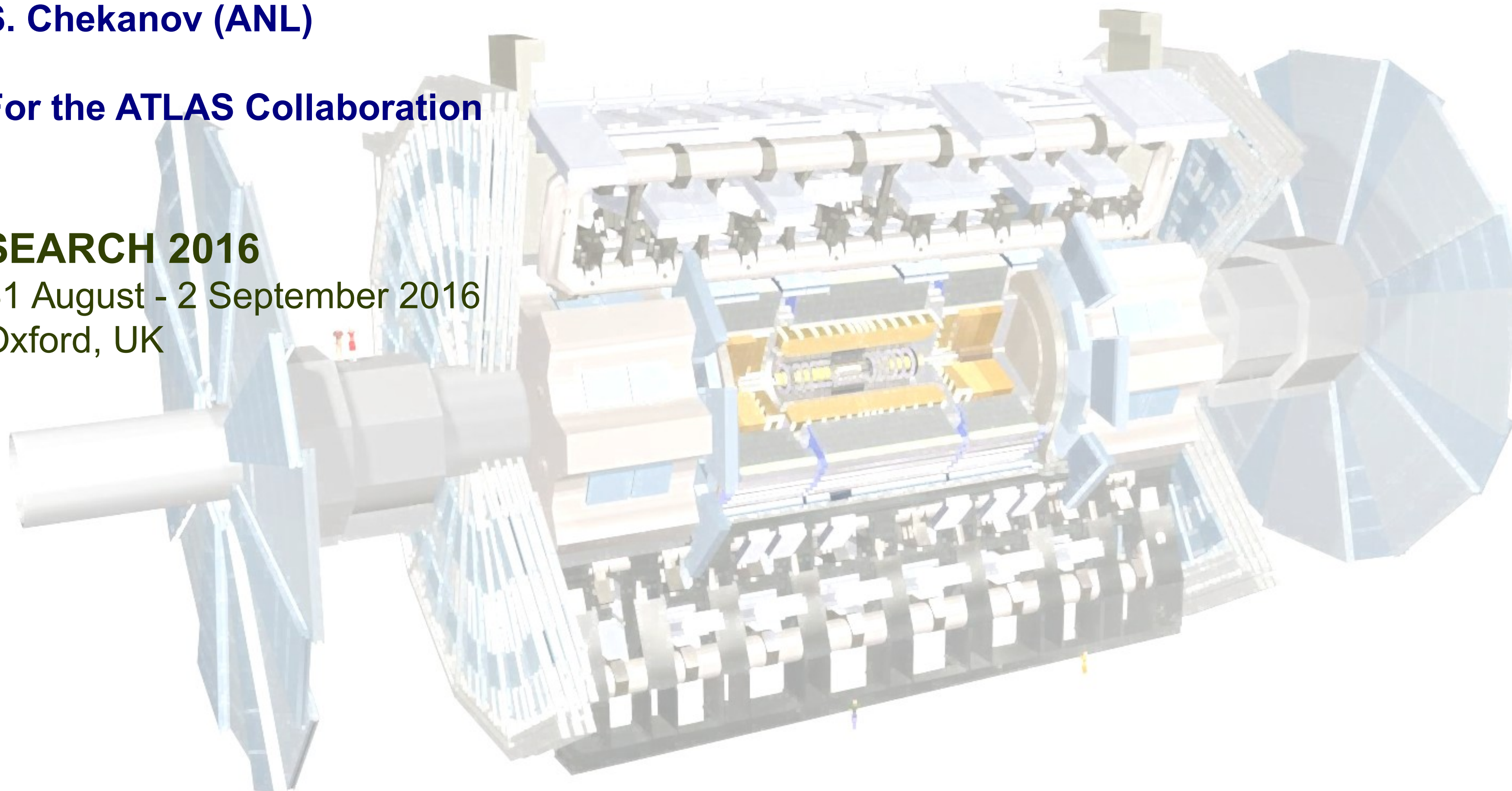
Standard Model (SM) measurements and general agreement with SM predictions

S. Chekanov (ANL)

For the ATLAS Collaboration

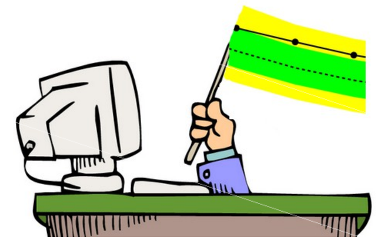


SEARCH 2016
31 August - 2 September 2016
Oxford, UK

Standard Model measurements
(and how they are related to the Search 2016 workshop)

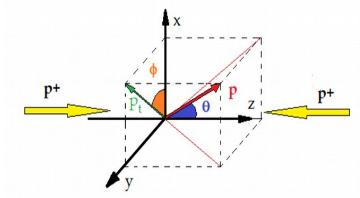
- **Searches:**
  - Act of searching for signatures of new physics (can use SM predictions)
  - Bumps are favorite signatures (do not require detailed understanding of backgrounds)
  - Generally, does not question the degree of validity of the SM (data-driven background)
  - Binary output:
    - **Yes**  or 

 → statistical limits on possible signatures

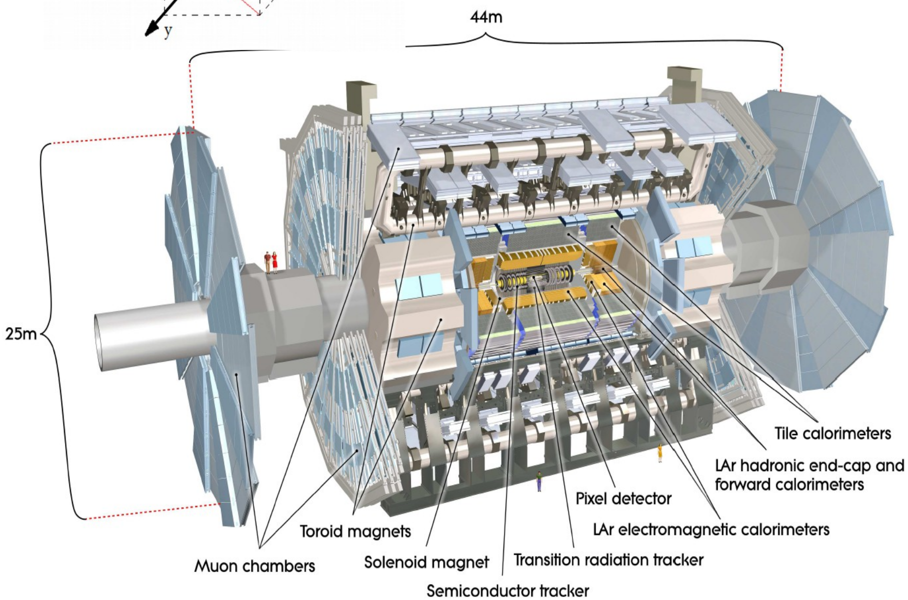


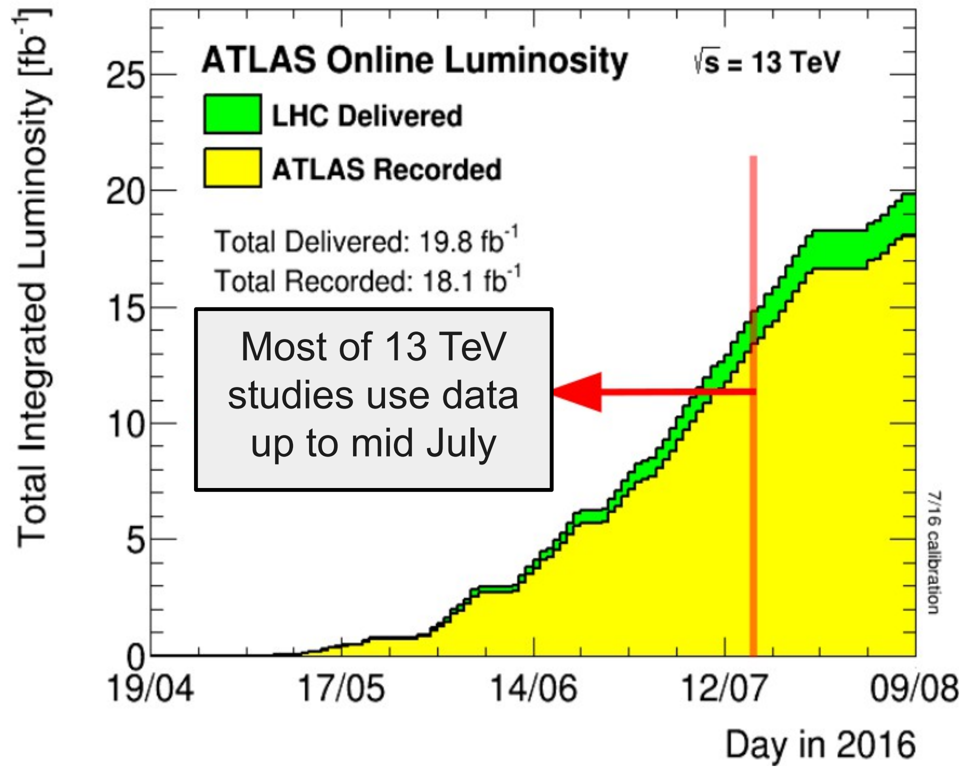
- **SM measurements:**
  - Systematic comparisons of data with SM predictions
  - Typically require “truth-level” (unfolded) results (i.e. free from detector effects)
  - Multiple outputs:
    - “Agrees” OR “Reasonably agrees but some deviations are seen”
    - Disagrees, but we know how to fix it. Use different model!
    - Disagrees, no SM processes explaining data. Optimize cuts for searches
      - .. maybe 

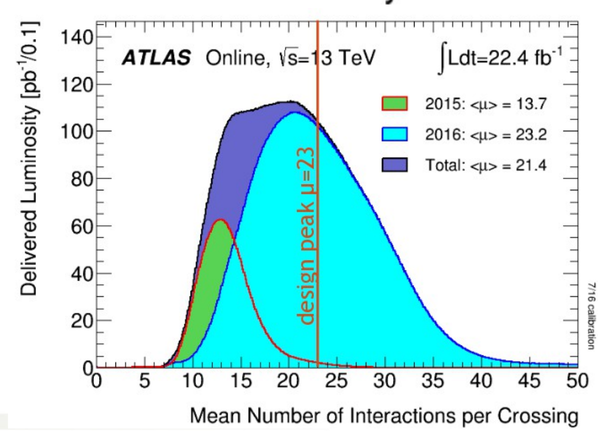
ATLAS detector in Run 2



$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$





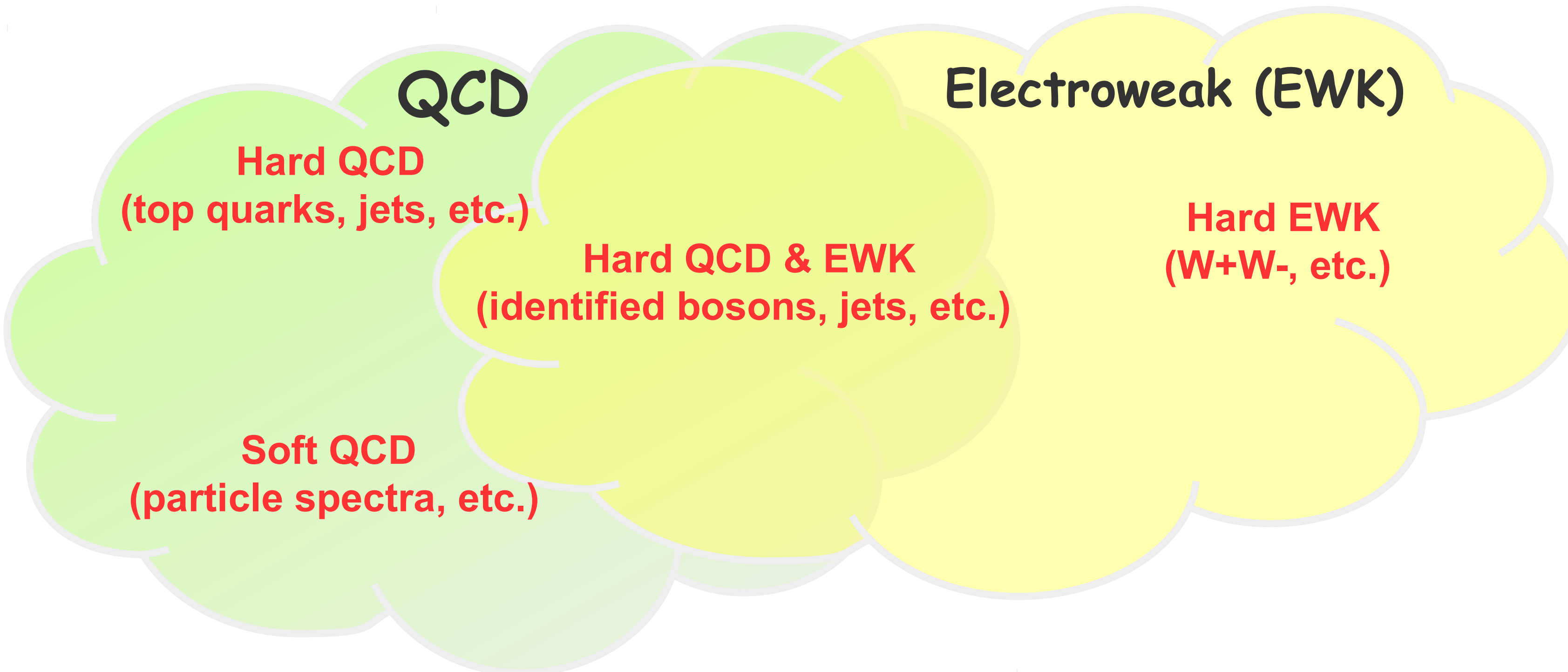


- Exceptional LHC performance in 2016
- Most new results use 3-15 fb^{-1} of data (before ICHEP16)
- Prel. luminosity uncertainty is ± 2.9% (2015+2016)

Testing Standard Model at the LHC (theory)

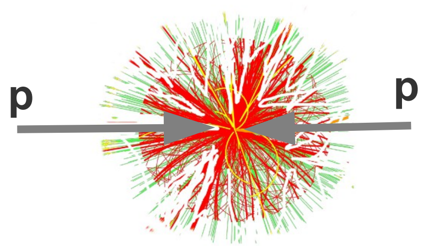
Standard Model - theory concerning the electroweak (EWK) and strong (QCD) interactions

Scope of the SM tests at the LHC:



Testing Standard Model at the LHC (experiment)

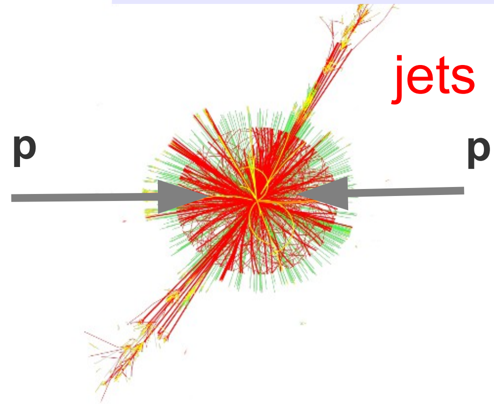
Soft QCD:
particle spectra
p_T < few GeV



>99.999% collisions:

SM Tests:
- LO matrix elements
- LL parton showers (PS)
- models for soft QCD
- consistency in tunings

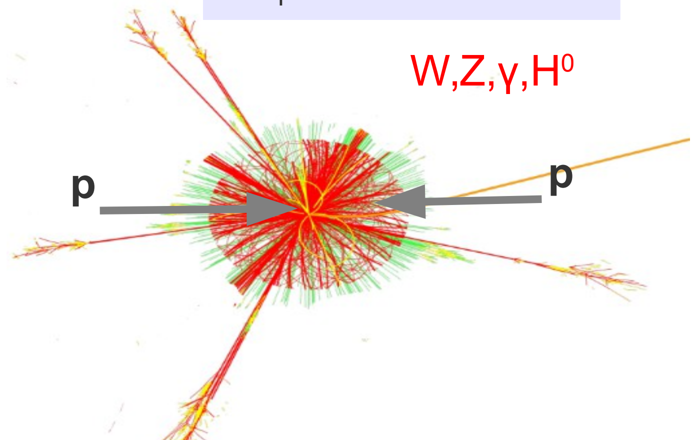
Hard QCD:
jets
p_T > tens of GeV



~10^{-5} % collisions

SM Tests:
- **NLO QCD ($O(\alpha_s^3)$)**
- running α_s
- PDF
- LO QCD $O(\alpha_s^2)$ +PS

Hard QCD/EWK
identified particles
p_T > tens of GeV



+ any combination of all three!

