α_s Determinations from CMS
Status & Plans

Winterseminar Saas-Grund

Klaus Rabbertz, KIT

Karlsruhe Institute of Technology

From LHC to FCC-ee

**Talk given at Workshop on
“High-precision α_s measurements from
LHC to FCC-ee”,
CERN, 12.-13. Oktober 2015**

Complemented with material from the workshop and proceedings.

**Workshop Proceeedings: arXiv: 1512.05194
Dedicated to the memory of Guido Altarelli
who normally would have been the summary speaker.**

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CERN Courier Article: →

**FCC-ee means:
Future Circular Colliders – e^+e^- Option**

CERN Courier December 2015

Faces & Places

Strong coupling: a workshop at CERN reviews latest advances

The latest progress in measurement of the strong interaction coupling was discussed in a recent workshop on “High precision measurements of α_s: from LHC to FCC-ee”, held at CERN on 12–13 October. The meeting brought together leading experts in the field to explore in-depth recent theoretical and experimental developments on the determination of α_s, new ways to measure this coupling in lepton–lepton, lepton–hadron and hadron–hadron collisions and, in particular, the improvements expected at the proposed Future Circular Collider e^+e^- (FCC-ee) facility.

In quantum chromodynamics (QCD), the coupling constant α_s sets the scale of the strength of the interaction at a given reference scale (usually taken at the Z boson mass), and it is one of the fundamental parameters of the Standard Model (SM). The α_s coupling, known up to now with $\delta\alpha_s \approx \pm 0.5\%$ uncertainty, is the least precisely known of all fundamental constants in nature, orders-of-magnitude less well known than the gravitational ($\delta G \approx \pm 10^{-5}$), Fermi's ($\delta G_F \approx \pm 10^{-8}$), and fine-structure ($\delta\alpha \approx \pm 10^{-10}$) constants. Improving our knowledge of α_s is a prerequisite to reduce the theoretical uncertainties in the calculations of all perturbative QCD (pQCD) processes whose cross-sections or decay rates depend on higher-order powers of α_s, as is the case for virtually all of those measured at the LHC. In the introductory session, S Bethke presented the preliminary 2015 update of the Particle-Data-Group (PDG) world-average α_s, obtained from comparison of next-to-next-to-leading-order (NNLO) pQCD calculations with a set of six groups of experimental data. Enlarged uncertainties from lattice QCD and tau–lepton decays, as well as the first NNLO extraction from top-pair cross-sections at the LHC, have doubled the uncertainty on α_s, which will move from $\alpha_s = 0.1185 \pm 0.0006$ to $\alpha_s = 0.1177 \pm 0.0013$. L Mihaila reviewed the impact on Higgs physics of α_s, which is the second major contributor – after the bottom mass – to the parametric uncertainties of its dominant $H \rightarrow b\bar{b}$ partial decay, and the largest source of uncertainty for the $c\bar{c}$ and gg decay modes. An accurate knowledge of the running of α_s at TeV energy scales is also crucial for physics searches beyond the SM. F Sannino presented generic exclusion bounds on masses of new coloured particles based on LHC data.

The second session of the workshop was devoted to low-energy studies of the QCD coupling, such as from lattice QCD (covered by P Mackenzie and X Garcia i Tormo), pion (J-L Kneur), τ (A Pich) and Υ (J Soto) decays, and soft parton-to-hadron fragmentation functions (FFs) (R Perez-Ramos). The comparison of pQCD predictions with computational lattice-QCD “data”, yielding $\alpha_s = 0.1184 \pm 0.0012$, still provides the most precise α_s extraction with a $\delta\alpha_s \approx \pm 1\%$ uncertainty. Hadronic decays of the tau lepton yield $\alpha_s = 0.1187 \pm 0.0023$ (i.e. $\delta\alpha_s = \pm 1.9\%$), although the results of different theoretical approaches are still a matter of debate. The pion decay factor was proposed as a new observable to extract $\alpha_s = 0.1174 \pm 0.0017$, notwithstanding the low scales involved, which challenge the pQCD applicability. Decays of the b–$\bar{b}$ bound state (Υ) used to constrain the QCD coupling until a few years ago ($\alpha_s = 0.1190 \pm 0.0070$), but their lower degree of (NLO) theoretical accuracy should be improved to be included in future PDG updates. Similarly, the energy evolution of the distribution of hadrons in jets has proven to be a novel robust method to extract $\alpha_s = 0.1205 \pm 0.0022$, but the calculations need to go beyond their current approximate-NNLO accuracy.

Future measurements

Determinations of α_s at higher energy scales – including global fits of parton distribution functions (PDFs) (reviewed by J Bluemlein), hard parton-to-hadron FFs (B Kniehl), jets in $e^{\pm}p$ (M Klasen), e^+e^- event shapes (S Kluth, A Hoang), jet cross-sections in e^+e^- (A Banfi), Z and W decays (K Moenig, M Srebre), and the $e^+e^- \rightarrow$ hadrons cross-section (J Kuehn) – were covered in the third workshop section. The NNLO analyses of PDFs have good precision ($\delta\alpha_s = \pm 1.7\%$), albeit yielding a central value lower than the rest of the methods: $\alpha_s = 0.1154 \pm 0.0020$.

Upcoming NNLO fits of the jet FFs will provide a QCD coupling that is more accurate than the current one at NLO ($\alpha_s = 0.1176 \pm 0.0055$). Similarly, a full-NNLO analysis of jet production in $e^{\pm}p$ is needed to improve the current $\alpha_s = 0.121 \pm 0.003$ extraction from these observables. Electron–positron event shapes and jet rates yield $\alpha_s = 0.1174 \pm 0.0051$ with a $\delta\alpha_s = \pm 4.3\%$ uncertainty, but new e^+e^- data at lower and higher energies than LEP are required for better control of hadronisation corrections. The hadronic decays of electroweak bosons are high-precision observables for extraction of the strong coupling. The current Z data provide $\alpha_s = 0.1196 \pm 0.0030$, i.e. $\delta\alpha_s = \pm 2.5\%$, which can be reduced to below ±0.3% with the huge statistical data sets expected at the FCC-ee. The W hadronic decay data are not as precise today, but promise the same α_s sensitivity with measurements at the FCC-ee. The final session was dedicated to α_s extractions at hadron colliders. Important NNLO theoretical developments for top-quark pair and jet cross-sections were reviewed by A Mitov, G Salam and J Pires. A lowish $\alpha_s = 0.1151 \pm 0.0028$ value with $\delta\alpha_s = \pm 2.5\%$ uncertainty is obtained using the only $t\bar{t}$ cross-sections published so far by CMS, although inclusion of all preliminary data increases it to $\alpha_s \approx 0.1201 \pm 0.0025$. The imminent release of the NNLO calculation for jets will provide a huge boost for PDFs, FFs and cross-section studies in pp, $e^{\pm}p$ and γp collisions. To date, the NLO combination of ATLAS, CMS and Tevatron jet results yields $\alpha_s = 0.1179 \pm 0.0023$. Existing and planned measurements of α_s at the LHC were also reviewed by B Malaescu (ATLAS) and K Rabbertz (CMS), clearly confirming asymptotic freedom at multi-TeV scales. The results of the workshop will be incorporated into the FCC Conceptual Design Report under preparation. Whereas the strong force decreases with energy, scientific interest in the QCD interaction clearly proves constant, if not increasing, with time.

- For more information, see indico.cern.ch/e/alphas2015.

Summary of the strong coupling extractions discussed in the workshop.

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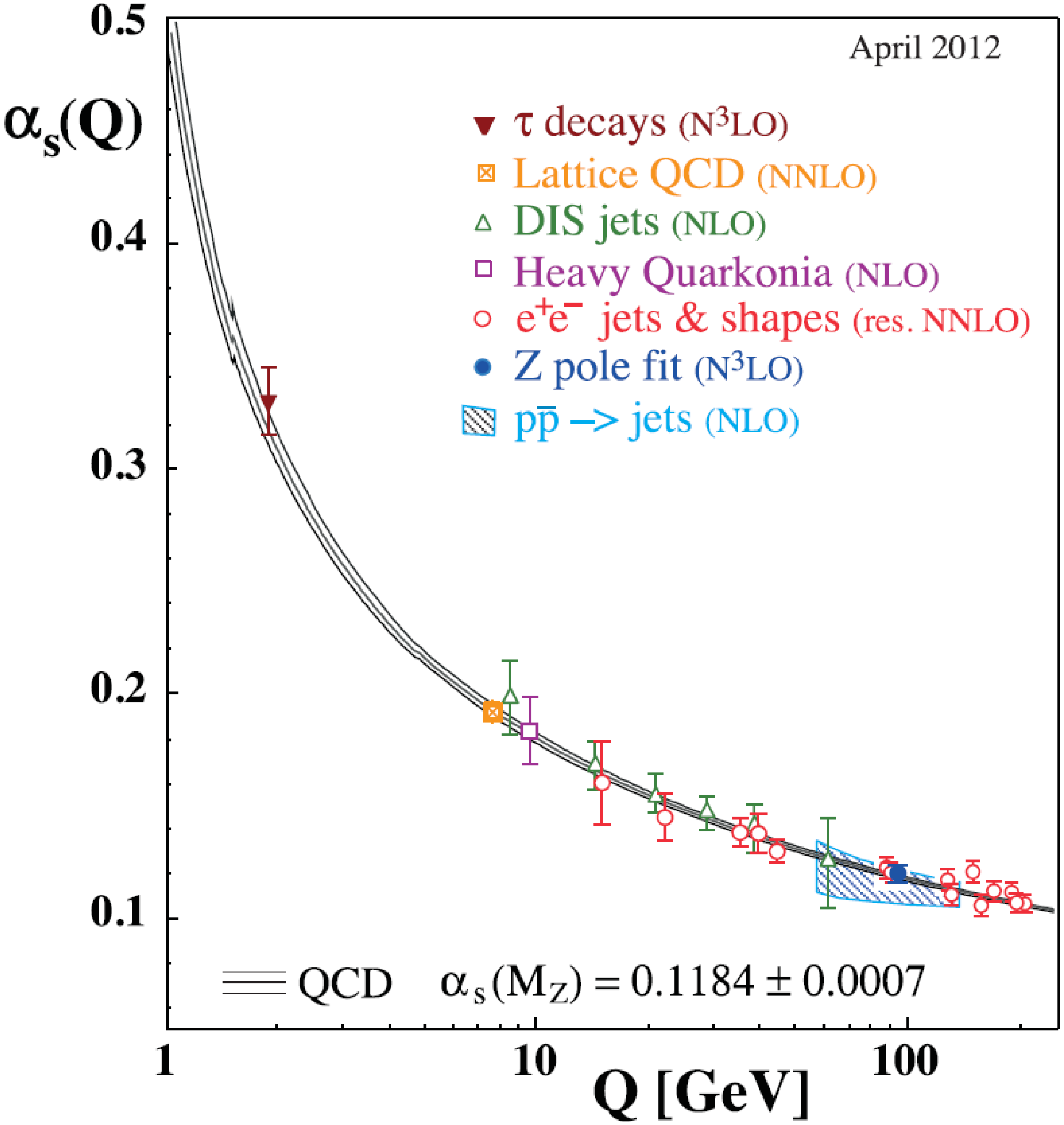
Outline

- **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

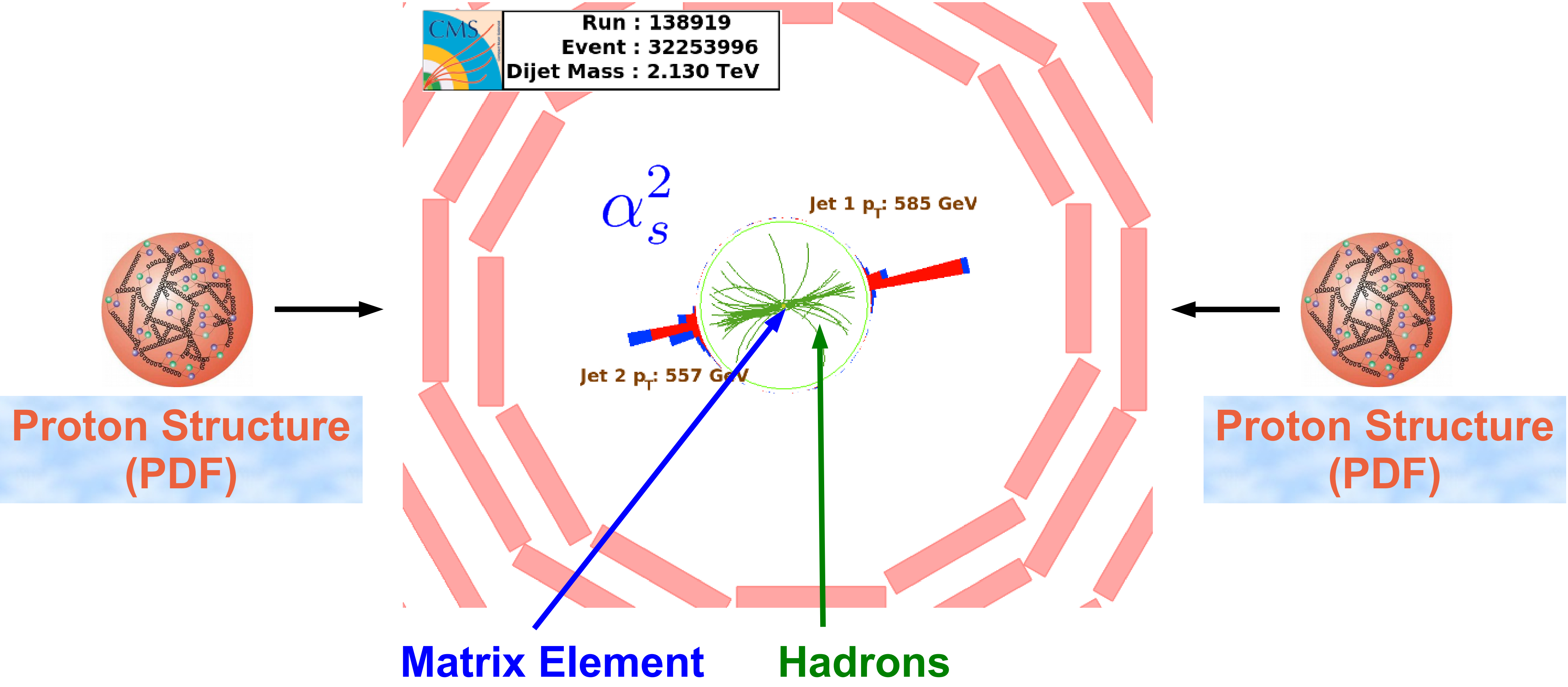
PDG2012



Jets at the LHC

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 hard QCD, the proton structure, non-perturbative effects, and electroweak effects at high Q



Proton Structure (PDF)

Proton Structure (PDF)

Matrix Element

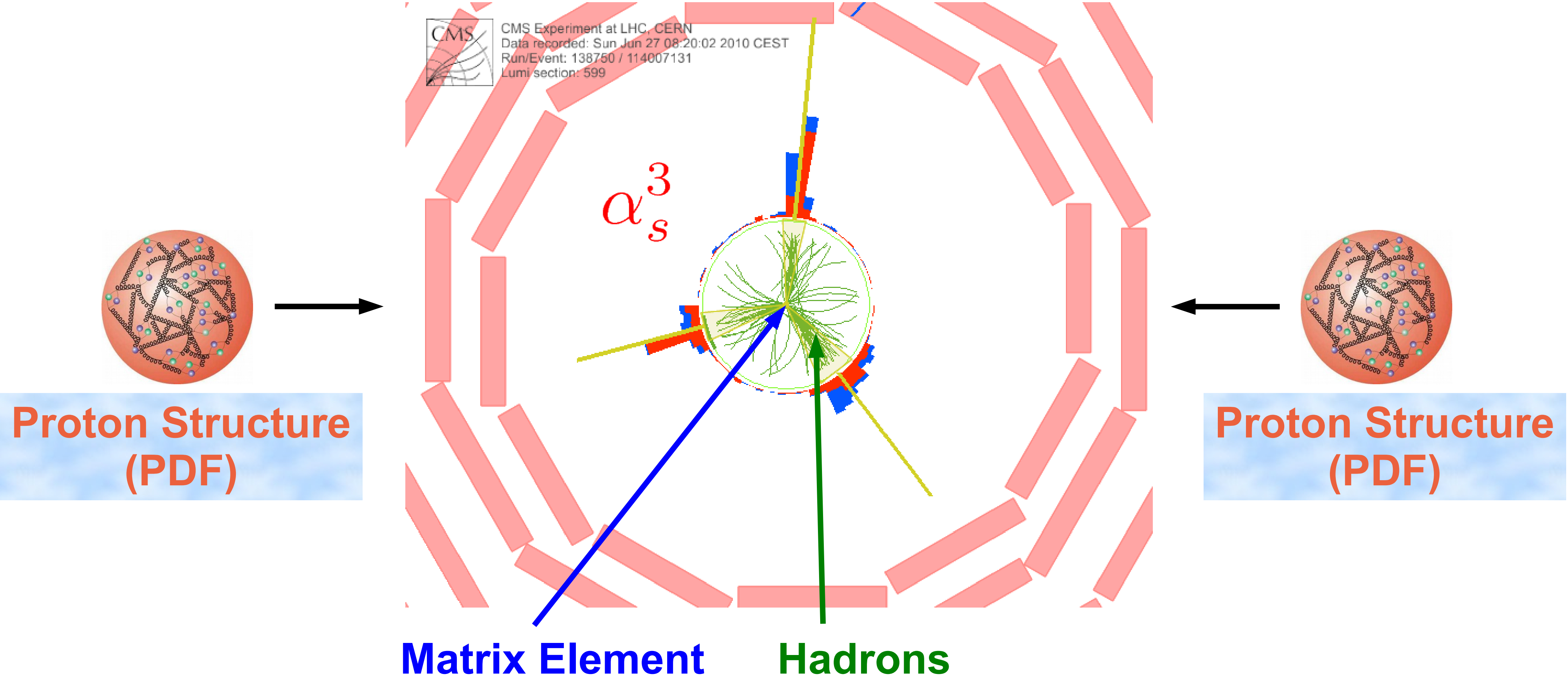
Hadrons

Jets at the LHC

Abundant production of jets:

- Extract $\alpha_s(M_Z)$, the least precisely known fundamental constant!

