Hadronic final states in high-pT QCD with the CMS detector

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(On behalf of CMS collaboration)

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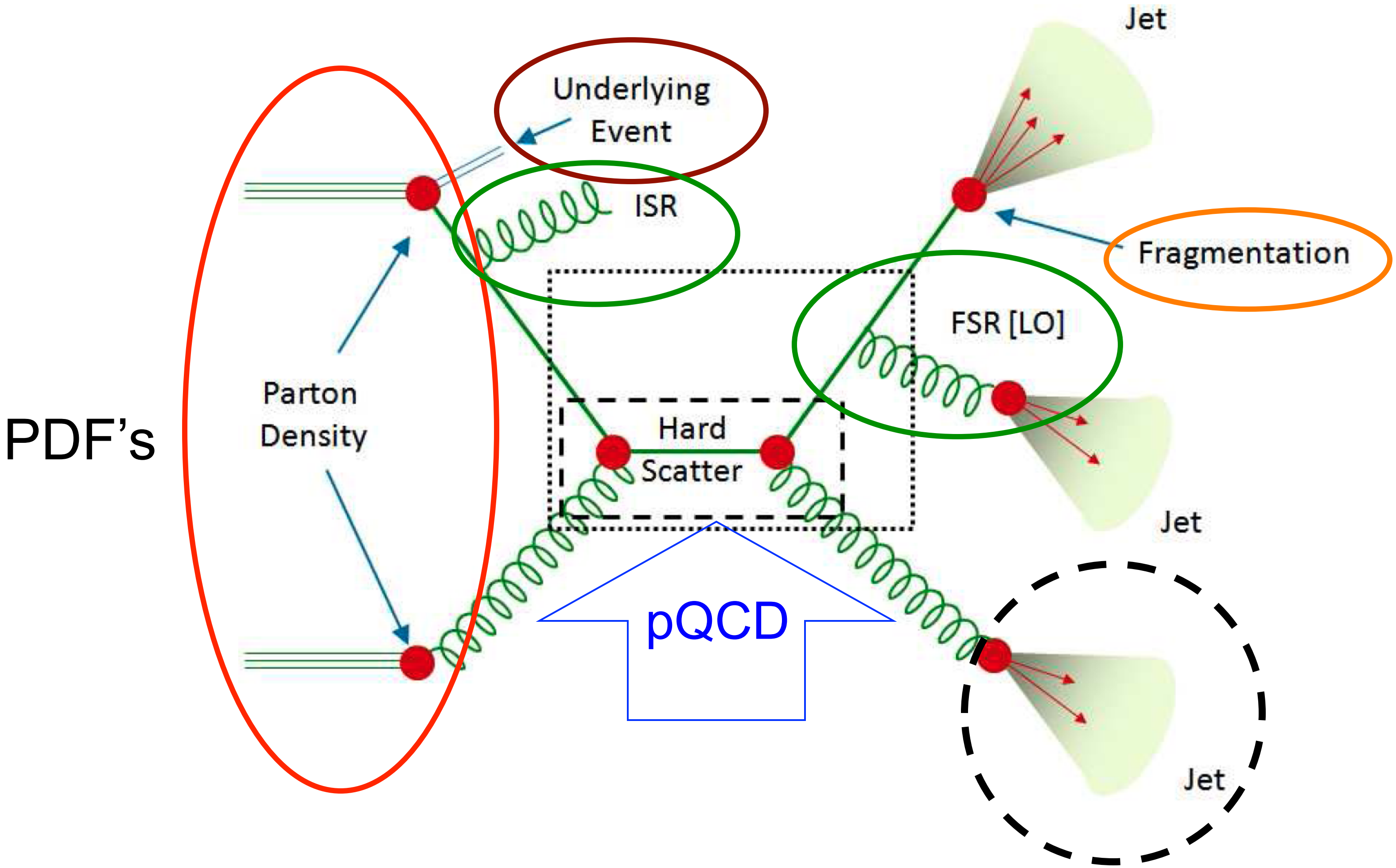
Outline

- Introduction
- Inclusive Jet production
  - at 7 TeV, 8 TeV
  - AK5/AK7 ratio
- Dijet Production
  - Differential cross section
  - Dijet mass and jet substructure
- Multi-jet Production
  - 3-Jet Mass cross section
  - 3/2 Inclusive Jet Cross section Ratio
  - Determination of α_S

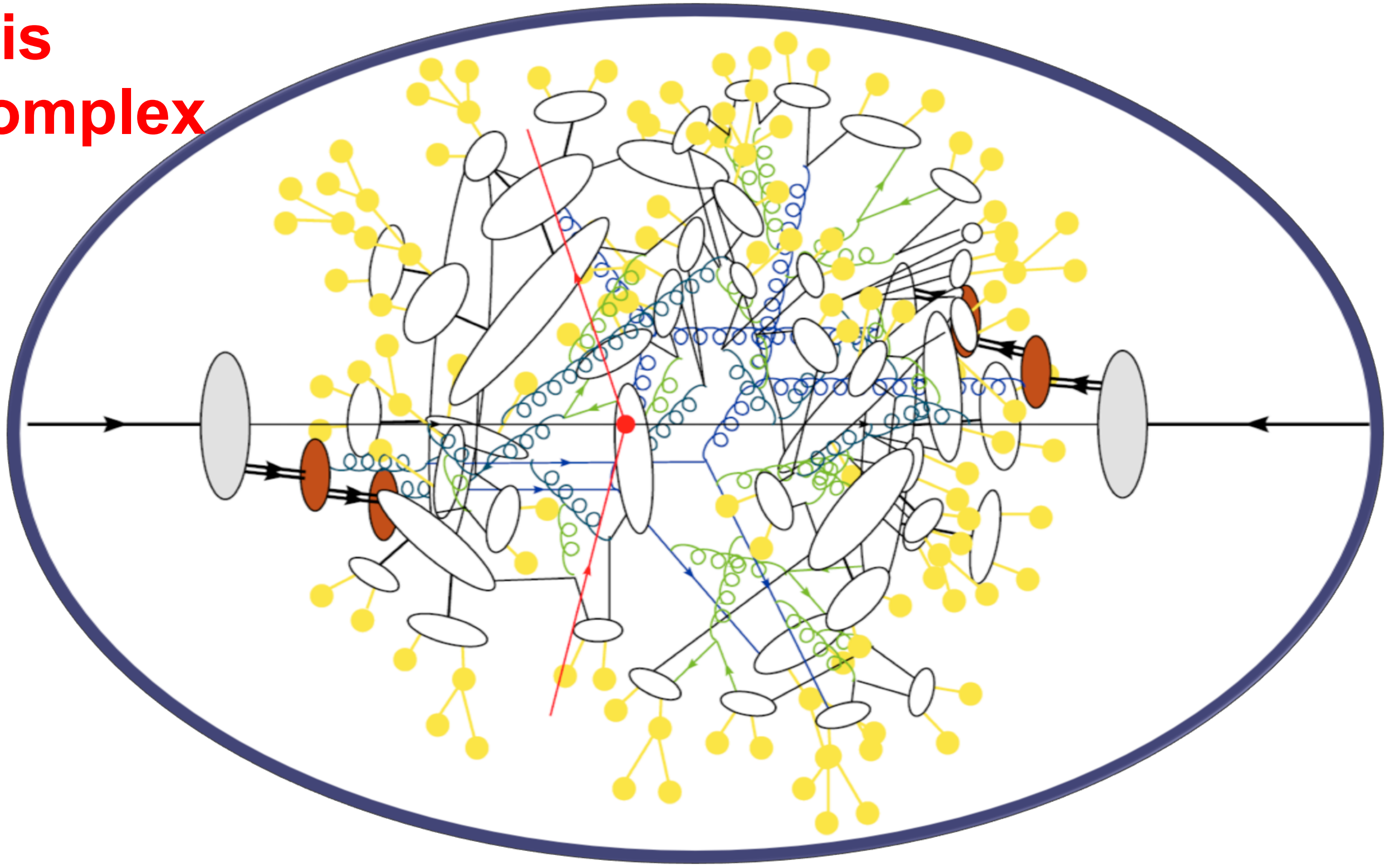
All data from published results are posted on the Durham database: http://hepdata.cedar.ac.uk/

For All public results in CMS Standard Model Physics: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

QCD at Hadron Colliders



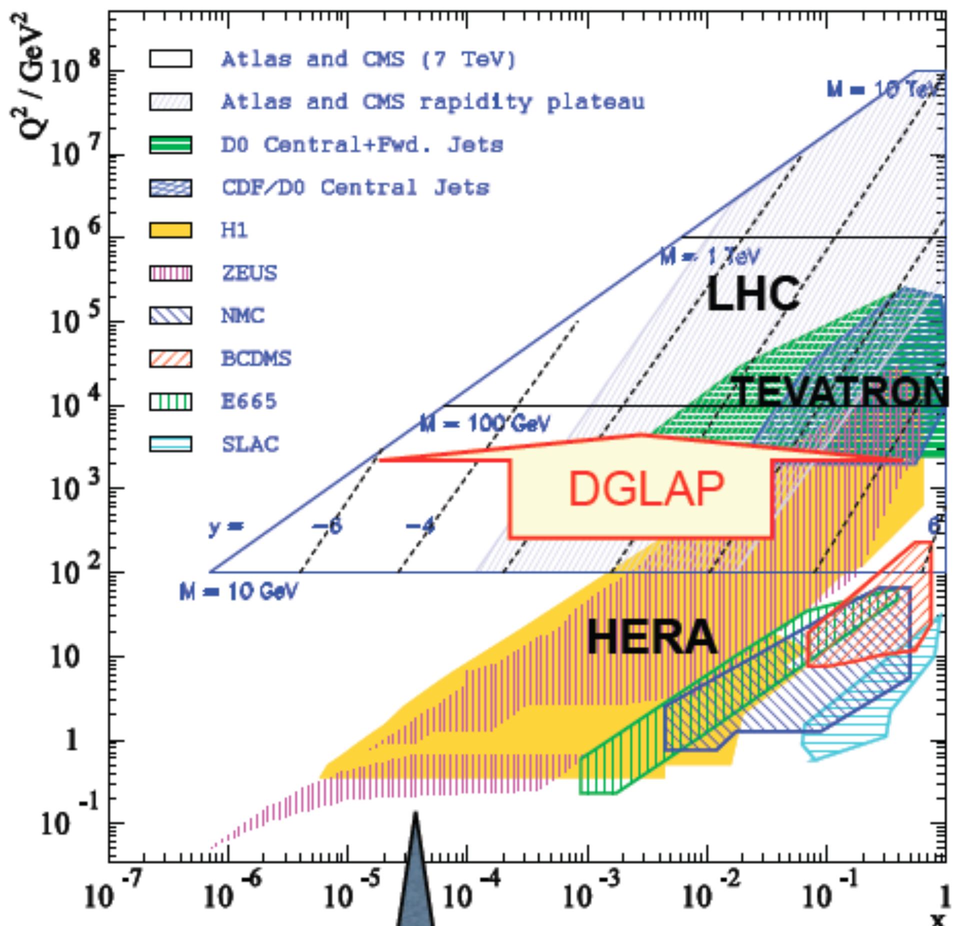
Reality is more complex



- Understanding of QCD is important for
  - Interpretation of data
  - Precision studies
  - Searches for New Physics

Why do we care about QCD?

