α_s determination at the LHC

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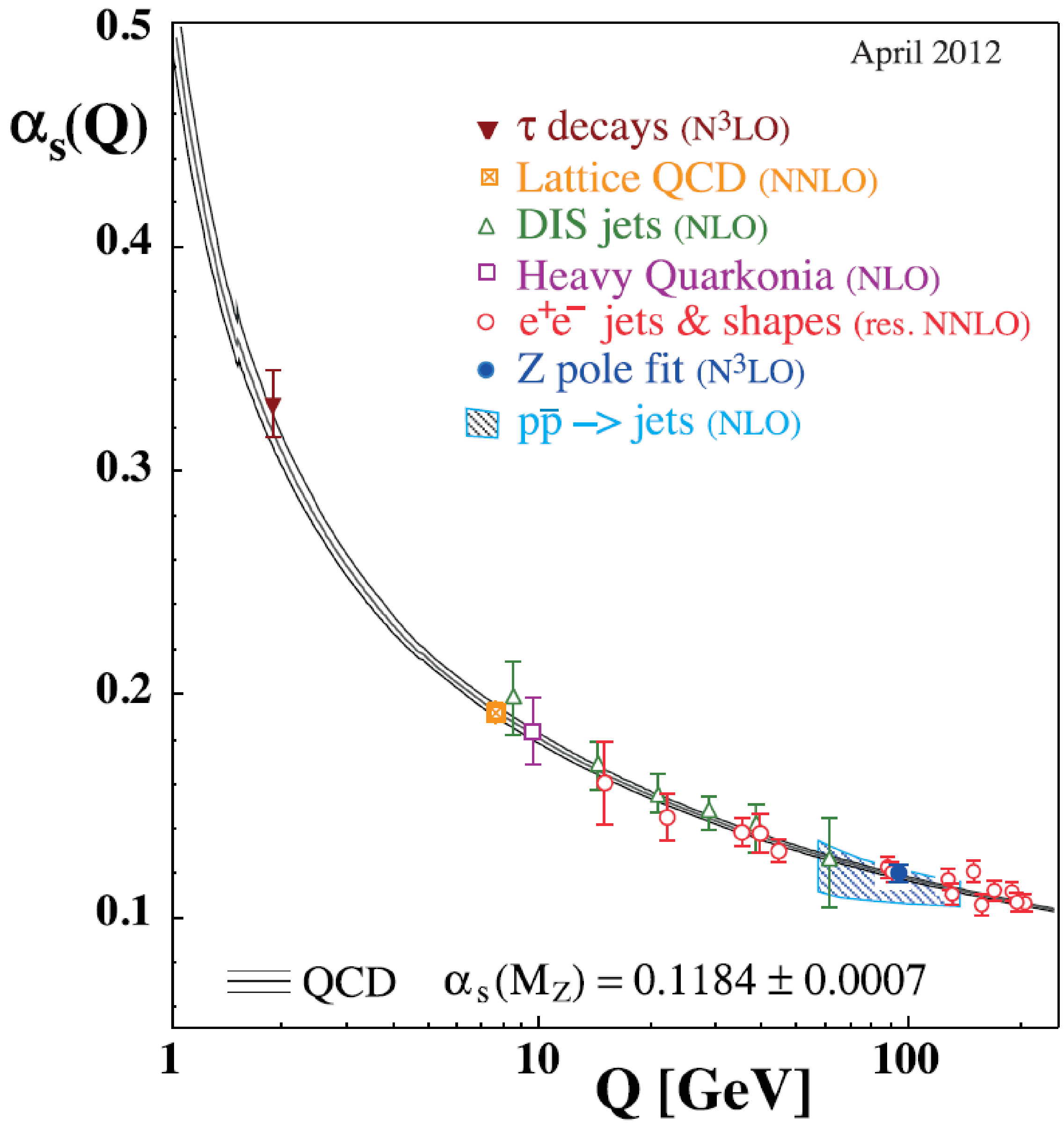
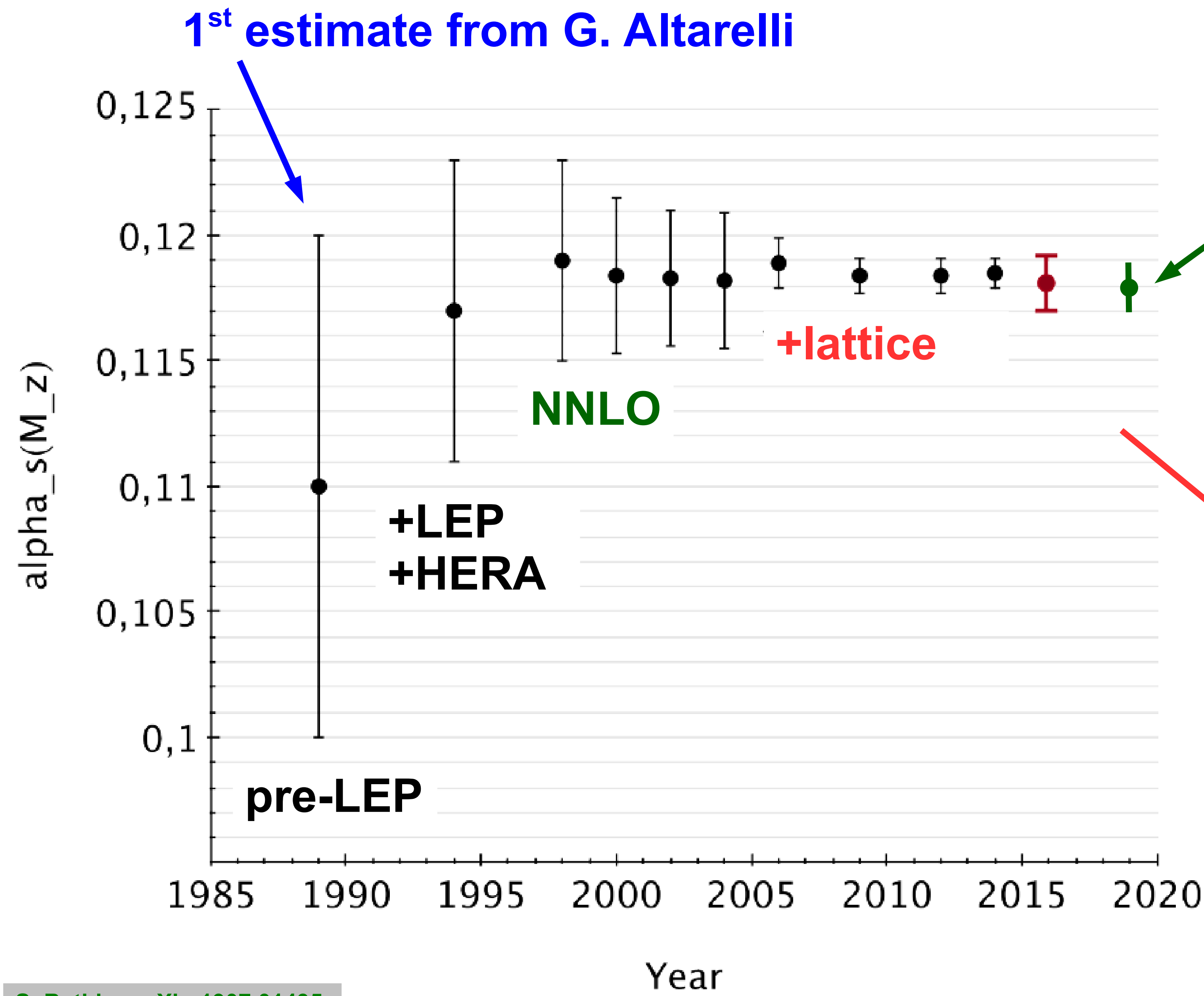
Outline

- Introduction
- Jet-like measurements
  - Cross sections
  - Ratios
  - Normalised distributions
- top-quark pair production
- W/Z bosons
- Summary & outlook

2012: No LHC results yet PDG2012



$\alpha_s(M_Z)$ world average versus time



Added: PDG 2019

Large theoretical uncertainty from (PDF + α_s) on Higgs x sections

In particular tTH & gg-Fusion: 7-13%

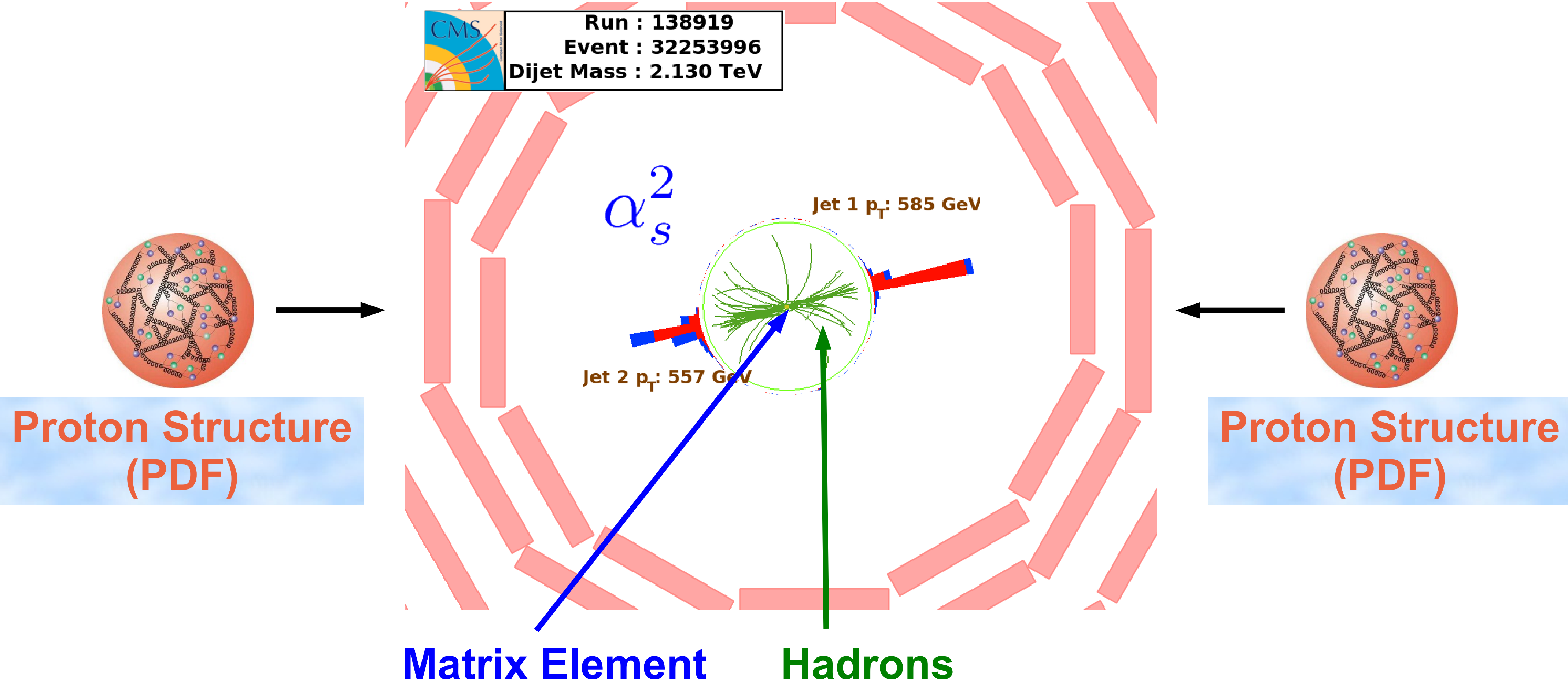
S. Bethke, arXiv:1907.01435.

CERN YR, LHC Higgs xs WG.

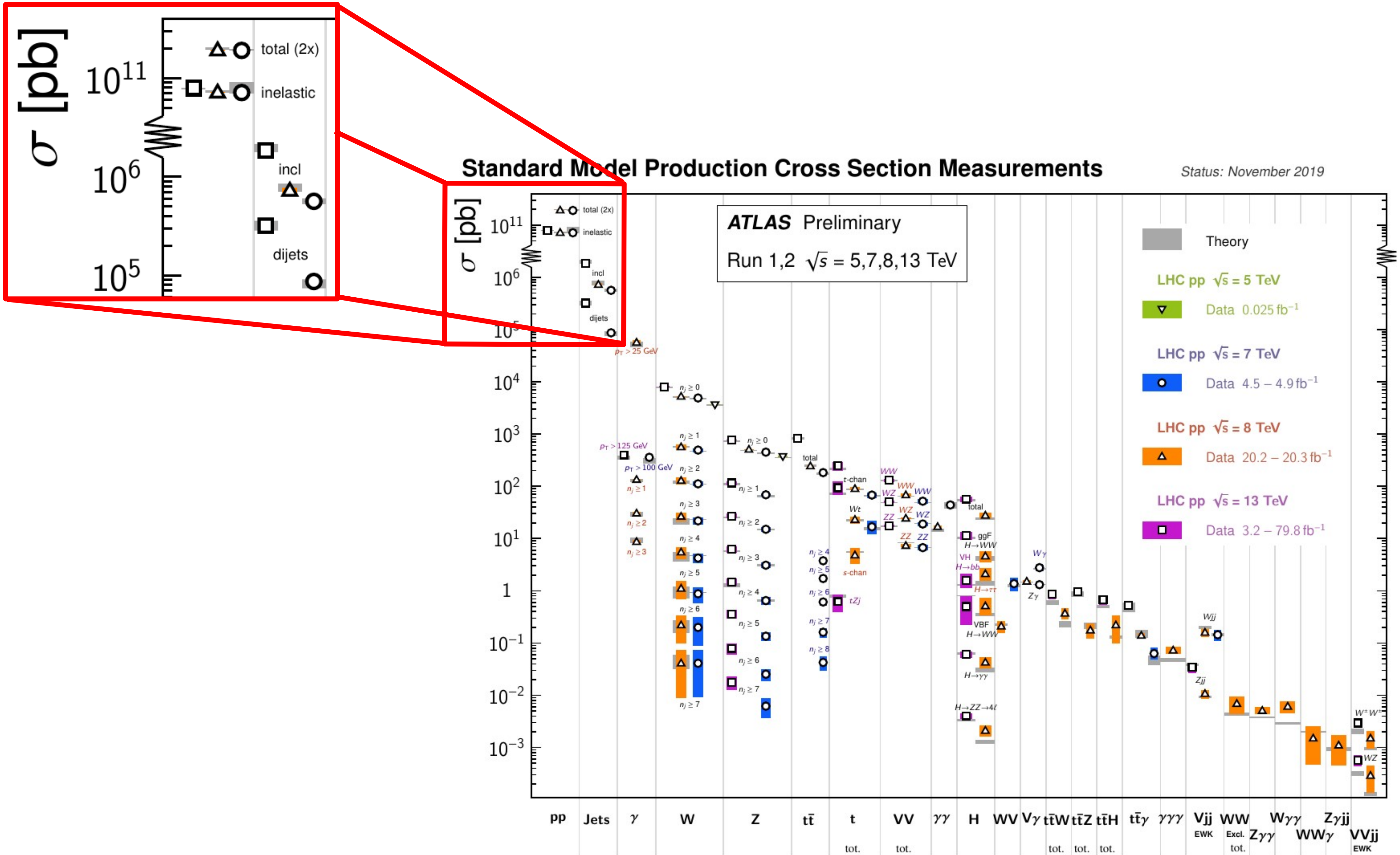
Jets at the LHC

Abundant production of jets:

- Jets at hadron colliders provide the largest dynamic range ever for $\alpha_s(Q^2)$
- Plus insights into high-p_T QCD, the proton structure, non-perturbative and electroweak effects at high Q



Jets at the LHC

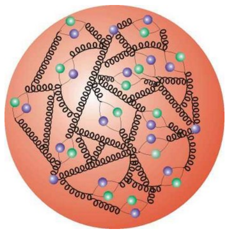


Jet cross sections ~ α_s^2

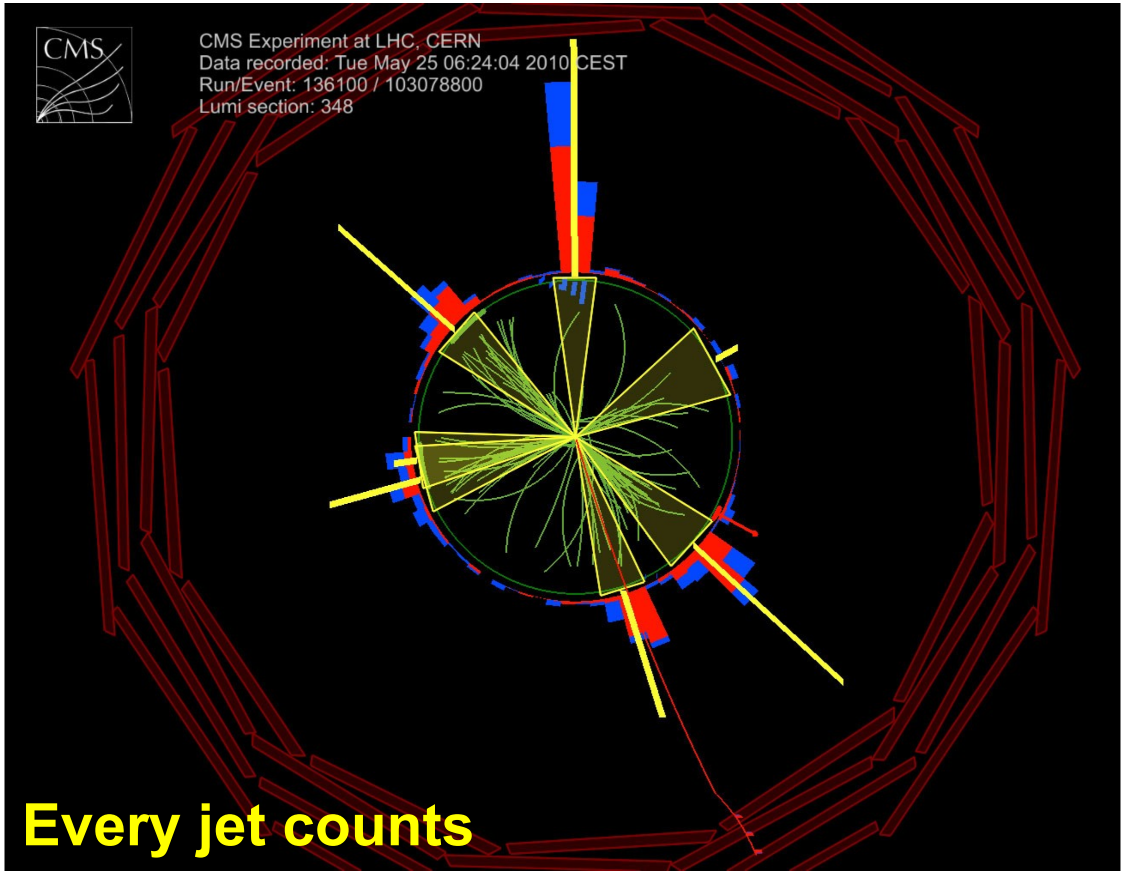
- Determination of $\alpha_s(M_Z)$ in single-parameter fit
- Test consistency of running of $\alpha_s(Q)$
- Multi-parameter fit of $\alpha_s(M_Z)$ & PDFs

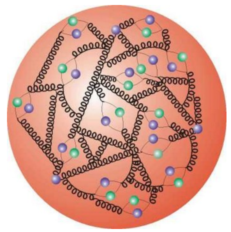
All inclusive

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.

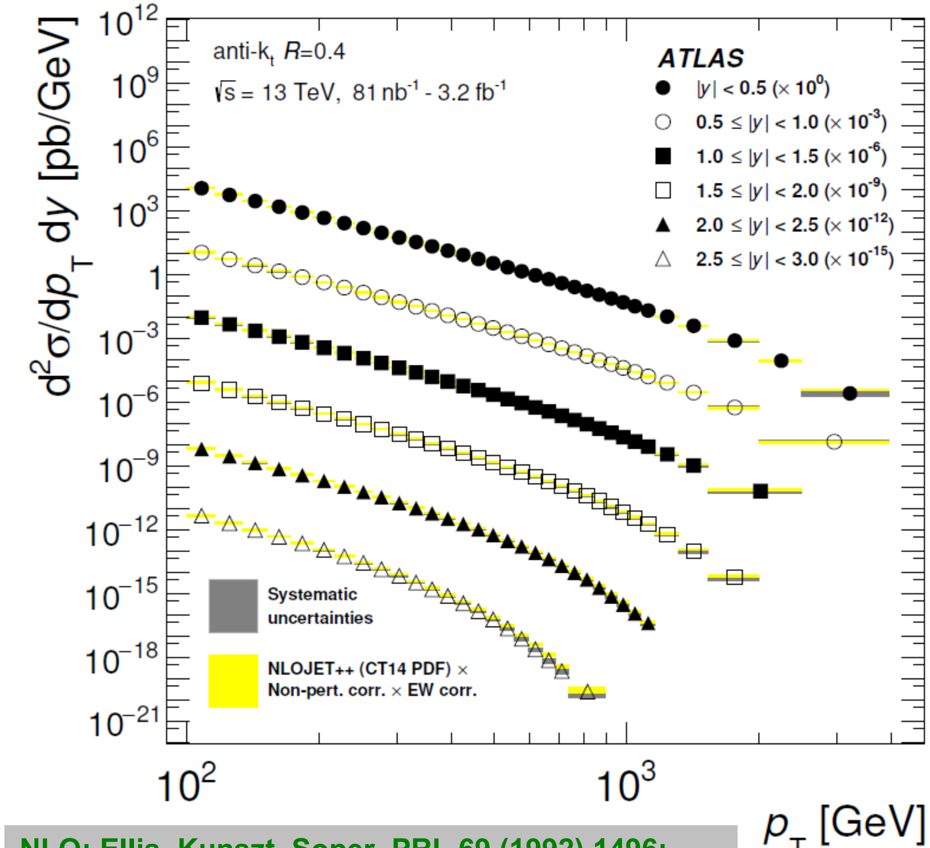
Inclusive jets: cross section

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.

