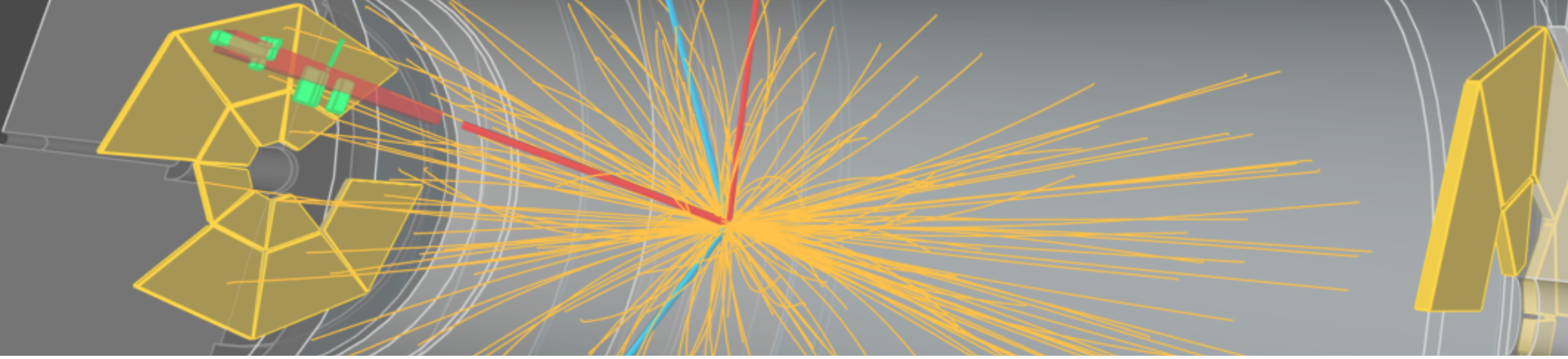


Status and Perspectives of LHC physics

Krisztian Peters
DESY

Matter and Universe Programmtage
12 December 2016, Mainz

ATLAS EXPERIMENT

DESY

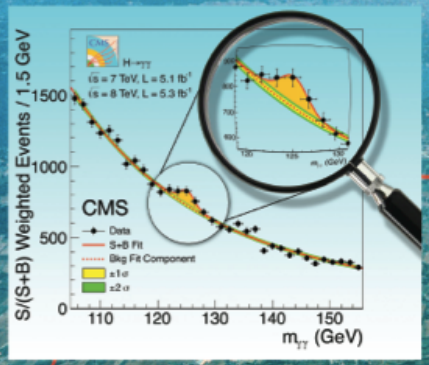
HELMHOLTZ ASSOCIATION

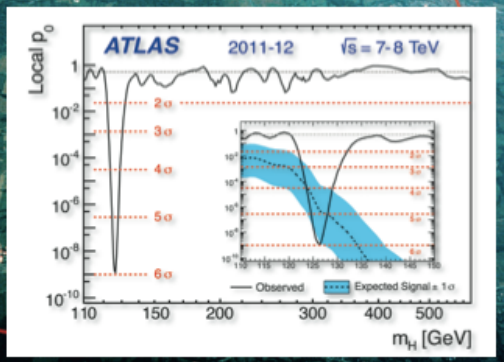
CMS

Volume 716, Issue 1, 17 September 2012 ISSN 0370-2693

ELSEVIER

PHYSICS LETTERS B





http://www.elsevier.com/locate/physletb

Origin of mass?

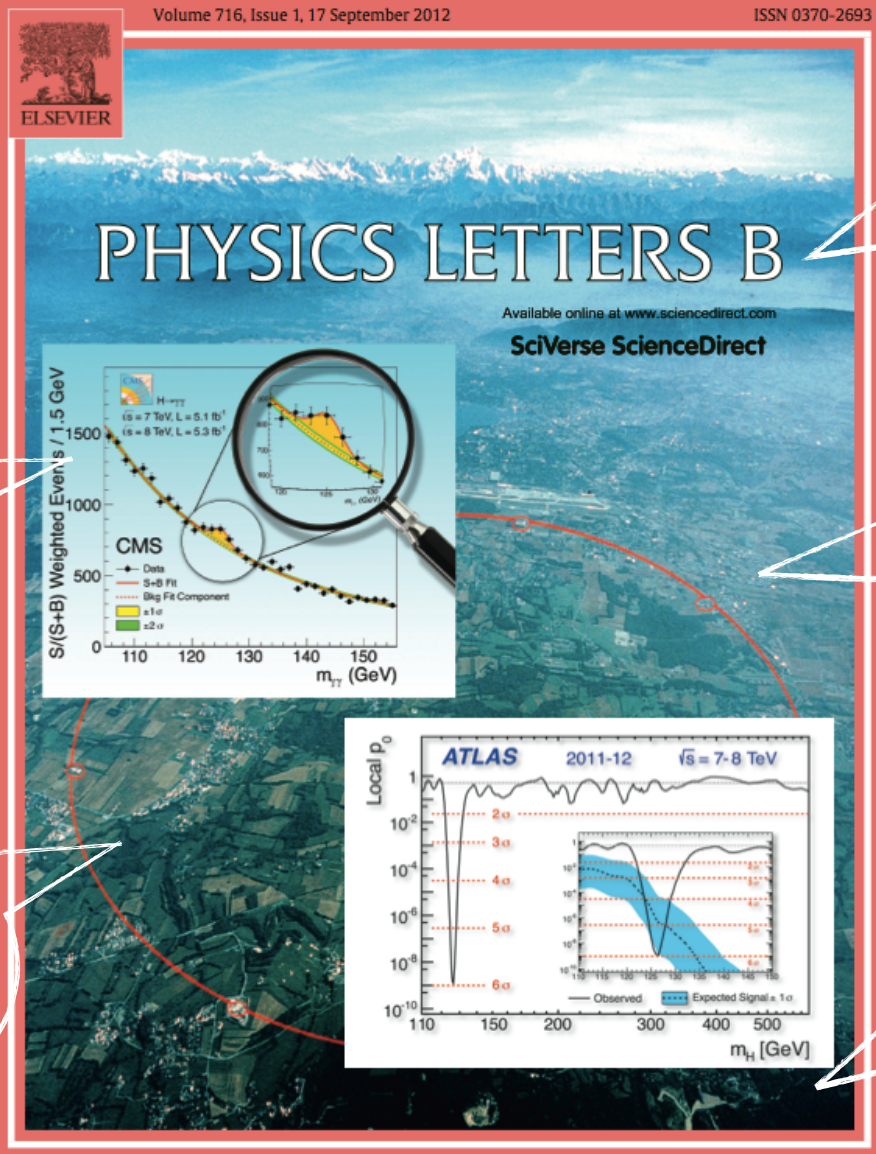
Structure of the vacuum?

Matter and anti-matter imbalance?

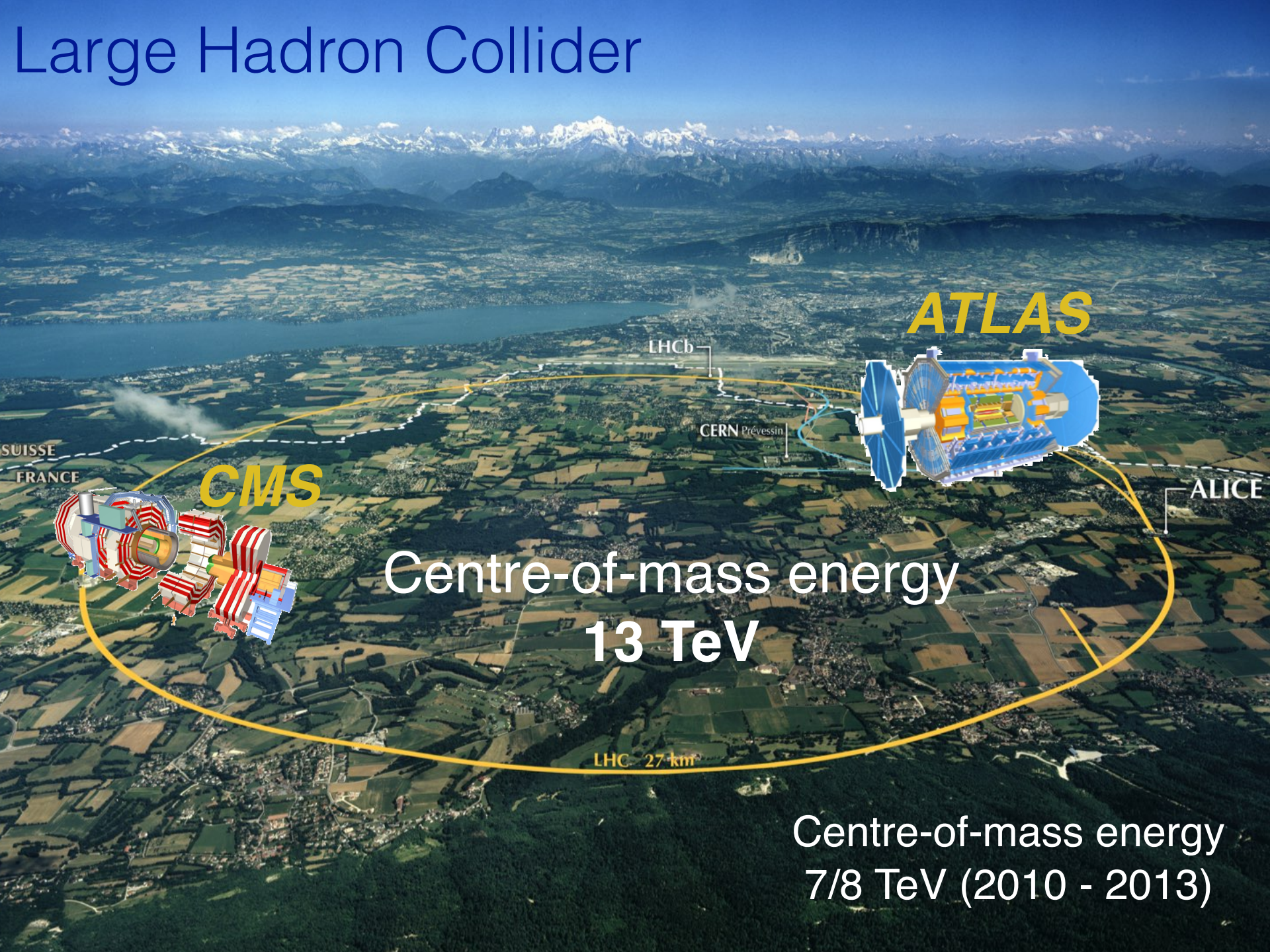
Nature of dark matter?

Hierarchy between the Planck and the weak scale?

...

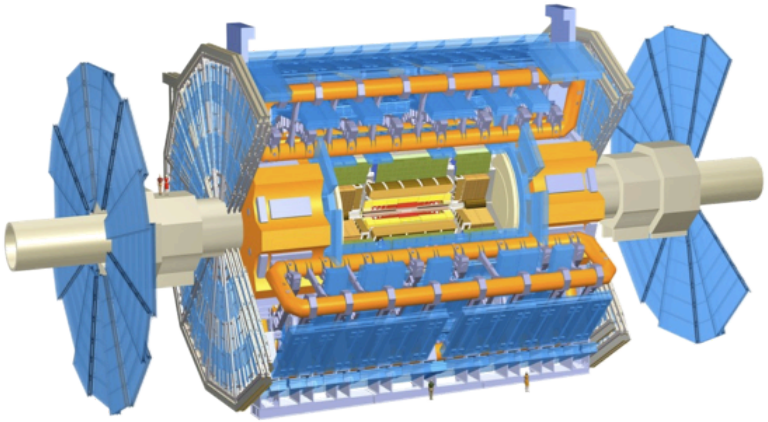


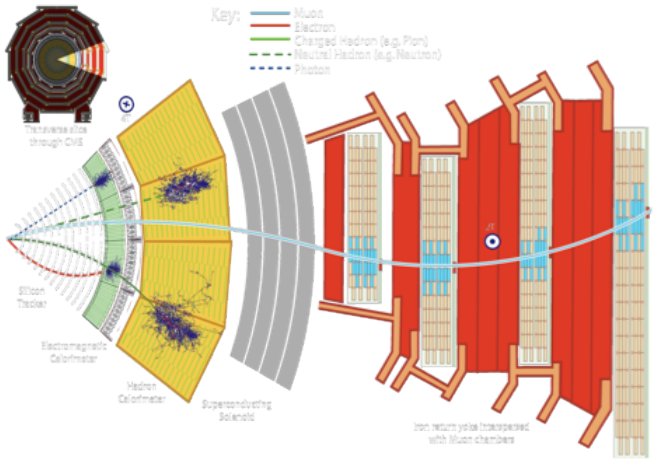
Large Hadron Collider



Centre-of-mass energy
7/8 TeV (2010 - 2013)

ATLAS and *CMS* experiments



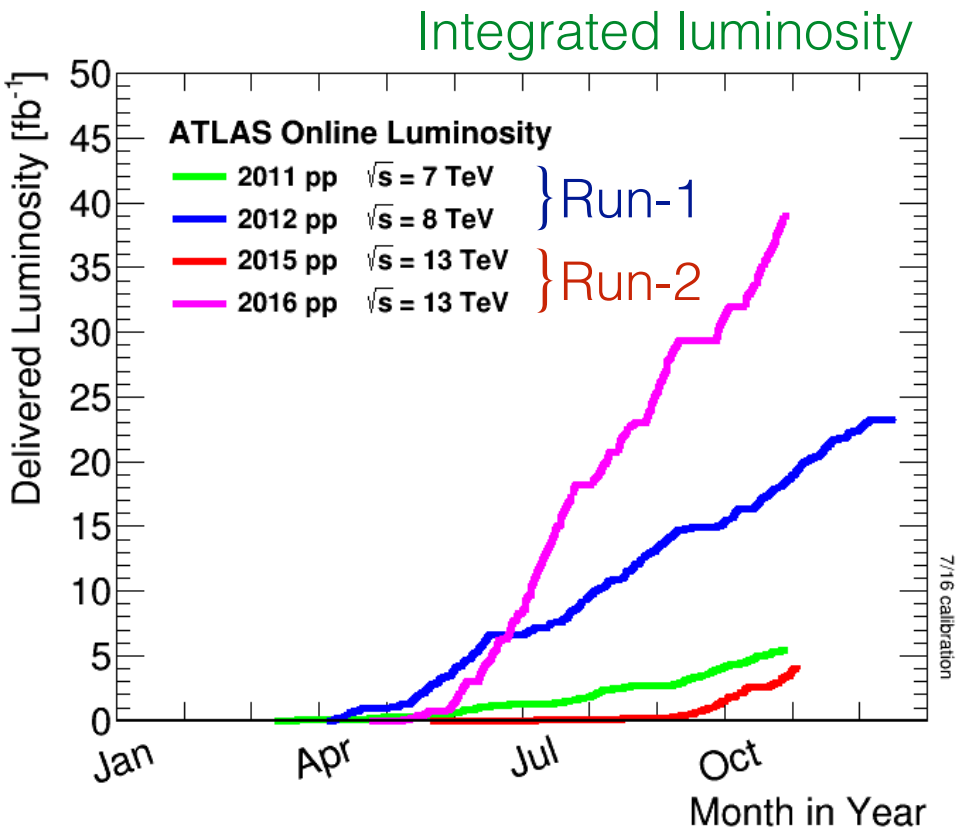


ATLAS: emphasis on excellent jet and missing E_T resolution, particle identification, and standalone muon measurement

CMS: emphasis on excellent electron/photon and tracking (muon) resolution

Detectors well understood, stable operation and data taking efficiencies above 90%

