15th Vienna Central European Seminar

on Particle Physics and Quantum Field Theory

Precision Physics at the LHC

Jets and α_s
Experimental status

Klaus Rabbertz, KIT

(on behalf of ATLAS & CMS)

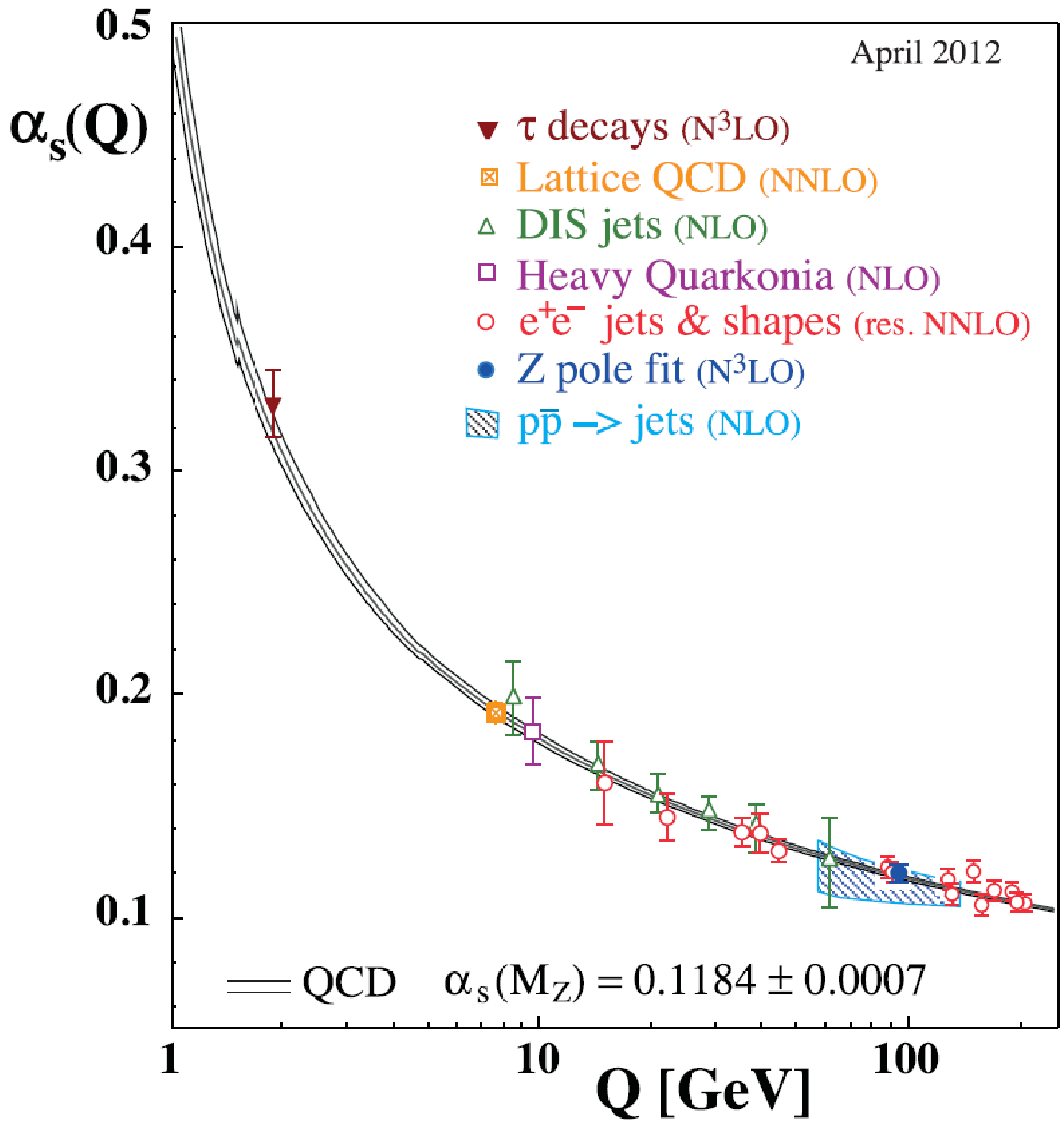
Karlsruhe Institute of Technology

Outline

- **Motivation**
- **Jet-like measurements**
  - **Cross sections**
  - **Ratios**
  - **Normalised distributions**
- **Issues & perspectives**
- **Summary & outlook**

2012: No LHC results yet

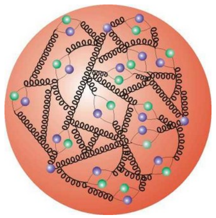
PDG2012



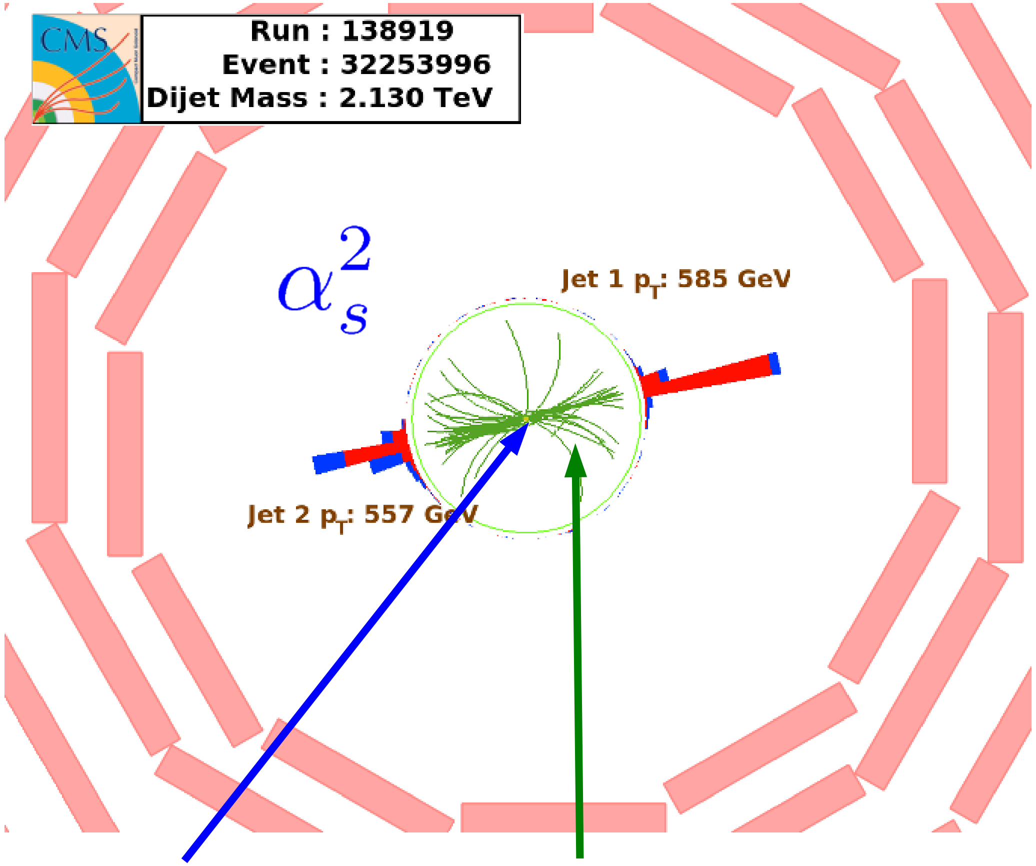
Jets at the LHC

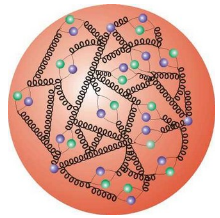
Abundant production of jets:

- 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)

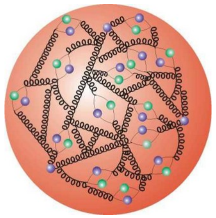
Matrix Element

Hadrons

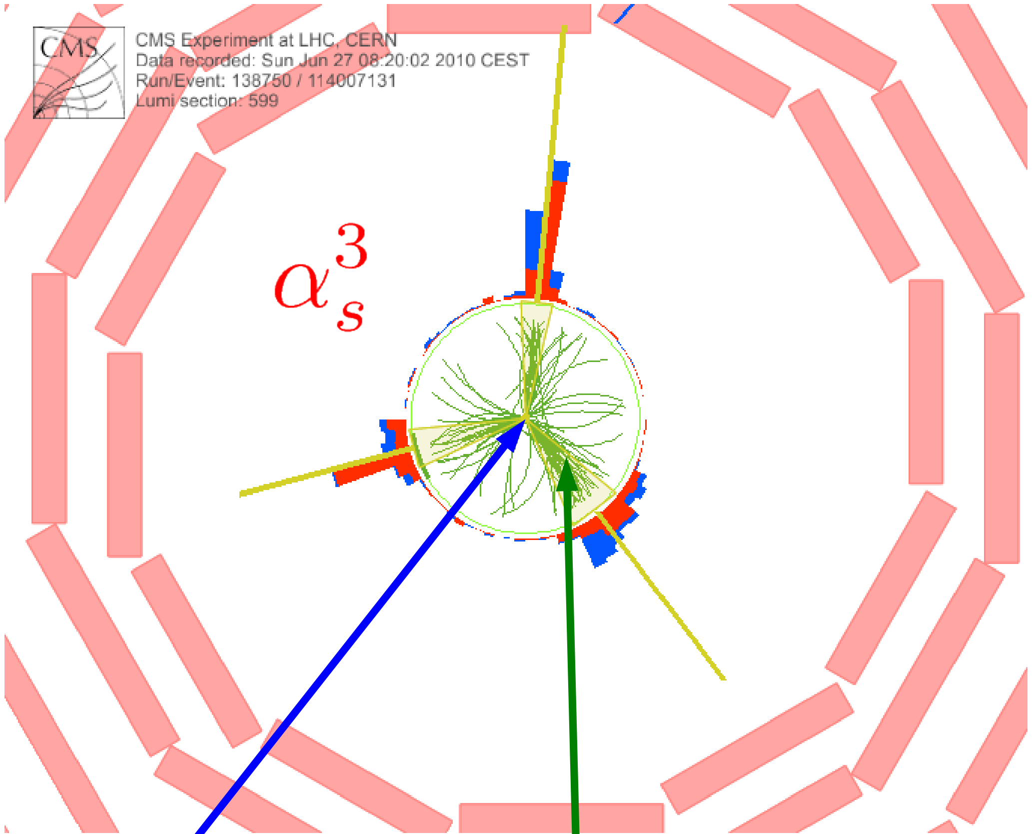
Jets at the LHC

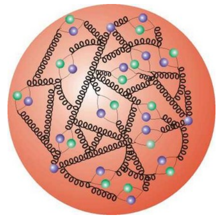
Abundant production of jets:

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



Proton Structure (PDF)

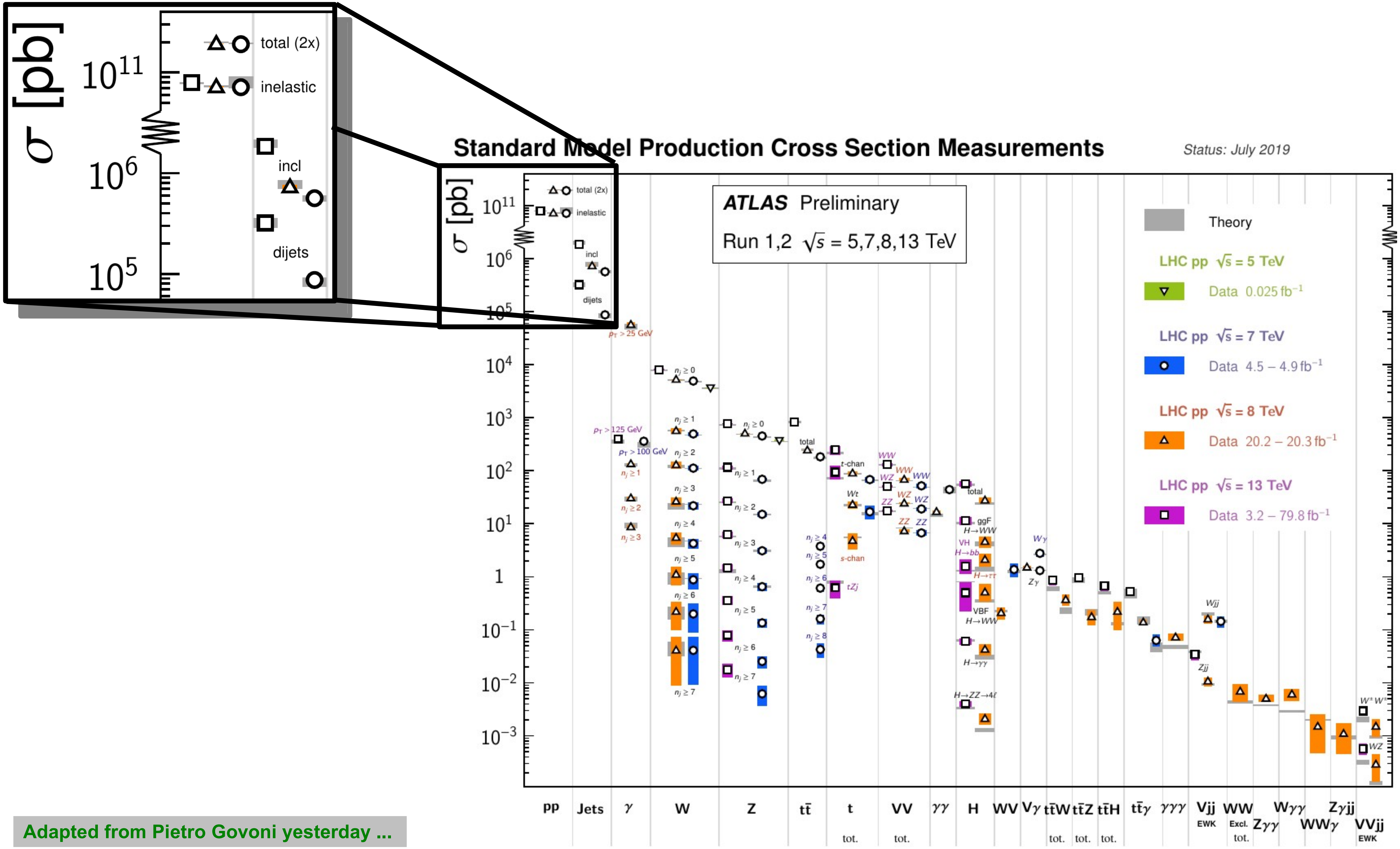




Proton Structure (PDF)

Matrix Element **Hadrons**

Jets at the LHC



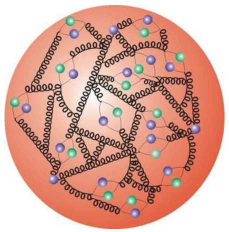
Adapted from Pietro Govoni yesterday ...