  $\delta\alpha \sim 3\cdot10^{-10}$, $\delta G_F \sim 5\cdot10^{-8}$, $\delta G \sim 10^{-5}$, $\delta\alpha_s \sim 10^{-2}$



Proton Structure (PDF)

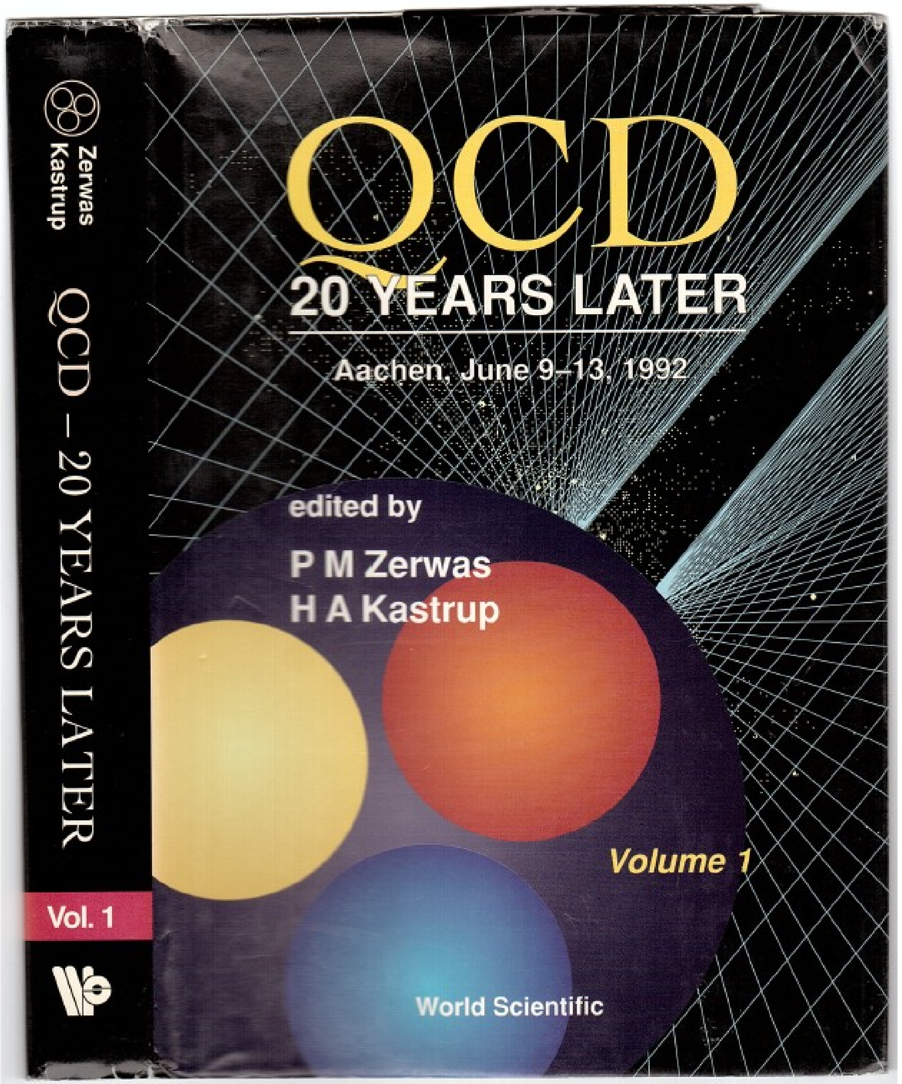
Proton Structure (PDF)

Matrix Element

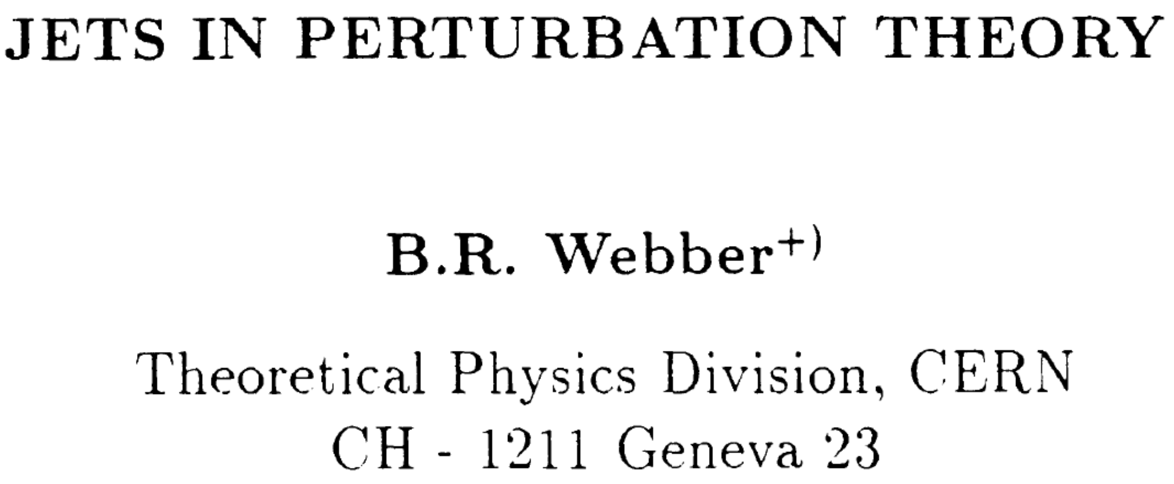
Hadrons

Some personal History

The very first physics conference I went to in Aachen, just starting my Diploma thesis 1992:



Didn´t understand overly much …
My Physics Seminars in Aachen were on “easy” electroweak stuff.
But I still remember talks by B. Webber on Jets and G. Altarelli on α_s



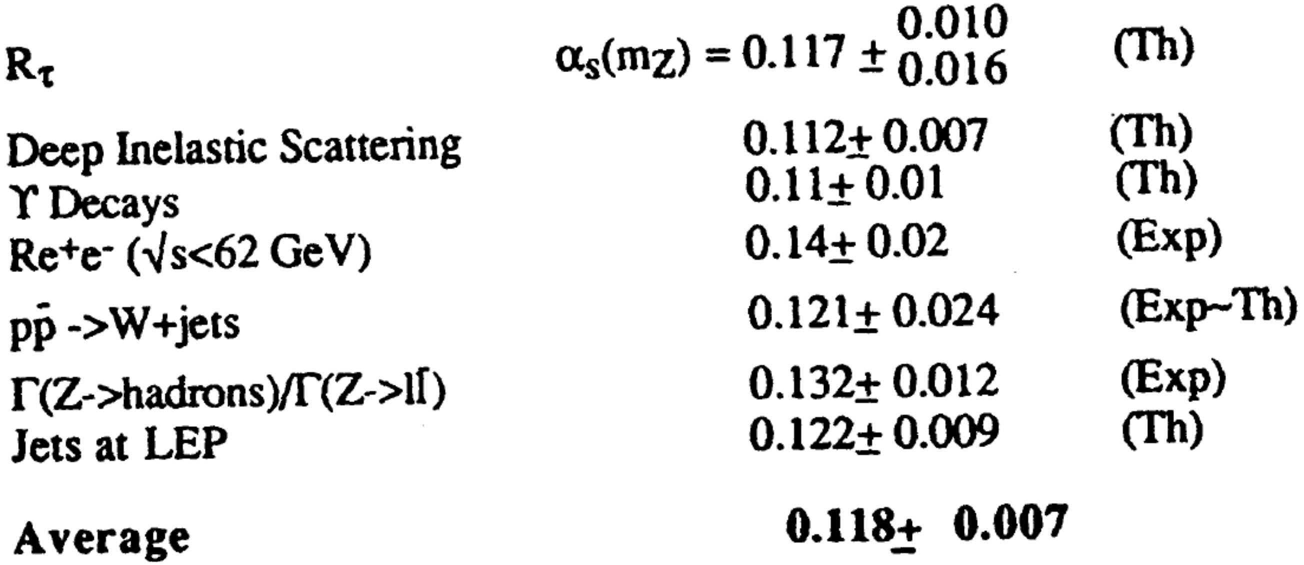
JETS IN PERTURBATION THEORY

B.R. Webber+)

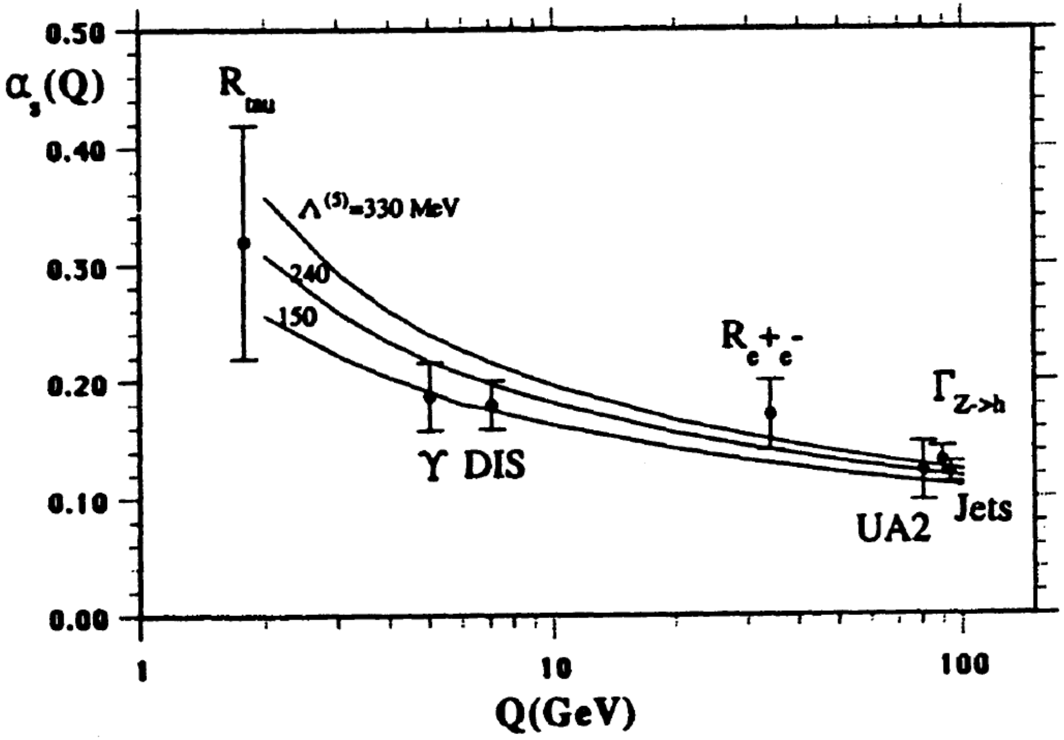
Theoretical Physics Division, CERN
CH - 1211 Geneva 23

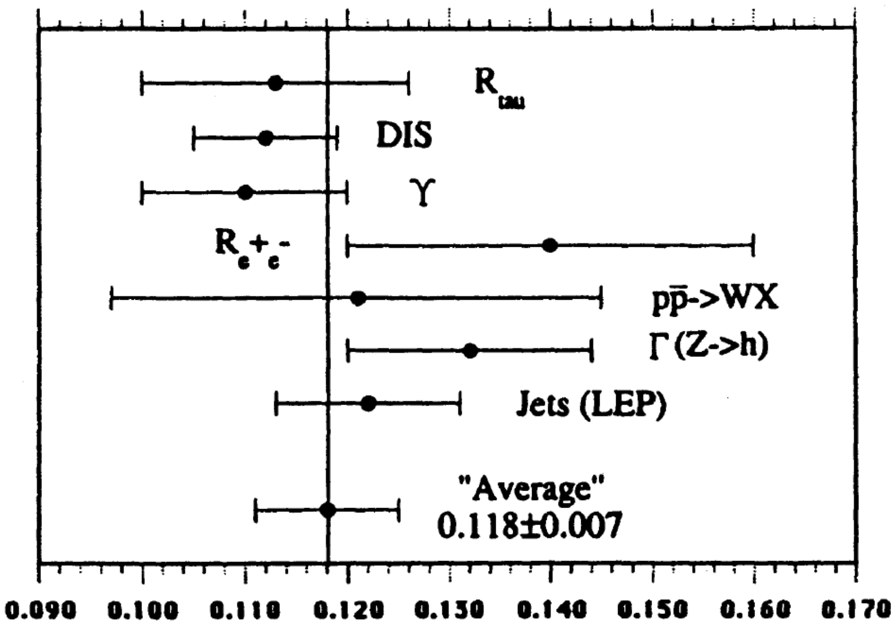
QCD and Experiment: Status of α_s

G. Altarelli: Rapporteur talk given at the Conference "QCD – 20 Years Later" Aachen, Germany, June 1992



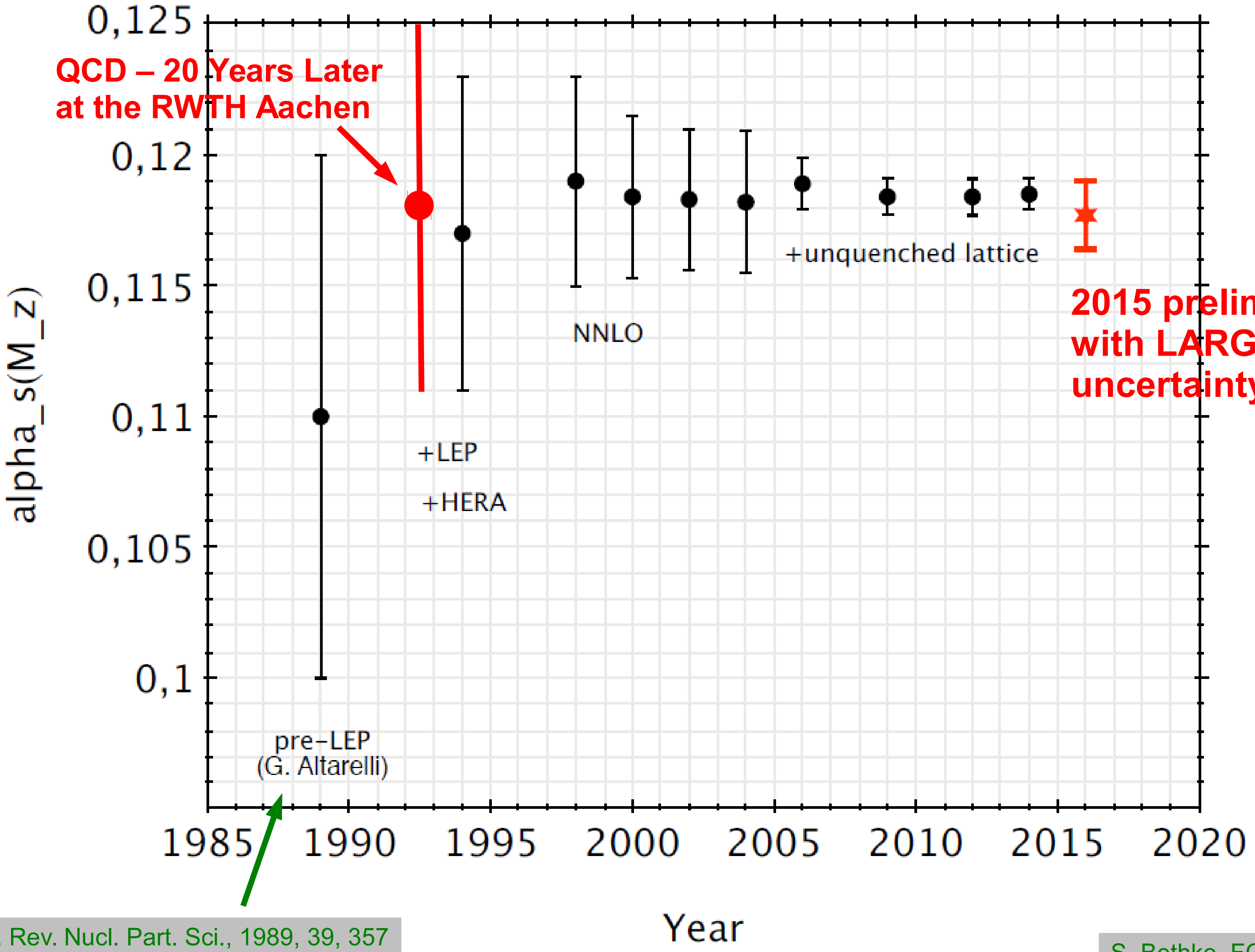
R_τ	$\alpha_s(m_Z) = 0.117 \pm^{0.010}_{0.016}$	(Th)
Deep Inelastic Scattering	0.112 ± 0.007	(Th)
Υ Decays	0.11 ± 0.01	(Th)
$R_{e^+e^-}$ ($\sqrt{s}$<62 GeV)	0.14 ± 0.02	(Exp)
$p\bar{p}$ ->W+jets	0.121 ± 0.024	(Exp~Th)
Γ(Z->hadrons)/Γ(Z->$l\bar{l}$)	0.132 ± 0.012	(Exp)
Jets at LEP	0.122 ± 0.009	(Th)
Average	**0.118 ± 0.007**	





G. Altarelli, QCD – 20 Years Later, Aachen, 1992

History of World Average of α_s



QCD – 20 Years Later at the RWTH Aachen

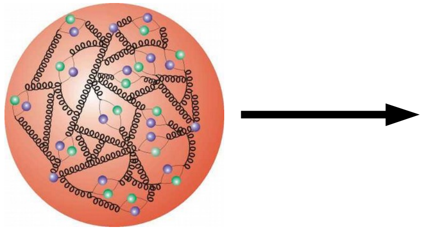
2015 preliminary ... with LARGER uncertainty

G. Altarelli, Ann. Rev. Nucl. Part. Sci., 1989, 39, 357

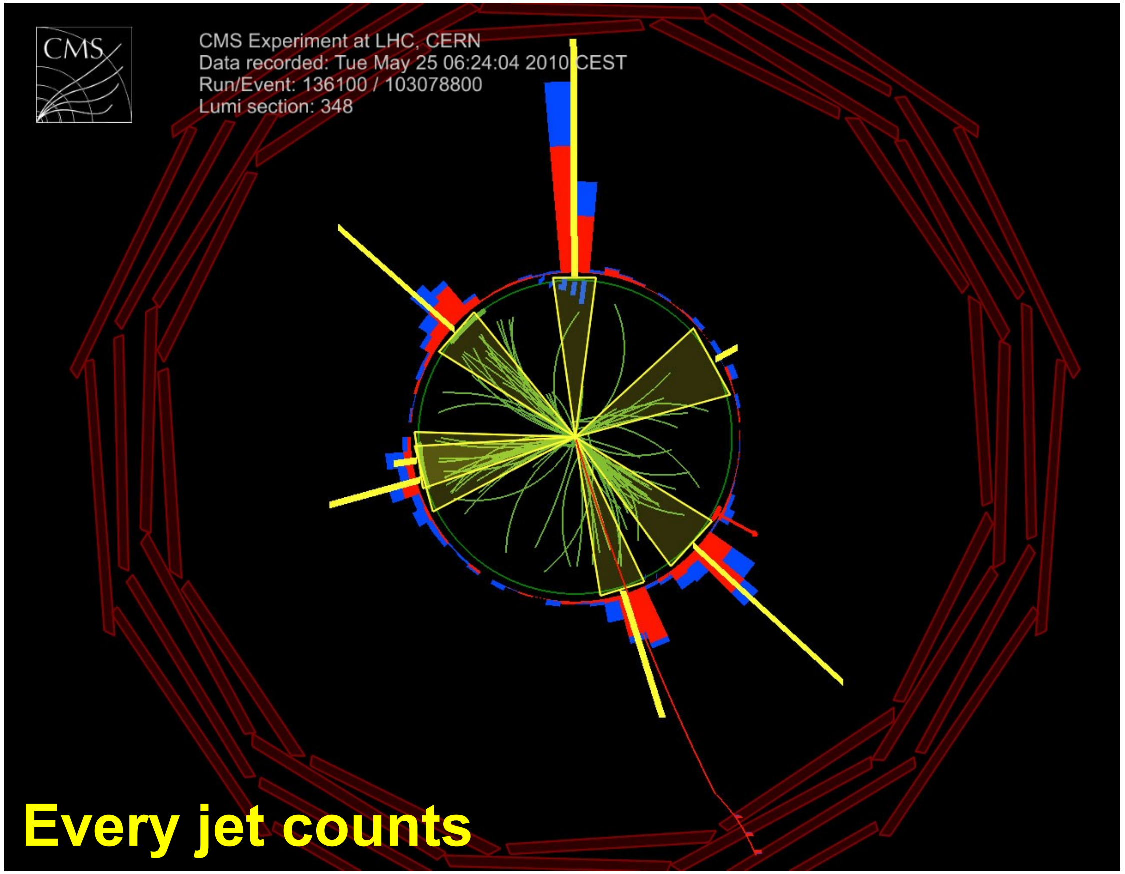
S. Bethke, FCC-ee Workshop

All Inclusive

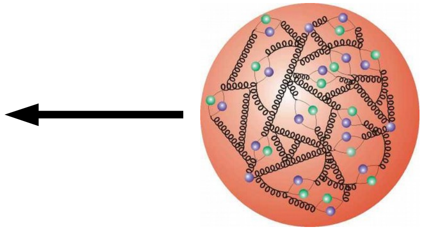
High transverse Momenta



Proton



Every jet counts



Proton

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

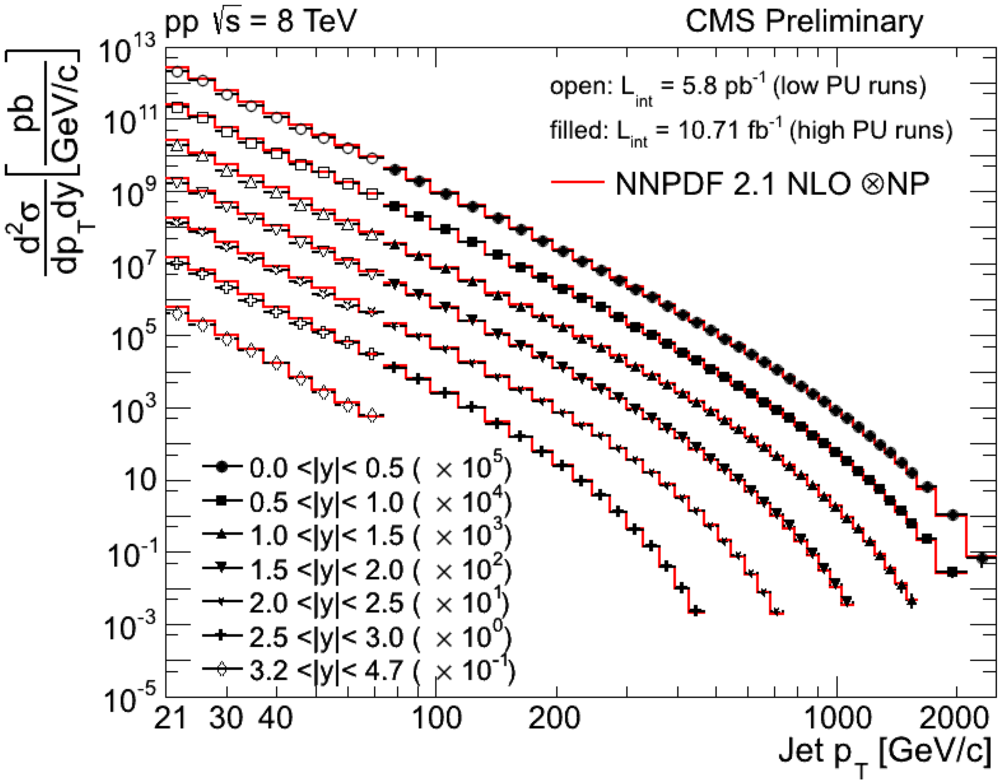
Similar picture at 7 TeV, 8 TeV (left) or NEW 2.76 TeV (right)

