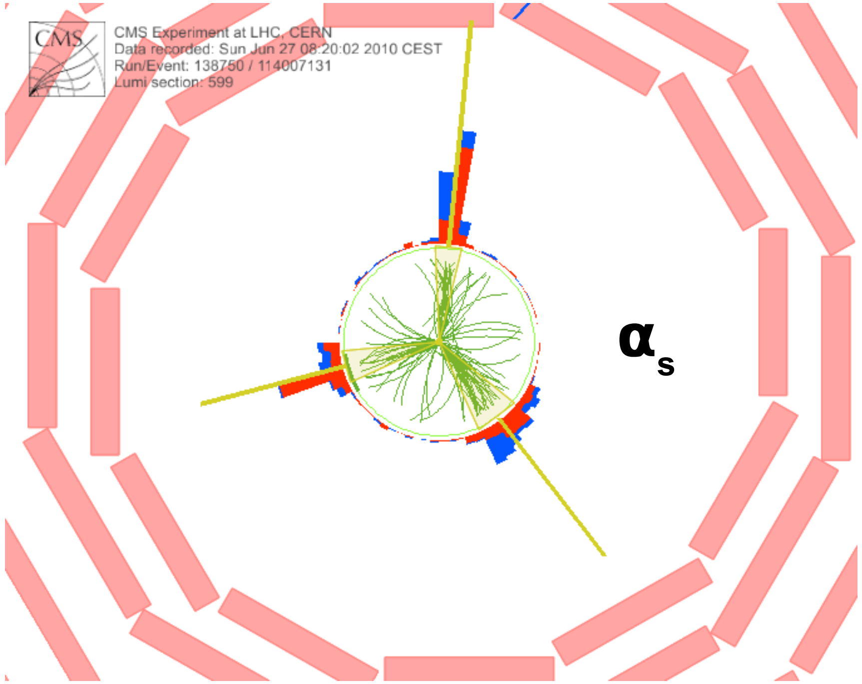
Jet and Event Shape Observables at LHC

Klaus Rabbertz
Institut für Experimentelle Kernphysik

Karlsruhe Institute of Technology

The Menu

- Experimental Uncertainties
- Absolute Measurements
- Shape Measurements
- Ratio Measurements
- Discussion



QCD at work ...

Experiment Pages for public Results:

ATLAS public results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic
CMS public results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResults
ALICE publications: http://aliweb.cern.ch/Documents/generalpublications
LHCb publications: https://lhcb-doc.web.cern.ch/lhcb-doc/Published Papers/default.htm

No extractions of α_s from LHC yet, good time for this workshop ...

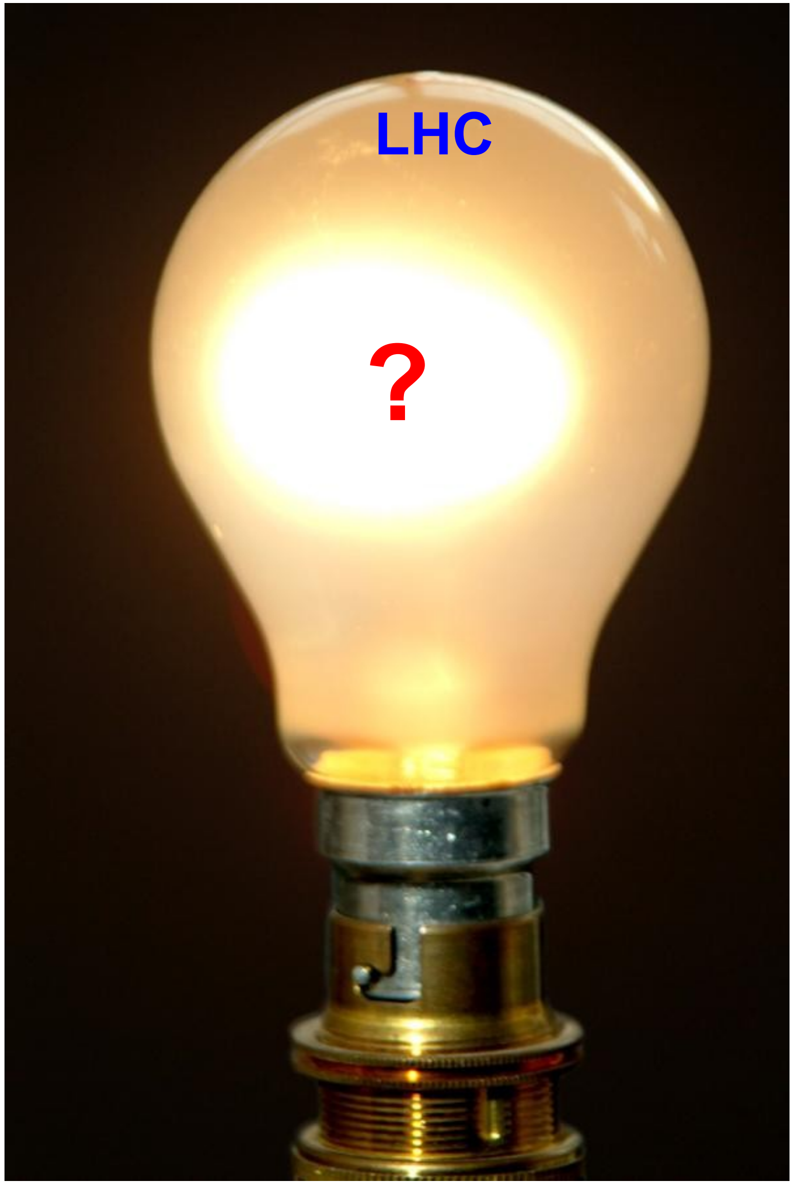
Jet Analysis Uncertainties

- Experimental Uncertainties (~ in order of importance):
  - Jet Energy Scale (JES)
    - Noise Treatment
    - Pile-Up Treatment
  - Luminosity
  - Jet Energy Resolution (JER)
  - Trigger Efficiencies
  - Resolution in Rapidity
  - Resolution in Azimuth
  - Non-Collision Background
  - • • •

- Theoretical Uncertainties:
  - PDF Uncertainty
  - pQCD (Scale) Dependence
  - Non-perturbative Corrections
  - PDF Parameterization
  - NLO-NLL matching schemes
  - Electroweak Corrections
  - Knowledge of $\alpha_s(M_Z)$
  - • • •

This is what we want to improve on here

Luminosity



Common to all cross section measurements:

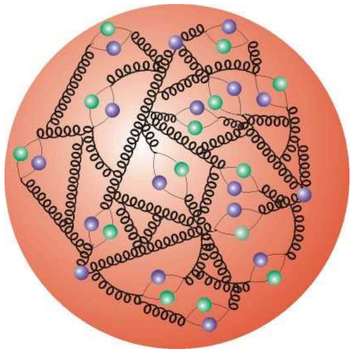
Initial Uncertainty: 11%

ATLAS arXiv:1101.2185v1, CMS-PAS-EWK-10-004

From van-der-Meer Scans:
Uncertainty dominated (10%) by beam intensity measurement

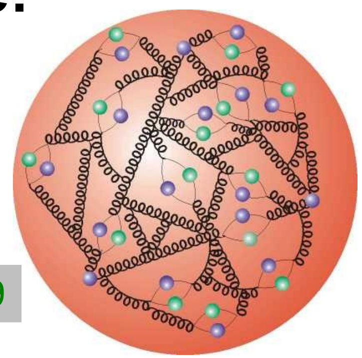
Ultimately achievable:

↘ 5% ?



?

S.White: CERN-THESIS-2010-139



HERA-Proton,DESY

Jet Energy Scale

Pre-Data Assumptions: **~ 10% → up to 60% uncertainty on cross sections**

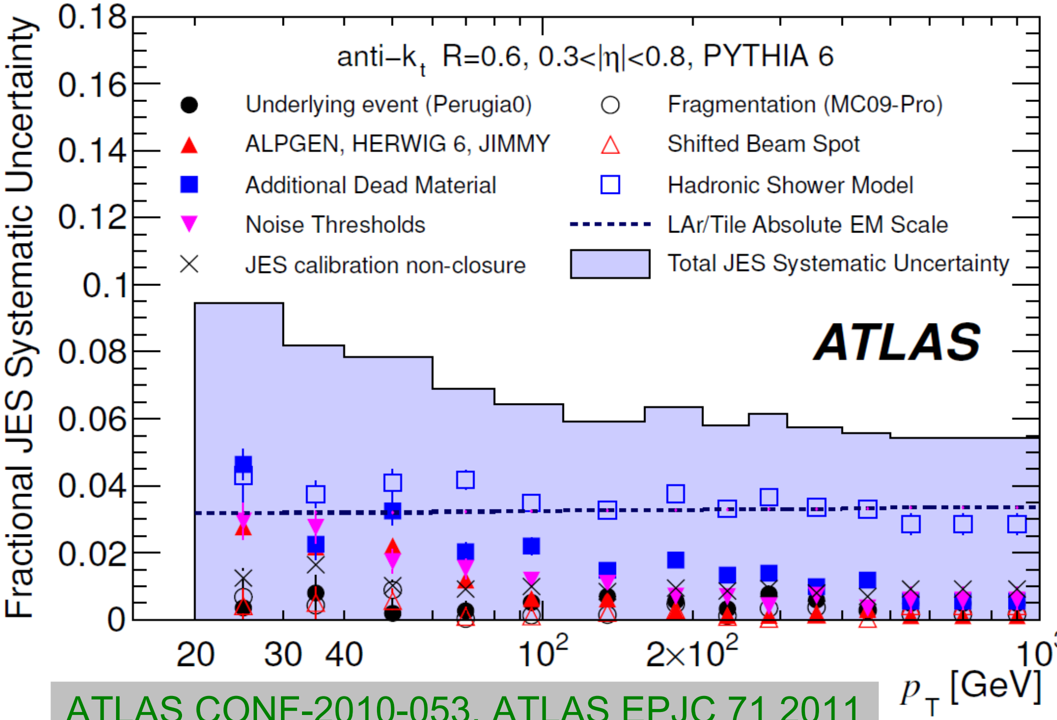
This year at ICHEP and later: **5 - 10%**

Very good detector performances observed, MC modelling works better than anticipated.

Can expect further improved results from both experiments ...

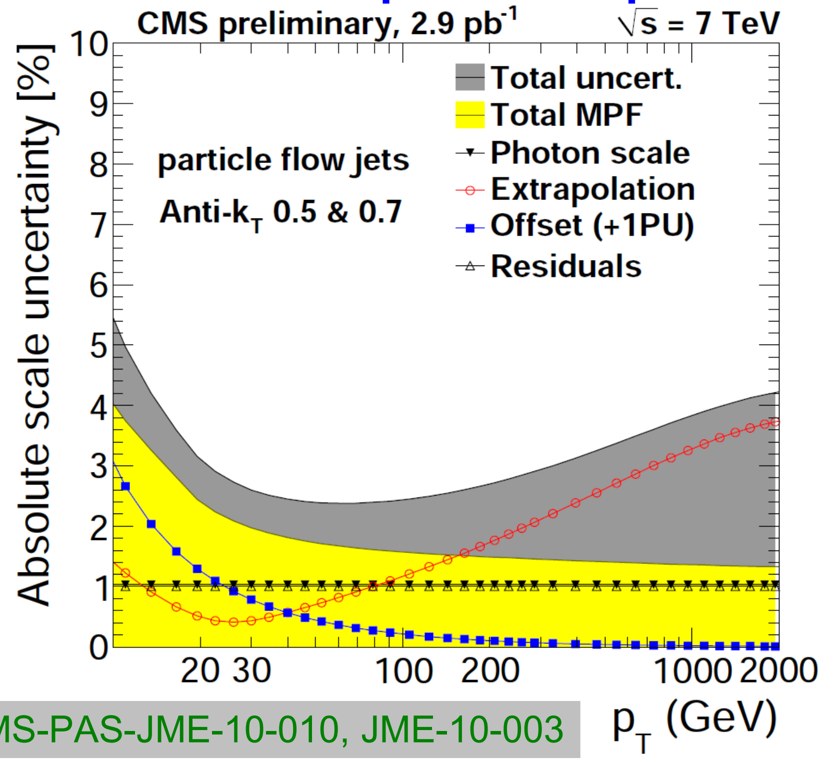
Enormous progress, took years at Tevatron.

Applied in ICHEP results



ATLAS CONF-2010-053, ATLAS EPJC 71 2011

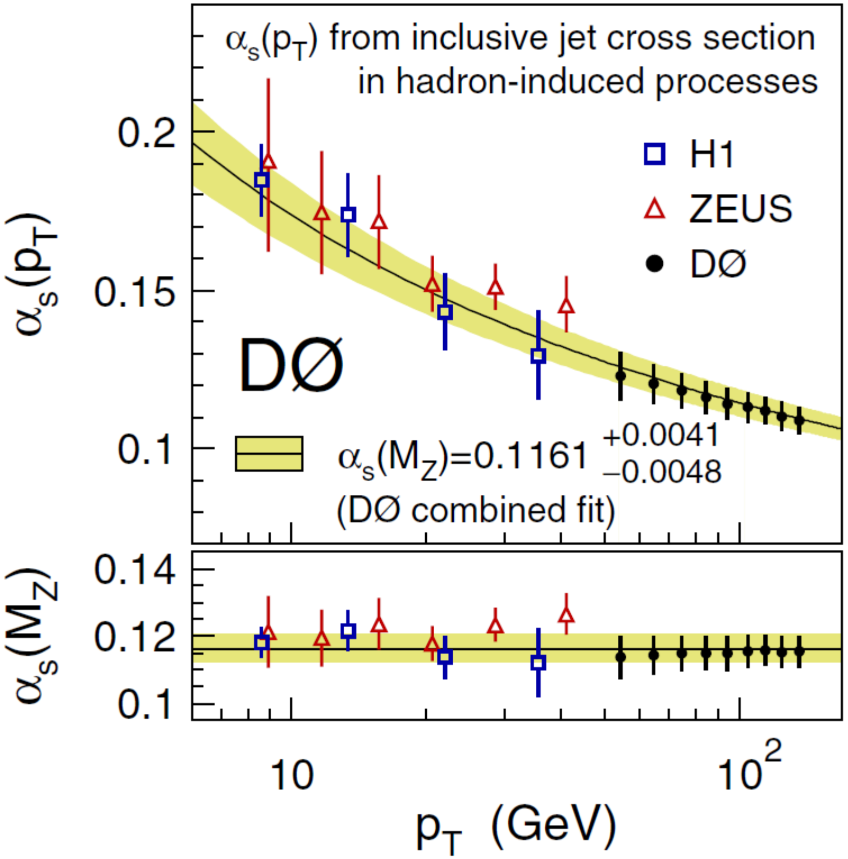
Derived from 2.9/pb until Sep. 2010



CMS-PAS-JME-10-010, JME-10-003

Absolute Measurements

Affected directly by large systematic uncertainties: JES, Luminosity, JER
Need to be careful to avoid circular reasoning when also used in PDFs
Not an easy way to go ...



Prospect of still improving a lot on systematic experimental uncertainties at LHC

Allows to measure $\alpha_s(p_T)$

CDF 2002: α_s = 0.1178 + 0.0081 – 0.0095
D0 2009: α_s = 0.1161 + 0.0041 – 0.0048

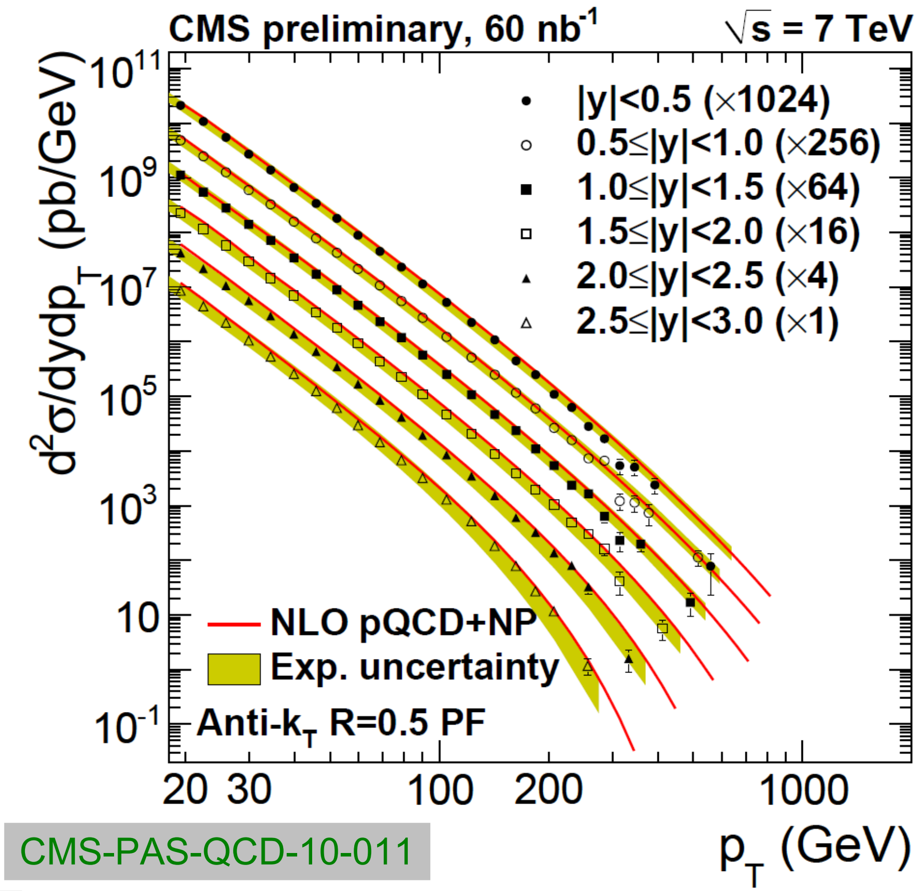
CDF PRL88 2002, D0 PRD80 2009

Available Results

Range in transverse momentum (ICHEP): ~ 0.7 TeV (Tevatron limit)
Range in dijet mass (ICHEP): ~ 1.5 TeV
Rapidities up to: 2.8 (ATLAS), 3.0 (CMS)
1000 times more luminosity about to be evaluated!

