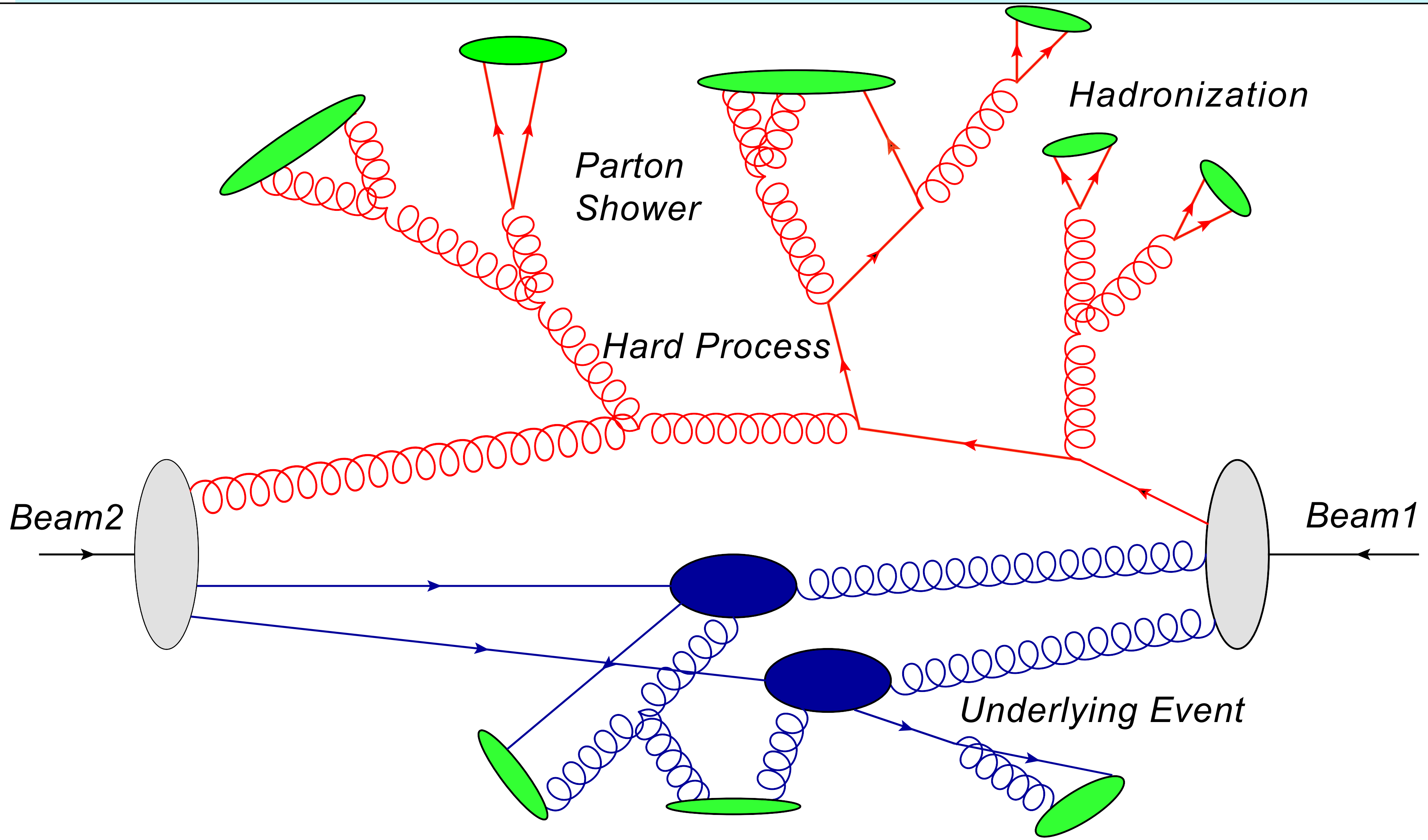
Overview of QCD measurements at high pT

Matthias Weber (UCLA)

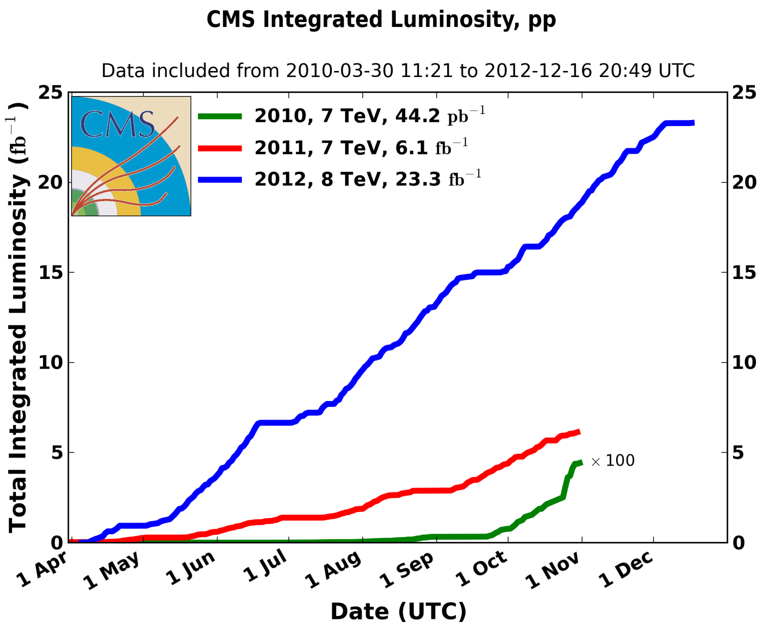
Material from ATLAS, CMS, LHCb and Tevatron

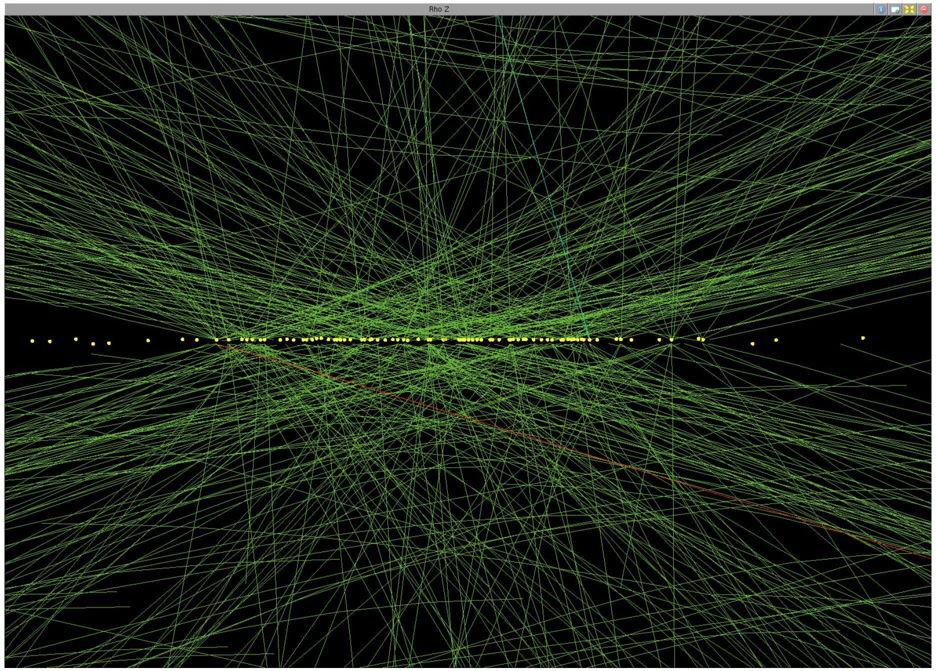
QCD in all its beauty in MCs



Challenges at the LHC

- Huge integrated luminosity delivered by the LHC, over 20 fb^{-1} in 2012 at 8 TeV



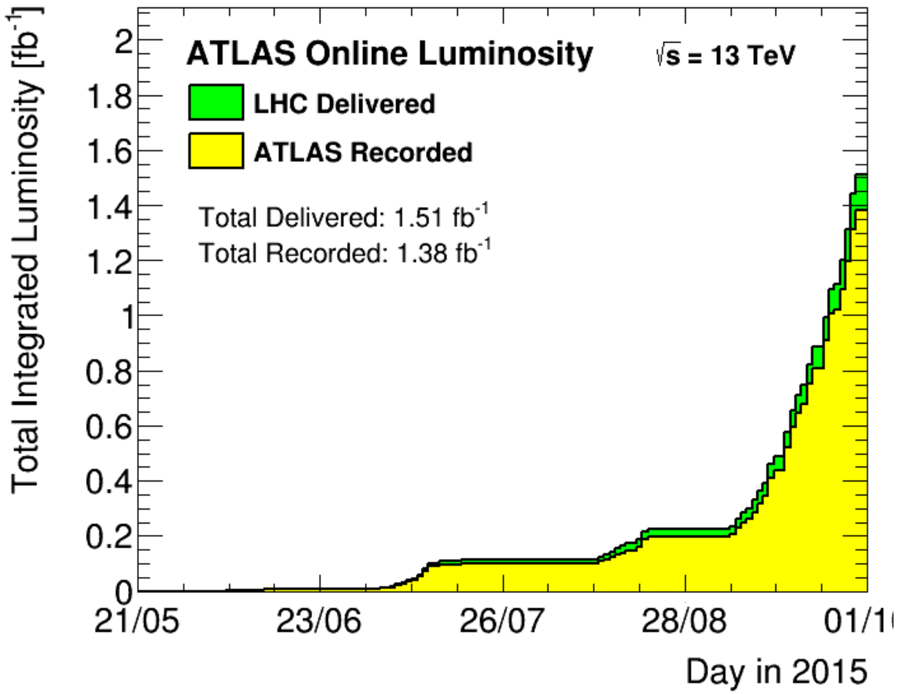


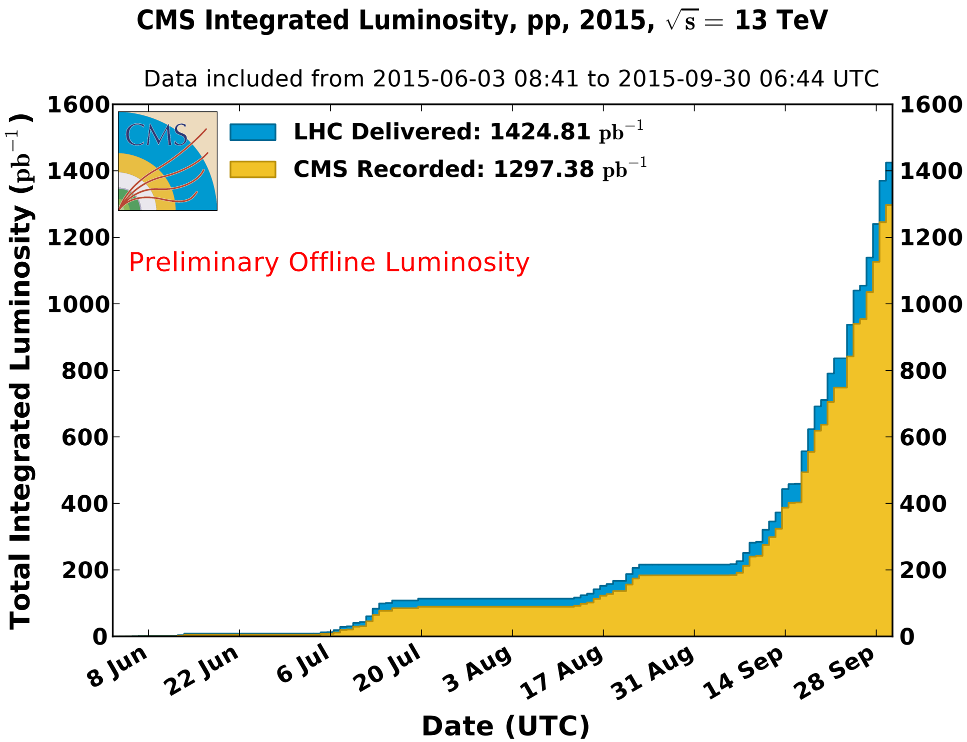
recorded integrated lumi **Reconstructed vertices**

- In order to cope with the large rate, need to filter events by different triggers which select events of physics interest
- Reconstruction deals with multiple additional events per collisions (pile-up)

