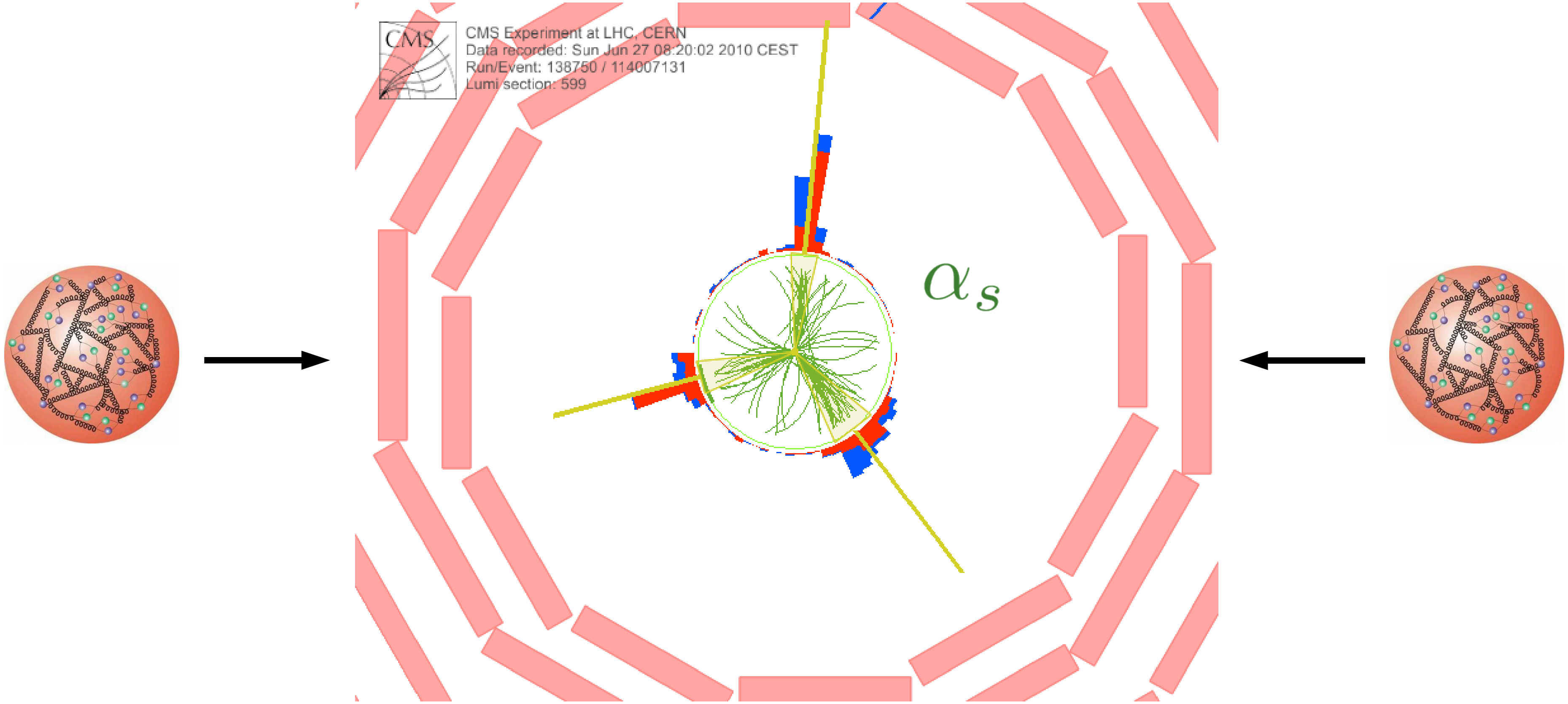
α_s Determinations from CMS



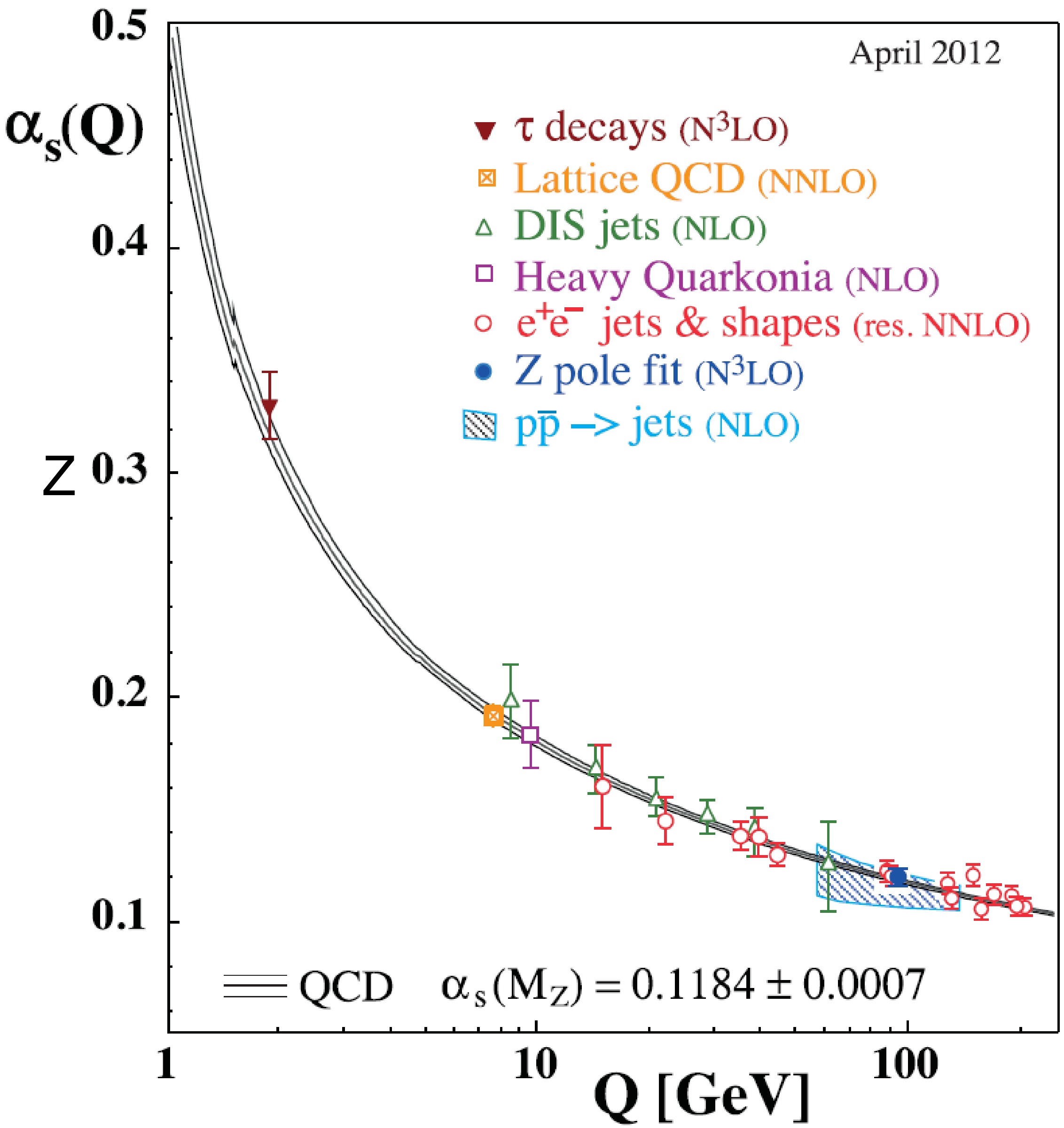
Klaus Rabbertz, KIT
(on behalf of CMS)

Karlsruhe Institute of Technology

Outline

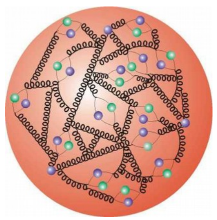
- **Motivation**
- **Jet-like measurements**
  - **Cross sections**
  - **Ratios**
- **top-antitop production**
- **Summary & Outlook**

2012: No LHC results yet PDG2012

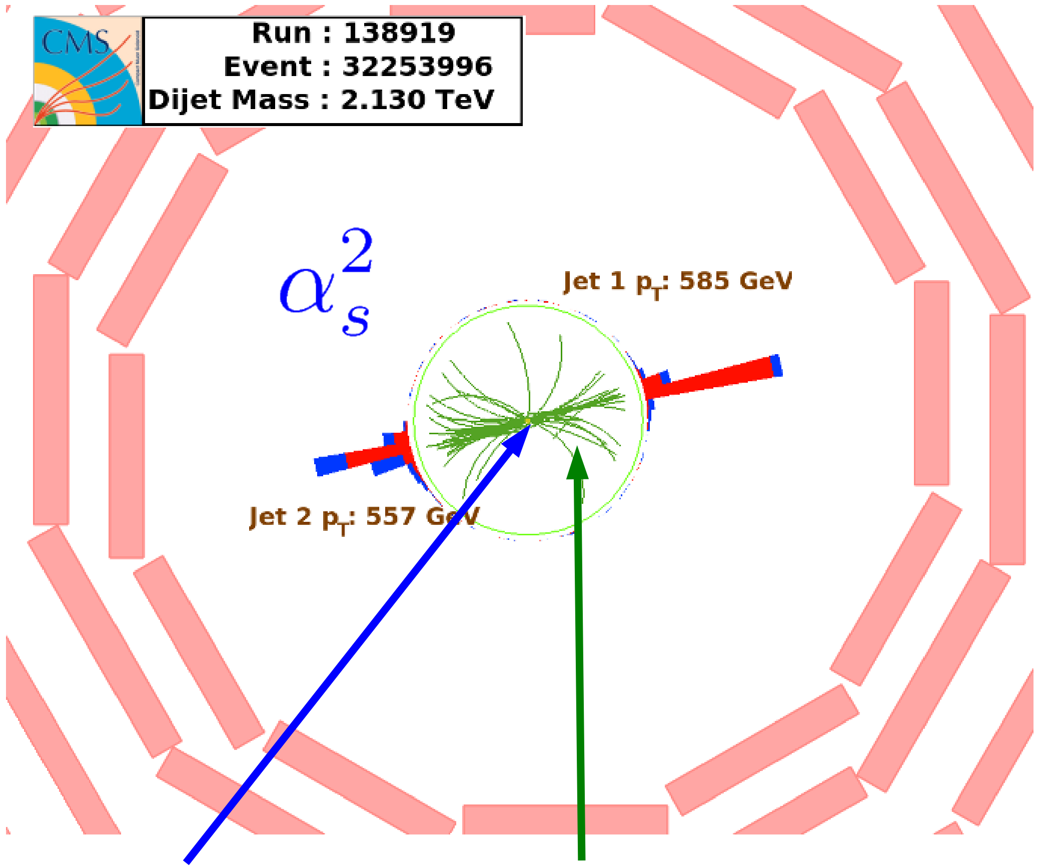


Abundant production of jets:

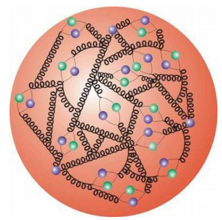
- Highest reach ever to determine the strong coupling constant at high p_T
- Also learn about hard QCD, electroweak effects at high p_T, the proton structure, and nonperturbative effects



Proton Structure (PDF)



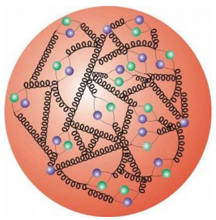
Matrix Element   Hadrons



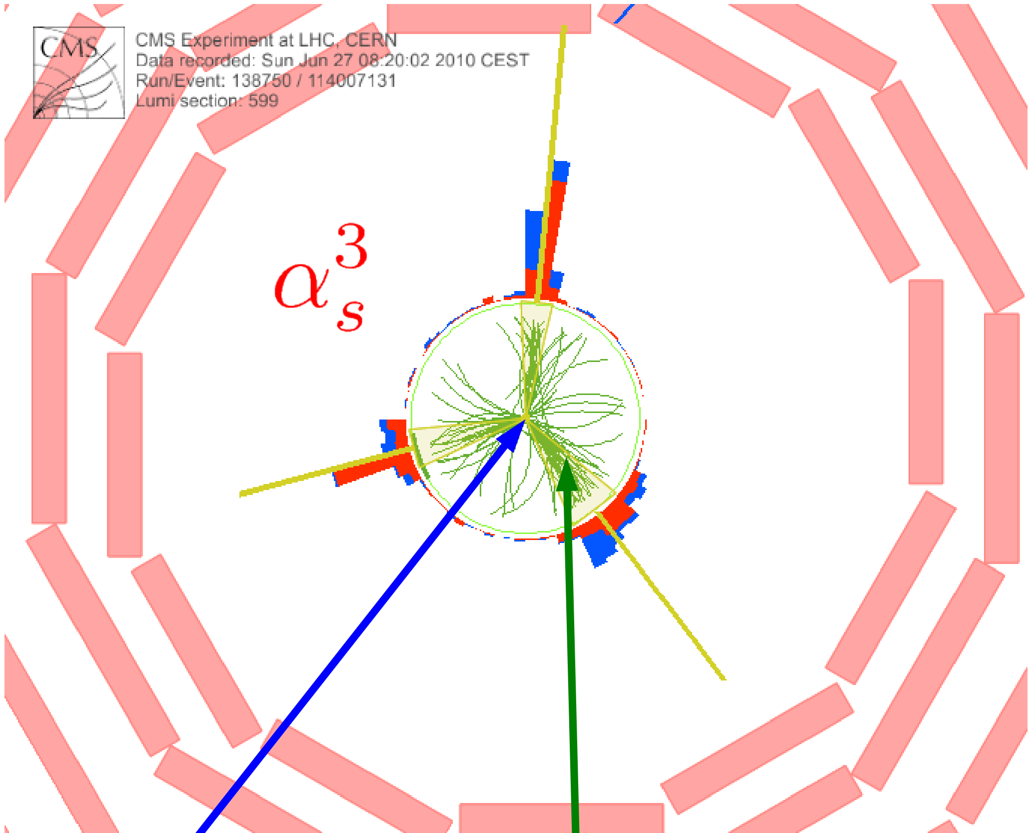
Proton Structure (PDF)