~10^{-6} - 10^{-8} % collisions

SM Tests:
- **NLO, NNLO QCD, NLL etc**
- resummed calculations
- PDF
- LO QCD $O(\alpha_s^2)$ +PS

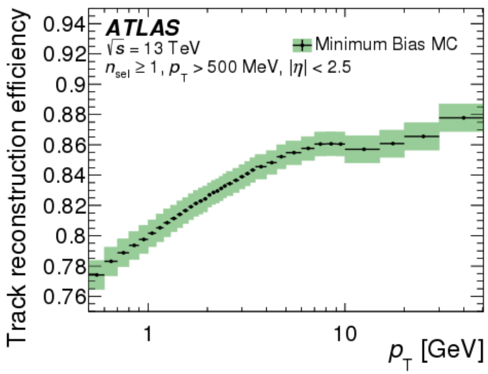
SM predictions in Monte Carlo simulations

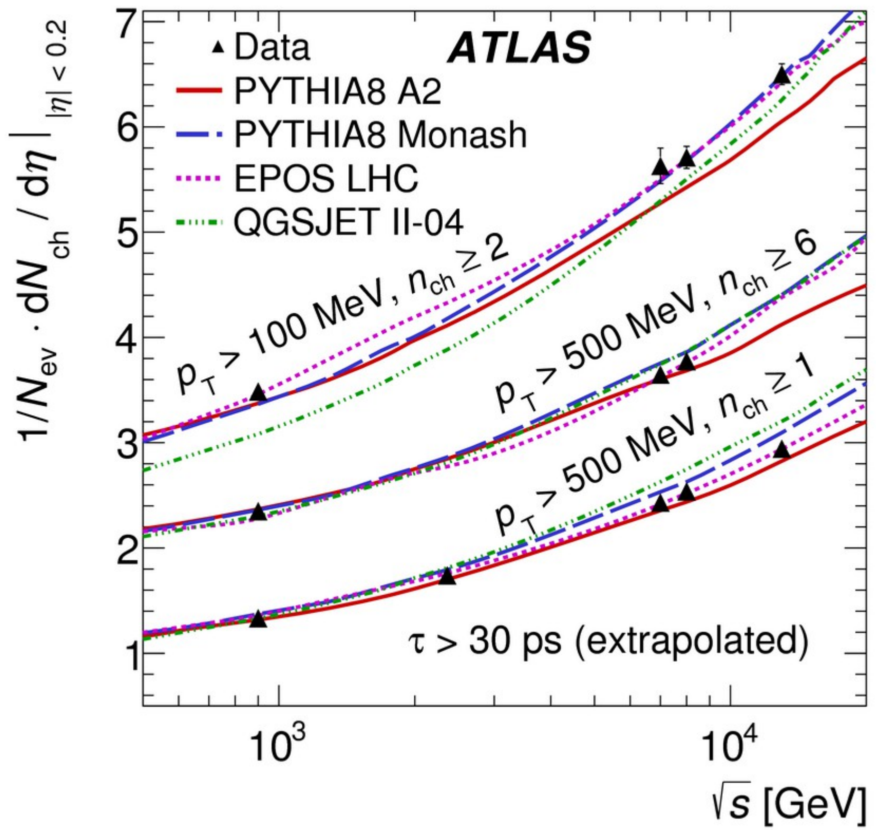
- **Parton level *(often require "hadronisation" correction):***
  - **MCFM:** fixed-order NLO → *vector bosons etc.*
  - **BLACKHAT+SHERPA :** NLO fixed order pQCD (up to 4p) → *vector bosons etc.*
  - **Jetphox:** Fixed-order NLO QCD → *photons*
  - **PeTeR**: resummed NNLO (NNNLL accuracy) → *photons*
  - **NLOjets++:** Fixed-order NLO QCD → *jets*
  - **FEWZ, DYNNLO, Njetti** *etc. – NNLO calculations for vector bosons*
- **Event generators at hadron/particle level:**
  - **PYTHIA6/8:** LO ME with parton showers – general-purpose generator
  - **HERWIG++:** LO ME with parton showers – general-purpose generator
  - **ALPGEN:** Tree level multipartons (up to 5p) at LO QCD+ Parton Shower
  - **SHERPA:** Tree level multipartons (up to 5p) at LO QCD + Parton Shower
  - **MADGRAPH+PYTHIA/HERWIG:**
    - LO Matrix Element + Parton Shower tree level multipartons up to 5p
    - NLO (up to 2 partones) + Parton Shower for high-orders
  - **MC@NLO+HERWIG:** NLO + Parton Shower
  - **POWHEG+PYTHIA:** NLO + Parton Shower

State of the art:
Parton level: NNLO, resummed logs
Hadron level: NLO+PS, LO tree level (5p)

Soft QCD - I

- Charge particles reflect non-perturbative region of QCD
- Use LO+PS "tunable" Monte Carlo models
  - 13 TeV. 170 μb^{-1}
  - Data unfolded to reduce effects from detector acceptance



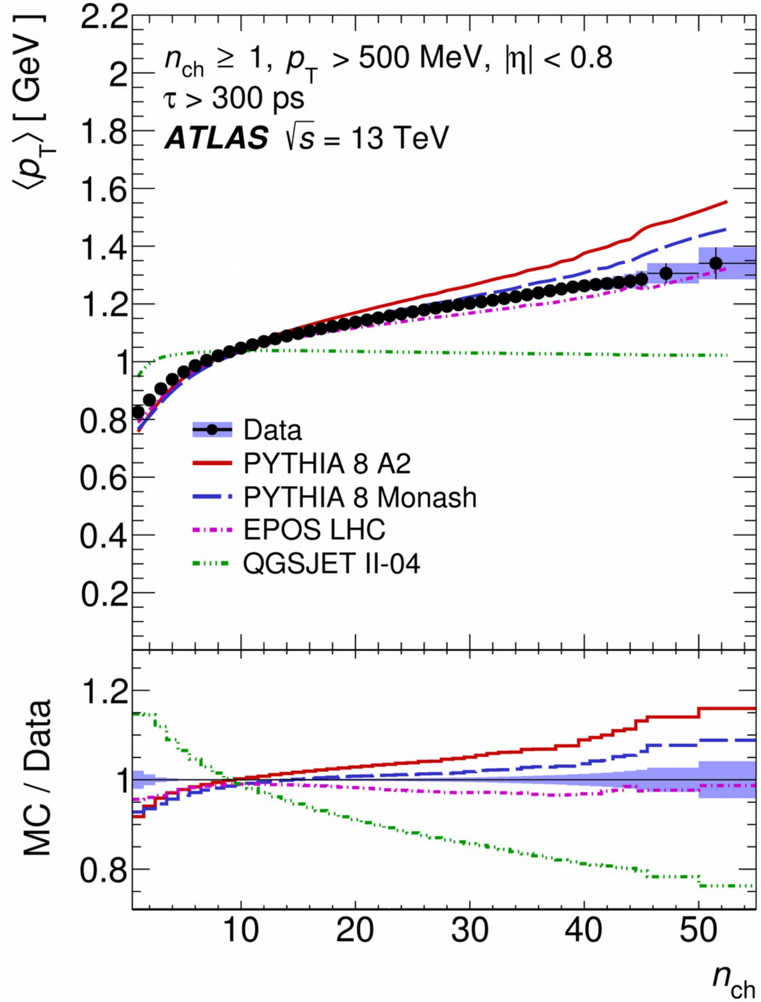


- **Models:**
  - PYTHIA8 with different tunes (+ single and double diffraction)
  - QGSJET (Reggeon field theory framework)
  - EPOS (Gribov-Regge effective theory for hard and soft QCD) → best description

Soft QCD - II

- Differences between MC models and the measured distributions
- EPOS simulation describes the data best
- Preferred over general-purpose Pythia8
  - Better tune for Pythia8 required?

ATLAS
Physics Letters B 758 (2016) 67–88

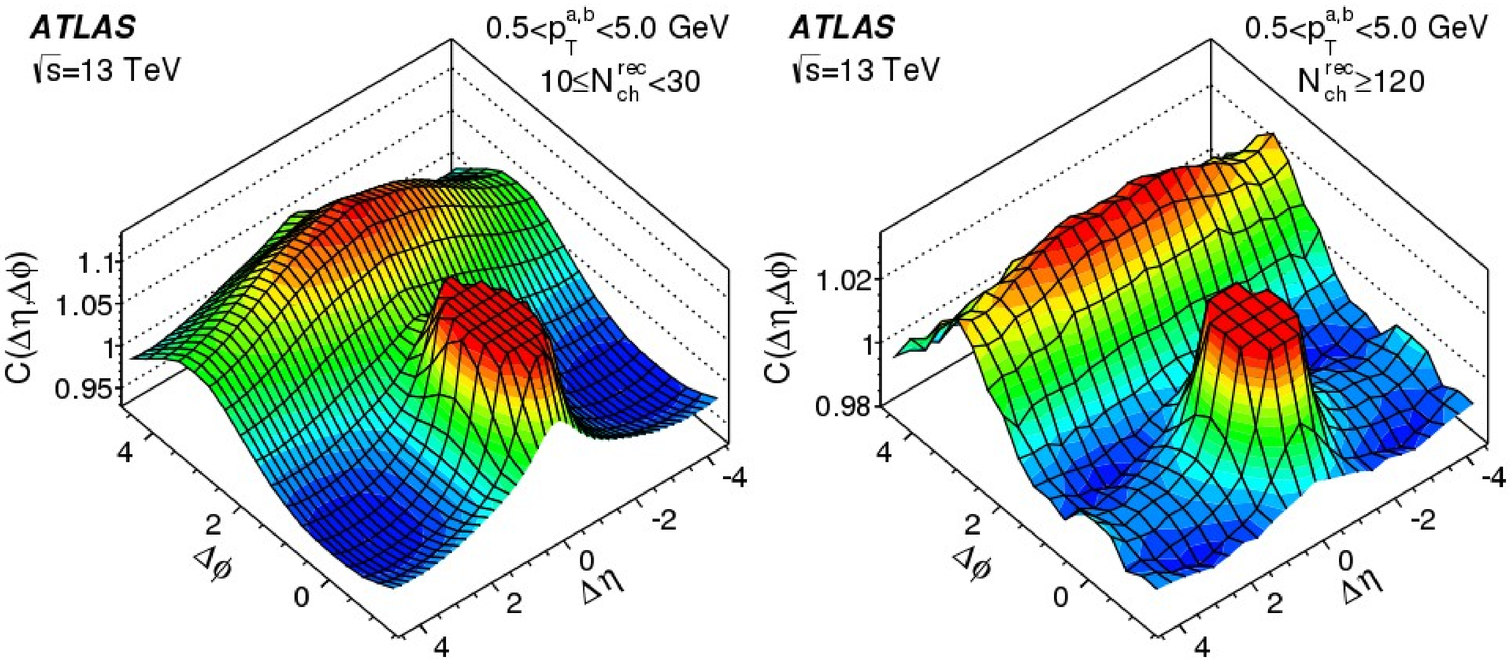


- Non-perturbative regime of Standard model included in "tunable" .. models
- Data guide constructions of such models and gives feedback for model builders

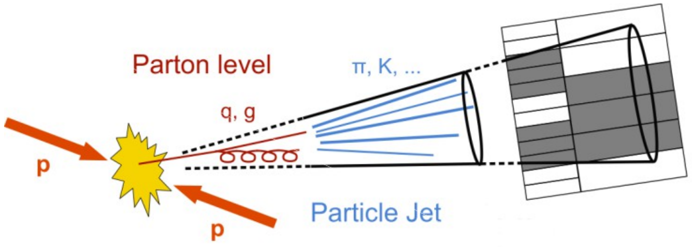
→ Reveals the basic problem for discoveries using SM measurements
→ Need models built from first principles!

Measurements of the ridge at 13TeV

- A matter of considerable debate
- pp Monte Carlo generators do not include it
- Amplitude extracted using a Fourier analysis is similar for 13 TeV and 2.76 pp energy
- Ridges in pp and p+Pb arise from a similar physics?



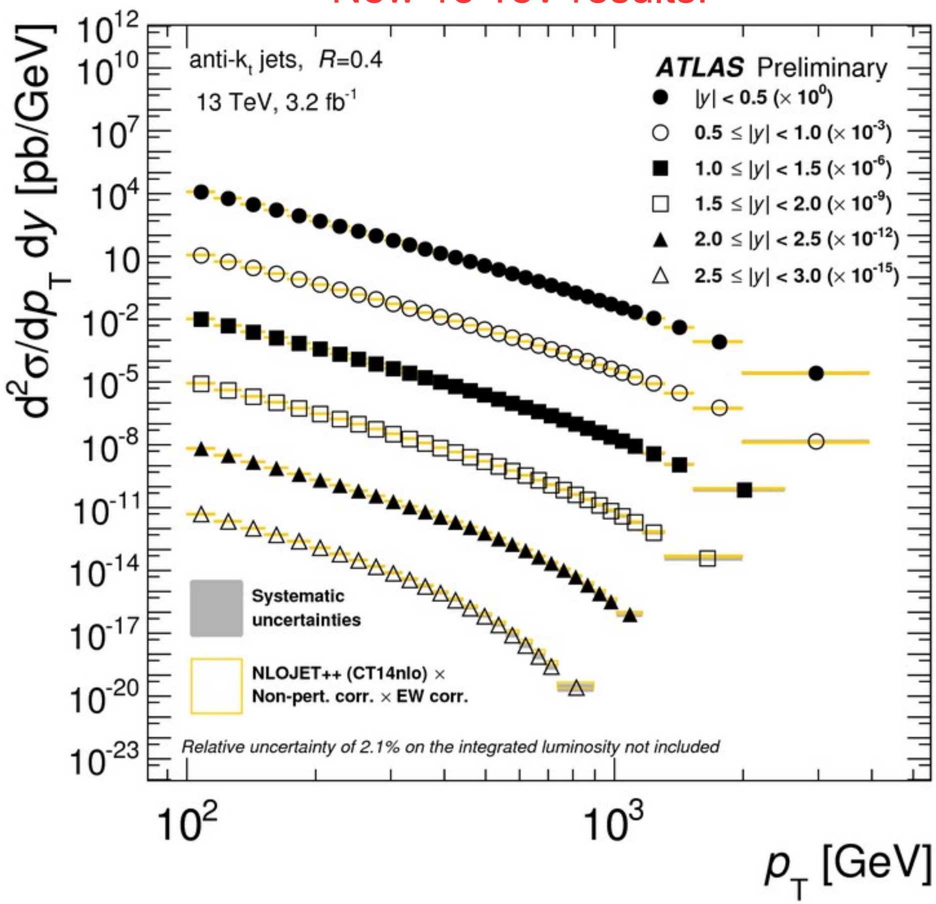
Jet production

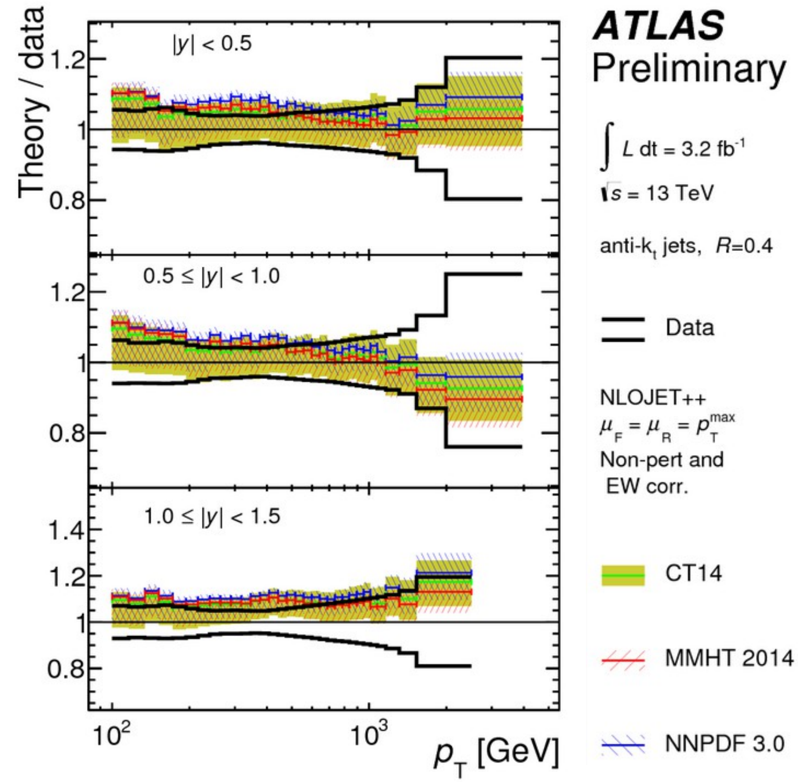


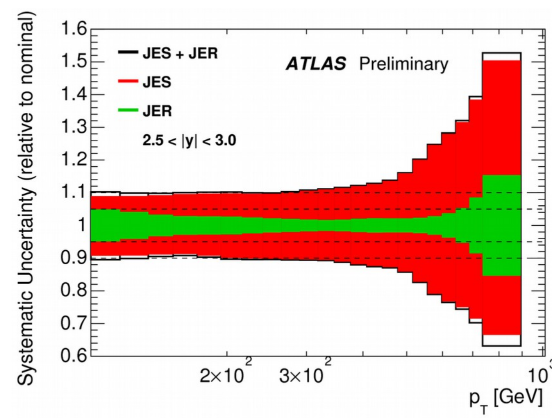
- Probe of perturbative (pQCD) at small distances ~ 1/ E_T ~ 10^{-19} m
- Straightforward comparison with theory
  - Testing QCD matrix elements & parton-density functions (PDF)
  - Reliable calculations at NLO QCD (NLOJet++)
- Simple observables
  - → Resonant-type enhancements mean discovery*

