QCD Studies with W and Z Measurements at LHC

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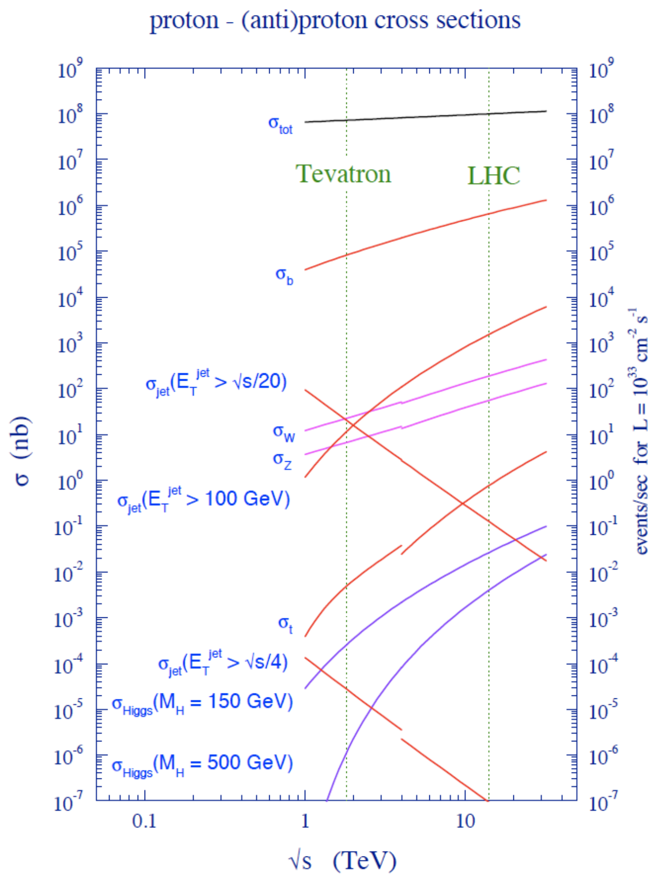
THE UNIVERSITY OF CHICAGO

Rediscovery of the SM at LHC

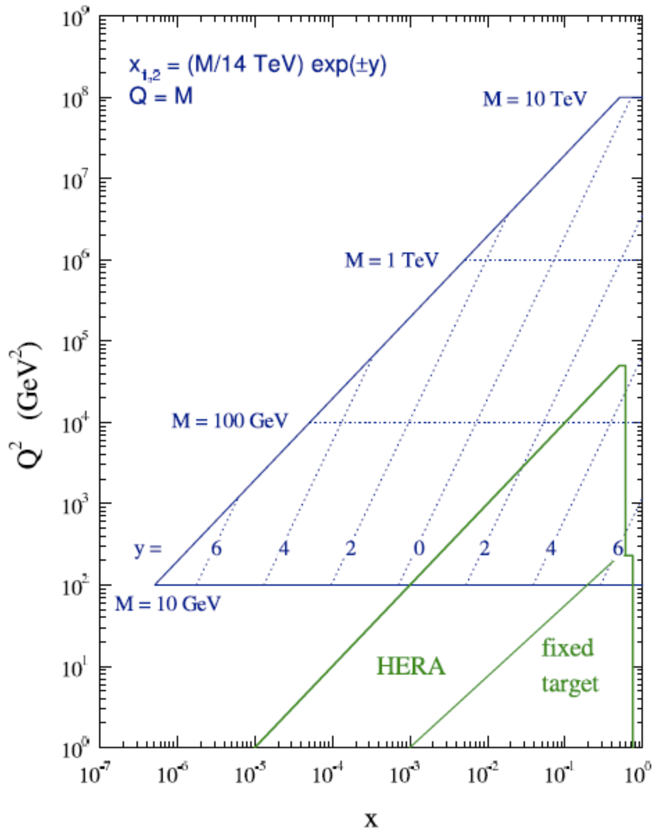
- Physics at the Large Hadron Collider will start with rediscovery of the Standard Model
  - New detector conditions and unprecedented energy
- $W^{\pm}$ and Z boson measurements will form a key component
  - Large statistics
  - Rich event topologies, exercising many detector subsystems
  - Opportunity to test predictions from perturbative QCD and evolution of parton distribution functions (PDFs)



Campbell, Huston, Stirling
Rep. Prog. Phys. ***70*** *(2007) 89*

QCD with Weak Bosons

- Next-to-leading order (NLO) perturbative QCD calculations available up to W+3 jets, Z+2 jets
  - Important to test these predictions at LHC energies
  - Examples: jet p_T distribution, cross-section vs. jet multiplicity
- Largest remaining theoretical uncertainty from PDFs
  - New territory at low x, high Q^2
  - Differential measurements can provide additional contraints
  - Examples: W charge asymmetry, Z rapidity distribution