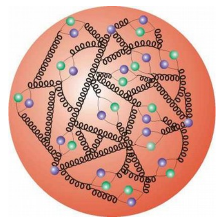
Abundant production of jets:

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



Proton Structure (PDF)



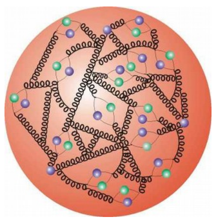


Proton Structure (PDF)

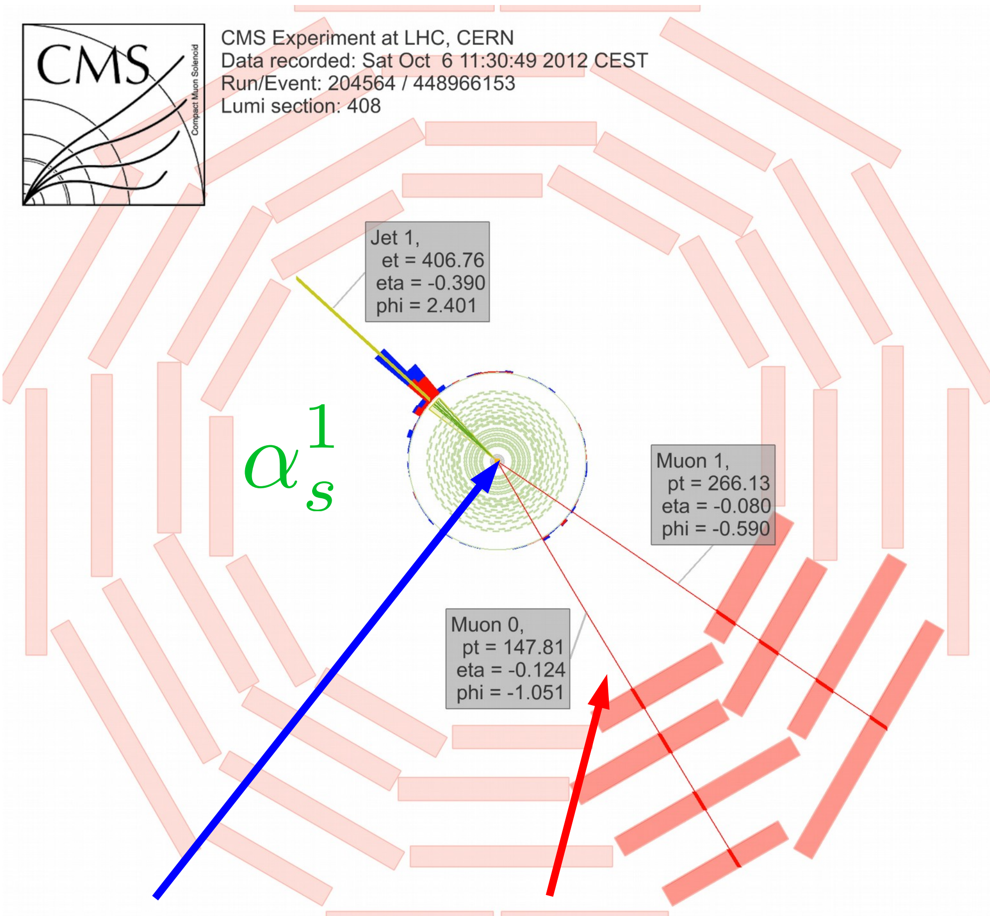
Matrix Element   Hadrons

High-precision lepton measurements:

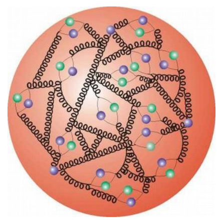
- W, Z, top measurements provide high-precision cross sections
- Also learn about electroweak parameters, the top mass, and the proton structure



Proton Structure (PDF)



Matrix Element   Muons



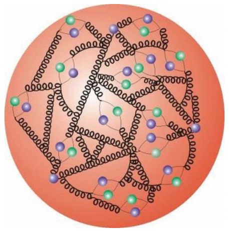
Proton Structure (PDF)

Jet cross sections ~ α_s^2

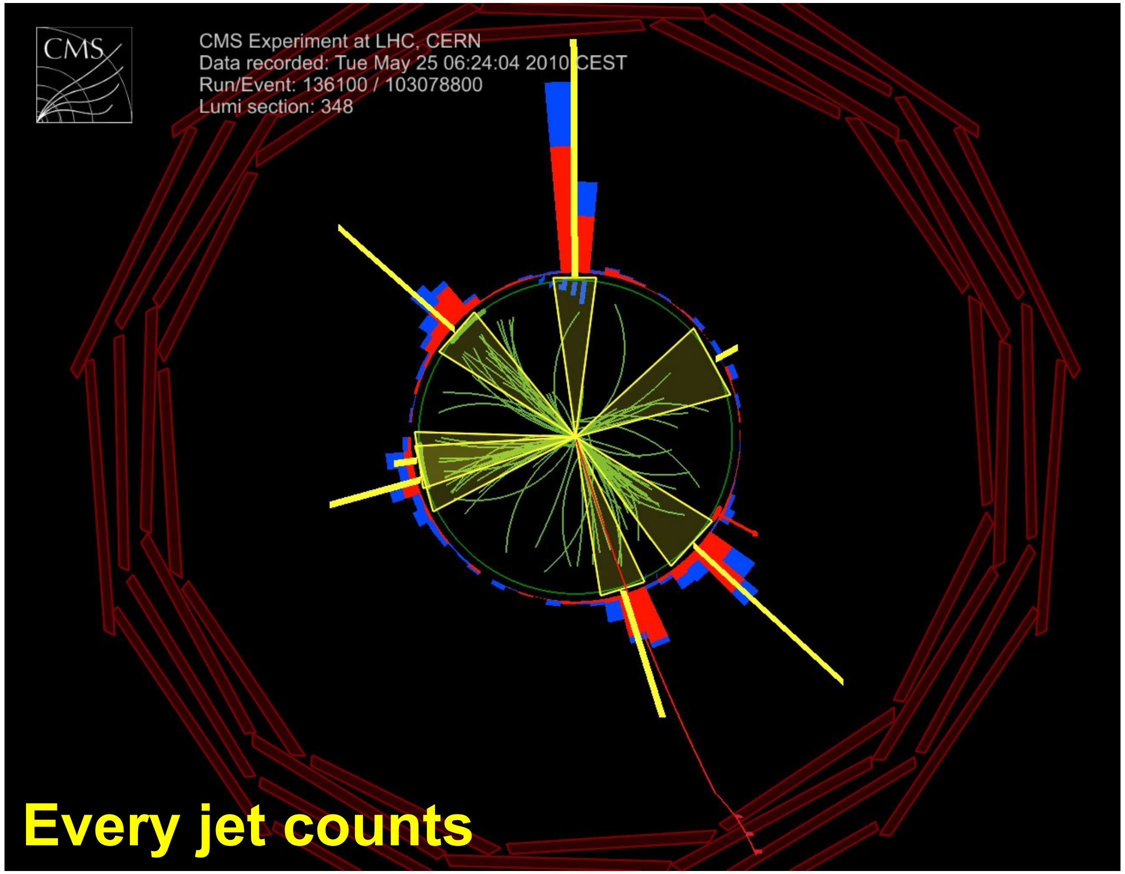
- Determination of $\alpha_s(M_Z)$ in single-parameter fit
- Test consistency of running of $\alpha_s(Q)$
- Multi-parameter fit of $\alpha_s(M_Z)$ & PDFs
- Jet measurements already in PDF fit?
- Theory at NNLO usable soon

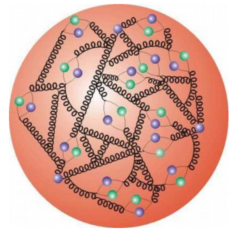
All inclusive

Large transverse momenta



Proton





Proton

Relevant CMS measurements:

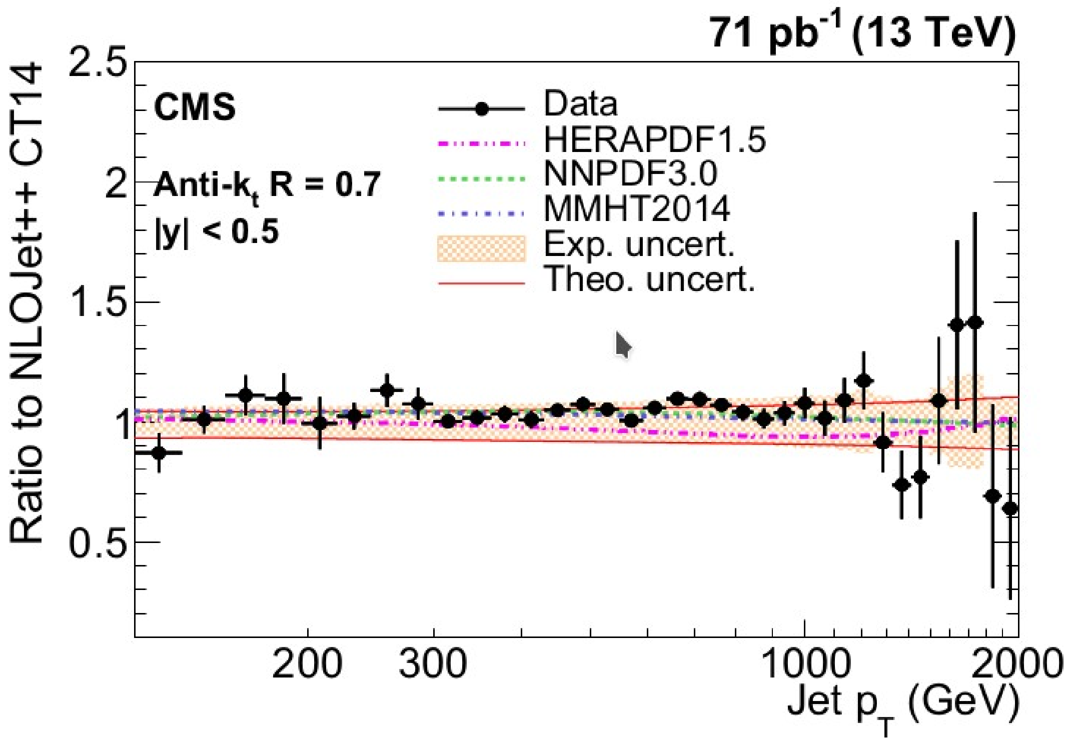
CMS:
PRD 87 (2013) 112002; PRD 90 (2014) 072006; EPJC 75 (2015) 288;
EPJC 76 (2016) 265; EPJC 76 (2016) 451; JHEP 03 (2017) 156.

Inclusive jets: measurement

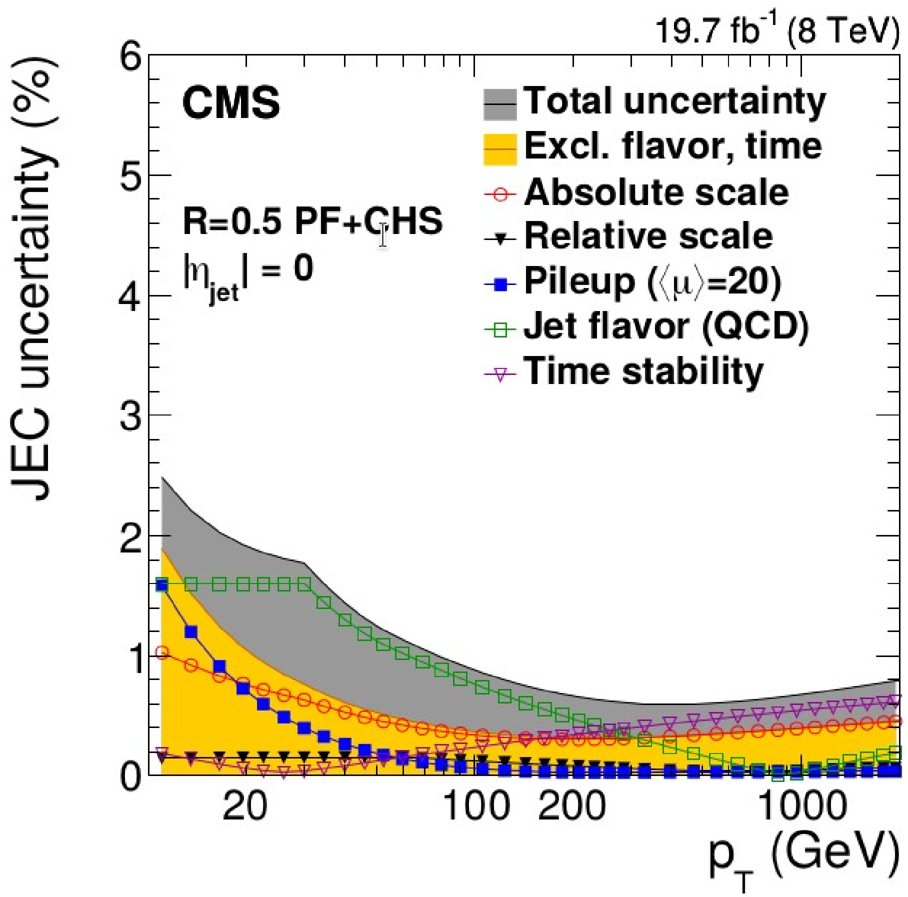
Overall agreement with predictions of QCD at NLO over many orders of magnitude in cross section and even beyond 2 TeV in jet p_T and for rapidities |y| up to 3 ~ 5 at $\sqrt{s}$ = 2.76, 7, 8, and 13 TeV.