Hard QCD: Jets

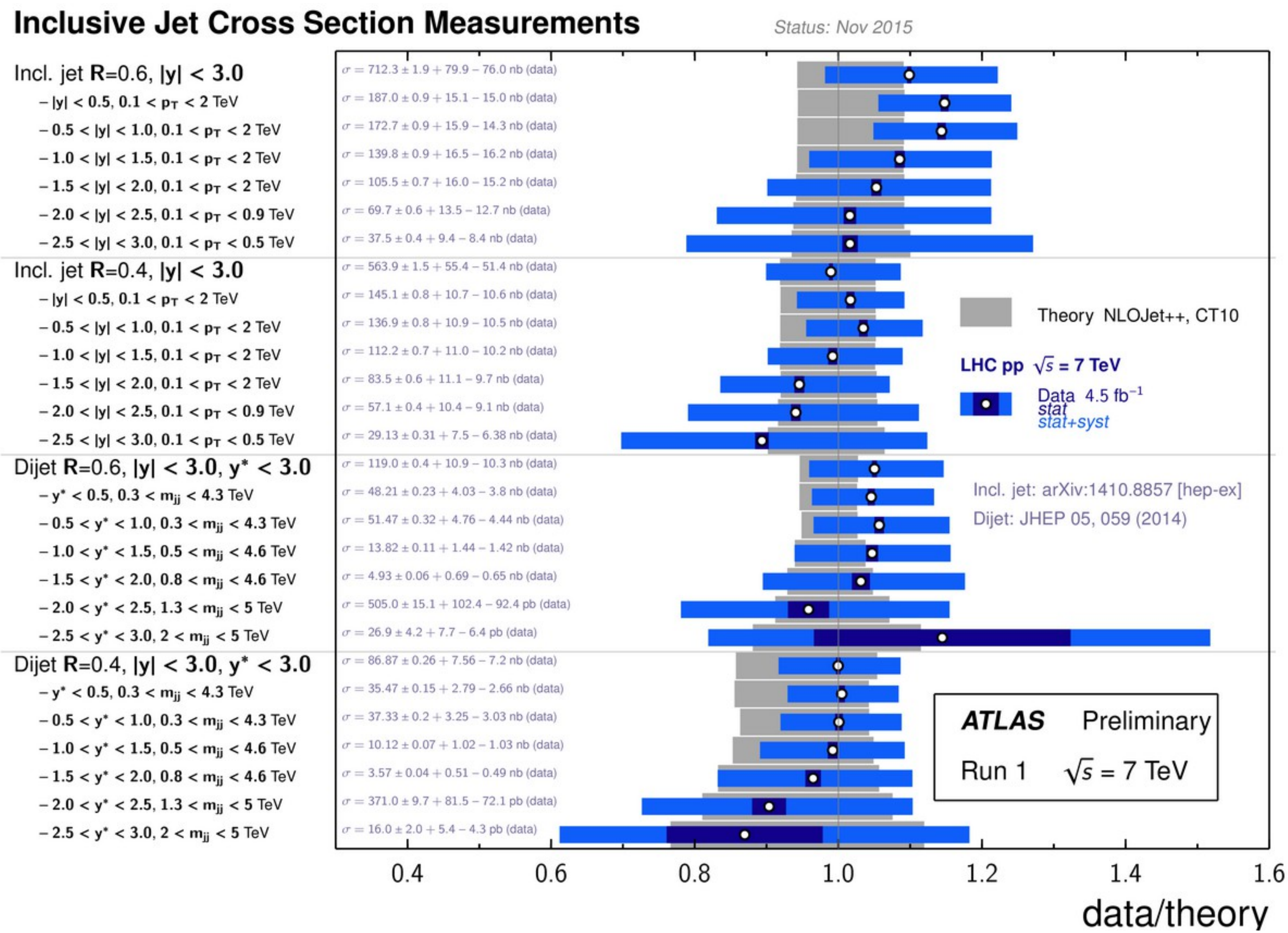
New 13 TeV results!







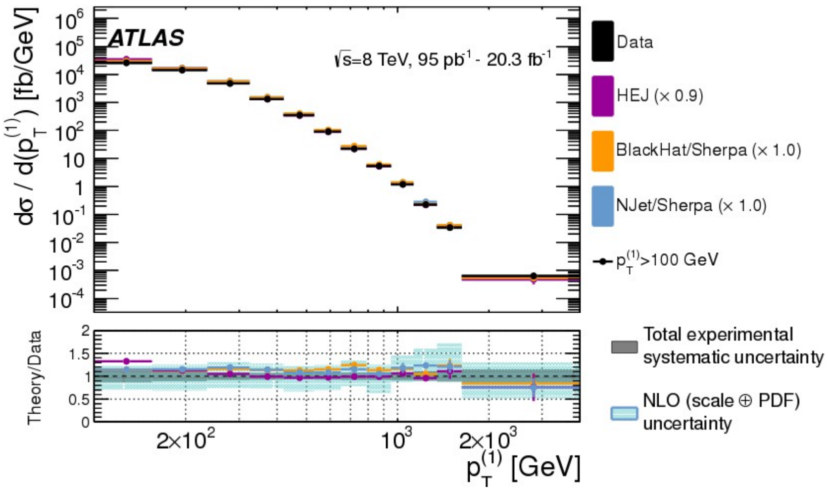
- Data are consistent with NLO QCD up to pT=3 TeV
- Sensitivity to PDF is observed
- Largest systematics: Jet Energy Scale at large pT

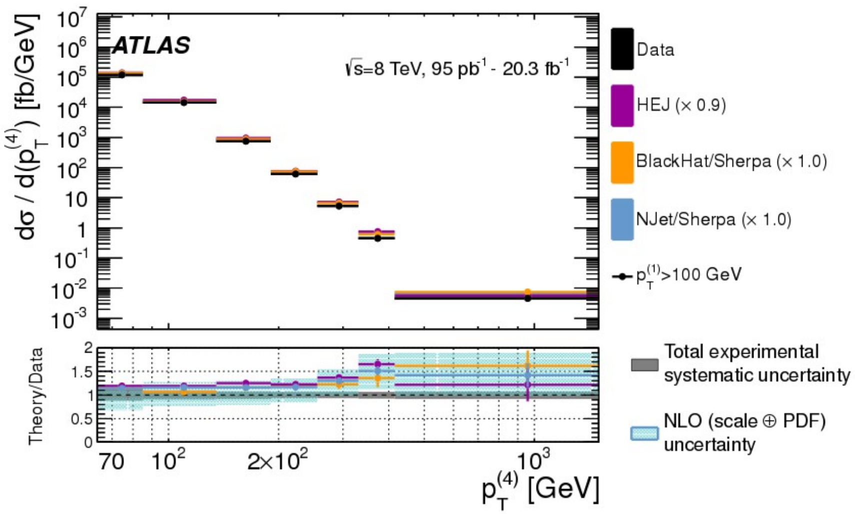


Good agreement with NLO QCD (NLOjet++, CT10 PDF)

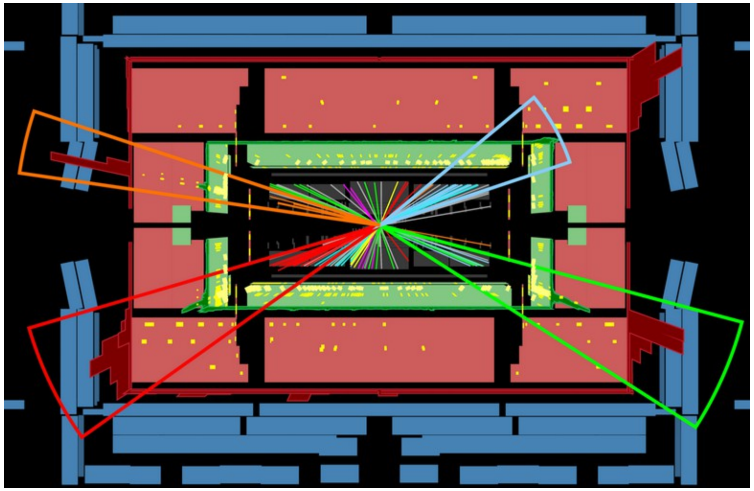
Multijet cross sections

ATLAS, JHEP 12 (2015) 105
http://arxiv.org/abs/1509.07335





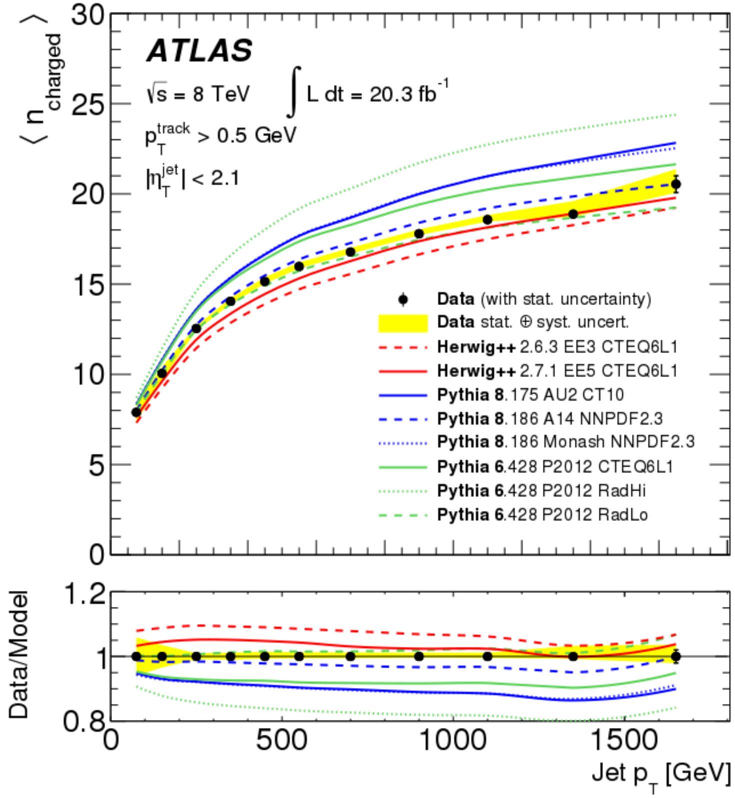
- Feynman diagrams require several vertices even at leading-order (LO) in α_S
- Exceptionally strong test of QCD ME
  - Example: Madgraph has ME up to 4 partons
- NLO NJet/Sherpa and BlackHat/Sherpa calculations agree well with the data
- Madgraph & LO+PS describe shapes too, but require additional normalization

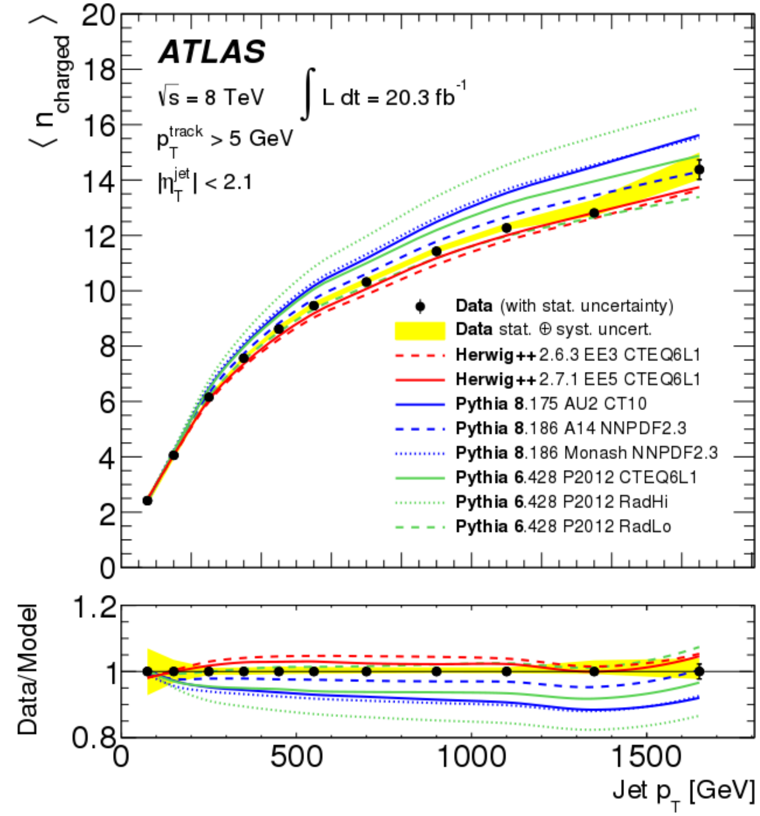


- At least one jet with E_T>100 GeV
- Other 3 jets E_T>64 GeV

Particle multiplicity inside jets

ATLAS
Eur. Phys. J. C76(6), 1-23 (2016)



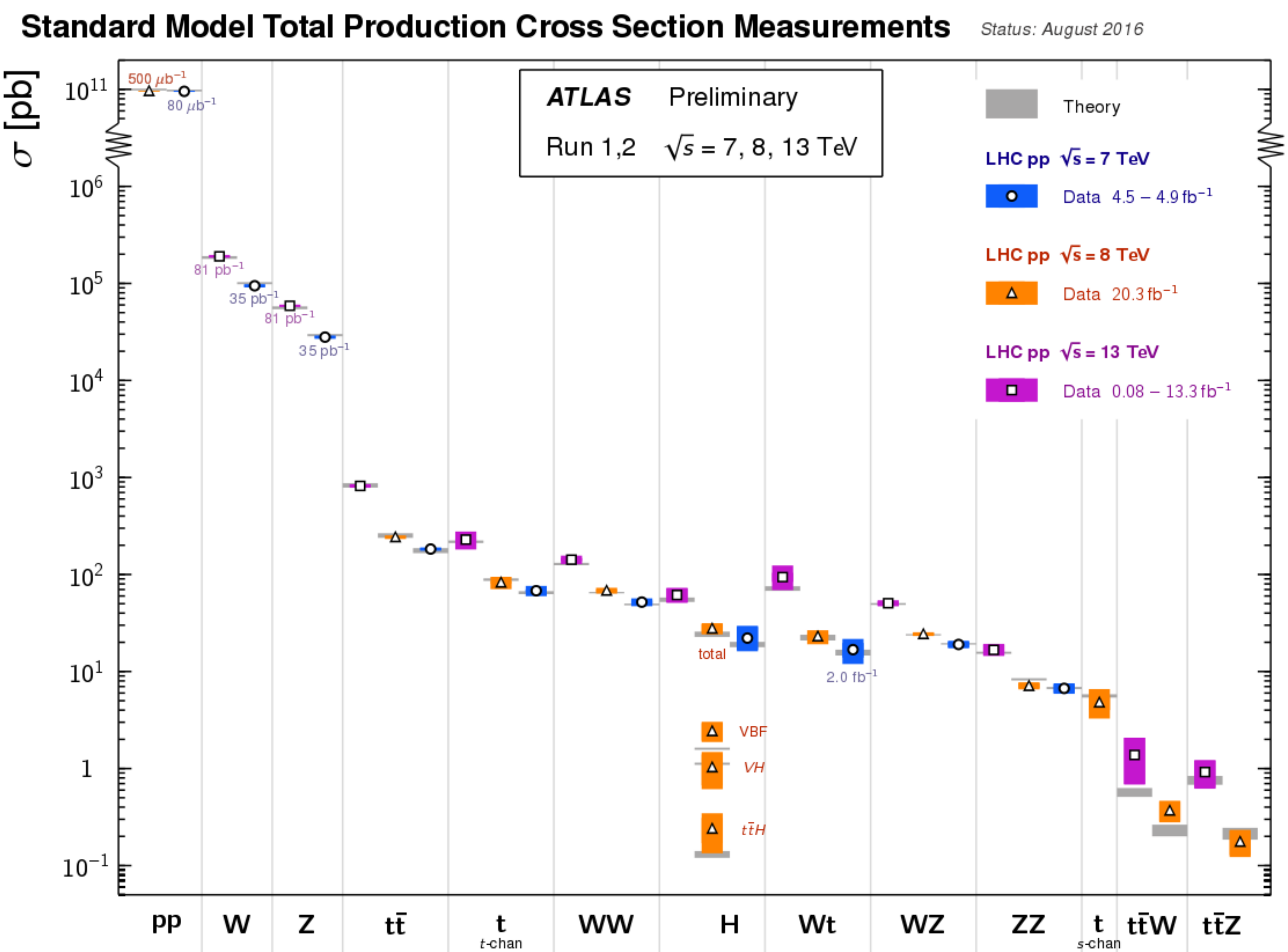


- Important jet property
- Sensitive to quark/gluon differences and α(s)
- PS Monte Carlo simulations indicate sensitivity of data to α_S (“Monash vs A14) and treatment of underlying event (HERWIG)
- Limitation for claiming new physics due to “tunability” of generators

