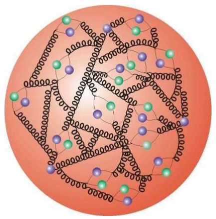
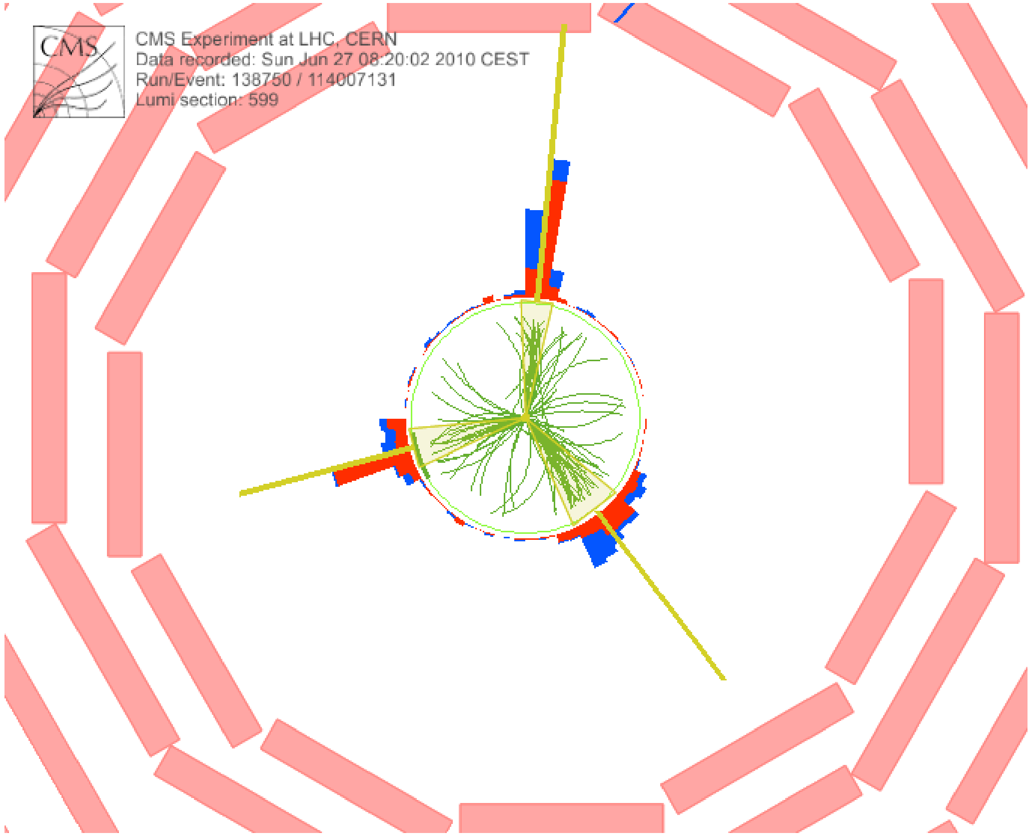
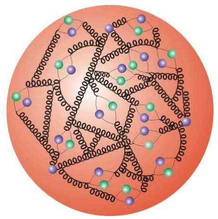
Jet Measurements at the LHC



Proton Structure
(PDF)





Proton Structure
(PDF)

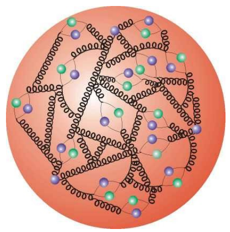
K. Rabbertz

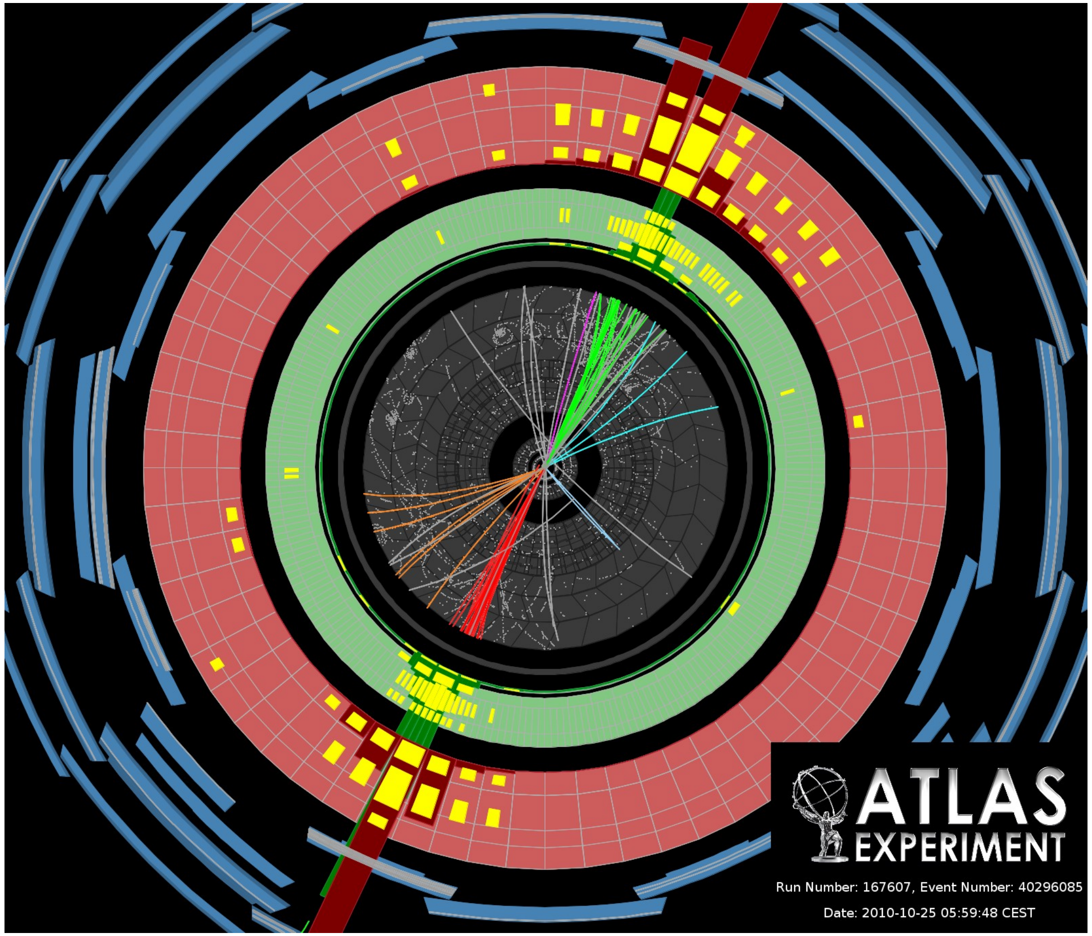
Karlsruhe Institute of Technology

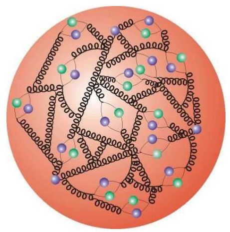
Outline

- **Lecture 1**
  - **A bit of history**
  - **Jet algorithms**
  - **Jet energy calibration**
  - **A first jet analysis:**
    - **Inclusive jet cross section**
- **Lecture 2**
  - **More cross sections**
  - **Reducing uncertainties**
  - **Ratios and shape comparisons**
  - **Some selected observables**
  - **Strong coupling**

2+ Jet Production







Dijet Mass

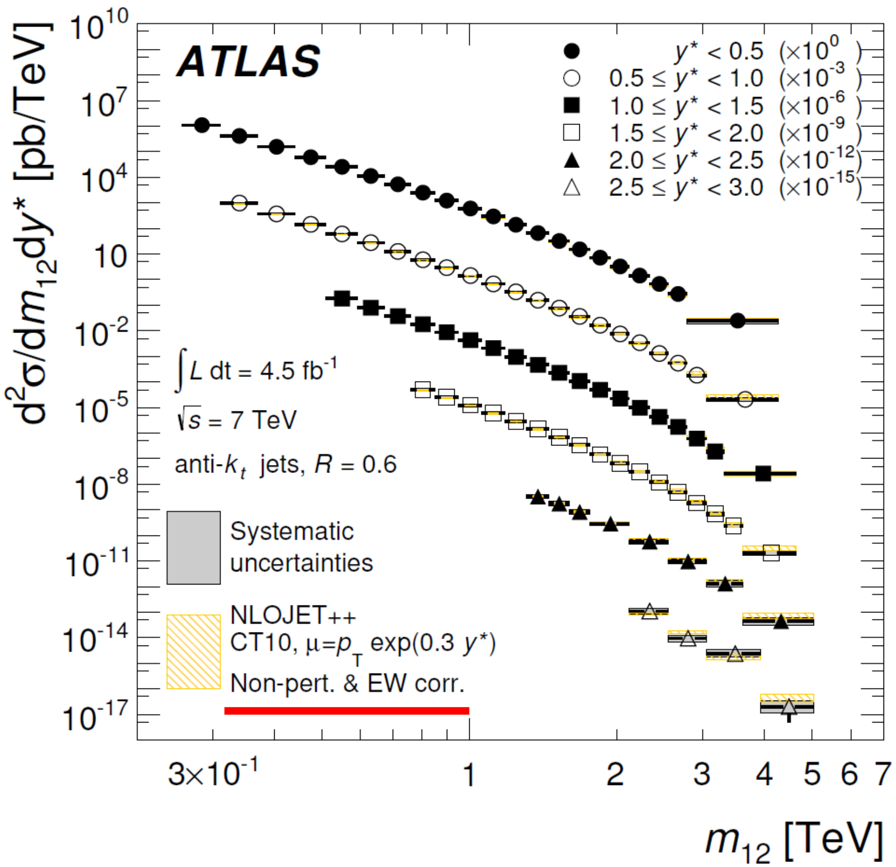
Compatible with QCD
- **over many orders of magnitude in σ**
- **over 2 orders of magnitude in M_{jj}**
- **up to rapidities of ~ 5**

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

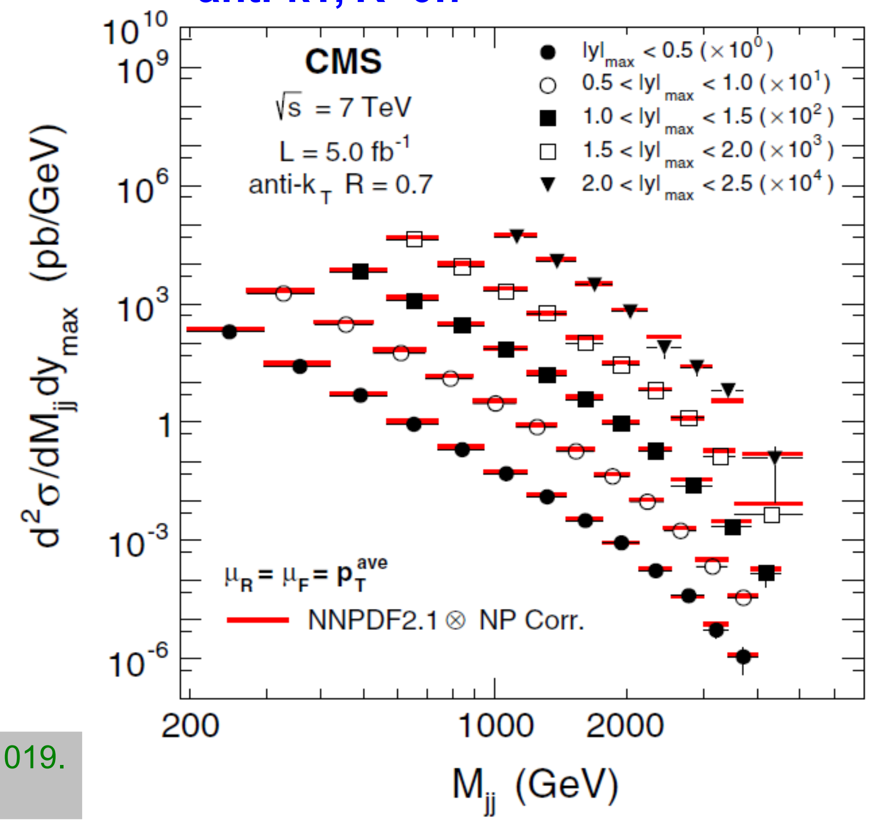
pQCD ⊗ nonperturbative and electroweak corrections

$$\frac{d^2\sigma}{\mathrm{d}M_{\mathrm{jj}}dy_{\mathrm{max}}} = \frac{1}{\epsilon \cdot \mathcal{L}_{\mathrm{eff}}} \cdot \frac{N}{\Delta M_{\mathrm{jj}}(2 \cdot \Delta|y|_{\mathrm{max}})}$$

anti-kT, R=0.6



anti-kT, R=0.7



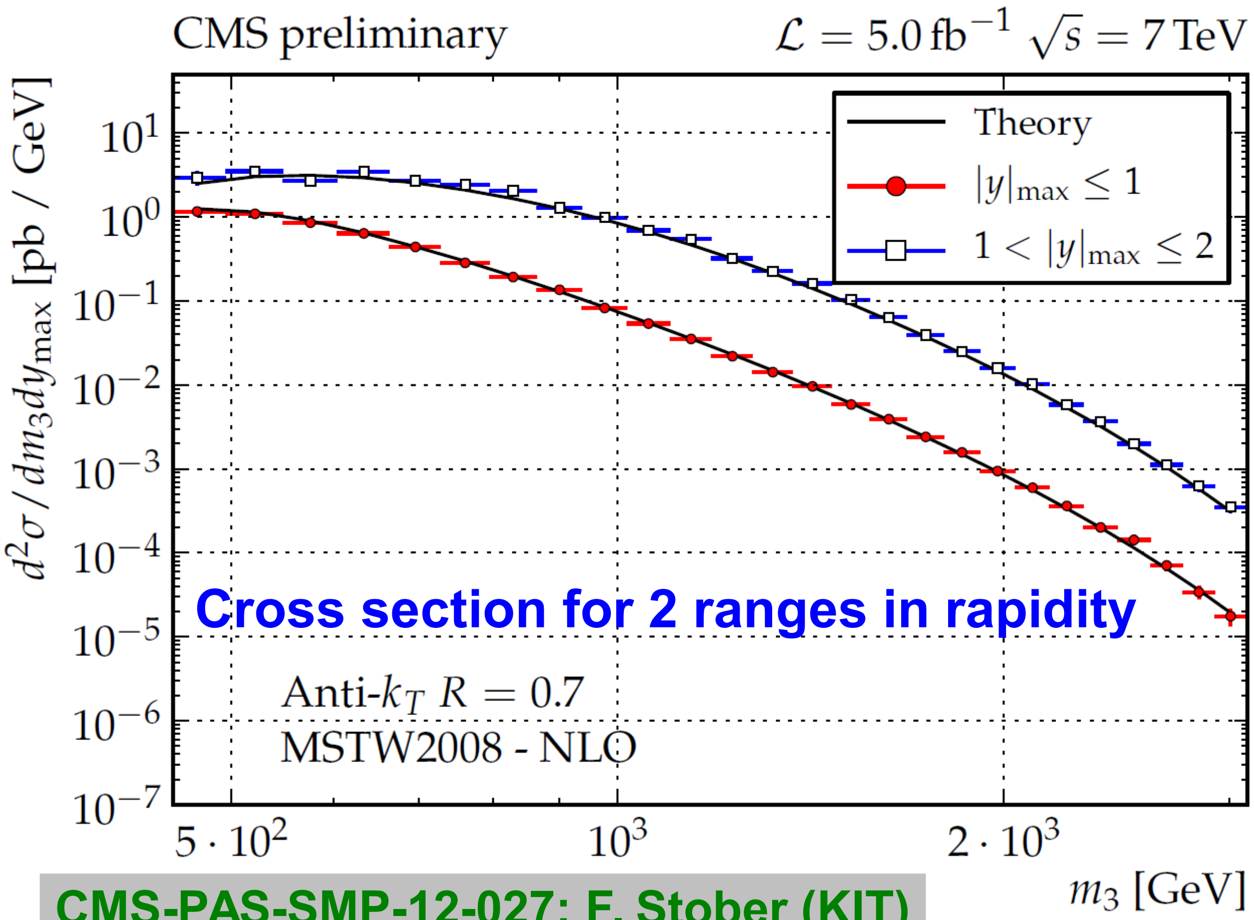
ATLAS, JHEP05 (2014) 019.
CMS, PRD87 (2013)

No EW for older CMS study.

