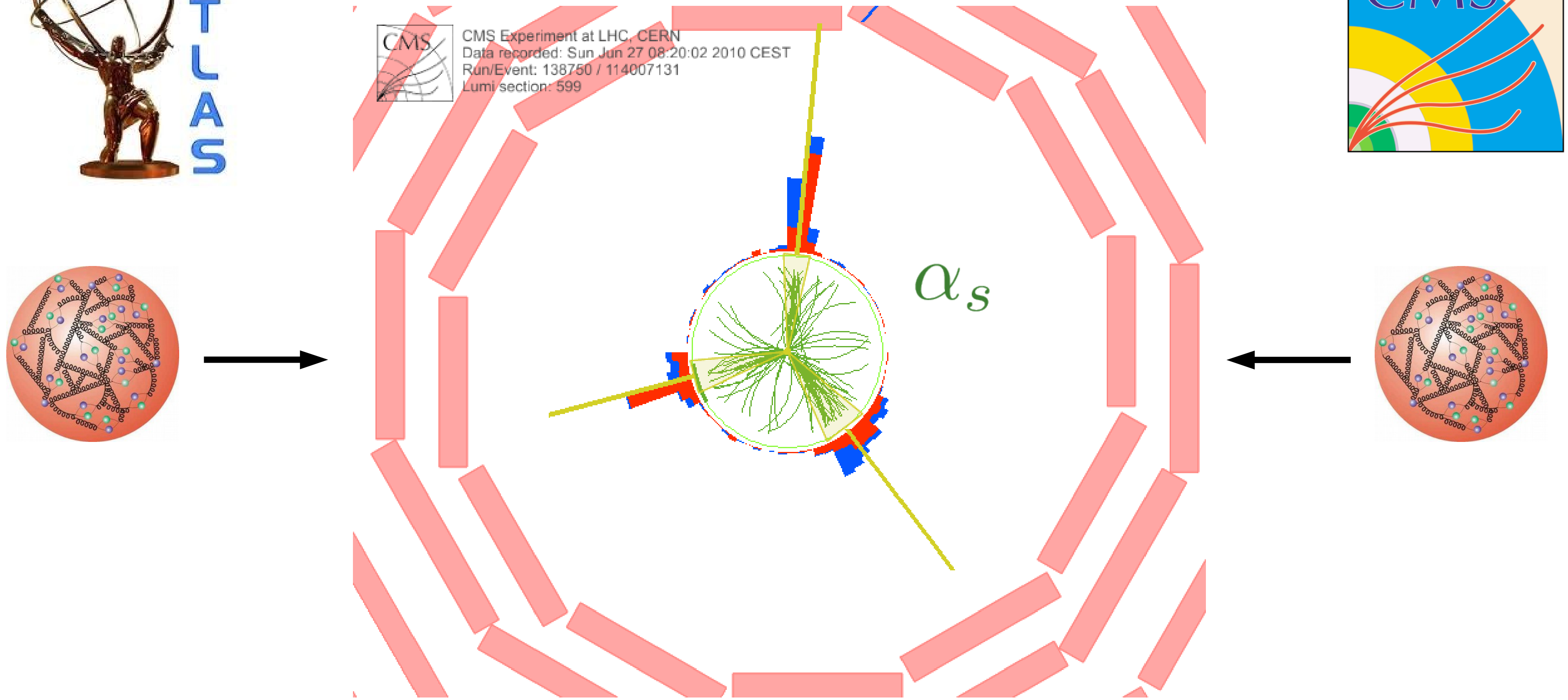
Determining the strong coupling constant α_s – Results from ATLAS & CMS



Klaus Rabbertz, KIT
(on behalf of ATLAS & CMS)

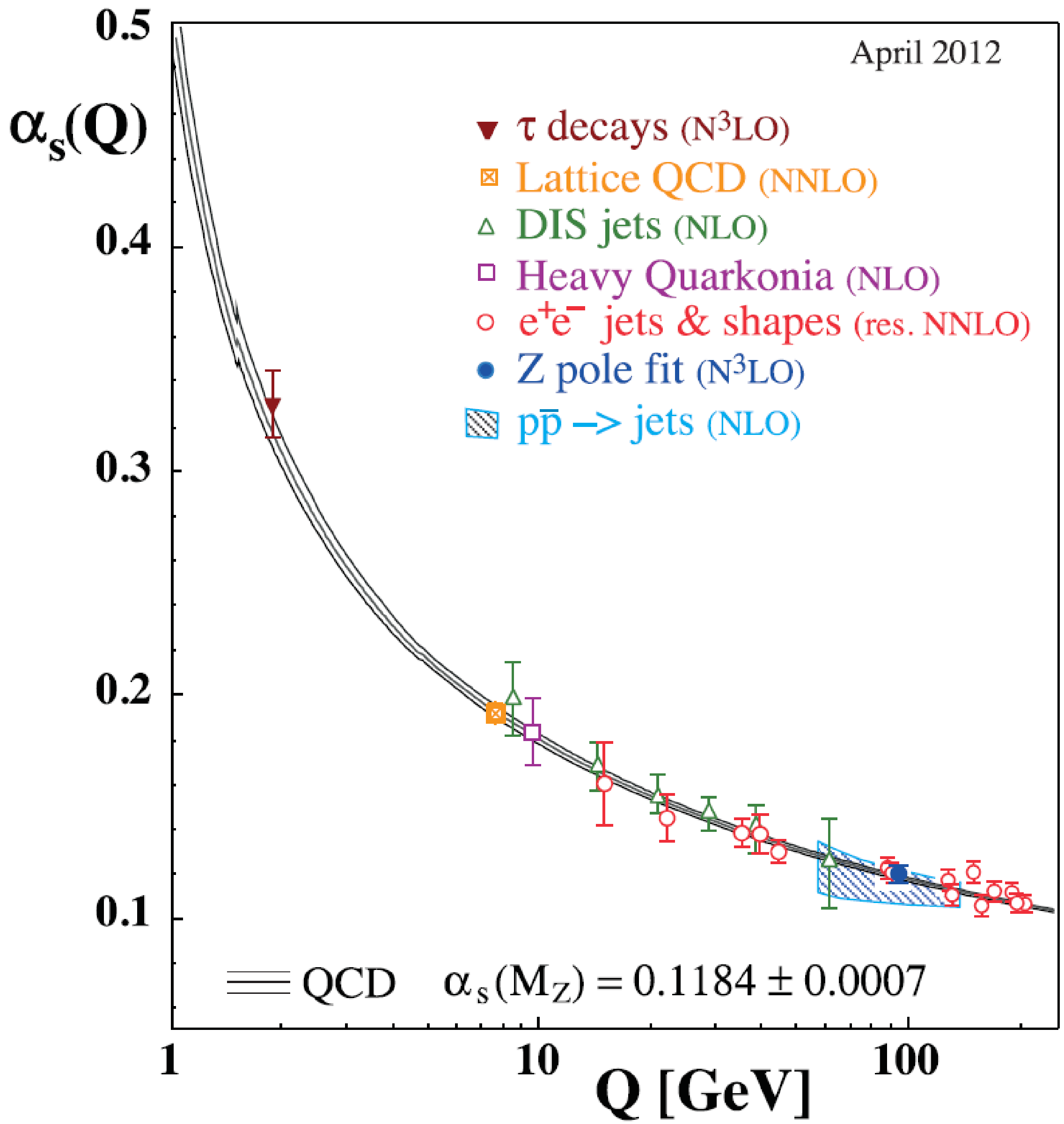
Karlsruhe Institute of Technology

Outline

- **Motivation**
- **Jet-like measurements**
  - **Cross sections**
  - **Ratios**
  - **Event shapes**
- **top-antitop production**
- **V + jets**
- **Issues & perspectives**
- **Summary & Outlook**

2012: No LHC results yet

PDG2012

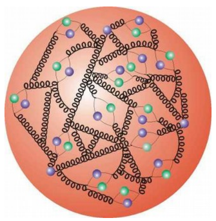


For α_s (M_Z) from global PDF fits
→ Next talk by Robert Thorne

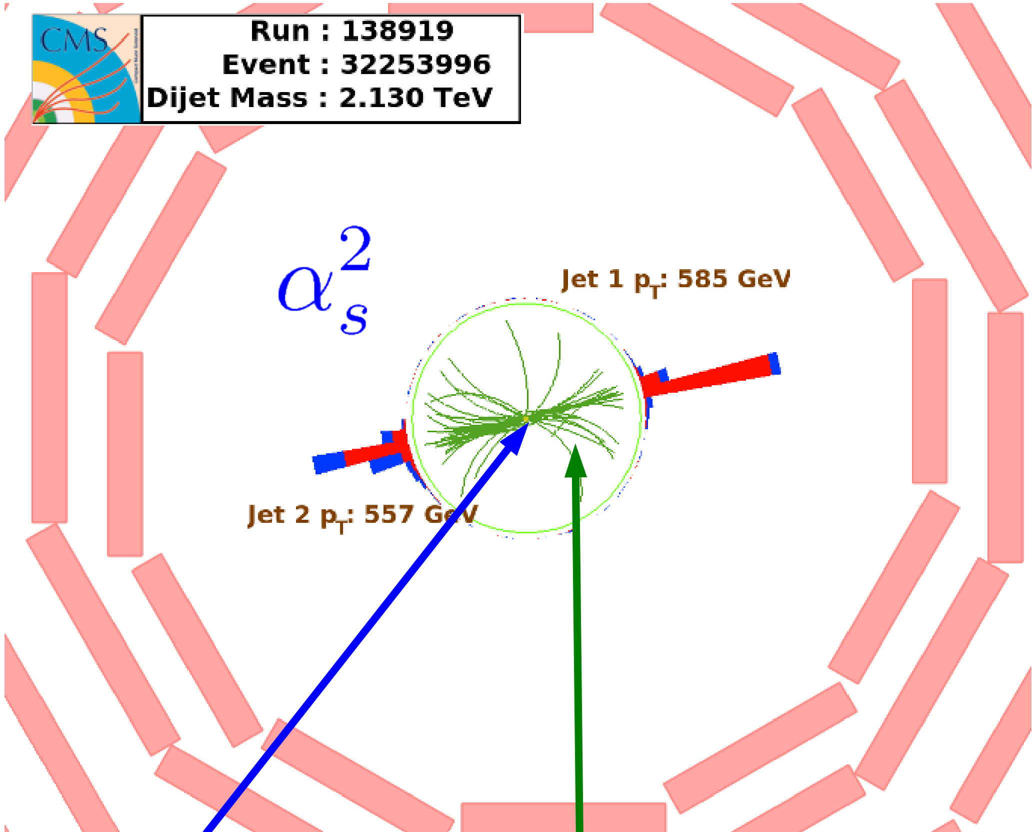
Jets at the LHC

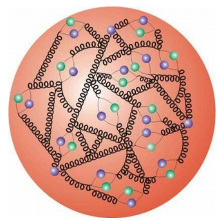
Abundant production of jets:

- 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)





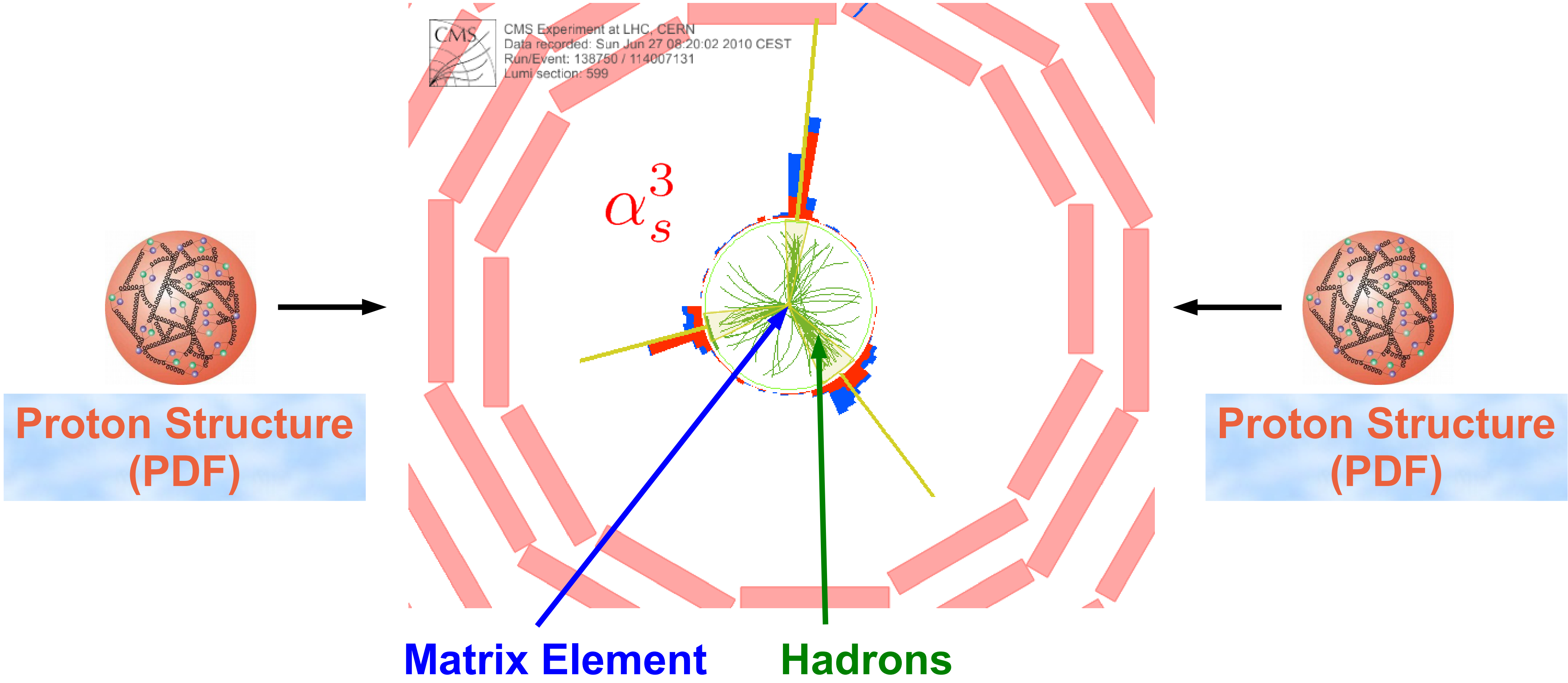
Proton Structure (PDF)

Matrix Element   Hadrons

Jets at the LHC

Abundant production of jets:

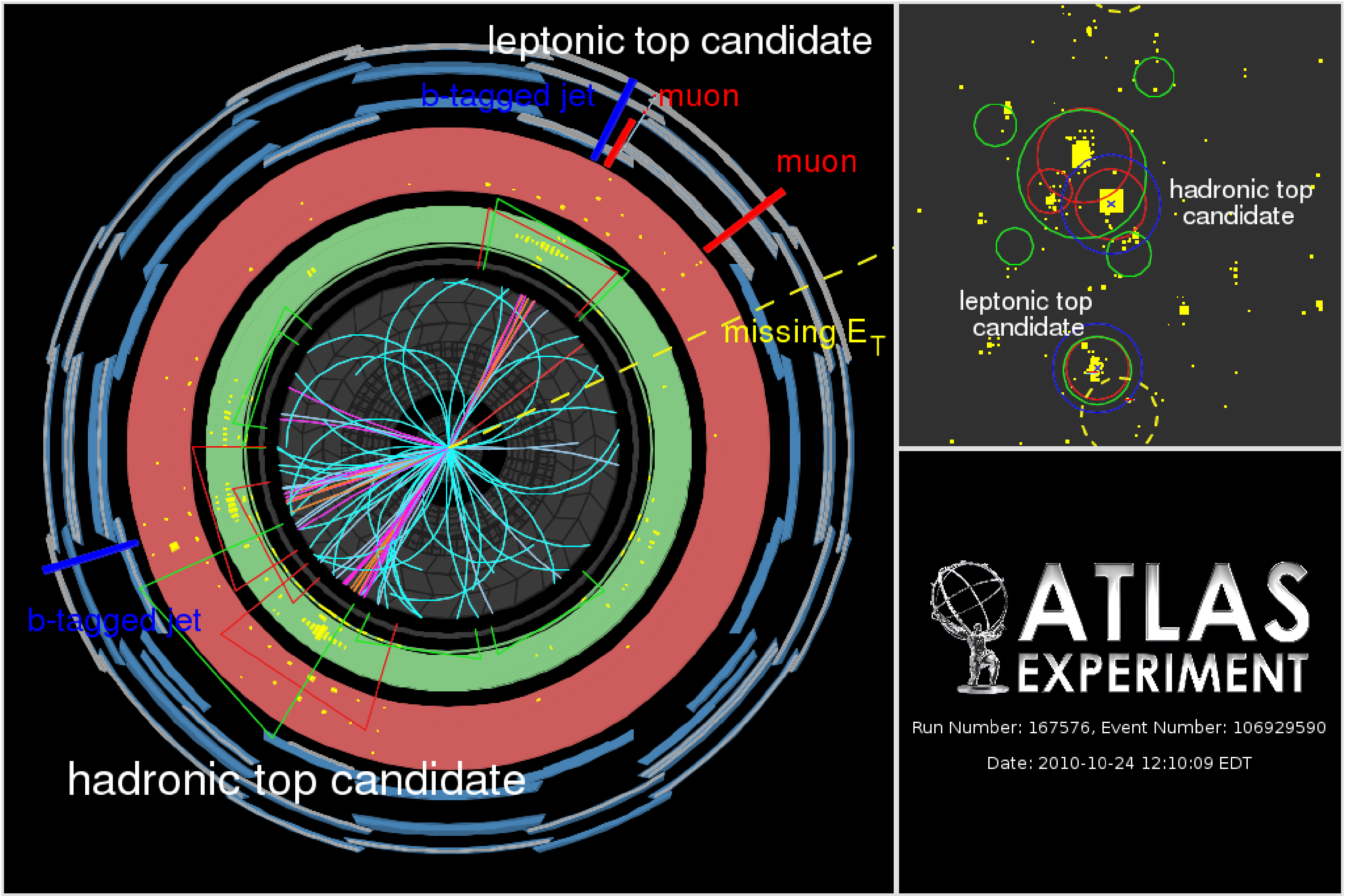
➔ **Extract $\alpha_s(M_Z)$, the least precisely known fundamental constant!**



W, Z, top at the LHC

High-precision lepton measurements:

- W, Z, top measurements provide high-precision cross sections
- Also learn about electroweak parameters, the top mass, and the proton structure

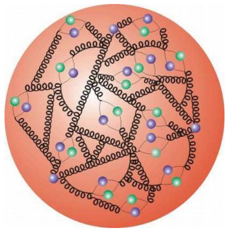


Jet cross sections ~ α_s^2

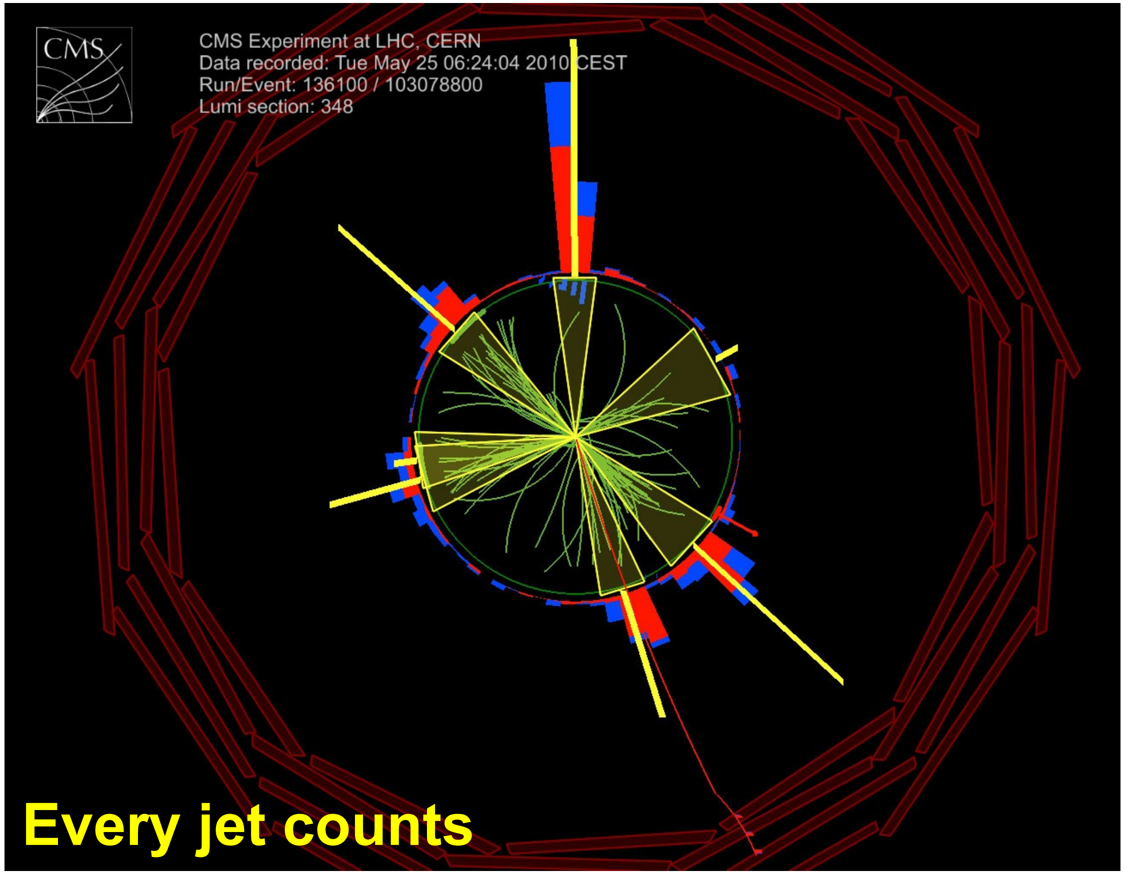
- Determination of $\alpha_s(M_Z)$ in single-parameter fit
- Test consistency of running of $\alpha_s(Q)$
- Multi-parameter fit of $\alpha_s(M_Z)$ & PDFs

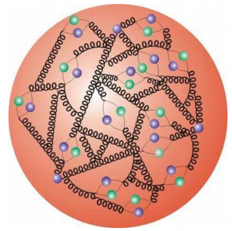
All inclusive

Large transverse momenta



Proton





Proton

Relevant ATLAS & CMS measurements:

ATLAS:
EPJC 73 (2013) 2509; JHEP 02 (2015) 153; JHEP 09 (2017) 020; JHEP 05 (2018) 195.
CMS:
PRD 87 (2013) 112002; PRD 90 (2014) 072006; EPJC 75 (2015) 288;
EPJC 76 (2016) 265; EPJC 76 (2016) 451; JHEP 03 (2017) 156.

