PDF and α_S constraints from jet measurements at CMS

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On behalf of the CMS Collaboration

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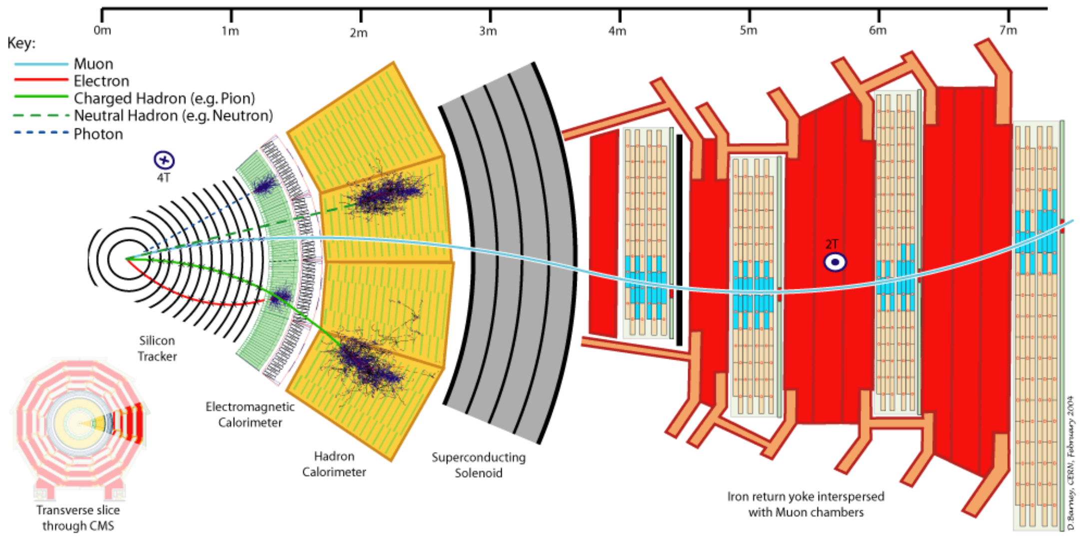
Outline

- Introduction & the CMS detector
- Jet reconstruction & energy scale calibration at CMS
- The CMS measurements at 7 TeV
  - 3/2 inclusive jet cross sections ratio (R_{32})
  - 3-jet mass cross section NEW
- Conclusions

Introduction & the CMS detector

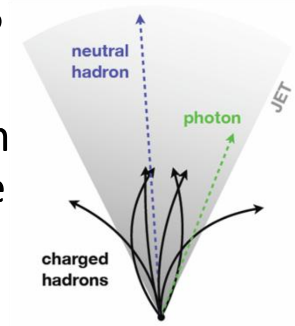
- Jet measurements at LHC are very important:
  - They provide a test of pQCD in a previously unexplored energy region.
  - Check SM predictions at high energy scales.
  - Measure and understand the main background to many new physics searches.
  - *Determine the strong coupling and test its running at high Q scales.*
  - *Provide constraints on PDF's.*



Tracking: $|\eta|<2.5$
Central Calorimetry: $|\eta|<3$
Forward Calorimetry: $3<|\eta|<5$

Jet Reconstruction & Energy Scale Calibration

- **Anti-k_T clustering algorithm** : Infrared and collinear safe. Used with R=0.5 and 0.7.
- **Particle Flow Jets (PF Jets)** : The CMS global event reconstruction (PF) is an event reconstruction technique which reconstructs and identifies all stable particles in the event, through the optimal combination of all CMS sub-detectors. PF Jets are the output of anti-k_T on the reconstructed particles.

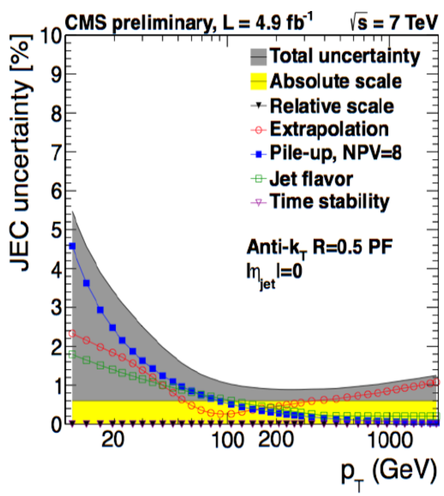


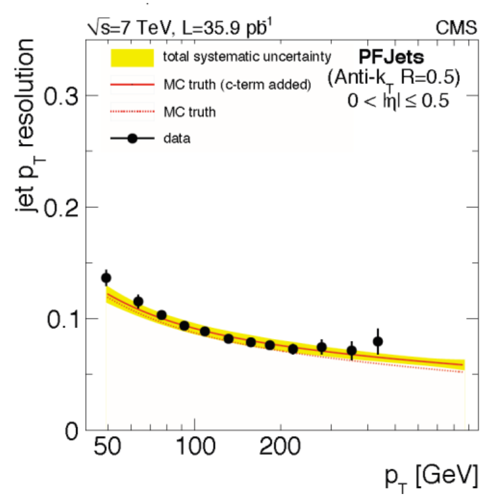
- For the Jet energy scale calibration CMS adopted a Factorized approach.

Calibrated Jet = Raw Jet × Offset Correction (pile-up) × Relative Correction (vs η) × Absolute Correction (vs p_T)

CMS :
JME-10-003
JME-10-010
JINST 6 2011
DP2012-006

See also EPS talk: "Jet performance in CMS" by H. Kirschenmann



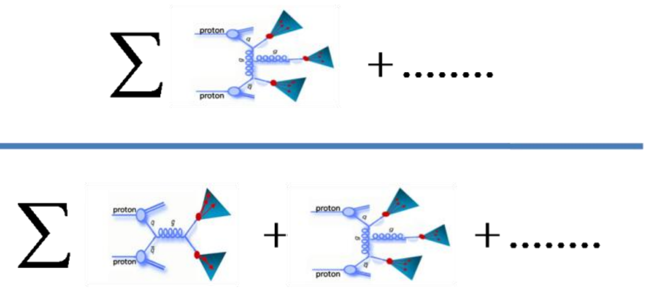


Jet p_T resolution: ≈9% at 100 GeV

3/2 inclusive jet cross sections ratio (R_{32})

- **The measurement**

$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \rightarrow n \;\; \text{jets} + X;\; n \geq 3)}{\sigma(pp \rightarrow n \;\; \text{jets} + X;\; n \geq 2)} =$$



$\Longleftrightarrow \alpha_s$

$$\text{vs} \quad \langle p_{T1,2} \rangle = \frac{p_{T1} + p_{T2}}{2}$$

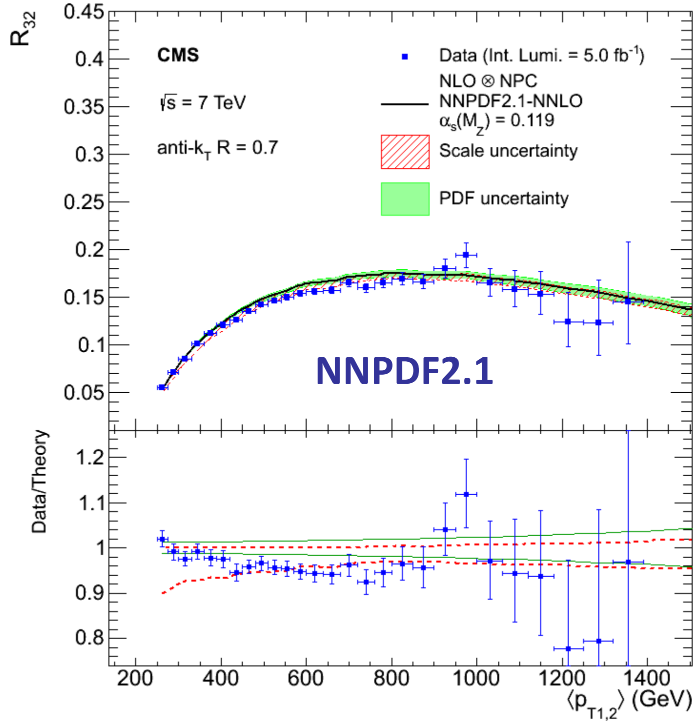
- Advantages of R_{32} :
  - Avoids direct dependence on PDFs and the RGE of QCD.
  - Reduces experimental and other theoretical uncertainties.
  - Does not depend on luminosity.