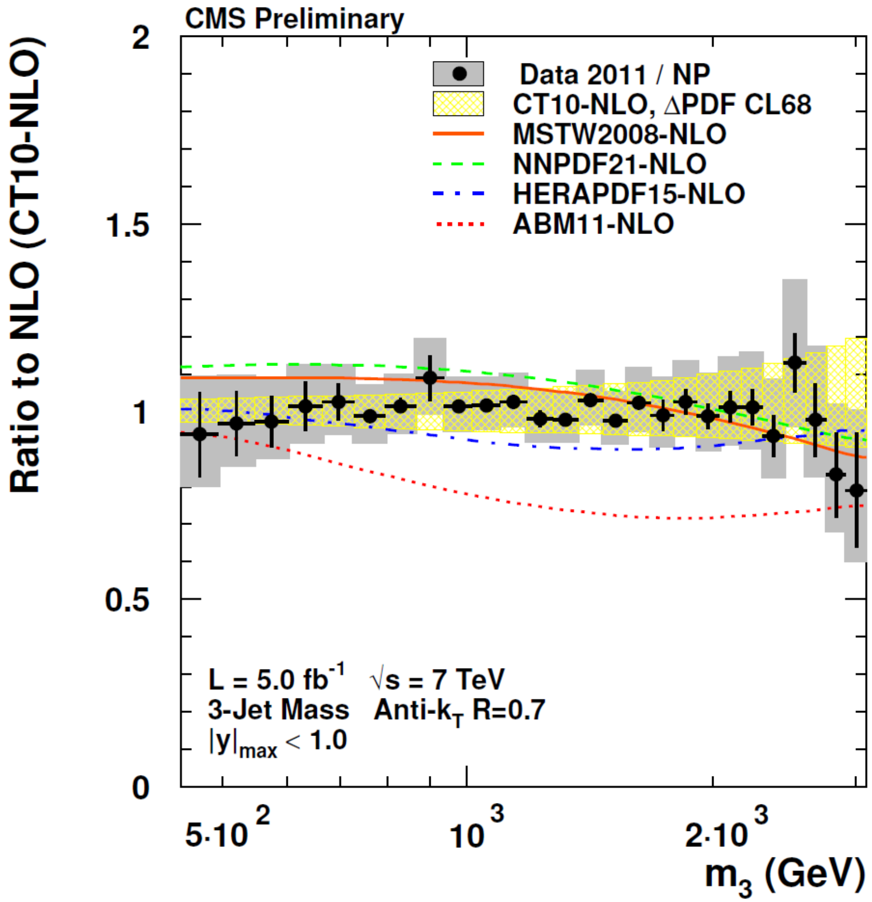
3-Jet Mass

- **Sensitive to α_s beyond 2→2**
- **Sensitive to PDFs**
- **Involves further scale $p_{T,3}$**
- **NLO with 3-4 partons (NLOJet++)**

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



Ratio to theory for various PDFs

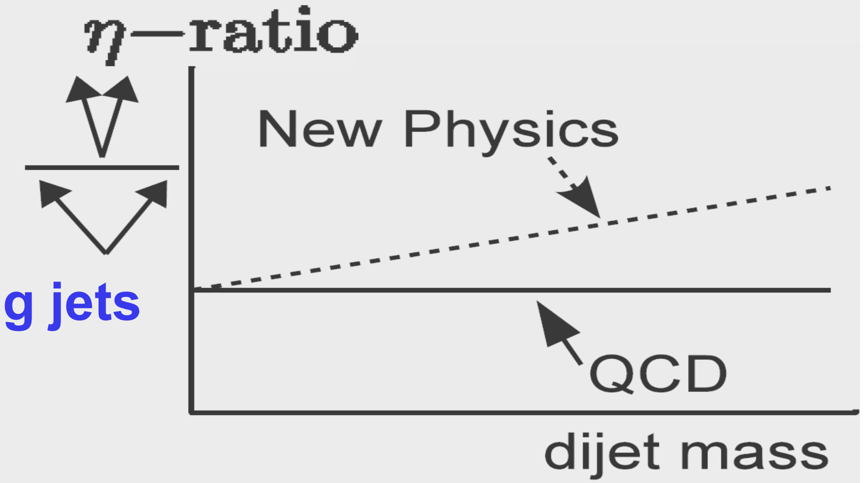


CMS-PAS-SMP-12-027: F. Stober (KIT)

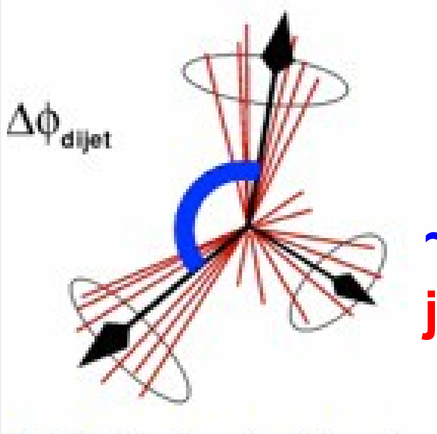
Reducing Uncertainties 1

- **Measurements so far: Absolute jet cross sections**
  - **Inclusive jet pT or dijet and 3-jet mass cross sections:**
    - **Most complicated, require all uncertainties to be under control!**
- **Reduction strategy 1: Jet cross section ratios**
  - **Dijet mass cross section ratios in rapidity ⟶ new physics ?**
  - **3-jet to 2-jet cross section ratio ⟶ strong coupling α_s**
    - **Many uncertainties cancelled (luminosity, …) or reduced (JES, ...)**

Centrality ratio $= \frac{N(|\eta_{1,2}|<0.5)}{N(0.5<|\eta_{1,2}|<1)}$



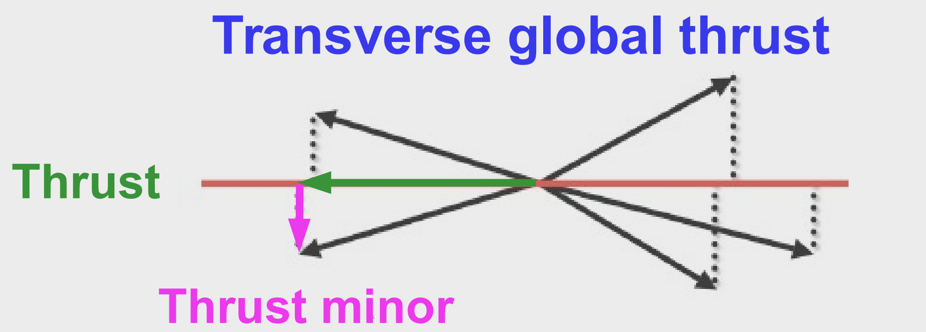
Both leading jets in specific η region



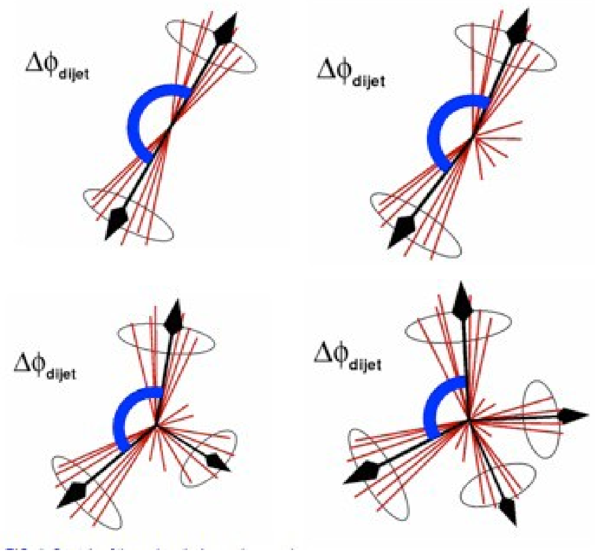
~ strong coupling α_s
jet 3

Reducing Uncertainties 2

- **Reduction strategy 2:** Jet angular measurements
  - Dijet chi distribution ⟶ new physics ?
  - Dijet azimuthal decorrelation ⟶ deviations from QCD radiation ?
    - Reduced sensitivity to jet energy scale (JES) or resolution (JER)
- **In addition:** Normalized distributions
  - Event shapes ⟶ Test of QCD, MC tuning
    - Less sensitive to JES, not dependent on luminosity

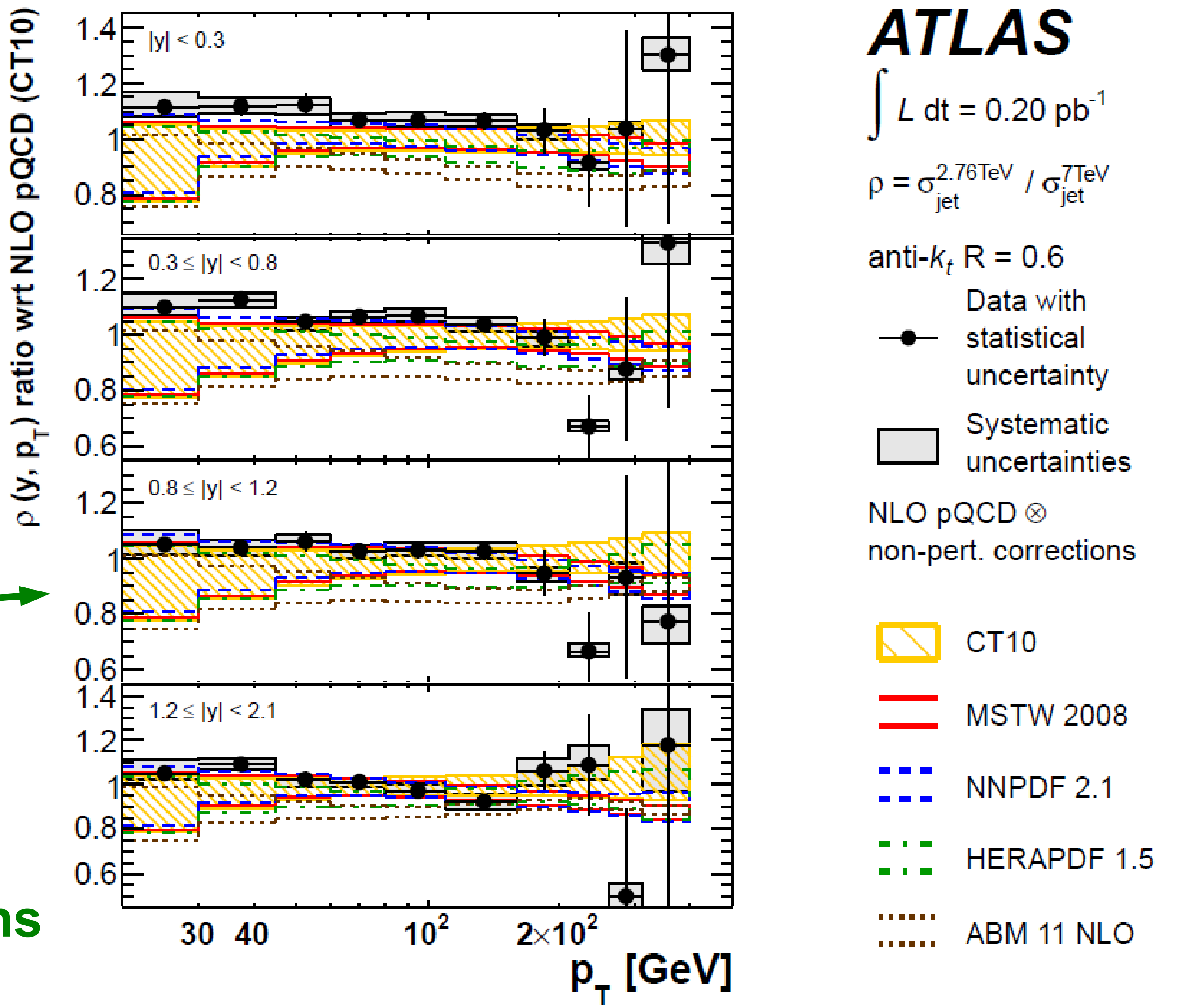


$$T_{\perp,g} = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$



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

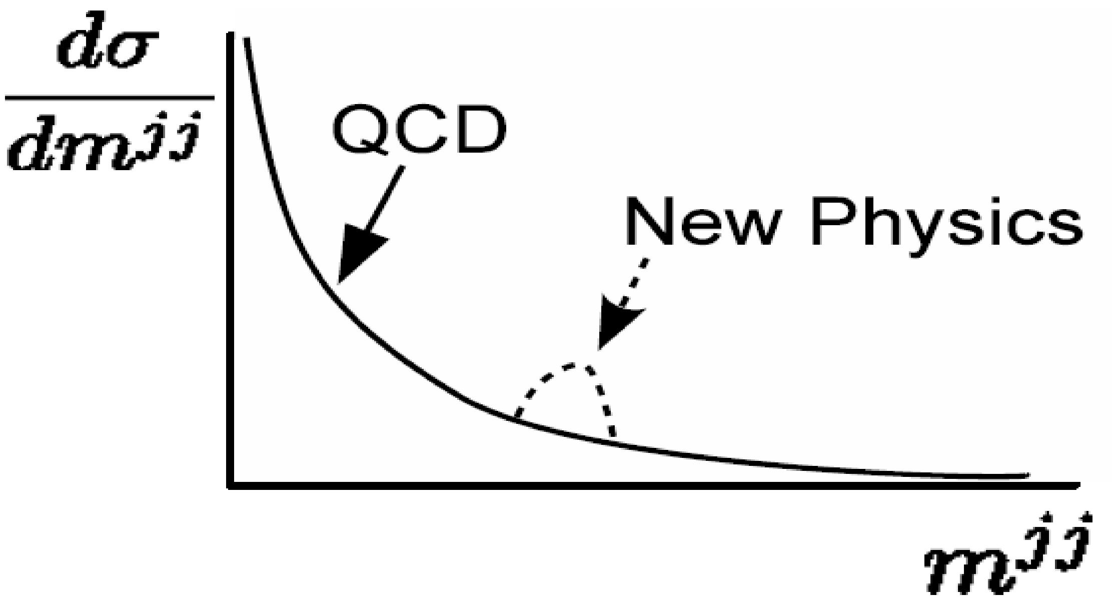
At least partial cancellation of uncertainties
→ more precise comparisons

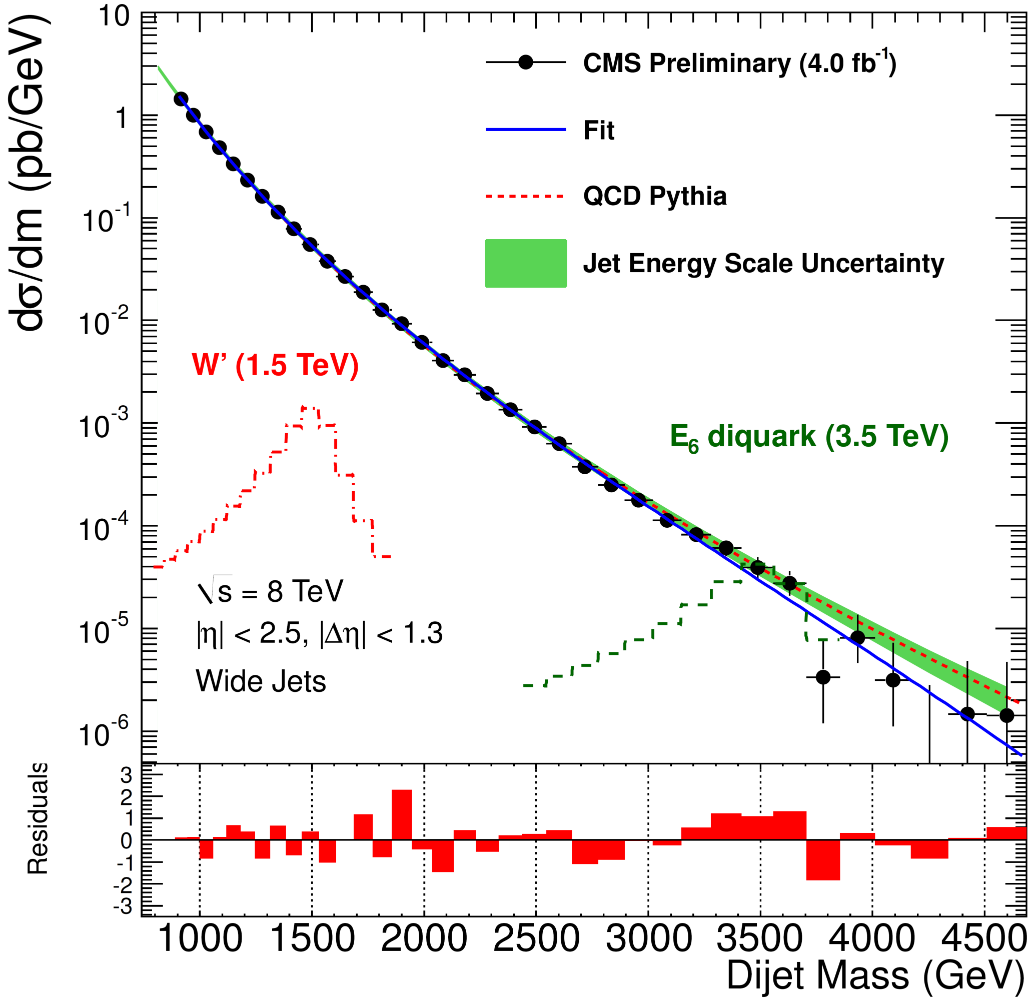
ATLAS, arXiv:1304.4739.

Simple search for new physics: Dijet resonance

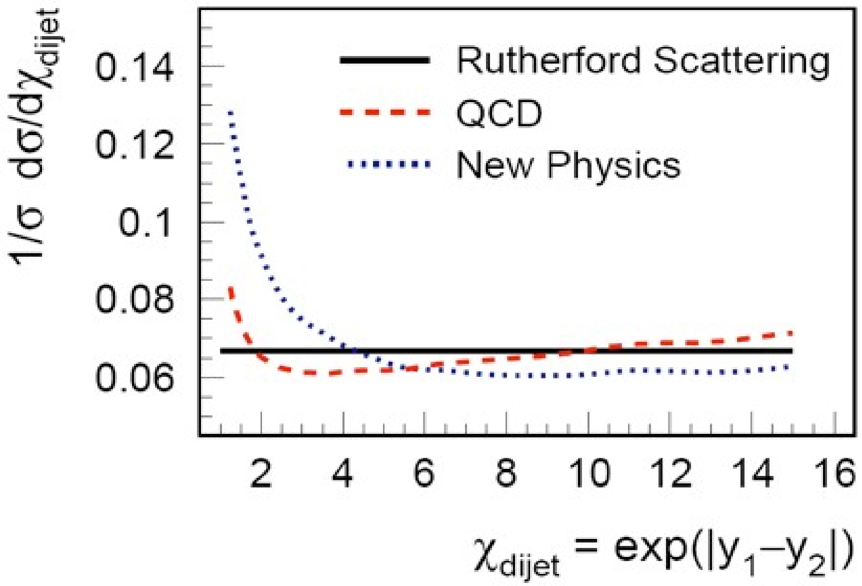
Absolut QCD cross sections not required, only shape needs to be described.

