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

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(On behalf of CMS collaboration)

ISMD 2013
Chicago

September 16 , 2013

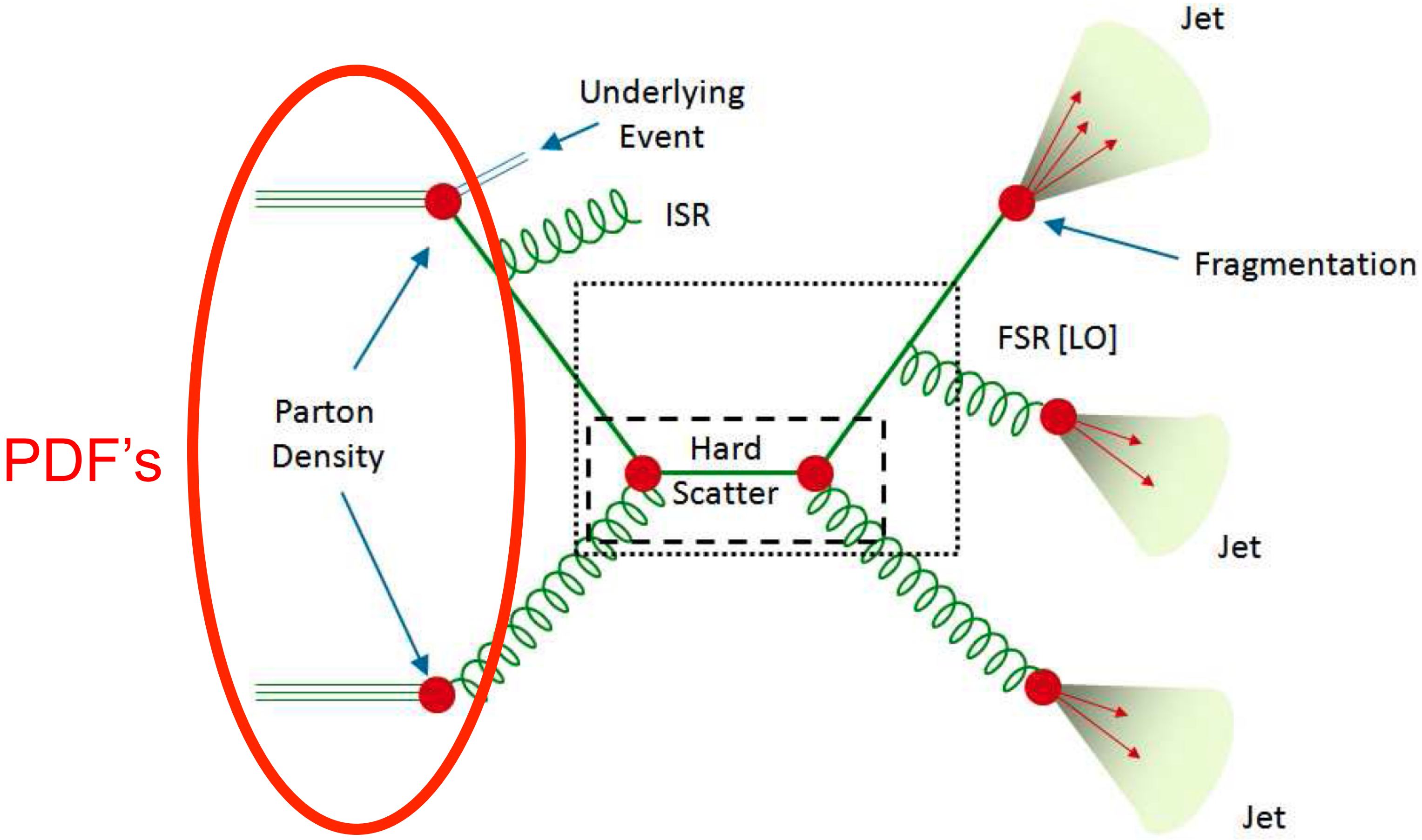
Outline

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

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

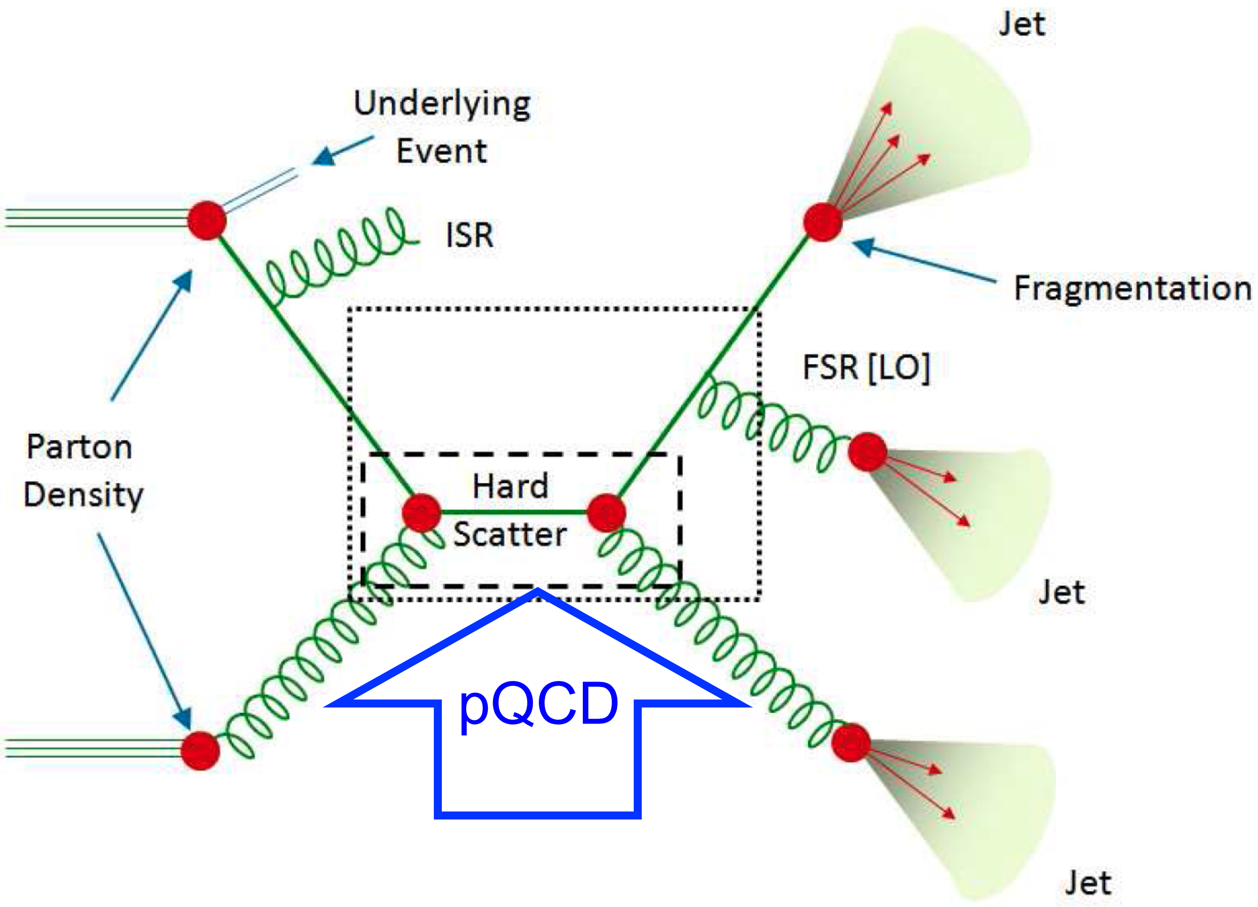
For all public results in CMS Standard Model Physics:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSMP

QCD at Hadron Colliders



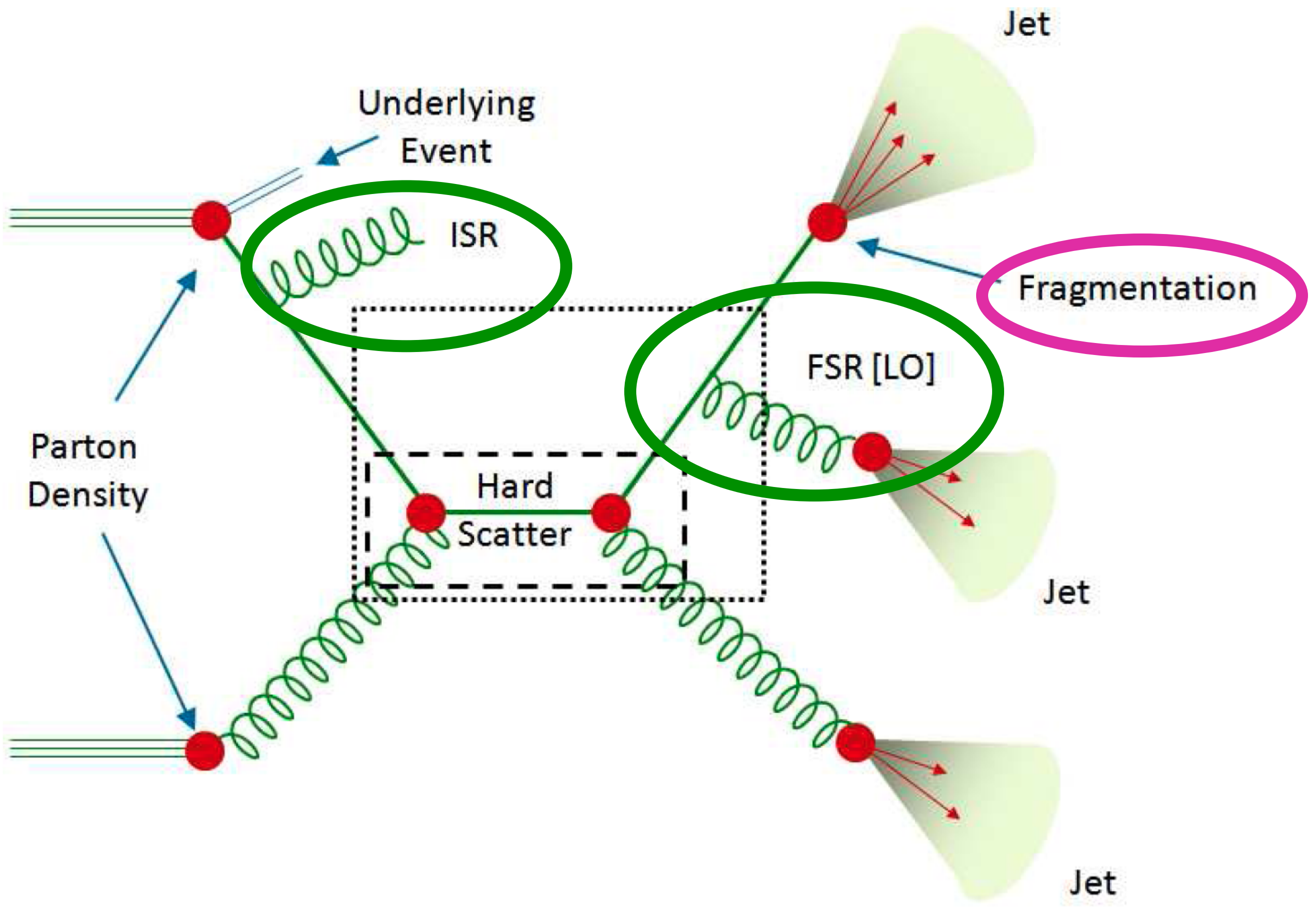
✧ structure of the proton
  - encapsulated into the universal PDF's

QCD at Hadron Colliders



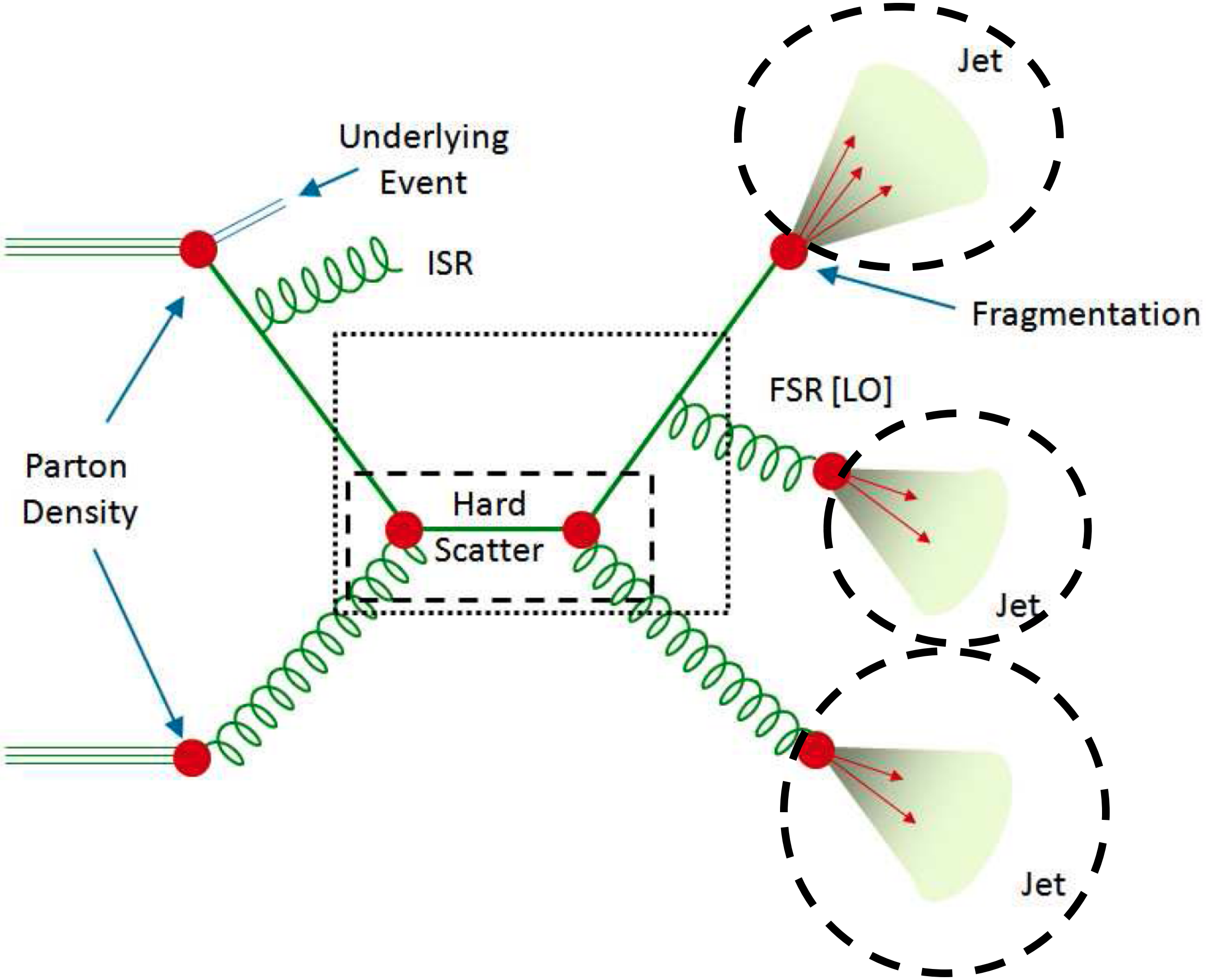
- ✧ hard scatter
  - evaluated in perturbation theory