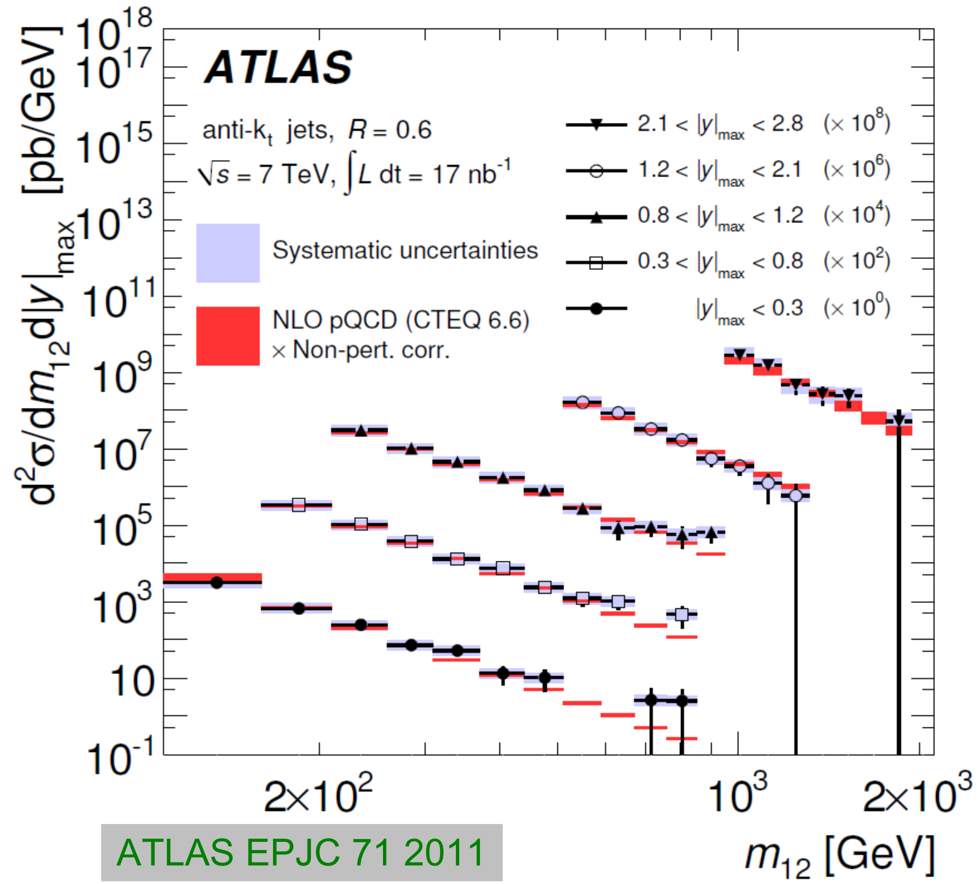
Z.Nagy,
NLOJet++
PRD68 2003
PRL88 2002

Inclusive jet pT cross section



CMS-PAS-QCD-10-011

Dijet mass cross section

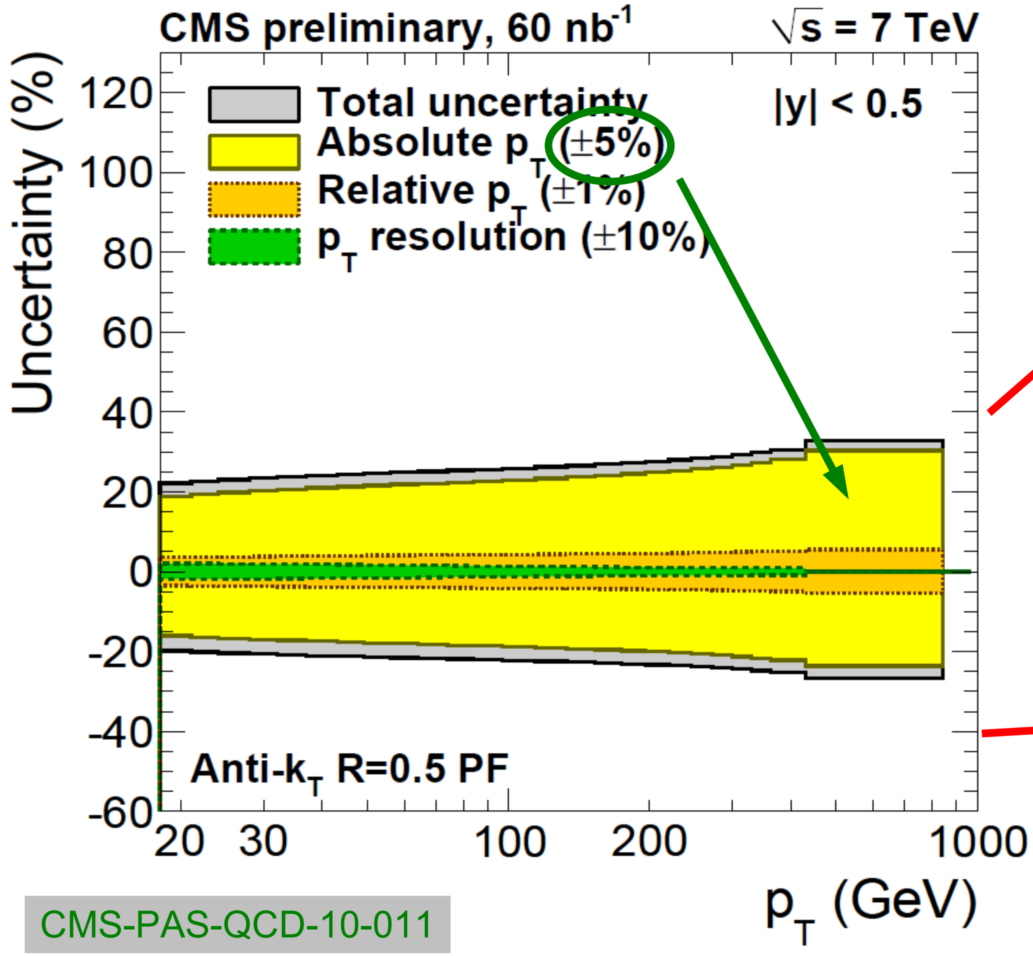


ATLAS EPJC 71 2011

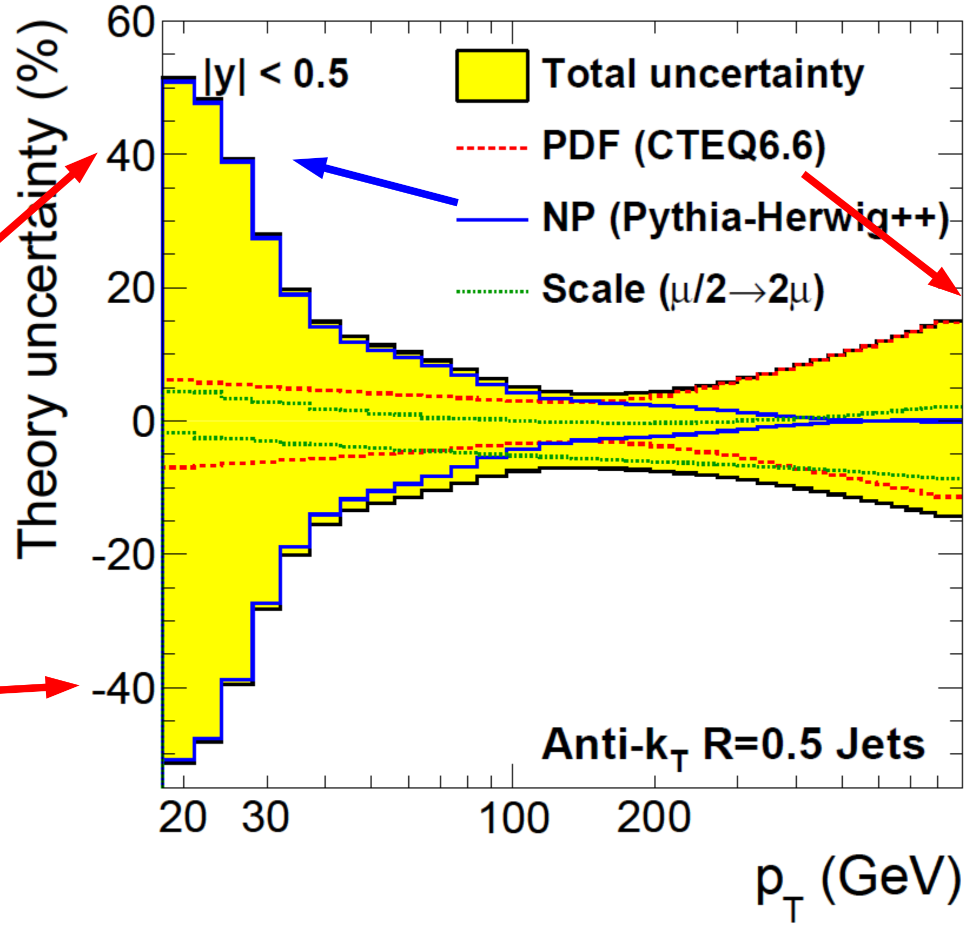
Contrasting Uncertainties

Dominant: JES
Luminosity: 11%, not shown

Dominant at low pT: NP Corrections
at high pT: PDF



40%

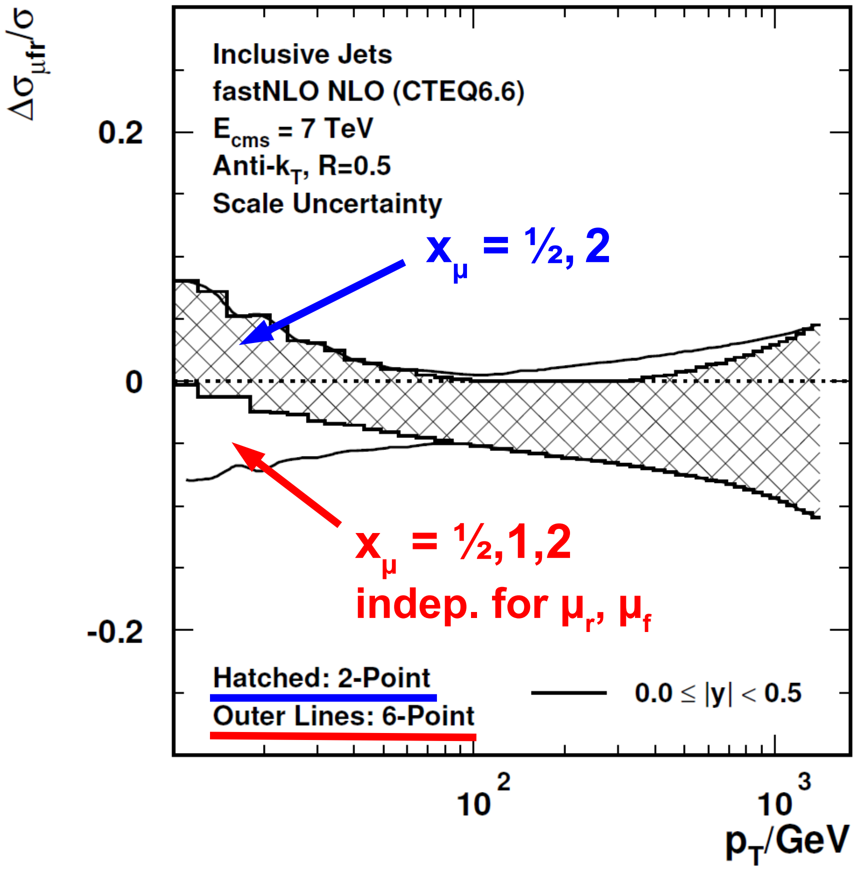


CMS-PAS-QCD-10-011

Scale and PDF revisited

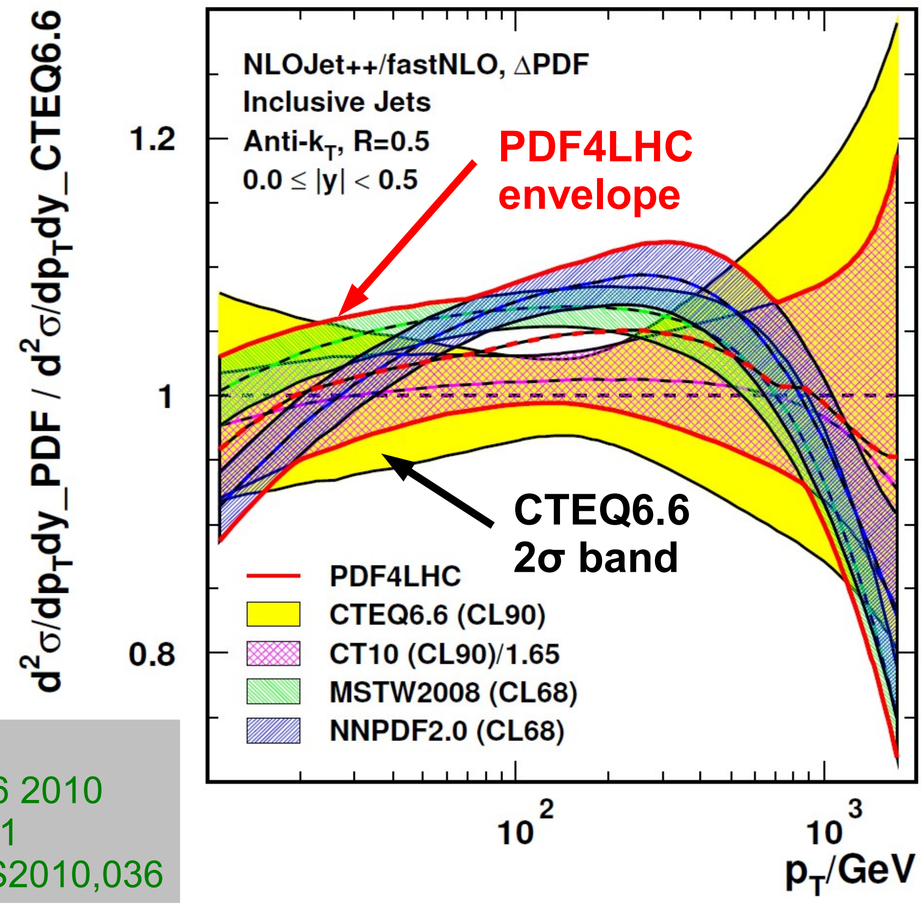
Asymmetric scale variations:

Independent variation of μ_r and μ_f
by factors of ½ and 2 avoiding rel. factors of 4
(6-point: (1/2,1/2), (1/2,1), (1,1/2), (1,2), (2,1), (2,2)
Compared to symmetric variation (2-point)



A la PDF4LHC:

Envelope of predictions of CTEQ, MSTW and NNPDF at CL68
Compared to CTEQ6.6 (CL90)



See e.g.:
A.Banfi et al.,JHEP06 2010
ATLAS EPJC 71 2011
J. Huston,POSCI,DIS2010,036

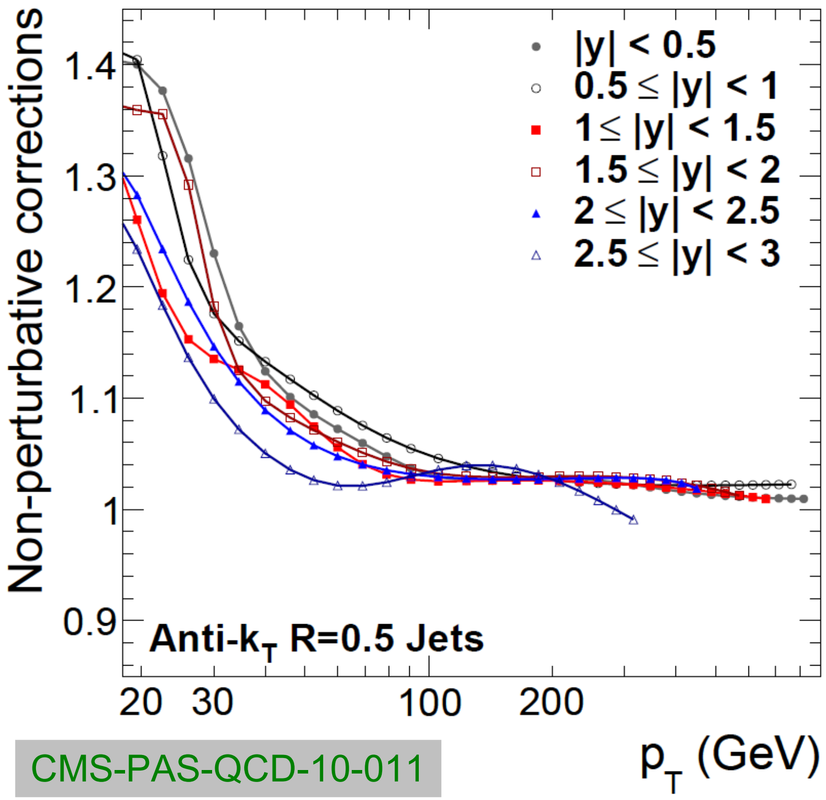
NP revisited and α_s

To compare with data correct NLO for:
- **Multiple Parton Interactions (MPI)**
- **Hadronization & Decays (Lund, Cluster)**

POWHEG Box for dijet production to be evaluated!

S. Alioli et al., arXiv:1012.3380

NP Correction Factors

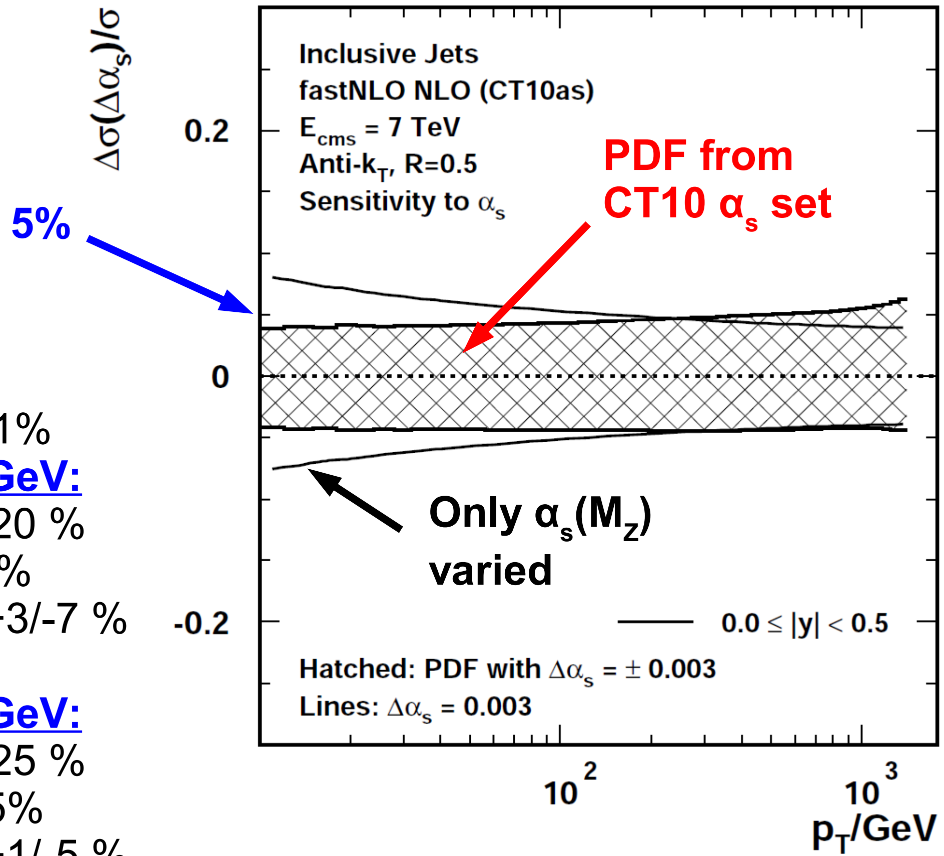


CMS-PAS-QCD-10-011

Effect of changing $\alpha_s(M_Z)$ by ±0.003:
- **Either by choosing PDF member (hatched)**
- **or by changing value seperately (lines)**

Recall:
Lumi: 11%
at 100 GeV:
JES: ~ 20 %
PDF: 5 %
Scale: +3/-7 %

at 500 GeV:
JES: ~ 25 %
PDF: 15%
Scale: +1/-5 %



Shape Measurements

- Reduction strategy 1: Normalized distributions
  - No luminosity uncertainty
  - Reduced sensitivity to jet energy scale (JES) or resolution (JER)
- Jet angular measurements
  - Dijet chi distribution: Nice for new physics, not for α_s ...
  - Dijet azimuthal decorrelation: Sensitive to QCD radiation, → α_s ?

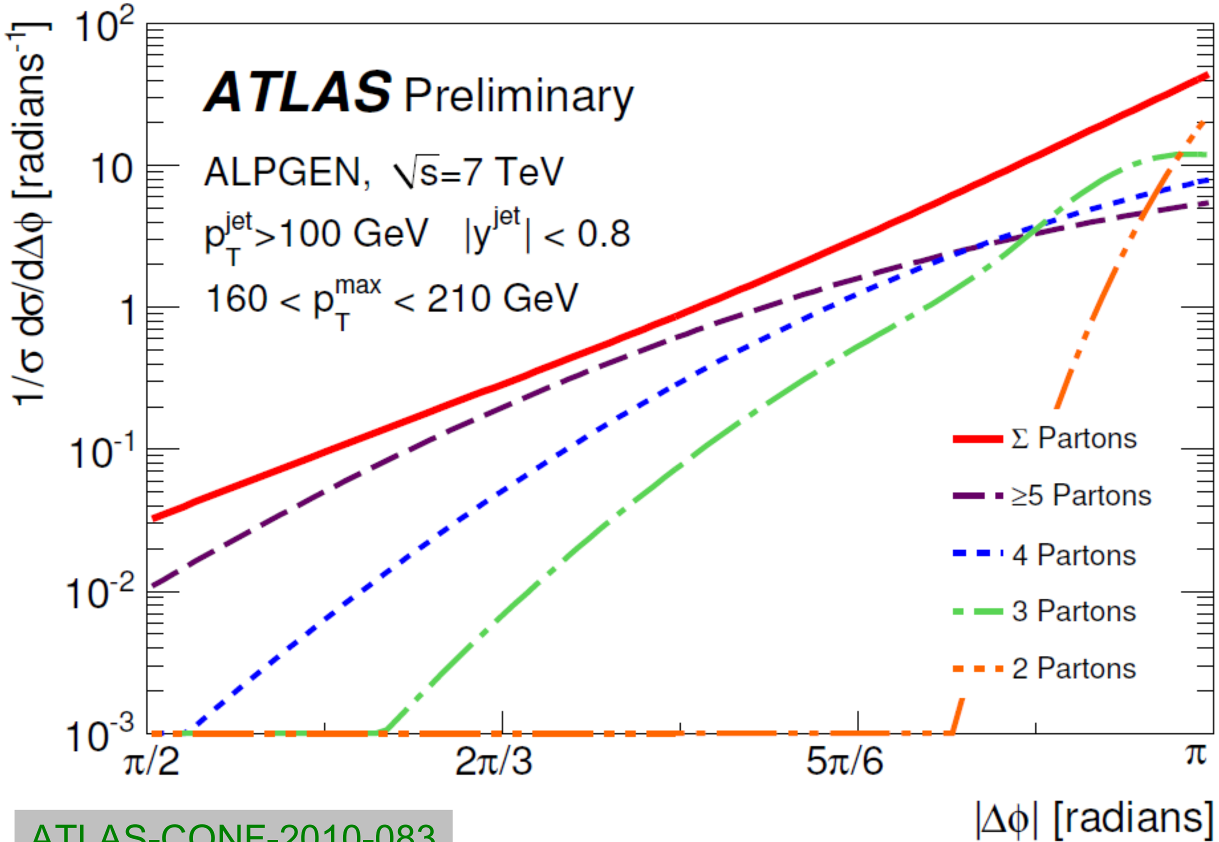
    NLO available, resummation in progress: A. Banfi, arXiv:0906.4958
- Event shapes
  - Long tradition of QCD measurements e.g. α_s, in particular in e+e-
  - Good description of data requires NLO + resummation

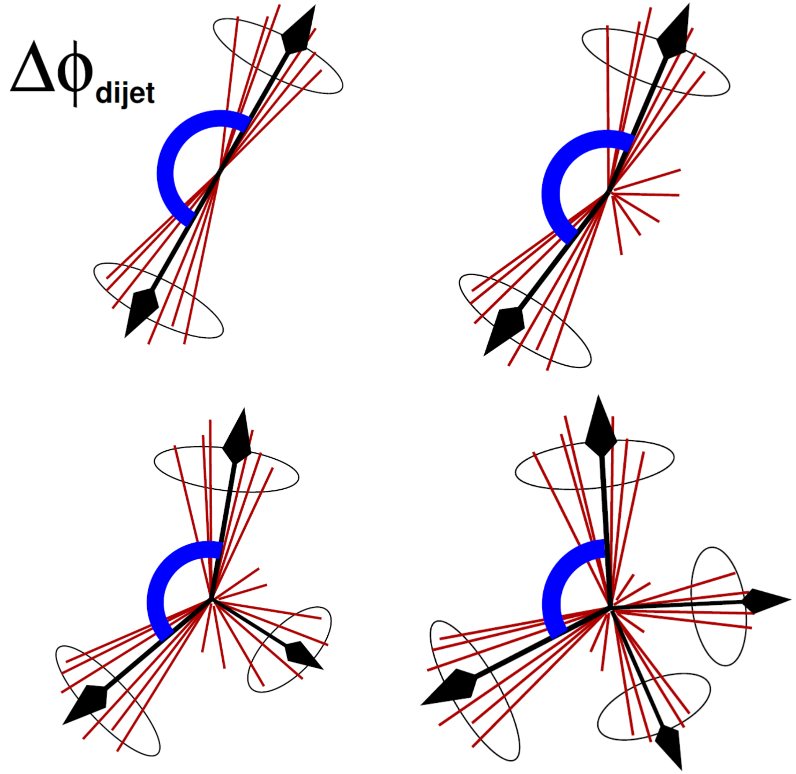
    from NNLO+NLLA:
    G. Dissertori et al., JHEP08 2009
    - Transverse thrust, transverse thrust minor, y_{23} ...
    - NLO like above, resummation requires the "global" versions, see

      A. Banfi et al., JHEP06 2010

Azimuthal Decorrelation

Born limit has dijets with $|\Delta\Phi| = \pi$
With increasing number of partons smaller separation angles become possible
Depends on α_s ...