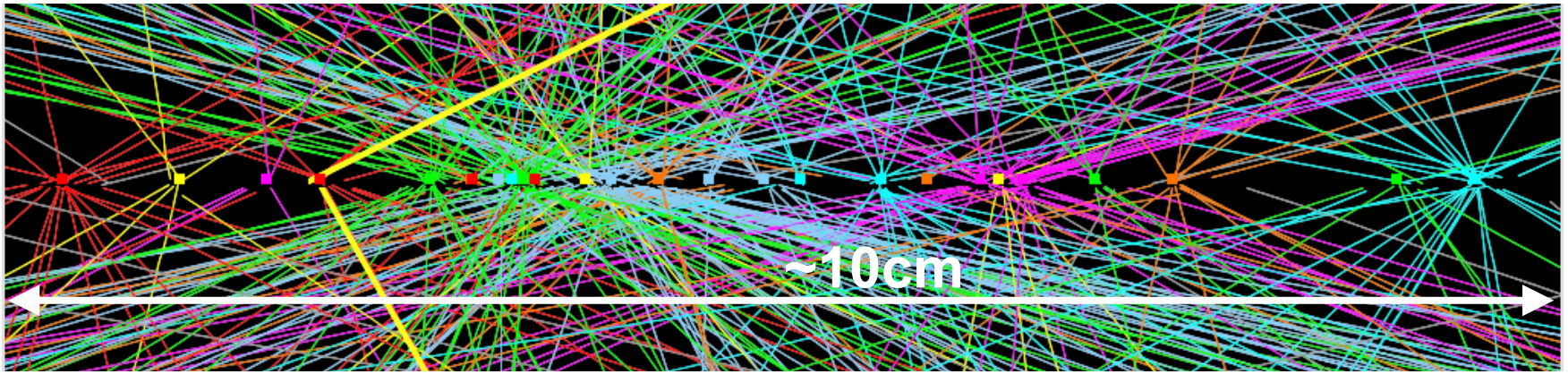
Data samples



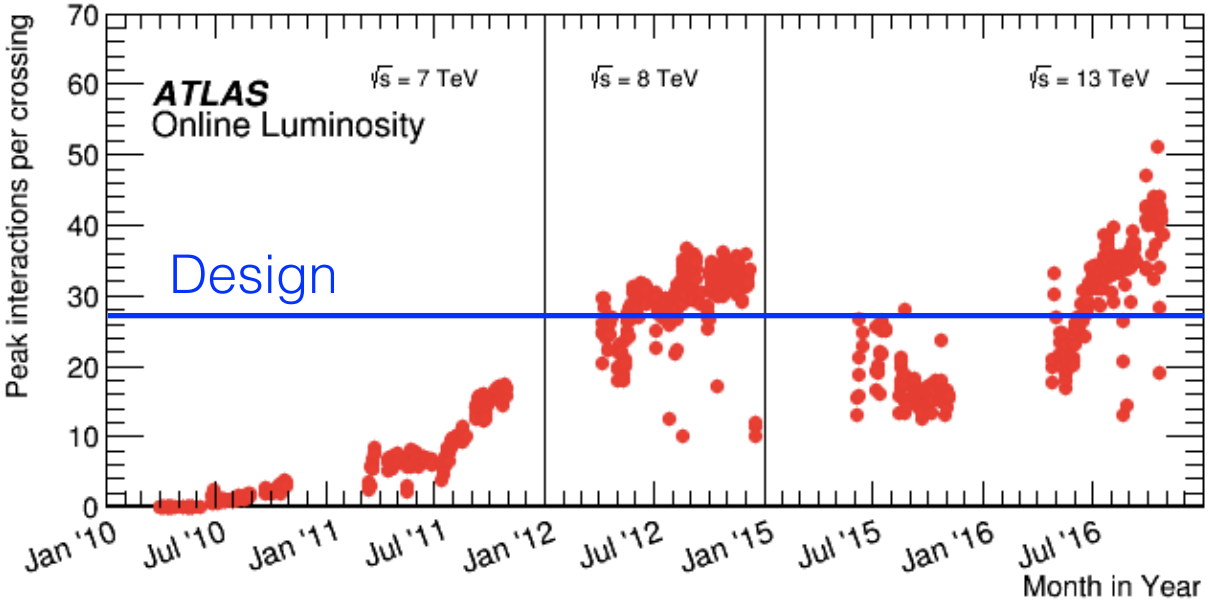
Record breaking LHC performance in 2016

- 30% higher machine availability
- Instantaneous luminosity exceeds design value

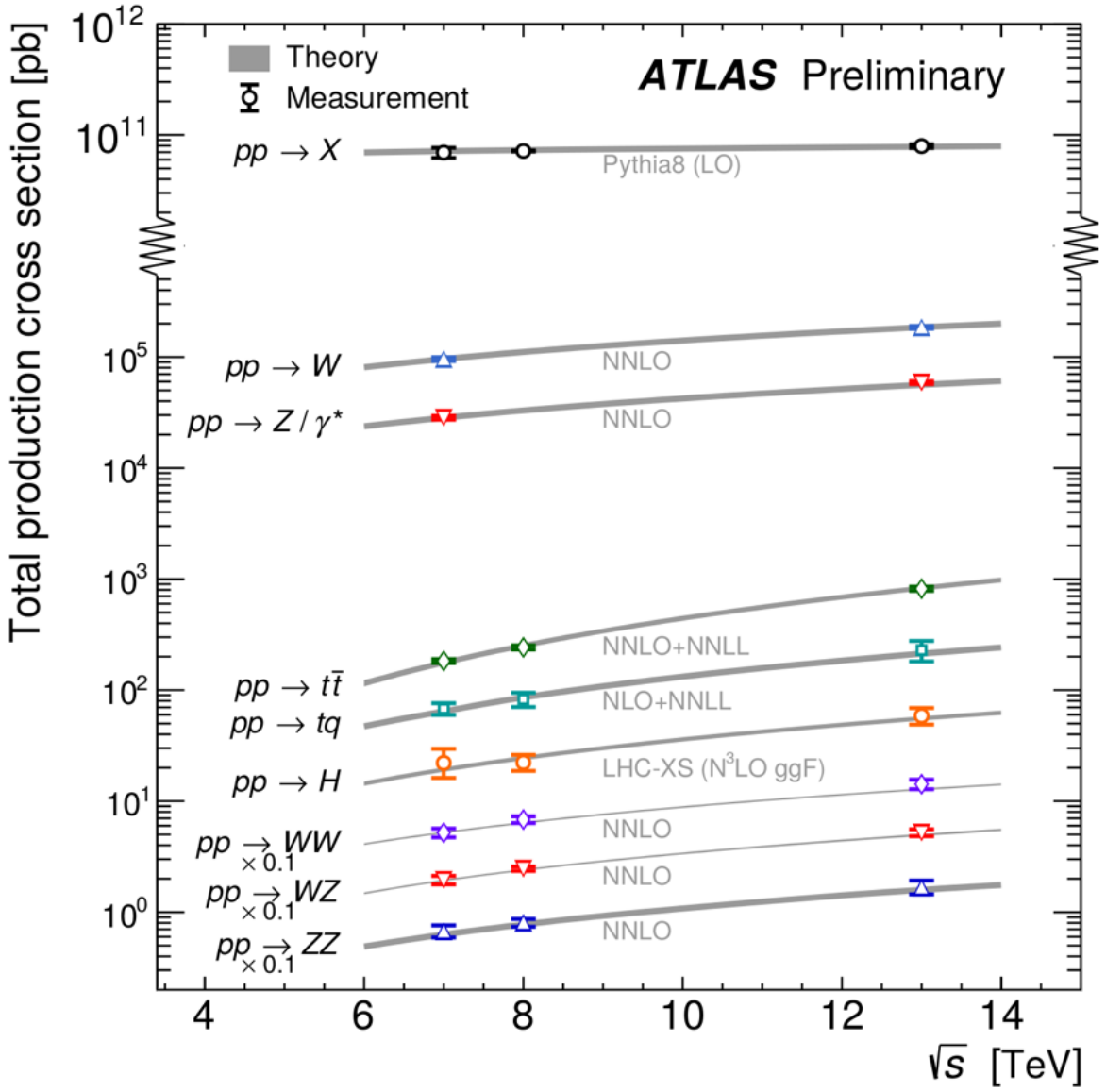
Experimental challenges



Peak interactions per bunch crossing

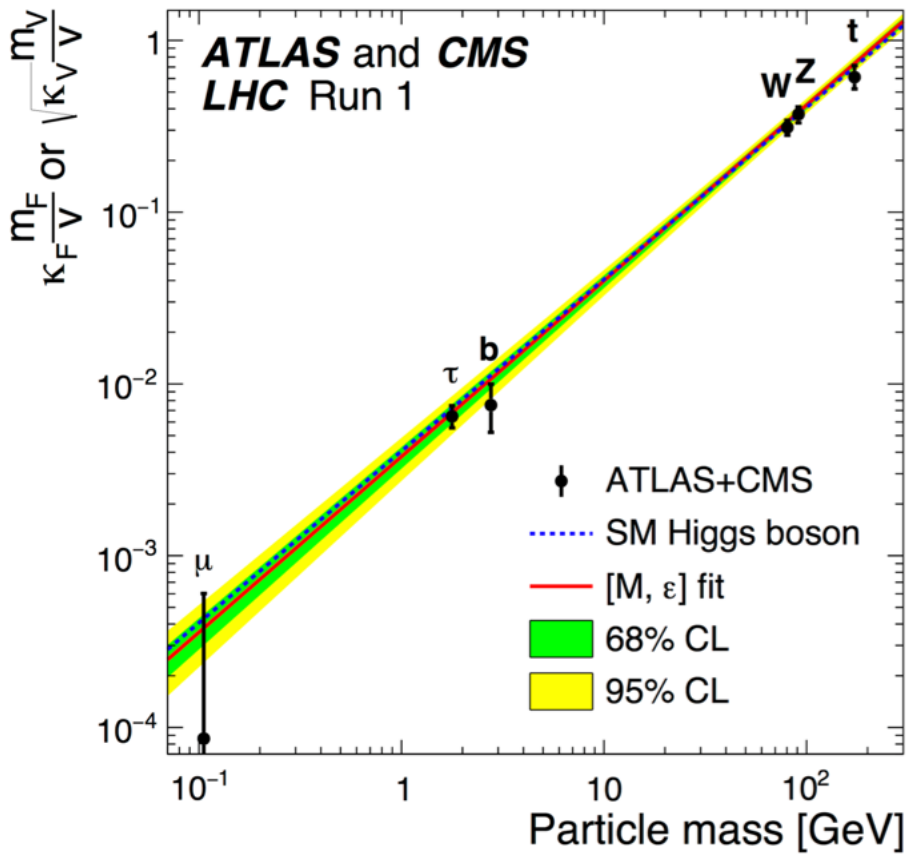


Precision measurements



The Higgs boson

Breathtaking progress in *O(2)* years



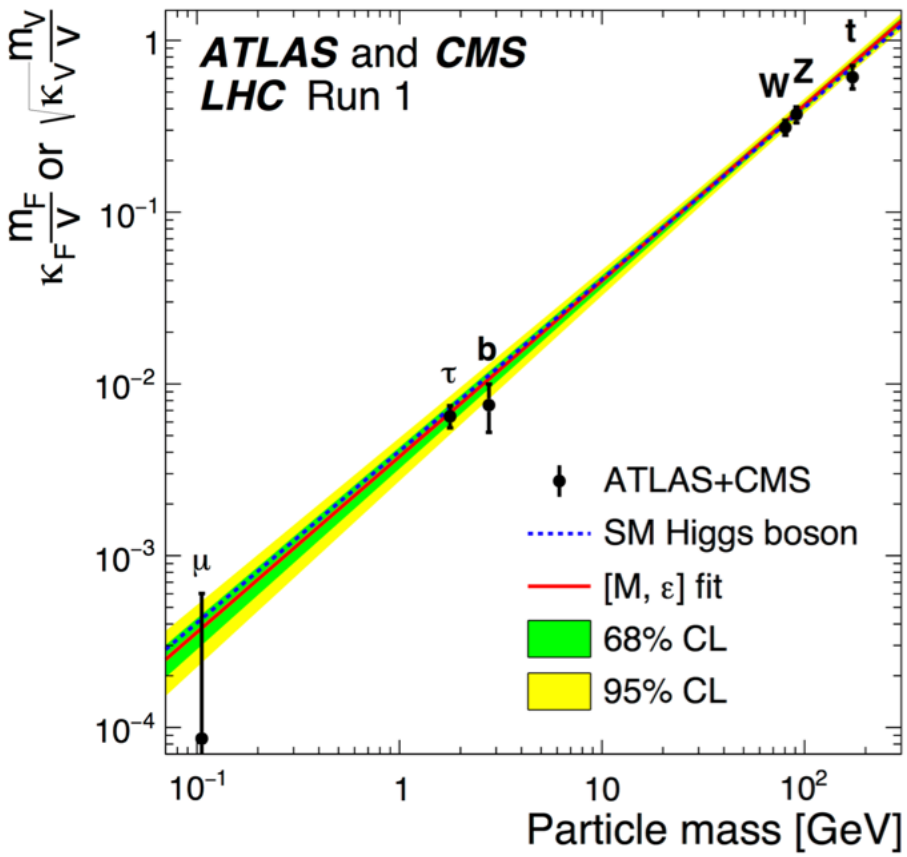
Higgs boson mass measured with 0.2% precision

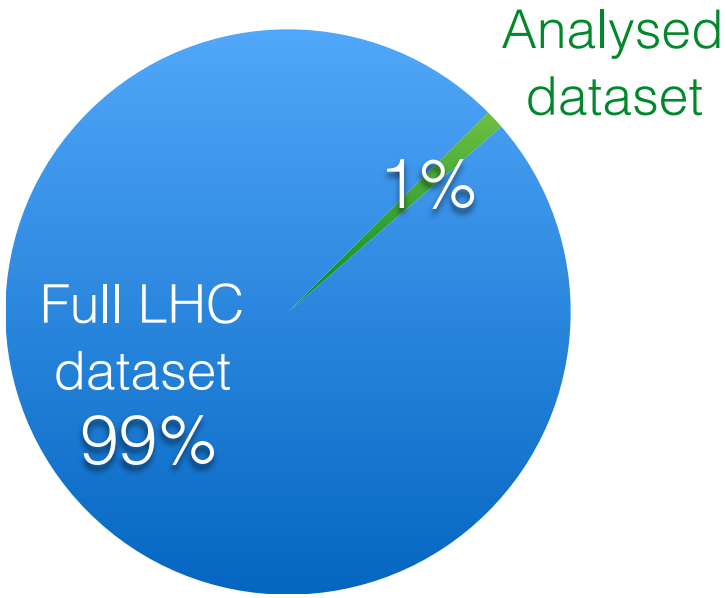
W/Z couplings measured with 10 to 20% precision

A plot for textbooks!

