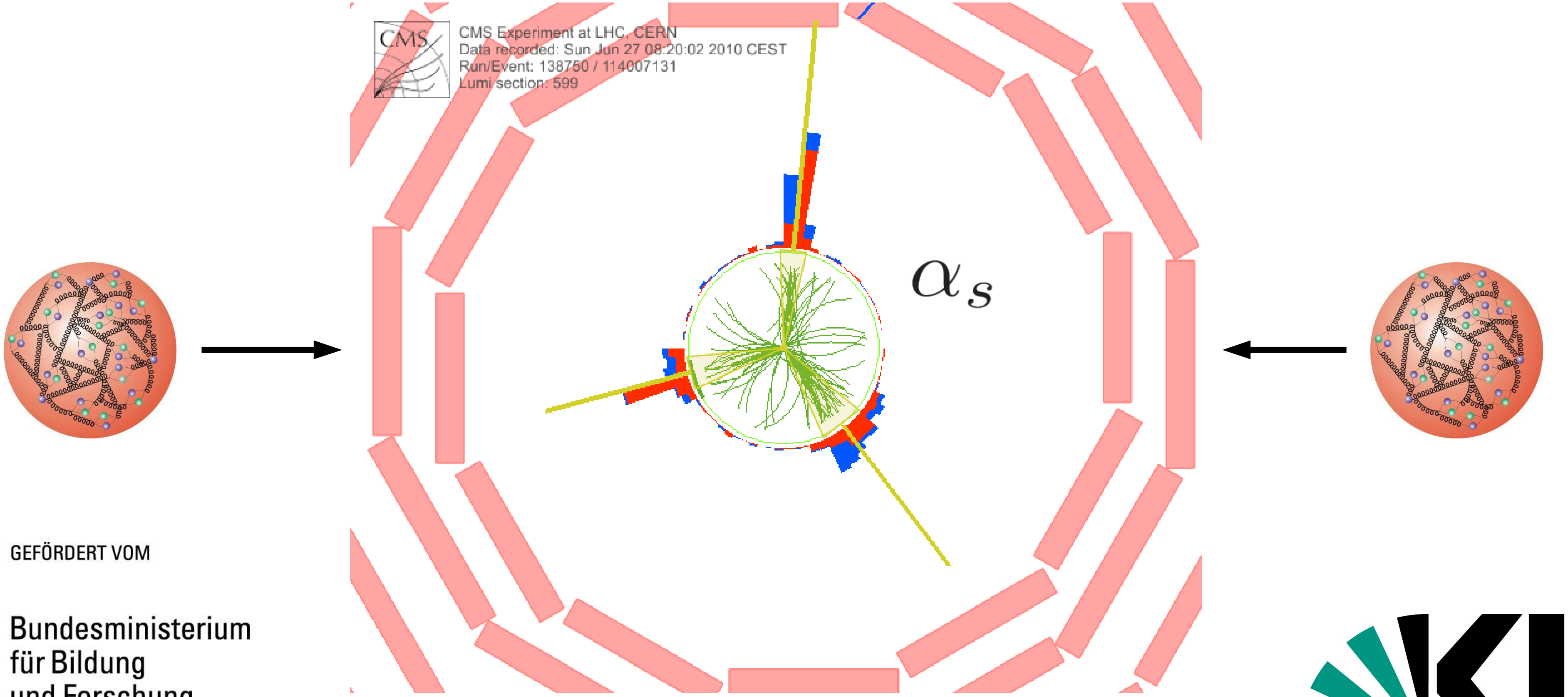
QCD ---
Neues von der starken Kraft



GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

Klaus Rabbertz, KIT

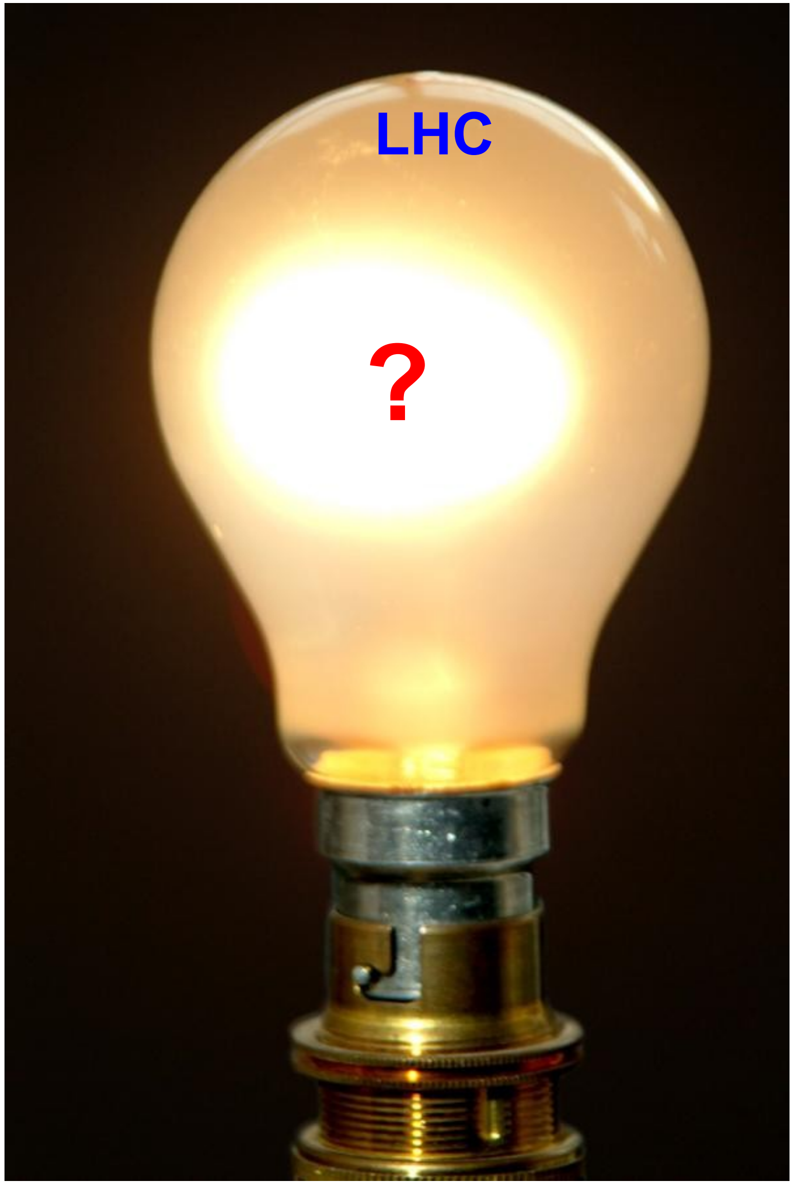
Karlsruhe Institute of Technology

The Menu

- Jet Algorithms
- Jet Areas
- Jets: All, Two, Three
- Photons: One and Two
- Bosons: Not alone
- Event Shapes
- Jet Mass and Jet Substructure
- Mass matters
- Outlook

See also Talk T2.1 by
Kristin Lohwasser

Luminosity



© www.freefoto.com

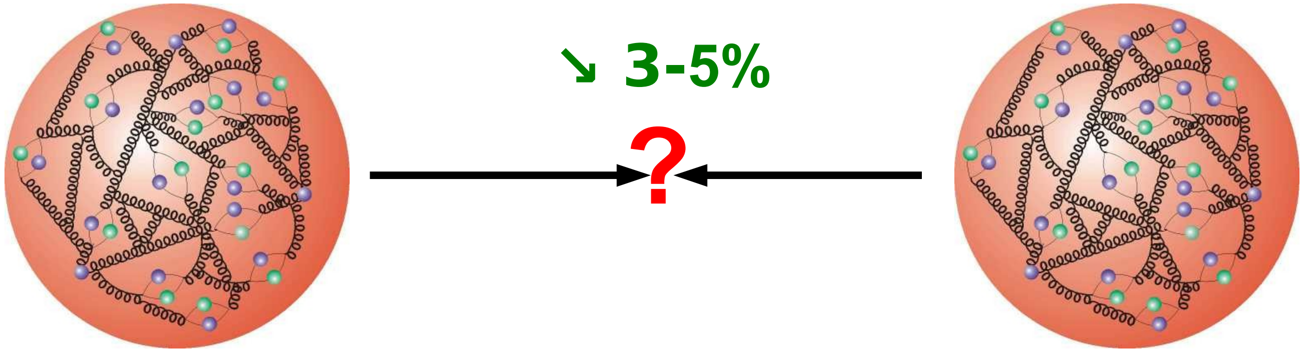
Common to all cross section measurements:

Initial Uncertainty at LHC: 11%

From van-der-Meer Scans:
Uncertainty dominated by beam intensity measurement

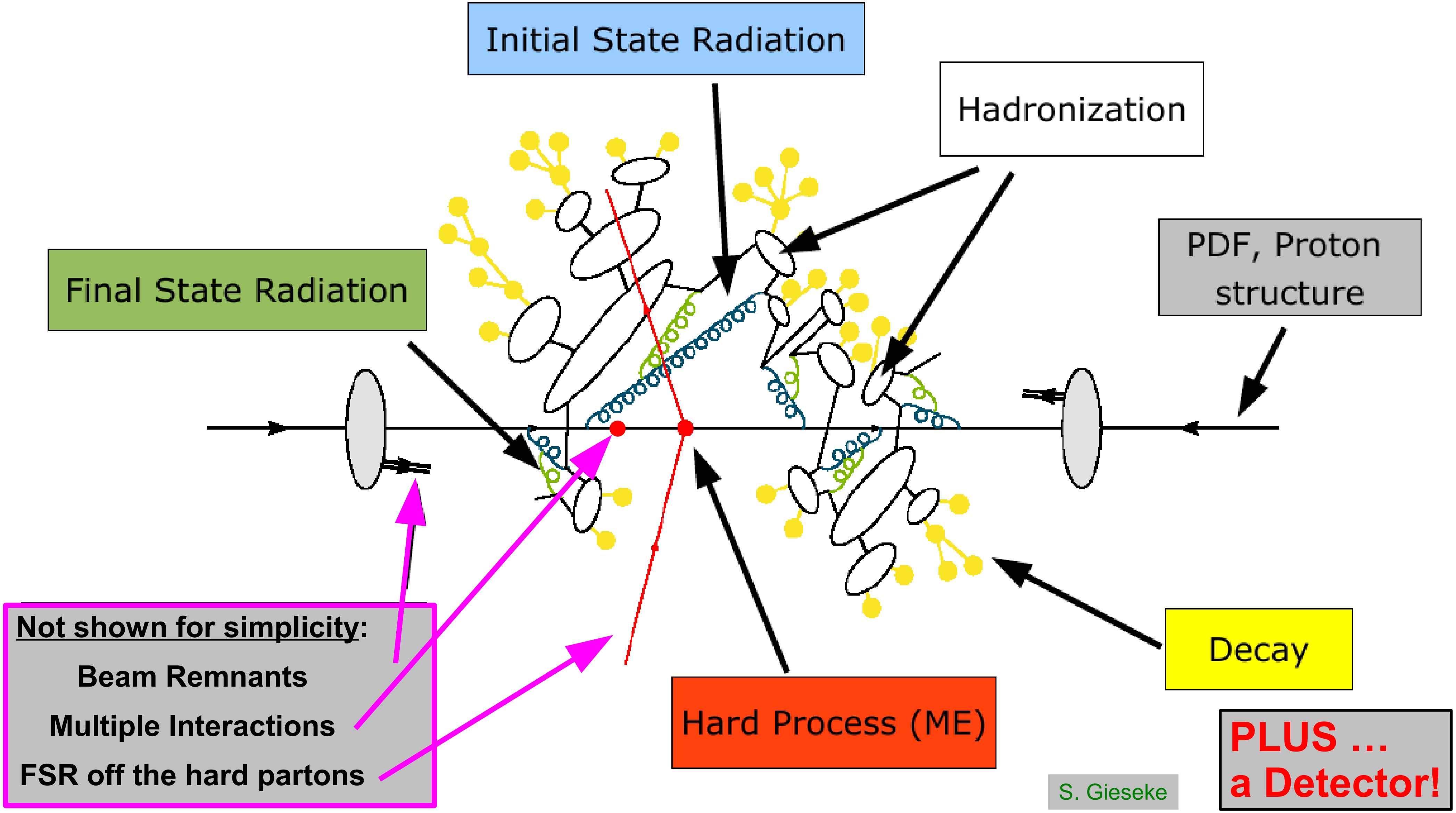
Reached by now:

↘ 3-5%



HERA-Proton,DESY

Sketch of a pp Scatter



Initial State Radiation

Hadronization

Final State Radiation

PDF, Proton structure

Not shown for simplicity:

Beam Remnants

Multiple Interactions

FSR off the hard partons

Hard Process (ME)

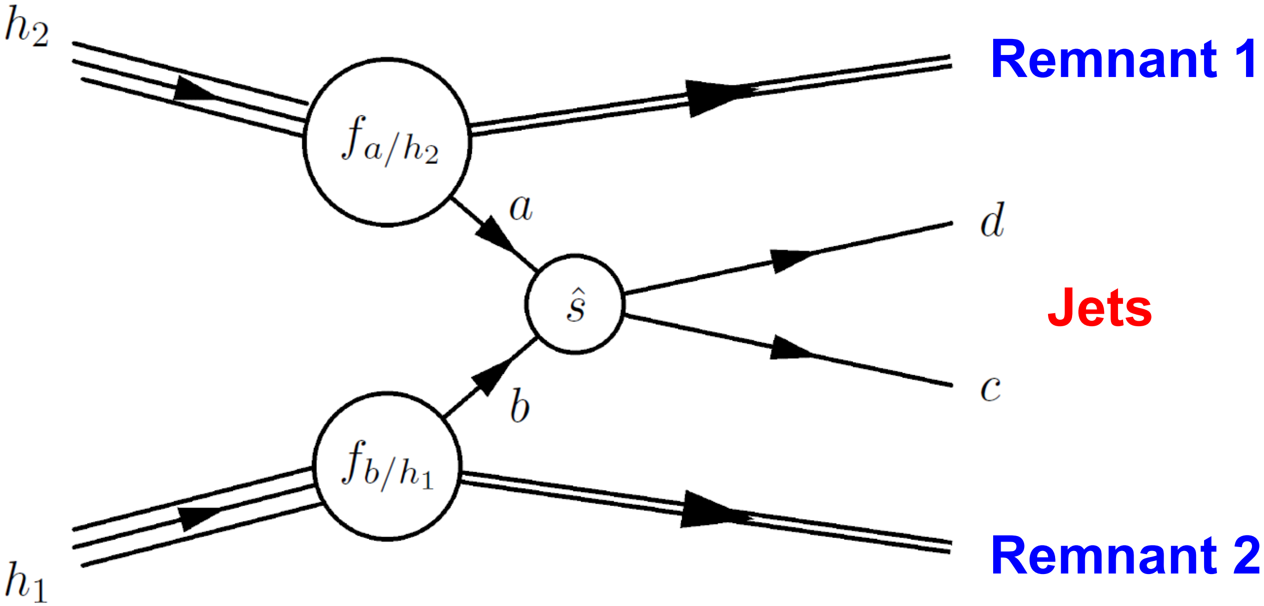
Decay

S. Gieseke

PLUS …
a Detector!

Jets

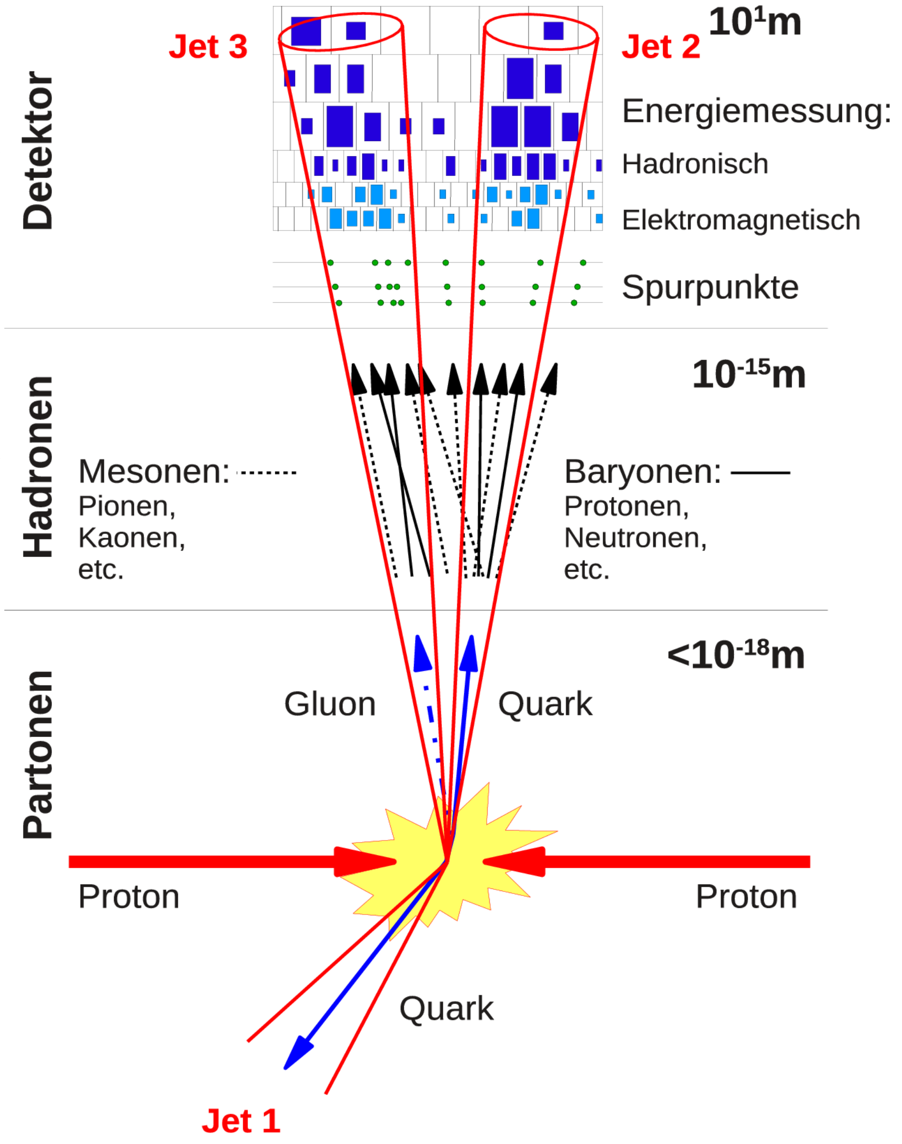
Lachlan Rogers, Wikimedia



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 LHC: anti-kT
Type 2 algorithm that looks like Type 1!

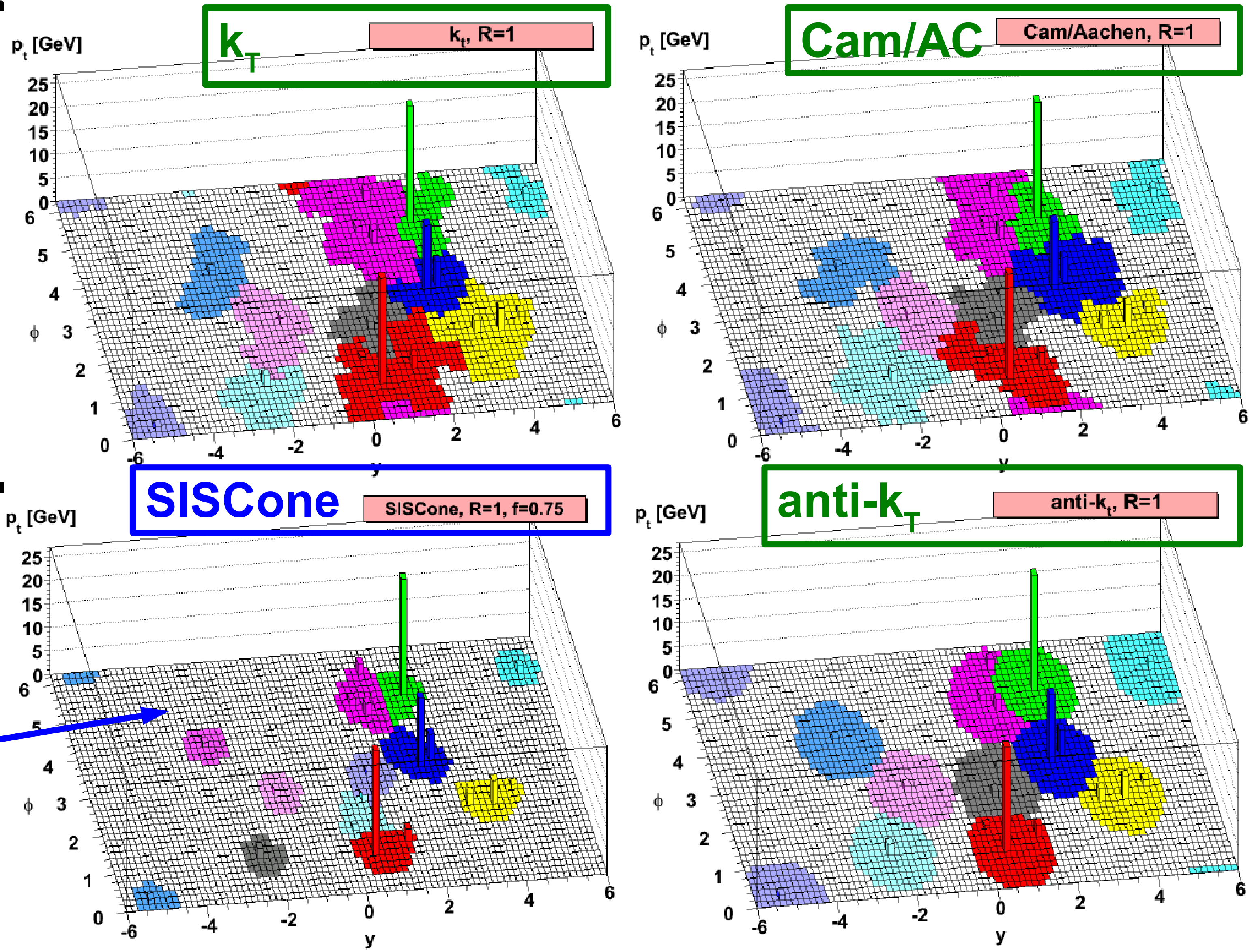
Jet Algorithms at LHC

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

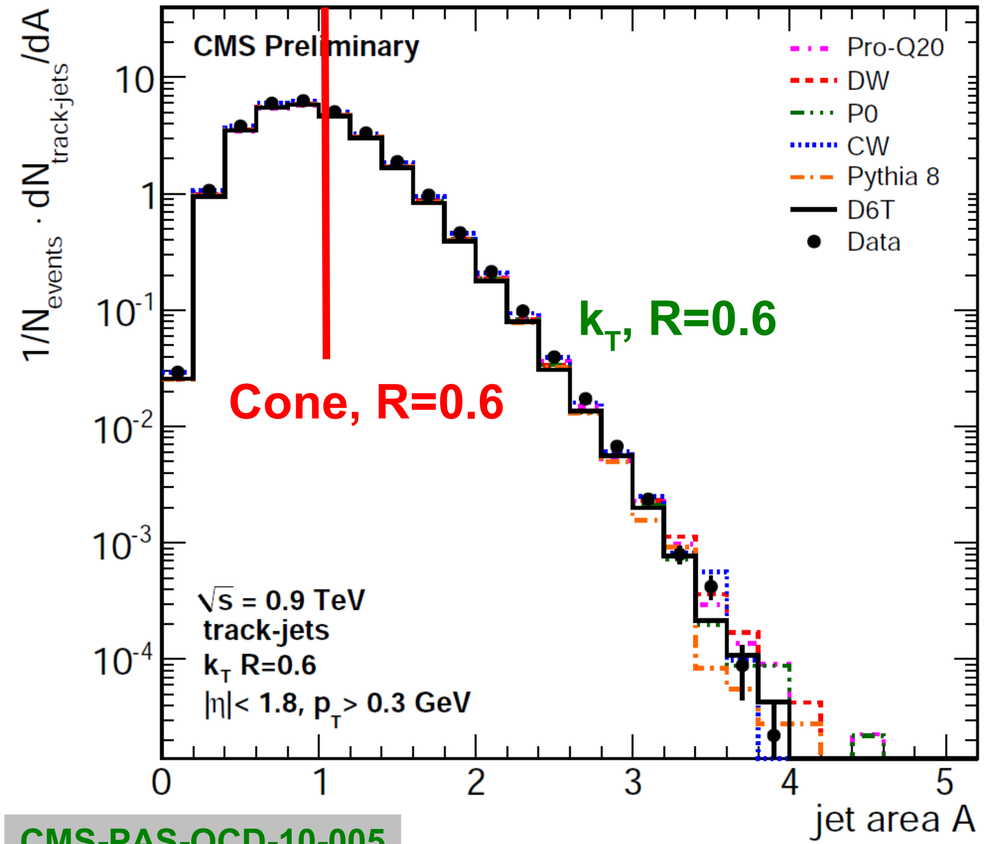
Jet Areas

Measured jet area distribution

k_T algorithm with R = 0.6

Naively expect for cone algorithm

R = 0.6 → A = π R^2 = 1.1



CMS-PAS-QCD-10-005

- **Jet Areas can be measured!**
- **More useful when not forced into fixed shape (cone) but adaptable to event activity**
  - **Measure the underlying event (UE)**
  - **Subtract additional energy in jets due to pile-up collisions**
  - **Use to differentiate jets from boosted heavy objects ?**

ignore outliers (leading jets)

jet pT per area

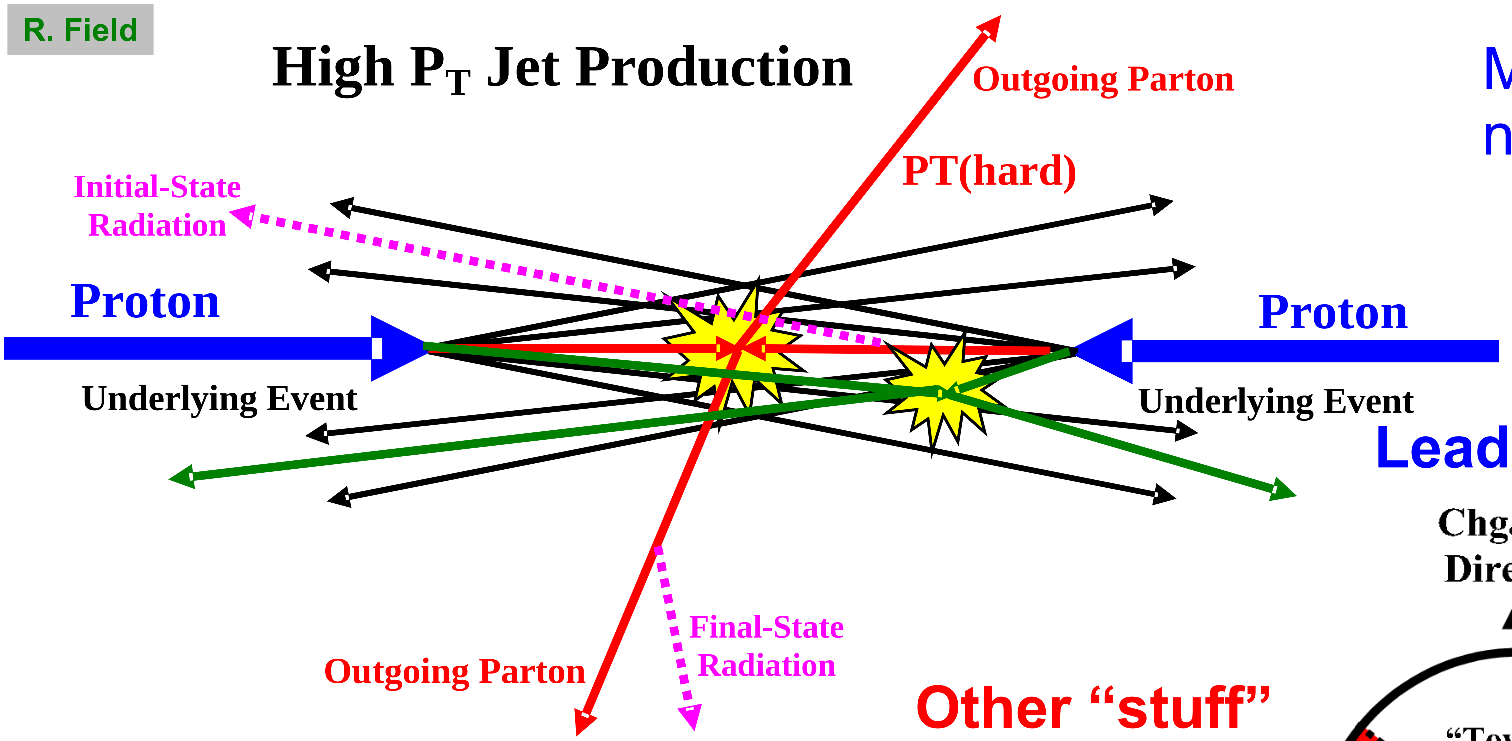
$$\rho' = \underset{j \in physical\ jets}{\text{median}} \left[\left\{ \frac{p_{T,j}}{A_j} \right\} \right] * C$$

event-wise measure of UE activity

correction for empty events

Underlying Event - Traditional Approach

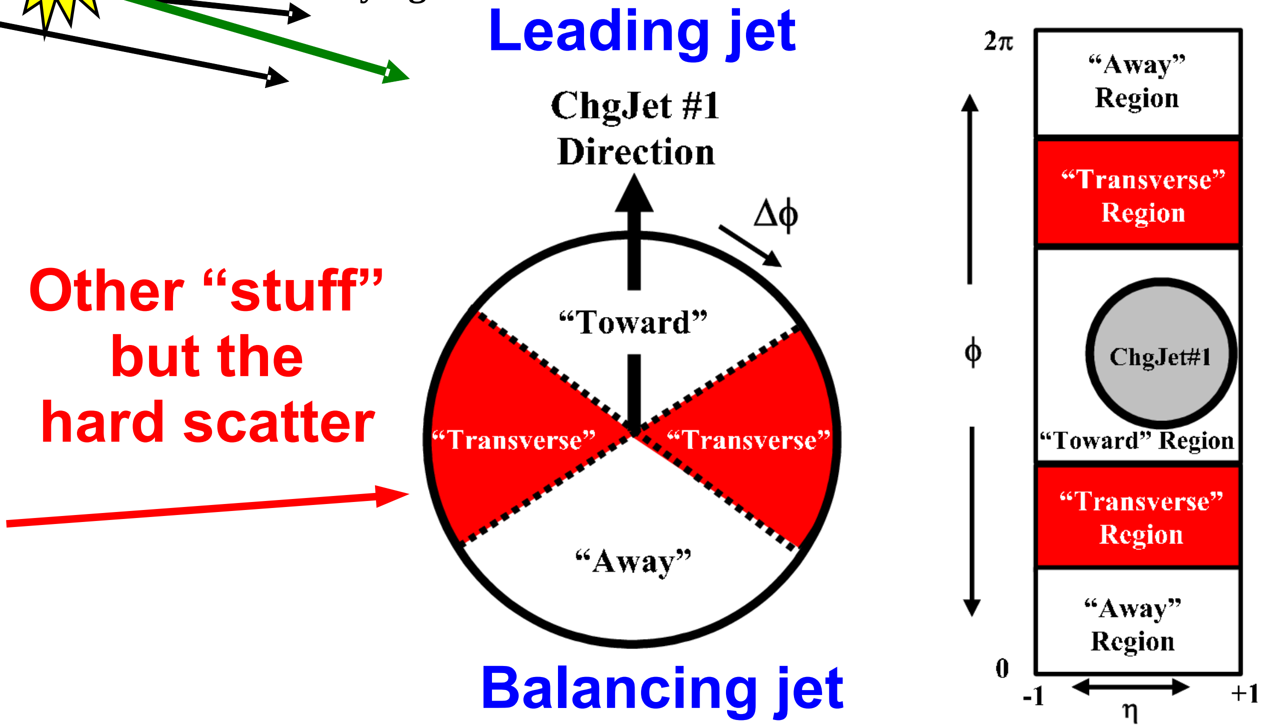
MPI, BBR, ISR and FSR
not uniquely differentiable



