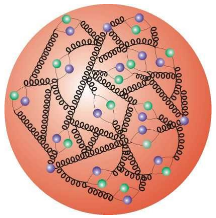
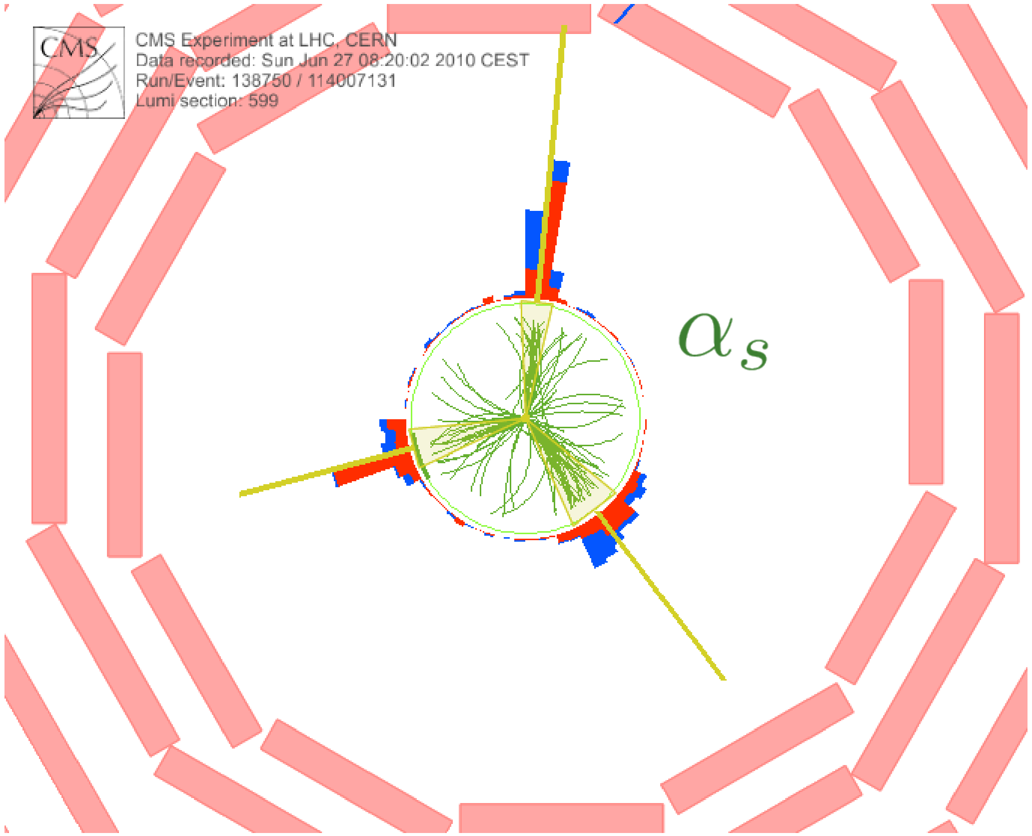
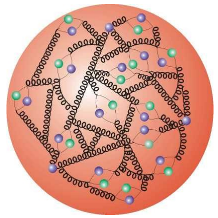
Jet Measurements at LHC and Tevatron



Proton Structure (PDF)





Proton Structure (PDF)

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Klaus Rabbertz, KIT

Karlsruhe Institute of Technology

The Menu

The Menu

- Motivation
- Accelerators and Detectors
- Jet Algorithms and Jet Calibration
- Inclusive Jets
- Dijet and 3-Jet Mass
- The strong Coupling from Jets
- Outlook
- Multi-jet events, V plus jet production, forward jets, dijet correlations at large rapidity etc. are covered in the next talks

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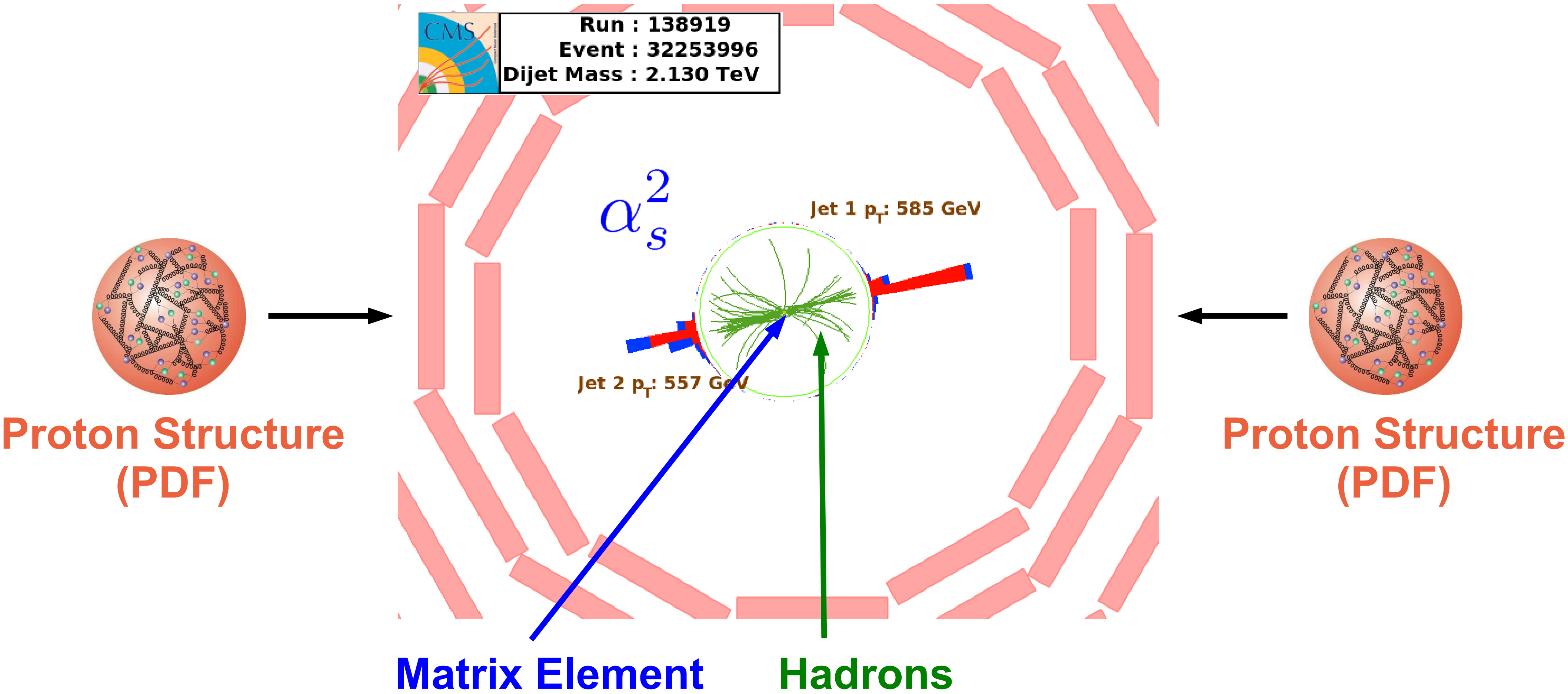
- Multi-jet events, V plus jet production, forward jets, dijet correlations at large rapidity etc. are covered in the next talks
- Another time that one theorist keeps multiple experimenters busy :-)

Jets ... so what?

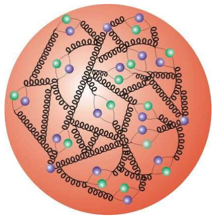
Abundant production of jets → hadron colliders are “jet laboratories”
Learn about hard QCD, the proton structure, non-perturbative effects ...



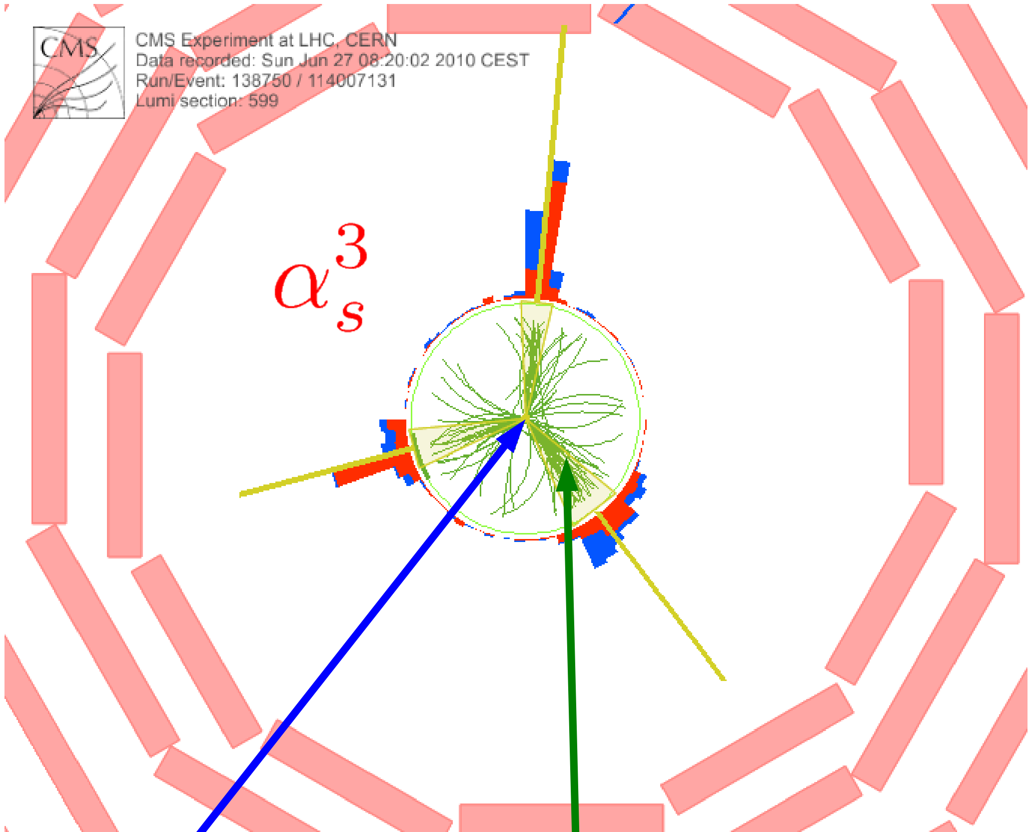
Jets … so what?

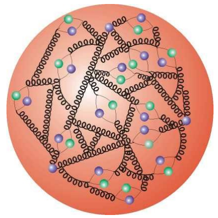
Abundant production of jets → hadron colliders are “jet laboratories”

… and the strong coupling alpha_s !



Proton Structure (PDF)

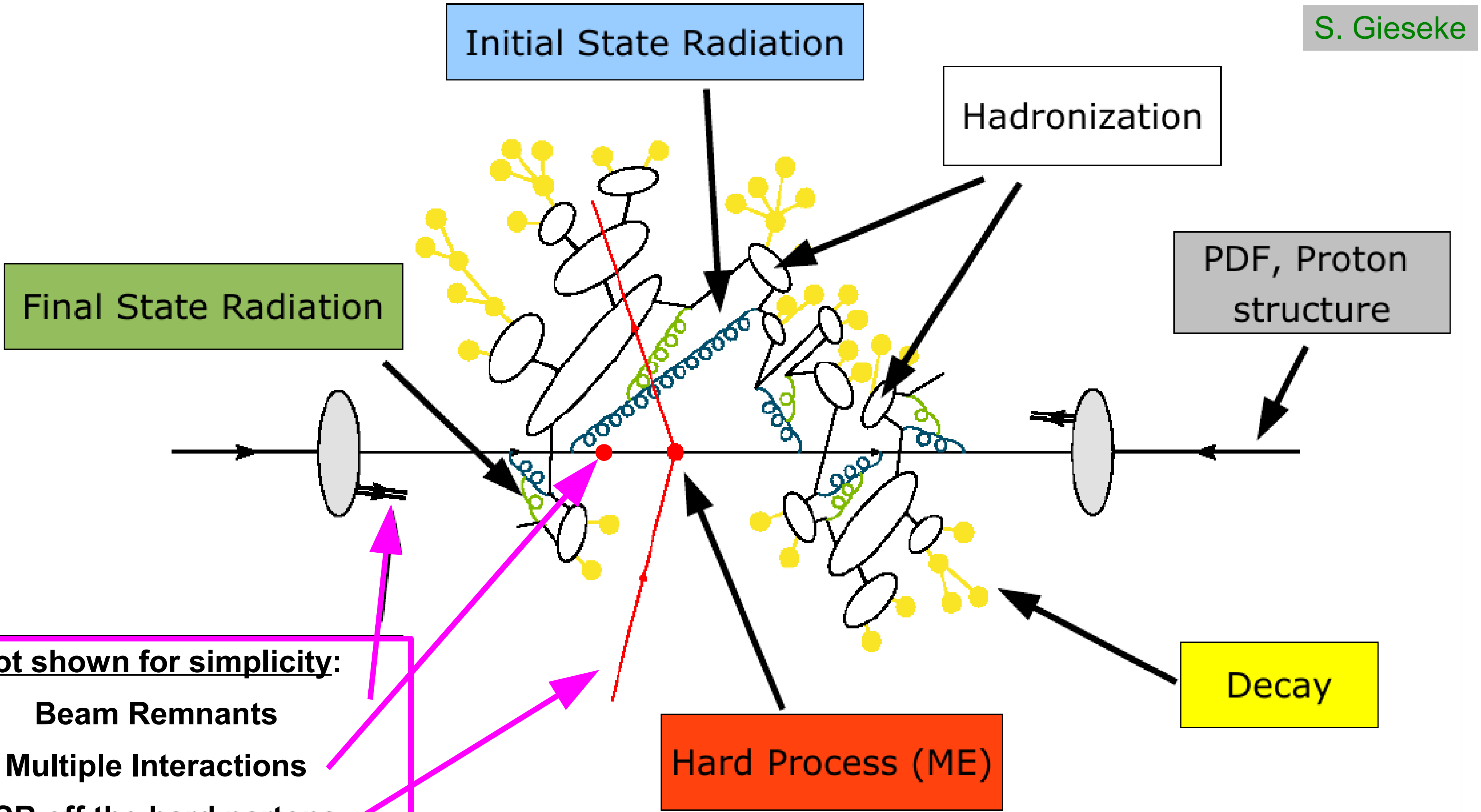




Proton Structure (PDF)

Matrix Element **Hadrons**

The central Pixel resolved ...



Not shown for simplicity:

Beam Remnants

Multiple Interactions

FSR off the hard partons

Achievements

30 years ago ...

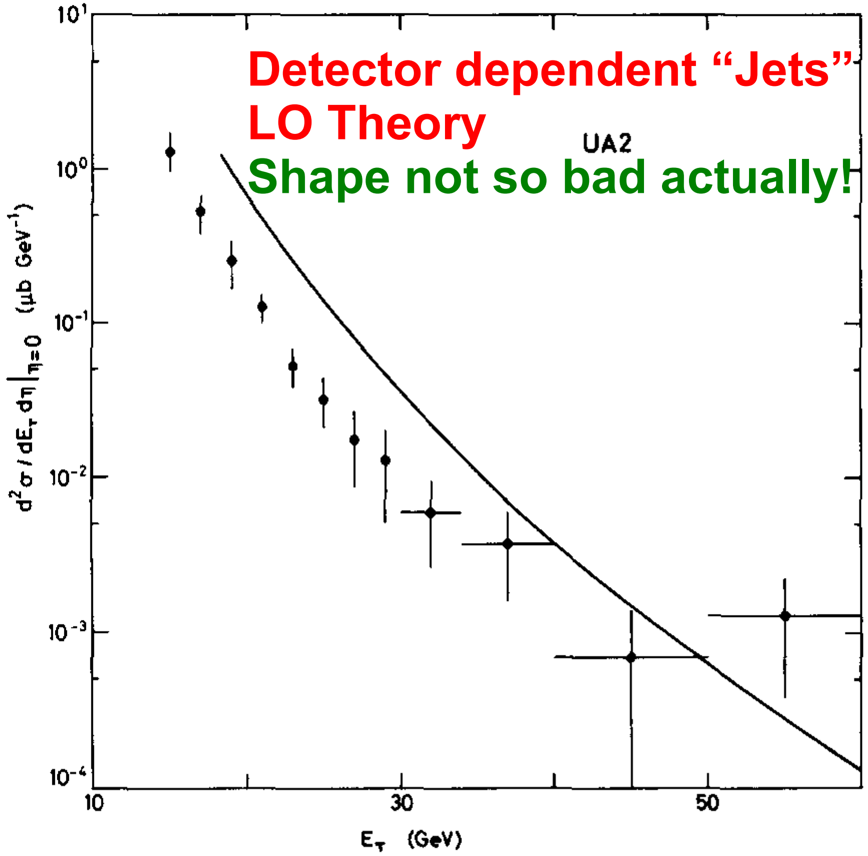


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

Achievements

30 years ago ...

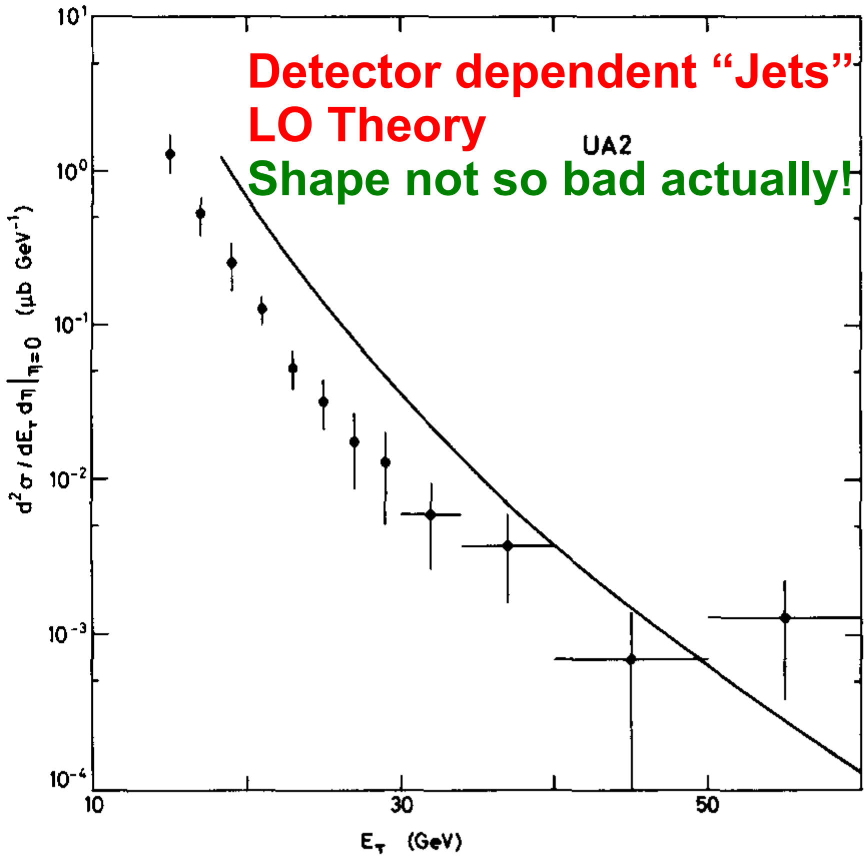
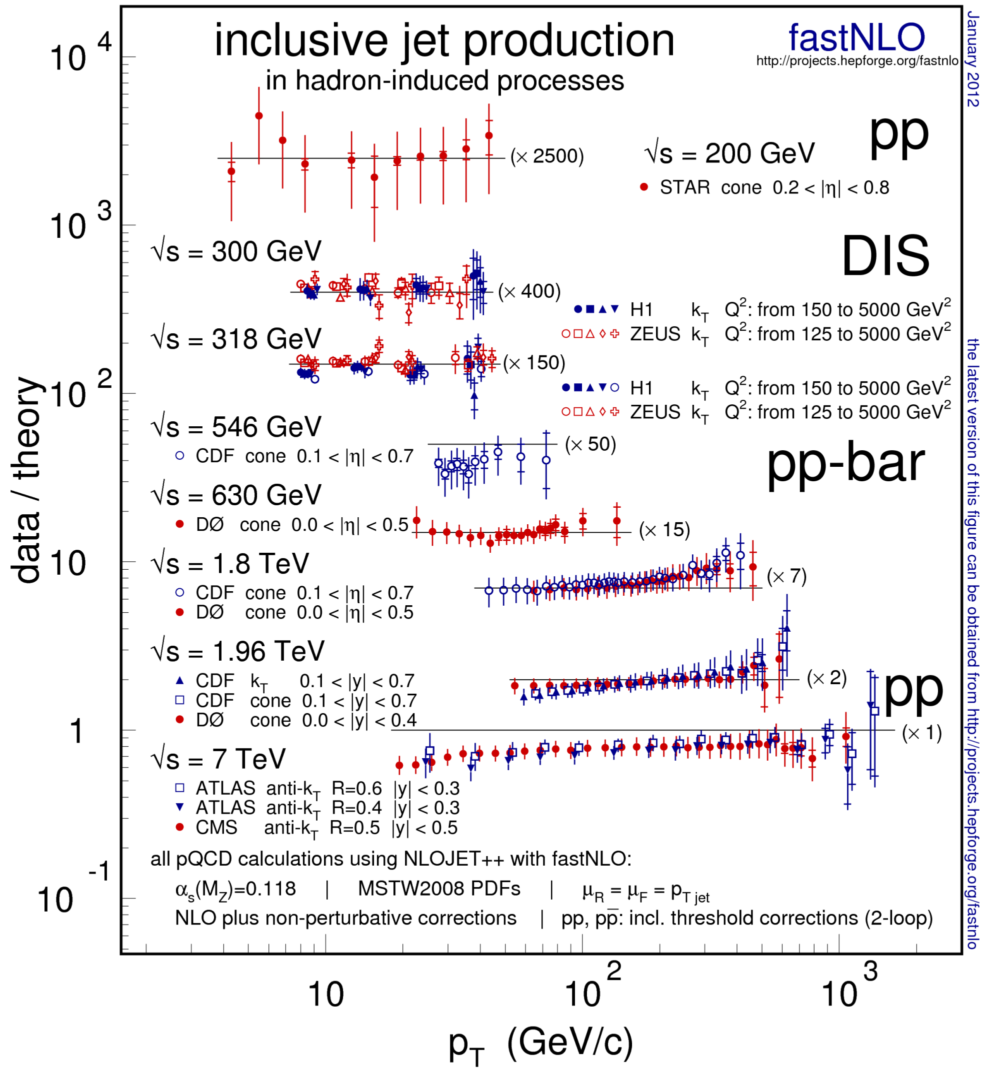


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

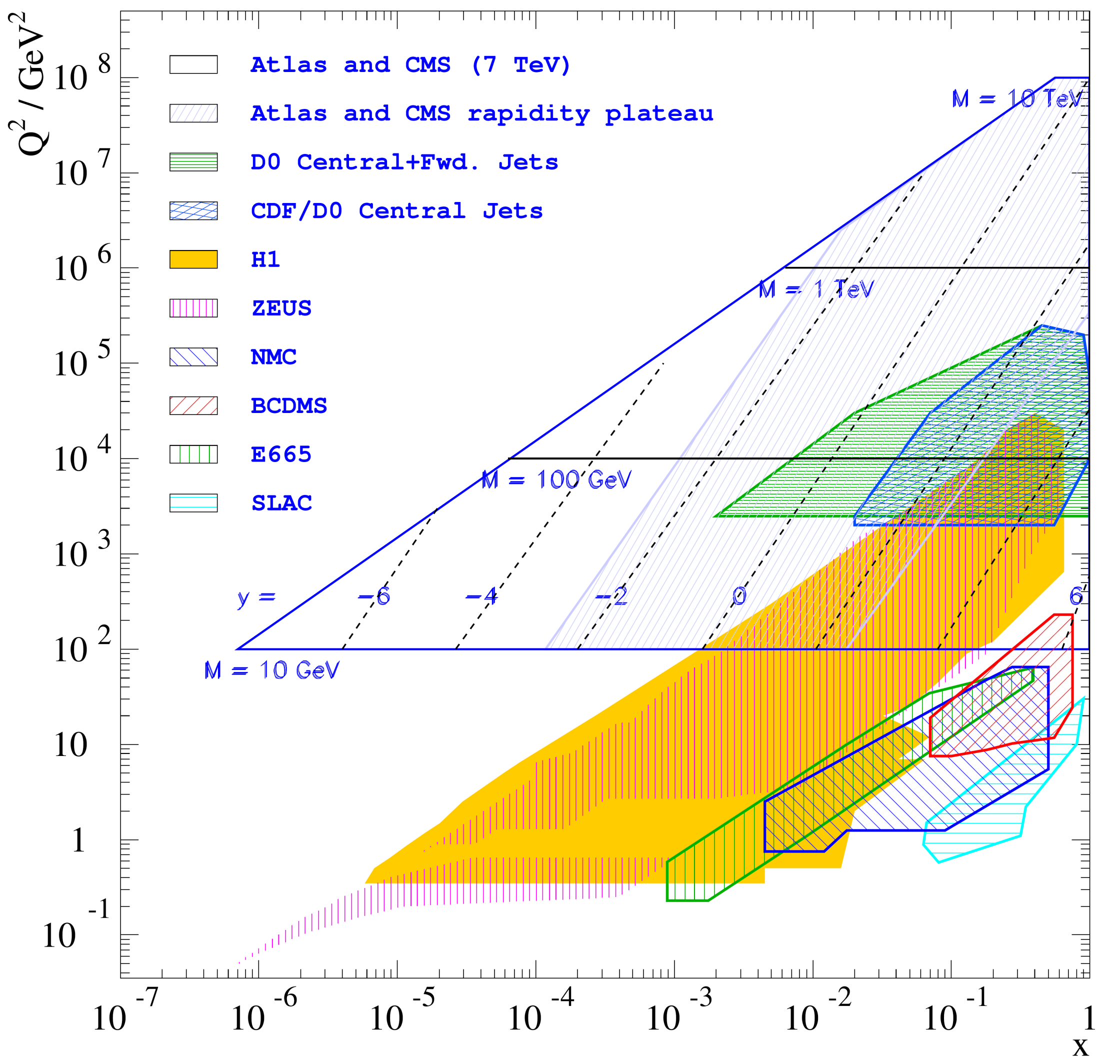
… and today !



fastNLO, to be updated, arXiv:1109:1310v2, 2012

Where to go ...

