CMS Experiment at LHC, CERN
Data recorded: Tue May 25 06:24:04 2010 CEST
Run/Event: 136100 / 103078800
Lumi section: 348

α_S Measurements

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On behalf of the ATLAS and CMS Collaborations

SM@LHC : Standard Model at LHC
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Program THALIS : "Search for new physics with the ATLAS and CMS experiments at the LHC: NewPhysAtLHC"

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European Union
European Social Fund

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EDUCATION AND LIFELONG LEARNING
investing in knowledge society
MINISTRY OF EDUCATION & RELIGIOUS AFFAIRS
MANAGING AUTHORITY
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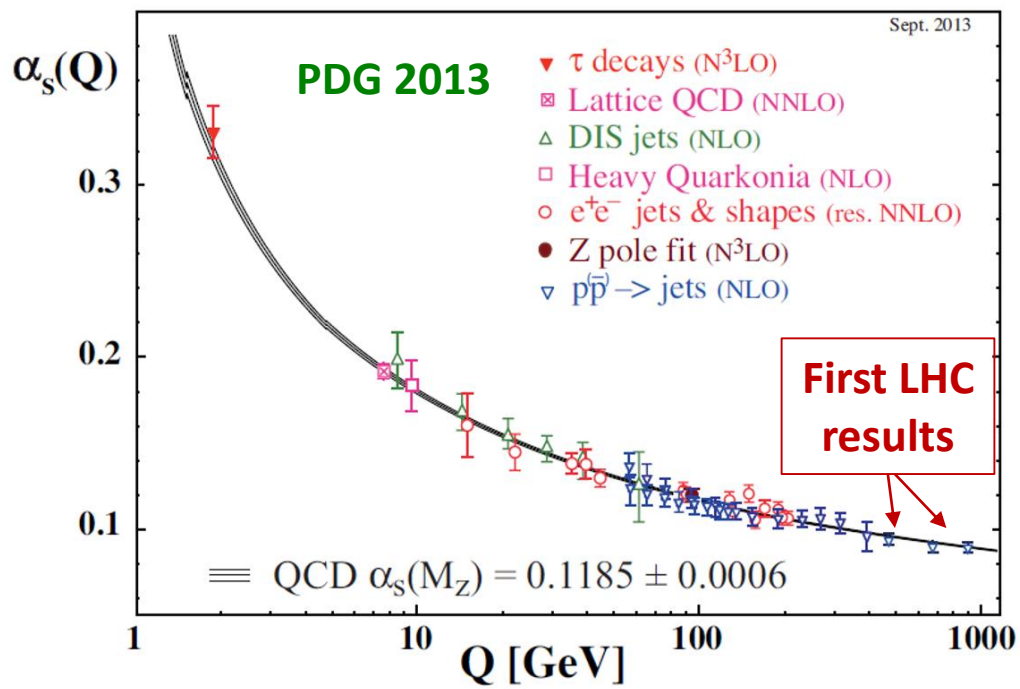
Outline

- Introduction
- Jet Reconstruction & Energy Scale Calibration
- Measurements of the Strong Coupling Constant
  - From the Inclusive jet cross section
  - From the 3-jet mass cross section
  - From the ratio 3/2 of incl. jet cross sections
  - From top-pair production cross section
- Summary

Introduction

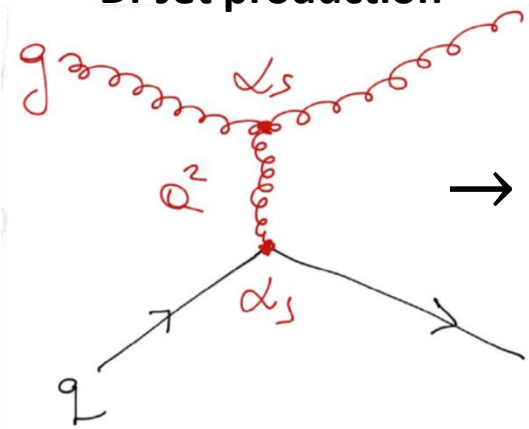
- QCD processes are dominant at LHC. **LHC is a jet factory**.
- Jet measurements @ LHC
  - provide a test of pQCD in a previously unexplored energy region.
  - Check SM predictions at high energy scales.
  - Measure and understand the main background to many new physics searches
  - Provide constraints on PDF's.

- **Jets at the LHC probe the highest energy transfers at which to determine the strong coupling.**



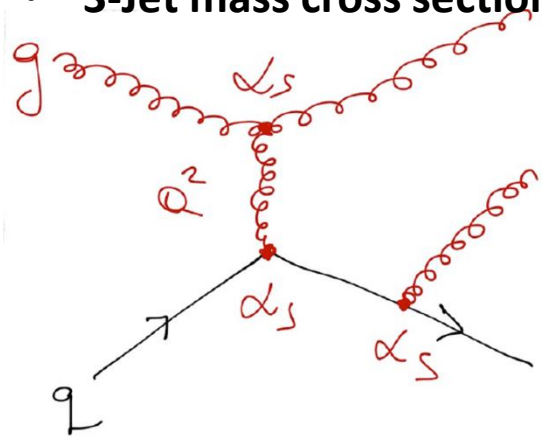
Introduction – α_S measurements with jets

LO diagram for
- **Incl. Jet production**
- **Di-Jet production**

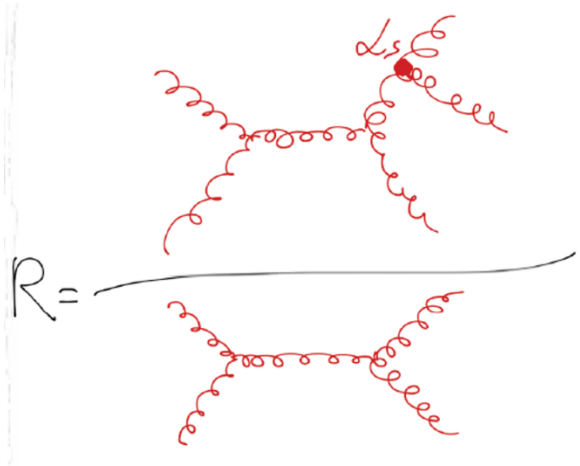


$\rightarrow \alpha_S^2$

LO diagram for
- **3-Jet production**
- **3-Jet mass cross section**



$\rightarrow \alpha_S^3$

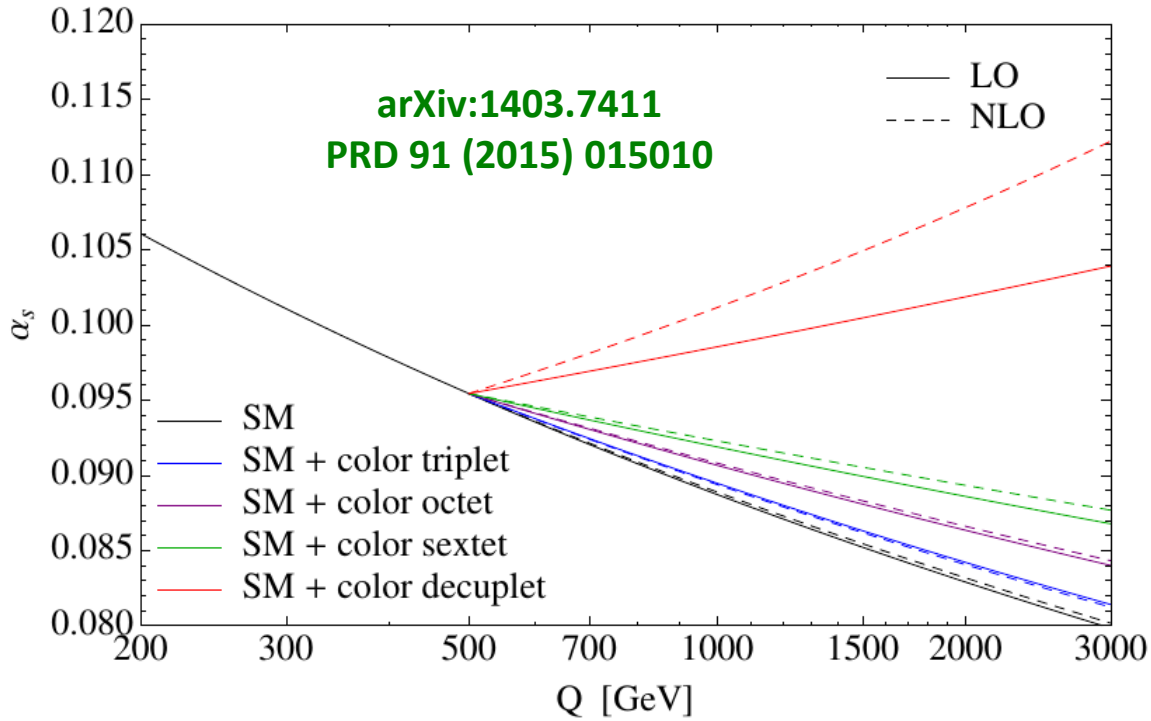


$\rightarrow \alpha_S$

Inclusive Jet cross section ratios : Cancelation or reduction of various uncertainties

G. Dissertori : "Proton Structure in the LHC era", DESY, 29.9.2014

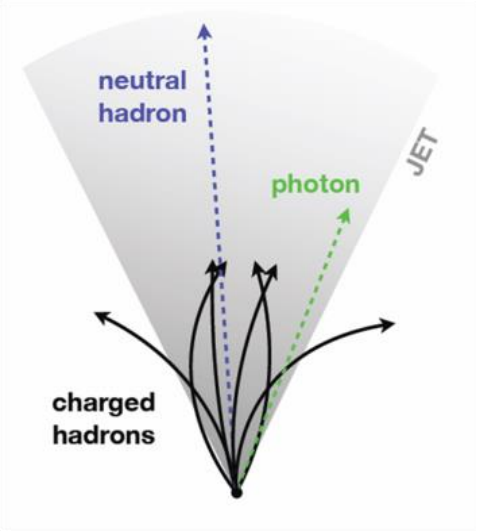
Introduction – α_S probes new physics



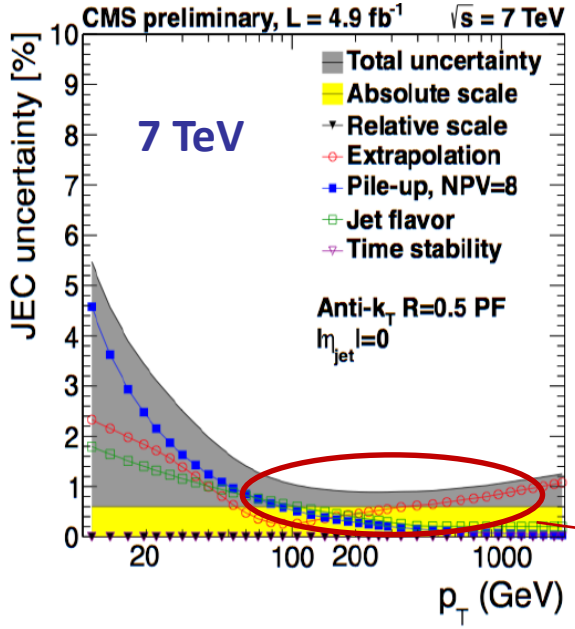
- Any deviation in the running of α_S probes to **New Physics**.
  - Test for the appearance of new colored matter at the TeV region (eg. new colored fermion at 500 GeV).

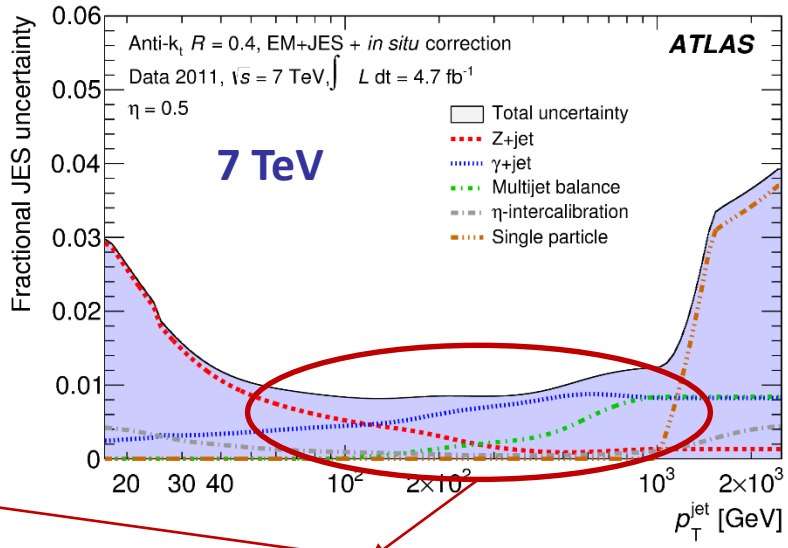
Jet Reconstruction & Energy Scale Calibration

- **Anti-k_T clustering algorithm** : Infrared and collinear safe. Used with R=0.5 and 0.7 for CMS and R=0.4 and 0.6 for ATLAS.
- **CMS** Particle Flow Jets (PF Jets) : Clustering of Particle Flow candidates constructed by combining information from all sub-detector systems.
- **ATLAS** : Clustering of Calorimeter Towers composed of ECAL and HCAL energy deposits



CMS : DP-2012-006



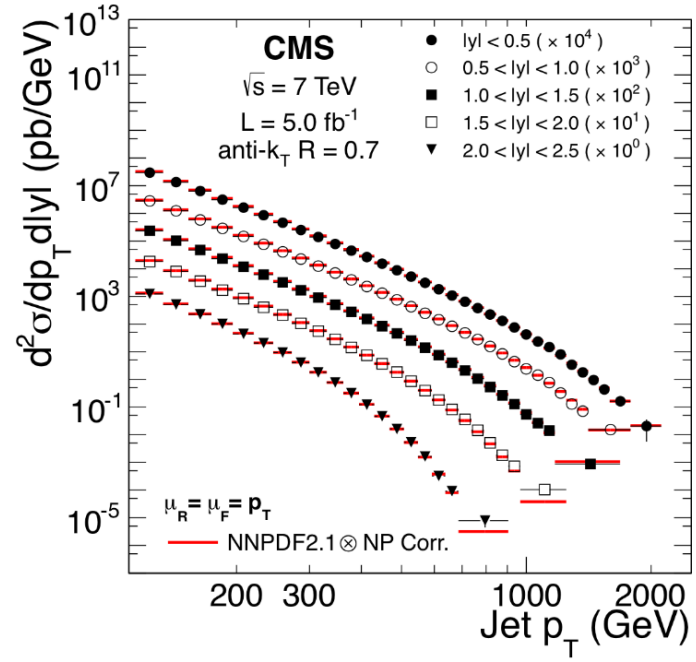


ATLAS : EPJC (2015) 75:17

JEC at 1% level

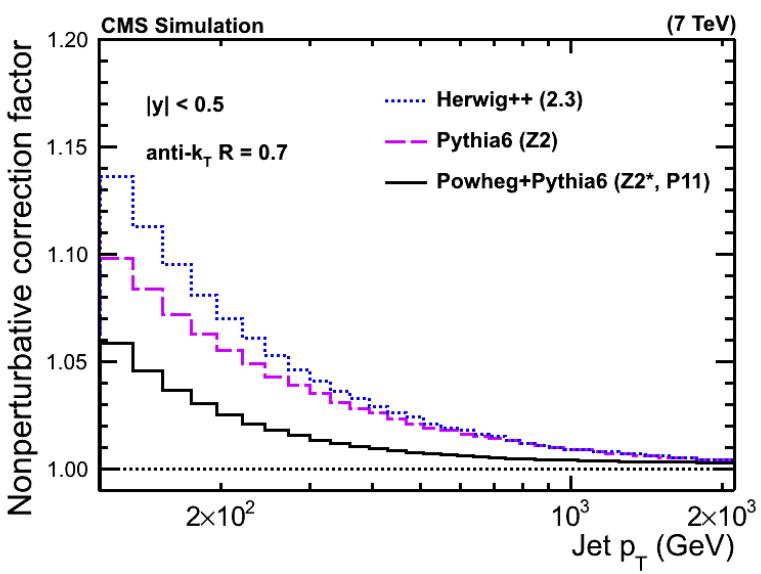
α_S from the inclusive jet cross section at 7 TeV

- Measurement is based on the 2011 inclusive jet cross section at 7 TeV published by **CMS**: PRD 87,112002(2013).
- Observable $$\frac{d^2\sigma}{dp_T\, dy} \propto \alpha_S^2$$
- Phase space : $|y| \leq 2.5$ and jet p_T: 114GeV-2TeV
- Scale choice : $\mu_r = \mu_f = p_T$



CMS : PRD 87 112002 (2013)

CMS : arXiv1410.6765

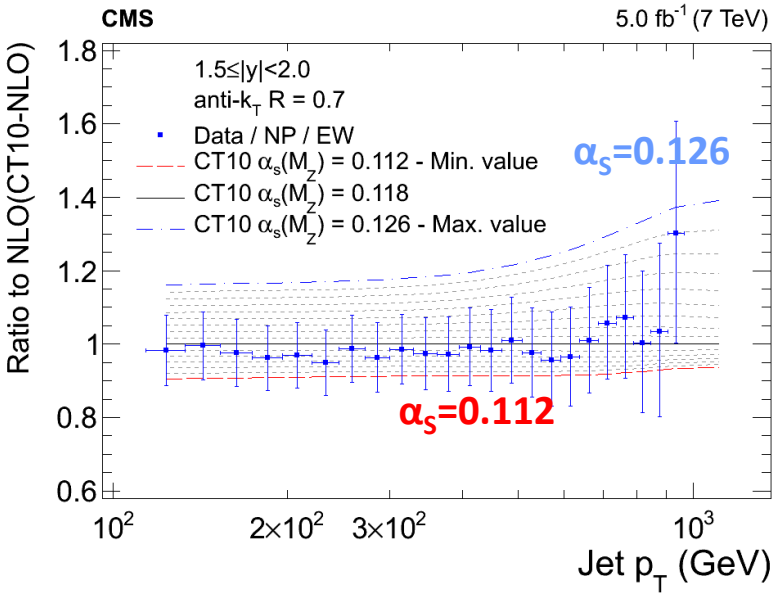


- NP corrections: account for multiparton interactions (MPI) and hadronization (HAD)
- Not included in perturbative L0, NLO calculations
- Derived with Monte Carlo calculations

$$\frac{d^2\sigma_{theo}}{dp_T dy} = \frac{d^2\sigma_{\mathrm{NLO}}}{dp_T dy} \cdot C_{\mathrm{NLO}}^{\mathrm{NP}}$$

$$C_{\mathrm{NLO}}^{\mathrm{NP}} = \frac{\sigma_{\mathrm{NLO+PS+HAD+MPI}}}{\sigma_{\mathrm{NLO+PS}}}$$

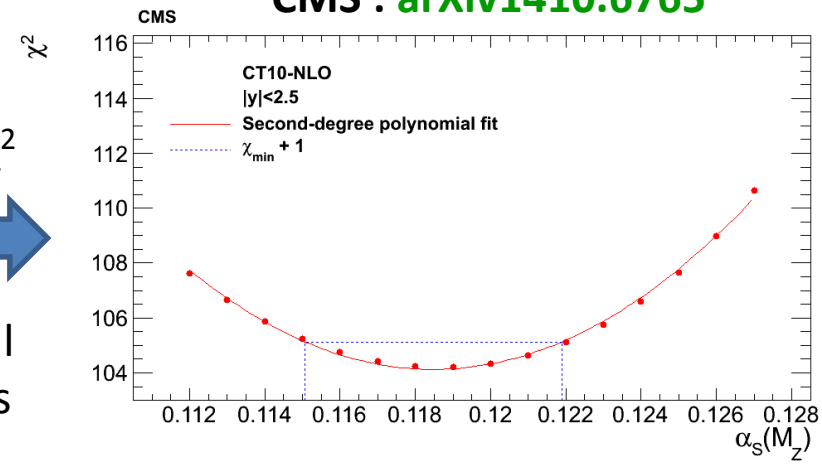
α_S from the inclusive jet cross section at 7 TeV



Construct χ^2

Including all correlations

CMS : arXiv1410.6765



$$\chi^2 = \sum_{ij}^{N} (D_i - T_i) C_{ij}^{-1} (D_i - T_i)$$

$$C = \mathrm{cov}_{\mathrm{stat}} + \mathrm{cov}_{\mathrm{uncor}} + \left(\sum_{\mathrm{sources}} \mathrm{cov}_{\mathrm{JES}} \right) + \mathrm{cov}_{\mathrm{unfolding}} + \mathrm{cov}_{\mathrm{lumi}} + \mathrm{cov}_{\mathrm{PDF}}$$

- **Systematics** :
  - **PDF uncertainty** : repeat fit for PDF sets errors following prescriptions of each set eigenvectors (CT10, MSTW2008) or replicas (NNPDF2.1)
  - **NP uncertainty** : vary the non-pertubative correction factor considering the half of the spread of the three MC calculations as uncertainty.
  - **Scale uncertainty** : repeat fit for different scale settings by varying independently μ_r/Q and μ_f/Q from ½ to 2, and get maximal deviation.

