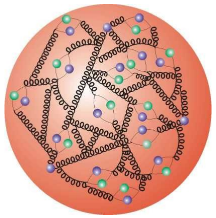
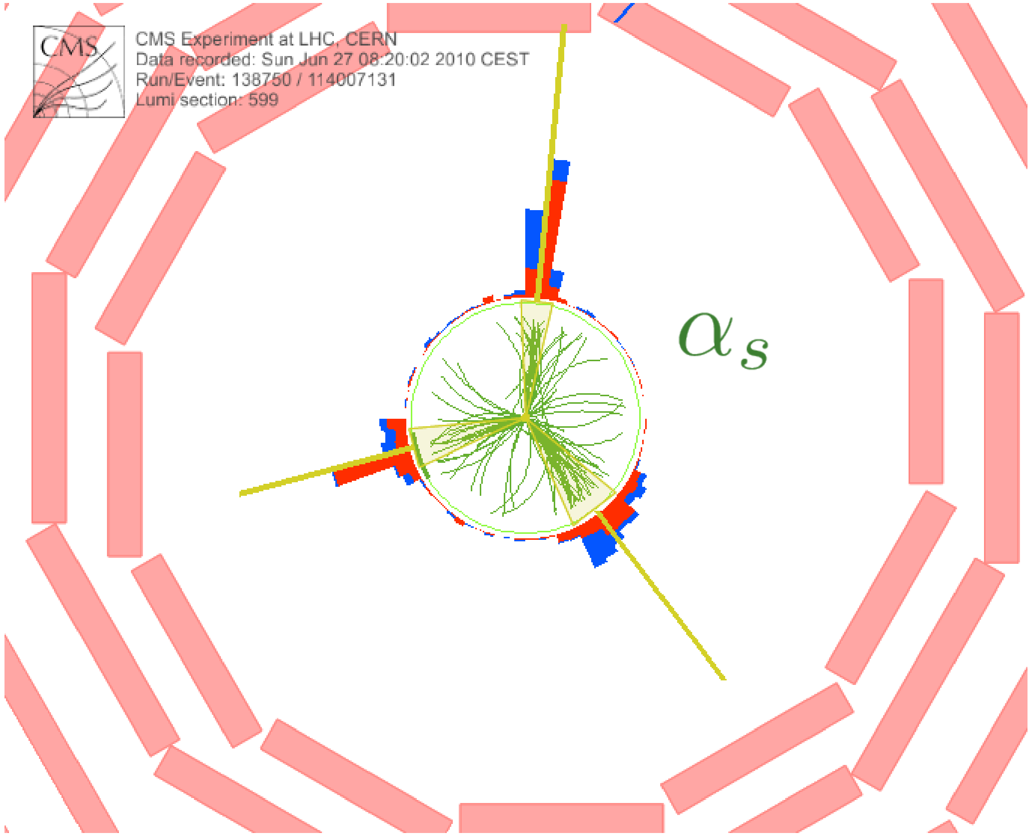
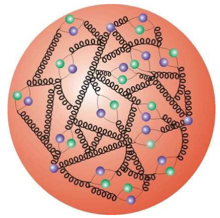
Status of α_s Determinations from CMS



Proton Structure
(PDF)





Proton Structure
(PDF)

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

Klaus Rabbertz, KIT

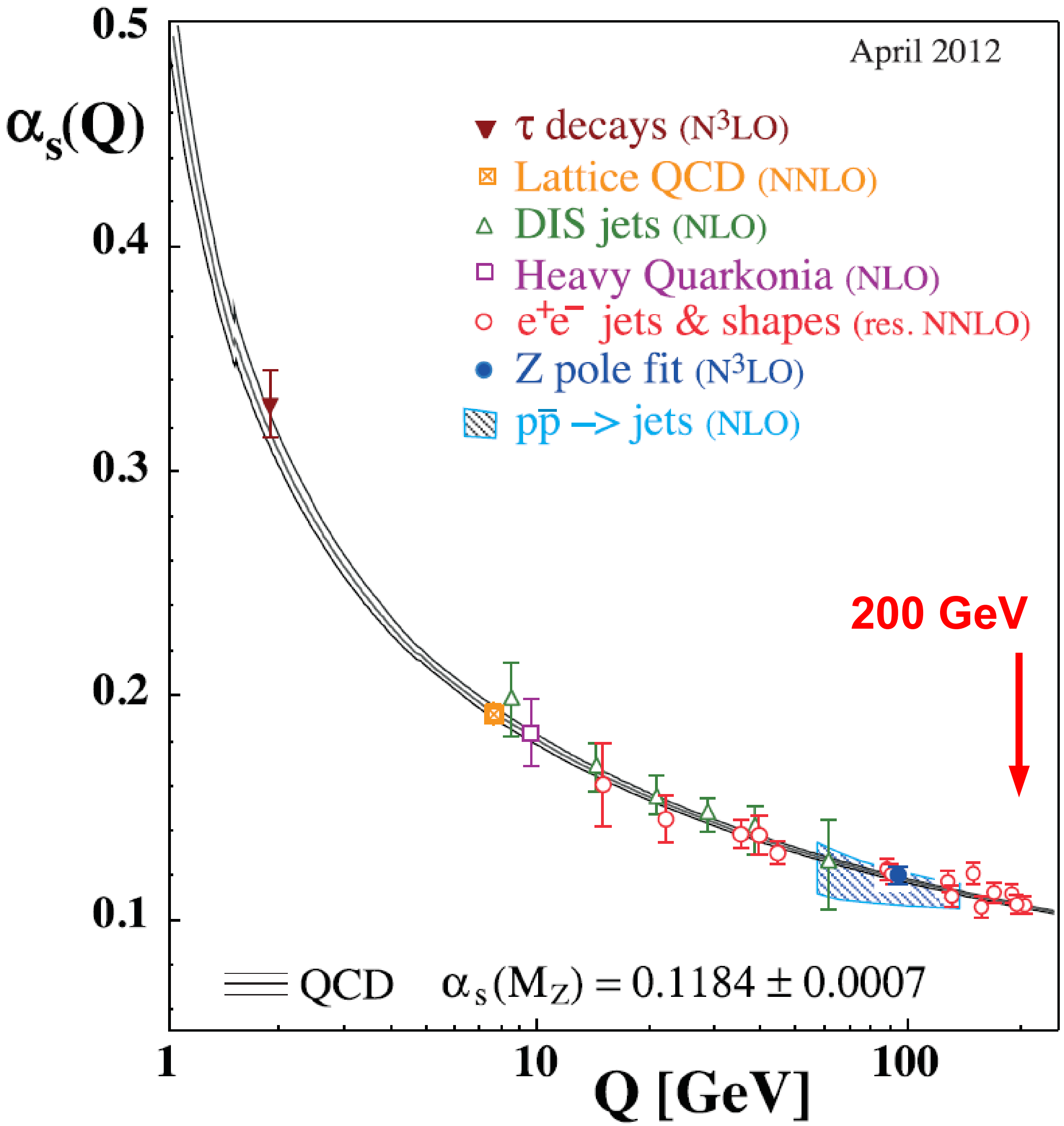
Karlsruhe Institute of Technology

Outline

- Motivation
- Jet energy scale
- α_s from jet cross sections
- α_s using ratios or normalized jet quantities
- Combined Fits
- Fits with top-pair production
- Summary
- Points for discussion

2012: No LHC results yet

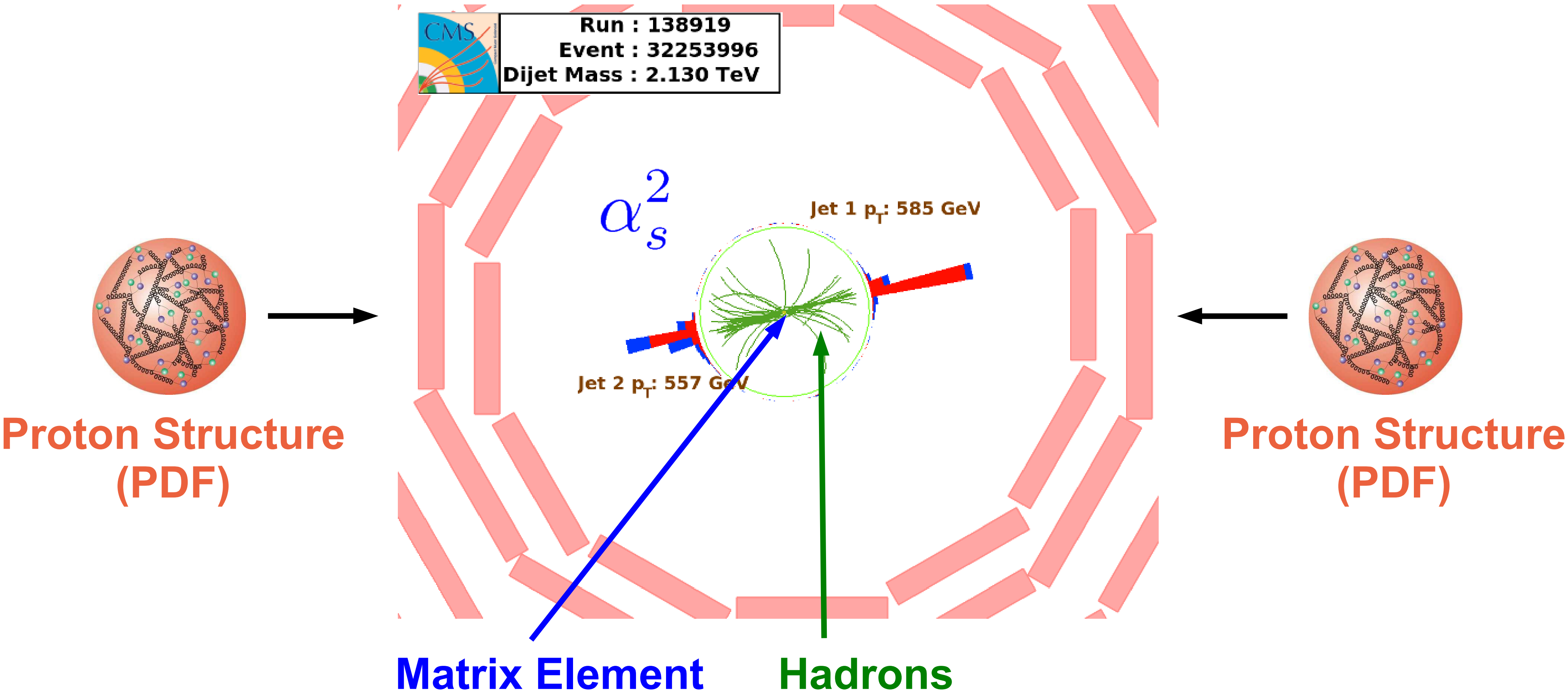
PDG2012



Jets and α_s

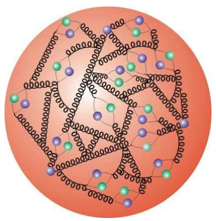
Abundant production of jets:

- Jets at hadron colliders provide the highest reach ever to determine the strong coupling constant at high scales Q
- Also learn about non-perturbative effects, the proton structure, hard QCD, cross talk with electroweak effects at high Q