So far nothing found.
CMS result @ 8 TeV, 4.0 / fb:



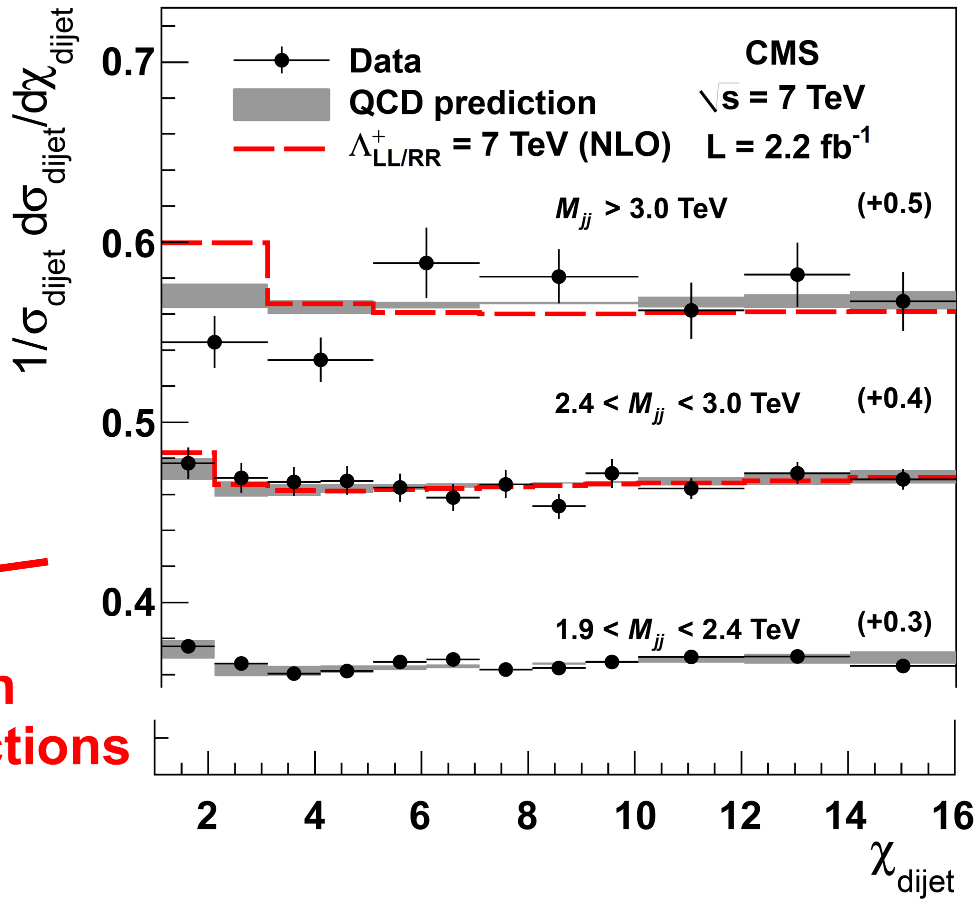


Dijet angular distribution

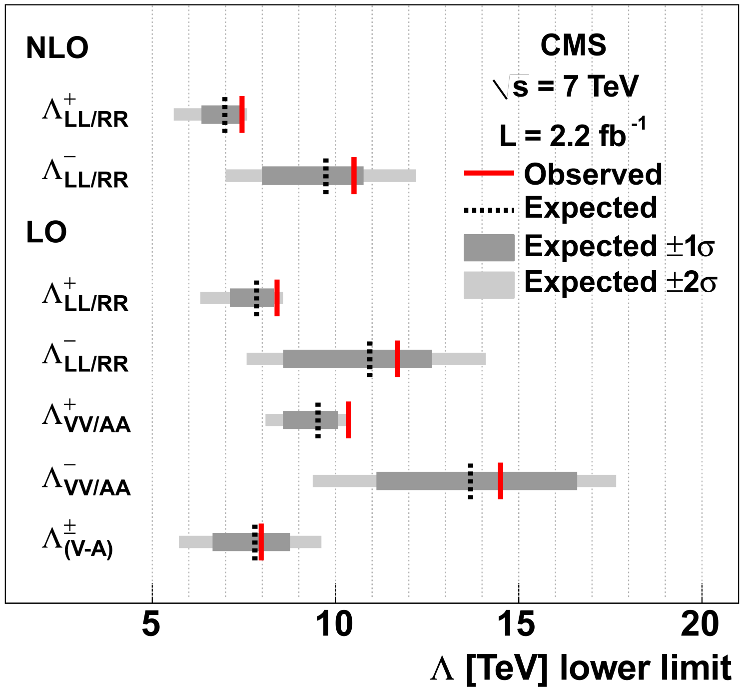


$$\frac{d^2\sigma}{dM_{JJ}d\chi_{JJ}} \propto \alpha_s^2$$

$$\chi = \exp(|\eta_1 - \eta_2|) = \frac{1+|\cos(\hat{\theta})|}{1-|\cos(\hat{\theta})|}$$



2011 Data

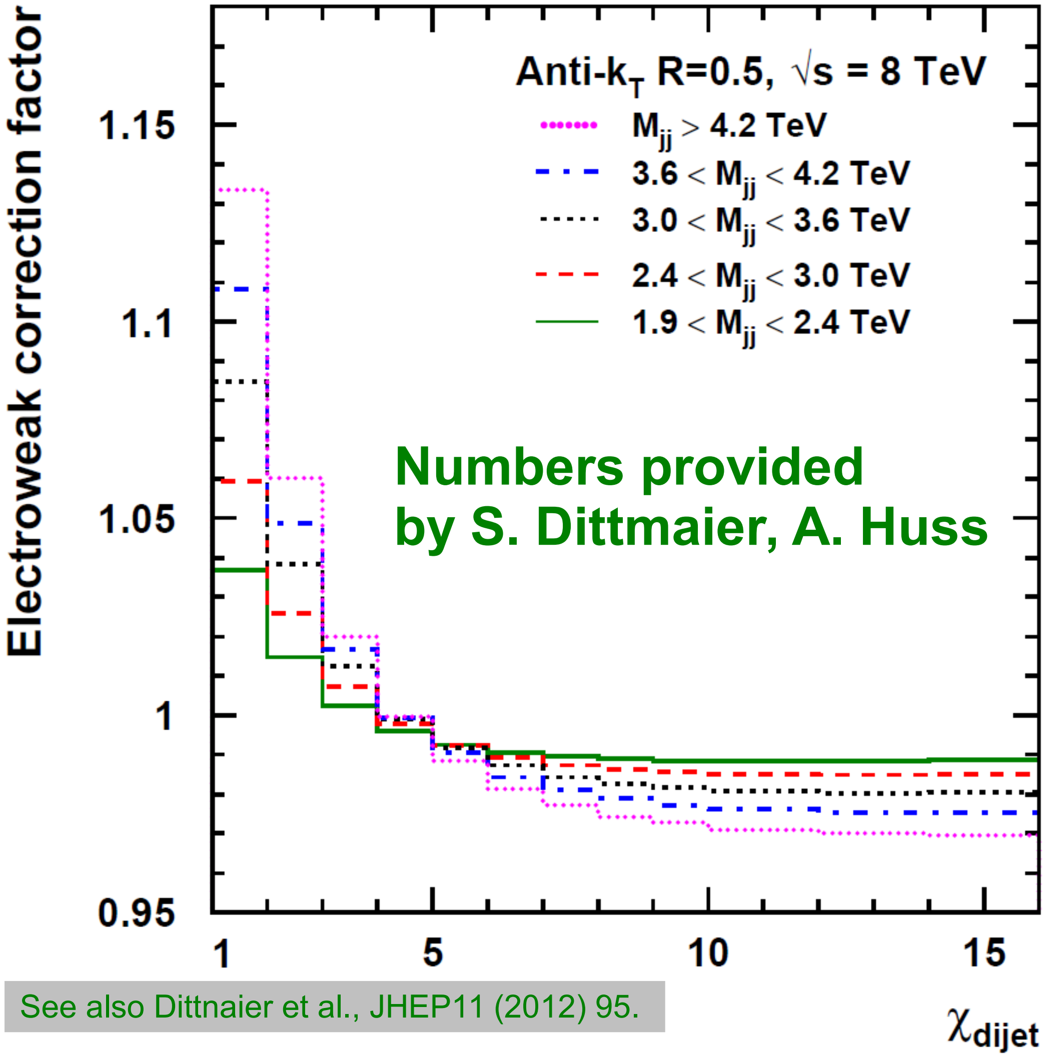


Lower limits on contact interactions

Dijet angular distribution

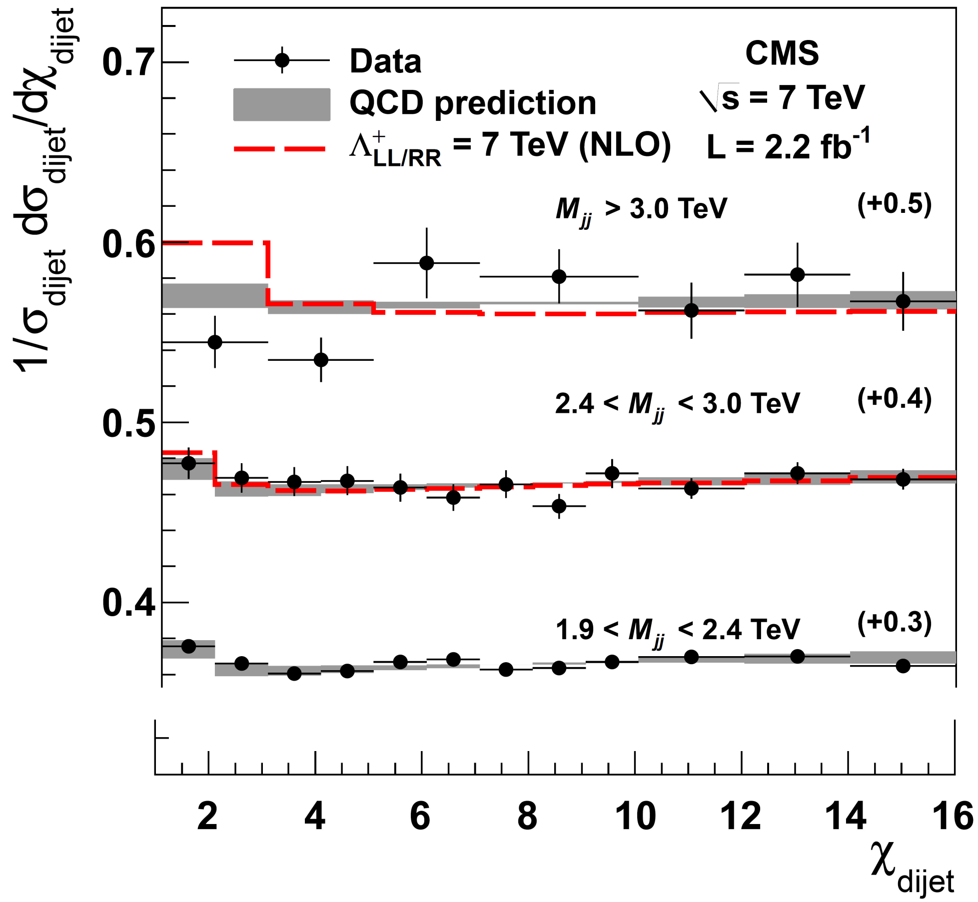
$$\frac{d^2\sigma}{dM_{JJ}d\chi_{JJ}} \propto \alpha_s^2$$

Update for full 2012 luminosity in progress
Accounts for electroweak corrections



See also Dittnaier et al., JHEP11 (2012) 95.

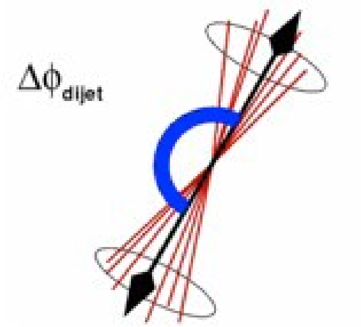
$$\chi = \exp(|\eta_1 - \eta_2|) = \frac{1+|\cos(\hat{\theta})|}{1-|\cos(\hat{\theta})|}$$



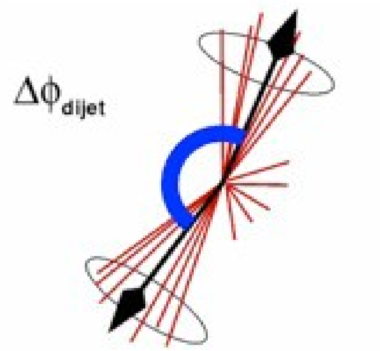
Azimuthal Decorrelation

Jet-pairs in pp collisions:

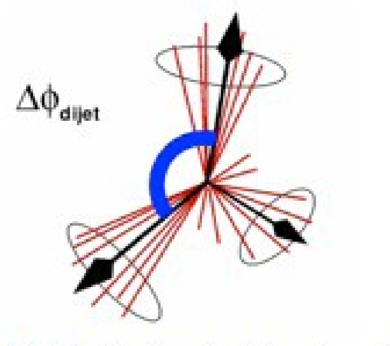
2-jet: correlated → π



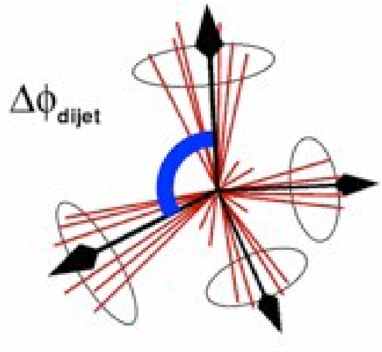
Δφ dijet = π →
Exactly 2 jets, no further radiation



Δφ dijet ≈ π →
Additional soft radiation



Δφ dijet ≈ 2π/3 →
At least one additional high-pT jet



Δφ dijet << 2π/3
Multiple hard jets

$$\frac{d^2\sigma}{dp_{\mathrm{T,max}}\, d\Delta\phi_{JJ}} \propto \alpha_s^3$$

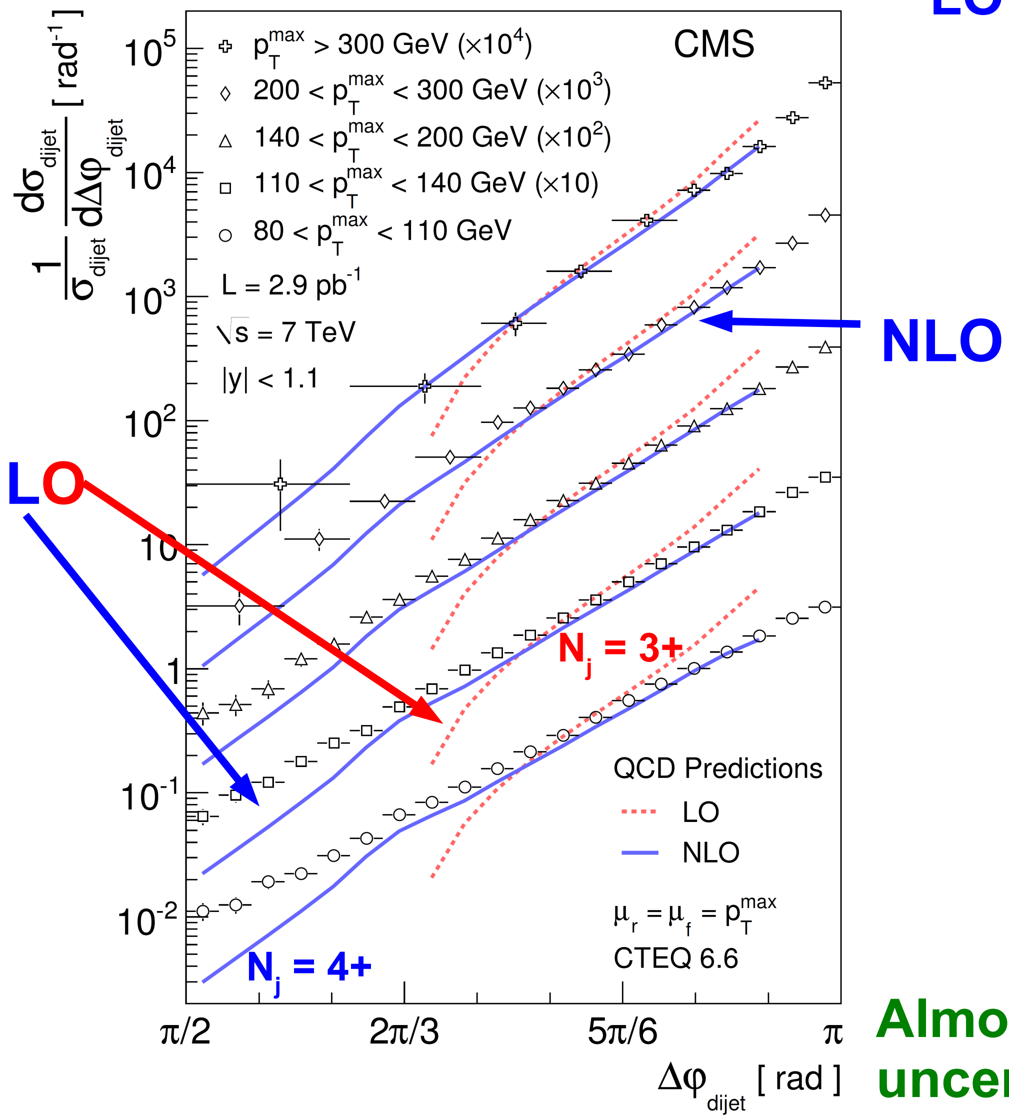
M. Wobisch

multi-jet: "uncorrelated" → < π

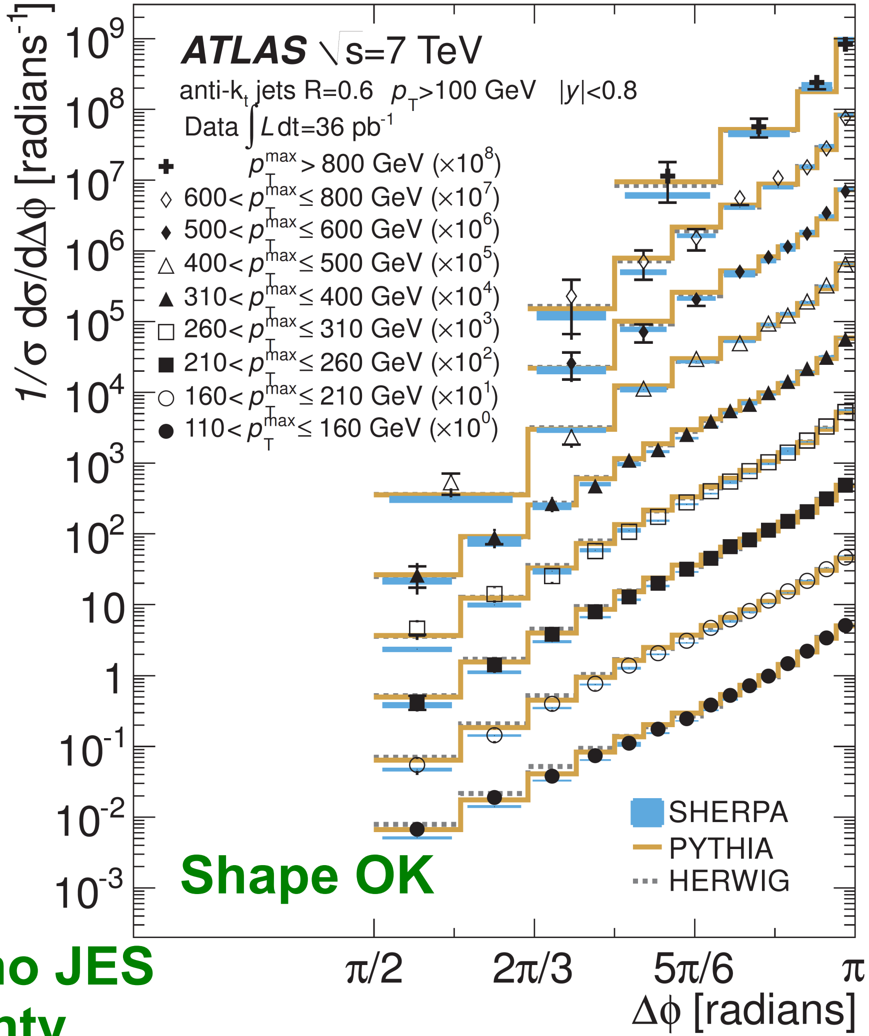
Azimuthal Decorrelation

Interesting quantity to study for ISR effects (MC tuning) or multijet production

CMS comparison with pQCD



ATLAS comparison with MC predictions
LO MC Pythia, Herwig++; n-jet-improved Sherpa