- It is interesting
  - very rich theory: deserves exploration and understanding
- It is inevitable
  - hadron collisions: QCD is always present
- Important background for new physics searches
  - enormous cross section: QCD can hide many possible signals of new physics
- Introduces uncertainties on other measurements
  - e.g. uncertainties on the PDFs affect the Higgs properties
- With LHC data
  - probing new territory



experimental access to an enormous phase space → stringent test of QCD

CMS: the detector

Total weight 14000 t
Diameter 15 m
Length 28.7 m

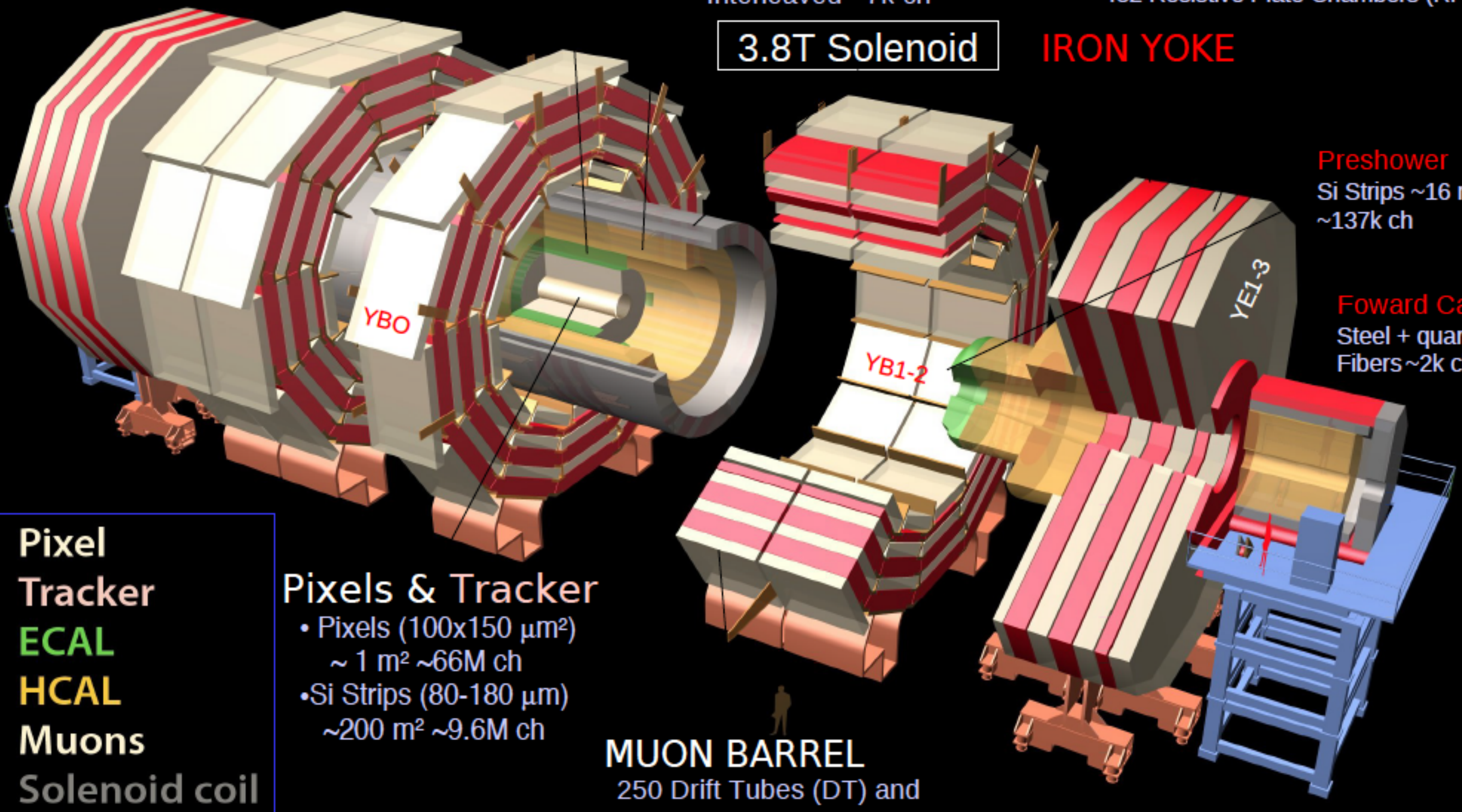
ECAL 76k scintillating $PbWO_4$ crystals

HCAL Scintillator/brass Interleaved ~7k ch

MUON ENDCAPS
473 Cathode Strip Chambers (CSC)
432 Resistive Plate Chambers (RPC)

3.8T Solenoid

IRON YOKE



Preshower
Si Strips ~16 m²
~137k ch

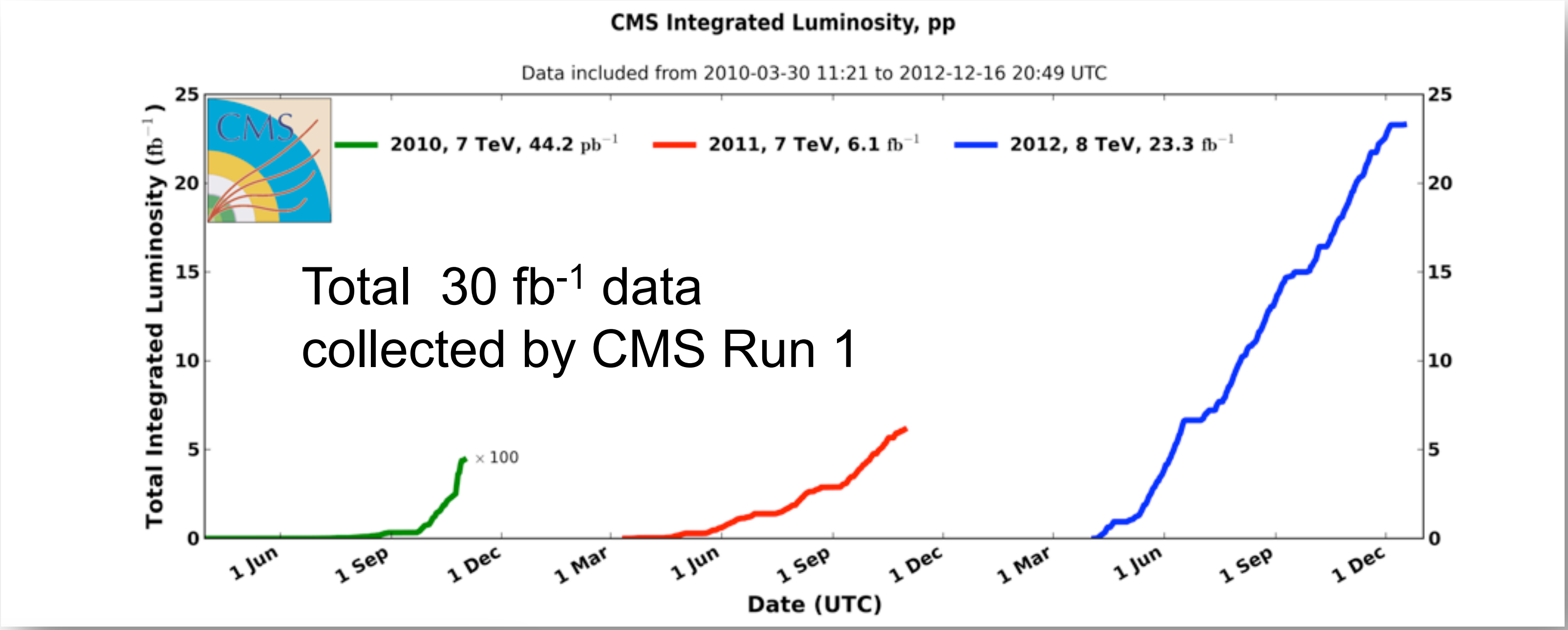
Foward Cal
Steel + quartz
Fibers~2k ch

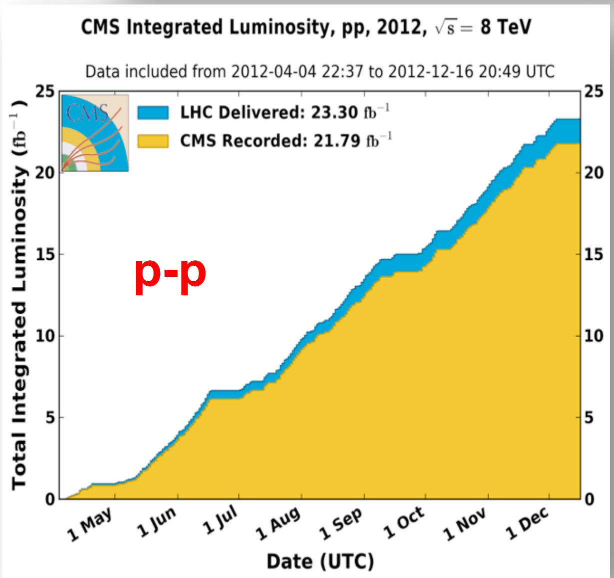
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

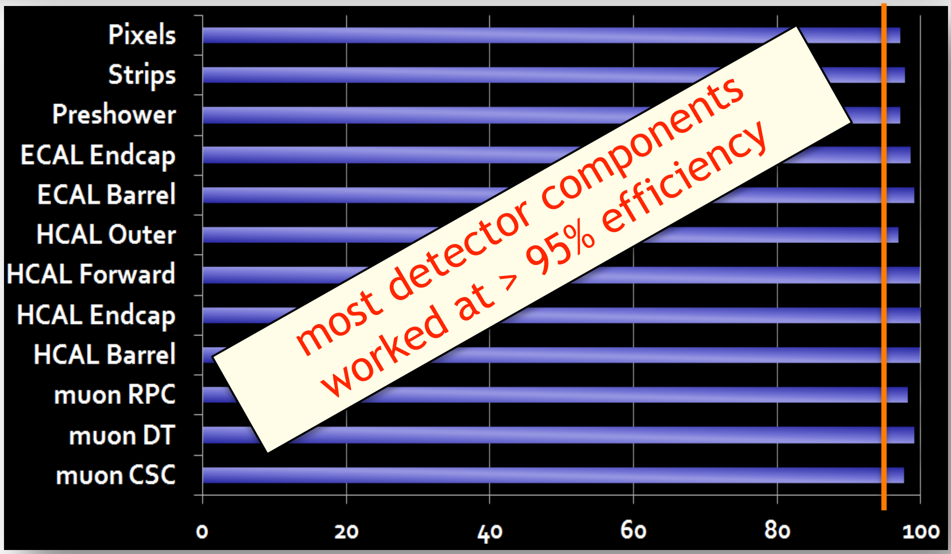
Pixels & Tracker
- Pixels (100x150 μm²) ~ 1 m² ~66M ch
- Si Strips (80-180 μm) ~200 m² ~9.6M ch

MUON BARREL
250 Drift Tubes (DT) and
480 Resistive Plate Chambers (RPC)

Thanks LHC for Fantastic 3 years!