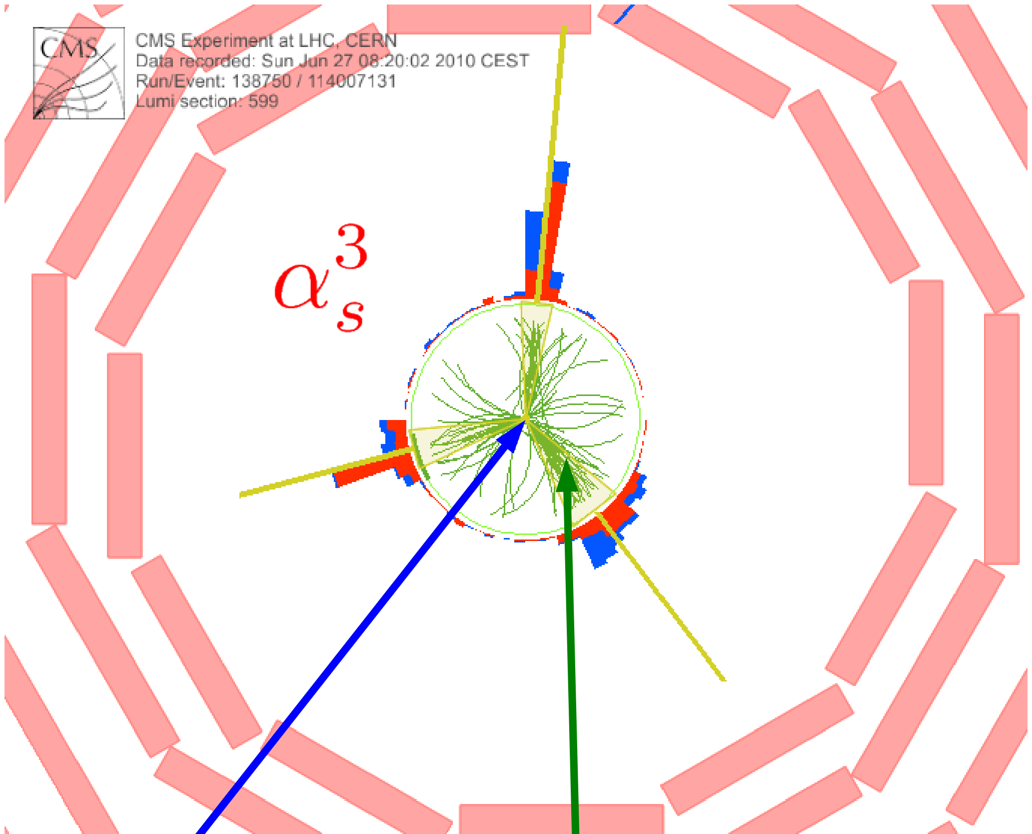


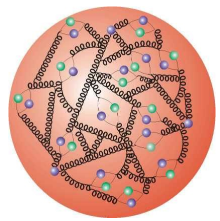
Jets and α_s

Can use cross section ratios or normalized quantities to reduce jet energy scale uncertainty (dominating experimental uncertainty)



Proton Structure
(PDF)





Proton Structure
(PDF)

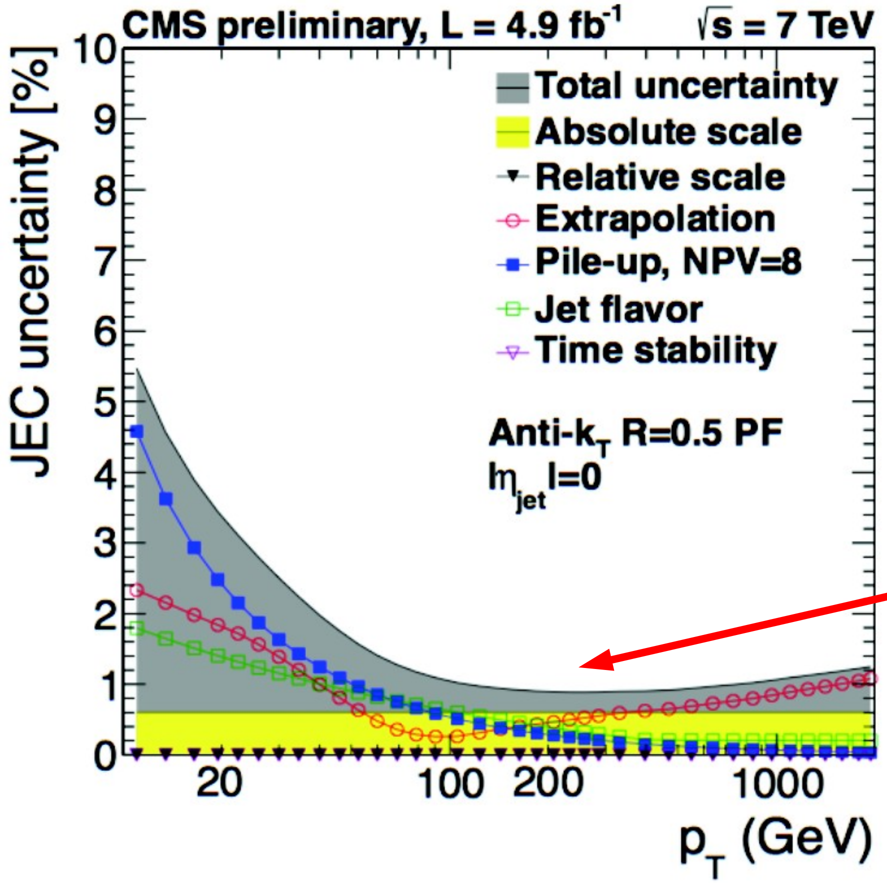
Matrix Element

Hadrons

Jet Energy Scale

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

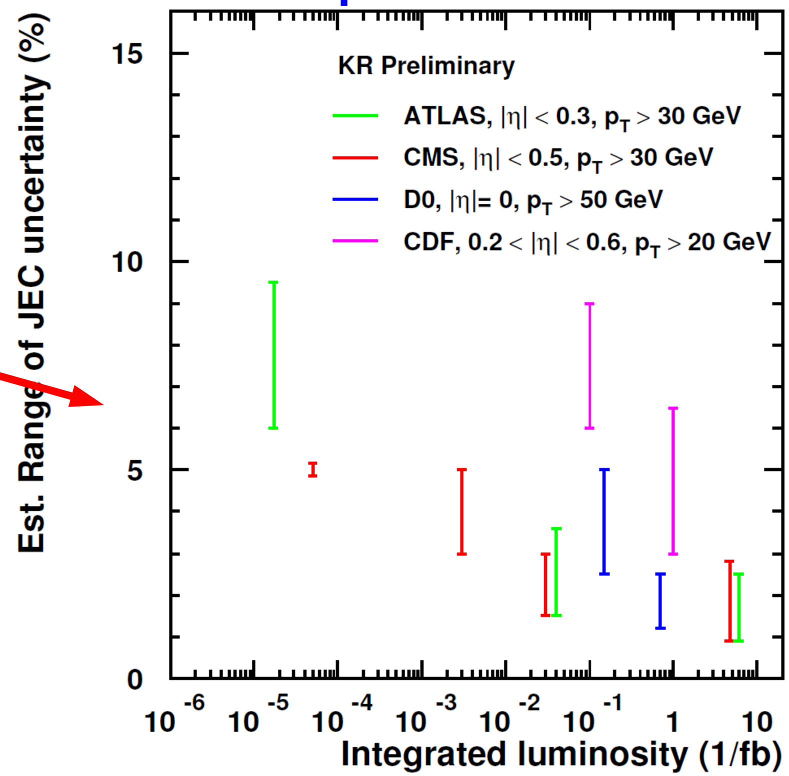
CMS from 5/fb (7 TeV, 2011)



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

Translates into 4 ~ 6 times higher uncertainty on cross section!

Approximate development of JEC precision

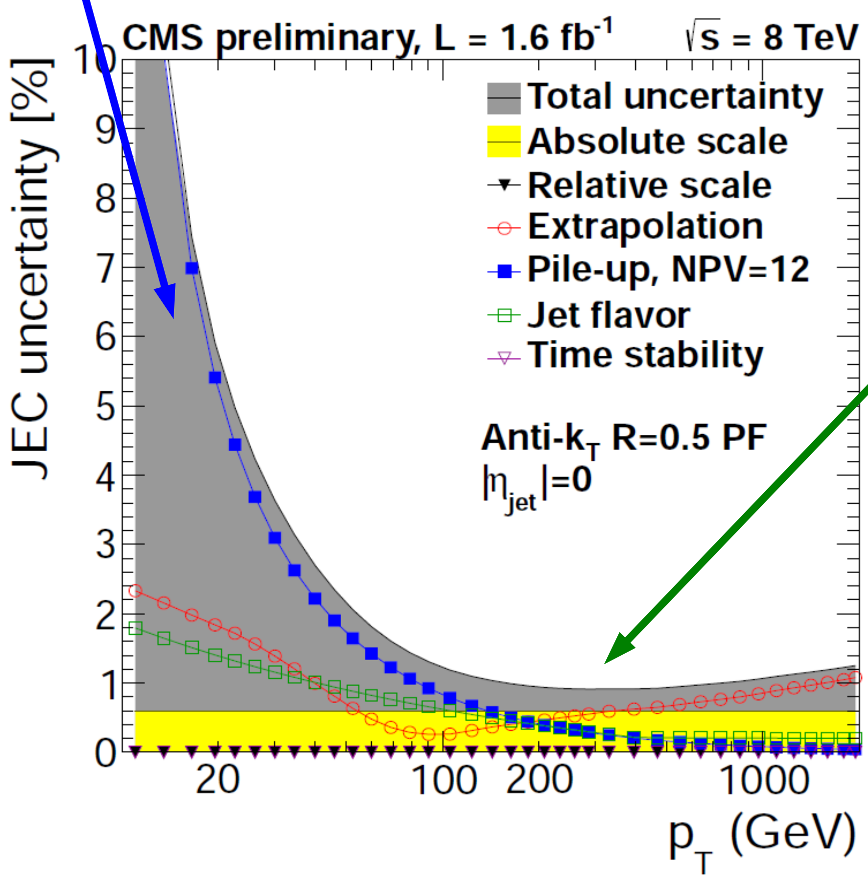


ATLAS, EPJC 71 2011; arXiv:1112.6297; CONF-2012-053; CONF-2012-063
CMS, JME-10-003; JME-10-010; JINST 6 2011; DP2012-006; DP2012-012
D0, arXiv:1110.3771; D0 prel. 2006

Jet Energy Scale and Goals for α_S

Pile-up effect

CMS from 1.6/fb (8 TeV, 2012)



But: Much more pile-up collisions in 2012 at 8 TeV. Record no. of vertices is beyond 70!

Will be even worse at 13 TeV in the near future.