Run II progress

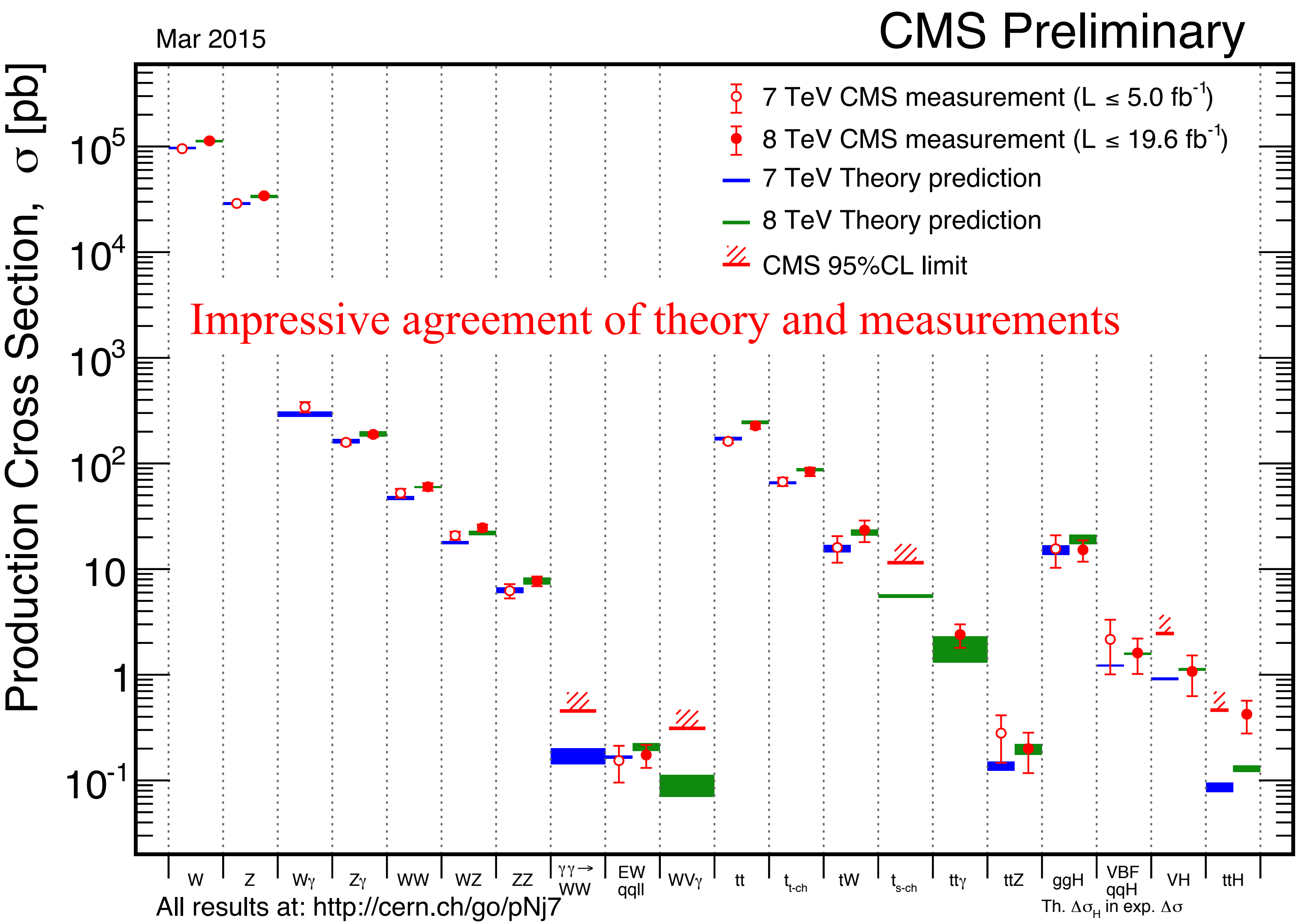
- LHC delivered around 1.5 fb^{-1} to the experiments at 13 TeV





- LHC runs now with a bunch spacing of 25 ns, compared to 50 ns at Run I

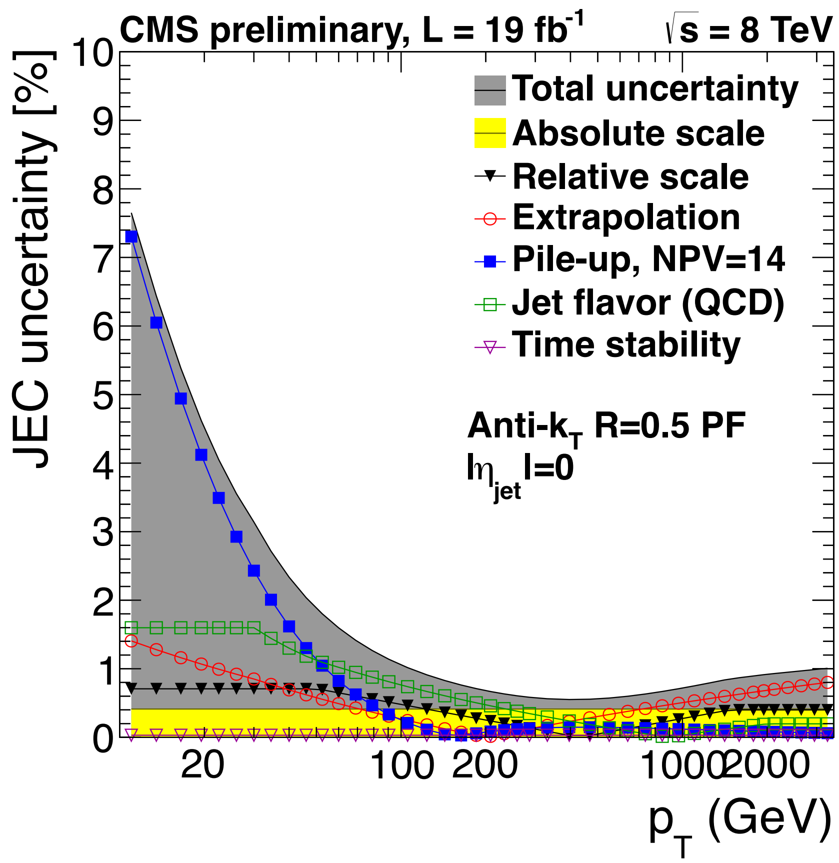
Standard Model Summary plot



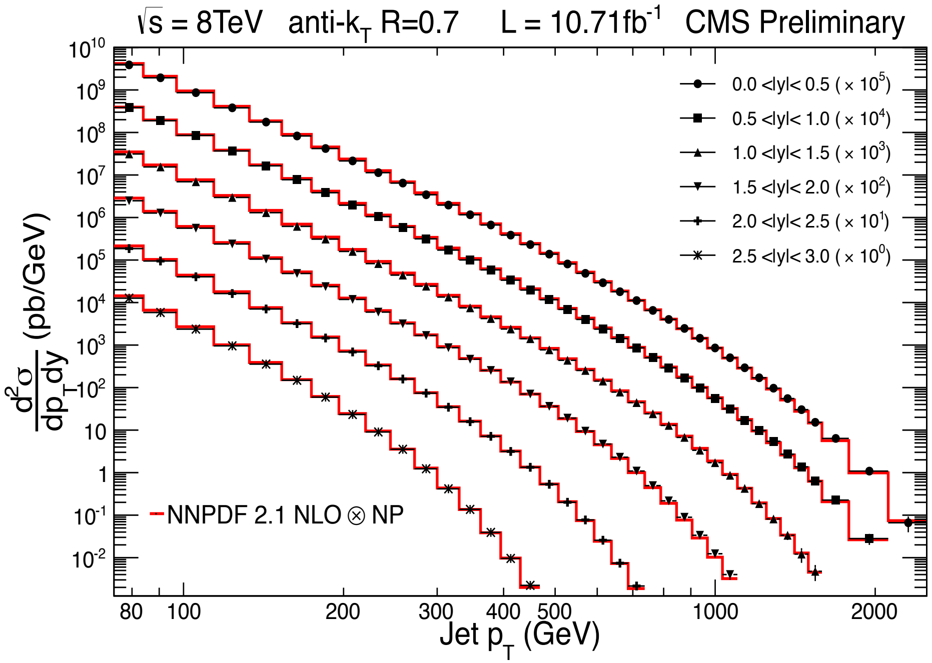
Inclusive jets

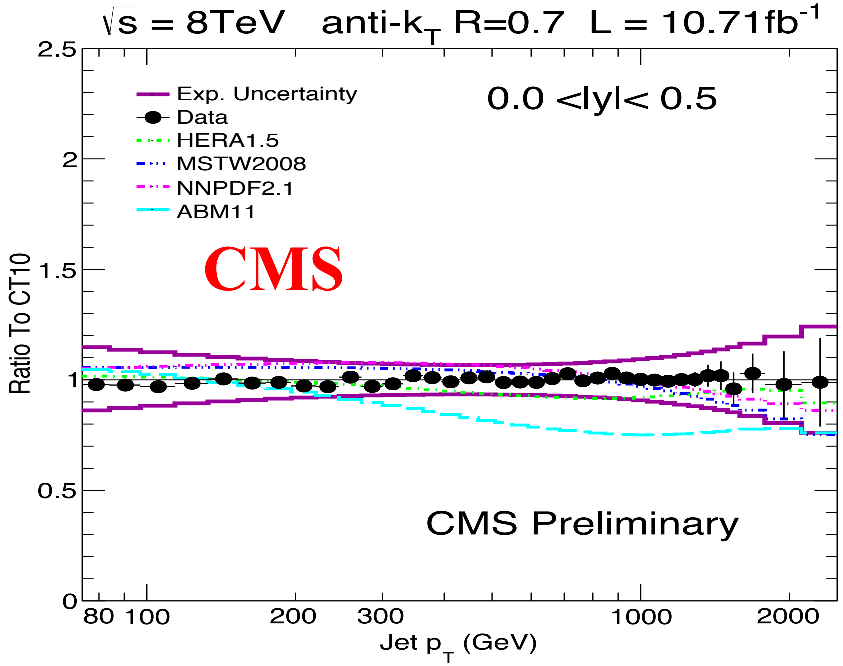
Jets in general

- Good understanding of jets crucial for many experimental signatures
- Test perturbative QCD calculations and MC predictions over several orders of magnitude
- Study parton distribution functions
- High precision measurements
  - Very small background rates
  - Small experimental uncertainty crucial (Jet energy scale)
- Study extreme kinematic selections of QCD



Inclusive high p_T jet cross-section at 8TeV

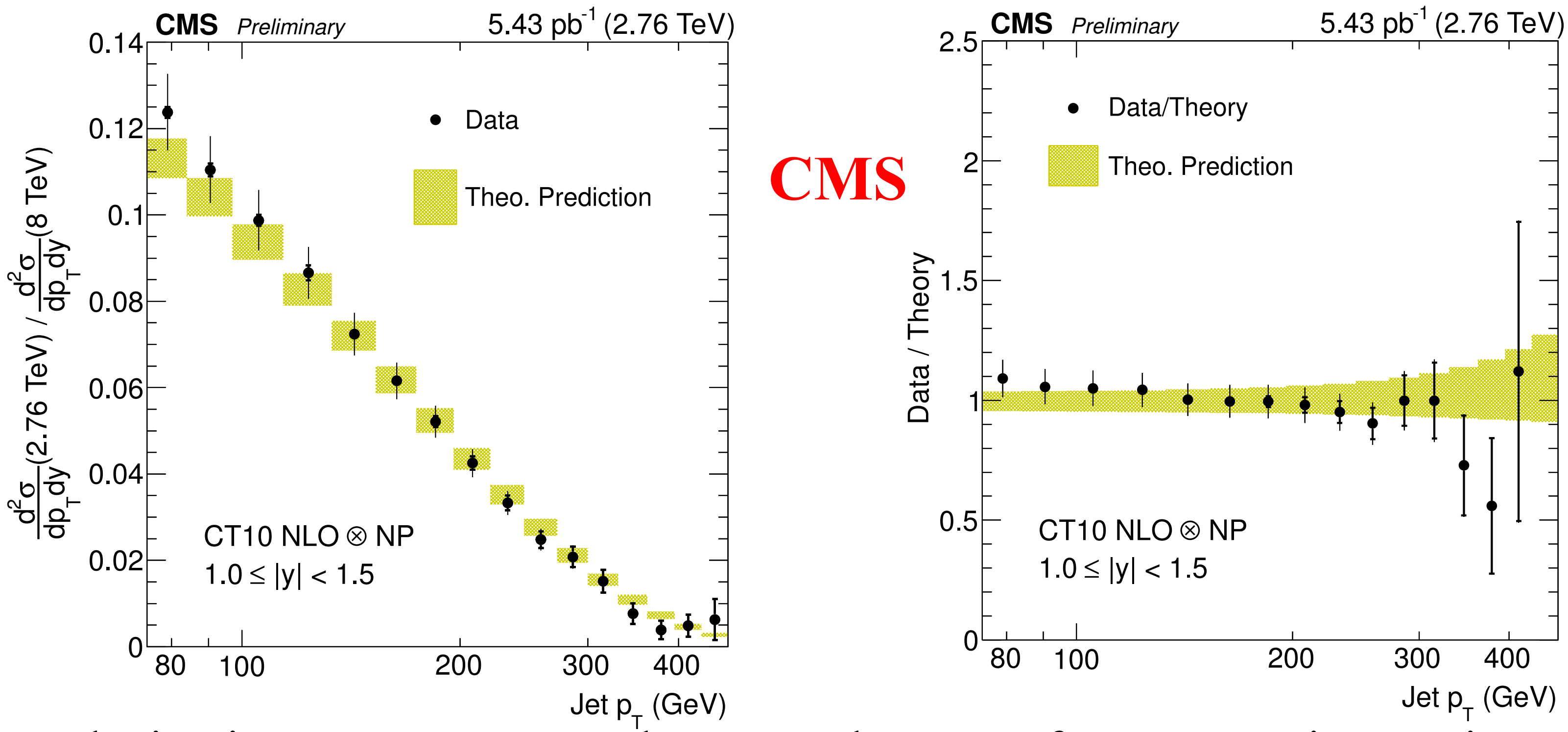




Inclusive jet p_T cross-section at 8 TeV in 6 rapidity bins from 75 to 2500 GeV (anti-k_T ΔR=0.7), over 10 orders of magnitude.