The Higgs boson

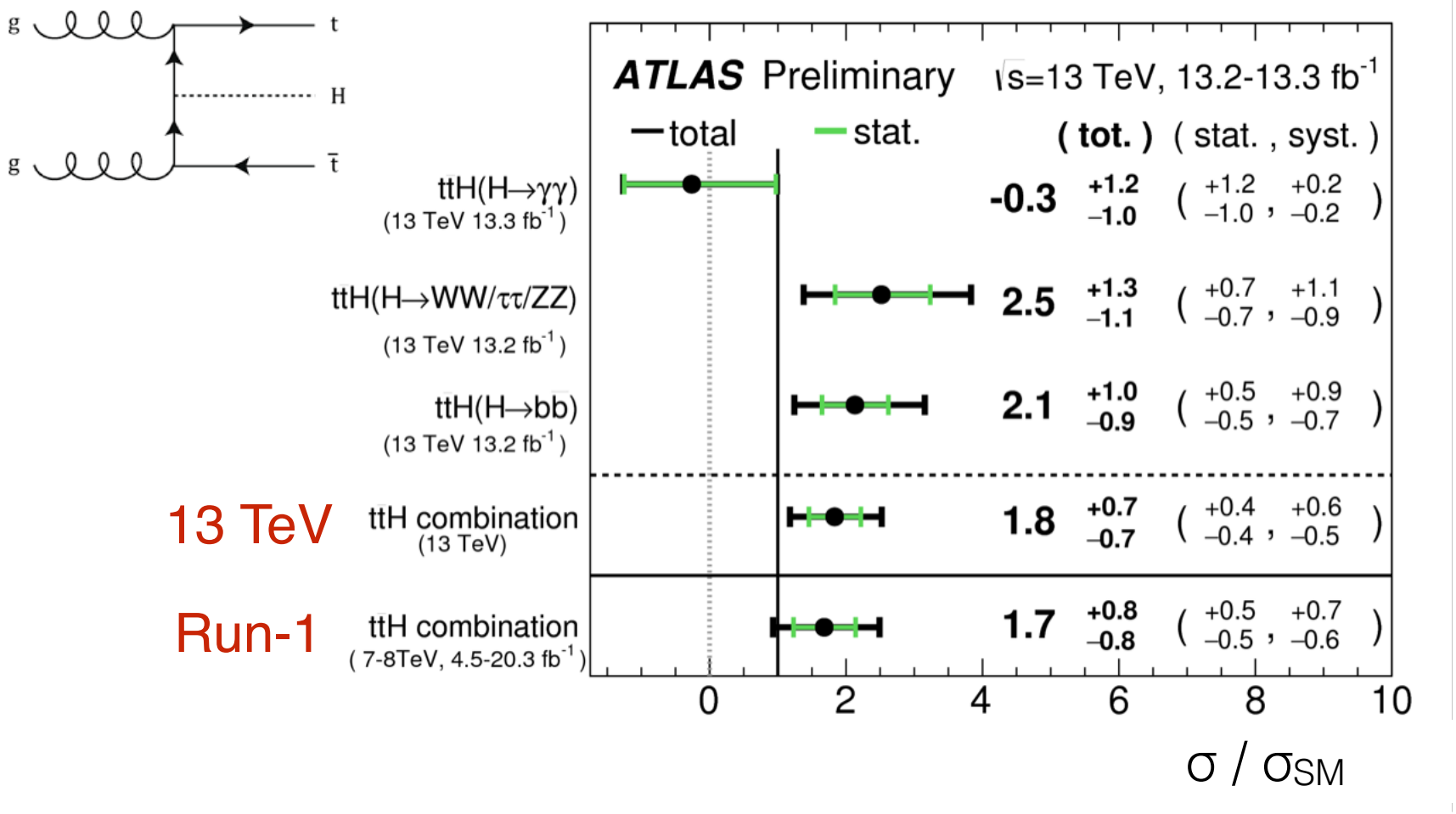
Breathtaking progress in *O(2)* years



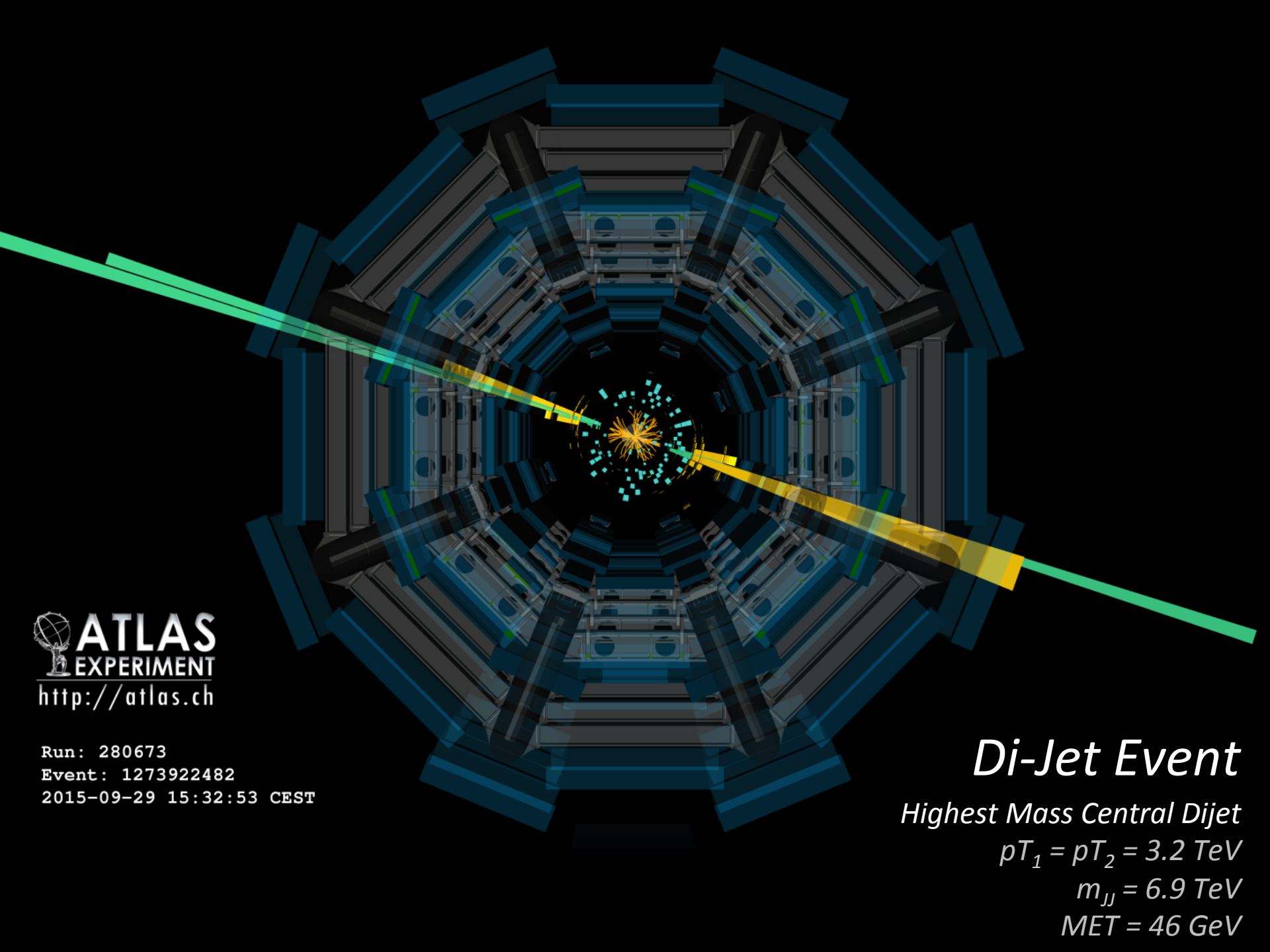


A plot for textbooks!

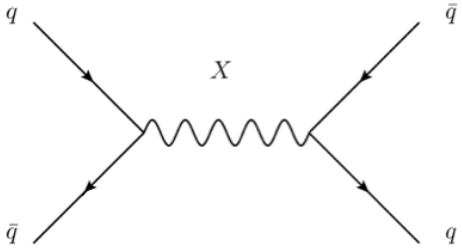
Top-Yukawa coupling

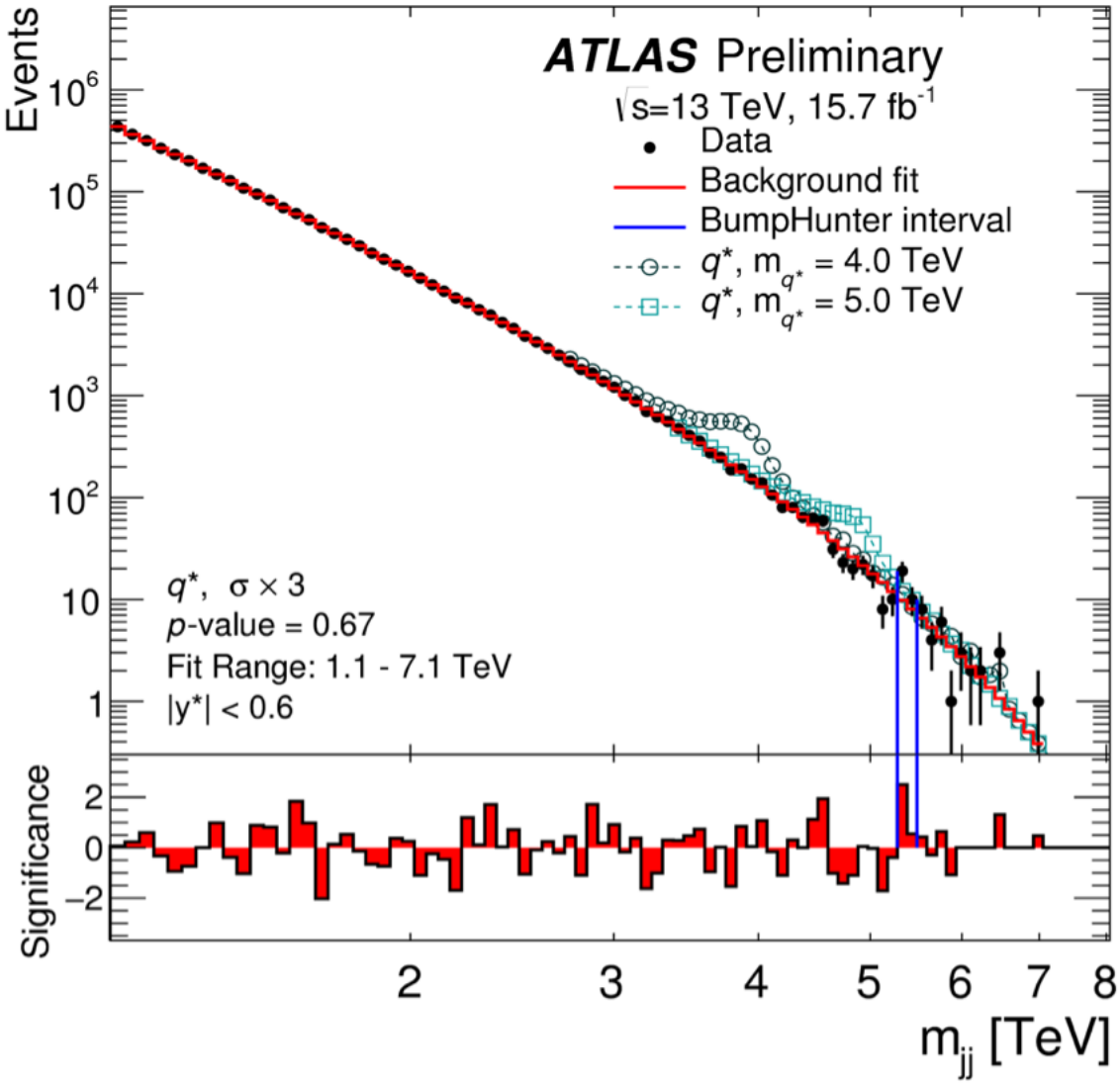


Uncertainties still large, no clear picture yet


ATLAS
EXPERIMENT
http://atlas.ch
Run: 280673
Event: 1273922482
2015-09-29 15:32:53 CEST
Di-Jet Event
Highest Mass Central Dijet
$pT_1 = pT_2 = 3.2$ TeV
$m_{JJ} = 6.9$ TeV
MET = 46 GeV

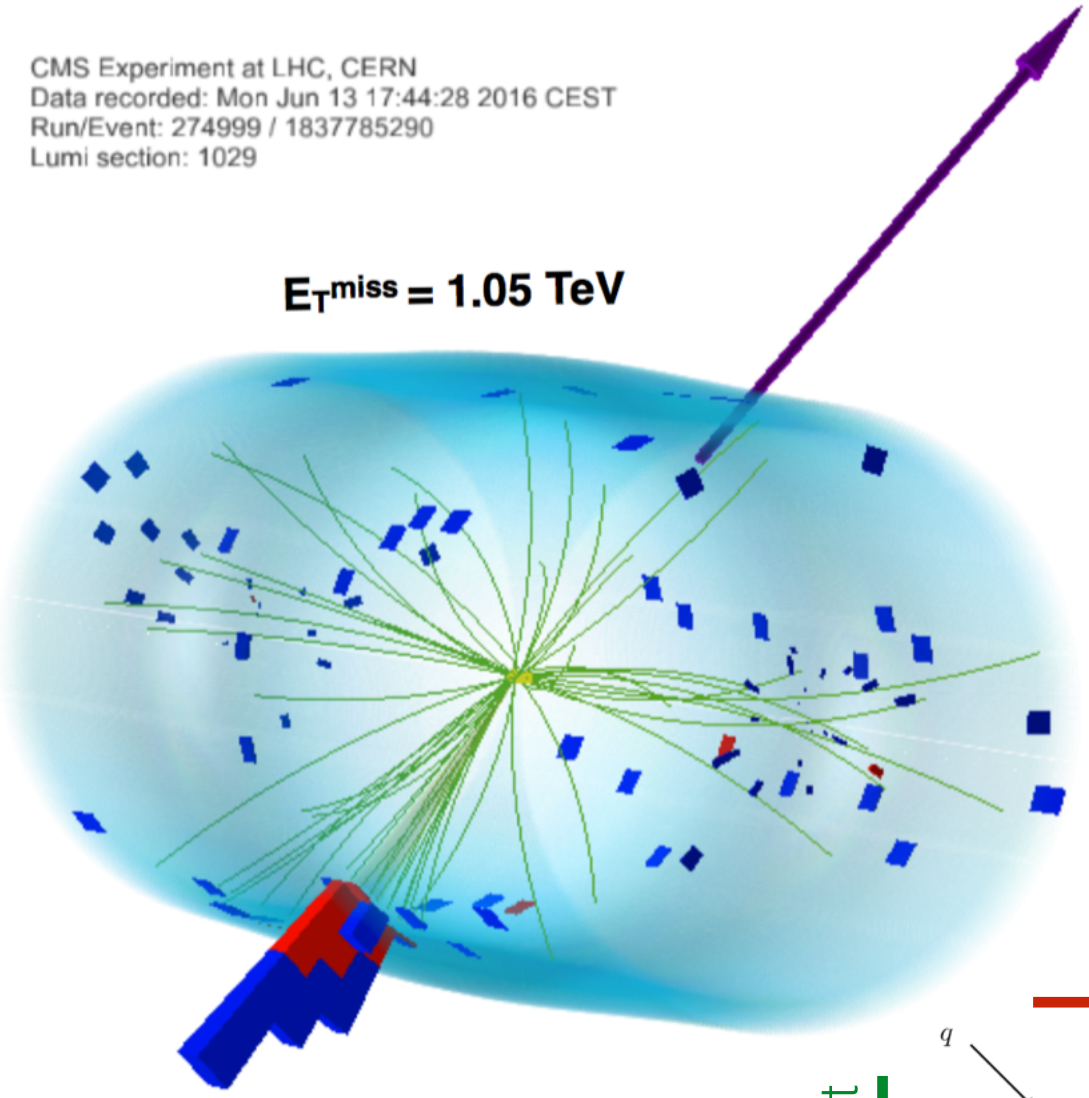
Search for new resonances





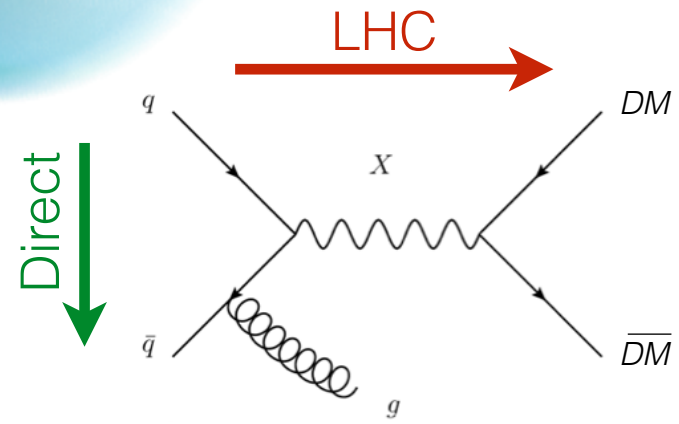
CMS Experiment at LHC, CERN
Data recorded: Mon Jun 13 17:44:28 2016 CEST
Run/Event: 274999 / 1837785290
Lumi section: 1029