Measurement possibility:

- Charged particle and p_T sum densities in transverse region of leading jet of charged particles

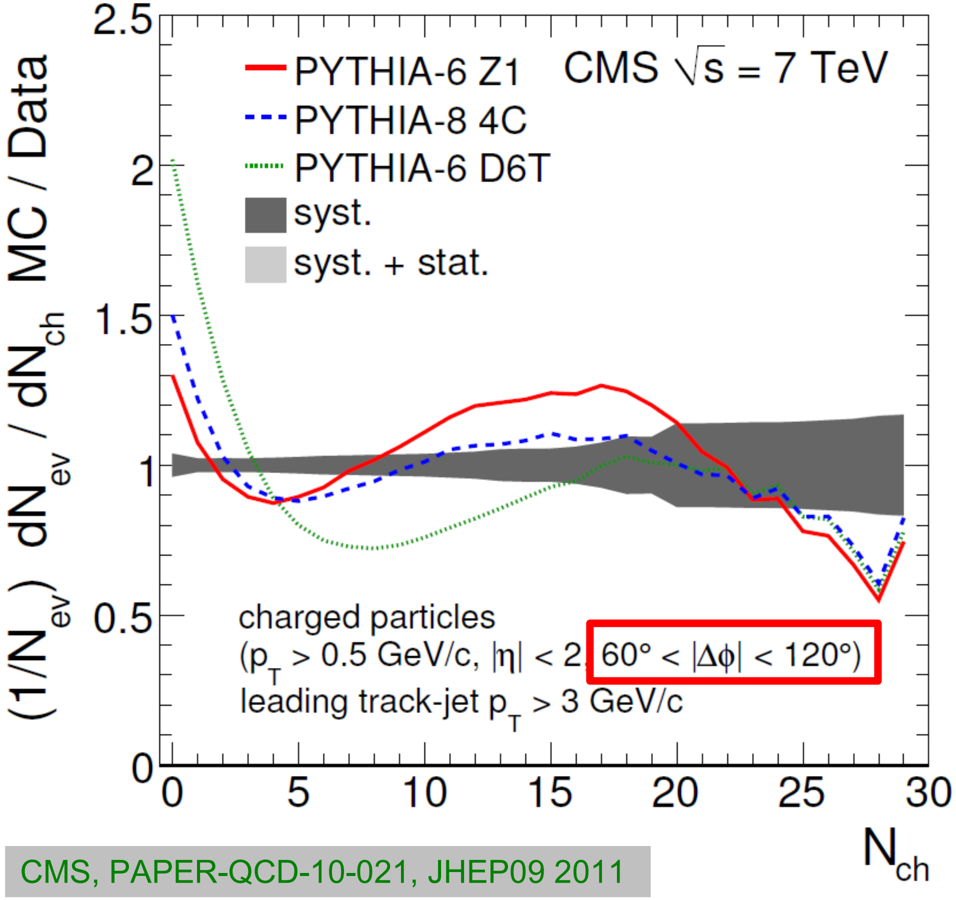
Other “stuff” but the hard scatter



Underlying Event - Jet Areas

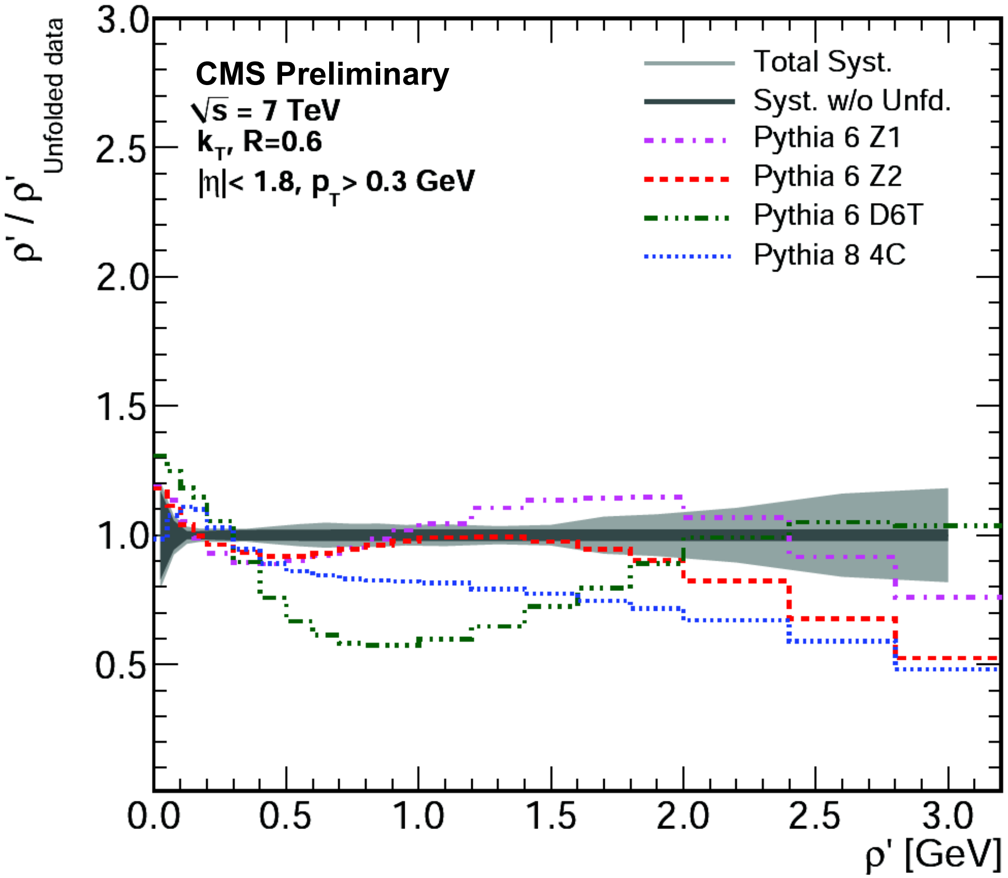
Ratio of MC to data, no MC works really well!

Conventional UE analysis, in the transverse plane. Charged particle density



CMS, PAPER-QCD-10-021, JHEP09 2011

Jet Area UE analysis, whole event analyzed. Charged particle jets

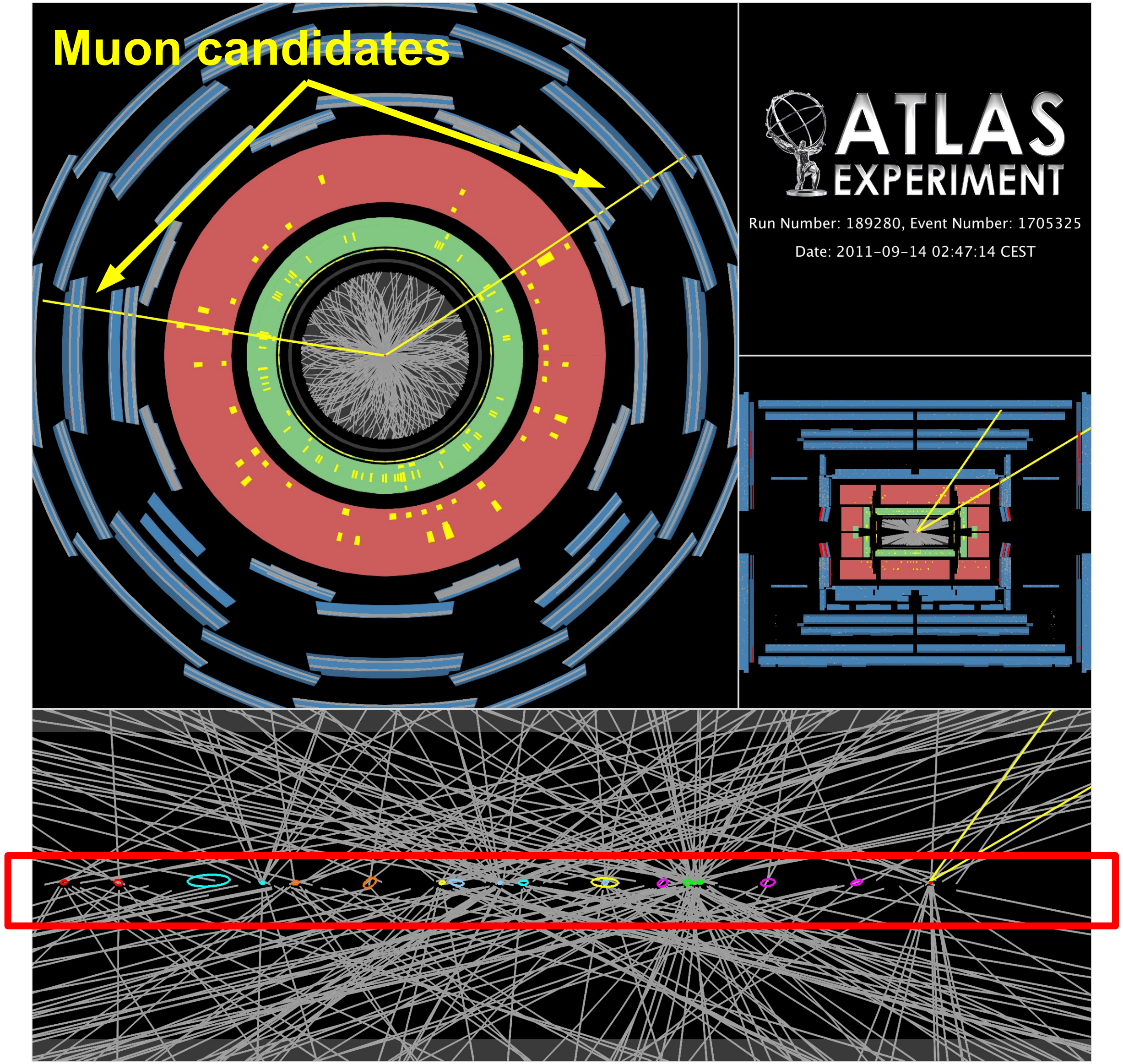


Jet Areas and Pile-Up

Increasing luminosities also bring additional proton-proton collisions measured within the same “event”!

Jet areas are used in jet energy calibration to subtract additional energy from multiple collisions.

ATLAS dimuon event with 11 reconstructed primary vertices



ATLAS, CERN Courier Nov. 2011

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
  - • • •

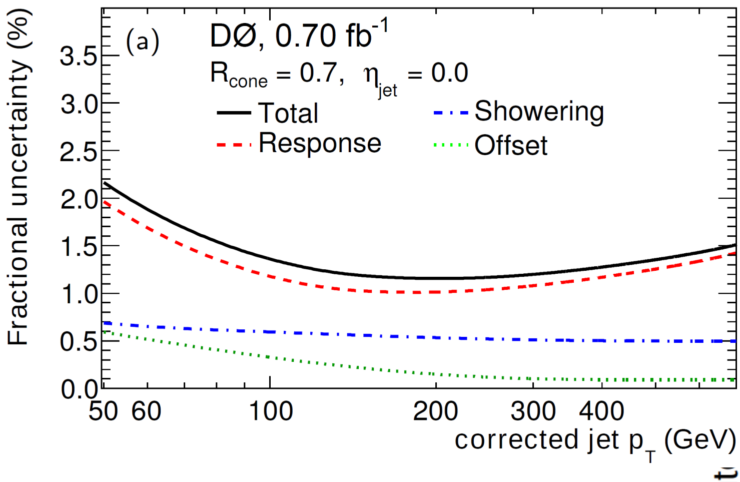
- Theoretical Uncertainties:
  - PDF Uncertainty
  - pQCD (Scale) Dependence
  - Non-perturbative Corrections
  - PDF Parameterization
  - NLO-NLL matching schemes
  - Electroweak Corrections
  - Knowledge of $\alpha_s(M_Z)$
  - • • •

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

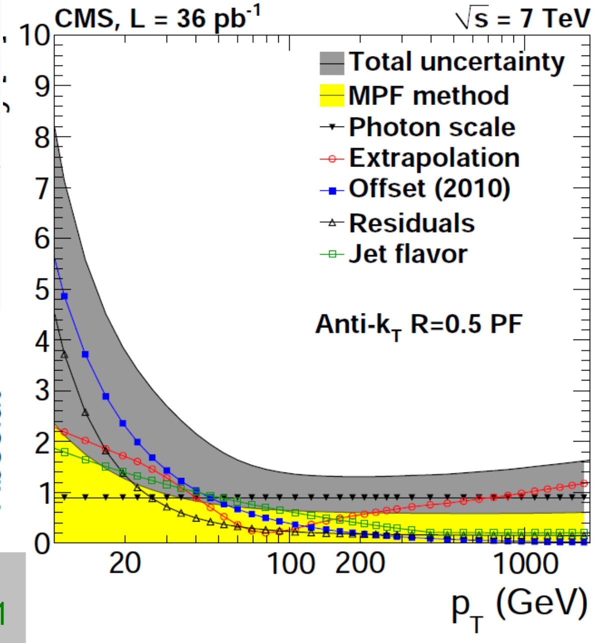
Jet Energy Scale

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!

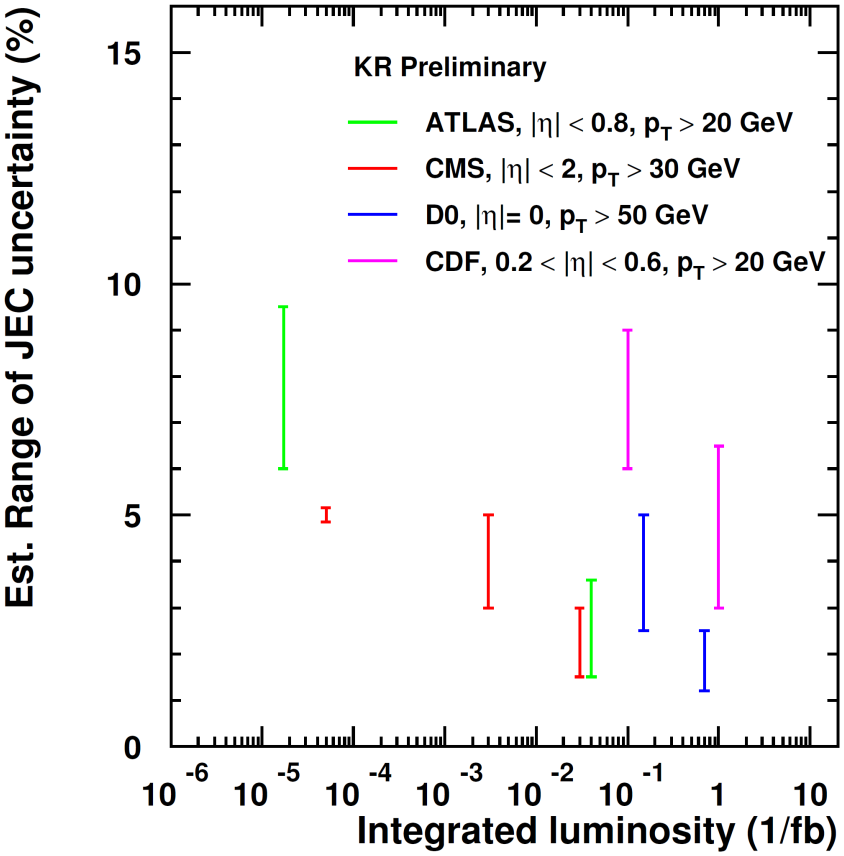
D0 from 0.7/fb (2011)



CMS from 36/pb (2010)

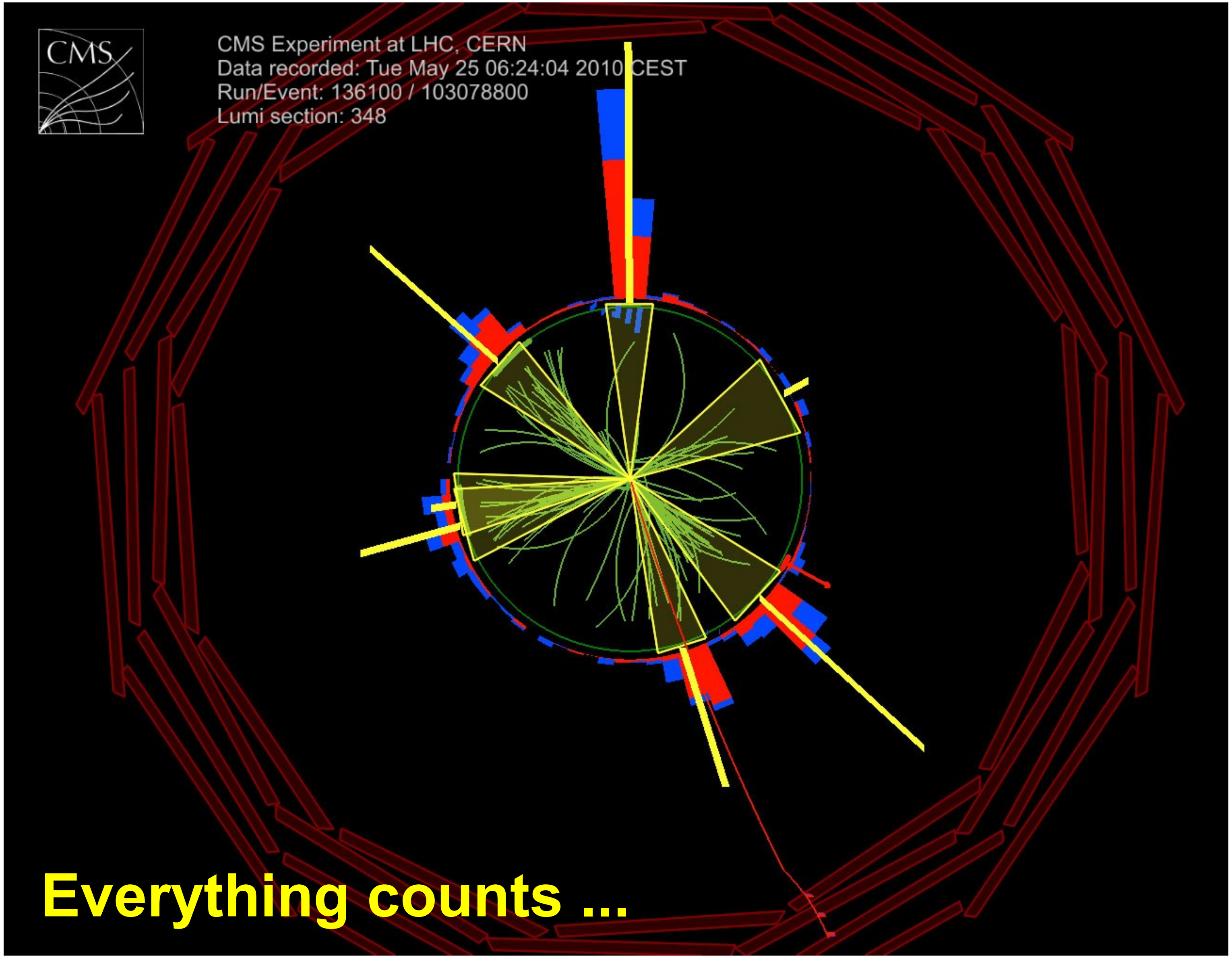


Development of JEC precision



ATLAS, EPJC 71 2011; arXiv:1112.6297
CMS, JME-10-003; JME-10-010; JINST 6 2011
D0, arXiv:1110.3771; D0 prel. 2006

All Inclusive



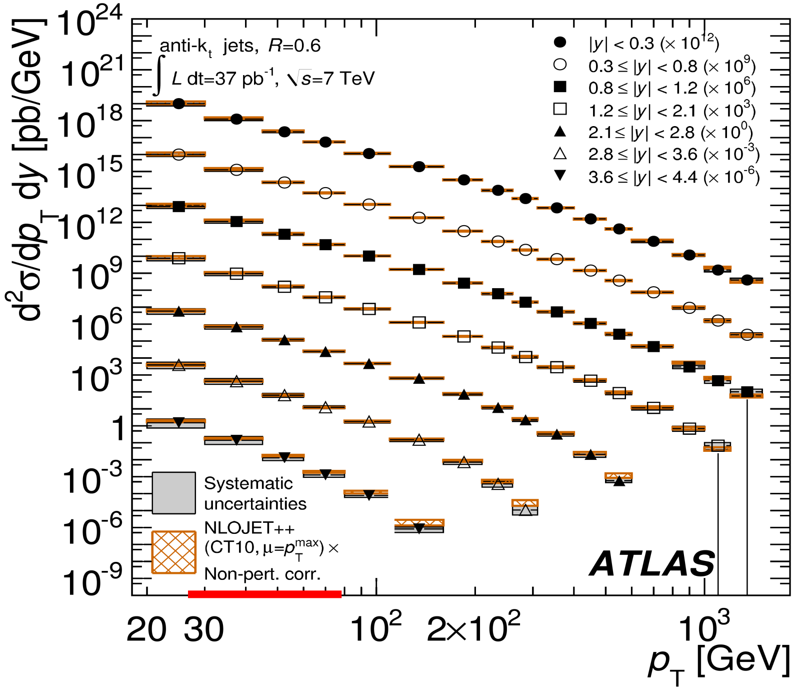
Everything counts ...

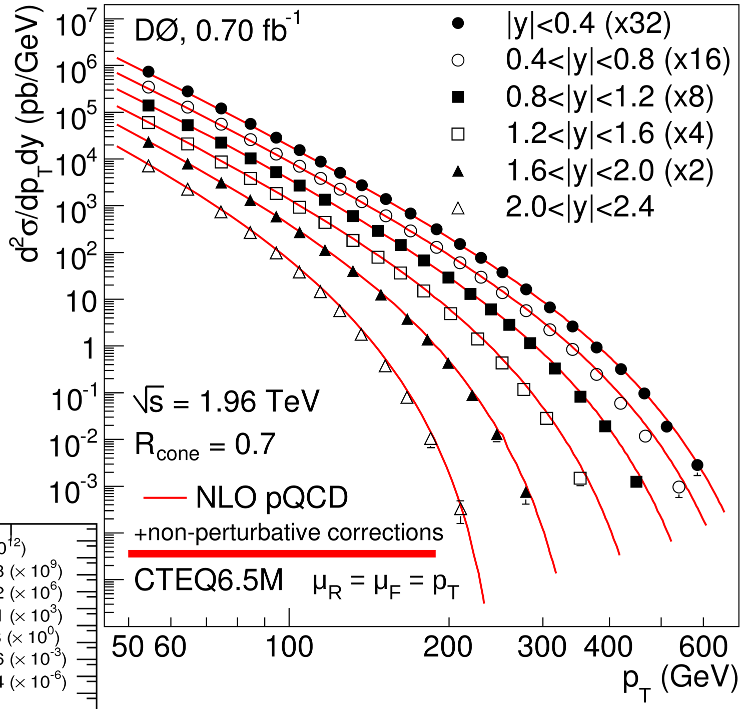
Inclusive Jets

Many new results. Agreement with predictions of QCD over many orders of magnitude up to ~ 1TeV in jet p_T

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

anti-kT, R=0.6

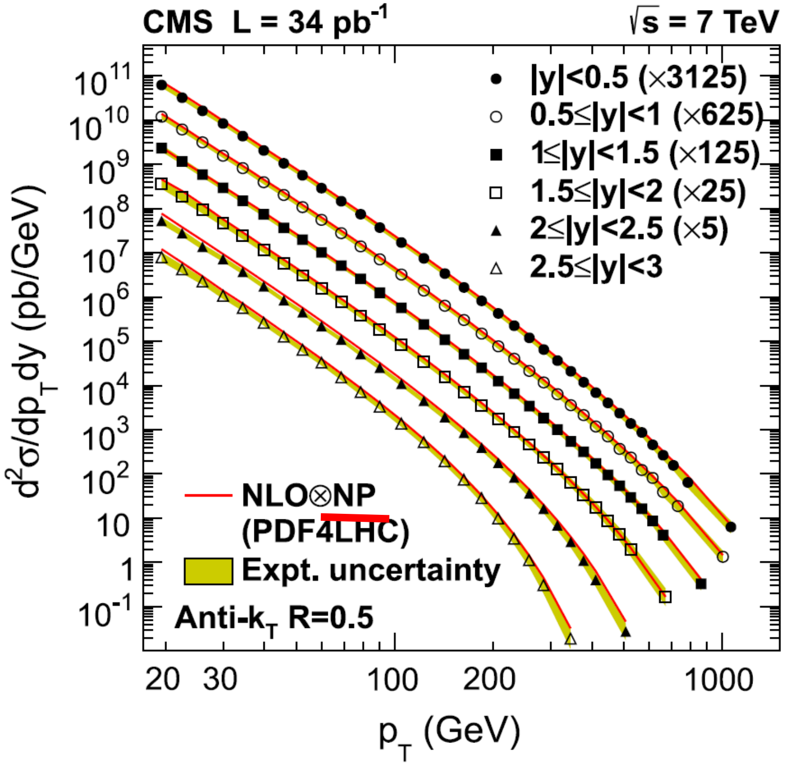




MidpointCone, R=0.7

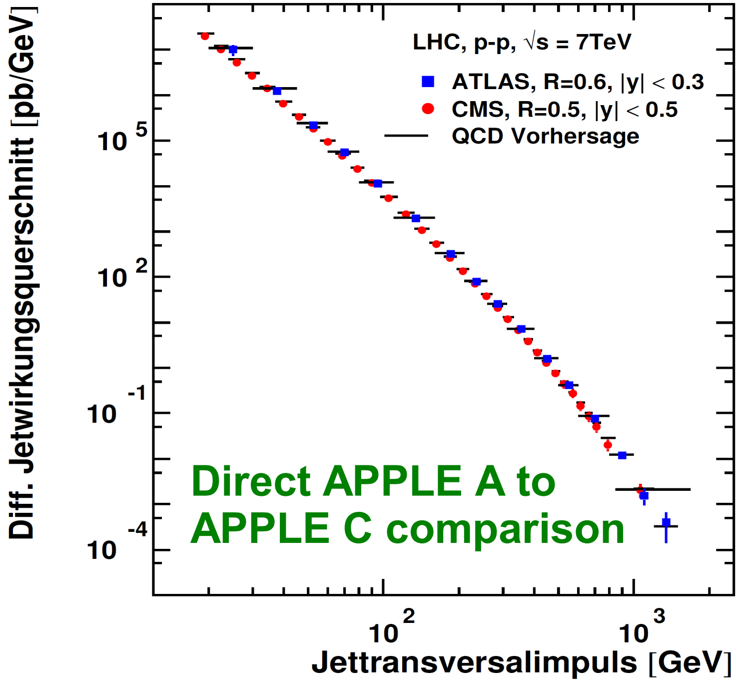
pQCD ⊗ non-perturbative corrections

anti-kT, R=0.5



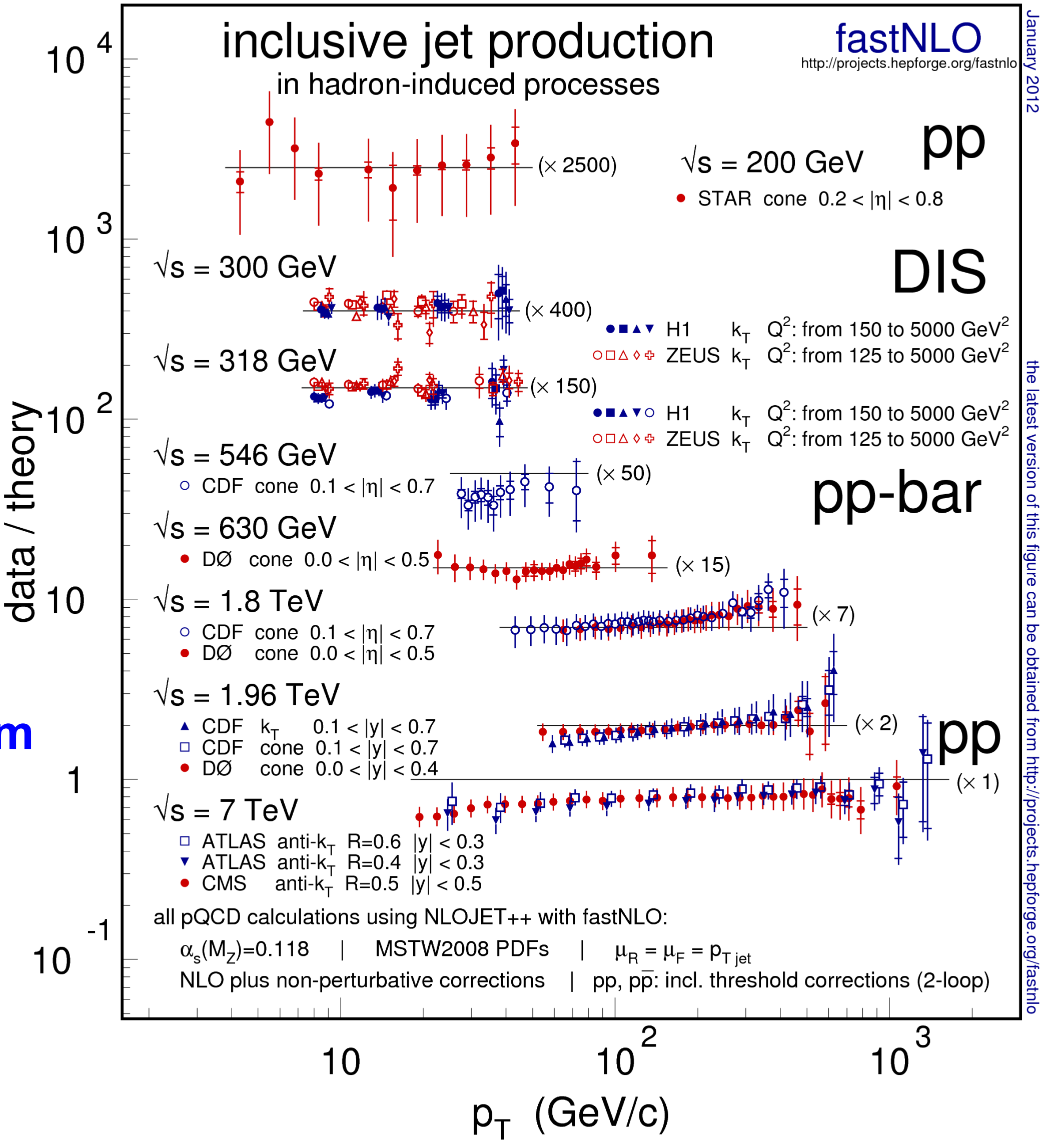
ATLAS, arXiv:1112.6297
CMS, PRL107 (2011)
D0, arXiv:1110.3771

