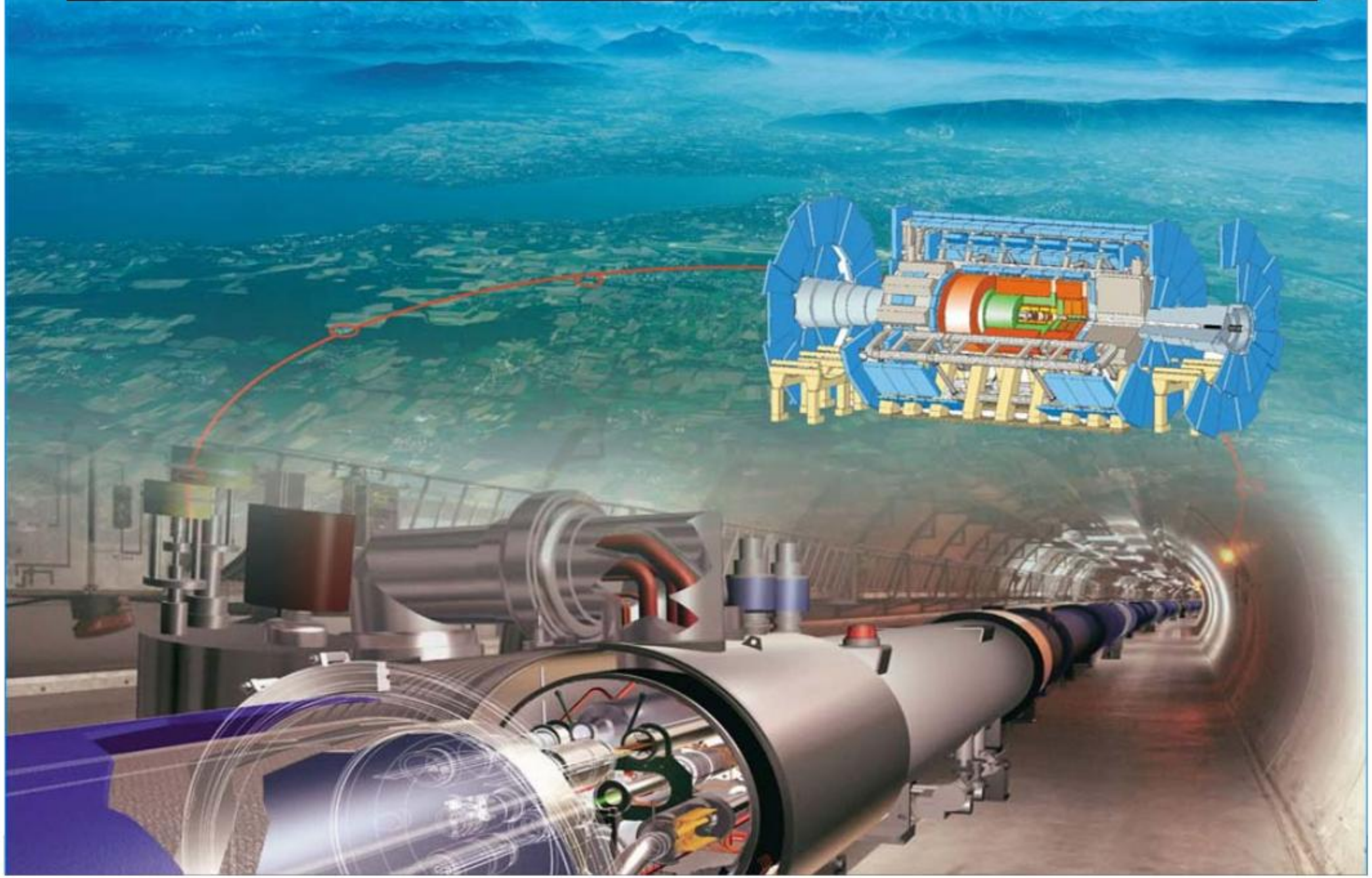
Testing the Standard Model of Elementary Particle Physics II

Introduction

23th April 2020

Introduction



Contact details

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Curriculum

1. Standard Model of Particle Physics
    1.1 Field Theories of Elementary Particle Physics
    1.2 Gauge Theories and Interactions
    1.3 Fundamental Forces and their Unification
    1.4 Origin of Particle Masses (i.e. the Higgs mechanism)
    1.5 Theory meets Experiment (using Feynman Diagrams)
2. Recent experimental Tests on the Standard Model of Particle Physics
    2.1 Precision Measurements of the Electroweak Interaction
    2.2 Physics at the Large Hadron Collider
    2.3 The Higgs Boson (Searches and Measurements)
    2.4 Ongoing Searches for Beyond the Standard Model Physics
    2.5 B-Hadron Decays and CP Violation
    2.6 Neutrino Masses and Oscillation

Curriculum

3. Extension of the Standard Model of Particle Physics
   - 3.1 Open Questions
   - 3.2 Great Unification
   - 3.3 Supersymmetry
   - 3.4 Dark Matter

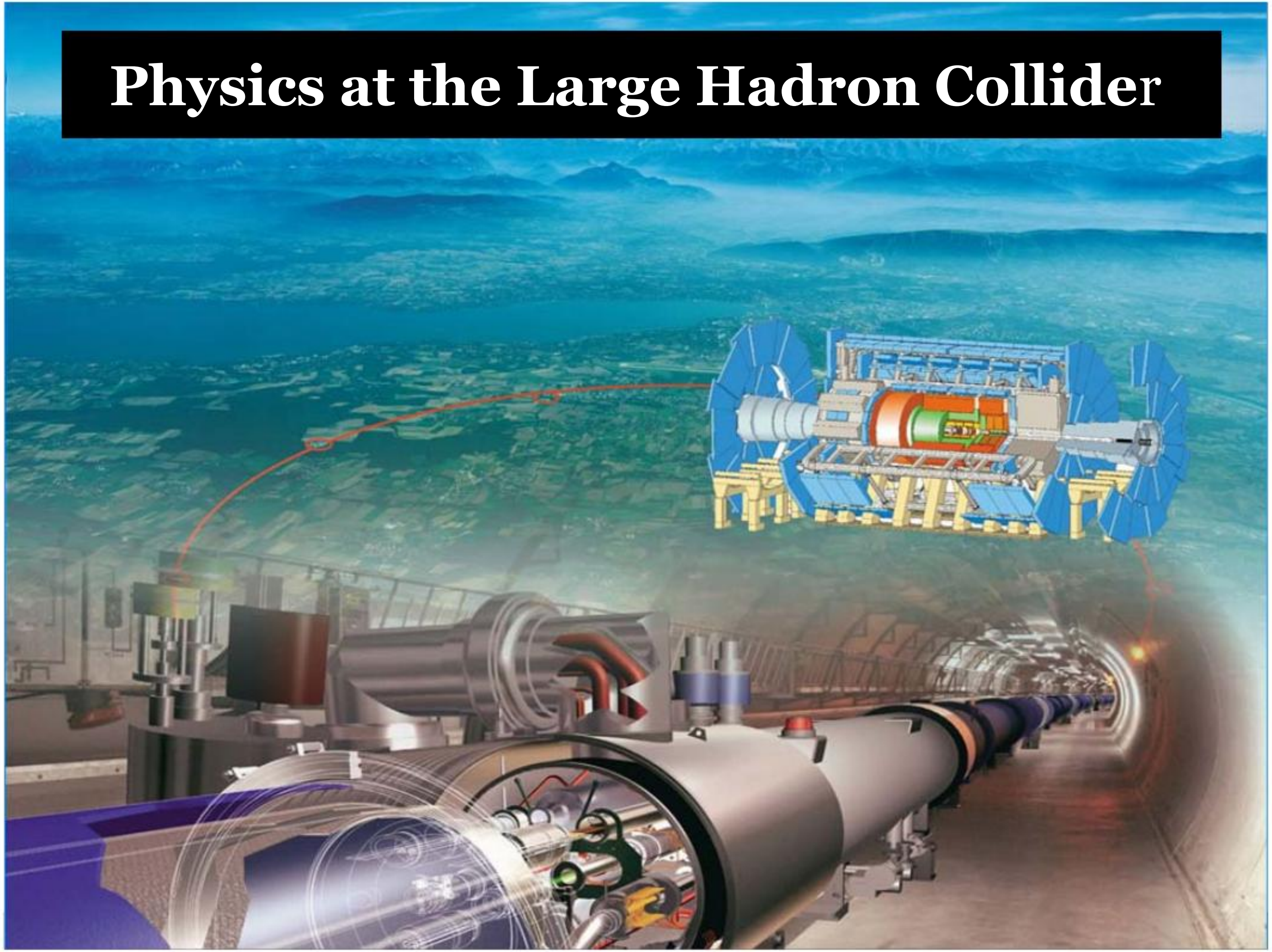
Literature

- B. Povh, K.Rith, Ch. Scholz, F. Zetsche:**Teilchen und Kerne**, Springer, 4th edition, 1997.
- Ch. Berger: **Elementarteilchenphysik**, Springer, 2002.
- P. Schmüser: **Feynmangraphen und Eichtheorien für Experimentalphysiker**, Springer, 2nd edition, 1995.
- I.J.R. Aitchison, A.J.G. Hey: **Gauge Theories in Particle Physics**, Vol. 1, Institute of Physics Publishing, new edition, 2002.
- W. Greiner, B. Müller: **Quantum Mechanics–Symmetries**, Springer, 2nd edition, 1994.
- Ian Brock, Thomas Schörner-Sadenius: **Physics at the Terascale**, WILEY-VCH, 2011
- D. Griffiths, **Introduction to Elementary Particles,** WILEY-VCH, 2008, 2nd edition
- Amitabha Lahiri, Palash B. Pal: **A first book of QUANTUM FIELD THEORY**, Alpha Science, 2nd edition, 2007

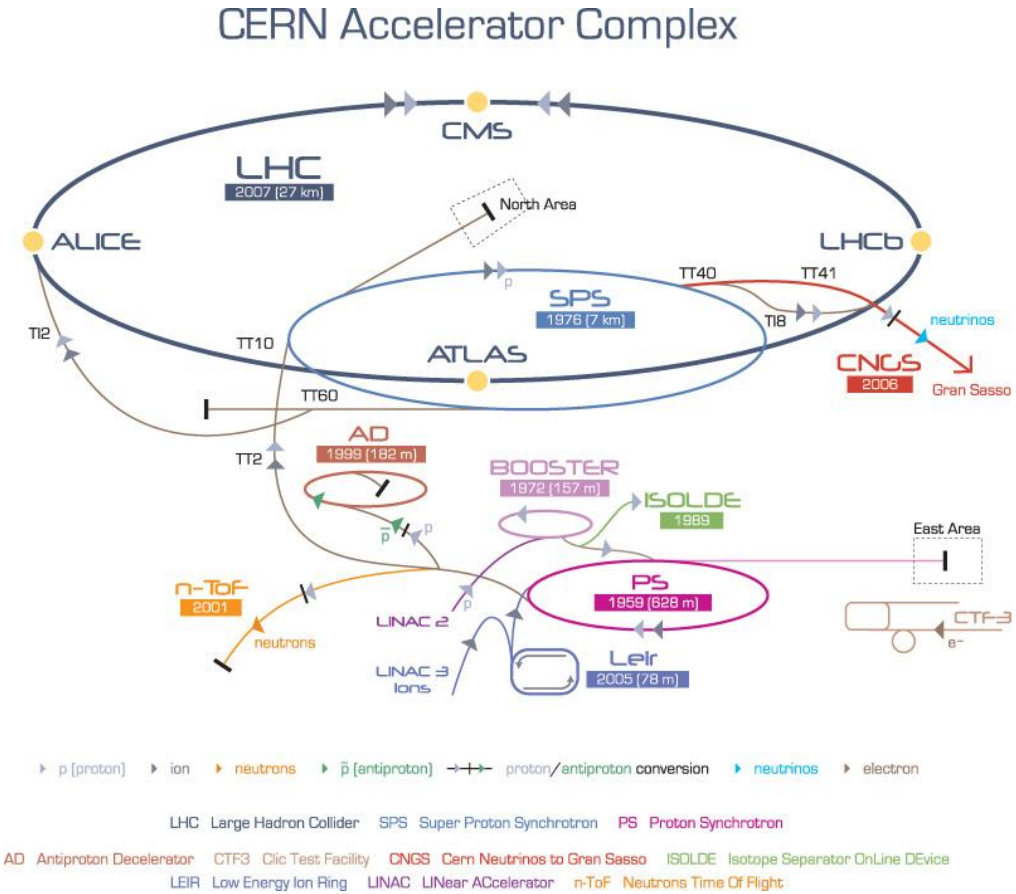
Testing the Standard Model of Elementary Particle Physics II

First lecture

23th April 2020


Physics at the Large Hadron Collider

The Large Hadron Collider



- Instantaneous luminosity

$$\mathcal{L} = fn\frac{N_1 N_2}{A}$$

N_1, N_2 = Number of hadrons per bunch

n = Number of bunches per beam

f = Resolution frequency

A = Beam cross section

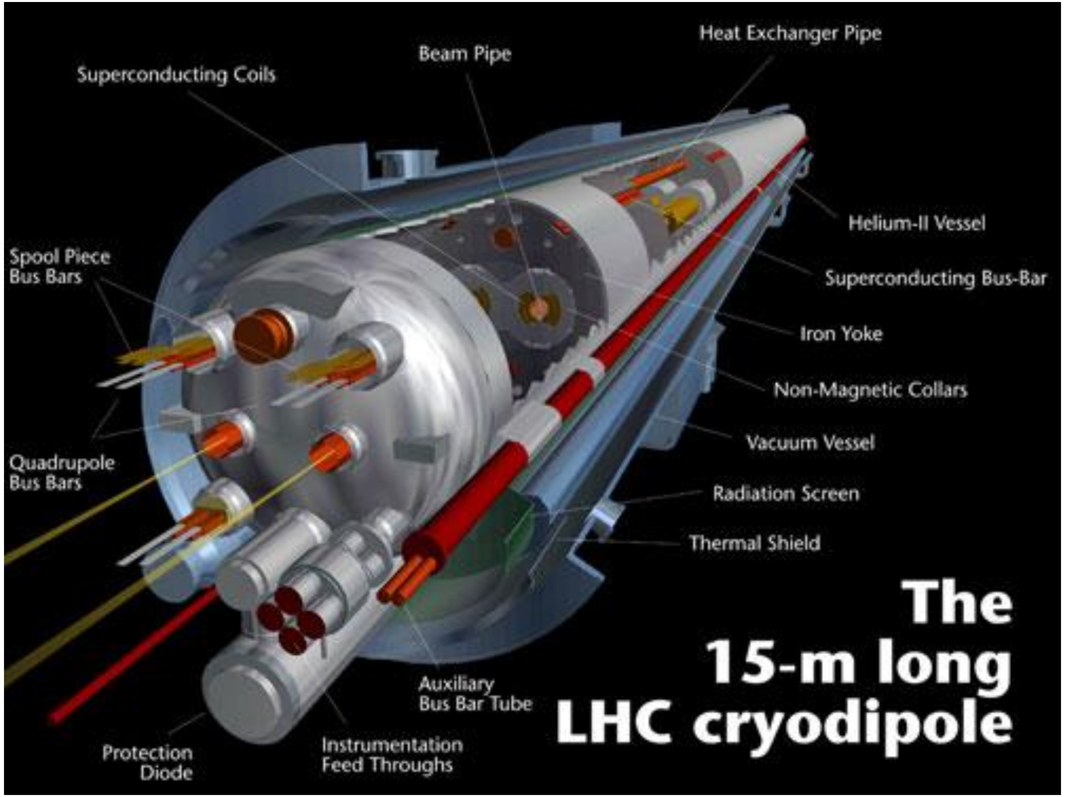
- Integrated luminosity

$$L = \int \mathcal{L} dt$$

- CoM energy: $\sqrt{s}$

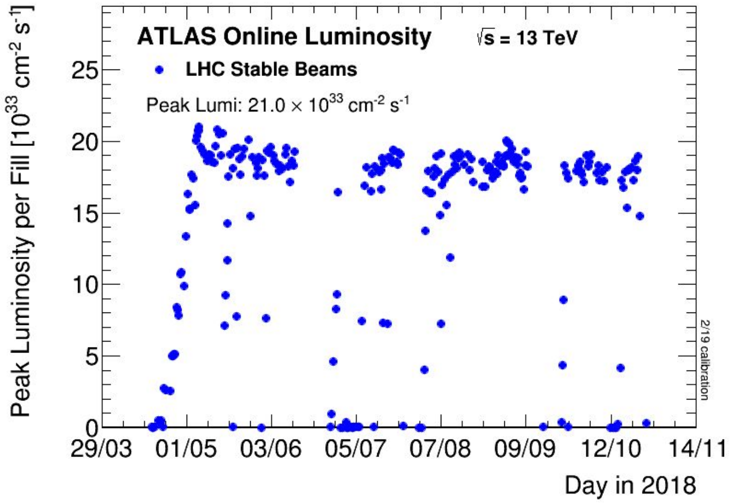
Magnet system

- Instantaneous luminosity



Luminosity

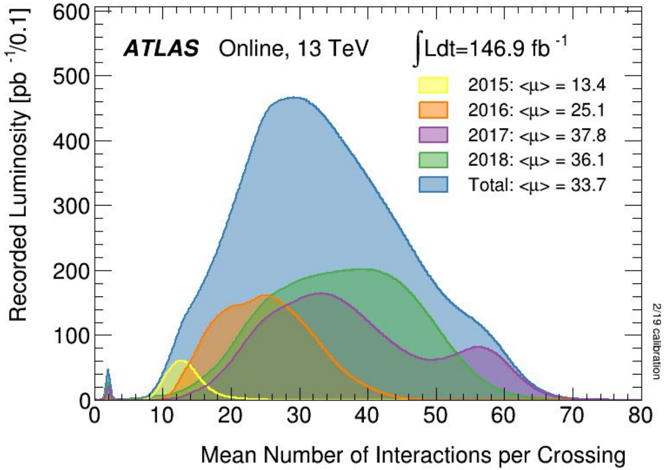
- Design goal of LHC:
  - **10^{34} cm^{-2} s^{-1}**
    - **n = 2835 proton bunches per beam**
    - **f = 40MHz**
    - **$N_1/N_2 = 10^{11}$ protons per bunch**

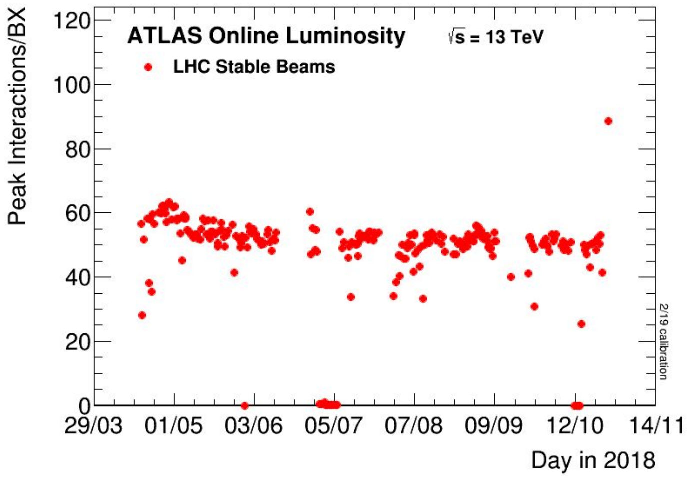


- **Already exceeded in Run-II**

- **Pile-up:**
  - Additional interactions next to the hard process

$$\mathcal{L} = fn\frac{N_1 N_2}{A}$$

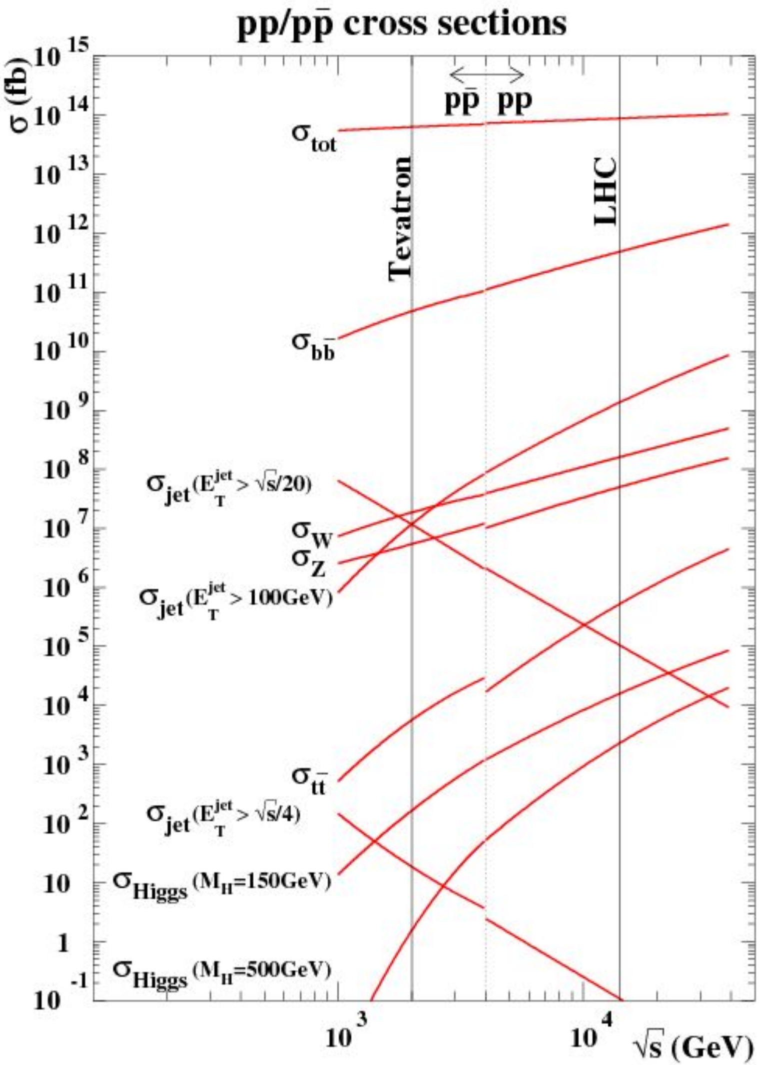




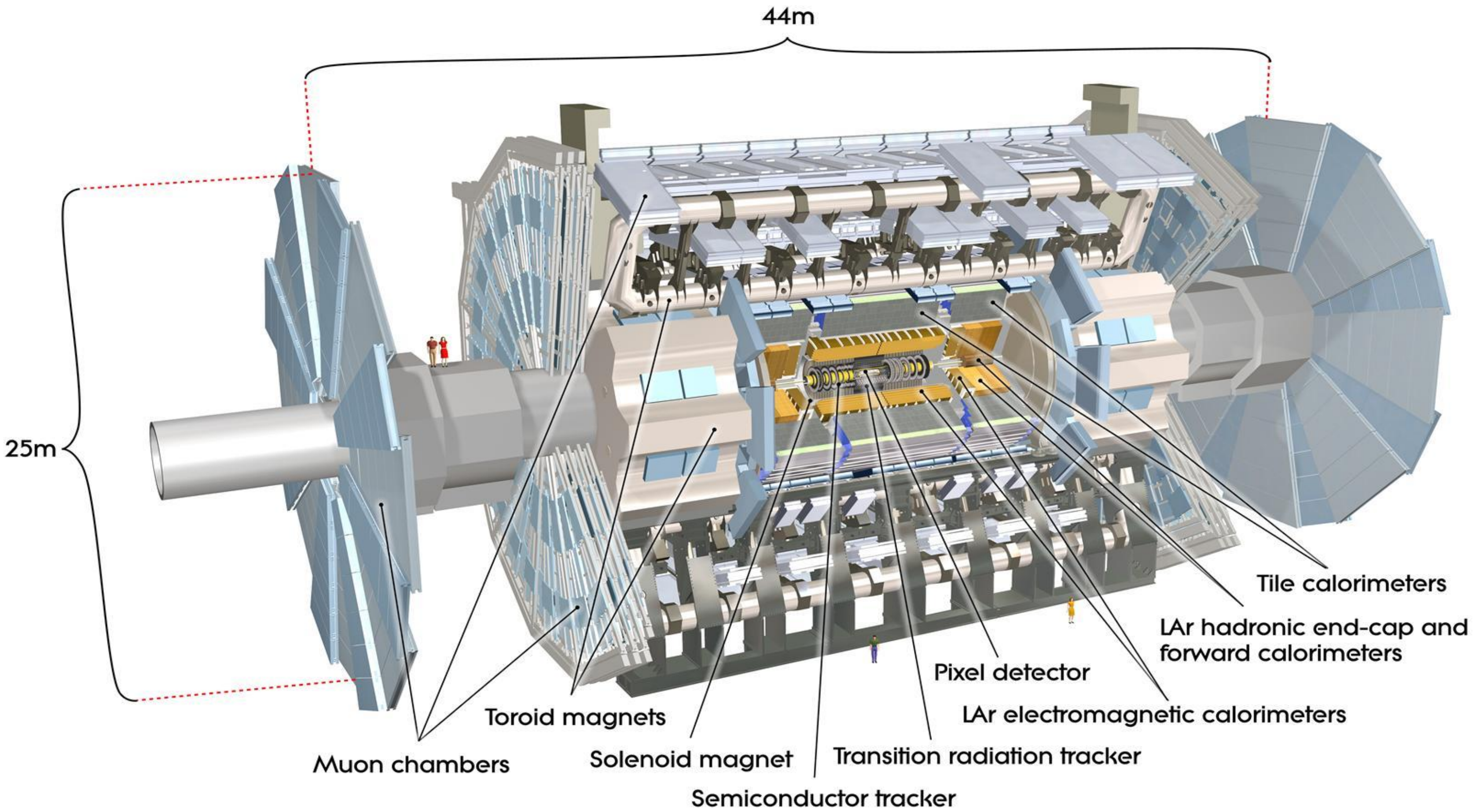
Event rates/cross sections

$$\frac{dN}{dt} = \mathcal{L} \cdot \sigma$$

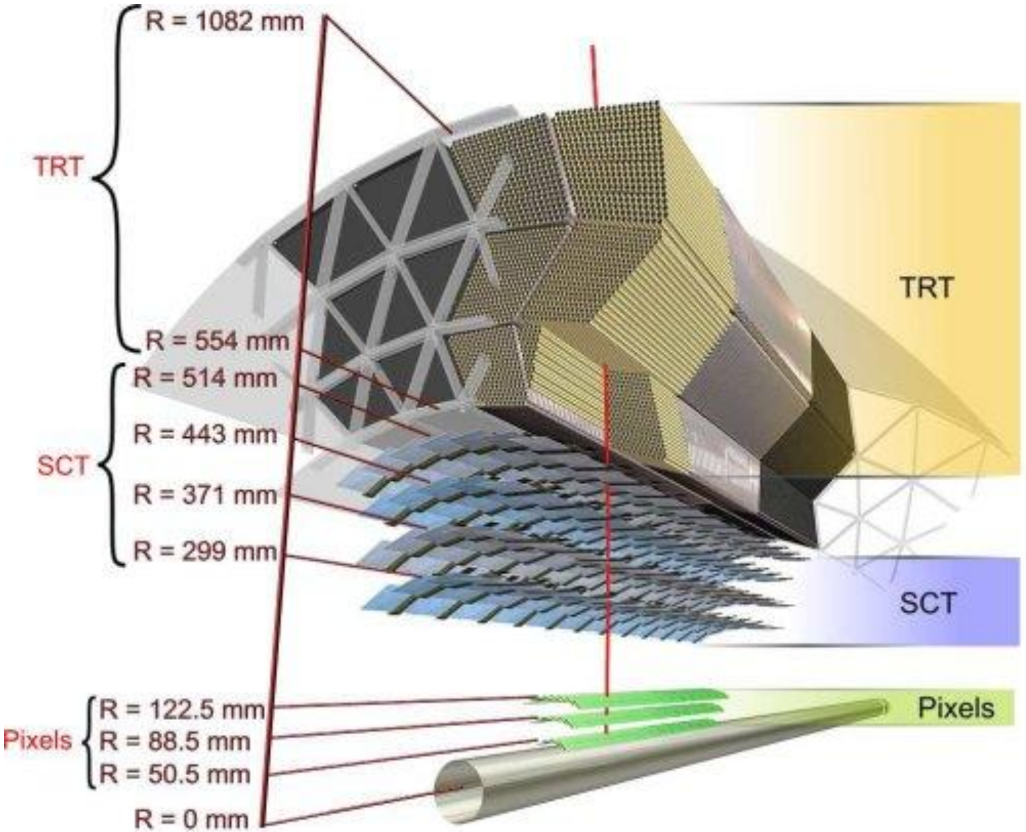
Inelastic pp collisions	~10^7 Hz
b-quark production	~10^4 Hz
Jet production E_T> 250 GeV	~1 Hz
W->lν	~1 Hz
top-quark production	~10^{-2}Hz
Higgs bosons	~10^{-4}Hz

