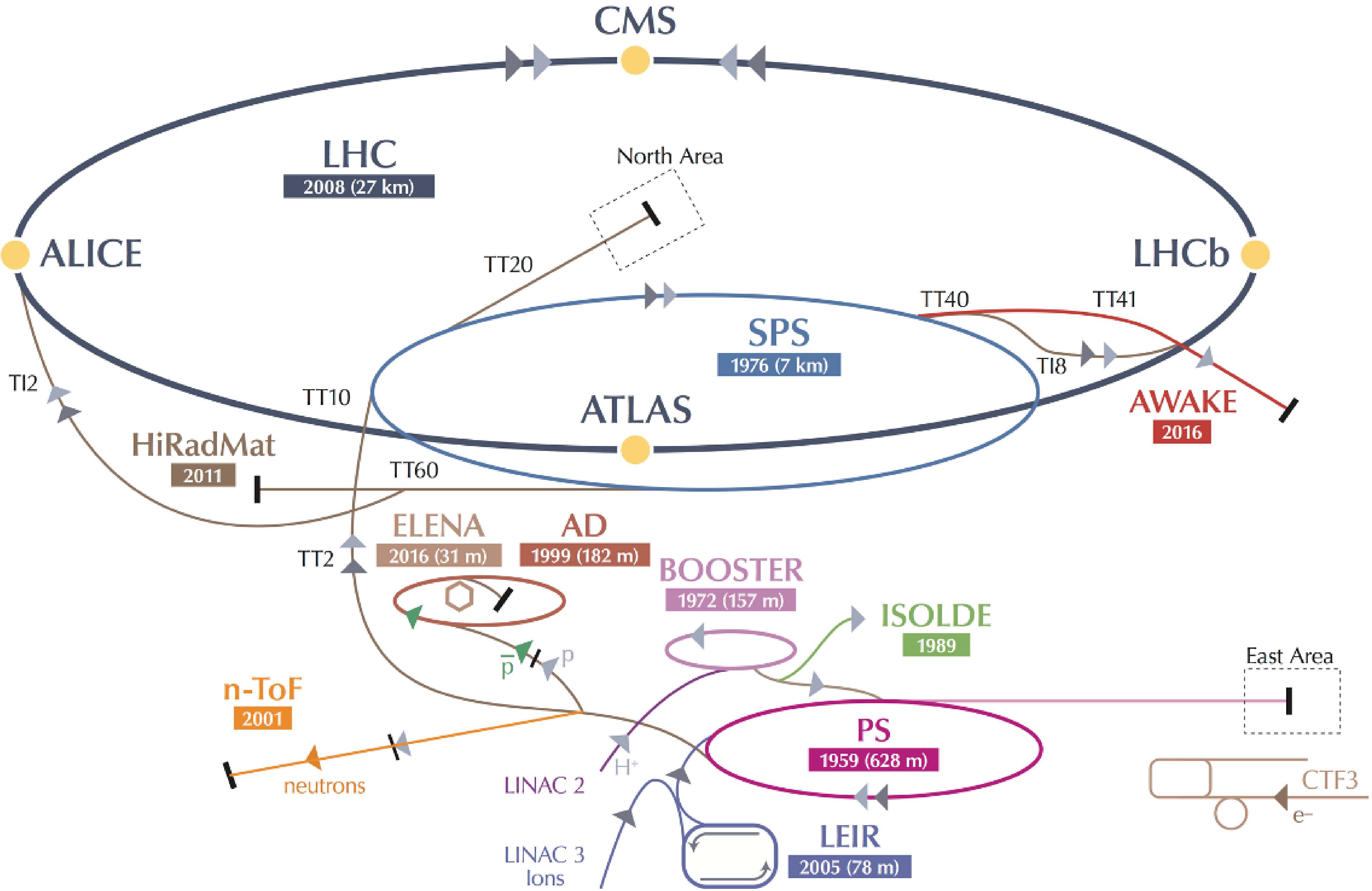
The LHC and ATLAS
Coming of Age

Large Hadron Collider

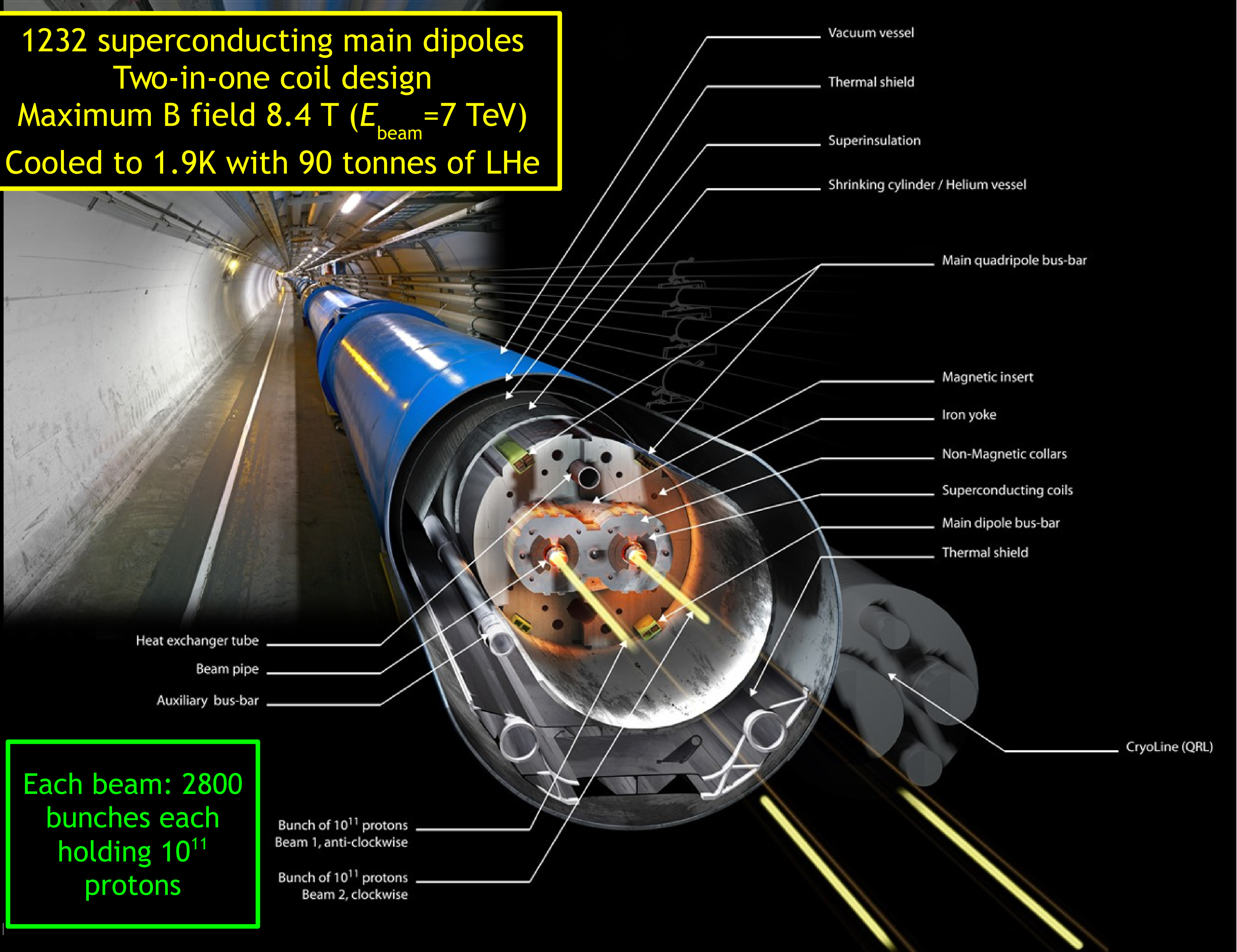
Proton-proton & heavy-ion collisions



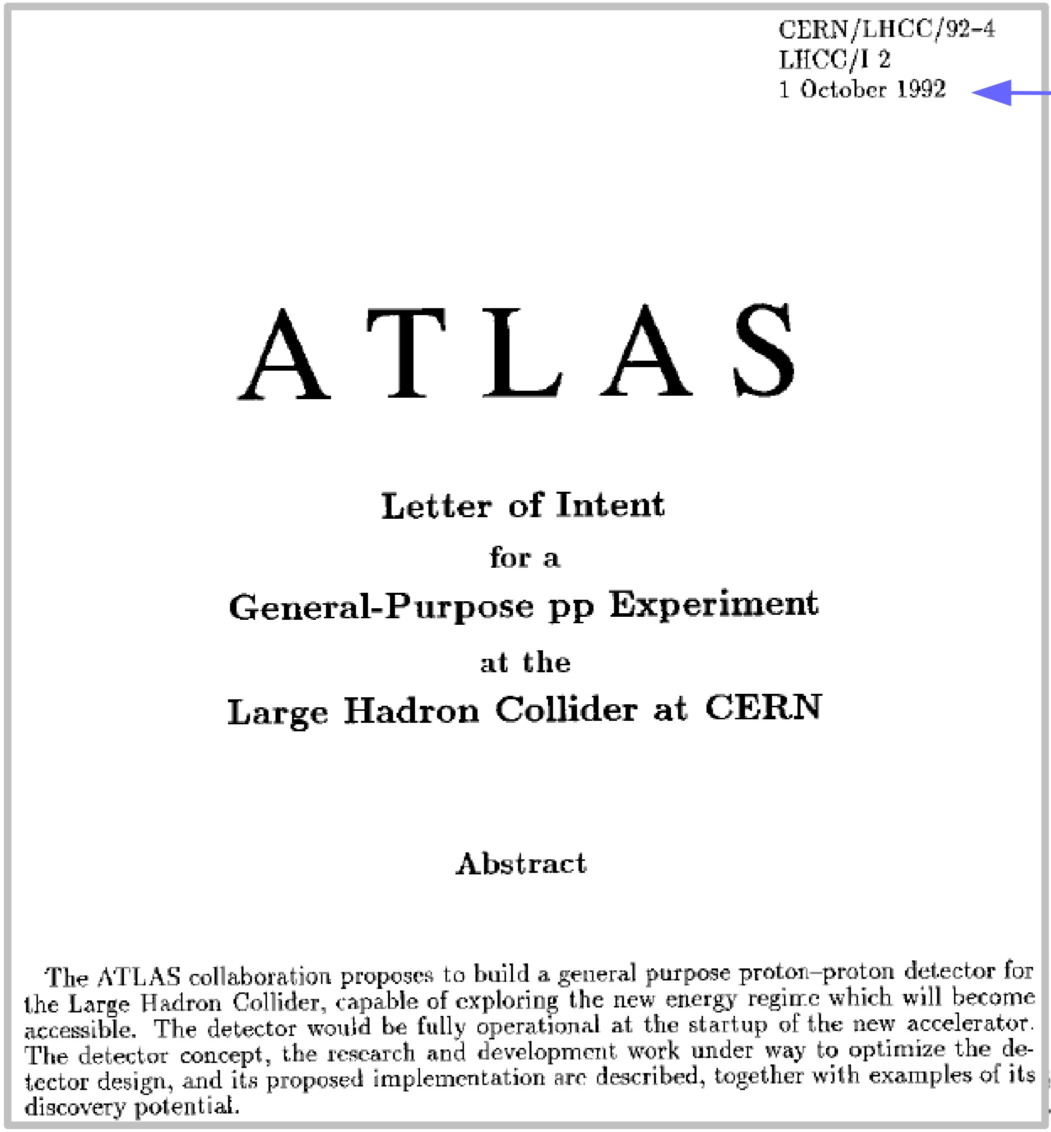
LHC ring:
27 km circumference
~100 m underground


CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT20
TT40
TT41
SPS
1976 (7 km)
TI8
TI2
TT10
ATLAS
AWAKE
2016
HiRadMat
2011
TT60
ELENA
2016 (31 m)
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
p̄
p
East Area
n-ToF
2001
PS
1959 (628 m)
neutrons
LINAC 2
H+
CTF3
e–
LINAC 3
Ions
LEIR
2005 (78 m)

1232 superconducting main dipoles
Two-in-one coil design
Maximum B field 8.4 T (E_{beam}=7 TeV)
Cooled to 1.9K with 90 tonnes of LHe



Each beam: 2800 bunches each holding 10^{11} protons



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

ATLAS

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

Abstract

The ATLAS collaboration proposes to build a general purpose proton–proton detector for the Large Hadron Collider, capable of exploring the new energy regime which will become accessible. The detector would be fully operational at the startup of the new accelerator. The detector concept, the research and development work under way to optimize the detector design, and its proposed implementation are described, together with examples of its discovery potential.

The early days: ATLAS Collaboration formed in 1992

R&D in the 1990's – construction started in 1997

Installation into cavern from 2003

Members of the ATLAS Collaboration

LoI: 88 Institutions

lérateur Linéaire, IN2P3-CNRS, Orsay, France
eton, R.L.Chase, J.C.Chollet, P.Delebecque, V.Dubois, A.Ducorps, C.de la Taille, L.Fayard, D.Fournier, A.Hrisoho, L.Iconomidou-Fayard, Ph.Jean, B.Merkel, J.Noppe, G.Parrour, P.Petroff, J.P.Repellin, A.Schaffer, N.Seguin, L.Serin, G.Unal, J.J.Veillet

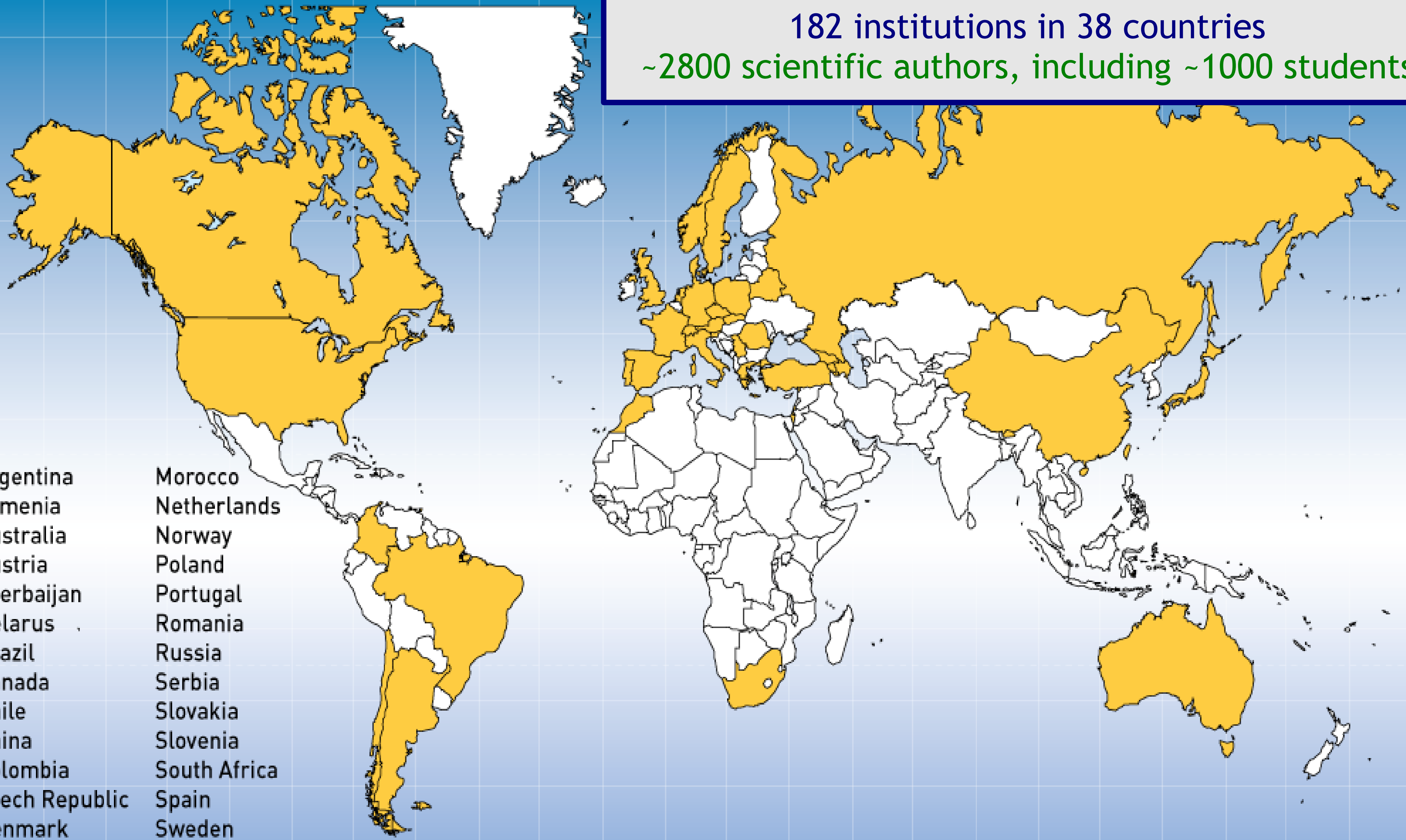
Oslo University, Oslo, Norway
T.Buran, E.Nygaard, S.Stapnes

Physics Department, Oxford University, Oxford, United Kingdom
J.H.Bibby, J.F.Harris, R.J.Hawkings, A.R.Holmes, P.B.Renton, A.R.Weidberg

Pierre & Marie Curie and Paris VII Universities and IN2P3-CNRS, Paris, France
S.Dagoret, D.Imbault, G.Hansl-Kozanecka, H.Lebbolo, P.Neyman, R.Zitoun

182 institutions in 38 countries

~2800 scientific authors, including ~1000 students



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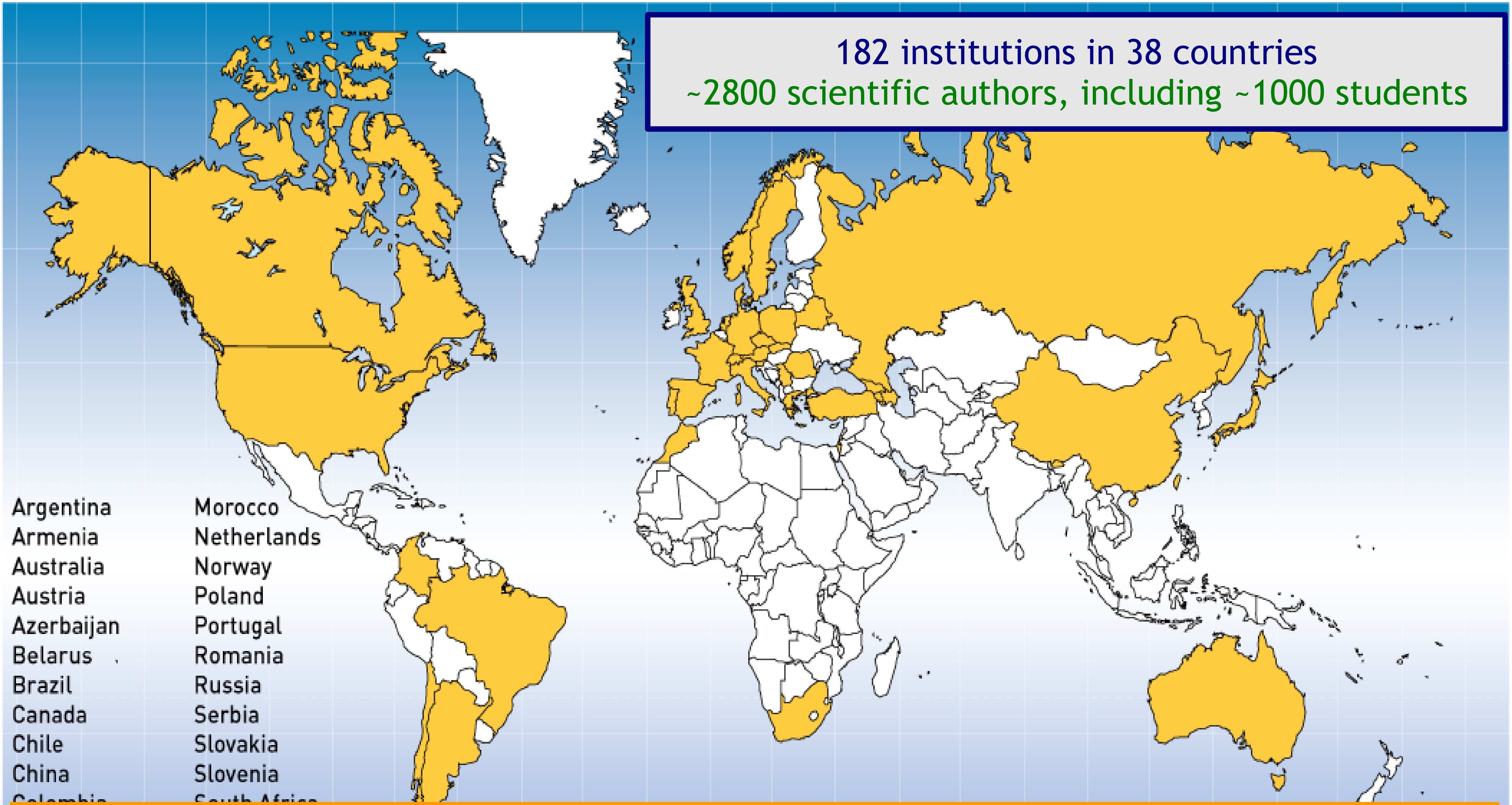
- Australia
- Austria
- Azerbaijan
- Belarus
- Brazil
- Canada
- Chile
- China
- Colombia
- Czech Republic
- Denmark
- France
- Georgia
- Germany
- Greece
- Israel
- Italy
- Japan
- Morocco
- Netherlands
- Norway
- Poland
- Portugal
- Romania
- Russia
- Serbia
- Slovakia
- Slovenia
- South Africa
- Spain
- Sweden
- Switzerland
- Taiwan
- Turkey
- UK
- USA
- CERN
- JINR

ATLAS Collaboration

July 2010

182 institutions in 38 countries
~2800 scientific authors, including ~1000 students



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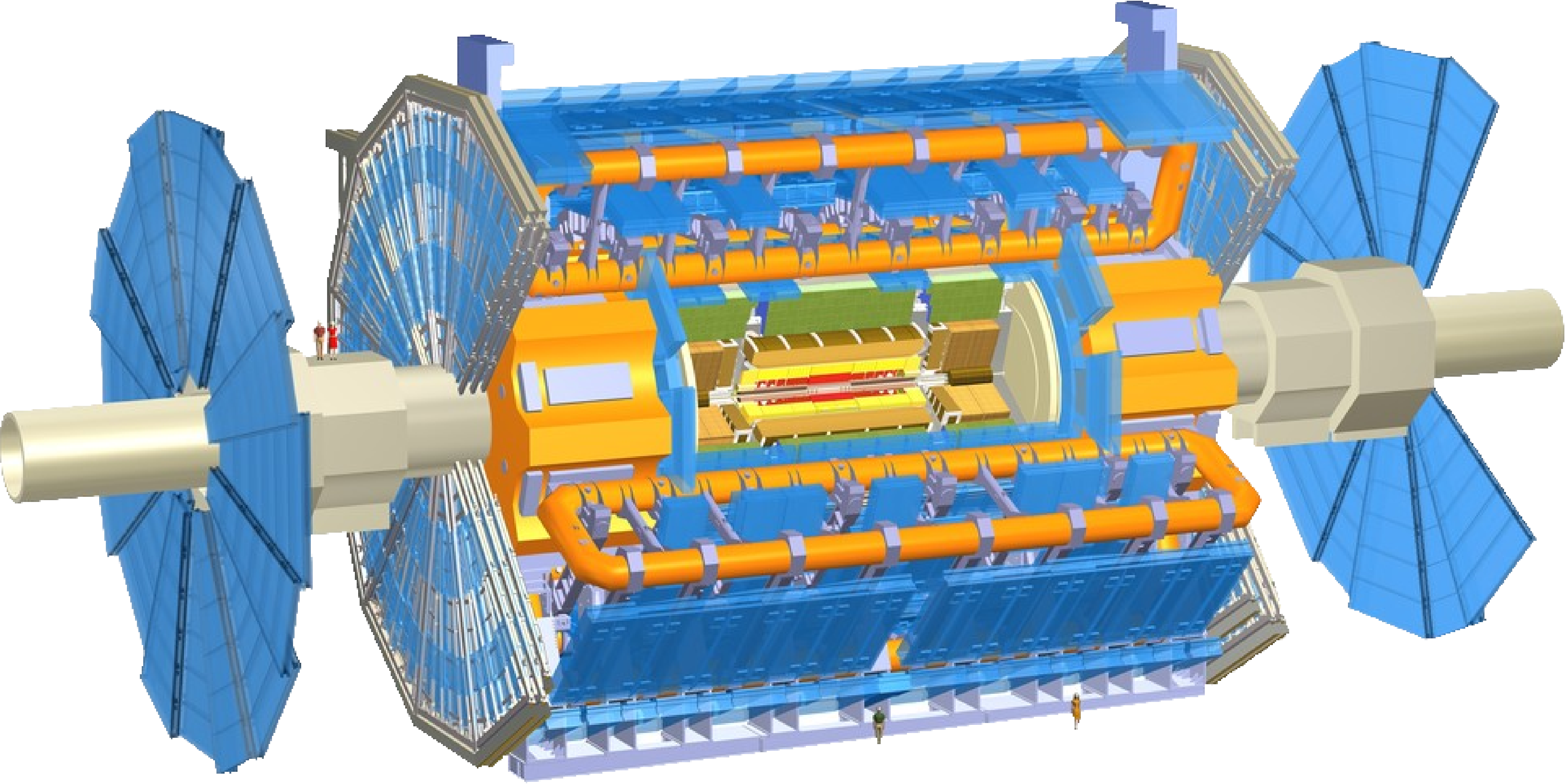
Romania
Russia
Serbia
Slovakia
Slovenia
South Africa

Adelaide, Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, UT Austin, Baku, IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Bratislava/SAS Kosice, Brazil Cluster, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, China IHEP-NJU-THU, China USTC-SDU-SJTU, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Harvard, Heidelberg, Hiroshima IT, Hong Kong, NTHU Hsinchu, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, KEK, Kobe, Kyoto, Kyoto UE, Kyushu, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QM London, RH London, UC London, Louisiana Tech, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois University, Novosibirsk BINP-NSU, NPI Petersburg, Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, **Oxford**, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Rome I, Rome II, Rome III, RAL-STFC, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, South Africa Cluster, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Tomsk SU, Toronto, Trento, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana, Valencia, UBC Vancouver, Victoria, Warwick, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

ATLAS Detector

7000t, 45m long x 25m diameter
Si+transition radiation tracker, 2T solenoid, LAr sampling calorimetry, large air-core toroid muon spectrometer



~110 M channels, with timing capable of separating particles from adjacent bunch-crossings (25ns)

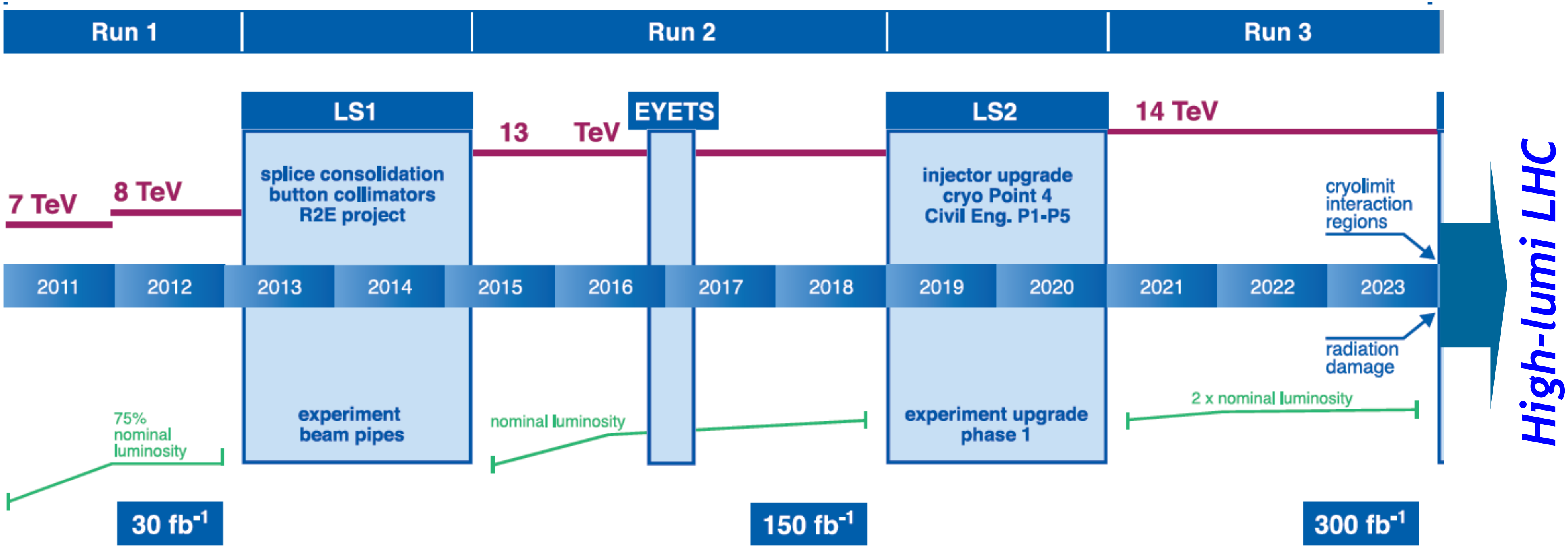

FRAGILE !
FRAGILE !
FRAGILE !
FRAGILE !

The first decade of LHC operation

Run-1: little data and low energy!

Run-2: 13 TeV, much more data

Run-3: 14 TeV, and doubled data sample



Proton-proton centre-of-mass energy √s = 2 E_{beam}

LHC design √s = 14 TeV

Why we push √s

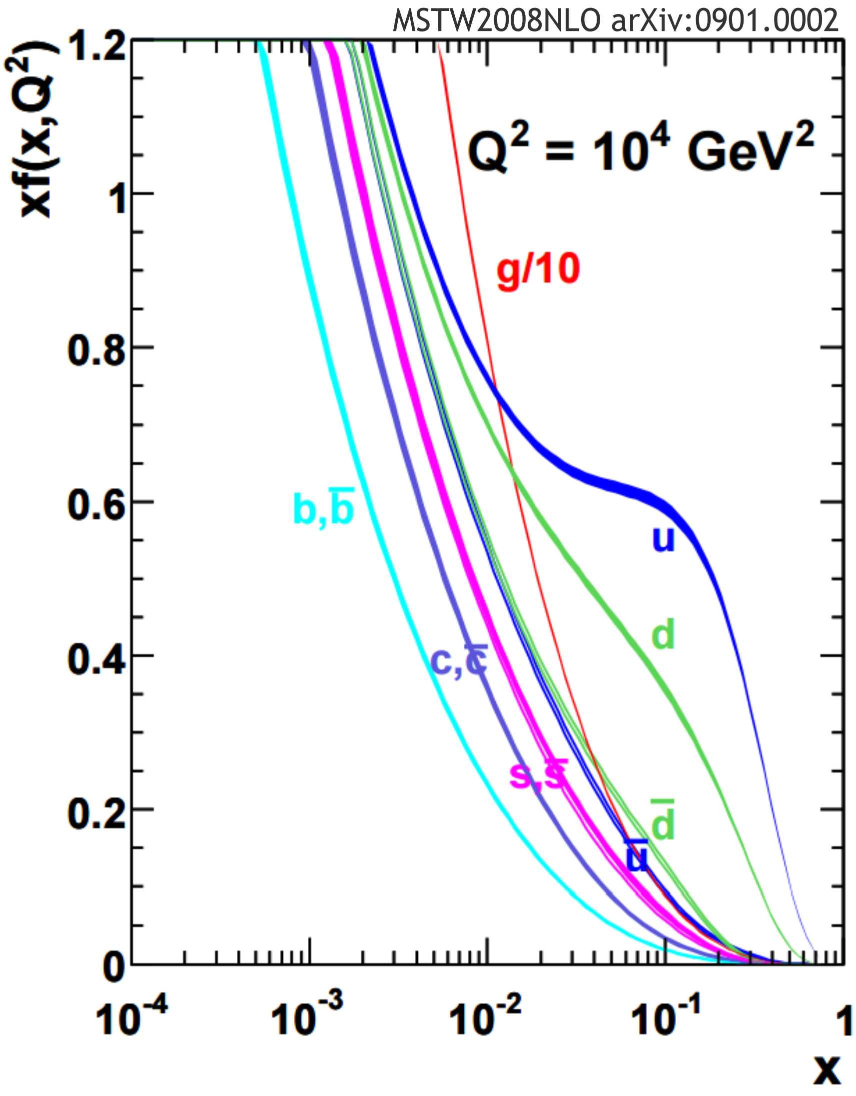
Partons (quarks, gluons) within the proton carry only a fraction, *x*, of the momentum of the proton

- Probability distribution described by *parton density function (pdf), f(x,Q^2)*