- Choices for the analysis
  - Jet p_T>150 GeV
  - Rapidity |y|<2.5
  - Average dijet p_T as scale $Q = \langle p_{T1,2} \rangle = \dfrac{p_{T1} + p_{T2}}{2}$

- Data sample : 2011 (L_{int}=5.0 fb^{-1})

3/2 inclusive jet cross sections ratio (R_{32})

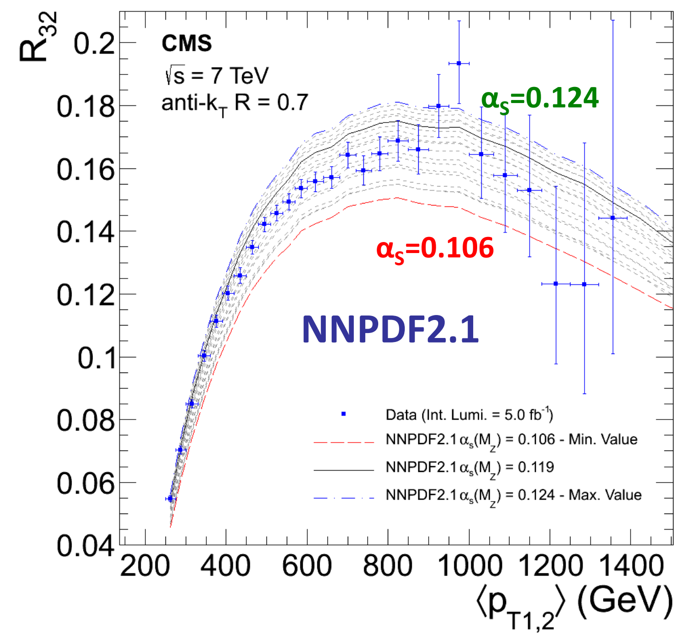
arXiv:1304.7498



- Measurement is compared with theoretical calculations using the NNPDF2.1, MSTW2008, CT10, and ABM11 PDF sets.

- Calculations using the NNPDF2.1, MSTW2008, and CT10 PDF sets are in agreement with the measured ratio R_{32} throughout the range of this measurement.

- R_{32} is sensitive to α_S and can be used for it's extraction.



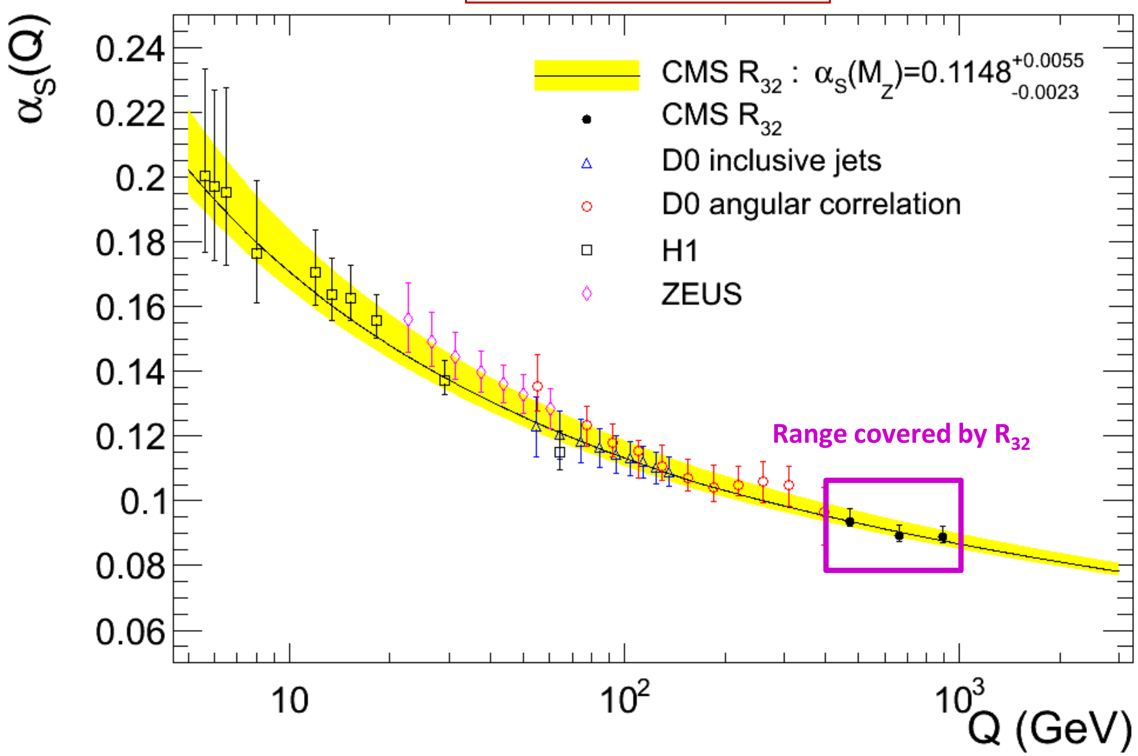
3/2 inclusive jet cross sections ratio (R_{32})

- Using PDFs as external input we can determine $\alpha_S(M_Z)$ (NNPDF2.1 PDF set)

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014(\exp) \pm 0.0018(PDF) \pm^{0.0050}_{0.0000}(scale)$$

- Small exp. uncertainty.
- Dominated by theoretical uncertainties (PDF and asymmetric scale uncertainty).
- Determination with other PDF sets are in agreement.
- Extraction also performed for three subranges in Q to test the α_S running.
- Comparison to Tevatron and HERA experiments.
- New CMS results are in agreement with the world measurements and extend the covered range in scale Q up to 1 TeV.
- No deviation from the expected behaviour is observed.

arXiv:1304.7498



Measurement of the 3-jet mass cross section at 7 TeV

- Measurement of the double differential 3-jet cross section in m_3 and y_{max}

NEW

$$\frac{d^2\sigma}{dm_3\, dy_{max}}$$

$$m_3^2 = (p_1 + p_2 + p_3)^2$$
$$|y|_{max} = \max(|y_1|, |y_2|, |y_3|)$$

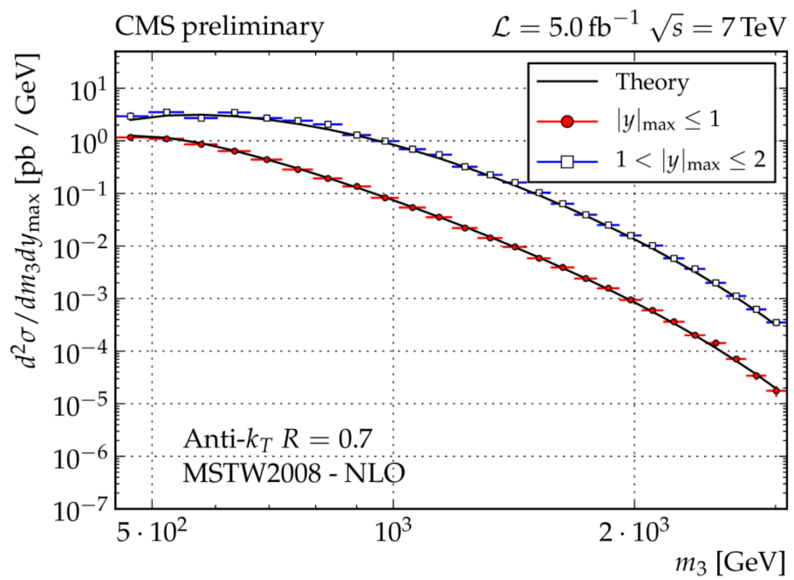
- Goal: Test pQCD by looking at higher jet multiplicities. Study the sensitivity of the observable to parameters of the theory like the PDFs of the proton and extract the strong coupling $\alpha_S(M_Z)$.

- Choices for the analysis
  - Accept jets with p_T>100 GeV
  - Measurement in two rapidity bins : $|y|_{max}<1$ and $1<|y|_{max}<2$
  - $m_3/2$ as Q scale

- Data sample : 2011 (L_{int}=5.0 fb^{-1})

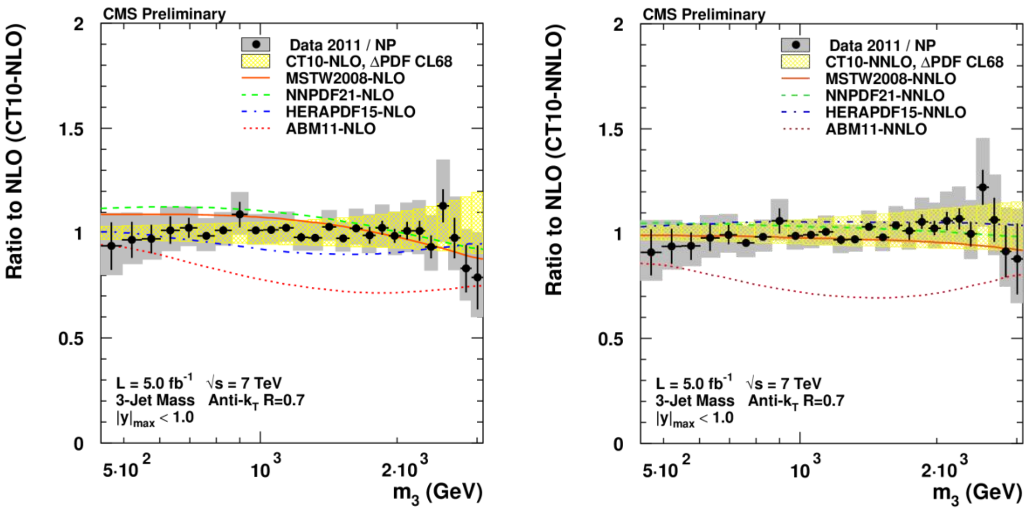
Measurement of the 3-jet mass cross section at 7 TeV

CMS PAS SMP-12-027



- Measurement is compared with the NLO prediction employing the MSTW2008 NLO PDF set.
- pQCD is able to describe the 3-jet mass cross section over five orders of magnitude and for 3-jet masses up to 3 TeV.

