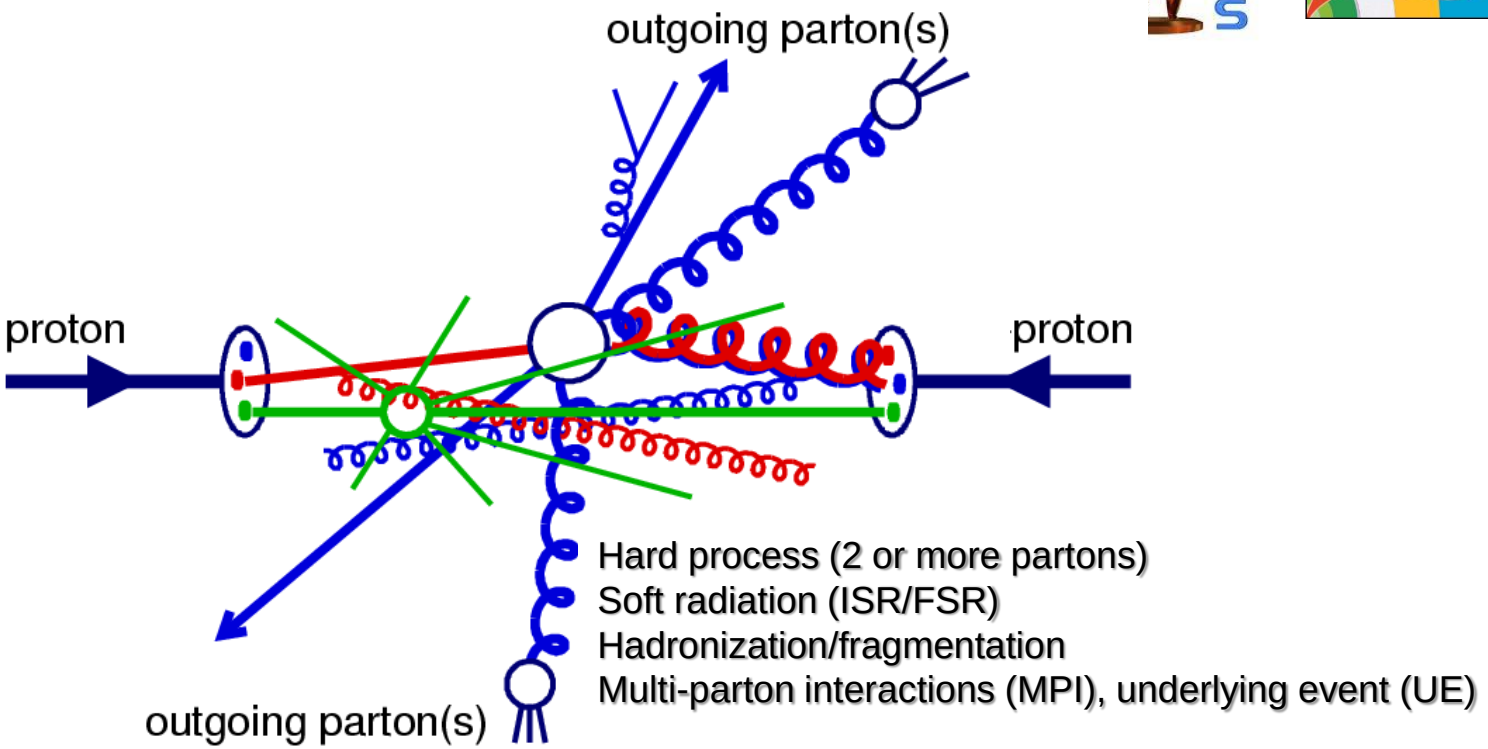
QCD Results from ATLAS and CMS

Emanuela Barberis
Northeastern University



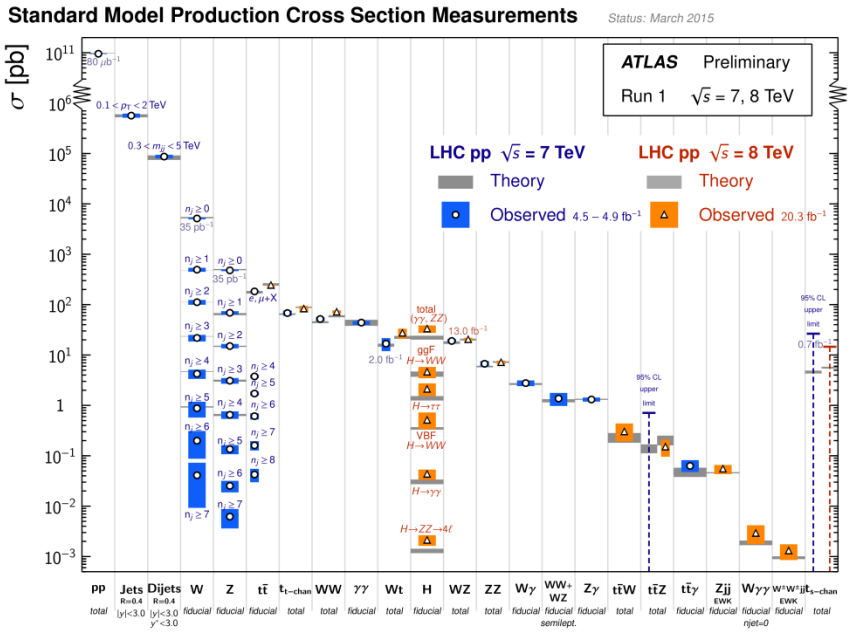
DPF2015, Ann Arbor MI, 4-8 August 2015

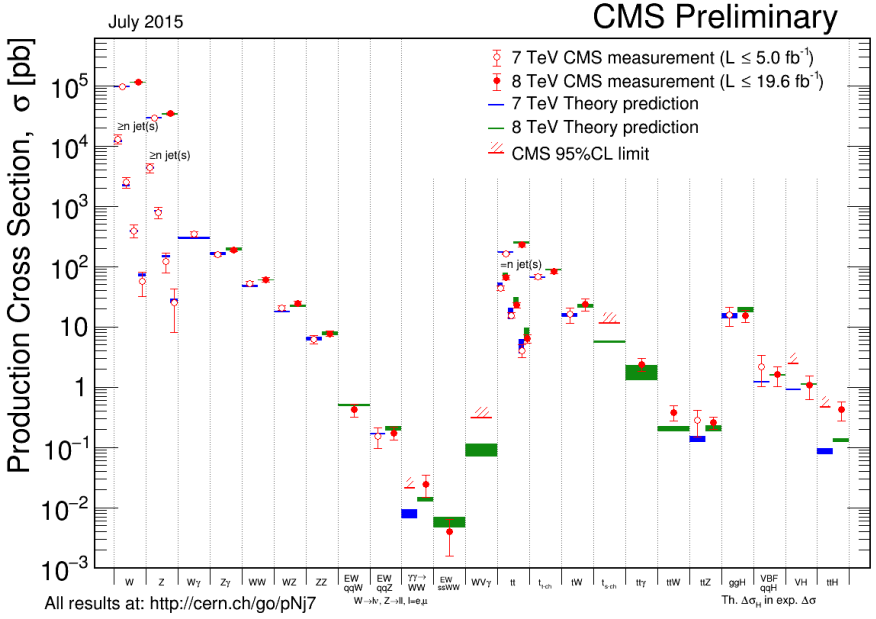
Introduction

A precise understanding of perturbative and soft QCD measurements at hadron colliders is essential for:

- ✓ extracting fundamental parameters of the SM (α_S)
- ✓ testing perturbative QCD theory predictions at the highest scales
- ✓ tuning MC generators and modeling of soft QCD effects
- ✓ constraining parton distribution functions and probing strange, heavy flavour, and gluon content in proton
- ✓ modeling backgrounds to rare SM and beyond SM signatures

Measurements test processes over several orders of magnitude in cross section:





Recent QCD measurements

Jet Physics

- Inclusive jet cross sections, 2-jet, 3-jet cross sections
- Extraction of α_s
- Dijet azimuthal decorrelations
- Double Parton Scattering (2 b- + 2-jets)
- Jet charge

Vector boson plus jets

- Differential V(W,Z) + jets and ratio
- W/Z + b(b)-jet
- W + charm

Inputs to PDFs

Photon(s) + jets

- Prompt di-photon

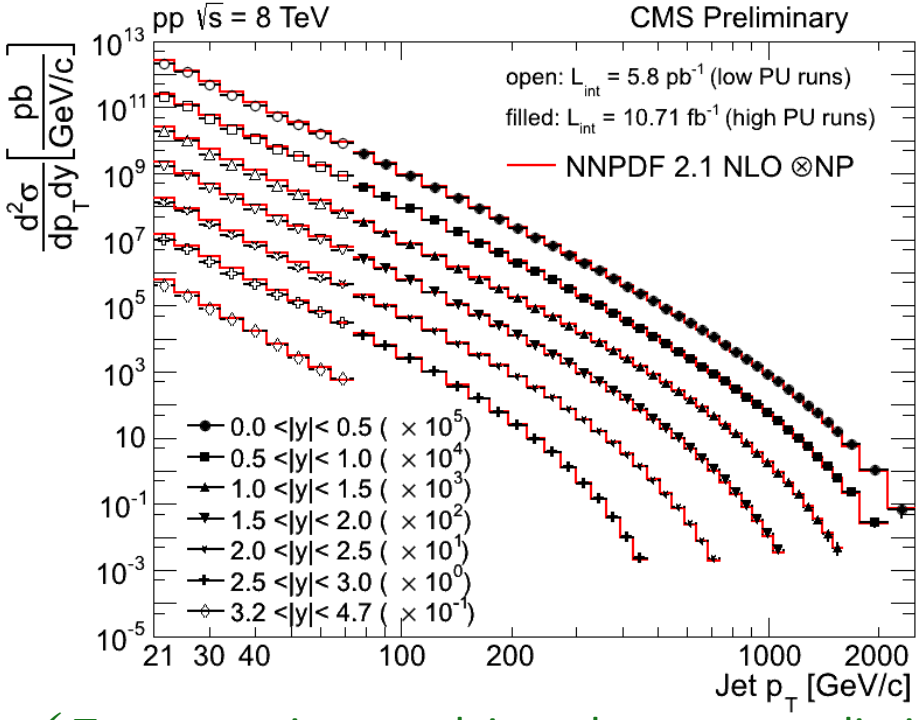
Soft QCD

- Soft particle emission
- Underlying Event
- Two particles Bose Einstein correlations

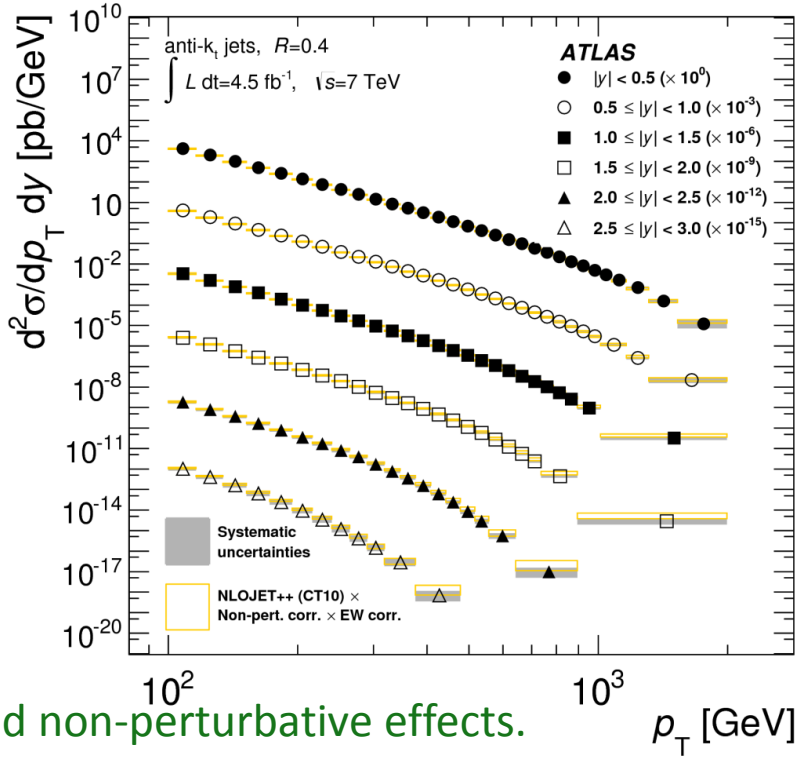
Jet Production

Inclusive jets cross-section: double differential (p_T, y) measurement over 11 orders of magnitude - from 20 GeV to 2.5 TeV – compared with fixed-order NLO calculations (corrected for non perturbative effects) allows for unprecedented test of pQCD predictions.

CMS-PAS-FSQ-12-031, CMS-PAS-SMP-12-012



JHEP02 (2015) 153



- ✓ Two cone sizes used in order to test radiative and non-perturbative effects.
- ✓ Measurements sensitive to PDFs, can be used to constraint PDFs over a wide (x,Q) range, in particular high-x gluon PDF and valence quark PDFs.
- ✓ Used to extract α_S.
- ✓ Very good agreement with NLO QCD predictions.