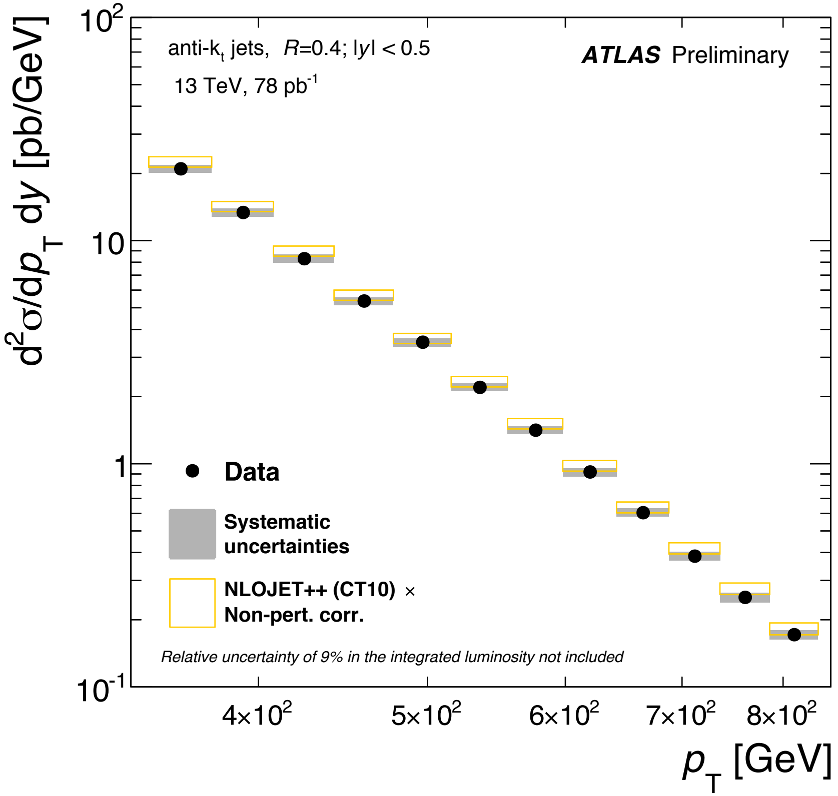
Comparisons to NLOJet++ prediction with many PDF sets. CT10 provides best description, ABM11 off, HERAPDF shows deviations for more forward rapidities

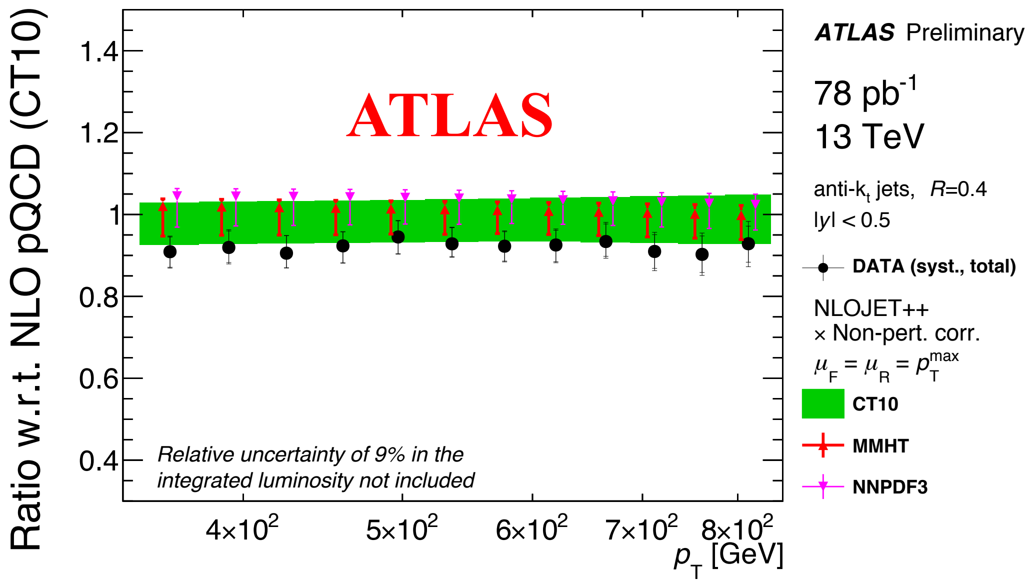
Inclusive jet cross-section ratios: 8 over 2.76 TeV



Inclusive jet spectra measured at several centre of mass energies. Ratios take into account correlations between uncertainties →many uncertainties cancel partially in ratios

Inclusive jet cross-sections: 13 TeV

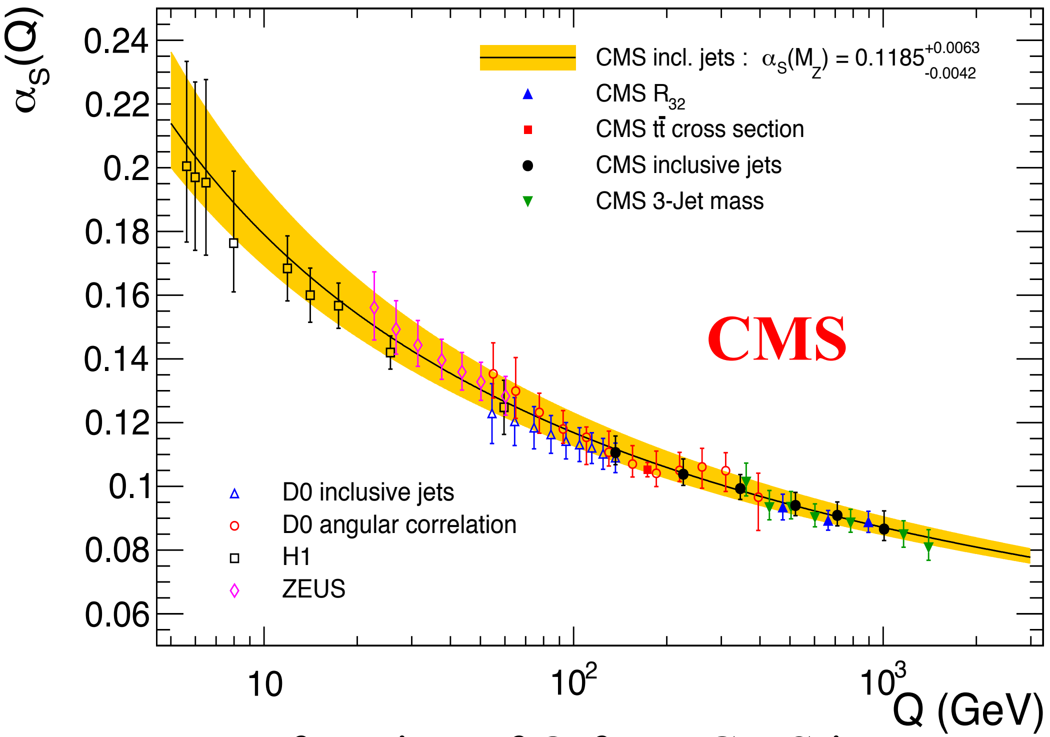




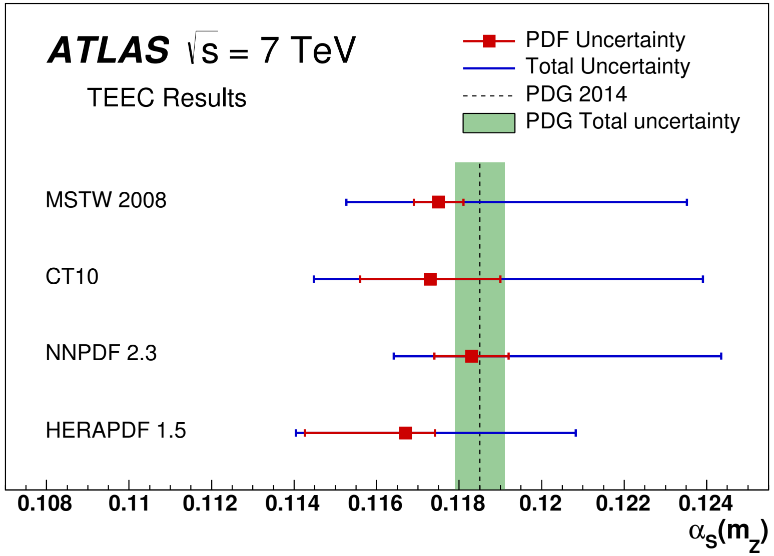
First comparison of inclusive jet data with predictions at 13 TeV using ak4 jets.
Prediction is higher than yield measured in data

⇒ offset in normalisation is completely within the jet+lumi systematics

Strong coupling constant α_S



ATLAS



Extract α_S as function of Q from CMS jet measurements at 7 TeV

$$\alpha_S(M_Z) = 0.1185 \pm 0.0019\,(\text{exp.}) \pm 0.0028\,(\text{PDF}) \pm 0.0004\,(\text{NP})^{+0.0055}_{-0.0022}\,(\text{scale})$$

Latest result from ATLAS transverse energy–energy correlations

$$\alpha_s(m_Z) = 0.1173 \pm 0.0010\,(\text{exp.})\,^{+0.0063}_{-0.0020}\,(\text{scale}) \pm 0.0017\,(\text{PDF}) \pm 0.0002\,(\text{NPC})$$

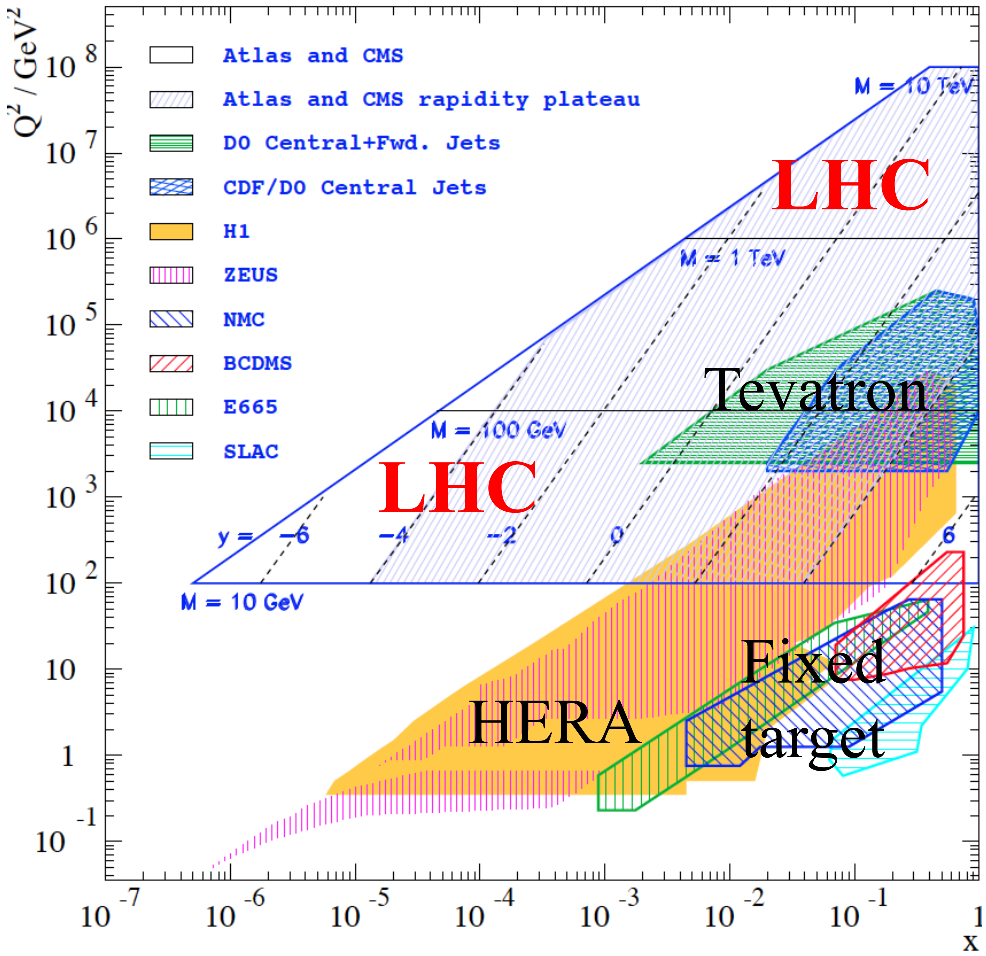
PDF sensitivity at the LHC

PDFs determined through global fits to many observables

- High precision on PDF's allows for more accurate extraction of theory parameters

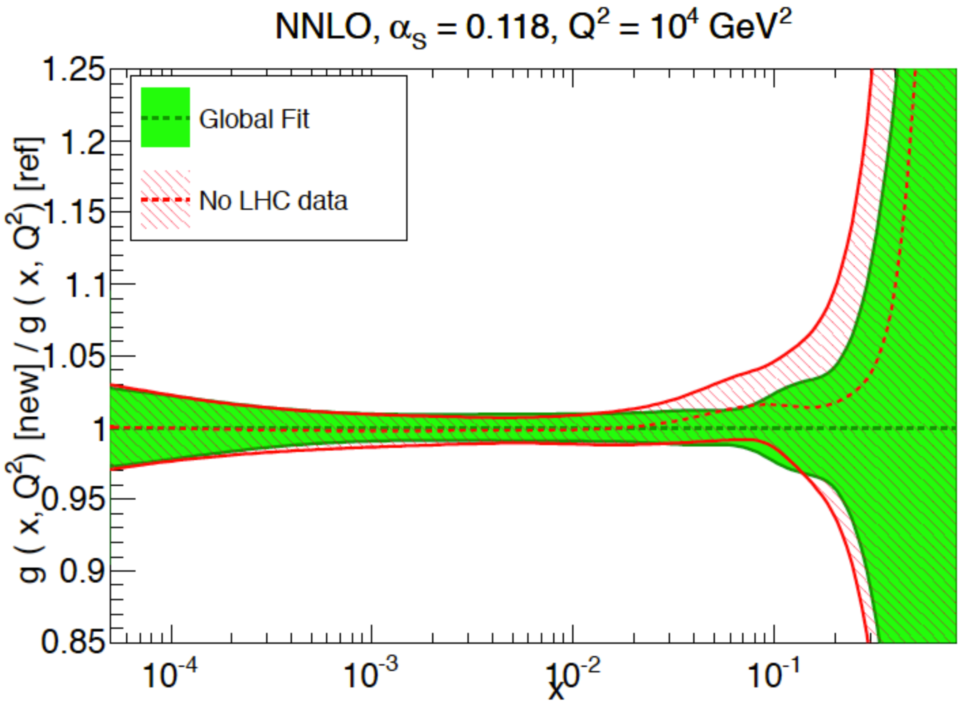
LHC data provides huge amount of data in unexplored kinematic regions