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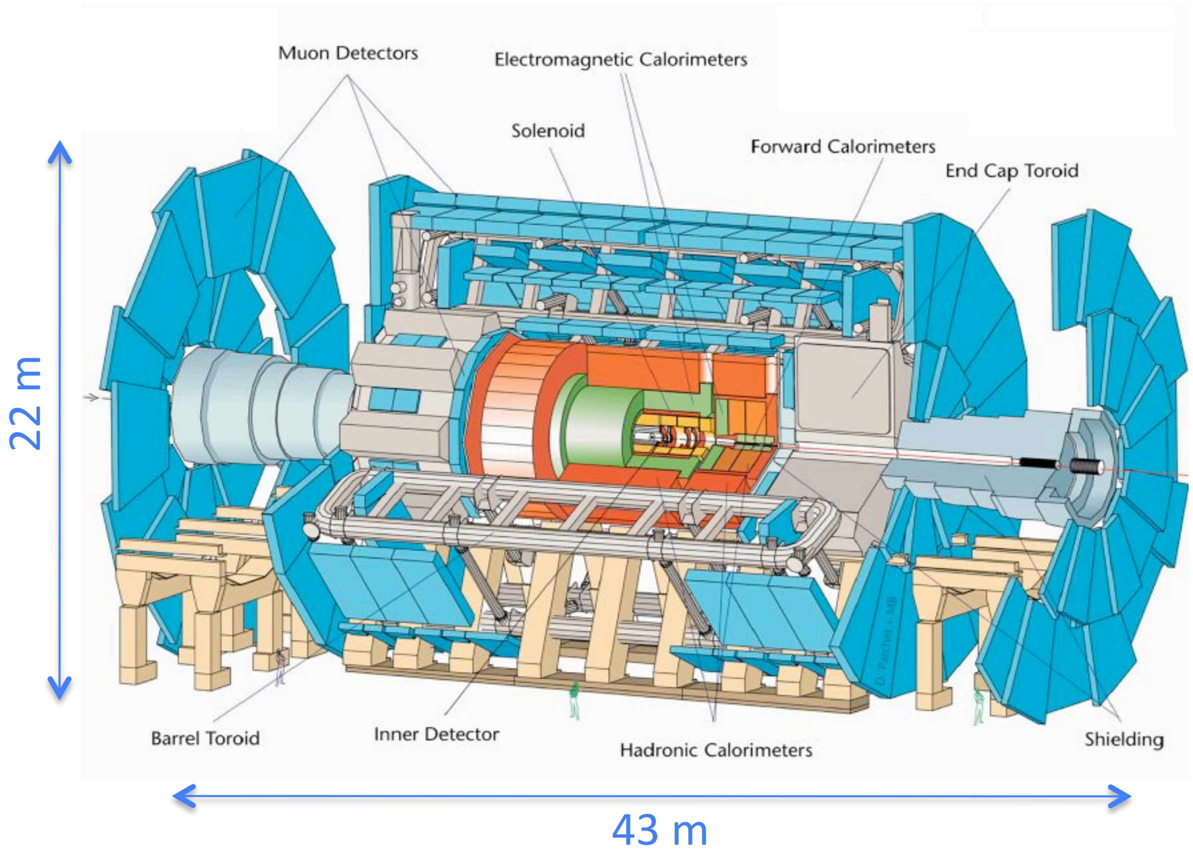
The ATLAS Detector



Total weight 7000 tons

Inner detector |η| < 2.5

- Silicon pixels and strips
- Transition radiation tracker
- 2T solenoid field

Calorimetry |η| < 4.9

- EM: lead/liquid argon
- Hadronic: iron/scintillator tile
- Forward: copper/liquid argon

Muon spectrometer |η| < 2.7

- ***Open structure***
- 4T toroid field

The CMS Detector

Inner detector |η| < 2.5

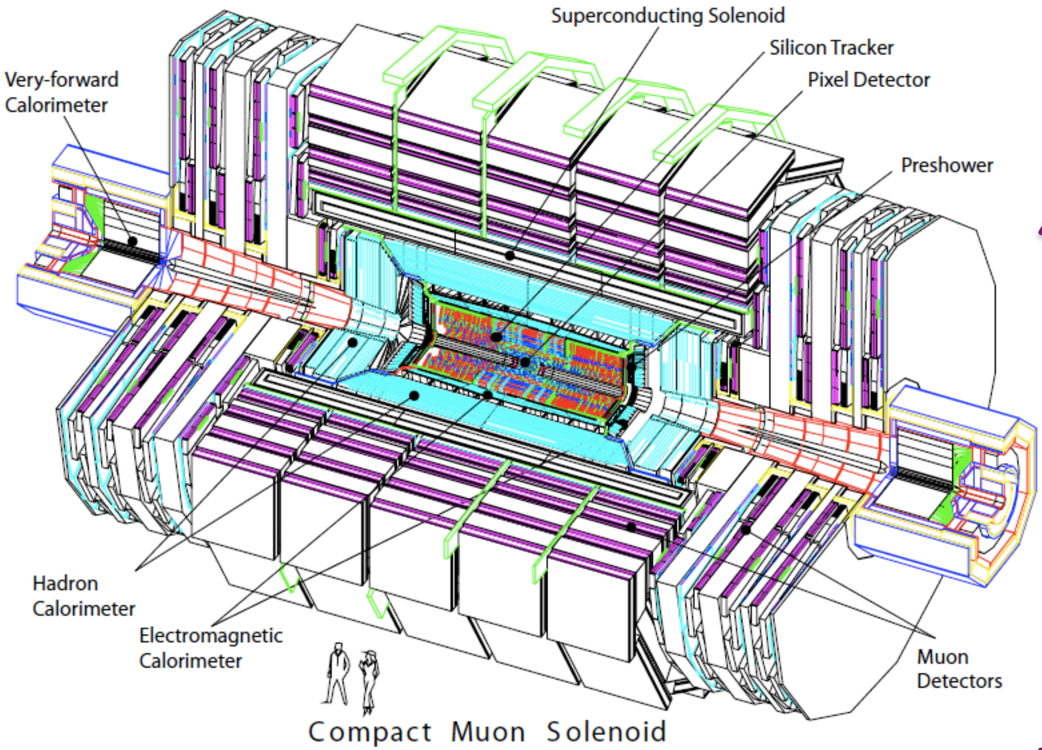
- ✧ Silicon pixels and strips
- ✧ 4T solenoid field

Calorimetry |η| < 5.0

- ✧ EM: lead tungstate crystal
- ✧ Hadronic: brass/scintillator tile
- ✧ Forward: iron/quartz fiber
- ✧ ***4T solenoid field***

Muon spectrometer |η| < 2.4

- ✧ Interleaved with magnetic field return



15 m

22 m

Total weight 12500 tons

Both detectors have similar coverage and performance

Z+Jets: Particle Identification

Example selection: ATLAS Z+Jets

Muons

- Isolated di-muon trigger
- Combined reconstruction using spectrometer and inner detector
- Muon $p_T > 15$ GeV
- $|\eta| < 2.4$ excluding barrel/endcap transition region (1.2, 1.3)
- Isolation within cone of 0.2

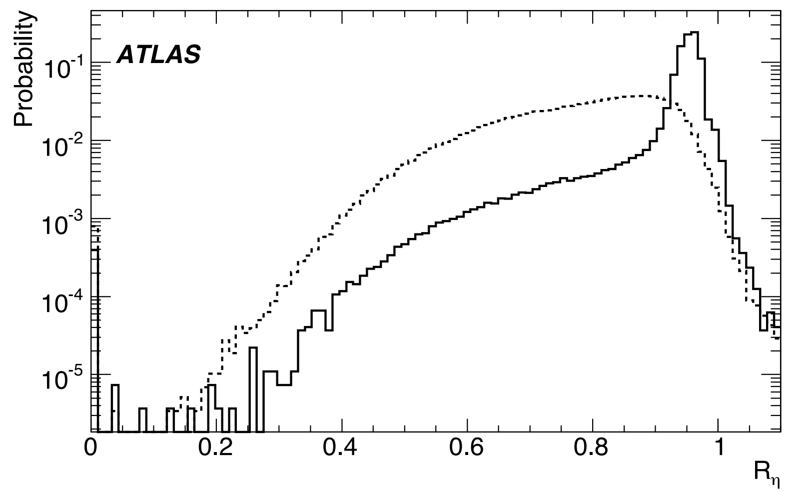
Electrons

- Isolated single or di-electron trigger
- Electron $p_T > 25$ GeV
- $|\eta| < 2.4$ excluding barrel/endcap calorimeter crack (1.37, 1.52)
- Shower shape and tracking requirements