Kinematic plane of process scale^2 vs. x



- Huge new phase space accessible in pp collisions at LHC
- Many different final states to examine with high accuracy
- A lot of progress on the theory side, see previous talk
- Check SM predictions at high scales, but watch out for corrections negligible up to now
- Determine the strong coupling and test its running at high scales
- Improve on PDFs and precision of SM predictions
- Any new “features”?

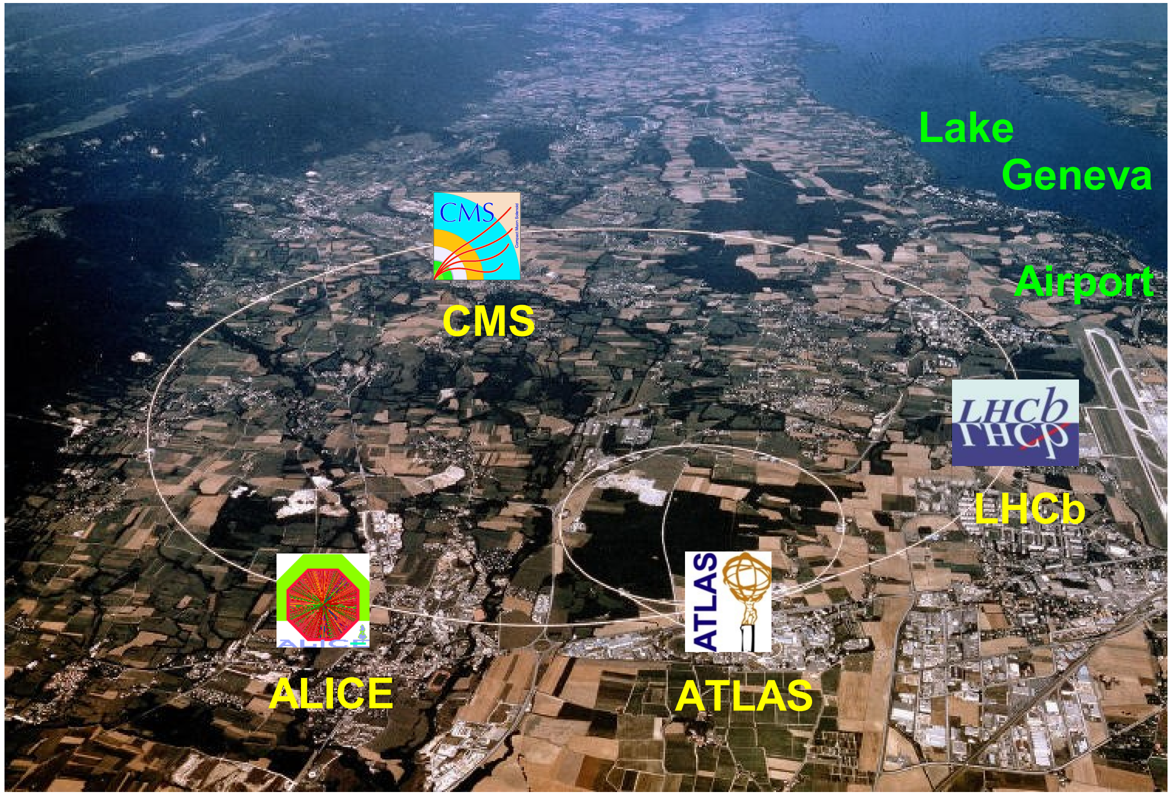
Tevatron and LHC

Tevatron: 1985 – 2011
26 years of p anti-p collisions

Run II: E_{cms} =1.96 TeV
Run II: record luminosity: 4.3 x 10^{32} $cm^{-2}s^{-1}$

LHC: 2009 – present
Collisions of p-p, Pb-Pb, and p-Pb (13.9.12)

2009 – 2012: E_{cms} = 0.9, 2.36, 2.76, 7, 8 TeV
2012: lumi approaching 8 x 10^{33} $cm^{-2}s^{-1}$



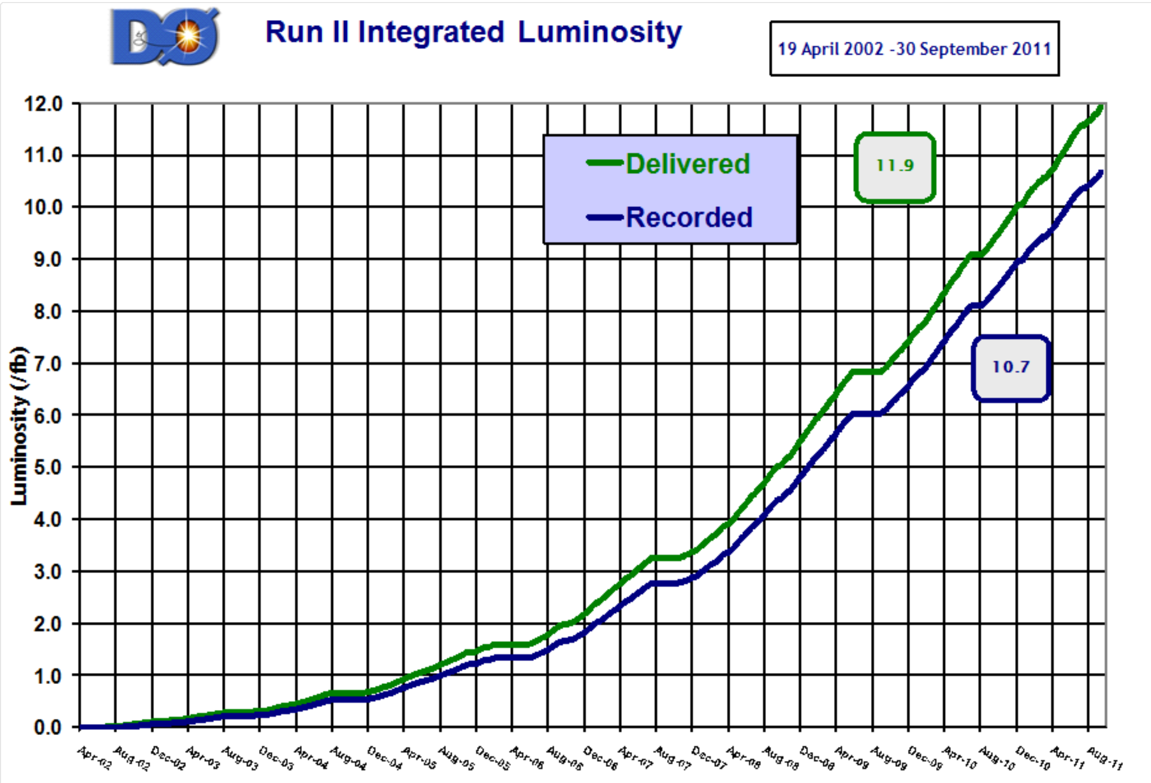
Luminosity

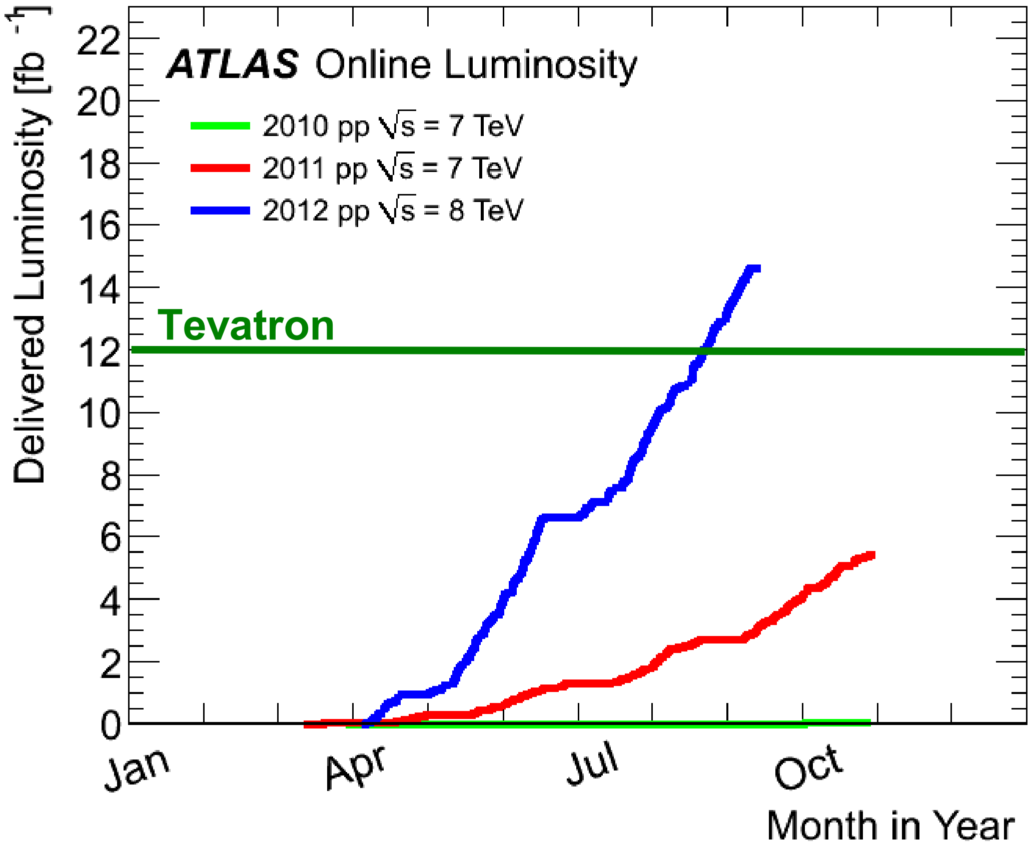
Tevatron: 1985 – 2011
26 years of p anti-p collisions

Run II: E_{cms} =1.96 TeV
Run II: delivered int. luminosity: 12 / fb

LHC: 2009 – present
Collisions of p-p, Pb-Pb, and p-Pb (13.9.12)

2009 – 2012: E_{cms} = 0.9, 2.36, 2.76, 7, 8 TeV
2012: delivered int. luminosity: ~ 15 / fb

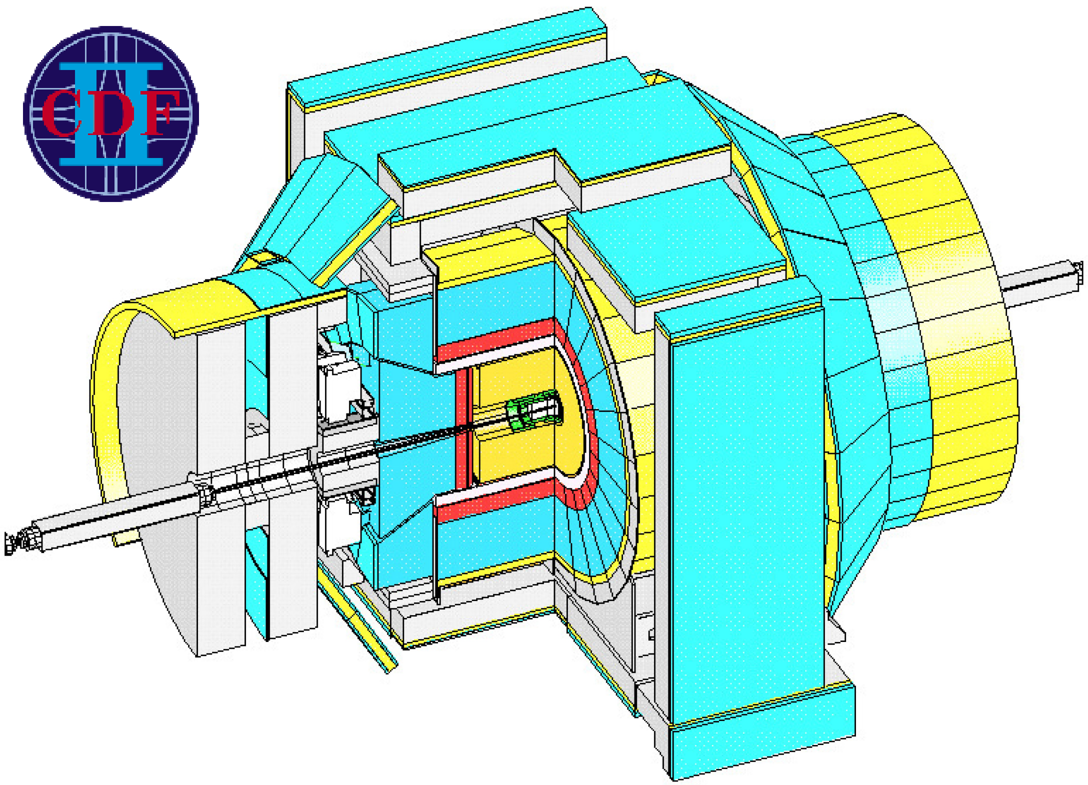


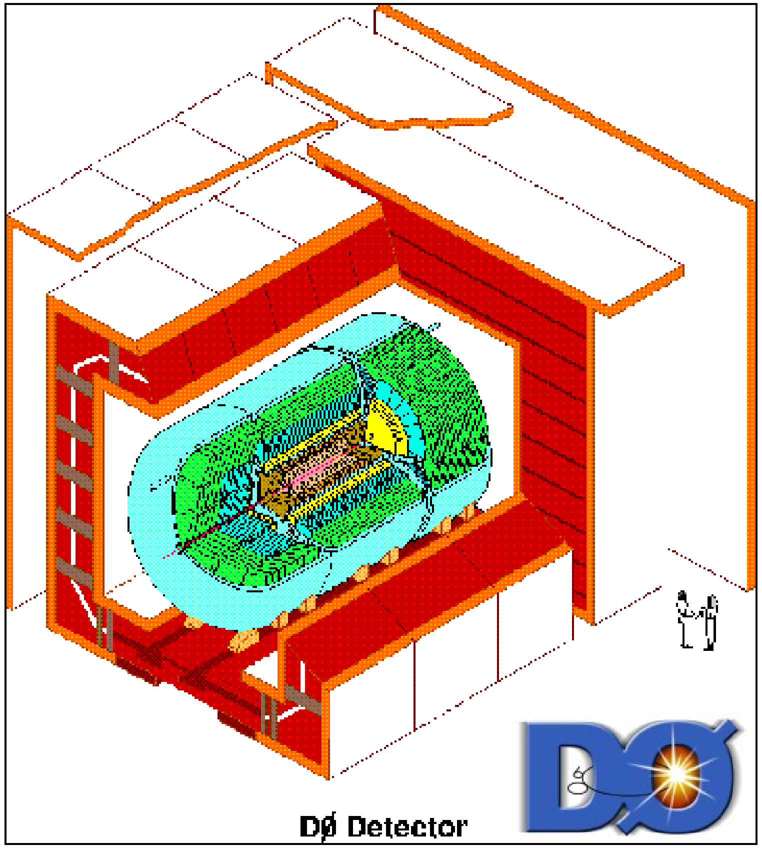


CDF and D0

Silicon tracker: Up to |η| = 2.0 – 2.5
Drift cell tracker: Up to |η| = 1.1
Calorimetry: Up to |η| = 3.2
Muon chambers: Up to |η| = 1.5
Jet energy scale: 2 – 3 % prec.

Silicon tracker: Up to |η| = 3.0
Fiber tracker: Up to |η| = 1.7
Calorimetry: Up to |η| = 4.0
Muon chambers: Up to |η| = 2.0
Jet energy scale: 1 – 2 % prec.

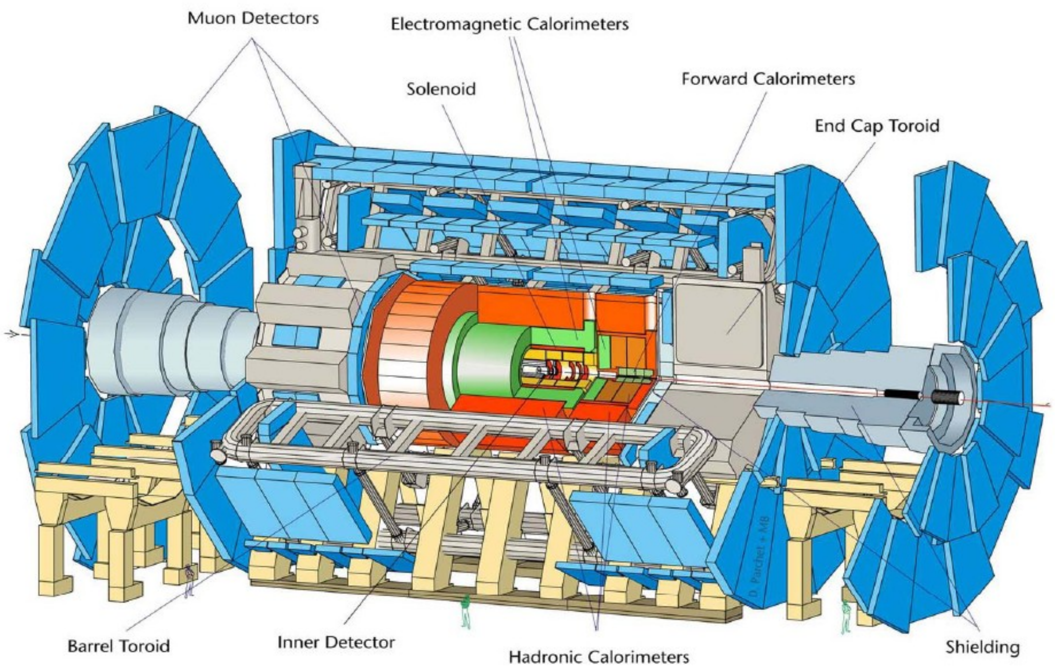


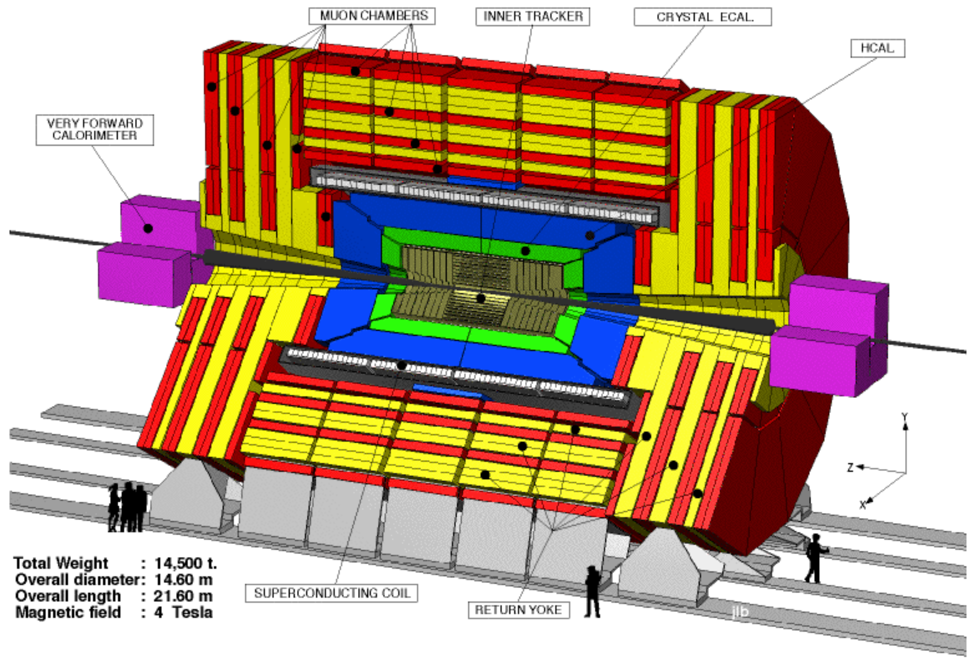


ATLAS and CMS

Silicon trackers:	Up to $|\eta|$ = 2.5	**Silicon trackers:**	Up to $|\eta|$ = 2.5
Calorimetry:	Up to $|\eta|$ = 4.9	**Calorimetry:**	Up to $|\eta|$ = 5.0
Muon chambers:	Up to $|\eta|$ = 2.7	**Muon chambers:**	Up to $|\eta|$ = 2.4
Jet energy scale:	1 – 3 % prec.	**Jet energy scale:**	1 – 3 % prec.

Both detectors are/will be complemented by further instrumentation at larger rapidities.



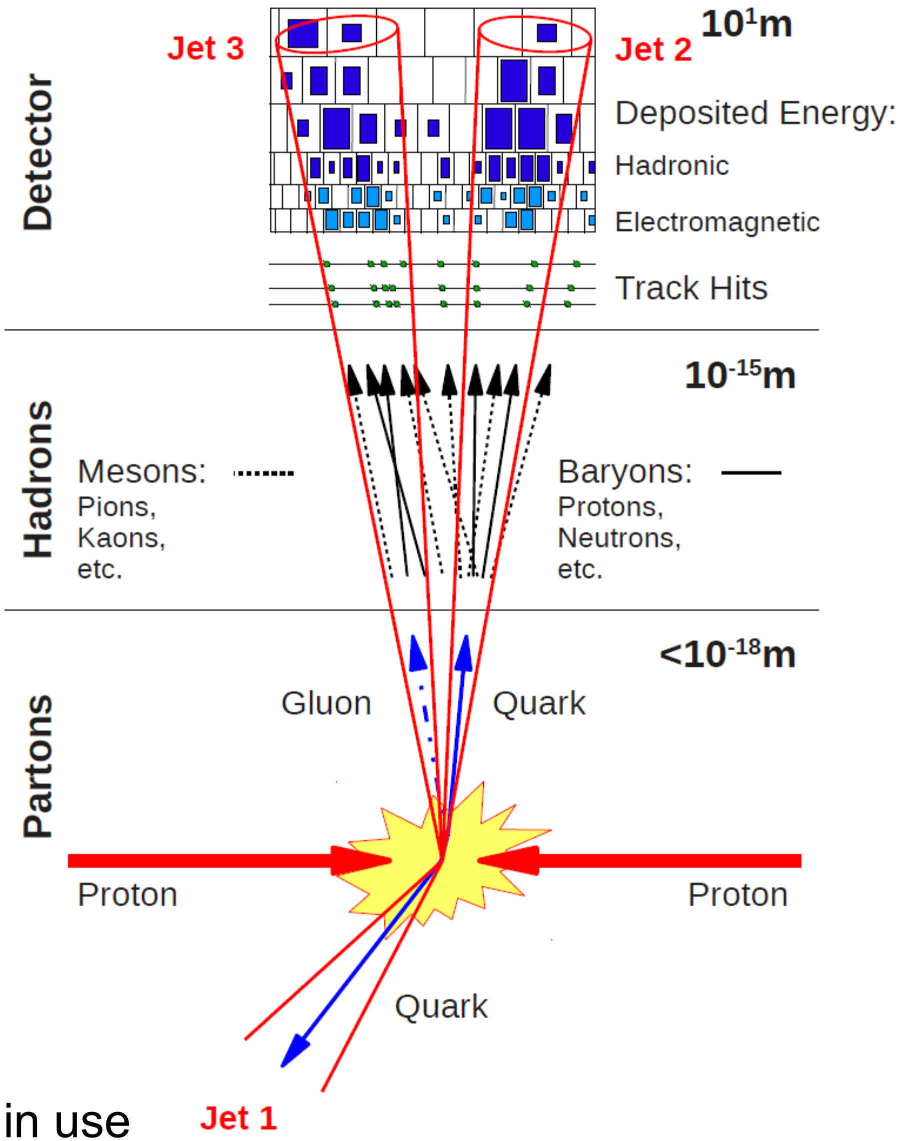


Jet Algorithms

Primary Goal:

Establish a good correspondence between:
- detector measurements
- final state particles and
- hard partons

Two classes of algorithms:
1. Cone algorithms: ”Geometrically” assign objects to the leading energy flow objects in an event (favorite choice at hadron colliders)
2. Sequential recombination: Repeatedly combine closest pairs of objects (favorite choice at e^+e^- & ep colliders)



Standard at Tevatron: MidPoint Cone
Standard at LHC: anti-kT

CDF also looked at kT; at LHC also kT, Cam/AC, SISCone in use

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
  - • • •

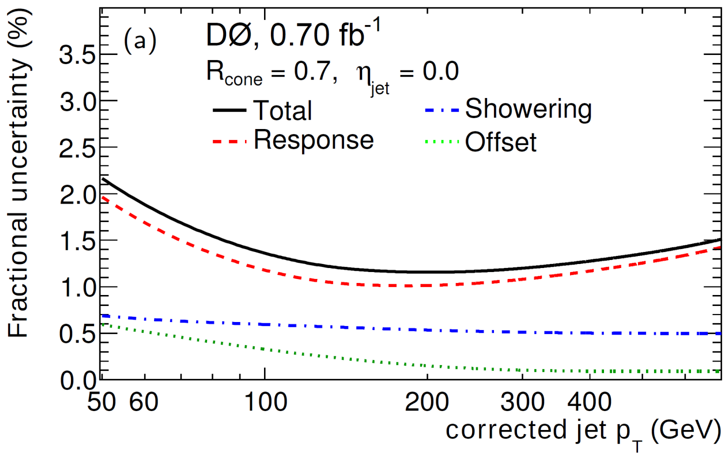
- **Theoretical Uncertainties:**
  - PDF Uncertainty
  - pQCD (Scale) Dependence
  - Non-perturbative Corrections
  - PDF Parameterization
  - NLO-NLL matching schemes
  - Electroweak Corrections
  - Knowledge of $\alpha_S(M_Z)$
  - • • •

There is a lot to learn here from Comparison to actual measurements!