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

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



Exp. uncertainties for |y| = 0 @ 8 TeV

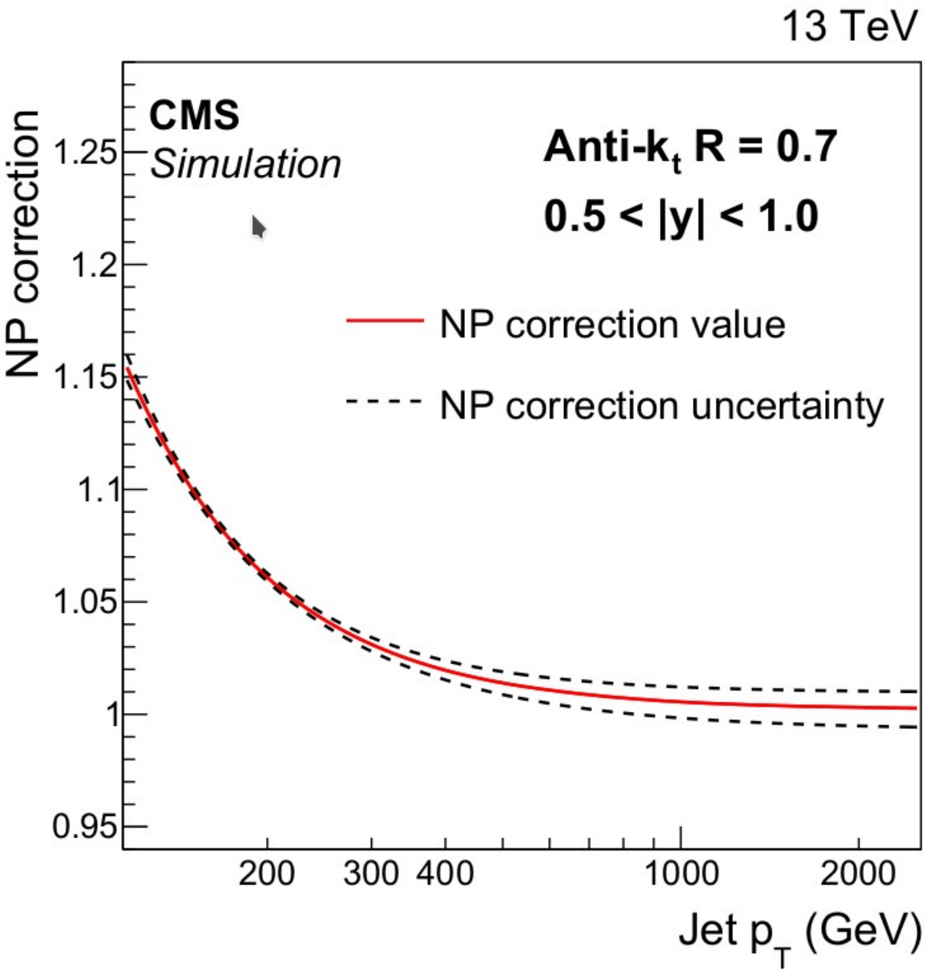


NLO: Ellis, Kunszt, Soper, PRL 69 (1992) 1496;
Giele, Glover, Kosower, NPB 403 (1993) 633;
Z. Nagy, PRD 68 (2003) 094002.

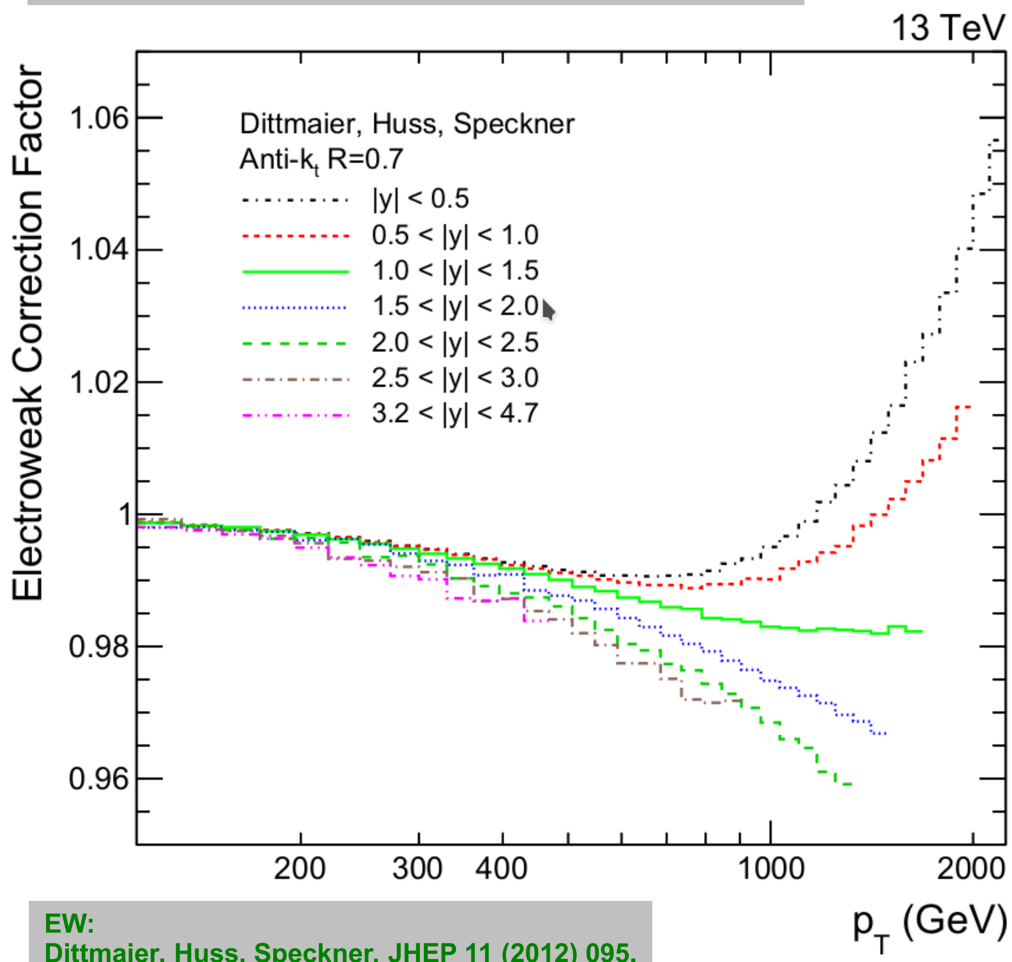
Inclusive jets: theory corrections

anti-kt, R=0.7, 13 TeV, |y| < 1.0

Nonperturbative correction factors:
- estimated from tuned MC event generators at LO+PS and NLO+PS
- non-negligible uncertainty
- 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

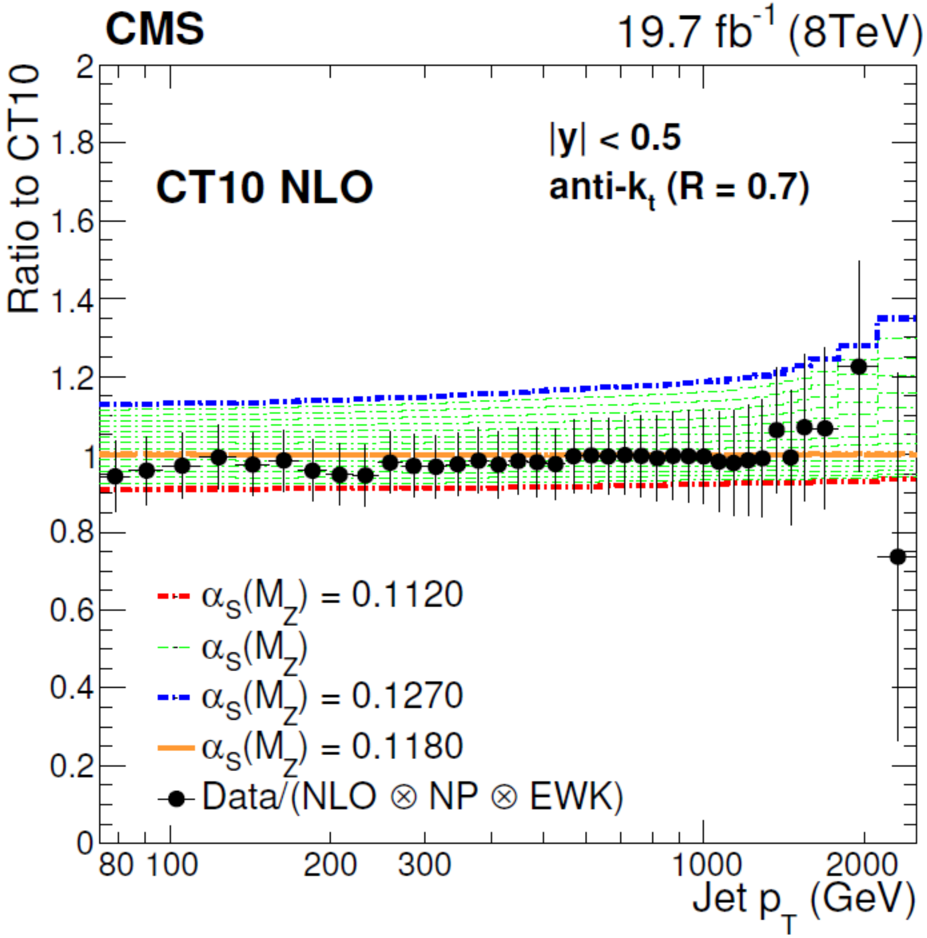


EW:
Dittmaier, Huss, Speckner, JHEP 11 (2012) 095.
Frederix et al., JHEP 04 (2017) 076.