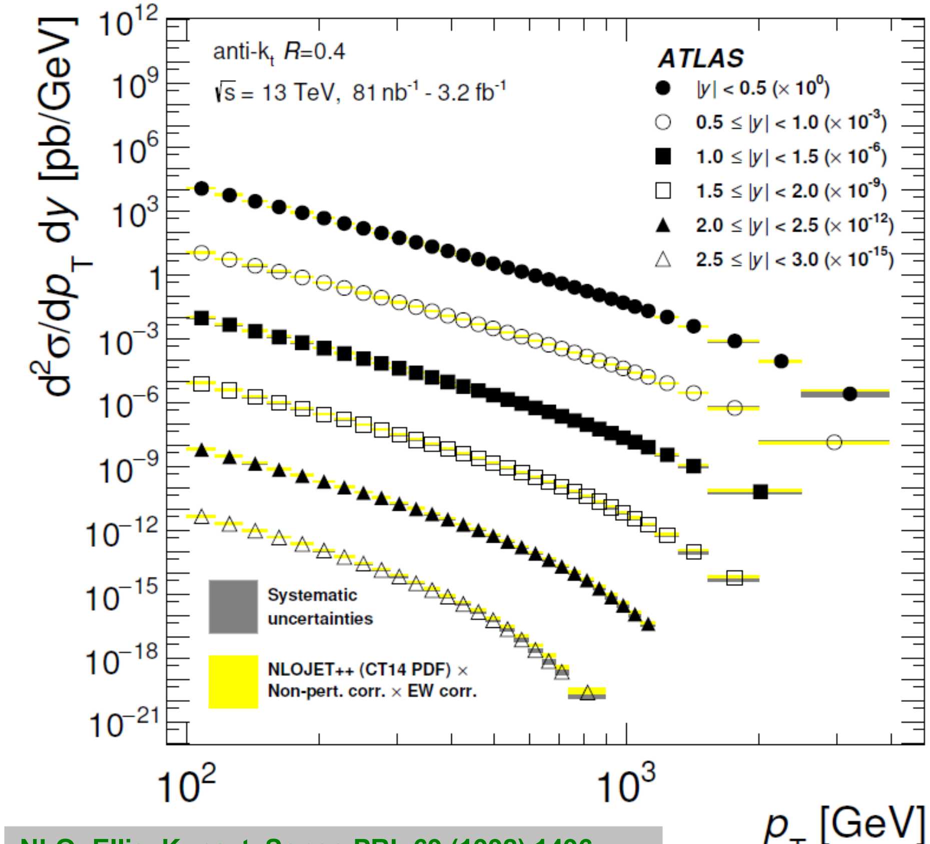
Inclusive jets: cross section

Overall 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 3 ~ 5 at $\sqrt{s}$ = 2.76, 7, 8, and 13 TeV.

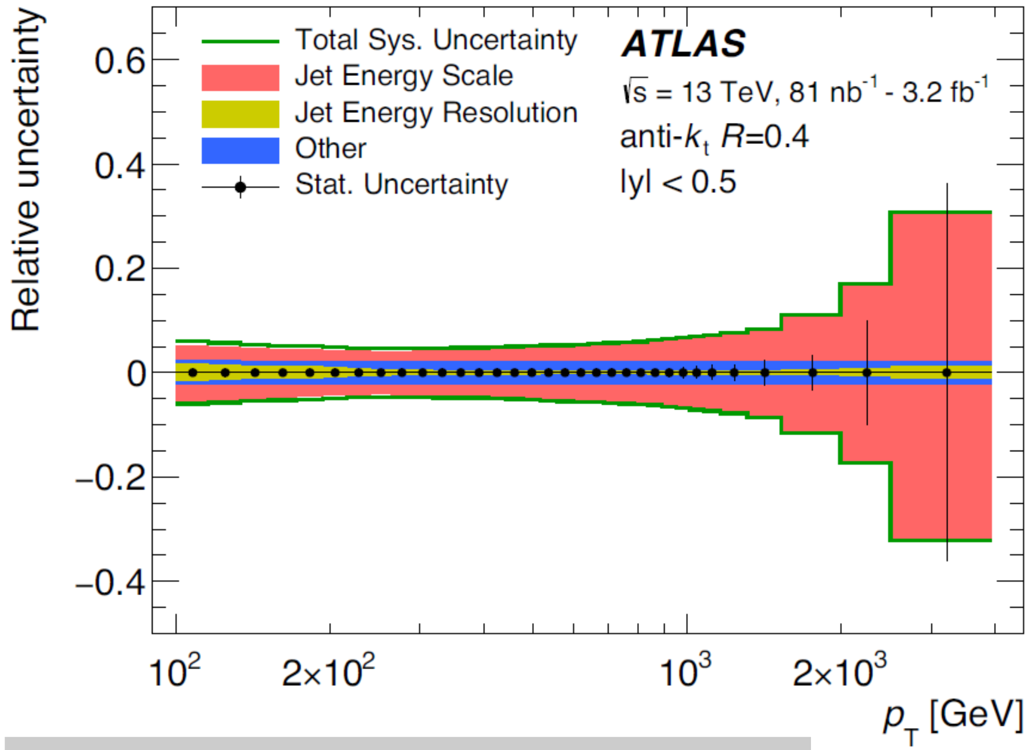
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

Here: anti-k_t, R=0.4, 13 TeV

Data vs. NLO pQCD x non-pert. x EW corrections



Exp. uncertainties for |y| < 0.5



NLO: Ellis, Kunszt, Soper, PRL 69 (1992) 1496;
Giele, Glover, Kosower, NPB 403 (1993) 633;
Z. Nagy, PRD 68 (2003) 094002.

For all details on ATLAS jet measurements:
→ Talk by Bogdan Malaescu on Wednesday

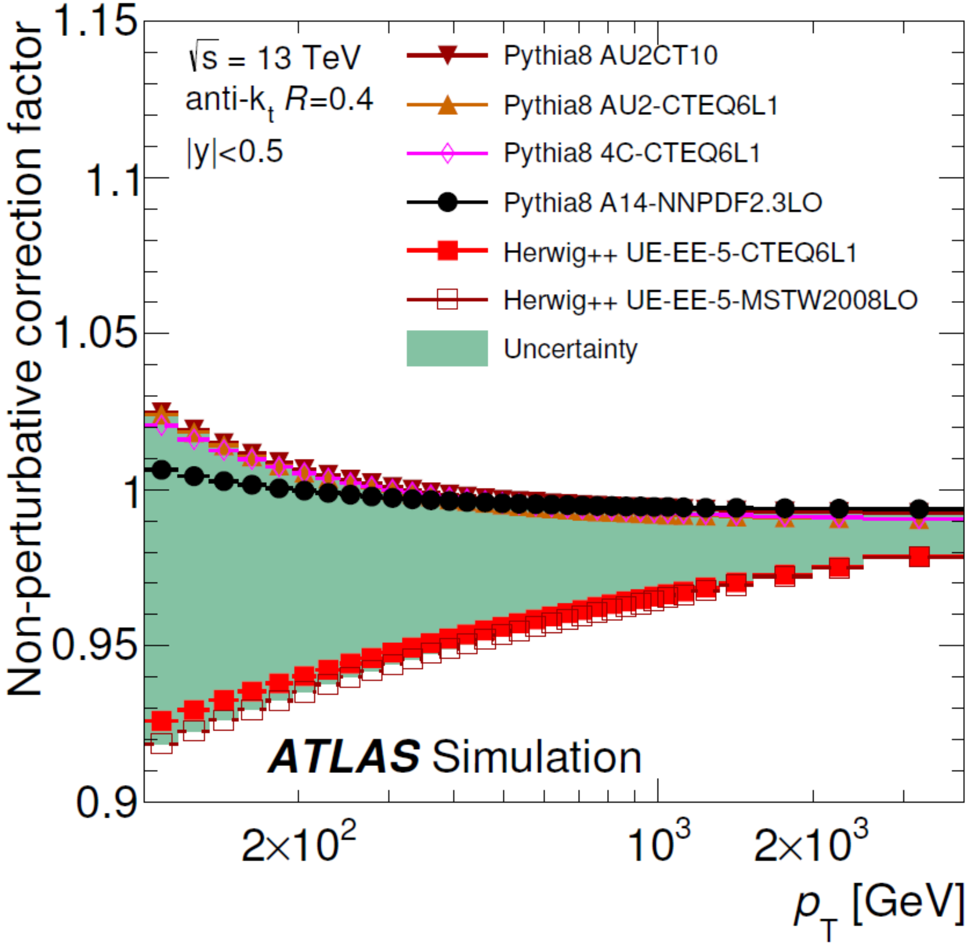
Inclusive jets: theory corrections

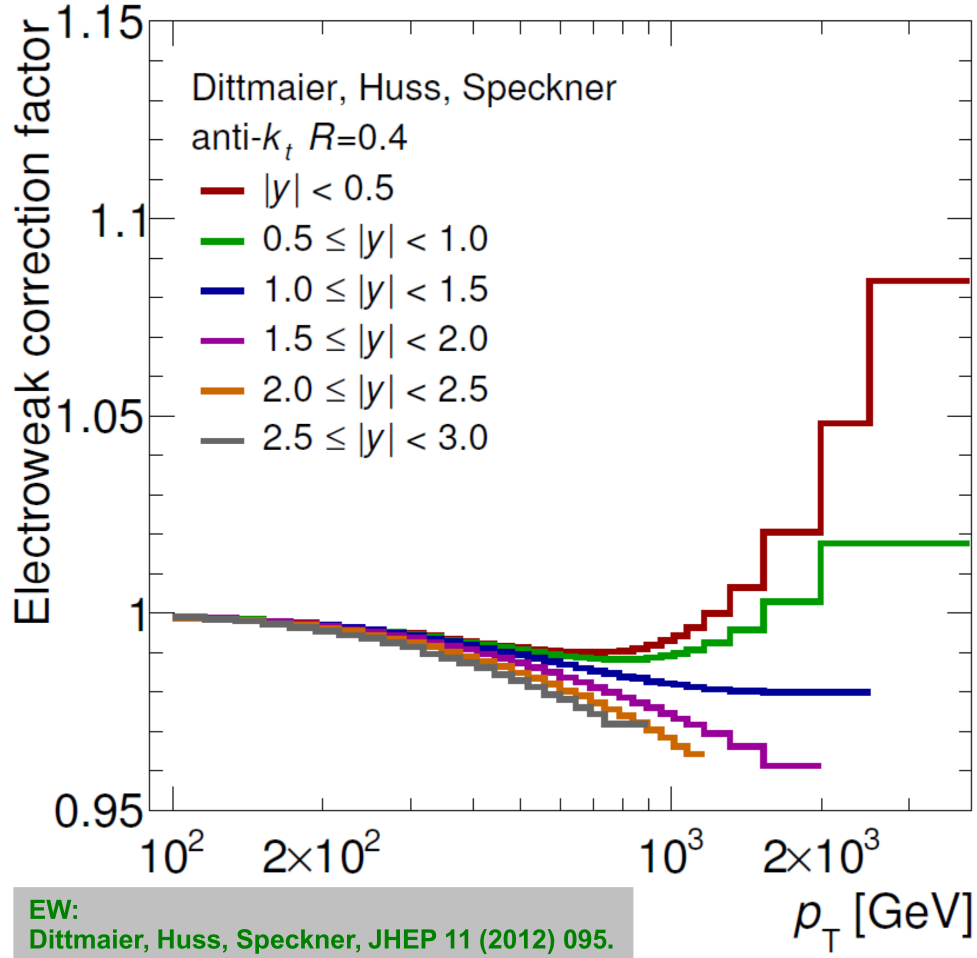
anti-kt, R=0.4, 13 TeV, |y| < 0.5

Nonperturbative correction factors:
- estimated from tuned MC event generators
- uncertainty of 5 – 15% at p_T = 100 GeV
- strongly dependent on jet size R
- less important at high p_T

Electroweak correction factors:
- calculated perturbatively
- uncertainty small
- strongly dependent on jet rapidity y
- very important at high p_T

→Talk by Marek Schönherr on Wednesday





EW:
Dittmaier, Huss, Speckner, JHEP 11 (2012) 095.
Frederix et al., JHEP 04 (2017) 076.

Inclusive jets: NNLO & scale choice

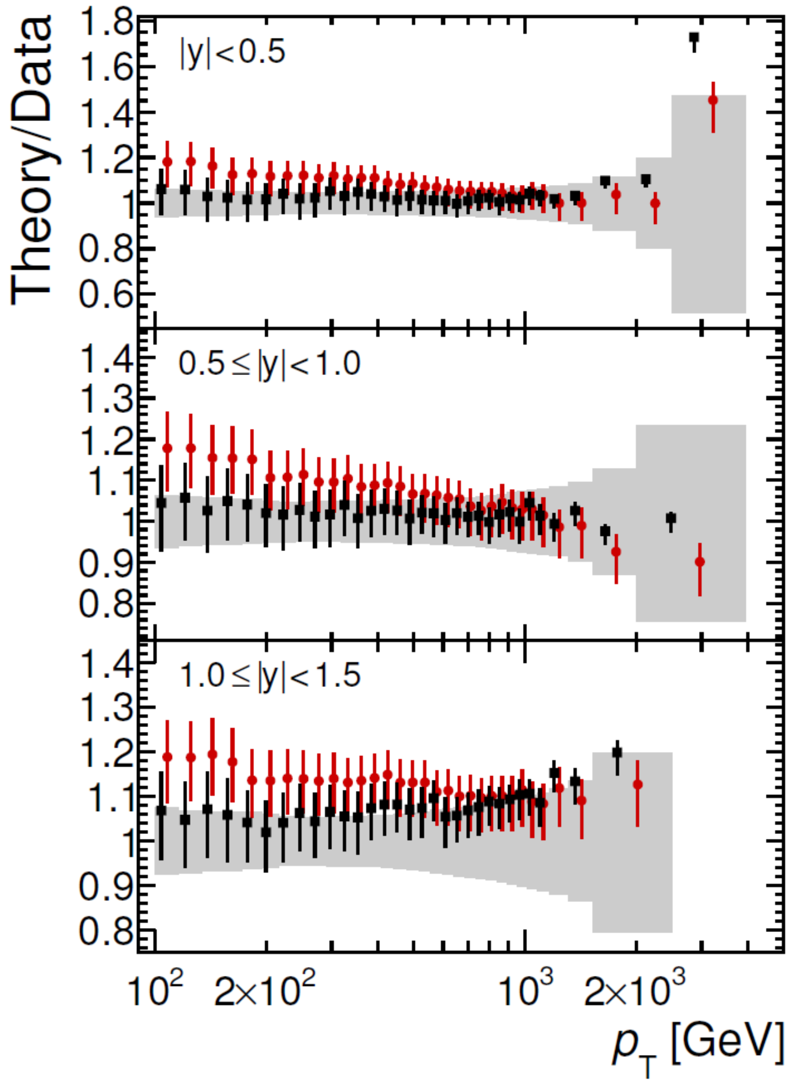
anti-kt, R=0.4, 13 TeV

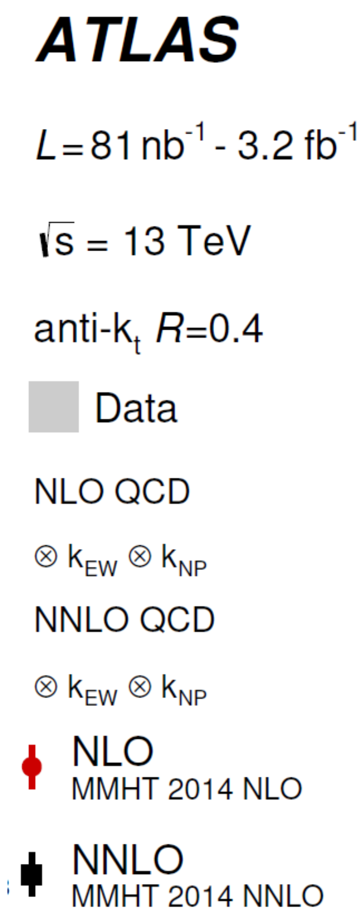
QCD scale choice: $\mu_R = \mu_F = p_{T,jet}$

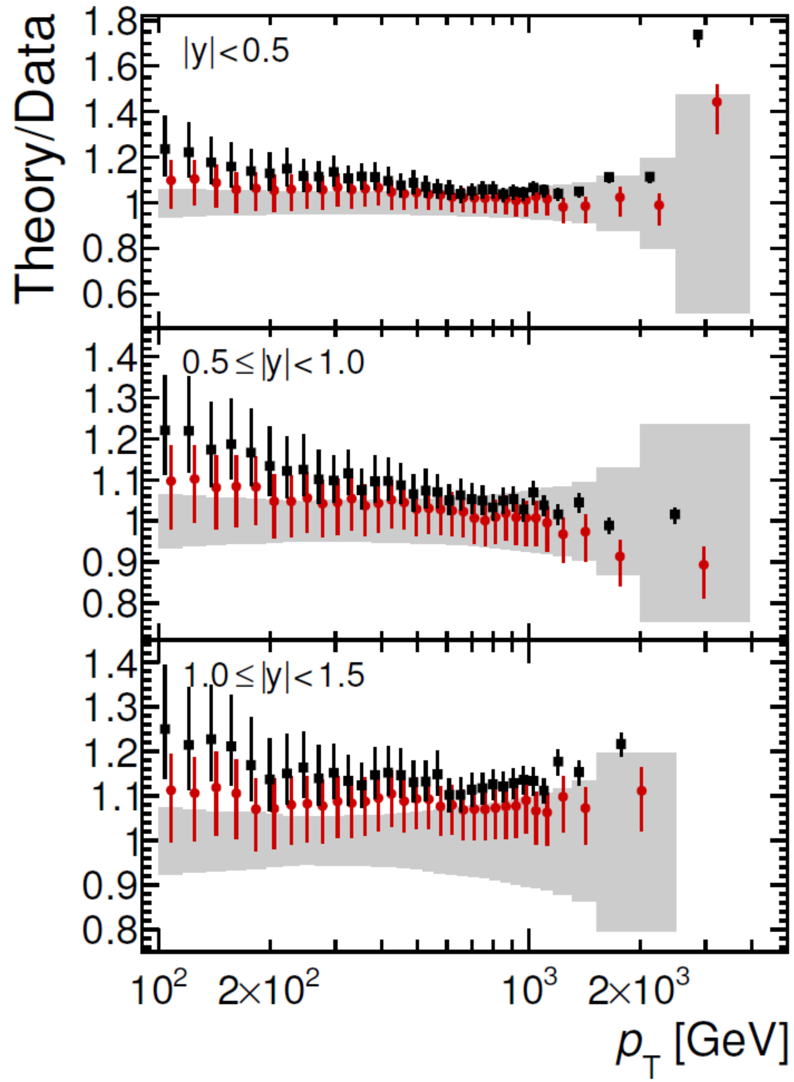
- for small p_T better agreement with NNLO