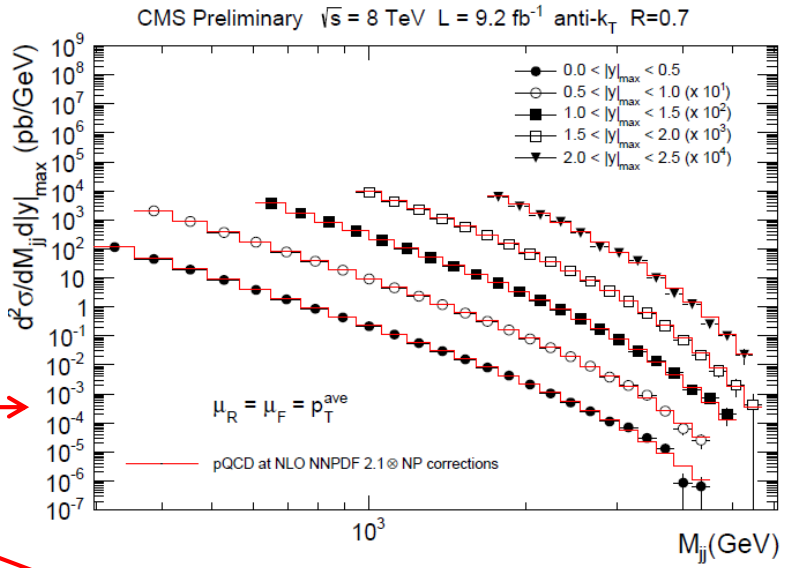
Jet Production

2- and 3-jets differential cross-sections: complementary to the inclusive jet cross section, sensitive to different sub-processes and overlapping (x,Q) regions in PDFs.

- ✓ Used to constraint PDFs
- ✓ Used to extract α_S.
- ✓ Very good agreement with NLO.

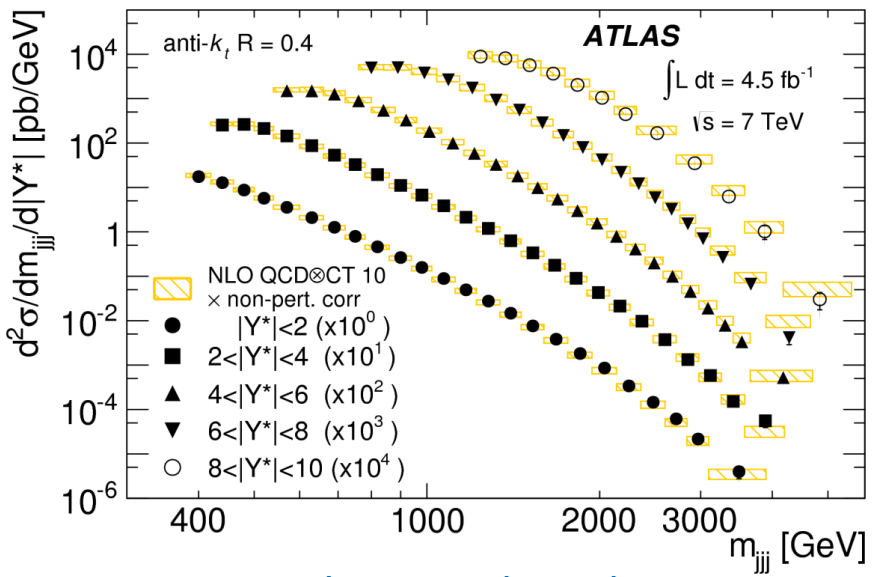
CMS-PAS-SMP-14-002

2-jets

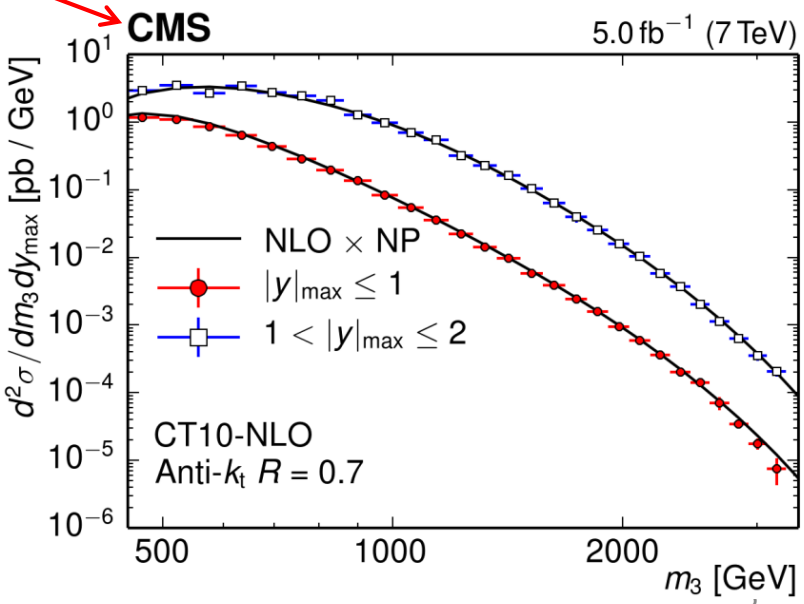


3-jets

$|Y^*| = |y_1 - y_2| + |y_2 - y_3| + |y_1 - y_3|$



Eur. Phys. J. C. (2015) 75

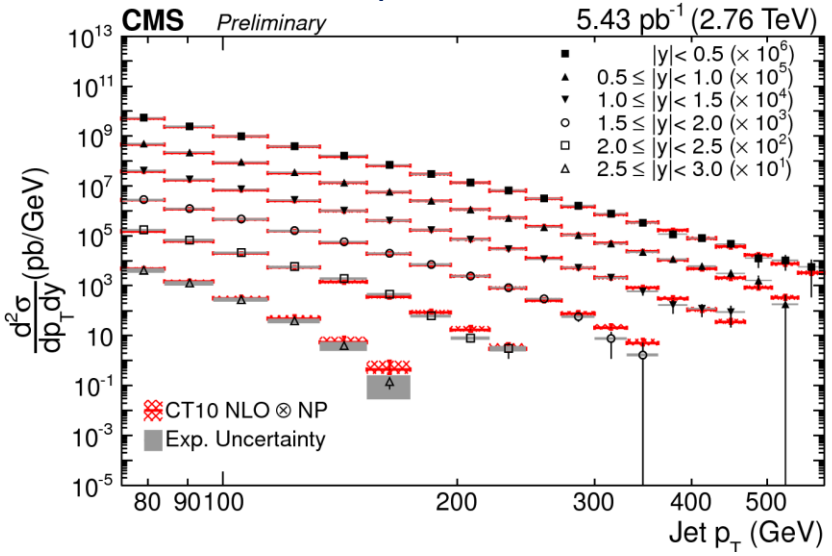


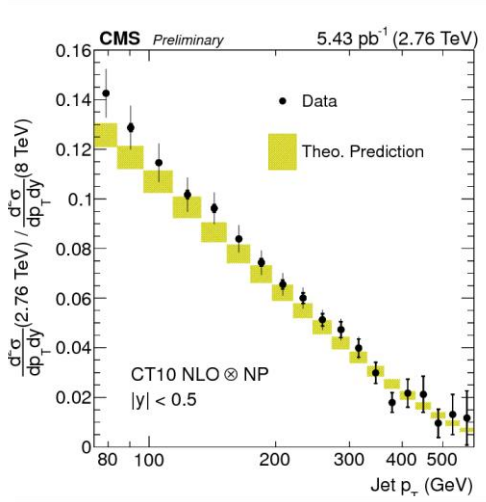
Eur. Phys. J. C 75 (2015) 186

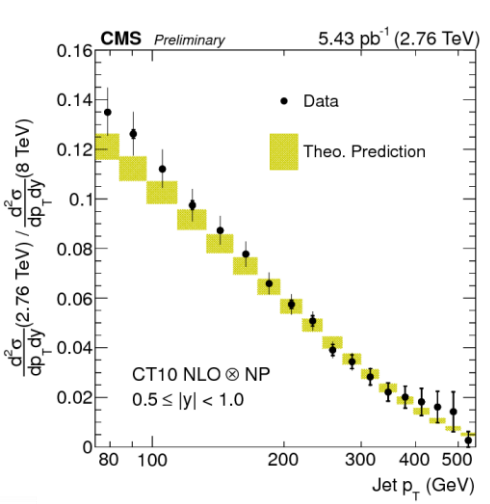
Jet Production

New

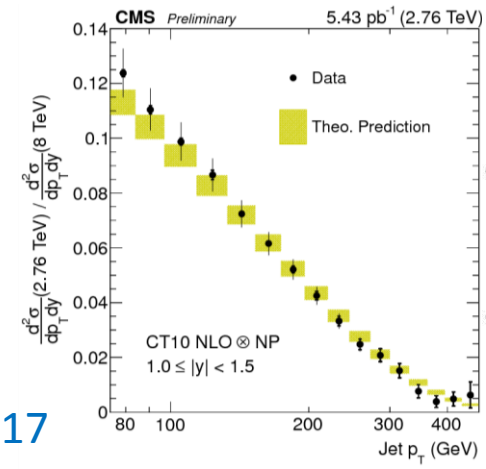
Inclusive jets cross-section at 2.76 TeV (and ratio with 8 TeV): new center-of-mass measurement, partial cancellation of uncertainties in ratio allows for improved accuracy

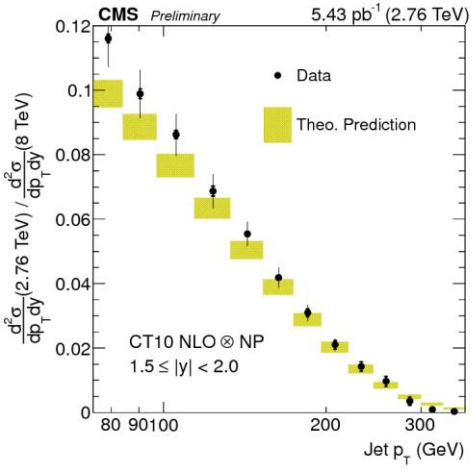


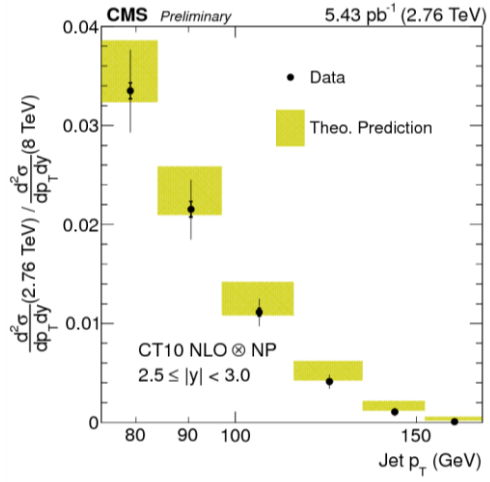




- ✓Agreement with NLO predictions.
- ✓The 2.76 TeV/8 TeV ratio is sensitive to PDFs.





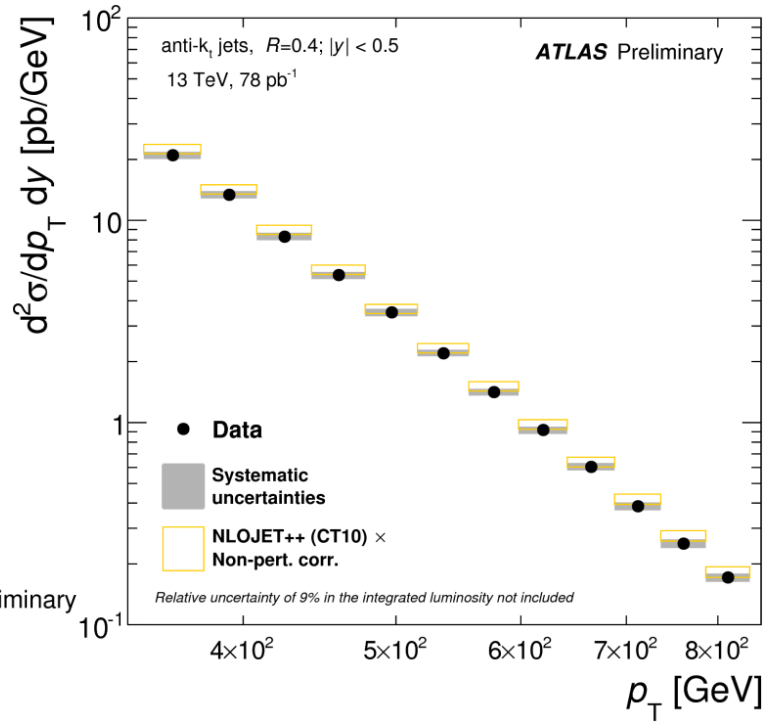


CMS-PAS-SMP-14-017

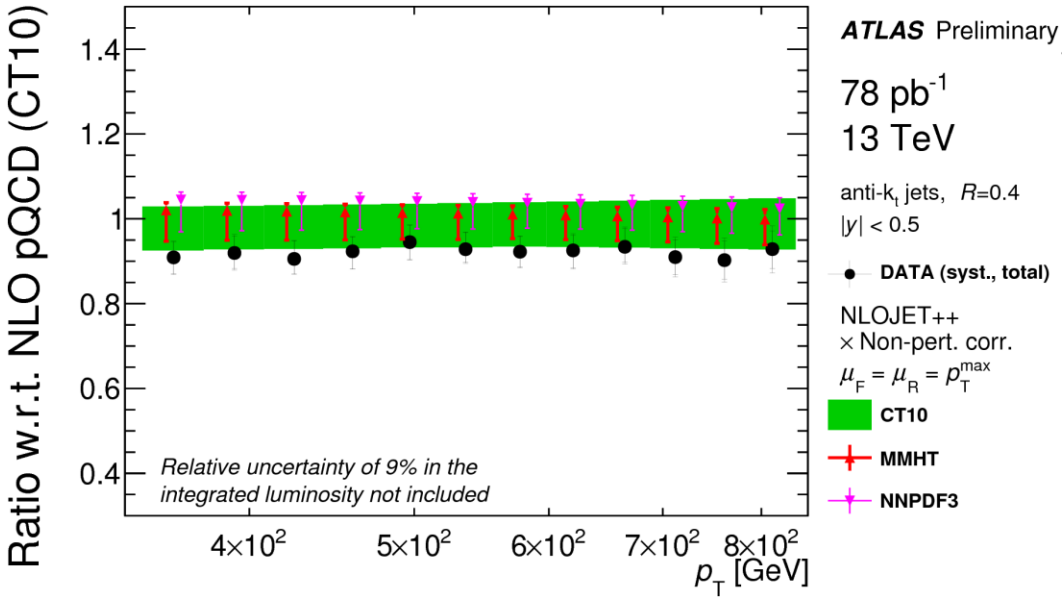
Jet Production

New

Inclusive jets cross-section at 13 TeV:
First results from 78 pb^{-1} of 13 TeV data, central rapidity region.