- Parton-parton centre-of-mass energy

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} \sim Q$$

High $\sqrt{\hat{s}}$ collisions are very rare



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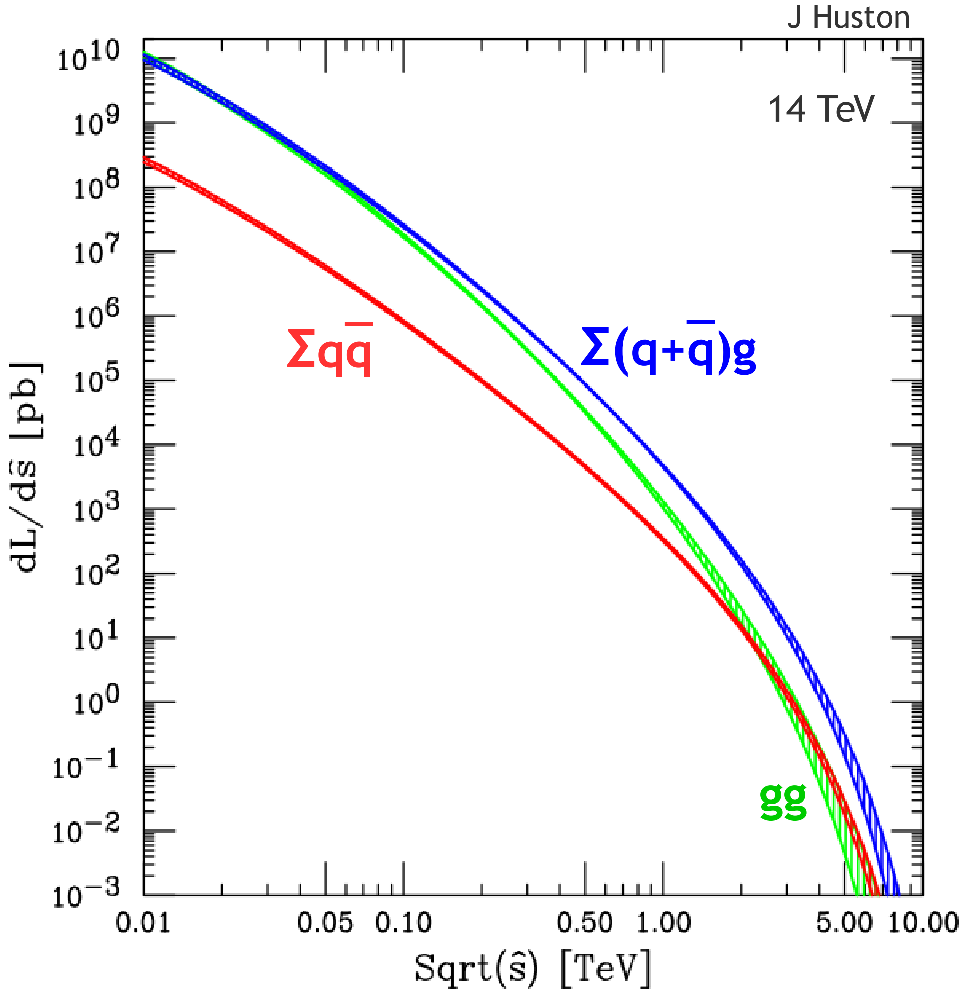
- Parton-parton centre-of-mass energy

$$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s} \sim Q$$

High $\sqrt{\hat{s}}$ collisions are very rare

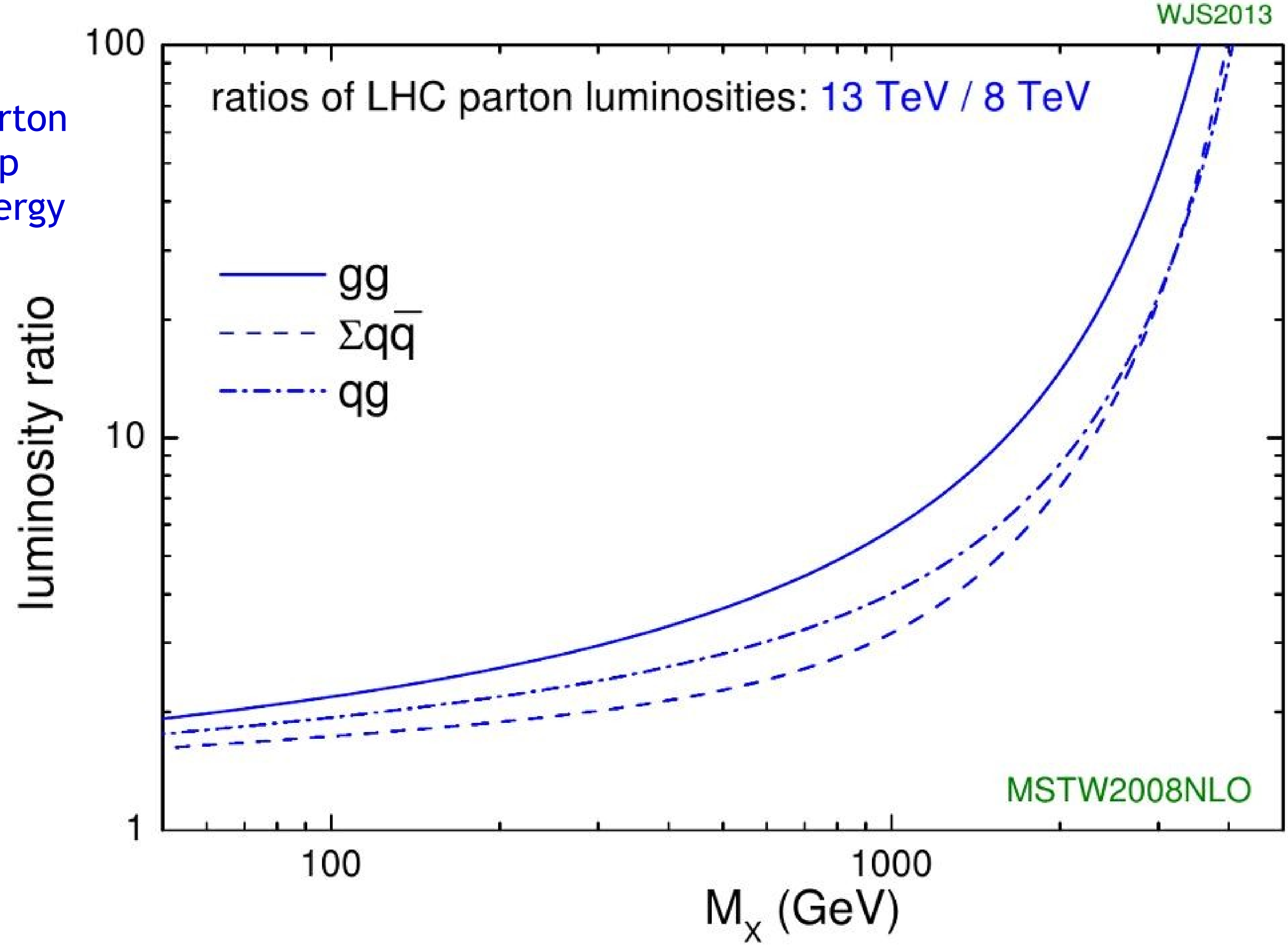
- *Parton-parton luminosity* integrates over x_1, x_2 for a fixed $\hat{s}$

$$\rightarrow \left(\frac{d\,L(a,b)}{d\,\hat{s}} \right)$$

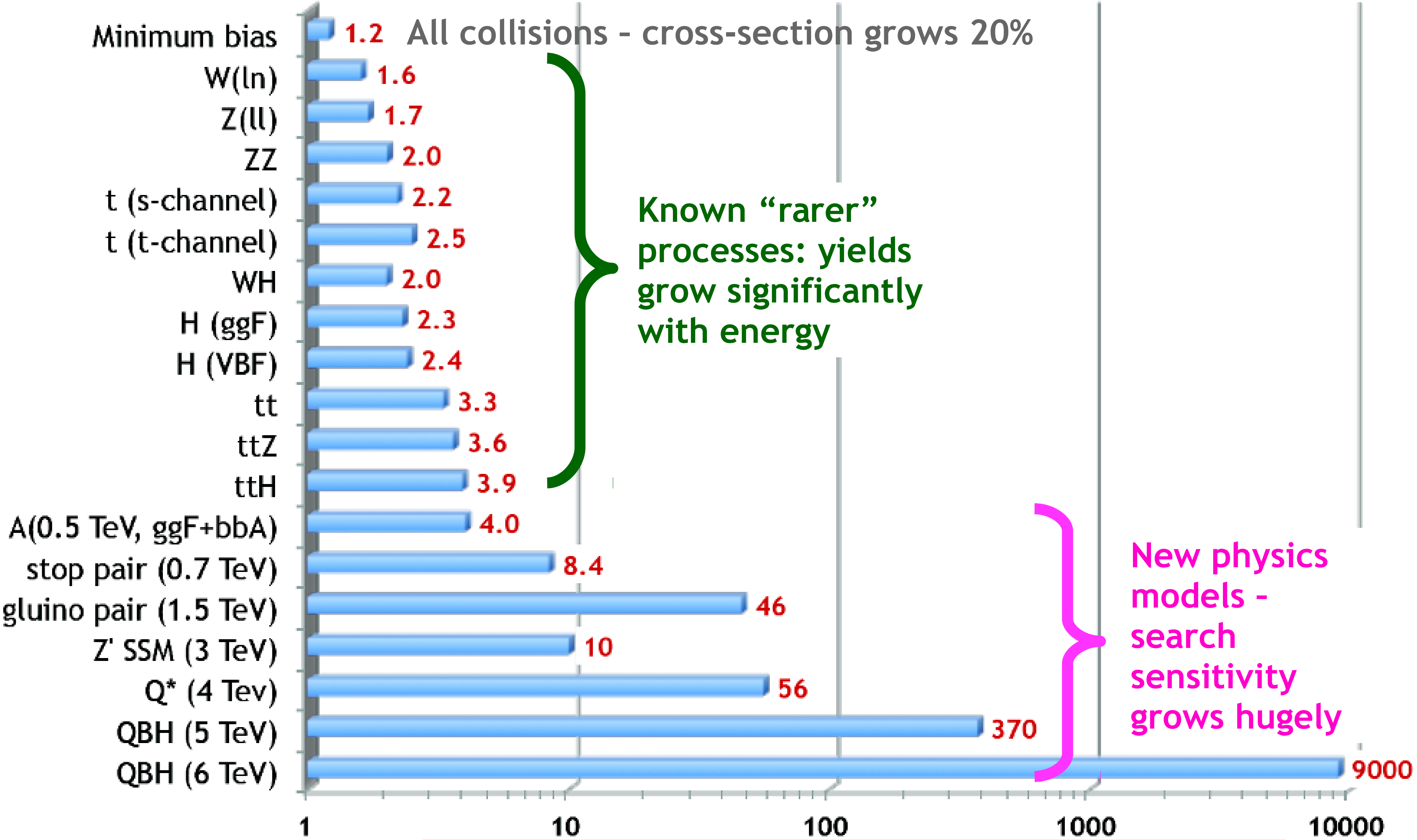


Why we push √s

Ratio of parton-parton luminosity for pp centre-of-mass energy 13 TeV / 8 TeV



Why we push √s



All collisions – cross-section grows 20%

Known "rarer" processes: yields grow significantly with energy

New physics models – search sensitivity grows hugely

Total cross-section ratio: σ(13 TeV) / σ(8 TeV)

The main 2013-14 LHC consolidations

1695 Openings and final reclosures of the interconnections

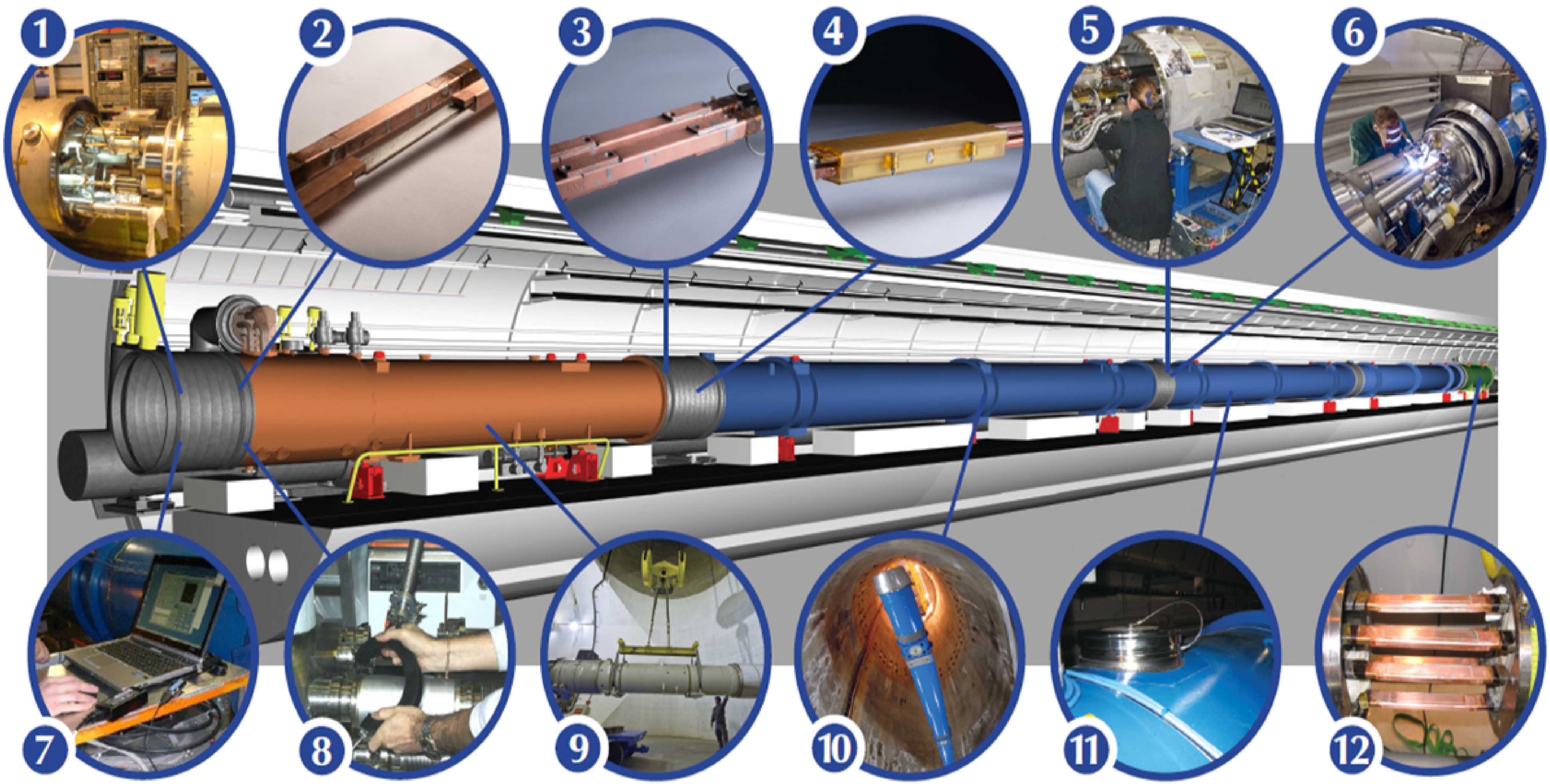
Complete reconstruction of 3000 of these splices

Consolidation of the 10170 13kA splices, installing 27 000 shunts

Installation of 5000 consolidated electrical insulation systems

300 000 electrical resistance measurements

10170 orbital welding of stainless steel lines



18 000 electrical Quality Assurance tests

10170 leak tightness tests

3 quadrupole magnets to be replaced

15 dipole magnets to be replaced

Installation of 612 pressure relief devices to bring the total to 1344

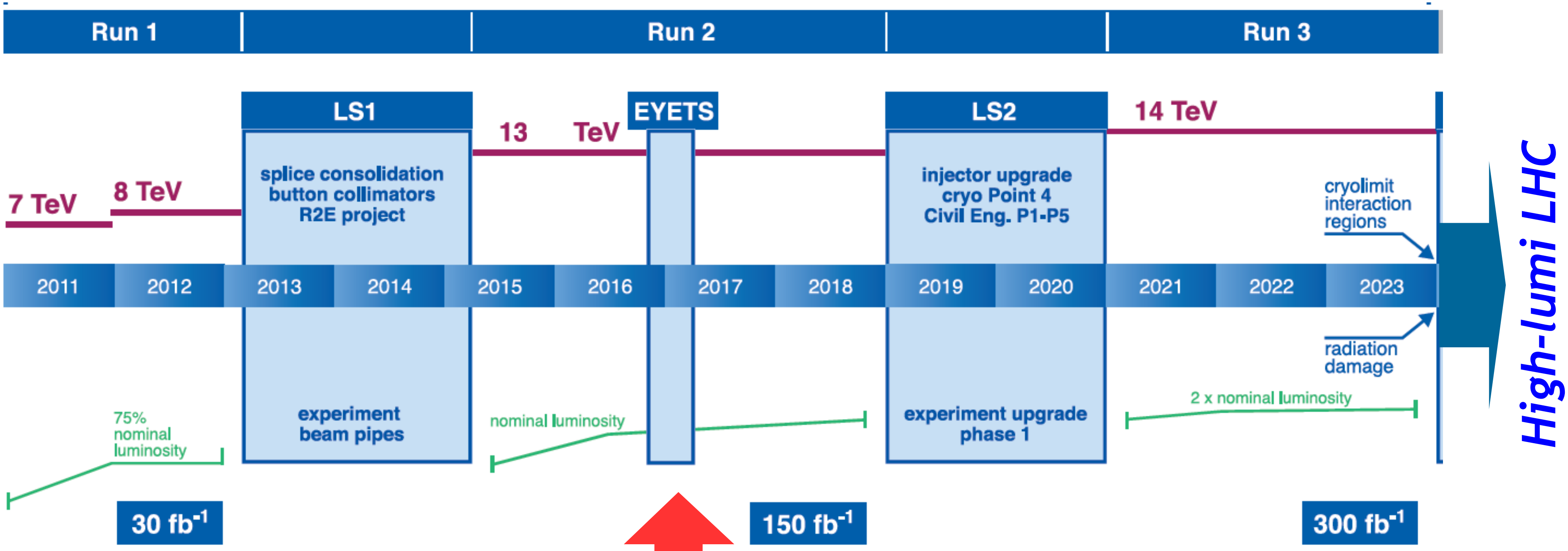
Consolidation of the 13 kA circuits in the 16 main electrical feed-boxes

The first decade of LHC operation

Run-1: little data and low energy!

Run-2: 13 TeV, much more data

Run-3: 14 TeV, and doubling data again



We are here

Half-way through the "standard lumi LHC" era in time, still close to the start in terms of integrated luminosity

2016 – a great production year

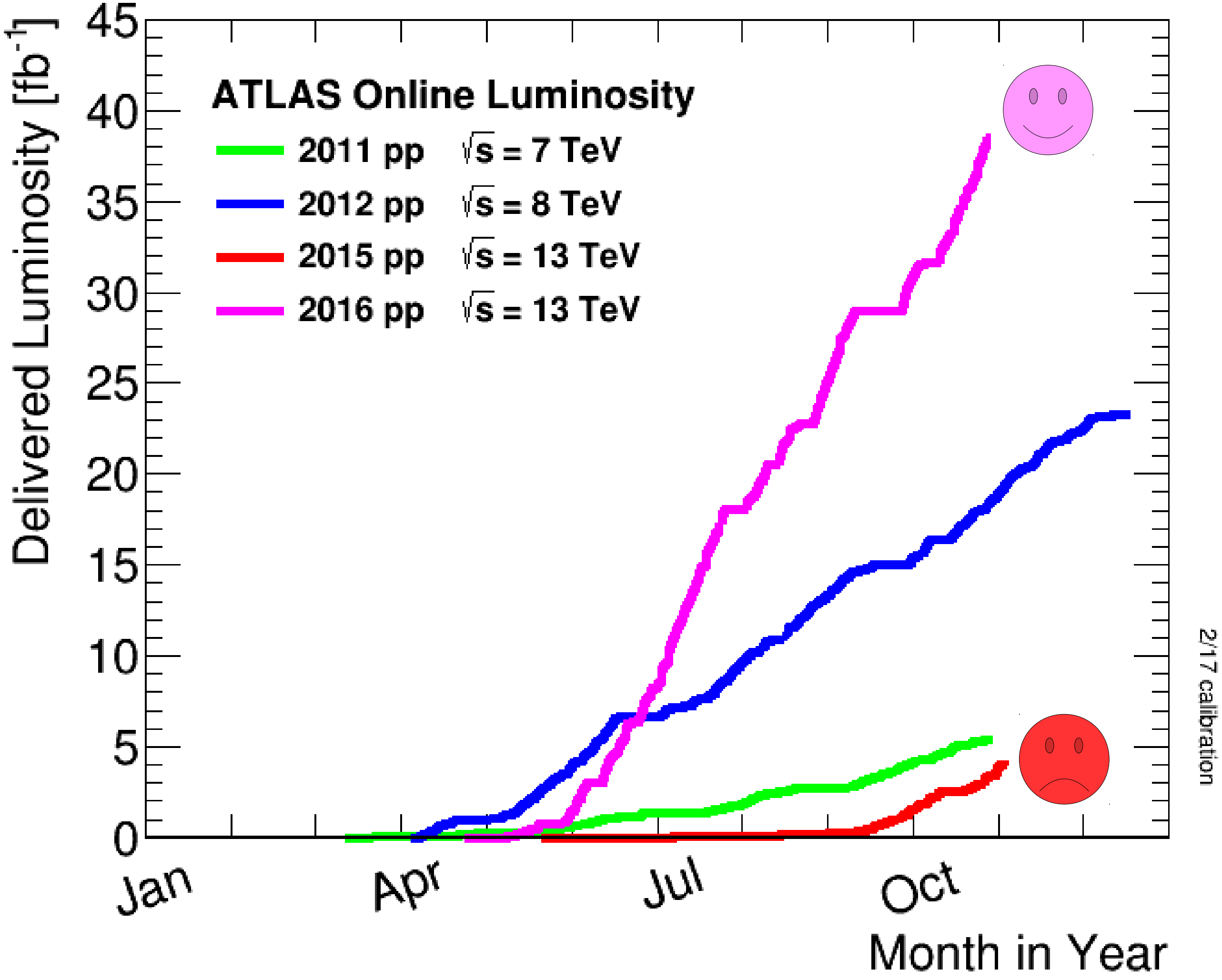
Integrated luminosity $\int L dt$ drives the signal event yield N_{obs}

$$N_{obs} = \sigma \, \varepsilon_{exp} \int L dt$$

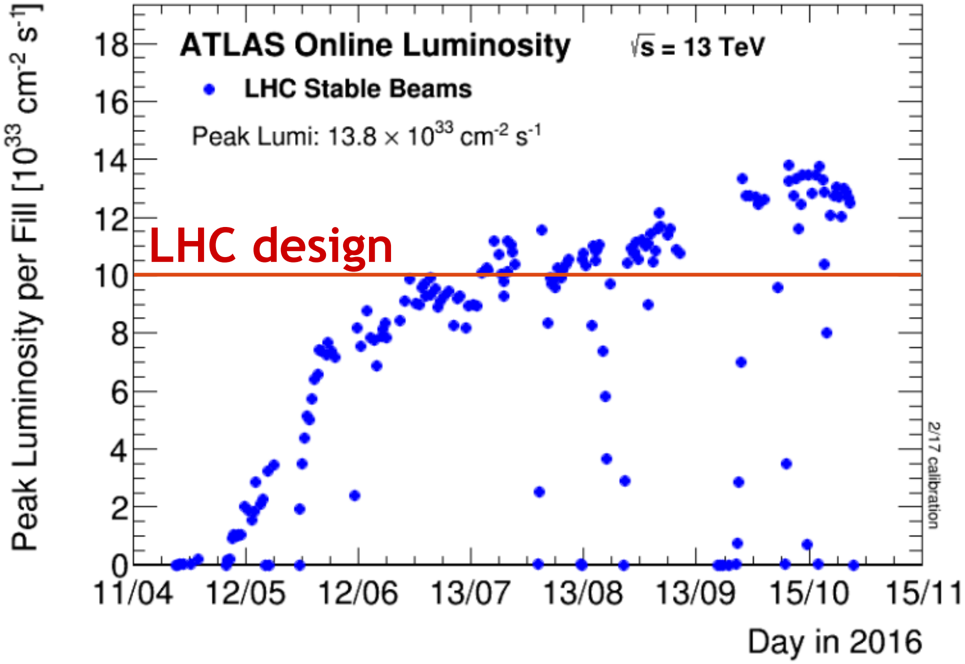
σ: cross-section

ε_{exp}: *experimental efficiency*

More integrated luminosity in 2016 than in all previous years together!



2016 – a great production year



Peak luminosity well above design

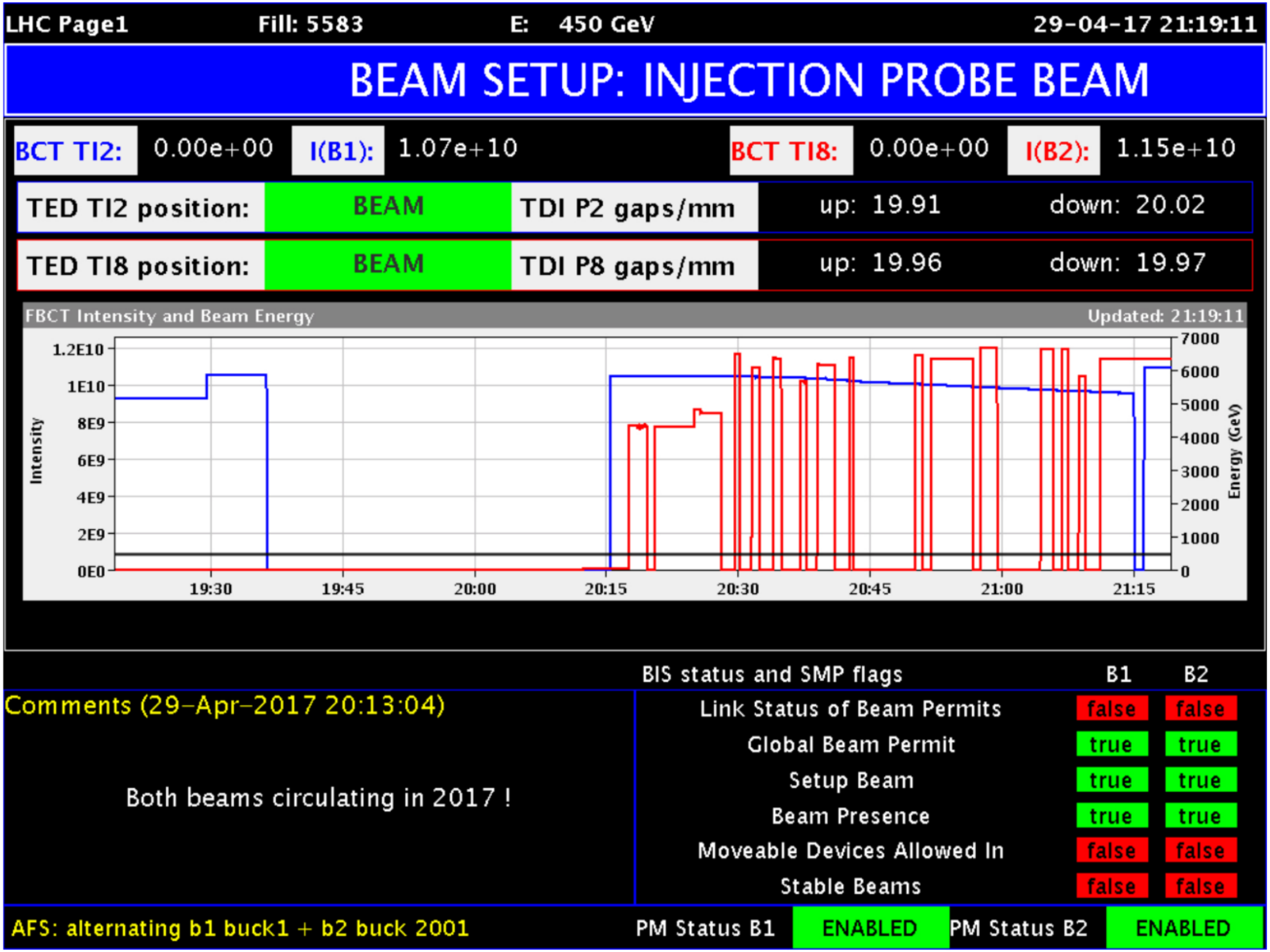
Gradual and sustained increase in luminosity over the year

- Good prospects to be get close to $2x10^{34}cm^{-2}s^{-1}$ (=twice design) in 2017, if LHC cooling can take it

Production operation: many days with similar samples of 0.4-0.5 fb^{-1} delivered

- With scheduled & unscheduled stops "as usual"..!

2017 – hot off the press



LHC Page1 Fill: 5583 E: 450 GeV 29-04-17 21:19:11

BEAM SETUP: INJECTION PROBE BEAM

BCT TI2: 0.00e+00 I(B1): 1.07e+10 BCT TI8: 0.00e+00 I(B2): 1.15e+10

TED TI2 position:	BEAM	TDI P2 gaps/mm	up: 19.91	down: 20.02
TED TI8 position:	BEAM	TDI P8 gaps/mm	up: 19.96	down: 19.97

FBCT Intensity and Beam Energy Updated: 21:19:11

Comments (29-Apr-2017 20:13:04)

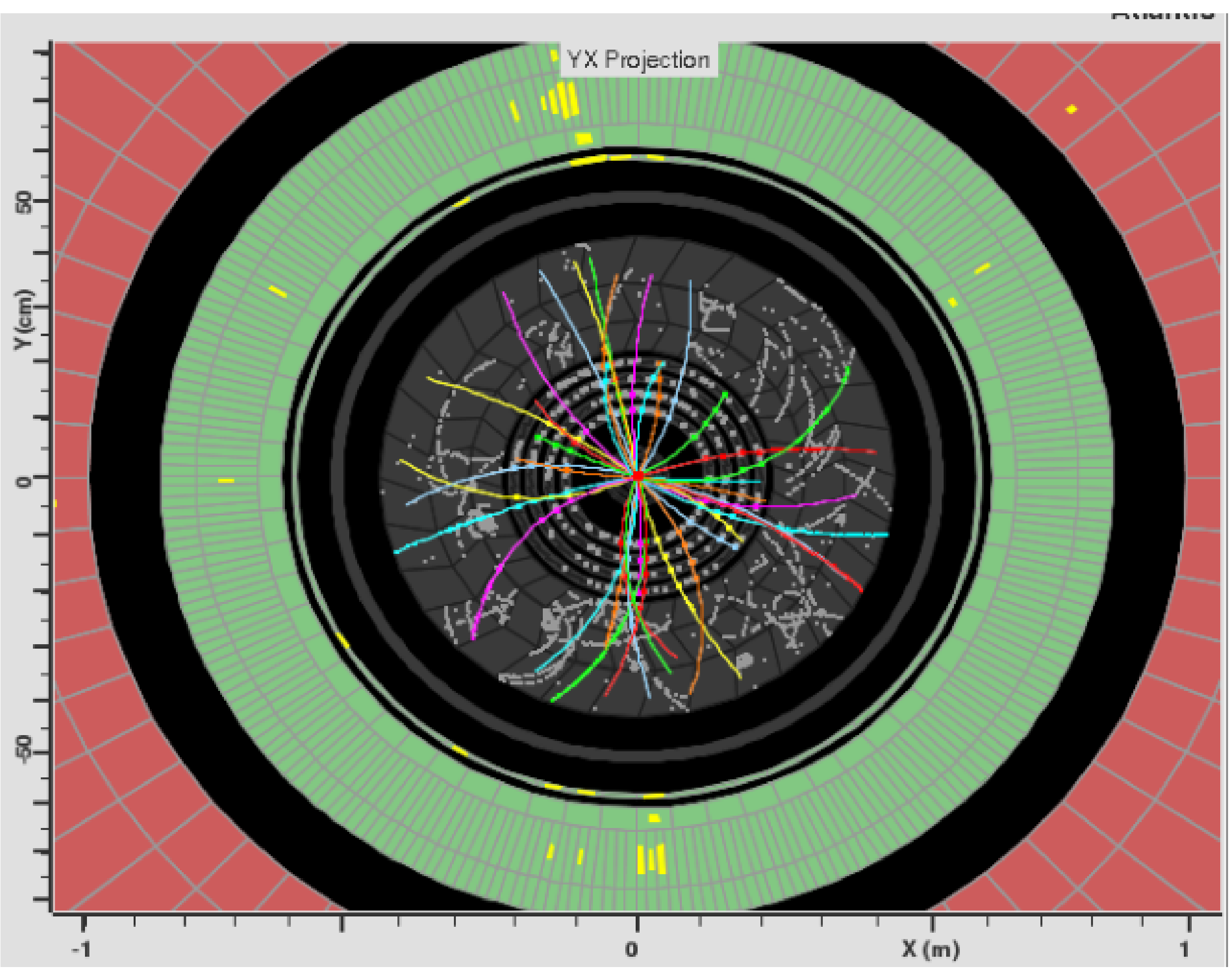
Both beams circulating in 2017 !