Two possible goals for α_S:

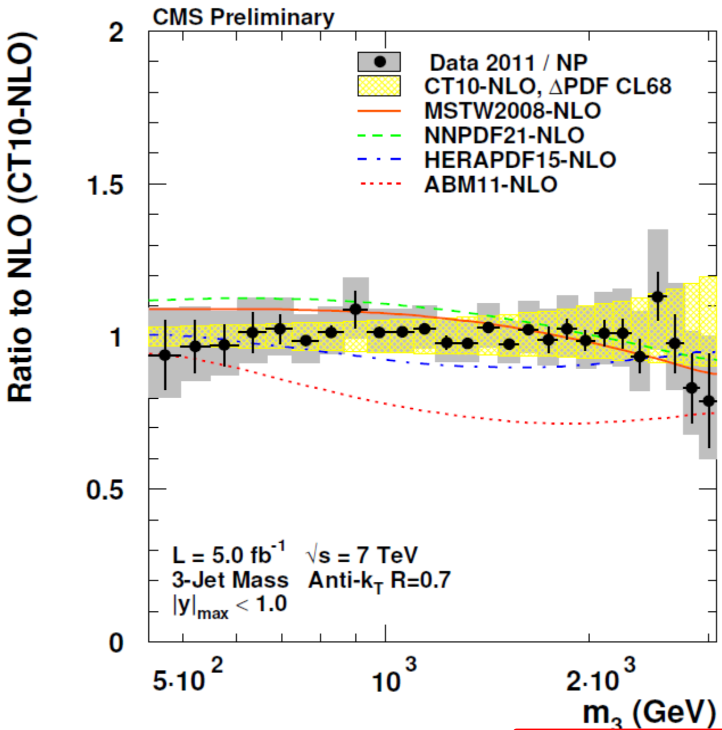
1. **Measure the running of $\alpha_S(Q)$ up to the highest scales possible**
2. **Measure $\alpha_S(M_Z)$ as precisely as possible**

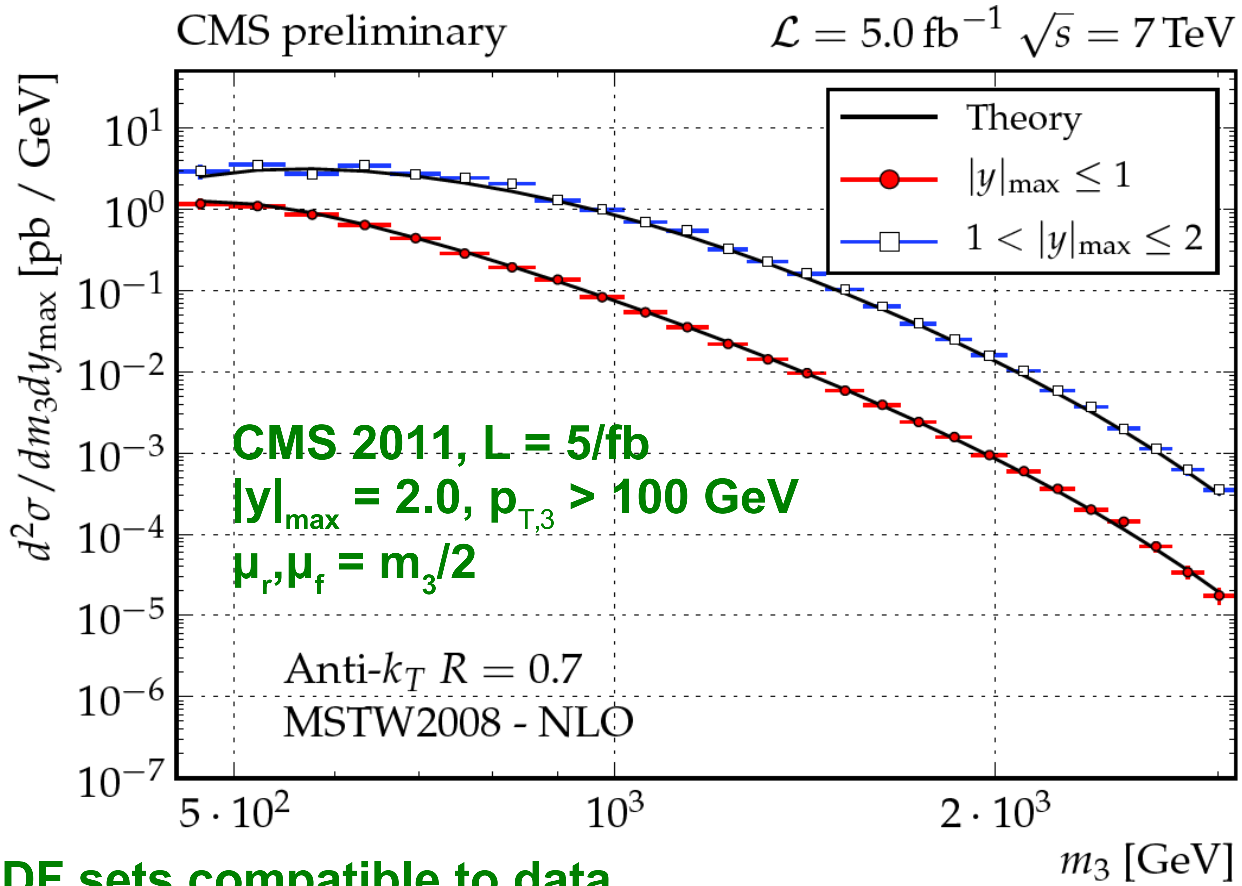
At the LHC up to now mostly concentrating on 1.

For 2. might want to stay at the minimum of the JEC uncertainty: 200 – 500 GeV!

α_s from 3-Jet Mass Cross Section

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





Most PDF sets compatible to data

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

Extraction of $\alpha_s(M_Z)$ from scales up to 1.4 TeV

Dominated by theory uncertainty! NLO only

$$\alpha_S(M_Z) = 0.1160^{+0.0025}_{-0.0023}(\text{exp}, \text{PDF}, \text{NP})^{+0.0068}_{-0.0021}(\text{scale})$$

CMS-PAS-SMP-12-027 (2013)

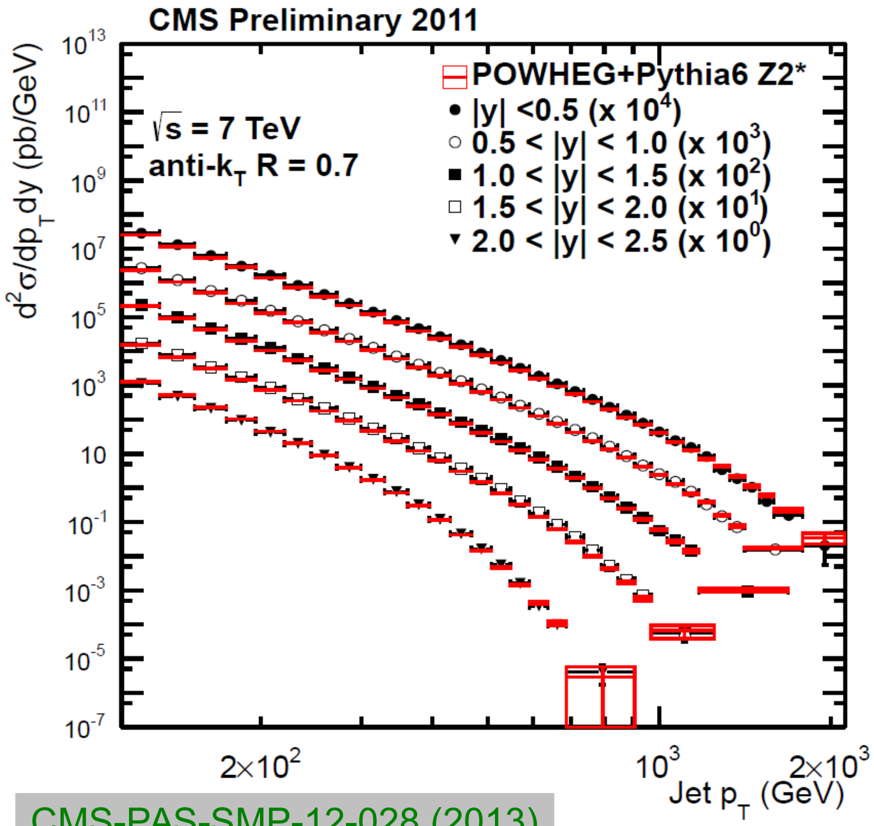
α_s from inclusive Jet Cross Section

Re-analysis of 2011 data at 7 TeV published in CMS, PRD 87, 112002 (2013)
Up to 2 TeV in jet p_T and 2.5 in rapidity |y|

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

→ **Modified correlations in JEC versus |y| (new recommendation!)**
→ **Include NLO+matchedPS MC (POWHEG+PYTHIA6) in estimation of NP effects**
→ **Include electroweak corrections thanks to Dittmaier/Huss/Speckner** JHEP 2011, 095 (2012)

anti-kT, R=0.7, 7 TeV, 2011
POWHEG+PYTHIA6 Z2*



CMS-PAS-SMP-12-028 (2013)

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019\,(\text{exp}) \pm 0.0028\,(\text{PDF}) \pm 0.0004\,(\text{NP}) \pm^{0.0055}_{0.0022}\,(\text{scale})$$

NLO

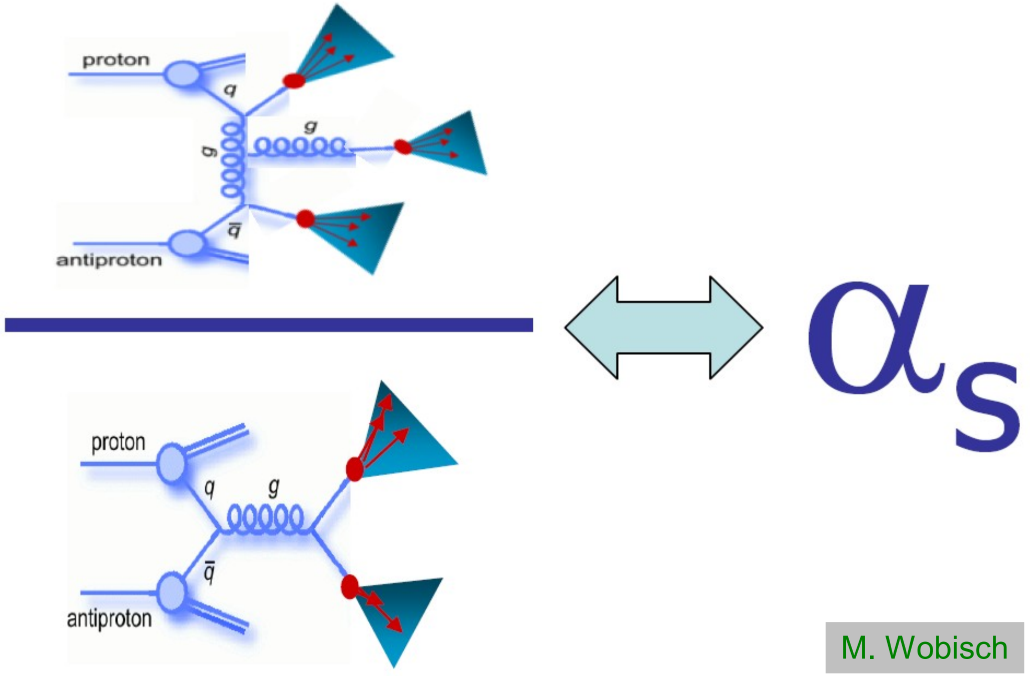
$\|y\|$ range	No. of data points	$\alpha_S(M_Z)$	χ^2/n_{dof}
$\|y\| < 0.5$	33	$0.1187 \pm 0.0024(\text{exp}) \pm 0.0029(\text{PDF}) \pm 0.0008(\text{NP})^{+0.0047}_{-0.0024}(\text{scale})$	16.5/32
$0.5 < \|y\| < 1.0$	30	$0.1181 \pm 0.0024(\text{exp}) \pm 0.0029(\text{PDF}) \pm 0.0008(\text{NP})^{+0.0052}_{-0.0023}(\text{scale})$	25.3/29
$1.0 < \|y\| < 1.5$	27	$0.1165 \pm 0.0027(\text{exp}) \pm 0.0024(\text{PDF}) \pm 0.0008(\text{NP})^{+0.0043}_{-0.0019}(\text{scale})$	9.6/26
$1.5 < \|y\| < 2.0$	24	$0.1146 \pm 0.0035(\text{exp}) \pm 0.0030(\text{PDF}) \pm 0.0013(\text{NP})^{+0.0038}_{-0.0020}(\text{scale})$	20.3/23
$2.0 < \|y\| < 2.5$	19	$0.1161 \pm 0.0046(\text{exp}) \pm 0.0053(\text{PDF}) \pm 0.0015(\text{NP})^{+0.0035}_{-0.0031}(\text{scale})$	12.8/18
$\|y\| < 2.5$	133	$0.1185 \pm 0.0019(\text{exp}) \pm 0.0028(\text{PDF}) \pm 0.0004(\text{NP})^{+0.0055}_{-0.0022}(\text{scale})$	104.6/132

2012 8 TeV data in progress

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!
- Avoid direct dependence on PDFs and the RGE
- Reduce exp. and scale uncertainties
- Eliminate luminosity dependence