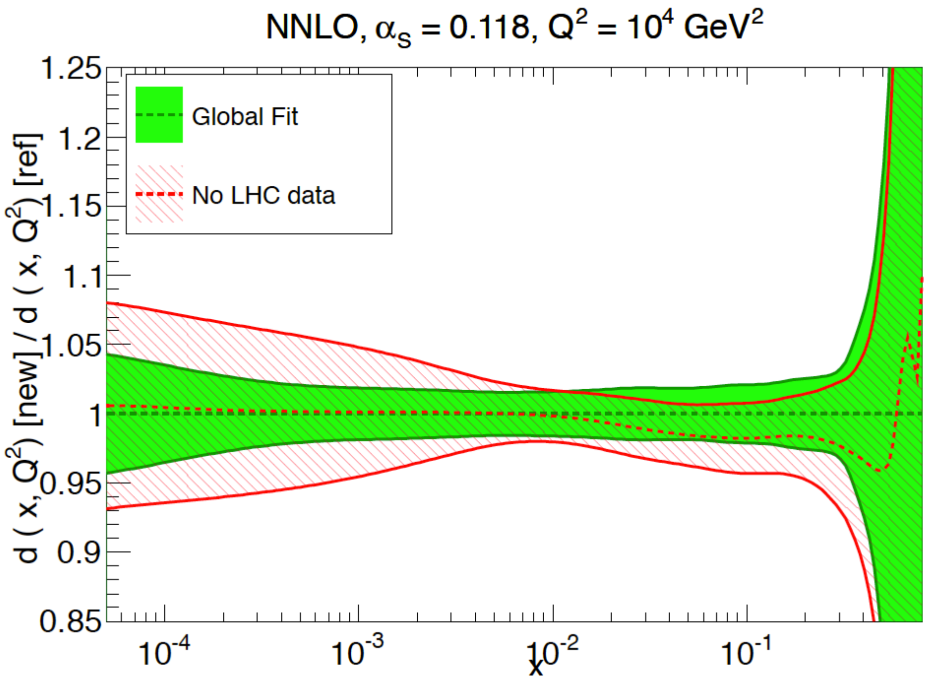
- Provide constraints on PDF in vastly unchartered space
- Largest reach in momentum scale Q^2 beyond the TeV range (using DGLAP evolution)
- Reach to very low momentum fraction x (10^{-4} CMS and ATLAS, reach to lower values using LHCb data)



S. Glazov, Braz.J.Ph. 37 (2007) 793

PDF extractions: example NNPDF





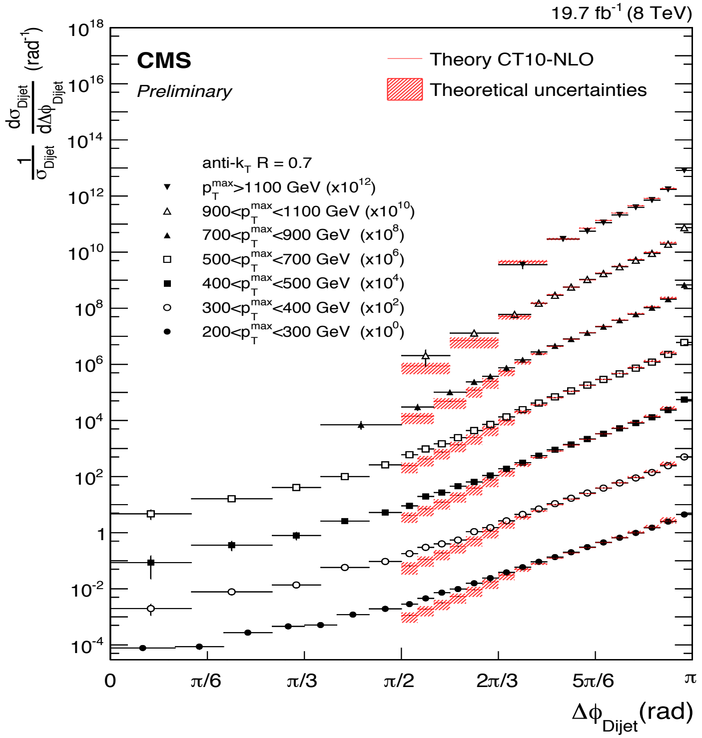
Large impact of LHC jet data on gluon PDF, especially at high x
For quark PDF's less contribution from inclusive jet spectrum, but e.g. W charge asymmetry measurement

EPJC 75 (2015) 288

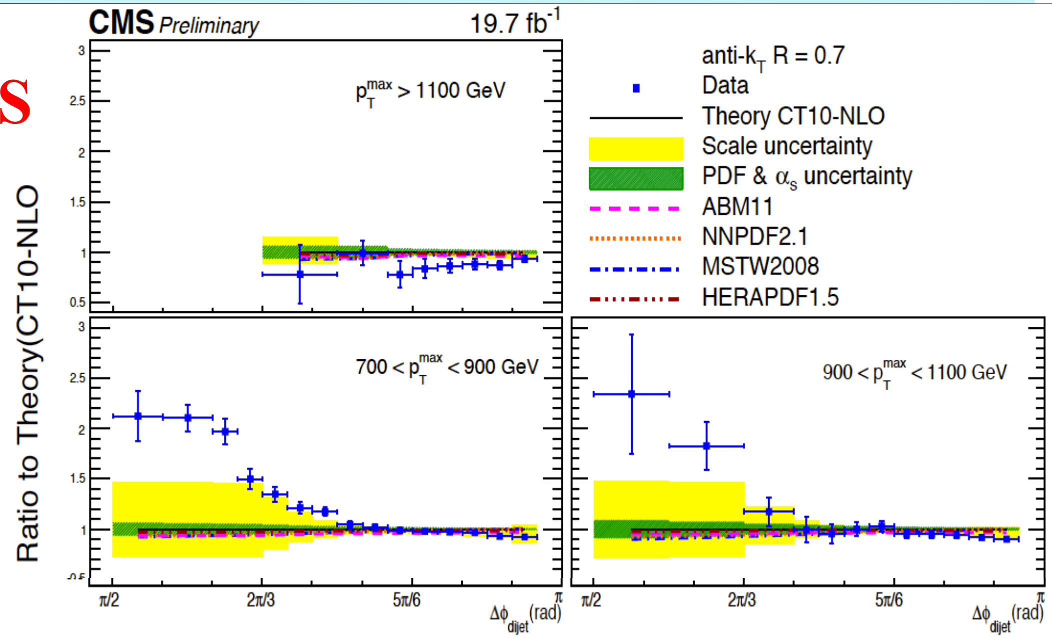
arXiv:1508.01579

Multijets

Dijet azimuthal decorrelation at 8 TeV



CMS

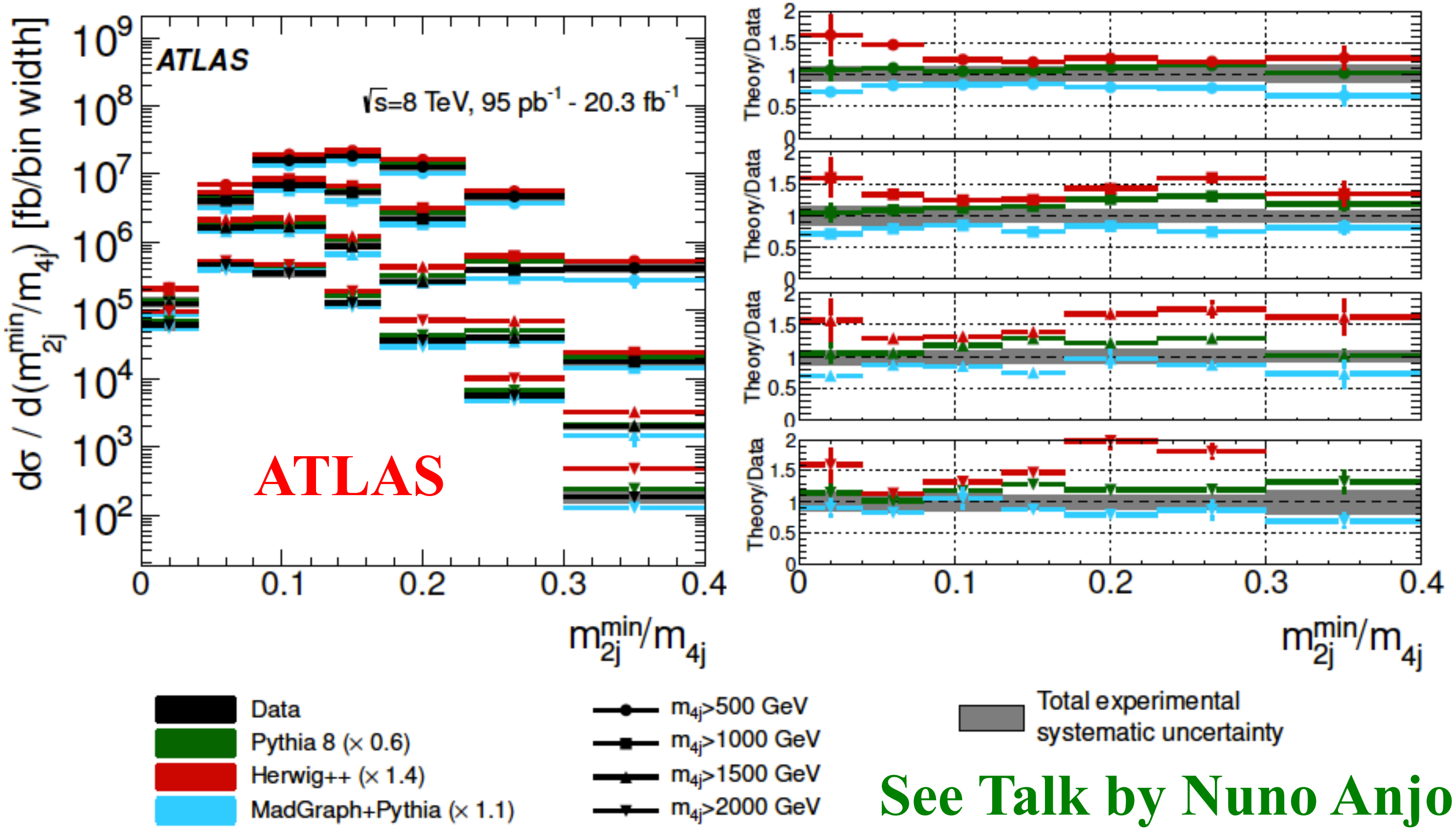


$\Delta\phi_{Dijet}$ Sensitive to higher order effects, $p_{T,j2}$>100 GeV fixed, 7 bins in jet1 p_T

Theory: NLOJet++ as 3 jet production at $\alpha_S{}^4$ accuracy

→ Good agreement in a subrange, missing higher orders for low $\Delta\phi_{Dijet}$ values, points close to π excluded in theory treatment, would need merging of fixed-order and resummation