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	true
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: alternating b1 buck1 + b2 buck 2001

PM Status B1 ENABLED PM Status B2 ENABLED

2017 - hot off the press



10 May – beams colliding again at 13 TeV

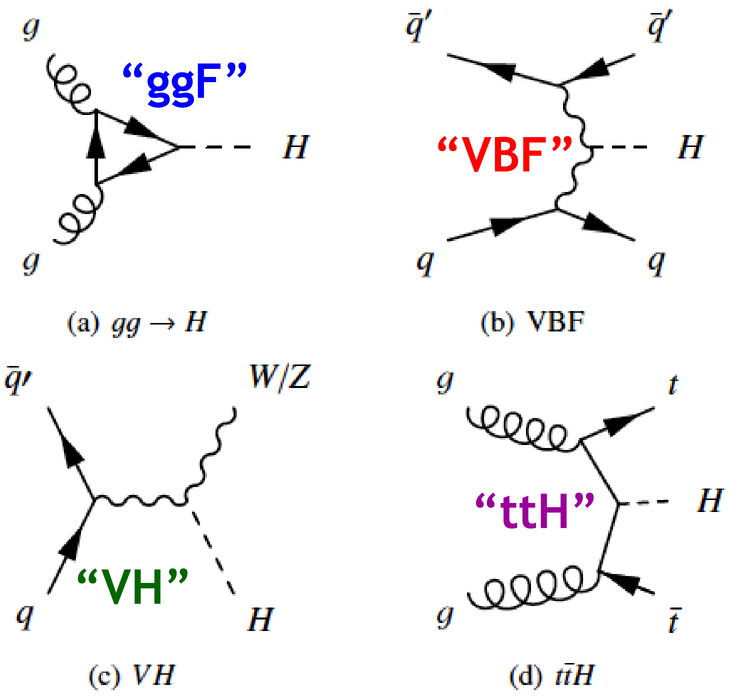
Expect to match or exceed 2016 sample in each of 2017 and 2018

The Higgs boson, beyond the discovery

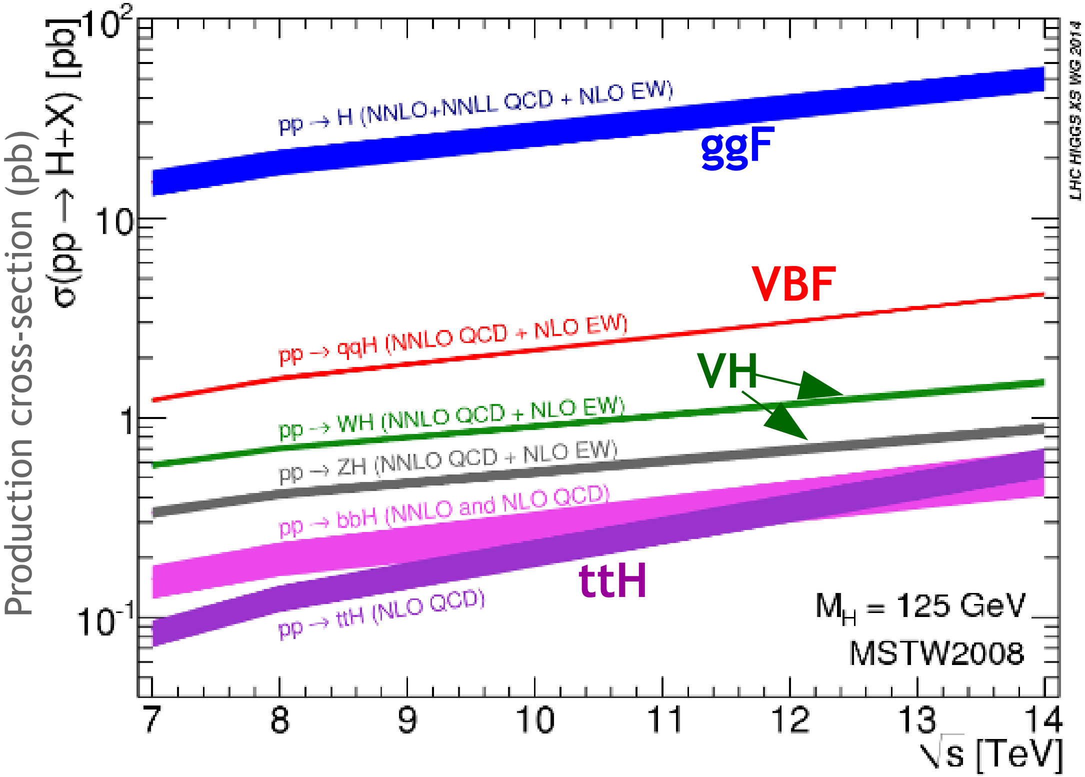
H(125) production & decay

A 125 GeV Higgs boson is a convenient object experimentally – many production and decay modes should be measurable

- *Is it the Standard Model Higgs or not?*
- Production and decay processes probe couplings of H to different particles



Main (single H) production diagrams

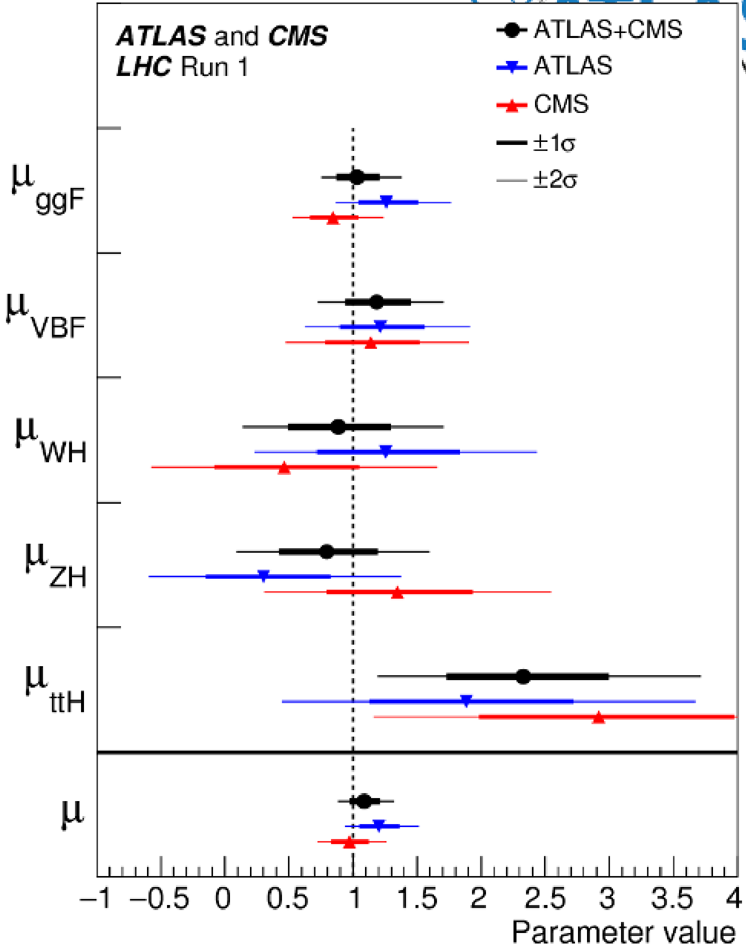


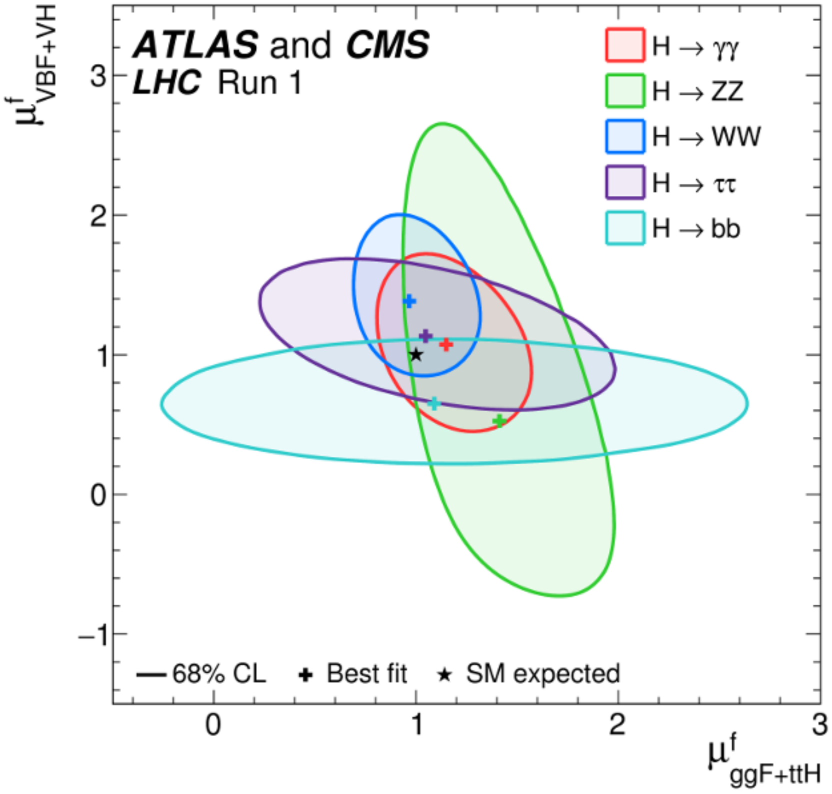
"ggF" dominates, but multiple processes accessible
(inclusive rates are not tiny)

H(125) production modes

Combined analysis of Run-1 data:
H(125) production & decays

With assumptions about decays, we can probe the different production processes (normalised rates "μ" (=1 in SM))





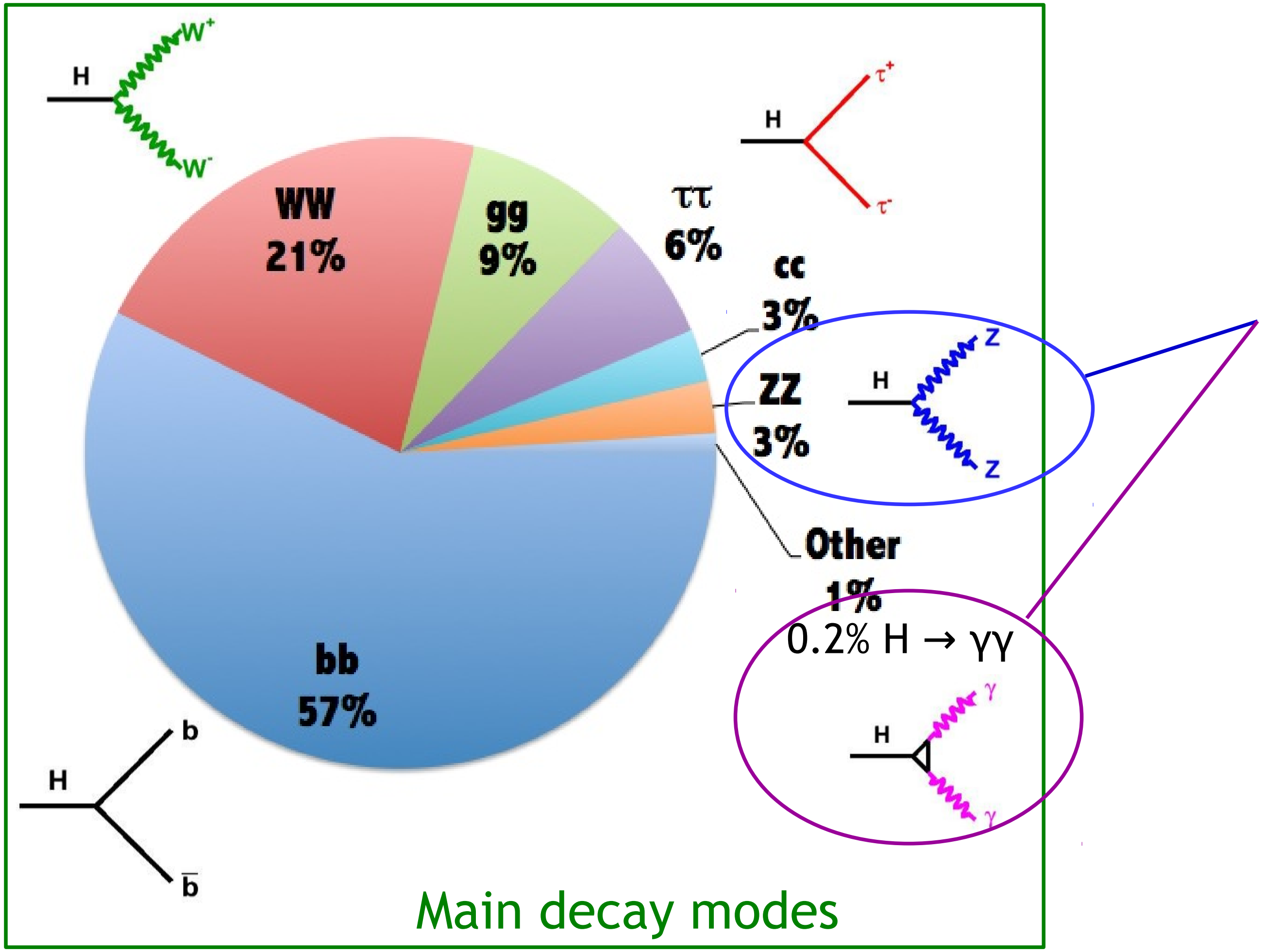
- Able to separate statistically the ggF and VBF processes
- Not yet VH or ttH at 5σ
- Observing ttH production is a key Run-2 goal

These are not yet precision measurements – but few percent errors should be obtainable with the expected LHC samples

H(125) production & decay

A 125 GeV Higgs boson is a convenient object experimentally – many production and decay modes should be observable

- *Is it the Standard Model Higgs or not?*
- Production and decay processes probe couplings of H to different particles



Main decay modes

Discovery channels

Low branching fractions

BF($H \to ZZ^* \to 4(e/\mu)$) ~ 0.01%

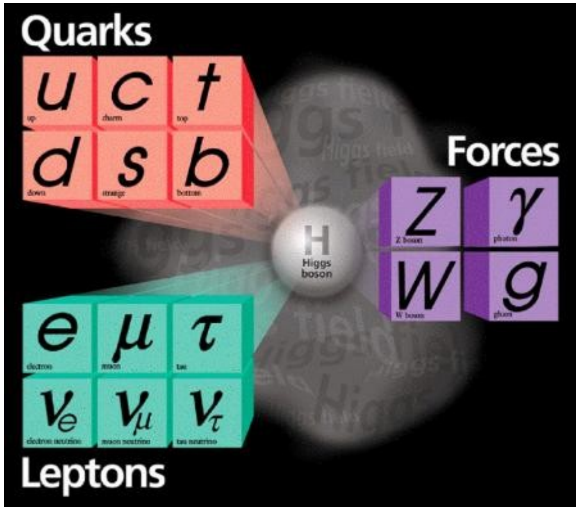
BF($H \to \gamma\gamma$) ~ 0.2%

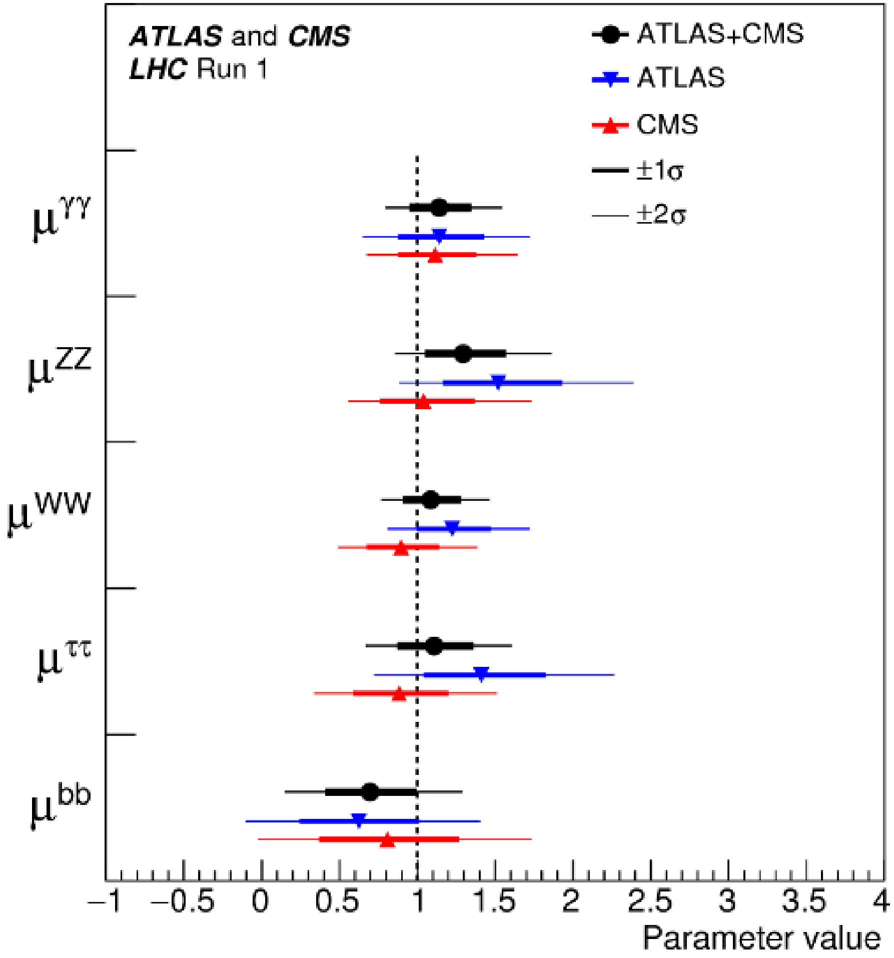
H(125) decay modes

Combining ATLAS and CMS Run-1 data, observed (at >5σ significance)

- H→γγ
- H→ZZ*(→4ℓ (ℓ=e,μ))
- H→WW*(→ℓνℓν)
- H→ττ

Run-1 data not yet sensitive to the dominant H→bb, or most rare, decays, e.g. to *second generation* fermions H→μμ, cc, ss





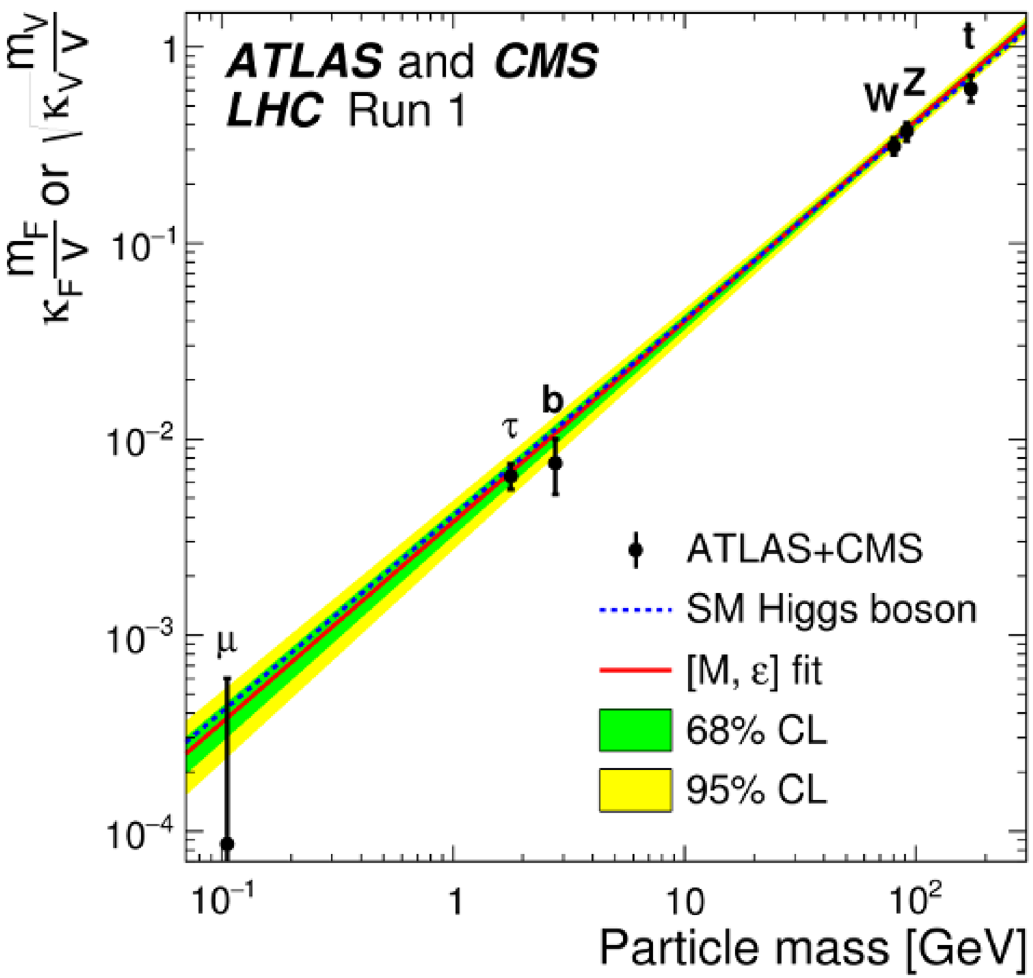
Decay signal strengths relative to Standard Model "μ" (=1 in SM)

H(125) coupling strengths

Combined analysis of Run-1 data:
H(125) production & decays

Recast coupling strength results in terms of the strength of the couplings of the H to each particle type

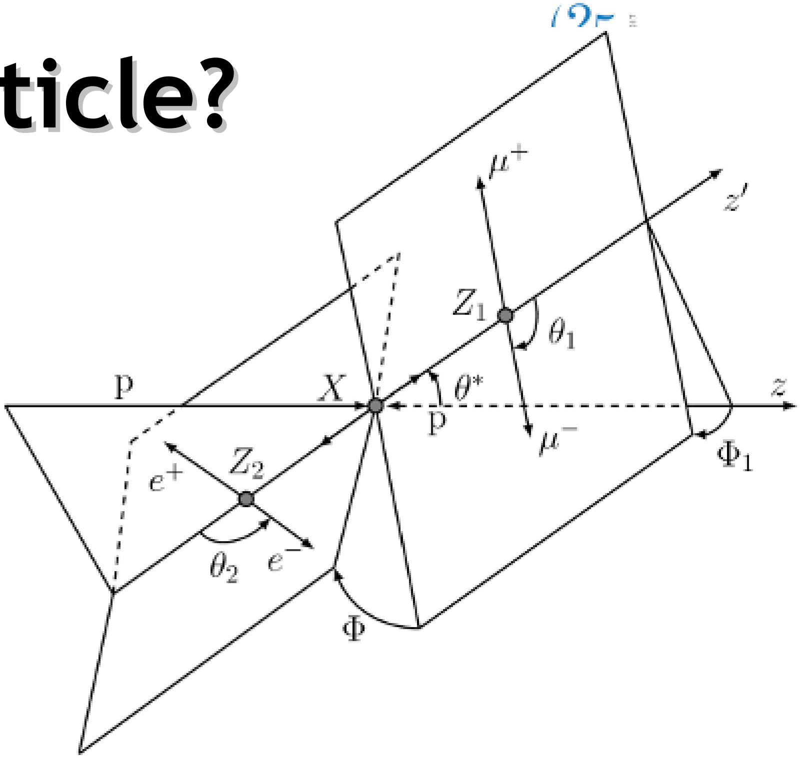
Characteristic of the Higgs is that it couples to mass…



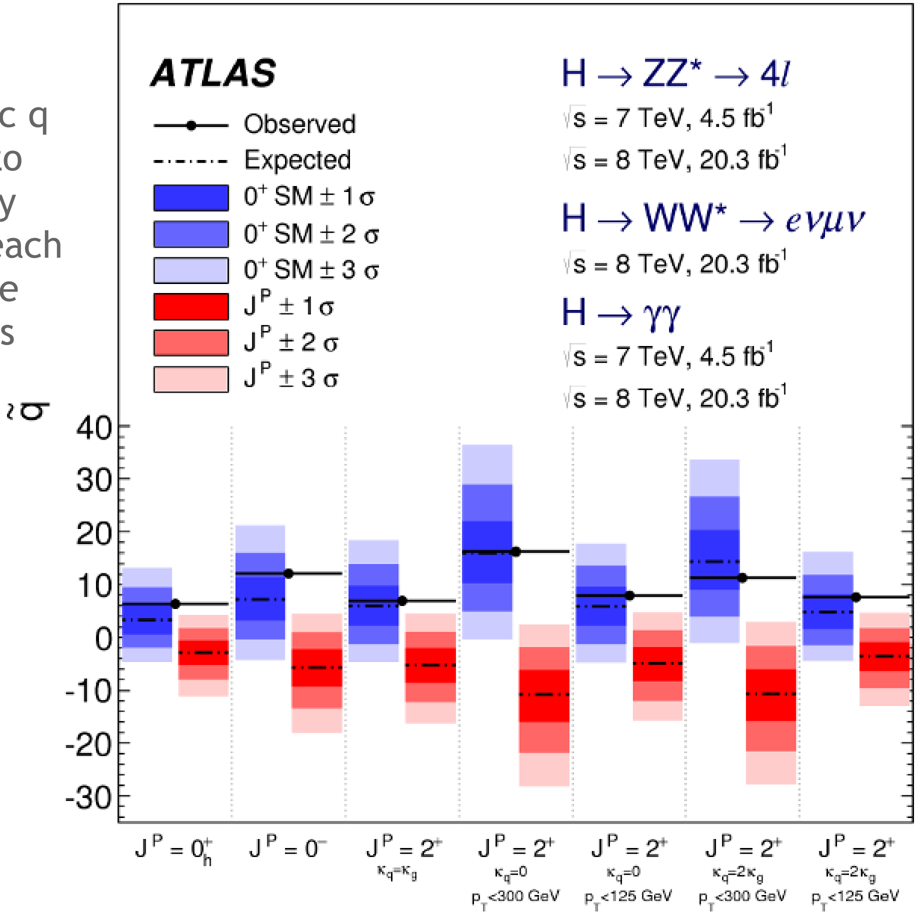
H(125) - is it a scalar particle?

Spin-analysis of the decay product angular distributions

- Is this a spin-parity $J^P=0^+$ object?



Test statistic q sensitive to spin-parity (differs for each alternative hypothesis tested)



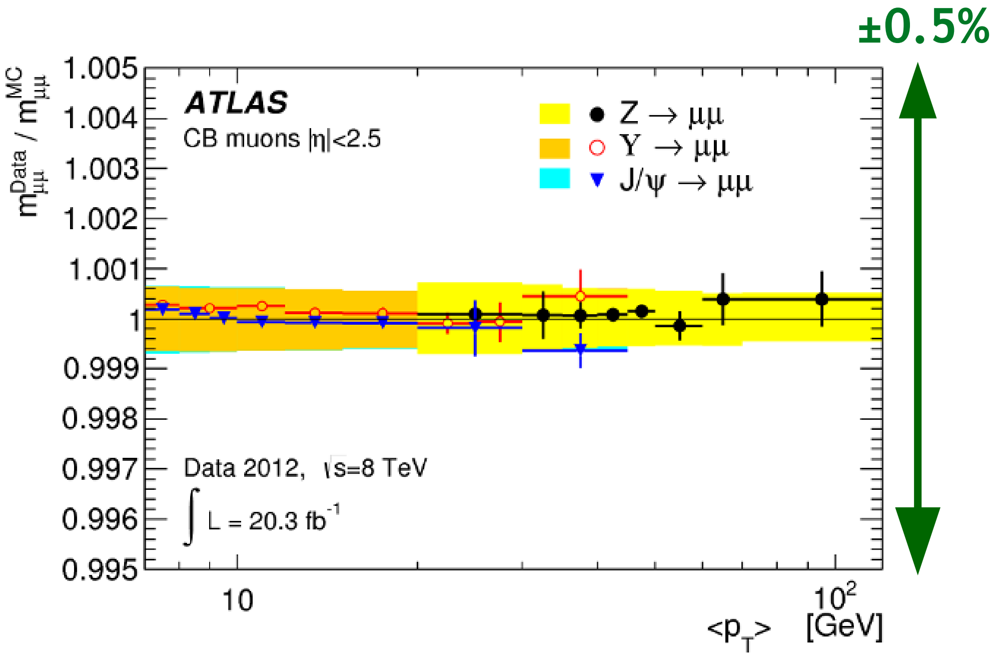
In all cases tested, strong preference for 0^+ assignment

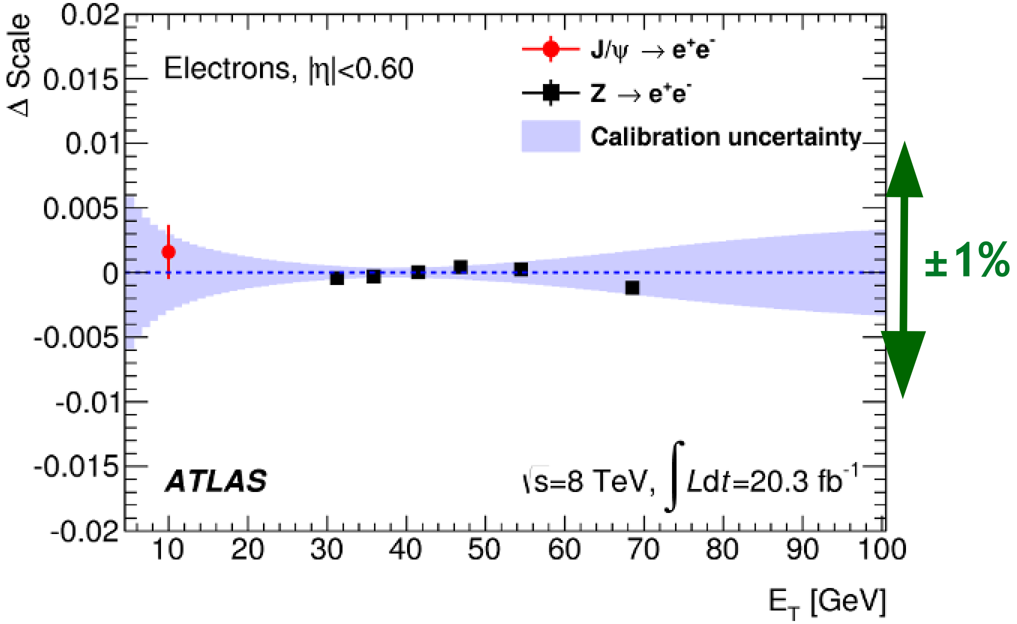
It is consistent with a 0^+ scalar particle, and not with any other model tested (at >>95% CL)

Mass of the H("125")

Recall that m_H is a free parameter in the Standard Model

- To measure m_H, we use γγ and 4ℓ decays, where we can reconstruct the mass event-by-event with high resolution
- Requires excellent understanding of energy scales for lepton/photons





Calibrate detector performance relative to simulations using very large and clean samples of decays of particles of known mass, here:

$J/\psi,\Upsilon,Z \rightarrow ee/\mu\mu$

Mass of the H("125")

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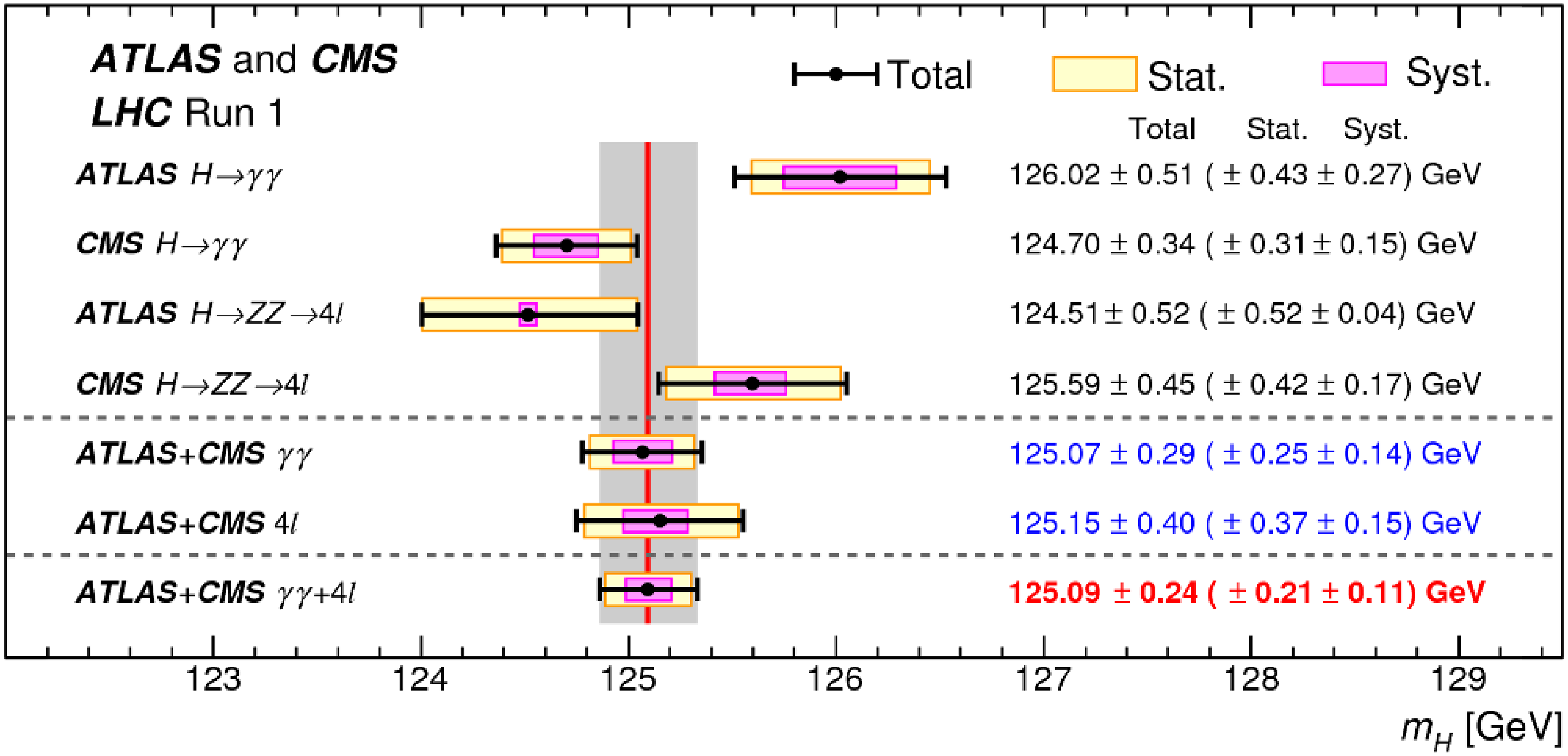


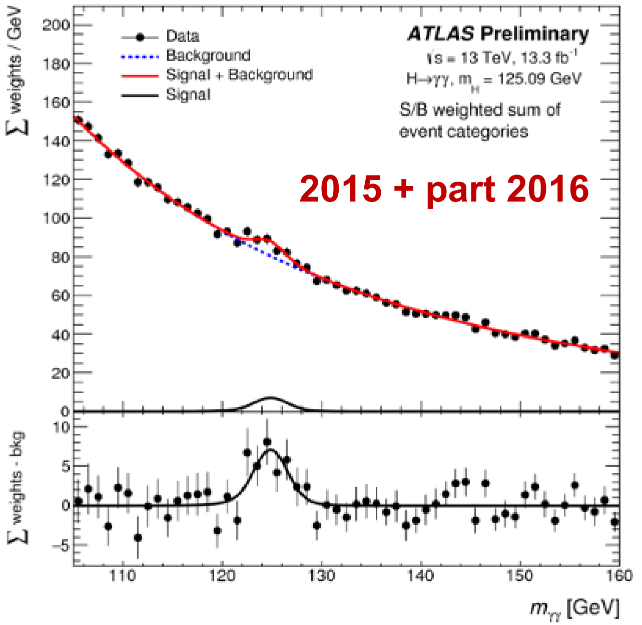
Already a precision measurement: 2 per-mille relative error – dominated by statistical not systematic uncertainties

