Determination of the strong coupling constant α_s at the LHC

Klaus Rabbertz, KIT

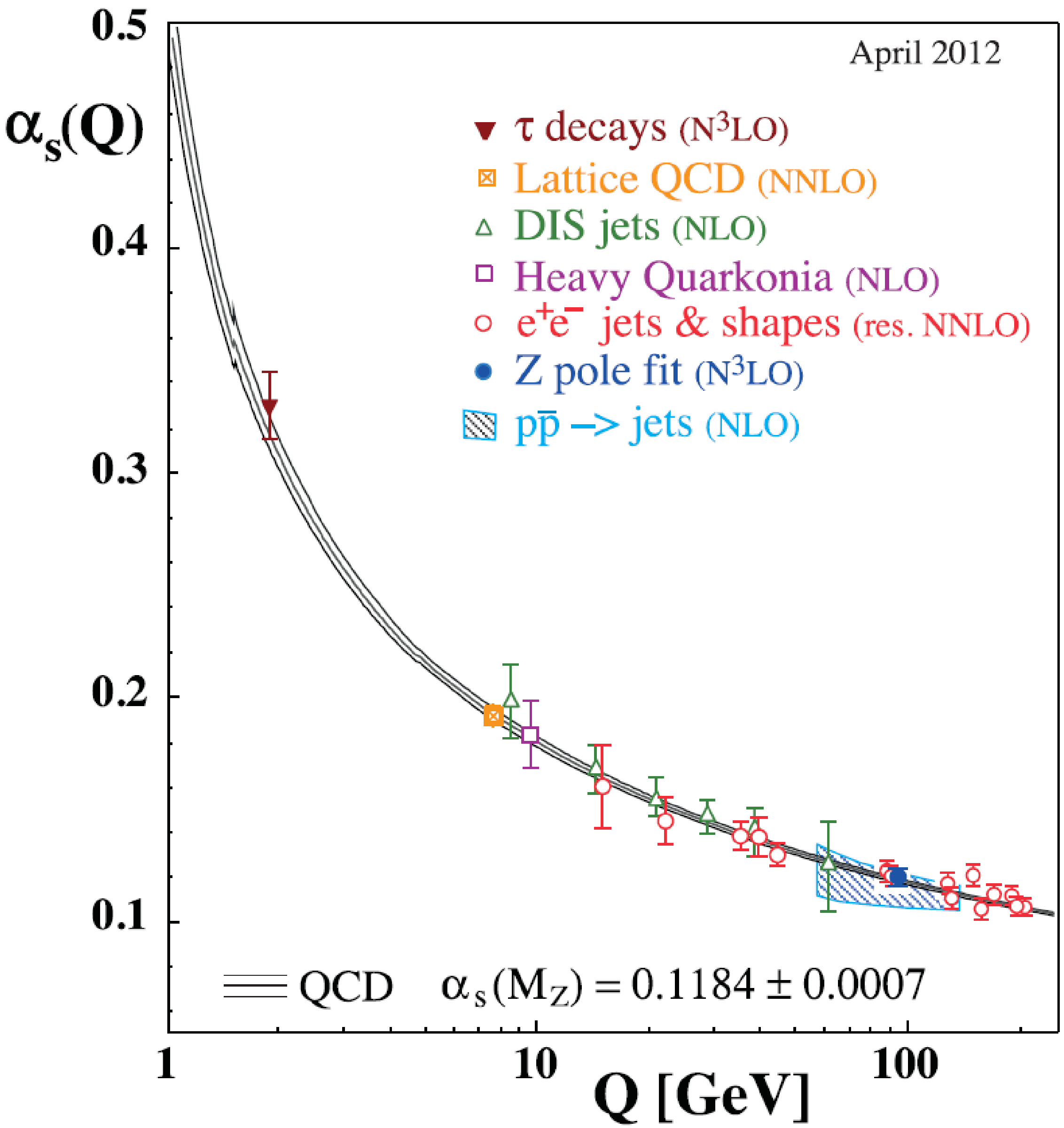
Masse und Symmetrien nach der Entdeckung des Higgs-Teilchens am LHC — GRK 2044