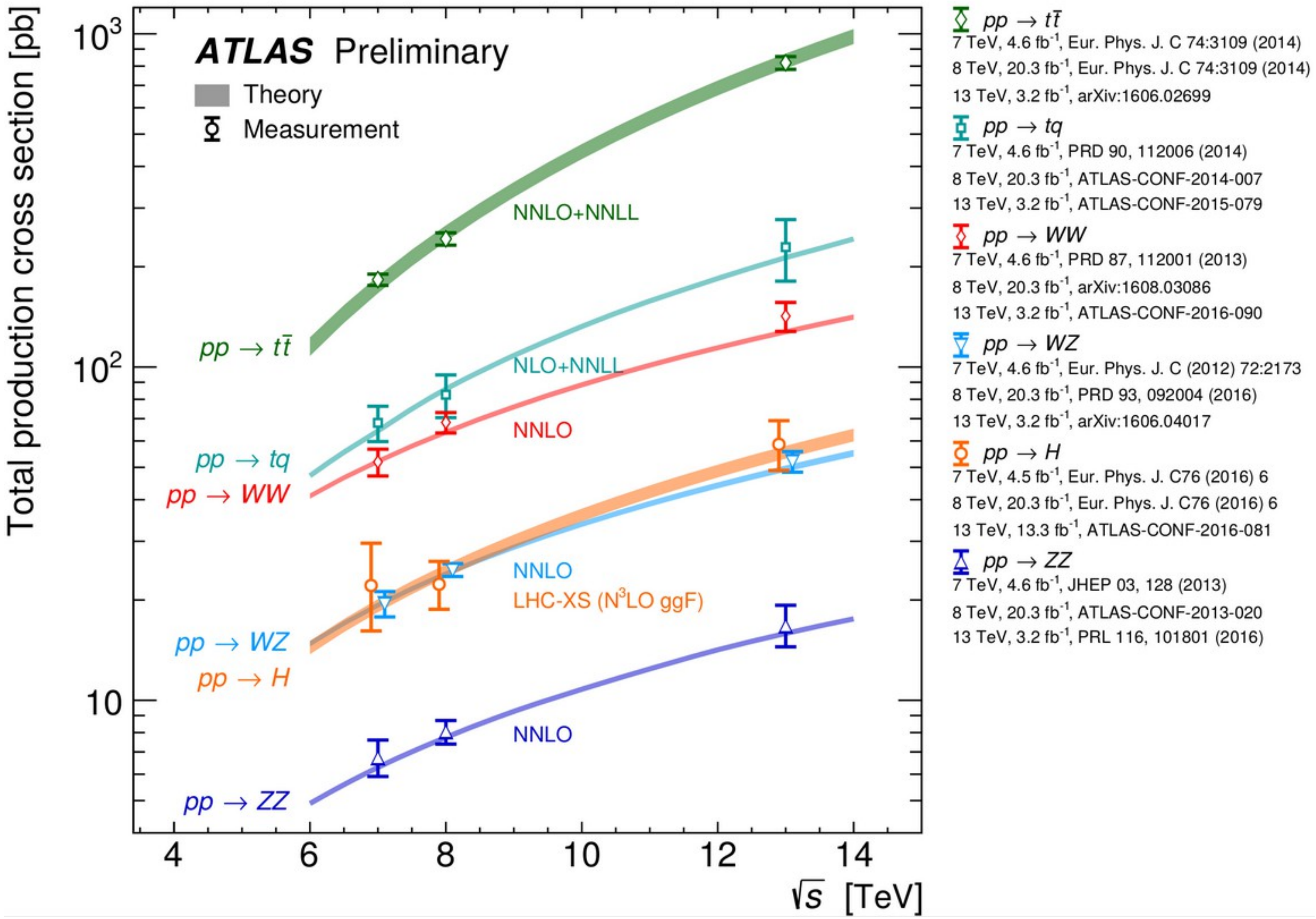
Single- and jet-associated boson production (V+jets)

- Testing EWK and perturbative QCD
- Constraining backgrounds for searches
- Better theoretically understood than jets (~1-2% precision at NNLO QCD)
- Simple environment to test SM (electron, photon and muon signatures)

SM total production cross section measurements

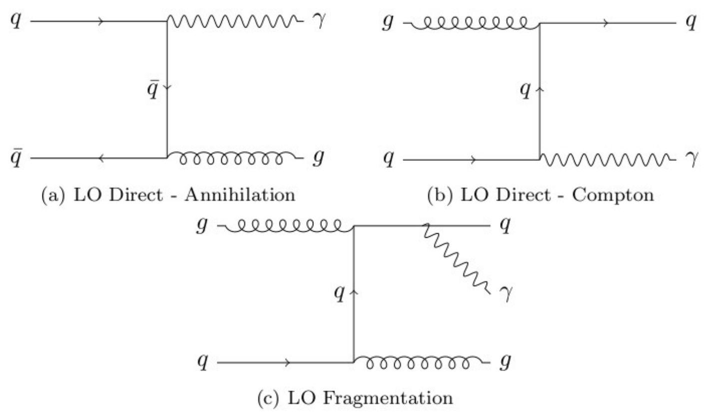


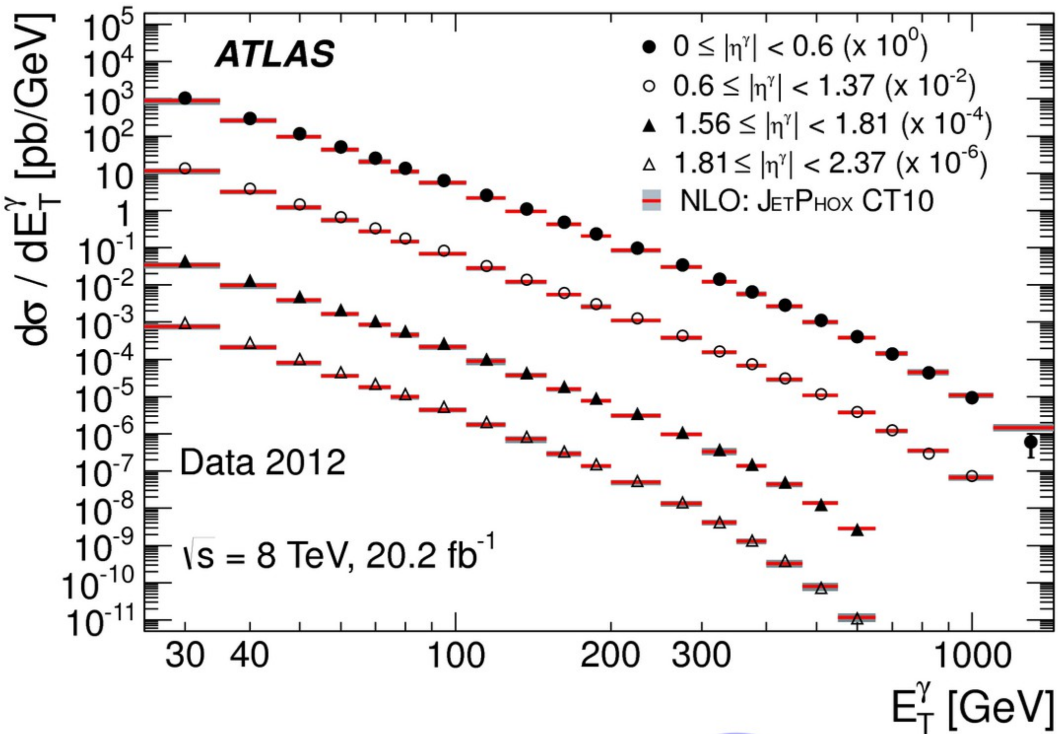
Inclusive production



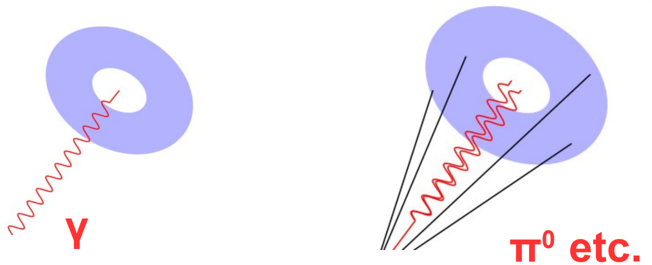
Good agreement with state-of-the-art predictions

Inclusive photons





- QCD tests in clear environment
  - ME LO, NLO, resummations
  - Parton density functions (PDF)
- Direct Compton is the dominant process at the LHC (~80%)
  - CDF: pT(γ)>100 – Direct annihilation
- Available models:
  - Jetphox (NLO)
  - PeTeR (NLO+resummed logs)



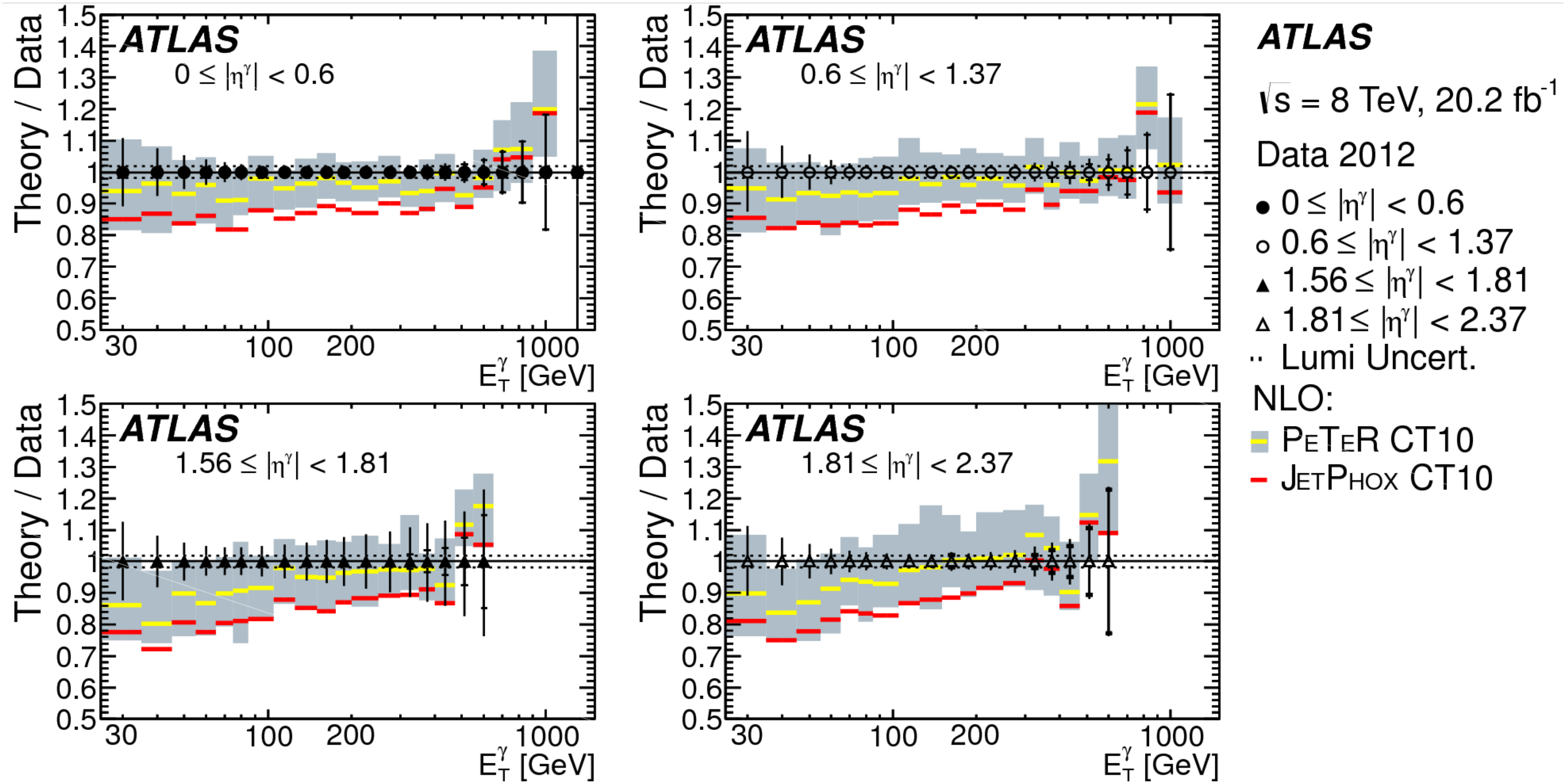
First measurement of photons above 1 TeV

Photon isolation:

- Require: E_T (iso)< 4.8 + 0.0042 x E_T (γ)
- Use data-driven subtraction method

Inclusive photons-II

ATLAS (2016)
http://arxiv.org/abs/1605.03495

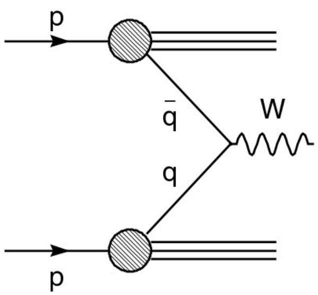


- JetPhox (NLO) shows some difference in shape. Waiting for NNLO!
- PeTer: Resummed logs to NNNLL accuracy + leading electroweak Sudakov logs
  - improvements in shapes! Also see arXiv:1606.02313 (M.Schwartz)

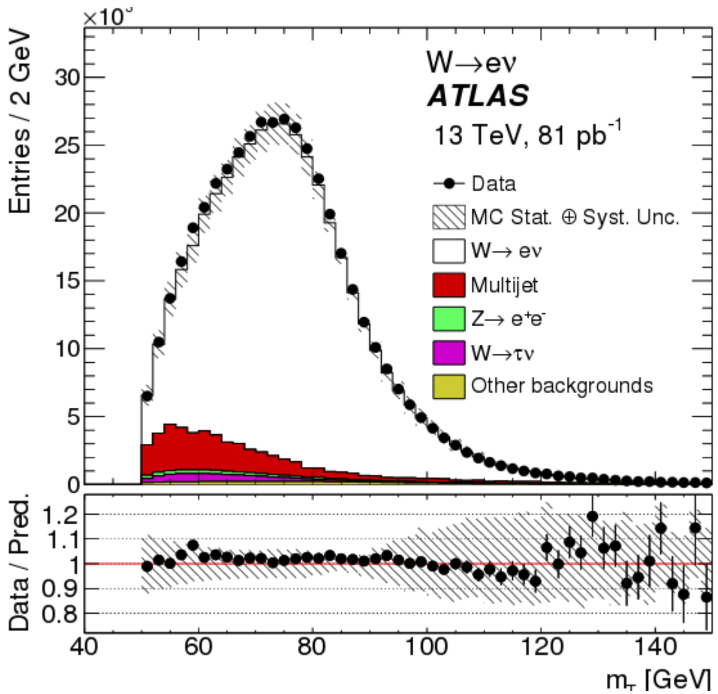
W boson cross sections

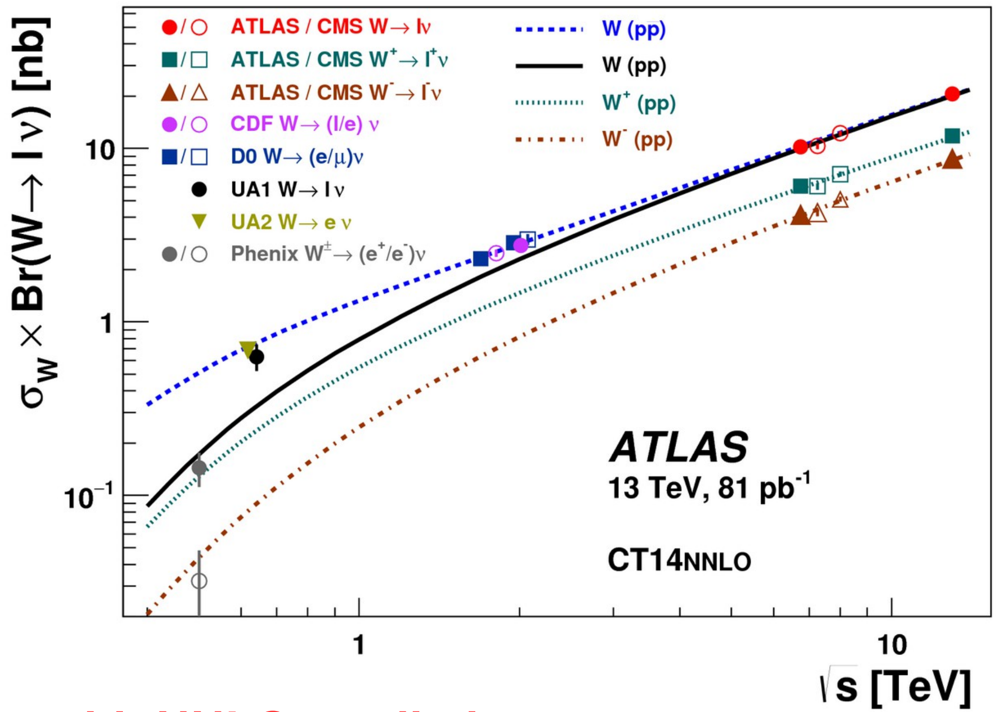
ATLAS
http://arxiv.org/abs/1603.09222

- Testing electroweak (EWK) + QCD
- Drell-Yan process is best known at the LHC
  - Quark initiated
  - NNLO QCD predictions (DYNNLO & FEWZ)
  - EW corrections up to NLO accuracy
- Simple signatures: transverse energy for W→ l ν