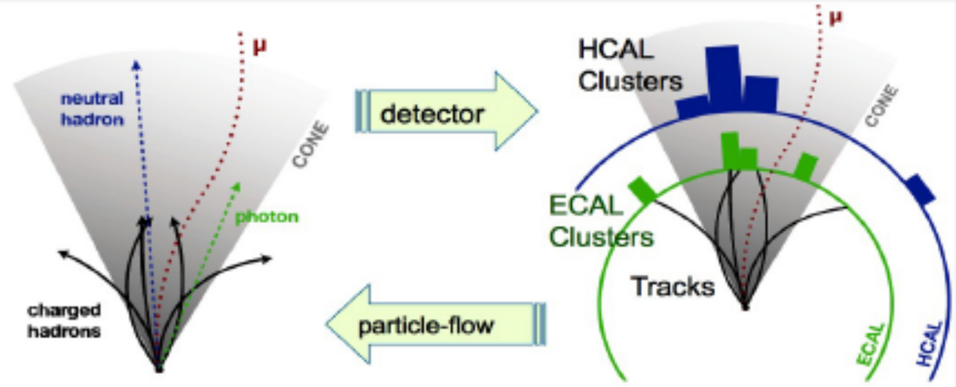




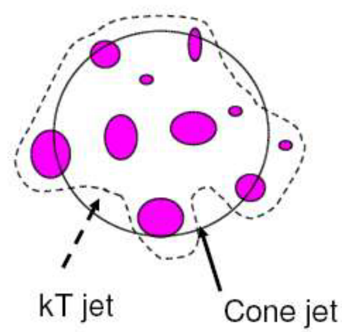


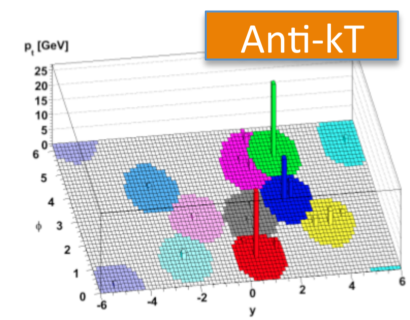
Jet reconstruction

Particle-Flow (PF) algorithms use:
e, μ, γ, charged & neutral hadrons
as building blocks for
jets, b-jets, τ's, ν (miss E_T), isolation



- Fixed cone algorithms:
  - Iterative Cone (CMS) / JetClu (ATLAS)
  - Seedless Infrared Safe Cone (SISCone)





- Successive recombination algorithms:

$$d_{ij} = p_{T,i}^{2p} \qquad d_{ij} = \min(p_{T,i}^{2p}, p_{T,j}^{2p})\frac{\Delta R_{ij}^2}{D^2}$$

p=1 -> k_T jet algorithm
p=0 -> CA jet algorithm
p=-1 -> "Anti-k_T" jet algorithm

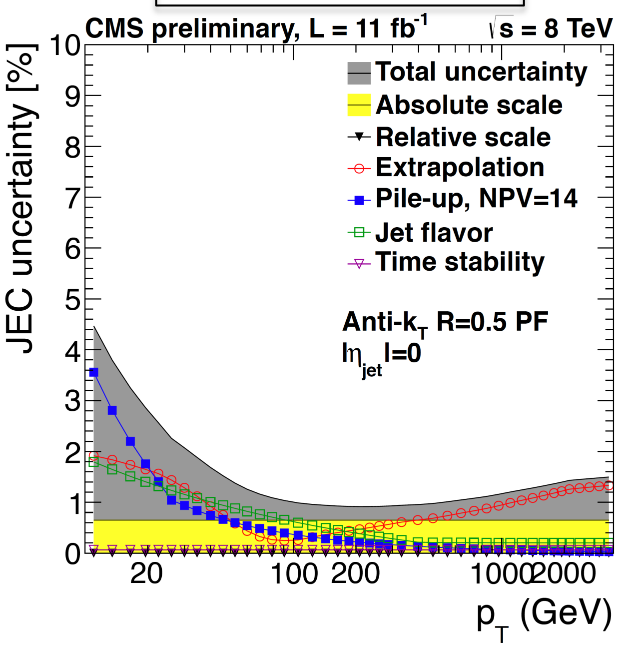
- Soft particles will first cluster with hard particles before among themselves
- Almost a cone jet near hard partons
- No merge/split

Jet Energy Calibration

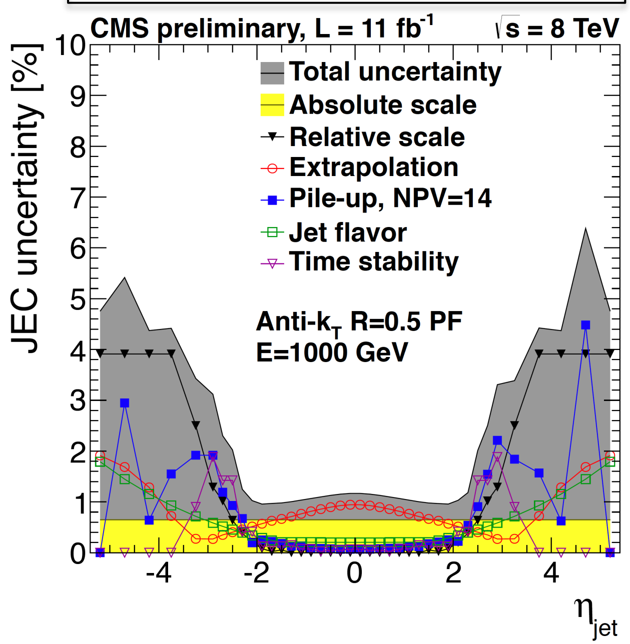
- Jet Energy Correction is necessary to measure the correct energy spectrum of Jets
- The main three type of corrections required are OffSet (PU Subtraction), Relative(for η dependent response) and Absolute(for p_T dependent response) + Residual corrections. [JINST 6 (2011) P11002]
- Offset –> Subtracting
- Relative –> Dijet Balance
- Absolute –> γ + jet and Z + jet (p_T Balance and MPF)

JEC (Jet Energy Correction) uncertainty ~1% for central high-pT jets

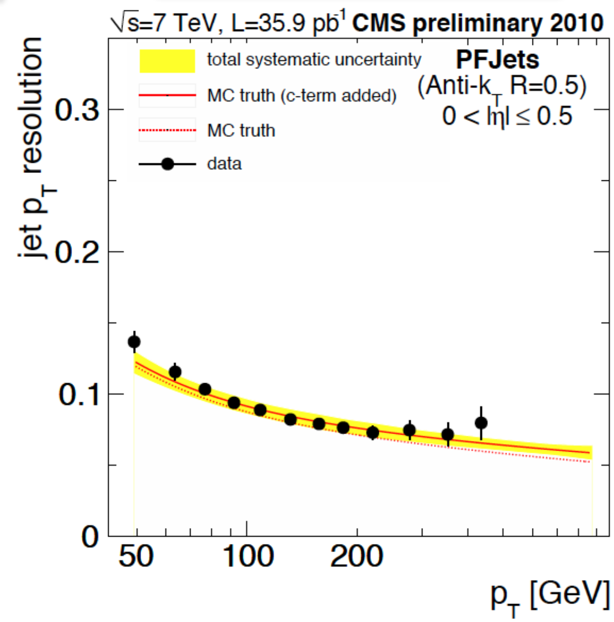
JEC unc vs p_T



JEC unc vs η @ E=1 TeV

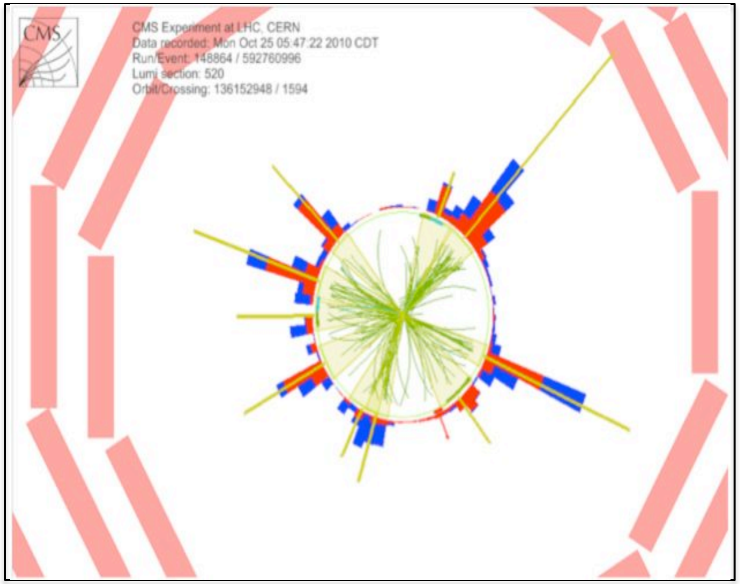


Jet p_T Resolution



Inclusive Jet Production

- Inclusive Jet Cross Section @ 7 TeV [QCD-11-004]
  [Phys. Rev. D 87 (2013) 112002]
- Inclusive Jet Cross Section @ 8 TeV [SMP-12-012, FSQ-12-031]
- Inclusive jet AK5/AK7 cross section ratio @ 7 TeV [SMP-13-002]