Almost no JES uncertainty

Color Coherence

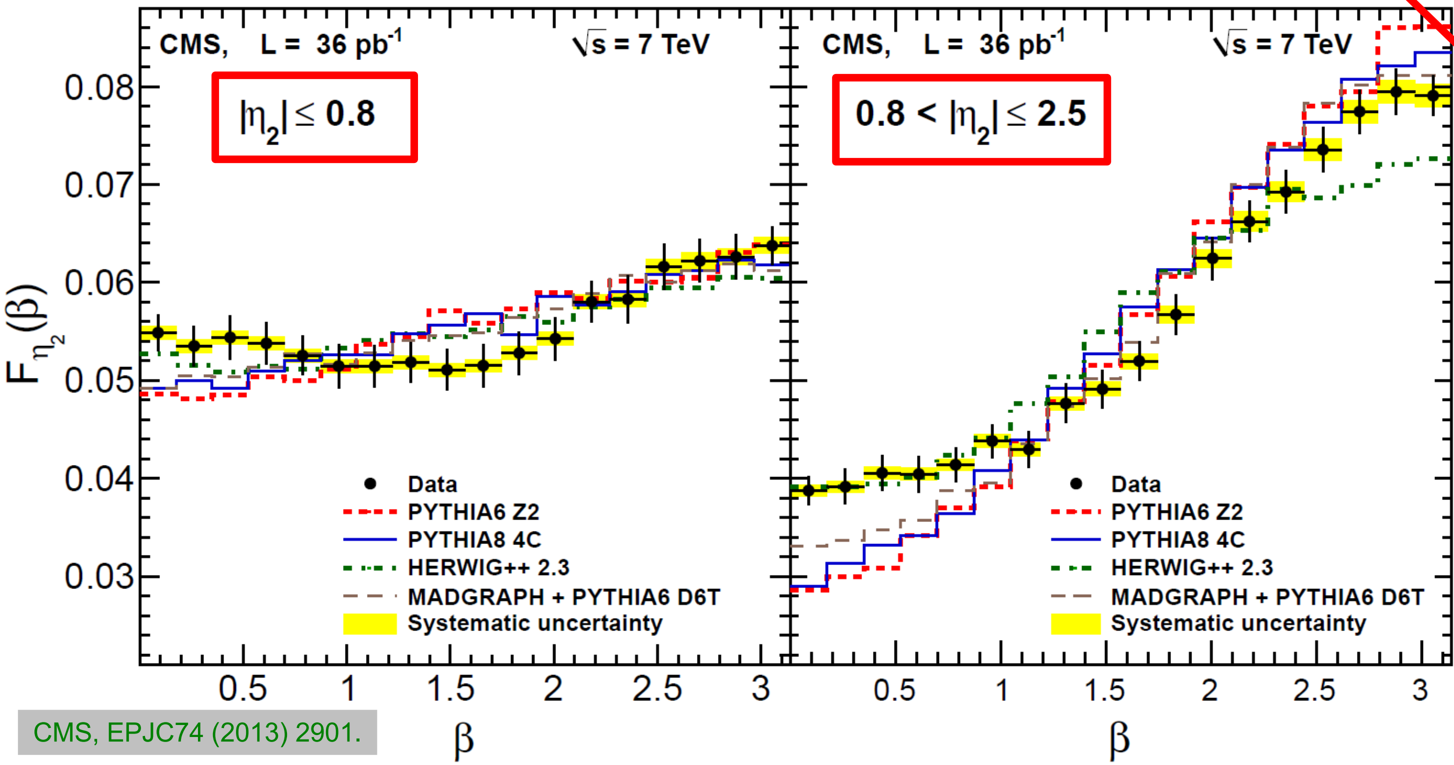
Study orientation of 3rd jet emission near 2nd → test interference in parton emissions

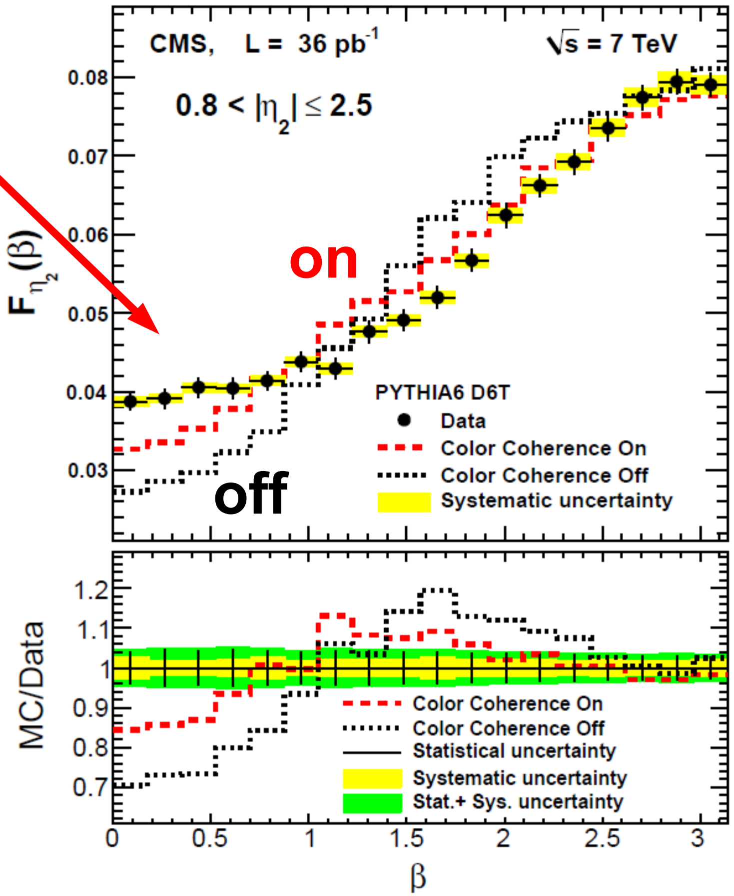
$$\beta = \left| \tan^{-1} \frac{\Delta\phi_{32}}{\mathrm{sign}(\eta_2)\Delta\eta_{32}} \right|$$

In MC approximated by angular ordering → improves description
still not perfect

β ~ 0 → emission between jet 2 and beam

No MC really good, better tunes required





CMS, EPJC74 (2013) 2901.

Dijet Flavours

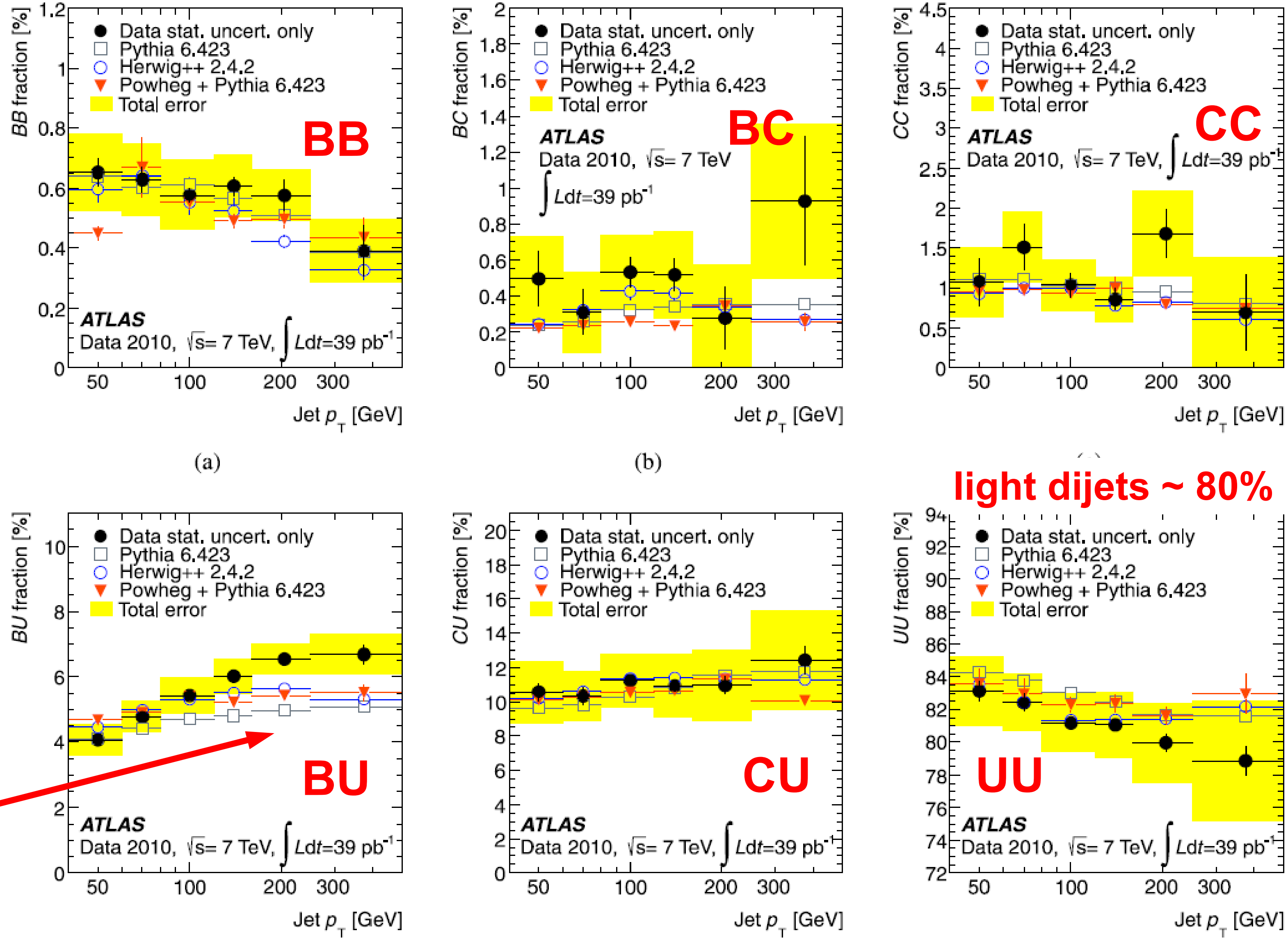
Study of flavour decomposition of both jets in dijet events

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

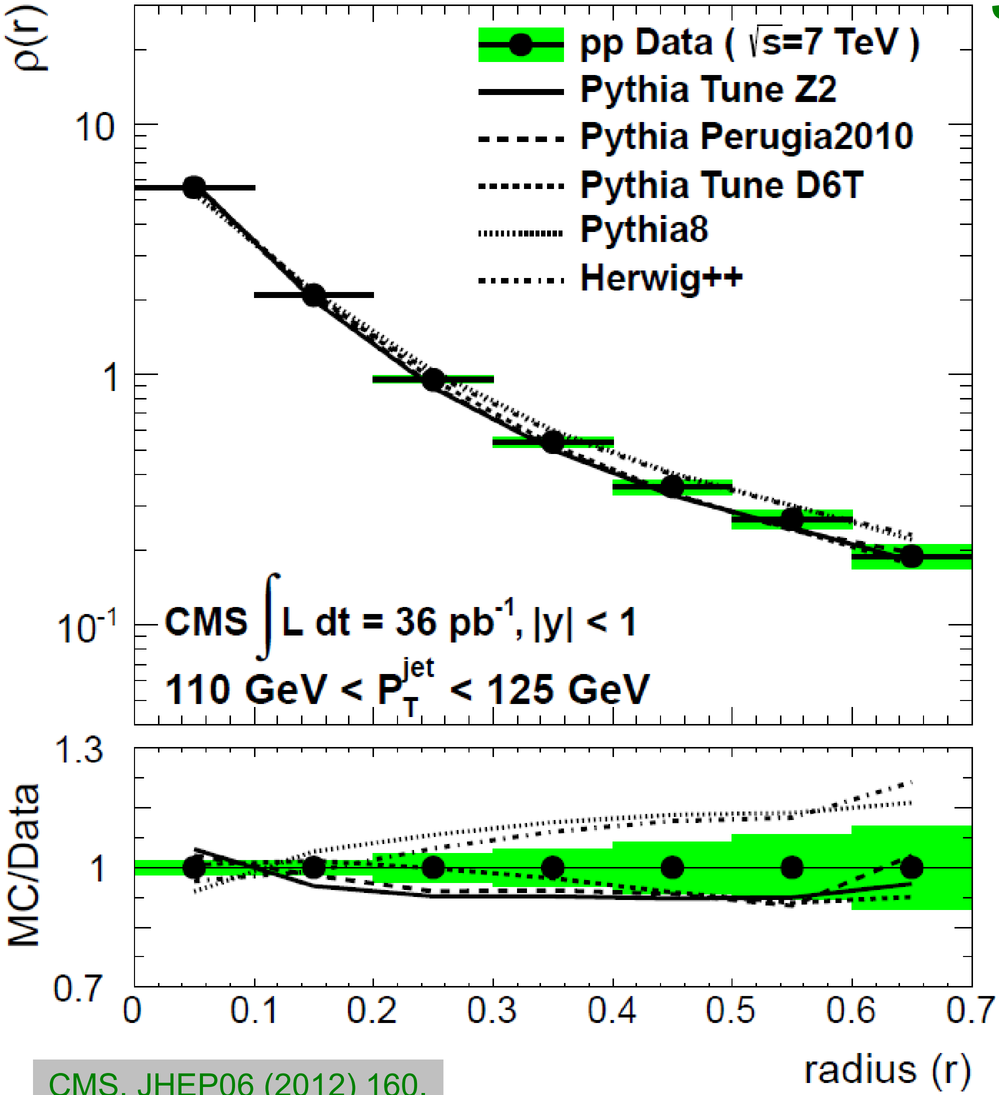
Some discrepancy for B-light (U) contribution at high pT



ATLAS, EPJC73, 2013

Jet Shapes

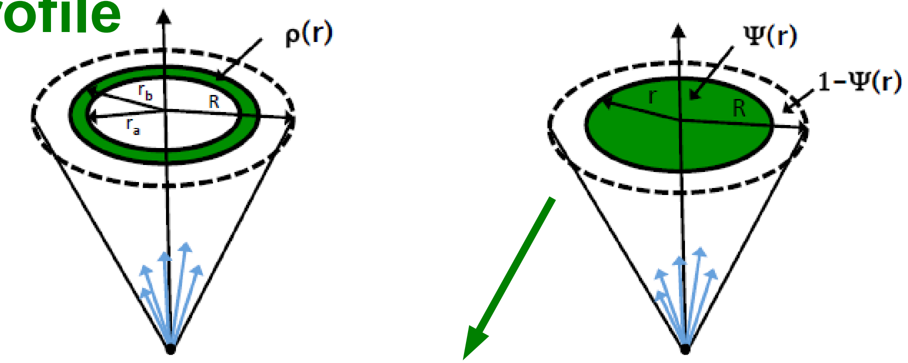
Jet substructure: Differentiate among g, q jets and heavy boosted Z´, t´, …
Here: "Traditional" jet profiles, sensitive to g-, q-jet differences

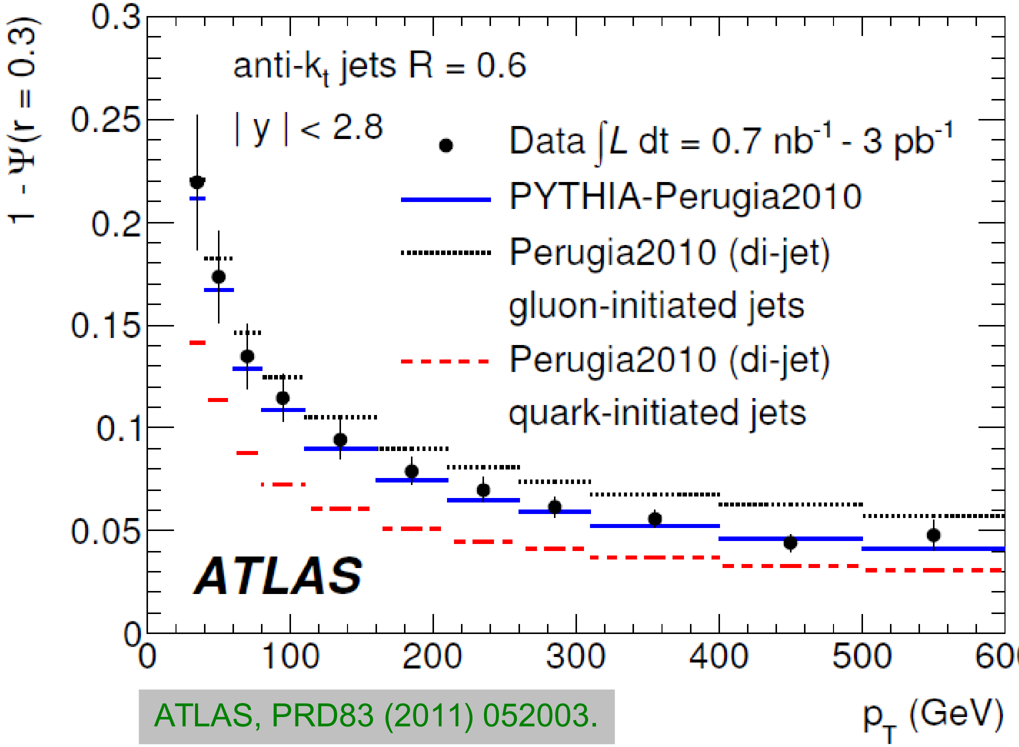


CMS, JHEP06 (2012) 160.

Jet pT profile

Integrated





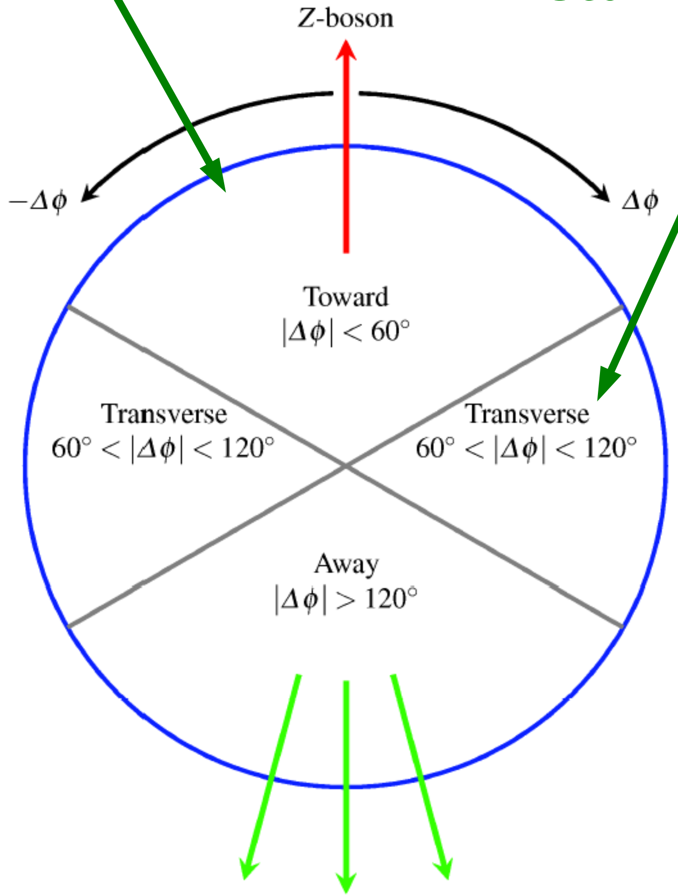
ATLAS, PRD83 (2011) 052003.