Inclusive jets: α_s

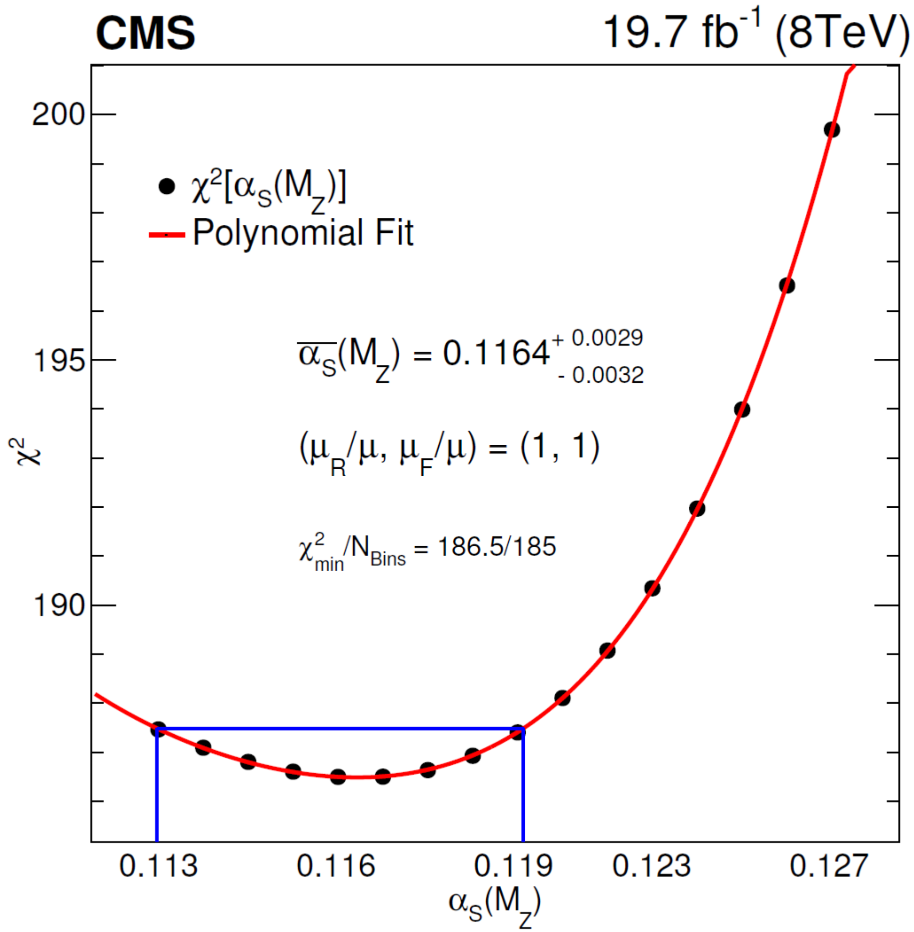
Sensitivity to $\alpha_s(M_Z)$ at NLO

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



χ^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 $\alpha_s(M_Z)$

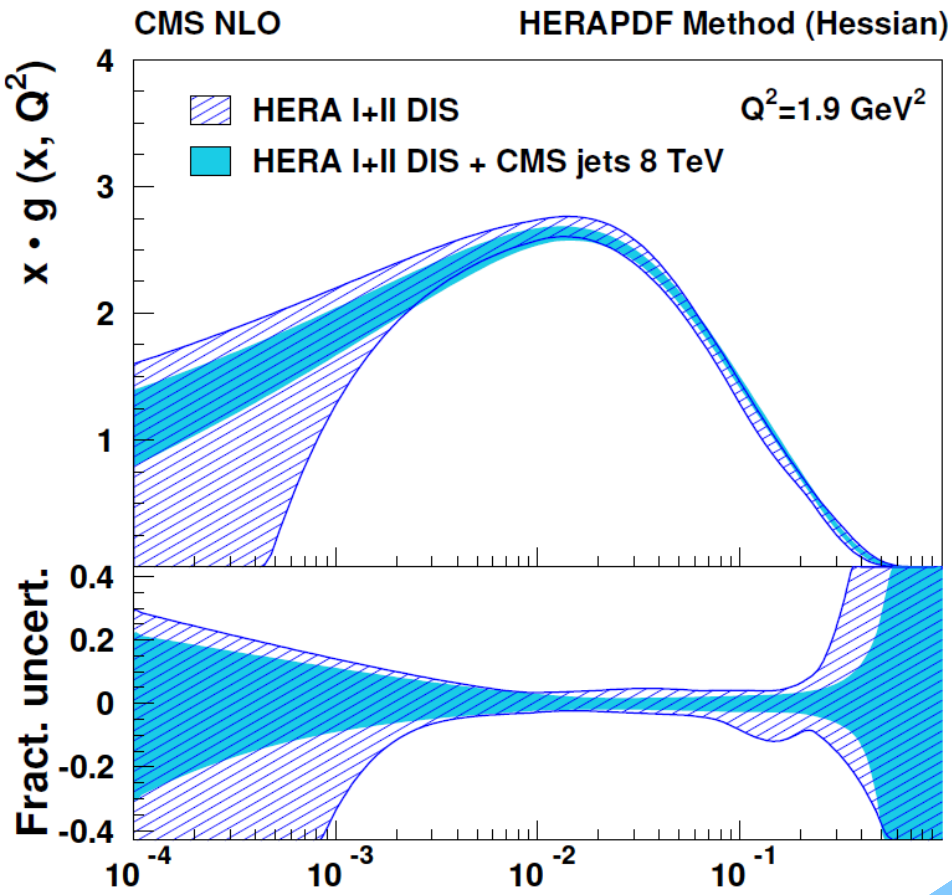


Jets @ NNLO in fits → work in progress, see previous talks by D. Britzger & J. Pires

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

Orange shading: external PDF sets

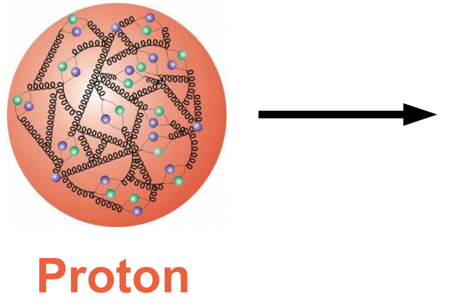
Bluish shading: PDF fit incl. HERA data

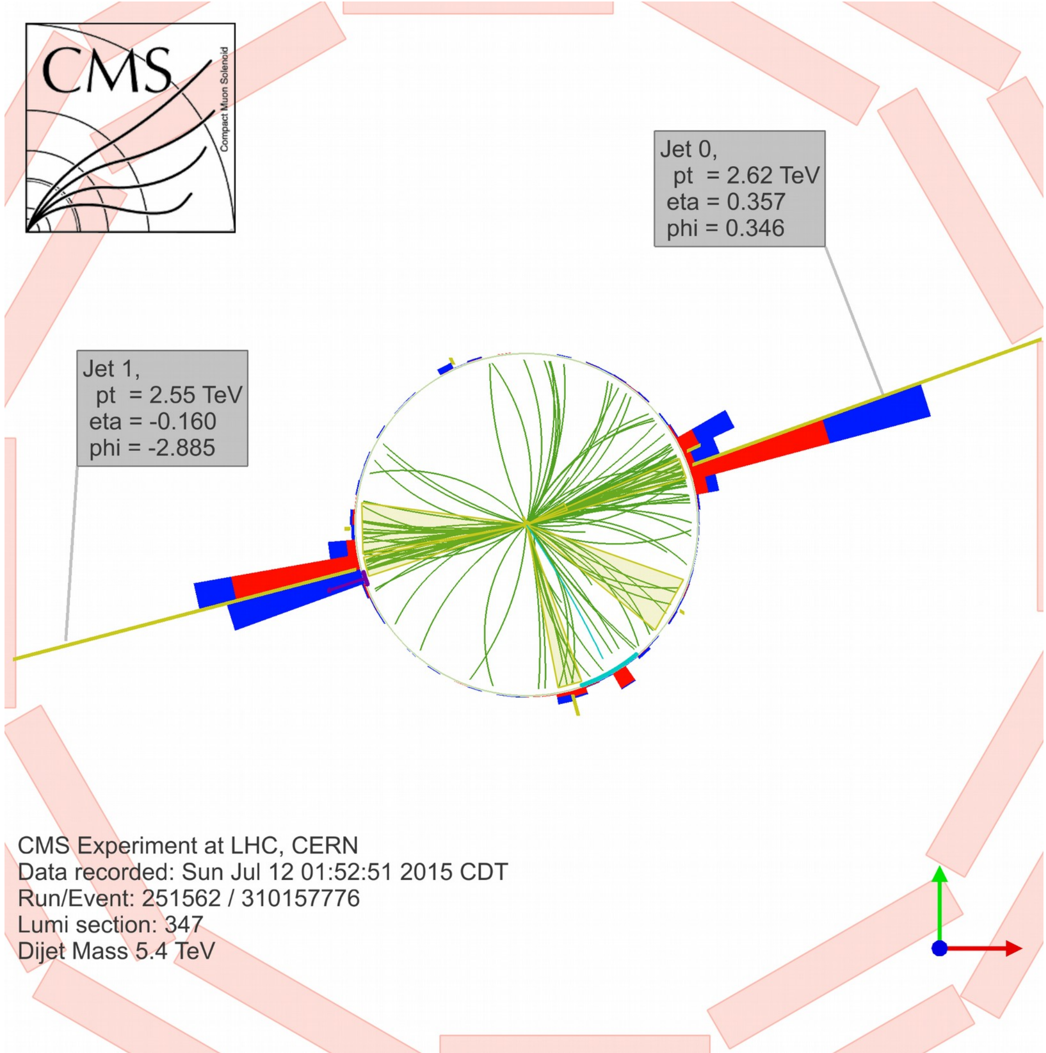
√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1185	35	$^{+53}_{-24}$
8	19.7	0.1164	$^{+29}_{-33}$	$^{+53}_{-28}$
7	5.0	0.1192	$^{+23}_{-19}$	$^{+24}_{-39}$
8	19.7	0.1185	$^{+19}_{-26}$	$^{+22}_{-18}$

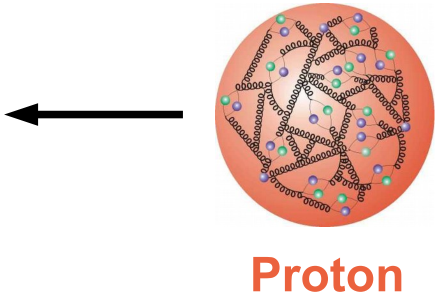
Question in progress: Uncertainty of missing higher orders (aka scale uncertainty) in PDF fits

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

Large masses







Relevant CMS measurements:

CMS:
PRD 87 (2013) 112002; EPJC 77 (2017) 746.

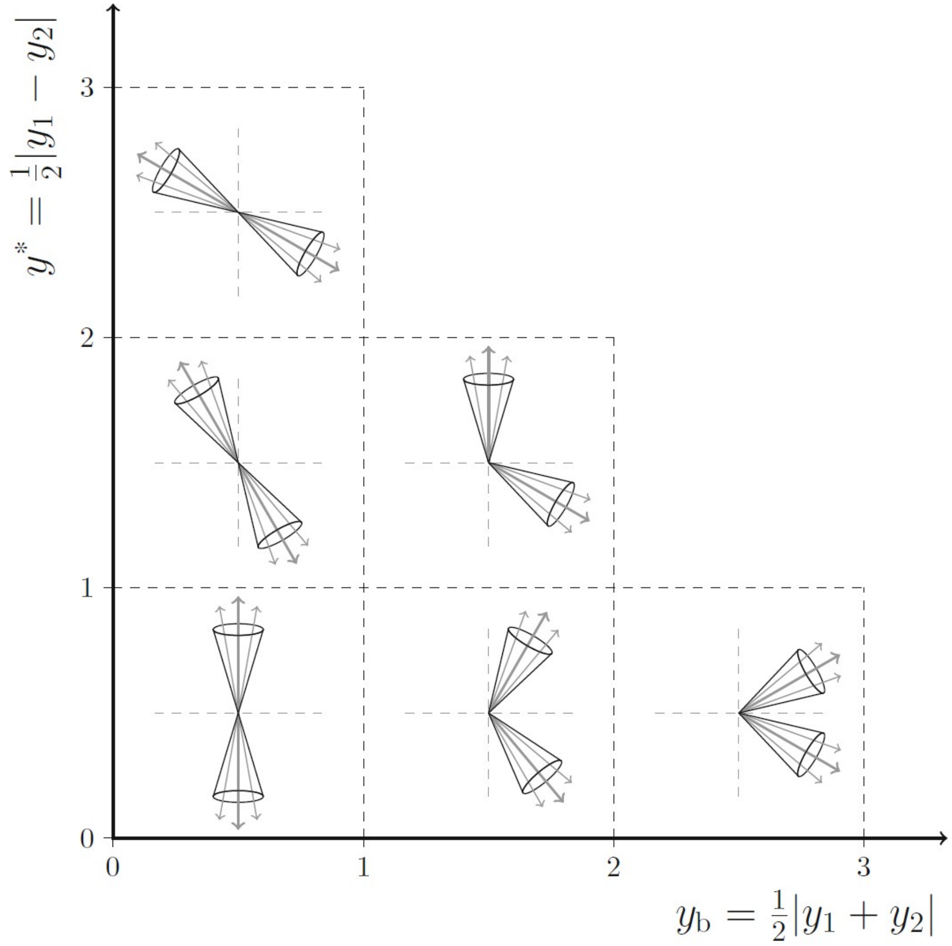
Triple-differential dijets

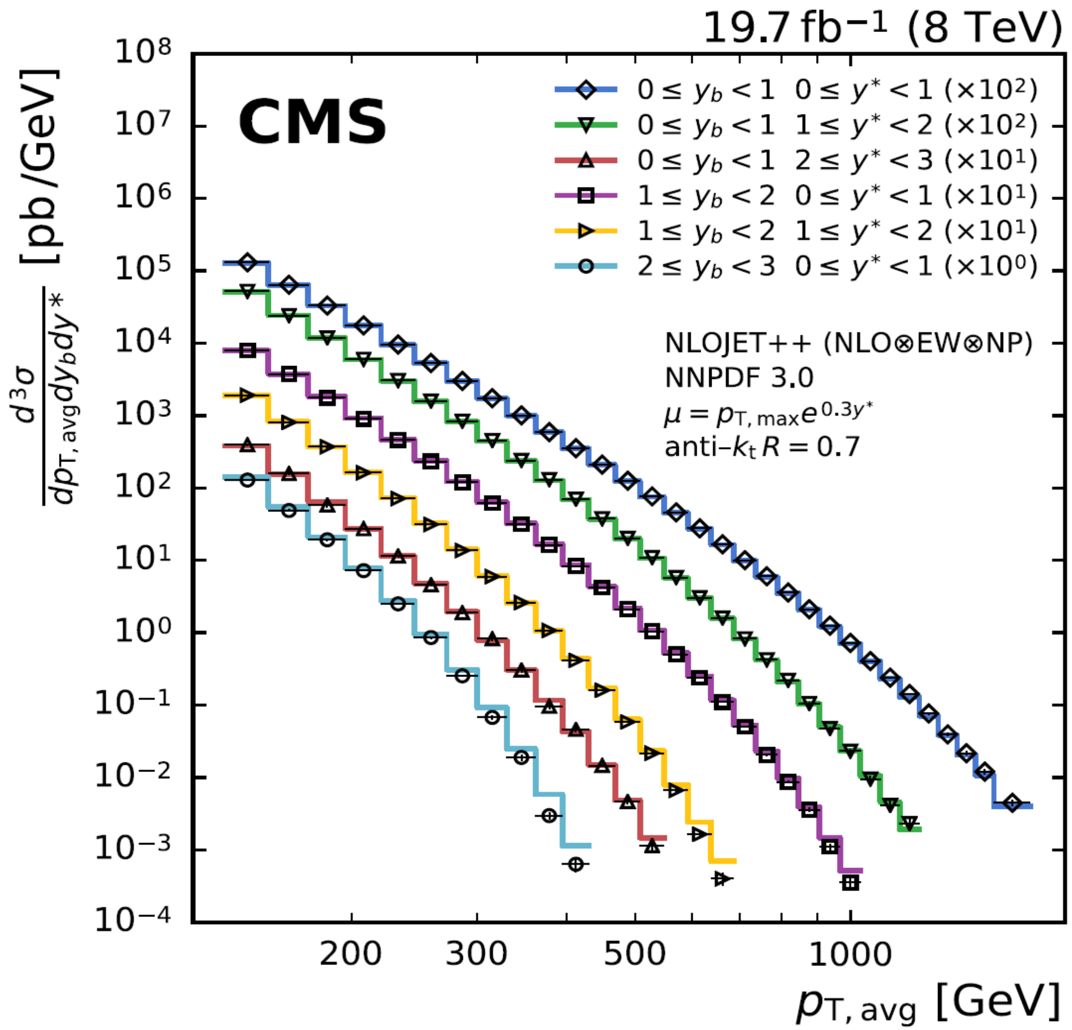
Most measurements 2-dimensional with respect to dijet mass and either max. rapidity $|y|_{max}$ or rapidity separation y^*