Measuring H(125) at 13 TeV in Run-2

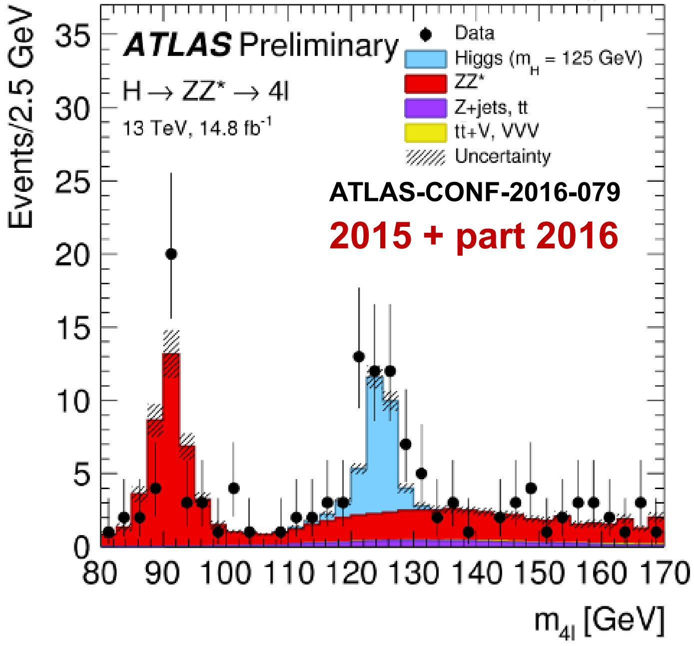
Clear signals in γγ and 4ℓ

→ combined σ(pp→H) at 13 TeV

→ overall significance at 13 TeV ~10σ

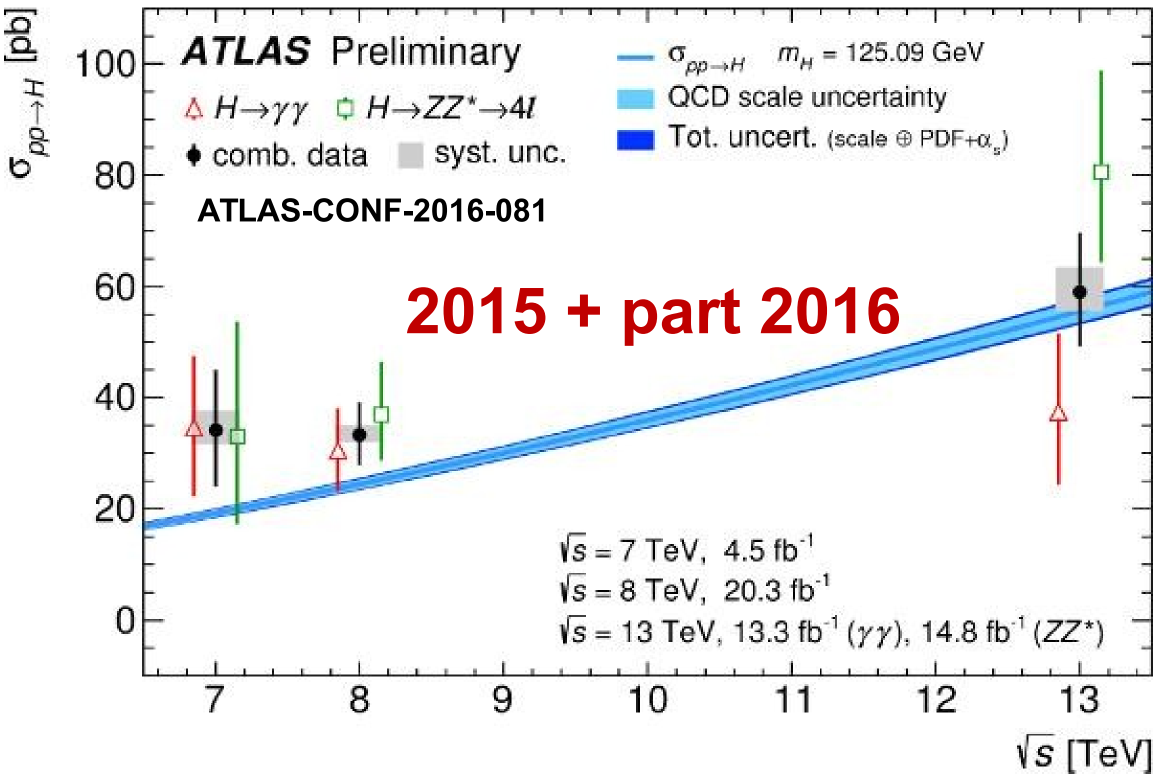


2015 + part 2016



ATLAS-CONF-2016-079

2015 + part 2016



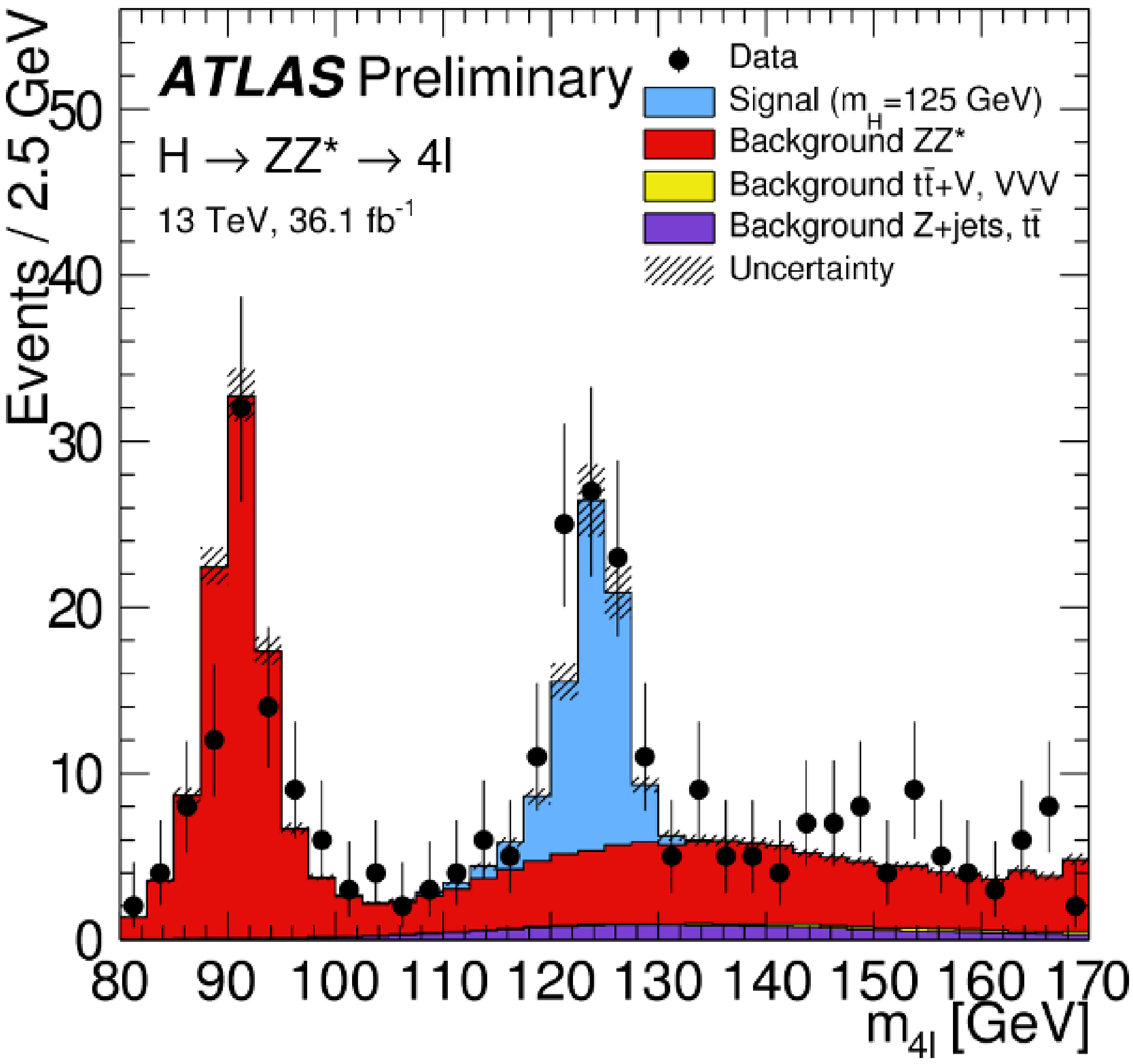
ATLAS-CONF-2016-081

2015 + part 2016

$\sigma = 59.0\,^{+9.7}_{-9.2}\,(\text{stat})\,^{+4.4}_{-3.5}\,(\text{syst})$ pb

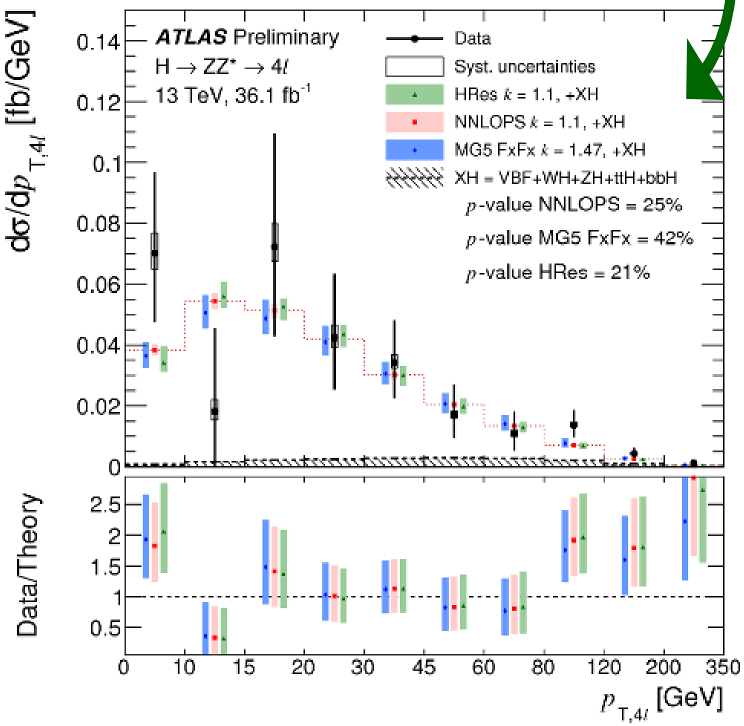
(SM: $55.5\,^{+2.4}_{-3.4}$ pb)

New: H→4ℓ full 2015+2016 statistics

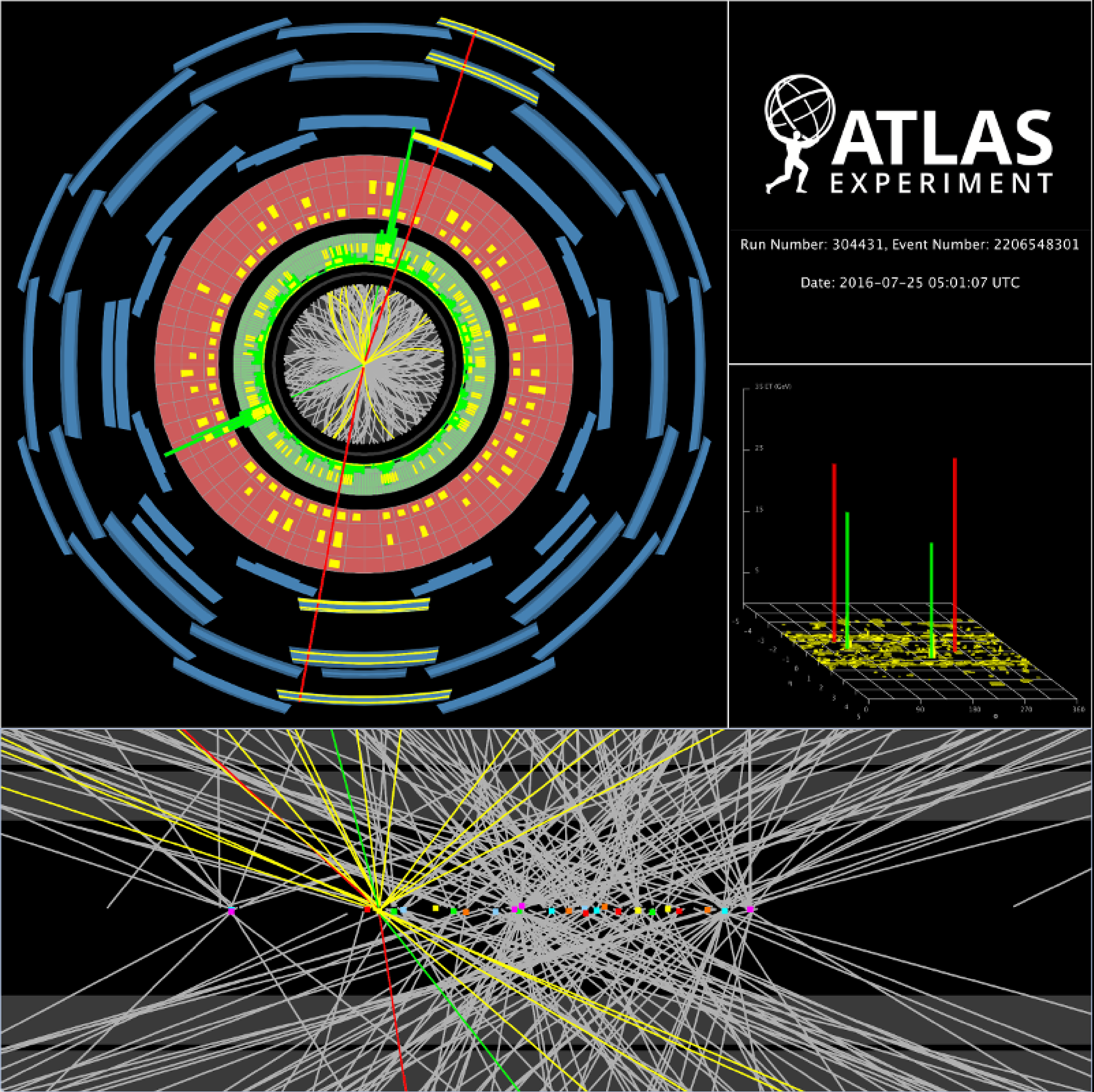


Results with full current statistics of 13 TeV data in H→4ℓ channel

- Fiducial and differential cross-sections measured
  - Illustrate with p_T(H) distribution
  - Statistics limited



Candidate H→ZZ*→ eeμμ from 2016



Run Number: 304431, Event Number: 2206548301

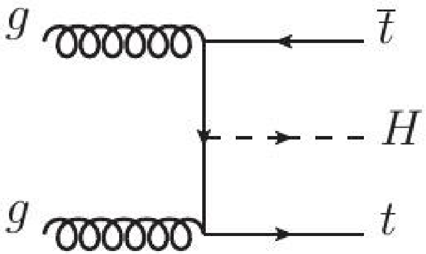
Date: 2016-07-25 05:01:07 UTC

Standard feature of Run-2 data – very high “pileup”, typically 30 pp interactions per bunch crossing

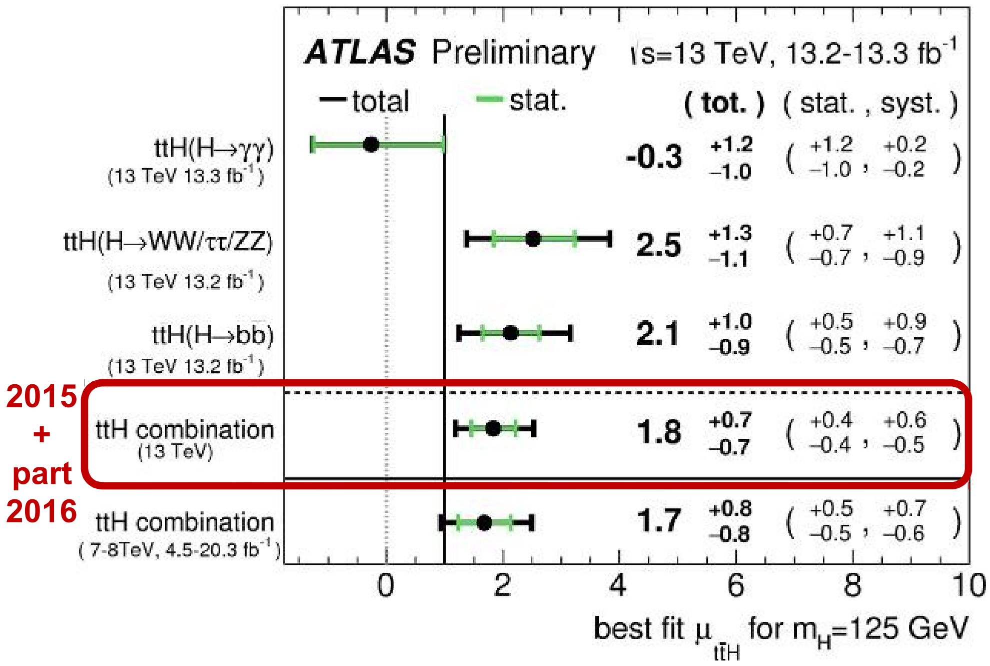
Homing in on new H channels

$t\bar{t}H$ production

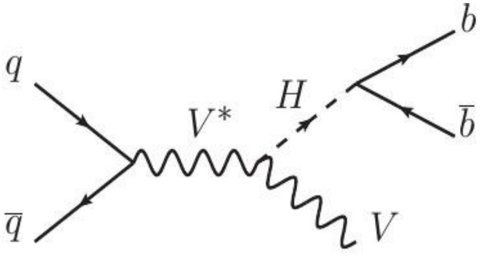
- Direct probe of ttH vertex
- 3 channels with 2015+2016 data
- Combined: 2.8σ observed (exp 1.8σ)



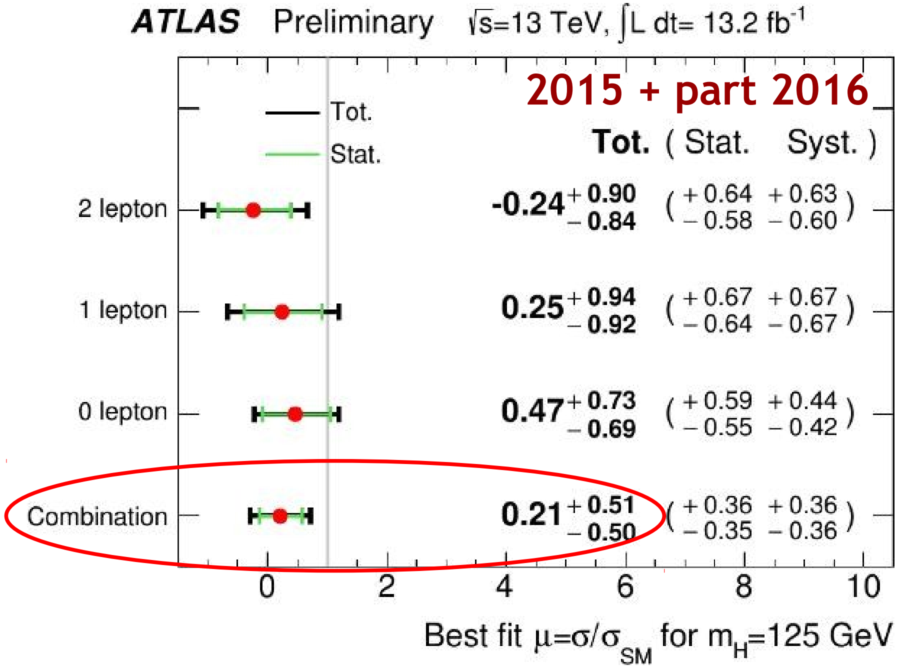
ATLAS-CONF-2016-068



Hunt for $H \to b\bar{b}$ decay in (W/Z)H associated production



- H → bb dominant decay BR~58%
- Significance 0.4σ (exp 1.9σ)



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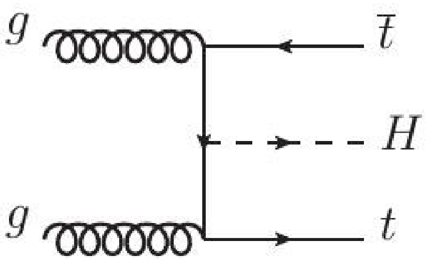
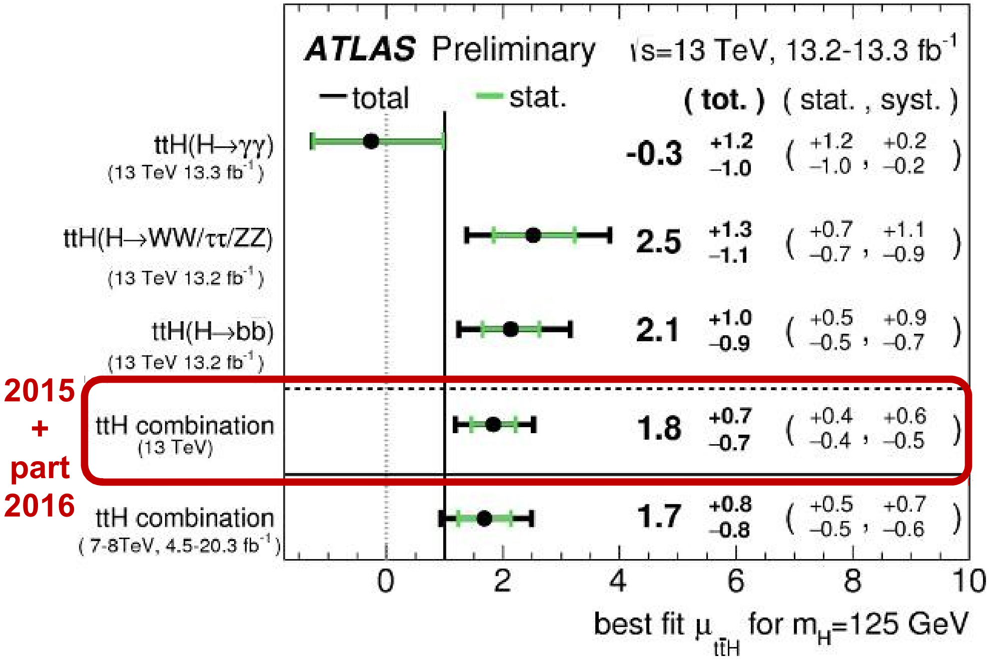


ATLAS-CONF-2016-068



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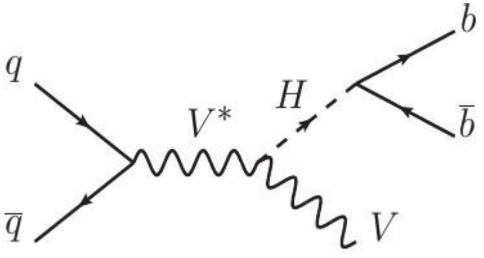
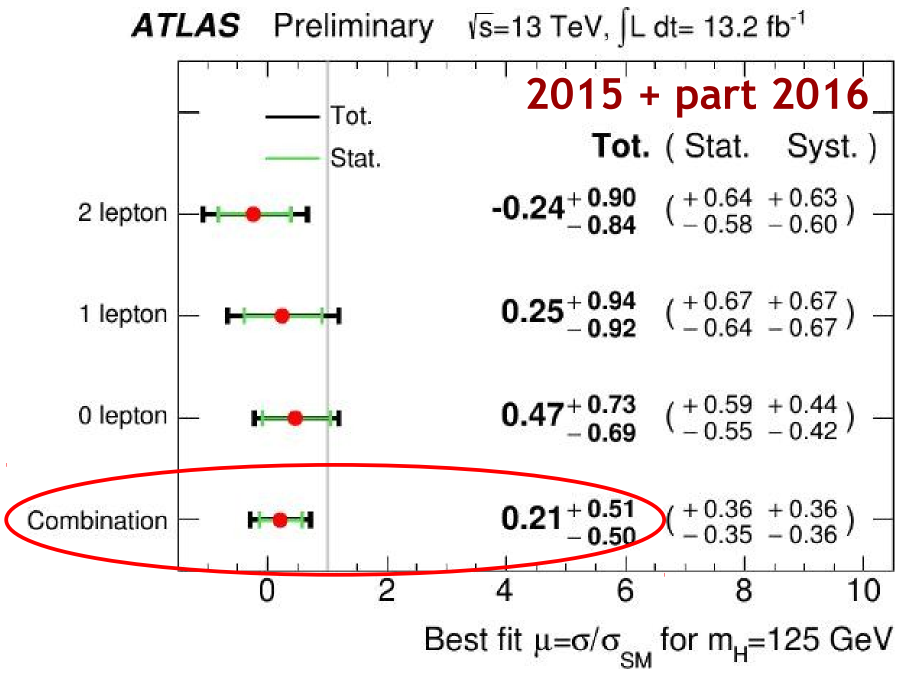
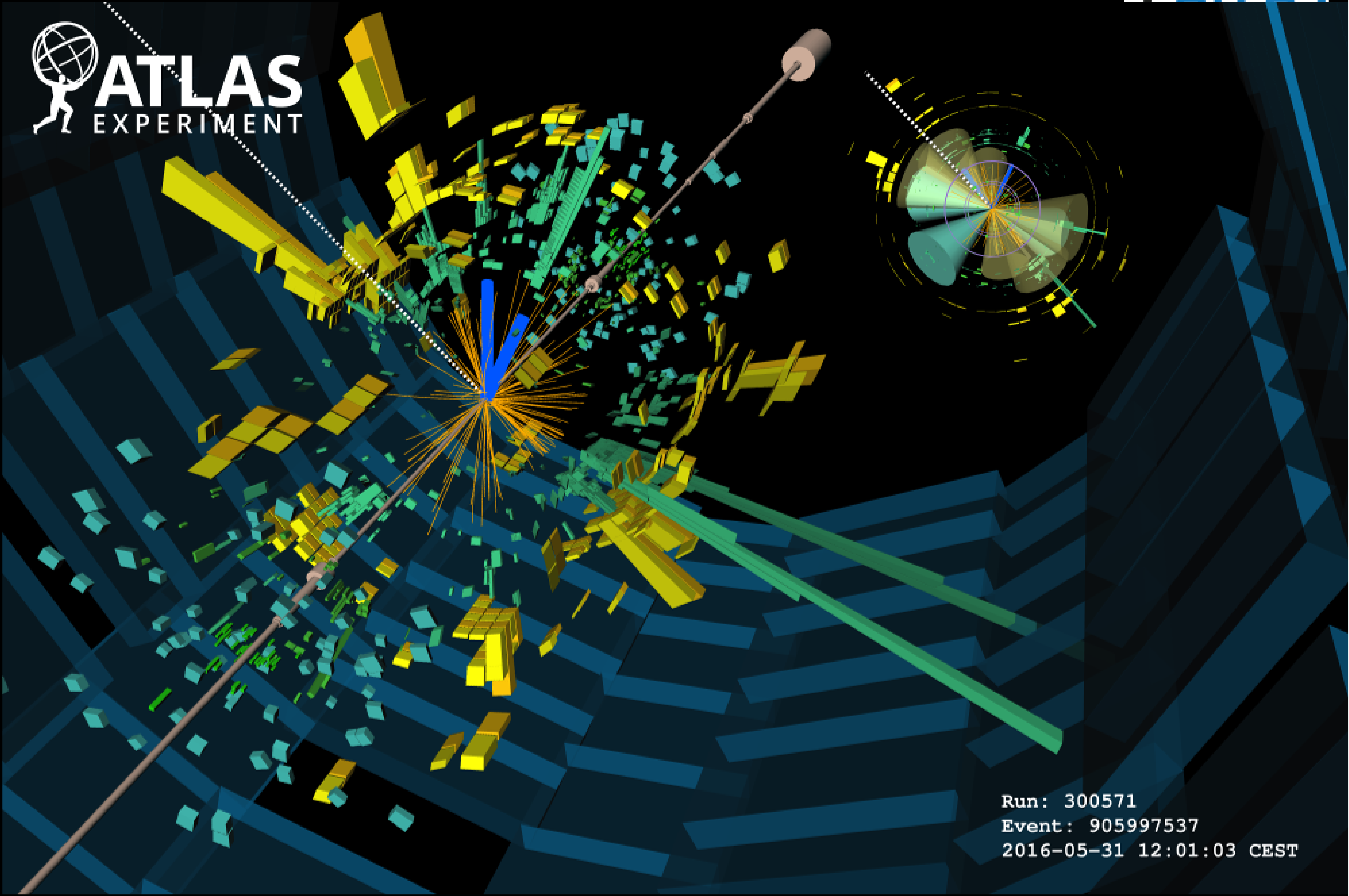




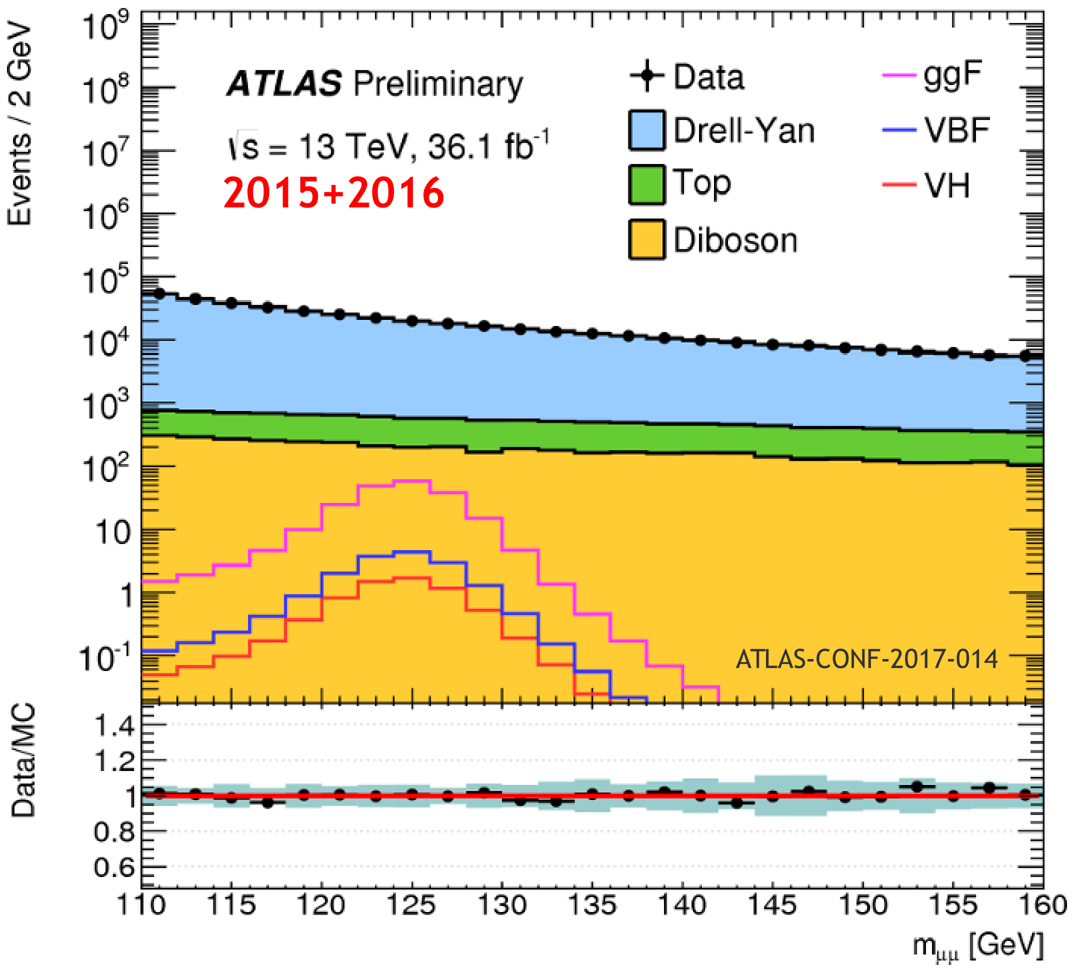
Observing these two channels remain key goals for Run-2

Event selected in ttH multilepton analysis



H→μμ - rare decay - 2nd generation

Inclusive distribution



dimuon invariant mass m(μμ)

Full 2015+2016 data, look for a peak in dimuon mass spectrum

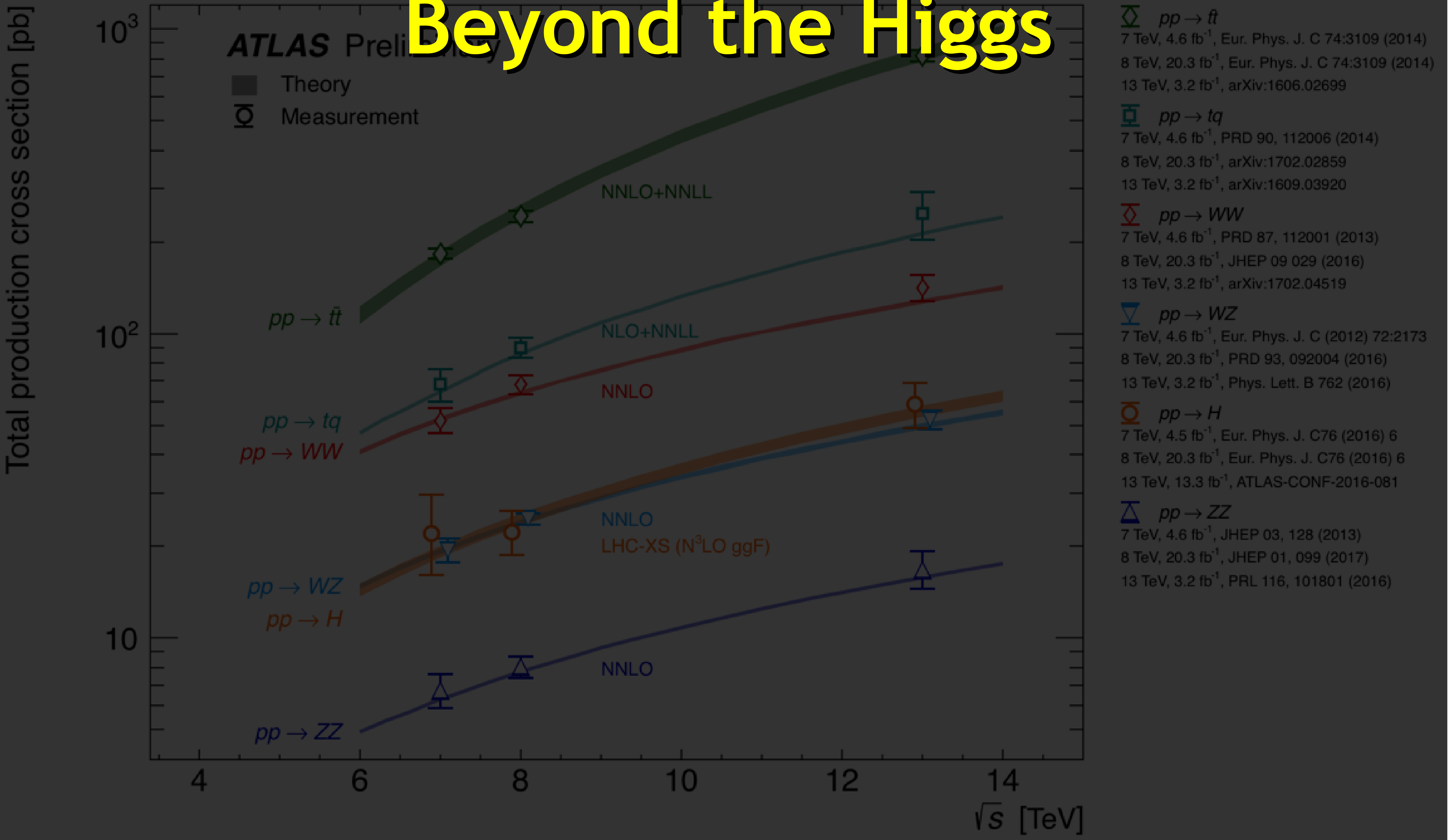
- Analyse multiple event categories → improves sensitivity (not shown)

No excess observed → place limits on signal strength μ_s relative to Standard Model, combining also with (weaker) Run-1 results:

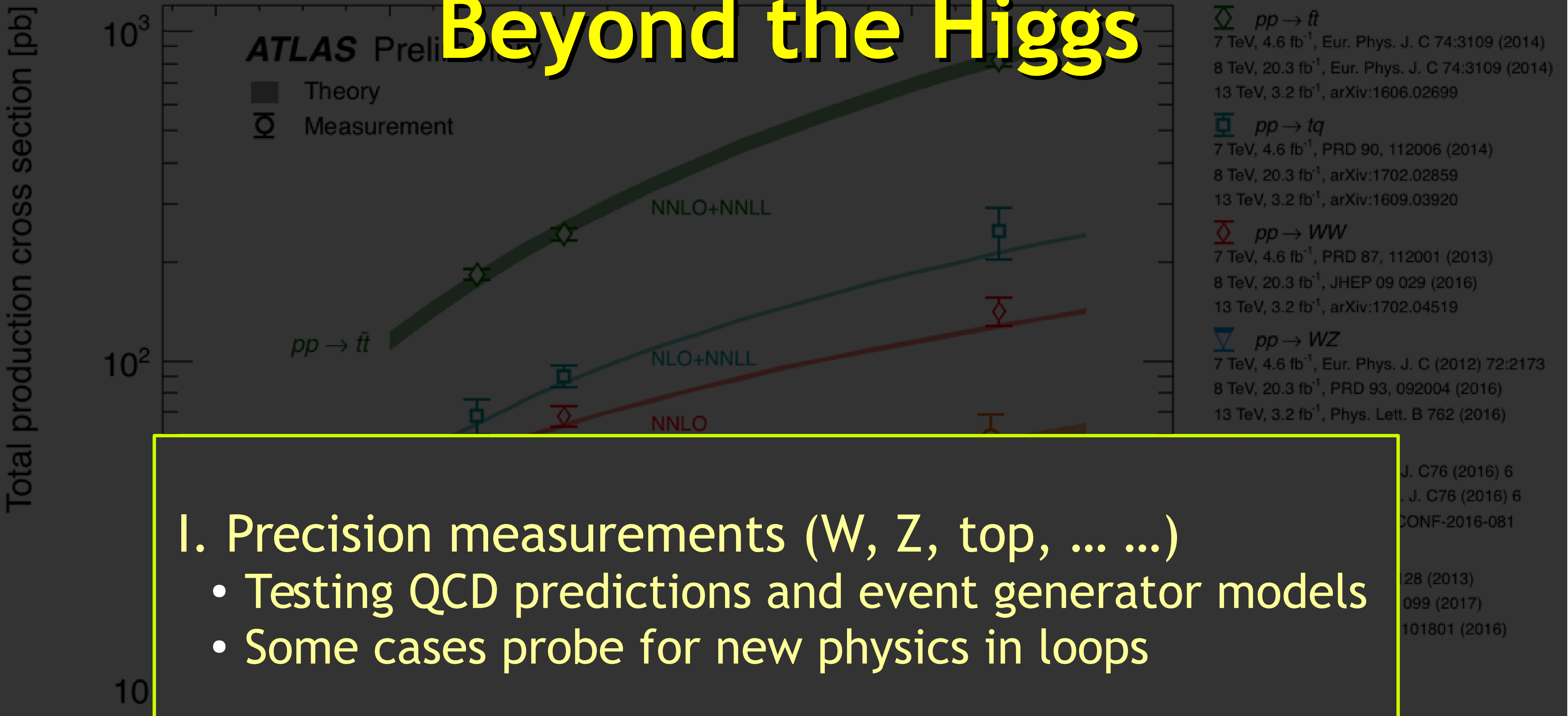
μ_s < 2.8 at 95% CL
(2.9 expected)