QCD at Hadron Colliders



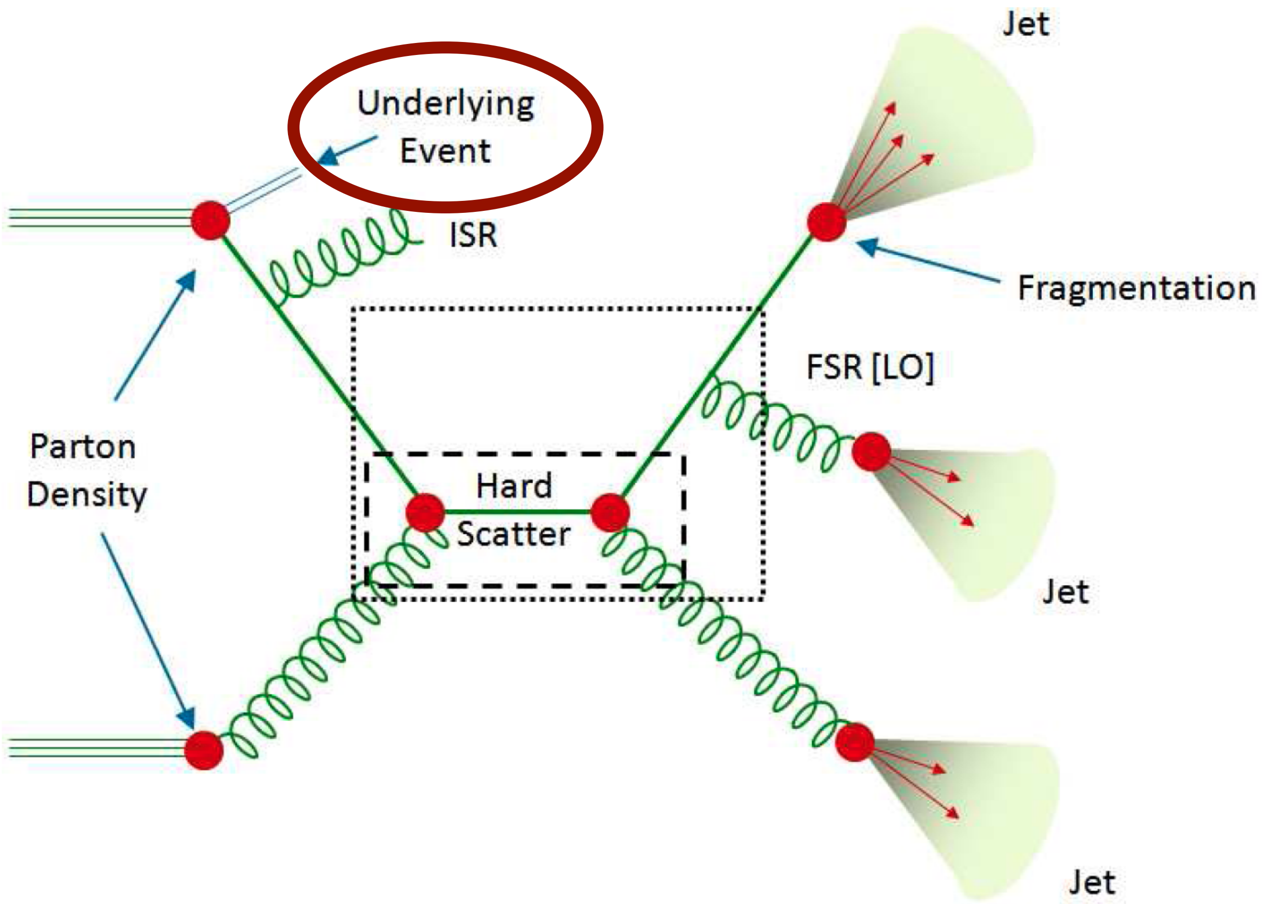
- ✧ parton shower & hadronization
    - ○ initial and final state radiations

QCD at Hadron Colliders



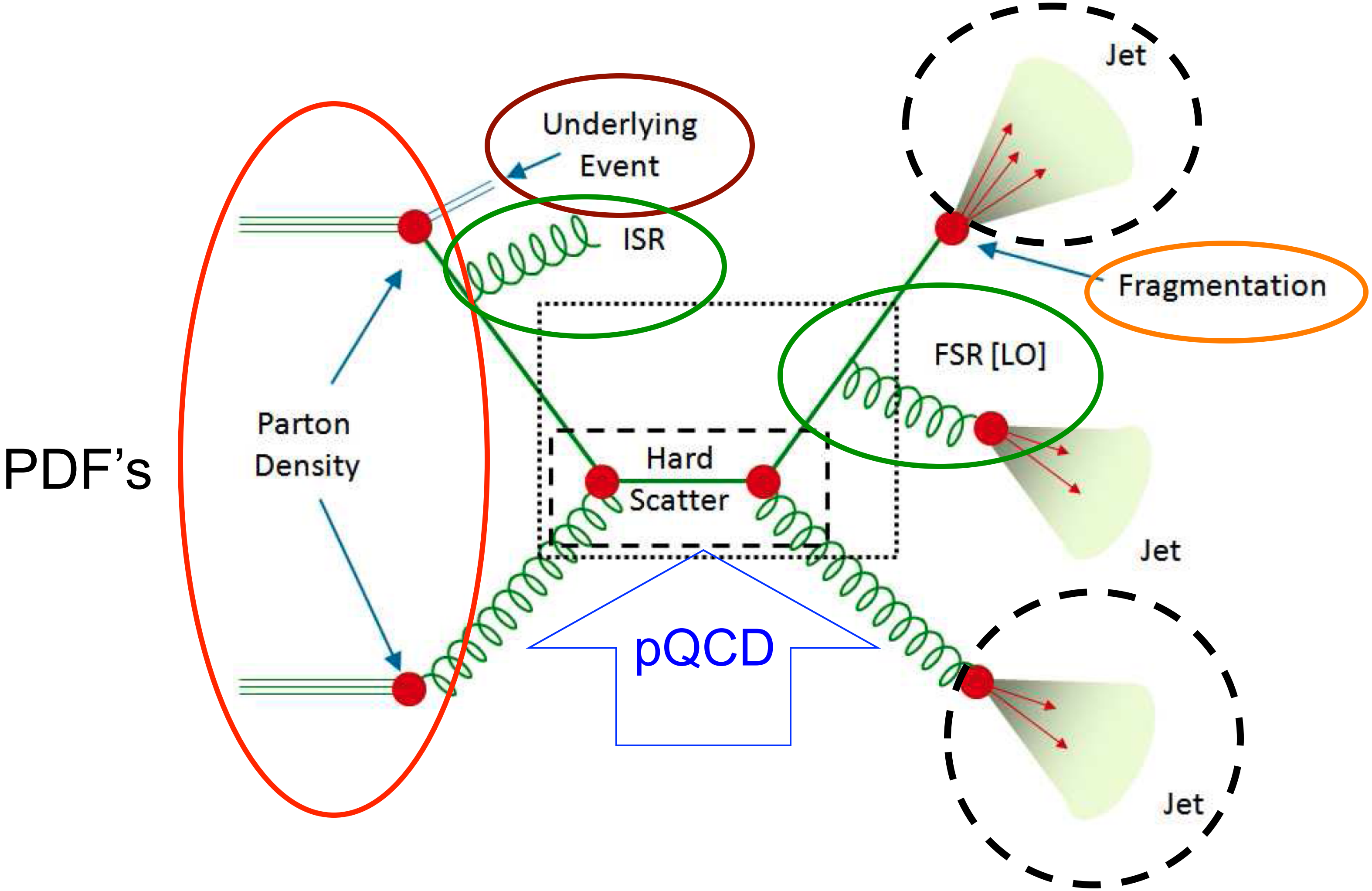
- ✧ sprays of highly collimated hadrons
  - ○ Jets

QCD at Hadron Colliders



✧ multiple parton scattering & underlying event activity
  ○ approximated by MC porgrams with few tunable parameters