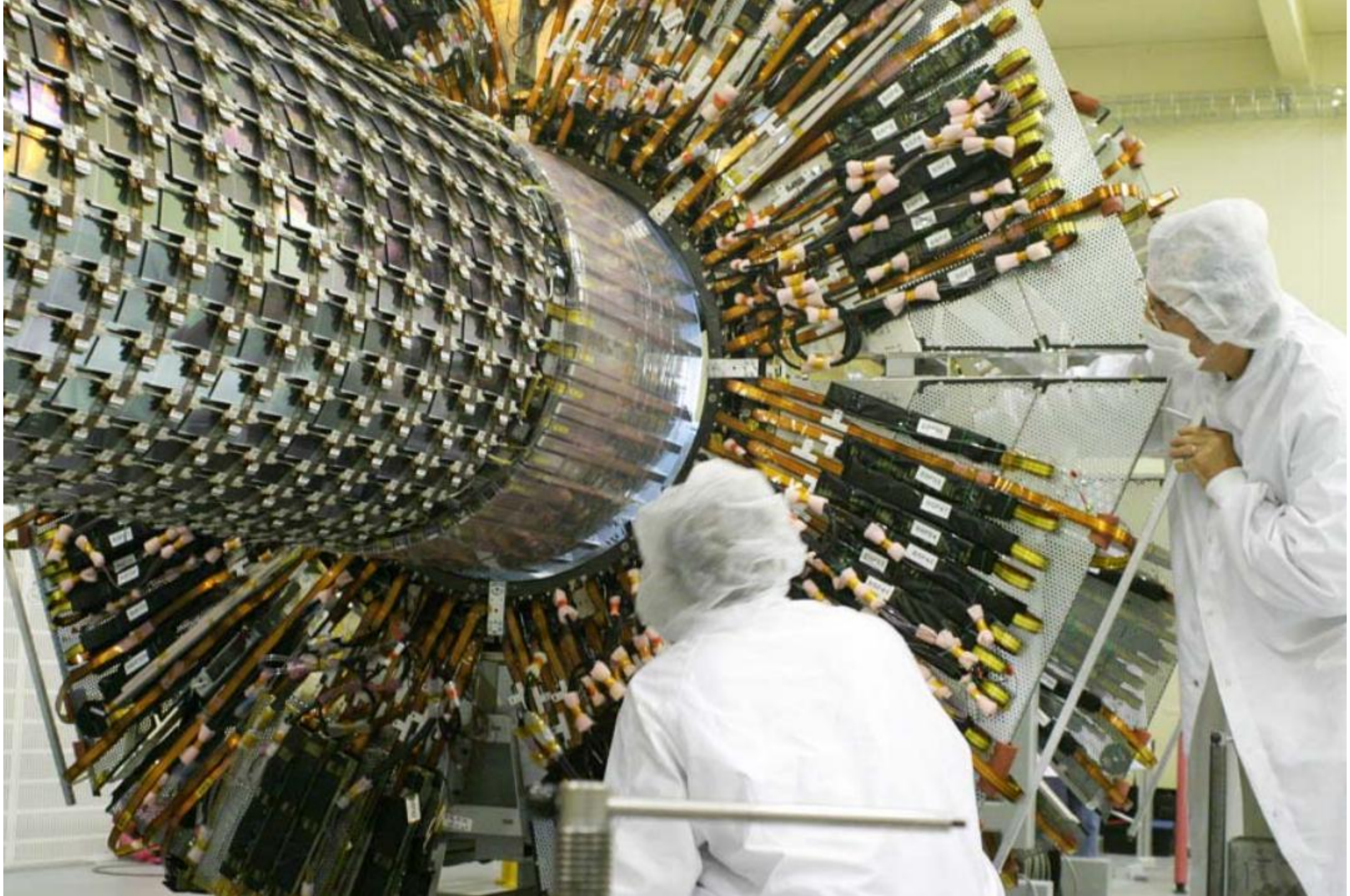


The ATLAS Detector

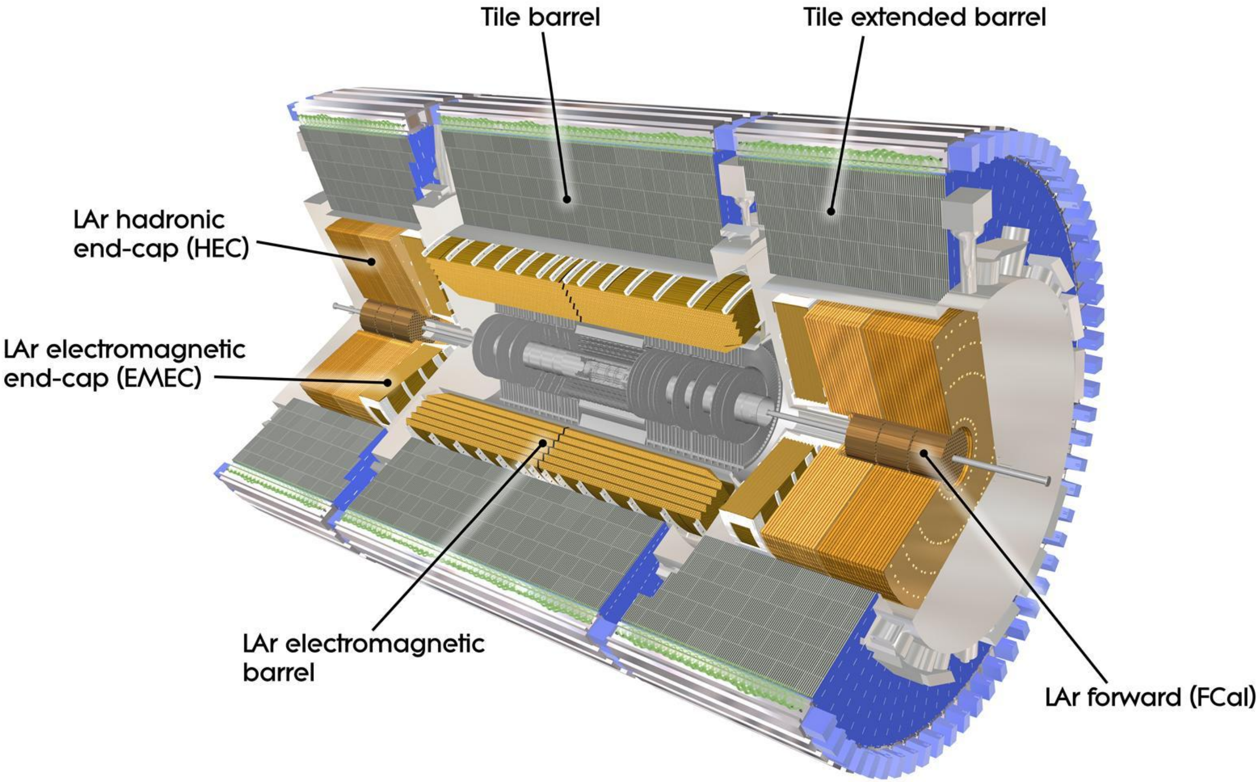


Inner Detector





Calorimeter system

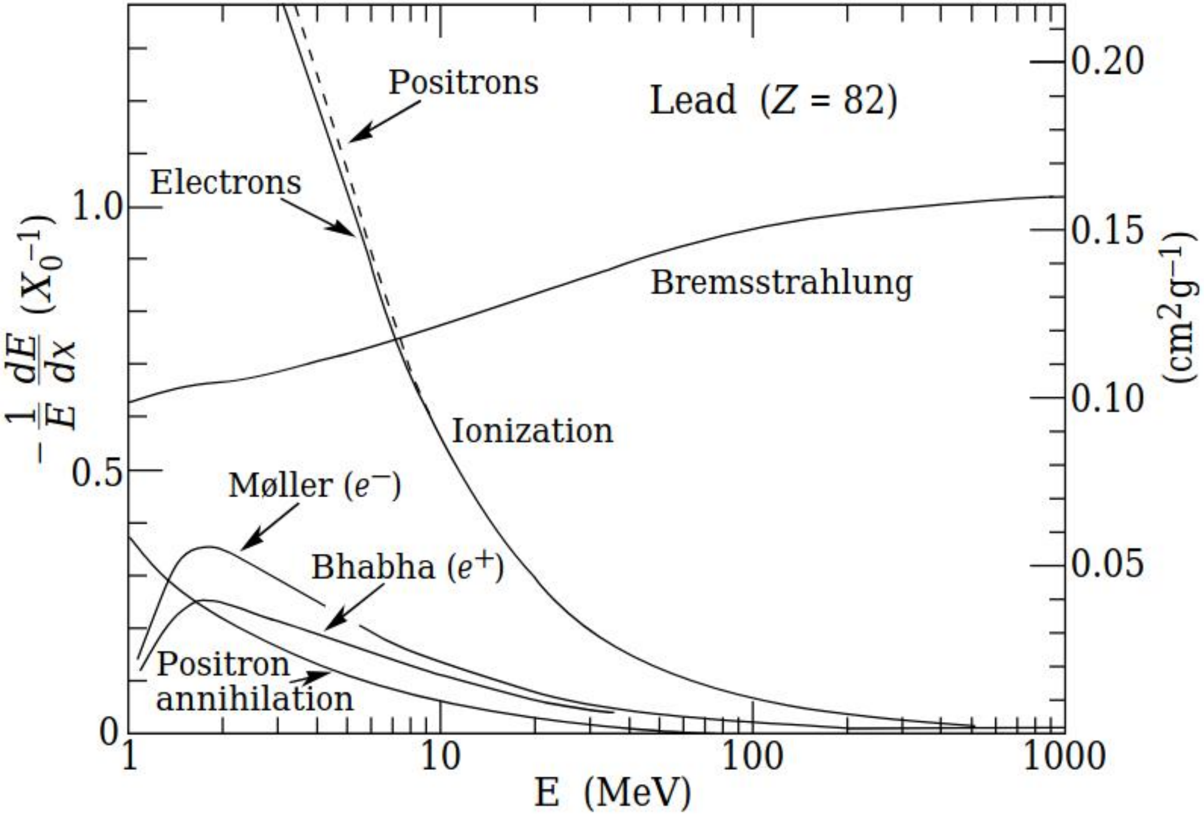


Calorimetry

$$-\frac{dE}{dx} = \frac{E}{X_0}$$

$$X_0 = \frac{716.4 \cdot A}{Z(Z+1)\log\left(287/\sqrt{Z}\right)}$$

Z = Atomic number of absorber
A = Atomic mass of absorber



http://pdg.lbl.gov/2009/reviews/rpp2009-rev-passage-particles-matter.pdf

Calorimetry

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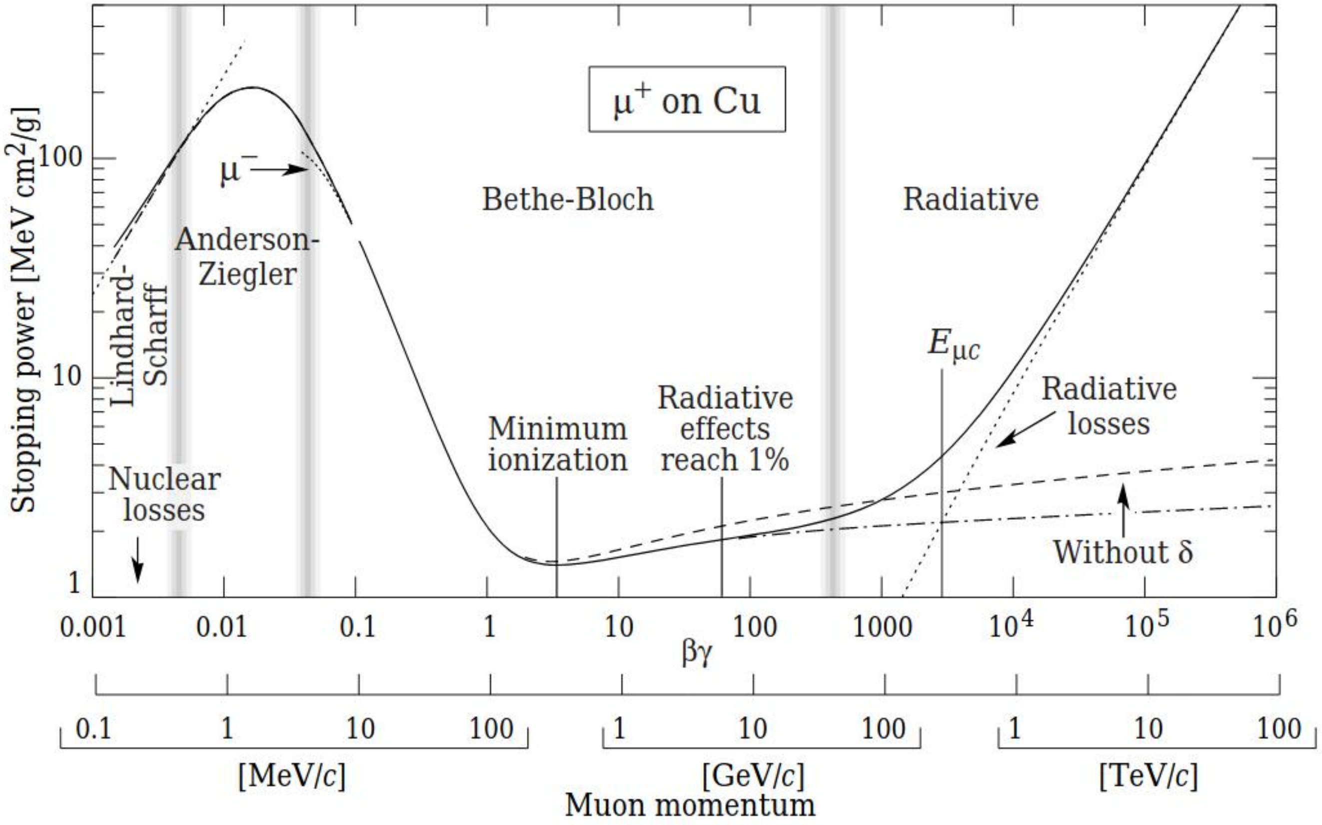
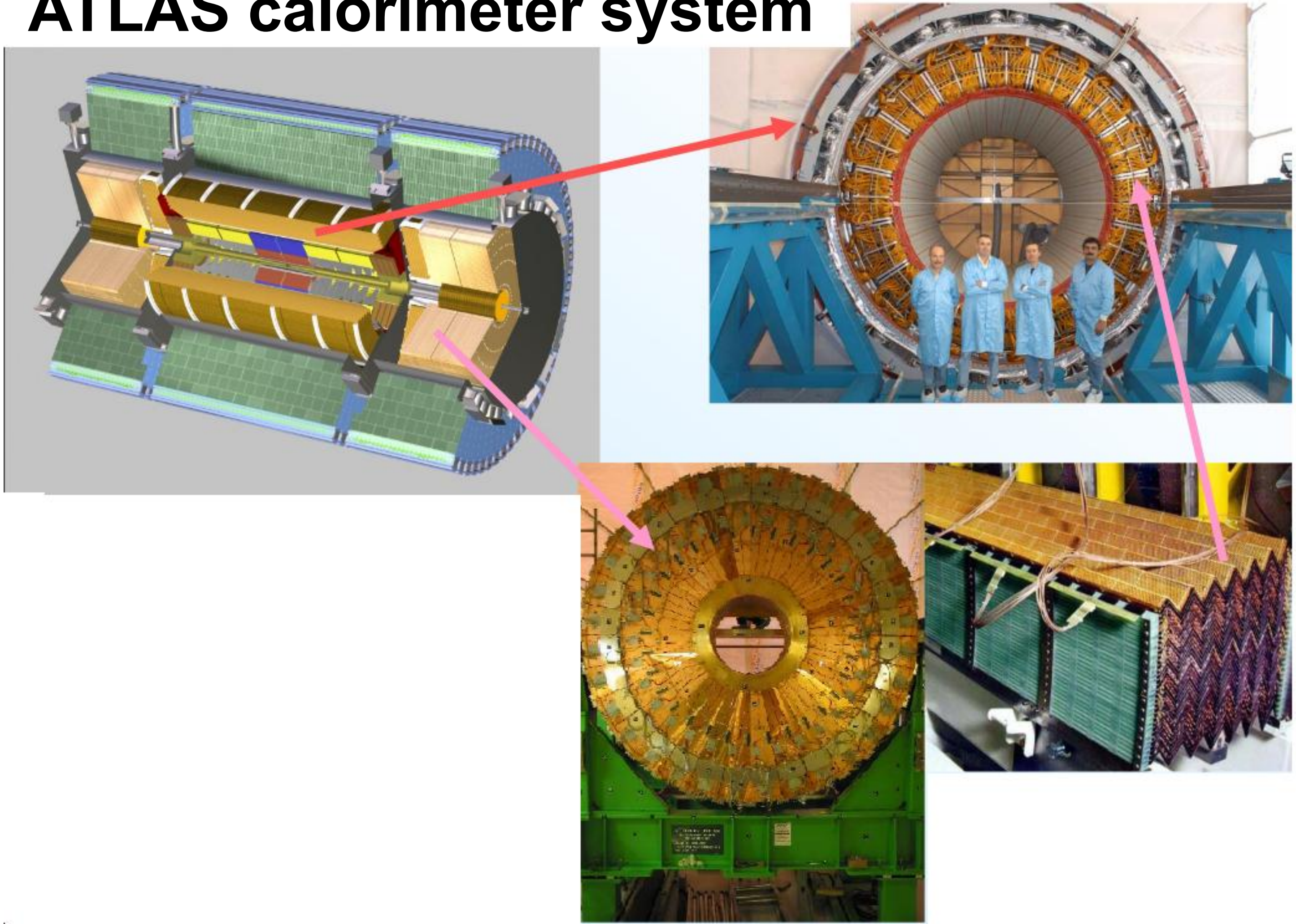
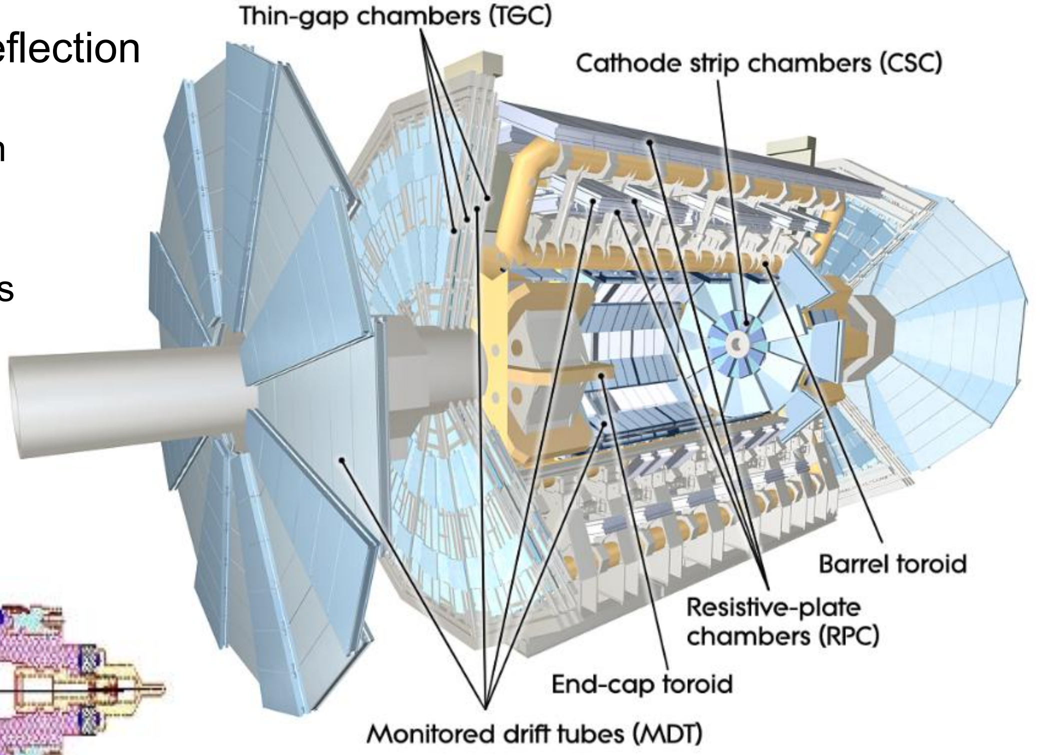


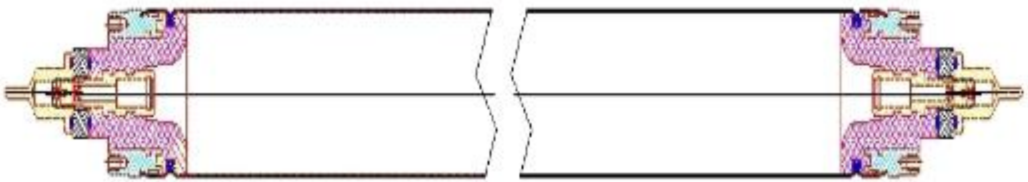
ATLAS calorimeter system



Muon spectrometer

- The muon spectrometer measures the deflection of the muon tracks in the magnetic field
  - Based on gaseous detectors for precision tracking and triggering
- Characteristics:
  - Momentum resolution of 2-10% for muons with a pT between 10GeV - 1TeV
  - Spatial resolution of 30 μm

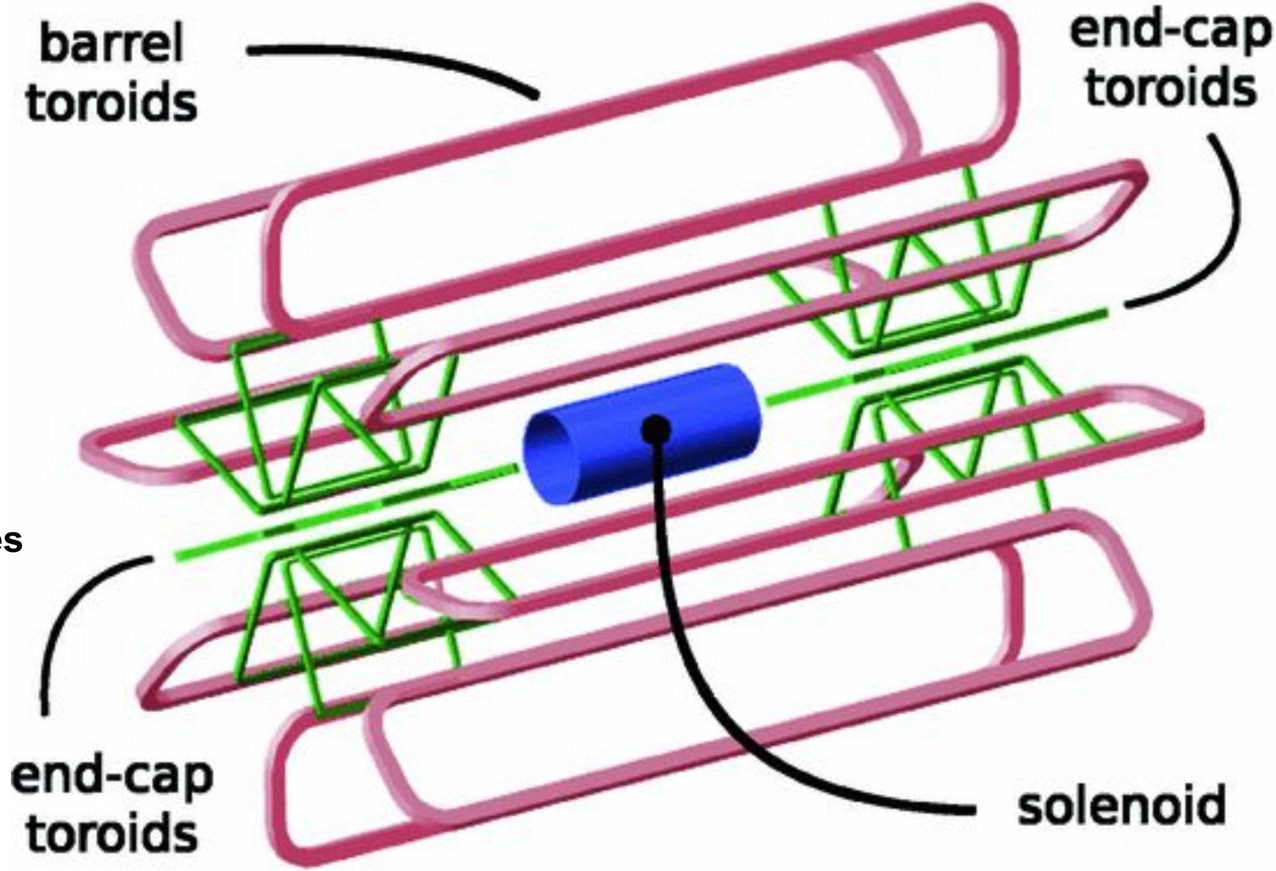




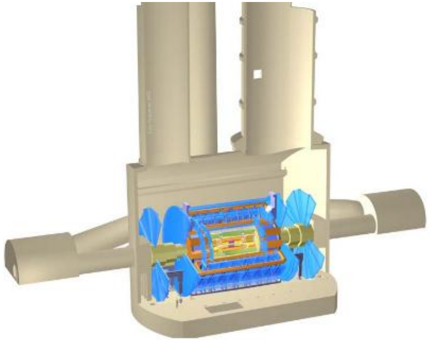
Construction of muon chambers

Magnet system

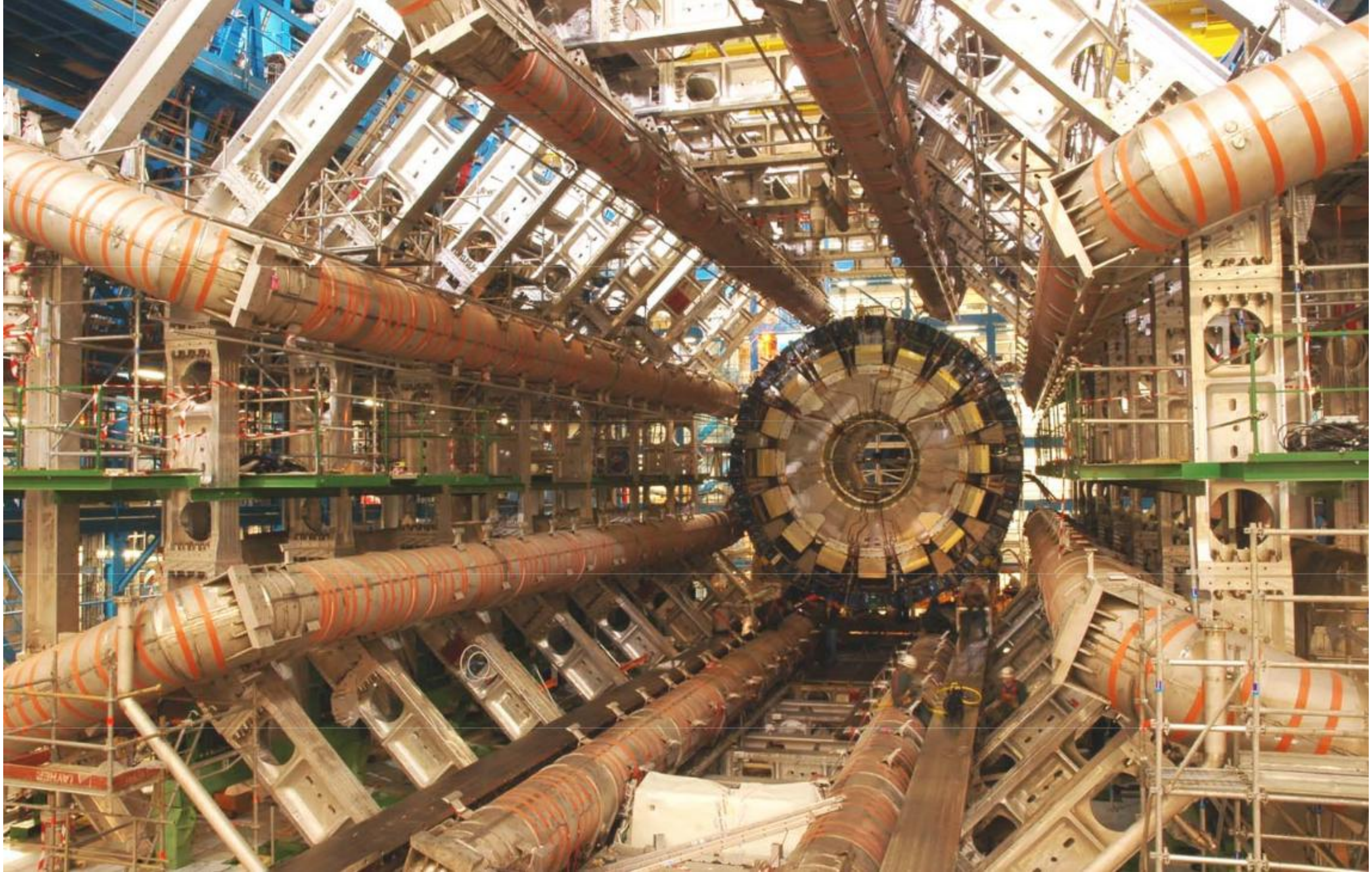
- Toroids:
  - Field strength: 4T
- Solenoid
  - Field strength: 2T
- **Responsible for bending trajectories of charged particles**
  - **Enables measurement of momenta**