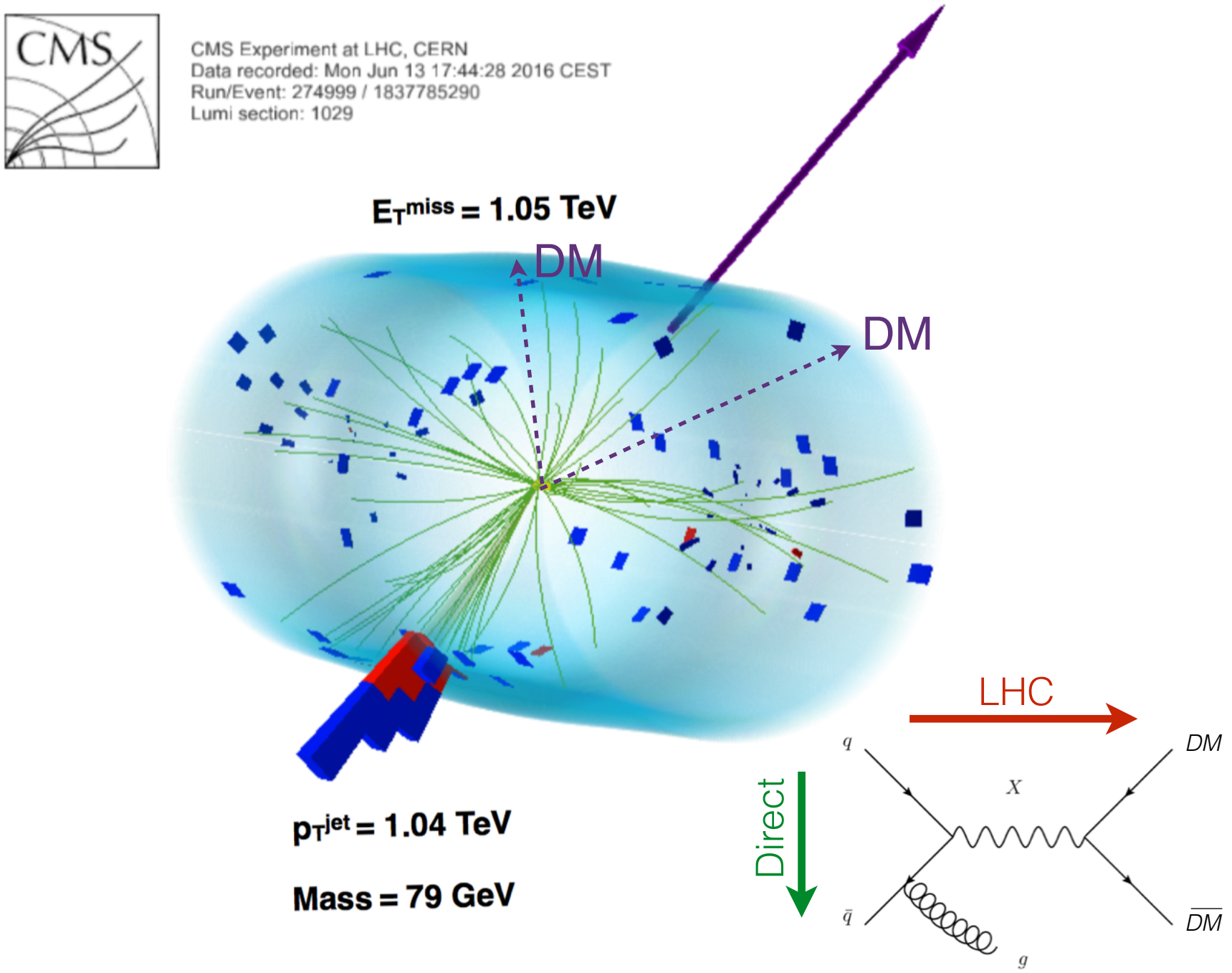
E_T^{miss} = 1.05 TeV



p_T^{jet} = 1.04 TeV

Mass = 79 GeV




CMS
CMS Experiment at LHC, CERN
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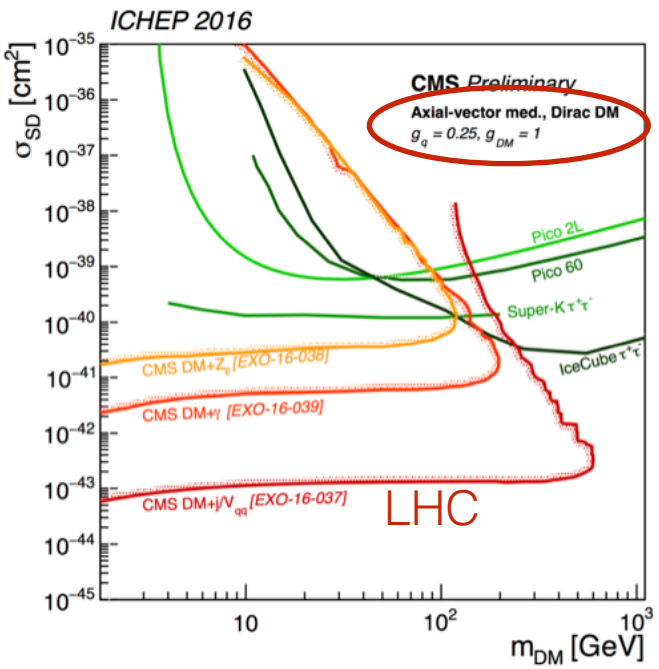
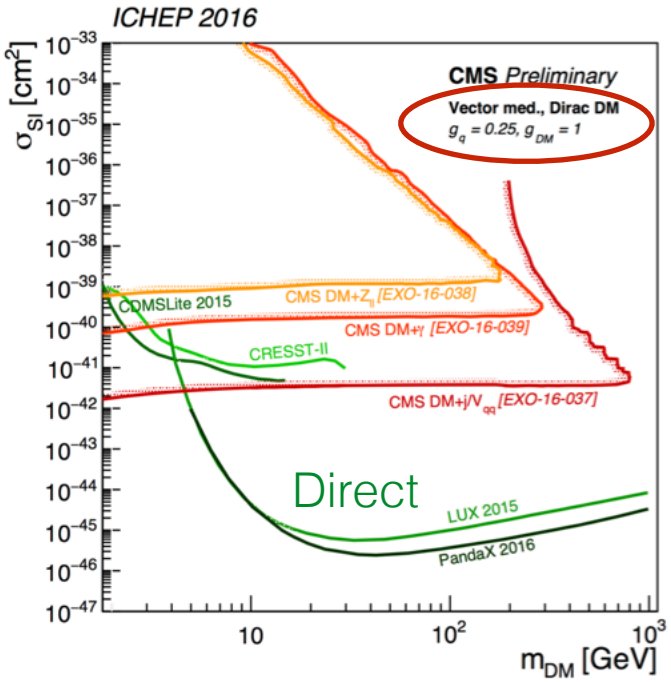
E_T^{miss} = 1.05 TeV
DM
DM
p_T^{jet} = 1.04 TeV
Mass = 79 GeV
LHC
Direct
q
$\bar{q}$
X
DM
$\overline{DM}$
g

Dark matter at the LHC

DM-nucleon scattering cross section

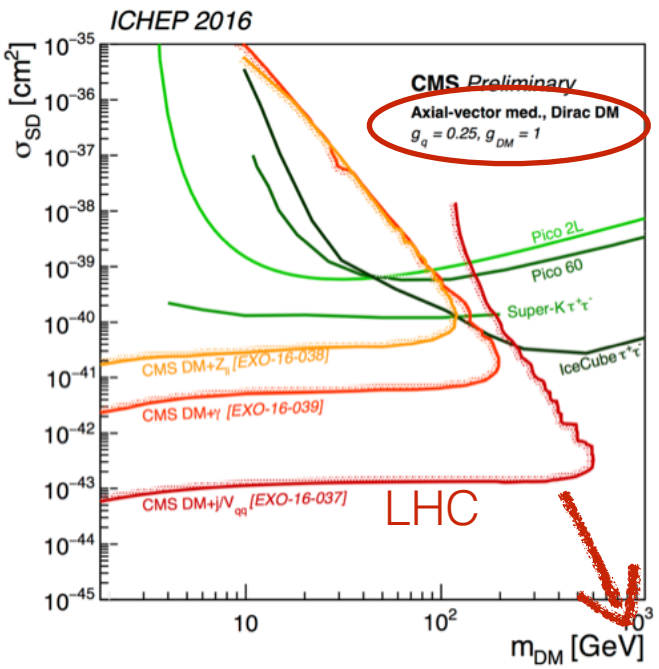


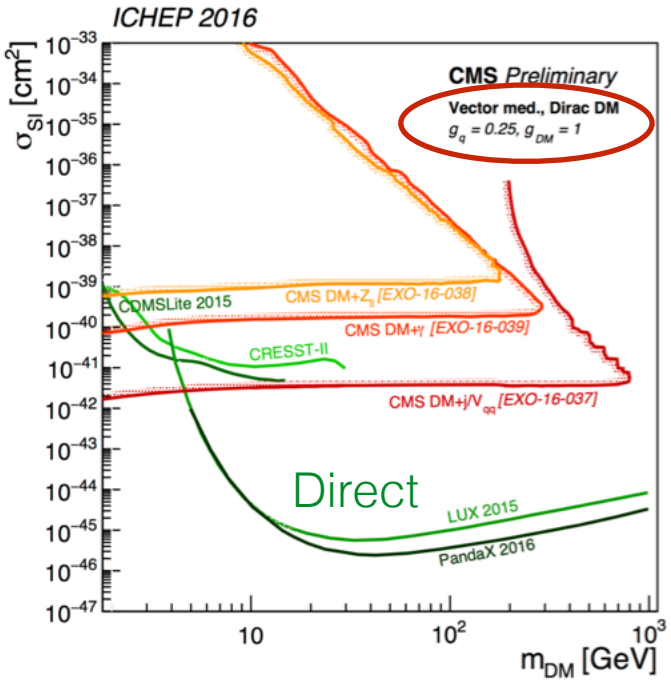


Complementary sensitivity to direct dark matter detection experiments

Dark matter at the LHC

DM-nucleon scattering cross section

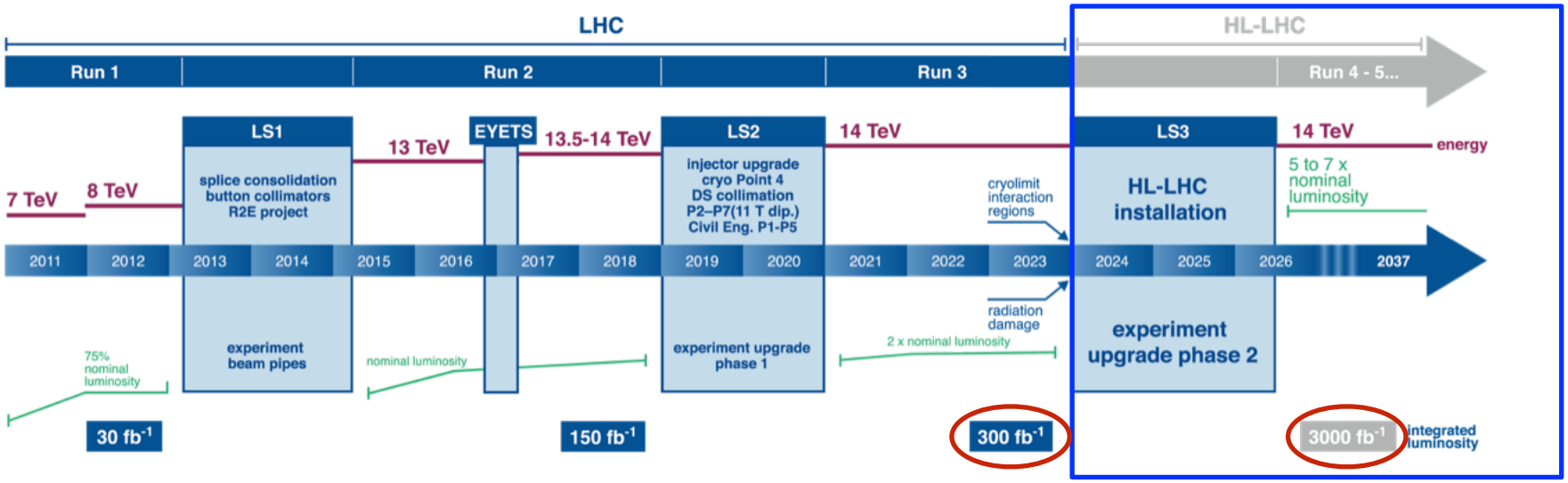




Complementary sensitivity to direct dark matter detection experiments

Towards the High Luminosity LHC

Upgrade LHC and detectors to accumulate a data sample of 3 ab^{-1} over a 10 year run period