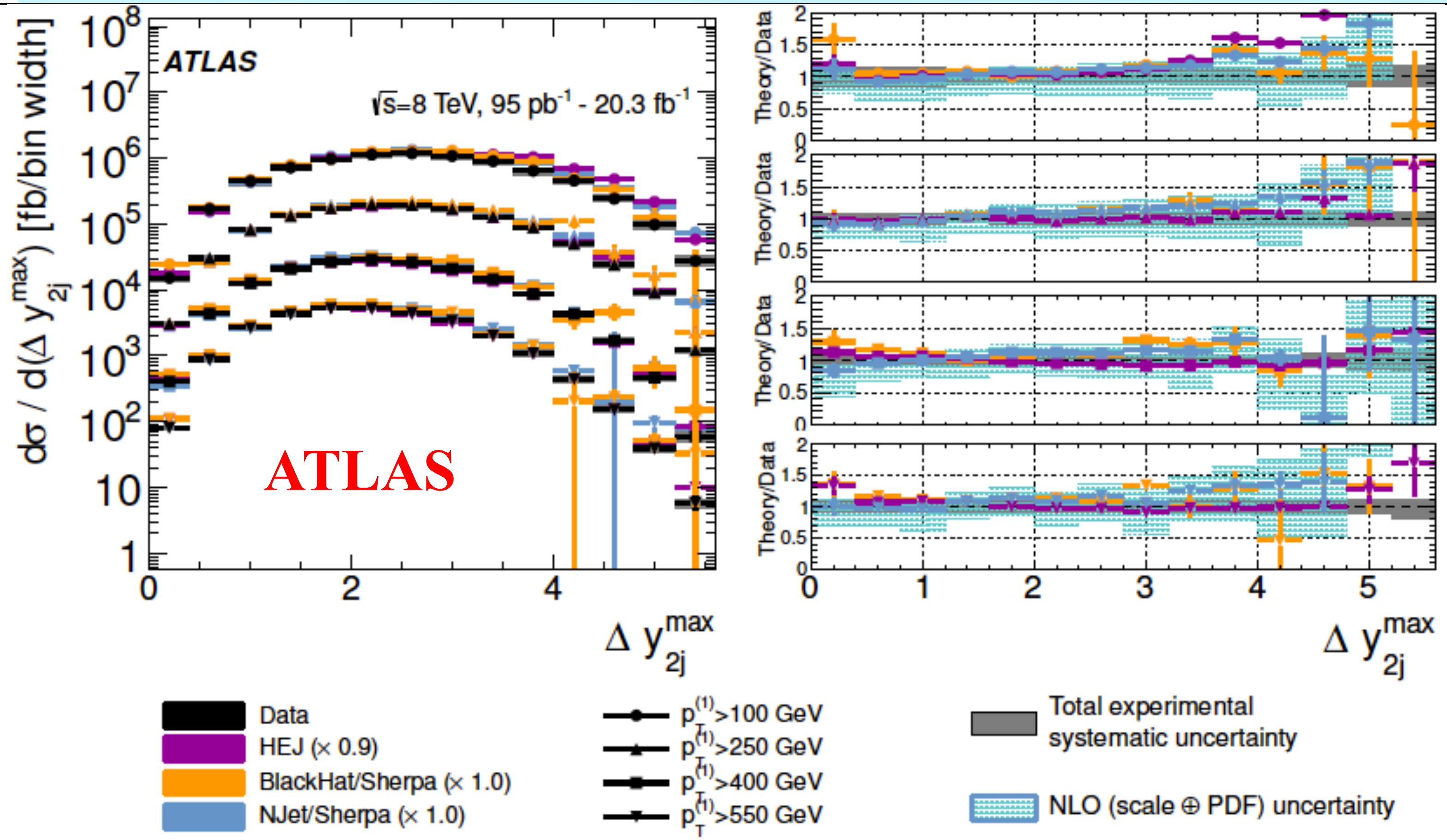
Multijets at 8 TeV



See Talk by Nuno Anjos

Several mass, momentum and angular variables are compared to several MC predictions and NLO calculations. MadGraph+Pythia give shapewise best prediction, within uncertainties NLO predictions provide good description as well

Multijets at 8 TeV (II)



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Hard QCD with jets in a nutshell

- Inclusive jet cross-section in good agreement with NLO prediction over orders of magnitude
- Theory predictions which can confront measurements of inclusive dijets and very high multiplicities of desire

  → so far theory predictions for pure hadronic multijet signatures rarely trusted enough to be used in searches

- First global PDF fits including 7 TeV LHC data show a sizable improvement especially for the gluon PDF
  - many production processes at the LHC involve gluons
  - More constrained PDF's lead to lower theory uncertainties on cross-section predictions
- First extraction of the strong coupling constant and testing of its running

Vector bosons

Vector Bosons

- W and Z an be measured very accurately through their leptonic decays, photon energies precisely measured in the electromagnetic calorimeter

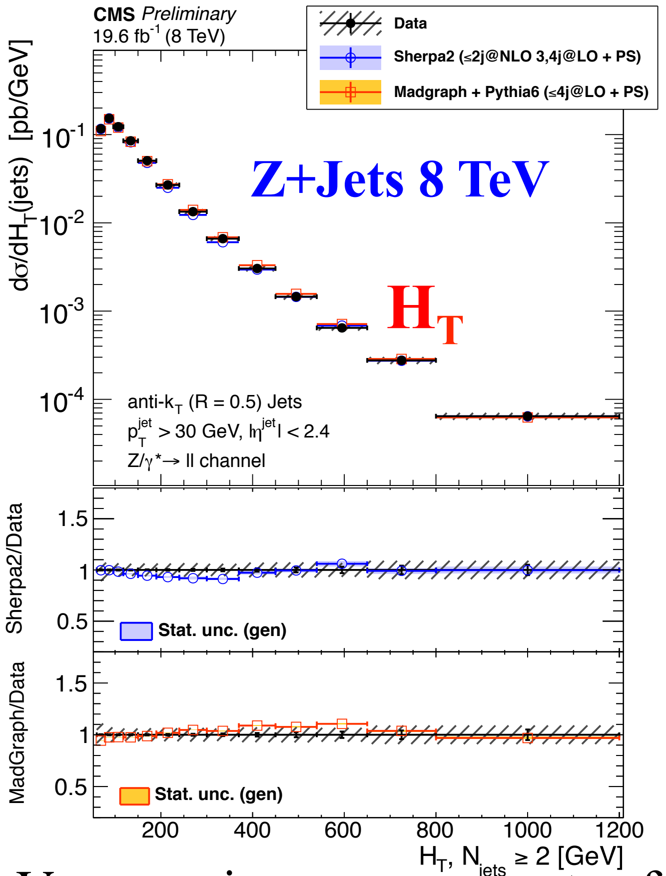
- Z and photons used for calibration of jets, Z used as candle to determine lepton efficiencies

- Charge asymmetry distribution of W^+ and W^- provide input for u and d valence quark PDF's

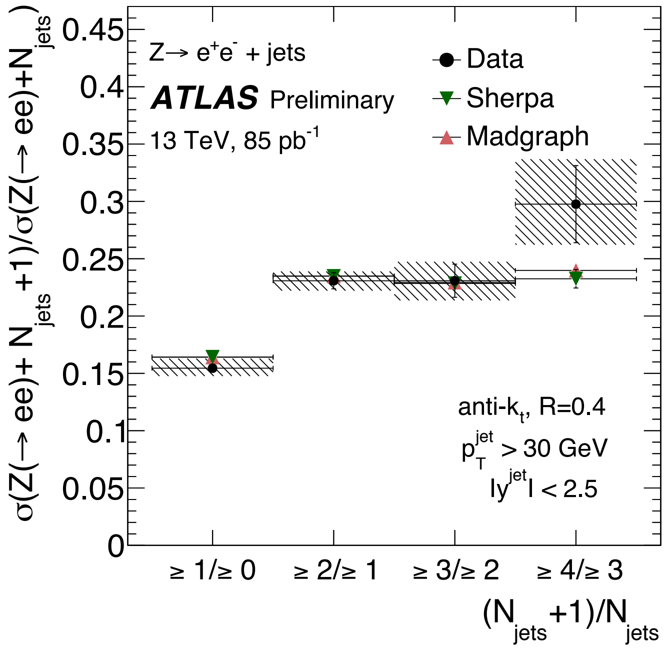
- Vector boson plus jets major backgrounds in beyond standard model searches and excellent testing ground for QCD NLO predictions

  → data allows for large amount of precise measurements to tune MC predictions, targeting better predictions in tails of important background processes for searches

V plus jets precision measurements

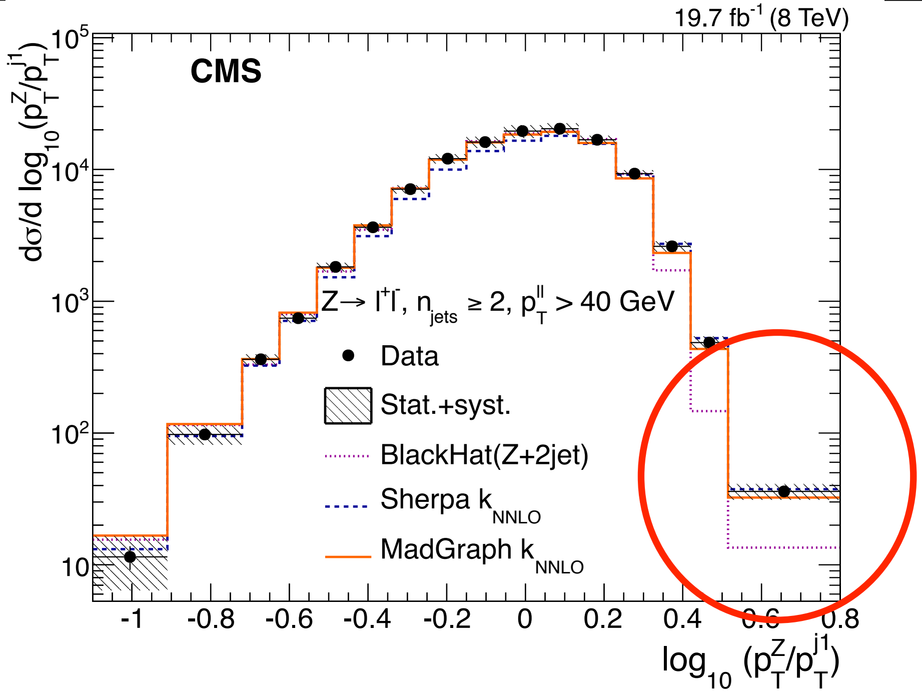


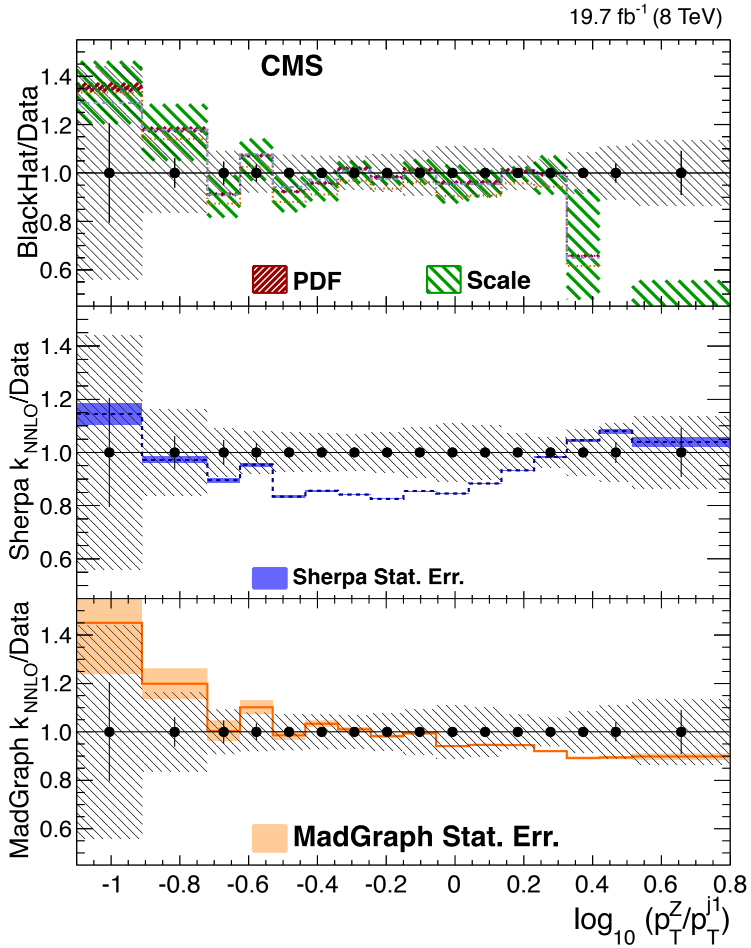
See Talk by Vieri Candelise



Very precise measurements of jets properties in Z+jets, W+Jets, γ +jets
First testing of Z+1 &2 jet NLO matrix element +PS generator Sherpa2 with 8 TeV CMS and 13 TeV ATLAS Z+jets data, performance on par with multileg LO+PS generator MadGraph

Z plus jets precision measurements (II)





Ratio of leading jet p_T and Z p_T

NLO predicts shape and rate for large subrange,

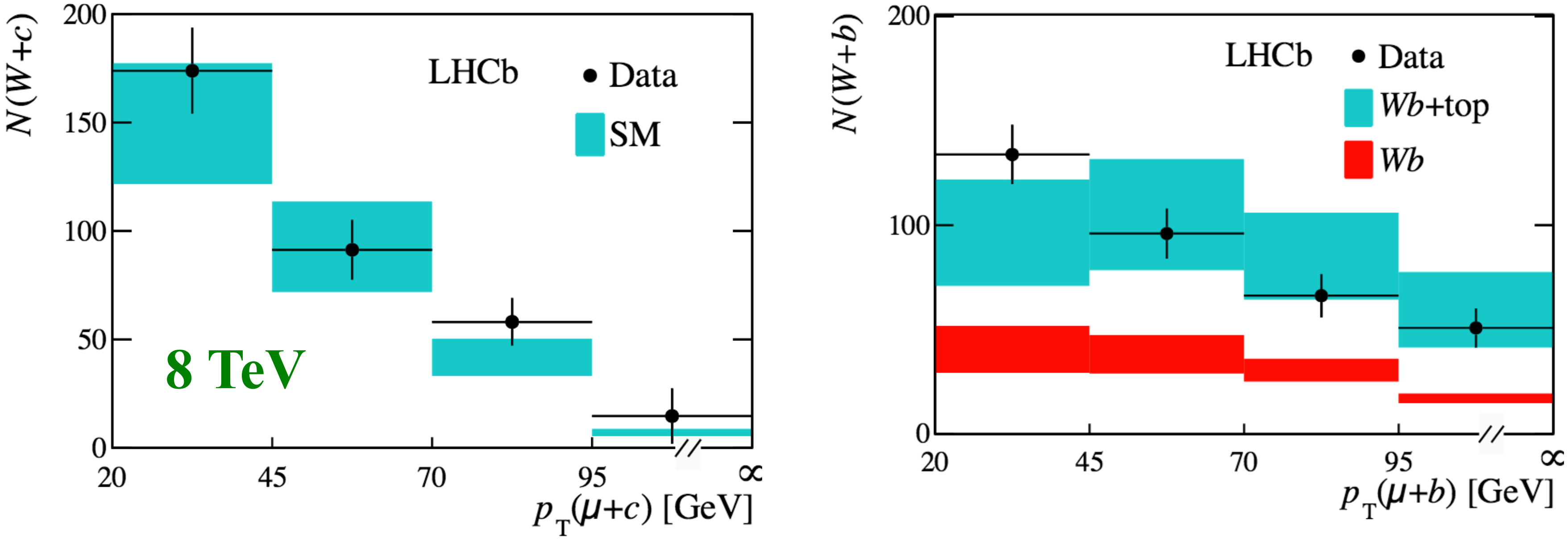
Parton shower necessary for mult-jet high end.