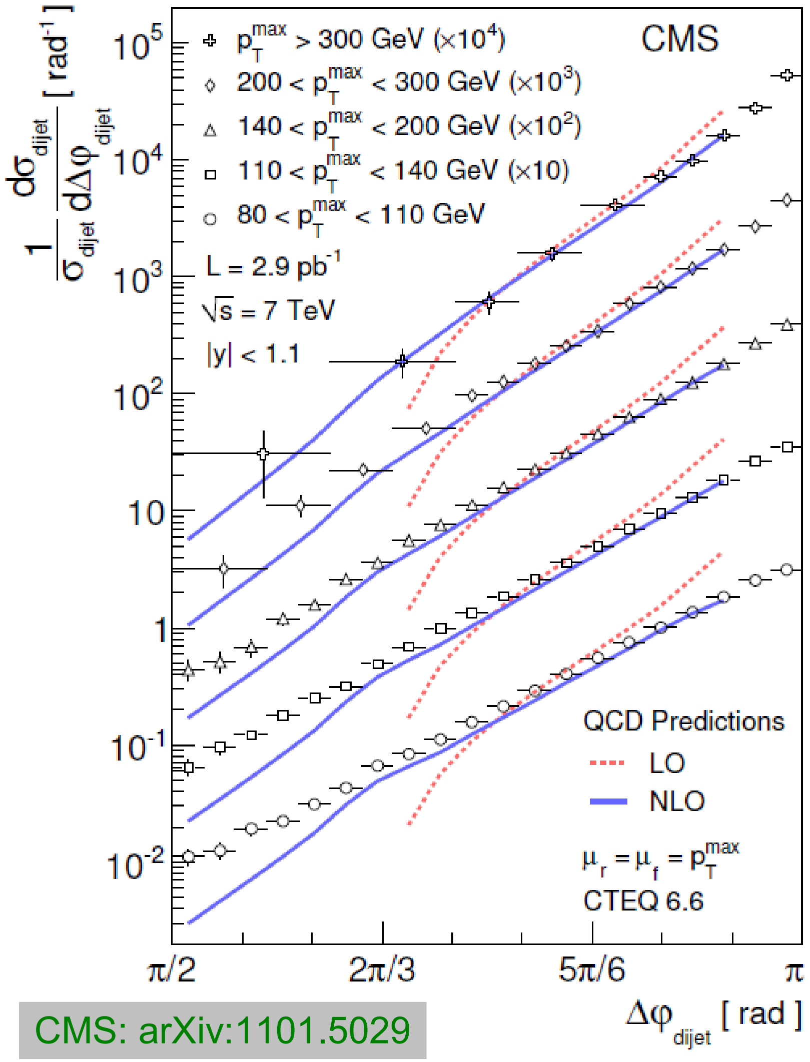




ATLAS-CONF-2010-083

ΔΦ: Available Data

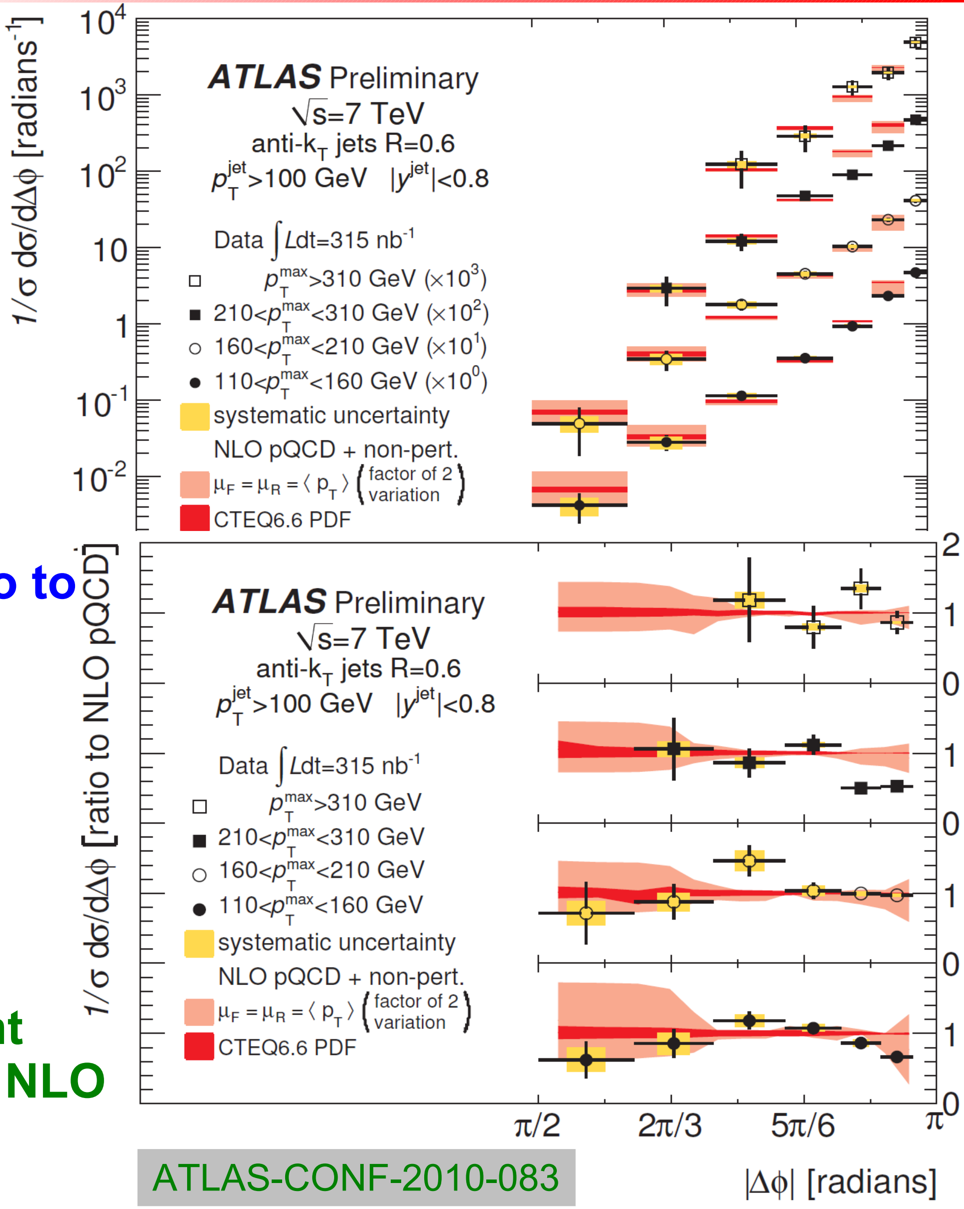
CMS, 2.9 / pb, Exp. Unc.11 - 3% **ATLAS, 0.3 / pb**



CMS: arXiv:1101.5029

ATLAS, Ratio to pQCD * NP

Good agreement where pQCD @ NLO



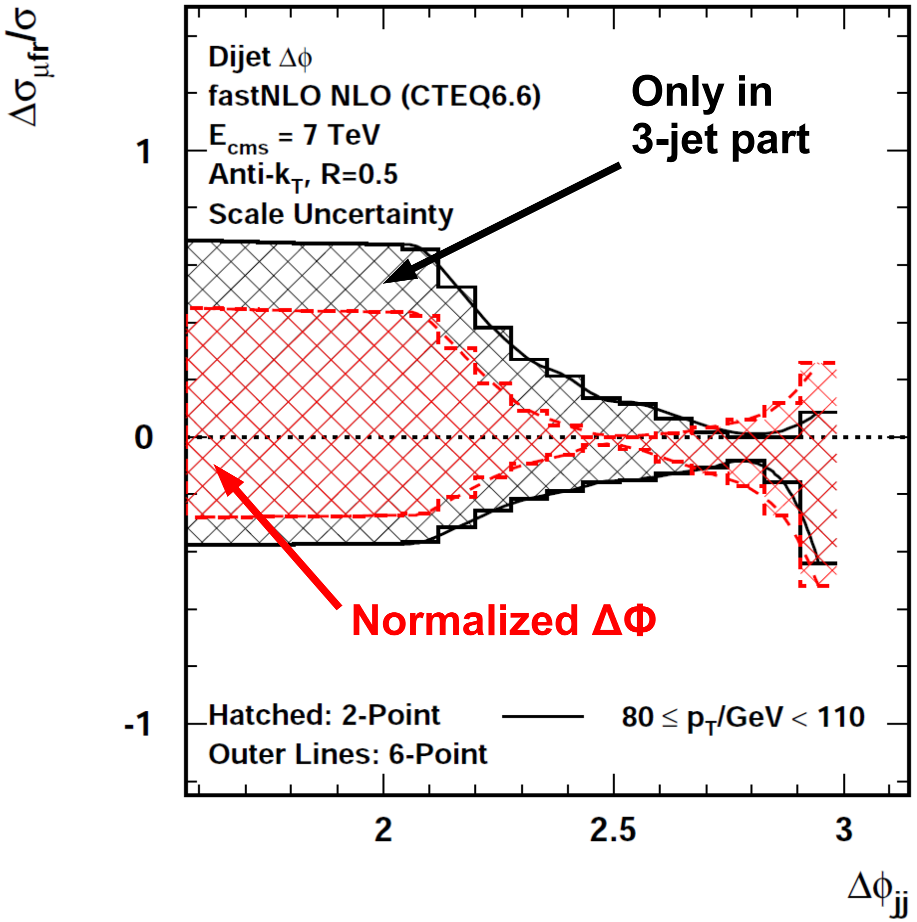
ATLAS-CONF-2010-083

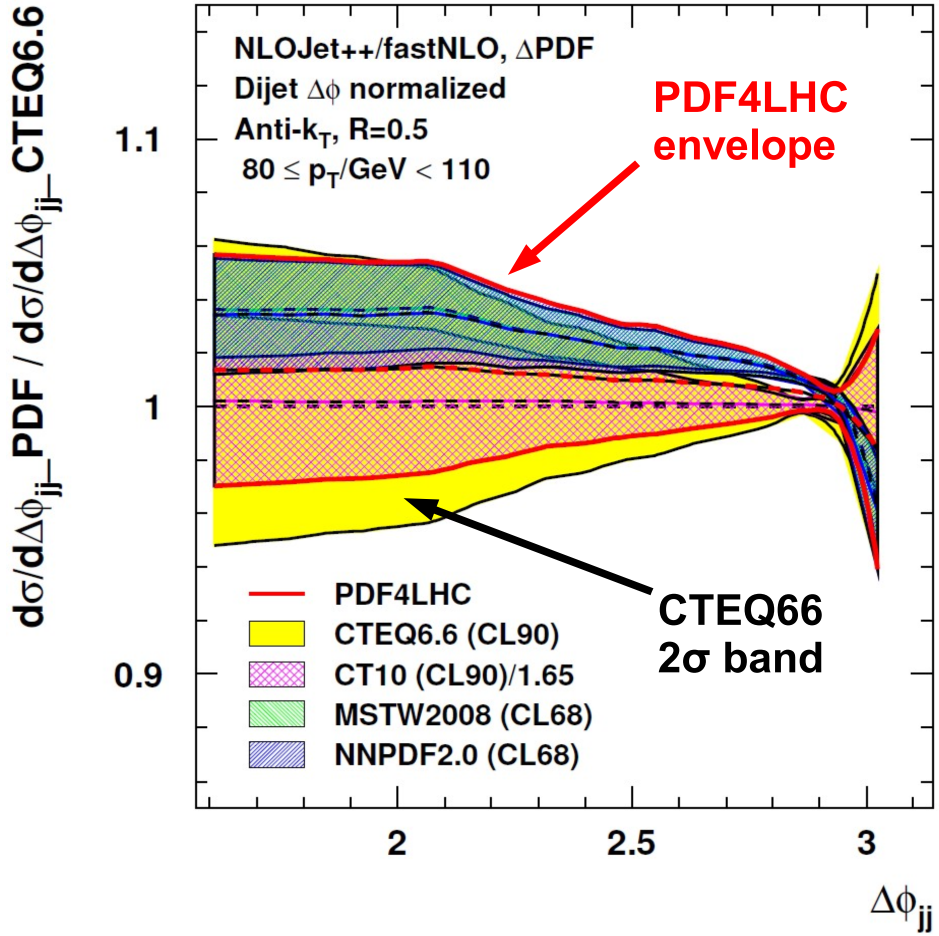
ΔΦ: Scale and PDF

Sensitivity to $\Delta\alpha_s = \pm 0.003$: ~3 % (Plot in backup slides)

Look into average ΔΦ (event shape mean) ?

Low pT bin: 80 < pT / GeV < 110

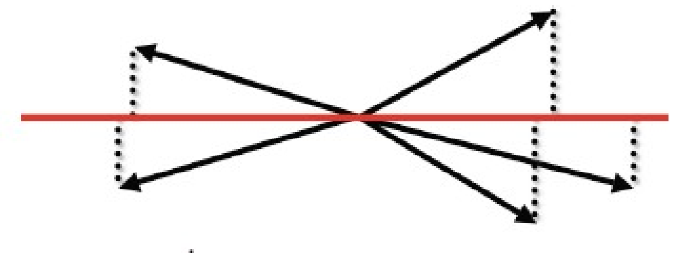




Event Shapes

Definition:

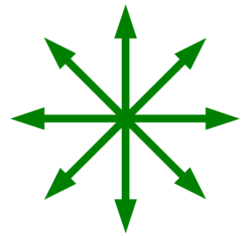
Transverse global Thrust



Similar as Event Shapes in e^+e^- and ep

- **In praxis, need to restrict rapidity range: $|\eta| < 1.3 \rightarrow$ Transverse central thrust**
- **Less sensitive to JES & JER uncertainty**
- **No luminosity uncertainty**
- **Useful for MC tuning**

$$T_{\perp,g} \equiv \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$



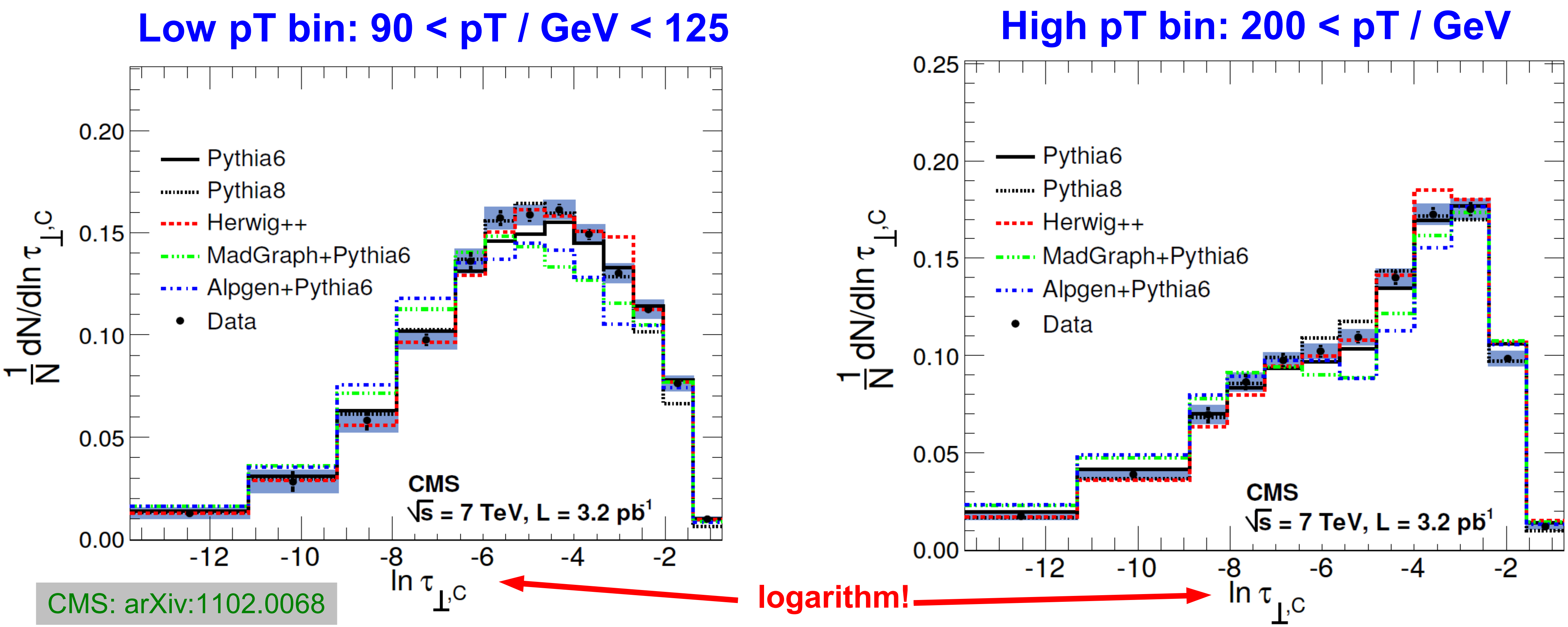
linear ~ dijet | **spherical ~ multijet**

$T \longrightarrow 0$ | $T \longrightarrow 2/\pi$

Redefine to get $\tau_{\perp,g} \equiv 1 - T_{\perp,g}$ $\longrightarrow 0$ in LO dijet case

Central Thrust: Available Data

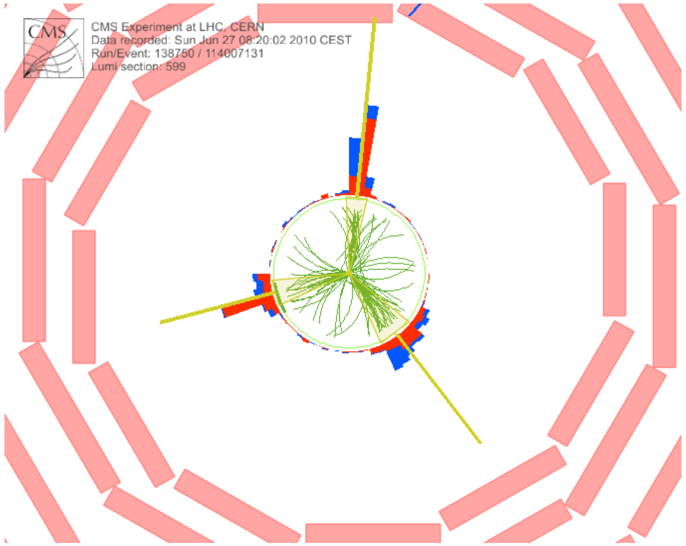
Good description by standard MC like Pythia or Herwig++ (NLO not yet checked)
Less so by multi-jet improved MadGraph or Alpgen ...
but improves when looking into multi-jet events (not shown)
Thrust Minor also available
Experimental Uncertainties of order ~ 5 %



CMS: arXiv:1102.0068

Ratio Measurements

- Reduction strategy 2: Jet cross section ratios
  - Dijet centrality ratio: Nice for new physics, not sensitive to α_s.
  - Jet cross-section ratio R=0.7 / R=0.5 or kT / SISCone: Interesting, but for α_s ?
  - 3+-jet to 2+-jet cross-section ratio: Directly sensitive to α_s !
  - Will not discuss ratios within jets (jet shapes, subjet multiplicity)
- Many uncertainties cancelled (luminosity) or reduced (JES, ...)

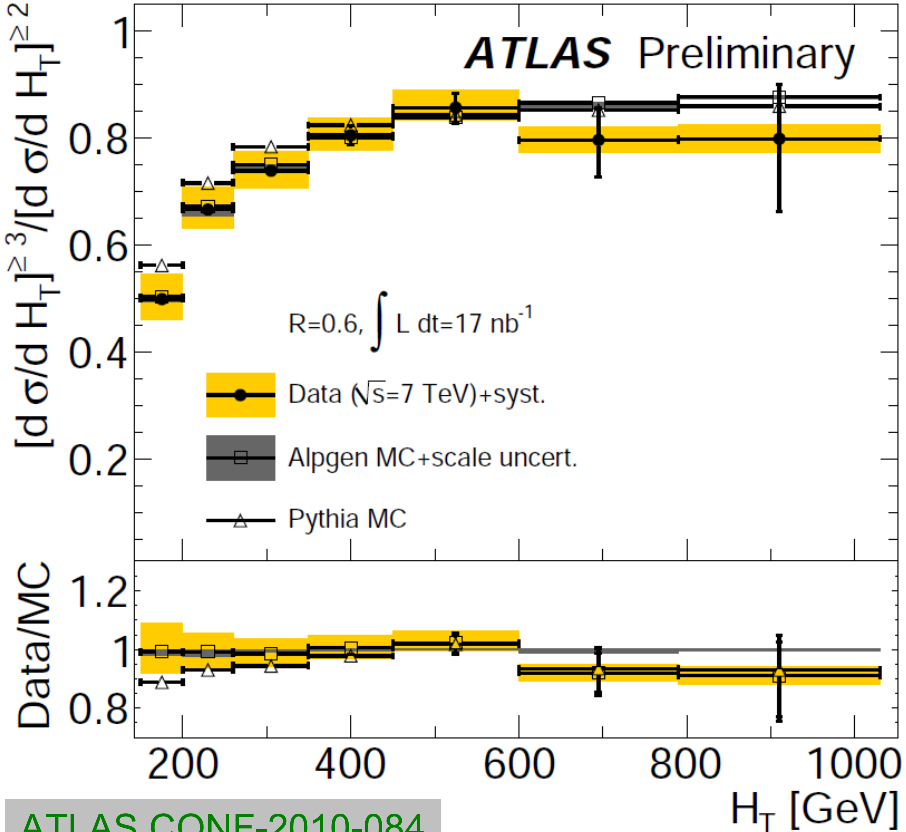


→ strong coupling α_s

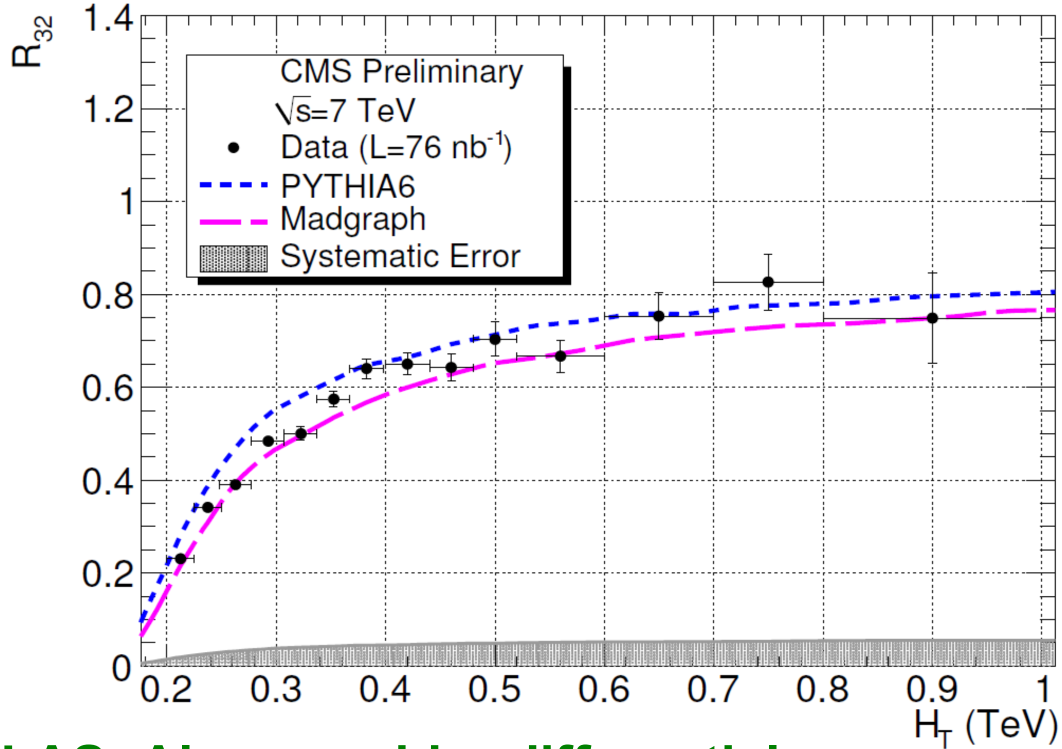
Inclusive 3+/2+ Jet Ratio

ATLAS: anti-kT R=0.6, |y| < 2.8
p_{Ti} > 30 GeV, p_{T1} > 60 GeV
$H_T = \Sigma |p_{Ti}|$
exp. Uncertainty < ~ 10%

CMS: anti-kT R=0.5, |y| < 2.5
p_{Ti} > 50 GeV, p_{T1} > 60 GeV
$H_T = \Sigma |p_{Ti}|$
exp. Uncertainty < ~ 10%



ATLAS CONF-2010-084

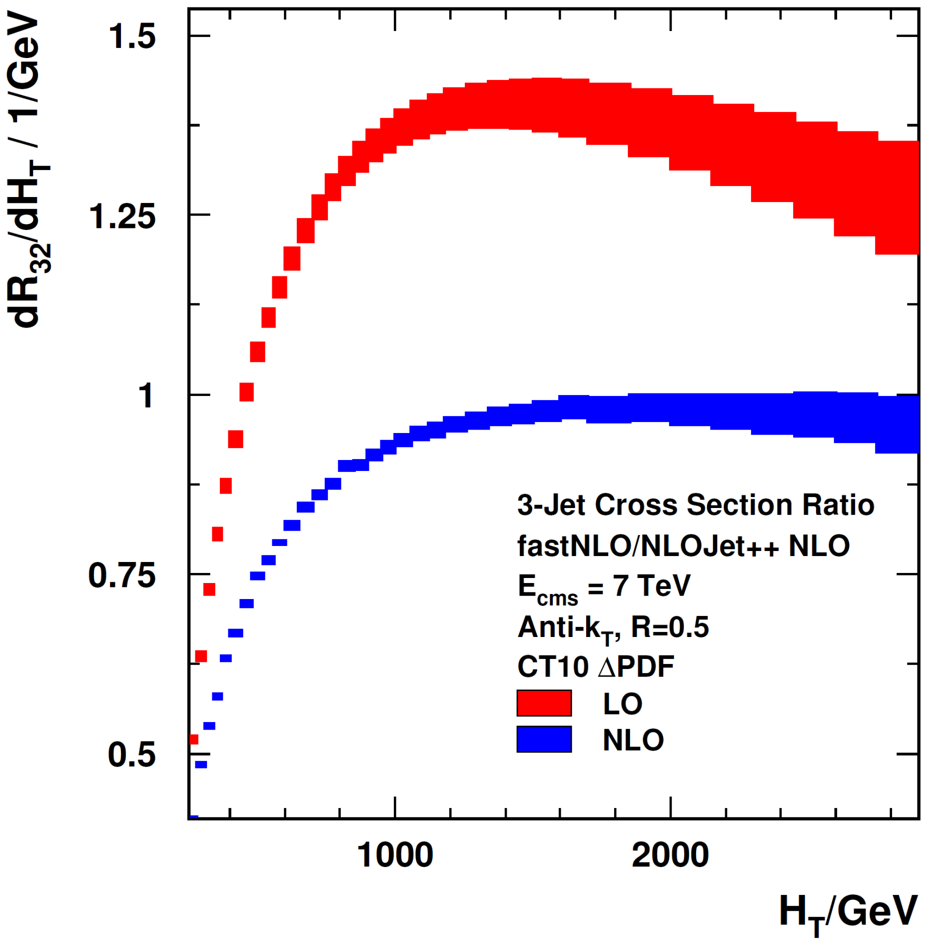


ATLAS: Also consider differential 2-jet Rate (~> event shape ...)