Karlsruhe Institute of Technology

Outline

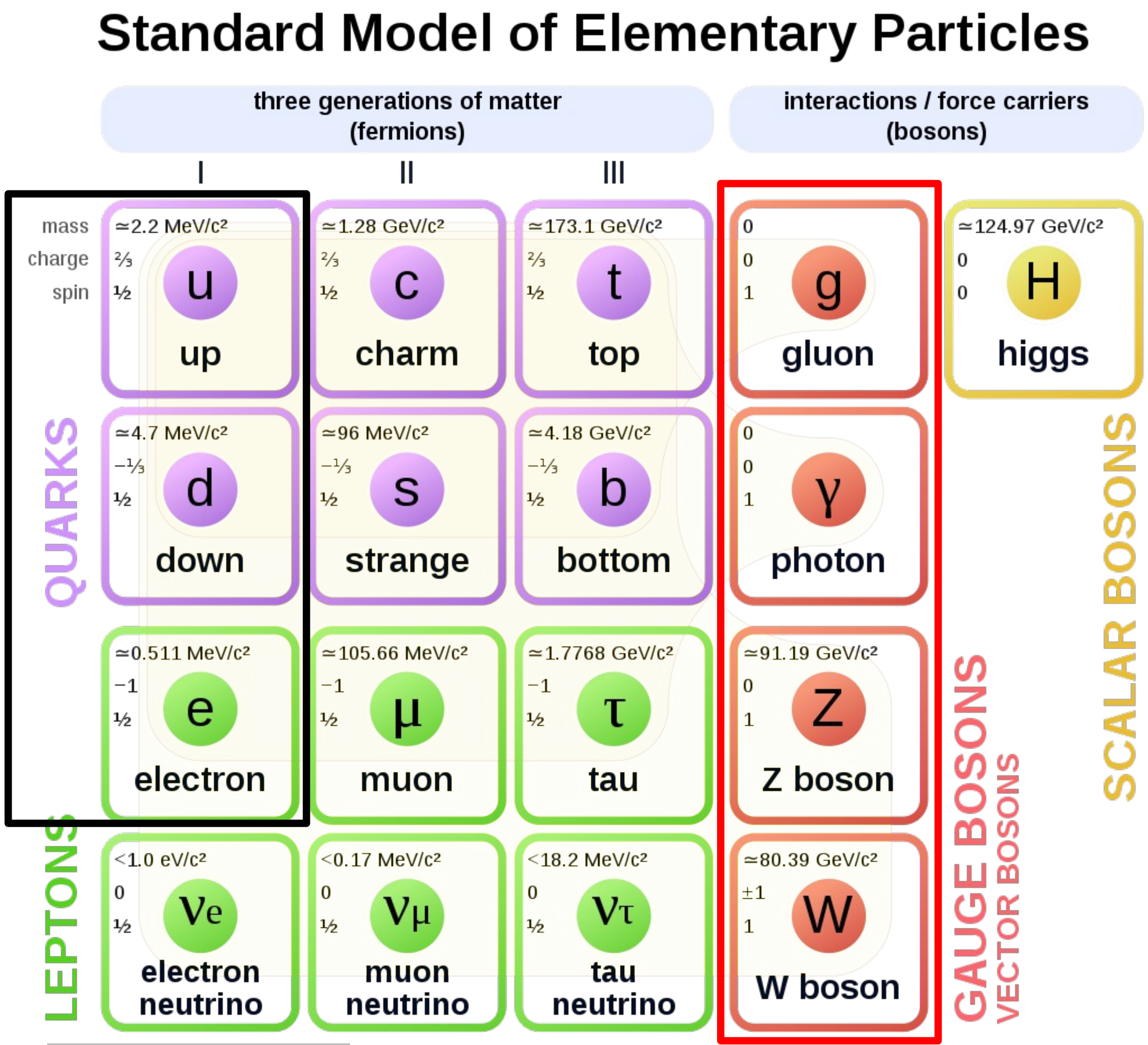
- Introduction
- Jet-like measurements
  - Cross sections
  - Ratios
  - Normalised distributions
- top-quark pair production
- W/Z bosons
- Issues & perspectives
- Summary & outlook

