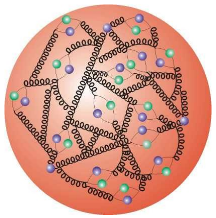
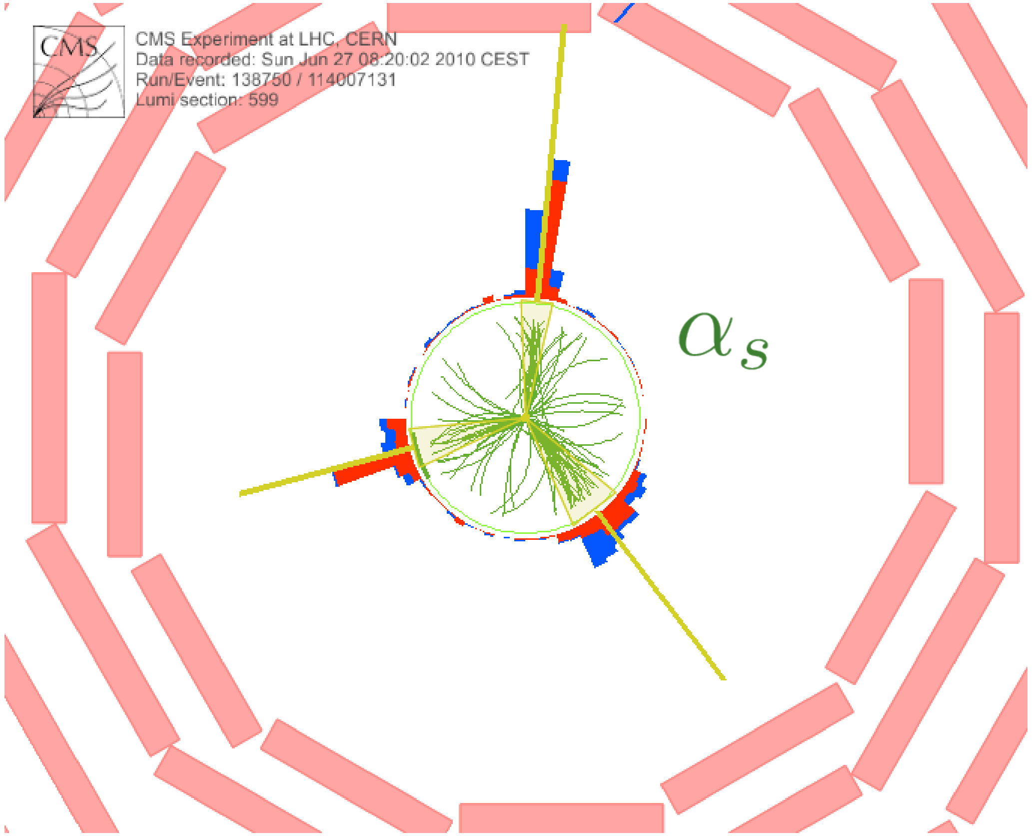
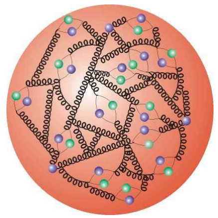
Latest Jets Results from the LHC



Proton Structure (PDF)





Proton Structure (PDF)

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Klaus Rabbertz, KIT

Karlsruhe Institute of Technology

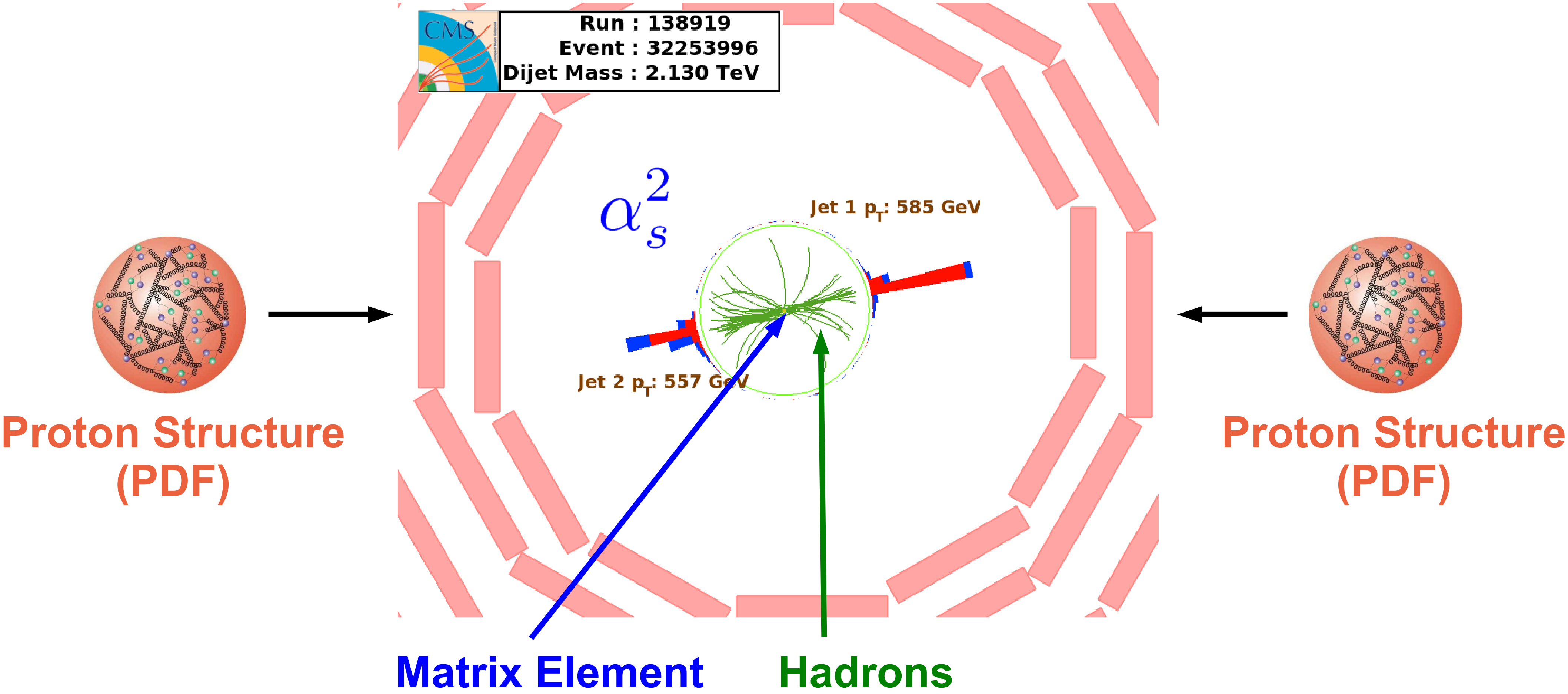
Flash Menu

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

For new results on photons or W/Z bosons plus jets see the dedicated talks this afternoon by R. Lafaye and K. Theofilatos!

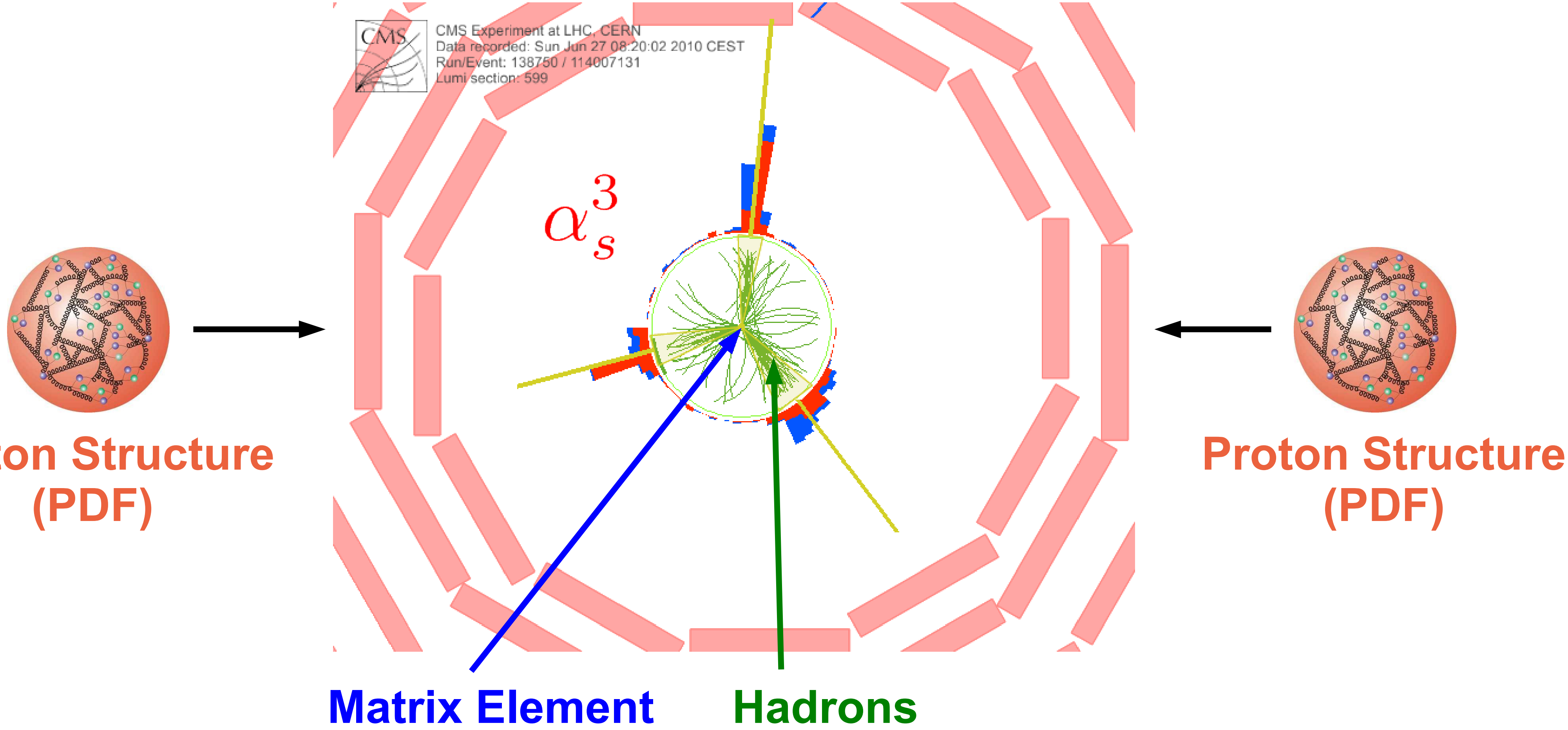
Jets … so what?

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



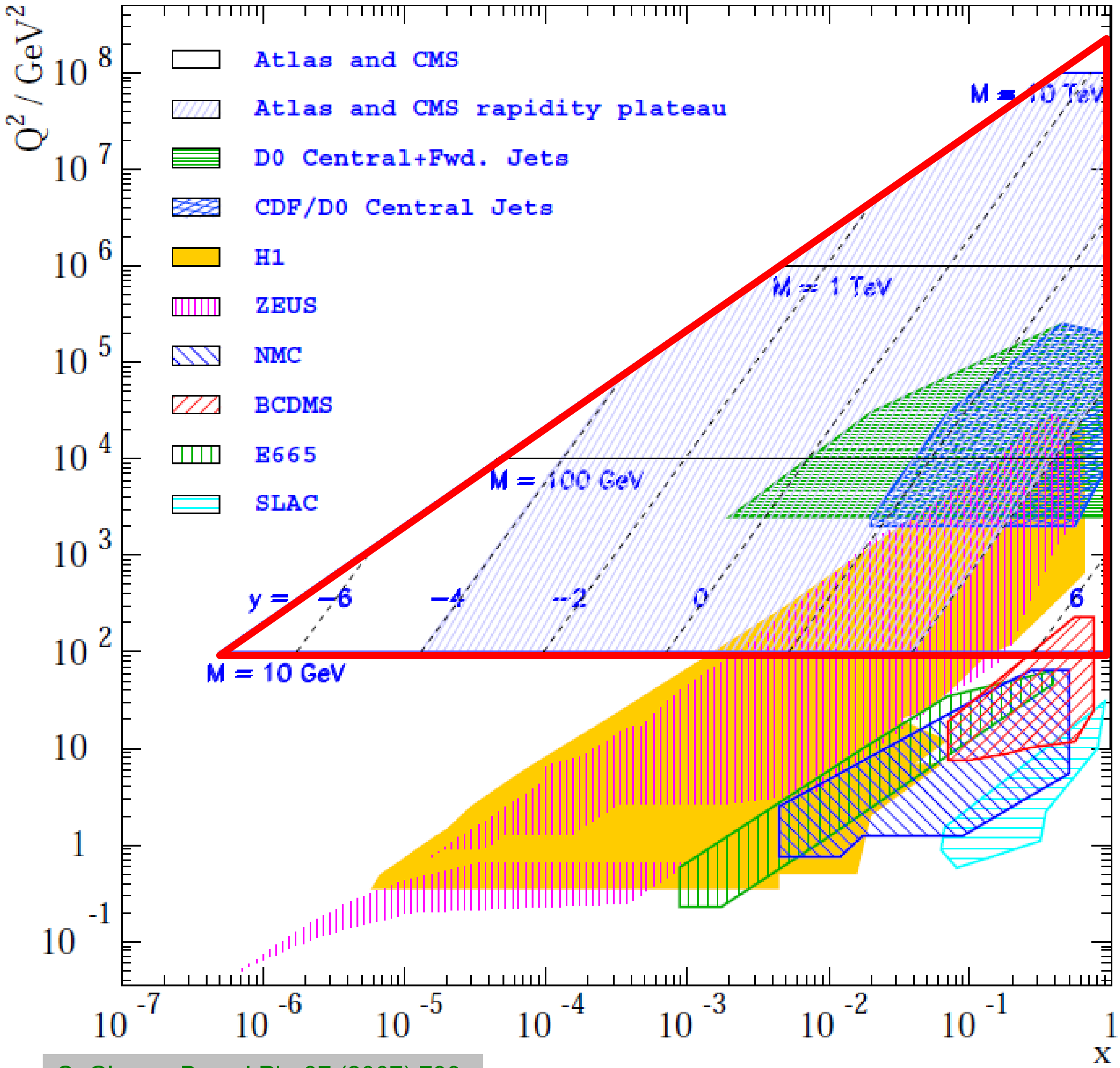
Jets … so what?

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



Where are we?

Kinematic plane of process scale² vs. x

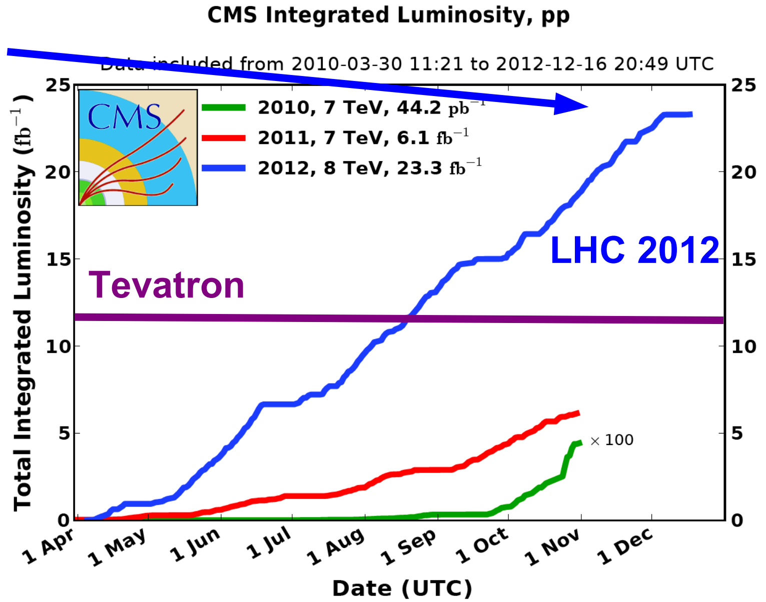


S. Glazov, Braz.J.Ph. 37 (2007) 793.

- 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 and Experiments

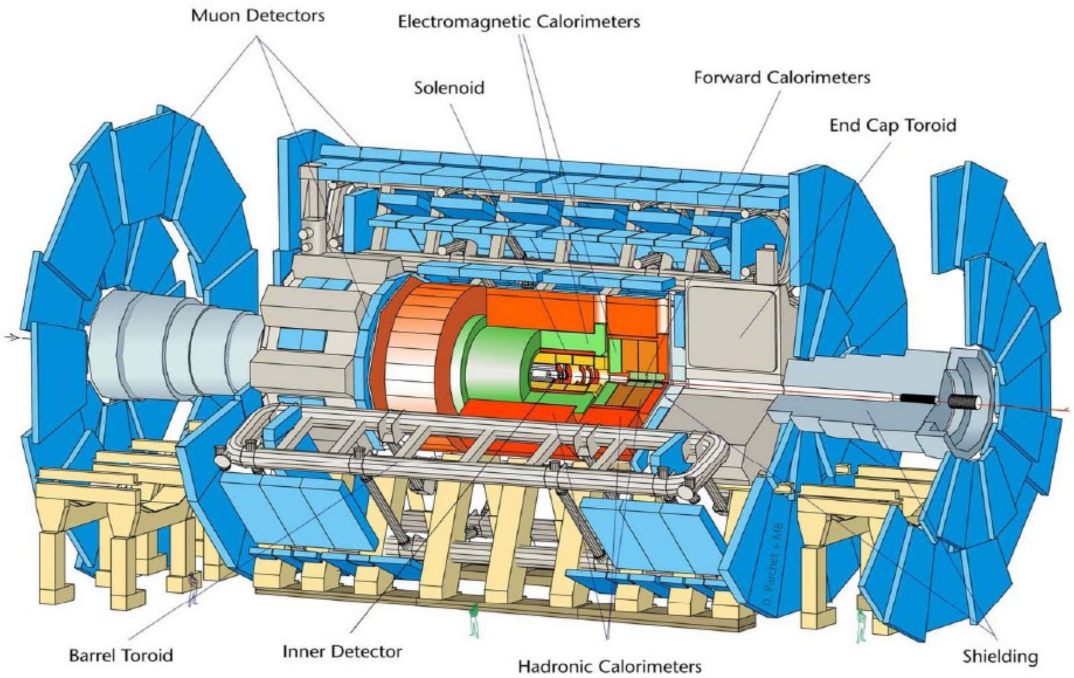
LHC: Collisions of Pb-Pb, p-Pb and p-p (23/fb)
E_{cms} = 0.9, 2.36, 2.76, 7, 8 TeV
peak inst. lumi almost 8 x 10^{33} $cm^{-2}s^{-1}$

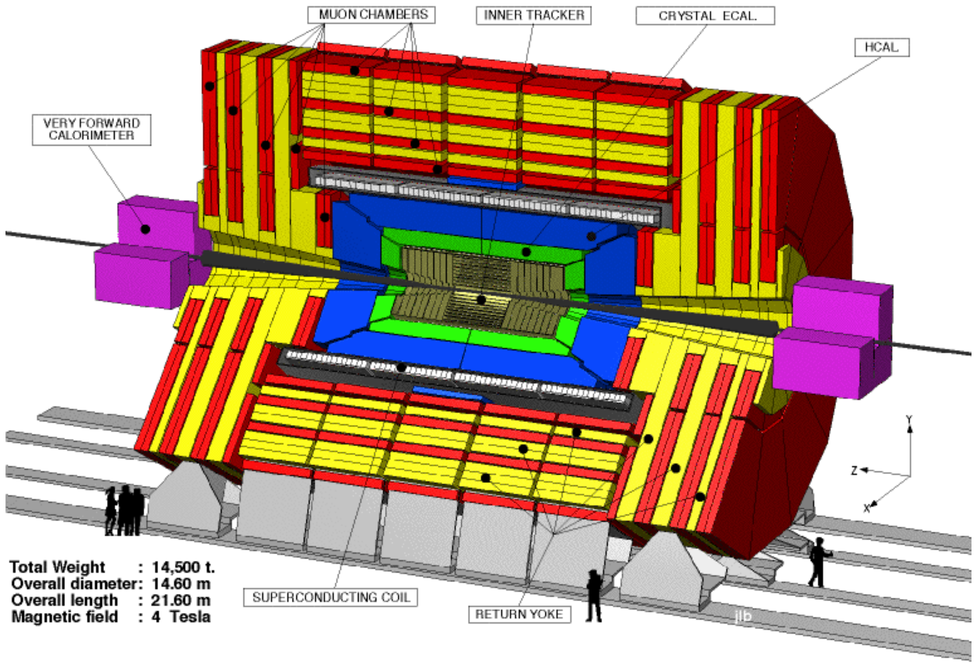


ATLAS/CMS global features:
- **Silicon trackers:** Up to |η| = 2.5
- **Calorimetry:** Up to |η| ~ 5.0
- **Muon chambers:** Up to |η| = 2.4-2.7
- **Jet energy scale:** 1 – 3 % prec.