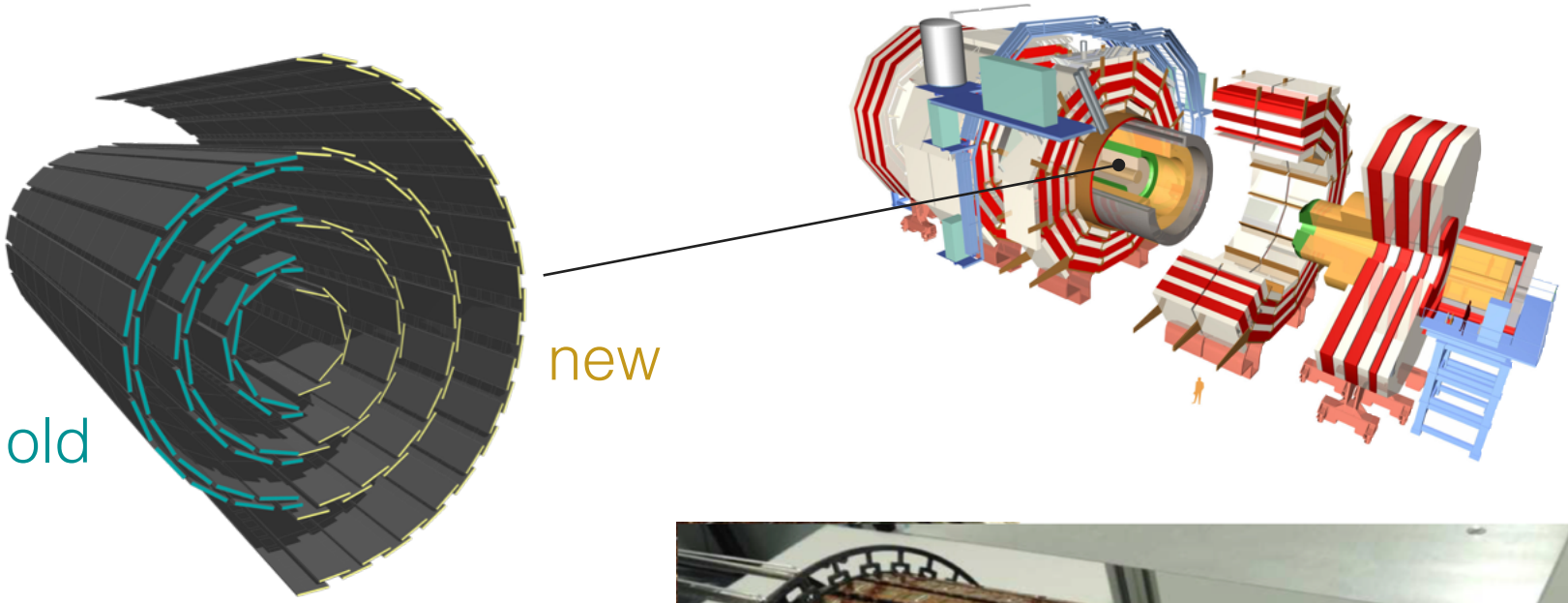


Go to design energy, nominal luminosity
$L = 10^{34}\ cm^{-2}s^{-2}$

Phase-1 upgrade to design luminosity
$L = 2*10^{34}\ cm^{-2}s^{-2}$
$\mu = 55$

Phase-2 upgrade
$L = 5\ (7.5) *10^{35}\ cm^{-2}s^{-2}$
$\mu = 140\ (200)$

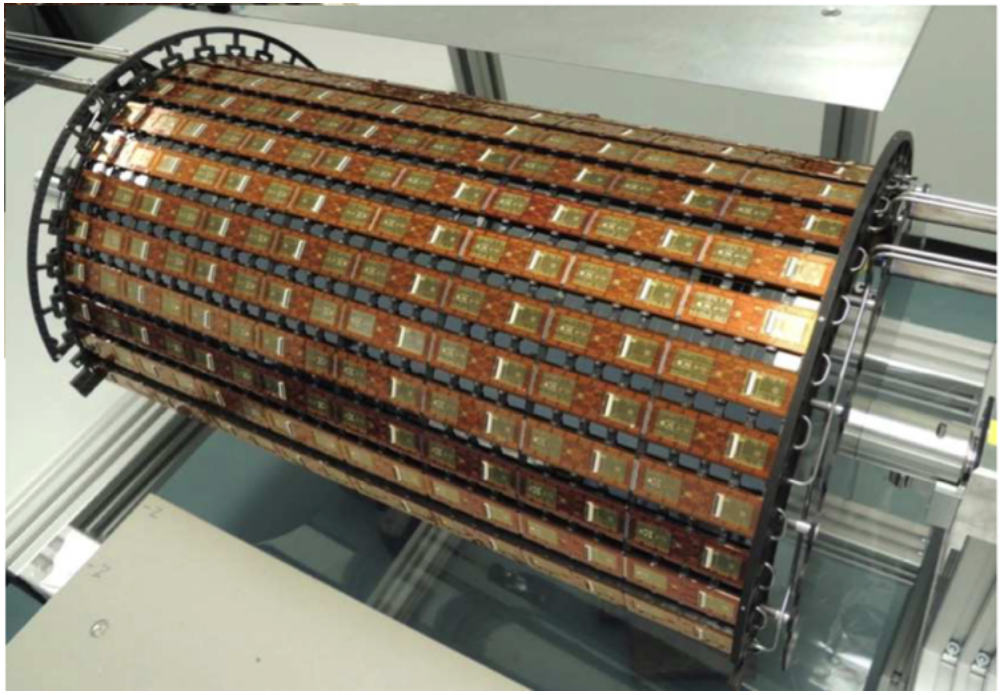
CMS Phase-1 upgrade



Outer layer of new pixel detector built by German institutes

- 512+ modules out of 12k

Installation beginning of 2017

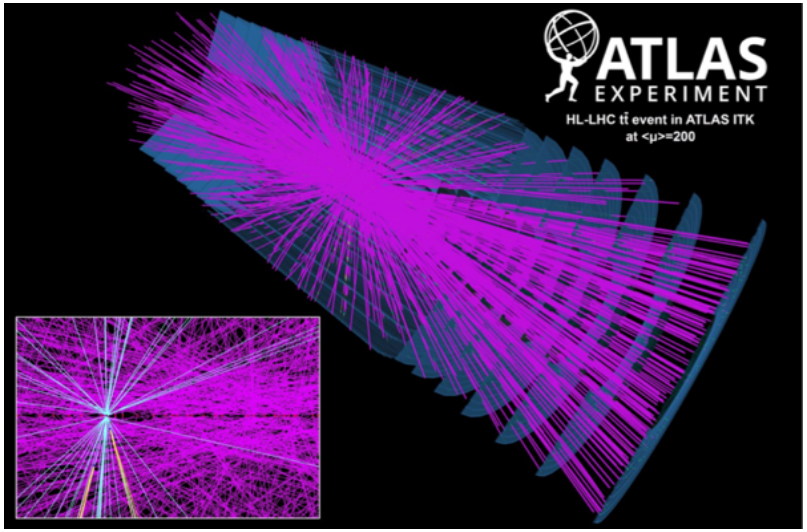


The need for new detectors

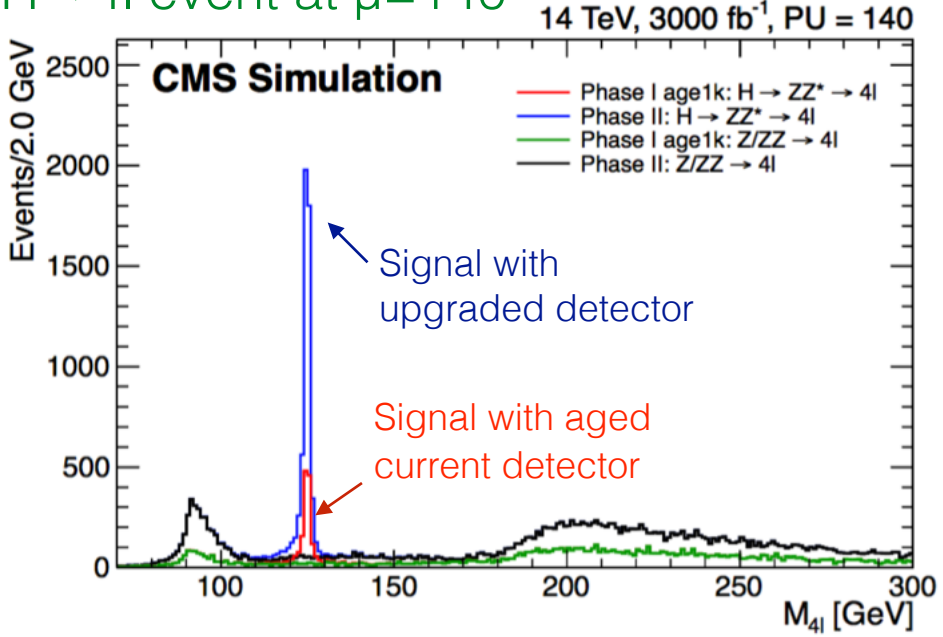
ATLAS and *CMS* designed for μ = 23. Major upgrades mandatory for the HL-LHC

- Cope with the huge pileup interactions and radiation damage
- Maintain similar levels of performance as of today

HL-LHC tt event at μ=200



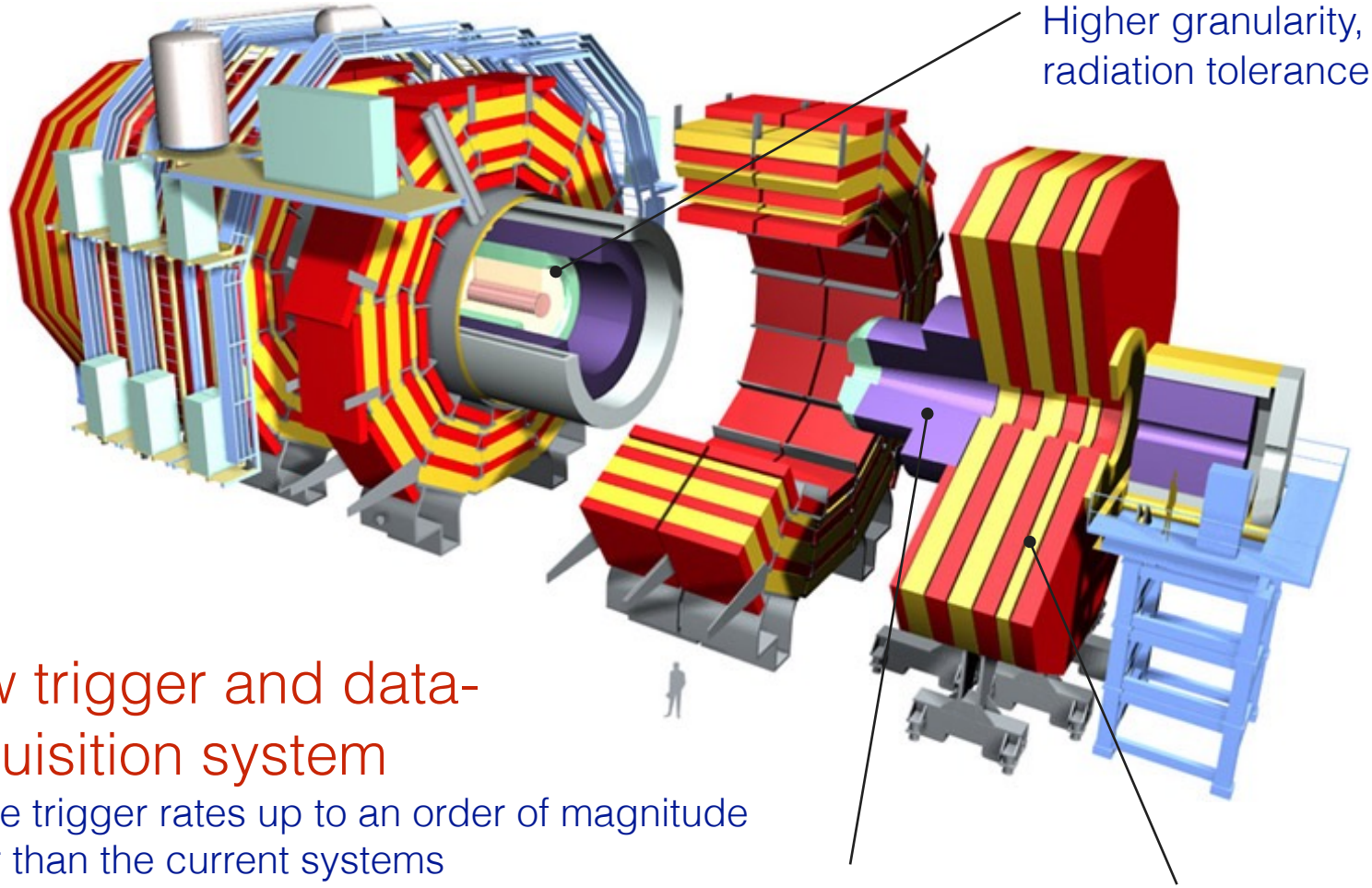
H→4l event at μ=140



ATLAS and *CMS* upgrades

New tracker

Fully silicon based
Higher granularity, better radiation tolerance



New trigger and data-acquisition system

Enable trigger rates up to an order of magnitude larger than the current systems
Requires replacing almost all of the current readout electronics

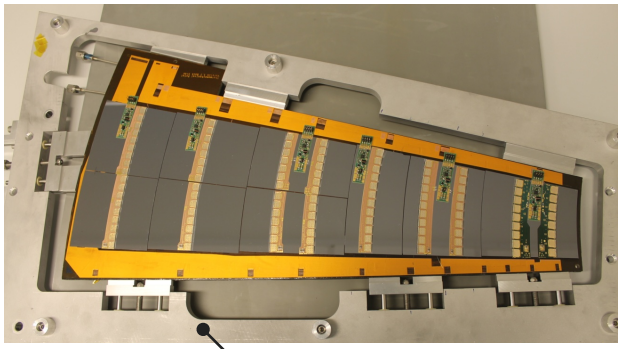
Upgrades to muon system and calorimetry in the forward region

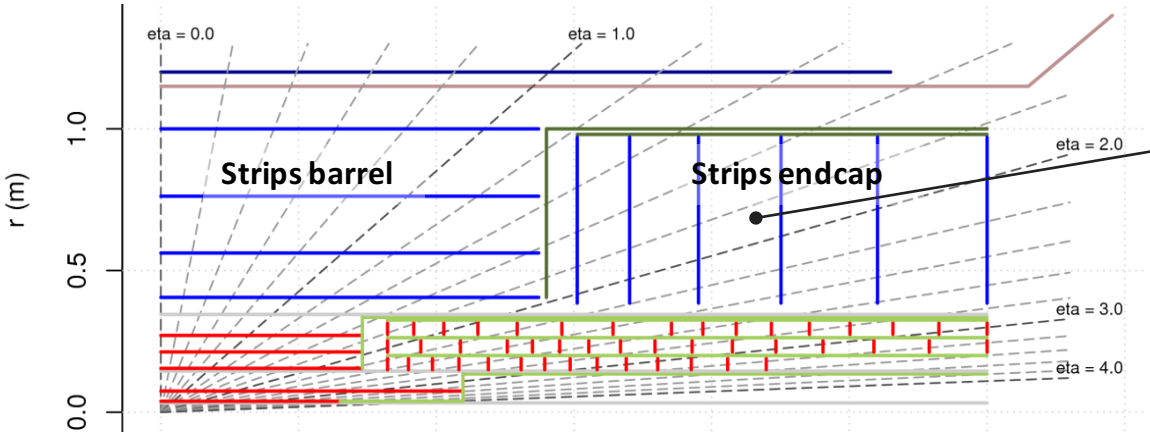
ATLAS and *CMS* tracker upgrade

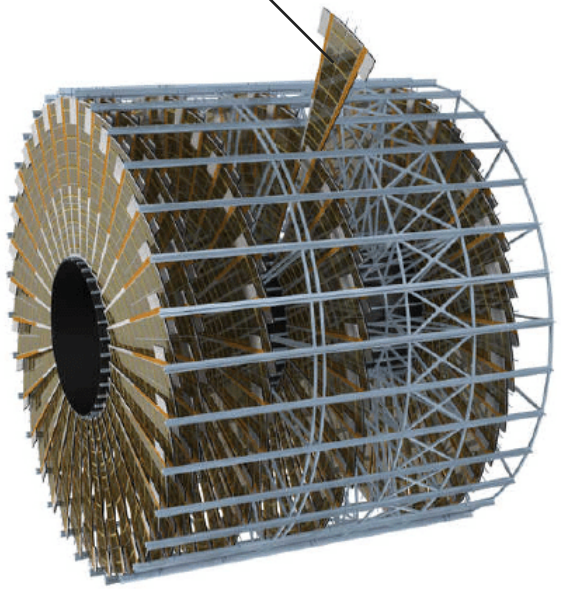
Both experiments: one Silicium Strip Detector End-Cap built by German institutes and assembled at DESY

Much improved performance:

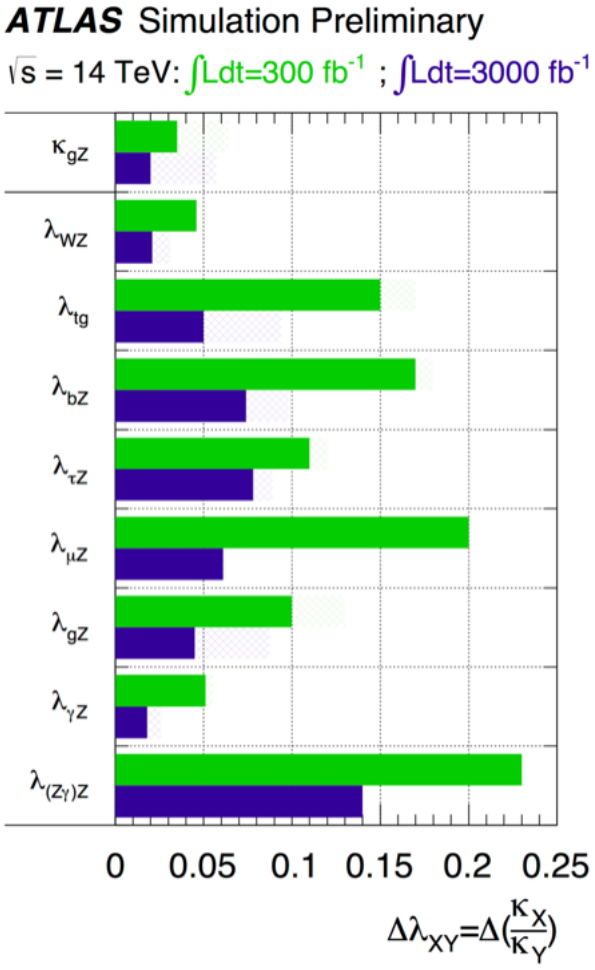
- Radiation hard sensor material and electronics
- Increase granularity
- Improve performance (light material)
- Extend to high rapidities