2012: No LHC results yet PDG2012



Solid matter

…

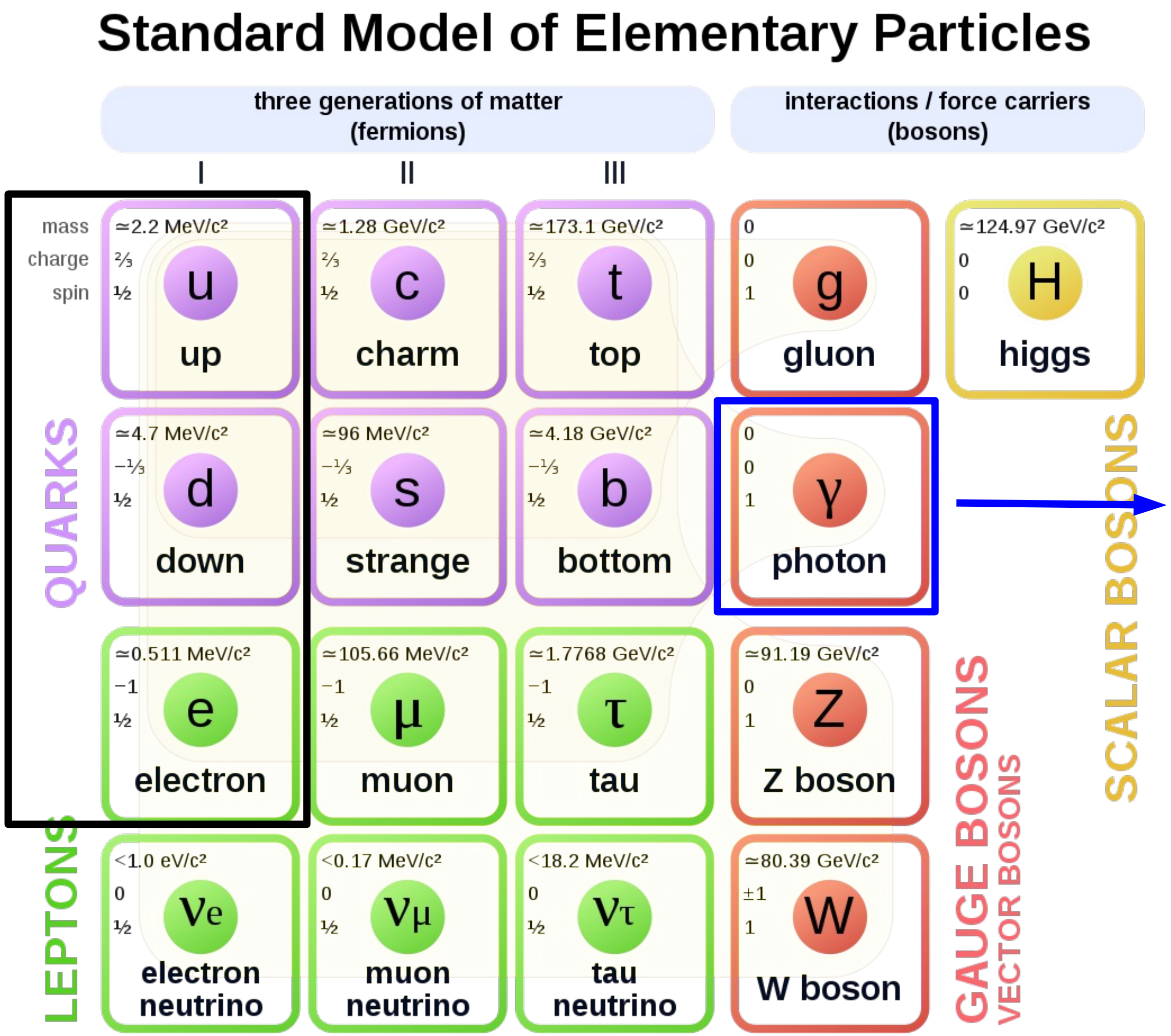


Cush, Wikipedia.

… and three fundamental interactions.
(no gravity)

Standard Model of Particle Physics

Solid matter ...