Construction



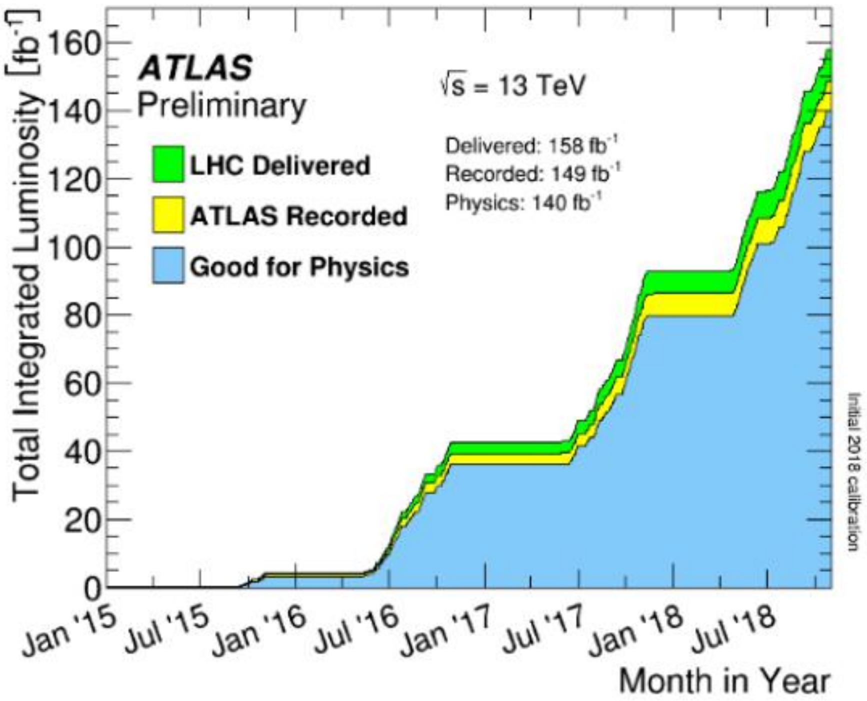

HWX 159

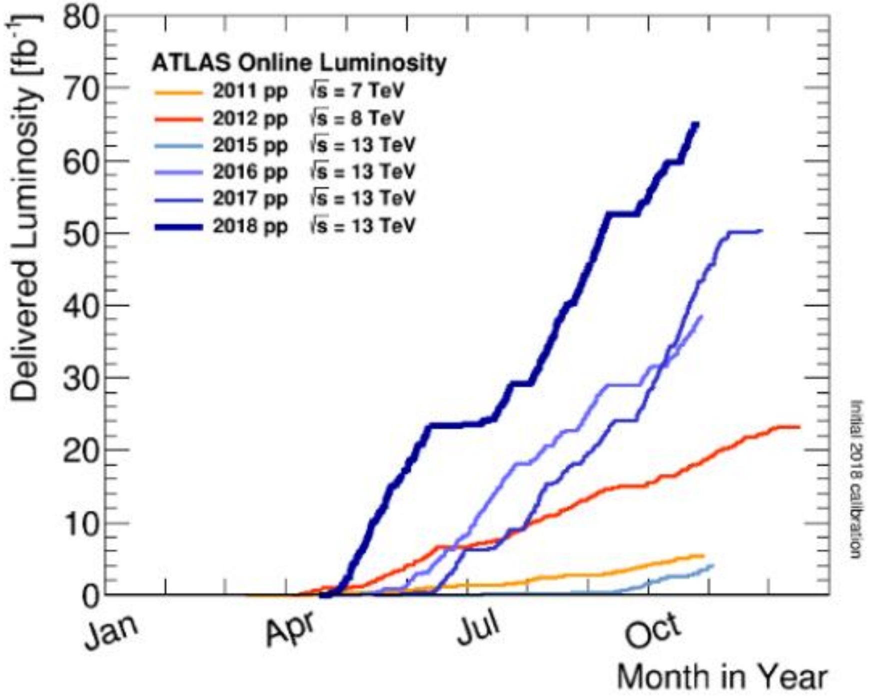


Trigger system

Grid computing

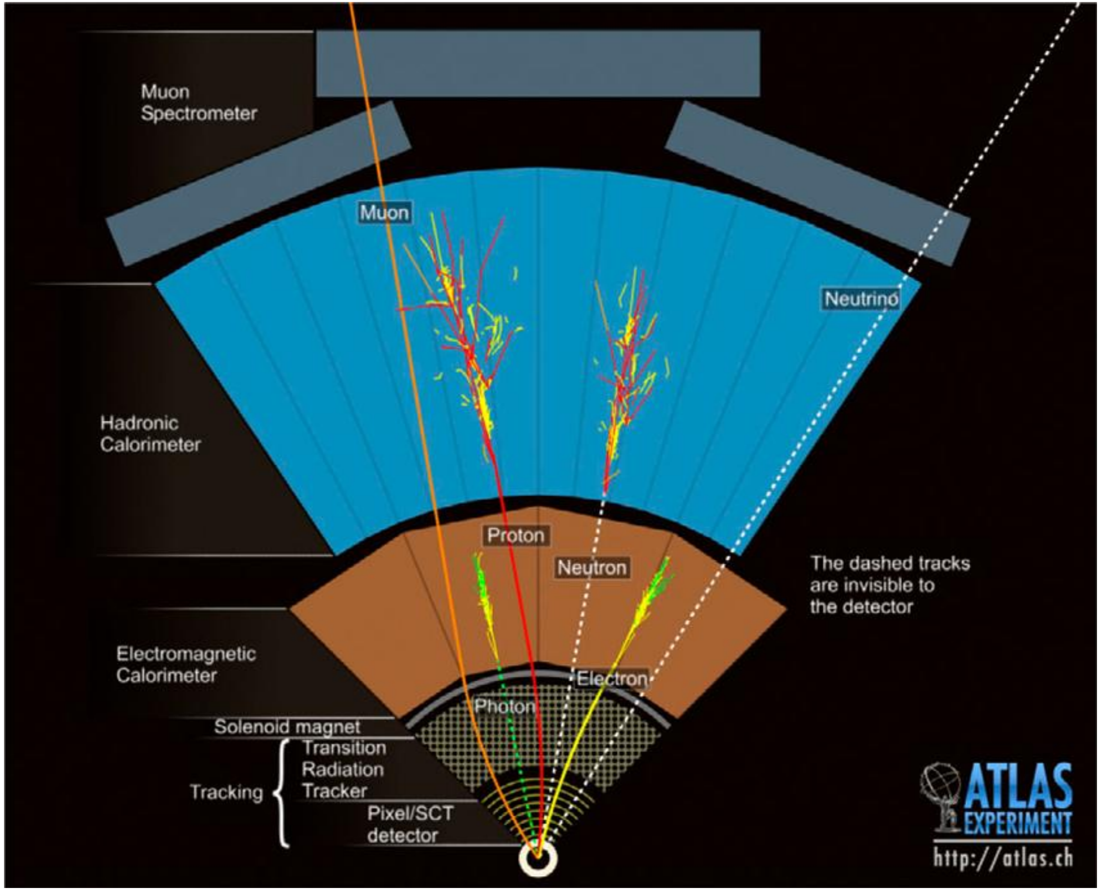
Data taking


ATLAS
Preliminary
√s = 13 TeV
Delivered: 158 fb⁻¹
Recorded: 149 fb⁻¹
Physics: 140 fb⁻¹
LHC Delivered
ATLAS Recorded
Good for Physics
Total Integrated Luminosity [fb⁻¹]
Month in Year
Jan '15
Jul '15
Jan '16
Jul '16
Jan '17
Jul '17
Jan '18
Jul '18
Initial 2018 calibration


ATLAS Online Luminosity
2011 pp √s = 7 TeV
2012 pp √s = 8 TeV
2015 pp √s = 13 TeV
2016 pp √s = 13 TeV
2017 pp √s = 13 TeV
2018 pp √s = 13 TeV
Delivered Luminosity [fb⁻¹]
Month in Year
Jan
Apr
Jul
Oct
Initial 2018 calibration

Particle identification

- **Hadronic particle shower**
  - Cone shaped jets build from calorimeter clusters or tracks
- **Muons**
  - Combined tracks from Inner Detector and Spectrometer
- **Electrons**
  - Inner Detector track
  - Energy clusters in calorimeter system

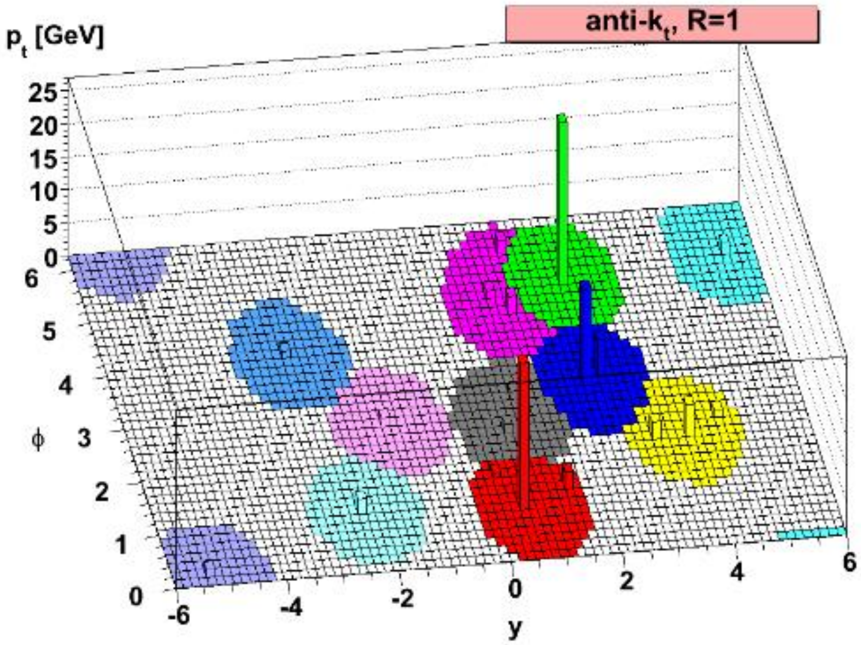


Jets

- **Jets:** Collimated bunches of stable hadrons, originating from partons (quarks and gluons) after fragmentation and hadronization
- Require collinear- and infrared-safety i.e. jets are unchanged by:
  - Collinear splitting
  - Soft emissions
- LHC experiments preferrably use so called **sequential clustering algorithms**
- Application: Calculate for all pairs of particles i an j:

$$d_{ij} = \min(k_{i,T}^{2p}, k_{j,T}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{i,T}^{2p}$$



The pair with the smallest d_{ij} is clustered if $d_{ij} < d_{iB}$, for $d_{iB} < d_{ij}$ object i is called a jet

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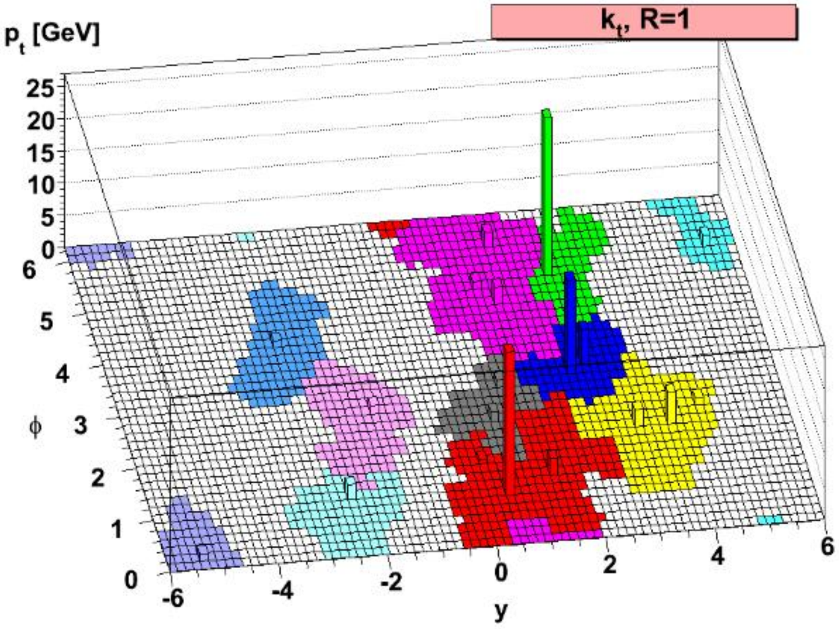

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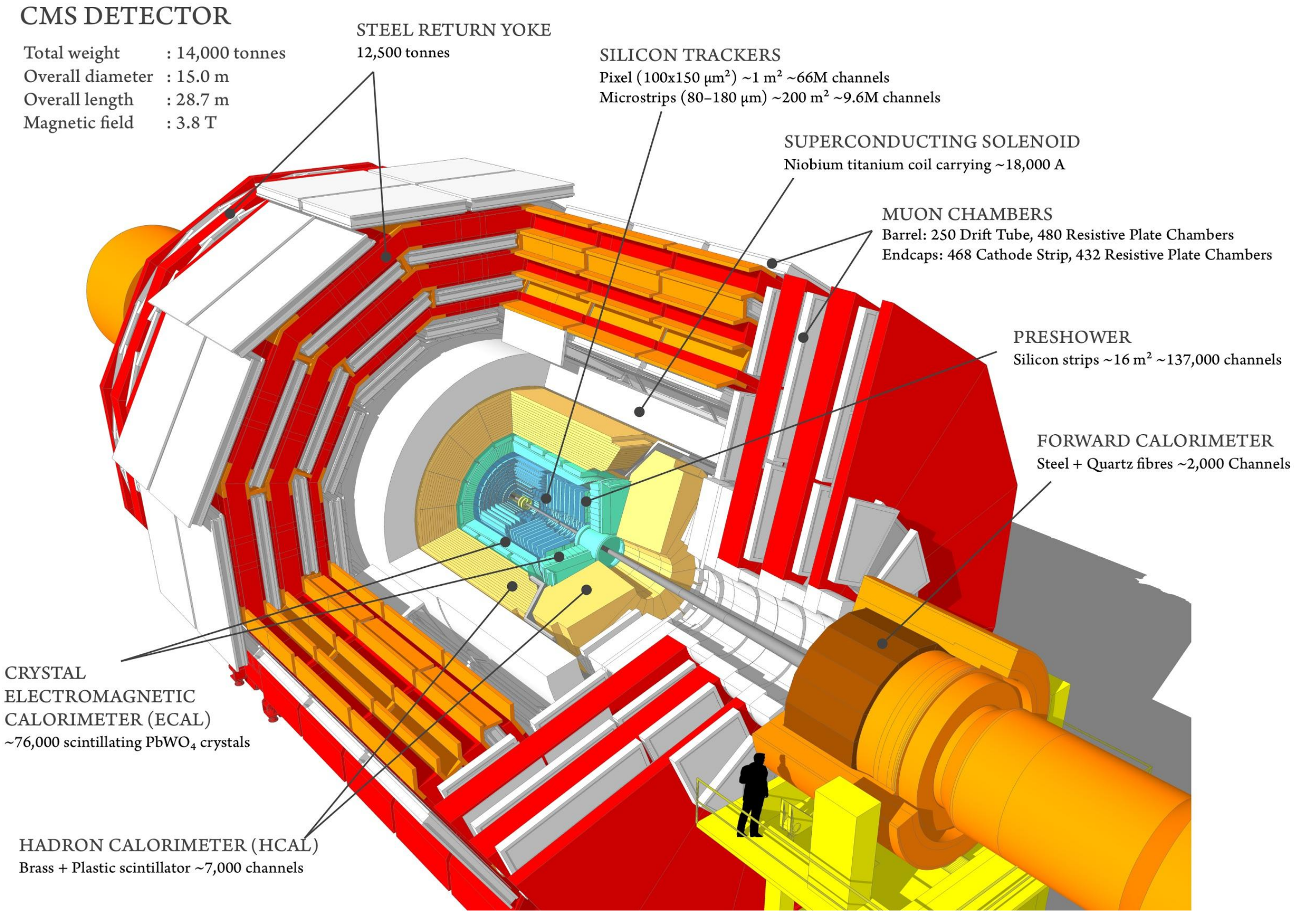
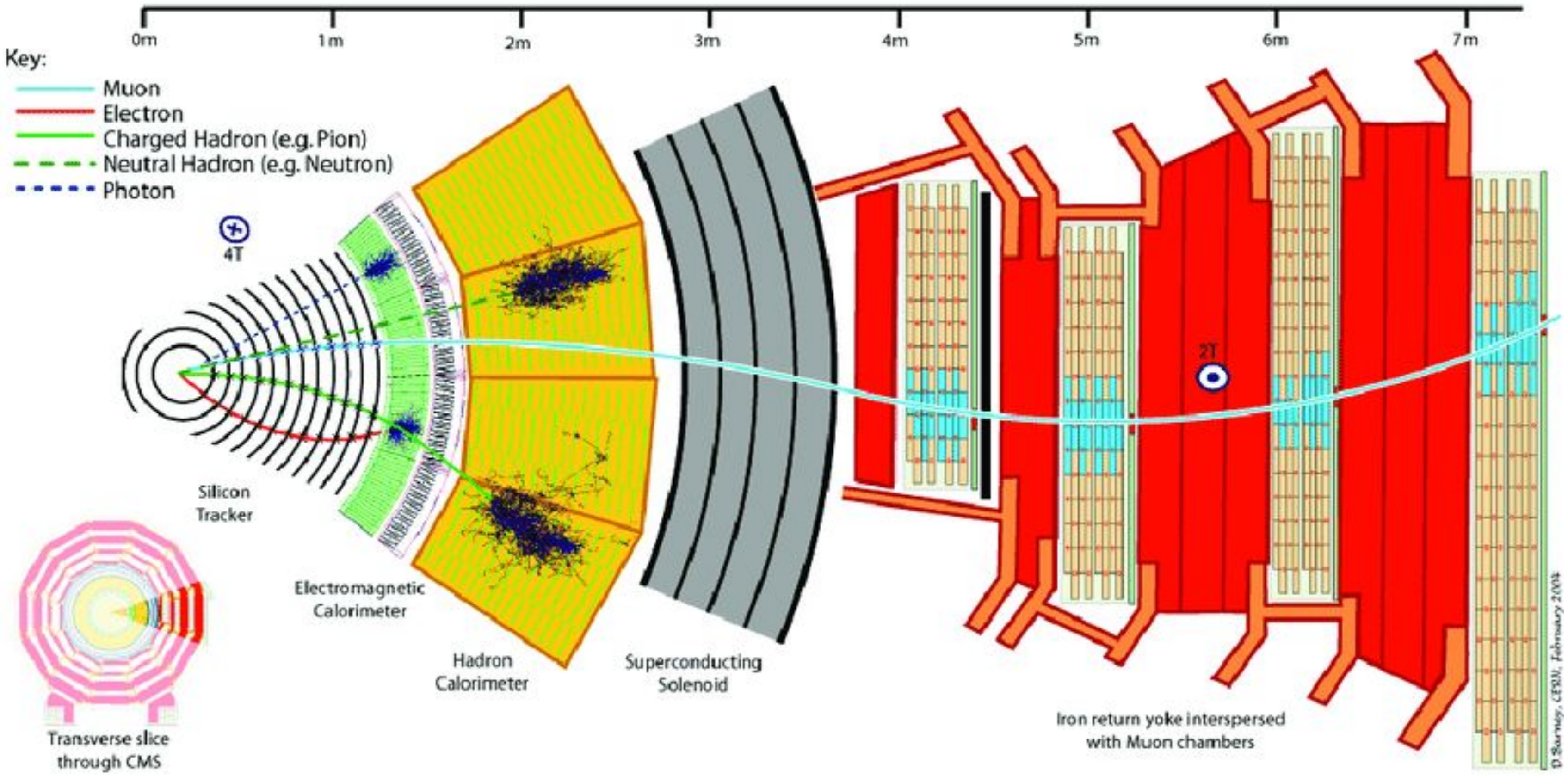
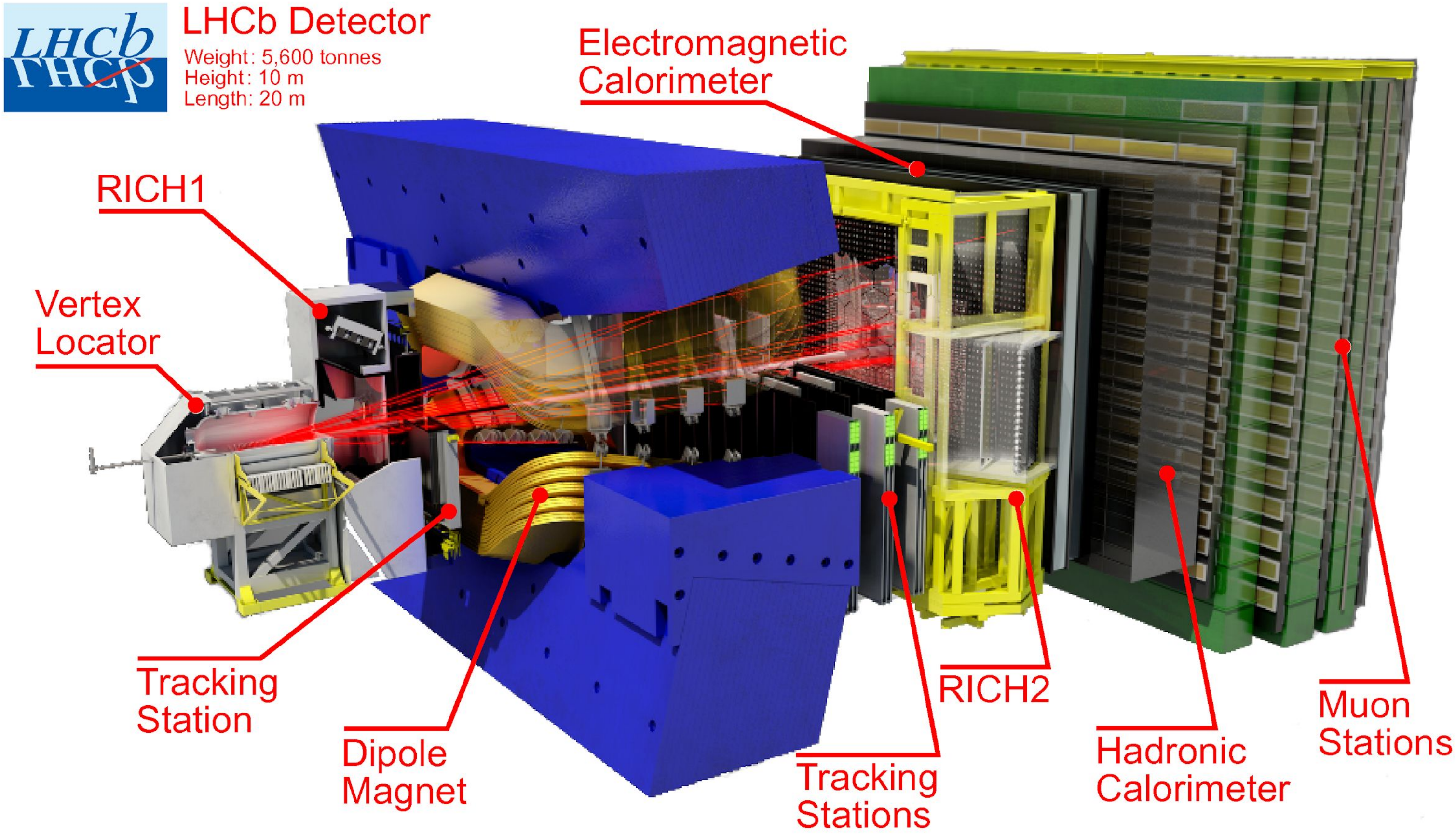
The CMS Detector



The CMS Detector

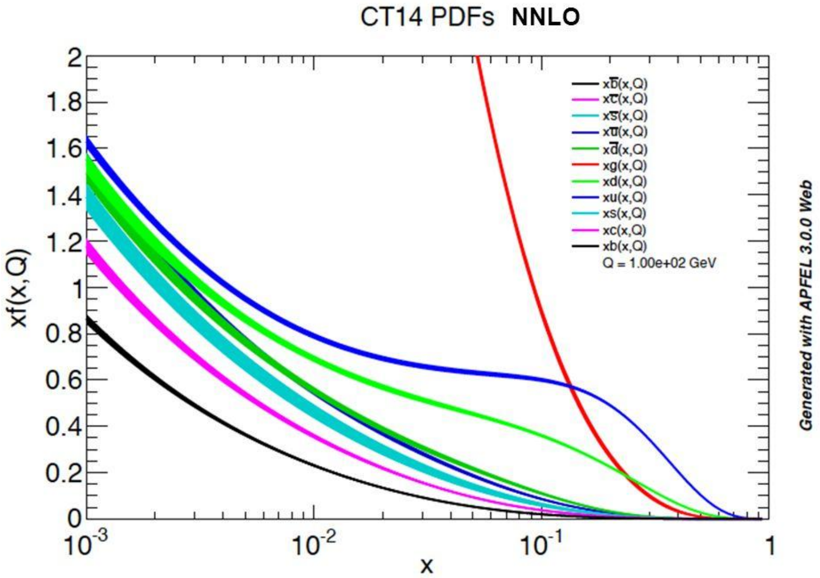


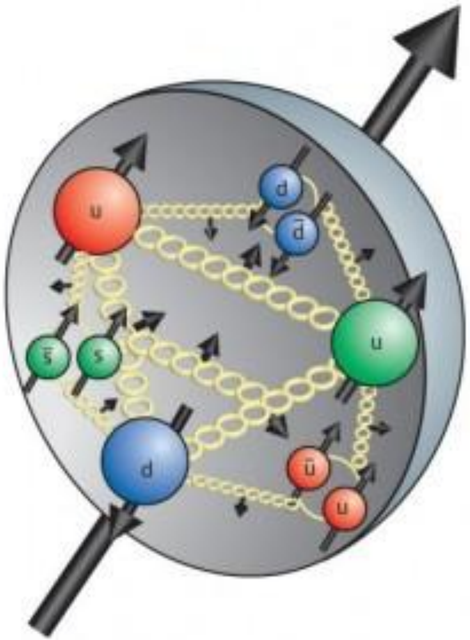
The LHCb Detector



Monte Carlo simulation

- Observations in data are compared to SM predictions (Monte Carlo simulations)
- **Use factorisation approach**:
  - Parton distribution functions (PDF)
  - Hard process (matrix element/scattering amplitude)
  - Parton shower (fragmentation, hadronization, decay of unstable particles)
  - Detector simulation (including overlay with pile-up)





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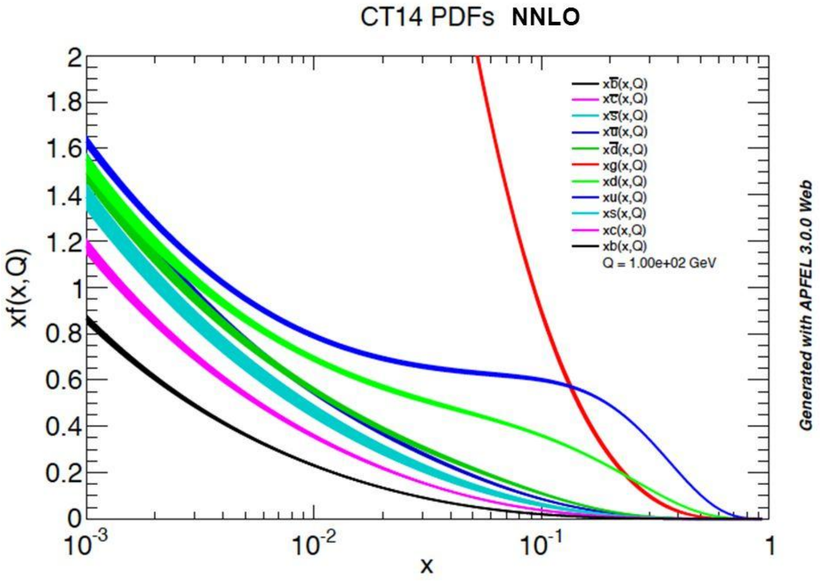
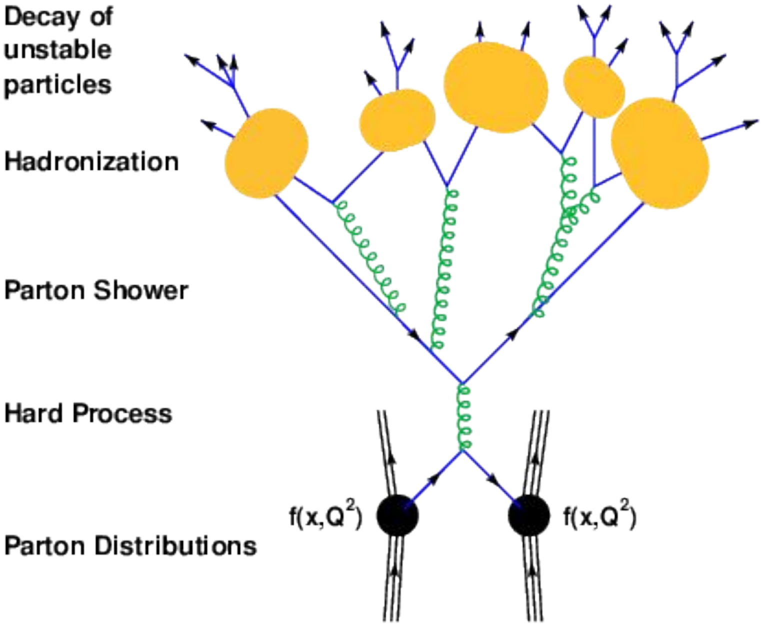
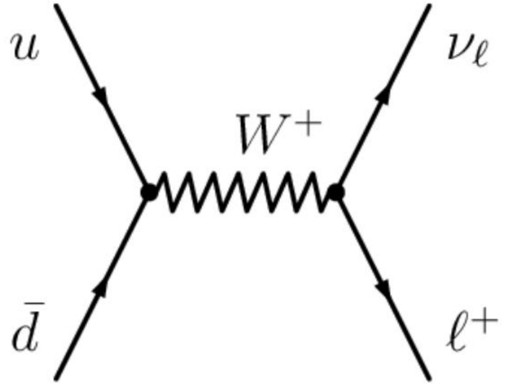


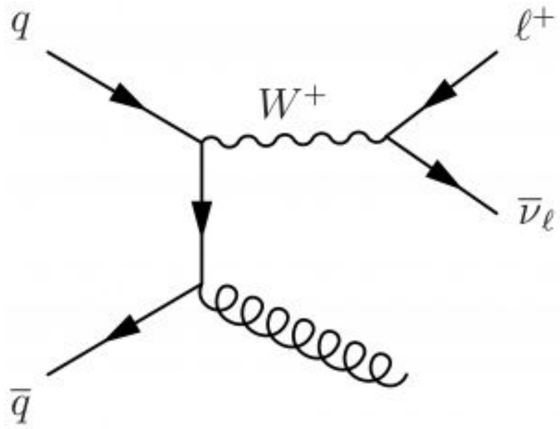


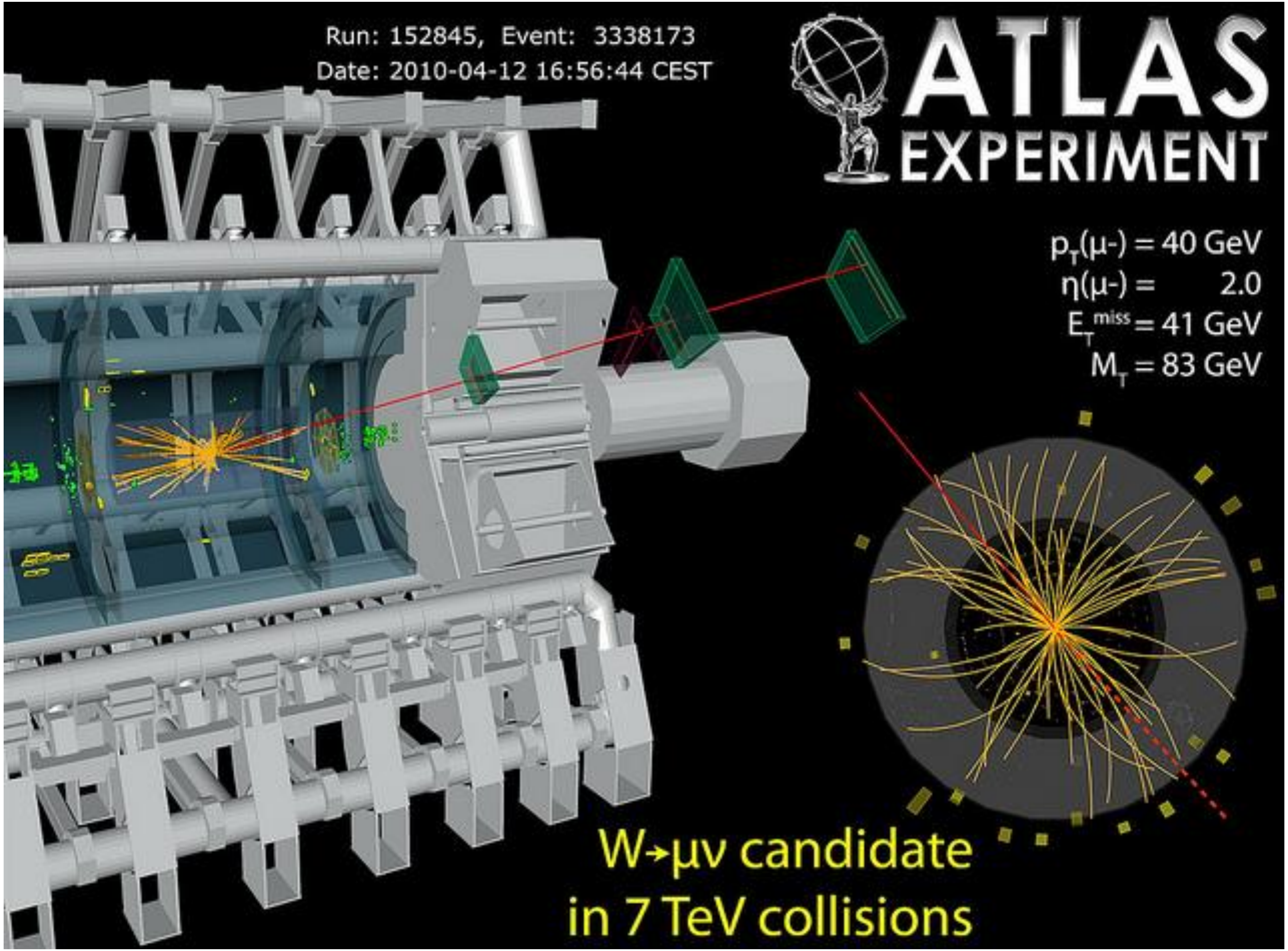
W boson production and decay

- W boson decay **(Lepton universality):**
  - All three types of charged lepton particles interact in the same way with other particles.
  - The three lepton types are created equally often in particle transformations, or decays (once differences in their mass are accounted for)