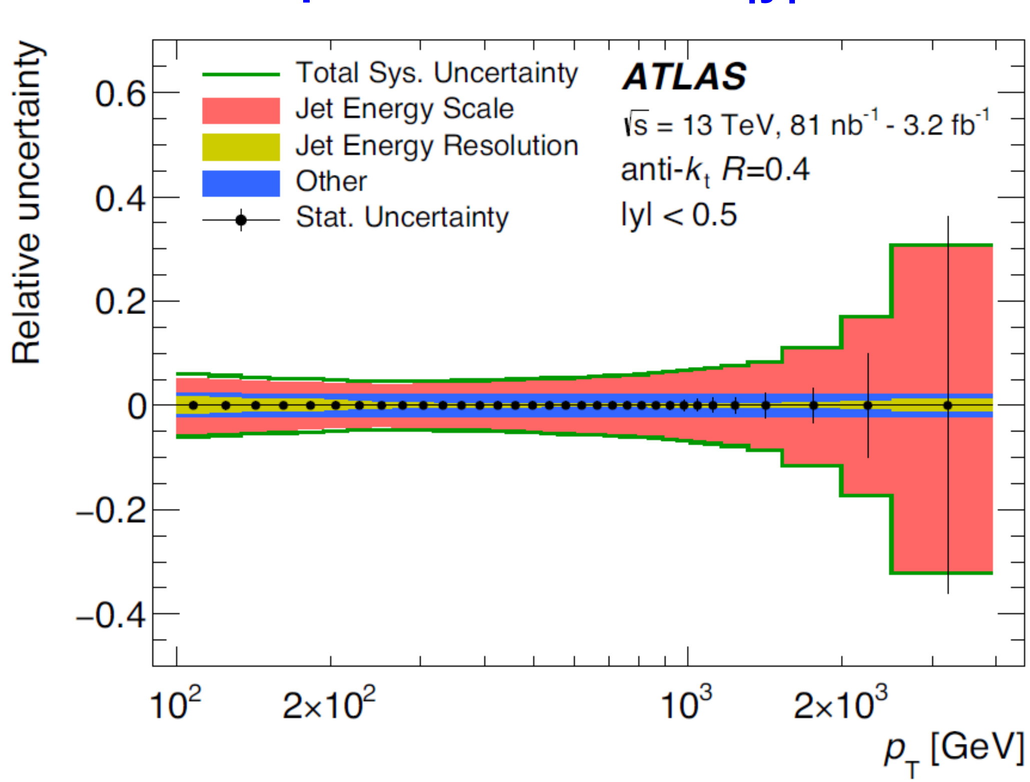
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

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

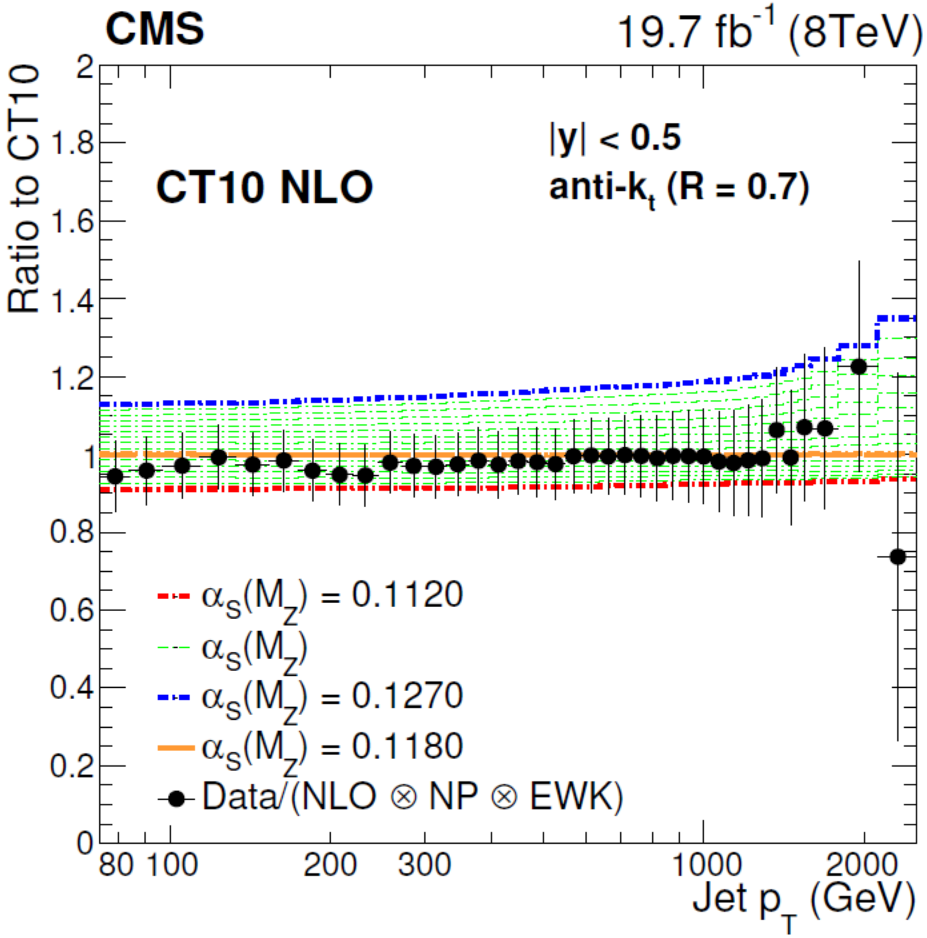


NLO: Ellis, Kunszt, Soper, PRL 69 (1992) 1496;
Giele, Glover, Kosower, NPB 403 (1993) 633;
Z. Nagy, PRD 68 (2003) 094002.

Inclusive jets: α_s

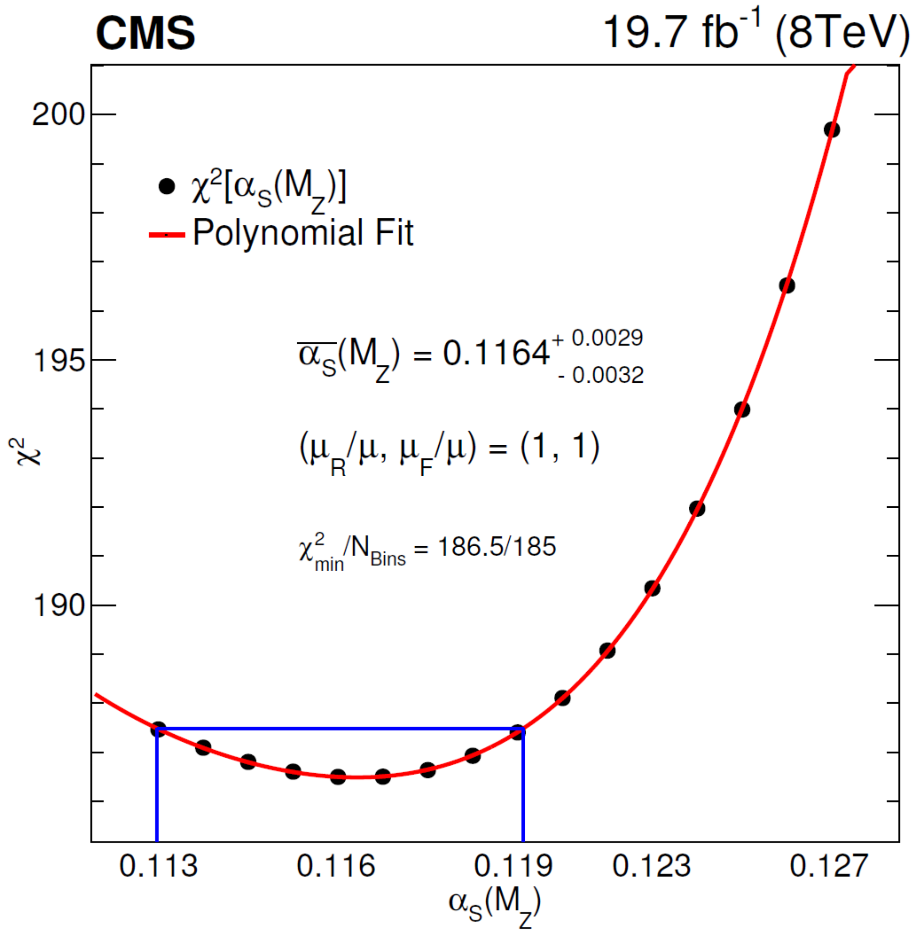
Sensitivity to $\alpha_s(M_Z)$ at NLO

- 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 $\alpha_s(M_Z)$



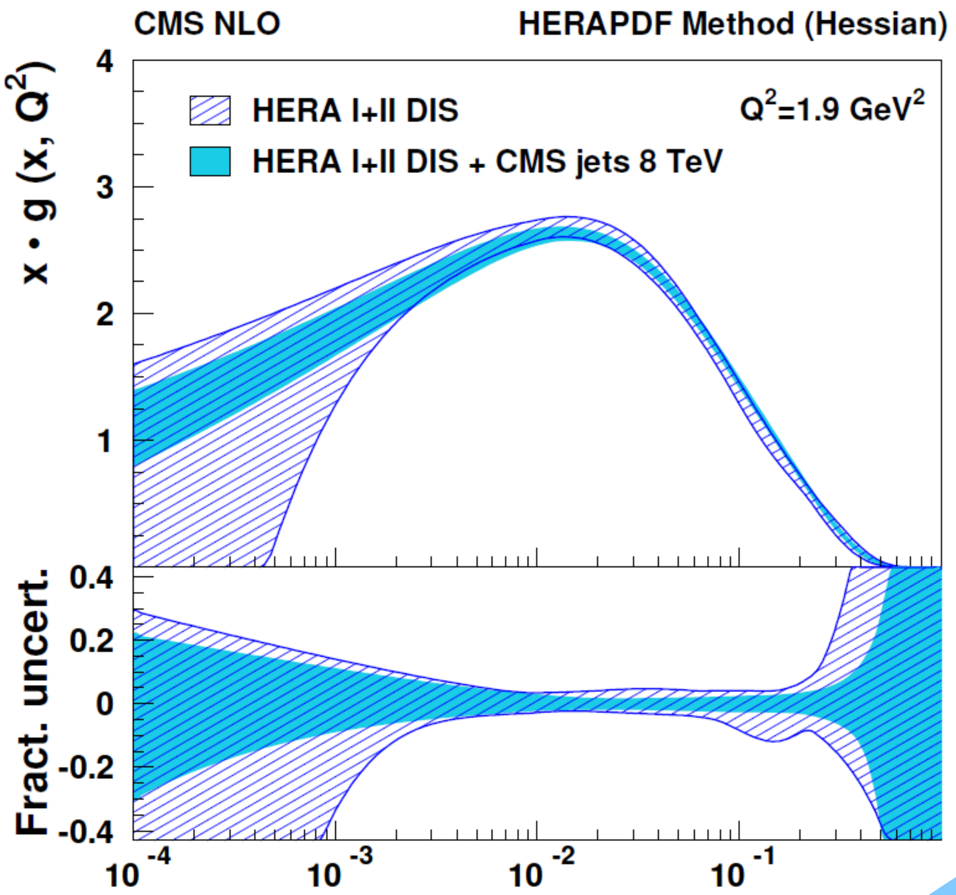
Jets @ NNLO not fully used yet in fits @ LHC → in progress

Results for ep: → Britzger et al., EPJC79 (2019) 845.

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

CMS 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	$^{+19}_{-26}$	$^{+22}_{-18}$

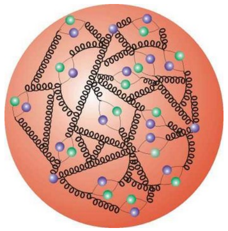
Question: How to deal with uncertainty of Missing higher orders (aka scale uncertainty) in PDF fits?

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

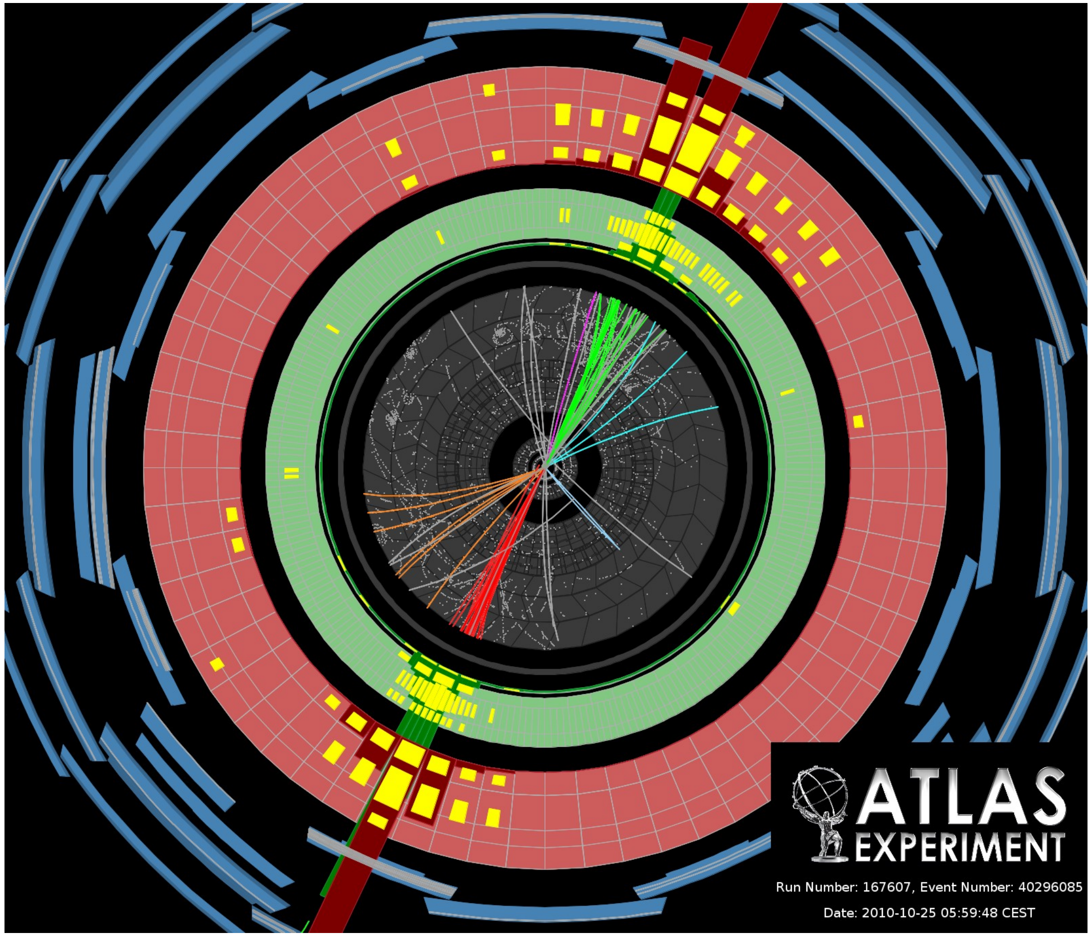
First progress → e.g. NNPDF, EPJC79 (2019) 931.

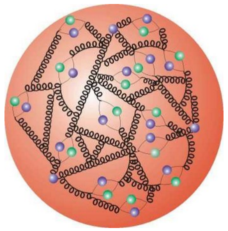
Dijets

Large masses



Proton





Proton

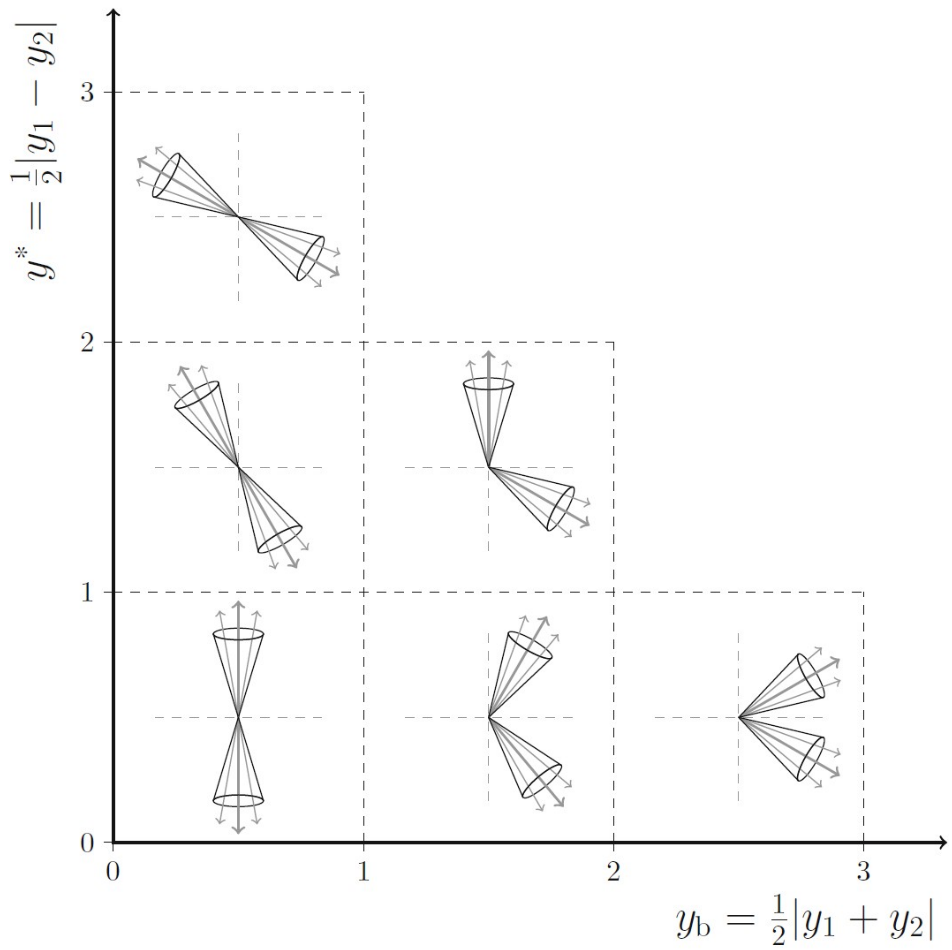
Relevant ATLAS & CMS measurements:

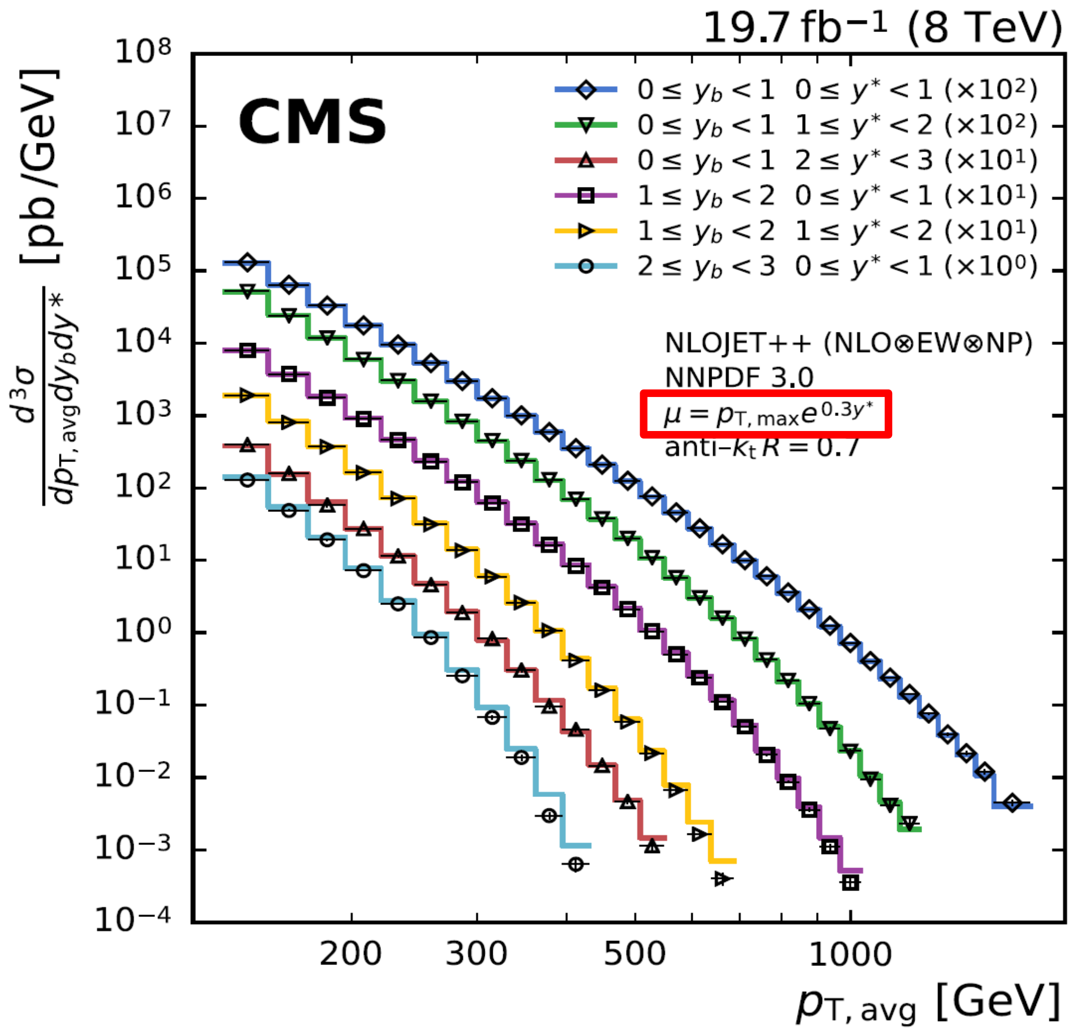
ATLAS:
JHEP 05 (2014) 059; JHEP 05 (2018) 195.
CMS:
PRD 87 (2013) 112002; EPJC 77 (2017) 746.