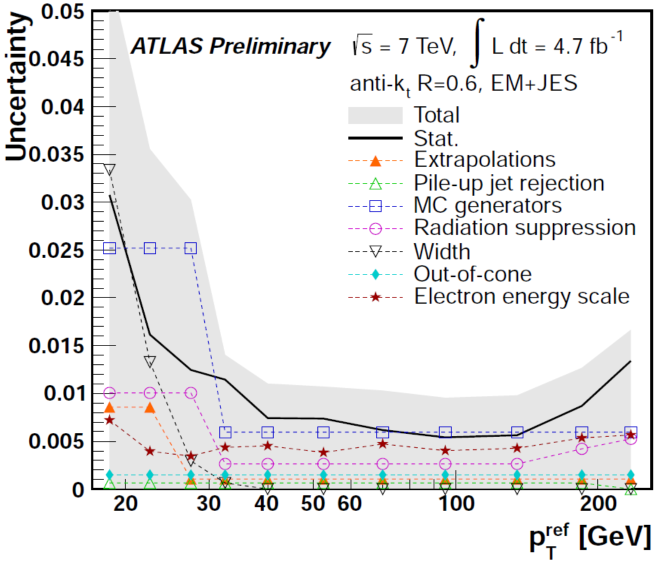
Jet Energy Scale

Dominant uncertainty for measurements of jet cross sections!
Enormous progress at Tevatron, and at LHC in just two years.
QCD at hadron colliders is becoming precision physics!

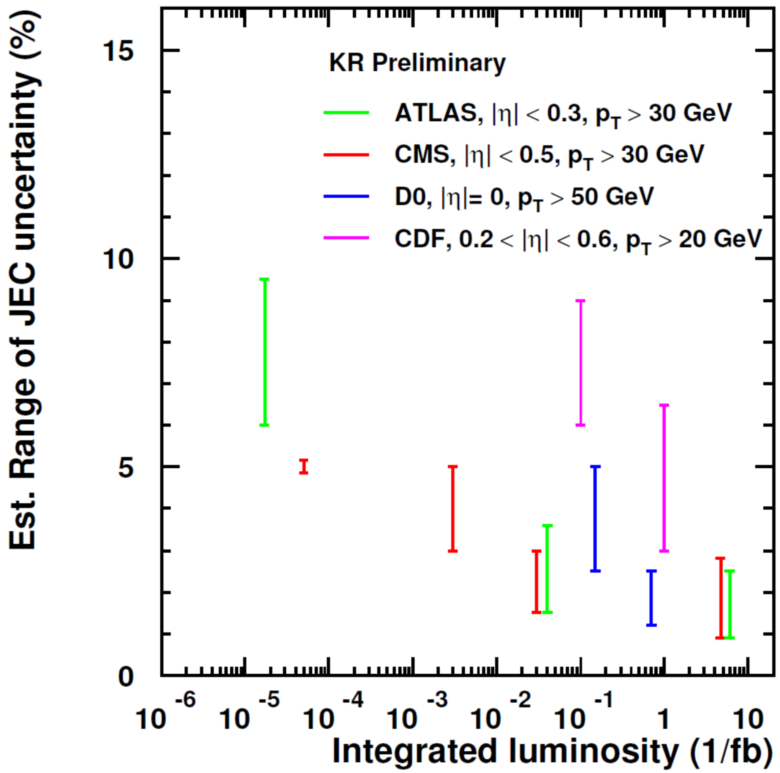
D0 from 0.7/fb (2011)



ATLAS from 5/fb (2011) (Z+jet channel)



Approximate development of JEC precision

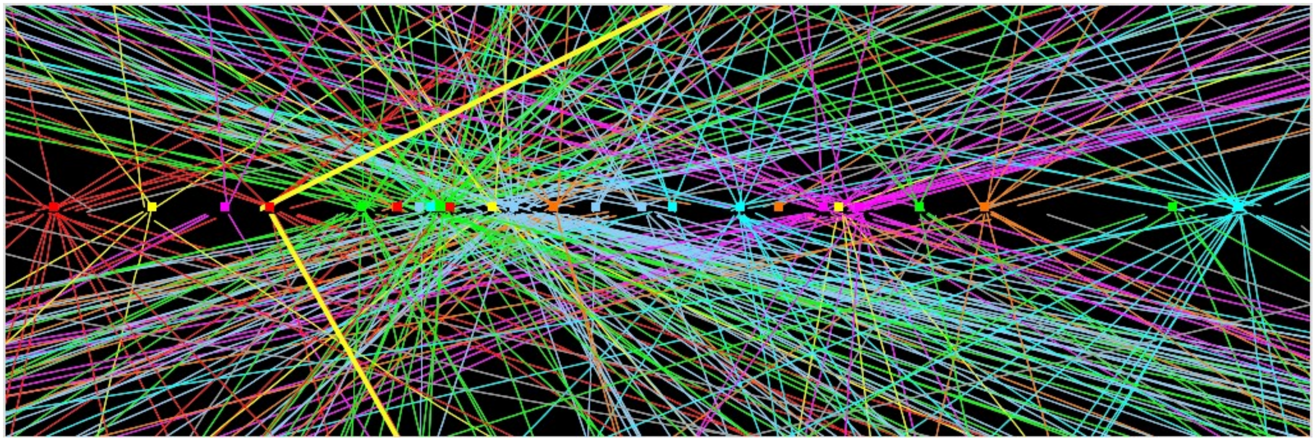


ATLAS, EPJC 71 2011; arXiv:1112.6297; CONF-2012-053; CONF-2012-063
CMS, JME-10-003; JME-10-010; JINST 6 2011; DP2012-006; DP2012-012
D0, arXiv:1110.3771; D0 prel. 2006

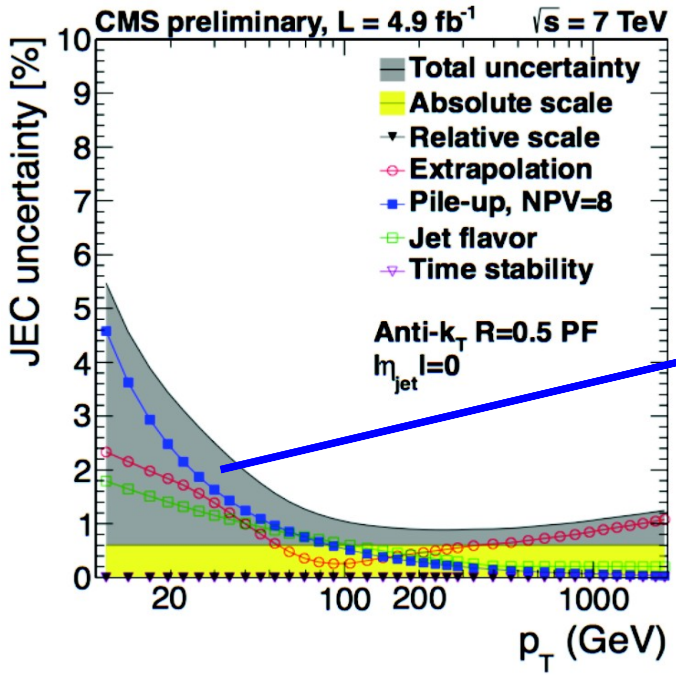
Jet Energy Scale and Pile Up

But:
New situation in 2012 at 8 TeV with many pile-up collisions!

ATLAS Z → μμ candidate with 25 reconstructed primary vertices:

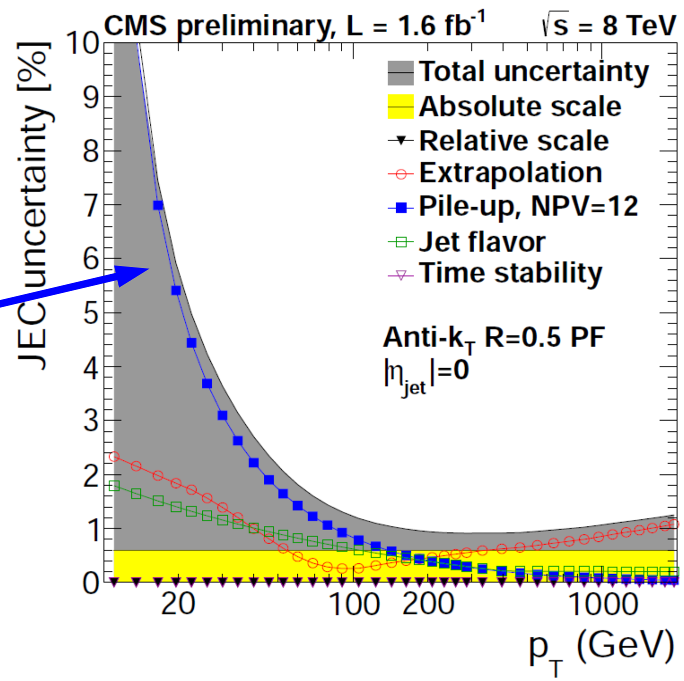


CMS from 5/fb (7 TeV, 2011)



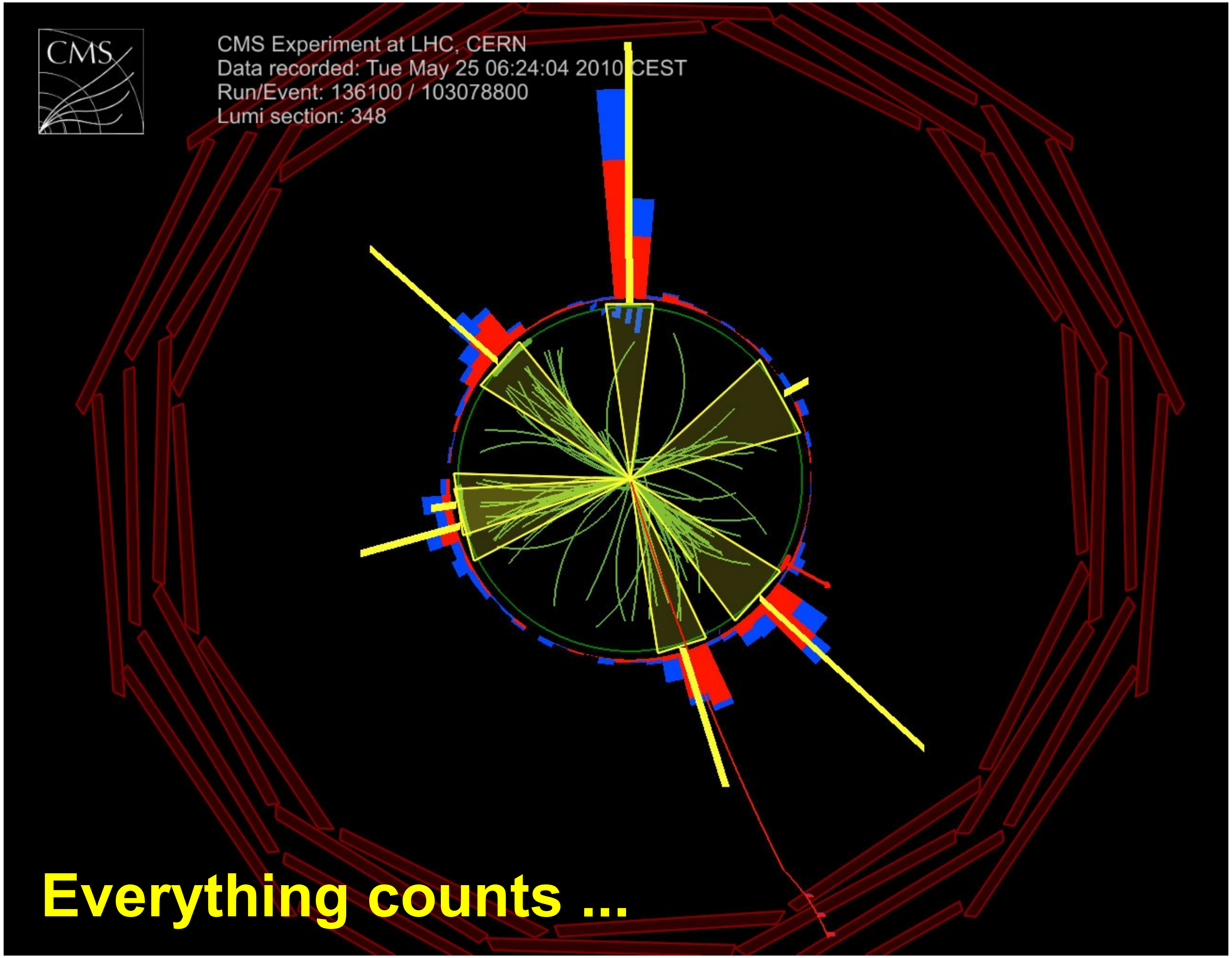
Pile-up effect

CMS from 1.6/fb (8 TeV, 2011)



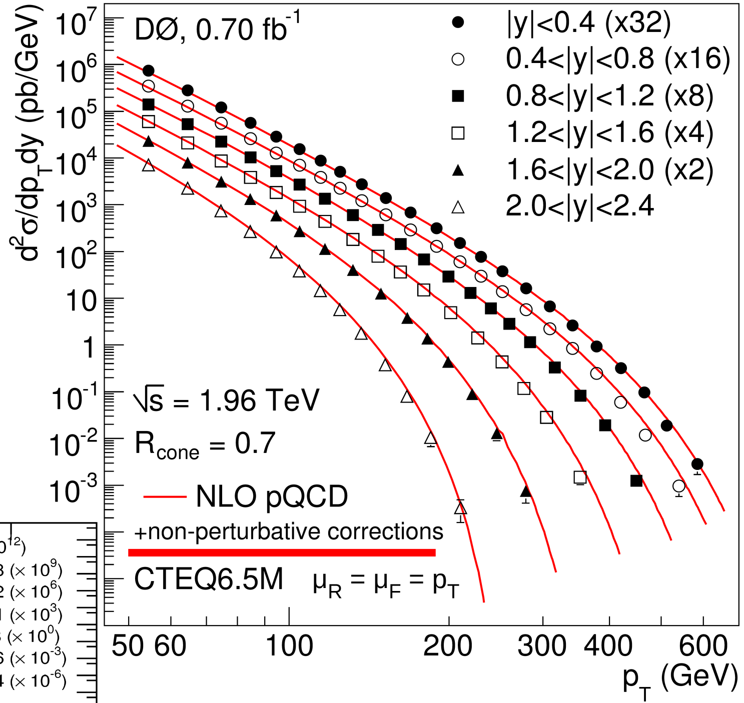
CMS, DP2012-006
CMS, DP2012-012

All Inclusive



Inclusive Jets

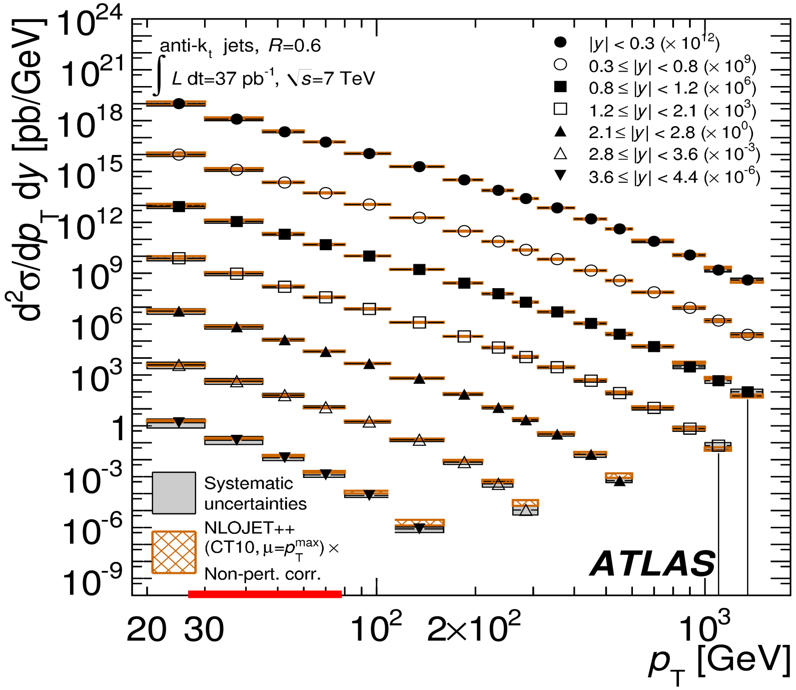
Many new results. Agreement with predictions of QCD over many orders of magnitude up to 2 TeV in jet p_T



MidpointCone, R=0.7, 1.96TeV

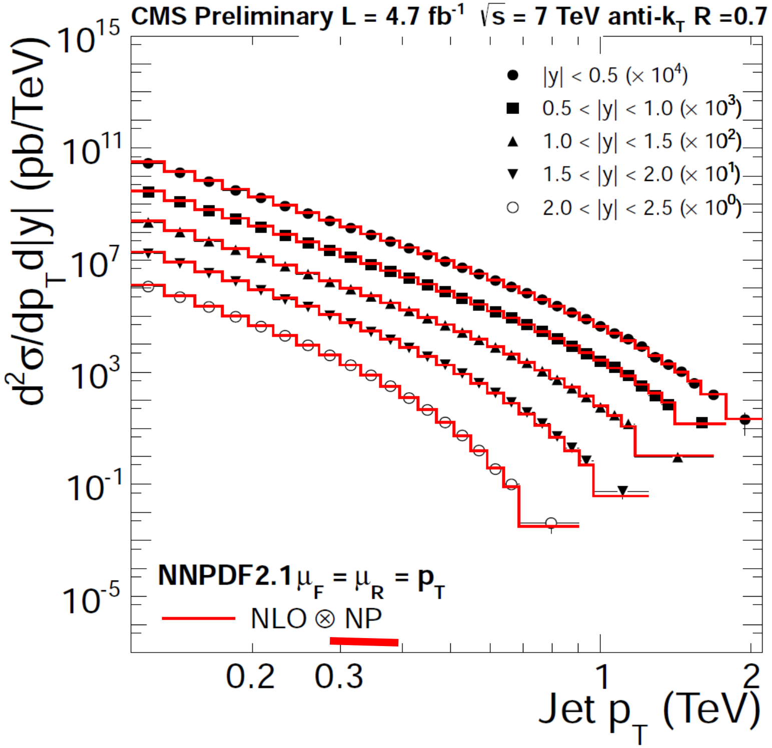
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

anti-kT, R=0.6, 7 TeV, 2010



pQCD ⊗ non-perturbative corrections

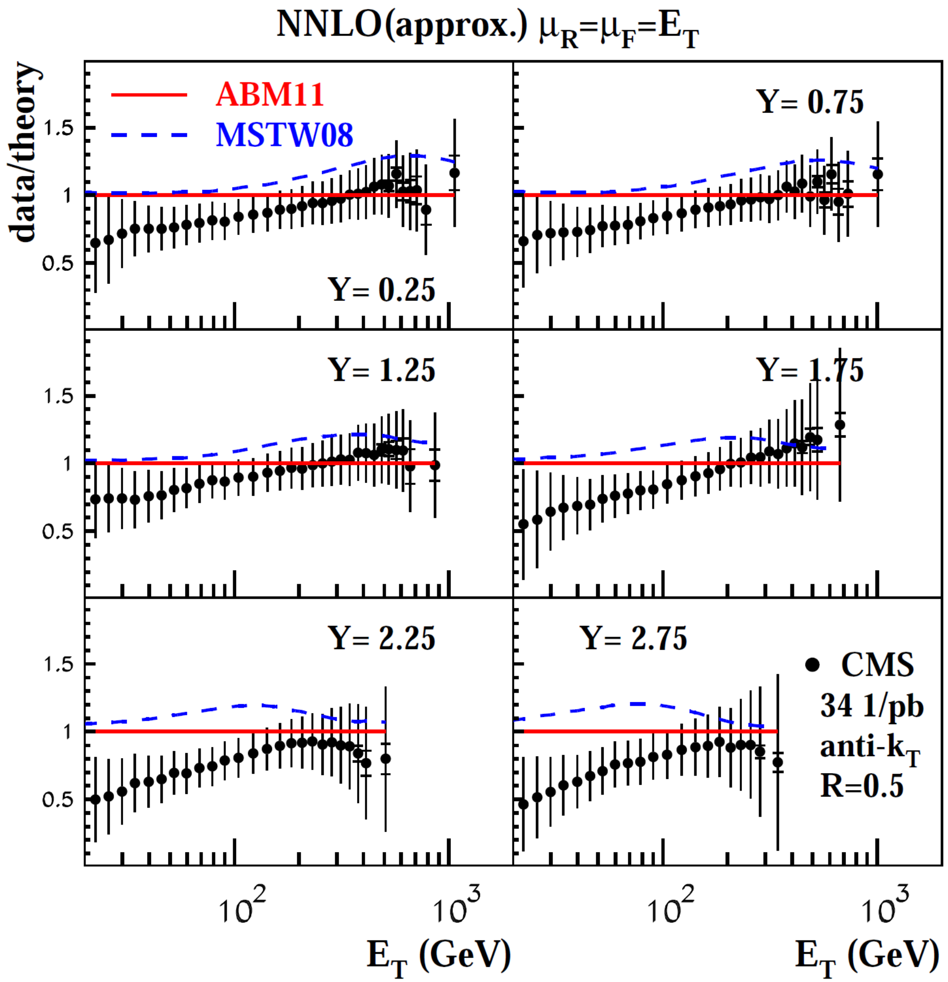
anti-kT, R=0.7, 7 TeV, 2011



ATLAS, arXiv:1112.6297
CMS, PAS-QCD-11-004 (2012)
D0, arXiv:1110.3771

LHC Data and PDFs

Comparison only of ABM11 PDFs with CMS inclusive jets (2010, 34/pb)



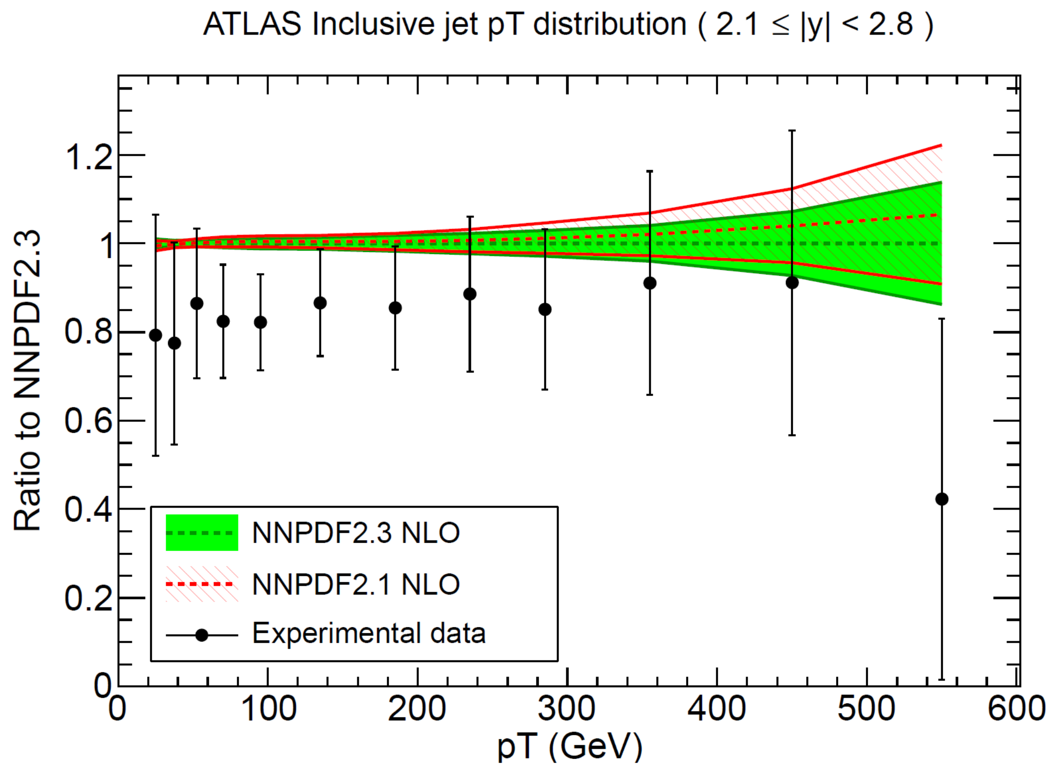
ABM11, S.Alekhin,J.Blümlein, S.Moch, arXiv:1208.1444

First global fits including LHC data !