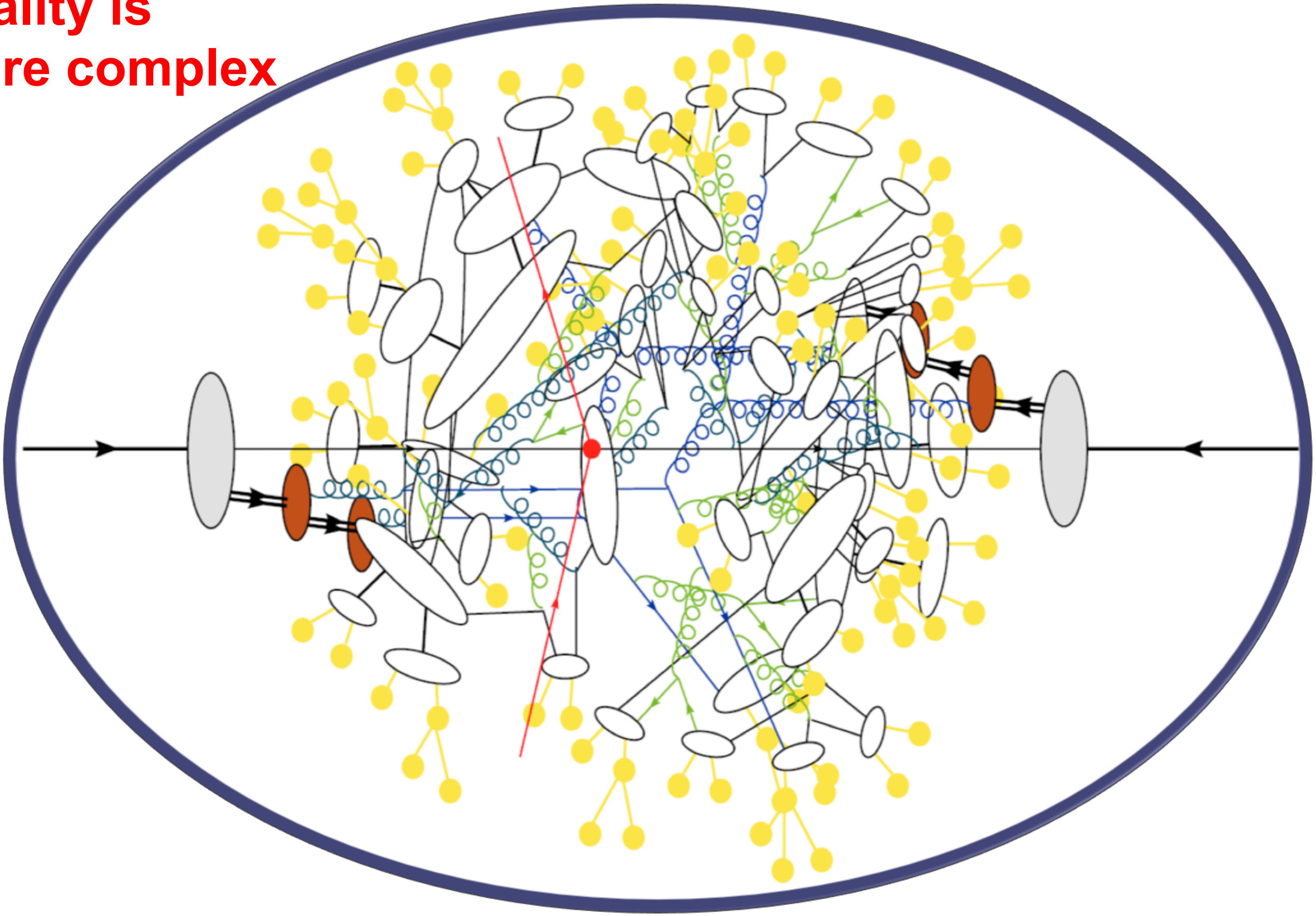
QCD at Hadron Colliders



✧ QCD events: immensely complicated
  ○ theoretical predictions very hard

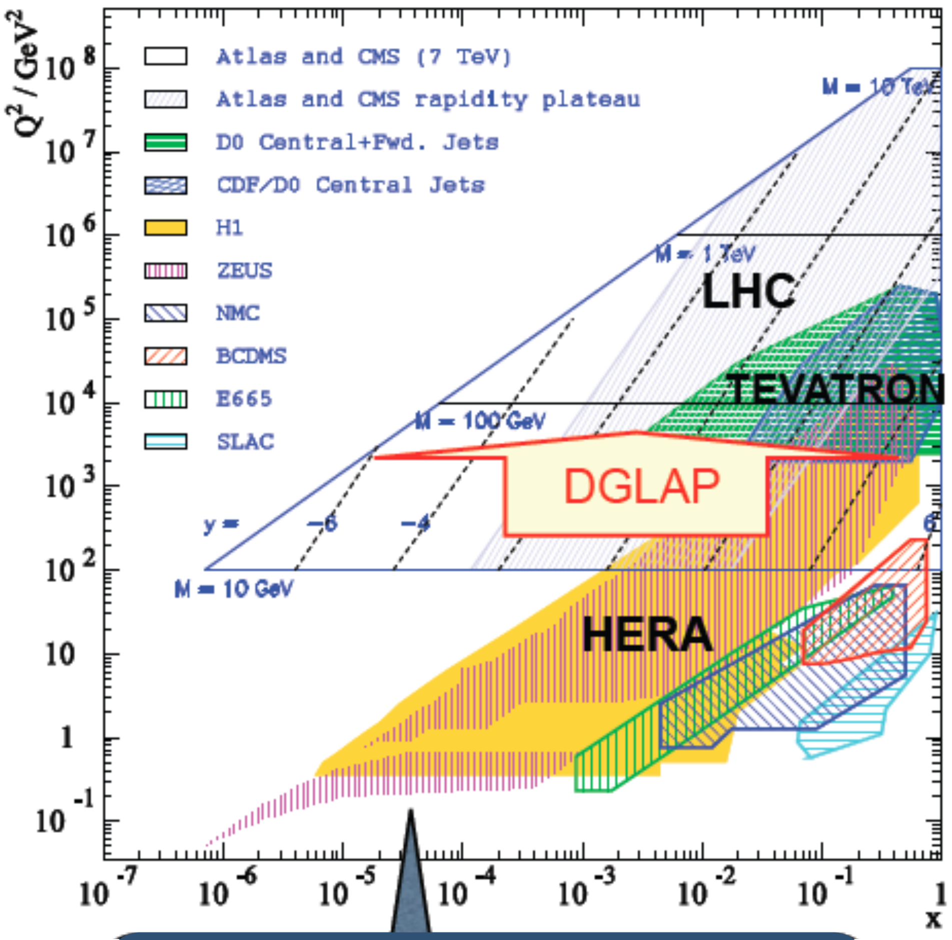
QCD at Hadron Colliders

Reality is more complex



Why do we care about QCD?

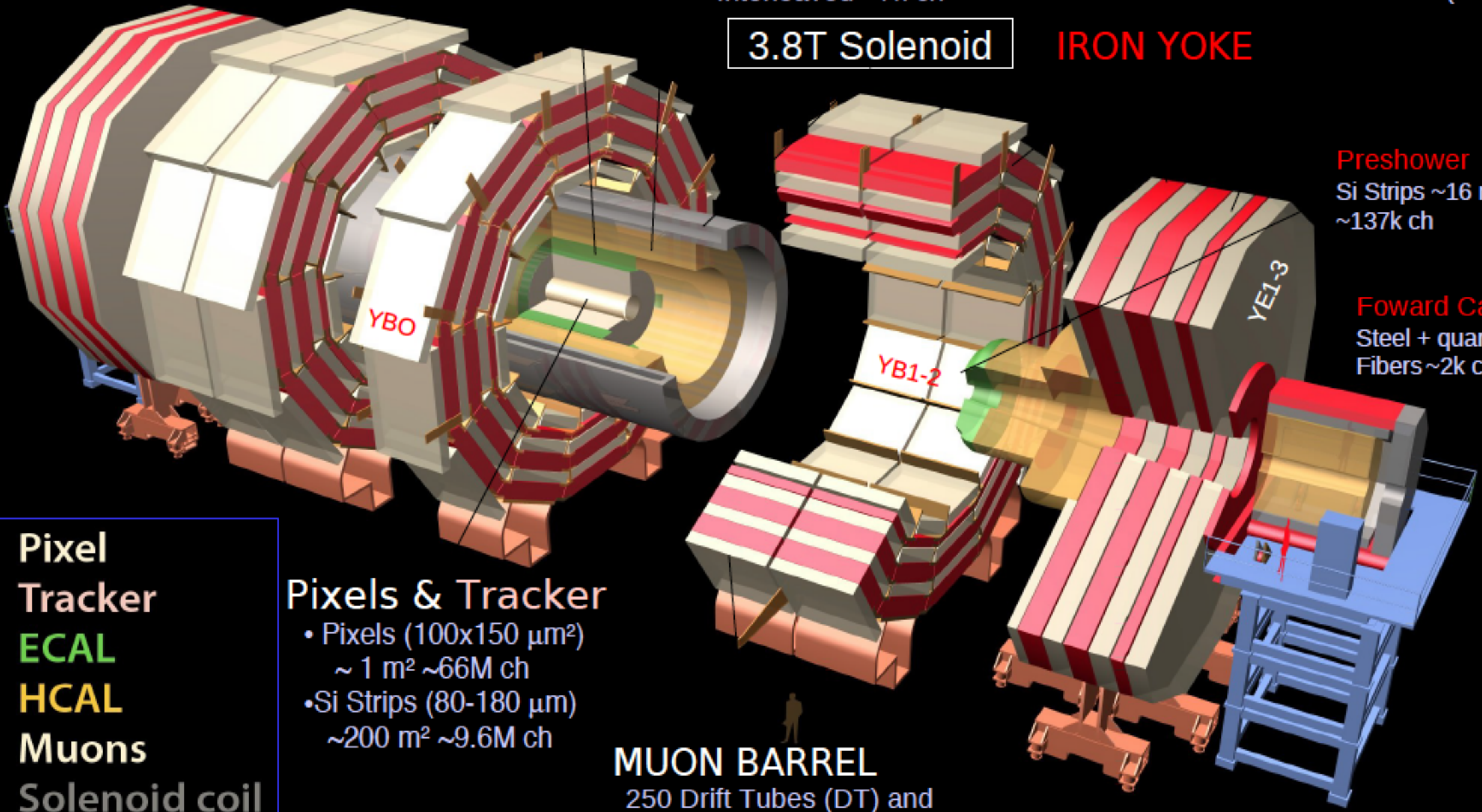
- It is interesting
  - very rich theory: deserves exploration and understanding
- It is inevitable
  - hadron collisions: QCD is always present
- Important background for new physics searches
  - enormous cross section: QCD can hide many possible signals of new physics
- Introduces uncertainties on 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

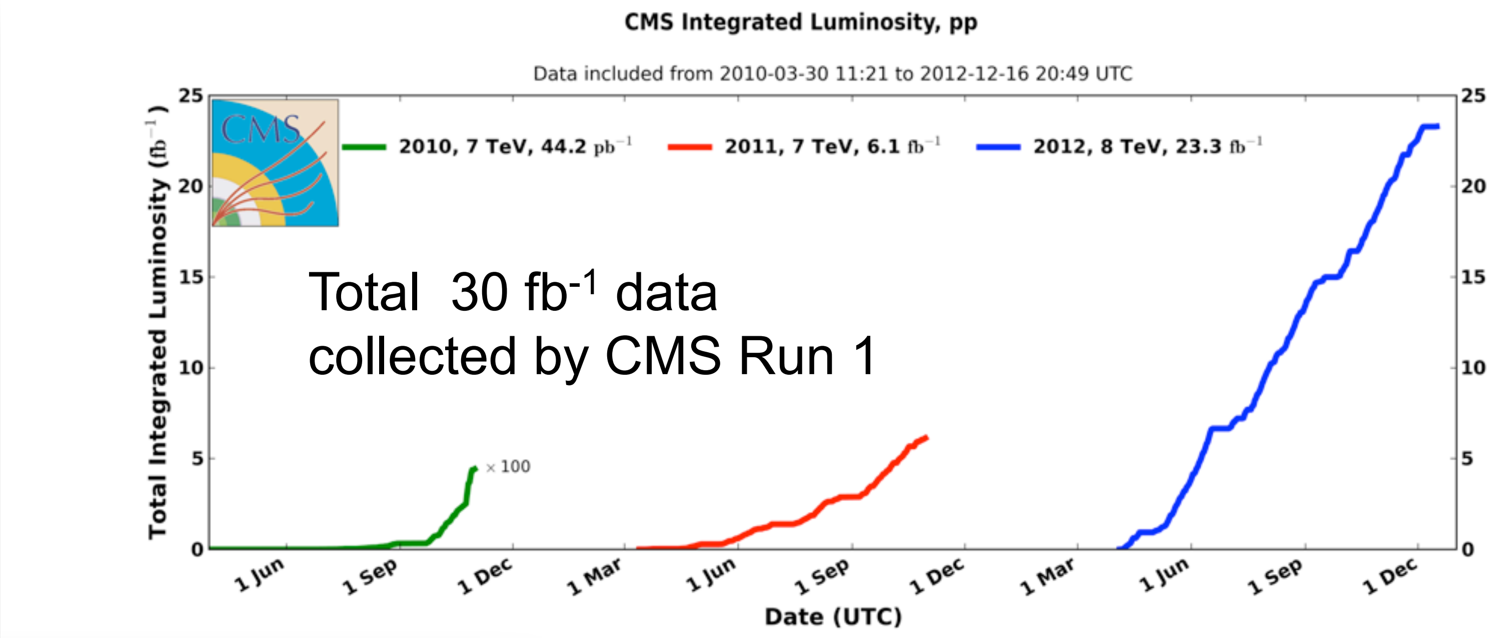
Pixel
Tracker
ECAL
HCAL
Muons
Solenoid coil

Pixels & Tracker

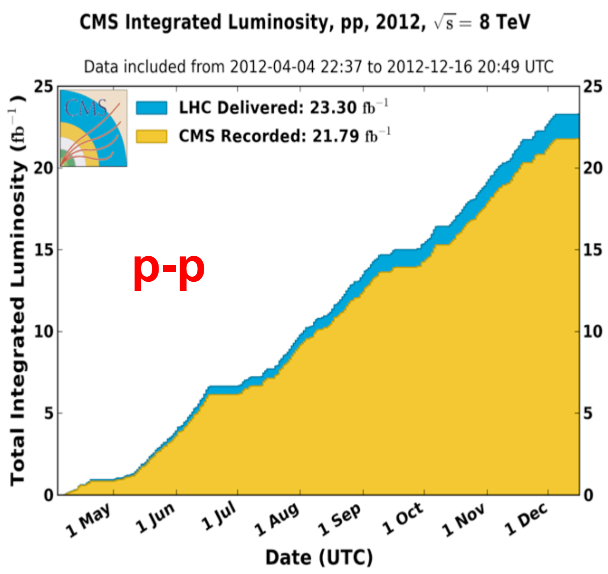
- Pixels (100x150 μm²)
  ~ 1 m² ~66M ch
- Si Strips (80-180 μm)
  ~200 m² ~9.6M ch

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

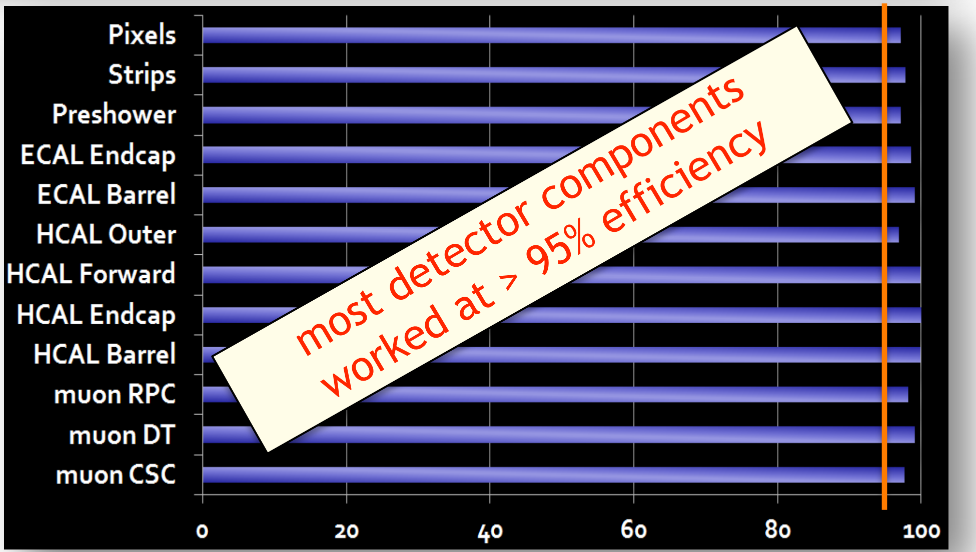
Thanks LHC for Fantastic 3 years!