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

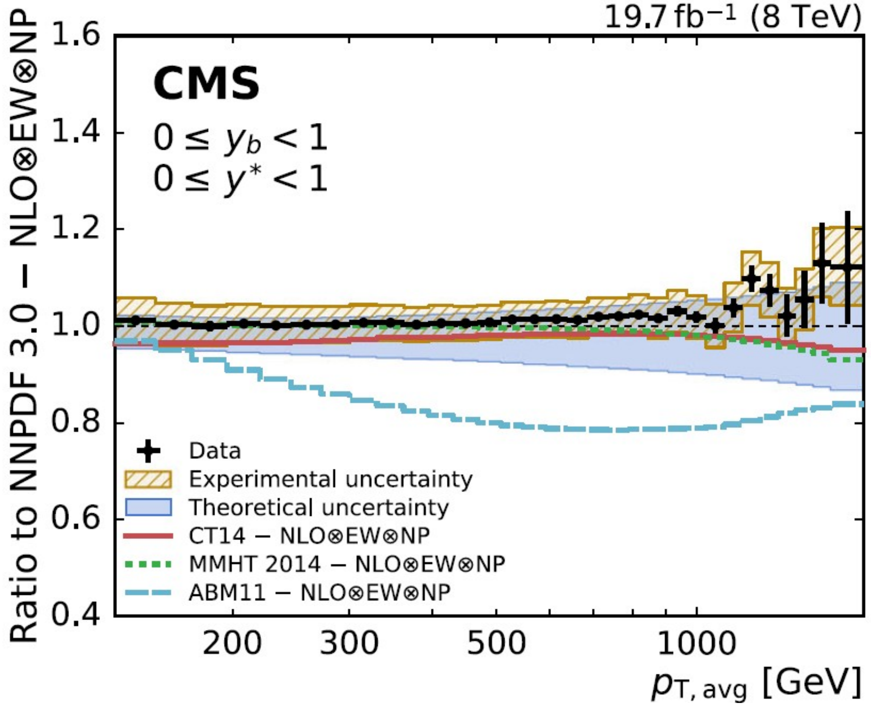




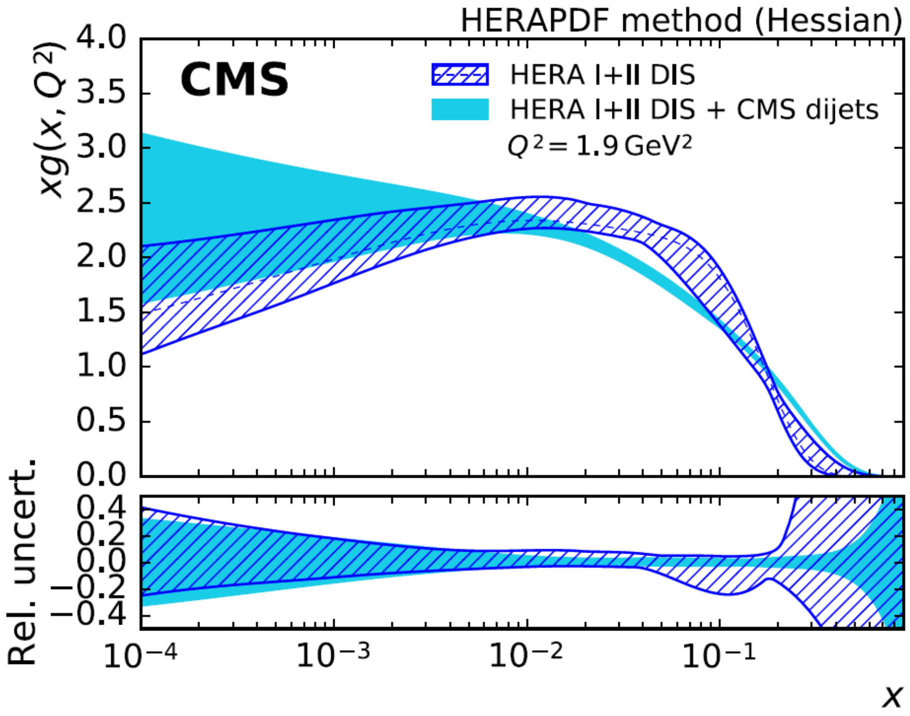
Triple-differential dijets

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

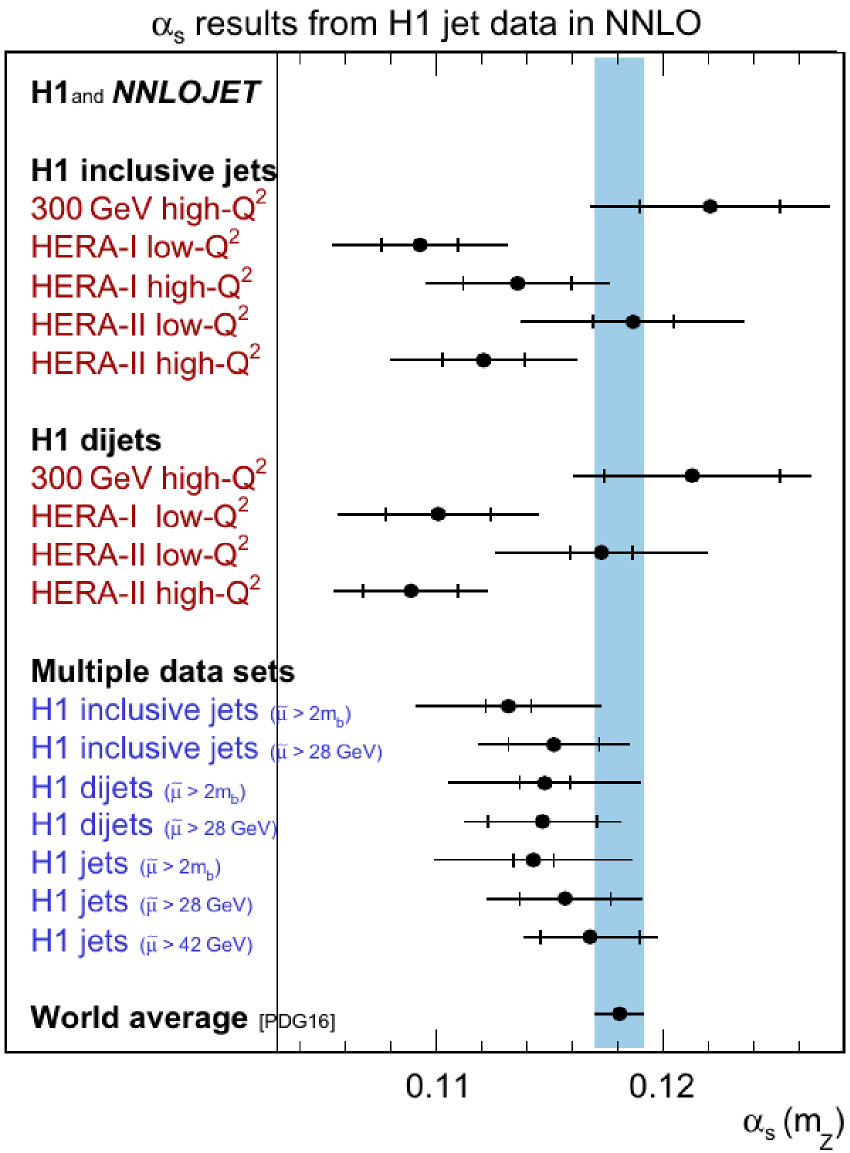


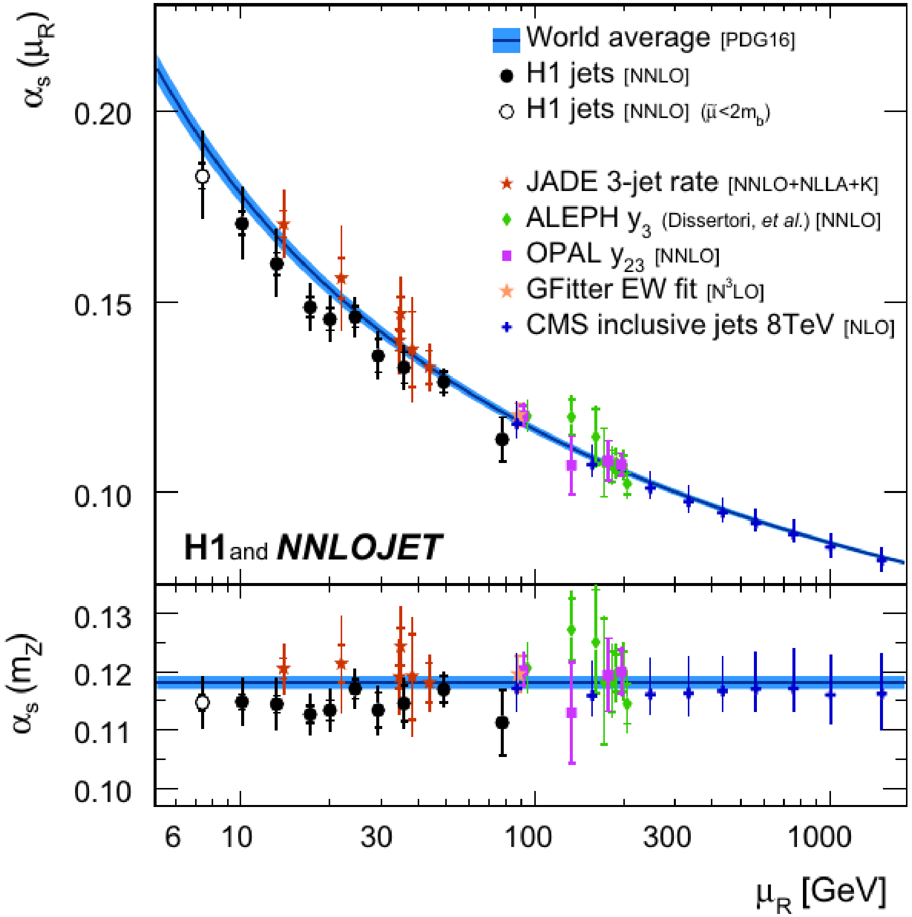
16-parameter fit

√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

Inclusive & Dijets at HERA

NNLO





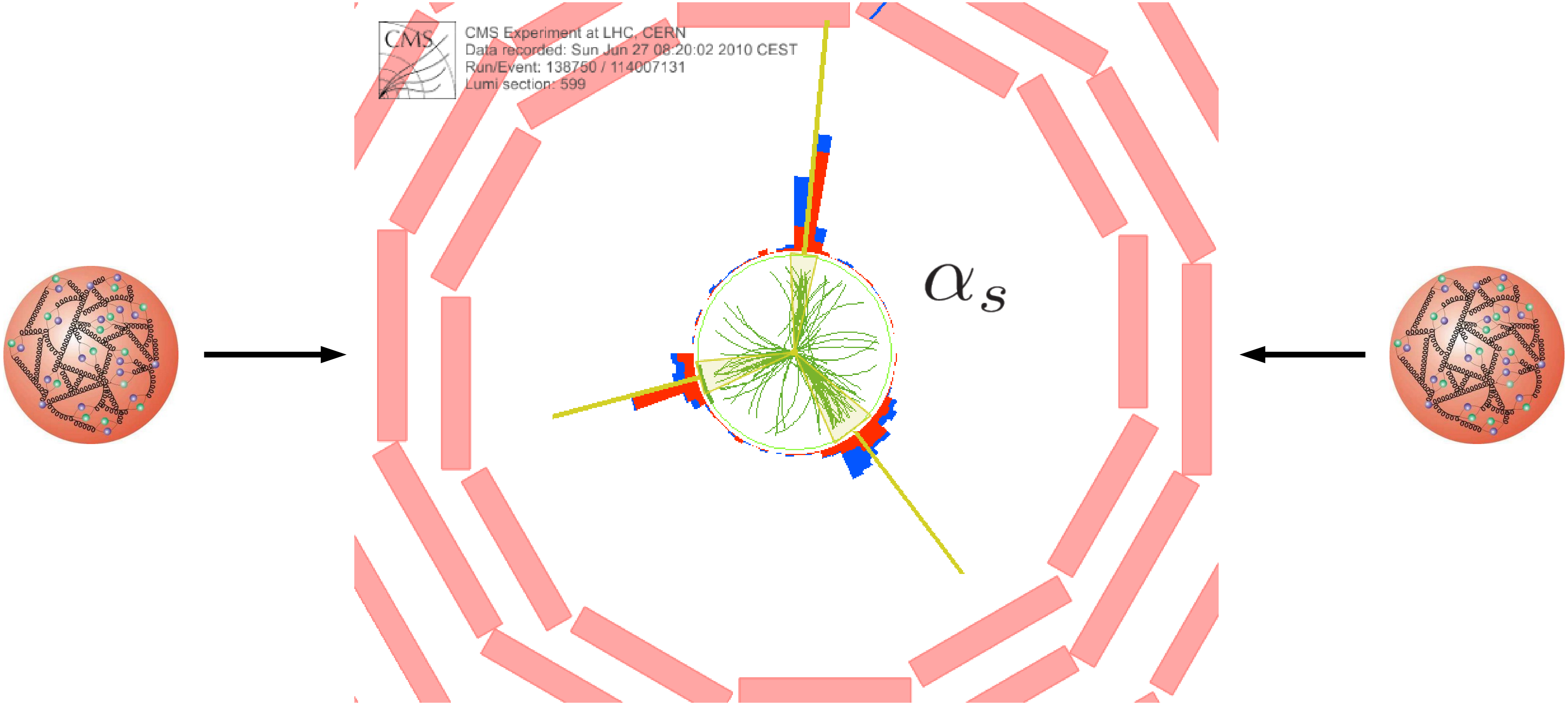
$$\alpha_s(M_Z) = 0.1157 \begin{smallmatrix}+0.0035\\-0.0035\end{smallmatrix}$$ **Fit α_s**

$$\alpha_s(M_Z) = 0.1142 \begin{smallmatrix}+0.0028\\-0.0028\end{smallmatrix}$$ **Fit PDF + α_s**

H1 & NNLOJET, EPJC 77 (2017) 791.

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).

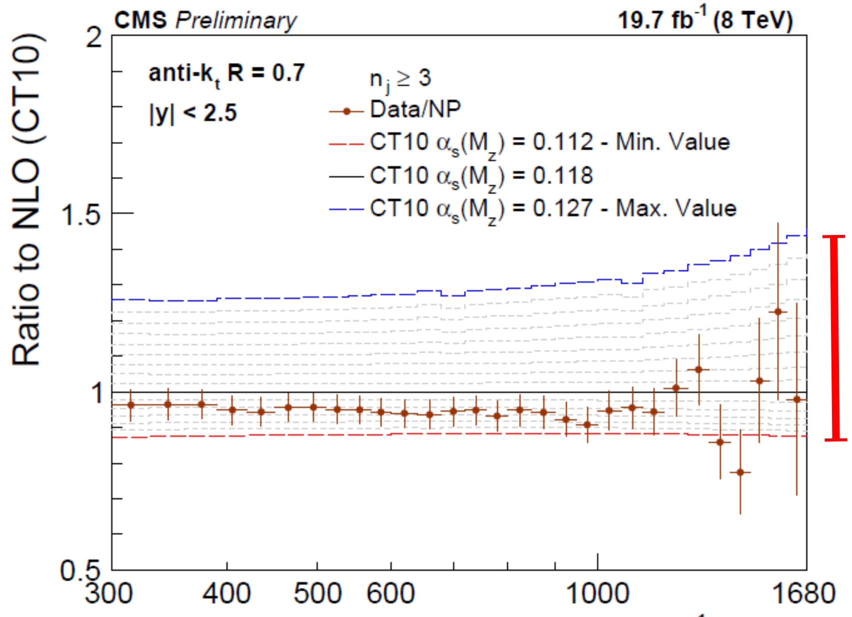
Jet cross section ratios

- 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

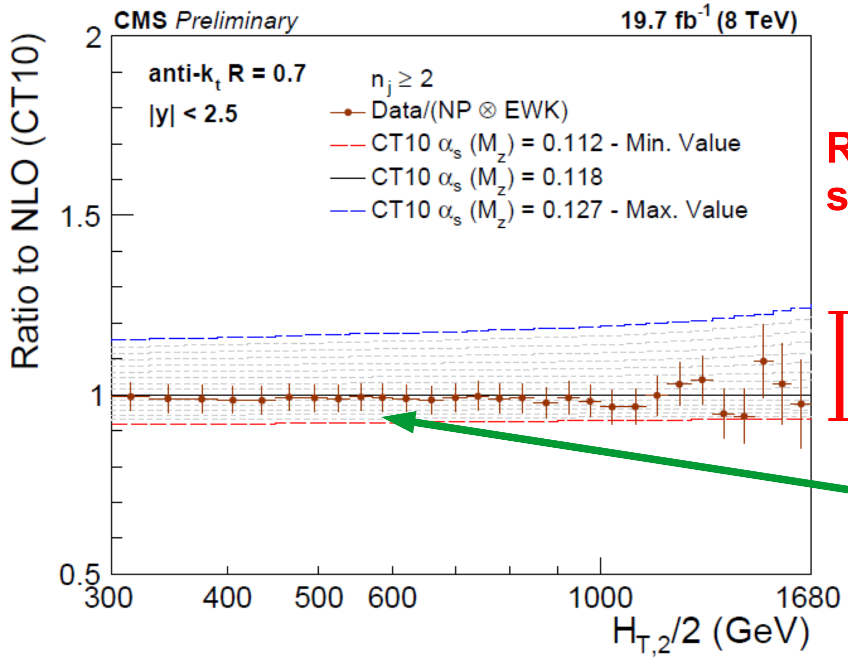
Inclusive 3-jet cross section

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



Inclusive 2-jet cross section

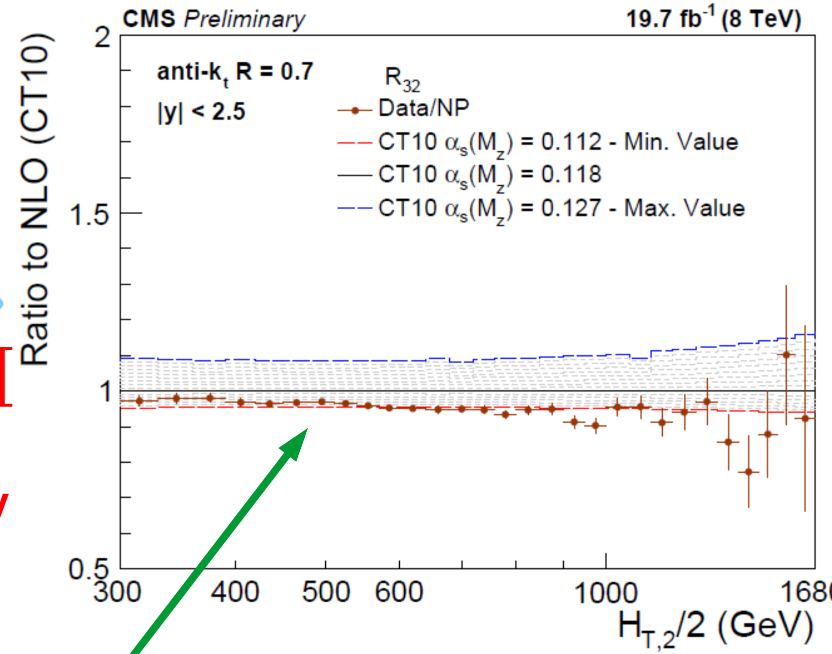
$$\sigma_{2\mathrm{j}} \propto \alpha_s^2$$