ALICE

LHCb



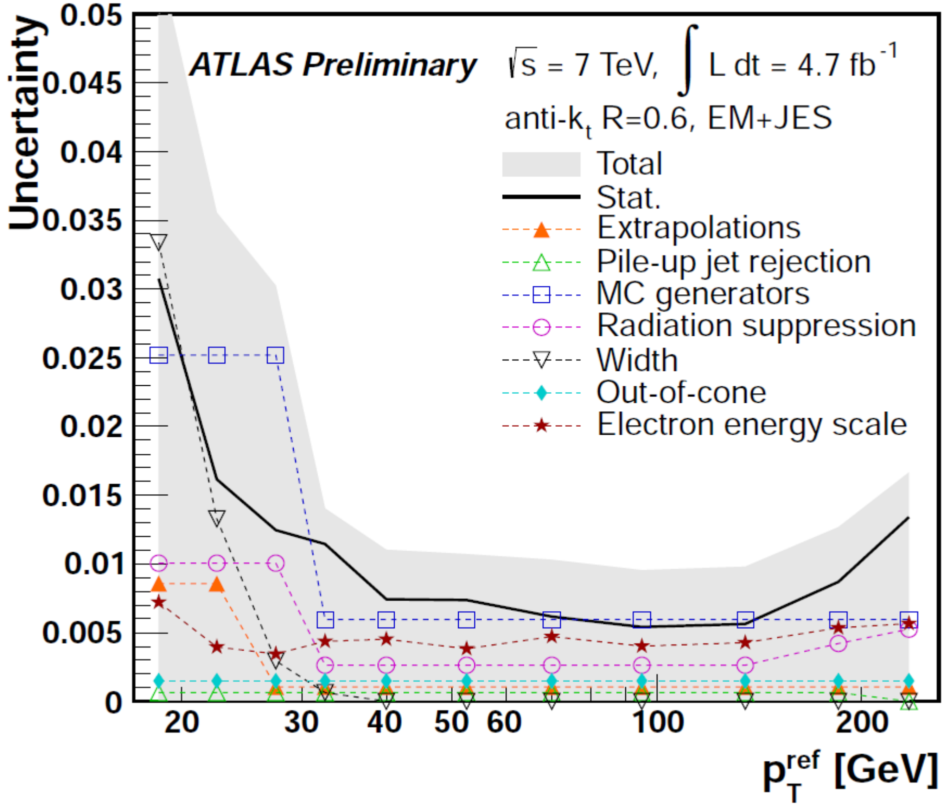


Jet Energy Scale

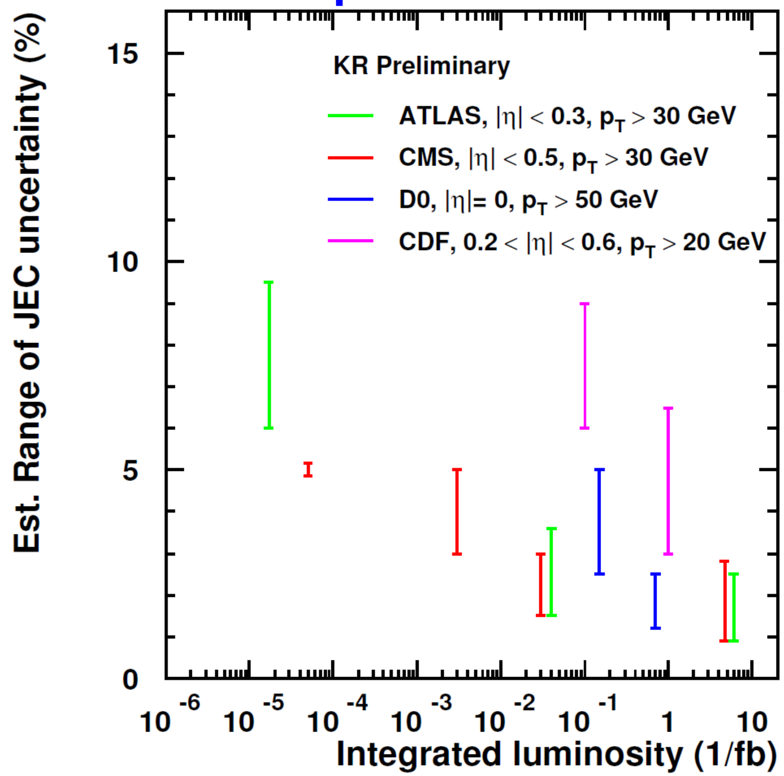
Dominant experimental uncertainties for jets!
Enormous progress in just three years.

- Jet Energy Scale (JES)
  - Noise Treatment
  - Pile-Up Treatment
- Luminosity
- Jet Energy Resolution (JER)
- ...

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



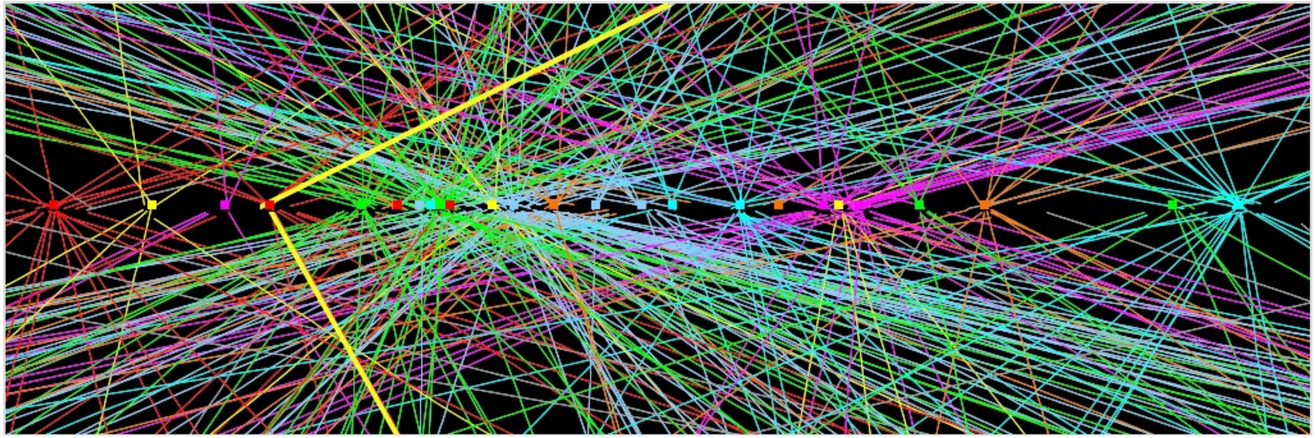
Approximate development of JEC precision



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

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

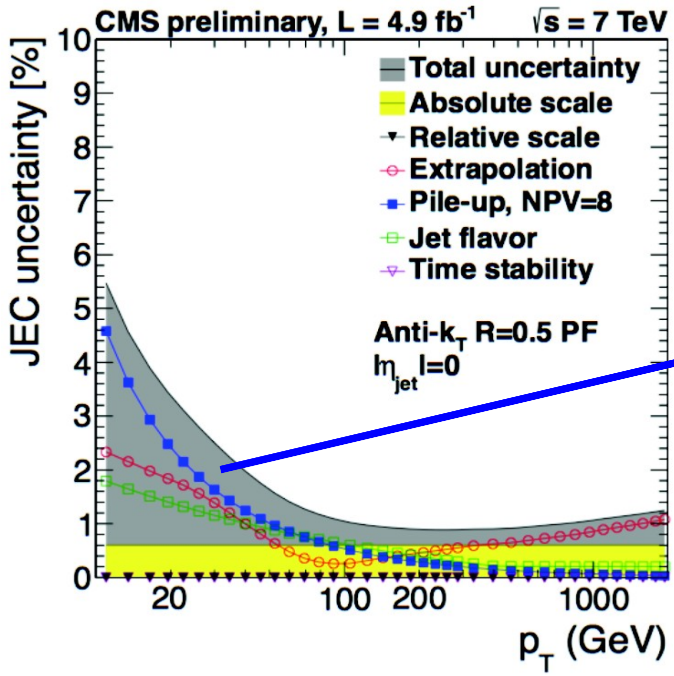
μ



μ

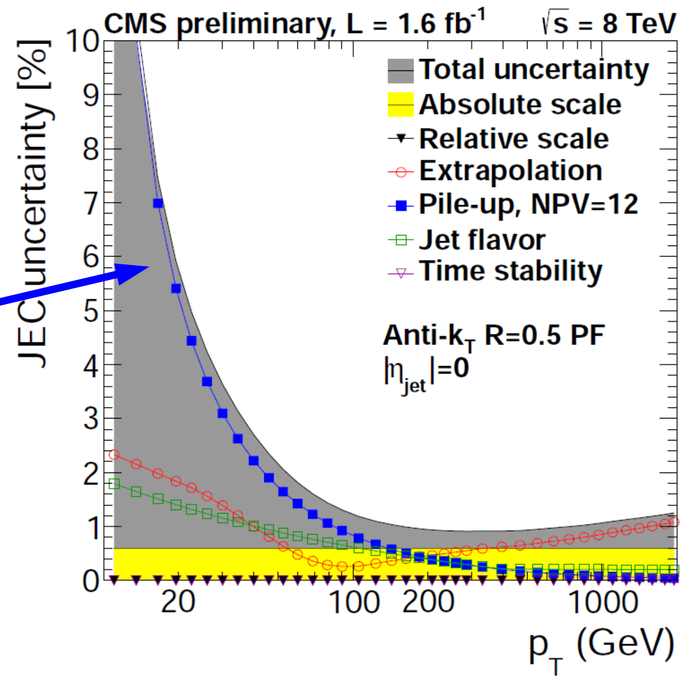
ATLAS Z → μμ candidate
with 25 reconstructed primary vertices:
(Record beyond 70!)

CMS from 5/fb (7 TeV, 2011)



Pile-up effect

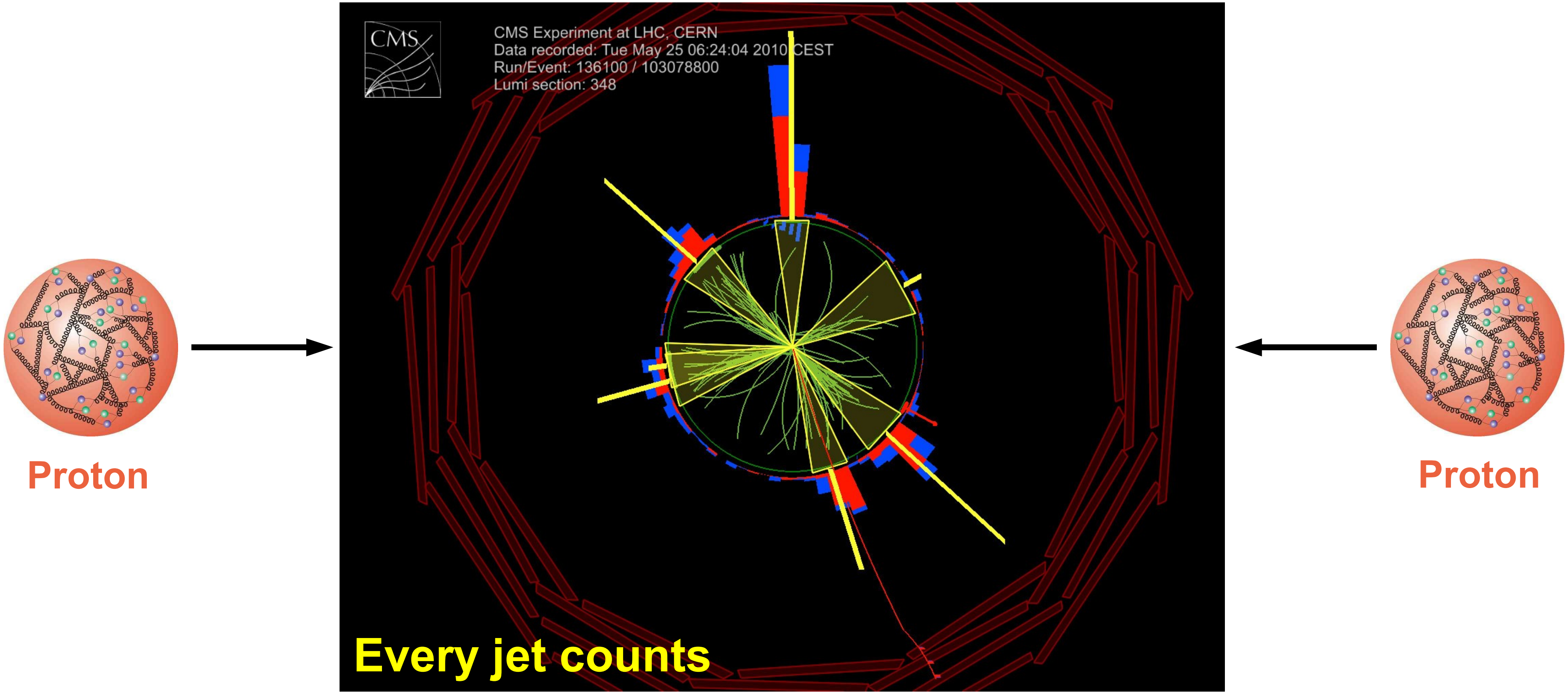
CMS from 1.6/fb (8 TeV, 2011)



CMS, DP2012-006
CMS, DP2012-012

All Inclusive

High transverse Momenta



Inclusive Jets

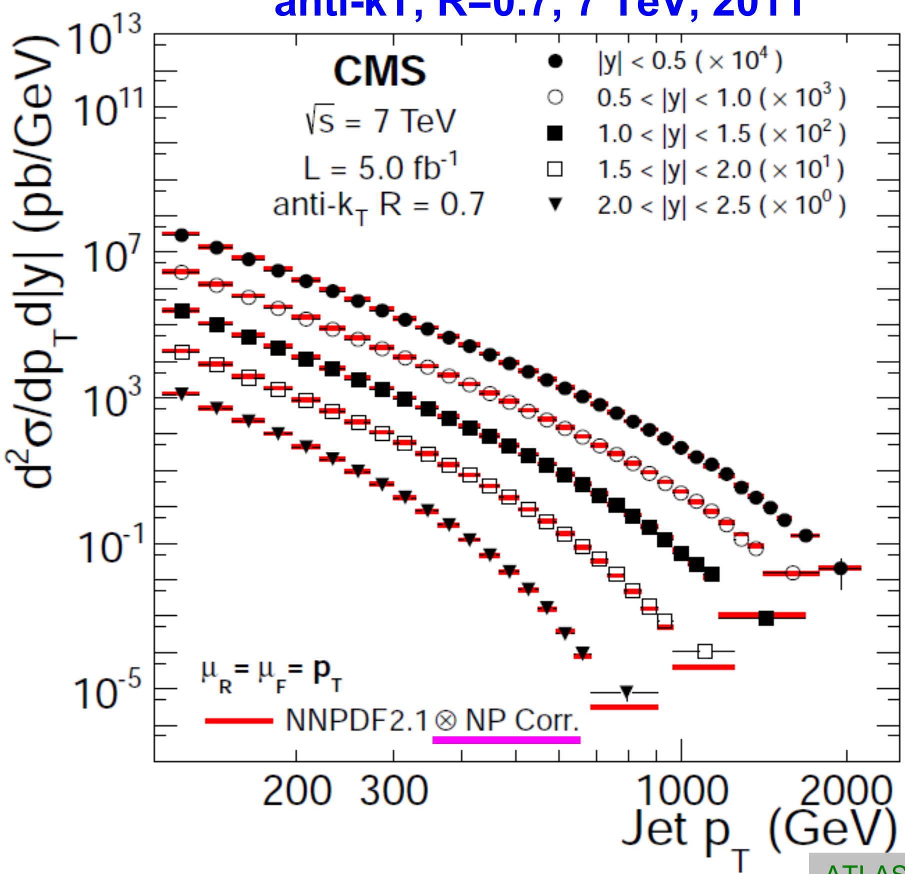
Agreement with predictions of QCD at NLO over many orders of magnitude up to 2 TeV in jet p_T

Data at 8 TeV in progress ...