Total 30 fb^{-1} data
collected by CMS Run 1



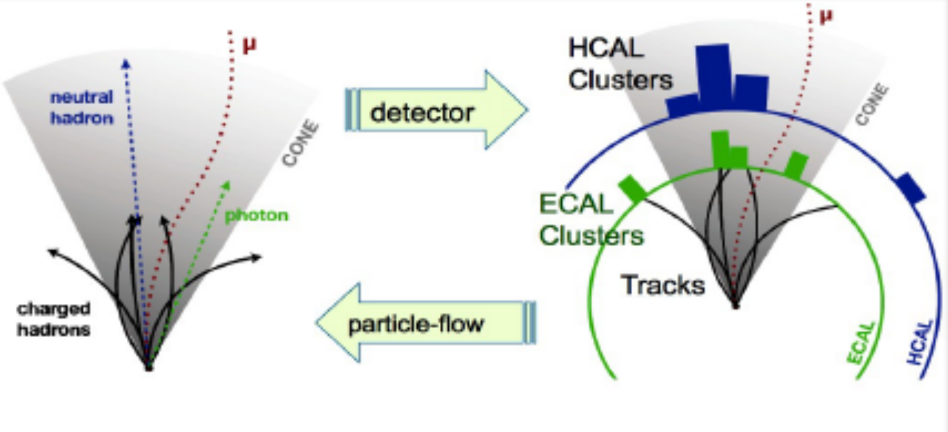
p-p



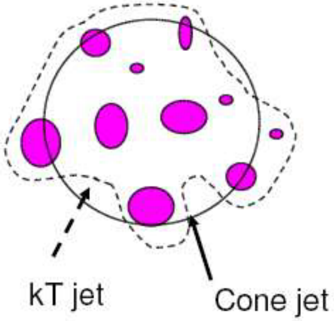
most detector components worked at > 95% efficiency

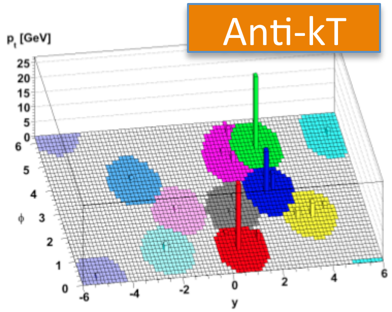
Jet Reconstruction

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



- ☐ 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

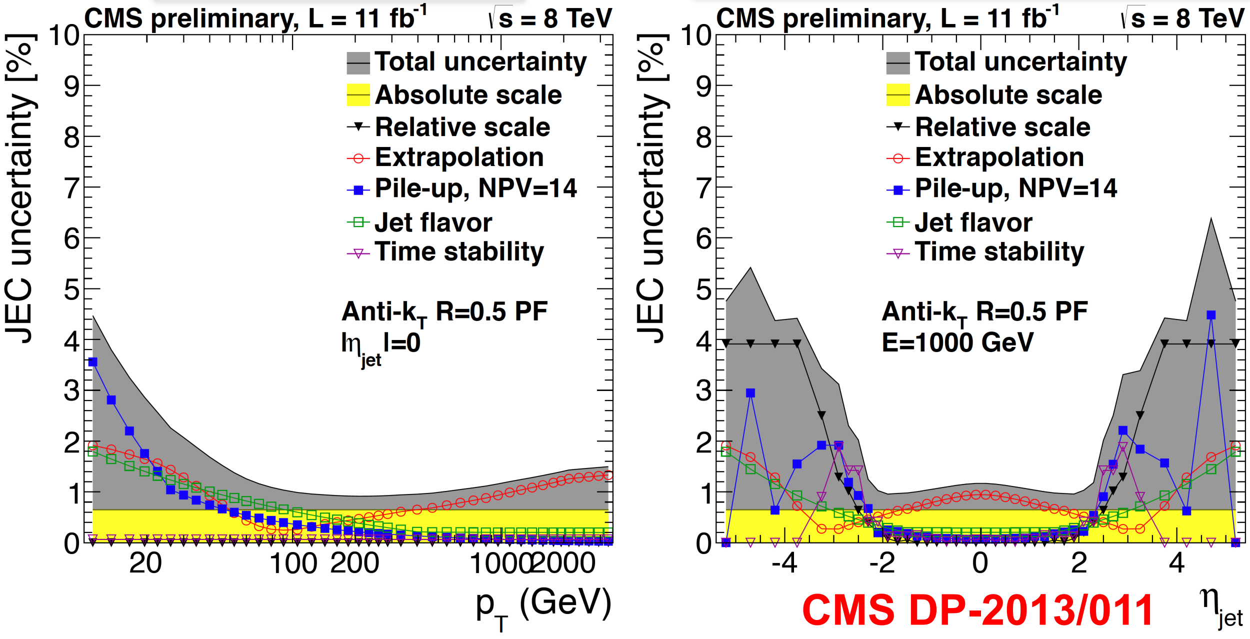
- Jet Energy Correction is necessary to measure the correct energy spectrum of Jets
- The main three type of corrections required are OffSet (pile up subtraction), Relative(for η dependent response) and Absolute(for p_T dependent response) + Residual corrections. [JINST 6 (2011) P11002]
  - Offset –>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

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

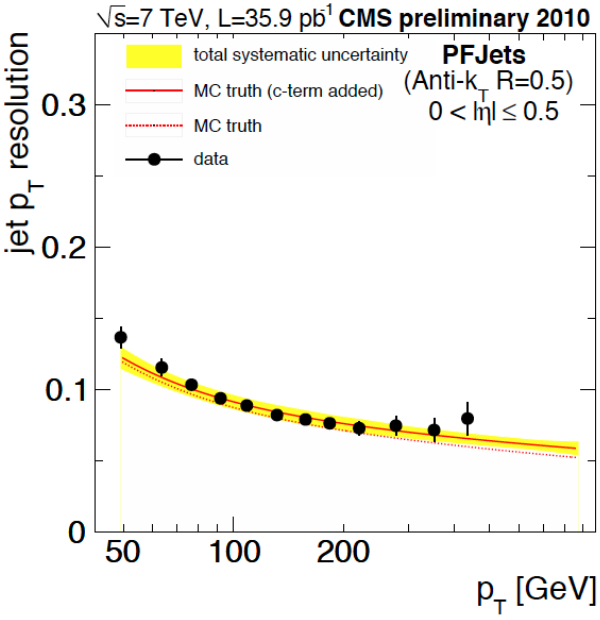
JEC unc vs p_T

JEC unc vs η @ E=1 TeV

Jet p_T Resolution

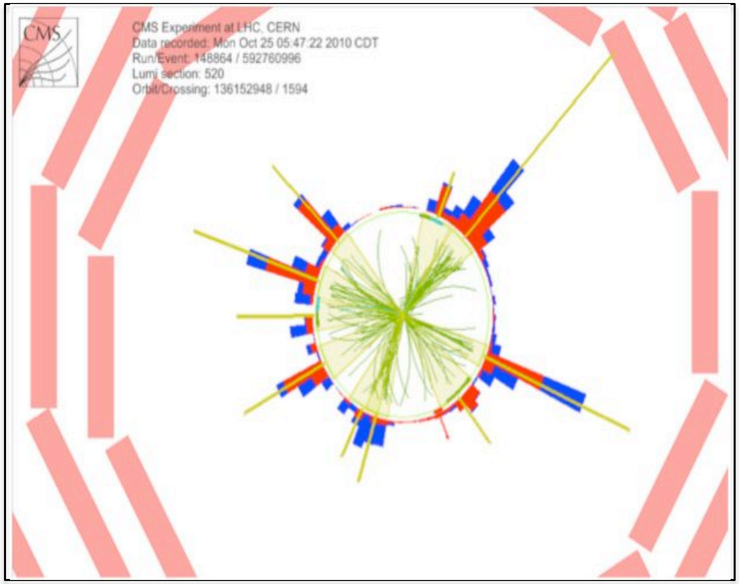


CMS DP-2013/011



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]



The Legacy Measurement

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

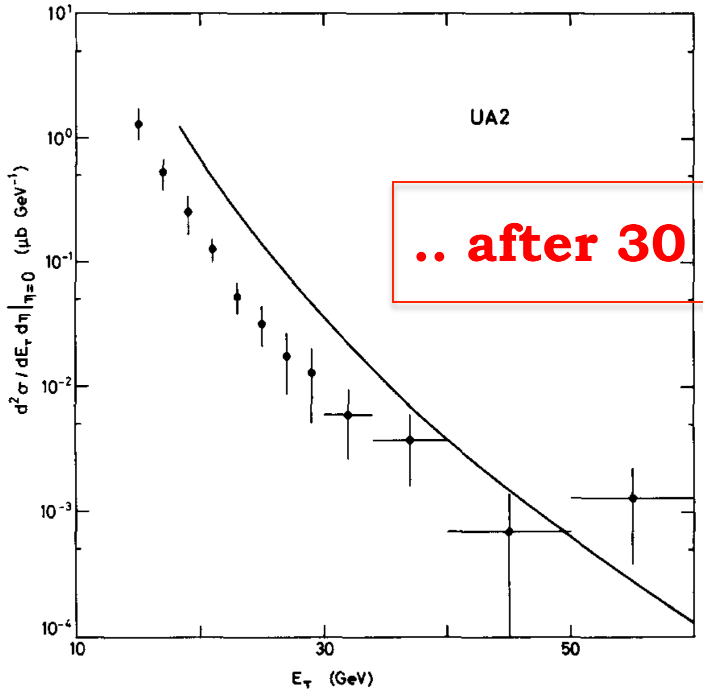
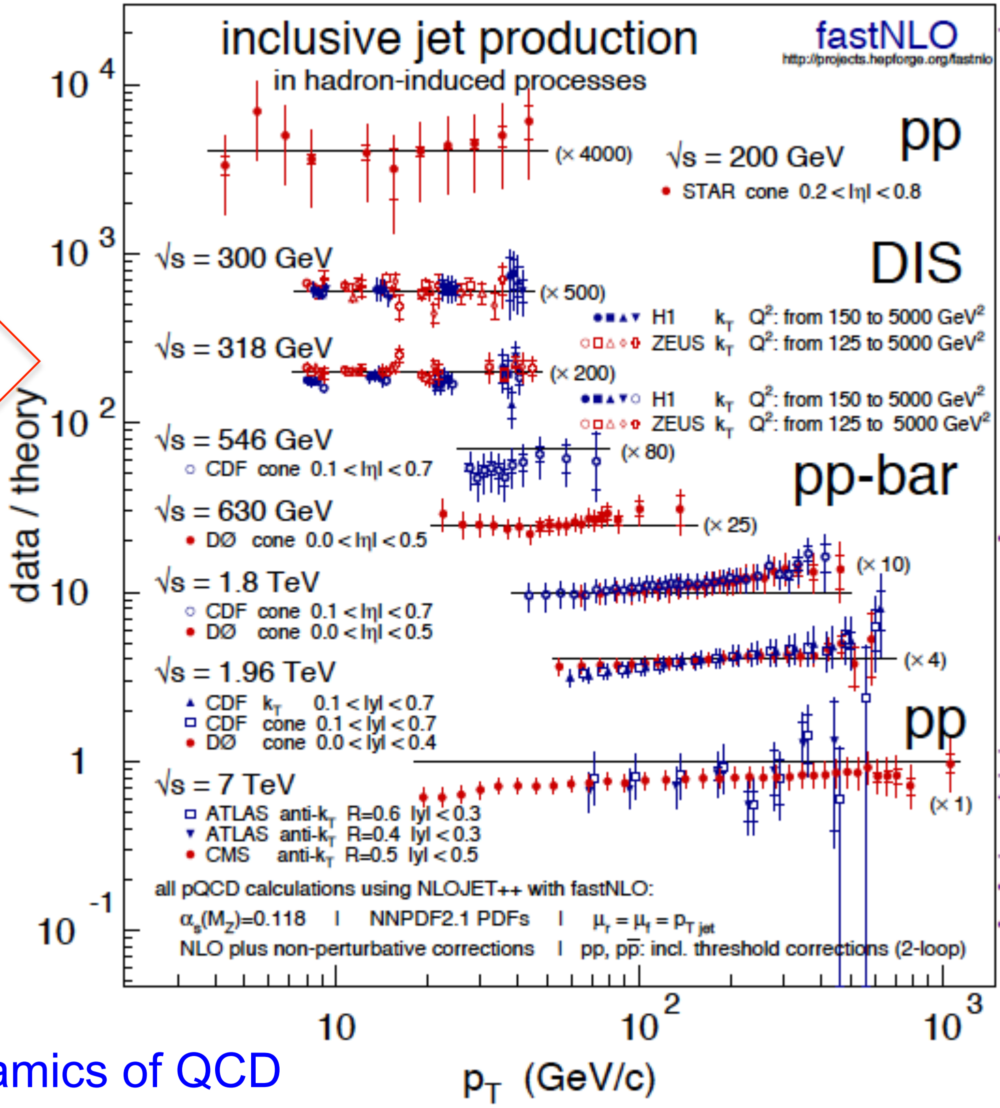