UA2: PLB 118 (1982)
CERN pp-bar √s = 540 GeV

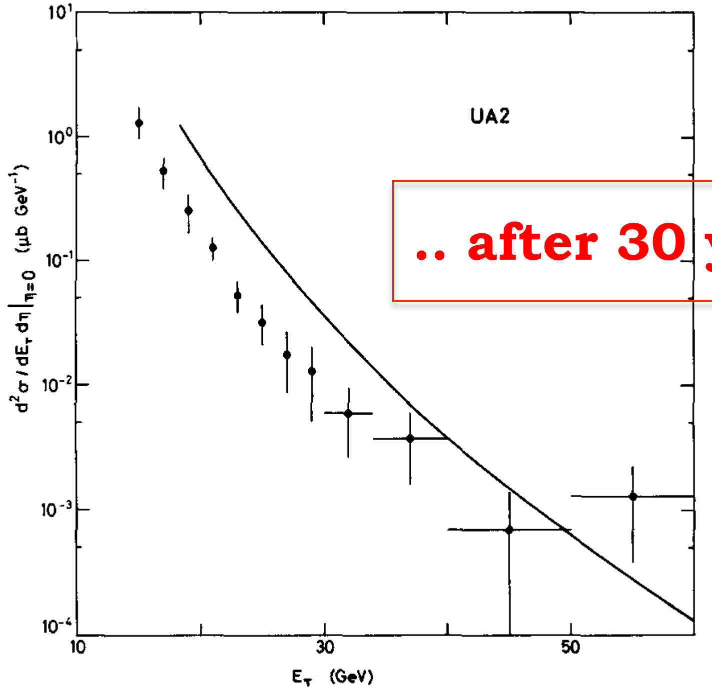
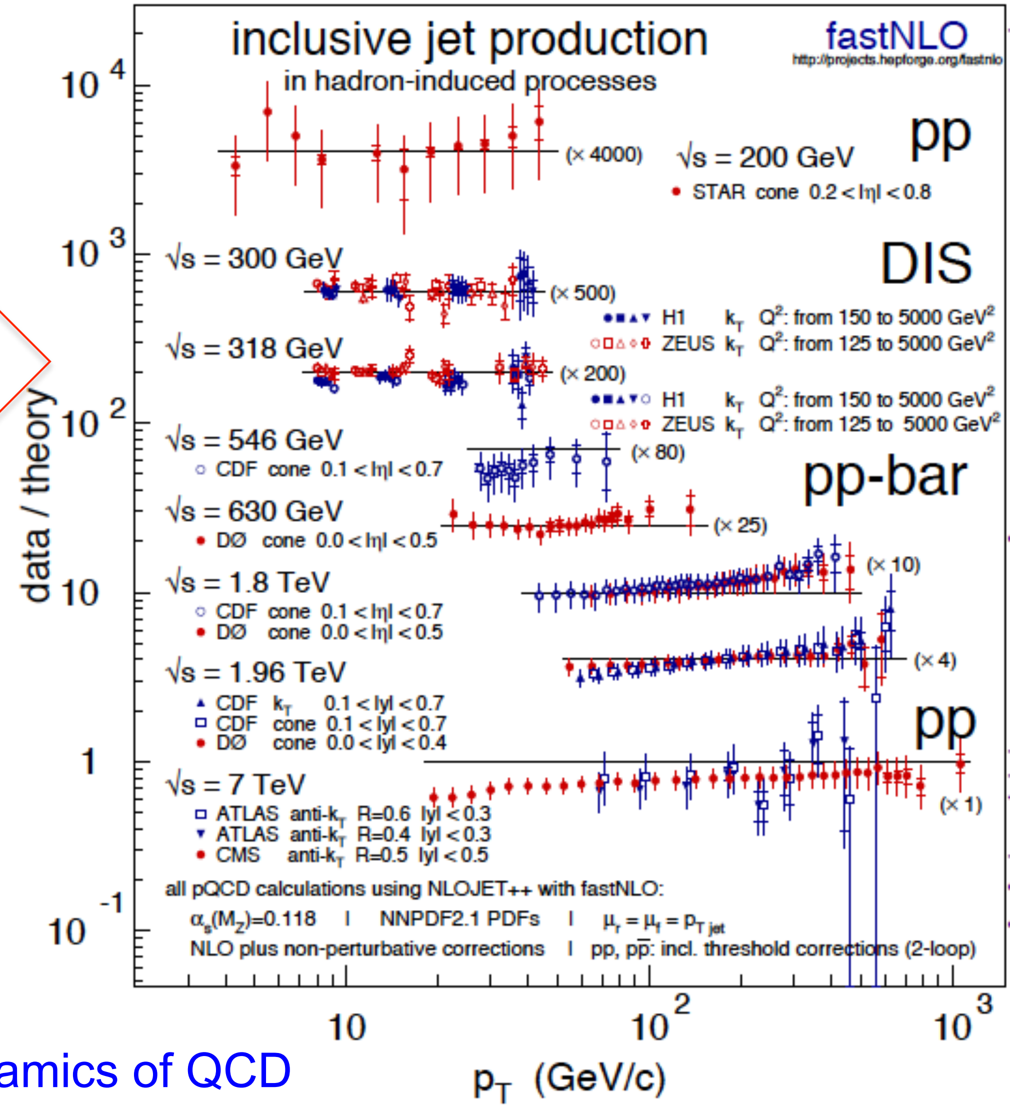


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

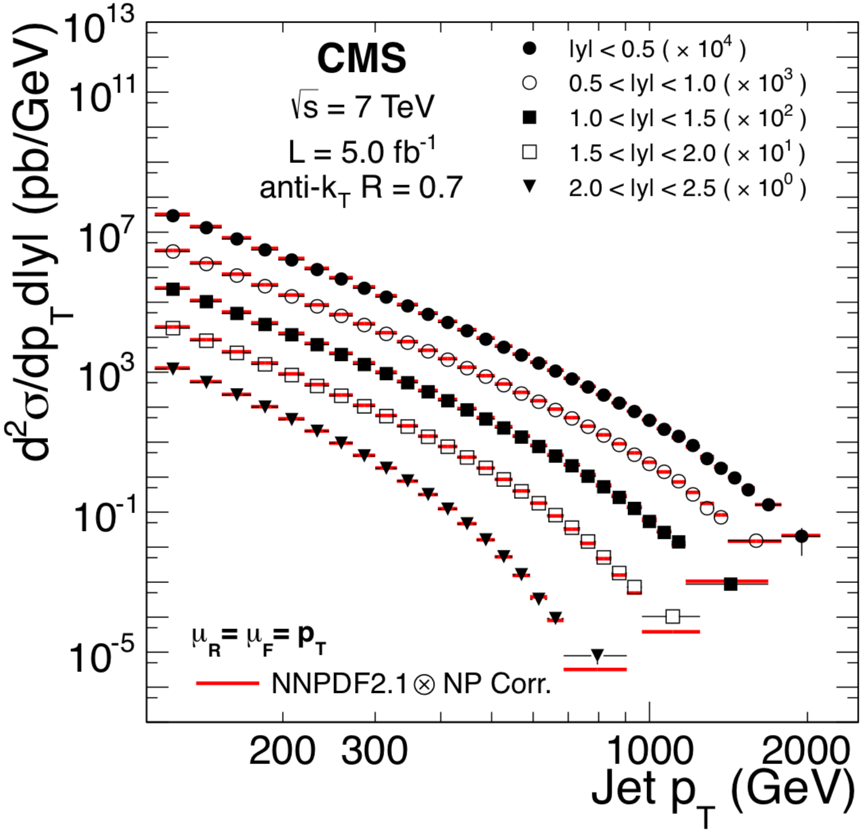
.. after 30 years

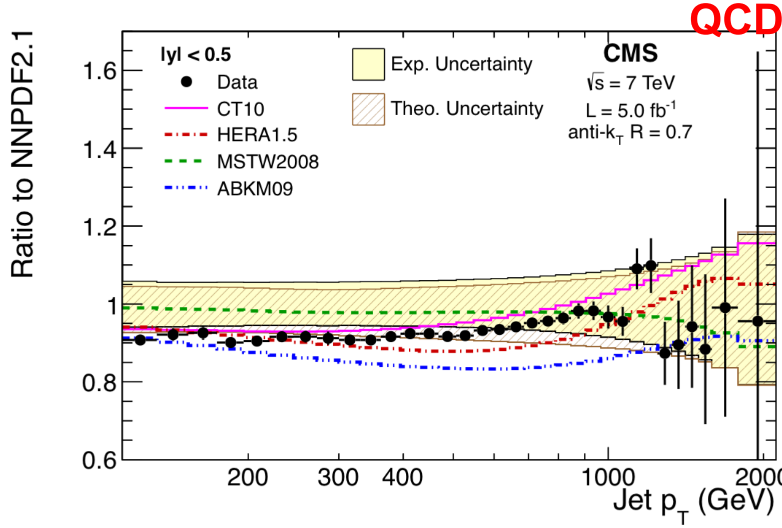


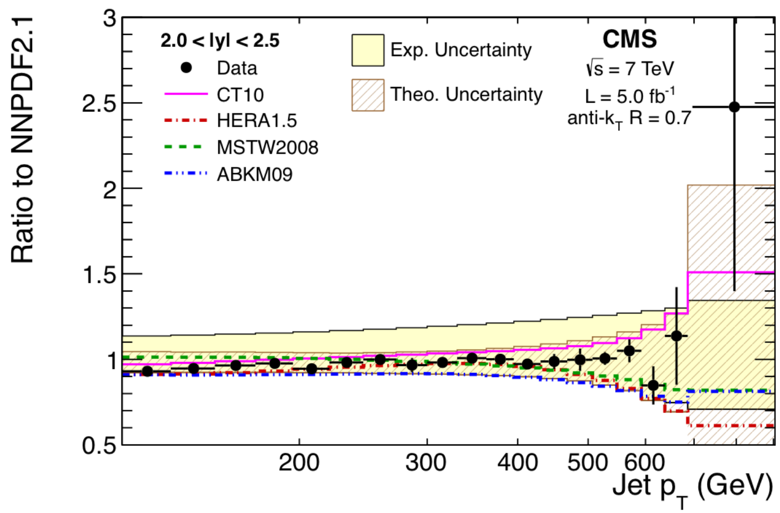
- Inclusive jet production probes the dynamics of QCD
  - counting the number of jets as a function of rapidity and p_T stringent test of QCD
  - PDFs, strong coupling constant, perturbative calculations