CMS PAS SMP-12-027



- Within uncertainties most PDF sets are able to describe the data.
- Same for rapidity bin $1 < |y|_{max} < 2$

Measurement of the 3-jet mass cross section at 7 TeV

- Using PDFs as external input we can determine $\alpha_S(M_Z)$ (MSTW2008 NLO & inner |y| bin)

CMS Preliminary

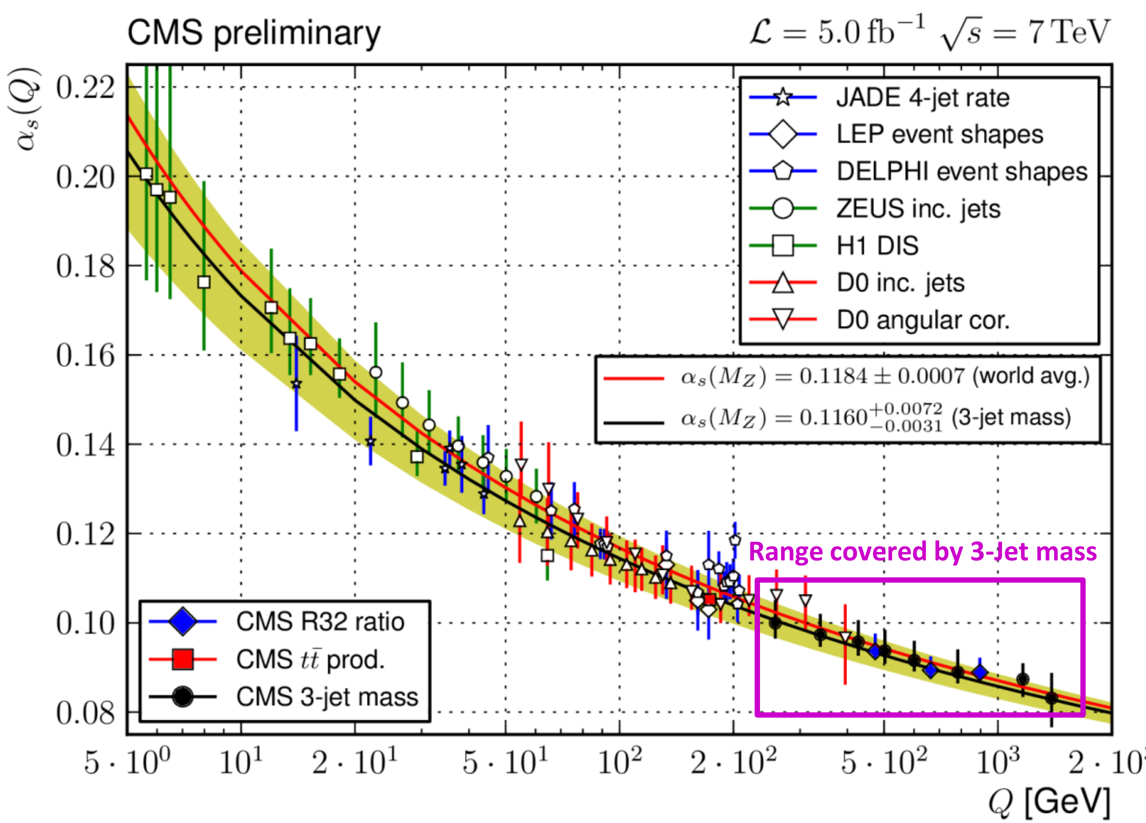
$$\alpha_S(M_Z) = 0.1160 \pm {}^{0.0025}_{0.0023}(\exp, PDF, NP) \pm {}^{0.0068}_{0.0021}(scale)$$

- Determination with other PDF sets are in agreement.

- Extraction also performed for eight subranges in Q to test the α_S running.
- Comparison also to other experiments.

- New CMS results are in agreement with the world measurements and extend the covered range in scale Q up to a new record value of ≈1.4 TeV.

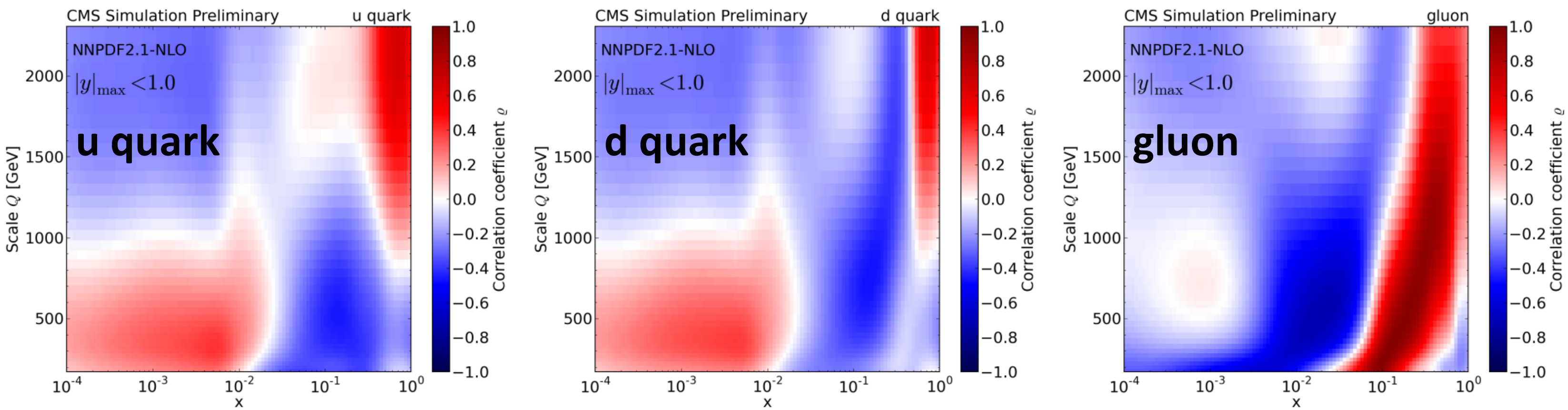
CMS PAS SMP-12-027



Measurement of the 3-jet mass cross section at 7 TeV

- Data are suitable to constrain also PDFs. Using the replicas of the NNPDF2.1 PDF set the correlation coefficient $\boldsymbol{\rho_i(x,Q^2)}$ between the 3-jet mass cross section $\sigma_{m3}\,(x,Q^2)$ and x times the parton distribution function $f_i(x,Q^2)$ is derived.

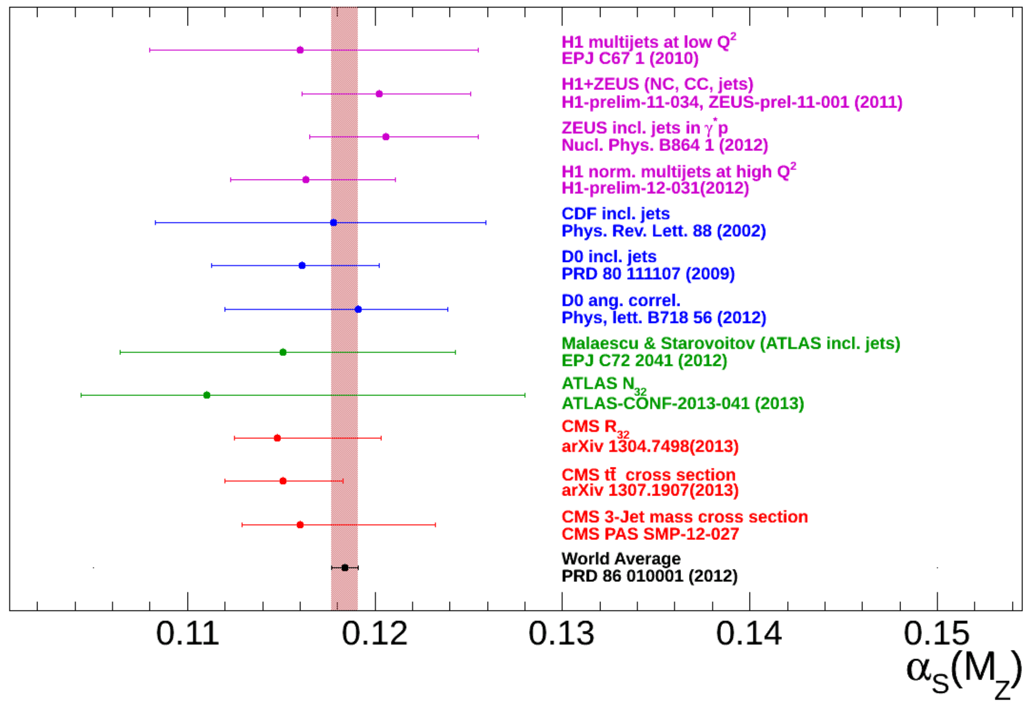
CMS PAS SMP-12-027



- The correlation coefficients are shown for the up- and down-quark, and the gluon in the inner rapidity bin $|y|_{max} < 1$
- They demonstrate the potential impact at high x, in particular for the gluon between 0.05 < x < 0.5.
- In a similar way the ***CMS inclusive jet cross sections at 7 TeV*** can be used to constrain PDFs (work in progress in CMS).