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

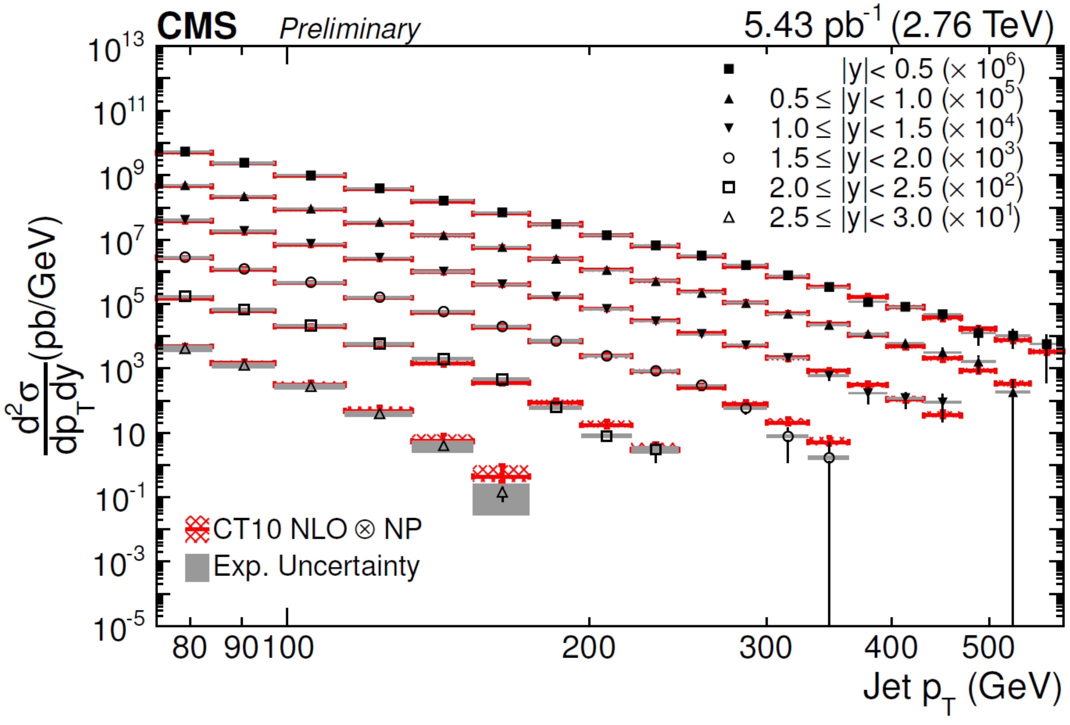
CMS-PAS-SMP-12-012 (2013),
CMS-PAS-FSQ-12-031 (2013),
CMS-PAS-SMP-14-017 (2015).

Data vs. NLO pQCD ⊗non-perturbative corrections

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

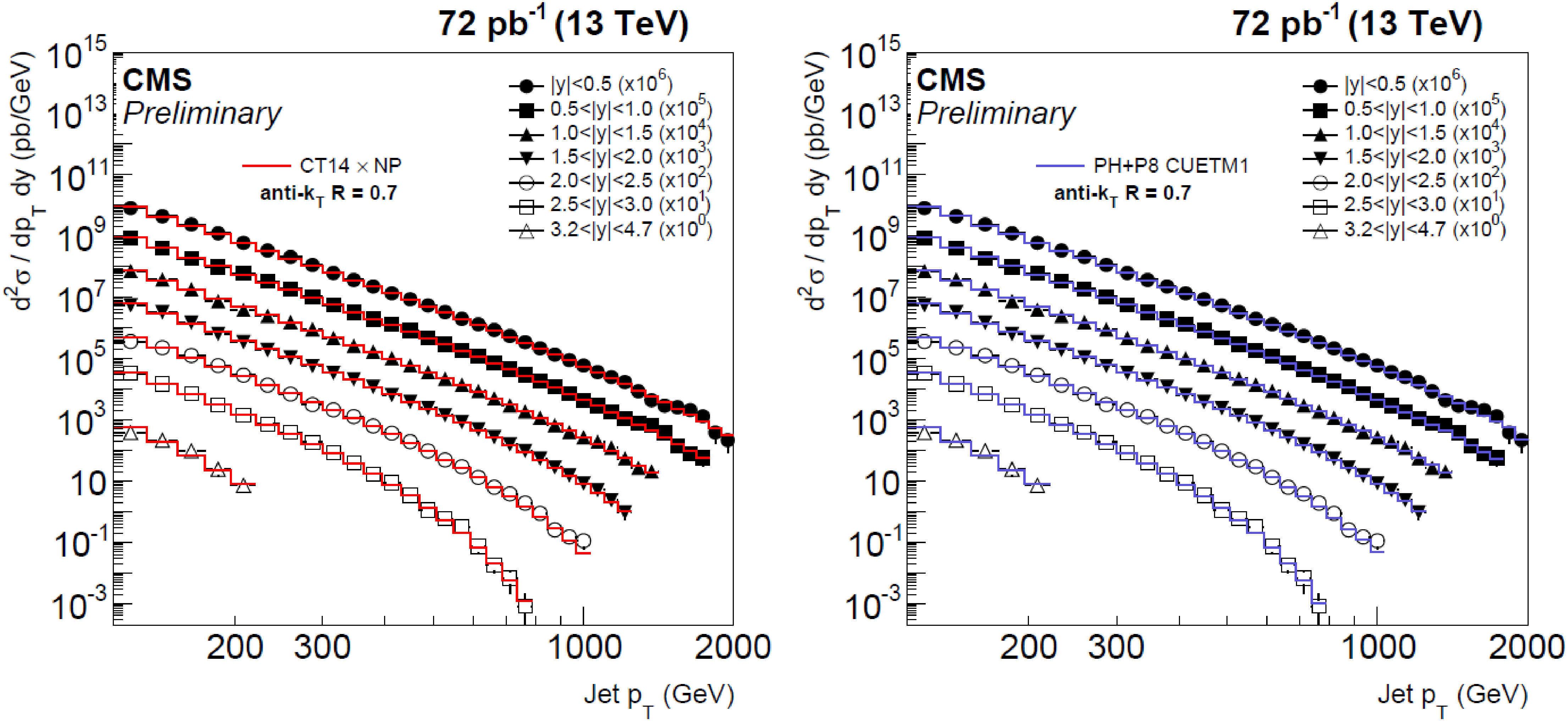


anti-kT, R=0.7, 2.76 TeV, 2012



Inclusive Jets at 13 TeV

Additional result presented at Dezember Jamboree



CMS-PAS-SMP-15-007 (2015).

Inclusive Jets + α_s & PDFs

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

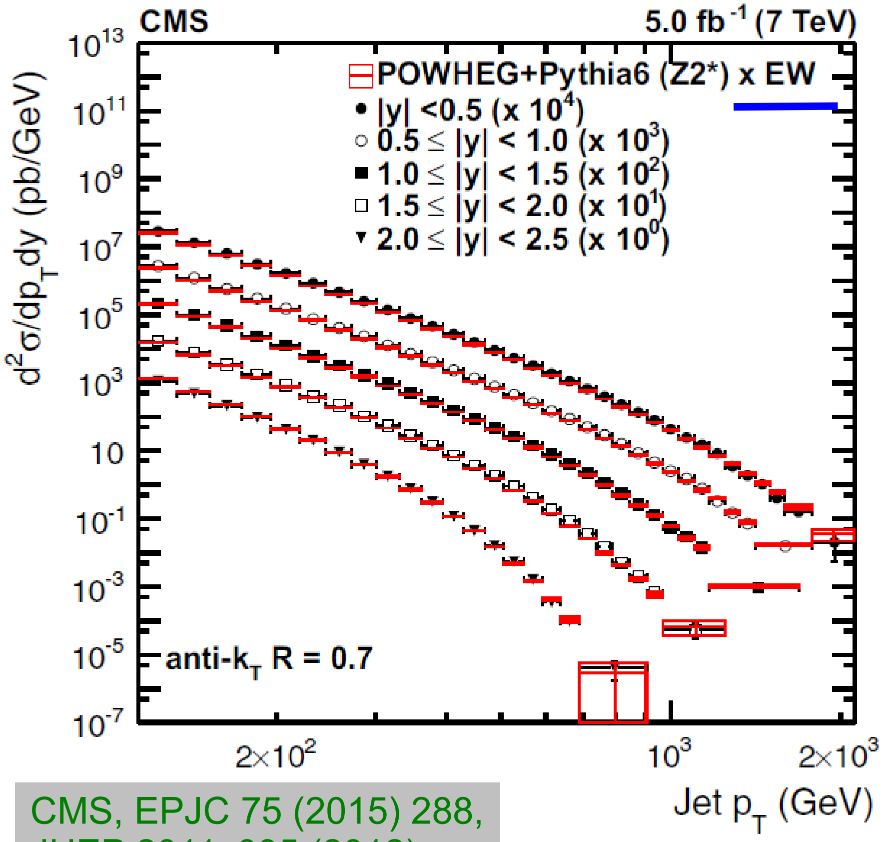
$$Q = p_{\mathrm{T,jet}}$$

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

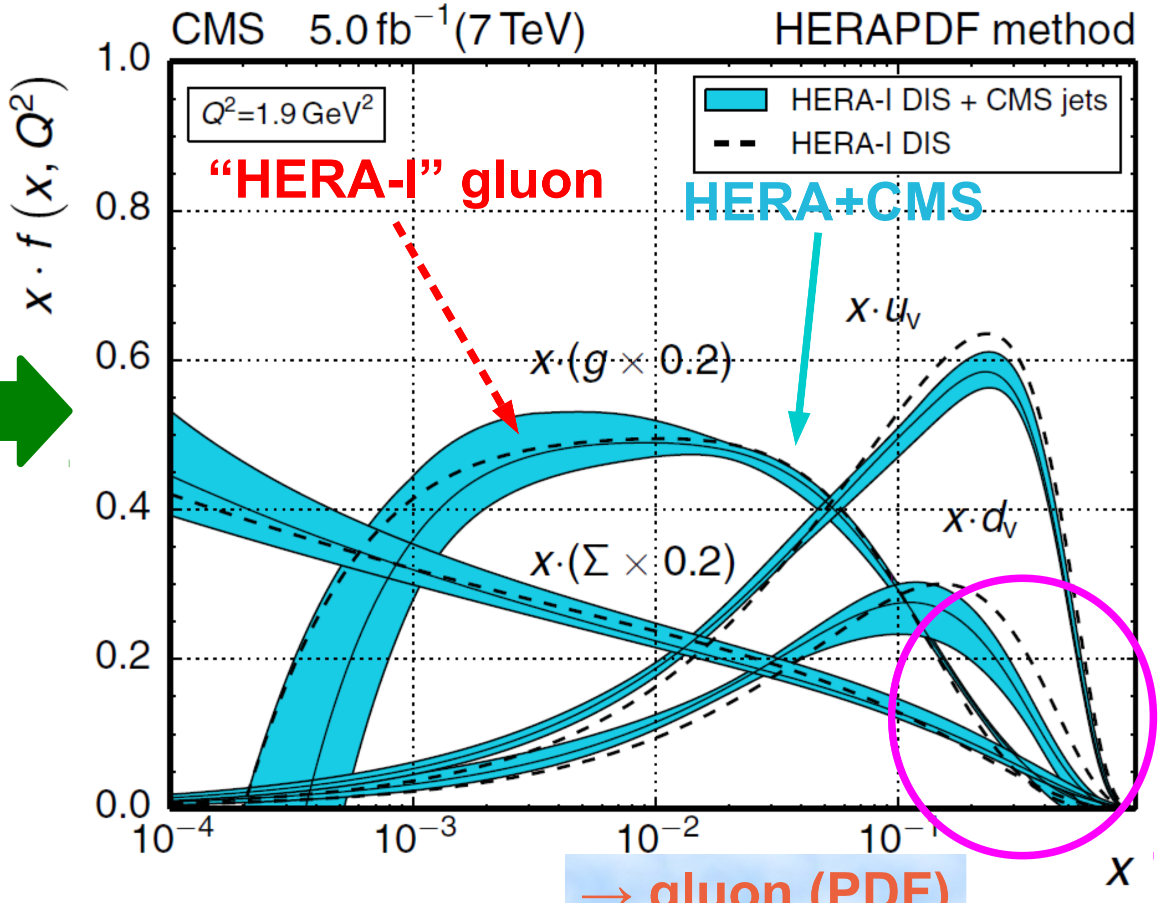
Data vs. NLO+PS ⊗ EW corrections
→ impact visible in norm. dijet angular obs.

"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

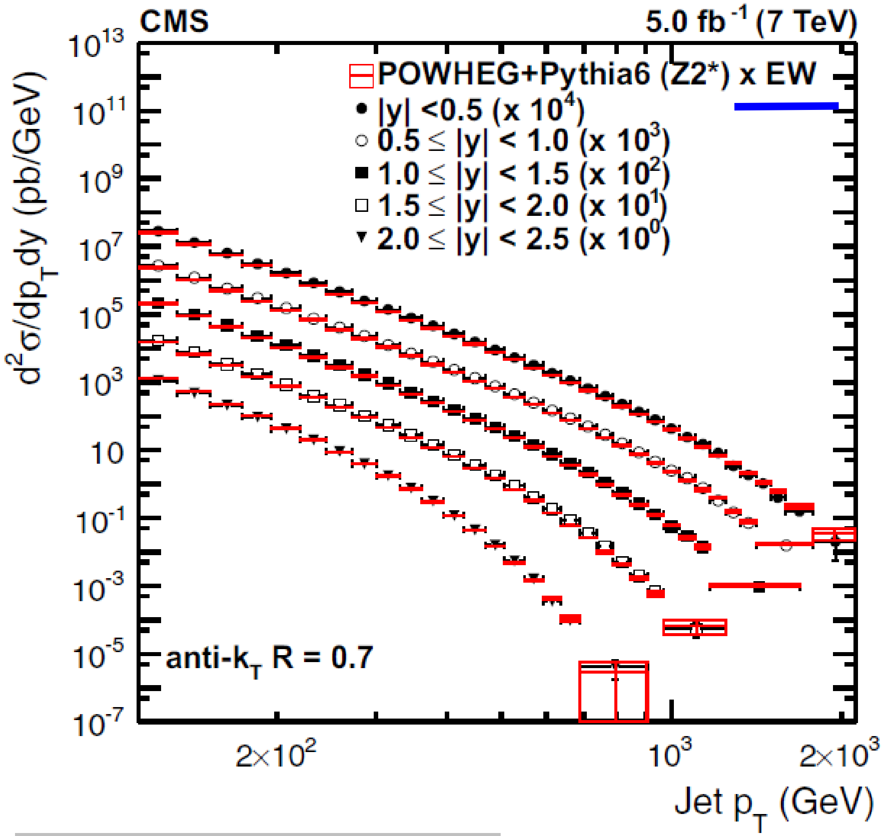
Simultaneous fit of α_s & PDFs possible combining HERA 1 DIS & CMS jet data using HERAFitter Tool

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

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

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

$$\alpha_s(M_Z) = 0.1185 \pm 0.0019\,(\mathrm{exp})$$

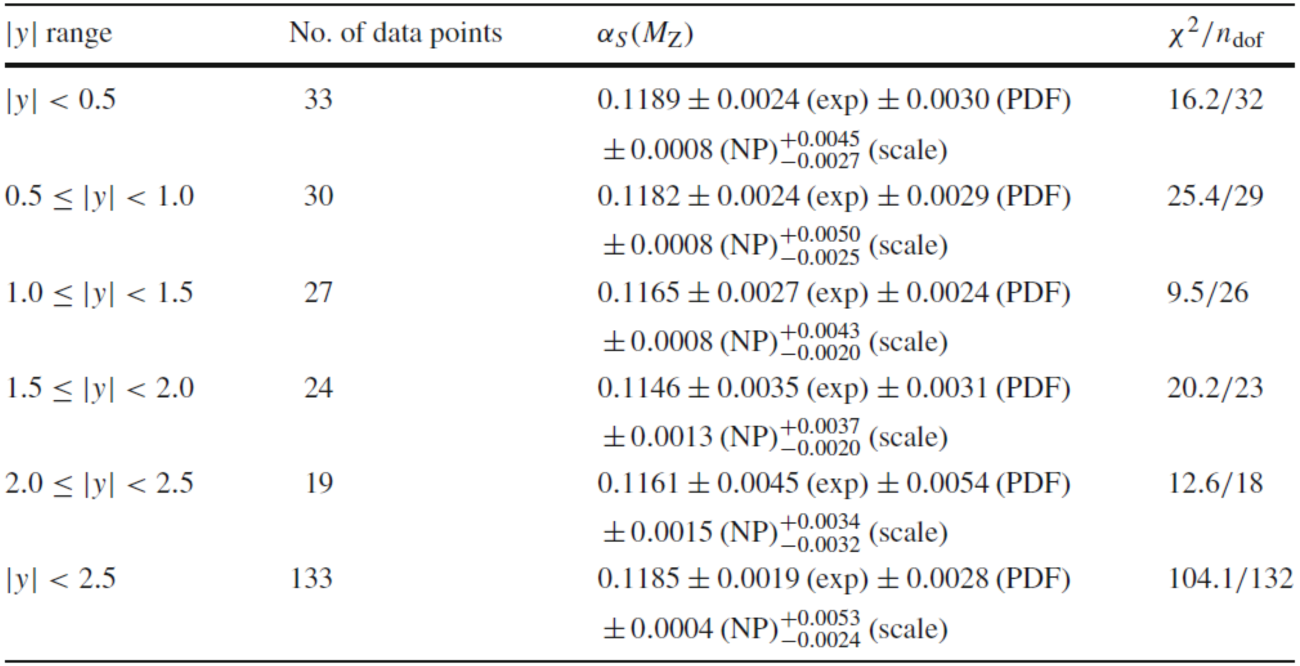
$$\pm 0.0028\,(\mathrm{PDF}) \pm 0.0004\,(\mathrm{NP}) \boxed{\pm^{0.0053}_{0.0024}}\,(\mathrm{scale})$$

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

→ α_s & gluon (PDF)

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

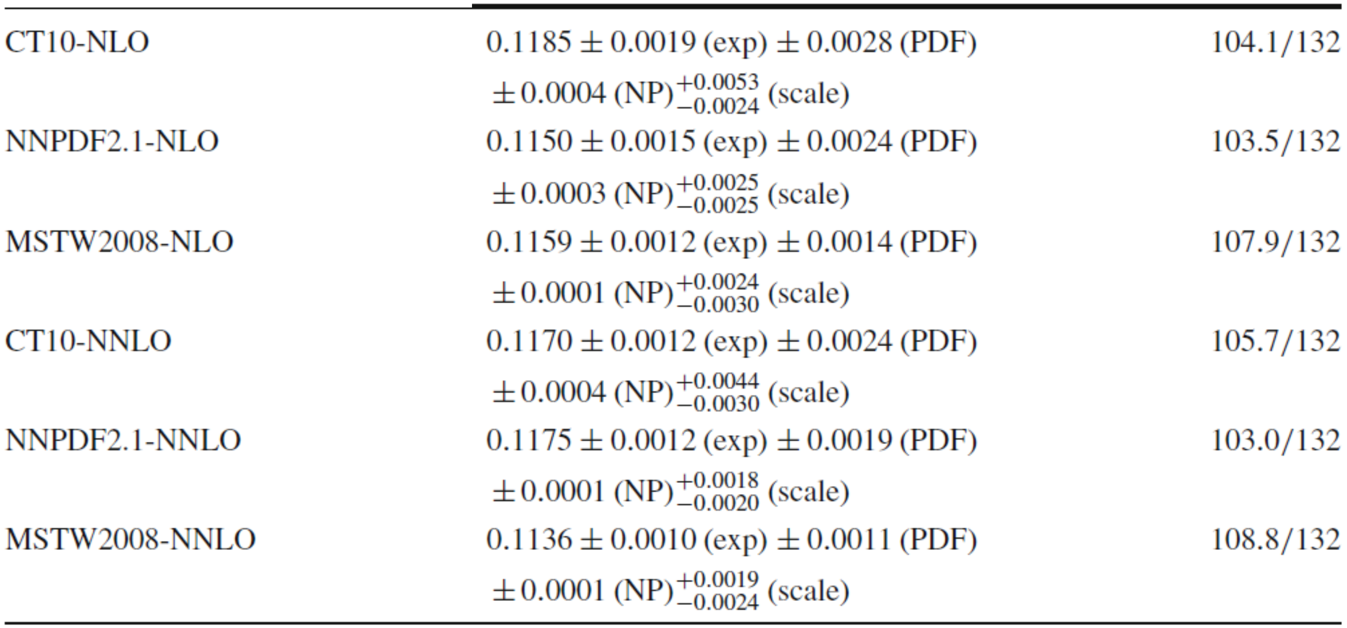
Details: α_s from inclusive Jets



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

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

Fit results for all |y| bins with other PDFs



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

CMS, EPJC 75 (2015) 288.