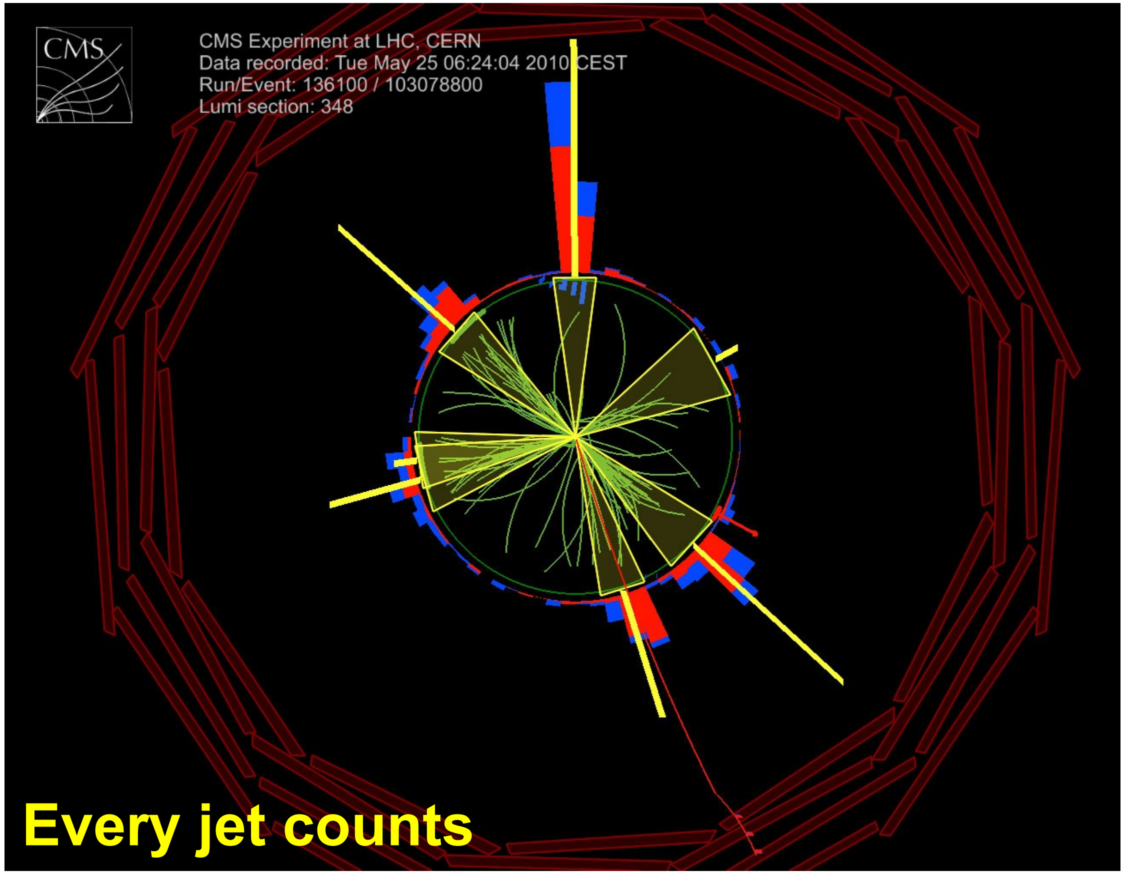
Jet cross sections ~ α_s^2

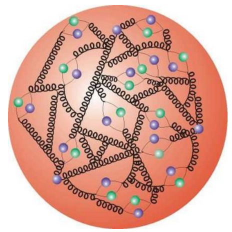
- Determination of $\alpha_s(M_Z)$ in single-parameter fit
- Test consistency of running of $\alpha_s(Q)$
- Multi-parameter fit of $\alpha_s(M_Z)$ & PDFs

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.

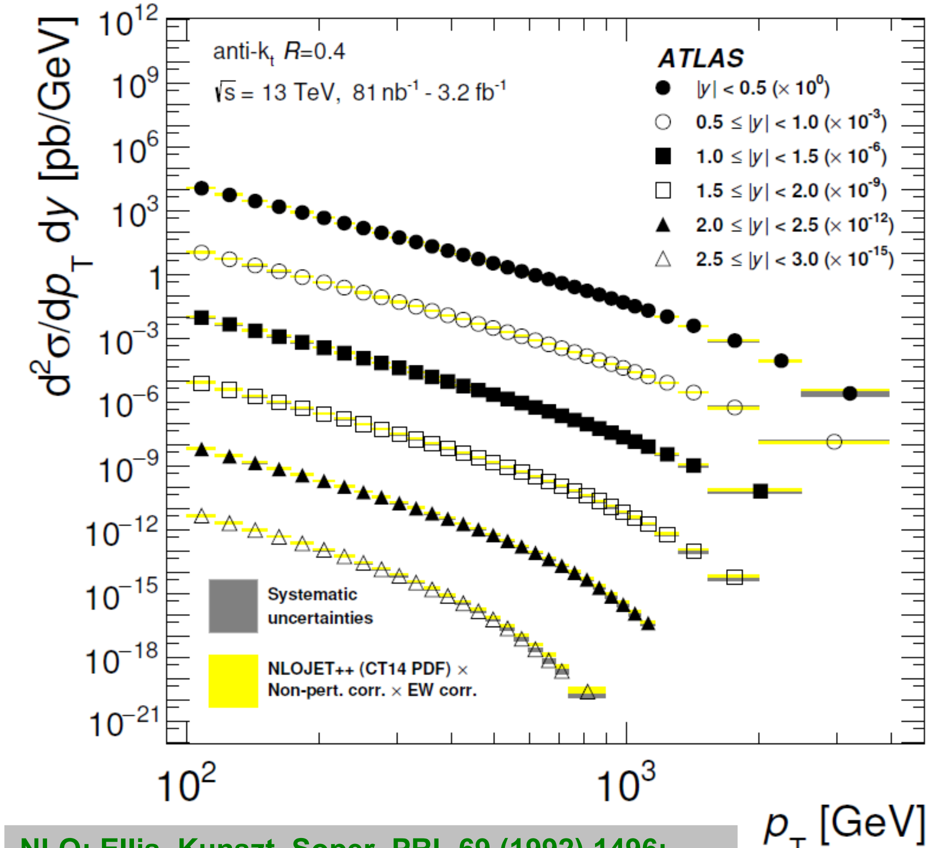
Inclusive jets: cross section

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 √s = 2.76, 7, 8, and 13 TeV.

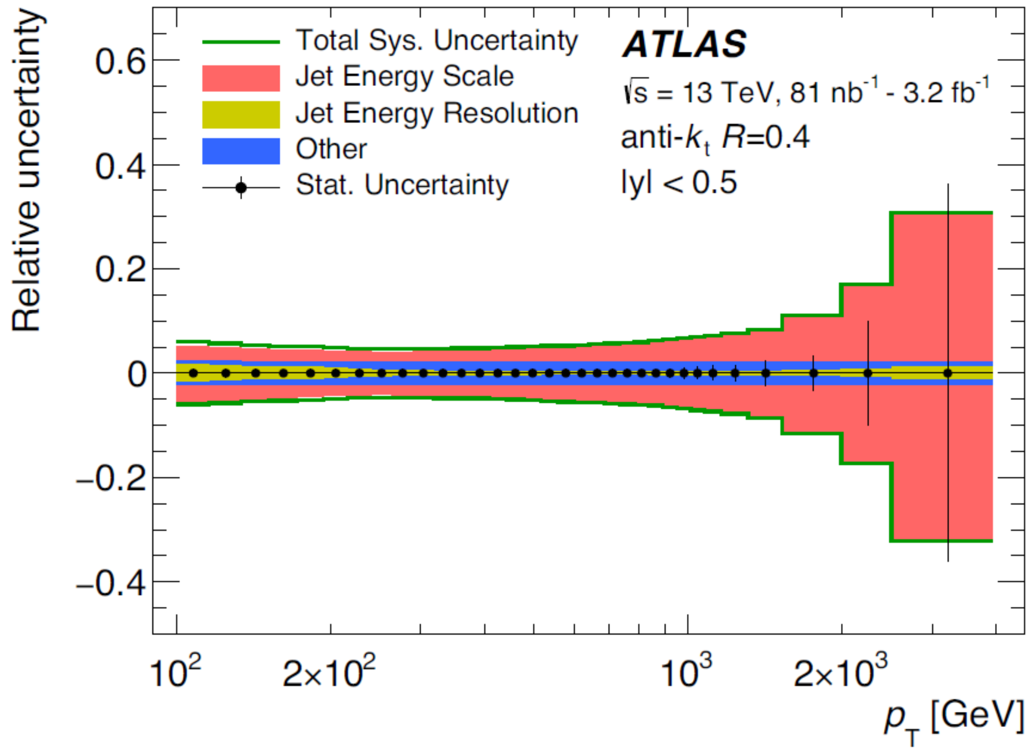
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

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

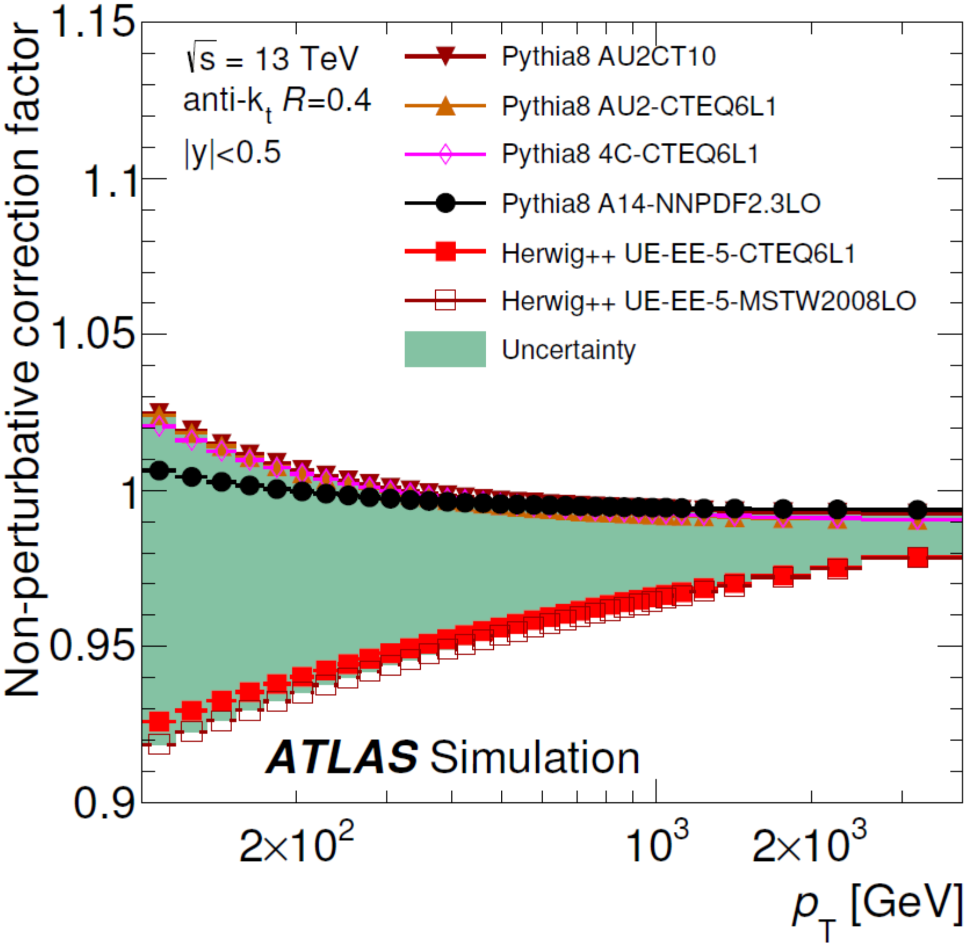


**NLO: Ellis, Kunszt, Soper, PRL 69 (1992) 1496;
Giele, Glover, Kosower, NPB 403 (1993) 633;
Z. Nagy, PRD 68 (2003) 094002.**

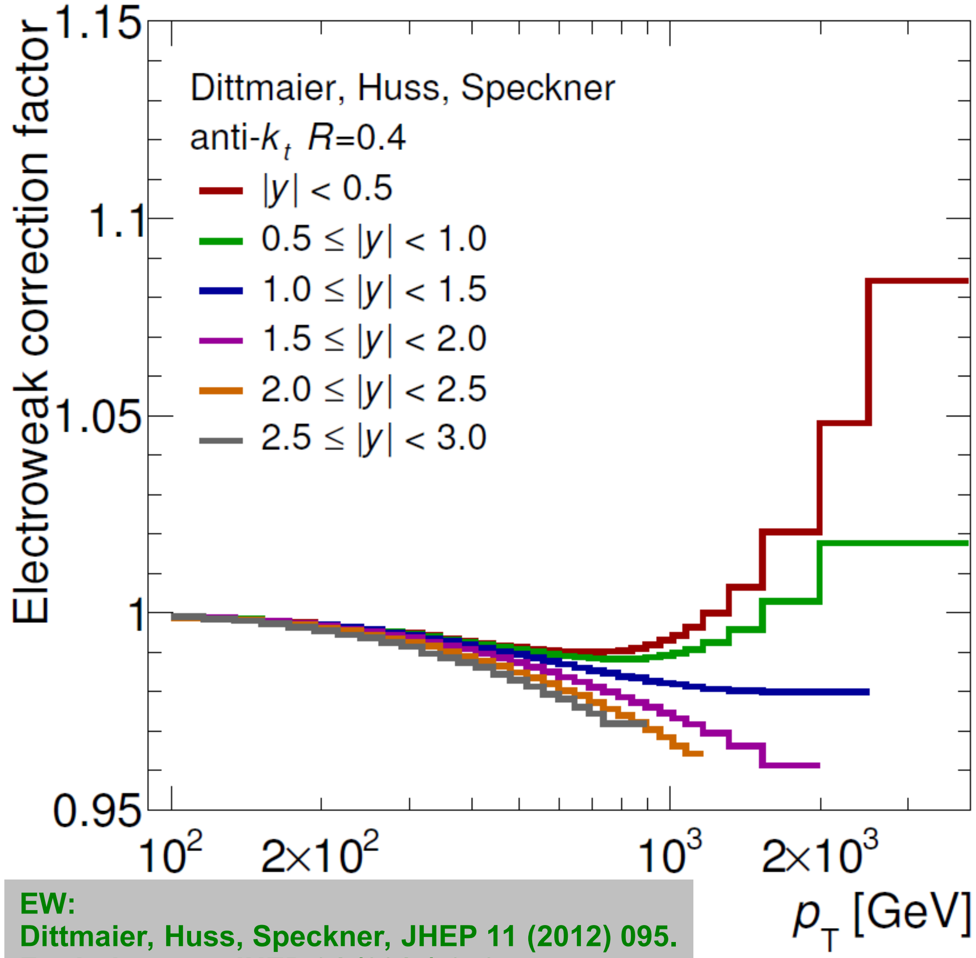
Inclusive jets: theory corrections

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

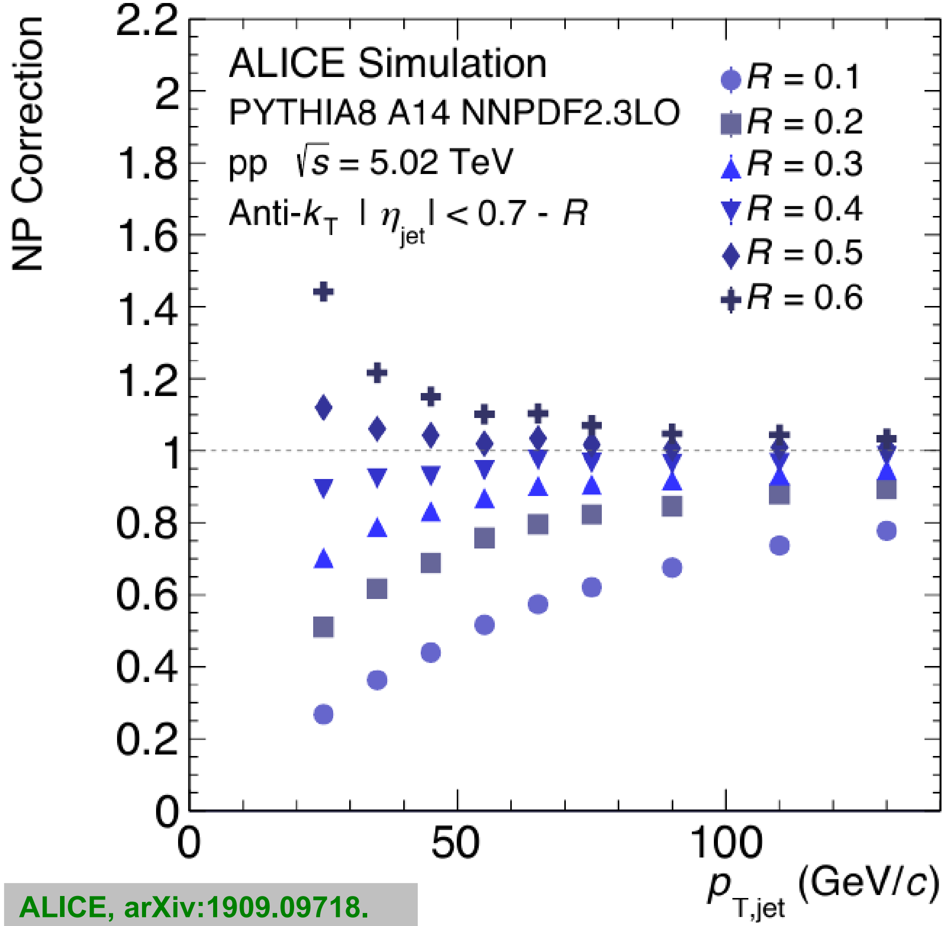


EW:
Dittmaier, Huss, Speckner, JHEP 11 (2012) 095.
Frederix et al., JHEP 04 (2017) 076.