W production via Drell-Yan process

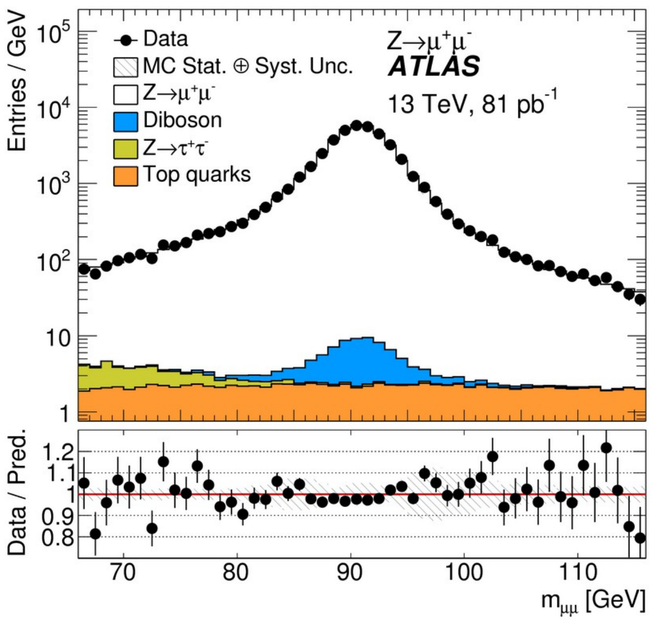


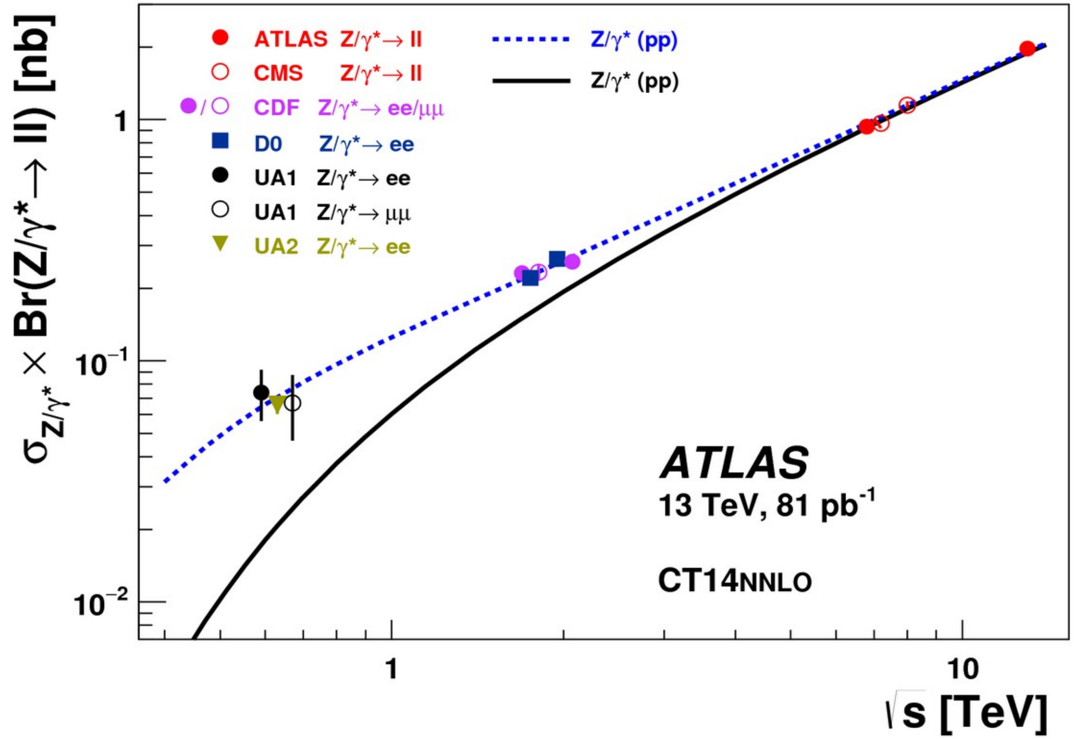


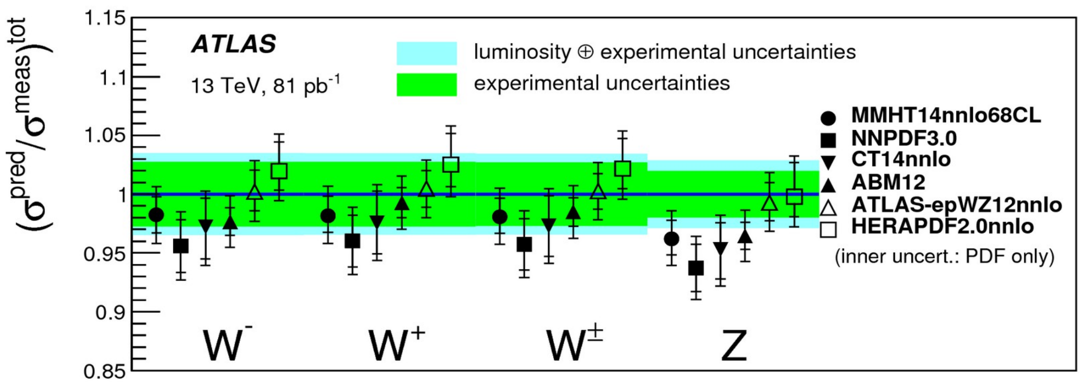
Good agreement with NNLO predictions

Z→ l+l- boson cross sections

ATLAS
Phys. Lett. B 759 (2016) 601

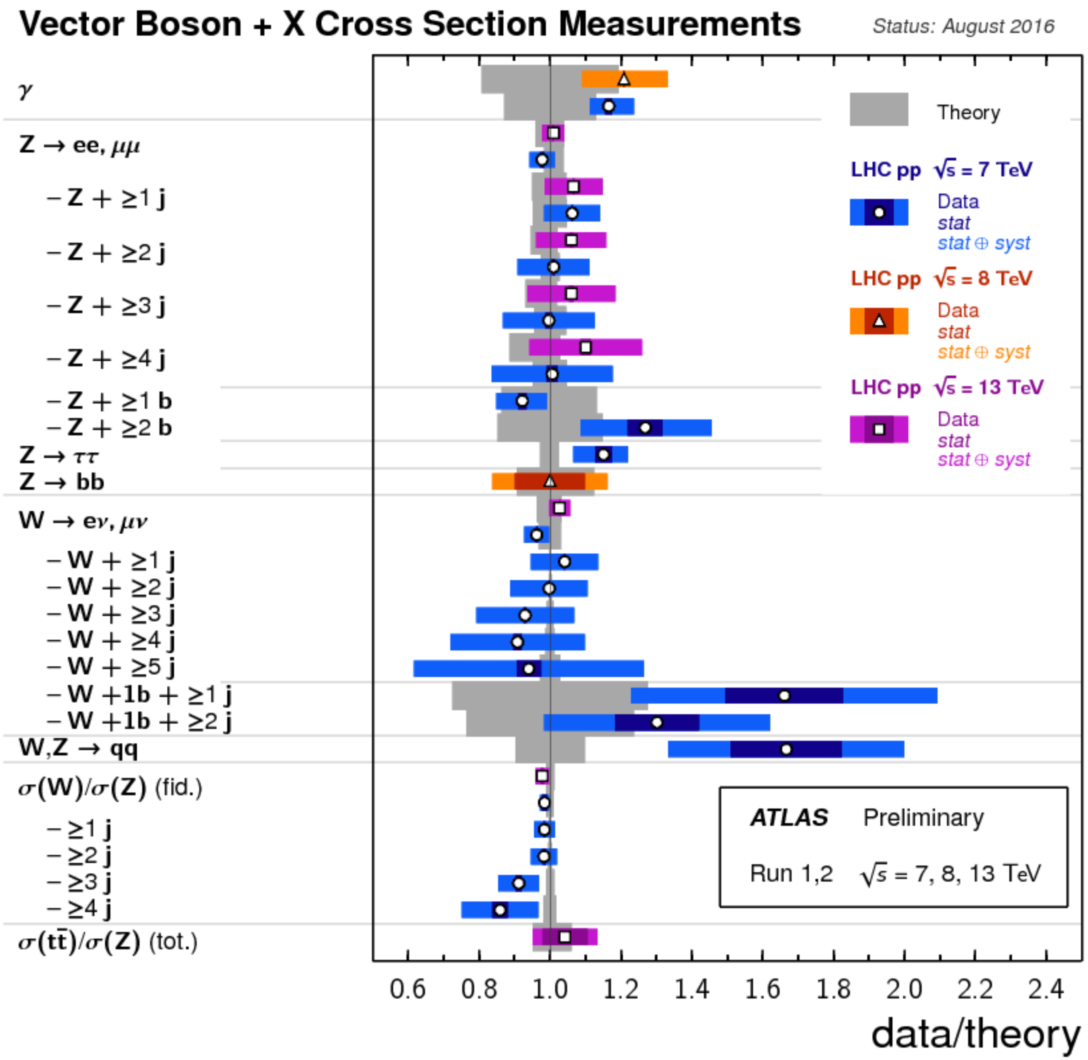






- χ2/ndf ~ 1 for the ratio with NNLO QCD
- Sensitivity to PDF
- Excellent agreement with the predictions

Vector bosons + X



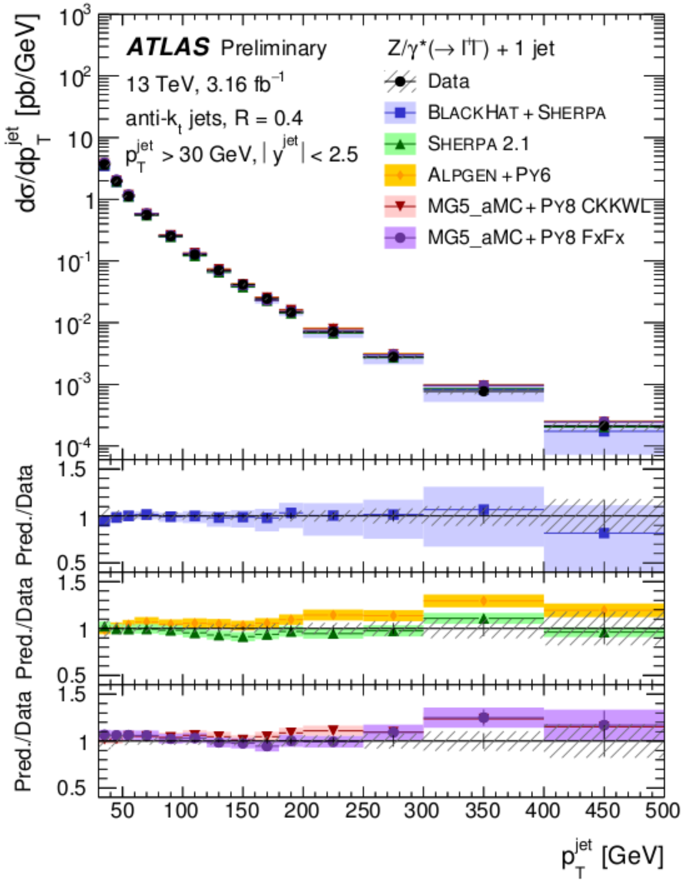
General good agreement between data and SM

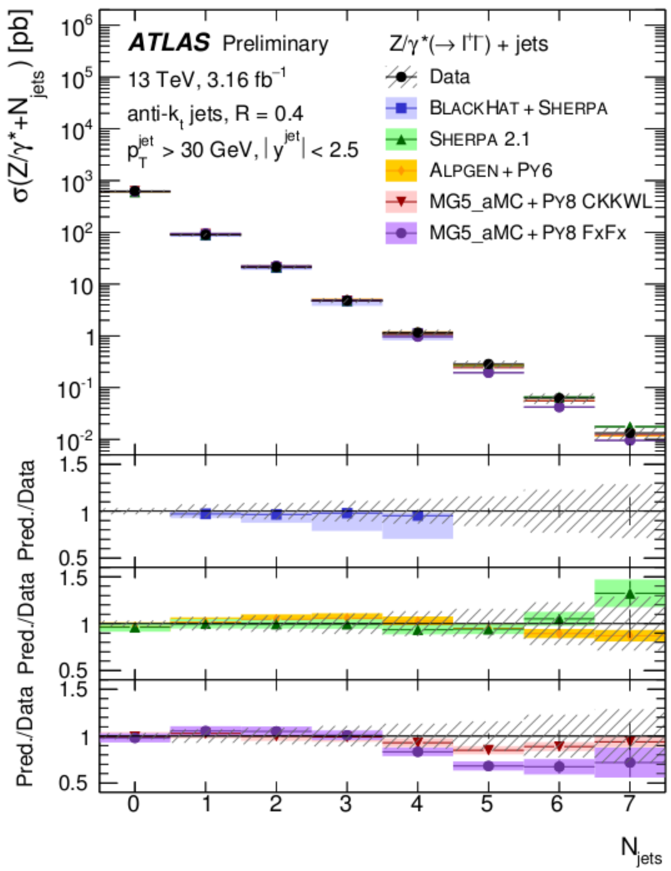
1-2 sigma excesses deserve future attention by theorists / new measurements

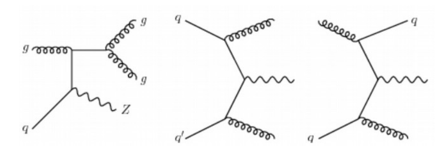
Z+jets production

Differential cross sections

New 13 TeV results!





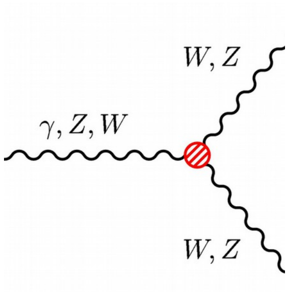


Examples of Z+ 2 jets at LO QCD

- Hard pT spectrum for ALPGEN+Pythia6 (LO+PS) for Z+1 jet
- Significantly improved description by ME+PS@NLO generators (Sherpa 2.1 and MG5_aMC+Py8 FxFx) which use NLO matrix elements for up to 2 additional partons

Multi-boson production
(>1 boson)

- Clean experimental signatures
- Well-understood predictions (i.e. NLO, NNLO)
- Irreducible background for Higgs physics
- Sensitivity to anomalous triple gauge couplings (aTGC)



Multiboson production: Zγ and Zγγ

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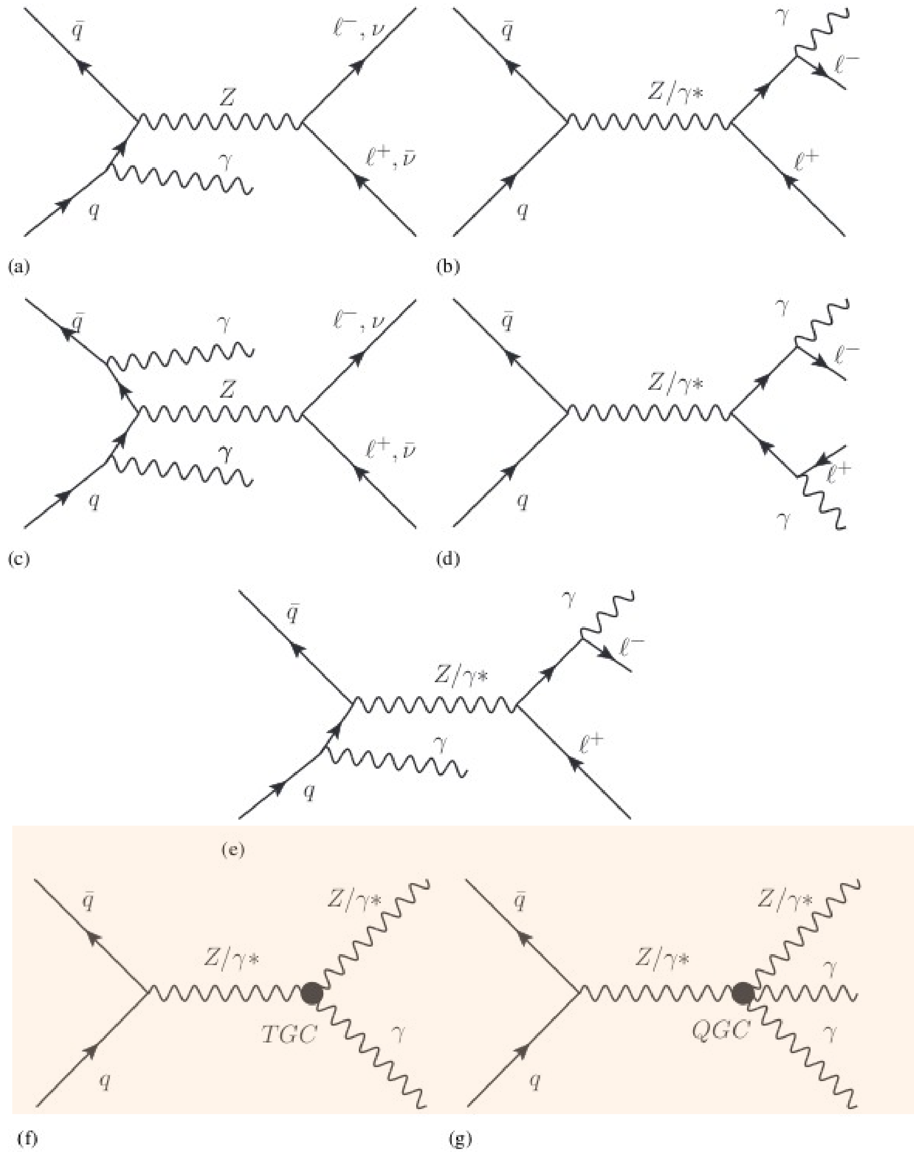
Phys. Rev. D 93, 112002 (2016)

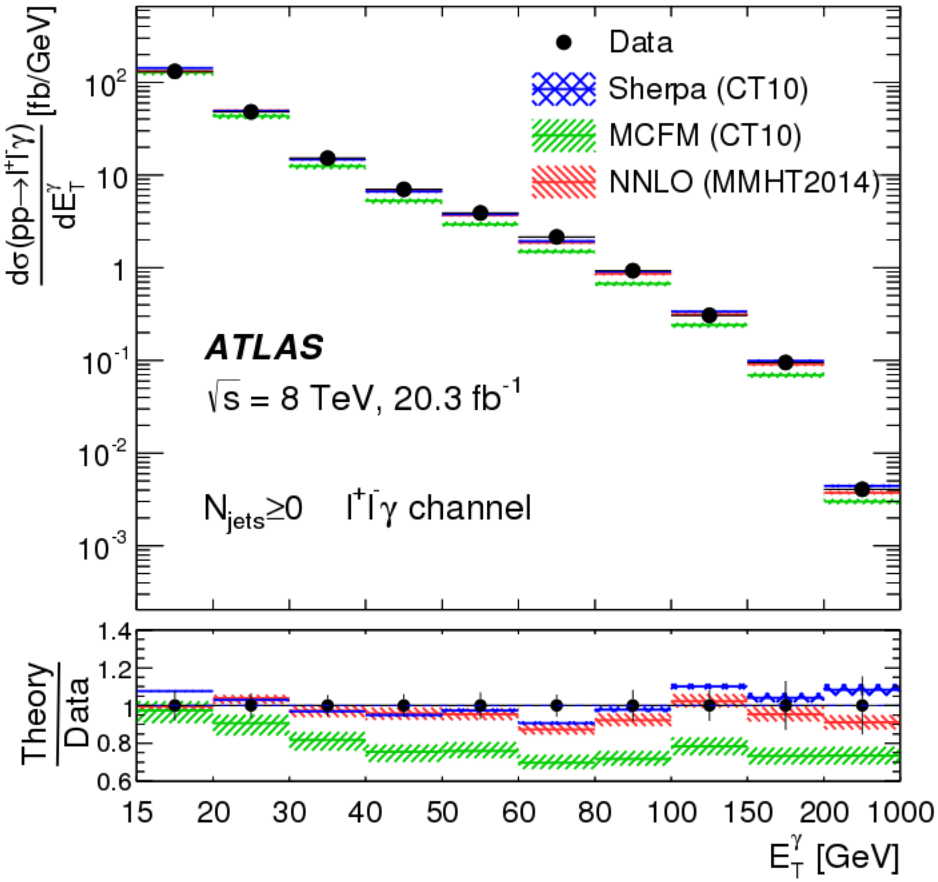


- Dominated by initial/final state photon radiation
- SM tests: NLO & NNLO ME
- Irreducible background for H→ Z γ

Beyond the Standard Model:
Triple- and quadratic gauge coupling?