ATLAS-CONF-2015-034



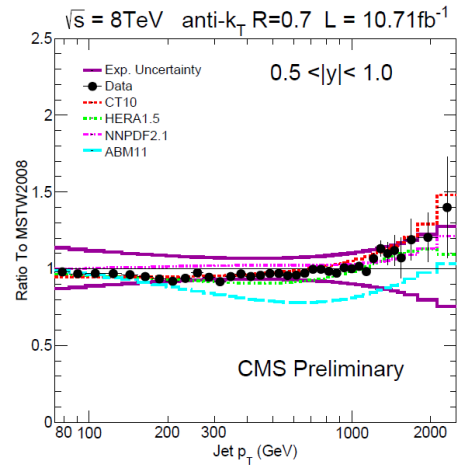
✓Very good agreement with NLO pQCD predictions.

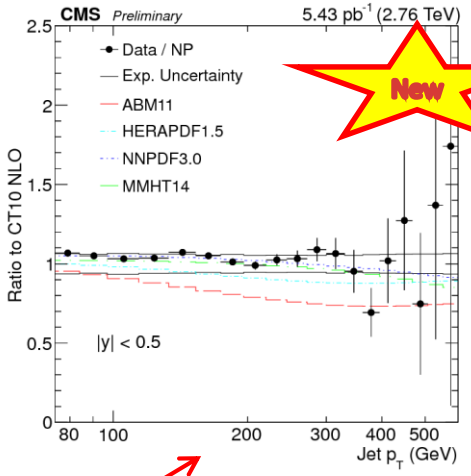
Jet Production

✓Sensitivity to parton distribution functions:

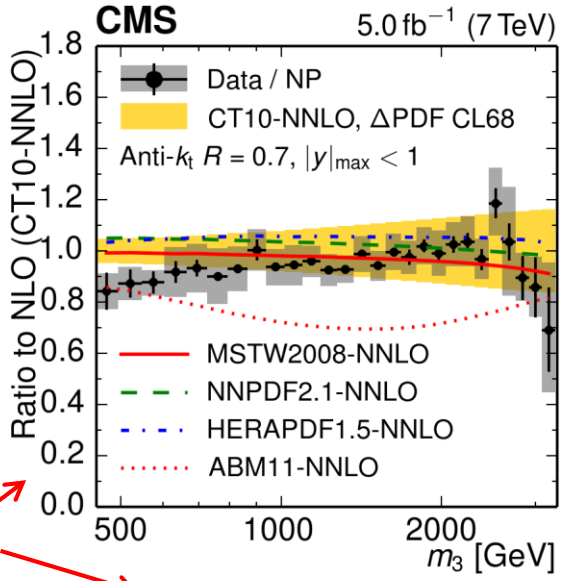
Eur. Phys. J. C 75 (2015) 186

CMS-PAS-FSQ-12-031
CMS-PAS-SMP-12-012





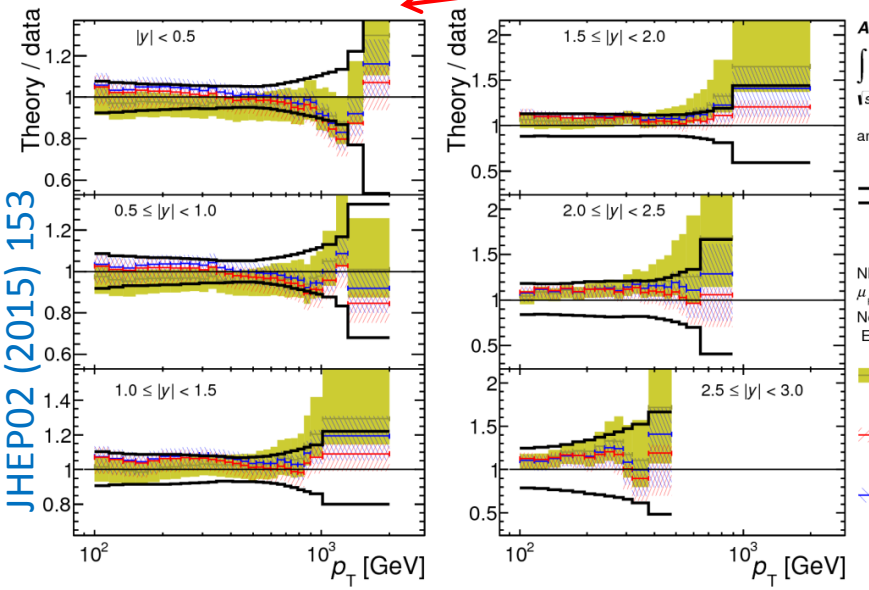
CMS-PAS-SMP-14-017

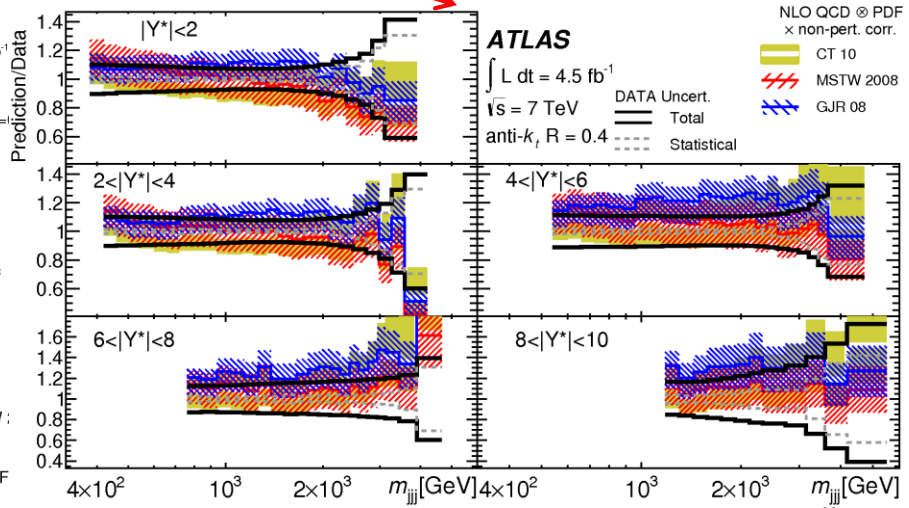


Inclusive Jet

3 Jets

JHEP02 (2015) 153

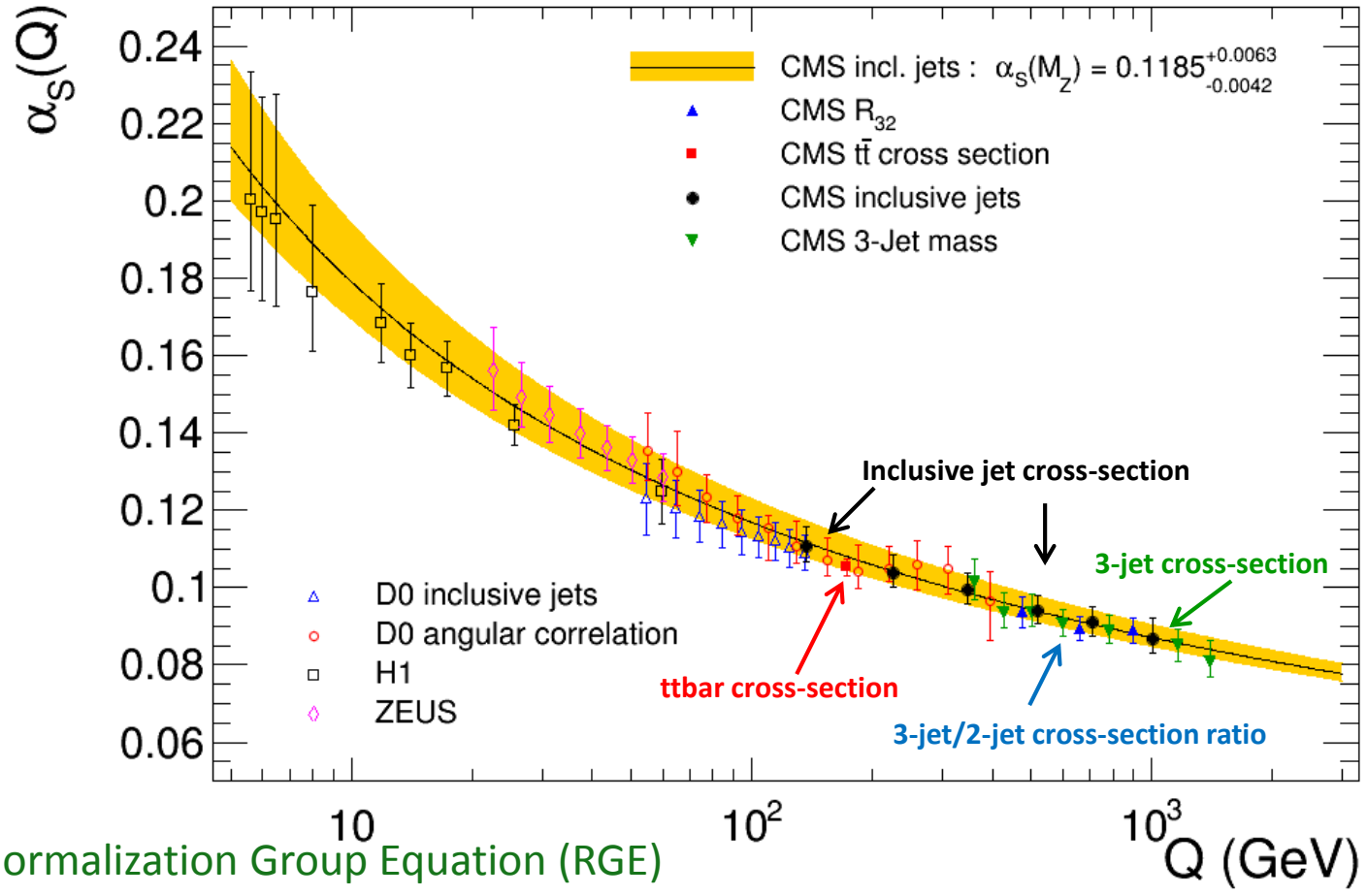




Eur. Phys. J. C. (2015) 75

Measurement of strong coupling α_S

Evolution of strong coupling extracted from different measurements at the LHC up to the TeV scale: α_S is a fundamental parameter in SM, modifications of running at higher scale could occur due to New Physics



Renormalization Group Equation (RGE) relates α_S values at different scales ($Q=p_T$)

Dijet azimuthal decorrelation

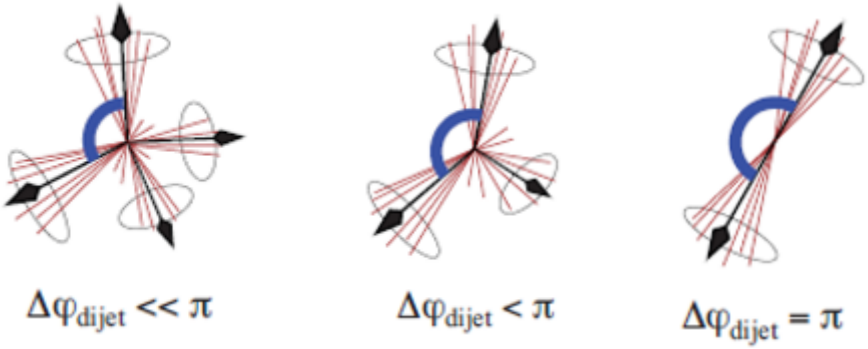
New

Dijet azimuthal decorrelation: normalized differential cross-section in $\Delta\Phi_{dijet}$ of the two leading p_T jets:

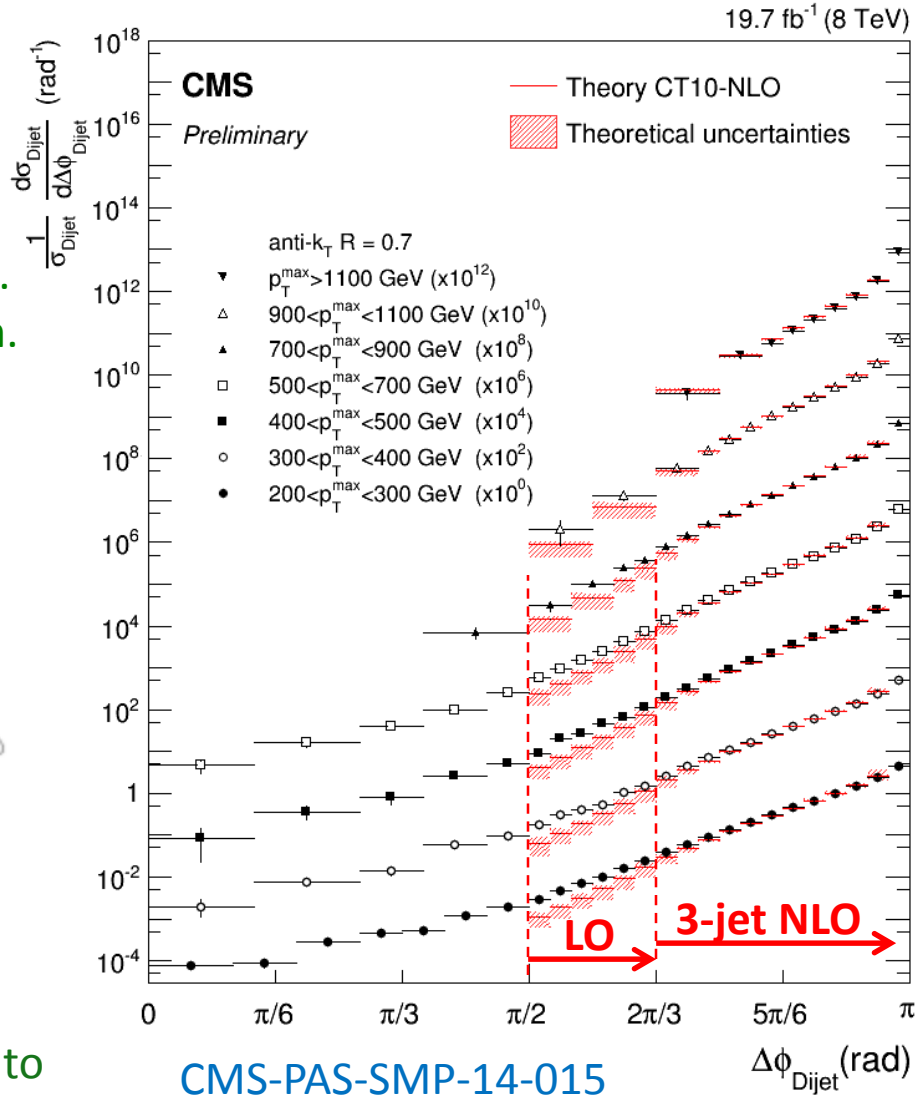
- ✓Sensitive to the radiation of additional jets .
- ✓Probes the dynamics of multijet production.
- ✓Results compared to fixed-order pQCD and to MC generators.