Inclusive Jet Differential Cross section @ 7 TeV

QCD-11-004



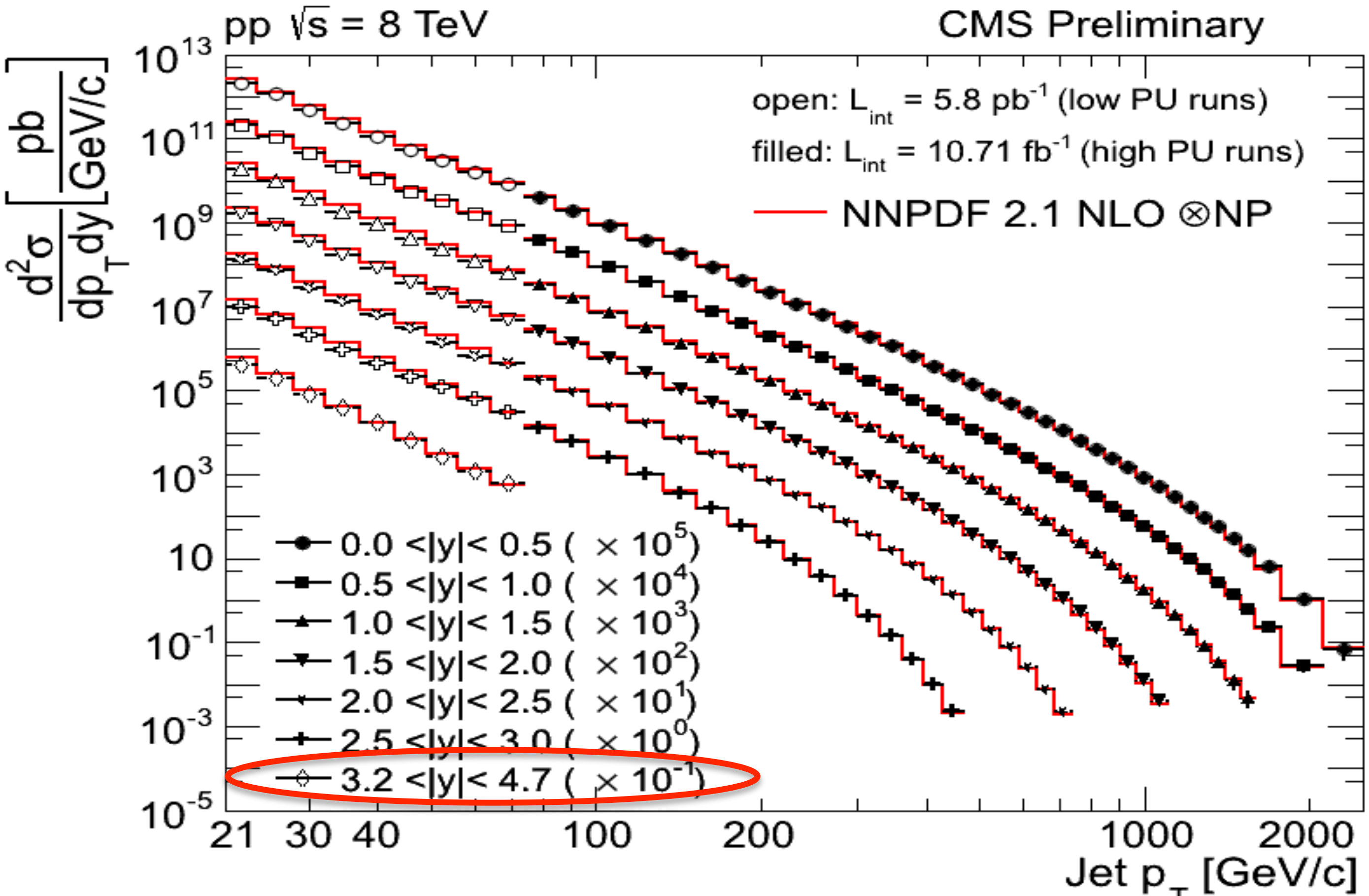




- Double differential Inclusive cross-section measured as a function of Jet-p_T
- Data over theory compared to ratio within several PDF sets for Inclusive and in all rapidity bins

Inclusive Jet Differential Cross section @ 8 TeV

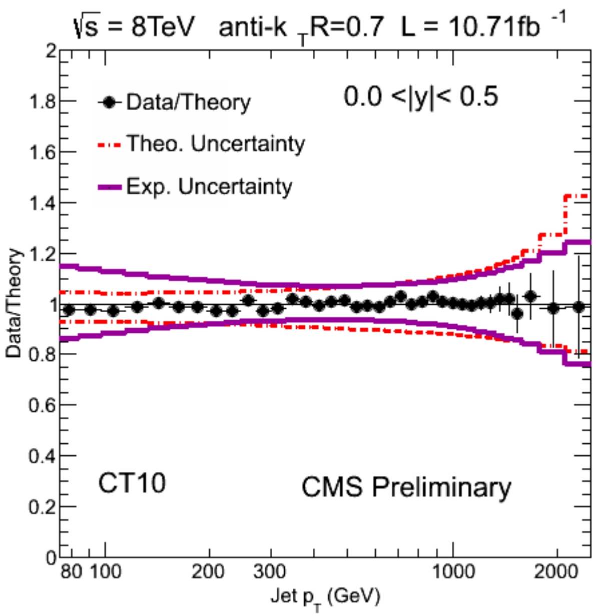
SMP-12-012

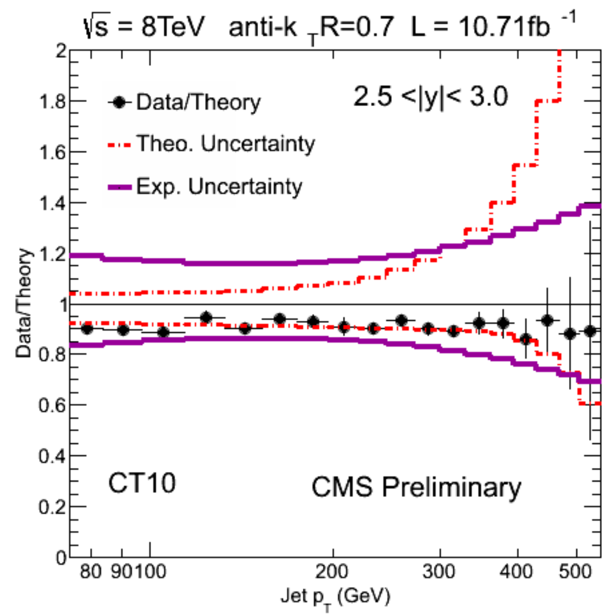


- Measurement at 7 and 8 TeV up to |y| = 4.7
- Comparisons to pQCD NLO⊗NP
  [NP: corrections for non-perturbative effects (MPI and hadronization):
  20% (~100 GeV) ➔ 1% (~2.5 TeV)]

Theory comparisons

SMP-12-012

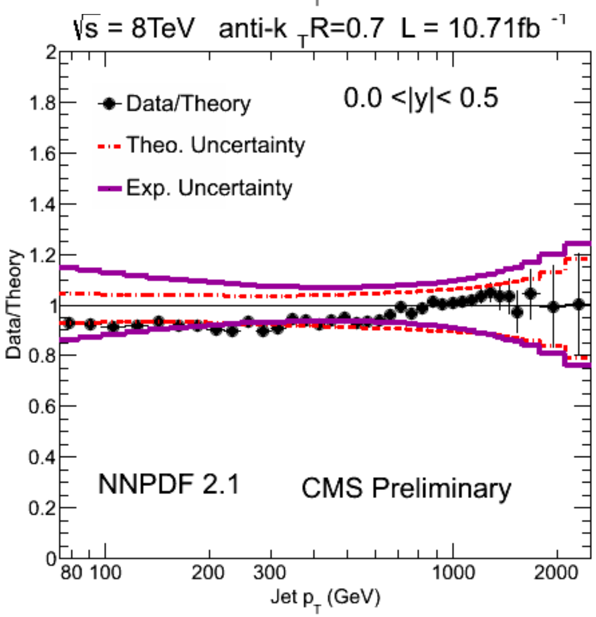


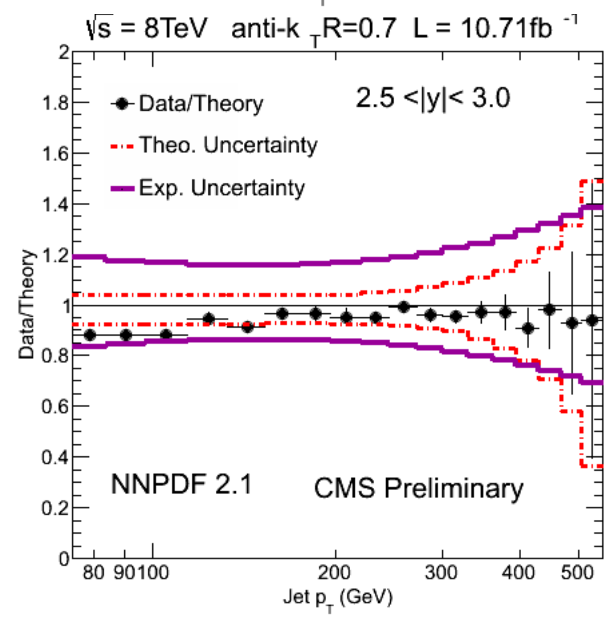


The total experimental uncertainty gets contribution from JES(12%-30%), Luminosity(4.4%) and Unfolding(1%-10%) resulting into 15%-40% <u>total relative experimental uncertainty</u>, across varying p_T bins, on the measured cross-section.

The <u>total theory uncertainty</u> gets contribution from PDF(5%-30%) and Scale(5%-40%) uncertainties.

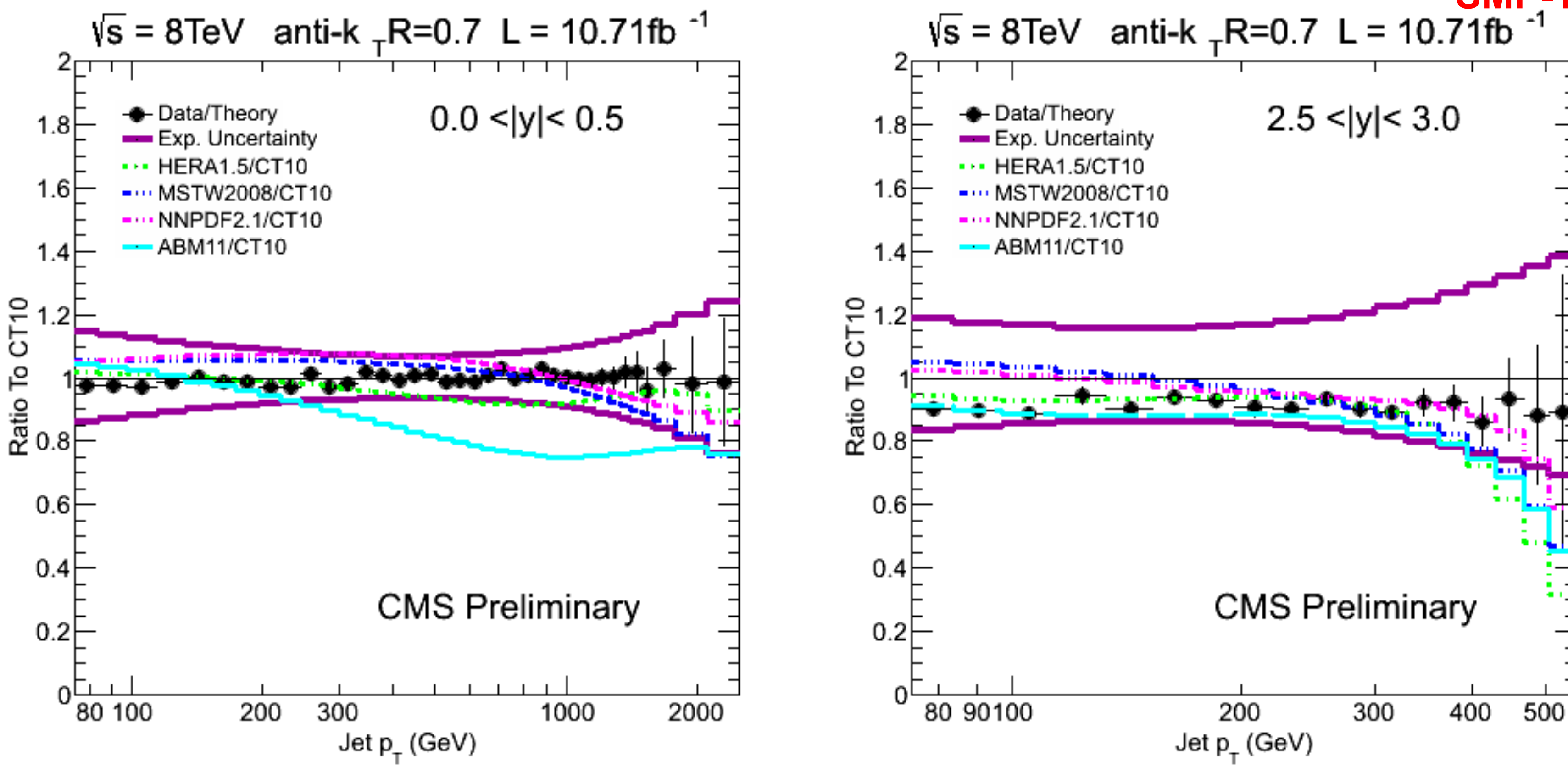
PDF uncertainty for CT10 in outer bins 100%.