Inclusive jets: theory corrections

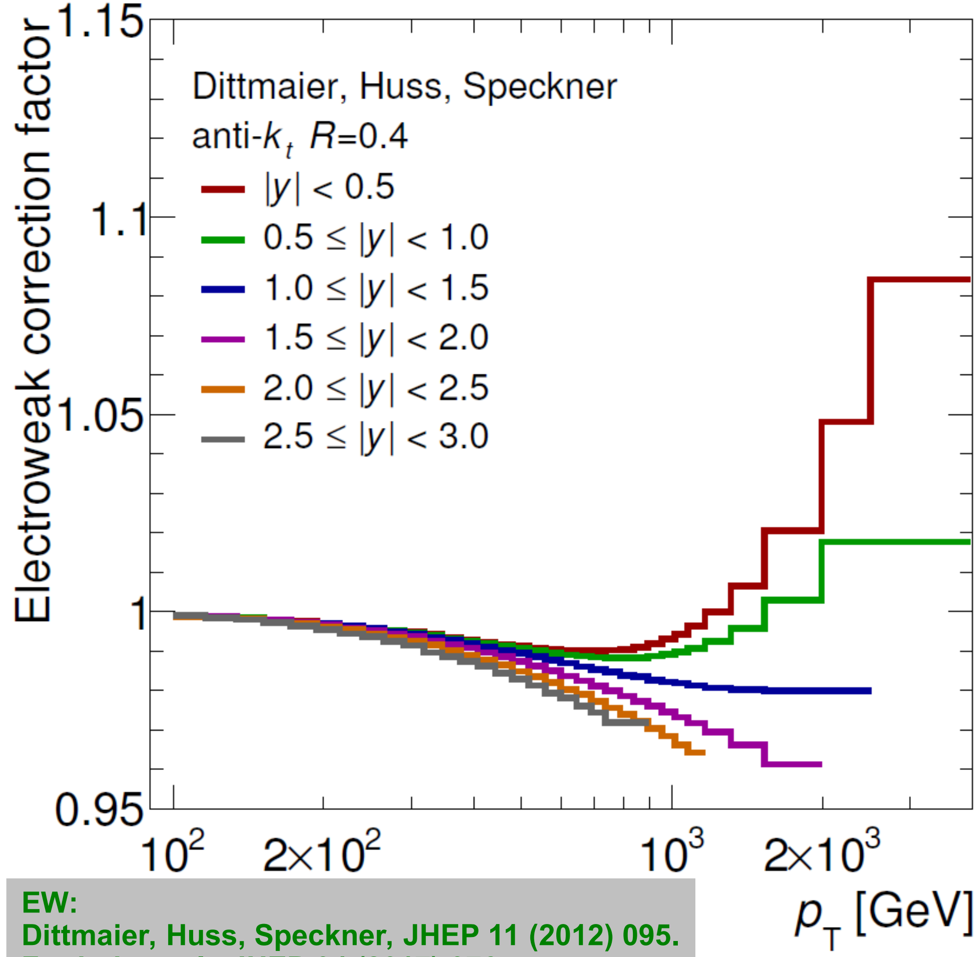
anti-kt, R=0.4, 13 TeV, |y| < 0.5

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



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

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.

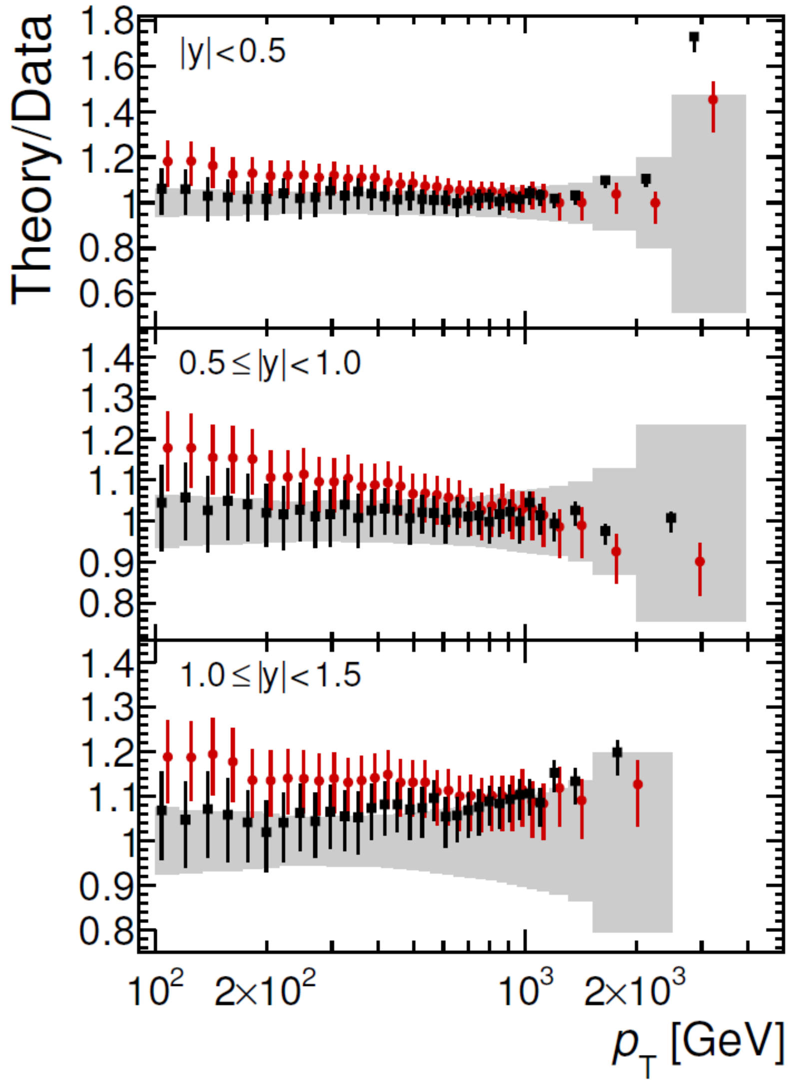
Inclusive jets: NNLO & scale choice

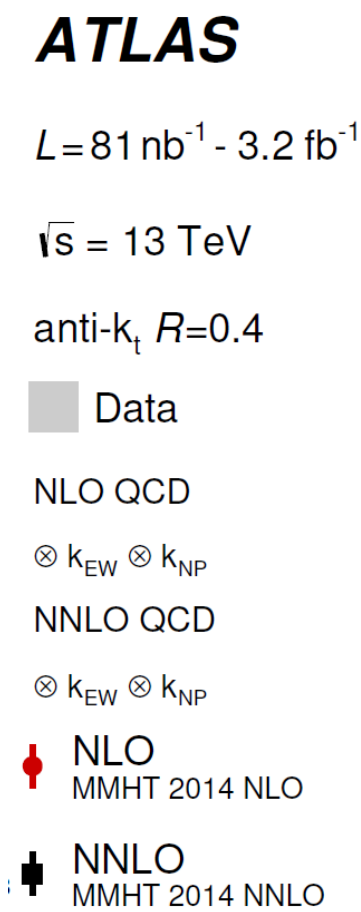
anti-kt, R=0.4, 13 TeV

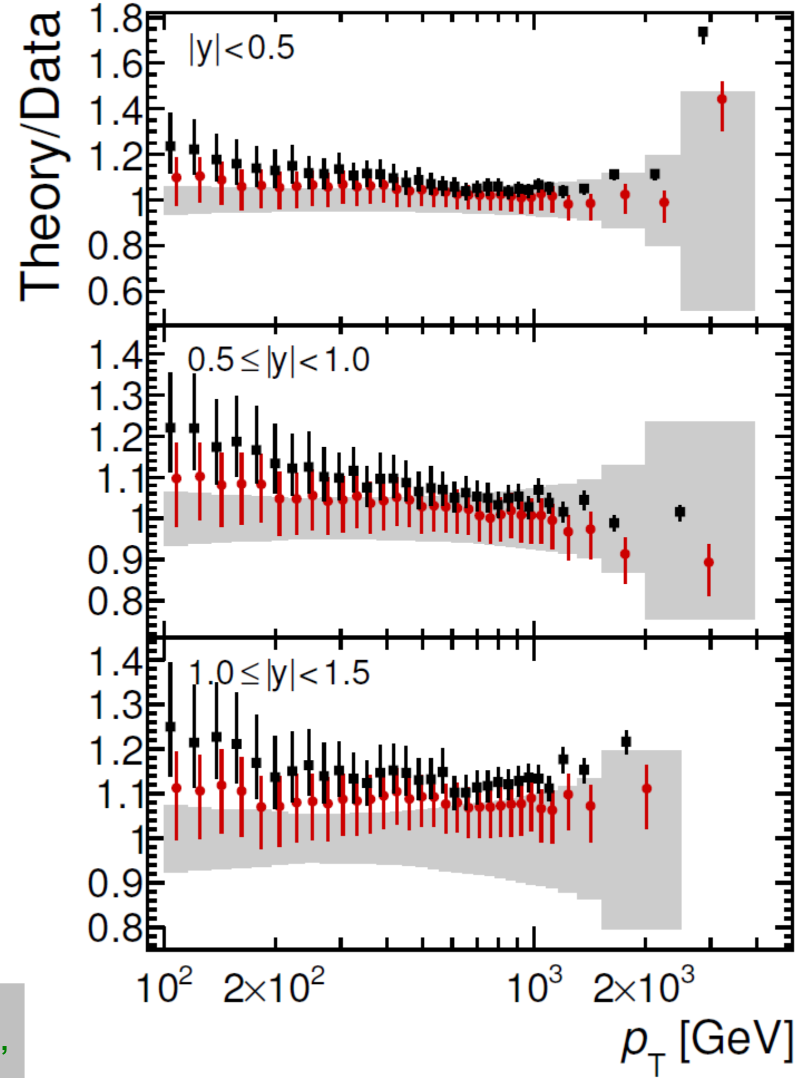
QCD scale choice: $\mu_R = \mu_F = p_{T,jet}$
- close to recommended one

→Talk by Joao Pires yesterday

QCD scale choice: $\mu_R = \mu_F = p_{T,max}$
- NOT recommended



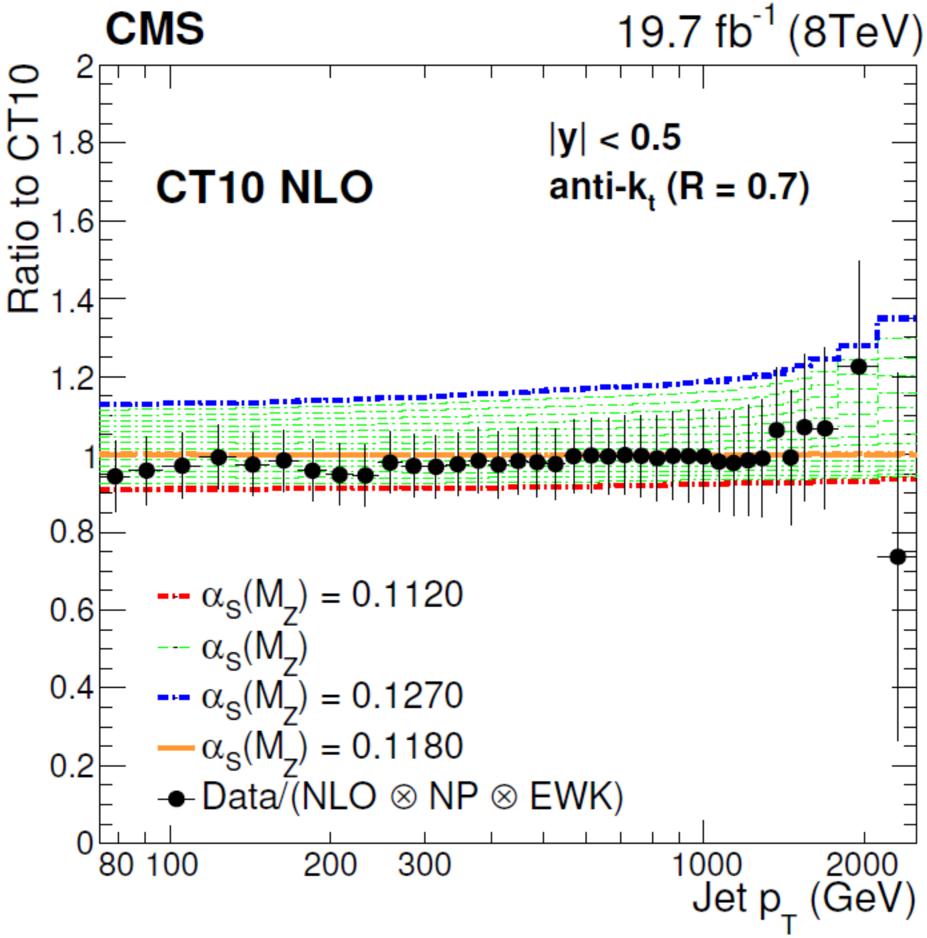




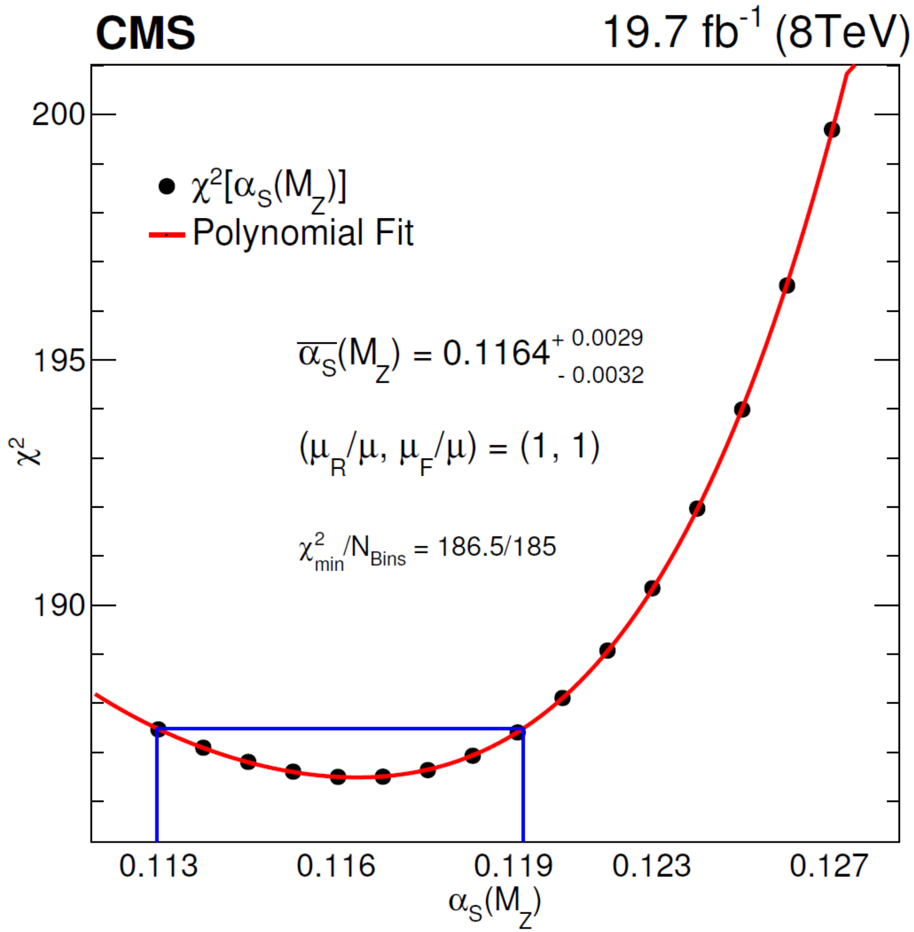
NNLO:
Currie et al., PRL 118 (2017) 072002,
Acta Phys. Pol. B48 (2017) 955.