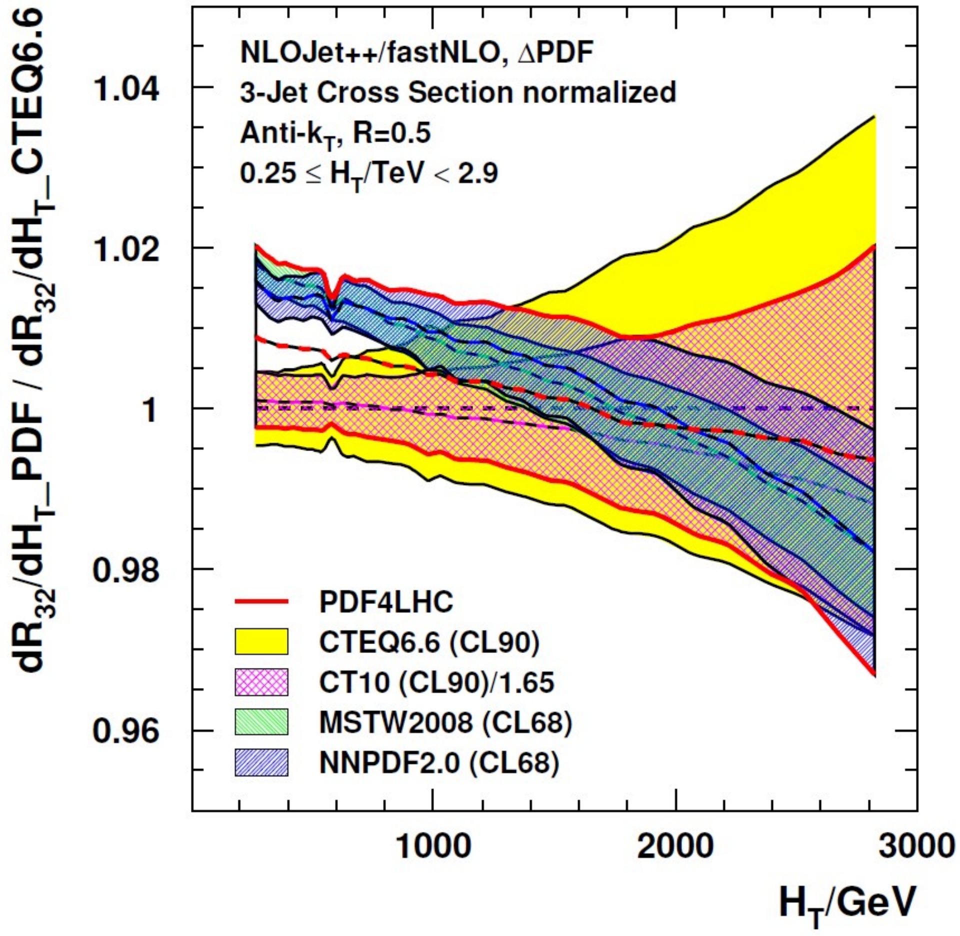
CMS-QCD-10-012

3+/2+: NLO Prediction & ΔPDF

CMS like selection
(ATLAS not very different)
LO > 1 ?!
K factors ~ 0.67



PDF uncertainty reduced by a factor ~ 10 in ratio



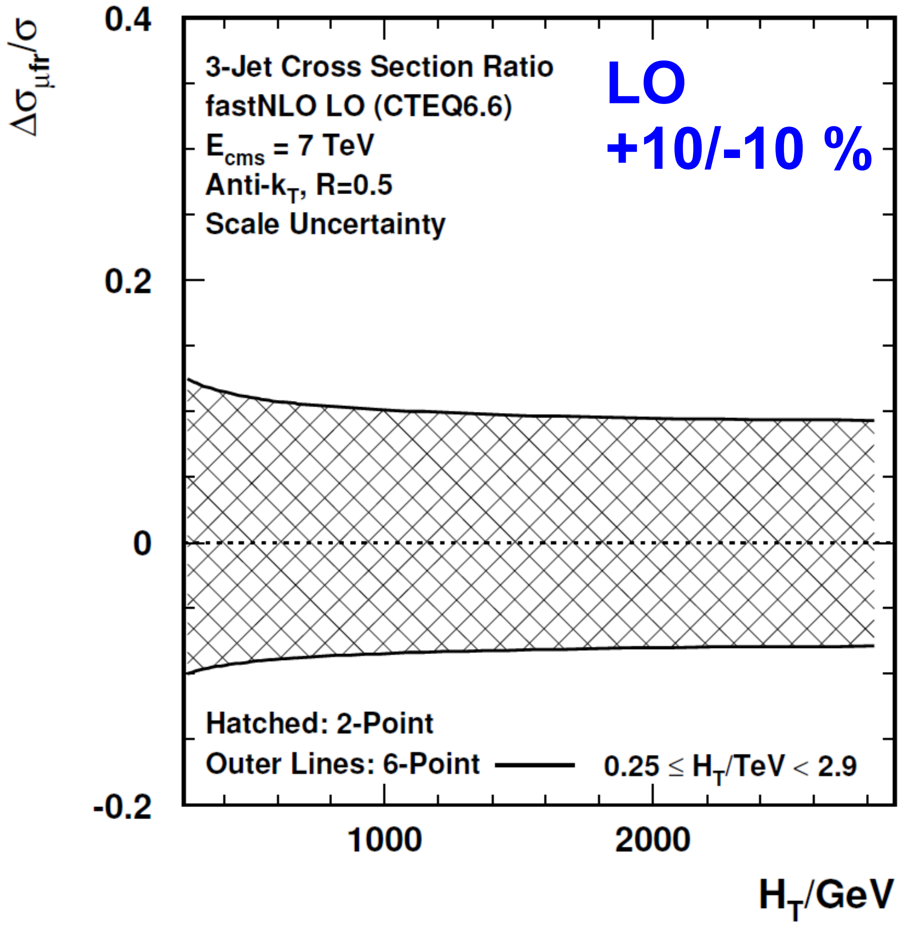
3+/2+: Scale Dependence

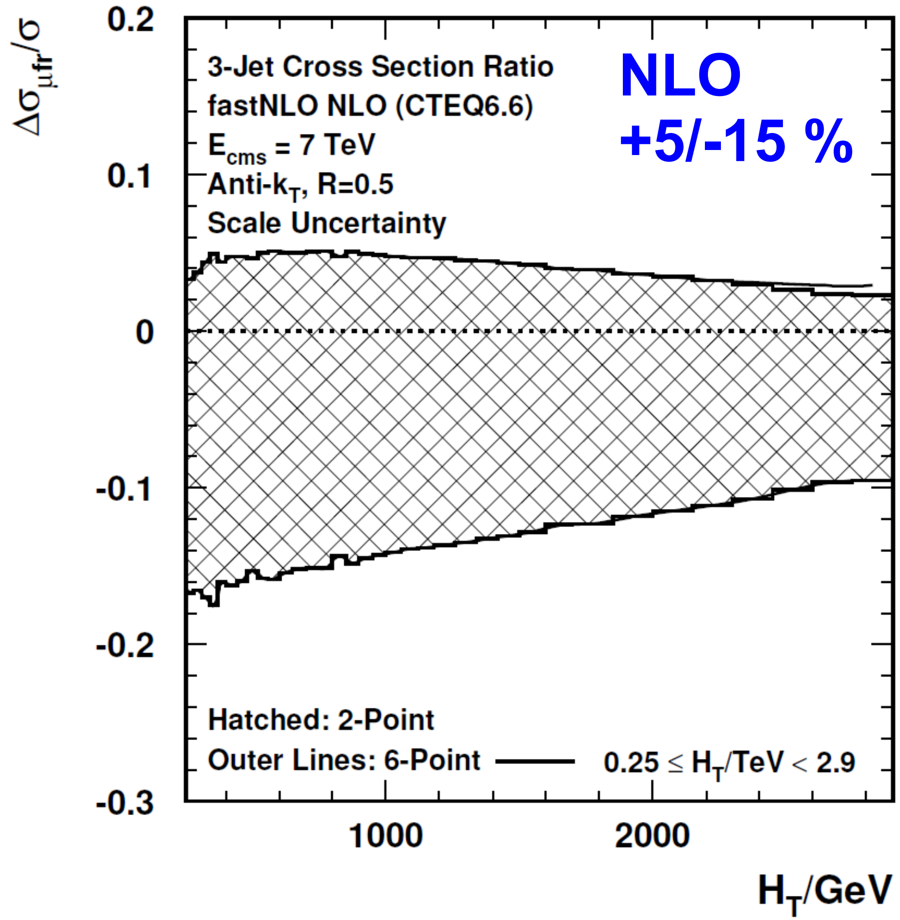
Simultaneous variation in numerator and denominator

No large difference between symmetric and add. asymm. scale variations

No real improvement when going to NLO …

ATLAS quotes 5 % from Alpgen



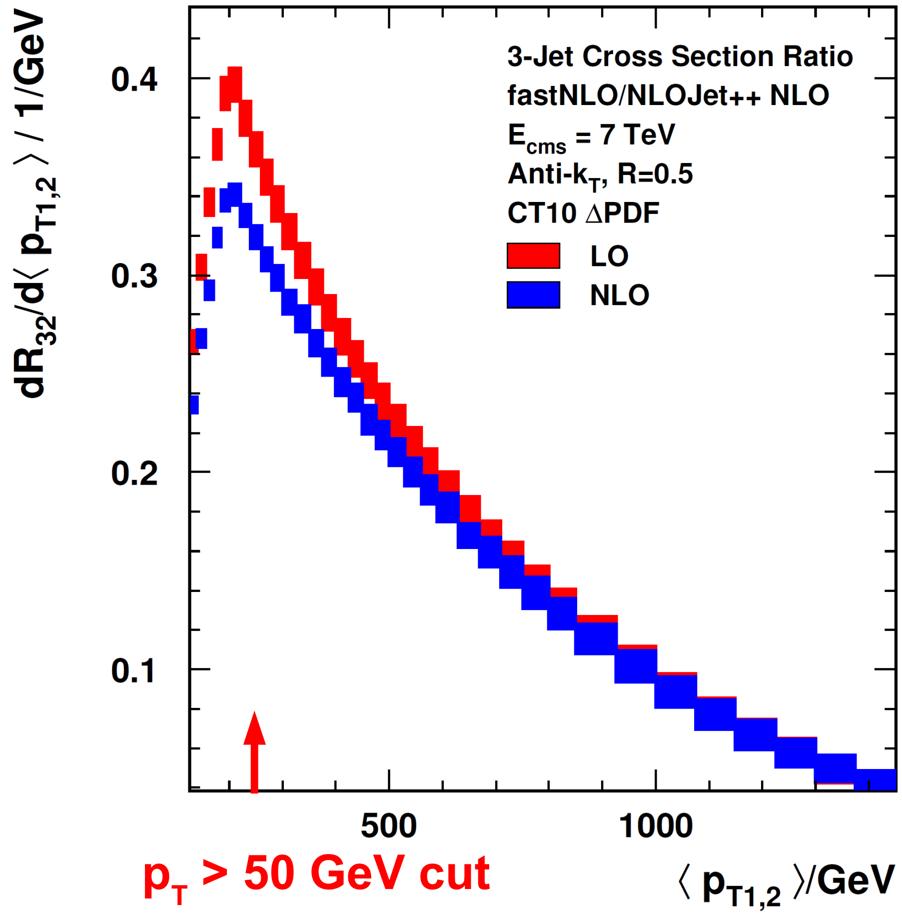


3+/2+ Revisited

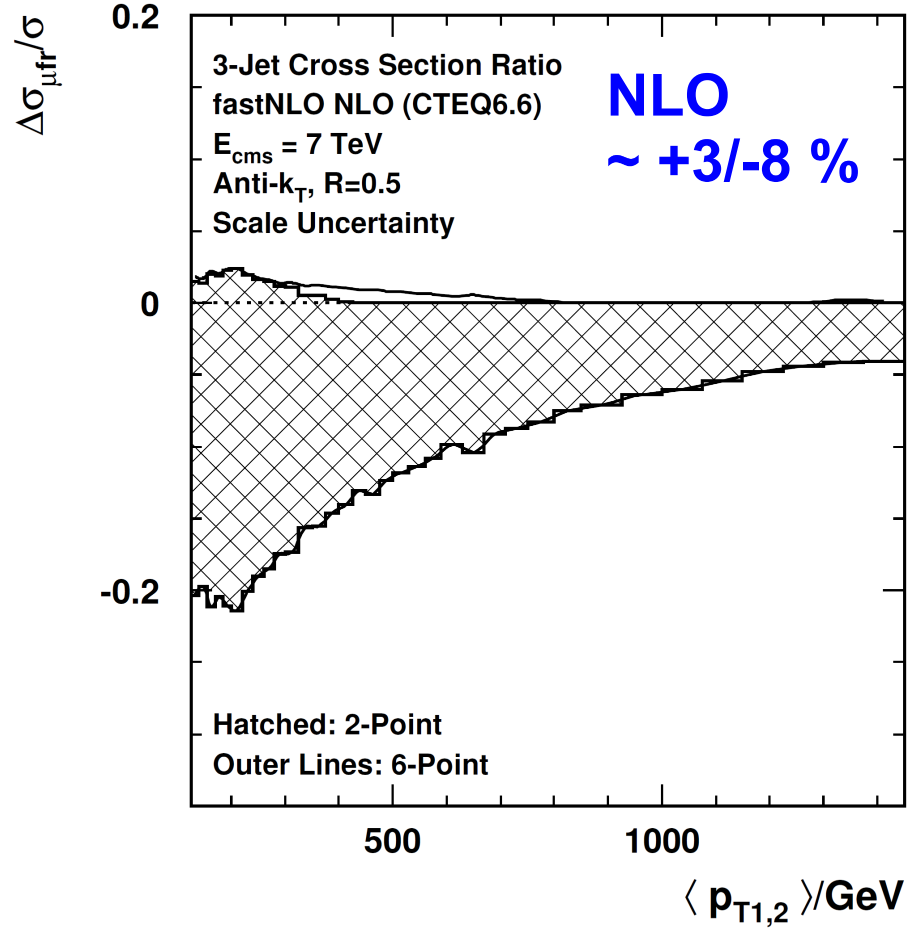
Made some adaptations after chat with Gavin Salam:

- changed scale from H_T to average dijet p_T: $\langle p_{T1,2} \rangle$
- require hard third jet: $p_{T3} > 0.25$ times $\langle p_{T1,2} \rangle$

Not optimal yet, but clearly better

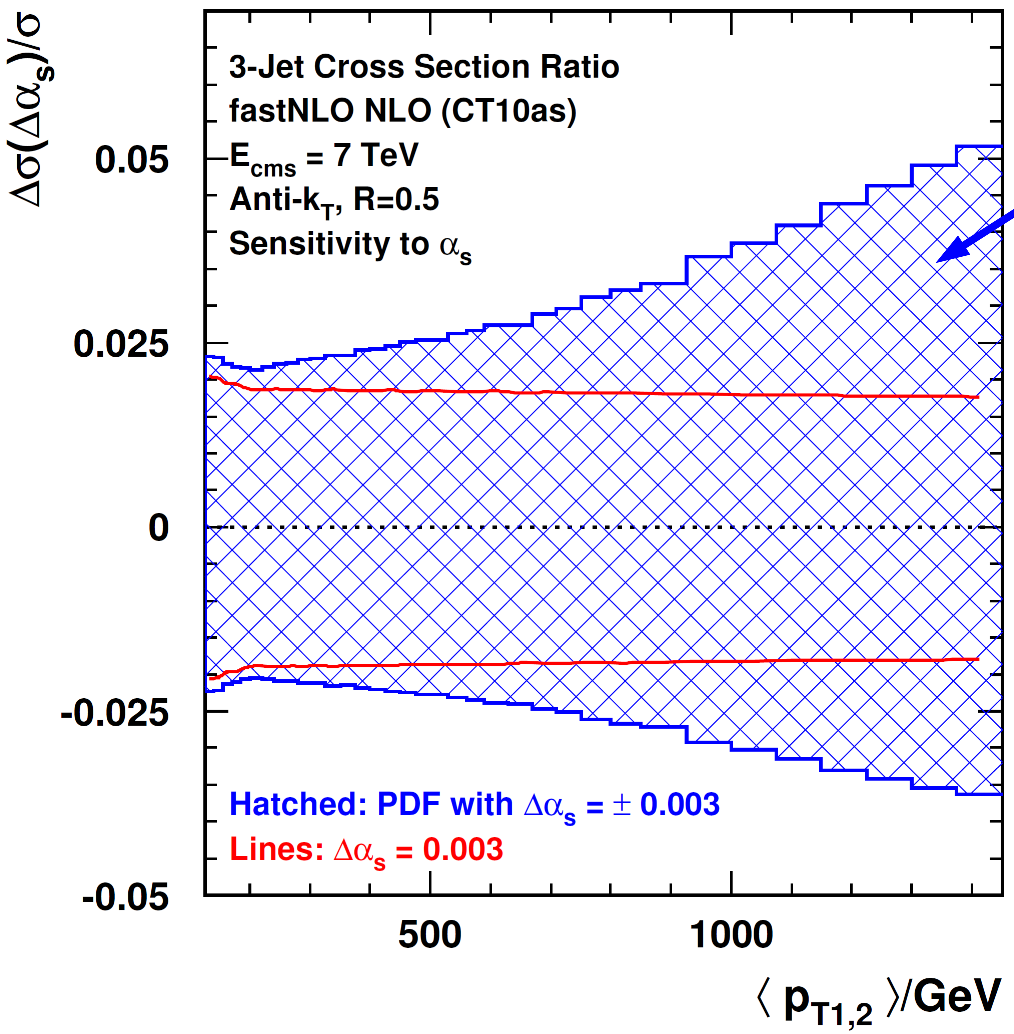


$p_T > 50$ GeV cut



3+/2+: Sensitivity to α_s

α_s Sensitivity



CT10as members with $\alpha_s = 0.118 \pm 0.003$

$\alpha_s(M_Z)$ only changed $\alpha_s = 0.118 \pm 0.003$

To be further investigated ...