SM sensitivity requires a lot more data

Beyond the Higgs



Beyond the Higgs



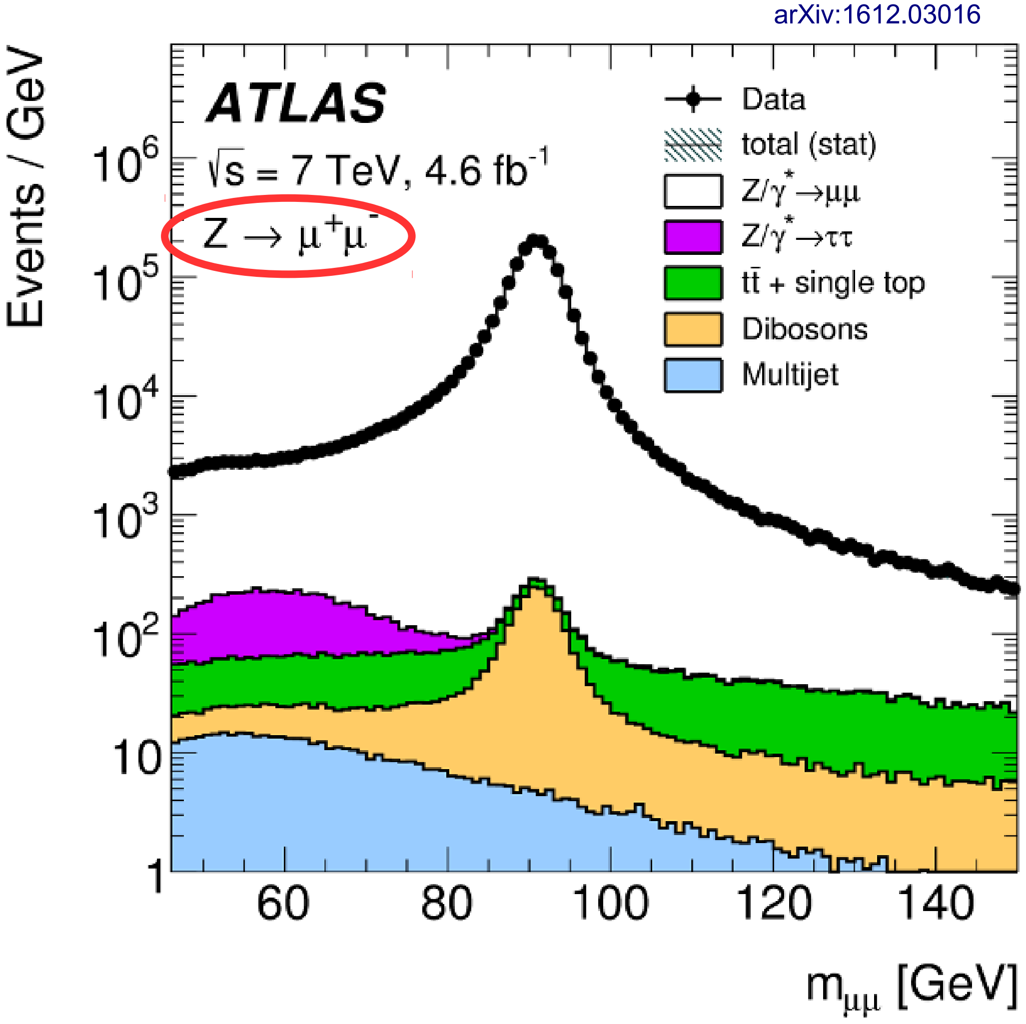
I. Precision measurements (W, Z, top, … …)

- Testing QCD predictions and event generator models
- Some cases probe for new physics in loops

II. Direct searches for new particles, new symmetries, and new interactions

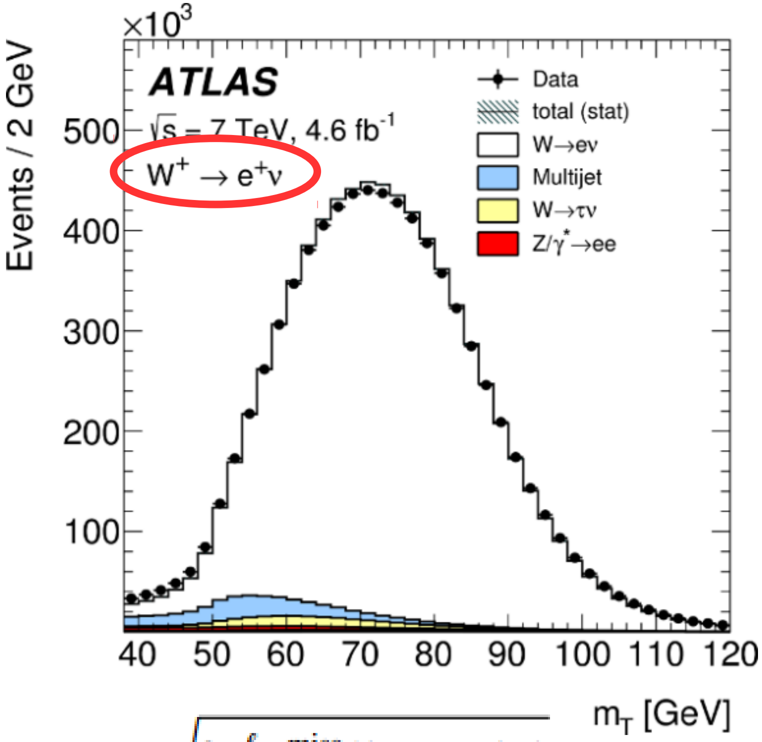
Precise W, Z production measurements

Detailed studies performed with 2011 data at 7 TeV: W^+,W^-, Z in e, μ decays



High statistics data well described by simulation

Backgrounds under excellent control



$$m_T = \sqrt{2 p_T^\ell p_T^{\text{miss}} (1 - \cos \Delta\phi)},$$

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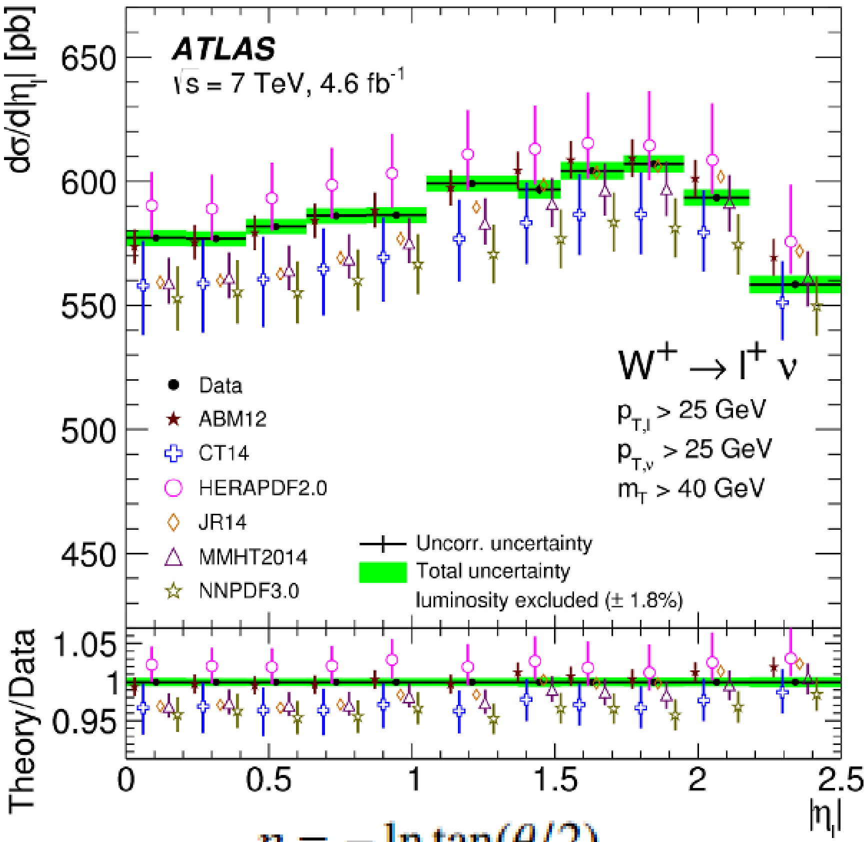
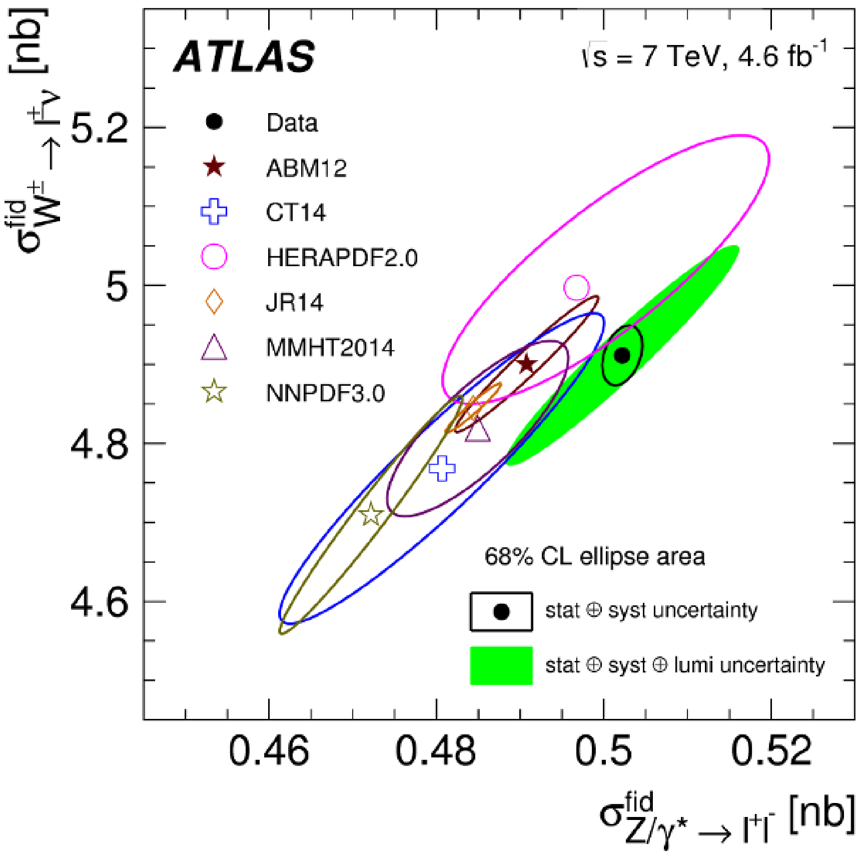
Detailed studies performed with 2011 data at 7 TeV: W^+,W^-,Z in e, μ decays



$$\eta = -\ln \tan(\theta/2).$$

arXiv:1612.03016



Differential cross-section as function of lepton scattering polar angle θ in lab frame – good separation between pdfs

Experimental errors better than theoretical/modelling uncertainties

W mass measurement

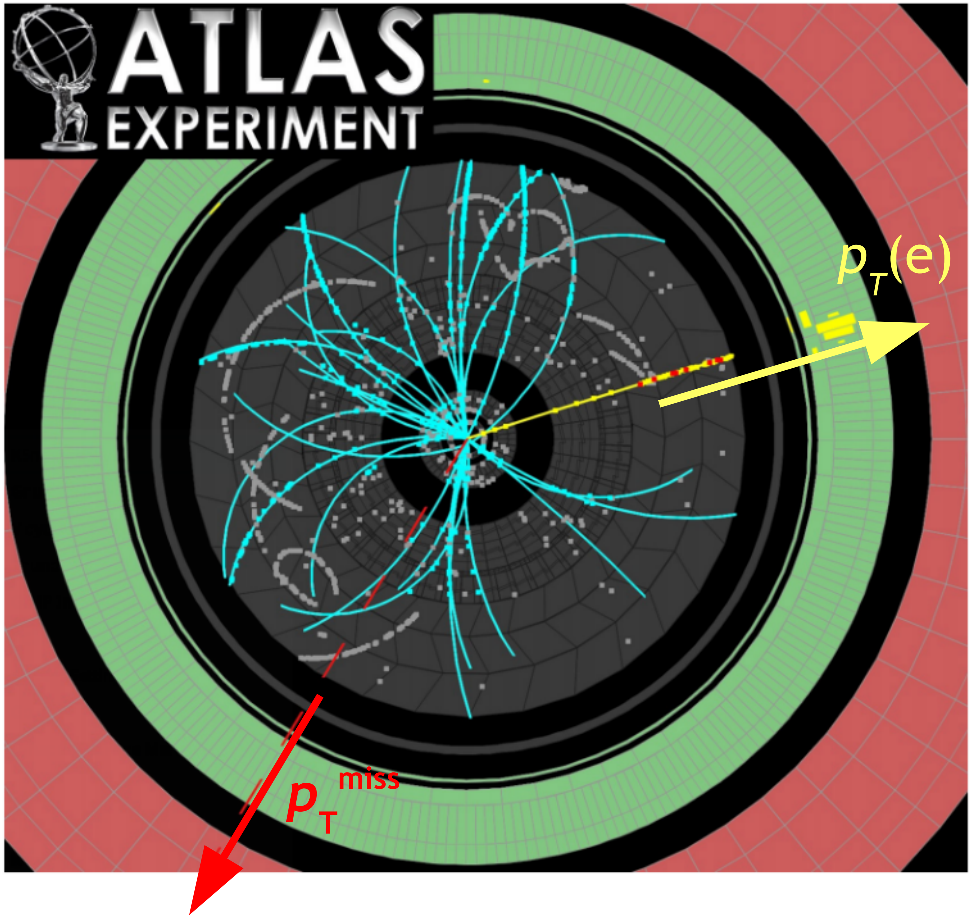
First LHC analysis, using well-understood 2011 data (7 TeV)

~15M W→ℓν decays

Used both lepton transverse momentum, $p_T(\ell)$, and transverse mass, m_T, as variables sensitive to m_W

- Lepton calibration using high statistics Z→ℓℓ sample
- Hadronic recoil (→p_T^{miss}) also calibrated against Z→ℓℓ
- LEP *Z* mass crucial input (2 MeV error)
- Detailed analysis of modelling uncertainties

W→eν event



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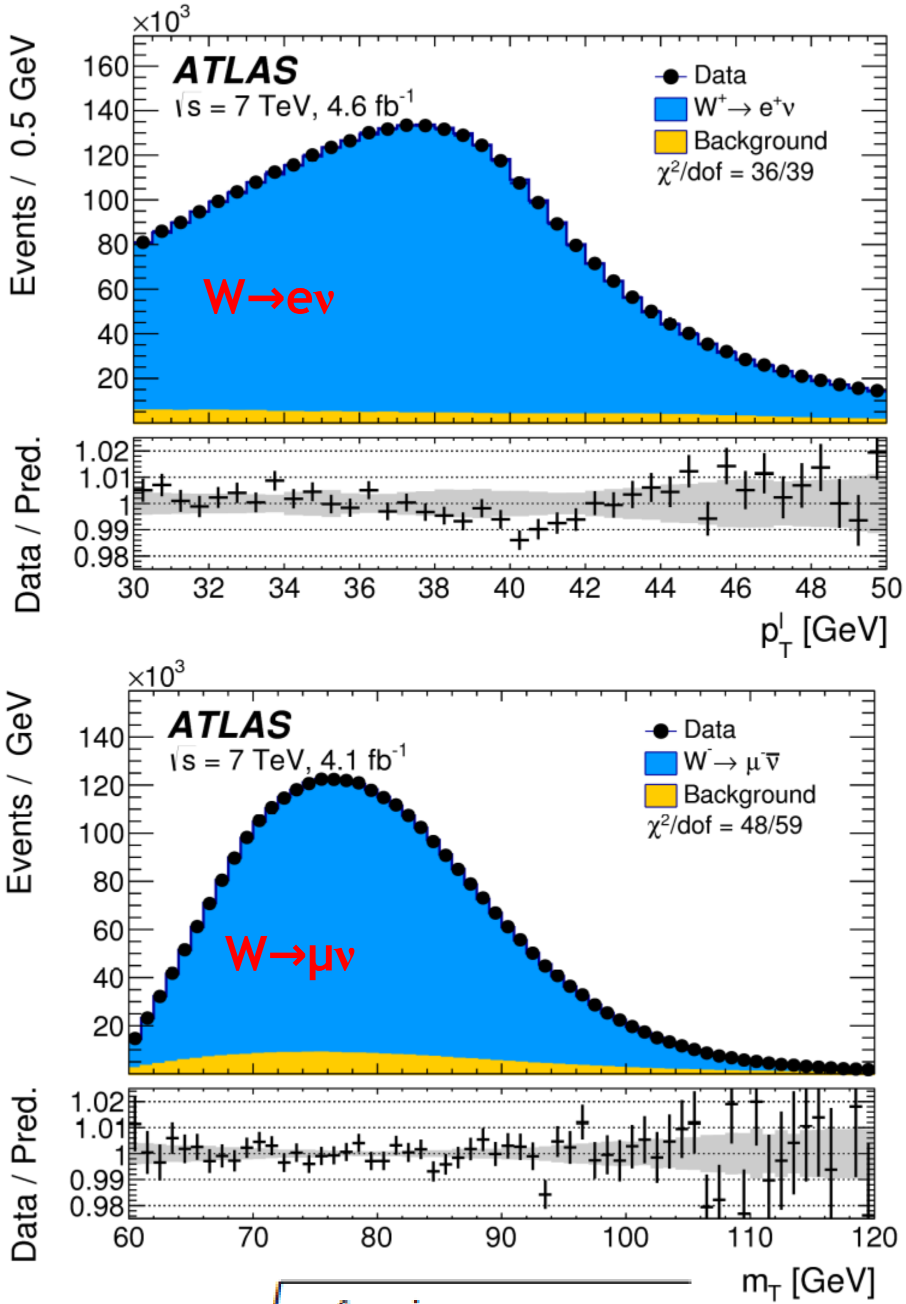


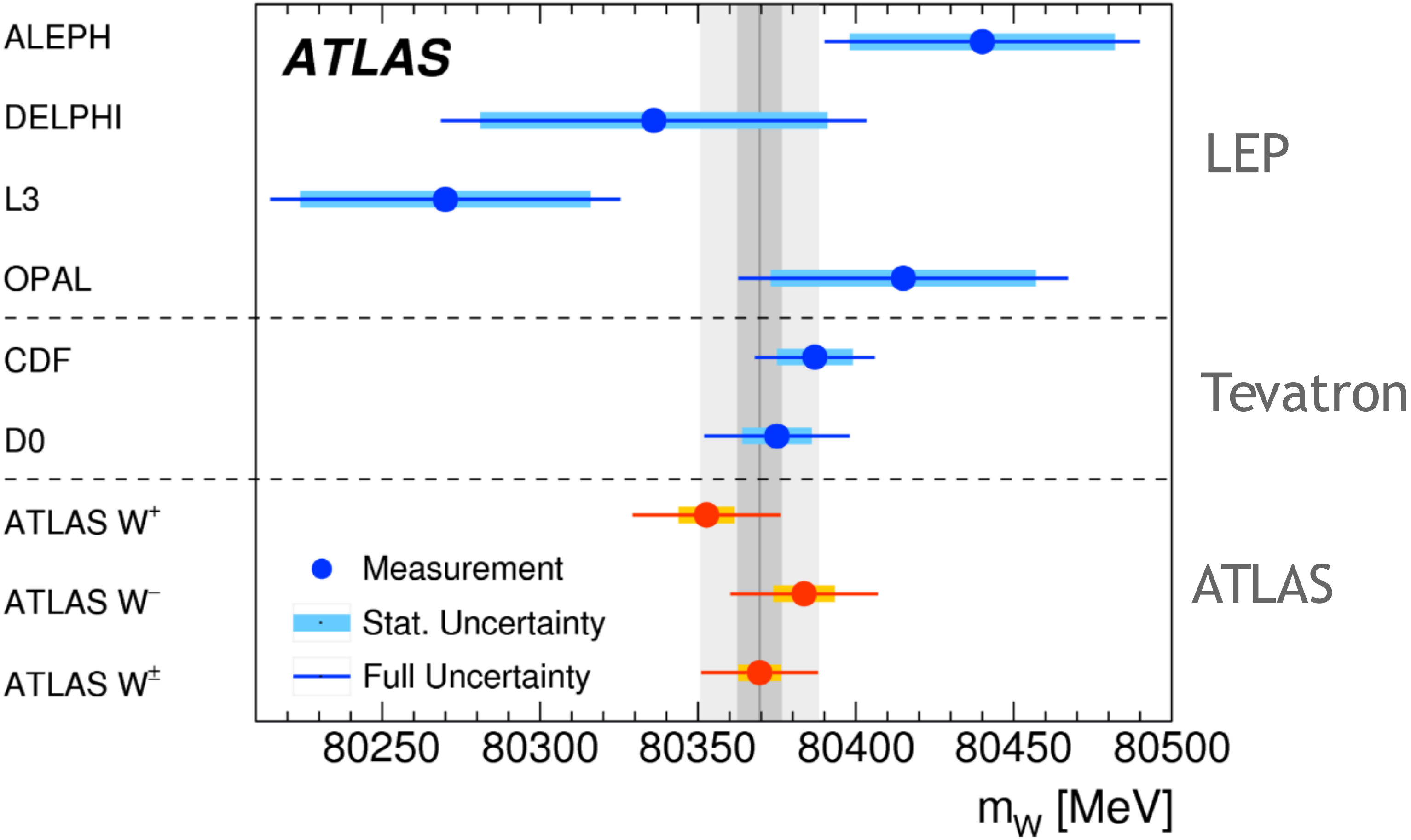
$$m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}p_{\mathrm{T}}^{\mathrm{miss}}(1-\cos\Delta\phi)},$$

W mass results

Combining the e and μ channels, charge signs and methods, overall:

$$m_W = 80370 \pm 19\ \text{MeV} \qquad \pm 7\ (\text{stat.}) \pm 11\ (\text{exp. syst.}) \pm 14\ (\text{mod. syst.})\ \text{MeV}$$

Measurement precision of 19 MeV (0.024%) equals best previous, from CDF



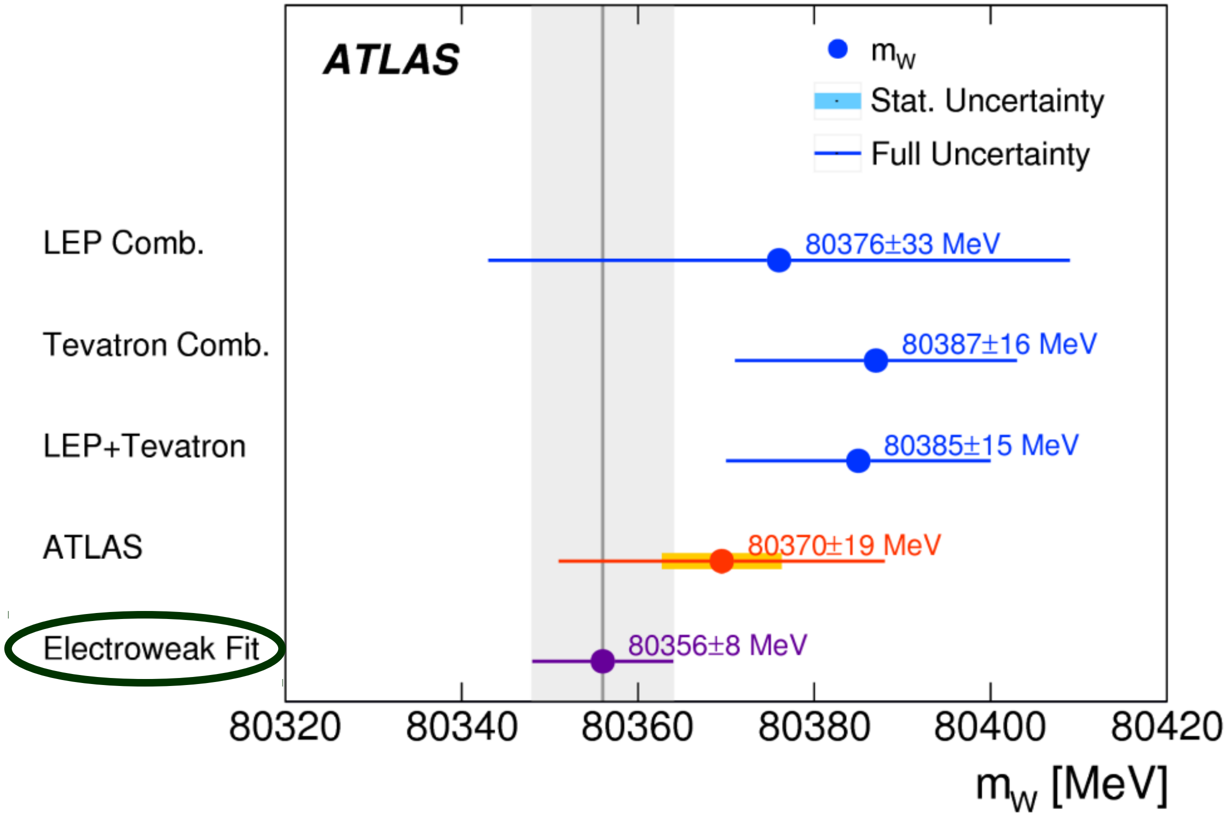
Electroweak precision test

Within the SM framework, m_W is related to other quantities via:

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r).$$

Δr includes radiative effects (loops), and so depends on m_H and m_{top}

Fits to precision electroweak data from LEP/SLD and others, plus the LHC m_H and Tevatron+LHC m_{top}, provides a prediction of m_W ("indirect measurement in the framework of the SM")



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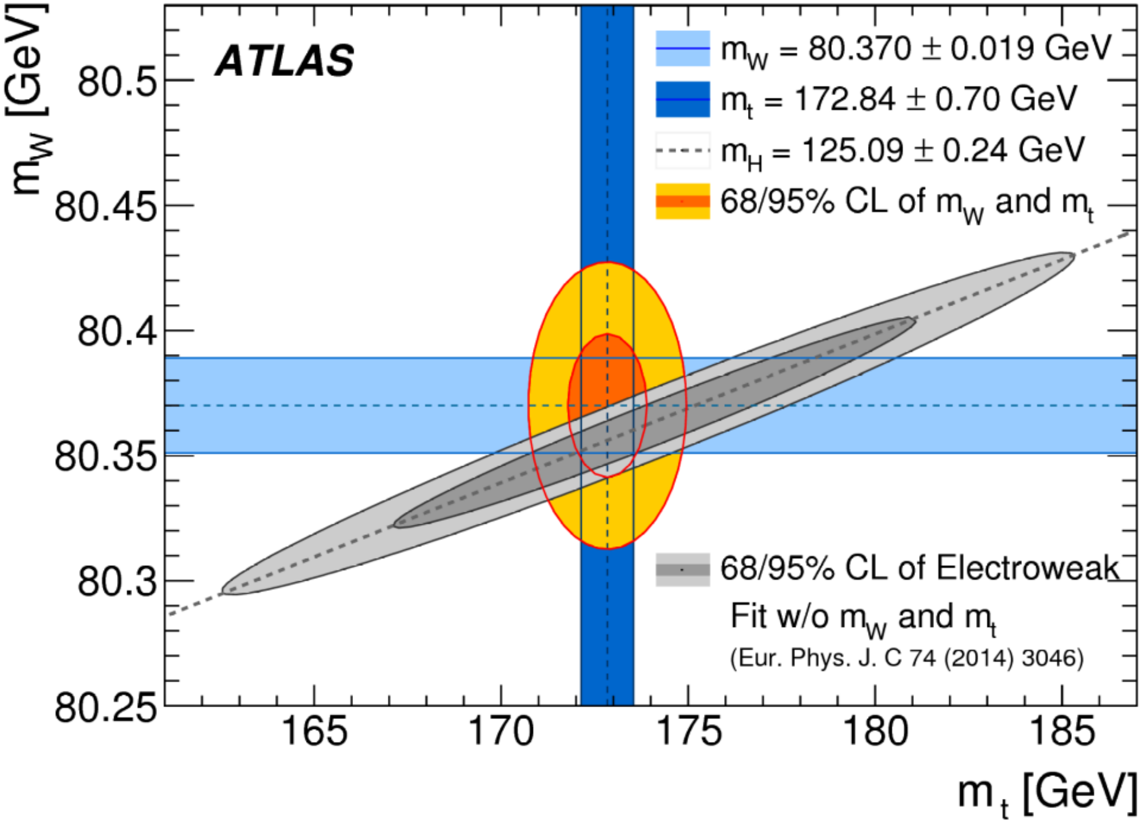
Δr includes radiative effects (loops), and so depends on m_H and m_{top}

Alternatively recast other results into a prediction of m_W vs m_{top} (grey ellipse)

Compare with direct measurements from ATLAS

Remarkable consistency - SM test at level of electroweak loop corrections

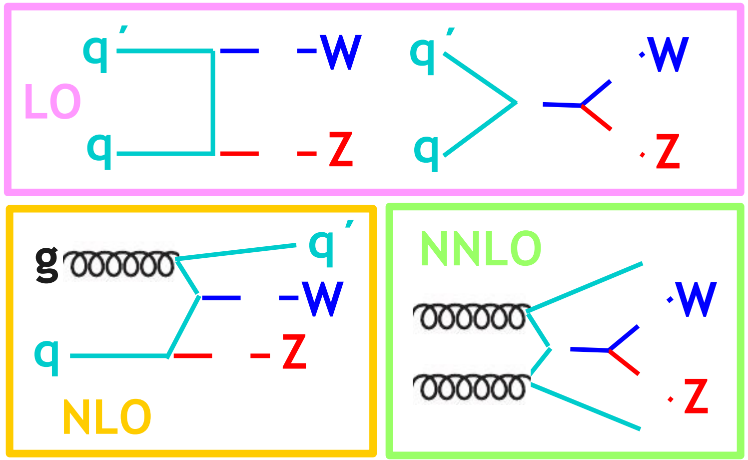


Massive diboson production

Run-1 puzzle to describe inclusive diboson cross-sections

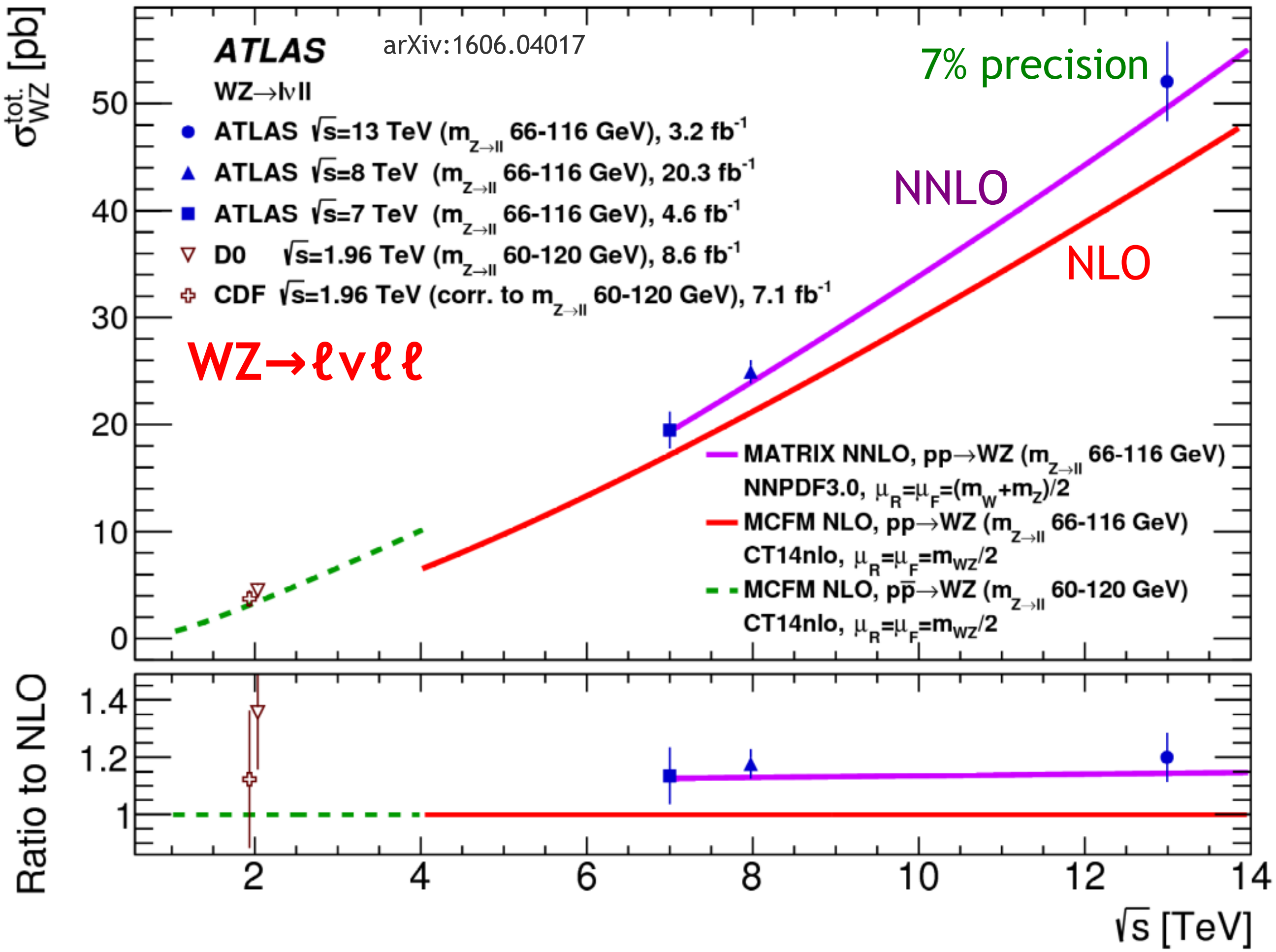
- Measurements tended to lie above next-to-leading order (NLO) calculations

NNLO calculations → ~+20% corrections and better agreement



Example:
WZ leptonic decays
NNLO calculations describe data much better than NLO

This run-1 puzzle appears to be solved!