Jets Data / Theory



Direct APPLE A to APPLE C comparison

ATLAS and CMS agree ...
at least on a log scale :-)

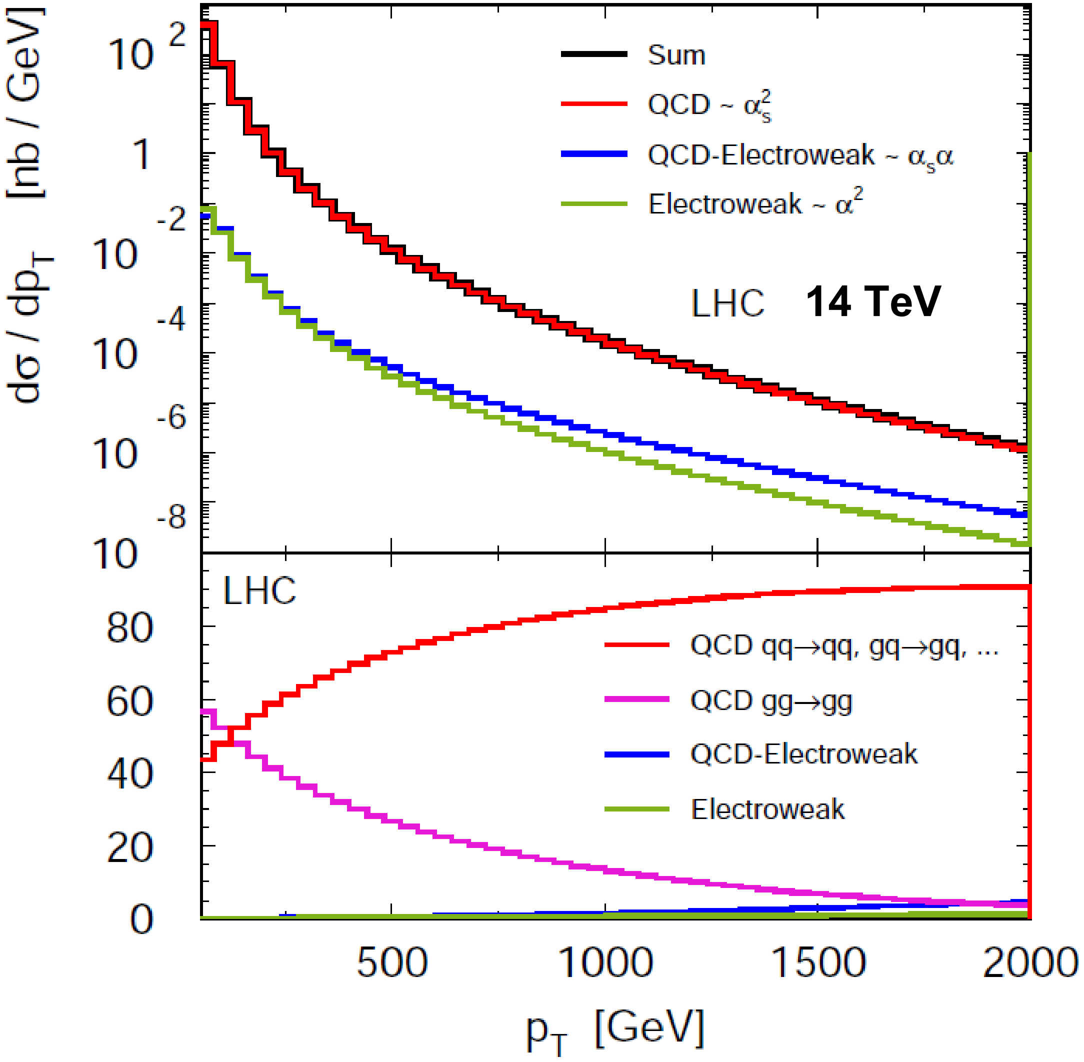


fastNLO, to be uploaded, arXiv:1109:1310v2, 2012

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

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

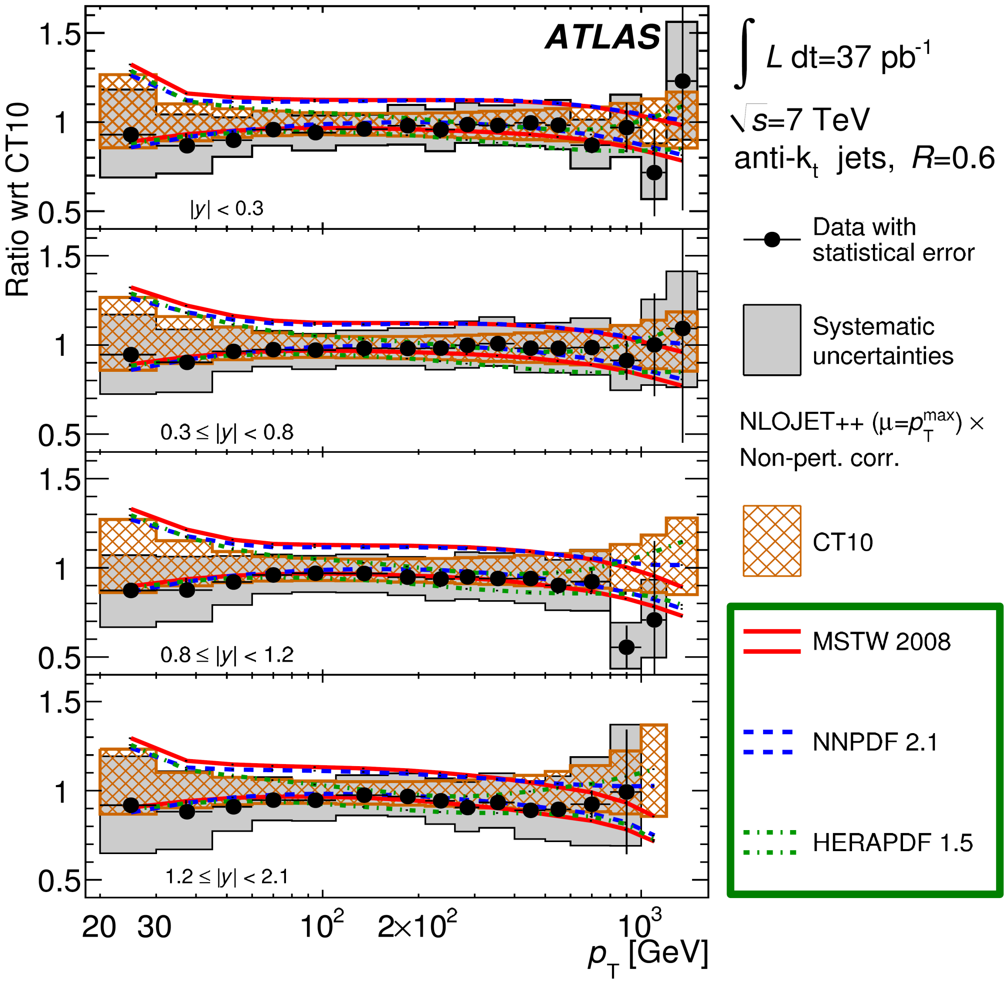


NLOJet++
Z.Nagy,
PRD68 2003
PRL88 2002

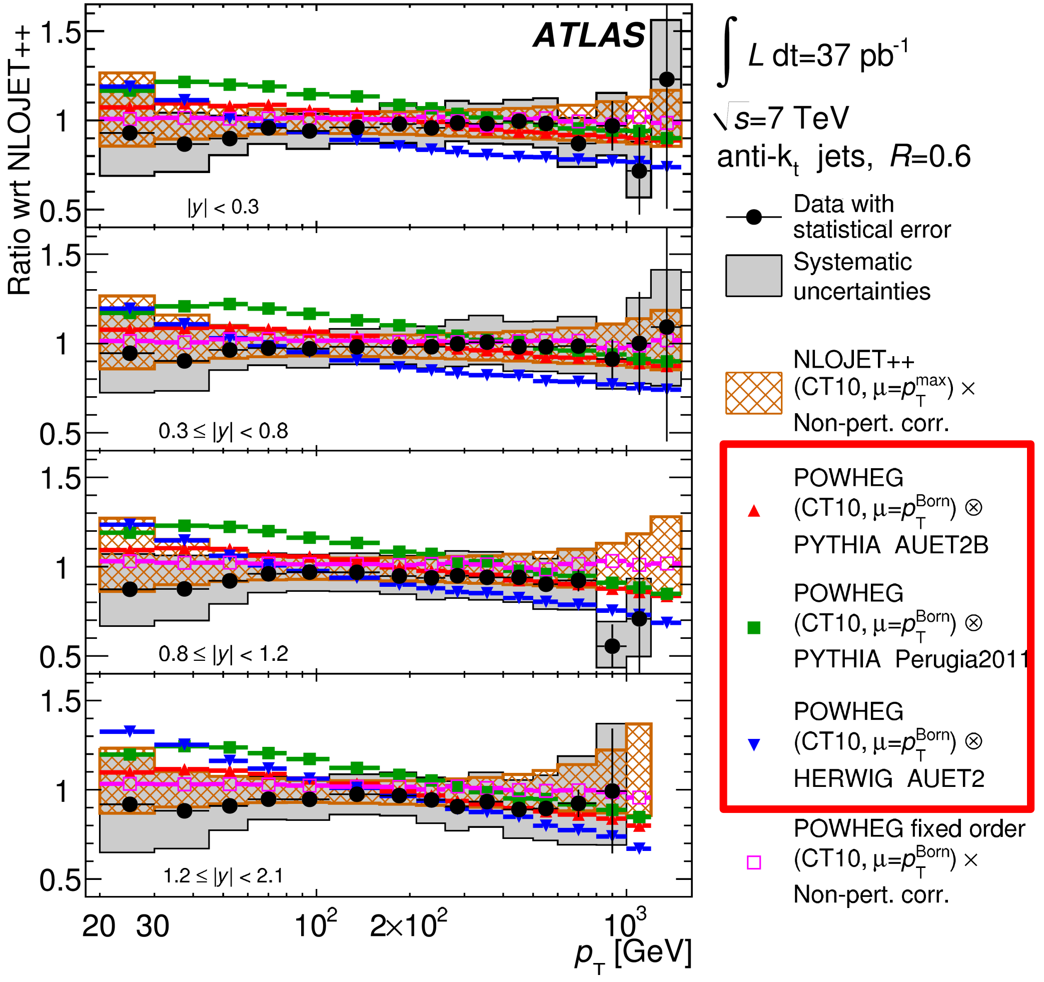
A. Scharf, arXiv:0910.0223

PDFs and matched Showers

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

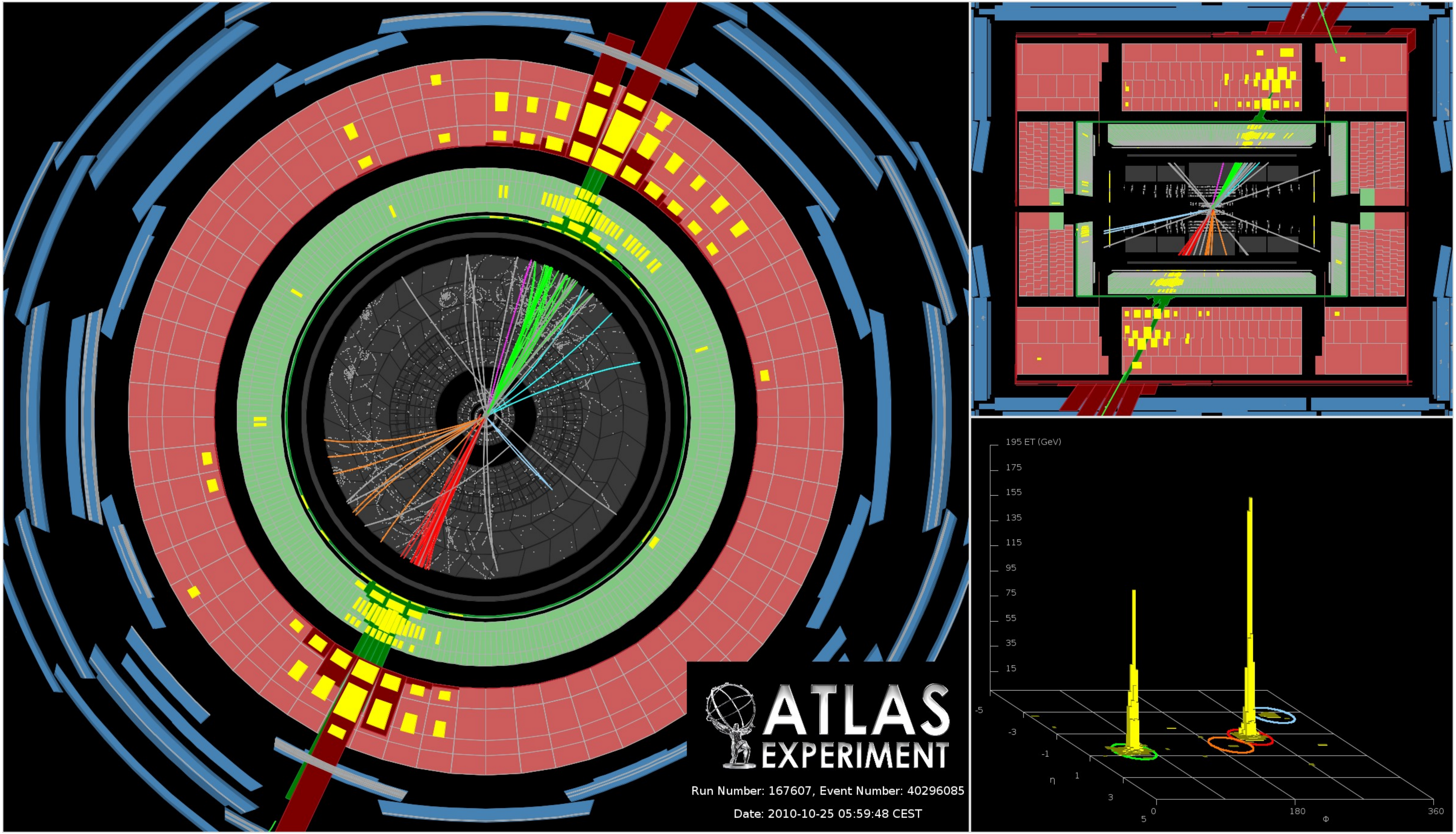


Agreement between NLO POWHEG vs. NLOJet++
POWHEG + matched parton showers ...
not a success story yet



POWHEG, S. Alioli et al., JHEP 1104 (2011)

Just the two of us



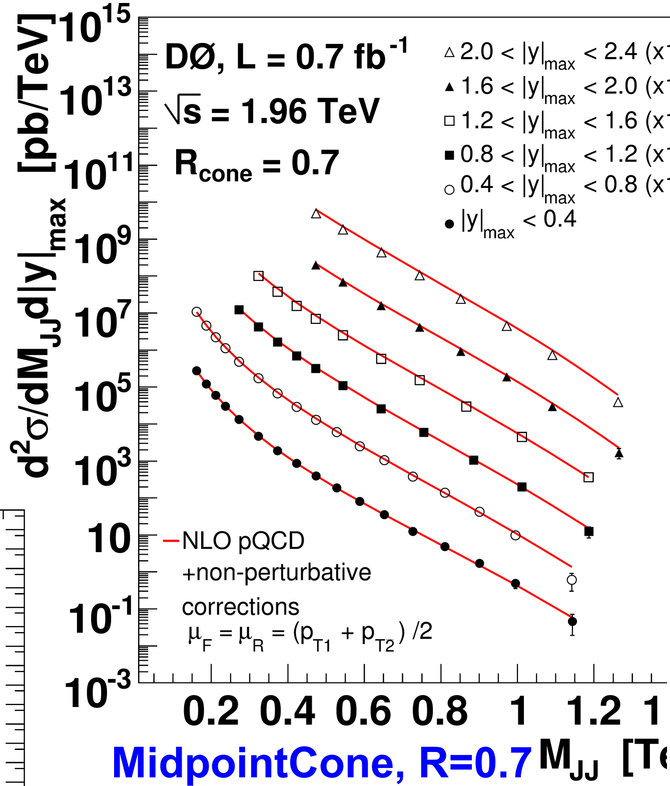
Run Number: 167607, Event Number: 40296085

Date: 2010-10-25 05:59:48 CEST

Dijet Mass

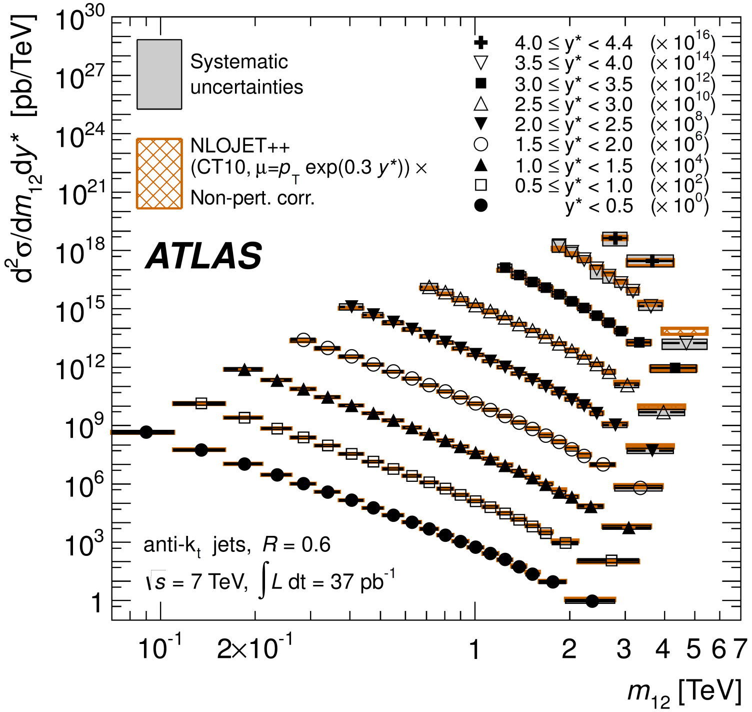
Many new results. Again agreement with predictions of QCD over many orders of magnitude!

$$\frac{d^2\sigma}{dM_{JJ}d|y_{max}|} \propto \alpha_s^2$$

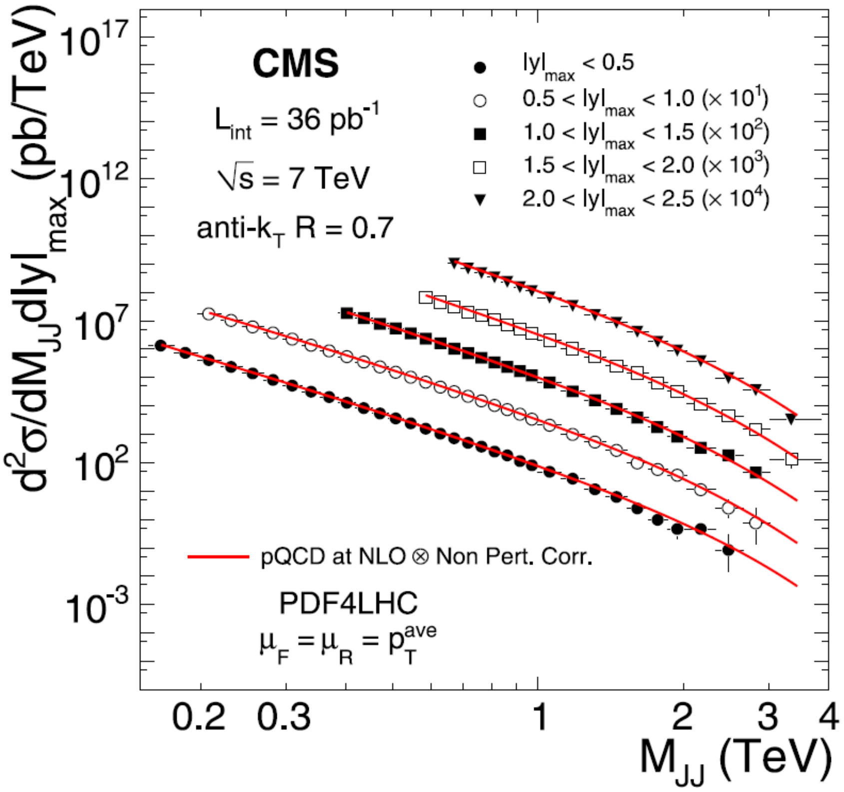


MidpointCone, R=0.7

anti-kT, R=0.6



anti-kT, R=0.7



ATLAS, arXiv:1112.6297
CMS, PLB700 (2011)
D0, PLB693 (2010)

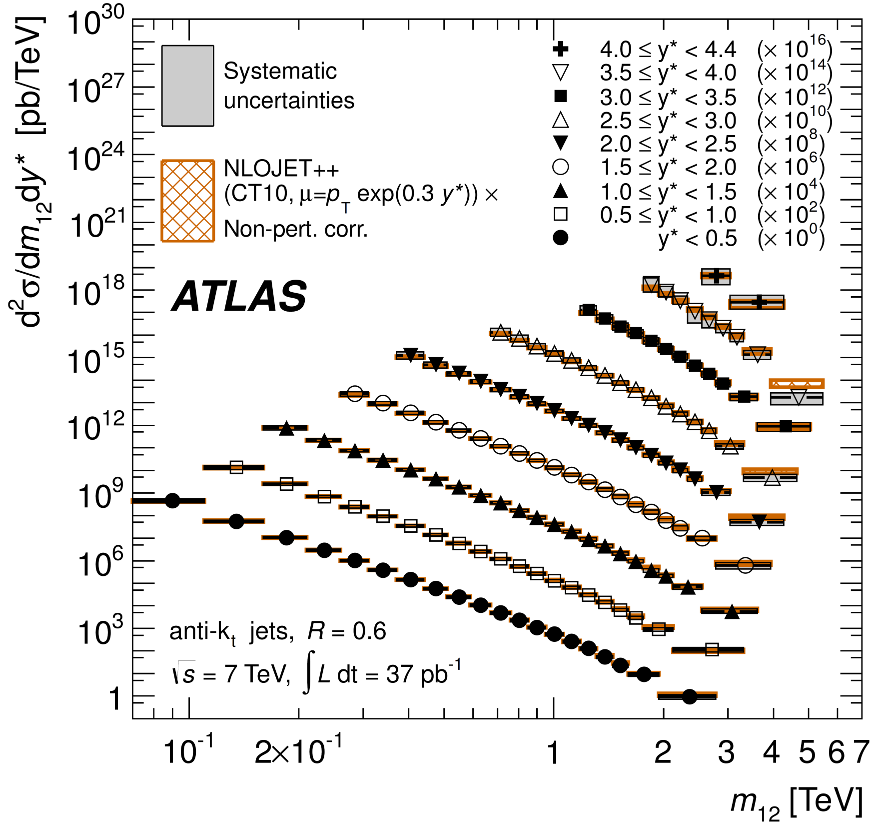
Dijet Mass ATLAS

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

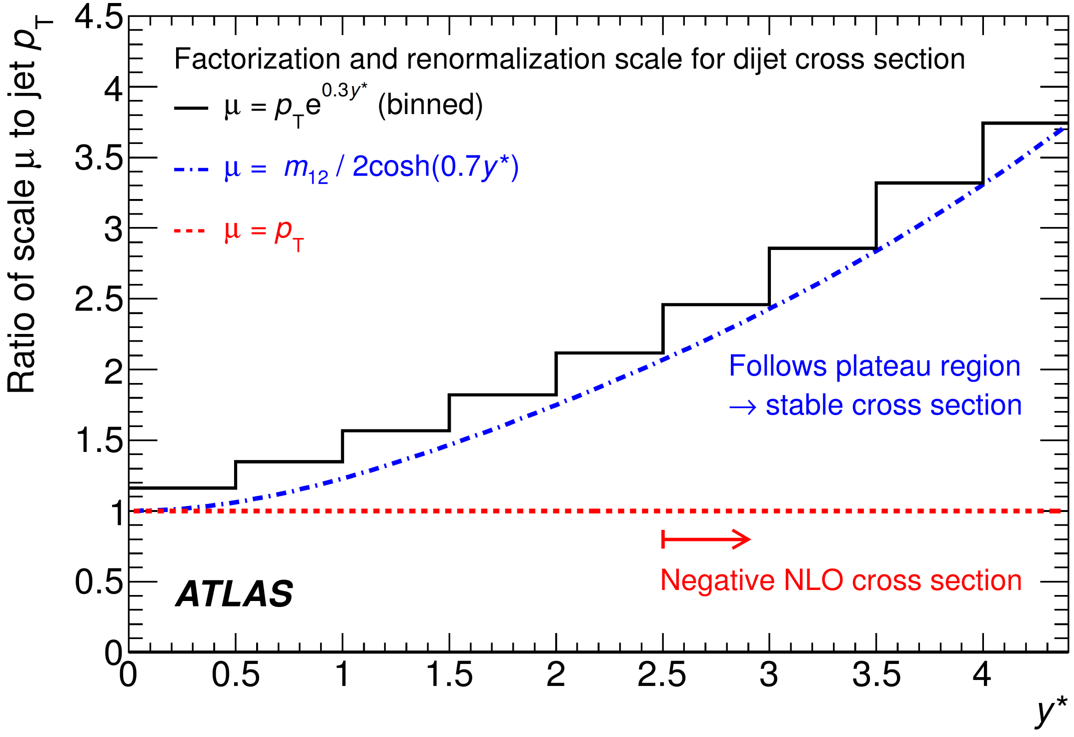
New choice for binning in rapidity by ATLAS
Also new choice for scale setting

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

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



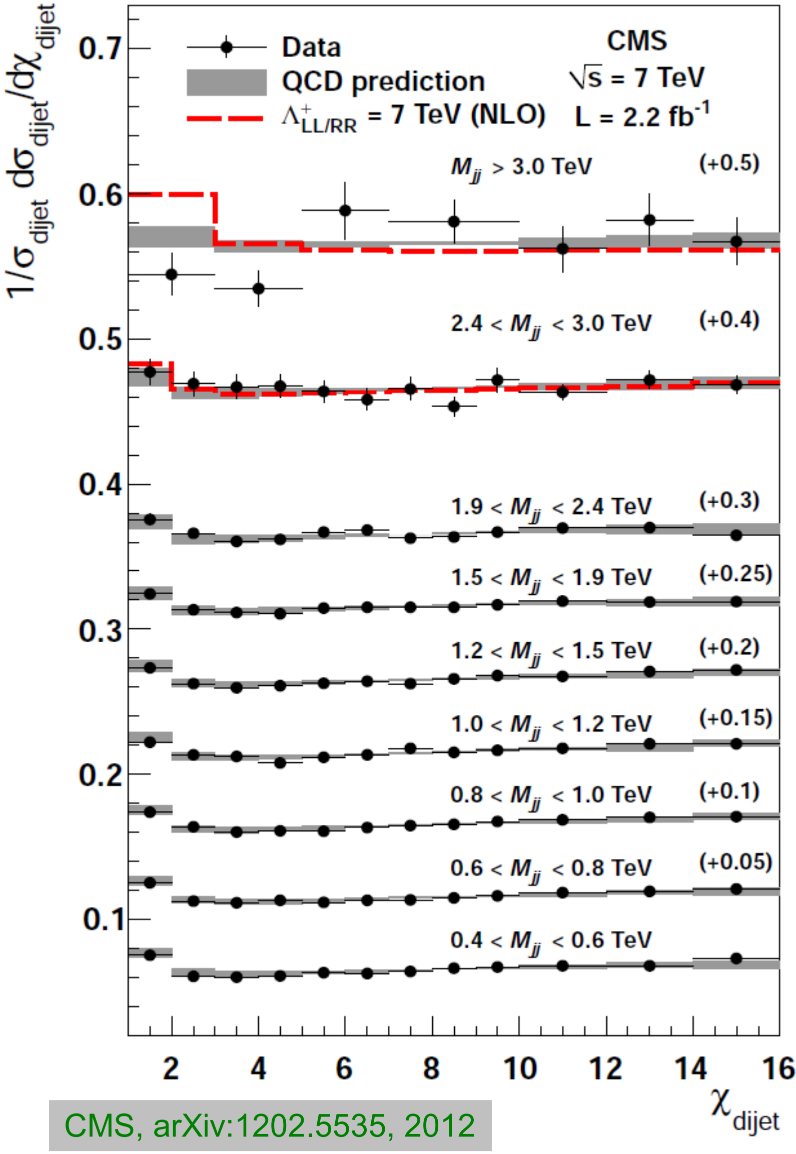
Attention: Figure somewhat misleading ...
Negative NLO cross sections appear
when checking scale uncertainties μ → μ/2