Conclusions

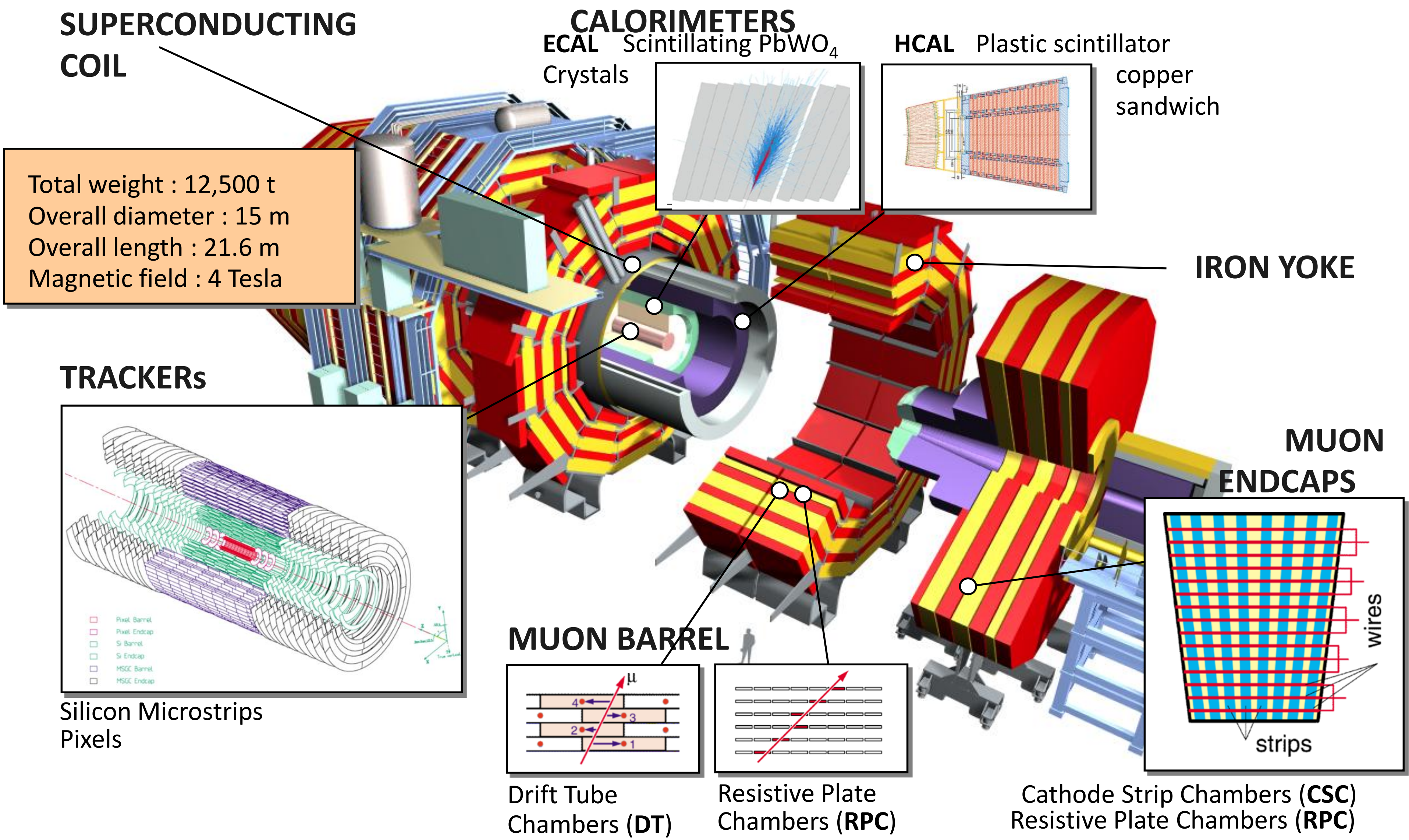
- CMS has an excellent understanding of the jet reconstruction and energy calibration and together with the high data quality make jet measurements PRECISION PHYSICS.
- We have already the first measurements of α_S at the 1 TeV region, with theoretical uncertainties being the dominant ones.
- CMS data from inclusive jet cross sections and 3-jet mass cross sections can be used for constraining PDF's.



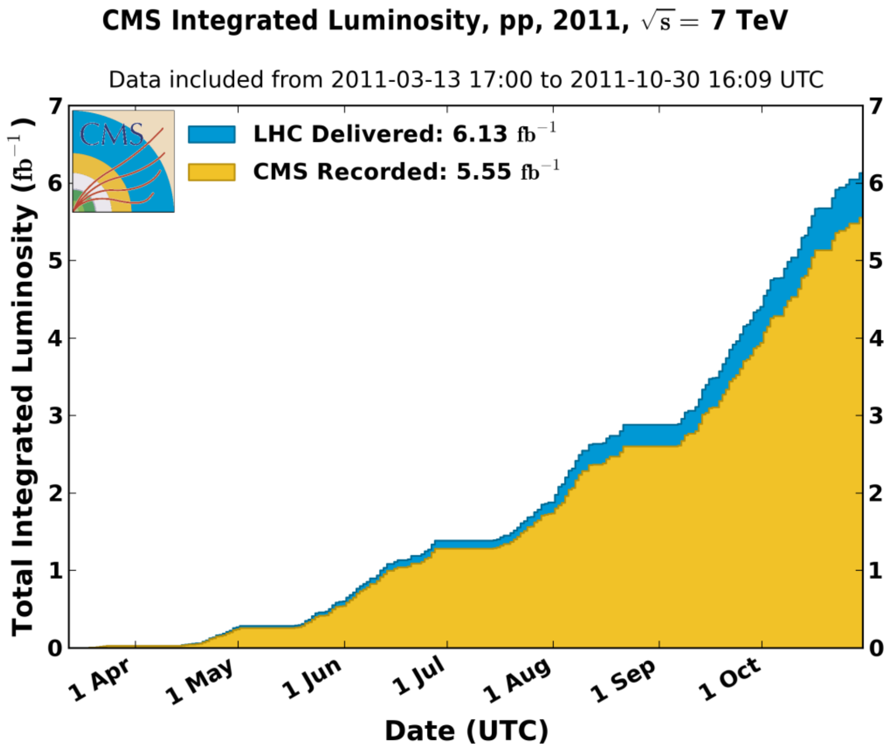
- More to come in the next months. So stay tuned.

Spare

The CMS Detector



2011 integrated luminosity

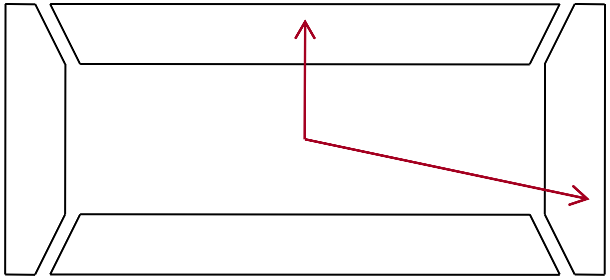


- During the 2011 data taking
  - The total Integrated Luminosity delivered to CMS was 6.13 fb^{-1}
  - 5.55 fb^{-1} was recorded by the experiment.
  - ≈90% recorded with all sub-detectors in perfect operational conditions

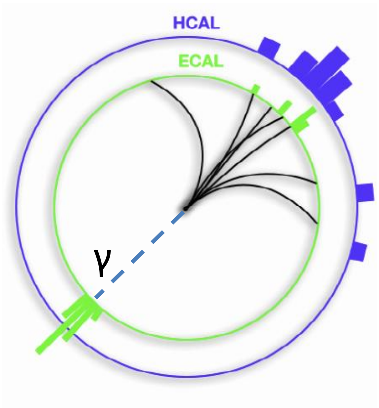
Jet Energy Scale Calibration

- Corrections derived using simulated events and in-situ measurements with dijet and photon+jet events.

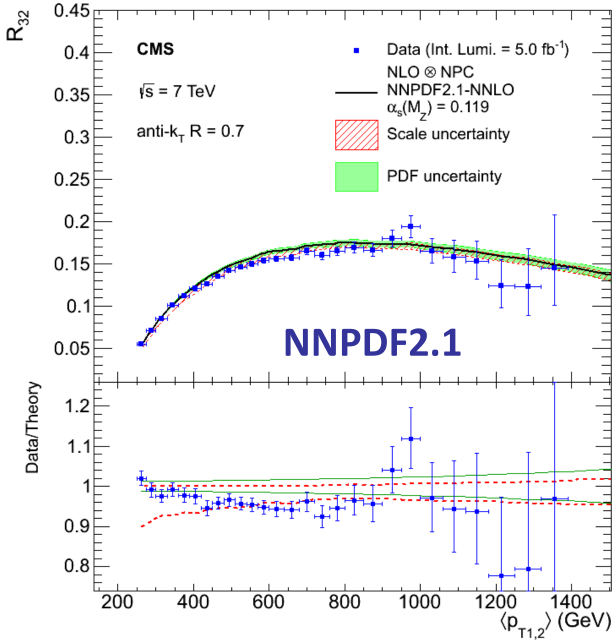
- For **relative** corrections:
  - The di-jet p_T balance technique is employed taking the barrel jet ($|\eta|<1.3$) as reference and the other jet (probe jet) at any η.



