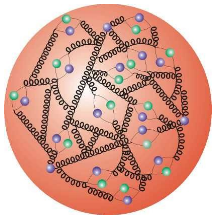
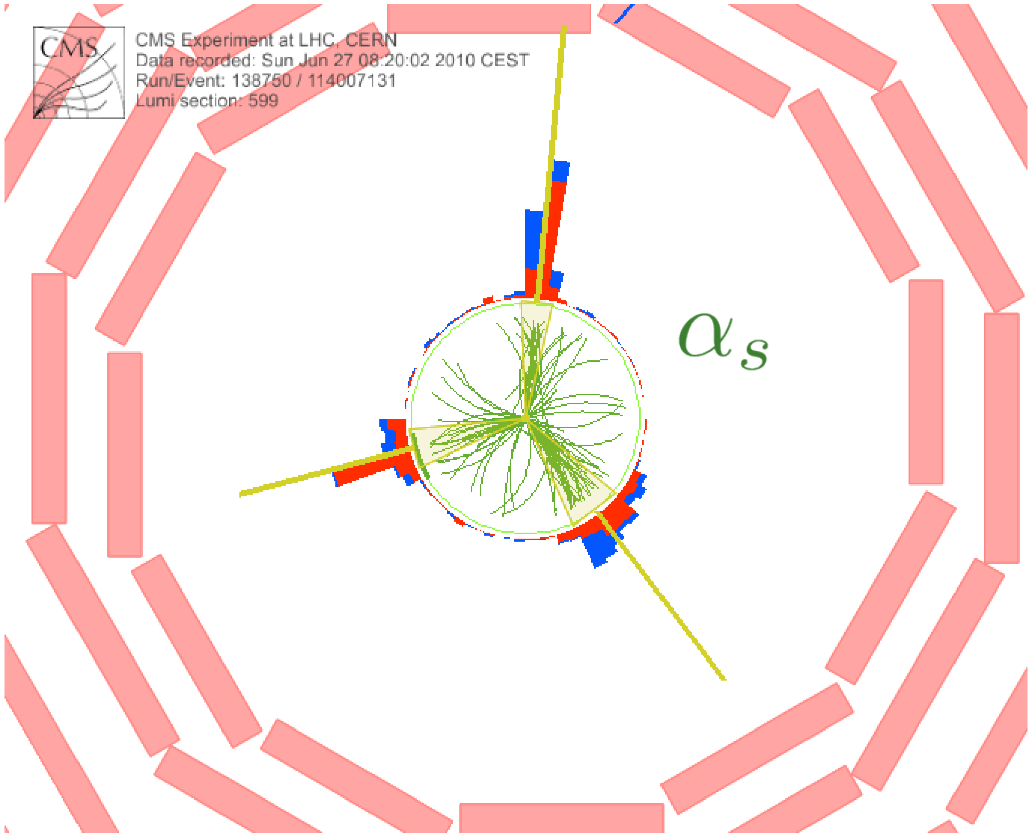
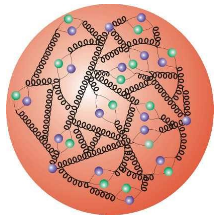
Jet physics at the LHC



Proton Structure
(PDF)





Proton Structure
(PDF)

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Klaus Rabbertz, KIT

Karlsruhe Institute of Technology

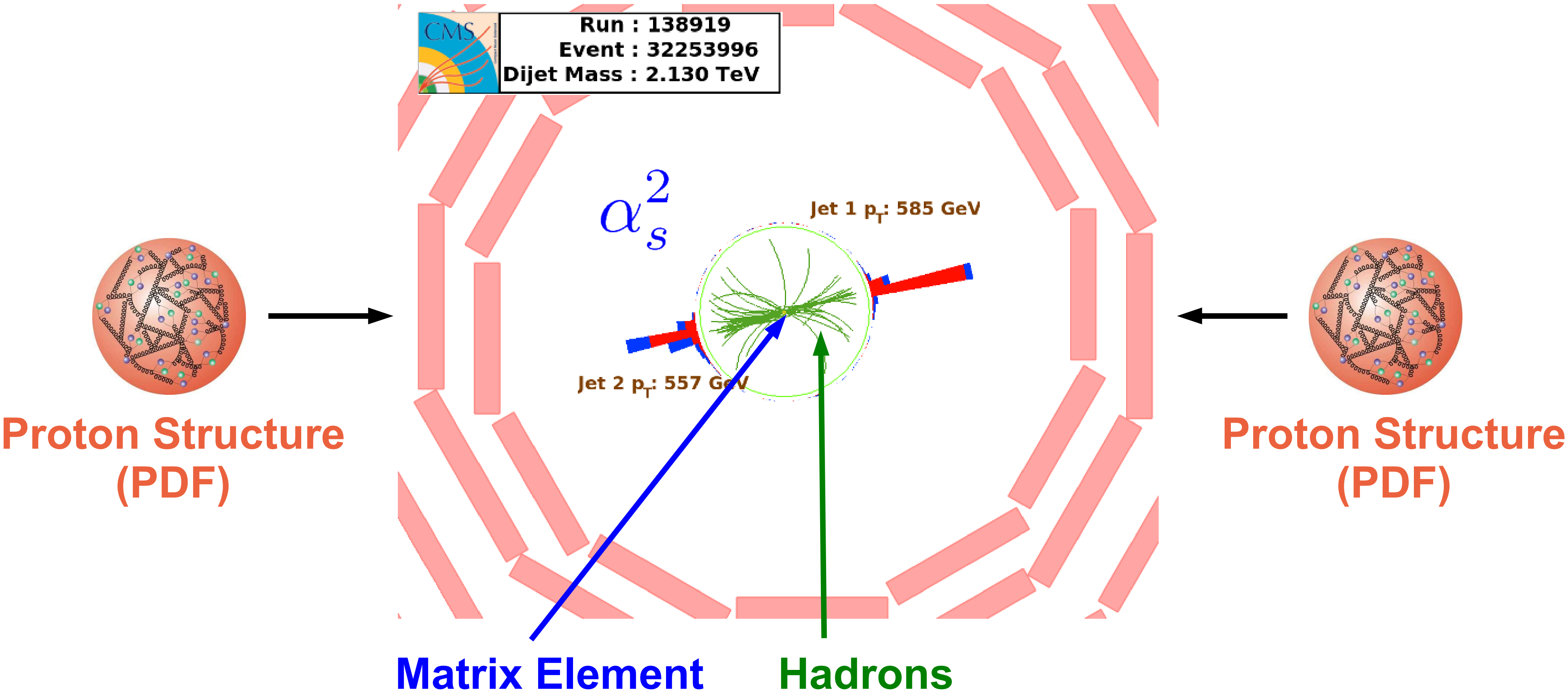
The Menu

- Motivation
- Accelerators and Detectors
- Jet Algorithms and Jet Calibration
- Inclusive Jets
- Dijet and 3-Jet Mass
- The strong Coupling from Jets
- Outlook

Will not cover or mention only briefly other very interesting subjects like event shapes, V plus jet production, forward jets, dijets at large rapidity.

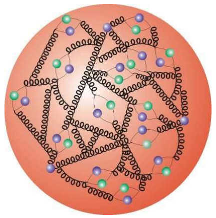
Jets … so what?

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

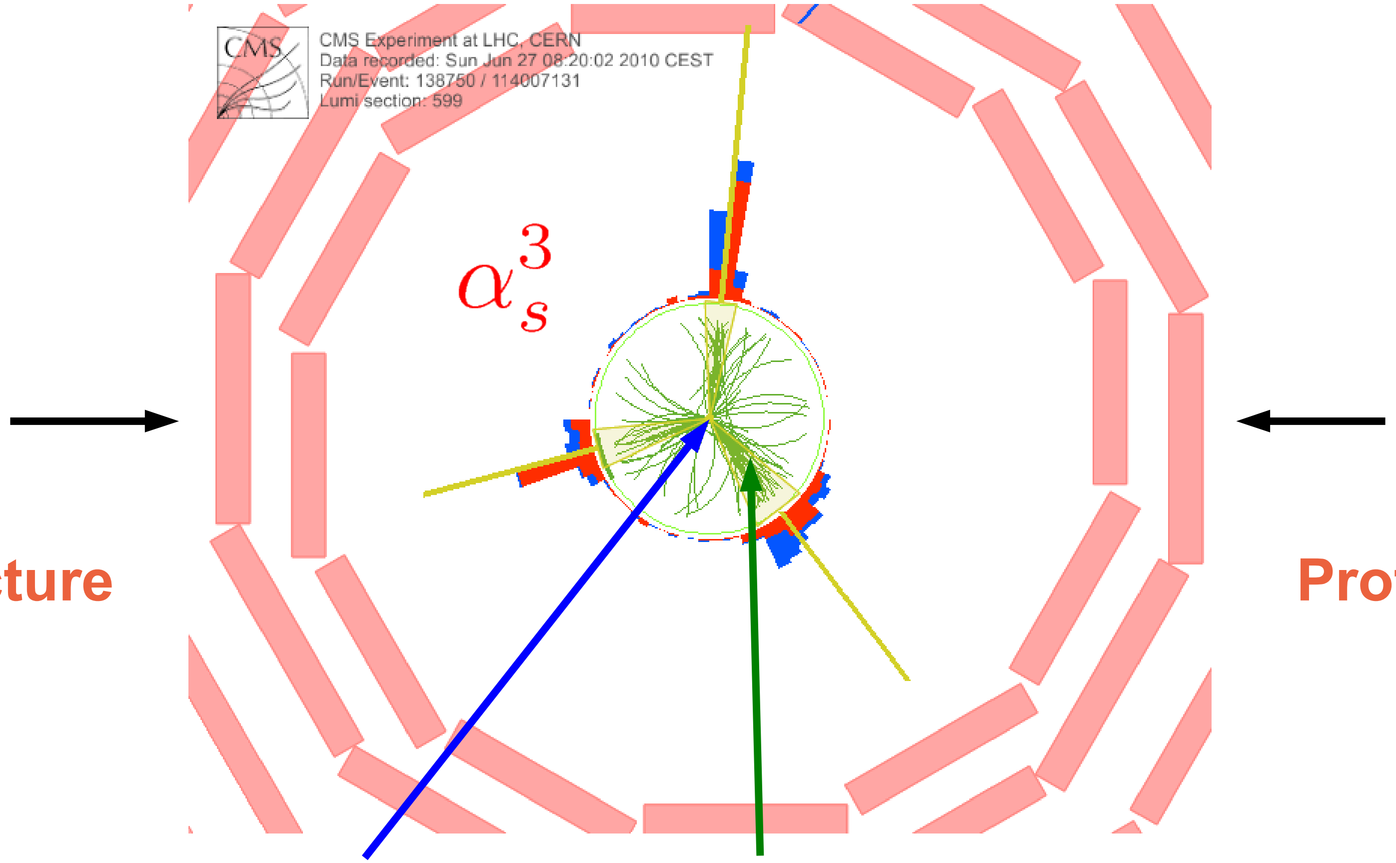


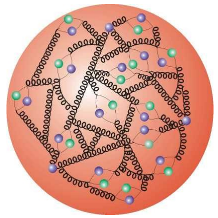
Jets … so what?

Abundant production of jets → hadron colliders are "jet laboratories"
… and the strong coupling alpha_s !



Proton Structure (PDF)

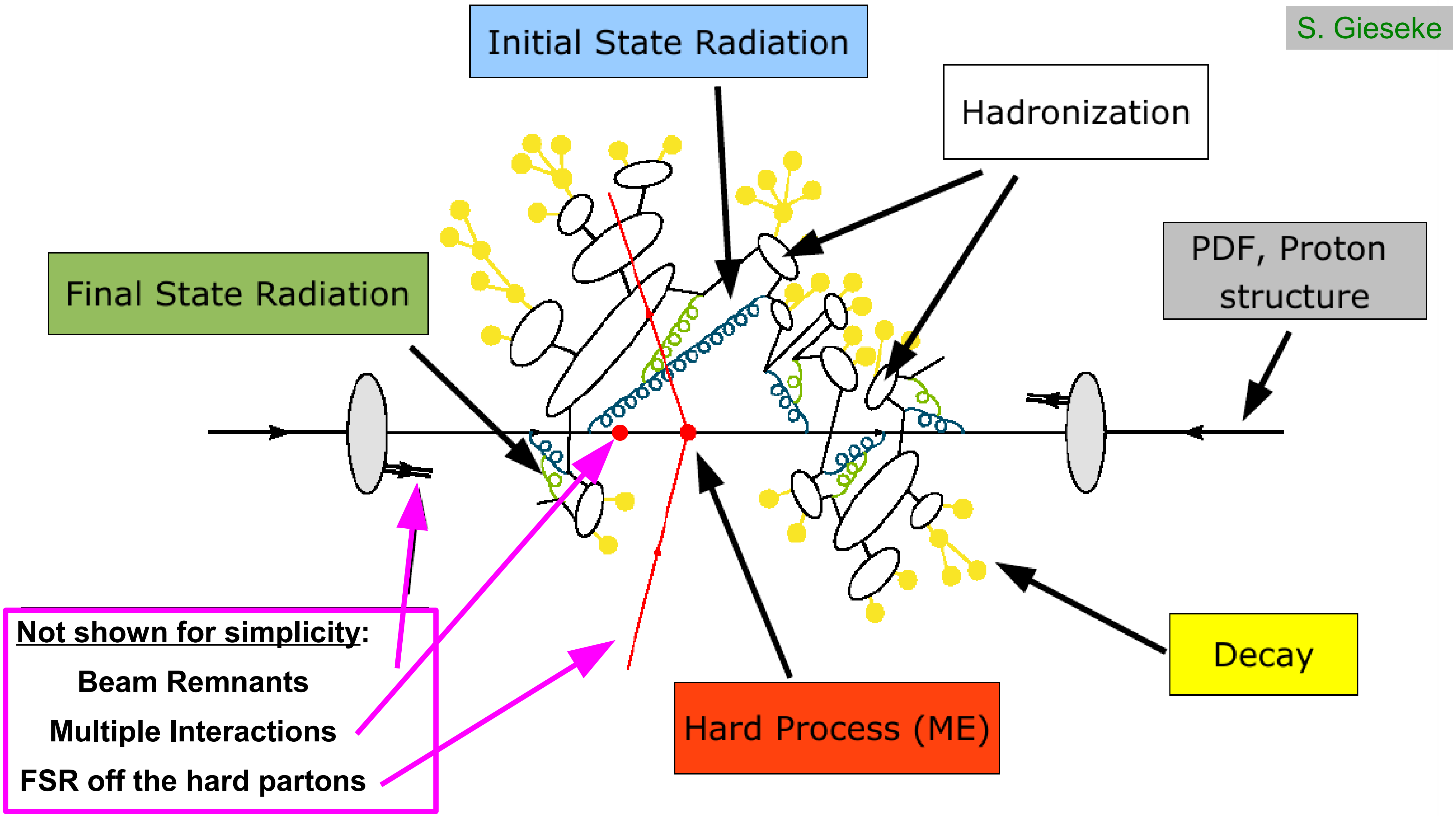




Proton Structure (PDF)

Matrix Element   Hadrons

The central Pixel resolved ...



30 years ago ...

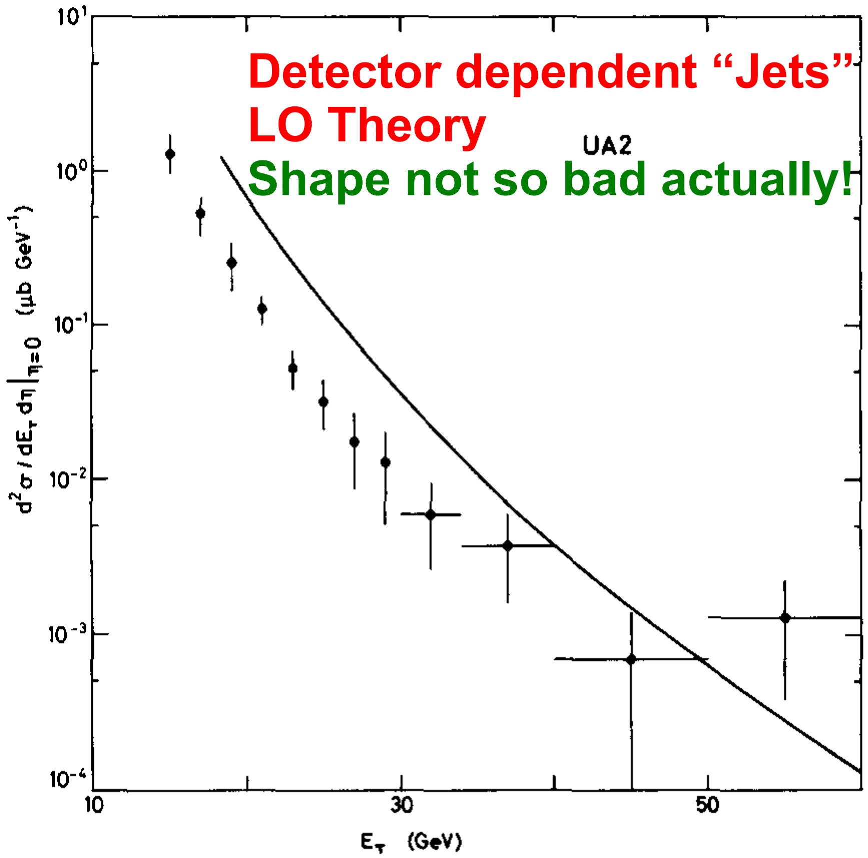


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

Achievements

30 years ago ...

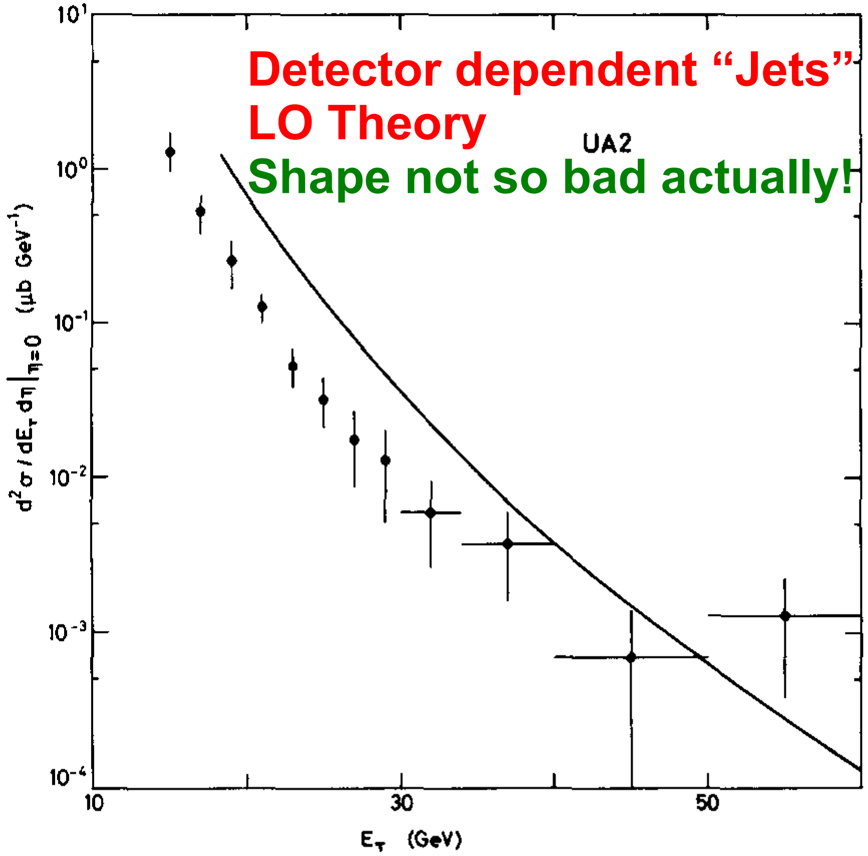
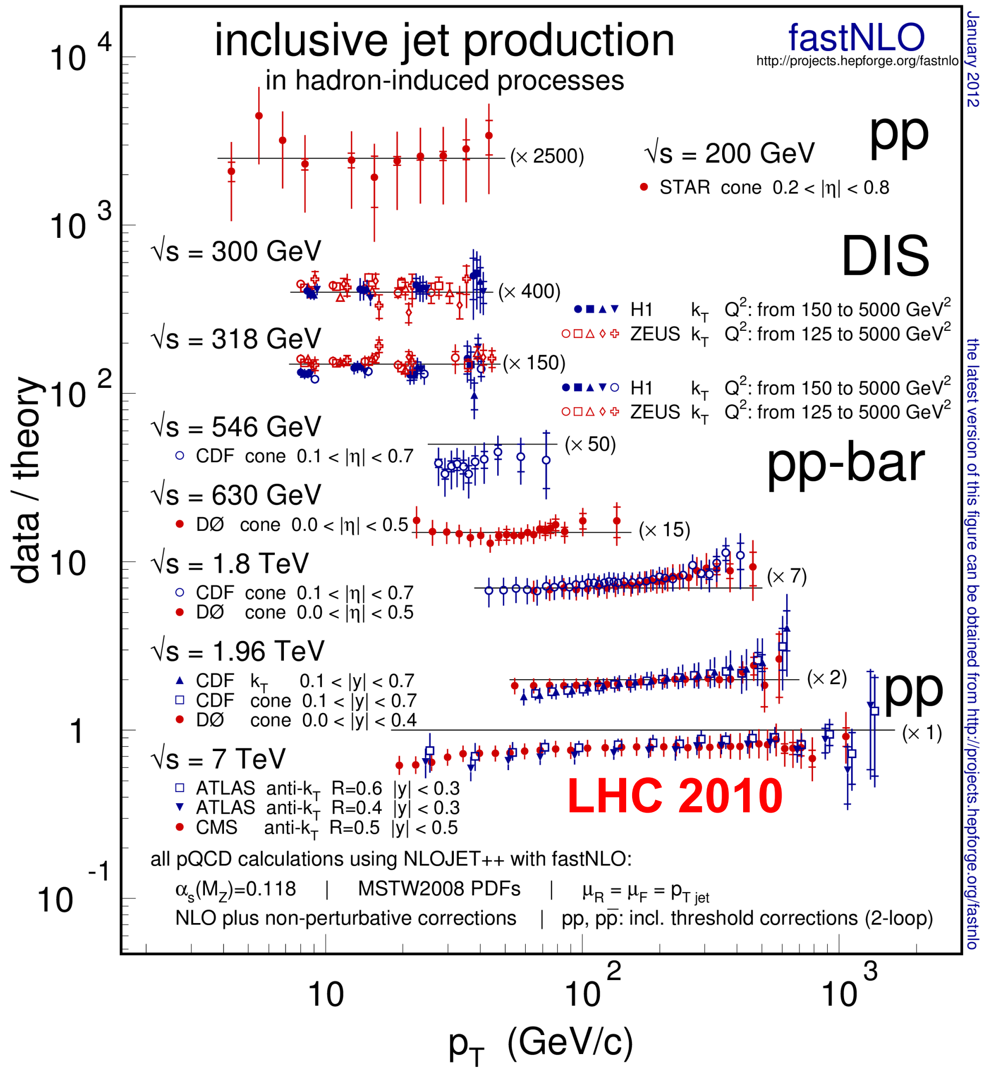


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

UA2, PLB 118 (1982).

... and today !

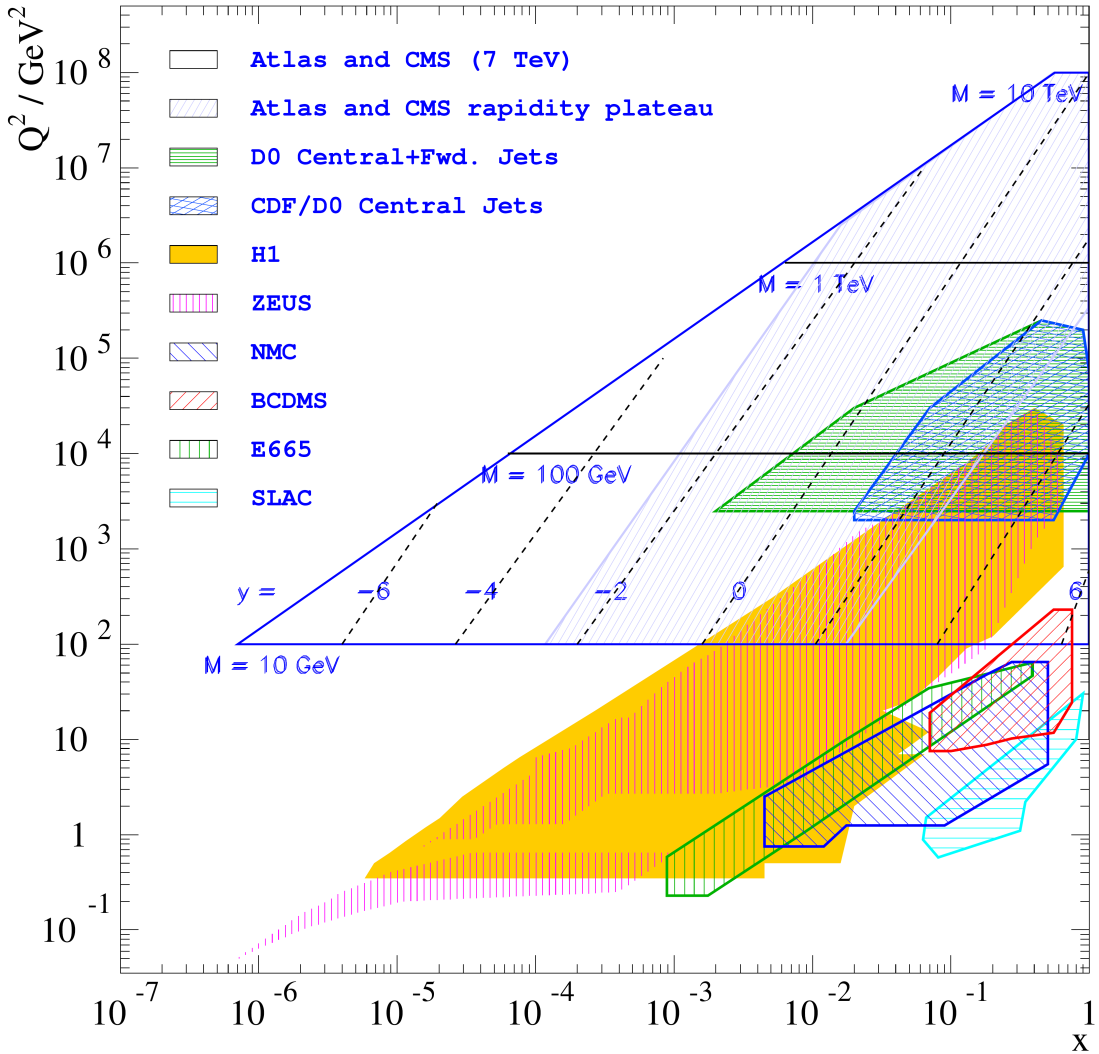


But much more to be learned!

fastNLO

Where to go ...