$$\Delta\Phi_{dijet} = |\Phi_{jet1} - \Phi_{jet2}|$$

Decorrelation



$\Delta\varphi_{dijet} << \pi$ $\Delta\varphi_{dijet} < \pi$ $\Delta\varphi_{dijet} = \pi$

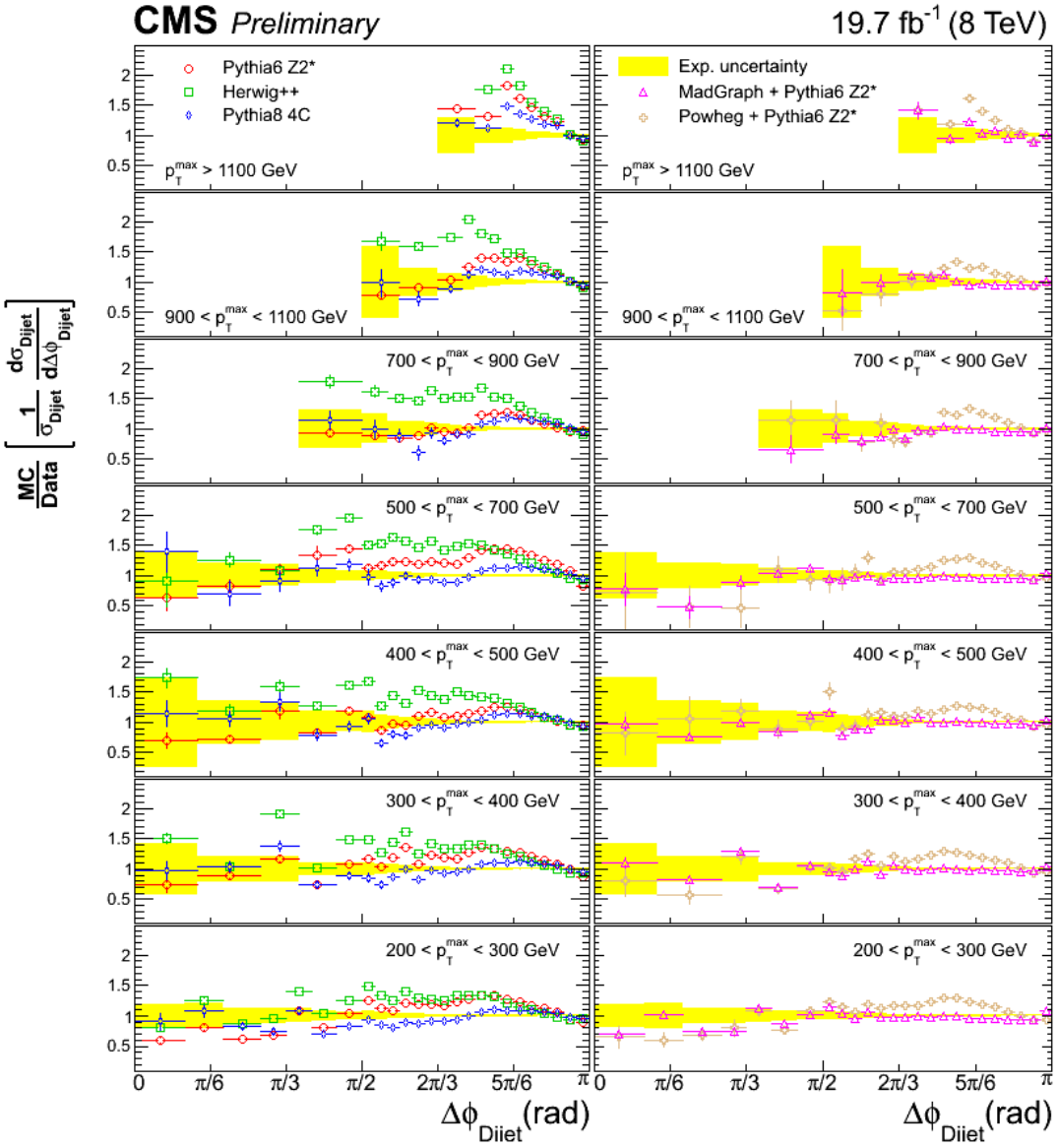


CMS-PAS-SMP-14-015

- ✓Agrees well with 3-jet NLO calculation up to α_S^4 terms (NLOJet++) in NLO-dominated region.

Dijet azimuthal decorrelation

New

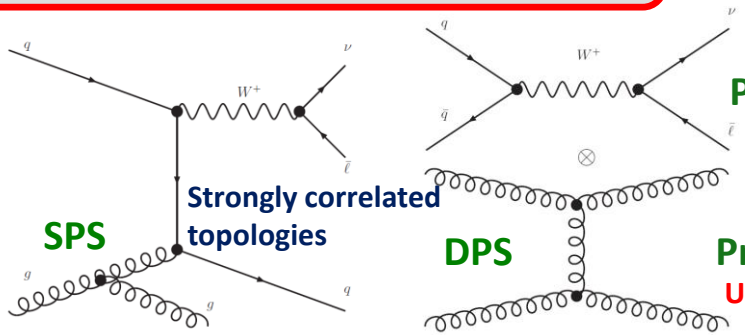


✓Good description from improved multijet MADGRAPH (LO 2→4) interfaced to PYTHIA6 for PS, hadronization, and MPI.

CMS-PAS-SMP-14-015

Double Parton Scattering

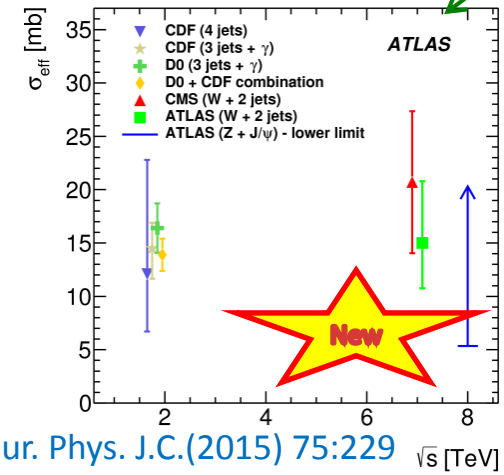
Studies of high p_T final states (e.g. W + 2 jets) with multiple particle interaction overlays: Insight on parton distributions, needed for estimating backgrounds to many rare multijet processes.



$$\sigma^{tot}_{A+B} = \sigma^{SPS}_{A+B} + \sigma^{DPS}_{A+B} = \sigma^{SPS}_{A+B} + \frac{\sigma_A \sigma_B}{\sigma_{eff}}$$

DPS component measured in many different processes.

Recent jet measurement: 2 b- + 2 iets differential cross section



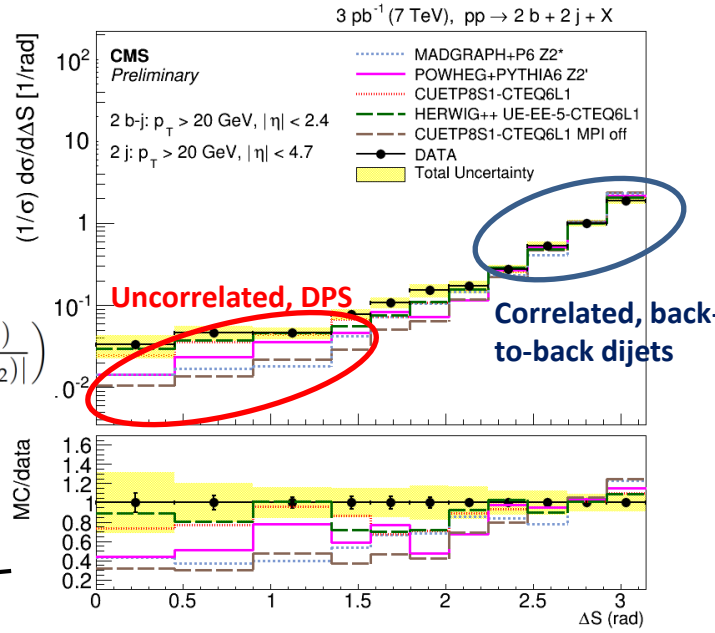
Eur. Phys. J.C.(2015) 75:229

CMS-PAS-FSQ-13-010

✓Using de-correlation observables to isolate DPS

$$\Delta S = \arccos\left(\frac{\vec{p}_T(\text{bottom}_1,\text{bottom}_2)\cdot\vec{p}_T(\text{light}_1,\text{light}_2)}{|\vec{p}_T(\text{bottom}_1,\text{bottom}_2)|\cdot|\vec{p}_T(\text{light}_1,\text{light}_2)|}\right)$$

azimuthal angle between the two dijet pairs



✓Low pileup runs.

✓Calculations can be tested in the heavy flavour scenario.

✓Several correlation variables are analyzed (ΔS being the most sensitive to DPS)

✓Not well described by theoretical models using a simulation of the UE tuned to soft MPI.

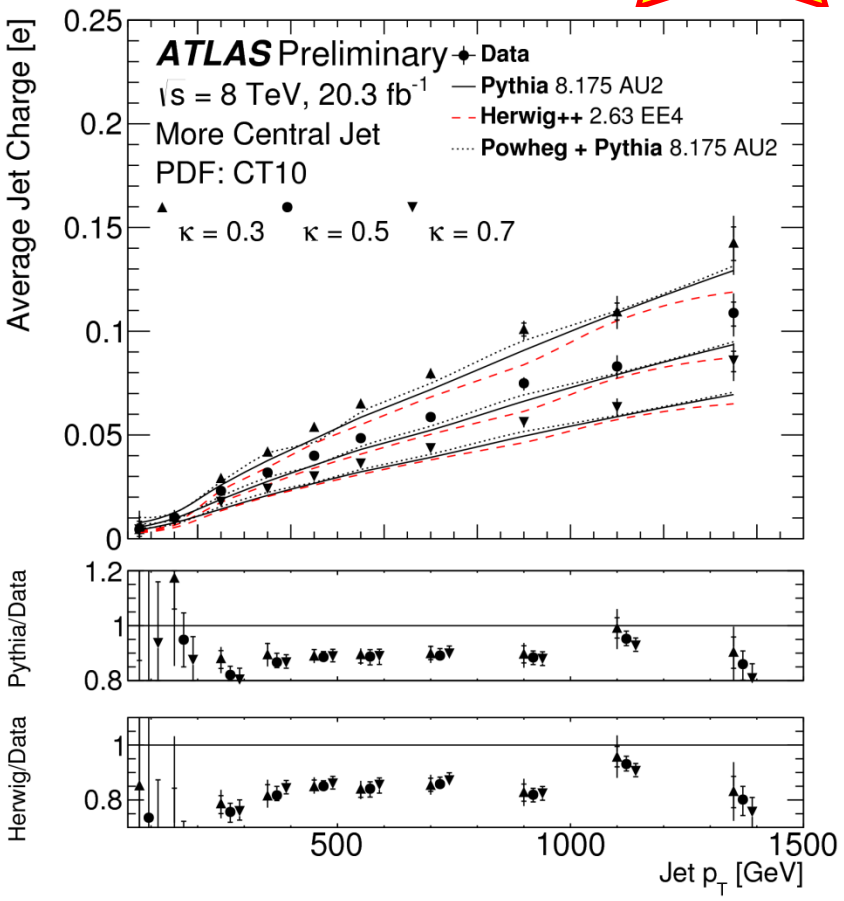
Jet Charge

New

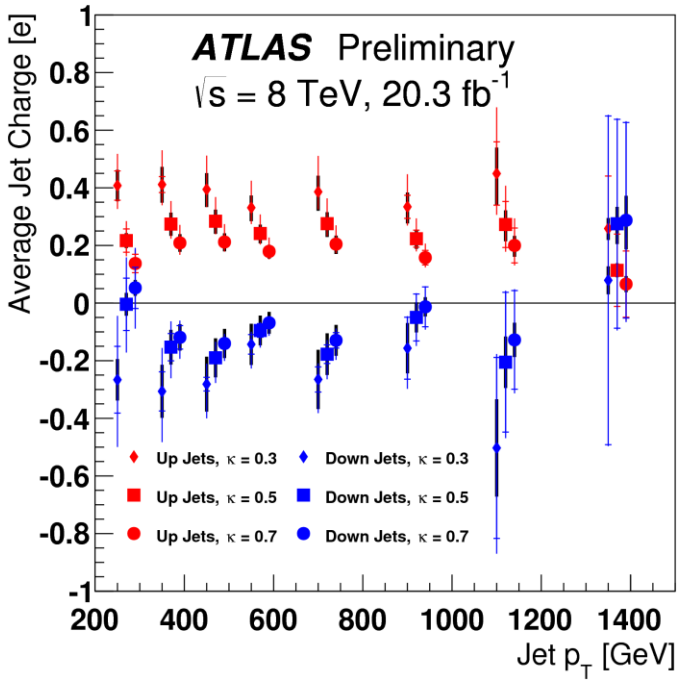
Average jet charge in dijet events: momentum-weighted sum of the charges of tracks in a jet. Sensitive to the charge of the initiating quark or gluon. Scale evolution is sensitive to fragmentation effects, ISR/FSR, and PDFs

✓Jet charge increases with p_T.

