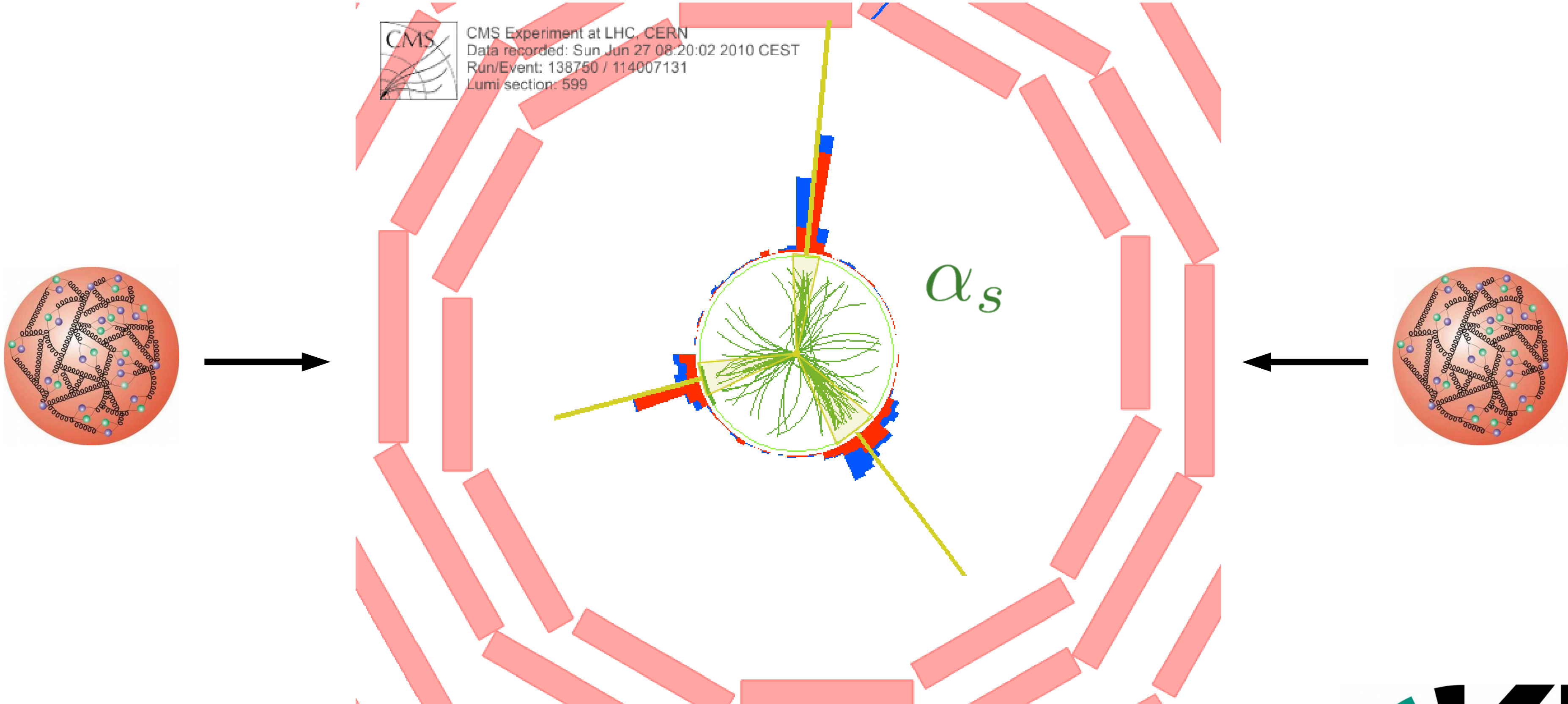
α_s Determinations from CMS
Status & Plans



Klaus Rabbertz, KIT

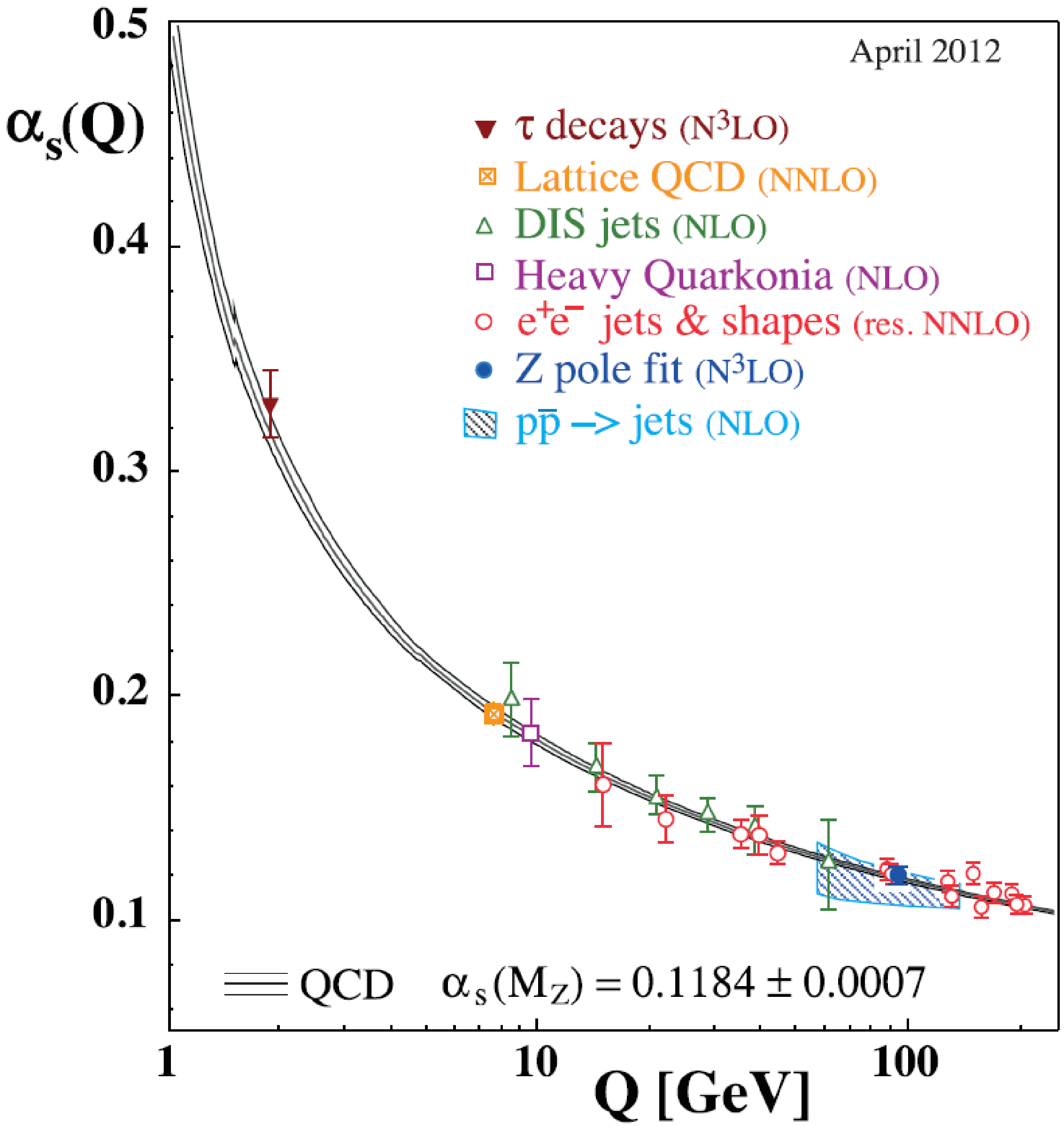
Karlsruhe Institute of Technology

Outline

- Motivation
- Jet Measurements
  - Inclusive Jets
  - Multi-Jets
  - Multi-Jet Ratios
- top-antitop Production
- α_s Summaries
- Perspectives with CMS and Beyond
- Summary

2012: No LHC results yet

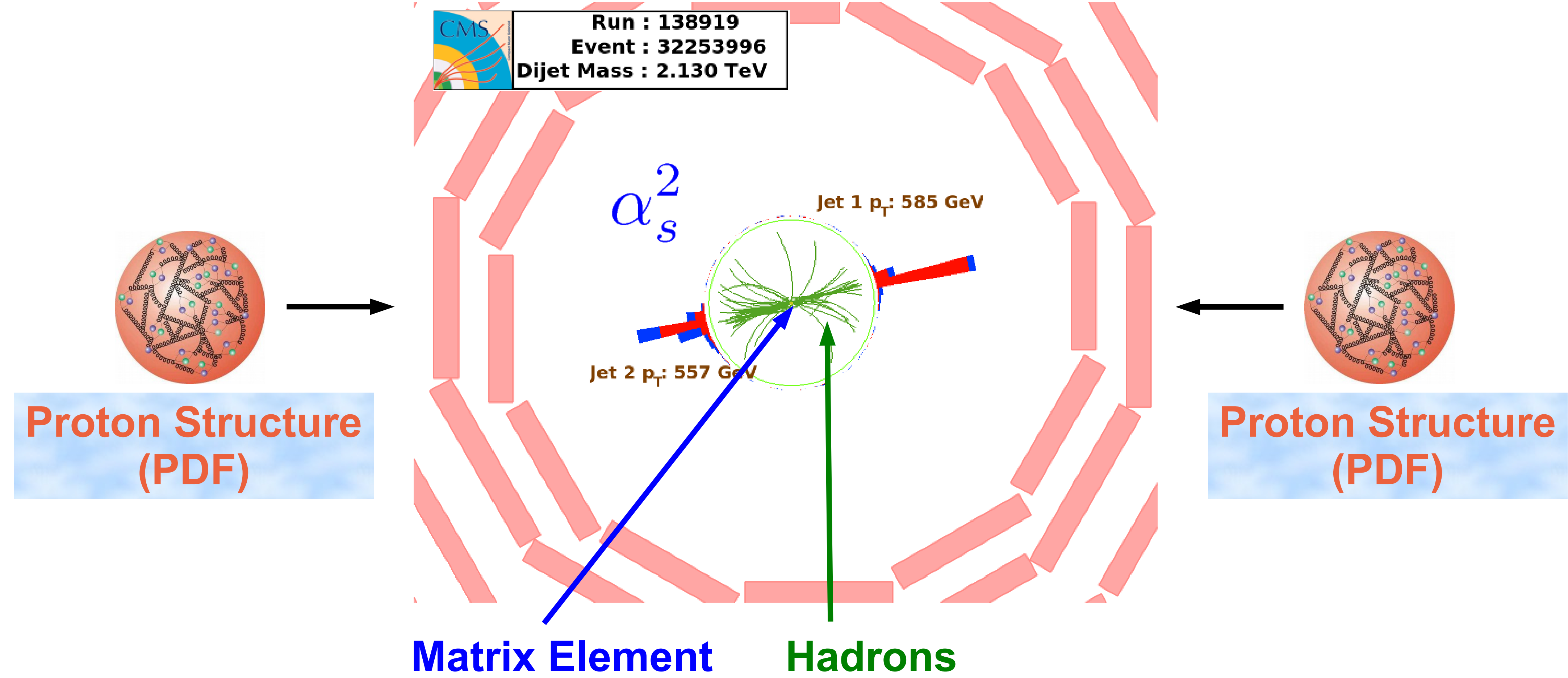
PDG2012



Jets at the LHC

Abandant production of jets:

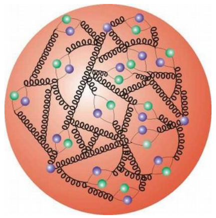
- Jets at hadron colliders provide the highest reach ever to determine the strong coupling constant at high scales Q
- Also learn about hard QCD, the proton structure, non-perturbative effects, and electroweak effects at high Q



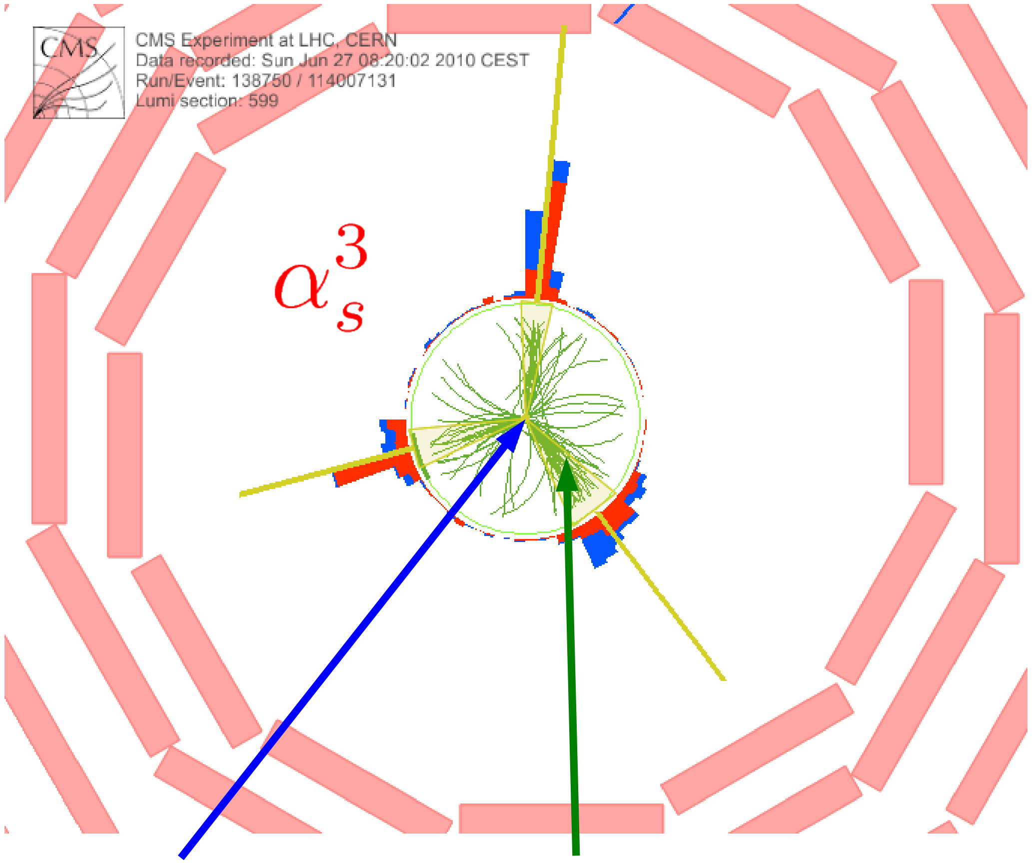
Jets at the LHC

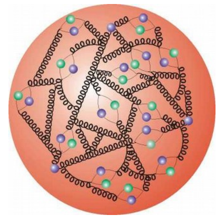
Abundant production of jets:

- Extract $\alpha_s(M_Z)$, the least precisely known fundamental constant!
- No multi-scale problem in this “Mercedes” start event :-)



Proton Structure (PDF)