Dijet Angular

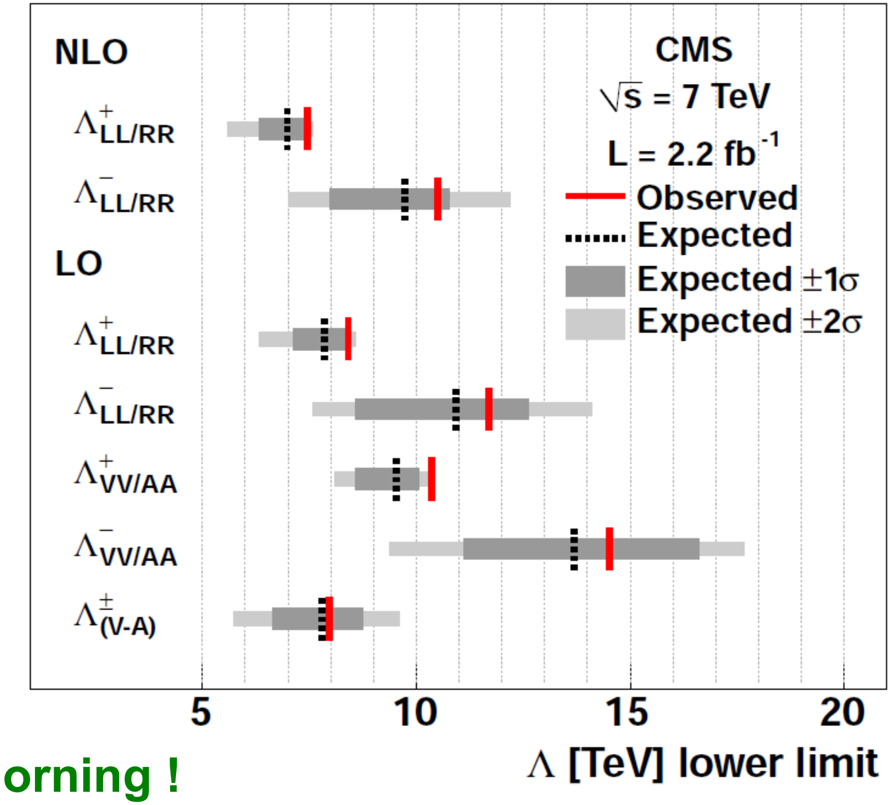
$$\chi = \exp(2y^*) = \exp(|y_1 - y_2|) = \frac{1 + |\cos\Theta^*|}{1 - |\cos\Theta^*|}$$

~ flat
for QCD



CMS, arXiv:1202.5535, 2012

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

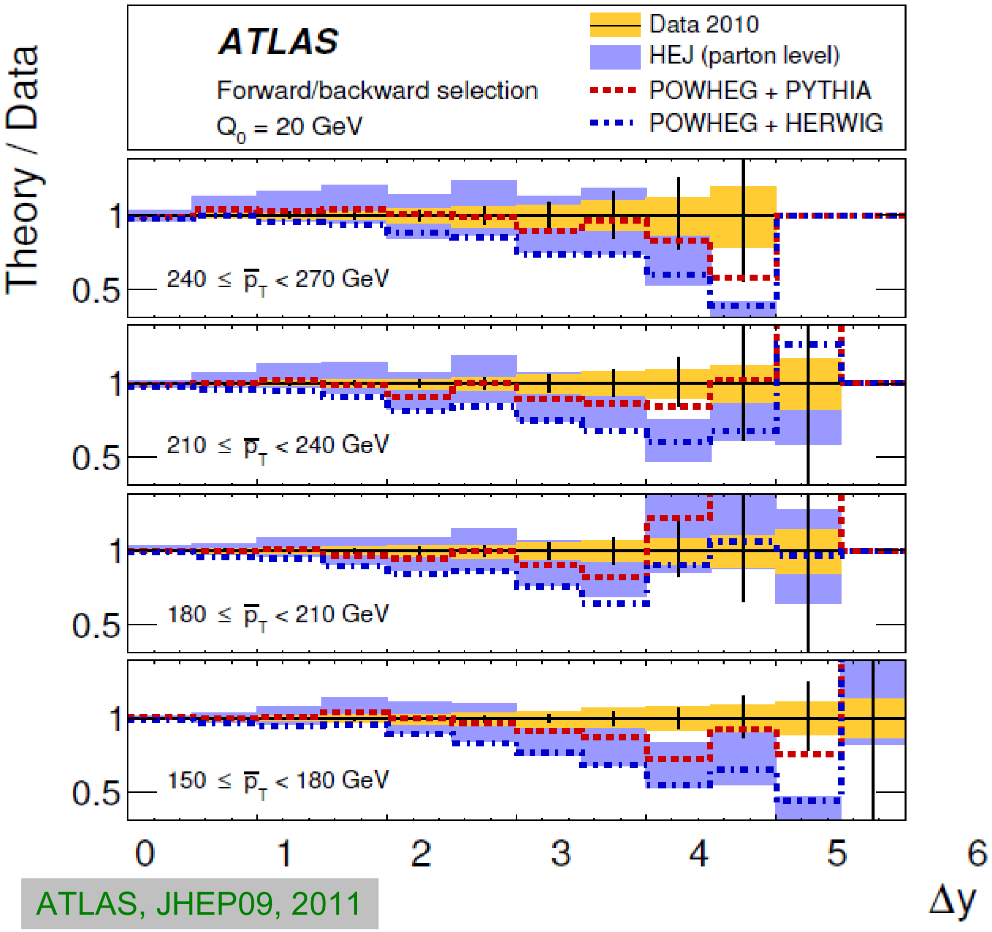
Submitted this morning !

Dijets separated in Rapidity

Quantities sensitive to potential deviations from DGLAP evolution at small x

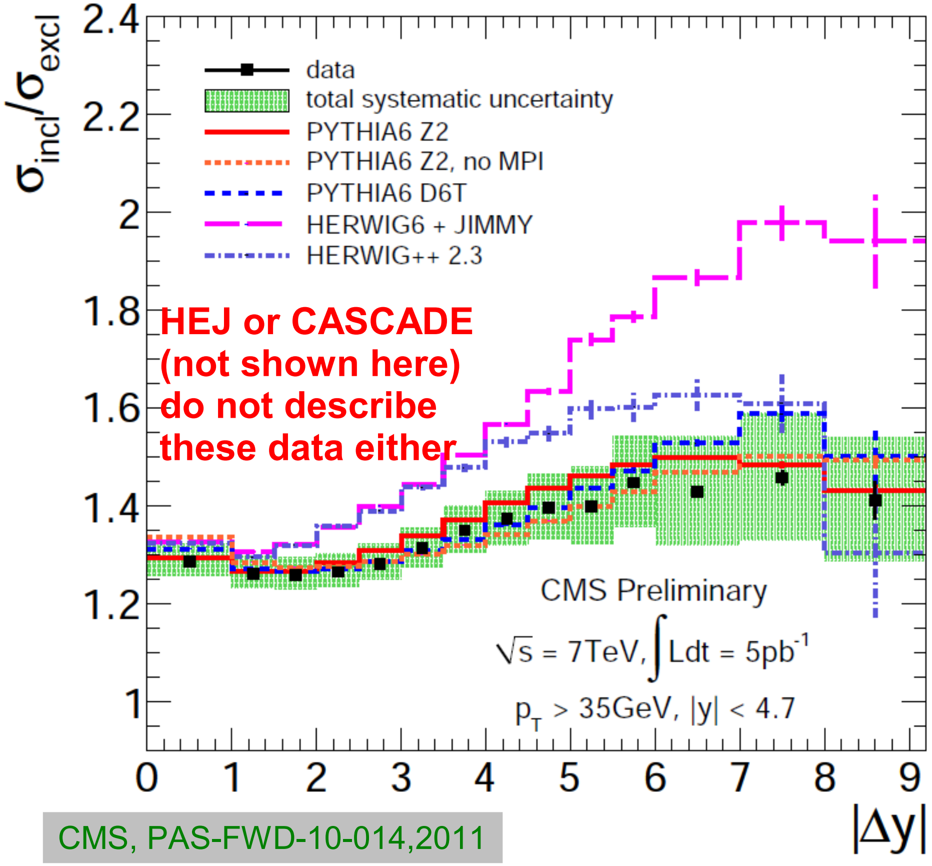
Some MC event generators run into problems … but also BFKL inspired ones!

Most forward-backward dijet selection



ATLAS, JHEP09, 2011

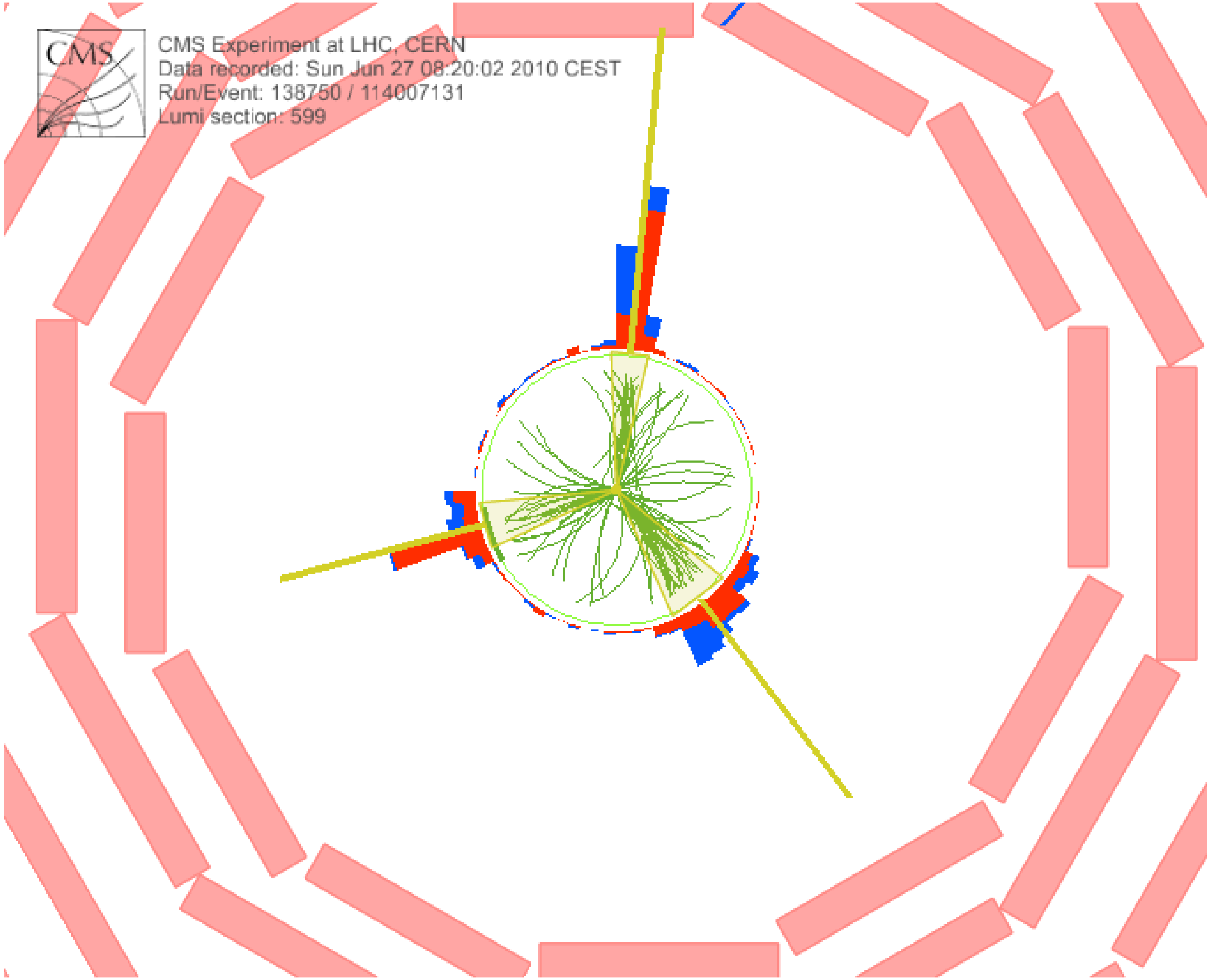
All possible dijet pair distances over leading dijet pair distance



HEJ or CASCADE (not shown here) do not describe these data either

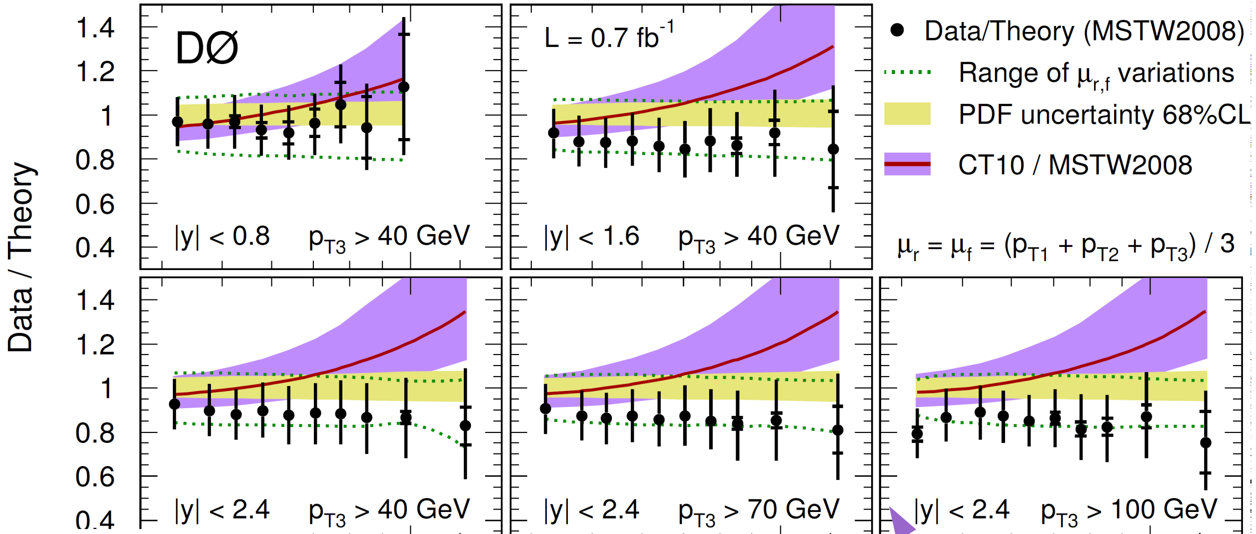
CMS, PAS-FWD-10-014,2011

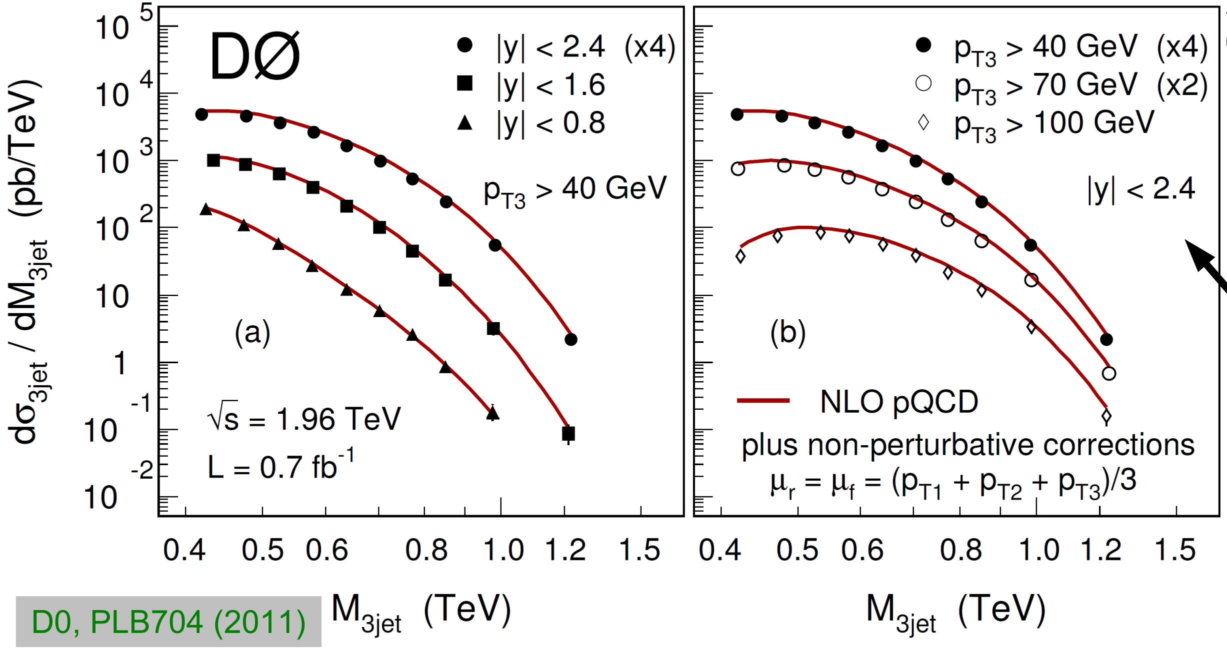
1 + 1 = 3


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” $p_{T,3}$





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

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

3-Jets and α_s

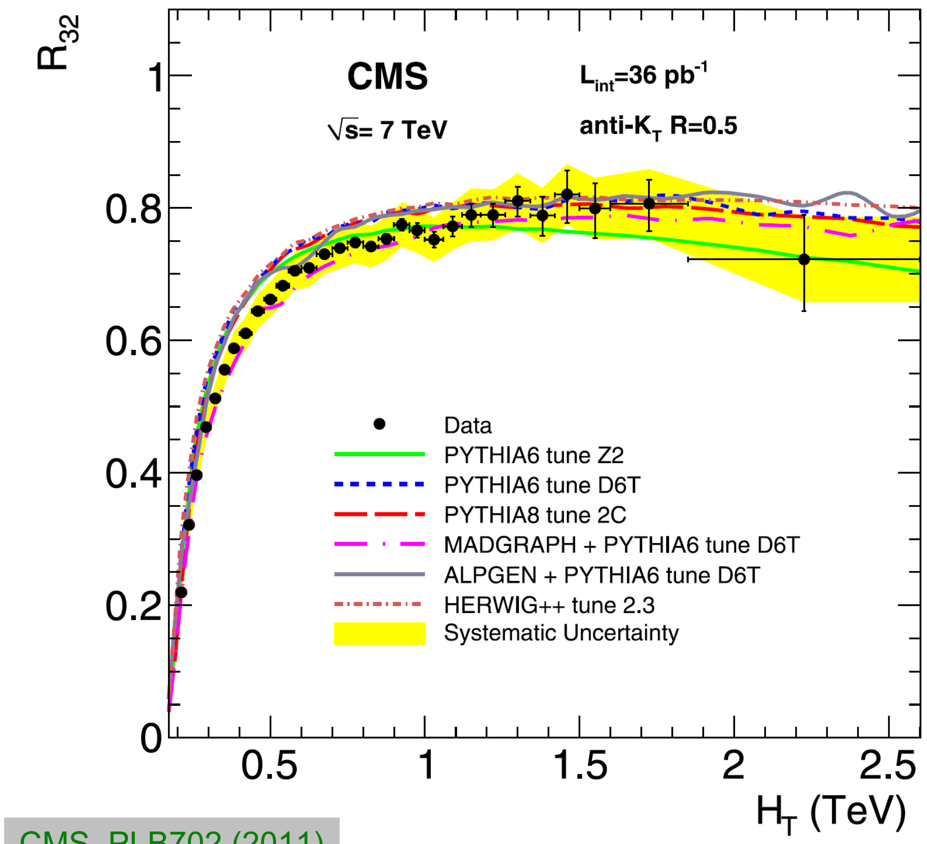
ATLAS, CMS and D0 look into 3-Jet Rates:

$$\frac{\sigma(3+)jets}{\sigma(2+)jets} \propto \alpha_s$$

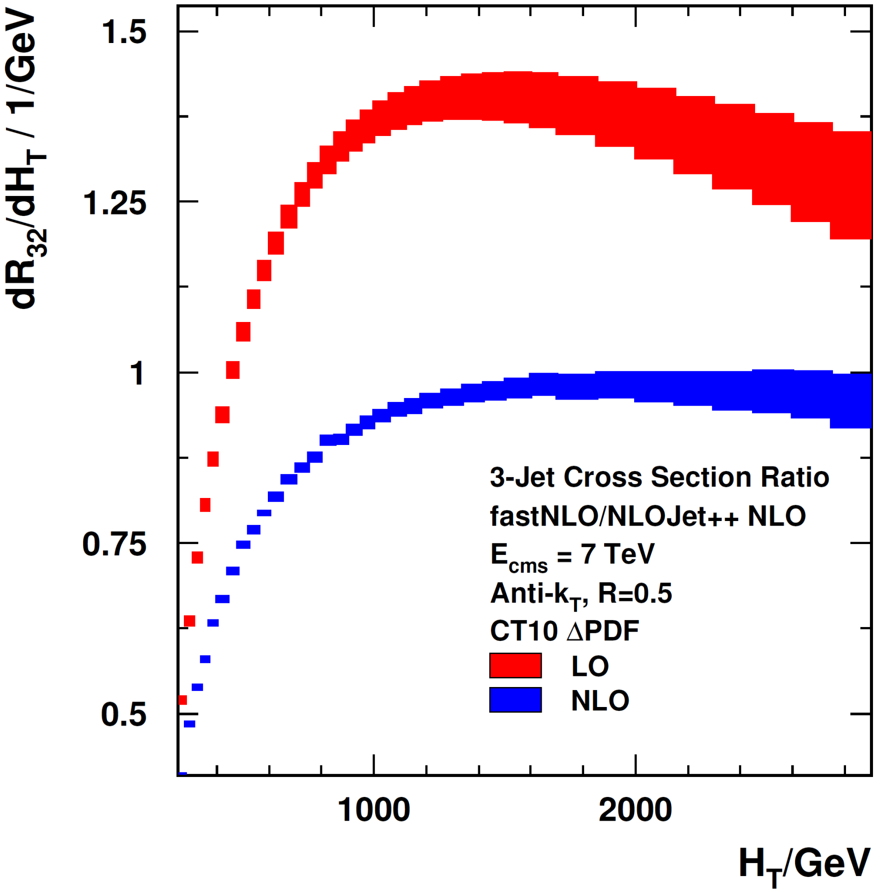
Up to now scenarios for MC comparison. Not optimzed for α_s determination, e.g.

CMS like selection LO > 1 ?!, K factors ~ 0.67

News for Moriond/DIS or Summer Confs?



CMS, PLB702 (2011)



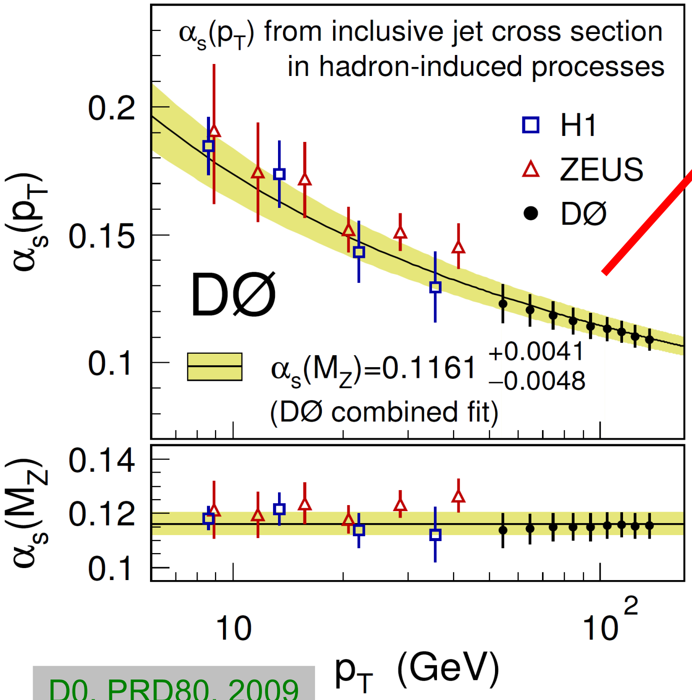
Strong Coupling α_s

Bethke "Very Preliminary 2011":

$$\alpha_s(M_{Z^0}) = 0.1183 \pm 0.0010 \; .$$

Process	Q [GeV]	$\alpha_s(M_{Z^0})$	excl. mean $\alpha_s(M_{Z^0})$	std. dev.
τ-decays	1.78	0.1197 ± 0.0016	0.11809 ± 0.00109	0.8
DIS $[F_2]$	2 - 170	0.1142 ± 0.0023	0.11866 ± 0.00132	1.7
DIS [e-p → jets]	6 - 100	0.1198 ± 0.0032	0.11827 ± 0.00097	0.5
Lattice QCD	7.5	0.1183 ± 0.0008	0.11838 ± 0.00164	0.0
Υ decays	9.46	$0.119^{+0.006}_{-0.005}$	0.11832 ± 0.00094	0.1
e^+e^- [jets & shps]	14 - 44	0.1172 ± 0.0051	0.11835 ± 0.00094	0.2
$p\bar{p}$ incl. jets	50 - 145	0.1161 ± 0.0045	0.11831 ± 0.00097	0.5
e^+e^- [ew prec. data]	91.2	0.1193 ± 0.0028	0.11829 ± 0.00095	0.3
e^+e^- [jets & shps]	91 - 208	0.1208 ± 0.0038	0.11826 ± 0.00099	0.7

Bethke et al., arXiv:1110:0016, 2011



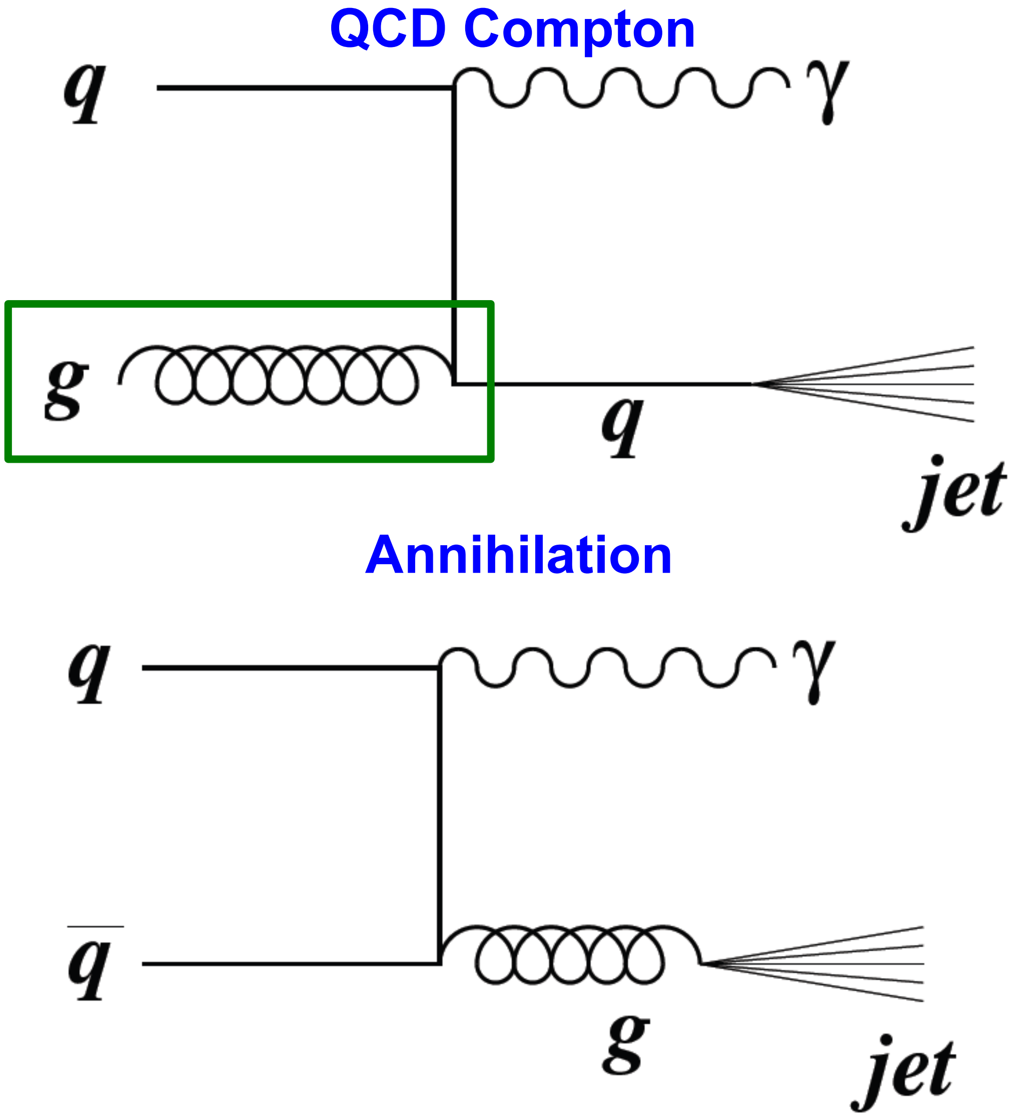
D0, PRD80, 2009

NLO alpha_s in global PDFs:

ABM11: 0.1180
CT10: 0.1180
GJR08: 0.1178
HERAPDF1.5: 0.1176
MSTW2008: 0.1200
NNPDF2.1: 0.1190

There should be more to come from LHC! At the TeV Scale.