α_S from the inclusive jet cross section at 7 TeV

- PDF sets used for α_S extraction: CT10, MSTW2008, NNPDF2.1.
- Central fit : all rapidity bins with CT10-NLO.
- Determination at **NLO**

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

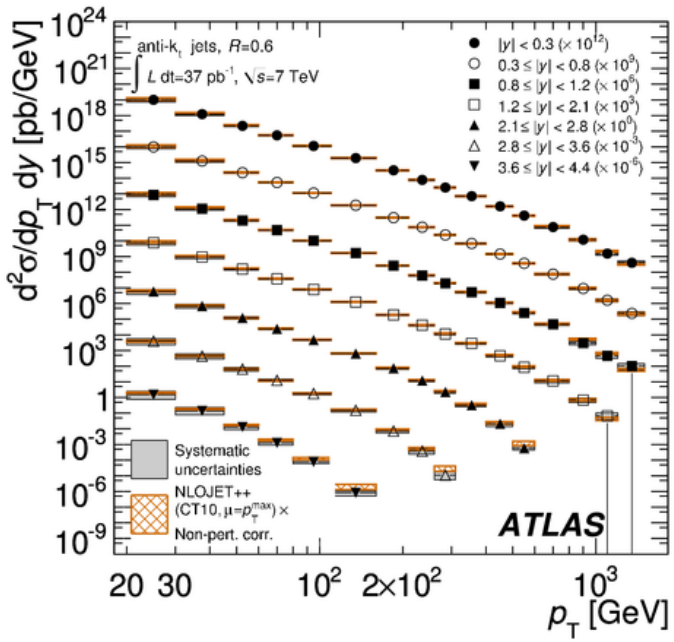
- Results using MSTW2018 and NNPDF2.1 are in agreement with central CT10 result
- Total uncertainty 3.5 to 5.5 %.
- Dominated by missing-order terms (μ_r, μ_f)

p_T range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/n_{dof}
114–196	136	$0.1172^{+0.0058}_{-0.0043}$	$0.1106^{+0.0052}_{-0.0038}$	20	6.2/19
196–300	226	$0.1180^{+0.0063}_{-0.0046}$	$0.1038^{+0.0048}_{-0.0035}$	20	7.6/19
300–468	345	$0.1194^{+0.0064}_{-0.0049}$	$0.0993^{+0.0044}_{-0.0034}$	25	8.1/24
468–638	521	$0.1187^{+0.0067}_{-0.0051}$	$0.0940^{+0.0041}_{-0.0032}$	20	10.6/19
638–905	711	$0.1192^{+0.0074}_{-0.0056}$	$0.0909^{+0.0042}_{-0.0033}$	22	11.2/21
905–2116	1007	$0.1176^{+0.0111}_{-0.0065}$	$0.0866^{+0.0057}_{-0.0036}$	26	33.6/25

- α_S running : Perform fit for separate p_T bins
- Test consistency with the α_S running

α_S from the inclusive jet cross section at 7 TeV

- α_S determination by B.Malaescu & P.Starovoitov **EPJC(2012) 72:2041**
- Based on the inclusive jet cross sections measured by **ATLAS** (2010 data 37pb^{-1}) **PRD 86 (2012) 014022**
- Phase space : $|y| \leq 4.4$ and jet p_T: 20GeV-1TeV
- Scale choice : $\mu_r = \mu_f = p_T$
- PDF sets used for α_S extraction: CT10, MSTW2008, HERAPDF1.5 and NNPDF2.1.
- Use two cone sizes: R=0.4 and R=0.6



ATLAS : PRD 86 (2012) 014022

$$\alpha_S(M_Z) = 0.1151 \pm 0.0001(stat) \pm 0.0047(\exp syst) \pm 0.0014(p_T\ range)$$
$$\pm 0.0060(jet\ size) \pm {}^{0.0044}_{0.0011}(scale) \pm {}^{0.0022}_{0.0015}(PDF\ choice)$$
$$\pm 0.0010(PDF\ eig) \pm {}^{0.0009}_{0.0034}(NP)$$

- Total uncertainty 8%
- Observed differences when using different jet sizes!

α_S from the 3-jet mass cross section at 7 TeV

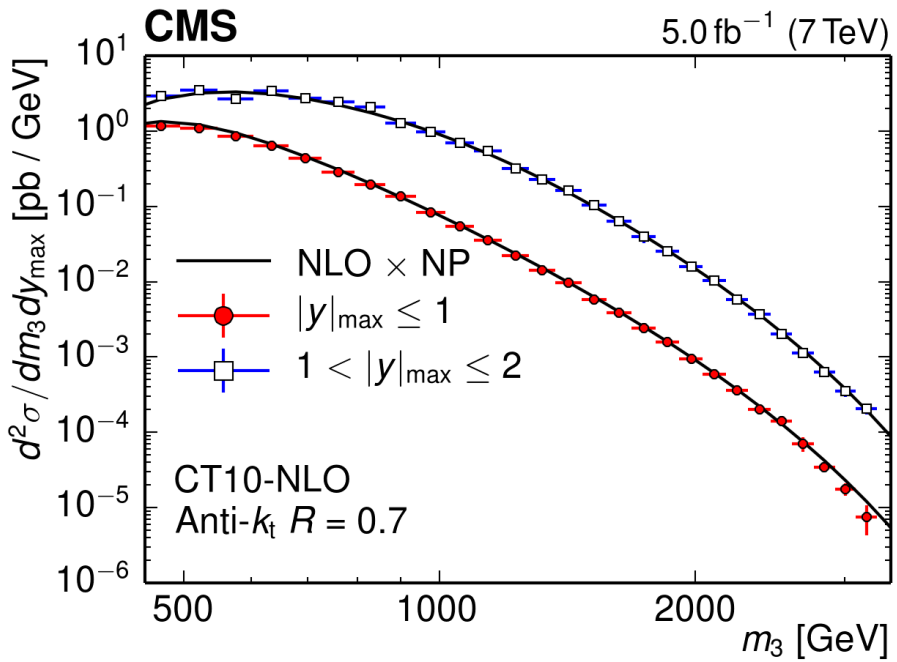
- Measurement by **CMS** of the double differential 3-jet cross section in m_3 and y_{max} (**CMS : arXiv:1412.1633** accepted in **EPJC**)

$$\frac{d^2\sigma}{dm_3\, dy_{max}} \propto \alpha_S^3$$

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

- Phase space: Jets p_T>100 GeV, Two rapidity bins: $|y|_{max}$<1 and 1< $|y|_{max}$<2
- Scale choice: $\mu_r=\mu_f=m_3/2$

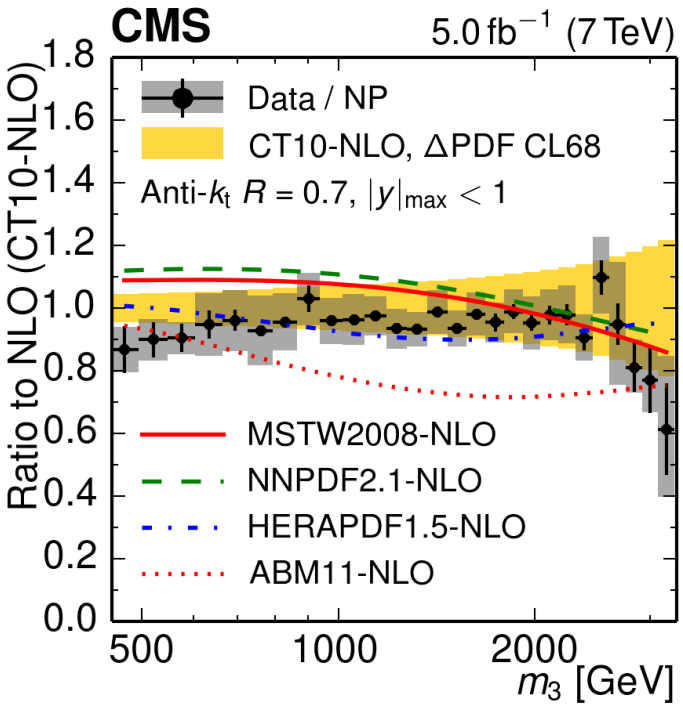
CMS : arXiv:1412.1633

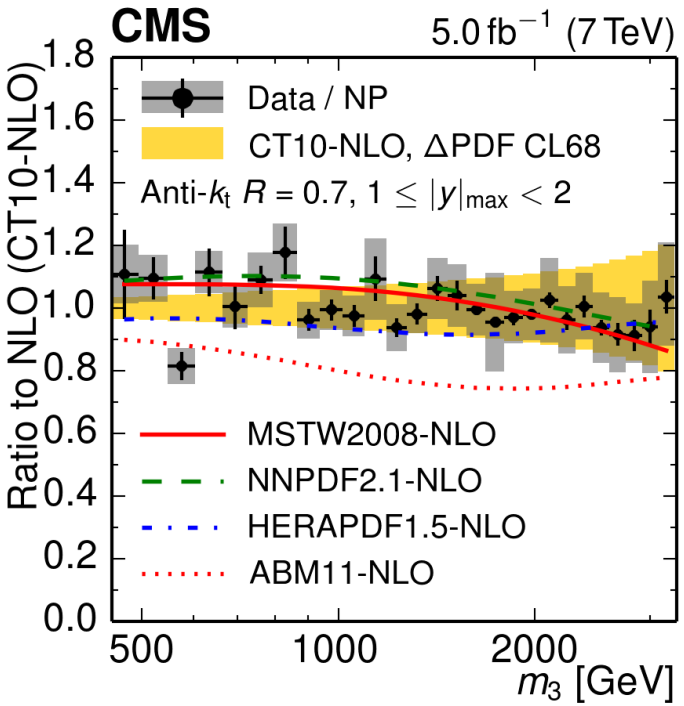


- pQCD is able to describe the 3-jet mass cross section over five orders of magnitude and for 3-jet masses up to 3 TeV.

α_S from the 3-jet mass cross section at 7 TeV

CMS : arXiv:1412.1633

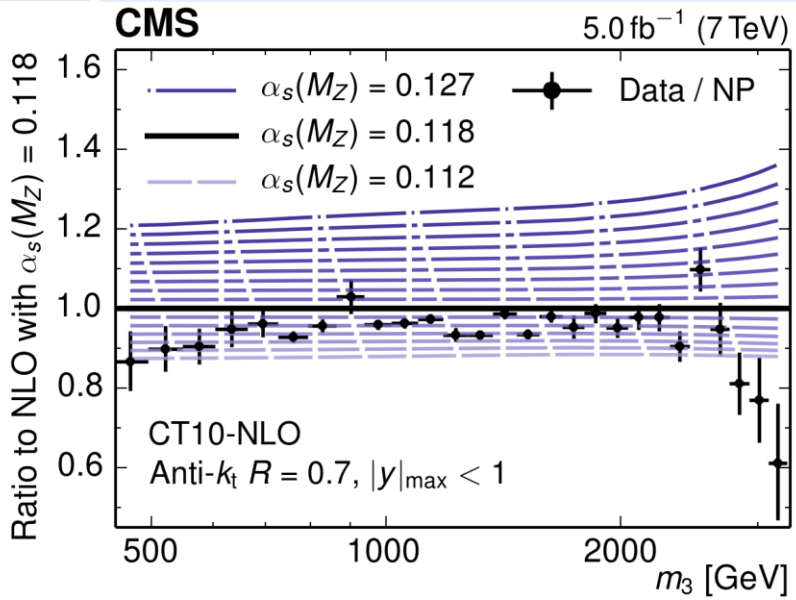




- Within uncertainties most PDF sets are able to describe the data.

α_S from the 3-jet mass cross section at 7 TeV

CMS : arXiv:1412.1633



- Central fit : Two rapidity bins with CT10-NLO
- Determination at **NLO**
- Total uncertainty 4 to 6 %
- Dominated by missing-order terms (μ_r, μ_f)

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

α_S Running

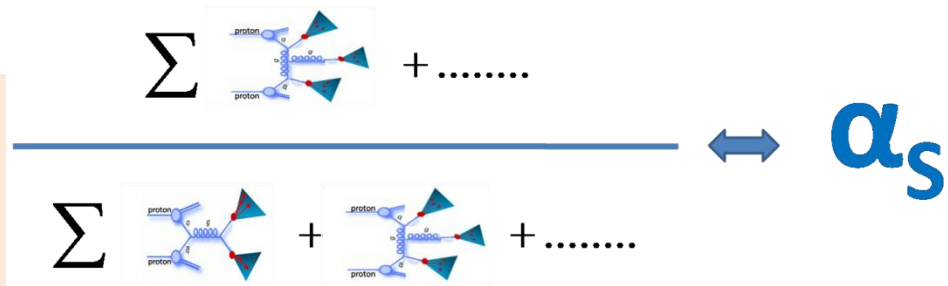
m_3[GeV]	$\langle Q \rangle$ [GeV]	χ^2/n_{dof}	$\alpha_S(Q)$	$\pm$(exp)	$\pm$(PDF)	$\pm$(NP)	$\pm$(scale)
664–794	361	4.5/3	0.1013	$\pm^{0.0027}_{0.0028}$	$\pm^{0.0013}_{0.0011}$	± 0.0005	$\pm^{0.0052}_{0.0030}$
794–938	429	7.8/3	0.0933	± 0.0022	$\pm^{0.0012}_{0.0011}$	± 0.0005	$\pm^{0.0048}_{0.0028}$
938–1098	504	0.6/3	0.0934	± 0.0021	± 0.0014	± 0.0005	$\pm^{0.0043}_{0.0025}$
1098–1369	602	2.6/5	0.0902	± 0.0016	± 0.0016	$\pm^{0.0005}_{0.0004}$	$\pm^{0.0036}_{0.0017}$
1369–2172	785	8.8/13	0.0885	$\pm^{0.0010}_{0.0011}$	$\pm^{0.0017}_{0.0018}$	$\pm^{0.0004}_{0.0003}$	$\pm^{0.0038}_{0.0020}$
2172–2602	1164	3.6/5	0.0848	$\pm^{0.0019}_{0.0023}$	$\pm^{0.0020}_{0.0023}$	± 0.0004	$\pm^{0.0034}_{0.0021}$
2602–3270	1402	5.5/7	0.0807	$\pm^{0.0022}_{0.0021}$	$\pm^{0.0028}_{0.0021}$	± 0.0001	$\pm^{0.0044}_{0.0026}$

α_S from 3/2 inclusive jet cross sections ratio (R_{32}) at 7 TeV

- **The measurement by CMS**

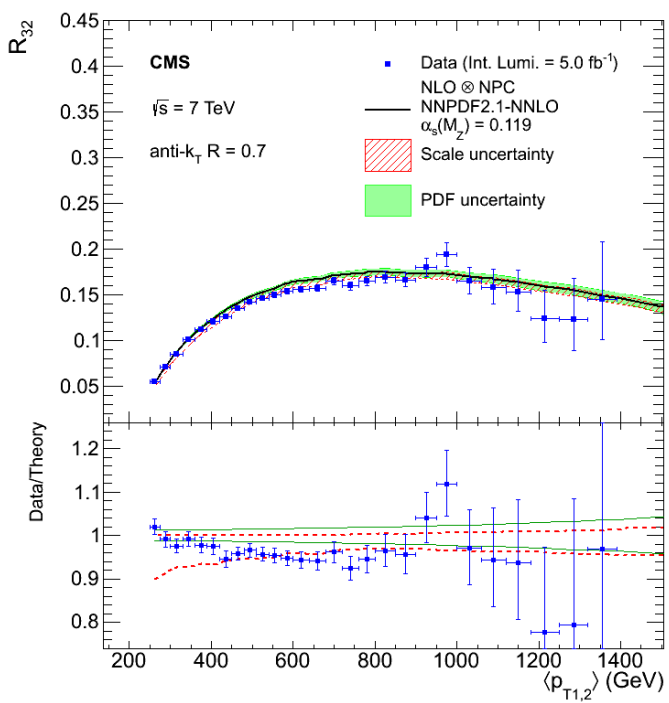
$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \to n\ \text{jets} + X;\ n \geq 3)}{\sigma(pp \to n\ \text{jets} + X;\ n \geq 2)} =$$

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



- Phase space: Jet p_T>150 GeV, |y|<2.5. Scale choice: $\mu_r=\mu_f=\langle p_{T1,2}\rangle$
- Advantages : Reduces experimental and other theoretical uncertainties.