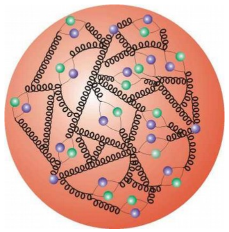


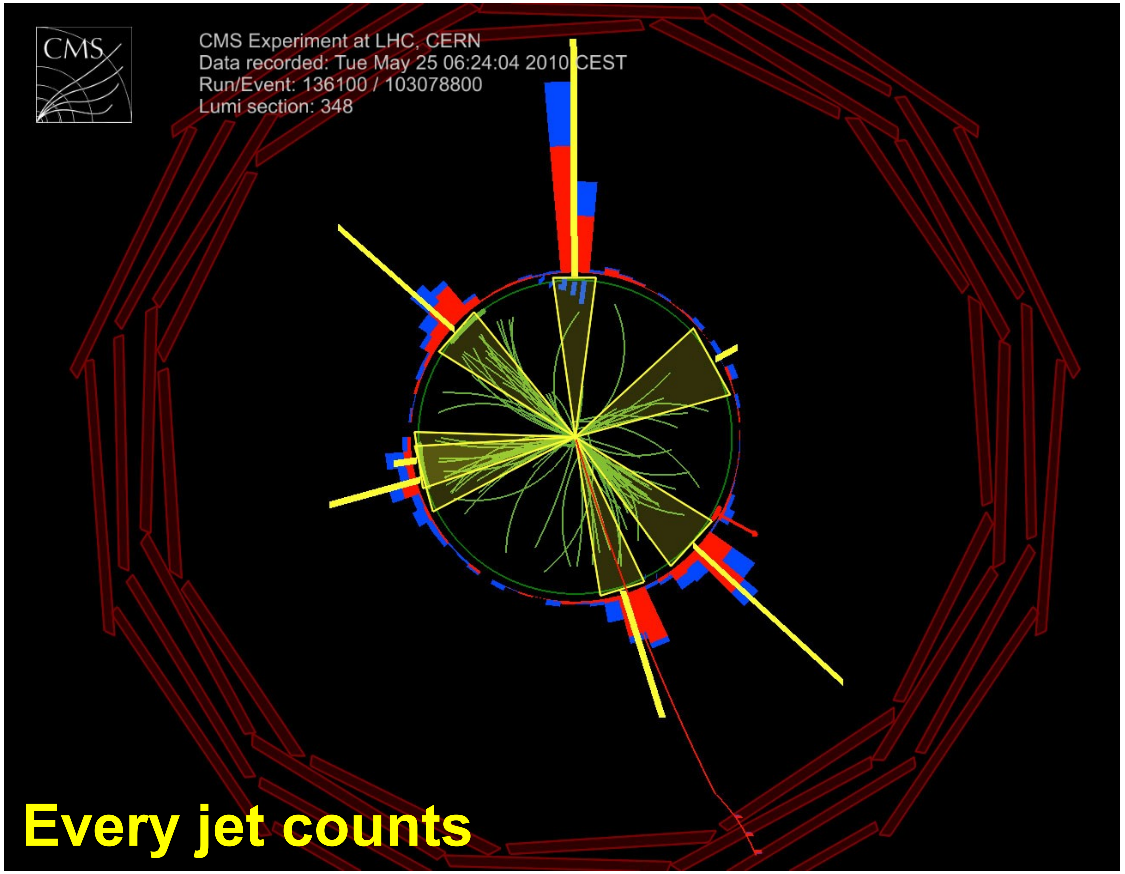


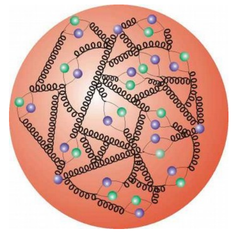
Proton Structure (PDF)

Matrix Element   Hadrons

High transverse Momenta







Inclusive Jets

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

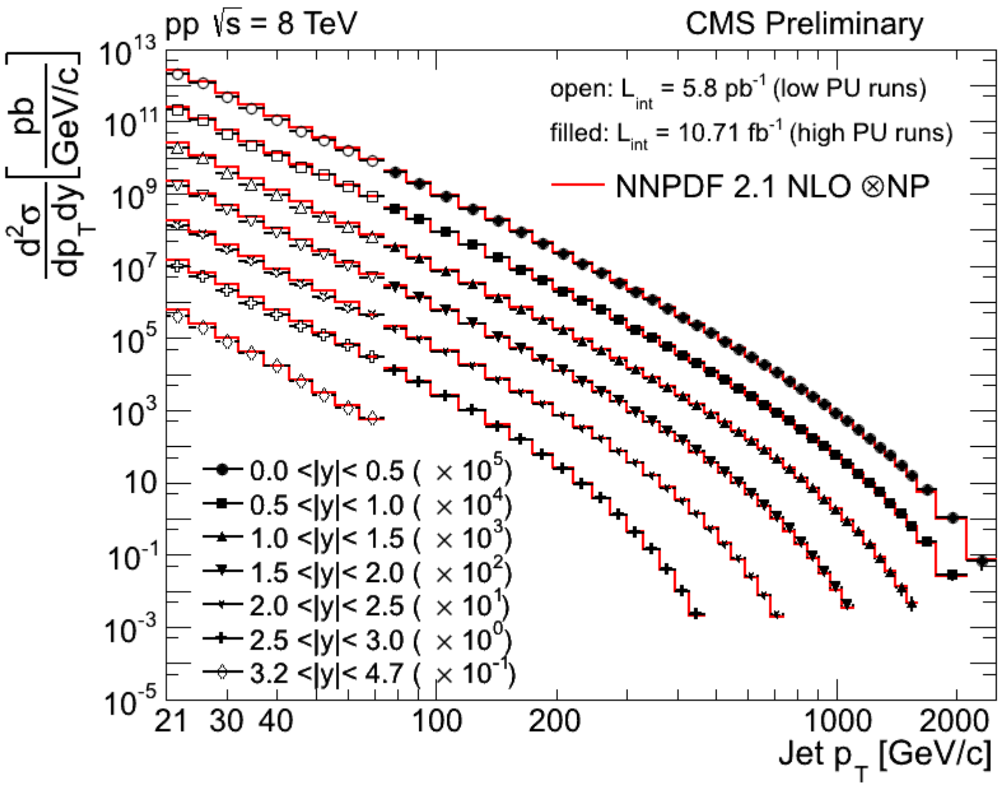
Similar picture at 7 TeV, 8 TeV (left) or NEW 2.76 TeV (right)

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

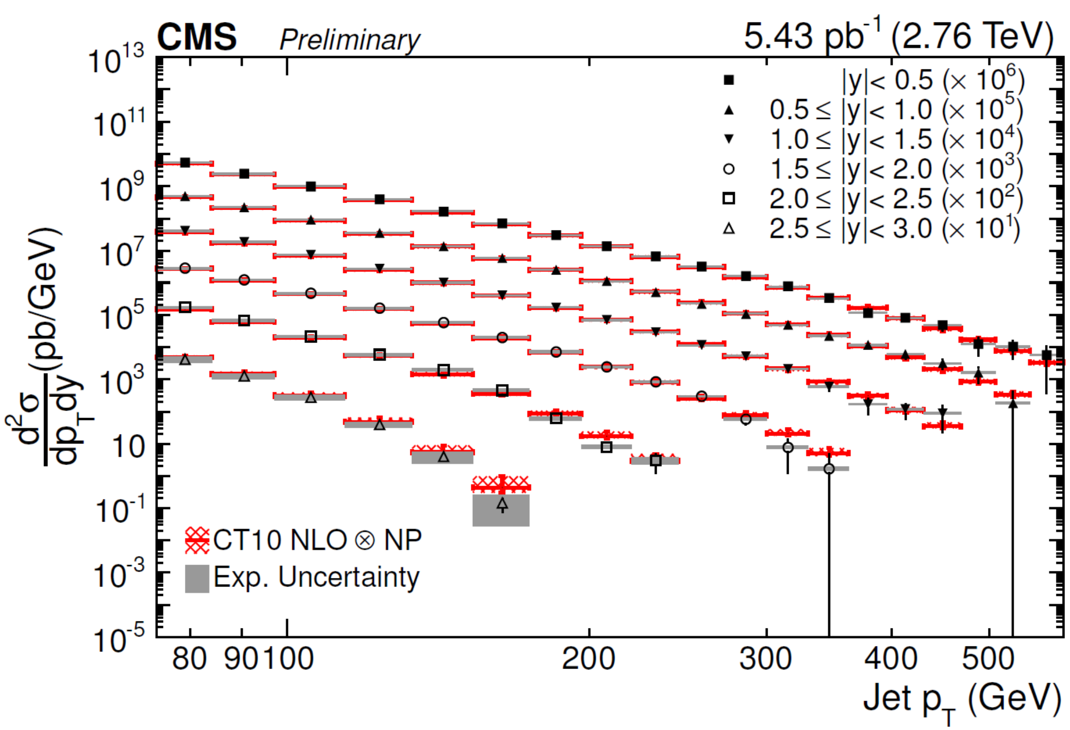
CMS-PAS-SMP-12-012 (2013),
CMS-PAS-FSQ-12-031 (2013),
CMS-PAS-SMP-14-017 (2015).

Data vs. NLO pQCD ⊗non-perturbative corrections

anti-kT, R=0.7, 8 TeV, 2012



anti-kT, R=0.6, 2.76 TeV, 2012



Inclusive Jets + α_s & PDFs

Simultaneous fit of α_s & PDFs possible combining HERA 1 DIS & CMS jet data using HERAFitter Tool

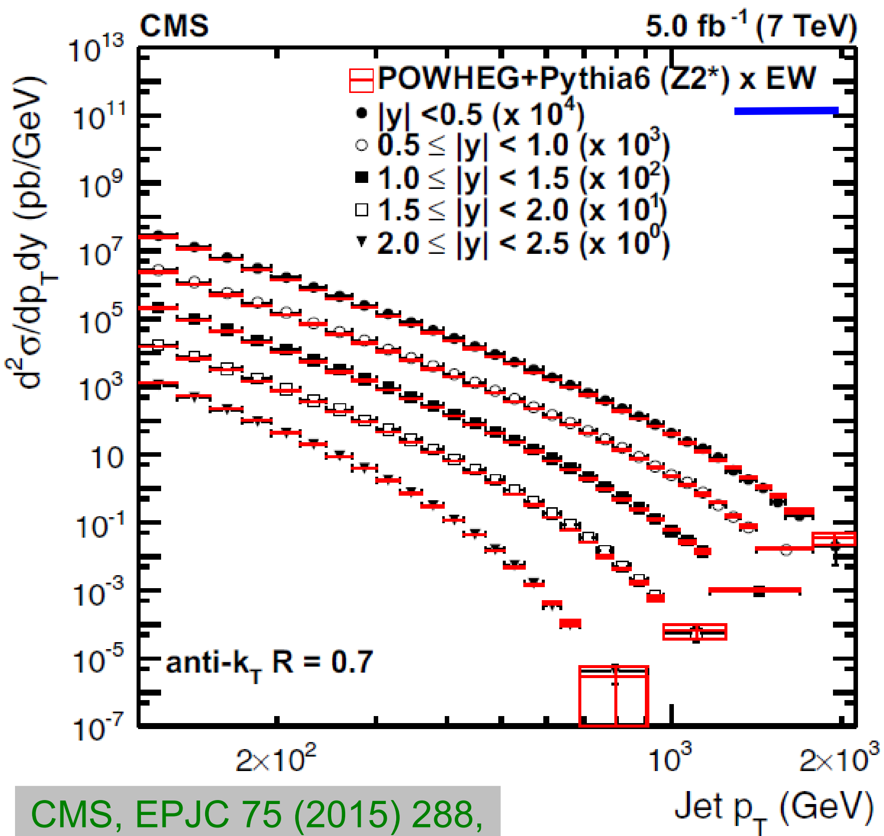
$Q = p_{\mathrm{T,jet}}$

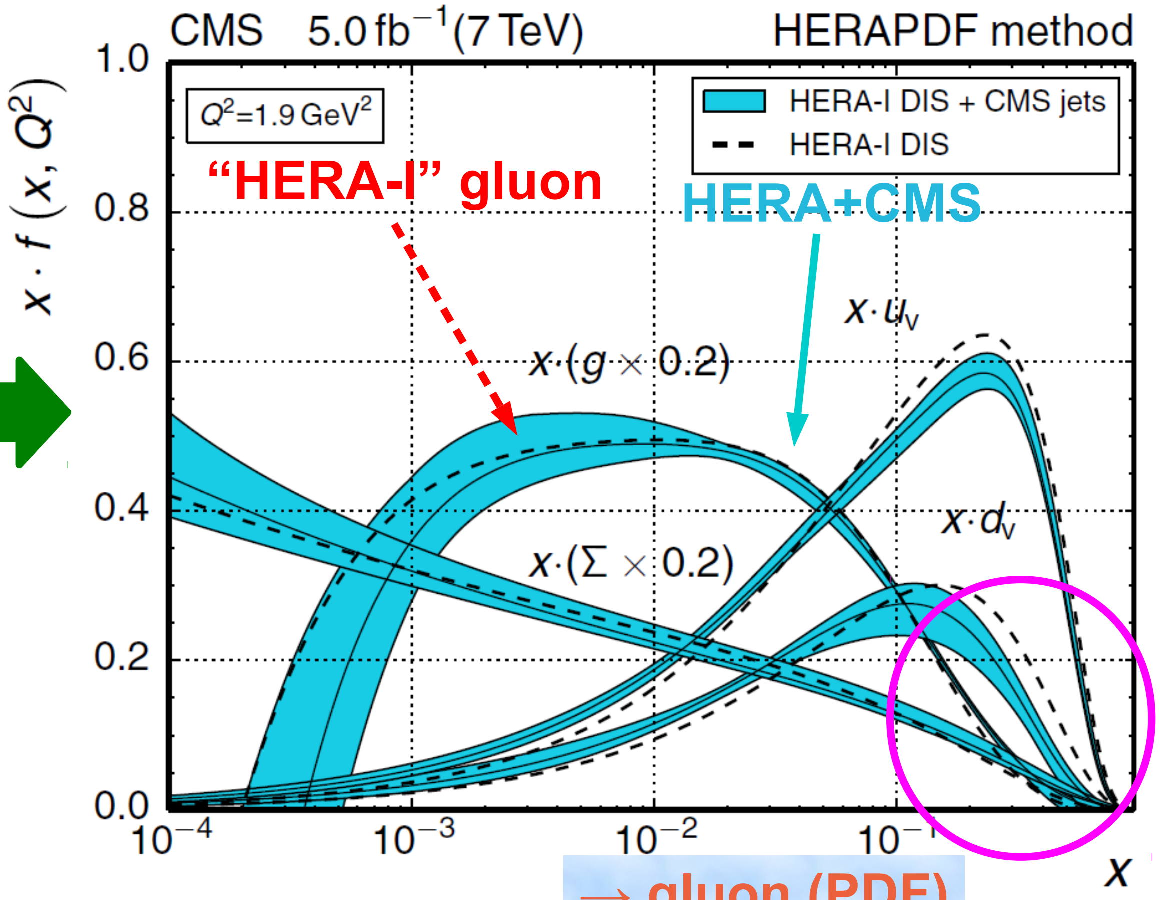
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

Data vs. NLO+PS ⊗ EW corrections
→ impact visible in norm. dijet angular obs.

“Harder” gluon at high x compared to DIS

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





CMS, EPJC 75 (2015) 288,
JHEP 2011, 095 (2012).