Inclusive Jet Ratios: “2.76 / 8.0”

New from CMS:

- cross sections at 2.76 TeV
- ratios to 8 TeV

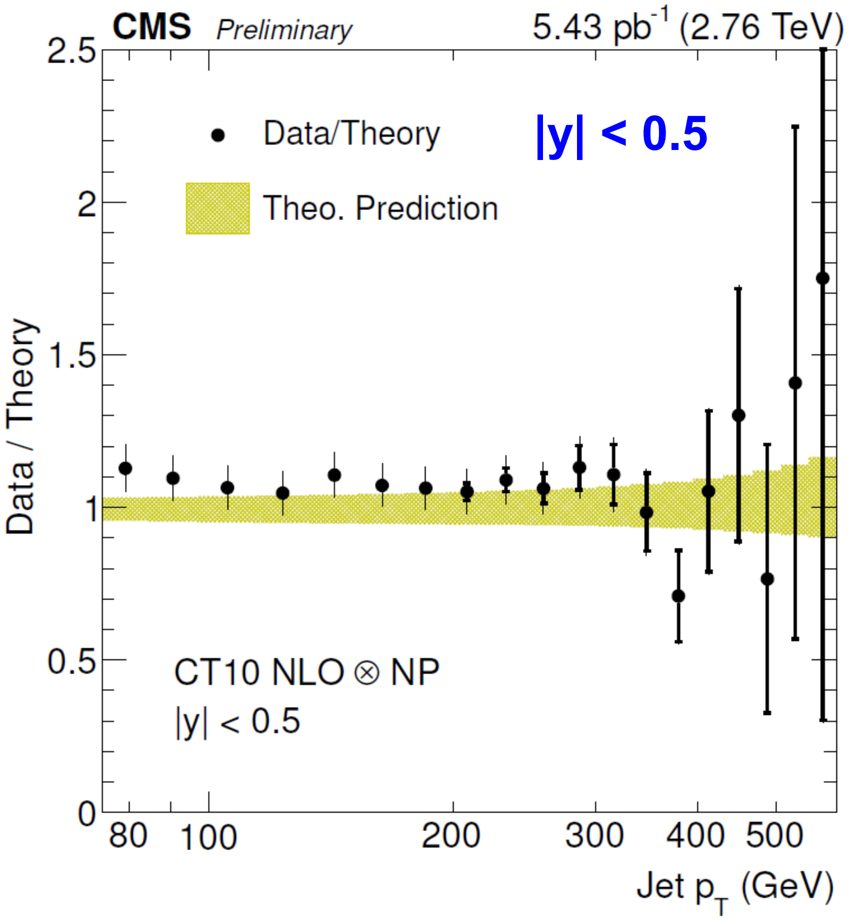
  Shown

- double ratio to theory

Ratio at E_{cms} = 2.76 and 8.0 TeV

→ at least partial cancellation of uncertainties

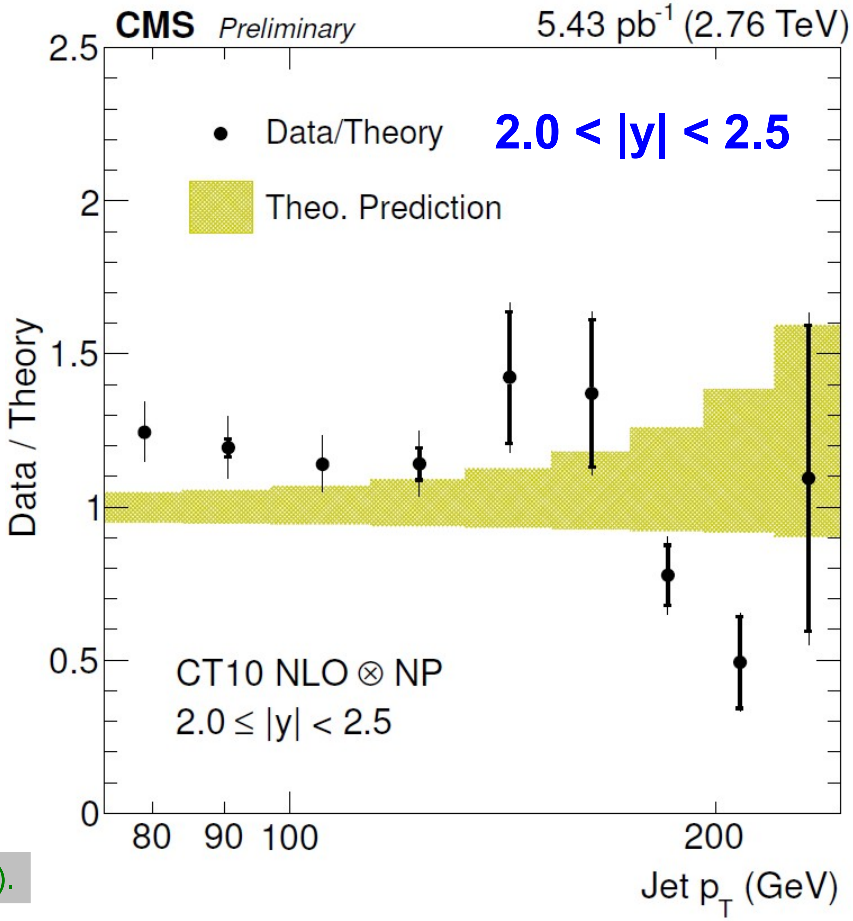
→ more precise comparisons



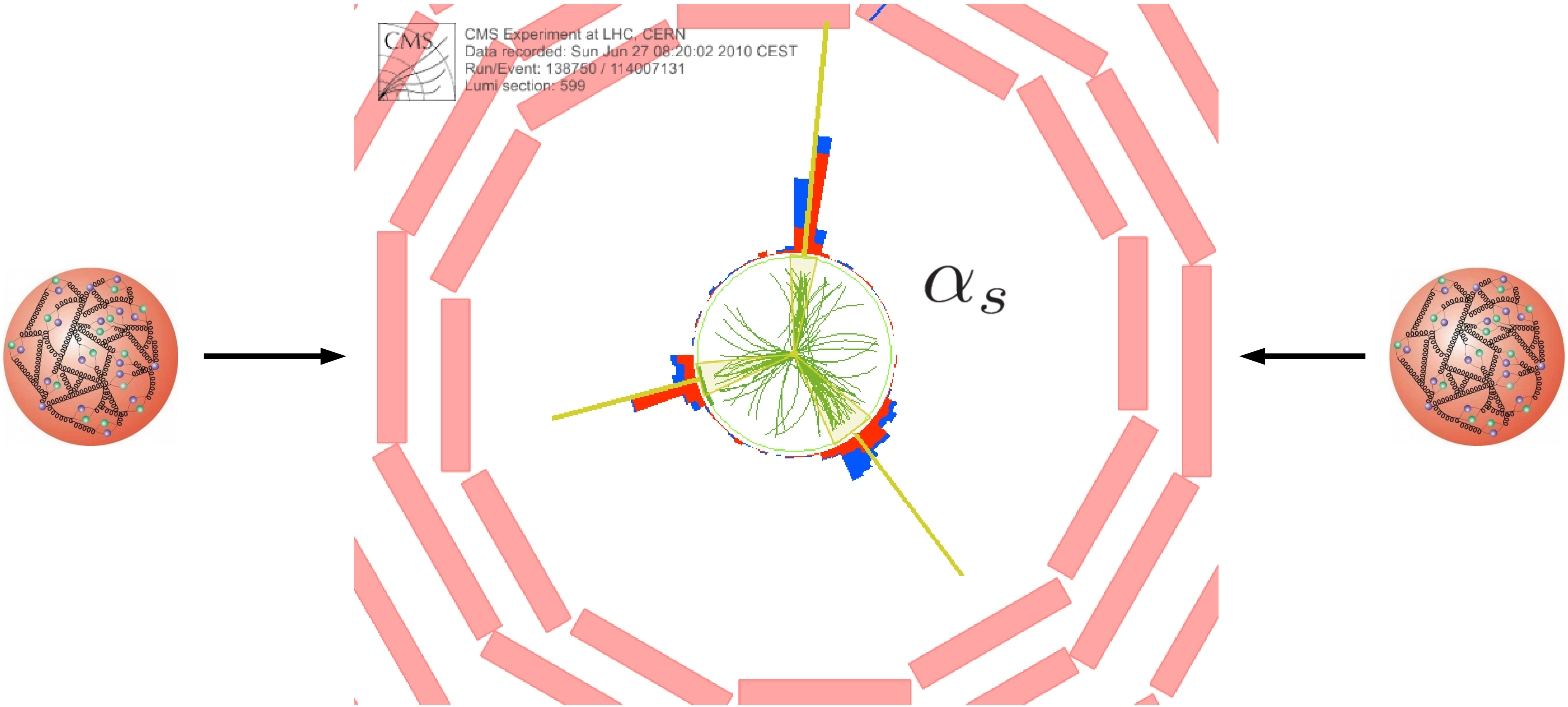
Disentangle α_s & g(x) by fitting in wide phase space of pT, y, and √s ?

→ gluon (PDF)

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



Multi-Jets and α_s

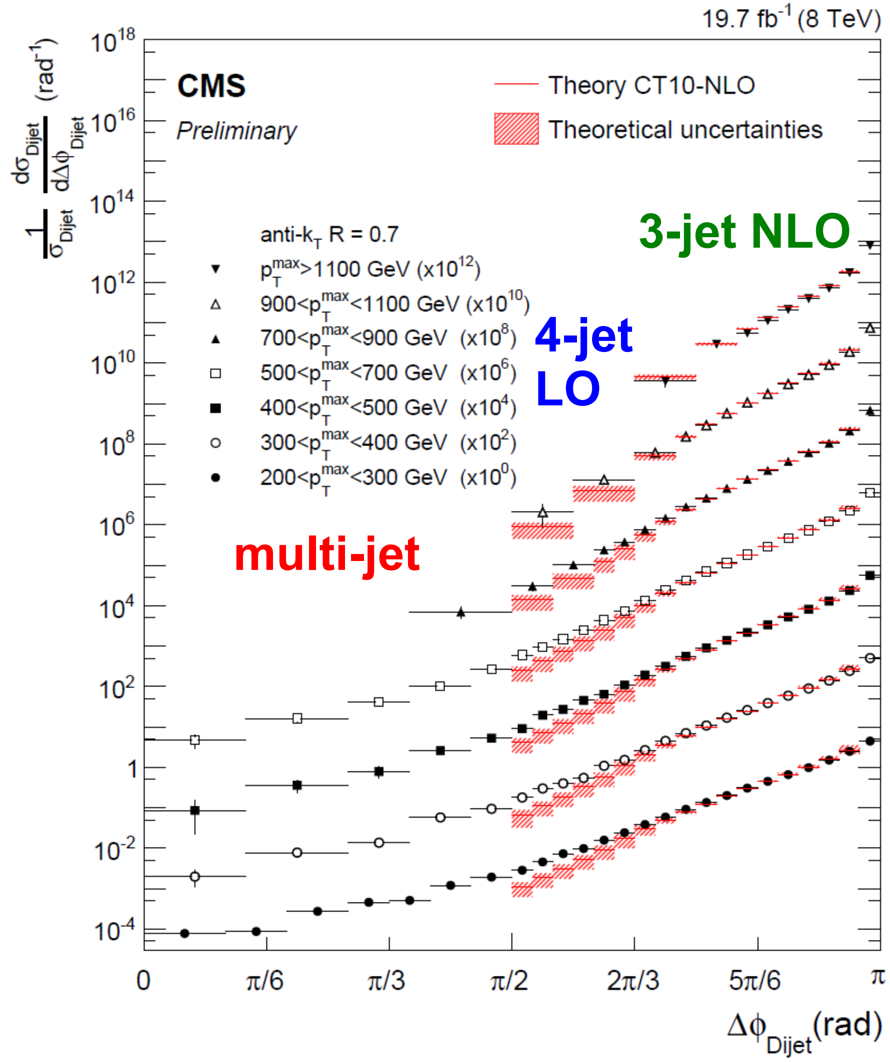


Azimuthal Decorrelations at 8 TeV

$\Delta\varphi_{jj}$ 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.



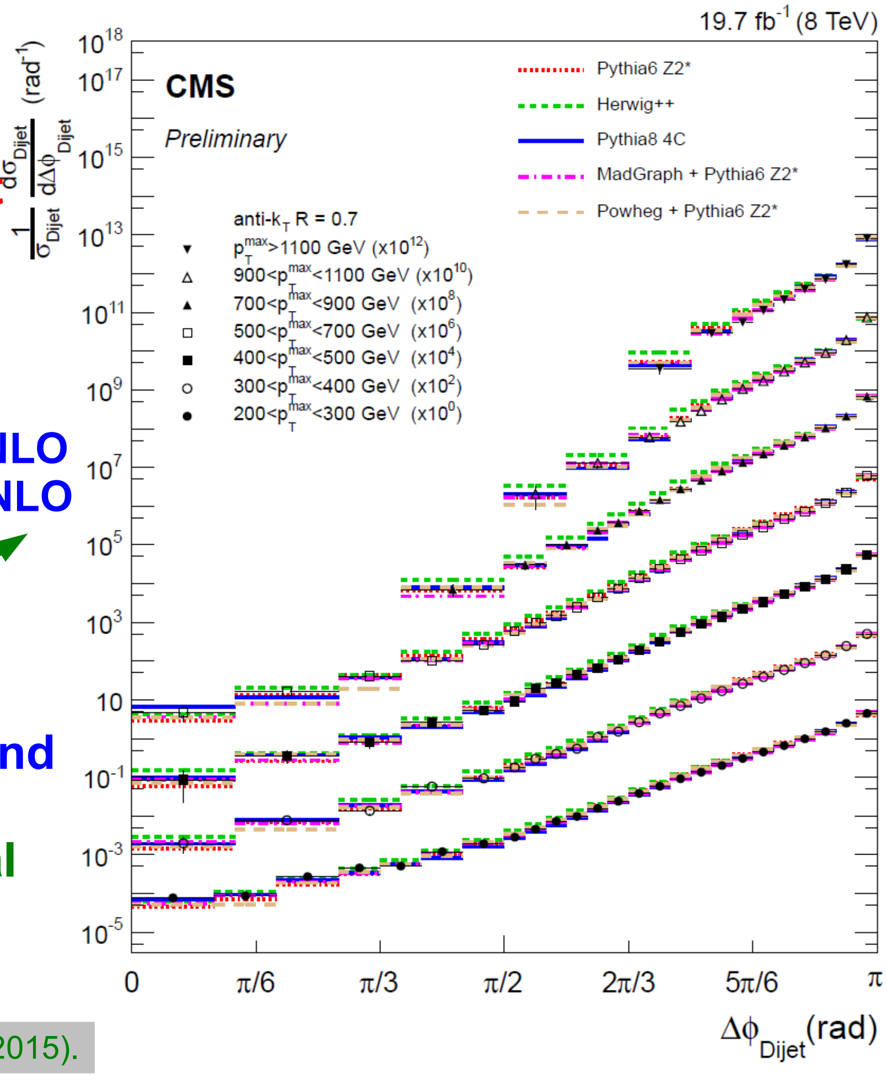
3-jet NLO

4-jet LO

multi-jet

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).