Summary/Discussion

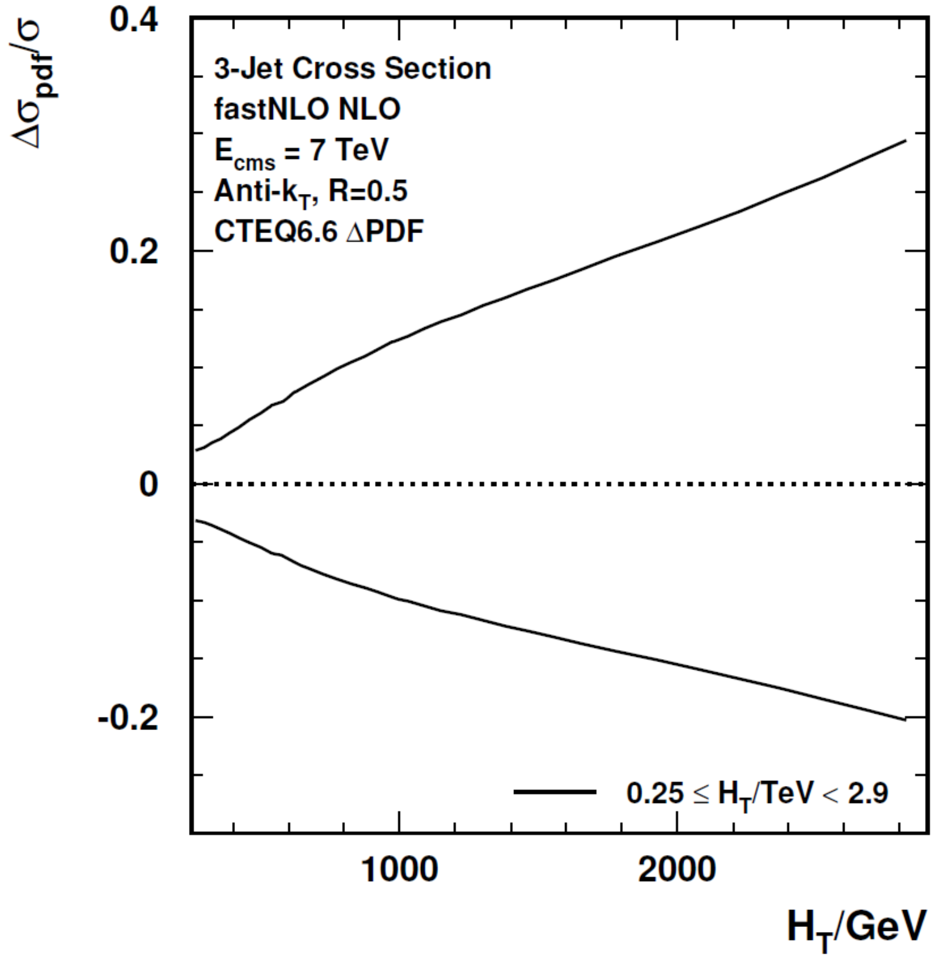
- Detector performances and MC modelling better than anticipated
- Improving rapidly on experimental systematics
- Can do much better jet measurements than originally hoped for
- Are there other (jet) observables to measure α_s at LHC?
- Comments/suggestions are welcome

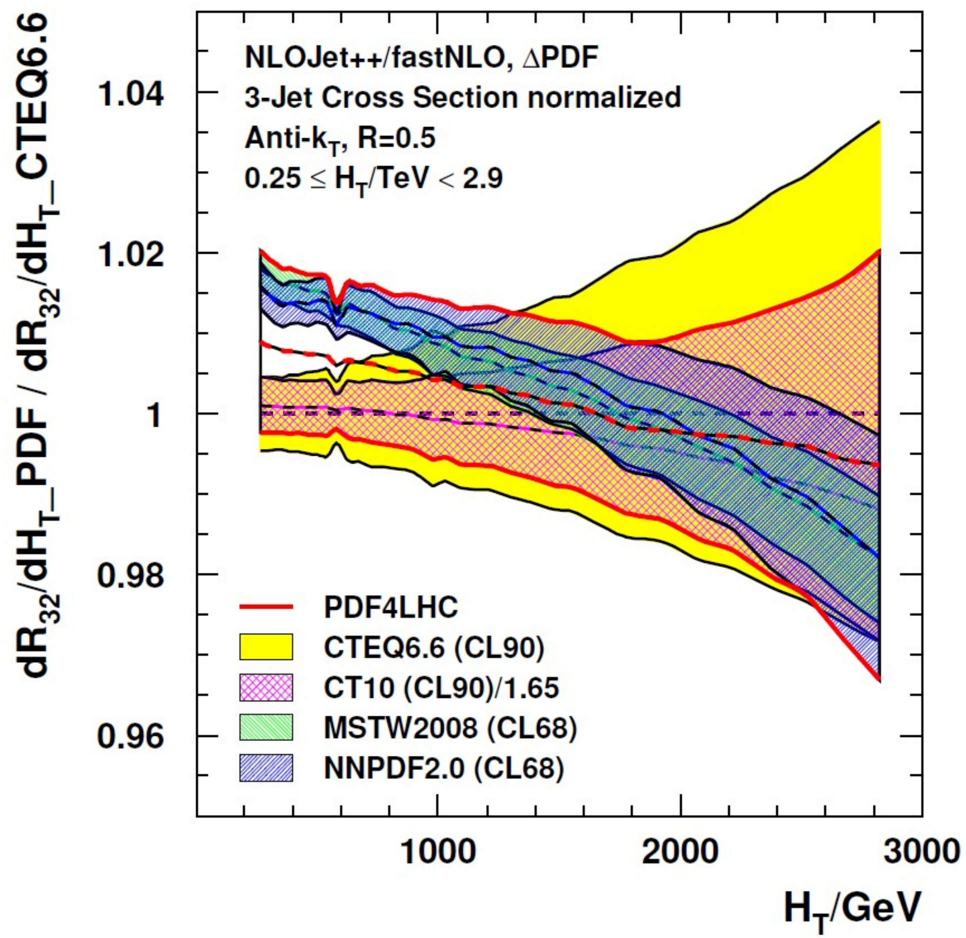
Thank you for your attention

Backup Slides

3+/2+: PDF Uncertainty

Only 3-jet part (numerator)

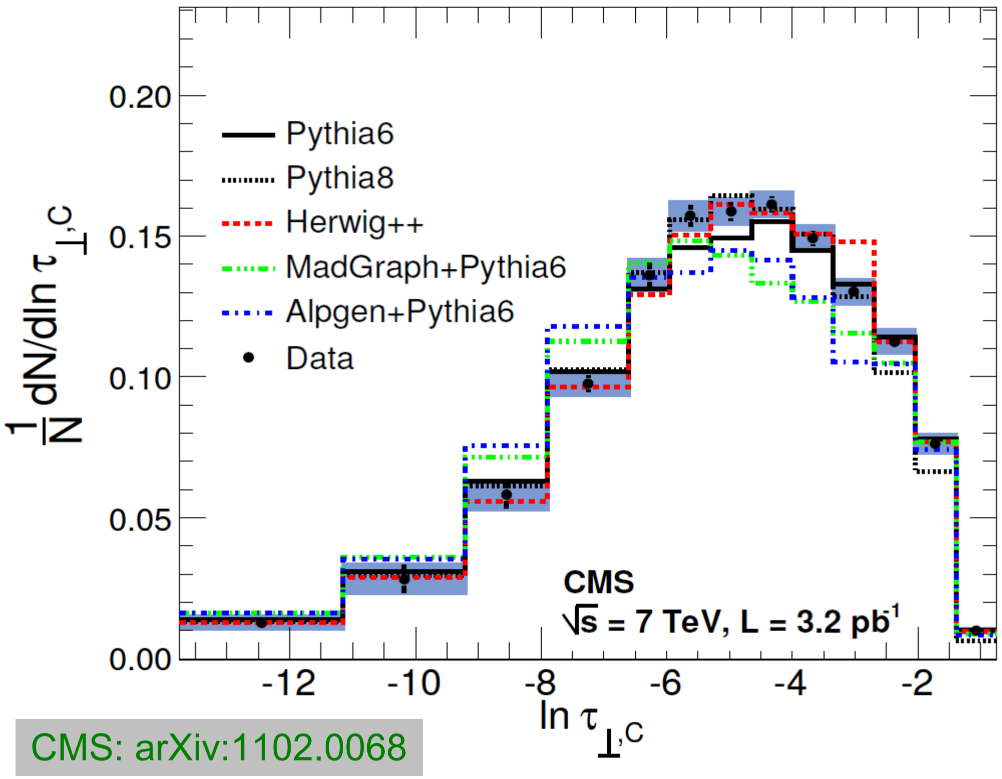




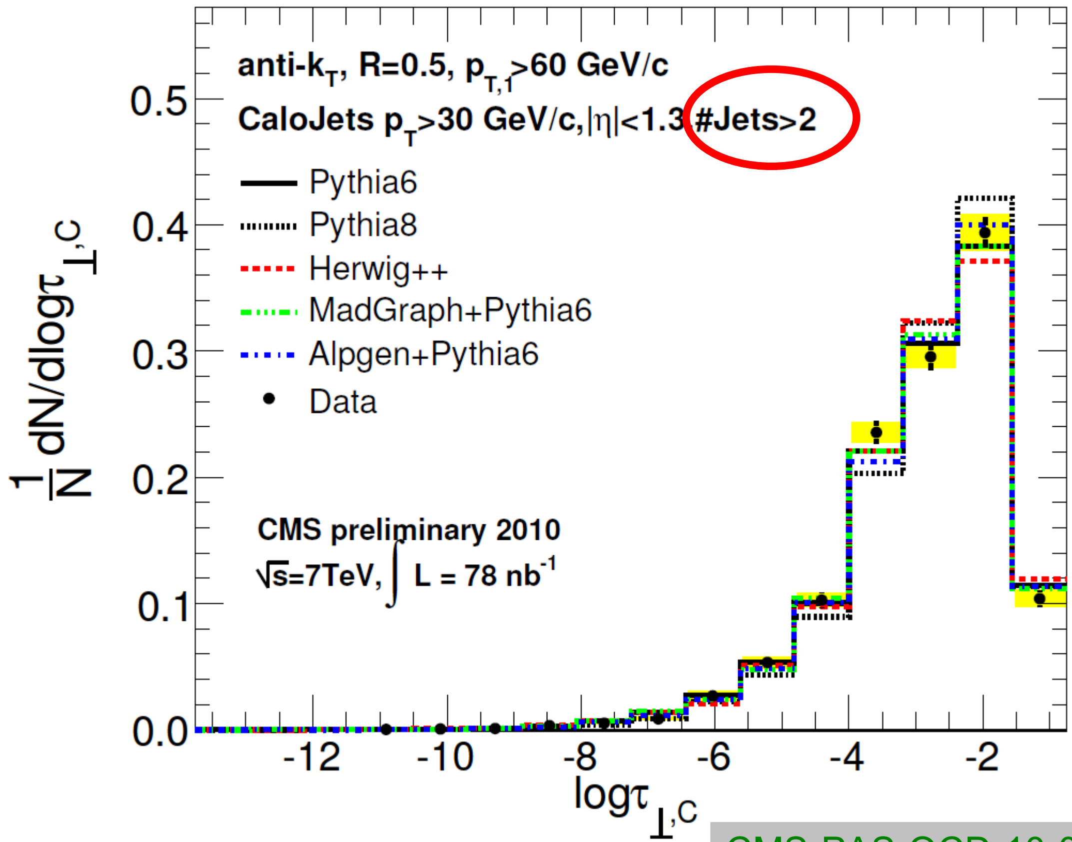
Central Thrust and Multi-Jets

- **Dijet case:**
  - **Good description by Pythia, Herwig++**
  - **Alpgen & MadGraph off**
- **Multijet case:**
  - **Pythia, Herwig++ ok**
  - **Alpgen & MadGraph better**