QCD scale choice: $\mu_R = \mu_F = p_{T,max}$

- for small p_T better agreement with NLO





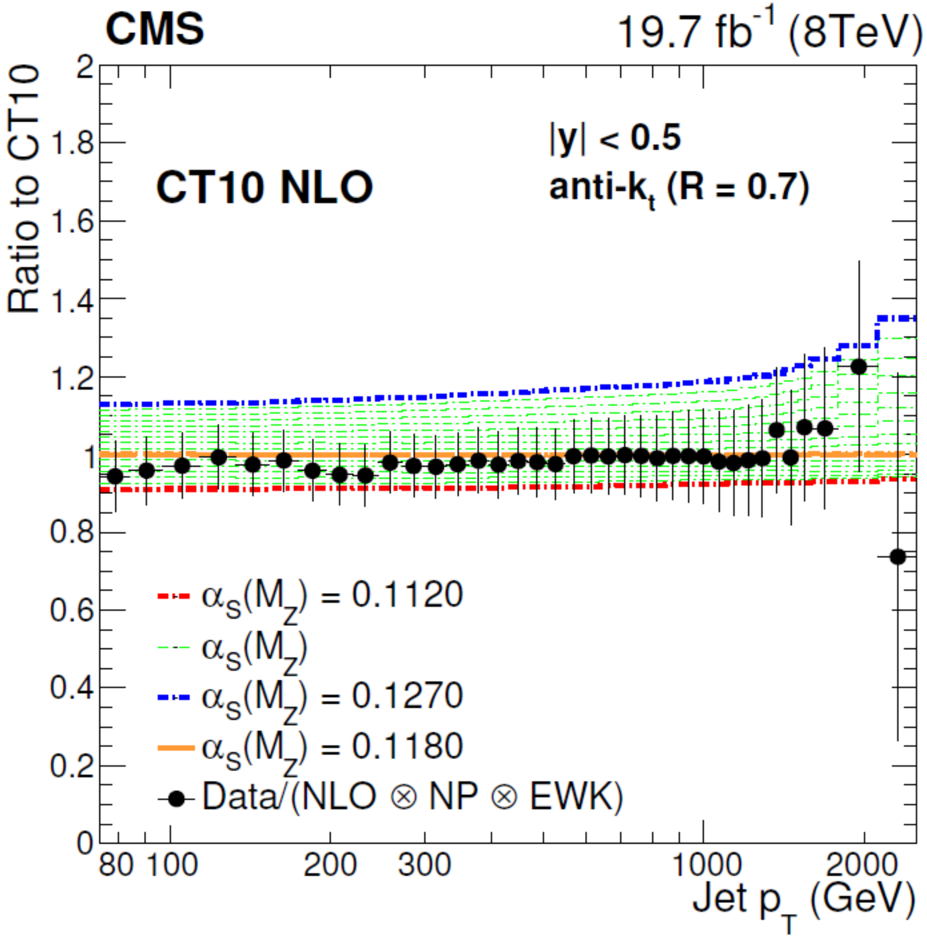


NNLO:
Currie et al., PRL 118 (2017) 072002,
Acta Phys. Pol. B48 (2017) 955.

Inclusive jets: α_s

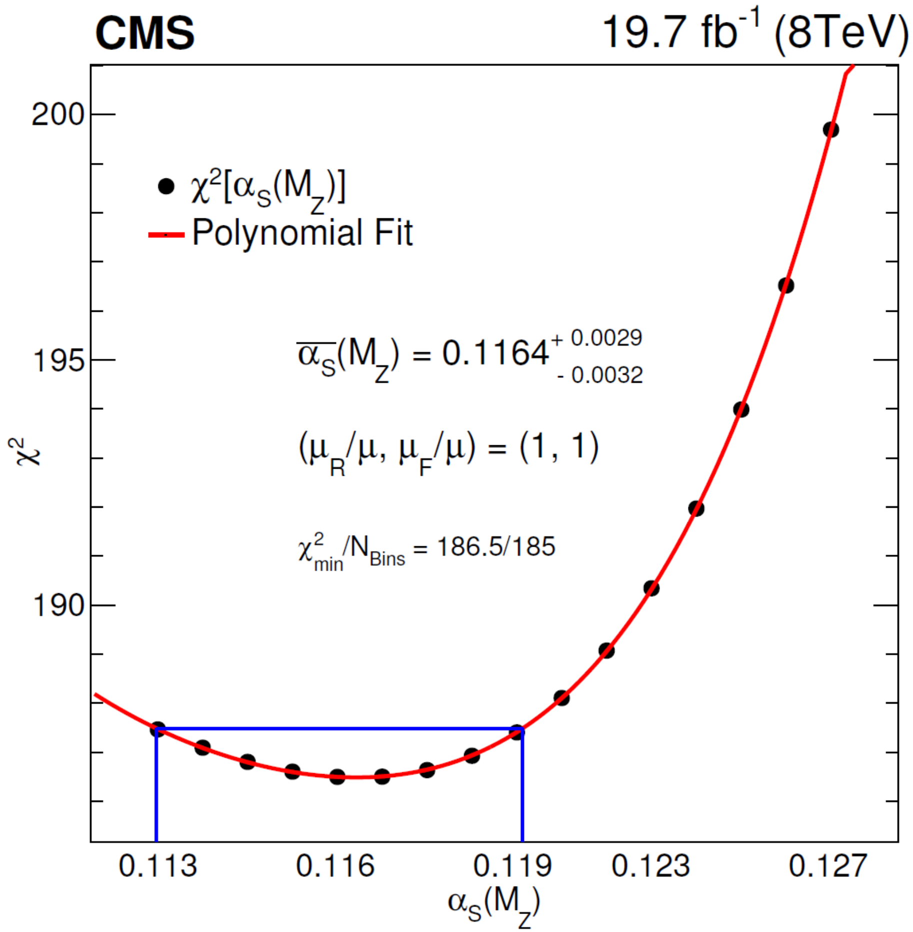
Sensitivity to $\alpha_s(M_Z)$ at NLO

- CMS: anti-k_t R = 0.7 at $\sqrt{s}$ = 8 TeV
- QCD scale choice: $\mu_R = \mu_F = p_{T,jet}$



X^2 fit of $\alpha_s(M_Z)$ for all jet p_T and |y| bins

- In fit: all exp. + PDF + NP uncertainties
- PDFs: CT10 NLO PDF sets for various $\alpha_s(M_Z)$

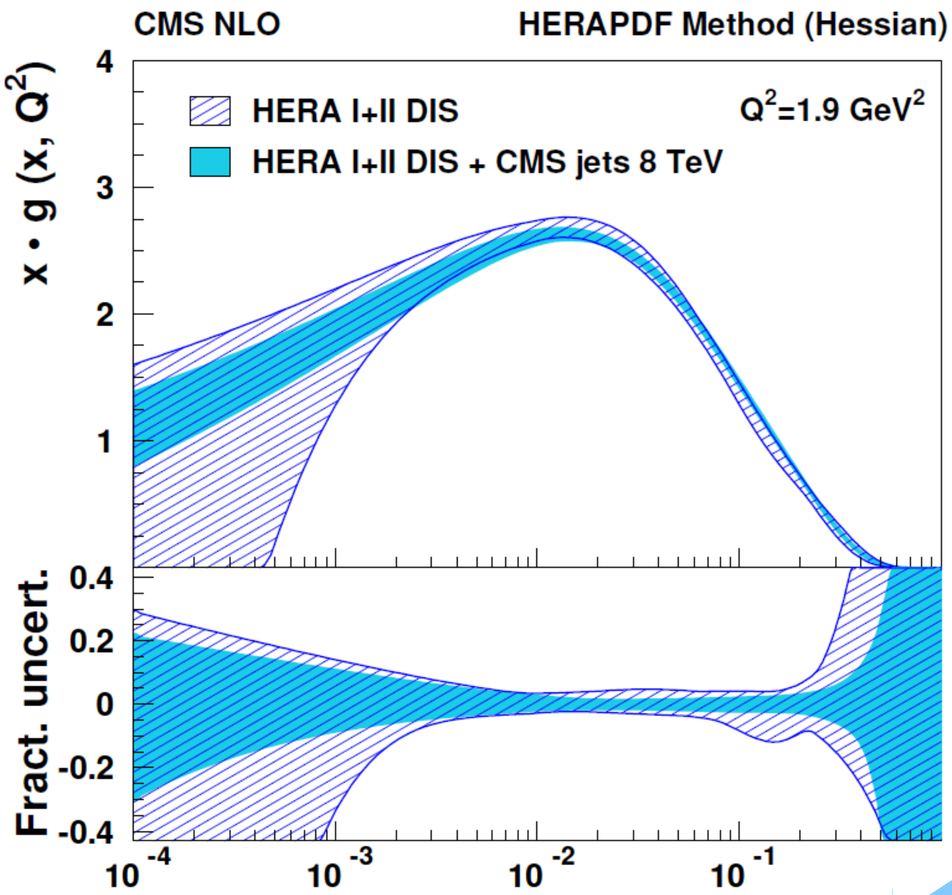


Jets @ NNLO not used yet in fits @ LHC; → Talk by Daniel Britzger tomorrow for results in ep scattering

Inclusive jets: α_s & PDFs

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

Reduced uncertainties of gluon PDF



13 (7 TeV) / 18 (8 TeV) parameter fit

Results for $\alpha_s(M_Z)$ at NLO from 7 and 8 TeV CMS jet data

$\alpha_s(M_Z)$	exp	PDF	NP	sum	scale
0.1185	19	28	4	35	$^{+53}_{-24}$
0.1164	$^{+14}_{-15}$	$^{+25}_{-29}$	1	$^{+29}_{-33}$	$^{+53}_{-28}$
0.1192				$^{+23}_{-19}$	$^{+24}_{-39}$
0.1185				$^{+19}_{-26}$	$^{+22}_{-18}$

Darker/lighter shading: 7 TeV / 8 TeV jet data

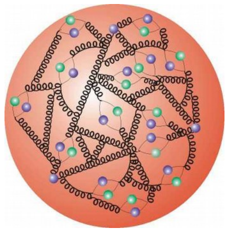
Reddish/bluish color: without / with PDF fit

Open question: Uncertainty of missing higher orders (aka scale uncertainty) in PDF fits

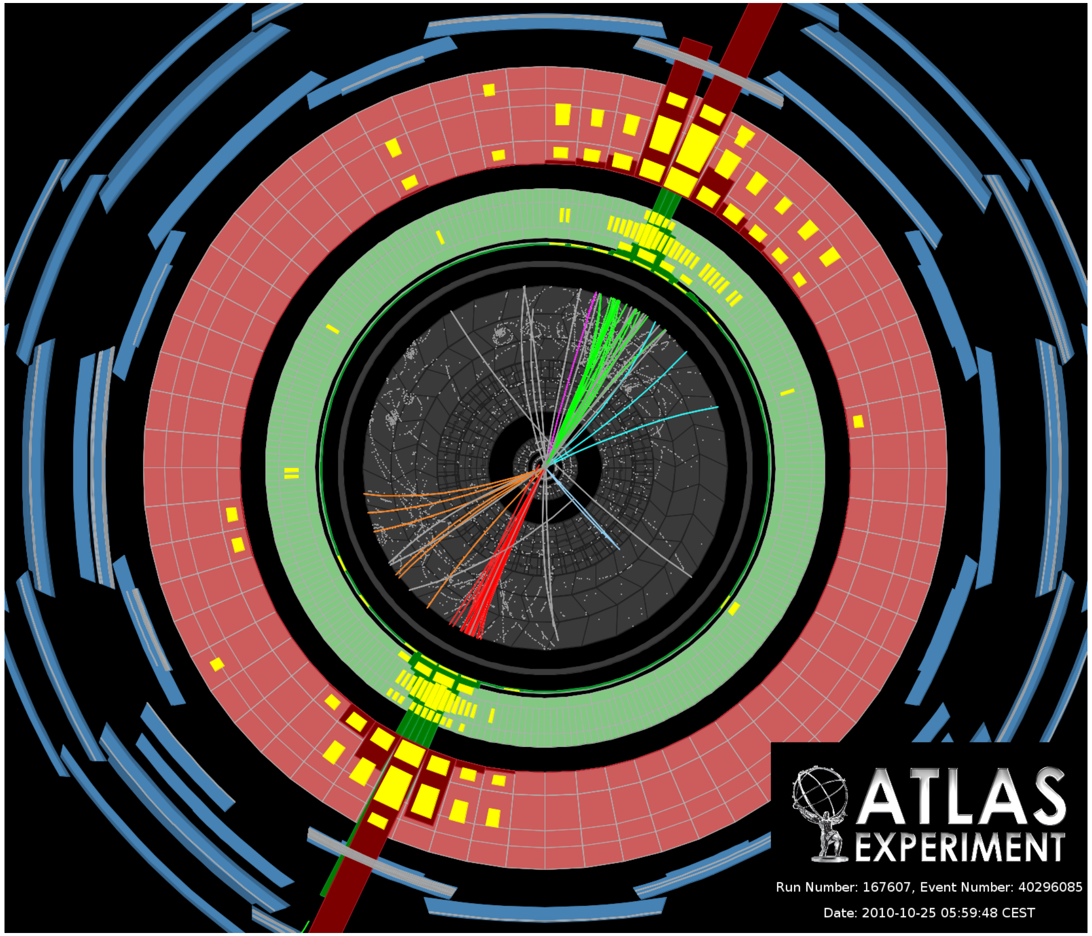
xFitter (HERAFitter): Alekhin et al., EPJC 75 (2015) 304.

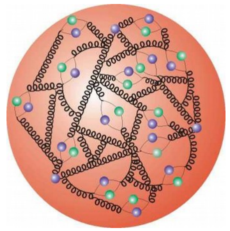
Dijets

Large masses



Proton





Proton

Relevant ATLAS & CMS measurements:

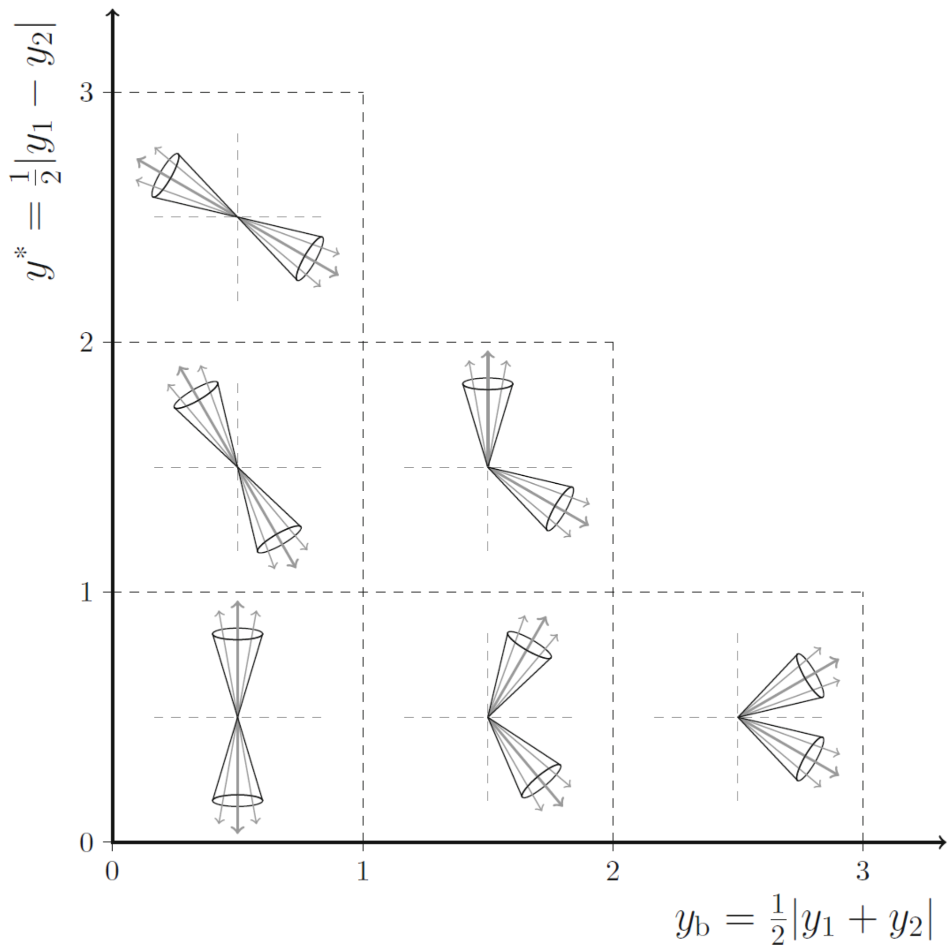
ATLAS:
JHEP 05 (2014) 059; JHEP 05 (2018) 195.
CMS:
PRD 87 (2013) 112002; EPJC 77 (2017) 746.

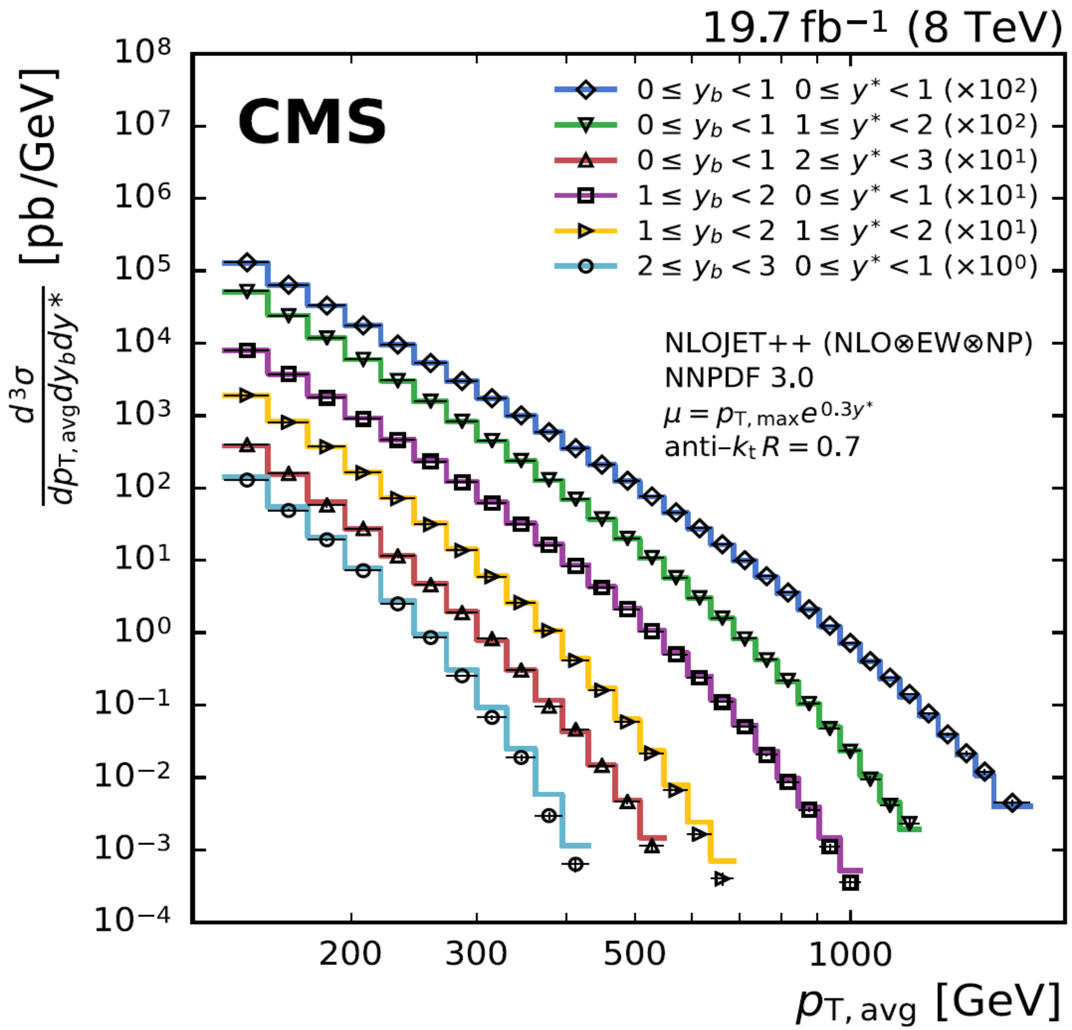
Triple-differential dijets

Most measurements done with respect to dijet mass and either max. rapidity $|y|_{max}$ (CMS) or rapidity separation y^* (ATLAS). One CMS result on $\alpha_s(M_Z)$:

$$\frac{d^3\sigma}{dp_{\mathrm{T,avg}}\,dy_b\,dy^*} \propto \alpha_s^2$$

Illustration of dijet event topologies

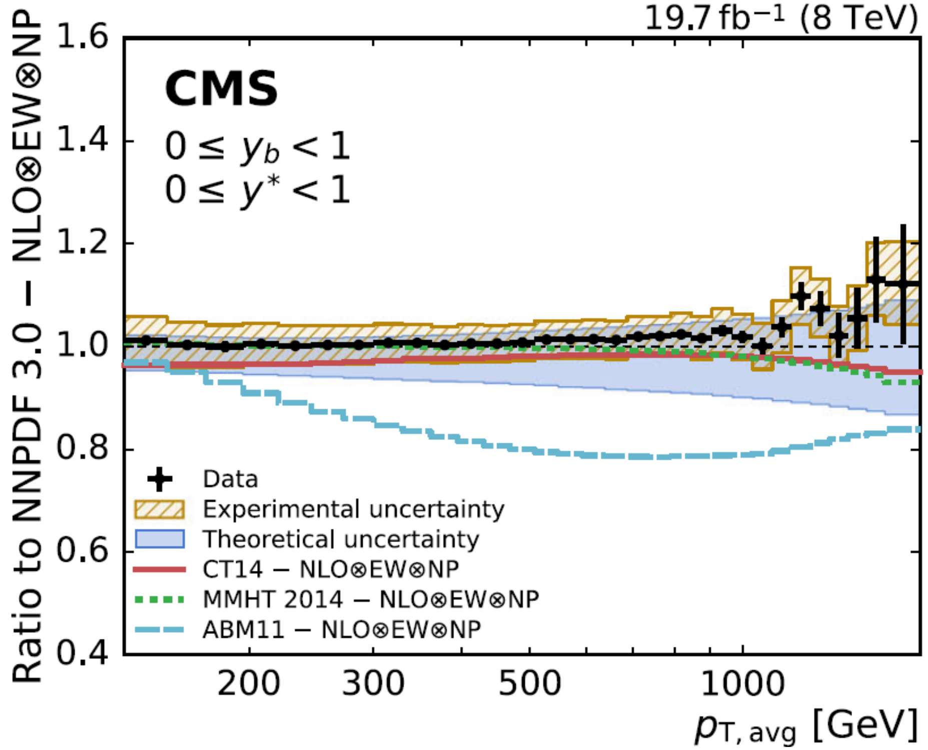




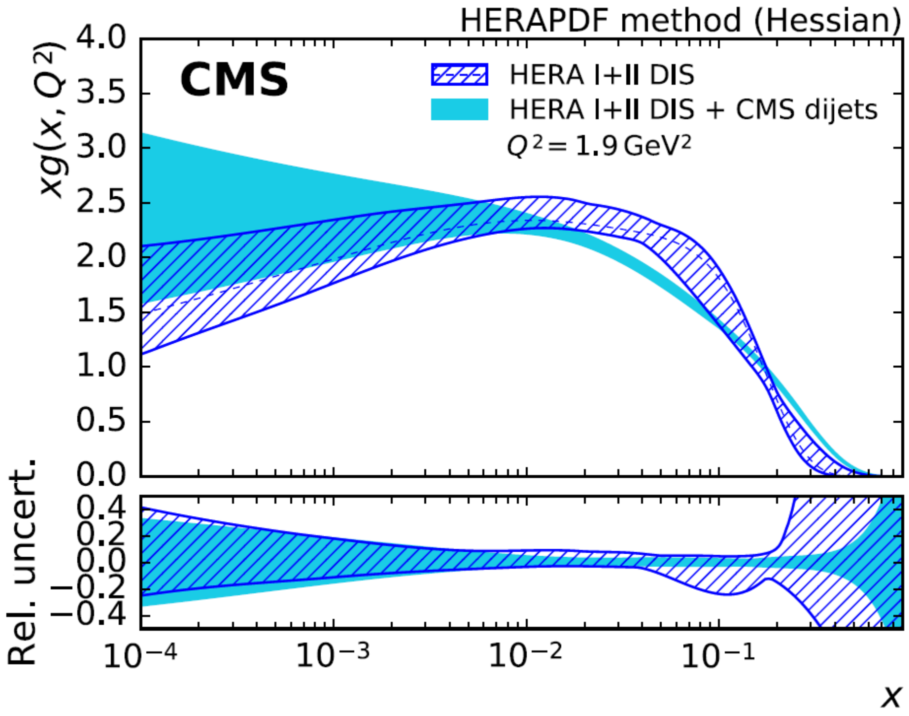
Triple-differential dijets

Simultaneous fit of α_s & PDFs combining HERA DIS & CMS djet data using xFitter Tool

Data over NLO pQCD x non-pert. x EW corrections



Reduced uncertainties of gluon PDF

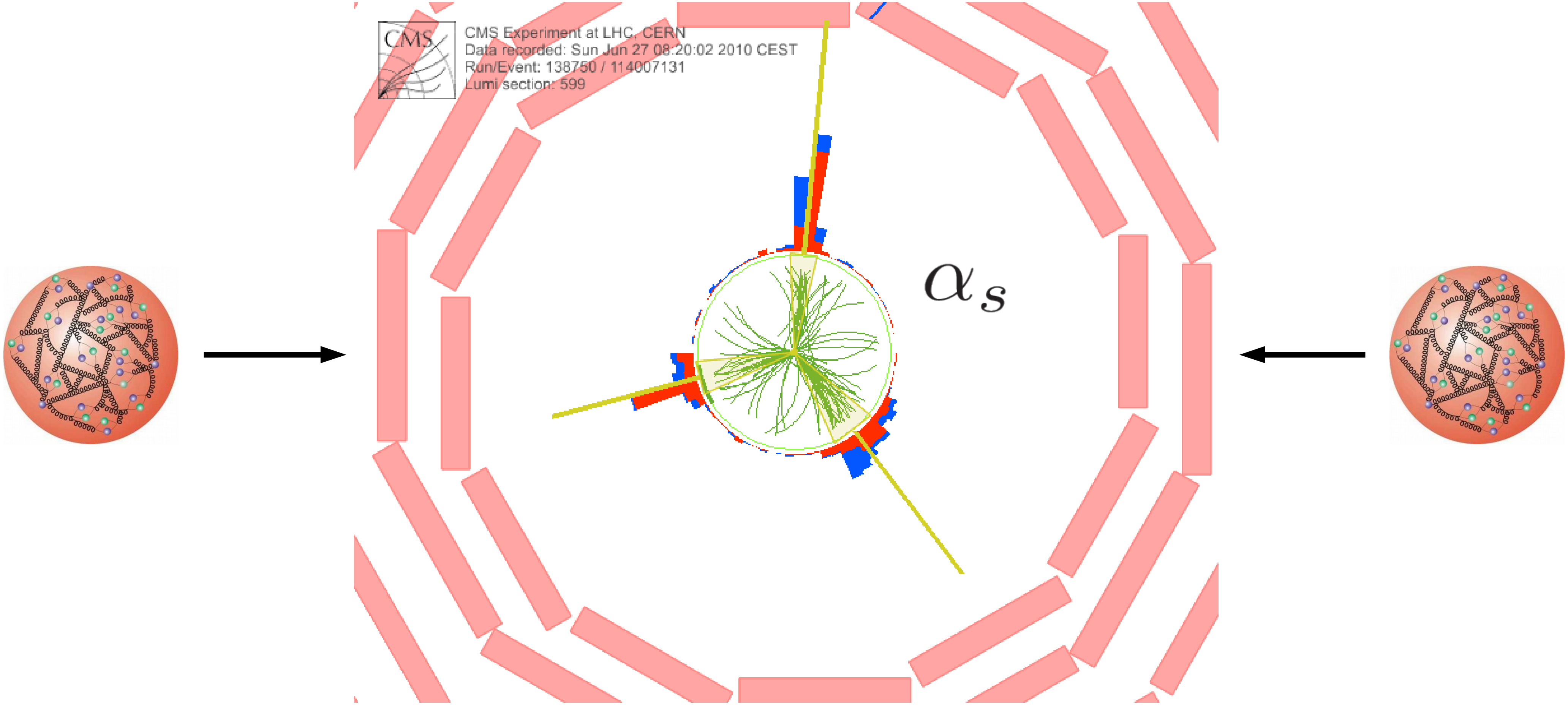


16-parameter fit

$\alpha_s(M_Z)$	exp	PDF	NP	sum	scale
0.1185	19	28	4	35	$^{+53}_{-24}$
0.1164	$^{+14}_{-15}$	$^{+25}_{-29}$	1	$^{+29}_{-33}$	$^{+53}_{-28}$
0.1192	–	–	–	$^{+23}_{-19}$	$^{+24}_{-39}$
0.1185	–	–	–	$^{+19}_{-26}$	$^{+22}_{-18}$
0.1199	–	–	–	$^{+15}_{-16}$	$^{+31}_{-19}$

Multi-jets and α_s

Higher multiplicity



Relevant ATLAS & CMS measurements:

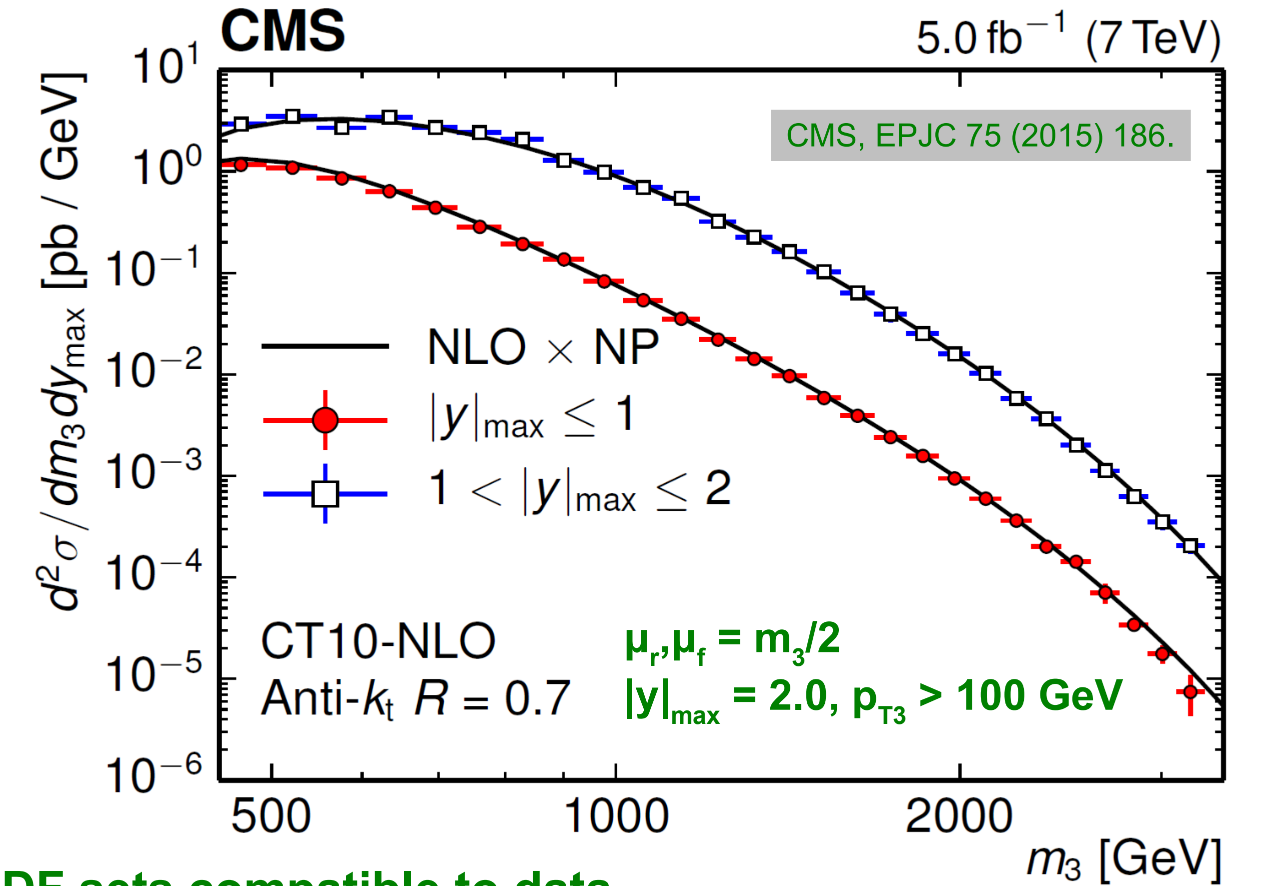
ATLAS:
EPJC 75 (2014) 288.
CMS:
EPJC 73 (2013) 2604; EPJC 75 (2015) 186;
PAS-SMP-16-008 (2017).

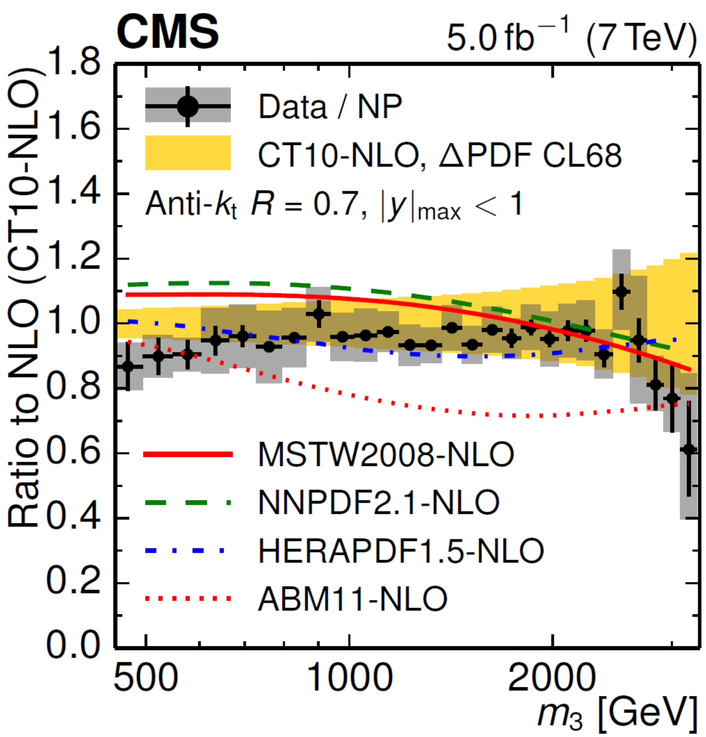
Cross sections ~ α_s^3

- Same as before but:
  - Higher sensitivity
  - Smaller statistical precision
  - Smaller dynamical range
  - More scale choices

3-jet mass

- **Sensitive to α_s beyond 2→2 process**
- **NLO with 3-4 partons (NLOJet++)**
- **Sensitive to PDFs**
- **Involves additional "scale" $p_{T,3}$**





Most PDF sets compatible to data

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

Extraction of $\alpha_s(M_Z)$: → α_s

$\alpha_s(M_Z)$	exp	PDF	NP	scale
0.1171	13	24	8	$^{+69}_{-40}$

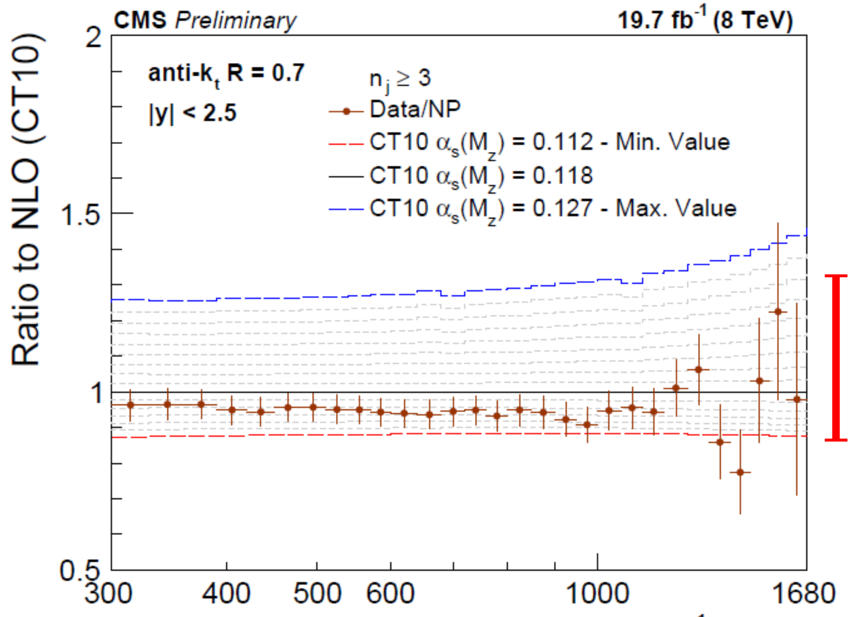
Jet cross section ratios

- Determination of $\alpha_s(M_Z)$ in single-parameter fit
- Test running of $\alpha_s(Q)$ (reduced PDF dependence)
- Some reduction in sensitivity
- But cancellation of many systematic effects
- More scale choices