Cush, Wikipedia.

Electromagnetic interaction (magnets, electricity, ...)

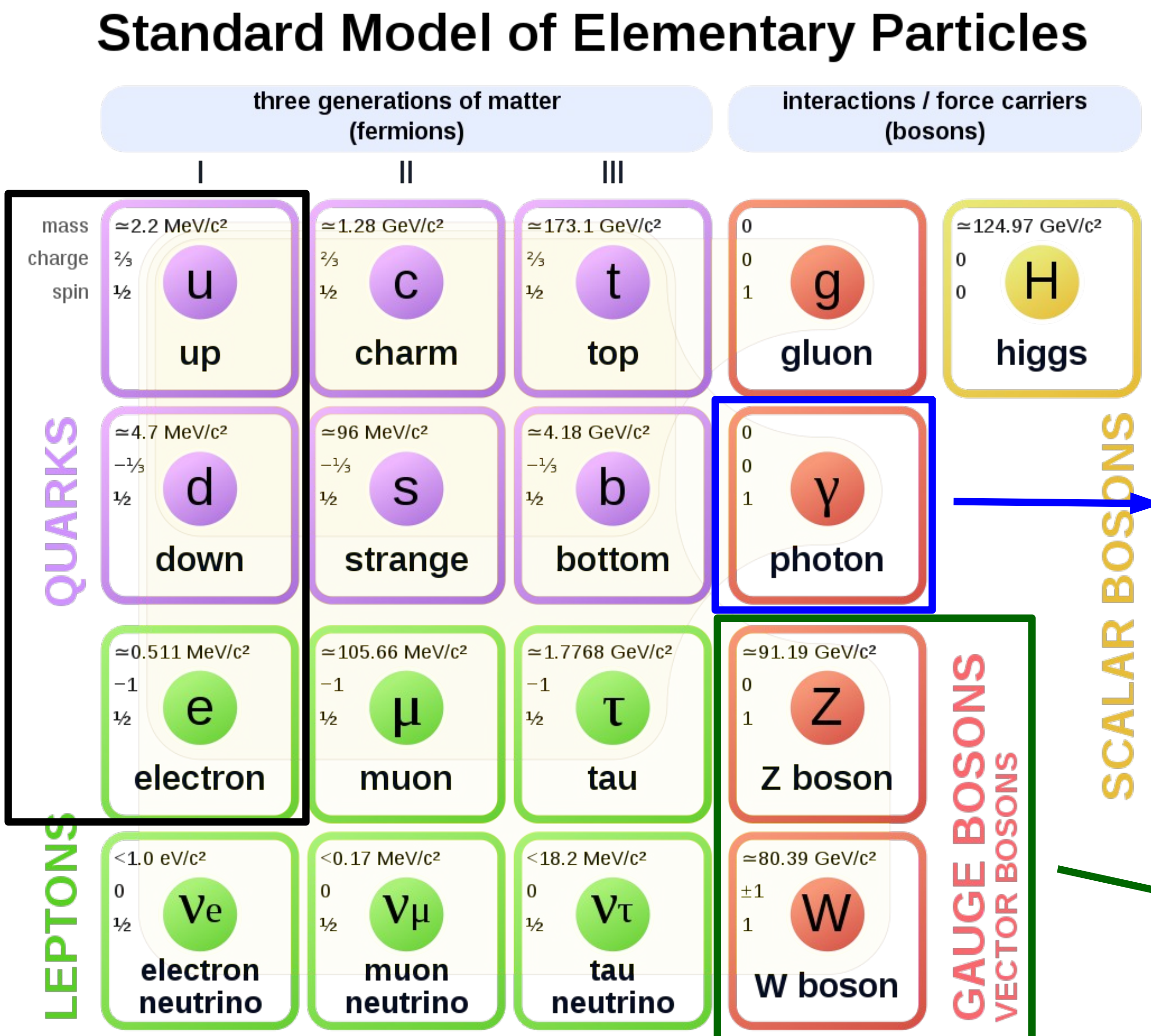
$$\alpha \approx 1/137$$

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

... and three fundamental interactions. (no gravity)

Standard Model of Particle Physics

Solid matter …



Cush, Wikipedia.