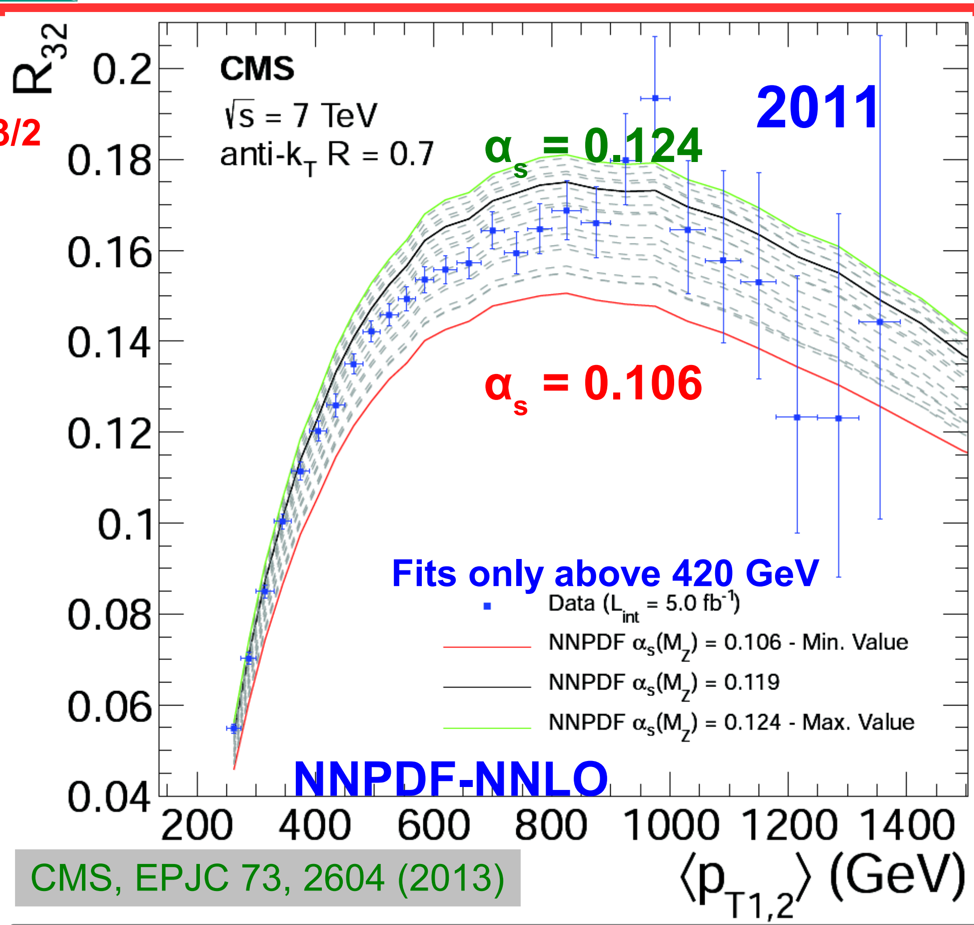
Three observables investigated:

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

α_s from 3- to 2-Jet Event Ratio



CMS, EPJC 73, 2604 (2013)

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

Dominated by theory uncertainty (NLO)!

Similarly described by CT10 or MSTW2008
Discrepancies observed with ABM11

$\mu_r / \langle p_{T1,2} \rangle$	$\mu_f / \langle p_{T1,2} \rangle$	$\alpha_S(M_Z) \pm$ (exp.)	χ^2 / N_{dof}
1	1	0.1148 ± 0.0014	22.0/20
1/2	1/2	0.1198 ± 0.0021	30.6/20
1/2	1	0.1149 ± 0.0014	22.2/20
1	1/2	0.1149 ± 0.0014	22.2/20
1	2	0.1150 ± 0.0015	21.9/20
2	1	0.1159 ± 0.0014	20.7/20
2	2	0.1172 ± 0.0018	21.3/20

Scale Variation

$\langle p_{T1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2 / N_{dof}
420–600	474	0.1147 ± 0.0061	0.0936 ± 0.0041	6	4.4/5
600–800	664	0.1132 ± 0.0050	0.0894 ± 0.0031	5	5.9/4
800–1390	896	0.1170 ± 0.0058	0.0889 ± 0.0034	10	5.7/9

Combined Fits: α_s & $g(x,\mu_f^2)$

Of course, jet cross sections do not depend on α_s alone!

In particular, in inclusive jets α_s and the gluon PDF are correlated.

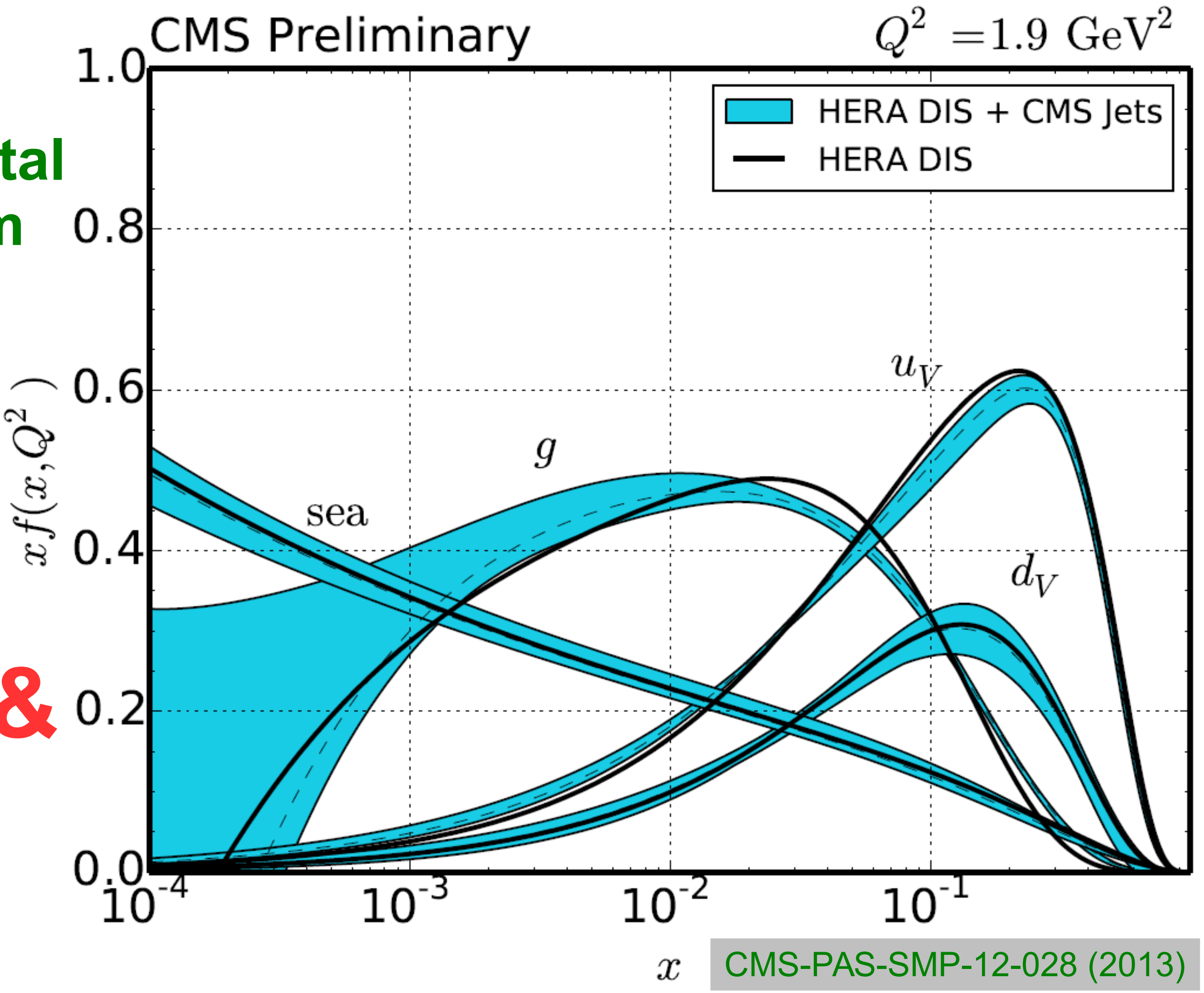
Sufficient amounts of data in channels sensitive in different ways to fundamental parameters allow to perform simultaneous fits!

Example:

Combined fit of α_s & $g(x,\mu_f^2)$ with HERA I DIS + CMS jets in HERAFitter framework

$$\alpha_s(M_Z) = 0.1192^{+0.0017}_{-0.0015} \quad (\text{exp\&NP})$$

&



CMS-PAS-SMP-12-028 (2013)

Issue: How to deal with corr. systematic uncertainties, e.g. scales ?

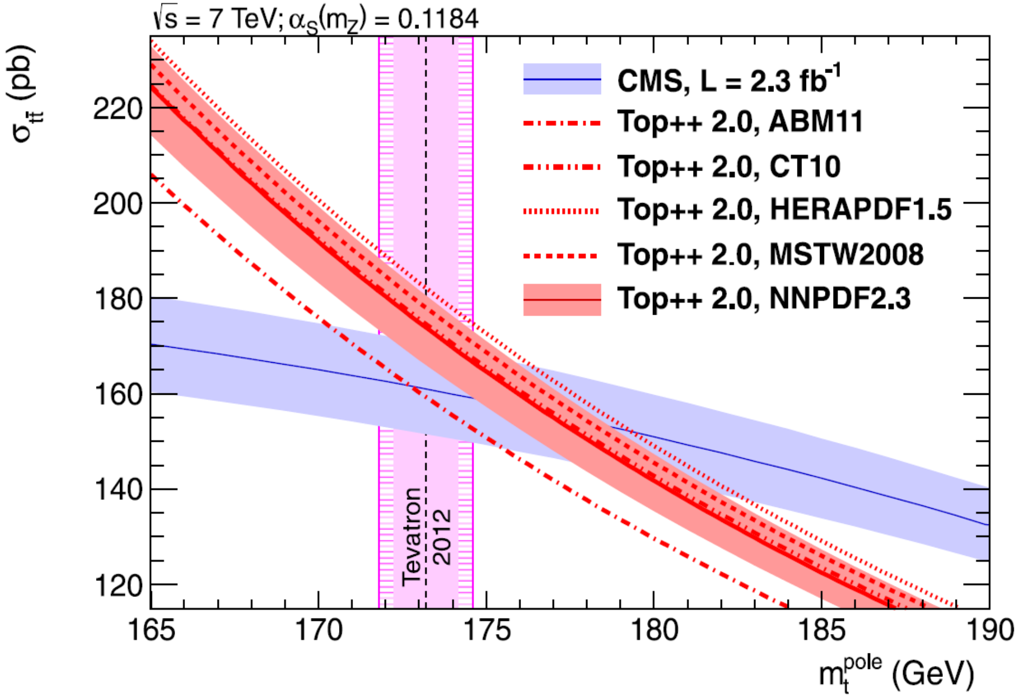
Fits with top-pair Production

Top-pair production is especially sensitive to:

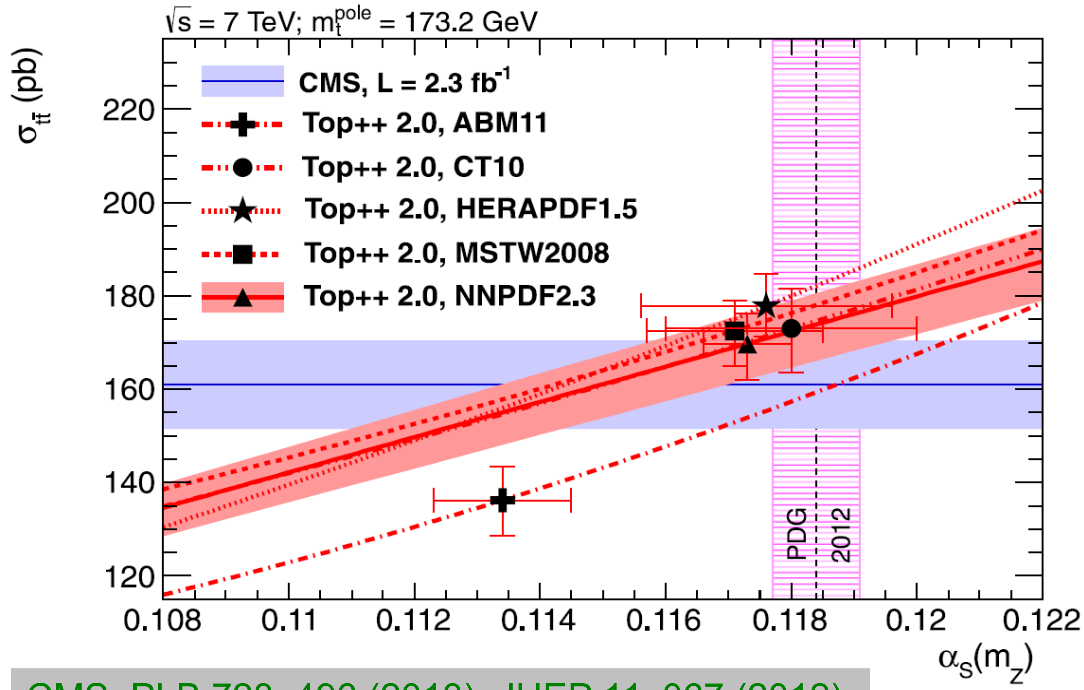
m_t^{pole} and α_s and $g(x,\mu_f^2)$ as the main production process at LHC is from gg

Using only the ttbar cross section measurement (dilepton channel) combined fits are not possible. Fixing the gluon to one of 5 PDF sets, however, it is possible to extract m_t^{pole} while fixing α_s or vice versa.

Fix α_s → constrain m_t^{pole}



Fix m_t^{pole} → constrain α_s



CMS, PLB 728, 496 (2013), JHEP 11, 067 (2012).

Fits with top-pair Production

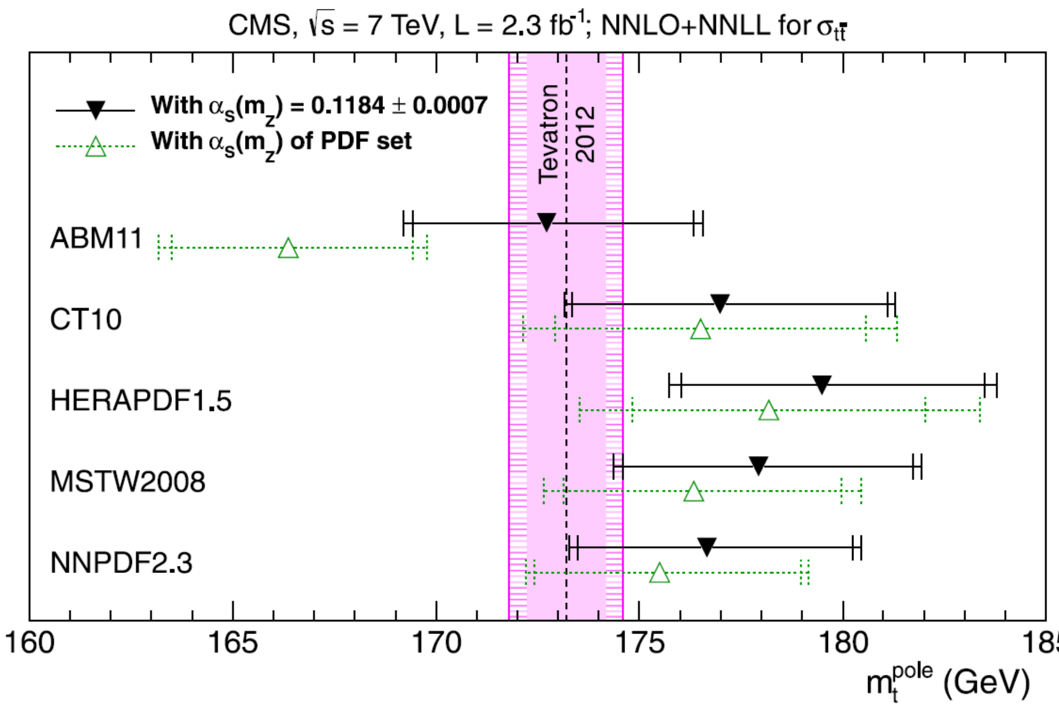
Scale uncertainty is small since NNLO+NNLL!

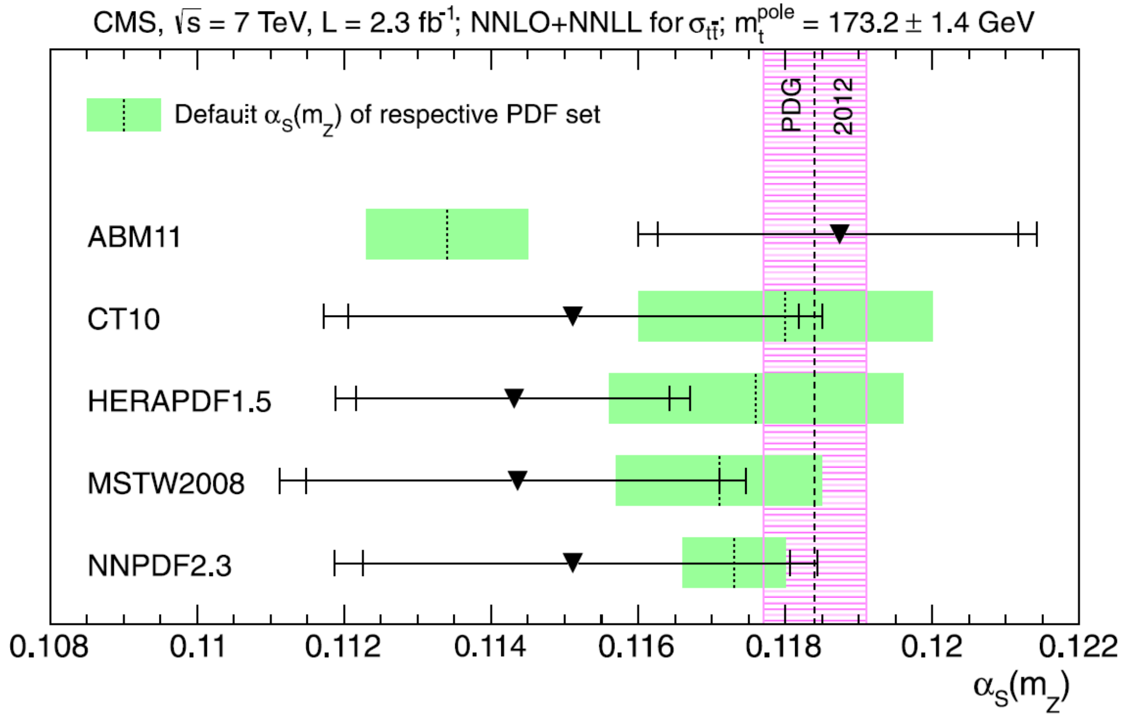
But: Additional uncertainties from m_t^{pole} and the precision of the LHC center-of-mass energy E_{LHC}!

$$\alpha_s(M_Z) = 0.1151 \pm 0.0013\,(m_t^{pole}) \pm 0.0025\,(\mathrm{exp}) \pm 0.0008\,(E_{LHC}) {}^{+0.0013}_{-0.0011}\,(\mathrm{PDF}) {}^{+0.0009}_{-0.0008}\,(\mathrm{scale})$$

NNPDF2.3

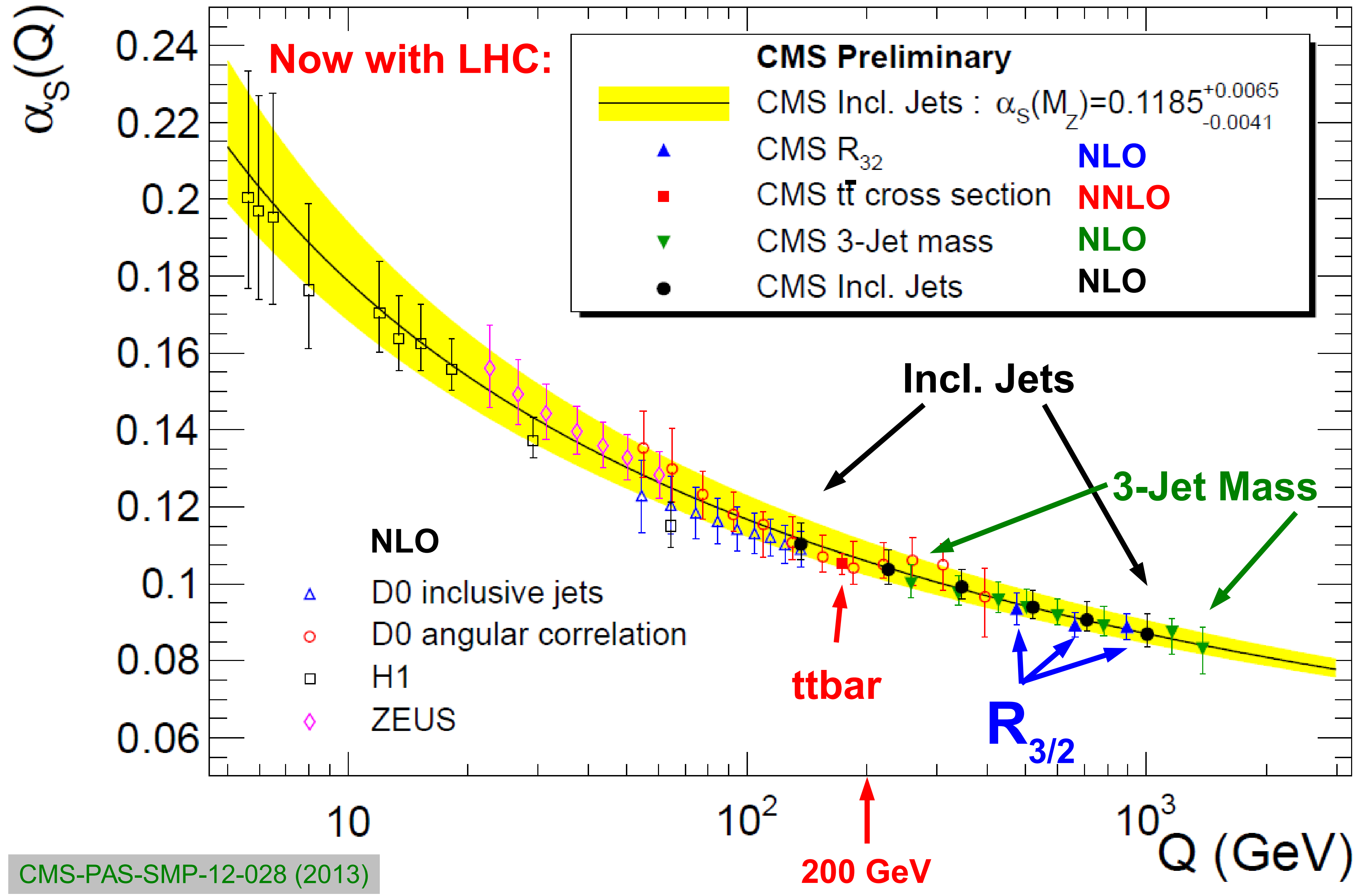
Theory at NNLO + NNLL





CMS, PLB 728, 496 (2013)