Kinematic plane of process scale² vs. x

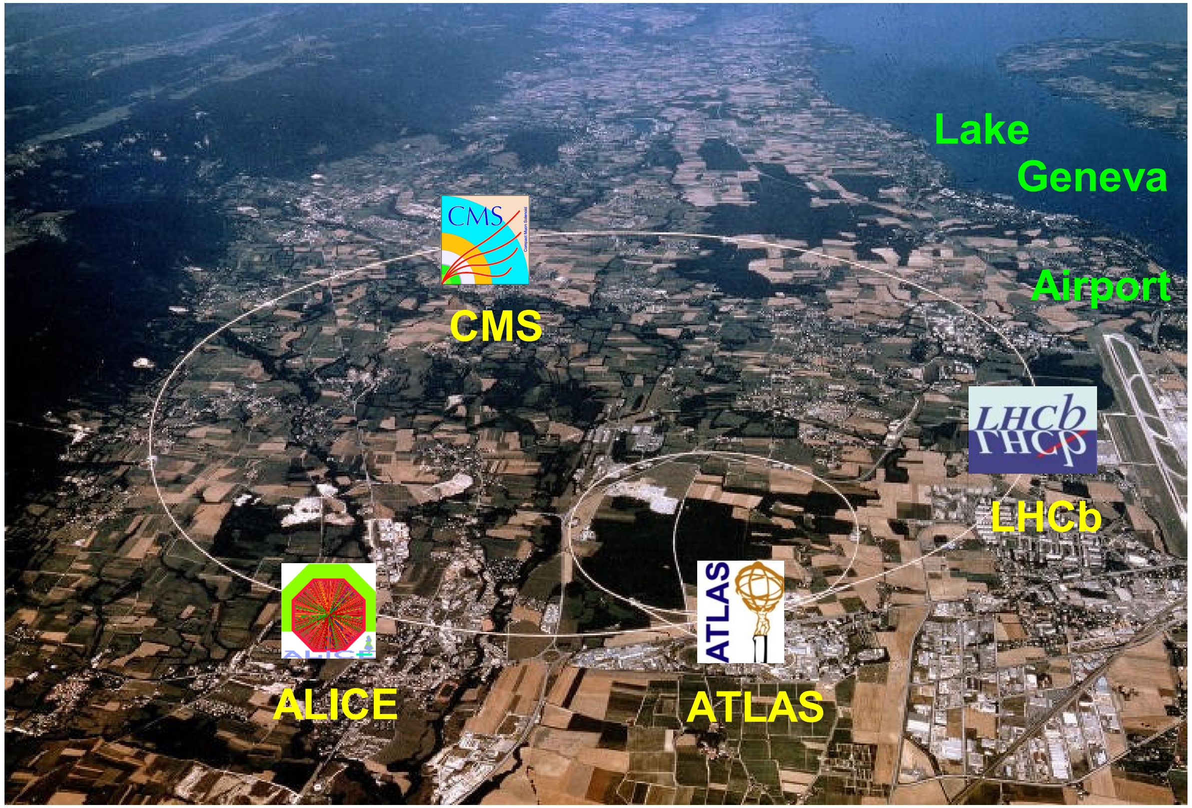


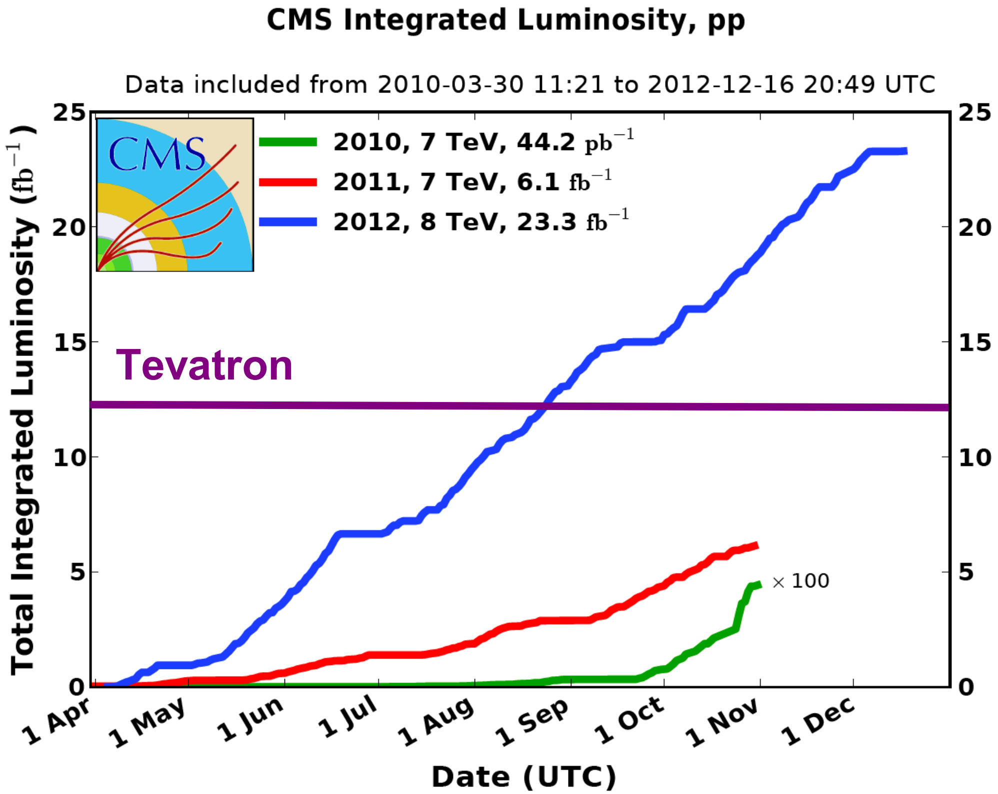
- Huge new phase space accessible in pp collisions at LHC
- Many different final states to examine with high accuracy
- A lot of progress on the theory side
- Check SM predictions at high scales, but watch out for corrections negligible up to now
- Determine the strong coupling and test its running at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

LHC Luminosity

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

2009 – 2013: E_{cms} = 0.9, 2.36, 2.76, 7, 8 TeV
2012: peak inst. lumi almost 8 x 10^{33} $cm^{-2}s^{-1}$

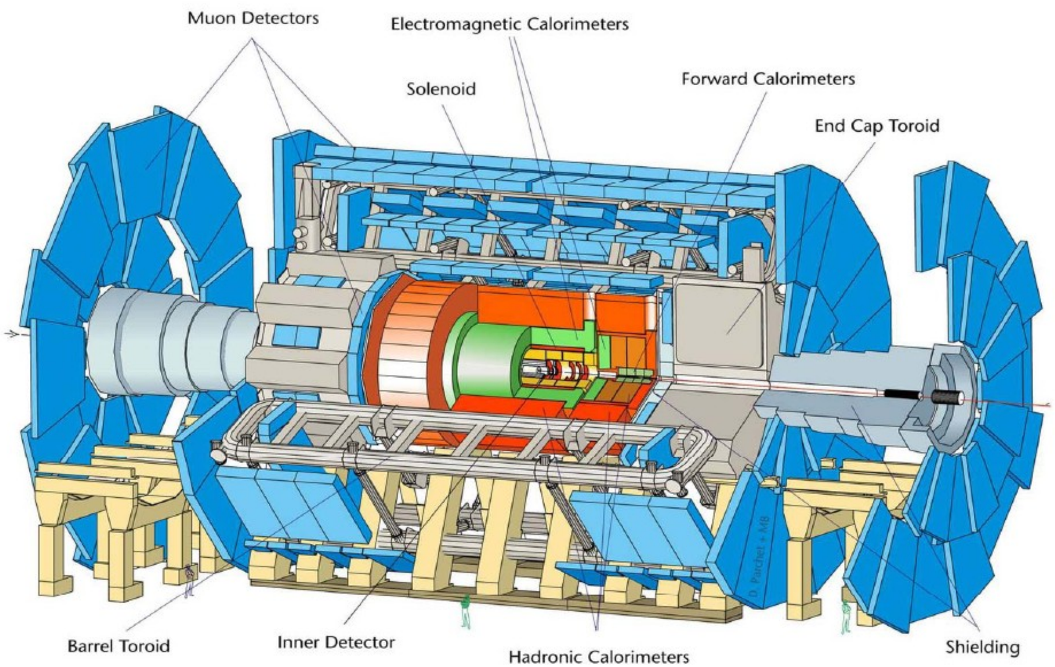


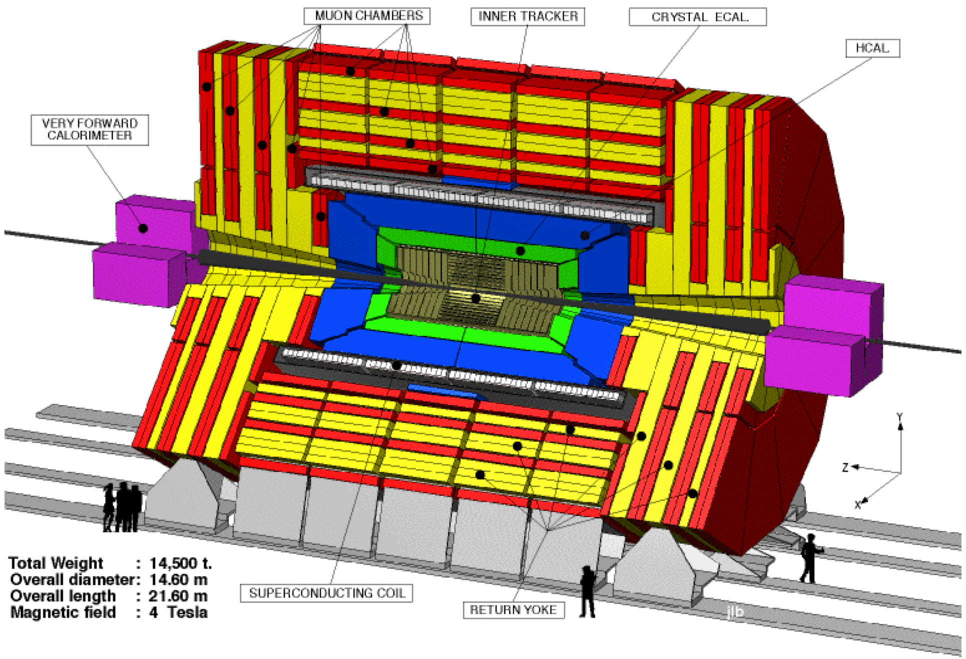


ATLAS and CMS

Silicon trackers:	**Up to |η| = 2.5**	**Silicon trackers:**	**Up to |η| = 2.5**
Calorimetry:	**Up to |η| = 4.9**	**Calorimetry:**	**Up to |η| = 5.0**
Muon chambers:	**Up to |η| = 2.7**	**Muon chambers:**	**Up to |η| = 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.





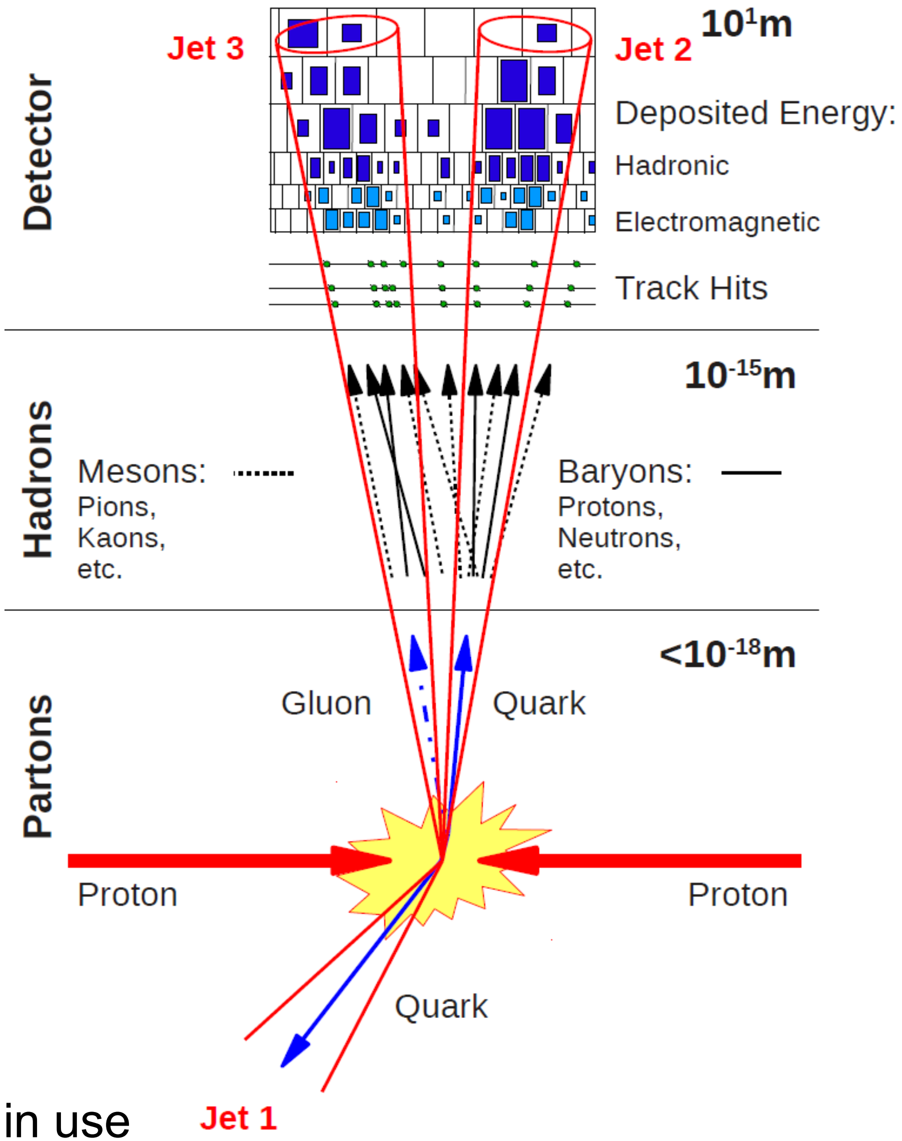
Jet Algorithms

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
  - • • •

Huge exp. progress since 2009

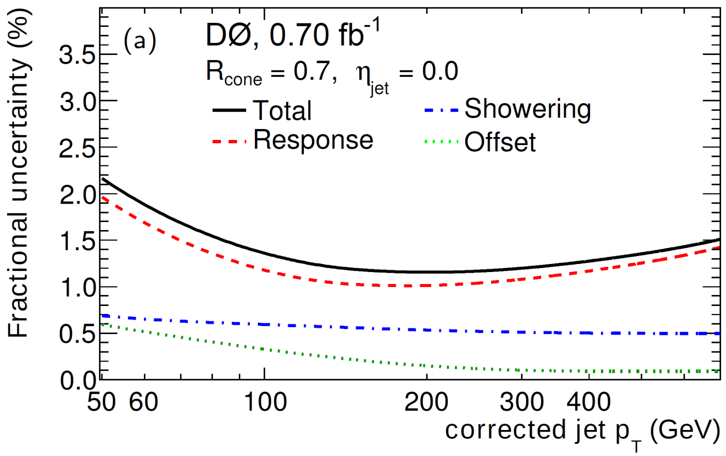
- **Theoretical Uncertainties:**
  - PDF Uncertainty
  - pQCD (Scale) Dependence
  - Non-perturbative Corrections
  - PDF Parameterization
  - NLO-NLL matching schemes
  - Electroweak Corrections
  - Knowledge of $\alpha_S(M_Z)$
  - • • •

There is a lot to learn here from comparison to measurements possible at the LHC!

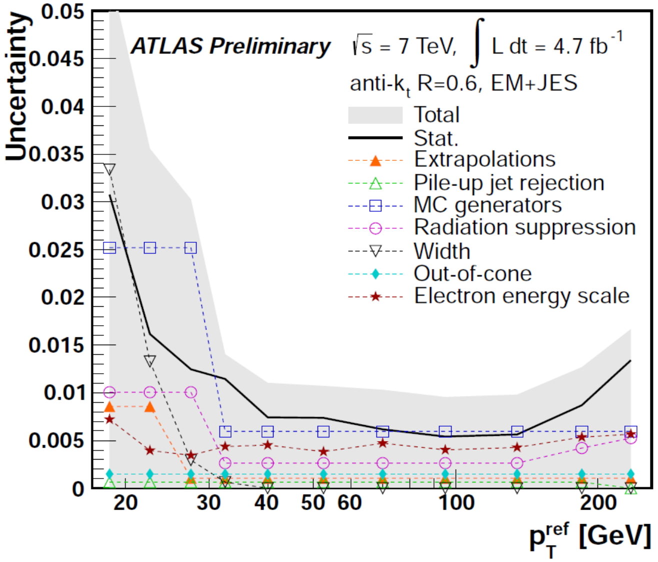
Jet Energy Scale

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

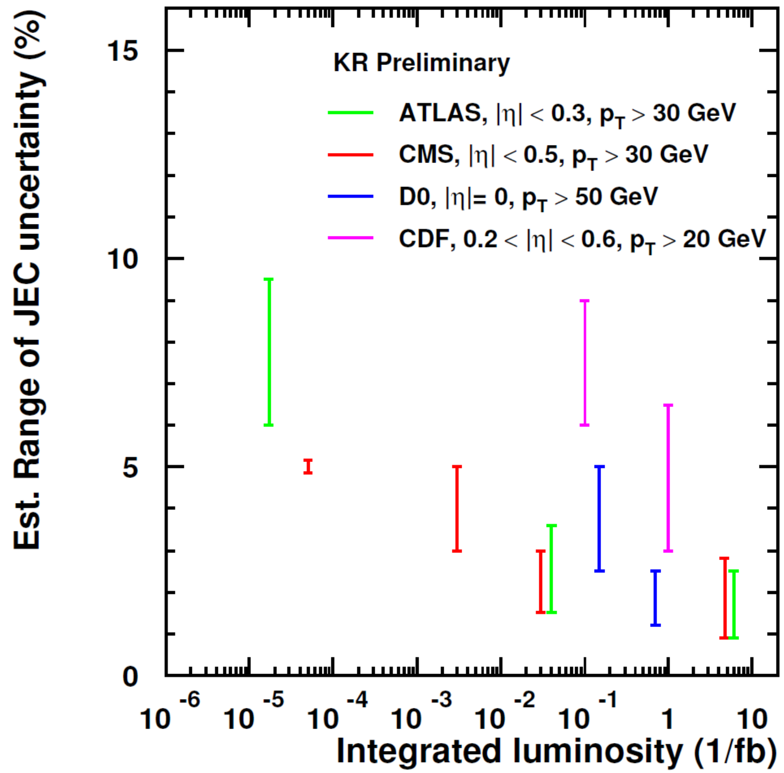
D0 from 0.7/fb (2011)



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



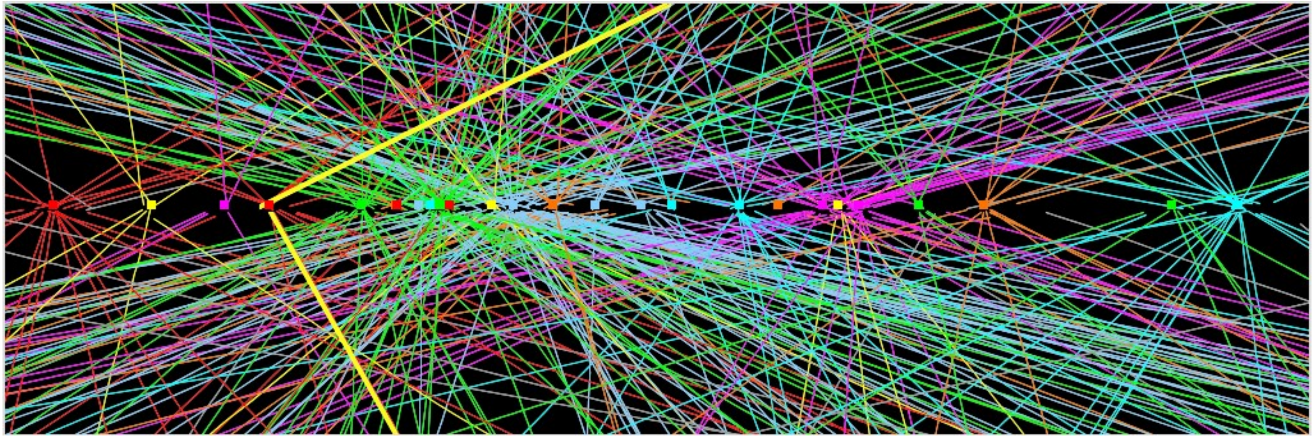
Approximate development of JEC precision



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

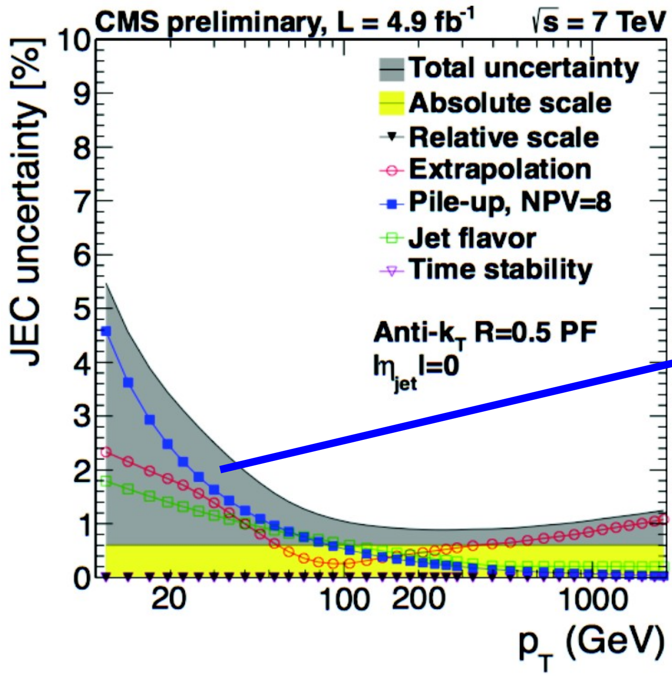
Jet Energy Scale and Pile Up

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



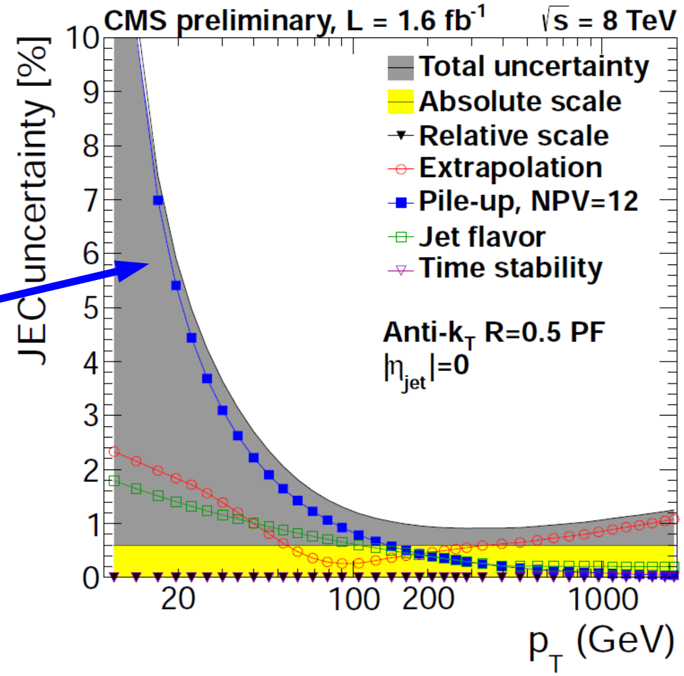
ATLAS Z → μμ candidate with 25 reconstructed primary vertices:
(Record beyond 70 by now.)