Multiboson production: Zγ and Zγγ

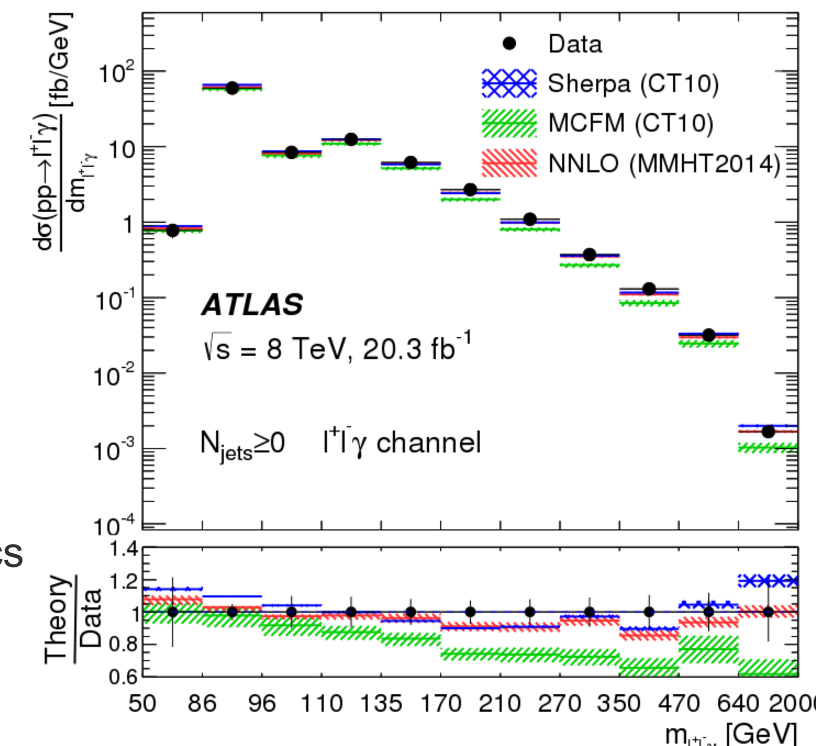
ATLAS
Phys. Rev. D 93, 112002 (2016)



- NNLO and Sherpa describe the data
- MCFM (NLO) fails
- All models describe exclusive production (N_{jet} = 0)

Invariant mass

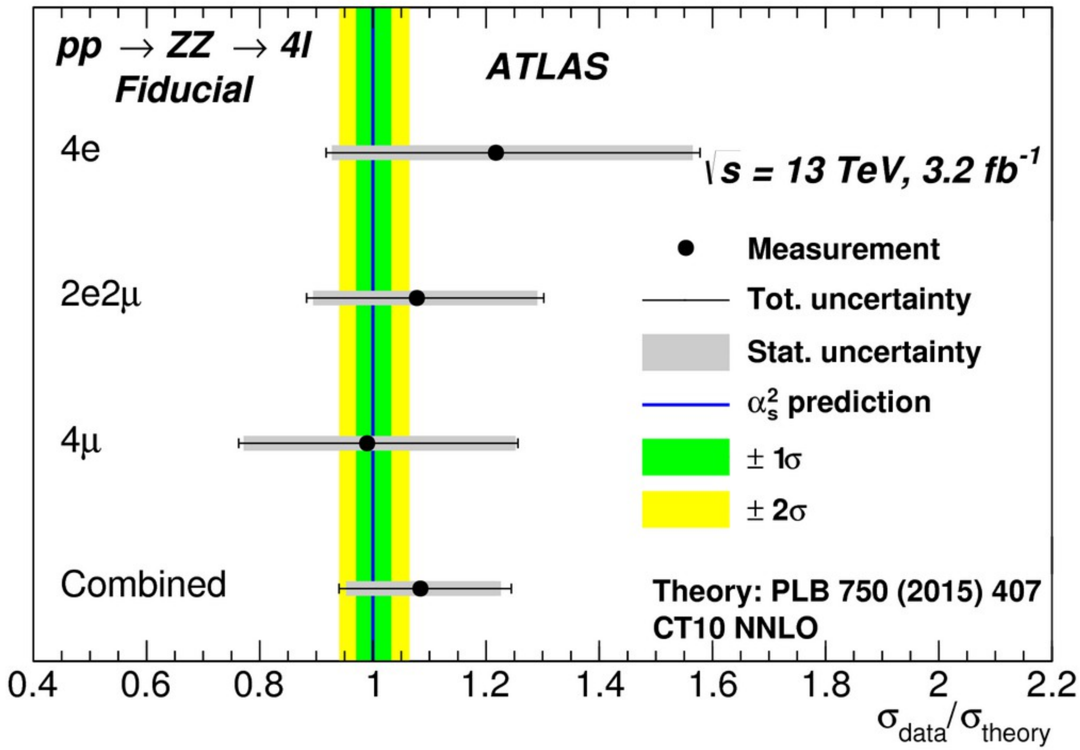
(best place to see new particles)

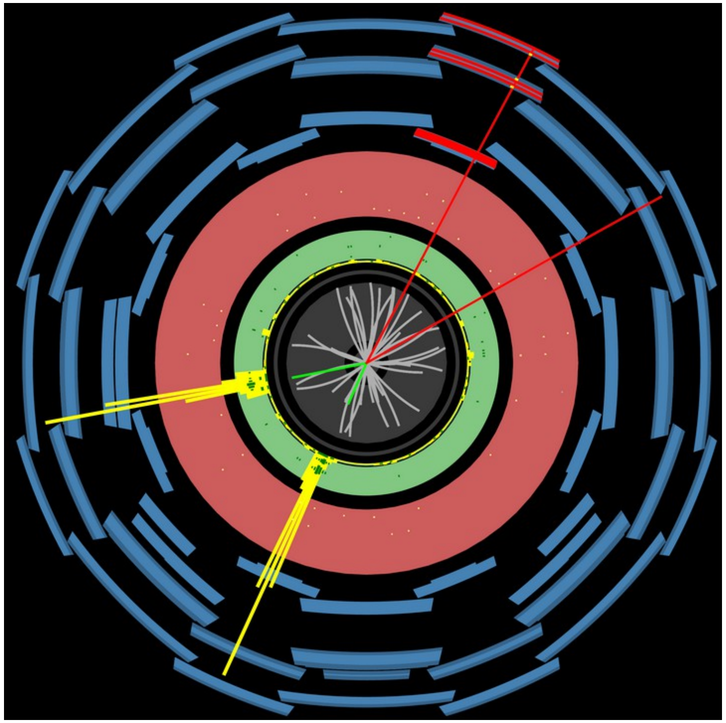


- Invariant mass is the best for finding a new physics
- Reasonable agreements with NNLO
- Also good agreements for l+l-γγ (low statistics)

Multiboson production: ZZ

ATLAS
Phys. Rev. Lett. 116, 101801 (2016)



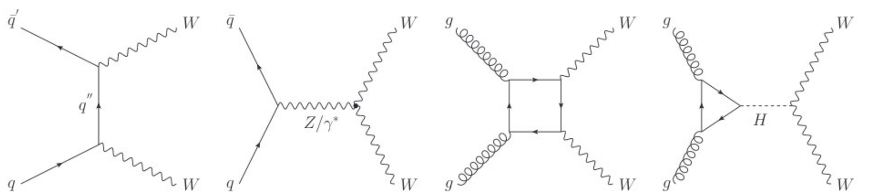


- Measurements in the fiduciual region using lepton channels (ZZ→ 4 leptons)
- Stringent test of the EWK sector of SM
- Background for Higgs, sensitive to triple neutral-gauge coupling
- Good agreement with NNLO (~O(α_s^2))

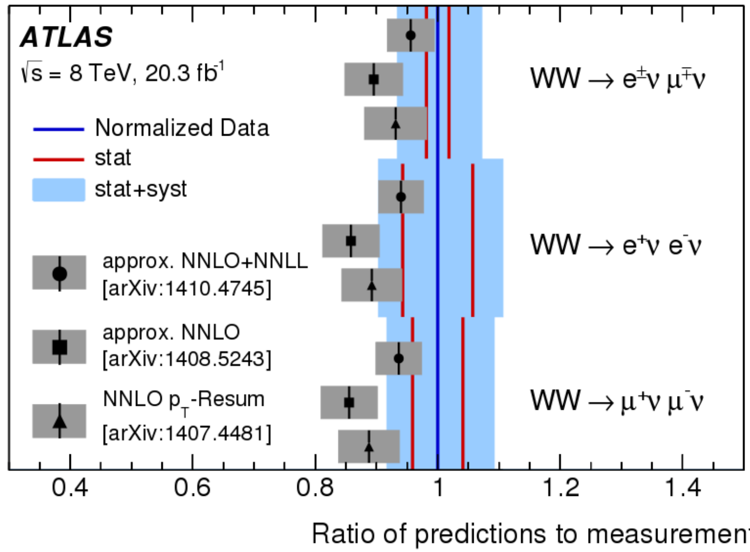
Multiboson production: $W^+ W^-$

ATLAS
e-print arXiv:1603.01702

- Test EWK physics at TeV scale
- Probe gauge-boson self-couplings
- Irreducible background for Higgs searches

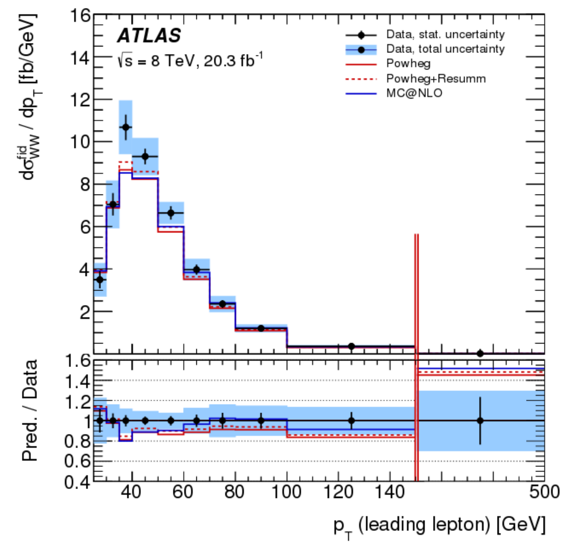


(a) t- channel (b) s- channel (TGC vertex) (c) gluon fusion (d) Higgs boson production



- Use leptonic decays (l+v)
- Use MC (at NNLO) to estimate background
- Unfold cross sections and compare to NLO/NNLO
- Data are ~1.4 sigma higher compared to NLO
  - due to pT(e/mu)~50 GeV region
- Agrees with NNLO+resummation (~10% higher)

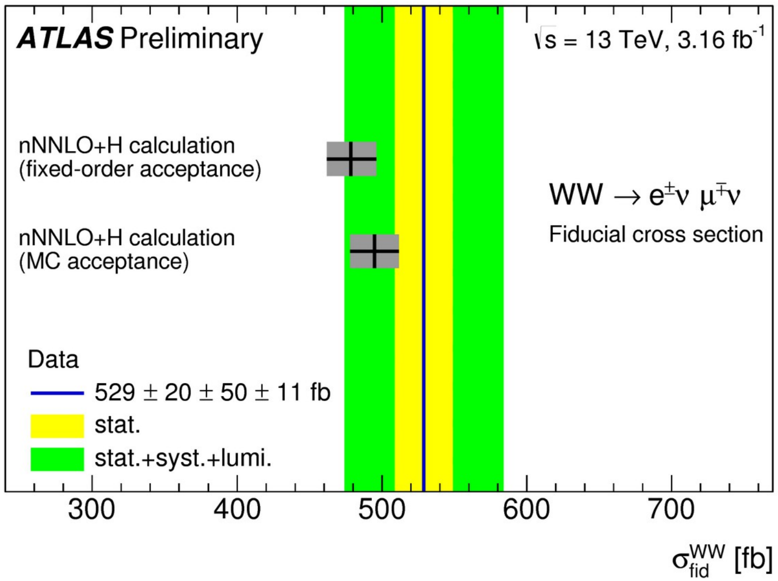
Final state	Total cross section $pp \to WW$ [pb]
$e\mu$	$70.6\pm1.3(\text{stat})\ ^{+5.8}_{-5.1}(\text{syst})\ \pm1.4(\text{lumi})$
ee	$73.6^{+4.2}_{-4.1}(\text{stat})\ ^{+7.5}_{-6.4}(\text{syst})\ \pm1.5(\text{lumi})$
$\mu\mu$	$74.0\pm3.0(\text{stat})\ ^{+7.1}_{-5.9}(\text{syst})\ \pm1.5(\text{lumi})$
Combined	$71.1\pm1.1(\text{stat})\ ^{+5.7}_{-5.0}(\text{syst})\ \pm1.4(\text{lumi})$
$\sigma(\text{NNLO}_{\text{tot}})$ theory prediction [3]+[45]	$63.2^{+1.6}_{-1.4}(\text{scale})\pm1.2(\text{PDF})$



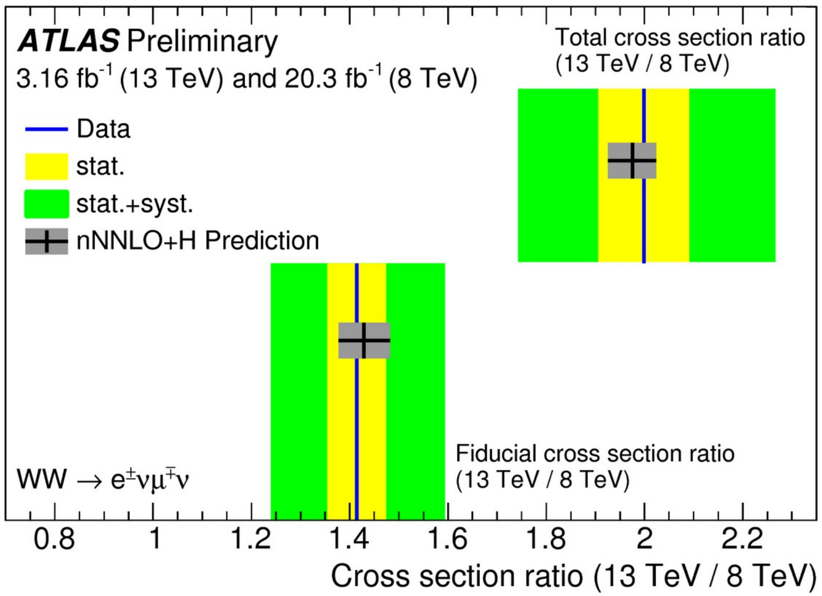
Multiboson production: $W^+ W^-$

ATLAS
ATLAS-CONF-2016-090

- Using 2015 runs (13 TeV). Decay eν and μν channels combined
- Use NNLO (~O(α^2)) to estimate background plus $gg \rightarrow H \rightarrow WW$