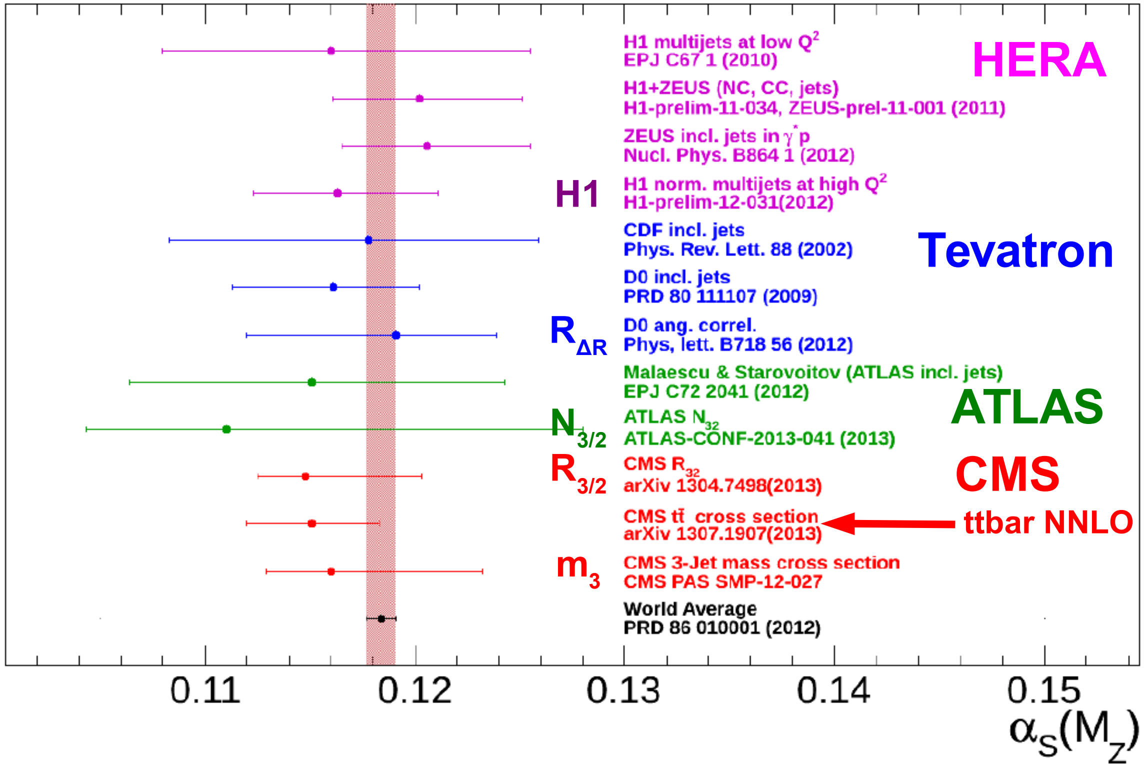
Determinations of α_s



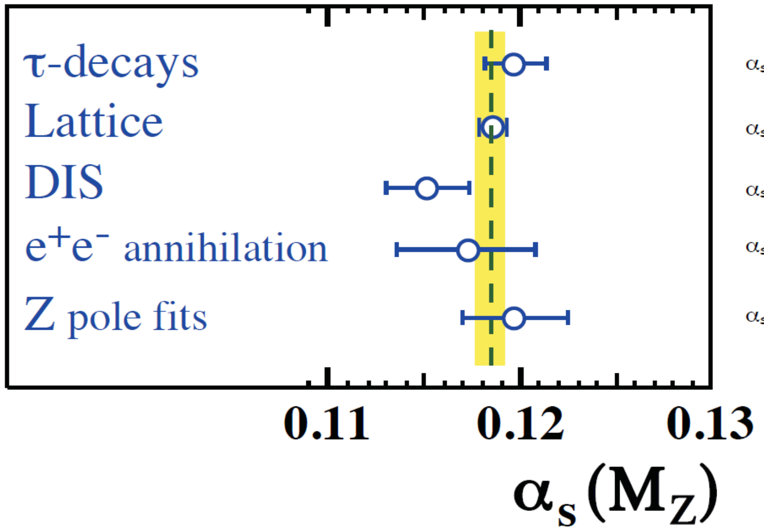
CMS-PAS-SMP-12-028 (2013)

α_s Summary

P. Kokkas, EPSHEP 2013: **NLO**



S. Bethke, 2012: **NNLO**



$\alpha_s(M_Z)$= 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

With recent jet data from hadron colliders can measure up to 2 TeV!

Uncertainties dominated by theory →
- **need jets at NNLO for inclusion into world summary**
- **→ inclusive jets in progress by Gehrmann-de Ridder et al.**
- **and electroweak corrections**
- **→ done by Dittmaier et al.**

Summary

- LHC at 7 TeV and 8 TeV enables measurements up to scales of 2 TeV
- 13 TeV data yet to come
- Good data quality and detector understanding make measurements PRECISION PHYSICS
- Theory at NLO is minimum
- NNLO is a must (plus additional electroweak contributions ...)
- Typical uncertainties on $\alpha_s(M_Z)$:
  - Experimental: ~ 1 – 2 %
  - PDF: ~ 1 – 2 %
  - Scale: 4 – 5 %
  - Nonpert. Effects: < 1 %
  - Other theory uncertainties ?

Points for Discussion

<u>From an experimentalists point of view:</u>

- **What is a "good" choice as process scale Q ?**
- **How to best deal with multiple scales, e.g. p_{T3} and $p_{T1,2}$ in 3-jet production ?**
- **How to derive uncertainties on α_s in combined fits with gluon, in particular scale uncertainties ?**
- **How to deal with top quark as 6^{th} flavour in matrix elements, PDF, or α_s evolution ?**
- **Are there sizable photonic corrections ?**
- **What other theoretical issues might arise with increasing scales and/or precision ?**

Backup Slides

Table of considered PDF sets

Base set	Refs.	Evol.	N_f	M_t (GeV)	M_Z (GeV)	$\alpha_S(M_Z)$	$\alpha_S(M_Z)$ range
ABM11	[13]	NLO	5	180.	91.174	0.1180	0.110–0.130
ABM11	[13]	NNLO	5	180.	91.174	0.1134	0.104–0.120
CT10	[14]	NLO	≤ 5	172.	91.188	0.1180	0.112–0.127
CT10	[14]	NNLO	≤ 5	172.	91.188	0.1180	0.110–0.130
HERAPDF15	[15]	NLO	≤ 5	180.	91.187	0.1176	0.114–0.122
HERAPDF15	[15]	NNLO	≤ 5	180.	91.187	0.1176	0.114–0.122
MSTW2008	[16, 17]	NLO	≤ 5	10^{10}	91.1876	0.1202	0.110–0.130
MSTW2008	[16, 17]	NNLO	≤ 5	10^{10}	91.1876	0.1171	0.107–0.127
NNPDF21	[18]	NLO	≤ 6	175.	91.2	0.1190	0.114–0.124
NNPDF21	[18]	NNLO	≤ 6	175.	91.2	0.1190	0.114–0.124

CMS-PAS-SMP-12-028 (2013)

α_s from inclusive Jets

Other PDF sets

PDF set	$\alpha_S(M_Z)$	χ^2/n_{dof}
CT10-NLO	$0.1185 \pm 0.0019(\mathrm{exp}) \pm 0.0028(\mathrm{PDF}) \pm 0.0004(\mathrm{NP})^{+0.0055}_{-0.0022}(\mathrm{scale})$	104.6/132
MSTW2008-NLO	$0.1157 \pm 0.0012(\mathrm{exp}) \pm 0.0013(\mathrm{PDF}) \pm 0.0001(\mathrm{NP})^{+0.0029}_{-0.0028}(\mathrm{scale})$	108.3/132
CT10-NNLO	$0.1170 \pm 0.0012(\mathrm{exp}) \pm 0.0024(\mathrm{PDF}) \pm 0.0004(\mathrm{NP})^{+0.0046}_{-0.0027}(\mathrm{scale})$	106.1/132
NNPDF2.1-NNLO	$0.1173 \pm 0.0012(\mathrm{exp}) \pm 0.0018(\mathrm{PDF}) \pm 0.0001(\mathrm{NP})^{+0.0020}_{-0.0018}(\mathrm{scale})$	104.1/132
MSTW2008-NNLO	$0.1133 \pm 0.0010(\mathrm{exp}) \pm 0.0011(\mathrm{PDF}) \pm 0.0001(\mathrm{NP})^{+0.0020}_{-0.0021}(\mathrm{scale})$	107.6/132

Q dependence

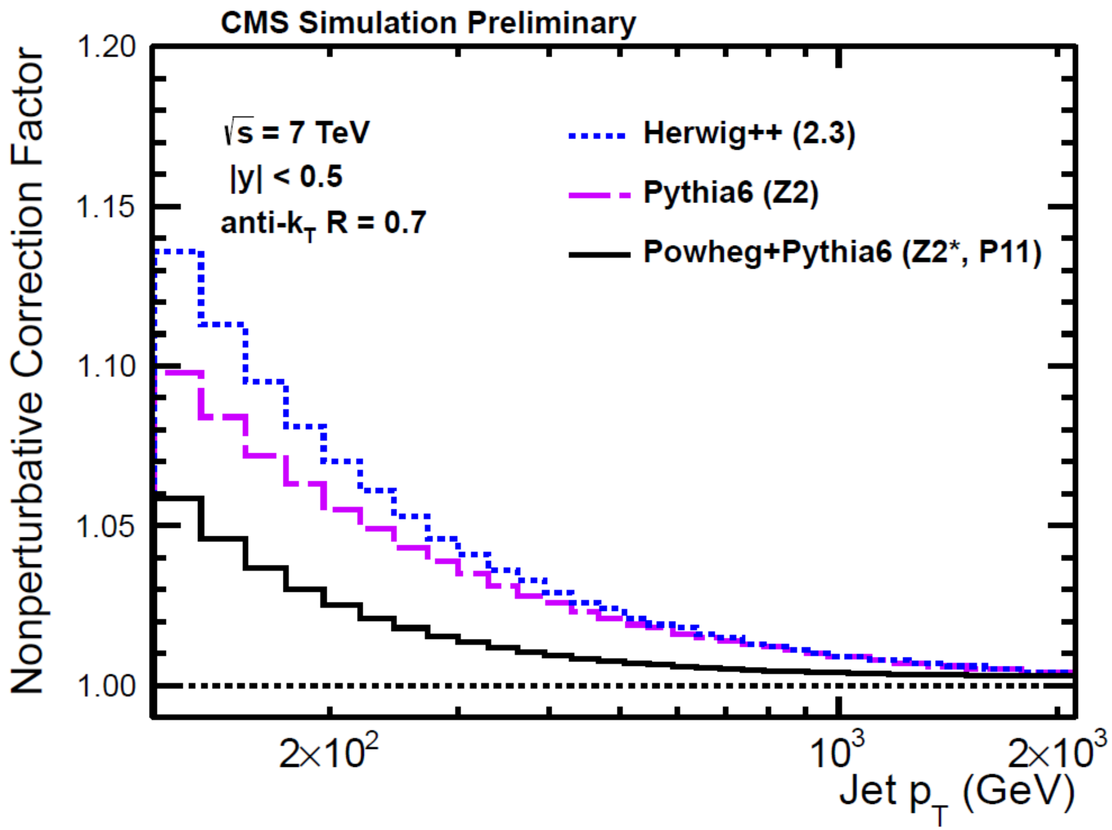
p_T range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/n_{dof}
114–196	136	$0.1170^{+0.0062}_{-0.0045}$	$0.1103^{+0.0054}_{-0.0039}$	20	6.2/19
196–300	226	$0.1179^{+0.0067}_{-0.0049}$	$0.1037^{+0.0052}_{-0.0037}$	20	7.6/19
300–468	345	$0.1194^{+0.0067}_{-0.0049}$	$0.0993^{+0.0045}_{-0.0033}$	25	8.2/24
468–638	521	$0.1188^{+0.0072}_{-0.0051}$	$0.0940^{+0.0044}_{-0.0032}$	20	10.6/19
638–905	711	$0.1193^{+0.0080}_{-0.0056}$	$0.0910^{+0.0044}_{-0.0033}$	22	11.4/21
905–2116	1007	$0.1180^{+0.0104}_{-0.0061}$	$0.0868^{+0.0054}_{-0.0033}$	26	39.4/25