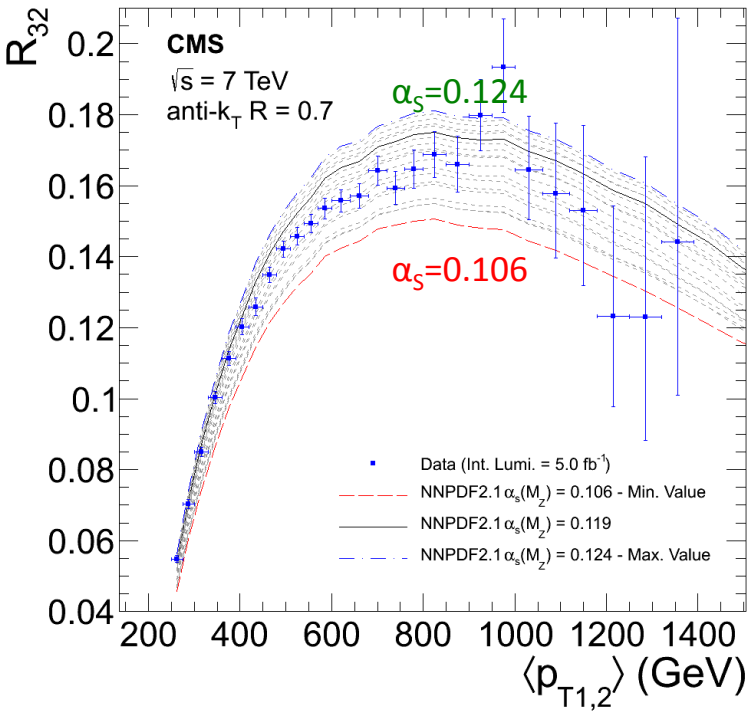
CMS : Eur. Phys. J.C (2013)73:2604



- 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.

α_S from 3/2 inclusive jet cross sections ratio (R_{32}) at 7 TeV

CMS : Eur. Phys. J.C (2013)73:2604



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

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014(\exp) \pm 0.0018(PDF) \pm 0.0050(Theory)$$

- Total uncertainty 4.7 %
- Dominated by missing-order terms (μ_r, μ_f)

α_S Running

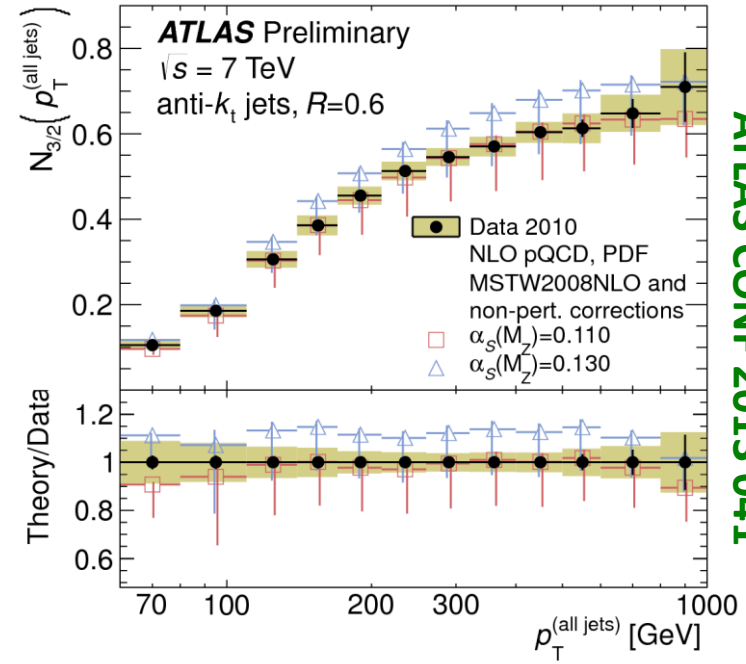
$\langle p_{T1,2} \rangle$ range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/N_{dof}
420–600	474	0.1147 ± 0.0061	0.0936 ± 0.0041	6	4.4/5
600–800	664	0.1132 ± 0.0050	0.0894 ± 0.0031	5	5.9/4
800–1390	896	0.1170 ± 0.0058	0.0889 ± 0.0034	10	5.7/9

α_S from 3/2 inclusive jet cross sections ratio ($N_{3/2}$) at 7 TeV

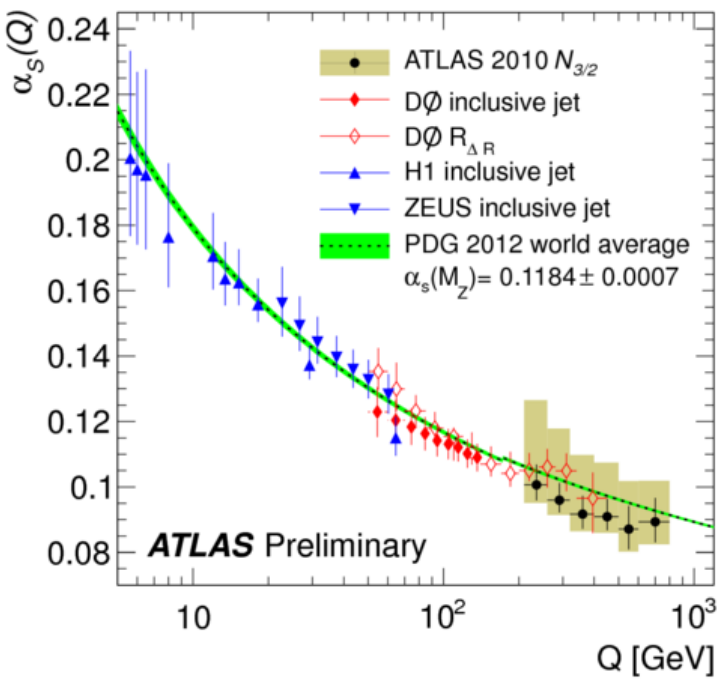
- The measurement by **Atlas**:

$$N_{3/2}\left(p_T^{(all\ jets)}\right) = \frac{\sum_i^{N_{jet}}\left(d\sigma_{N_{jet}\geq 3}/dp_{T,j}\right)}{\sum_i^{N_{jet}}\left(d\sigma_{N_{jet}\geq 2}/dp_{T,j}\right)}$$

- Data : 2010
- Phase space: jet p_T>40 GeV, p_T^{lead}>60 GeV, |y|<2.8
- Scale choice: $\mu_r=\mu_f=p_{T,j}$



ATLAS CONF 2013 041



ATLAS CONF 2013 041

- Central fit : MSTW2008-NLO
- Determination at **NLO**

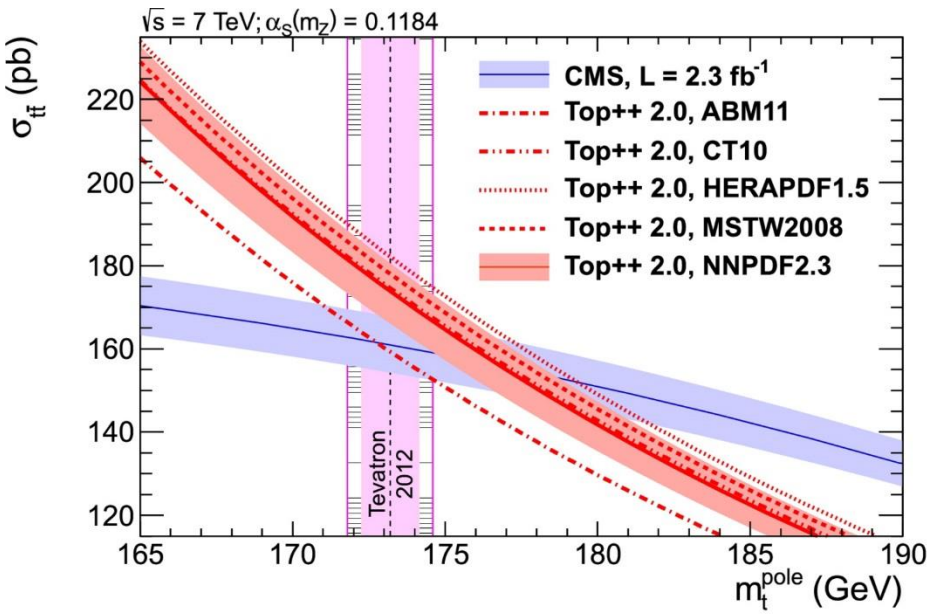
$$\alpha_S(M_Z) = 0.111 \pm 0.006(\exp.) \pm^{0.016}_{0.003}(scale)$$

- Total uncertainty 6-15 %
- Dominated by missing-order terms (μ_r, μ_f)

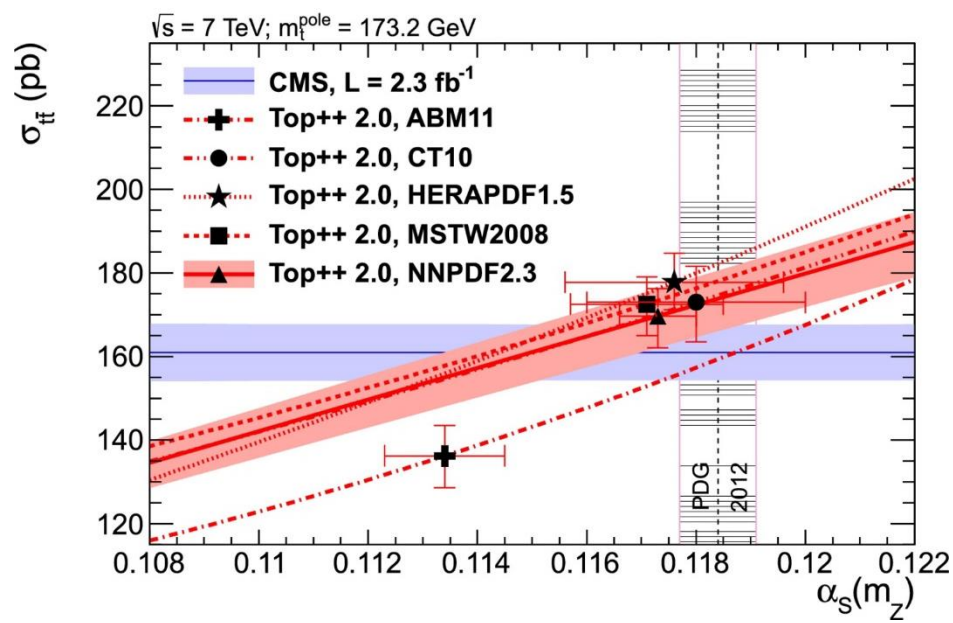
Determination of α_S from top-pair production cross section

- α_S determination from the top-pair production cross section in the dilepton channel. (7 TeV CMS **Phys. Rev.D 85(2012) 112007**)
- The top-pair production is sensitive to m_t^{pole} and α_S.

Fix α_S = 0.1184±0.0007
→ constrain m_t^{pole}



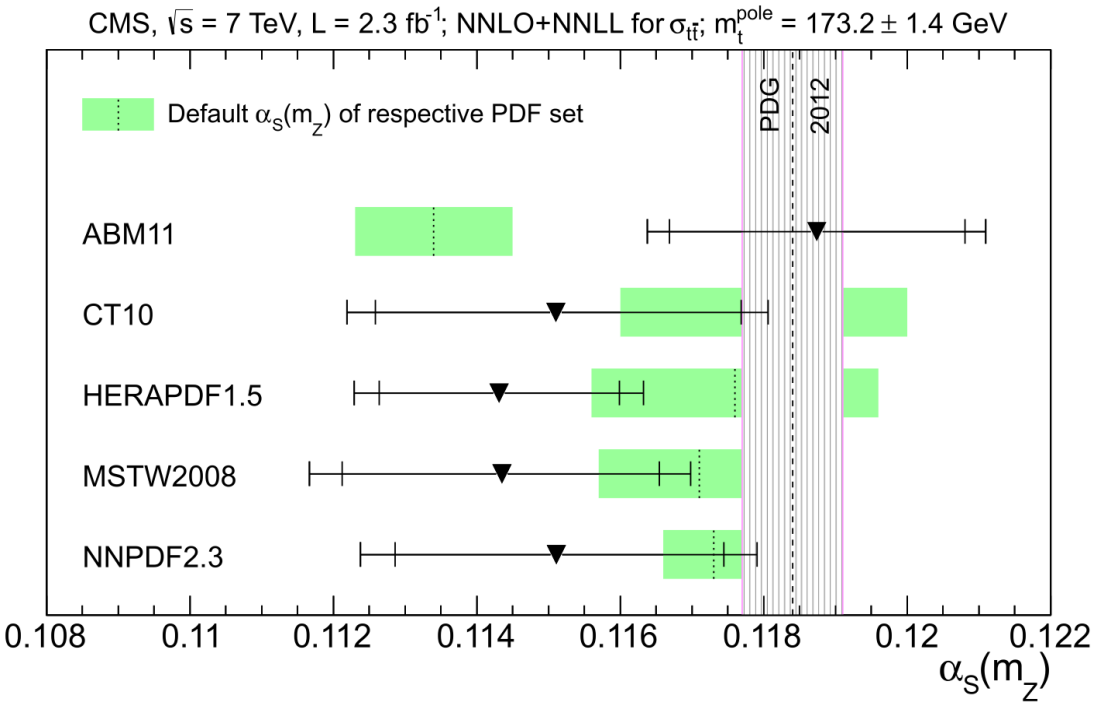
Fix m_t^{pole} =173.2±1.4 GeV
→ constrain α_S



CMS : PLB 728 (2014) 496

Determination of α_S from top-pair production cross section

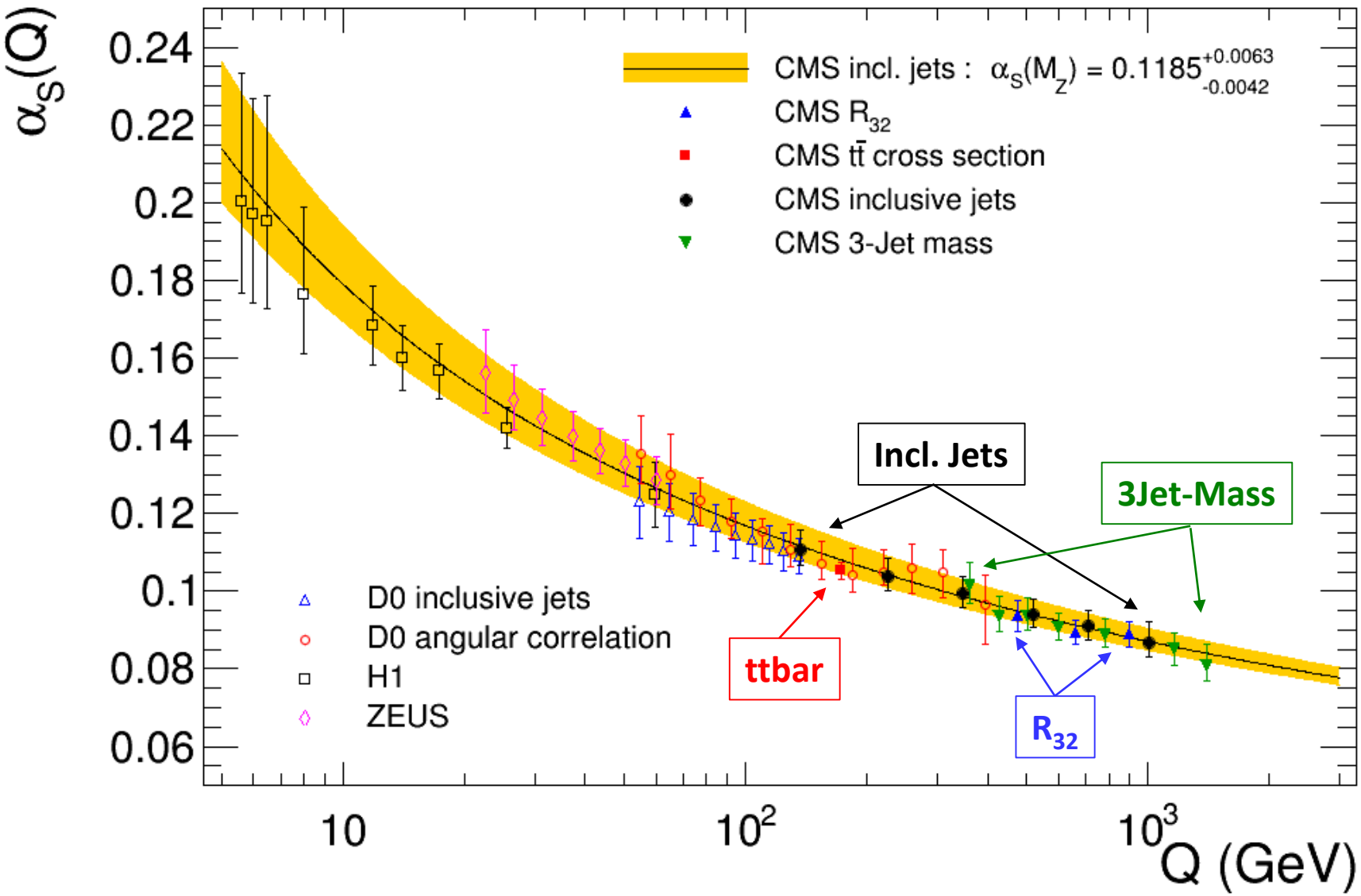
CMS : PLB 728 (2014) 496



- Central fit : NNPDF2.3-NNLO (Theory at **NNLO+NNLL**)
- Most precise measurement at Hadron collider : total uncertainty 2.4 %.
- Large difference of α_S with ABM11 compared to the intrinsic value.