→ gluon (PDF)

Inclusive Jets + α_s & PDFs

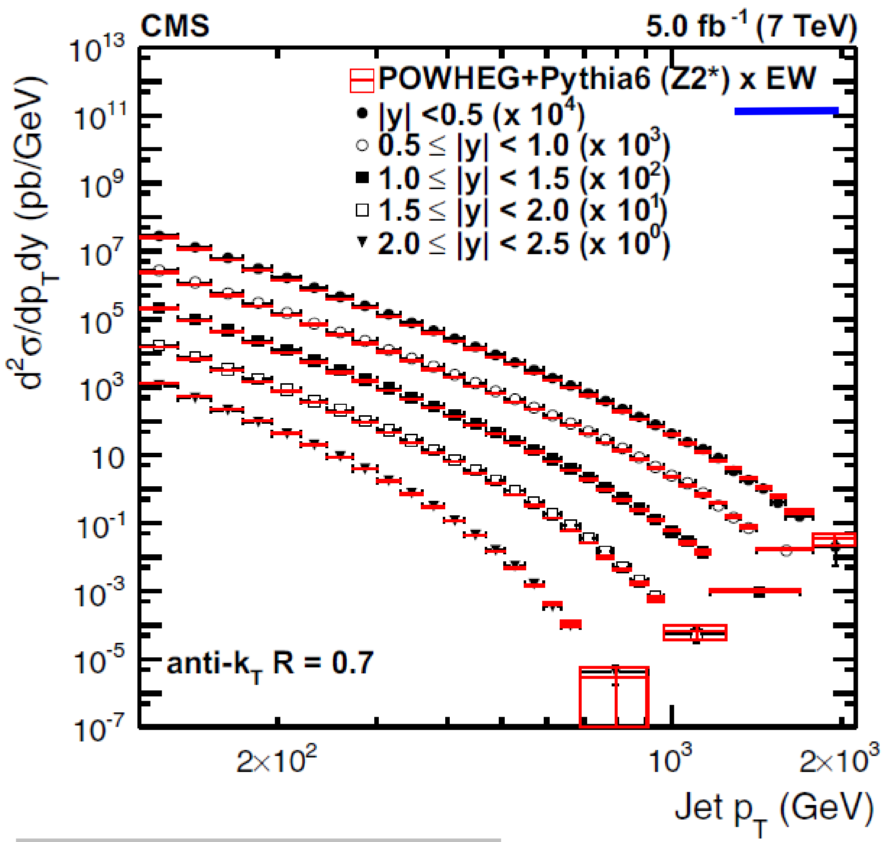
Simultaneous fit of α_s & PDFs possible combining HERA 1 DIS & CMS jet data using HERAFitter Tool

$Q = p_{\mathrm{T,jet}}$

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

Data vs. NLO+PS ⊗ EW corrections
→ impact visible in norm. dijet angular obs.

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



JHEP 2011, 095 (2012).

→ α_s

CT10-NLO: $\alpha_s(M_Z) = 0.1180$

NLO

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019\,(\mathrm{exp}) \pm 0.0028\,(\mathrm{PDF}) \pm 0.0004\,(\mathrm{NP}) \pm^{0.0053}_{0.0024}\,(\mathrm{scale})$$

$$= 0.1185 \pm 0.0035\,(\text{all w/o scale})$$

→ α_s & gluon (PDF)

$$\alpha_s(M_Z) = 0.1192^{+0.0023}_{-0.0019}\,(\text{all w/o scale})$$

Details: α_s from inclusive Jets

$\|y\|$ range	No. of data points	$\alpha_S(M_Z)$	χ^2/n_{dof}
$\|y\| < 0.5$	33	$0.1189 \pm 0.0024\,(\mathrm{exp}) \pm 0.0030\,(\mathrm{PDF}) \pm 0.0008\,(\mathrm{NP})^{+0.0045}_{-0.0027}\,(\mathrm{scale})$	16.2/32
$0.5 \leq \|y\| < 1.0$	30	$0.1182 \pm 0.0024\,(\mathrm{exp}) \pm 0.0029\,(\mathrm{PDF}) \pm 0.0008\,(\mathrm{NP})^{+0.0050}_{-0.0025}\,(\mathrm{scale})$	25.4/29
$1.0 \leq \|y\| < 1.5$	27	$0.1165 \pm 0.0027\,(\mathrm{exp}) \pm 0.0024\,(\mathrm{PDF}) \pm 0.0008\,(\mathrm{NP})^{+0.0043}_{-0.0020}\,(\mathrm{scale})$	9.5/26
$1.5 \leq \|y\| < 2.0$	24	$0.1146 \pm 0.0035\,(\mathrm{exp}) \pm 0.0031\,(\mathrm{PDF}) \pm 0.0013\,(\mathrm{NP})^{+0.0037}_{-0.0020}\,(\mathrm{scale})$	20.2/23
$2.0 \leq \|y\| < 2.5$	19	$0.1161 \pm 0.0045\,(\mathrm{exp}) \pm 0.0054\,(\mathrm{PDF}) \pm 0.0015\,(\mathrm{NP})^{+0.0034}_{-0.0032}\,(\mathrm{scale})$	12.6/18
$\|y\| < 2.5$	133	$0.1185 \pm 0.0019\,(\mathrm{exp}) \pm 0.0028\,(\mathrm{PDF}) \pm 0.0004\,(\mathrm{NP})^{+0.0053}_{-0.0024}\,(\mathrm{scale})$	104.1/132

Fit results in separate |y| bins
PDF: CT10-NLO
(best consistency between fit and PDF preferred $\alpha_s(M_Z)$)

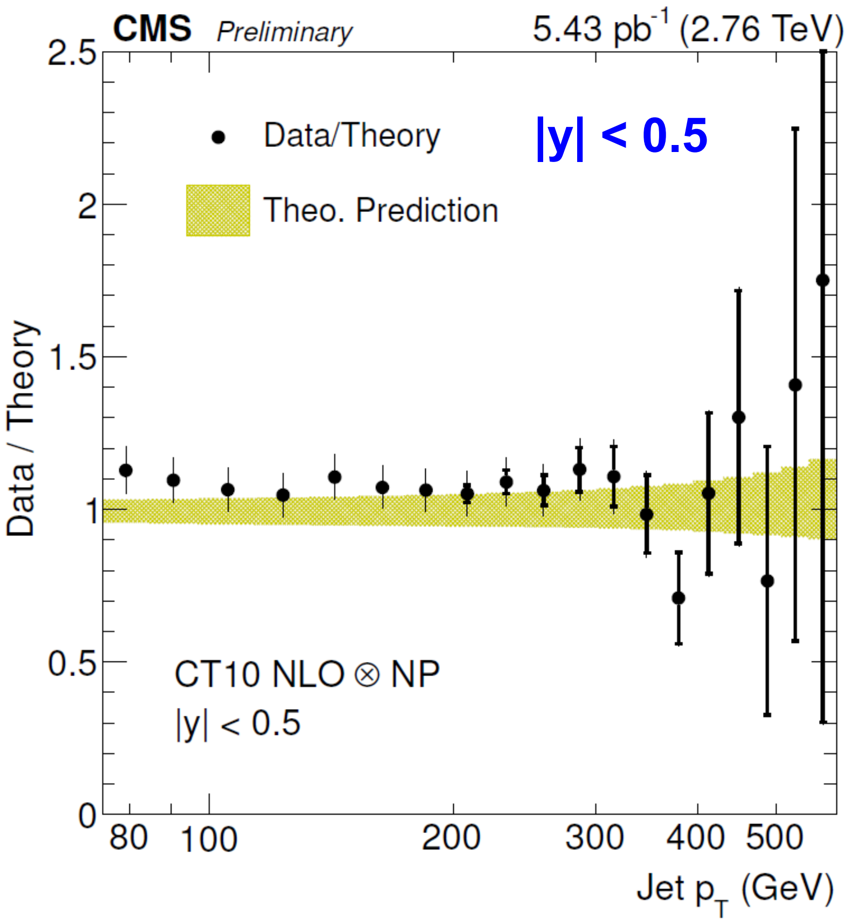
	$\alpha_S(M_Z)$	χ^2/n_{dof}
CT10-NLO	$0.1185 \pm 0.0019\,(\mathrm{exp}) \pm 0.0028\,(\mathrm{PDF}) \pm 0.0004\,(\mathrm{NP})^{+0.0053}_{-0.0024}\,(\mathrm{scale})$	104.1/132
NNPDF2.1-NLO	$0.1150 \pm 0.0015\,(\mathrm{exp}) \pm 0.0024\,(\mathrm{PDF}) \pm 0.0003\,(\mathrm{NP})^{+0.0025}_{-0.0025}\,(\mathrm{scale})$	103.5/132
MSTW2008-NLO	$0.1159 \pm 0.0012\,(\mathrm{exp}) \pm 0.0014\,(\mathrm{PDF}) \pm 0.0001\,(\mathrm{NP})^{+0.0024}_{-0.0030}\,(\mathrm{scale})$	107.9/132
CT10-NNLO	$0.1170 \pm 0.0012\,(\mathrm{exp}) \pm 0.0024\,(\mathrm{PDF}) \pm 0.0004\,(\mathrm{NP})^{+0.0044}_{-0.0030}\,(\mathrm{scale})$	105.7/132
NNPDF2.1-NNLO	$0.1175 \pm 0.0012\,(\mathrm{exp}) \pm 0.0019\,(\mathrm{PDF}) \pm 0.0001\,(\mathrm{NP})^{+0.0018}_{-0.0020}\,(\mathrm{scale})$	103.0/132
MSTW2008-NNLO	$0.1136 \pm 0.0010\,(\mathrm{exp}) \pm 0.0011\,(\mathrm{PDF}) \pm 0.0001\,(\mathrm{NP})^{+0.0019}_{-0.0024}\,(\mathrm{scale})$	108.8/132

Fit results for all |y| bins with other PDFs

CMS, EPJC 75 (2015) 288.

New from CMS:
- cross sections at 2.76 TeV
- ratios to 8 TeV
  Shown
- double ratio to theory

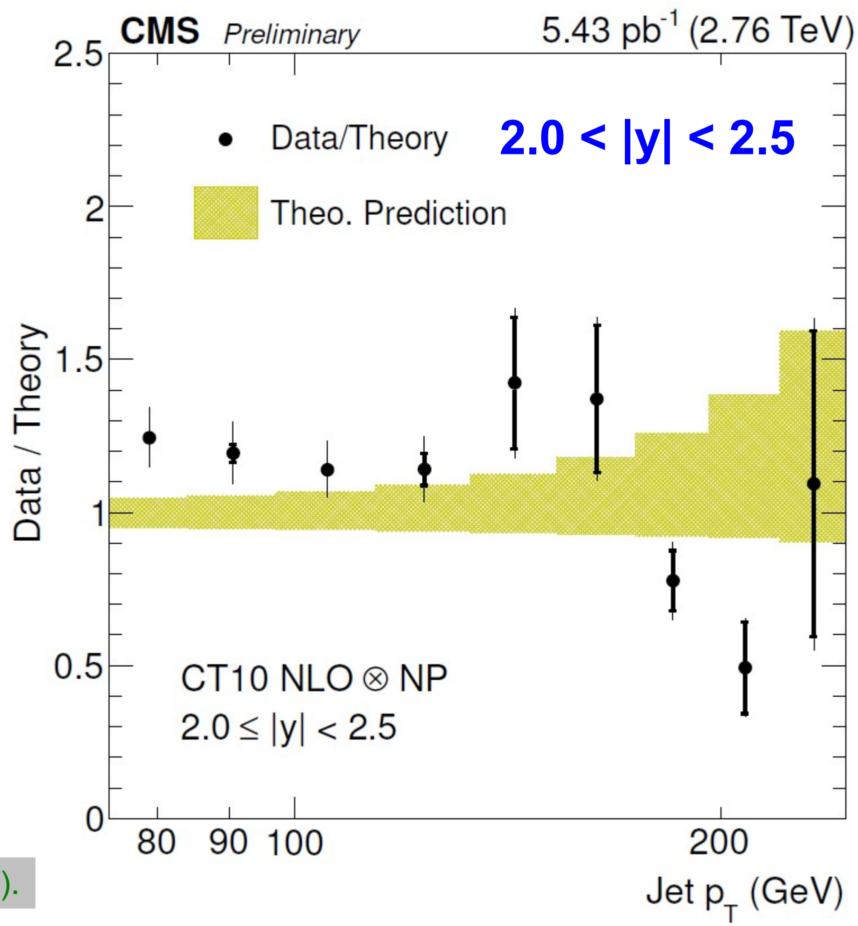
Ratio at E_{cms} = 2.76 and 8.0 TeV
→ at least partial cancellation of uncertainties
→ more precise comparisons



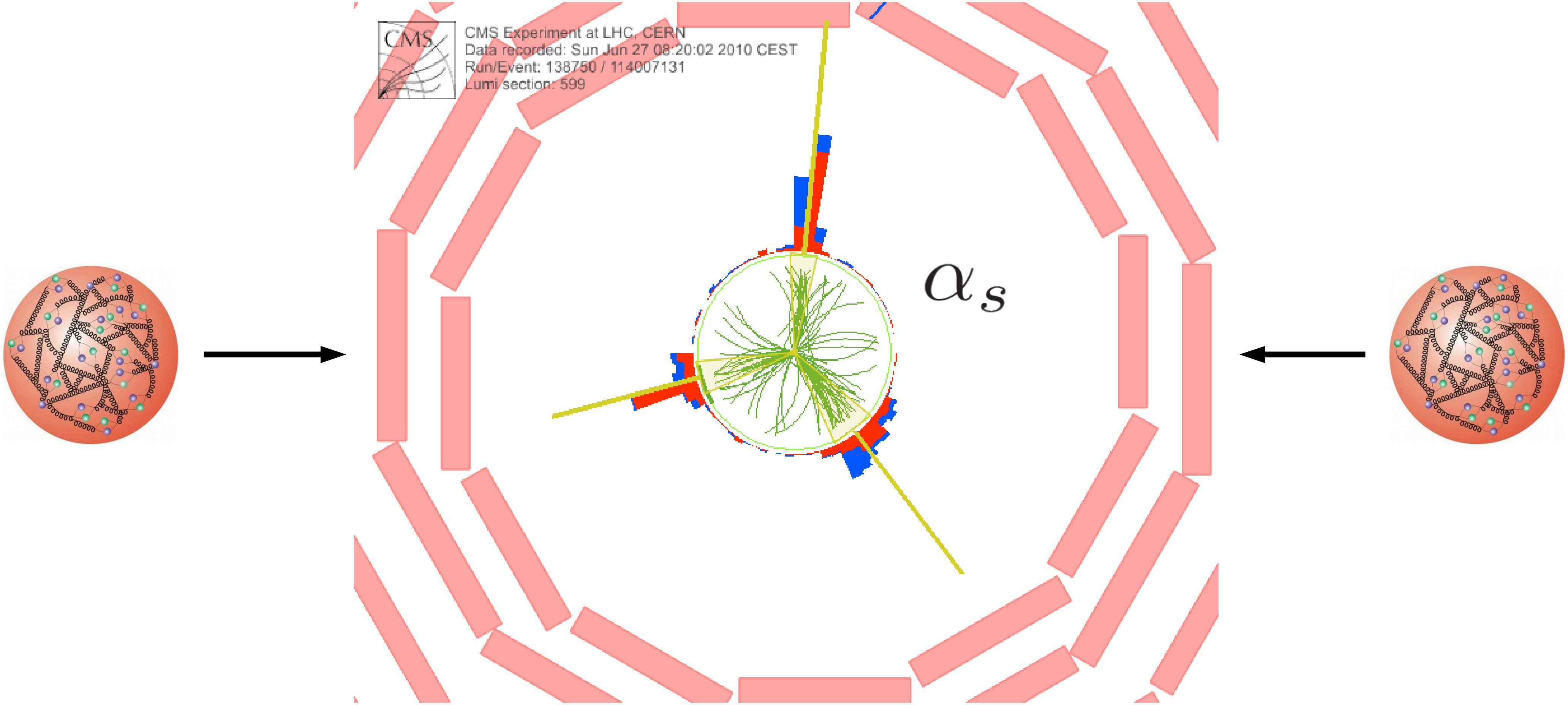
Disentangle α_s & g(x) by fitting in wide phase space of pT, y, and √s ?