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

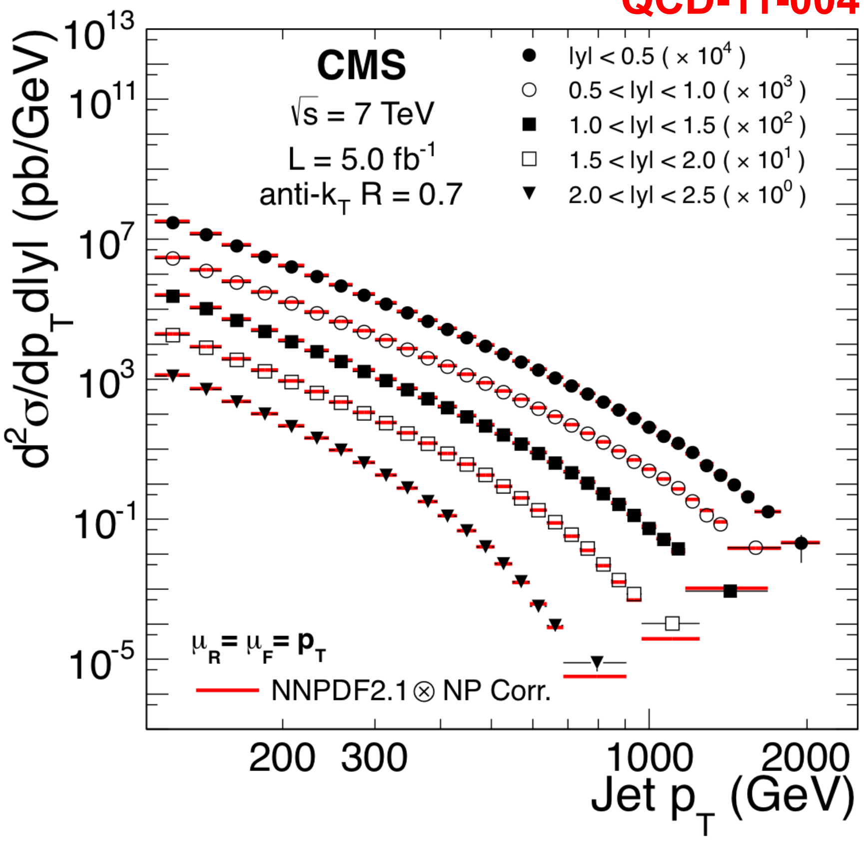
.. after 30 years

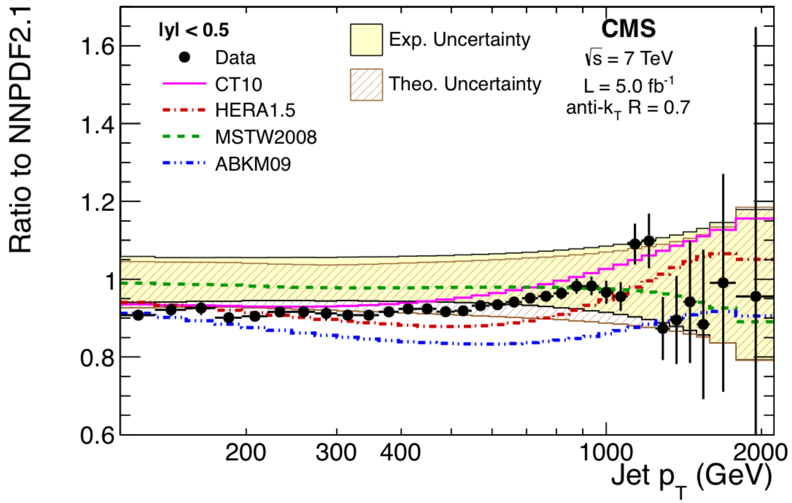


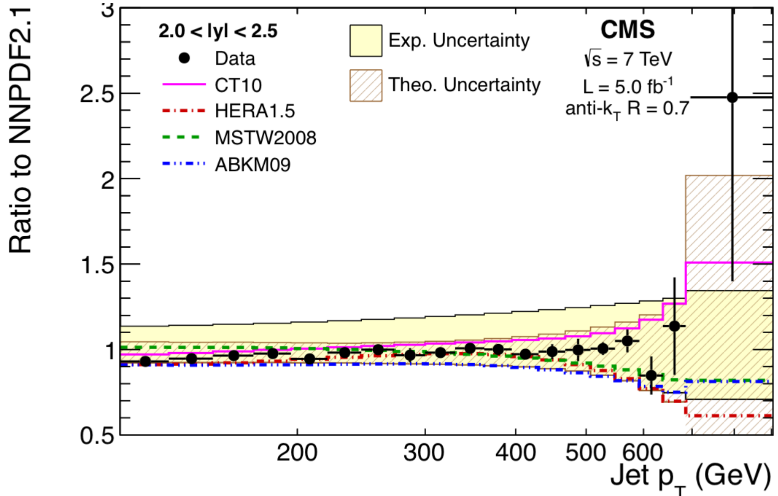
- ☐ Inclusive jet production probes the dynamics of QCD
- counting the number of jets as a function of rapidity and p_T stringent test of QCD
- PDFs, strong coupling constant, perturbative calculations

Inclusive Jet Differential Cross section @ 7 TeV

QCD-11-004



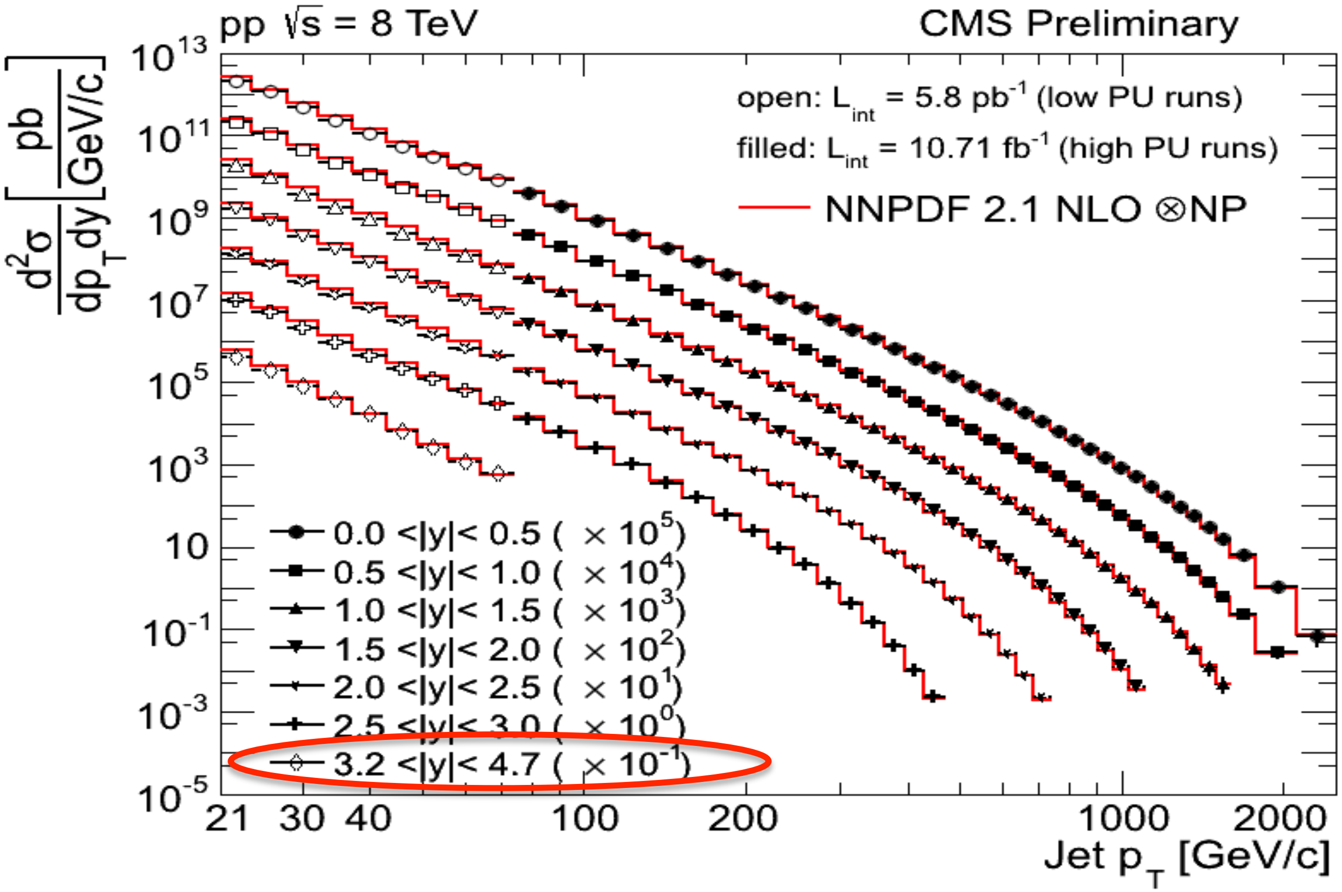




- Double differential Inclusive jet cross-section measured from p_T 0.1 to 2 TeV
- Measured cross sections agree with the predictions of perturbative QCD at next-to-leading order obtained with five different PDF sets
- Theoretical and experimental uncertainties are comparable, even at the limits of the experimental phase space

Inclusive Jet Differential Cross section @ 8 TeV

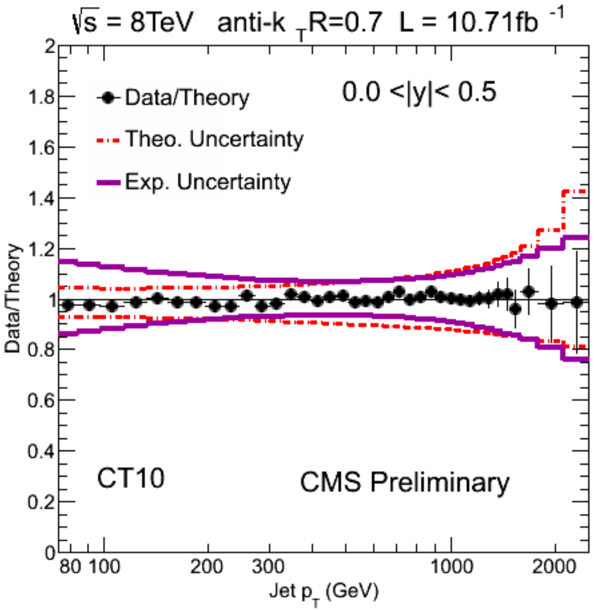
SMP-12-012
FSQ-12-031

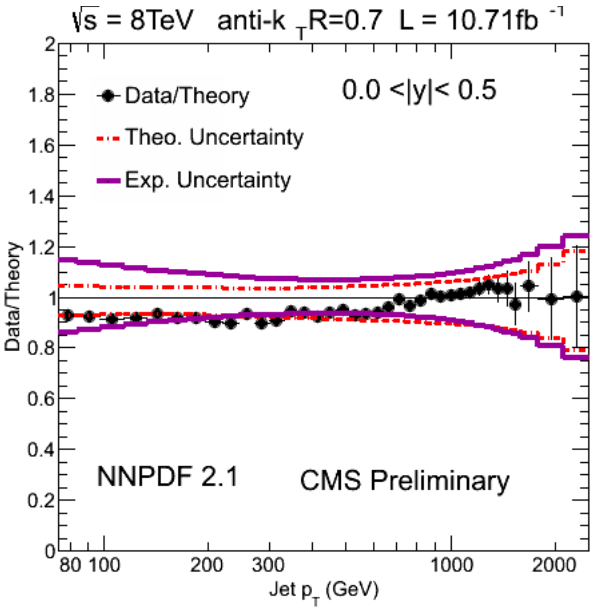


- ☐ Measurement at 8 TeV up to **|y| = 4.7**
- ☐ **O(14)** magnitude in cross section
- ☐ Comparisons to pQCD NLO⊗NP
  [NP: corrections for non-perturbative effects (MPI and hadronization):
  20% (~100 GeV) ➔ 1% (~2.5 TeV)]

Theory Comparisons

SMP-12-012





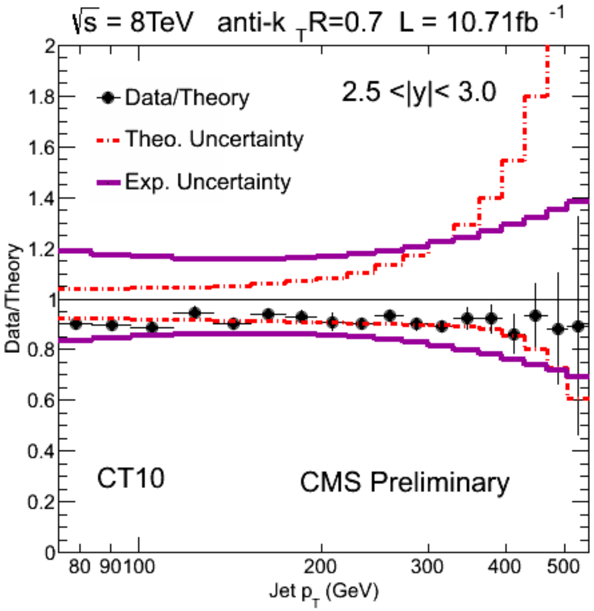
Experimental uncertainty:

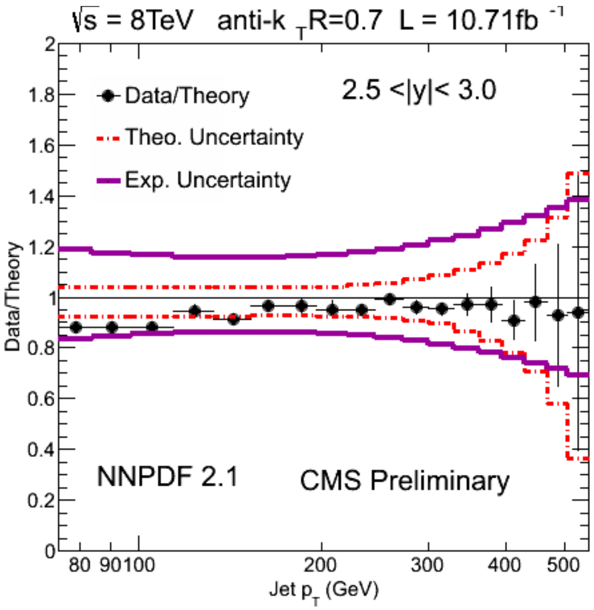
- JES(12%-30%),
- Luminosity(4.4%)
- Unfolding(1%-10%)
- Total: 15%-40%

Theory uncertainty:

- PDF(5%-30%)
- Scale(5%-40%)