Comparison among different PDFs

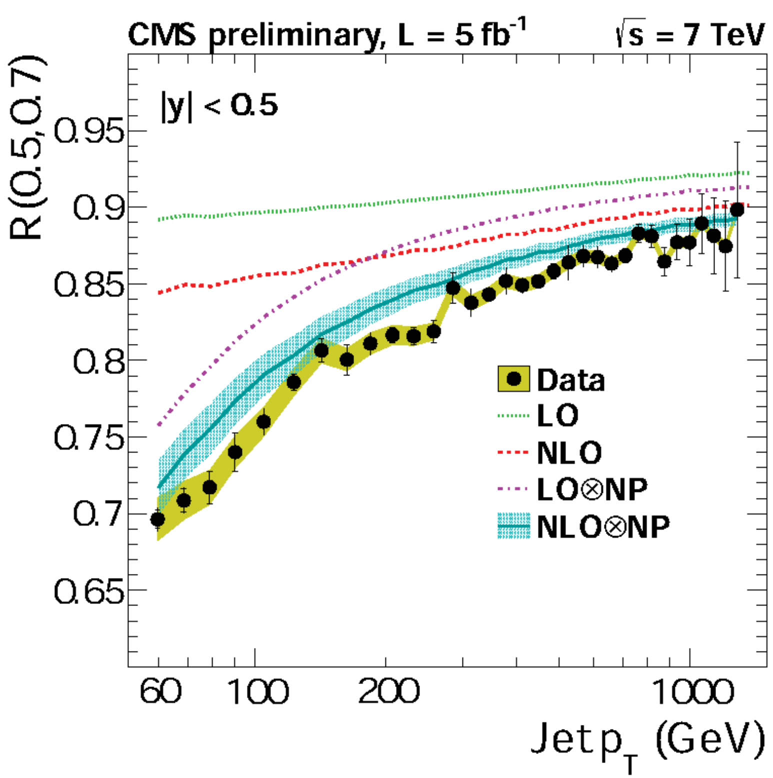
SMP-12-012

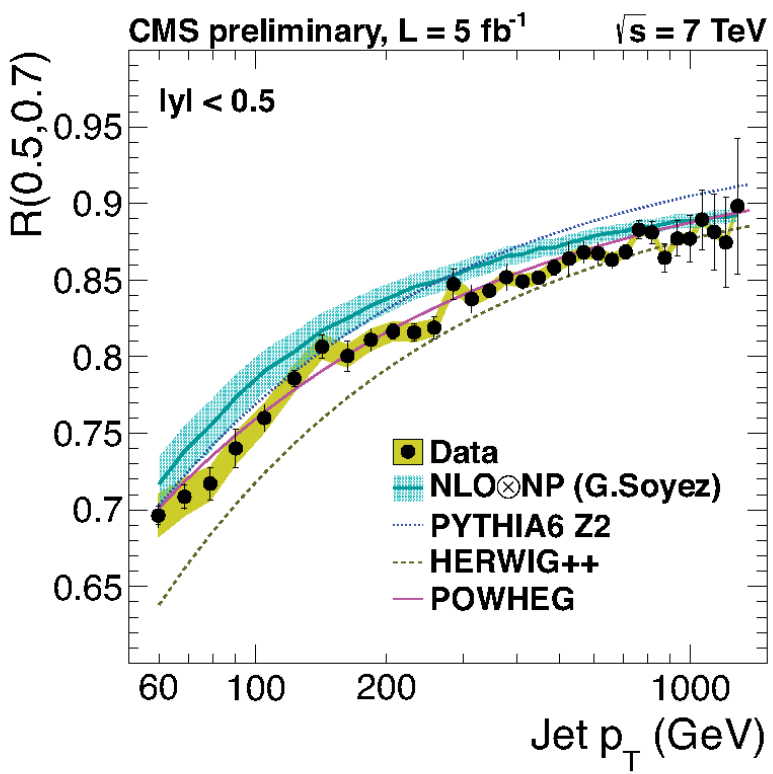


- ❑ Data over theory compared to ratio with other PDF sets for CT10 PDF.
- ❑ The theory predictions are computed for ve dierent PDF sets, viz. ABM11, HERA1.5, CT10, MSTW2008, NNPDF2.1.
- ❑ In the central rapidity region dierent theory predictions are in agreement with data except ABM11.
- ❑ The fluctuations are covered by total theoretical and experimental uncertainty bands.

- Measurement at √s=7 TeV with different jet sizes R=0.5 (AK5), 0.7 (AK7)
- Ratio of cross sections R(0.5, 0.7) vs p_T and rapidity

SMP-13-002





- Several systematic uncertainties cancel in ratio
- The ratio gradually increases towards unity with increasing Jet-p_T.
- Powheg(NLO+PS) prediction has the describes the data best

Dijet Production

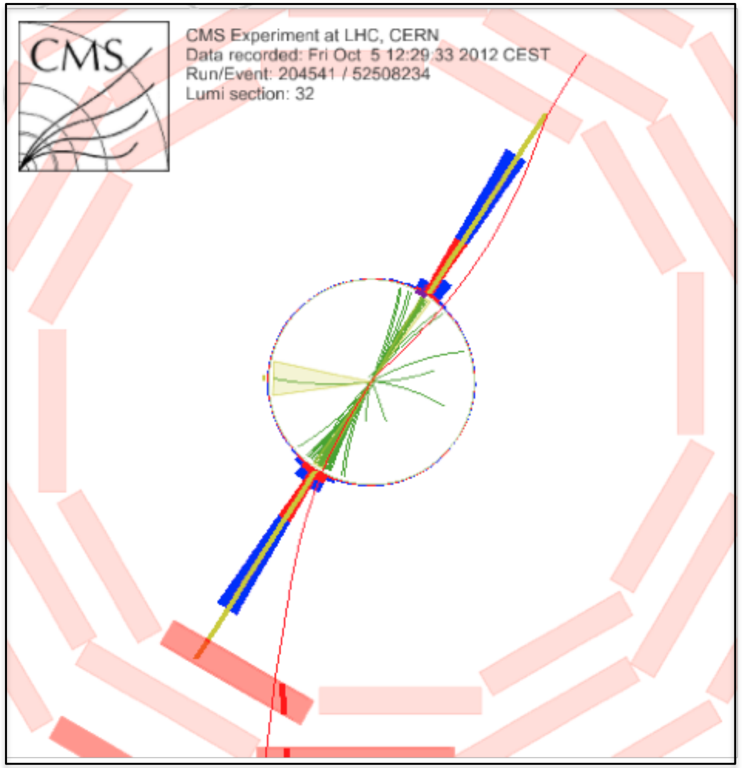
- Dijet Differential Cross Section

@ 7 TeV [QCD-11-004]

Phys. Rev. D 87 (2013) 112002

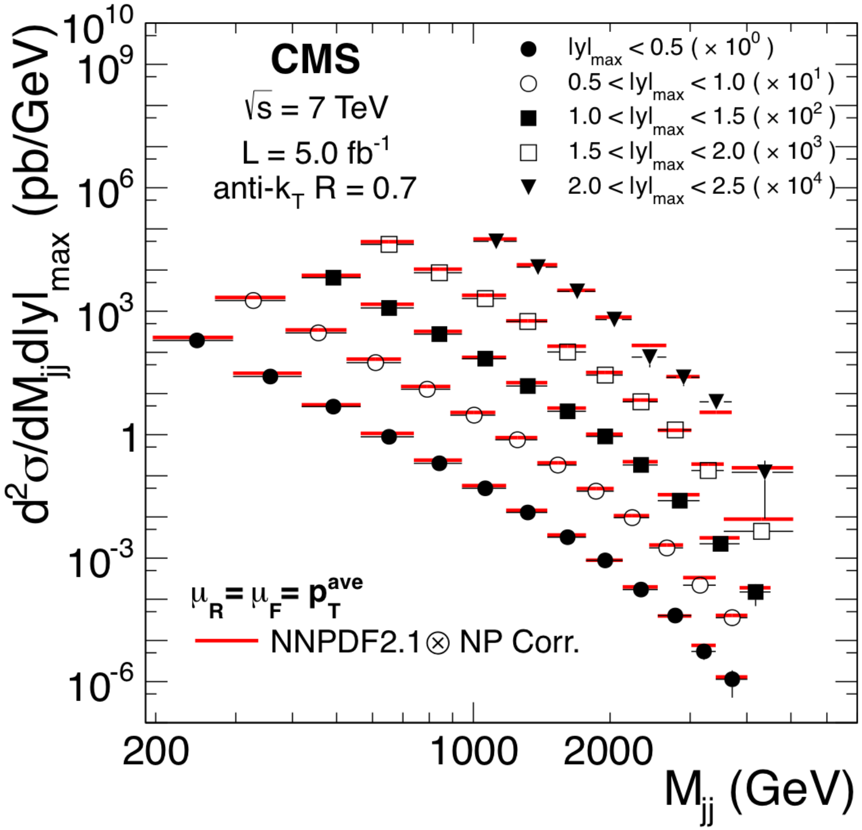
- Dijets and V+jets, jet mass and substructure at 7 TeV [SMP-12-019]