Ratio 13 TeV / 8 TeV

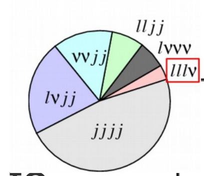


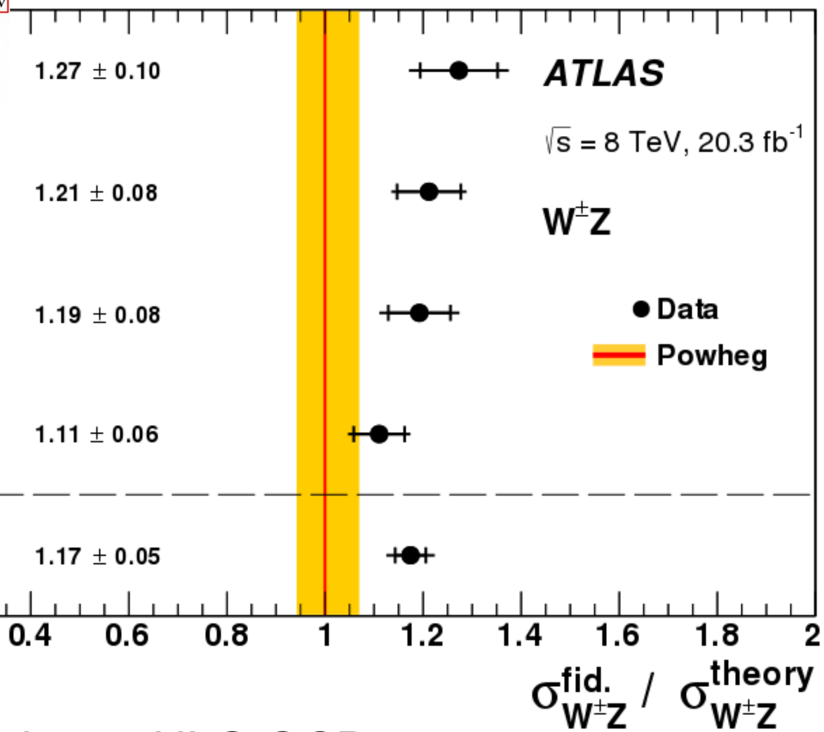
- Lower statistics than for 8 TeV studies
- 13 TeV data agree with NNLO QCD

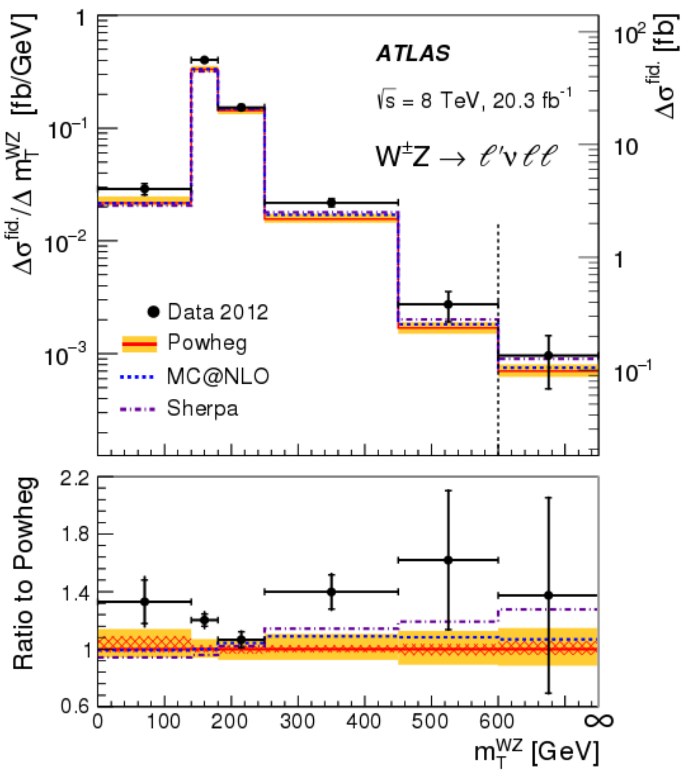
Multiboson production: WZ

ATLAS
Phys. Rev. D 93, 092004 (2016)

- Use only leptonic decays (l+ν)
- Use MC (at NLO) for background
- Unfold cross sections and compare to
  - NLO + PS (Powheg)
  - Sherpa (LO up to 3 partons)
  - MC@NLO (NLO)



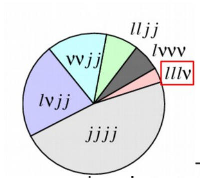


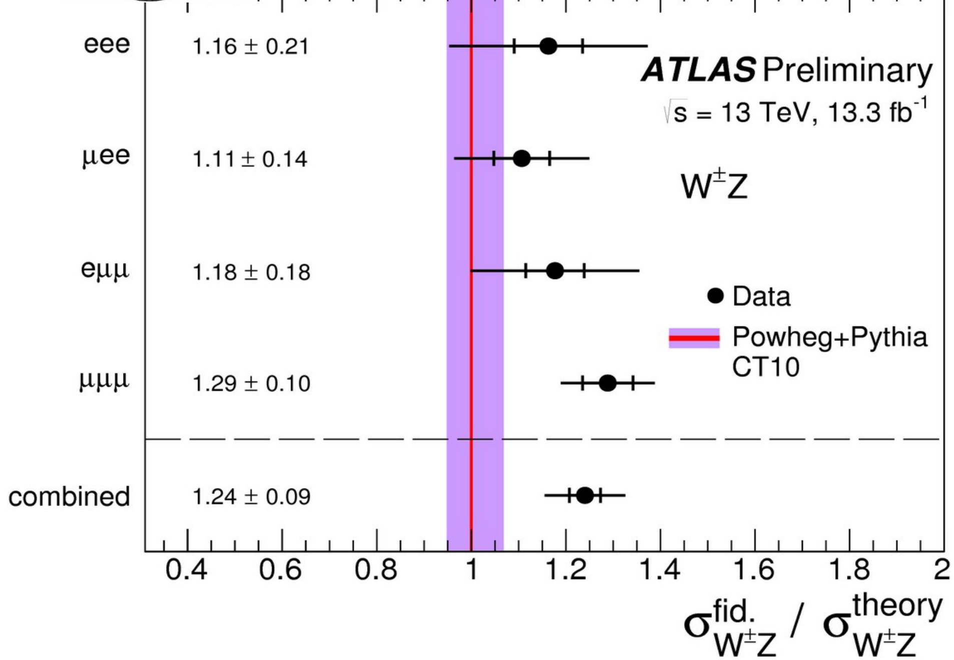


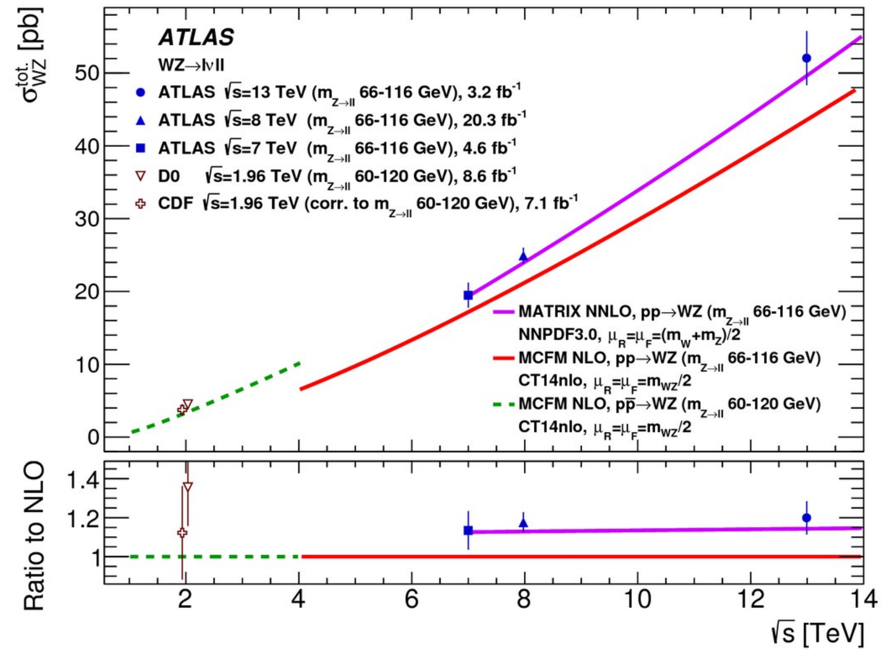
- Data are above NLO QCD
- No identifiable region with enhancement when using transverse mass
  - Non-resonant? Missing high-order QCD terms?
- Waiting for NNLO calculations for differential distributions

WZ cross section in 13 TeV data

ATLAS
ATLAS-CONF-2016-043

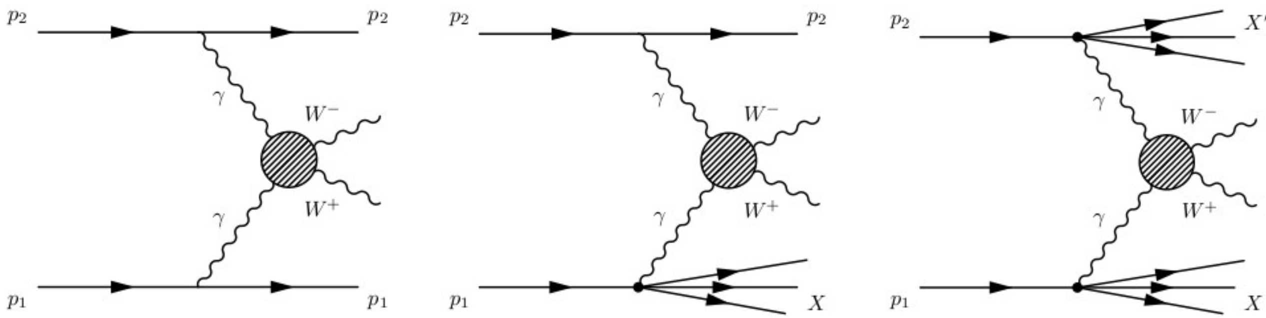




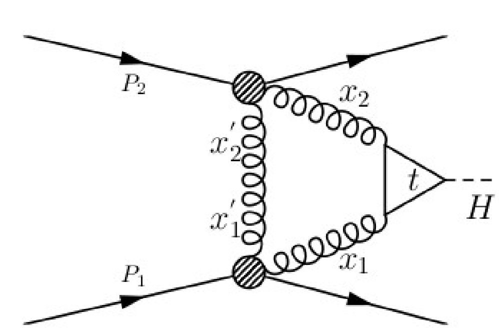


- Data are ~2 sigma above NLO (Powheg)
- Good agreement with NNLO

Exclusive $W^+ W^-$ production

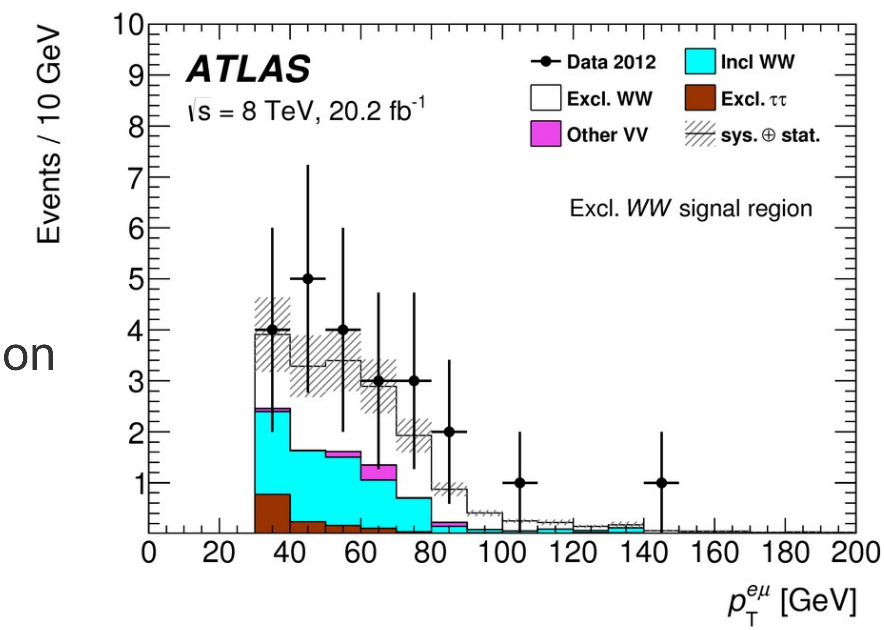


(a) Elastic production (b) Single-dissociation (c) Double-dissociation



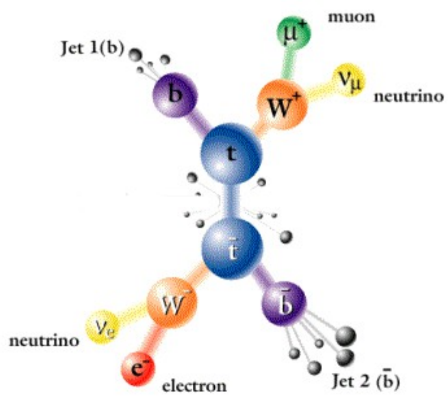
- Clean events: 2 leptons + missing ET
- Exclusivity achieved by selecting events with 2 tracks associated with leptons

Exclusive W^+W^- event yields: Data=23,
Background $= 8.3 \pm 2.6$, Signal $= 9.3 \pm 1.2$



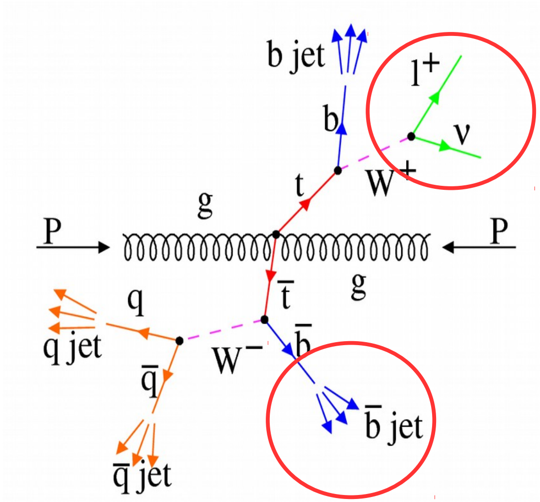
- ~3 σ evidence for exclusive W+W- production
- No evidence for exclusive Higgs
- Statistically limited measurement

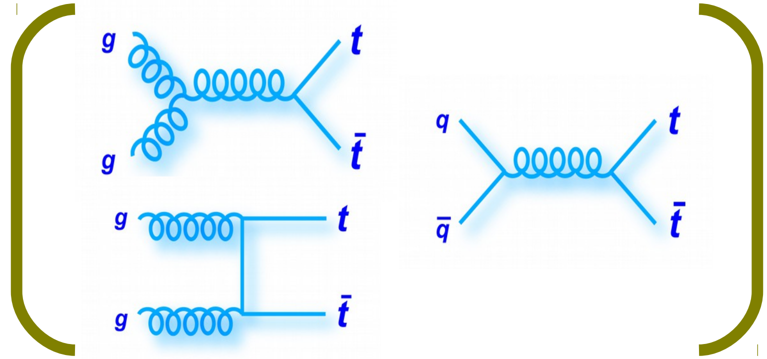
Top production



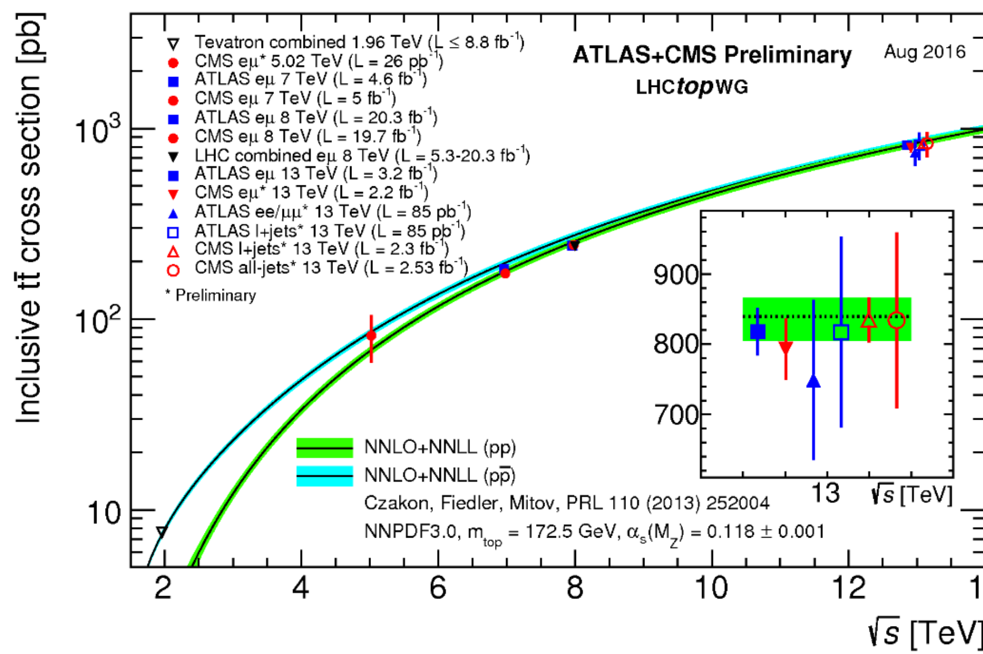
- Heaviest elementary particle
- Key for fundamental interactions at the EWK breaking scale at beyond
- Core tests of pQCD:
  - Well-understood predictions available at NLO, NNLO + resummations
- Irreducible background for many searches