The origin of mass



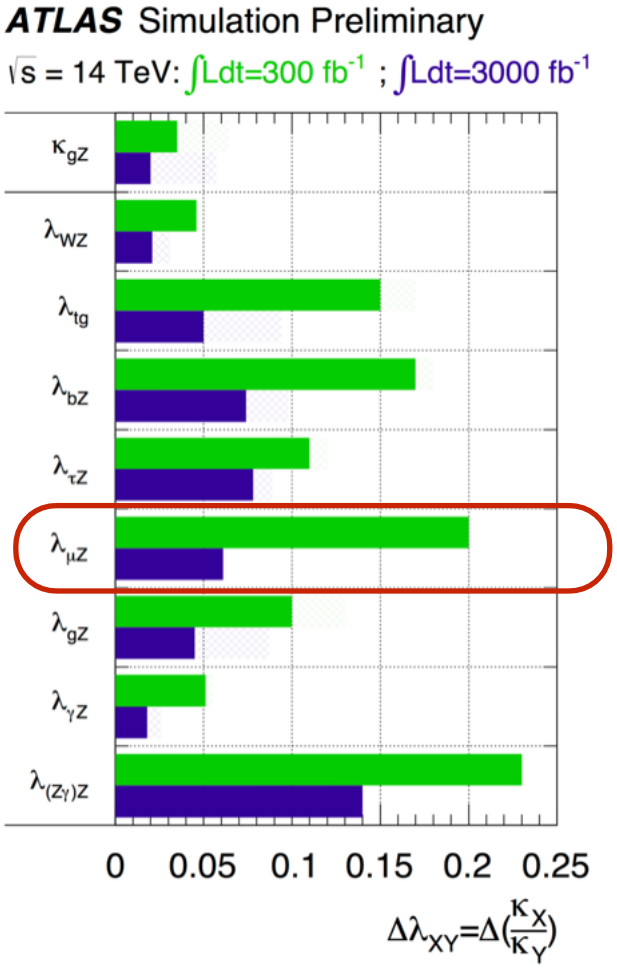
Higgs Snowmass report (arXiv:1310.8361)
Deviation from SM due to particles with M=1 TeV

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$\sim -.4\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

HL-LHC a Higgs boson factory

- Couplings measured with 2-8% precision
- Access to rare decays

The origin of mass



H→μμ

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HL-LHC a Higgs boson factory

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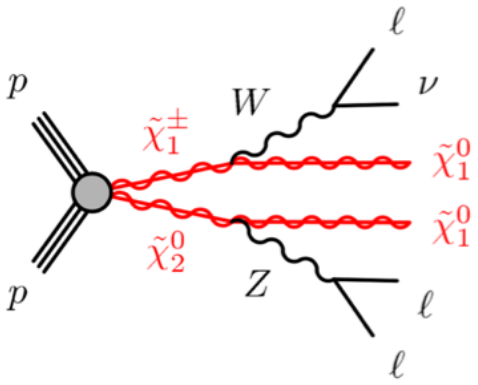
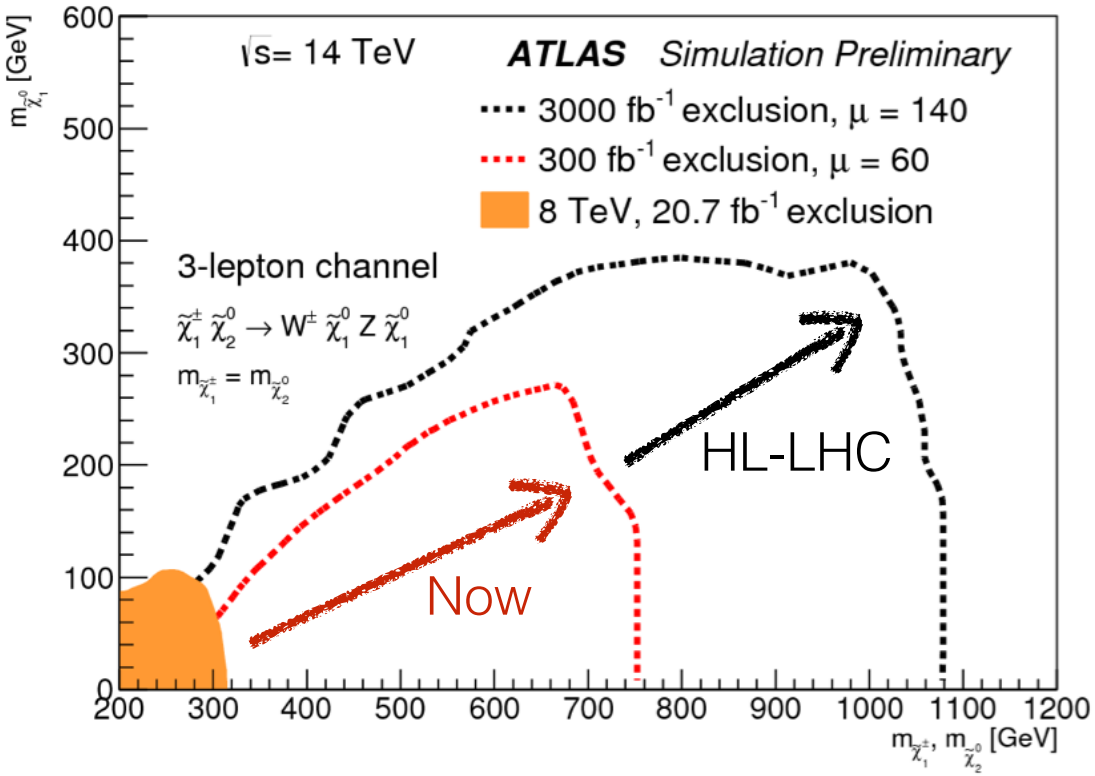
Supersymmetry





Run-2/3 at LHC will ~double mass reach compared to Run-1

Significant further increase with 3000 fb-1

- ~50 to 100% for electroweak production of neutralinos and charginos
- ~20% for gluino, squark, stop

Conclusions

The LHC Run-1 has been a tremendous success

An exceptionally well performing LHC delivered the first large 13 TeV dataset. Exploration of huge uncharted territory

Experiments are entering the area of precision measurements and rare phenomena searches

The LHC will provide exciting science for the next two decades

Conclusions

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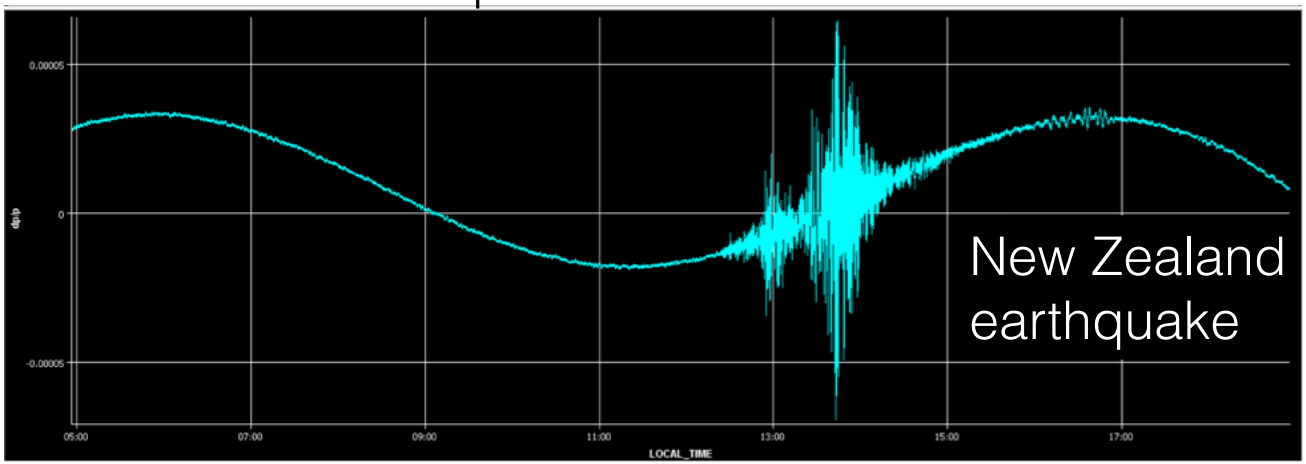
LHC beam orbit displacement

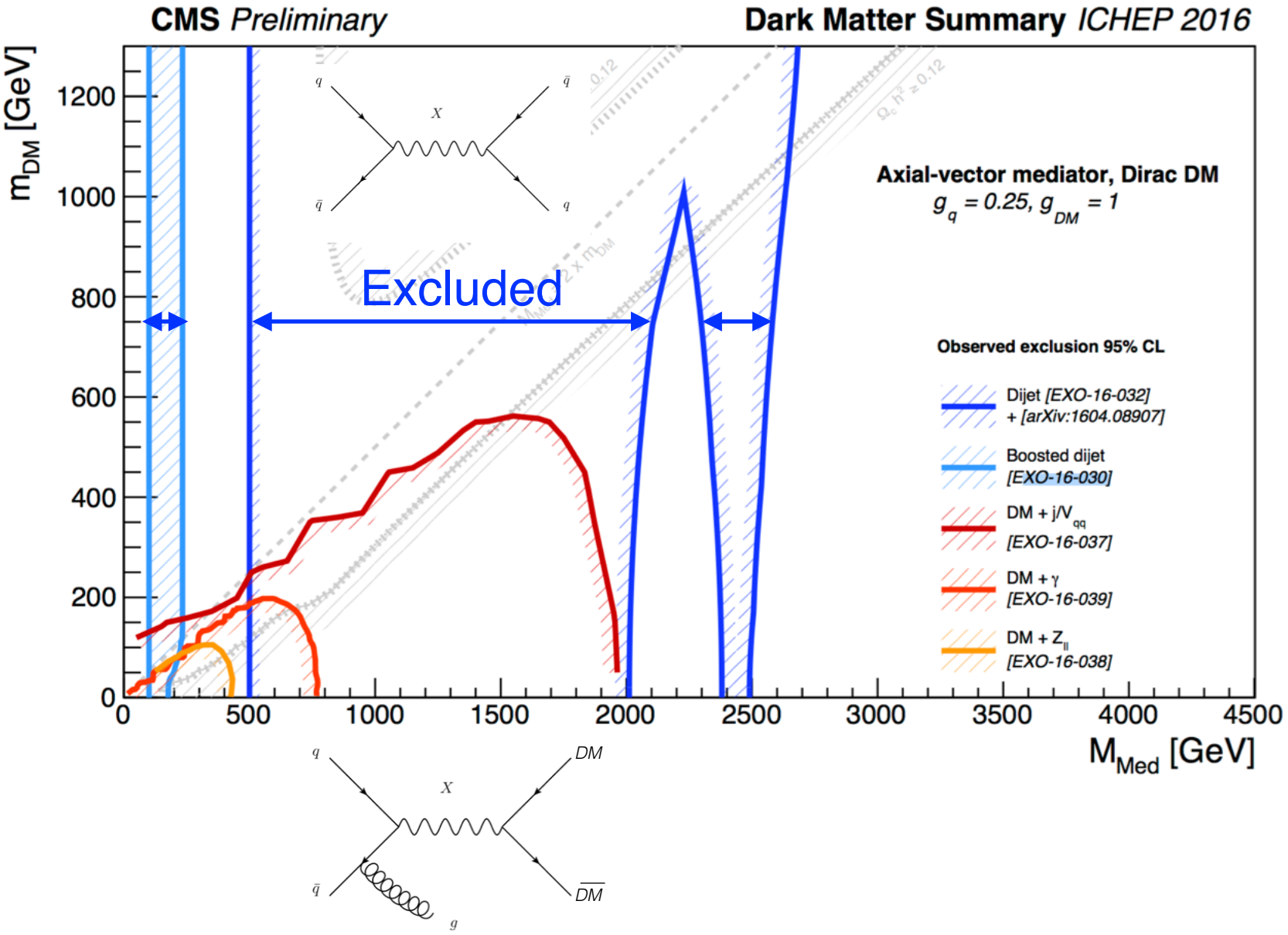


Experiments are entering the area of precision measurements and rare phenomena searches