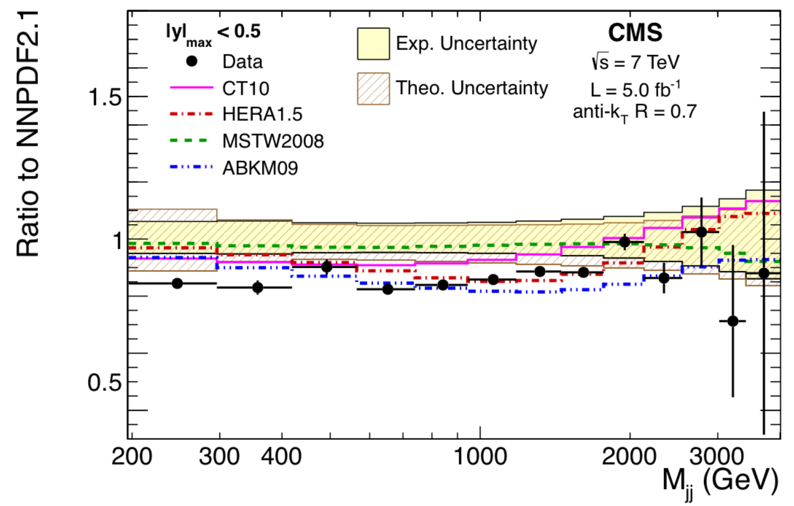
JHEP, May 2013, 2013:90

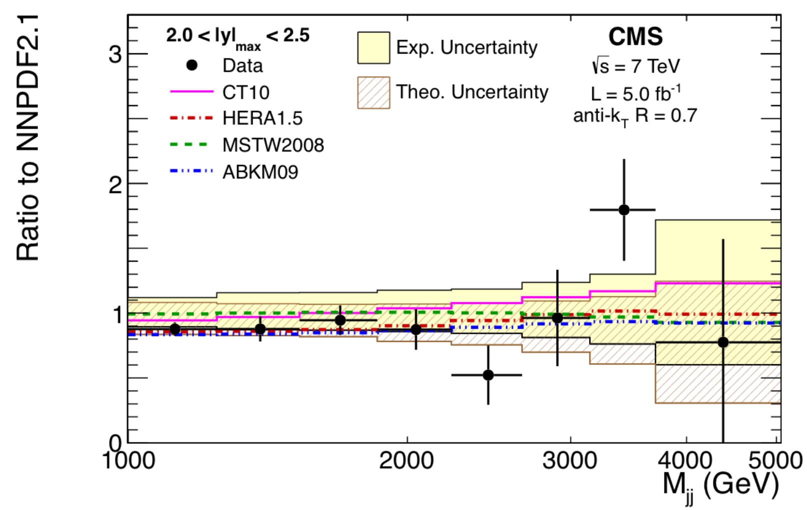


Dijet Cross section at 7 TeV

QCD-11-004





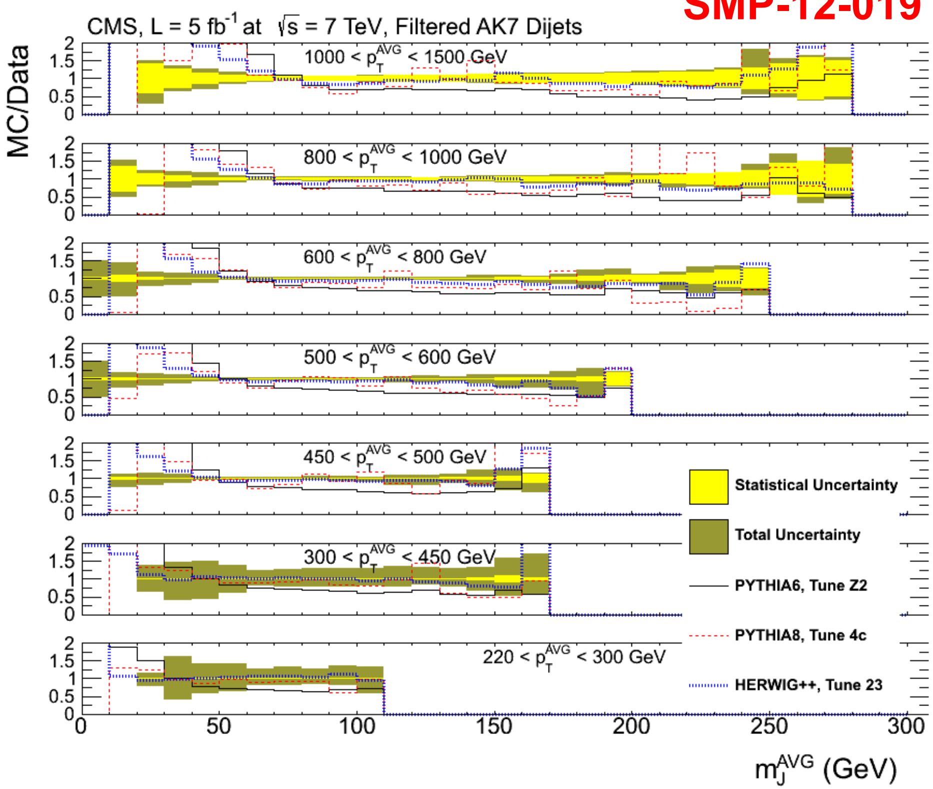


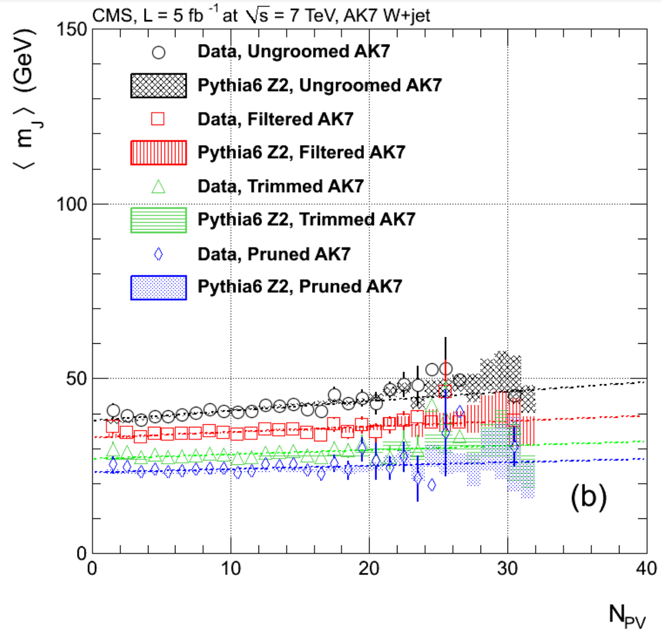
- Reach up to Mjj ~ 5.5 TeV
- Complementary to Inclusive jets
- Agreement with pQCD@NLO ⊗ NP

Dijet Mass and Jet substructure

- Differential distributions in jet mass for inclusive dijet events, defined through the anti-k_T algorithm for a size parameter of 0.7 for jets groomed through filtering, trimming, and pruning.

SMP-12-019





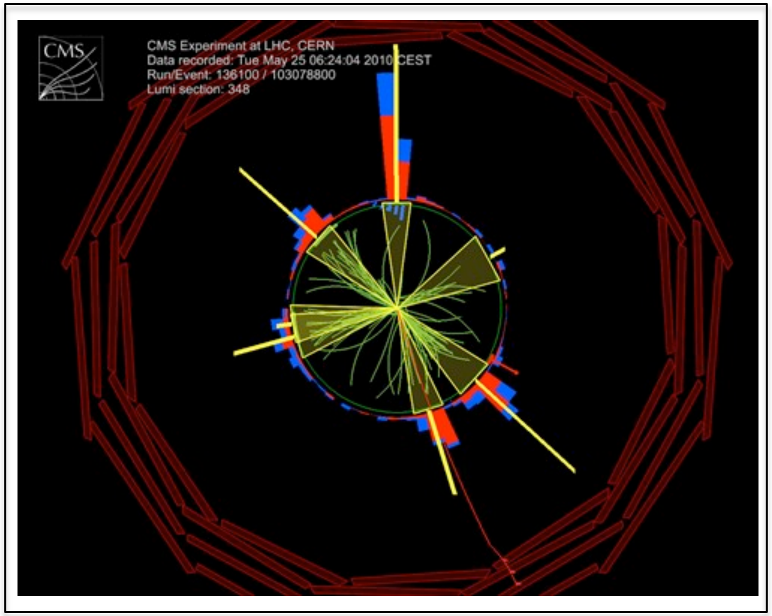
The intrinsic stability of these algorithms to pileup effects contribute to a more rapid and widespread use of these techniques in future high-luminosity runs at the LHC.

- Better agreement at larger jet masses.
- Trimming and pruning algorithms provide an important benchmark for their use in searches for massive particles.

➢ More details in Ivan Marchesini's talk on Jet substructure.

MultiJet Production

- 3-Jet Mass cross section [SMP-12-027]
- 3/2 Inclusive Jet Cross section Ratio [QCD-11-003] arXiv:1304.7498
- Determination of α_S [SMP-12-027]

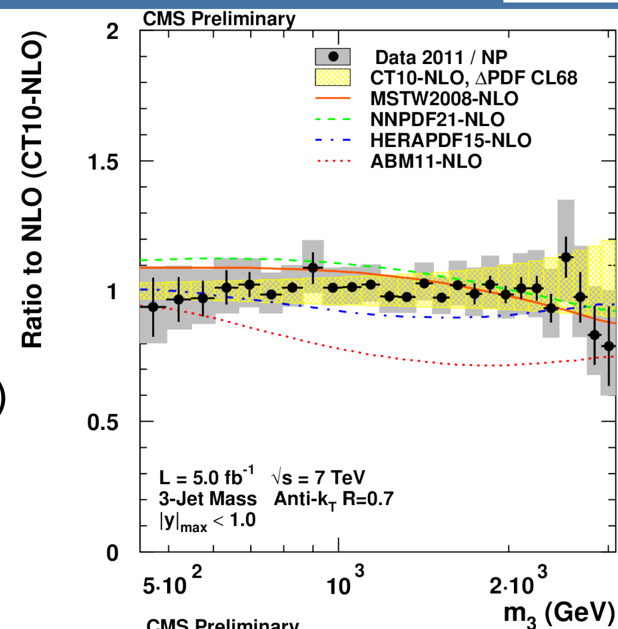


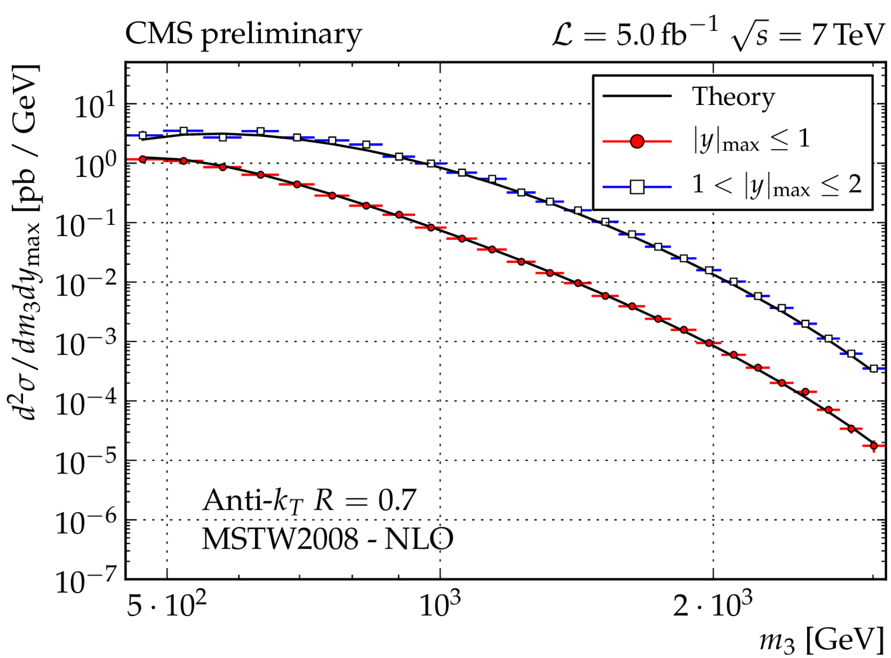
3-Jet Mass Cross Sections at 7 TeV

Measurement of double diffrential cross section: $d^2\sigma/dm_3dy_{max}$
- sensitivity to PDFs and α_S