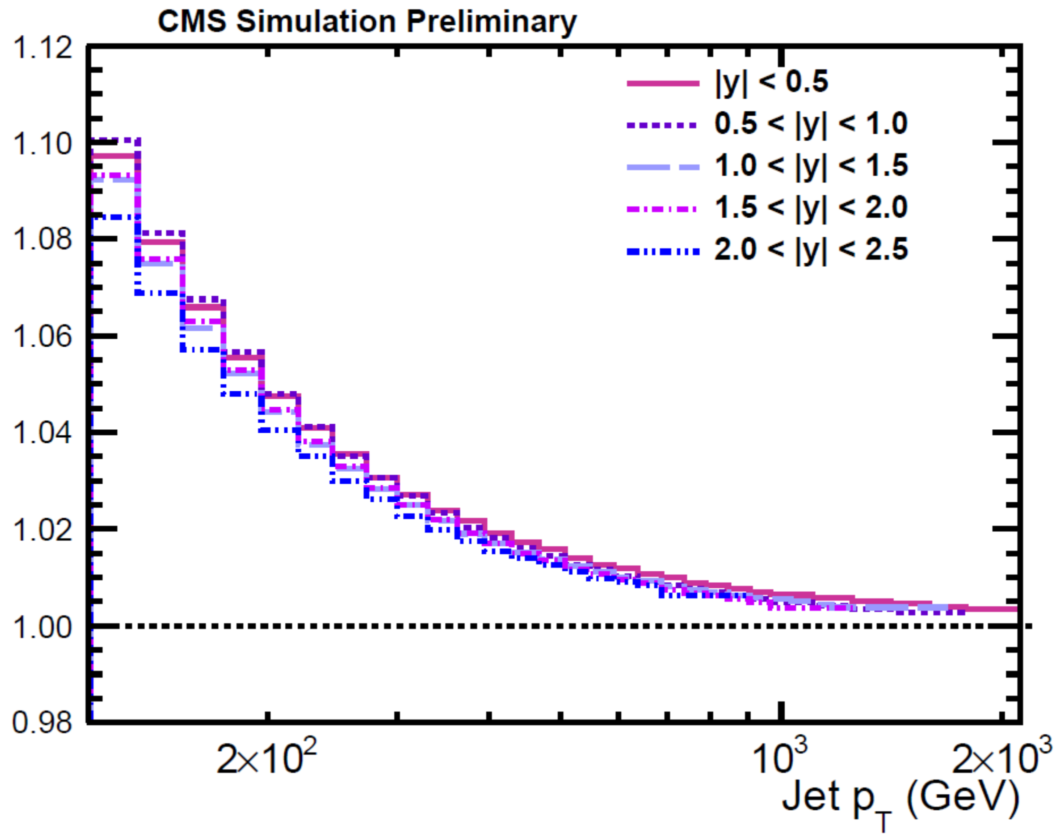
CMS-PAS-SMP-12-028 (2013)

α_s from inclusive Jets

Nonperturbative corrections from Herwig++ 2.3, Pythia 6 Z2 and Powheg+Pythia6 (Z2*,P11) (central rapidity)

Estimated NP corrections from Herwig++ 2.3, Pythia 6 Z2 and Powheg+Pythia6 (Z2*,P11) envelope for all rapidities





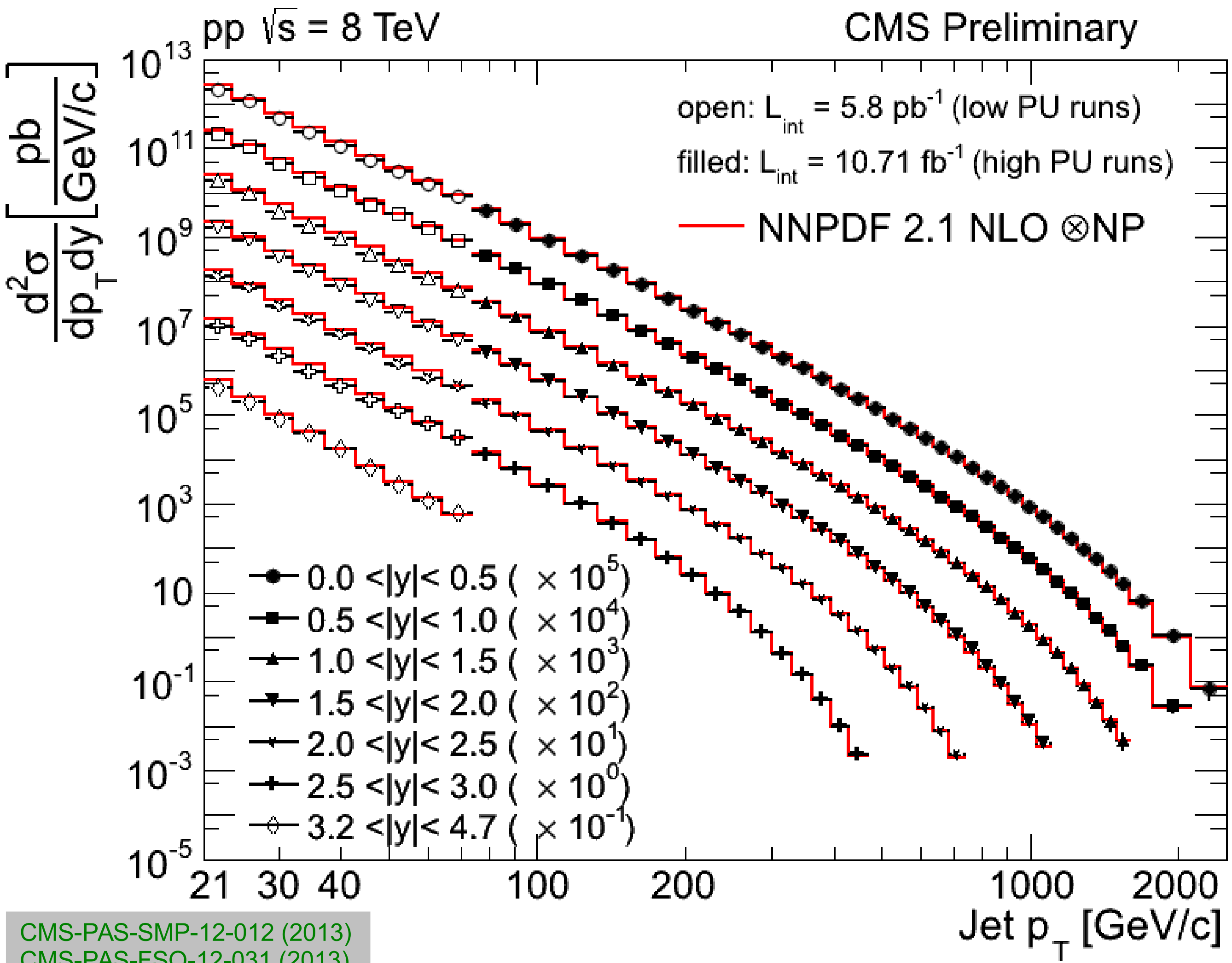
CMS-PAS-SMP-12-028 (2013)

Inclusive Jets at 8 TeV

Agreement with predictions of QCD at NLO over many orders of magnitude in cross section and even beyond 2 TeV in jet p_T and for rapidities |y| up to ~ 5

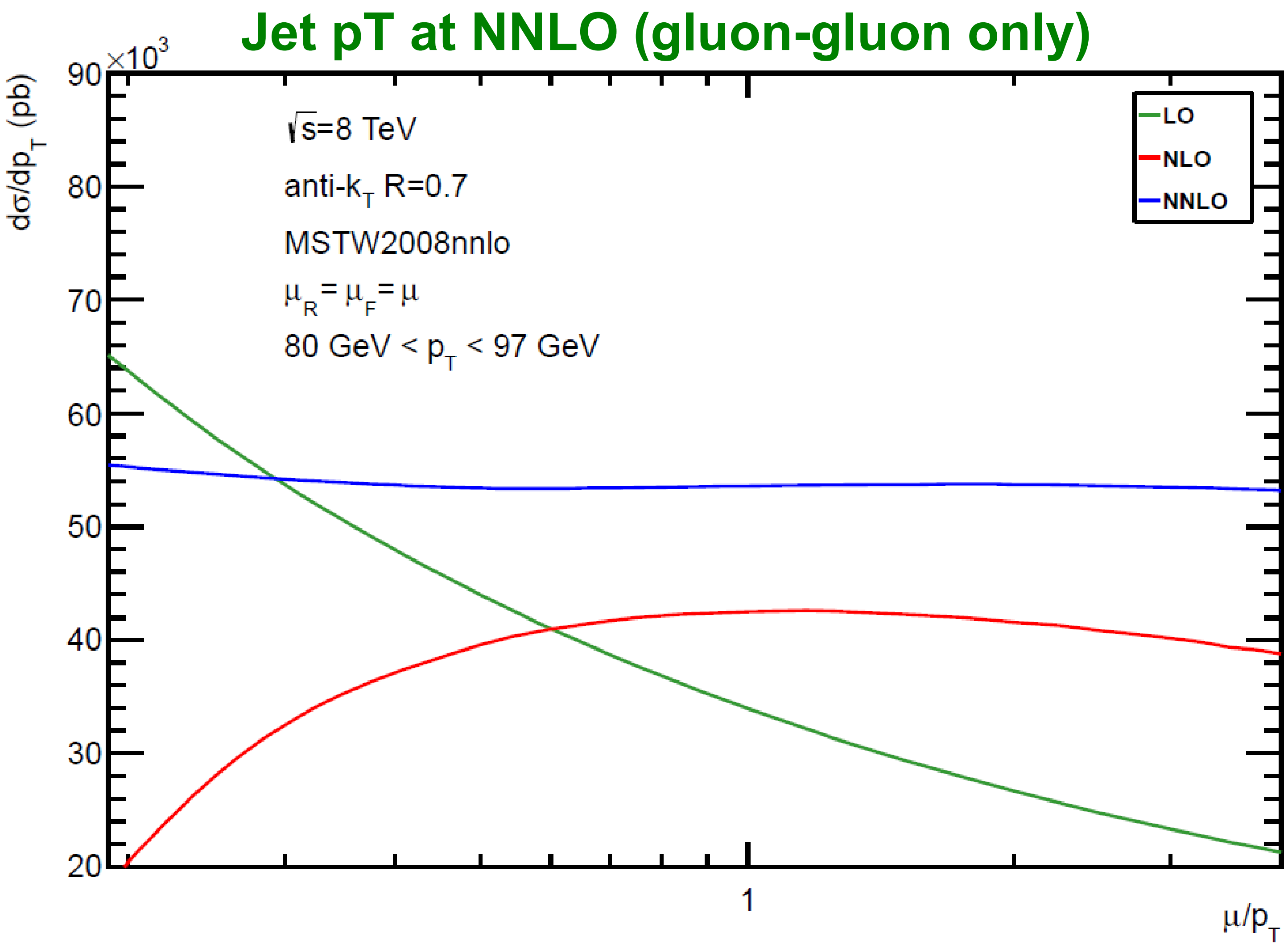
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

2012 8 TeV data in progress



CMS-PAS-SMP-12-012 (2013)
CMS-PAS-FSQ-12-031 (2013).

NNLO Scale Dependence



New

Drastically reduced scale dependence!