Jets

- Seeded cone algorithm, radius 0.4
- Require $\Delta R > 0.4$ angular separation from leptons
- Infrared and collinear safe algorithms under study

CERN-OPEN-2008-020



Ratio of energy in EM calorimeter 2nd layer in $\Delta\eta \times \Delta\varphi = 0.075 \times 0.175$ versus 0.175×0.175

—— $Z \rightarrow ee$

- - - - QCD jets faking electrons

Z+Jets: Detector to Hadron Level

- Correct data to hadron level for comparison with theory
  - Largest correction, electron efficiency, also measured in-situ with tag and probe method using Z→ee events

Hadron level

↑

Jet corrections: efficiency, scale, resolution

↑

Electron efficiency corrections

↑

Detector level

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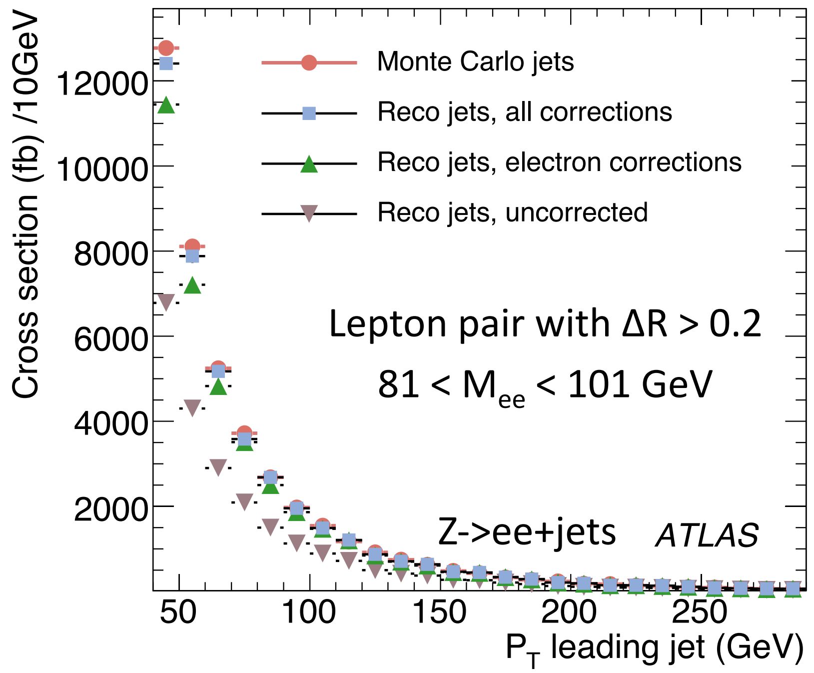