CMS from 5/fb (7 TeV, 2011)



Pile-up effect

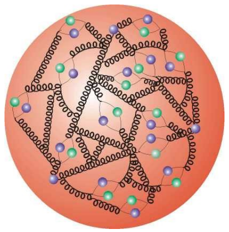
CMS from 1.6/fb (8 TeV, 2011)



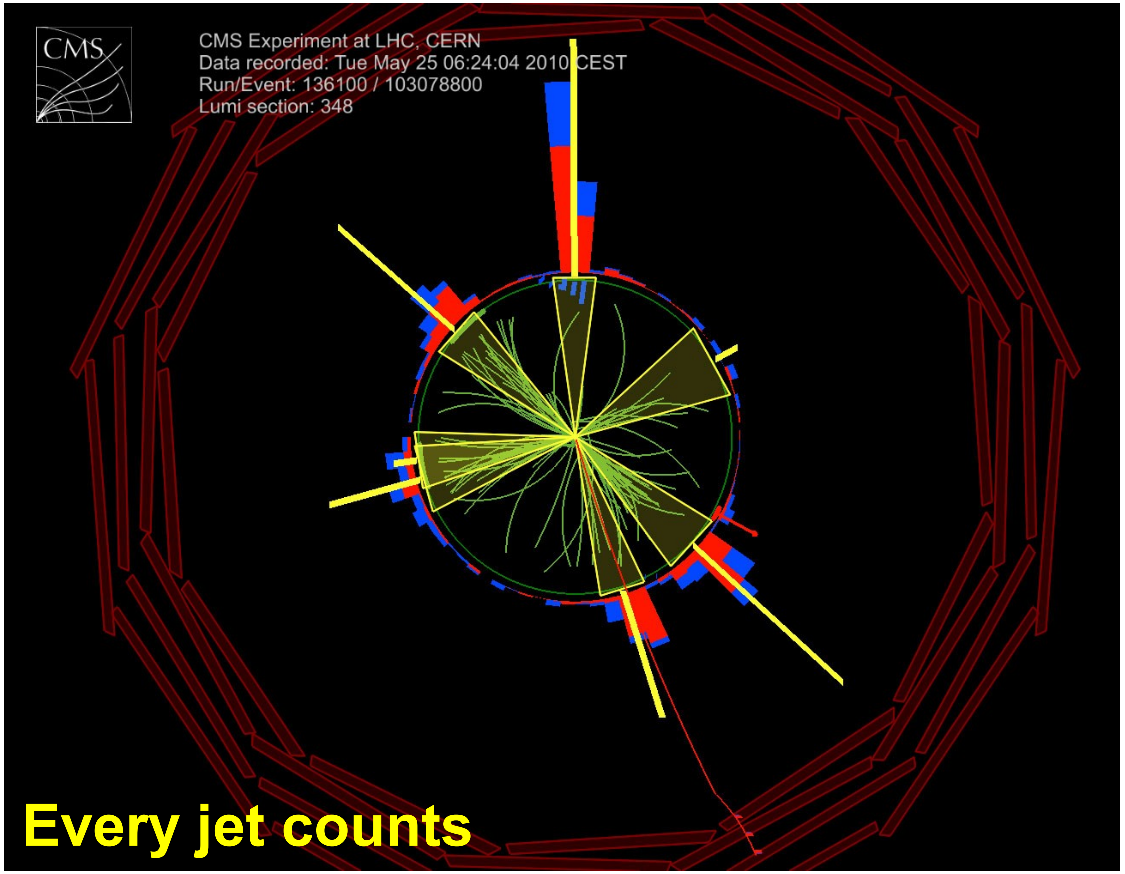
CMS, DP2012-006
CMS, DP2012-012

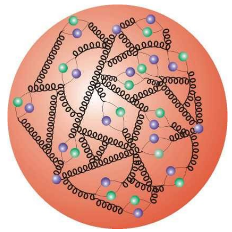
All Inclusive

High transverse Momenta



Proton





Proton

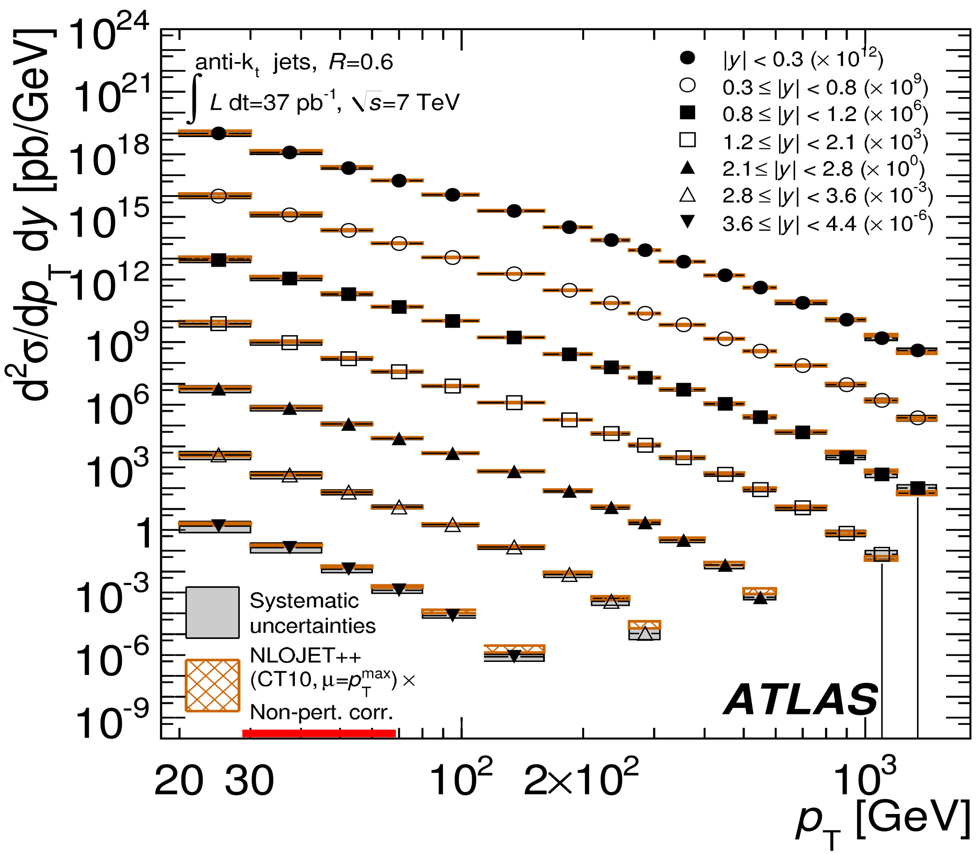
Inclusive Jets

Agreement with predictions of QCD at NLO over many orders of magnitude up to 2 TeV in jet p_T

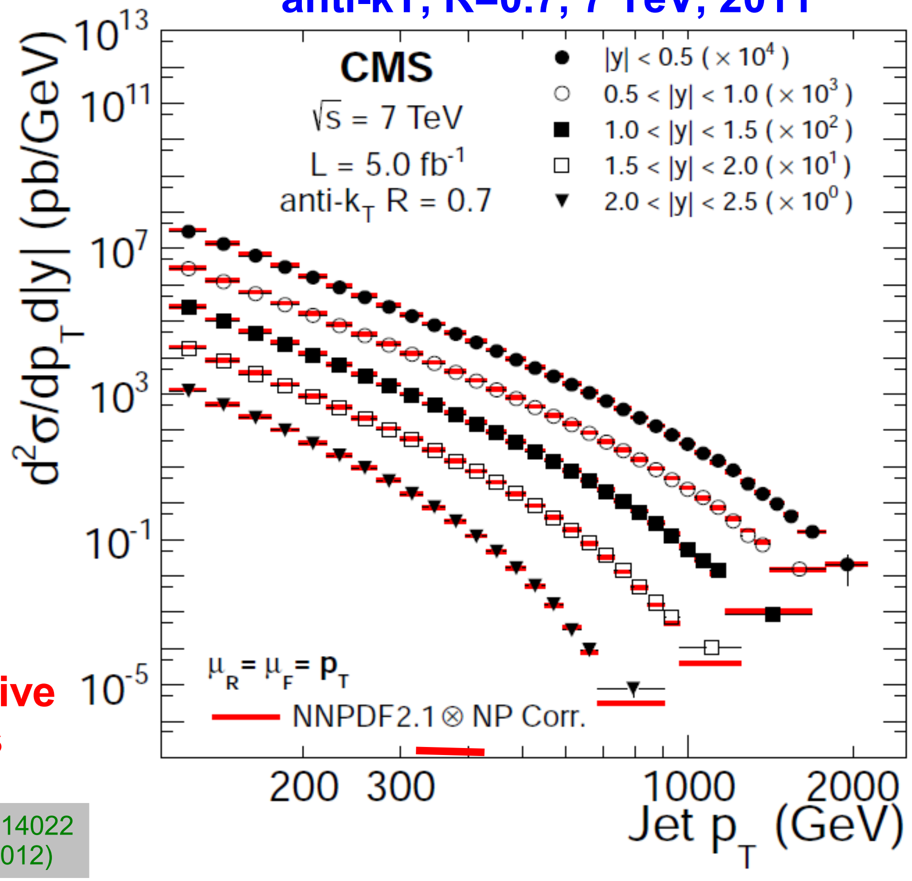
Data at 8 TeV in progress ...

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

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



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

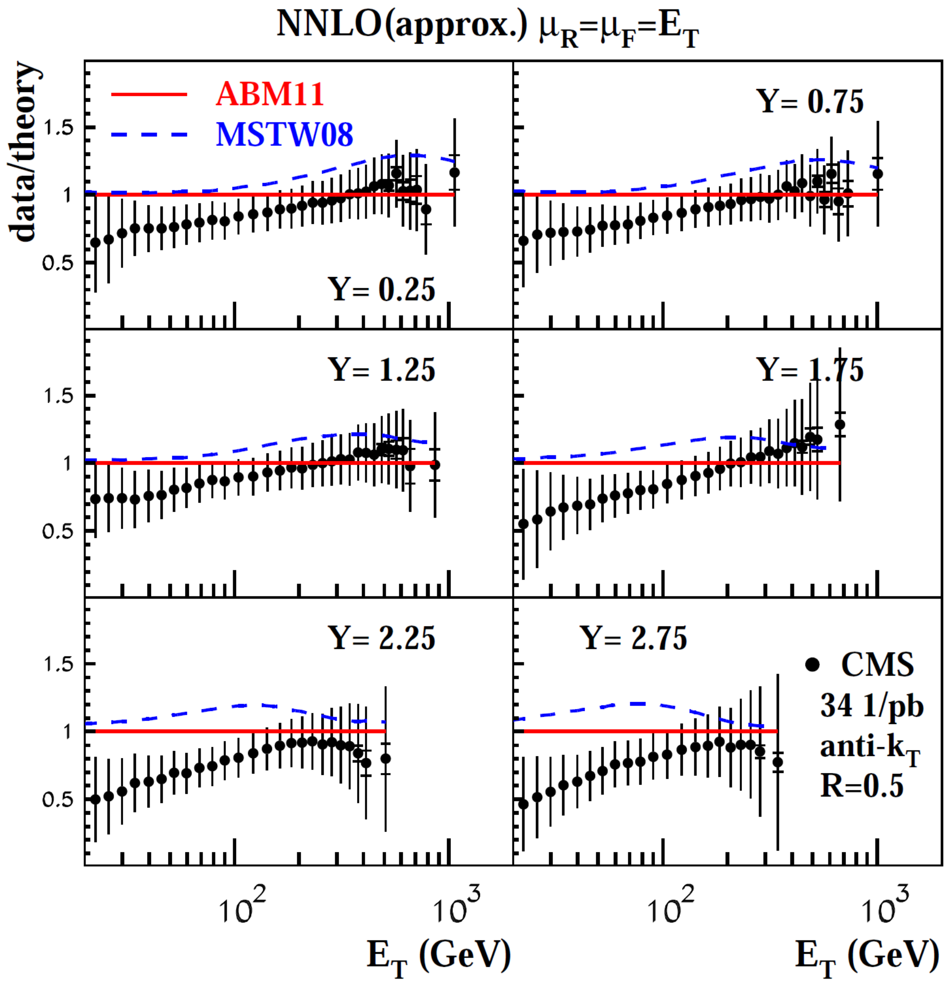


pQCD ⊗ non-perturbative corrections

ATLAS, PRD 86 (2012) 014022
CMS, arXiv:1212.6660 (2012)

LHC Data and PDFs

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

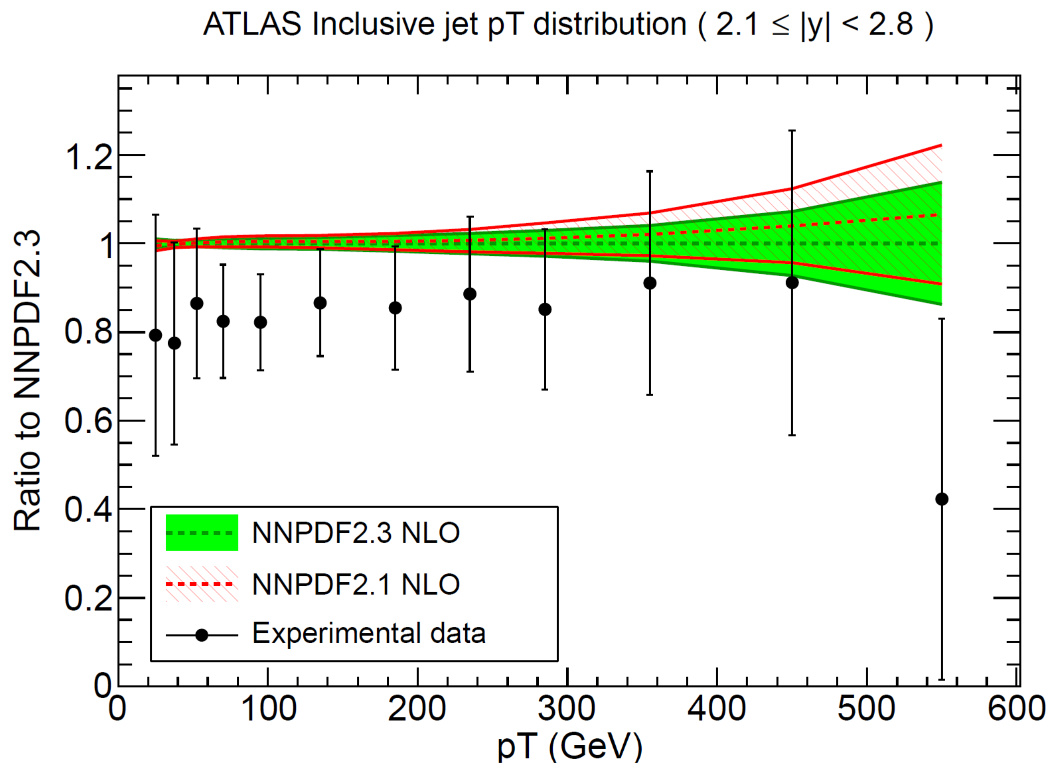


First global fits including LHC data !

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**

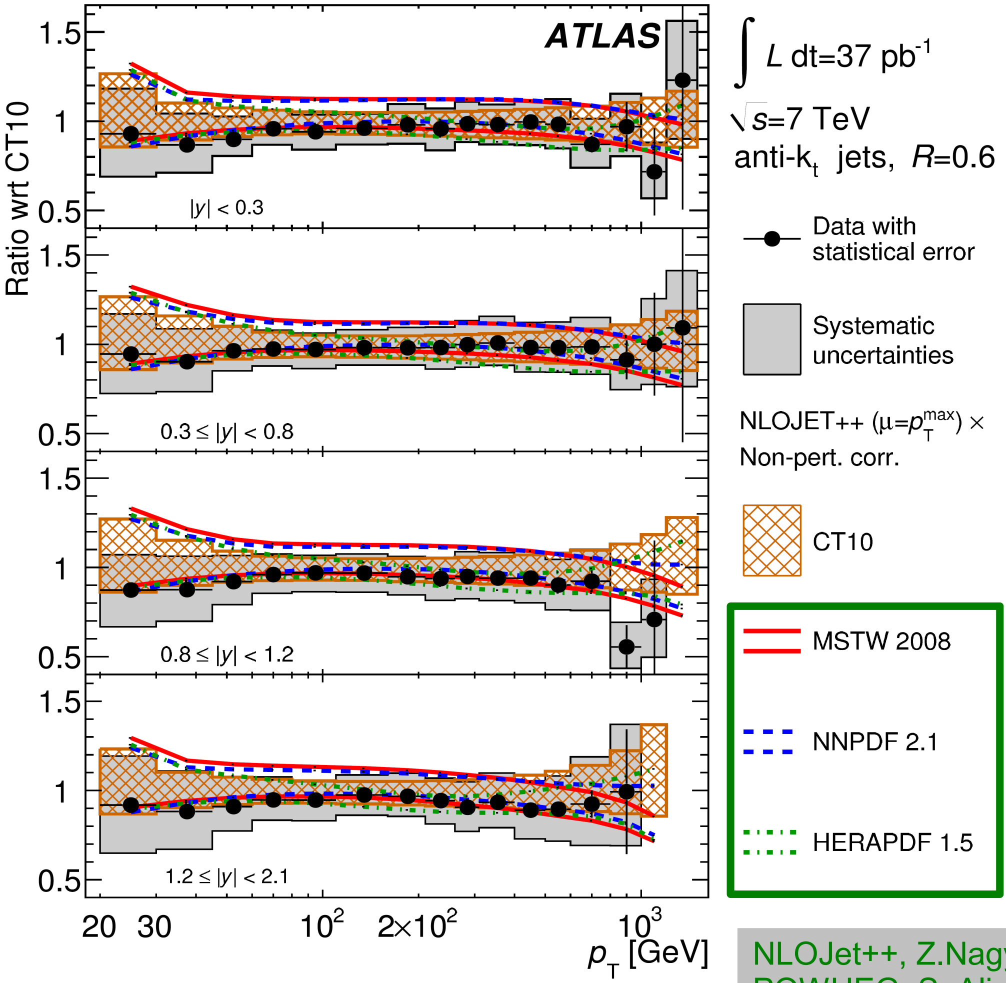


ABM11, S.Alekhin,J.Blümlein, S.Moch, arXiv:1208.1444

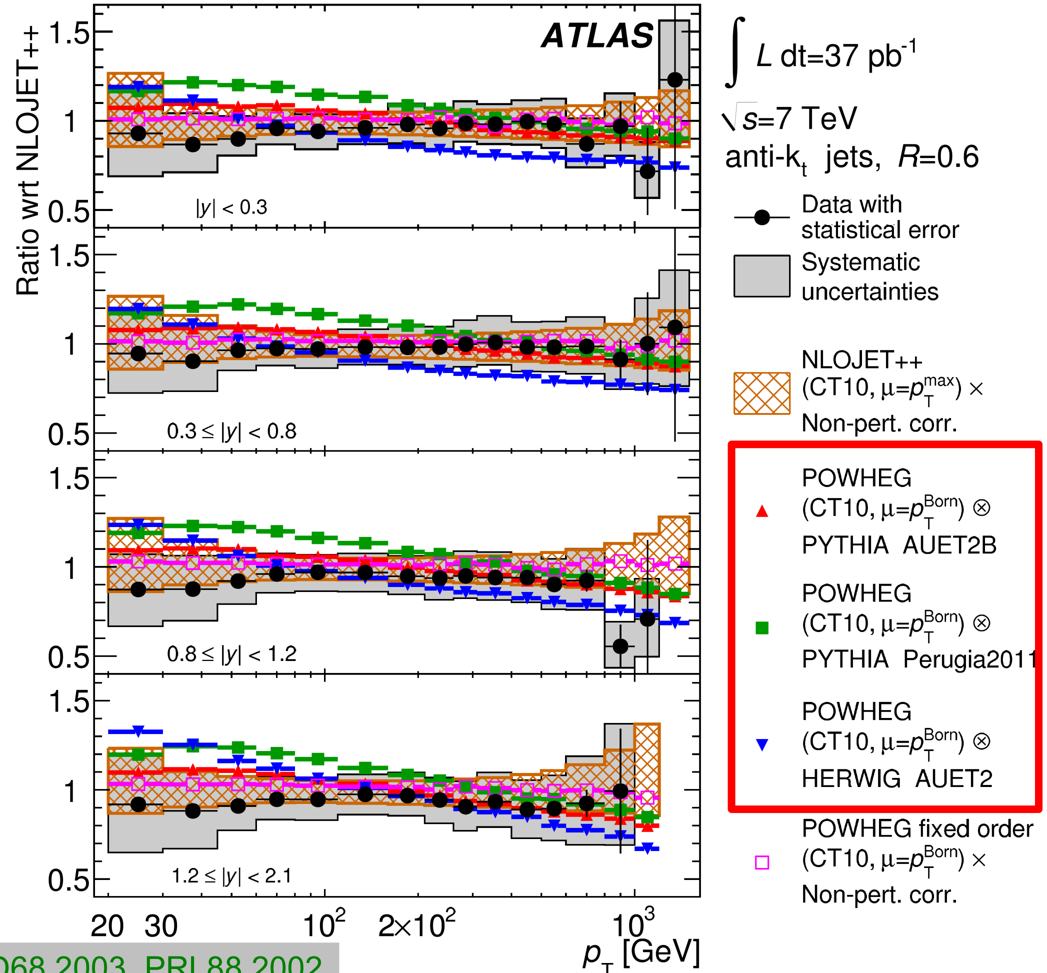
NNPDF23, R.D.Ball et al., arXiv:1207.1303

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)

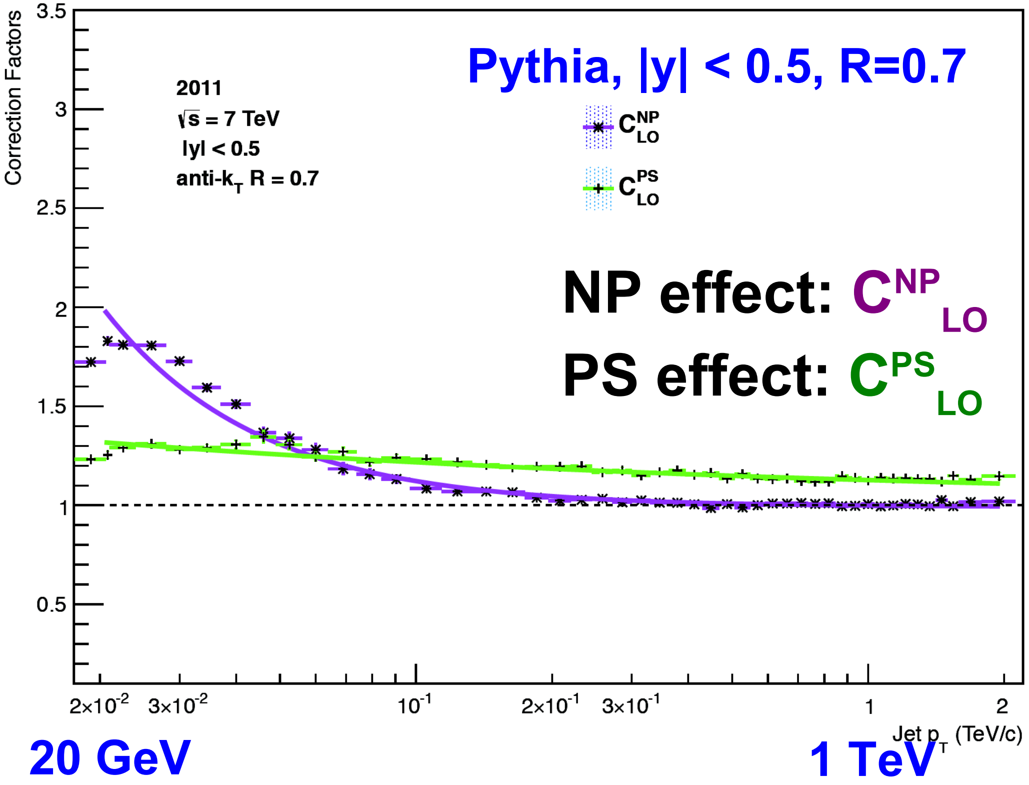
Non-perturbative Corrections

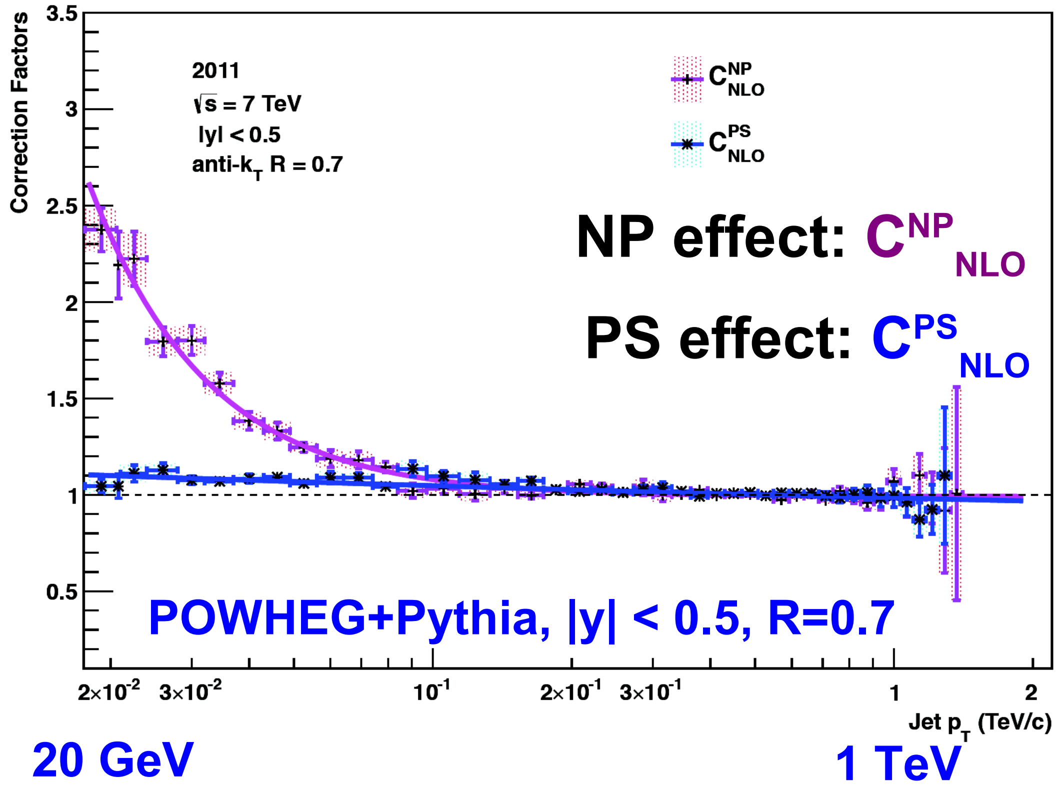
Recipe used at Tevatron & LHC:

- 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 (s. also arXiv:1212.6164)

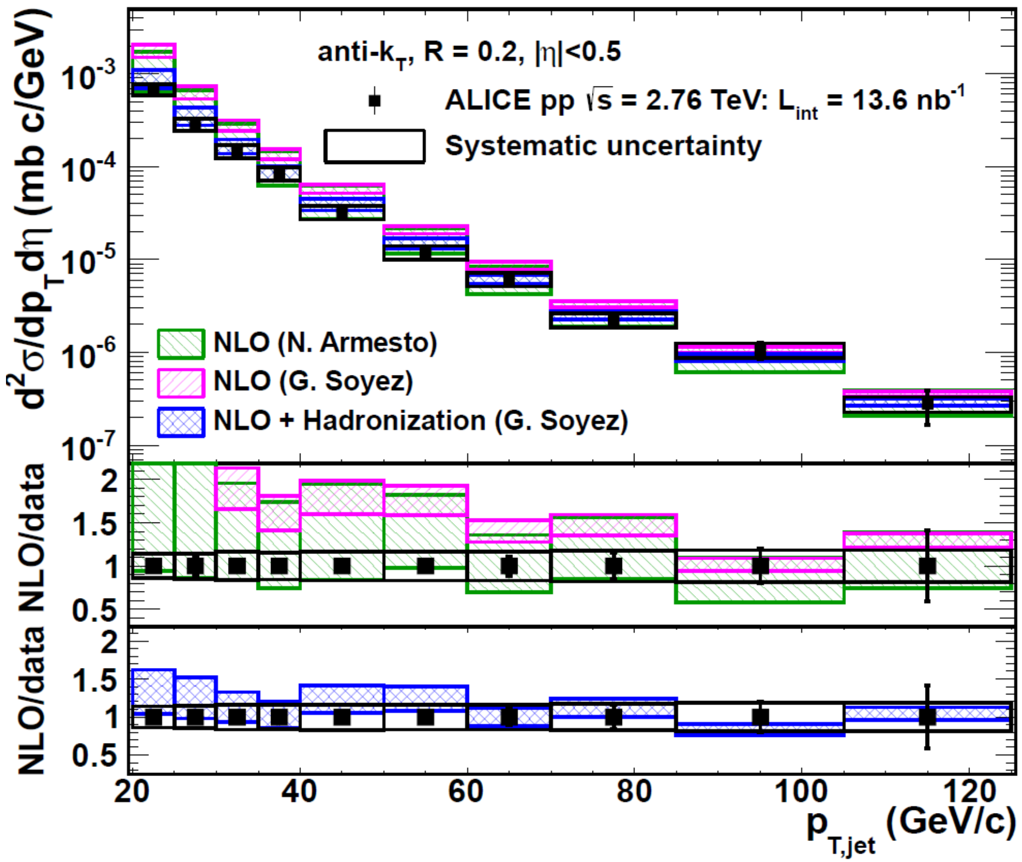
Inclusive Jet Ratios: 0.2 / 0.4

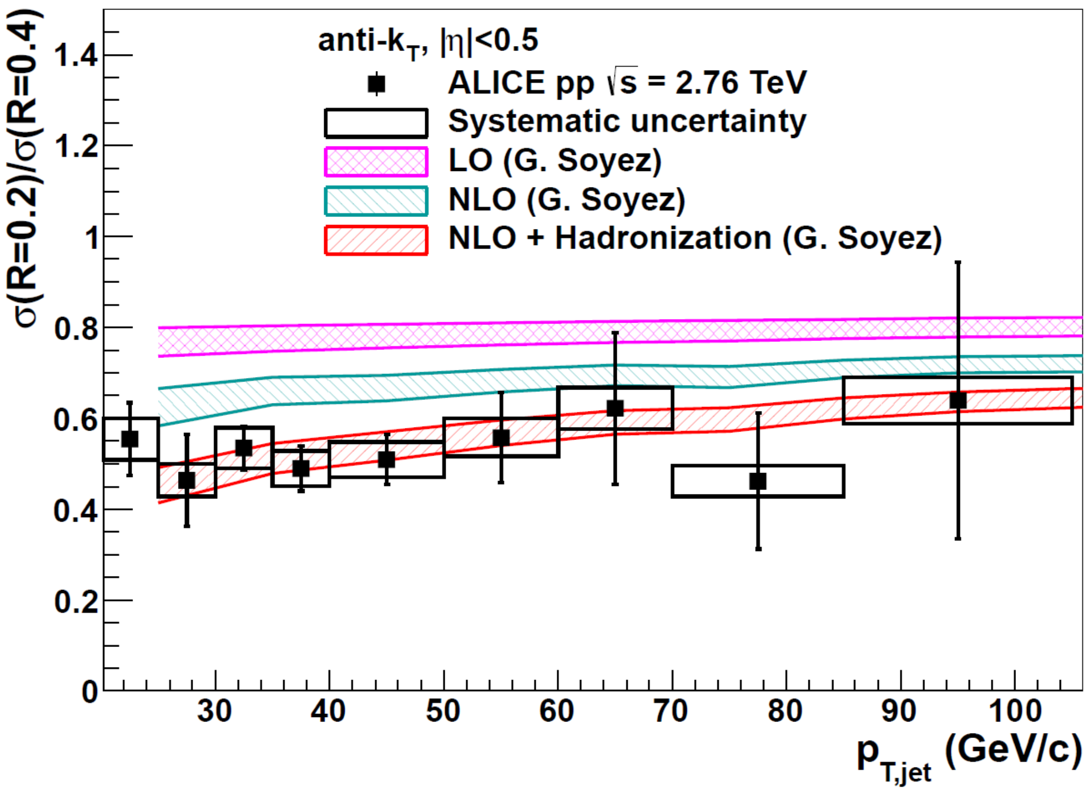
Here:
Ratio with different jet sizes
R = 0.2 and 0.4

ALICE measurement:

G. Soyez, PLB698 (2011).

following proposal from G . Soyez
Emphasizes effects of showering and hadronization!

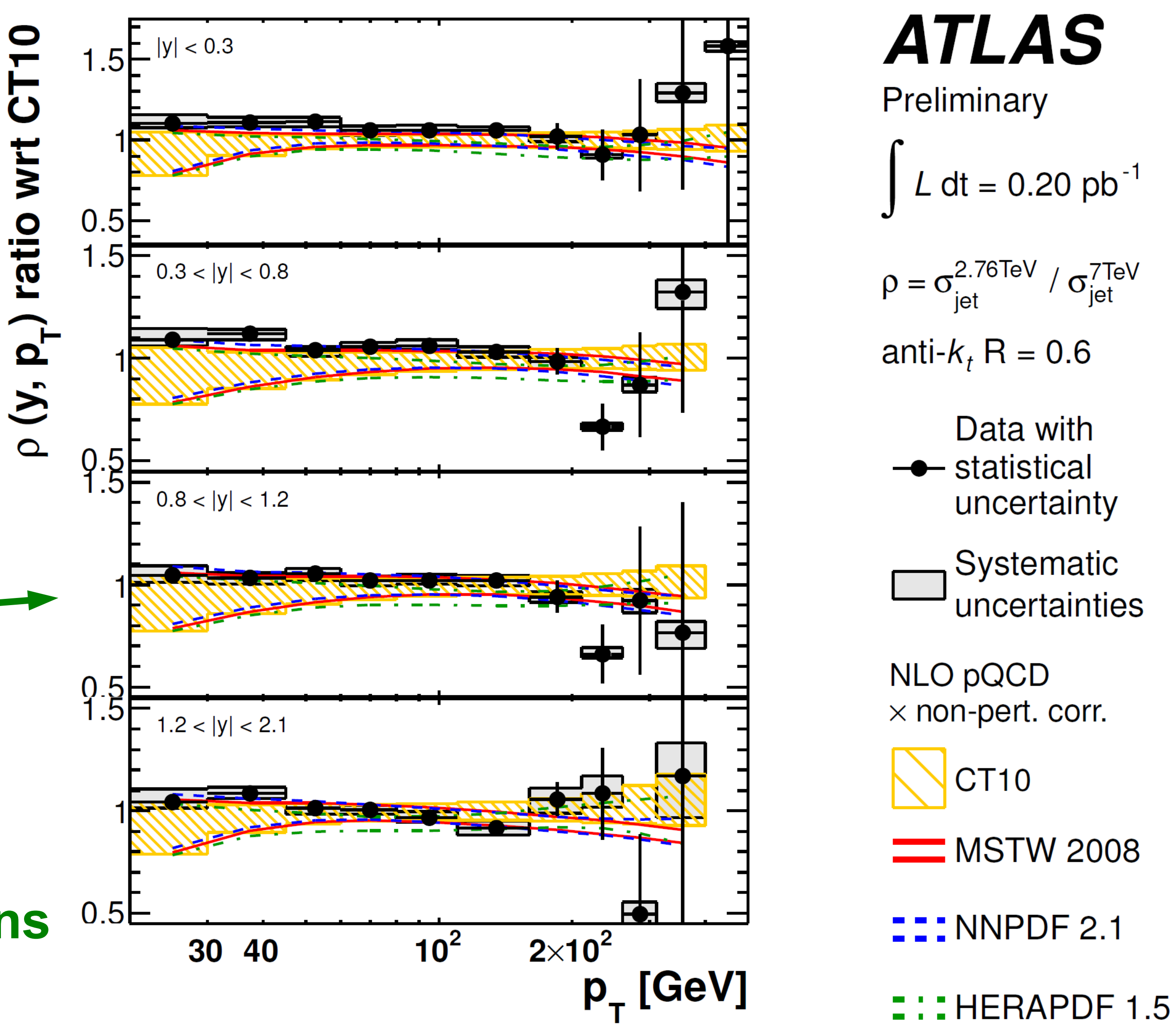




ALICE, arXiv:1301.3475

Inclusive Jet Ratios: 2.76 / 7.0

Here:
Ratio at different energies
E_{cms} = 2.76 and 7.0 TeV



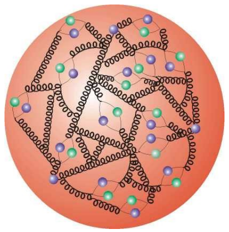
Result from ATLAS:
- **cross sections at 2.76 TeV**
- **ratios to 7 TeV**
- **ratio to 7 TeV divided by theory prediction (NLO, CT10, X NP)**
  Shown
- **study on PDF impact**

At least partial cancellation of uncertainties
→ more precise comparisons

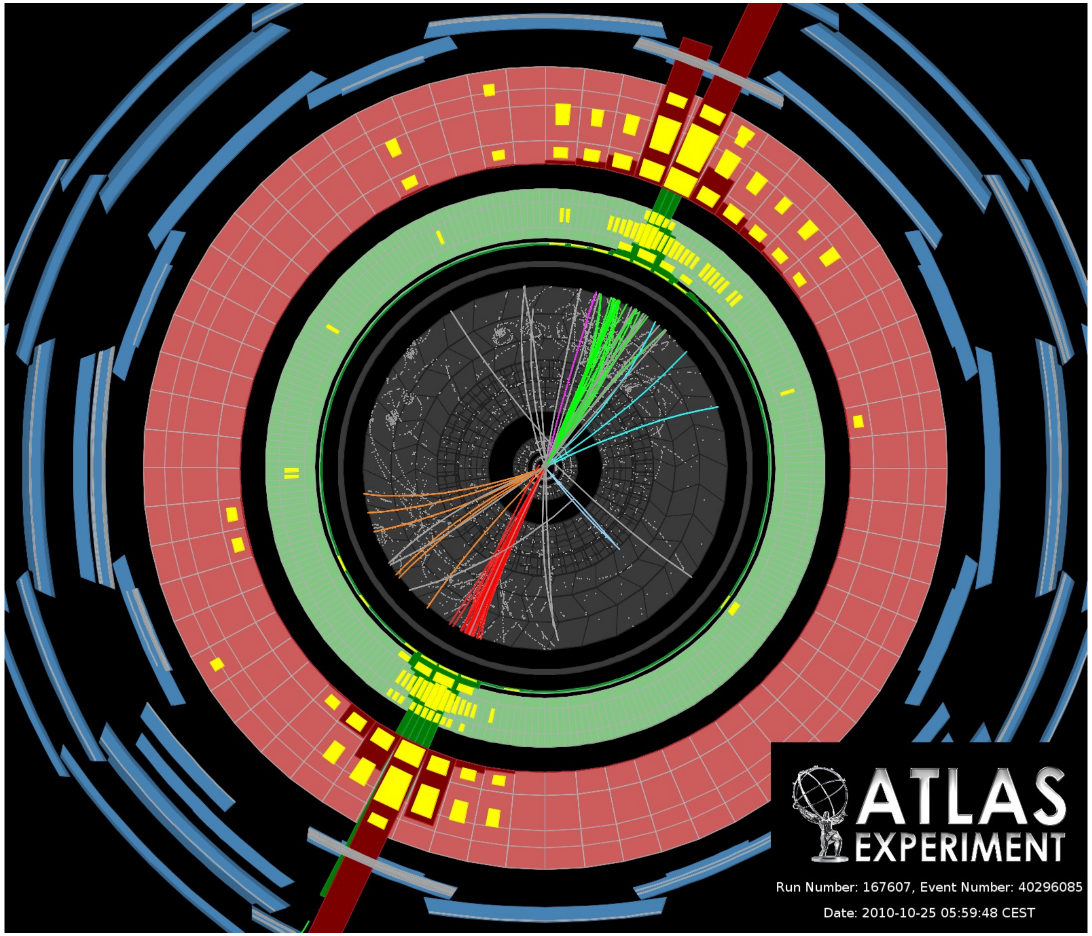
ATLAS, CONF-2012-128

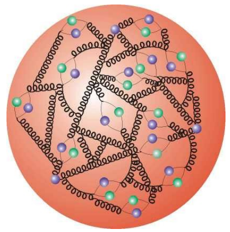
Dijets

High Masses



Proton





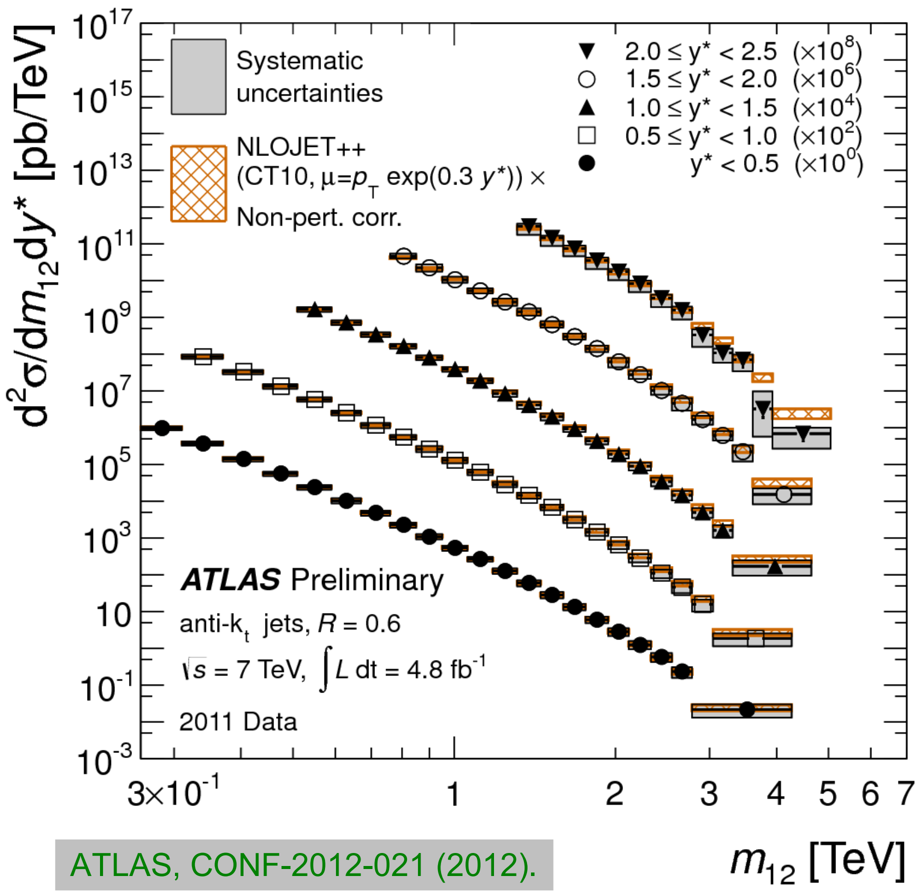
Proton

Dijet Mass

Again agreement with predictions of QCD over many orders of magnitude!

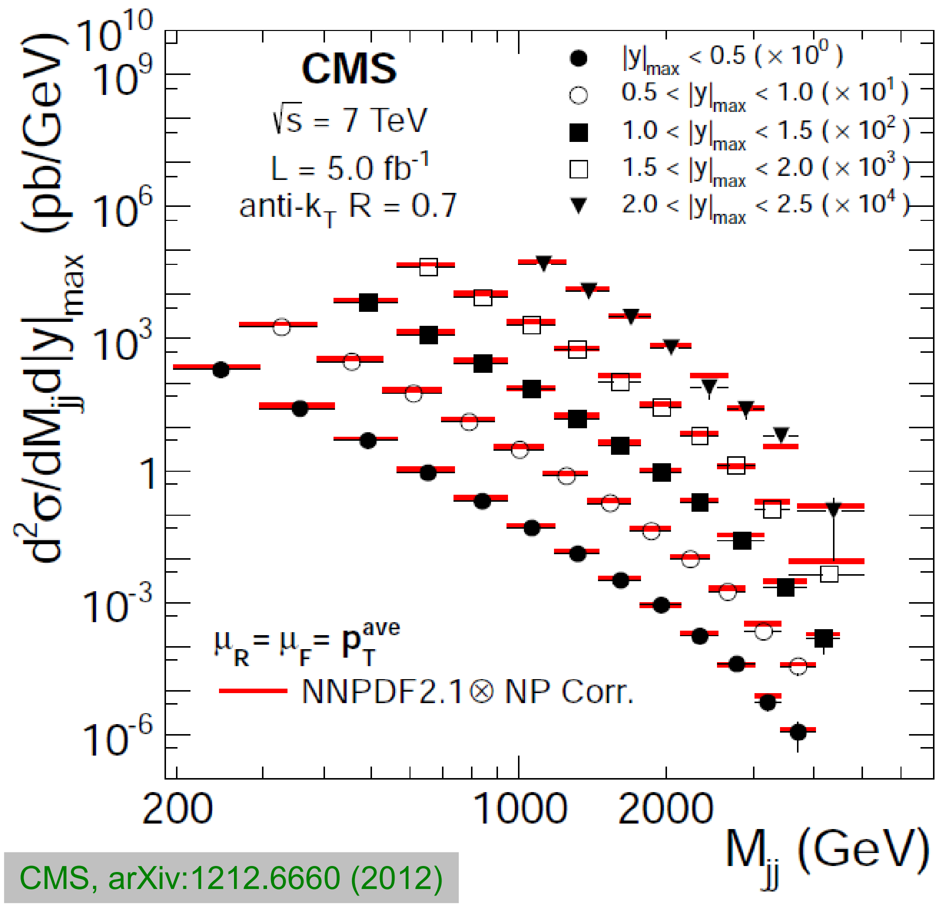
$$\frac{d^2\sigma}{dM_{JJ}d[|y|_{max}, y^*]} \propto \alpha_s^2$$

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



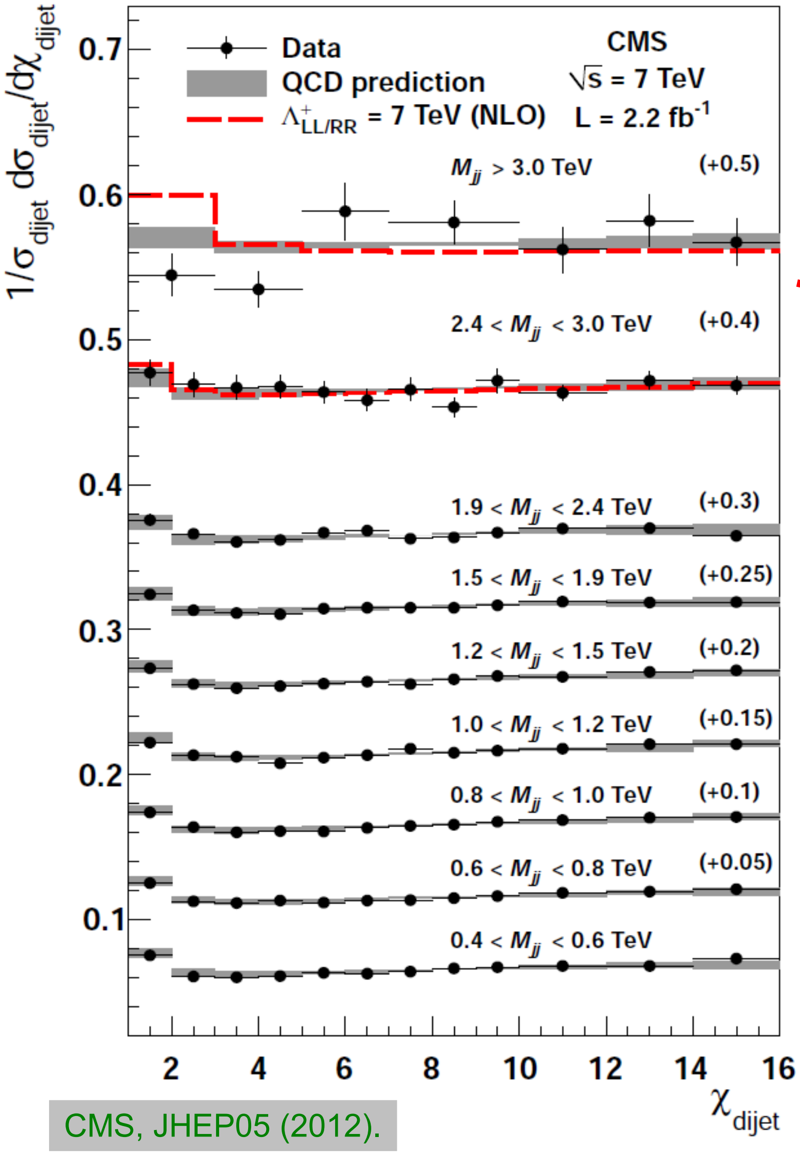
ATLAS, CONF-2012-021 (2012).

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



CMS, arXiv:1212.6660 (2012).

Dijet Angular



CMS, JHEP05 (2012).

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

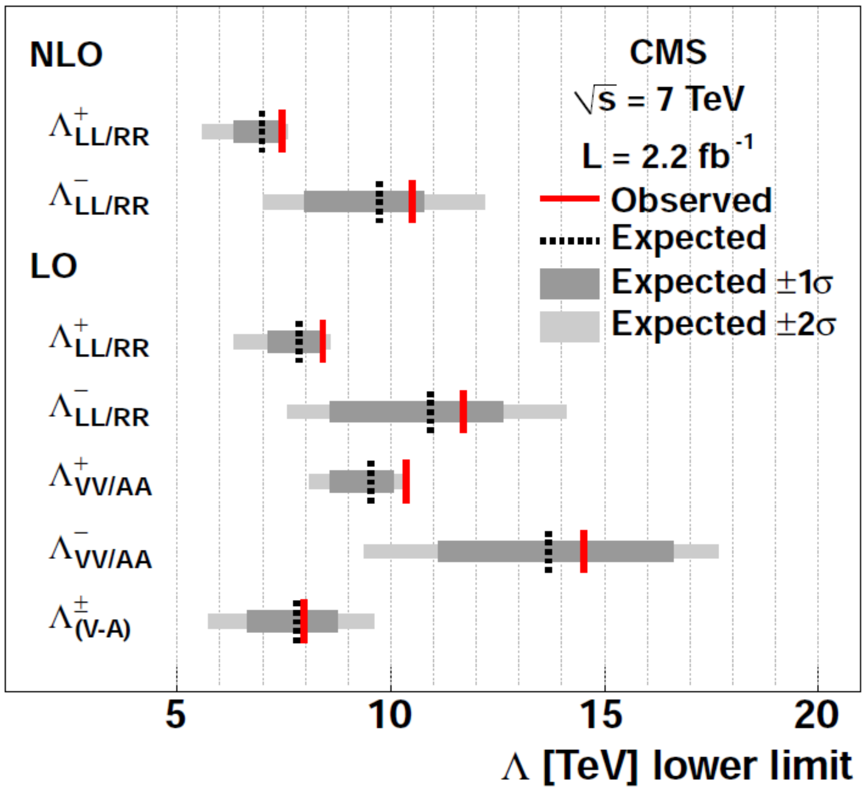
~ flat for QCD

Agreement with predictions of QCD →
Set lower limits on contact interaction scale Λ

NEW:
NLO means CI corrections to QCD at NLO

Decreases limits!