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$\alpha \approx 1/137$

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

Weak interaction (β decays, sun, …)

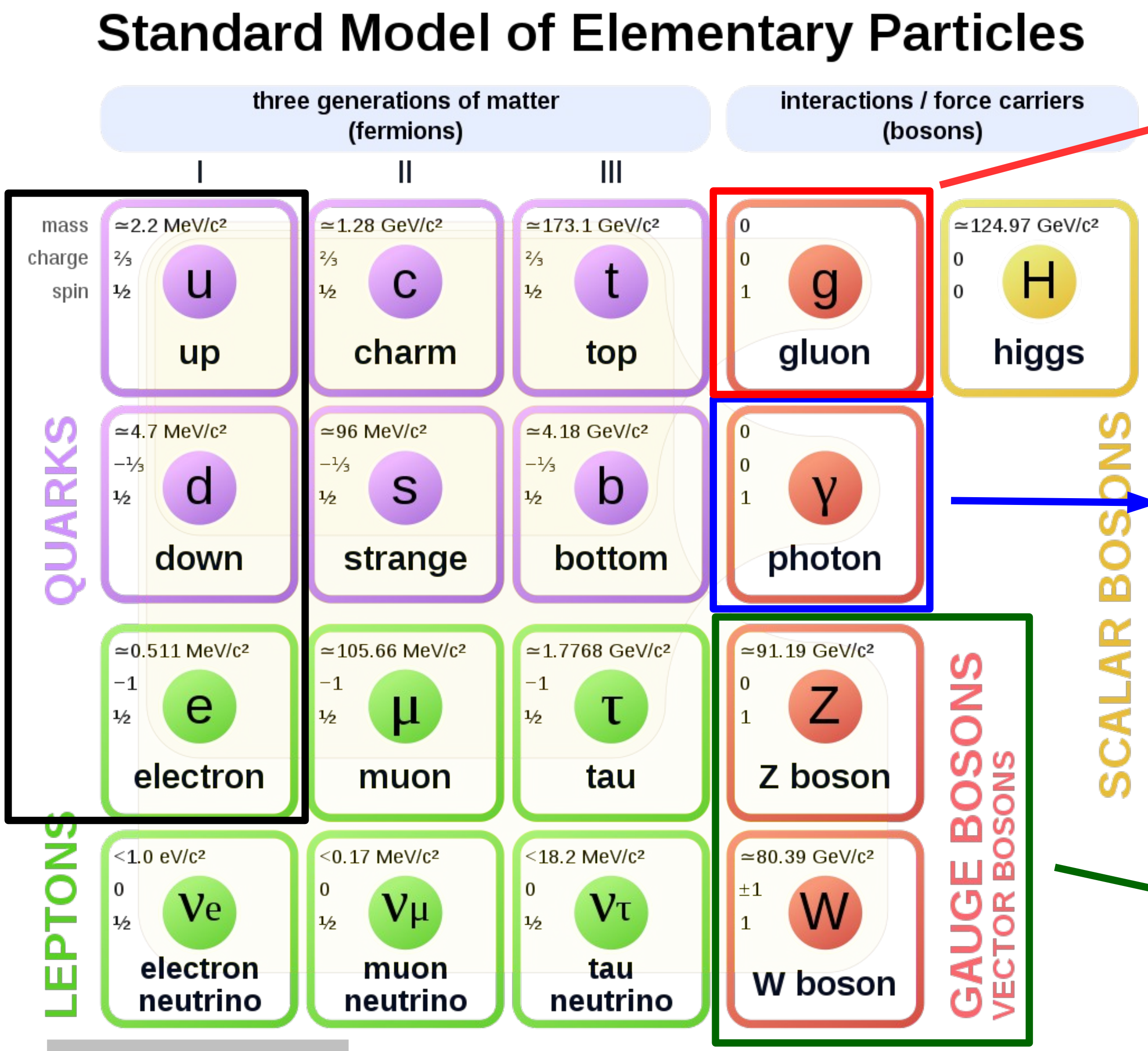
$G_F \approx 1.17 \cdot 10^{-5}/\mathrm{GeV}^2$

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

… and three fundamental interactions. (no gravity)

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, ...)