Reduced sensitivity

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

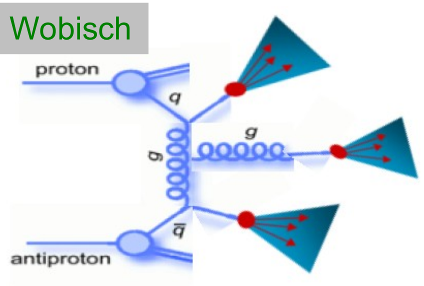
$$R_{3/2} \propto \alpha_s$$

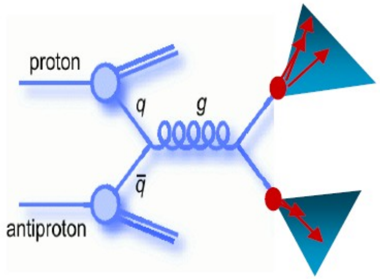


Much reduced systematic uncertainty

3- to 2-jet ratios

M. Wobisch

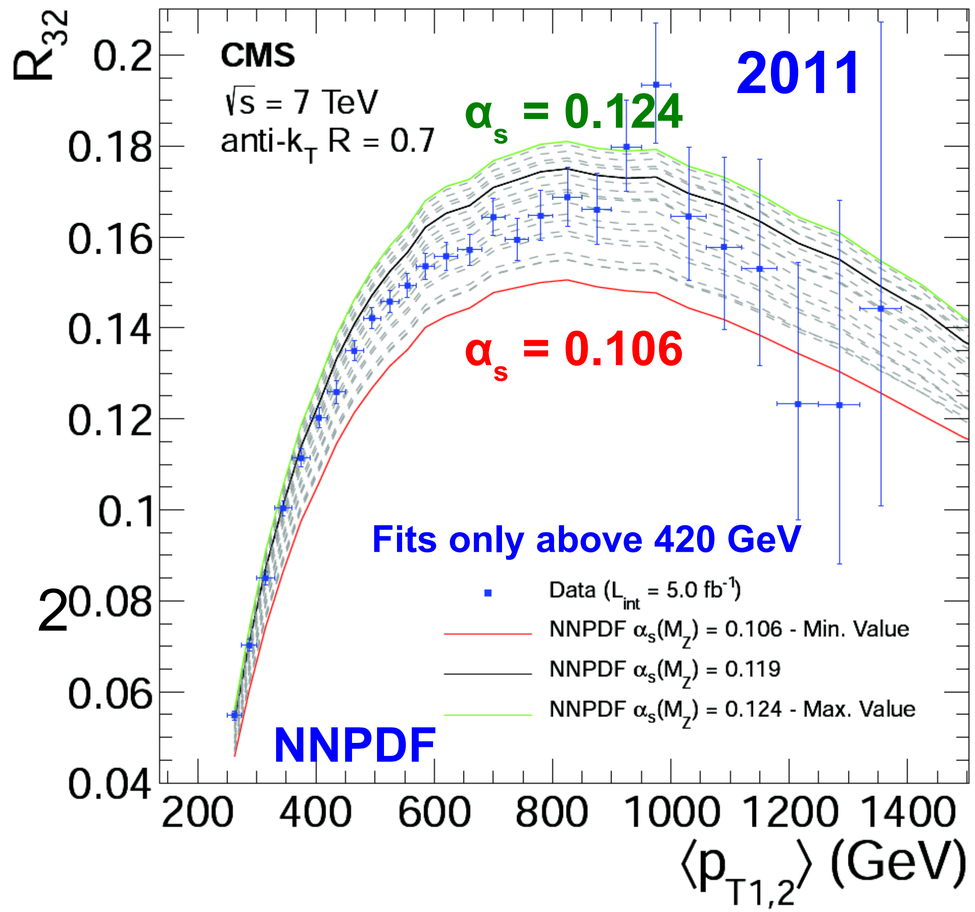




$R_{3/2}$ ⇔ α_s

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

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



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

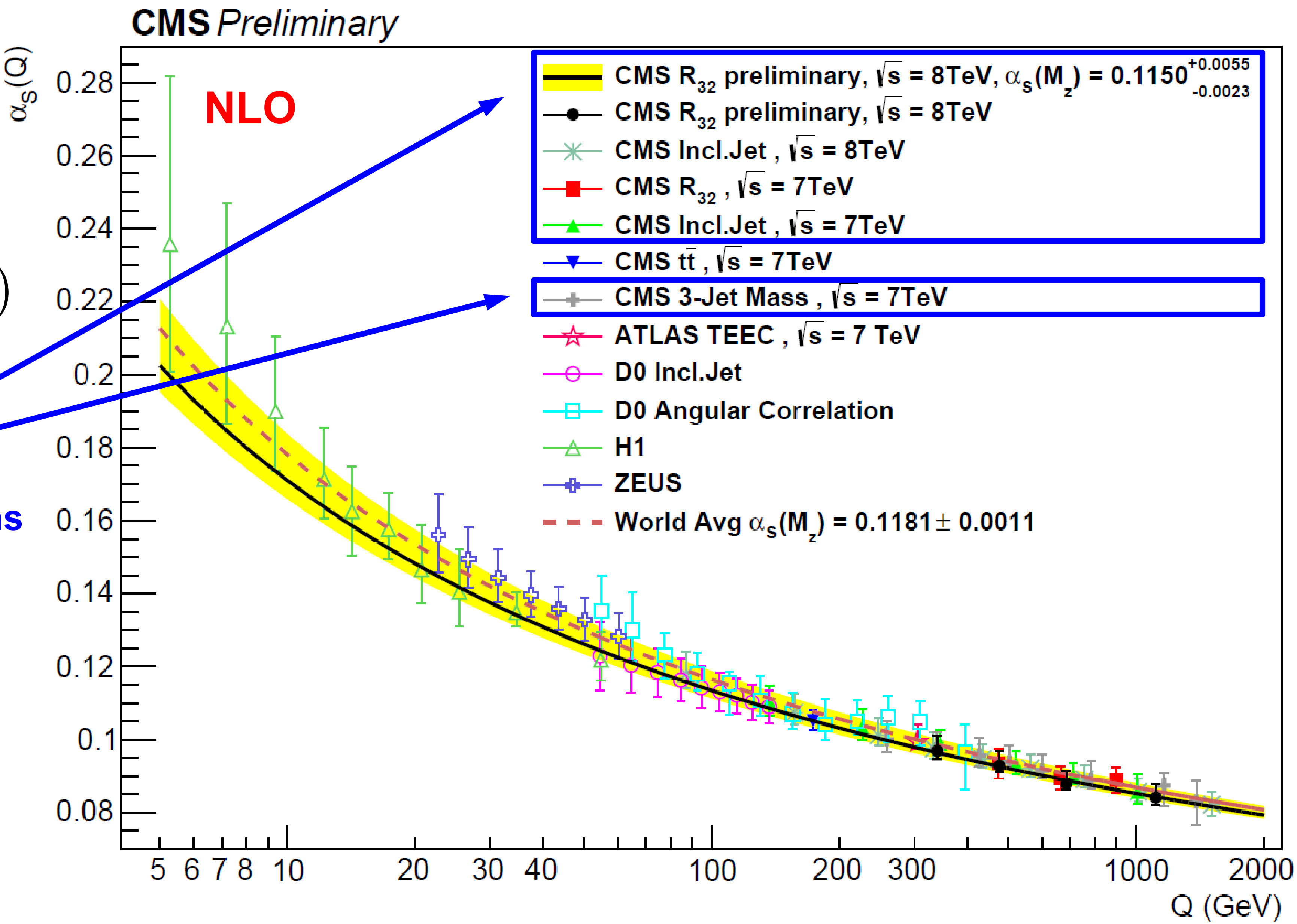
√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1148	23	50
8	19.7	0.1150	22	+50

Running of $\alpha_s(Q)$

Perform fits in fixed intervals of the chosen scale Q

$\Rightarrow \alpha_s(Q)$

Jet cross sections and ratios

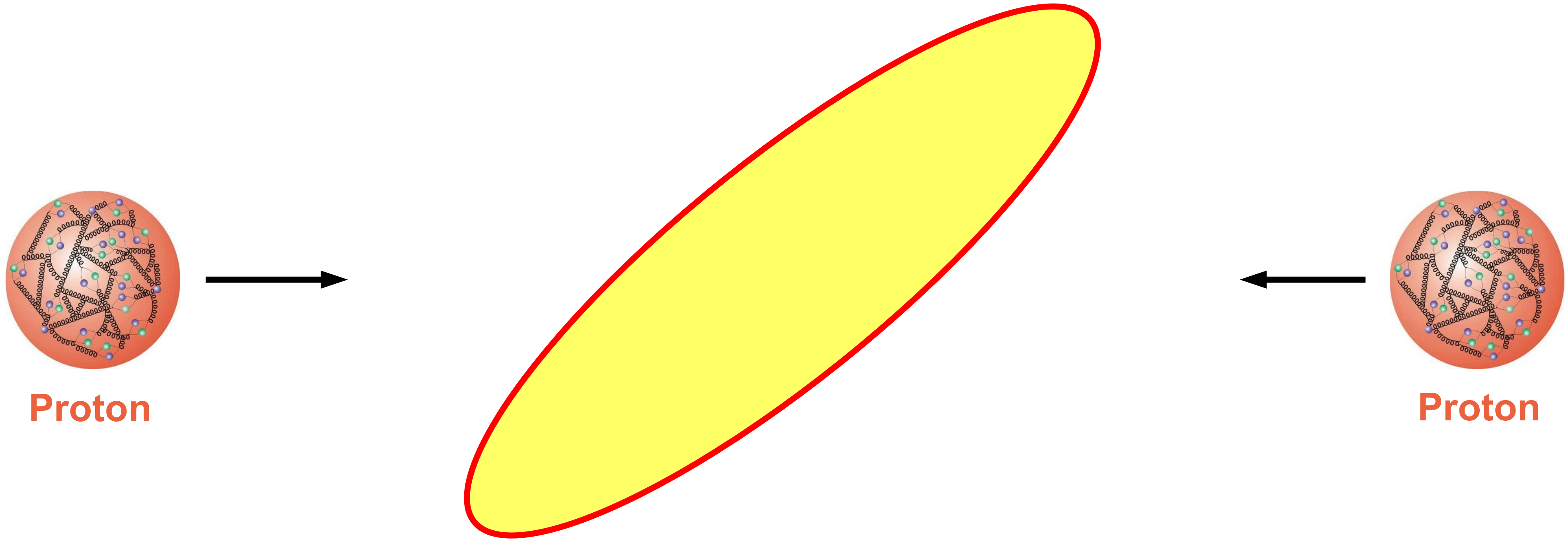


Needs an update for latest ATLAS, CMS, & H1 points ...

New range explored at LHC →

Normalised distributions

Event shapes



Relevant ATLAS & CMS measurements:

ATLAS:
PLB 750 (2015) 427; EPJC 77 (2017) 872; PRD98 (2018) 092004.

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

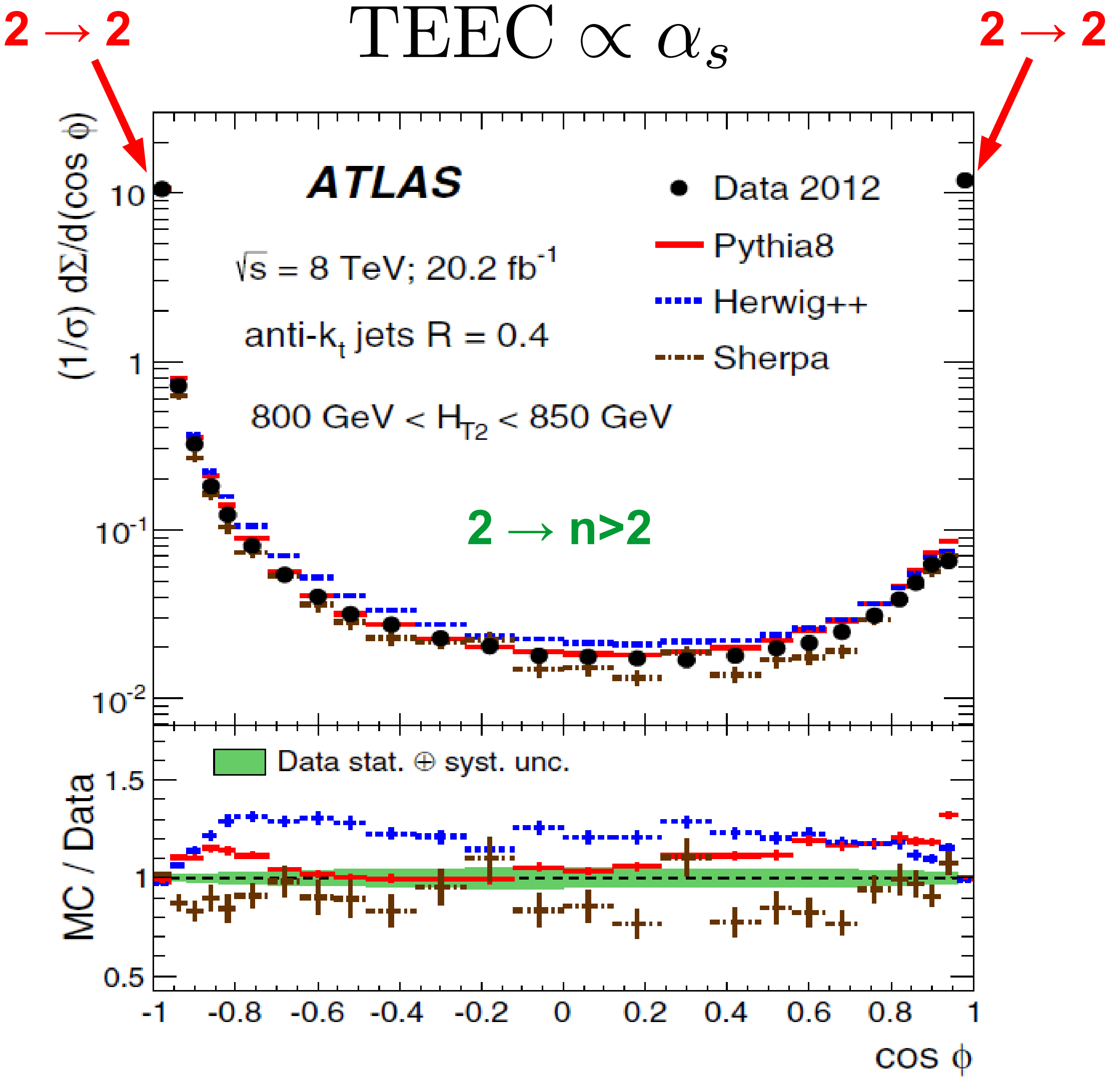
Transverse energy-energy correlation

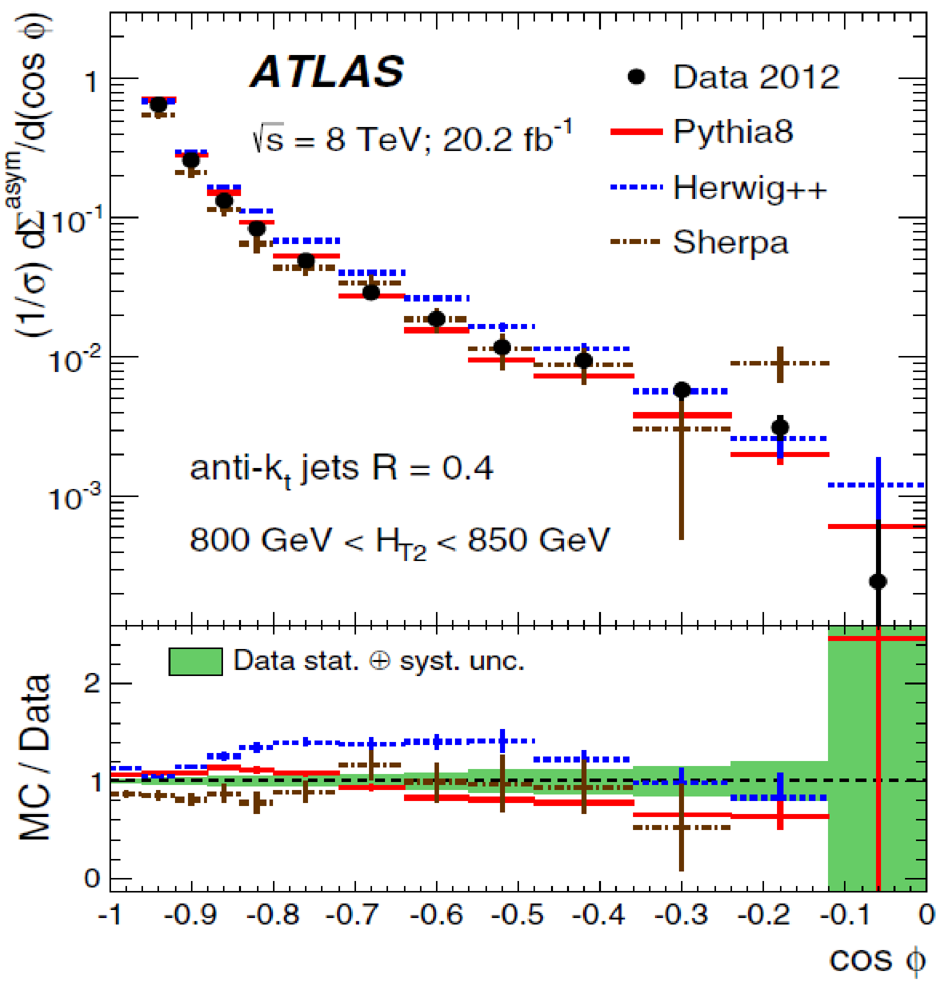
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

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

TEEC $\propto \alpha_s$

ATEEC $\propto \alpha_s$



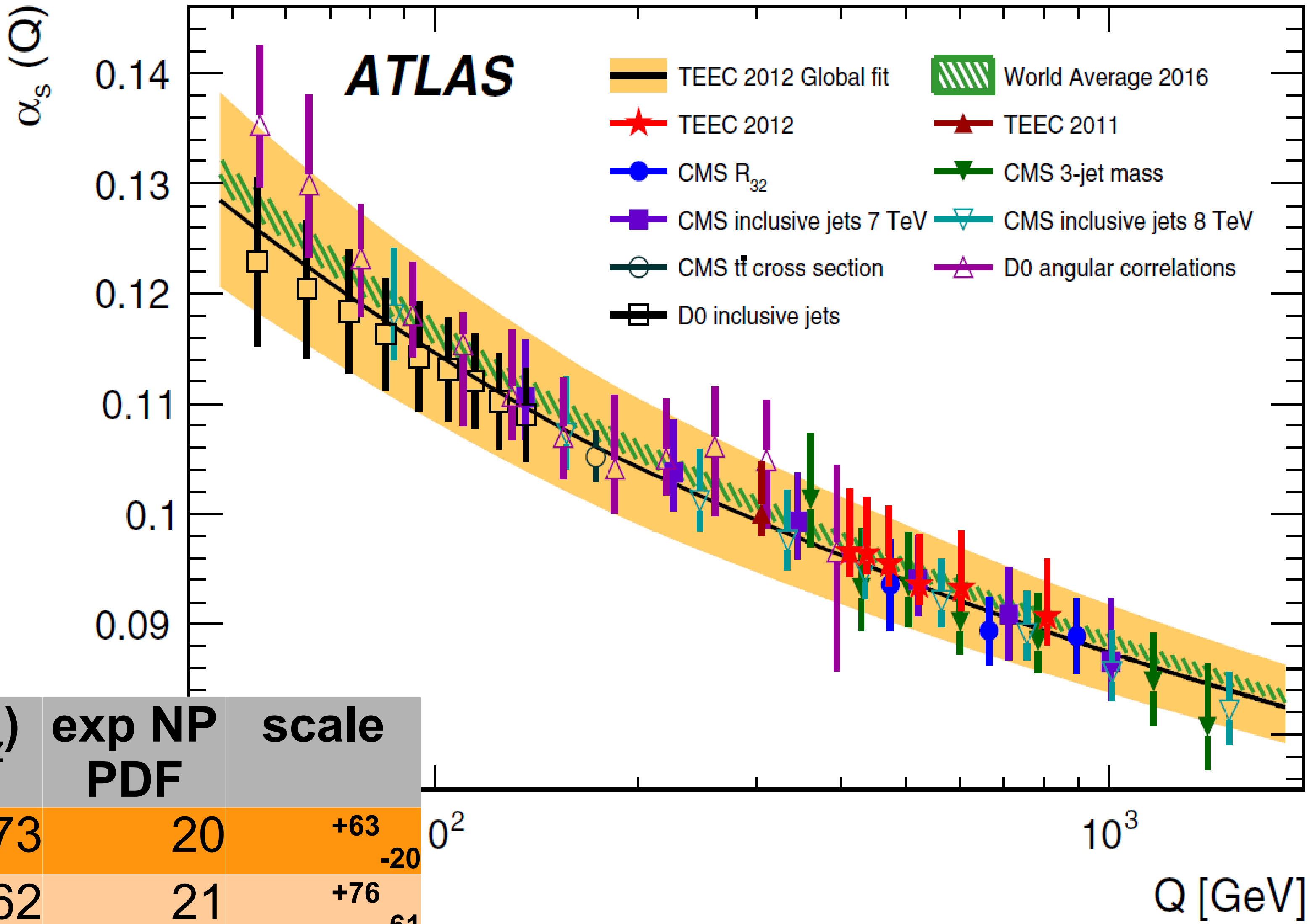


Theory:
3-jet NLOJet++

Scale choice:

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

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



$\sqrt{s}$ [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	0.16	0.1173	20	$^{+63}_{-20}$
8	20.2	0.1162	21	$^{+76}_{-61}$
7	0.16	0.1195	24	$^{+60}_{-15}$
8	20.2	0.1196	22	$^{+61}_{-13}$

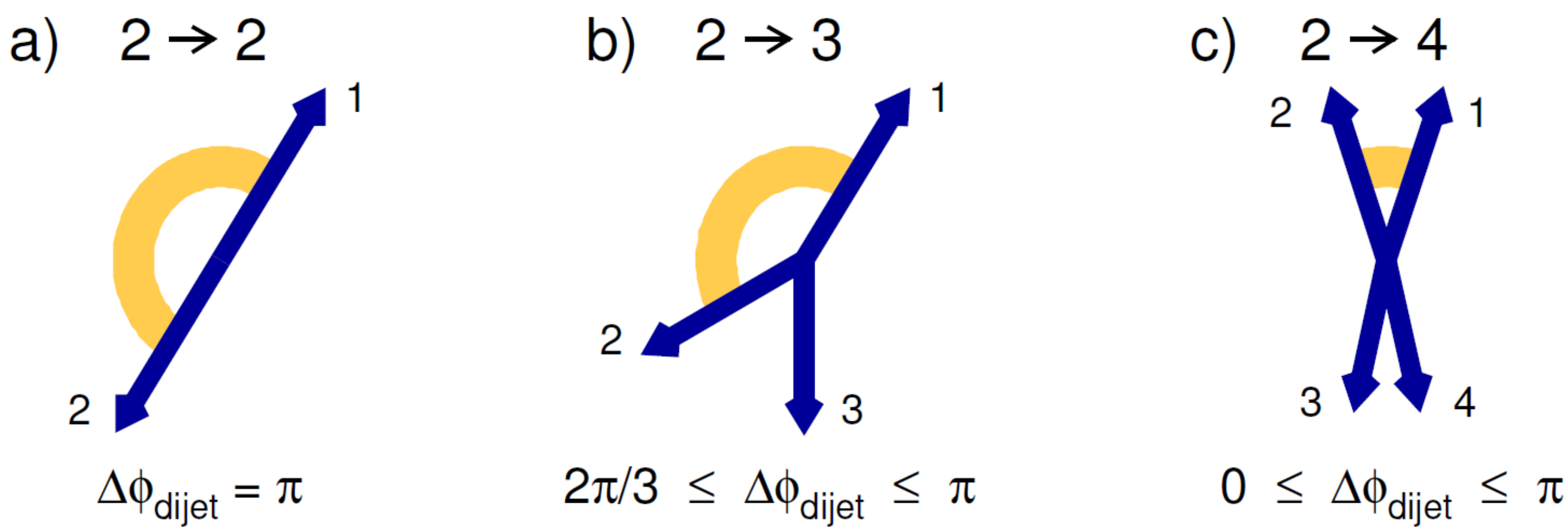
Orange: TEEC
Blue: ATEEC

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^*.

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

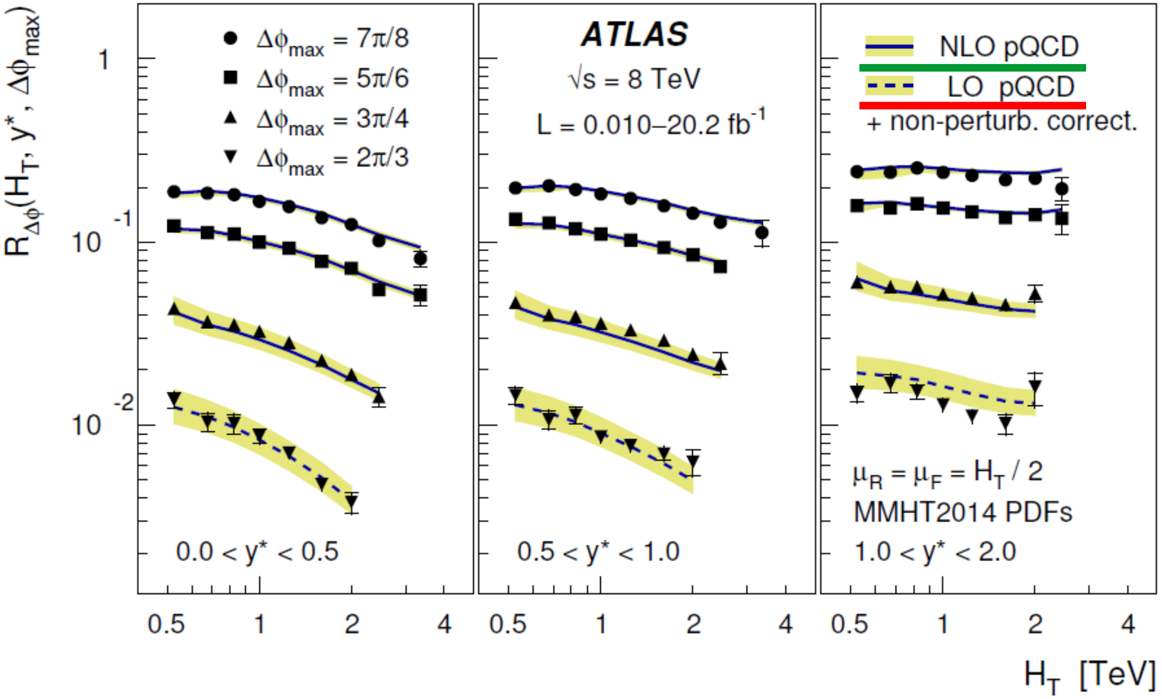
$$R_{\Delta\phi} \propto \alpha_s$$



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

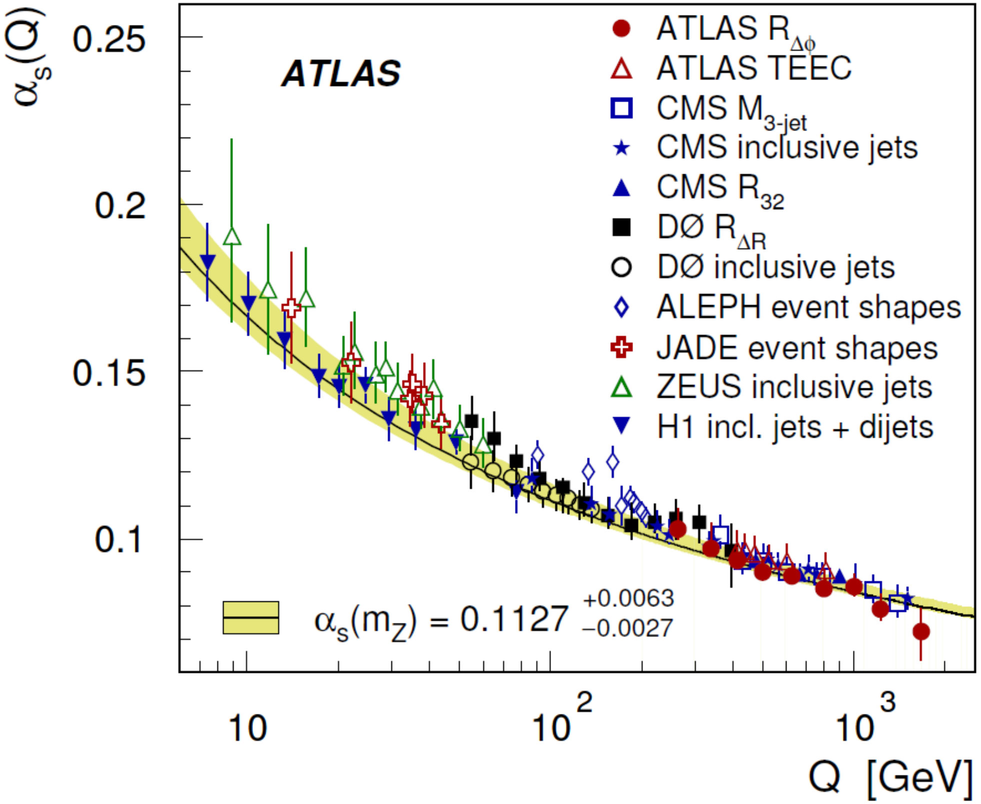
Wobisch et al., JHEP 01 (2013) 172;
KR, M. Wobisch, JHEP 12 (2015) 024.

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



Theory:
3-jet NLOJet++

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



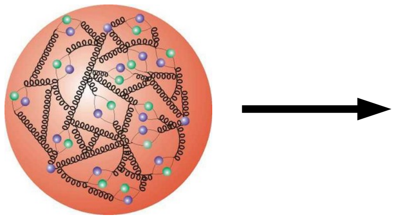
From more precise results with
$\Delta\varphi_{max} = 7\pi/8$ in the two y* regions below 1.0:

$\sqrt{s}$ [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp NP PDF	scale
8	20.2	0.1127	$^{+36}_{-19}$	$^{+52}_{-19}$

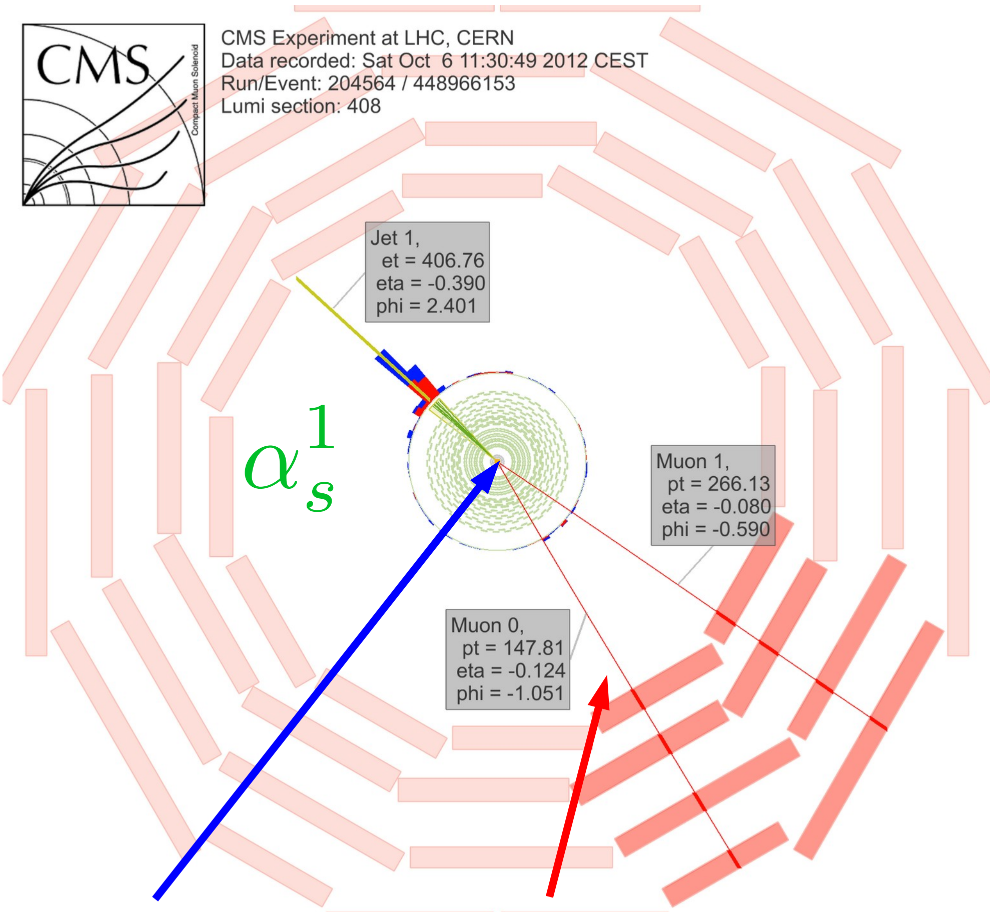
W, Z, top at the LHC

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

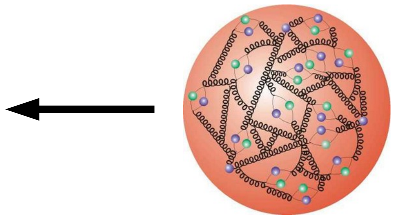


Proton Structure (PDF)



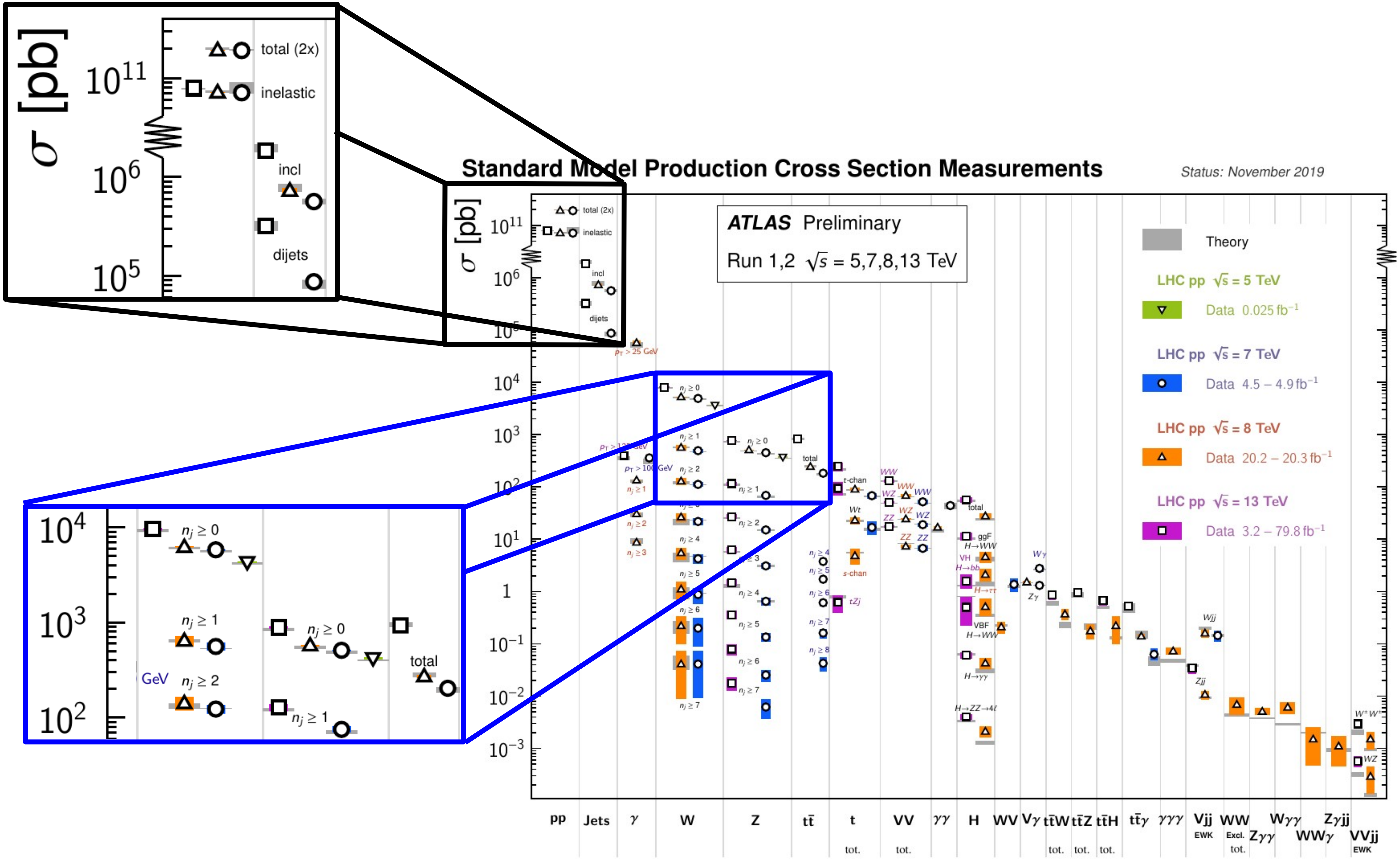
Matrix Element

Muons



Proton Structure (PDF)

W, Z, tT at the LHC



top-antitop production

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

Relevant CMS measurements:

PLB 728, 496 (2013), JHEP 11, 067 (2012) [Erratum: PLB 738, 526 (2014)], EPJC 79 (2019) 368, arXiv:1904.05237.

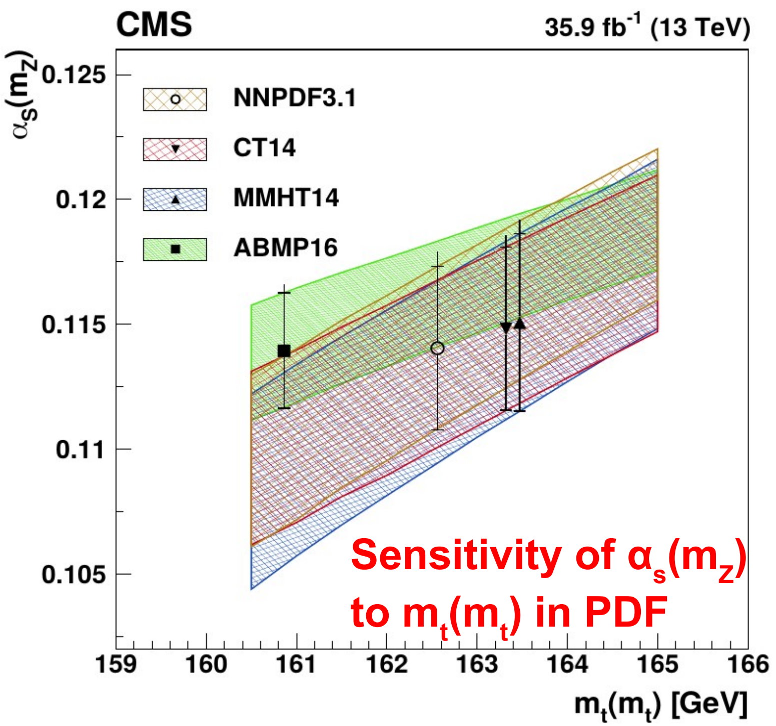
Fits with tt production cross section

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 →

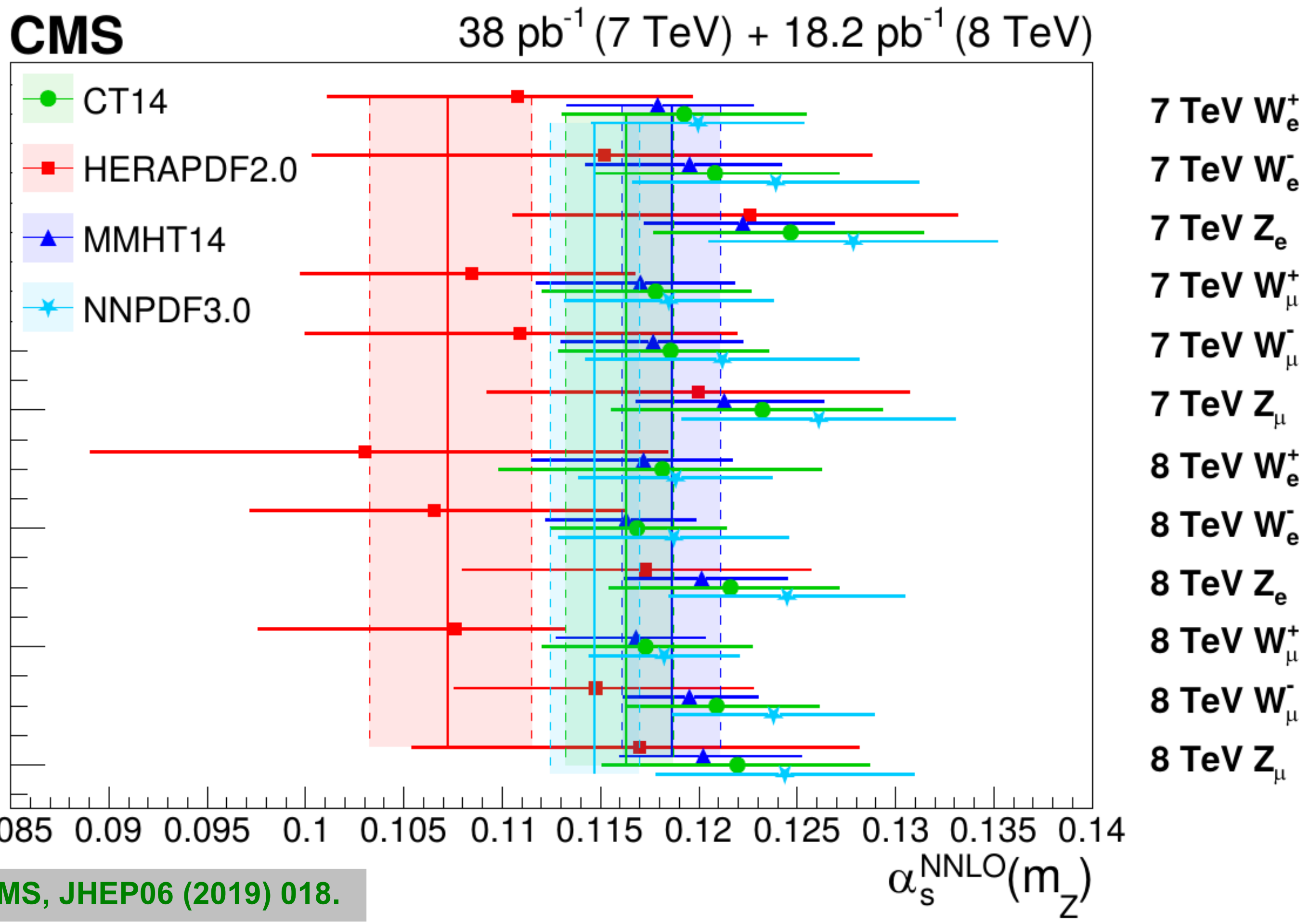
√s [TeV]	lum [fb-1]	$\alpha_s(M_Z)$	exp m_t PDF ...	scale
7	2.3	0.1151	$^{+27}_{-26}$	$^{+9}_{-8}$
13	35.9	**0.1139**	23	$^{+14}_{-1}$

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

Inclusive W,Z production

Recent result from combined fit for set of inclusive W and Z cross section measurements, e and μ decay final states only.

$$\sigma_{\mathrm{LO}} \propto \alpha_s^0$$



CMS, JHEP06 (2019) 018.