→ gluon (PDF)

CMS-PAS-SMP-14-017 (2015).



Multi-Jets and α_s

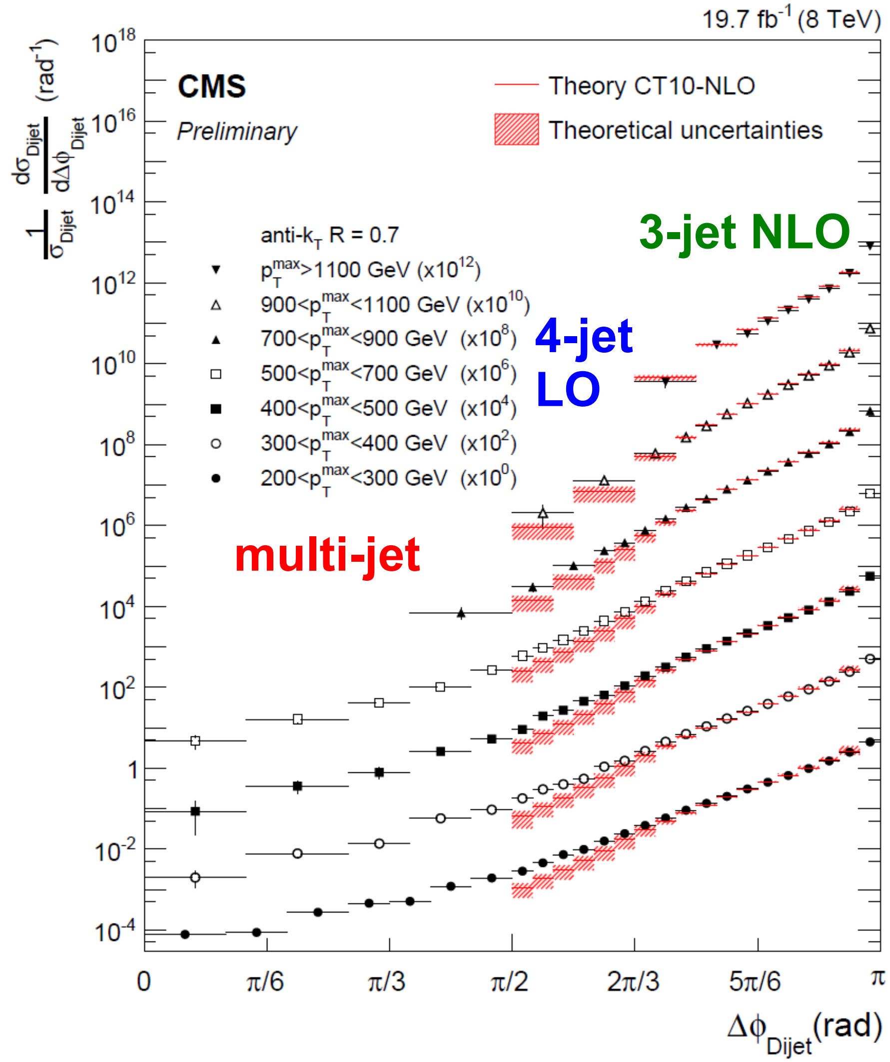


Azimuthal Decorrelations at 8 TeV

$\Delta\varphi_{jj}$ in bins of p_{T1}
- dijet LO has always $\Delta\varphi_{jj} = \pi$
- deviations through multi-jets

Related ratio observable $R_{\Delta\varphi}$ proposed for α_s det.

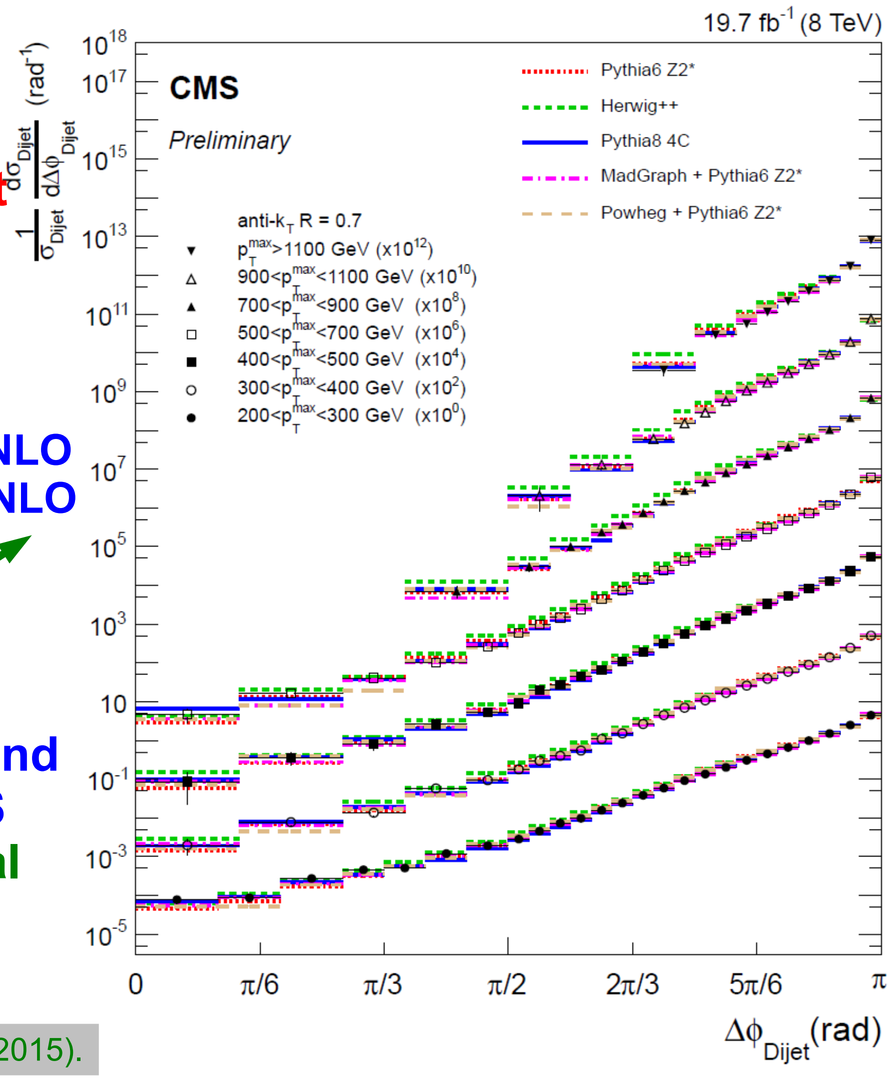
Wobisch et al., JHEP01 (2013) 172, D0, PLB 721 (2013) 212.



Comparison to fixed-order PQCD → need multijet NLO

Sherpa + BlackHat → 4-jet NLO
Njet → 5-jet NLO
to be checked

Comparison to LO ME+PS and multijet ME+PS → good general description



CMS-PAS-SMP-14-015 (2015).

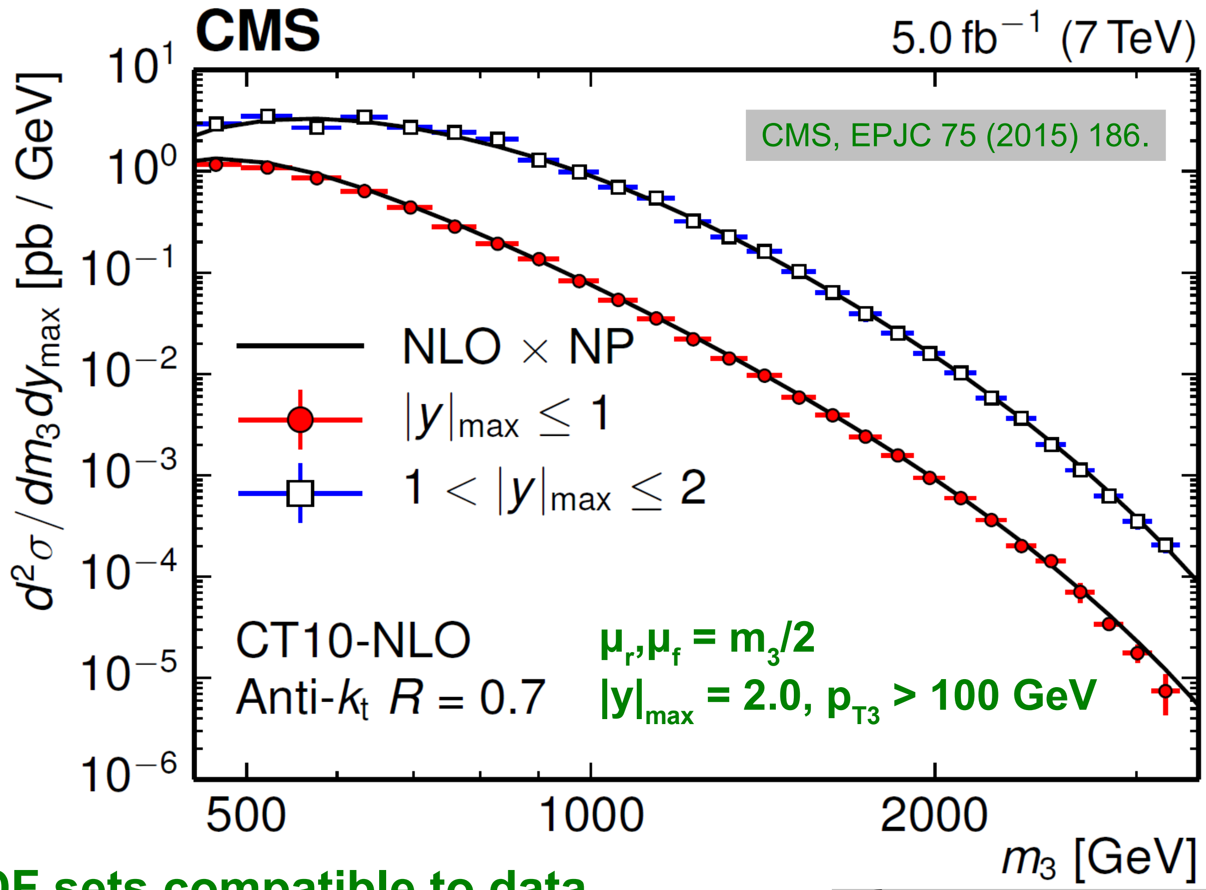
3-Jet Mass

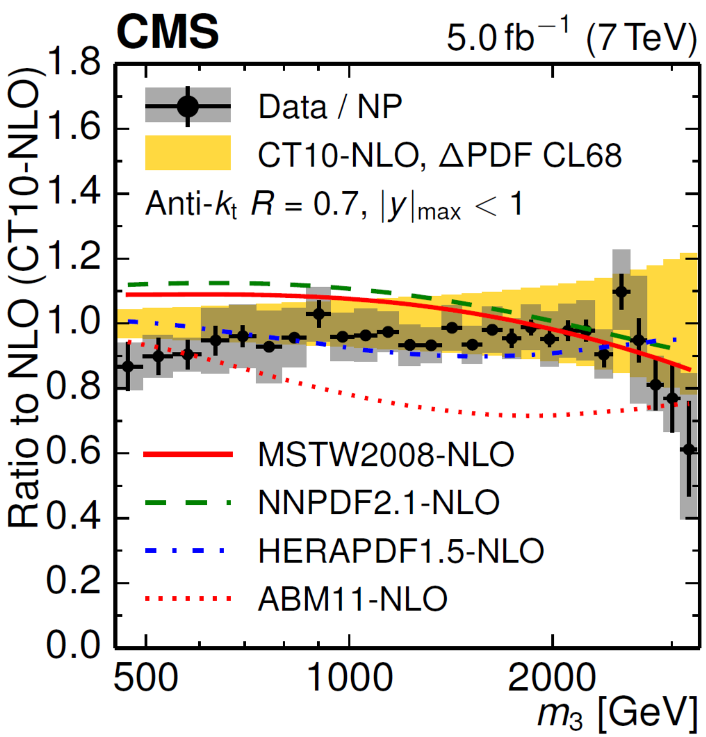
Sensitive to α_s beyond 2→2 process

NLO with 3-4 partons (NLOJet++)

Sensitive to PDFs

Involves additional "scale" $p_{T,3}$





Most PDF sets compatible to data

$$Q = m_3/2 \qquad \frac{d\sigma_{3jet}}{dm_{3jet}} \propto \alpha_s^3$$

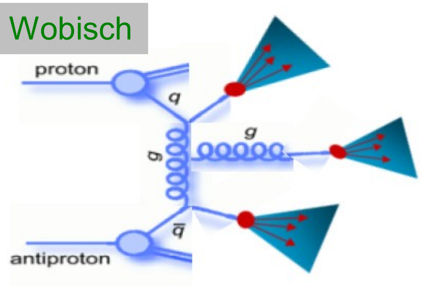
Extraction of $\alpha_s(M_Z)$: → α_s

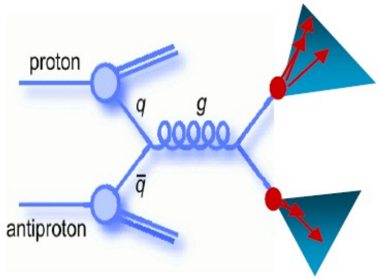
Dominated by theory uncertainty (NLO)!

$$\alpha_S(M_Z) = 0.1171 \pm 0.0013(\mathrm{exp}) \pm 0.0024(\mathrm{PDF}) \pm 0.0008(\mathrm{NP})^{+0.0069}_{-0.0040}(\mathrm{scale})$$

3- to 2-Jet Ratios

M. Wobisch

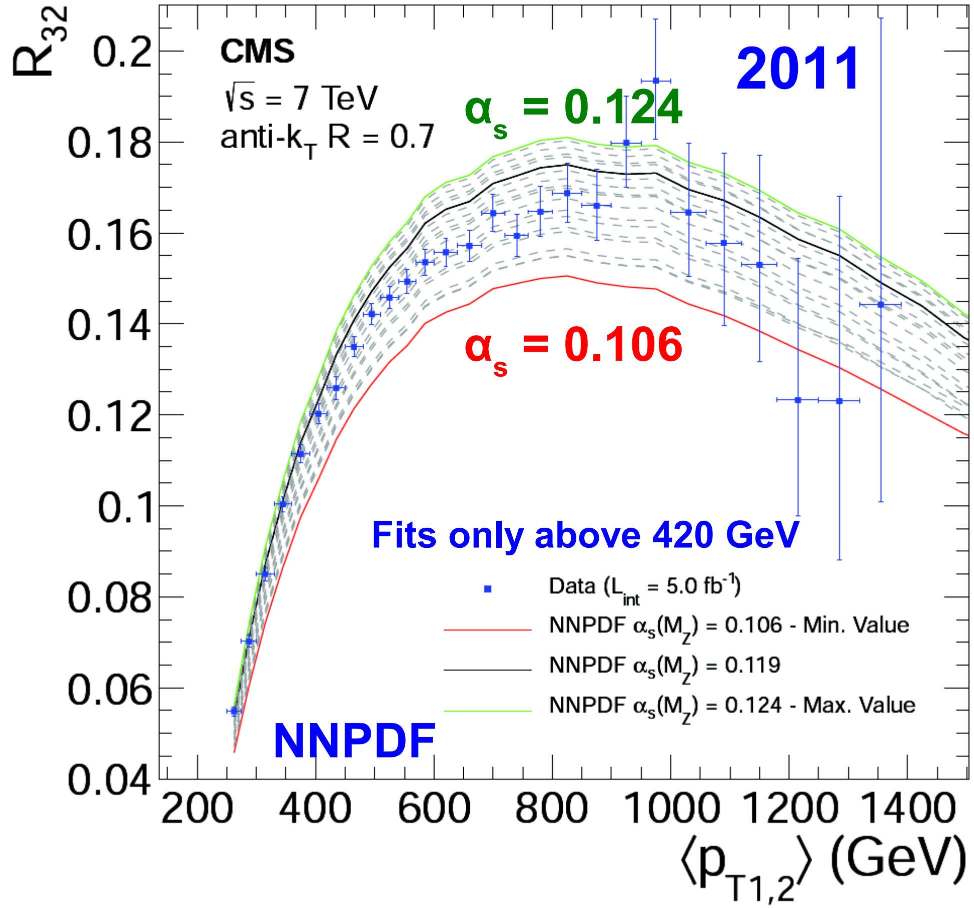




$R_{3/2}$ ⟺ α_s

$$\frac{\sigma_{3+\mathrm{jet}}}{\sigma_{2+\mathrm{jet}}} \propto \alpha_s^1$$

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



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**
- **Data 2011, 5/fb**

CMS, EPJC 73 (2013) 2604.