ATLAS Z+Jets

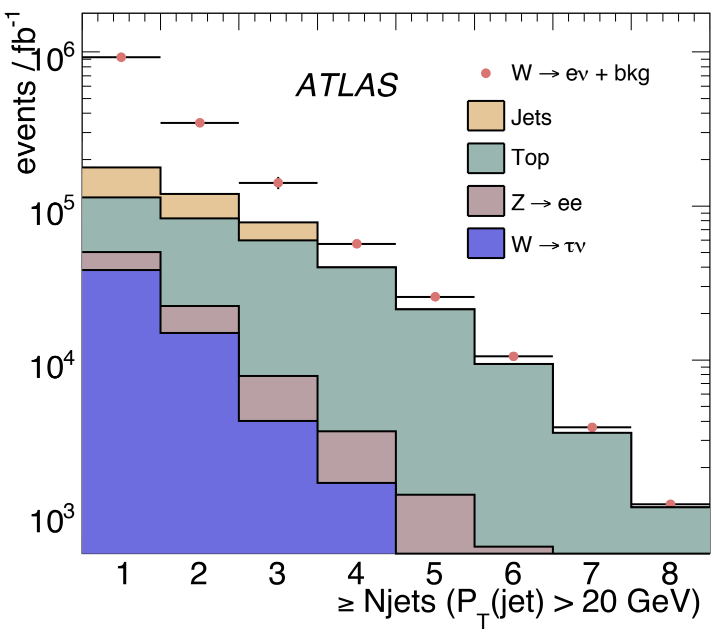
√s = 14 TeV

L = 1 fb-1

ALPGEN+HERWIG
CTEQ6L1 PDFs

W+Jets: Background Estimation

- Relative background contributions vary with jet multiplicity



ATLAS W+Jets

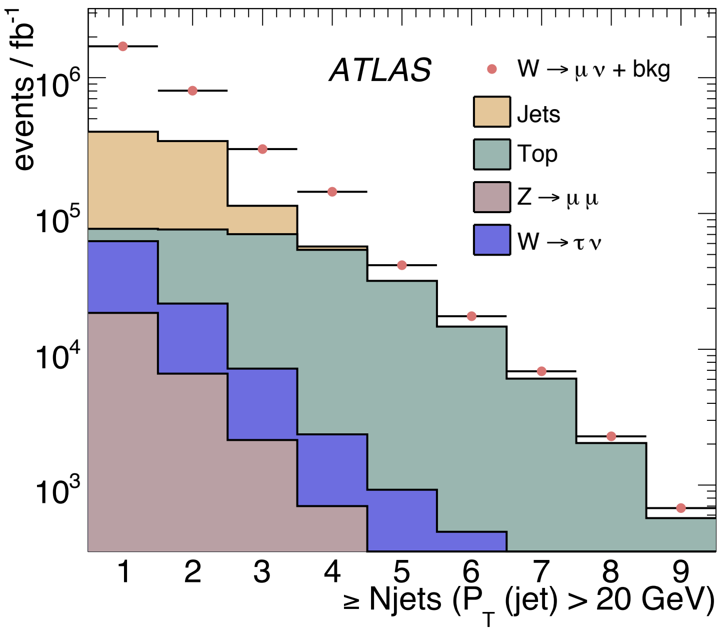
√s = 14 TeV

L = 1 fb-1

Signal:
ALPGEN+HERWIG

Backgrounds:
PYTHIA

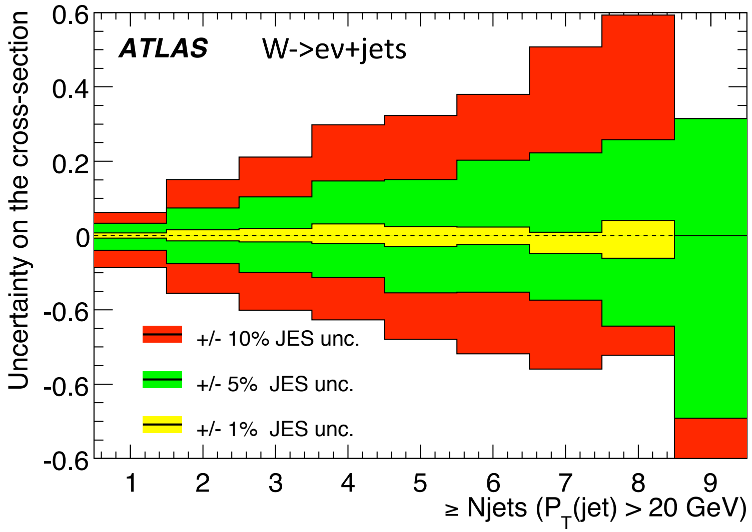
CTEQ6L1 PDFs

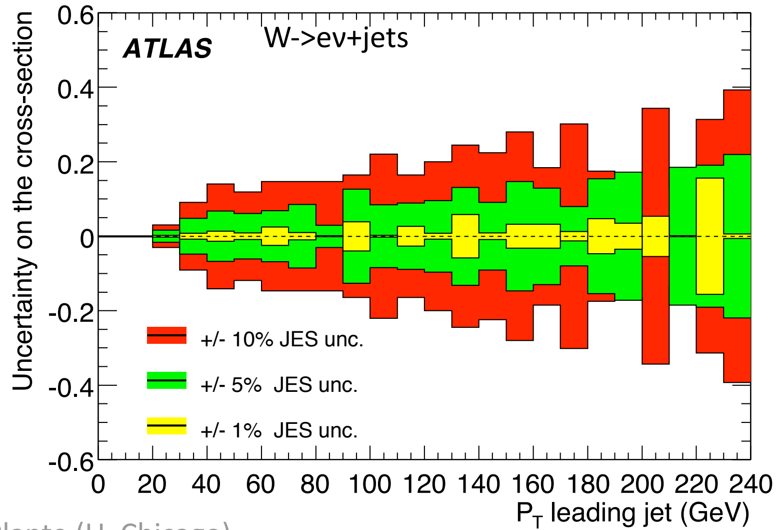


- Difficult to determine QCD background using Monte Carlo
  - Developing data-driven techniques based on identification criteria

W+Jets: Experimental Uncertainty

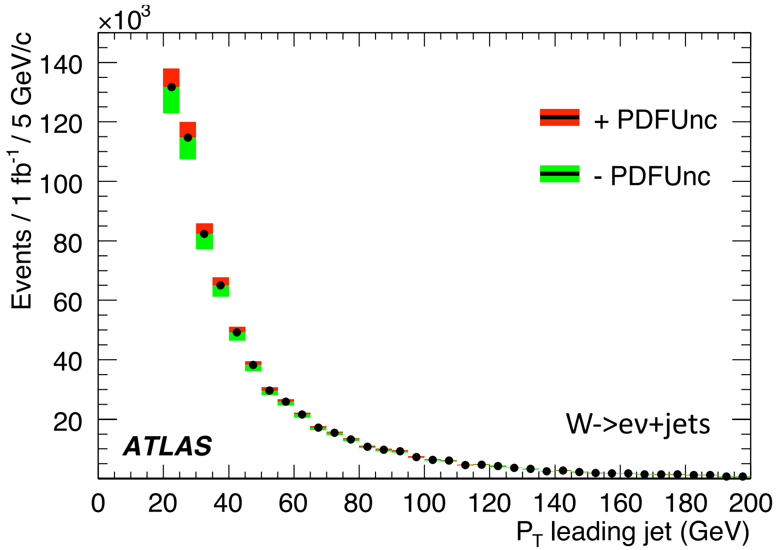
- Expect dominant uncertainty from jet energy scale (JES)
  - **10% energy shift** leads to 20% change in the cross-section for W+3 jets
  - Similar size effect to ratio of NLO to LO
  - Measurements such as dijet, γ+jet, and Z+jet balance can reduce uncertainty with data, toward **design goal of 1%**

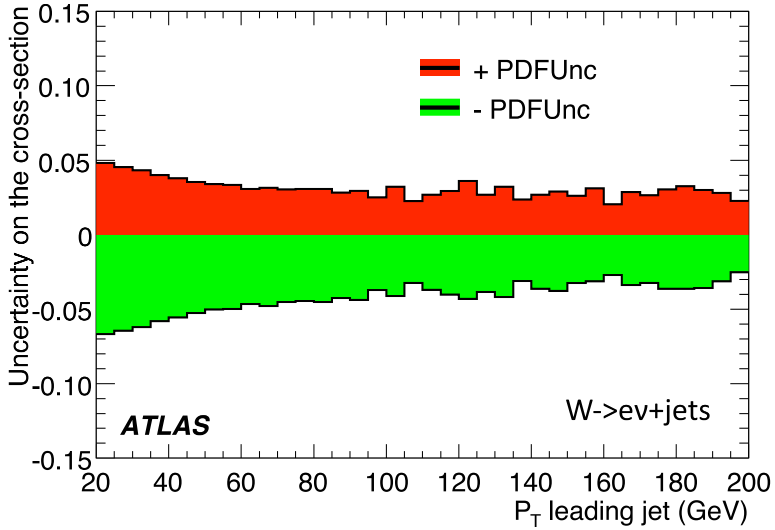




W+Jets: Theoretical Uncertainty

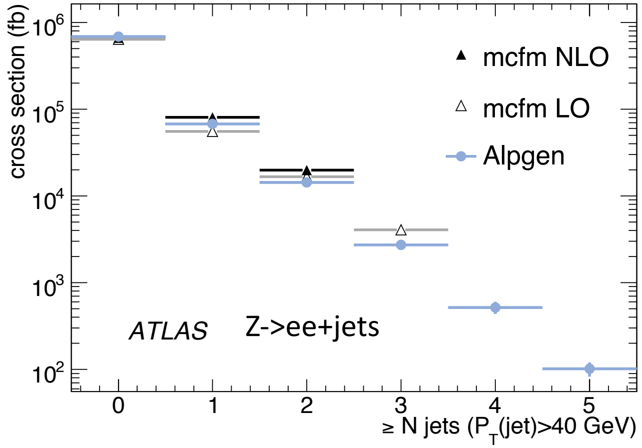
- Dominant theoretical uncertainty from PDFs
  - Impact on acceptance and jet counting
- Uncertainty estimated by reweighting using CTEQ6M error sets
  - Effect of up to 5% at low p_T
  - Could decrease with constraints from W and Z differential measurements