ATLAS inclusive jets (2010, 37/pb), ATLAS/LHCb W,Z rap. (2010), CMS W el. Asymmetry (2011)

2 observations:

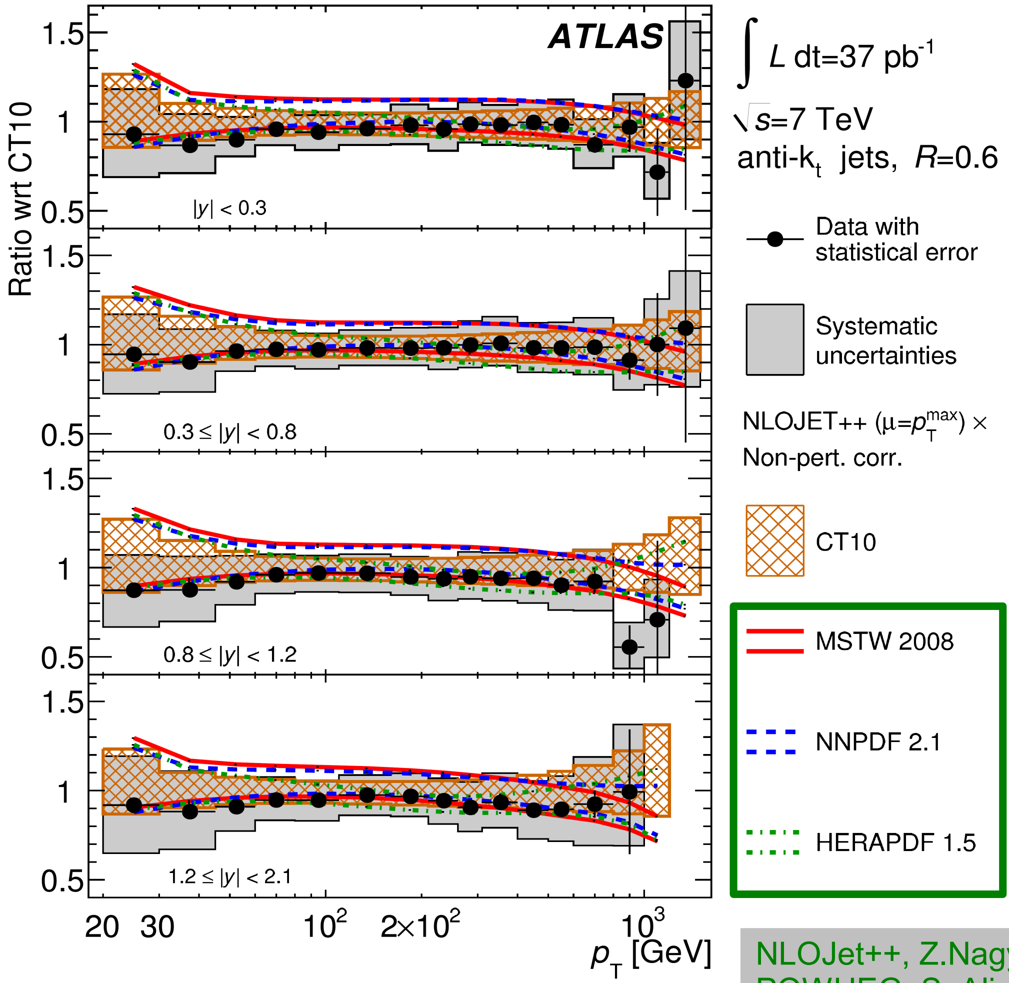
- slightly smaller uncertainties in NNPDF23
- measurement always lowish at high y



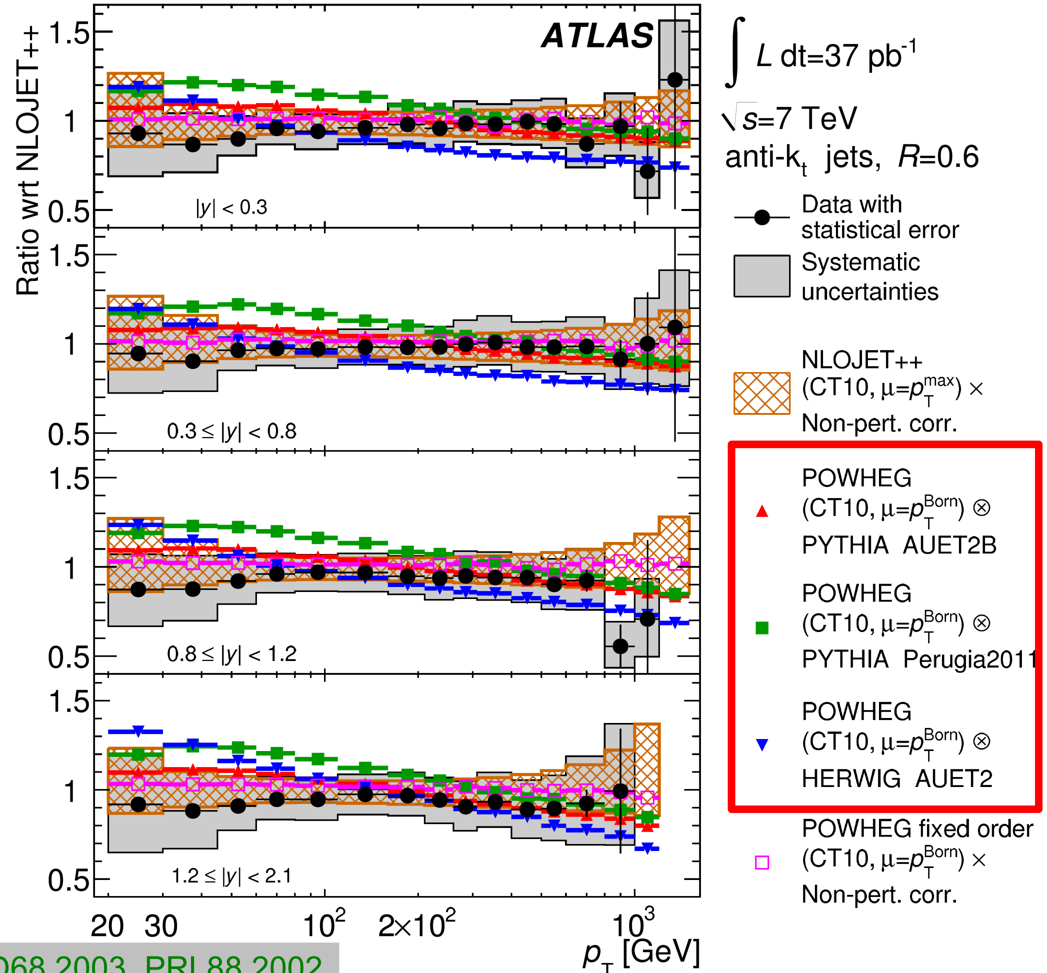
NNPDF23, R.D.Ball et al., arXiv:1207.1303

PDFs and matched Showers

Agreement with QCD using diverse PDFs
Use to improve PDFs (high x gluon)



Agreement between NLO POWHEG vs. NLOJet++
POWHEG + matched parton showers ...
to be worked on



NLOJet++, Z.Nagy, PRD68 2003, PRL88 2002
POWHEG, S. Alioli et al., JHEP 1104 (2011)

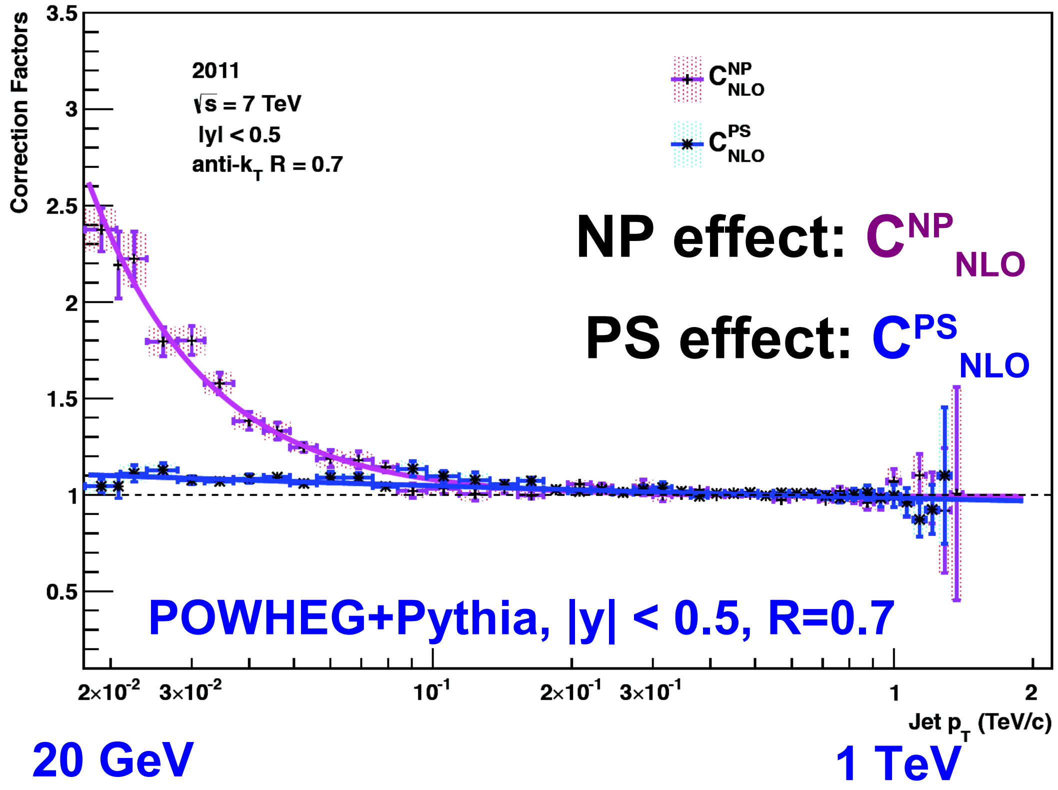
Non-perturbative Corrections

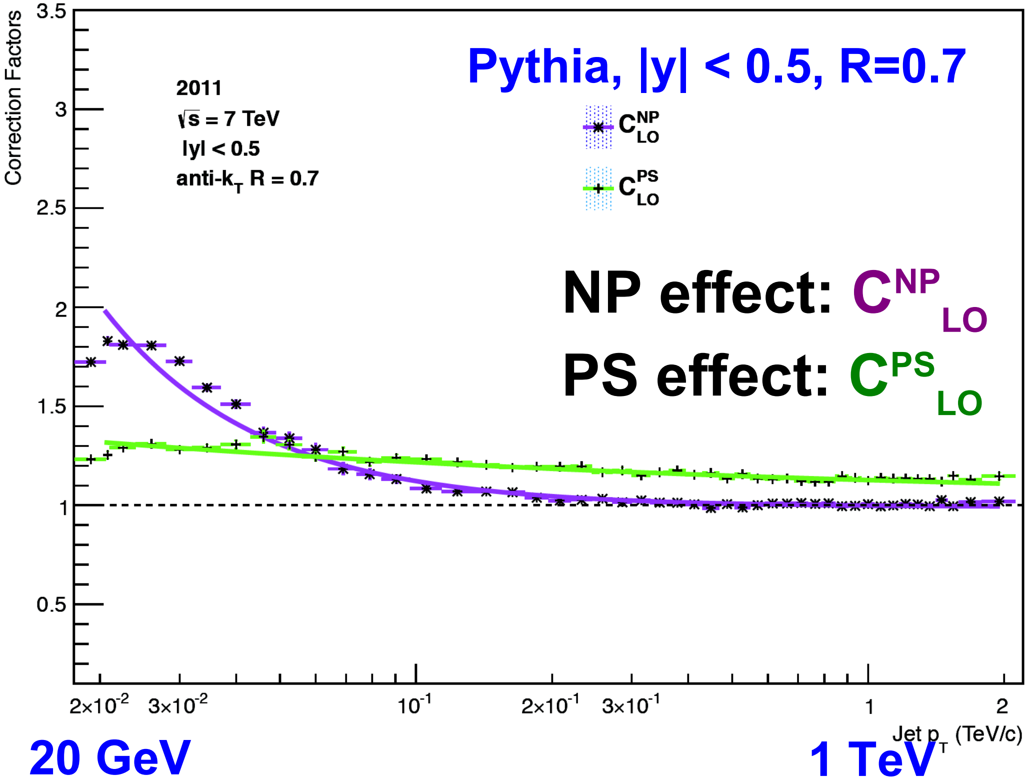
Recipe used at Tevatron & LHC:

- take LO parton shower (PS) MC
- derive corr. for non-pert. (NP) effects, i.e. multiple parton interactions and hadronization

→ assume PS effect small on NLO

→ assume NP effects similar for LO,NLO





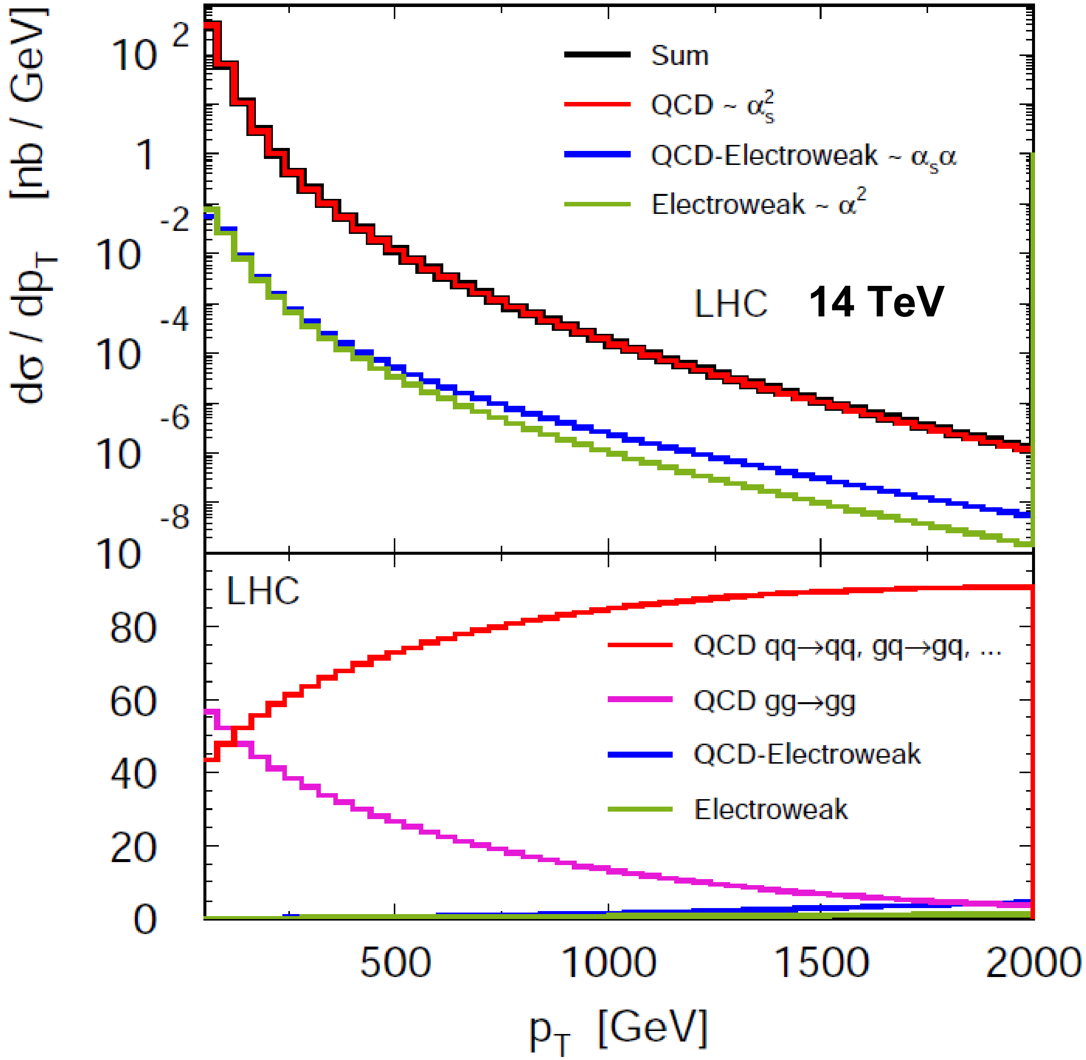
Observations:

- assumptions fine at central rapidity (not shown here)
- NP corrections larger for R=0.7 than 0.5
- for |y| > 2 PS effects visible

Figures courtesy of S.Dooling, H.Jung, P.Gunnellini, P.Katsas, A.Knutsson

Corrections at high pT ?

- More jet data to come from LHC at very high p_T
- Interesting comparisons to PDFs and extractions of αs to be made
- But need to think about
  - Electroweak corrections $\propto \alpha\alpha_s^2$ → effects up O(10%) ?
  - top as 6th flavour (NLOJet++ uses only 5)
  - Validity of evolution equations, could be modified by new physics
- Also need urgently NNLO, since only at this precision will alpha_s results be considered in Bethkes world averages!



A. Scharf, arXiv:0910.0223

alpha_s from inclusive Jets

CDF: $\alpha_s(M_Z) = 0.1178 \pm 0.0001(\text{stat})^{+0.0081}_{-0.0095}(\text{expt.syst})$

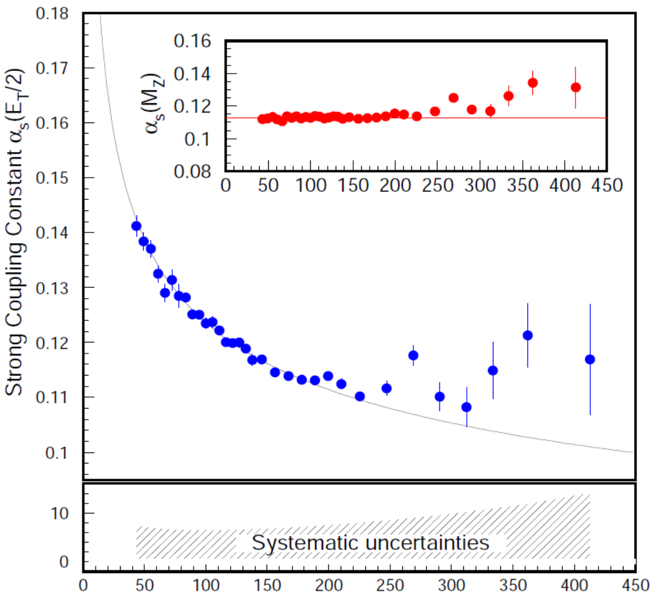
D0: $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}(\text{total})$

M/S: $\alpha_s(M_Z) = 0.1151 \pm 0.0001(\text{stat}) \pm 0.0047(\text{expt.syst})^{+0.0080}_{-0.0073}(p_T, R, \mu, \text{PDF}, \text{NP})$

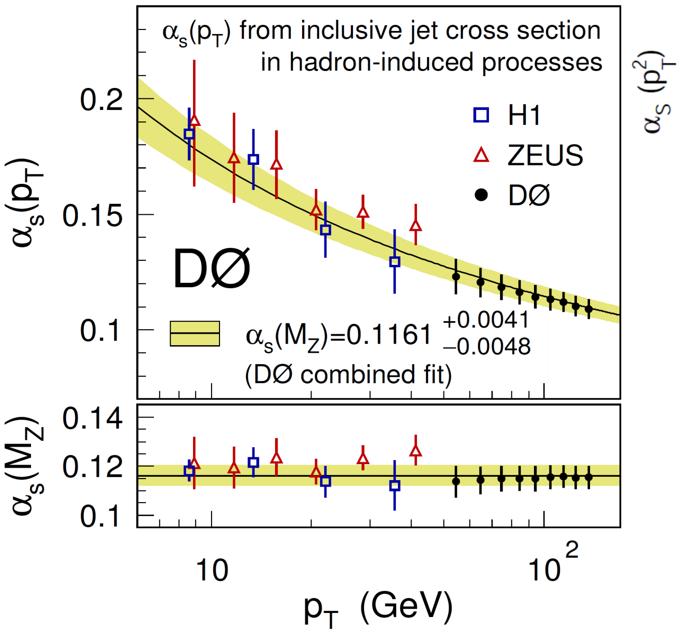
Problem:

Via the PDFs assumes the validity of the running of alpha_s according to the RGE

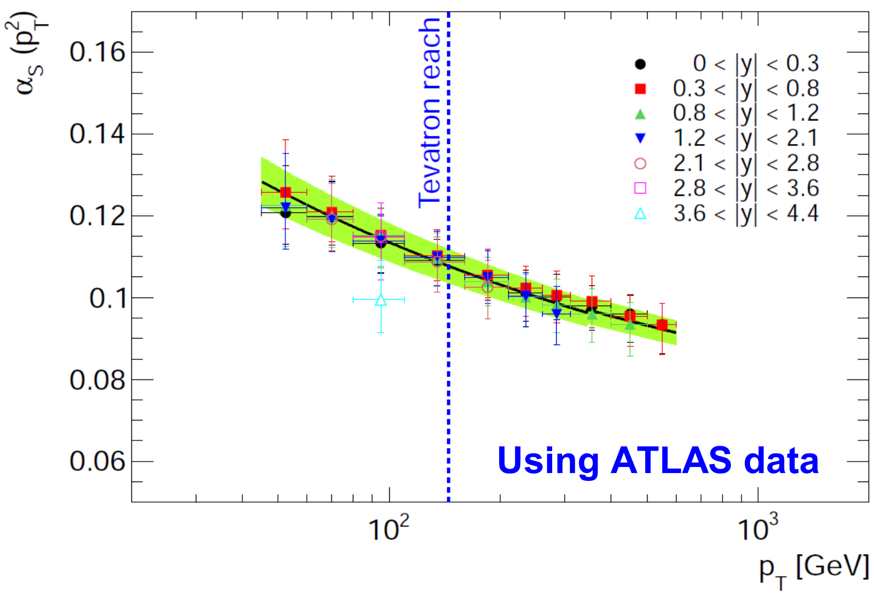
D0 explicitly restricts phase space to where the RGE is already established.