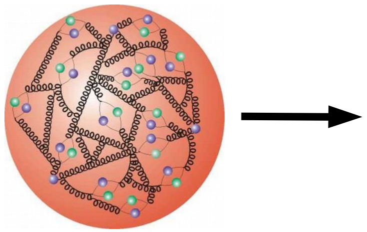
Similarly described by CT10 or MSTW2008

→ α_s

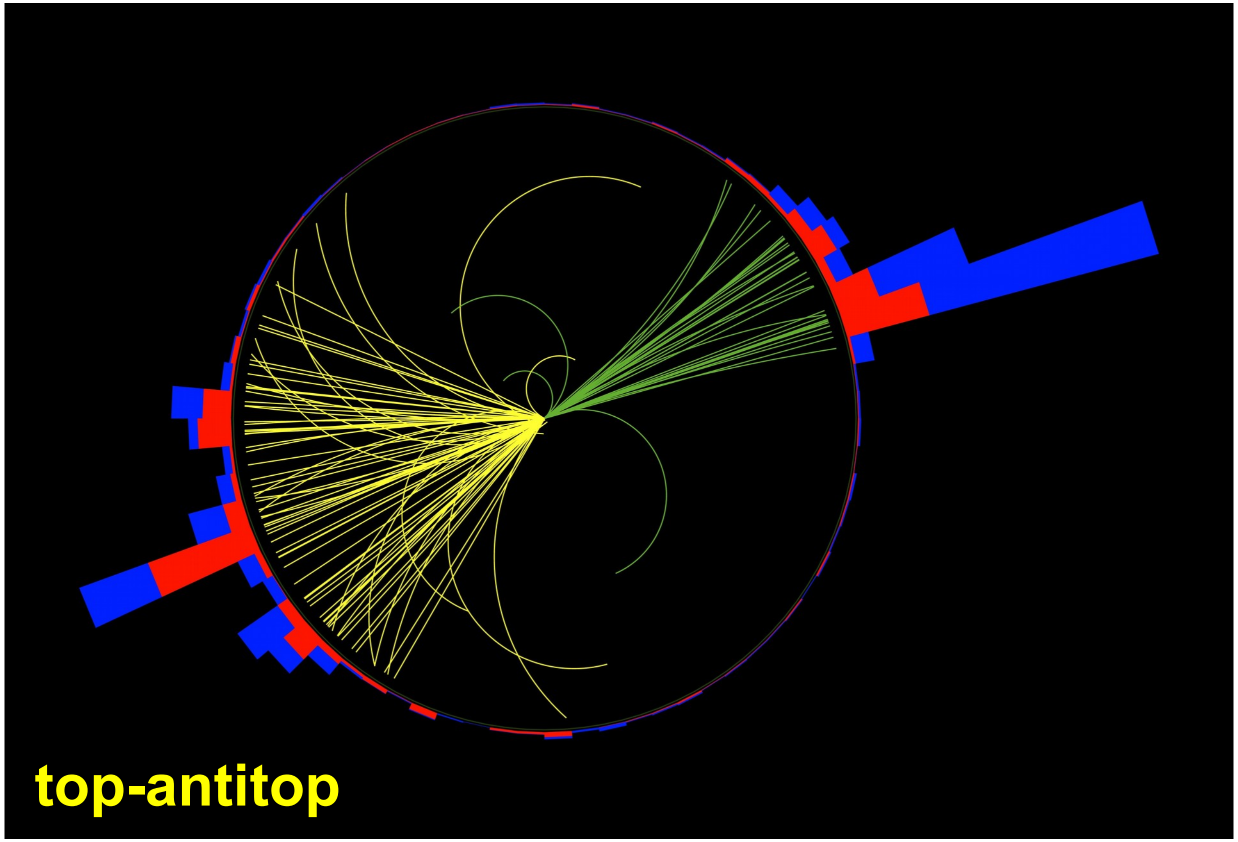
$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp}) \pm 0.0018\,(\mathrm{PDF}) \pm 0.0050\,(\mathrm{theory})$$

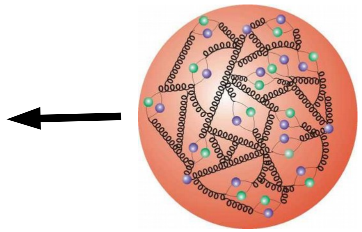
Dominated by NLO theory uncertainty!

High Masses



Proton





Proton

Fits with top-pair Production

Top-pair production is especially sensitive to:

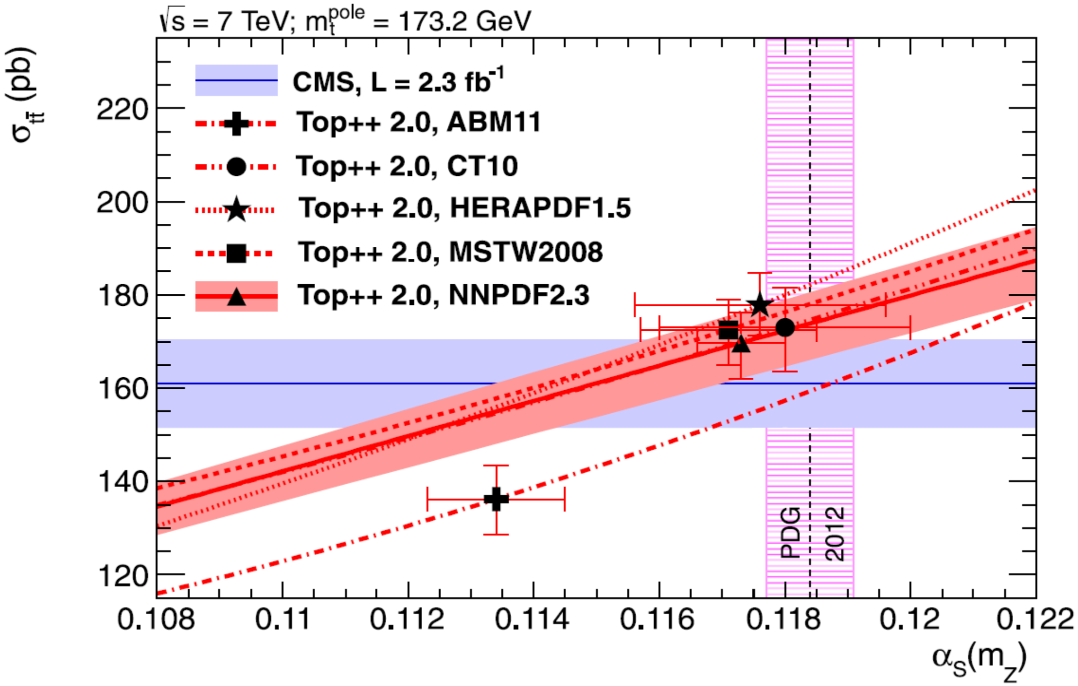
m_t^{pole} and α_s and $g(x,\mu_f^2)$ as the main production process at LHC is from gg

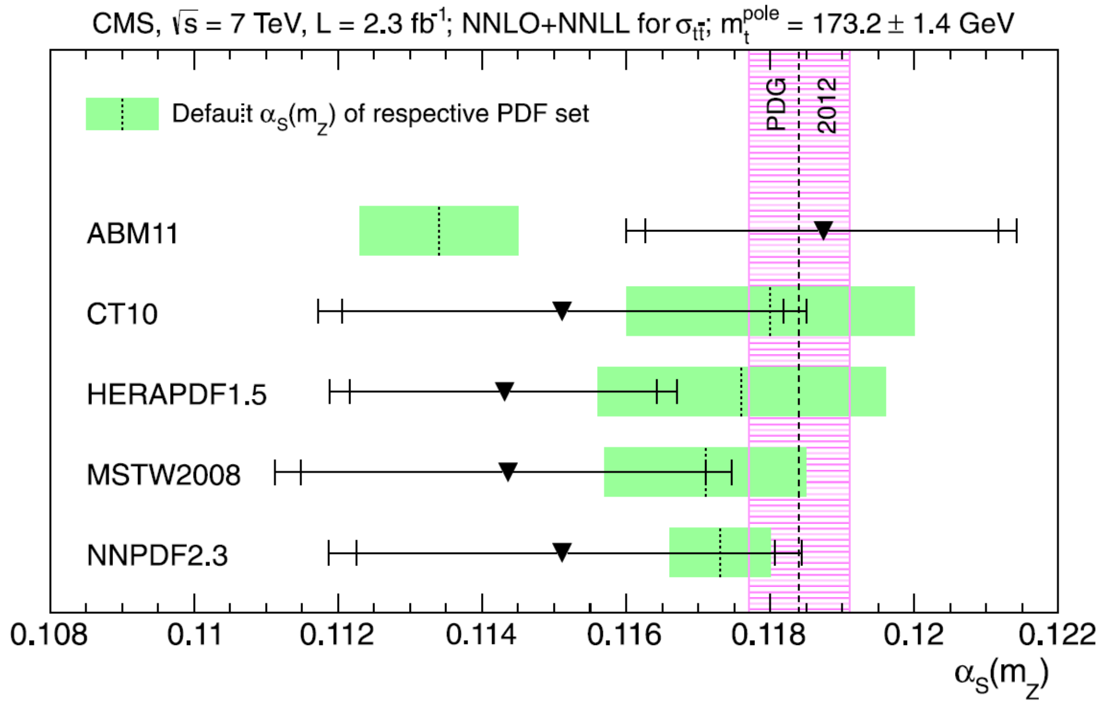
Using only the ttbar cross section measurement (dilepton channel) combined fits are not possible. Fixing the gluon to one of 5 PDF sets, however, it is possible to extract m_t^{pole} while fixing α_s or vice versa.

$$\alpha_s(M_Z) = 0.1151 \pm 0.0025(\mathrm{exp})^{+0.0013}_{-0.0011}(\mathrm{PDF})$$

NNLO + NNLL $\quad {}^{+0.0009}_{-0.0008}(\mathrm{scale}) \pm 0.0013(\mathrm{m_t^{pole}}) \pm 0.0008(\mathrm{E_{LHC}})$ new top related

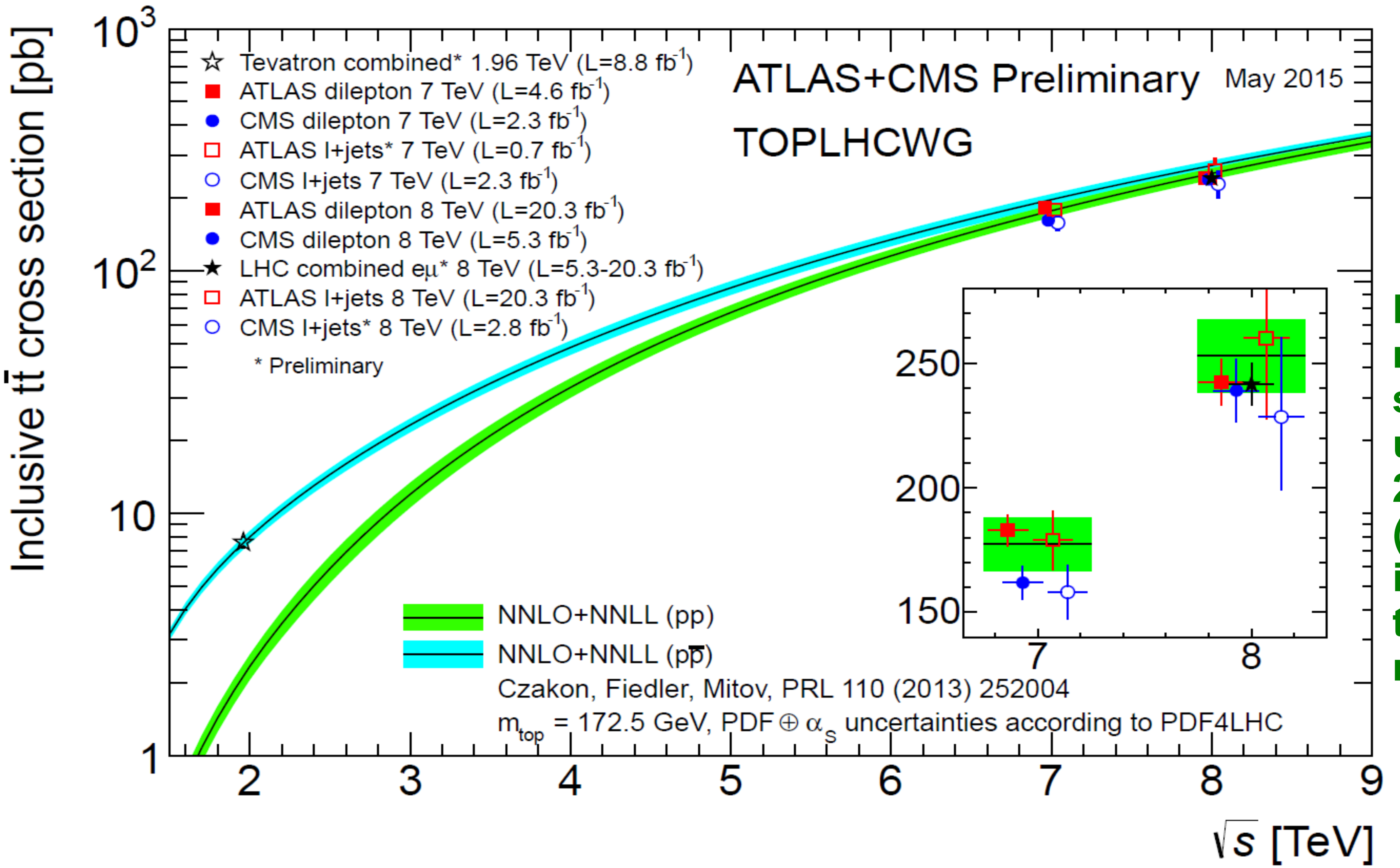
Fix $m_t^{pole} \rightarrow$ constrain α_s