Decay Mode	BR
$W \to e\nu$	$(10.71 \pm 0.16)\%$
$W \to \mu\nu$	$(10.63 \pm 0.15)\%$
$W \to \tau\nu$	$(11.38 \pm 0.21)\%$
$W \to$ hadrons	$(67.41 \pm 0.27)\%$

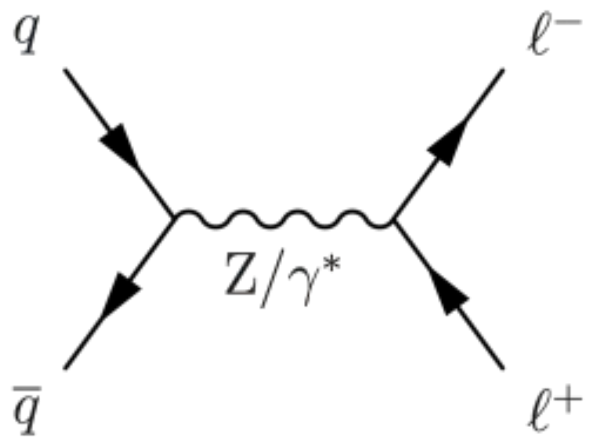


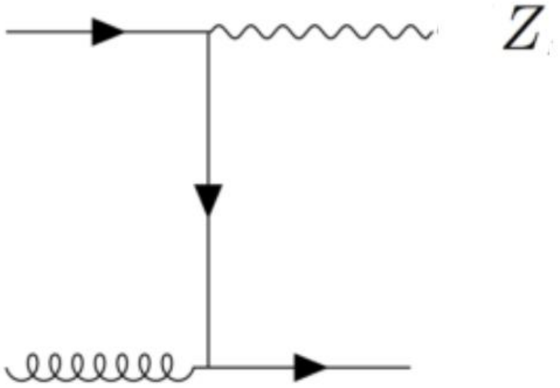


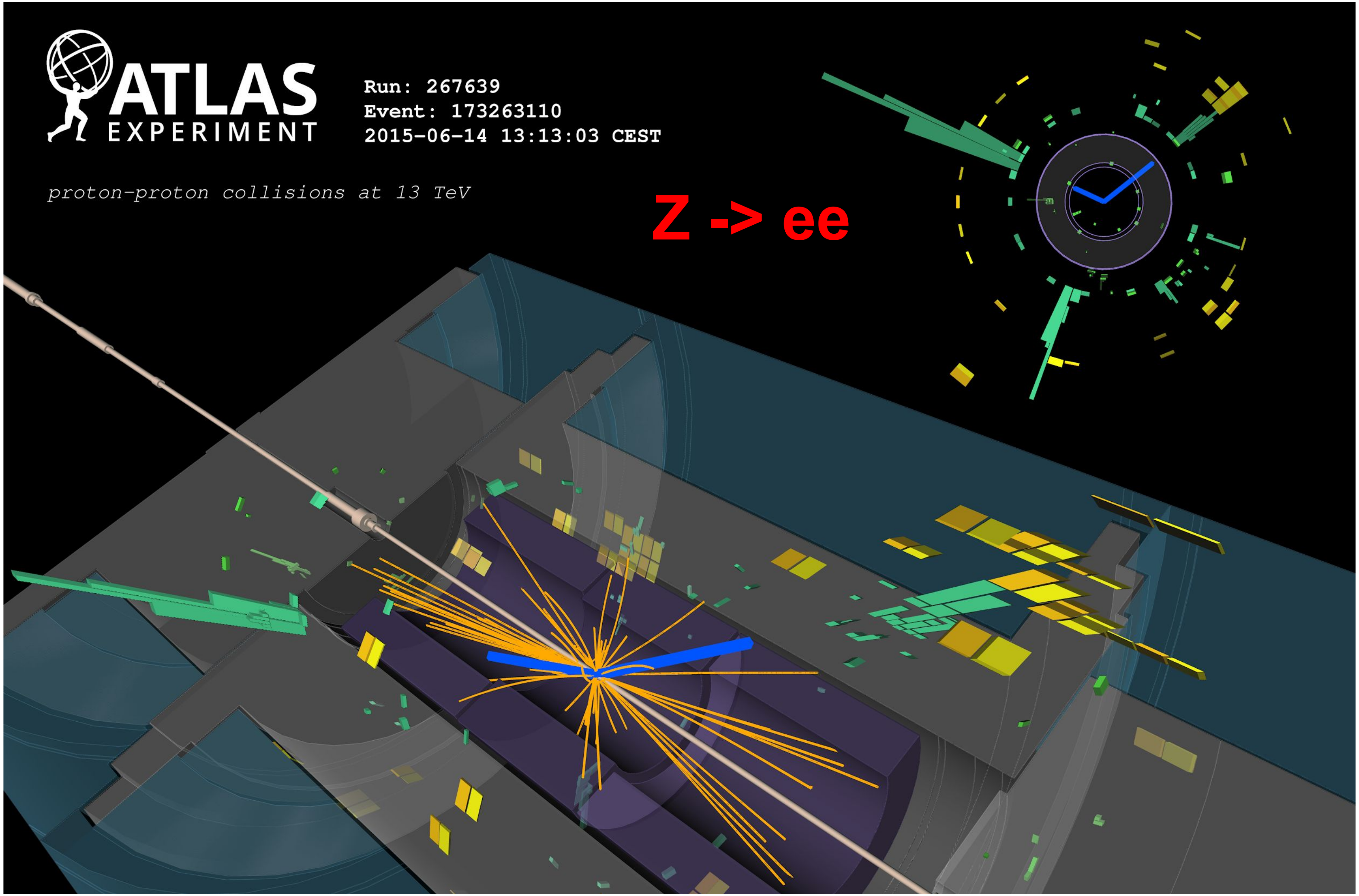

Run: 152845, Event: 3338173
Date: 2010-04-12 16:56:44 CEST
ATLAS
EXPERIMENT
$p_T(\mu-) = 40$ GeV
$\eta(\mu-) = 2.0$
$E_T^{miss} = 41$ GeV
$M_T = 83$ GeV
W→μν candidate
in 7 TeV collisions

Z + jets production and decay

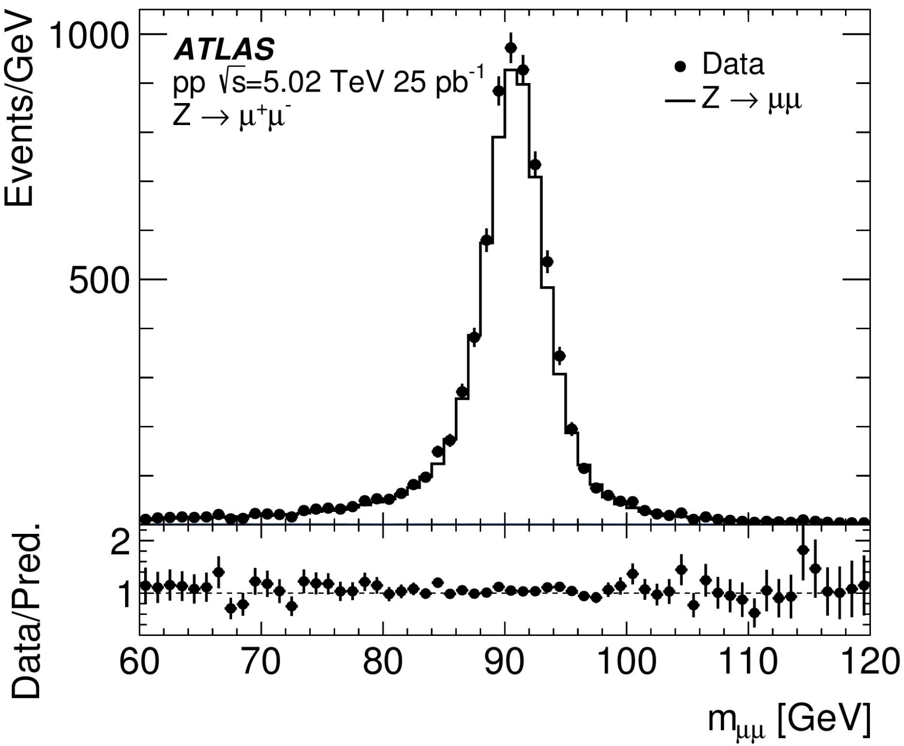
Decay Mode	BR
$Z \rightarrow e^+ e^-$	$(3.3632 \pm 0.0042)\%$
$Z \rightarrow \mu^+ \mu^-$	$(3.3662 \pm 0.0066)\%$
$Z \rightarrow \tau^+ \tau^-$	$(3.3696 \pm 0.0083)\%$
$Z \rightarrow$ invisible	$(20.000 \pm 0.055)\%$
$Z \rightarrow$ hadrons	$(69.911 \pm 0.056)\%$

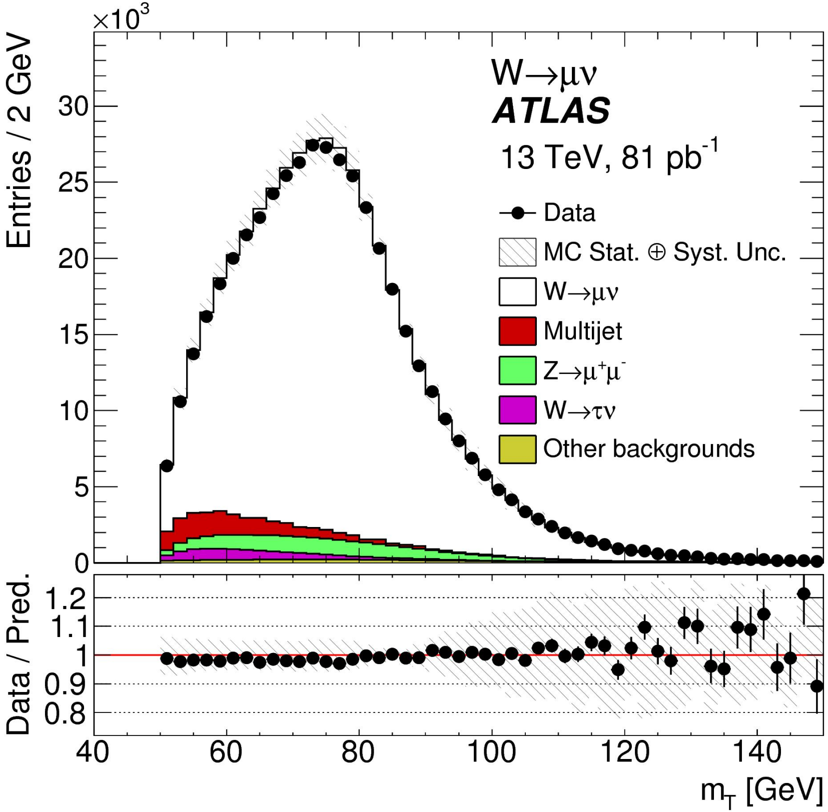


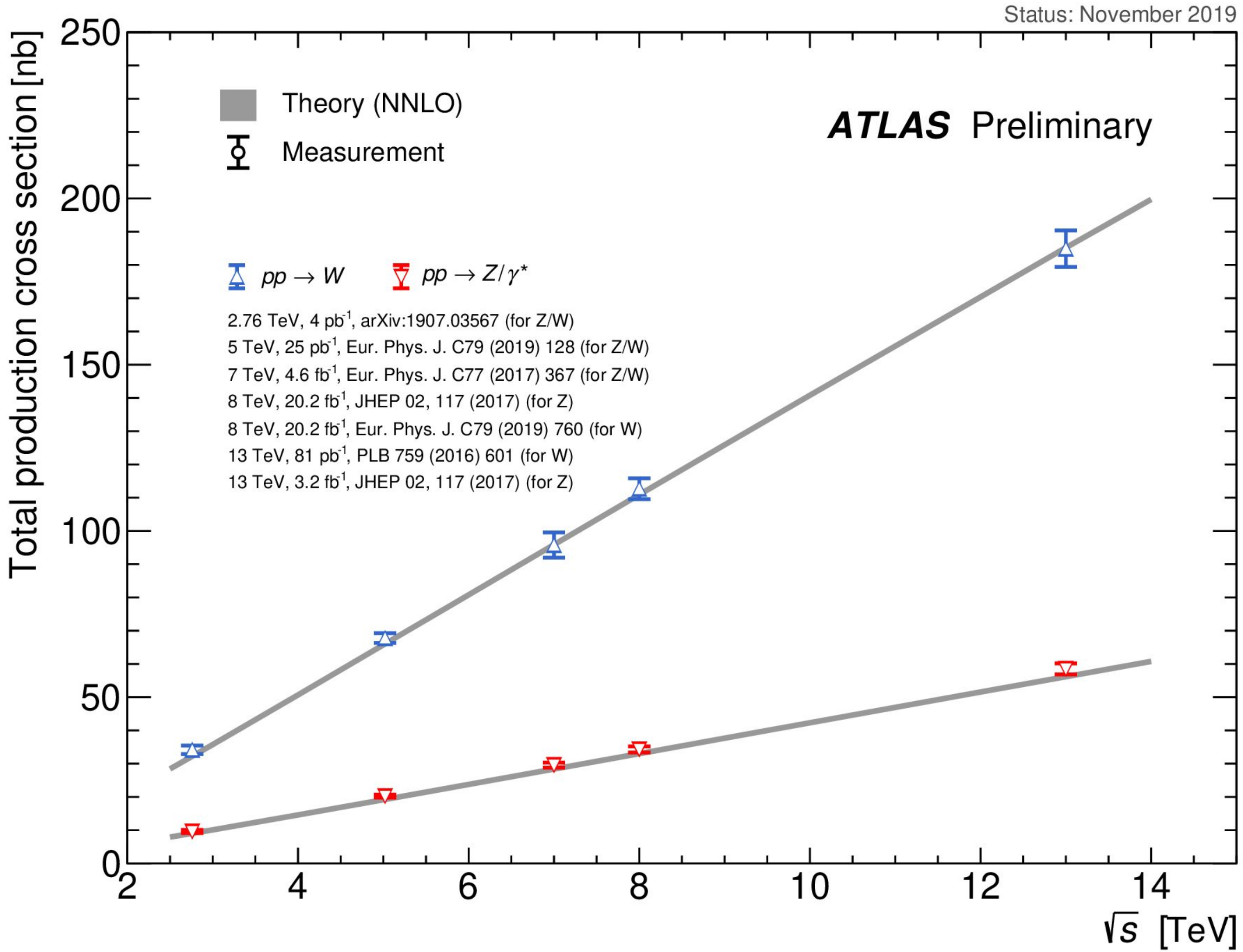



ATLAS
EXPERIMENT
Run: 267639
Event: 173263110
2015-06-14 13:13:03 CEST
proton-proton collisions at 13 TeV
Z -> ee

W/Z production



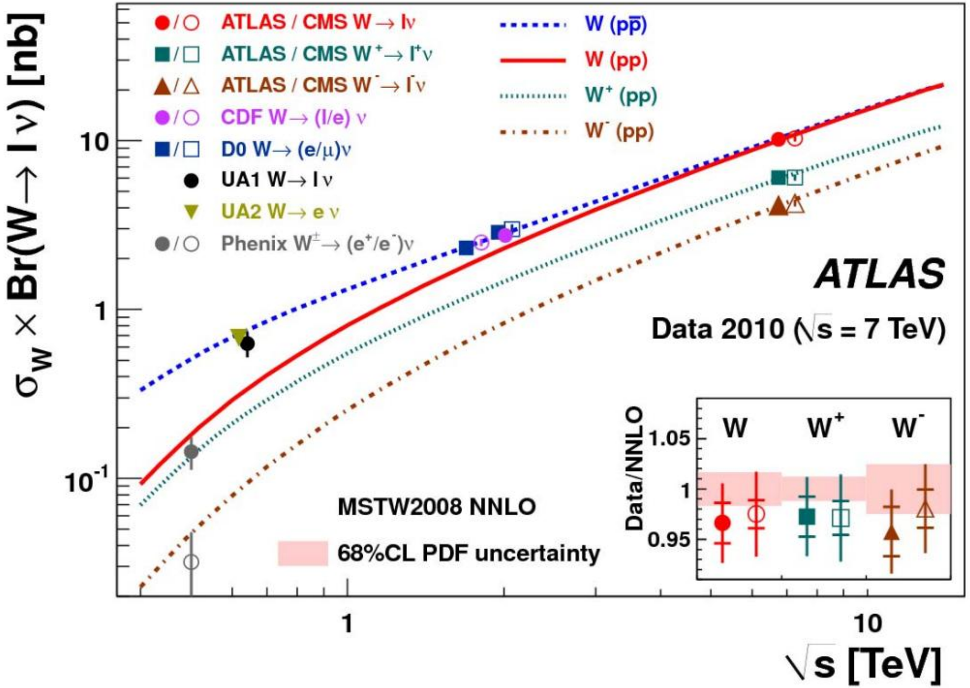


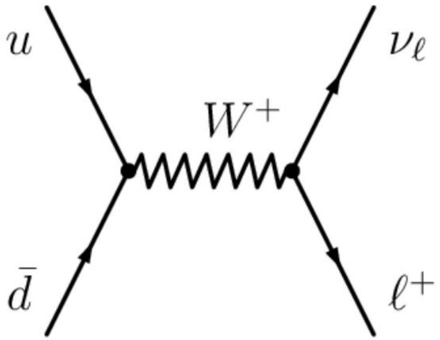


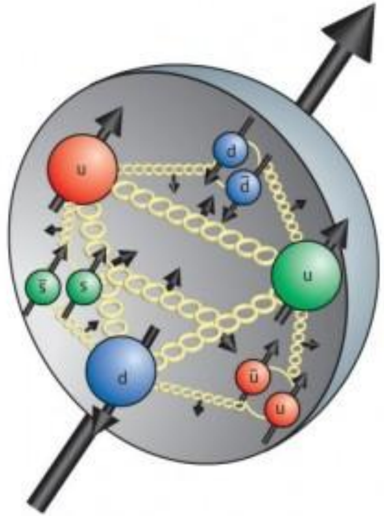
Status: November 2019
Total production cross section [nb]
Theory (NNLO)
Measurement
ATLAS Preliminary
pp → W
pp → Z/γ*
2.76 TeV, 4 pb-1, arXiv:1907.03567 (for Z/W)
5 TeV, 25 pb-1, Eur. Phys. J. C79 (2019) 128 (for Z/W)
7 TeV, 4.6 fb-1, Eur. Phys. J. C77 (2017) 367 (for Z/W)
8 TeV, 20.2 fb-1, JHEP 02, 117 (2017) (for Z)
8 TeV, 20.2 fb-1, Eur. Phys. J. C79 (2019) 760 (for W)
13 TeV, 81 pb-1, PLB 759 (2016) 601 (for W)
13 TeV, 3.2 fb-1, JHEP 02, 117 (2017) (for Z)
√s [TeV]

Charge asymmetry in W boson production

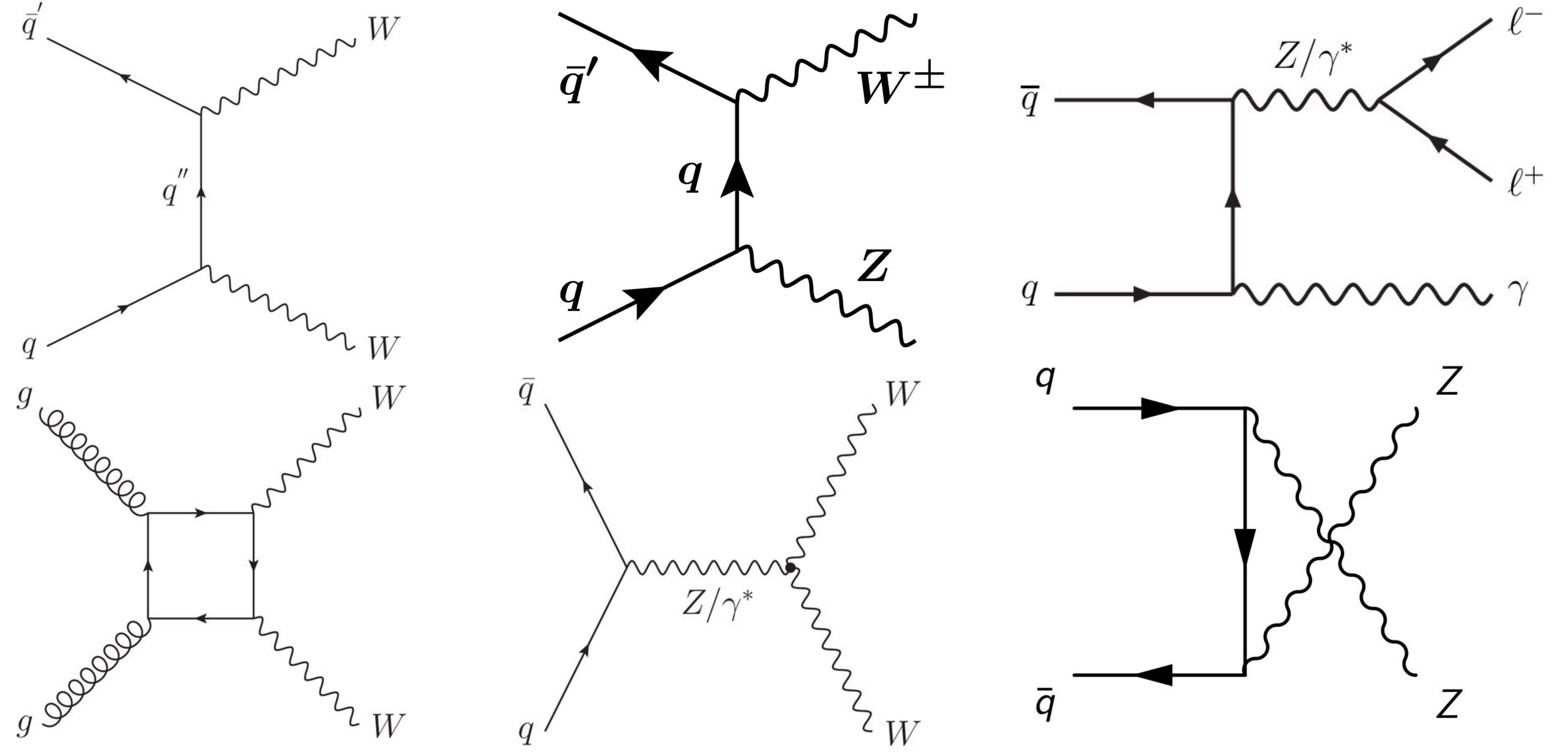
- **PDFs of u and d quarks in the proton differ** (as largely due to there being two valence u quarks and one valence d quark)

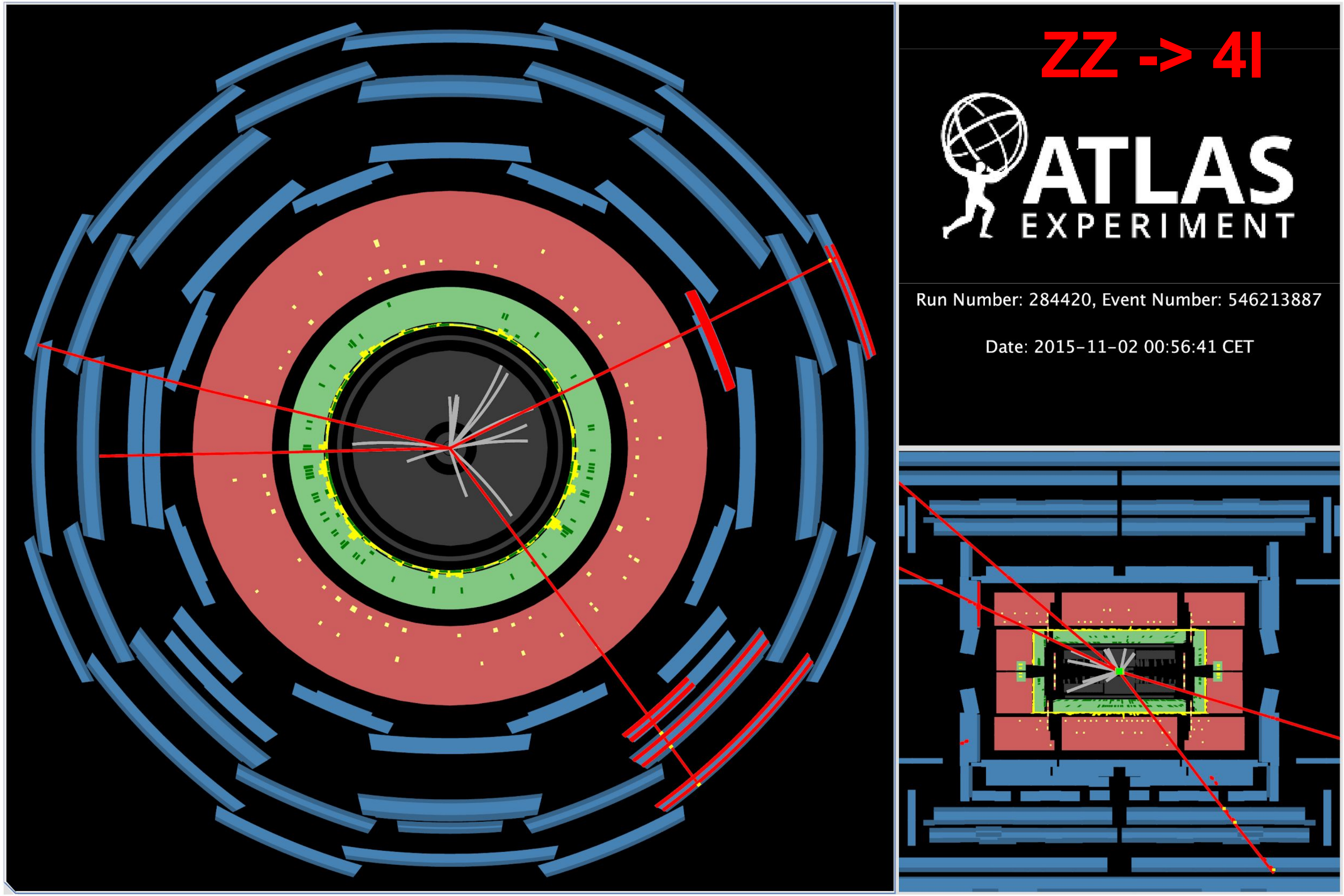






Diboson production (WW, WZ, ZZ)