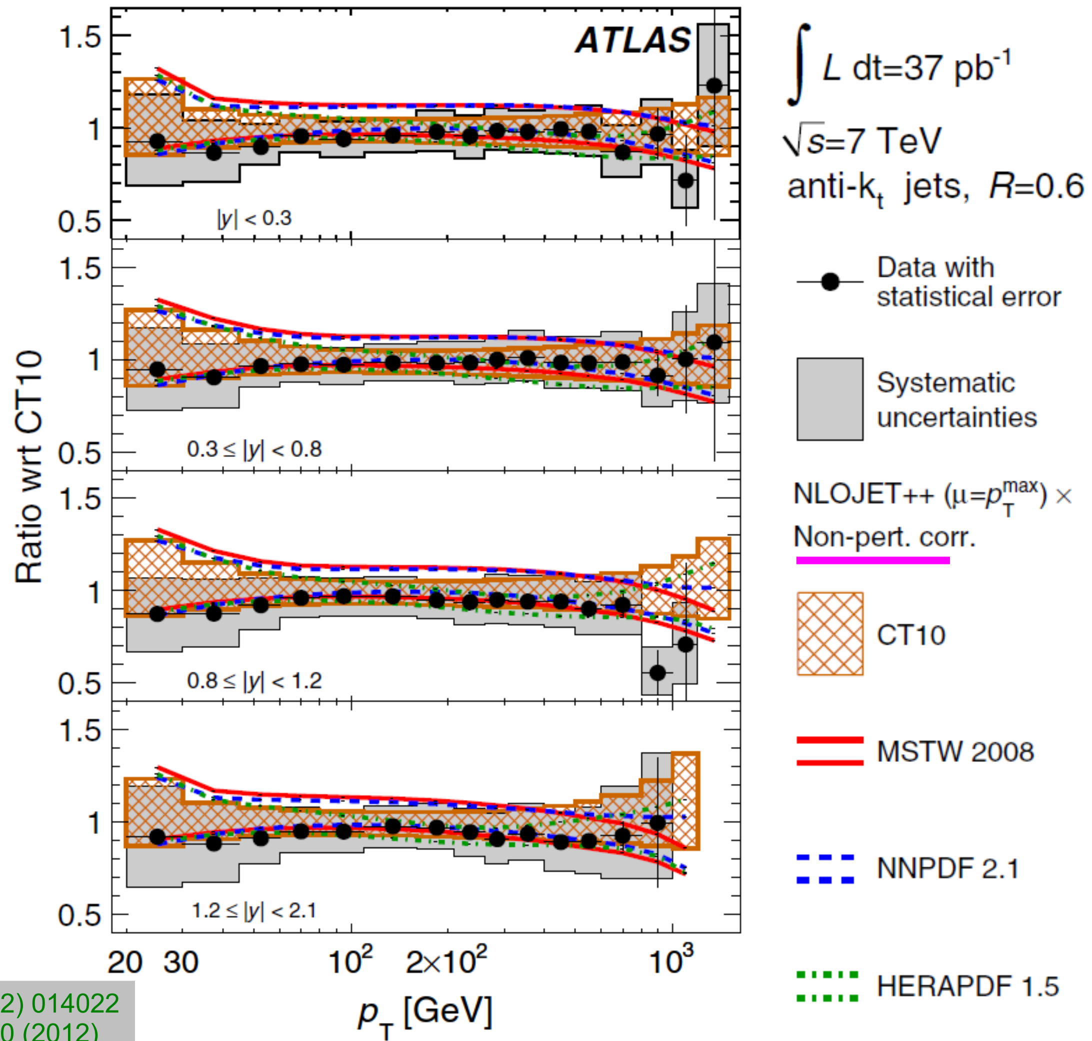
pQCD ⊗ non-perturbative corrections

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

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



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



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

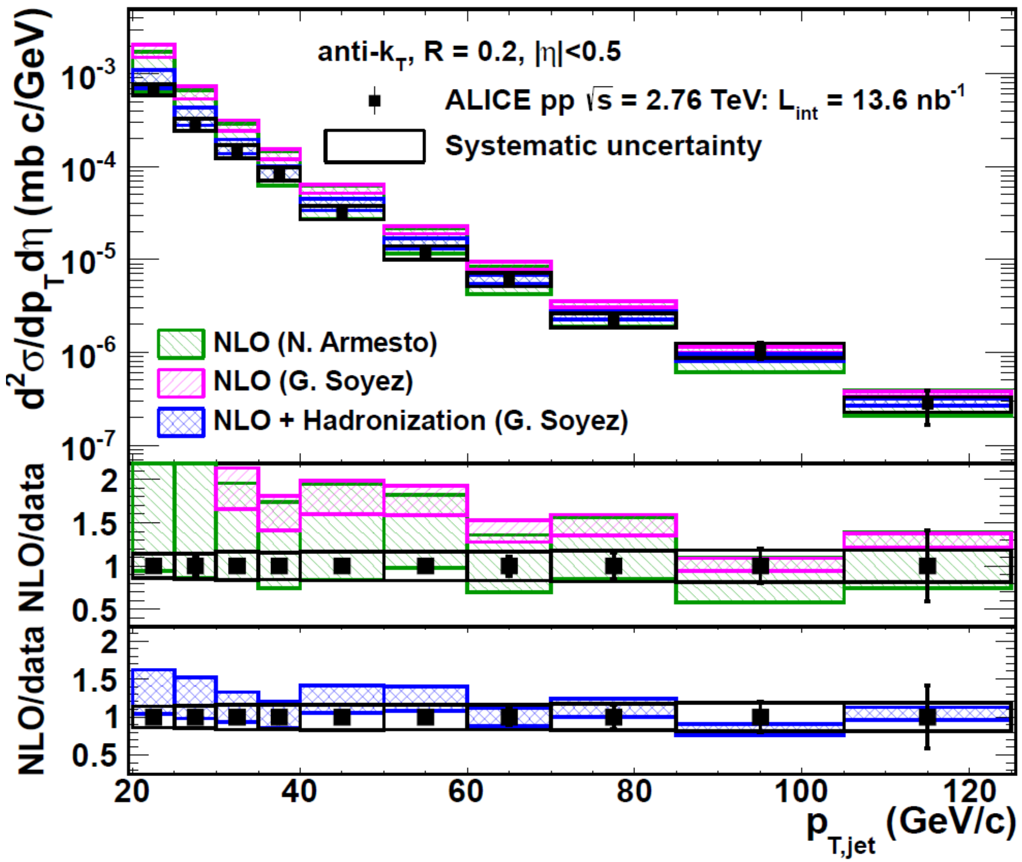
Inclusive Jet Ratios: 0.2 / 0.4

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

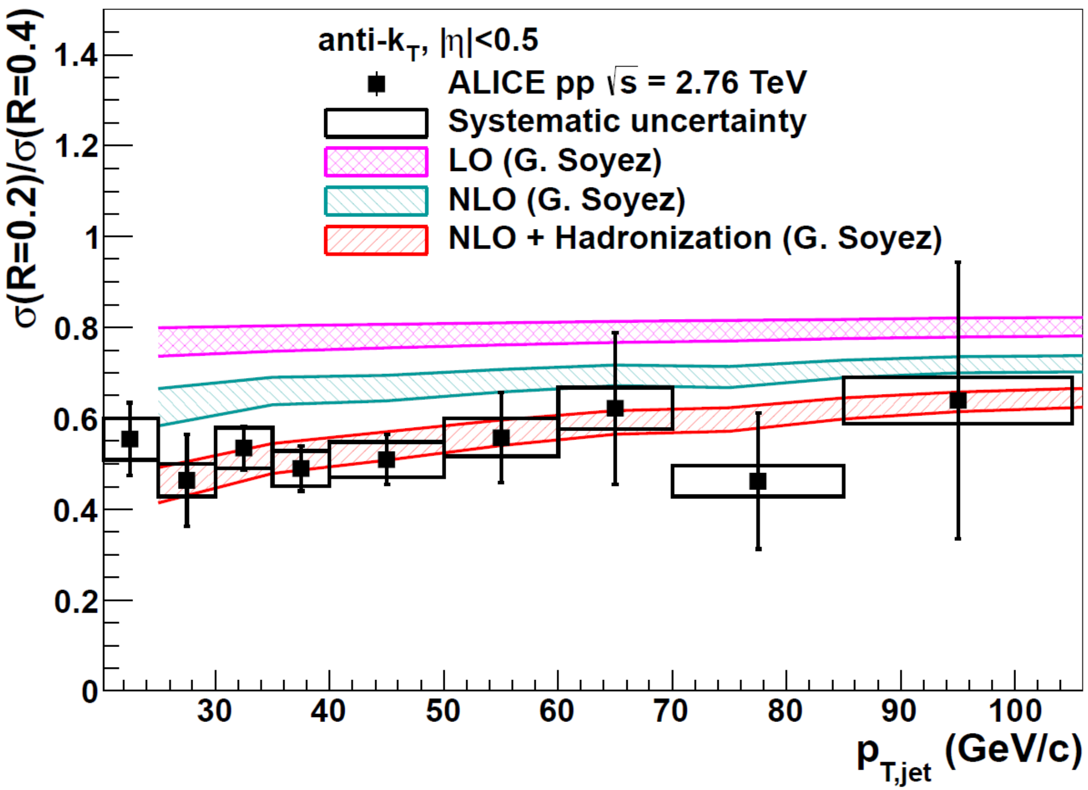
ALICE measurement:
following proposal from G . Soyez
Emphasizes effects of showering and hadronization!

G. Soyez, PLB698 (2011).

Cross section, R=0.2



Ratio, R=0.2 / R=0.4



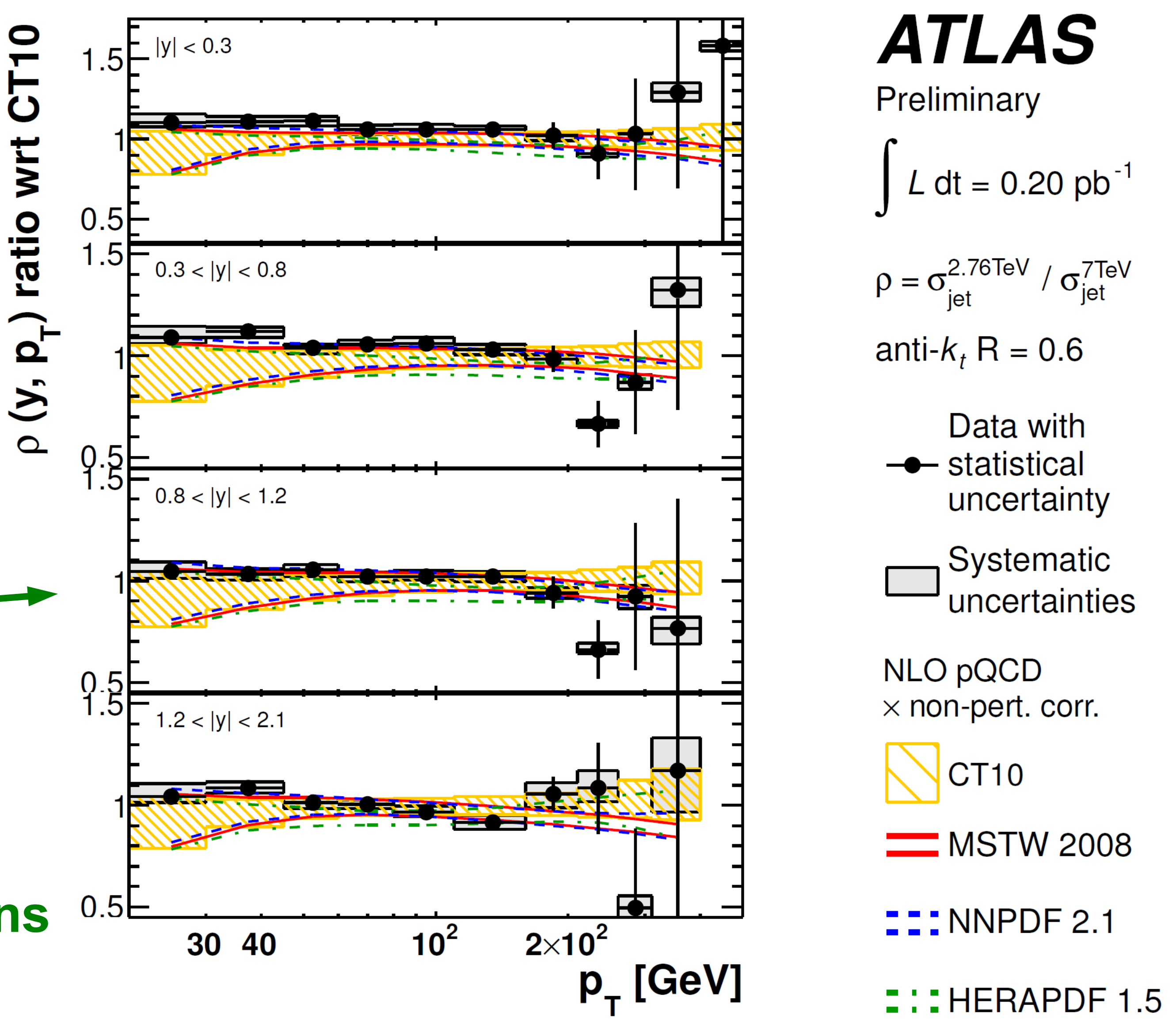
ALICE, arXiv:1301.3475

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

Event Shapes

Example: **Central Transverse Thrust**

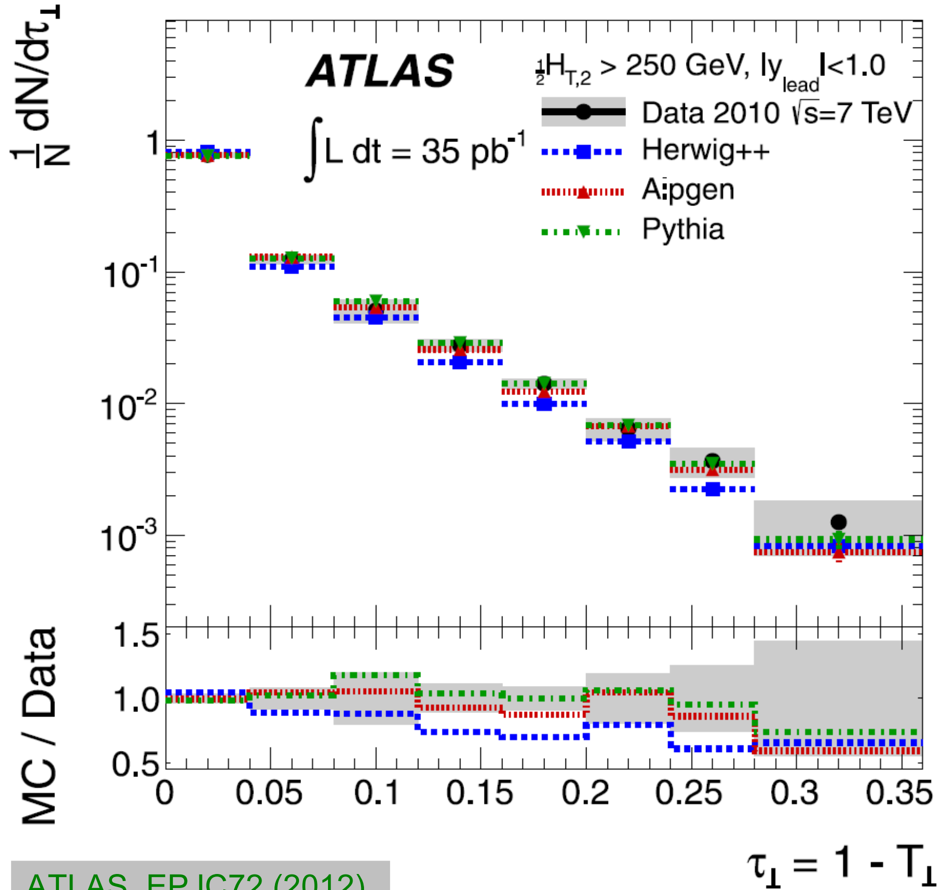
$$T_{\perp,c} \equiv \max_{\vec{n}_T} \frac{\Sigma_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\Sigma_i p_{\perp,i}}$$

High pT jets:
ATLAS: Advantage Pythia & Alpgen
CMS: Advantage Pythia6/8,Herwig++

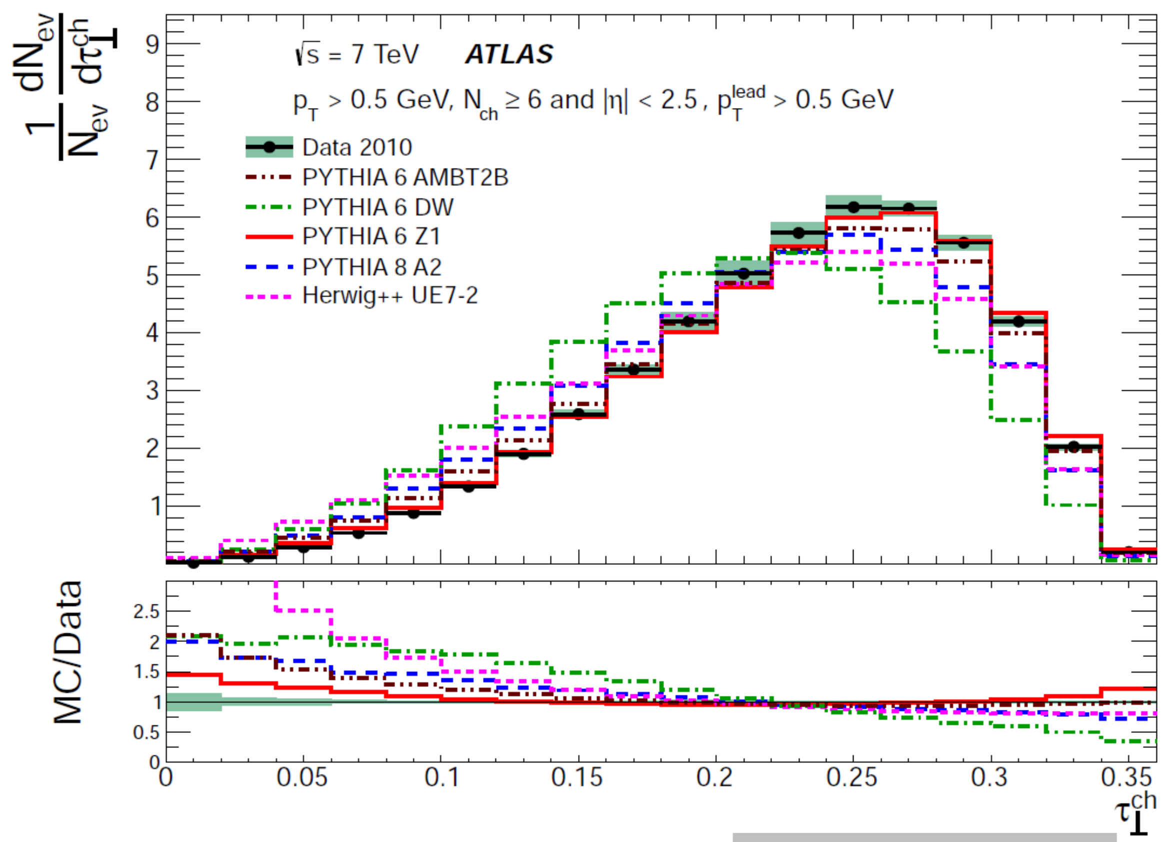
CMS, PLB699 (2011).

New: low pT, charged particles:
ATLAS: Advantage Pythia6 Z1

Better tuning necessary!

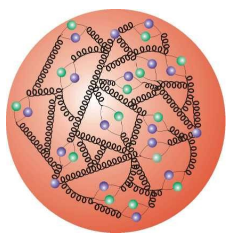


ATLAS, EPJC72 (2012).