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

ttbar Dilepton X Section in Comparison

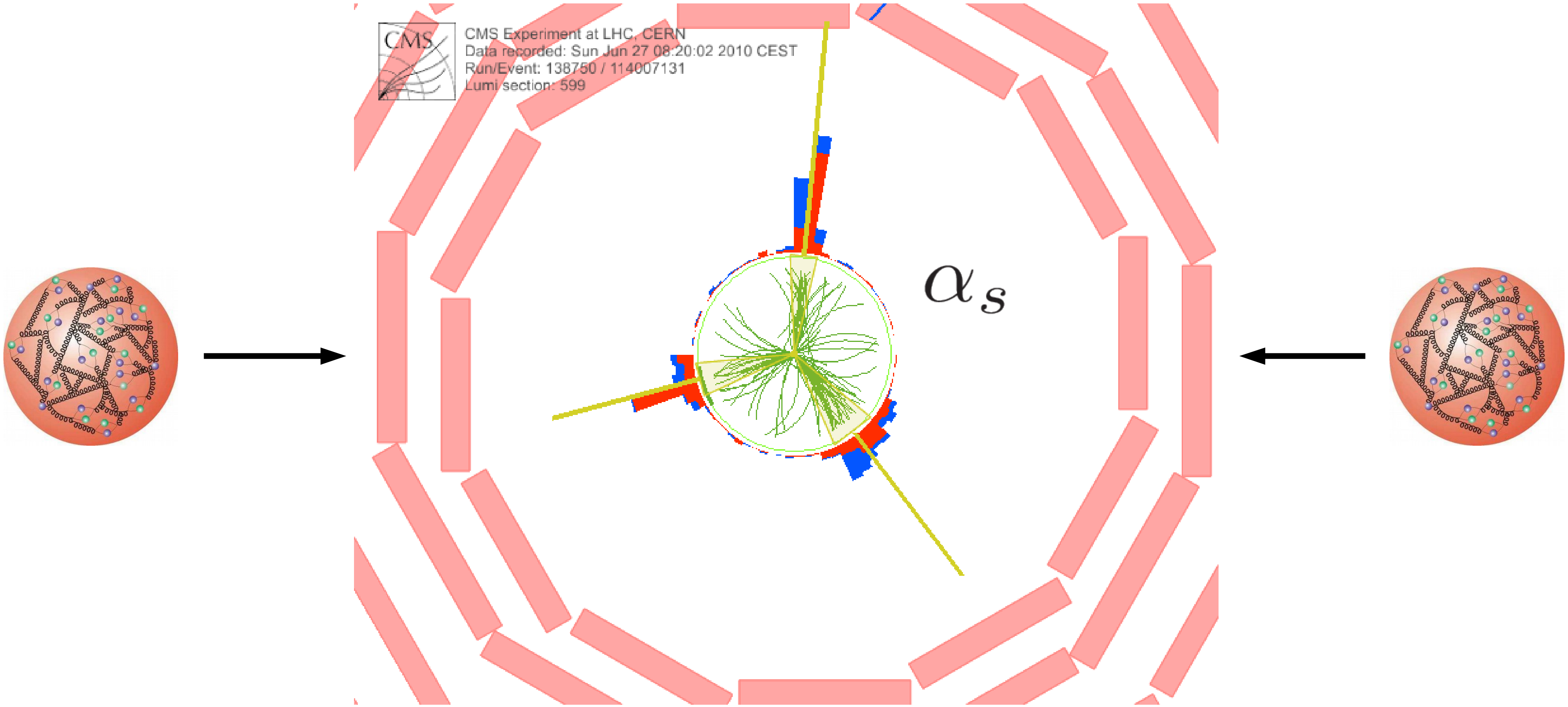


New CMS prelim. results move up somewhat, but within uncertainty.
2 X (@ 7 TeV) and 4 X (@ 8 TeV) more data, improved reconstruction, plus further refinements.

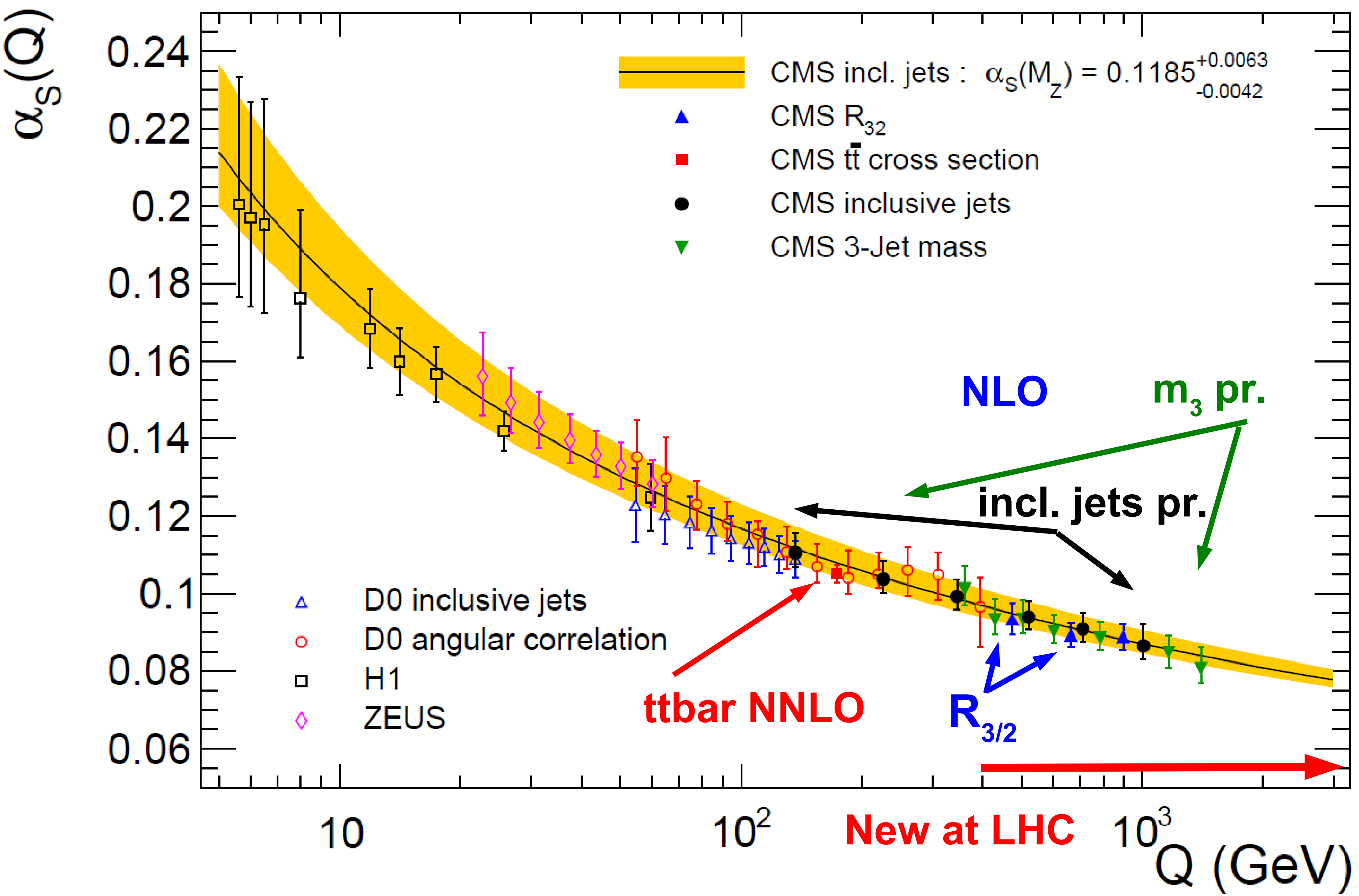
$$\sigma_{t\bar{t}} = 174.5 \pm 2.1(\mathrm{stat}) \pm^{4.5}_{4.0} (\mathrm{syst}) \pm 3.8(\mathrm{lumi})\ \mathrm{pb} \quad \text{at } \sqrt{s} = 7\ \mathrm{TeV}\ \text{and}$$
$$\sigma_{t\bar{t}} = 245.6 \pm 1.3(\mathrm{stat}) \pm^{6.6}_{5.5} (\mathrm{syst}) \pm 6.5(\mathrm{lumi})\ \mathrm{pb} \quad \text{at } \sqrt{s} = 8\ \mathrm{TeV},$$

CMS-TOP-13-004 (2012).

α_s (1 TeV) ?

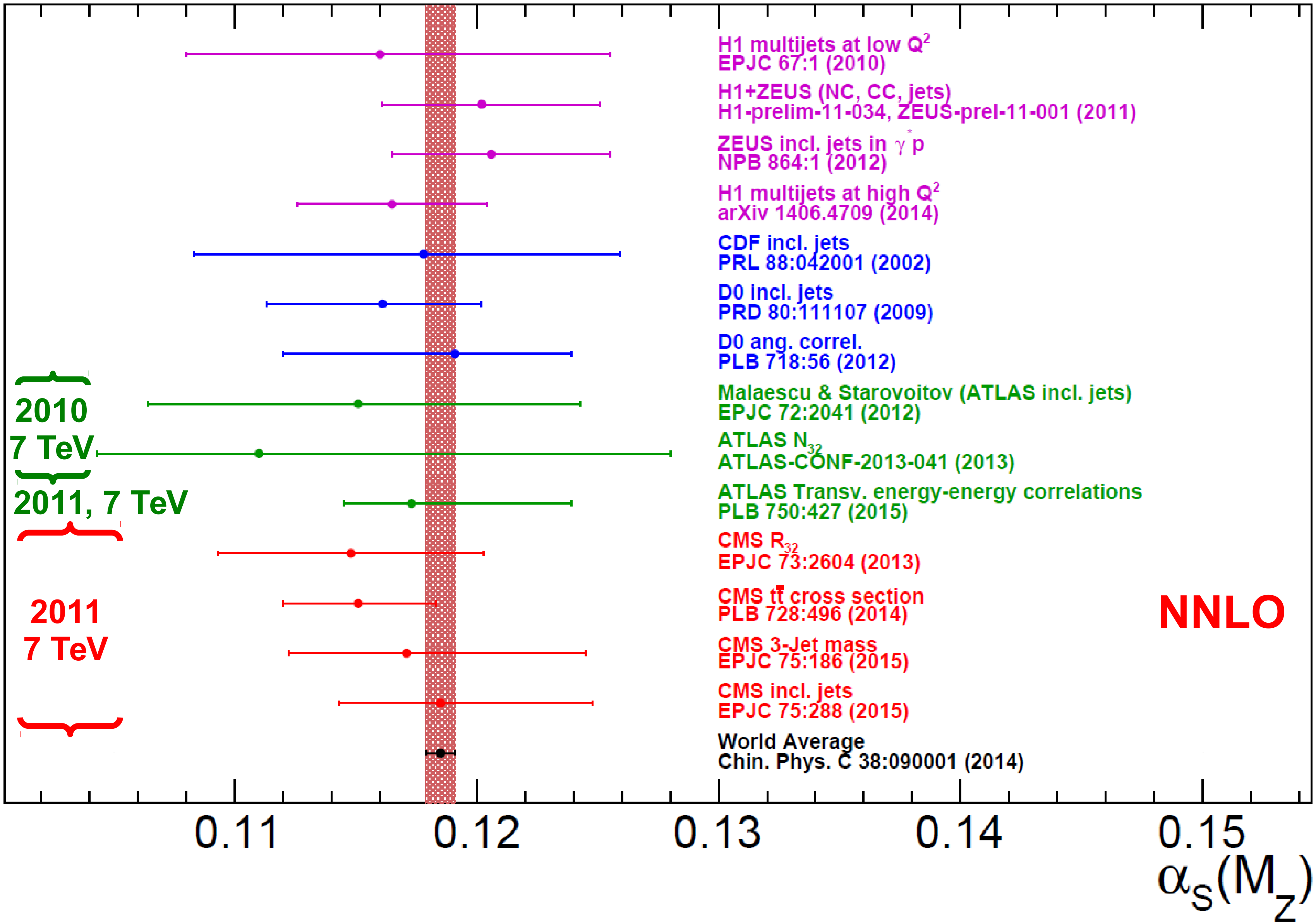

CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Jun 27 08:20:02 2010 CEST
Run/Event: 138750 / 114007131
Lumi section: 599
α_s

CMS Summary



$\alpha_S(Q)$
CMS incl. jets : $\alpha_S(M_Z) = 0.1185^{+0.0063}_{-0.0042}$
CMS R_{32}
CMS $t\bar{t}$ cross section
CMS inclusive jets
CMS 3-Jet mass
D0 inclusive jets
D0 angular correlation
H1
ZEUS
NLO
m_3 pr.
incl. jets pr.
ttbar NNLO
$R_{3/2}$
New at LHC
Q (GeV)