LO+PS of MadGraph shows trend, but within uncertainty band, Sherpa off both in shape and rate

W plus heavy (forward) jets at the LHC

Forward muons (p_T>25 GeV, 2.0<η<4.5)
tagged jets (50<p_T<100 GeV, 2.2<η<4.2)

LHCb

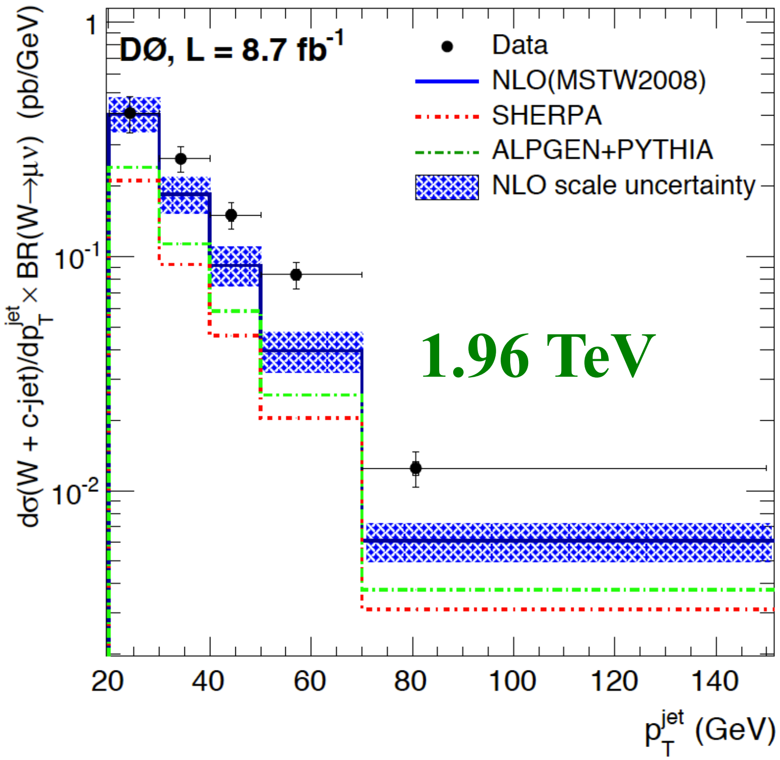


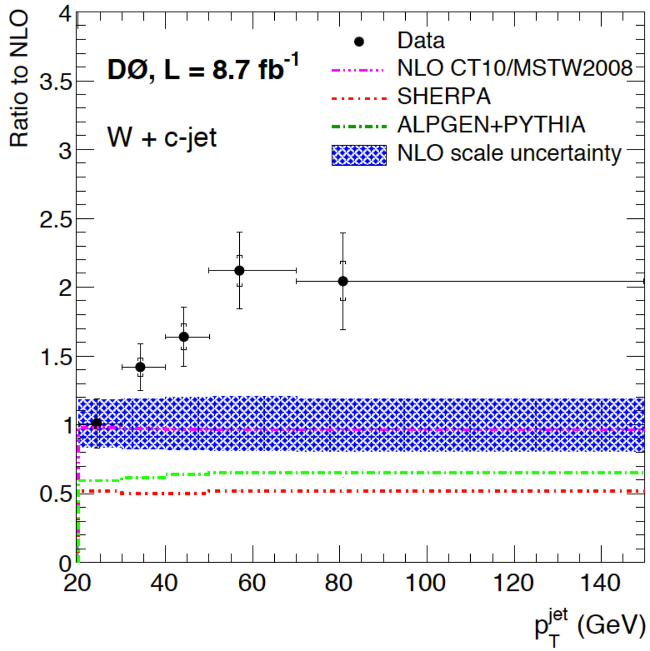
NLO SM W+c prediction from MCFM agrees with data distribution of vector sum p_T of muon plus tagged jets

Need sum of NLO SM Wb and top production to reproduce yield of muon plus b-tagged jets in data

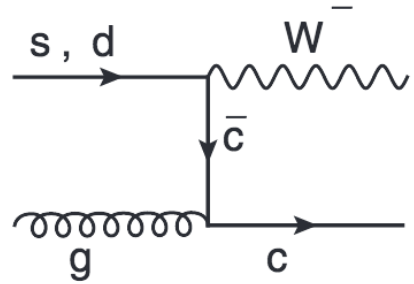
W plus heavy jets at the DØ

muons (p_T>20 GeV, $|\eta|$<1.7)
central jets (20<p_T<100 GeV, $|\eta|$<1.5)

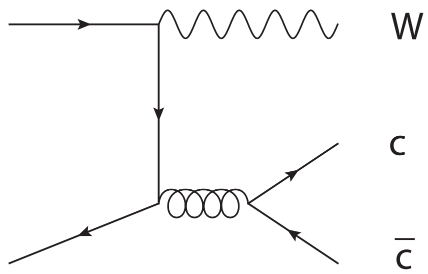




dominant



More important at high p_T



MCFM underpredicts data at high p_T, Alpgen & Sherpa off in shape and scale
→ Missing higher orders?, gluon splitting? s-quark PDF enhanced

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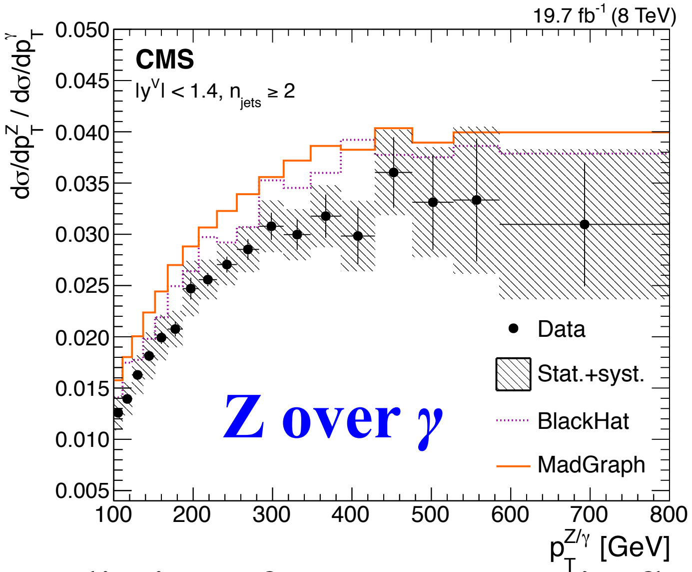
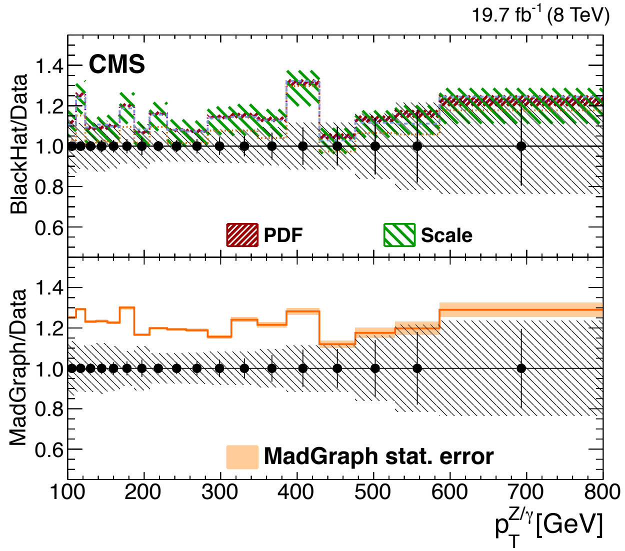
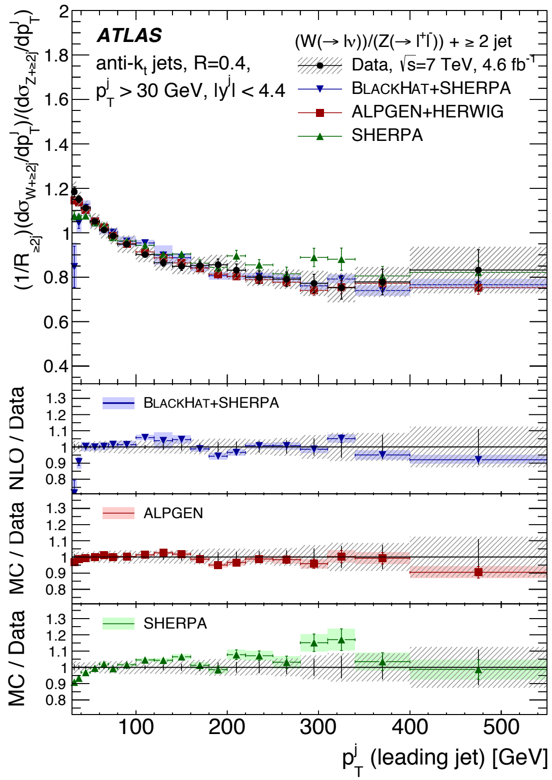
Cross Section Ratios

Cross-section ratios

Differential cross section ratios: large cancellation of systematics
→more stringent test of theory predictions possible
In full hadronic searches photon p_T spectrum used to describe high end tail of Z→νν
W+jets can be used to predict Z+jets as well (or vice versa)







predictions for Z over γ ratio flat, but even NLO prediction off by 10% in scale
Z over W ratio reproduced by NLO in shape and rate,
Alpgen agrees in shape, sherpa a bit more off

Summary

- Only a handful of results out of the rich long list of measurements performed by several experiments
- Run I data analysis at the LHC still going strong, Run II LHC results start to show up, keep an eye on final results from Tevatron

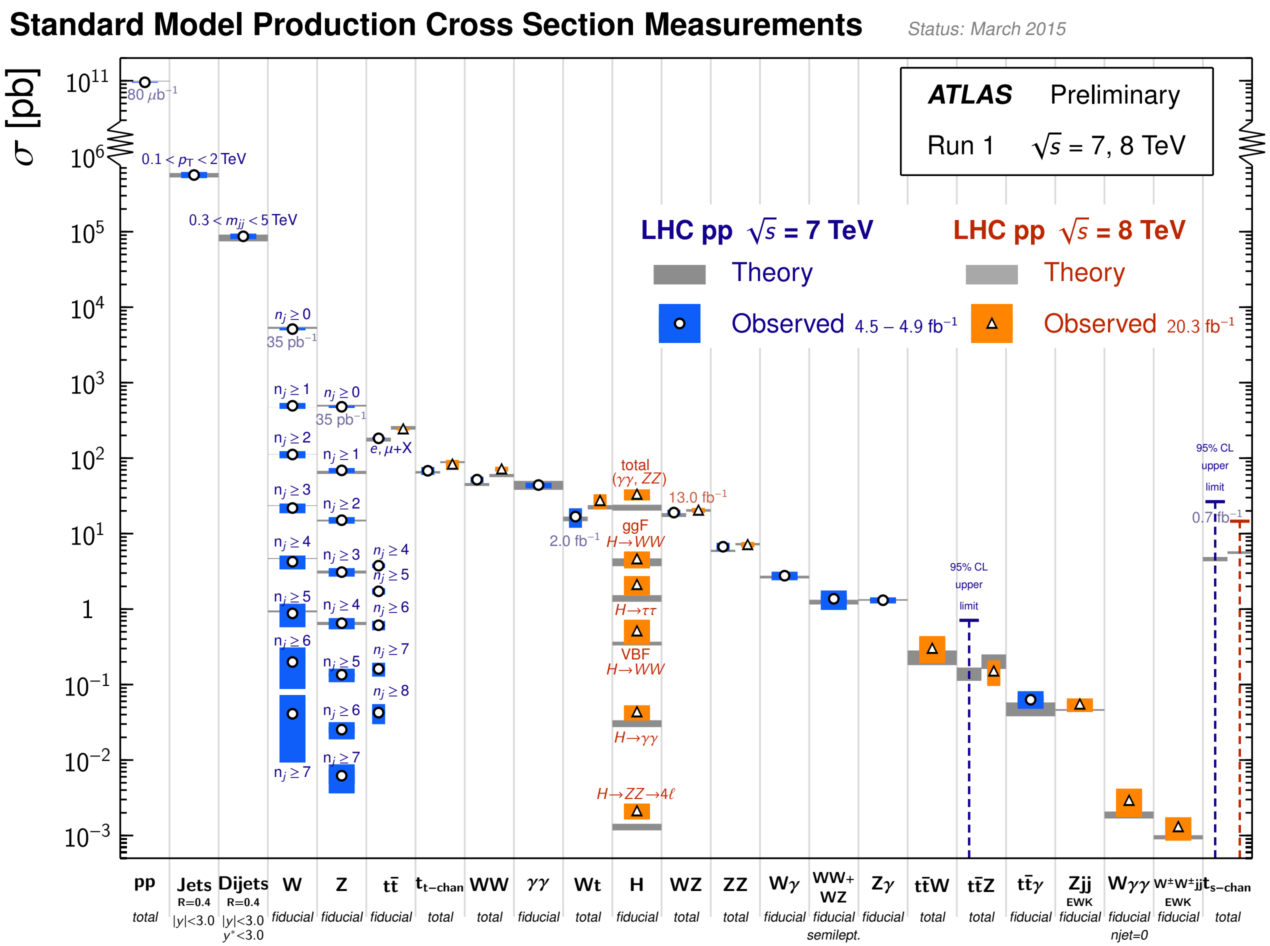
In general predictions provide a good description of data