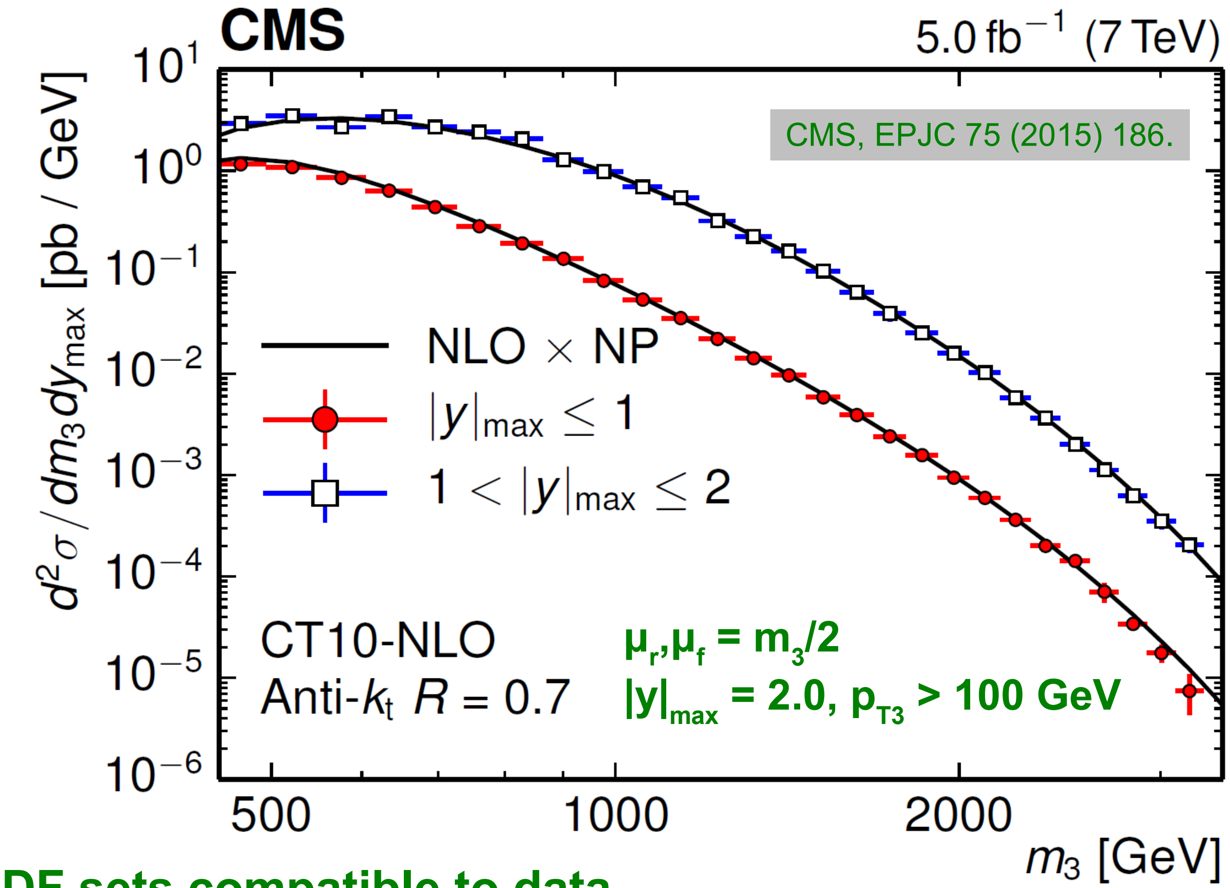
3-Jet Mass

Sensitive to α_s beyond 2→2 process

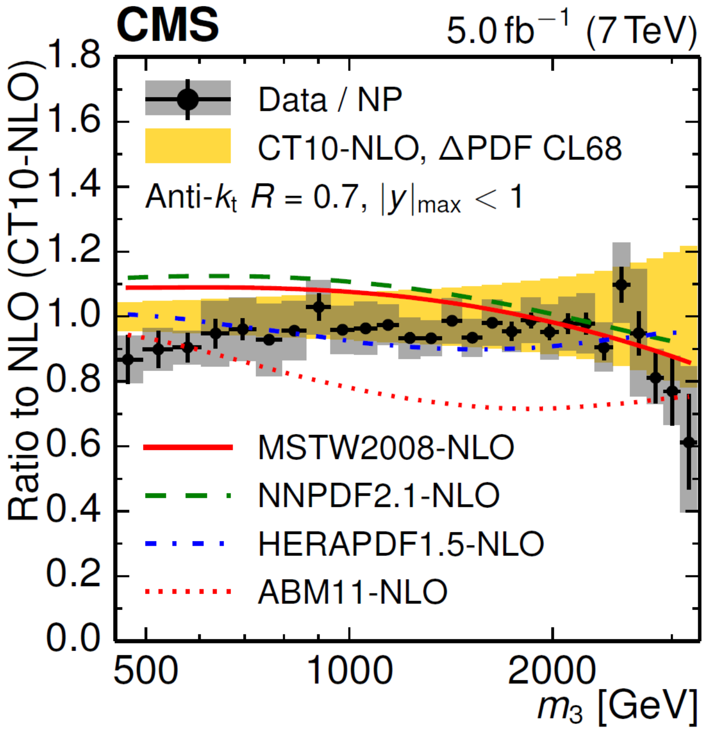
NLO with 3-4 partons (NLOJet++)

Sensitive to PDFs

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



CMS, EPJC 75 (2015) 186.



Most PDF sets compatible to data

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

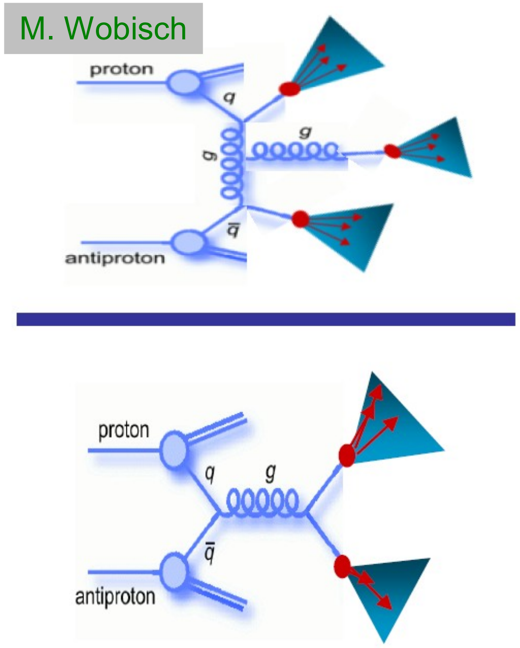
Extraction of $\alpha_s(M_Z)$: $\rightarrow \alpha_s$

Dominated by theory uncertainty (NLO)!

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

3- to 2-Jet Ratios

M. Wobisch

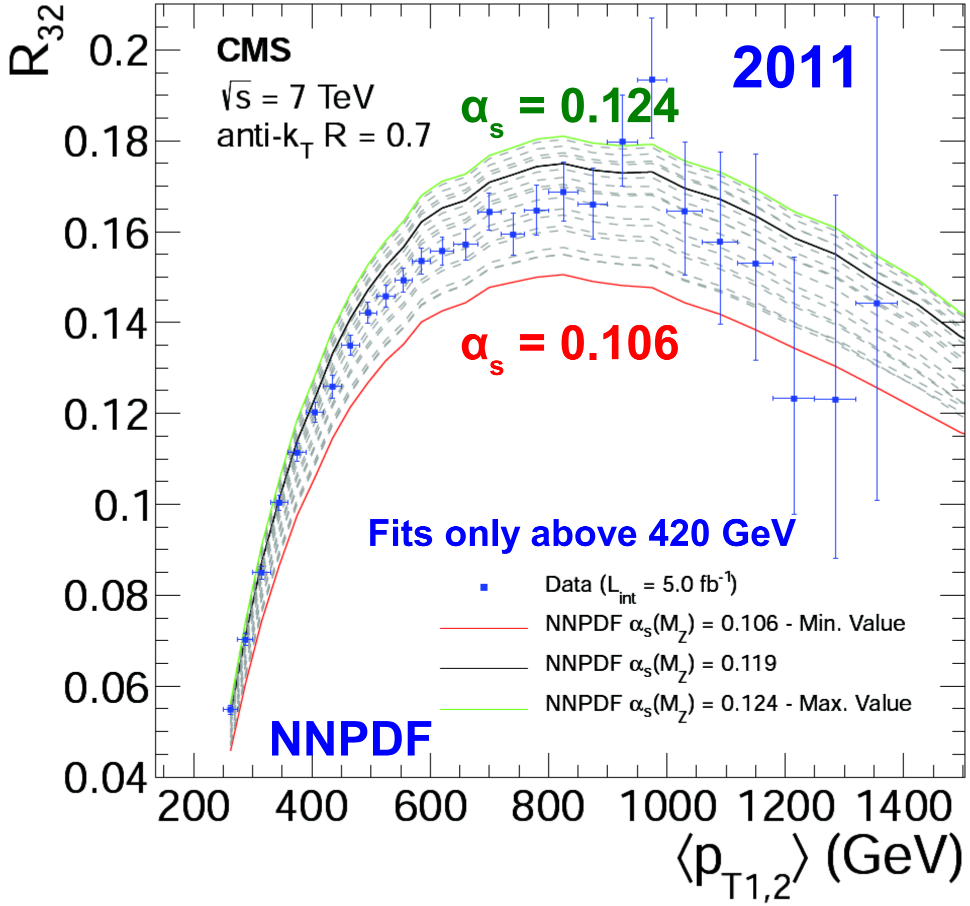


$R_{3/2}$

⟺ α_s

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

$$Q = \langle p_{\mathrm{T}1,2} \rangle$$



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

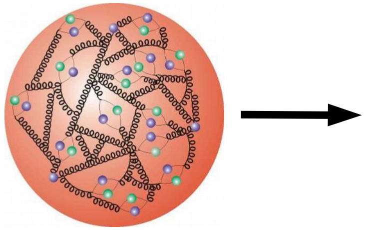
→ α_s

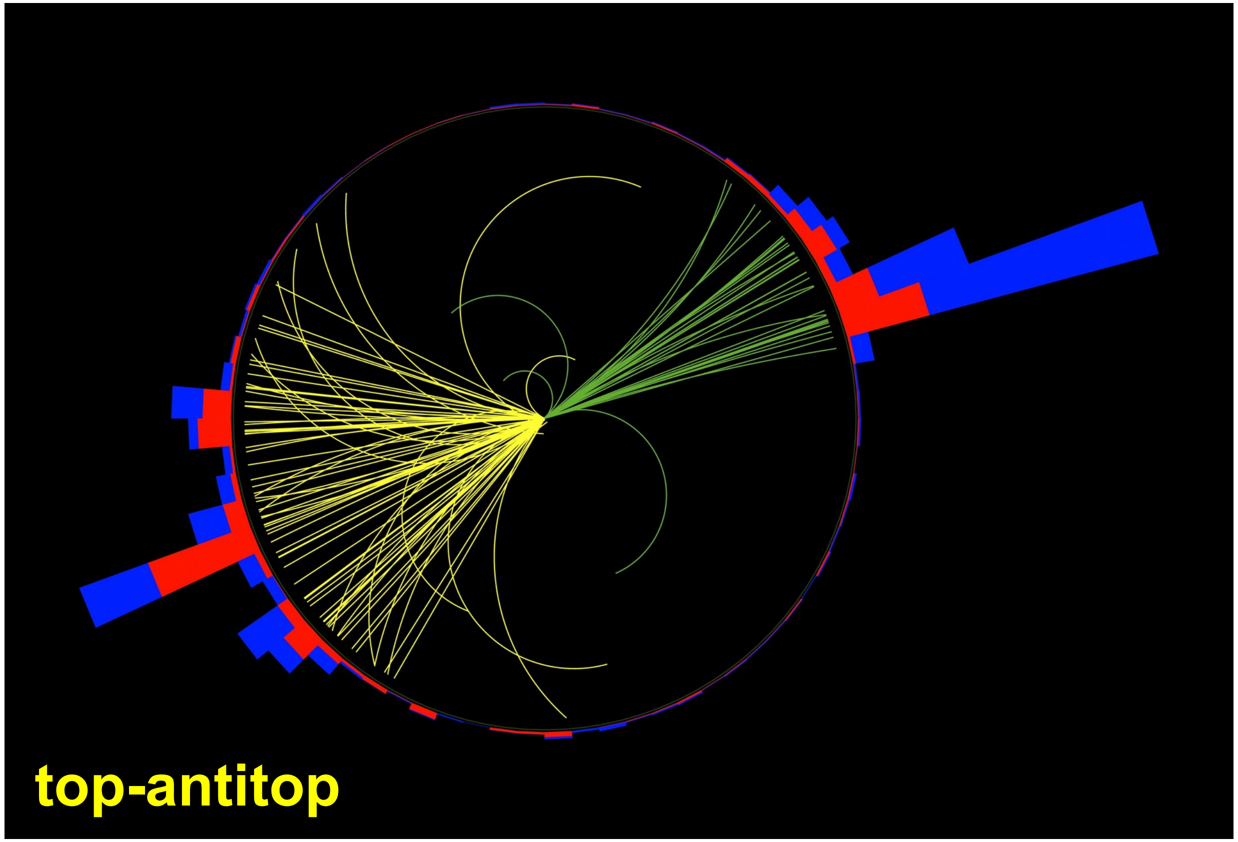
$$\alpha_s(M_Z) = 0.1148 \pm 0.0014\,(\mathrm{exp}) \pm 0.0018\,(\mathrm{PDF}) \pm \boxed{0.0050\,(\mathrm{theory})}$$

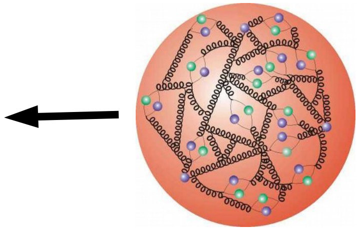
Dominated by NLO theory uncertainty!

Pairwise

High Masses







Fits with top-pair Production

Top-pair production is especially sensitive to:

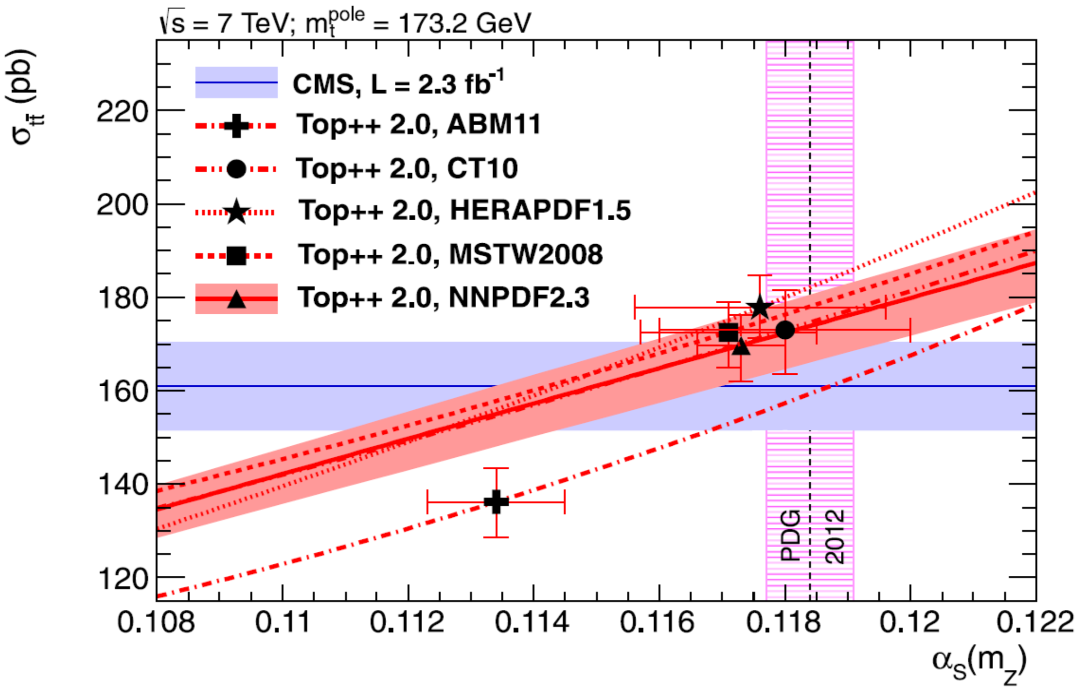
m_t^{pole} and α_s and $g(x,\mu_f^2)$ as the main production process at LHC is from gg

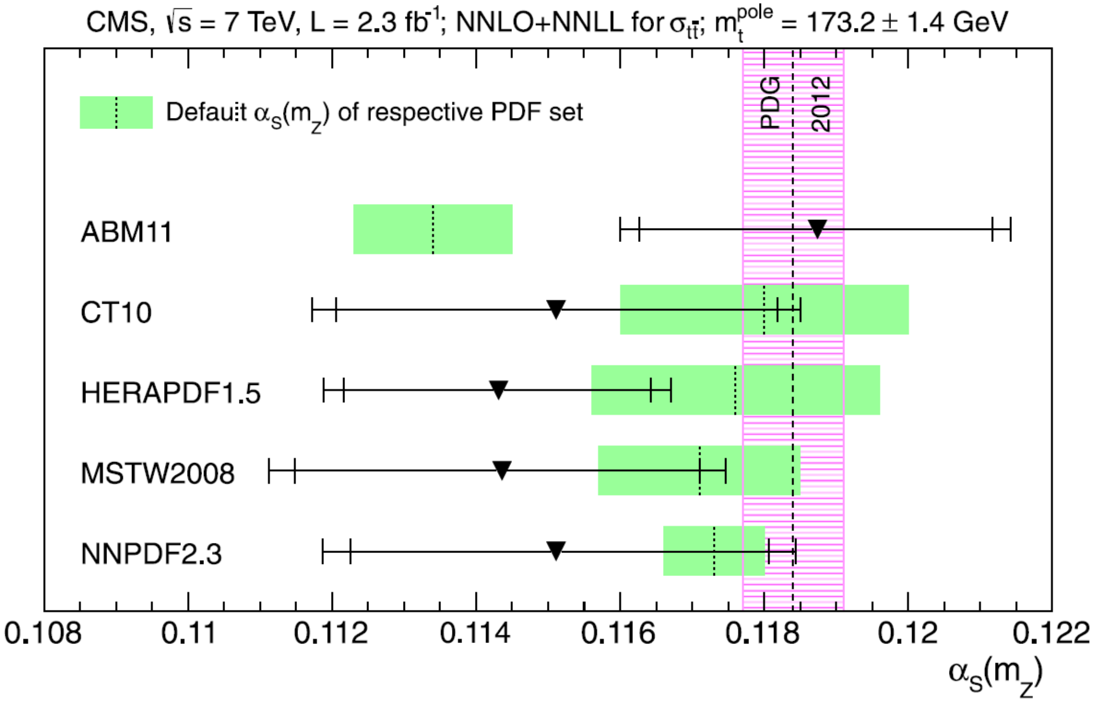
Using only the ttbar cross section measurement (dilepton channel) combined fits are not possible. Fixing the gluon to one of 5 PDF sets, however, it is possible to extract m_t^{pole} while fixing α_s or vice versa.

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

NNLO + NNLL $$\boxed{^{+0.0009}_{-0.0008}(\mathrm{scale})} \pm \boxed{0.0013(\mathrm{m}_t^{\mathrm{pole}}) \pm 0.0008(\mathrm{E}_{\mathrm{LHC}})}$$ **new top related**