Isolated Prompt Photons

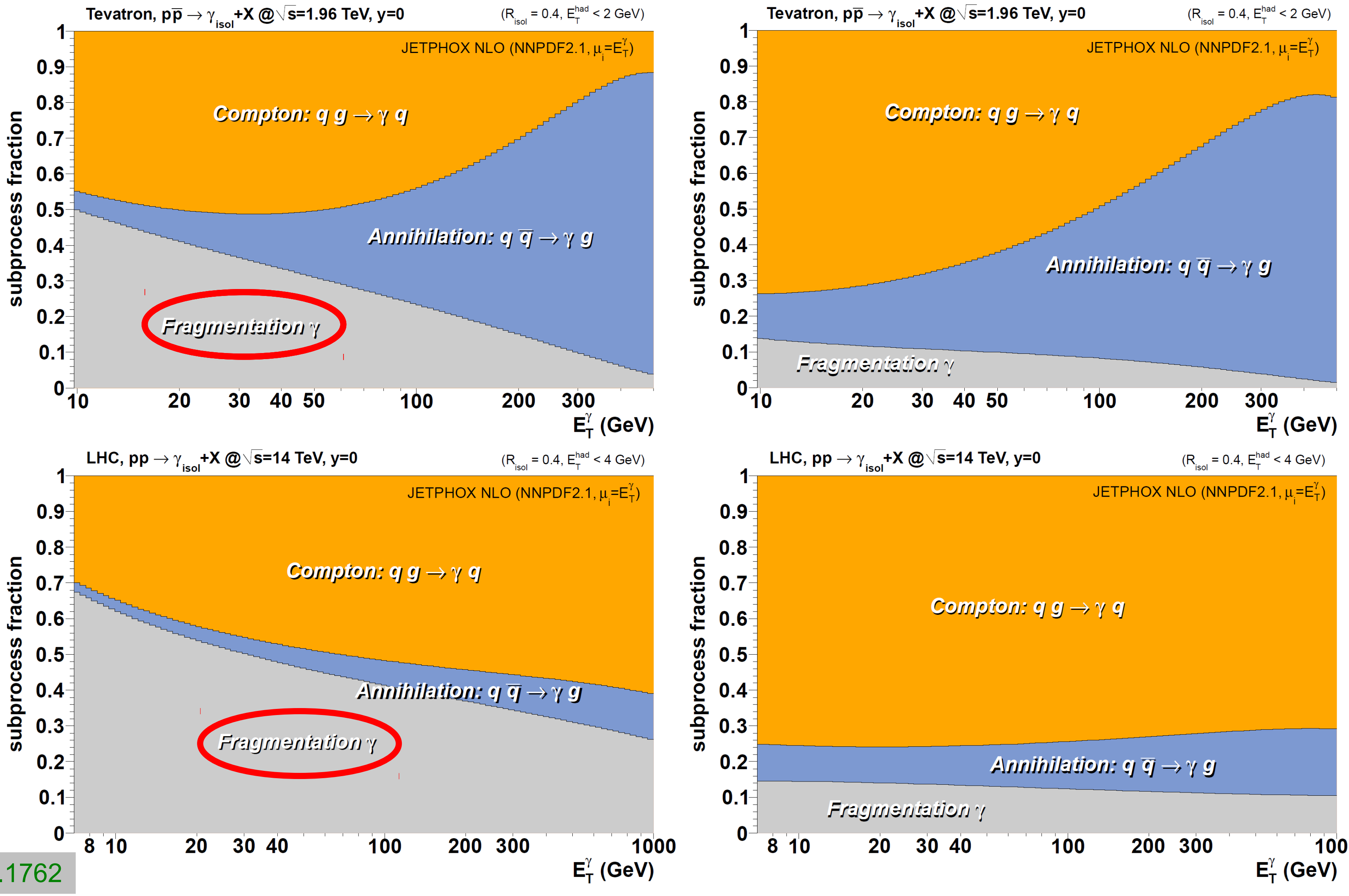


Signal Process Fractions

Inclusive **Isolated**

Tevatron

LHC 14 TeV



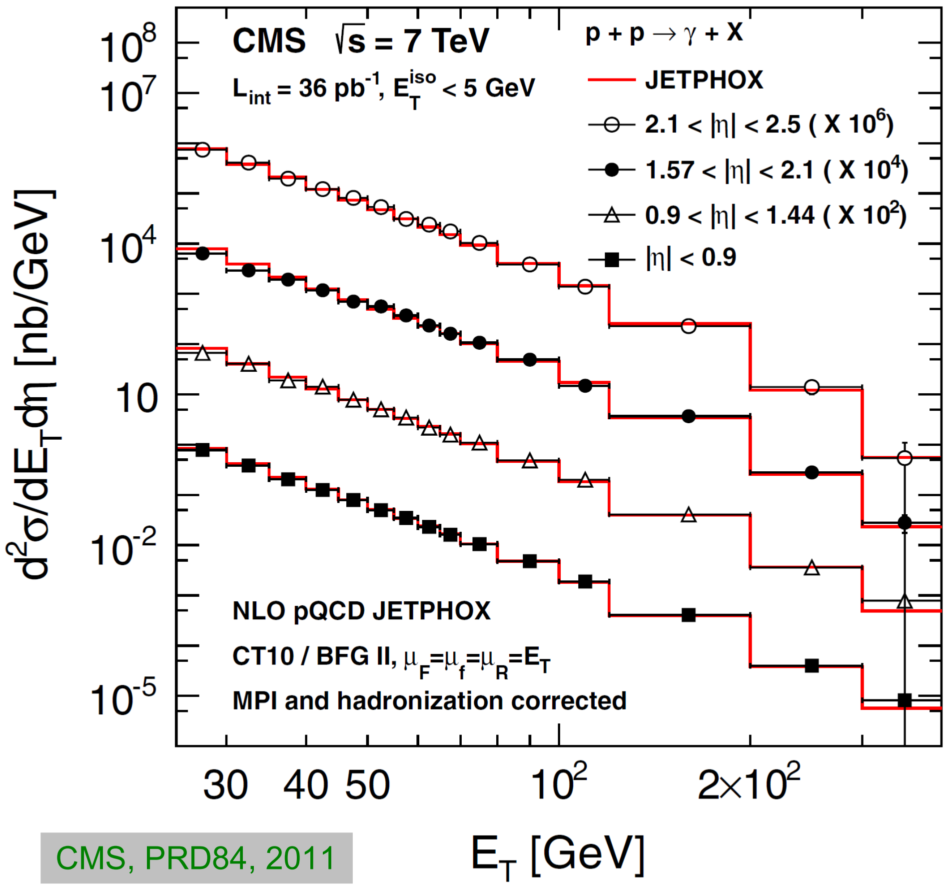
Background: Non-prompt Photons from Decays, e.g. π^0, η

d'Enterria, Rojo, arXiv:1202.1762

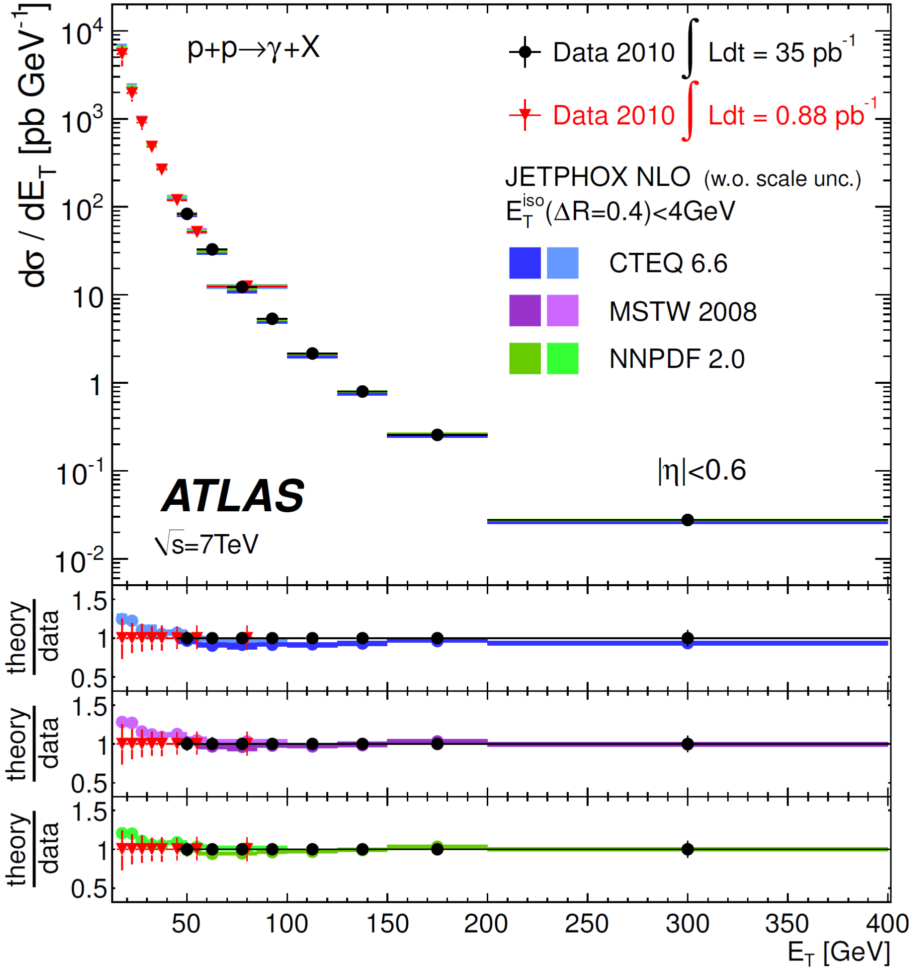
Isolated Prompt Photons

- Sensitive to the gluon density in the proton.
- In agreement with NLO (JetPhox) from ~25 up to 400 GeV, |η| < 2.5
- Limiting factor: Scale uncertainties in theory

JetPhox, Catani et al., JHEP05, 2002



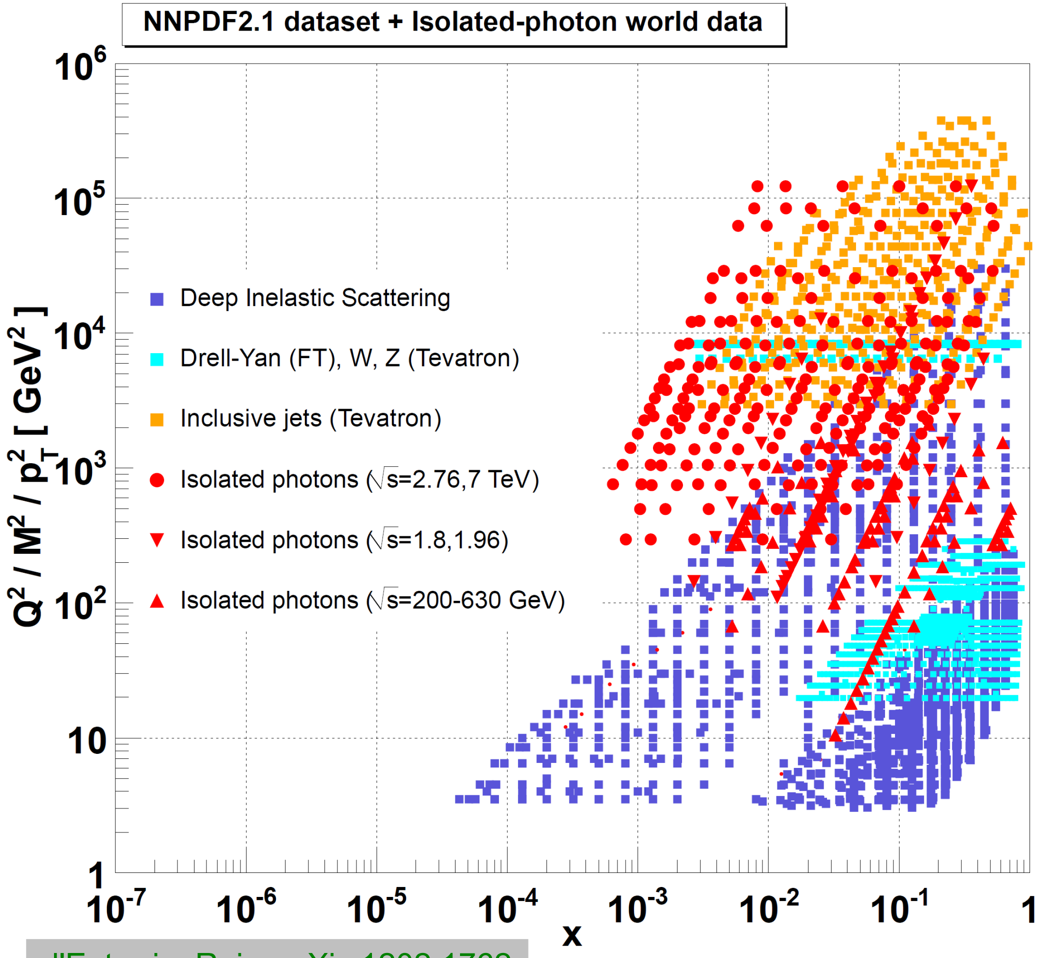
CMS, PRD84, 2011



ATLAS, PLB706, 2011:ATL-PHYS-PUB-2011-013

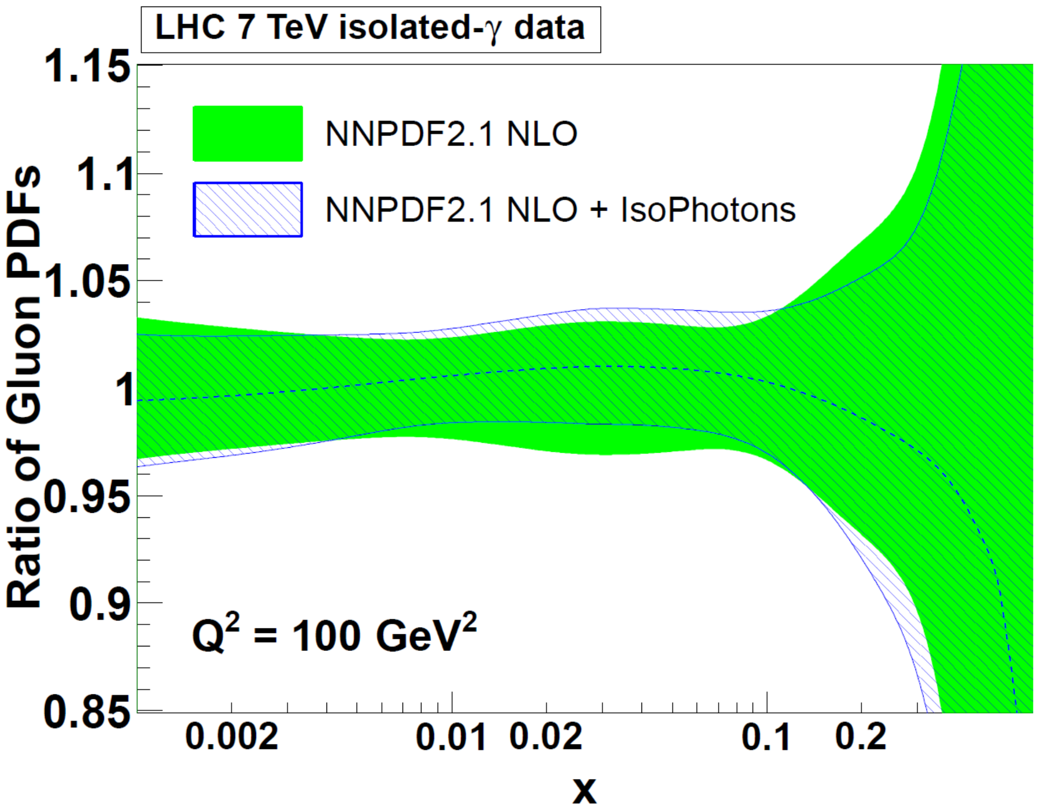
Photons and PDFs

Kinematic plane including photon data



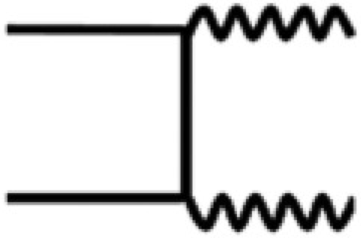
d'Enterria, Rojo, arXiv:1202.1762

- Were abandoned for PDF fits due to discrepancies with fixed target experiments at E_{cms} of 20 – 40 GeV
- new investgation without inclusive data and At E_{CMS} > 200 GeV
- Moderate reduction in uncertainty of the gluon density at x around 0.02 by ~ 20%

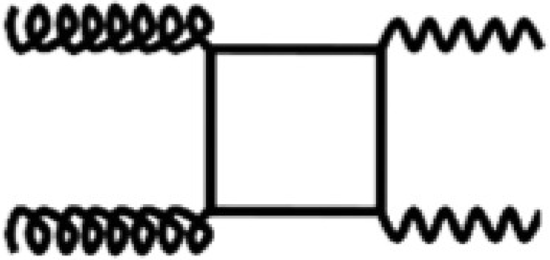


Di-Photons

© www.freefoto.com



$q\bar{q} \rightarrow \gamma\gamma$

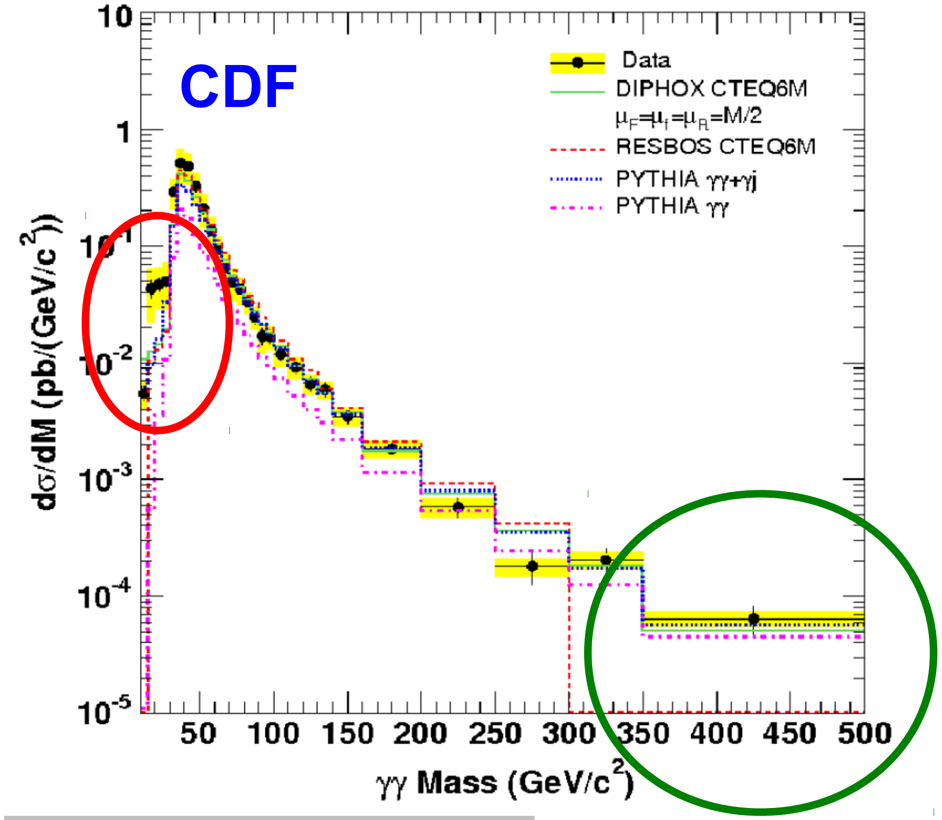


$gg \rightarrow \gamma\gamma$

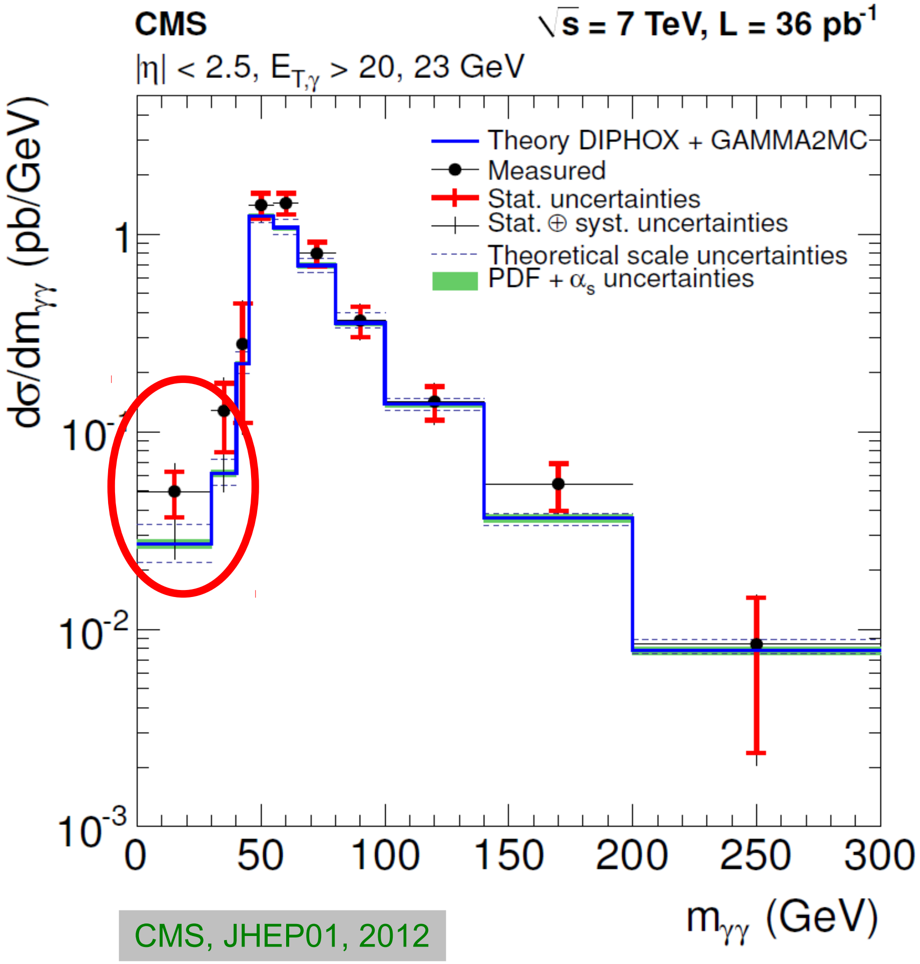
plus ISR, FSR & fragmentation photons

Di-Photons: Mass

- Irreducible background to Higgs → γγ
- In agreement with NLO in p_T, and mass spectra above ~50 GeV up to 400 GeV



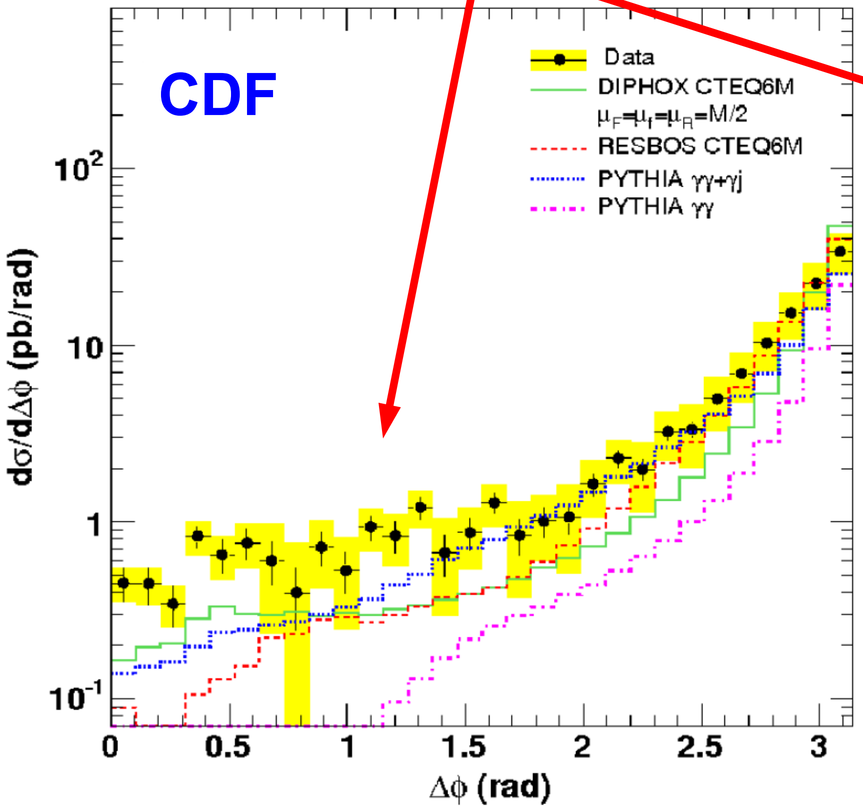
CDF, PRL107, 2011; PRD84, 2011



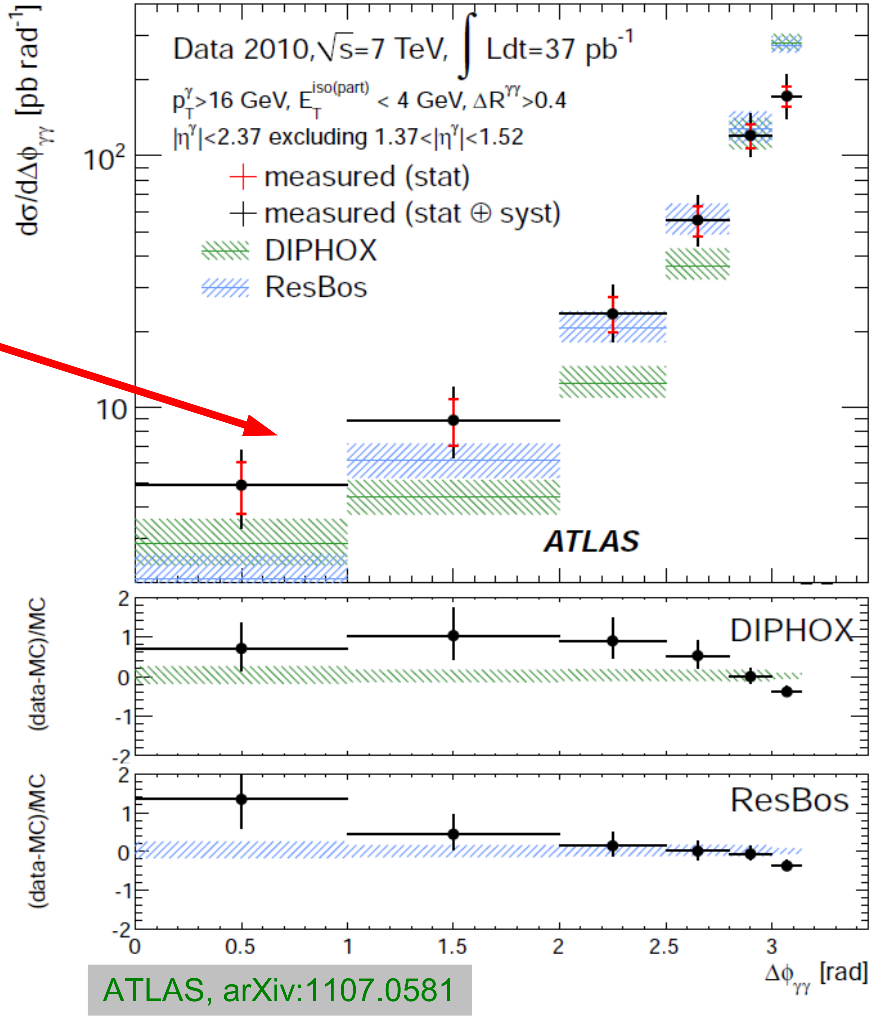
CMS, JHEP01, 2012

Di-Photons

- **Azimuthal difference not well described, somewhat better by RESBOS than DIPHOX**