Low pT bin: 90 < pT / GeV < 125

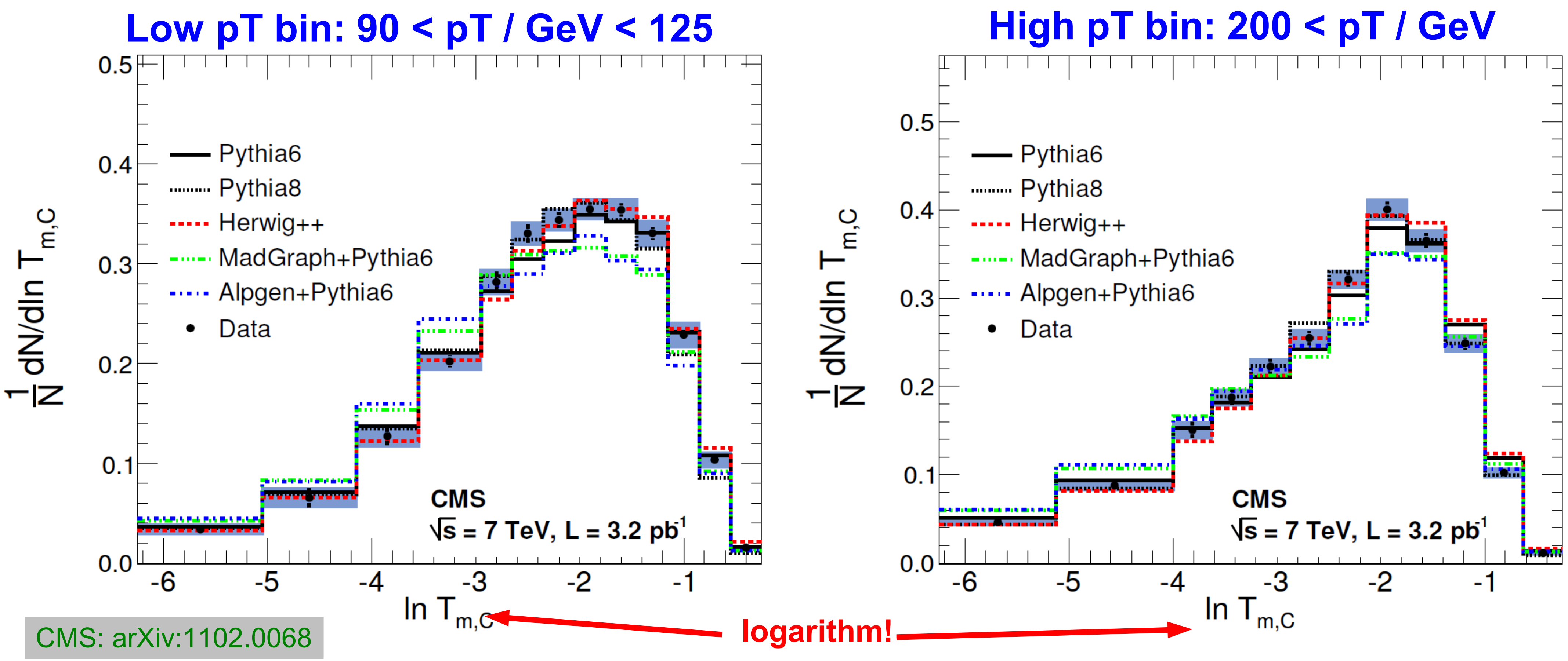


CMS: arXiv:1102.0068



CMS-PAS-QCD-10-013

Thrust Minor: Available Data

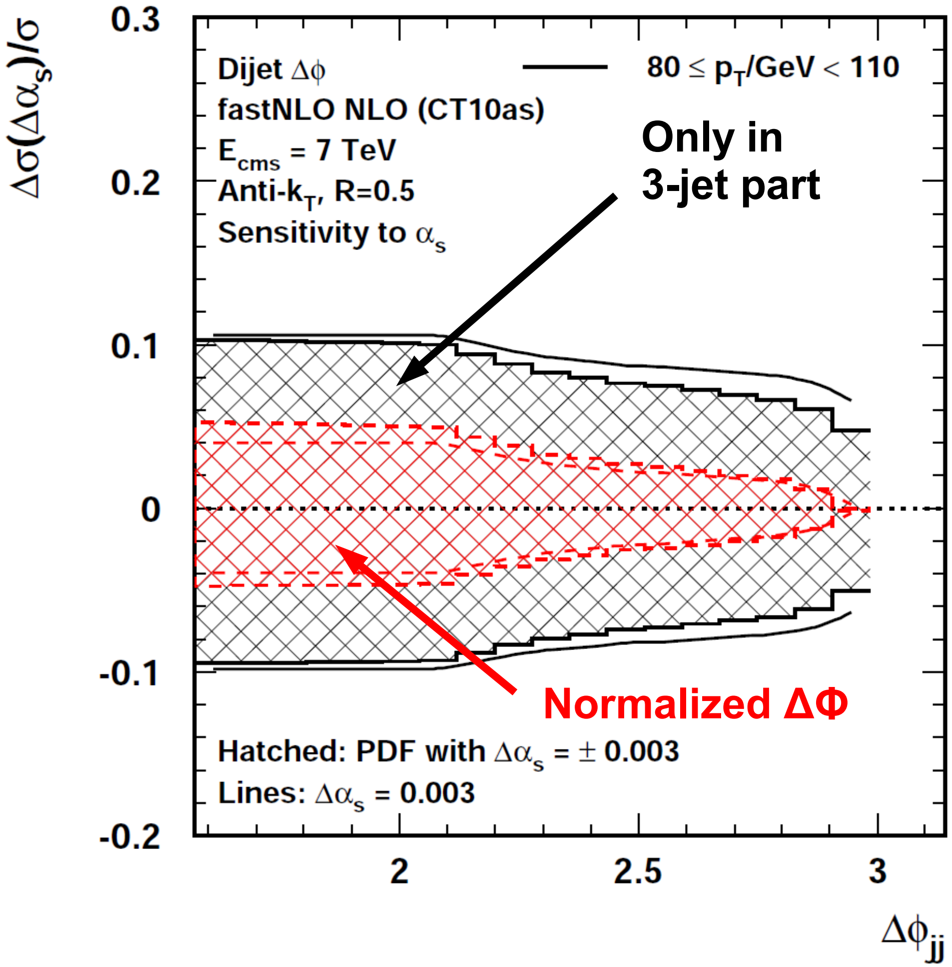


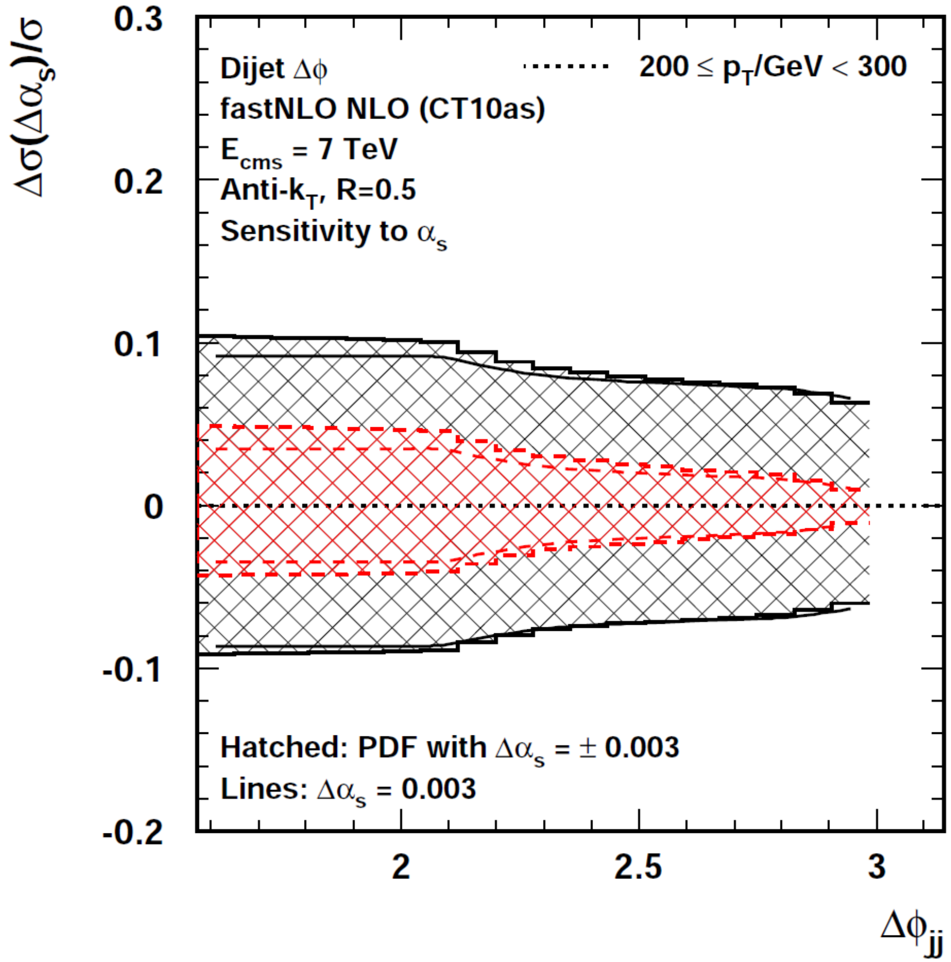
CMS: arXiv:1102.0068

ΔΦ: Sensitivity to α_s

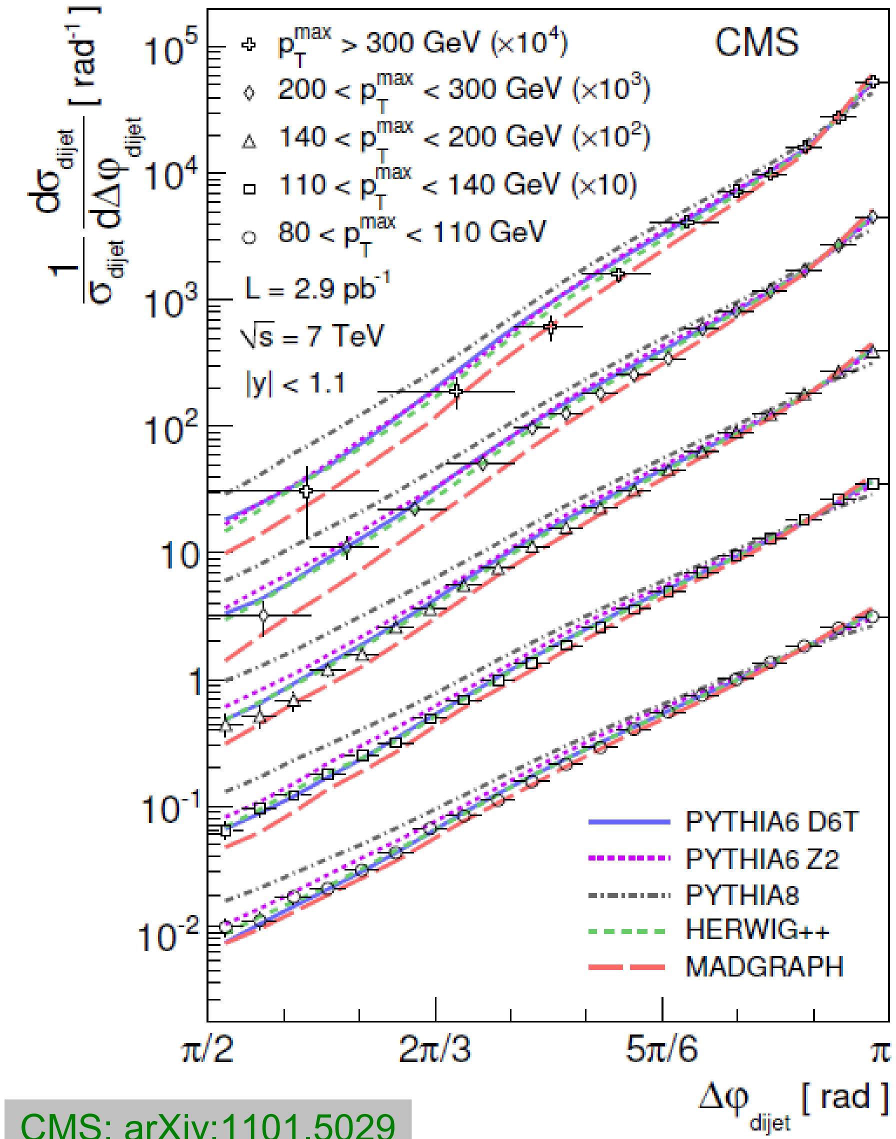
Low pT bin: 80 < pT / GeV < 110

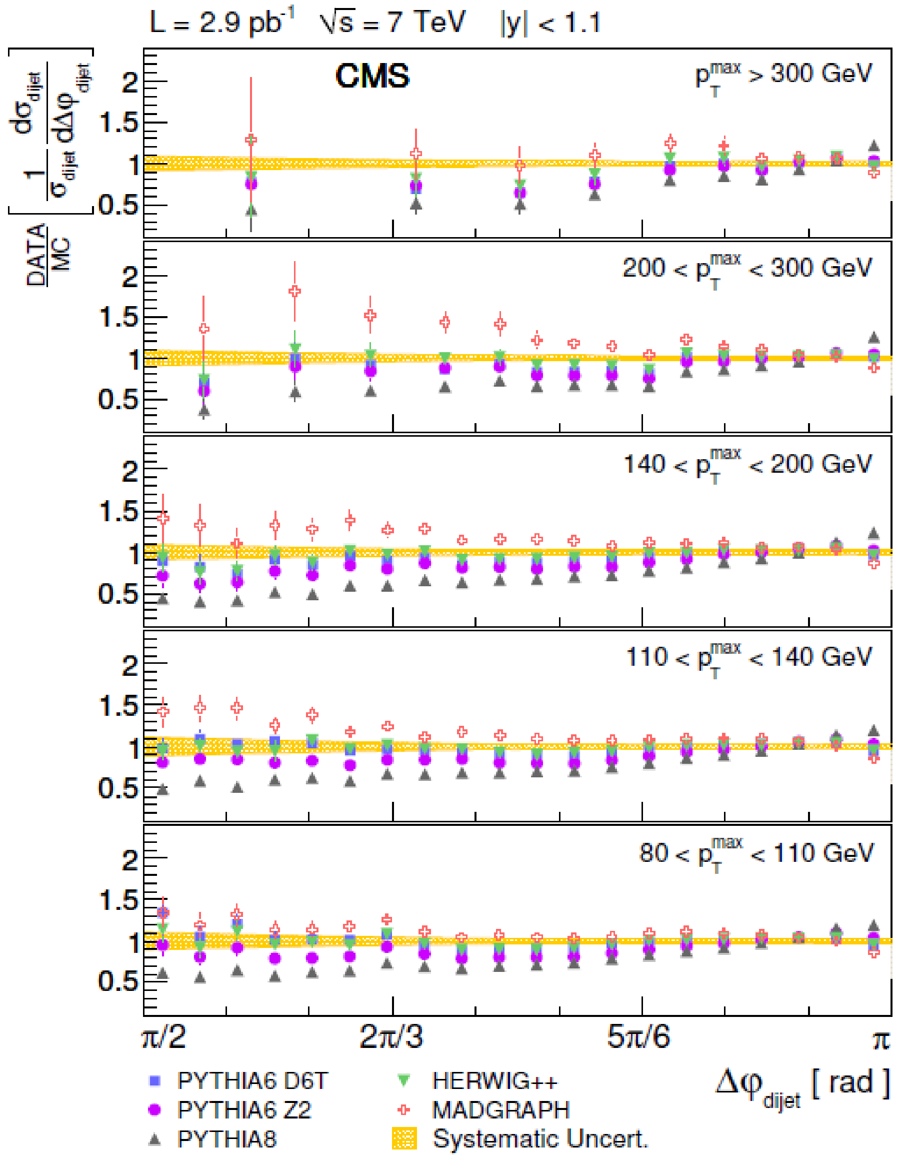
High pT bin: 200 < pT / GeV < 300





ΔΦ: Comparison to MC

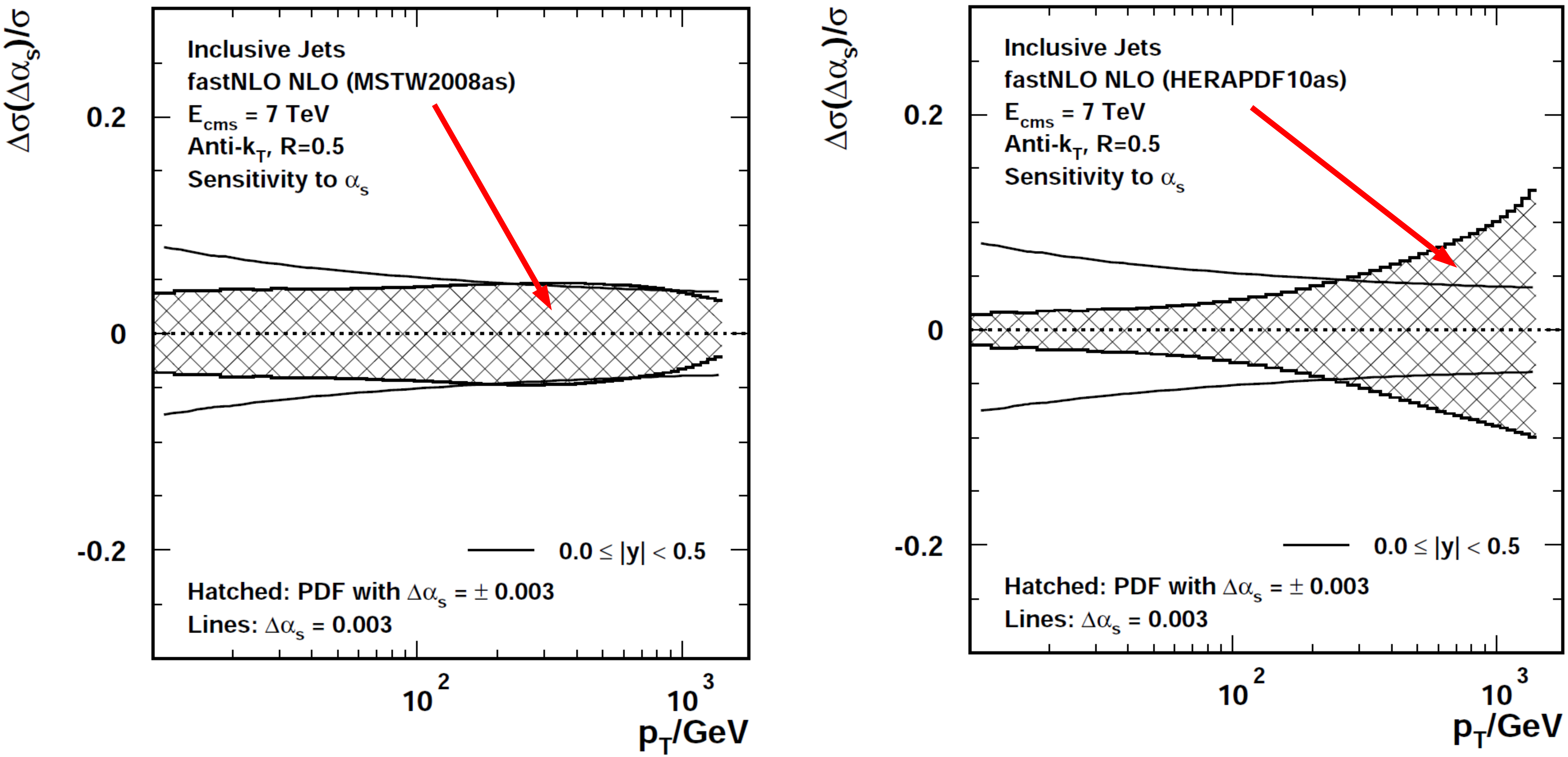




CMS: arXiv:1101.5029

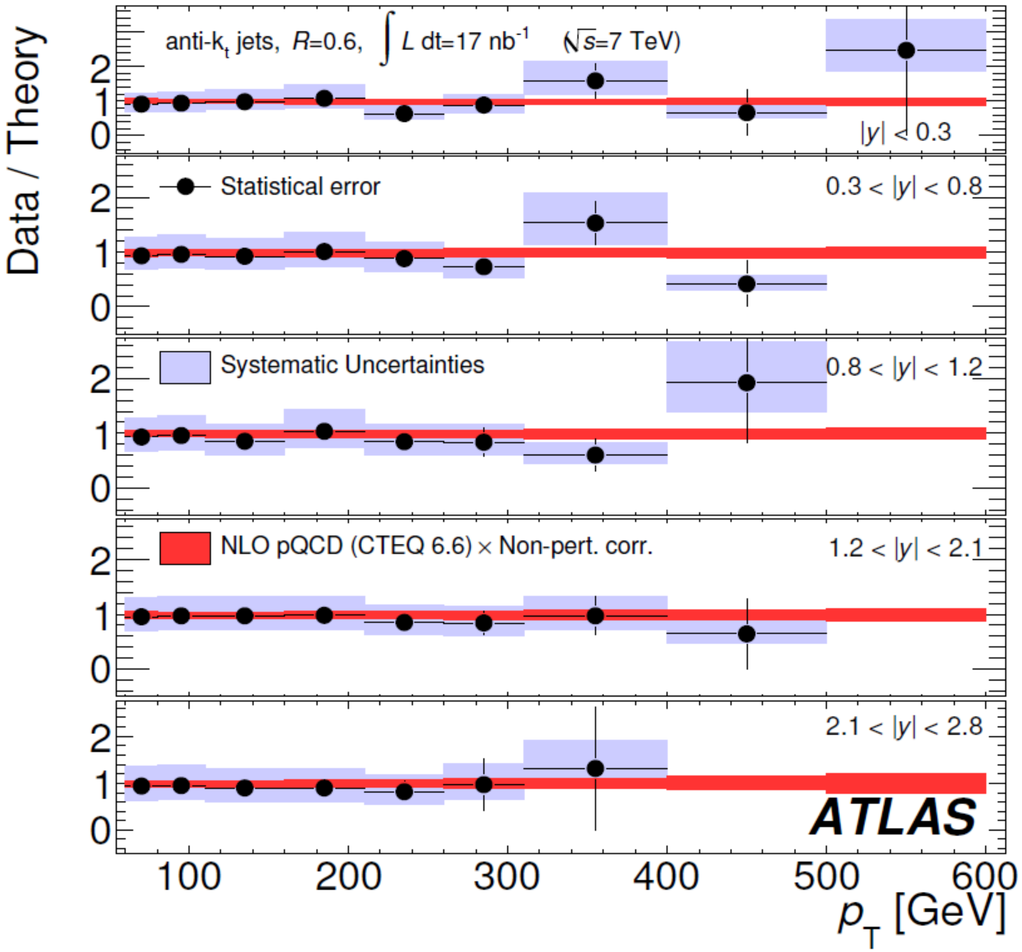
Sensitivity to alpha_s

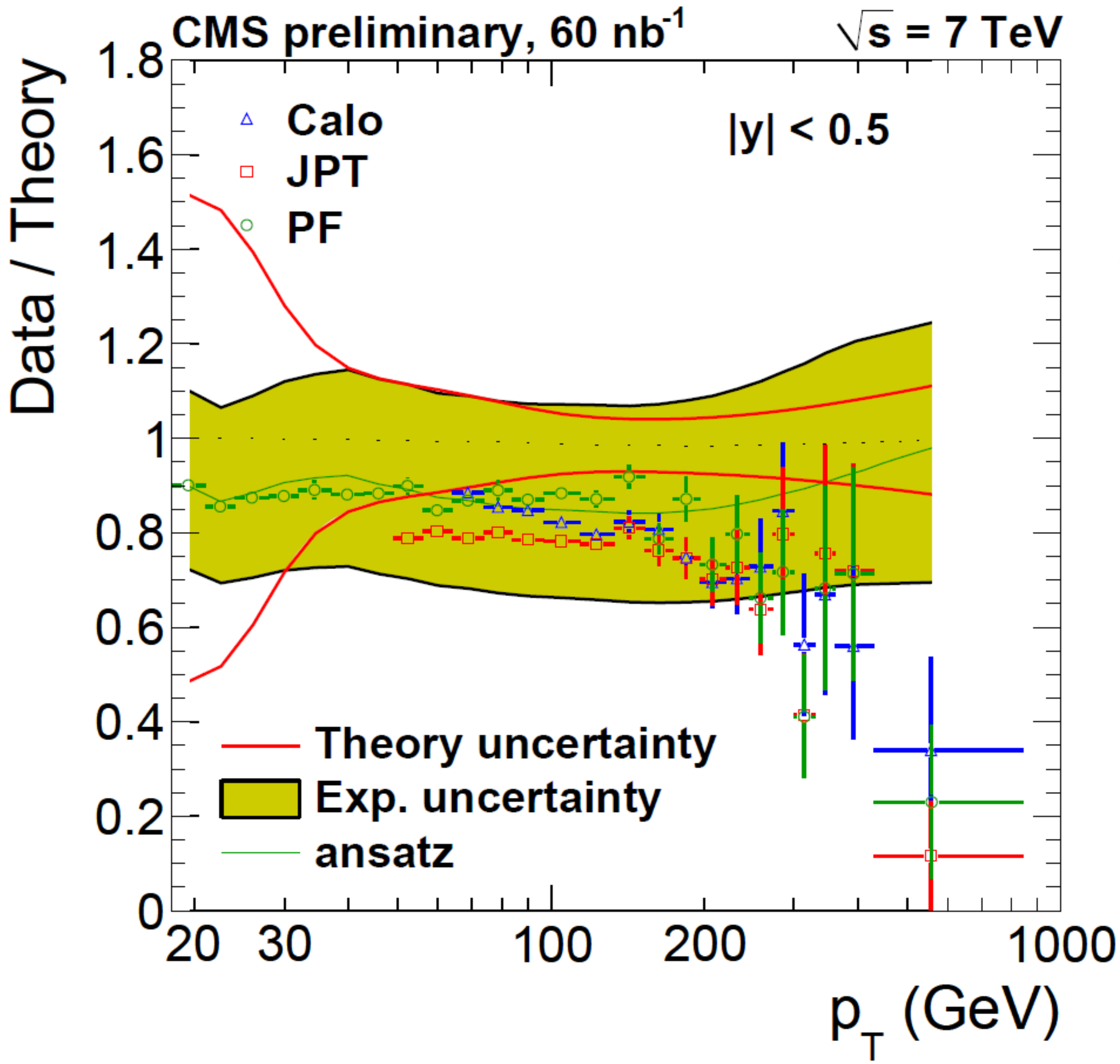
Inclusive Jet pT



Incl. Jet pT: Data / Theory

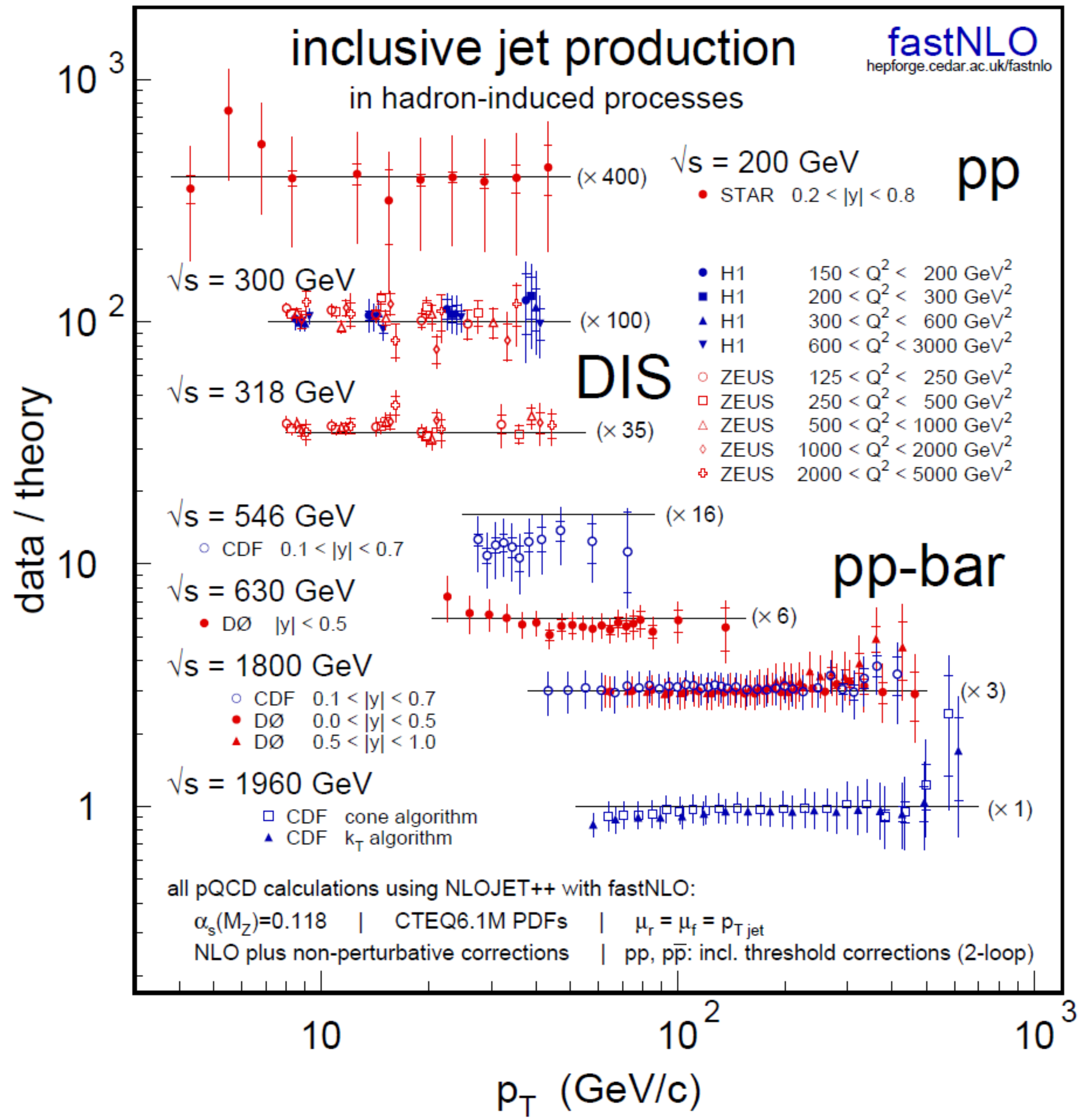
Compatible within uncertainties!





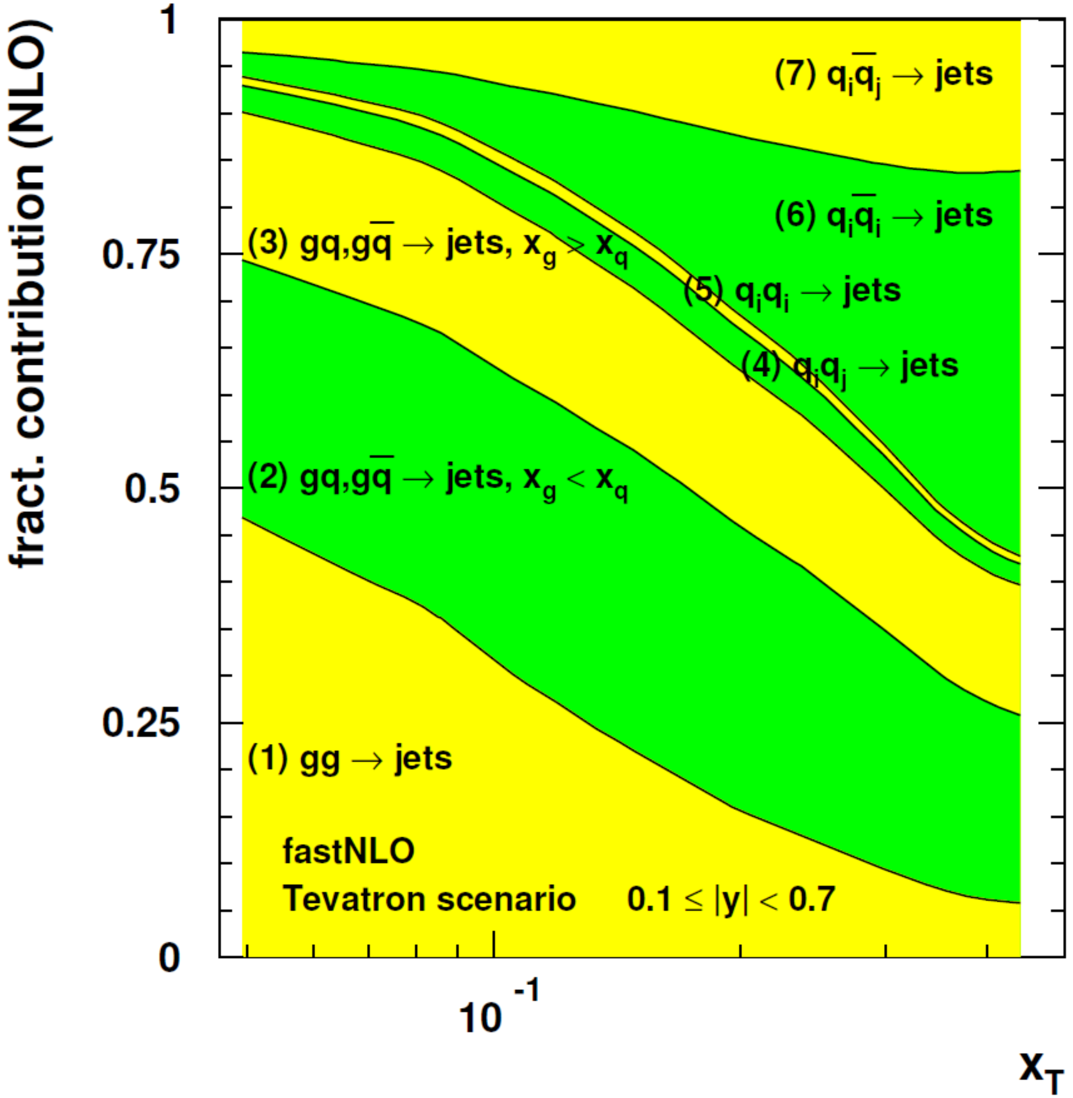
Previous Jets Data / Theory

- **Comparison of jet data from**
  - **STAR at RHIC**
  - **H1 and ZEUS at HERA**
  - **CDF and D0 at Tevatron**
- **Compatible with NLO pQCD**