Underlying Event

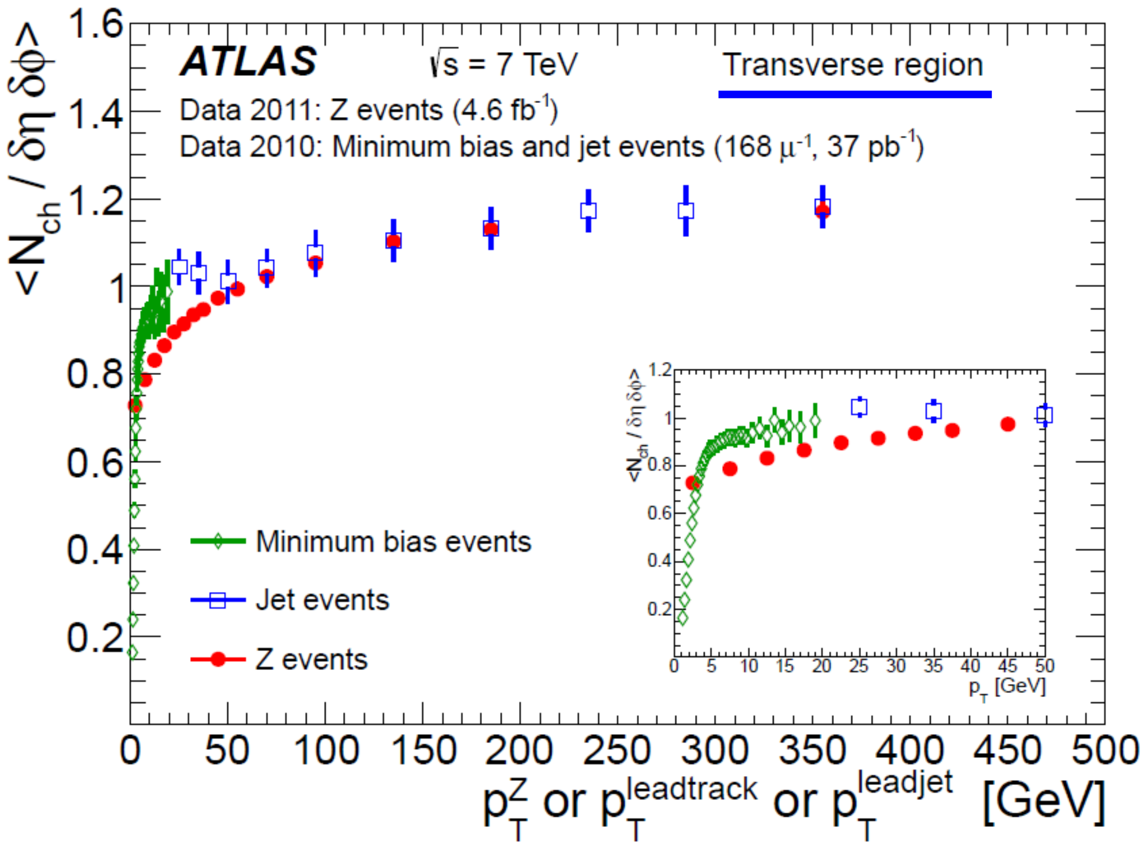
New ATLAS result investigating the UE in Z+jet events

Also here if Z → μμ

Look for soft stuff here



No indication of unexpected differences among UE in MinBias, jet, or Z+jet events



ATLAS, arXiv:1409.3334

Jet-radius Ratio

Cross section ratio for R = 0.5/0.7

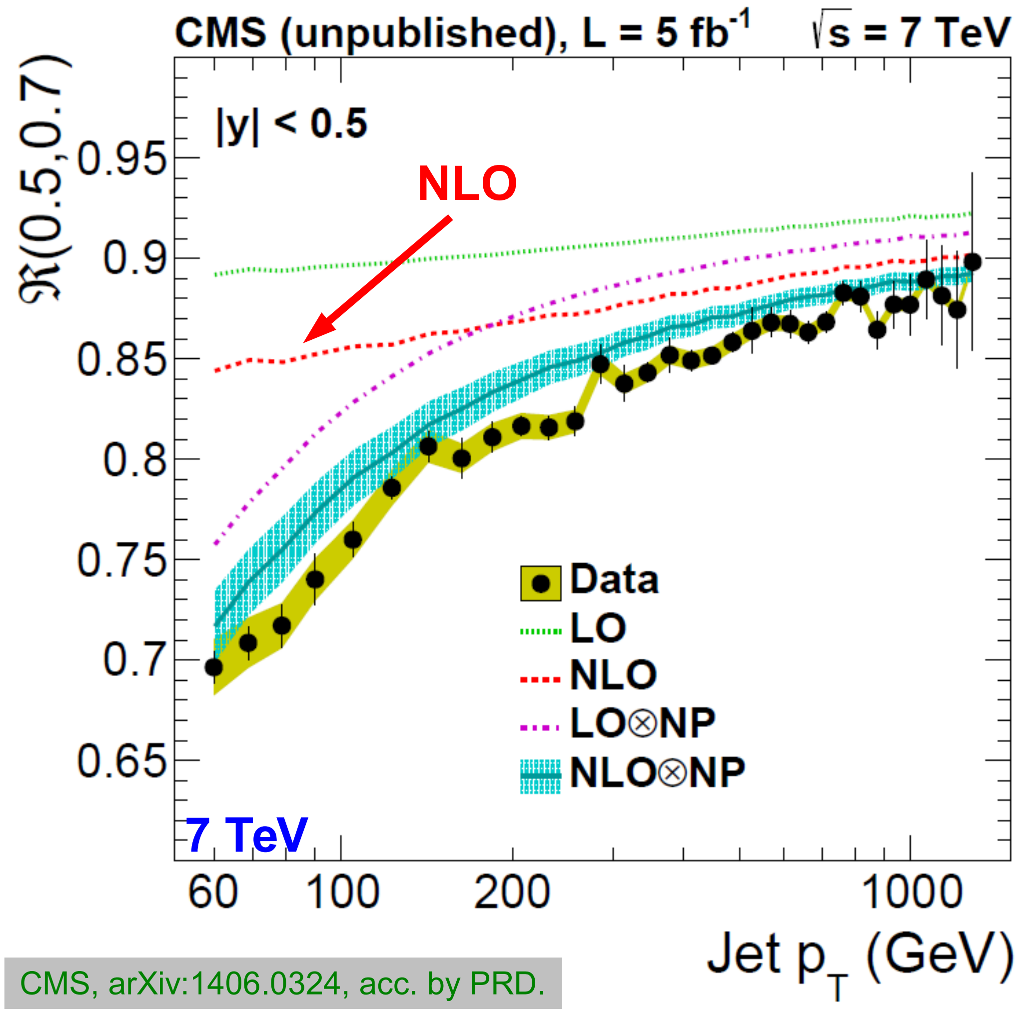
Emphasizes effects of showering and hadronization
→ NLO insufficient to describe data!

Requires event generators:
LO+PS+HAD → better (Pythia6,Herwig++)
NLO+PS+HAD → best (POWHEG+Pythia)

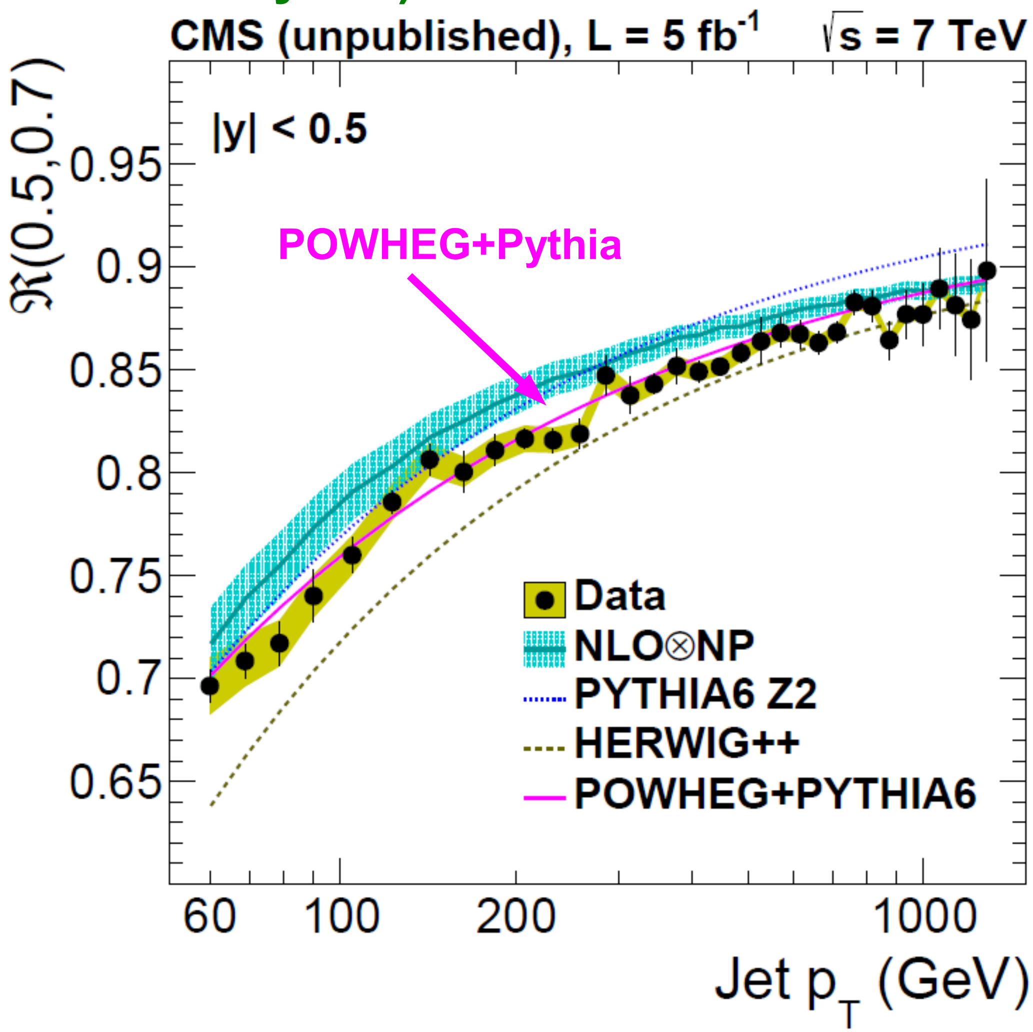
G. Soyez, PLB698 (2011).

ALICE study R=0.2 / R=0.4

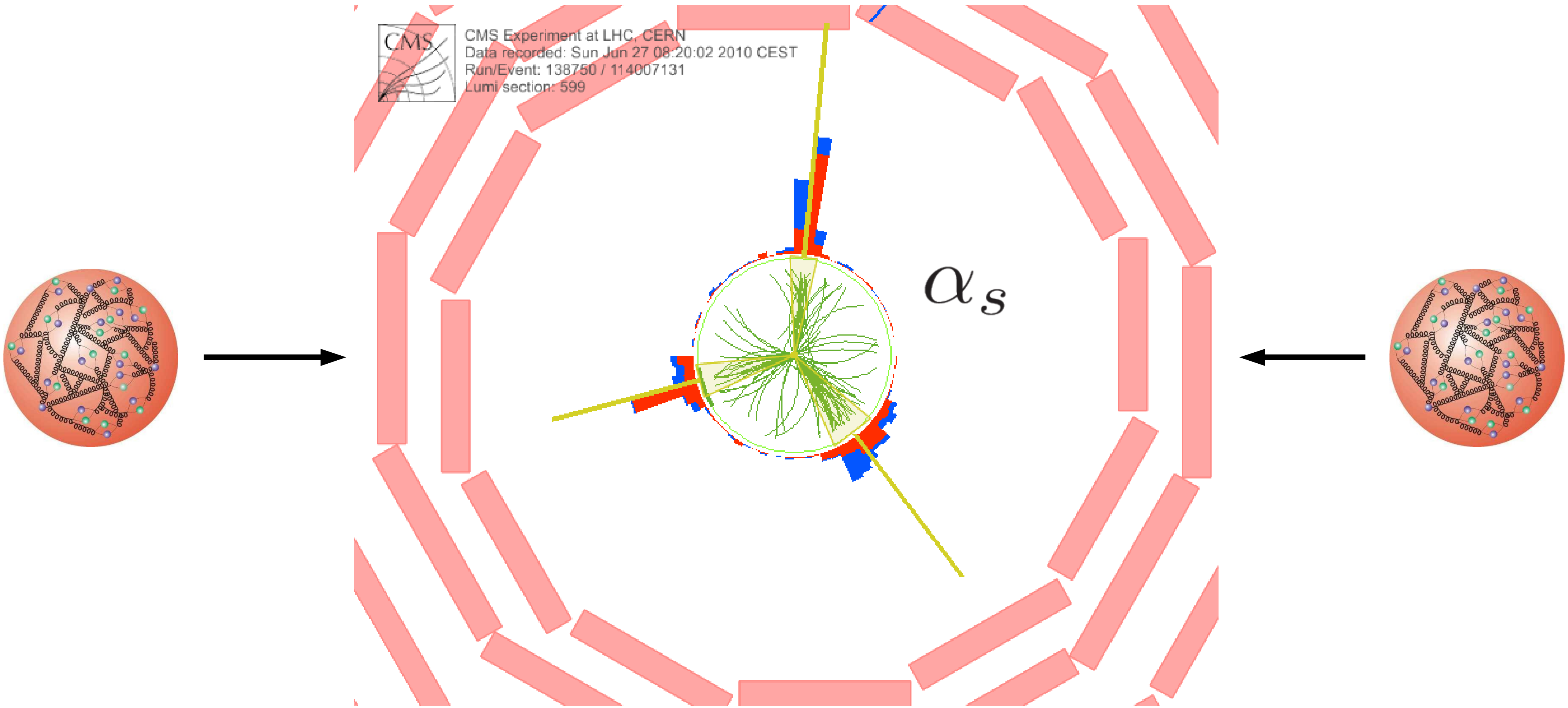
ALICE, PLB722 (2013).



CMS, arXiv:1406.0324, acc. by PRD.



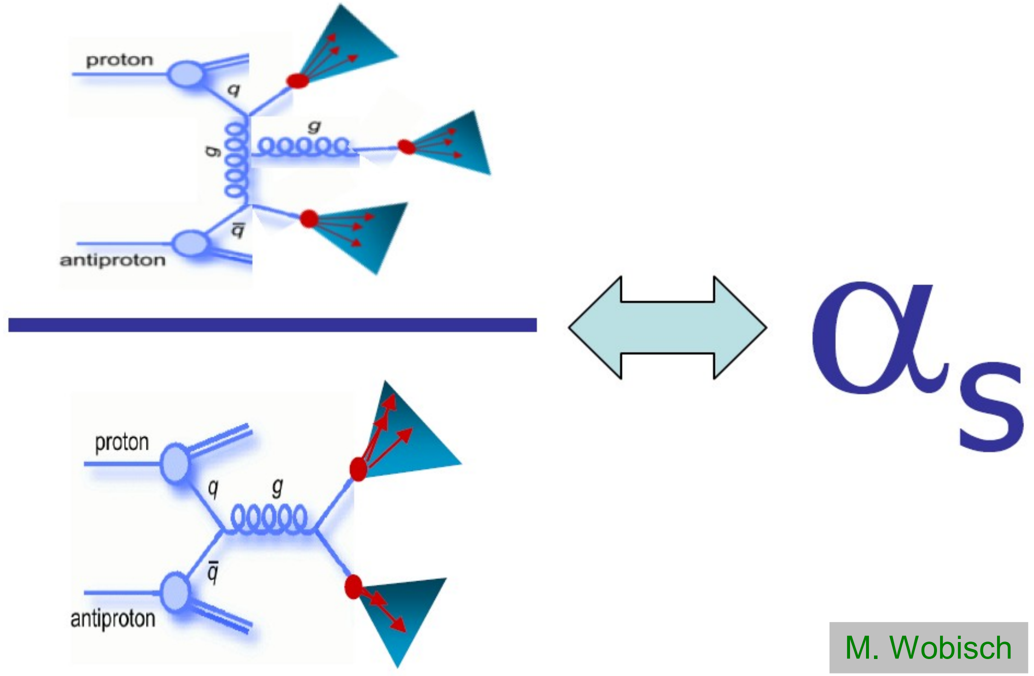
α_s (1 TeV) ?