Results using NNLO pQCD for four PDF sets with CMS data.

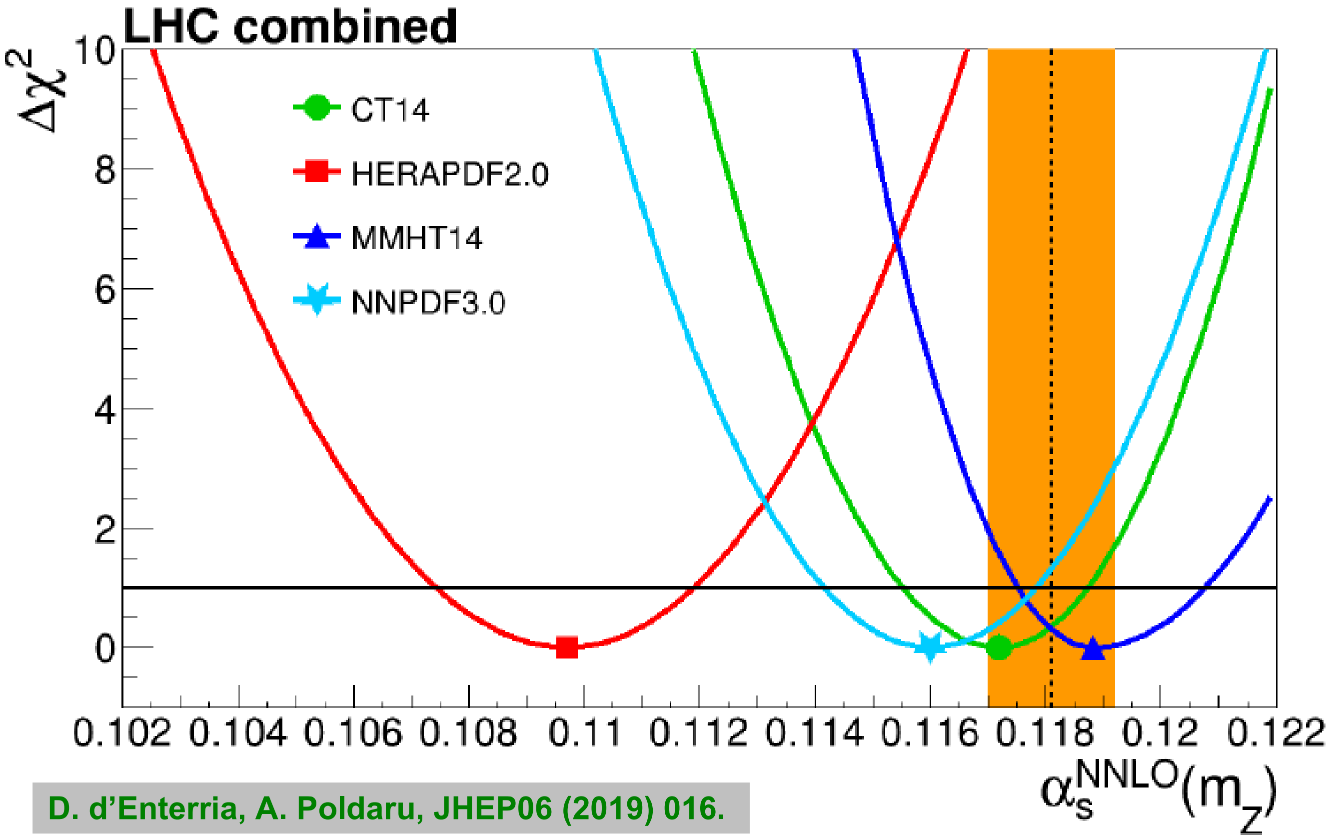
$$\alpha_s(M_Z) = 0.1186\,^{+0.0025}_{-0.0025}$$

MMHT14 only

Inclusive W,Z production

Recent result from combined fit for set of inclusive W and Z cross section measurements, e and μ decay final states only.

$$\sigma_{\mathrm{LO}} \propto \alpha_s^0$$



D. d'Enterria, A. Poldaru, JHEP06 (2019) 016.

Results using NNLO pQCD for four PDF sets with 28 LHC datasets:

ATLAS 7
CMS 12
LHCb 9

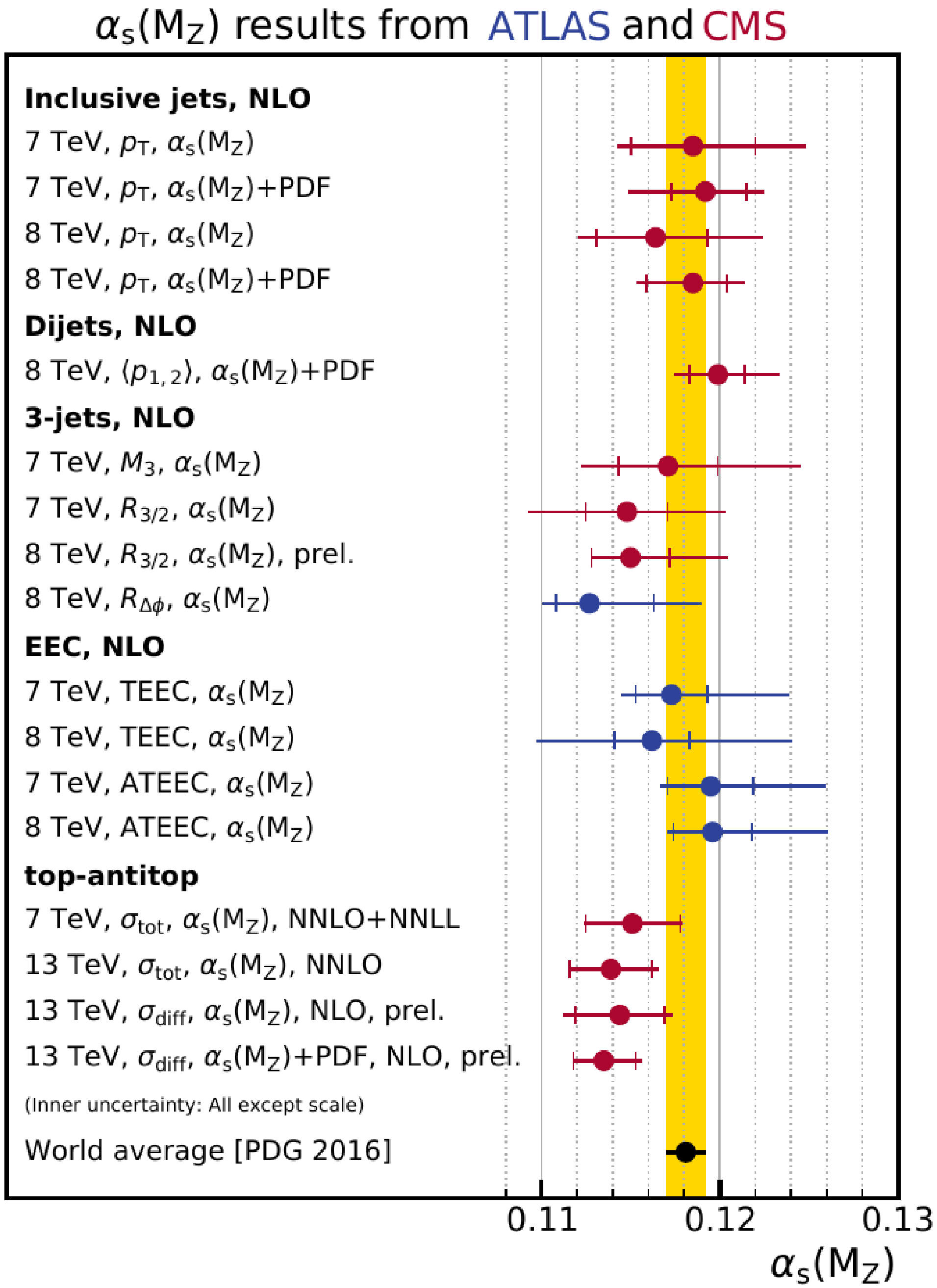
$$\alpha_s(M_Z) = 0.1188\,^{+0.0019}_{-0.0013}$$

MMHT14 only

CT14 & MMHT14 & NNPDF30

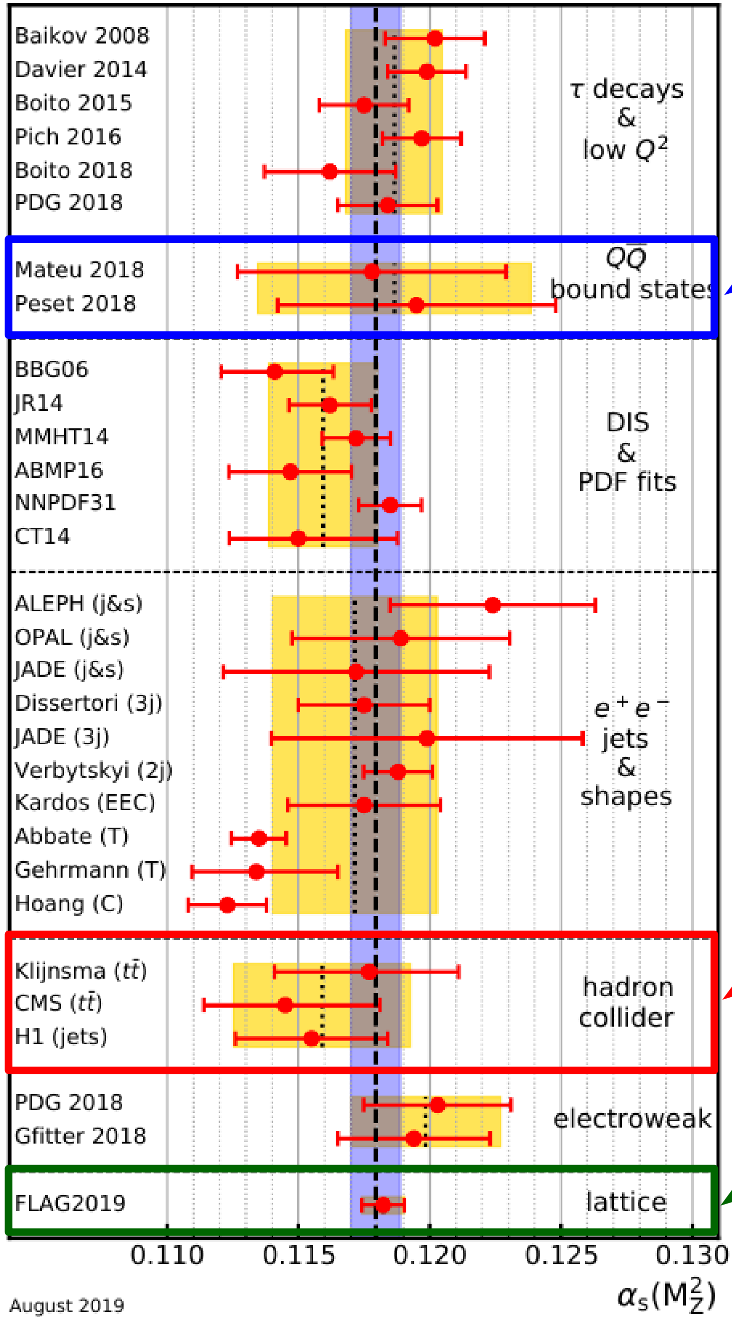
√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	total symm.
7,8,13	var.	0.1173	$^{+17}_{-17}$

Wrap up & concerns



- **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 …!**

PDG Summary 2019

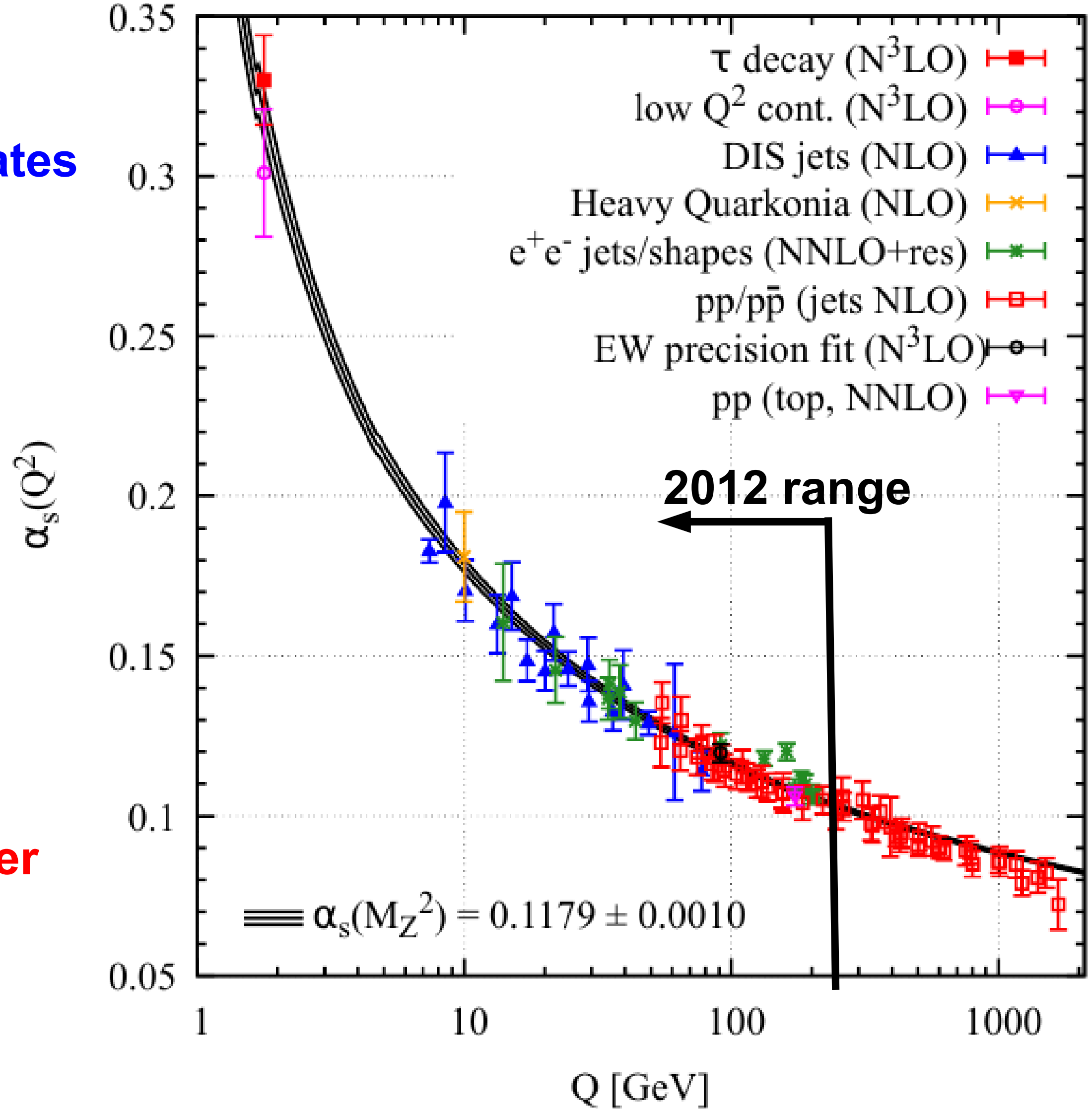


PDG2019

New:
QQ bound states

New:
hadron collider

Most precise:
Lattice



$$\frac{\Delta\alpha_S(M_Z)}{\alpha_S(M_Z)} = 0.8\%$$

PDG´92: 2.4%

Summary & Outlook

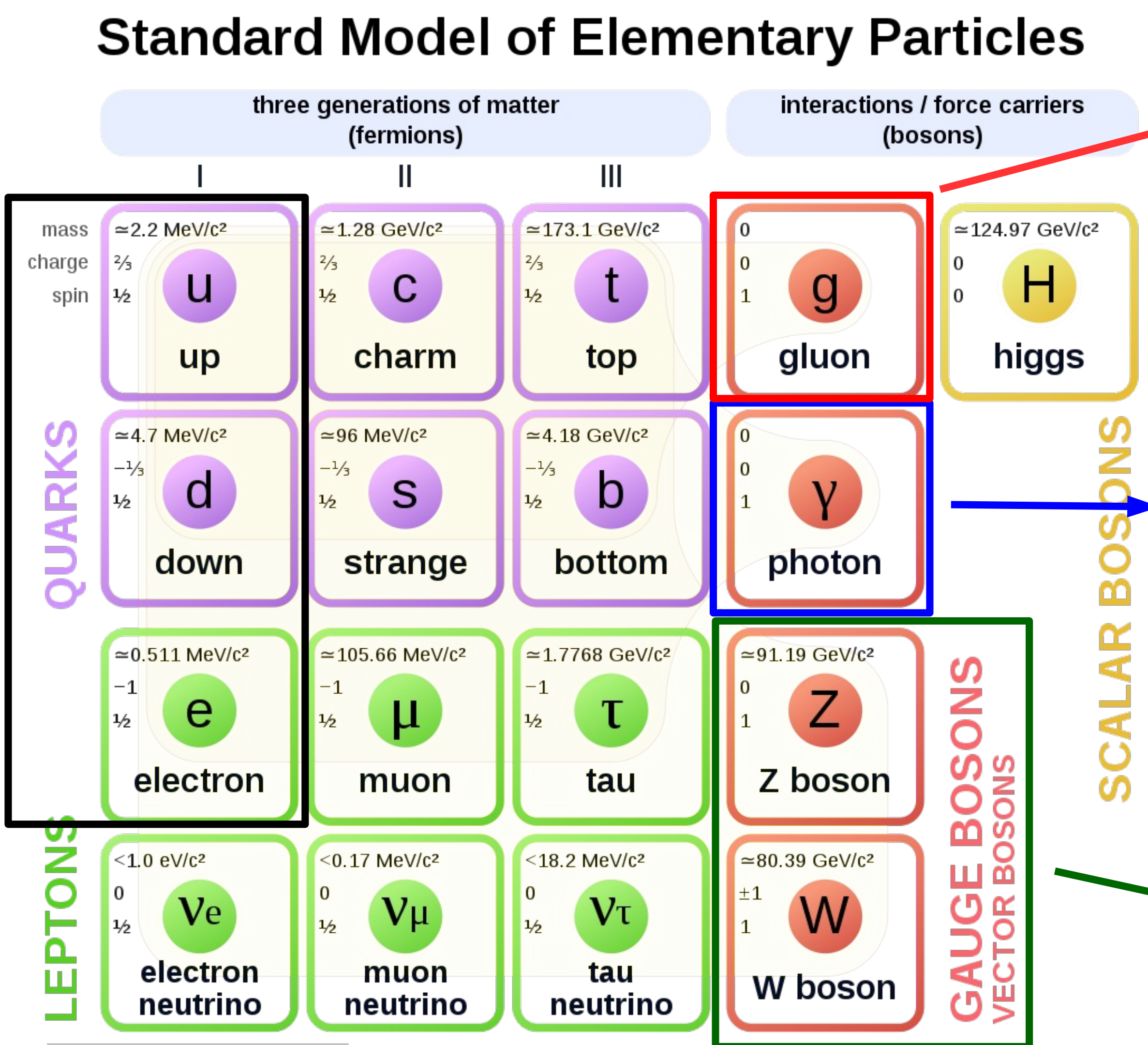
- LHC at 7 TeV and 8 TeV enables measurements up to scales of 2 TeV
- 13 TeV data yet to be fully evaluated
- Theory at NNLO QCD + electroweak corrections are a must!
- Typical uncertainties on $\alpha_s(M_Z)$:
  - Experimental: ~ 1 – 2 %
  - PDF: ~ 1 – 2 %
  - Scale: 3 – 5 % → 1 – 2% at NNLO ? Central scale choice?
  - Nonpert. Effects: 1 % (really?)
- Beyond one experiment started ...
  - 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!