Hadron Collider Summary



$\Delta\alpha_S/\alpha_S$ / %

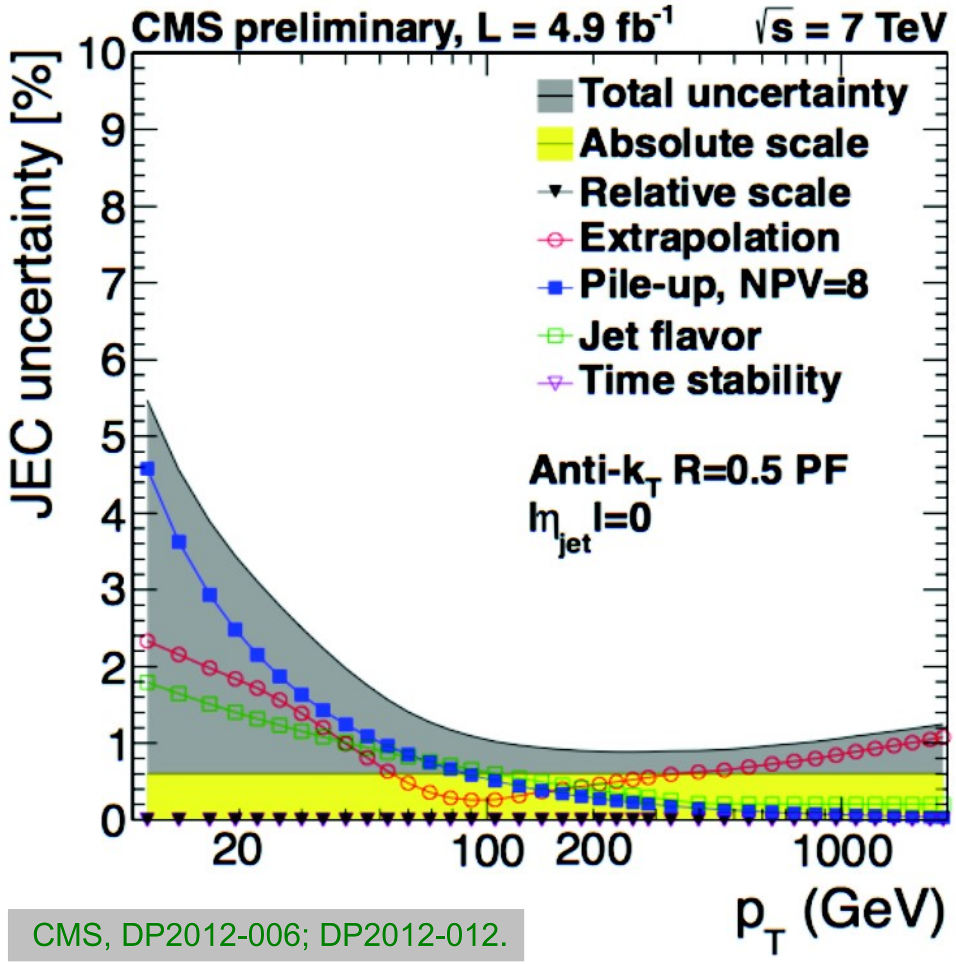
exp	PDF	scale
1.2	1.4	7.3
no final publ.		
1.9	1.9	2.5
0.7	0.8	3.1
7.5	5.0	5.0
2.9	1.0	2.3
0.7	1.2	4.7
4.1	1.8	2.4
no final publ.		
0.9	1.4	3.5
1.2	1.6	4.4
2.3	1.0	0.7
1.1	2.0	4.7
1.6	2.4	3.2

Perspectives with CMS and Beyond

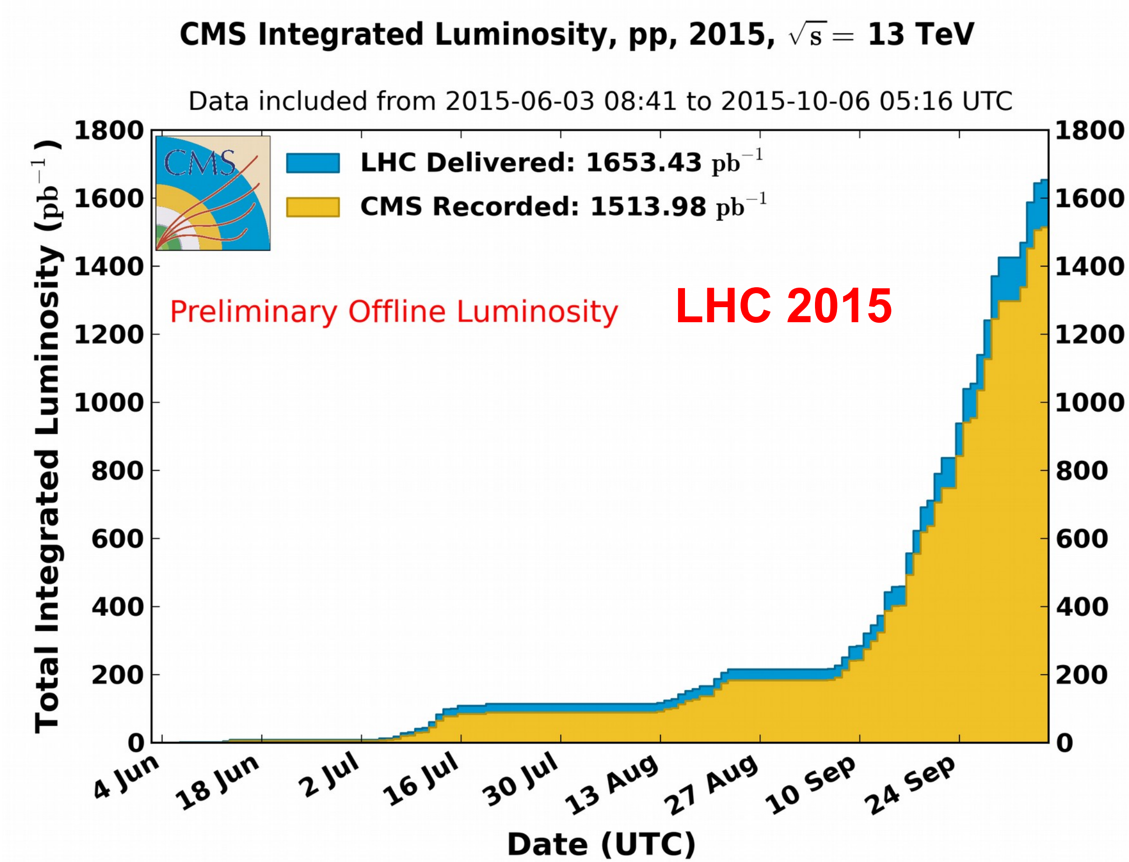
CMS: Jet energy scale **1 – 3 % prel. (Run 1)**
→ **percent level precision at medium p_T**
→ **more precise $\alpha_s(M_Z)$**

LHC: E_{cms} = 0.9, 2.36, 2.76, 7, 8, and **now 13 TeV**
→ **much higher reach to check $\alpha_s(Q)$**

CMS from 5/fb (7 TeV, 2011)



CMS, DP2012-006; DP2012-012.



Jet Energy Scale and α_s

Two goals for α_s:

1. Measure the running of $\alpha_s(Q)$ up to the highest scales possible

→ In CMS mostly looked into $\alpha_s(Q)$!

2. Measure $\alpha_s(M_Z)$ as precisely as possible

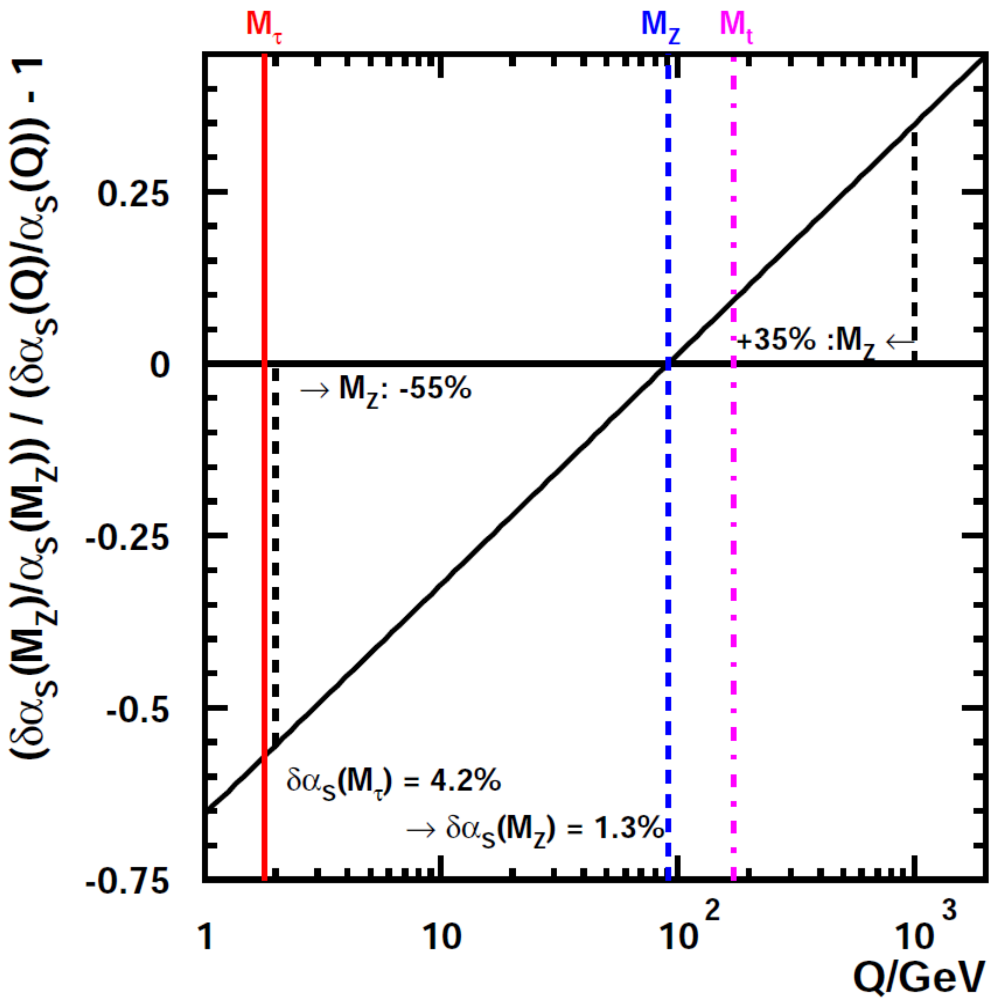
→ For $\alpha_s(M_Z)$ might want to stay at minimal JEC uncertainty:
200 – 800 GeV, central rapidity

Better in:
- JEC uncertainty
- PDF uncertainty
- Evolution to M_Z

Worse in: NP effects

Incredibly shrinking error →

← Uncomfortably growing error



Perspectives & Educated Guesses

- **Experiment:**
  - Done: Observables $\sigma \sim \alpha_s^2, \alpha_s^3$; $R_{3/2} \sim \alpha_s$; 7 TeV; full phase space
  - 8 TeV data: Reduce experimental uncertainty by some permille?
  - Best JEC phase space: Another reduction by some permille?
  - Other observables: Ratios (n+m) / n jets (incl. γ, W, Z), $R_{\Delta\Phi}$, $R_{\Delta R}$ (→ D0)
    Normalized cross sections
- **Theory:**
  - Scales: NNLO important (see Joao´s Talk) → reduction by some percent!?
  - PDFs: Much improved after LHC I, also HERA 2 data available
    - Better known gluon (Attention circularity jets → g(x) & jets → α_s)
    - Fits combining observables at various √s to disentangle g(x), M_t, α_s
  - NNLO ratios?

Summary

- LHC at 7 TeV and 8 TeV enables measurements up to scales of 2 TeV
- 13 TeV data yet to come
- Theory at NNLO QCD + electroweak corrections are a must!
- Typical uncertainties on $\alpha_s(M_Z)$:
  - Experimental: ~ 1 – 2 %
  - PDF: ~ 1 – 2 %
  - Scale: 3 – 5 %
  - Nonpert. Effects: < 1 %
- Beyond CMS:
  - Combined fits of ATLAS & CMS (LHC) measurements
  - Combined fits of HERA, Tevatron & LHC measurements

➡ CHALLENGE

Triple Five:

- Within the next FIVE years
- Check running of $\alpha_s(Q)$ up to FIVE TeV and
- Determine $\alpha_s(M_Z)$ to FIVE permille accuracy

**Thank you for your attention
and the invitation to speak here!**

Backup Slides

PDF Sets

Base set	Refs.	Evol.	N_f	M_t (GeV)	M_Z (GeV)	$\alpha_S(M_Z)$	$\alpha_S(M_Z)$ range
ABM11	[17]	NLO	5	180	91.174	0.1180	0.110–0.130
ABM11	[17]	NNLO	5	180	91.174	0.1134	0.104–0.120
CT10	[18]	NLO	≤ 5	172	91.188	0.1180	0.112–0.127
CT10	[18]	NNLO	≤ 5	172	91.188	0.1180	0.110–0.130
HERAPDF1.5	[19]	NLO	≤ 5	180	91.187	0.1176	0.114–0.122
HERAPDF1.5	[19]	NNLO	≤ 5	180	91.187	0.1176	0.114–0.122
MSTW2008	[20,21]	NLO	≤ 5	10^{10}	91.1876	0.1202	0.110–0.130
MSTW2008	[20,21]	NNLO	≤ 5	10^{10}	91.1876	0.1171	0.107–0.127
NNPDF2.1	[22]	NLO	≤ 6	175	91.2	0.1190	0.114–0.124
NNPDF2.1	[22]	NNLO	≤ 6	175	91.2	0.1190	0.114–0.124

CMS, EPJC 75 (2015) 288.

Details: α_s from inclusive Jets

Fit results in separate |y| bins
PDF: CT10-NNLO

$\lvert y \rvert$ range	No. of data points	$\alpha_S(M_Z)$	χ^2/n_{dof}
$\lvert y \rvert < 0.5$	33	$0.1180 \pm 0.0017\,(\text{exp}) \pm 0.0027\,(\text{PDF}) \pm 0.0006\,(\text{NP})^{+0.0031}_{-0.0026}\,(\text{scale})$	15.4/32
$0.5 \leq \lvert y \rvert < 1.0$	30	$0.1176 \pm 0.0016\,(\text{exp}) \pm 0.0026\,(\text{PDF}) \pm 0.0006\,(\text{NP})^{+0.0033}_{-0.0023}\,(\text{scale})$	23.9/29
$1.0 \leq \lvert y \rvert < 1.5$	27	$0.1169 \pm 0.0019\,(\text{exp}) \pm 0.0024\,(\text{PDF}) \pm 0.0006\,(\text{NP})^{+0.0033}_{-0.0019}\,(\text{scale})$	10.5/26
$1.5 \leq \lvert y \rvert < 2.0$	24	$0.1133 \pm 0.0023\,(\text{exp}) \pm 0.0028\,(\text{PDF}) \pm 0.0010\,(\text{NP})^{+0.0039}_{-0.0029}\,(\text{scale})$	22.3/23
$2.0 \leq \lvert y \rvert < 2.5$	19	$0.1172 \pm 0.0044\,(\text{exp}) \pm 0.0039\,(\text{PDF}) \pm 0.0015\,(\text{NP})^{+0.0049}_{-0.0060}\,(\text{scale})$	13.8/18
$\lvert y \rvert < 2.5$	133	$0.1170 \pm 0.0012\,(\text{exp}) \pm 0.0024\,(\text{PDF}) \pm 0.0004\,(\text{NP})^{+0.0044}_{-0.0030}\,(\text{scale})$	105.7/132

CMS, EPJC 75 (2015) 288.