$\alpha \approx 1/137$

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

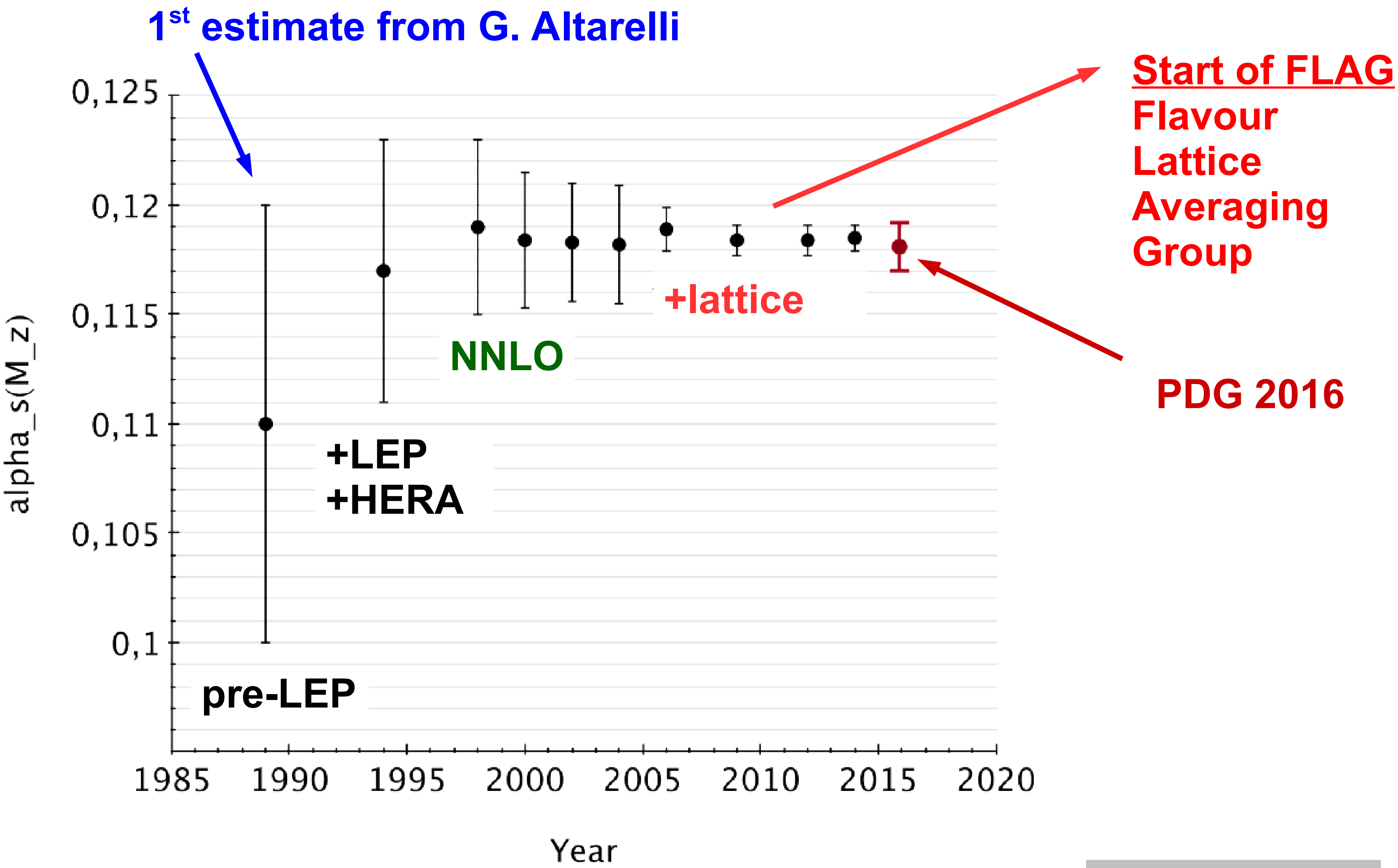
Weak interaction (β decays, sun, ...)