The LHC will provide exciting science for the next two decades

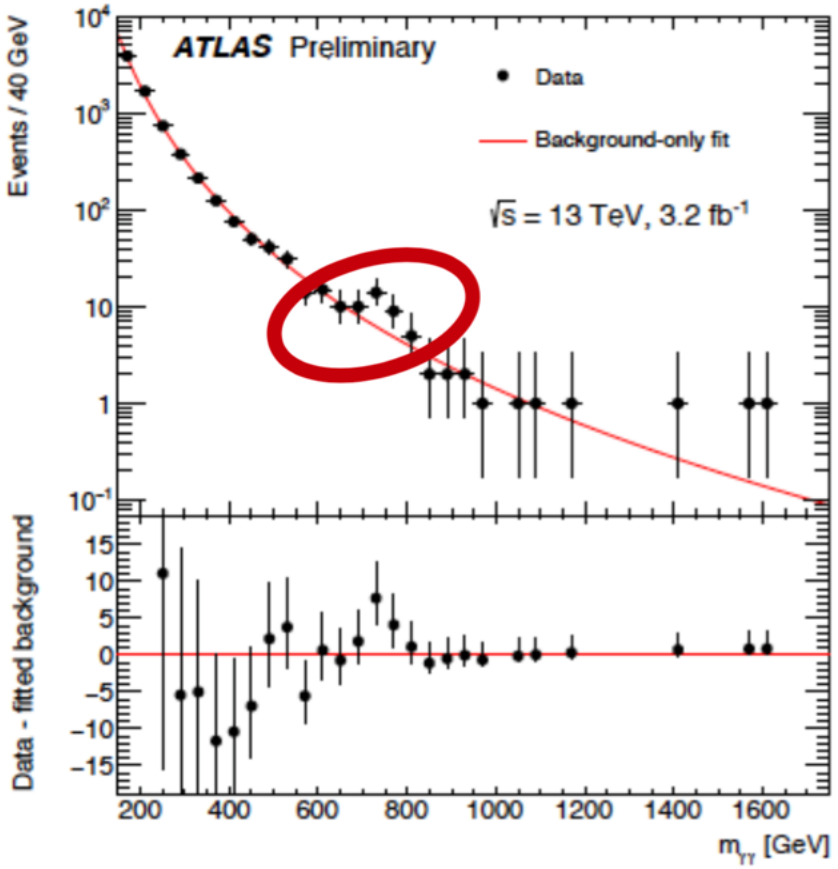
Additional material

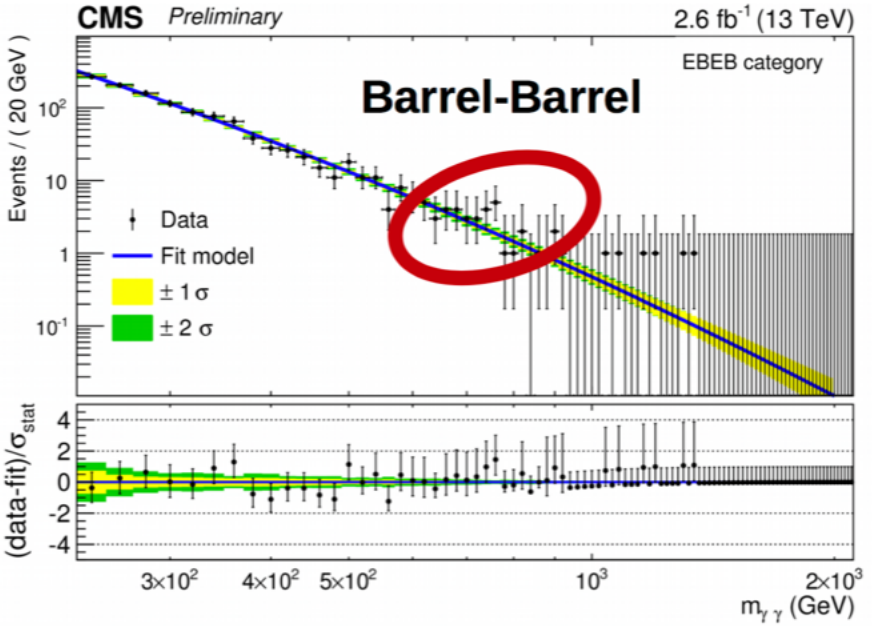
Dark matter at the LHC

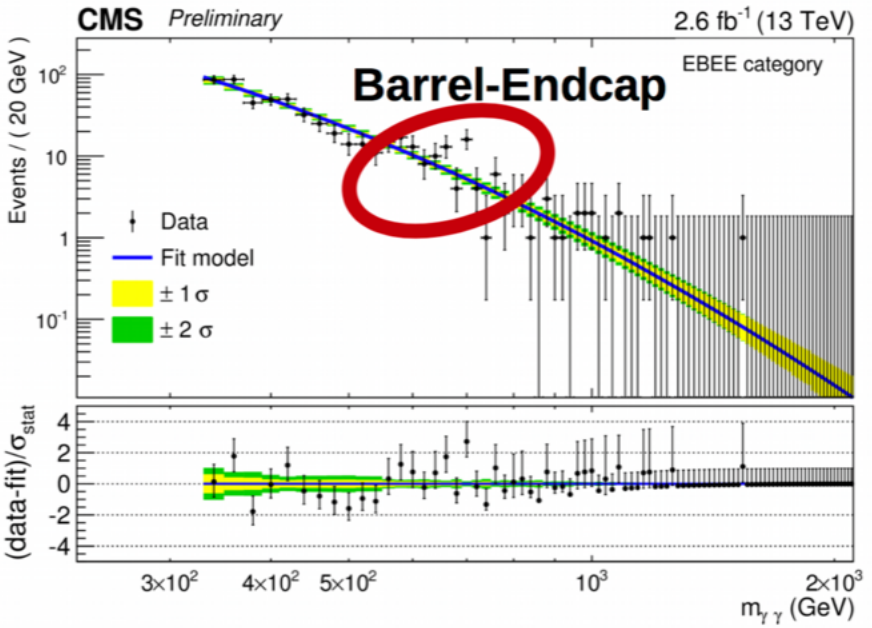


Di-photon search

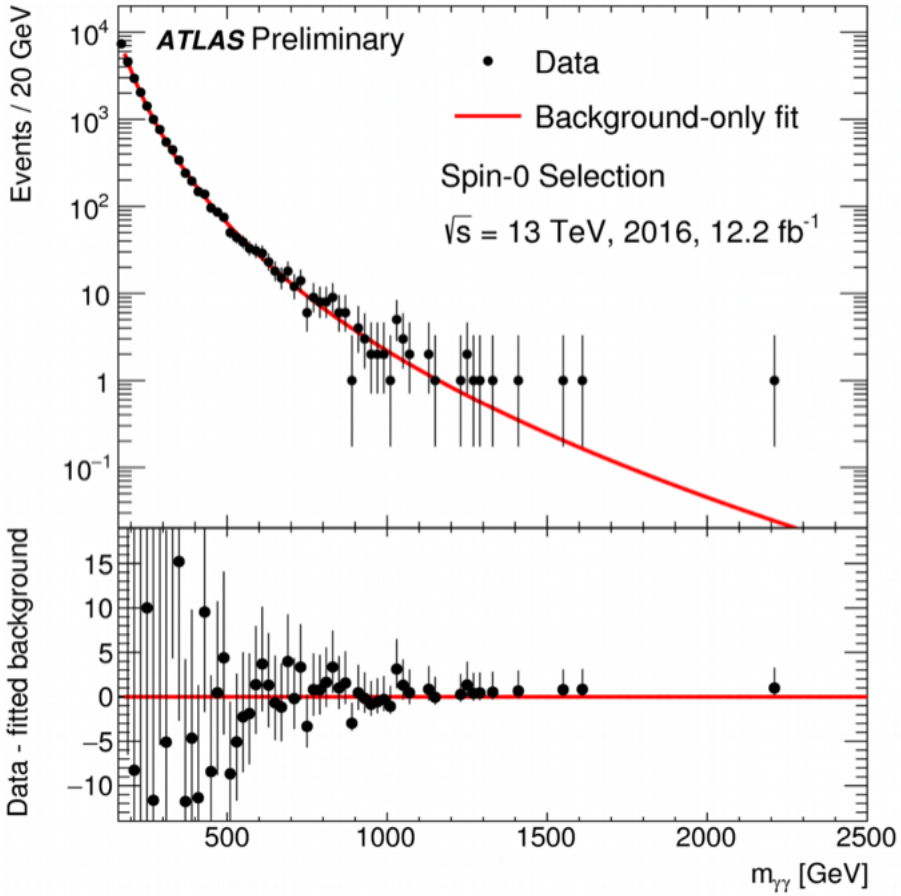
December 2015

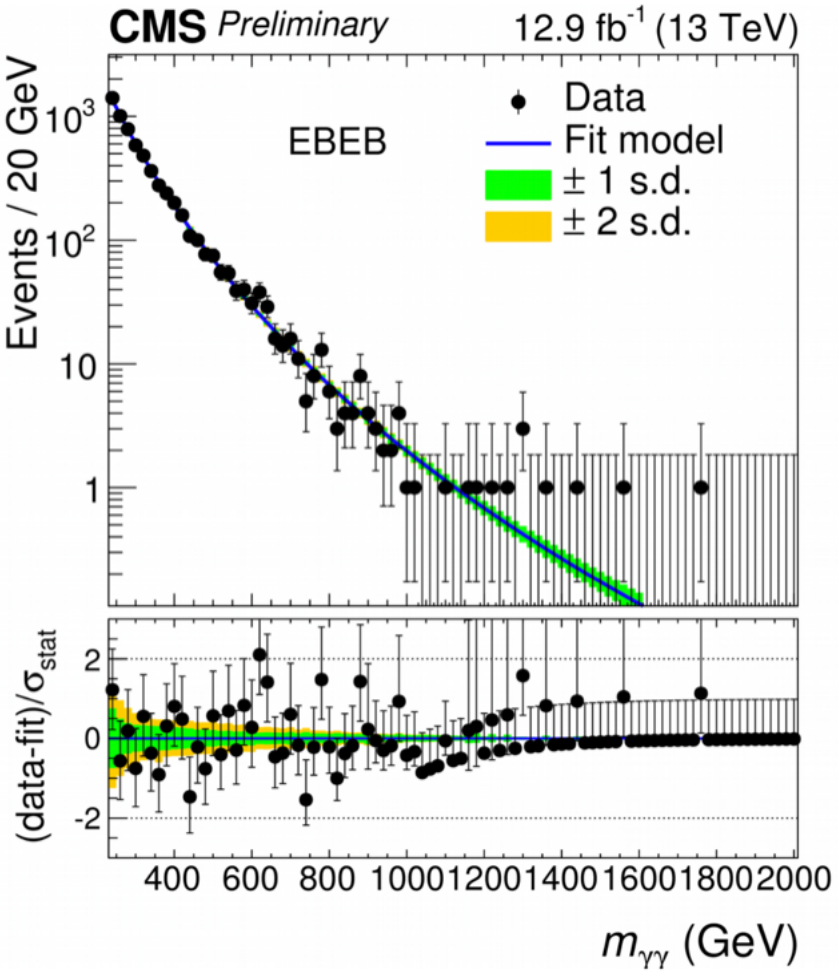






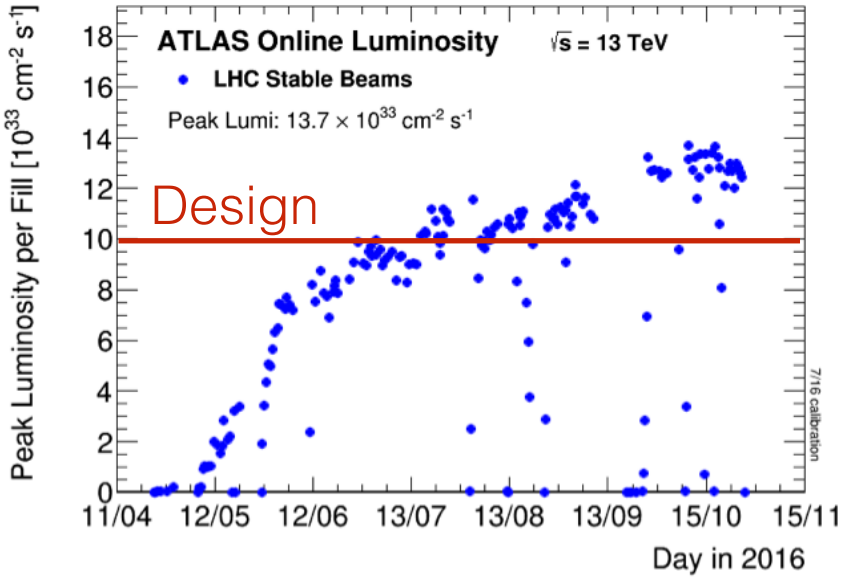
Di-photon search



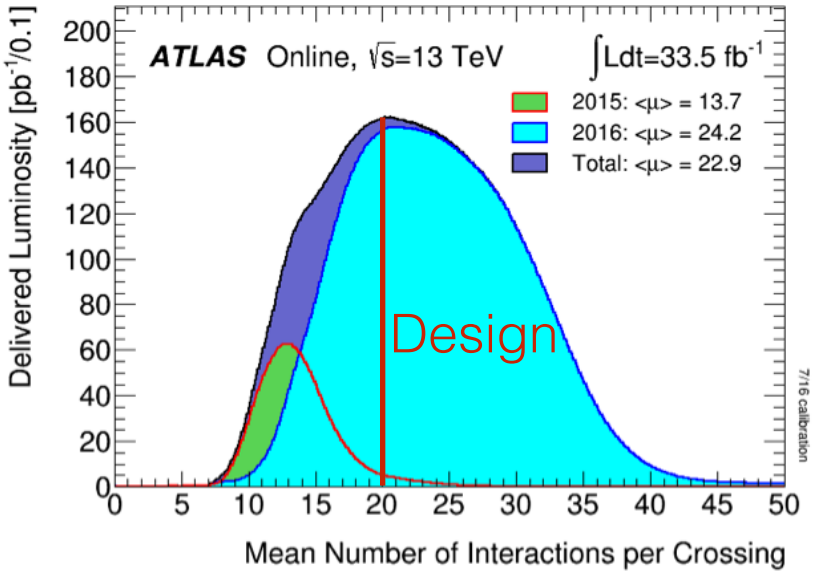


Challenges with high-luminosity

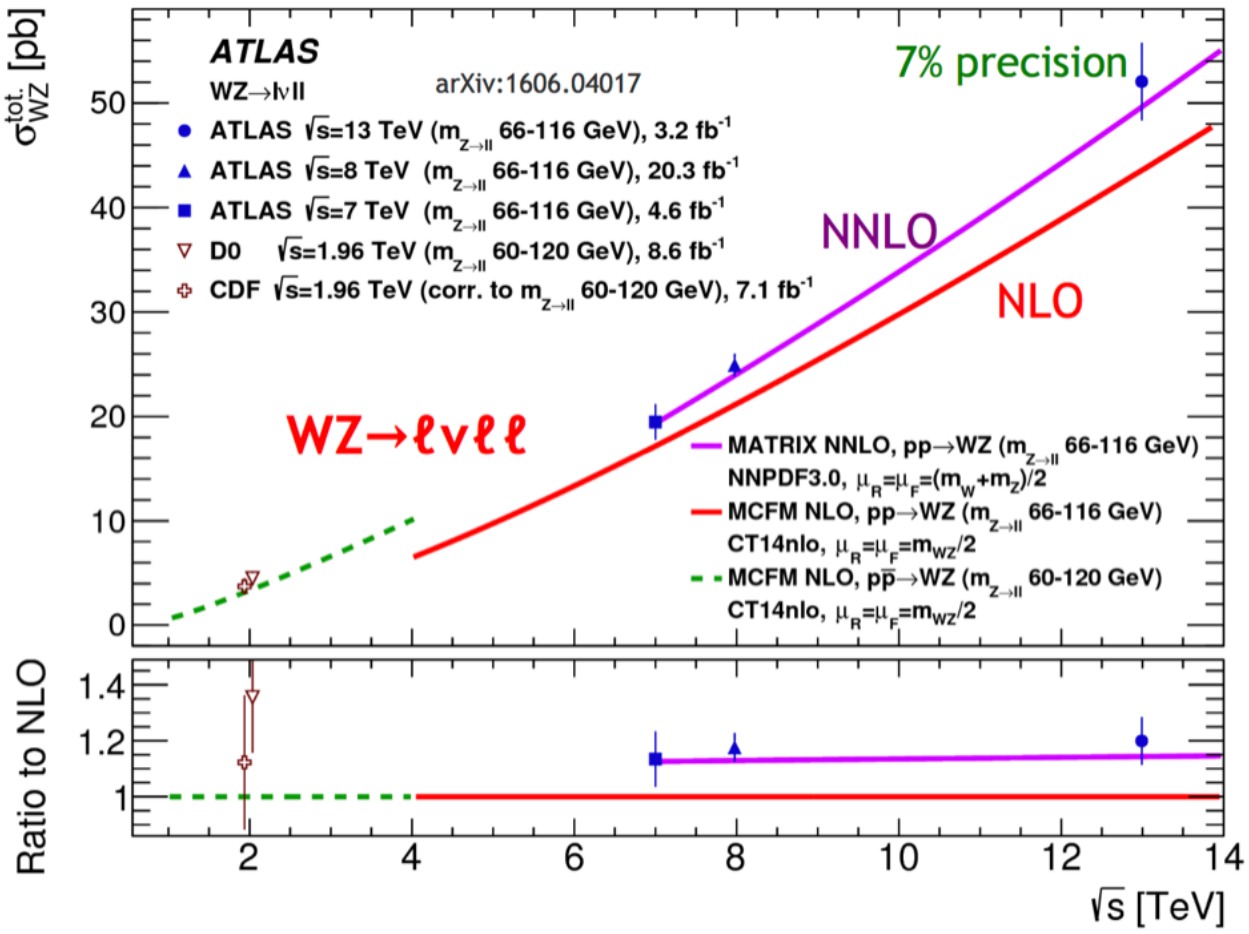
Peak-instantaneous luminosity



Number of interactions



Precision measurements



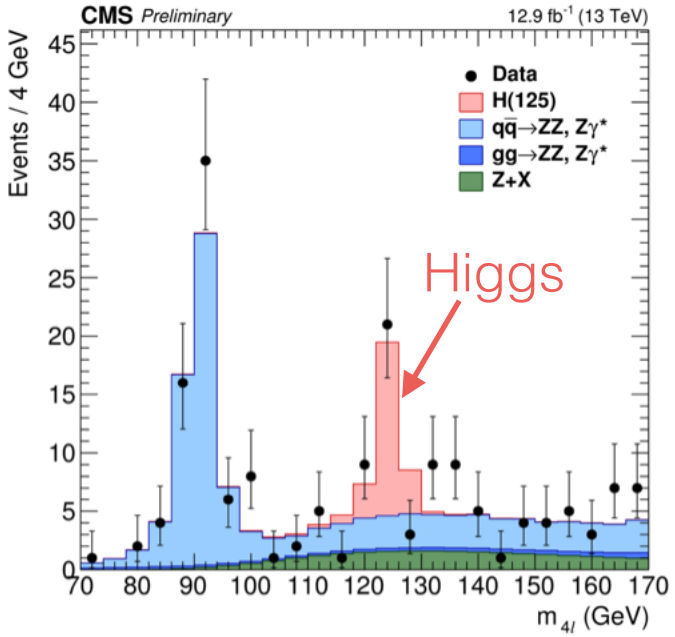
Run-1 puzzle to describe inclusive diboson cross-sections