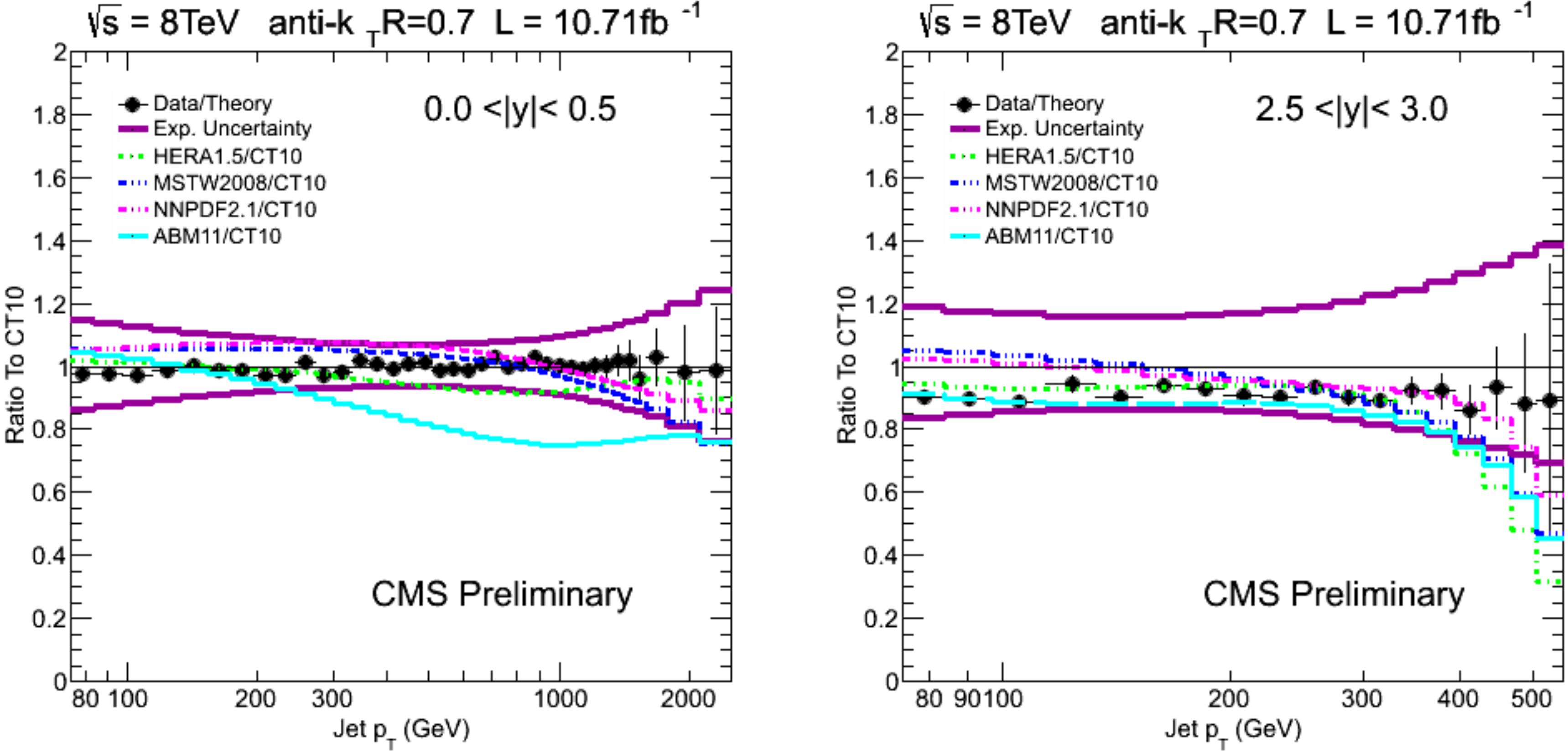
PDF uncertainty for CT10 in outer bins 100%





Comparison among Different PDFs

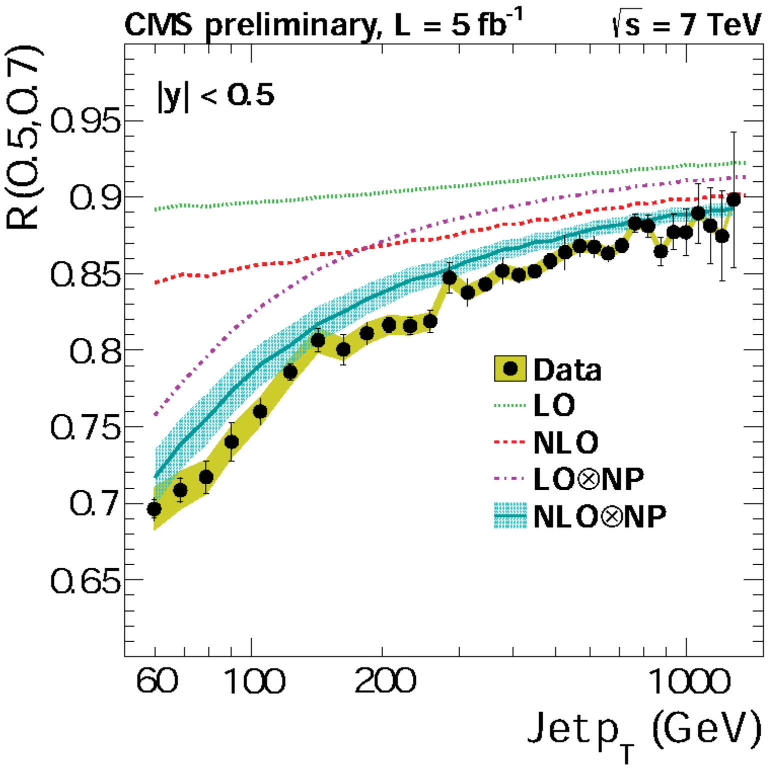
SMP-12-012

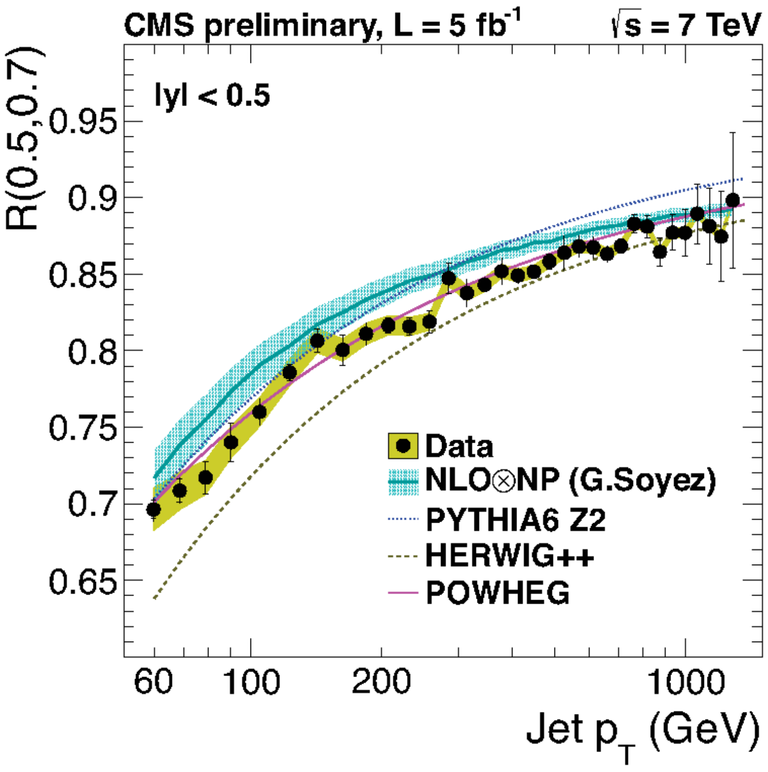


- ☐ Data over theory compared to ratio with other PDF sets for CT10
- ☐ The theory predictions are computed for five different PDF sets, viz. ABM11, HERA1.5, CT10, MSTW2008, NNPDF2.1
- ☐ In the central rapidity region (0.0<|y|<0.5) different theory predictions are in agreement with data except ABM11
- ☐ The fluctuations are covered by total theoretical and experimental uncertainty bands

Inclusive Jet AK5/AK7 Cross Section Ratio

- Motivation: AK5/Ak5 ratio gives insight to QCD effect beyond fixed order
- 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

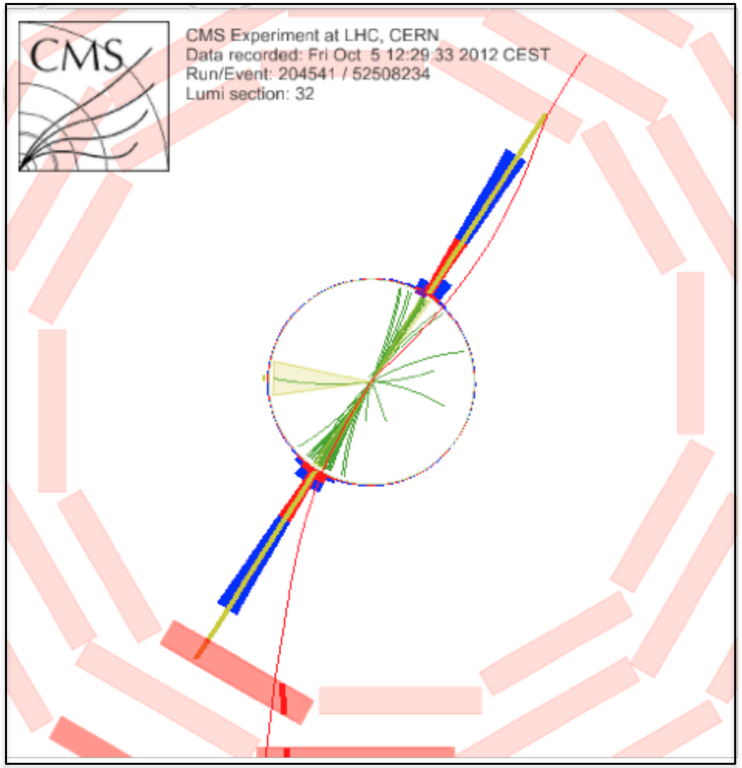
- Several systematic uncertainties cancel in ratio
- The ratio gradually increases towards unity with increasing Jet-p_T
- pQCD predictions without NP corrections in clear disagreement with data
- Powheg(NLO+PS) prediction describes the data best

Dijet Production

- Dijet Differential Cross Section @ 7 TeV [QCD-11-004]

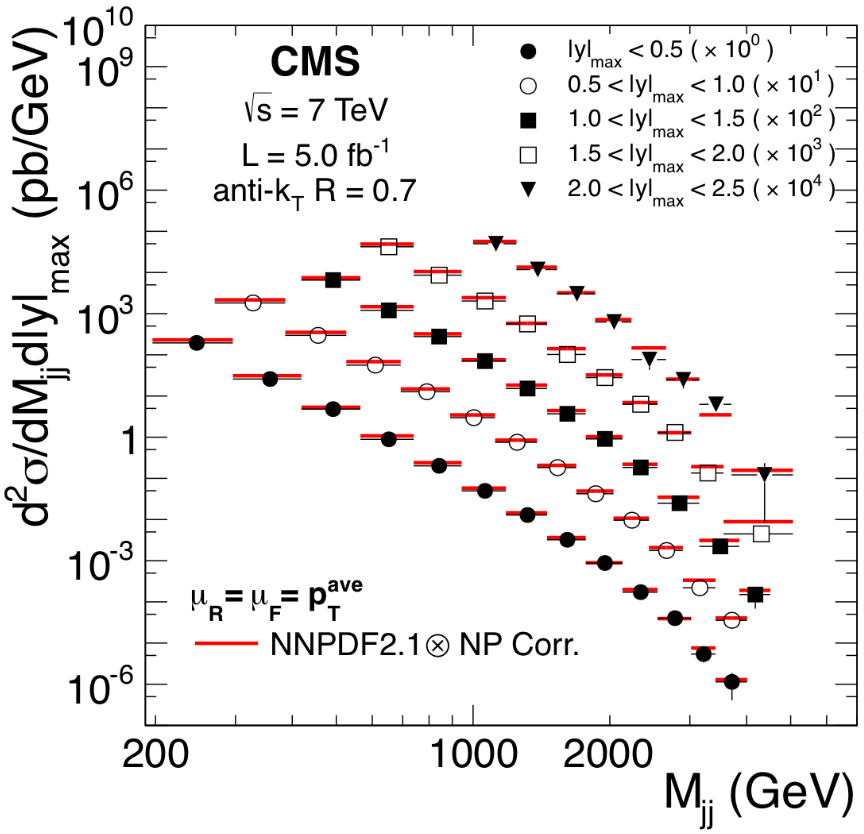
  [Phys. Rev. D **87** (2013) 112002]
- Dijets and V+jets, jet mass and substructure at 7 TeV [SMP-12-019]

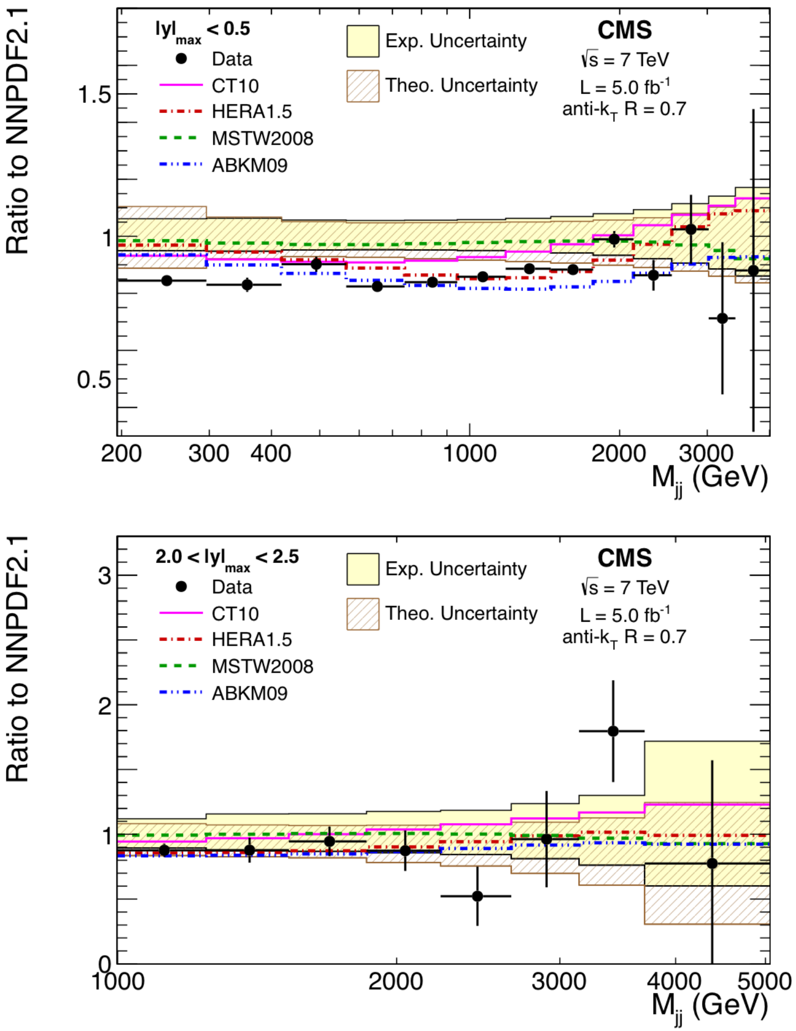
  [JHEP **05** (2013) 090]