- The **absolute** jet energy response is measured using photons+jet events, with two different methods:
  - The MPF (missing E_T projection fraction)
  - And the p_T balance
- Both methods exploit the balance in the transverse plane between the photon and the recoiling jet.

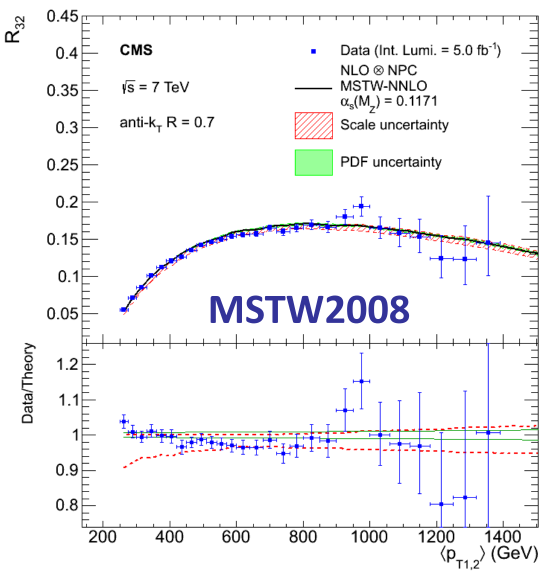


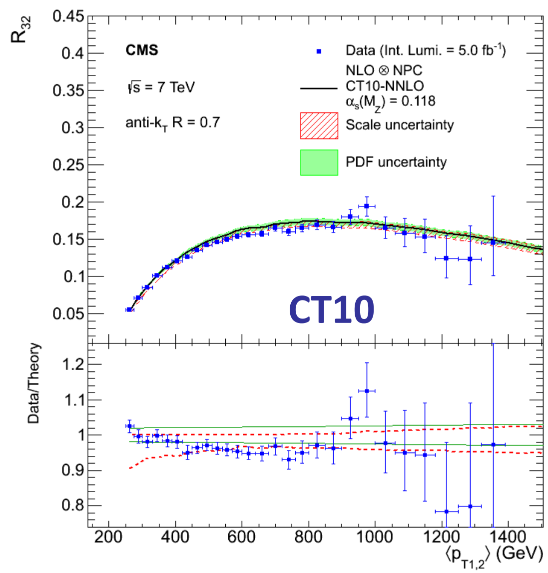
3/2 inclusive jet cross sections ratio (R_{32})

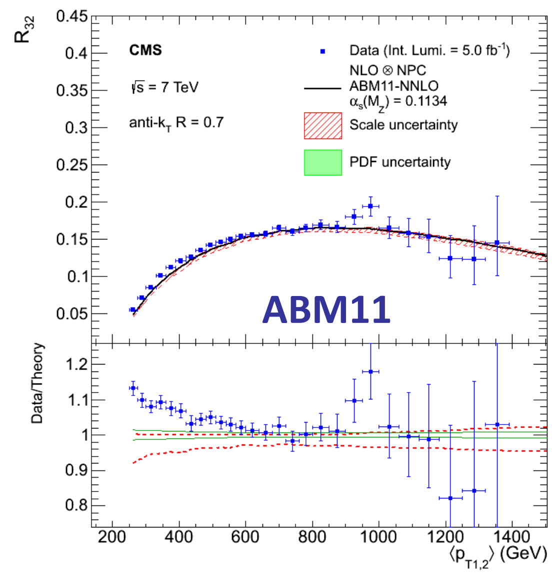


- Measurement is compared with theoretical calculations using the NNPDF2.1, ABM11, MSTW2008 and CT10 PDF sets.
- Calculations using the NNPDF2.1, MSTW2008 and CT10 PDF sets are in agreement with the measured ratio R_{32} throughout the range of this measurement.
- Discrepancies are observed with ABM11.

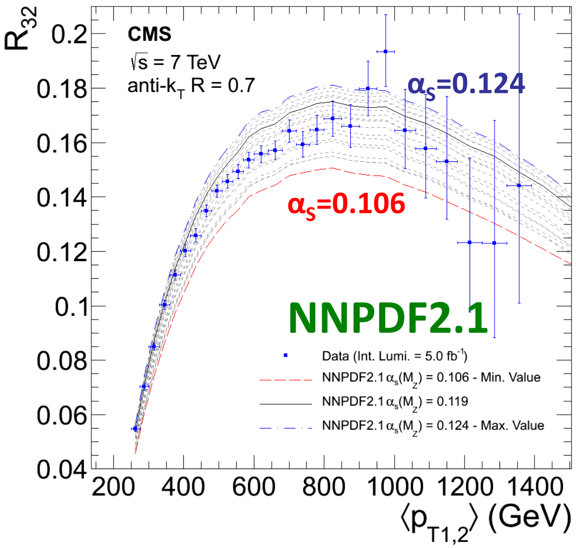
arXiv:1304.7498

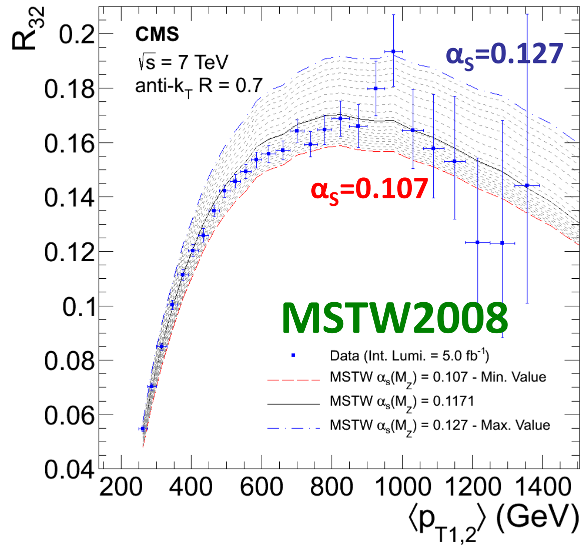


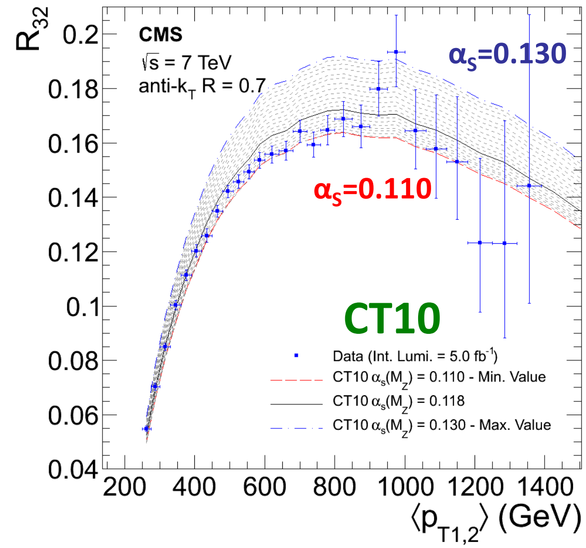


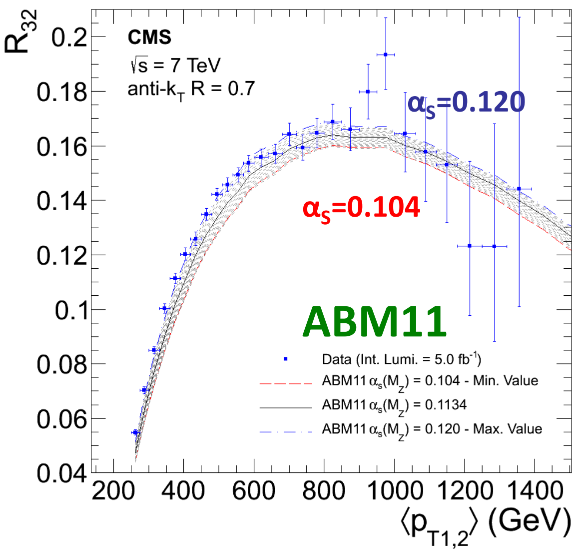


R_{32} – Sensitivity to α_S









arXiv:1304.7498

- R_{32} is sensitive to α_S and can be used for it's extraction.