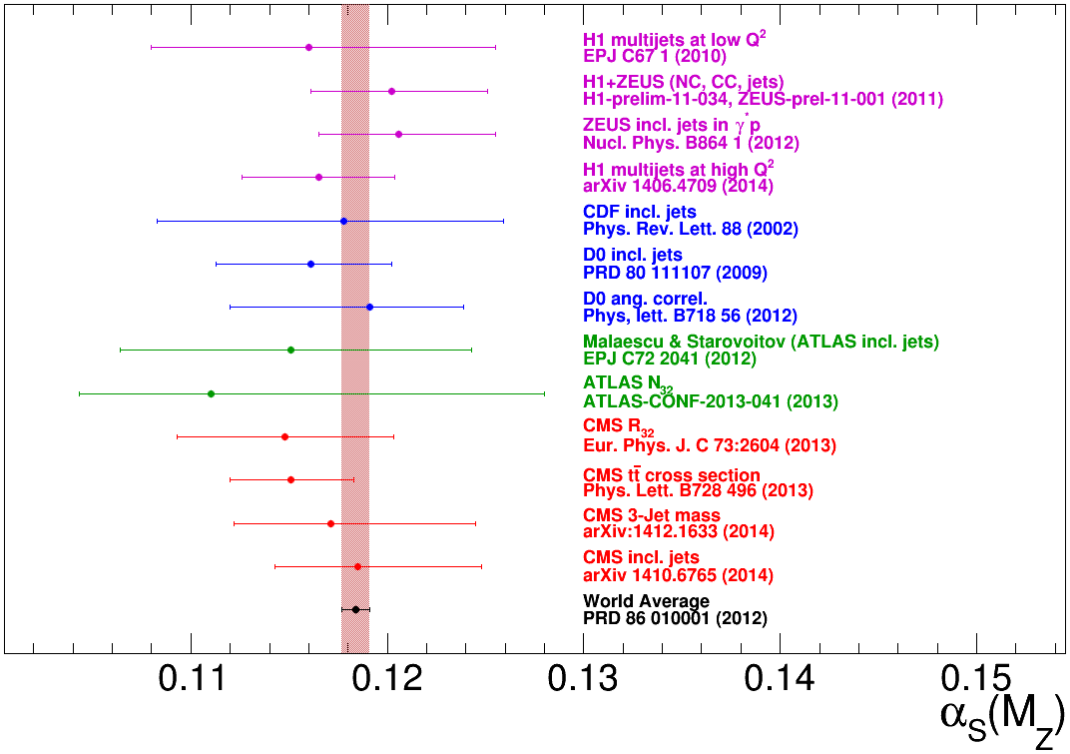
$$\alpha_S(M_Z) = 0.1151 \pm {}^{0.0017}_{0.0018}(\exp) \pm {}^{0.0013}_{0.0011}(PDF) \pm 0.0013\left(m_t^{pole}\right) \pm 0.0008(E_{LHC}) \pm {}^{0.0009}_{0.0008}(scale)$$
$$= 0.1151 \pm {}^{0.0028}_{0.0027}$$

The running of α_S



No deviation from the predicted running of α_S is observed.

Summary



- **LHC RUN I** : Already several measurements of α_S from 7 TeV analysis.
- Excellent precision reached for a hadron collider.
- We have even the first **NNLO** measurement done at a hadron collider.
- All new measurements are in agreement with previous measurements with hadrons, and with the word average value.

- **α_S running** has been checked at the **1 TeV** region, for first time**.** No deviation from the predicted running is observed.
- **NNLO calculations** are needed to make the next major step.
- New results at 7 & 8 TeV are on the way. And more to come at 13 TeV.

Definition of the observables

Inclusive Jet cross section

- Publications CMS : **PRD 87,112002(2013)** and **arXiv1410.6765**
- **Observable** : Double differential inclusive jet cross section vs the jet p_T and y.

$$\frac{d^2\sigma}{dp_T dy} = \frac{1}{\epsilon\mathcal{L}} \frac{N_{jets}}{\Delta p_T (2\Delta|y|)}$$

ϵ : *Efficiency*
$\mathcal{L}$: *Luminosity*
N_{jets}: *Number of jets*

- **Jet Reconstruction** : anti-kt with size 0.7
- **Selection** : jet p_T > 114 GeV,

  Five rapidity bins: |y|<2.5 with bin Δ|y|=0.5

3-Jet mass cross section

- Publication CMS : **arXiv:1412.1633**
- **Observable** : Double-differential 3-jet production cross section vs the invariant 3-jet mass m_3 and the maximum rapidity y_{max} of the three jets with the highest transverse momenta.

$$\frac{d^2\sigma}{dm_3 dy_{max}} = \frac{1}{\epsilon\mathcal{L}} \frac{N}{\Delta m_3 (2\Delta|y|_{max})}$$

ϵ : *Efficiency*
$\mathcal{L}$: *Luminosity*
N : Number of events

$$m_3^2 = (p_1 + p_2 + p_3)^2$$
$$y_{max} = \mathrm{sgn}\left(|\max(y_1, y_2, y_3)| - |\min(y_1, y_2, y_3)|\right) \cdot \max(|y_1|, |y_2|, |y_3|)$$

- **Jet Reconstruction** : anti-kt with size 0.7
- **Selection** : minimum jet p_T =100 GeV,

  Two rapidity bins: $|y|_{max}<1$ and $1< |y|_{max}<2$

Ratios R_{32} and N_{32}

- Publication CMS : **Eur. Phys. J.C (2013)73:2604**
- **Observable** : Ratio of inclusive 3 to 2-jet cross section

$$R_{32} = \frac{\sigma_3}{\sigma_2} = \frac{\sigma(pp \to n \text{ jets } + X;\ n \geq 3)}{\sigma(pp \to n \text{ jets } + X;\ n \geq 2)} \qquad \text{vs} \qquad \langle p_{T1,2} \rangle = \frac{p_{T1} + p_{T2}}{2}$$

- **<u>Jet Reconstruction</u>** : anti-kt with size 0.7
- **<u>Selection</u>** : minimum jet p_T =150 GeV and two leading jet |y|<2.5

- Conference Note ATLAS : **CONF 2013 041**
- **Observable** : Ratio of inclusive 3 to 2-jet cross section

$$N_{3/2}\left(p_T^{(all\ jets)}\right) = \frac{\sum_i^{N_{jet}} \left(d\sigma_{N_{jet}\geq 3}/dp_{T,j}\right)}{\sum_i^{N_{jet}} \left(d\sigma_{N_{jet}\geq 2}/dp_{T,j}\right)} \qquad \text{vs jet } p_T$$

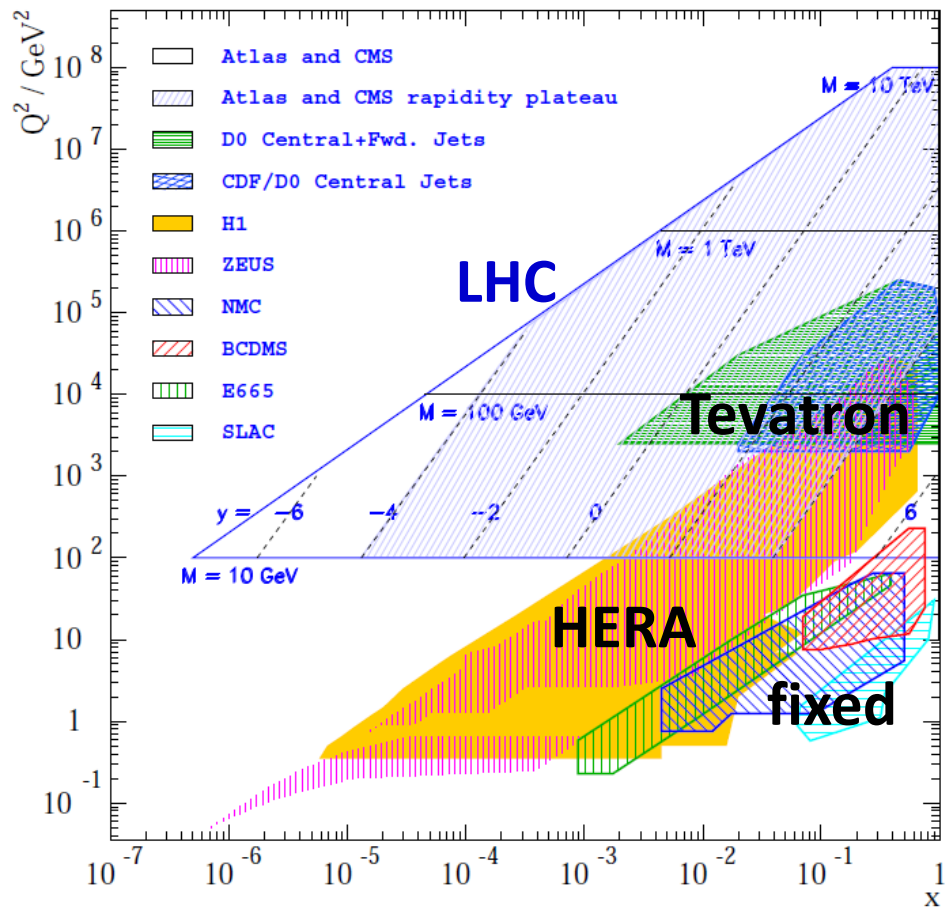
- **<u>Jet Reconstruction</u>** : anti-kt with size 0.6
- **<u>Selection</u>** : jet p_T>40 GeV, p_T^{lead}>60 GeV and jet |y|<2.8

Other Spare Slides

LHC – Phase Space

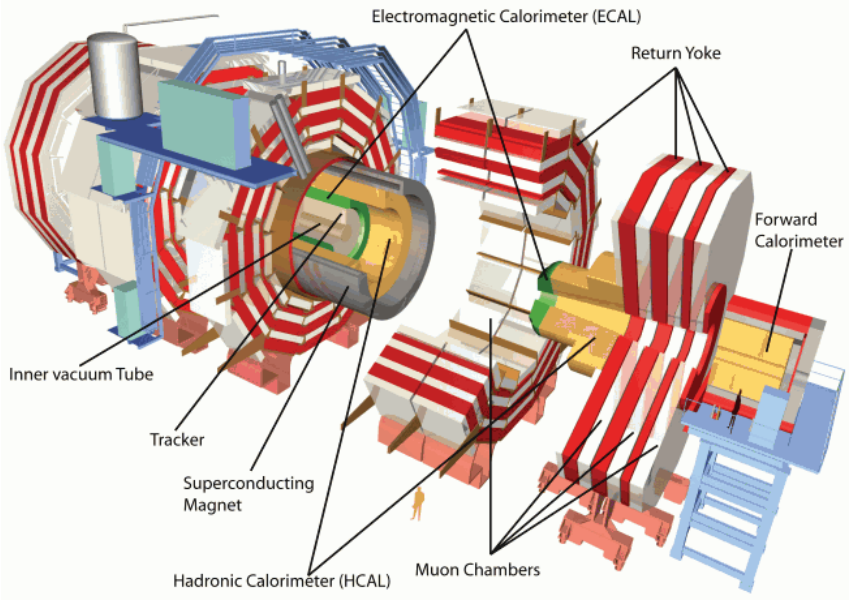
- QCD processes are dominant @ LHC. LHC is a jet factory.
- Jet measurements at LHC are very important:
  - They provide a test of pQCD in a previously unexplored energy region. A huge new phase space is accessible at LHC.
  - Check SM predictions at high energy scales.
  - Measure and understand the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

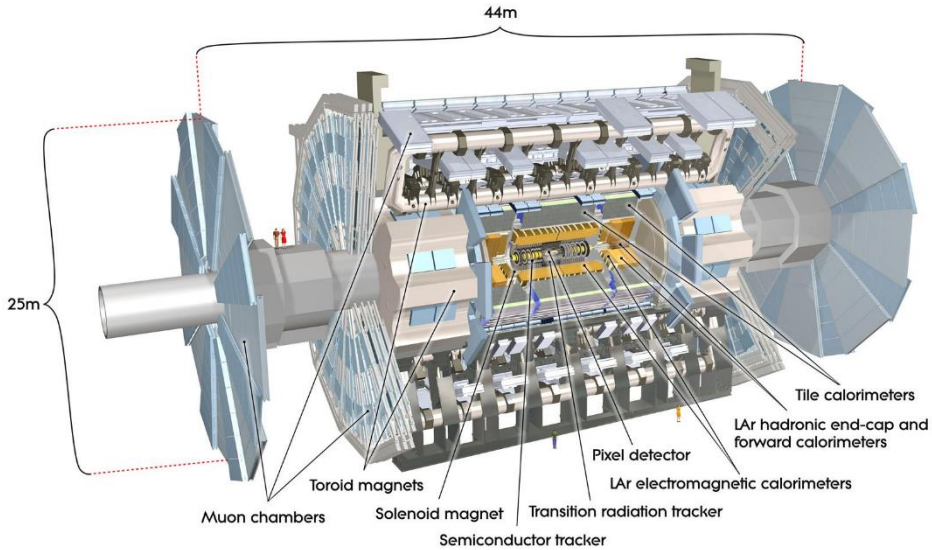
Kinematic plane of process Q^2 vs x



S.Glazov, Braz.J.Ph. 37 (2007) 793

CMS & ATLAS Detectors





Pixels, Si strips

$\sigma/p_T \sim 1.5 \cdot 10^{-4} p_T(GeV) \oplus 0.005$

ECAL

$\sigma E/E \sim 2.9\%/\sqrt{E}(GeV) \oplus 0.5\% \oplus 0.13 GeV/E$

HCAL

$\sigma E/E \sim 120\%/\sqrt{E}(GeV) \oplus 6.9\%$

Muons

$\sigma p_T/p_T \sim 1\%$ for low p_T muons

$\sigma p_T/p_T \sim 5\%$ for 1 TeV muons

Pixels, Si strips, Straw tubes

$\sigma/p_T \sim 3.8 \cdot 10^{-4} p_T(GeV) \oplus 0.015$

ECAL

$\sigma E/E \sim 10\%/\sqrt{E}(GeV) \oplus 0.7\% \oplus 0.2 GeV/E$

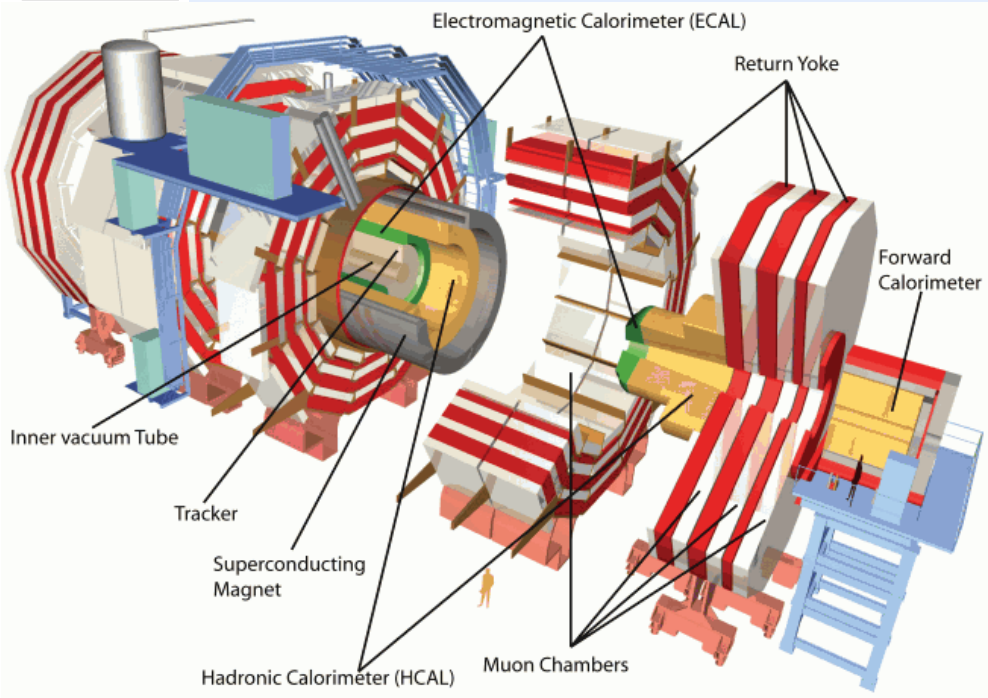
HCAL

$\sigma E/E \sim 60\text{-}100\%/\sqrt{E}(GeV) \oplus 3\%$

Muons

$\sigma p_T/p_T < 10\%$ up to 1TeV muons

CMS detector and Integrated Luminosity

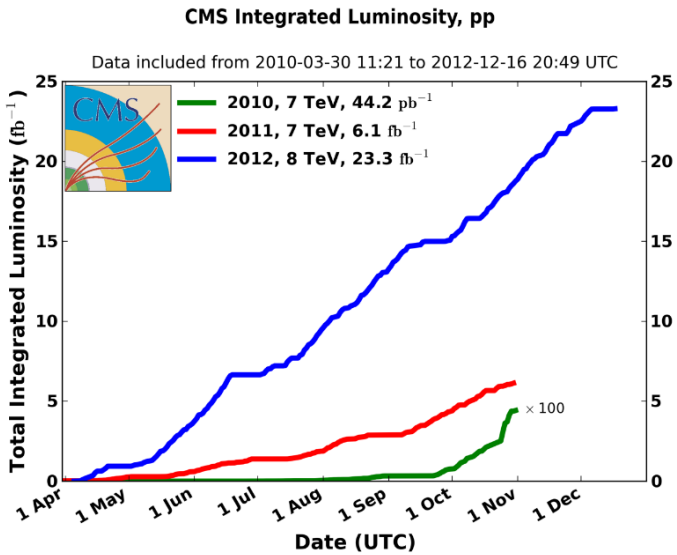


CMS detector pseudorapidity coverage:

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

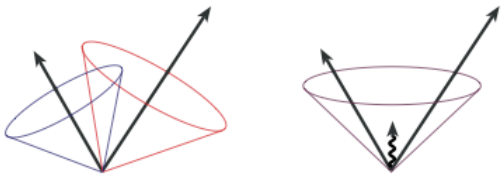
Very successful LHC operation and CMS data recording during Run 1 :

- 7 TeV (2010 & 2011)
- 8 TeV (2012)



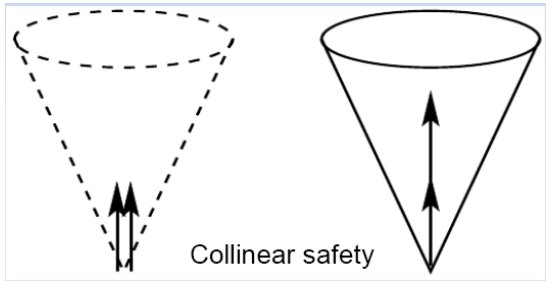
Jet reconstruction algorithm requirements

- Infrared safety
  - A jet algorithm is infrared safe if, for any n-parton configuration, adding an infinitely soft parton does not affect the result at all.



soft radiation may cause merging of 2 jets

- Collinear safety
  - A jet algorithm is collinear safe if, for any n-parton configuration, replacing any massless parton by an exactly collinear pair of massless partons does not affect the result at all.