CDF, PRL88, 2002



D0, PRD80, 2009

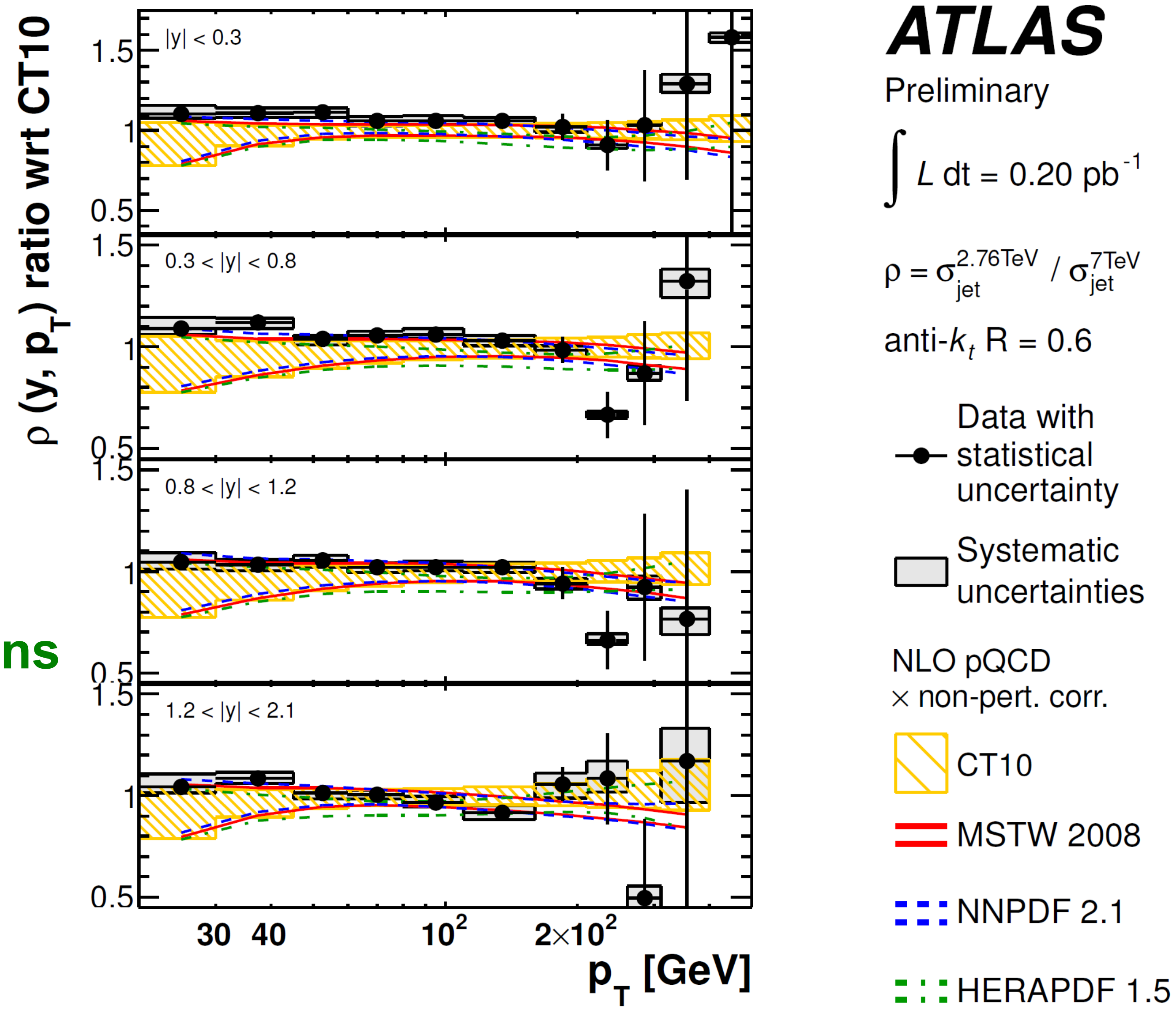


Malaescu/Starovoitov, EPJC72, 2012

Incl. jet Ratios of 2.76 / 7

New result from ATLAS:
- cross sections at 2.76 TeV
- ratios to 7 TeV
- ratio to 7 TeV divided by theory prediction (NLO, CT10, X NP)

  Shown →
- study on PDF impact

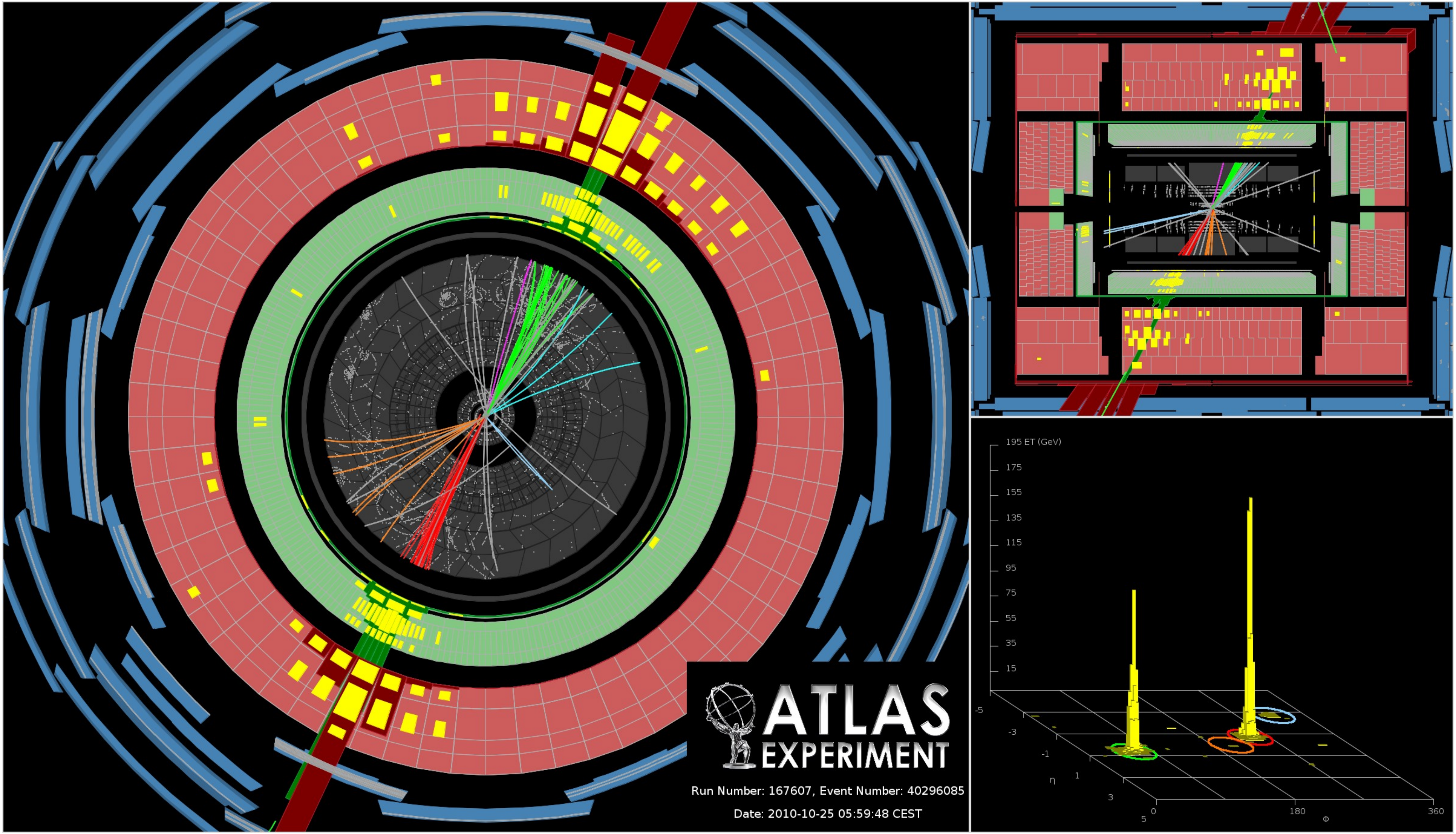


At least partial cancellation of uncertainties
→ more precise comparisons

Remark:
Other interesting ratios ...
different jet sizes

ATLAS, CONF-2012-128

Just the two of us

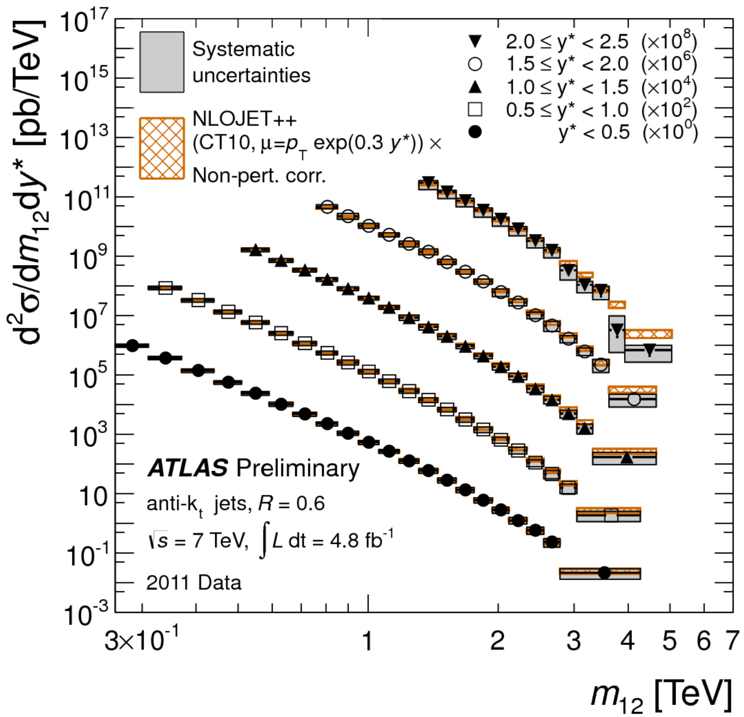


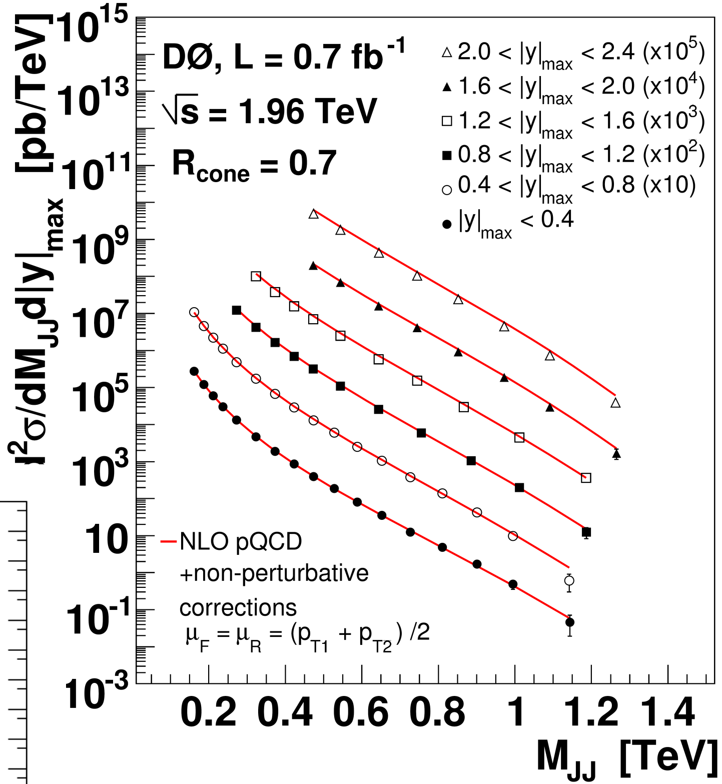
Dijet Mass

Many new results.
Again agreement with predictions of QCD over many orders of magnitude!

$$\frac{d^2\sigma}{dM_{JJ}d[|y|_{max}, y^*]} \propto \alpha_s^2$$

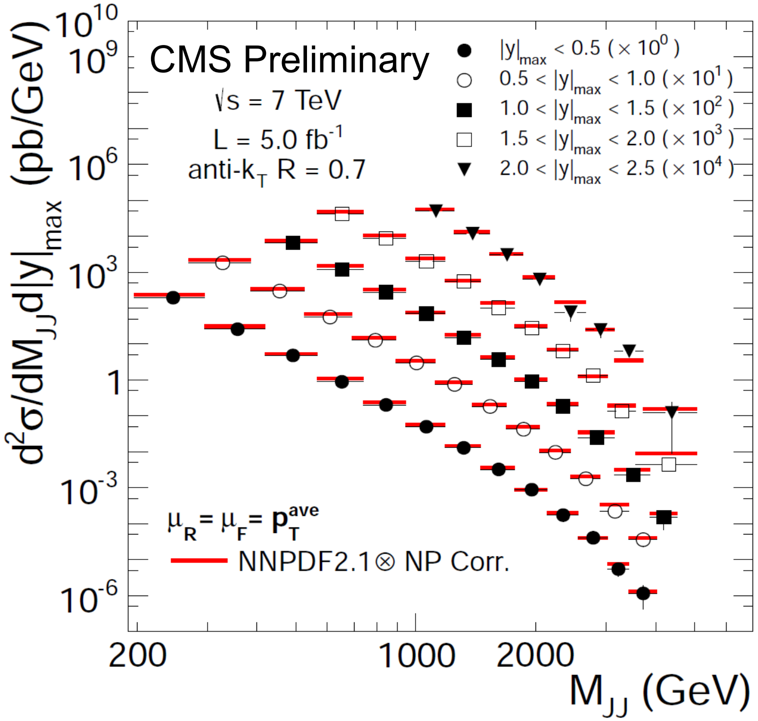
anti-kT, R=0.6, 7 TeV, 2011





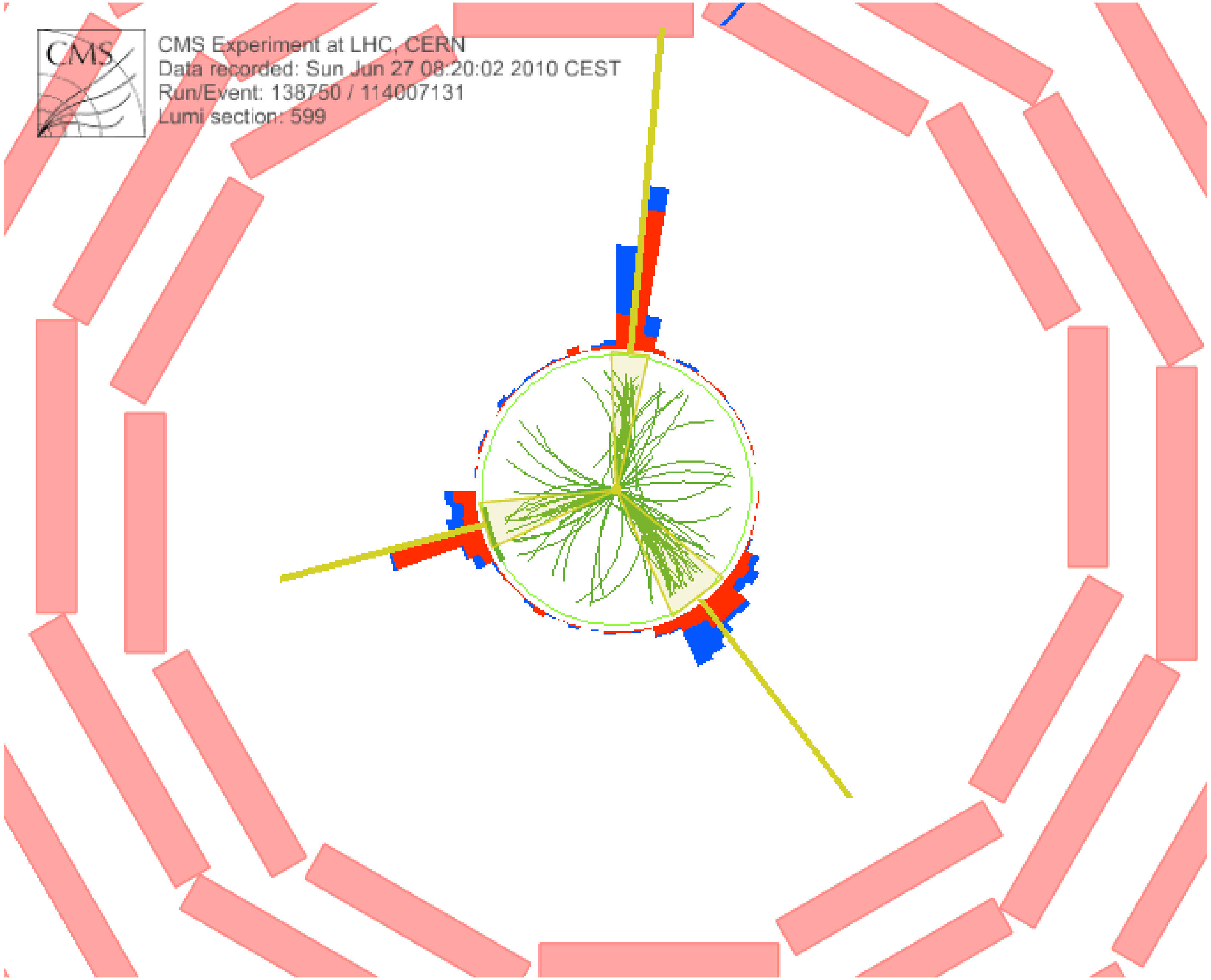
MidpointCone, R=0.7, 1.96 TeV

anti-kT, R=0.7, 7 TeV, 2011



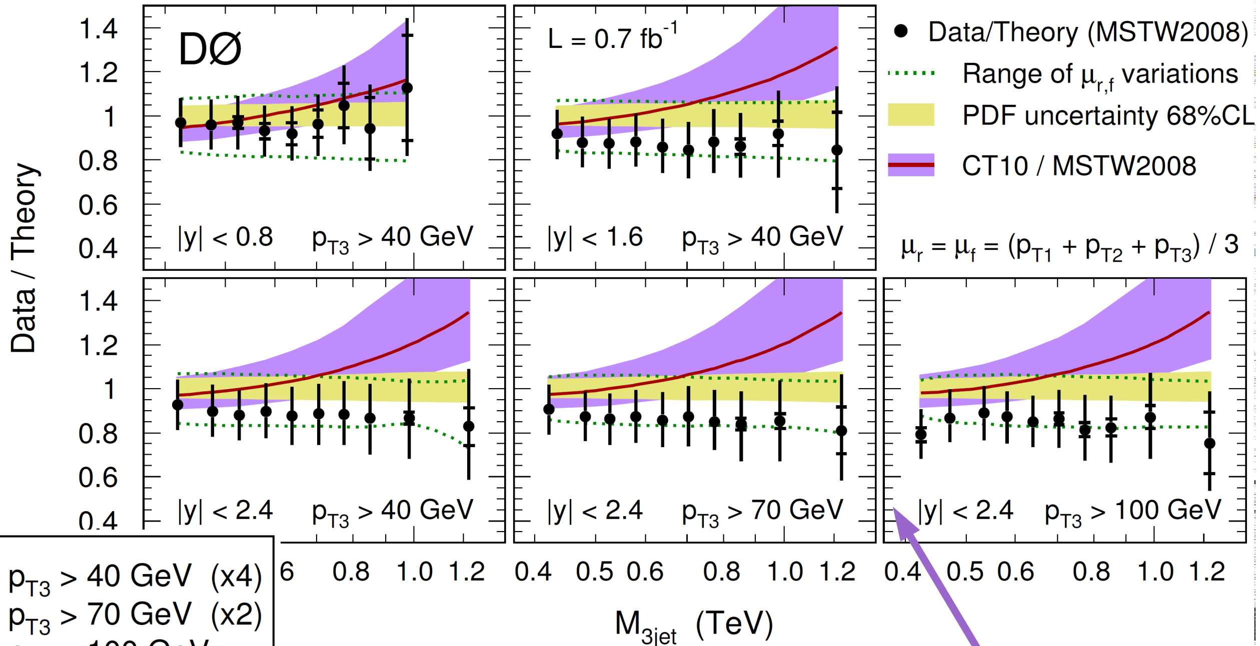
ATLAS, CONF-2012-021 (2012)
CMS, PAS-QCD-11-004 (2012)
D0, PLB693 (2010)

1 + 1 = 3

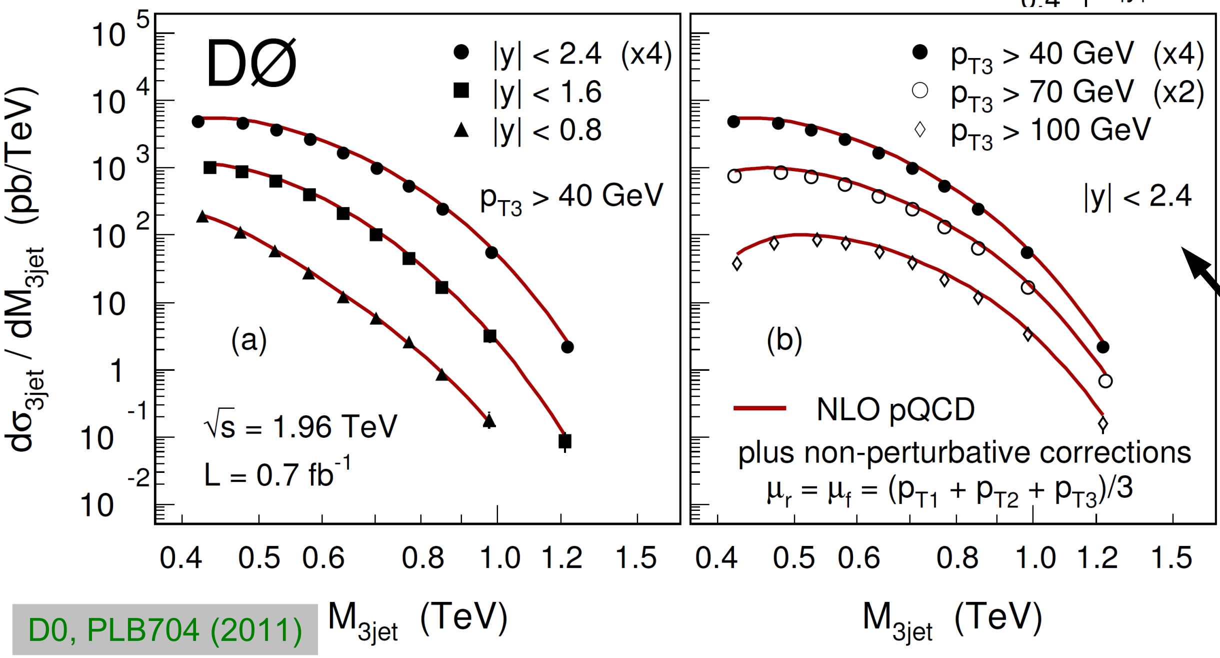

CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Jun 27 08:20:02 2010 CEST
Run/Event: 138750 / 114007131
Lumi section: 599

3-Jet Mass

- Sensitive to α_s beyond 2→2 process
- Known at NLO (NLOJet++)
- Sensitive to PDFs
- Involves additional "scale" $p_{T,3}$



Most PDFs work ok, CT10 is off

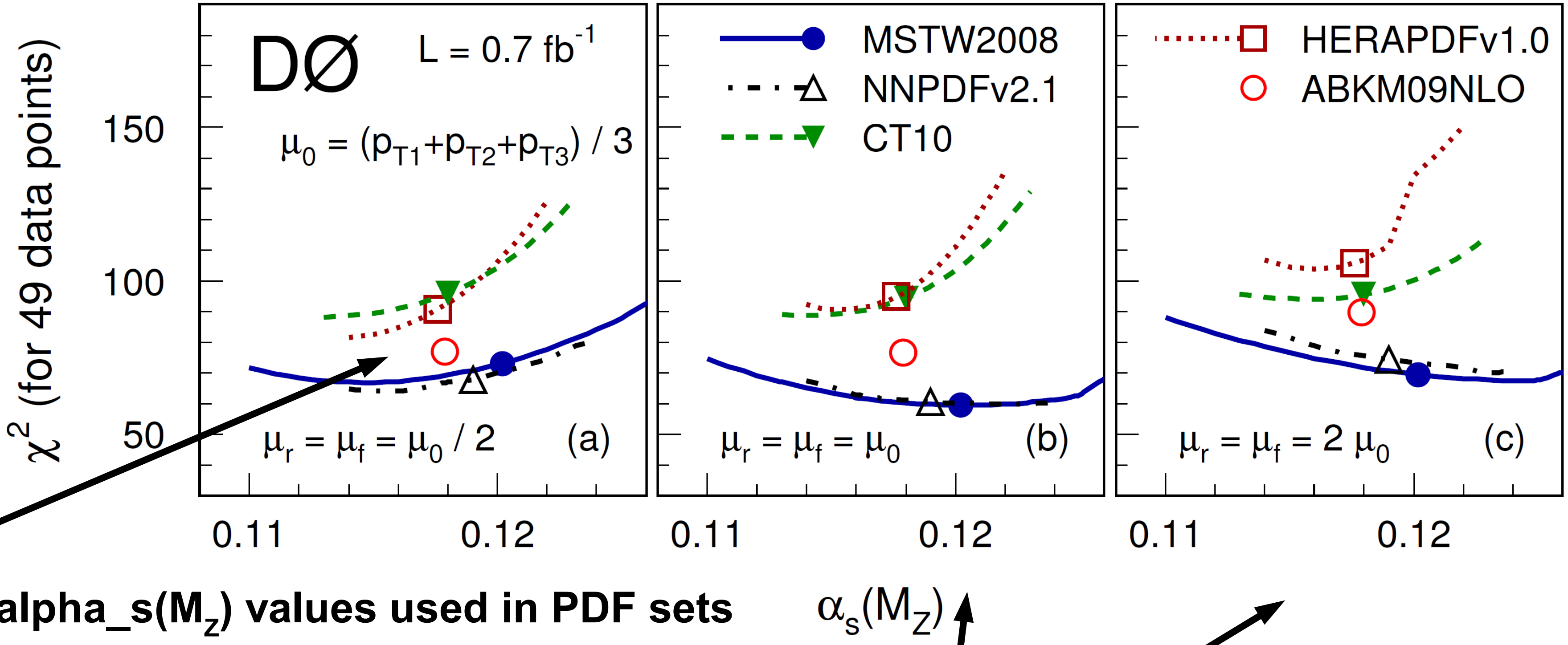


D0, PLB704 (2011)

D0 investigated 3 different lower pT thresholds $p_{T,3}$ and 3 max. rap. y

$$\frac{d\sigma_{3jet}}{dM_{3jet}} \propto \alpha_s^3$$

Chi² Comparison to central PDF



Points: alpha_s(M_Z) values used in PDF sets

Scale factors: 1/2, 1, 2

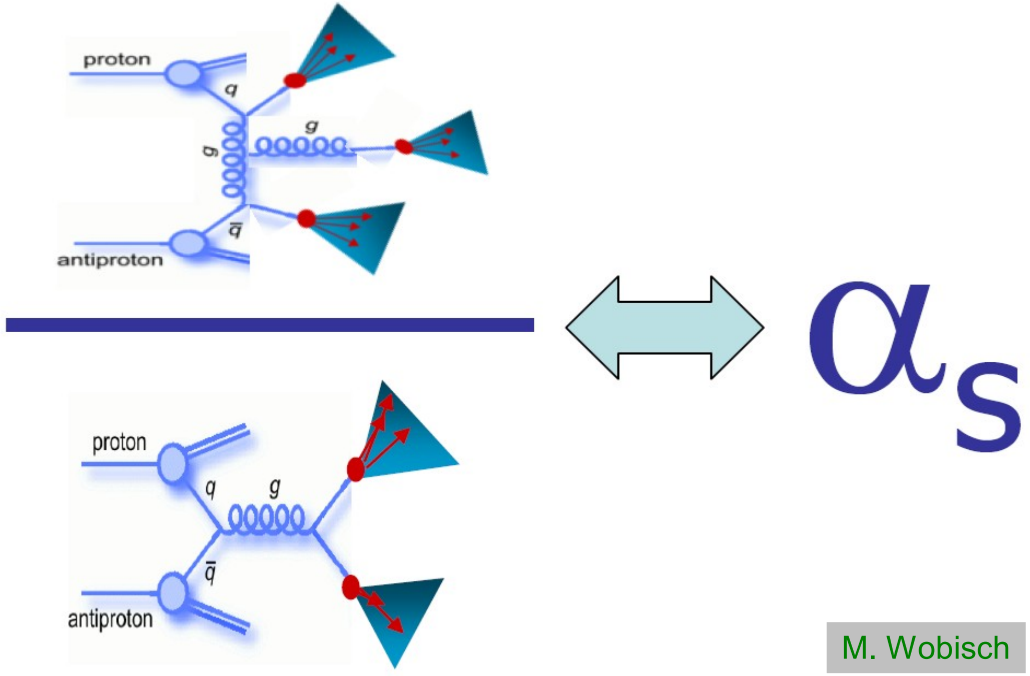
Takes into account correlations in experimental uncertainties