✓Data is ~10% larger than MC predictions.



ATLAS-CONF-2015-025

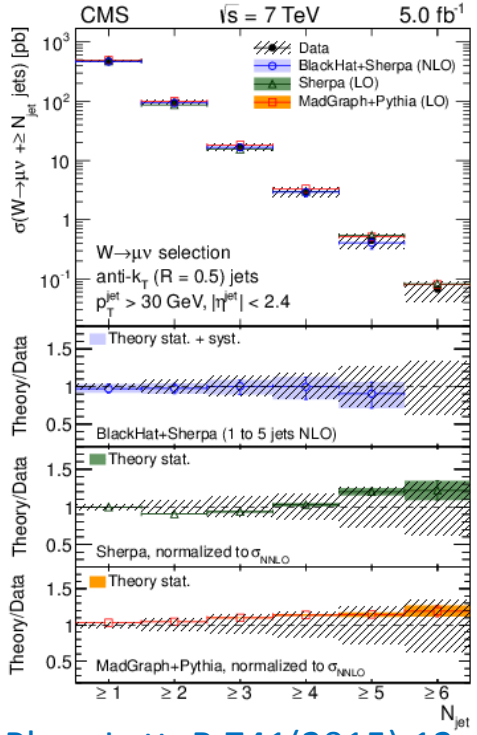


✓Flavor jet charges are extracted using information from PDFs and ME.

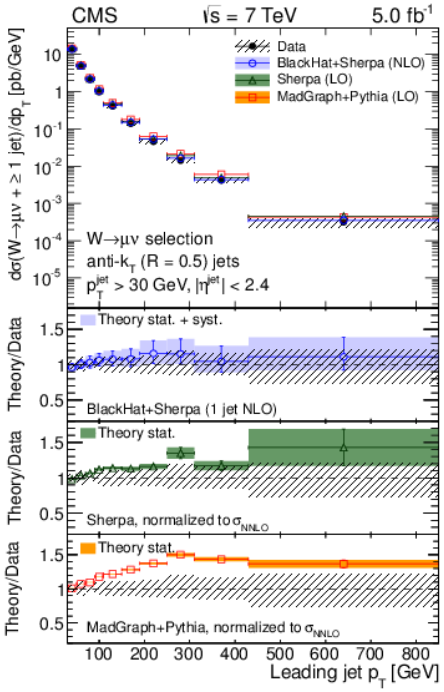
✓ Residual p_T dependence after taking into account PDFs is extracted.

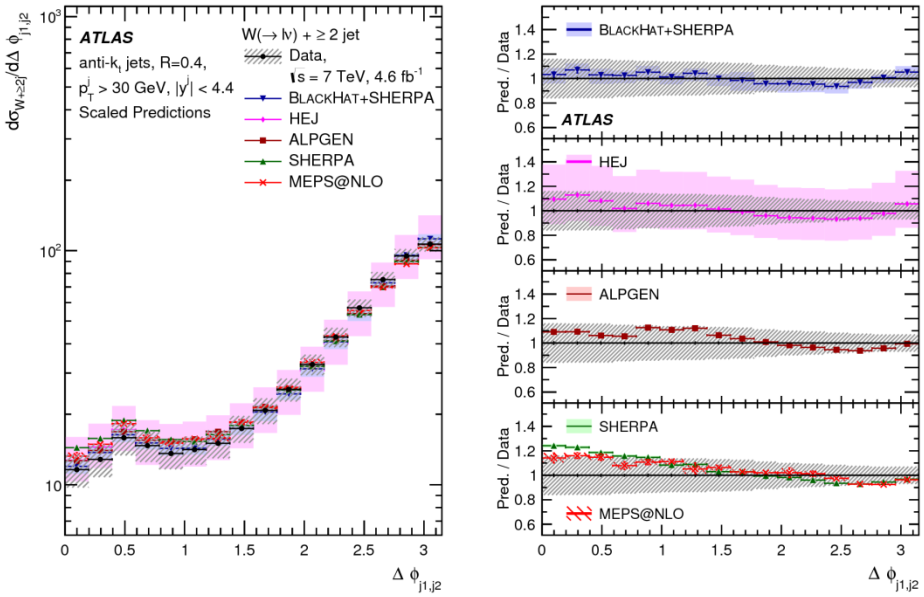
W+jets measurements

Differential V+jets cross section measurement as a function of several kinematic variables: tests of fixed order pQCD calculation and MC generator implementations, Sensitive to higher order effects but also soft QCD effects (particle emission, PS). Backgrounds to top, Higgs measurements and to searches for New Physics.



Phys. Lett. B 741(2015) 12





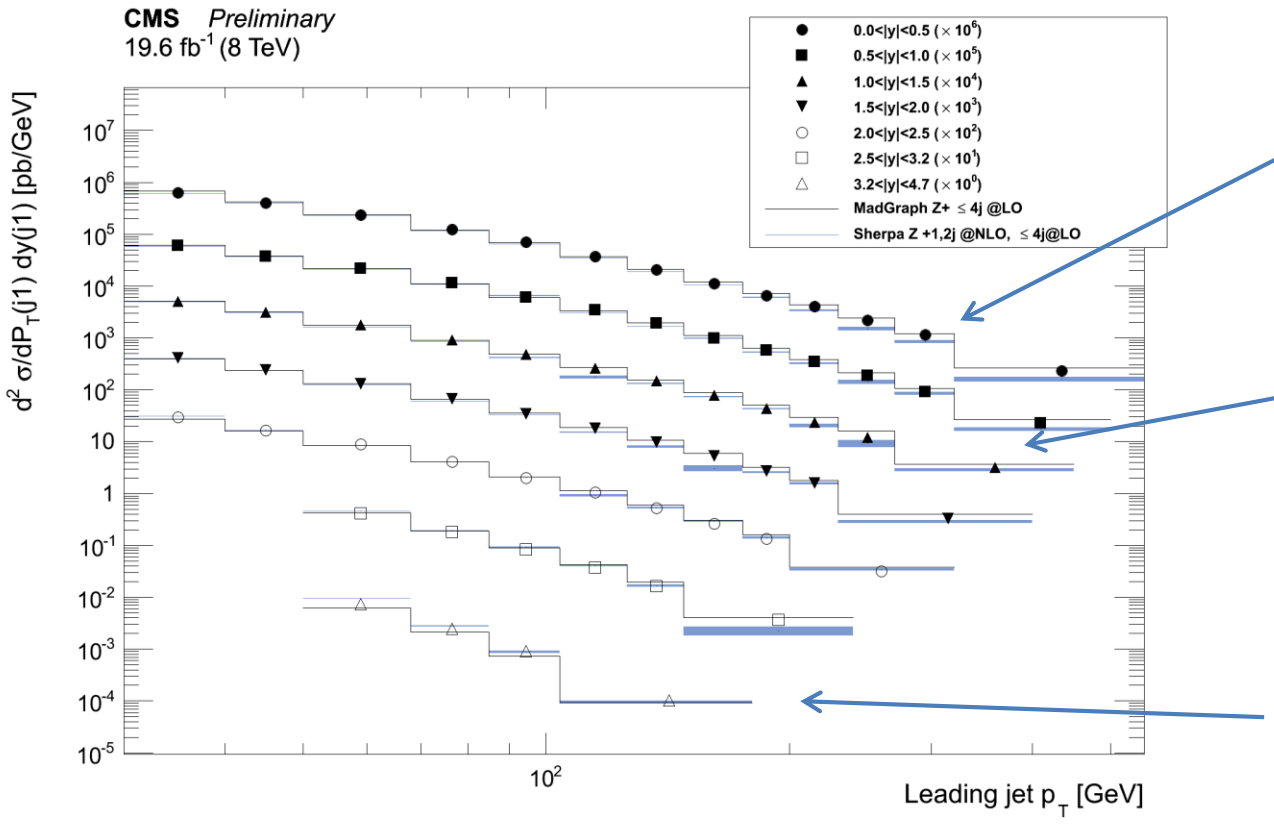
Eur. Phys. J.C.(2015) 75

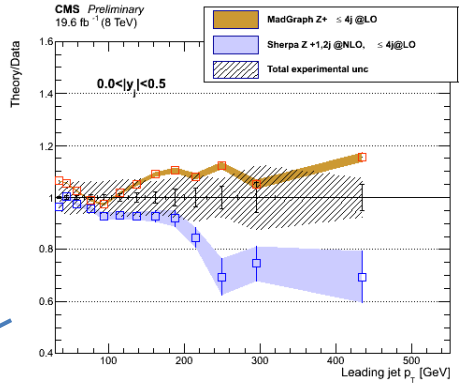
✓Final states with up to 7 jets. Testing NLO theory calculations up to 5 partons.

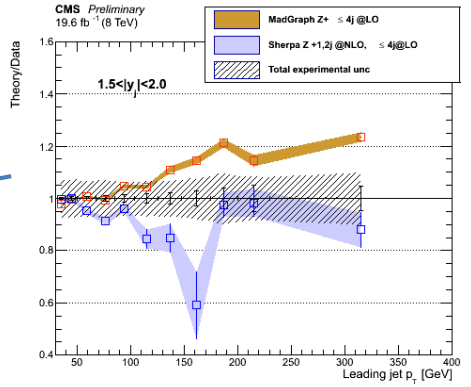
✓ Many advancements in MC generators, e.g.. multileg NLO interfaced with PS

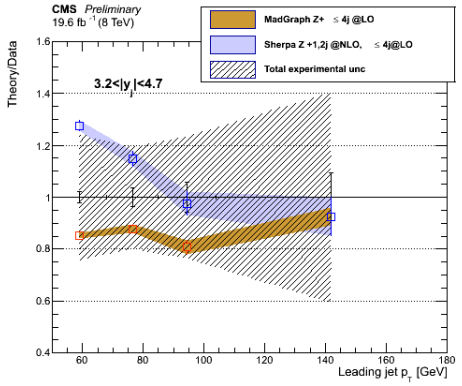
Z+jets measurements

Double differential cross section: first double (y, leading jet p_T) differential measurement.









✓Increased coverage at high rapidities

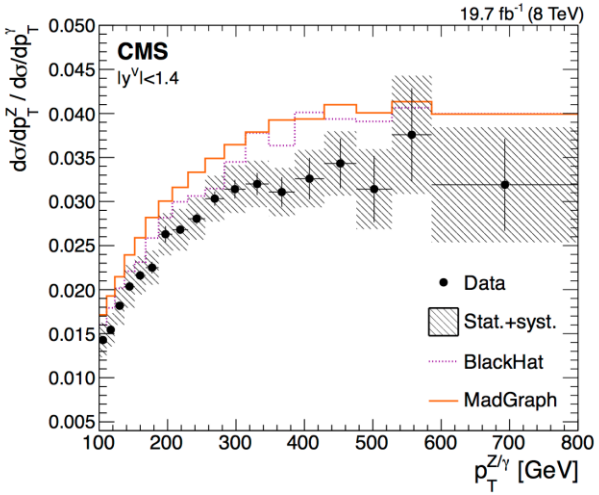
✓Good agreement with MADGRAPH for jet $p_T \leq 100$ GeV.

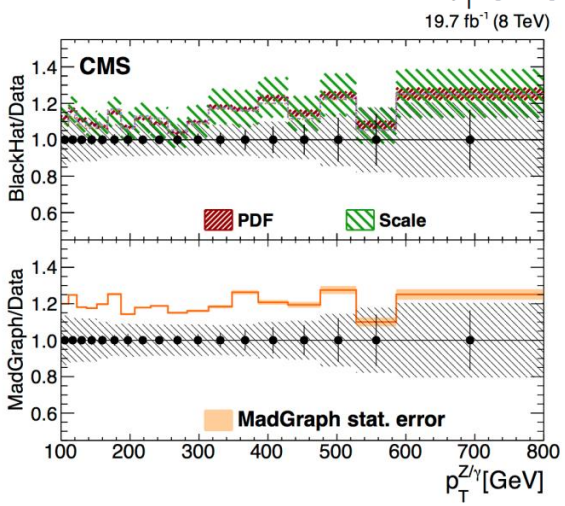
CMS-PAS-SMP-14-009

Z+jets measurements

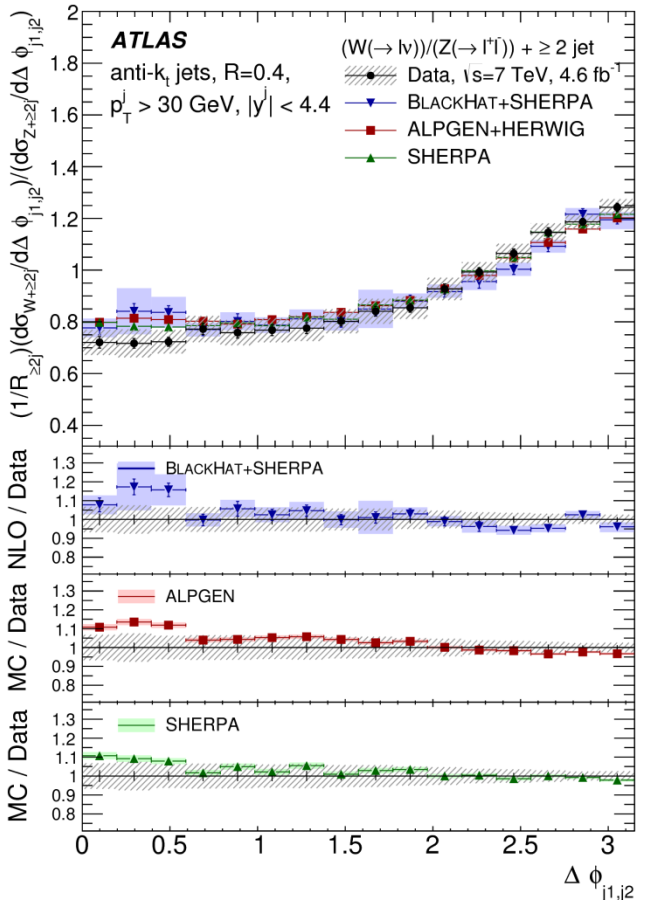
Ratios of differential cross sections (Z+jets / W+jets and Z+jets / γ+jets): experimental and theory uncertainties largely cancel in ratios, allowing accurate tests of differences in PS, radiation, and soft QCD effects

arXiv.1505.06250
Submitted to JHEP





Eur. Phys. J.C.(2014) 74

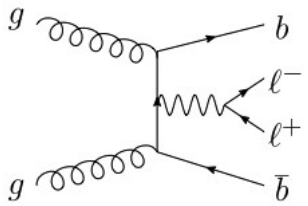


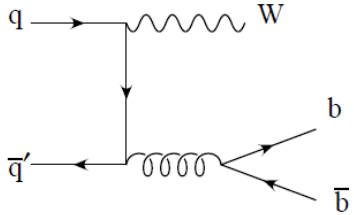
✓Good agreement (with NLO and LO+PS) in shape for Z+jets/γ+jets but ~20% overestimate.