Thank you for your attention!

Backup Slides

Standard Model of Particle Physics

Solid matter …



Cush, Wikipedia.

Strong interaction (nuclear forces, …)

$\alpha_s \approx 0.118$

$\Delta\alpha_s/\alpha_s = 8.5 \cdot 10^{-3}$

Electromagnetic interaction (magnets, electricity, …)

$\alpha \approx 1/137$

$\Delta\alpha/\alpha = 0.15 \cdot 10^{-9}$

Weak interaction (β decays, sun, …)

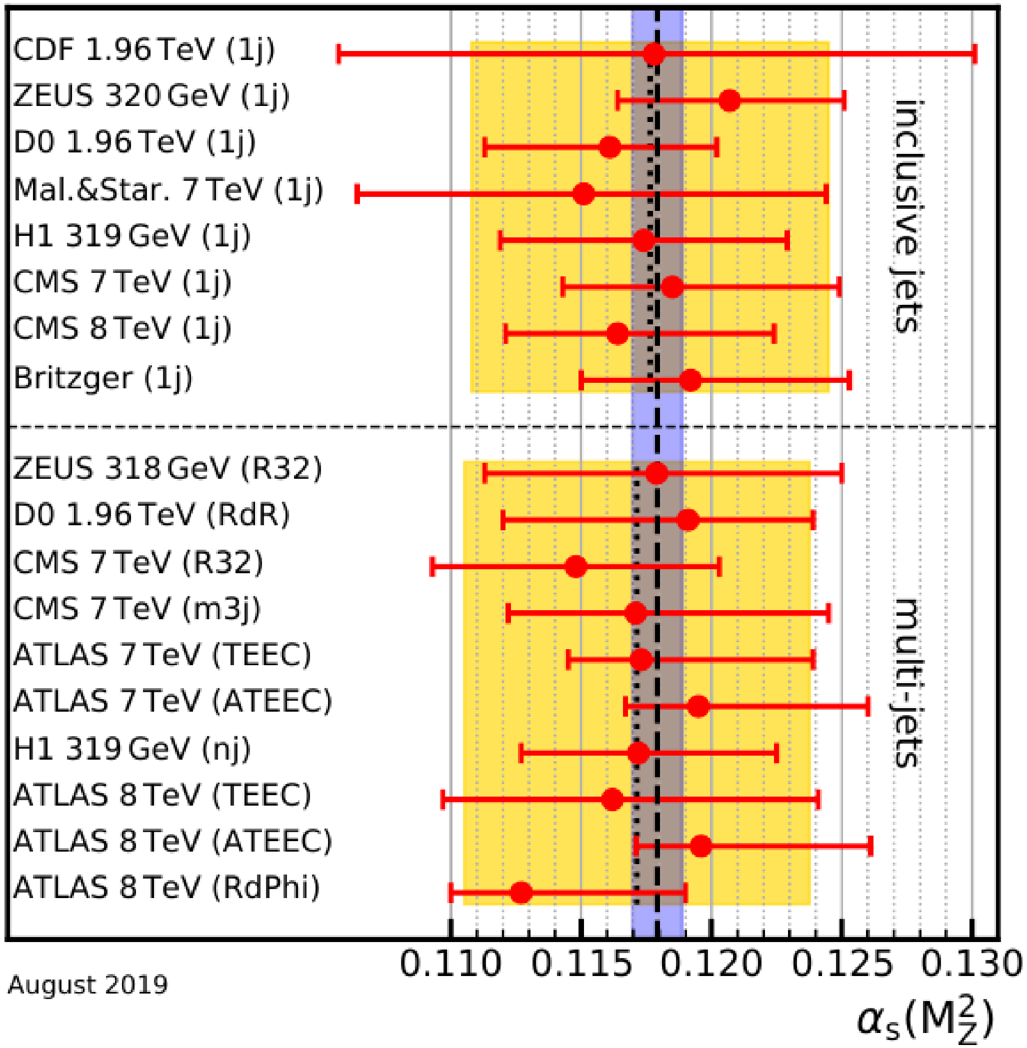
$G_F \approx 1.17 \cdot 10^{-5}/\mathrm{GeV}^2$

$\Delta G_F/G_F = 0.51 \cdot 10^{-6}$

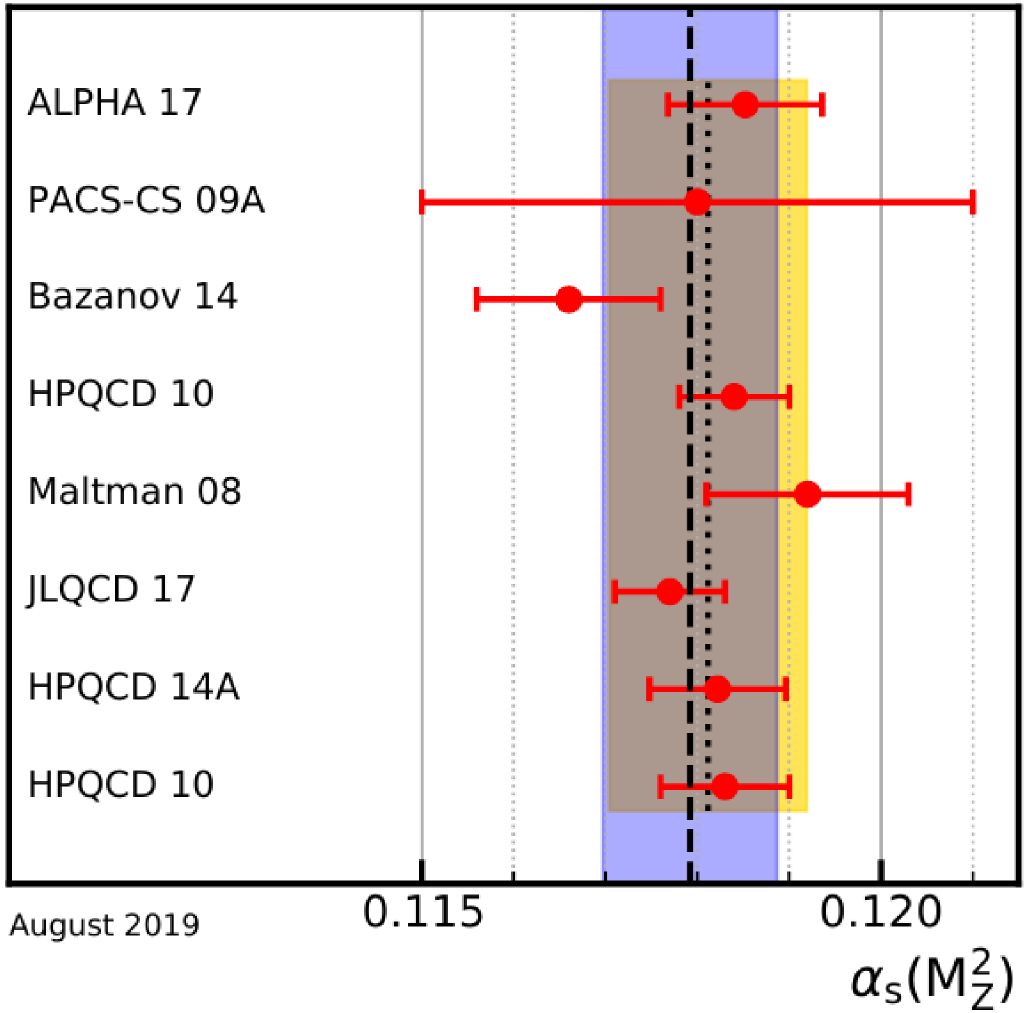
… and three fundamental interactions. (no gravity)

PDG 2019 Comparison

α_s at NLO from jet production



α_s from lattice groups



α_s at previous 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.)	~1%
e^+e^- jet rates	expt $\sim 2\%$ (LEP) thry $\sim 1\%$ (NNLO, n.p. moderate) [28]	$< 1\%$ possible (ILC/TLEP) $\sim 0.5\%$ (NLL missing)	
precision EW	expt $\sim 3\%$ (R_Z, LEP) thry $\sim 0.5\%$ (N^{3}LO, n.p. small) [9,29]	0.1% (TLEP [10]), 0.5% (ILC [11]) $\sim 0.3\%$ (N^{4}LO feasible, $\sim$ 10 yrs)	<1%
τ decays	expt $\sim 0.5\%$ (LEP, B-factories) thry $\sim 2\%$ (N^{3}LO, n.p. small) [8]	$< 0.2\%$ possible (ILC/TLEP) $\sim 1\%$ (N^{4}LO feasible, $\sim$ 10 yrs)	
ep colliders	~ 1–2% (pdf fit dependent) [30,31], (mostly theory, NNLO) [32,33]	0.1% (LHeC + HERA [23]) $\sim 0.5\%$ (at least N^{3}LO required)	<1%
hadron colliders	$\sim 4\%$ (Tev. jets), $\sim 3\%$ (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17,21,34]	$< 1\%$ challenging (NNLO jets imminent [22])	~1%
lattice	$\sim 0.5\%$ (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	$\sim 0.3\%$ ($\sim$ 5 yrs [38])	<0.5%

Snowmass QCD Report, arXiv:1310.5189.

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?**

Scale choices

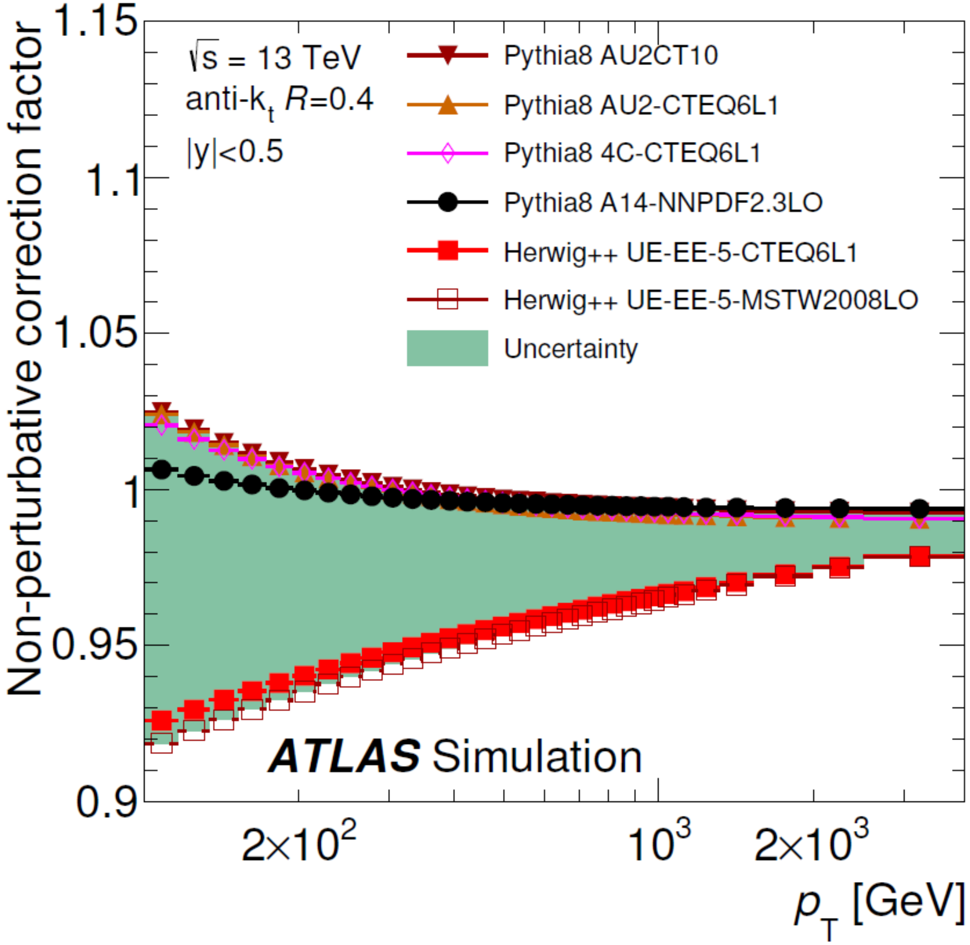
- **Inclusive jets** $\mu_0 = p_{\mathrm{T},1}, \quad p_{\mathrm{T,jet}}, \quad \hat{H}_{\mathrm{T}}?$
- **Dijets** $\mu_0 = p_{\mathrm{T},1}, \quad p_{\mathrm{T},1} \cdot \exp\left(0.3 y^*\right)?$
  $\mu_0 = \left(p_{\mathrm{T},1} + p_{\mathrm{T},2}\right)/2, \quad m_{jj}/2?$
- **3-jets** $\mu_0 =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

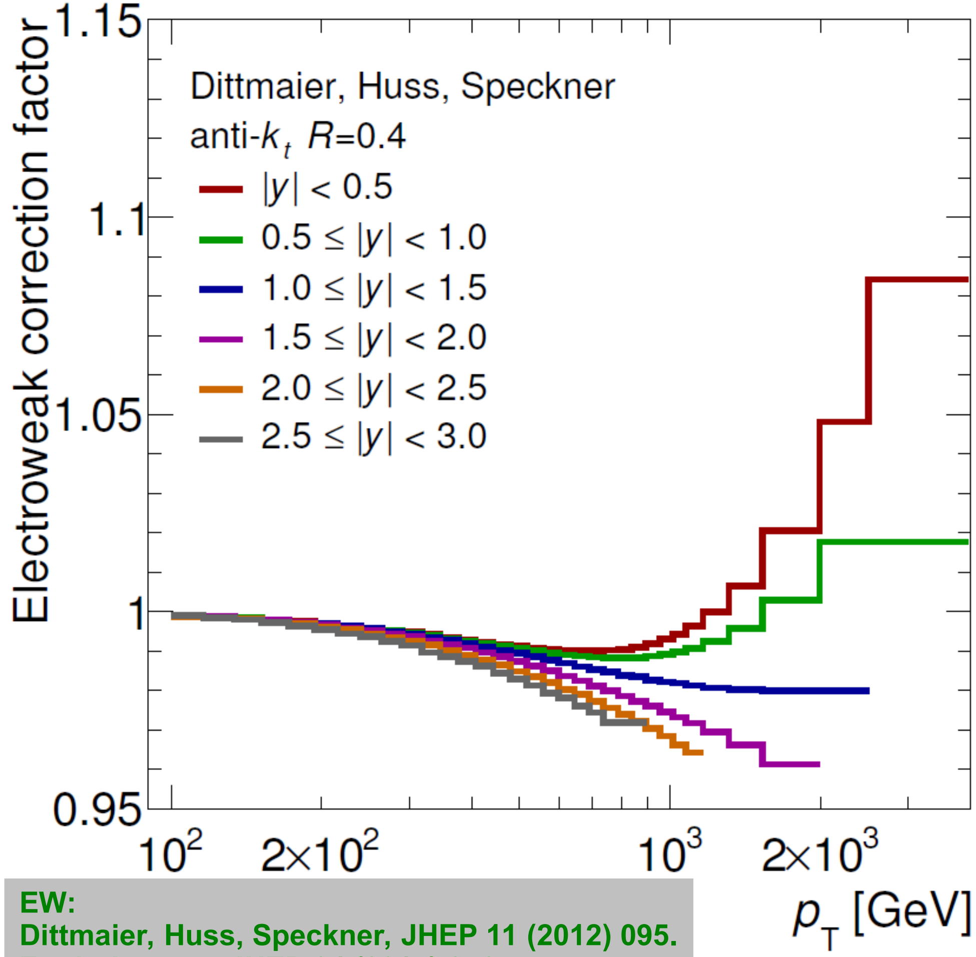
Inclusive jets: theory corrections

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





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

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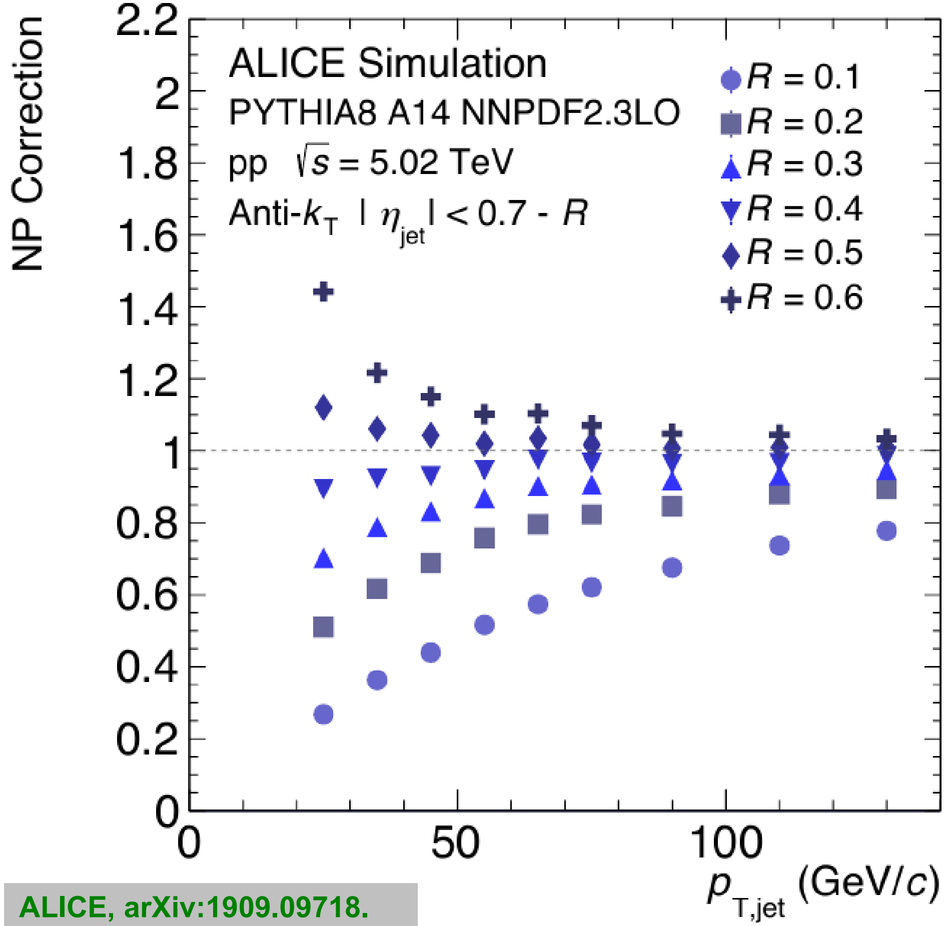
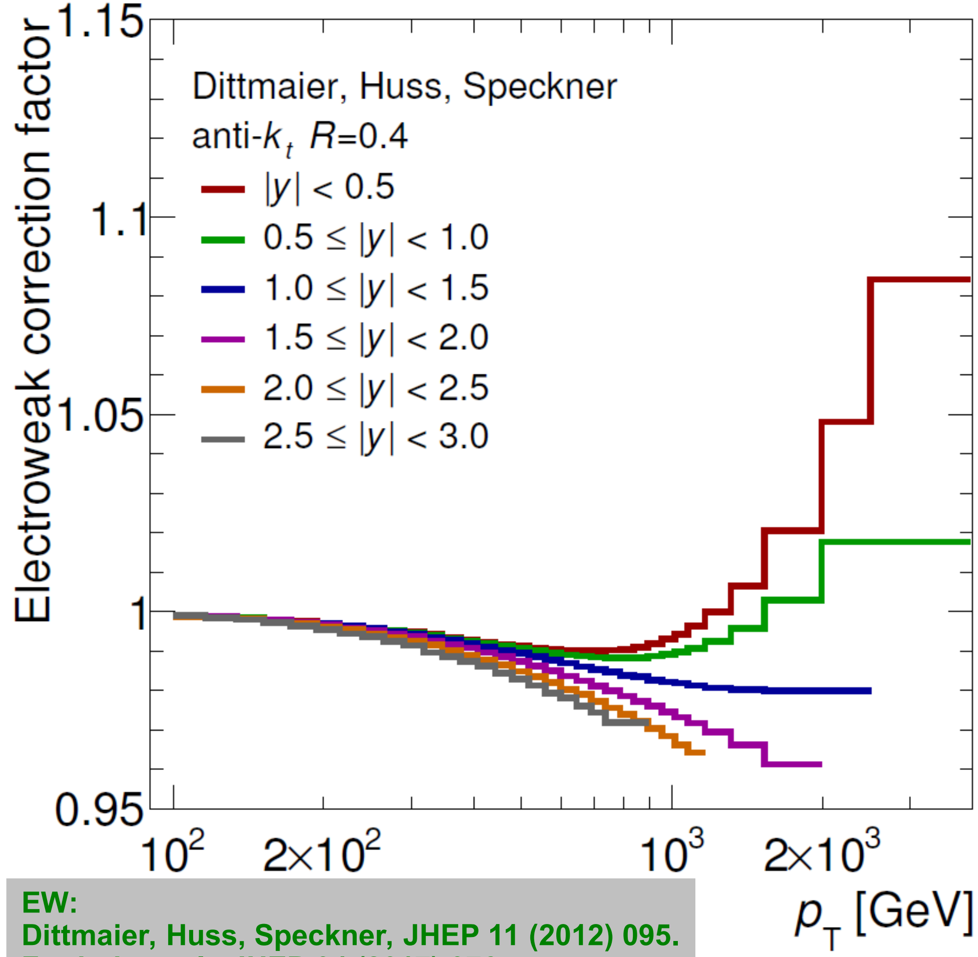




ALICE, arXiv:1909.09718.
See also CMS, SMP-19-003.