ZZ -> 4l
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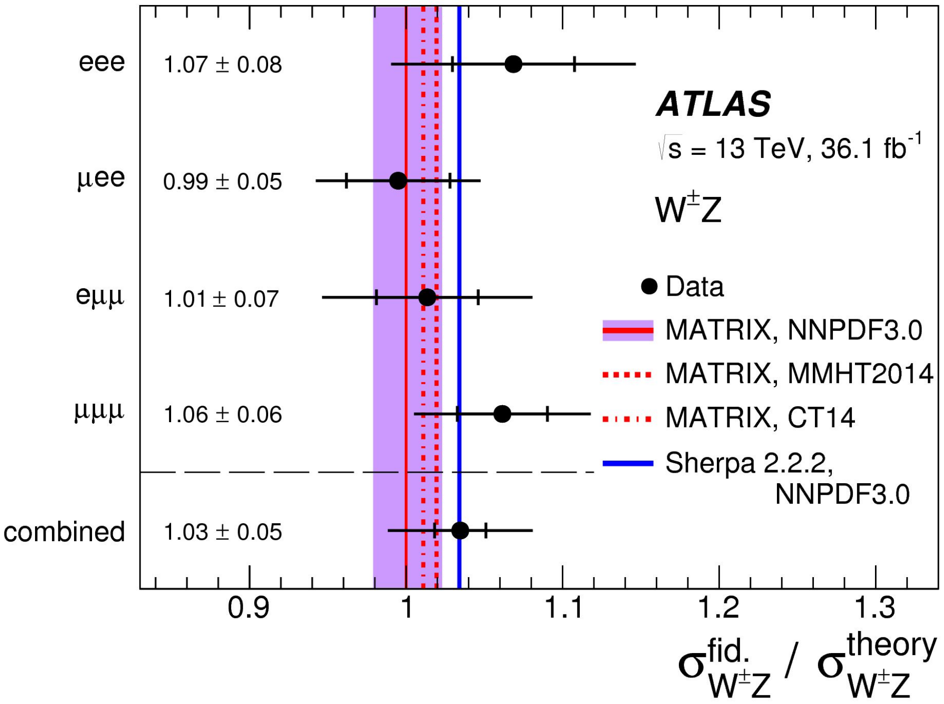
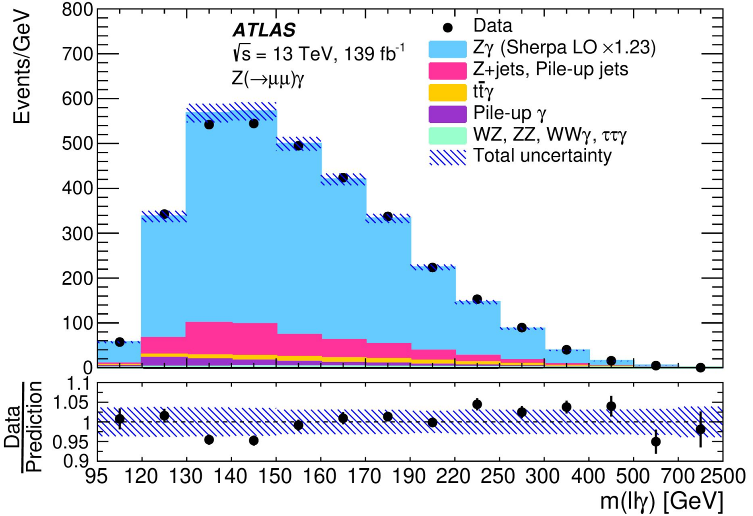
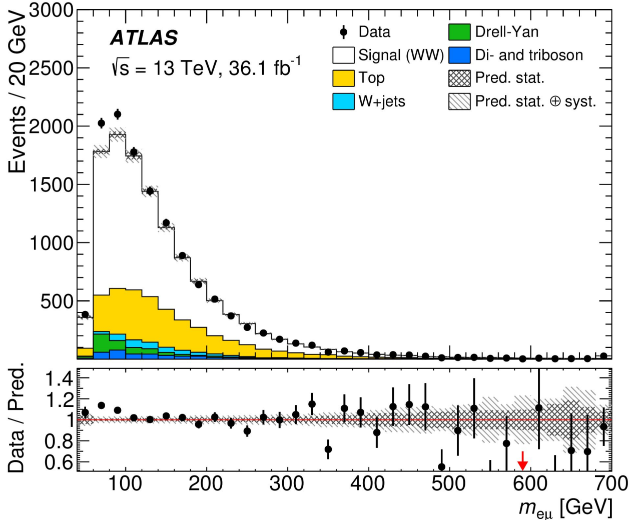
EXPERIMENT
Run Number: 284420, Event Number: 546213887
Date: 2015-11-02 00:56:41 CET

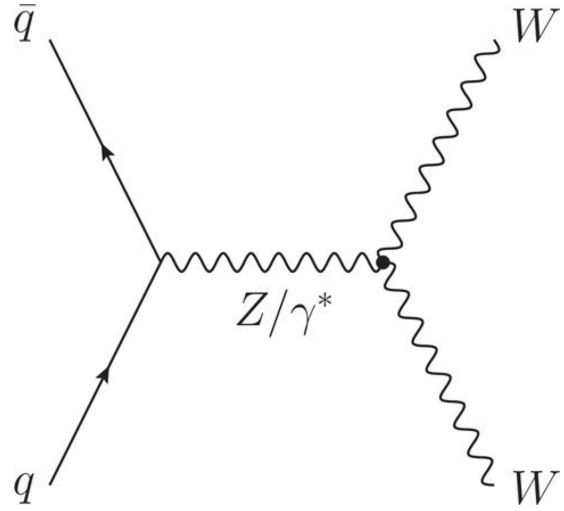

eee
1.07 ± 0.08
μee
0.99 ± 0.05
eμμ
1.01 ± 0.07
μμμ
1.06 ± 0.06
combined
1.03 ± 0.05
ATLAS
√s = 13 TeV, 36.1 fb-1
W±Z
Data
MATRIX, NNPDF3.0
MATRIX, MMHT2014
MATRIX, CT14
Sherpa 2.2.2, NNPDF3.0
0.9
1
1.1
1.2
1.3
σfid. W±Z / σtheory W±Z

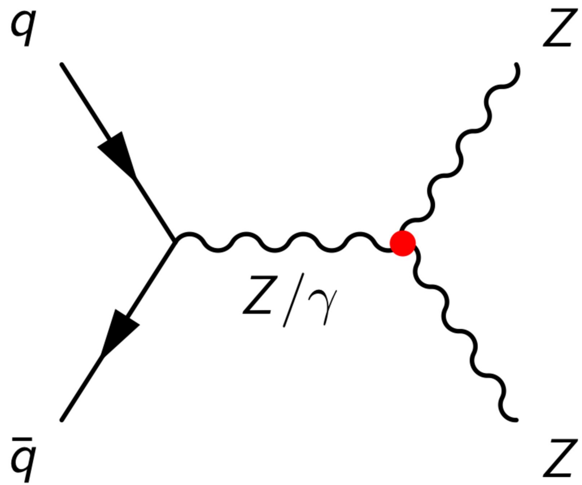

ATLAS
√s = 13 TeV, 139 fb-1
Z(→μμ)γ
Data
Zγ (Sherpa LO ×1.23)
Z+jets, Pile-up jets
tt̄γ
Pile-up γ
WZ, ZZ, WWγ, ττγ
Total uncertainty
Events/GeV
Data / Prediction
m(llγ) [GeV]


ATLAS
√s = 13 TeV, 36.1 fb-1
Data
Signal (WW)
Top
W+jets
Drell-Yan
Di- and triboson
Pred. stat.
Pred. stat. ⊕ syst.
Events / 20 GeV
Data / Pred.
m_eμ [GeV]

Triple-Gauge-Coupling (TGC)

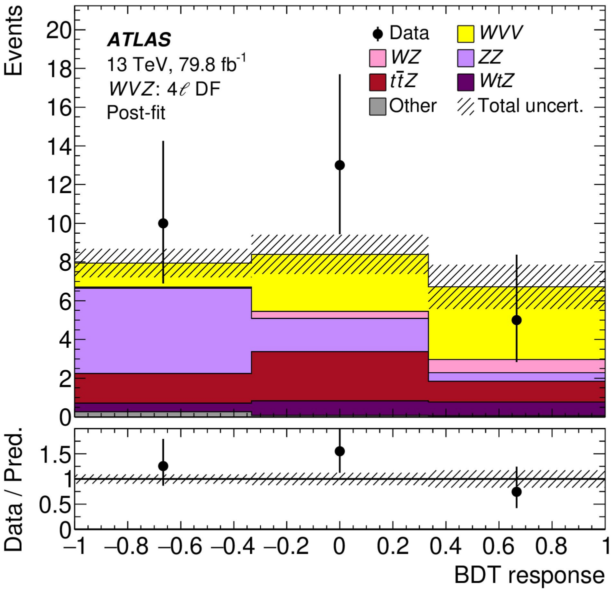
-
- Diagrams with the ZZZ and ZZgamma neutral TGC vertices **do not exist in the SM.**

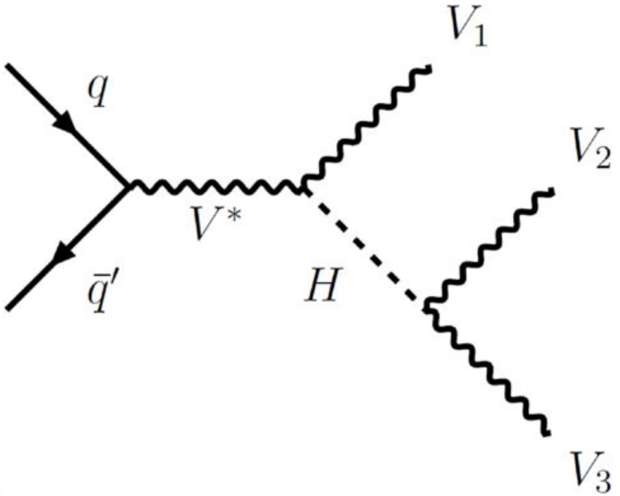


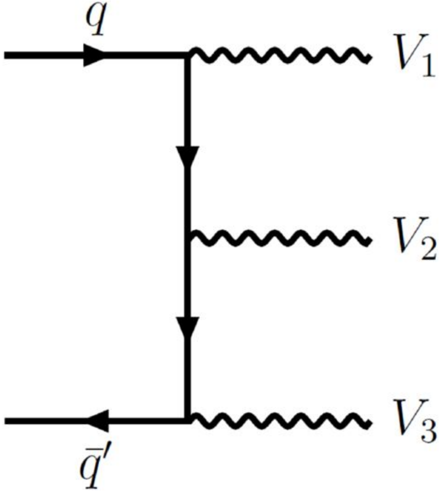


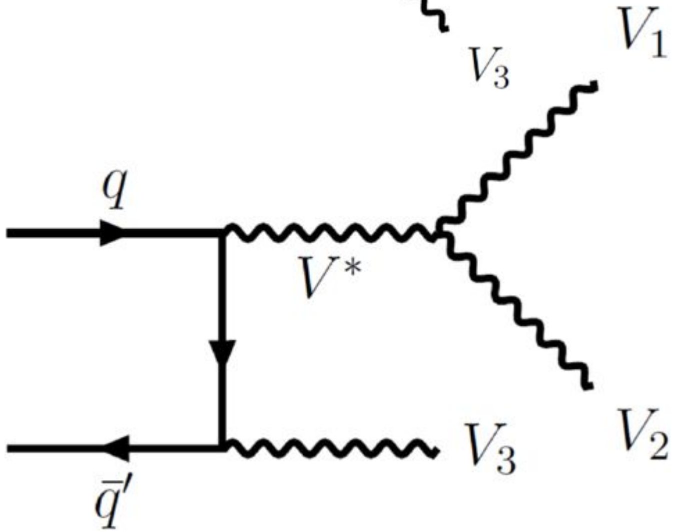
Triboson production

- Rare processes with cross sections in the order of 1pb
- Important background to Di-Higgs searches



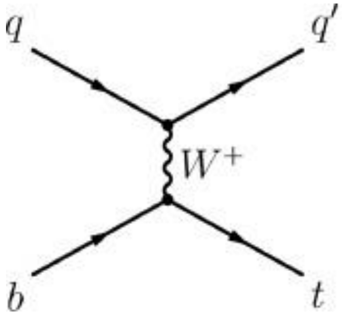




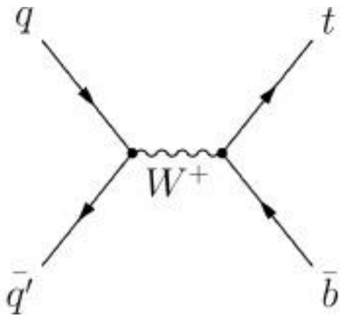


Top quark production

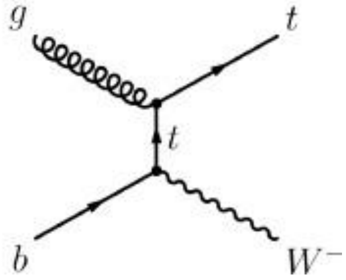
- Single top quarks:



t-channel



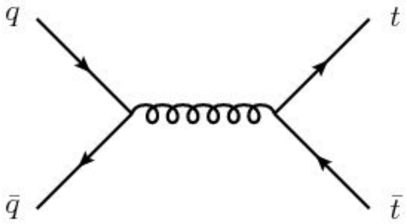
s-channel



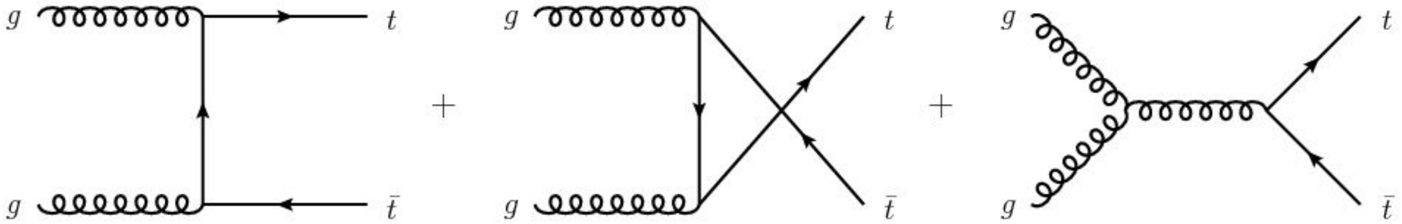
Wt-channel

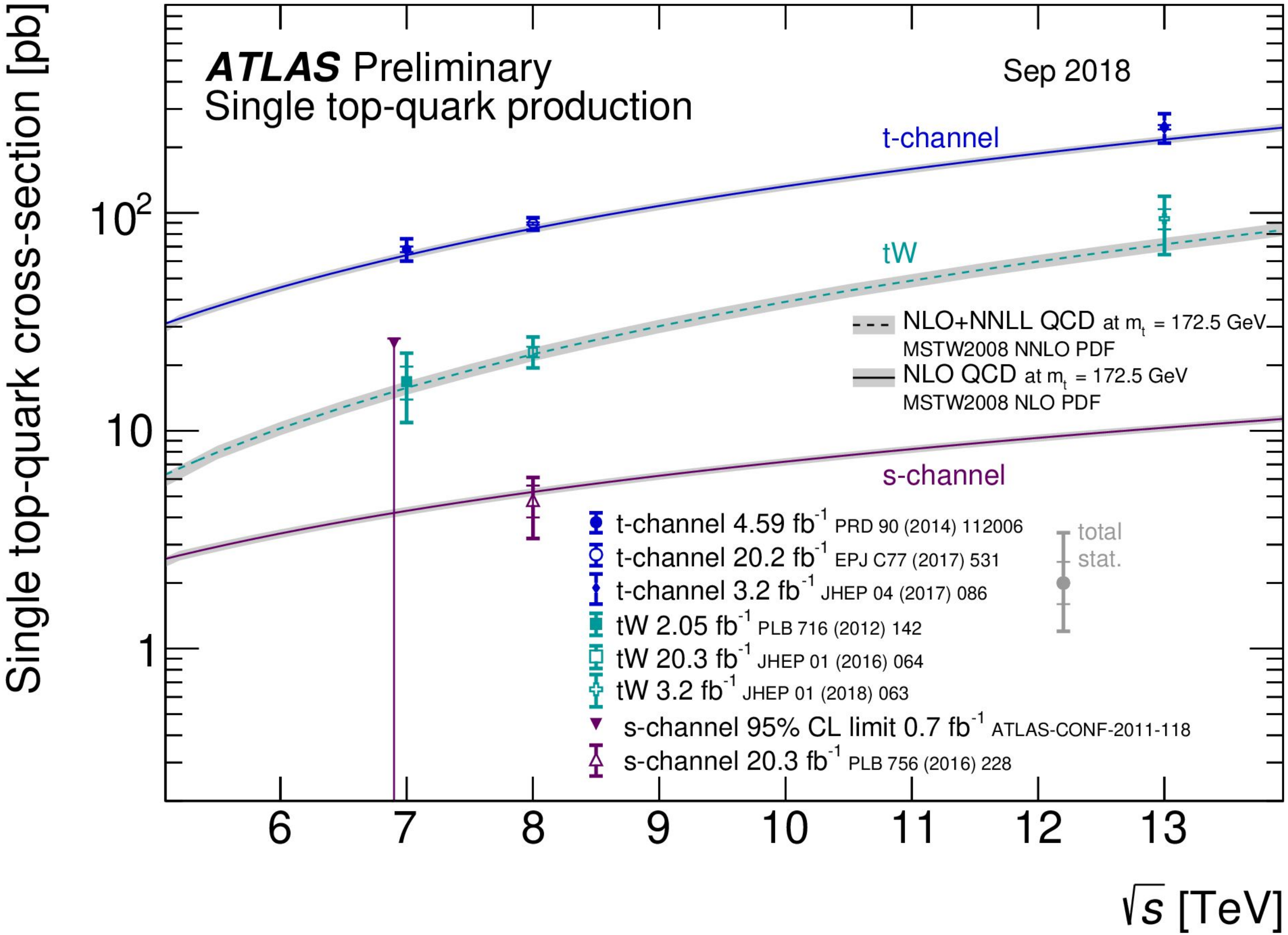
- Top quark pairs:

15%

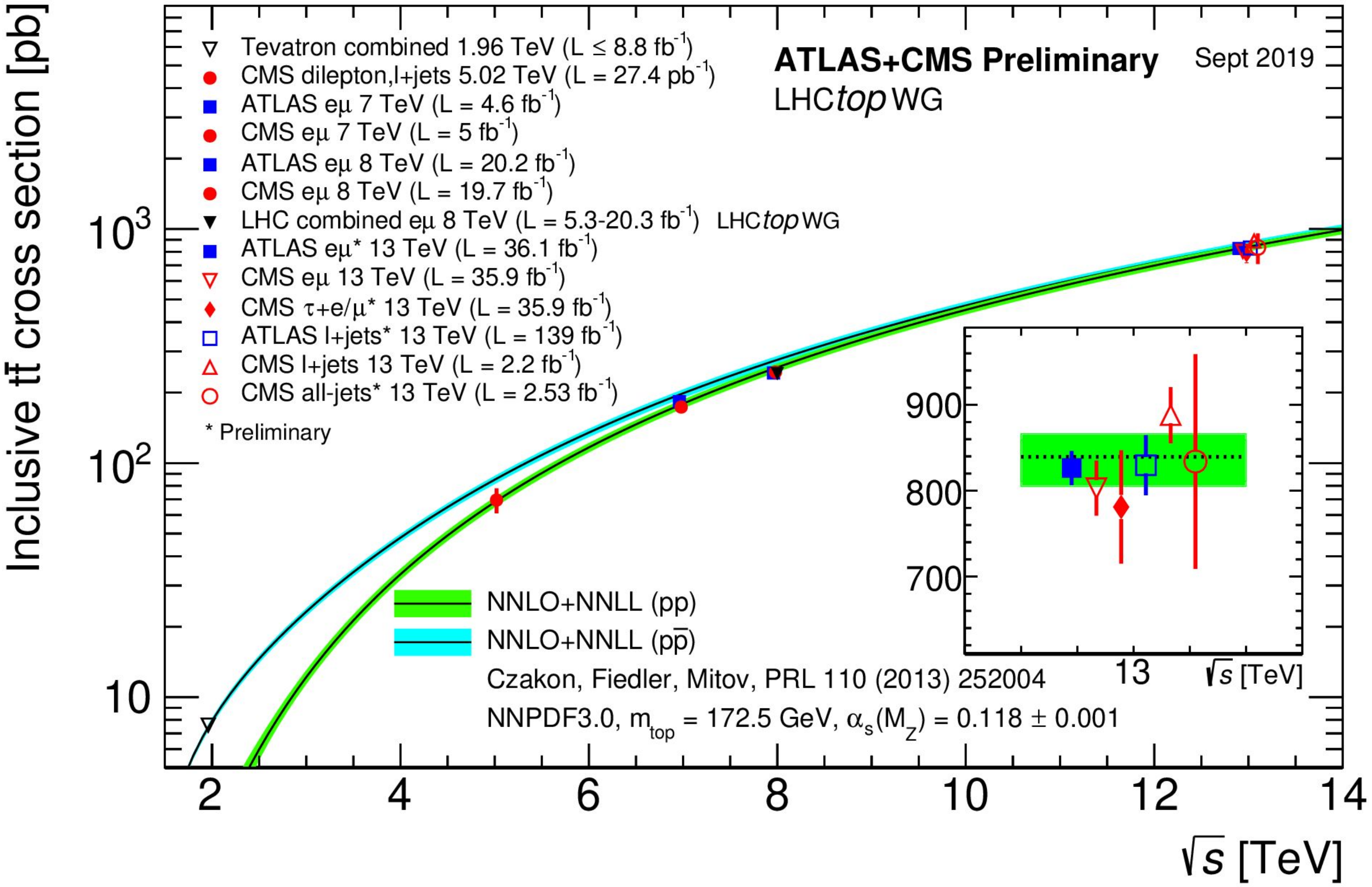


85%





ATLAS Preliminary
Single top-quark production
Sep 2018
t-channel
tW
s-channel
NLO+NNLL QCD at m_t = 172.5 GeV
MSTW2008 NNLO PDF
NLO QCD at m_t = 172.5 GeV
MSTW2008 NLO PDF
t-channel 4.59 fb^-1 PRD 90 (2014) 112006
t-channel 20.2 fb^-1 EPJ C77 (2017) 531
t-channel 3.2 fb^-1 JHEP 04 (2017) 086
tW 2.05 fb^-1 PLB 716 (2012) 142
tW 20.3 fb^-1 JHEP 01 (2016) 064
tW 3.2 fb^-1 JHEP 01 (2018) 063
s-channel 95% CL limit 0.7 fb^-1 ATLAS-CONF-2011-118
s-channel 20.3 fb^-1 PLB 756 (2016) 228
total
stat.
Single top-quark cross-section [pb]
√s [TeV]

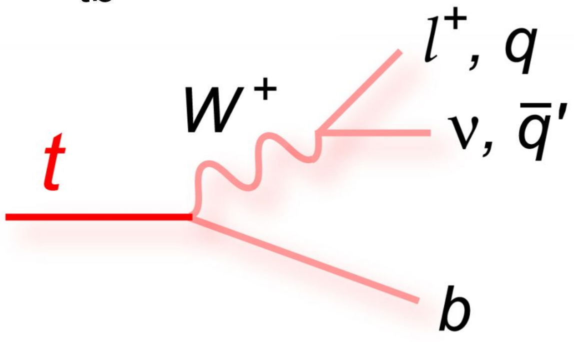


Inclusive tt̄ cross section [pb]
Tevatron combined 1.96 TeV (L ≤ 8.8 fb^{-1})
CMS dilepton,l+jets 5.02 TeV (L = 27.4 pb^{-1})
ATLAS eμ 7 TeV (L = 4.6 fb^{-1})
CMS eμ 7 TeV (L = 5 fb^{-1})
ATLAS eμ 8 TeV (L = 20.2 fb^{-1})
CMS eμ 8 TeV (L = 19.7 fb^{-1})
LHC combined eμ 8 TeV (L = 5.3-20.3 fb^{-1}) LHCtopWG
ATLAS eμ* 13 TeV (L = 36.1 fb^{-1})
CMS eμ 13 TeV (L = 35.9 fb^{-1})
CMS τ+e/μ* 13 TeV (L = 35.9 fb^{-1})
ATLAS l+jets* 13 TeV (L = 139 fb^{-1})
CMS l+jets 13 TeV (L = 2.2 fb^{-1})
CMS all-jets* 13 TeV (L = 2.53 fb^{-1})
* Preliminary
ATLAS+CMS Preliminary
Sept 2019
LHCtopWG
NNLO+NNLL (pp)
NNLO+NNLL (pp̄)
Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
NNPDF3.0, m_{top} = 172.5 GeV, $\alpha_s(M_Z)$ = 0.118 ± 0.001
10^3
10^2
10
2
4
6
8
10
12
14
√s [TeV]
900
800
700
13
√s [TeV]

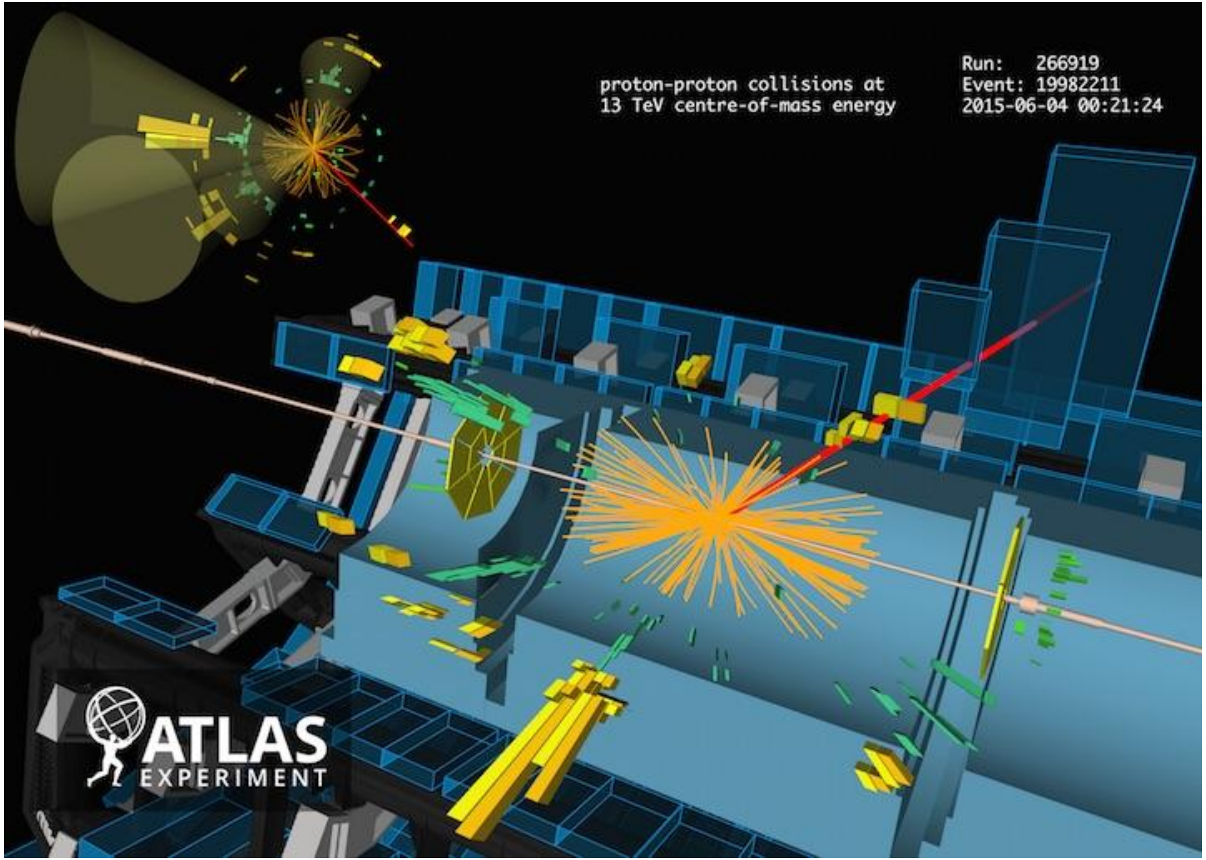
Top quark decay

- Top quark decays almost exclusively via t->bW

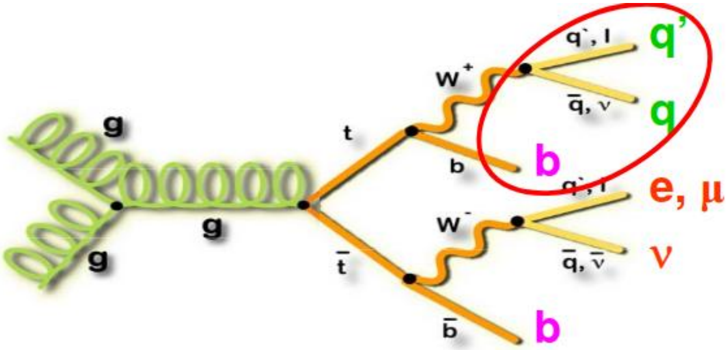
$$|V_{tb}| \approx 1$$

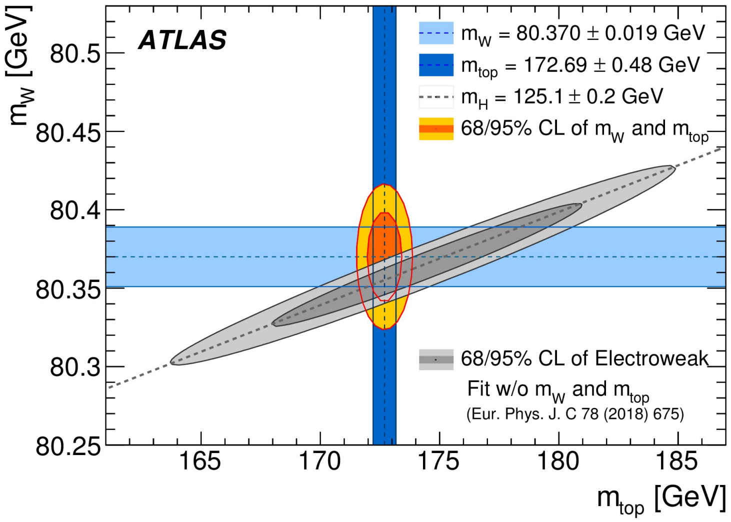


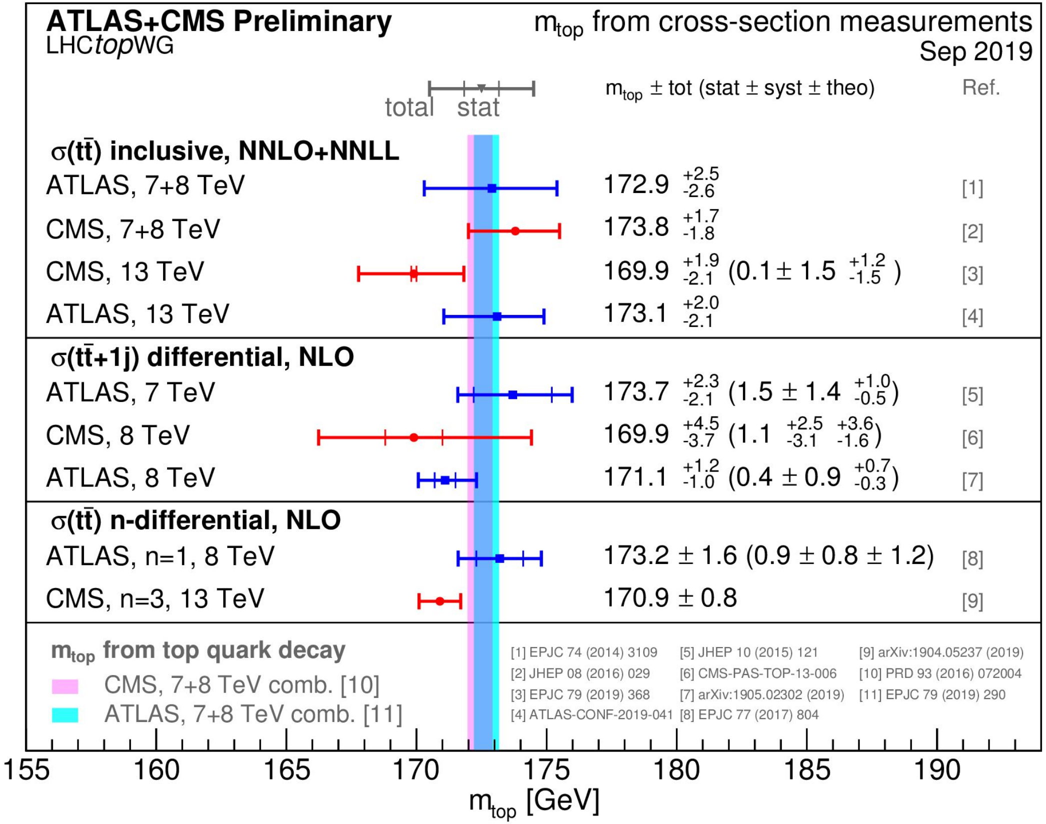
- Top quark decays are characterised by high pT leptons, jets and missing transverse momentum