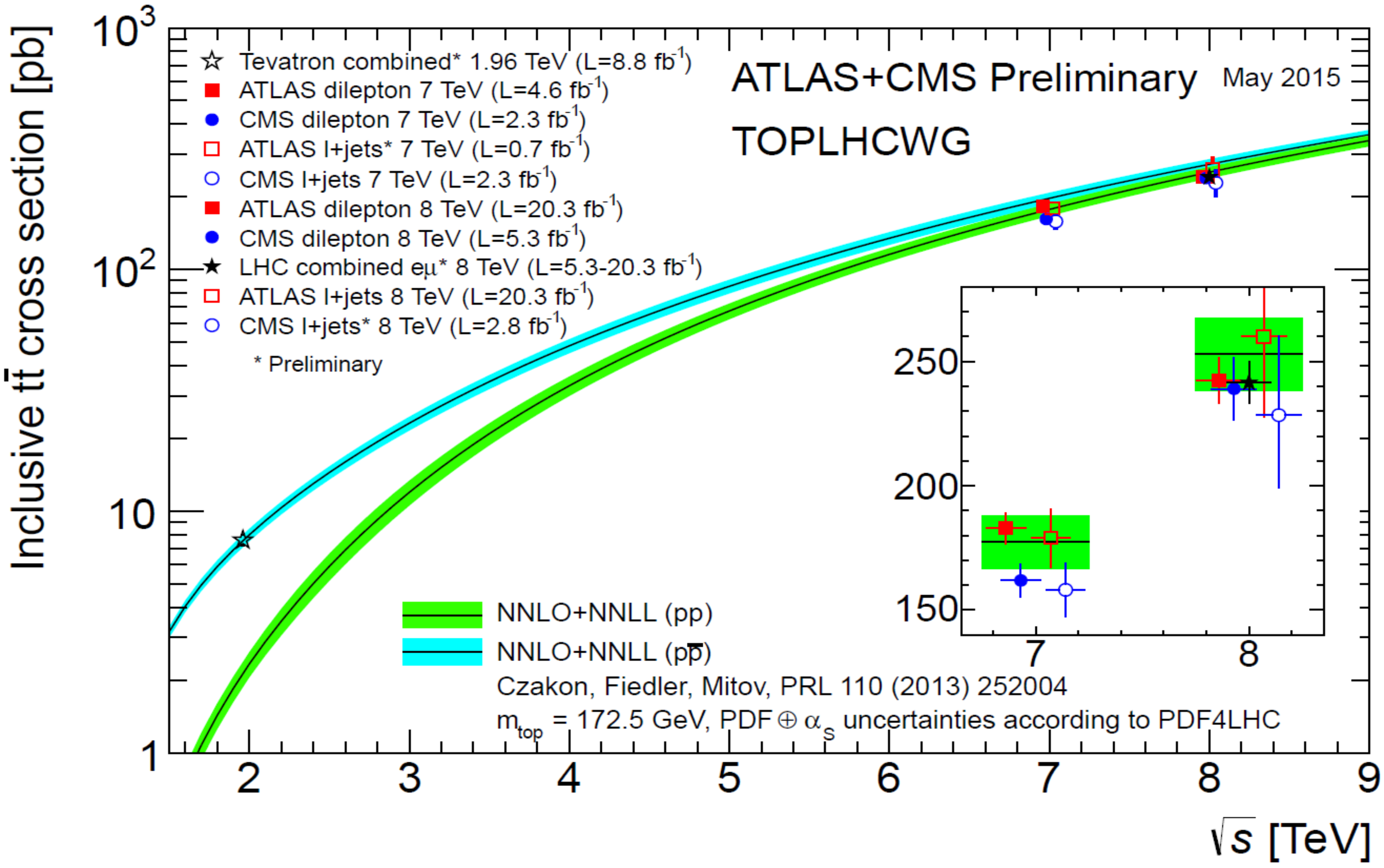
Fix m_t^{pole} → constrain α_s





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

ttbar Dilepton X Section in Comparison



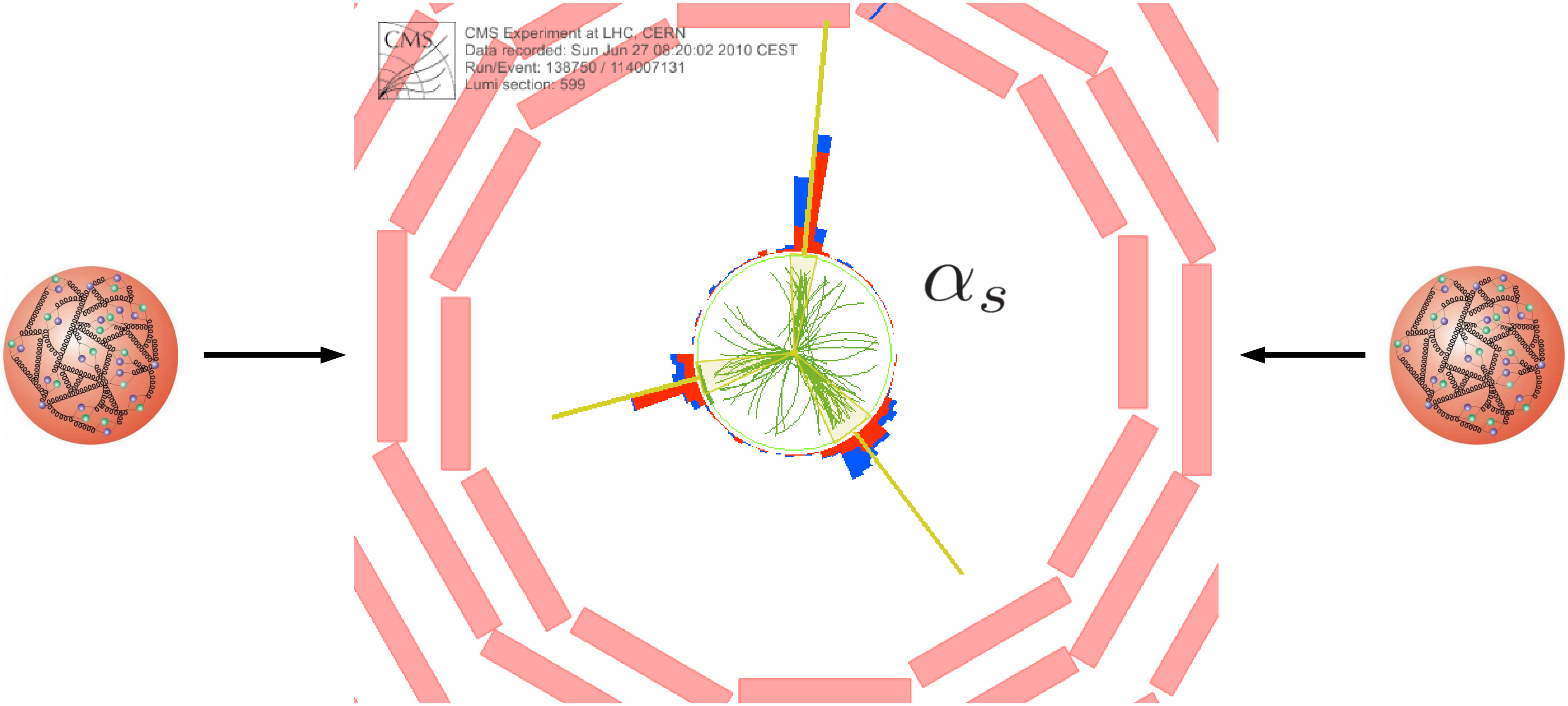
New CMS prelim. results move up somewhat, but within uncertainty.
2 X (@ 7 TeV) and 4 X (@ 8 TeV) more data, improved reconstruction, plus further refinements.

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

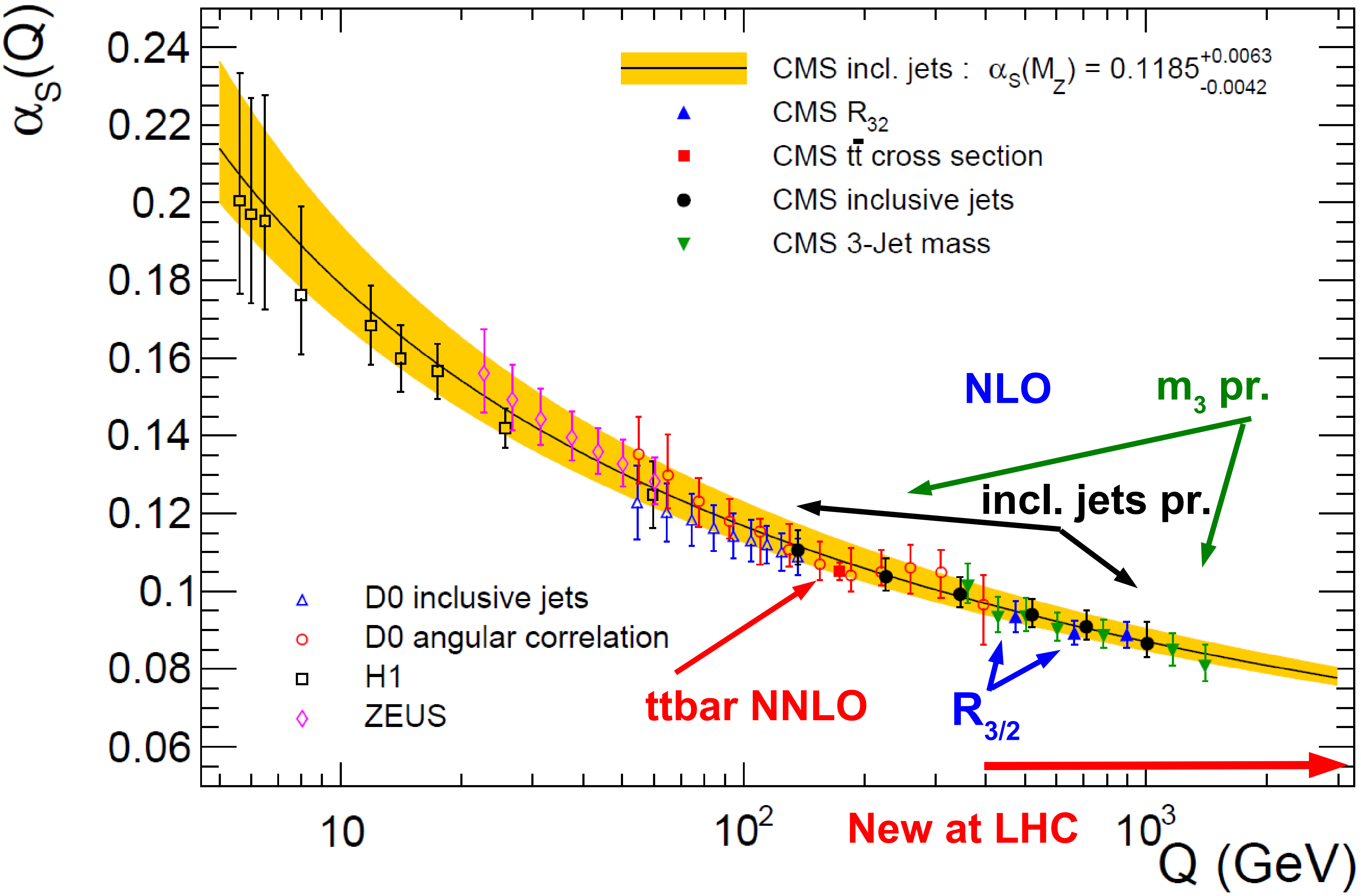
$$\sigma_{t\bar{t}} = 245.6 \pm 1.3(\mathrm{stat}) \pm^{6.6}_{5.5} (\mathrm{syst}) \pm 6.5(\mathrm{lumi})\ \mathrm{pb} \quad \text{at } \sqrt{s} = 8\ \mathrm{TeV},$$

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



NLO

m_3 pr.

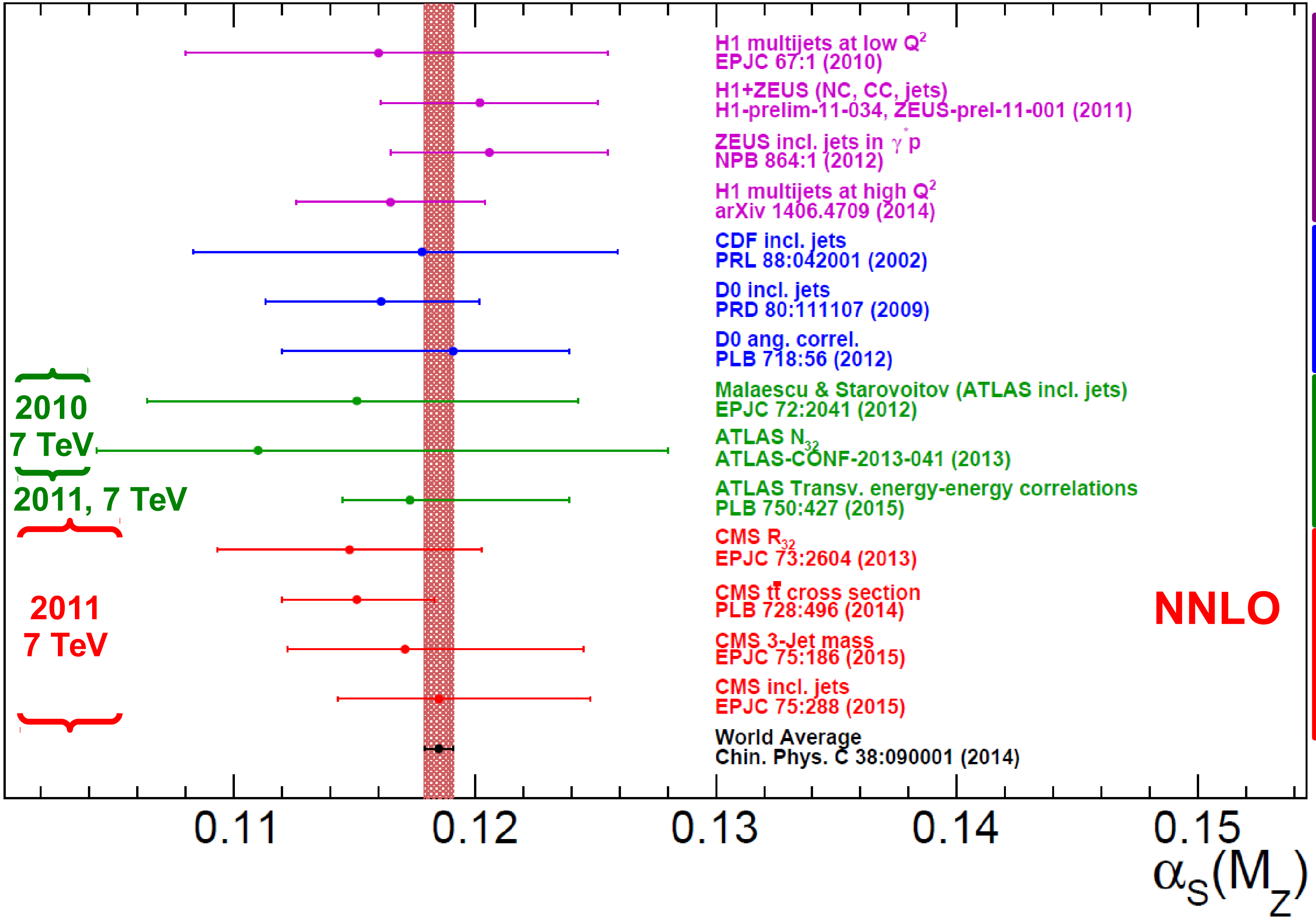
incl. jets pr.

ttbar NNLO

$R_{3/2}$

New at LHC

Hadron Collider Summary



$\Delta\alpha_S/\alpha_S$ / %

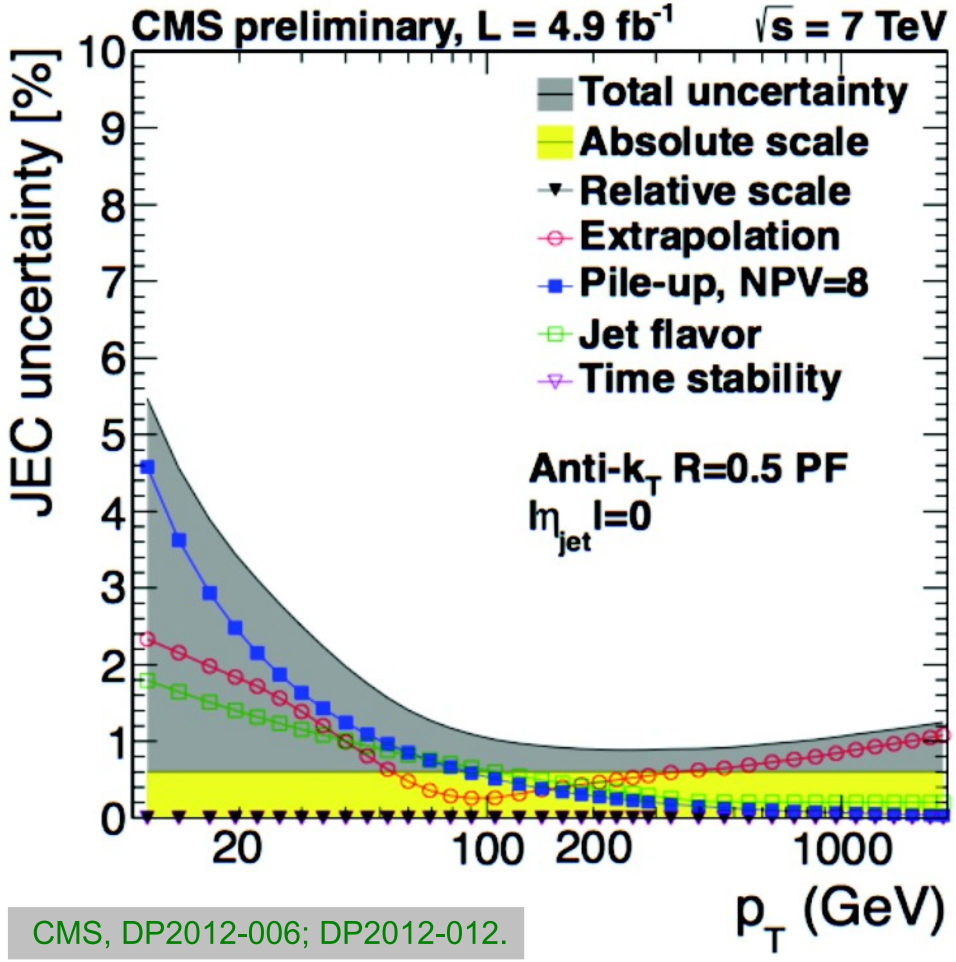
exp	PDF	scale
1.2	1.4	7.3
no final publ.		
1.9	1.9	2.5
0.7	0.8	3.1
7.5	5.0	5.0
2.9	1.0	2.3
0.7	1.2	4.7
4.1	1.8	2.4
no final publ.		
0.9	1.4	3.5
1.2	1.6	4.4
2.3	1.0	0.7
1.1	2.0	4.7
1.6	2.4	3.2

Perspectives with CMS and Beyond

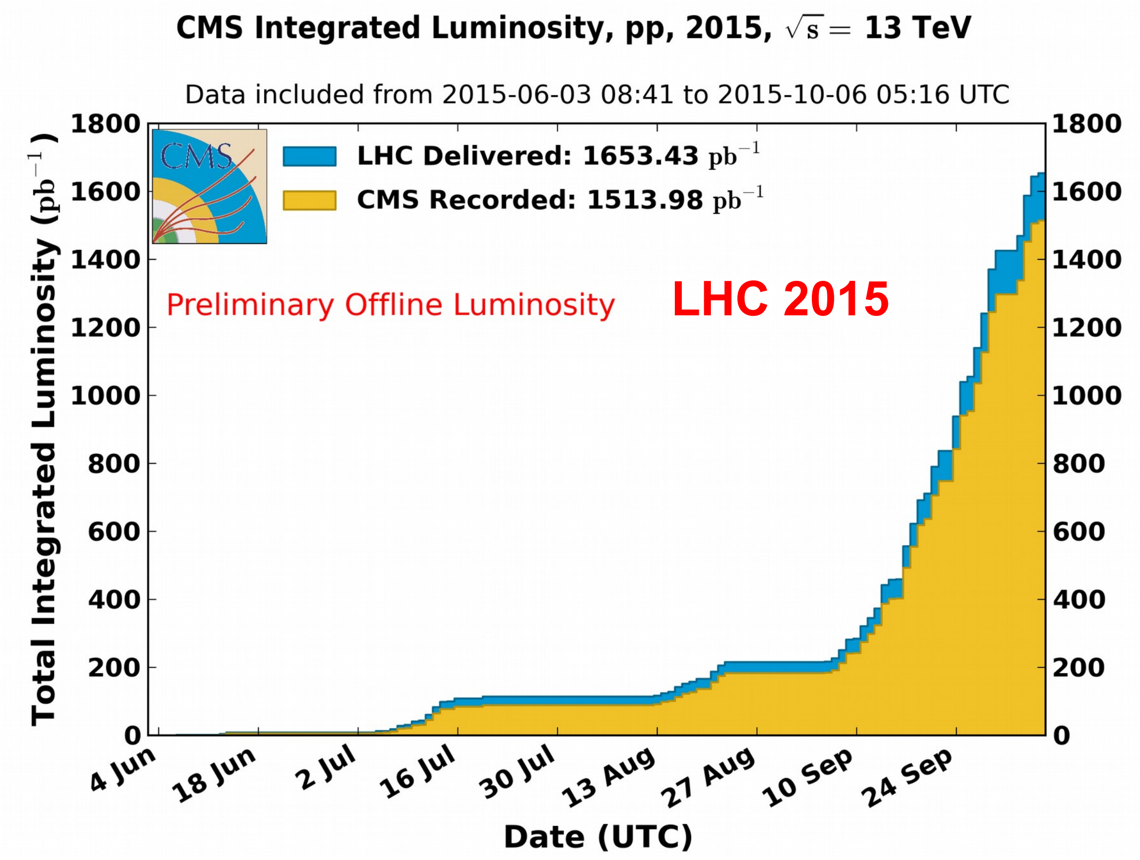
CMS: Jet energy scale 1 – 3 % prel. (Run 1)
→ percent level precision at medium p_T
→ more precise $\alpha_s(M_Z)$