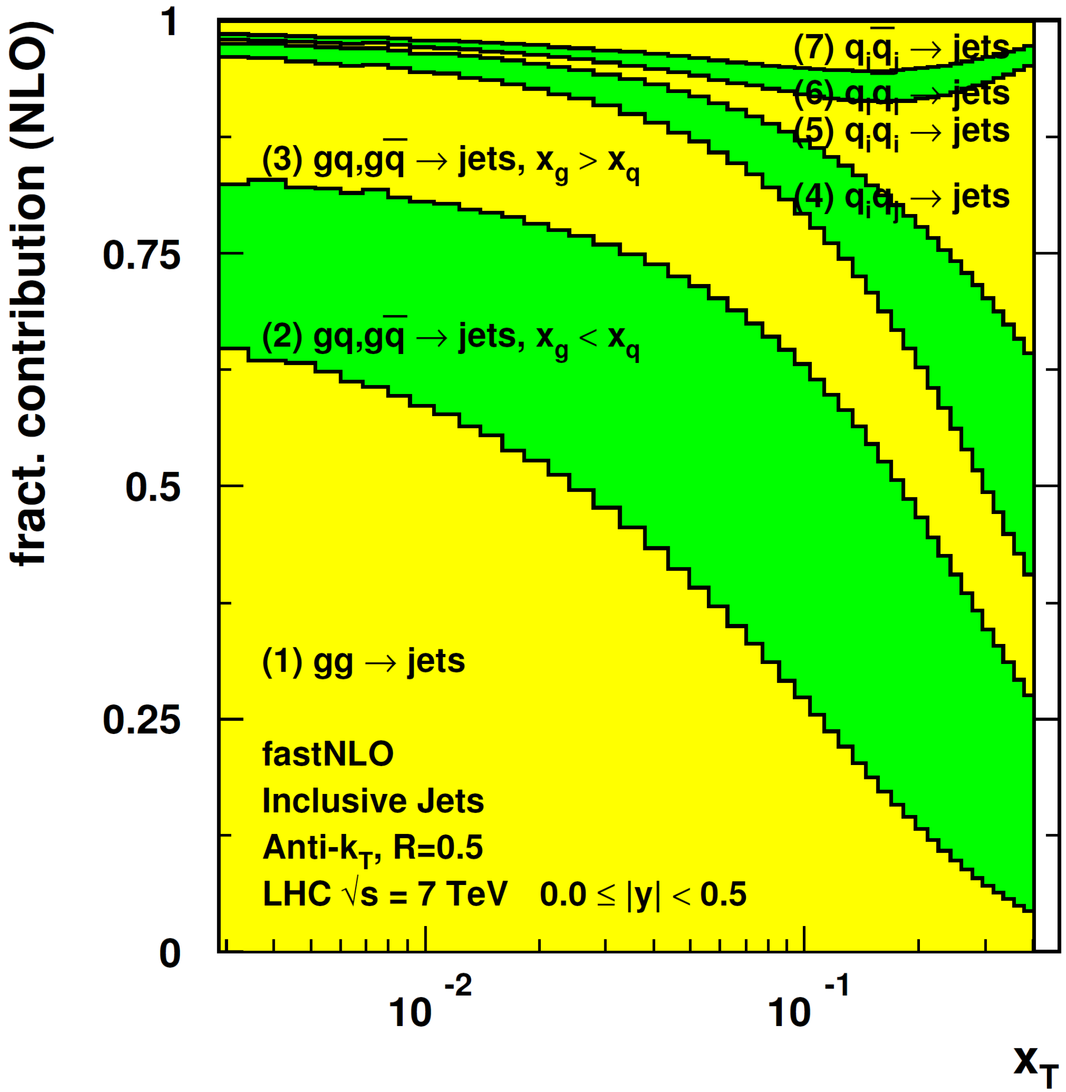


Jet Cross Section Decomposition

Tevatron, 1.96 TeV



LHC, 7 TeV

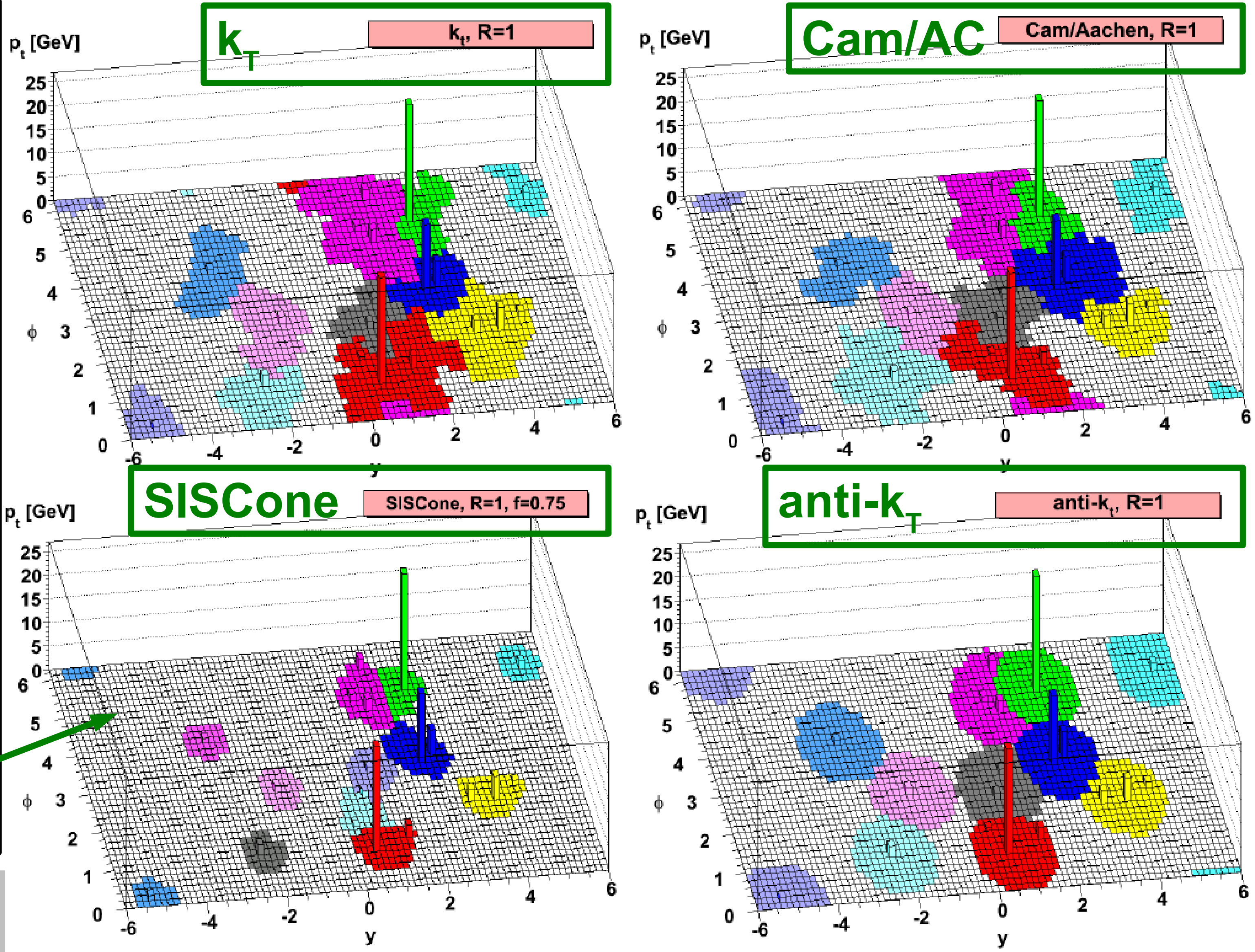


Jet Algorithms at LHC

Primary algorithm at LHC:

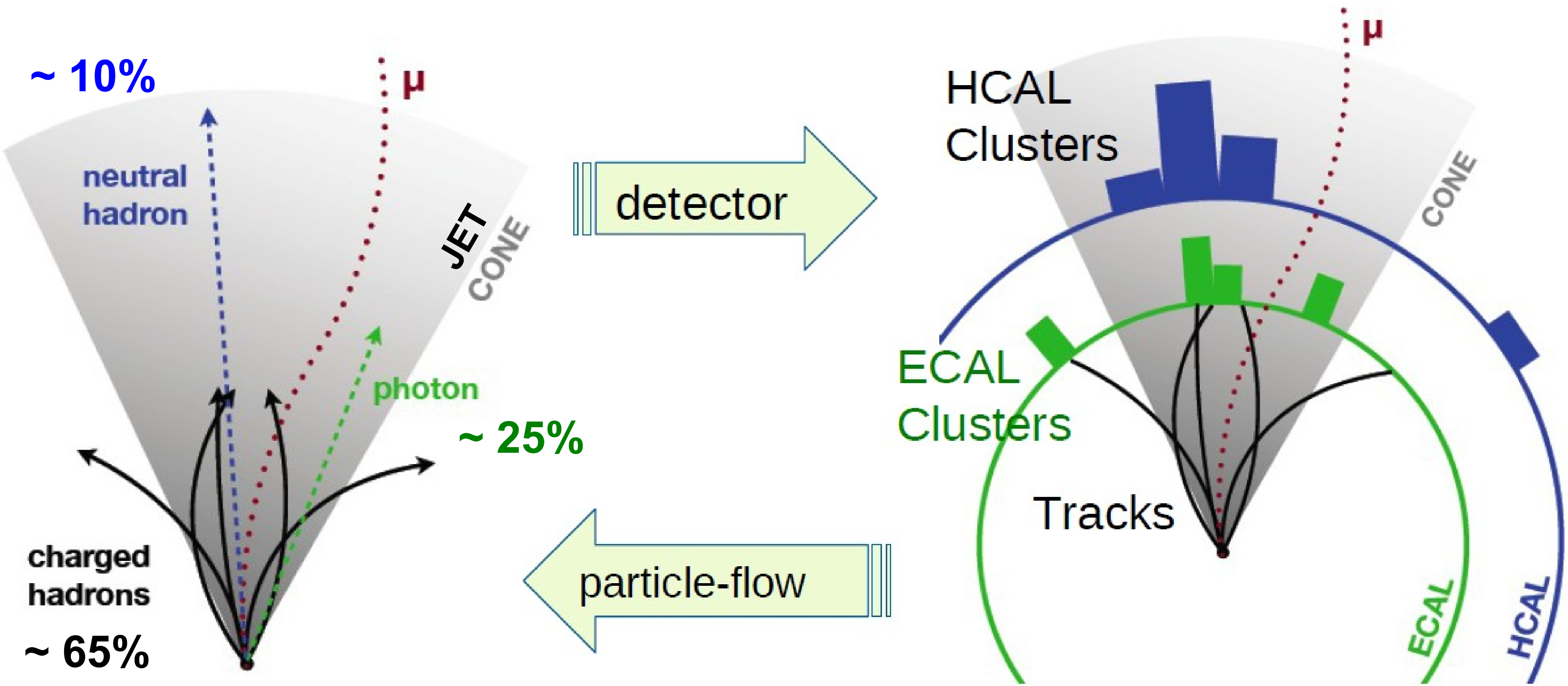
- **Anti-k_T:**
  ATLAS R = 0.4, 0.6
  CMS R = 0.5, 0.7
- k_T: R = 0.4, 0.6 (ATLAS & CMS)
- SISCone: R = 0.5, 0.7 (CMS)
- Cambridge/Aachen used in jet substructure, for example in boosted top

General interest to work with all four



Fast kT, Cacciari/Salam, PLB641, 2006
SISCone, Salam/Soyez, JHEP05, 2007
anti-kT, Cacciari et al., JHEP04, 2008

Particle Flow Concept



Associate particle types to all measurements, apply type-dependent corrections

Jet Calibration and Uncertainty

Jet calibration:

Simple $P_{T,jet}$ and y dependent correction applied to measured jets at the electro-magnetic scale.
Using particle level (truth) from Monte Carlo simulation as reference.

Jet energy scale uncertainty:

Evaluated using MC using various detector configurations, hadronic shower and physics models
Based on large test-beam experience.

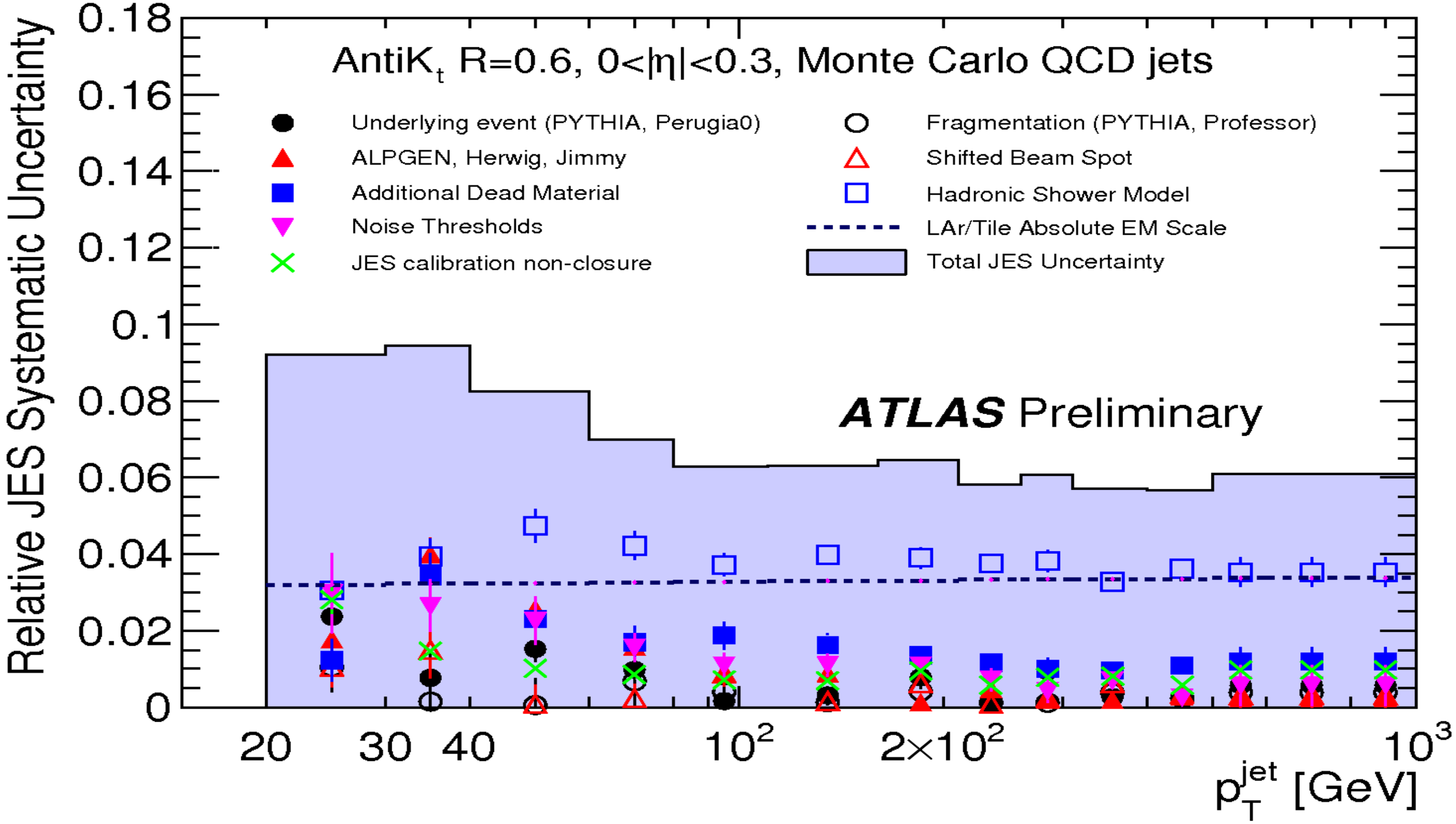
In-situ measurements:

1) Using Di-jet balance to transport uncertainty central -> forward

2) Additional uncertainty for pile-up from average tower energy per vertex

3) Cross-checked with single isolated hadron response measurement (E_{calo}/p_{track})
Uncertainty via: deconvolution of jets in individual particles

Example:

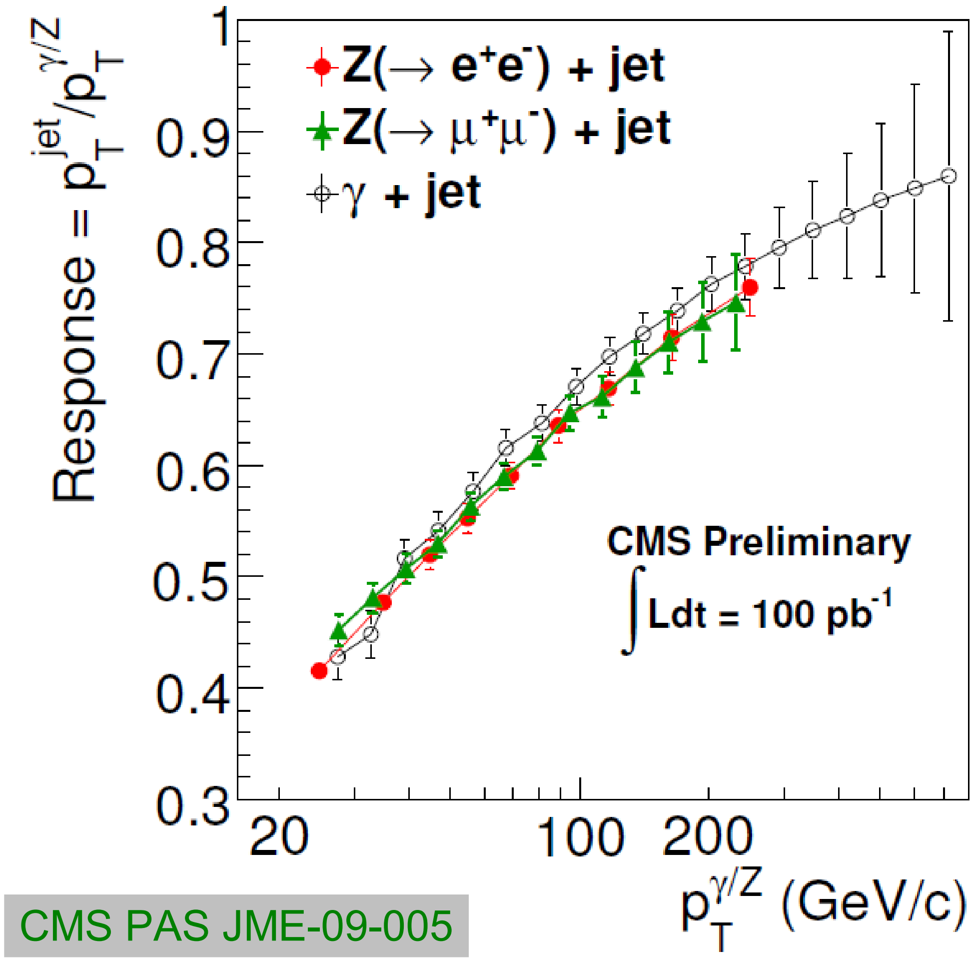


Jet energy scale uncertainty smaller than 7% for $p_{t,jet}$>100 GeV

Absolute Correction (Simulation Result)

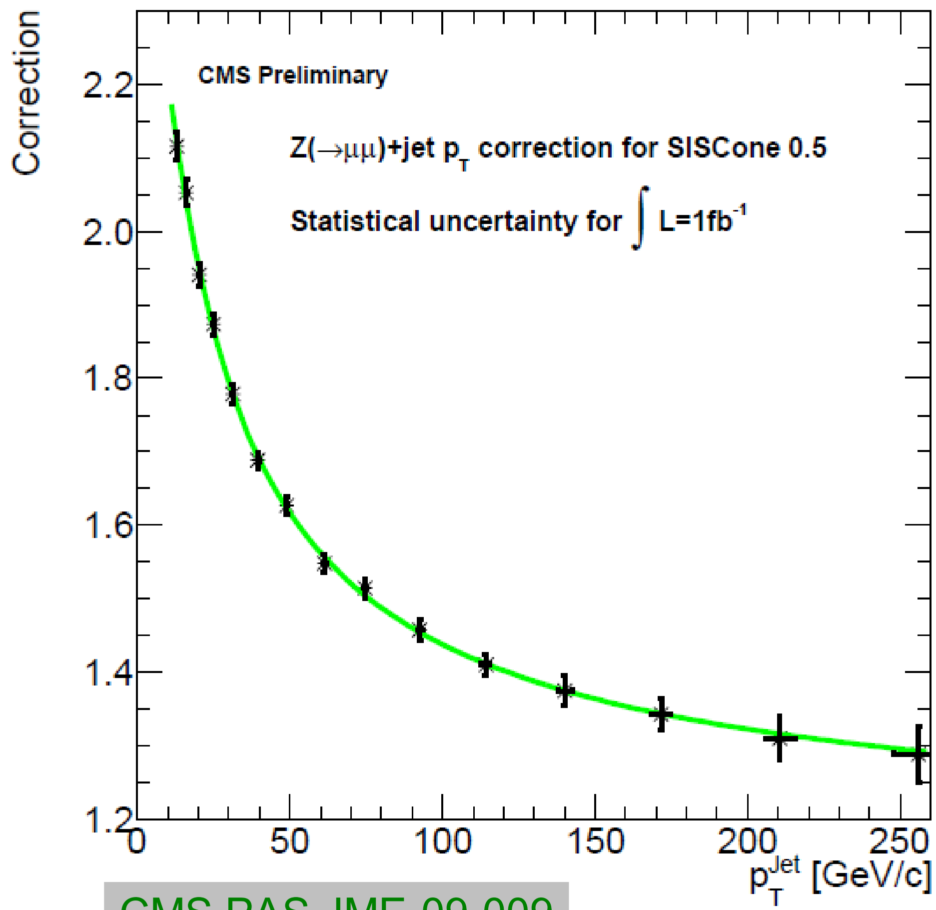
CMS detector simulation, calorimeter towers, E_{CMS} = 10 TeV

Comparison of jet responses



CMS PAS JME-09-005

Derived correction at the example of Z(→μμ) + 1jet



CMS PAS JME-09-009

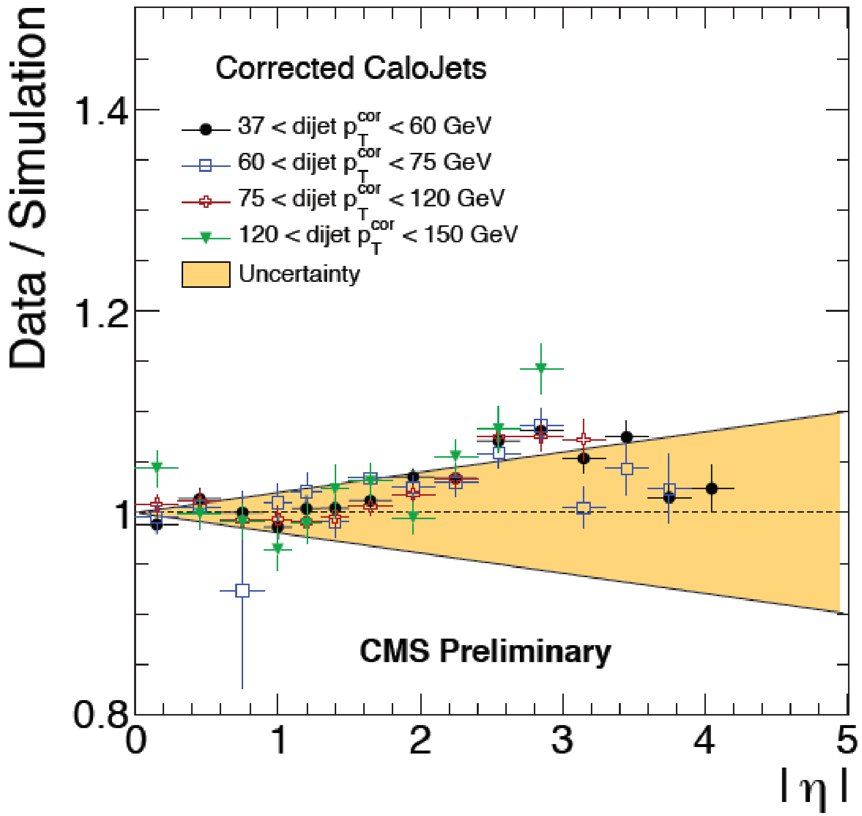
Relative Jet Corrections

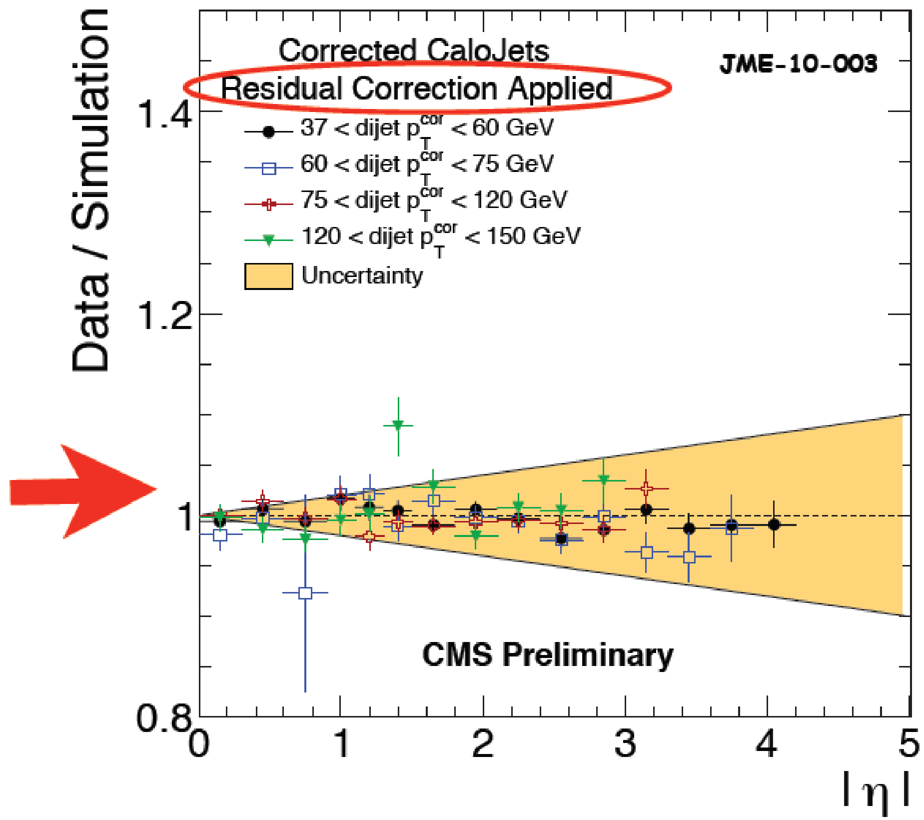
- Response rapidity dependence is extracted from dijet asymmetry