One CMS result vs. y^*, y_b, <pT1,2> → $\alpha_s(M_Z)$

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

Illustration of dijet event topologies

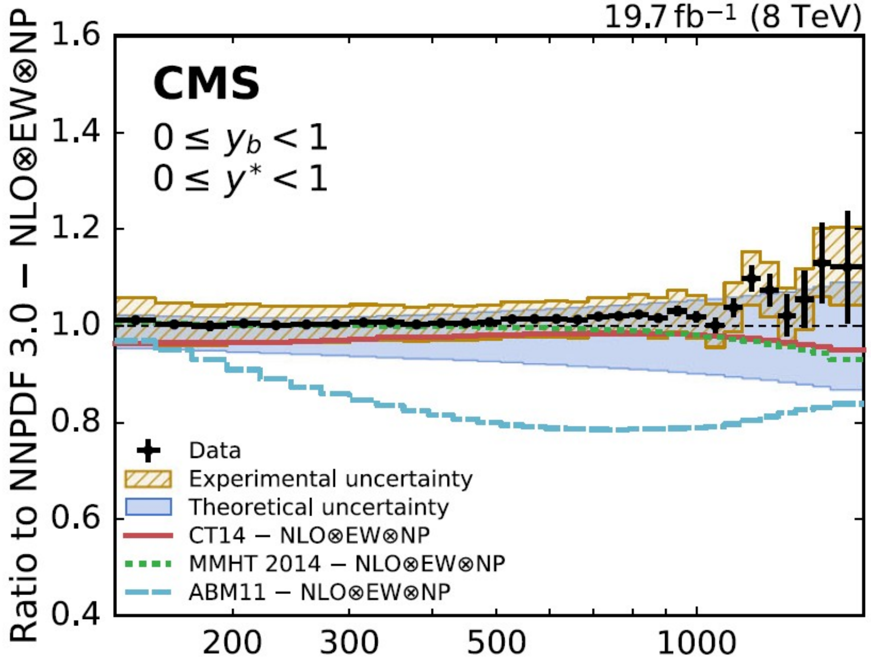




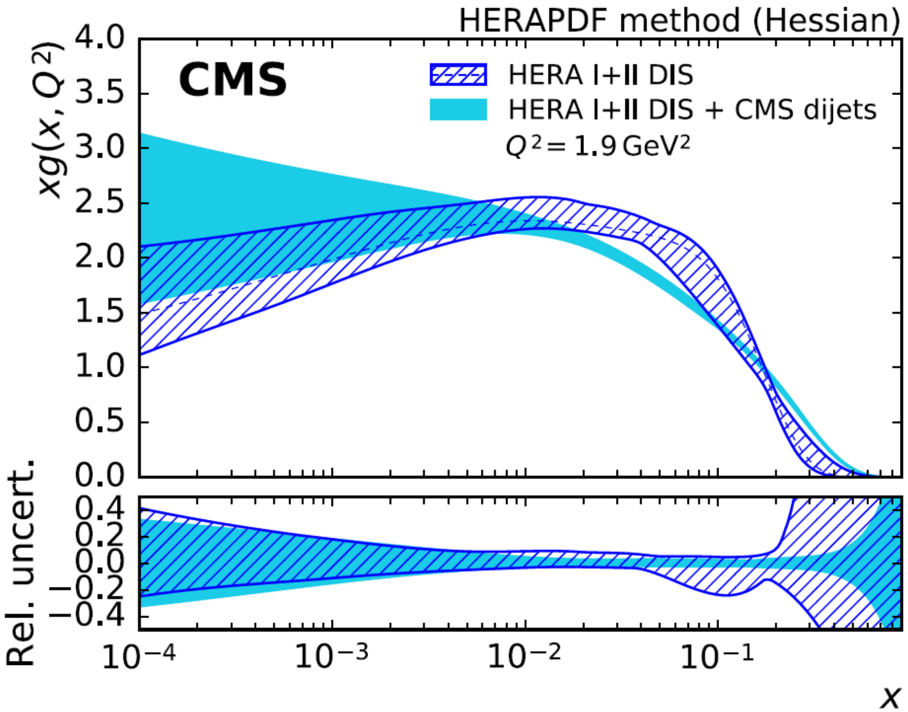
Triple-differential dijets

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



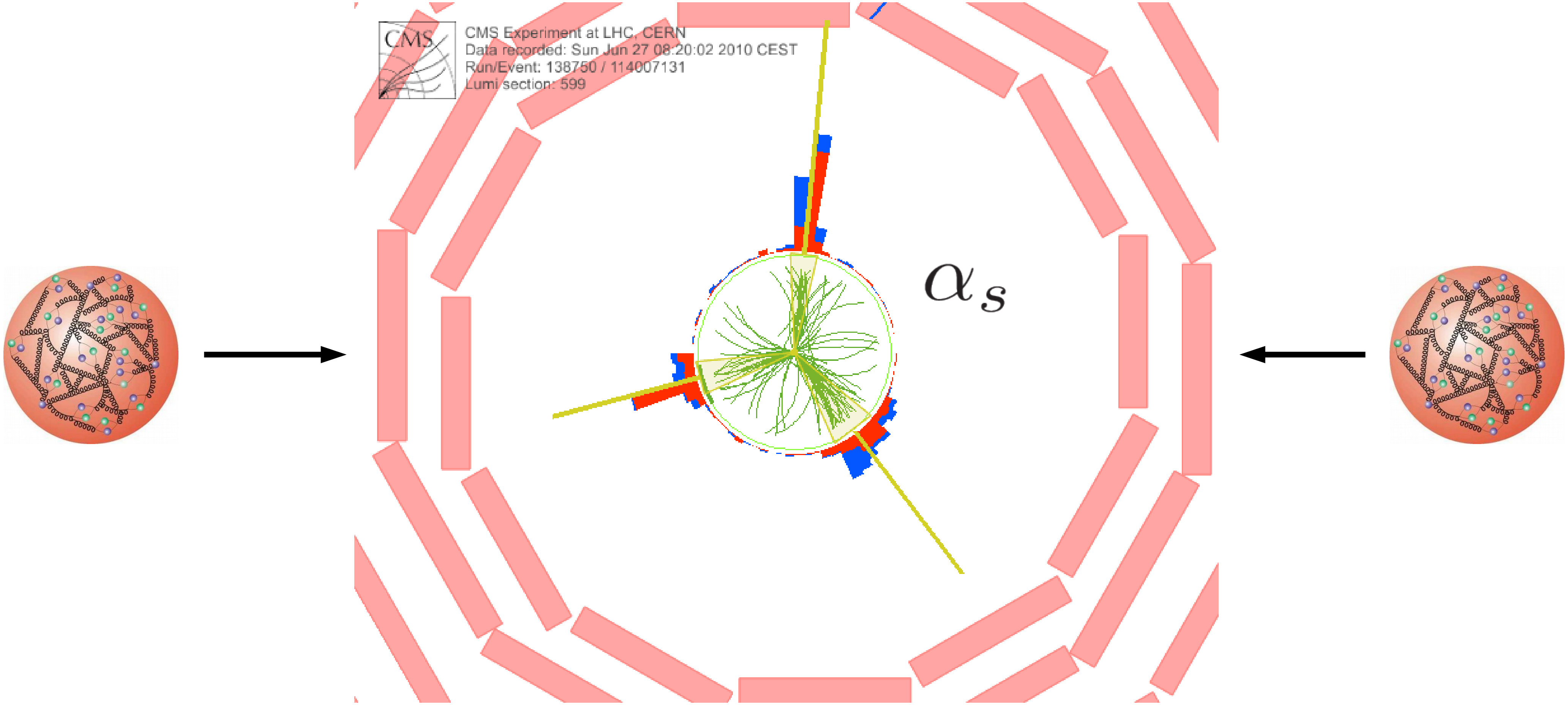
Reduced uncertainties of gluon PDF



16-parameter fit

√s [TeV]	lum [fb⁻¹]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1185	35	$^{+53}_{-24}$
8	19.7	0.1164	$^{+29}_{-33}$	$^{+53}_{-28}$
7	5.0	0.1192	$^{+23}_{-19}$	$^{+24}_{-39}$
8	19.7	0.1185	$^{+19}_{-26}$	$^{+22}_{-18}$
8	19.7	0.1199	$^{+15}_{-16}$	$^{+31}_{-19}$

Higher multiplicity



Relevant CMS measurements:

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

Cross sections ~ α_s^3

- As compared to α_s^2:
  - Higher sensitivity
  - Smaller statistical precision
  - Smaller dynamical range
  - More scale choices
  - Theory at NNLO not available