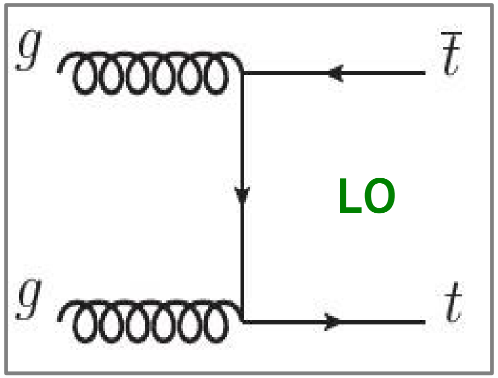
7% precision

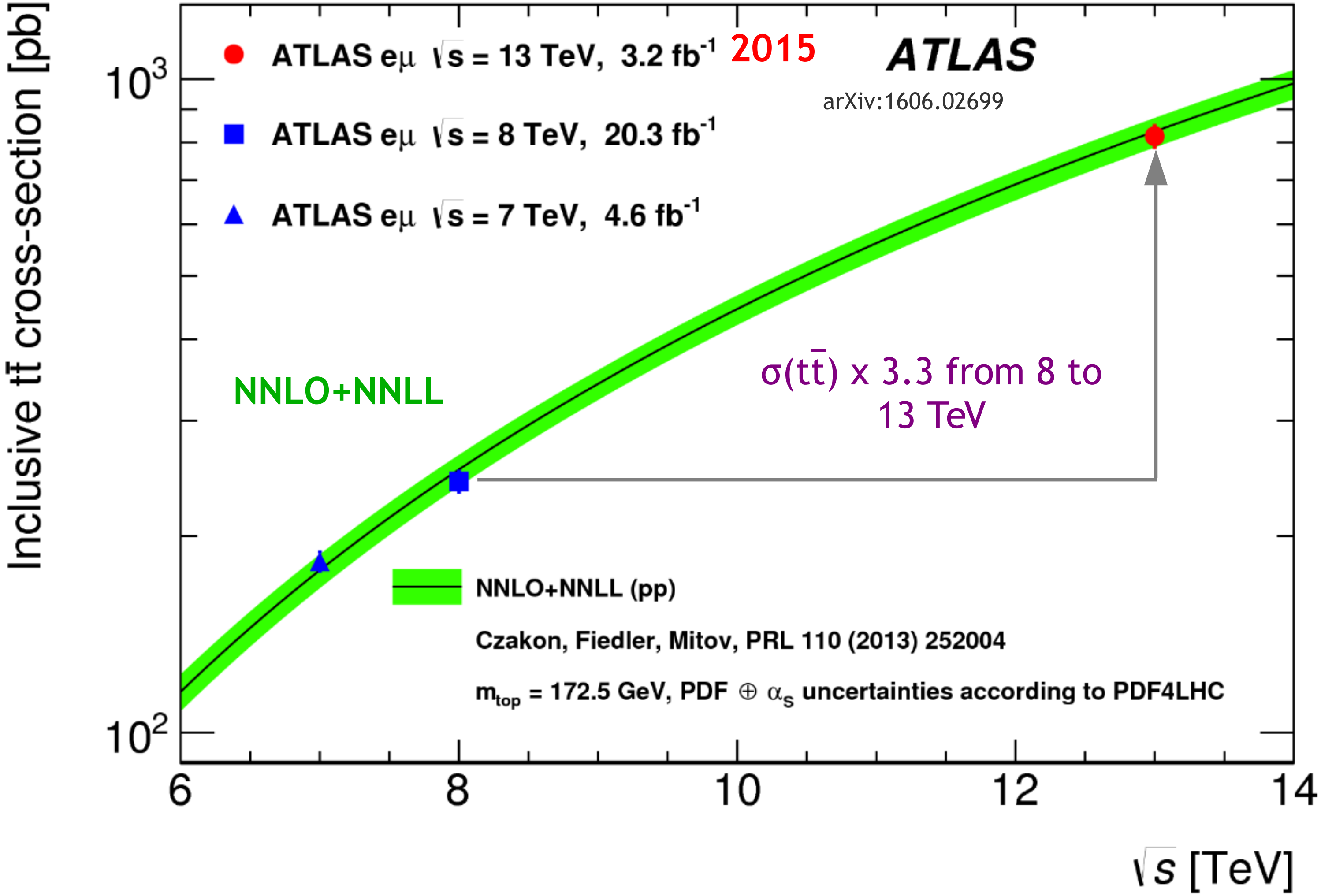
WZ→ℓνℓℓ

$t\bar{t}$ production

Single and double b-tagged $t\bar{t} \rightarrow b e \bar{\nu} \bar{b} \mu \bar{\nu}$ events allow to measure $t\bar{t}$ cross-section and b-tagging efficiency simultaneously

Precision ±(3.9-4.4)% (7-13 TeV) betters NNLO+NNLL predictions (~5%)

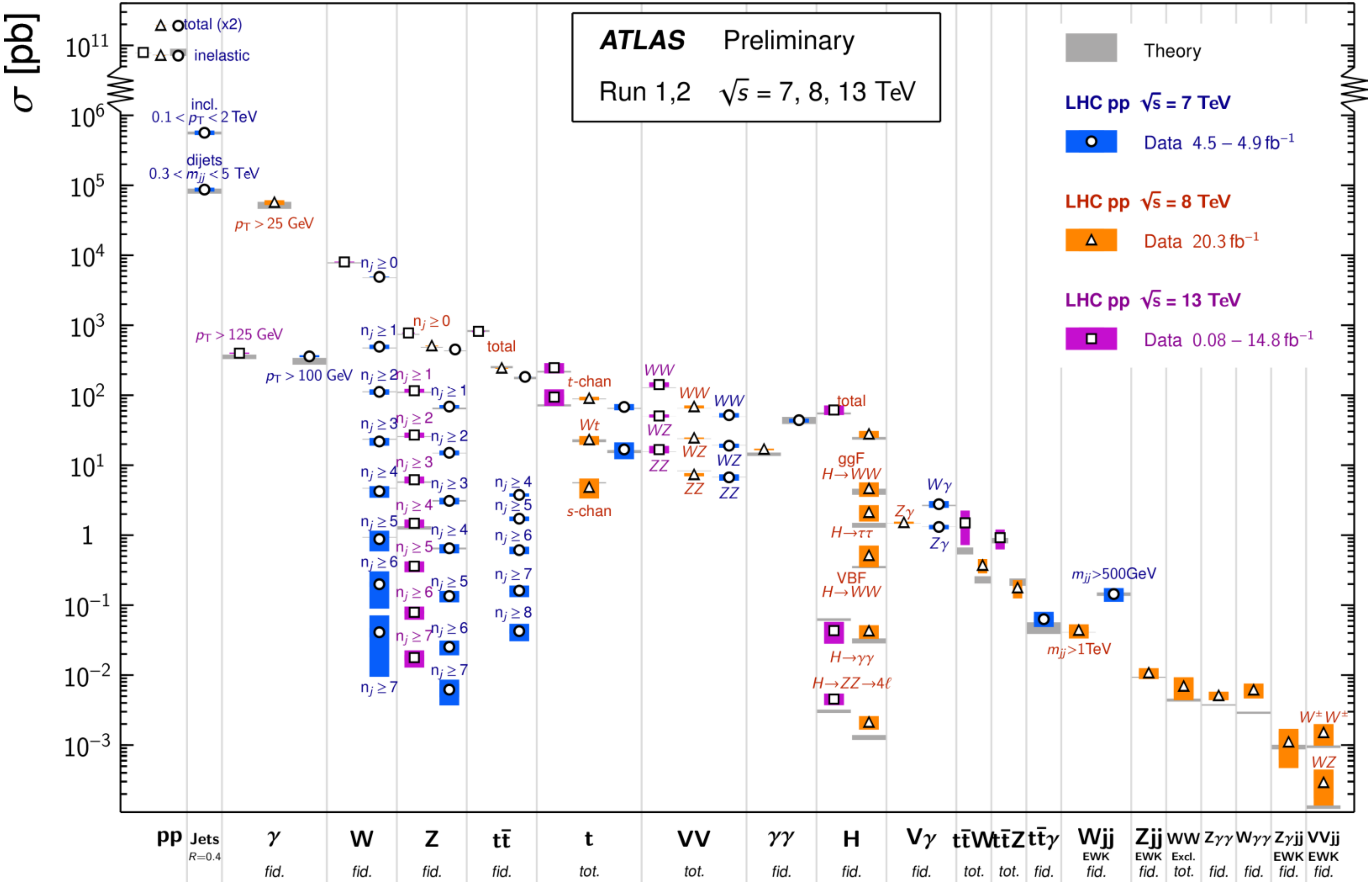




36 fb^{-1} @ 13 TeV
~30M $t\bar{t}$ produced

Standard Model Production Cross Section Measurements

Status: March 2017



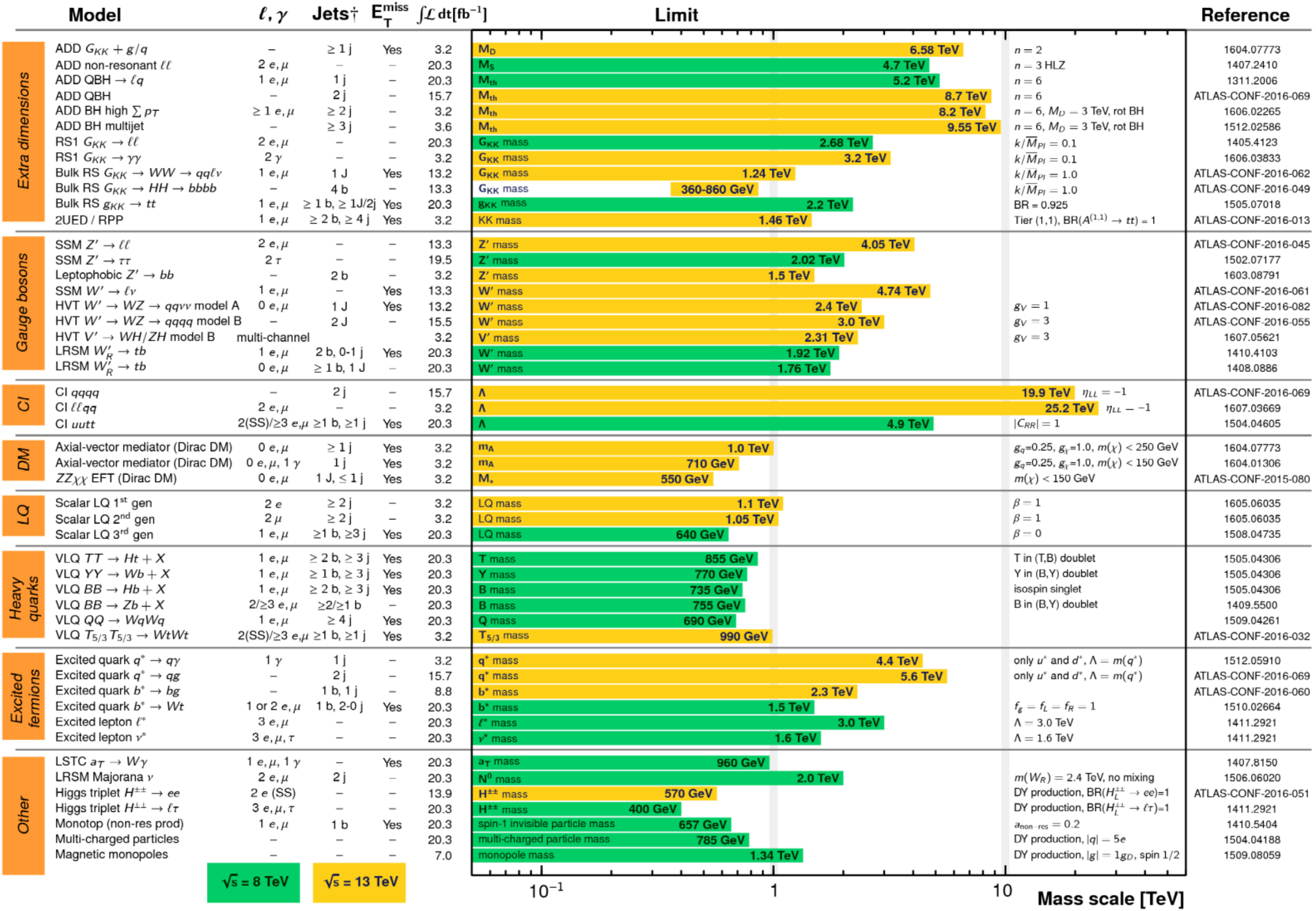
ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 20.3)\ \mathrm{fb}^{-1}$

$\sqrt{s} = 8,\ 13$ TeV



	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\mathrm{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	–	≥ 1 j	Yes	3.2	🟨 M_D 6.58 TeV	$n = 2$	1604.07773
	ADD non-resonant $\ell\ell$	2 e, μ	–	–	20.3	🟩 M_S 4.7 TeV	$n = 3$ HLZ	1407.2410
	ADD QBH $\to \ell q$	1 e, μ	1 j	–	20.3	🟩 M_{th} 5.2 TeV	$n = 6$	1311.2006
	ADD QBH	–	2 j	–	15.7	🟨 M_{th} 8.7 TeV	$n = 6$	ATLAS-CONF-2016-069
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	🟨 M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	🟨 M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \ell\ell$	2 e, μ	–	–	20.3	🟩 G_{KK} mass 2.68 TeV	$k/\overline{M}_{Pl} = 0.1$	1405.4123
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	3.2	🟨 G_{KK} mass 3.2 TeV	$k/\overline{M}_{Pl} = 0.1$	1606.03833
	Bulk RS $G_{KK} \to WW \to qq\ell\nu$	1 e, μ	1 J	Yes	13.2	🟨 G_{KK} mass 1.24 TeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-062
	Bulk RS $G_{KK} \to HH \to bbbb$	–	4 b	–	13.3	🟨 G_{KK} mass 360-860 GeV	$k/\overline{M}_{Pl} = 1.0$	ATLAS-CONF-2016-049
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	20.3	🟩 g_{KK} mass 2.2 TeV	BR = 0.925	1505.07018
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 4 j	Yes	3.2	🟨 KK mass 1.46 TeV	Tier (1,1), BR($A^{(1,1)} \to tt$) = 1	ATLAS-CONF-2016-013
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	13.3	🟨 Z′ mass 4.05 TeV		ATLAS-CONF-2016-045
	SSM $Z' \to \tau\tau$	2 τ	–	–	19.5	🟩 Z′ mass 2.02 TeV		1502.07177
	Leptophobic $Z' \to bb$	–	2 b	–	3.2	🟨 Z′ mass 1.5 TeV		1603.08791
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	13.3	🟨 W′ mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W' \to WZ \to qq\nu\nu$ model A	0 e, μ	1 J	Yes	13.2	🟨 W′ mass 2.4 TeV	$g_V = 1$	ATLAS-CONF-2016-082
	HVT $W' \to WZ \to qqqq$ model B	–	2 J	–	15.5	🟨 W′ mass 3.0 TeV	$g_V = 3$	ATLAS-CONF-2016-055
	HVT $V' \to WH/ZH$ model B	multi-channel			3.2	🟨 V′ mass 2.31 TeV	$g_V = 3$	1607.05621
	LRSM $W'_R \to tb$	1 e, μ	2 b, 0-1 j	Yes	20.3	🟩 W′ mass 1.92 TeV		1410.4103
	LRSM $W'_R \to tb$	0 e, μ	≥ 1 b, 1 J	–	20.3	🟩 W′ mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	🟨 Λ 19.9 TeV	$\eta_{LL} = -1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e, μ	–	–	3.2	🟨 Λ 25.2 TeV	$\eta_{LL} - -1$	1607.03669
	CI $uutt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	20.3	🟩 Λ 4.9 TeV	$\lvert C_{RR} \rvert = 1$	1504.04605
DM	Axial-vector mediator (Dirac DM)	0 e, μ	≥ 1 j	Yes	3.2	🟨 m_A 1.0 TeV	g_q=0.25, g_χ=1.0, $m(\chi) < 250$ GeV	1604.07773
	Axial-vector mediator (Dirac DM)	0 e, μ, 1 γ	1 j	Yes	3.2	🟨 m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi) < 150$ GeV	1604.01306
	$ZZ_{\chi\chi}$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	🟨 M_* 550 GeV	$m(\chi) < 150$ GeV	ATLAS-CONF-2015-080
LQ	Scalar LQ 1st gen	2 e	≥ 2 j	–	3.2	🟨 LQ mass 1.1 TeV	$\beta = 1$	1605.06035
	Scalar LQ 2nd gen	2 μ	≥ 2 j	–	3.2	🟨 LQ mass 1.05 TeV	$\beta = 1$	1605.06035
	Scalar LQ 3rd gen	1 e, μ	$\geq$1 b, $\geq$3 j	Yes	20.3	🟩 LQ mass 640 GeV	$\beta = 0$	1508.04735
Heavy quarks	VLQ $TT \to Ht + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 T mass 855 GeV	T in (T,B) doublet	1505.04306
	VLQ $YY \to Wb + X$	1 e, μ	≥ 1 b, ≥ 3 j	Yes	20.3	🟩 Y mass 770 GeV	Y in (B,Y) doublet	1505.04306
	VLQ $BB \to Hb + X$	1 e, μ	≥ 2 b, ≥ 3 j	Yes	20.3	🟩 B mass 735 GeV	isospin singlet	1505.04306
	VLQ $BB \to Zb + X$	2/$\geq$3 e, μ	$\geq$2/$\geq$1 b	–	20.3	🟩 B mass 755 GeV	B in (B,Y) doublet	1409.5500
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	🟩 Q mass 690 GeV		1509.04261
	VLQ $T_{5/3} T_{5/3} \to WtWt$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	3.2	🟨 $T_{5/3}$ mass 990 GeV		ATLAS-CONF-2016-032
Excited fermions	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	3.2	🟨 q* mass 4.4 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1512.05910
	Excited quark $q^* \to qg$	–	2 j	–	15.7	🟨 q* mass 5.6 TeV	only u^* and d^*, $\Lambda = m(q^*)$	ATLAS-CONF-2016-069
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	8.8	🟨 b* mass 2.3 TeV		ATLAS-CONF-2016-060
	Excited quark $b^* \to Wt$	1 or 2 e, μ	1 b, 2-0 j	Yes	20.3	🟩 b* mass 1.5 TeV	$f_g = f_L = f_R = 1$	1510.02664
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	🟩 ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	🟩 ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	LSTC $a_T \to W\gamma$	1 e, μ, 1 γ	–	Yes	20.3	🟩 a_T mass 960 GeV		1407.8150
	LRSM Majorana ν	2 e, μ	2 j	–	20.3	🟩 N^0 mass 2.0 TeV	$m(W_R) = 2.4$ TeV, no mixing	1506.06020
	Higgs triplet $H^{\pm\pm} \to ee$	2 e (SS)	–	–	13.9	🟨 $H^{\pm\pm}$ mass 570 GeV	DY production, BR($H_L^{\pm\pm} \to ee$)=1	ATLAS-CONF-2016-051
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	🟩 $H^{\pm\pm}$ mass 400 GeV	DY production, BR($H_L^{\pm\pm} \to \ell\tau$)=1	1411.2921
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	🟩 spin-1 invisible particle mass 657 GeV	$a_{\text{non-res}} = 0.2$	1410.5404
	Multi-charged particles	–	–	–	20.3	🟩 multi-charged particle mass 785 GeV	DY production, $\lvert q \rvert = 5e$	1504.04188
	Magnetic monopoles	–	–	–	7.0	🟩 monopole mass 1.34 TeV	DY production, $\lvert g \rvert = 1 g_D$, spin 1/2	1509.08059

🟩 $\sqrt{s}$ = 8 TeV

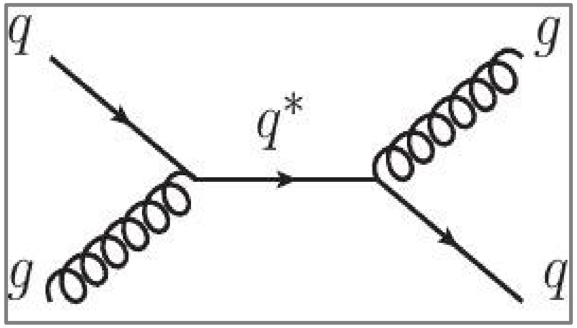
🟨 $\sqrt{s}$ = 13 TeV

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large-radius) jets are denoted by the letter j (J).

"Simple" search: two jet final state

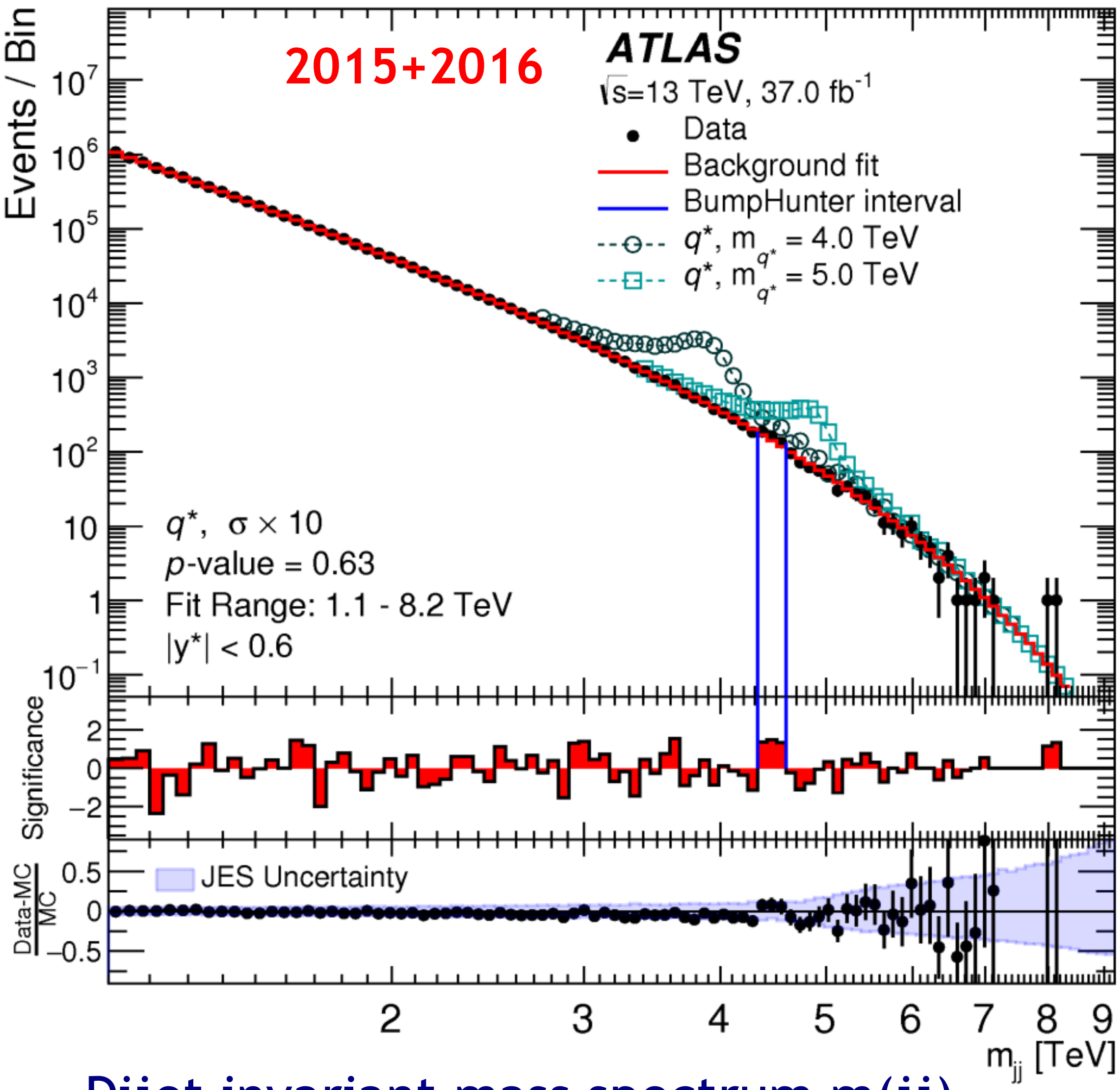
Search for new particles decaying into dijets



Examples (at 95% CL):

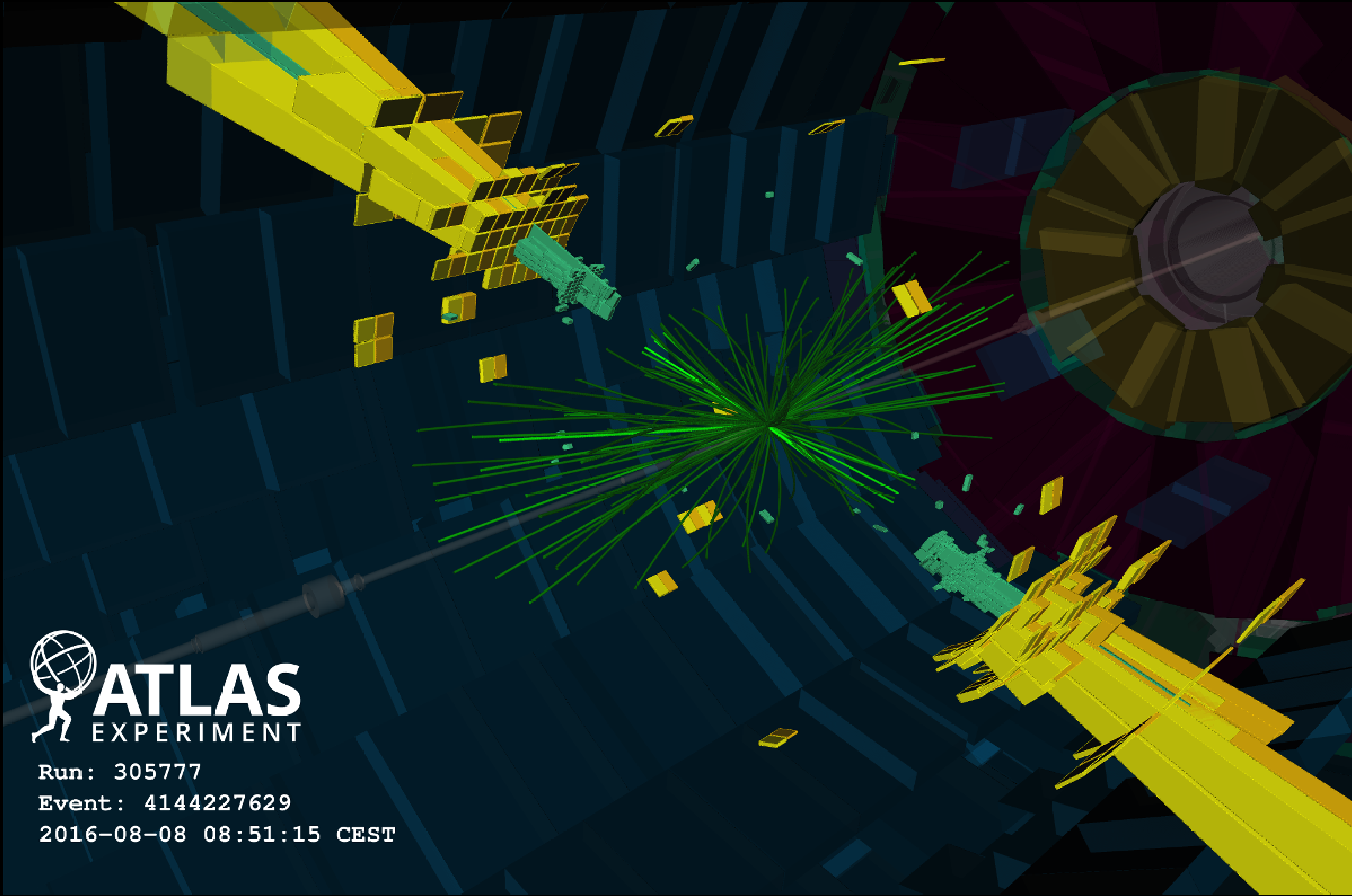
m(q*) > 6.0 TeV
(Cf Run-1: 4.1 TeV)

arxiv:1703.09127



Dijet invariant mass spectrum m(jj)

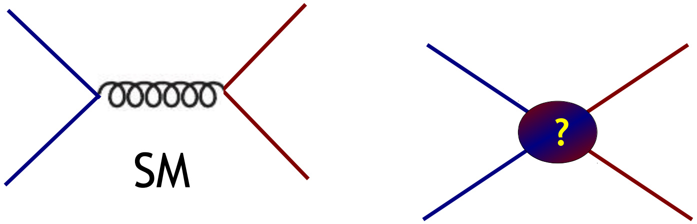
Highest-mass central dijet event - m(jj)=8.2 TeV



Dijet angular distributions

Search for new physics in dijet angular distributions

$$\chi = e^{2|y^*|} \sim \frac{1+\cos\theta^*}{1-\cos\theta^*}$$



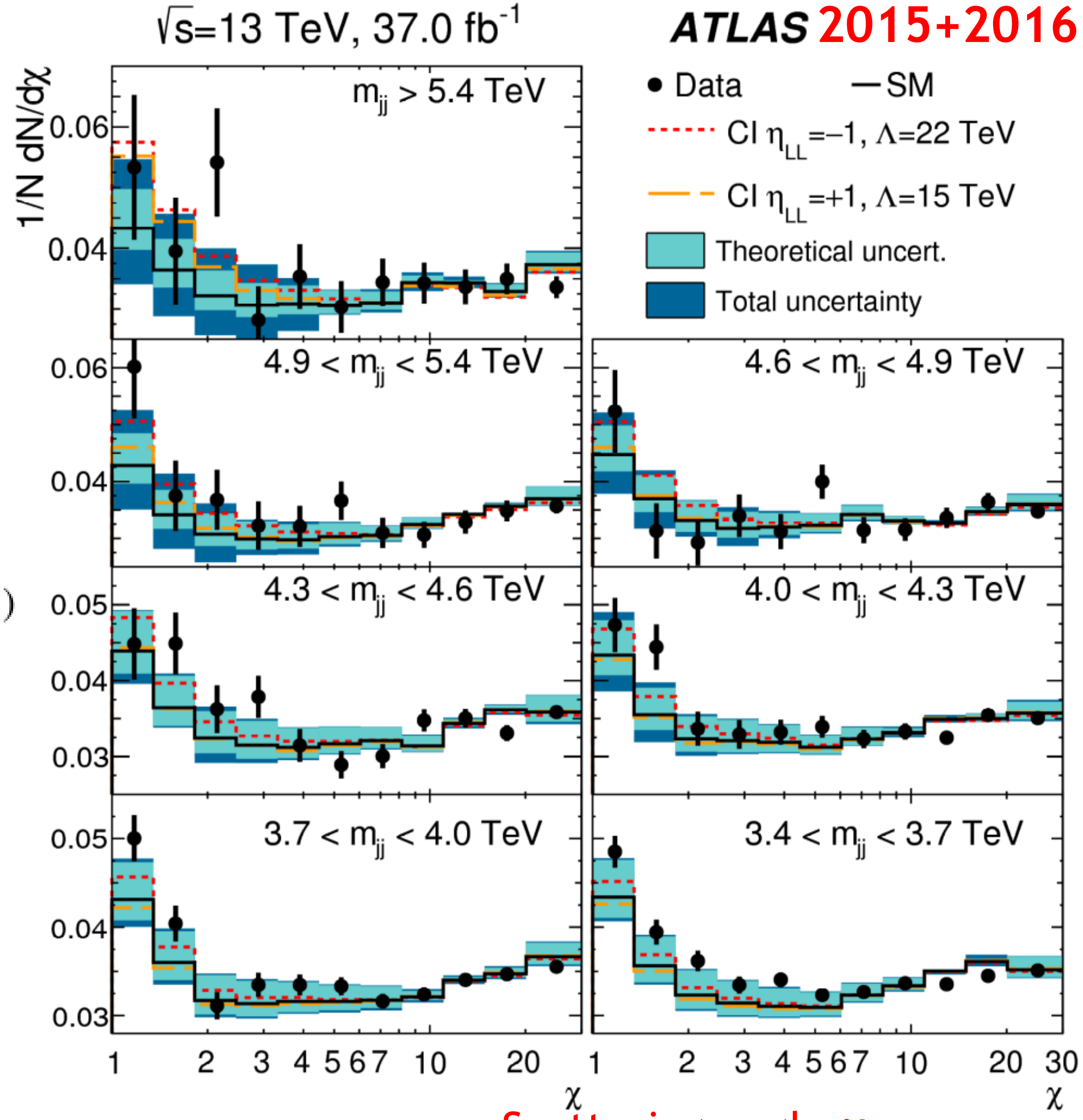
$$L_{qq} = \frac{2\pi}{\Lambda^2}\eta_{\rm LL}(\bar{q}_{\rm L}\gamma^\mu q_{\rm L})(\bar{q}_{\rm L}\gamma_\mu q_{\rm L})$$

From high-mass angular distributions, place 95% CL lower limits on contact interaction scale (for η_{LL}=+1/-1)

Λ > 13.1* / 21.8 TeV

*=also exclude 17.4-29.5 TeV

(Run-1: 8.1/12.0 TeV)