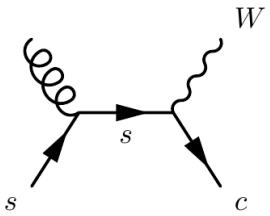
✓Good agreement for Z+jets/W+jets , except for some parts of the parameter space.

W/Z + heavy flavour (HF) jets

Measurements of the Z+b(b), W+bb, W+c processes are crucial for the understanding of SM Higgs VH production, H→bb decays, single top, and searches for new physics

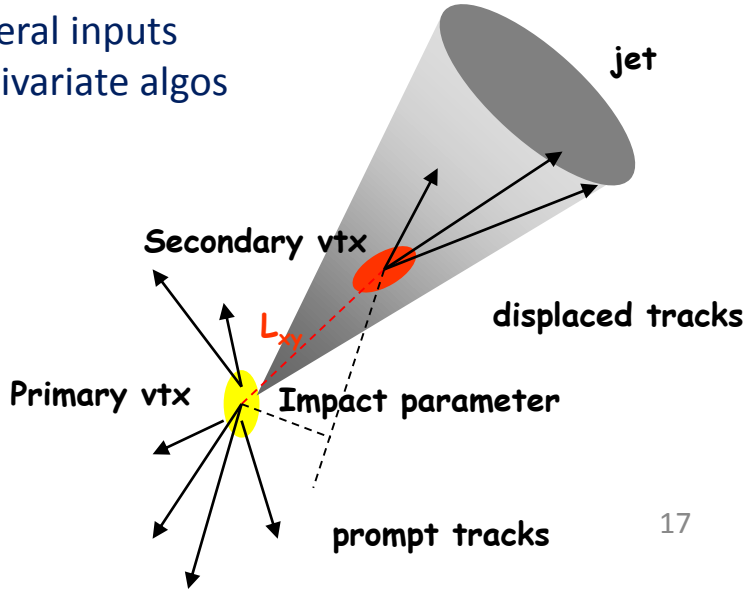






Rely on displaced vertex reconstruction (HF jet tagging) and bottom/charm separation:

- ❖ Signature of a B hadrons decay is a displaced vertex:
  - ✓ Long lifetime of B hadrons ($c\tau$~450μm)+boost
  - ✓ B hadrons travel L_{xy} ~ 3mm before decaying with large charged track multiplicity
  - ✓ improved tagging performance from combining several inputs (displaced vertex, lifetime, jet kinematics) with multivariate algos
- ❖ c-jets and b-jets separation achieved by explicit reconstruction of D mesons or statistical discriminants.



Background levels are higher than for V+light jets channels. Added model uncertainties include choice of flavour scheme (FS), quark masses, etc.

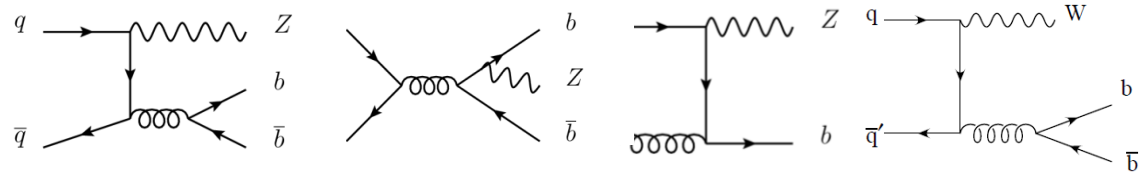
Z/W + b(b)

Z+b(b) and Wbb cross sections:

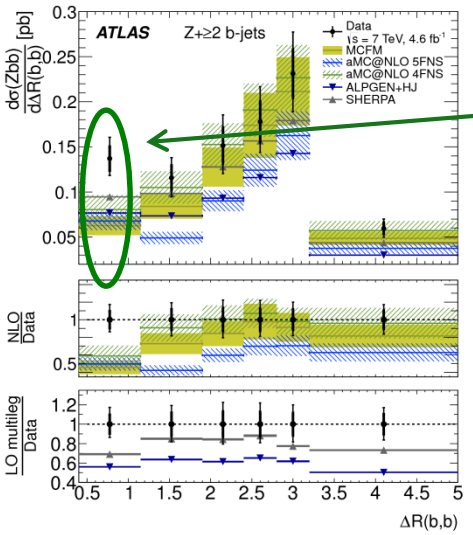
Z+bb sensitive to gluon splitting,

Z+b can probe b-quark PDF,

W+bb important background to Higgs and BSM searches.

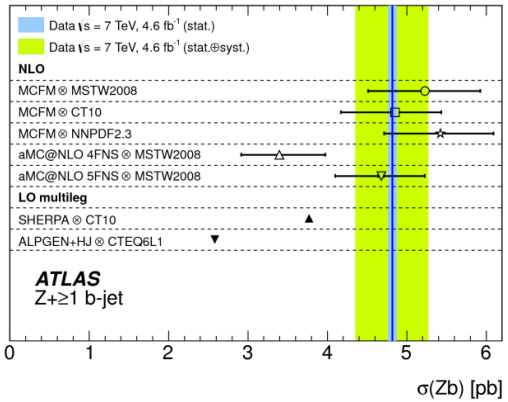


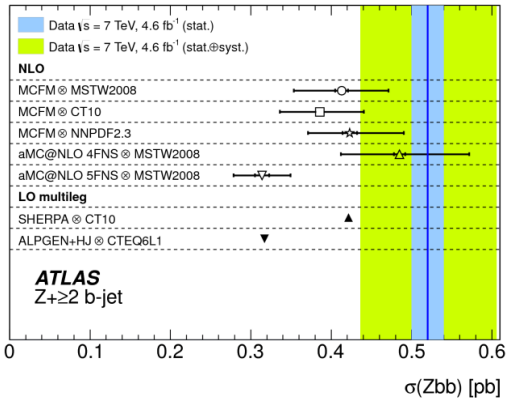
JHEP 10 (2014) 141



✓Good agreement with NLO predictions

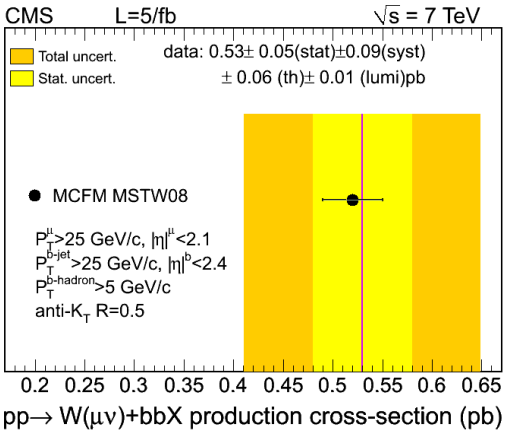
✓ Kinematic discrepancy for nearby jets (gluon splitting)

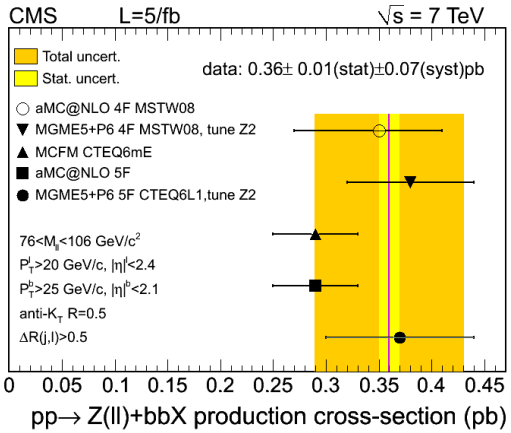


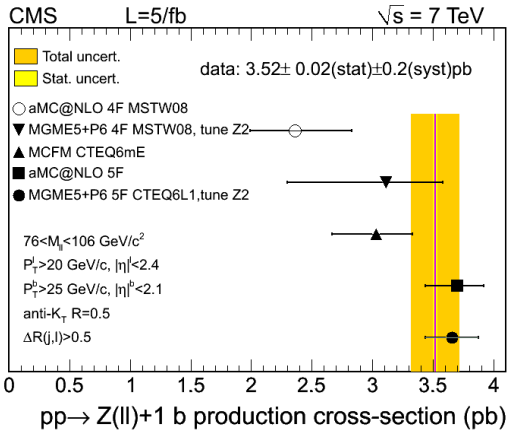


PLB 735 (2014) 204

JHEP 06 (2014) 120

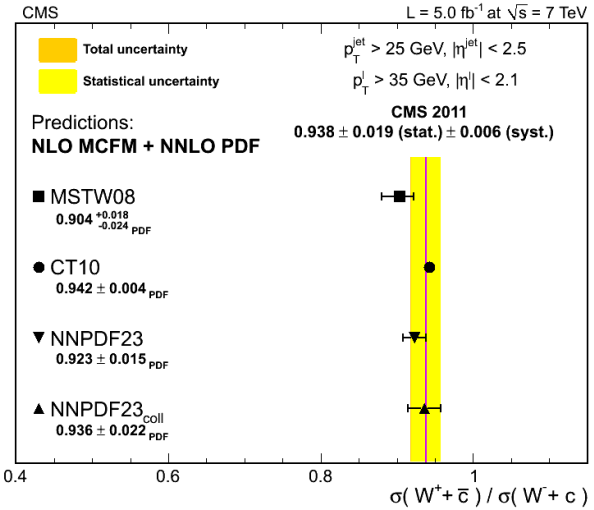


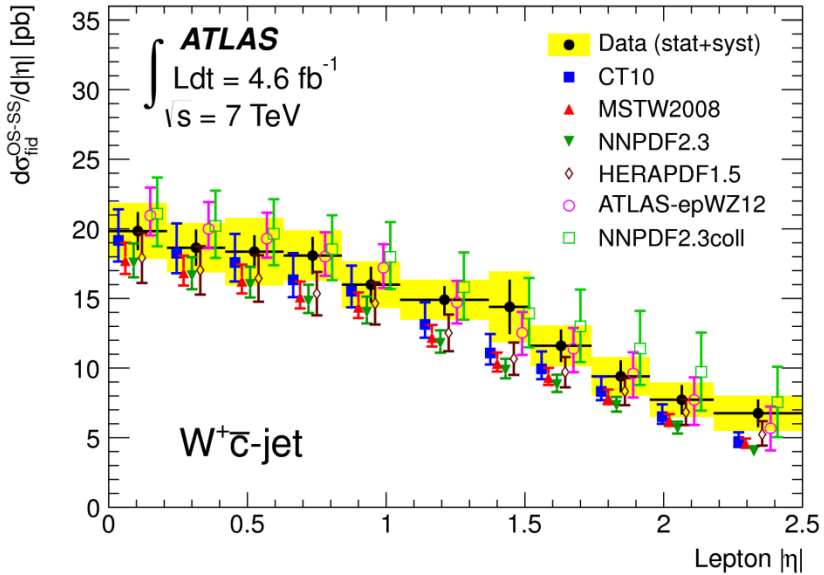




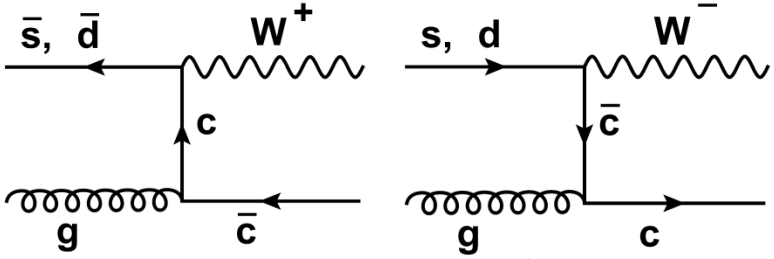
W+c

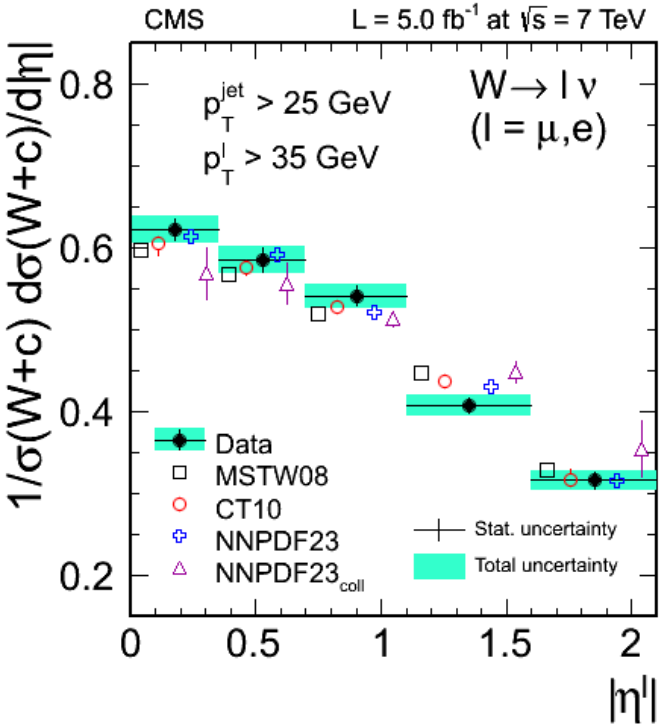
W+c cross-section: W^+/W^- ratio and differential cross sections, measurements sensitive to the strange quark content of the proton