Sensitivity vs. systematic effects

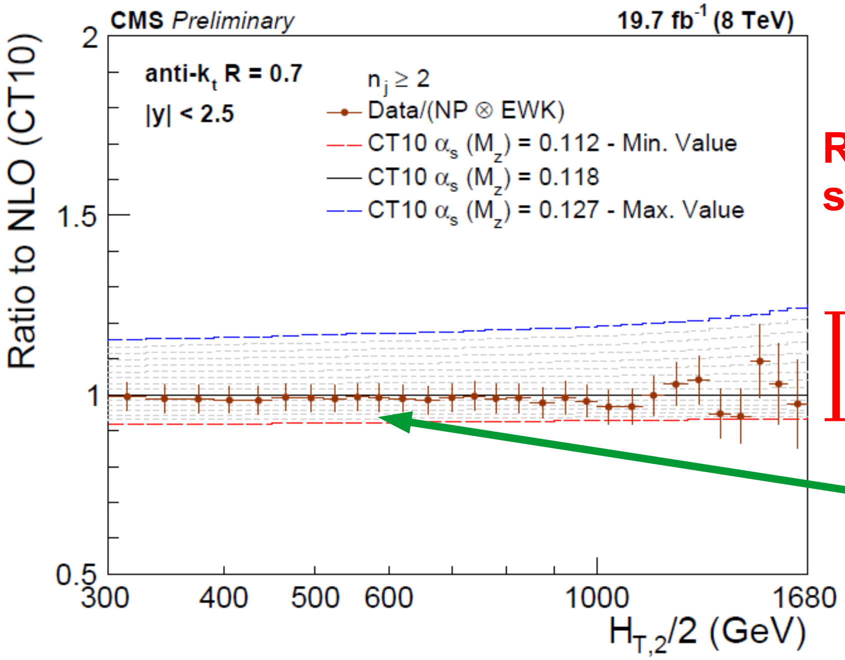
Inclusive 3-jet cross section

$$\sigma_{3j} \propto \alpha_s^3$$



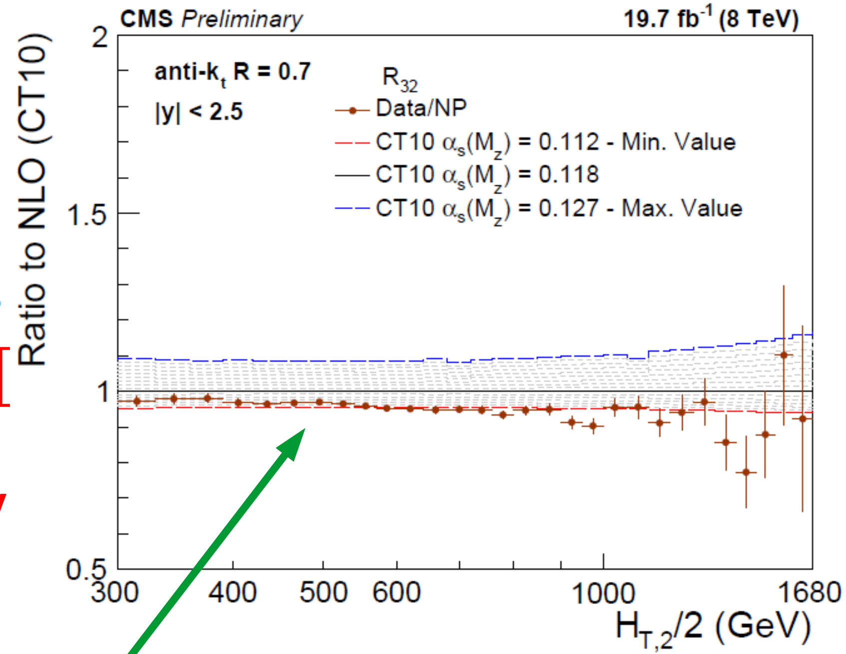
Inclusive 2-jet cross section

$$\sigma_{2j} \propto \alpha_s^2$$



Inclusive 3-jet to inclusive 2-jet cross section ratio

$$R_{3/2} \propto \alpha_s$$

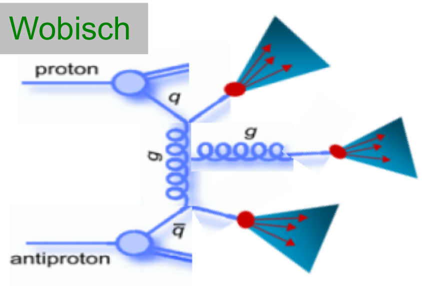


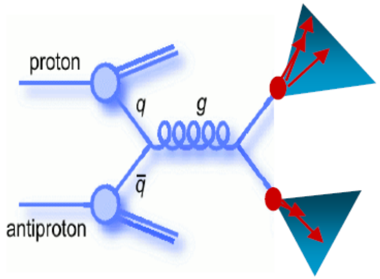
Reduced sensitivity

Much reduced systematic uncertainty

3- to 2-jet ratios

M. Wobisch



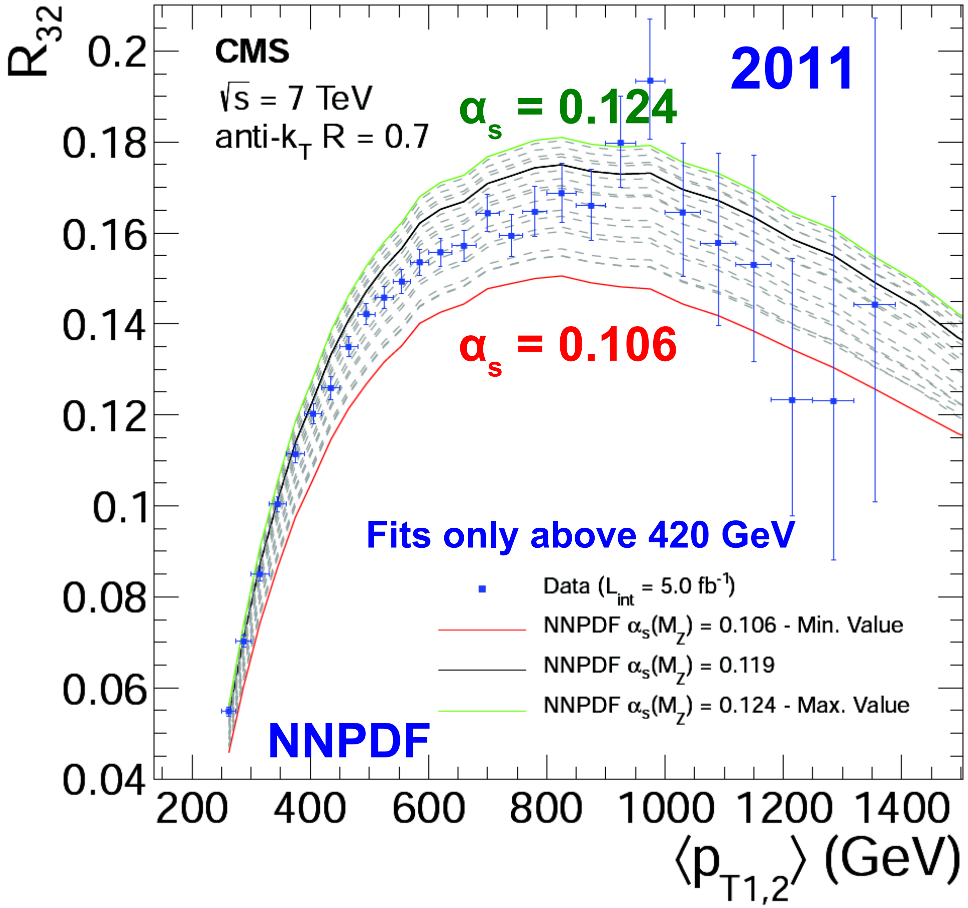


$R_{3/2}$

α_s

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

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



CMS: $R_{3/2}$
- Ratio of inclusive 3- to inclusive 2-jet events
- anti-kT R=0.7
- Min. jet pT: 150 GeV
- Max. rap.: |y| < 2.5
- Data 2011 7 TeV, and 2012 8 TeV prel.

→ α_s

LO+PS → NP

LO+PS & NLO+PS → NP

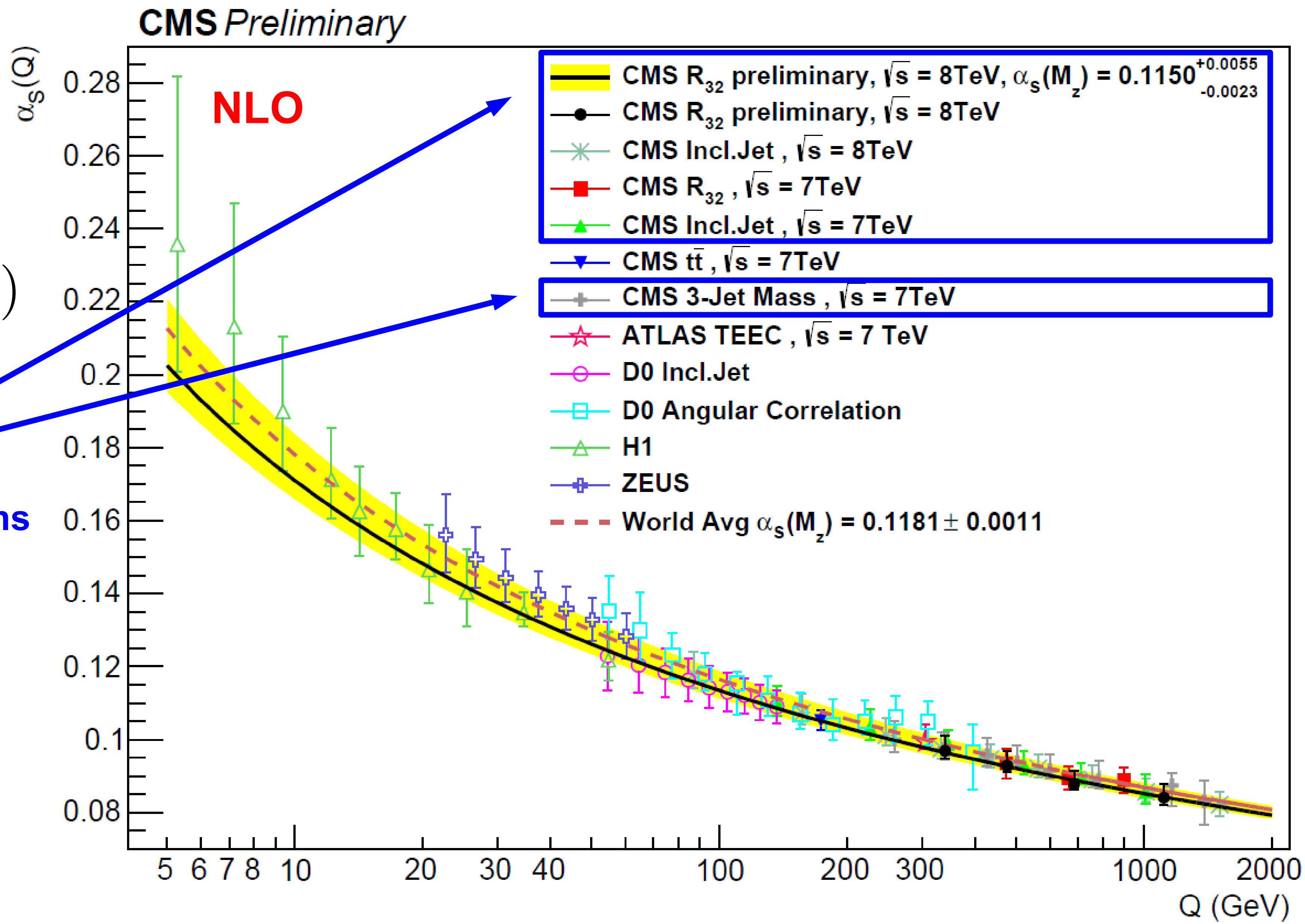
$\alpha_s(M_Z)$	exp	PDF	NP	scale
0.1148	14	18	–	50
0.1150	10	13	15	50

Running of $\alpha_s(Q)$

Perform fits in fixed intervals of the chosen scale Q

➡ $\alpha_s(Q)$

Jet cross sections and ratios



New range explored at LHC →

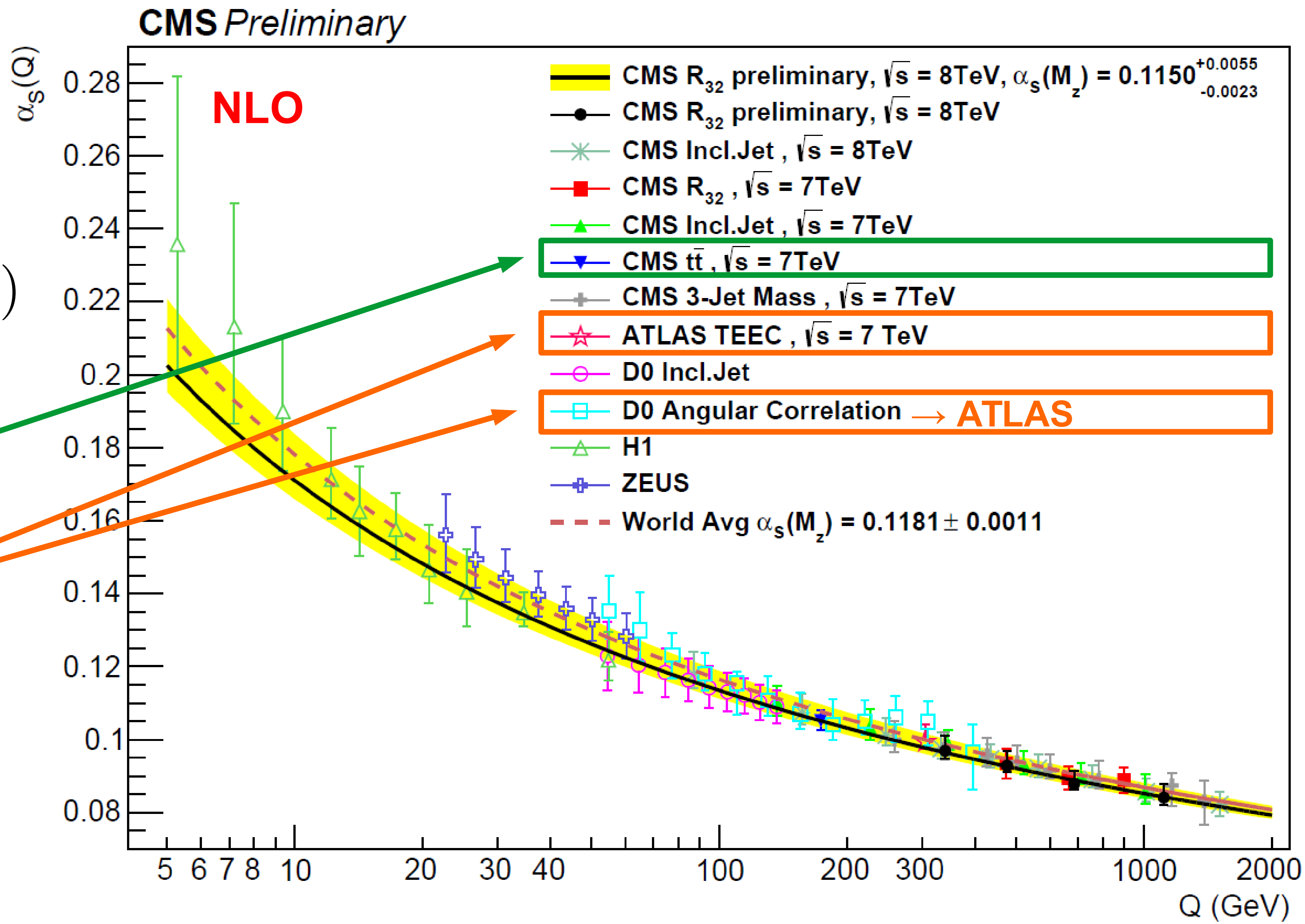
Running of $\alpha_s(Q)$

Perform fits in fixed intervals of the chosen scale Q

→ $\alpha_s(Q)$

ttbar NNLO

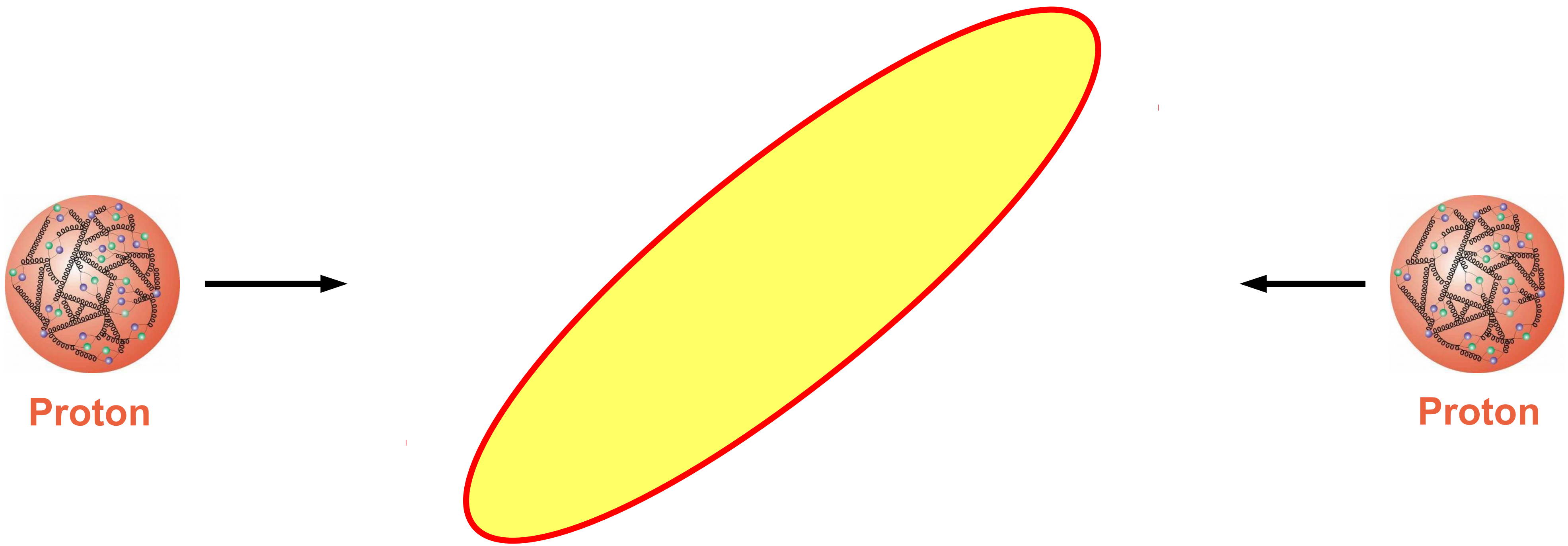
Normalised distributions



New range explored at LHC →

Normalised distributions

Event shapes



Relevant ATLAS & CMS measurements:

ATLAS:
PLB 750 (2015) 427; EPJC 77 (2017) 872; arXiv:1805.04691.

Normalised distributions

Pros & cons similar as for cross section ratios ...

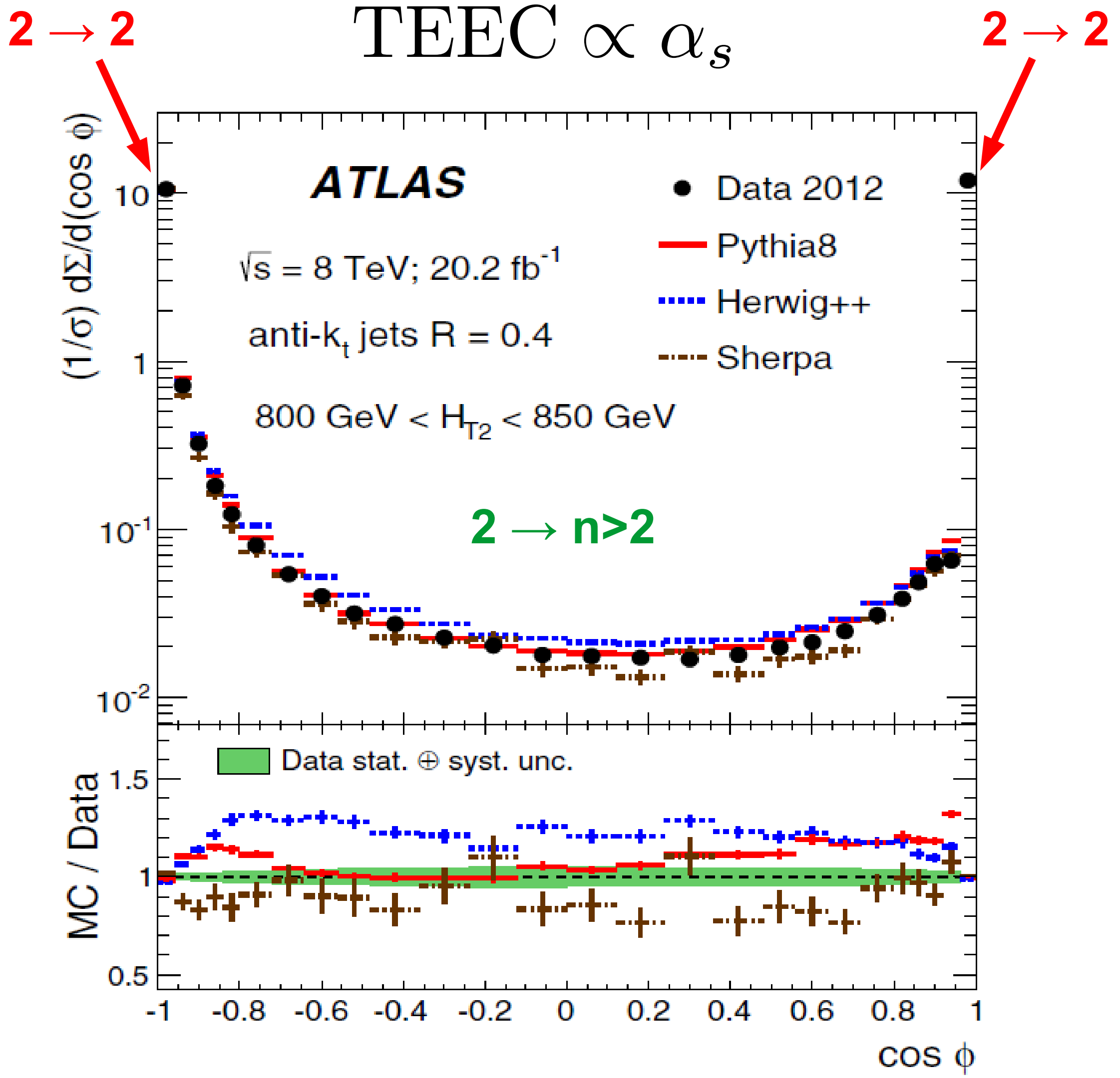
- Determination of $\alpha_s(M_Z)$ in single-parameter fit
- Test running of $\alpha_s(Q)$ (reduced PDF dependence)
- Some reduction in sensitivity
- But cancellation of many systematic effects
- More scale choices

Transverse energy-energy correlation

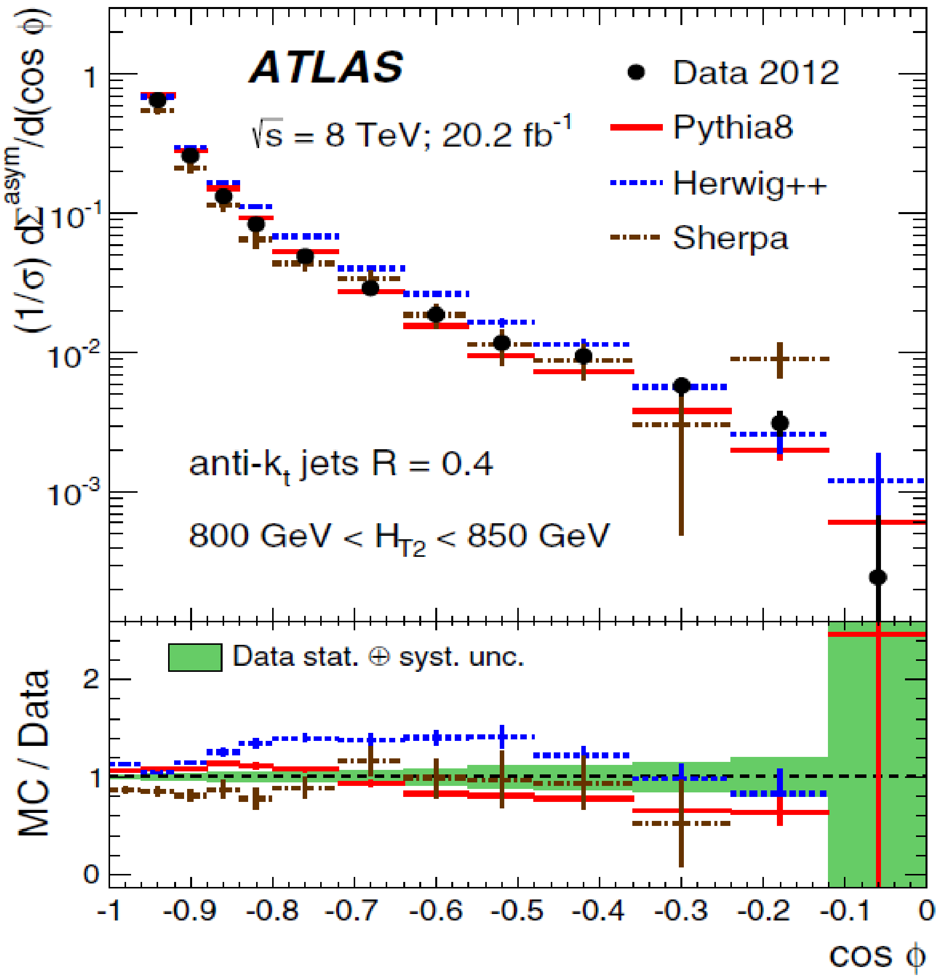
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

$$\frac{1}{\sigma}\frac{d\Sigma^{\mathrm{asym}}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