CDF, PRL107, 2011; PRD84, 2011



ATLAS, arXiv:1107.0581

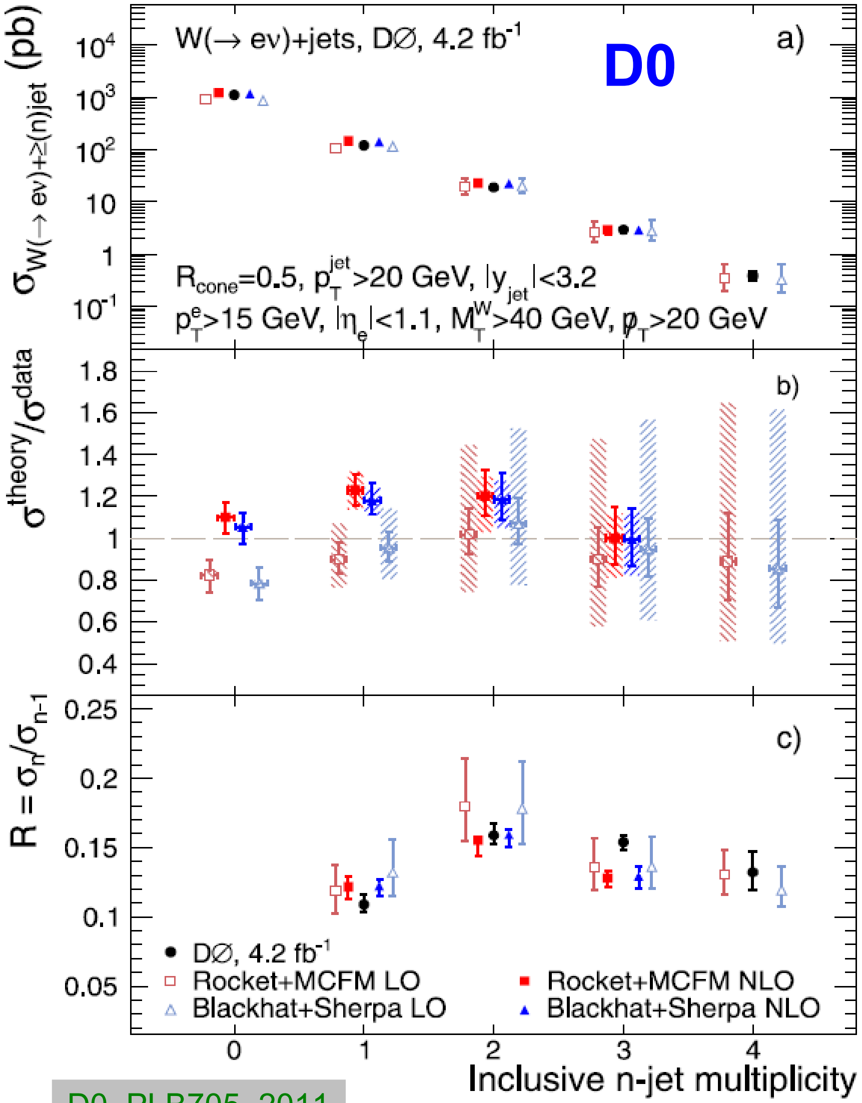
Weak Bosons: Not alone

© www.freefoto.com

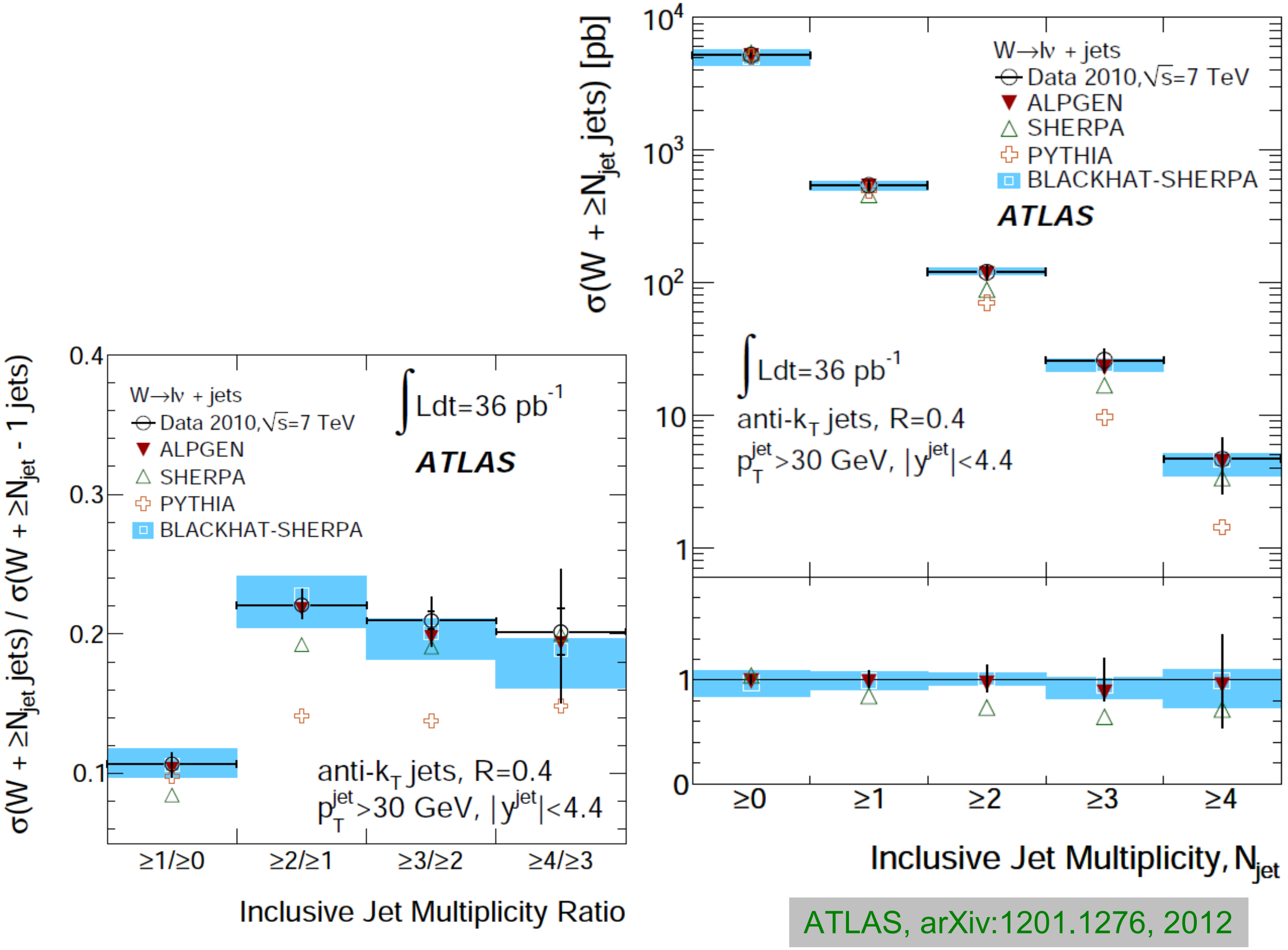
+

W/Z + Inclusive Jet Multiplity

In general agreement between data and theory @ NLO up to 4 jets



D0, PLB705, 2011



ATLAS, arXiv:1201.1276, 2012

W Polarization

W bosons with high $p_T > 50$ GeV

$(f_L - f_R)^- = 0.240 \pm 0.036 \pm 0.031$

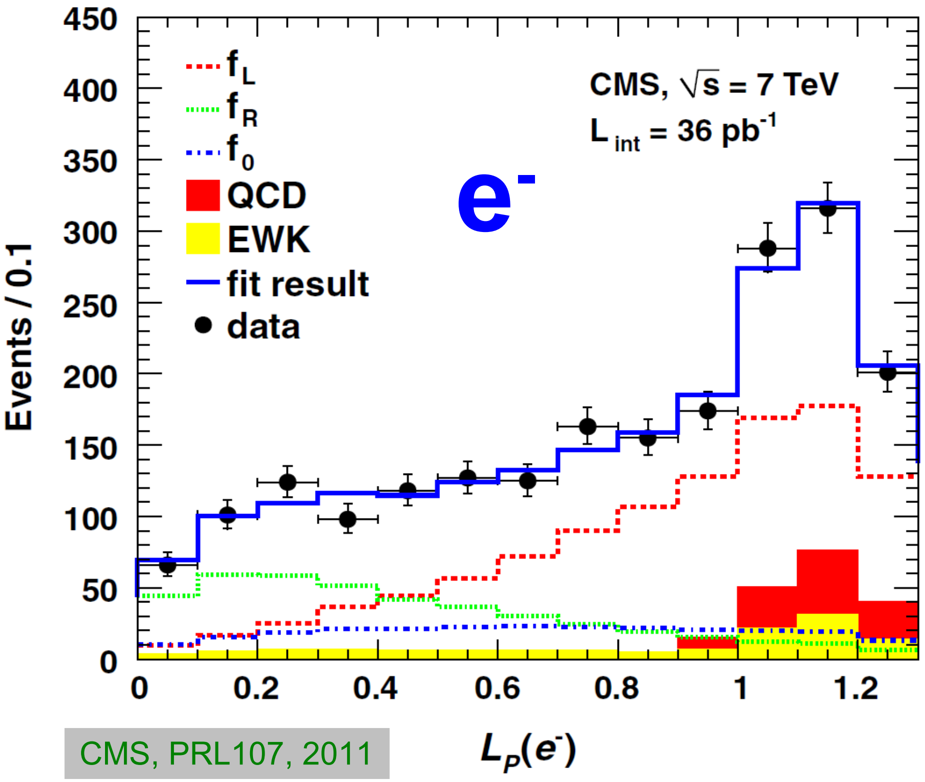
$(f_L - f_R)^+ = 0.310 \pm 0.036 \pm 0.017$

Dominance of left-handed W not evident at large p_T(W)

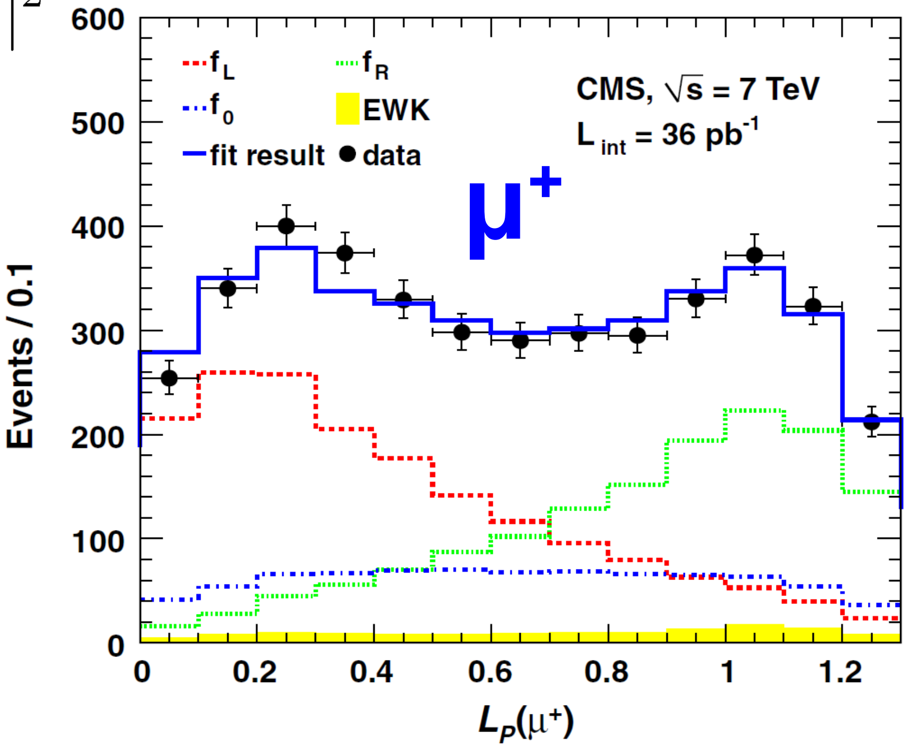
Consequence of left-handed charged weak-interactions, pp initial state and QCD

Berger et al., PRD80, 2009;
Bern et al., PRD84, 2011

$$L_P = \frac{\vec{p}_T(l) \cdot \vec{p}_T(W)}{|\vec{p}_T(W)|^2}$$



CMS, PRL107, 2011

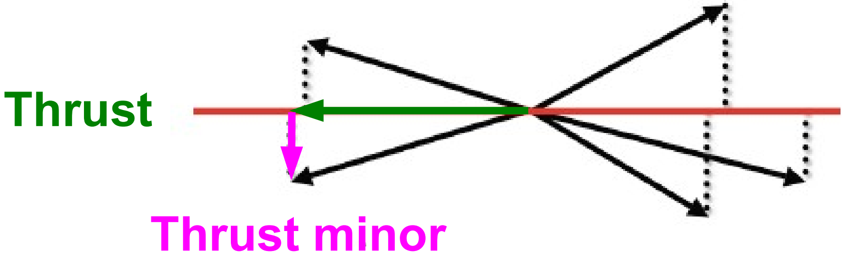


Shapes

Event Shapes

Definition:

Transverse global thrust



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

- In praxis, need to restrict rapidity range: $|\eta| < \eta_{max}$ →

  Transverse central thrust
- Less sensitive to JES & JER uncertainty
- No luminosity uncertainty
- Useful for MC tuning
- Comparison to perturbative QCD

& resummation possible

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

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

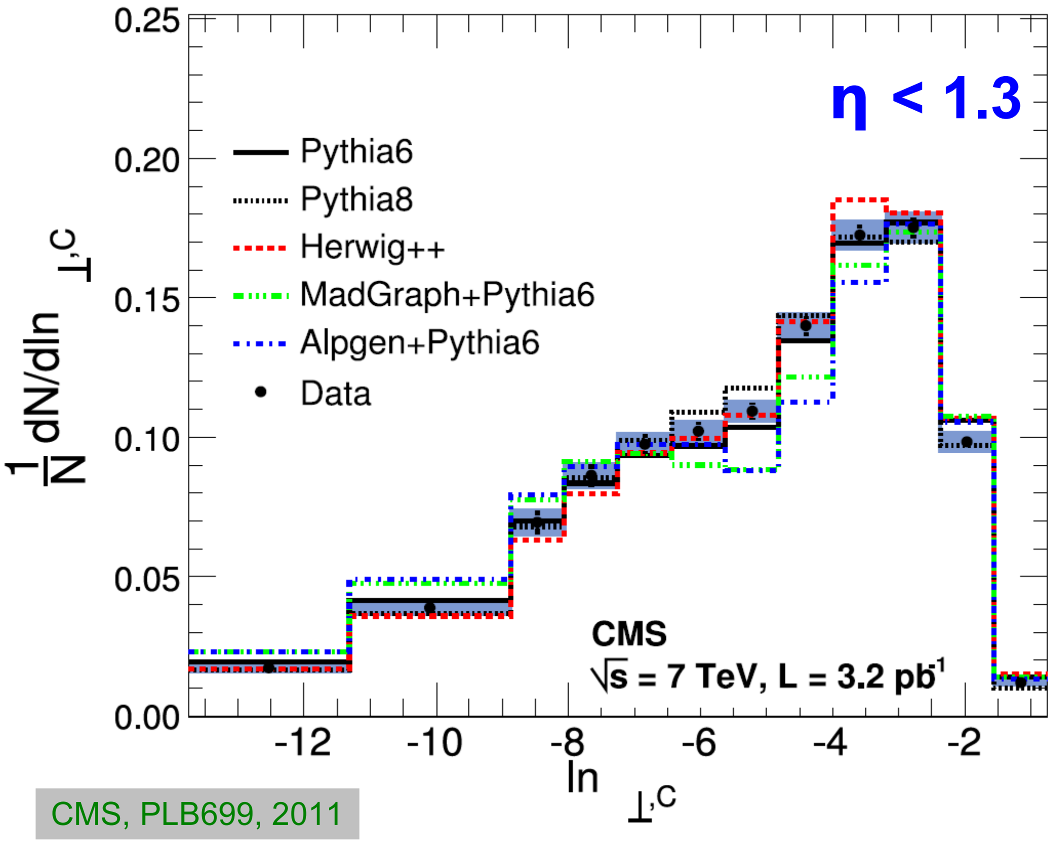
See e.g. A. Banfi, G. Zanderighi et al., JHEP06, 2010

Transverse Thrust

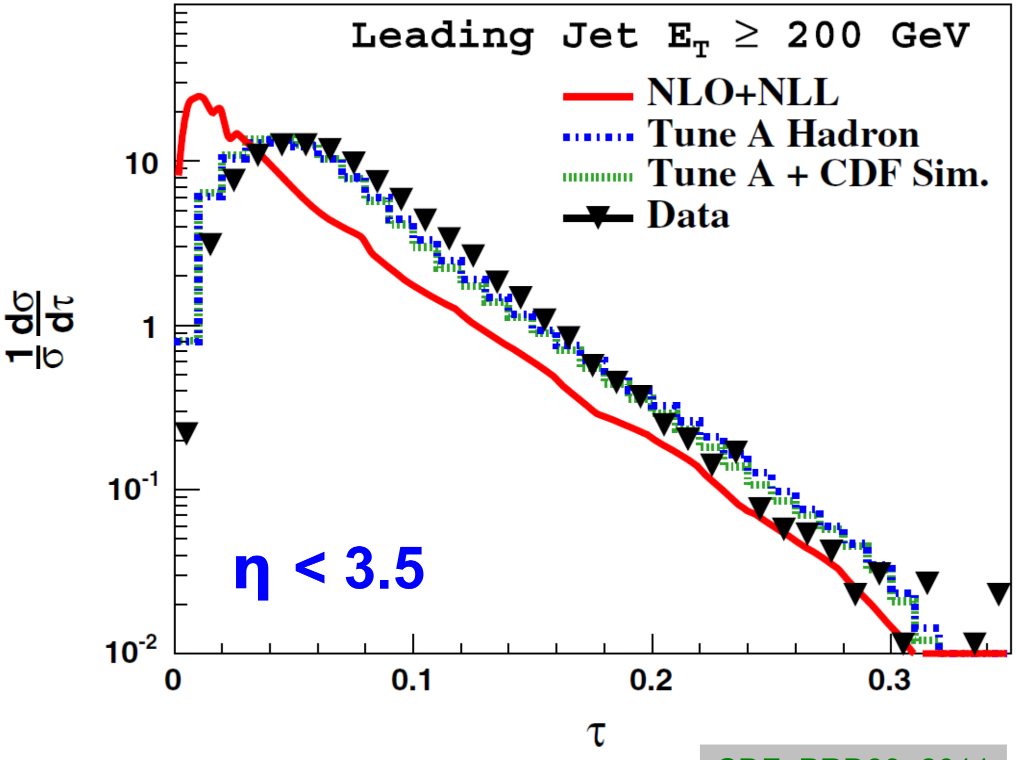
CMS early comparison to MC event generators

CDF uncorrected data vs. MC simulation

$$\tau_{\perp,C} \equiv 1 - \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$



CMS, PLB699, 2011



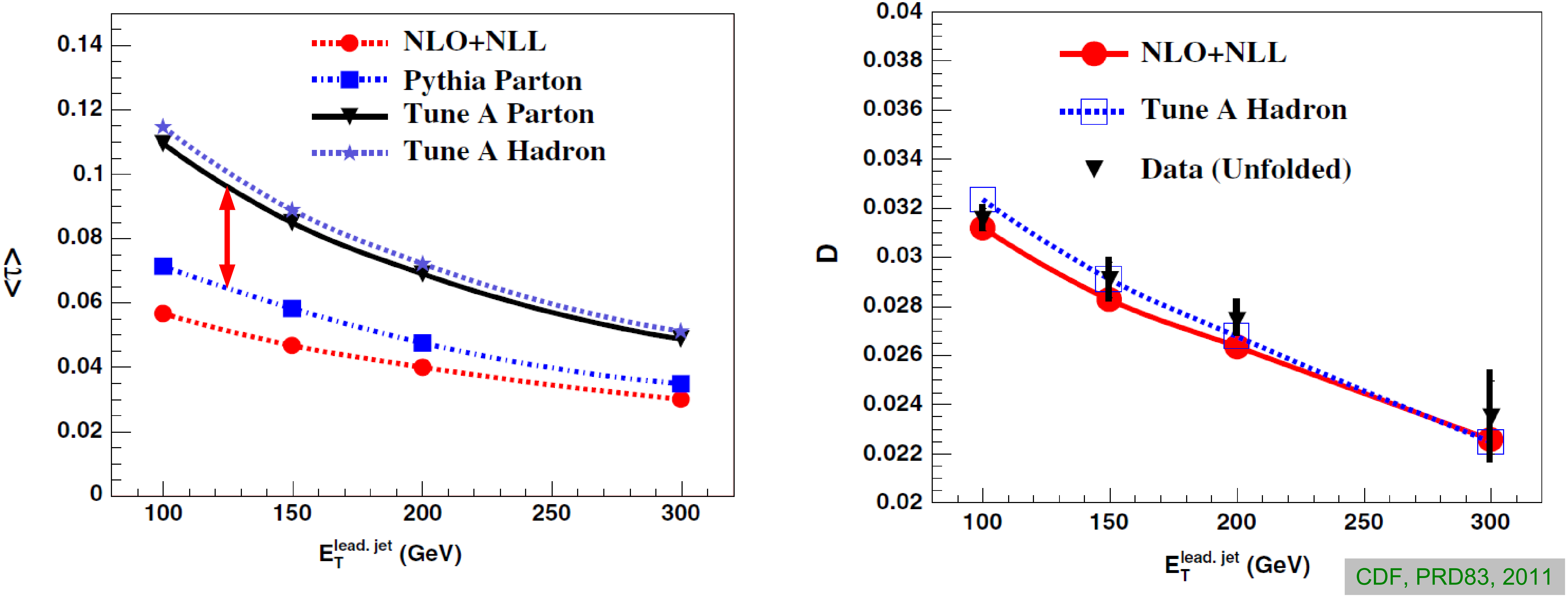
CDF, PRD83, 2011

“Thrust Differential D”

CDF: Strong impact of UE
Pythia Parton means “without UE”

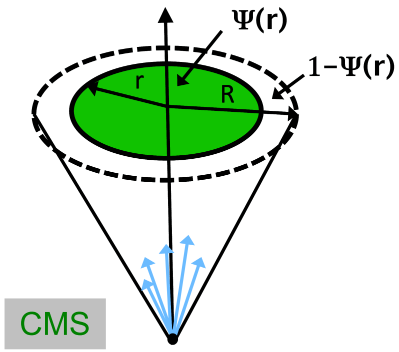
Define less sensitive difference D
Not sure this is the end of the story, can ask Giulia ...

$$D\left(\langle\tau\rangle,\langle T_{min}\rangle\right)=\gamma_{MC}\left(\alpha\langle T_{min}\rangle-\beta\langle\tau\rangle\right)$$



CDF, PRD83, 2011

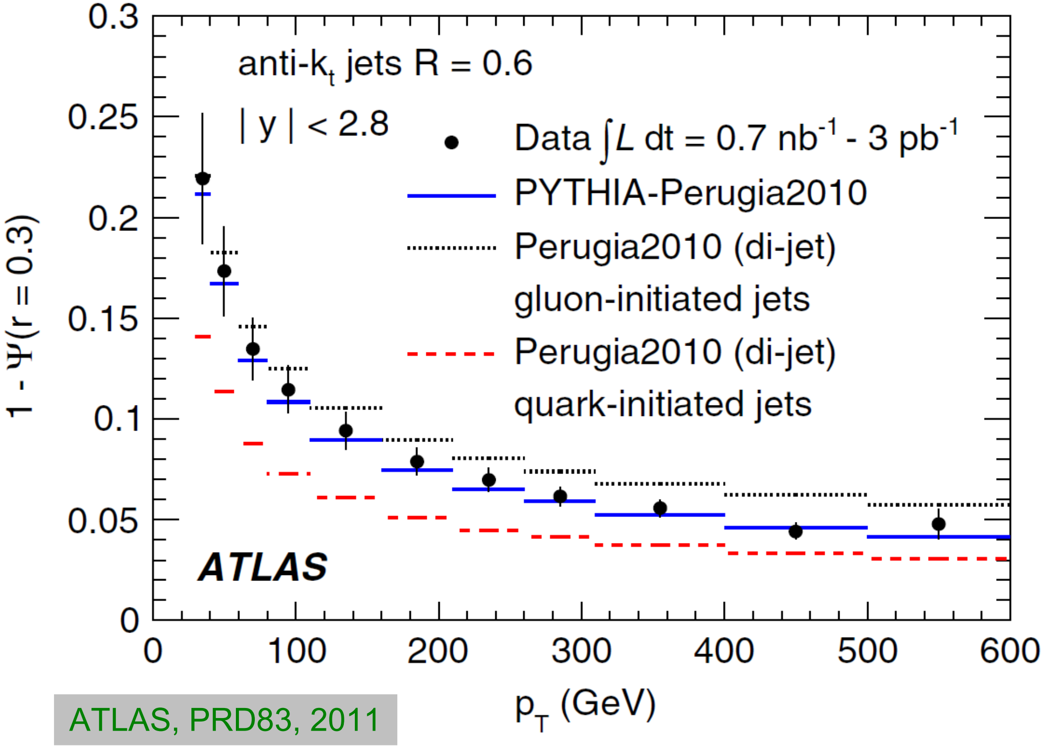
Jet Substructure



CMS

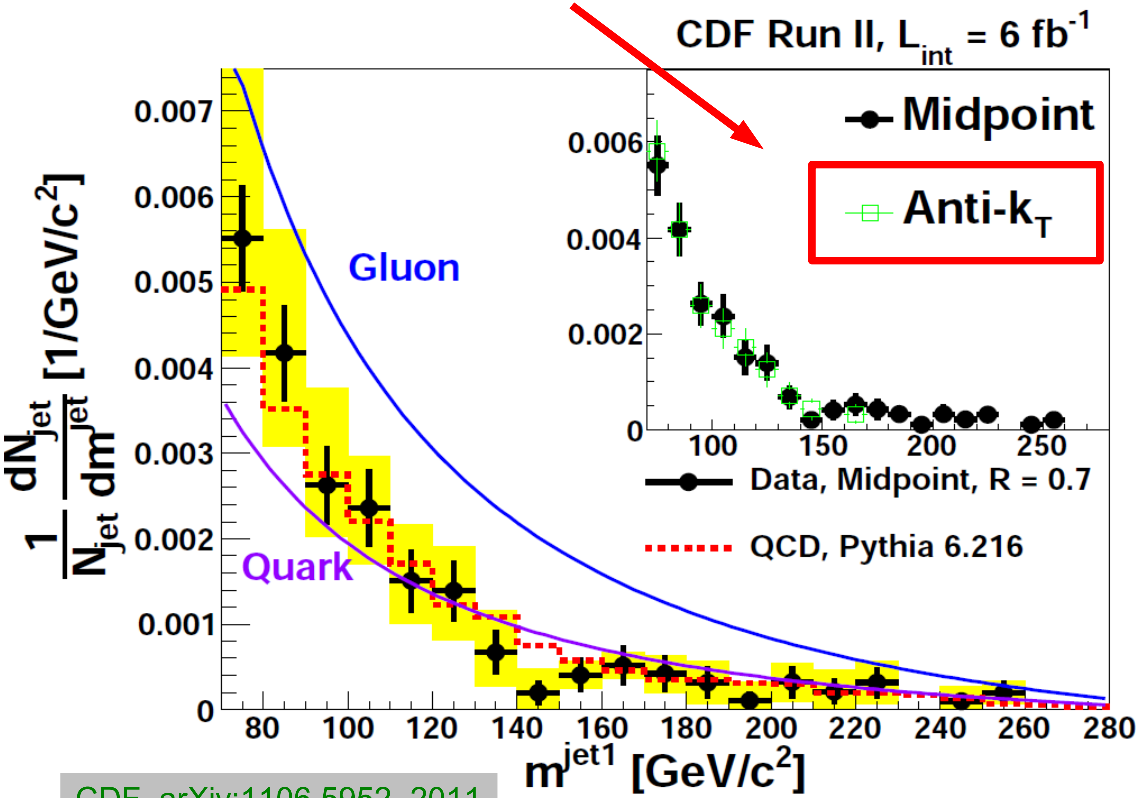
Jet shape (left) and jet mass (right) sensitive to differences in quark and gluon initiated jets

Can help also in differentiating boosted jets of heavy objects like Z' or t' ...



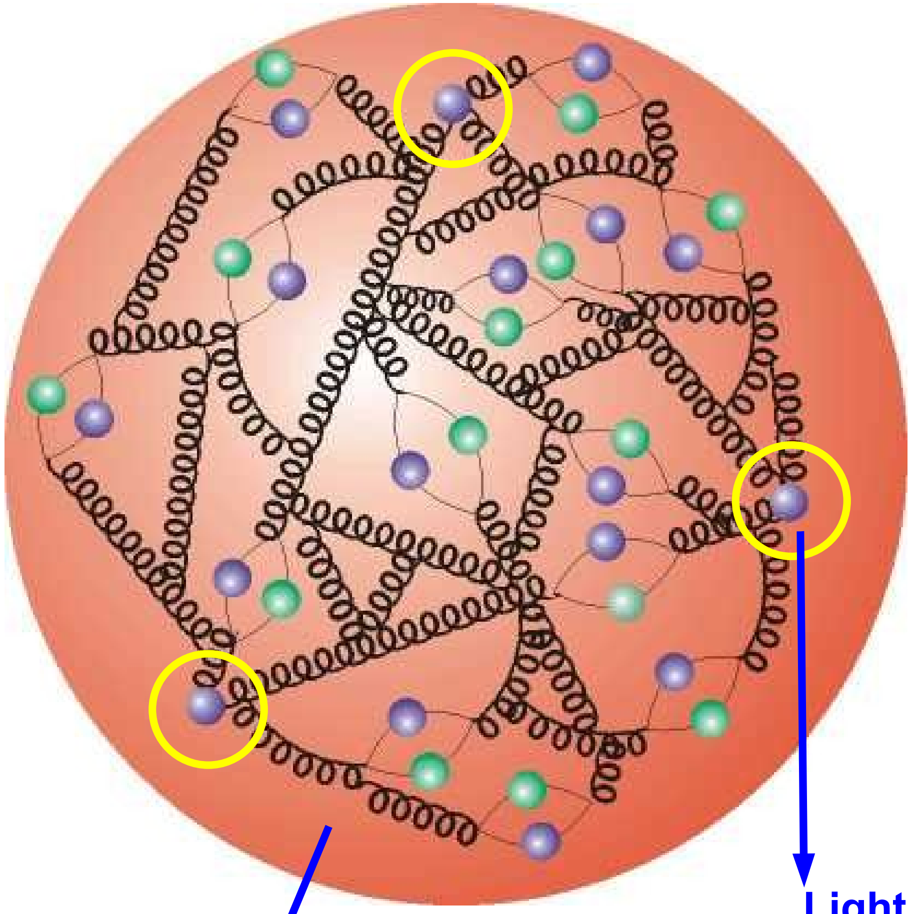
ATLAS, PRD83, 2011

Anti-kT at Tevatron!



CDF, arXiv:1106.5952, 2011

Mass matters ...



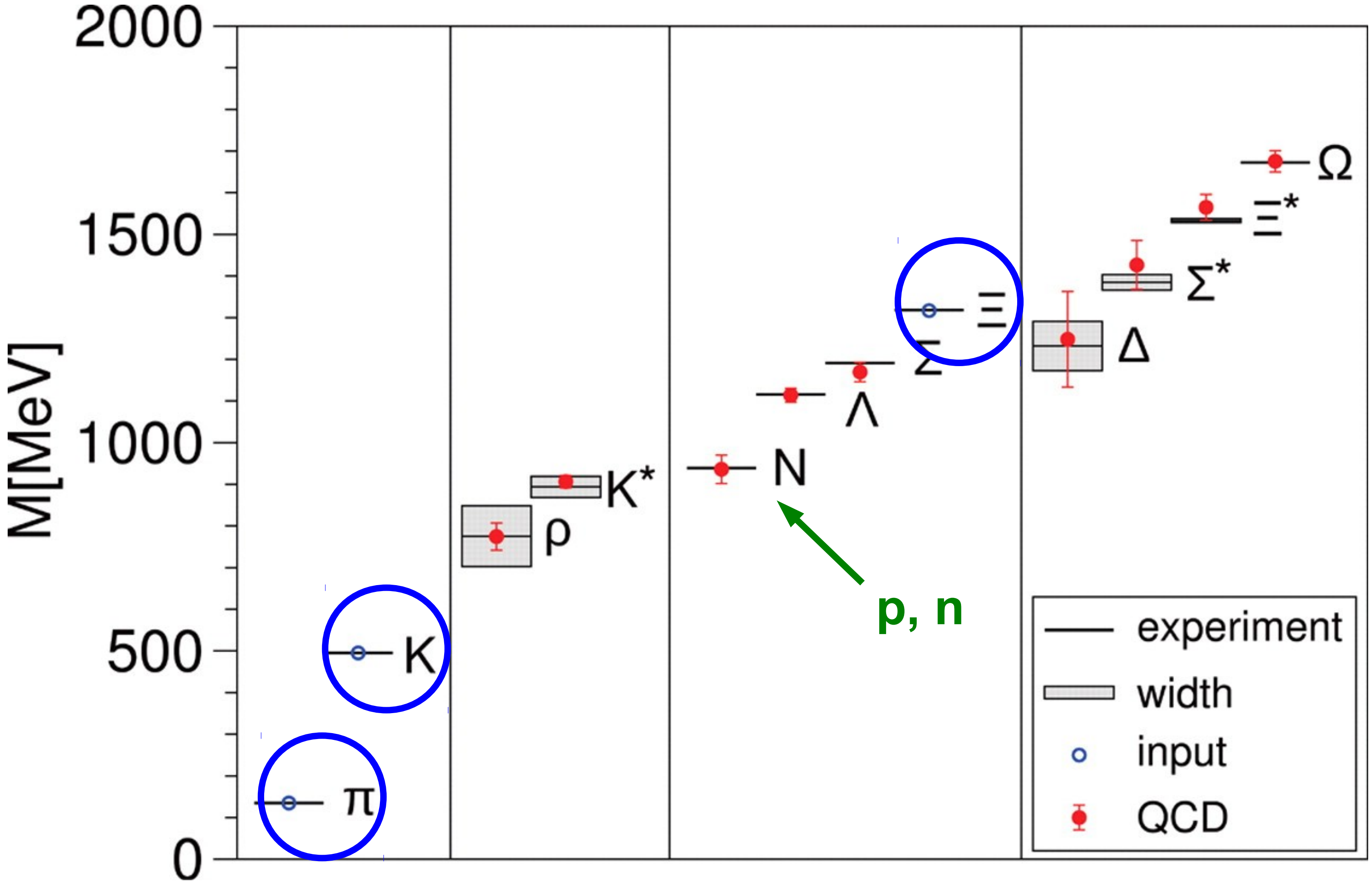
Proton Mass:
~1000 MeV

Light Quark Mass:
~5 MeV

HERA-Proton, DESY

- More than 99% of the visible (ordinary) mass in the universe is made of protons and neutrons
- About 95% of a proton's mass is coming from the strong interaction QCD
- The quark masses provided presumably by the Higgs Mechanism are almost negligible in this context ...