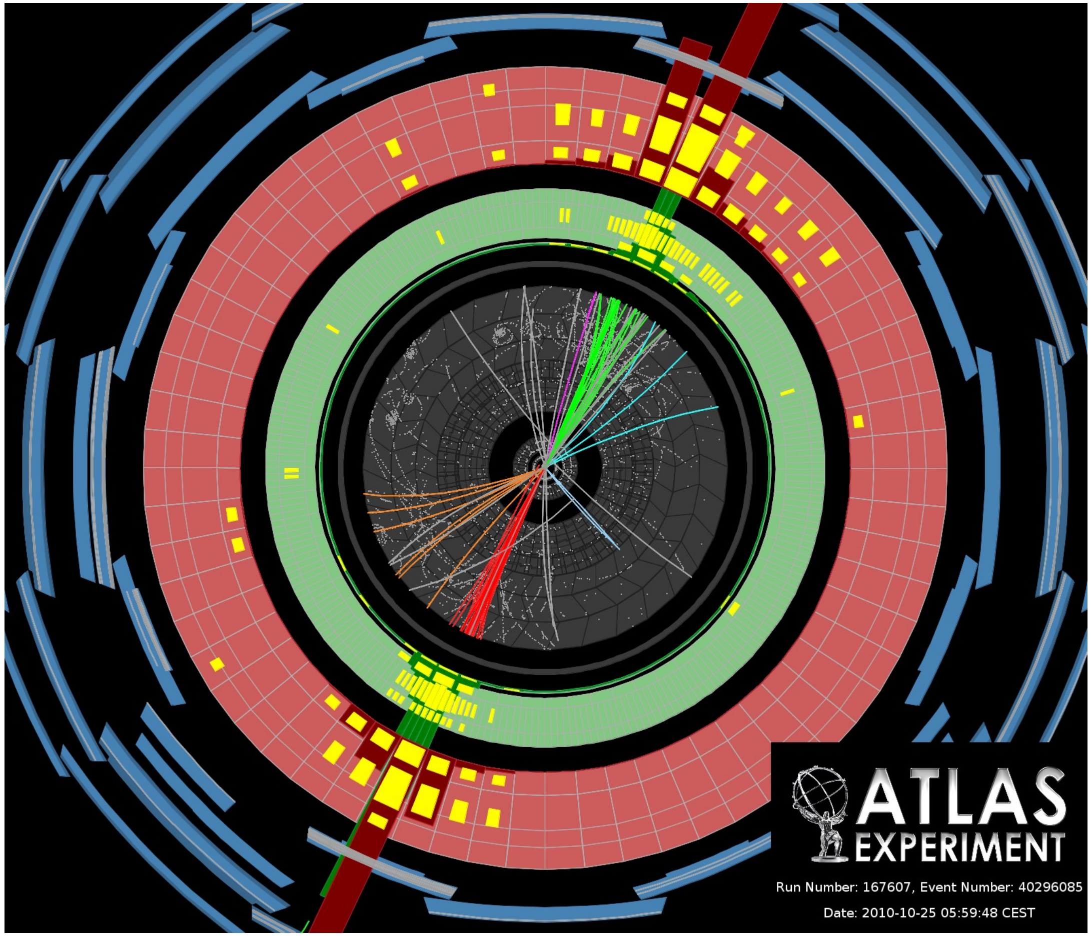


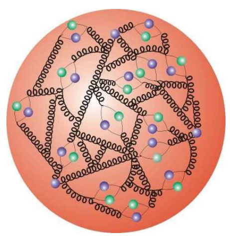
ATLAS, arXiv:1207.6915

High Masses



Proton





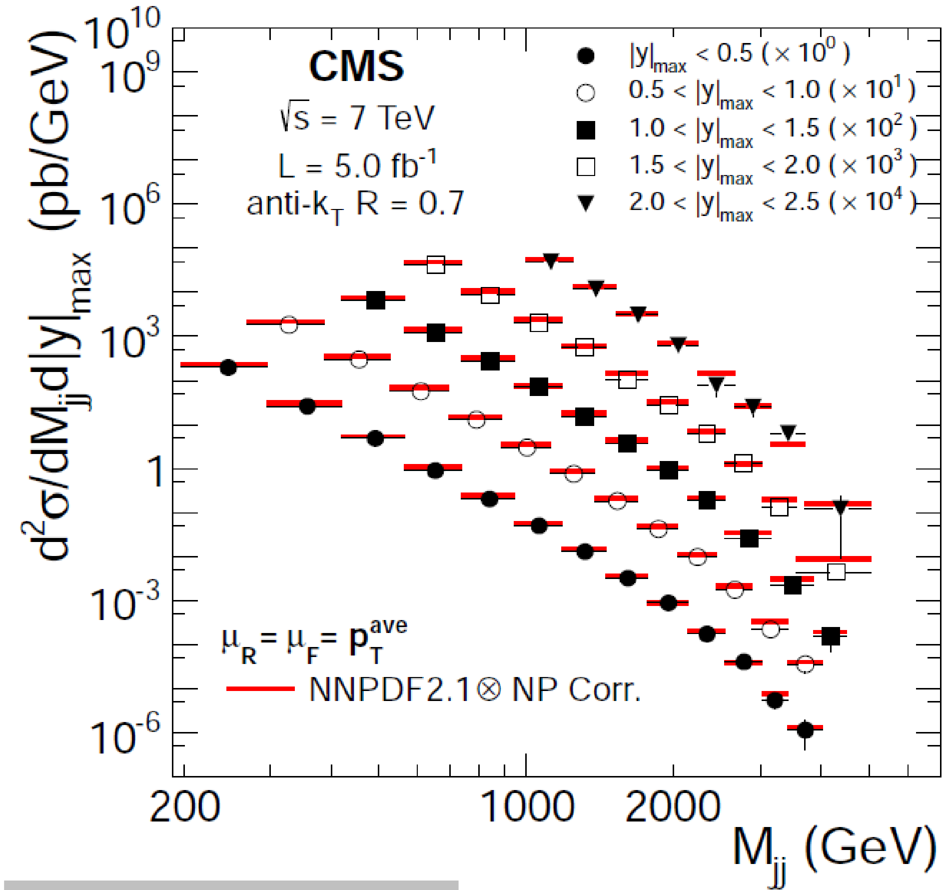
Proton

Dijet Mass

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

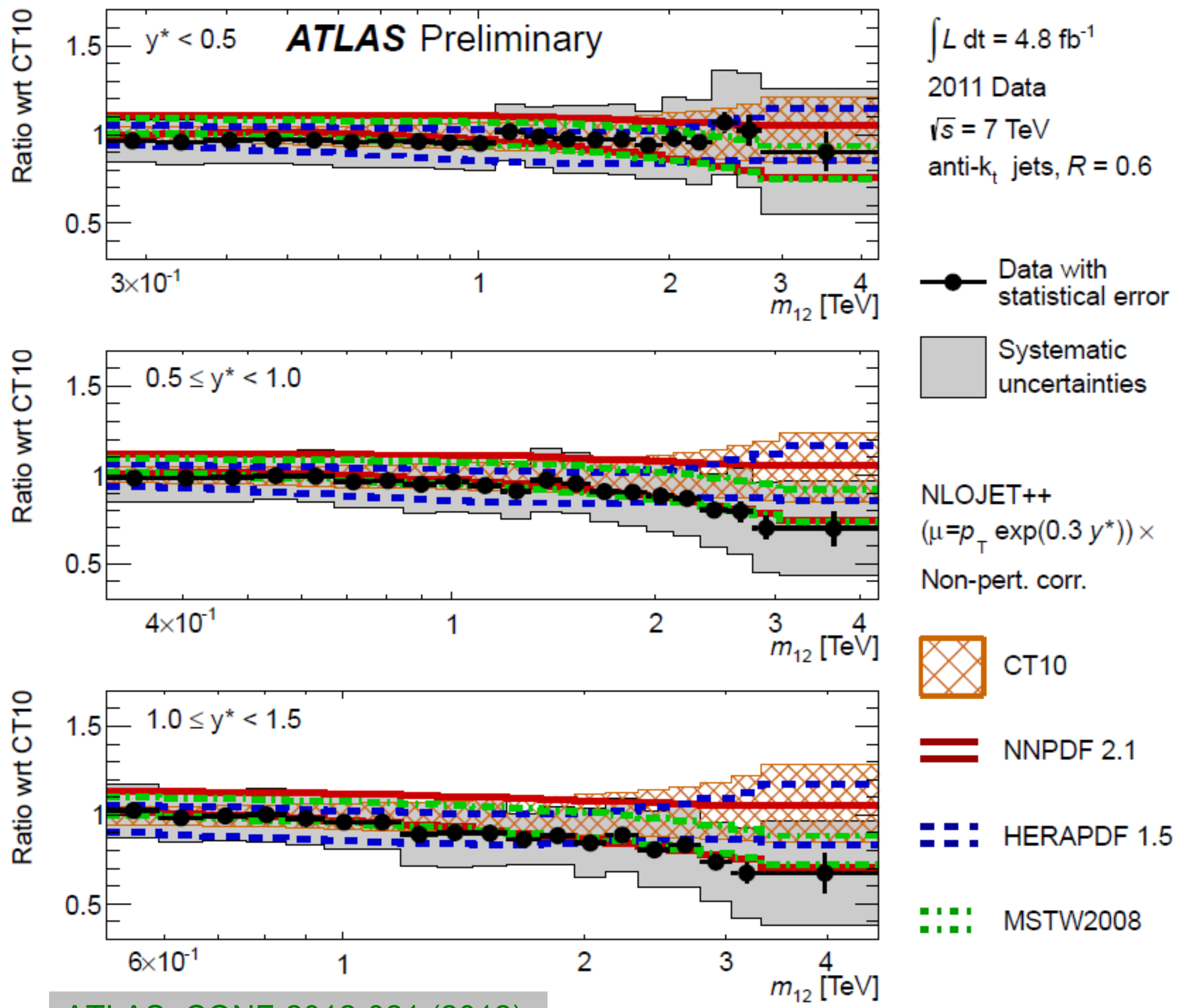
$$\frac{d^2\sigma}{dM_{JJ}d[|y|_{max}, y^*]} \propto \alpha_s^2$$

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



CMS, arXiv:1212.6660 (2012)

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

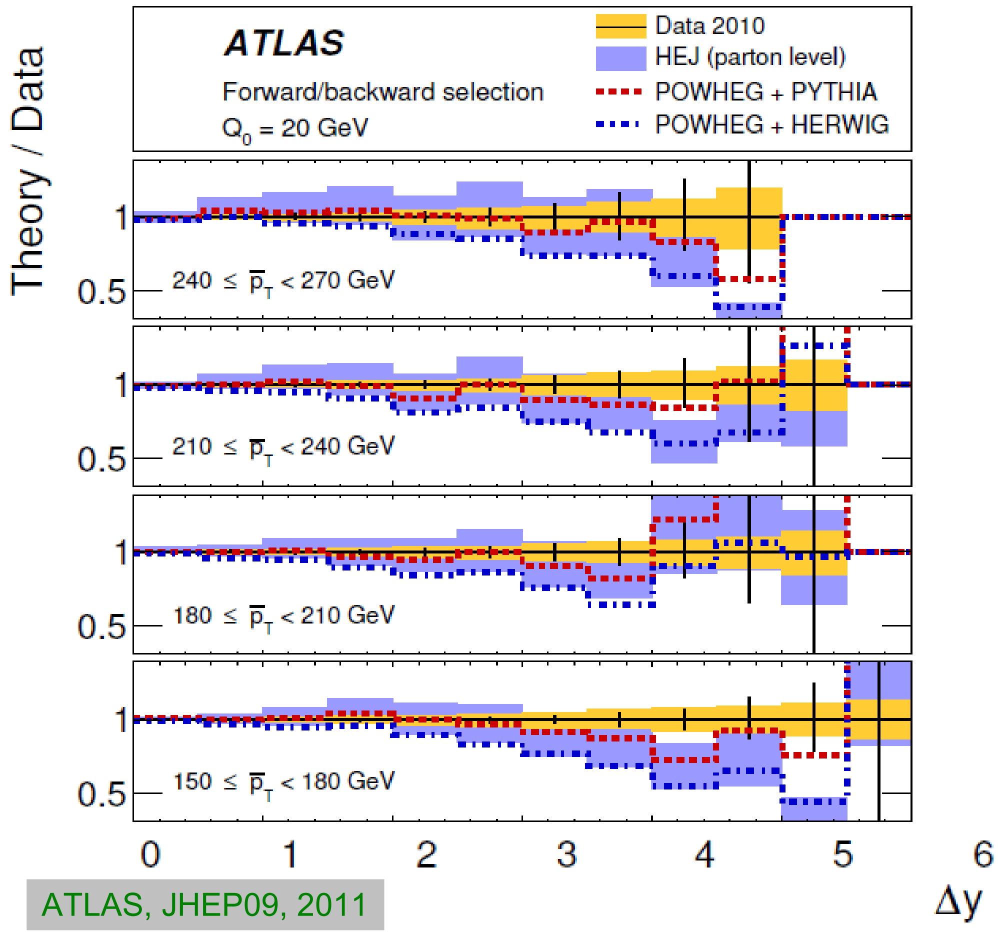


ATLAS, CONF-2012-021 (2012).

Dijets separated in Rapidity

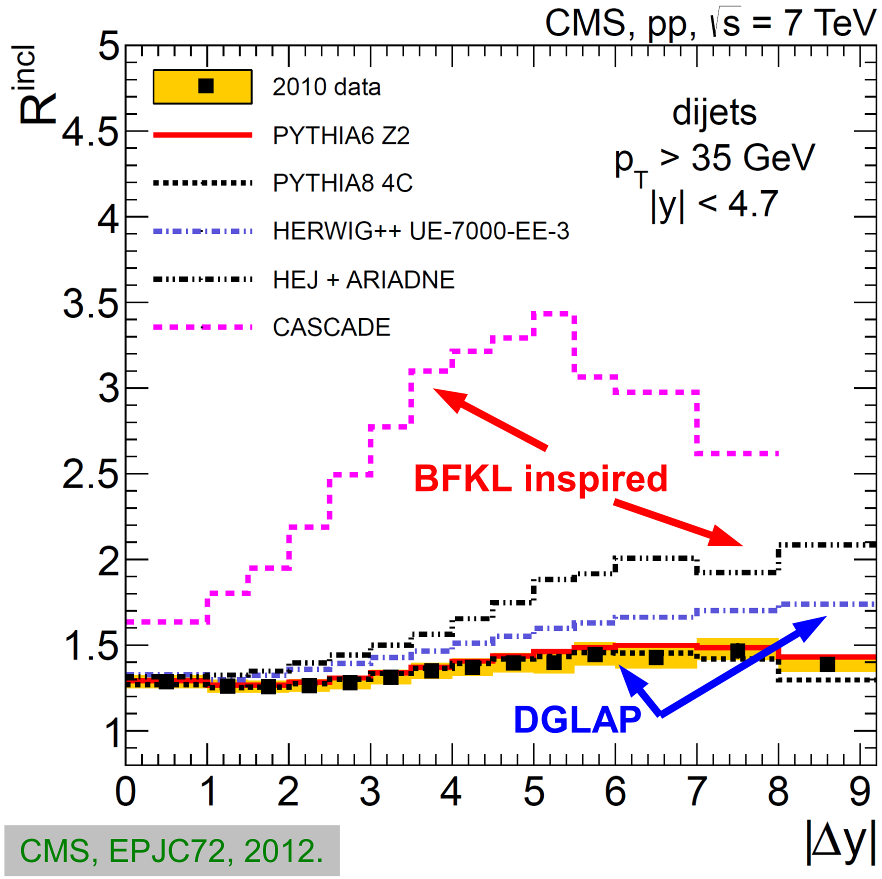
Quantities sensitive to potential deviations from DGLAP evolution at small x
Some MC event generators run into problems … but also BFKL inspired ones!
Large y coverage needed, also useful for WBF tagging jets.

Most forward-backward dijet selection



ATLAS, JHEP09, 2011

All possible dijet pair distances over leading dijet pair distance



CMS, EPJC72, 2012.

Dijet Flavours

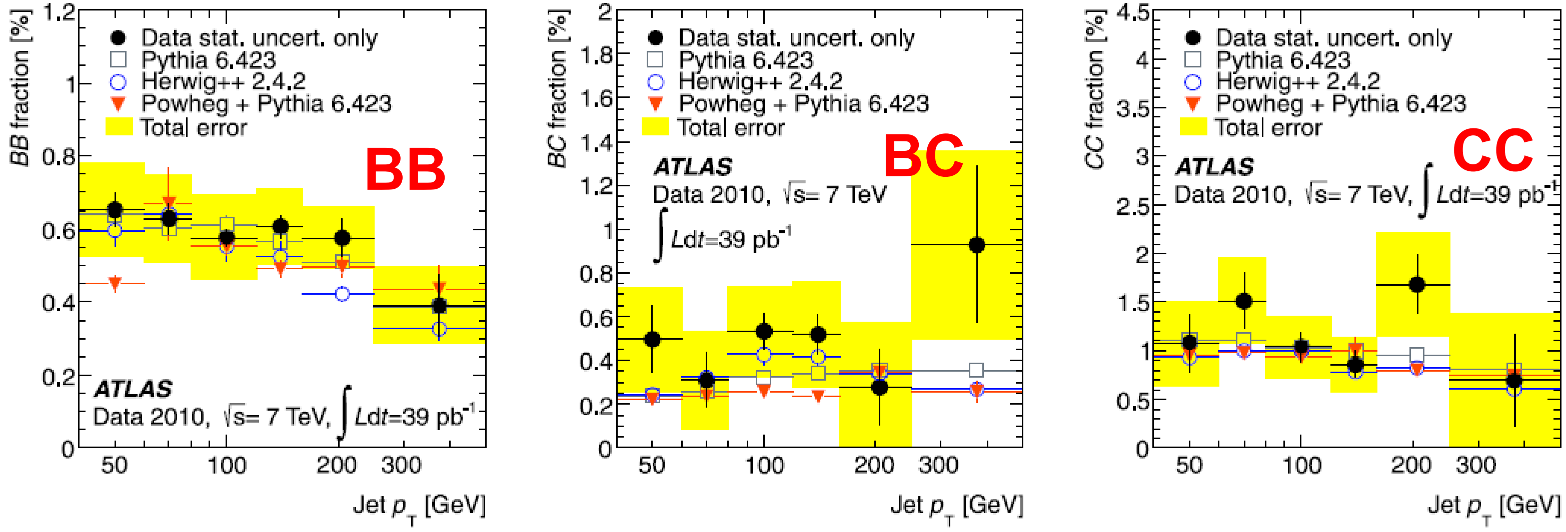
Study of flavour decomposition of both jets in dijet events

Jet flavour determined via template fits to kinematic properties of secondary vertices inside jets

Templates differentiate between B, C and light (U) quarks

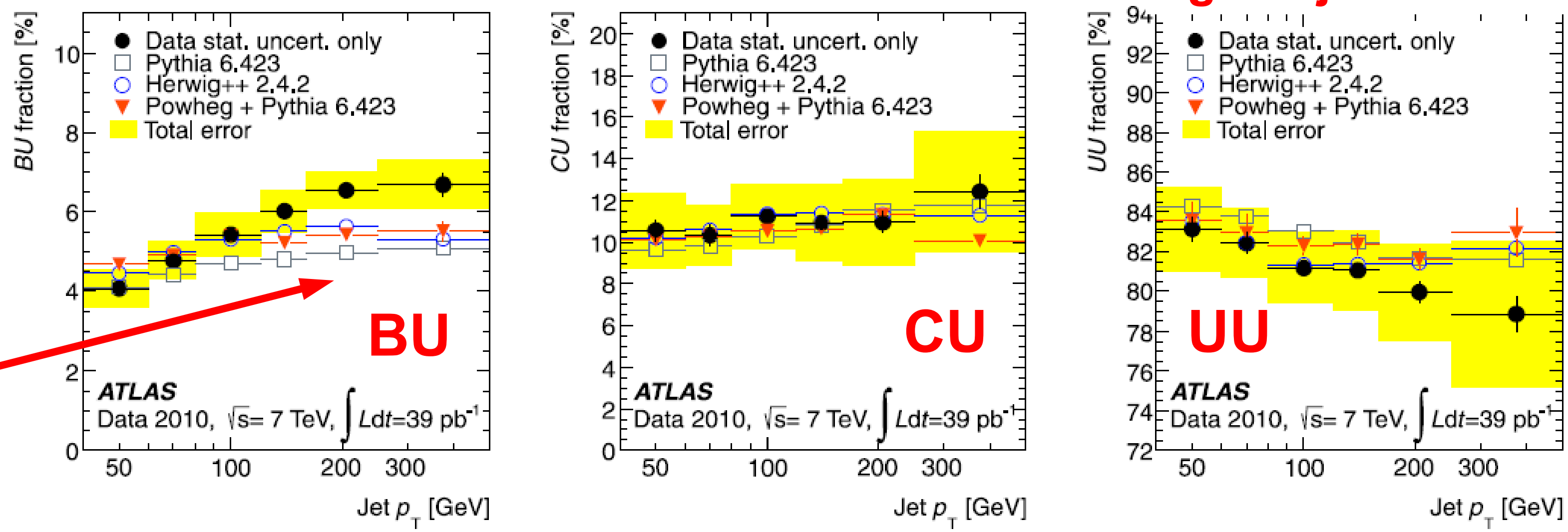
Well described by MC For most flavour pairs

Some discrepancy for B-light (U) contribution at high pT



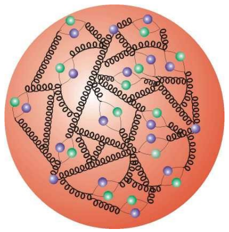
(a) (b)

light dijets ~ 80%

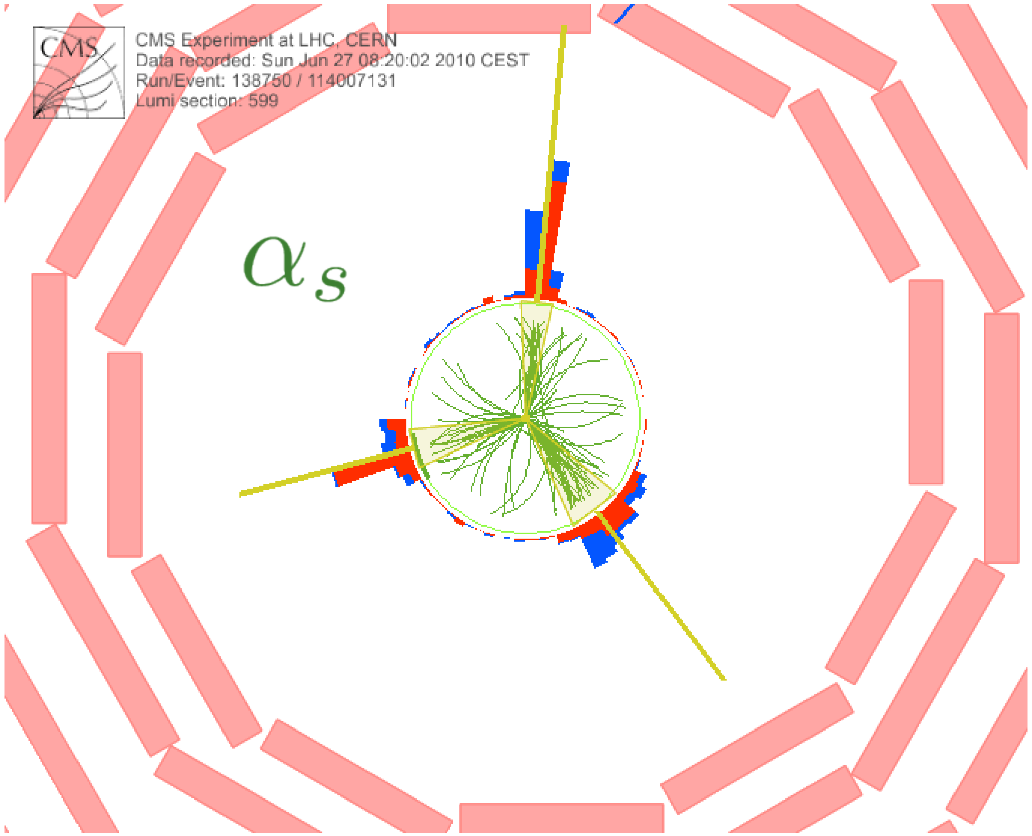


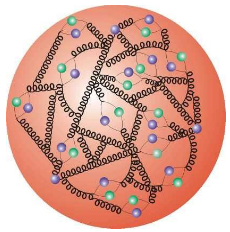
ATLAS, EPJC73, 2013

α_s at High Scales



Proton



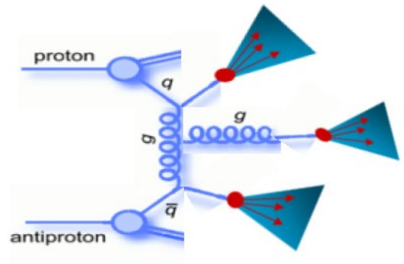


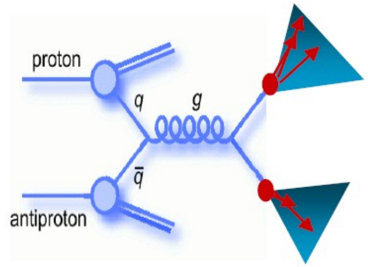
Proton

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
- → reduces other theor. and exp. uncertainties along the way
- → eliminates luminosity dependence (normalization)