Gao et al., PRL106, 2011



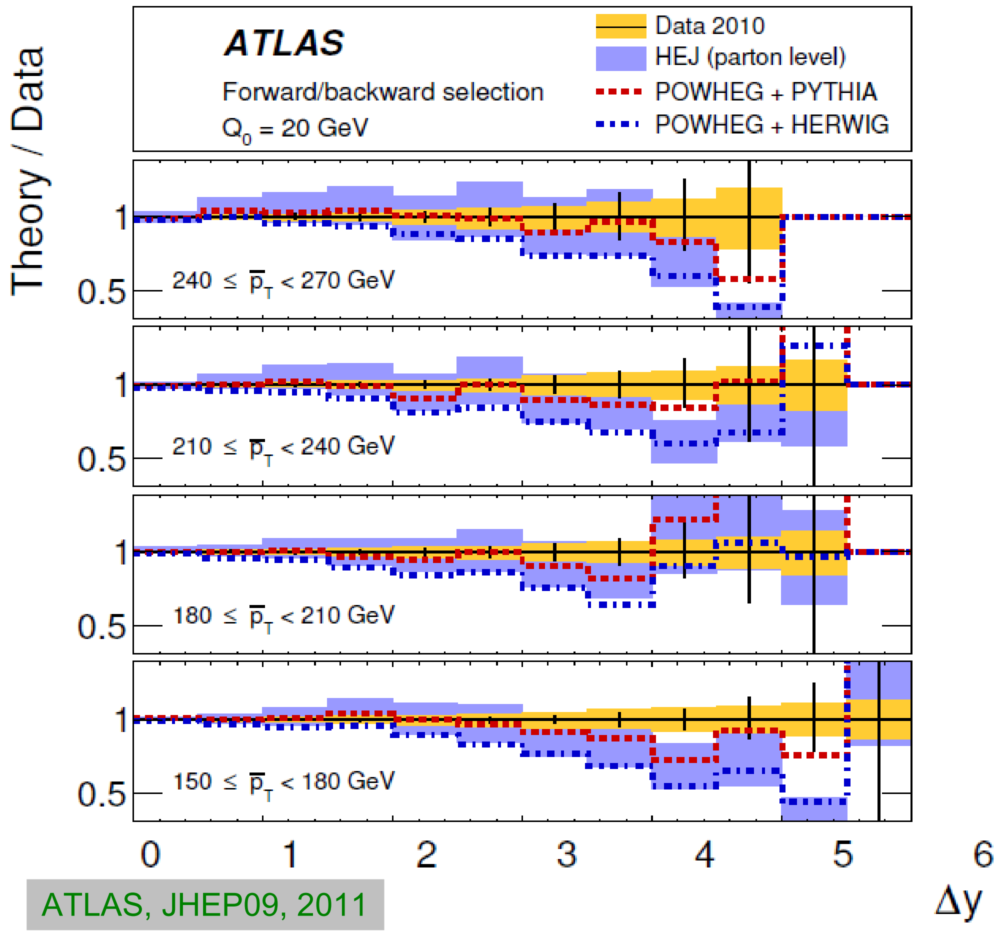
Dijets separated in Rapidity

Quantities sensitive to potential deviations from DGLAP evolution at small x

Some MC event generators run into problems … but also BFKL inspired ones!

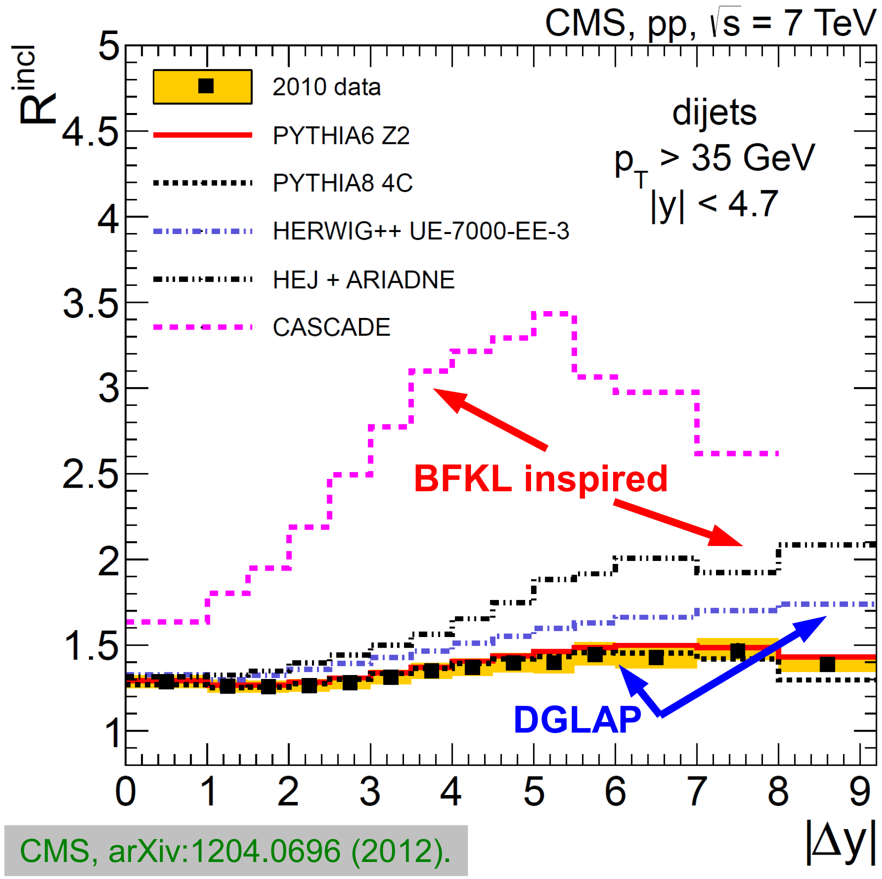
Large y coverage needed, also useful for WBF tagging jets.

Most forward-backward dijet selection



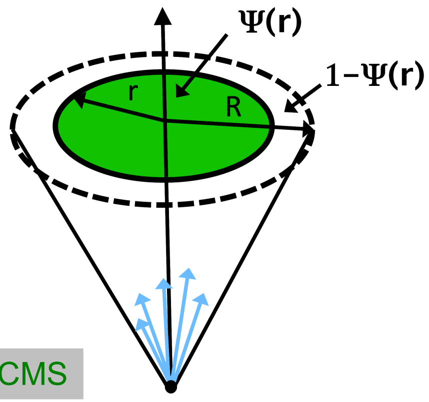
ATLAS, JHEP09, 2011

All possible dijet pair distances over leading dijet pair distance



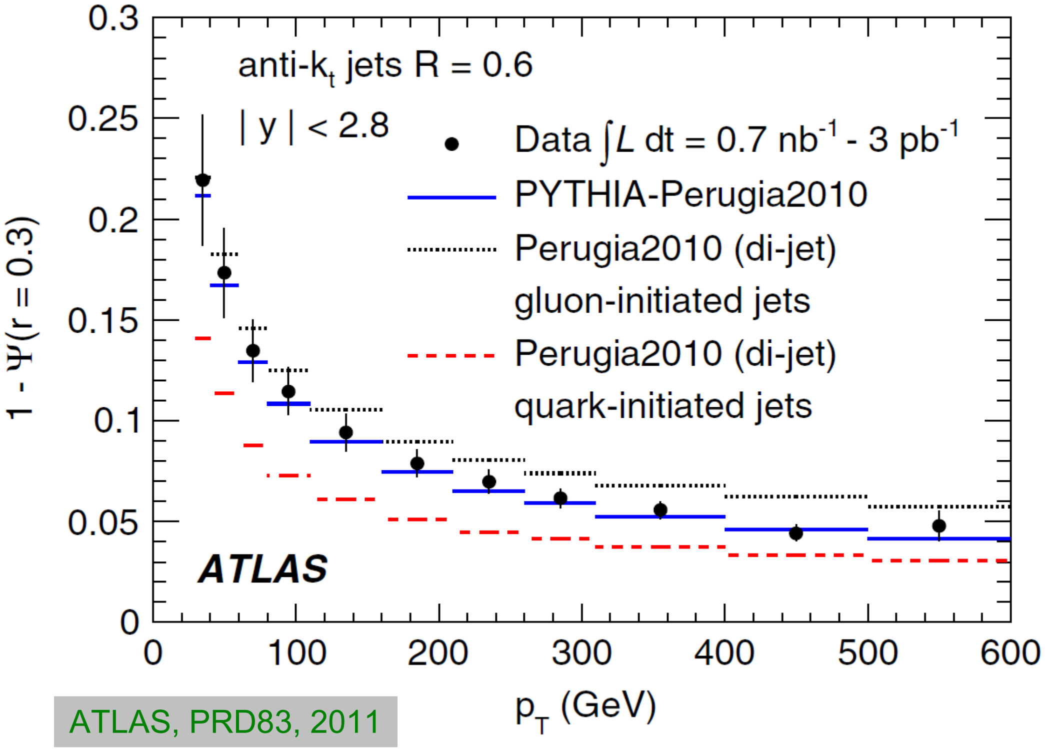
CMS, arXiv:1204.0696 (2012).

Jet Substructure

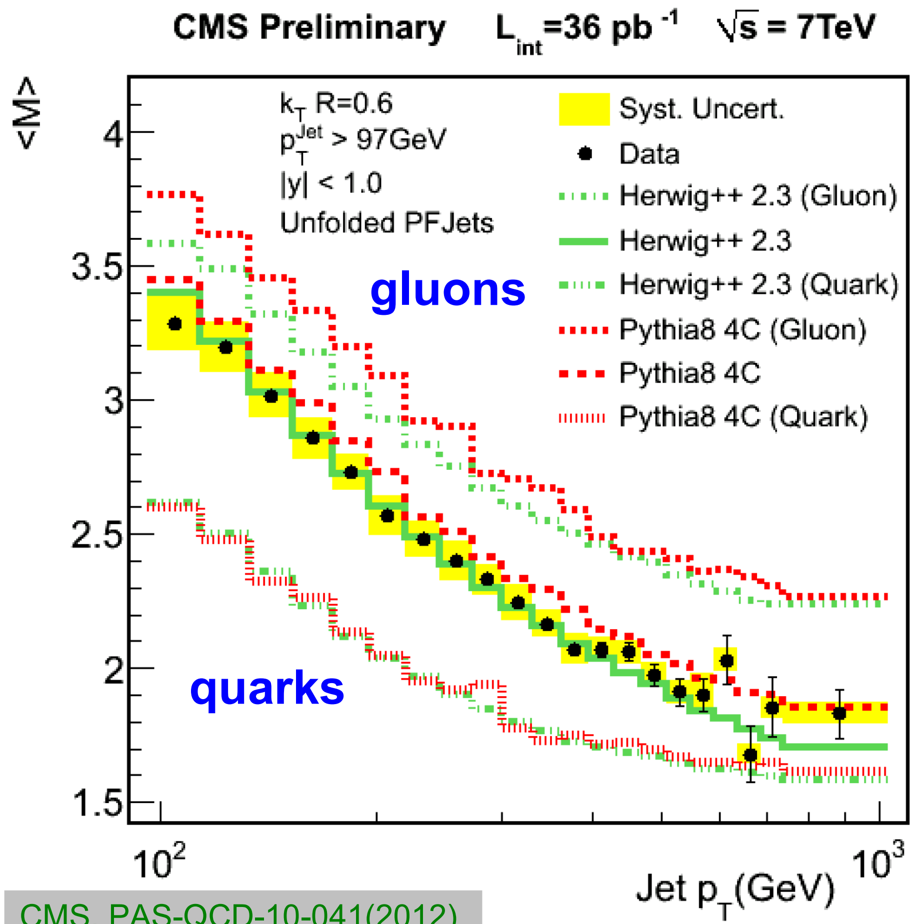


CMS

Jet shape (left) and subjet multiplicity (right) sensitive to differences in quark and gluon initiated jets
Can help also in differentiating boosted jets of heavy objects like Z' or t' … → whole new topic of boosted jets!



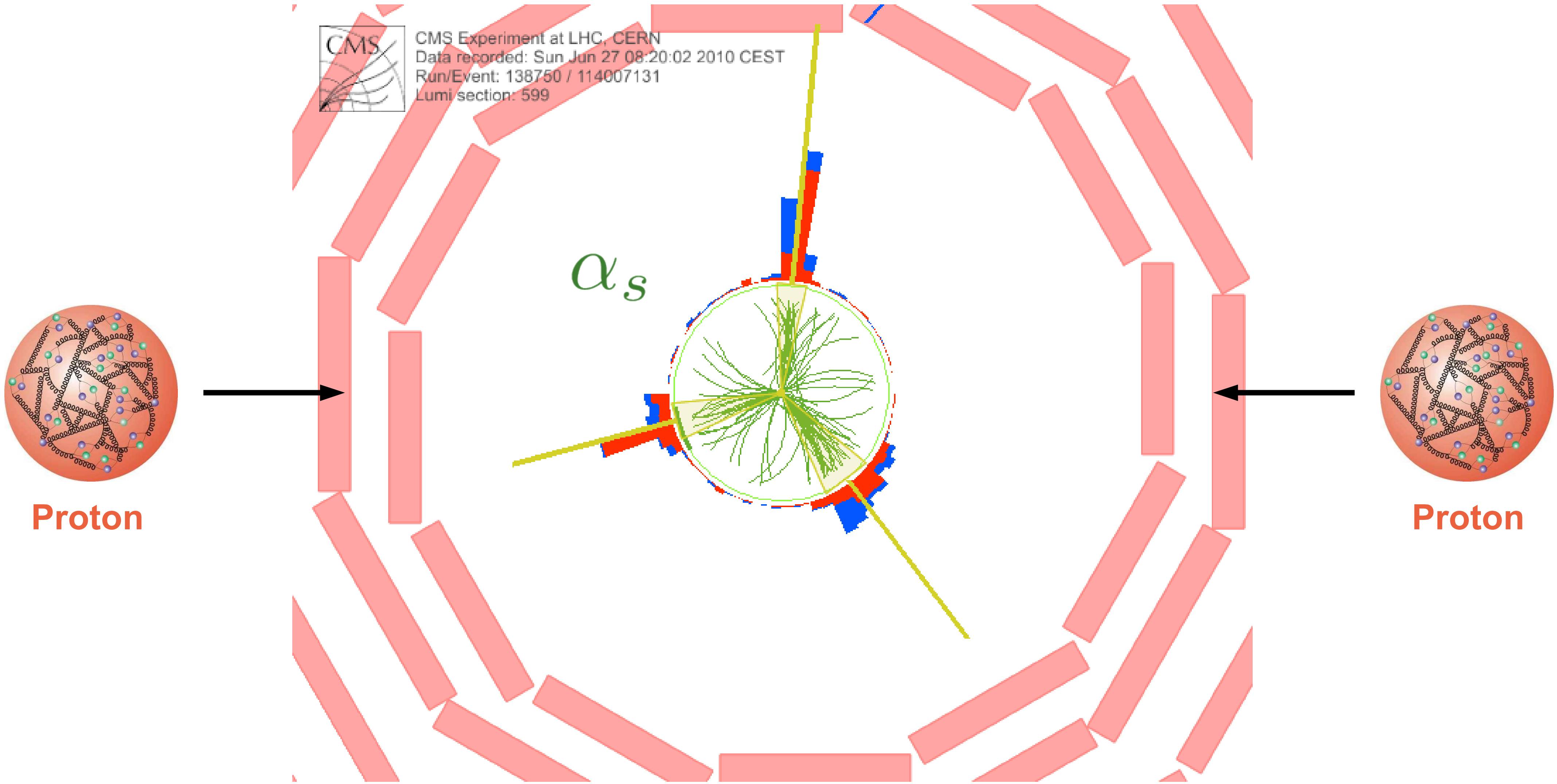
ATLAS, PRD83, 2011



CMS, PAS-QCD-10-041(2012).

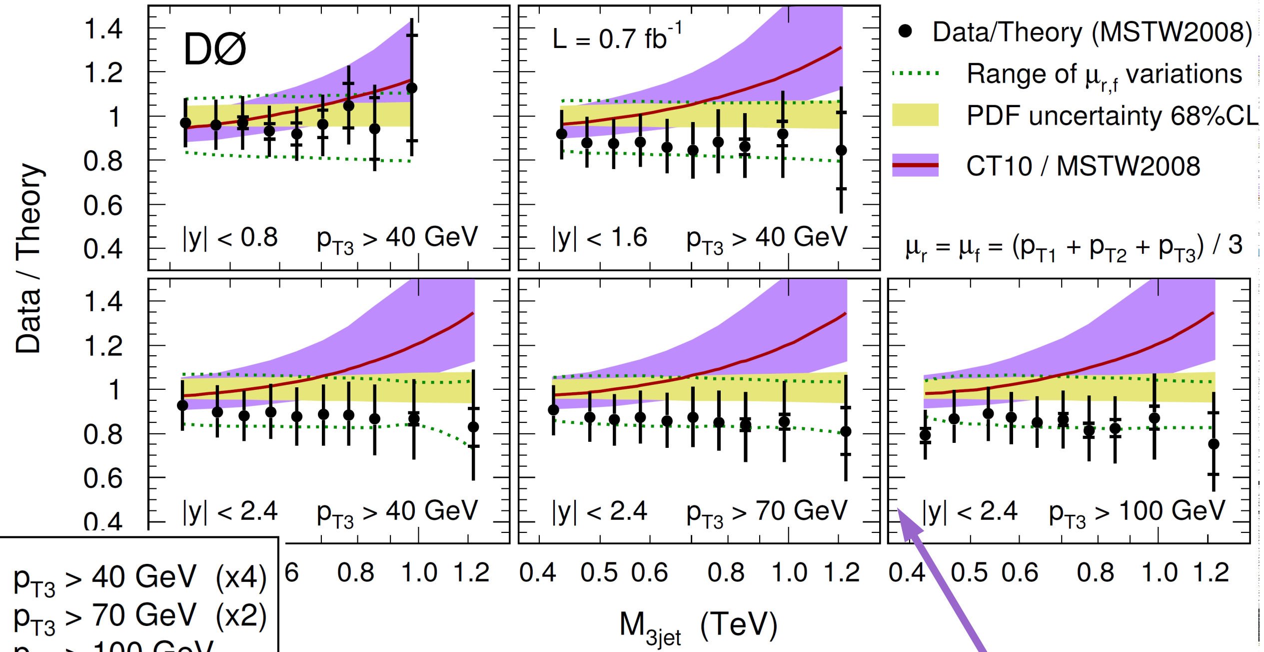
Multijets and α_s

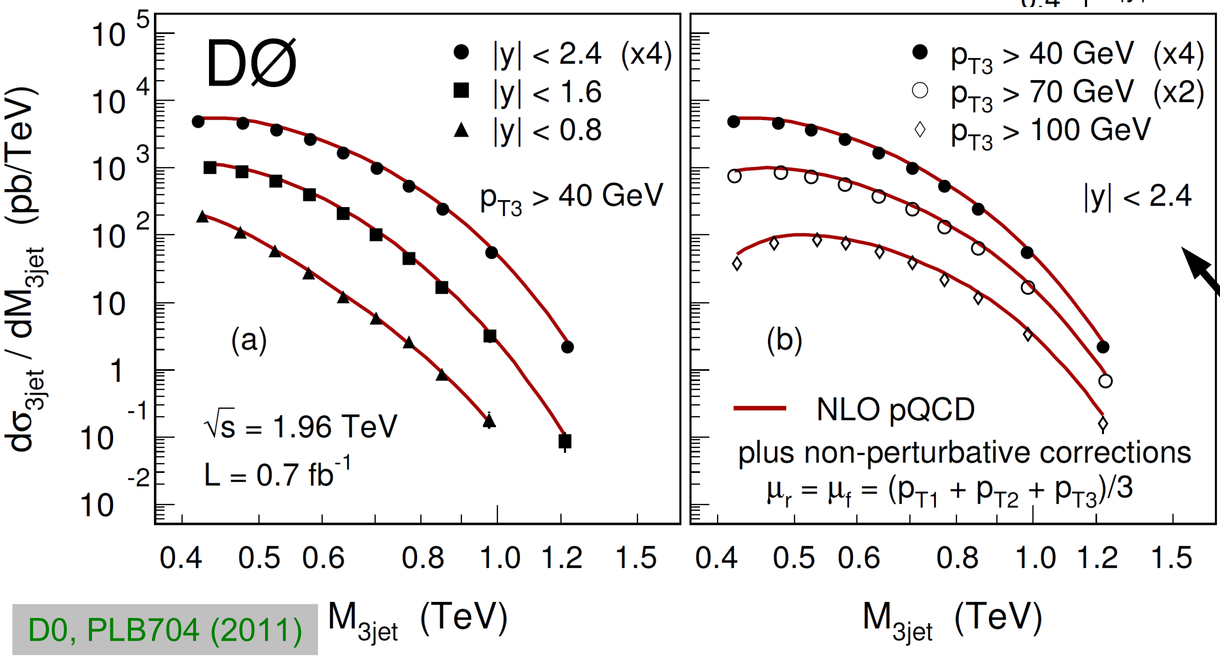
α_s at High Scales



3-Jet Mass, D0

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





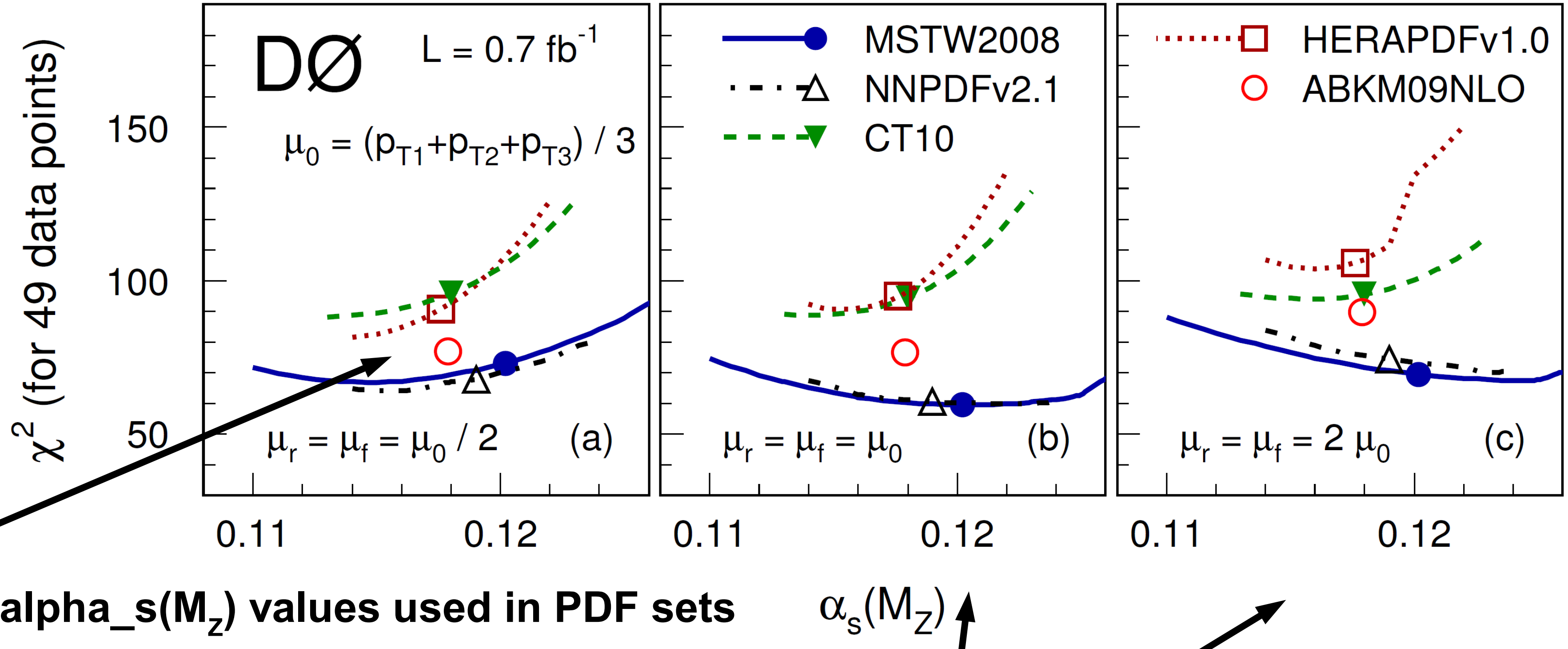
D0, PLB704 (2011)

Most PDFs work ok, CT10 is off

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

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

Chi^2 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

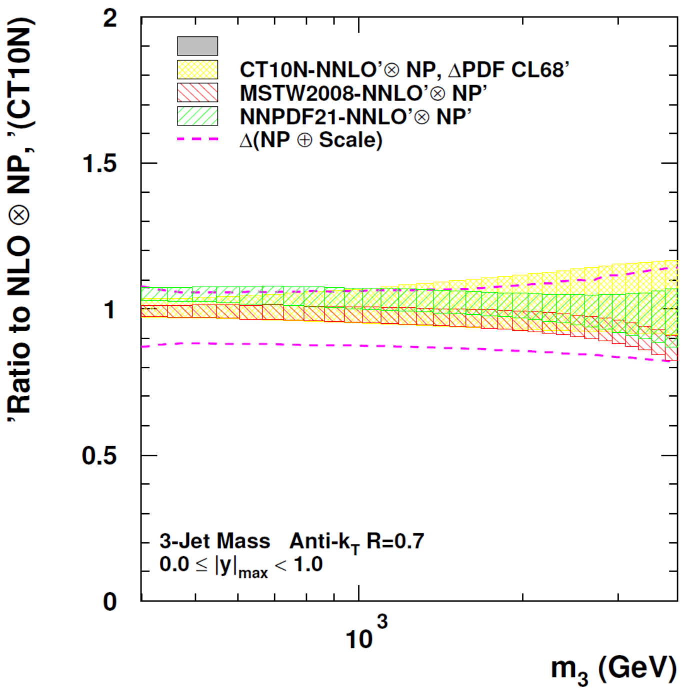
D0, PLB704 (2011)

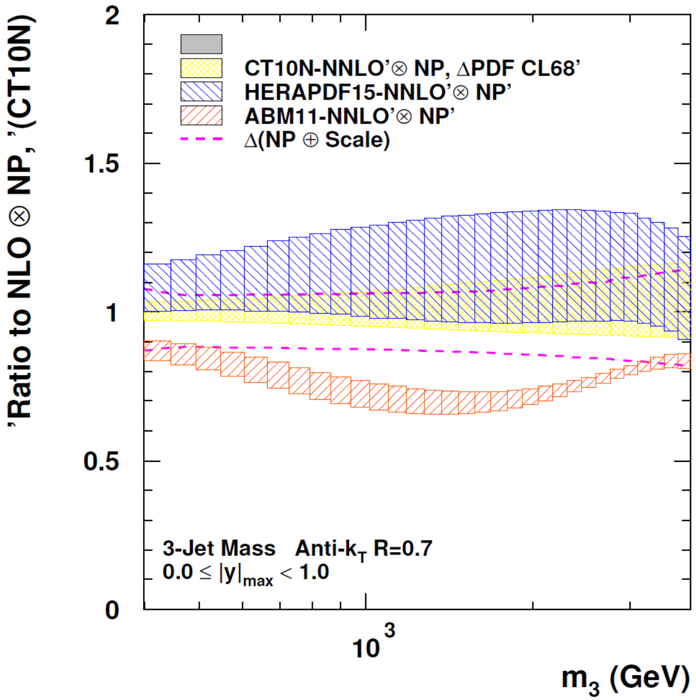
3-Jet Mass, CMS (in prep.)