M. Voutilainen, ICHEP2010

- Residual correction is applied for inclusive jets, other studies are covered by the systematic uncertainty band of **2% times unit of rapidity**

Jet correction = Absolute(p_T) [MC] × Relative(η) [MC+data]





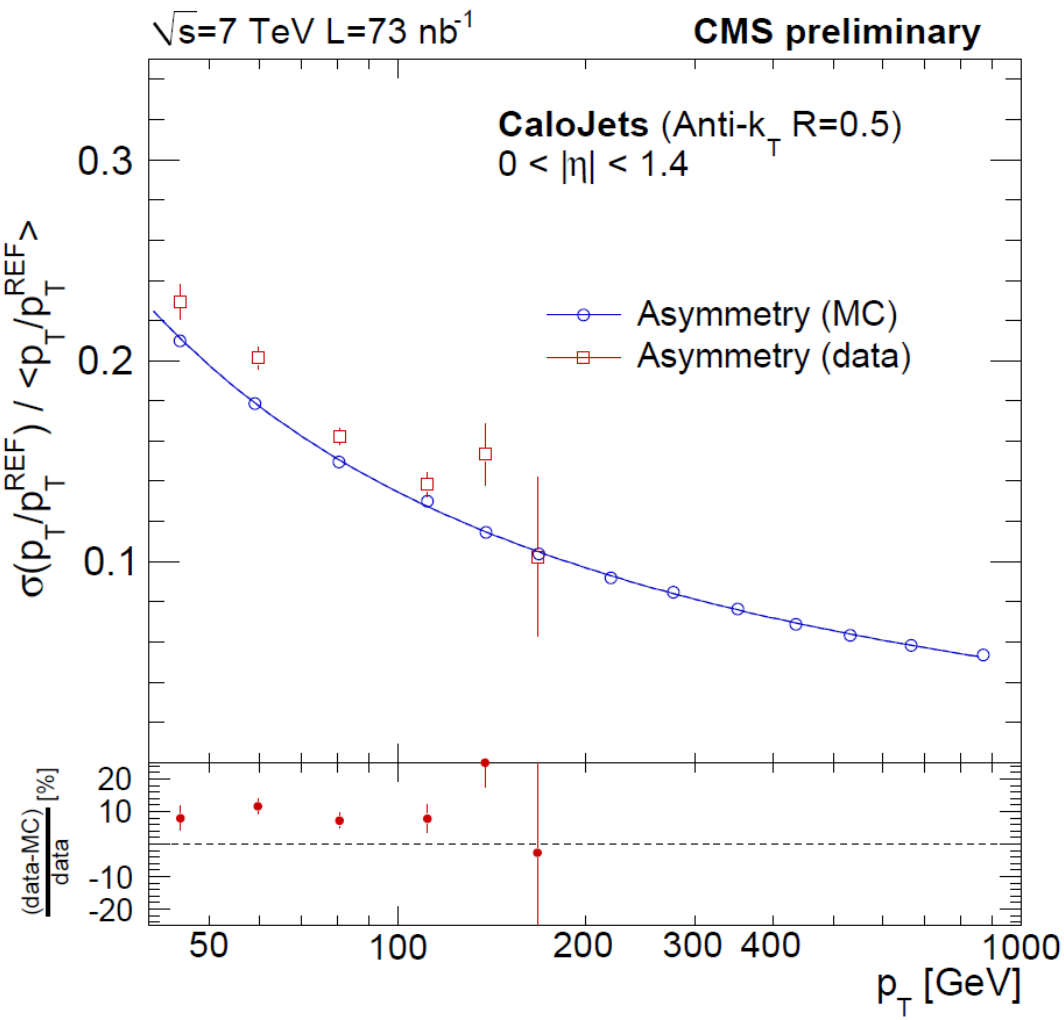
Jet Energy Resolution

Jet energy resolution (JER):

- Can be measured from data using Asymmetry Method used:
  For dijet events:

$$A = \frac{(p_T^{jet1} - p_T^{jet2})}{(p_T^{jet1} + p_T^{jet2})} \Rightarrow \left(\frac{\sigma_{p_T}}{p_T}\right) = \sqrt{2}\sigma_A$$

  Used at Tevatron.
- Comparison using MC information (matched jets) gives consistent results



CMS PAS JME-10-003

The ATLAS Detector

Inner Detector (ID) tracker:

- Si pixel and strip + transition rad. tracker
- $\sigma(d_0)$ = 15µm@20GeV
- $\sigma/p_T \approx 0.05\% p_T \oplus 1\%$

Calorimeter

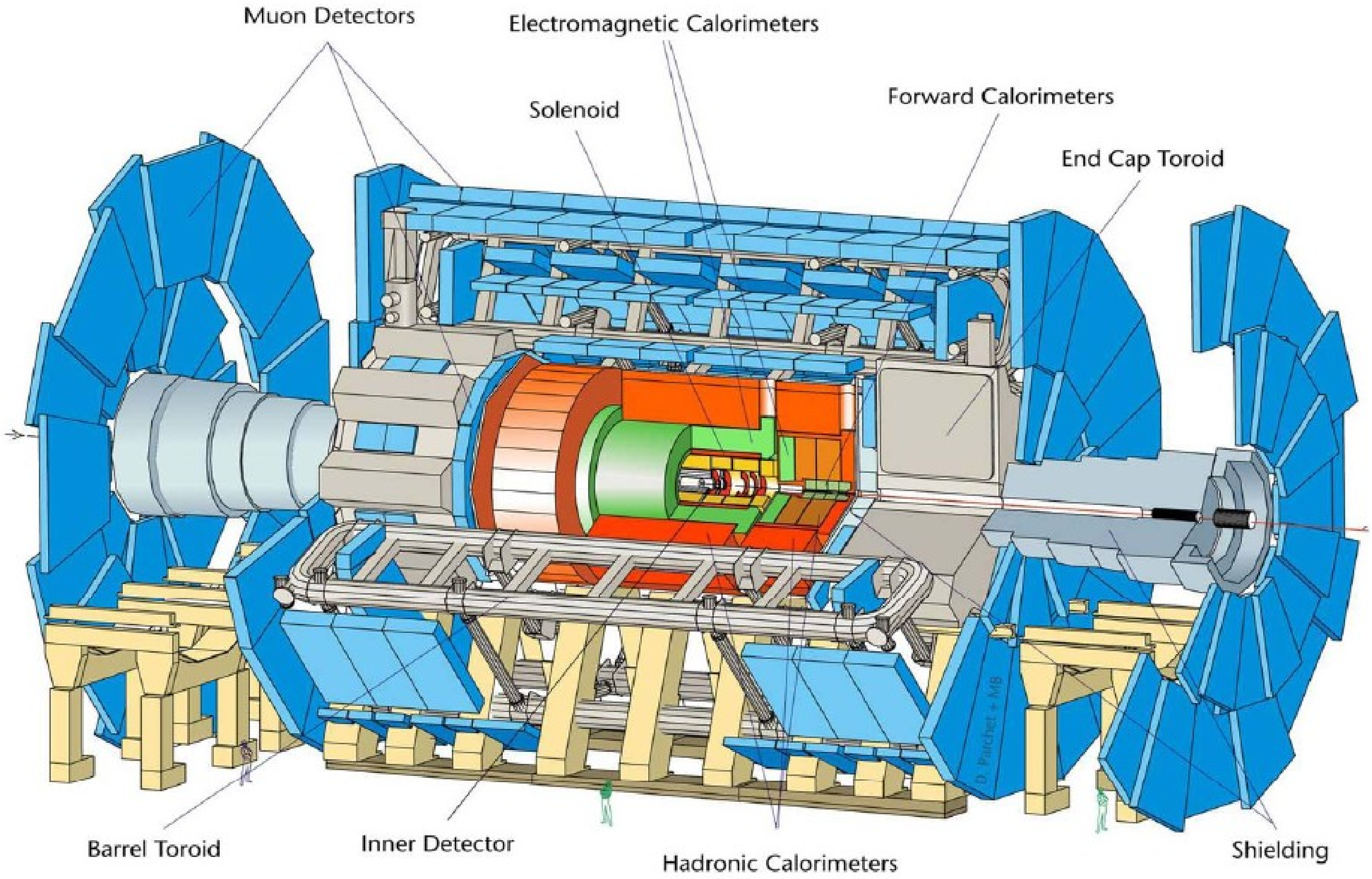
- Liquid Ar EM Cal, Tile Had.Cal
- EM: $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
- Had: $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$

Muon spectrometer

- Drift tubes, cathode strips: precision tracking +
- RPC, TGC: triggering
- $\sigma/p_T \approx 2\text{-}7\%$

Magnets

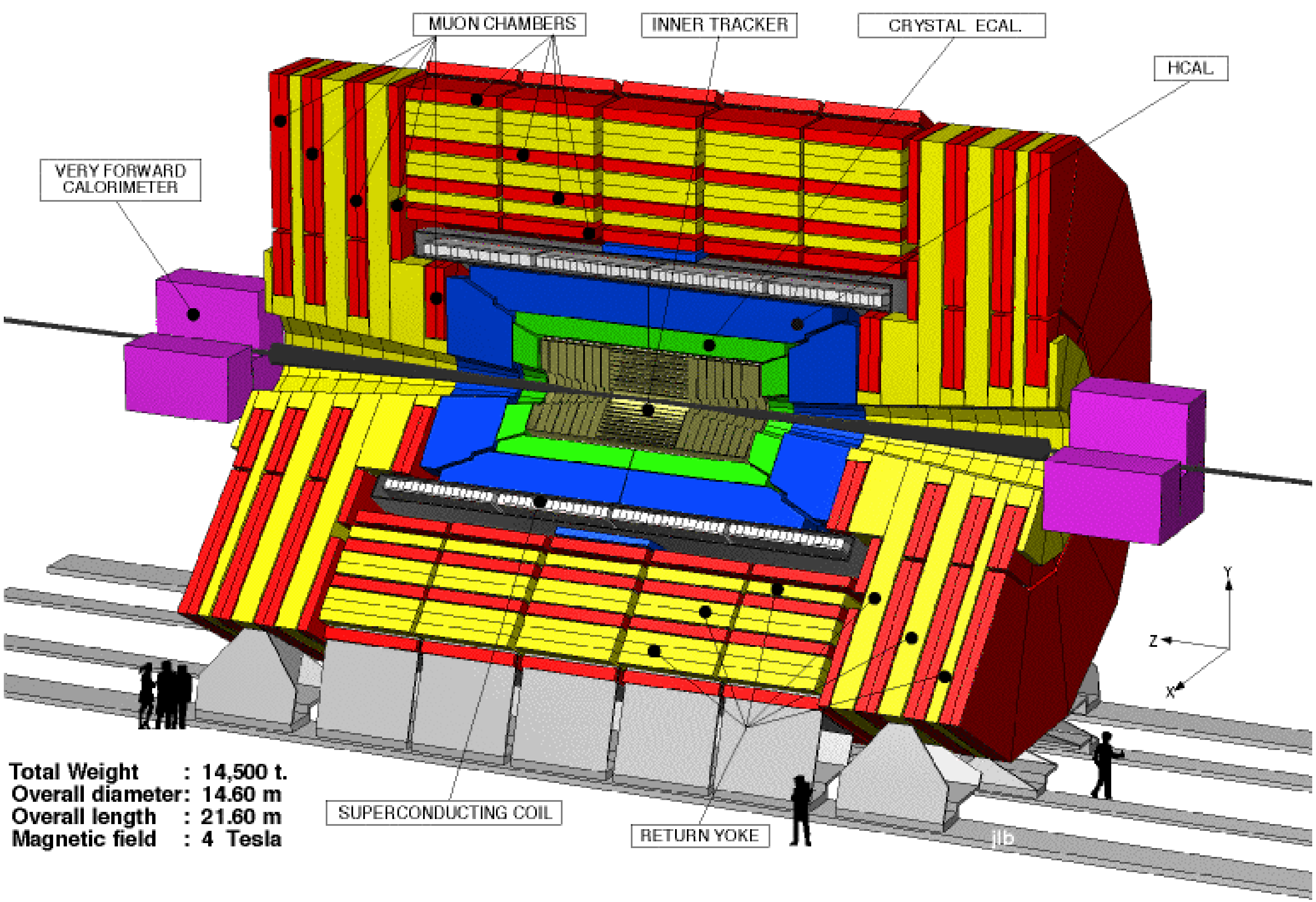
- Solenoid (ID) → 2T
- Air toroids (muon) → up to 4T



Full coverage for |η|<2.5, calorimeter up to |η|<5

See also JINST 3 2008 S08003

The CMS Detector



Inner detector (tracker):

- Si pixel & strip tracker
- $\sigma/p_T \approx$ 1-2% (μ at 100 GeV)

Calorimeter:

- PbWO4 crystal ECAL, brass/scintillator HCAL
- ELM: $\sigma_E/E = 2.8\% /\sqrt{E} + 0.3\%$
- HAD: $\sigma_E/E = 100\% /\sqrt{E} + 5\%$

Muon system:

- Drift tubes, cathode strips, resistive plate chambers
- $\sigma/p \approx$ 10 – 50% (muon alone)
- $\approx$ 0.7 – 20% (with tracker)

Magnet:

- Solenoid → 3.8T

See also:
PTDR I LHCC-2006-001,
JINST 3 2008 S08003

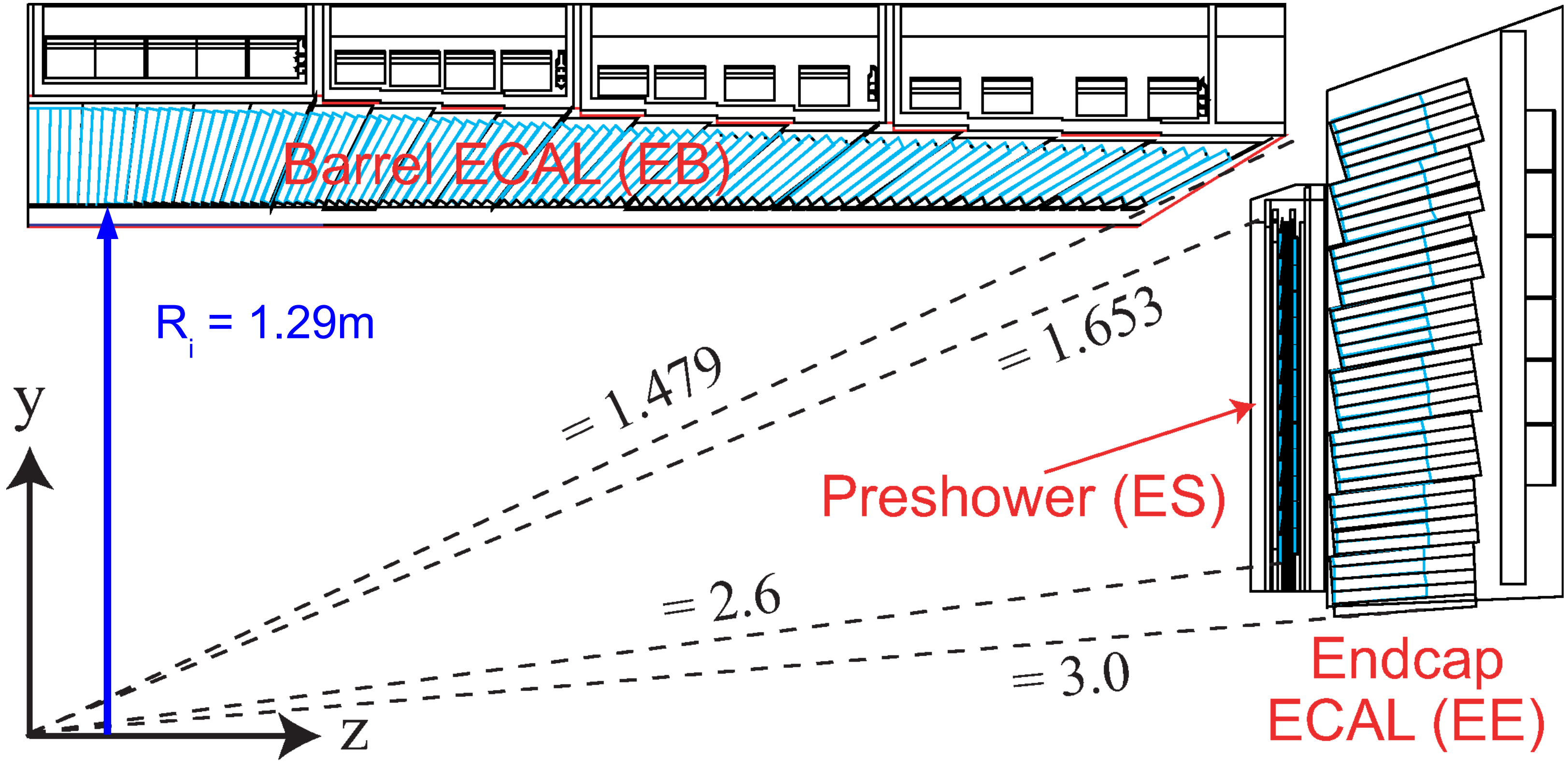
Electromagnetic Calorimeter

Barrel (EB):
- η segments: 2x85
- φ segments: 360

→ 61200 crystals
($PbWO_4$, 26 X_0)

→ Δη x Δφ ≈
0.0174 x 0.0174

Segmentation



Energy resolution from test beam:
S = 2.8%, N = 120 MeV, C = 0.30%

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2$$

Segmentation

Endcaps (EE):
- (x,y) grid on two halfs
- front face 28 x 28 mm^2

→ 2 x 2 x 3662 crystals = 14648
($PbWO_4$, 25 X_0)

Hadronic Calorimeter

<u>HCAL (tower structure)</u>:
- Barrel (HB): $|\eta| < 1.4$, 2592 towers
- Endcaps (HE): $1.3 < |\eta| < 3.0$, 2592 "
- Outside coil (HO): $|\eta| < 1.26$, 2160 "

→ Depth (Brass abs. & plast. scint., ≈ 6 - 10 λ_N)

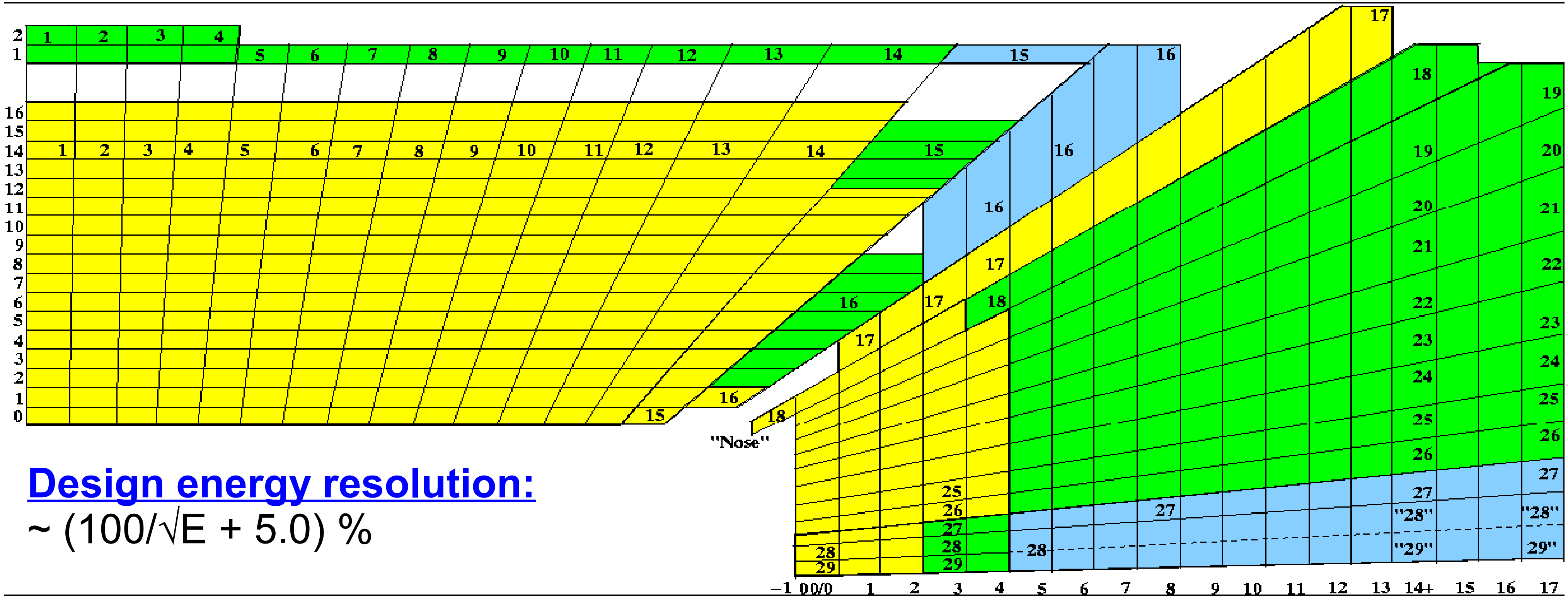
→ $\Delta\eta \times \Delta\varphi \approx 0.087 \times 0.087 \rightarrow 0.350 \times 0.175$

- Forward (HF): $2.9 < |\eta| < 5.0$ (not shown)

→ 2 x 864 towers (Brass,quartz fibers, ≈ 10 λ_N)

→ $\Delta\eta \times \Delta\varphi \approx 0.111 \times 0.175 \rightarrow 0.302 \times 0.350$

<u>CASTOR calorimeter</u> (not shown):
- $5.1 < |\eta| < 6.5$, ≈ 22 X_0, ≈ 10 λ_N



Design energy resolution:

~ $(100/\sqrt{E} + 5.0)$ %