↔ α_s

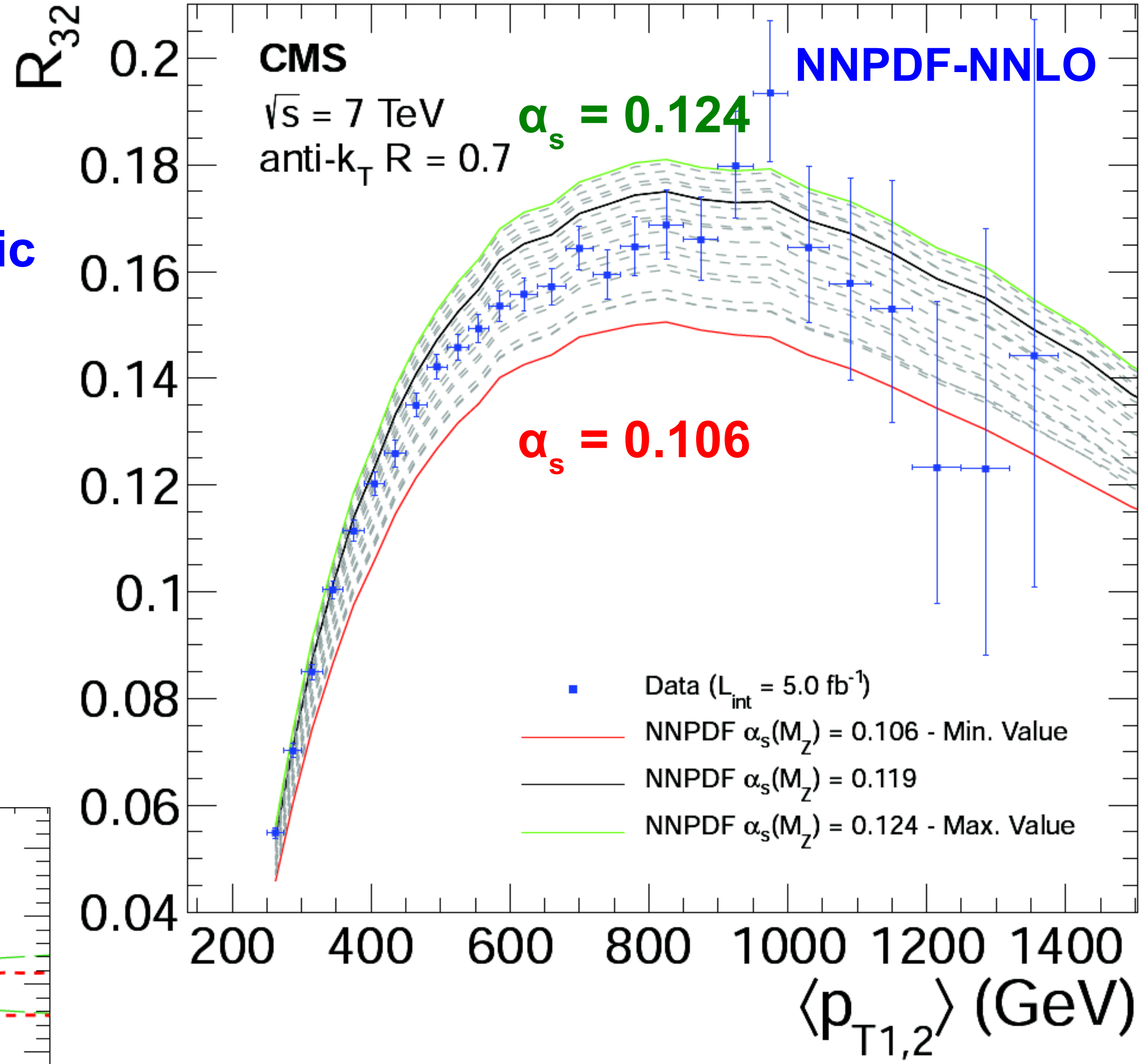
M. Wobisch

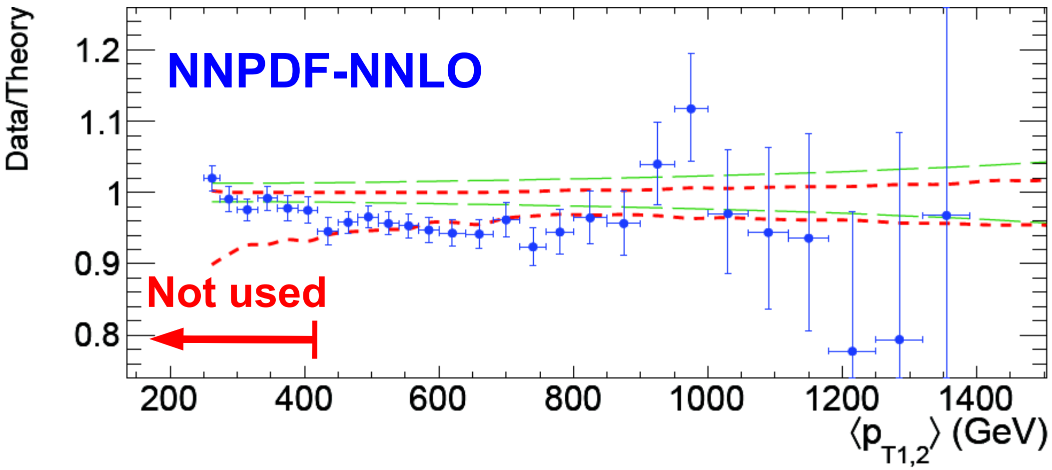
- Choices of CMS:
  - Ratio of inclusive 3-jet to 2-jet production $R_{32} = \frac{d\sigma_{3+}/dp_\mathrm{T}}{d\sigma_{2+}/dp_\mathrm{T}} \propto \alpha_s(Q)$
  - Minimal jet pT: $p_\mathrm{T} > 150\,\mathrm{GeV}$
  - Maximal jet rapidity: $|y| < 2.5$
  - Average dijet p_T as scale $Q = \langle p_{\mathrm{T}1,2}\rangle = \frac{p_{\mathrm{T}1} + p_{\mathrm{T}2}}{2}$

- Data sample: 2011 $\mathcal{L}_\mathrm{int} = 5.0\,\mathrm{fb}^{-1}$

Comparison to Theory

- Fits only above 420 GeV to avoid threshold effects
- Error bars show full uncertainty including the correlated systematic ones
- Agreement within uncertainties
- Similarly described by CT10 and even better by MSTW2008
- Discrepancies observed with ABM11





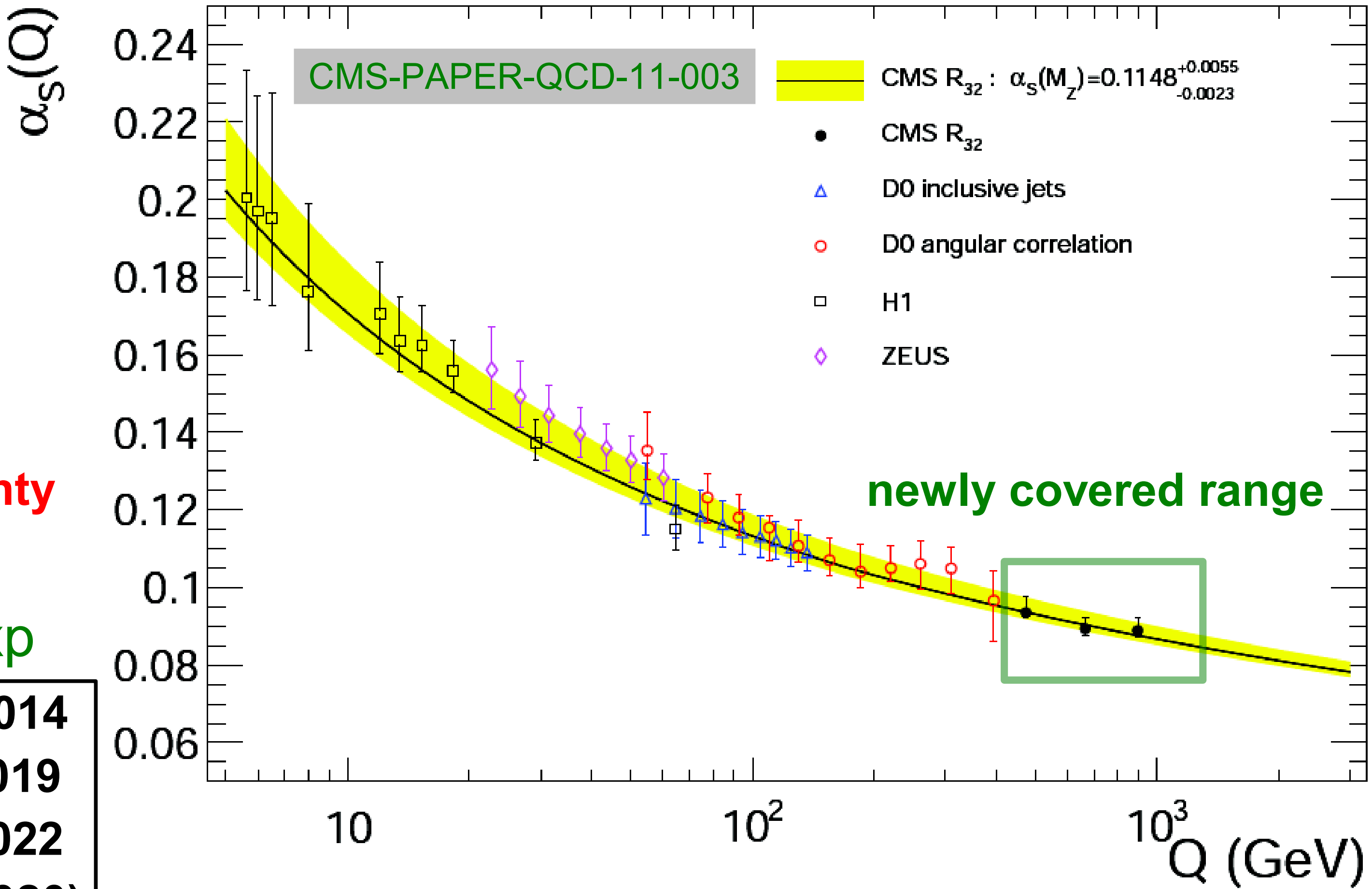
CMS-PAPER-QCD-11-003

Determination of α_s (NLO)

- Comparison to other hadron collider experiments
- Extraction also performed for three subranges in Q
- Small exp. uncertainty
- Dominated by th. uncertainty:
  - asymmetric scale uncertainty
  - PDF uncertainty

exp

NNPDF21:	$\alpha_s(M_Z) = 0.1148 \pm 0.0014$
CT10:	$\alpha_s(M_Z) = 0.1135 \pm 0.0019$
MSTW2008:	$\alpha_s(M_Z) = 0.1141 \pm 0.0022$
(ABM11:	$\alpha_s(M_Z) = 0.1214 \pm 0.0020$)



PDF uncertainty: Repeat fit for each NNPDF replica → get estimators for μ and σ

Scale uncertainty: Repeat fit for six variations of (μ_r,μ_f) → get maximal deviation

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp}) \pm 0.0018\,(\mathrm{PDF}) \pm^{0.0050}_{0.0000}\,(\mathrm{scale})$$

Outlook

- Already at 7 TeV LHC opened up new regimes in phase space
- Results for 8 TeV will come soon
- Data quality makes jet measurements PRECISION PHYSICS
- More precise theory required (see next talk)
- New ideas for analyses are explored
- Be prepared for interesting comparisons

Outlook

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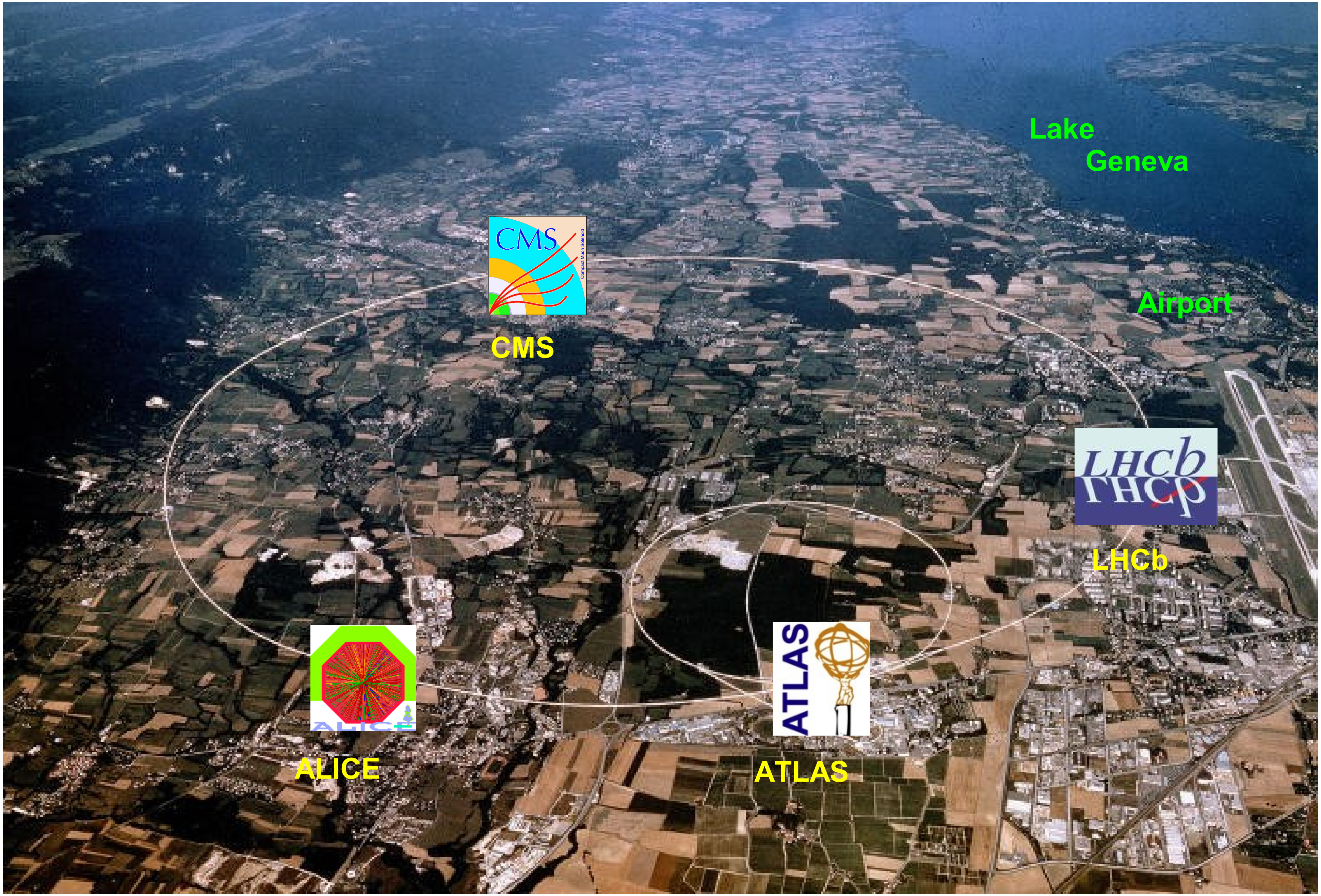
Thank you for your attention and to the Organizers for the opportunity to speak here!