Top quark mass

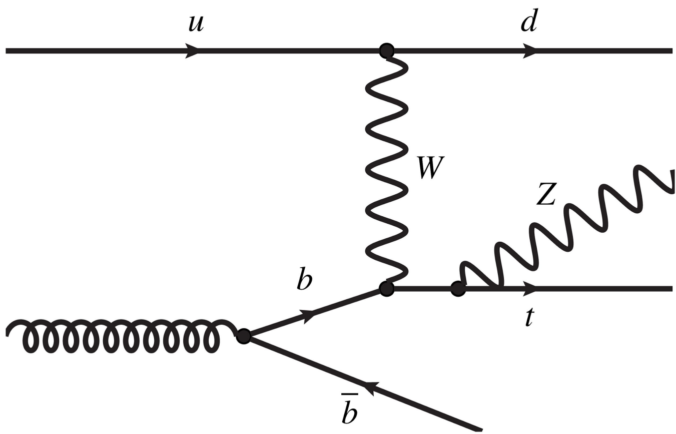


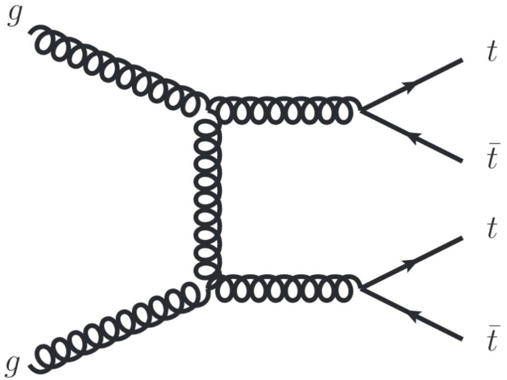


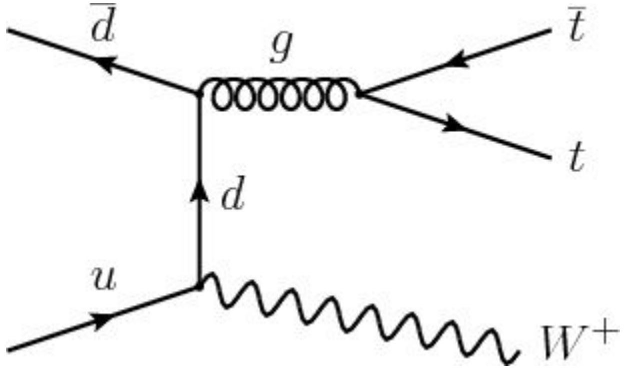


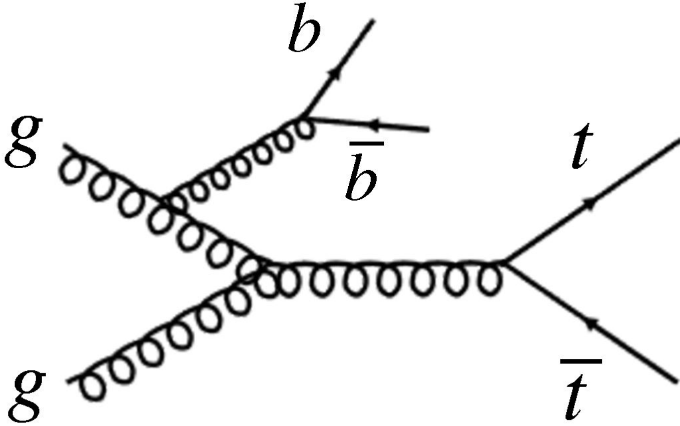
Production of top + X

- Rare processes (observed for the first time at the LHC)
  - Single top quark + *Z* boson
  - Top quark pairs + W/Z boson
  - Top quark pairs + bb
  - Four top quarks



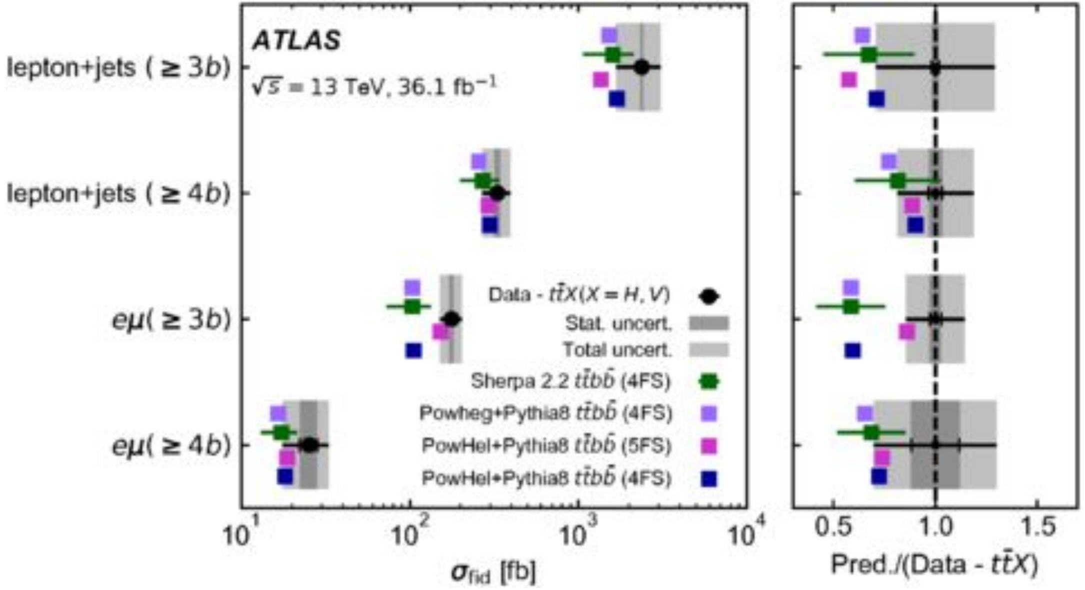


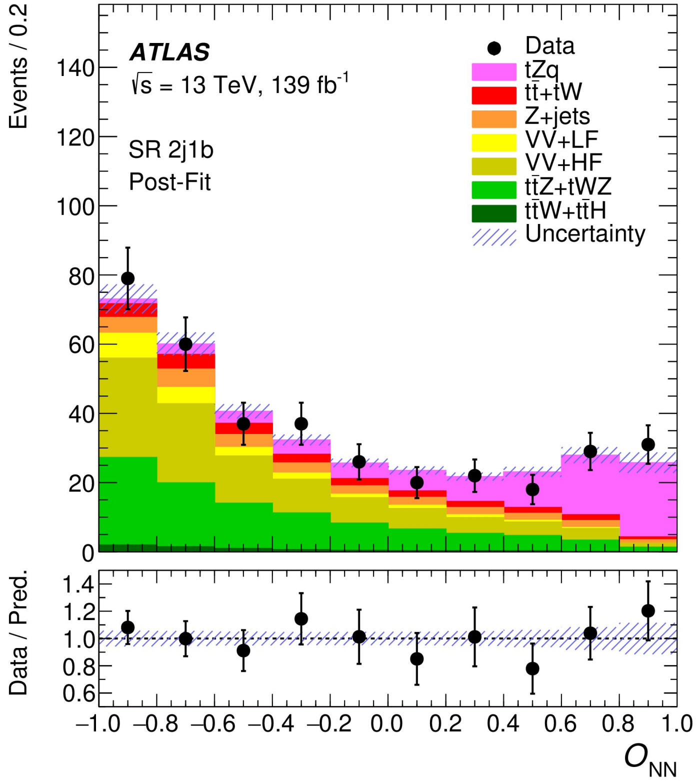


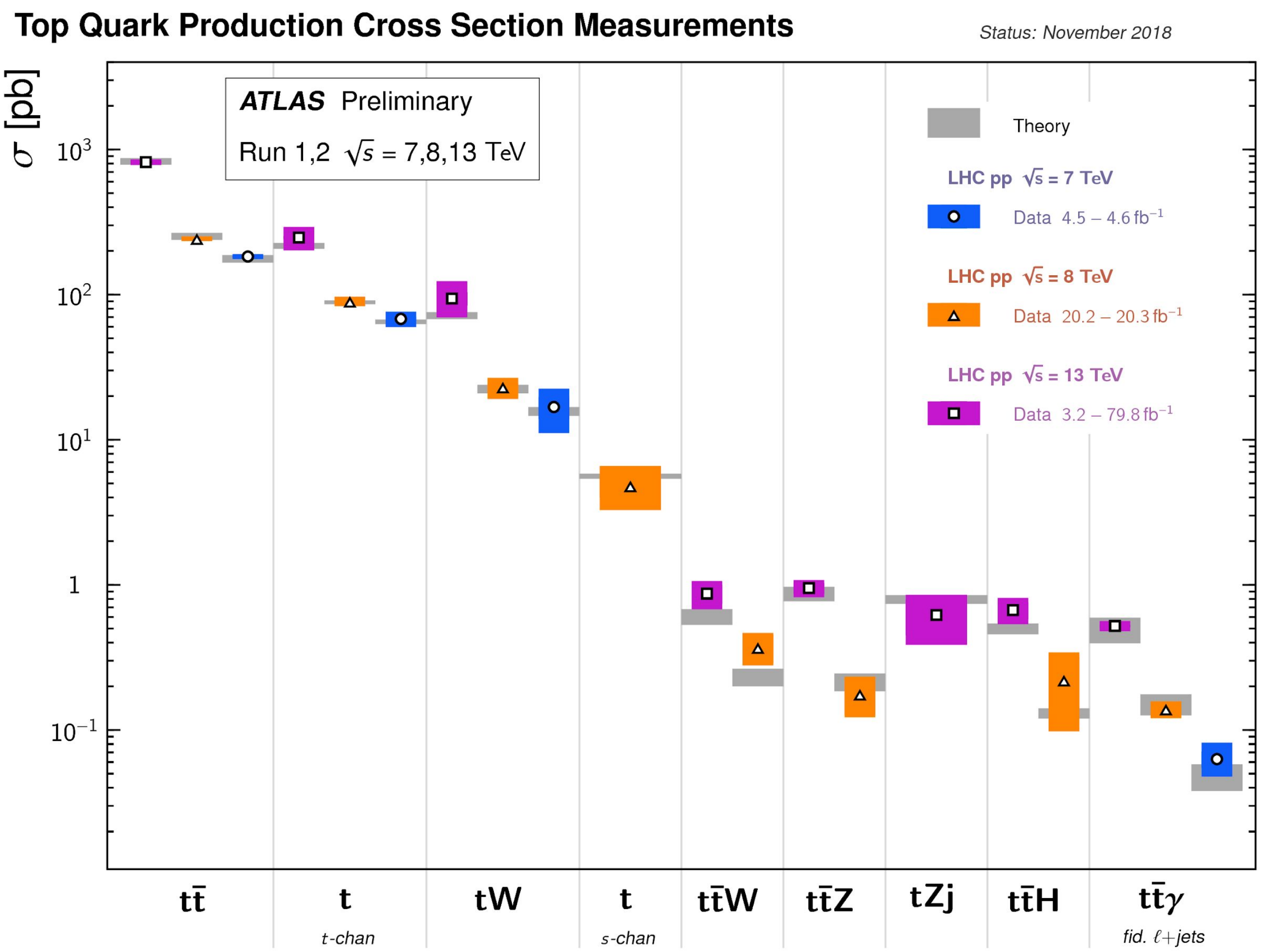


Production of top + X

- Rare processes:
  - Cross section ttV: ~ 1 pb
  - Cross section ttbb: ~ 0.1 pb
  - Cross section 4tops: ~ 0.01 pb







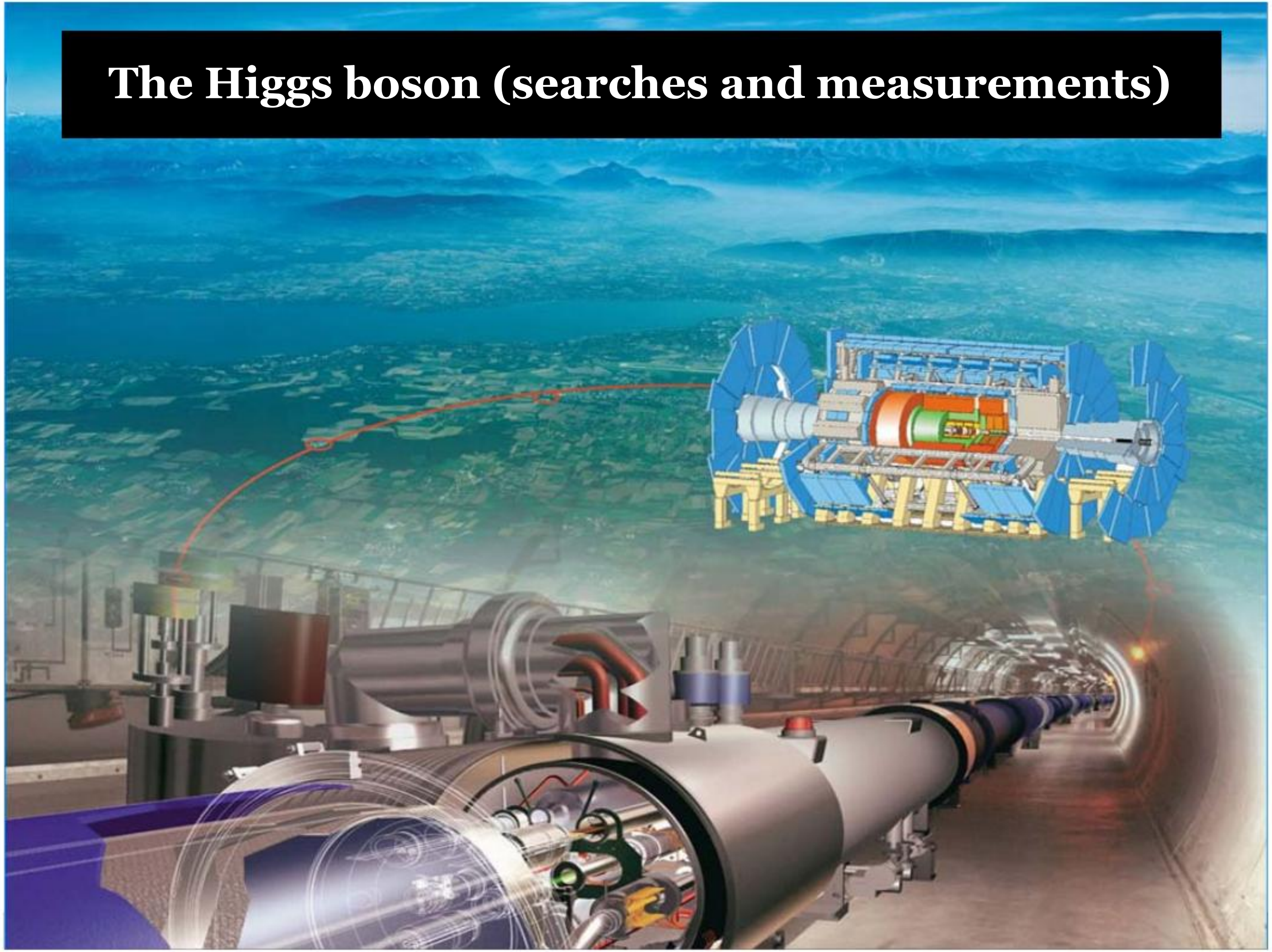
Top Quark Production Cross Section Measurements
Status: November 2018
ATLAS Preliminary
Run 1,2 √s = 7,8,13 TeV
σ [pb]
Theory
LHC pp √s = 7 TeV
Data 4.5 – 4.6 fb⁻¹
LHC pp √s = 8 TeV
Data 20.2 – 20.3 fb⁻¹
LHC pp √s = 13 TeV
Data 3.2 – 79.8 fb⁻¹
tt̄
t
t-chan
tW
t
s-chan
tt̄W
tt̄Z
tZj
tt̄H
tt̄γ
fid. ℓ+jets

Testing the Standard Model of Elementary Particle Physics II

Second lecture

30th April 2020

The Higgs boson (searches and measurements)



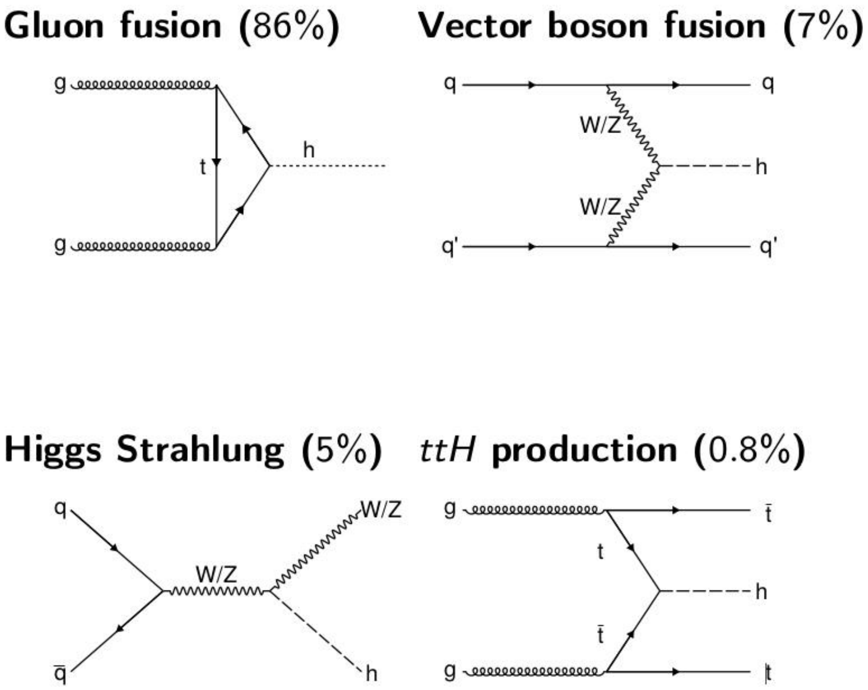
Need:

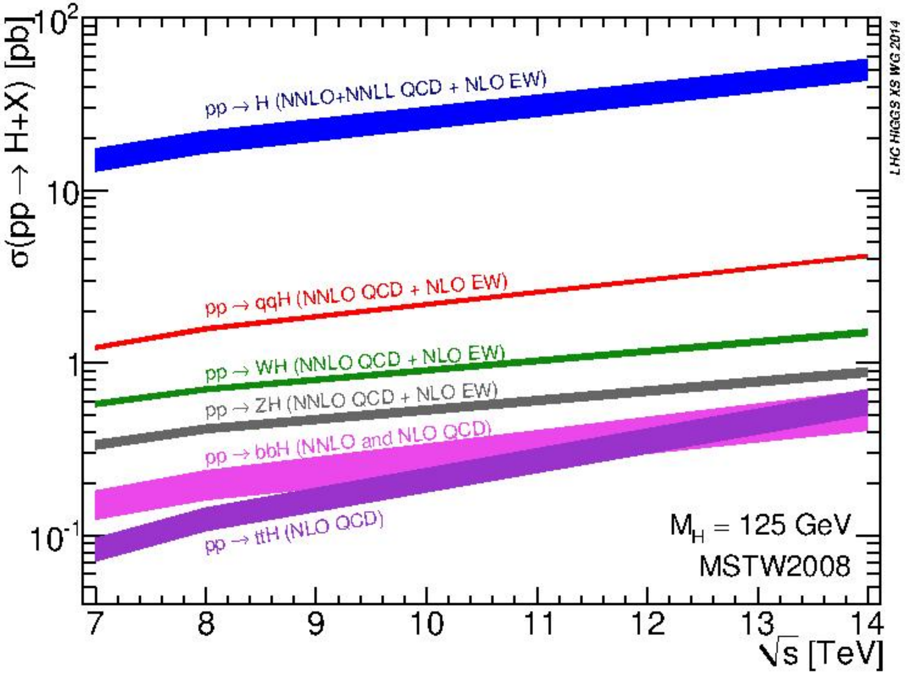
Intro

Higgs searches at LEP and Tevatron

ttH

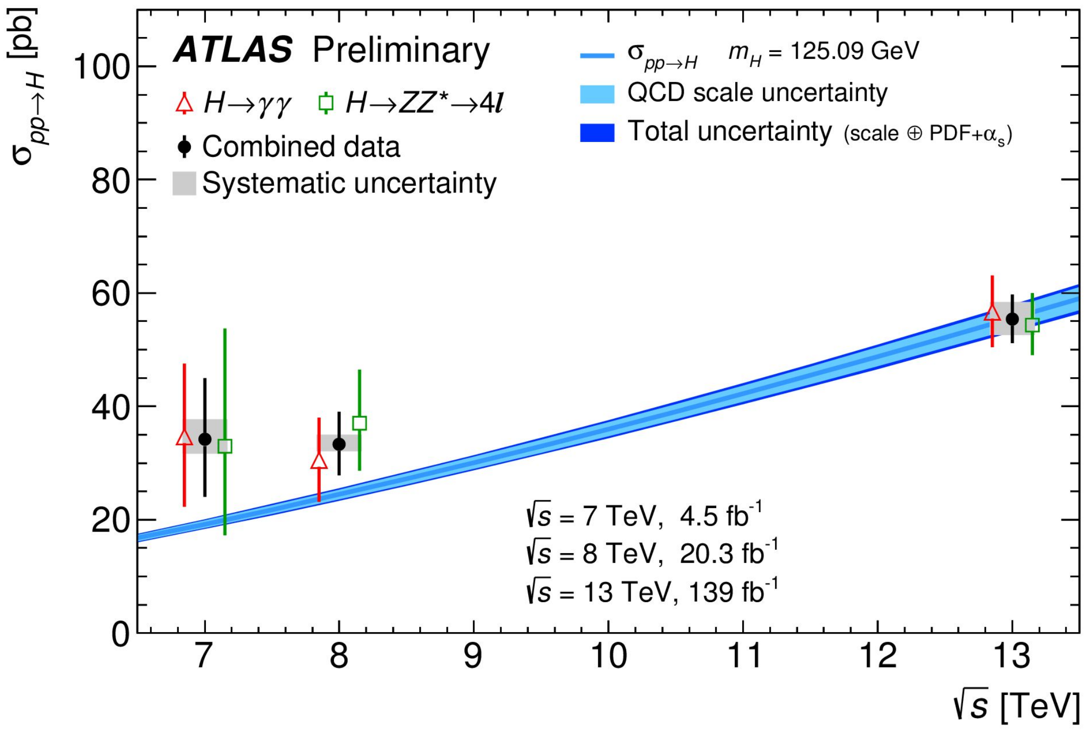
Higgs boson production at the LHC

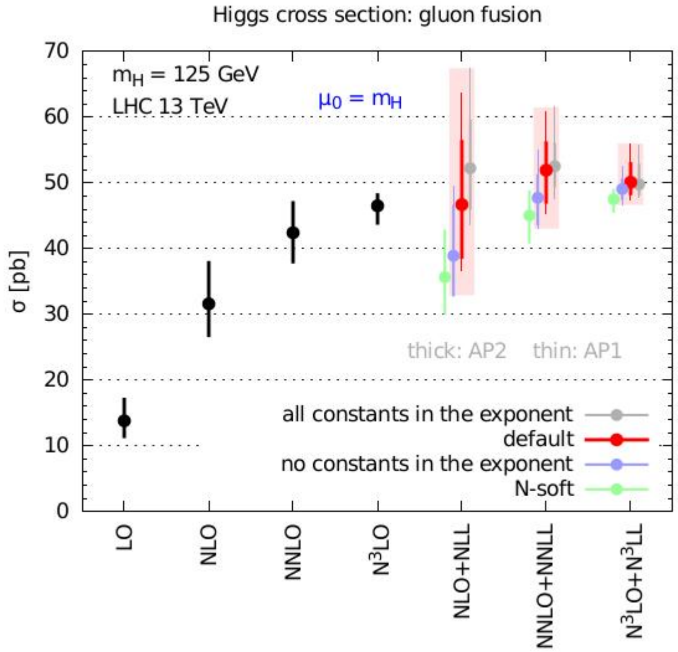




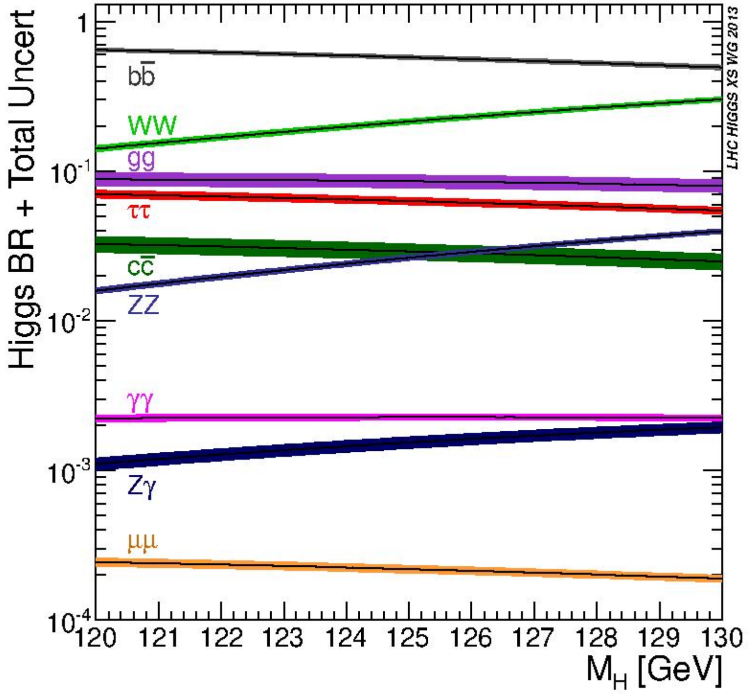
- All main production modes are probed at the LHC

Higgs boson production cross section





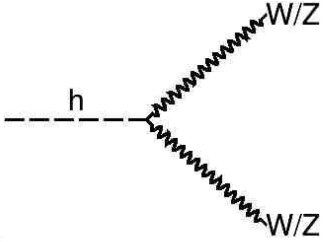
Higgs boson decay



Decay mode	Branching fraction [%]
$H \to b\bar{b}$	57.5 ± 1.9
$H \to WW^*$	21.6 ± 0.9
$H \to gg$	8.56 ± 0.86
$H \to \tau\tau$	6.30 ± 0.36
$H \to c\bar{c}$	2.90 ± 0.35
$H \to ZZ^*$	2.67 ± 0.11
$H \to \gamma\gamma$	0.228 ± 0.011
$H \to Z\gamma$	0.155 ± 0.014
$H \to \mu\mu$	0.022 ± 0.001

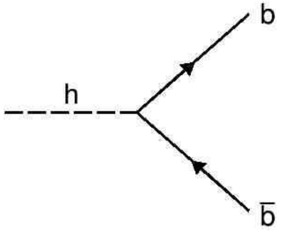
- **Some channels with low BR have a clean signature in the detector**
  - e.g. H -> ZZ and H->yy

Higgs boson decays

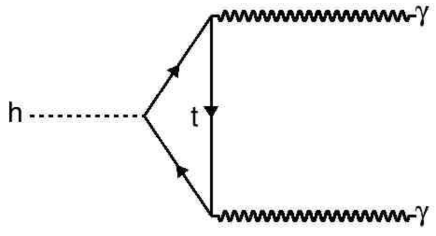


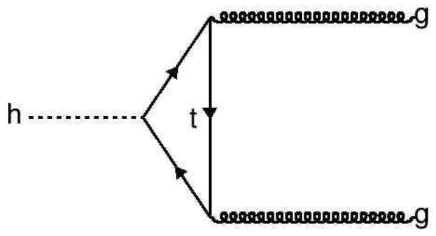
- Strength of the coupling between the Higgs boson and other particles is proportional to the particle mass:

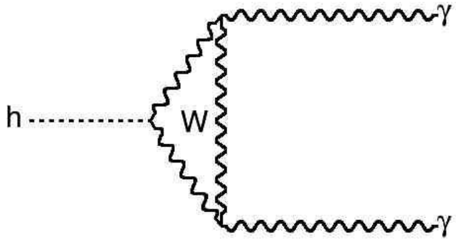
$$\mathcal{L}_{Hff} = -\frac{m_f}{v} h f \bar{f} \qquad \text{and} \qquad \mathcal{L}_{HVV} = \frac{1}{v}\left(2m_W^2 W_\mu^+ W^{-\mu} + 2m_Z^2 Z_\mu Z^\mu\right) h$$

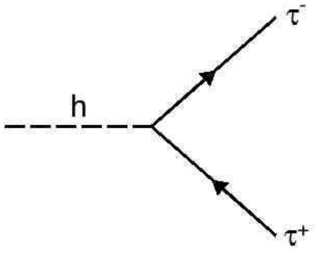


- Thus decays to massless particles such as photon or gluons is only possible via top quark (or W boson) loops
- The masses of the particles running in these loops are large and thus such decay modes can compete with decays to fermions or W and Z bosons