Dijet Cross Section @ 7 TeV

QCD-11-004



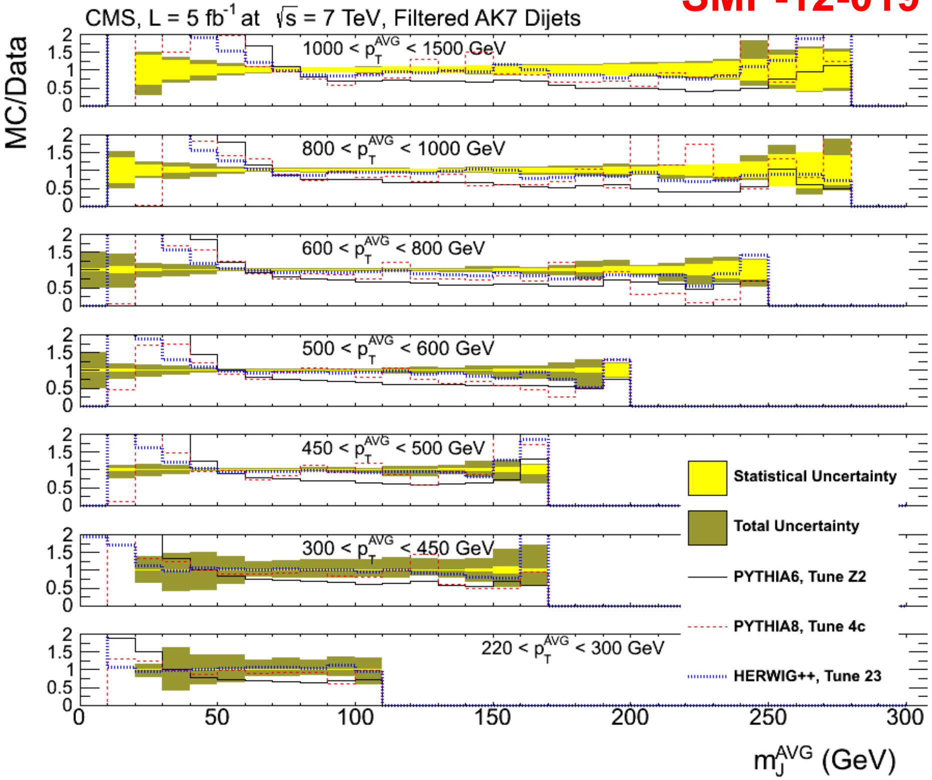


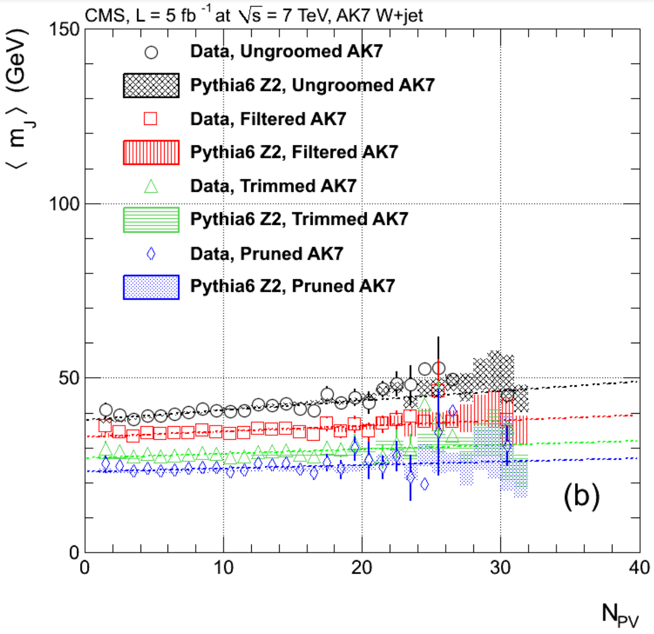
- ☐ Reach up to M_{jj} ~ 5.5 TeV
- ☐ Complementary to Inclusive jets
- ☐ Agreement with pQCD@NLO⊗NP

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





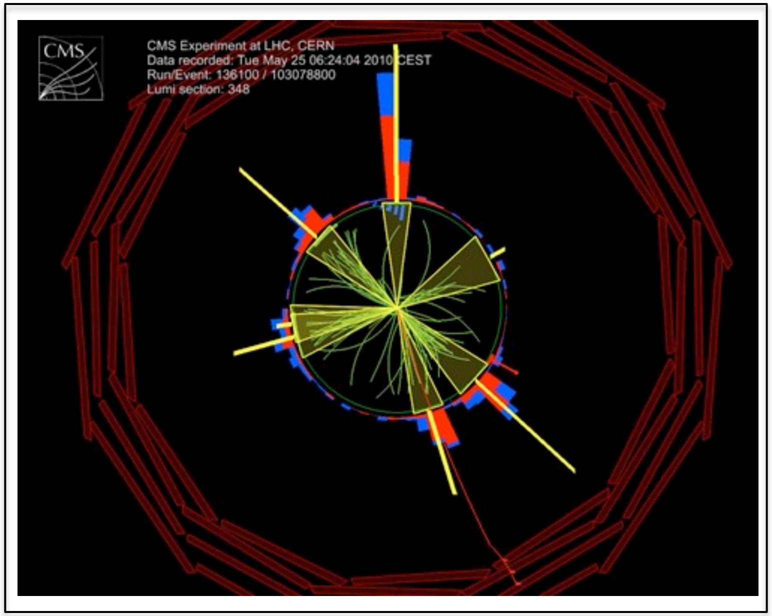
The intrinsic stability of these algorithms to pileup effects contribute to a more rapid and widespread use of these techniques in future high-luminosity runs at the LHC.

- 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 (Today at 3 pm)

MultiJet Production

- Colour Coherence [SMP-12-010]
- 3-Jet Mass cross section [SMP-12-027]
- 3/2 Inclusive Jet Cross section Ratio [QCD-11-003] arXiv:1304.7498
- Measurement of α_S [SMP-12-027, QCD-11-003]



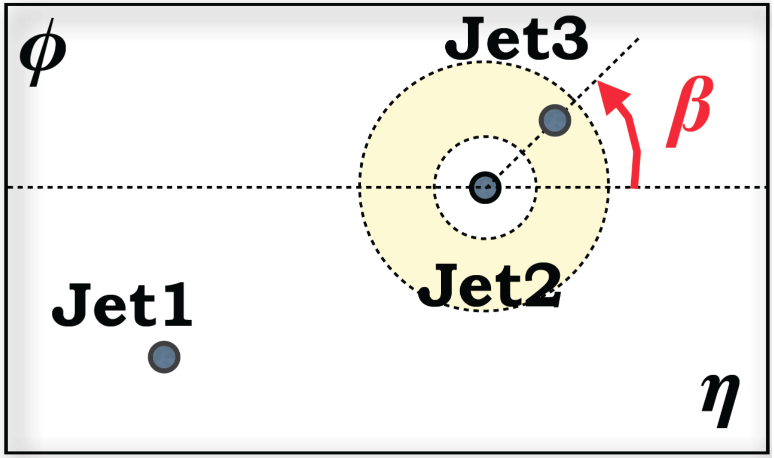
Colour Coherence Effect

- ☐ In QCD color coherence effects are due to the interference of soft gluon radiation emitted along color connected partons
- ☐ In LO model with FSR the 3rd jet tends to be between second jet and proton remnant
- ☐ Measure the angular distribution of softer 3rd jet around the 2nd highest-p_T jet in the event

$$\beta = \tan^{-1}\left[\frac{\mathrm{sign}(\eta_2)\Delta\phi_{32}}{\Delta\eta_{32}}\right]$$

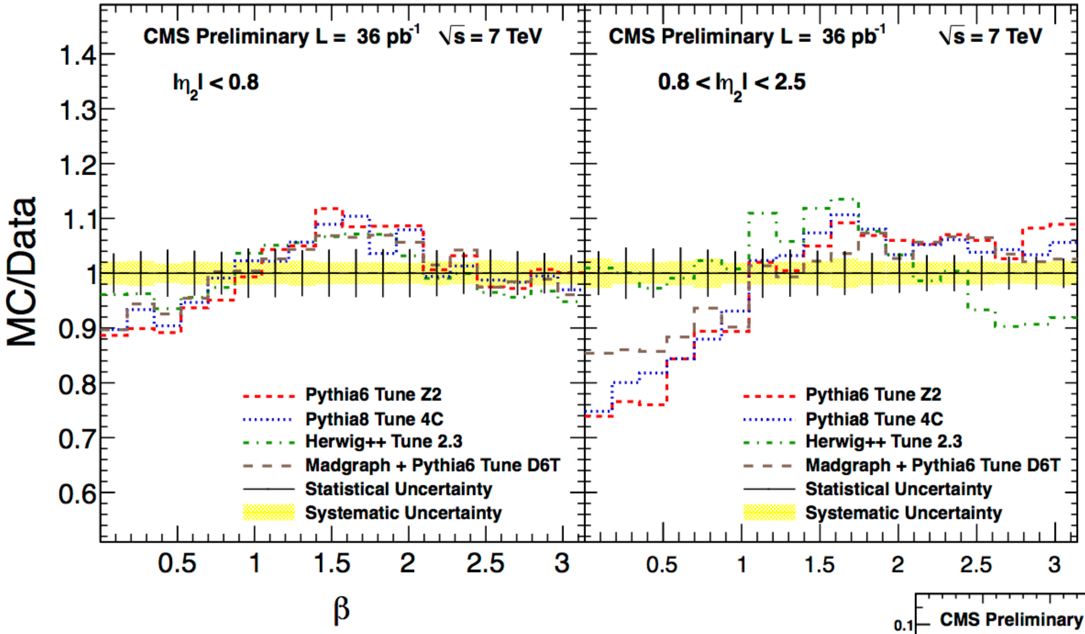
β=0: 3rd jet between 2nd & closest proton remnant

β=π: 3rd jet between 2nd & far most proton remnant



- ☐ Ideally, e+ e- collider is the best place to do the measurement
  - No color interference from the initial state
- ☐ In pp, both initial and final states have color constituents
  - Complicate the signatures
  - Comparison with MC is crucial
- ☐ Compare data to event generators with different color coherence implementations

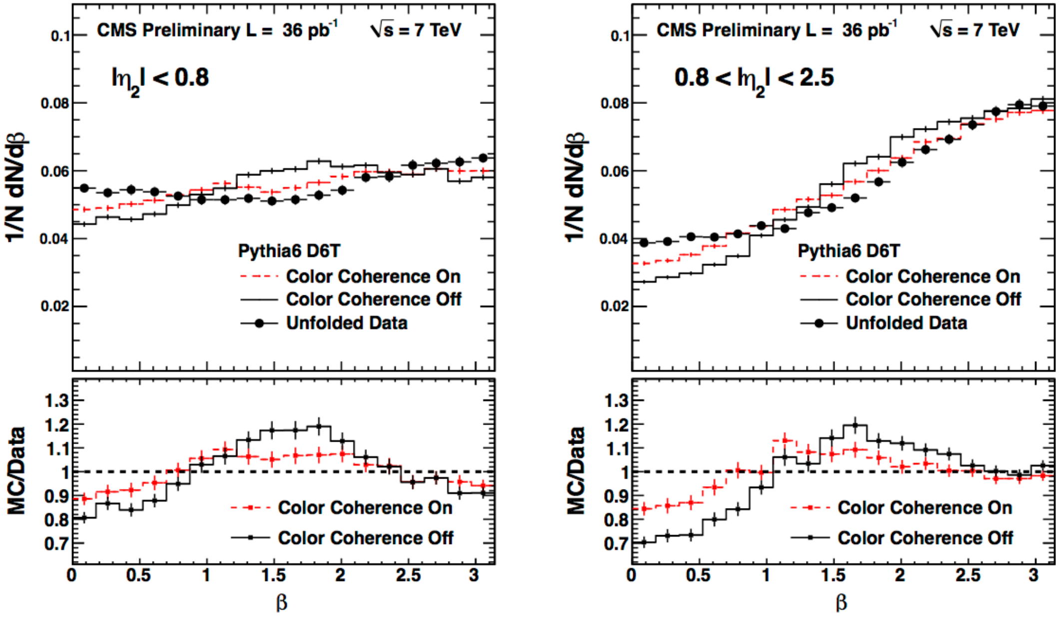
Colour Coherence Results



- Data are unfolded to the particle level
- The data exhibit a clear enhancement of events compared with the PYTHIA and MADGRAPH generators near the event plane (β = 0) and a suppression in the transverse plane (β = π/2)

SMP-12-010

- Comparisons of the β distributions to various MC predictions
  - Herwig++ describes the data β distributions best
- Data clearly support larger color coherence effects in Pythia 6