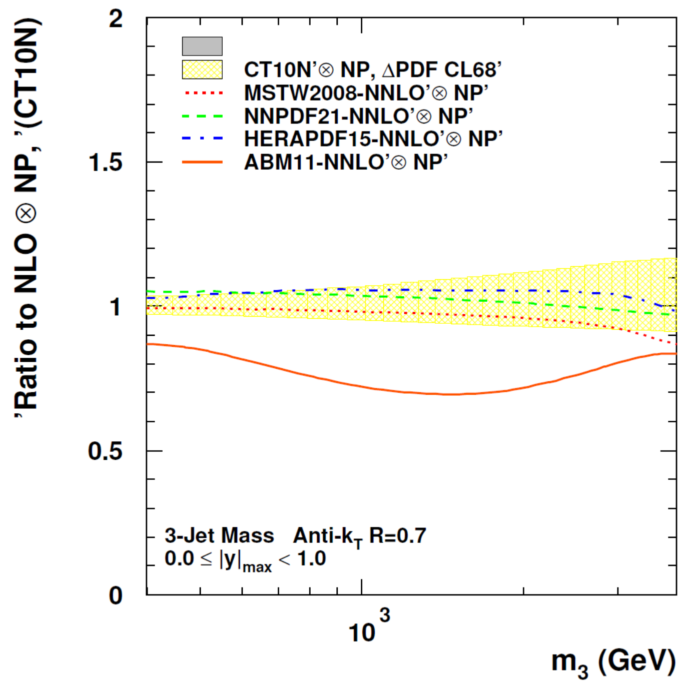
Anti-kT:	R=0.7	(looked also into R=0.5)
All jets:	pT > 100 GeV	(other also rel. cuts $p_{T3}/<p_{T1,2}>$ examined)
Binned in:	$\lvert y\rvert_{max}$ of leading three jets up to 2	
Scale choice:	$\mu_r = \mu_f = m_3/2$	(alternativ $<pT_{1,2,3}>$ abandoned)

Theory predictions rel. to CT10 PDF set

Data under examination, to come soon!





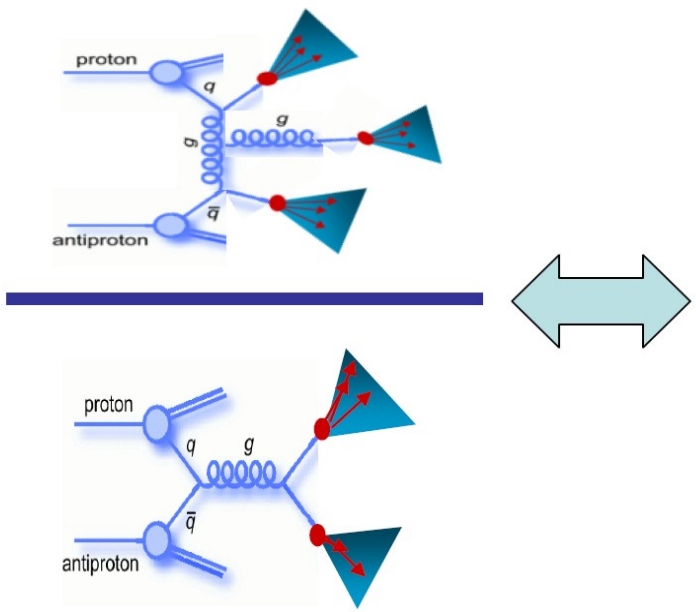


Inclusive Jet Ratios: 3 / 2

Now: Ratio for different multiplicity N_{jet} = 3 over 2

- **Avoids direct dependence on PDFs and the RGE of QCD**
- **Use cross-section ratios!**
- **→ reduces other theor. and exp. uncertainties along the way**
- **→ eliminates luminosity dependence (normalization)**
- **Choices of CMS:**
  - **Ratio of inclusive 3-jet to 2-jet production**
  - **Average dijet p_T as scale**
- **Other 3-jet observables possible, see e.g. propositions by D0** D0, PLB718 (2012) 56-63

M. Wobisch



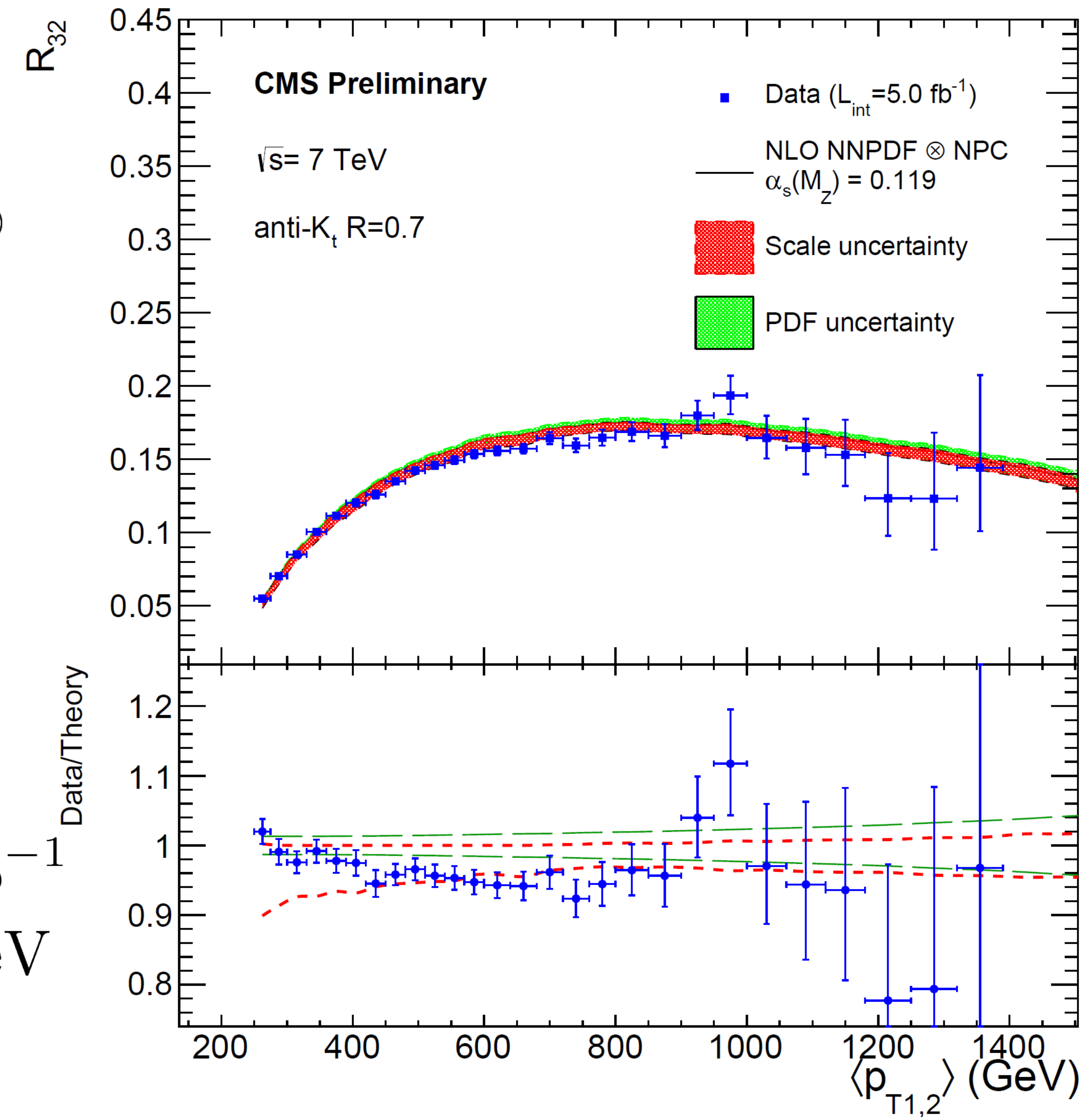
α_s

$$R_{32} = \frac{d\sigma_{3+}/dp_T}{d\sigma_{2+}/dp_T} \propto \alpha_s(Q)$$

$$Q = \langle p_{T1,2} \rangle = \frac{p_{T1} + p_{T2}}{2}$$

Data comparison to NNPDF21

- **Agreement within uncertainties**
  - **Scale uncertainty:** $^{+2}_{-5}\%$
  - **PDF uncertainty:** $1.5-2.3\%$
- **Fits only above 400 GeV to avoid threshold effects**
- **Similarly described by CT10 and even better by MSTW2008**
- **Discrepancies observed with ABM11**

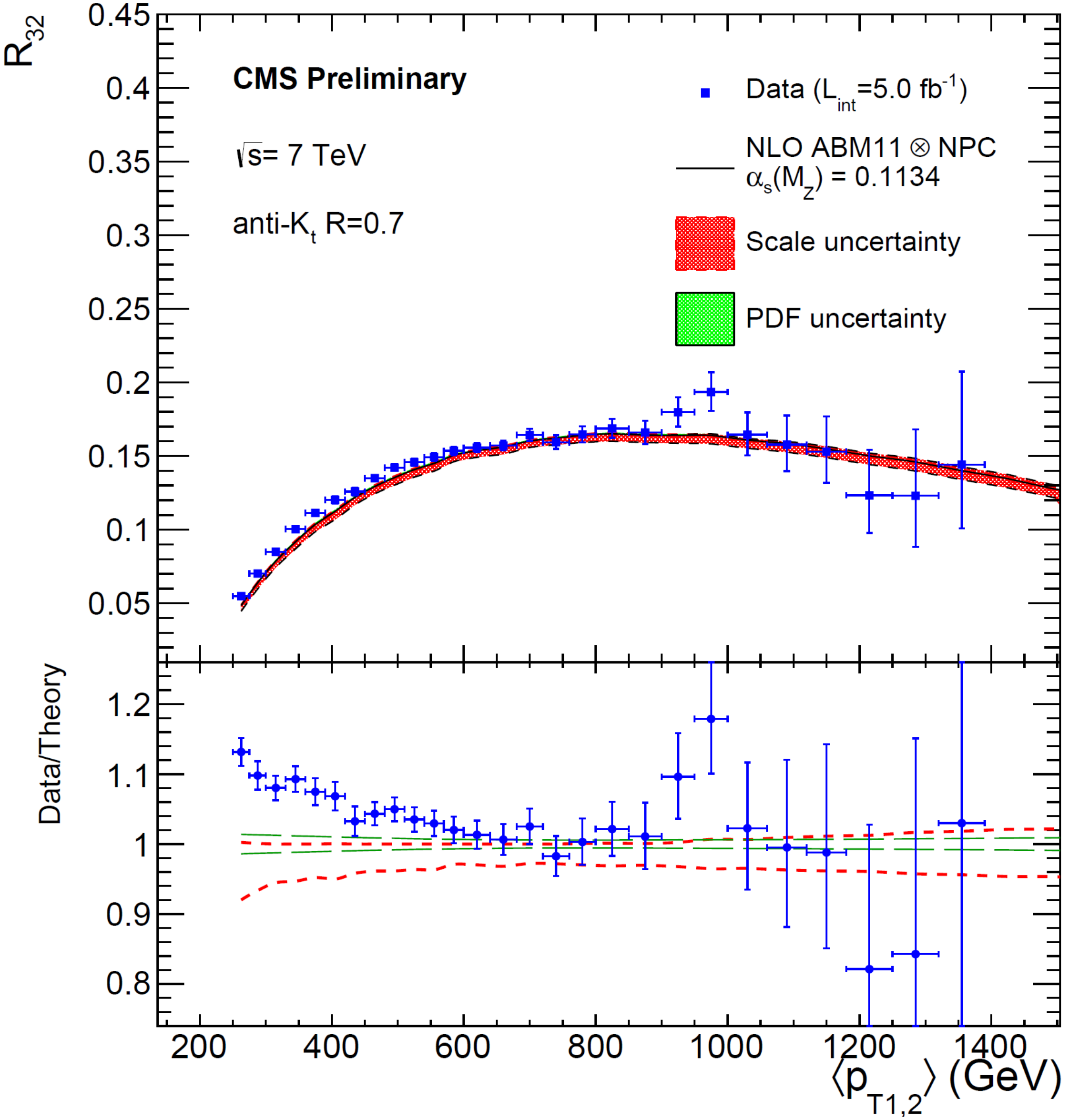


Measurement setup:

- **Integrated luminosity:** $\mathcal{L}_{\rm int} = 5.0\,{\rm fb}^{-1}$
- **Minimal jet pT:** $p_{\rm T} > 150\,{\rm GeV}$
- **Maximal jet rapidity:** $|y| < 2.5$

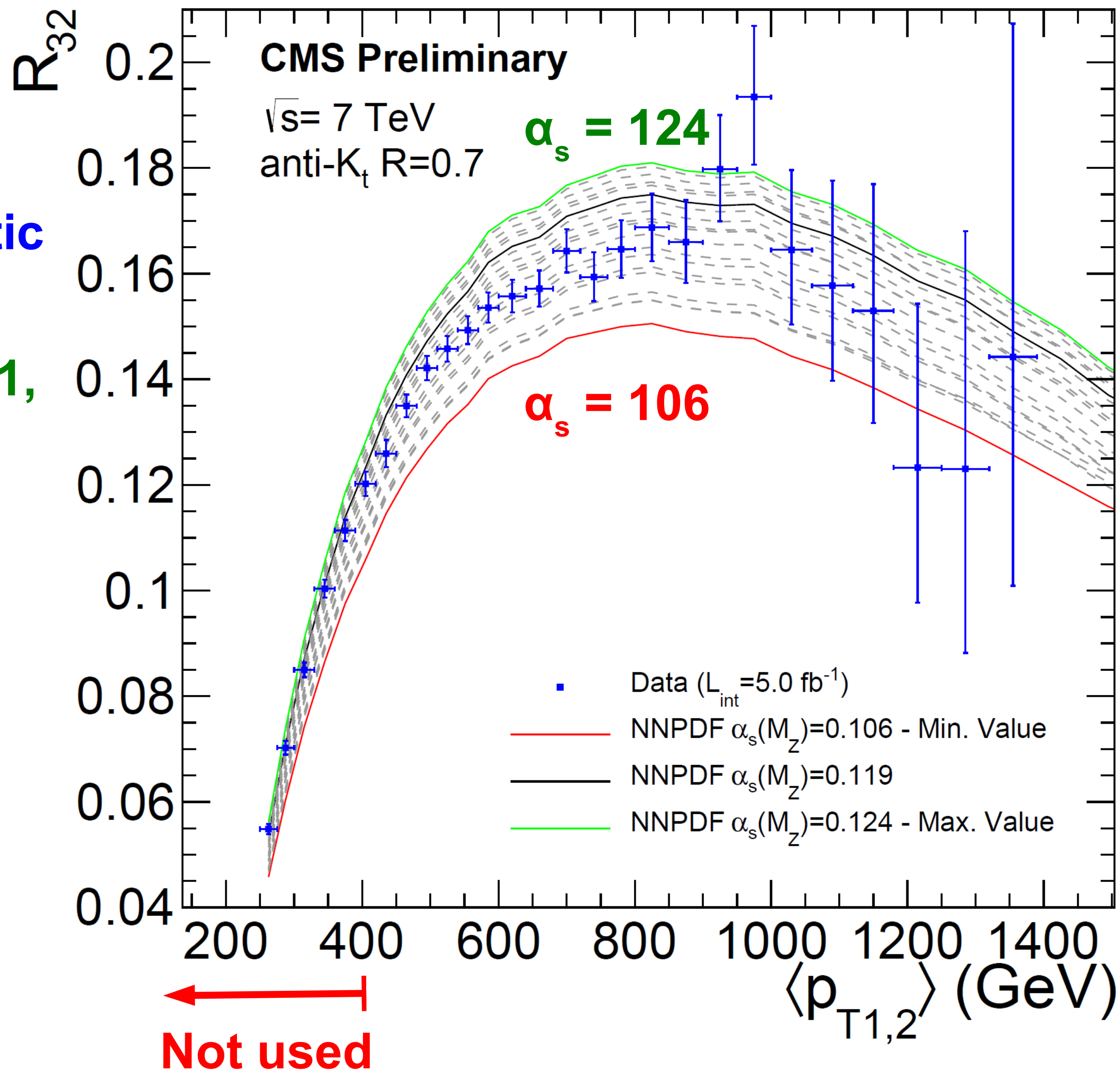
Data comparison to ABM11

- Discrepancies with ABM11 especially below 600 GeV
- Fits of the strong coupling tend versus the upper edge of the available series in alpha_s
  - No result with ABM11 to report
- Much smaller gluon down to 50% at high x at the same time as preference for smaller couplings
- To be further discussed/resolved ...



Sensitivity to alpha_s

- Fits only above 400 GeV to avoid threshold effects
- Error bars show full uncertainty including the correlated systematic ones
- Compatible results from NNPDF21, CT10 and MSTW2008 with χ^2 fit using correlated experimental uncertainties:



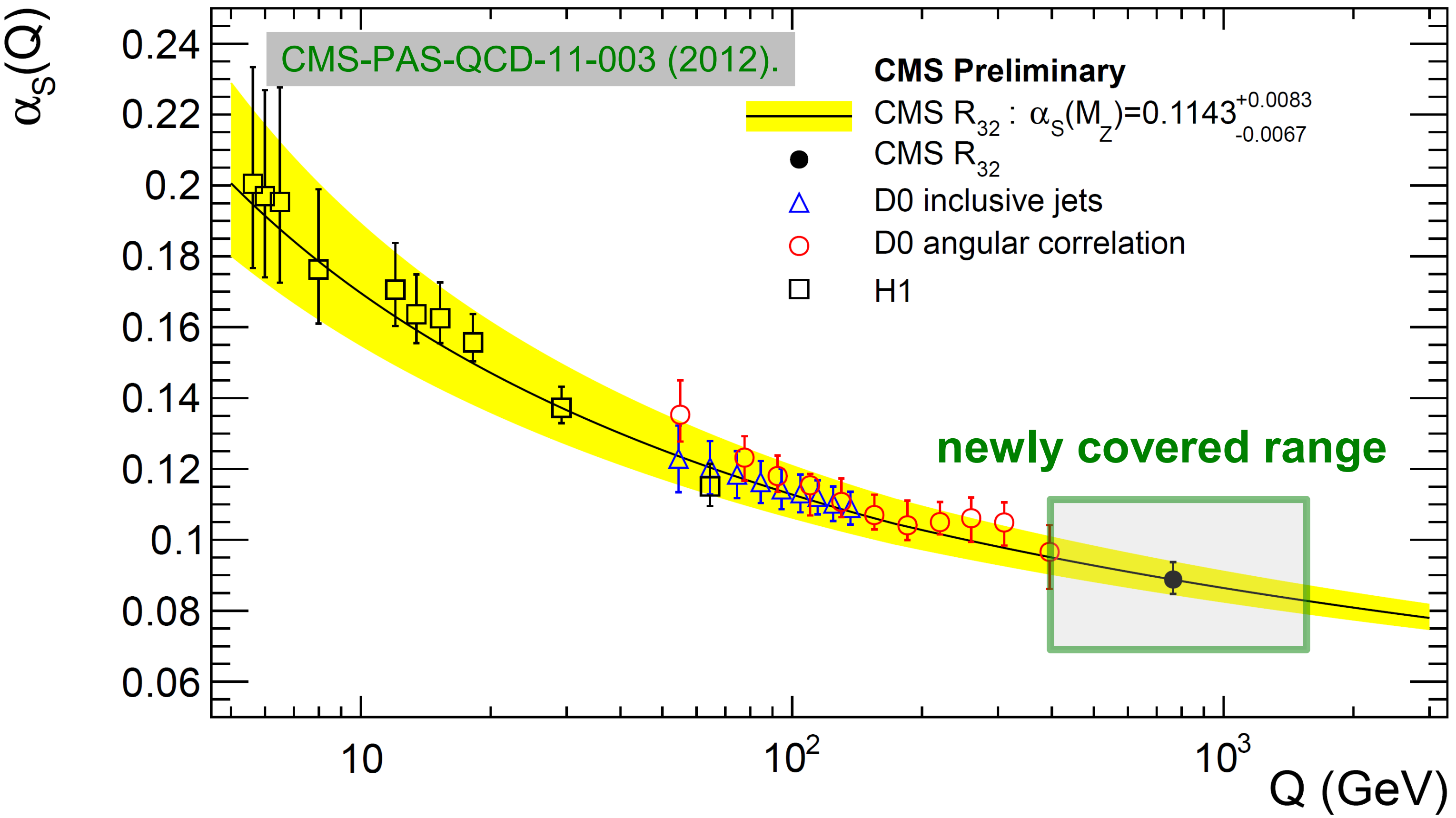
NNPDF21: $\alpha_s(M_Z) = 0.1143 \pm 0.0064$

CT10: $\alpha_s(M_Z) = 0.1130 \pm 0.0080$

MSTW2008: $\alpha_s(M_Z) = 0.1135 \pm 0.0096$

Determination of α_s (NLO)

- Comparison to extractions from other hadron collider experiments
- Although only one point shown here extraction works equally well in e.g. three subranges

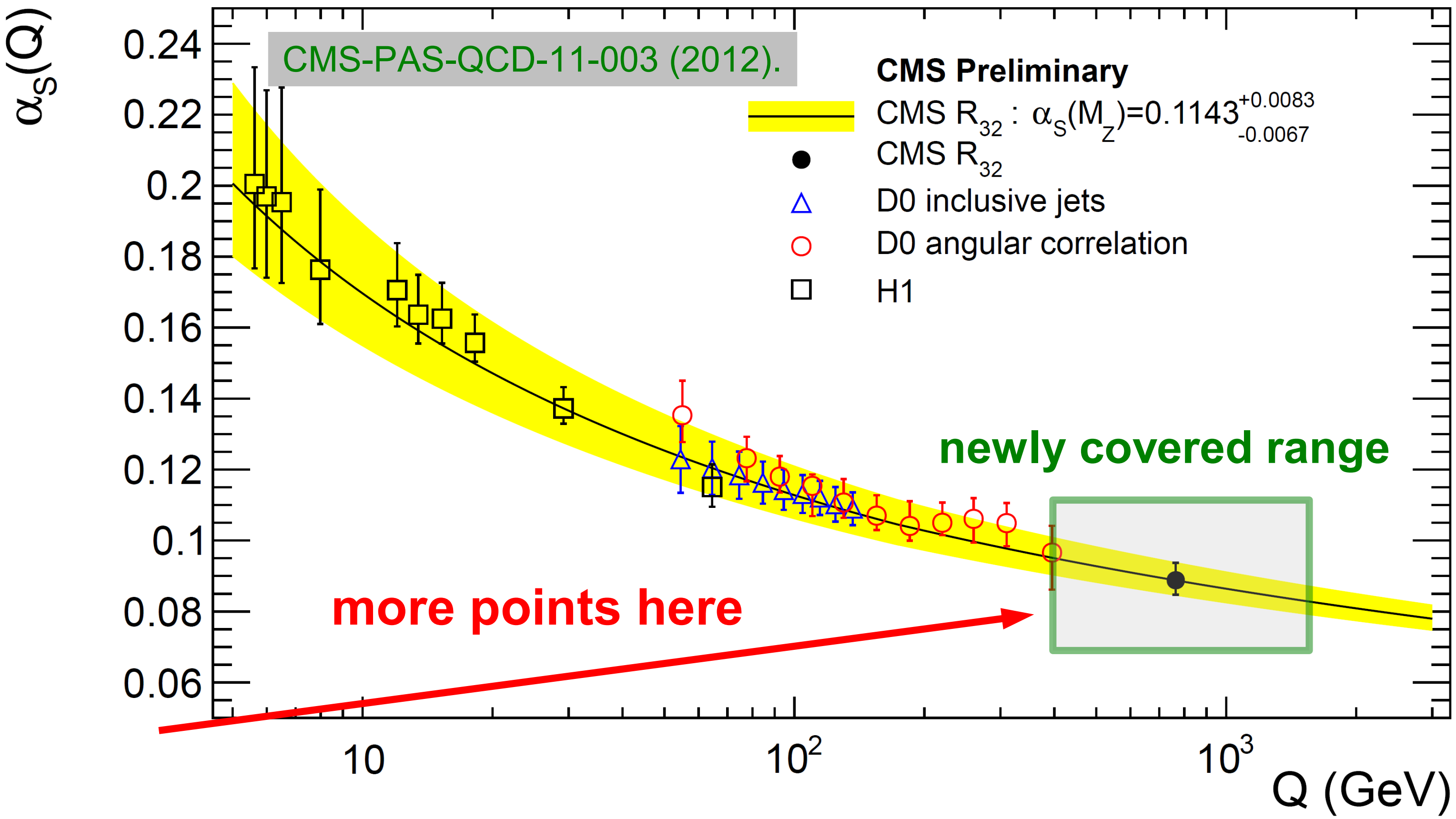


PDF uncertainty: Repeat fit for each replica → get estimators for μ and σ
Scale uncertainty: Repeat fit for all six variations → get maximal deviation

$$\alpha_s(M_Z) = 0.1143 \pm 0.0064\,(\mathrm{exp}) \pm 0.0019\,(\mathrm{PDF}) \pm^{0.0050}_{0.0000}\,(\mathrm{scale})$$