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



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 $\alpha_s(M_Z)$



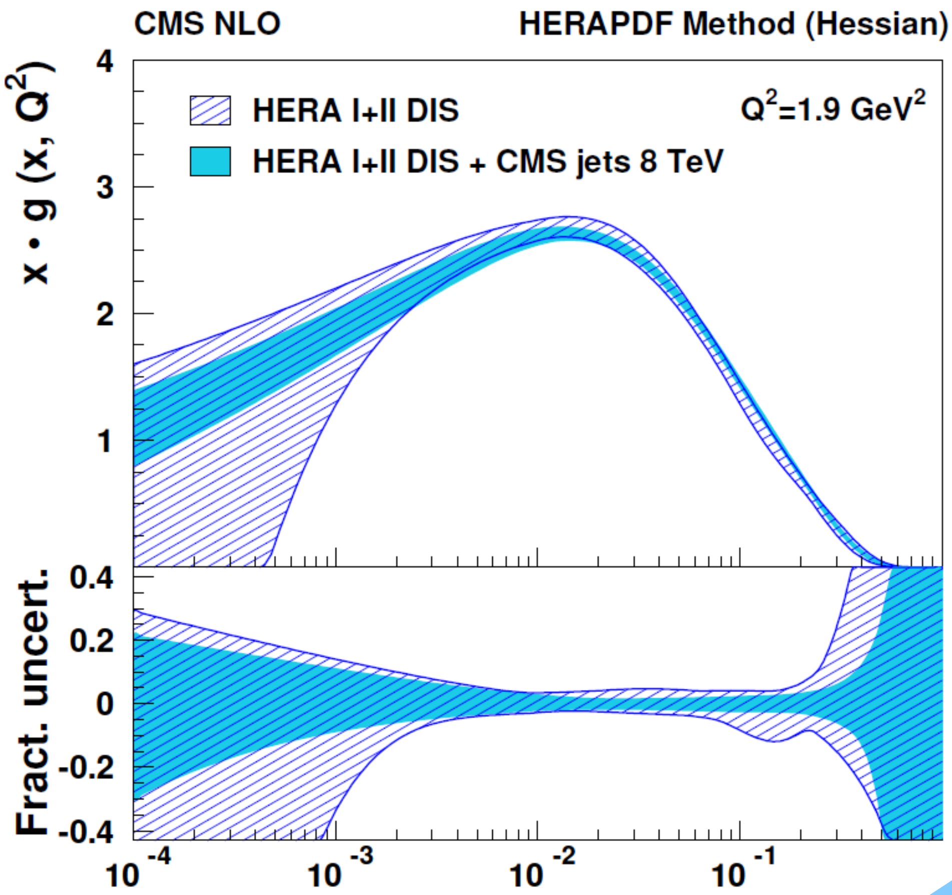
Jets @ NNLO not fully used yet in fits @ LHC → in progress

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

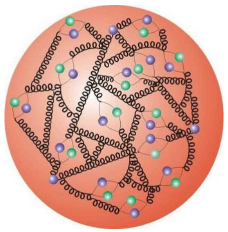
Question: How to deal with uncertainty of Missing higher orders (aka scale uncertainty) in PDF fits?

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

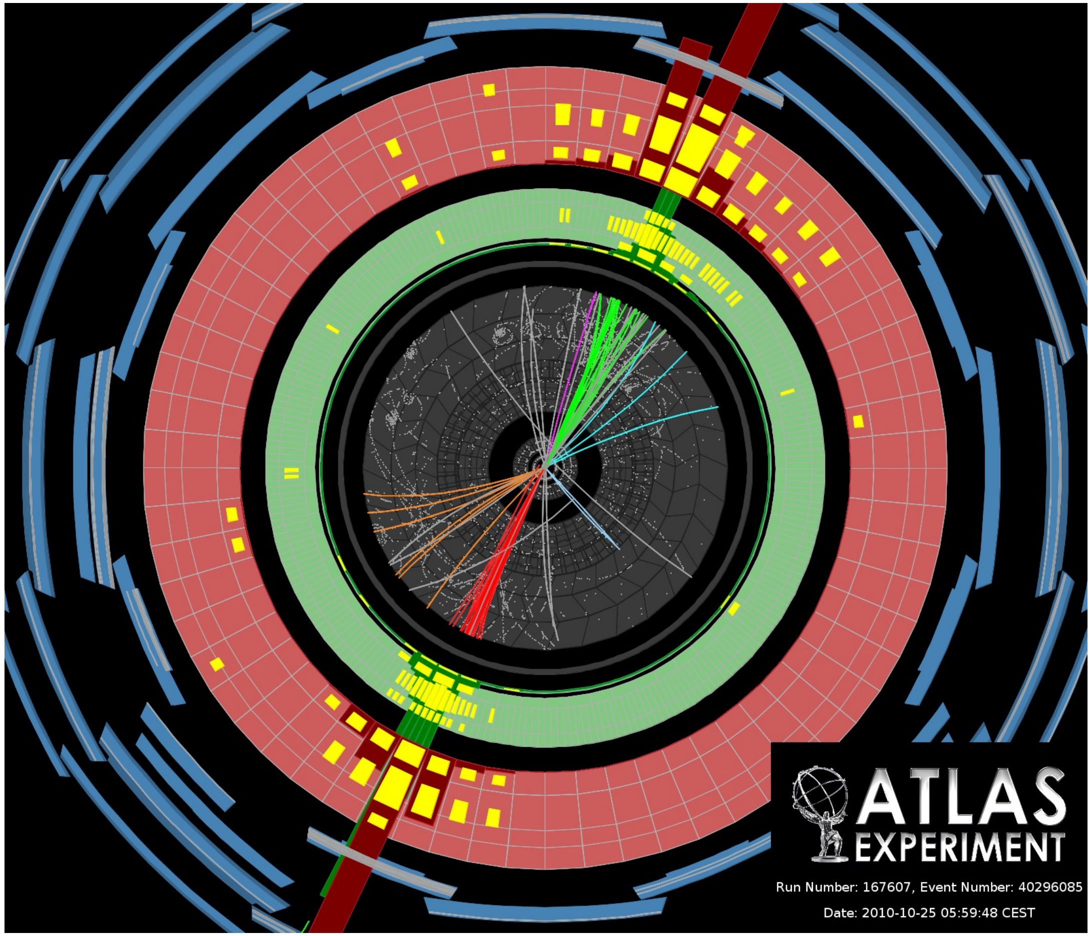
xFitter (HERAFitter): Alekhin et al., EPJC 75 (2015) 304.

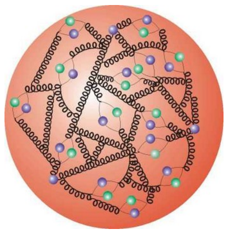
Dijets

Large masses



Proton





Proton

Relevant ATLAS & CMS measurements:

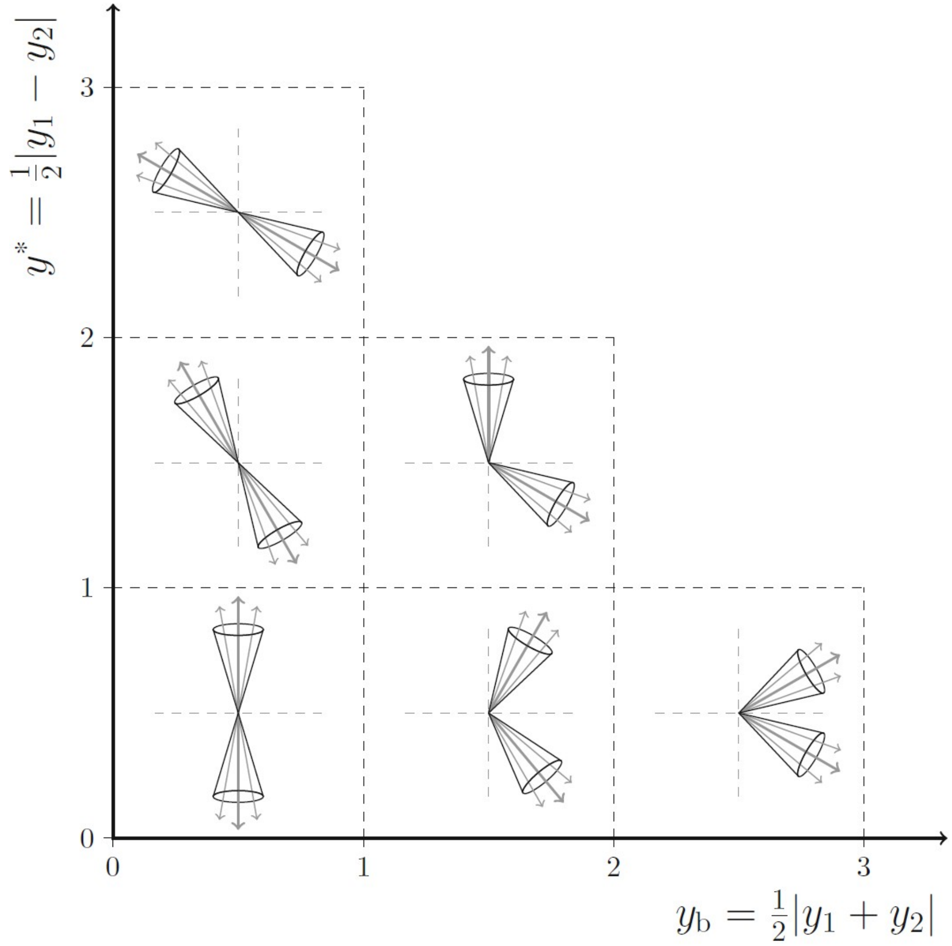
ATLAS:
JHEP 05 (2014) 059; JHEP 05 (2018) 195.
CMS:
PRD 87 (2013) 112002; EPJC 77 (2017) 746.