Z+Jets: Cross-Section Measurement

- Parton level predictions from MCFM corrected to hadron level
  - Include effects of underlying event and jet fragmentation
  - Plan to re-evaluate corrections using underlying event measurements from data
- Uncertainty dominated by jet energy scale, based on conservative estimates
  - Priority to reduce using data, including Z+jet balance
  - Also sensitive to uncertainty on integrated luminosity



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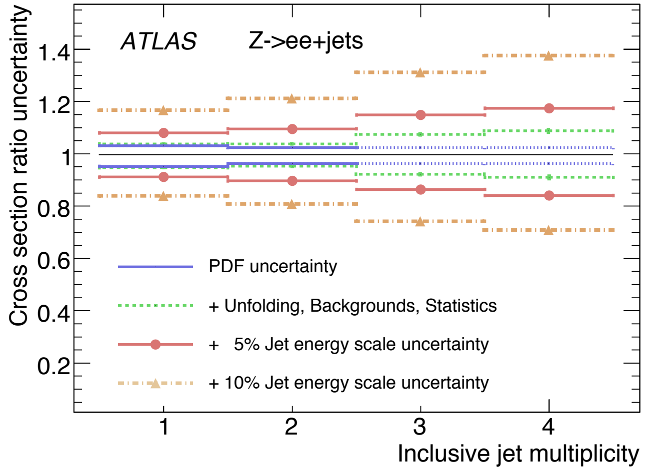


ATLAS Z+Jets

√s = 14 TeV

L = 1 fb-1

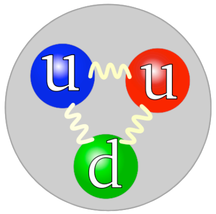
ALPGEN+HERWIG
CTEQ6L1 PDFs

MCFM
CTEQ6.1 PDFs

W Charge Asymmetry

- $W^{\pm}$ production asymmetry expected for p-p collisions; observed lepton pseudorapidity distribution correlated

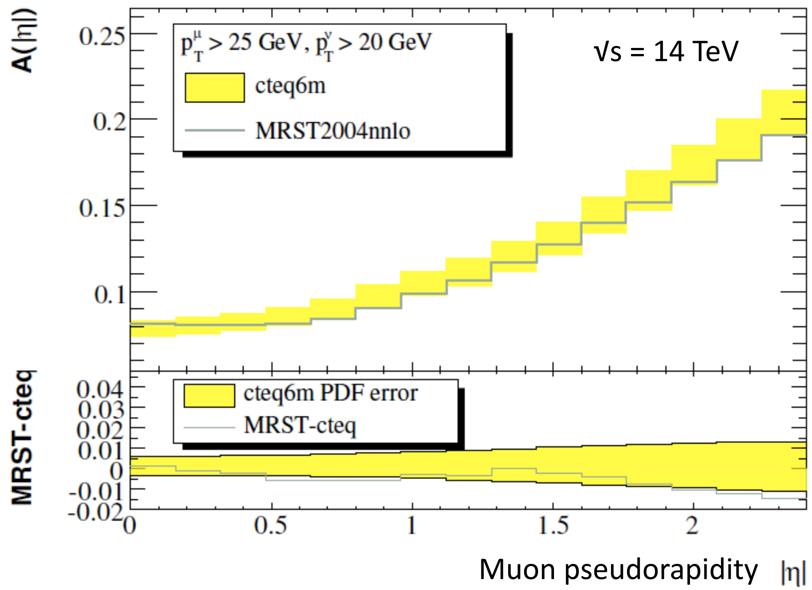
$$u\bar{d} \rightarrow W^{+} \rightarrow \mu^{+}\nu$$
$$d\bar{u} \rightarrow W^{-} \rightarrow \mu^{-}\nu$$



$$A(\eta) = \frac{d\sigma(W^{+} \rightarrow \mu^{+}\nu)/d\eta - d\sigma(W^{-} \rightarrow \mu^{-}\nu)/d\eta}{d\sigma(W^{+} \rightarrow \mu^{+}\nu)/d\eta + d\sigma(W^{-} \rightarrow \mu^{-}\nu)/d\eta}$$

- Asymmetry is senstive to PDF modeling
  - Direct dependence on u and d quark PDFs
  - Sea partons and $g \rightarrow q\bar{q}$ also important

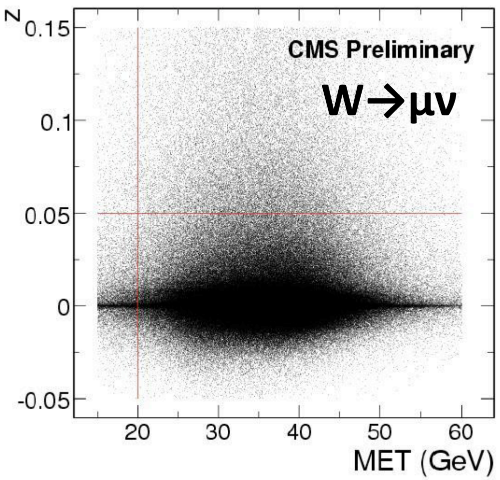
CMS PAS EWK-08-002

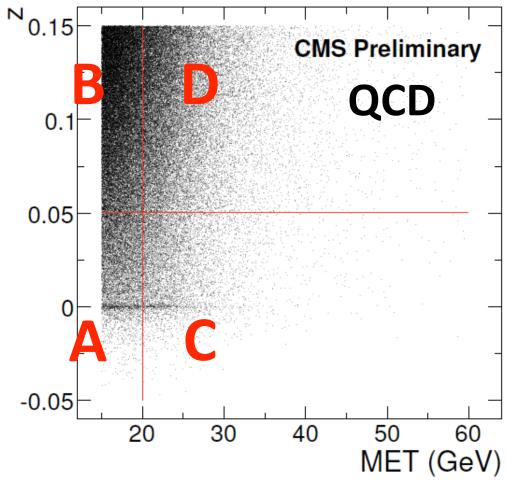


W Charge Asymmetry: Backgrounds

- Data-driven estimation used to subtract QCD background
  - Require isolation within cone of 0.3, excluding muon energy loss in calorimeters, $z = 1 - \frac{p_T}{p_T + Iso} < 0.05$