Backup Slides

LHC Aerial View



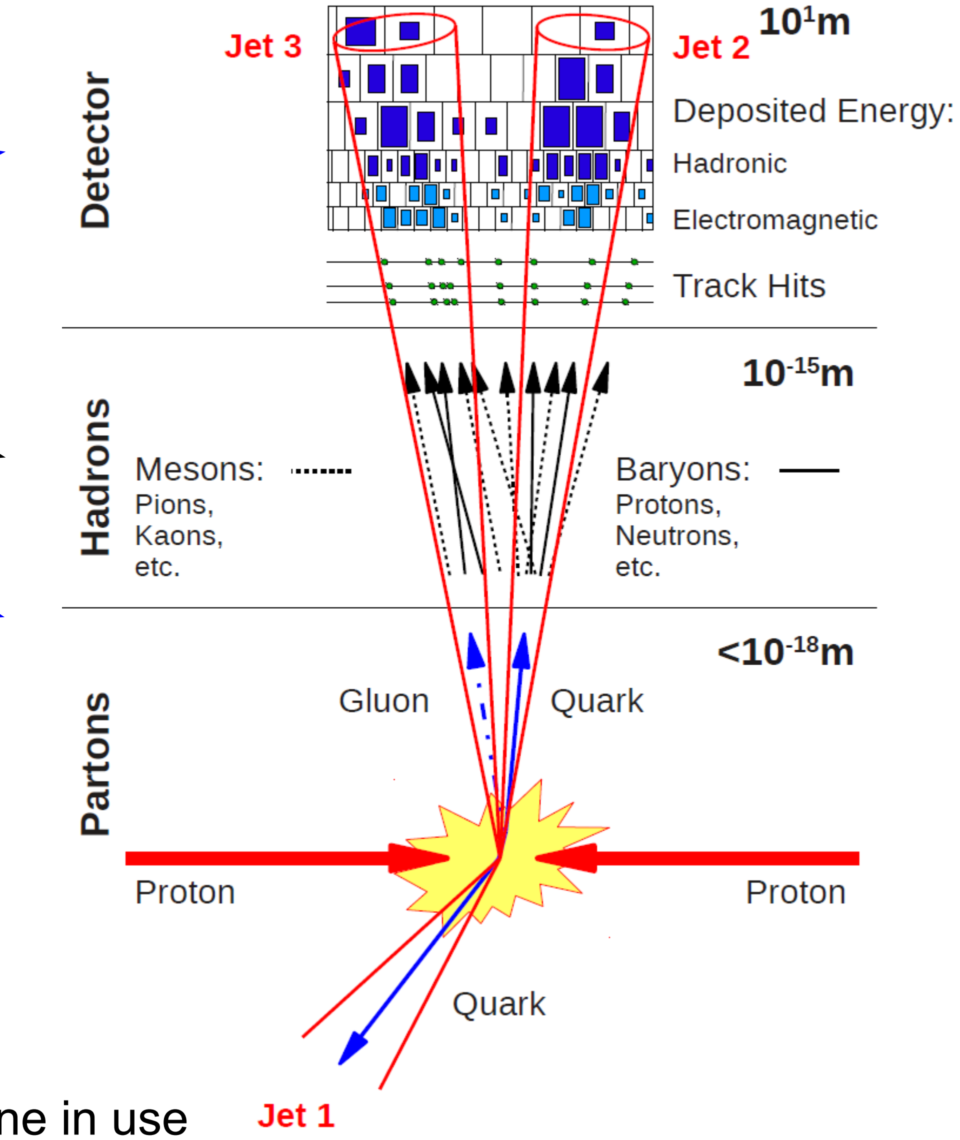
Jet Algorithms

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

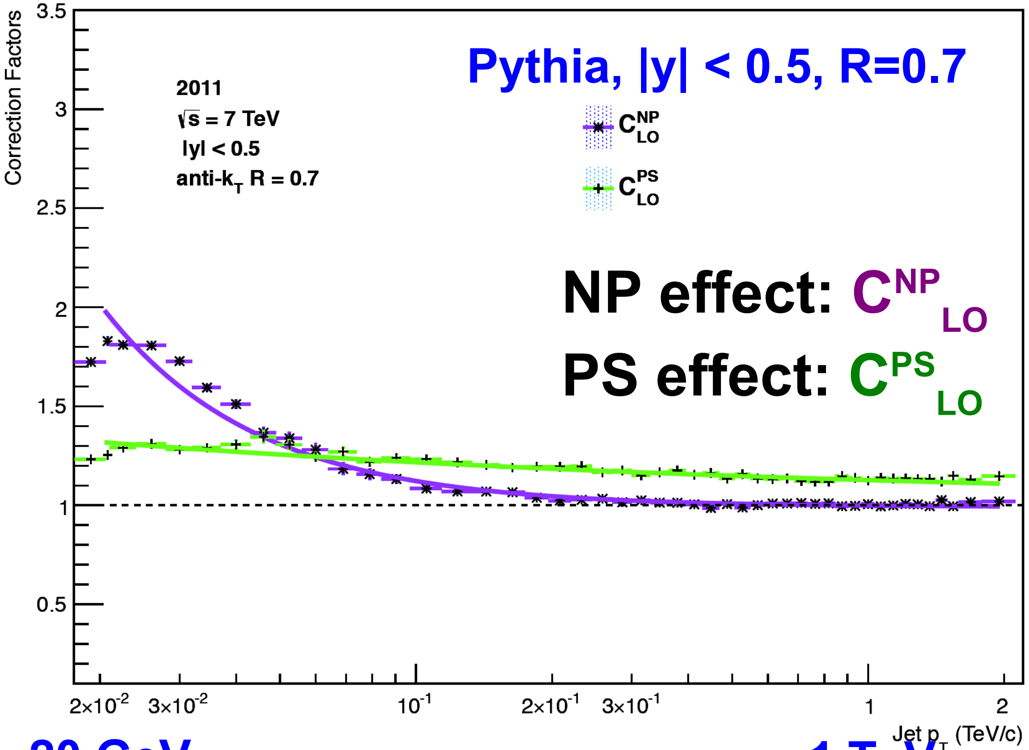
Standard at LHC: anti-kT

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

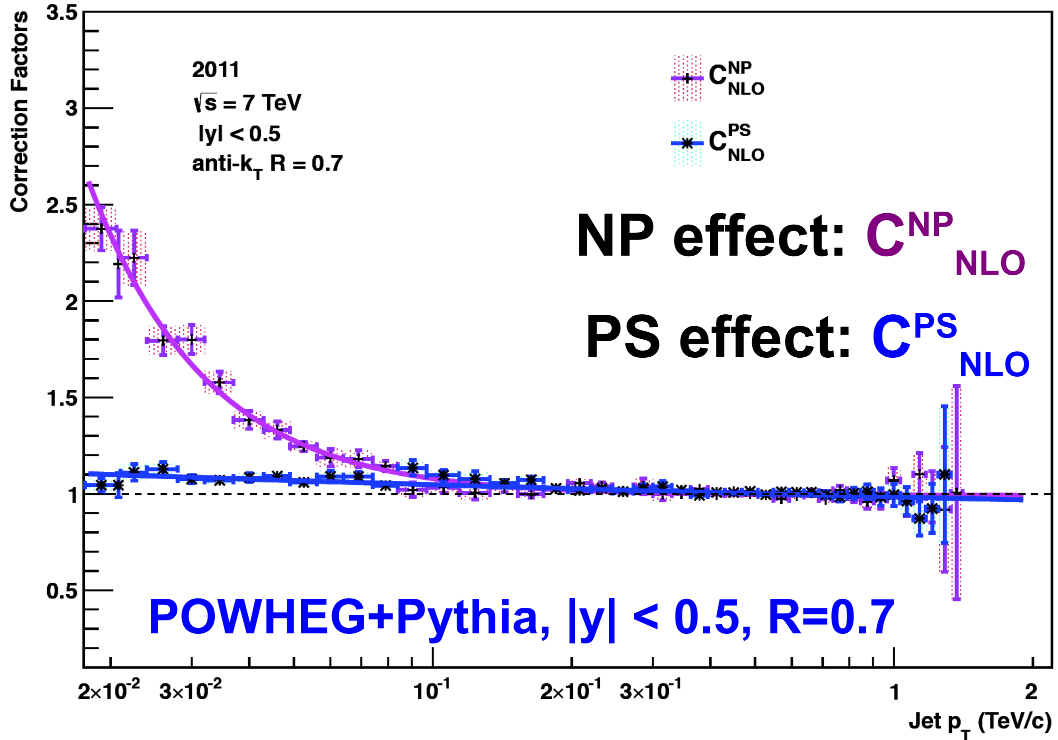
Non-perturbative Corrections

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



20 GeV 1 TeV



20 GeV 1 TeV

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)

Data comparison to ABM11

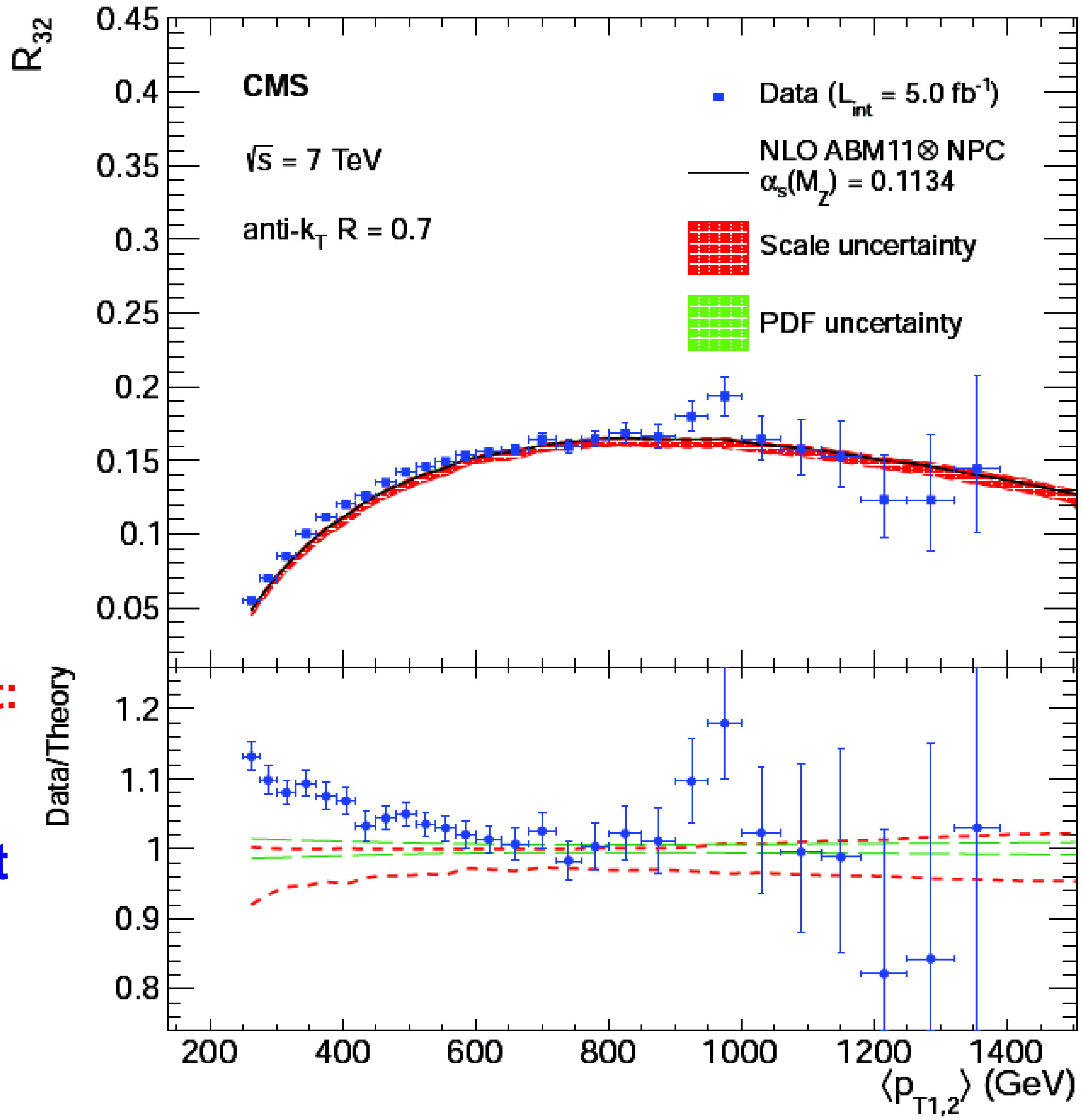
- **Discrepancies with ABM11 especially below 600 GeV**
- **Fits of the strong coupling tend versus the upper edge of the available series in alpha_s**
  - **With ABM11 NNLO PDF set extrapolation beyond α_s = 0.120 required:**

    $$\alpha_S(M_Z) = 0.1214 \pm 0.0020(\text{exp.})$$

  - **Consistent with ABM11 NLO PDF set:**

    $$\alpha_S(M_Z) = 0.1214 \pm 0.0018(\text{exp.})$$

- **Much smaller gluon down to 50% at high x at the same time as preference for smaller couplings**
- **To be further discussed/resolved ...**