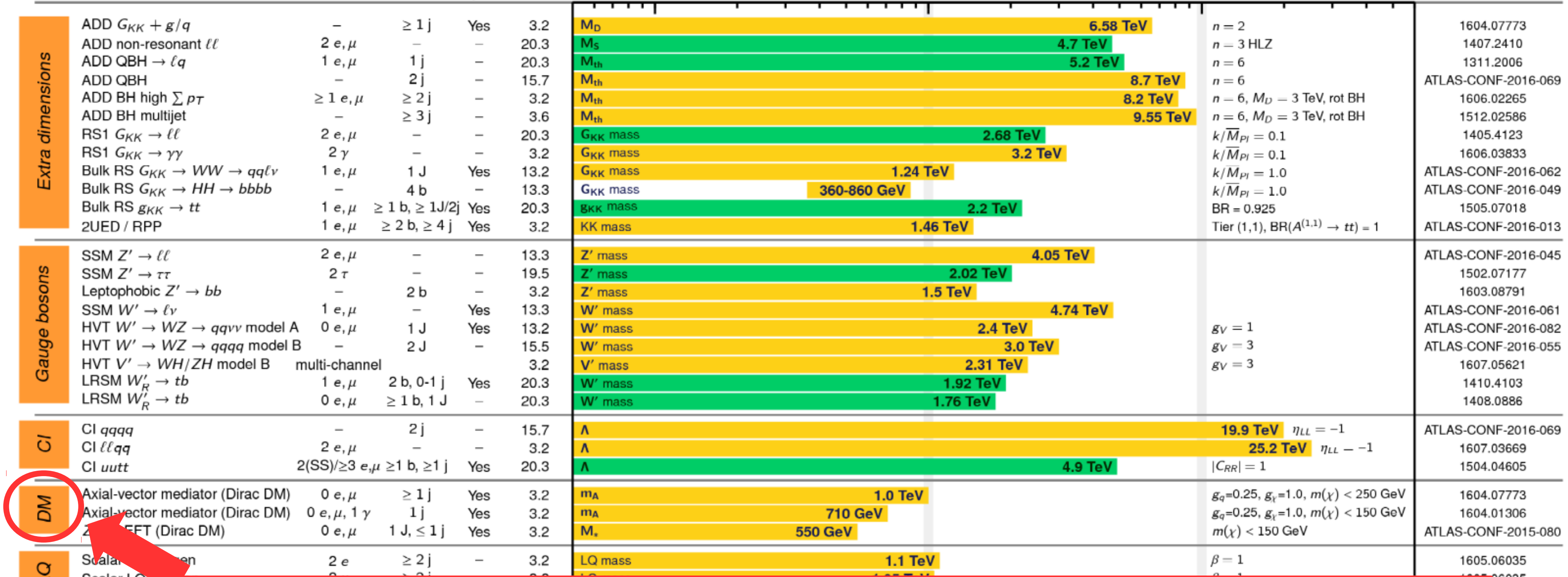
Scattering angle χ

ATLAS Exotics Searches* - 95% CL Exclusion

Status: August 2016

ATLAS Preliminary

$\int\mathcal{L}\,dt$ = (3.2 - 20.3) fb^{-1} $\sqrt{s}$ = 8, 13 TeV



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	ADD BH high $\sum p_T$	≥ 1 e,μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n=6$, $M_D=3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n=6$, $M_D=3$ TeV, rot BH	1512.02586
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	SSM $Z'\to\tau\tau$	2 τ	–	–	19.5	Z' mass 2.02 TeV		1502.07177
	Leptophobic $Z'\to bb$	–	2 b	–	3.2	Z' mass 1.5 TeV		1603.08791
	SSM $W'\to\ell\nu$	1 e,μ	–	Yes	13.3	W' mass 4.74 TeV		ATLAS-CONF-2016-061
	HVT $W'\to WZ\to qq\nu\nu$ model A	0 e,μ	1 J	Yes	13.2	W' mass 2.4 TeV	$g_V=1$	ATLAS-CONF-2016-082
	HVT $W'\to WZ\to qqqq$ model B	–	2 J	–	15.5	W' mass 3.0 TeV	$g_V=3$	ATLAS-CONF-2016-055
	HVT $V'\to WH/ZH$ model B	multi-channel			3.2	V' mass 2.31 TeV	$g_V=3$	1607.05621
	LRSM $W'_R\to tb$	1 e,μ	2 b, 0-1 j	Yes	20.3	W' mass 1.92 TeV		1410.4103
	LRSM $W'_R\to tb$	0 e,μ	≥ 1 b, 1 J	–	20.3	W' mass 1.76 TeV		1408.0886
CI	CI $qqqq$	–	2 j	–	15.7	Λ 19.9 TeV	$\eta_{LL}=-1$	ATLAS-CONF-2016-069
	CI $\ell\ell qq$	2 e,μ	–	–	3.2	Λ 25.2 TeV	$\eta_{LL}=-1$	1607.03669
	CI $uutt$	2(SS)/≥3 e,μ	≥1 b, ≥1 j	Yes	20.3	Λ 4.9 TeV	$\|C_{RR}\|=1$	1504.04605
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	Axial-vector mediator (Dirac DM)	0 e,μ, 1 γ	1 j	Yes	3.2	m_A 710 GeV	g_q=0.25, g_χ=1.0, $m(\chi)<150$ GeV	1604.01306
	EFT (Dirac DM)	0 e,μ	1 J, ≤ 1 j	Yes	3.2	M_* 550 GeV	$m(\chi)<150$ GeV	ATLAS-CONF-2015-080
LQ	Scala en	2 e	≥ 2 j	–	3.2	LQ mass 1.1 TeV	$\beta=1$	1605.06035
	Scalar LQ 2							06035
	Scalar LQ 3rd g							04735
Heavy quarks	VLQ $TT\to Ht$							04306
	VLQ $YY\to W$							04306
	VLQ $BB\to Hb$							04306
	VLQ $BB\to Zb$							5500
	VLQ $QQ\to W$							04261
	VLQ $T_{5/3}T_{5/3}$							F-2016-032
Excited fermions	Excited quark q							05910
	Excited quark q							F-2016-069
	Excited quark b							F-2016-060
	Excited quark b							02664
	Excited lepton ℓ							2921
	Excited lepton ν							2921
Other	LSTC $a_T\to W$							8150
	LRSM Majoran							06020
	Higgs triplet H							F-2016-051
	Higgs triplet H							2921
	Monotop (non-r							5404
	Multi-charged p							04188
	Magnetic monopoles	–	–	–	7.0	monopole mass 1.34 TeV	DY production, $\|g\|=1g_D$, spin 1/2	1509.08059

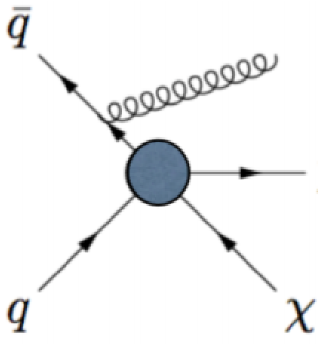
🟩 $\sqrt{s}$ = 8 TeV 🟨 $\sqrt{s}$ = 13 TeV

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

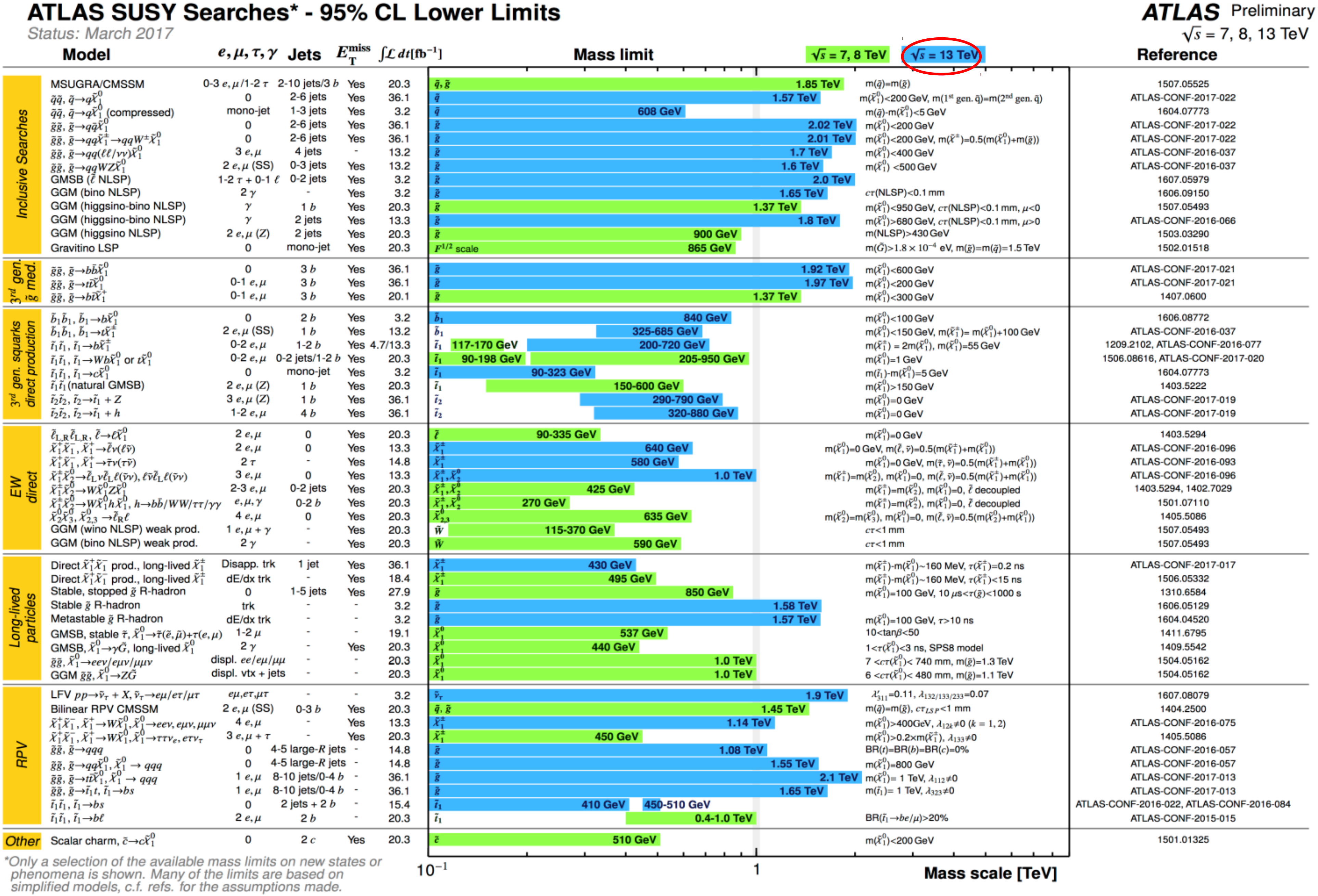
†Small-radius (large-radius) jets are denoted by the letter j (J).

Searches for Dark Matter are ongoing in Run-2

- Generic production with other objects
- Model-specific searches in SUSY models



SUSY Searches



ATLAS SUSY Searches* - 95% CL Lower Limits

Status: March 2017

ATLAS Preliminary

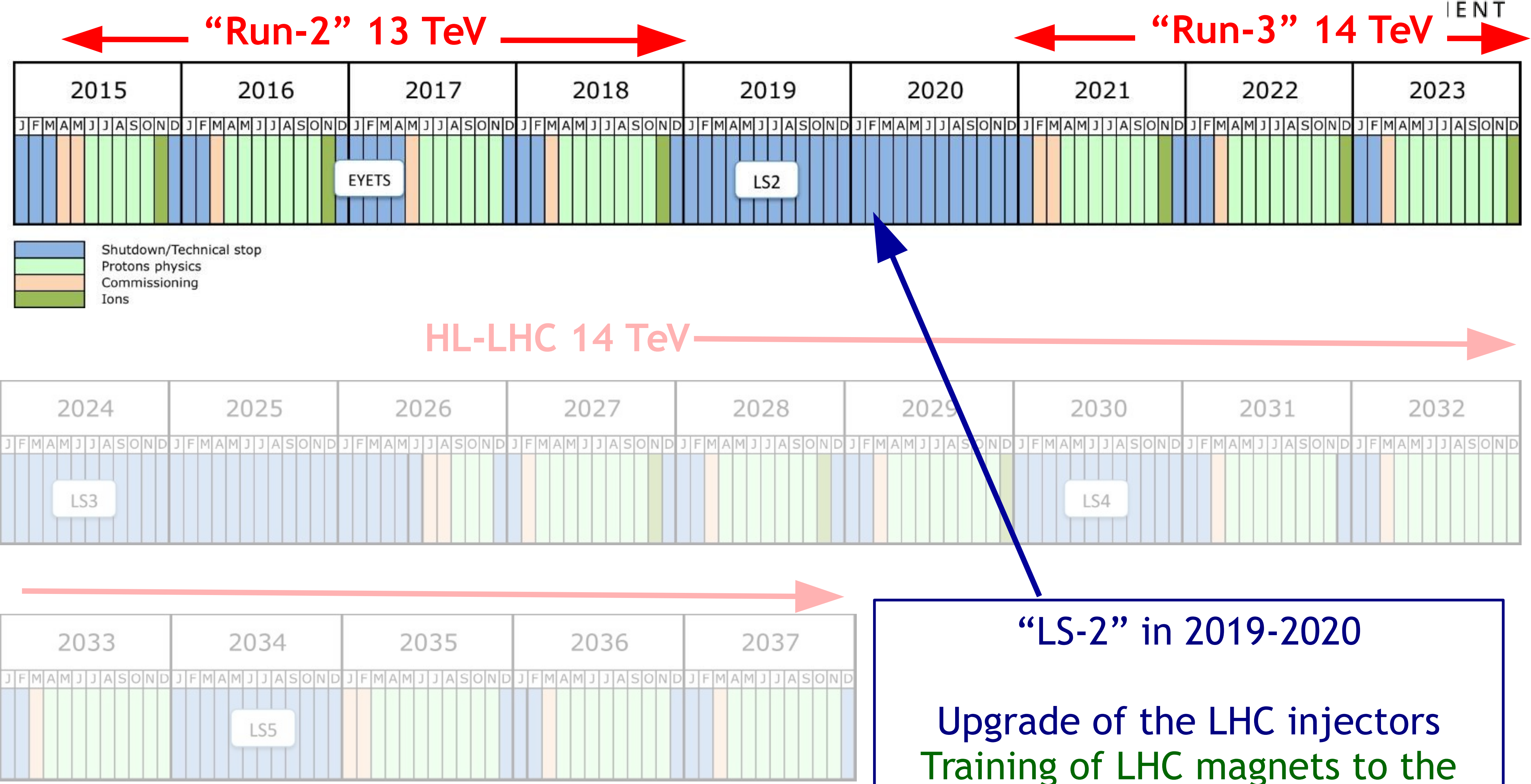
$\sqrt{s}$ = 7, 8, 13 TeV

🟩 $\sqrt{s}$ = 7, 8 TeV 🟦 $\sqrt{s}$ = 13 TeV

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\text{fb}^{-1}]$	Mass limit		Reference
Inclusive Searches	MSUGRA/CMSSM	0-3 e,μ/1-2 τ	2-10 jets/3 b	Yes	20.3	🟩 $\tilde{q},\tilde{g}$ 1.85 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1507.05525
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde{q}$ 1.57 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	ATLAS-CONF-2017-022
	$\tilde{q}\tilde{q}$, $\tilde{q}\to q\tilde{\chi}^0_1$ (compressed)	mono-jet	1-3 jets	Yes	3.2	🟦 $\tilde{q}$ 608 GeV	m($\tilde{q}$)-m($\tilde{\chi}^0_1$)<5 GeV	1604.07773
	$\tilde{g}\tilde{g}$, $\tilde{g}\to q\bar{q}\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.02 TeV	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^\pm_1\to qqW^\pm\tilde{\chi}^0_1$	0	2-6 jets	Yes	36.1	🟦 $\tilde{g}$ 2.01 TeV	m($\tilde{\chi}^0_1$)<200 GeV, m($\tilde{\chi}^\pm$)=0.5(m($\tilde{\chi}^0_1$)+m($\tilde{g}$))	ATLAS-CONF-2017-022
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq(\ell\ell/\nu\nu)\tilde{\chi}^0_1$	3 e,μ	4 jets	-	13.2	🟦 $\tilde{g}$ 1.7 TeV	m($\tilde{\chi}^0_1$)<400 GeV	ATLAS-CONF-2016-037
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqWZ\tilde{\chi}^0_1$	2 e,μ (SS)	0-3 jets	Yes	13.2	🟦 $\tilde{g}$ 1.6 TeV	m($\tilde{\chi}^0_1$) <500 GeV	ATLAS-CONF-2016-037
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	3.2	🟦 $\tilde{g}$ 2.0 TeV		1607.05979
	GGM (bino NLSP)	2 γ	-	Yes	3.2	🟦 $\tilde{g}$ 1.65 TeV	$c\tau$(NLSP)<0.1 mm	1606.09150
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	20.3	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}^0_1$)<950 GeV, $c\tau$(NLSP)<0.1 mm, μ<0	1507.05493
	GGM (higgsino-bino NLSP)	γ	2 jets	Yes	13.3	🟦 $\tilde{g}$ 1.8 TeV	m($\tilde{\chi}^0_1$)>680 GeV, $c\tau$(NLSP)<0.1 mm, μ>0	ATLAS-CONF-2016-066
	GGM (higgsino NLSP)	2 e,μ (Z)	2 jets	Yes	20.3	🟩 $\tilde{g}$ 900 GeV	m(NLSP)>430 GeV	1503.03290
	Gravitino LSP	0	mono-jet	Yes	20.3	🟩 $F^{1/2}$ scale 865 GeV	m($\tilde{G}$)>1.8×10^{-4} eV, m($\tilde{g}$)=m($\tilde{q}$)=1.5 TeV	1502.01518
3rd gen. $\tilde{g}$ med.	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{b}\tilde{\chi}^0_1$	0	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.92 TeV	m($\tilde{\chi}^0_1$)<600 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$	0-1 e,μ	3 b	Yes	36.1	🟦 $\tilde{g}$ 1.97 TeV	m($\tilde{\chi}^0_1$)<200 GeV	ATLAS-CONF-2017-021
	$\tilde{g}\tilde{g}$, $\tilde{g}\to b\bar{t}\tilde{\chi}^+_1$	0-1 e,μ	3 b	Yes	20.1	🟩 $\tilde{g}$ 1.37 TeV	m($\tilde{\chi}^0_1$)<300 GeV	1407.0600
3rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to b\tilde{\chi}^0_1$	0	2 b	Yes	3.2	🟦 $\tilde{b}_1$ 840 GeV	m($\tilde{\chi}^0_1$)<100 GeV	1606.08772
	$\tilde{b}_1\tilde{b}_1$, $\tilde{b}_1\to t\tilde{\chi}^\pm_1$	2 e,μ (SS)	1 b	Yes	13.2	🟦 $\tilde{b}_1$ 325-685 GeV	m($\tilde{\chi}^0_1$)<150 GeV, m($\tilde{\chi}^\pm_1$)= m($\tilde{\chi}^0_1$)+100 GeV	ATLAS-CONF-2016-037
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\tilde{\chi}^\pm_1$	0-2 e,μ	1-2 b	Yes	4.7/13.3	$\tilde{t}_1$ 🟩 117-170 GeV 🟦 200-720 GeV	m($\tilde{\chi}^\pm_1$) = 2m($\tilde{\chi}^0_1$), m($\tilde{\chi}^0_1$)=55 GeV	1209.2102, ATLAS-CONF-2016-077
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to Wb\tilde{\chi}^0_1$ or $t\tilde{\chi}^0_1$	0-2 e,μ	0-2 jets/1-2 b	Yes	20.3	$\tilde{t}_1$ 🟩 90-198 GeV 🟩 205-950 GeV	m($\tilde{\chi}^0_1$)=1 GeV	1506.08616, ATLAS-CONF-2017-020
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to c\tilde{\chi}^0_1$	0	mono-jet	Yes	3.2	🟦 $\tilde{t}_1$ 90-323 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}^0_1$)=5 GeV	1604.07773
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e,μ (Z)	1 b	Yes	20.3	🟩 $\tilde{t}_1$ 150-600 GeV	m($\tilde{\chi}^0_1$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + Z$	3 e,μ (Z)	1 b	Yes	36.1	🟦 $\tilde{t}_2$ 290-790 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2017-019
	$\tilde{t}_2\tilde{t}_2$, $\tilde{t}_2\to\tilde{t}_1 + h$	1-2 e,μ	4 b	Yes	36.1	🟦 $\tilde{t}_2$ 320-880 GeV	m($\tilde{\chi}^0_1$)=0 GeV	ATLAS-CONF-2017-019
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}$, $\tilde{\ell}\to\ell\tilde{\chi}^0_1$	2 e,μ	0	Yes	20.3	🟩 $\tilde{\ell}$ 90-335 GeV	m($\tilde{\chi}^0_1$)=0 GeV	1403.5294
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e,μ	0	Yes	13.3	🟦 $\tilde{\chi}^\pm_1$ 640 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2016-096
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to\tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	14.8	🟦 $\tilde{\chi}^\pm_1$ 580 GeV	m($\tilde{\chi}^0_1$)=0 GeV, m($\tilde{\tau}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2016-093
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu)$, $\ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e,μ	0	Yes	13.3	🟦 $\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2$ 1.0 TeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^\pm_1$)+m($\tilde{\chi}^0_1$))	ATLAS-CONF-2016-096
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 Z\tilde{\chi}^0_1$	2-3 e,μ	0-2 jets	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2$ 425 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1403.5294, 1402.7029
	$\tilde{\chi}^\pm_1\tilde{\chi}^0_2\to W\tilde{\chi}^0_1 h\tilde{\chi}^0_1$, $h\to b\bar{b}/WW/\tau\tau/\gamma\gamma$	e,μ,γ	0-2 b	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$, $\tilde{\chi}^0_2$ 270 GeV	m($\tilde{\chi}^\pm_1$)=m($\tilde{\chi}^0_2$), m($\tilde{\chi}^0_1$)=0, $\tilde{\ell}$ decoupled	1501.07110
	$\tilde{\chi}^0_2\tilde{\chi}^0_3$, $\tilde{\chi}^0_{2,3}\to\tilde{\ell}_R\ell$	4 e,μ	0	Yes	20.3	🟩 $\tilde{\chi}^0_{2,3}$ 635 GeV	m($\tilde{\chi}^0_2$)=m($\tilde{\chi}^0_3$), m($\tilde{\chi}^0_1$)=0, m($\tilde{\ell}$, $\tilde{\nu}$)=0.5(m($\tilde{\chi}^0_2$)+m($\tilde{\chi}^0_1$))	1405.5086
	GGM (wino NLSP) weak prod.	1 $e,\mu + \gamma$	-	Yes	20.3	🟩 $\tilde{W}$ 115-370 GeV	$c\tau$<1 mm	1507.05493
	GGM (bino NLSP) weak prod.	2 γ	-	Yes	20.3	🟩 $\tilde{W}$ 590 GeV	$c\tau$<1 mm	1507.05493
Long-lived particles	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	Disapp. trk	1 jet	Yes	36.1	🟦 $\tilde{\chi}^\pm_1$ 430 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)=0.2 ns	ATLAS-CONF-2017-017
	Direct $\tilde{\chi}^+_1\tilde{\chi}^-_1$ prod., long-lived $\tilde{\chi}^\pm_1$	dE/dx trk	-	Yes	18.4	🟩 $\tilde{\chi}^\pm_1$ 495 GeV	m($\tilde{\chi}^\pm_1$)-m($\tilde{\chi}^0_1$)~160 MeV, τ($\tilde{\chi}^\pm_1$)<15 ns	1506.05332
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	🟩 $\tilde{g}$ 850 GeV	m($\tilde{\chi}^0_1$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	Stable $\tilde{g}$ R-hadron	trk	-	-	3.2	🟦 $\tilde{g}$ 1.58 TeV		1606.05129
	Metastable $\tilde{g}$ R-hadron	dE/dx trk	-	-	3.2	🟦 $\tilde{g}$ 1.57 TeV	m($\tilde{\chi}^0_1$)=100 GeV, τ>10 ns	1604.04520
	GMSB, stable $\tilde{\tau}$, $\tilde{\chi}^0_1\to\tilde{\tau}(\tilde{e},\tilde{\mu})+\tau(e,\mu)$	1-2 μ	-	-	19.1	🟩 $\tilde{\chi}^0_1$ 537 GeV	10<tanβ<50	1411.6795
	GMSB, $\tilde{\chi}^0_1\to\gamma\tilde{G}$, long-lived $\tilde{\chi}^0_1$	2 γ	-	Yes	20.3	🟩 $\tilde{\chi}^0_1$ 440 GeV	1<τ($\tilde{\chi}^0_1$)<3 ns, SPS8 model	1409.5542
	$\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to ee\nu/e\mu\nu/\mu\mu\nu$	displ. $ee/e\mu/\mu\mu$	-	-	20.3	🟩 $\tilde{\chi}^0_1$ 1.0 TeV	7 <$c\tau$($\tilde{\chi}^0_1$)< 740 mm, m($\tilde{g}$)=1.3 TeV	1504.05162
	GGM $\tilde{g}\tilde{g}$, $\tilde{\chi}^0_1\to Z\tilde{G}$	displ. vtx + jets	-	-	20.3	🟩 $\tilde{\chi}^0_1$ 1.0 TeV	6 <$c\tau$($\tilde{\chi}^0_1$)< 480 mm, m($\tilde{g}$)=1.1 TeV	1504.05162
RPV	LFV $pp\to\tilde{\nu}_\tau + X$, $\tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$	$e\mu$,$e\tau$,$\mu\tau$	-	-	3.2	🟦 $\tilde{\nu}_\tau$ 1.9 TeV	λ'_{311}=0.11, $\lambda_{132/133/233}$=0.07	1607.08079
	Bilinear RPV CMSSM	2 e,μ (SS)	0-3 b	Yes	20.3	🟩 $\tilde{q}$, $\tilde{g}$ 1.45 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to ee\nu, e\mu\nu, \mu\mu\nu$	4 e,μ	-	Yes	13.3	🟦 $\tilde{\chi}^\pm_1$ 1.14 TeV	m($\tilde{\chi}^0_1$)>400GeV, $\lambda_{12k}\neq0$ ($k = 1, 2$)	ATLAS-CONF-2016-075
	$\tilde{\chi}^+_1\tilde{\chi}^-_1$, $\tilde{\chi}^+_1\to W\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to\tau\tau\nu_e, e\tau\nu_\tau$	3 $e,\mu + \tau$	-	Yes	20.3	🟩 $\tilde{\chi}^\pm_1$ 450 GeV	m($\tilde{\chi}^0_1$)>0.2×m($\tilde{\chi}^\pm_1$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.08 TeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	0	4-5 large-R jets	-	14.8	🟦 $\tilde{g}$ 1.55 TeV	m($\tilde{\chi}^0_1$)=800 GeV	ATLAS-CONF-2016-057
	$\tilde{g}\tilde{g}$, $\tilde{g}\to t\bar{t}\tilde{\chi}^0_1$, $\tilde{\chi}^0_1\to qqq$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 2.1 TeV	m($\tilde{\chi}^0_1$)= 1 TeV, $\lambda_{112}\neq0$	ATLAS-CONF-2017-013
	$\tilde{g}\tilde{g}$, $\tilde{g}\to\tilde{t}_1 t$, $\tilde{t}_1\to bs$	1 e,μ	8-10 jets/0-4 b	-	36.1	🟦 $\tilde{g}$ 1.65 TeV	m($\tilde{t}_1$)= 1 TeV, $\lambda_{323}\neq0$	ATLAS-CONF-2017-013
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$	0	2 jets + 2 b	-	15.4	$\tilde{t}_1$ 🟦 410 GeV 🟦 450-510 GeV		ATLAS-CONF-2016-022, ATLAS-CONF-2016-084
	$\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$	2 e,μ	2 b	-	20.3	🟩 $\tilde{t}_1$ 0.4-1.0 TeV	BR($\tilde{t}_1\to be/\mu$)>20%	ATLAS-CONF-2015-015
Other	Scalar charm, $\tilde{c}\to c\tilde{\chi}^0_1$	0	2 c	Yes	20.3	🟩 $\tilde{c}$ 510 GeV	m($\tilde{\chi}^0_1$)<200 GeV	1501.01325

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

A look to the future



"LS-2" in 2019-2020

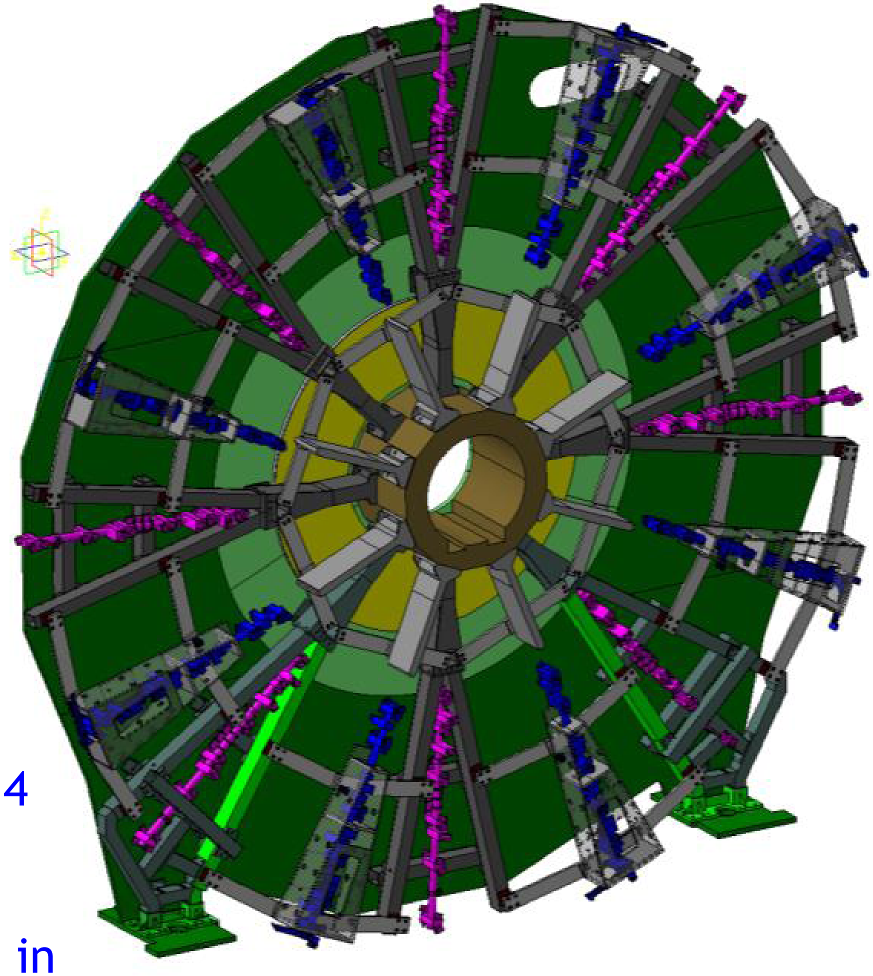
Upgrade of the LHC injectors
Training of LHC magnets to the field needed for 14 TeV operation
Significant upgrades to the experiments - "Phase-I"

Phase-I upgrades

LHC luminosity (collision rate) has exceeded LHC design already by 40%

Could exceed design luminosity by a factor ~2.5 in “Run-3”

→ *Phase-1 upgrades give us better trigger performance (better selectivity in hardware within ~3 μs), and also provide better tracking close to the interaction point*

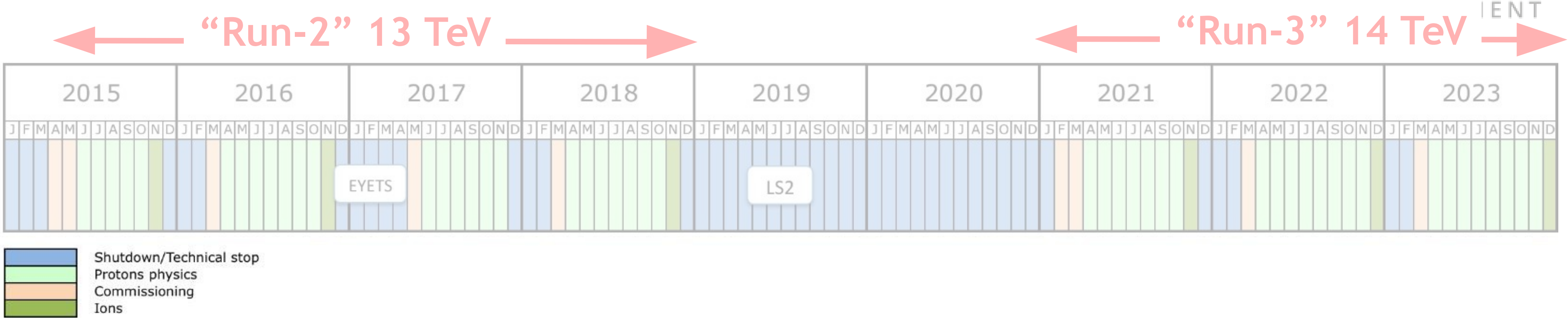


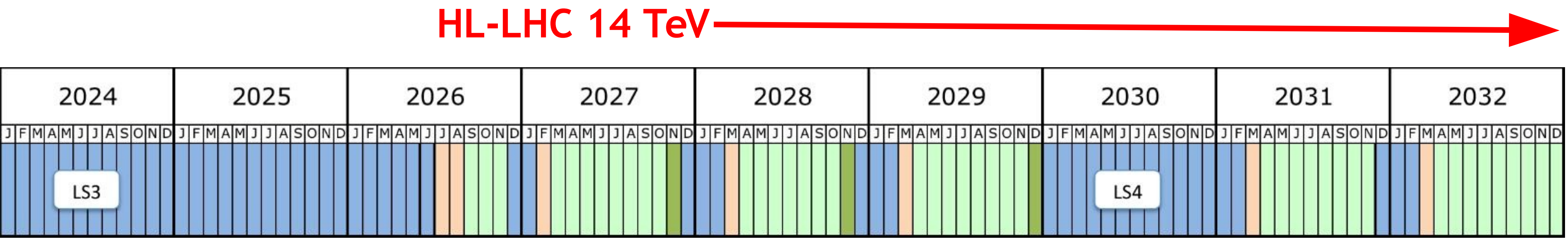
NSW design

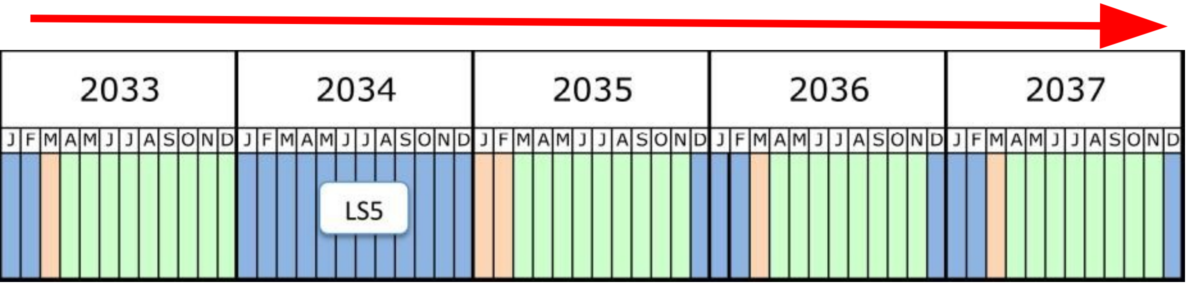
Main ATLAS Phase-I upgrades:

- New inner pixel layer installed already in 2014
- New track & calorimeter trigger electronics
- New “small muon wheel” (9.3m diameter)

Big international hardware & electronics projects in their own right (total capital cost 35 MCHF)







HL-LHC accelerator upgrade was approved by CERN Council in June 2016 (cost: 930M CHF)

HL-LHC: “levelled” luminosity 5-7 times the original design, until ~2035

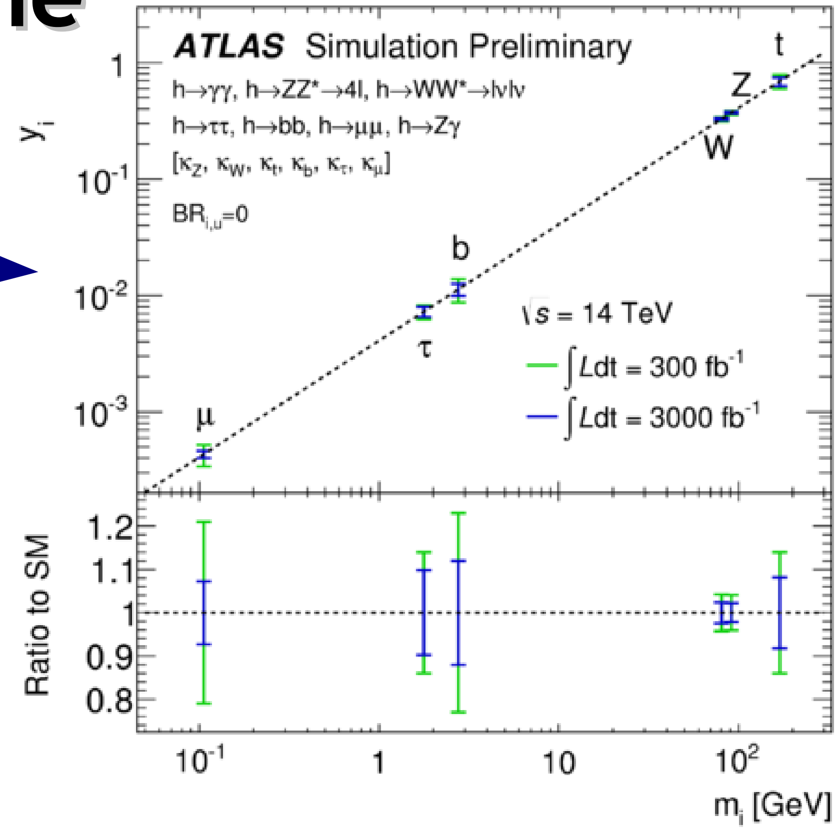
Accumulate 10x more data than in Runs 1-3 combined – era of high precision, and very high pileup!