  – Results provide valuable input for theory e.g. updated PDF sets and couplings
  – Differential measurements more challenging for predictions
  – Ready to test new generators, e.g. multileg NLO ME+PS type

- Measurements of strong coupling constant and its running compatible with world average
- With new data coming in at the highest center of mass energies achieved more exciting times to come for LHC physicists

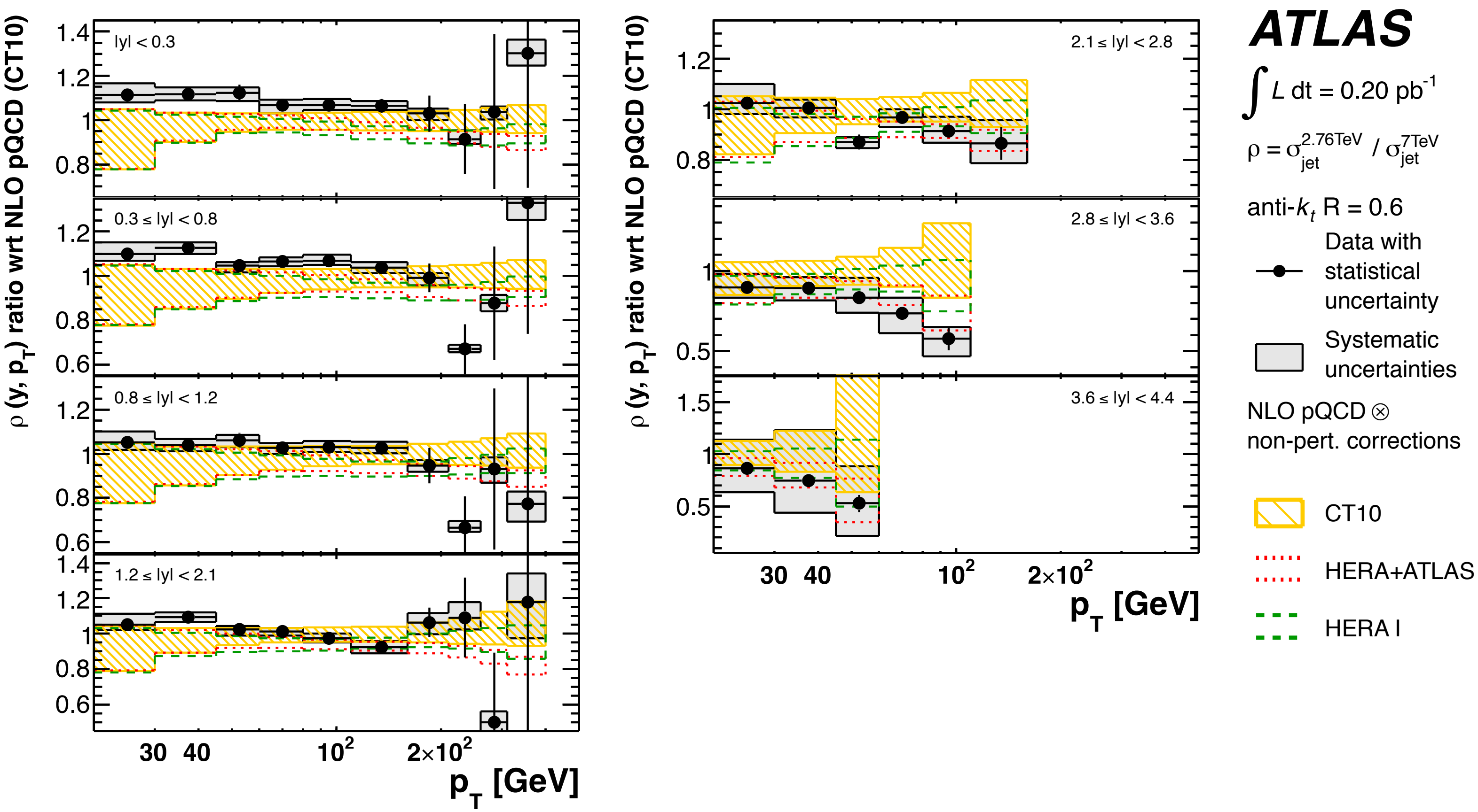
BACKUP

Cross Section Measurements Summary



Remarkable agreement between data and SM theory predictions

Inclusive jet cross-section ratio: 7 vs 2.76 TeV



Similar data/MC trend than observed for 2.76 over 8 TeV data by CMS

Transverse Energy-Energy Correlation

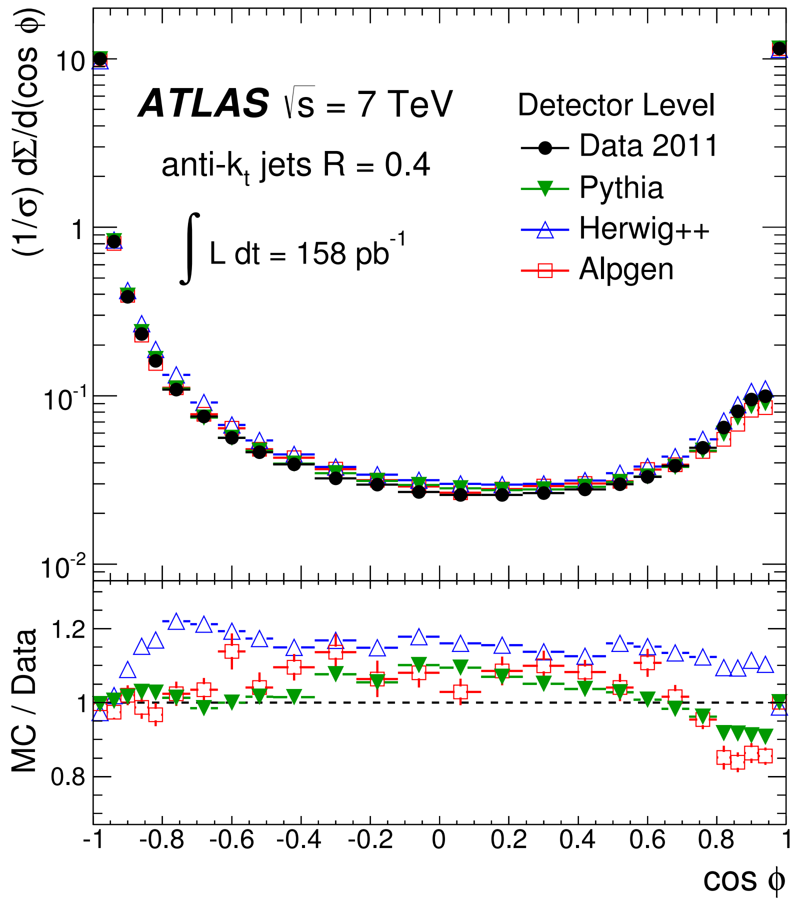
$$\frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)} = \frac{1}{\sigma}\sum_{ij}\int \frac{d\sigma}{dx_{Ti}dx_{Tj}d(\cos\phi)} x_{Ti}x_{Tj}dx_{Ti}dx_{Tj},$$

$$x_{Ti} = E_{Ti}/E_T \qquad E_T = \sum_i E_{Ti}$$

ϕ is the azimuthal angle between jet i and j

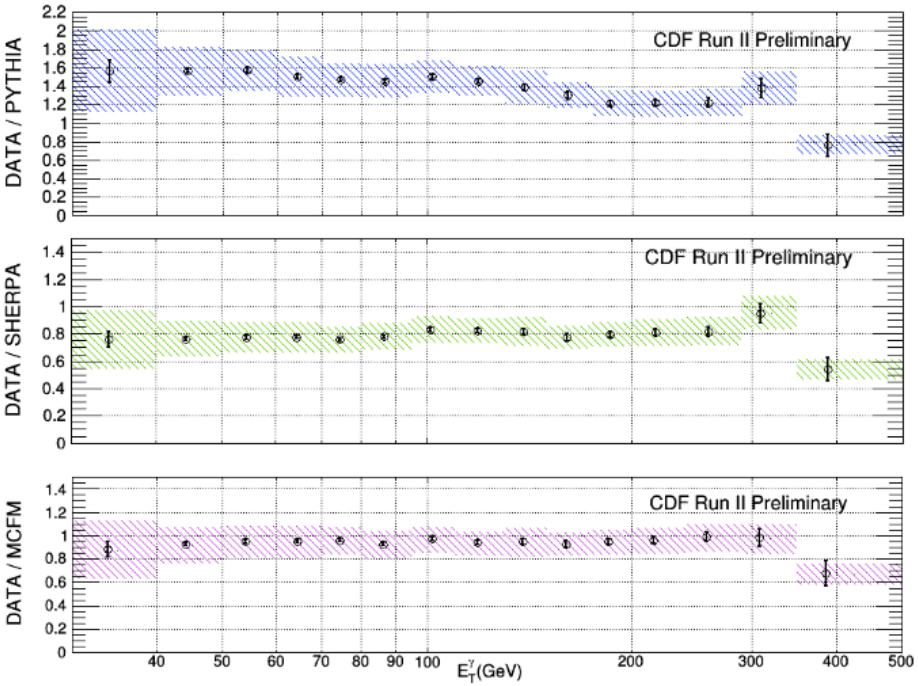
The transverse energy-energy correlation is proportional to α_S squared

Distribution fairly well described by Pythia6 and Alpgen, Herwig++ shows larger deviation



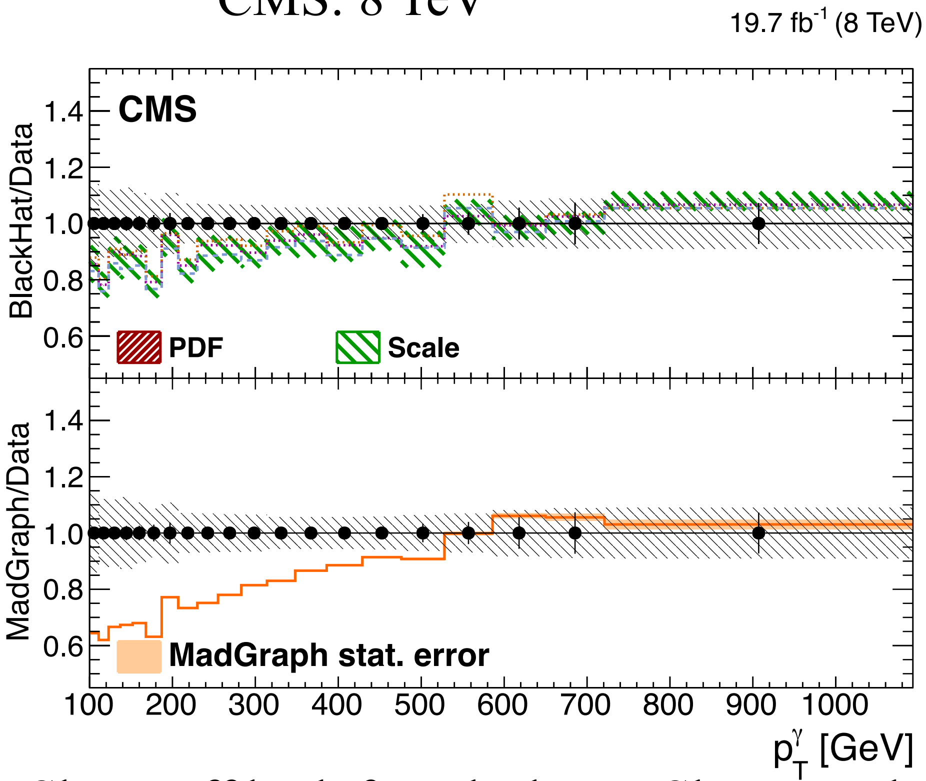
Photon plus Jets: CDF and CMS

CDF: 1.96 TeV



CDF photon inclusive E_T spectrum agrees with MCFM and Sherpa prediction, Pythia6 off in shape