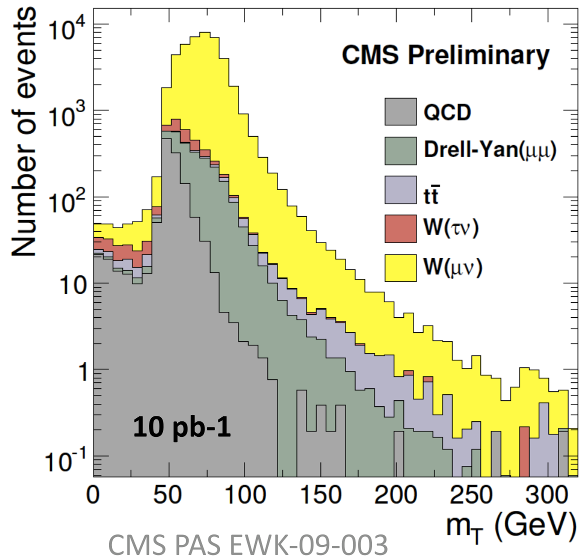
CMS PAS EWK-09-003



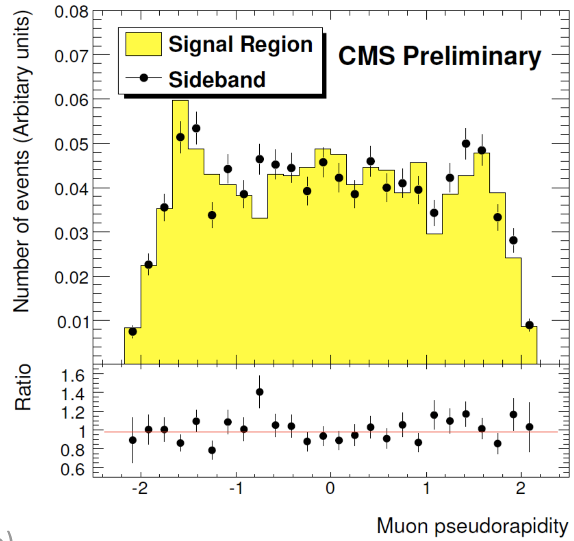


  - Estimate QCD in signal region from sideband $N_C = \frac{N_A N_D}{N_B}$

CMS PAS EWK-09-003



CMS PAS EWK-09-003



CMS W→μν

√s = 10 TeV

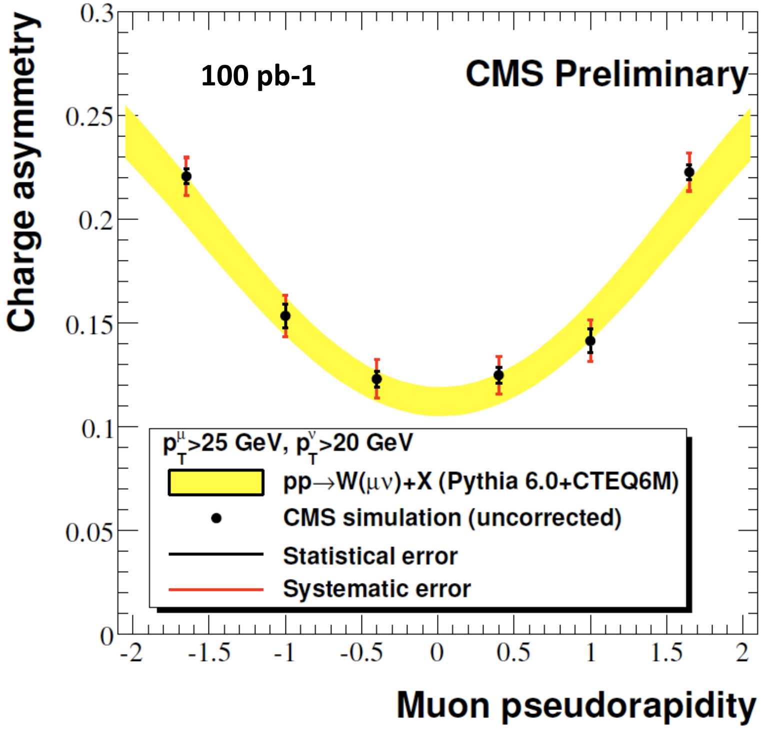
Pythia

CTEQ6L PDFs

W Charge Asymmetry: Measurement

- Uncertainties small enough to constrain PDFs with 100 pb-1
  - Yellow band shows PDF uncertainty (CTEQ6M) obtained by reweighting
  - Statistical uncertainty ~0.5%
  - Systematic uncertainty dominated by assumed trigger and offline efficiency ratio of 1 from Drell-Yan MC

CMS PAS EWK-09-003



CMS W→μν

√s = 10 TeV

Pythia

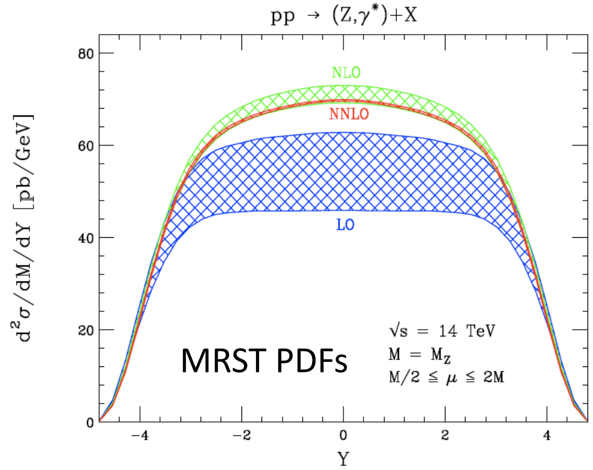
CTEQ6L PDFs

$$A(\eta) = \frac{\frac{dN^+}{d\eta} - \frac{dN^-}{d\eta}\cdot\frac{\epsilon^+_{HLT}\cdot\epsilon^+_{offline}\cdot\epsilon^+_{acceptance}}{\epsilon^-_{HLT}\cdot\epsilon^-_{offline}\cdot\epsilon^-_{acceptance}}}{\frac{dN^+}{d\eta} + \frac{dN^-}{d\eta}\cdot\frac{\epsilon^+_{HLT}\cdot\epsilon^+_{offline}\cdot\epsilon^+_{acceptance}}{\epsilon^-_{HLT}\cdot\epsilon^-_{offline}\cdot\epsilon^-_{acceptance}}}$$