NNPDF2.1:	$\alpha_S(M_Z) = 0.1148 \pm 0.0014(\text{exp})$
MSTW2008:	$\alpha_S(M_Z) = 0.1141 \pm 0.0022(\text{exp})$
CT10:	$\alpha_S(M_Z) = 0.1135 \pm 0.0019(\text{exp})$
[ABM11:	$\alpha_S(M_Z) = 0.1214 \pm 0.0020(\text{exp})$]

R_{32} – PDF sets and N_f

PDF set	N_f	$\alpha_S(M_Z)$	$\alpha_S(M_Z)$ variation
ABM11	5	0.1134	0.104-0.120
CT10	<=5	0.1180	0.110-0.130
MSTW2008	<=5	0.1171	0.107-0.127
NNPDF2.1	<=6	0.1190	0.106-0.124

- A cross check on the impact of the top quark by imposing N_f=6 massless flavours revealed an increase by +0.0009 in the fitted value of $\alpha_S(M_Z)$ which is covered by the scale uncertainty.

R_{32} – Scales

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

arXiv:1304.7498

The values of $\alpha_S(M_Z)$ at the central scale and for the six scale factor combinations.

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

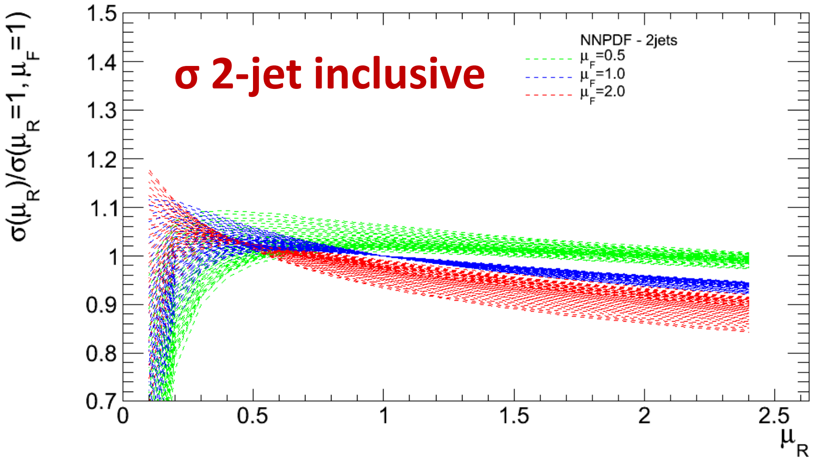
Lowest $\alpha_S(M_Z)$ value (first row)

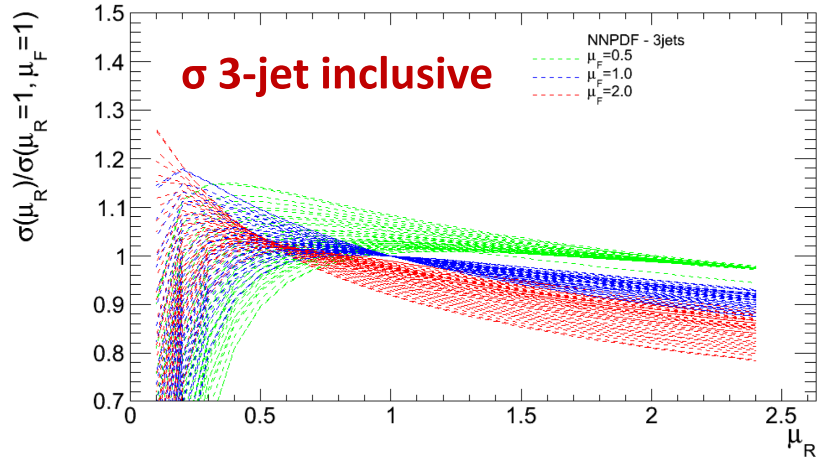
Highest $\alpha_S(M_Z)$ value (second row)

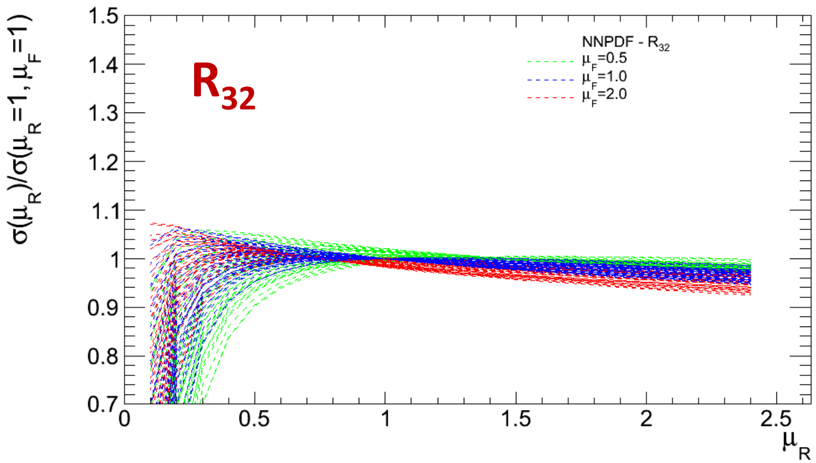
- The frequent observation of asymmetric scale uncertainties with larger downward uncertainties in the case of NLO cross sections is transformed into a purely upward uncertainty for the ratio.

R_{32} – Scale Dependence

- Plots show all changes relative to the default setting of $\mu_r=\mu_f= \langle p_{T1,2} \rangle$, i.e. (of $\mu_r=\mu_f=1$). Hence, only the curves for the of μ_f scale factor of 1 (blue) must cross at (1,1).
- The variation in the red and green lines in comparison to (1,1) expose the differences in μ_f dependence for the various σ/R ($\langle p_{T\_1,2} \rangle$) bins.



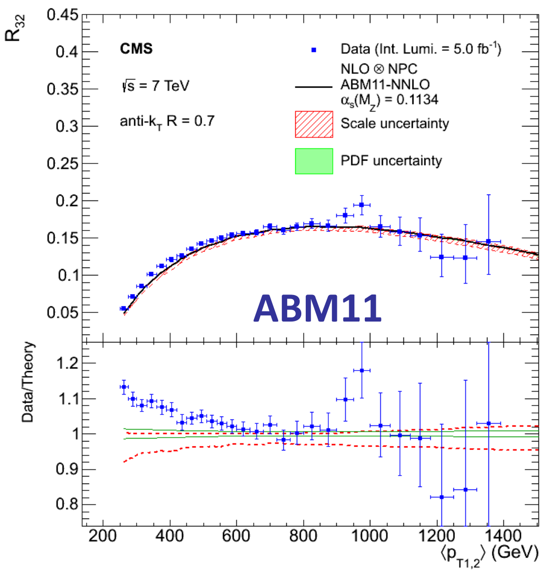


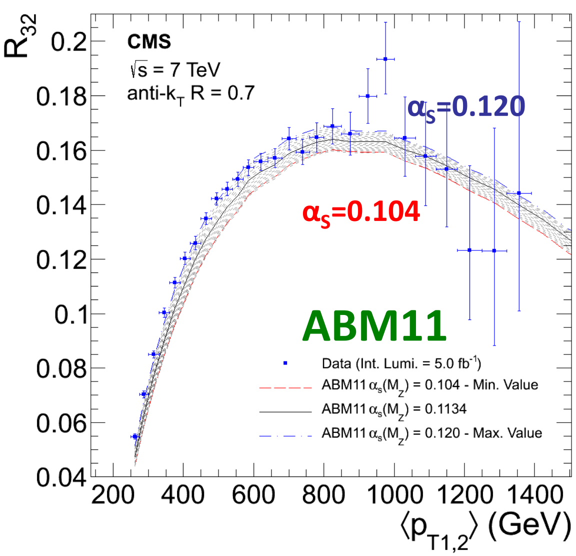


Partially cancelation of scale uncertainties in the ratio.

R_{32} – ABM11

arXiv:1304.7498





ABM11-NNLO:	$\alpha_S(M_Z) = 0.1214 \pm 0.0020(\text{exp})$	$\chi^2/\text{ndof}=20.6/20$
ABM11-NLO:	$\alpha_S(M_Z) = 0.1214 \pm 0.0018(\text{exp})$	$\chi^2/\text{ndof}=28.5/20$

- It is observed that with ABM11 PDFs a higher value of $\alpha_S(M_Z)$ is preferred.
- The ABM11 gluon density in the phase space relevant for this analysis is significantly smaller than that of all other PDF sets.
- So the fit favors a larger $\alpha_S(M_Z)$ value to compensate for this effect.
- **In summary:** The ABM11 PDF set does not describe the data as well as the alternative PDF sets, as shown in the upper figure, which leads to an inferior fit quality and a less consistent result for the strong coupling.

R_{32} – α_S running

- Extraction of α_S also performed for three subranges in Q:

arXiv:1304.7498

Table 3: The separate determinations of α_S in bins of $\langle p_{T1,2} \rangle$.