- Same jet algorithms for data and theoretical predictions.
  - so that perturbative calculations can be compared to experiments.
- Detector independence.
- Not too sensitive to underlying event and pile up.

k_T and anti-k_T : Sequential Recombination Algorithms

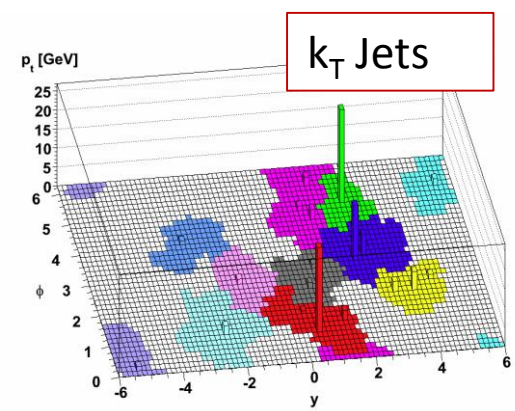
- The algorithm first defines for each protojet its beam distance: $d_{iB} = k_{ti}^n$
  and for each pair of protojets *i,j* their relative distance :

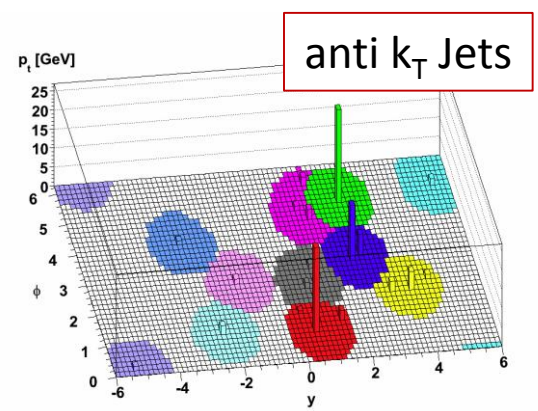
$$d_{ij} = \min\left(k_{ti}^n, k_{tj}^n\right)\frac{\Delta R_{ij}^2}{D^2} \qquad \text{where} \qquad \Delta R_{ij}^2 = \left(y_i - y_j\right)^2 + \left(\varphi_i - \varphi_j\right)^2$$

  with *D* a jet radious resolution parameter being of the order of unity and k_{ti}, y_i and φ_i the transverse momentum, rapidity and azimuth of particle *i*, respectively.

- In a second step, if $d_{ij} \geq d_{iB}$ the protojet *i* is defined as a jet and removed from the list, otherwise the two protojets *i* and *j* combine into a single object.

- **k_T algorithm** is defined for n=2 and favours clustering of low p_T protojets.
- **anti-k_T algorithm** is defined for n=-2 and favours clustering of high p_T protojets.
- Both algorithms are infrared and collinear safe.





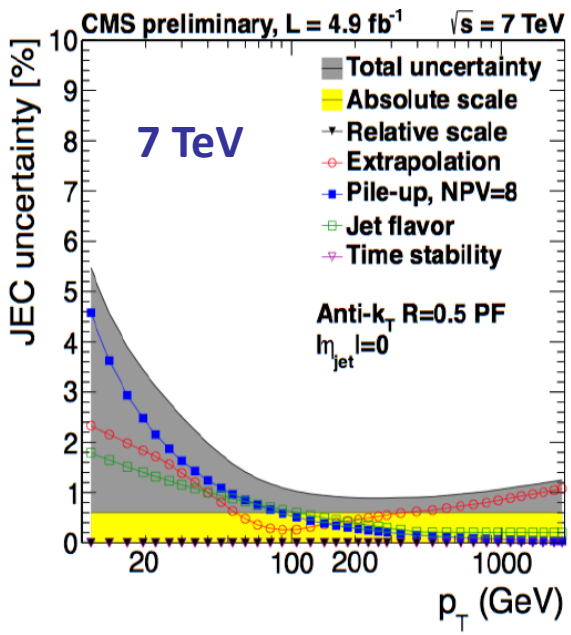
Jet Energy Scale Calibration (CMS)

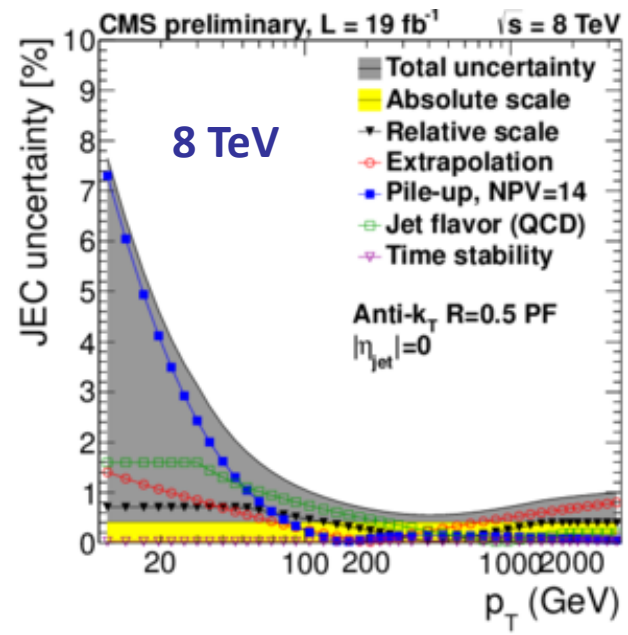
- For the jet energy scale calibration CMS adopted a Factorized approach.

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

- **Offset** → substruction $\rho \times A_{jet}$ (ρ : the global energy density, A_{jet}: the jet area)
- **Relative** → derived from Di-jet Balance
- **Absolute** → derived from $\gamma + jet$ and $Z + jet$ (p_T balance and MPF)

CMS DP-2012-006



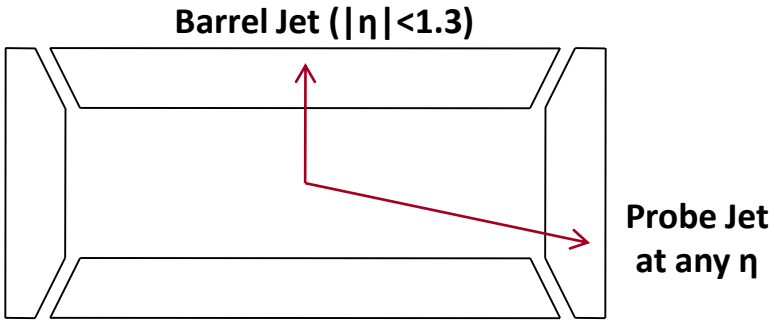


CMS DP-2013-033

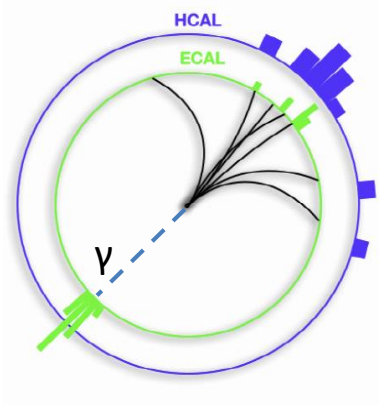
Jet Energy Scale Calibration (CMS)

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

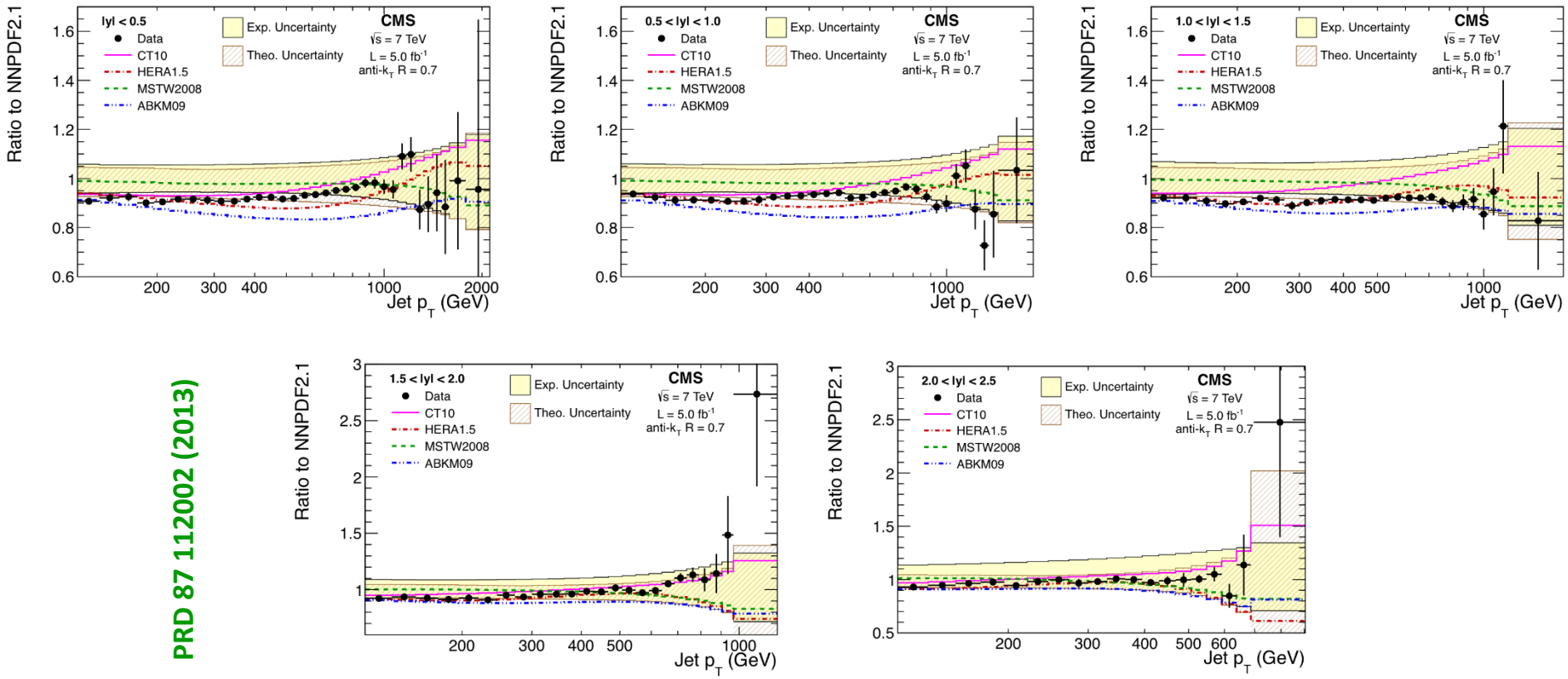
- For **relative** corrections:
  - The di-jet p_T balance technique is employed taking the barrel jet (|η|<1.3) as reference and the other jet (probe jet) at any η.



- 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.



Inclusive Jet cross section
Comparison to theory (7 TeV)



PRD 87 112002 (2013)

7 TeV : Agreement is observed between data and theory (using NNPDF2.1, CT10, HERA1.5, MSTW2008 and ABKM09 PDF sets) in all rapidity bins.

PDF sets used by CMS

CMS : arXiv1410.6765

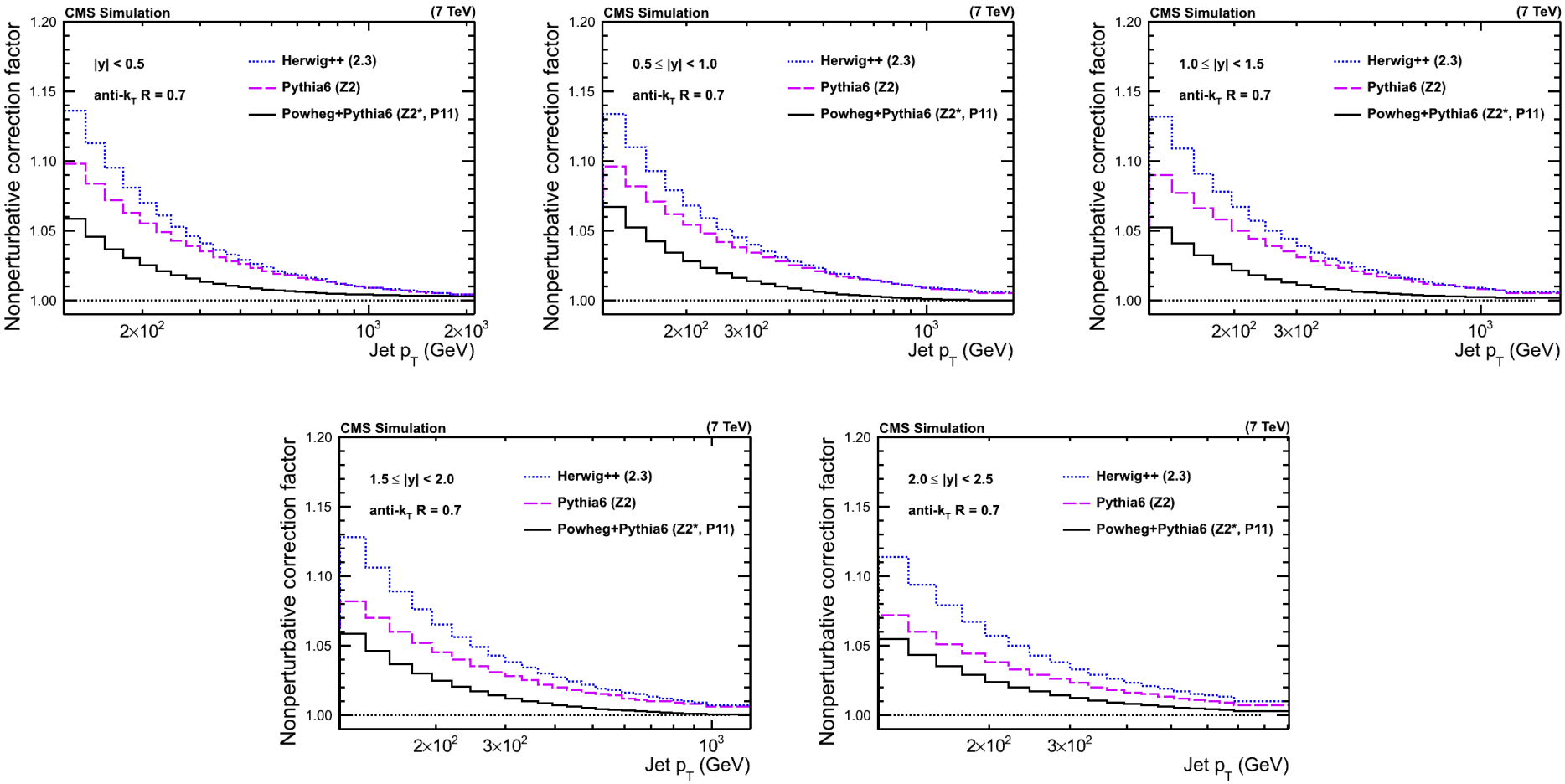
Table 1: The PDF sets used in comparisons to the data together with the evolution order (Evol.), the corresponding number of active flavours N_f, the assumed masses M_t and M_Z of the top quark and the Z boson, respectively, the default values of $\alpha_S(M_Z)$, and the range in $\alpha_S(M_Z)$ variation available for fits. For CT10 the updated versions of 2012 are taken.

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

α_S from the inclusive jet cross section at 7 TeV
NP corrections

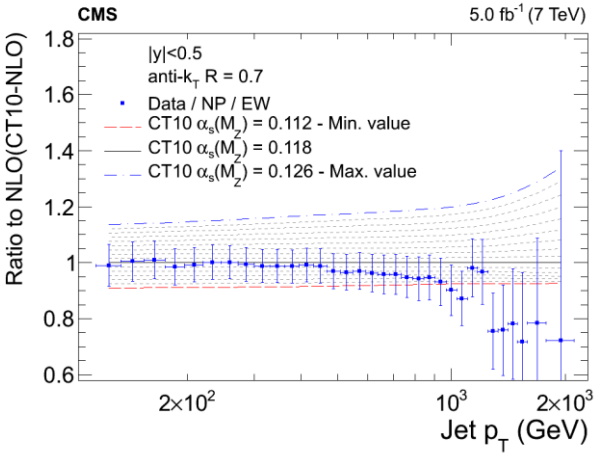
CMS : arXiv1410.6765

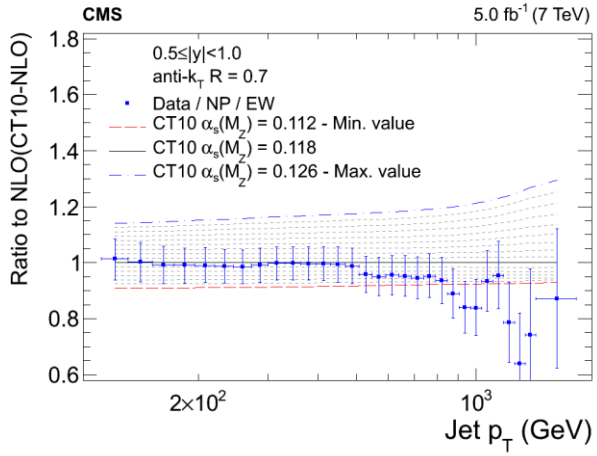
NP corrections derived by Pythia6 (Z2), Herwig++(2.3) and Powheg+Pythia6 (Z2*, P11)

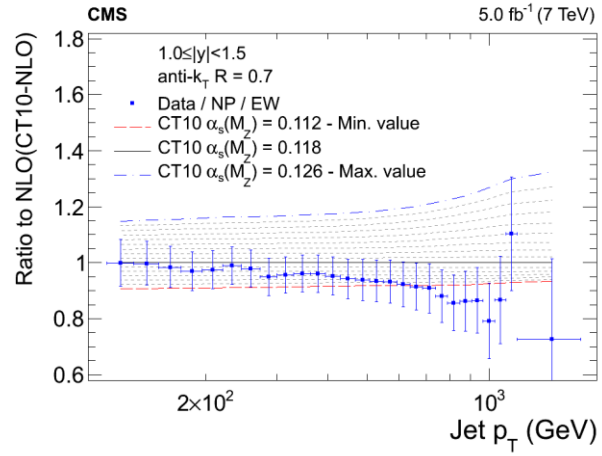


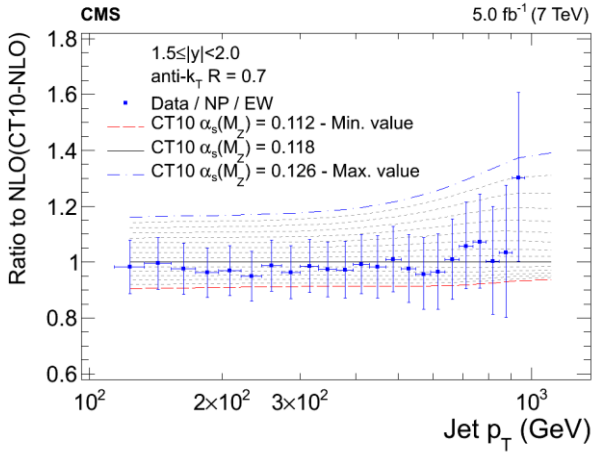
α_S from the inclusive jet cross section at 7 TeV Sensitivity plots (CT10-NLO)