Acceptance uncorrected; included in theory prediction

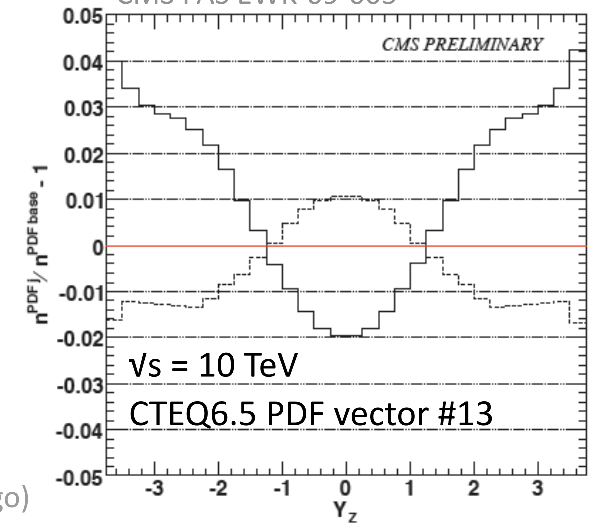
Z Rapidity

- Stable QCD prediction with low theoretical uncertainty
  - Shape unchanged by NNLO corrections
  - Error bands show effect of varying renormalization and factorization scale by a factor of 2
  - Uncertainty 6% at NLO, less than 1% at NNLO
- Particularly sensitive to PDFs at higher rapidity



Anastasiou, Dixon, Melnikov, Petriello, *Phys. Rev.* D **69** (2004) 094008

CMS PAS EWK-09-005



Z Rapidity: Measurement

- Bin-by-bin correction for efficiency and acceptance derived from measured single electron efficiencies
  - Include electrons with $3 < |\eta_e| < 5$ reconstructed using the forward hadron calorimeter