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

3-Jet Ratios and α_s in hh

Normalization or ratios for different multiplicity N_{jet} = 3 over 2:

- Similar as in H1 normalized cross Sections, see later.
- Reduce exp. and scale uncertainties
- Eliminate luminosity dependence
- Avoid direct dependence on PDFs and the RGE



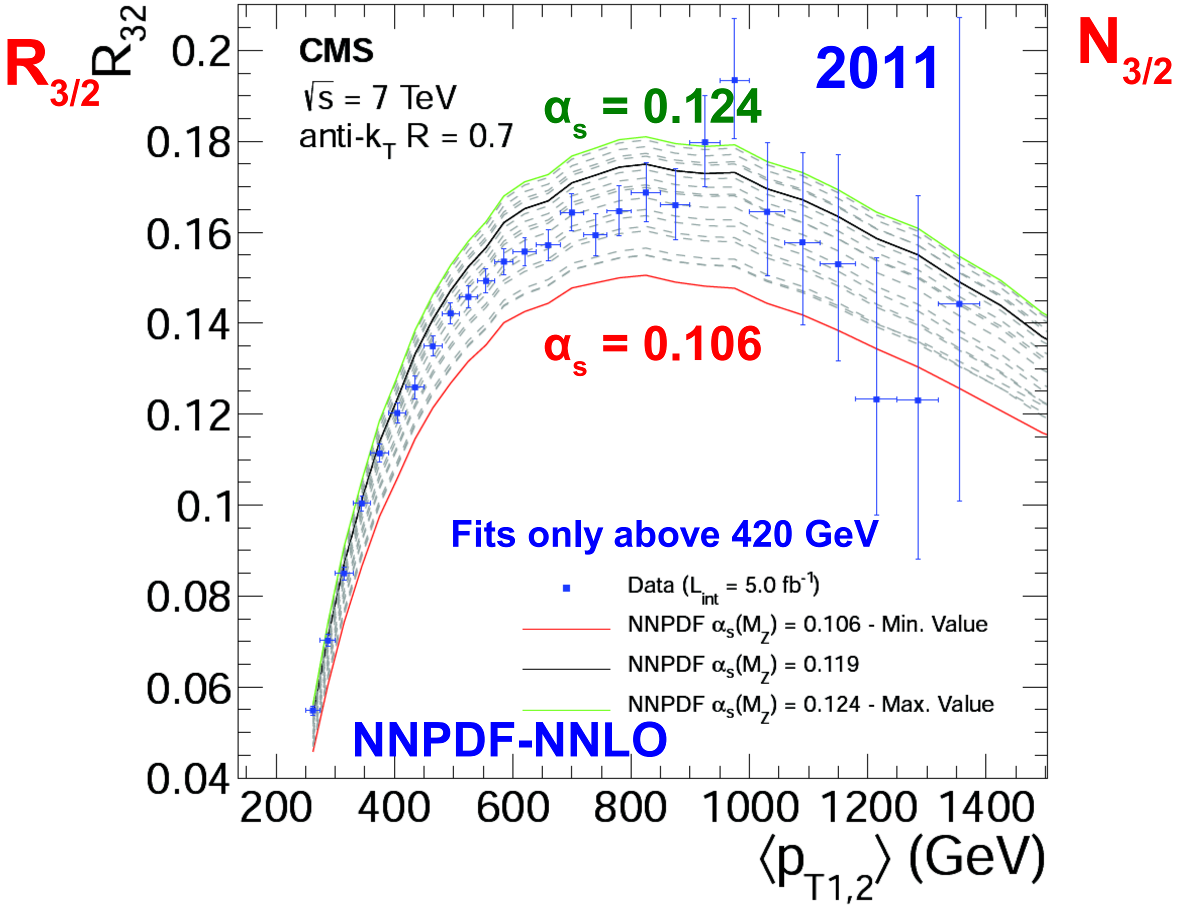
Three observables investigated:

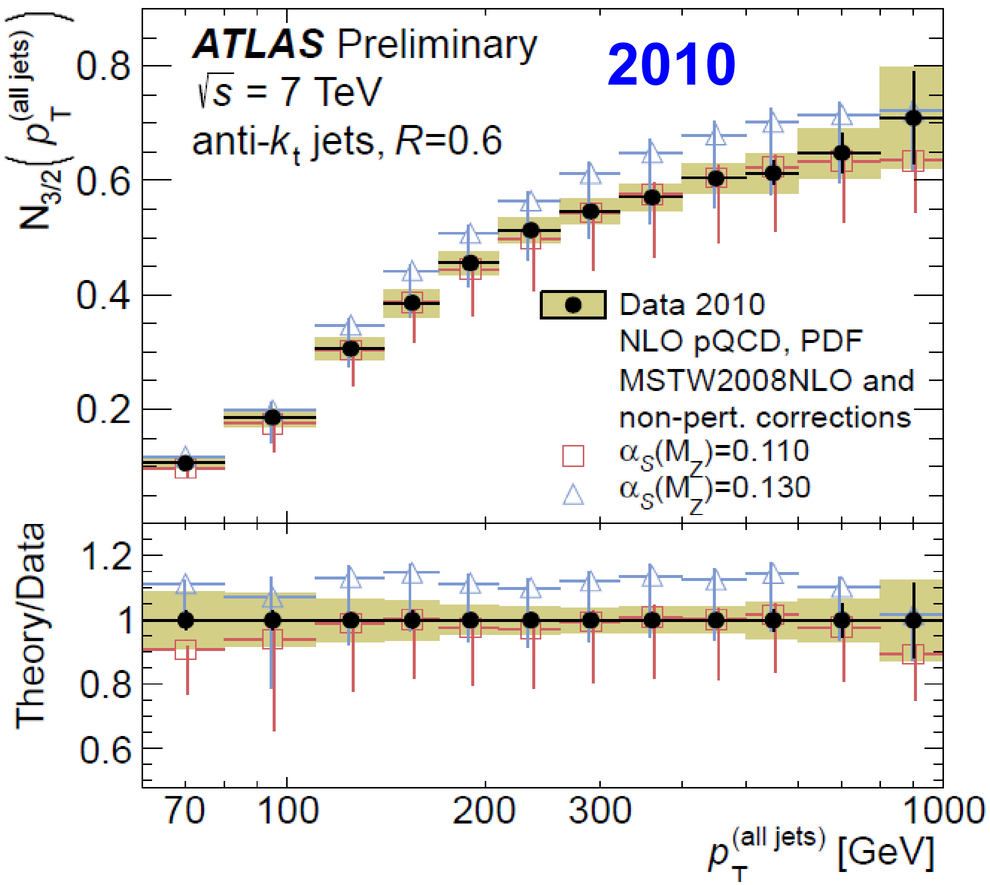
D0: $R_{\Delta R}$
- Average no. of neighbor jets within ΔR in incl. sample
- D0 midpoint cone R=0.7
- Min. jet pT: 50 GeV
- Max. rap.: |y| < 1.0
- Scale: Jet pT
- Data 0.7/fb

CMS: $R_{3/2}$
- Ratio of inclusive 3- to inclusive 2-jet events
- anti-kT R=0.7
- Min. jet pT: 150 GeV
- Max. rap.: |y| < 2.5
- Scale: Average dijet pT
- Data 2011, 5/fb

ATLAS: $N_{3/2}$
- Ratio of inclusive 3- to inclusive 2-jets
- anti-kT R=0.6
- Min. jet pT: 40 GeV
- Max. rap.: |y| < 2.8
- Scale: Jet pT
- Data 2010, 36/pb

3- to 2-Jet Ratios





Similarly described by CT10 or MSTW2008

Discrepancies observed with ABM11

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\text{exp}) \pm 0.0018\,(\text{PDF}) \pm 0.0050\,(\text{theory})$$

$$\alpha_s(M_Z) = 0.111 \pm 0.006\,(\text{exp}) \pm^{0.016}_{0.003}\,(\text{theory})$$

CMS, EPJC 73 (2013) 2604

Dominated by theory uncertainty!

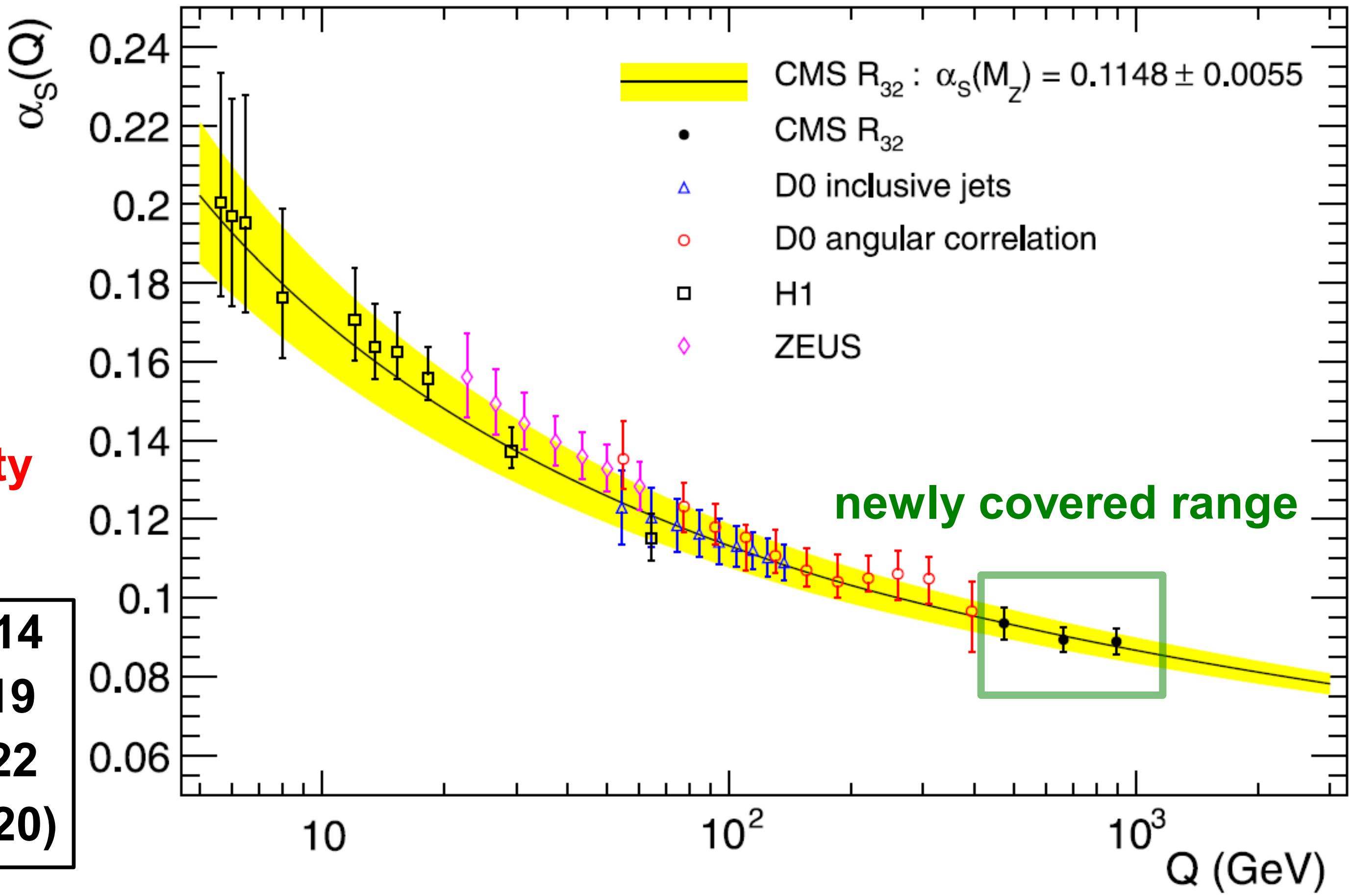
ATLAS-CONF-2013-041 (2013)

Determination of α_s from $R_{3/2}$ (NLO)

CMS, EPJC 73 (2013) 2604

- 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

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

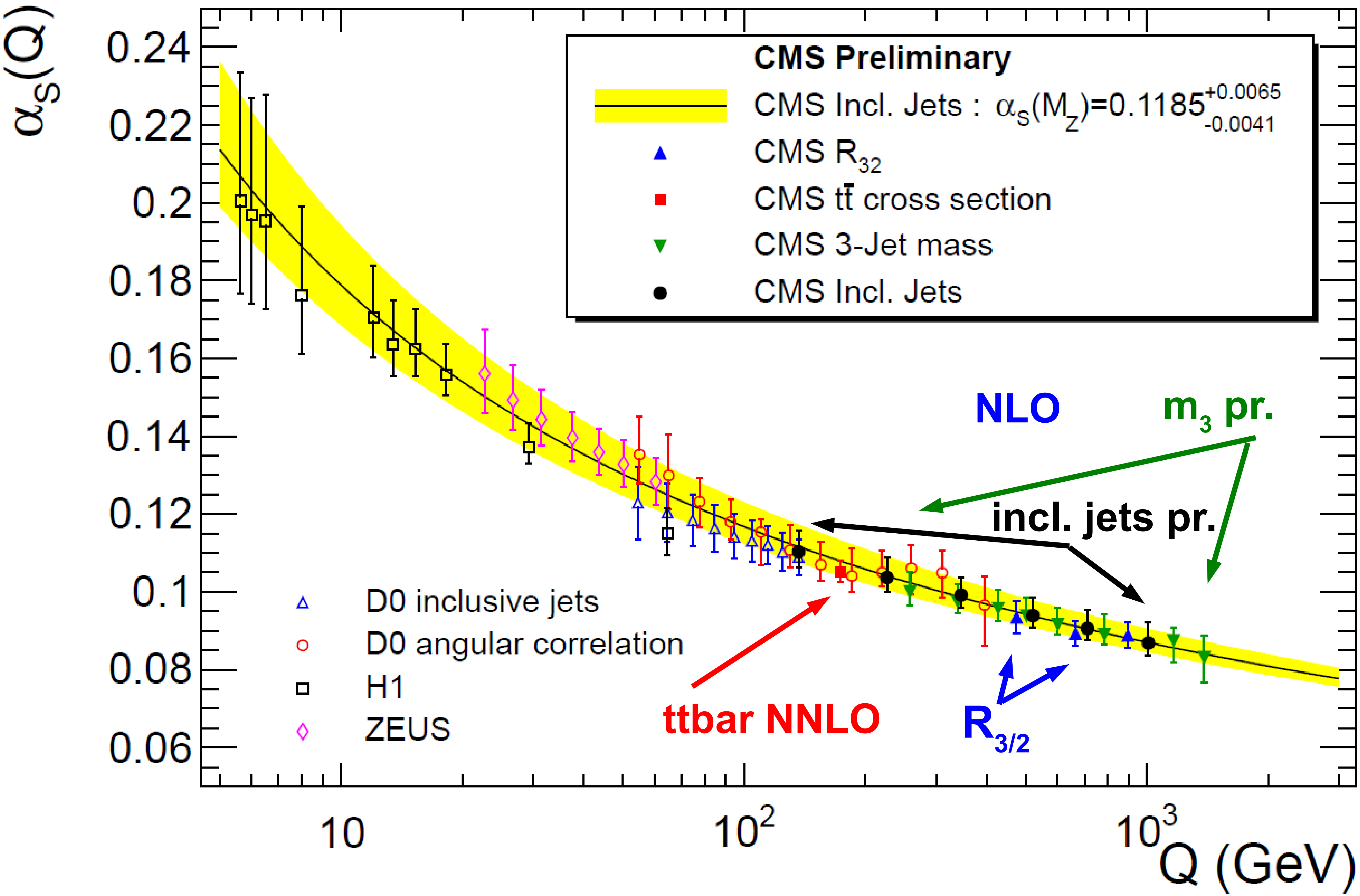


PDF uncertainty: Repeat fit for each NNPDF replica → get estimators for μ and σ

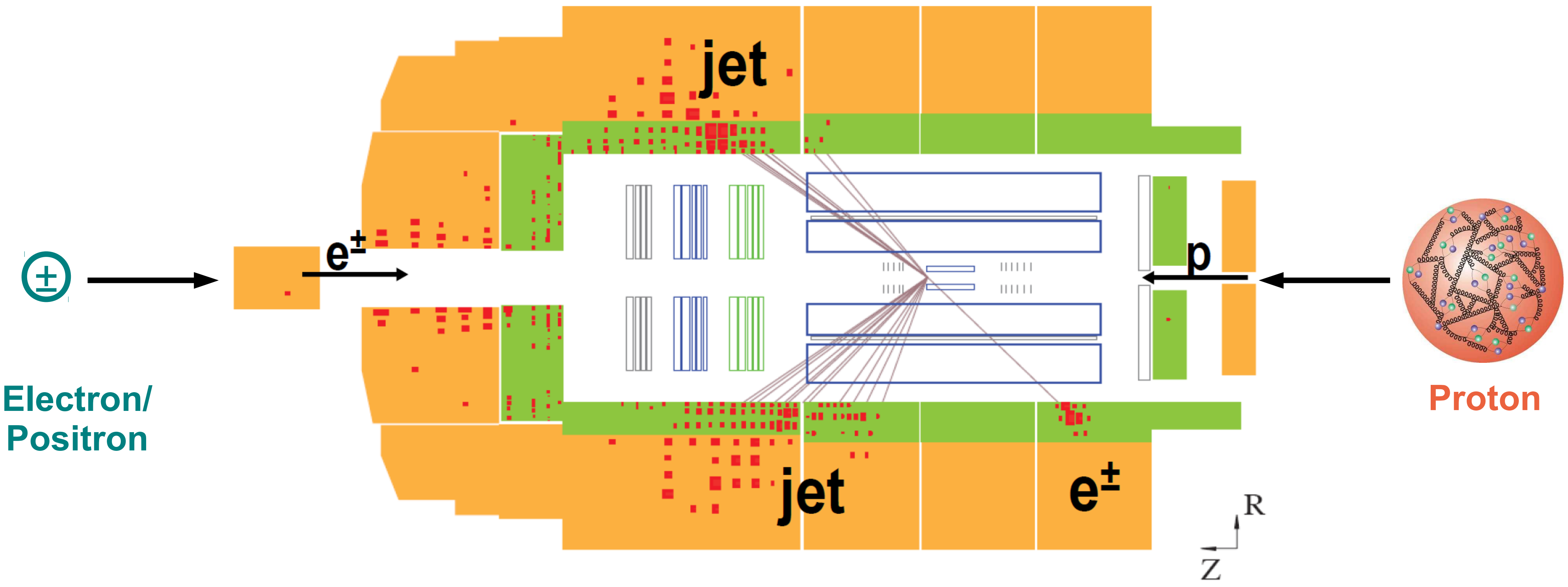
Scale uncertainty: Repeat fit for six variations of (μ_r,μ_f)→ get maximal deviation

$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp}) \pm 0.0018\,(\mathrm{PDF}) \pm 0.0050\,(\mathrm{theory})$$