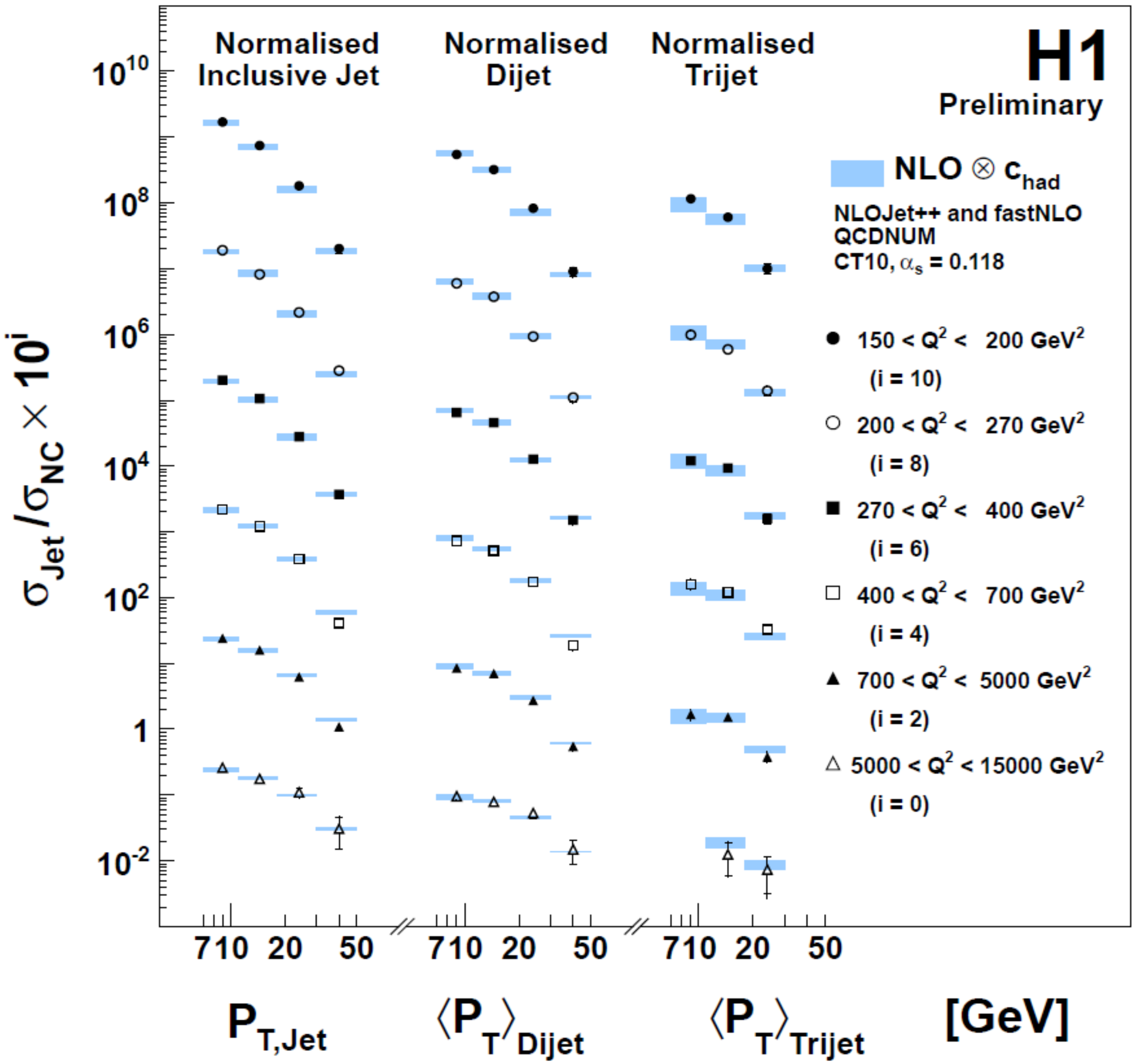
$$|y| < 4.4, \text{ 80 GeV} < p_T < \text{97 GeV}$$

From talk by N. Glover, see also: Gehrmann- de Ridder et al., PRL110 (2013), JHEP1302 (2013).

Normalized Multi-Jets in DIS

$Q^2 = (k-k')^2$

$x := Q^2/(2p\cdot q)$
$= \xi$ (LO)



Jet phase space:

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

$7 < pT < 50$ GeV

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

Scales: $\mu_r^2 = (Q^2+E_T^2)/2$

$\mu_f^2 = Q^2$

Normalization: NC DIS

Normalized Multijet (k < 1.3)

NLO only

$\alpha_s(M_Z) = 0.1163 \pm 0.0011(\text{exp}) \pm 0.0014\ (\text{PDF}) \pm 0.0008\ (\text{had}) \pm 0.0040\ (\text{theo})$

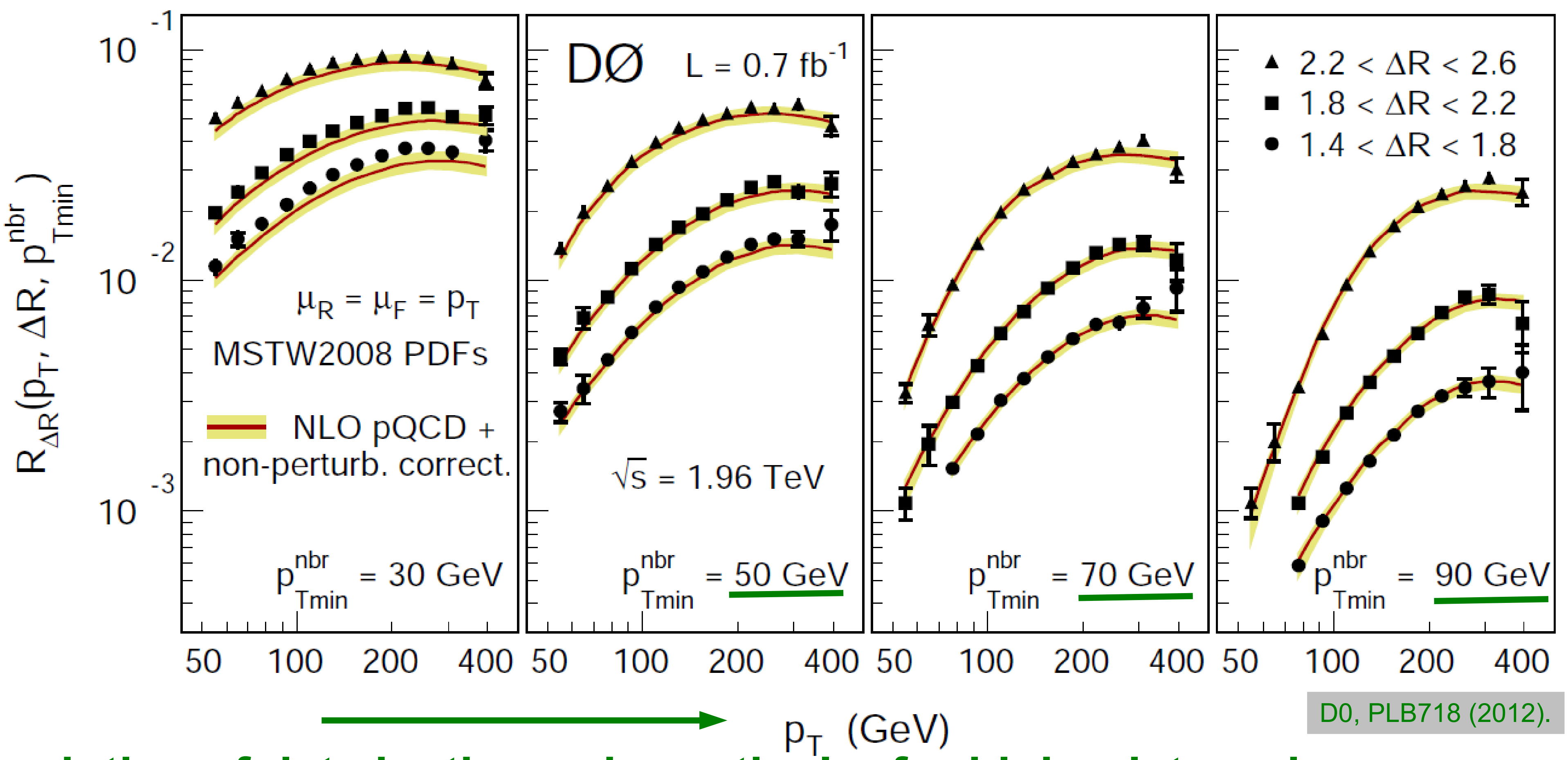
χ^2 / ndf = 53.3 / 41 = 1.30

H1prelim-12-031

Dominated by theory uncertainty!

Jet Angular Correlation

$R_{\Delta R}$



D0, PLB718 (2012).

Good description of data by theory in particular for higher jet $p_T$min

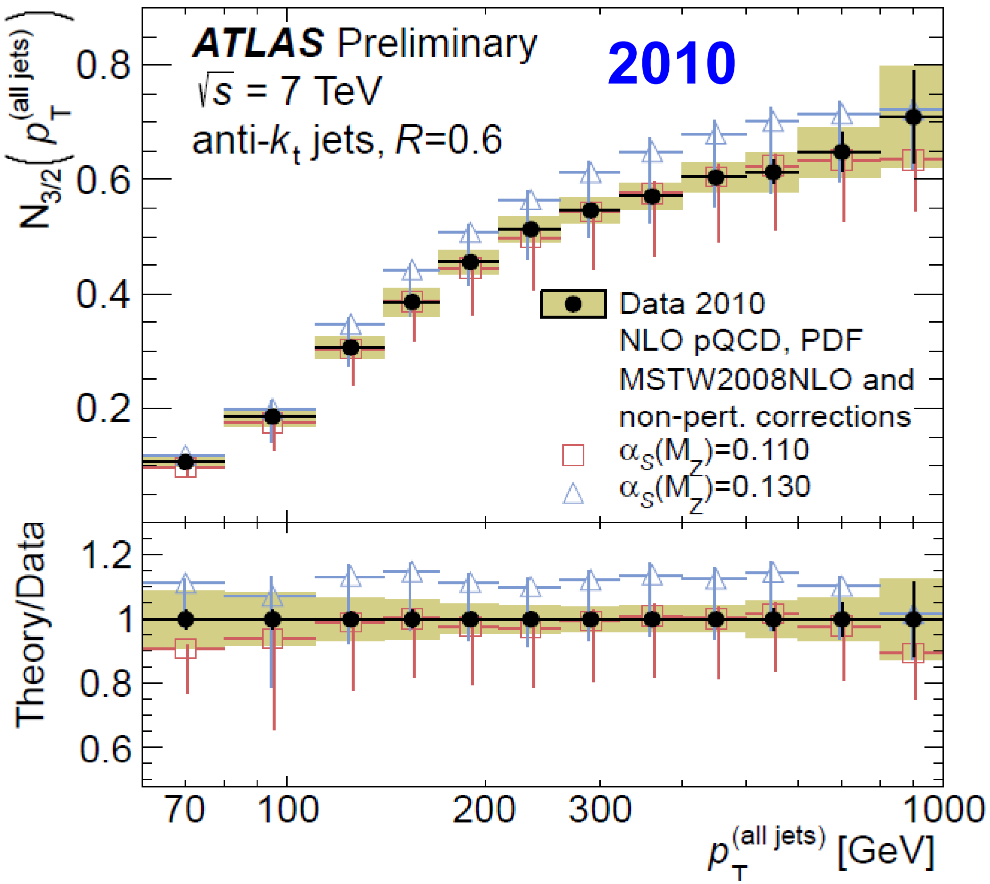
$$\alpha_s(M_Z) = 0.1191^{+0.0048}_{-0.0071}(\text{total})$$

Dominated by theory uncertainty! NLO only

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

3- to 2-Jet Result from ATLAS

$N_{3/2}$



$$\alpha_s(M_Z) = 0.111 \pm 0.006\,(\mathrm{exp})$$

$$\pm^{0.016}_{0.003}\,(\mathrm{theory})$$

Dominated by theory uncertainty!

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