Best agreement found with MSWT2008 and NNPDF2.1

D0, PLB704 (2011)

3-Jets and α_s

- Avoid direct dependence on PDFs and the RGE
- Use cross-section ratios!
- → reduces also scale and exp. uncertainties along the way
- → eliminates luminosity dependence



M. Wobisch

D0 proposes a new observable:
The average number of neighbouring Jets in an inclusive jet sample:

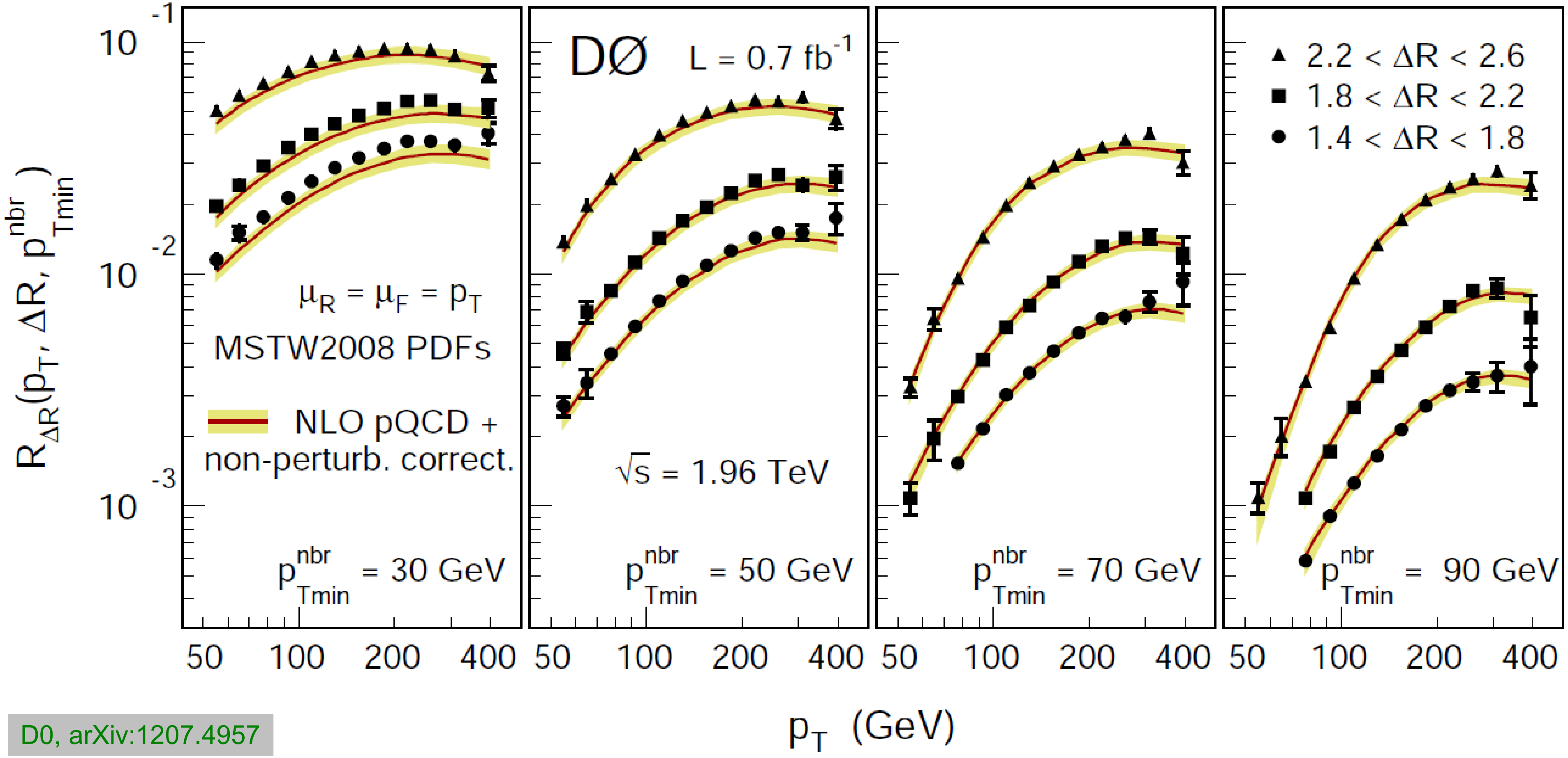
$$R_{\Delta R}$$

Depends on 3 variables:
- inclusive jet pT
- distance ΔR (in Δy,ΔΦ) to neighbour
- min. pT to count neighbour jet

For other interesting 3-jet quantities see talk by N. Varelas

D0, arXiv:1207.4957

New jet angular correlation Observable from D0

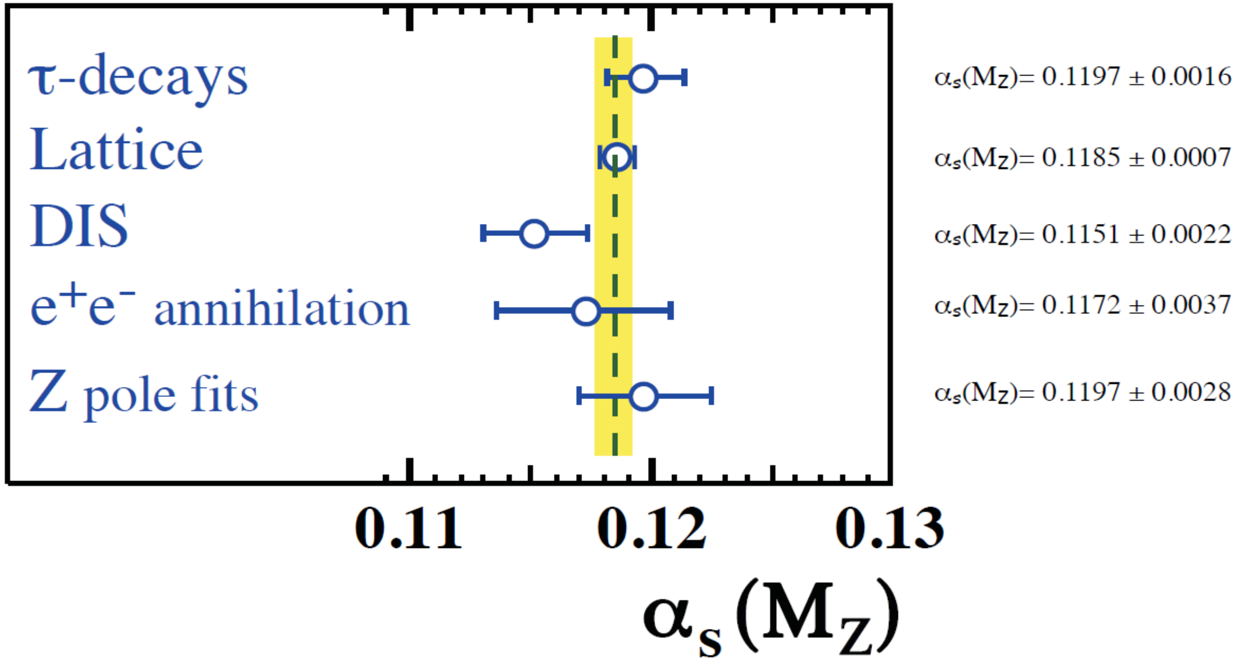


D0, arXiv:1207.4957

$$\alpha_s(M_Z) = 0.1191^{+0.0048}_{-0.0071}(\text{total})$$

$$\pm 0.0003(\text{stat}) +^{+0.0007}_{-0.0009}(\text{exp.}) +^{+0.0002}_{-0.0001}(\text{NP}) +^{+0.0010}_{-0.0005}(\text{MSTW}) +^{+0.0000}_{-0.0024}(\text{PDFset}) +^{+0.0046}_{-0.0066}(\text{scale})$$

World Summary of alpha_s 2012, S. Bethke:

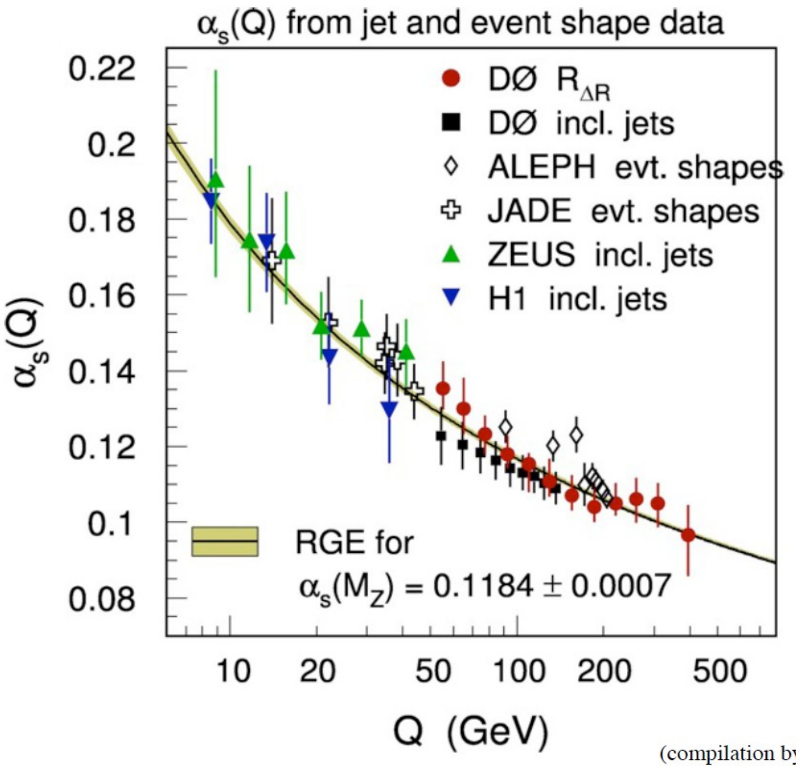


-> $\alpha_s(M_Z) = 0.1184 \pm 0.0007$ PDG2012

NLO alpha_s in global PDFs:

ABM11: 0.1134 (NNLO)
CT10: 0.1180
GJR08: 0.1178
HERAPDF1.5: 0.1176
MSTW2008: 0.1200
NNPDF2.1: 0.1190

But:
Jet data from hadron colliders not included!
Jets at NNLO urgently needed!
Recent progress reported by Th. Gehrmann at QCD@LHC.



(compilation by D0)

Outlook

- Hadron colliders are (multi-) jet laboratories
- Jet measurements at hadron colliders are becoming PRECISION PHYSICS
- Must be accompanied by precise theory (Jets at NNLO ...)
- Interplay between strong and electroweak interactions becomes important at the TeV scale
- Data quantity and quality at the LHC open up new regimes in phase space and precision to be exploited
- Many “established facts” need to be carefully checked to avoid missing something NEW

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Many thanks to you for your attention and to the organizers for the invitation to speak here!

Backup Slides

Jet Algorithms at LHC

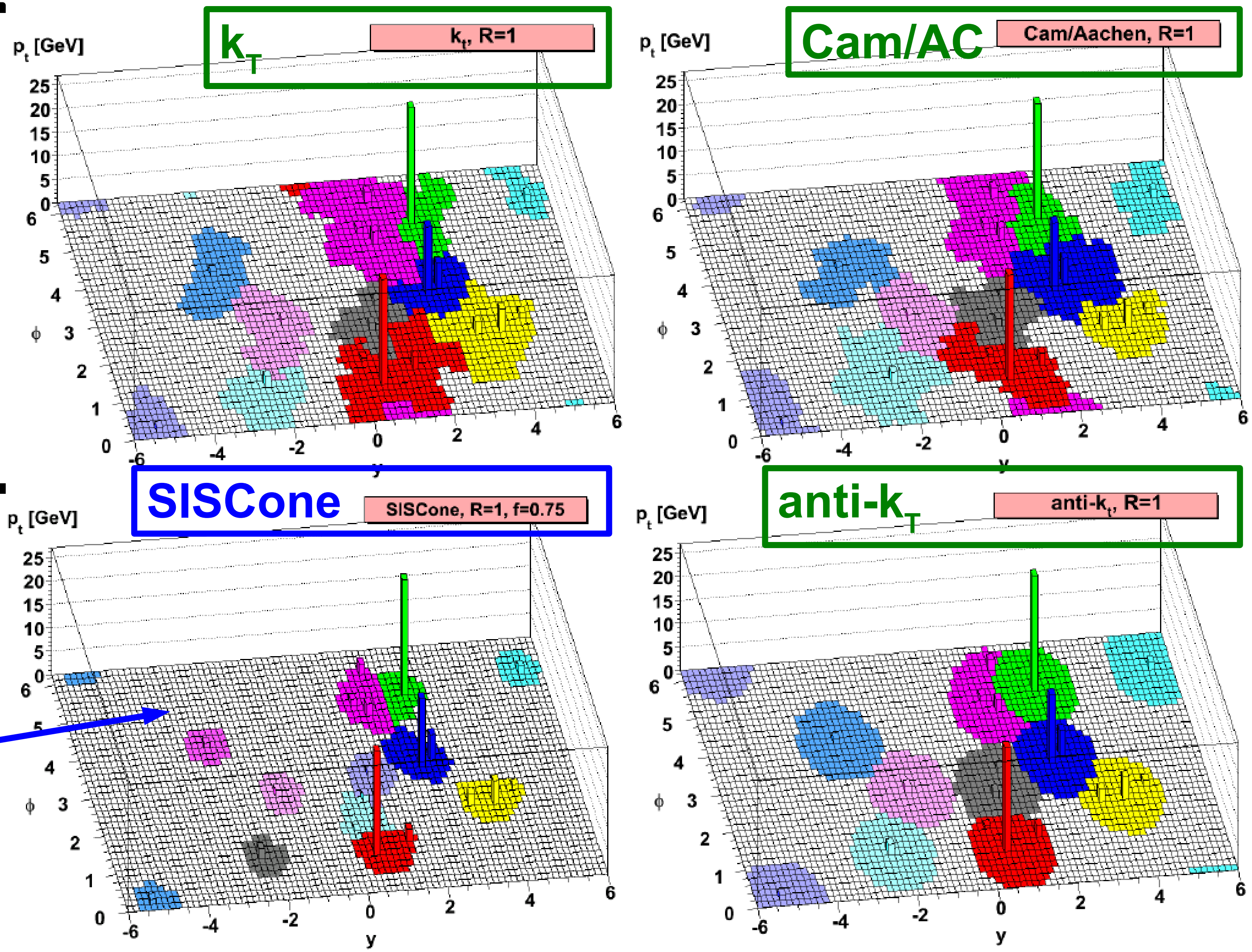
Primary algorithm at LHC:

- **Anti-k_T:**
  ATLAS R = 0.4, 0.6
  CMS R = 0.5, 0.7

- k_T
- SISCone ("real" cone algo)
- Cambridge/Aachen
  used in jet substructure, for example in boosted top

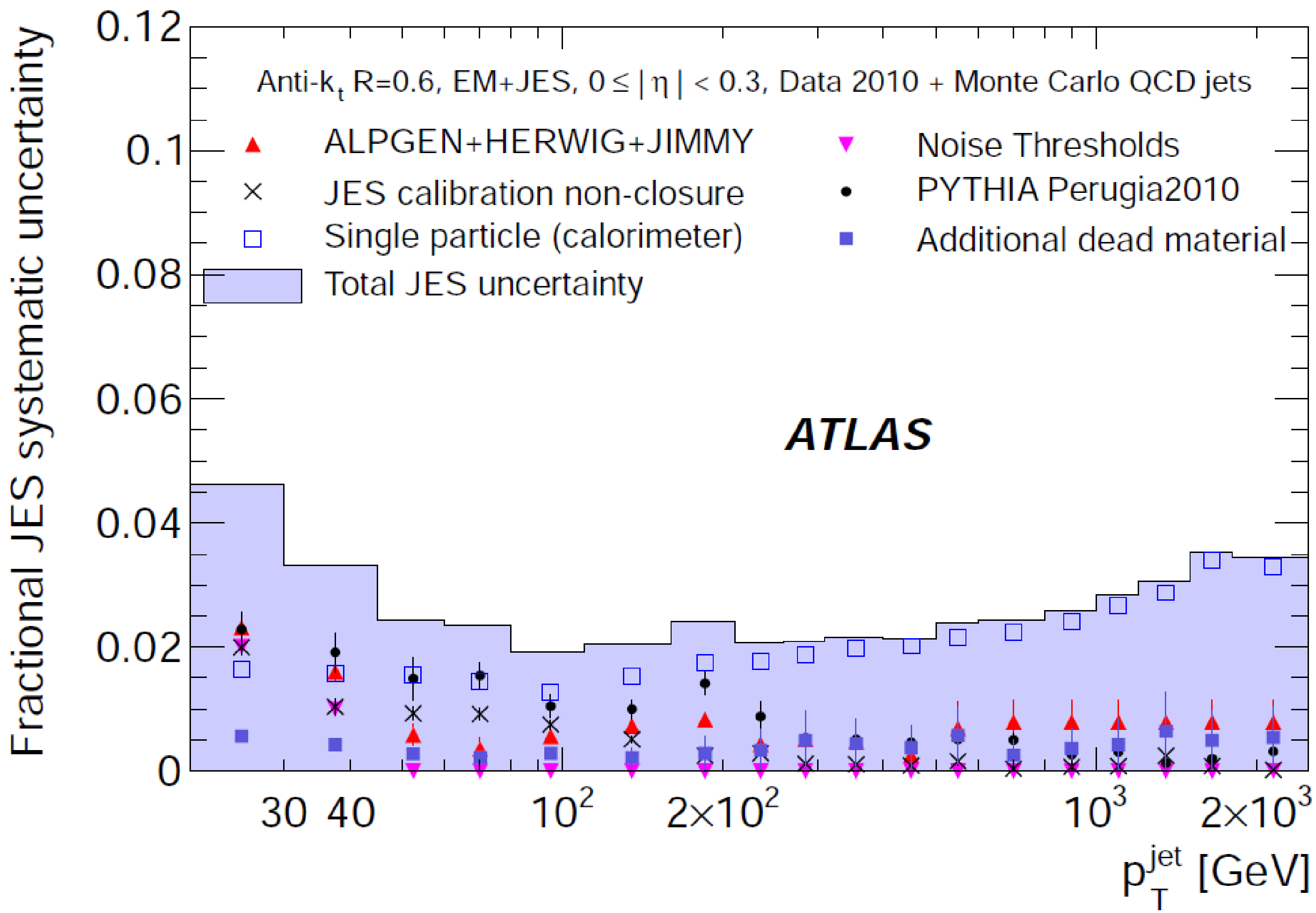
General interest to work with all four!

Only "real" cone algorithm!



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

ATLAS JES 2010



Inclusive Jet Measurements

All jets in the event satisfying the selection criteria

$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{jets}}{\epsilon \cdot L \cdot \Delta p_T \cdot \Delta y} \times C_{unsm}$$

Master Equation

- Jet Efficiency
- Event Efficiency

Bins of **corrected** Jet Pt and Jet rapidity

Unsmearing correction (due to the finite detector Pt resolution)

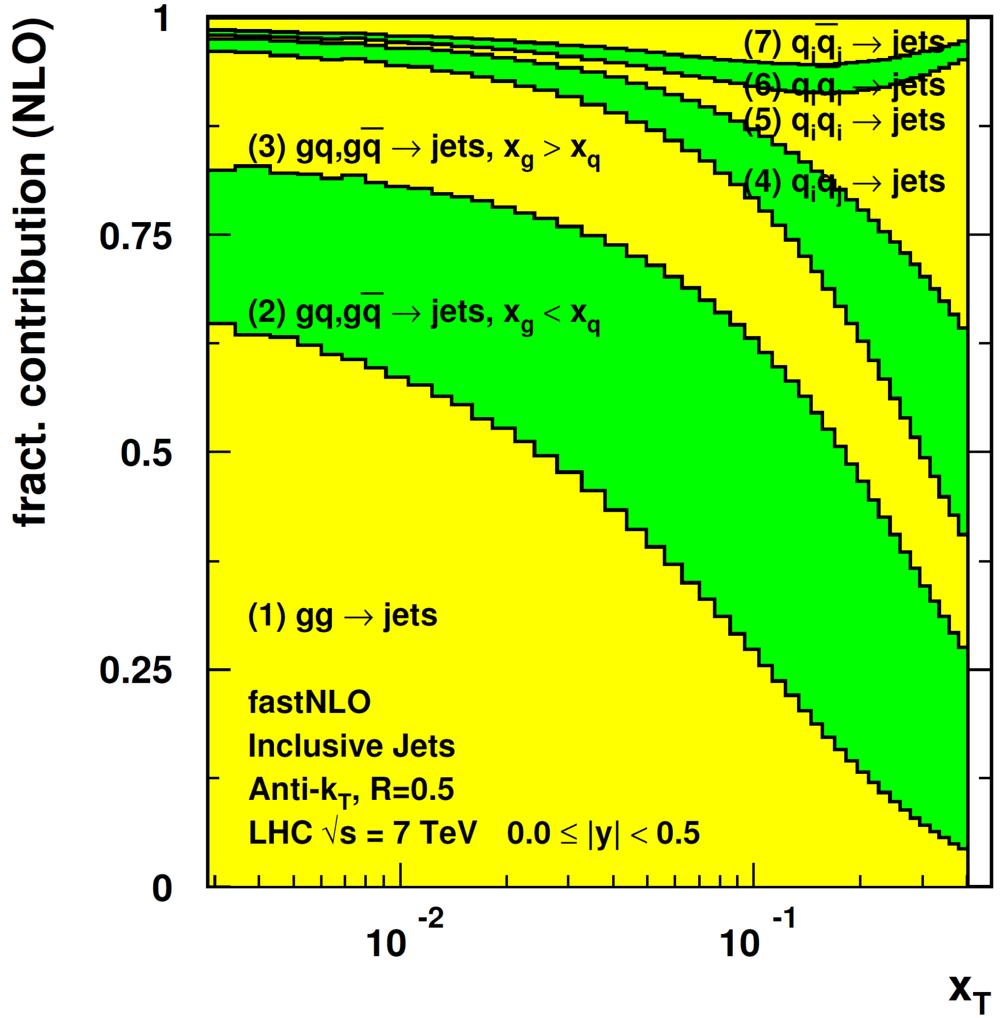
Luminosity, common uncertainty to all measurements

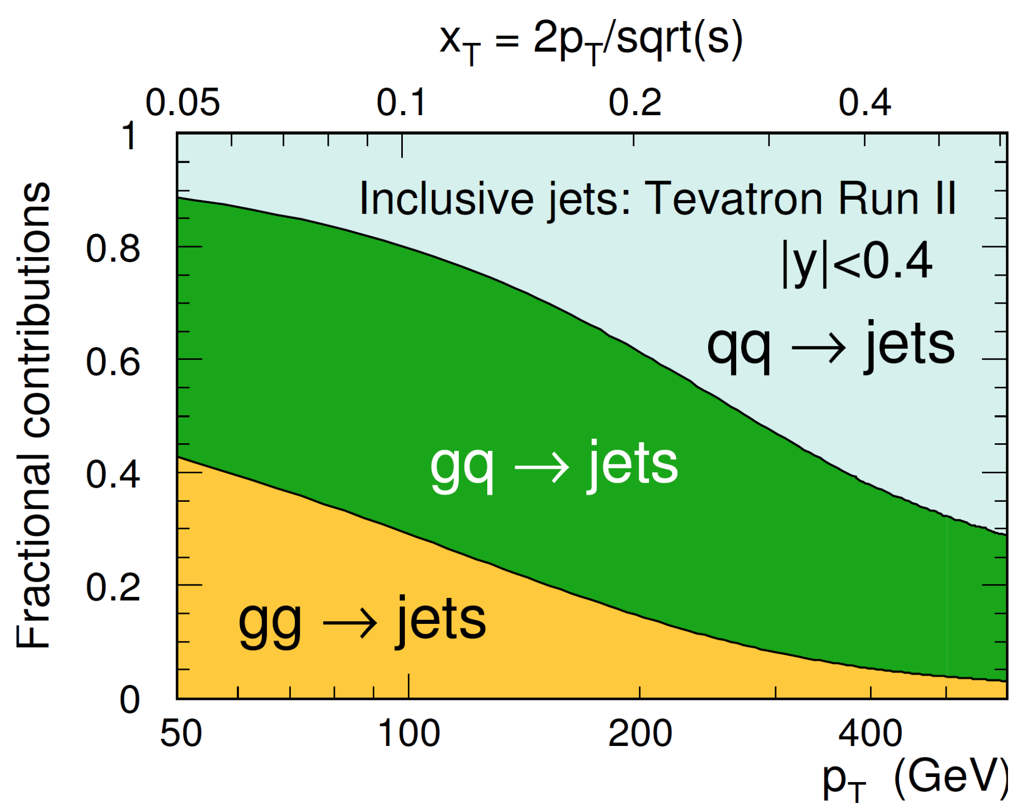
The JES dominates the total uncertainty of the measurement