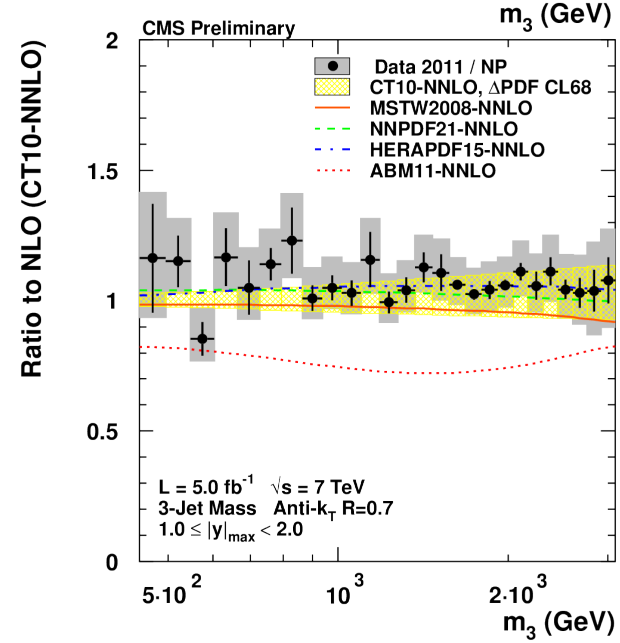
- ❑ $m_3^2 = (p_1+p_2+p_3)^2$ $|y_{max}|=\max(|y_1|,|y_2|,|y_3|)$ $Q=m_3/2$

- ❑ Require jet p_T > 100 GeV
- ❑ Regions: $|y_{max}|$ < 1 and $1<|y_{max}|<2$ - reach up to m_3 ~ 3 TeV
- ❑ Agreement with pQCD @ NLOxNP (*NP correction 8% -> 1%*)
  - Deviations observed with NLO + ABM11 PDFs



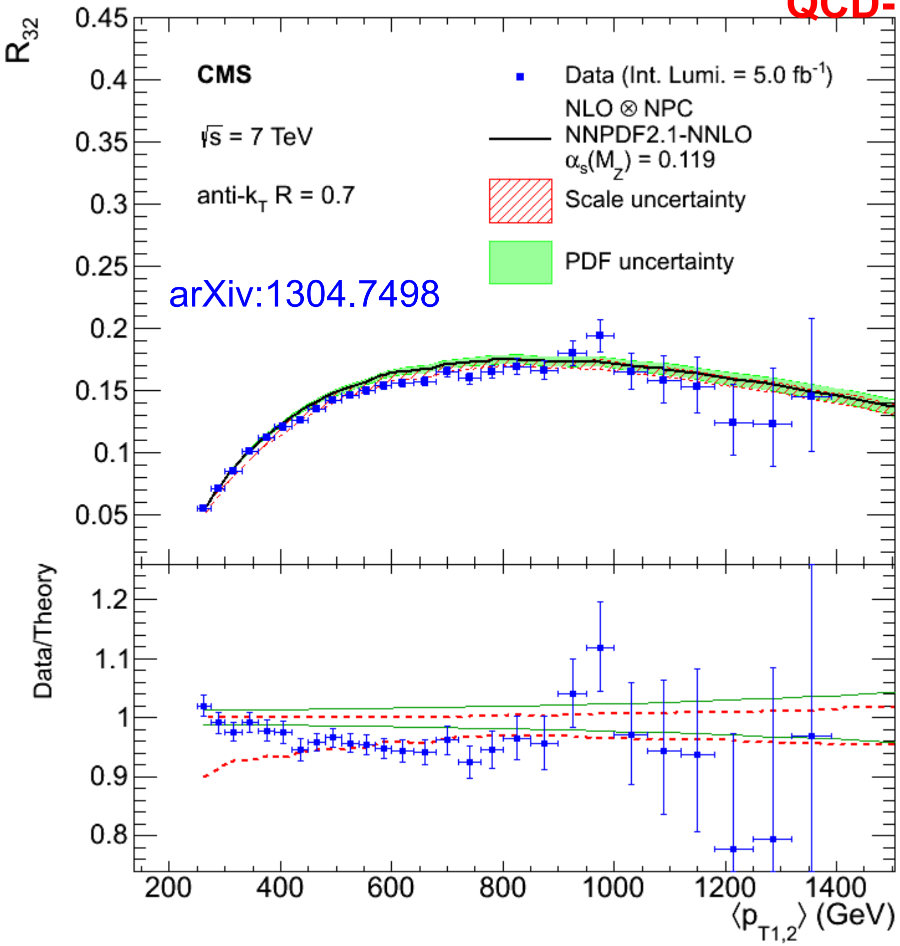


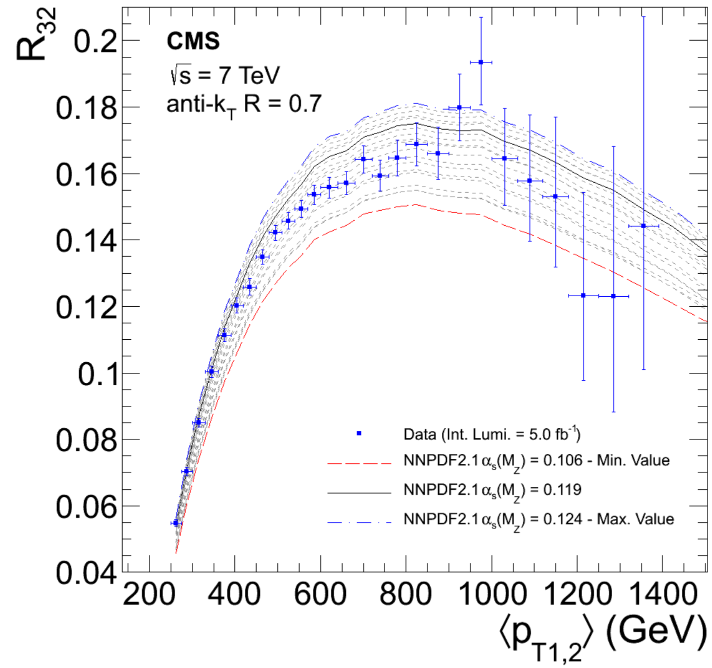
SMP-12-027

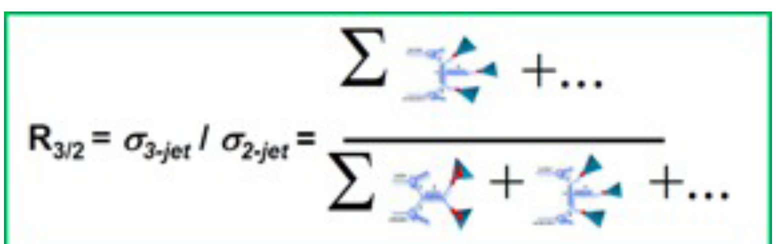


3-jet over 2-jet cross section ratio

QCD-11-003



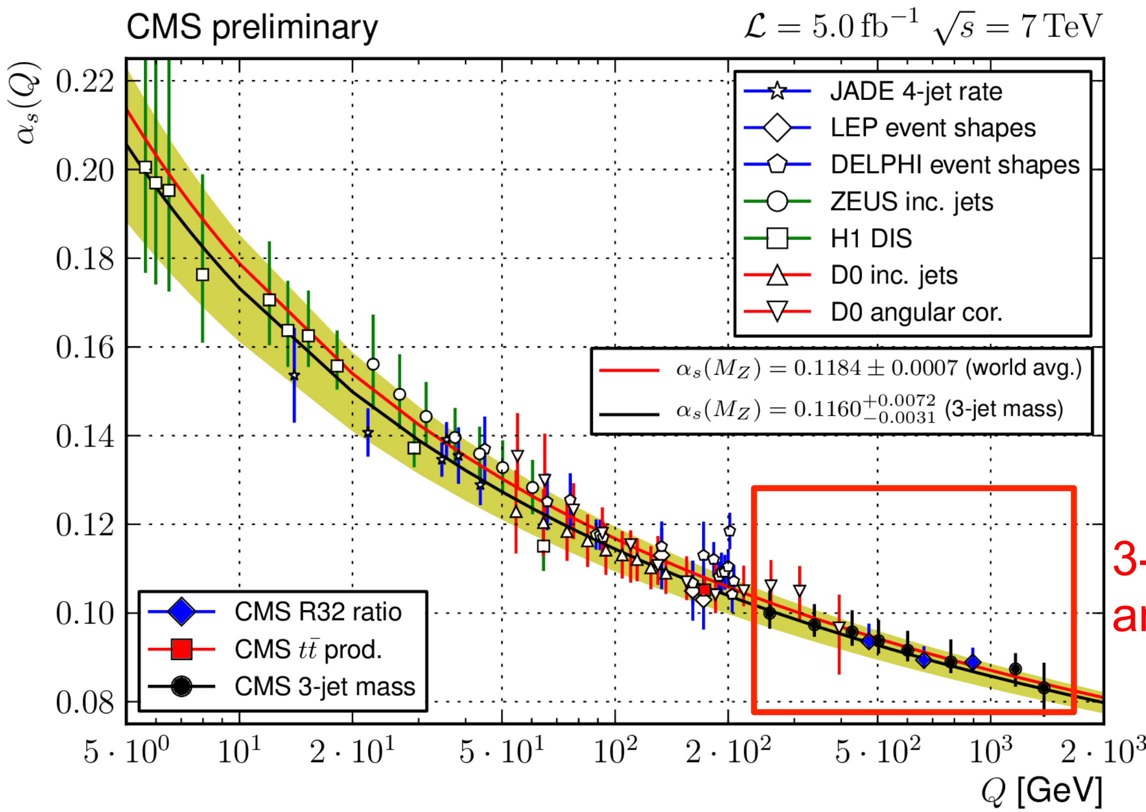




- Cross-section ratio R_{32}:
  - inclusive 3-jet over 2-jet production
  - sensitive to α_S
- Multiple alternative phase-space options
  - depending on the cut imposed on the 3rd jet p_T
  - expressed vs. different observables
  - measuring the α_S: vital to reduce scale uncertainty

Measurement of α_S

SMP-12-012



3-jet mass and R_{32}

- Extract α_S from the R_{32} and 3-jet mass cross section measurements
  - Results are comparable with world average $\alpha_S(M_z)$= 0.1184 ± 0.0007
  - For the first time probing the > 1 TeV scale, reaching up to ~ 1.5 TeV
- Dominated by theoretical uncertainties (PDF and scale)

R_{32}: $\alpha_S(M_z)$=0.1148 ± 0.0014 (exp.) ± 0.0018 (PDF)$^{+0.0050}_{-0.0000}$ (scale)

3-jet mass: $\alpha_S(M_z)$ = 0.1160+0.0025 – 0.0023 (exp, PDF, NP)$^{+0.0068}_{-0.0021}$ (scale)

Conclusions and Outlook

- Significant ongoing effort to improve our understanding of QCD
  - both experimental and theoretical
  - rich QCD programs pursued LHC
- Large datasets available
  - LHC has provided access to a huge phase space
  - will take a long time to analyze and digest all the data on tape
- Much recent progress
  - jet data have considerable impact on gluon and u/d quark PDFs
  - measurements of α_S at the TeV scale for the first time
- Comments on the theoretical tools
  - in many areas the exp. precision reached makes the NLO predictions insufficient: NNLO needed for further progress!!
  - with some tuning of the parameters, the LO ME or NLO interfaced with PS models provide good description of the data