Nucleon Mass ... Calculated



Calculated from first principles in lattice gauge theory of QCD

Input: Three particle masses representative for the light quark masses

S. Dürr et al., Science 322 no. 5905, 21. Nov. 2008

Outlook

- QCD at hadron colliders is becoming PRECISION PHYSICS
- Interplay between strong and electroweak interactions are 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
- Fresh results to be expected for Moriond/DIS and the Summer Conferences. Stay tuned!

Disclaimer

- The presented topics results from a personal selection I had to make
- Concentrated on LHC and Tevatron; for HERA & The Proton

Behnke et al, Physik Journal 02/2012

- Numerous interesting topics did not fit in any more :-(, i.a.
    - Jet production with heavy flavours
    - Particle production
    - Minimum bias & diffractive measurements
    - Hadr. interaction at highest energies
    - Heavy ion measurements

See Talk T3.1 by Ralph Engel

- But more than 99% of the talks are still to come ! Have fun !

Vielen Dank an Sie für Ihre Aufmerksamkeit und an die Organisatoren für die Einladung zu diesem Vortrag!

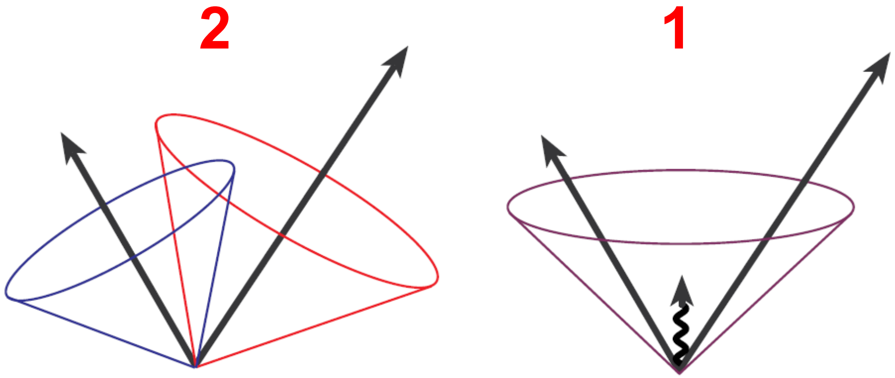
War das alles?

Backup Slides

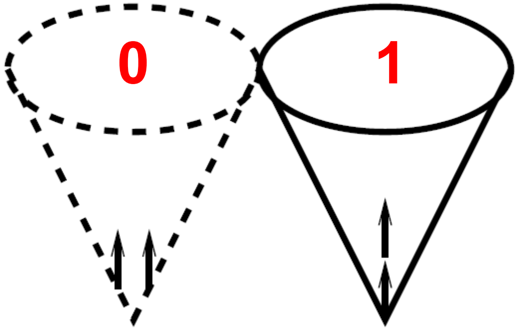
Jet Algorithms 2

Jet Algorithm Desiderata (Theory):

- **Infrared safety**
- **Collinear safety**
- **Longitudinal boost invariance**
  (recombination scheme!)
- **Boundary stability**
  (→ 4-vector addition, rapidity y)
- **Order independence**
  (parton, particle, detector)
- **Ease of implementation**
  (standardized public code?)



IR unsafe: Sensitive to the addition of soft particles



Coll. unsafe: Sensitive to the splitting of a 4-vector (seeds!)

See also:
"Snowmass Accord", FNAL-C-90-249-E
Tevatron Run II Jet Physics, hep-ex/0005012
Les Houches 2007 Tools and Jets Summary , arXiv:0803.0678

Jet Algorithms 3

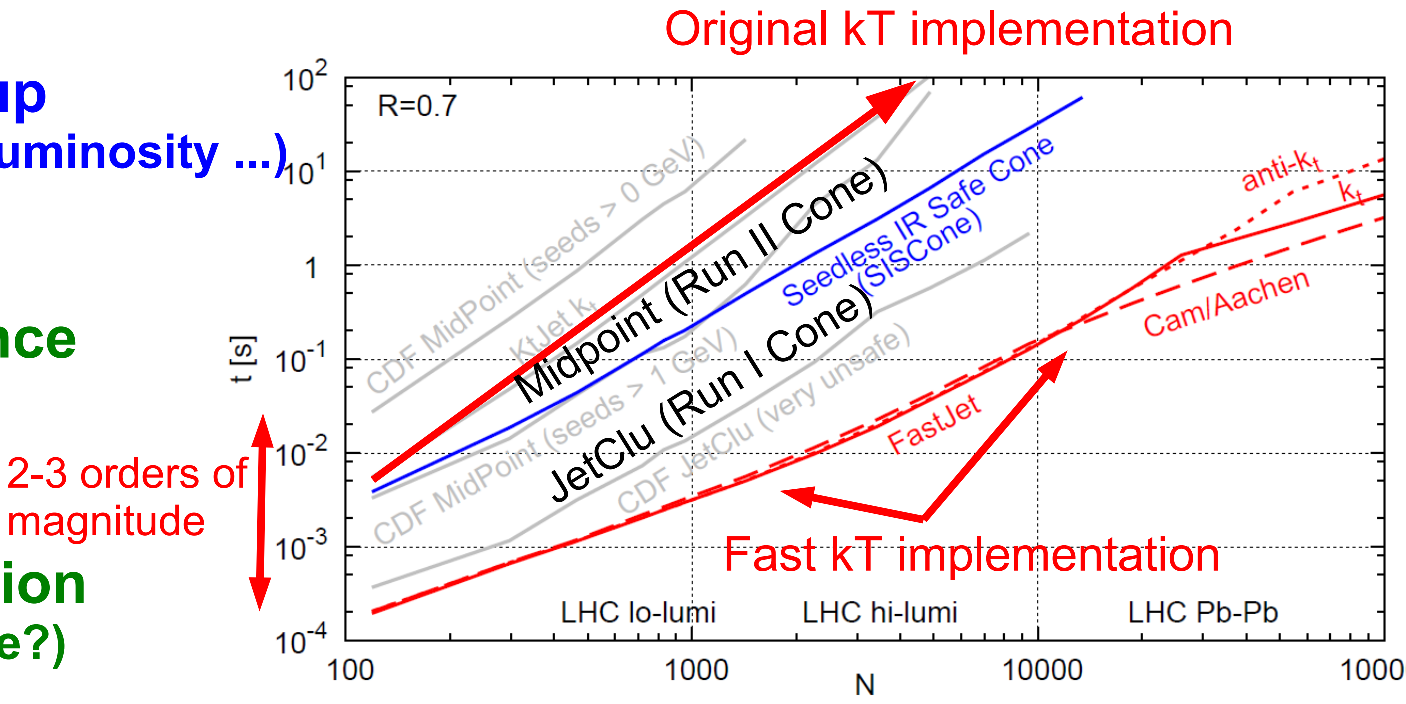
- **Jet Algorithm Desiderata (Experiment):**
  - **Computational efficiency and predictability**
    (use in trigger?, reconstruction times?)
  - **Maximal reconstruction efficiency**
  - **Minimal resolution smearing and angular biasing**
  - **Insensitivity to pile-up**
    (mult. collisions at high luminosity ...)
  - **Ease of calibration**
  - **Detector independence**
  - **Fully specified**
    (details?, code?)
  - **Ease of implementation**
    (standardized public code?)

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p}\,,$$

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

p = 1: kT
p = 0: Cambridge/Aachen
p = -1: anti-kT



Original kT implementation

Midpoint (Run II Cone)

JetClu (Run I Cone)

2-3 orders of magnitude

Fast kT implementation

Jetography, G. Salam, hep-ph/0906.1833

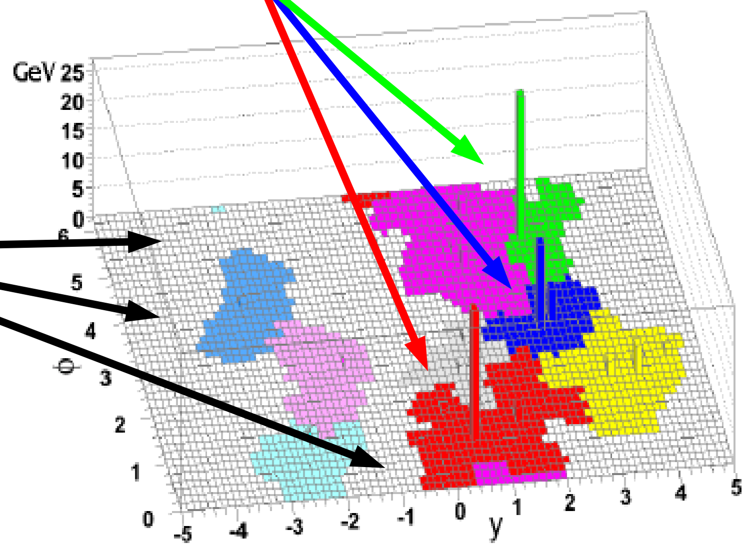
Jet Area/Median Approach

- **Jet Areas:**
- Jet area is determined with **active area clustering**
  - See “The Catchment Area of Jets”, JHEP04(2008)005, M. Cacciari et al.
-

pT infinitesimally small

- A uniform grid of extremely soft “ghost particles” is clustered with the physical input particles
  - Number of ghosts in a jet determines its area
  - Requires a fast infrared & collinear safe jet algorithm
  - Cambridge-Aachen, kT, anti-kT
  - Empty regions are covered with **ghost jets**

physical jets

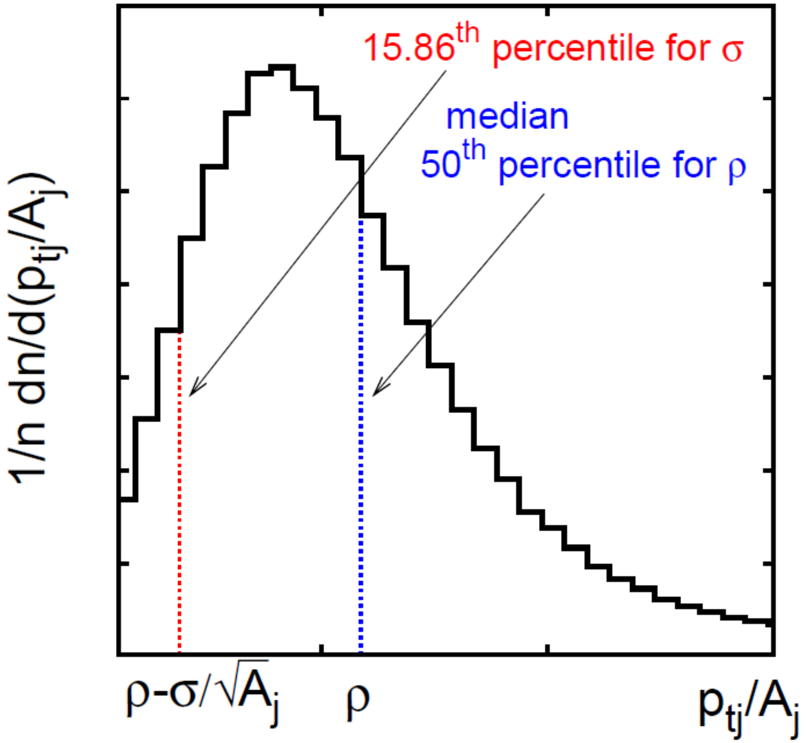


$$\boxed{A_j = \frac{N_j^{\text{ghosts}}}{\rho^{\text{ghosts}}} = \frac{N_j^{\text{ghosts}}}{N_{\text{tot}}^{\text{ghosts}}} A_{\text{tot}}}$$

Figure 4: Active area for the same event as in figure 3, once again clustered with the k_t algorithm and $R = 1$. Only the areas of the hard jets have been shaded — the pure ‘ghost’ jets are not shown.

Jet Area/Median Approach

- **New Observable:**
  - **ρ = median(pt/area) of all jets in an event**
  - **Determination of leading objects (jets) inherent**
  - **Suited for different event topologies**
  - **Looks into complete region in η, Φ**
  - **Has never been used in tuning**
-
- **Event and Track Selection identical to previous one, only differences:**
  - **pT track > 0.3 GeV instead of 0.5 GeV**
  - **$|\eta|$ track < 2.3**
  - **$|\eta|$ track-jet < 1.8**



Event Occupancy

- **Define** event occupancy **as sum of all jet areas in an event divided by overall considered detector area (defined to be 4 * 2π = 8π).**
  - **If occupancy is smaller than 0.5**

    most of the detector is covered

    with ghost jets

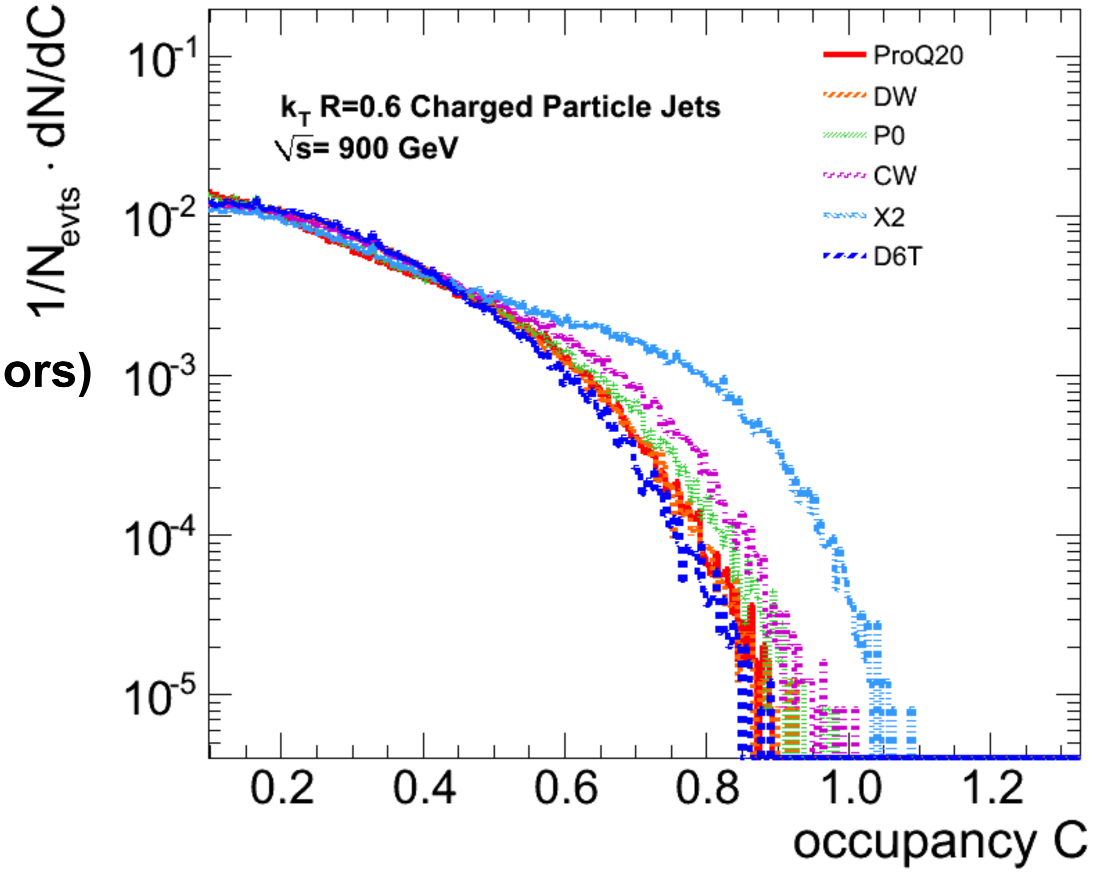
    → Median(pt/area) = 0 in this case
  - **Adjustment of ρ (discussed with authors) is necessary**

Adjusted observable:

$$\rho' = \underset{j \in physical\ jets}{median} \left[\left\{ \frac{p_{T,j}}{A_j} \right\} \right] * C$$

$$C = \frac{\Sigma_j A_j}{A_{tot}}$$

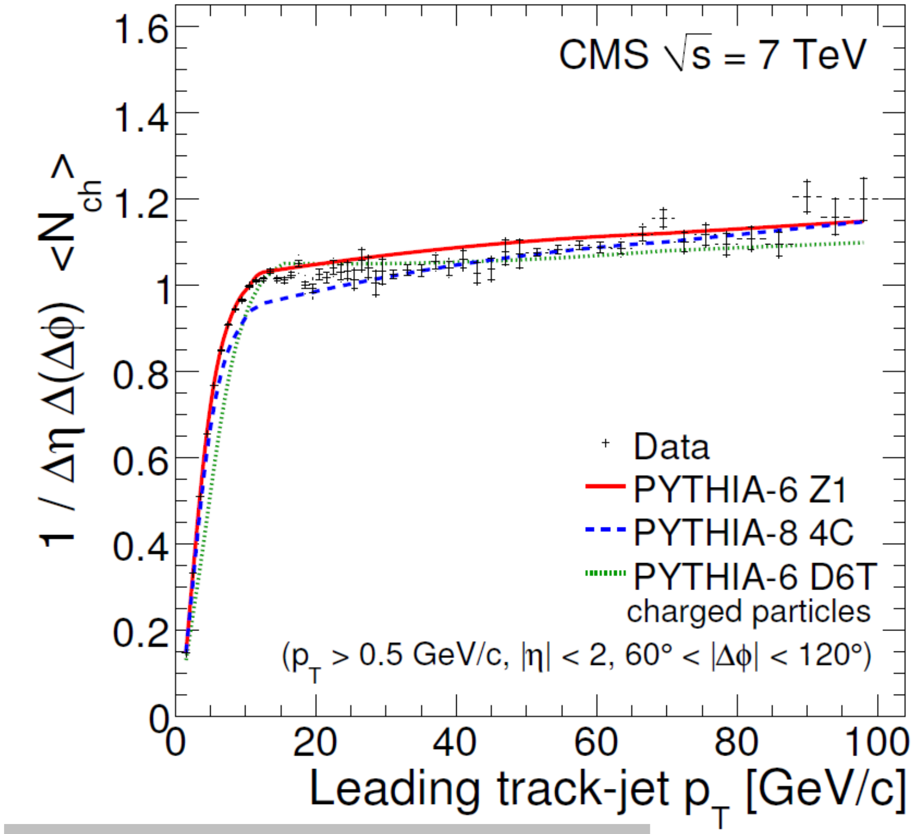
takes into account only physical jets



Jet areas extending beyond |η|=2 may give values > 1 with the definition above

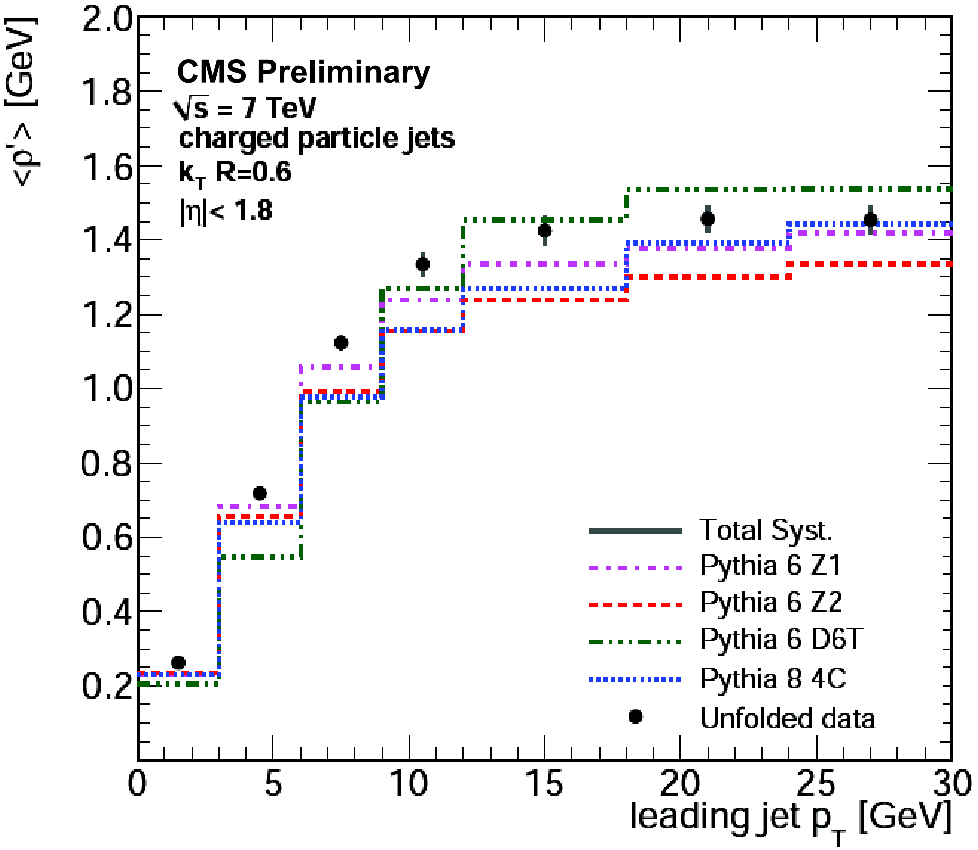
UE - Event Scale Dependence

Conventional UE analysis,
in the transverse plane.
Charged particle density

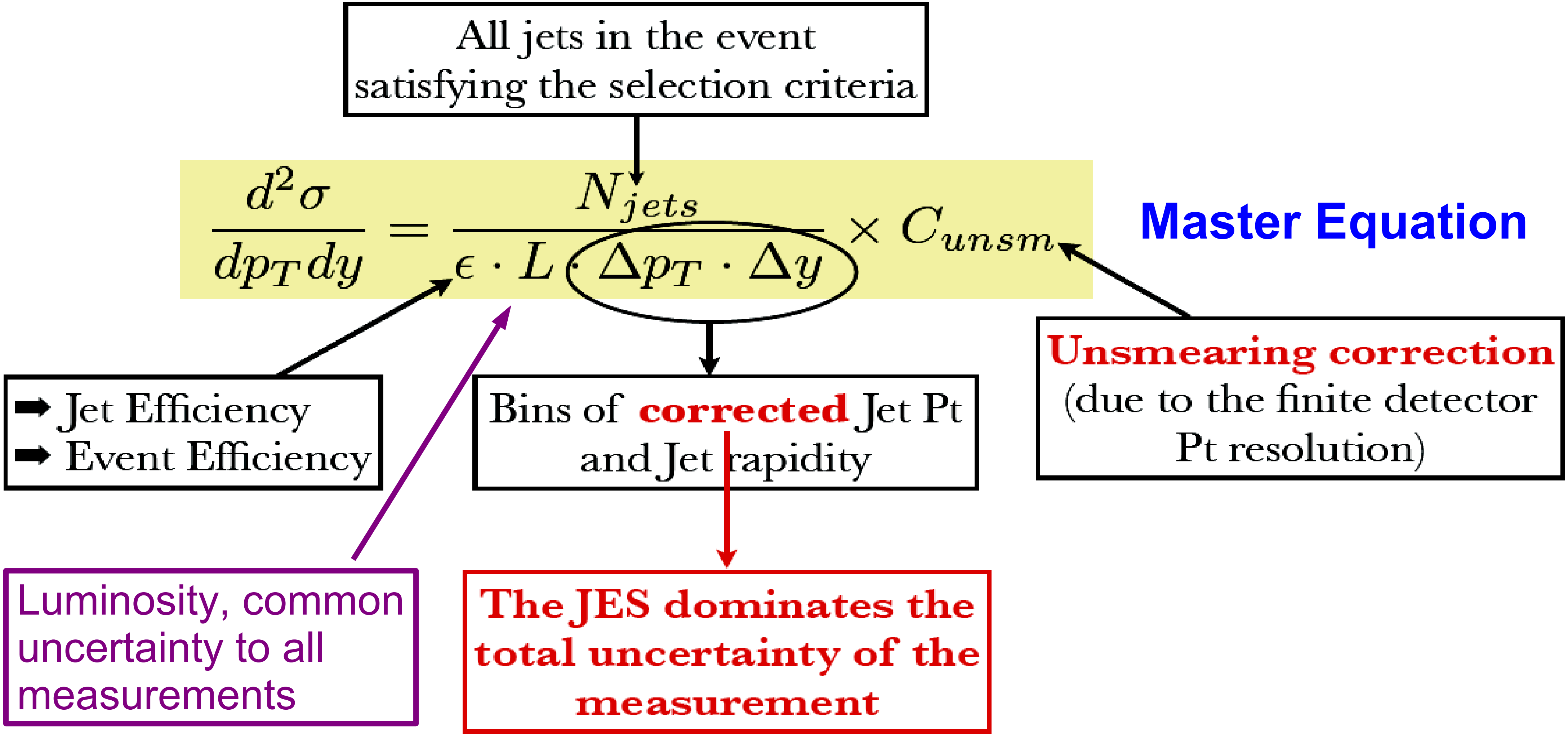


CMS, PAPER-QCD-10-021, JHEP09 2011

Jet Area UE analysis,
whole event analyzed.
Charged particle density



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)

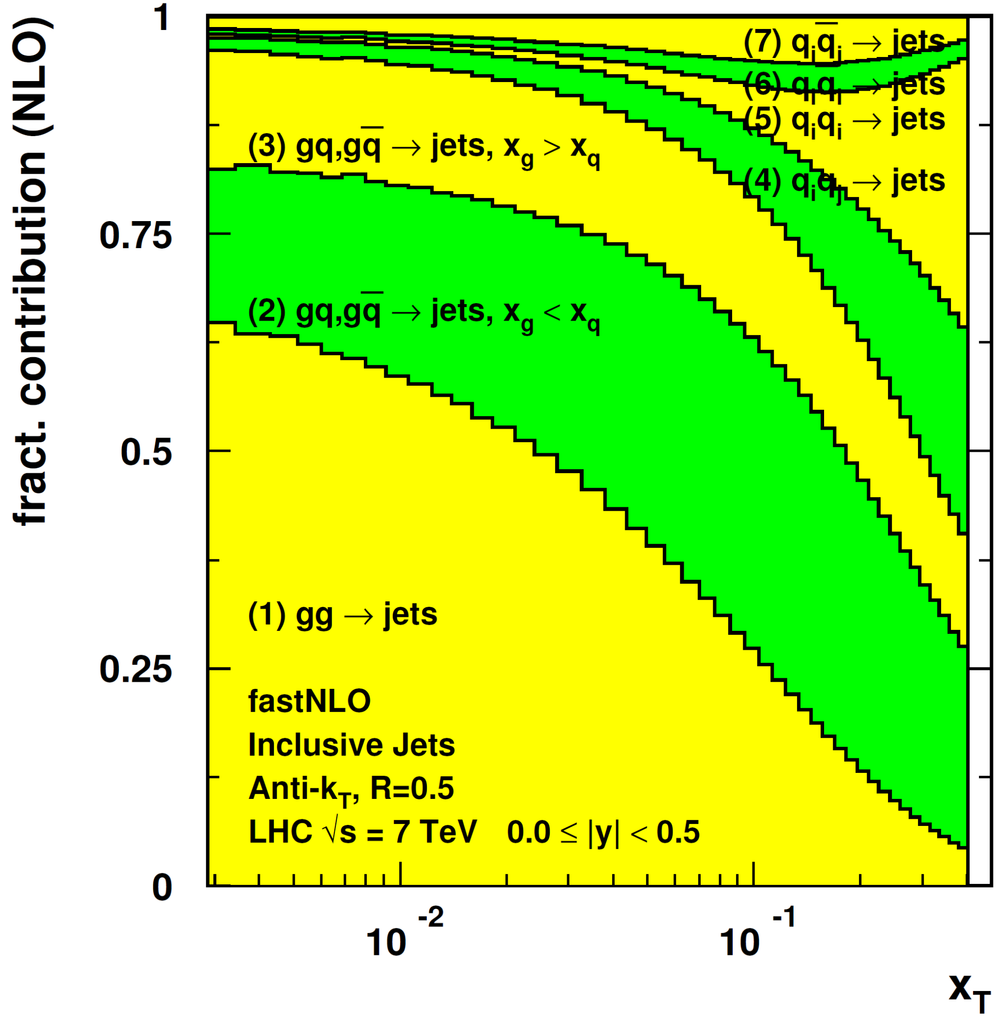
Luminosity, common uncertainty to all measurements

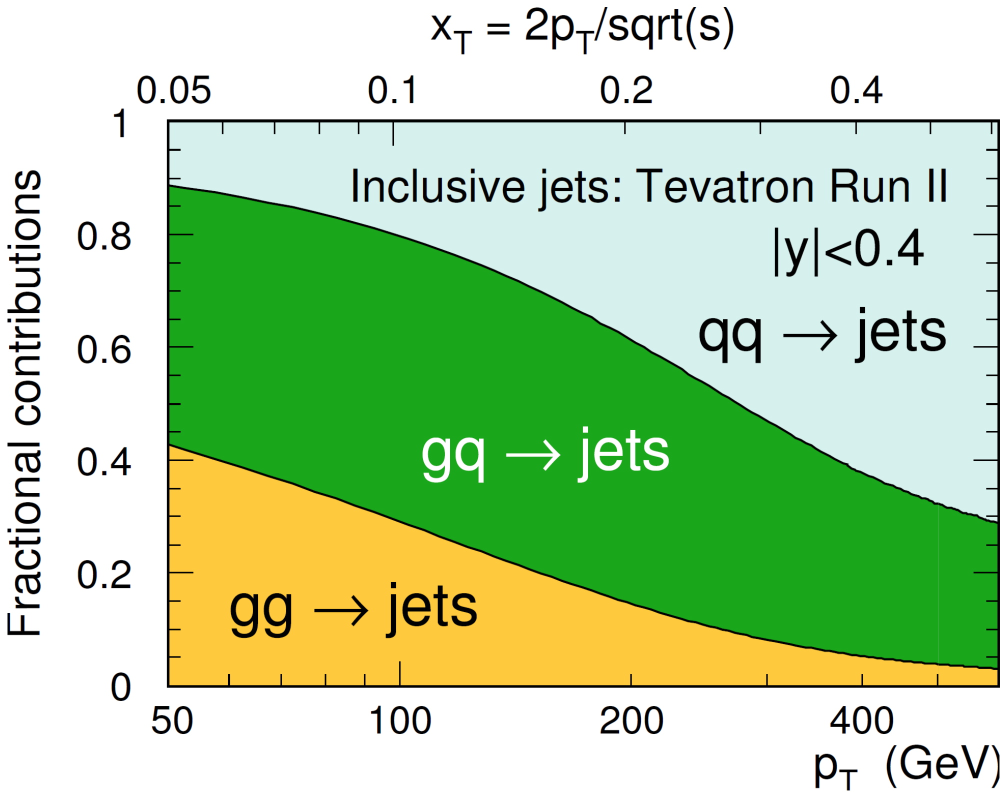
The JES dominates the total uncertainty of the measurement