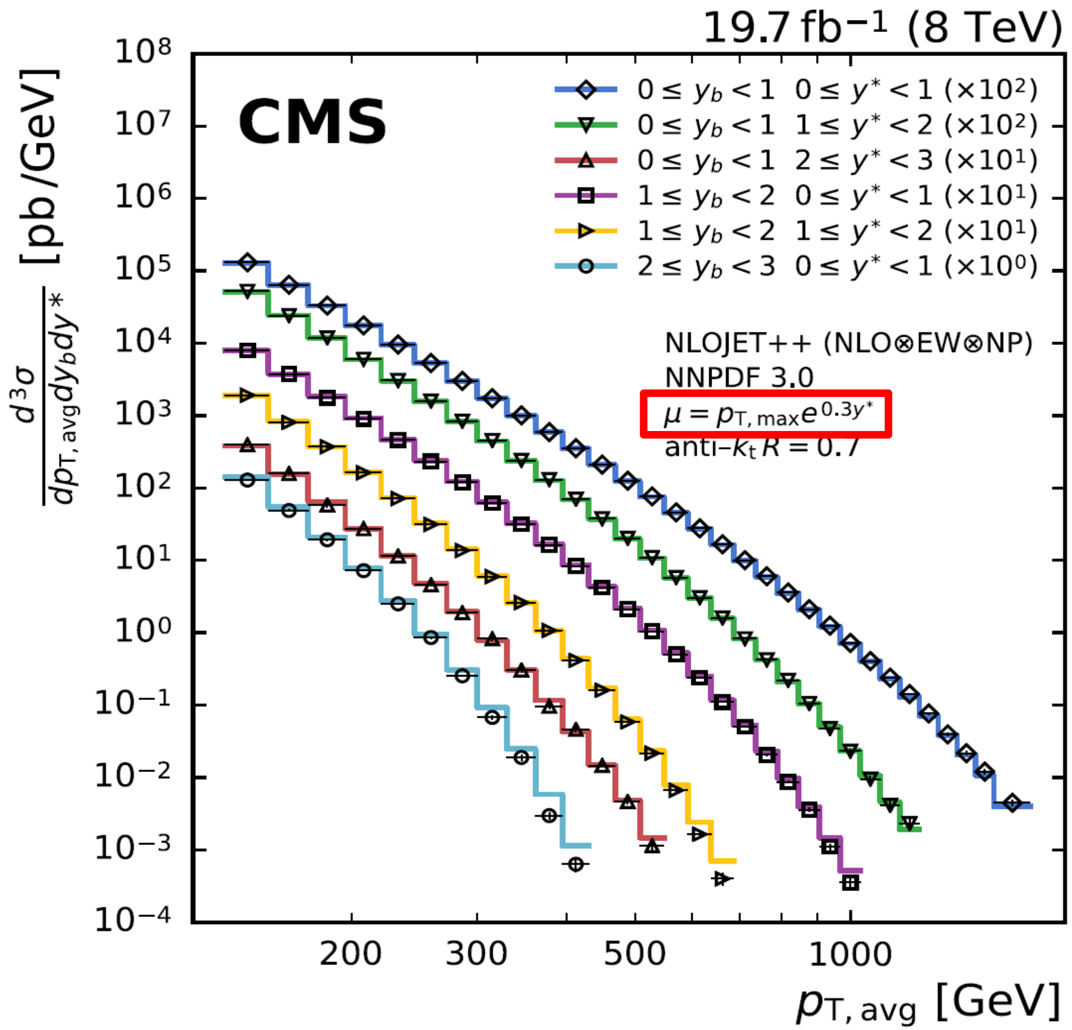
Triple-differential dijets

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

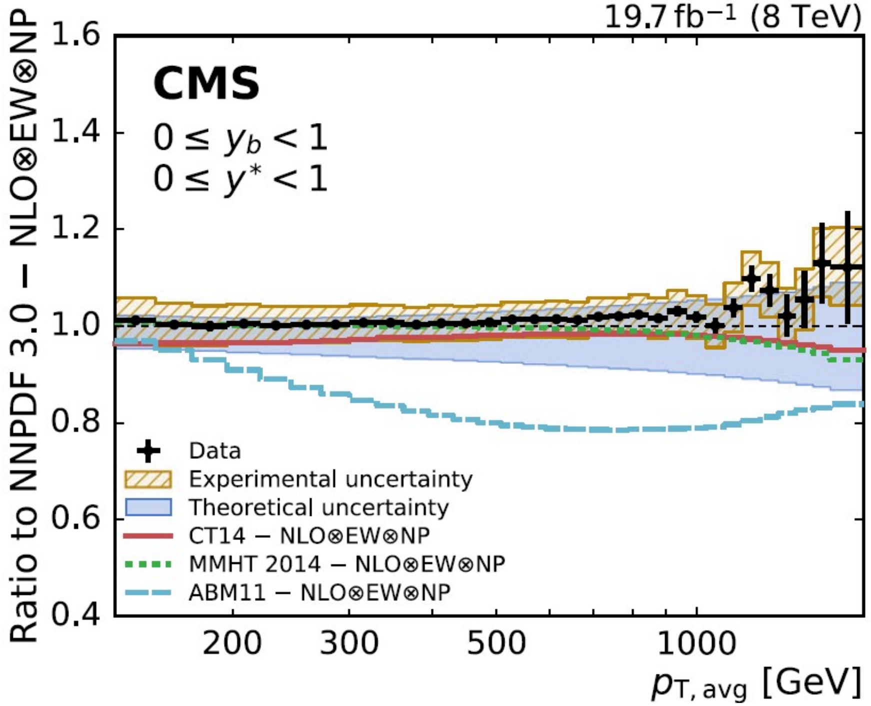




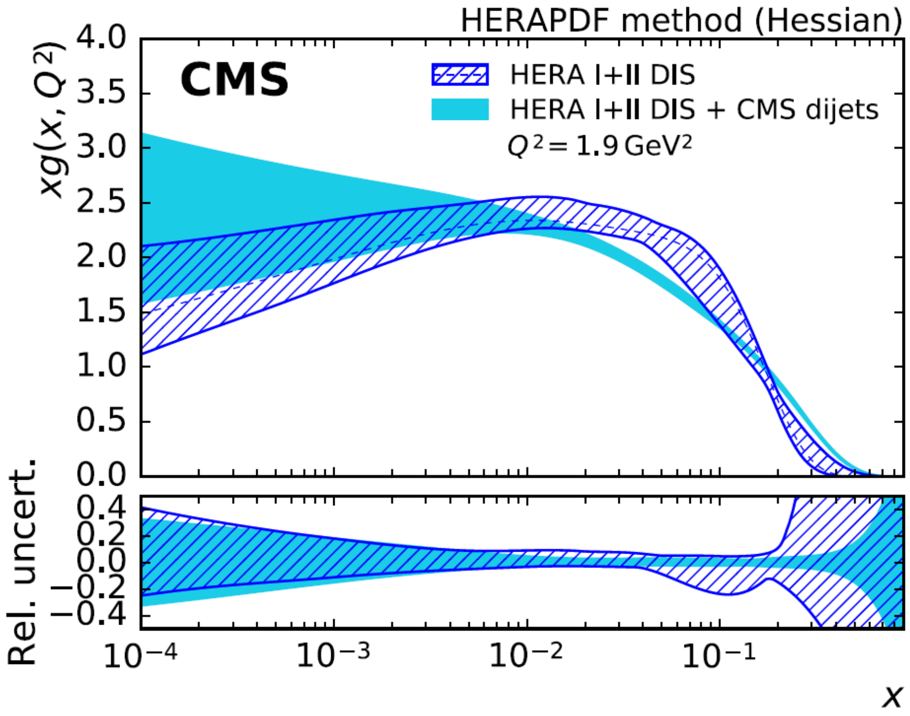
Triple-differential dijets

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

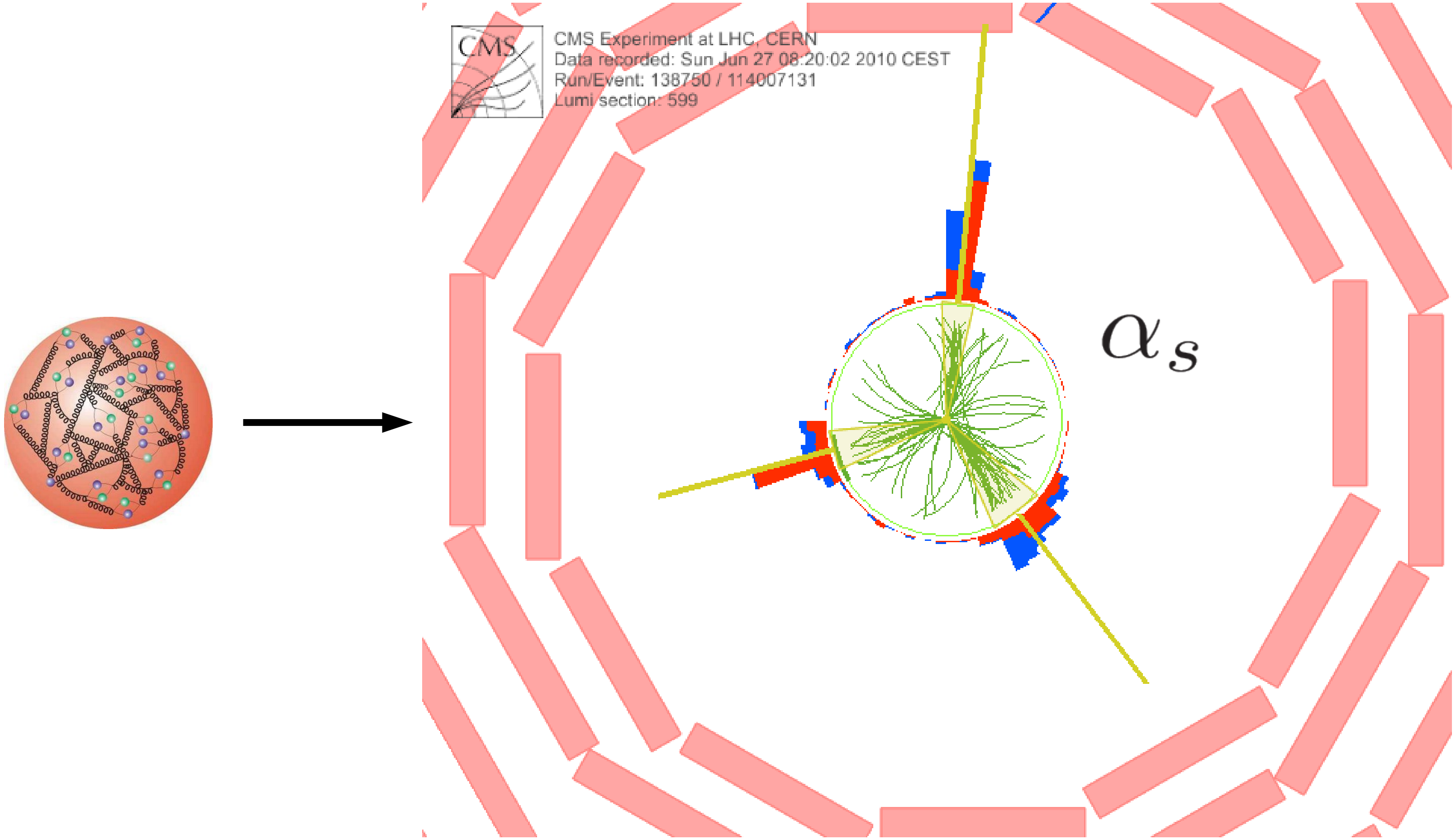


16-parameter fit

√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	$^{+15}_{-16}$	$^{+31}_{-19}$