$\langle p_{T1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/N_{dof}
420–600	474	$0.1147^{+0.0061}_{-0.0021}$	$0.0936^{+0.0040}_{-0.0014}$	6	4.4/5
600–800	664	$0.1132^{+0.0050}_{-0.0031}$	$0.0894^{+0.0031}_{-0.0019}$	5	5.9/4
800–1390	896	$0.1170^{+0.0058}_{-0.0032}$	$0.0889^{+0.0033}_{-0.0018}$	10	5.7/9

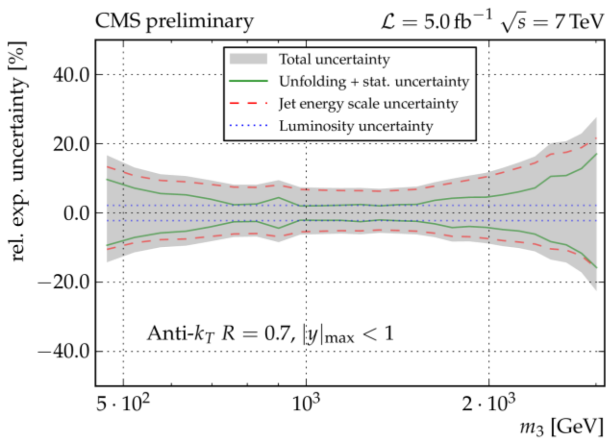
Table 4: Uncertainty composition for $\alpha_S(M_Z)$ from the determination of α_S in bins of $\langle p_{T1,2} \rangle$.

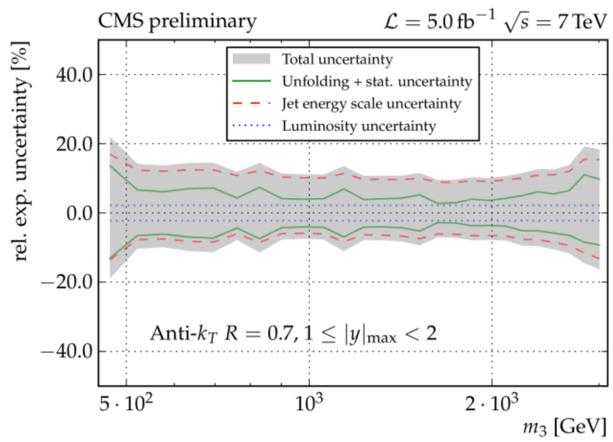
$\langle p_{T1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	exp.	PDF	scale
420–600	474	0.1147	± 0.0015	± 0.0015	$^{+0.0057}_{-0.0000}$
600–800	664	0.1132	± 0.0018	± 0.0025	$^{+0.0039}_{-0.0000}$
800–1390	896	0.1170	± 0.0024	± 0.0021	$^{+0.0048}_{-0.0003}$

3-jet mass: Uncertainties

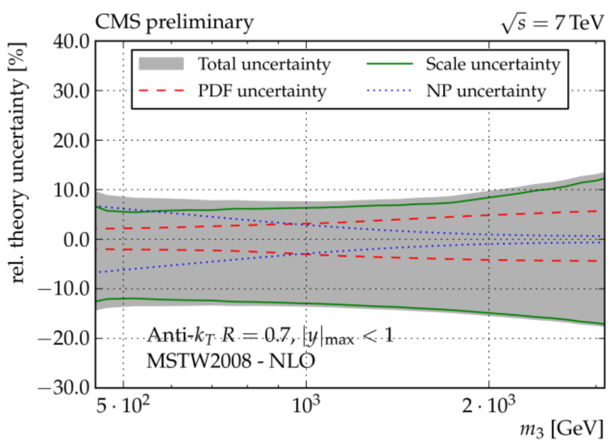
CMS PAS SMP-12-027

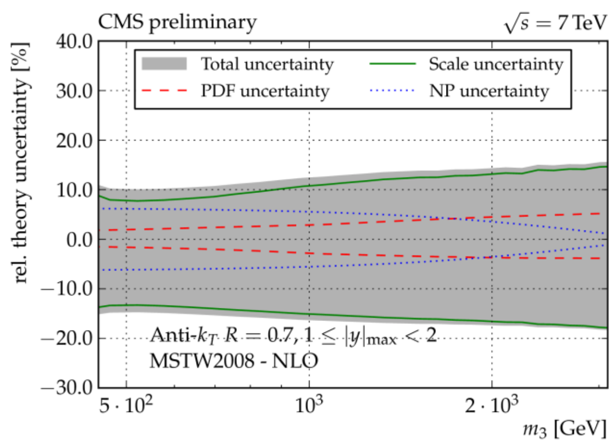
Experimental Uncertainties





Theoretical Uncertainties





3-jet mass: PDFs

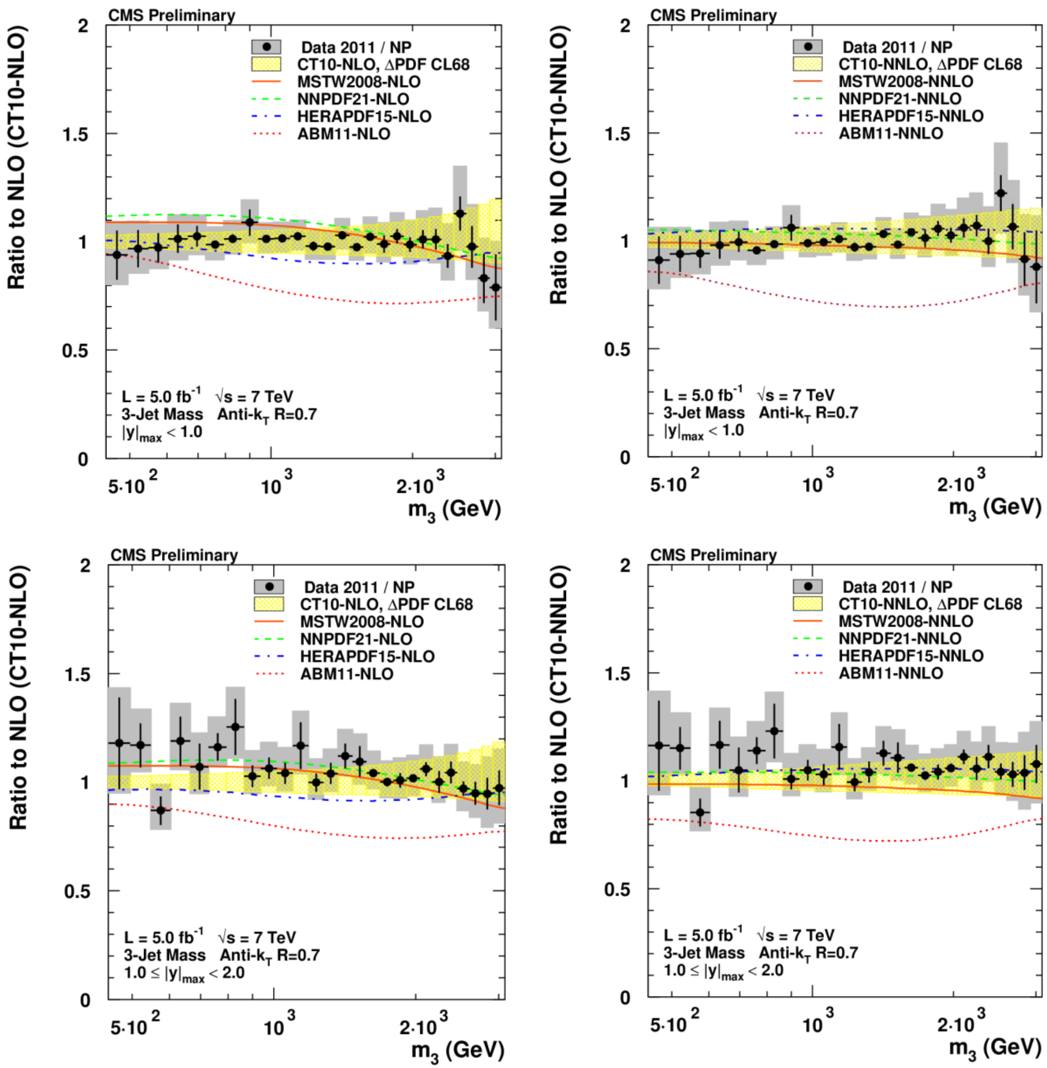
CMS PAS SMP-12-027

Table 1: PDF sets used in comparisons to the data together with the corresponding number of active flavours N_f, the default values of the strong coupling constant $\alpha_S(M_Z)$ and the ranges in $\alpha_S(M_Z)$ available for fits. For CT10 the updated versions of 2012 are taken.