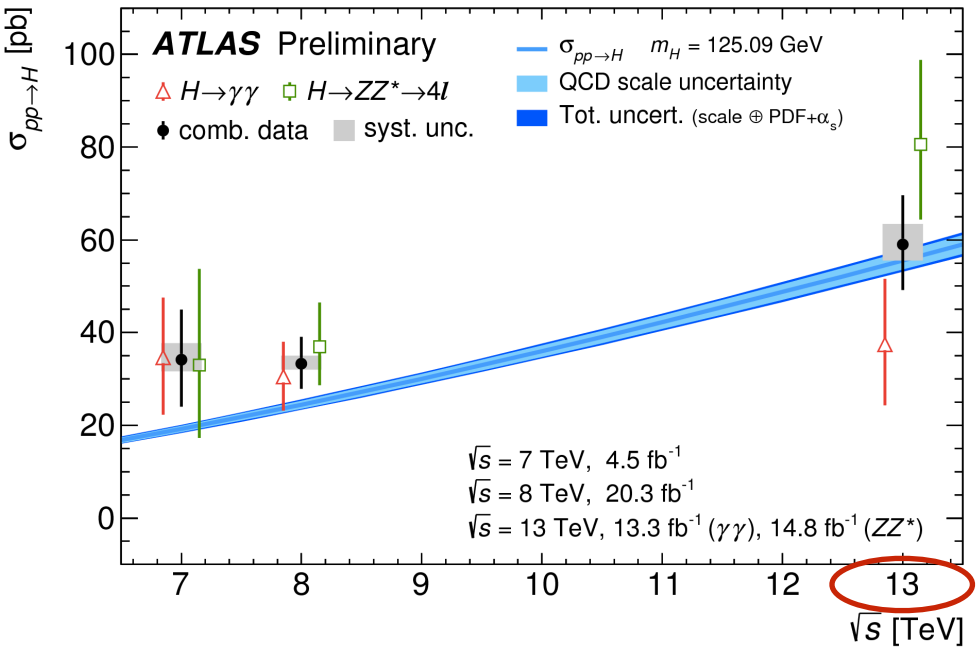
- Measurements tended to lie above NLO calculations

NNLO calculations → ~20% corrections and better agreement

The Higgs boson

… still there in Run-2



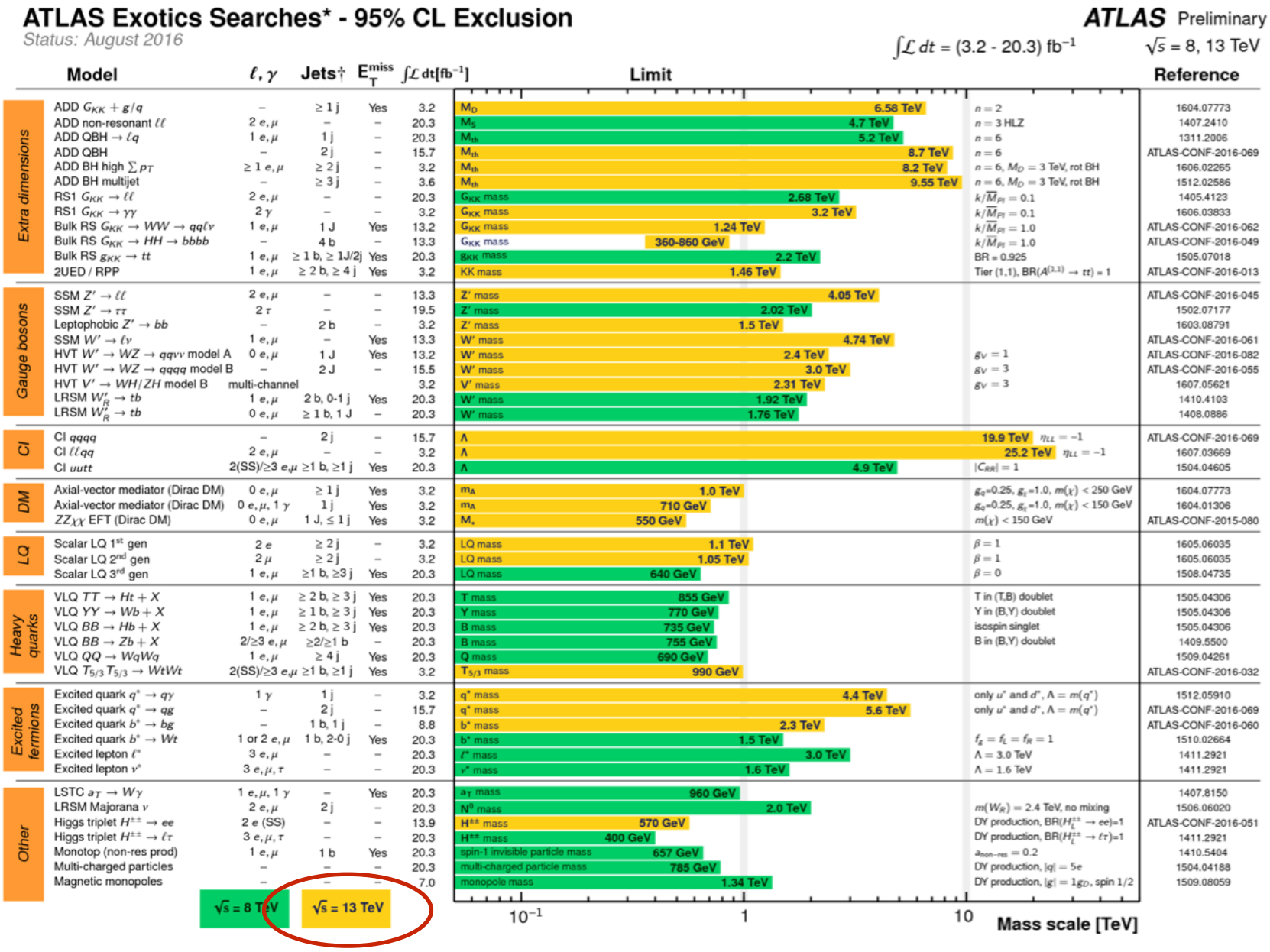


Overall significance at 13 TeV ~10σ

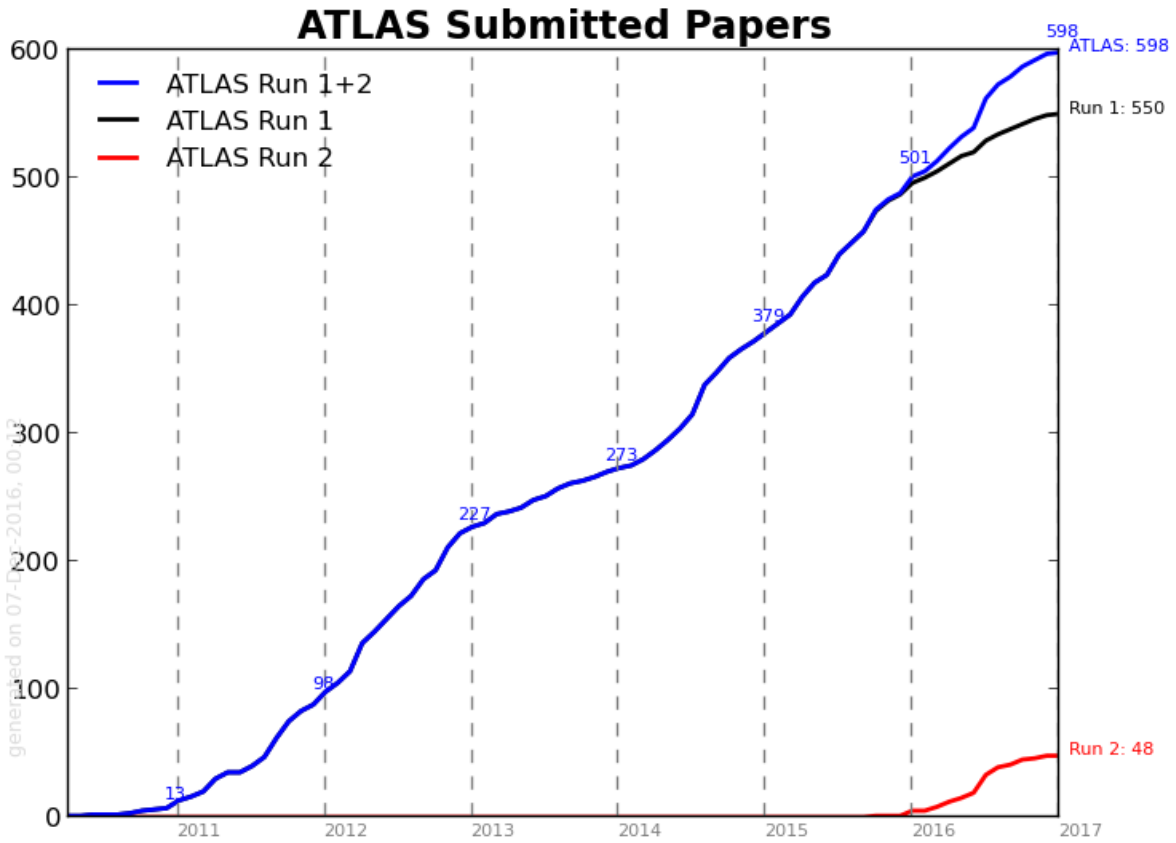
Rate consistent with SM prediction

Increasing dataset allows for differential cross section measurements and tests of top and bottom-Yukawa couplings

Searches


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
Model
ℓ, γ
Jets†
E_T^{miss}
$\int \mathcal{L}\,dt$[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 $\rightarrow \ell q$ 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 $G_{KK} \rightarrow \ell\ell$ 2 e, μ – – 20.3 G_{KK} mass 2.68 TeV $k/\overline{M}_{Pl} = 0.1$ 1405.4123
RS1 $G_{KK} \rightarrow \gamma\gamma$ 2 γ – – 3.2 G_{KK} mass 3.2 TeV $k/\overline{M}_{Pl} = 0.1$ 1606.03833
Bulk RS $G_{KK} \rightarrow WW \rightarrow qq\ell\nu$ 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 $G_{KK} \rightarrow HH \rightarrow bbbb$ – 4 b – 13.3 G_{KK} mass 360-860 GeV $k/\overline{M}_{Pl} = 1.0$ ATLAS-CONF-2016-049
Bulk RS $g_{KK} \rightarrow tt$ 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($A^{(1,1)} \rightarrow tt$) = 1 ATLAS-CONF-2016-013
Gauge bosons
SSM $Z' \rightarrow \ell\ell$ 2 e, μ – – 13.3 Z' mass 4.05 TeV ATLAS-CONF-2016-045
SSM $Z' \rightarrow \tau\tau$ 2 τ – – 19.5 Z' mass 2.02 TeV 1502.07177
Leptophobic $Z' \rightarrow bb$ – 2 b – 3.2 Z' mass 1.5 TeV 1603.08791
SSM $W' \rightarrow \ell\nu$ 1 e, μ – Yes 13.3 W' mass 4.74 TeV ATLAS-CONF-2016-061
HVT $W' \rightarrow WZ \rightarrow qq\nu\nu$ model A 0 e, μ 1 J Yes 13.2 W' mass 2.4 TeV $g_V = 1$ ATLAS-CONF-2016-082
HVT $W' \rightarrow WZ \rightarrow qqqq$ model B – 2 J – 15.5 W' mass 3.0 TeV $g_V = 3$ ATLAS-CONF-2016-055
HVT $V' \rightarrow WH/ZH$ model B multi-channel 3.2 V' mass 2.31 TeV $g_V = 3$ 1607.05621
LRSM $W'_R \rightarrow tb$ 1 e, μ 2 b, 0-1 j Yes 20.3 W' mass 1.92 TeV 1410.4103
LRSM $W'_R \rightarrow tb$ 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
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 ≥1 b, ≥3 j Yes 20.3 LQ mass 640 GeV $\beta = 0$ 1508.04735
Heavy quarks
VLQ $TT \rightarrow Ht + X$ 1 e, μ ≥ 2 b, ≥ 3 j Yes 20.3 T mass 855 GeV T in (T,B) doublet 1505.04306
VLQ $YY \rightarrow Wb + X$ 1 e, μ ≥ 1 b, ≥ 3 j Yes 20.3 Y mass 770 GeV Y in (B,Y) doublet 1505.04306
VLQ $BB \rightarrow Hb + X$ 1 e, μ ≥ 2 b, ≥ 3 j Yes 20.3 B mass 735 GeV isospin singlet 1505.04306
VLQ $BB \rightarrow Zb + X$ 2/≥3 e, μ ≥2/≥1 b – 20.3 B mass 755 GeV B in (B,Y) doublet 1409.5500
VLQ $QQ \rightarrow WqWq$ 1 e, μ ≥ 4 j Yes 20.3 Q mass 690 GeV 1509.04261
VLQ $T_{5/3}T_{5/3} \rightarrow WtWt$ 2(SS)/≥3 e, μ ≥1 b, ≥1 j Yes 3.2 $T_{5/3}$ mass 990 GeV ATLAS-CONF-2016-032
Excited fermions
Excited quark $q^* \rightarrow q\gamma$ 1 γ 1 j – 3.2 q^* mass 4.4 TeV only u^* and d^*, $\Lambda = m(q^*)$ 1512.05910
Excited quark $q^* \rightarrow qg$ – 2 j – 15.7 q^* mass 5.6 TeV only u^* and d^*, $\Lambda = m(q^*)$ ATLAS-CONF-2016-069
Excited quark $b^* \rightarrow bg$ – 1 b, 1 j – 8.8 b^* mass 2.3 TeV ATLAS-CONF-2016-060
Excited quark $b^* \rightarrow Wt$ 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 Λ = 3.0 TeV 1411.2921
Excited lepton ν^* 3 e, μ, τ – – 20.3 ν^* mass 1.6 TeV Λ = 1.6 TeV 1411.2921
Other
LSTC $a_T \rightarrow W\gamma$ 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 $H^{\pm\pm} \rightarrow ee$ 2 e (SS) – – 13.9 $H^{\pm\pm}$ mass 570 GeV DY production, BR($H_L^{\pm\pm} \rightarrow ee$)=1 ATLAS-CONF-2016-051
Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$ 3 e, μ, τ – – 20.3 $H^{\pm\pm}$ mass 400 GeV DY production, BR($H_L^{\pm\pm} \rightarrow \ell\tau$)=1 1411.2921
Monotop (non-res prod) 1 e, μ 1 b Yes 20.3 spin-1 invisible particle mass 657 GeV $a_{non-res} = 0.2$ 1410.5404
Multi-charged particles – – – 20.3 multi-charged particle mass 785 GeV DY production, $|q| = 5e$ 1504.04188
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
10^{-1}
1
10
Mass scale [TeV]

LHC publications



The four LHC experiments together:
→ 1 publication per working day!