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

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

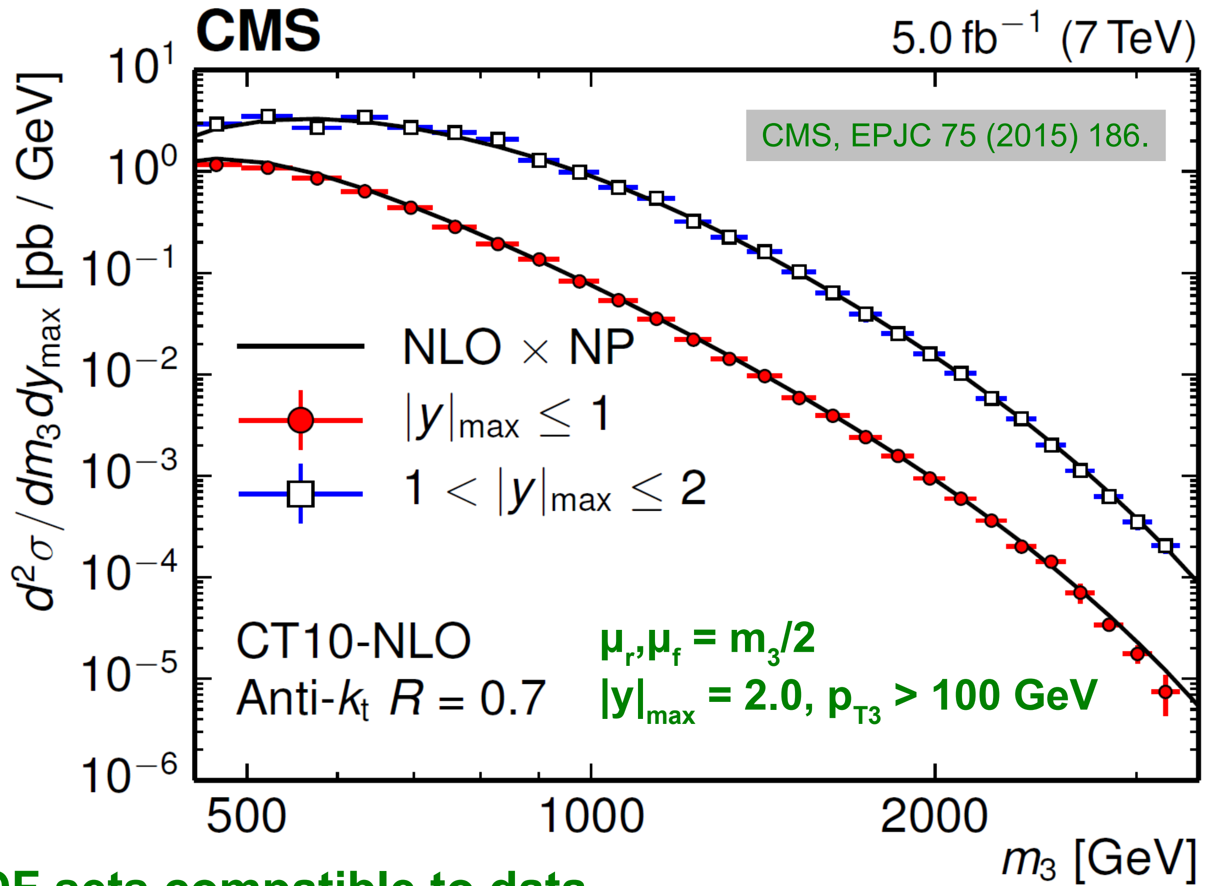
3-jet mass

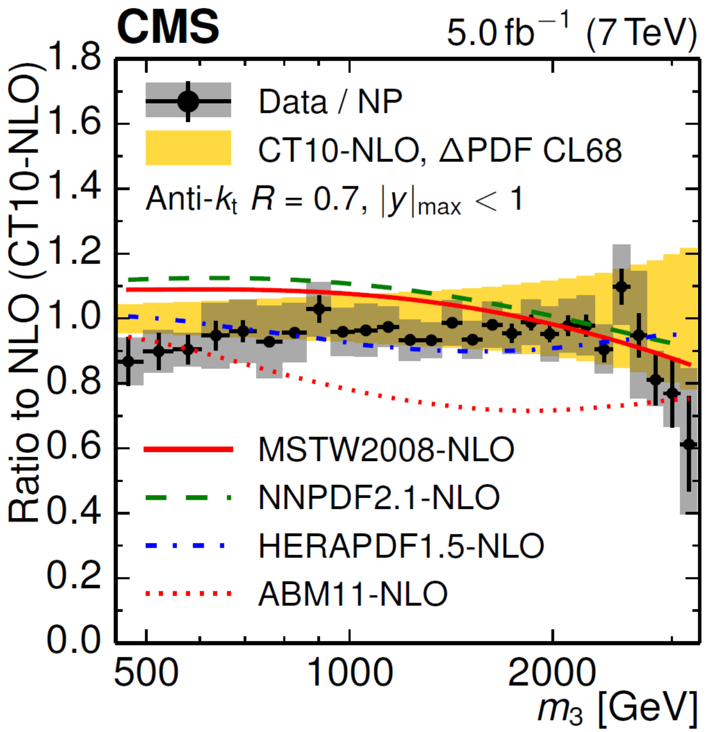
Sensitive to α_s beyond 2→2 process

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

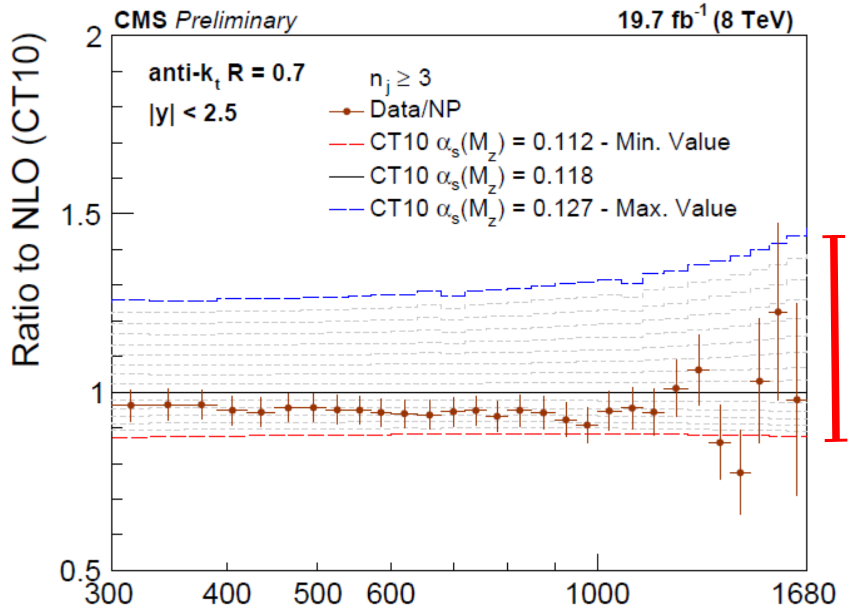
Jet cross section ratios

- 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

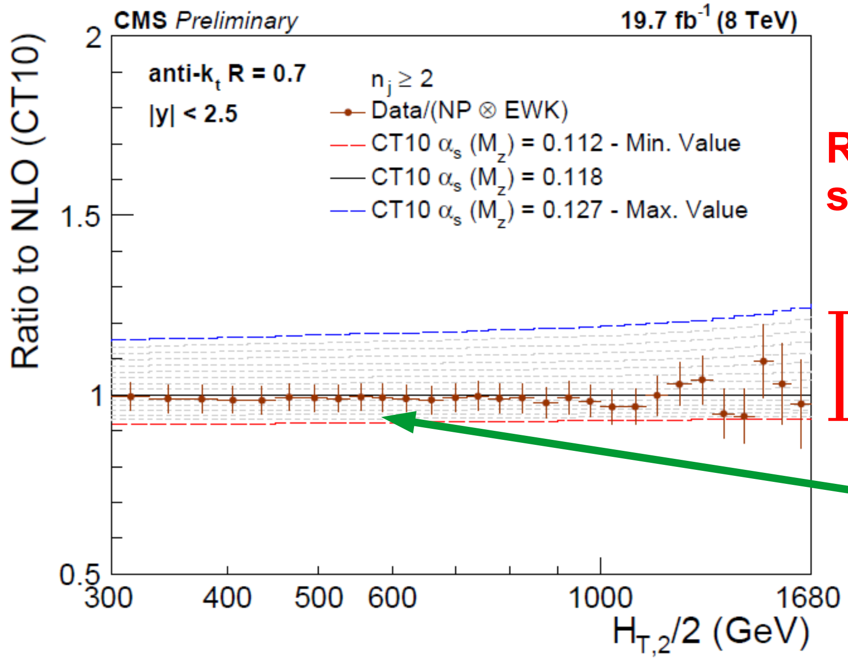
Inclusive 3-jet cross section

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



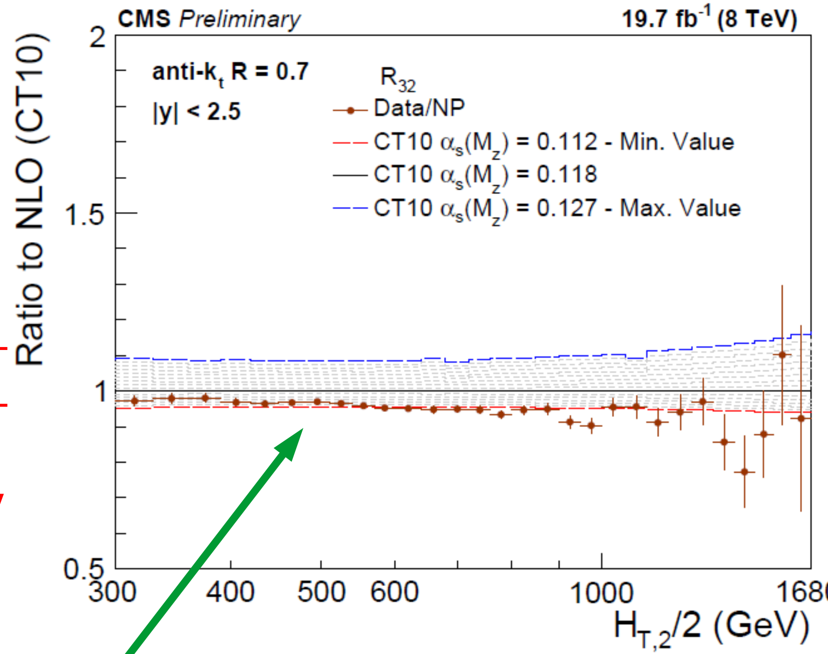
Inclusive 2-jet cross section

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



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

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

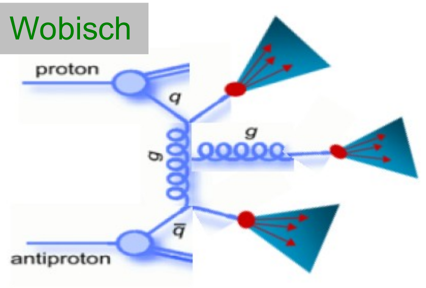


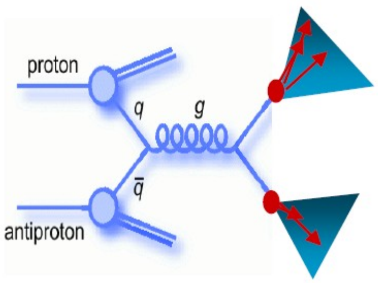
Reduced sensitivity

Much reduced systematic uncertainty

3- to 2-jet ratios

M. Wobisch



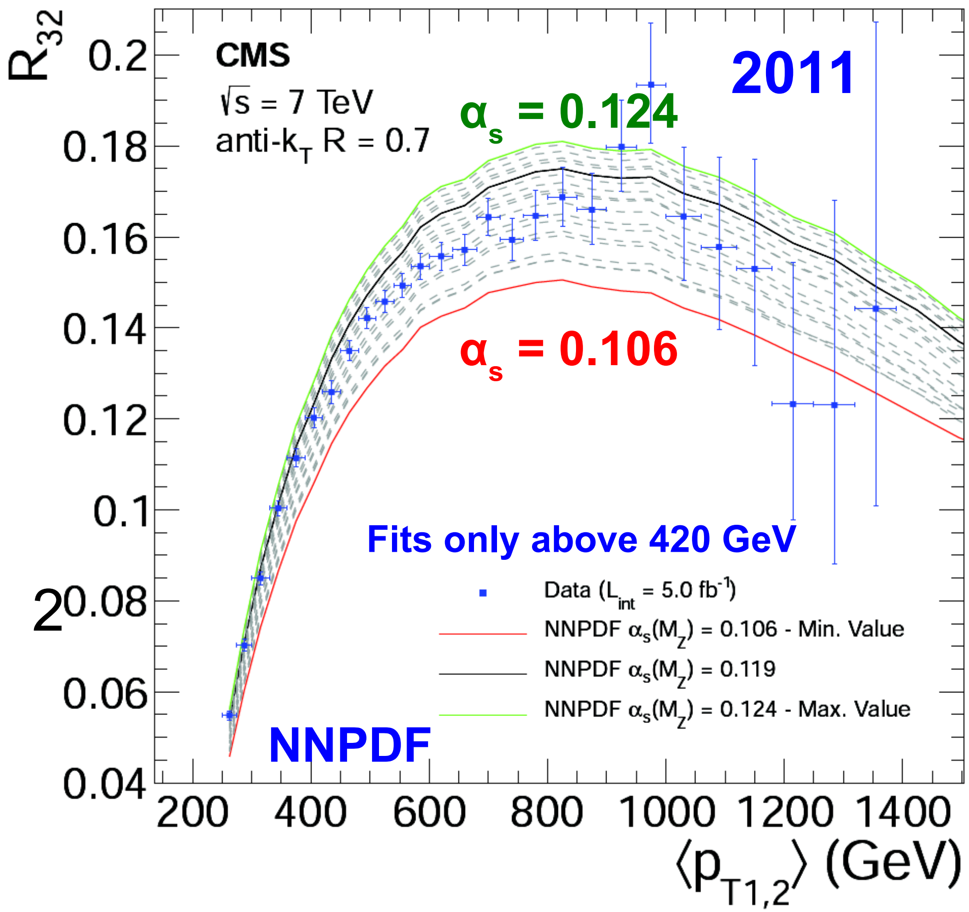


$R_{3/2}$

$\Leftrightarrow \alpha_s$

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

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



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.**

$\rightarrow \alpha_s$

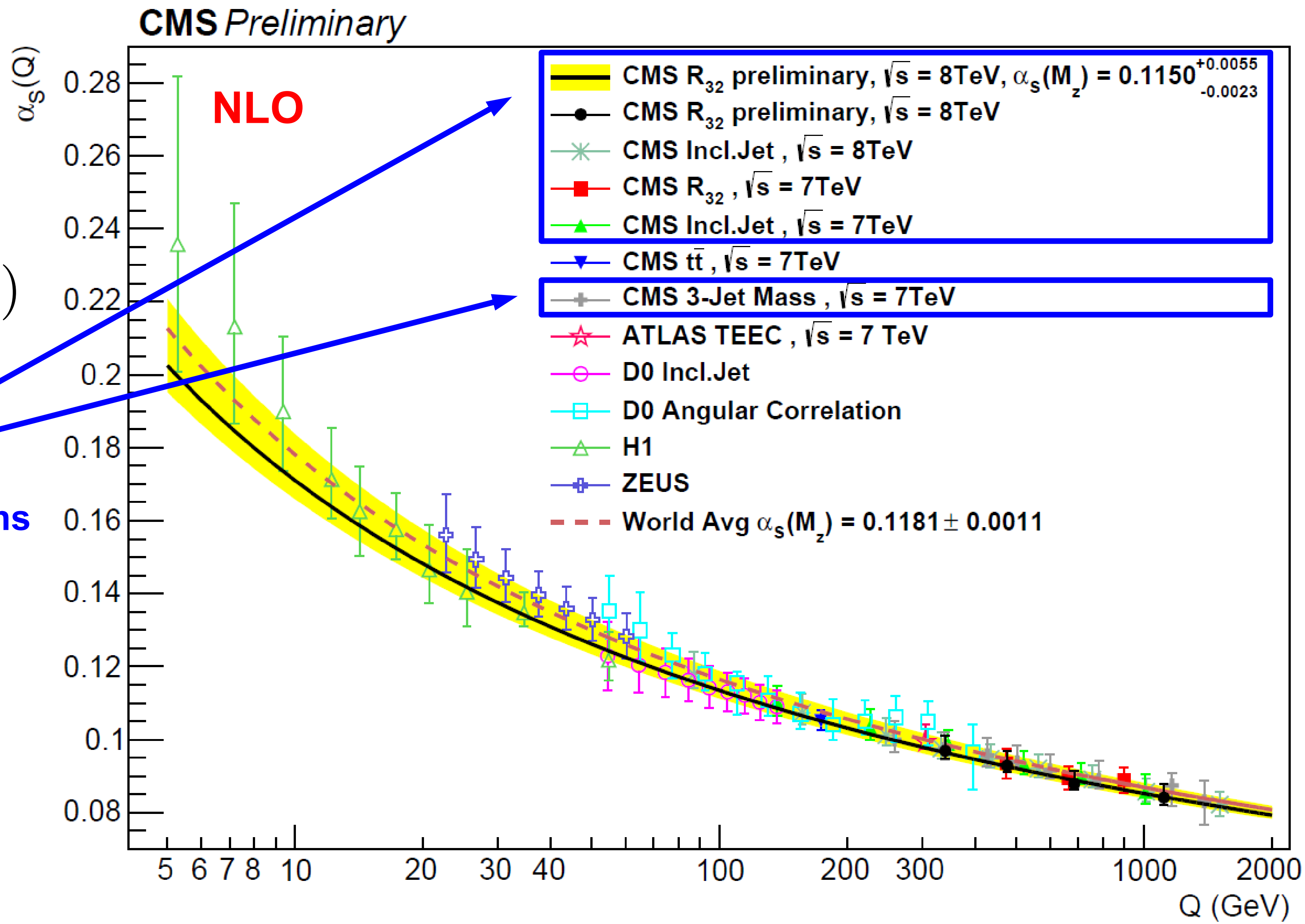
√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1148	23	50
8	19.7	0.1150	22	+50

Running of $\alpha_s(Q)$

Perform fits in fixed intervals of the chosen scale Q

$\alpha_s(Q)$

Jet cross sections and ratios



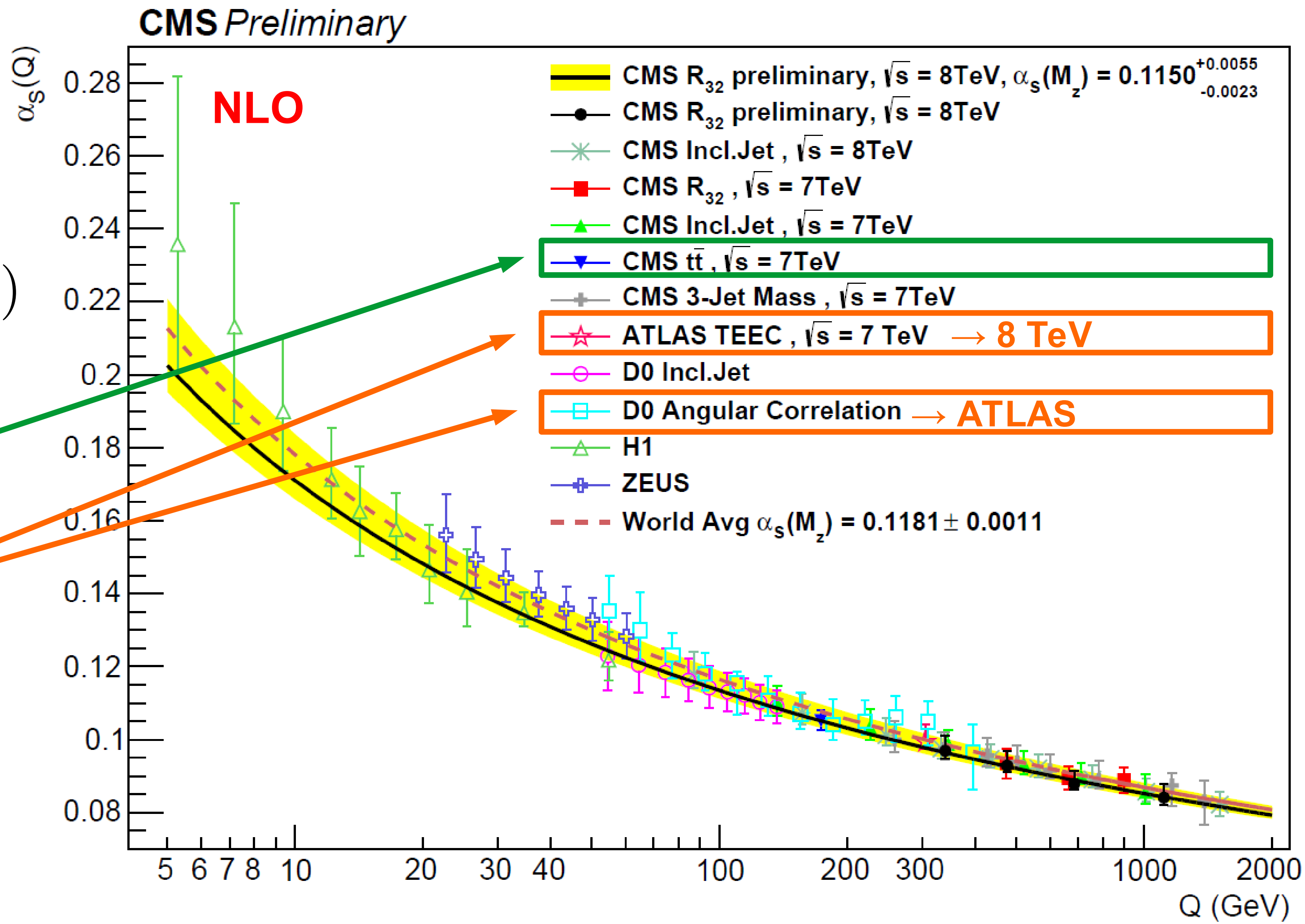
Needs an update for latest ATLAS, CMS, & H1 points ...

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

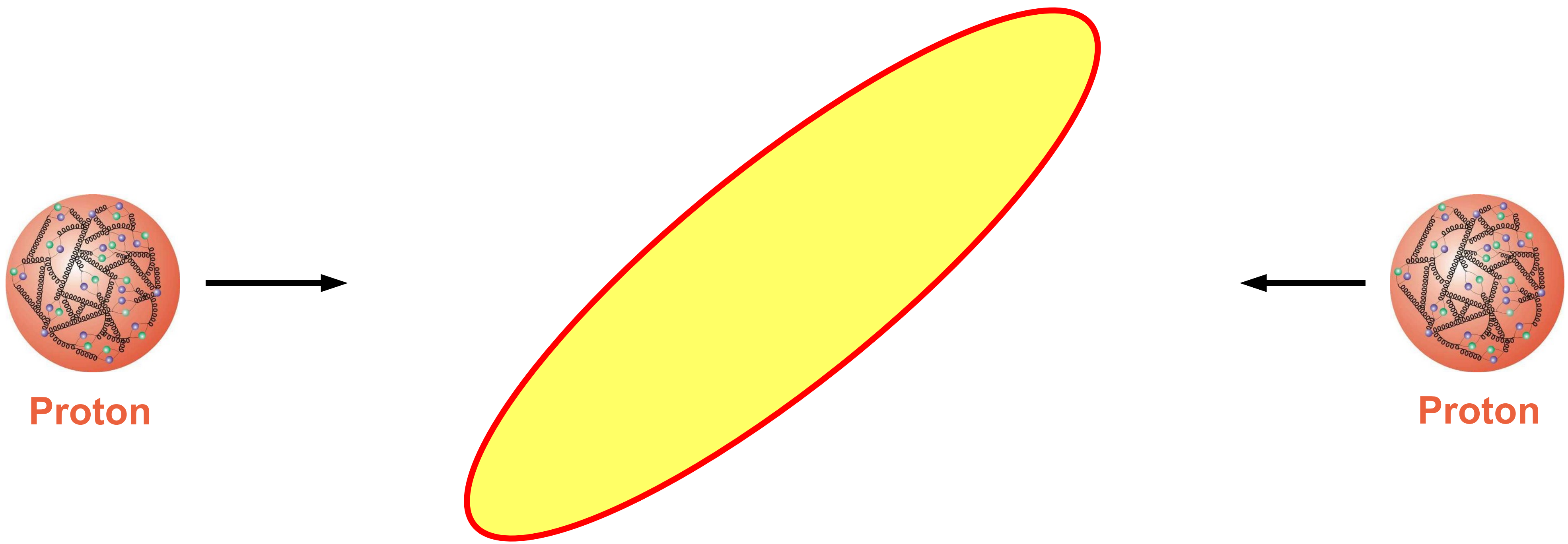
Normalised distributions

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 ...

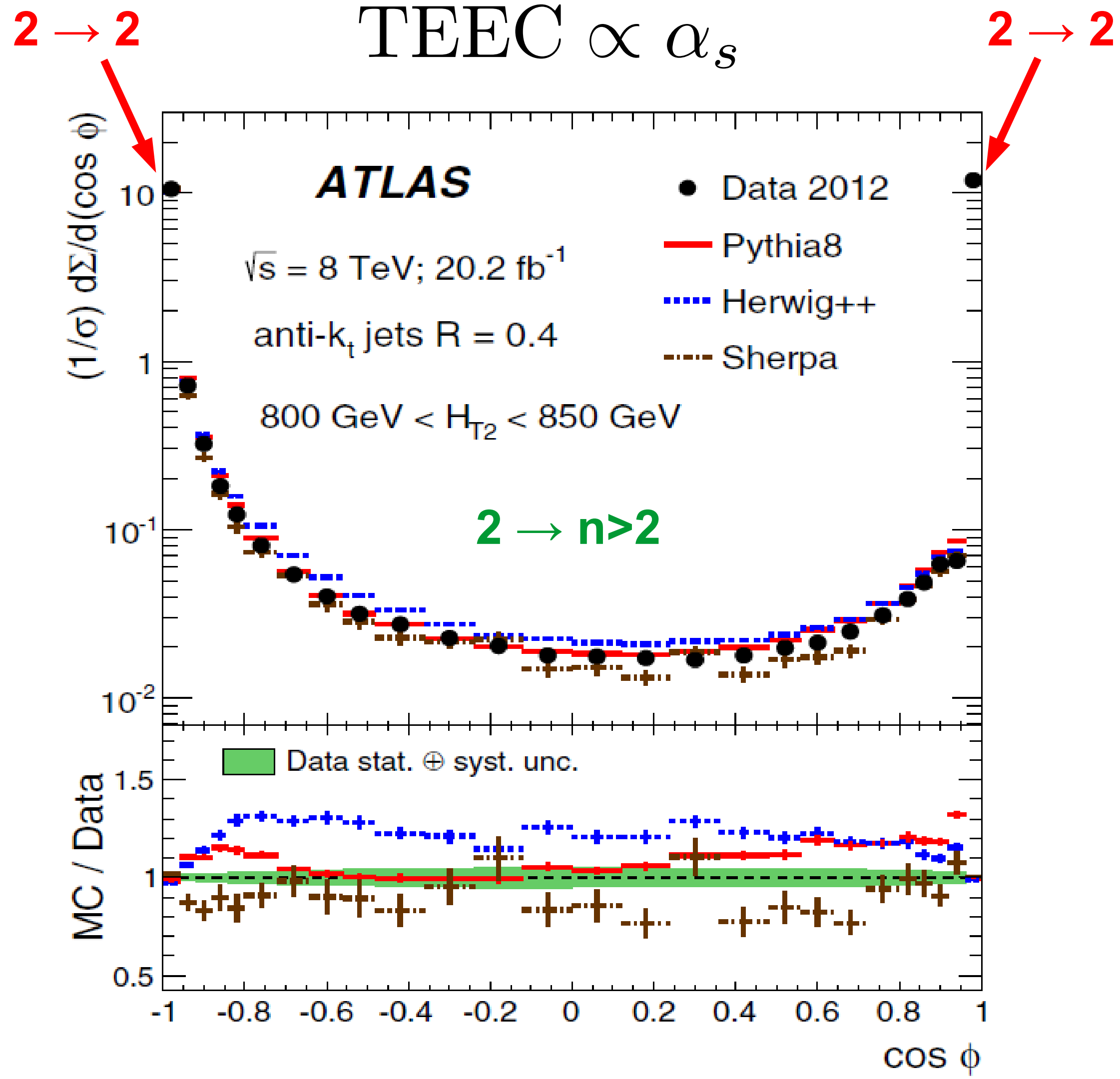
- Determination of $\alpha_s(M_Z)$ in single-parameter fit
- Test running of $\alpha_s(Q)$ (reduced PDF dependence)
- Some reduction in sensitivity
- But cancellation of many systematic effects
- More scale choices