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
HERAPDF15	[26]	NLO	≤ 5	0.1176	0.114–0.122
HERAPDF15	[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
NNPDF21	[29]	NLO	≤ 6	0.1190	0.114–0.124
NNPDF21	[29]	NNLO	≤ 6	0.1190	0.114–0.124

3-jet mass: Comparison to theory

CMS PAS SMP-12-027

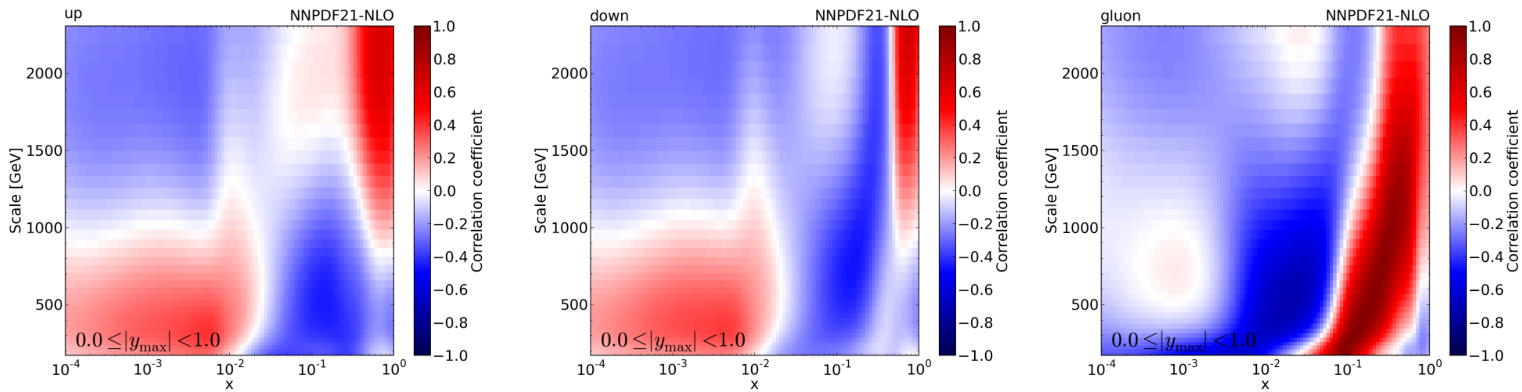


- Within uncertainties most PDF sets are able to describe the data.
- Small deviations are visible with the HERAPDF1.5 NLO set.
- Significant disagreements are exhibited by the ABM11 PDFs.

3-jet mass: Constrain PDFs

CMS PAS SMP-12-027

- Using the replicas of the NNPDF2.1 PDF set the correlation coefficient $\rho_i(x,Q^2)$ between the 3-jet mass cross section $\sigma m_3\,(x,Q^2)$ and x times the parton distribution function $f_i(x,Q^2)$ is derived.



$$\rho_i\left(x,Q^2\right)=\frac{N_{rep}}{\left(N_{rep}-1\right)}\cdot\frac{\left\langle \sigma_{m_3}\left(x,Q^2\right)xf_i\left(x,Q^2\right)\right\rangle-\left\langle \sigma_{m_3}\left(x,Q^2\right)\right\rangle\left\langle xf_i\left(x,Q^2\right)\right\rangle}{\Delta_{\sigma_{m_3}\left(x,Q^2\right)}\Delta_{xf_i\left(x,Q^2\right)}}$$

N_{rep} : NNPDF2.1 PDF set replicas

σ_{m_3} : 3-jet mass cross section

f_i : the parton distribution function for parton flavour i

x : the fractional parton momentum x

$Q = m_3/2$: the relevant momentum scale

Δ : the standard variation around the ensemble mean of $\sigma_{m_3}\left(x,Q^2\right)$ and $xf_i\left(x,Q^2\right)$

i : runs over all quark, anti-quark and gluon flavours.

3-jet mass: Central result & running

CMS PAS SMP-12-027

Table 2: Determinations of $\alpha_S(M_Z)$ in the considered m_3 ranges for the inner rapidity bin. The relevant scale in each 3-jet mass range is calculated from the cross-section weighted average as given by the theory prediction using the MSTW2008 PDF set with NLO evolution. The overall fit is using the whole 3-jet mass range in the inner rapidity region. The quoted uncertainties are the combined uncertainty from experimental sources, the PDFs, and the NP corrections. The scale uncertainty is given separately.

m_3 [GeV]	$\langle Q \rangle$ [GeV]	$\chi^2/N_{\rm dof}$	$\alpha_S(M_Z)$	$\pm$(exp, PDF, NP)	$\pm$(scale)
445–604	258 ± 12	0.05/3	0.1152	$\pm^{0.0044}_{0.0042}$	$\pm^{0.0053}_{0.0019}$
604–794	339 ± 14	0.28/3	0.1163	$\pm^{0.0034}_{0.0032}$	$\pm^{0.0058}_{0.0022}$
794–938	427 ± 12	0.46/2	0.1179	$\pm^{0.0042}_{0.0041}$	$\pm^{0.0063}_{0.0023}$
938–1098	502 ± 13	0.01/2	0.1177	± 0.0039	$\pm^{0.0065}_{0.0024}$
1098–1369	600 ± 20	0.70/3	0.1174	$\pm^{0.0032}_{0.0031}$	$\pm^{0.0066}_{0.0025}$
1369–2172	783 ± 32	2.22/7	0.1175	± 0.0034	$\pm^{0.0085}_{0.0027}$
2172–2602	1163 ± 31	1.40/3	0.1218	$\pm^{0.0037}_{0.0060}$	$\pm^{0.0061}_{0.0048}$
2602–3092	1386 ± 34	0.33/3	0.1166	$\pm^{0.0075}_{0.0100}$	$\pm^{0.0088}_{0.0075}$
445–3092	304 ± 15	9.11/26	0.1160	$\pm^{0.0025}_{0.0023}$	$\pm^{0.0068}_{0.0021}$

3-jet mass: Results with various PDFs

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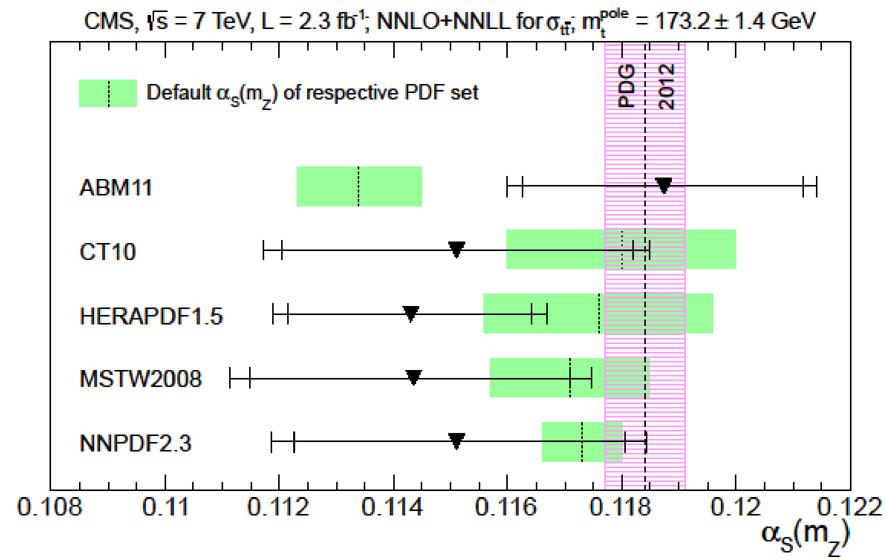
Table 3: Determinations of $\alpha_S(M_Z)$ with different PDFs using the whole 3-jet mass range in the inner rapidity region. The quoted uncertainties are the combined uncertainty from experimental sources, the PDF uncertainty, and the NP corrections. The scale uncertainty is given separately. Note that for the NNPDF2.1-NLO PDF set, the scale uncertainty had to be determined from an extrapolation of the χ^2 curve.

PDF	χ^2/N_{dof}	$\alpha_S(M_Z)$	$\pm$(exp, PDF, NP)	$\pm$(scale)
CT10-NLO	8.92/26	0.1169	$\pm^{0.0031}_{0.0032}$	$\pm^{0.0059}_{0.0025}$
CT10-NNLO	8.51/26	0.1164	± 0.0028	$\pm^{0.0055}_{0.0022}$
HERAPDF15-NLO	14.76/26	0.1200	± 0.0014	$\pm^{0.0063}_{0.0010}$
HERAPDF15-NNLO	9.00/26	0.1159	$\pm^{0.0012}_{0.0011}$	$\pm^{0.0028}_{0.0007}$
MSTW2008-NLO	9.11/26	0.1160	$\pm^{0.0025}_{0.0023}$	$\pm^{0.0068}_{0.0021}$
MSTW2008-NNLO	9.54/26	0.1167	$\pm^{0.0026}_{0.0024}$	$\pm^{0.0059}_{0.0026}$
NNPDF21-NLO	9.01/26	0.1140	$\pm^{0.0027}_{0.0026}$	$\pm^{0.0049}_{0.0014}$
NNPDF21-NNLO	9.47/26	0.1168	$\pm^{0.0021}_{0.0024}$	$\pm^{0.0042}_{0.0018}$

Determination of α_S from $t\bar{t}$ production cross section

arXiv:1307.1907

- Comparison of measured cross section of inclusive $t\bar{t}$ production to QCD calculations at NNLO+NNLL.
- Using five NNLO PDF sets:
  - ABM11
  - CT10
  - HERAPDF
  - MSTW2008
  - NNPDF2.3
- $\alpha_S(M_Z)$ is obtained by constraining $m_t^{pole} = 173.2 \pm 1.4\,\mathrm{TeV}$



$$\alpha_S(M_Z) = 0.1151^{+0.0033}_{-0.0032}$$

- This is the first determination of $\alpha_S(M_Z)$ from top-quark production and the first result at full NNLO QCD obtained at a hadron collider.