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

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

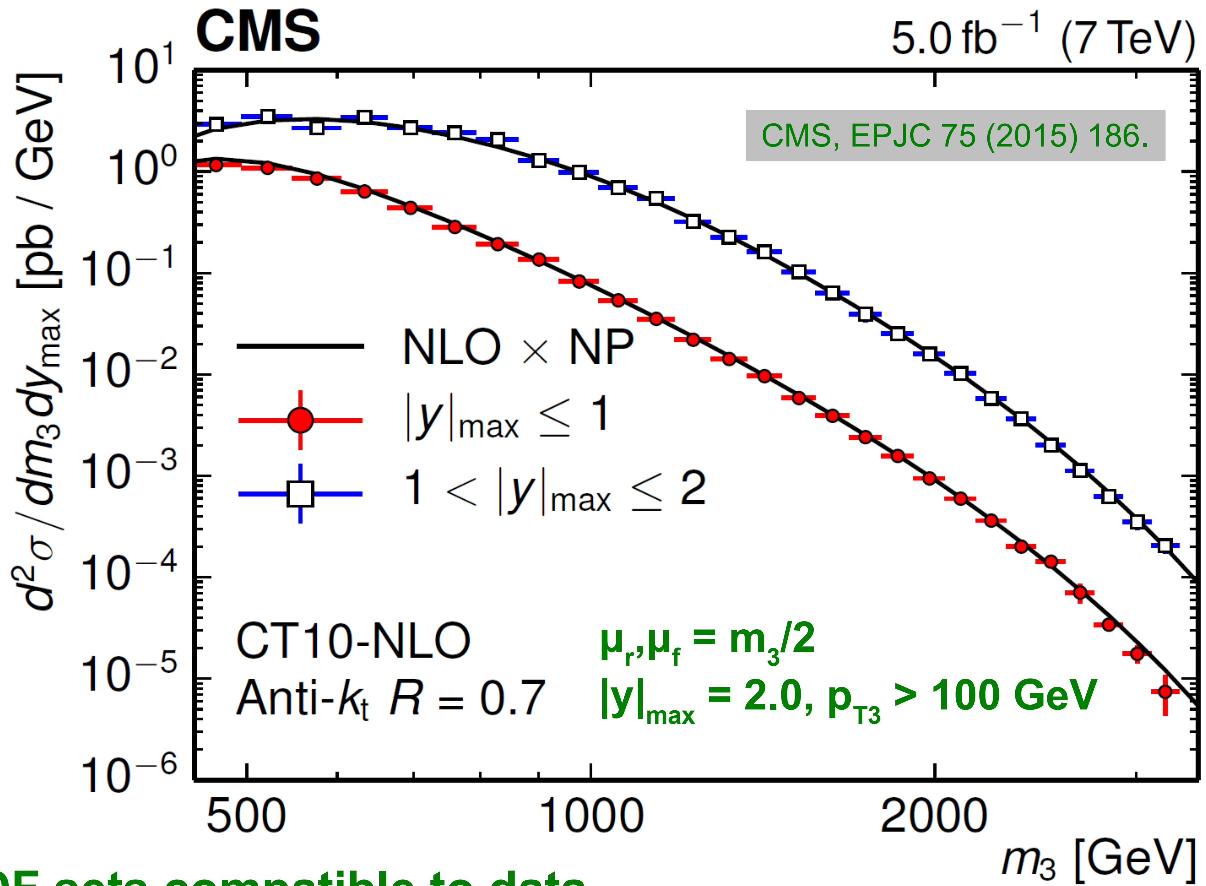
3-jet mass

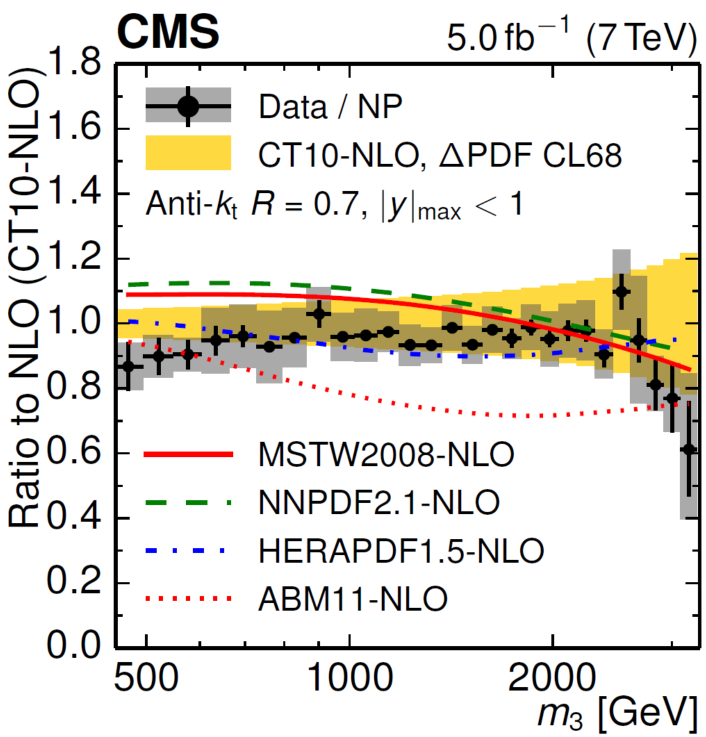
Sensitive to α_s beyond 2→2 process

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	$^{+69}_{-40}$

Sensitivity of differential cross section

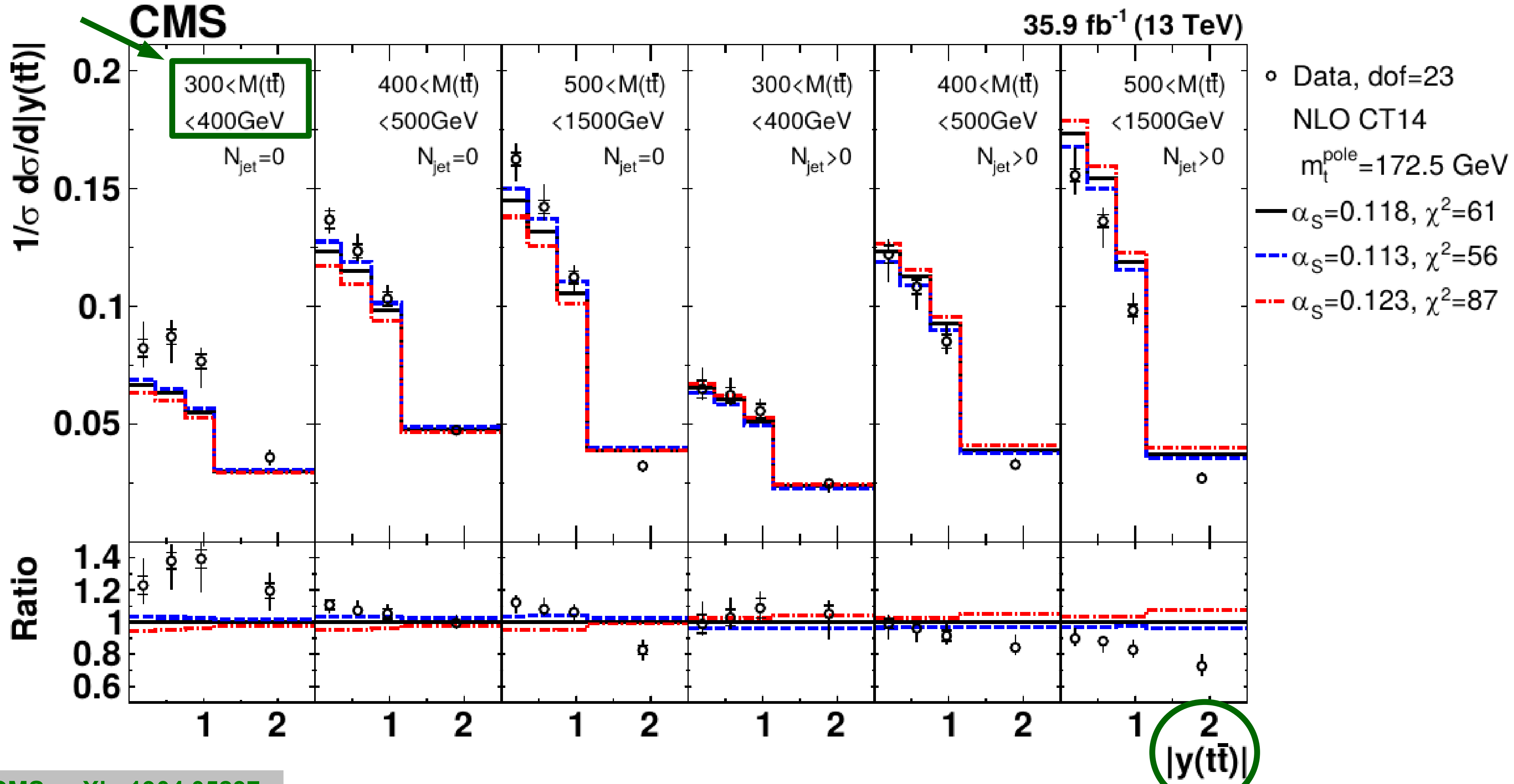
NLO

Normalised

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

$N_{jet} = 0$ $N_{jet} > 0$

Mass bins



CMS, arXiv:1904.05237.

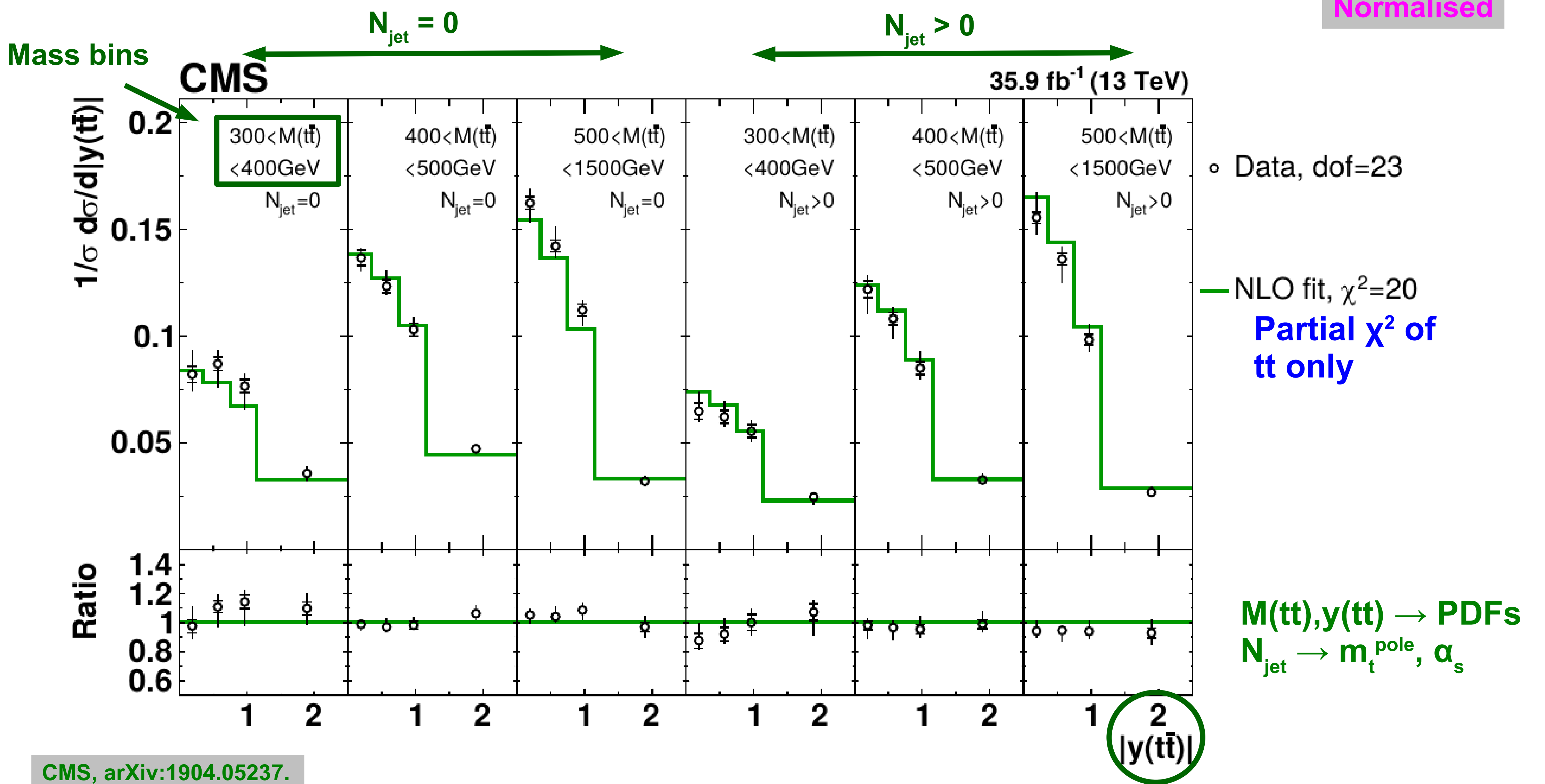
Initial description of data at NLO with CT14 PDFs for 3 values of $\alpha_s(M_Z)$

Fits using tt differential distributions

NLO

Normalised

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



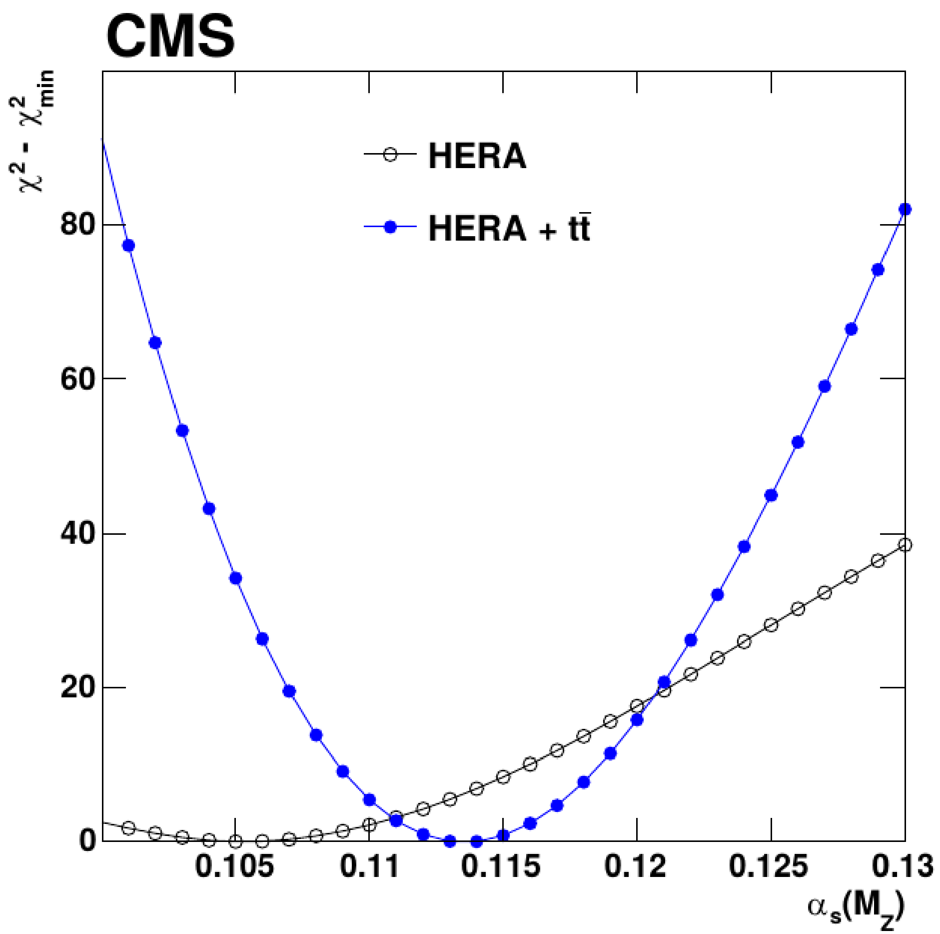
CMS, arXiv:1904.05237.

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

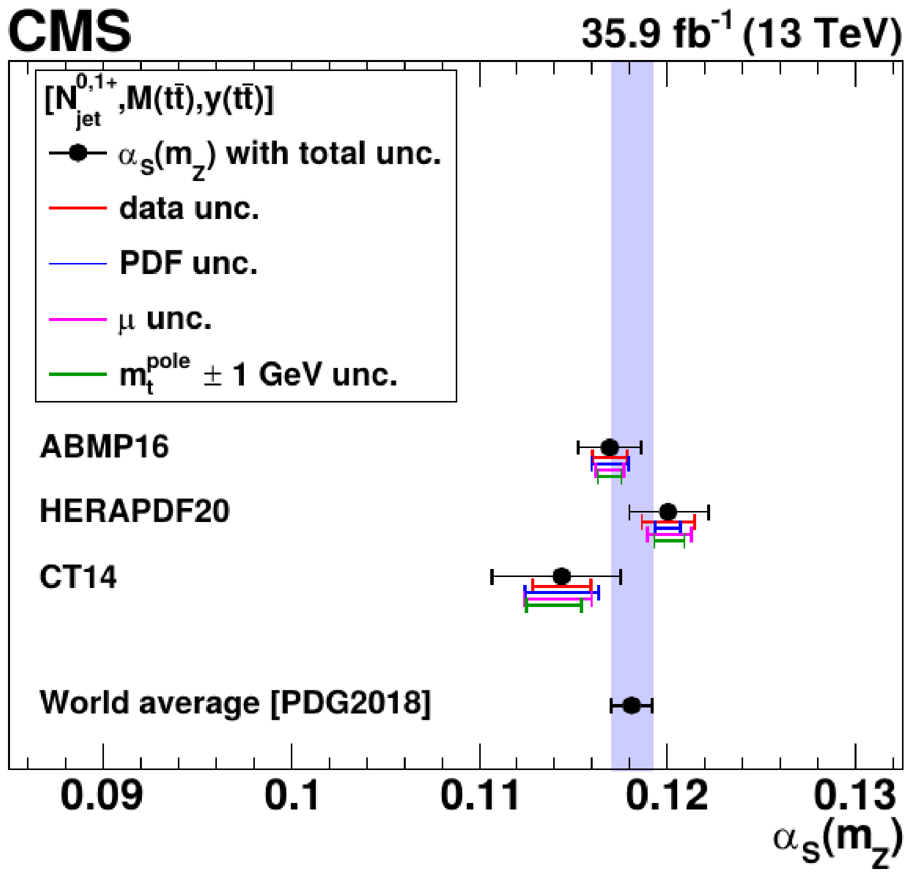
Fits using tt differential distributions

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



CMS, arXiv:1904.05237.

Combining LHC & Tevatron tt 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.