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**

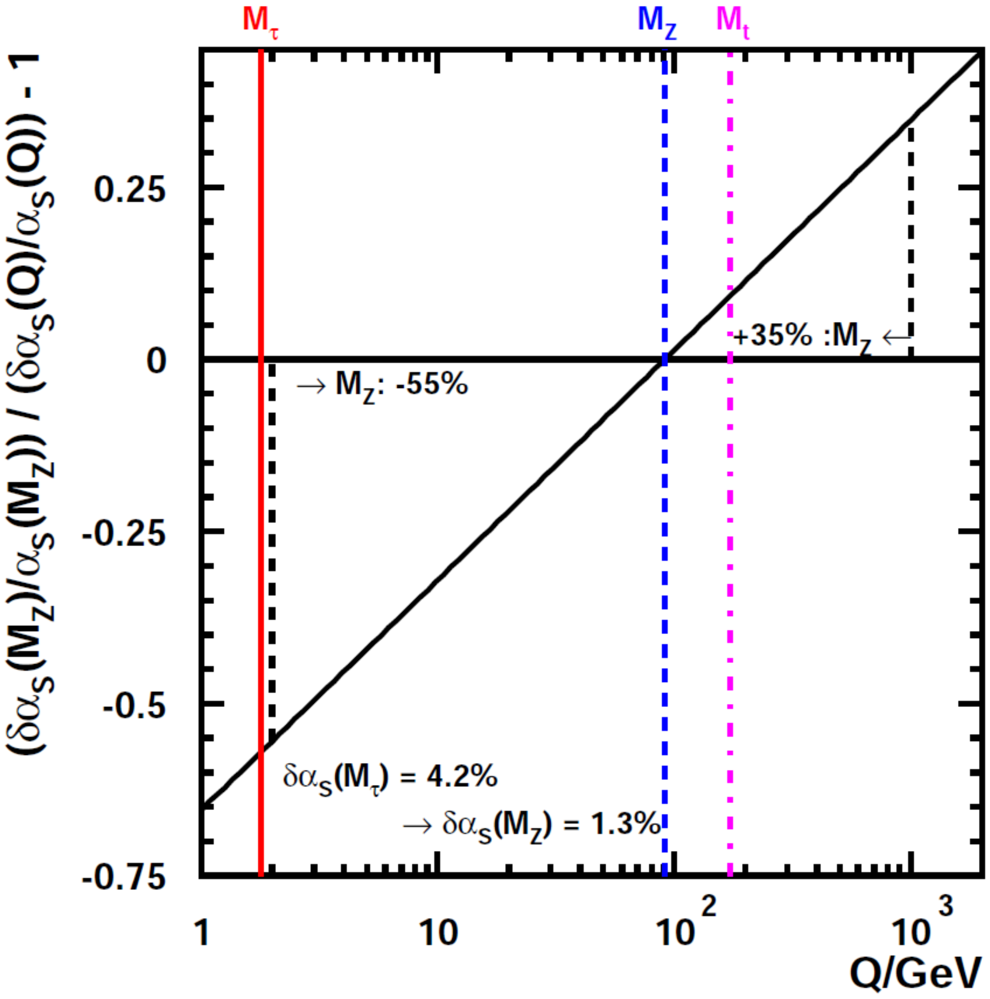
→ For $\alpha_s(M_Z)$ might want to stay at minimal JEC uncertainty:
200 – 800 GeV, central rapidity

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 $\sqrt{s}$ 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

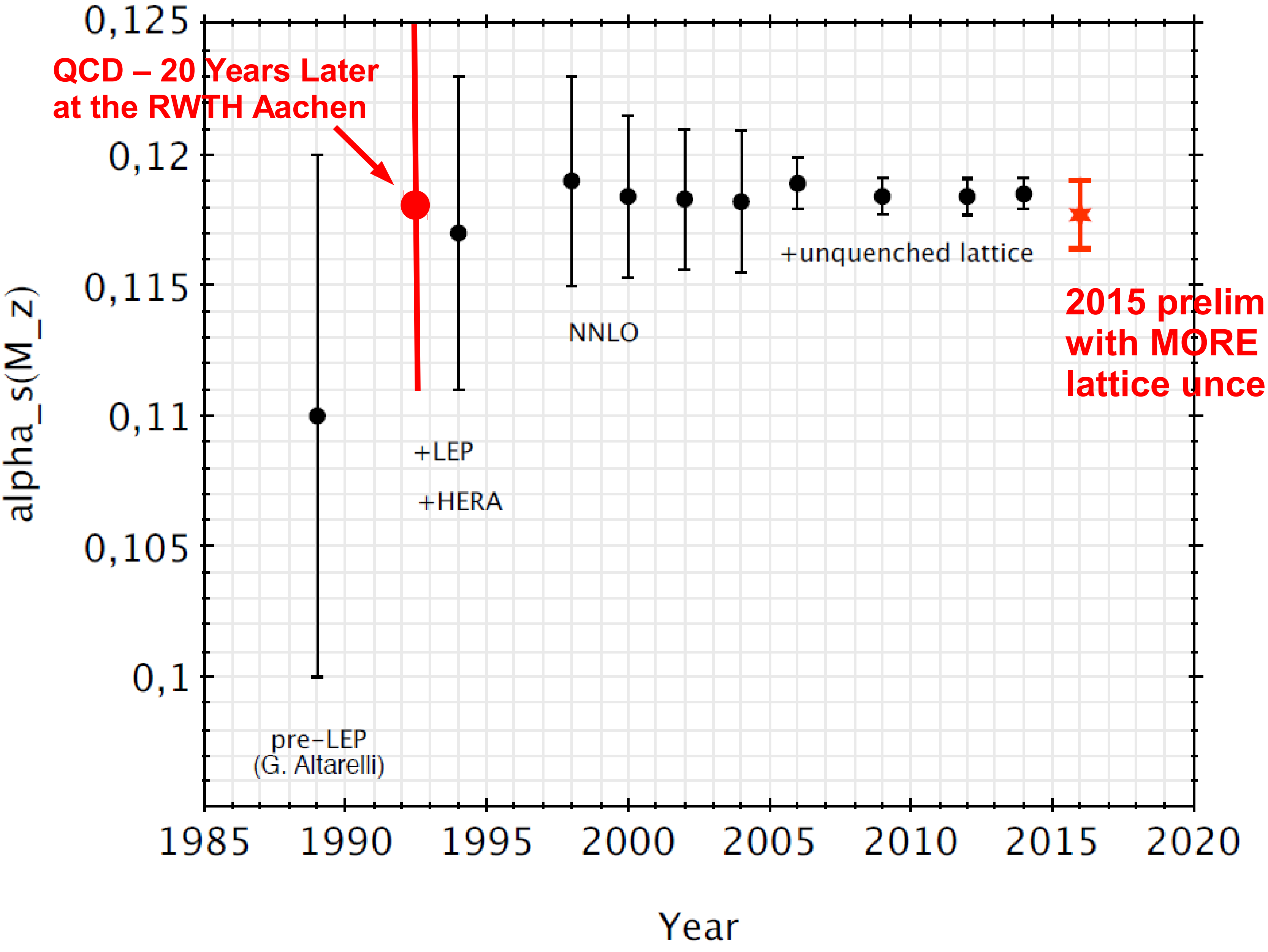
➔ CHALLENGE

Hadron Collider 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

History of World Average of α_s

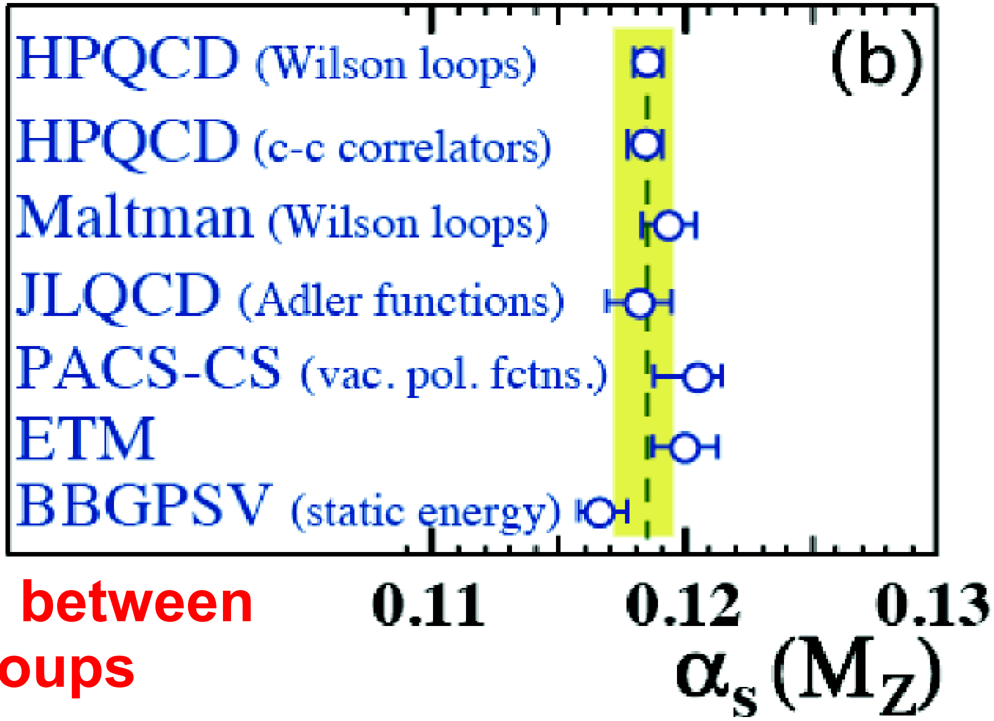


QCD – 20 Years Later at the RWTH Aachen

2015 preliminary ... with MORE realistic lattice uncertainty!

α_s from lattice QCD

our RPP summary 2015:



Result of collaboration between lattice gauge theory groups

shown: FLAG summary, $\alpha_s(M_Z) = 0.1184 \pm 0.0012$

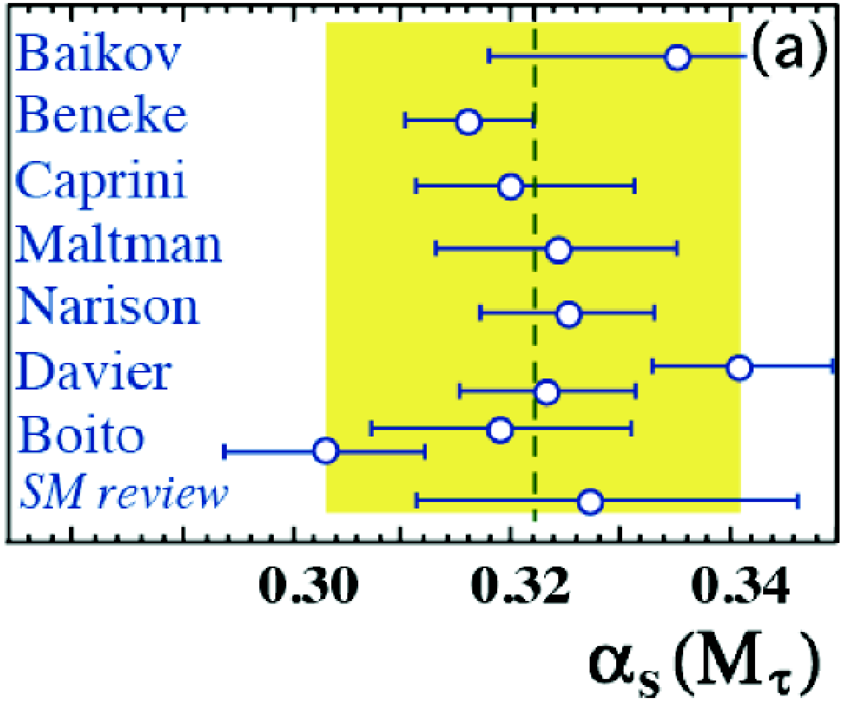
(if done as in previous RPP: $\alpha_s(M_Z) = 0.1185 \pm 0.0005$)

S. Bethke, FCC-ee Workshop

α_s from τ-decays

- complete N3LO prediction (Baikov, Chetyrkin, Kühn; arXiv:0801.1821)
- strong theor. activities, all based on ~same (ALEPH) datasets
- large dependence on details of perturbative expansion: FOPT vs. CIPT; some dependence on nonpert. corrections

Still unresolved differences in pert. theory treatment: fixed-order (FO) vs. contour-improved (CI) pert. theory



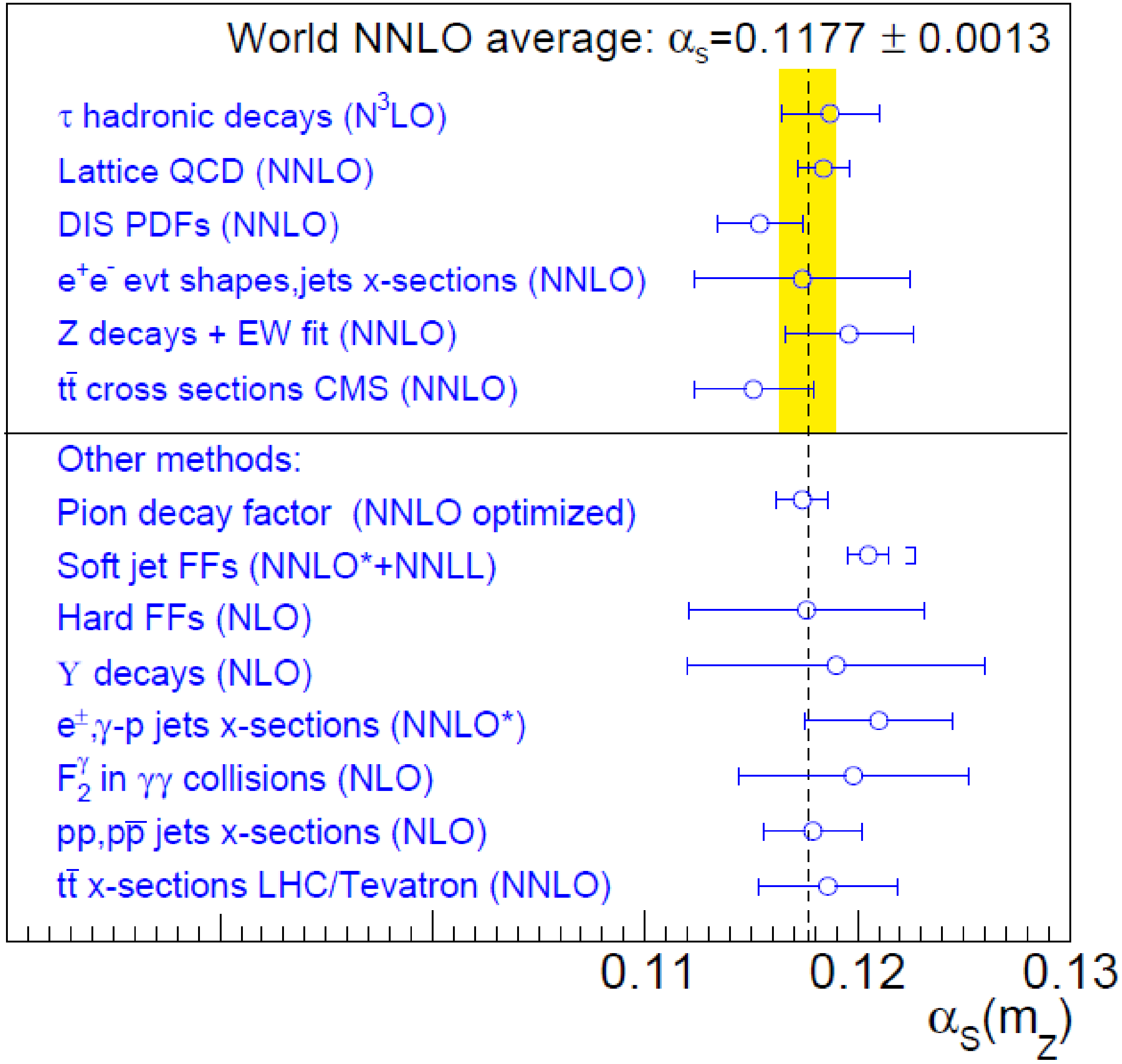
note: same new ALEPH data, large systematics between different authors!