K. Kousouris

Inclusive Jets

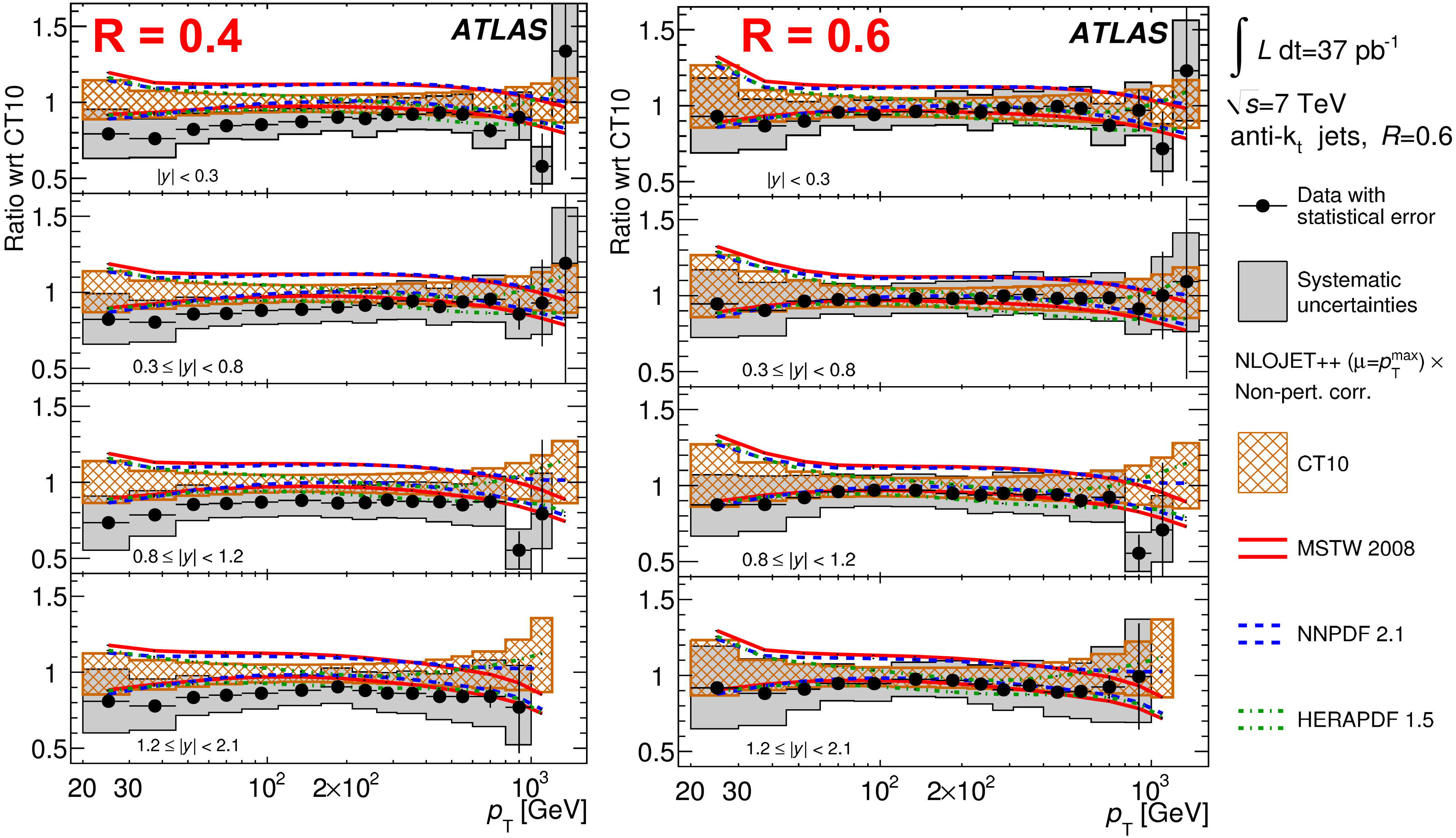
$$\frac{d^2\sigma}{dp_T d|y|} \propto \alpha_s^2$$



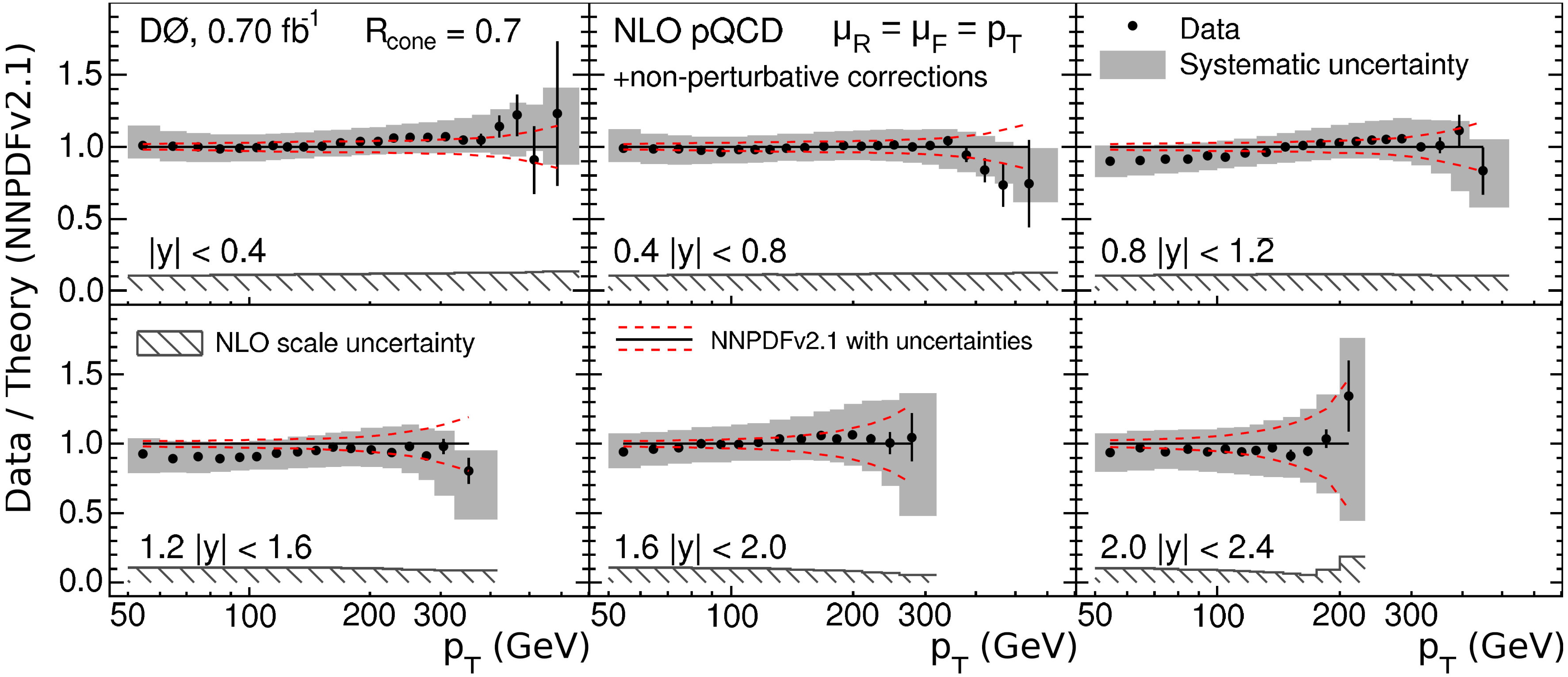


Inclusive Jets with 2 Jet Sizes

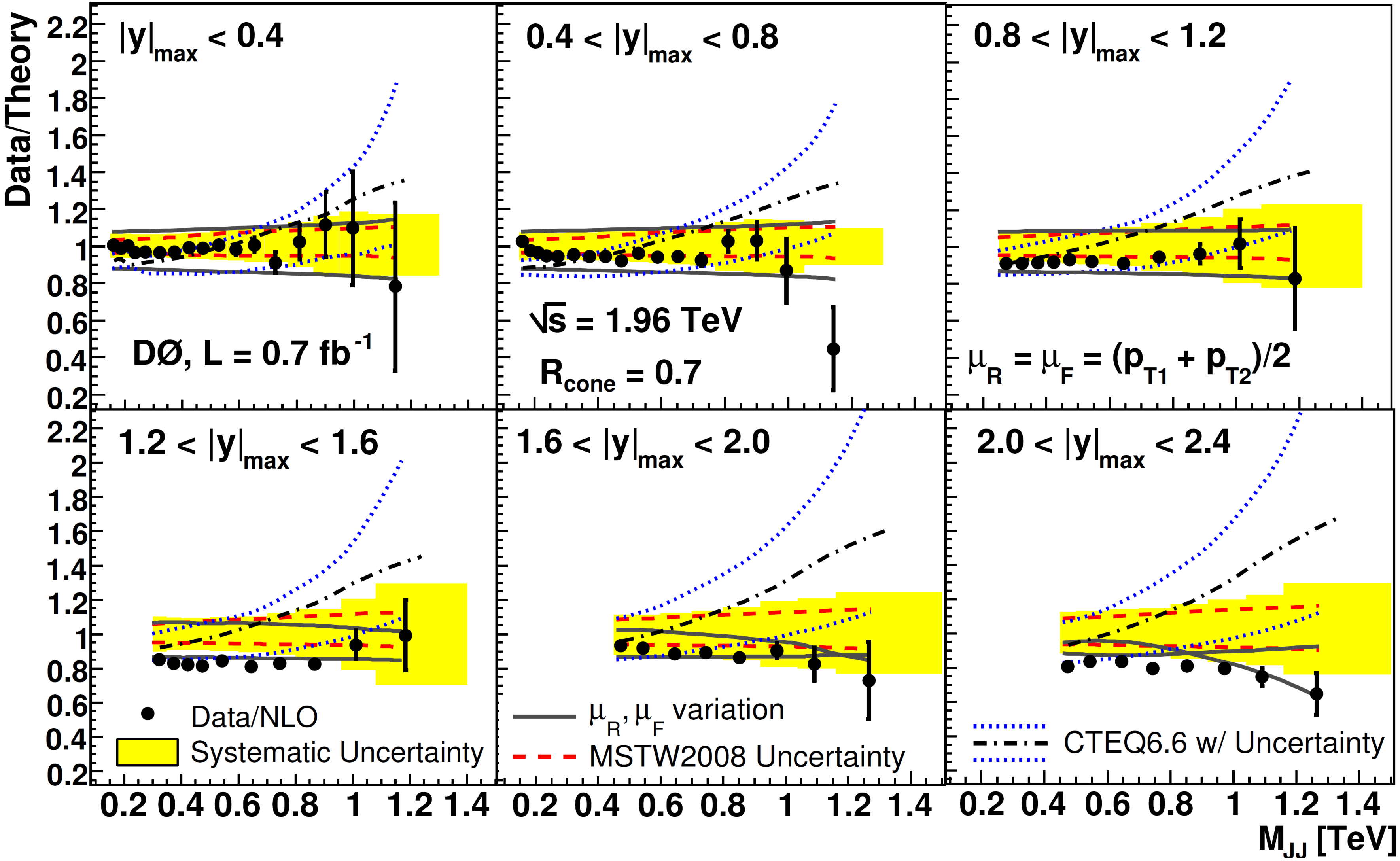
Comparison of measurement to QCD for various PDFs with two jet sizes



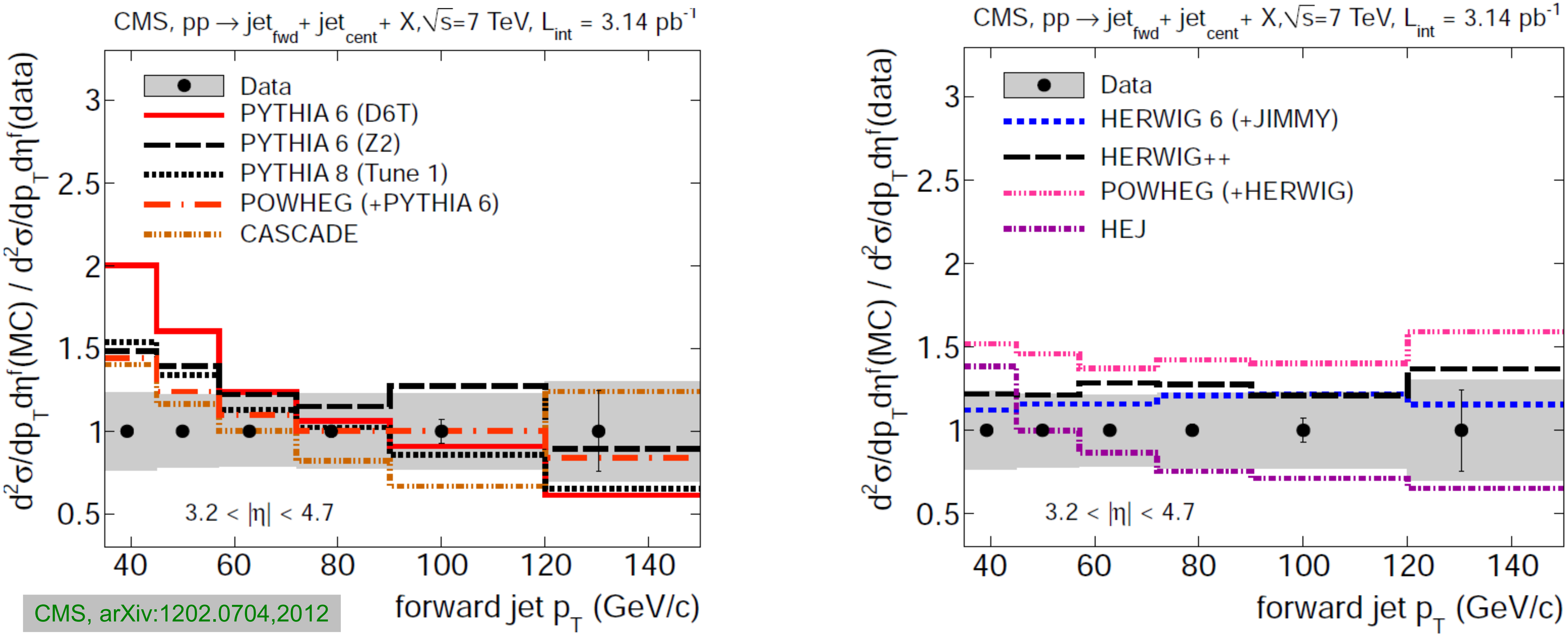
D0 Inclusive Jets - PDFs



D0 Dijet Mass - PDFs

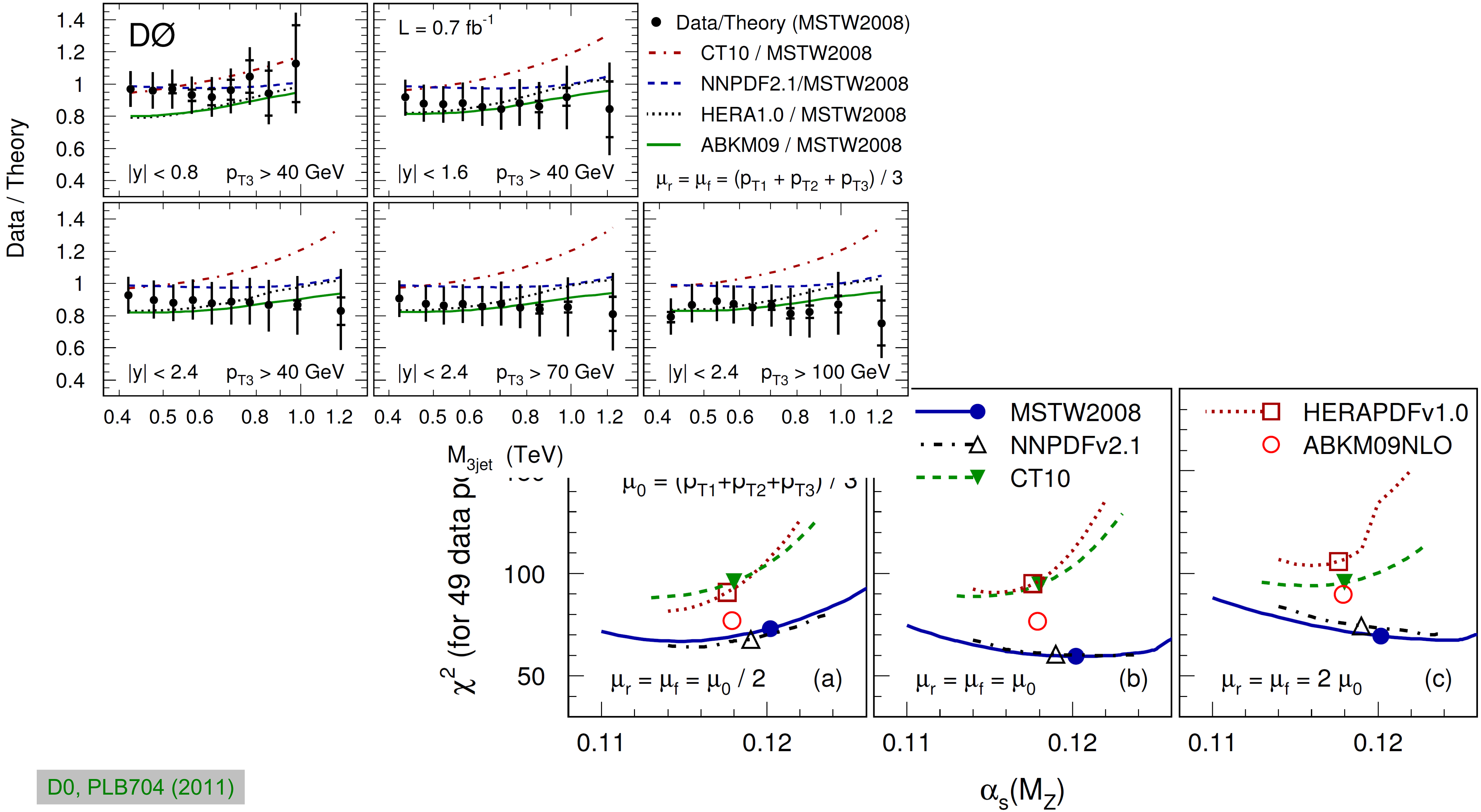


Correlated Central-Forward Dijet Production



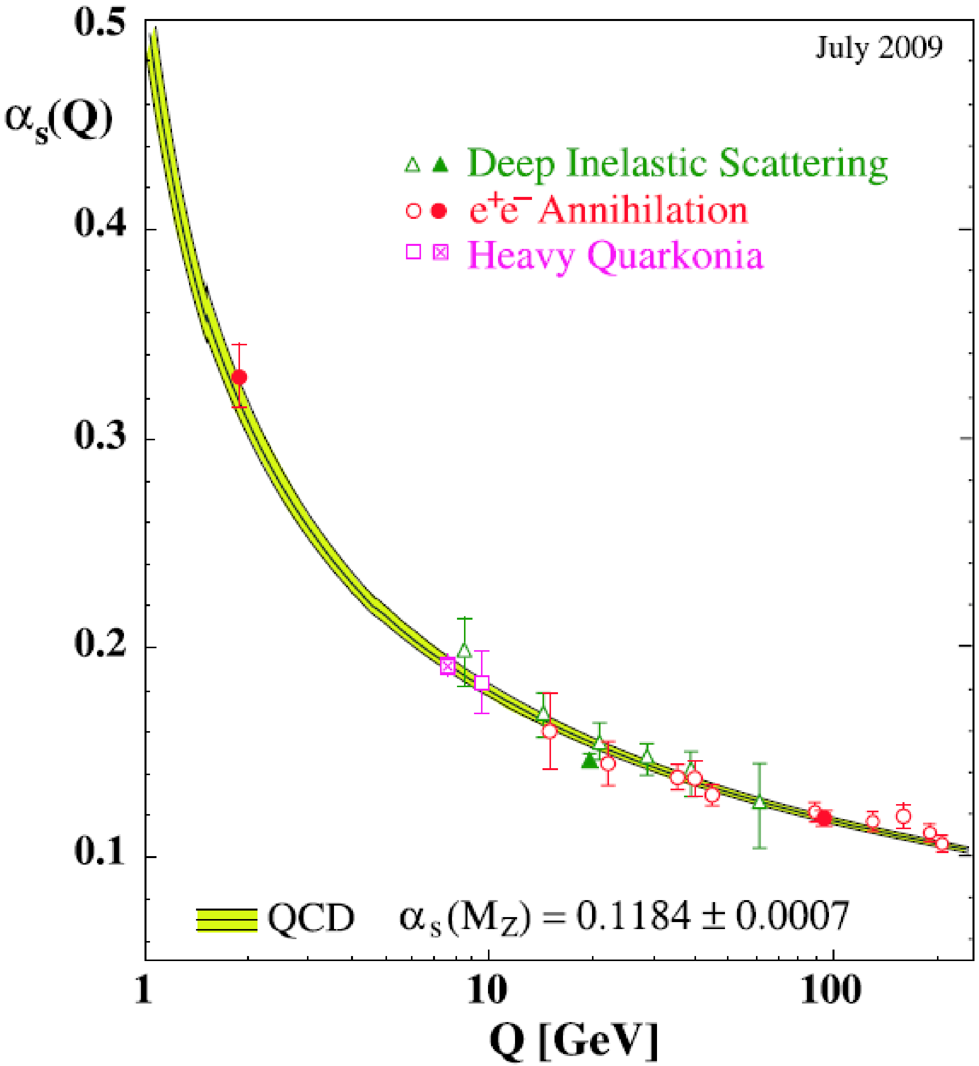
CMS, arXiv:1202.0704,2012

D0 3-Jet Mass – PDFs & α_s



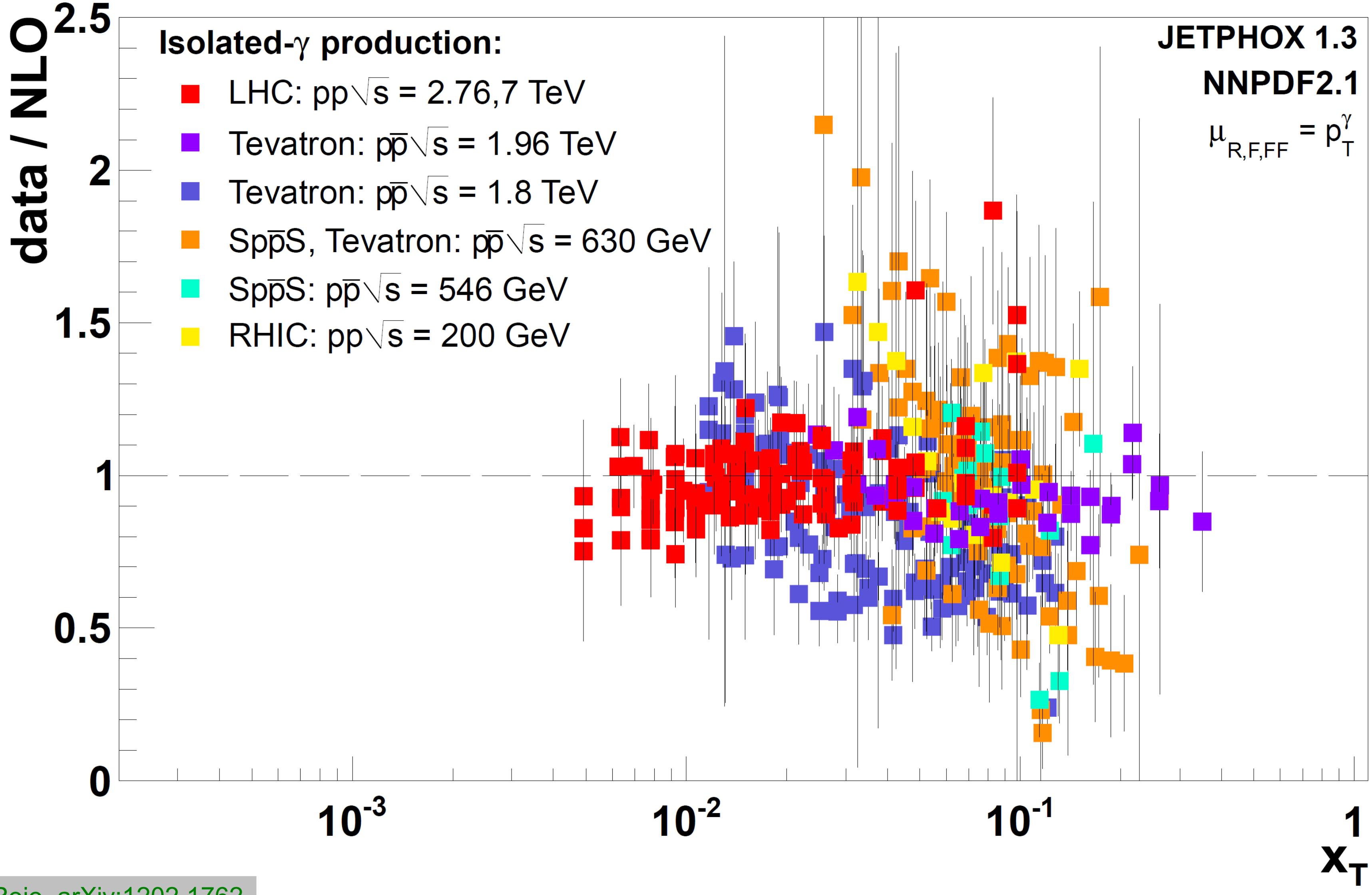
D0, PLB704 (2011)

Evolution of α_s



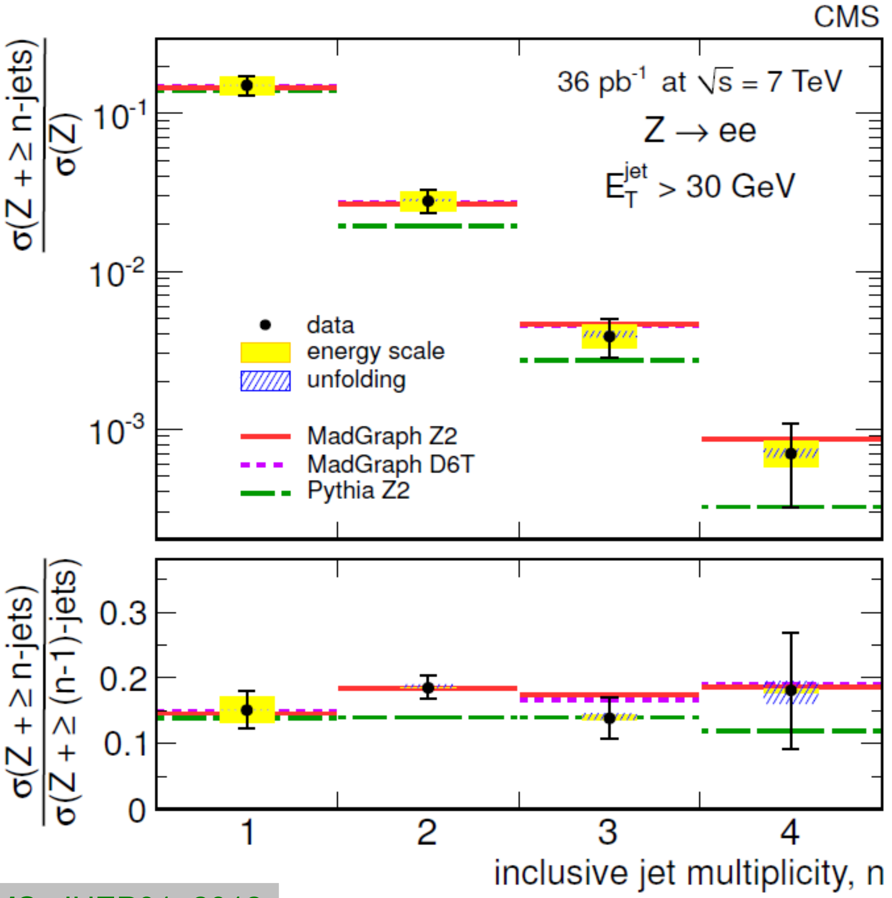
Bethke, EPJC64, 2009

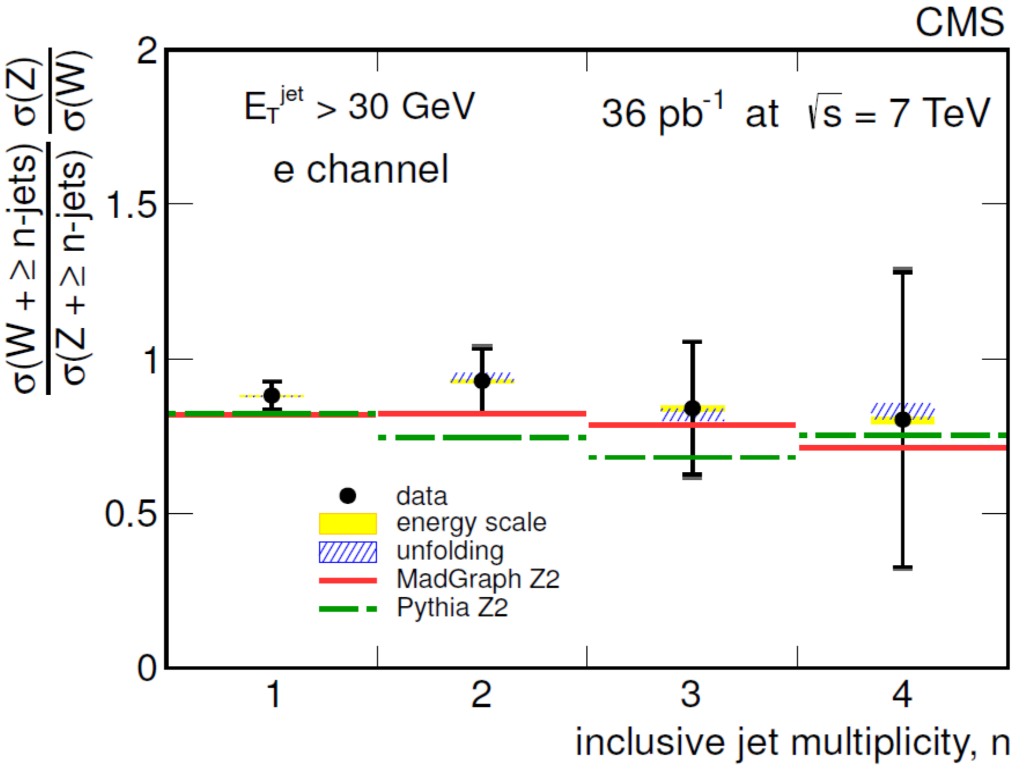
Isol. Photons Data/Theory



d'Enterria, Rojo, arXiv:1202.1762

W/Z+ Inclusive Jet Multiplicity





CMS, JHEP01, 2012