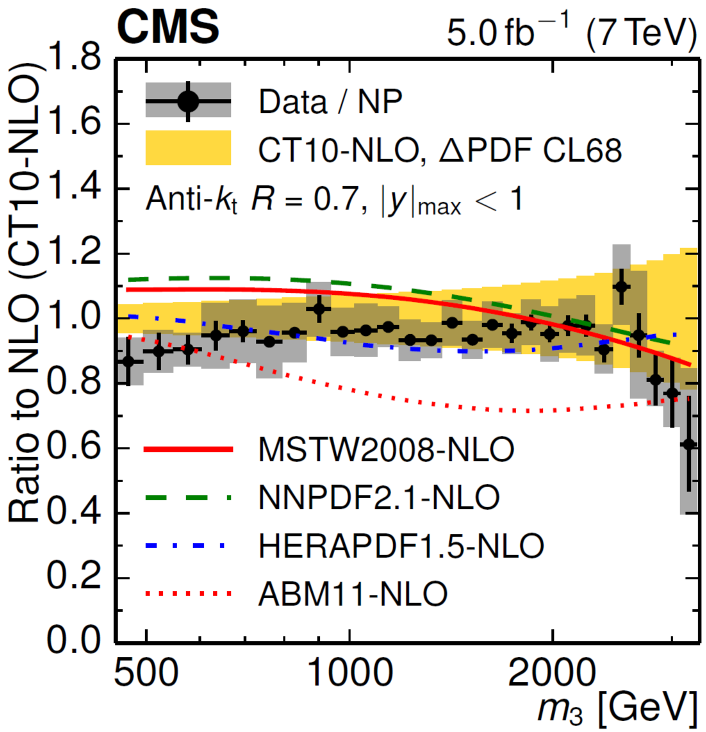
3-jet mass

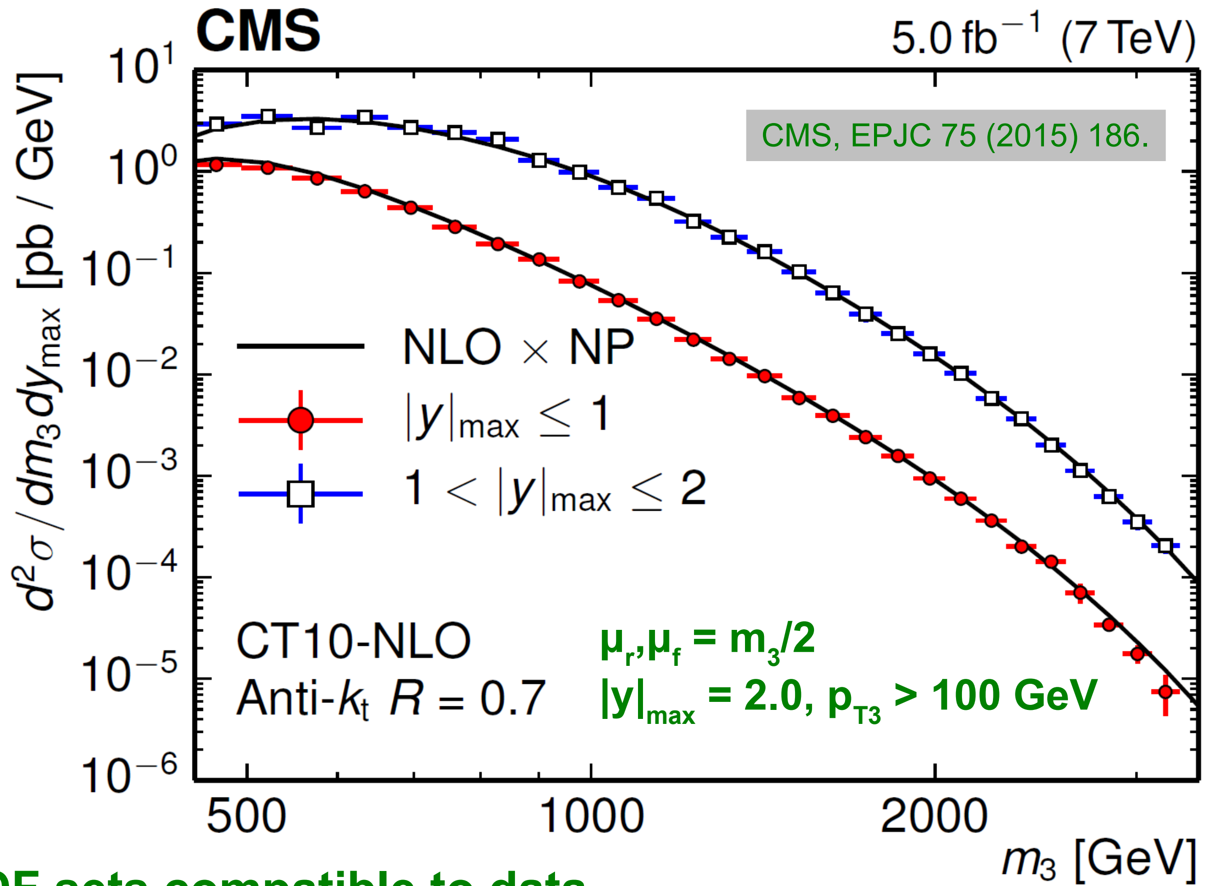
Sensitive to α_s beyond 2→2 process

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

√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1171	28	$^{+69}_{-40}$

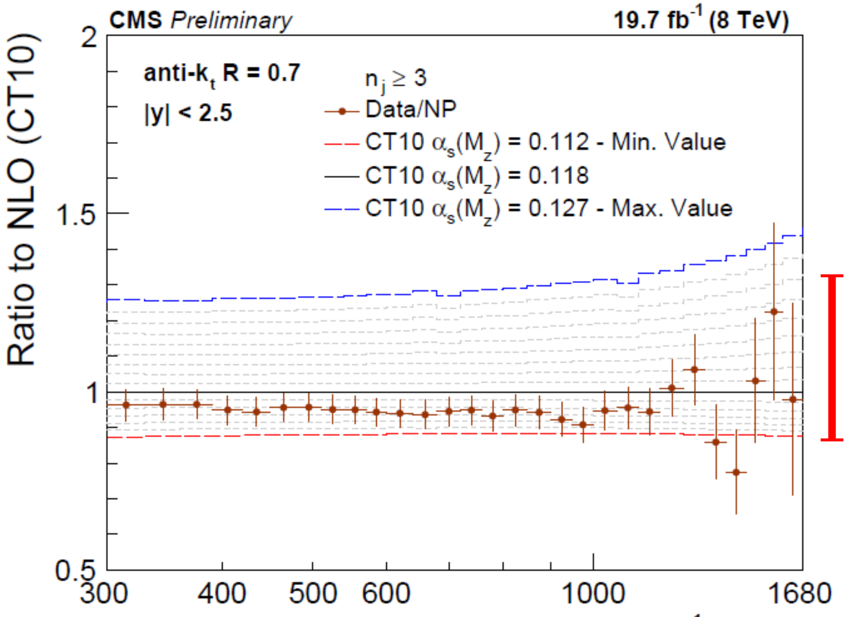
Jet cross section ratios

- 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

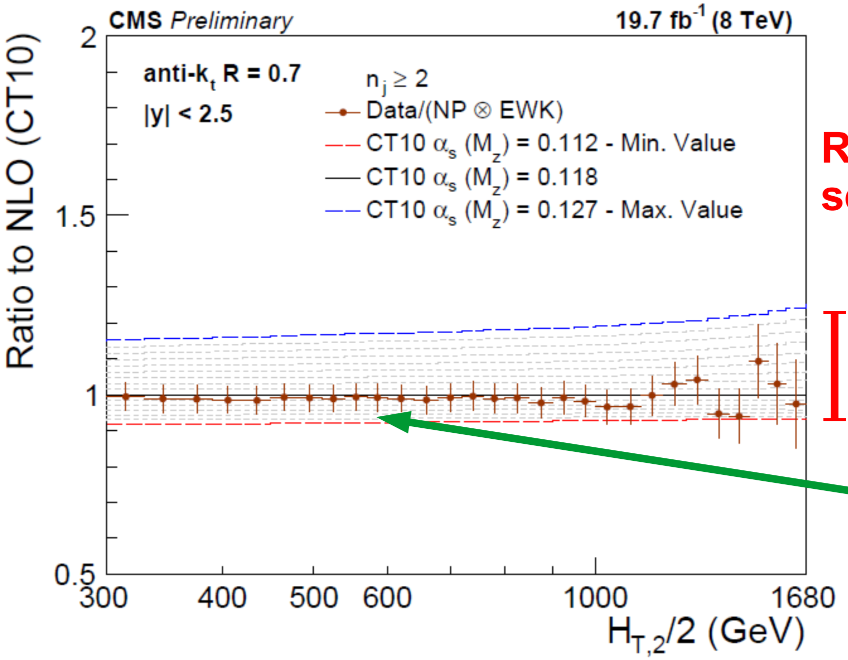
Inclusive 3-jet cross section

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



Inclusive 2-jet cross section

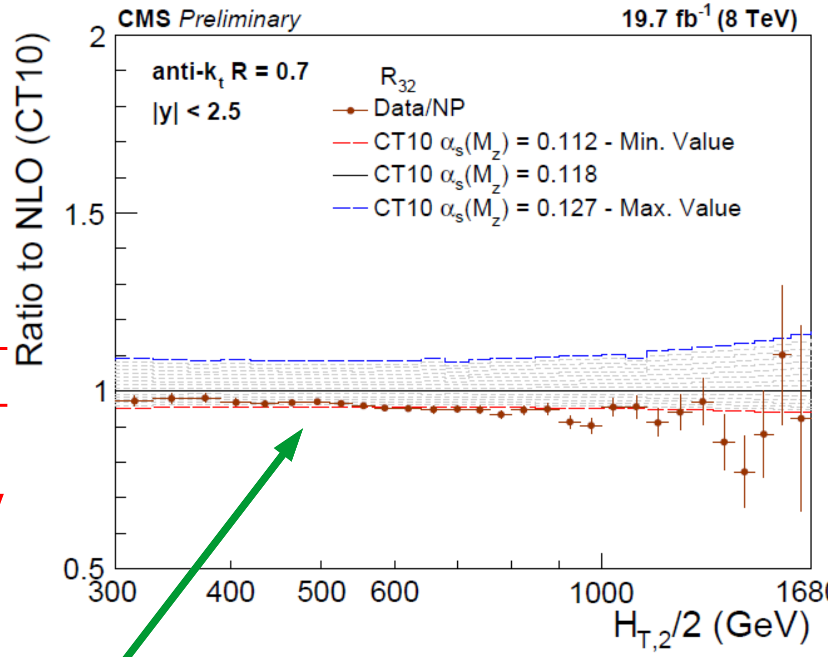
$$\sigma_{2j} \propto \alpha_s^2$$



Reduced sensitivity

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

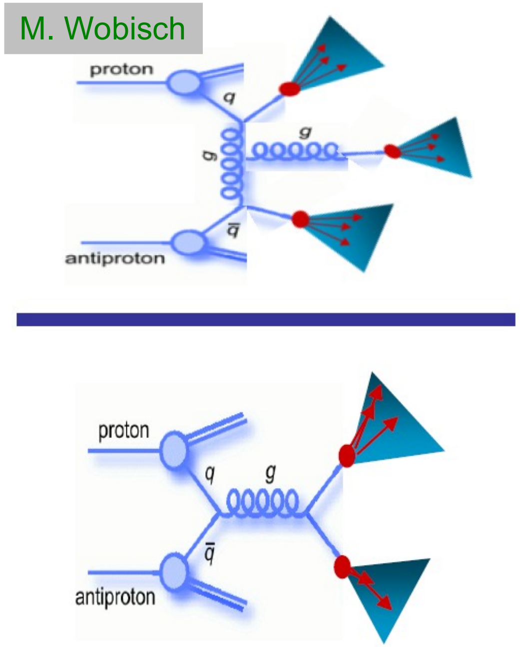
$$R_{3/2} \propto \alpha_s$$



Much reduced systematic uncertainty

3- to 2-jet ratios

M. Wobisch

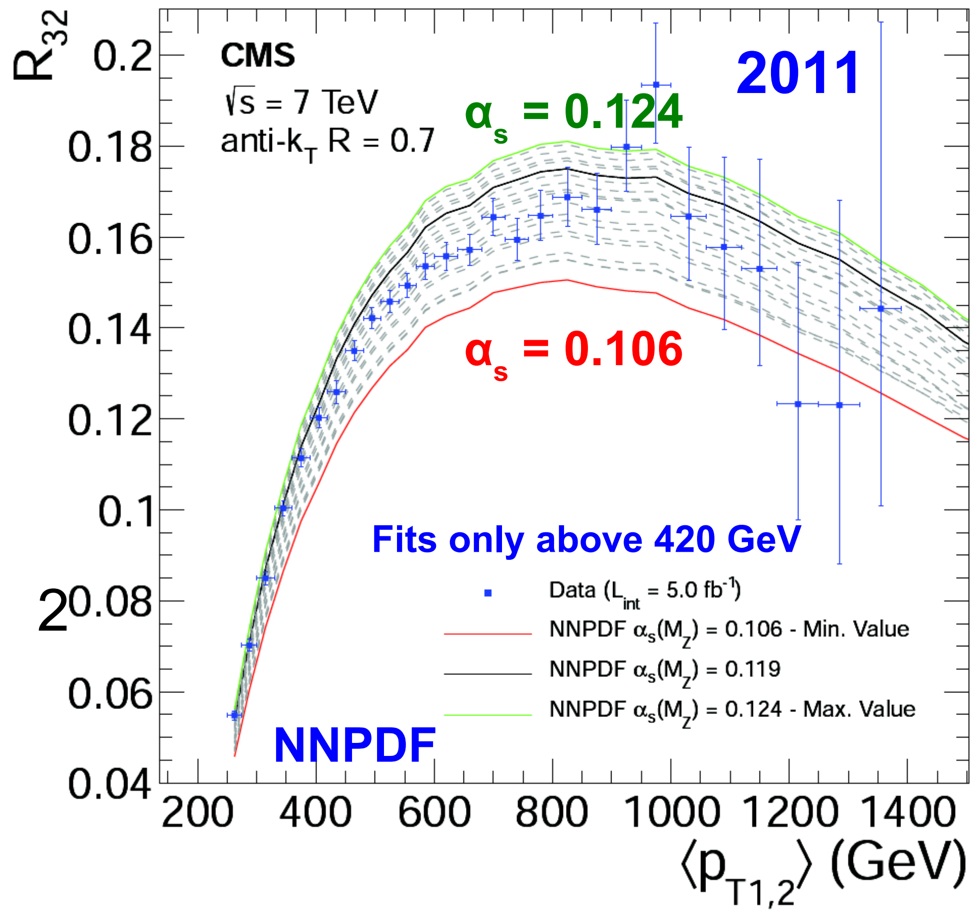


$R_{3/2}$

⟷ α_s

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

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



CMS: $R_{3/2}$

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

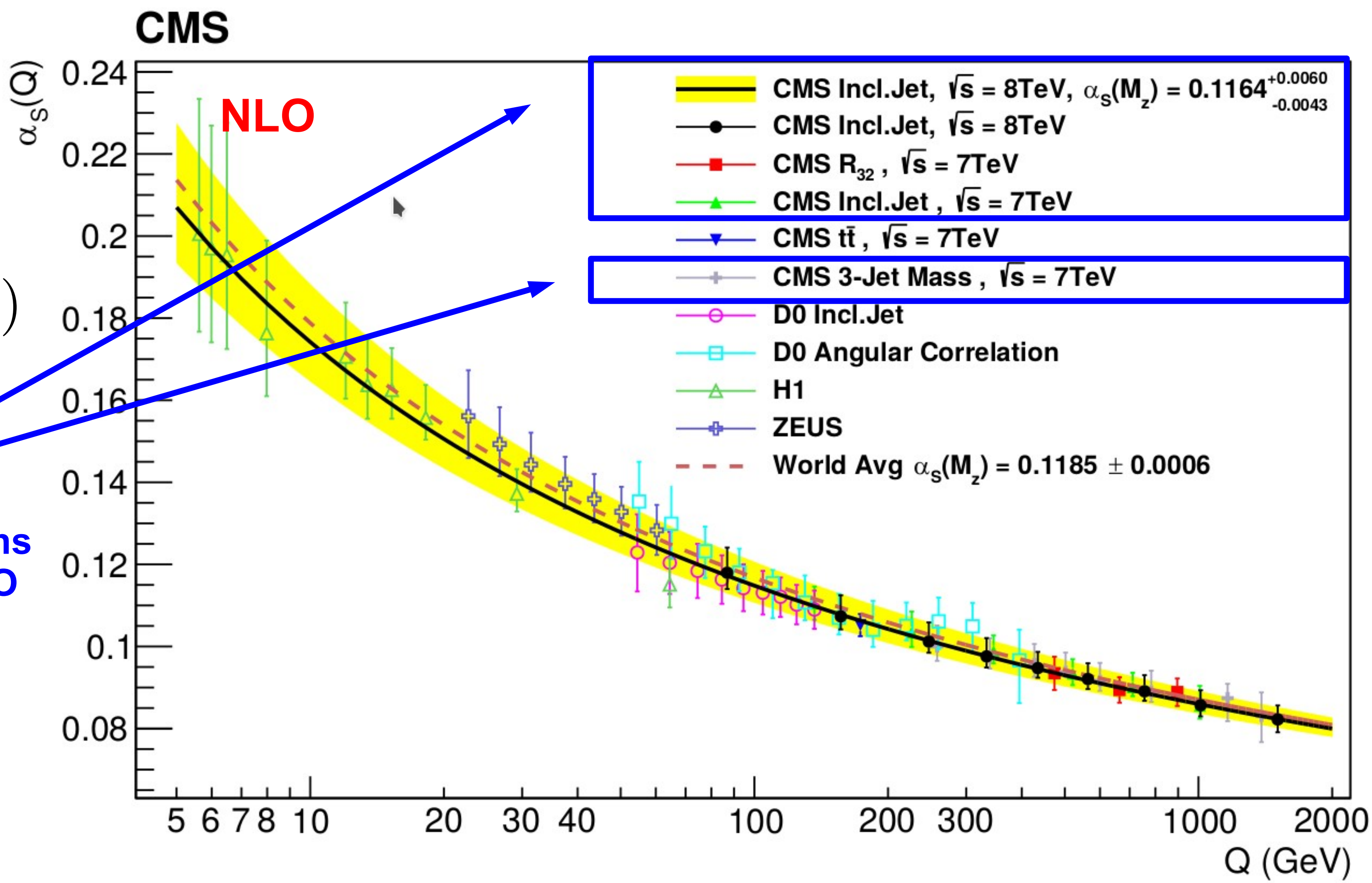
→ α_s

√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1148	23	50
8	19.7	0.1150	22	+50

Running of $\alpha_s(Q)$

Perform fits in fixed intervals of the chosen scale Q

$\Rightarrow \alpha_s(Q)$



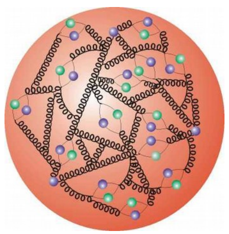
Jet cross sections and ratios at NLO

Needs an update for latest ATLAS, CMS, & H1 points ...