K. Kousouris

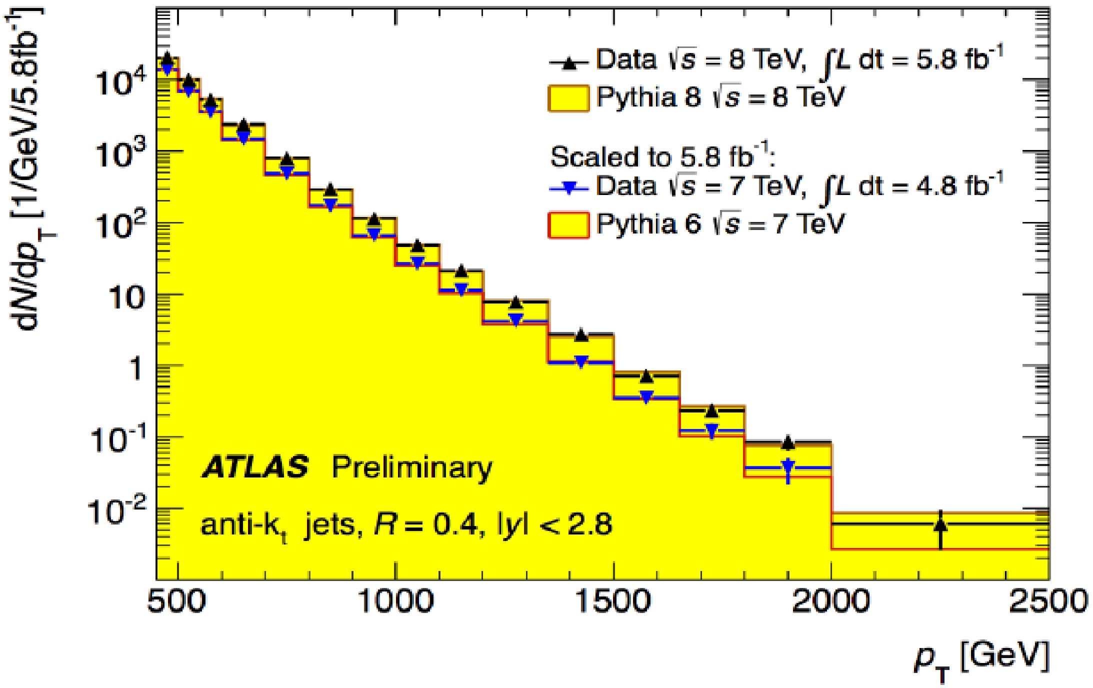
Inclusive Jets

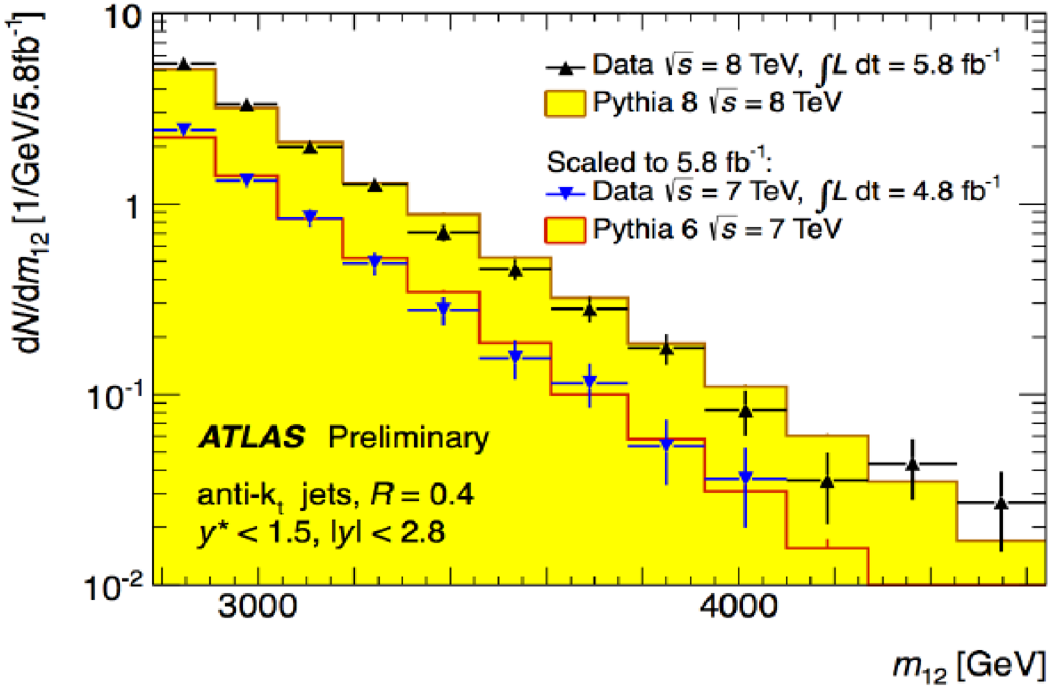
$$\frac{d^2\sigma}{dp_T d|y|} \propto \alpha_s^2$$





Jets @ √s = 8 TeV





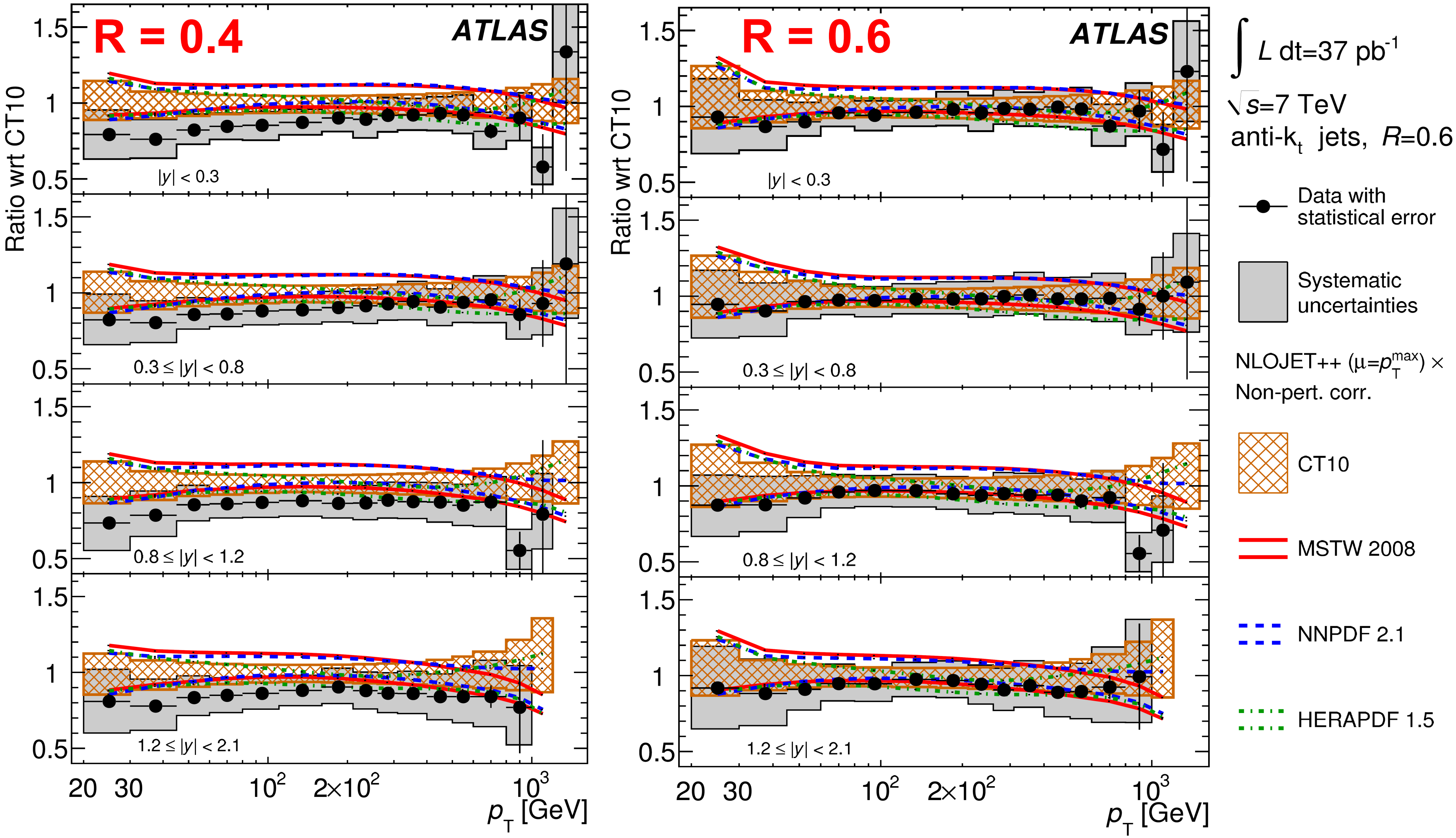
• Inclusive jet pT (left) and dijet mass (right) spectrum for *pp* collisions at √s = 8 TeV for anti-k_t R=0.4 jets.

• Comparison with √s = 7 TeV 2011 data and to Pythia 6 (Pythia 8) MC predictions at √s = 7 TeV (√s = 8 TeV).

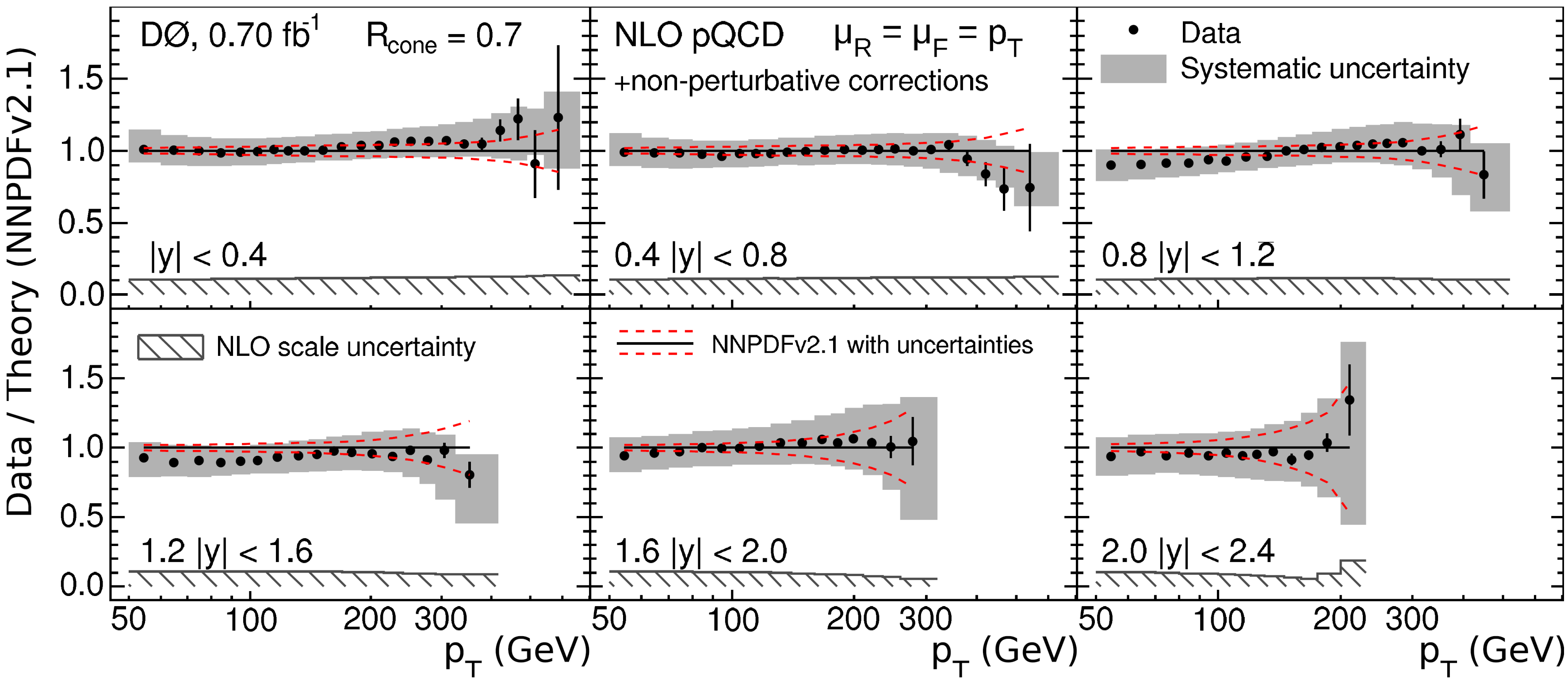
→ lower center of mass energy in 2011; therefore, lower cross section.

Inclusive Jets with 2 Jet Sizes

Comparison of measurement to QCD for various PDFs with two jet sizes



D0 Inclusive Jets - PDFs



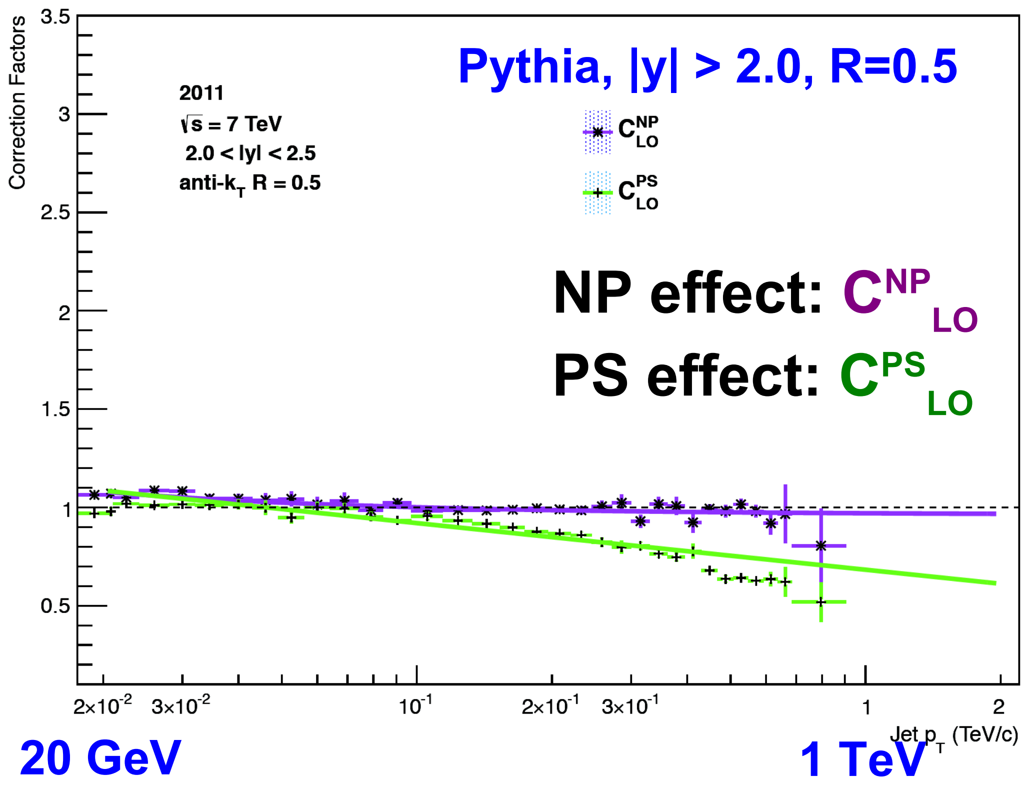
Non-perturbative Corrections

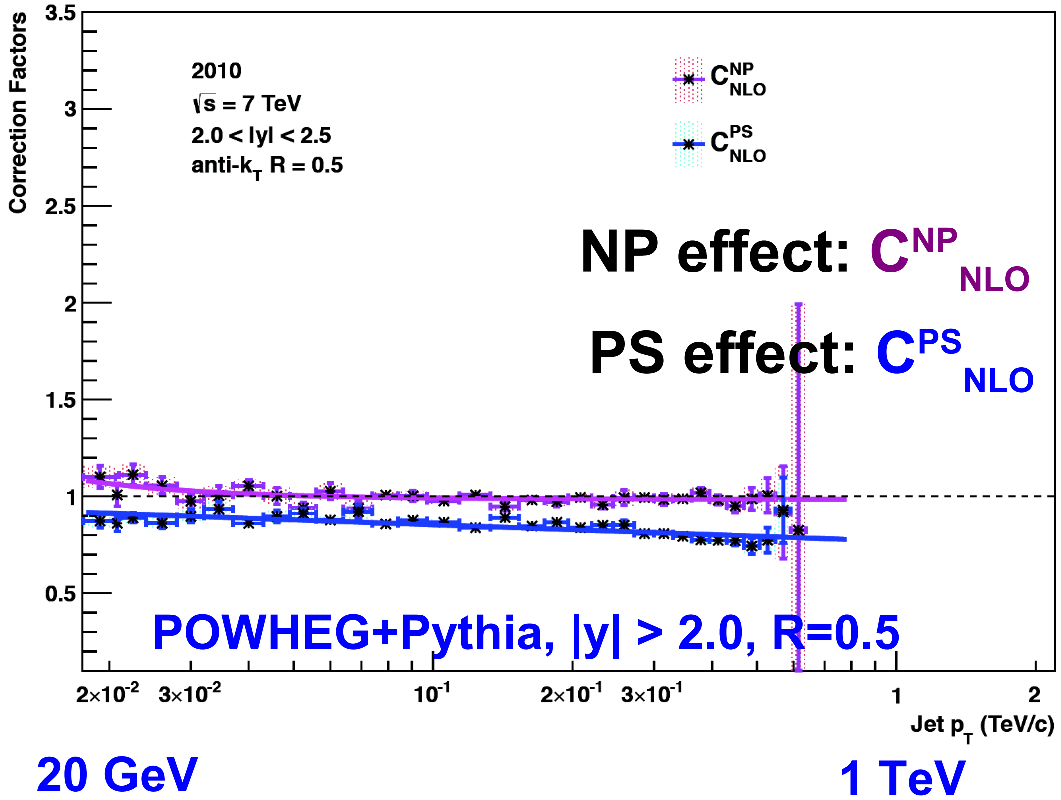
Recipe used at Tevatron & LHC:

- take LO parton shower (PS) MC
- derive corr. for non-pert. (NP) effects, i.e. multiple parton interactions and hadronization

→ assume PS effect small on NLO

→ assume NP effects similar for LO,NLO





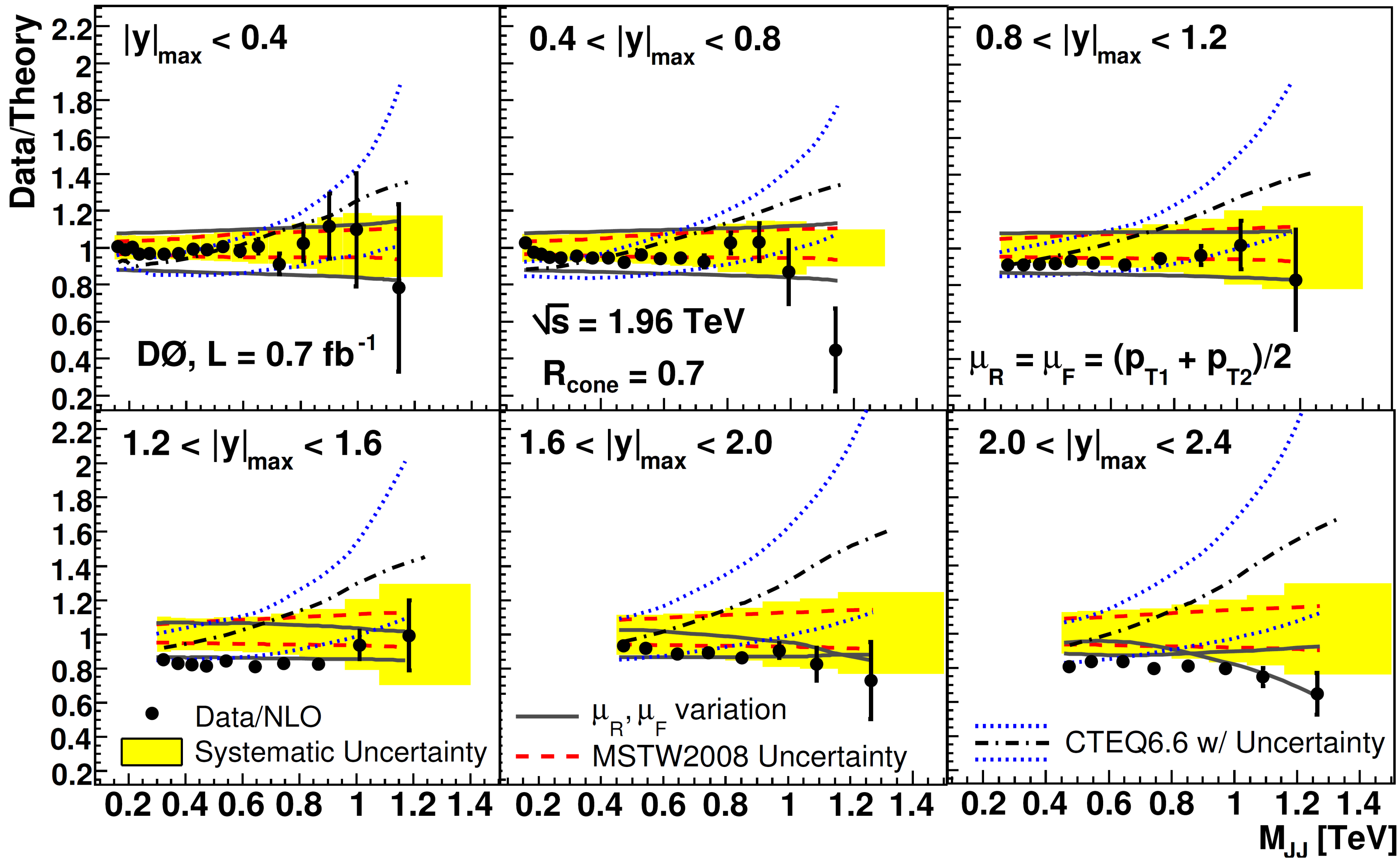
Observations:

- assumptions fine at central rapidity

- NP corrections larger for R=0.7 than 0.5
- for |y| > 2 PS effects visible

Figures courtesy of S.Dooling, H.Jung, P.Gunnellini, P.Katsas, A.Knutsson

D0 Dijet Mass - PDFs



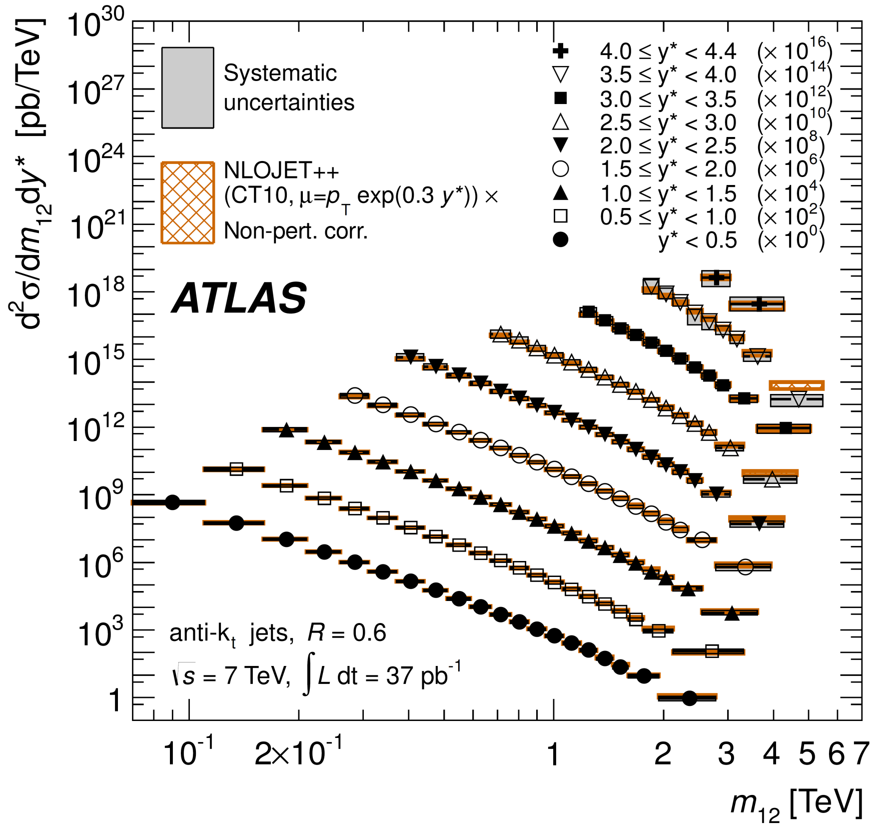
Dijet Mass ATLAS

$$\frac{d^2\sigma}{dM_{JJ}dy^*} \propto \alpha_s^2$$

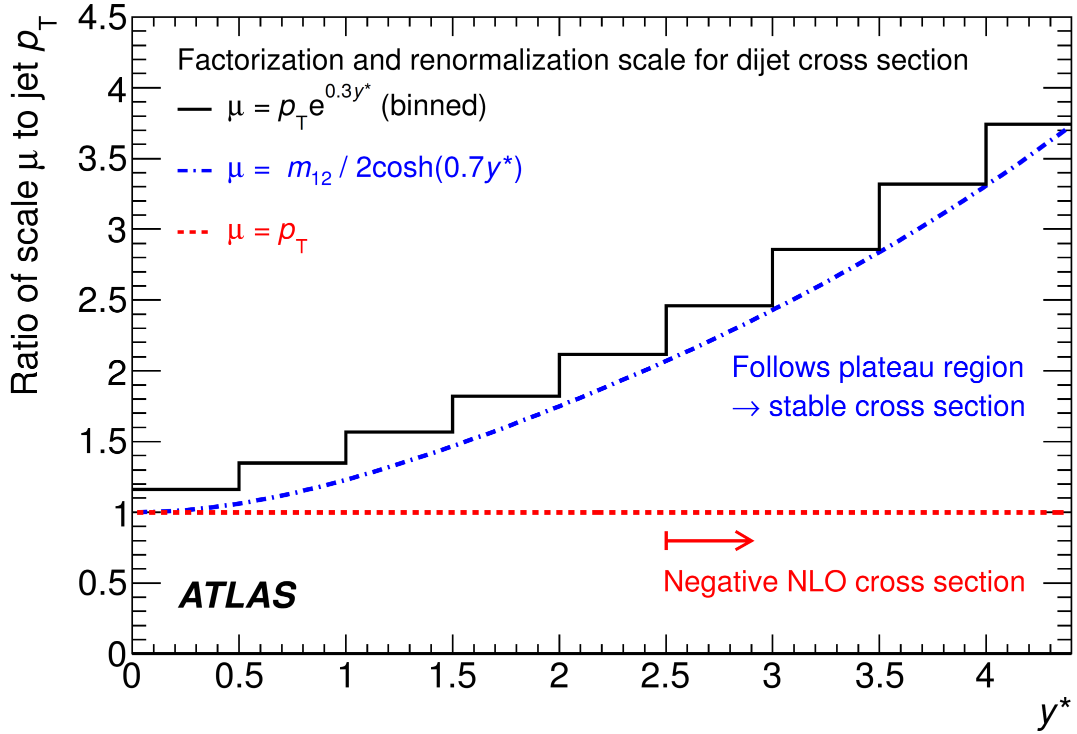
New choice for binning in rapidity by ATLAS
Also new choice for scale setting

$$\mu = p_T e^{0.3y^*}$$

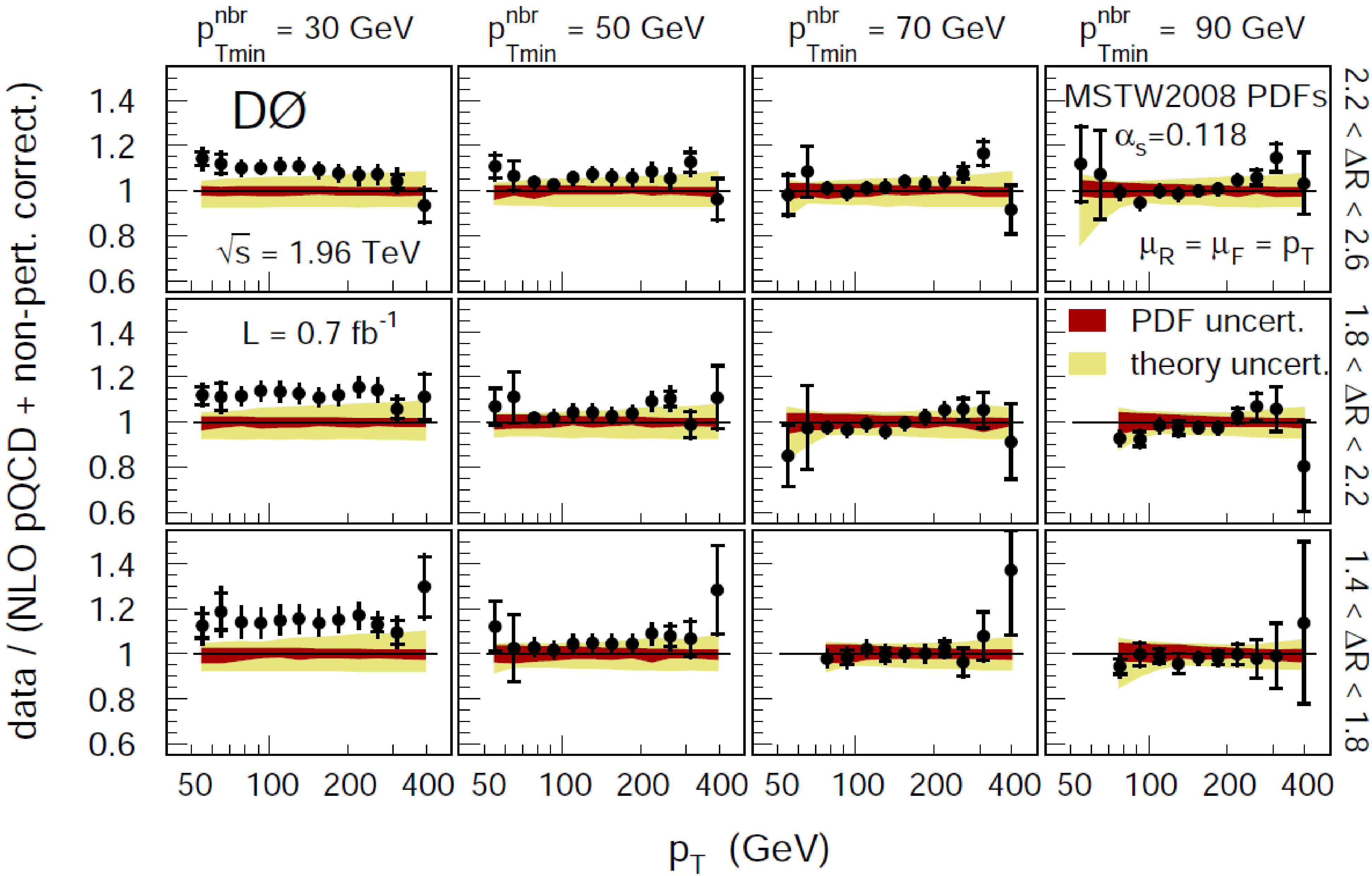
$$y^* = \frac{1}{2}|y_1 - y_2| = \frac{1}{2}\ln\left(\frac{1+|\cos\Theta^*|}{1-|\cos\Theta^*|}\right)$$



Attention: Figure somewhat misleading ...
Negative NLO cross sections appear
when checking scale uncertainties $\mu \rightarrow \mu/2$



D0 Angular Correlation --- Ratios



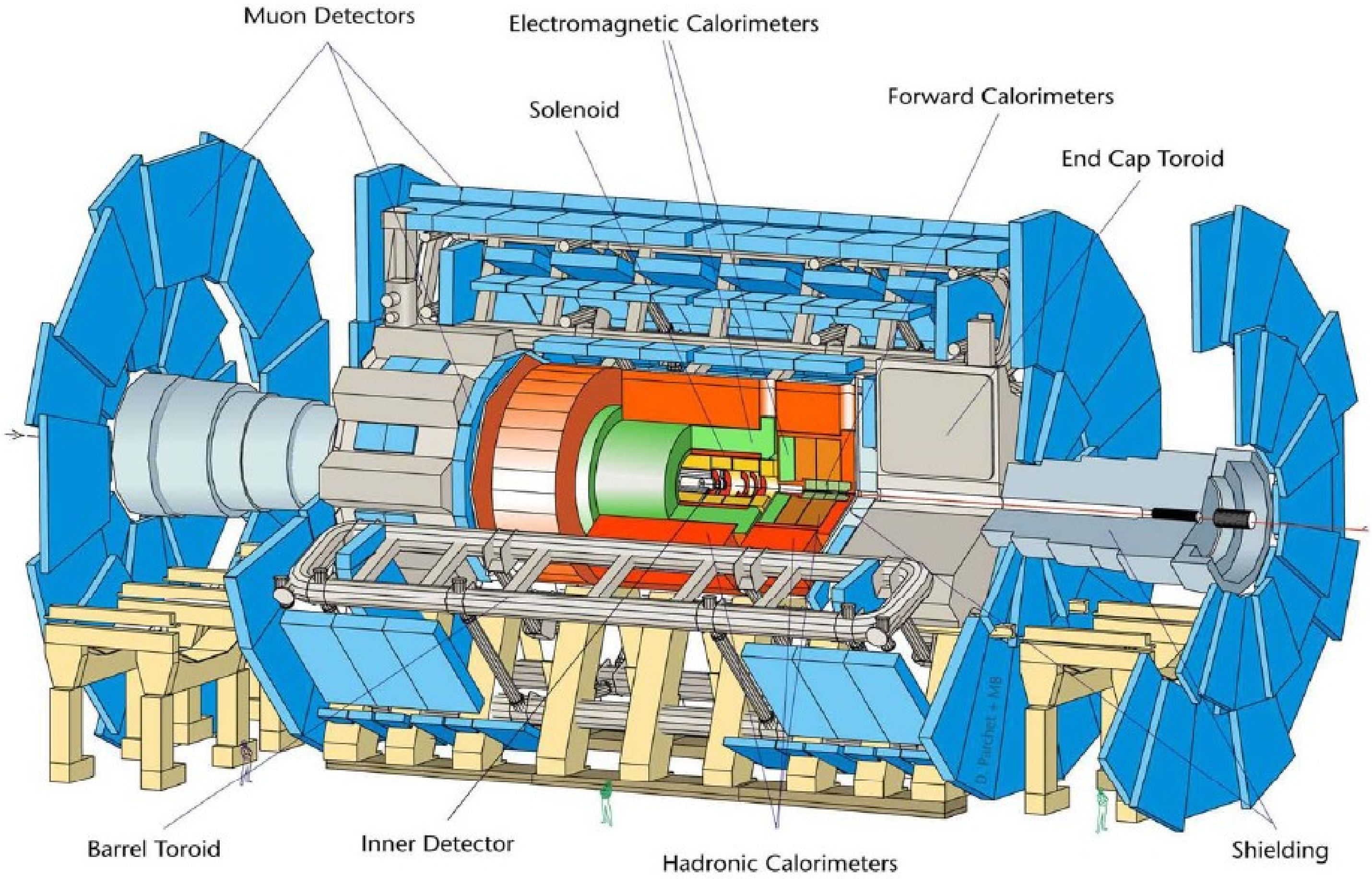
The ATLAS Detector

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
- $\sigma/p_T \approx 2\text{-}7\%$

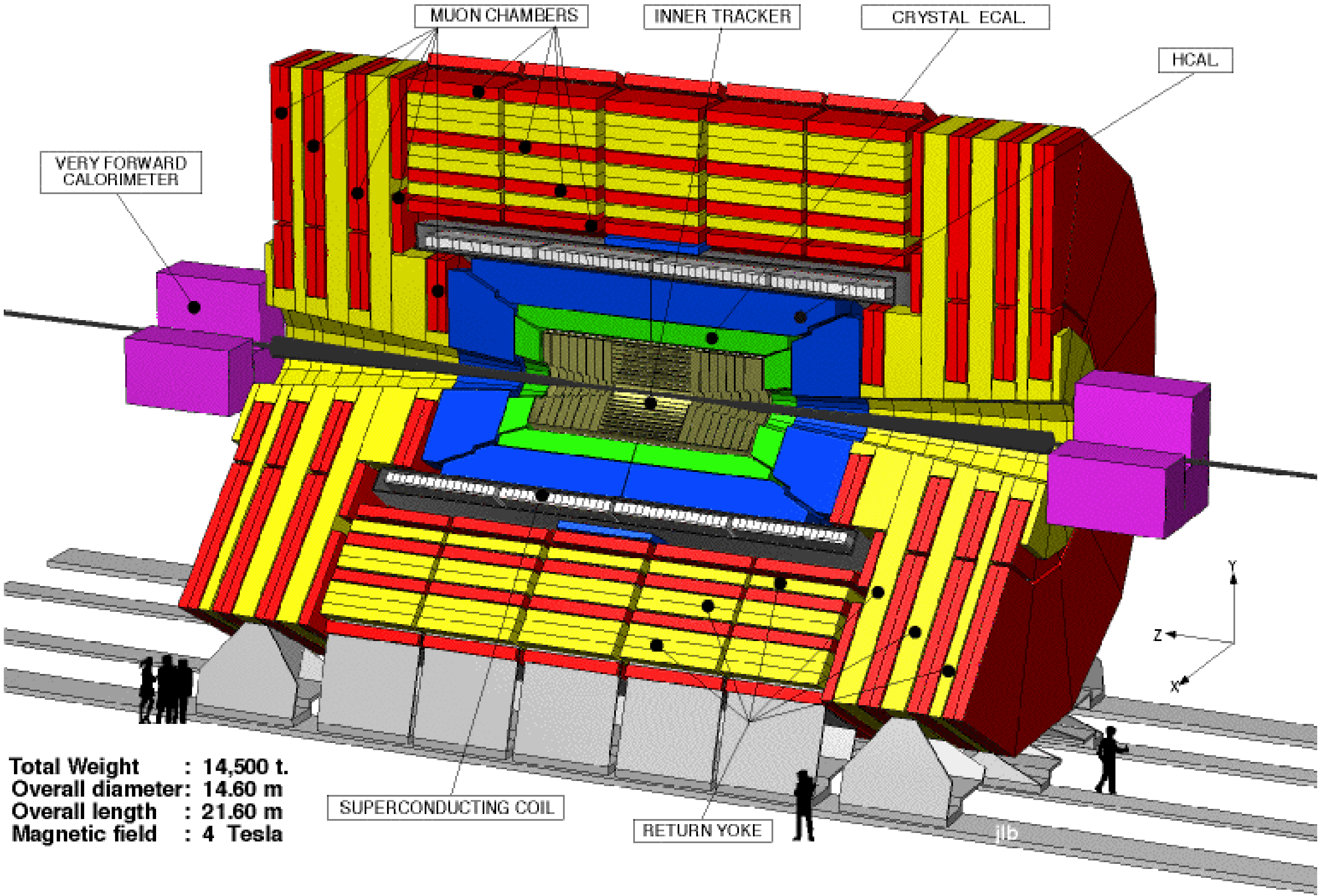
Magnets
- Solenoid (ID) → 2T
- Air toroids (muon) → up to 4T



Full coverage for $|\eta|<2.5$, calorimeter up to $|\eta|<5$

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)

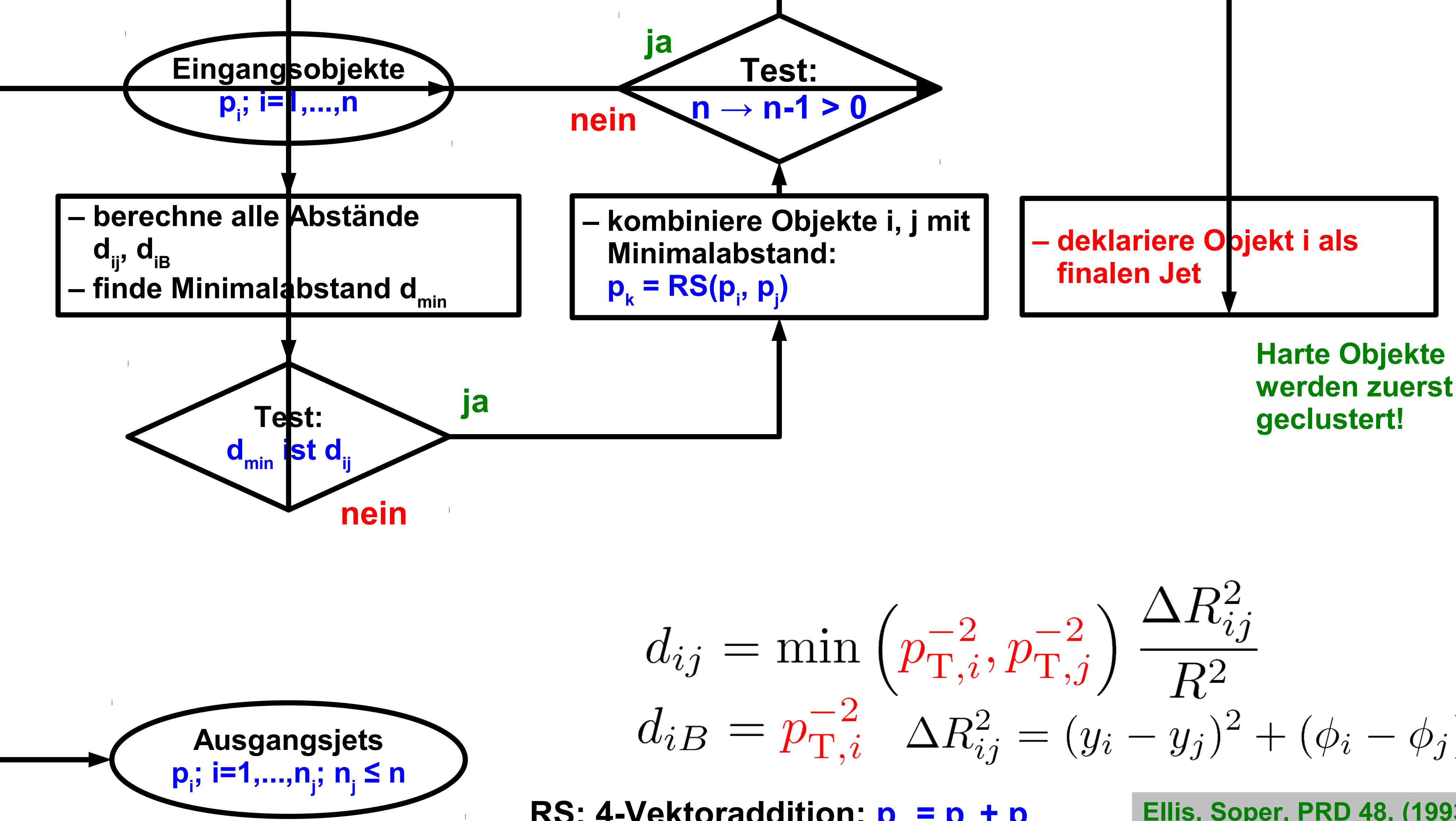
Calorimeter:
- PbWO4 crystal ECAL, brass/scintillator HCAL
- ELM: σ_E/E = 2.8% /$\sqrt{E}$ + 0.3%
- HAD: σ_E/E = 100% /$\sqrt{E}$ + 5%

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

anti-k_T – hh



Harte Objekte werden zuerst geclustert!

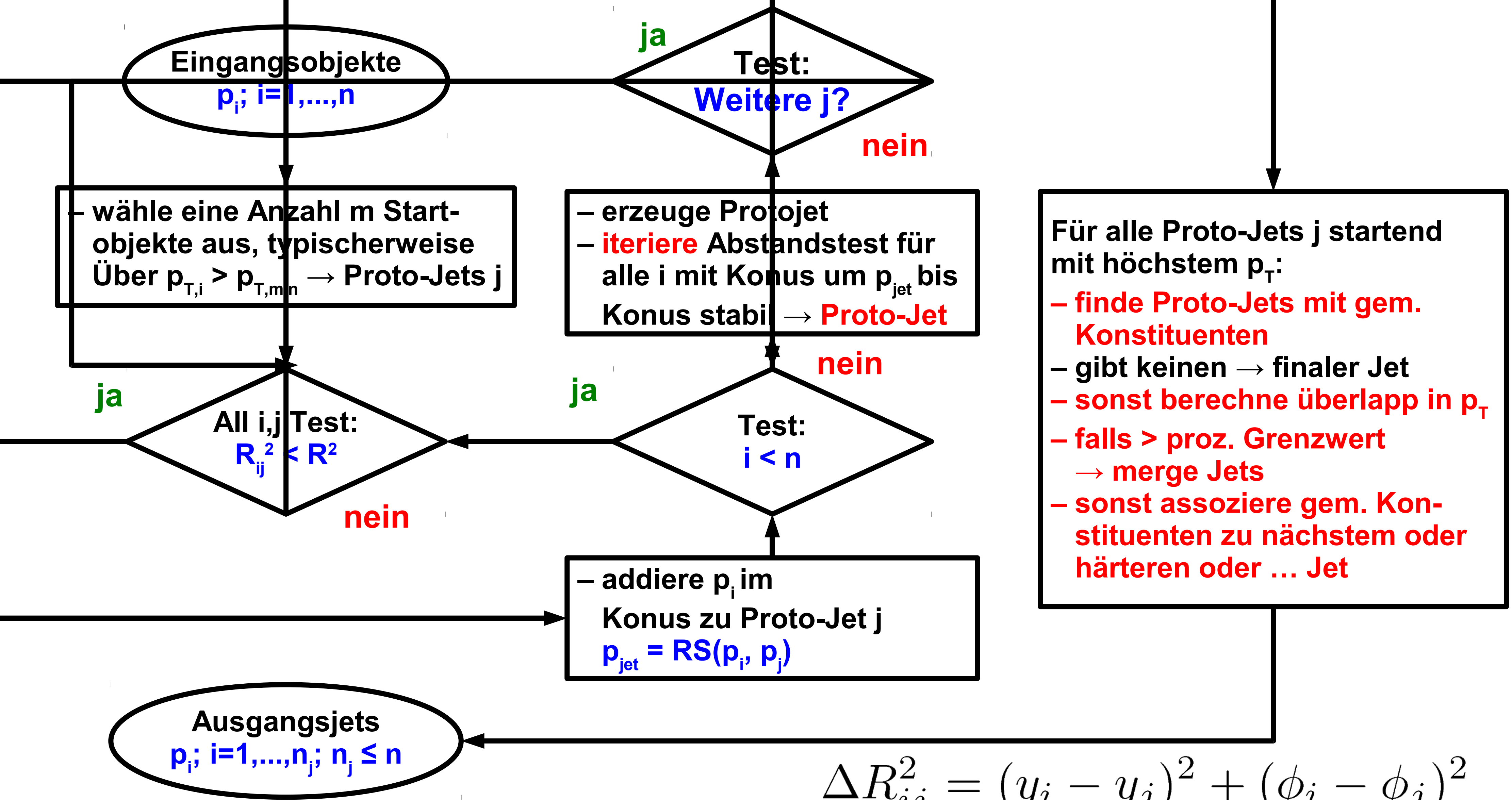
$$d_{ij} = \min\left(p_{\mathrm{T},i}^{-2}, p_{\mathrm{T},j}^{-2}\right)\frac{\Delta R_{ij}^2}{R^2}$$

$$d_{iB} = p_{\mathrm{T},i}^{-2} \quad \Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

RS: 4-Vektoraddition: $p_k = p_i + p_j$

Ellis, Soper, PRD 48, (1993).

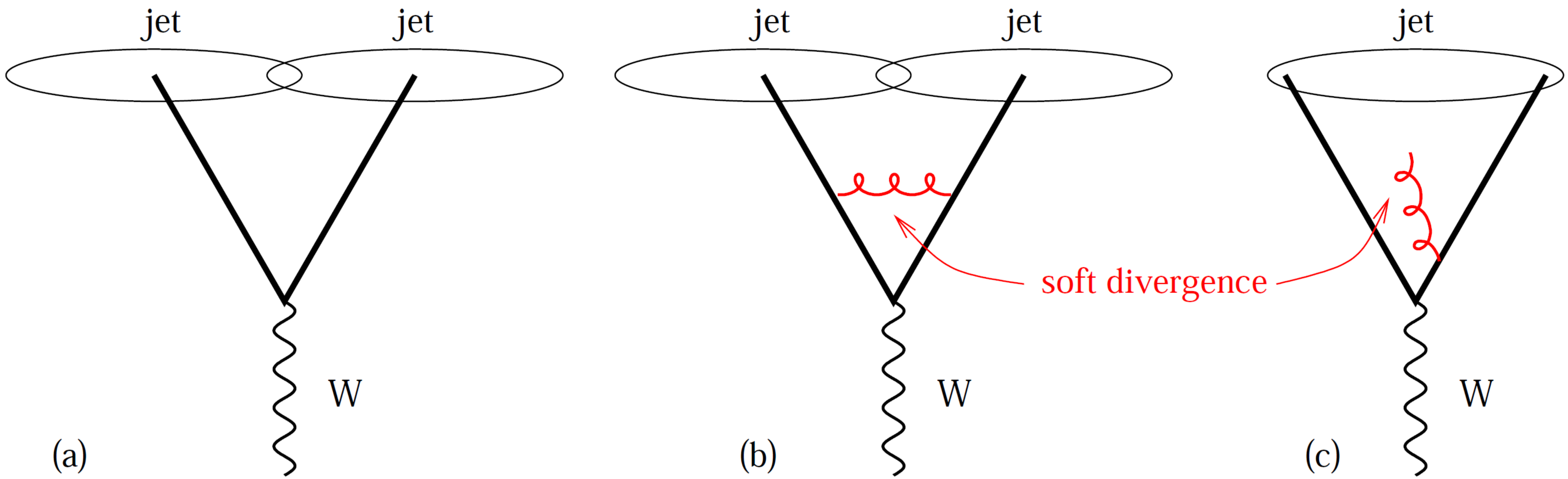
IC-SM



$$\Delta R_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

IC-SM Problem

Iterativer Konusalgorithmus mit "Aufspaltung und Fusion" (Iterative Cone with Split/Merge, IC-SM) → nicht alle Objekte enden in Jets, z.B. falls kein Startkonus in der Nähe (dark Jets)
→ kollinear unsicher wegen minimum pT auf Startwerte
→ infrarot unsicher ...



Reparaturversuch: MidPoint Cone → Untersuche zus. alle Mittelpunkte zwischen Startkoni
→ ebenfalls unsicher, fällt aber erst bei komplexerer Topologie auf
Erst spät gefunden: Wirklich sicherer Algorithmus Seedless Infrared-Safe Cone (SISCone)
→ wegen 2 Grössenordnungen grösserem Rechenbedarf kaum benutzt

Jetography, G. Salam, hep-ph/0906.1833