CMS: 8 TeV



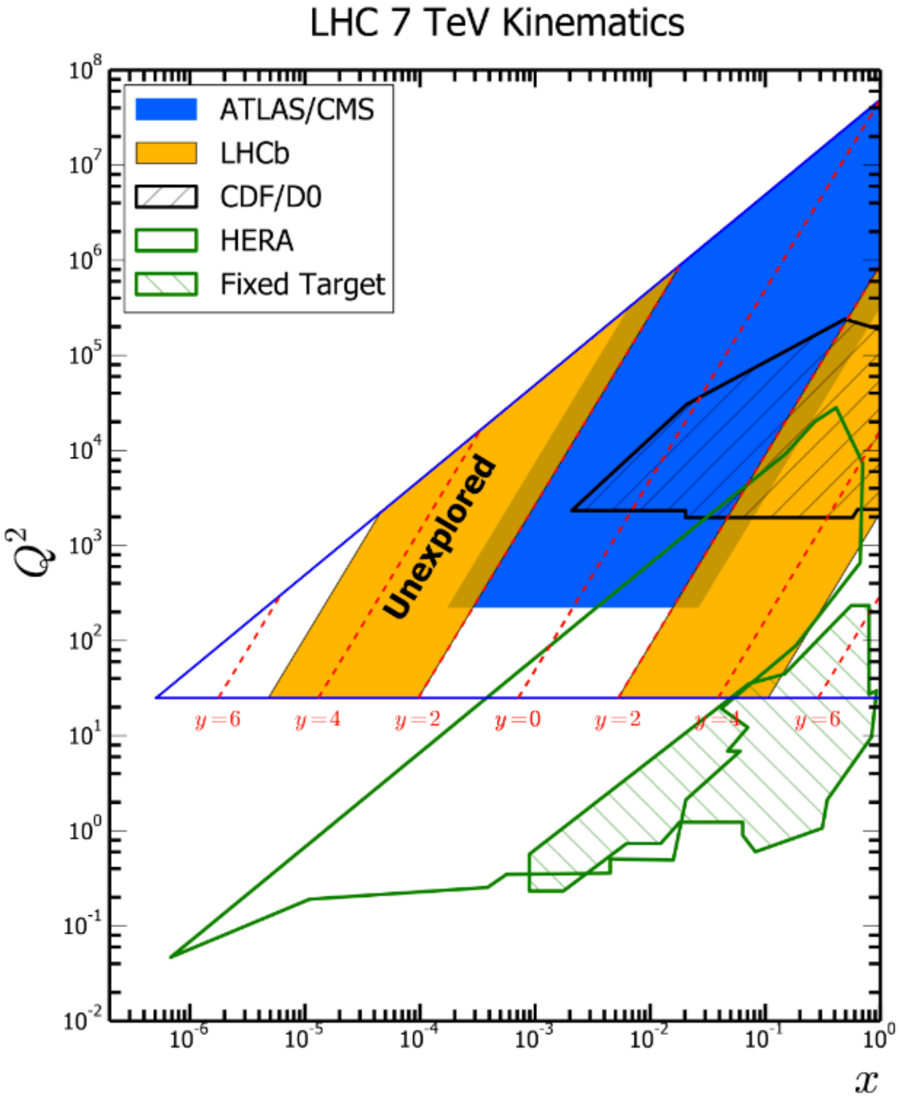
Shape off both for BlackHat+Sherpa and MadGraph+Pythia6, but rather flat for BlackHat, also closer in scale than for MG

For ATLAS results: see talk by Claudia Kuguel

PDF reach of LHC experiments at 7 TeV

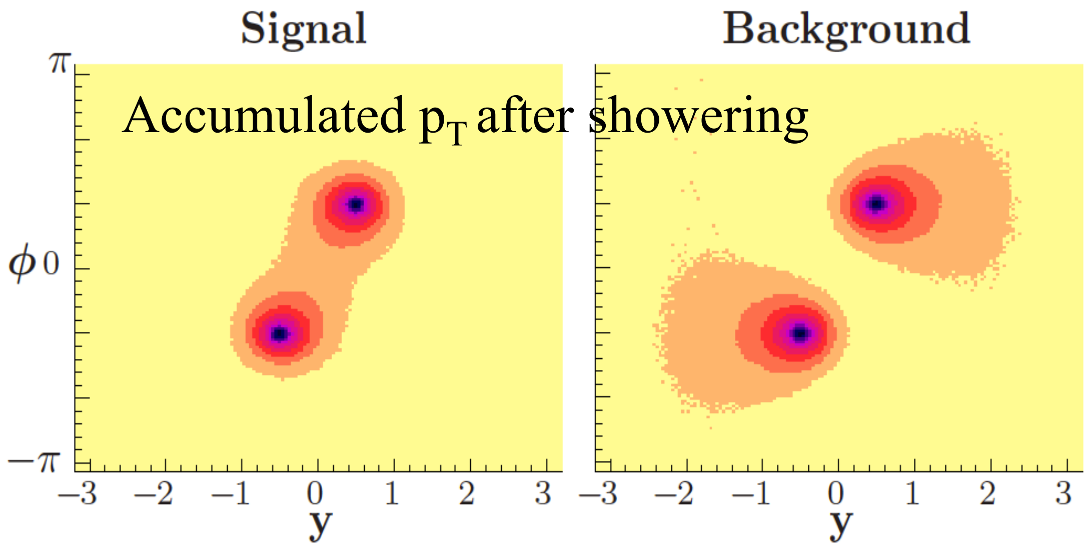
LHC data provides huge amount of data in unexplored kinematic regions

- Provide constraints on PDF in vastly unchartered space
- Largest reach in momentum scale Q^2 beyond the TeV range (using DGLAP evolution)
- Reach to very low momentum fraction x (10^{-5} CMS and ATLAS, below 10^{-6} for LHCb)

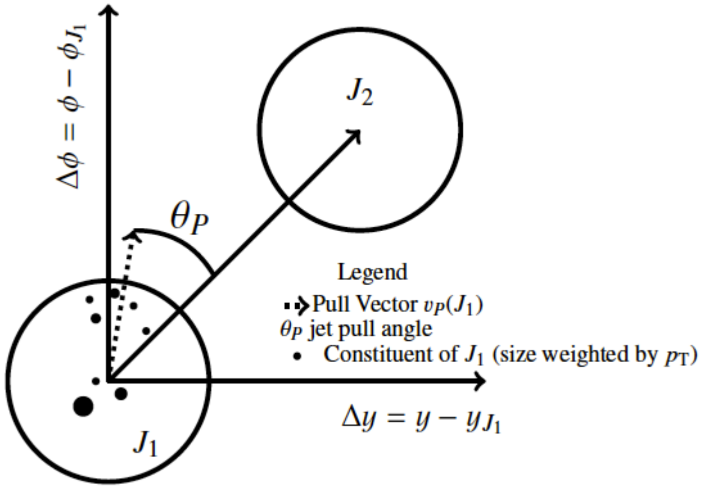


Jet pull

Jet pull handle to study color connection between jets, can be used to discriminate between jets originating from color singlets (Higgs) and color octets (e.g. gluons)



PRL 105, 022001 (2010)



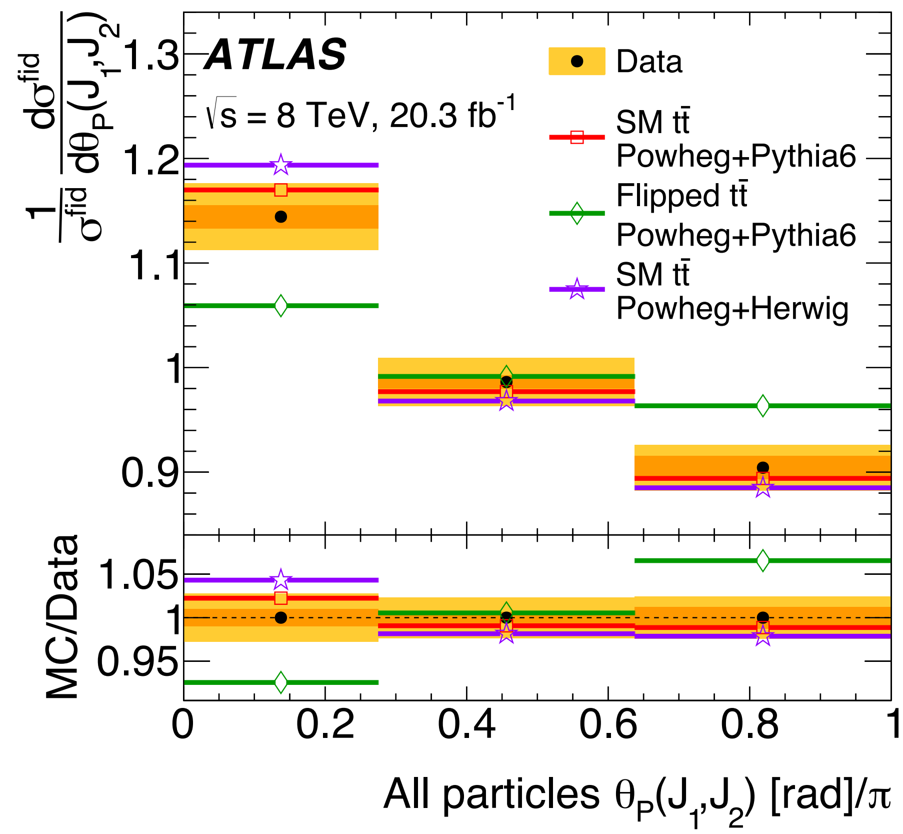
Definition jet pull vector:

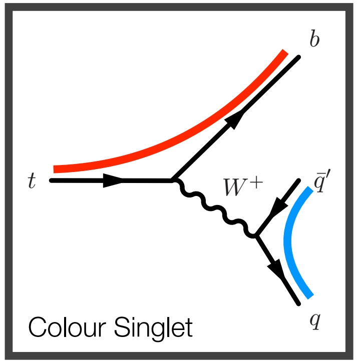
$$v_P(J) = \sum_{i \in J} \frac{p_T^i |\vec{r}_i|}{p_T^J} \vec{r}_i$$

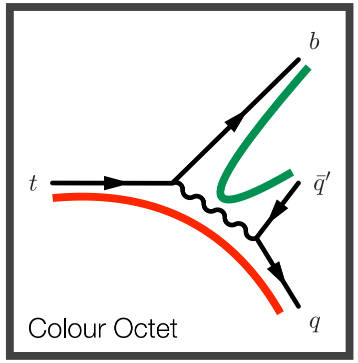
$$\vec{r}_i = (\Delta y_i, \Delta\phi_i)$$ Vectors of constituents relative to jet axis

Jet pull (II)

Jet pull tested in ttbar decays using hadronic W decays, alernative: hypothetical W octet model

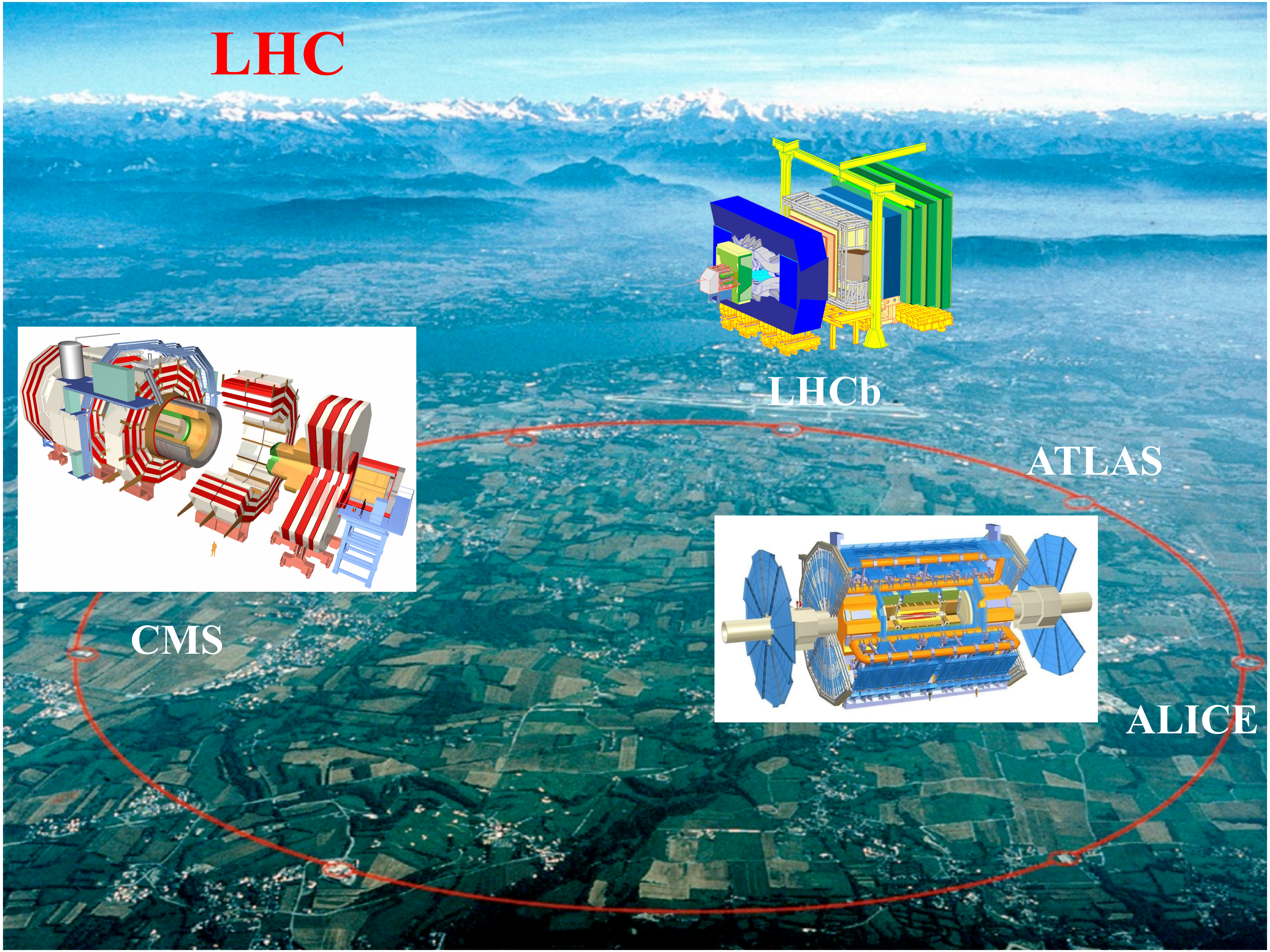






Data agrees with ttbar SM model (i.e. W as Colour Singlet)

MC prediction from Powheg with Pythia6 shows best agreement



LHC
LHCb
ATLAS
CMS
ALICE