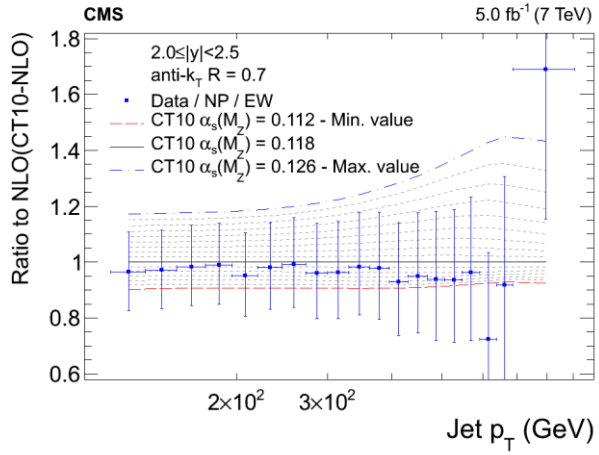
CMS : arXiv1410.6765





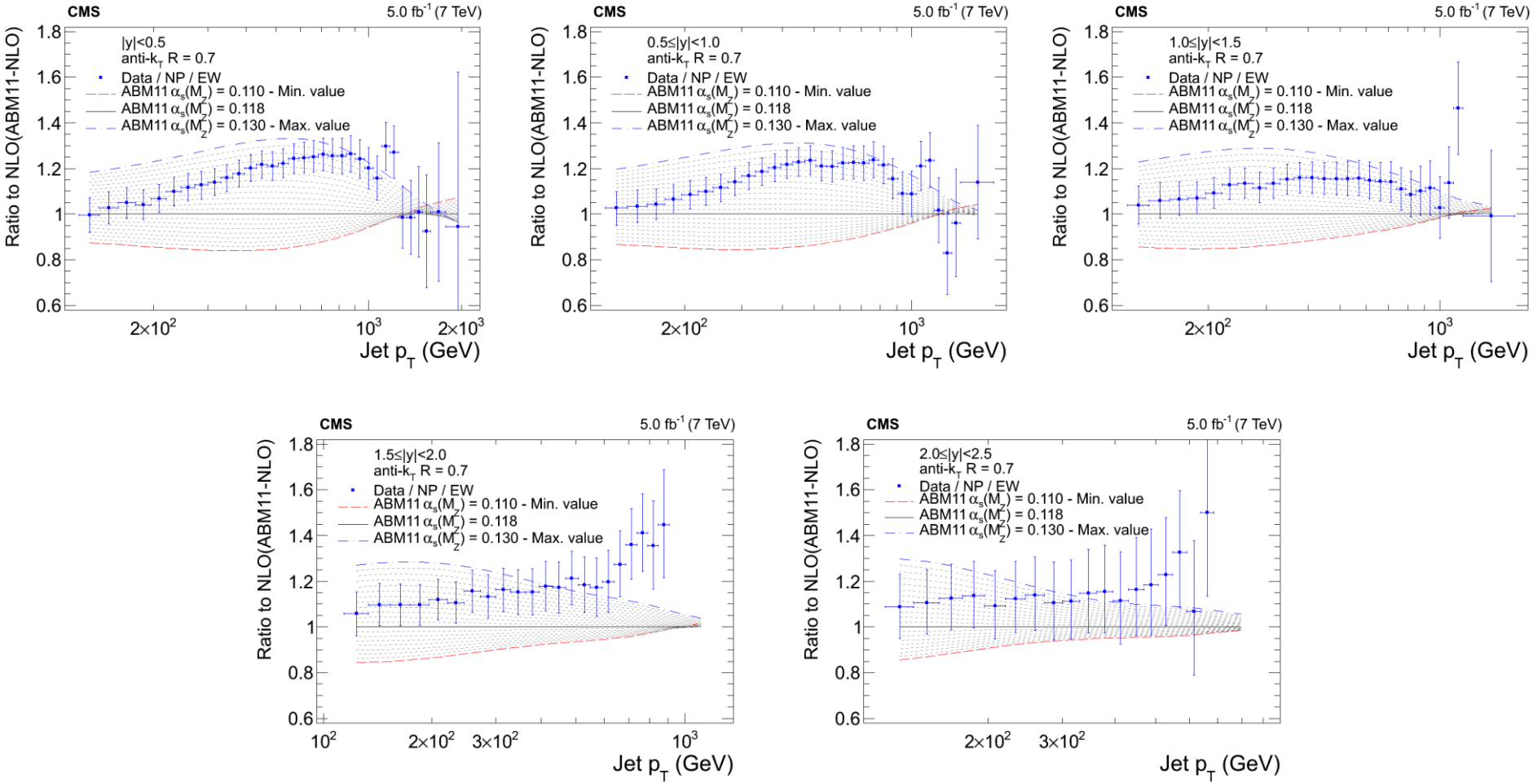






α_S from the inclusive jet cross section at 7 TeV Sensitivity plots (ABM11-NLO)

CMS : arXiv1410.6765



α_S from the inclusive jet cross section at 7 TeV Determination for each rapidity bin

CMS : arXiv1410.6765

Table 2: Determination of $\alpha_S(M_Z)$ in bins of rapidity using the CT10-NLO PDF set. The last row presents the result of a simultaneous fit in all rapidity bins.

$\lvert y\rvert$ 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

α_S from the inclusive jet cross section at 7 TeV Determination for various PDF sets

CMS : arXiv1410.6765

Table 4: Determination of $\alpha_S(M_Z)$ using the CT10 and MSTW2008 PDF sets at NLO and the CT10, NNPDF2.1, MSTW2008 PDF sets at NNLO. The results are obtained by a simultaneous fit to all rapidity bins.

PDF set	$\alpha_S(M_Z)$	χ^2/n_{dof}
CT10-NLO	$0.1185 \pm 0.0019\,(\mathrm{exp}) \pm 0.0028\,(\mathrm{PDF})$ $\pm 0.0004\,(\mathrm{NP})^{+0.0053}_{-0.0024}\,(\mathrm{scale})$	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

α_S from the inclusive jet cross section at 7 TeV
α_S running

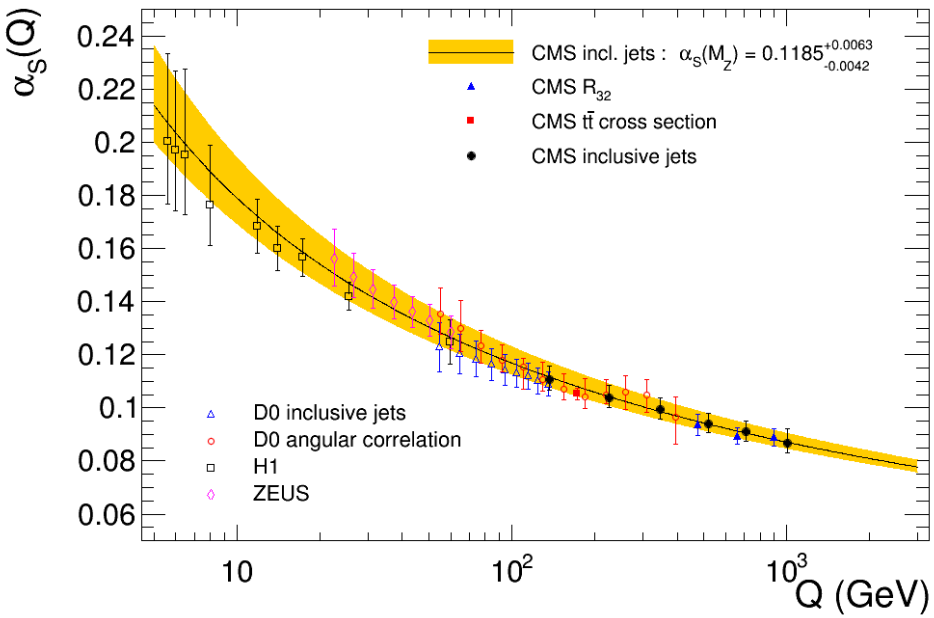
CMS : arXiv1410.6765

Table 5: Determination of α_S in separate bins of jet p_T using the CT10-NLO PDF set.

p_T range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	$\alpha_S(Q)$	No. of data points	χ^2/n_{dof}
114–196	136	$0.1172^{+0.0058}_{-0.0043}$	$0.1106^{+0.0052}_{-0.0038}$	20	6.2/19
196–300	226	$0.1180^{+0.0063}_{-0.0046}$	$0.1038^{+0.0048}_{-0.0035}$	20	7.6/19
300–468	345	$0.1194^{+0.0064}_{-0.0049}$	$0.0993^{+0.0044}_{-0.0034}$	25	8.1/24
468–638	521	$0.1187^{+0.0067}_{-0.0051}$	$0.0940^{+0.0041}_{-0.0032}$	20	10.6/19
638–905	711	$0.1192^{+0.0074}_{-0.0056}$	$0.0909^{+0.0042}_{-0.0033}$	22	11.2/21
905–2116	1007	$0.1176^{+0.0111}_{-0.0065}$	$0.0866^{+0.0057}_{-0.0036}$	26	33.6/25

Table 6: Uncertainty composition for $\alpha_S(M_Z)$ from the determination of $\alpha_S(Q)$ in bins of p_T using the CT10-NLO PDF set.

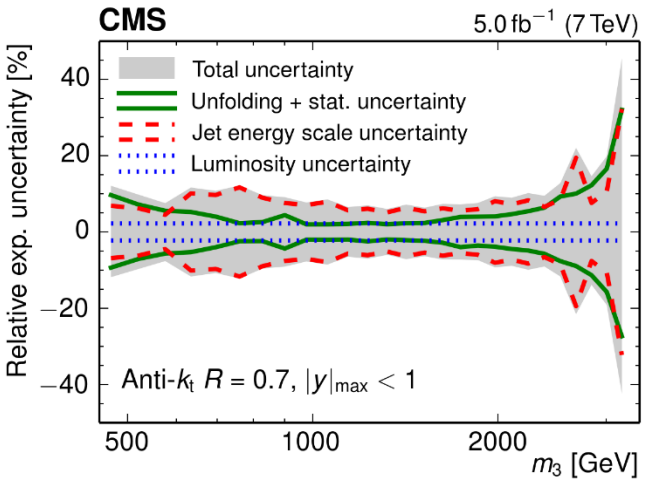
p_T range (GeV)	Q (GeV)	$\alpha_S(M_Z)$	exp.	PDF	NP	scale
114–196	136	0.1172	±0.0031	±0.0018	±0.0007	$^{+0.0045}_{-0.0022}$
196–300	226	0.1180	±0.0034	±0.0019	±0.0011	$^{+0.0048}_{-0.0025}$
300–468	345	0.1194	±0.0032	±0.0023	±0.0010	$^{+0.0049}_{-0.0027}$
468–638	521	0.1187	±0.0029	±0.0031	±0.0006	$^{+0.0052}_{-0.0027}$
638–905	711	0.1192	±0.0034	±0.0032	±0.0005	$^{+0.0057}_{-0.0030}$
905–2116	1007	0.1176	±0.0047	±0.0040	±0.0002	$^{+0.0092}_{-0.0020}$

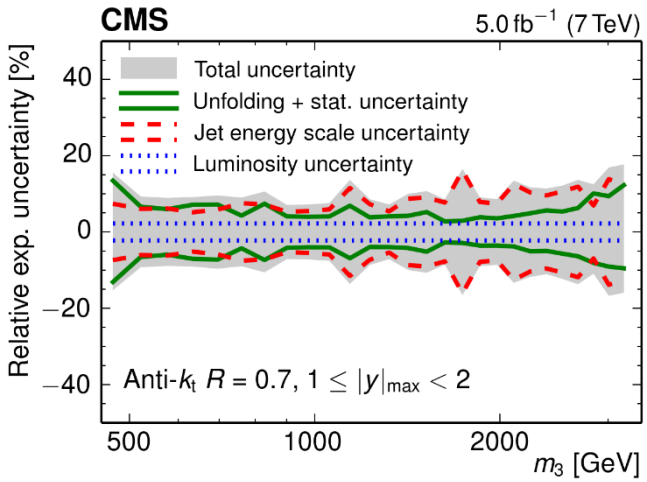


α_S from the 3-jet mass cross section at 7 TeV Uncertainties

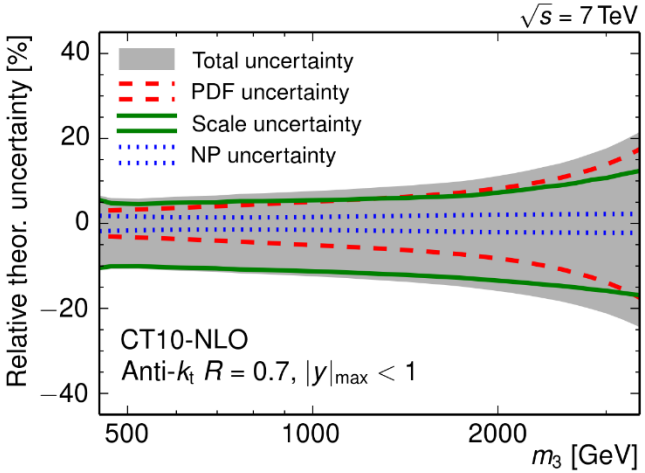
CMS : arXiv:1412.1633

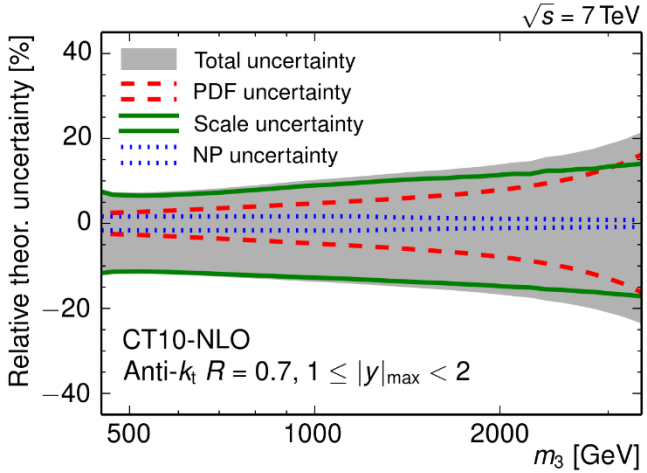
Experimental Uncertainties





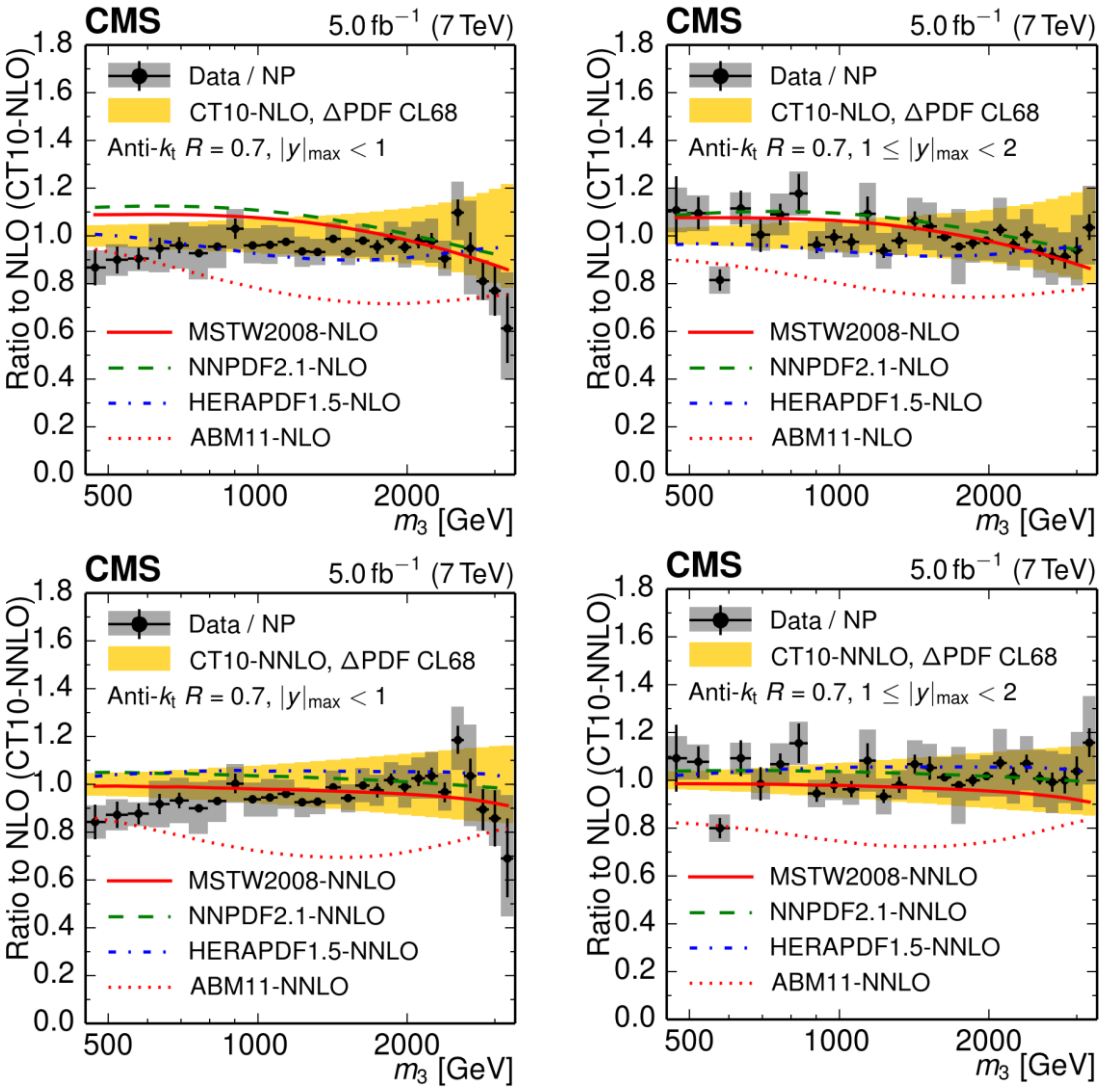
Theoretical Uncertainties





α_S from the 3-jet mass cross section at 7 TeV
Comparison to theory

CMS : arXiv:1412.1633



- Within uncertainties, most PDF sets are able to describe the data.
- Some deviations are visible for small m3.
- Significant deviations are exhibited when using the ABM11 PDFs, which therefore are not considered in our fits of $\alpha_S(M_Z)$.