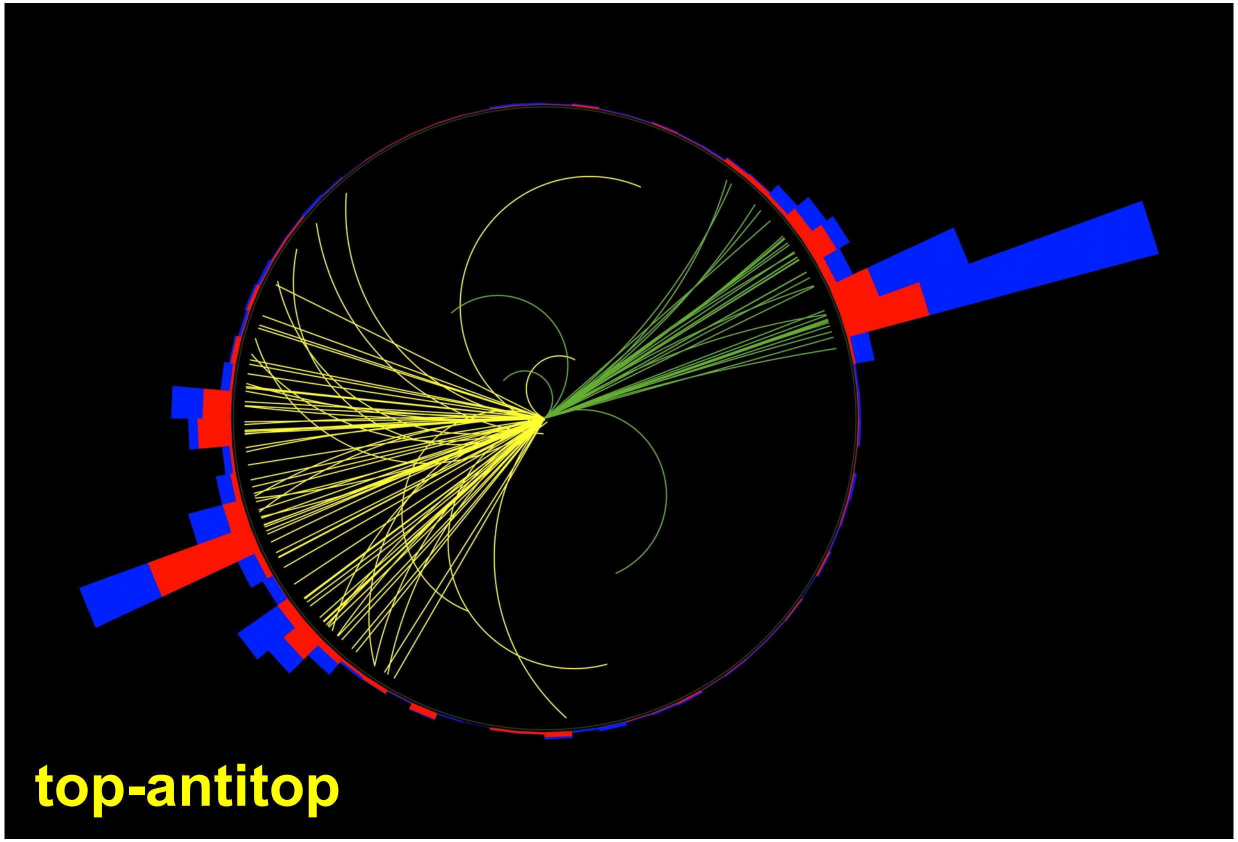
New range explored at LHC →

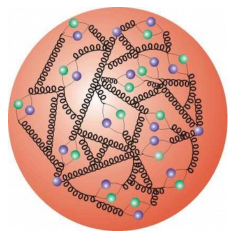
Heavy stuff

Heavy quarks



Proton





Proton

Relevant CMS measurements:

PLB 728, 496 (2013), JHEP 11, 067 (2012) [Erratum: PLB 738, 526 (2014)], CMS-TOP-17-001, arXiv:1812.10505 CMS-PAS-TOP-18-004.

top-antitop production

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

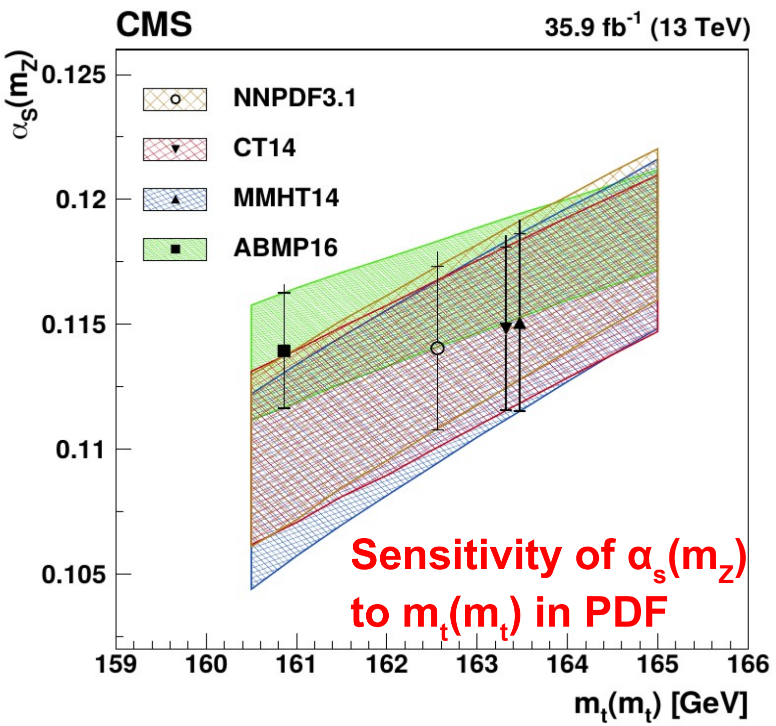
Fits with tt production cross section

Top-pair production is especially sensitive to: NNLO

m_t 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.

Fix m_t (& PDF) → constrain α_s (or vice versa)



- **Analysis @ 13 TeV much improved:**
  - Obtain σ_{tt} in sim. fit from data with m_t^{MC} as nuisance parameter
  - Running MS_{bar} mass $m_t(m_t)$ as scale
  - Conventional scale uncertainty
  - Choose PDF and fix $m_t(m_t)$ as given
  - Determine $\alpha_s(M_Z)$ from fit to σ_{tt}
  - Try various PDF sets

OLD: 7 TeV, NNLO + NNLL, NNPDF23 →

NEW: 13 TeV, NNLO, ABMP16 →

HATHOR, Aliev et al., CPC 182 (2011) 1034.

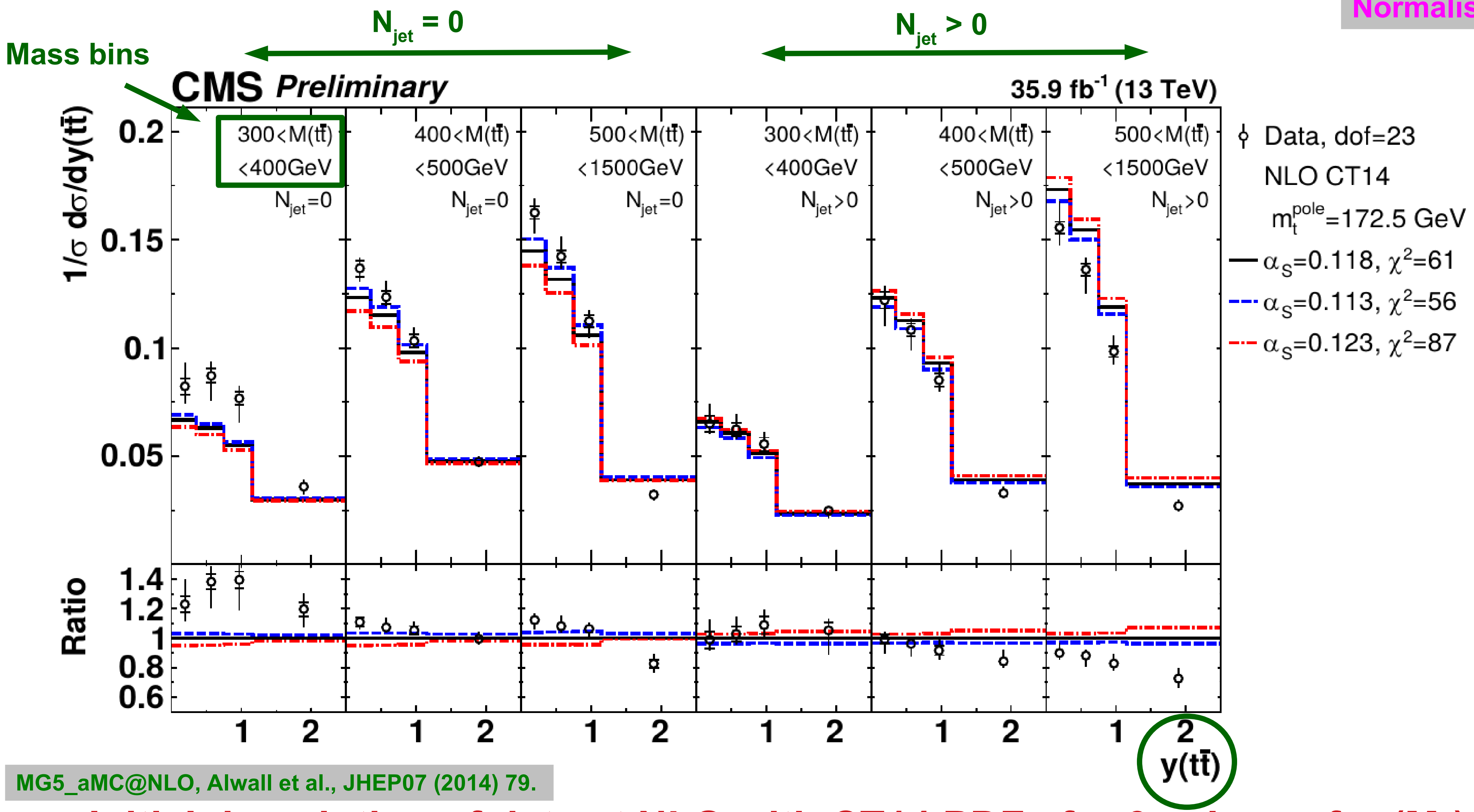
√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp m_t PDF ...	scale
7	2.3	0.1151	$^{+27}_{-26}$	$^{+9}_{-8}$
13	35.9	0.1139	23	$^{+14}_{-1}$

Sensitivity of differential cross section

NLO

Normalised

Binning in y(tt), M(tt), and jet multiplicity N_{jet}



MG5_aMC@NLO, Alwall et al., JHEP07 (2014) 79.

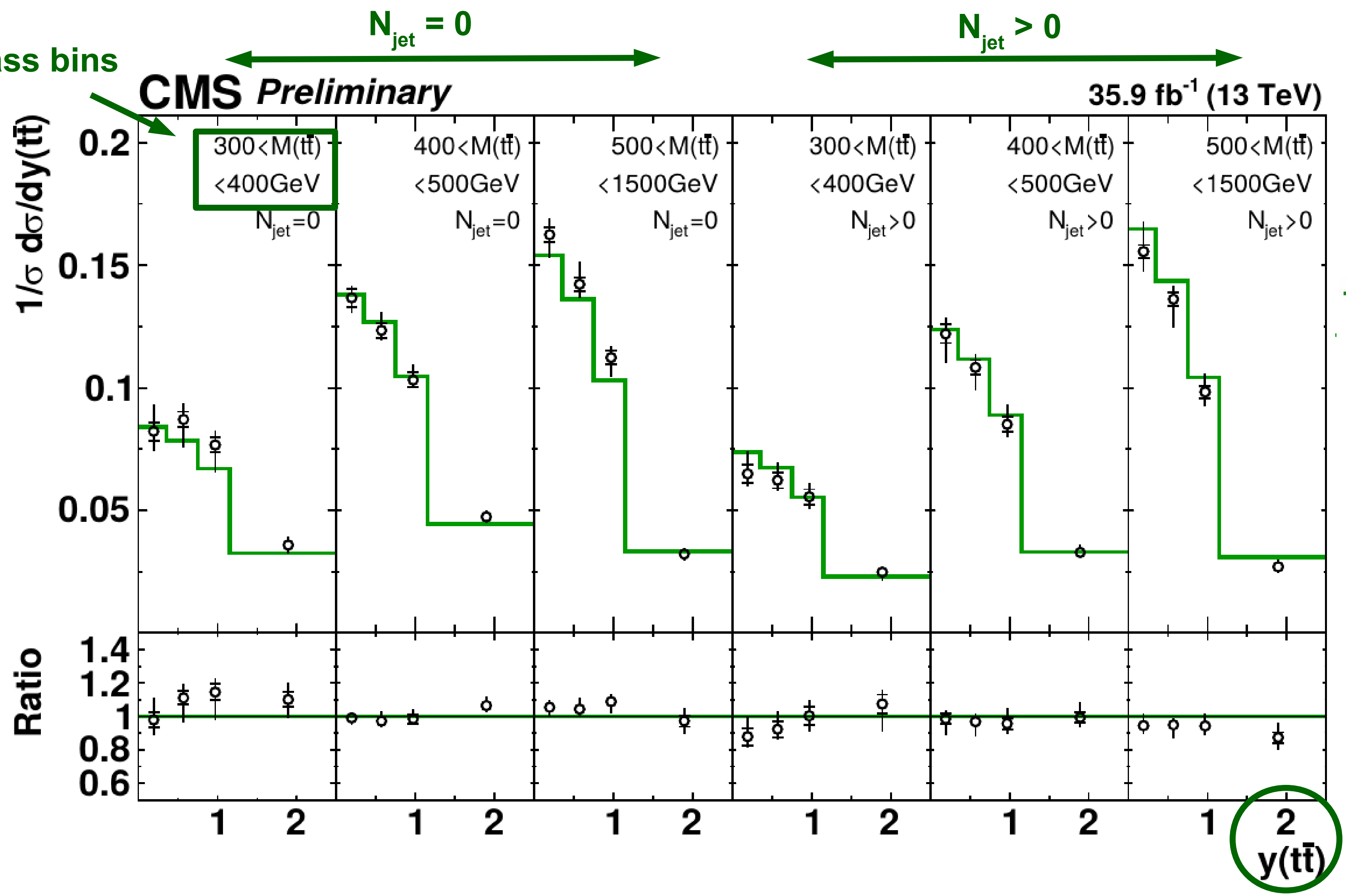
Initial description of data at NLO with CT14 PDFs for 3 values of $\alpha_s(M_Z)$