Transverse energy-energy correlation

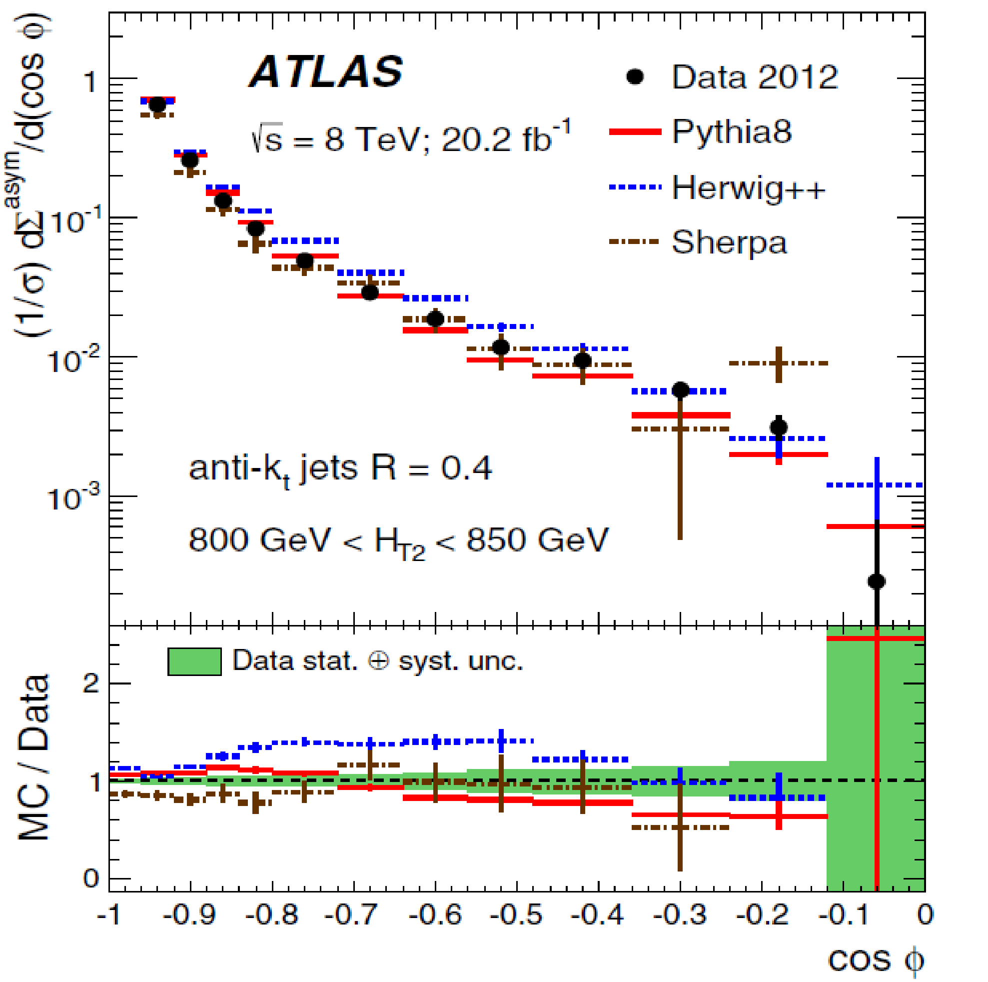
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

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

TEEC $\propto \alpha_s$



ATEEC $\propto \alpha_s$



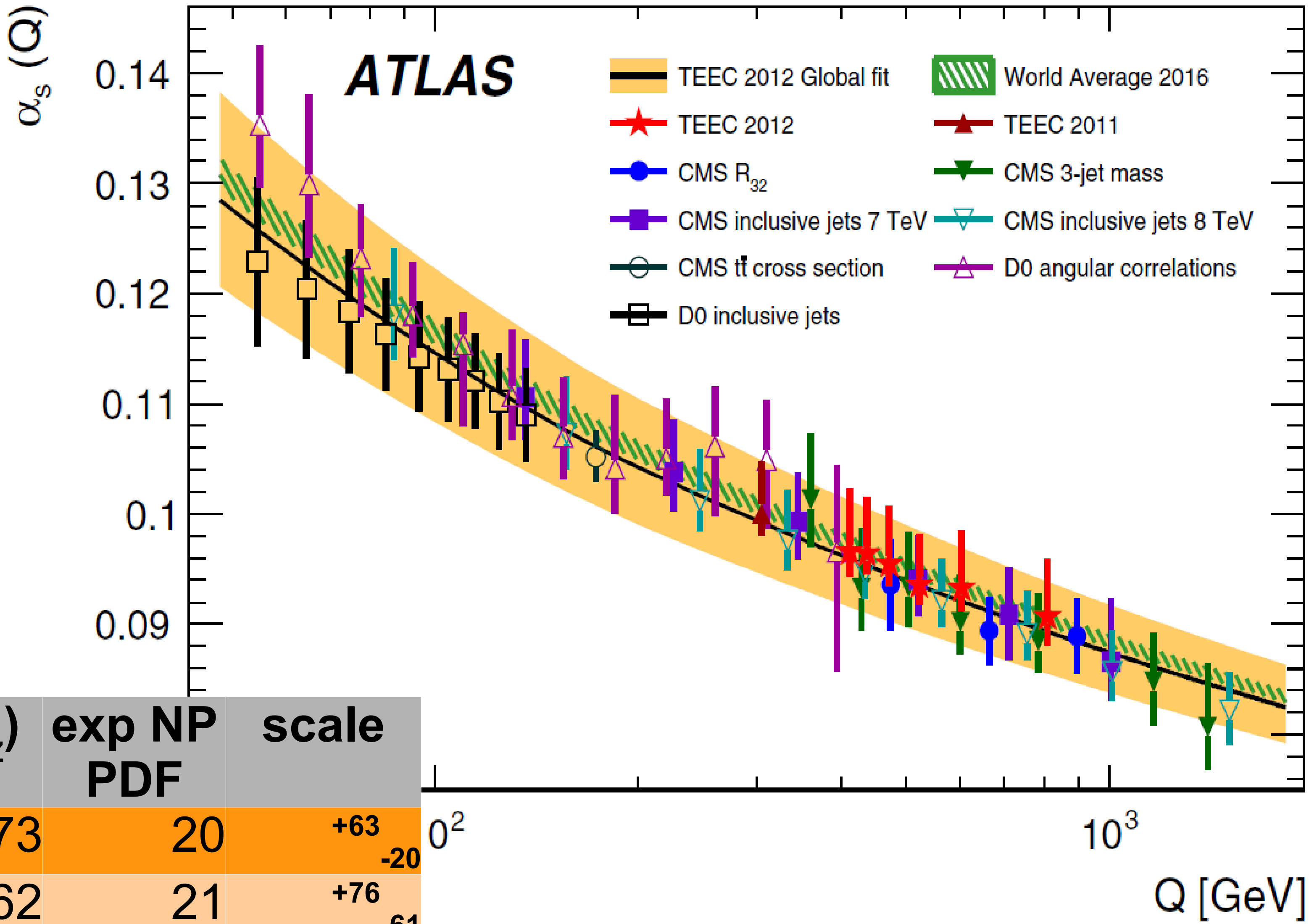
(A)TEEC in bins of $Q = (p_{T1}+p_{T2})/2$

Theory:
3-jet NLOJet++

Scale choice:

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

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



√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	$^{+61}_{-13}$

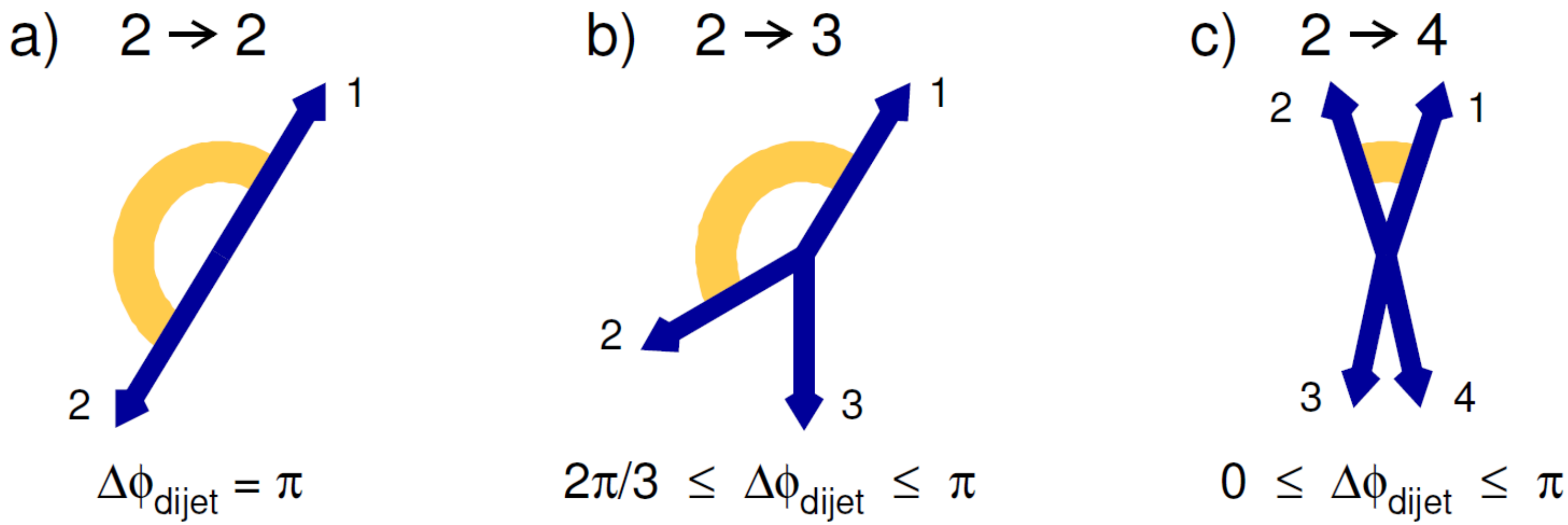
Orange: TEEC
Blue: ATEEC

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^*.

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

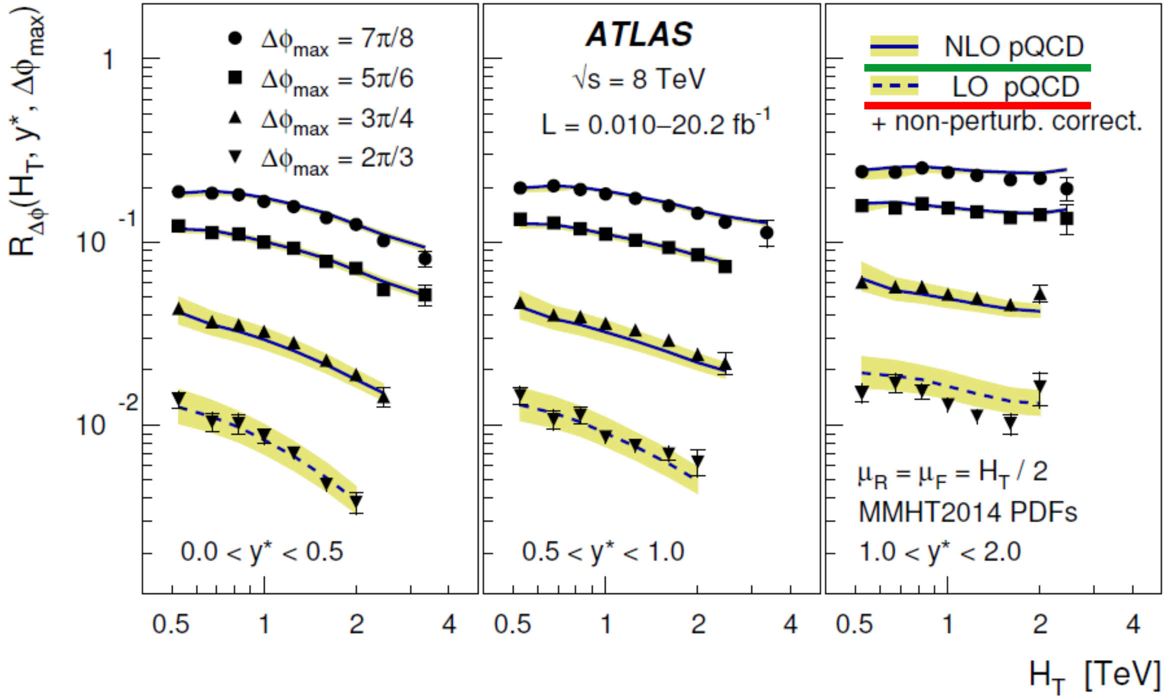
$$R_{\Delta\phi} \propto \alpha_s$$



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

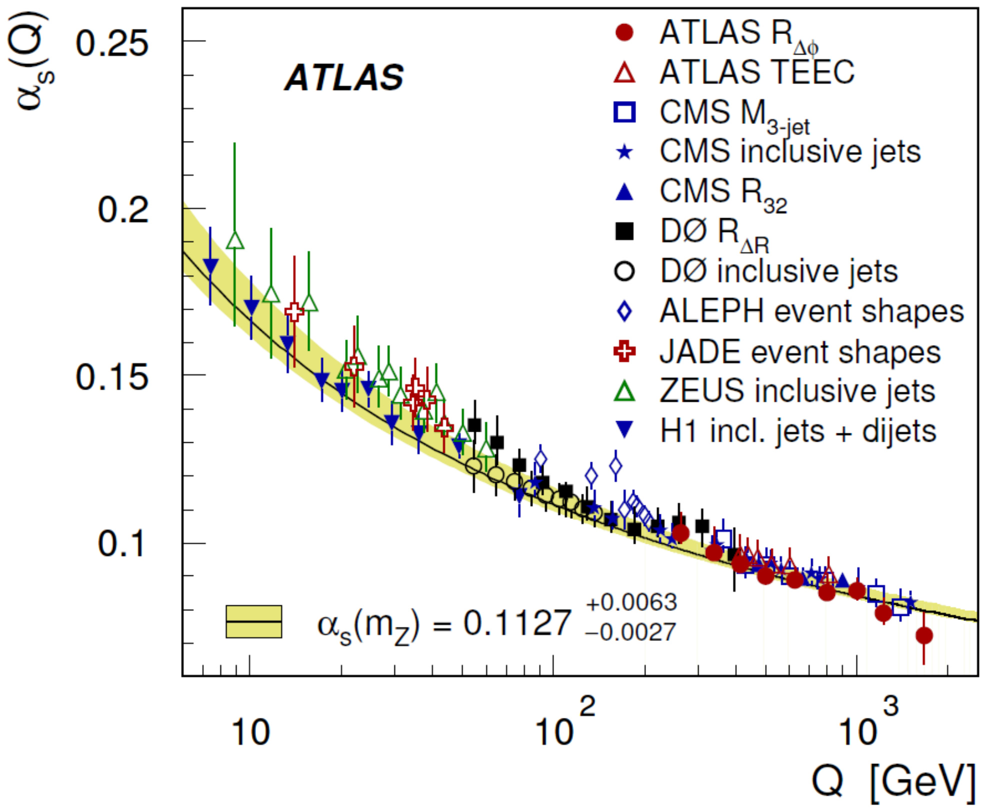
Wobisch et al., JHEP 01 (2013) 172;
KR, M. Wobisch, JHEP 12 (2015) 024.