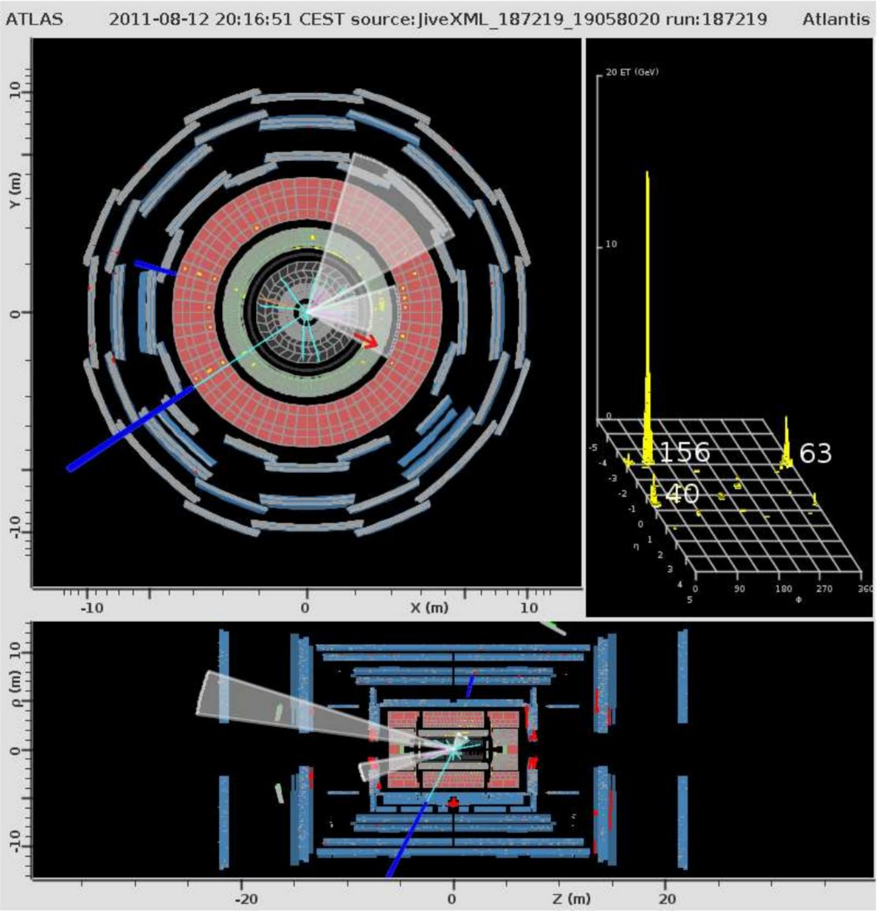




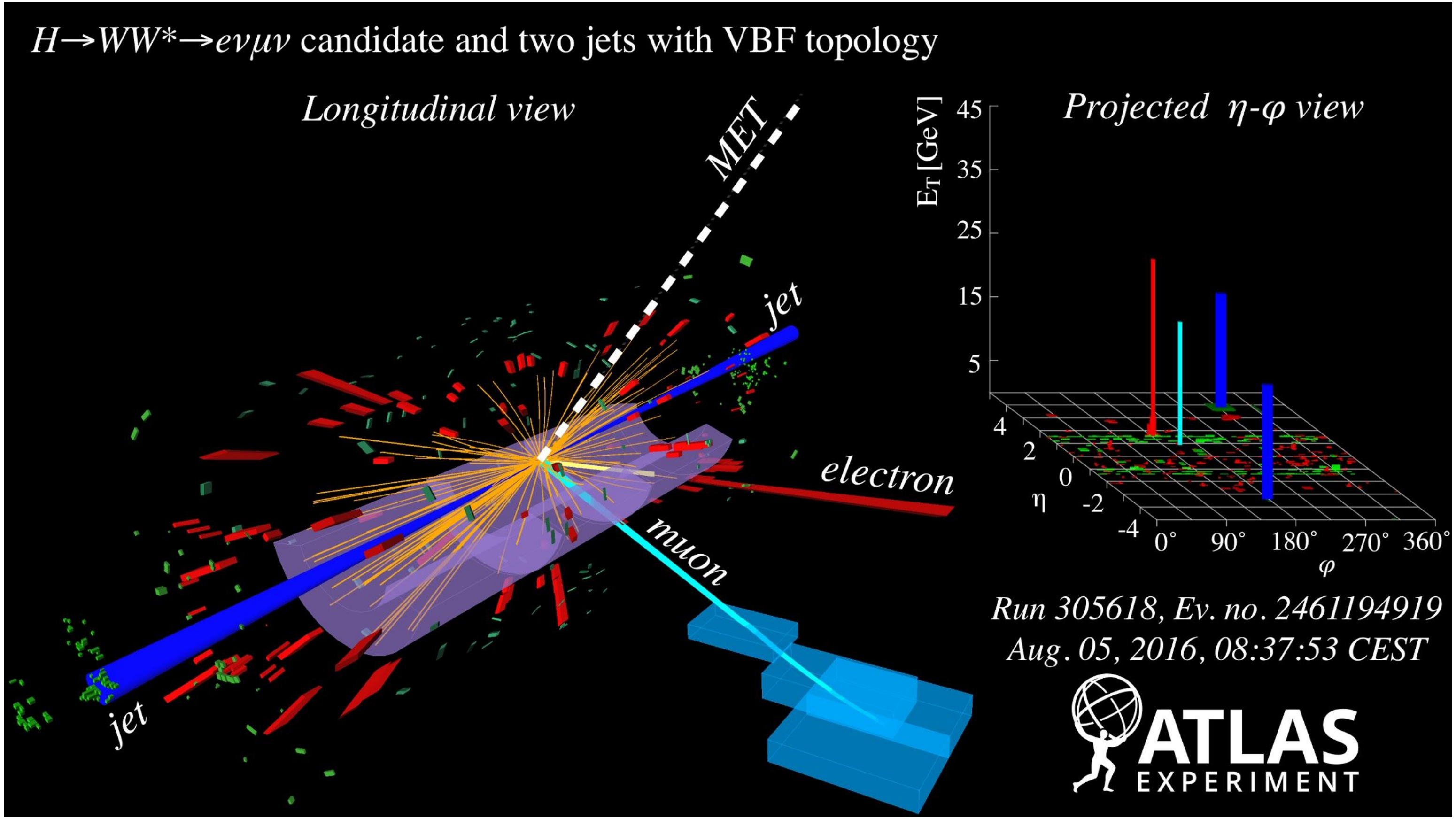




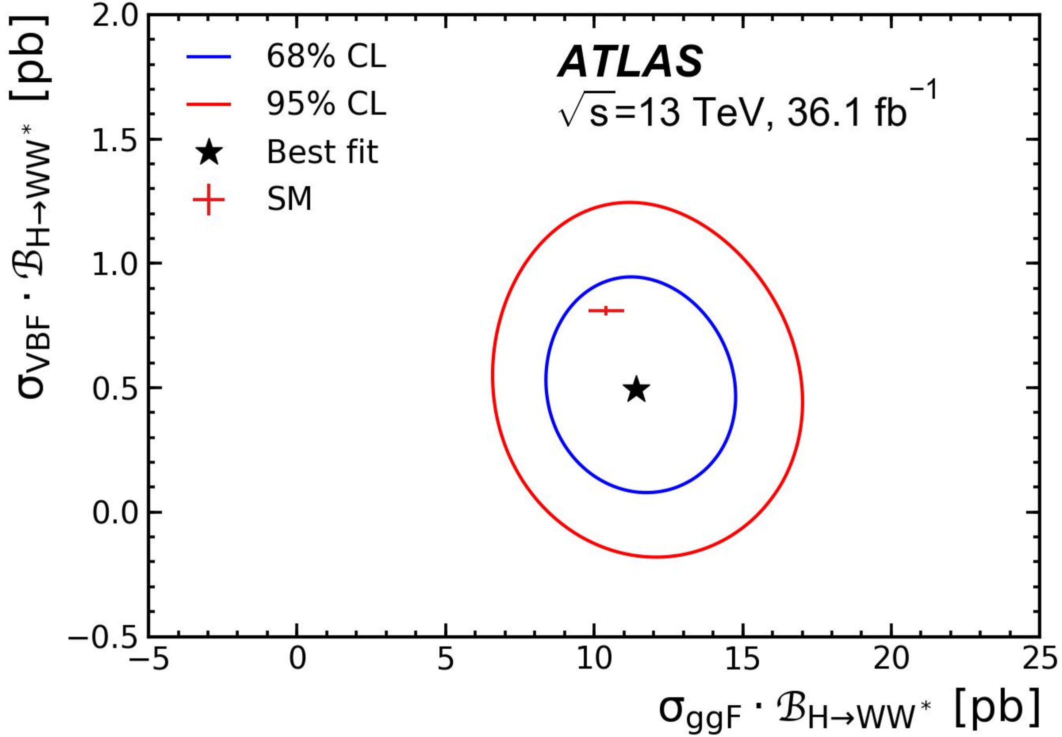
H->bb


ATLAS
2011-08-12 20:16:51 CEST source:JiveXML_187219_19058020 run:187219
Atlantis
Y (m)
X (m)
ρ (m)
Z (m)
20 ET (GeV)
156
63
40
η
Φ

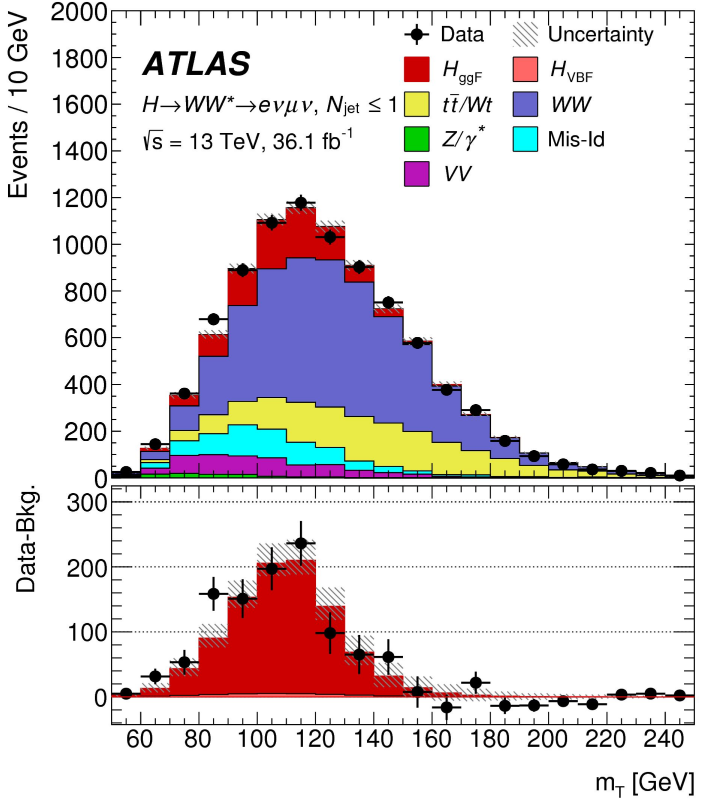
H->WW*


$H \rightarrow WW^* \rightarrow e\nu\mu\nu$ candidate and two jets with VBF topology
Longitudinal view
MET
jet
electron
muon
jet
Projected η-φ view
E_T [GeV]
45
35
25
15
5
4
2
0
-2
-4
η
0°
90°
180°
270°
360°
φ
Run 305618, Ev. no. 2461194919
Aug. 05, 2016, 08:37:53 CEST
ATLAS
EXPERIMENT

H->WW*

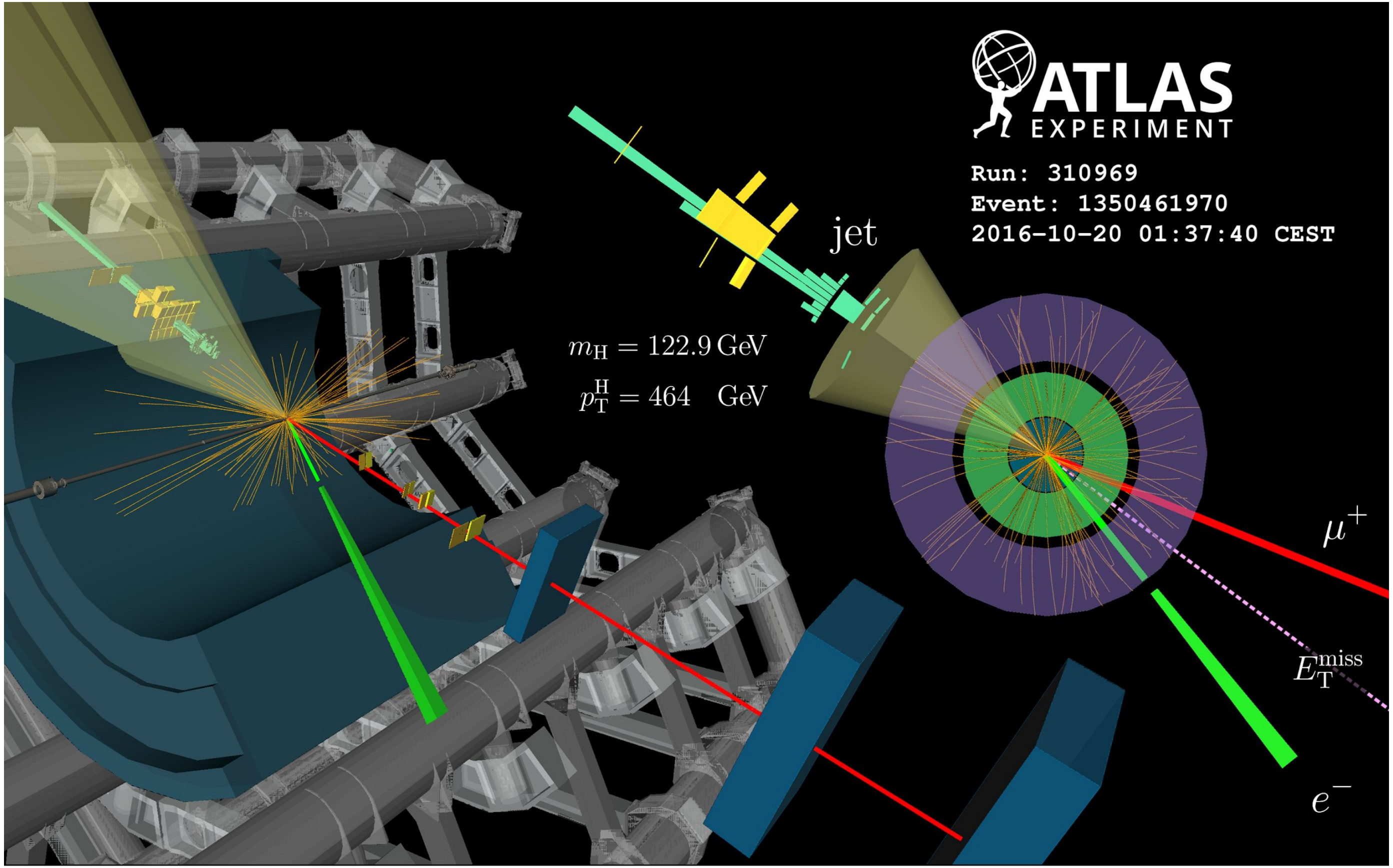


68% CL
95% CL
Best fit
SM
ATLAS
$\sqrt{s}$=13 TeV, 36.1 fb^{-1}
$\sigma_{VBF} \cdot \mathcal{B}_{H\to WW^*}$ [pb]
$\sigma_{ggF} \cdot \mathcal{B}_{H\to WW^*}$ [pb]

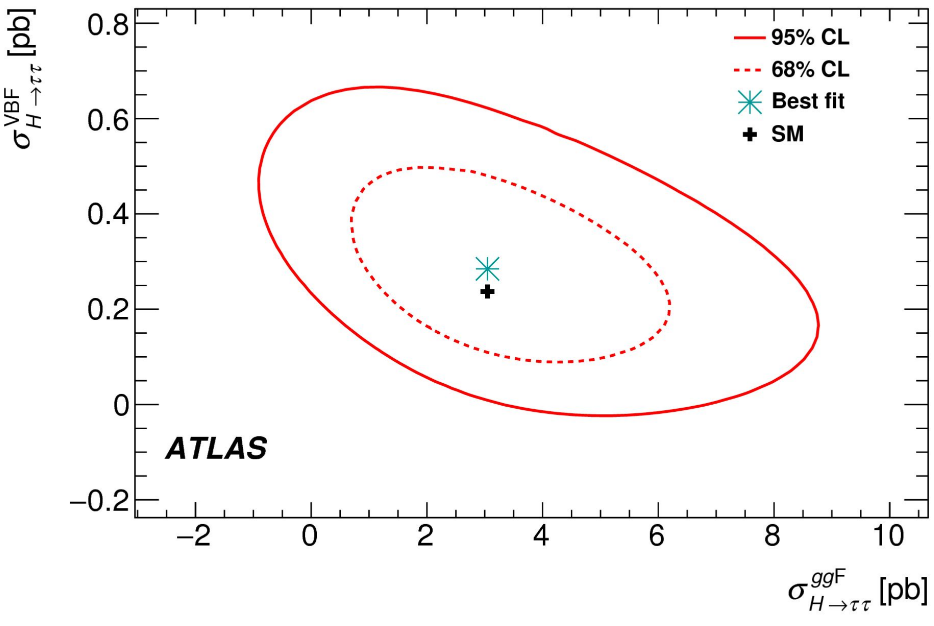


ATLAS
$H\to WW^*\to e\nu\mu\nu$, $N_{jet} \leq 1$
$\sqrt{s}$ = 13 TeV, 36.1 fb^{-1}
Data
Uncertainty
H_{ggF}
H_{VBF}
$t\bar{t}/Wt$
WW
Z/γ^*
Mis-Id
VV
Events / 10 GeV
Data-Bkg.
m_T [GeV]

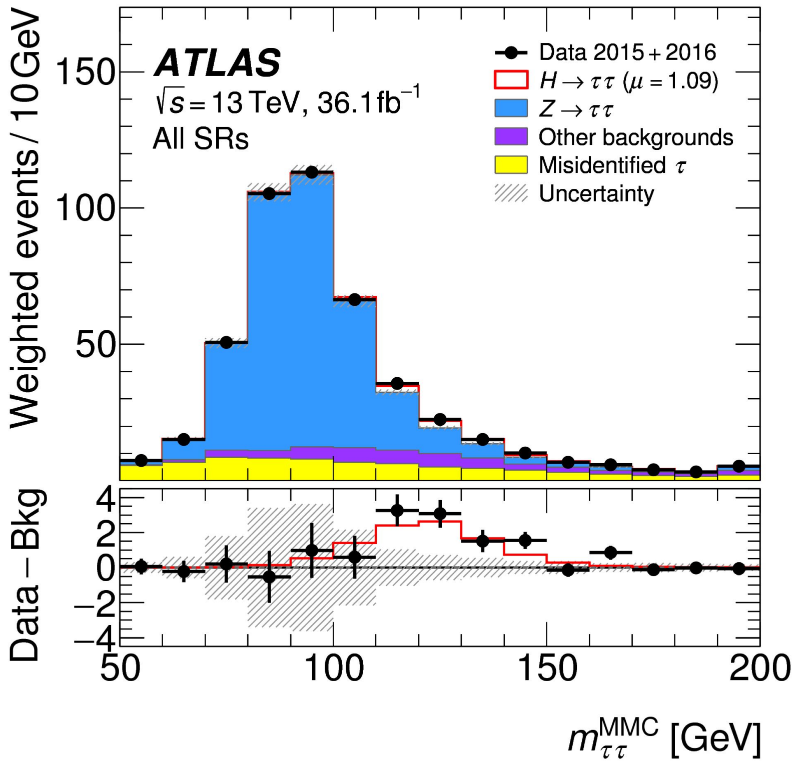
H-> tau tau


ATLAS
EXPERIMENT
Run: 310969
Event: 1350461970
2016-10-20 01:37:40 CEST
jet
$m_H = 122.9$ GeV
$p_T^H = 464$ GeV
μ^+
E_T^{miss}
e^-

H-> tau tau

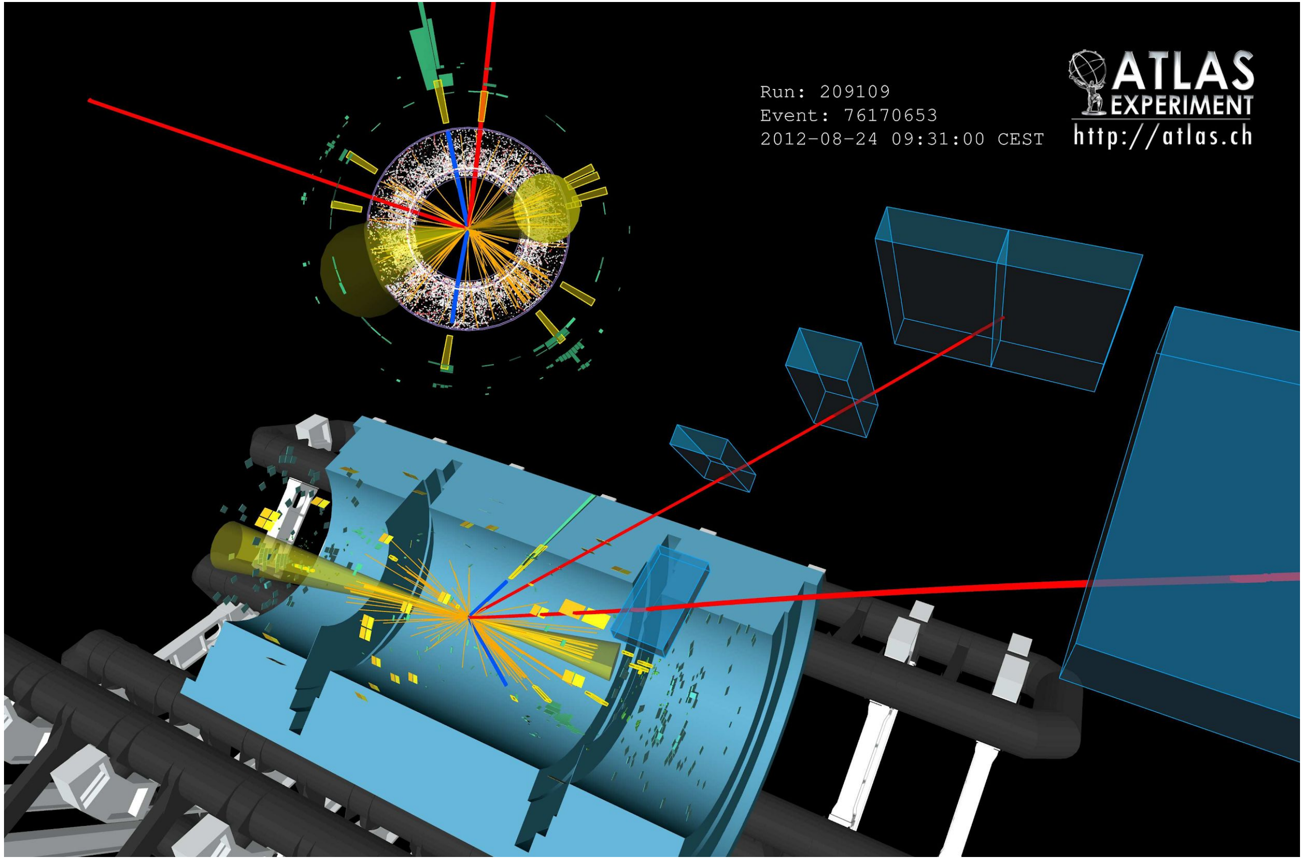


95% CL
68% CL
Best fit
SM
ATLAS
0.8
0.6
0.4
0.2
0
−0.2
−2
0
2
4
6
8
10
$\sigma^{VBF}_{H\to\tau\tau}$ [pb]
$\sigma^{ggF}_{H\to\tau\tau}$ [pb]



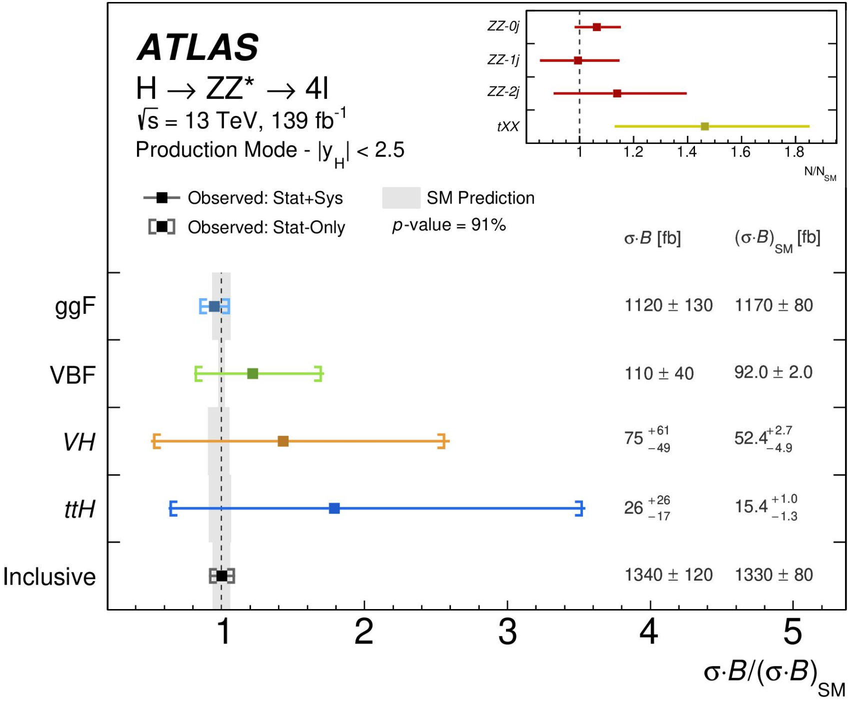
ATLAS
$\sqrt{s} = 13$ TeV, 36.1 fb^{-1}
All SRs
Data 2015+2016
$H\to\tau\tau$ ($\mu = 1.09$)
$Z\to\tau\tau$
Other backgrounds
Misidentified τ
Uncertainty
Weighted events / 10GeV
150
100
50
Data − Bkg
4
2
0
−2
−4
50
100
150
200
$m^{MMC}_{\tau\tau}$ [GeV]

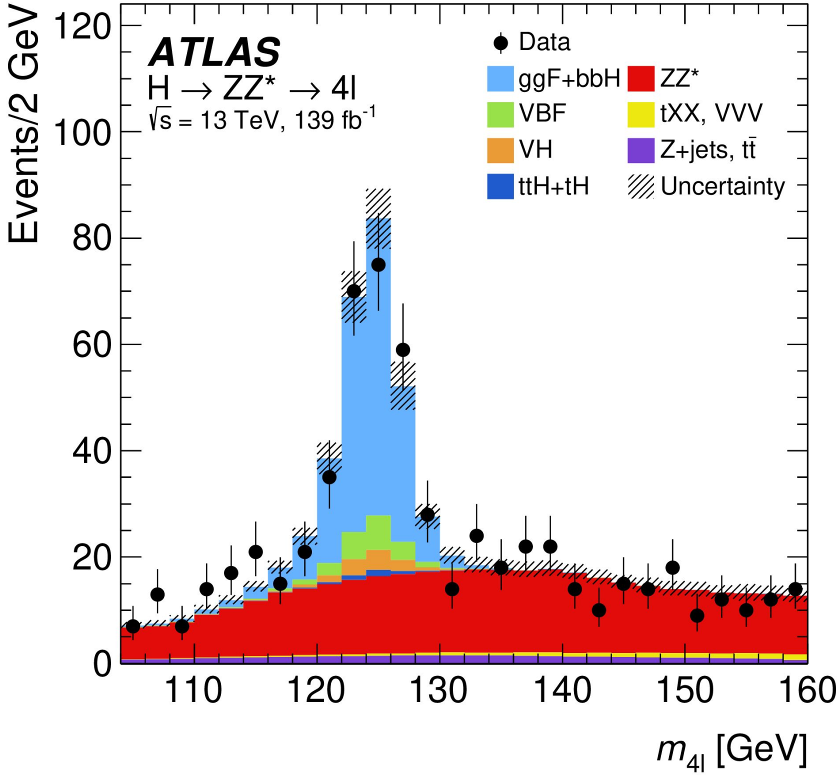
H-> ZZ*



Run: 209109
Event: 76170653
2012-08-24 09:31:00 CEST
ATLAS
EXPERIMENT
http://atlas.ch

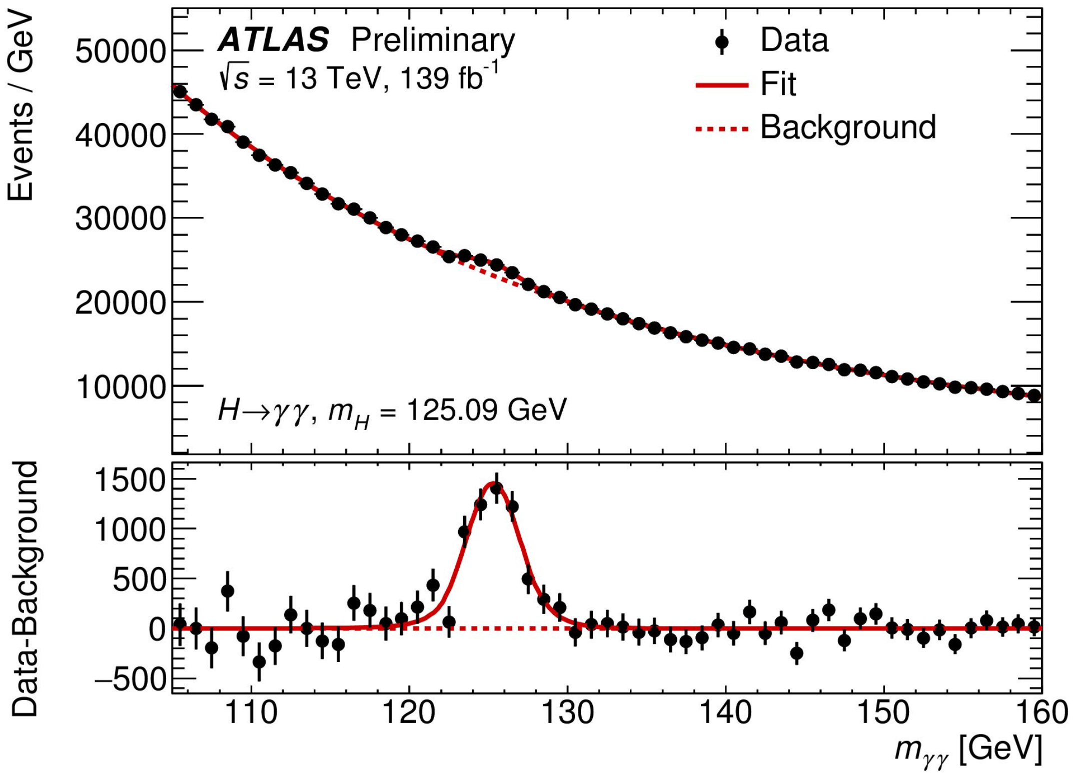
H-> ZZ*


ATLAS
H → ZZ* → 4l
√s = 13 TeV, 139 fb-1
Production Mode - |yH| < 2.5
Observed: Stat+Sys
Observed: Stat-Only
SM Prediction
p-value = 91%
σ·B [fb]
(σ·B)SM [fb]
ggF
VBF
VH
ttH
Inclusive
1120 ± 130
1170 ± 80
110 ± 40
92.0 ± 2.0
75 +61 −49
52.4 +2.7 −4.9
26 +26 −17
15.4 +1.0 −1.3
1340 ± 120
1330 ± 80
σ·B/(σ·B)SM
ZZ-0j
ZZ-1j
ZZ-2j
tXX
N/NSM