Inclusive top cross sections

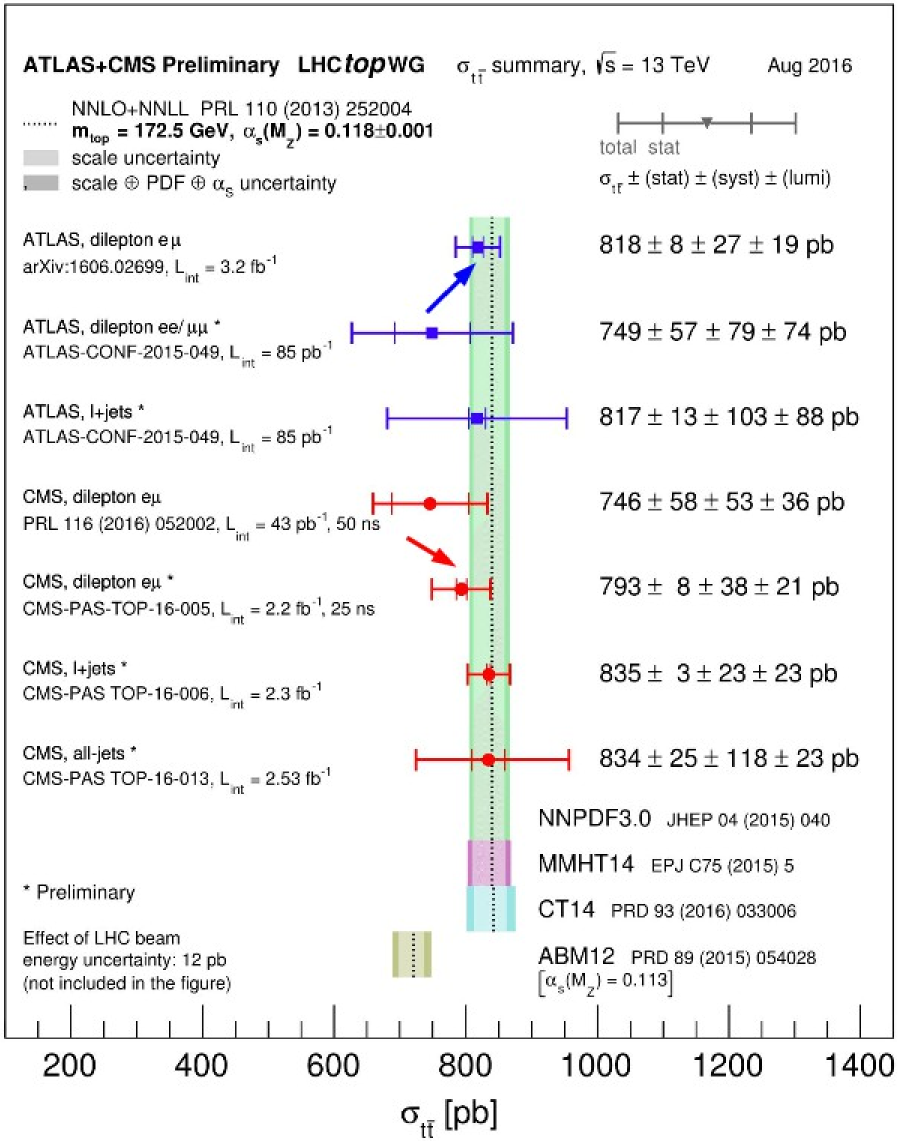


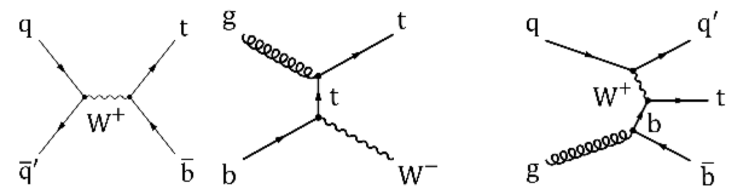


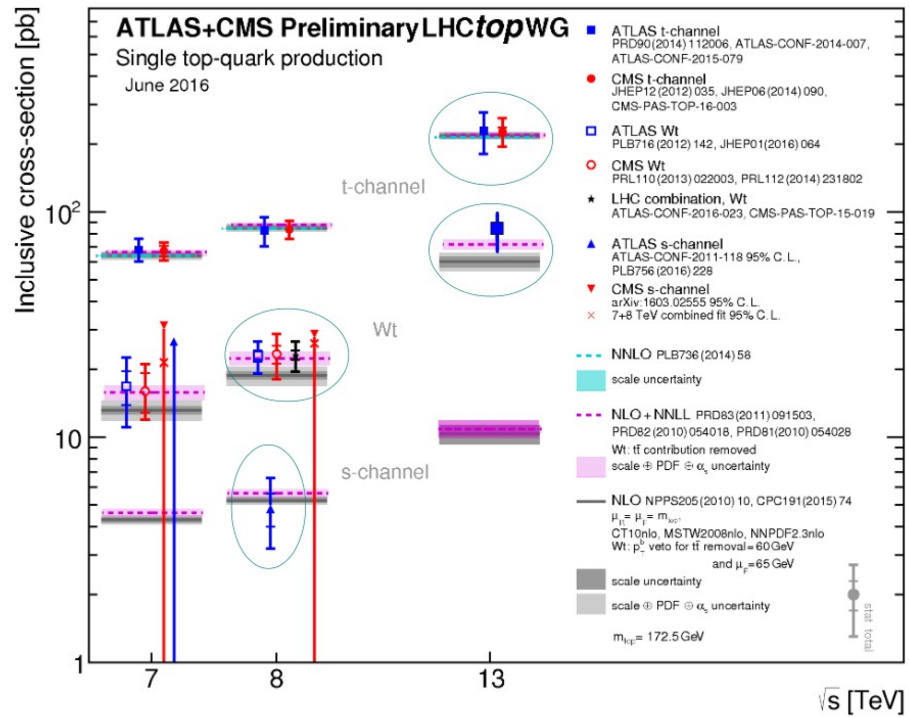
- Unlike TEVATRON, dominated by gg→ $t\bar{t}$ process at the LHC (~80%)
- First 13 TeV ATLAS measurements are based on electron-muon final state + b-jet
  - golden channel used in early top-quark discoveries at TEVATRON
- Good agreement with NNLO+NNLL predictions



Top pair & single-top cross sections

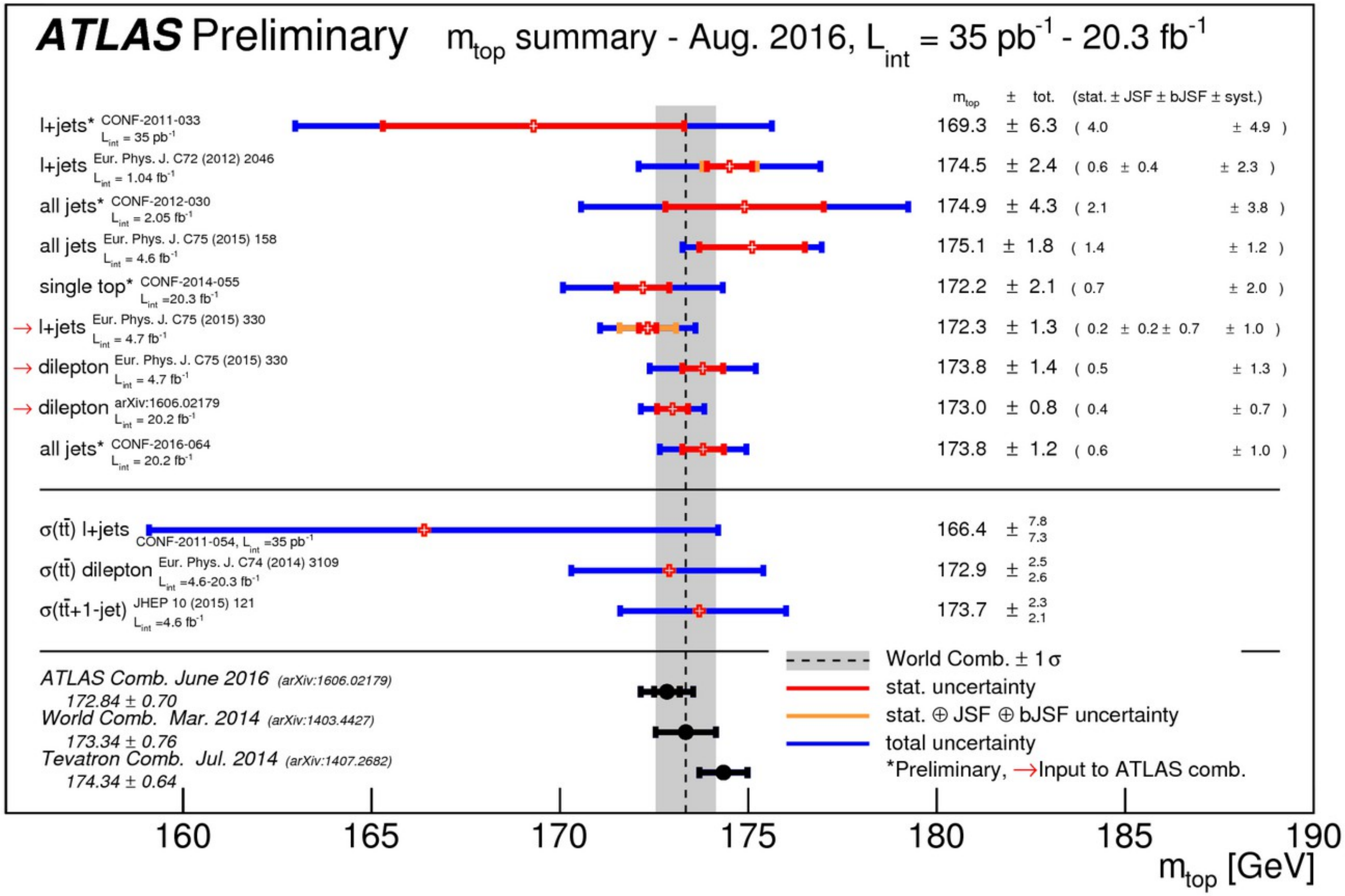






Measurements comparable to theory precision (NNLO+NNLO)

Direct top mass measurements

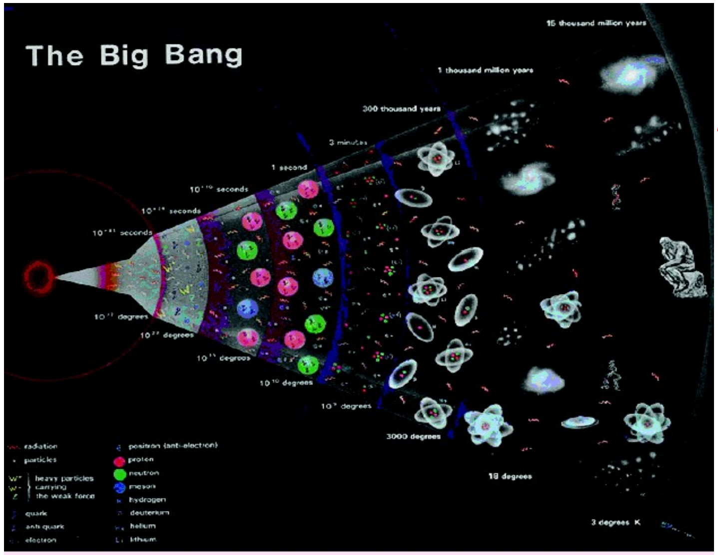


m_t = 172.84 ± 0.70 GeV (largest systematics: MC modeling and jet energy scale)

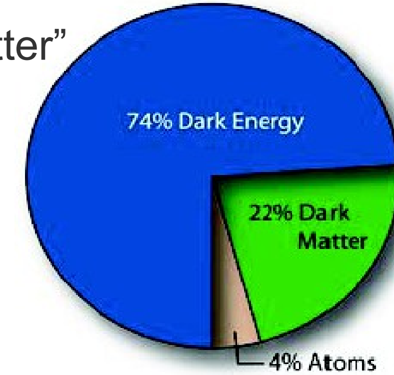
Combined with CMS: **172.44 ± 0.48 GeV**

Tevatron combination: **174.30 ± 0.65 GeV**

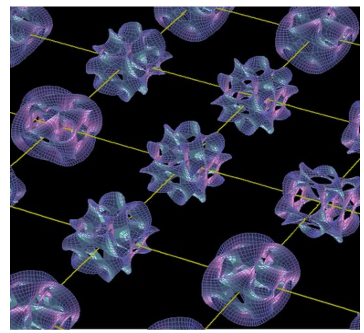
Where are discoveries?

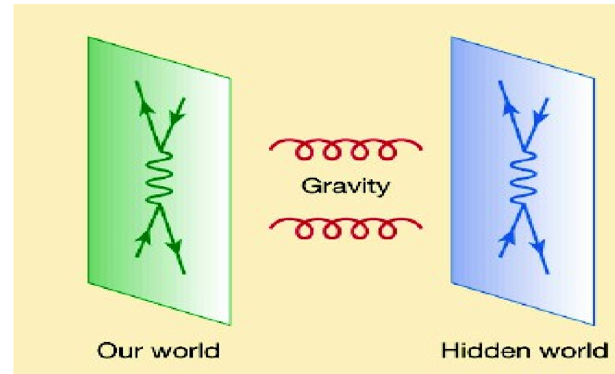


“dark matter”

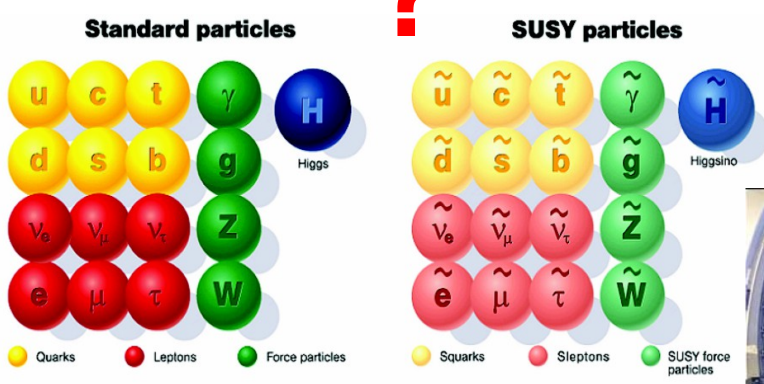


“extra dimensions”





“SUSY”

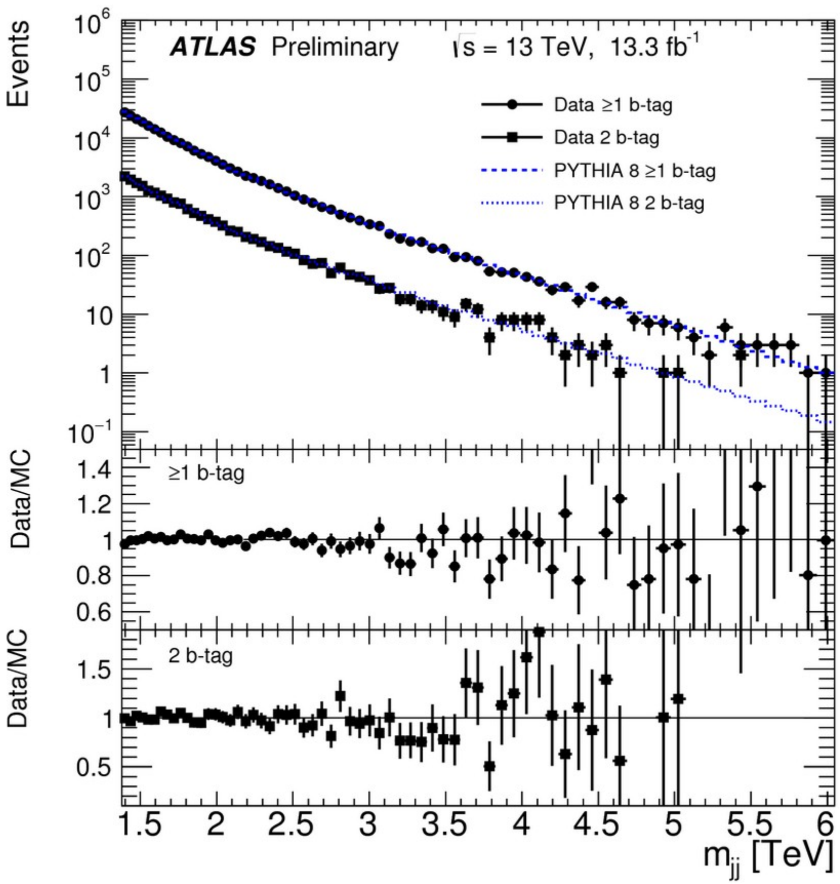


“black holes”

For many, many discovery signatures, the knowledge of the SM processes is the limiting factor!

Not covered: testing Standard Models in Searches

- SM measurements used for searches
- .. and many search papers include SM measurements – do not miss them!
  - Even if search results do not have unfolded distributions, many give good assessment of the level of possible discrepancies with the SM



- Example from a search paper ATLAS-CONF-2016-060:
  - Good description of the shape of dijets (b-jets) invariant mass by LO+PS Pythia8 simulation

Summary

- SM measurements are important on their own + foundation for New Physics searches
- Precision SM tests are enabled by an excellent performance of the ATLAS detector
- Impressive agreements of ATLAS data with the SM predictions across several orders of magnitude in transverse energies
- Uncertainties ~7% for QCD measurements and unprecedented precision for EWK measurements (1-2%)

Time for precision measurements:

- If there is a new physics at the EWK scale ~ 1 TeV, it must be within the level of uncertainties currently seen for the SM measurements
- Most of 2015/2016 data need to be analyzed → improved precision is expected


The grandest discoveries of science
have been but the rewards
of accurate measurement
and patient long-continued
labour in the minute sifting
of numerical results.
Lord Kelvin
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Backup

- PDF & jets as a function of jet pT