NLO

Normalised

Binning in y(tt), M(tt), and jet multiplicity N_{jet}

Mass bins



Partial χ^2 of tt only

M(tt),y(tt) → PDFs

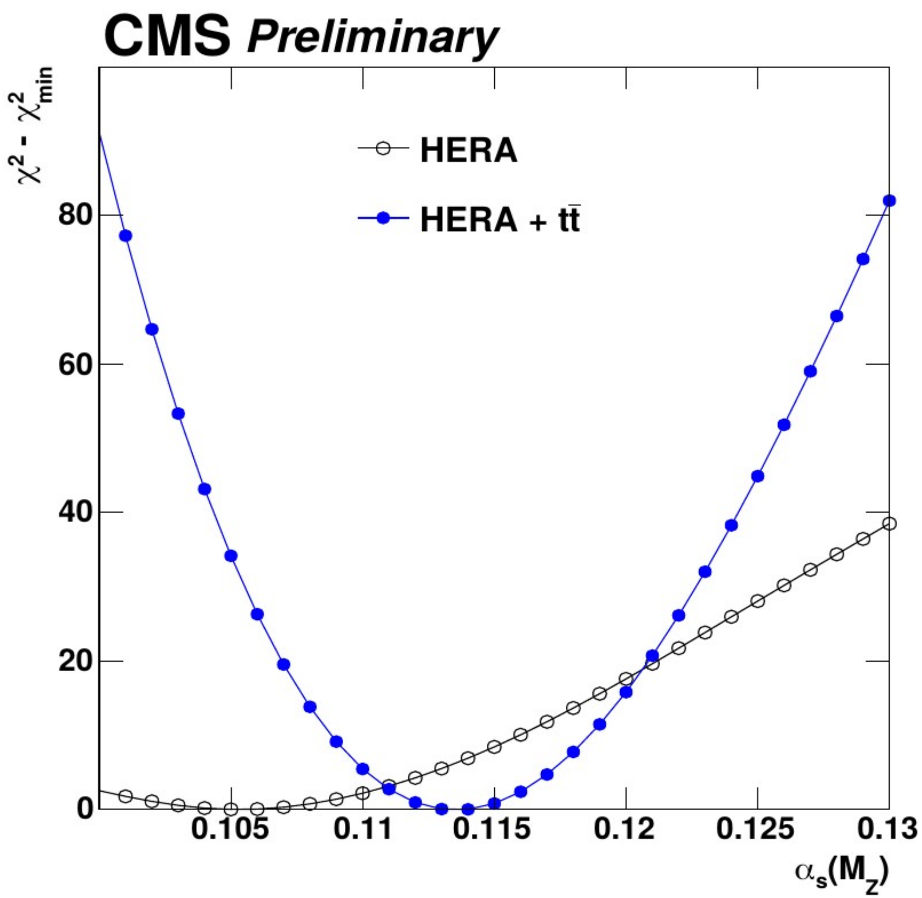
N_{jet} → m_t^{pole}, α_s

Description of data after fit of $\alpha_s(M_Z)$, m_t^{pole}, PDFs to HERA + tt data

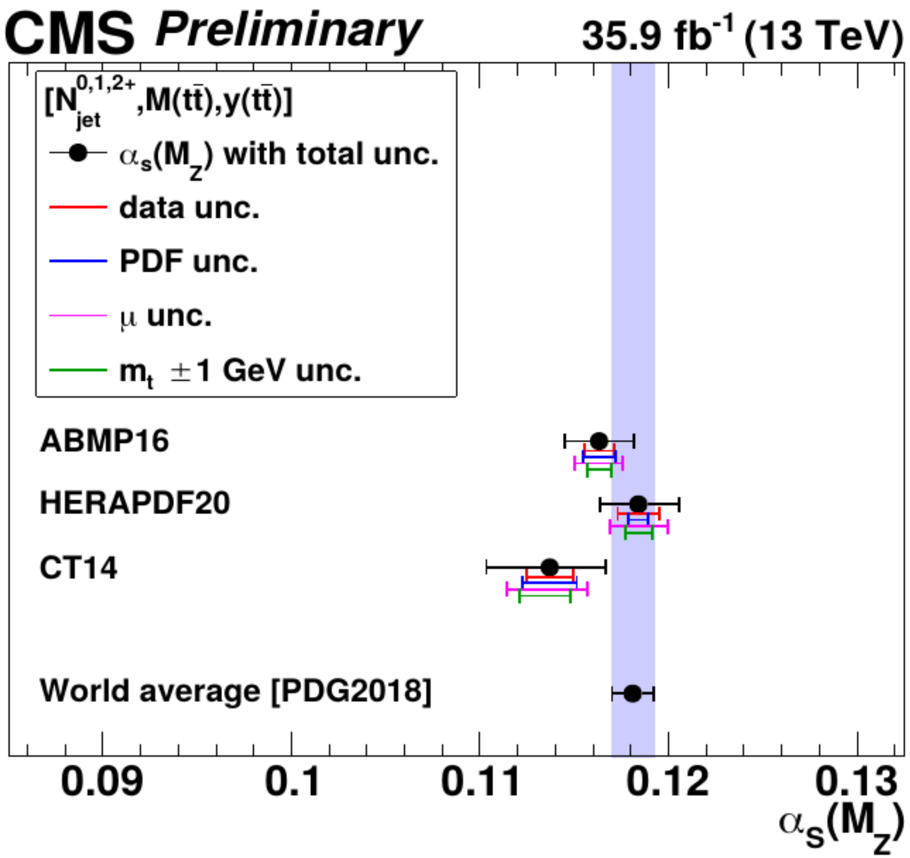
Fits using tt differential distributions

NLO

Comparison of χ^2 for $\alpha_s(M_Z)$ with HERA only and with additional tt data



Cross check $\alpha_s(M_Z)$ fit @ NLO with external PDFs ABMP16, HERAPDF20, and CT14



Summary α_s from CMS

Jet cross sections at NLO

Inclusive jets

PDF fit

Dijets

3-jet x section

3-jet ratios

tt cross sections at NLO & NNLO

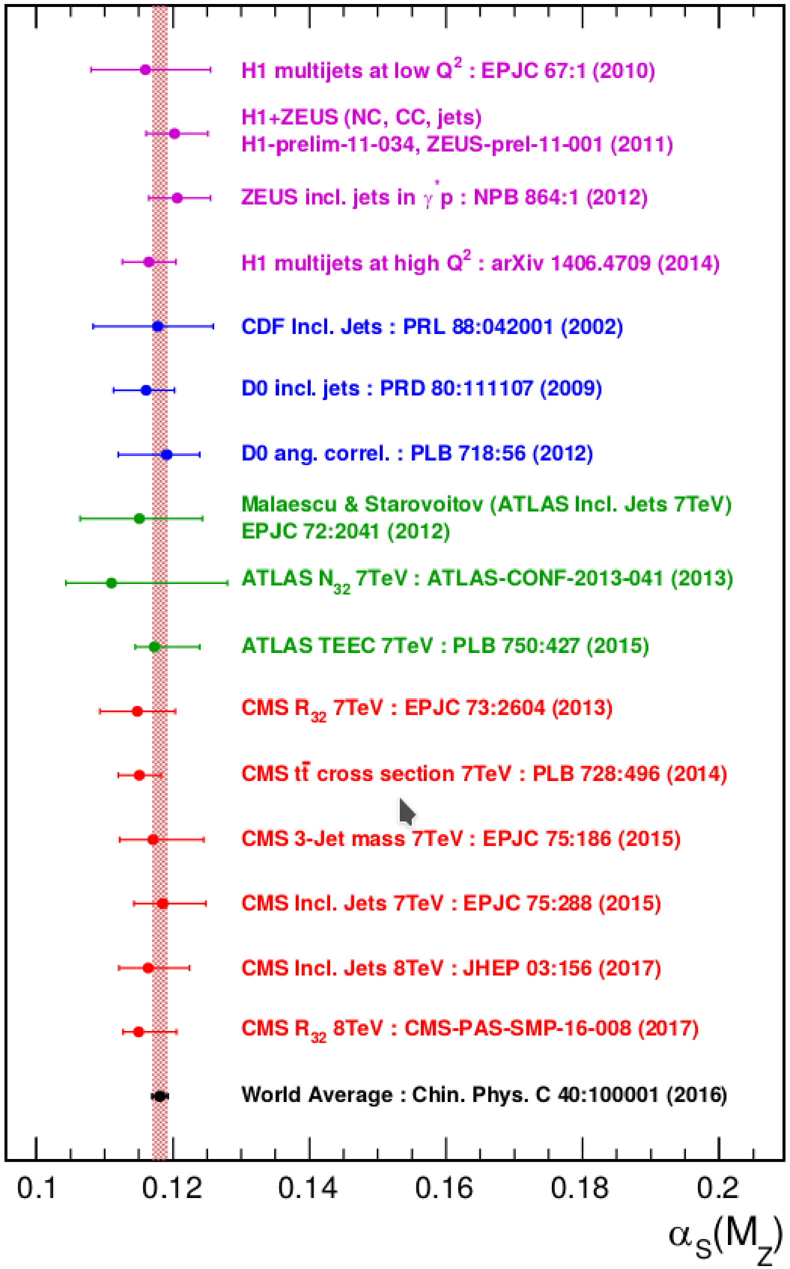
Total x section — NNLO + NNLL; NNLO

Differential — NLO

PDF fit

√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	other	scale
7	5.0	0.1185	35	$^{+53}_{-24}$
8	19.7	0.1164	$^{+29}_{-33}$	$^{+53}_{-28}$
7	5.0	0.1192	$^{+23}_{-19}$	$^{+24}_{-39}$
8	19.7	0.1185	$^{+19}_{-26}$	$^{+22}_{-18}$
8	19.7	0.1199	$^{+15}_{-16}$	$^{+31}_{-19}$
7	5.0	0.1171	28	$^{+69}_{-40}$
7	5.0	0.1148	23	50
8	19.7	0.1150	22	+50
7	2.3	0.1151	$^{+27}_{-26}$	$^{+9}_{-8}$
13	35.9	0.1139	23	$^{+14}_{-1}$
13	35.9	0.1144	25	$^{+16}_{-20}$
13	35.9	0.1135	$^{+18}_{-17}$	$^{+11}_{-5}$

α_s overview plot



Summary & Outlook

- Jet data at 7 and 8 TeV → running of α_s up to scales of 2 TeV
- Jet data at 13 TeV with NNLO+EW yet to be evaluated
- tt production cross section at 7 & 13 TeV → $\alpha_s(M_Z)$ at NNLO (or m_t)
- Top pair+jet differential distributions provide input to α_s, m_t, and PDFs
- 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? Asymmetry?
  - Nonpert. Effects: <1 % (really?)
- Beyond CMS (see also → LHC EW Working Group):
  - Combined fits of ATLAS & CMS (LHC), and of HERA & Tevatron data
- CHALLENGE: $\alpha_s(M_Z)$ at 1% from hadron colliders!

Summary & Outlook

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

Backup Slides

Scale choices

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

Some general issues

- 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 …!

Perspectives & educated guesses

- **Experiment:**
  - Done: Observables $\sigma \sim \alpha_s^2, \alpha_s^3$; $R_{3/2} \sim \alpha_s$; 7, 8 TeV; full phase space
  - In progress, 13 TeV data: Some reduction in experimental uncertainty
  - 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, $R_{\Delta\Phi}$, $R_{\Delta R}$ (→ ATLAS)
- **Theory:**
  - Scales: NNLO important → reduction by 2 – 3 percent!?
  - PDFs: Much improved after LHC I &HERA 2 data available
    - Better known gluon (Circularity jets → g(x) & jets → α_s)
    - Fits combining observables at various $\sqrt{s}$ to disentangle g(x), M_t, α_s
  - NNLO ratios?
  - NP effects?