Details: 3-Jet Mass

Fit results in separate |y| bins (CT10-NLO) and with other PDFs

CMS, EPJC 75 (2015) 186.

m_3 (GeV)	$\langle Q \rangle$ (GeV)	χ^2/n_{dof}	$\alpha_S(M_Z)$	±(exp)	±(PDF)	±(NP)	±(scale)
664–794	361	4.5/3	0.1232	$^{+0.0040}_{-0.0042}$	$^{+0.0019}_{-0.0016}$	$^{+0.0008}_{-0.0007}$	$^{+0.0079}_{-0.0044}$
794–938	429	7.8/3	0.1143	$^{+0.0034}_{-0.0033}$	$^{+0.0019}_{-0.0016}$	±0.0008	$^{+0.0073}_{-0.0042}$
938–1098	504	0.6/3	0.1171	$^{+0.0033}_{-0.0034}$	±0.0022	±0.0007	$^{+0.0068}_{-0.0040}$
1098–1369	602	2.6/5	0.1152	±0.0026	$^{+0.0027}_{-0.0026}$	$^{+0.0008}_{-0.0007}$	$^{+0.0060}_{-0.0027}$
1369–2172	785	8.8/13	0.1168	$^{+0.0018}_{-0.0019}$	$^{+0.0030}_{-0.0031}$	$^{+0.0007}_{-0.0006}$	$^{+0.0068}_{-0.0034}$
2172–2602	1164	3.6/5	0.1167	$^{+0.0037}_{-0.0044}$	$^{+0.0040}_{-0.0044}$	±0.0008	$^{+0.0065}_{-0.0041}$
2602–3270	1402	5.5/7	0.1120	$^{+0.0043}_{-0.0041}$	$^{+0.0056}_{-0.0040}$	±0.0001	$^{+0.0088}_{-0.0050}$
$\|y\|_{max} < 1$	413	10.3/22	0.1163	$^{+0.0018}_{-0.0019}$	±0.0027	±0.0007	$^{+0.0059}_{-0.0025}$
$1 \leq \|y\|_{max} < 2$	441	10.6/22	0.1179	$^{+0.0018}_{-0.0019}$	±0.0021	±0.0007	$^{+0.0067}_{-0.0037}$
$\|y\|_{max} < 2$	438	47.2/45	0.1171	±0.0013	±0.0024	±0.0008	$^{+0.0069}_{-0.0040}$

PDF set	χ^2/n_{dof}	$\alpha_S(M_Z)$	±(exp)	±(PDF)	±(NP)	± (scale)
CT10-NLO	47.2/45	0.1171	±0.0013	±0.0024	±0.0008	$^{+0.0069}_{-0.0040}$
CT10-NNLO	48.5/45	0.1165	$^{+0.0011}_{-0.0010}$	$^{+0.0022}_{-0.0023}$	$^{+0.0006}_{-0.0008}$	$^{+0.0066}_{-0.0034}$
MSTW2008-NLO	52.8/45	0.1155	$^{+0.0014}_{-0.0013}$	$^{+0.0014}_{-0.0015}$	$^{+0.0008}_{-0.0009}$	$^{+0.0105}_{-0.0029}$
MSTW2008-NNLO	53.9/45	0.1183	$^{+0.0011}_{-0.0016}$	$^{+0.0012}_{-0.0023}$	$^{+0.0011}_{-0.0019}$	$^{+0.0052}_{-0.0050}$
HERAPDF1.5-NNLO	49.9/45	0.1143	±0.0007	$^{+0.0020}_{-0.0035}$	$^{+0.0003}_{-0.0008}$	$^{+0.0035}_{-0.0027}$
NNPDF2.1-NNLO	51.1/45	0.1164	±0.0010	$^{+0.0020}_{-0.0019}$	$^{+0.0010}_{-0.0009}$	$^{+0.0058}_{-0.0025}$

$R_{3/2}$ Details

Fit results in separate Q ranges (NNPDF21-NNLO) and with other PDFs

$\langle p_{T1,2} \rangle$ 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

$\langle p_{T1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	exp.	PDF	theory
420–600	474	0.1147	± 0.0015	± 0.0015	± 0.0057
600–800	664	0.1132	± 0.0018	± 0.0025	± 0.0039
800–1390	896	0.1170	± 0.0024	± 0.0021	± 0.0048

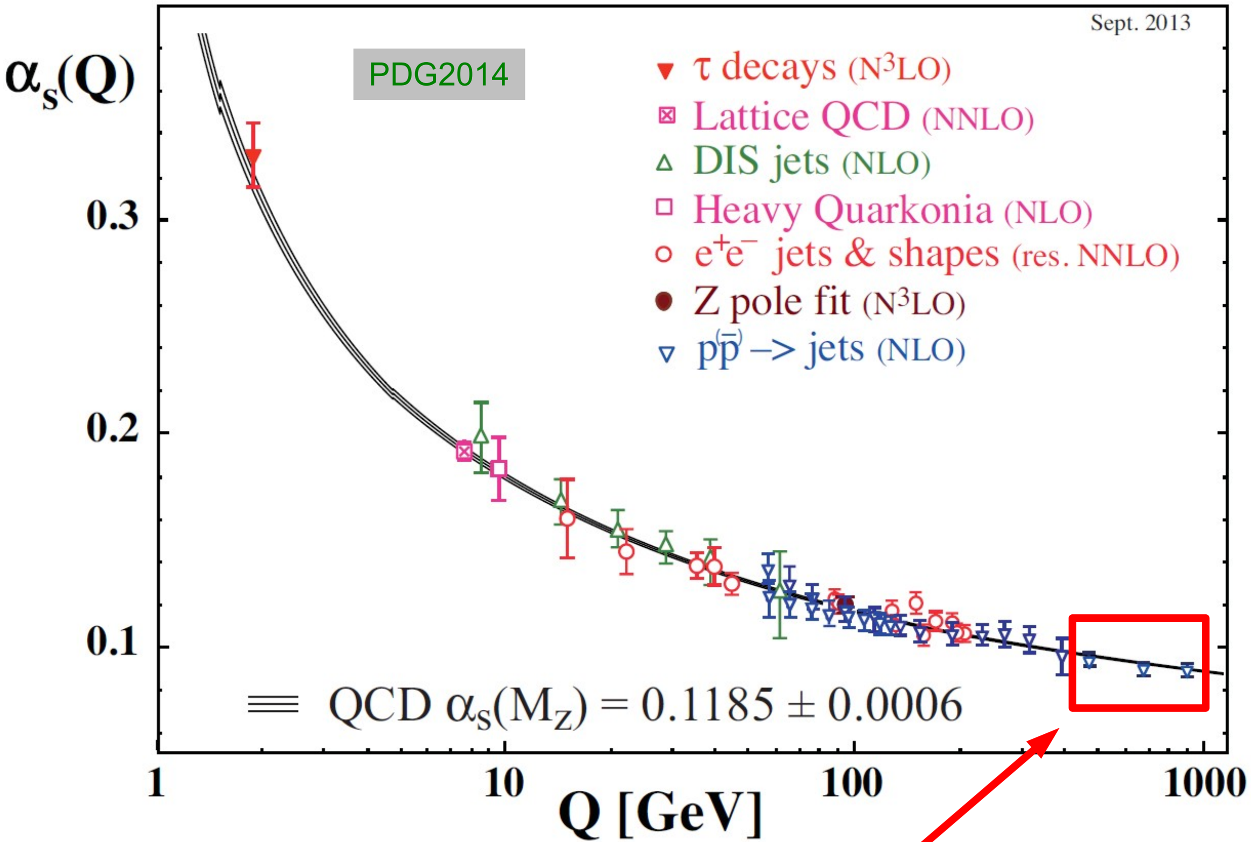
$\mu_r / \langle p_{T1,2} \rangle$	$\mu_f / \langle p_{T1,2} \rangle$	$\alpha_S(M_Z) \pm$ (exp.)	χ^2/N_{dof}
1	1	0.1148 ± 0.0014	22.0/20
1/2	1/2	0.1198 ± 0.0021	30.6/20
1/2	1	0.1149 ± 0.0014	22.2/20
1	1/2	0.1149 ± 0.0014	22.2/20
1	2	0.1150 ± 0.0015	21.9/20
2	1	0.1159 ± 0.0014	20.7/20
2	2	0.1172 ± 0.0018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

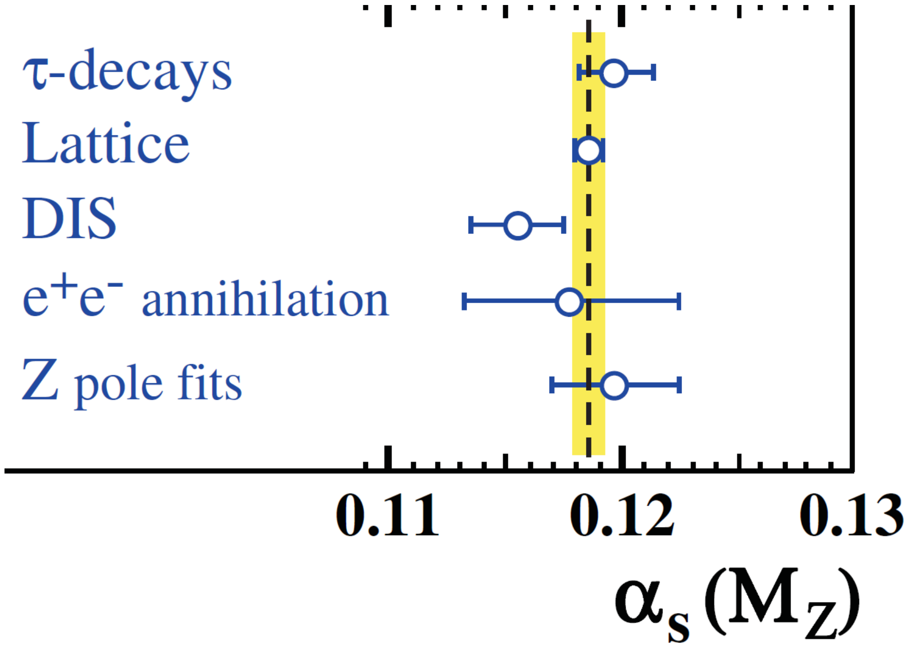
$$\text{MSTW2008:} \quad \alpha_S(M_Z) = 0.1141 \pm 0.0022 \text{ (exp.)},$$

$$\text{CT10:} \quad \alpha_S(M_Z) = 0.1135 \pm 0.0019 \text{ (exp.)},$$

CMS, EPJC 73 (2013) 2604.

PDG Summary





Dominated by Lattice Gauge Theory

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

$$\alpha_s(M_Z) = 0.1177 \pm 0.0013\ ?$$

$$\frac{\Delta\alpha_S(M_Z)}{\alpha_S(M_Z)} = 1.1\%$$

PDG´92: 2.4%

PDG, Chin. Phys. C 38 (2014) 090001.

α_s Projections

Still at LHC:

Only jets probe running α_s at highest scales

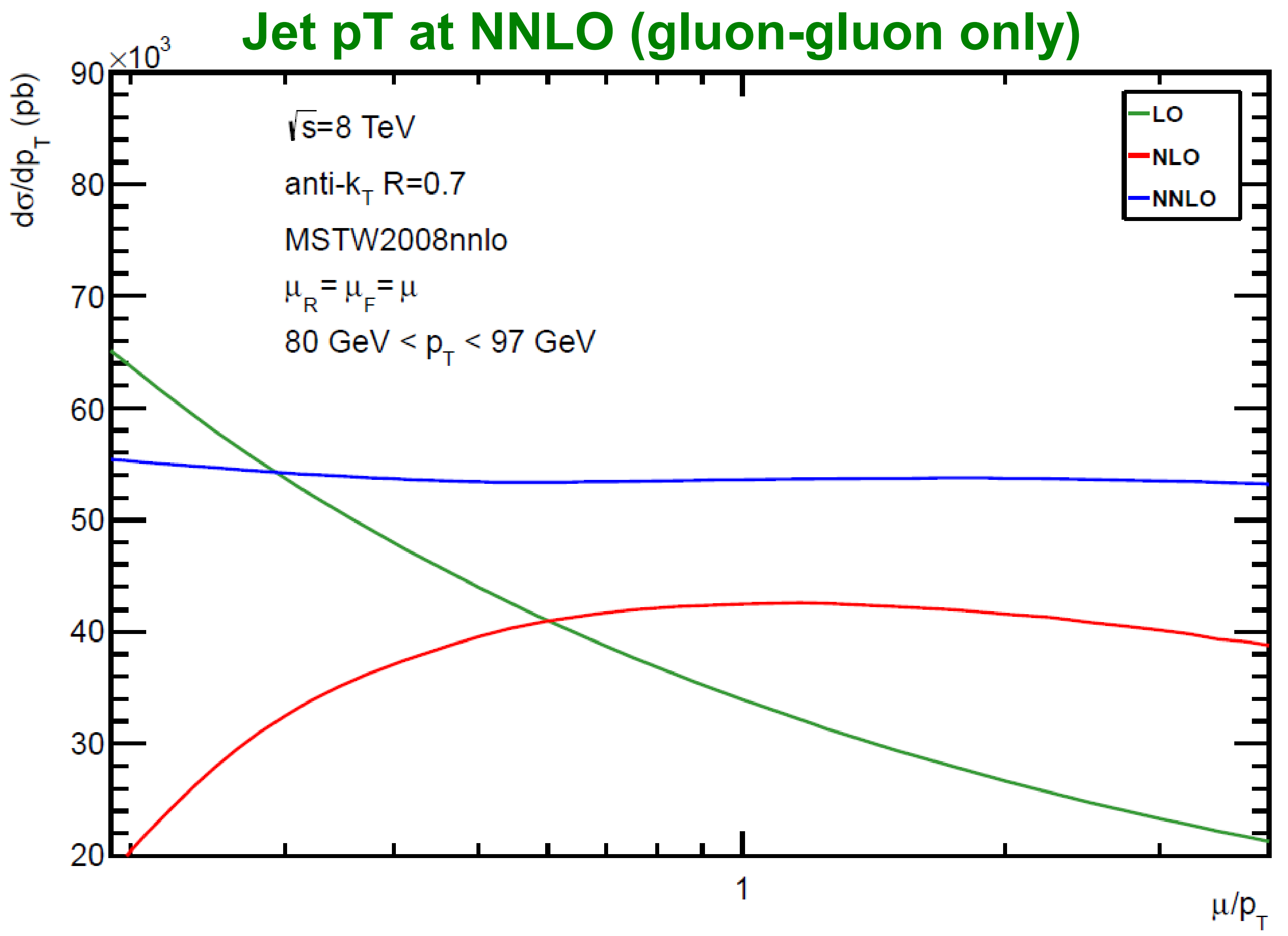
< 1% uncertainty at M_Z challenging, but not impossible

Need NNLO and improved PDFs (gluon) plus some experimental optimization

Method	Current relative precision	Future relative precision	
e^+e^- evt shapes	expt $\sim$ 1% (LEP) thry $\sim$ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	< 1% possible (ILC/TLEP) $\sim$ 1% (control n.p. via Q^2-dep.)	~1%
e^+e^- jet rates	expt $\sim$ 2% (LEP) thry $\sim$ 1% (NNLO, n.p. moderate) [28]	< 1% possible (ILC/TLEP) $\sim$ 0.5% (NLL missing)	
precision EW	expt $\sim$ 3% (R_Z, LEP) thry $\sim$ 0.5% (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim$ 0.3% (N^{4}LO feasible, $\sim$ 10 yrs)	<1%
τ decays	expt $\sim$ 0.5% (LEP, B-factories) thry $\sim$ 2% (N^{3}LO, n.p. small) [8]	< 0.2% possible (ILC/TLEP) $\sim$ 1% (N^{4}LO feasible, $\sim$ 10 yrs)	
ep colliders	$\sim$ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) $\sim$ 0.5% (at least N^{3}LO required)	<1%
hadron colliders	$\sim$ 4% (Tev. jets), $\sim$ 3% (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	< 1% challenging (NNLO jets imminent [22])	~1%
lattice	$\sim$ 0.5% (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim$ 0.3% ($\sim$ 5 yrs [38])	<0.5%

Snowmass QCD Report, arXiv:1310.5189.

NNLO Scale Dependence



Drastically reduced scale dependence!

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

Gehrmann- de Ridder et al., PRL110 (2013), JHEP1302 (2013).