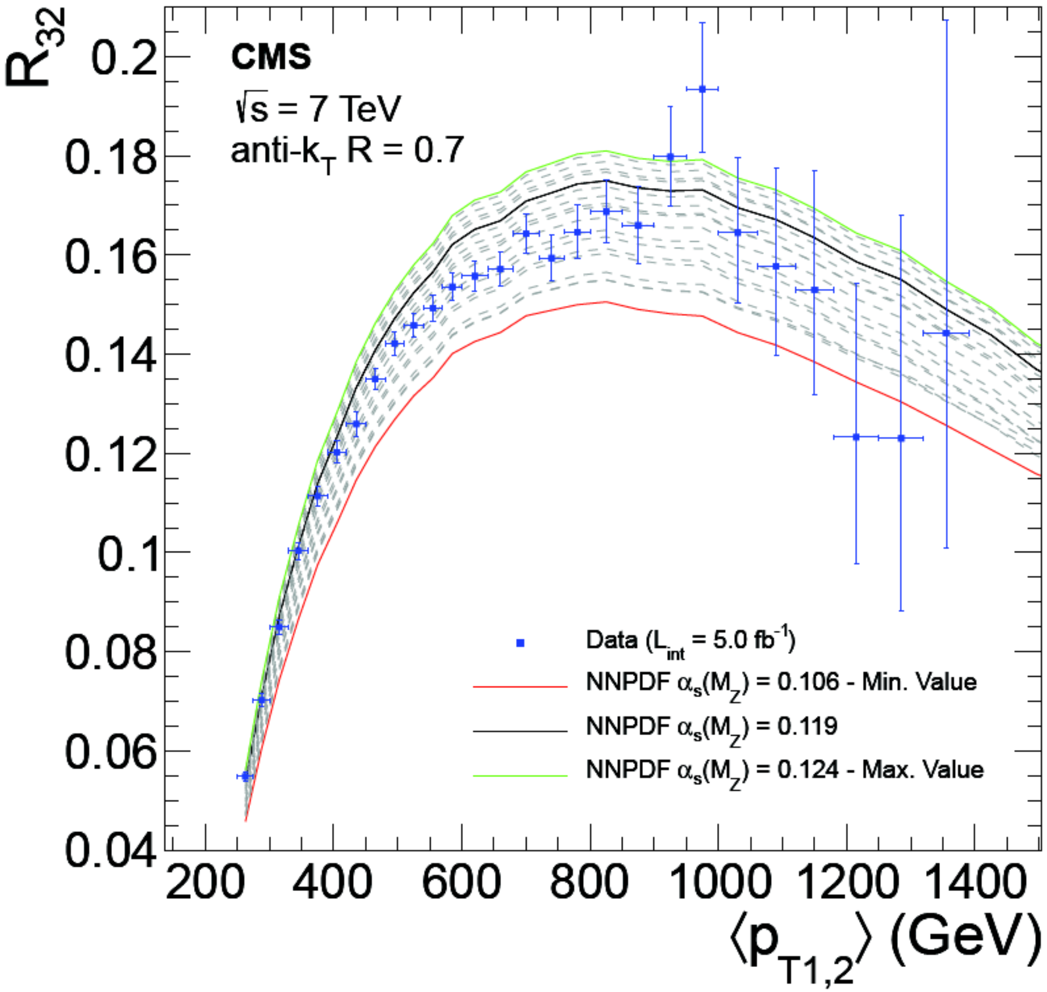


CMS-PAPER-QCD-11-003

Comparison of Sensitivity 1

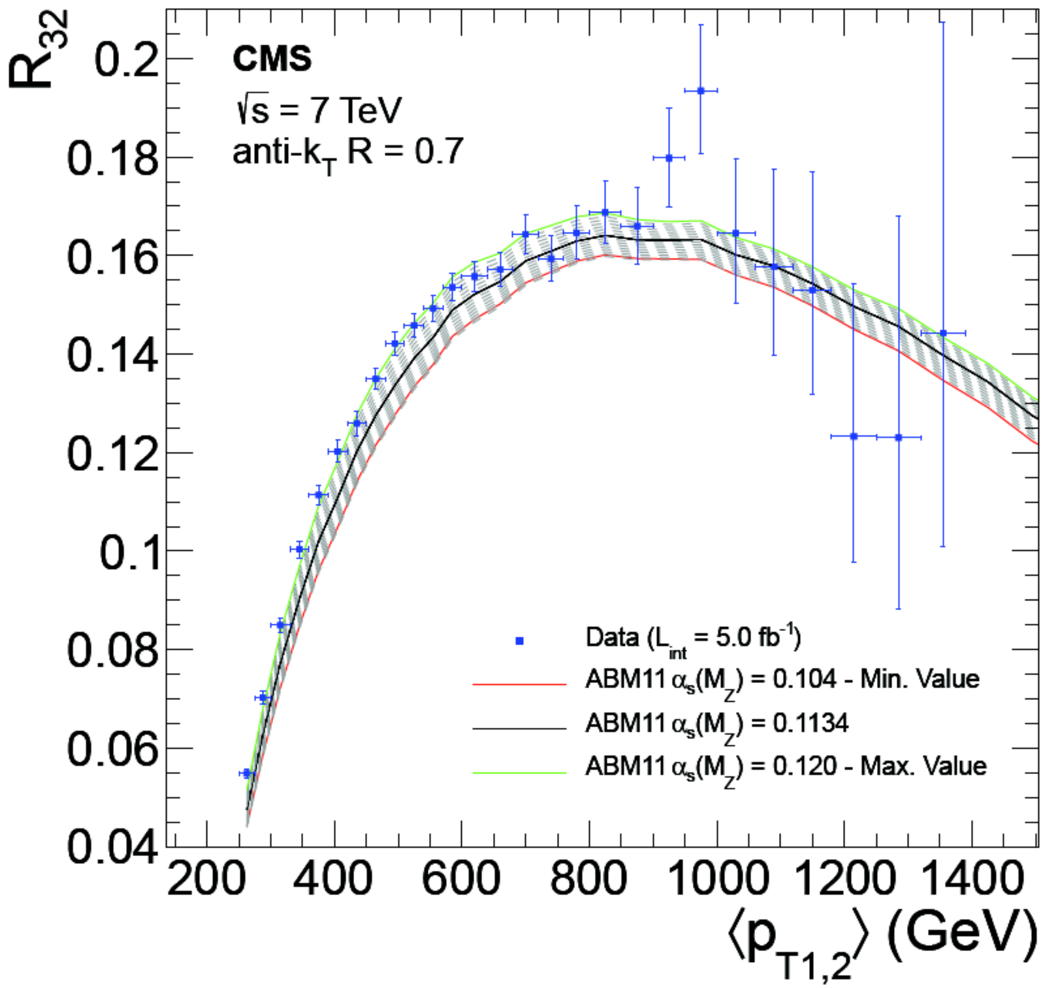
NNPDF21-NNLO

$$\alpha_S(M_Z) = 0.106 \ldots 0.124$$



ABM11-NNLO

$$\alpha_S(M_Z) = 0.104 \ldots 0.120$$

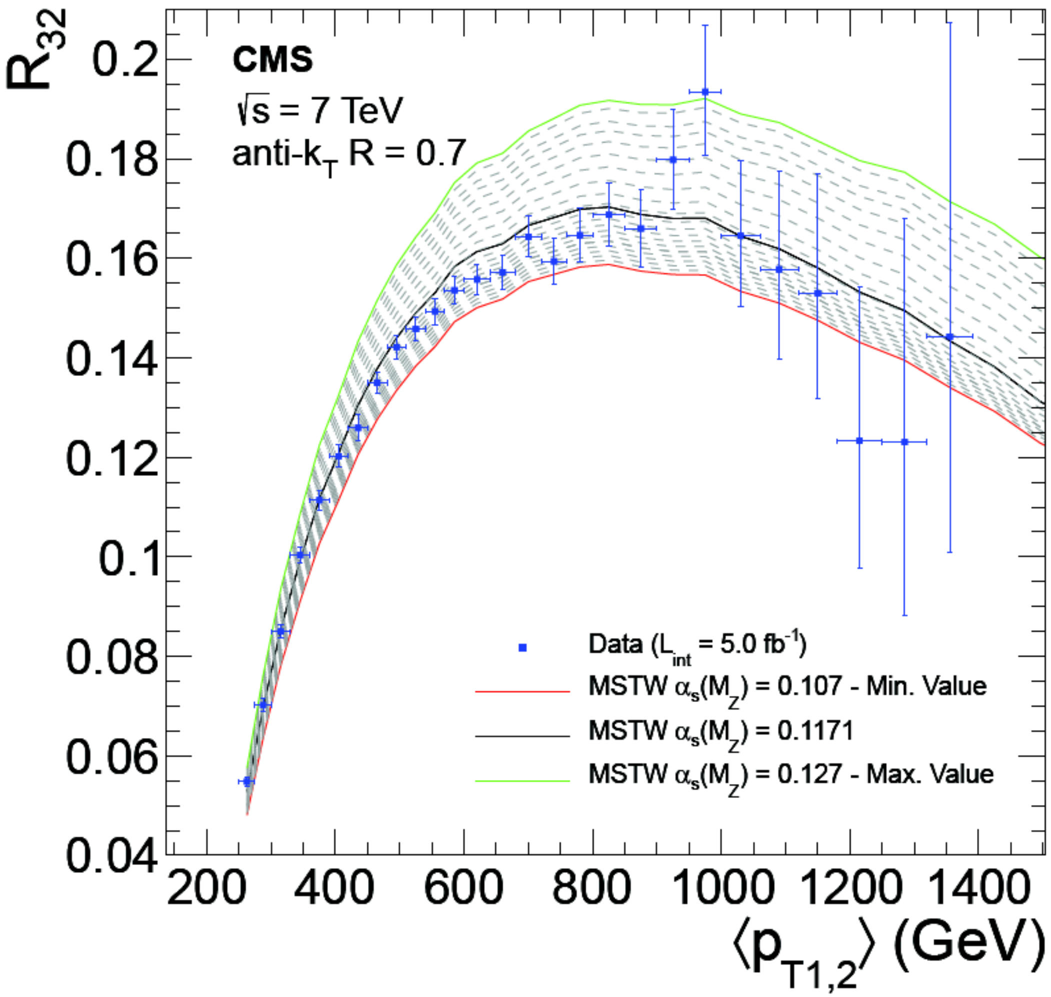


CMS-PAPER-QCD-11-003

Comparison of Sensitivity 2

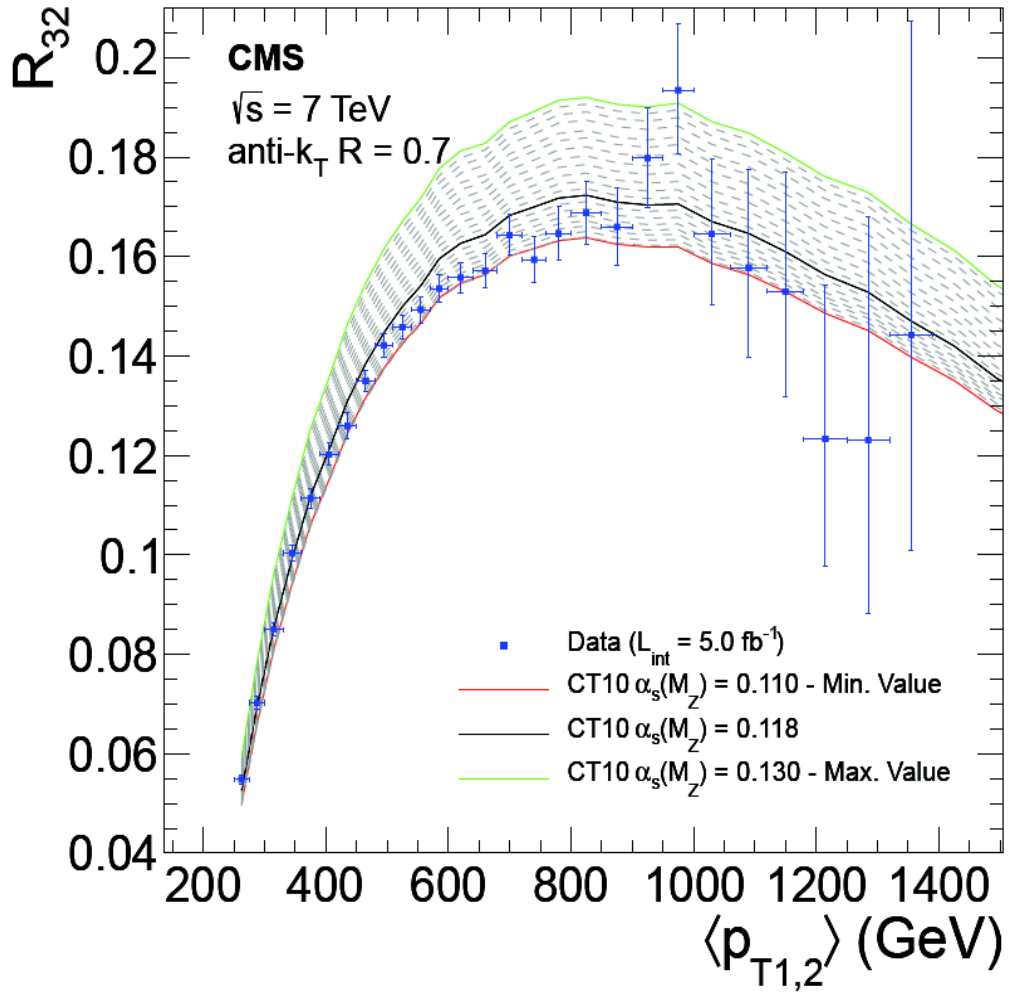
MSTW2008-NNLO

$$\alpha_S(M_Z) = 0.107 \ldots 0.127$$



CT10-NNLO

$$\alpha_S(M_Z) = 0.110 \ldots 0.130$$



CMS-PAPER-QCD-11-003

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:** $c_{\text{JEC}} \approx 1.2 \ldots 1.0$
- **Correction of detector effects using Bayesian iterative unfolding (RooUnfold)** $c_{\text{DET}} < 5\%$
  - **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%:**
  - **Provided as 16 mutually uncorrelated sources; fully correlated within source; Gaussian behaviour assumed**
  - **Dominated by absolute scale, followed by high pT extrapolation**

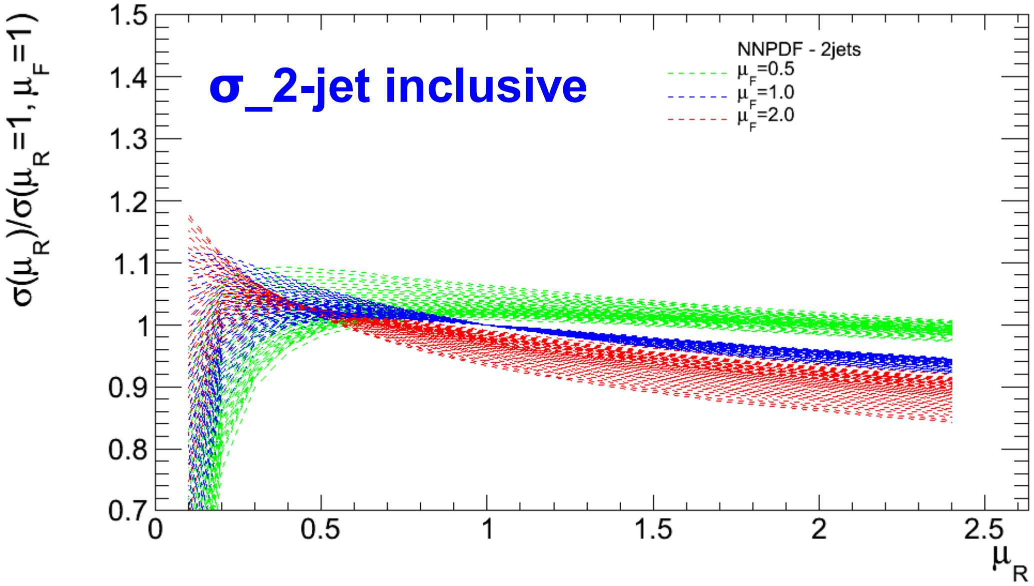
$$\Delta R/R \approx 1.2\%$$

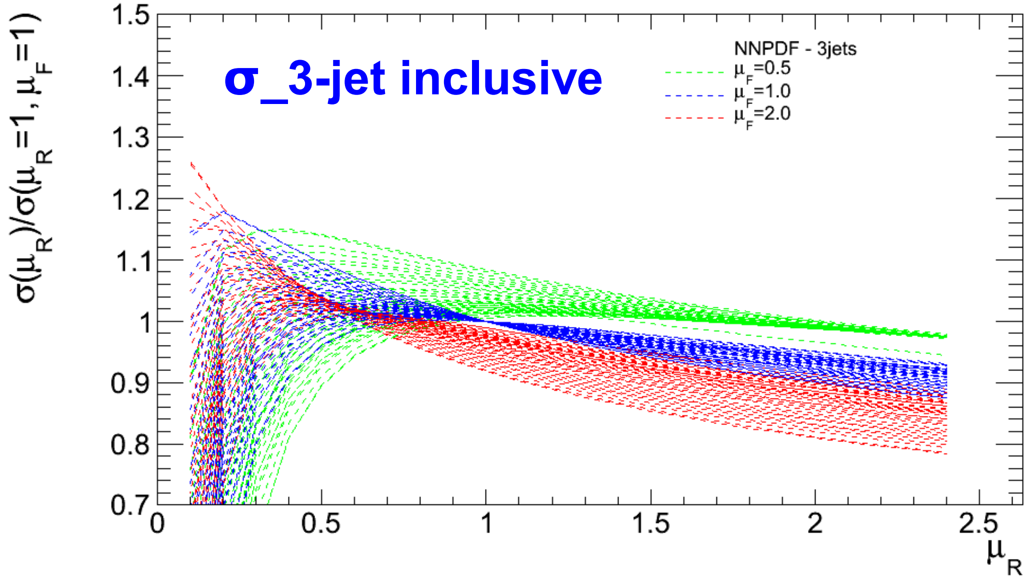
- **Unfolding uncertainty accounting for:**
  - **Variation of jet p_T spectral slopes following differences from Pythia6 Z2 (agrees with MadGraph) and Herwig++ 2.3**
  - **Variation of jet energy resolution (JER)**
  - **Addition of non-Gaussian tails to JER**

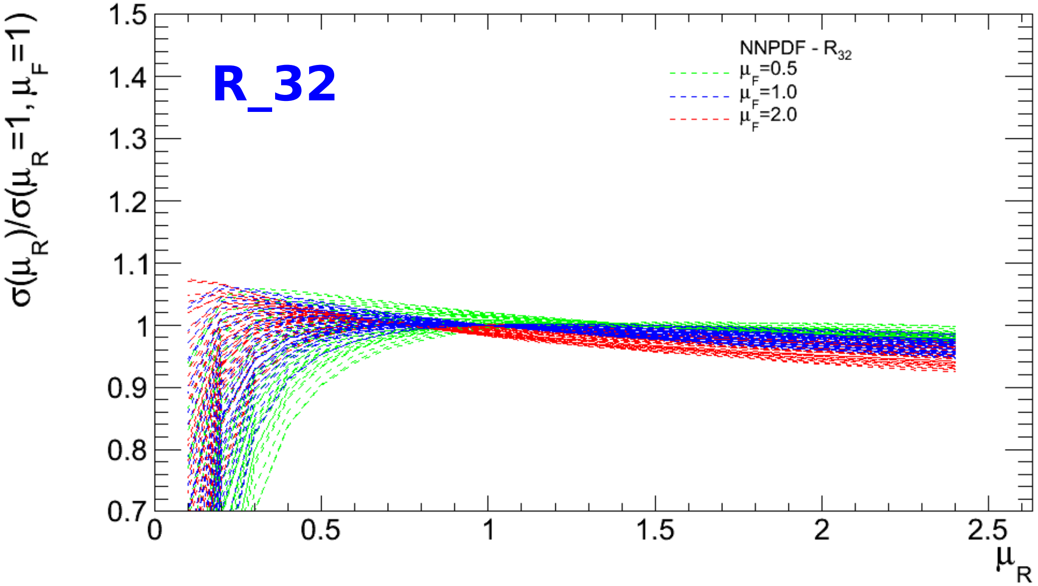
$$\Delta R/R < 1.0\%$$

- **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**

R_32 Scale Dependence







fastNLO & G. Flouris

α_s from inclusive Jets (NLO)

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

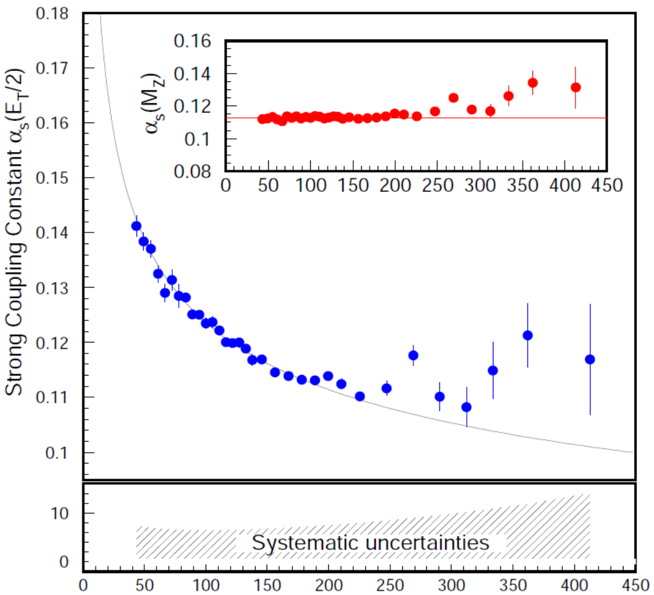
D0: $\alpha_s(M_Z) = 0.1161^{+0.0041}_{-0.0048}(\mathrm{total})$

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

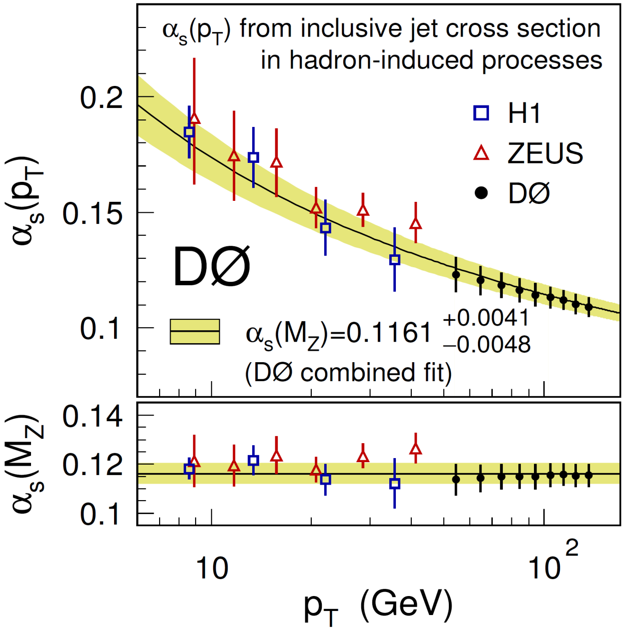
D0: ± 0.004 total

M/S: ± 0.005 exp.

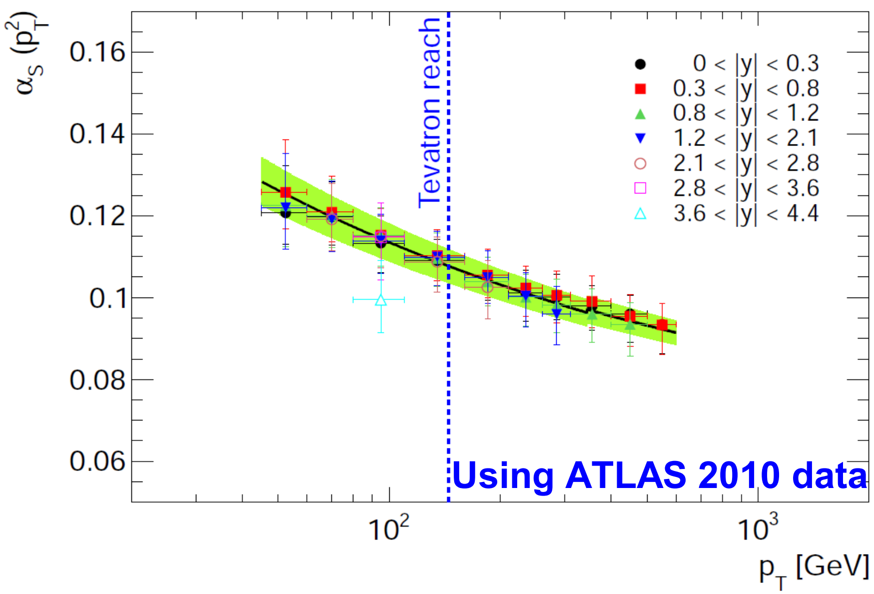
Attention:
Evolution of PDFs from low to high Q assumes the validity of the RGEs ...



CDF, PRL88, 2002



D0, PRD80, 2009

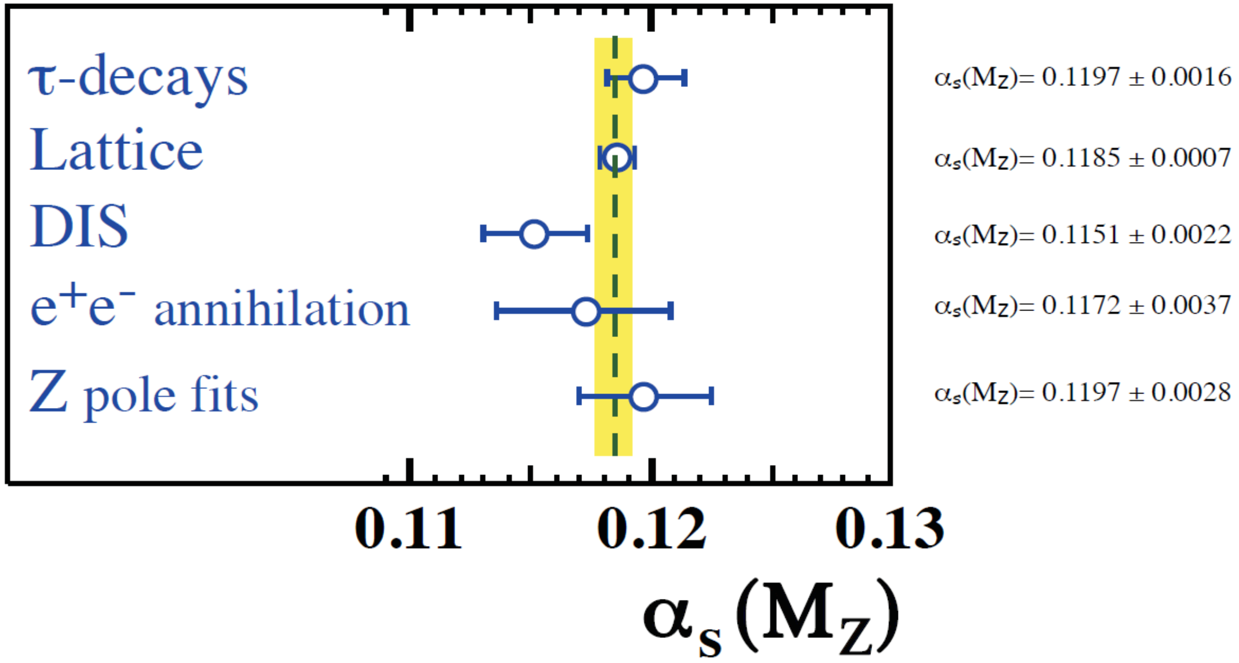


Malaescu/Starovoitov, EPJC72, 2012

α_s World Summary

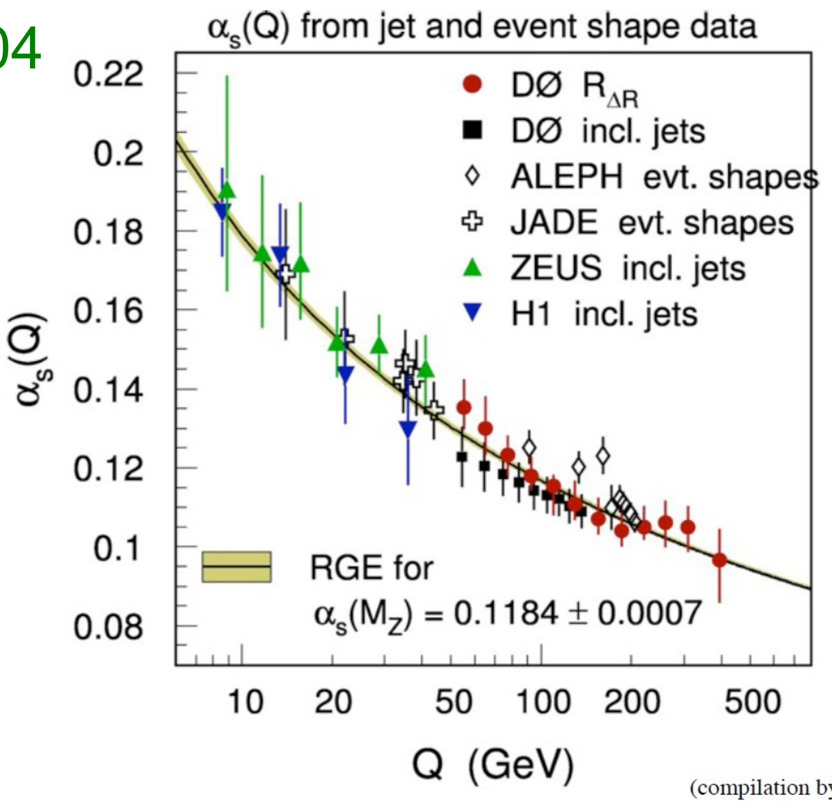
S. Bethke, 2012:

NNLO: ± 0.002 – 0.004



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

PDG2012



D0, PLB718 (2012) 56-63

(compilation by D0)