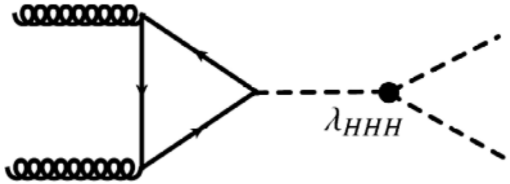
Must upgrade detectors!

HL-LHC physics programme

"Known goals"

- High-precision studies of the Higgs boson production and decay
- Rare Higgs boson decays
- HH (di-Higgs) production

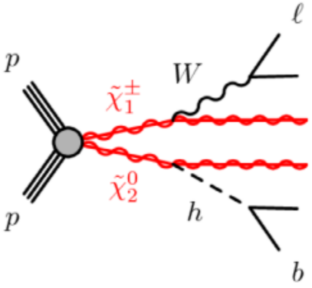


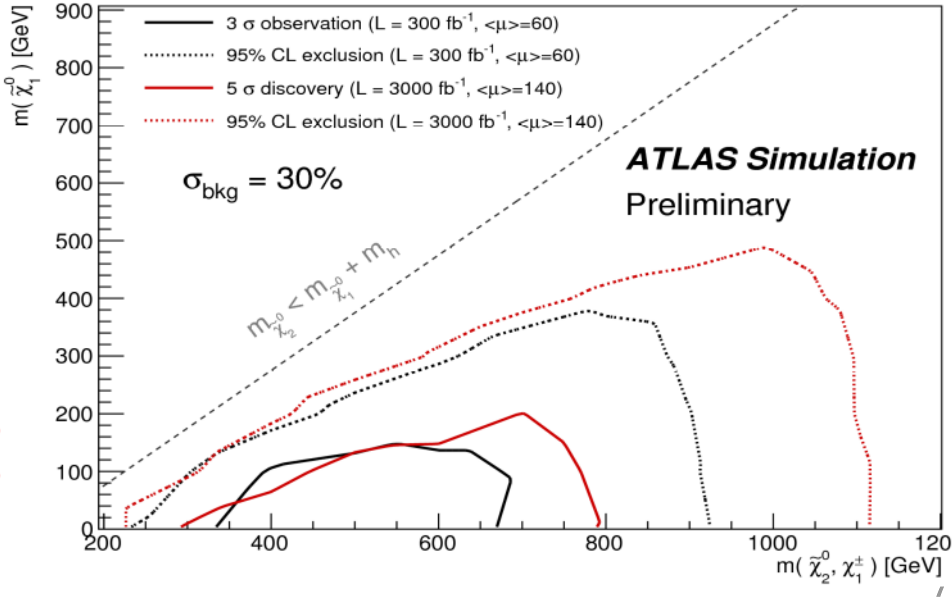


- High precision studies in other areas – vector-boson scattering, top decays …

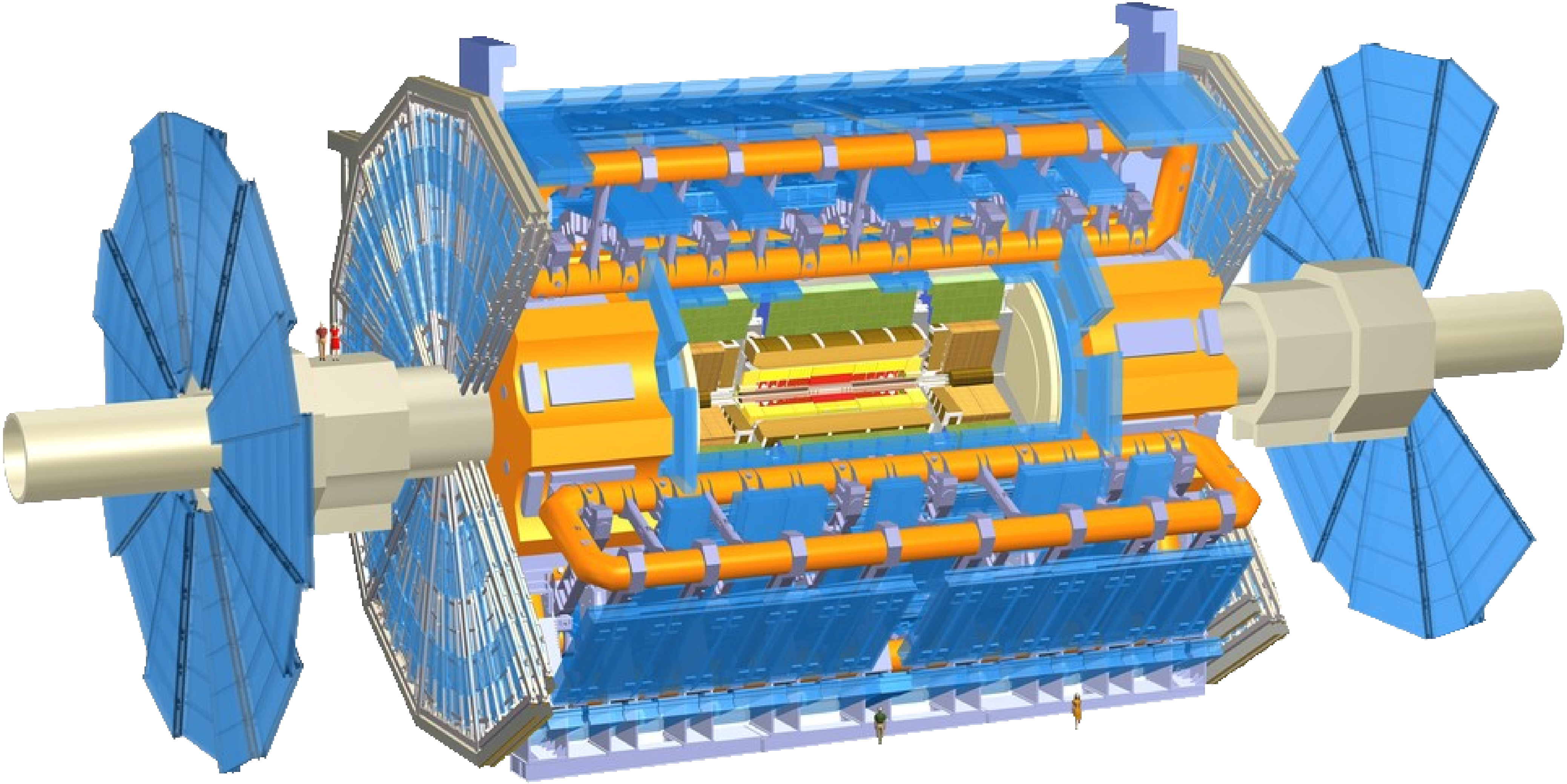
"Unknown goals"

- Measure and study properties of any/whatever new physics which was already discovered in Run-2/3
- Continue search programme: ~30% increase in mass reach

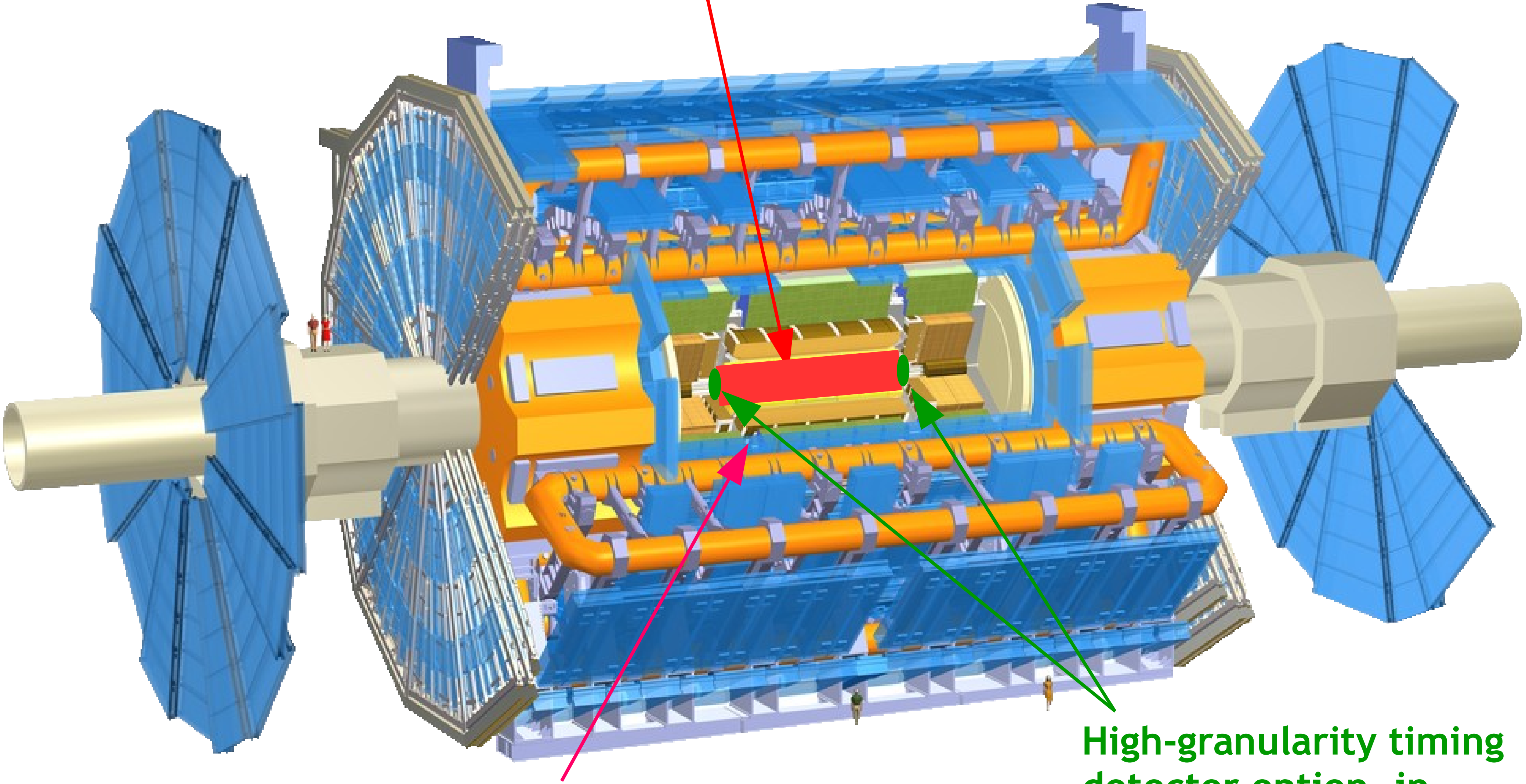




Current ATLAS



Phase-II



New central tracker (ITk)

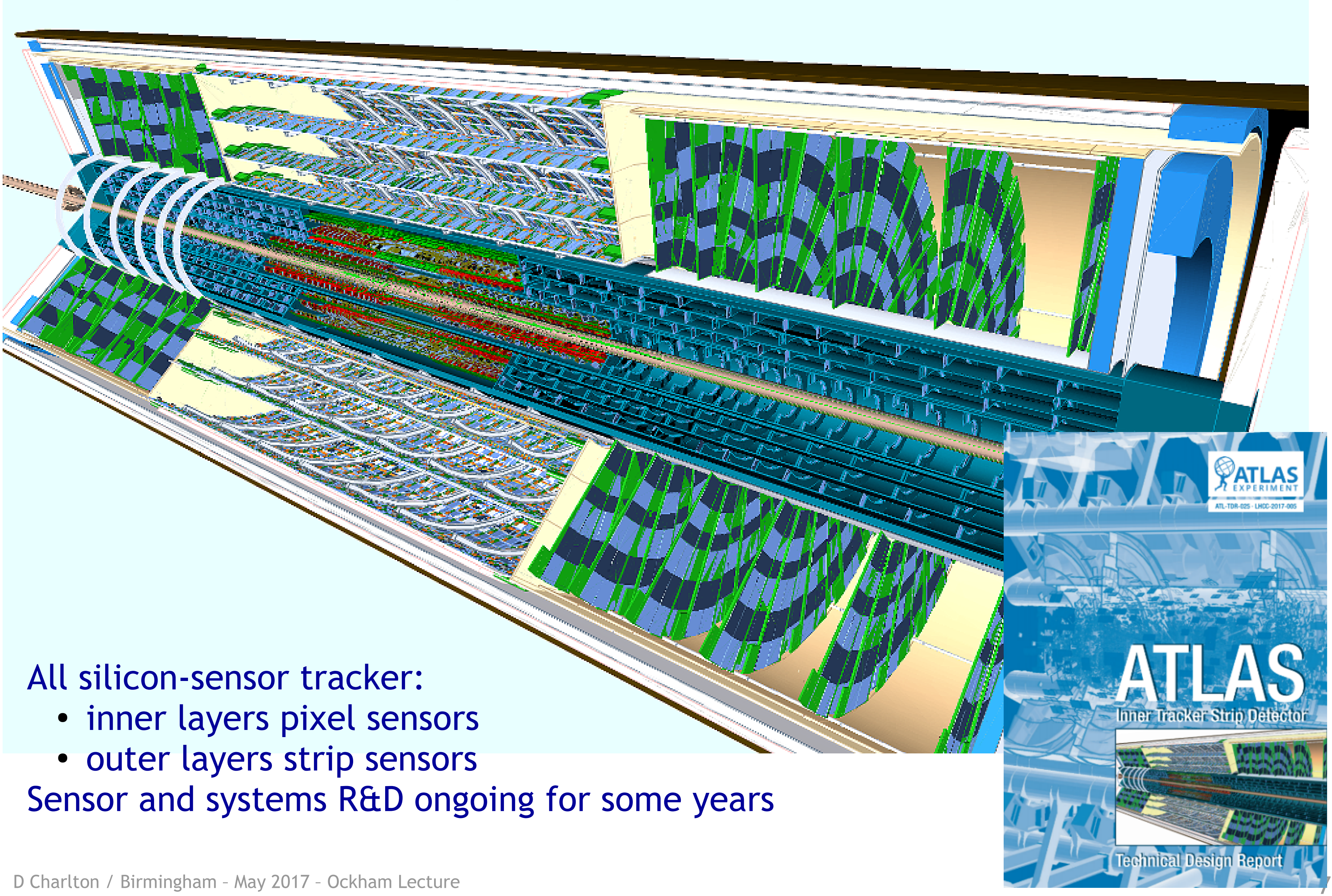
New muon chambers (inner layer RPC)

High-granularity timing detector option, in front of LAr at high-|η|

Major readout electronics rework (~all detectors)
New trigger/readout architecture

Total capital cost ~250 MCHF

Phase-II tracking detector: ITk



ATLAS EXPERIMENT

ATL-TDR-025 · LHCC-2017-005

ATLAS

Inner Tracker Strip Detector

Technical Design Report

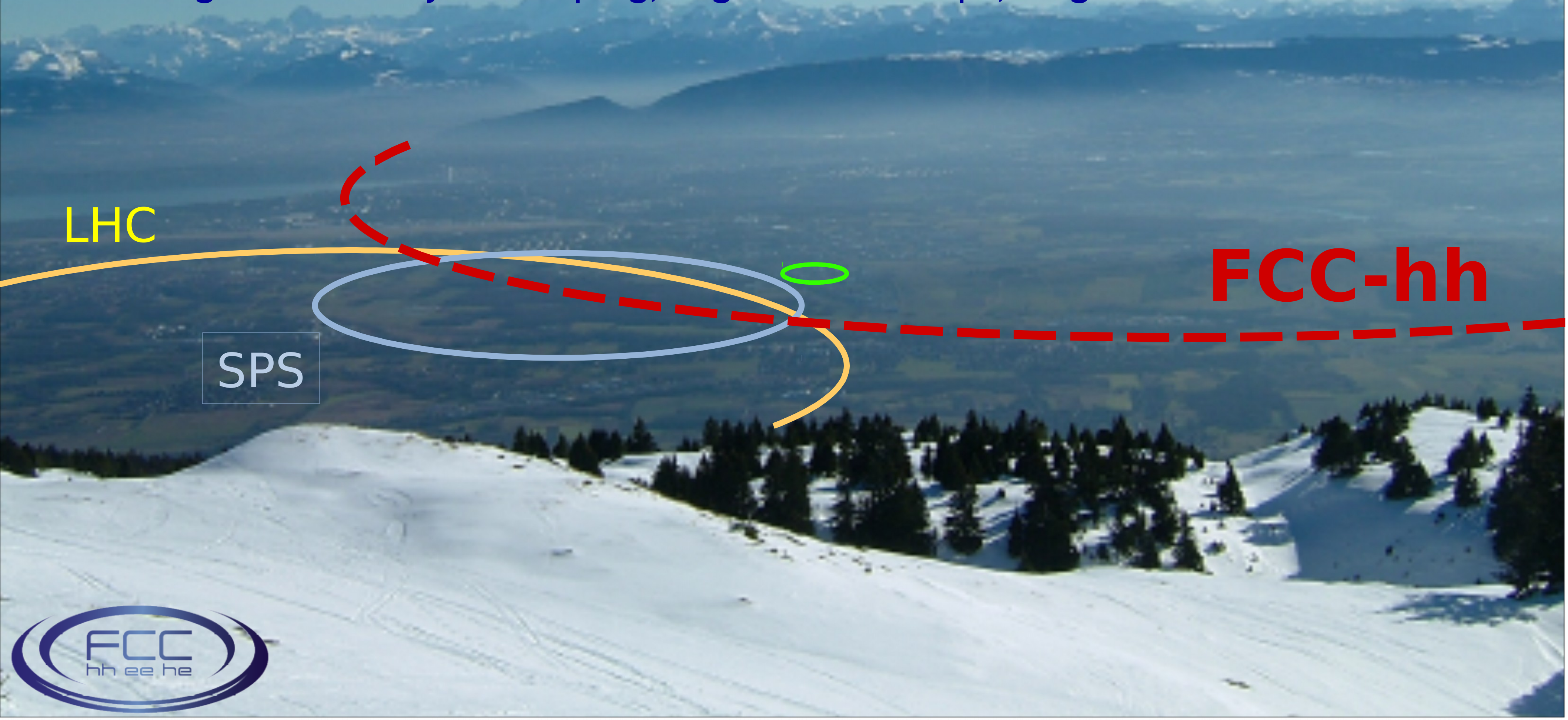
All silicon-sensor tracker:
- inner layers pixel sensors
- outer layers strip sensors

Sensor and systems R&D ongoing for some years

Beyond LHC: the FCC project

Concept for a 100 TeV pp collider in a new 100km tunnel around CERN & Geneva, with luminosity up to $3x10^{35}$ cm^{-2} s^{-1}

- direct new physics sensitivity to ~10 TeV scale, way beyond LHC
- additionally $e^{+}e^{-}$ and e-p options
- could start operation around 2040
- large community developing, regular workshops, large attendances



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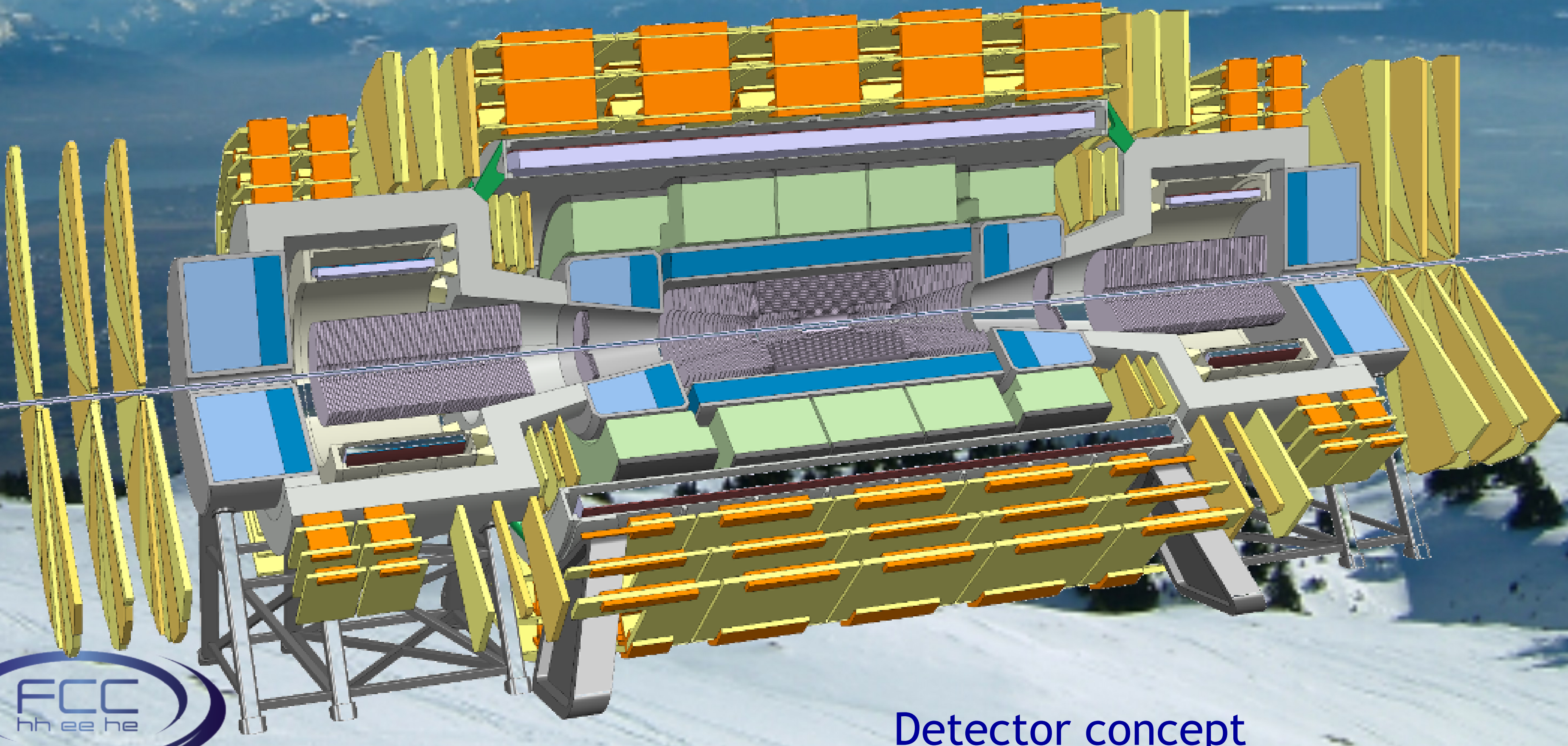
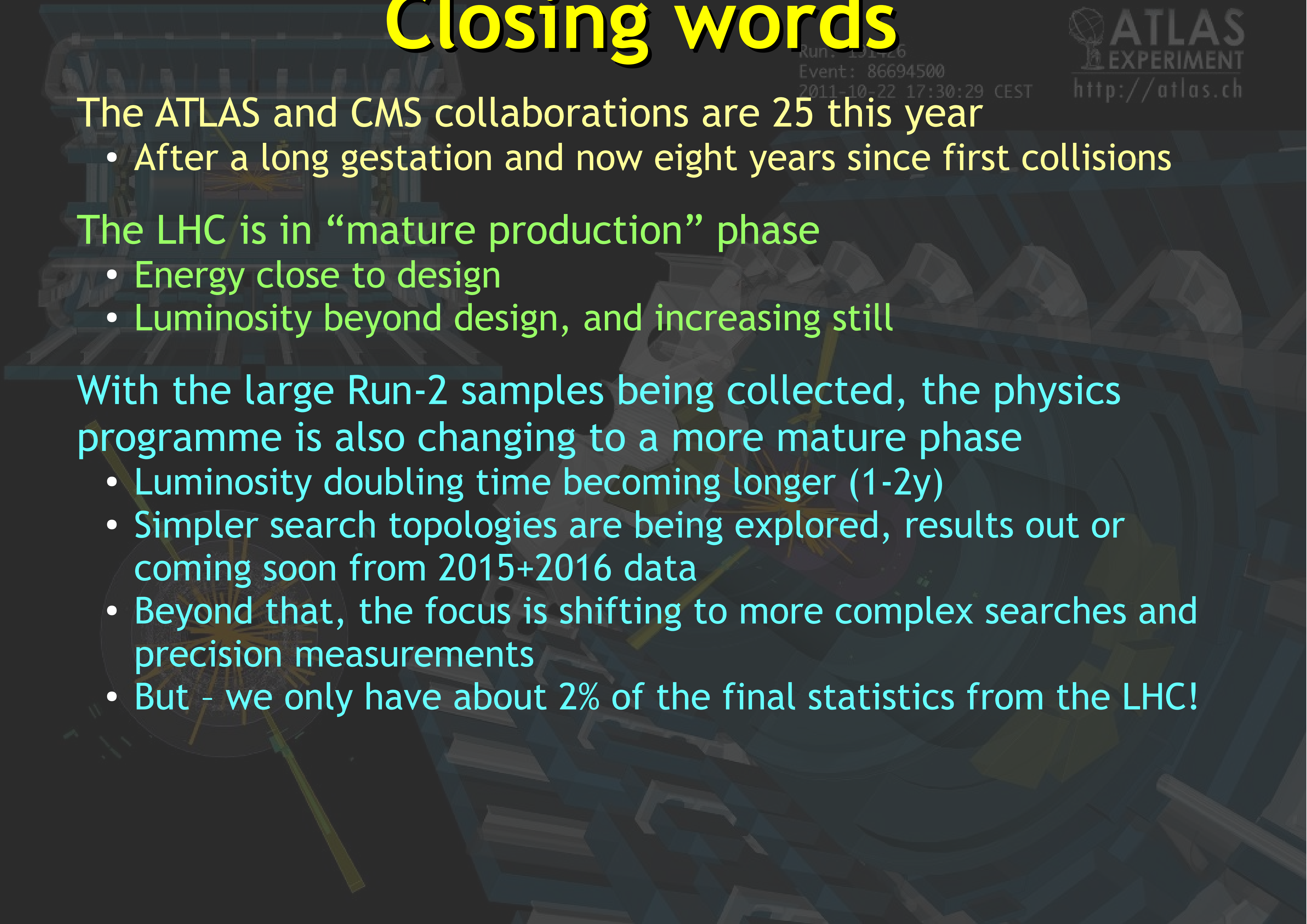


Detector concept

Closing words



The ATLAS and CMS collaborations are 25 this year

- After a long gestation and now eight years since first collisions

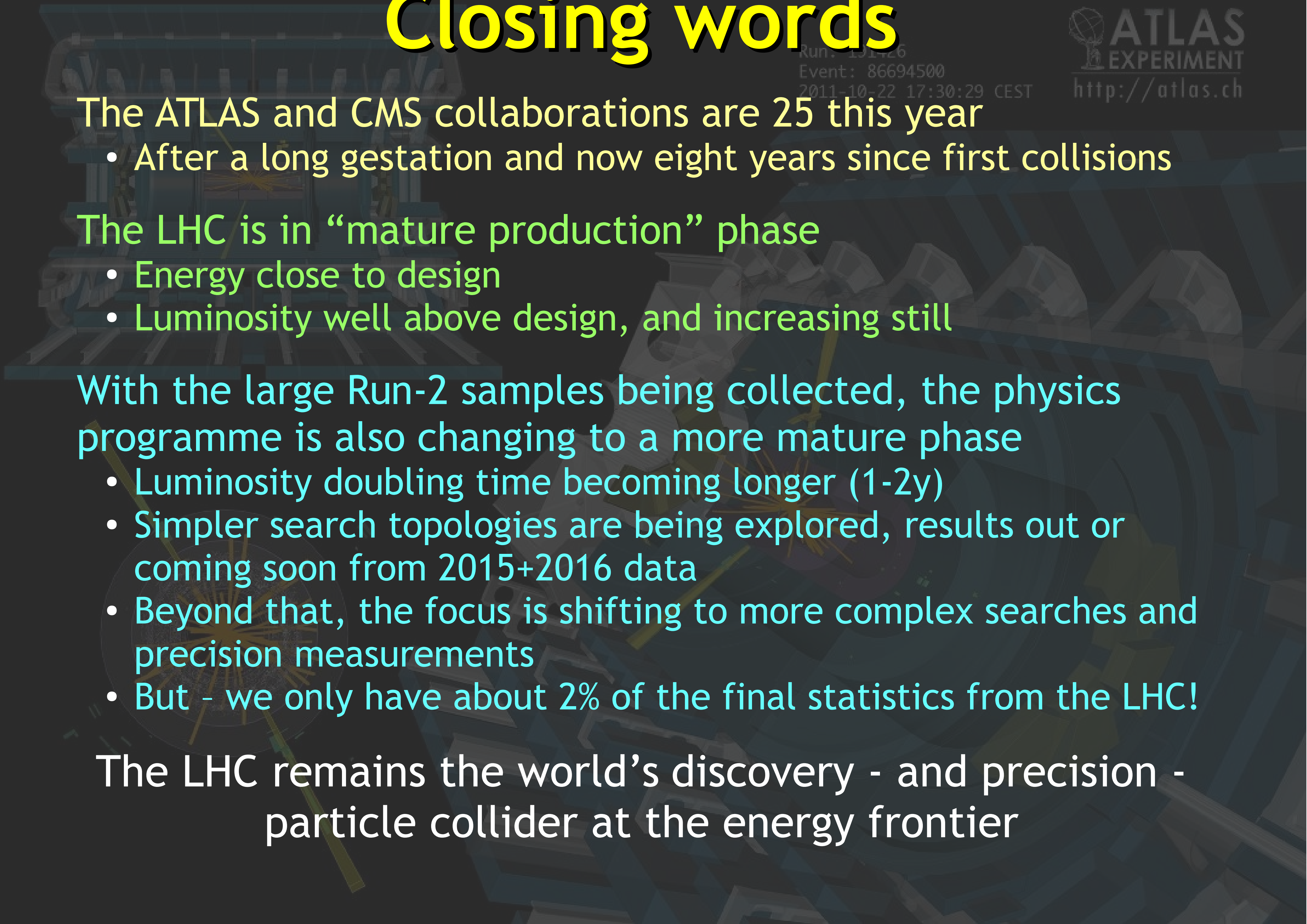
The LHC is in "mature production" phase

- Energy close to design
- Luminosity beyond design, and increasing still

With the large Run-2 samples being collected, the physics programme is also changing to a more mature phase

- Luminosity doubling time becoming longer (1-2y)
- Simpler search topologies are being explored, results out or coming soon from 2015+2016 data
- Beyond that, the focus is shifting to more complex searches and precision measurements
- But – we only have about 2% of the final statistics from the LHC!

Closing words



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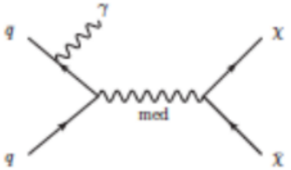
The LHC remains the world’s discovery - and precision - particle collider at the energy frontier

Dark matter search - Photon+p_T^{miss}

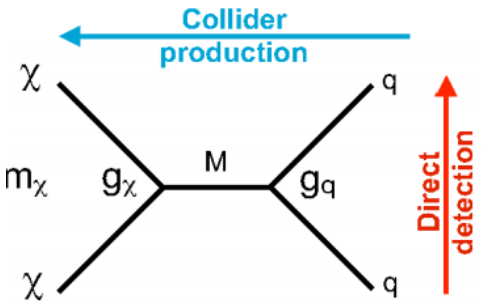
Many signatures in which one can search for dark matter production at LHC

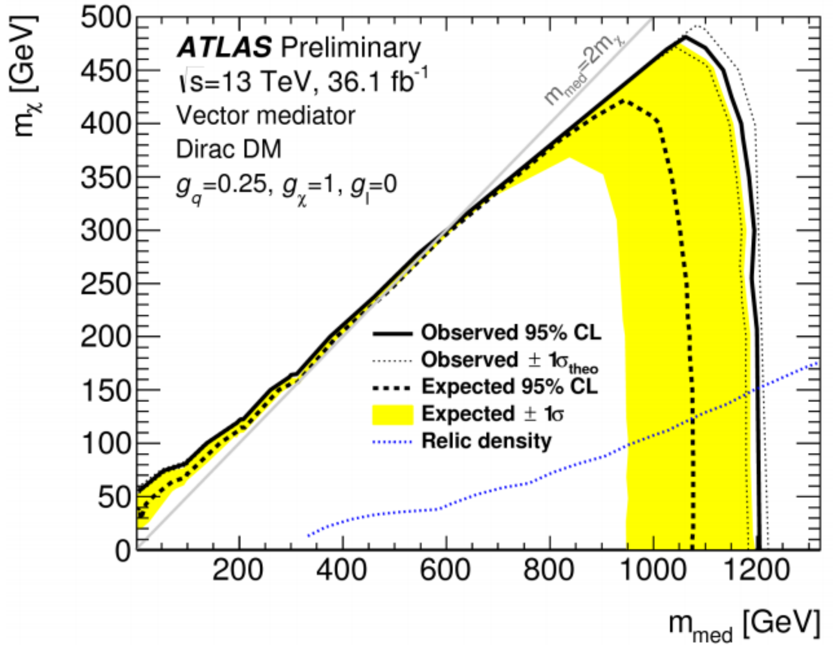
Many rely on producing it (and not observing it) with other particles → missing-momentum signature

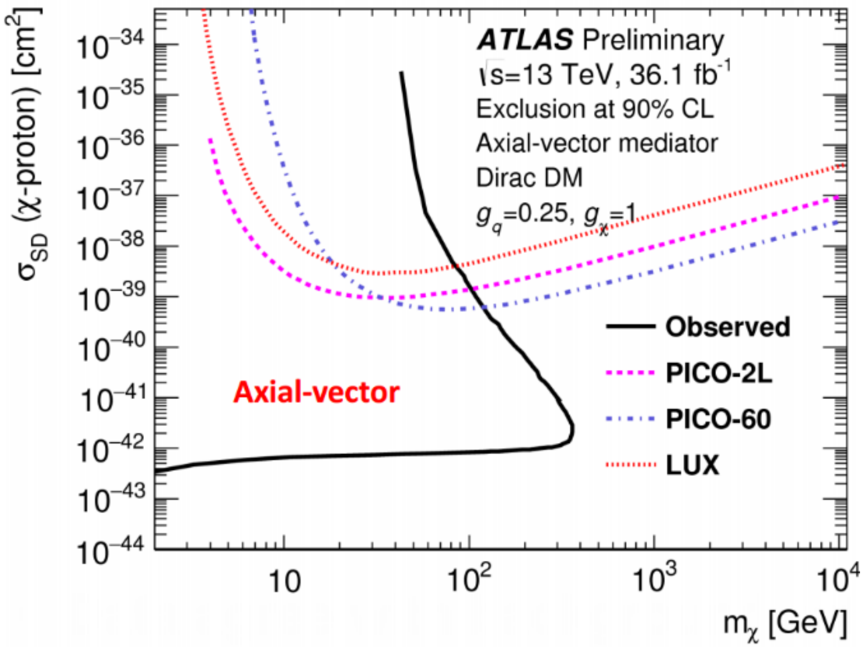
One example: γ+p_T^{miss}



Comparison with direct DM search experiments is model-dependent, but is possible in specific models







Dark matter searches