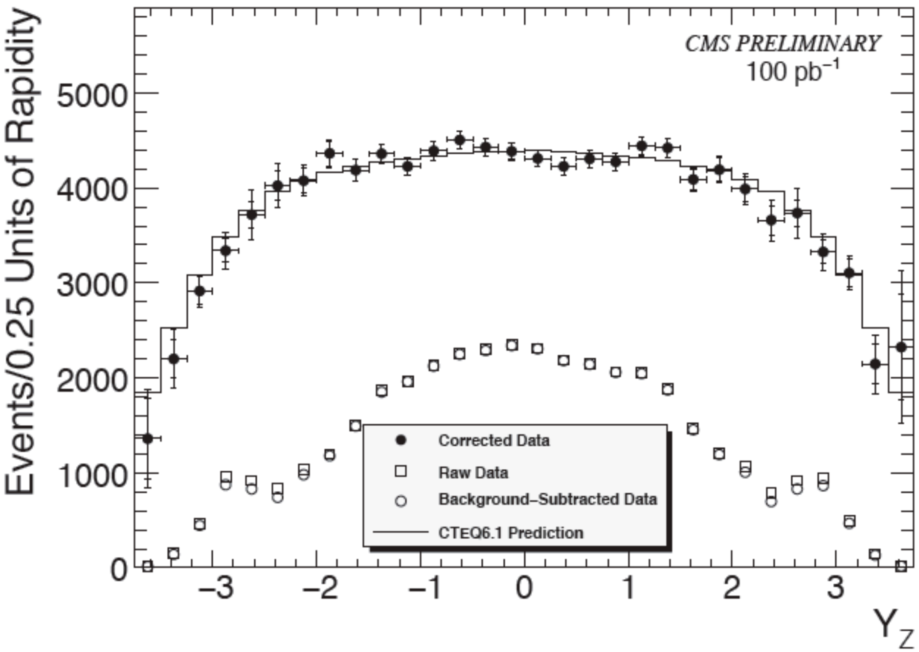
CMS Z→ee

√s = 10 TeV

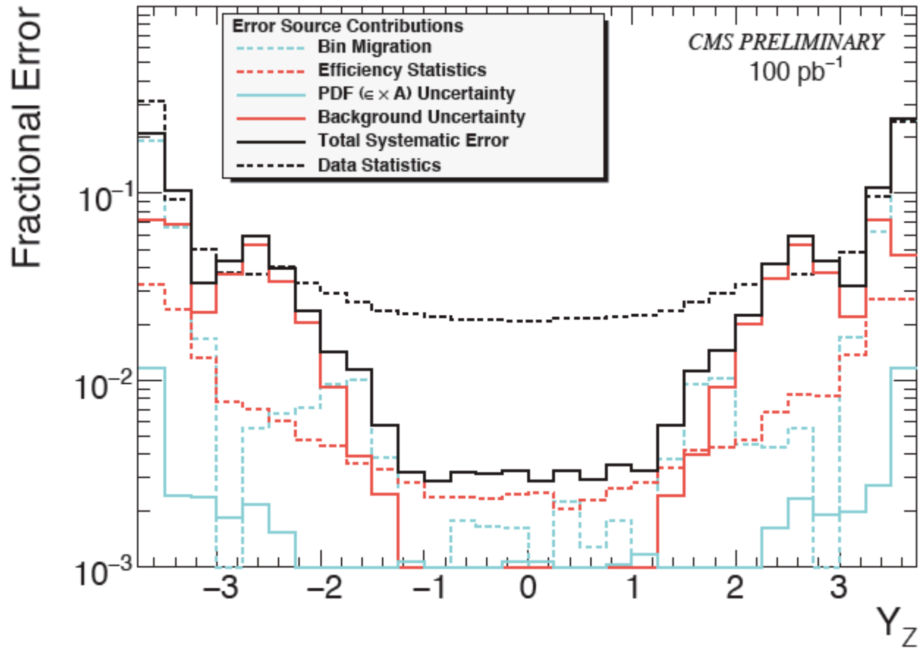
Pythia

CTEQ6.1 PDFs

CMS PAS EWK-09-005



CMS PAS EWK-09-005



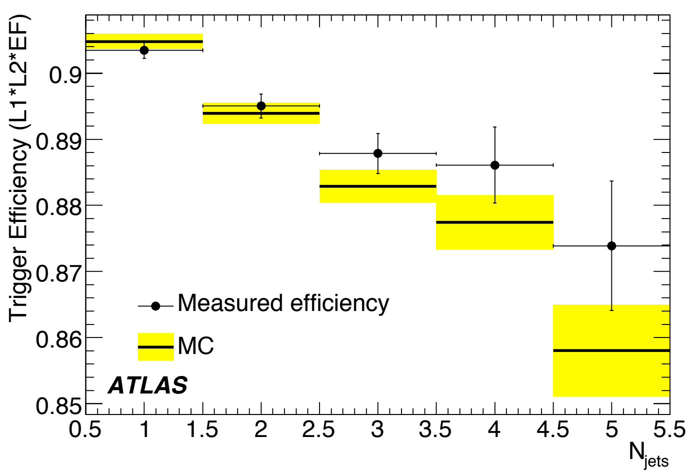
Conclusions & Outlook

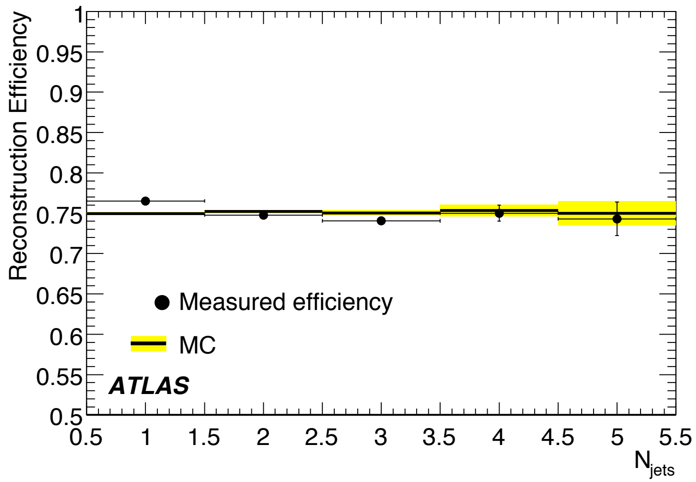
- Ready to measure W+jets and Z+jets cross-sections with the first LHC collision data
  - Important test of expectations from perturbative QCD
  - Will compare to theoretical predictions at hadron level
- Estimated uncertainties indicate useful early measurements, improving with detector experience
  - Dominant experimental uncertainty from jet energy scale
- Also prepared for differential measurements, including W charge asymmetry and Z rapidity distribution
  - PDF constraints possible with the first 100-200 pb^{-1}

Backup Slides

Efficiencies from Tag and Probe

- Select "tag" electron in Z→ee events, then measure efficiency to find second "probe" electron

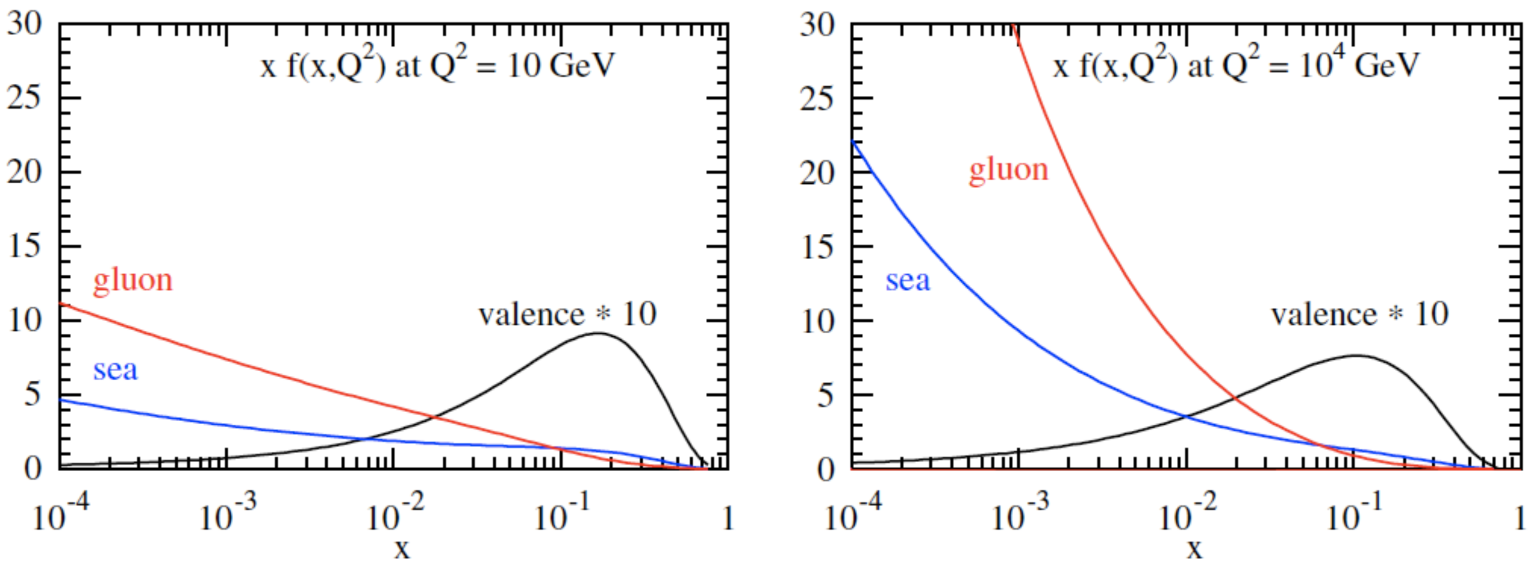




- Trigger efficiency decreases with jet multiplicity
  - Isolation requirement sensitive to increased hadronic activity
- Reconstruction efficiency including offline selection criteria is stable

Evolution to LHC Energies

- Gluon momentum distribution enhanced at low x
  - $g \rightarrow q\bar{q}$ contributions become important



S. Moch, J. Phys. G: Nucl. Part. Phys. **35** (2008) 073001