ATLAS
H → ZZ* → 4l
√s = 13 TeV, 139 fb-1
Events/2 GeV
Data
ggF+bbH
ZZ*
VBF
tXX, VVV
VH
Z+jets, tt̄
ttH+tH
Uncertainty
m4l [GeV]

H-> yy

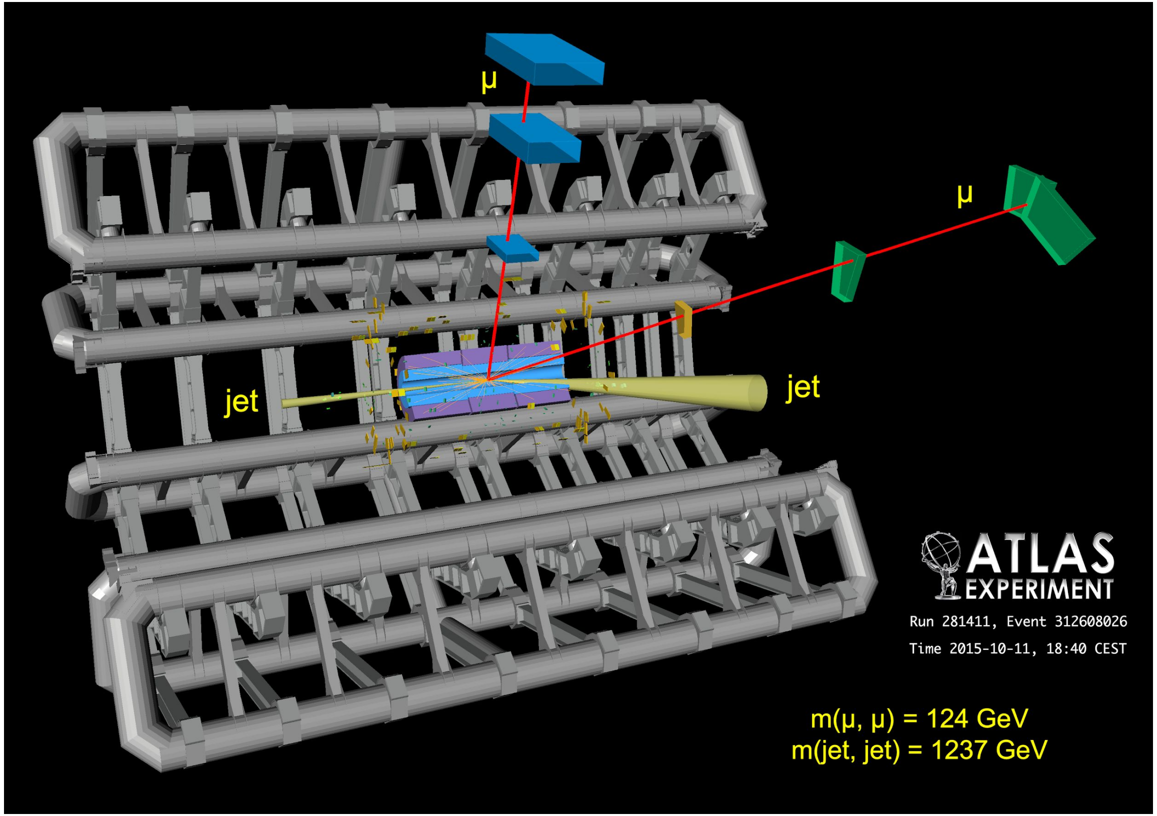
H-> yy



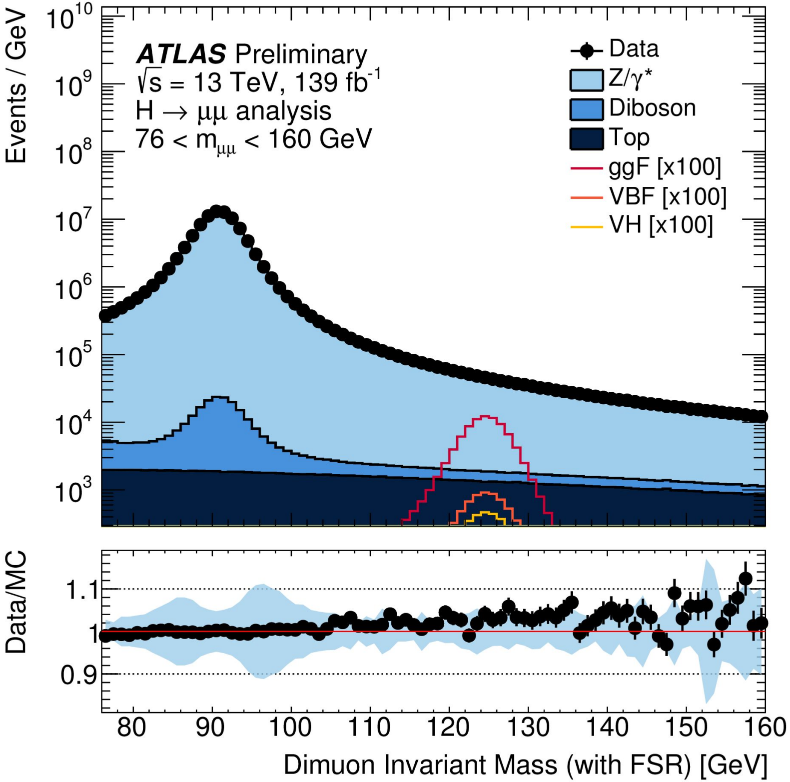
ATLAS Preliminary
√s = 13 TeV, 139 fb-1
Data
Fit
Background
H→γγ, m_H = 125.09 GeV
Events / GeV
50000
40000
30000
20000
10000
Data-Background
1500
1000
500
0
−500
110
120
130
140
150
160
m_γγ [GeV]

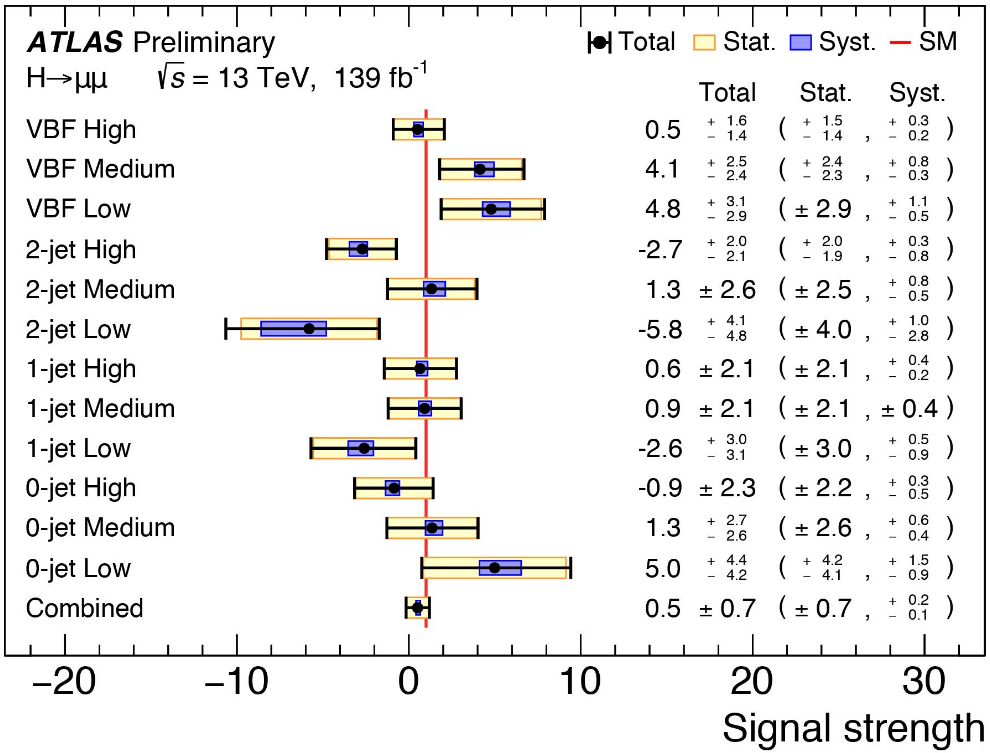
H-> mu mu

- **Probe Higgs couplings to 2nd generation fermions**
  - Low BR
- Here: Higgs production in VBF channel



H-> mu mu


ATLAS Preliminary
√s = 13 TeV, 139 fb-1
H → μμ analysis
76 < mμμ < 160 GeV
Data
Z/γ*
Diboson
Top
ggF [x100]
VBF [x100]
VH [x100]
Events / GeV
Data/MC
Dimuon Invariant Mass (with FSR) [GeV]


ATLAS Preliminary
H→μμ √s = 13 TeV, 139 fb-1
Total Stat. Syst. SM
Total Stat. Syst.
VBF High 0.5 +1.6 −1.4 (+1.5 −1.4 , +0.3 −0.2)
VBF Medium 4.1 +2.5 −2.4 (+2.4 −2.3 , +0.8 −0.3)
VBF Low 4.8 +3.1 −2.9 (± 2.9 , +1.1 −0.5)
2-jet High -2.7 +2.0 −2.1 (+2.0 −1.9 , +0.3 −0.8)
2-jet Medium 1.3 ± 2.6 (± 2.5 , +0.8 −0.5)
2-jet Low -5.8 +4.1 −4.8 (± 4.0 , +1.0 −2.8)
1-jet High 0.6 ± 2.1 (± 2.1 , +0.4 −0.2)
1-jet Medium 0.9 ± 2.1 (± 2.1 , ± 0.4)
1-jet Low -2.6 +3.0 −3.1 (± 3.0 , +0.5 −0.9)
0-jet High -0.9 ± 2.3 (± 2.2 , +0.3 −0.5)
0-jet Medium 1.3 +2.7 −2.6 (± 2.6 , +0.6 −0.4)
0-jet Low 5.0 +4.4 −4.2 (+4.2 −4.1 , +1.5 −0.9)
Combined 0.5 ± 0.7 (± 0.7 , +0.2 −0.1)
Signal strength

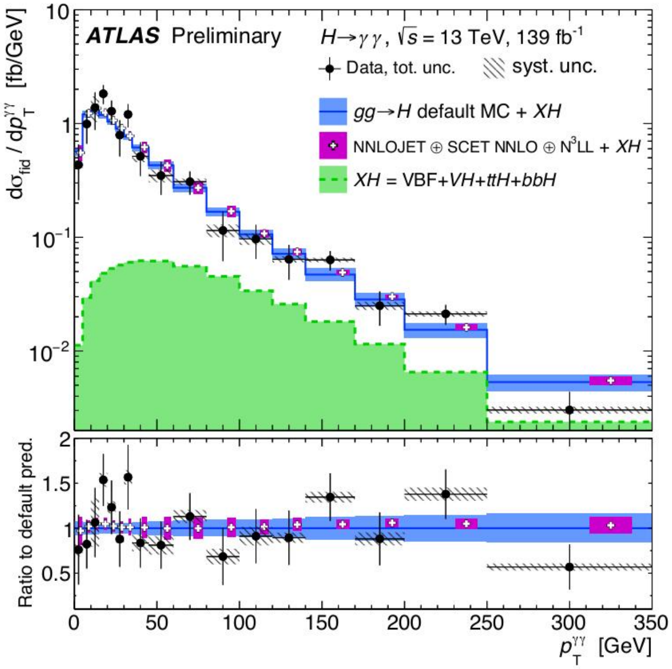
Differential measurements

- With large statistics of full Run-II dataset, we can explore differential distribution
  - To isolate phase space regions that are particular sensitive to new physics effects
- Measurement of **differential** cross sections
  1. Measure number of Higgs signal events N^{signal} in i-th p_T^H bin (or of any other observable)
  2. Background subtraction
  3. **Unfolding:** Derive correction factor from MC information:

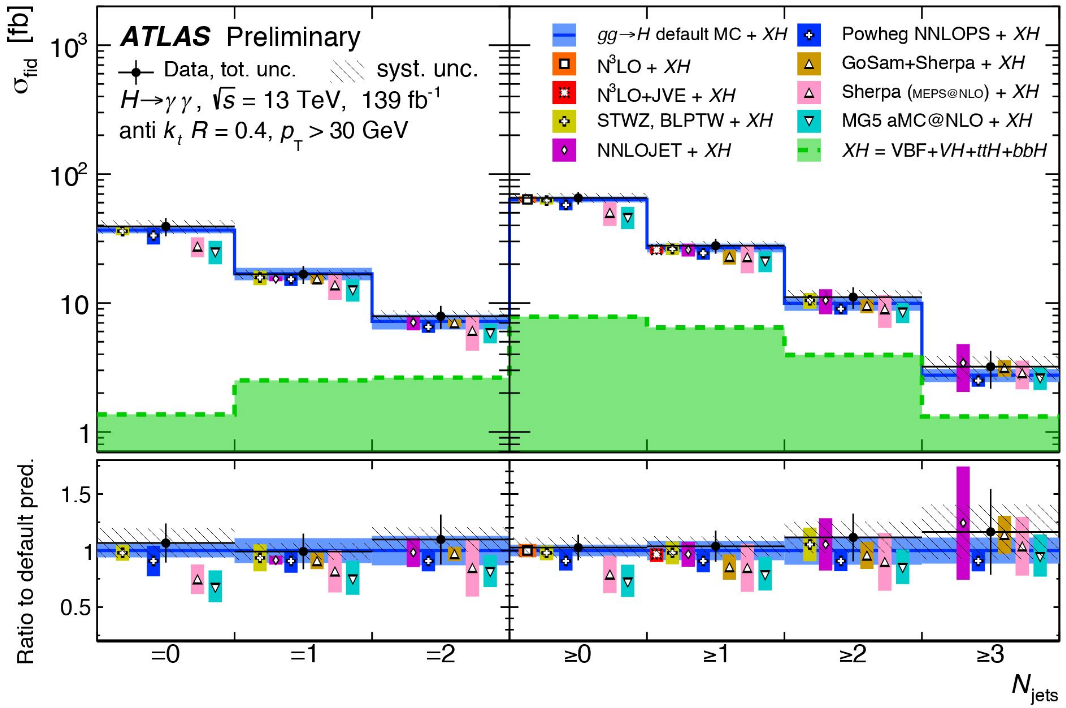
$$c_i = \frac{N^{\mathrm{reco}}}{N^{\mathrm{part}}}$$

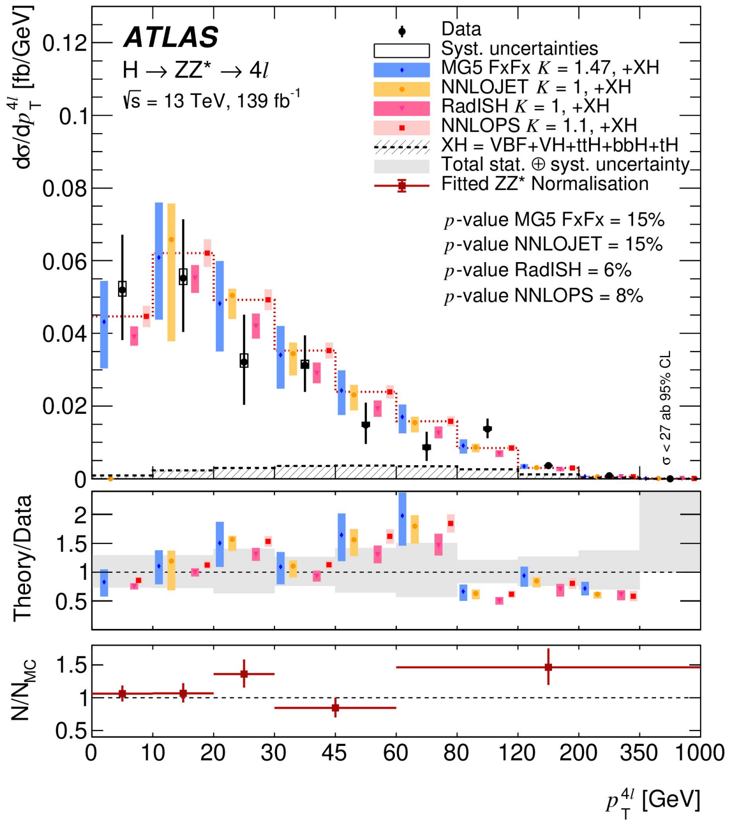
4. Calculate differential cross section:

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{N^{\mathrm{signal}}}{c_i \Delta p^H_{i,\mathrm{T}} \mathcal{L}_{\mathrm{int}}}$$

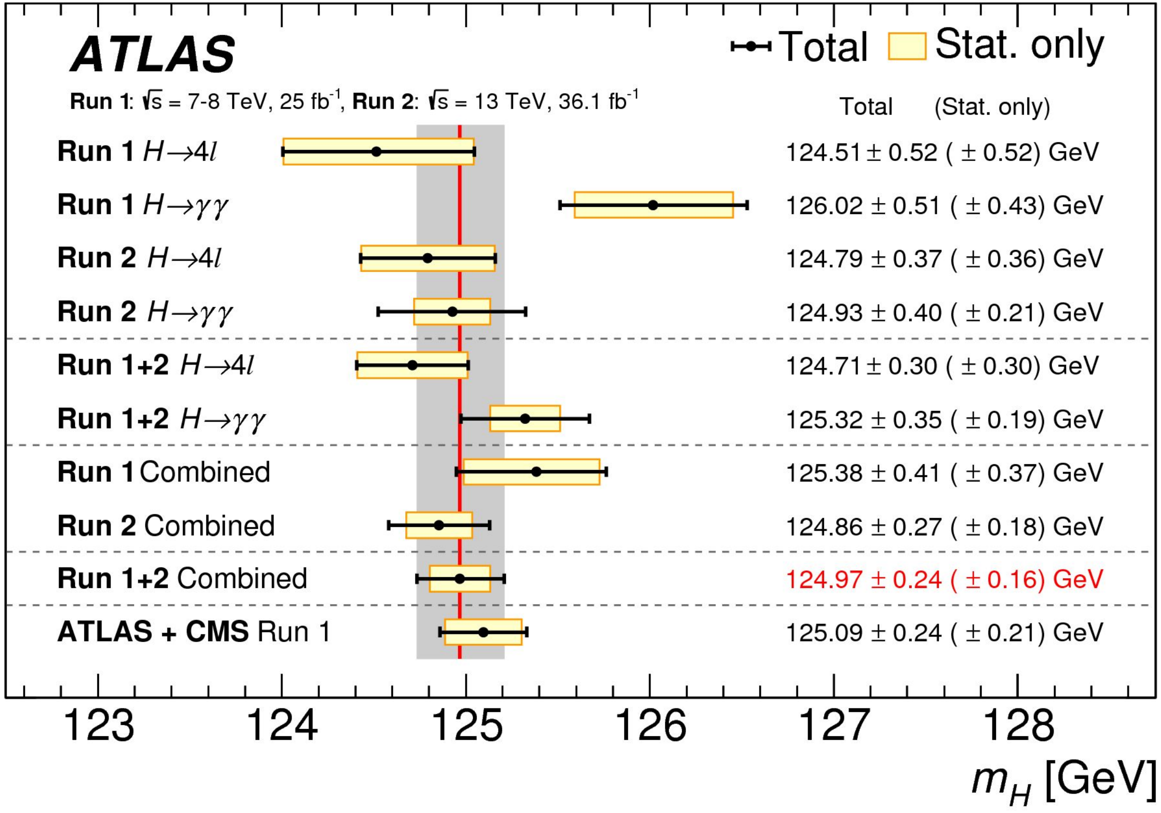


Differential measurements



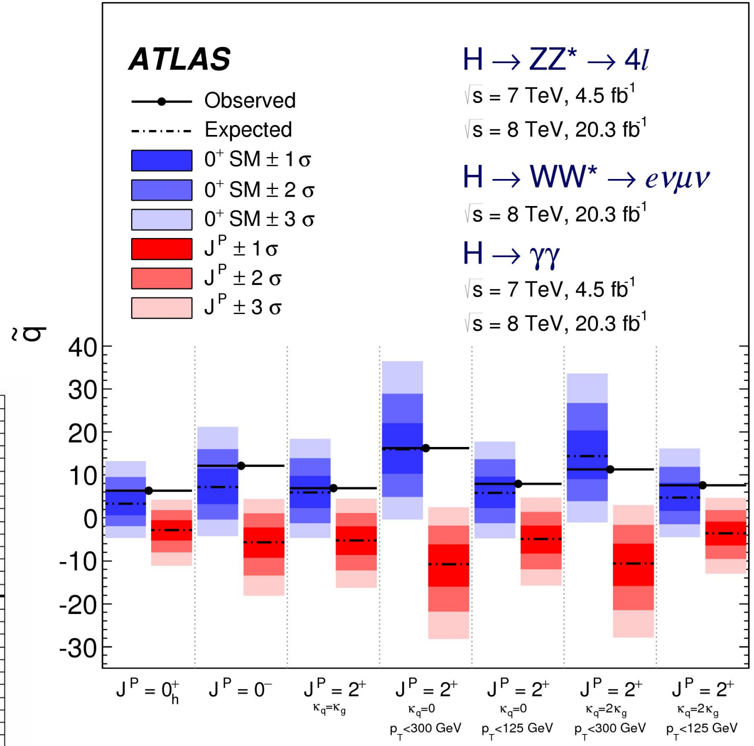


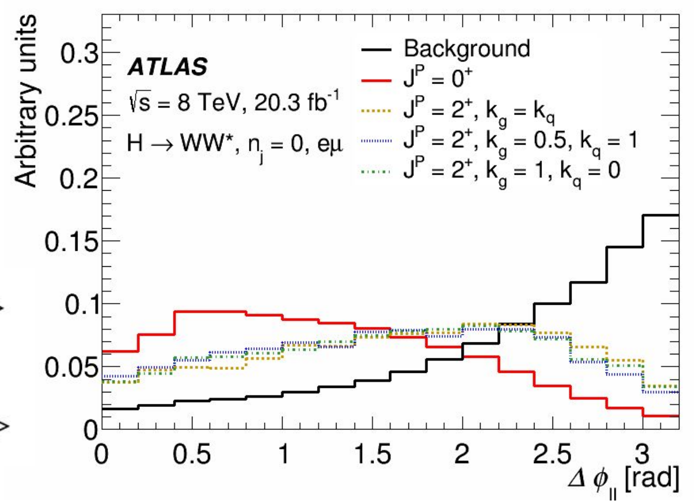
Higgs boson mass



Higgs CP/Spin

- Spin and CP state of Higgs-boson are determined probing angular distribution of decay products
  - Data hints very strongly to a Spin CP state of 0+
  - Alternative models are rejected with a CL of more than 99 .9 %
- Spin-1 hypothesis was theoretically excluded by observation of H->yy decay mode (**Yang's theorem**):
  - *A massive spin-1 particle cannot decay into a pair of identical massless spin-1 particles.*



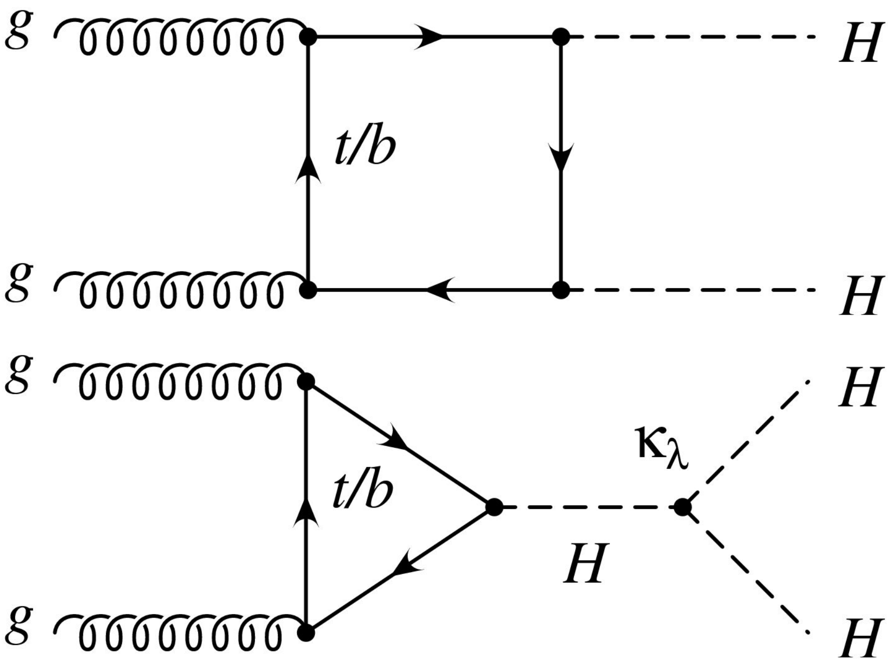


$$\text{CP}-\text{even}: \quad CP|\Phi>=|\Phi>$$

$$\text{CP}-\text{odd}: \quad CP|\Phi>=-|\Phi>$$

Di-Higgs and Higgs self-coupling

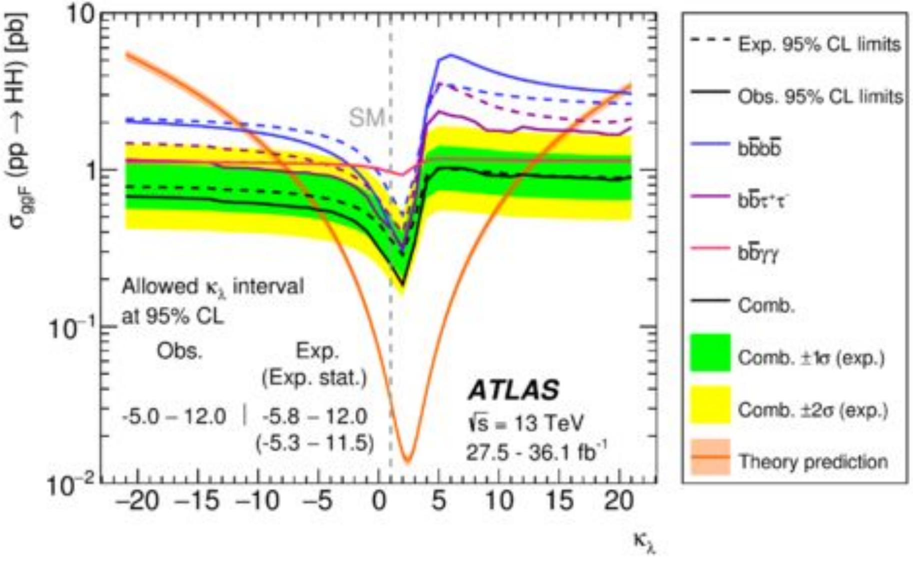
- Higgs-mechanism of electroweak symmetry breaking and mass generation does not only predict the existence of a scalar boson, but also its self-coupling
- Probing the self-coupling of the Higgs boson allows us to verify the form of the Higgs potential
- Di-Higgs production mode is very sensitive to contribution from BSM physics

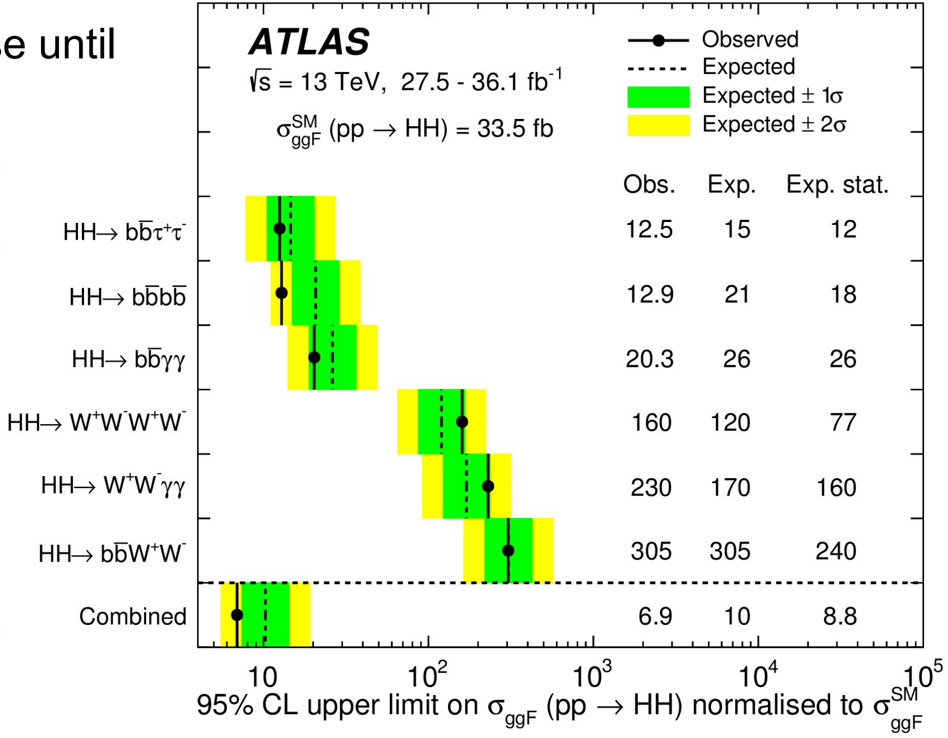


$$\sigma_{pp\rightarrow HH} = 33.5^{+2.4}_{-2.8}\ \text{fb}$$

Di-Higgs and Higgs self-coupling

- So far, we can only set limits on the self-coupling strength and the Di-Higgs production cross section
- Will need the full data from HL-LHC phase until we can measure these observables





Di-Higgs prospects