Determination of α_s (NLO)

- **Comparison to extractions from other hadron collider experiments**
- **Although only one point shown here extraction works equally well in e.g. three subranges**



To be finalized soon with

PDF uncertainty: **Repeat fit for each replica → get estimators for μ and σ**
Scale uncertainty: **Repeat fit for all six variations → get maximal deviation**

Much smaller uncertainty here

$$\alpha_s(M_Z) = 0.1143 \pm 0.0064\,(\text{exp}) \pm 0.0019\,(\text{PDF}) \pm^{0.0050}_{0.0000}\,(\text{scale})$$

α_s from inclusive Jets (NLO)

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

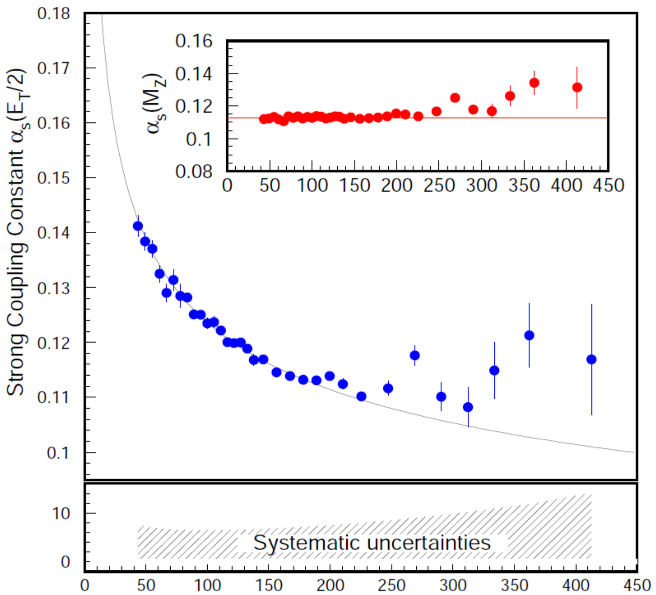
D0: $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}(\mathrm{total})$

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

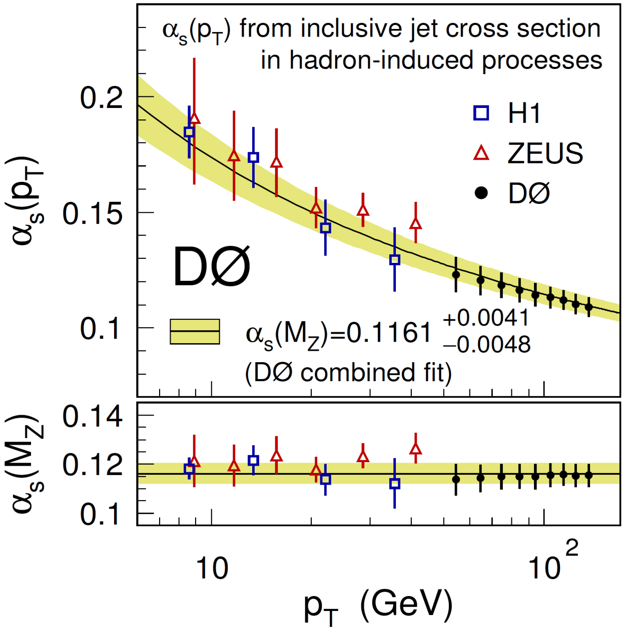
D0: ± 0.004 total

M/S: ± 0.005 exp.

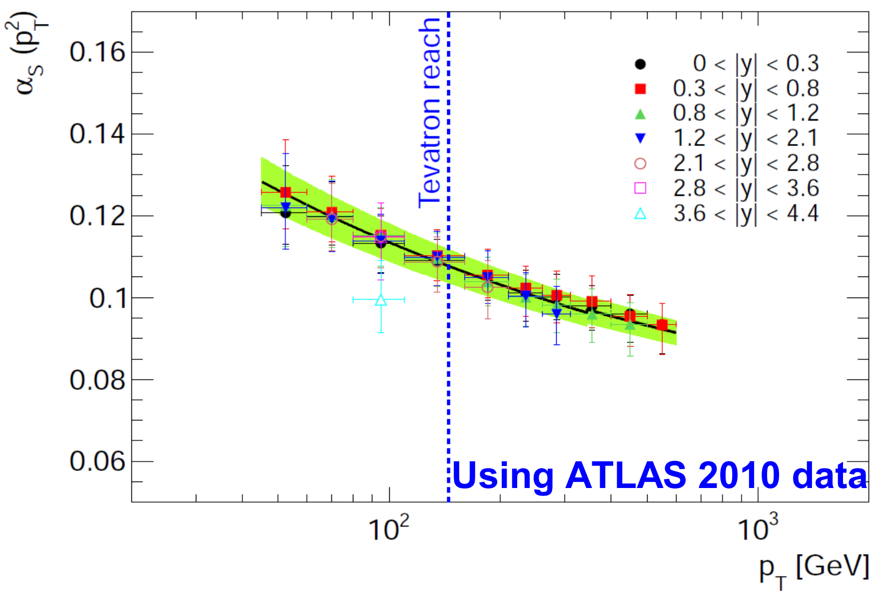
Attention:
Evolution of PDFs from low to high Q assumes the validity of the RGEs ...



CDF, PRL88, 2002



D0, PRD80, 2009

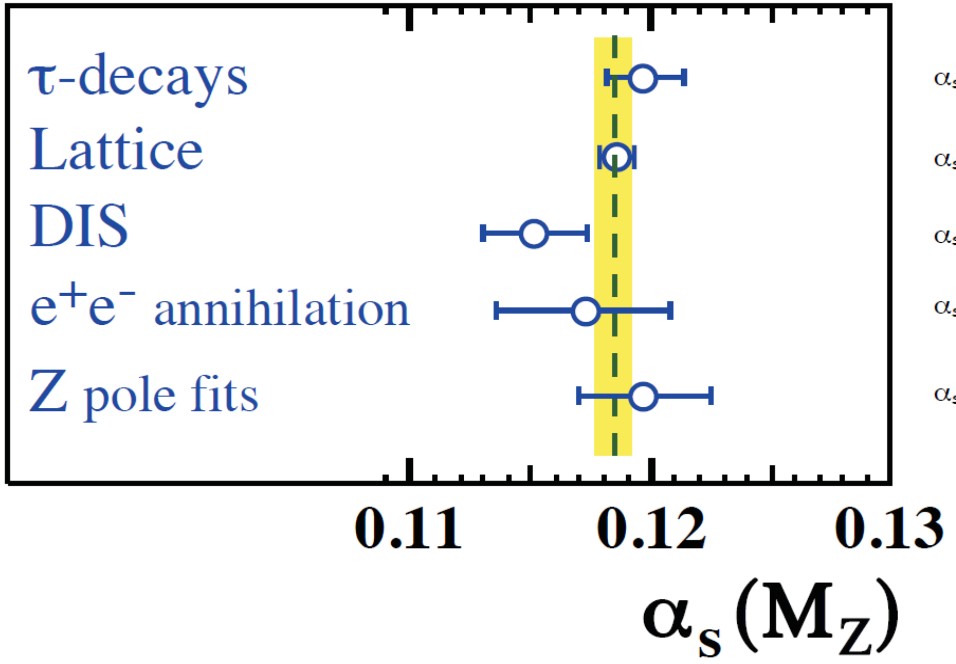


Malaescu/Starovoitov, EPJC72, 2012

α_s World Summary

S. Bethke, 2012:

NNLO: ± 0.002 – 0.004



$\alpha_s(M_Z)$= 0.1197 ± 0.0016

$\alpha_s(M_Z)$= 0.1185 ± 0.0007

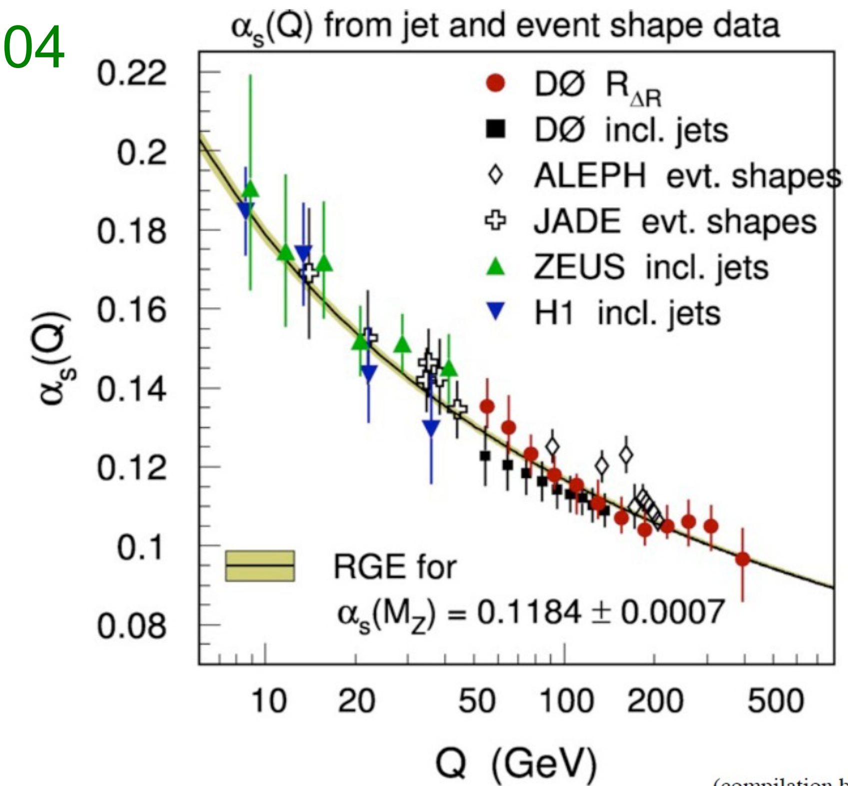
$\alpha_s(M_Z)$= 0.1151 ± 0.0022

$\alpha_s(M_Z)$= 0.1172 ± 0.0037

$\alpha_s(M_Z)$= 0.1197 ± 0.0028

$$\alpha_s(M_Z) = 0.1184 \pm 0.0007$$

PDG2012



D0, PLB718 (2012) 56-63

(compilation by D0)

D0: < ± 0.001 exp.

But: Jet data from hadron colliders not included!
Jets at NNLO might come this year!
A lot of progress by groups around
Th. Gehrmann et al. and N. Glover et al.

Tevatron limit, published this year

LHC from jets starts here ...

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
  - • • •

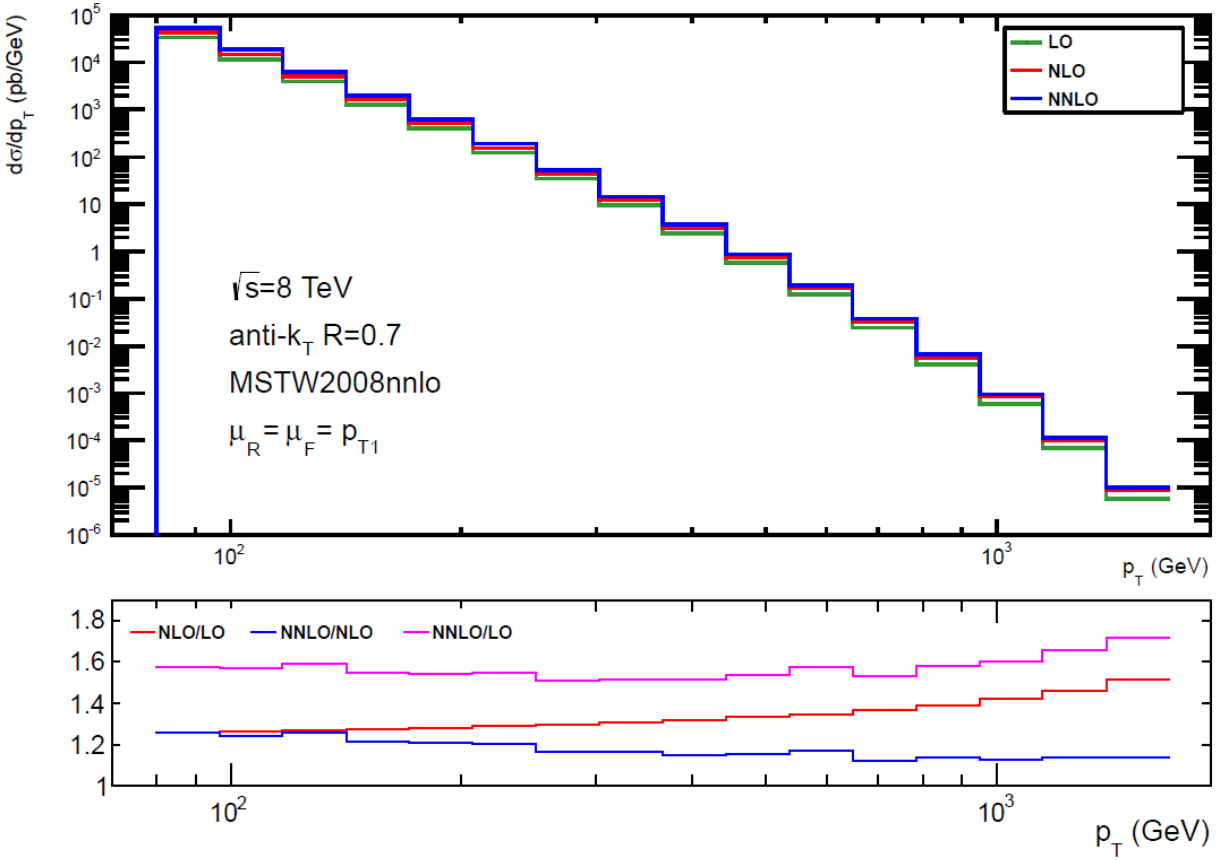
- **Theoretical Uncertainties:**
  - PDF Uncertainty
  - pQCD (Scale) Dependence
  - Non-perturbative Corrections
  - PDF Parameterization
  - NLO-NLL matching schemes
  - Electroweak Corrections
  - Knowledge of $\alpha_s(M_Z)$
  - • • •

Expected exp. Precision for $\alpha_s(M_Z)$ from cross jet sections (inclusive, 3-jet, ...) of the order of ± 0.001 !

To be addressed!
These become limiting factors ...

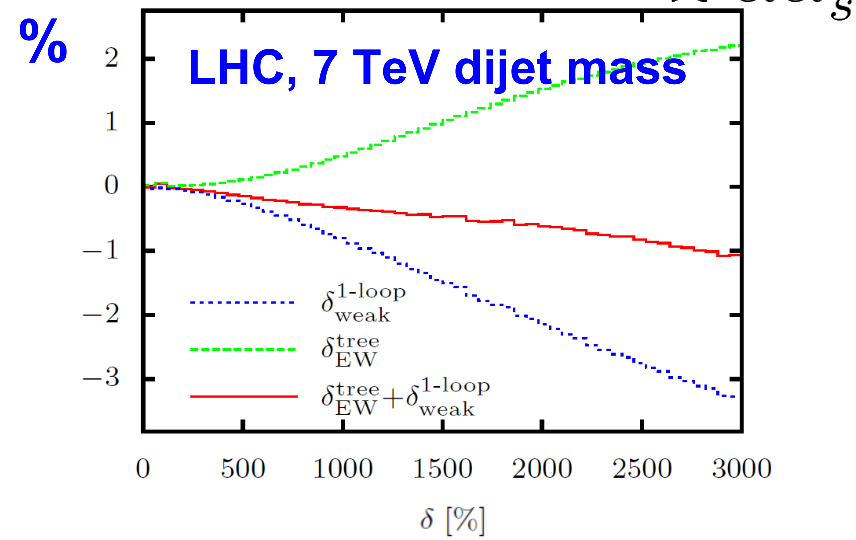
Latest Progress in Theory

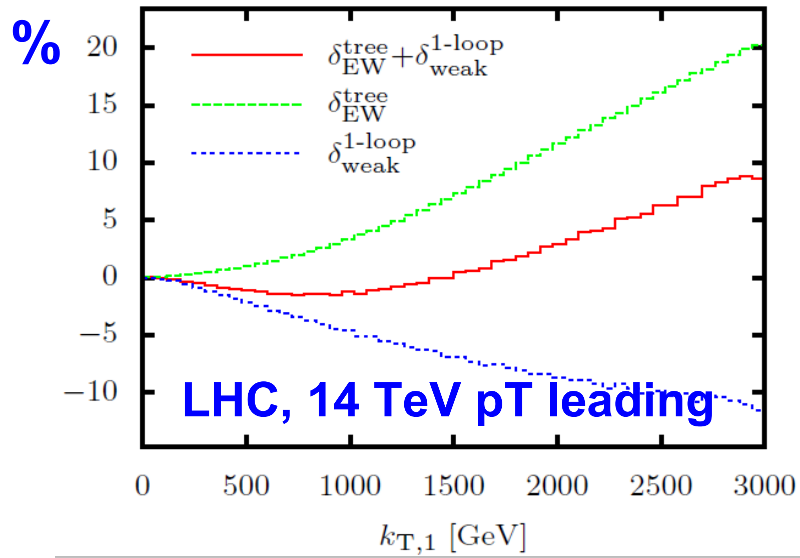
Jet pT at NNLO (gluon-gluon only)



K factors

Electroweak corrections x $\alpha\alpha_s^2$





From talk by N. Glover:
Gehrmann- de Ridder, Gehrmann, Glover, Pires

S. Dittmaier, A. Huss, C. Speckner, JHEP11 (2012).

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
- I didn´t even mention possibilities with jets with associated boson production!

We are entering an extremely interesting period with huge advances experimental data quality and quantity as well as theory predictions!

Outlook

- Hadron colliders are (multi-) jet laboratories
- Jet measurements at hadron colliders are becoming PRECISION PHYSICS
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Many thanks to you for your attention and the invitation to this seminaire!

Backup Slides

Jet Algorithms at LHC

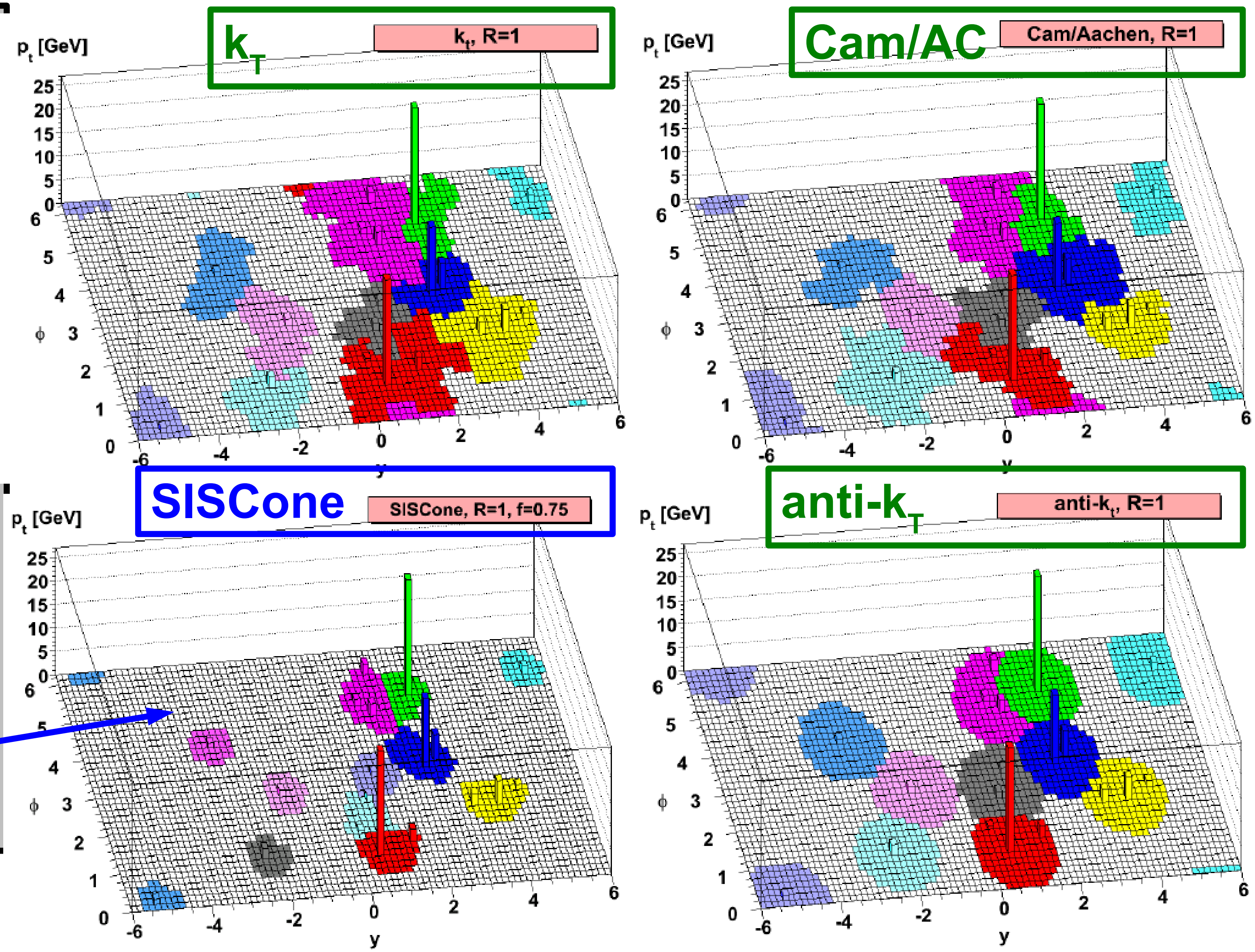
Primary algorithm at LHC:

- **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!

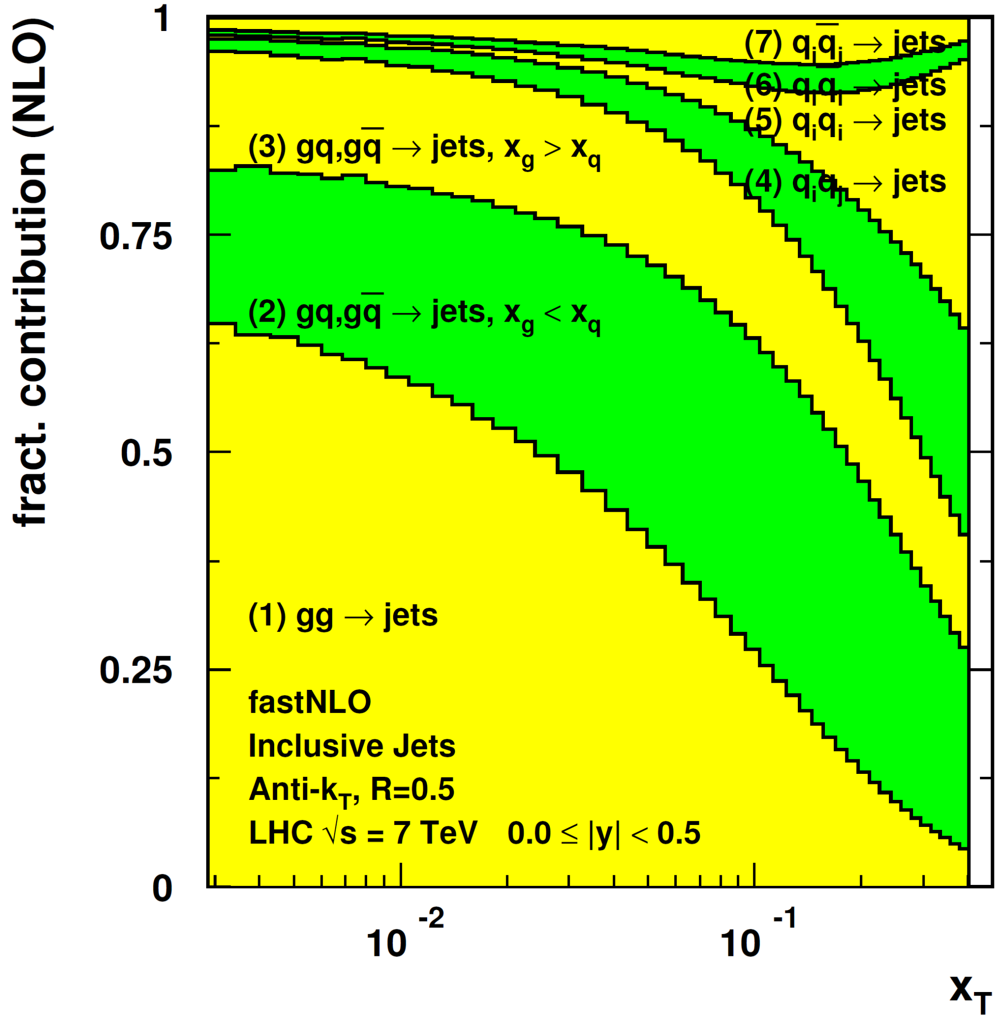
Only "real" cone algorithm!