$\mathrm{TEEC} \propto \alpha_s$



$\mathrm{ATEEC} \propto \alpha_s$



(A)TEEC in bins of $Q = (p_{T1}+p_{T2})/2$

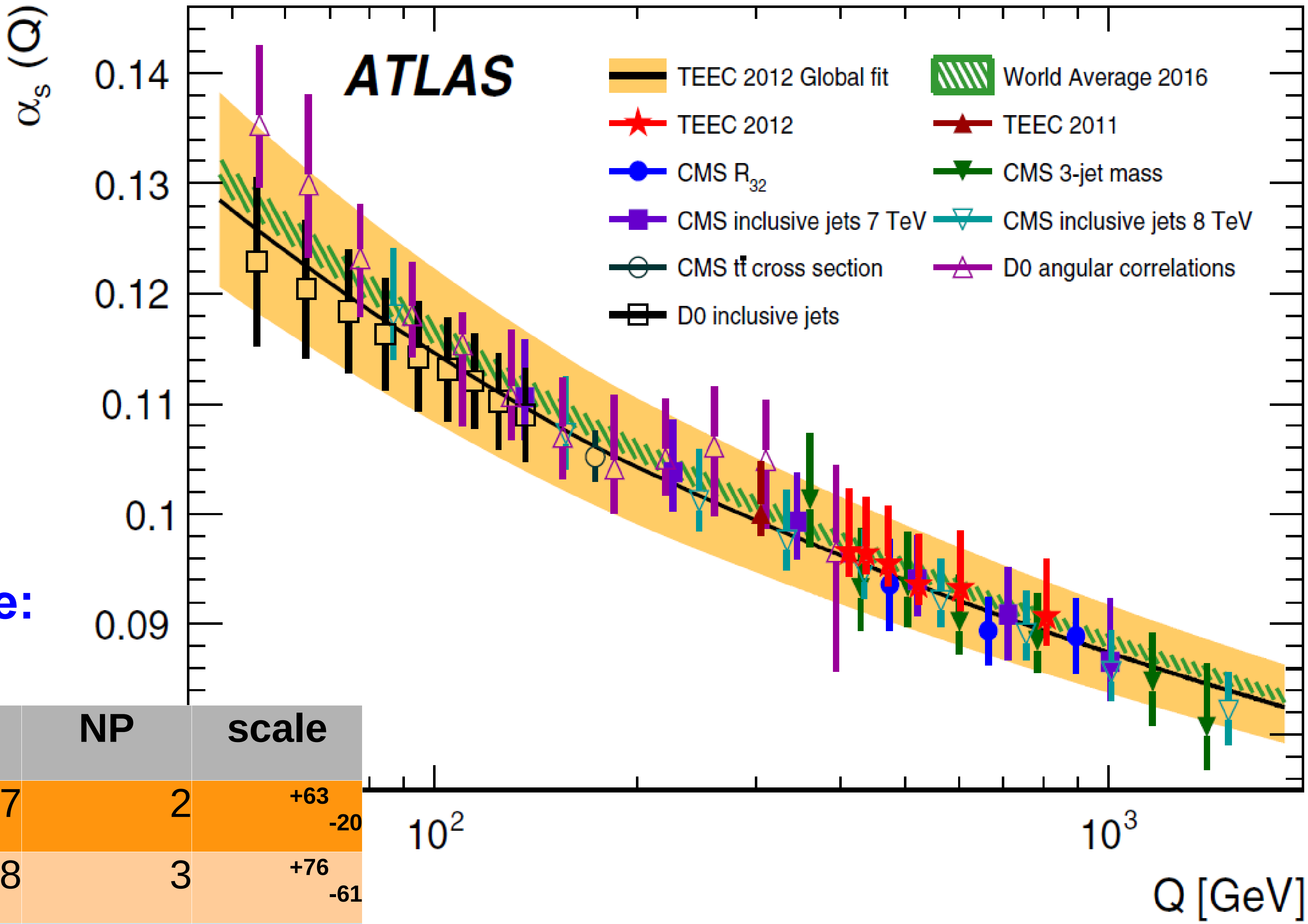
Theory:
3-jet NLOJet++

Scale choice:

2011 7 TeV:
$\mu_R = \mu_F = (p_{T1}+p_{T2})/2$

2012 8 TeV:
$\mu_R = (p_{T1}+p_{T2})/2$
$\mu_F = (p_{T1}+p_{T2})/4$

Darker / lighter shade:
7 TeV / 8 TeV



$\alpha_s(M_Z)$	exp	PDF	NP	scale
0.1173	10	17	2	$^{+63}_{-20}$
0.1162	11	18	3	$^{+76}_{-61}$
0.1195	18	16	0	$^{+60}_{-15}$
0.1196	13	17	4	$^{+61}_{-13}$

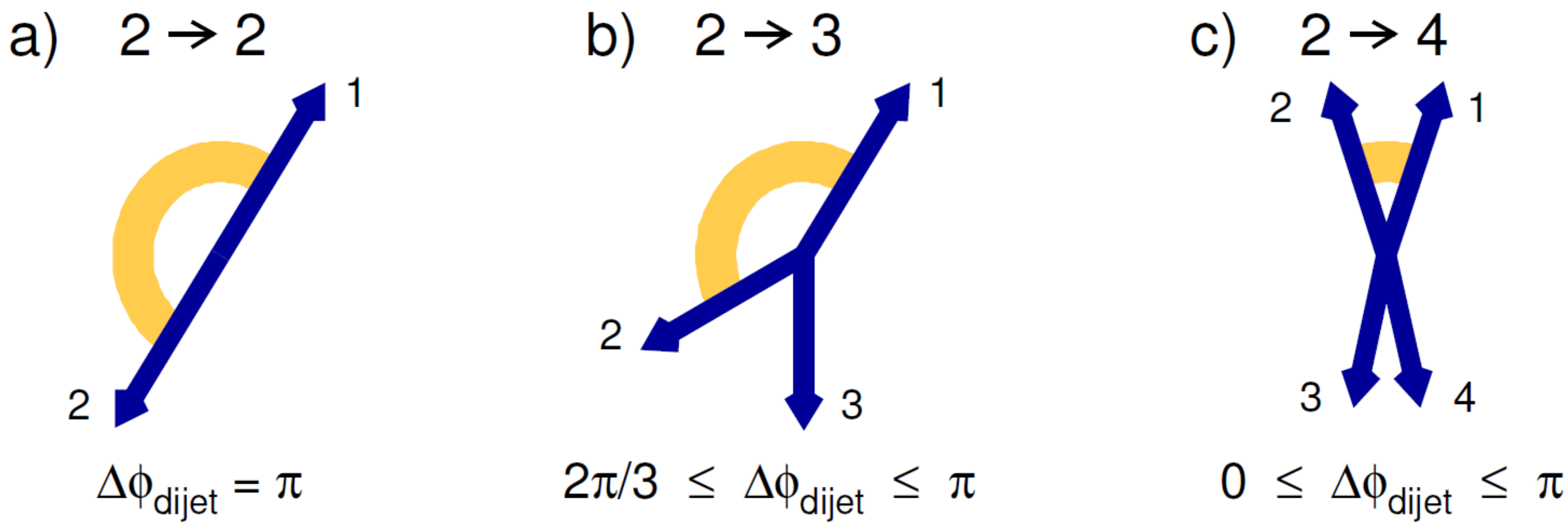
Orange: TEEC
Blue: ATEEC

Dijet azimuthal decorrelation

Determine $\alpha_s(Q)$ from additonal parton branchings separated in Φ around the two leading jets.
Binning in sum of scalar transverse momentum H_T and rapidity separation y^*.

$$R_{\Delta\phi}(H_T, y^*; \Delta\phi_{\max}) = \frac{\frac{d^2\sigma_{\text{dijet}}(\Delta\phi_{\text{dijet}} < \Delta\phi_{\max})}{dH_T dy^*}}{\frac{d^2\sigma_{\text{dijet}}(\text{inclusive})}{dH_T dy^*}}$$

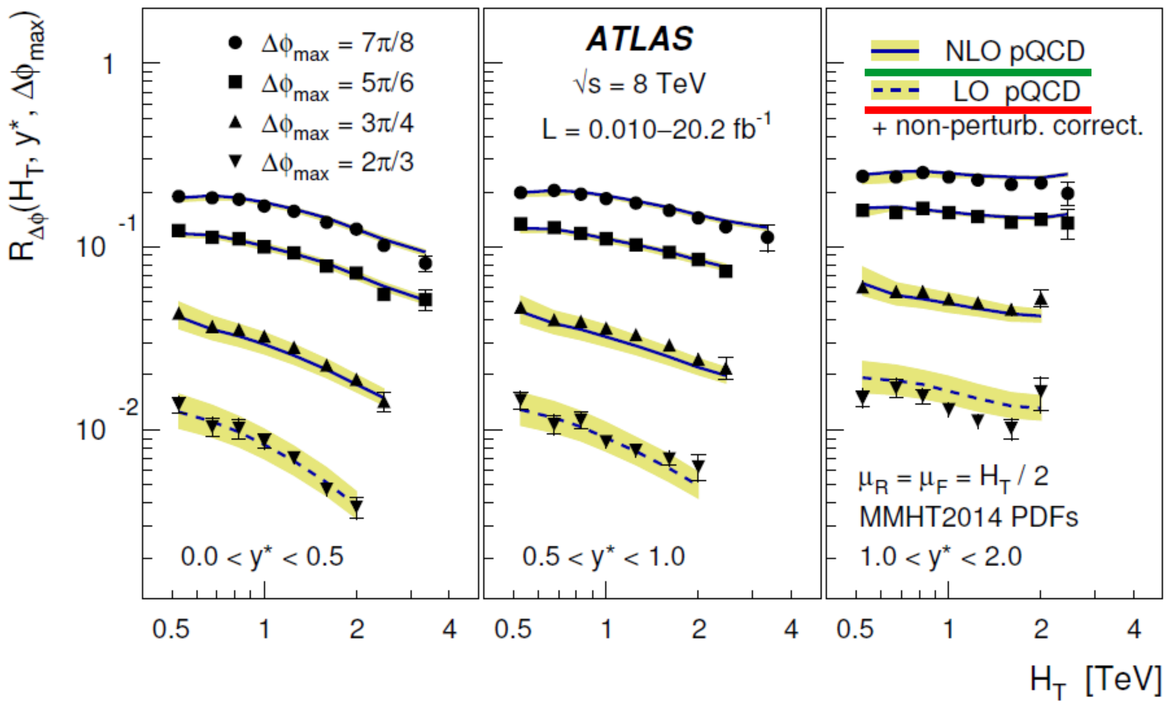
$$R_{\Delta\phi} \propto \alpha_s$$



If $\Delta\varphi_{max}$ in 3-jet region

Wobisch et al., JHEP 01 (2013) 172;
KR, M. Wobisch, JHEP 12 (2015) 024.

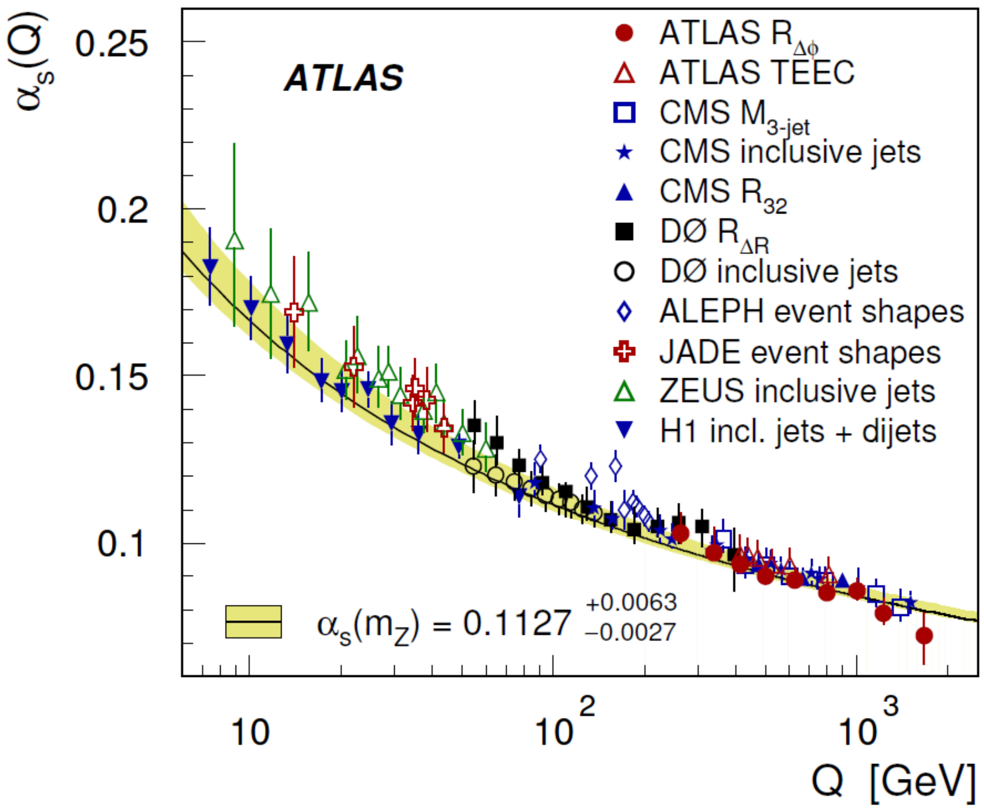
$R_{\Delta\phi}$ in bins of $Q = H_T/2$



Theory:

3-jet NLOJet++

Scale choice: $\mu_R = \mu_F = H_T/2$

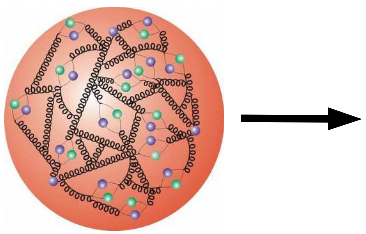


From more precise results with
$\Delta\varphi_{max} = 7\pi/8$ in the two y* regions below 1.0:

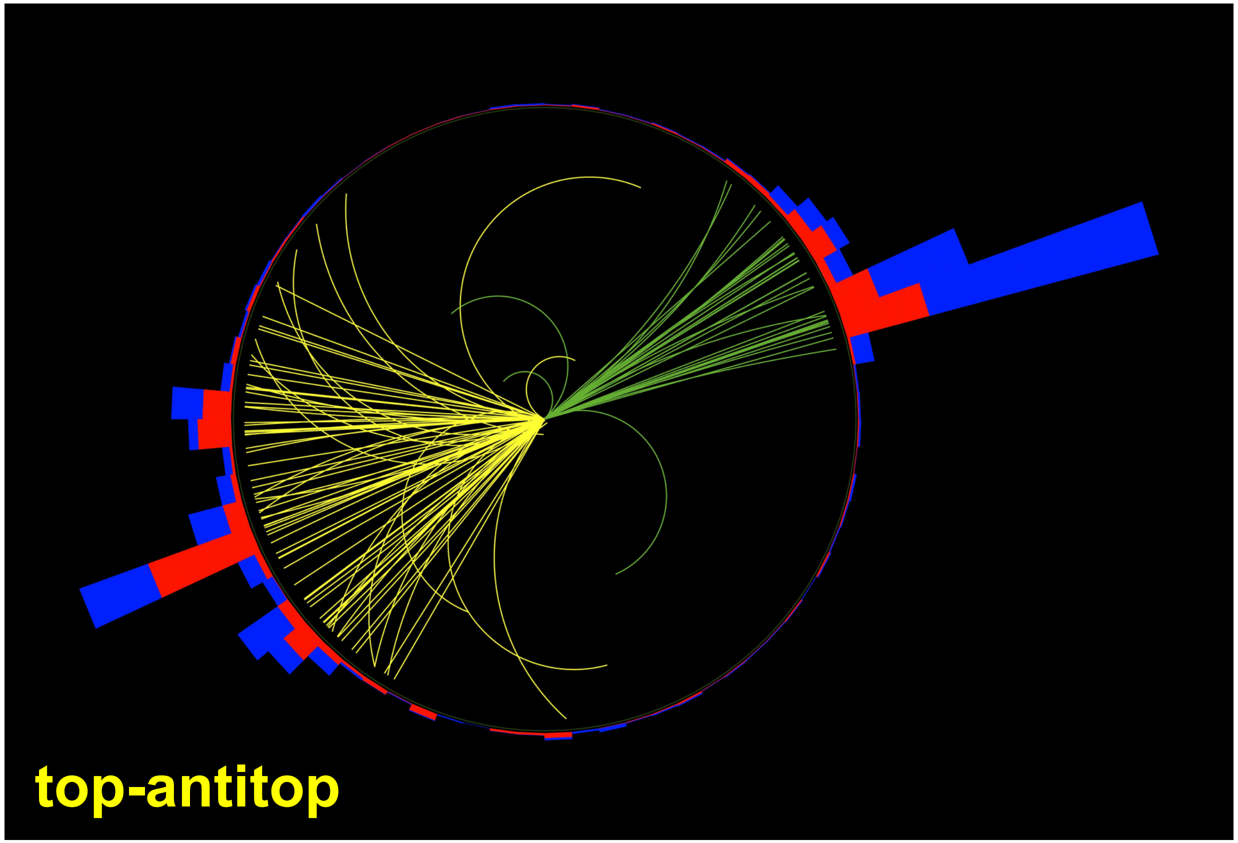
$\alpha_s(M_Z)$	exp	PDF	NP	scale
0.1127	$^{+19}_{-18}$	$^{+30}_{-6}$	$^{+3}_{-1}$	$^{+52}_{-19}$

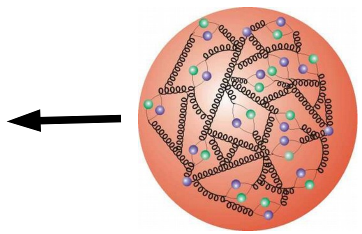
Heavy stuff

Heavy quarks



Proton





Proton

Relevant ATLAS & CMS measurements:

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

top-antitop production

- **Theory at NNLO or NNLO+NNLL!**
- **Determination of $\alpha_s(M_Z)$ correlated with M_{top} (and gluon like for jets)**
- **What top mass? Pole? MS_{bar}?**
- **Top measurements already in PDF?**

Fits with top-quark pair production

Top-pair production is especially sensitive to:

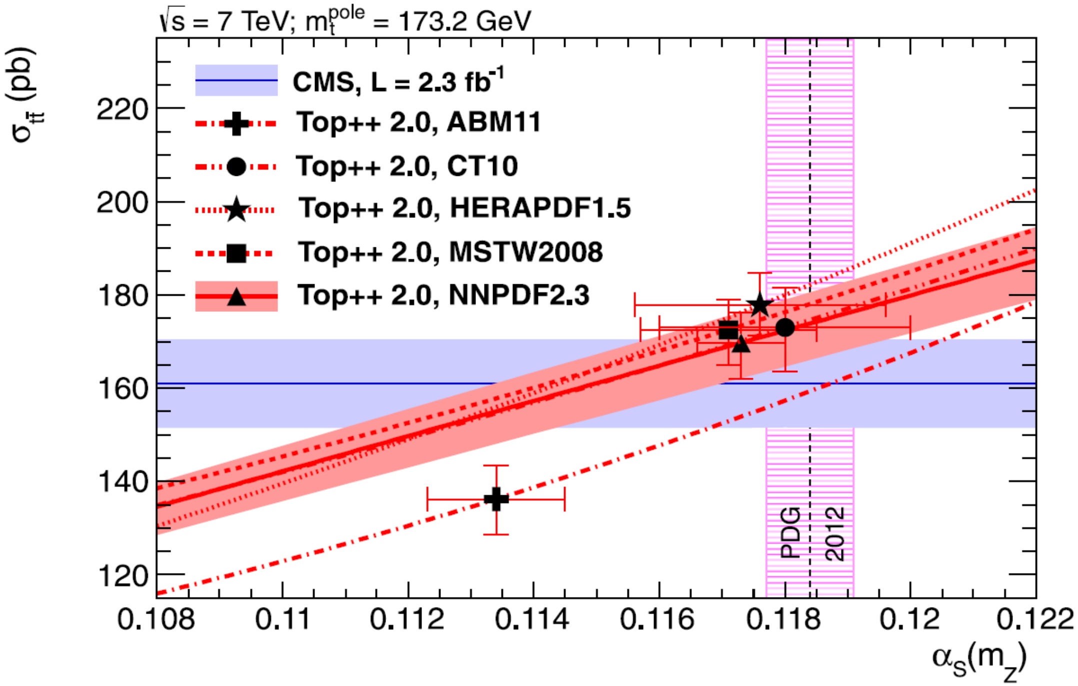
m_t^{pole} and α_s and $g(x,\mu_f^2)$ as the main production process at LHC is from gg

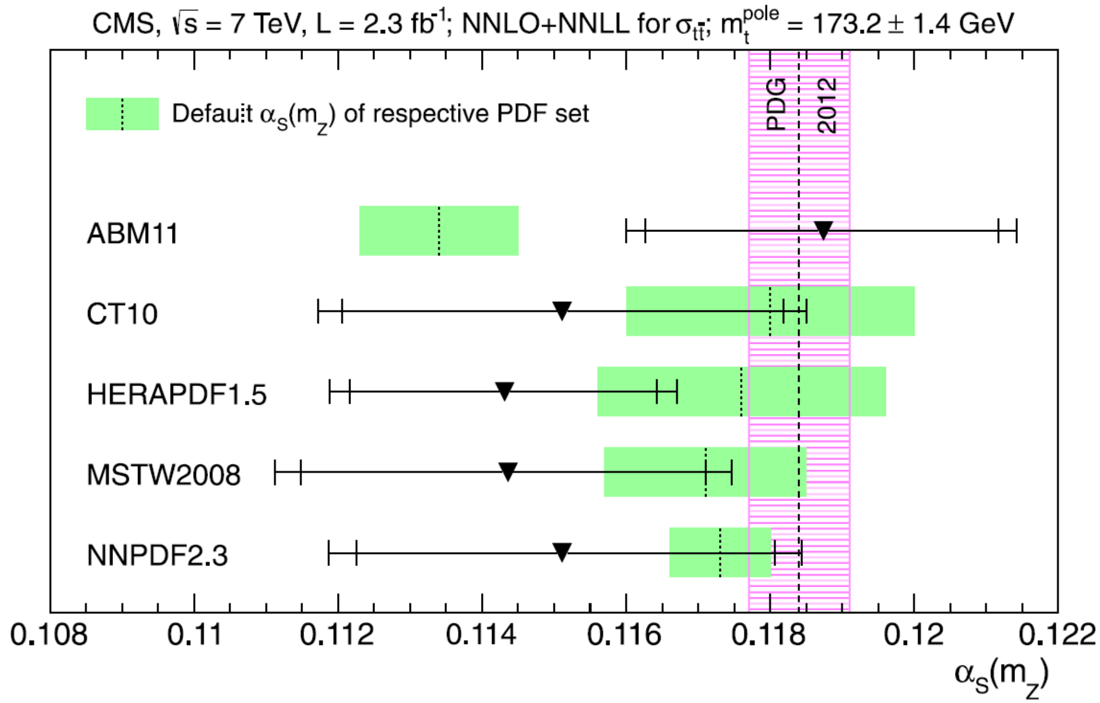
Using only the ttbar cross section measurement (dilepton channel) combined fits are not possible. Fixing the gluon to one of 5 PDF sets, however, it is possible to extract m_t^{pole} while fixing α_s or vice versa.

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

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

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





Combining LHC & Tevatron data

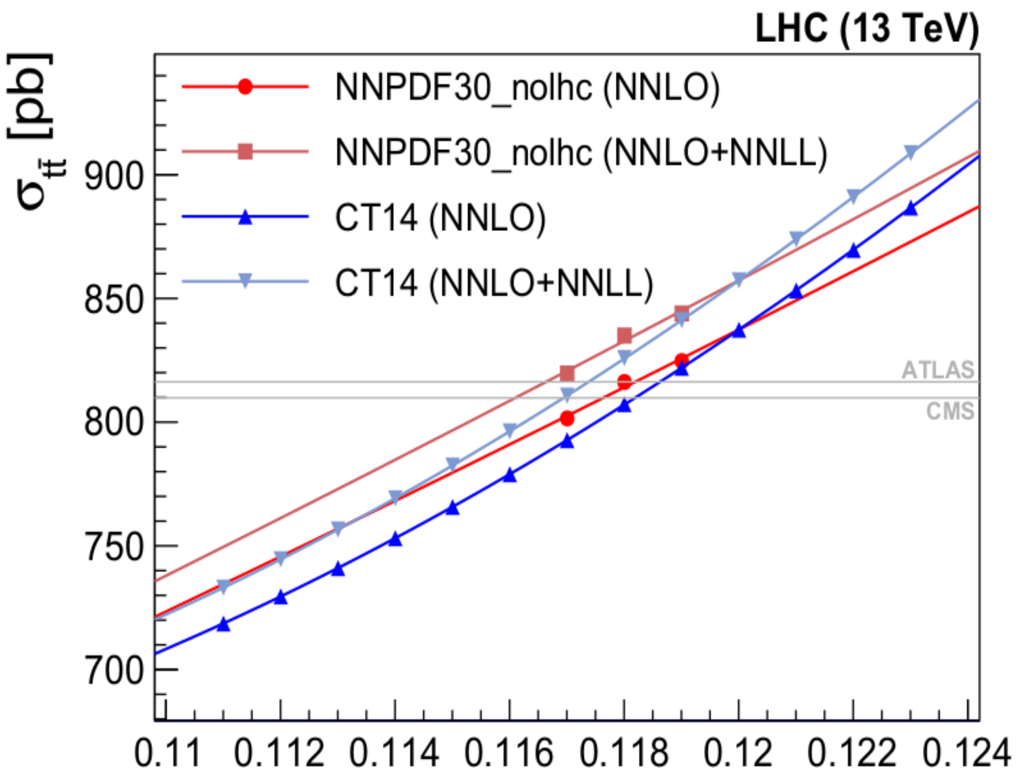
- fitting procedure similar to CMS; more conservative scale dependence treatment
- combines results using NNLO or NNLO+NNLL for theory prediction
- updated and complemented set of ttbar cross section measurements from LHC
- includes Tevatron results
- consideration of correlations among measurements
- combine results only from PDF sets without ttbar data (CT14nnlo, NNPDF30_nolhc)

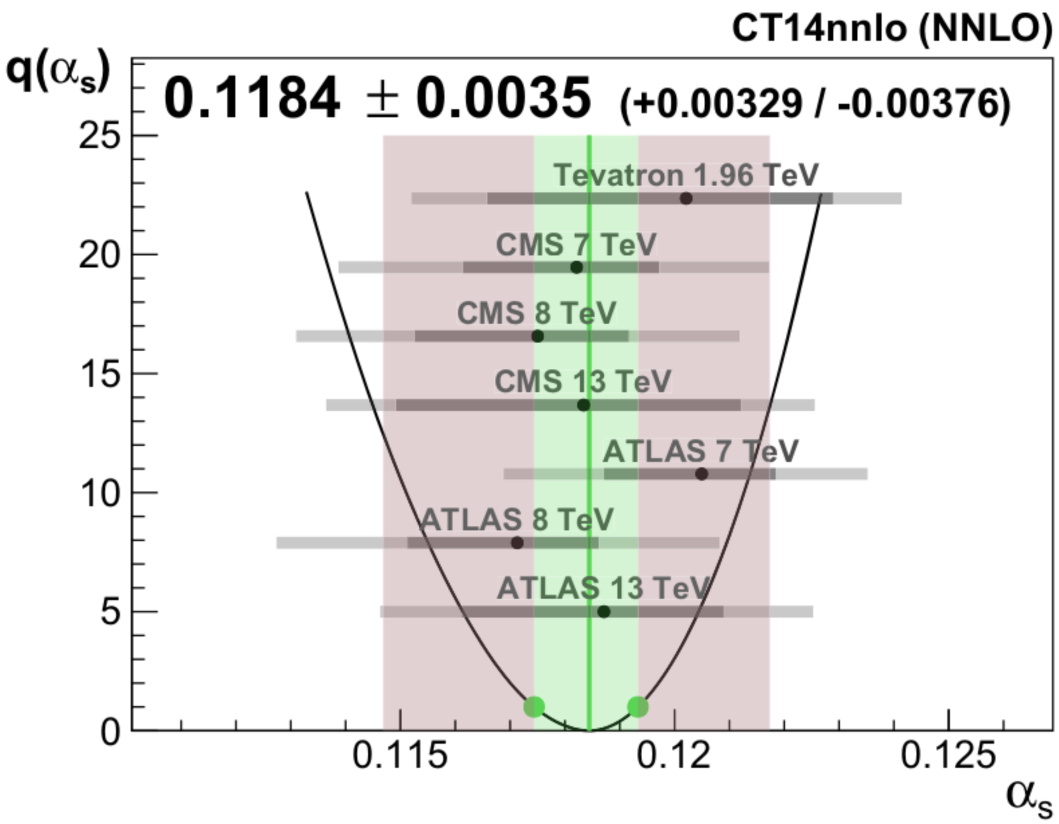
Datasets:

	$\sigma_{t\bar{t}}$ (pb)	Statistical unc. (%)	Systematic unc. (%)	Luminosity unc. (%)	E_{beam} unc. (%)	Exp. m_t unc. (%)
ATLAS (7 TeV) [16]	182.5	1.7	2.3	2.0	0.3	$^{-0.2}_{+0.2}$
ATLAS (8 TeV) [16]	242.4	0.7	2.3	2.1	0.3	$^{-0.2}_{+0.2}$
ATLAS (13 TeV) [17]	816.3	1.0	3.3	2.3	0.2	$^{-0.3}_{+0.3}$
CMS (7 TeV) [13]	173.4	1.2	2.5	2.2	0.3	$^{-0.2}_{+0.2}$
CMS (8 TeV) [13]	244.1	0.6	2.4	2.6	0.3	$^{-0.4}_{+0.4}$
CMS (13 TeV) [14]	809.8	1.1	4.7	2.3	0.2	$^{-0.8}_{+0.8}$
Tevatron (1.96 TeV) [18]	7.52	2.7	3.9	2.8	0.0	$^{-1.1}_{+1.4}$

Bethke et al., NPPP 282-284 (2017) 139.

Combining LHC & Tevatron data





No LHC top data in NNPDF3_nolhc or CT14

Bias between NNLO & NNLO+NNLL ...

	$\alpha_s(M_Z)$	exp	lumi	E_{beam}	M_{top}	PDF	scale
CMS, NNLO+NNLL, NNPDF2.3	0.1151	25	←	8	13	$^{+13}_{-11}$	$^{+9}_{-8}$
LHC+Tev., NNLO | NNLO+NNLL	0.1177	8	$^{+6}_{-7}$	1	$^{+12}_{-13}$	$^{+20}_{-24}$	$^{+22}_{-21}$

Bethke et al., NPPP 282-284 (2017) 139.

V+jets production

- Very precisely measurable, in particular in leptonic decay modes
- NNLO available for V and V+1jet
- NLO available for up to V+4/5jets
- Not used so far for $\alpha_s(M_Z)$ or $\alpha_s(Q)$ by LHC experiments

New study of published ATLAS data on inclusive Z+2/3/4 jet observables @ NLO for extraction of $\alpha_s(M_Z)$!

(No ratios [n+1]/n though ...)

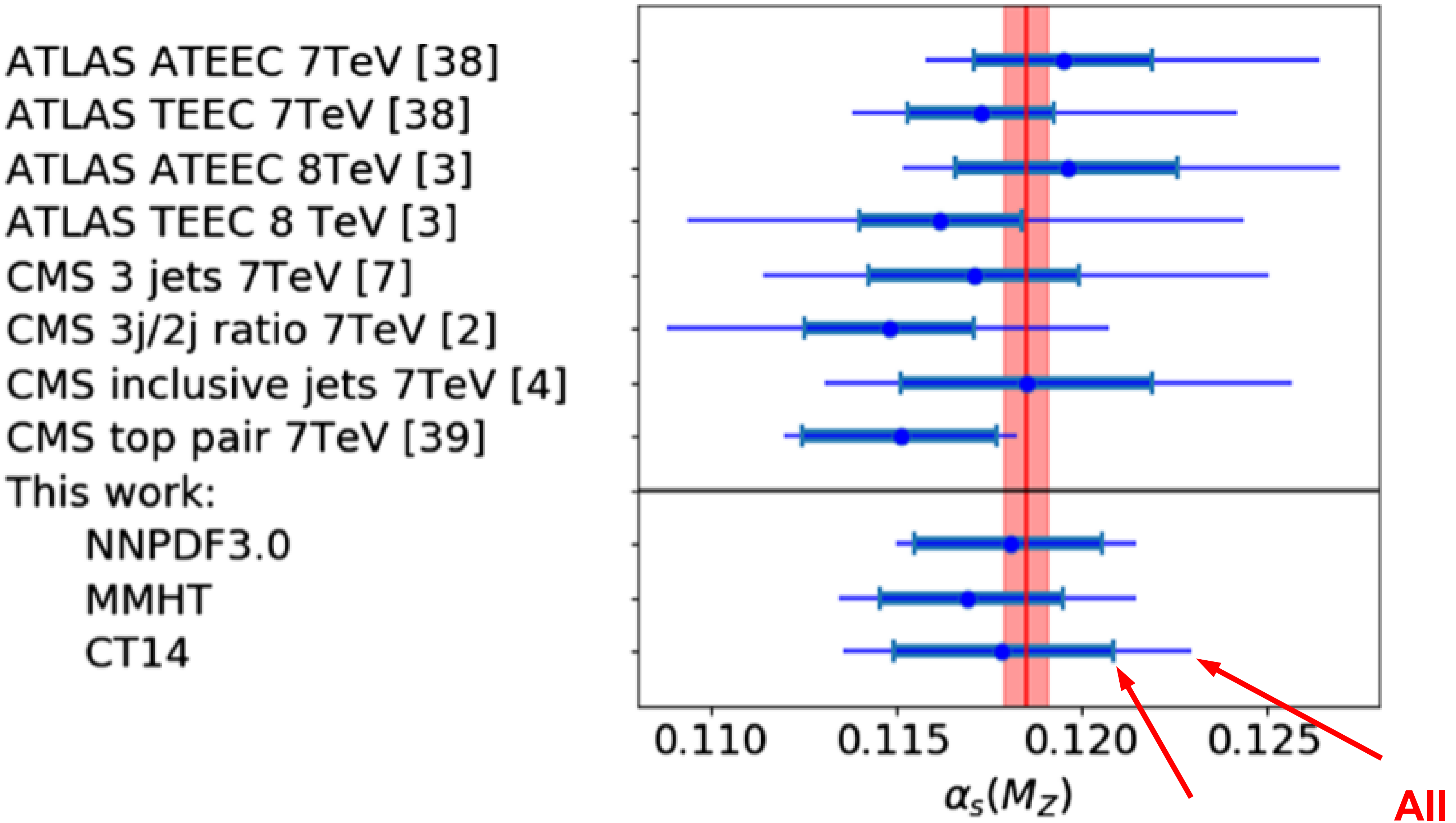
For more details on α_s (M_Z) from Z production:
→ Talks on Tuesday by
– Daniel Maître (Z+jets)
– Stefano Camarda (Z pT, CDF)

TABLE I. Observables and labels for the fits.

Label	Observable(s)
all	Combination of all histograms
2j, incl	Combination of the transverse momentum and rapidity of the second jet for the two-jet inclusive sample
3j, incl	Combination of the transverse momentum and rapidity of the third jet for the three-jet inclusive sample
4j, incl	Combination of the transverse momentum and rapidity of the fourth jet for the four-jet inclusive sample
all y	Combination of all the rapidity distributions
all $p^\perp$	Combination of all three transverse momentum distributions
y_i	Rapidity for the i-jet inclusive sample
$p_i^\perp$	Transverse momentum for the i-jet inclusive sample

M. Johnson, D. Maitre, PRD 97 (2018) 054013.

Z+2/3/4jets production



Scale dependence & NP effects evaluated with "standard" method & profile X2 resp. nuisance parameter

M. Johnson, D. Maitre, PRD 97 (2018) 054013.

Issues & uncertainties

- Correlations to LHC data already in PDF fits
- Correlations between $\alpha_s(M_Z)$, M_{top}, g(x)
- (Gu)estimation of nonperturbative effects:
  - Different event generators & tunes, different orders, different ...
  - Incoherent among ATLAS, CMS, Tevatron, …
- Conventional scale variation by factors of ½, 2 and 1σ assumption
- Central scale choice …!

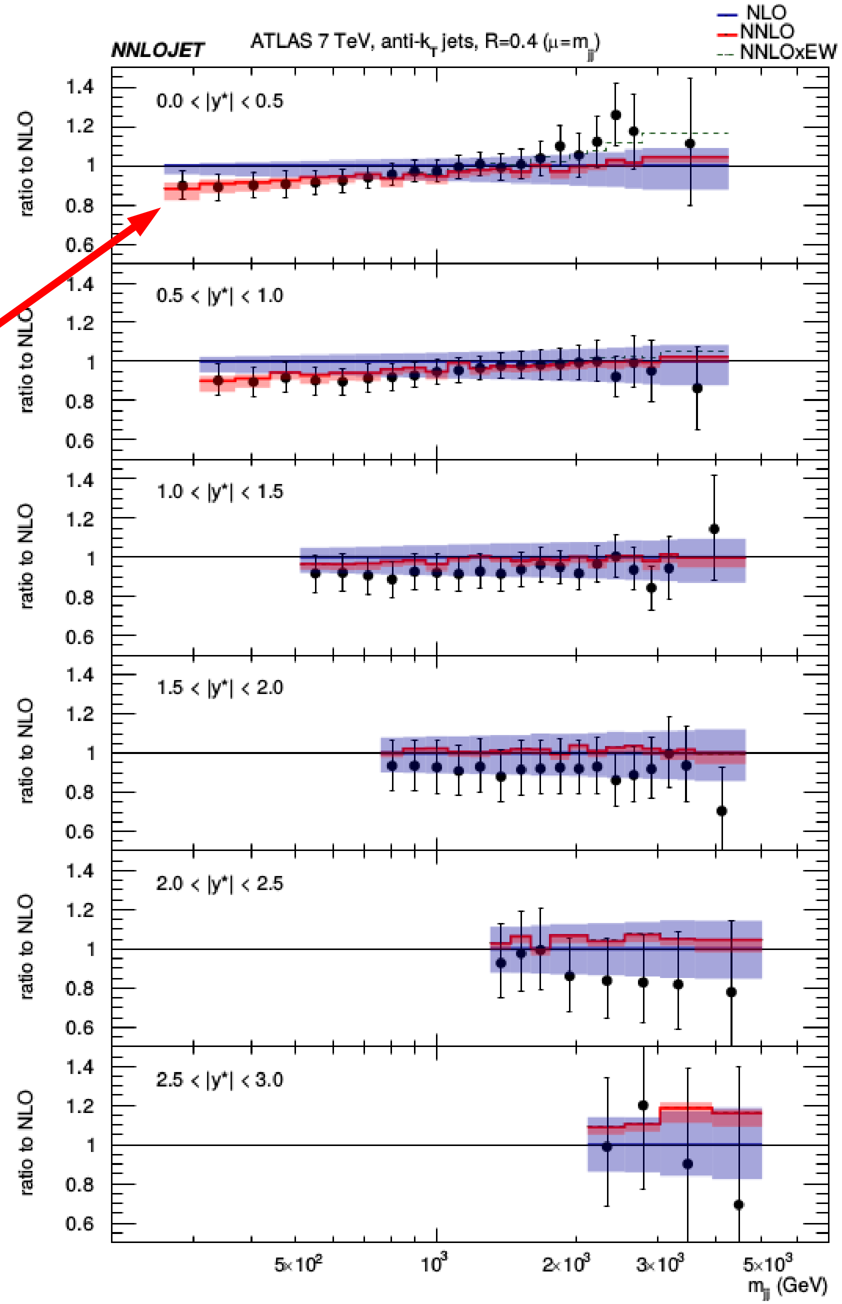
Scale choices

- **Inclusive jets** $\mu_0 = p_{\mathrm{T},1}, \quad p_{\mathrm{T,jet}}, \quad \hat{H}_{\mathrm{T}}?$
- **Dijets** $\mu_0 = p_{\mathrm{T},1}, \quad p_{\mathrm{T},1} \cdot \exp\left(0.3y^*\right)?$
  $\mu_0 = \left(p_{\mathrm{T},1} + p_{\mathrm{T},2}\right)/2, \quad m_{jj}/2?$
- **3-jets** $\mu_0 = p_{\mathrm{T},3}, \quad \left(p_{\mathrm{T},1} + p_{\mathrm{T},2}\right)/2, \quad m_{jjj}/2?$
- **Ratios**
- **Shapes**
- **V+jets** $\mu_0 = \sqrt{M_Z^2 + p_{\mathrm{T}Z}^2} + H_{\mathrm{T,jet}}?$