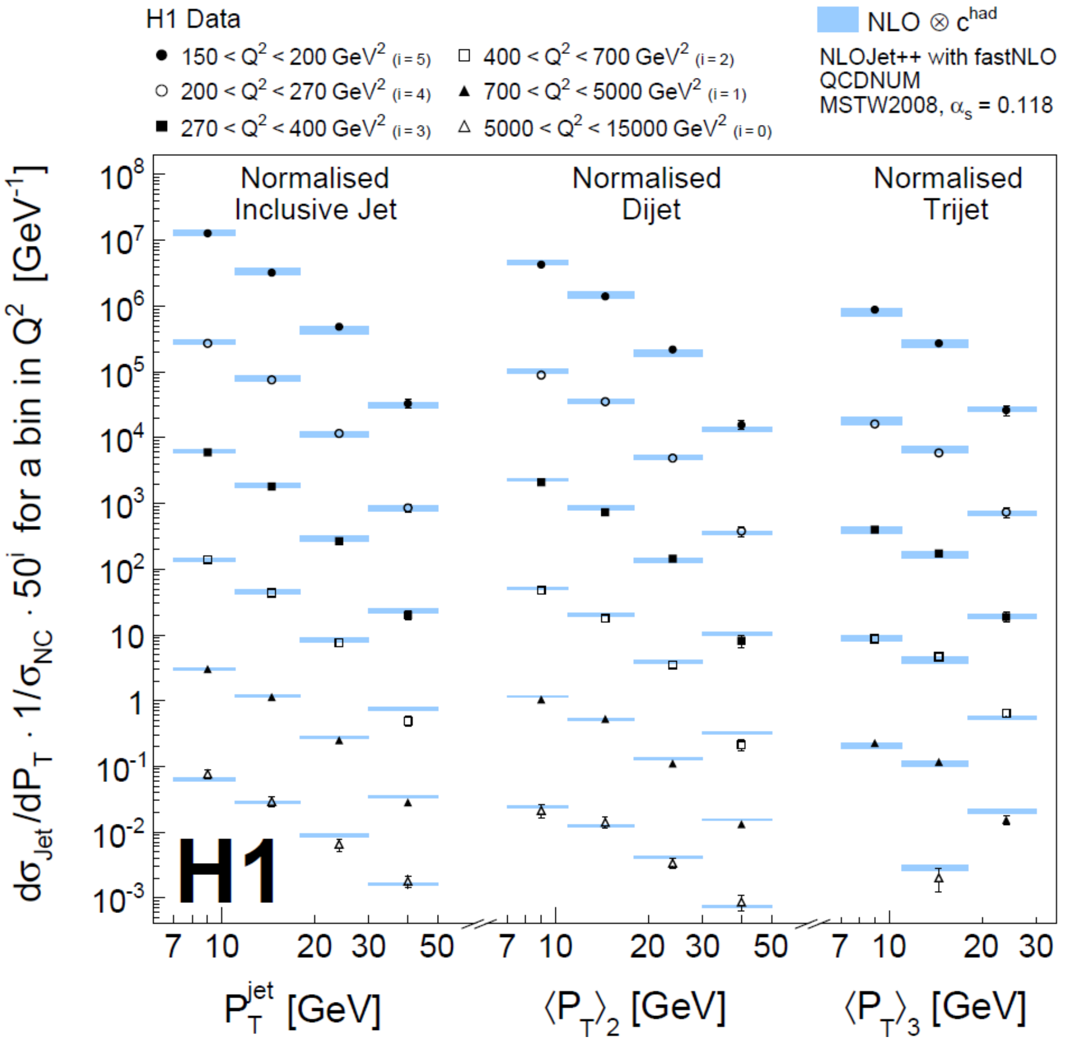
CMS α_s Summary

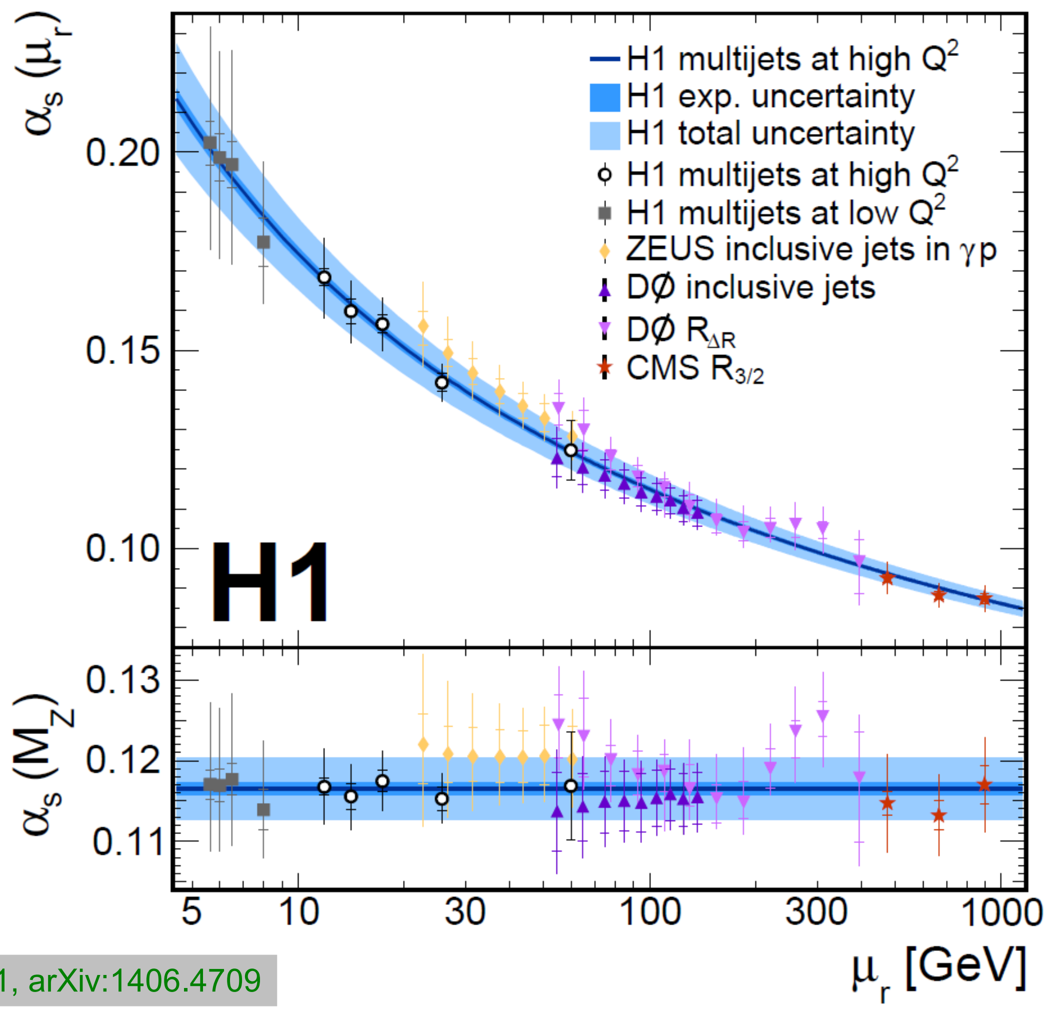


Normalized Multi-Jets and α_s



Normalized Multi-Jets in DIS





H1, arXiv:1406.4709

$$\alpha_s(M_Z) = 0.1165 \pm 0.0008(\text{exp.}) \pm 0.0038(\text{theor.})$$

NLO: Dominated by theory uncertainty!

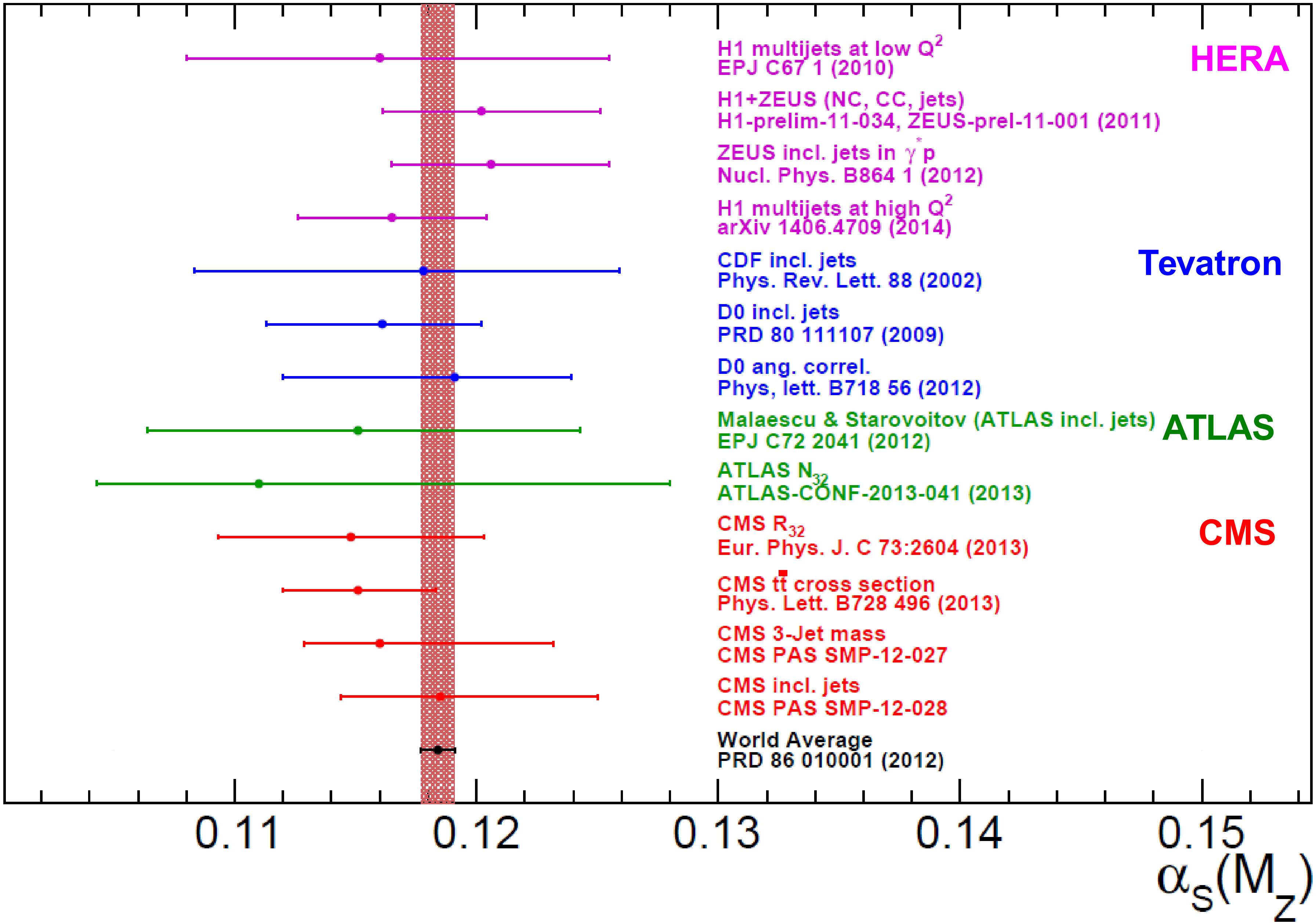
Jet phase space:

Jets incl.: $-1.0 < \eta_{lab} < 2.5$

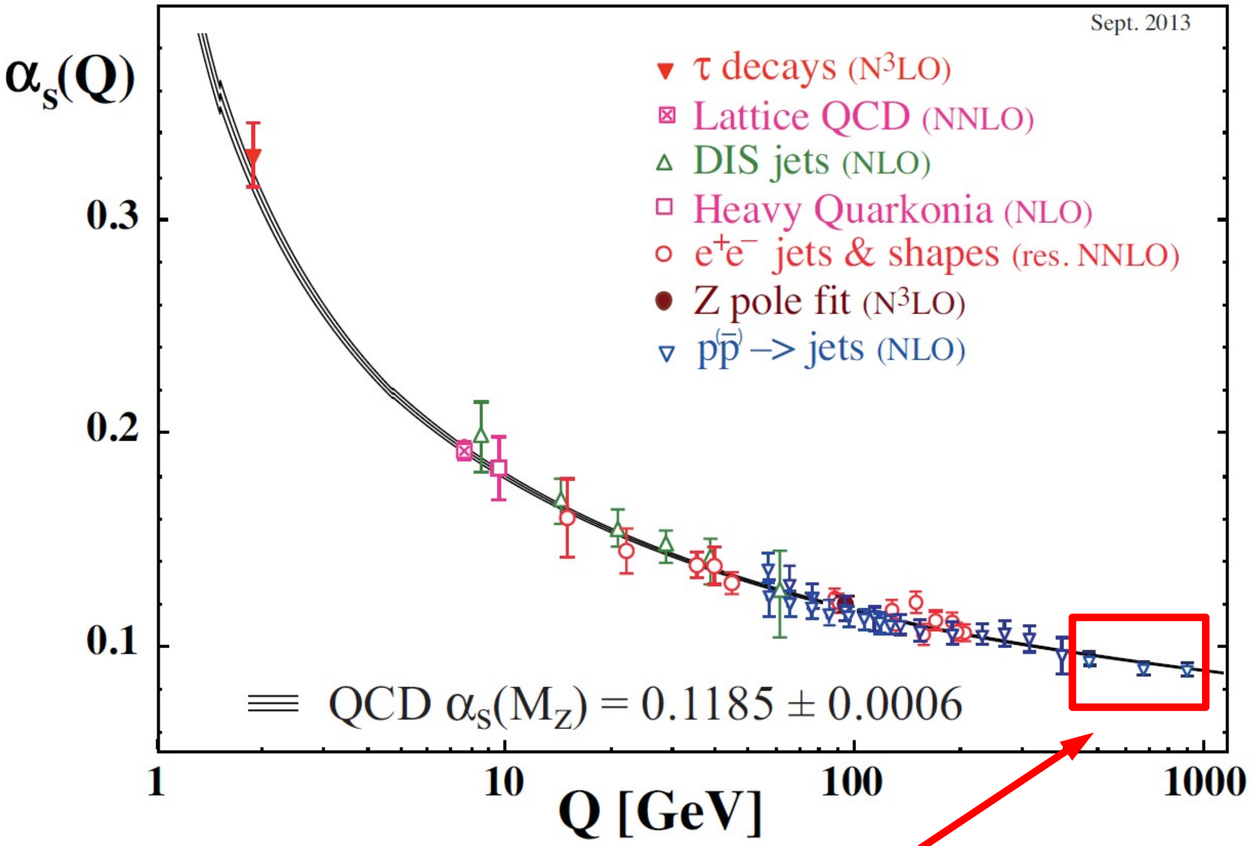
$7 < pT < 50$ GeV

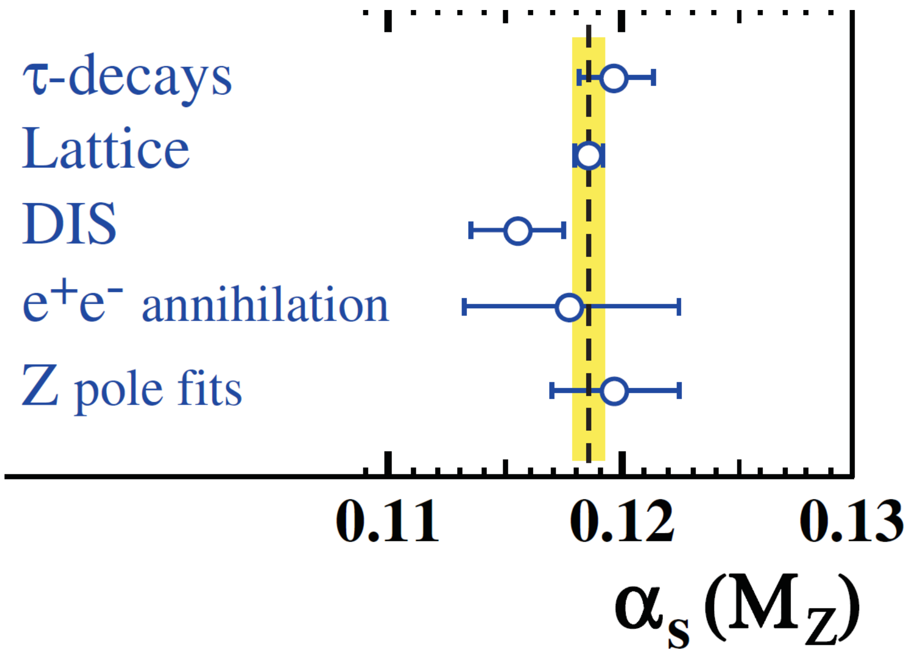
2-,3-Jets: $5 < pT < 50$ GeV

Hadron Collider Summary



PDG α_s Summary





CMS data, but not in average since only NLO theory!

$$\alpha_s(M_Z) = 0.1185 \pm 0.0006$$

PDG2014

Outlook

- Still new precise measurements from HERA (and Tevatron)!
- Huge new phase space opened up at 7-8 TeV LHC …
  13 TeV will be another very interesting step, not only for searches
- Data quality makes jet measurements PRECISION PHYSICS

  → better determine gluon PDF, strong coupling, and … gg → H
- Theory definitely entered regime of NLO as Standard
- More precise theory required (NNLO, EW) ...
- … and under heavy development → will be very welcome!
- Mentioned only briefly other exciting topics like jet substructure,
  or not at all, gap fractions, W+jets, Z+jets
- New ideas for analyses are explored

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Thank you for your attention!