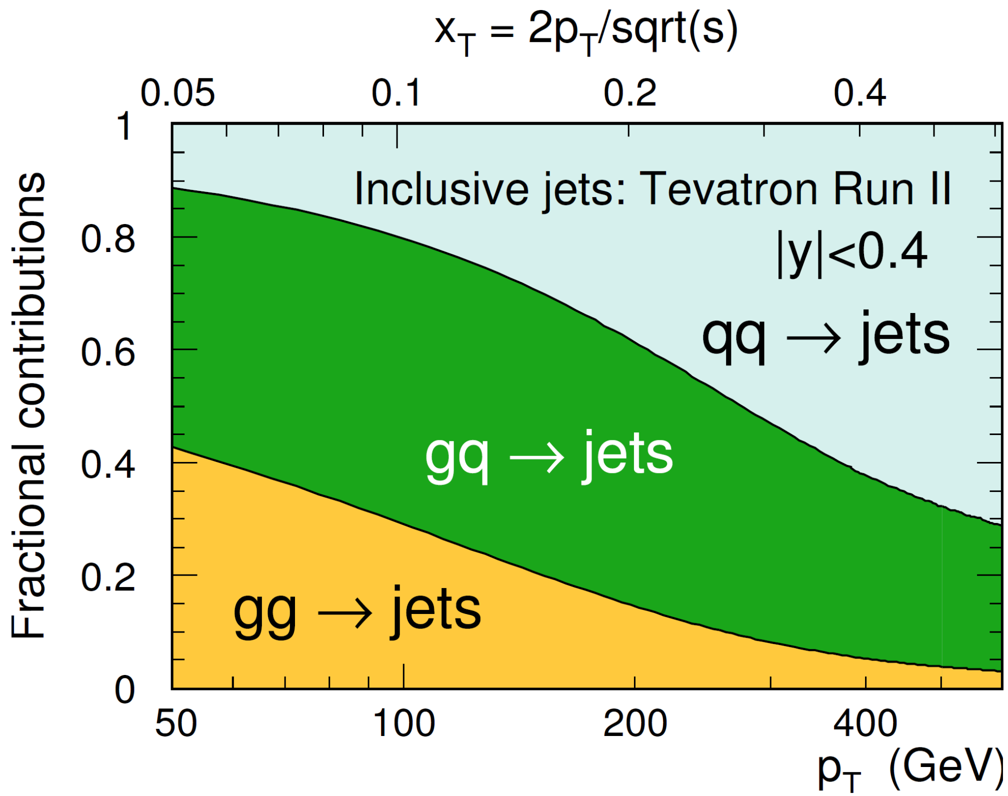


Fast kT, Cacciari/Salam, PLB641, 2006
SISCone, Salam/Soyez, JHEP05, 2007
anti-kT, Cacciari et al., JHEP04, 2008

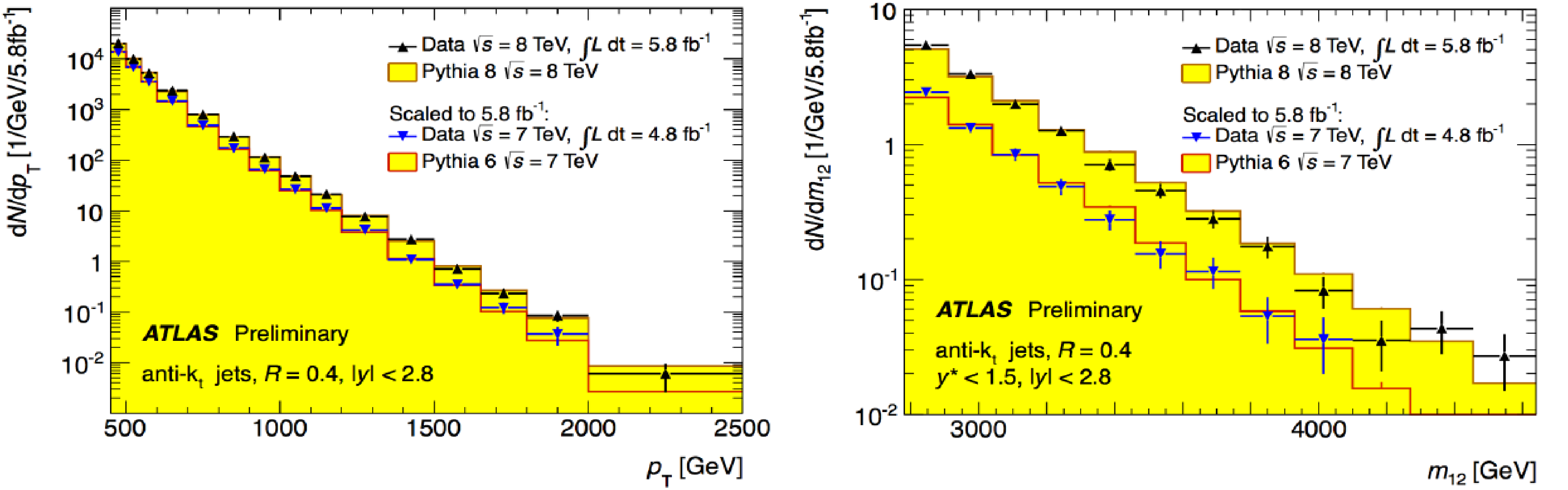
Process Decomposition

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





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.

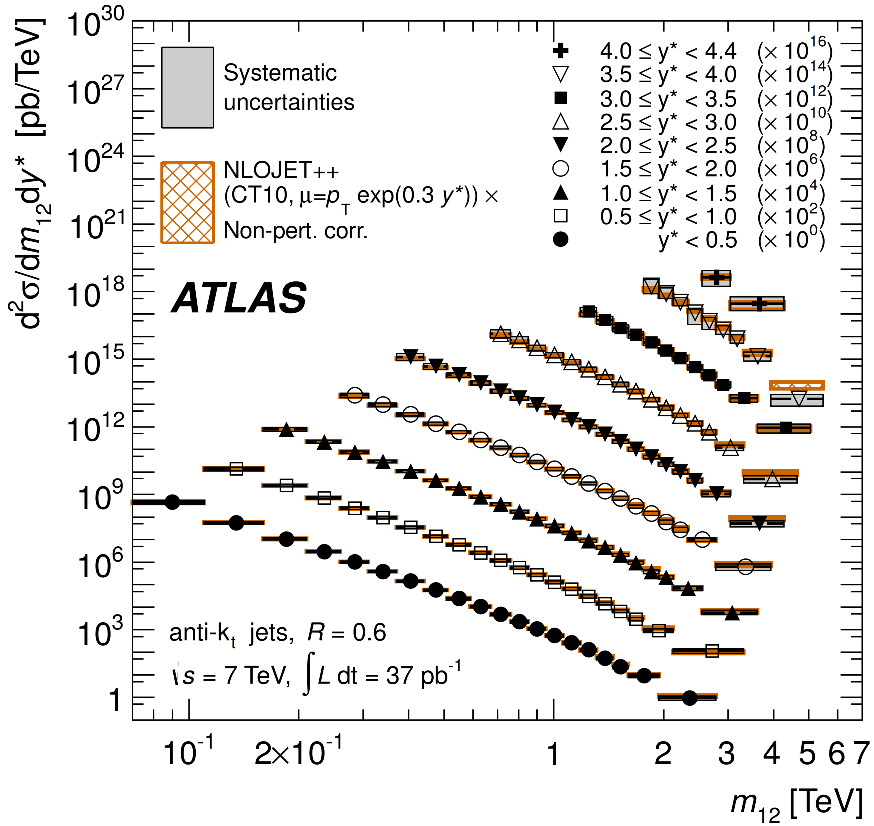
Dijet Mass ATLAS

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

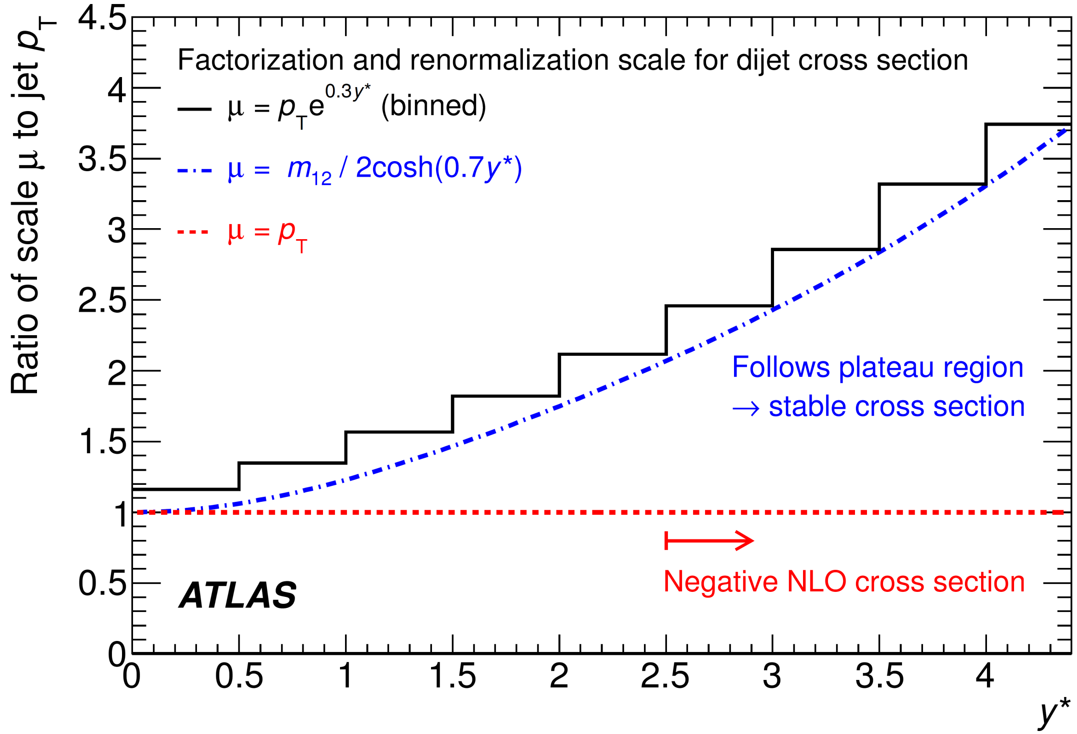
New choice for binning in rapidity by ATLAS
Also new choice for scale setting

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

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

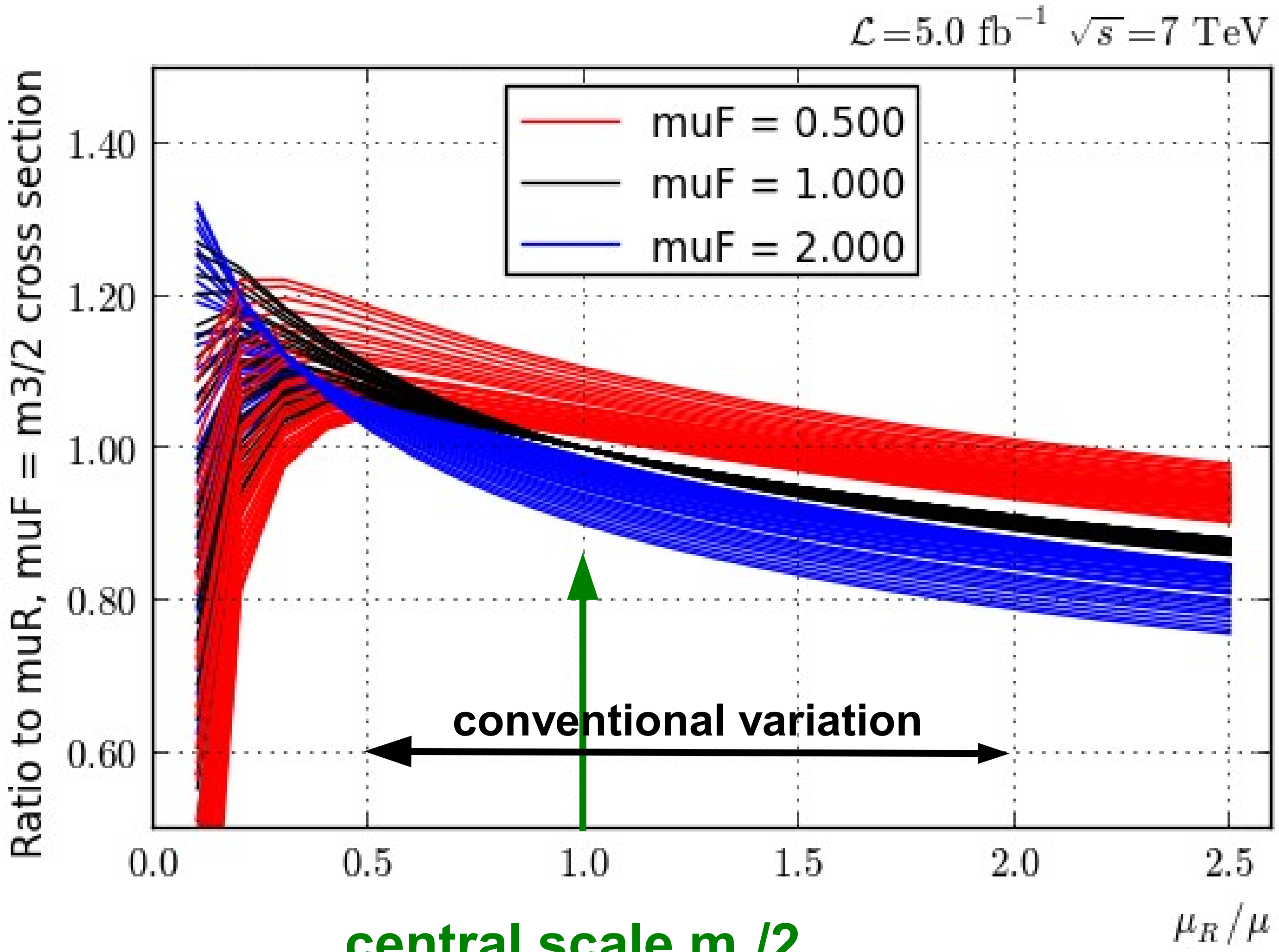


Attention: Figure somewhat misleading ...
Negative NLO cross sections appear
when checking scale uncertainties μ → μ/2



m_3 Scale Dependence

One line per cross section bin for three choices of μ_F scale factors

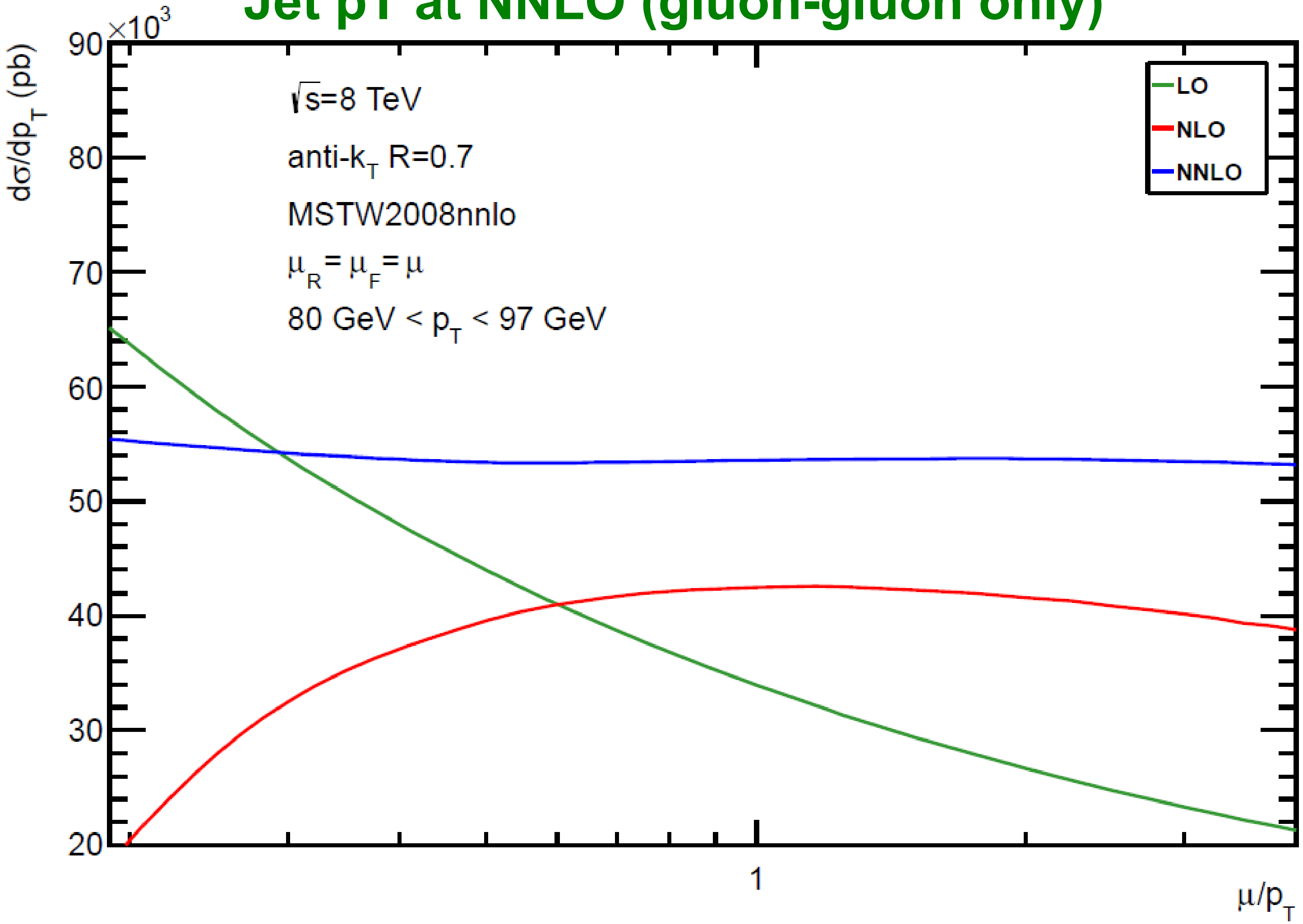


central scale $m_3/2$

F. Stober

NNLO Scale Dependence

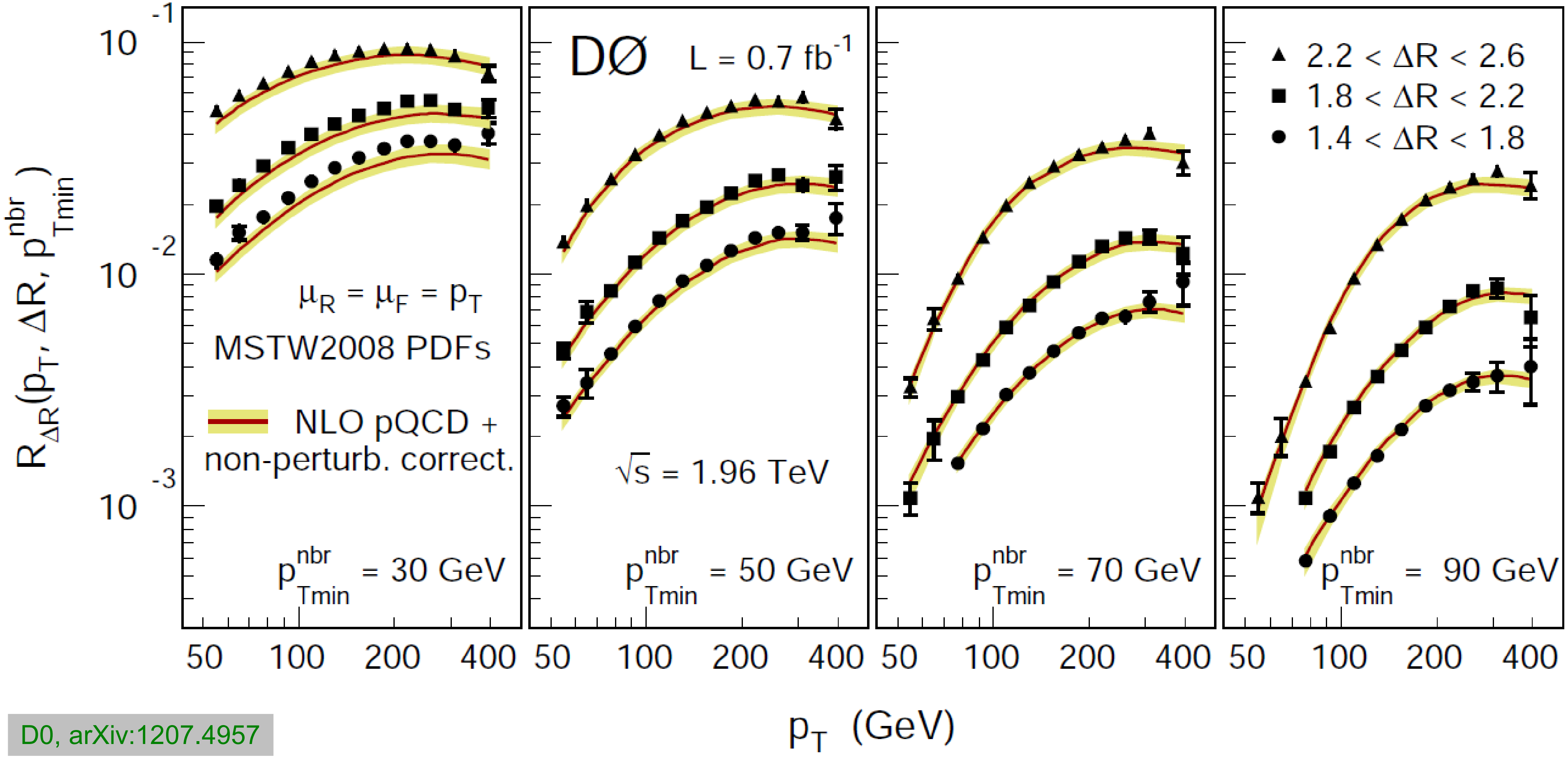
Jet pT at NNLO (gluon-gluon only)



$|y| < 4.4$, 80 GeV $< p_T <$ 97 GeV

From talk by N. Glover:
Gehrmann- de Ridder, Gehrmann, Glover, Pires

New jet angular correlation Observable from D0



D0, arXiv:1207.4957

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

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

CMS R_{32}: Analysis Setup

- CMS data of 2011 $\mathcal{L}_{\mathrm{int}} = 5.0\,\mathrm{fb}^{-1}$
- Anti-kT jet algorithm with R = 0.7
  - Compatible results with R = 0.5 as alternative
- Selection in rapidity y (1 bin): $|y| < 2.5$
  - Ensure tracker coverage
  - Two jets leading in p_T must be selected
  - Ensure hard dijet event
- Minimal transverse momentum p_T: $p_{\mathrm{T}} > 150\,\mathrm{GeV}$
  - Alternative thresholds 50 and 100 GeV checked
  - Alternative relative cut on hardness of 3rd jet tested
- Minimal average 2-jet $\langle p_{T1,2} \rangle$ (27 bins): $\langle p_{\mathrm{T}1,2} \rangle > 250\,\mathrm{GeV}$
- O(2000) 2-jet ev. incl. O(300) 3-jet events above 1 TeV

CMS R_{32}: Data Treatment

- Three single-jet triggers (highest p_T threshold 370 GeV) $\epsilon = 100\%$
  - Efficiency checked separately for incl. 2- and 3-jet events
- Particle-flow technique to reconstruct input objects to jet clustering $\epsilon > 99\%$
- Standard CMS event and jet selection criteria apply
- (η, p_T)-dependent jet energy correction factors, typically: $c_{\mathrm{JEC}} \approx 1.2 \ldots 1.0$
- Correction of detector effects using Bayesian iterative unfolding (RooUnfold) $c_{\mathrm{DET}} < 5\%$
  - Propagation of stat. uncertainties & correlations with MC toy method
  - Cross-checked with SVD unfolding
  - Comparison of directly unfolded ratio R_{32} versus separate unfolding of inclusive 2- and 3-jet spectra

CMS R_{32}: Exp. Uncertainties

- Jet energy correction, known to 2.0 - 2.5%: $\Delta R/R \approx 1.2\%$
  - Provided as 16 mutually uncorrelated sources; fully correlated within source; Gaussian behaviour assumed
  - Dominated by absolute scale, followed by high pT extrapolation
- Unfolding uncertainty accounting for: $\Delta R/R < 1.0\%$
  - Variation of jet p_T spectral slopes following differences from Pythia6 Z2 (agrees with MadGraph) and Herwig++ 2.3
  - Variation of jet energy resolution (JER)
  - Addition of non-Gaussian tails to JER
- Luminosity (normalization) uncertainty cancels
- No assumptions on bin-to-bin correlations with respect to y necessary, only 1 bin considered
- Statistical uncertainties propagated via unfolding