Dijets

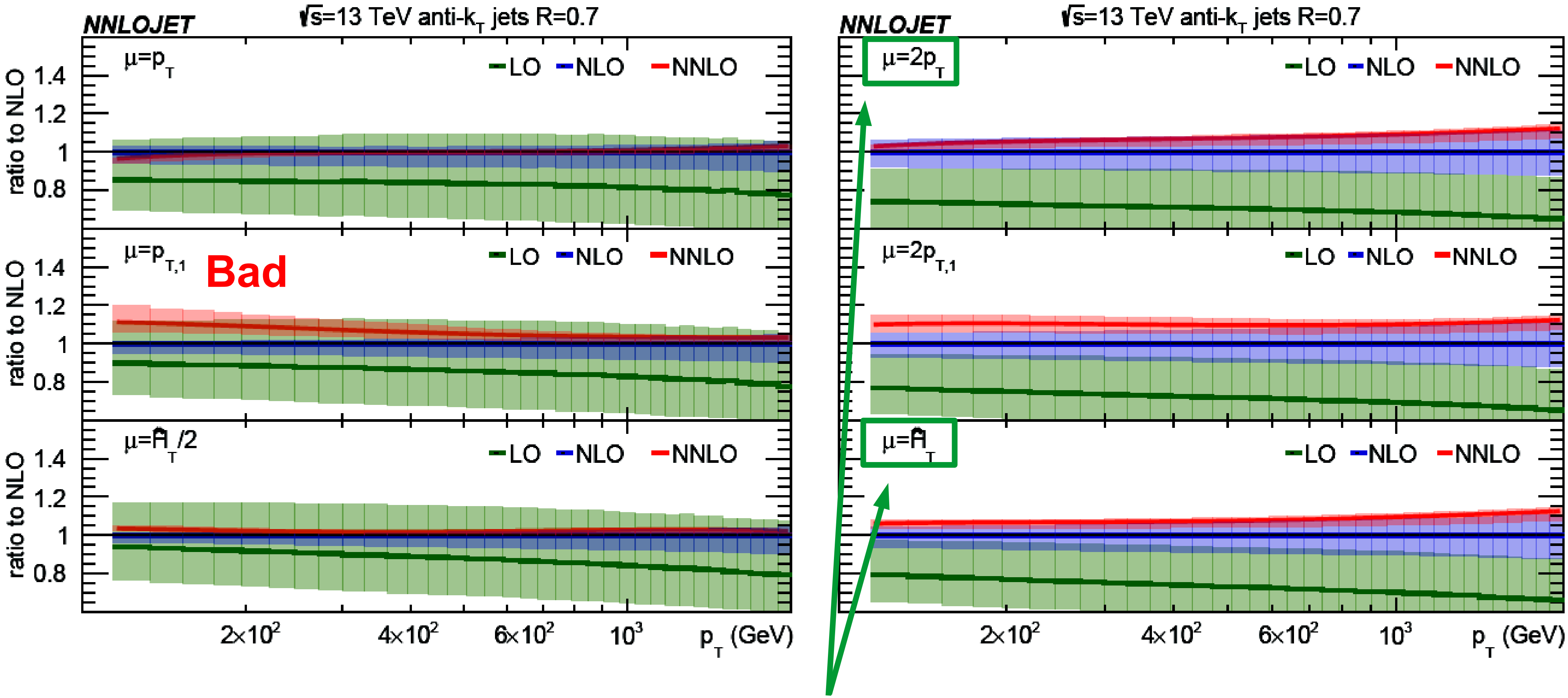
Good description of dijets with NNLO and m_{jj} as scale choice!

NNLO



Dijets: Currie et al., PRL 119 (2017) 152001;
Incl. Jets: Currie et al., arXiv:1807.03692..

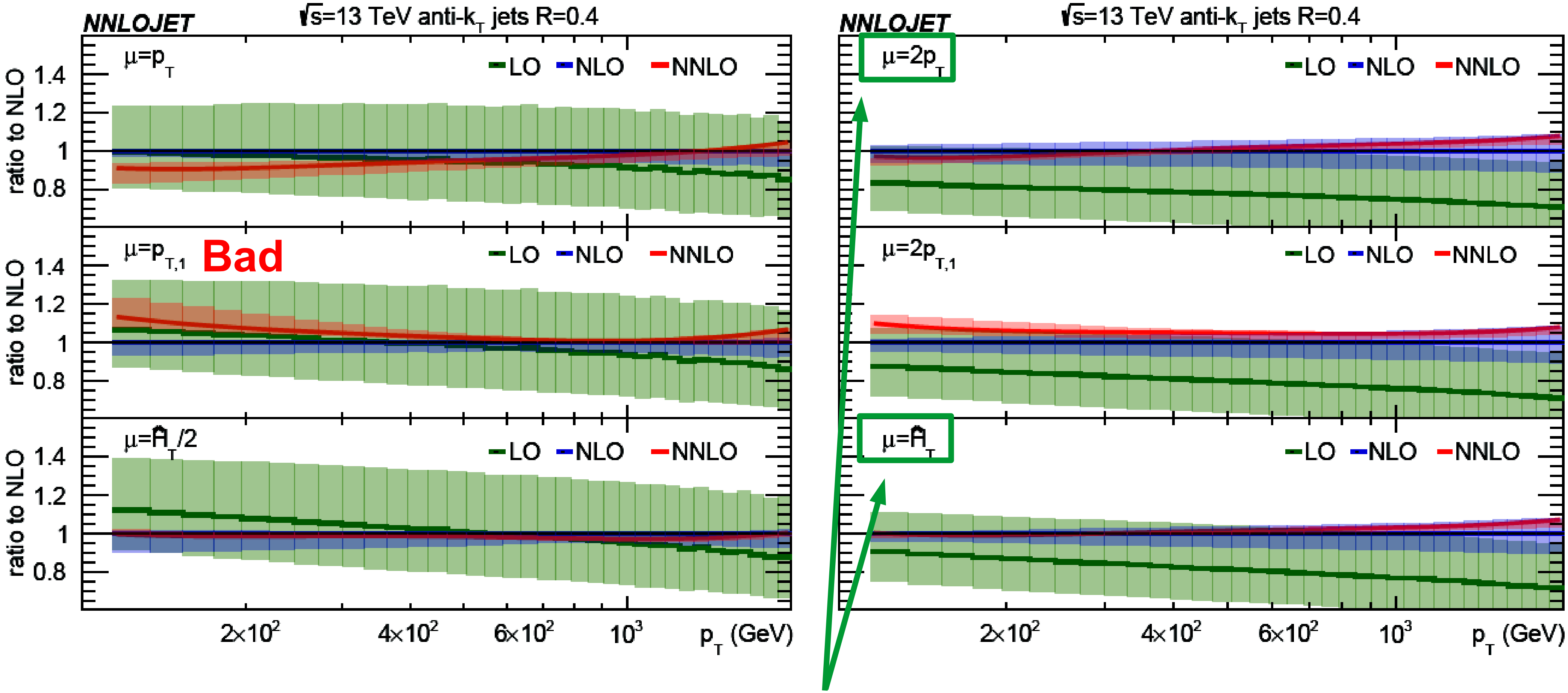
Inclusive jets, R = 0.7



Favored by authors

Dijets: Currie et al., PRL 119 (2017) 152001;
Incl. Jets: Currie et al., arXiv:1807.03692..

Inclusive jets, R = 0.4



Favored by authors

Dijets: Currie et al., PRL 119 (2017) 152001;
Incl. Jets: Currie et al., arXiv:1807.03692..

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

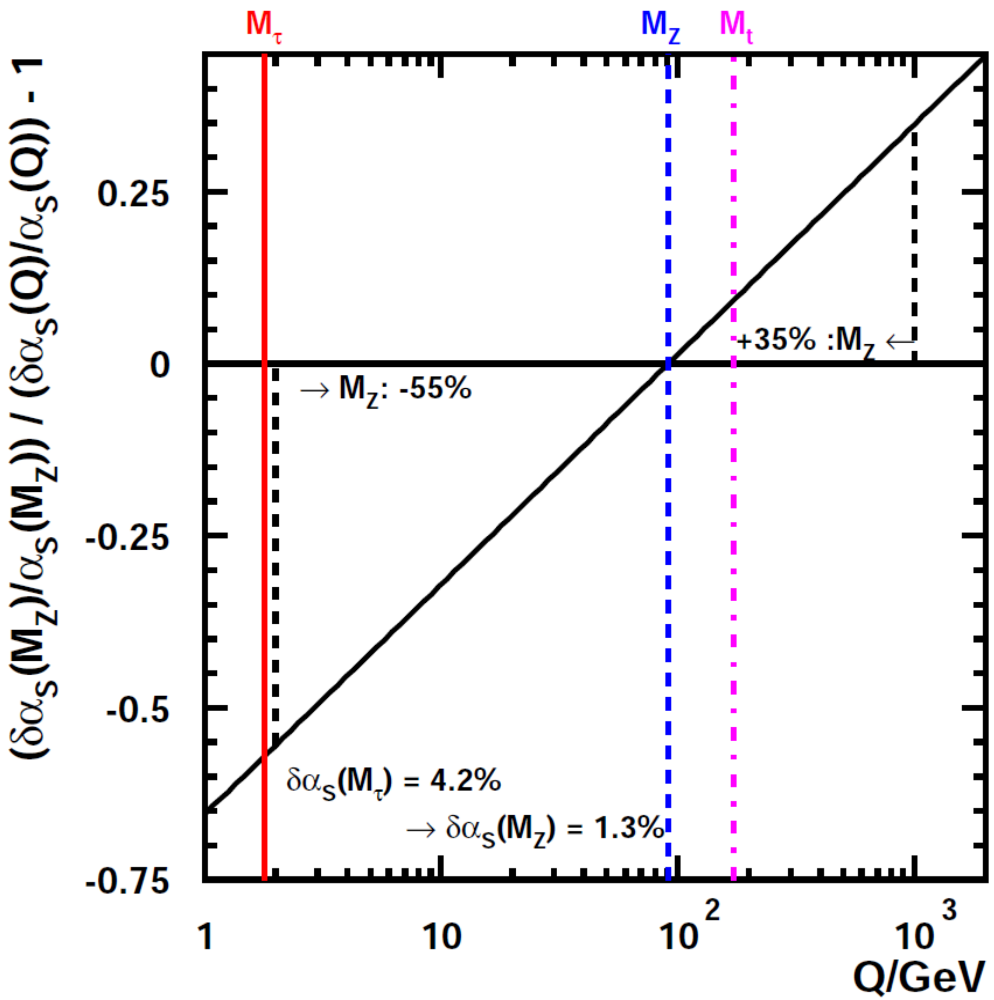
→ For $\alpha_s(M_Z)$ might want to stay at minimal JEC uncertainty: 200 – 800 GeV, central rapidity

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

Worse in: NP effects

Incredibly shrinking error →

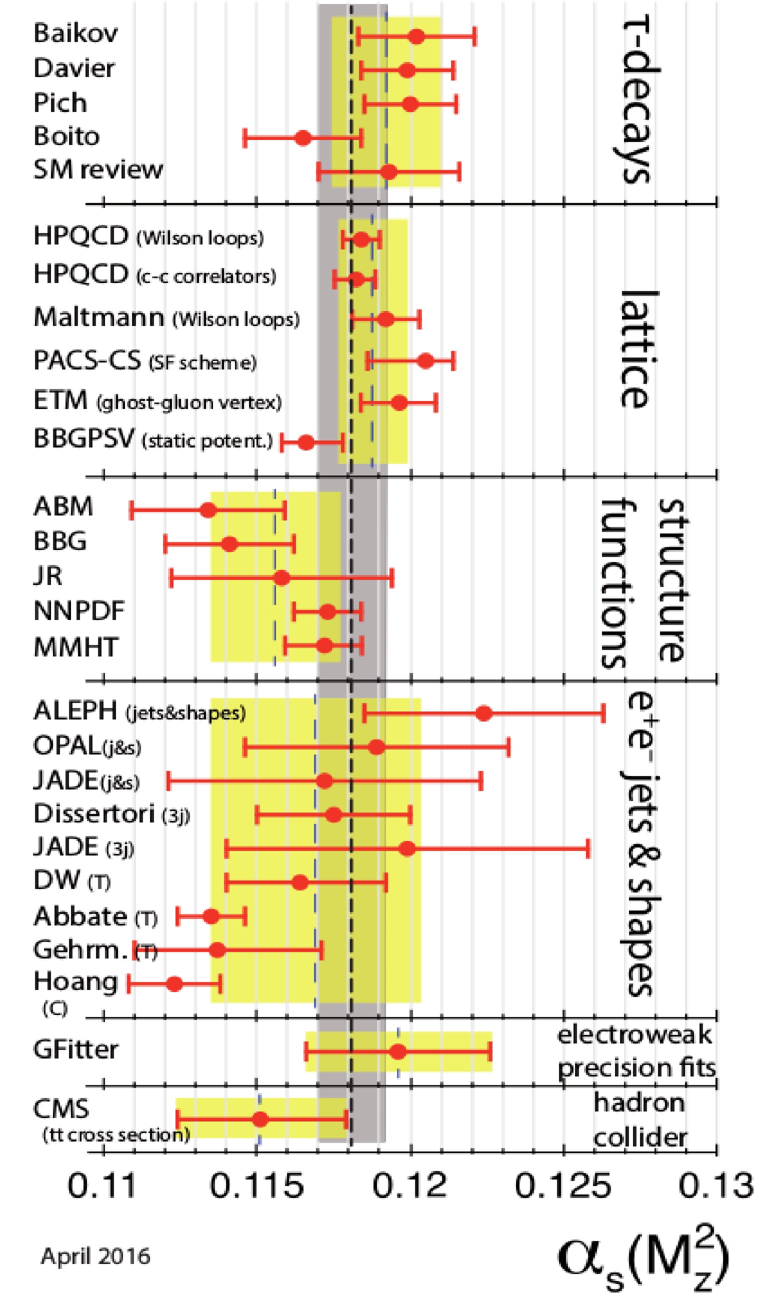
← Uncomfortably growing error

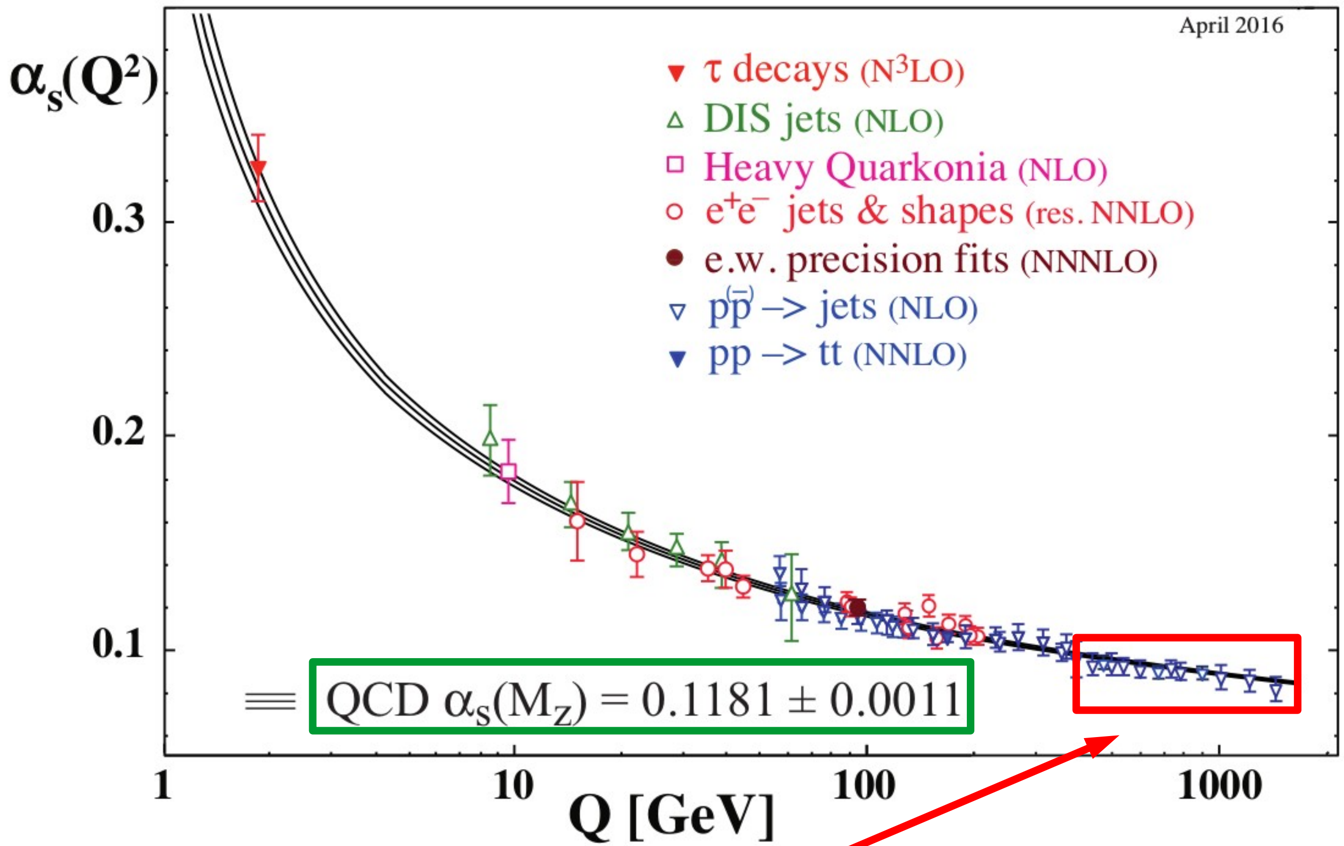


Perspectives & educated guesses

- **Experiment:**
  - Done: Observables $\sigma \sim \alpha_s^2, \alpha_s^3$; $R_{3/2} \sim \alpha_s$; 7 TeV; full phase space
  - Mostly done, 8 TeV data: Some reduction in experimental uncertainty
  - Partially done, 13 TeV: Final precision?
  - Best JEC phase space: Further reduction by some permille?
  - Other observables: Ratios (n+m) / n jets (incl. γ, W, Z),
    Normalized cross sections (A)TEEC, $R_{\Delta\Phi}$, $R_{\Delta R}$ (→ D0)
- **Theory:**
  - Scales: NNLO important → reduction by 2 – 3 percent!?
  - PDFs: Much improved after LHC I, also HERA 2 data available
    - Better known gluon (Attention circularity jets → g(x) & jets → α_s)
    - Fits combining observables at various √s to disentangle g(x), M_t, α_s
  - NNLO ratios?
  - NP effects?

PDG Summary





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

Dominated by Lattice Gauge Theory

$$\frac{\Delta\alpha_S(M_Z)}{\alpha_S(M_Z)} = 0.9\%$$

PDG, Chin. Phys. C 40 (2016) 100001.

PDG´92: 2.4%

Summary & Outlook

- LHC at 7 TeV and 8 TeV enables measurements up to scales of 2 TeV
- 13 TeV data yet to be fully evaluated
- 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 % → 1 – 2% at NNLO(?) but still an issue. Central scale choice?
  - Nonpert. Effects: 1 % (really?)
- Beyond one experiment (see also → LHC EW Working Group):
  - Combined fits of ATLAS & CMS (LHC) measurements
  - Combined fits of HERA, Tevatron & LHC measurements

➡ CHALLENGE: $\alpha_s(M_Z)$ at 1% or better from hadron colliders!

Summary & Outlook

I wish you a fruitful conference!

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

Backup Slides

α_s Projections from Snowmass

Still at LHC:

Only jets probe running α_s at highest scales

< 1% uncertainty at M_Z challenging ...

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 ~ 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.)
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)
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	~ 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)
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])
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ ($\sim$ 5 yrs [38])

~1%

<1%

<1%

~1%

<0.5%

Snowmass QCD Report, arXiv:1310.5189.