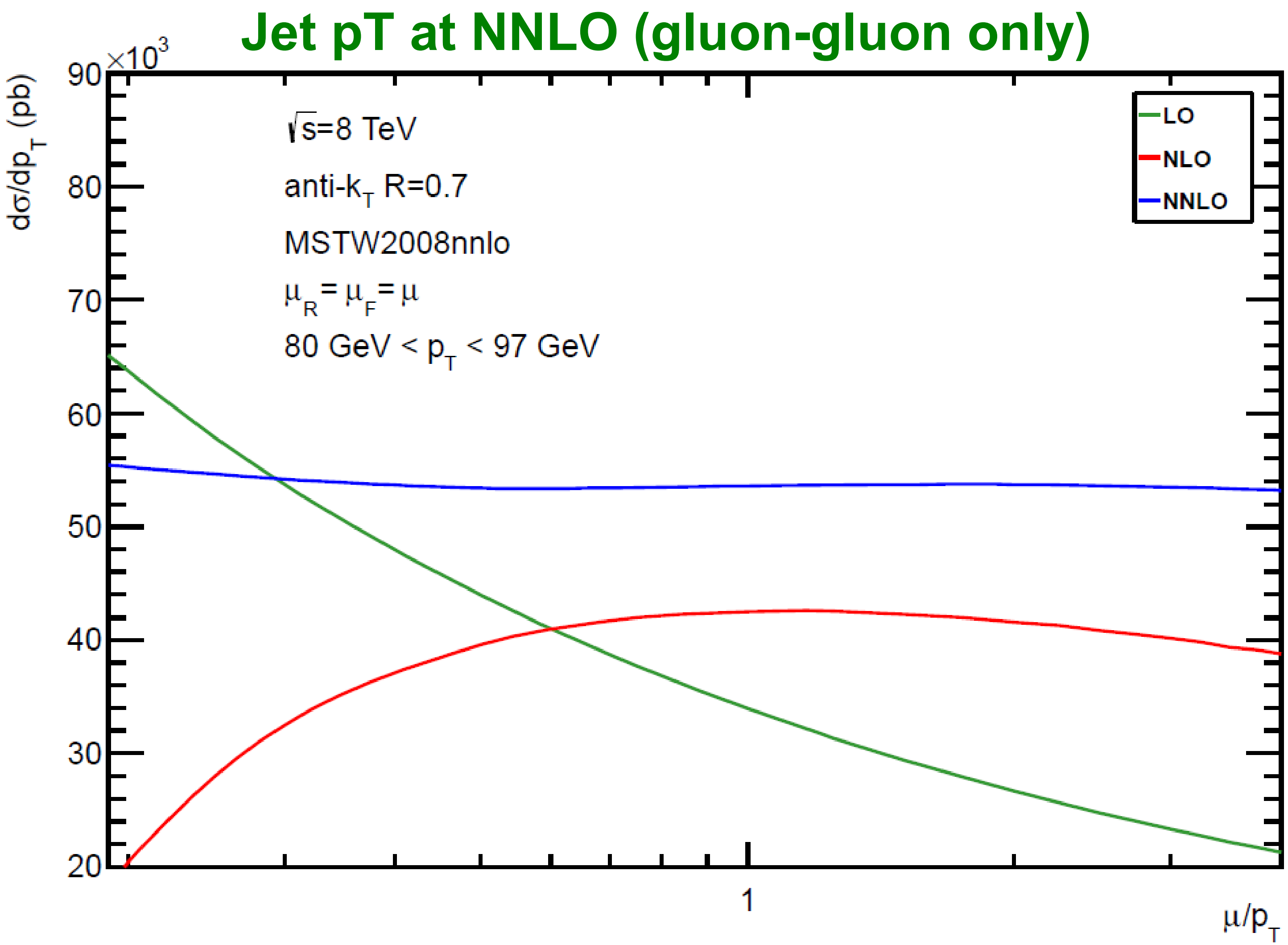
D0: < ± 0.001 exp.

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

Tevatron limit, published last year

LHC from jets starts here ...

NNLO Scale Dependence

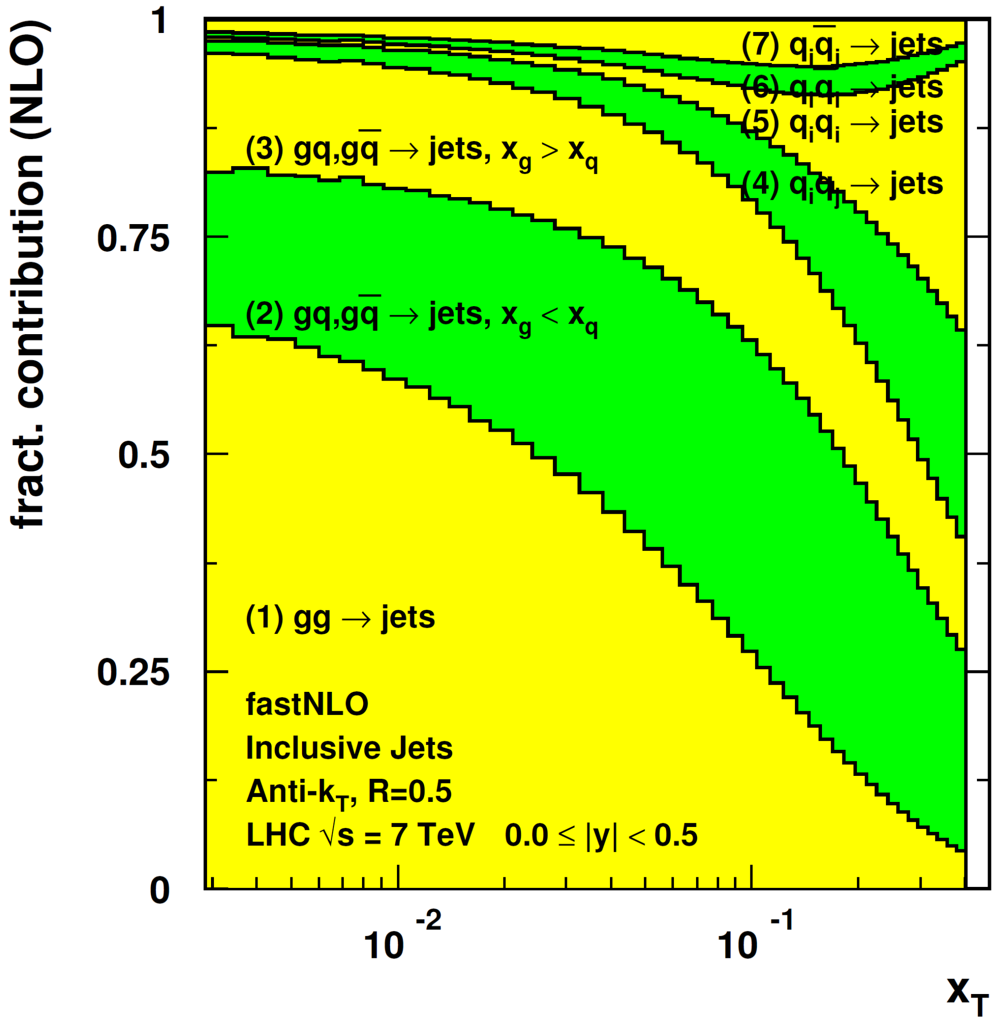


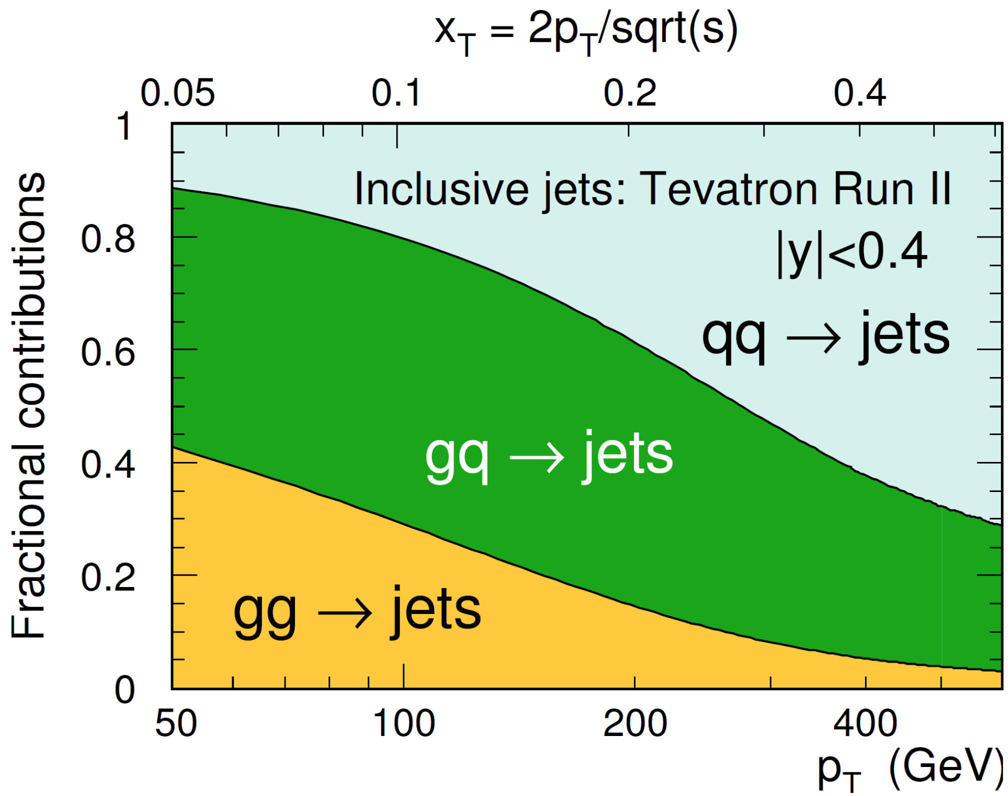
$|y| < 4.4$, 80 GeV $< p_T <$ 97 GeV

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

Process Decomposition

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





Achievements

30 years ago ...

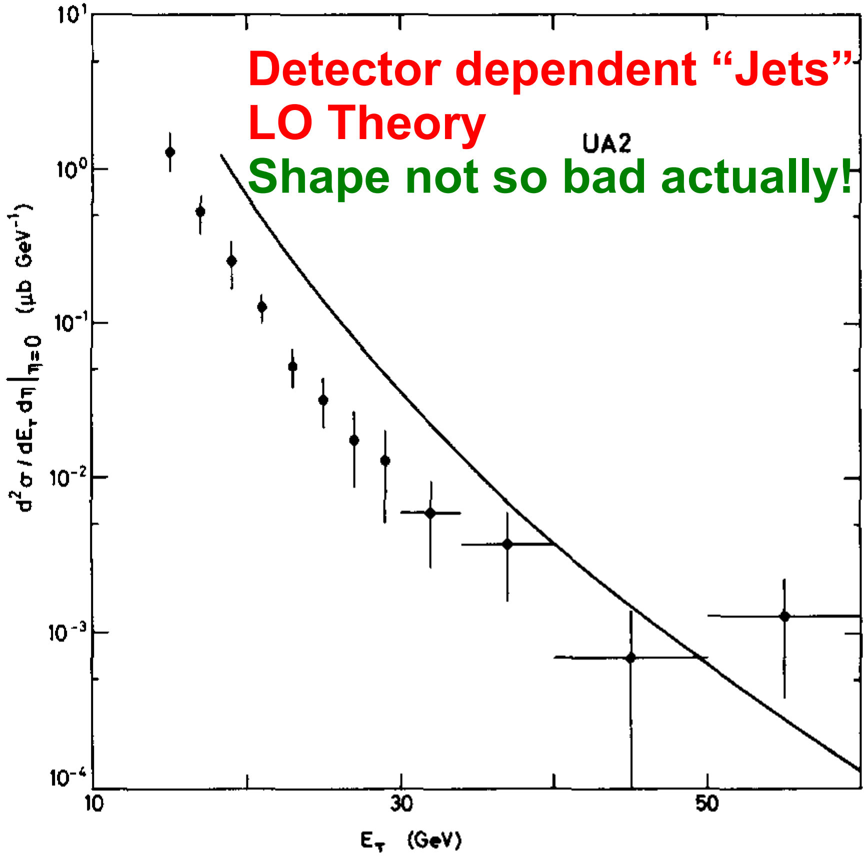
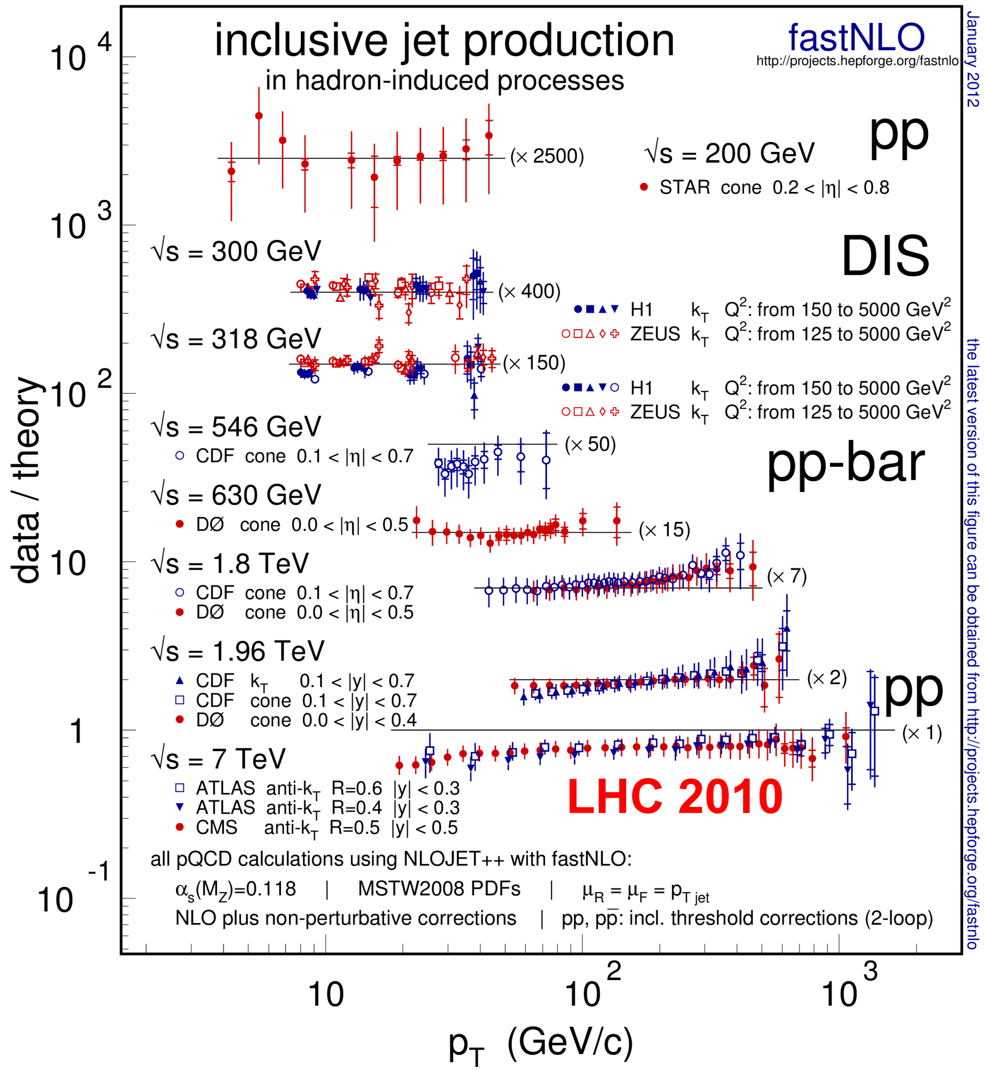


Fig. 6. Inclusive jet production cross section. The solid line (ref. [6]) uses Λ = 0.5 GeV while Λ = 0.15 GeV would bring the calculated rates in better agreement with the data. However various uncertainties preclude a determination of Λ from the data [13].

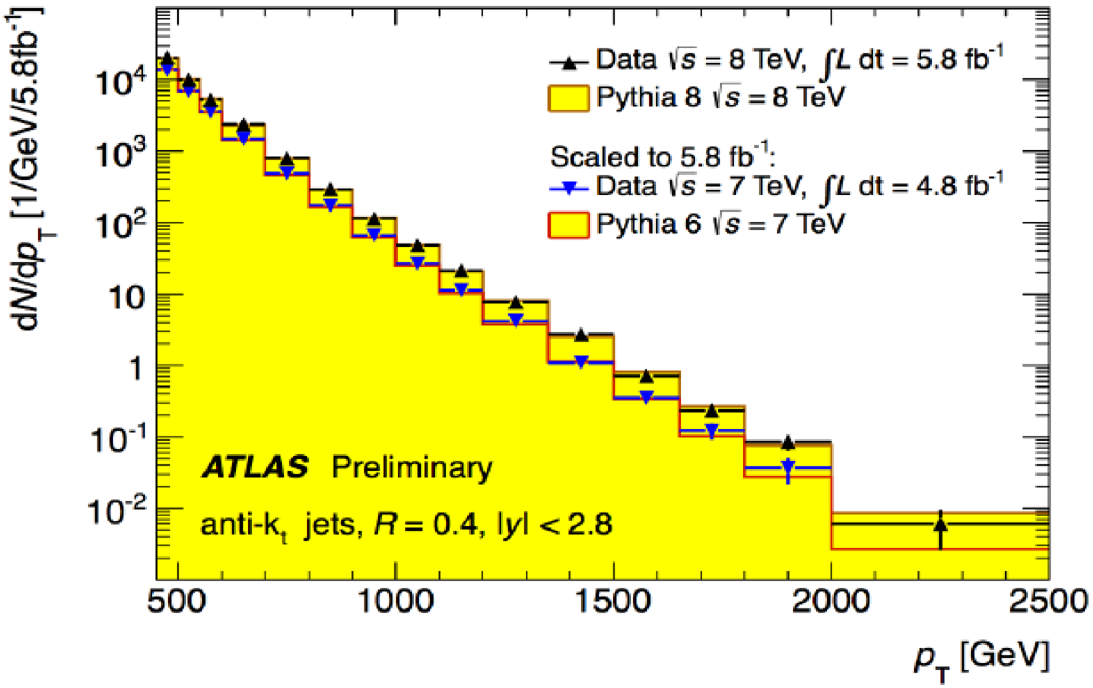
UA2, PLB 118 (1982).

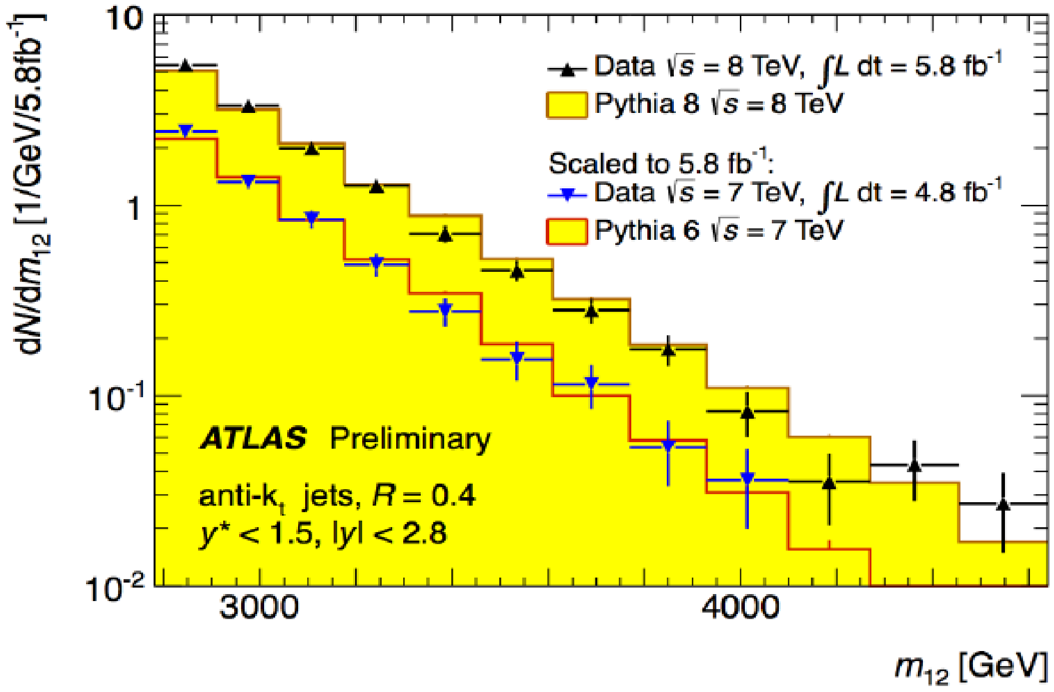
... and today !



fastNLO

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.