Backup Slides

PDG Pre-averages

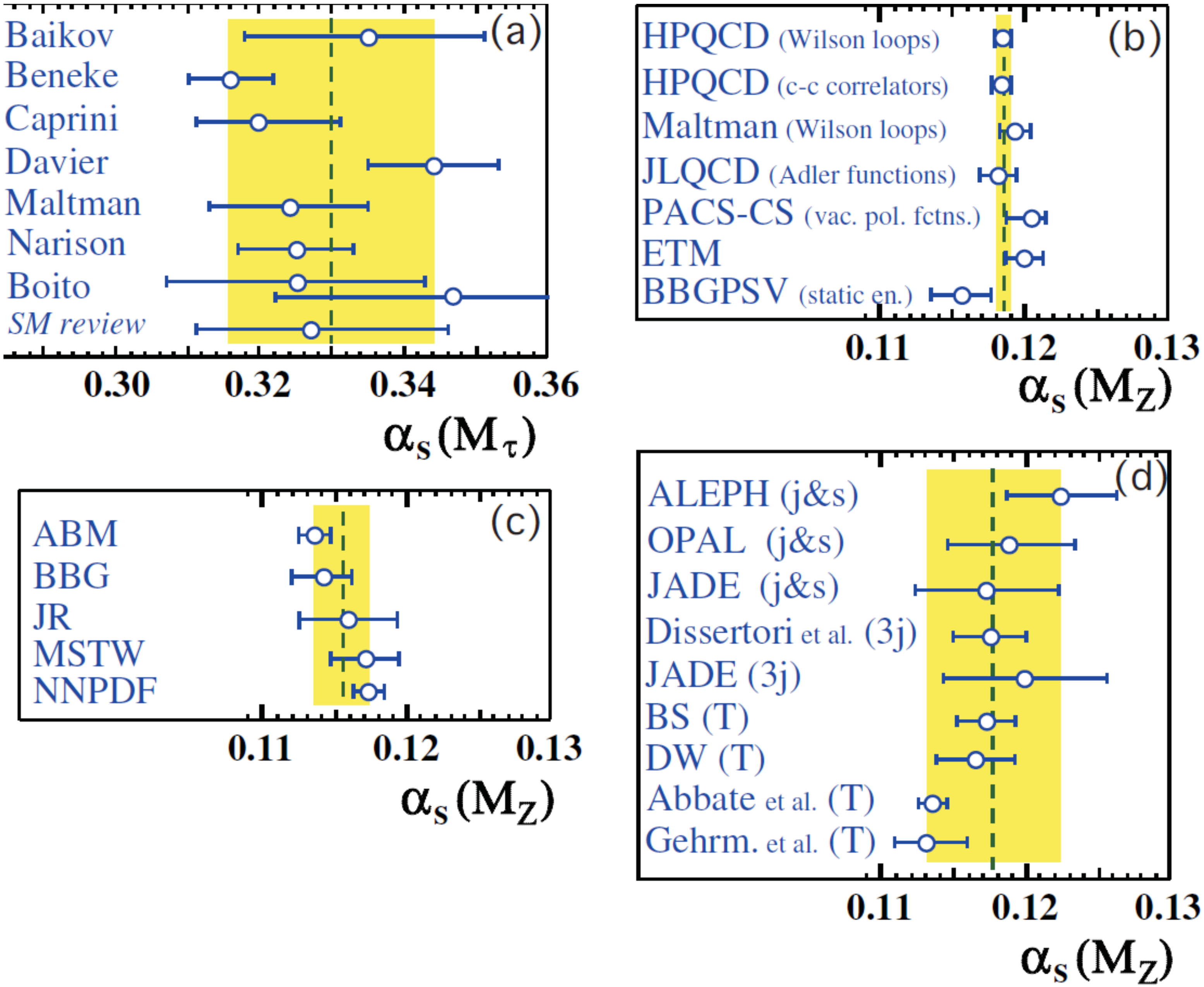

Table of PDF sets with α_s series

Base set	Reference(s)	Evol. order	N_f	$\alpha_S(M_Z)$	$\alpha_S(M_Z)$ variations
ABM11	[24]	NLO	5	0.1180	0.110–0.130
ABM11	[24]	NNLO	5	0.1134	0.104–0.120
CT10	[25]	NLO	≤ 5	0.1180	0.112–0.127
CT10	[25]	NNLO	≤ 5	0.1180	0.110–0.130
HERAPDF1.5	[26]	NLO	≤ 5	0.1176	0.114–0.122
HERAPDF1.5	[26]	NNLO	≤ 5	0.1176	0.114–0.122
MSTW2008	[27, 28]	NLO	≤ 5	0.1202	0.110–0.130
MSTW2008	[27, 28]	NNLO	≤ 5	0.1171	0.107–0.127
NNPDF2.1	[29]	NLO	≤ 6	0.1190	0.114–0.124
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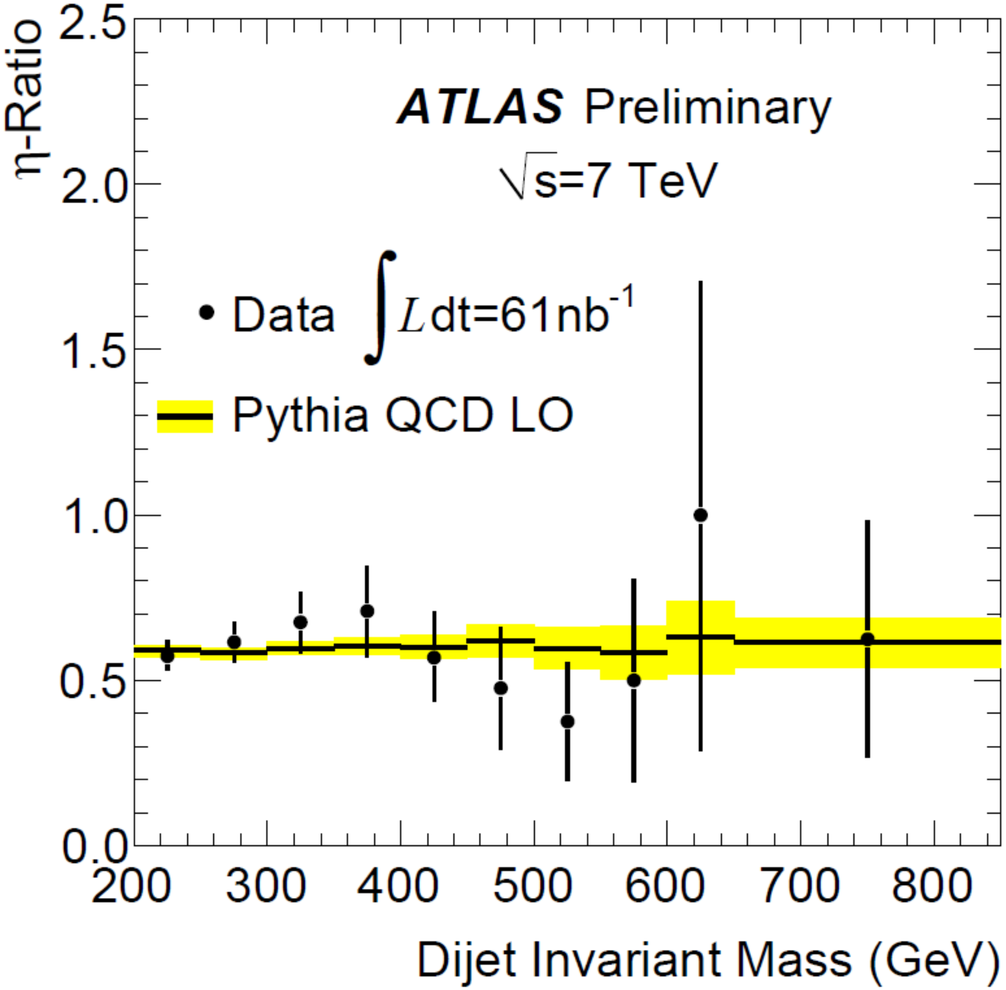
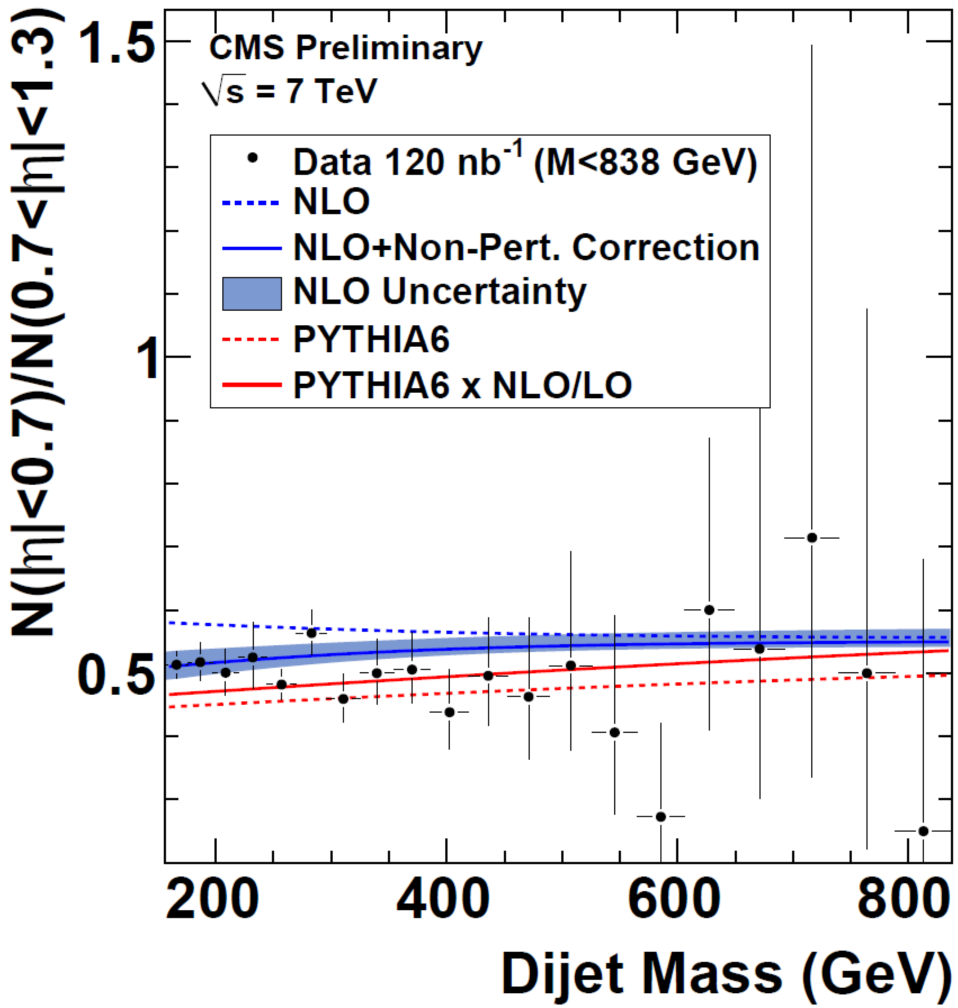
Dijet Centrality Ratio

Outdated figures, anyway no deviations from QCD observed!

$$\eta\text{-ratio} = \frac{N(|\eta_{1,2}|<0.5)}{N(0.5<|\eta_{1,2}|<1)}$$



$$R = \frac{N(|\eta| < 0.7)}{N(0.7 < |\eta| < 1.3)}$$



Event Shapes

Originally:

Event Shapes in e^+e^- (and ep)
Played a key role in the discovery of the gluon at DESY in 1978!

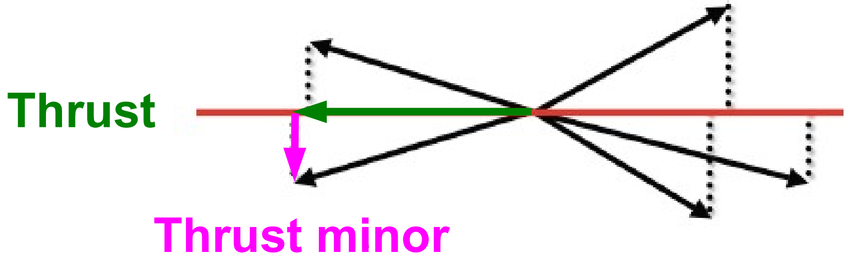
Old but still-used definition since collinear and infrared safe: Thrust

S. Brandt et al., PL12 (1964),
E. Farhi, PRL39 (1977).

At LHC: Transverse global thrust
➔ **In praxis, need to restrict rapidity range: $|\eta| < \eta_{max}$ → Transverse central thrust**

Definition:

Transverse global thrust

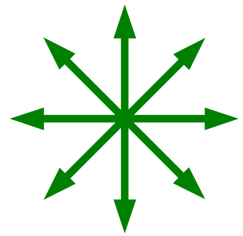


$$T_{\perp,g} = \max_{\vec{n}_T} \frac{\sum_i |\vec{p}_{\perp,i} \cdot \vec{n}_T|}{\sum_i p_{\perp,i}}$$

Redefine to get $\tau_{\perp,g} \equiv 1 - T_{\perp,g}$

linear ~ dijet

$\tau_{\perp,g} \to 0$



spherical ~ multijet

$\tau_{\perp,g} \to 1 - 2/\pi$

See also A. Banfi et al., JHEP06, 2010

Central Transverse Thrust

Basic description by MC ok

Some deviations visible
→ good for tuning!

Great tools in e+e-, known to NNLO+NLLA resummation
→ precise determination of α_s

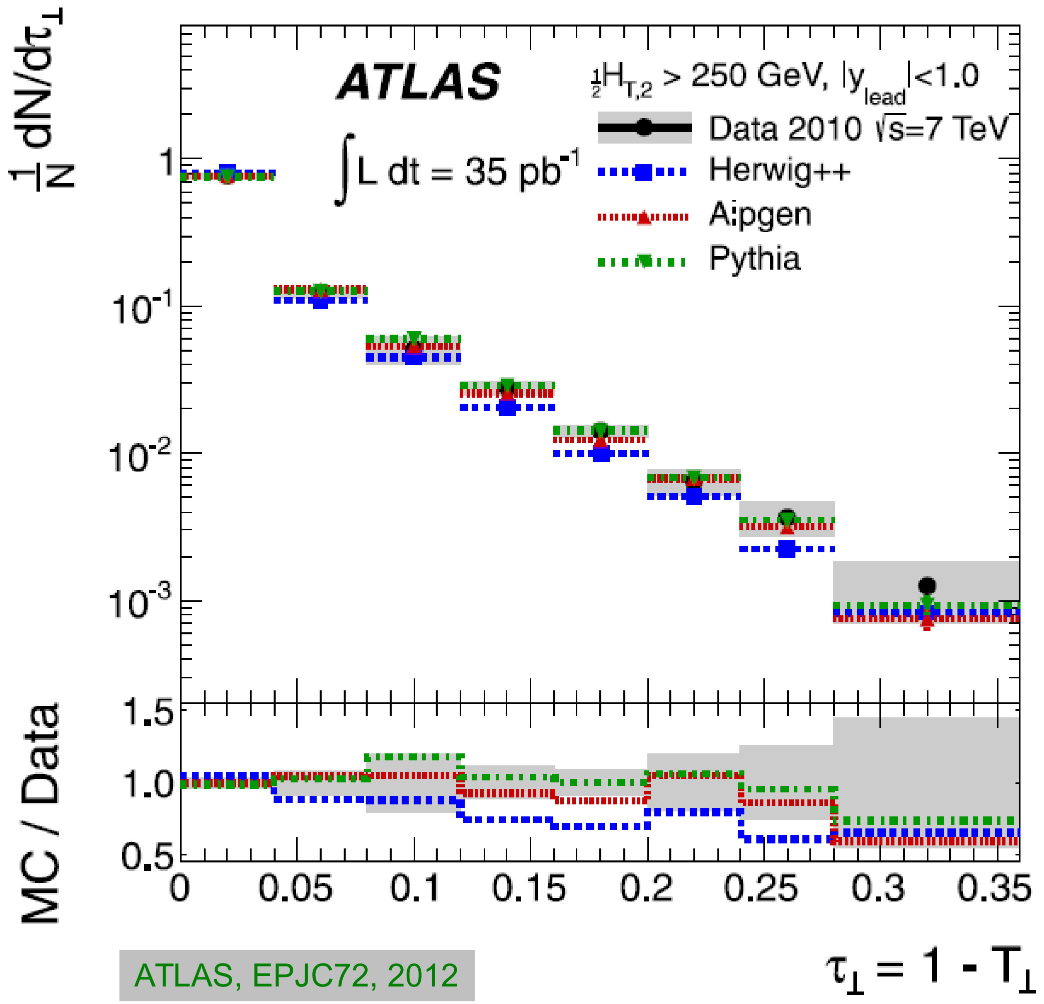
Dissertori et al, JHEP0908 (2009).

Also used successfully in ep

<u>In hh collisons:</u>
- only NLO so far
- in praxis, need to restrict rapidity range: $|\eta| < \eta_{max}$
→ central transverse thrust
→ spoils resummation

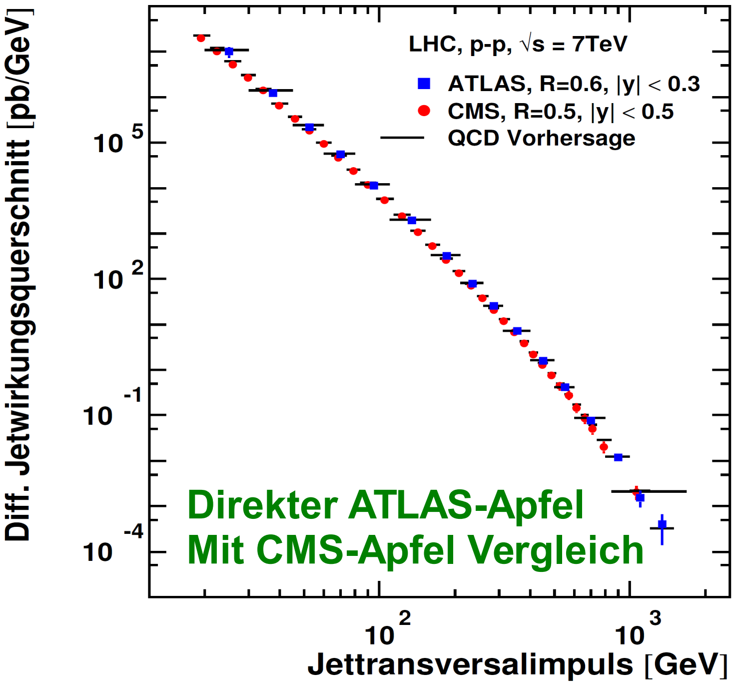
Banfi et al., JHEP06 (2010).

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

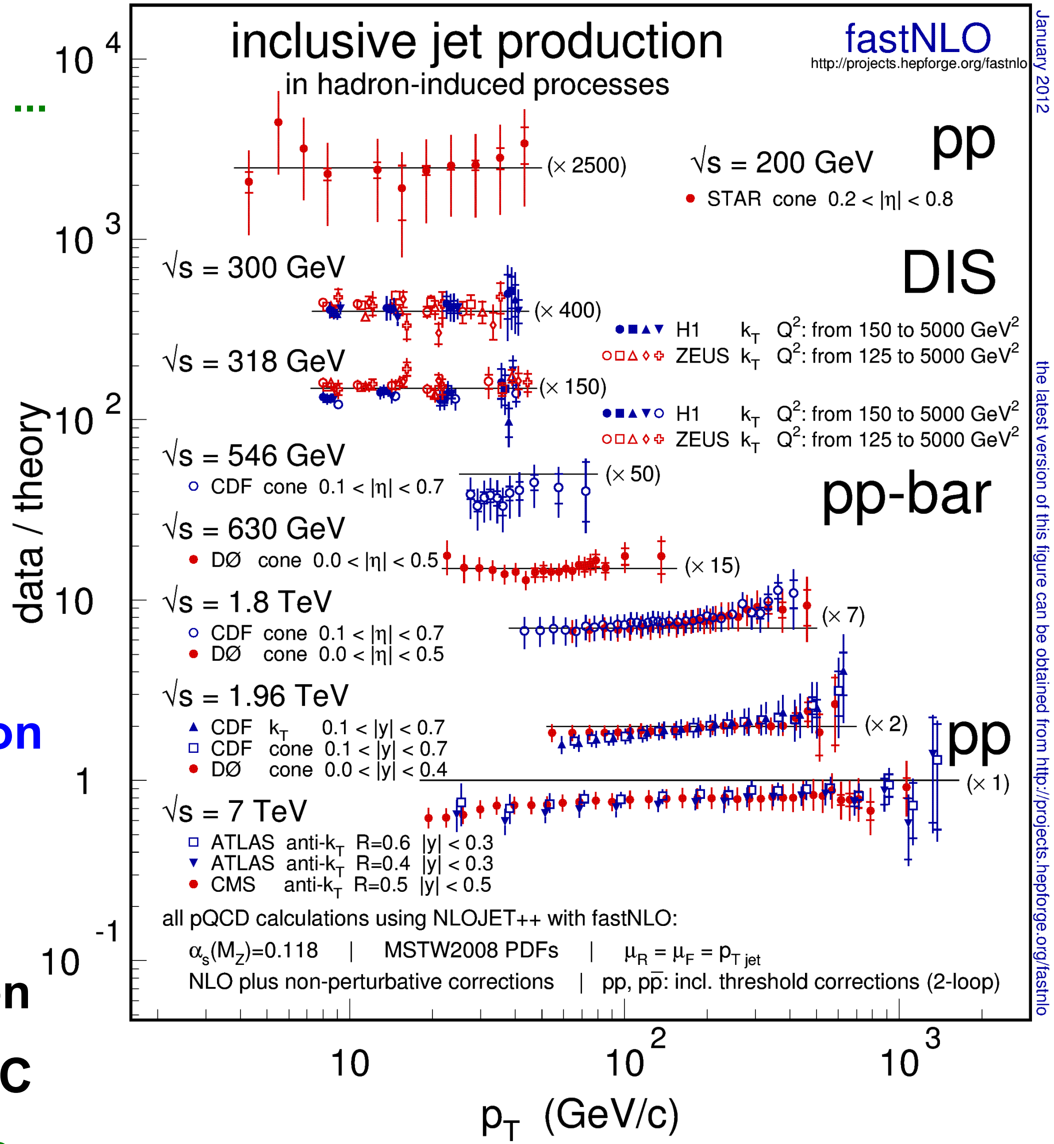


ATLAS, EPJC72, 2012

Jets Daten / Theorie



ATLAS und CMS Stimmen überein ... auf log. Skala :-)



- **Vergleich von Jet-Daten von**
  - **STAR am RHIC**
  - **H1 und ZEUS bei HERA**
  - **CDF und D0 am Tevatron**
  - **ATLAS und CMS am LHC**
- **Kompatibel mit NLO pQCD**