JHEP 05 (2014) 068





JHEP 02 (2014) 13

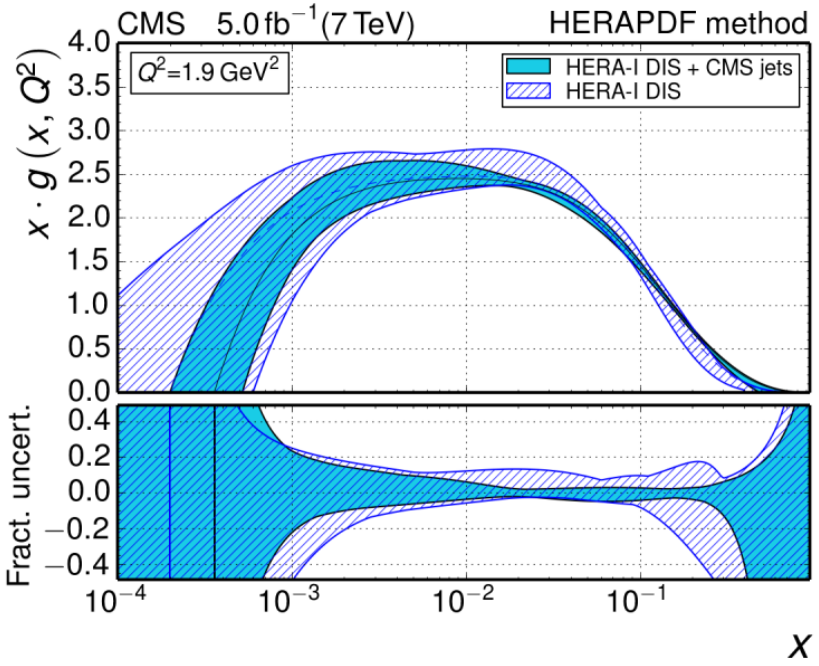
✓Good agreement with NLO predictions.

✓ Measurements allow to test strange quark component of PDFs.

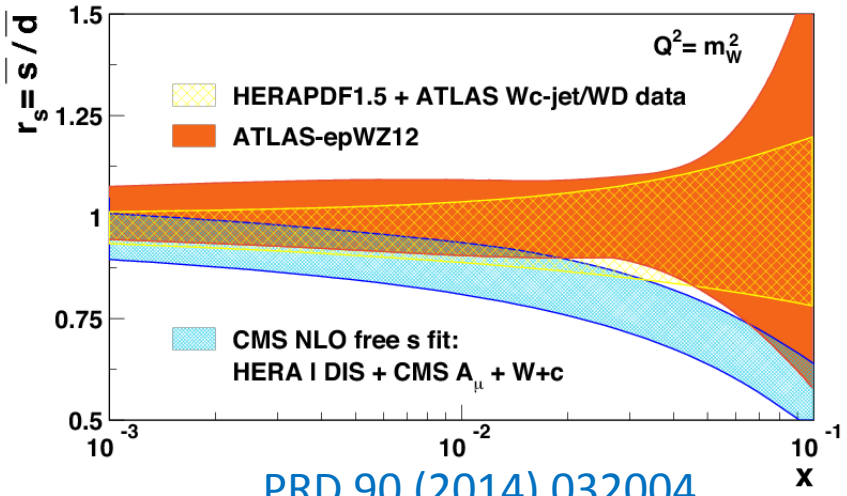
Inputs to PDFs

ATLAS and CMS inputs to PDFs:

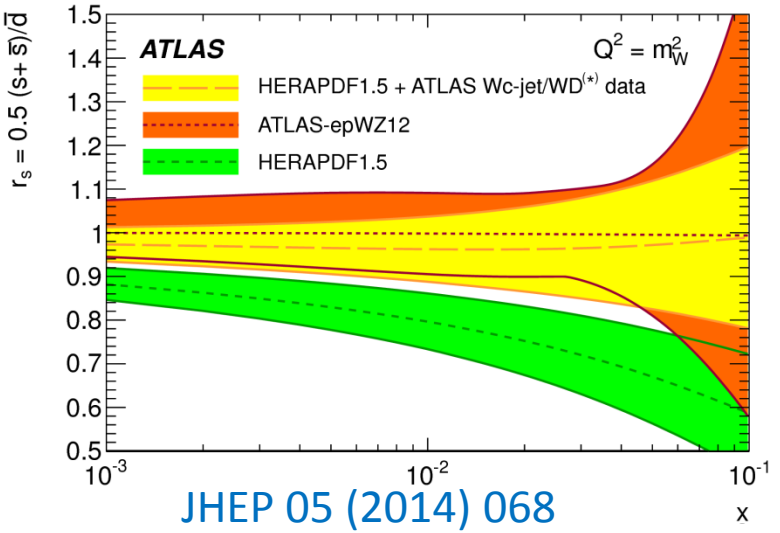
- ✓ Inclusive jet measurements improve description of gluon PDF at medium/large x.
- ✓ W+charm measurements constrain strange quark PDF.



Eur. Phys. J. C 75 (2015) 288



PRD 90 (2014) 032004

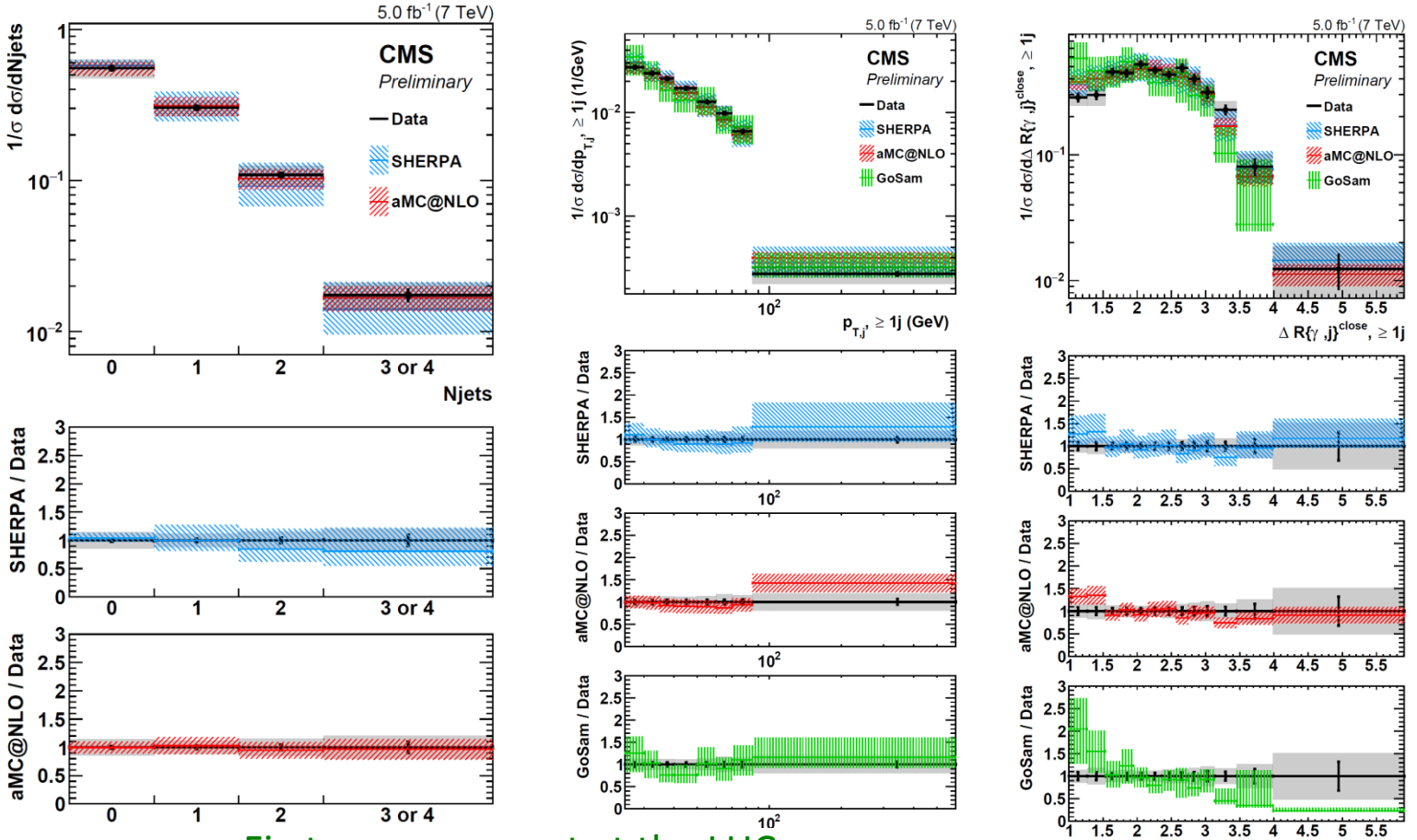


JHEP 05 (2014) 068

γγ + jets

New

γγ+jets differential cross section measurement: sensitive to pQCD and non pQCD effects (soft ISR emission, hadronization). Background to VBF production of Higgs →γγ



CMS-PAS-SMP-14-021

✓ First measurement at the LHC.

✓ Good agreement with SHERPA and aMC@NLO.

Soft particle emission

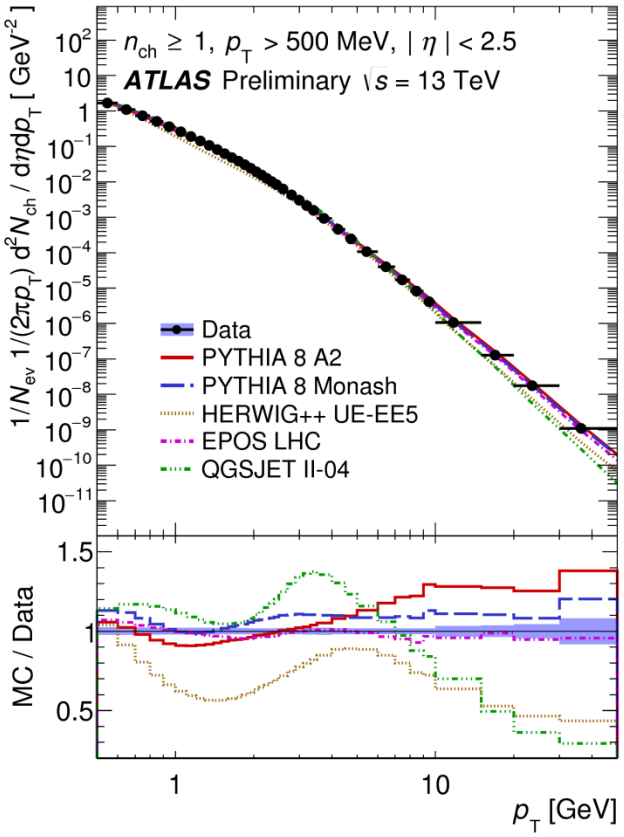
New

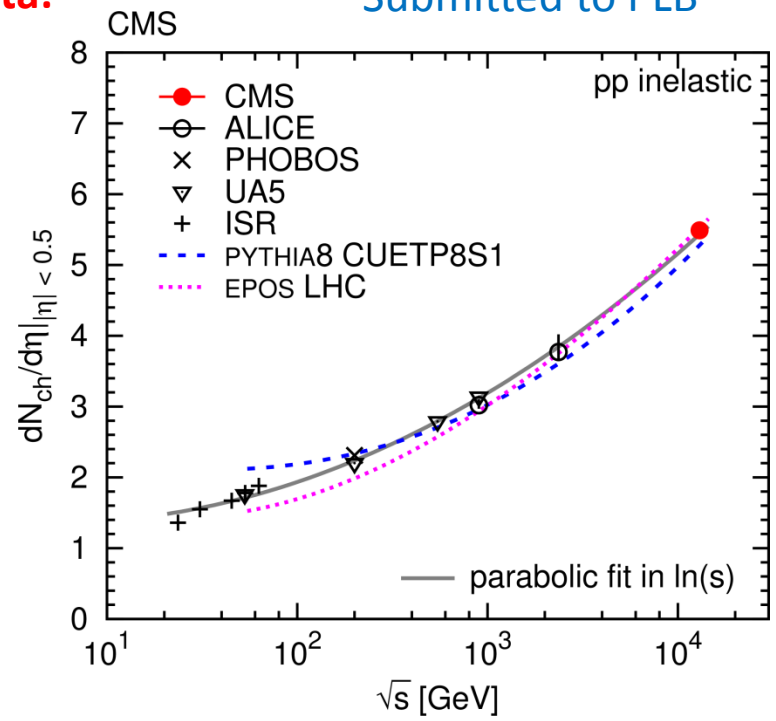
Soft particle emission is measured in data, from charged particle emission in inelastic collisions. Properties of charged particle distributions are used to constraint the modeling of perturbative and non-perturbative QCD aspects in MC generators.