- averaging and summarising: $\alpha_s(M_\tau) = 0.322 \pm 0.019$

–> $\alpha_s(M_Z) = 0.1187 \pm 0.0023$

S. Bethke, FCC-ee Workshop

Preliminary Average 2015



Workshop Proceeedings:
arXiv: 1512.05194

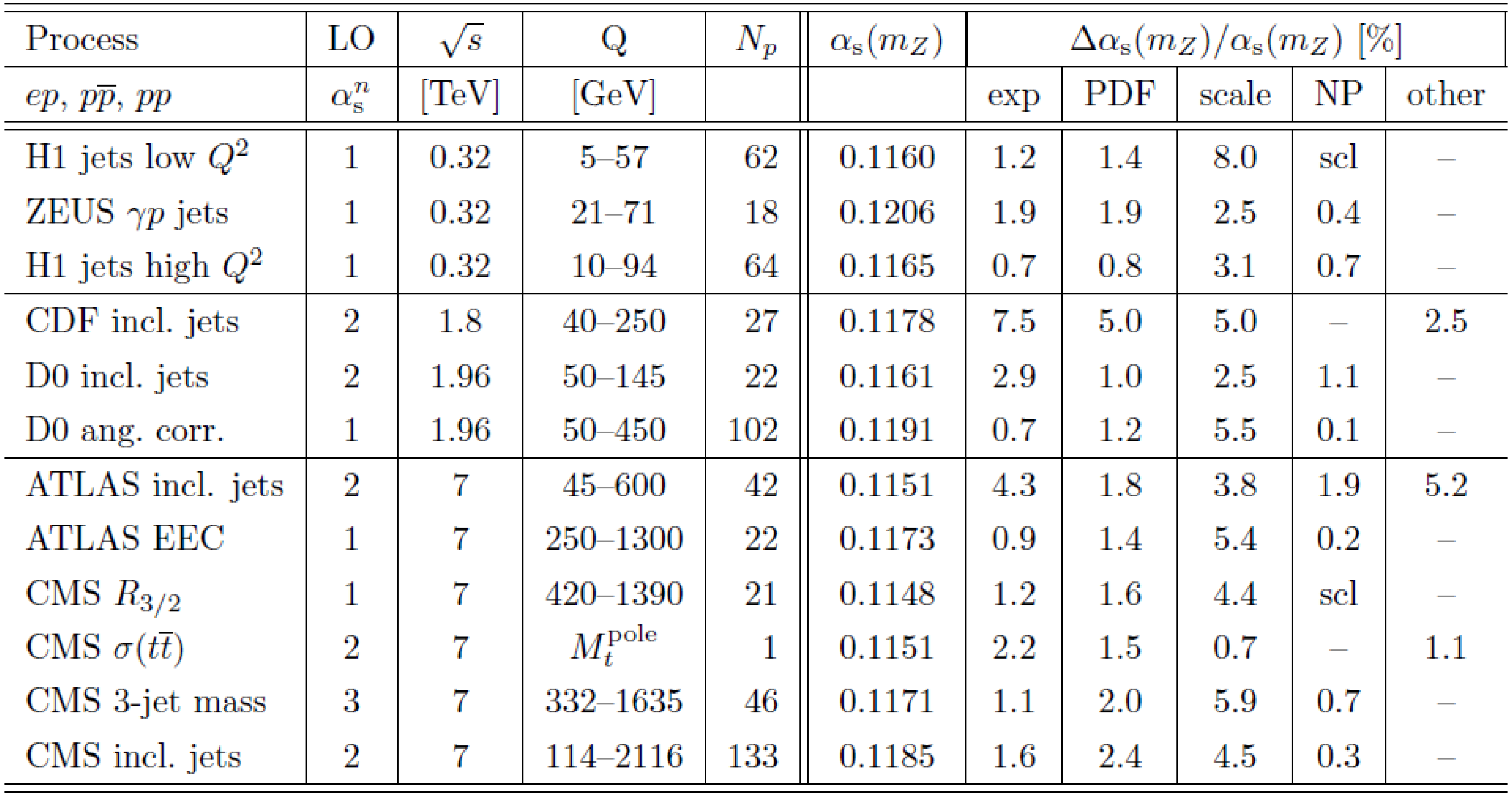
Backup Slides

Uncertainty Projections

Method	Current $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment state-of-the-art)	Future $\delta\alpha_s(m_Z^2)/\alpha_s(m_Z^2)$ uncertainty (theory & experiment progress)
lattice	$\approx 1\%$ (latt. stats/spacing, N^{3}LO pQCD)	$\approx 0.1\%$ ($\sim$10 yrs) (improved computing power, N^{4}LO pQCD)
π decay factor	$1.5\%_{\rm th} \oplus 0.05\%_{\rm exp} \approx 1.5\%$ (N^{3}LO RGOPT)	$1\%_{\rm th} \oplus 0.05\%_{\rm exp} \approx 1\%$ (few yrs) (N^{4}LO RGOPT, explicit $m_{u,d,s}$)
τ decays	$1.4\%_{\rm th} \oplus 1.4\%_{\rm exp} \approx 2\%$ (N^{3}LO CIPT vs. FOPT)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ (+B-factories), $<1\%$ (FCC-ee) (N^{4}LO, $\sim$10 yrs. Improved spectral function data)
$Q\overline{Q}$ decays	$4\%_{\rm th} \oplus 4\%_{\rm exp} \approx 6\%$ (NLO only. Υ only)	$1.4\%_{\rm th} \oplus 1.4\%_{\rm exp} \approx 2\%$ (few yrs) (NNLO. More precise LDME and $R_\gamma^{\rm exp}$)
soft FFs	$1.8\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 2\%$ (NNLO* only (+NNLL), npQCD small)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ ($\sim$2 yrs), $<1\%$ (FCC-ee) (NNLO+NNLL. More precise e^+e^- data: 90–350 GeV)
hard FFs	$1\%_{\rm th} \oplus 5\%_{\rm exp} \approx 5\%$ (NLO only. LEP data only)	$0.7\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2\%$ (+B-factories), $<1\%$ (FCC-ee) (NNLO. More precise e^+e^- data)
global PDF fits	$1.5\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.7\%$ (Diff. NNLO PDF fits. DIS+DY data)	$0.7\%_{\rm th} \oplus 0.7\%_{\rm exp} \approx 1\%$ (few yrs), 0.15% (LHeC/FCC-eh) (N^{3}LO. Full DIS+hadronic data fit)
jets in $e^\pm$p, γ-p	$2\%_{\rm th} \oplus 1.5\%_{\rm exp} \approx 2.5\%$ (NNLO* only)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (few yrs), $< 1\%$ (FCC-eh) (NNLO. Combined DIS + (extra?) γ-p data)
F_2^γ in γ-γ	$3.5\%_{\rm th} \oplus 3\%_{\rm exp} \approx 4.5\%$ (NLO only)	$1\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2\%$ ($\sim$2 yrs), $<1\%$ (FCC-ee) (NNLO. More precise new F_2^γ data)
e^+e^- evt shapes	$(1.5\text{–}4)\%_{\rm th} \oplus 1\%_{\rm exp} \approx (1.5\text{–}4)\%$ (NNLO+N$^{(3)}$LL, npQCD significant)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (+B-factories), $< 1\%$ (FCC-ee) (NNLO+N^{3}LL. Improved npQCD via $\sqrt{s}$-dep. New data)
jets in e^+e^-	$(2\text{–}5)\%_{\rm th} \oplus 1\%_{\rm exp} \approx (2\text{–}5)\%$ (NNLO+NLL, npQCD moderate)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (few yrs), $< 1\%$ (FCC-ee) (NNLO+NNLL. Improved npQCD. New high-$\sqrt{s}$ data)
W decays	$0.7\%_{\rm th} \oplus 37\%_{\rm exp} \approx 37\%$ (N^{3}LO, npQCD small. Low-stats data)	$(0.7\text{–}0.1)\%_{\rm th} \oplus (10\text{–}0.1)\%_{\rm exp} \approx (10\text{–}0.15)\%$ (LHC,FCC-ee) (N^{4}LO, $\sim$10 yrs. High-stats/precise W data)
Z decays	$0.7\%_{\rm th} \oplus 2.4\%_{\rm exp} \approx 2.5\%$ (N^{3}LO, npQCD small)	$0.1\%_{\rm th} \oplus (0.5\text{–}0.1)\%_{\rm exp} \approx (0.5\text{–}0.15)\%$ (ILC,FCC-ee) (N^{4}LO, $\sim$10 yrs. High-stats/precise Z data)
jets in p-p, p-$\overline{\rm p}$	$3.5\%_{\rm th} \oplus (2\text{–}3)\%_{\rm exp} \approx (4\text{–}5)\%$ (NLO only. Combined exp. observables)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (Tevatron+LHC, $\sim$2 yrs) (NNLO. Multiple datasets+observables)
$t\bar{t}$ in p-p, p-$\overline{\rm p}$	$1.5\%_{\rm th} \oplus 2\%_{\rm exp} \approx 2.5\%$ (NNLO+NNLL. CMS only)	$1\%_{\rm th} \oplus 1\%_{\rm exp} \approx 1.5\%$ (Tevatron+LHC, $\sim$2 yrs) (Improved $m_{\rm top}^{\rm pole}$ & PDFs. Multiple datasets)

Workshop Proceeedings:
arXiv: 1512.05194

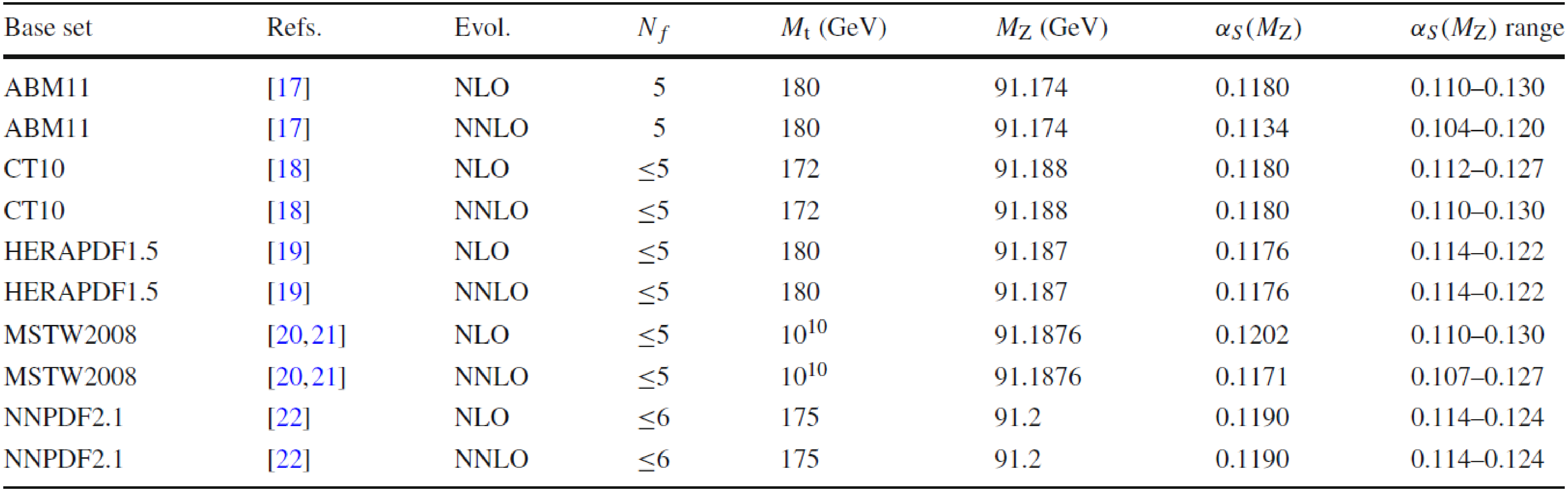
Uncertainties at Hadron Colliders



Process	LO	$\sqrt{s}$	Q	N_p	$\alpha_s(m_Z)$	$\Delta\alpha_s(m_Z)/\alpha_s(m_Z)$ [%]				
ep, $p\bar{p}$, pp	α_s^n	[TeV]	[GeV]			exp	PDF	scale	NP	other
H1 jets low Q^2	1	0.32	5–57	62	0.1160	1.2	1.4	8.0	scl	–
ZEUS γp jets	1	0.32	21–71	18	0.1206	1.9	1.9	2.5	0.4	–
H1 jets high Q^2	1	0.32	10–94	64	0.1165	0.7	0.8	3.1	0.7	–
CDF incl. jets	2	1.8	40–250	27	0.1178	7.5	5.0	5.0	–	2.5
D0 incl. jets	2	1.96	50–145	22	0.1161	2.9	1.0	2.5	1.1	–
D0 ang. corr.	1	1.96	50–450	102	0.1191	0.7	1.2	5.5	0.1	–
ATLAS incl. jets	2	7	45–600	42	0.1151	4.3	1.8	3.8	1.9	5.2
ATLAS EEC	1	7	250–1300	22	0.1173	0.9	1.4	5.4	0.2	–
CMS $R_{3/2}$	1	7	420–1390	21	0.1148	1.2	1.6	4.4	scl	–
CMS $\sigma(t\bar{t})$	2	7	M_t^{pole}	1	0.1151	2.2	1.5	0.7	–	1.1
CMS 3-jet mass	3	7	332–1635	46	0.1171	1.1	2.0	5.9	0.7	–
CMS incl. jets	2	7	114–2116	133	0.1185	1.6	2.4	4.5	0.3	–

Workshop Proceeedings:
arXiv: 1512.05194

PDF Sets

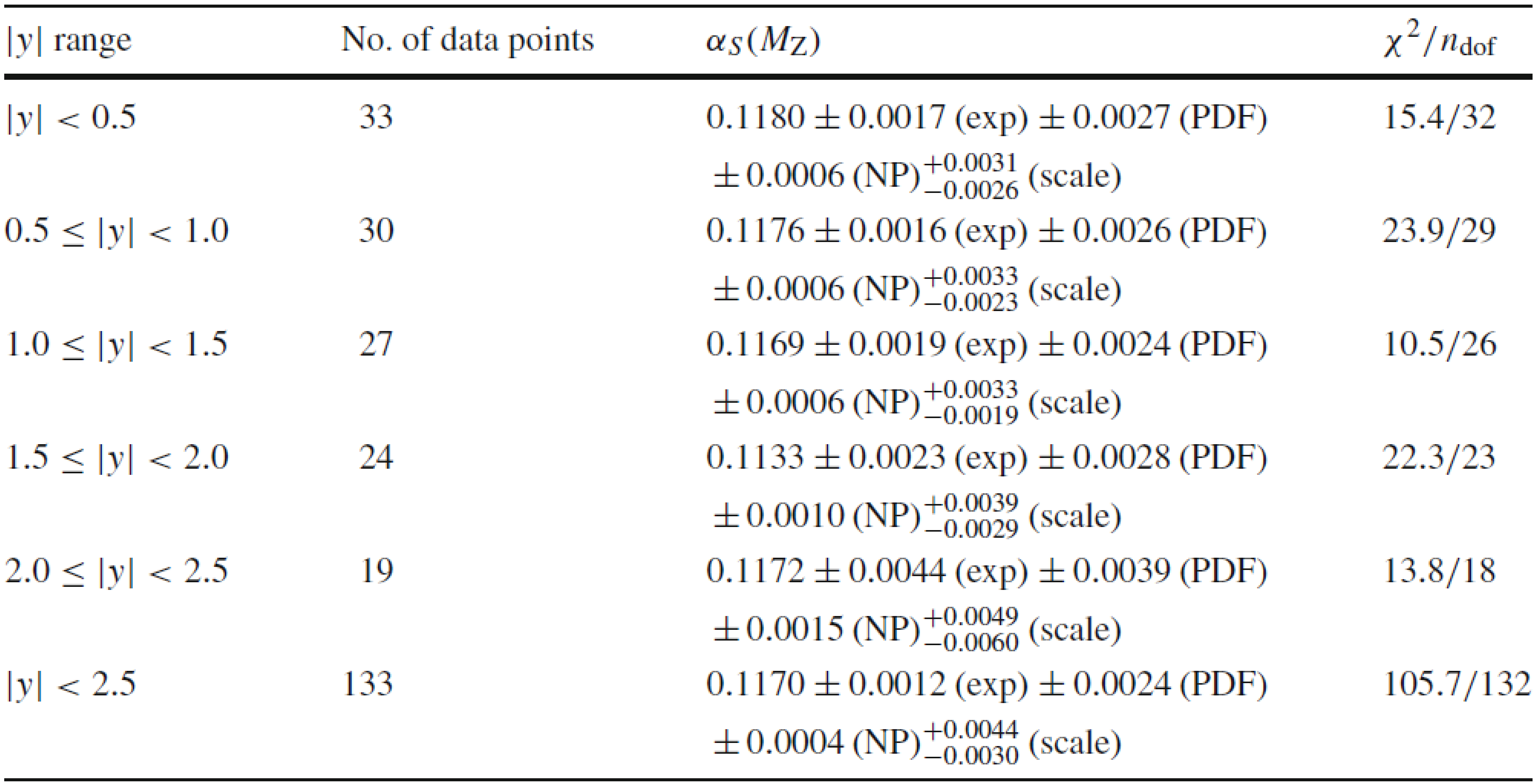


Base set	Refs.	Evol.	N_f	M_t (GeV)	M_Z (GeV)	$\alpha_S(M_Z)$	$\alpha_S(M_Z)$ range
ABM11	[17]	NLO	5	180	91.174	0.1180	0.110–0.130
ABM11	[17]	NNLO	5	180	91.174	0.1134	0.104–0.120
CT10	[18]	NLO	≤ 5	172	91.188	0.1180	0.112–0.127
CT10	[18]	NNLO	≤ 5	172	91.188	0.1180	0.110–0.130
HERAPDF1.5	[19]	NLO	≤ 5	180	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	$0.1180 \pm 0.0017\,(\mathrm{exp}) \pm 0.0027\,(\mathrm{PDF})$ $\pm 0.0006\,(\mathrm{NP})^{+0.0031}_{-0.0026}\,(\mathrm{scale})$	15.4/32
$0.5 \leq \lvert y \rvert < 1.0$	30	$0.1176 \pm 0.0016\,(\mathrm{exp}) \pm 0.0026\,(\mathrm{PDF})$ $\pm 0.0006\,(\mathrm{NP})^{+0.0033}_{-0.0023}\,(\mathrm{scale})$	23.9/29
$1.0 \leq \lvert y \rvert < 1.5$	27	$0.1169 \pm 0.0019\,(\mathrm{exp}) \pm 0.0024\,(\mathrm{PDF})$ $\pm 0.0006\,(\mathrm{NP})^{+0.0033}_{-0.0019}\,(\mathrm{scale})$	10.5/26
$1.5 \leq \lvert y \rvert < 2.0$	24	$0.1133 \pm 0.0023\,(\mathrm{exp}) \pm 0.0028\,(\mathrm{PDF})$ $\pm 0.0010\,(\mathrm{NP})^{+0.0039}_{-0.0029}\,(\mathrm{scale})$	22.3/23
$2.0 \leq \lvert y \rvert < 2.5$	19	$0.1172 \pm 0.0044\,(\mathrm{exp}) \pm 0.0039\,(\mathrm{PDF})$ $\pm 0.0015\,(\mathrm{NP})^{+0.0049}_{-0.0060}\,(\mathrm{scale})$	13.8/18
$\lvert y \rvert < 2.5$	133	$0.1170 \pm 0.0012\,(\mathrm{exp}) \pm 0.0024\,(\mathrm{PDF})$ $\pm 0.0004\,(\mathrm{NP})^{+0.0044}_{-0.0030}\,(\mathrm{scale})$	105.7/132

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	$^{+0.0088}_{-0.0050}$
$\lvert y \rvert_{\text{max}} < 1$	413	10.3/22	0.1163	$^{+0.0018}_{-0.0019}$	±0.0027	±0.0007	$^{+0.0059}_{-0.0025}$
$1 \leq \lvert y \rvert_{\text{max}} < 2$	441	10.6/22	0.1179	$^{+0.0018}_{-0.0019}$	±0.0021	±0.0007	$^{+0.0067}_{-0.0037}$
$\lvert y \rvert_{\text{max}} < 2$	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

MSTW2008: $\alpha_S(M_Z) = 0.1141 \pm 0.0022$ (exp.),

CT10: $\alpha_S(M_Z) = 0.1135 \pm 0.0019$ (exp.),

$\mu_r/\langle p_{T1,2}\rangle$	$\mu_f/\langle p_{T1,2}\rangle$	$\alpha_S(M_Z) \pm$ (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

CMS, EPJC 73 (2013) 2604.

α_s Projections

Still at LHC:

Only jets probe running α_s at highest scales

< 1% uncertainty at M_Z challenging, but not impossible

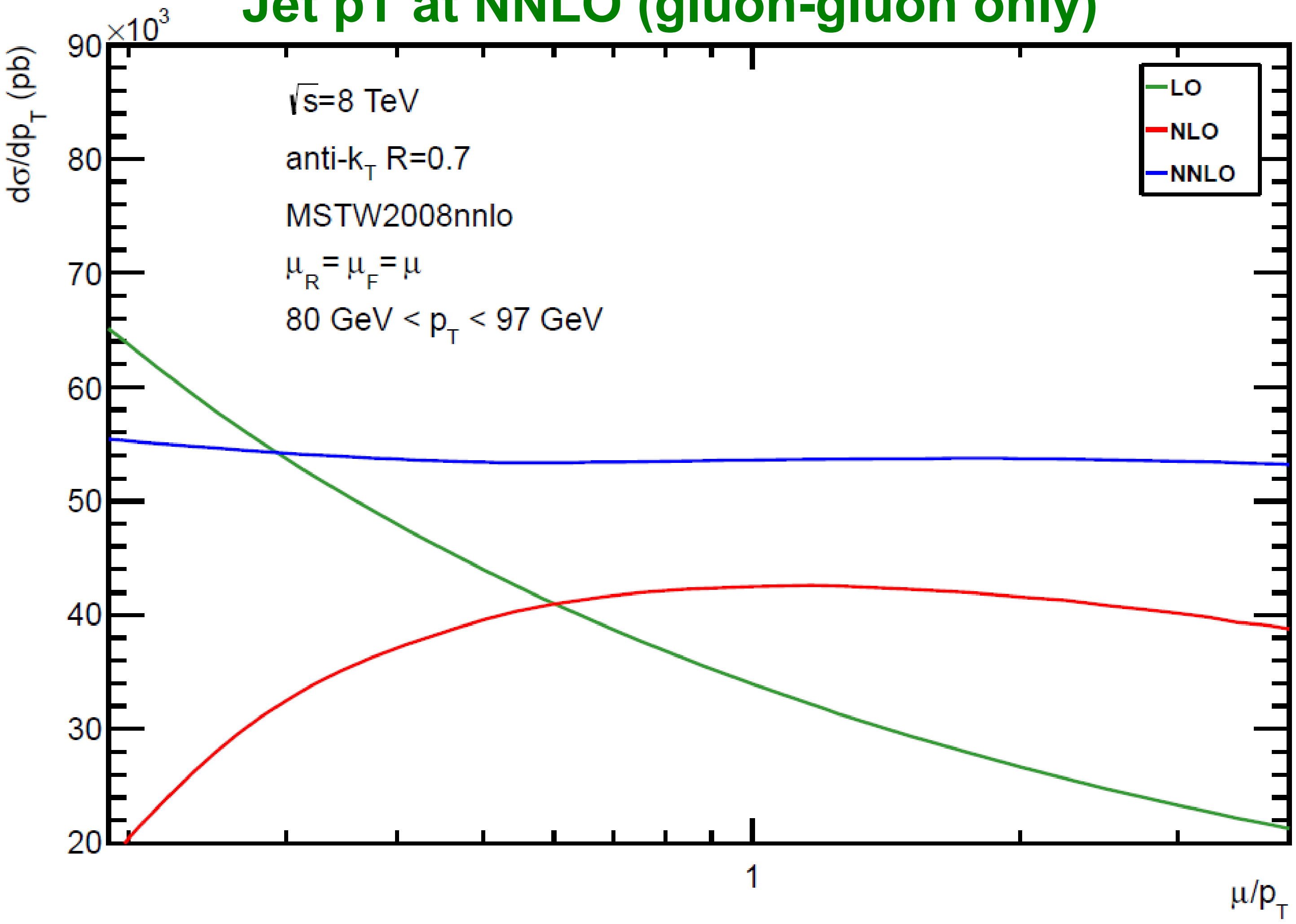
Need NNLO and improved PDFs (gluon) plus some experimental optimization

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

Jet pT at NNLO (gluon-gluon only)



Drastically reduced scale dependence!

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

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