α_S from the 3-jet mass cross section at 7 TeV
Results with various PDFs

CMS : arXiv:1412.1633

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

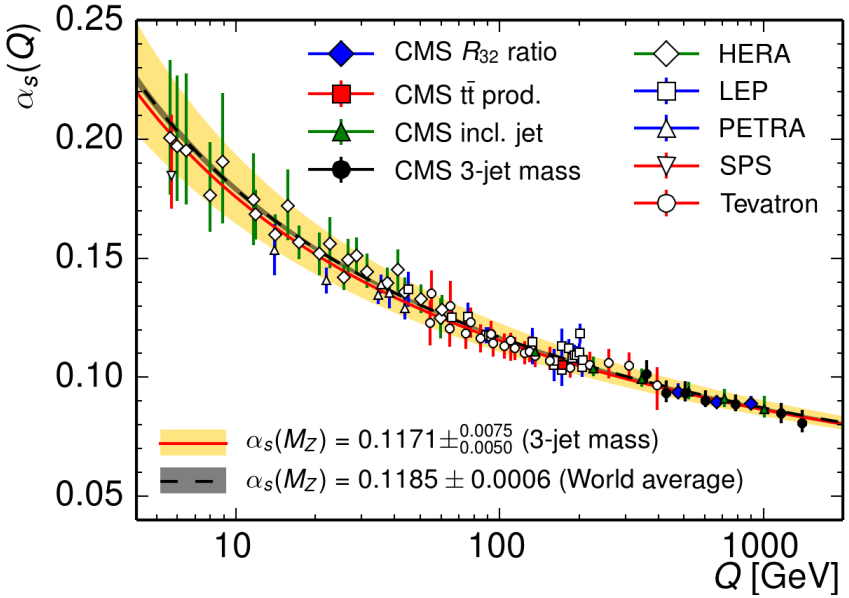
- Results using other PDF sets are in agreement with central CT10-NLO result (deviations < 5%)

α_S from the 3-jet mass cross section at 7 TeV
α_S running

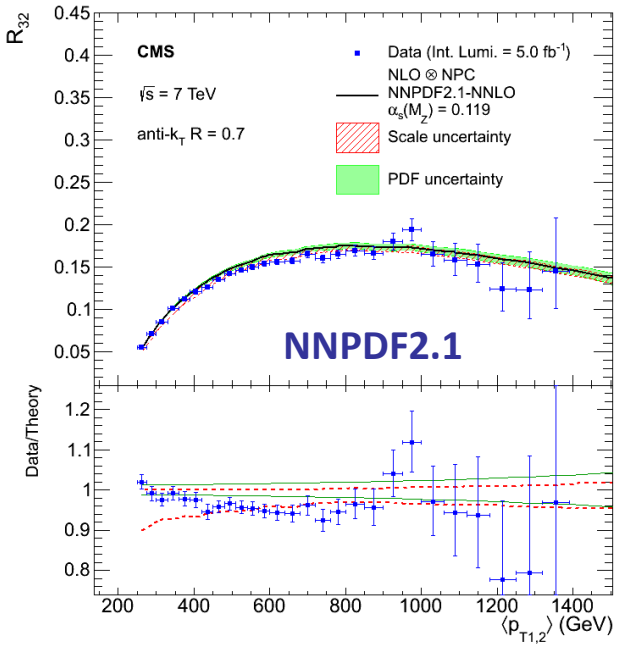
CMS : arXiv:1412.1633

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

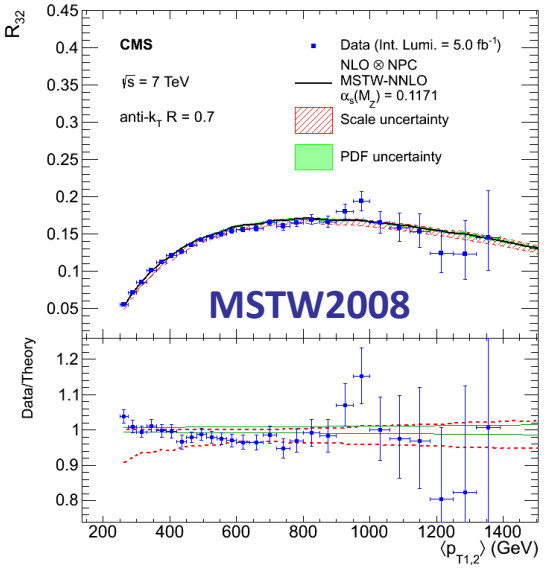
m_3[GeV]	$\langle Q \rangle$ [GeV]	$\chi^2/n_{\rm dof}$	$\alpha_S(Q)$	±(exp)	±(PDF)	±(NP)	±(scale)
664–794	361	4.5/3	0.1013	$\pm^{0.0027}_{0.0028}$	$\pm^{0.0013}_{0.0011}$	±0.0005	$\pm^{0.0052}_{0.0030}$
794–938	429	7.8/3	0.0933	±0.0022	$\pm^{0.0012}_{0.0011}$	±0.0005	$\pm^{0.0048}_{0.0028}$
938–1098	504	0.6/3	0.0934	±0.0021	±0.0014	±0.0005	$\pm^{0.0043}_{0.0025}$
1098–1369	602	2.6/5	0.0902	±0.0016	±0.0016	$\pm^{0.0005}_{0.0004}$	$\pm^{0.0036}_{0.0017}$
1369–2172	785	8.8/13	0.0885	$\pm^{0.0010}_{0.0011}$	$\pm^{0.0017}_{0.0018}$	$\pm^{0.0004}_{0.0003}$	$\pm^{0.0038}_{0.0020}$
2172–2602	1164	3.6/5	0.0848	$\pm^{0.0019}_{0.0023}$	$\pm^{0.0020}_{0.0023}$	±0.0004	$\pm^{0.0034}_{0.0021}$
2602–3270	1402	5.5/7	0.0807	$\pm^{0.0022}_{0.0021}$	$\pm^{0.0028}_{0.0021}$	±0.0001	$\pm^{0.0044}_{0.0026}$

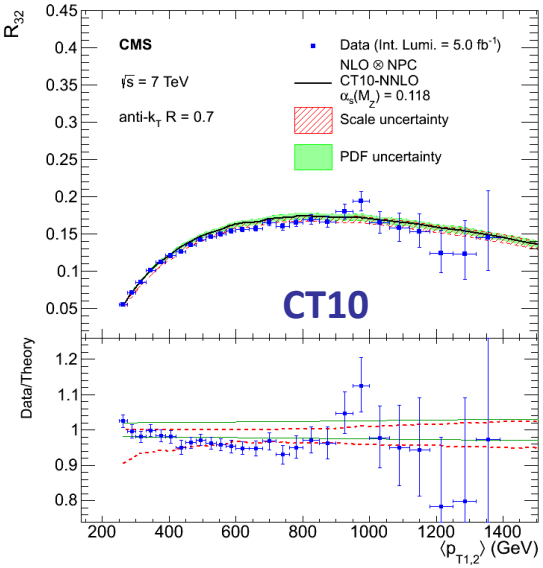


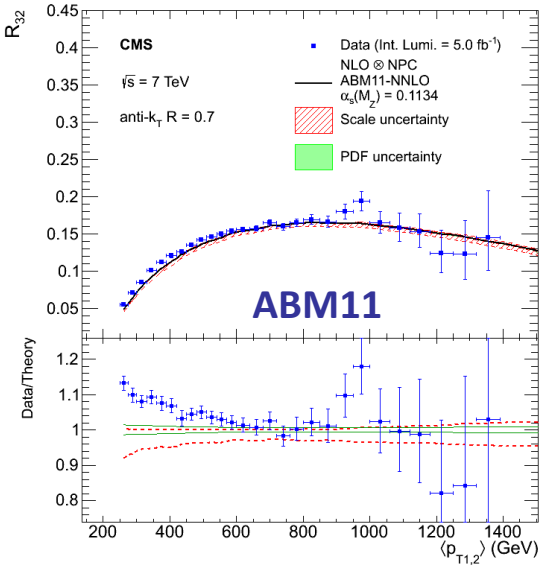
α_S from 3/2 inclusive jet cross sections ratio (R_{32}) at 7 TeV Comparison to Theory



- 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.







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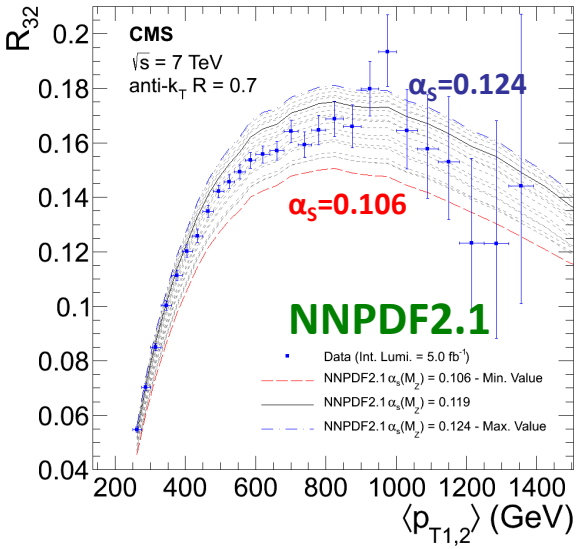
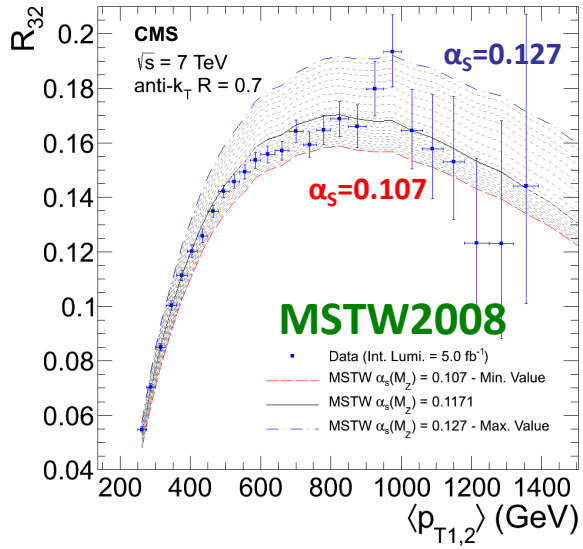
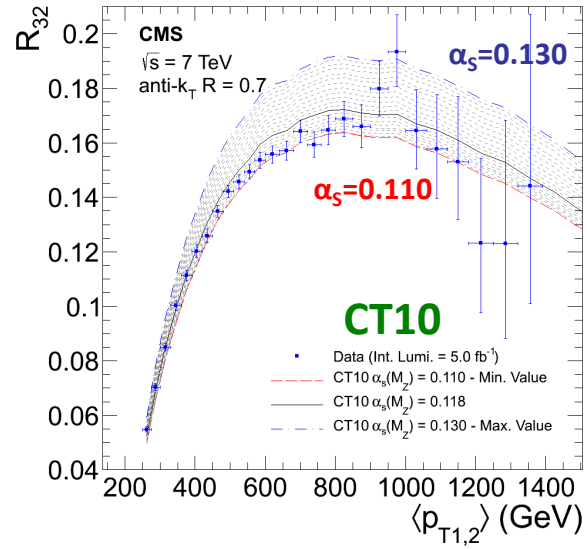
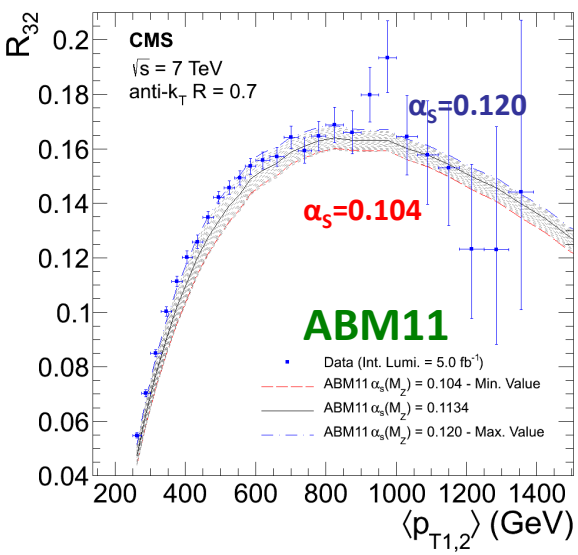
α_S from 3/2 inclusive jet cross sections ratio (R_{32}) at 7 TeV Sensitivity to α_S









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

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

α_S from 3/2 inclusive jet cross sections ratio (R_{32}) at 7 TeV Scales

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

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Table 2 The values of $\alpha_S(M_Z)$ at the central scale and for the six scale factor combinations

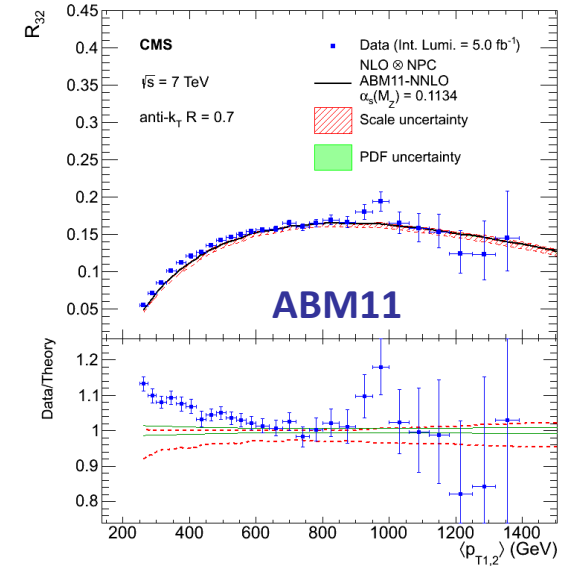
$\mu_r/\langle p_{T1,2}\rangle$	$\mu_f/\langle p_{T1,2}\rangle$	$\alpha_S(M_Z) \pm$ (exp.)	χ^2/N_{dof}
1	1	0.1148 ± 0.0014	22.0/20
1/2	1/2	0.1198 ± 0.0021	30.6/20
1/2	1	0.1149 ± 0.0014	22.2/20
1	1/2	0.1149 ± 0.0014	22.2/20
1	2	0.1150 ± 0.0015	21.9/20
2	1	0.1159 ± 0.0014	20.7/20
2	2	0.1172 ± 0.0018	21.3/20

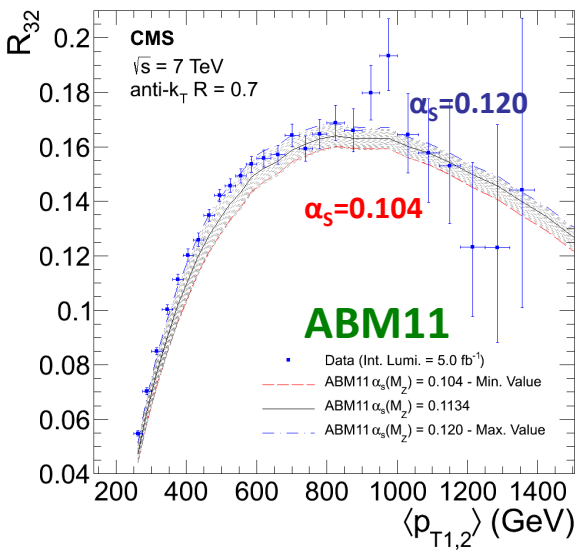
Lowest $\alpha_S(M_Z)$ value

Highest $\alpha_S(M_Z)$ value

- Scale uncertainties are symmetrized to take into account
  - The N_f=6 massless flavours in the NLO matrix elements (+-0.0009).
  - The evolution of α_S and the PDF with 5 or 6 flavours
  - Multijet production via full hadronic decays in pp-> ttbar+X
  - Incomplete cancelations of EW corrections (~1%)

α_S from 3/2 inclusive jet cross sections ratio (R_{32}) at 7 TeV ABM11





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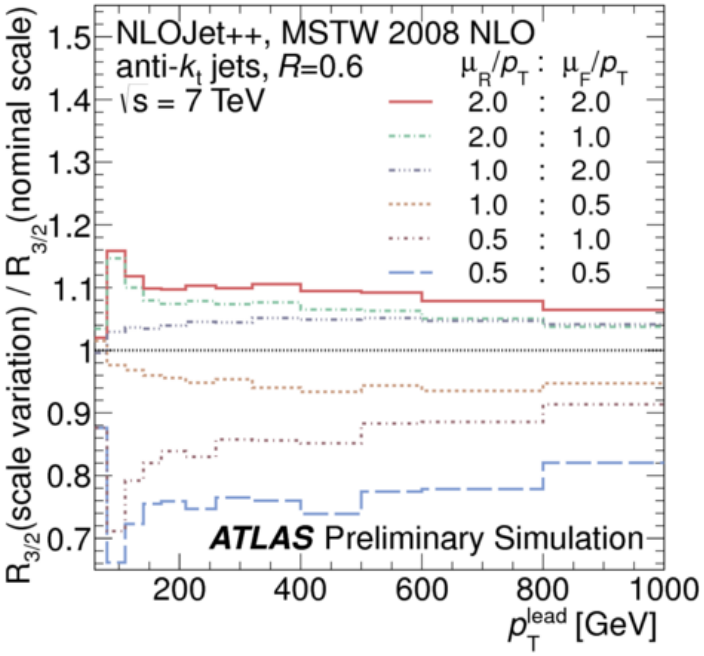
ABM11-NNLO:	$\alpha_S(M_Z) = 0.1214 \pm 0.0020(exp)$	$\chi^2/ndof=20.6/20$
ABM11-NLO:	$\alpha_S(M_Z) = 0.1214 \pm 0.0018(exp)$	$\chi^2/ndof=28.5/20$

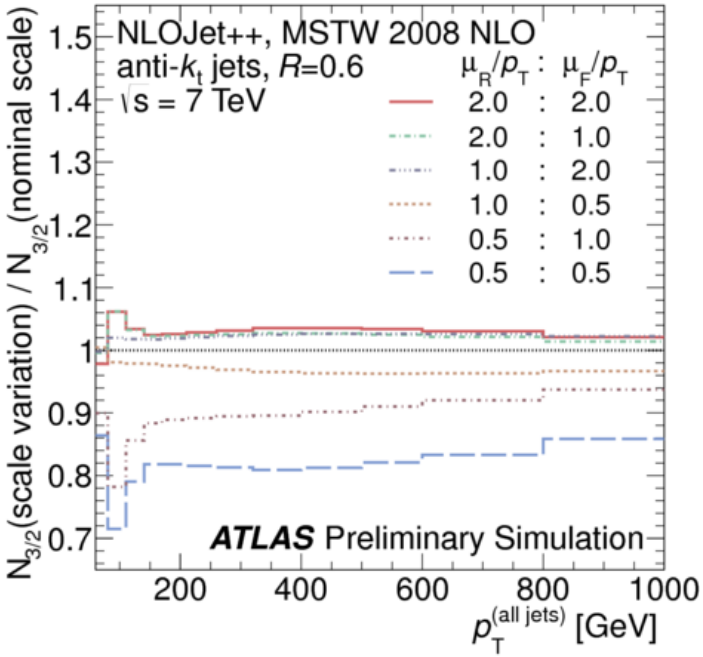
- It is observed that with ABM11 PDFs a higher value of $\alpha_S(M_Z)$ is preferred.
- The ABM11 gluon density in the phase space relevant for this analysis is significantly smaller than that of all other PDF sets.
- So the fit favors a larger $\alpha_S(M_Z)$ value to compensate for this effect.