CERN-PH-EP-2015-180
Submitted to PLB

New measurements of N_{ch} with 13 TeV data:

ATLAS-CONF-2015-028

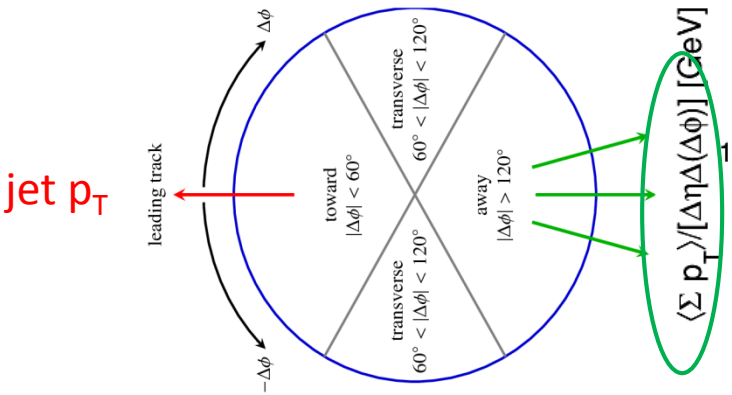


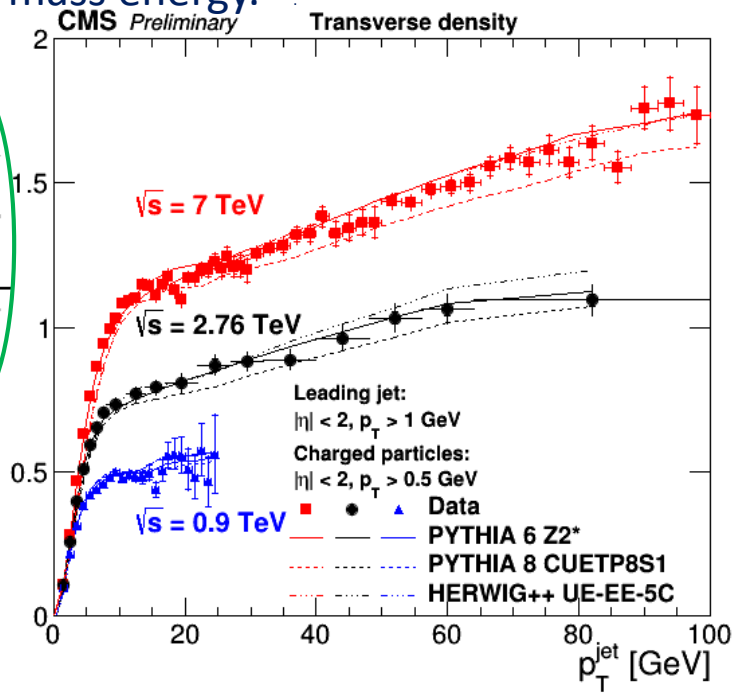


✓ Good agreement with PYTHIA8 and EPOS (with LHC tunes).

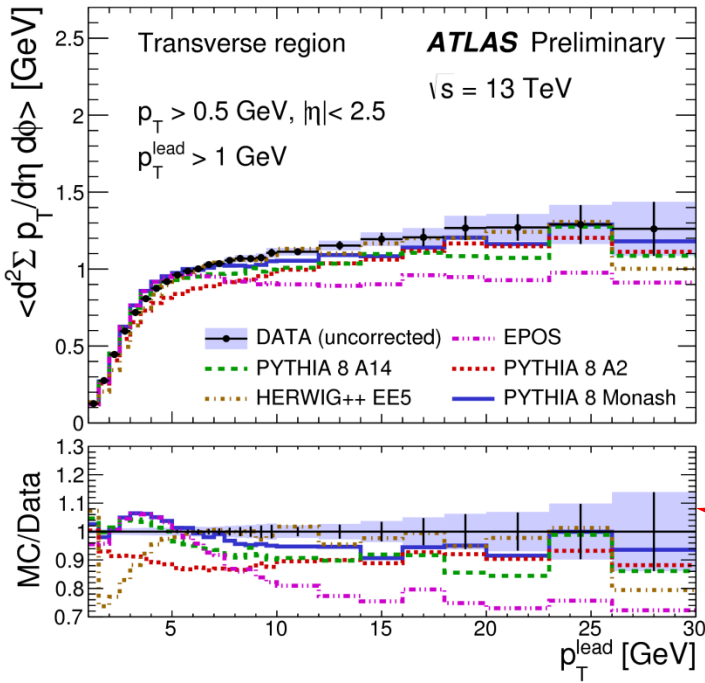
Underlying Event (UE)

Measurements of Σp_T density as a function of leading charged-particle jet p_T: studies of UE activity evolution as a function of center-of-mass energy.





CMS-PAS-FSQ-12-025



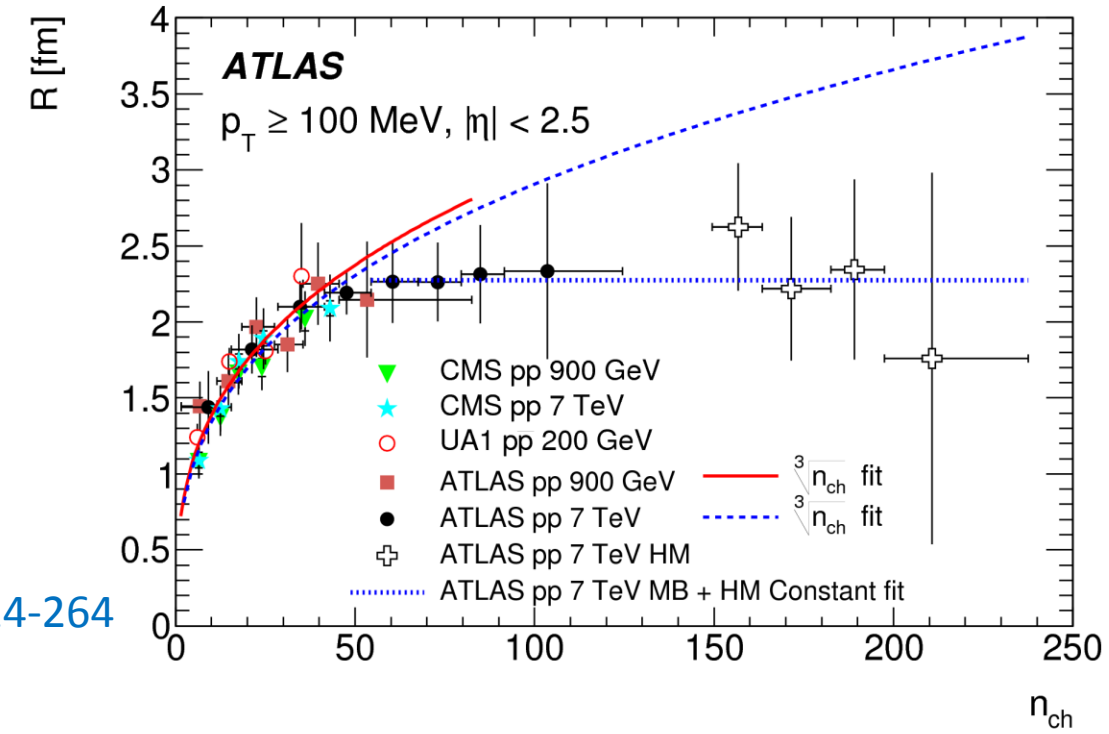
ATL-PHYS-PUB-2015-019

✓Measurements important for the tuning of UE in MC generators.

New

Two particles Bose Einstein Correlation

Measurement of two-particle Bose–Einstein (BEC) correlations of like-sign hadrons: measurement extended to high-multiplicity data samples. Studies of the dependence of BEC on particle multiplicity and transverse momentum help to understand the multiparticle production mechanism.

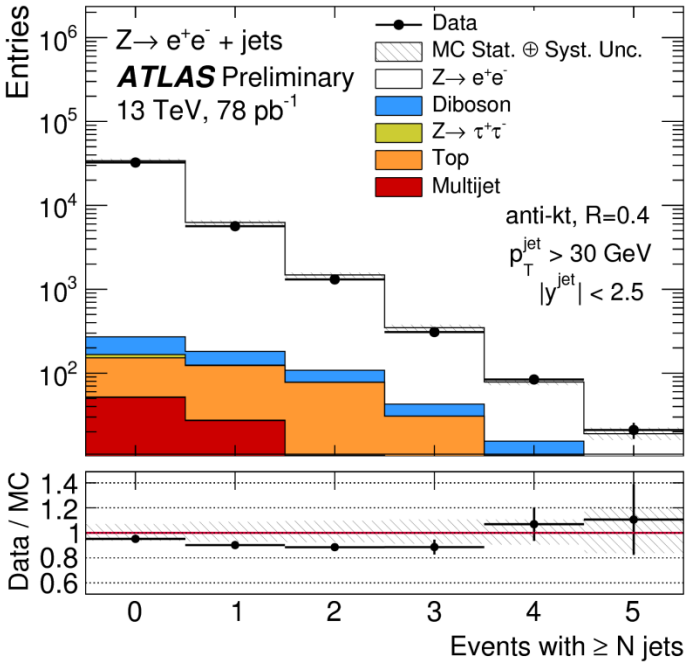


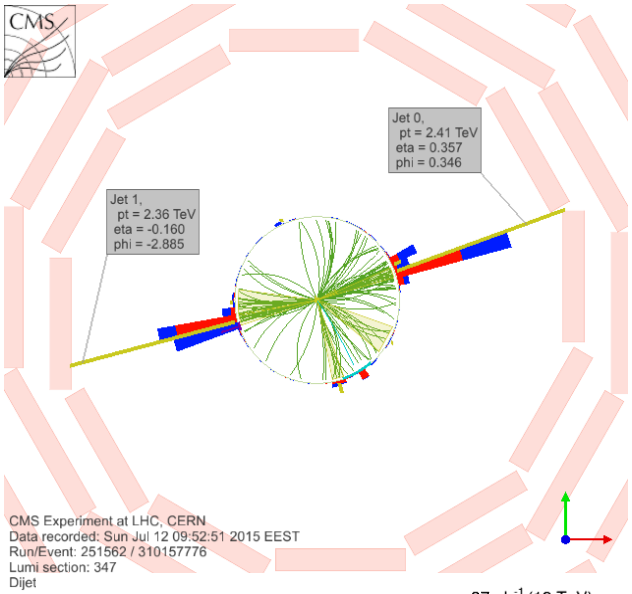
CERN-PH-EP-2014-264

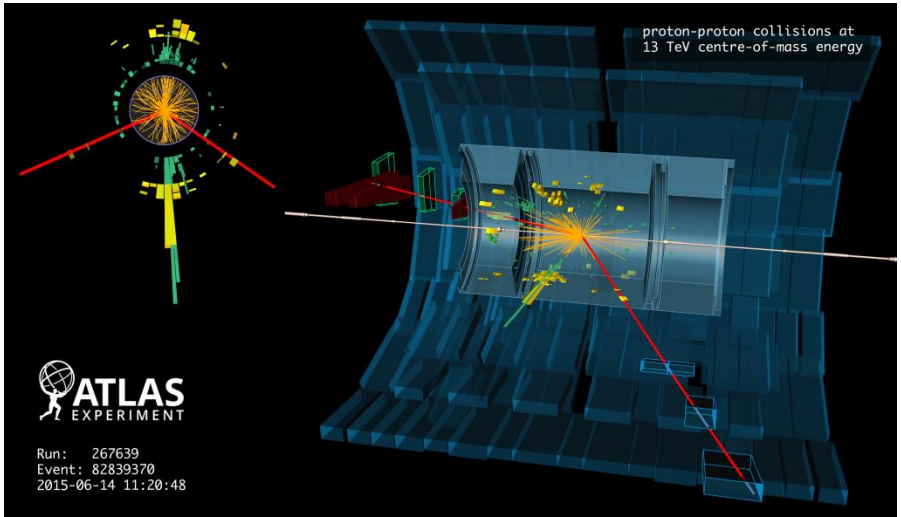
✓A saturation effect in the multiplicity dependence of the correlation source size is observed.

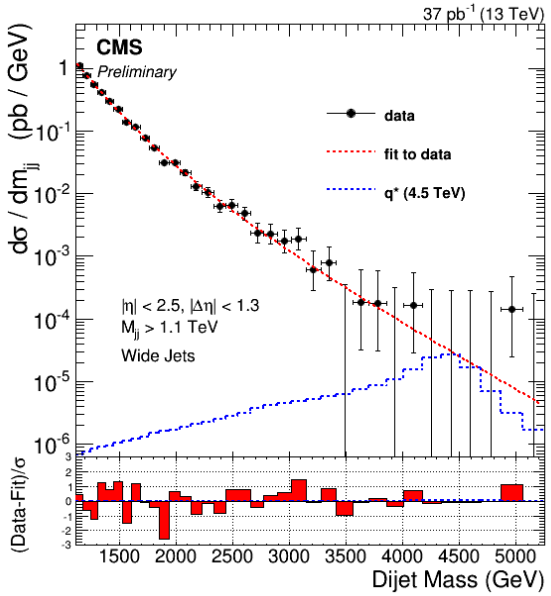
More snapshots of 13 TeV data

ATL-PHYS-PUB-2015-021









CMS DP-2015/17

Conclusions

- ✓ Many results from the LHC experiments are available to probe and constraint pQCD calculations and non-perturbative effects
  - Jet production, V (W/Z/γ) + jet production, multi-particle production.
  - Measurements are providing important inputs to the PDF global fits and to the tuning of MC generators.
  - The strong coupling constant α_S is measured up to the 1 TeV scale.
- ✓ QCD measurements are becoming precision measurements: Experimental accuracy approaching theory uncertainties for parts of the parameter space.
- ✓ Several Run I results still in the pipeline, first results with 13 TeV data emerging.