3-Jet Mass Cross Sections @ 7 TeV

Measurement of double diffrential cross section: $d^2\sigma/dm_3dy_{max}$

- sensitivity to PDFs and α_S

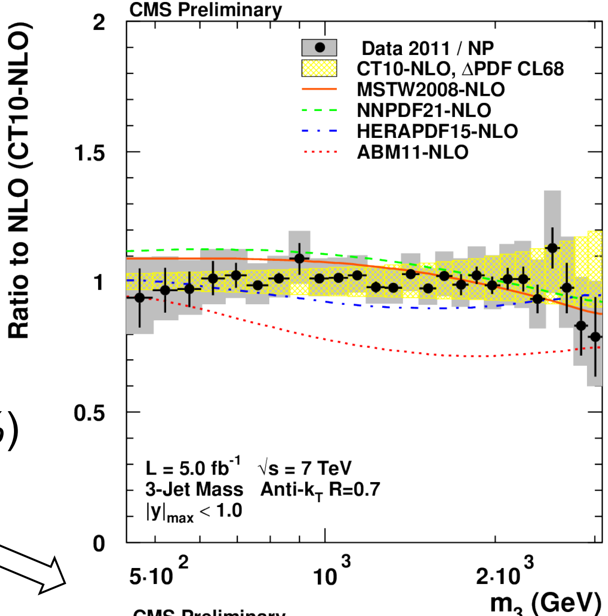
☐ $m_3^2 = (p_1+p_2+p_3)^2$ $|y_{max}|=\max(|y_1|,|y_2|,|y_3|)$ $Q=m_3/2$

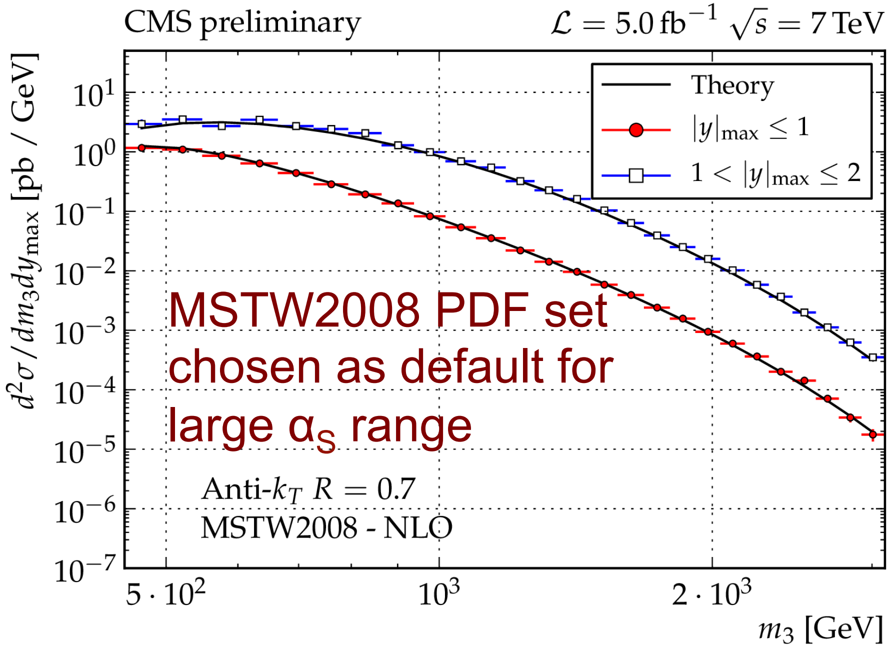
☐ Require jet p_T > 100 GeV

☐ Regions: $|y_{max}| < 1$ and $1<|y_{max}|<2$

☐ Agreement with pQCD @ NLO $\otimes$ NP (*NP correction 8% -> 1%*)

- Deviations observed with NLO + ABM11 PDFs

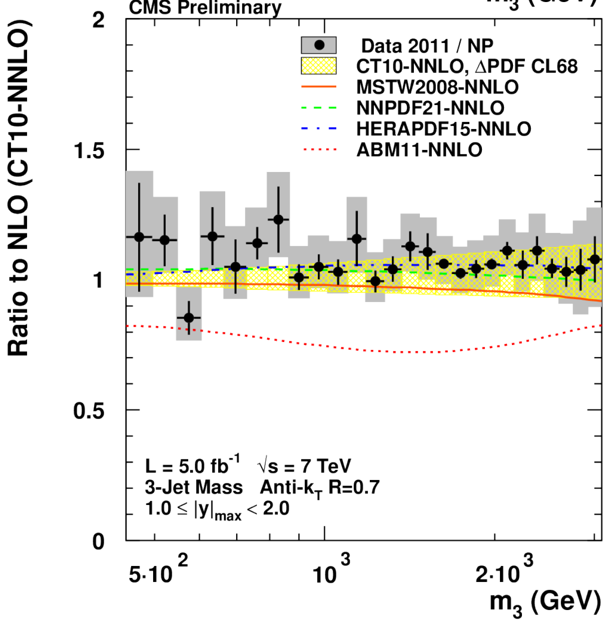




MSTW2008 PDF set chosen as default for large α_S range

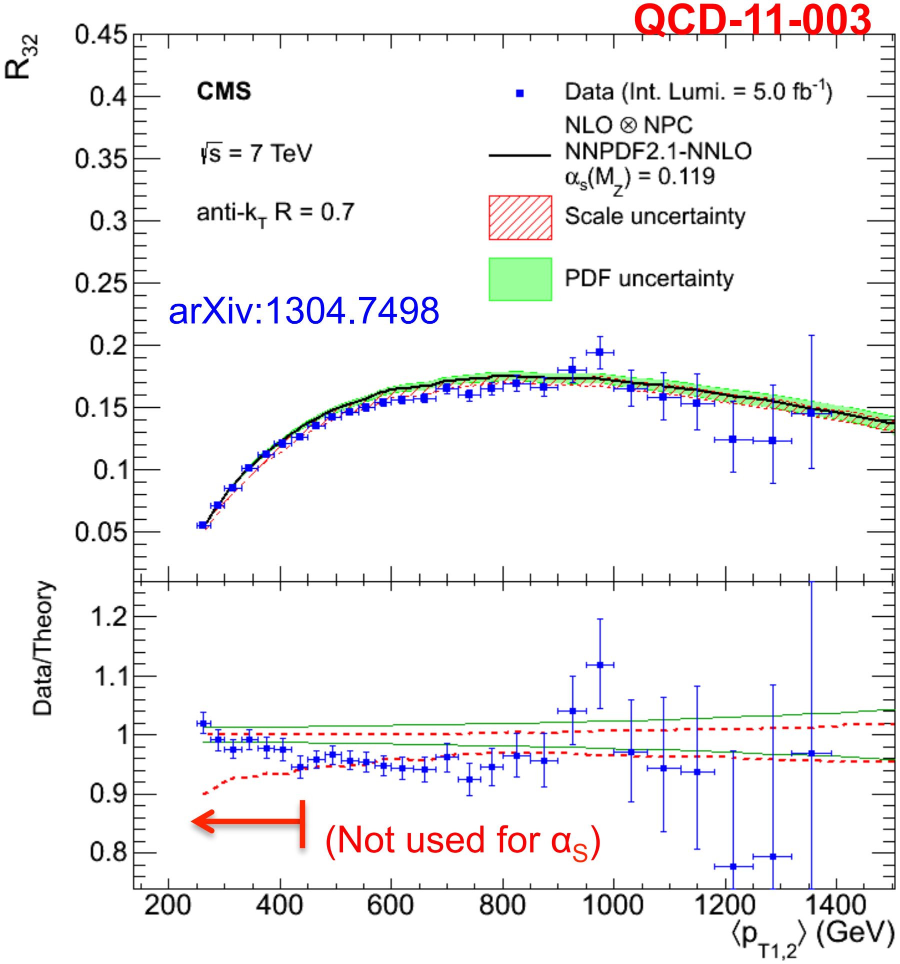
SMP-12-027

Reach up to m_3 ~ 3 TeV



3-jet over 2-jet Cross Section Ratio

QCD-11-003

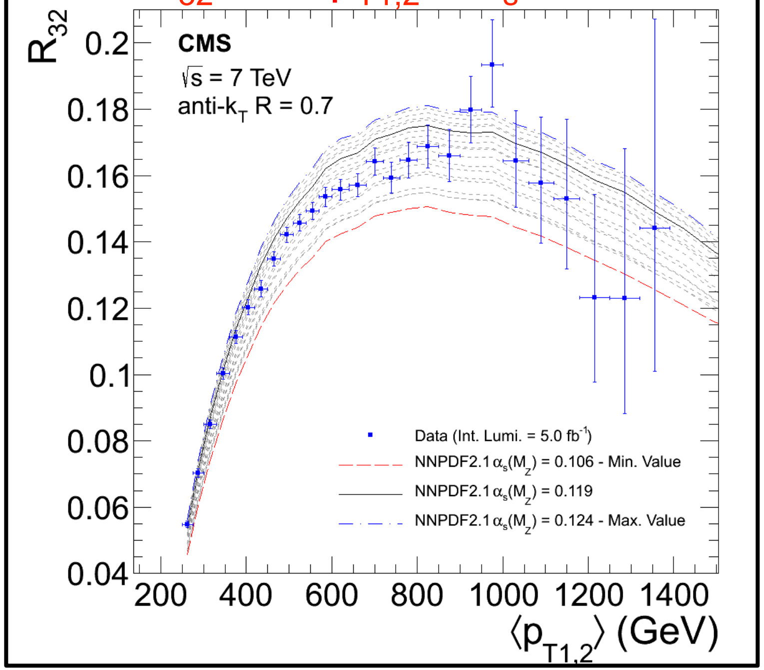


arXiv:1304.7498

(Not used for α_S)

- **R_{32}**: Probability to find a 3rd jet in an inclusive dijet event
- Sensitive to higher order radiation and α_S
- Almost independent of PDFs
- NLO QCD predictions with NNPDF2.1, MSTW2008, CT10 PDFs in agreement with the measured R_{32}
- $R_{32} \propto \alpha_S(Q)$ data are used to extract α_S

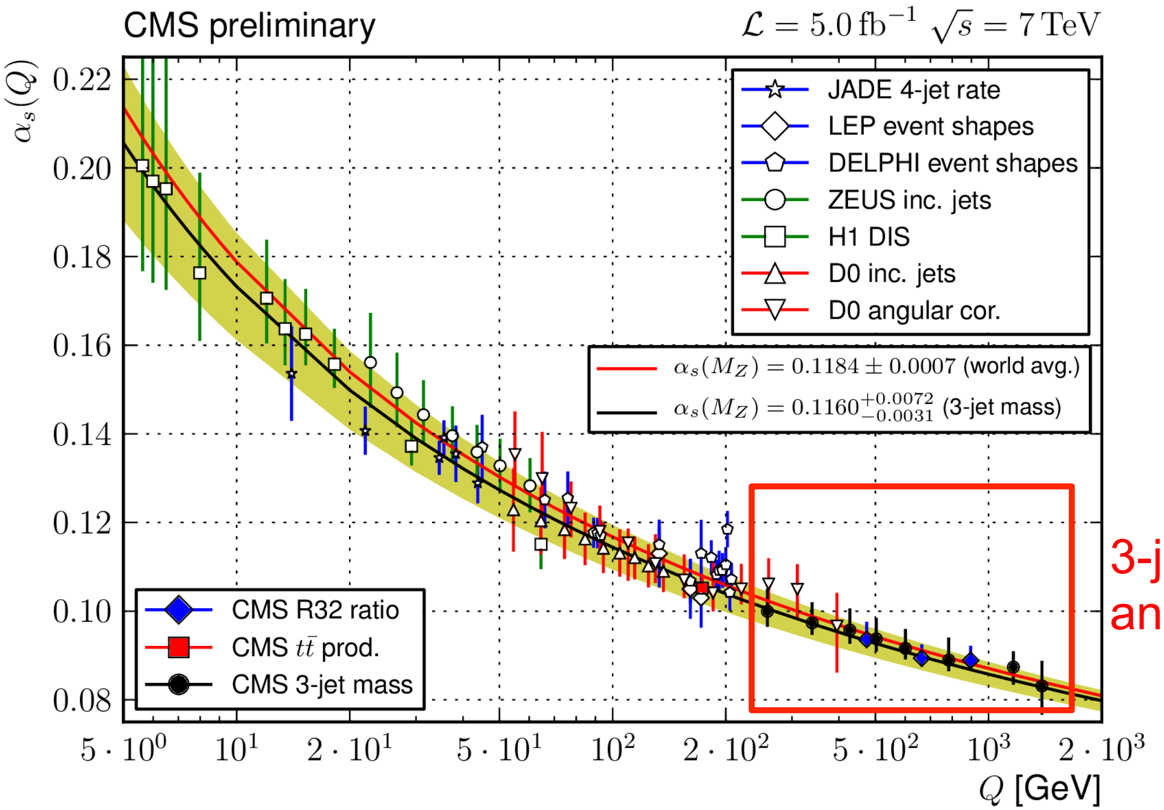
R_{32} vs. $\langle p_{T1,2} \rangle$: α_s scan



$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \to n \ \ jets \ + X; \ n \geq 3)}{\sigma(pp \to n \ \ jets \ + X; \ n \geq 2)} \quad \text{vs} \ \langle p_{T1,2} \rangle = \frac{p_{T1} + p_{T2}}{2}$$

Measurement of α_S

SMP-12-027
QCD-11-003
arXiv:1304.7498



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 $\alpha_S(M_z)= 0.1184 \pm 0.0007$
  - **For the first time probing the > 1 TeV scale, reaching upto ~ 1.5 TeV**
- Dominated by theoretical uncertainties (PDF and scale)

R_{32}: $\alpha_S(M_z)=0.1148 \pm 0.0014$ (exp.) $\pm$ 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 at 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 $\boldsymbol{\alpha}_S$ 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