- **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.

α_S from 3/2 inclusive jet cross sections ratio ($N_{3/2}$) at 7 TeV

ATLAS CONF 2013 041

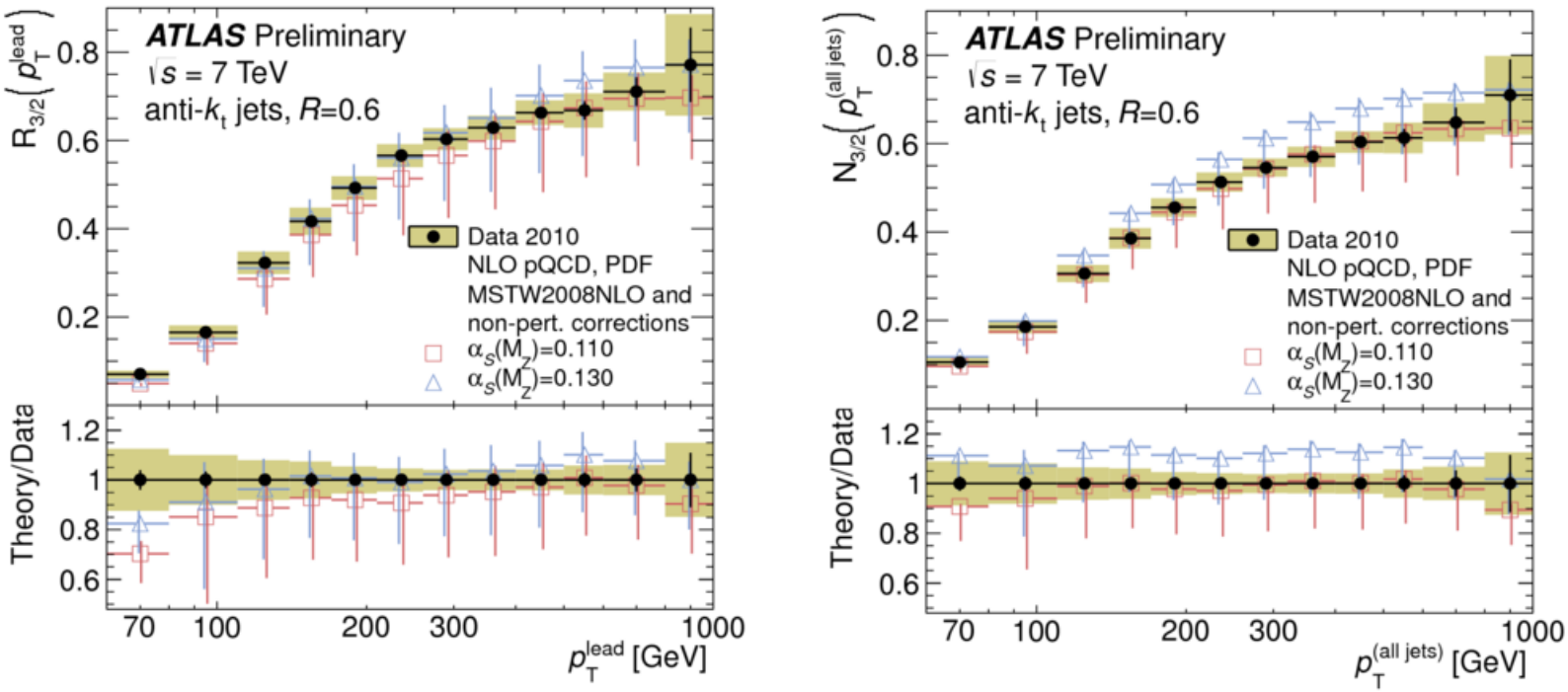




- Scale sensitivity of the theoretical predictions for $R_{3/2}$ and $N_{3/2}$ computed for $\alpha_S(MZ)=0.120$.
- The ratio $N_{3/2}$ is found to be less sensitive to the choice of scales, and it is used to extract α_S.

α_S from 3/2 inclusive jet cross sections ratio ($N_{3/2}$) at 7 TeV

ATLAS CONF 2013 041



- The measurements of $R_{3/2}$ and $N_{3/2}$ form ATLAS.
- NLO pQCD theoretical predictions, corrected for non-perturbative effects, are also shown for a value of $\alpha_s(M_Z)$ of 0.110 and 0.130.

Determination of α_S from top-pair production cross section

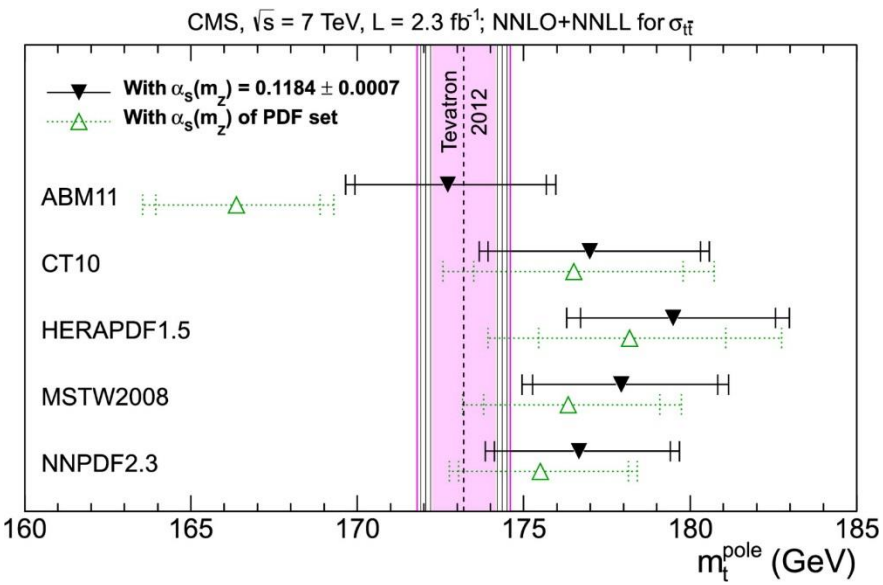
CMS : PLB 728 (2014) 496

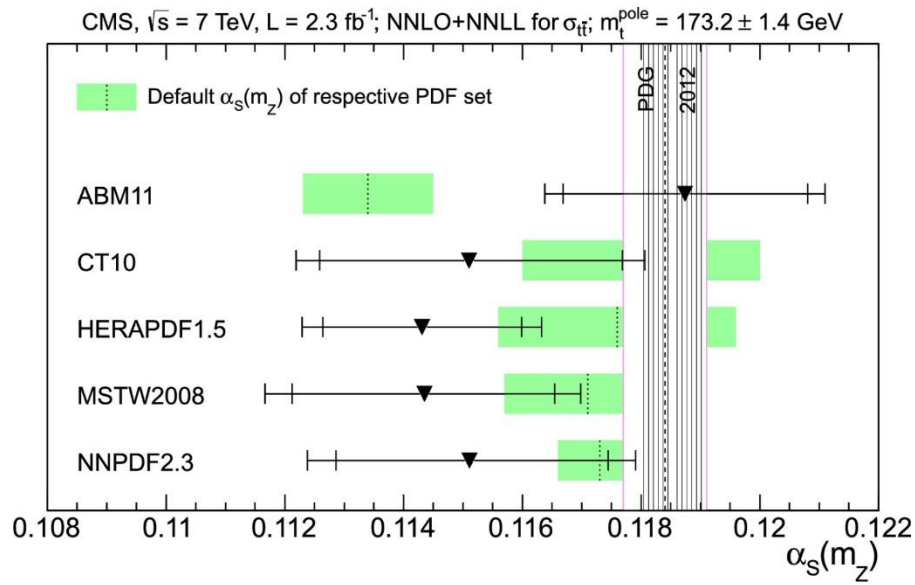
Table 1
Default $\alpha_S(m_Z)$ values and $\alpha_S(m_Z)$ variation ranges of the NNLO PDF sets used in this analysis. Because the NNPDF2.3 PDF set does not have a default value of $\alpha_S(m_Z)$, preferring to provide the full uncertainties and systematic variations for various $\alpha_S(m_Z)$ points, the $\alpha_S(m_Z)$ value obtained by the NNPDF Collaboration with NNPDF2.1 [49] is used. The step size for the $\alpha_S(m_Z)$ scans is 0.0010 in all cases. The uncertainties on the default values are shown for illustration purposes only.

	Default $\alpha_S(m_Z)$	Uncertainty	Provided $\alpha_S(m_Z)$ scan	
			Range	# of points
ABM11	0.1134	±0.0011	0.1040–0.1200	17
CT10	0.1180	±0.0020	0.1100–0.1300	21
HERAPDF1.5	0.1176	±0.0020	0.1140–0.1220	9
MSTW2008	0.1171	±0.0014	0.1070–0.1270	21
NNPDF2.3	0.1174	±0.0007	0.1140–0.1240	11

Determination of α_S from top-pair production cross section

CMS : PLB 728 (2014) 496

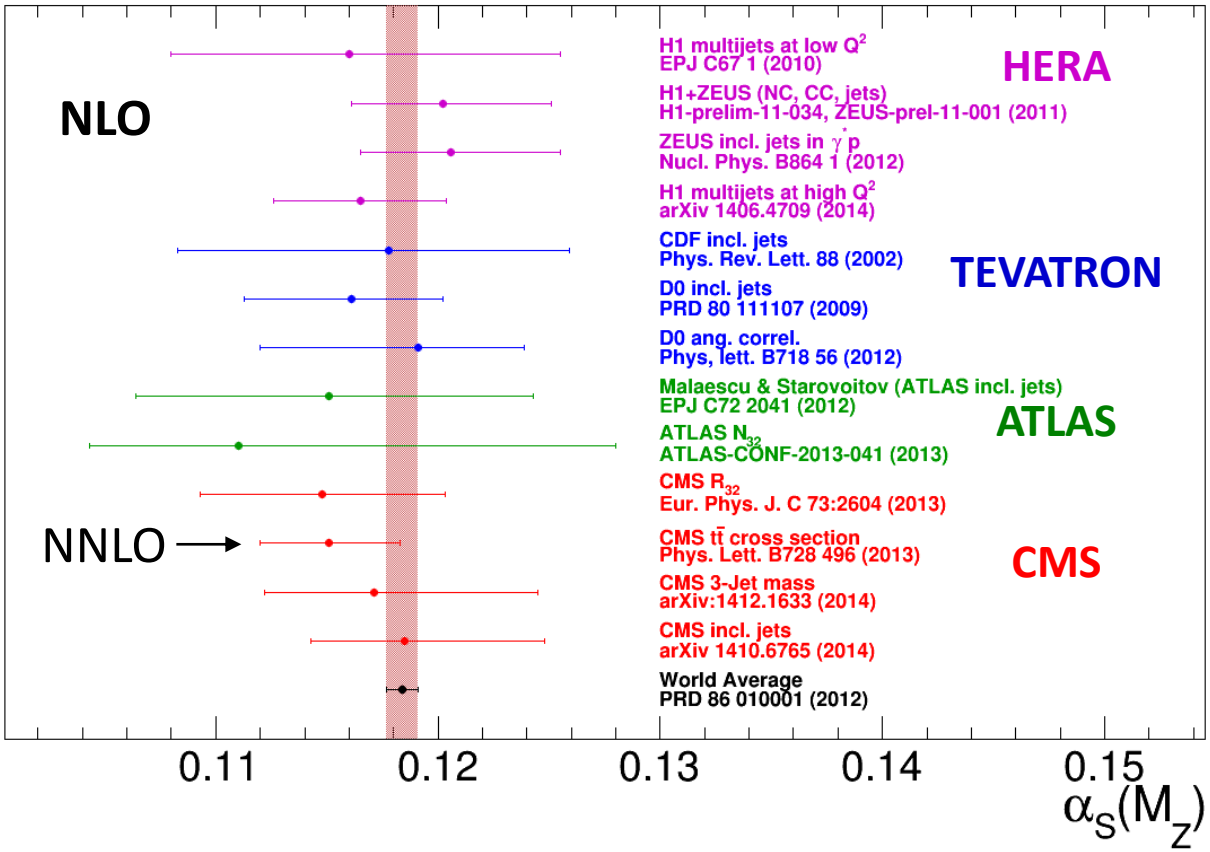




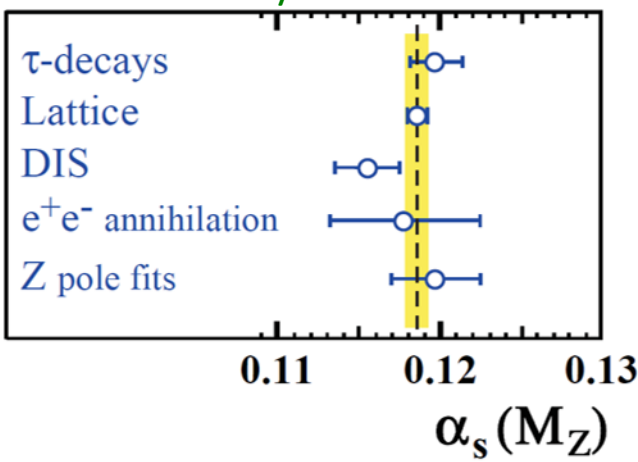
	m_t^{pole} (GeV)	Uncertainty on m_t^{pole} (GeV)						
		Total	$\sigma_{t\bar{t}}^{meas}$	PDF	μR, F	αS	ELHC	m_t^{MC}
ABM11	172.7	$^{+3.2}_{-3.1}$	$^{+1.8}_{-1.8}$	$^{+2.2}_{-2.0}$	$^{+0.7}_{-0.7}$	$^{+1.0}_{-1.0}$	$^{+0.8}_{-0.8}$	$^{+0.4}_{-0.3}$
CT10	177.0	$^{+3.6}_{-3.3}$	$^{+2.2}_{-2.1}$	$^{+2.4}_{-2.0}$	$^{+0.9}_{-0.9}$	$^{+0.8}_{-0.8}$	$^{+0.9}_{-0.9}$	$^{+0.5}_{-0.4}$
HERAPDF1.5	179.5	$^{+3.5}_{-3.2}$	$^{+2.4}_{-2.2}$	$^{+1.7}_{-1.5}$	$^{+0.9}_{-0.8}$	$^{+1.2}_{-1.1}$	$^{+1.0}_{-1.0}$	$^{+0.6}_{-0.5}$
MSTW2008	177.9	$^{+3.2}_{-3.0}$	$^{+2.2}_{-2.1}$	$^{+1.6}_{-1.4}$	$^{+0.9}_{-0.9}$	$^{+0.9}_{-0.9}$	$^{+0.9}_{-0.9}$	$^{+0.5}_{-0.5}$
NNPDF2.3	176.7	$^{+3.0}_{-2.8}$	$^{+2.1}_{-2.0}$	$^{+1.5}_{-1.3}$	$^{+0.9}_{-0.9}$	$^{+0.7}_{-0.7}$	$^{+0.9}_{-0.9}$	$^{+0.5}_{-0.4}$

	αS(mZ)	Uncertainty on αS(mZ)					
		Total	$\sigma_{t\bar{t}}^{meas}$	PDF	μR, F	m_t^{pole}	ELHC
ABM11	0.1187	$^{+0.0024}_{-0.0024}$	$^{+0.0013}_{-0.0015}$	$^{+0.0015}_{-0.0014}$	$^{+0.0006}_{-0.0005}$	$^{+0.0010}_{-0.0010}$	$^{+0.0006}_{-0.0006}$
CT10	0.1151	$^{+0.0030}_{-0.0029}$	$^{+0.0018}_{-0.0018}$	$^{+0.0018}_{-0.0016}$	$^{+0.0008}_{-0.0007}$	$^{+0.0012}_{-0.0013}$	$^{+0.0007}_{-0.0007}$
HERAPDF1.5	0.1143	$^{+0.0020}_{-0.0020}$	$^{+0.0012}_{-0.0013}$	$^{+0.0010}_{-0.0009}$	$^{+0.0005}_{-0.0004}$	$^{+0.0010}_{-0.0010}$	$^{+0.0006}_{-0.0006}$
MSTW2008	0.1144	$^{+0.0026}_{-0.0027}$	$^{+0.0017}_{-0.0018}$	$^{+0.0012}_{-0.0011}$	$^{+0.0008}_{-0.0007}$	$^{+0.0012}_{-0.0013}$	$^{+0.0007}_{-0.0008}$
NNPDF2.3	0.1151	$^{+0.0028}_{-0.0027}$	$^{+0.0017}_{-0.0018}$	$^{+0.0013}_{-0.0011}$	$^{+0.0009}_{-0.0008}$	$^{+0.0013}_{-0.0013}$	$^{+0.0008}_{-0.0008}$

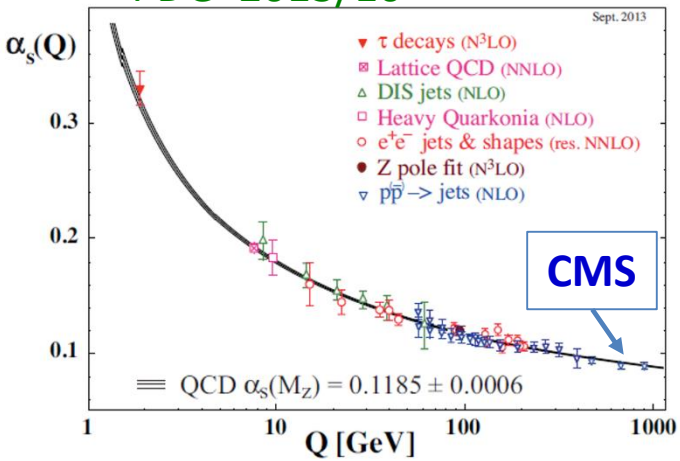
Overview of $\alpha_s(M_Z)$ measurements



PDG 2013/10 NNLO



PDG 2013/10



- **Uncertainties dominated by theory → need jets at NNLO for inclusion into the world average.**