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



Theory:
3-jet NLOJet++

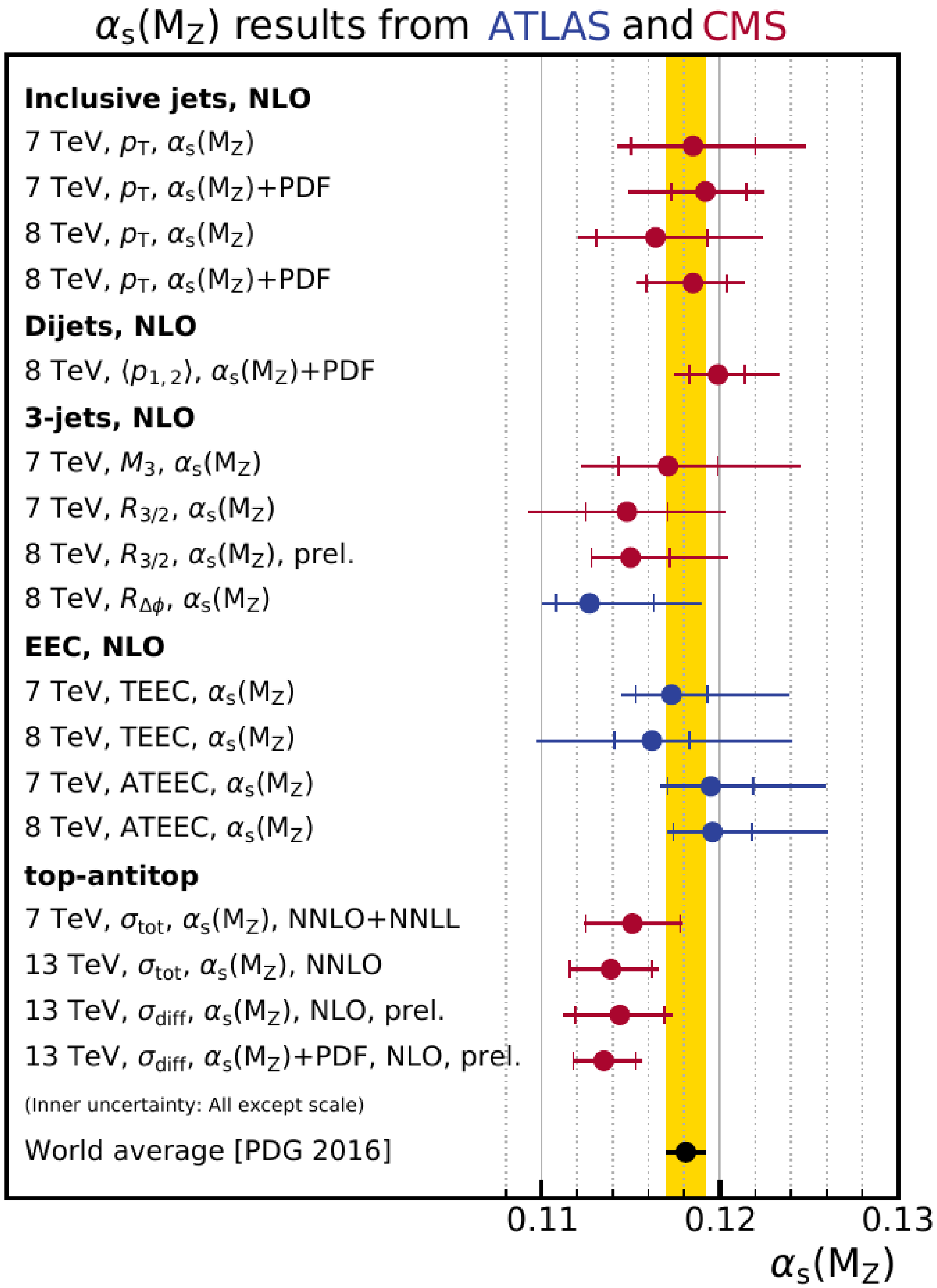
Scale choice: $\mu_R = \mu_F = H_T/2$



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	$^{+36}_{-19}$	$^{+52}_{-19}$

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 …!

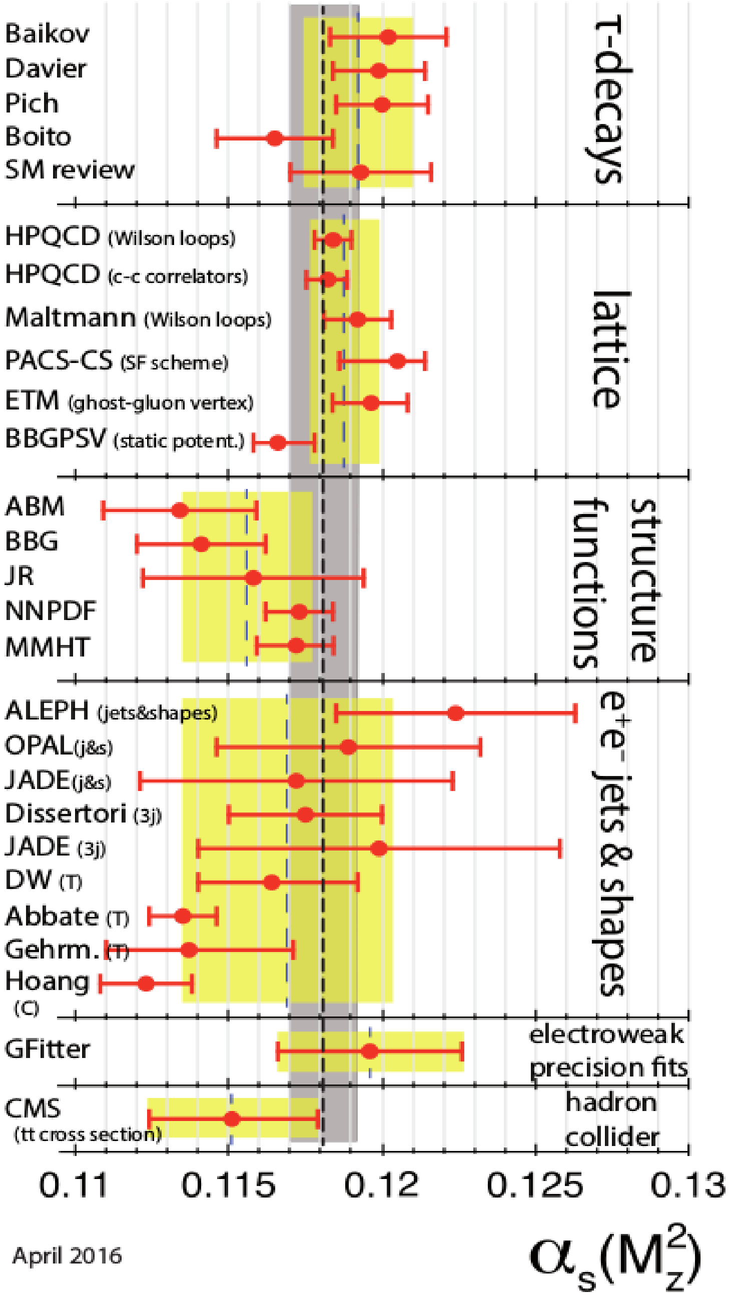
Scale choices

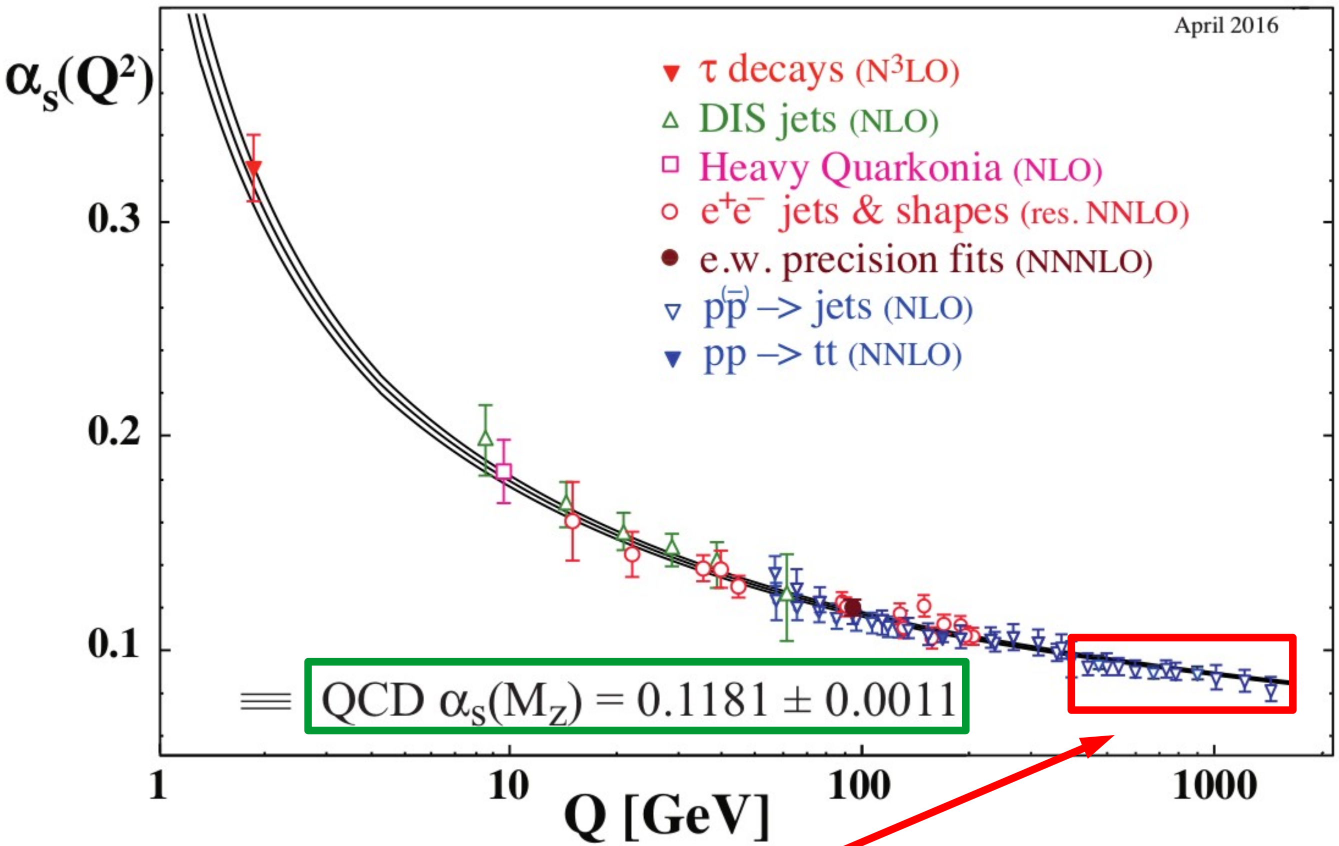
- **Inclusive jets** $\mu_0 = p_{\mathrm{T},1}, \quad p_{\mathrm{T,jet}}, \quad \hat{H}_{\mathrm{T}}?$
- **Dijets** $\mu_0 = p_{\mathrm{T},1}, \quad p_{\mathrm{T},1} \cdot \exp\left(0.3y^*\right)?$ $\mu_0 = \left(p_{\mathrm{T},1} + p_{\mathrm{T},2}\right)/2, \quad m_{jj}/2?$
- **3-jets** $\mu_0 = p_{\mathrm{T},3},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

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 $\sqrt{s}$ to disentangle g(x), M_t, α_s
  - NNLO ratios?
  - NP effects?

PDG Summary





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

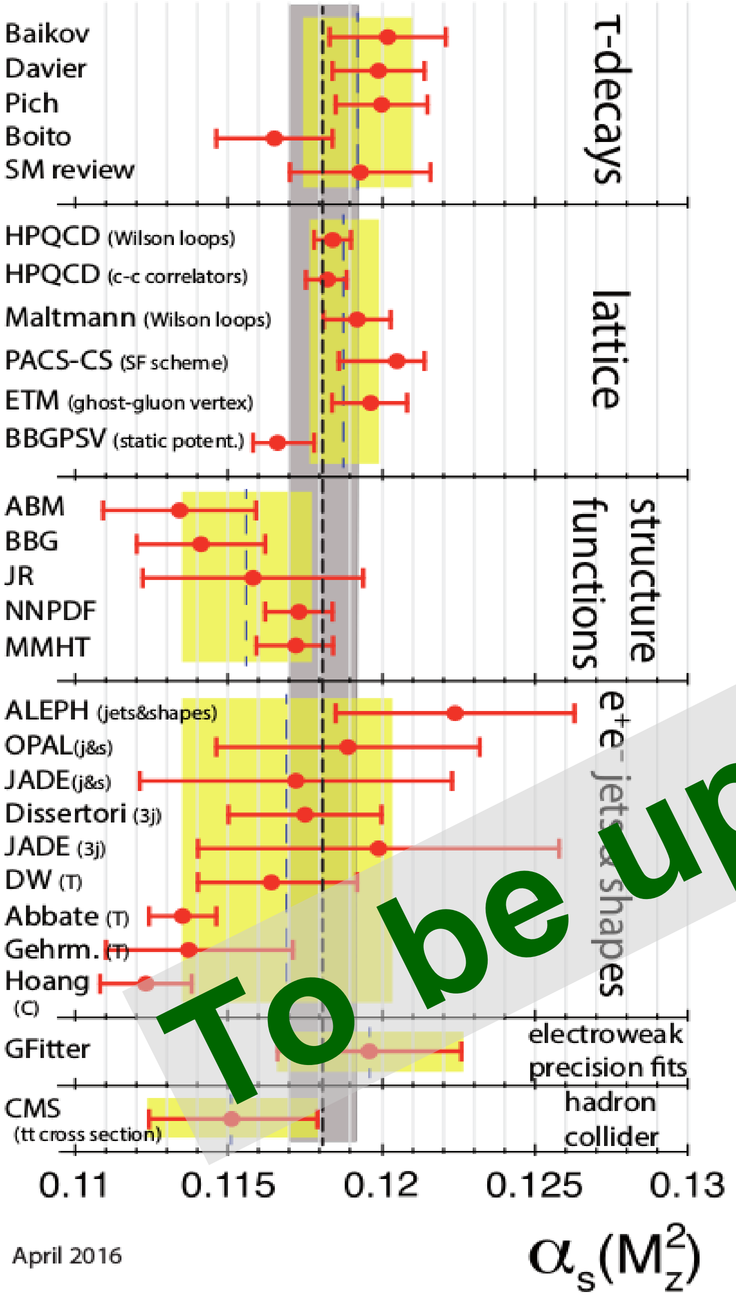
PDG, Chin. Phys. C 40 (2016) 100001.

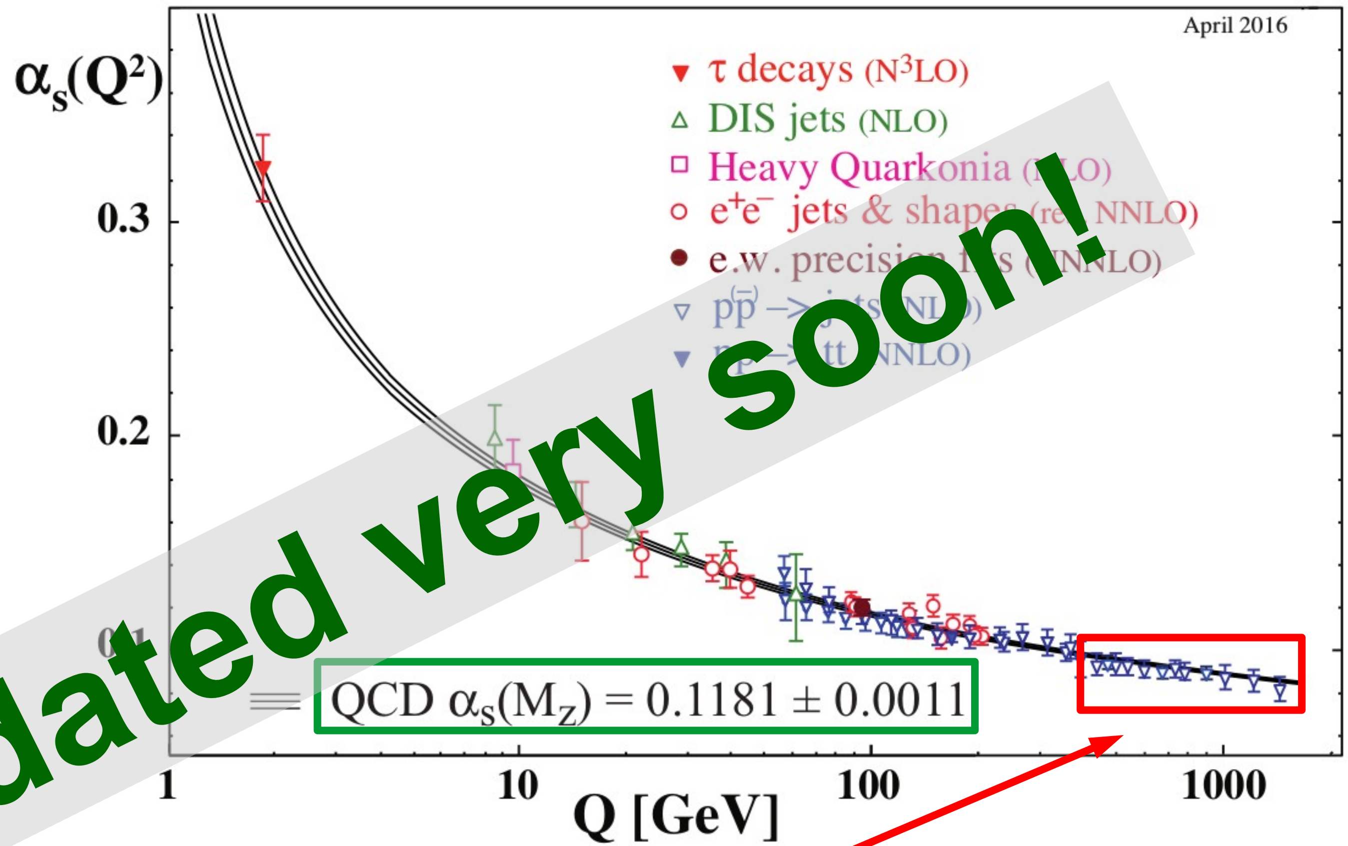
Dominated by Lattice Gauge Theory

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

PDG´92: 2.4%

PDG Summary





To be updated very soon!

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!

15th Vienna Central European Seminar
on Particle Physics and Quantum Field Theory
Precision Physics at the LHC

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