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

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

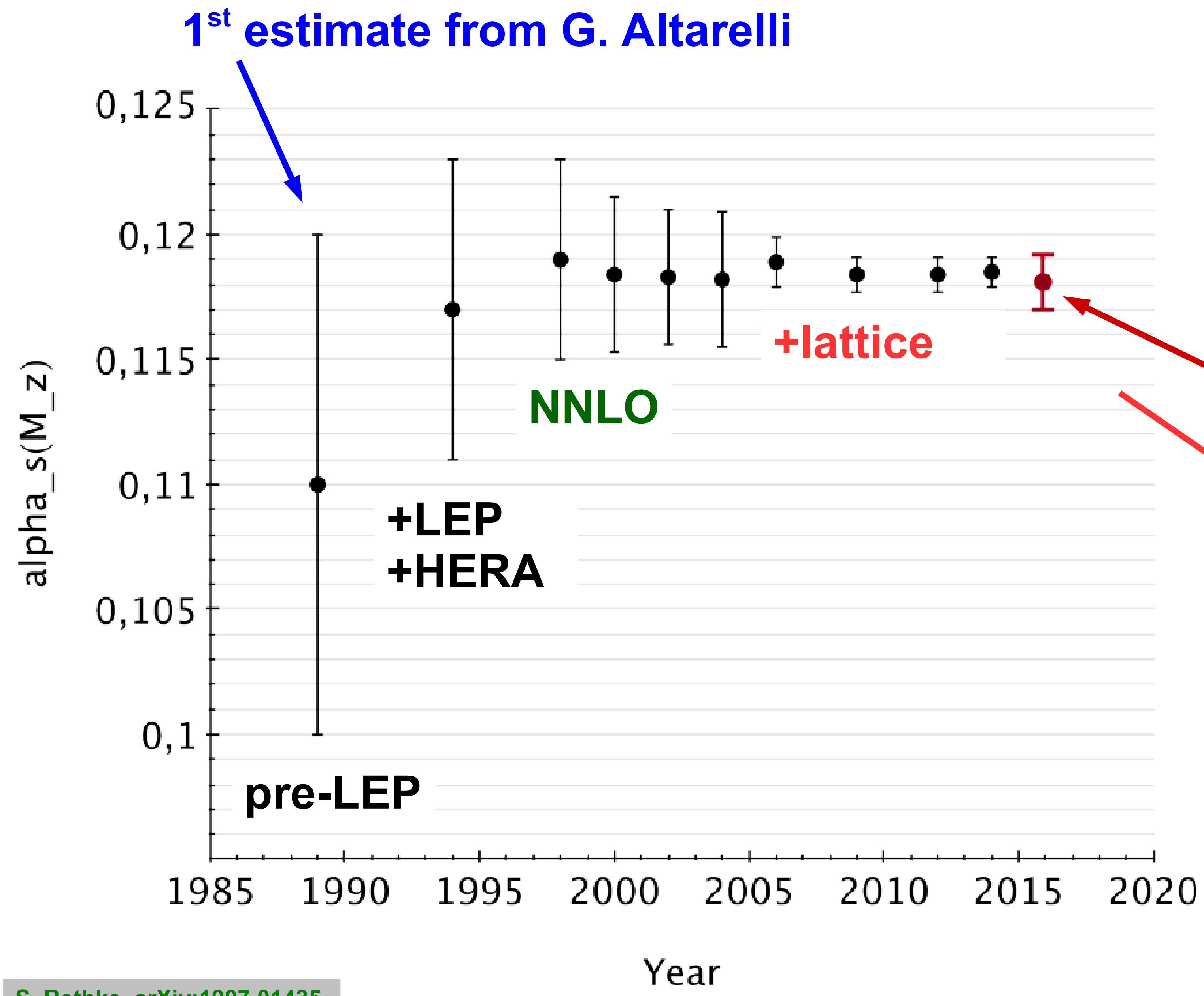
… and three fundamental interactions. (no gravity)

$\alpha_s(M_Z)$ world average versus time



S. Bethke, arXiv:1907.01435.

$\alpha_s(M_Z)$ world average versus time



PDG 2016

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.

QCD and asymptotic freedom

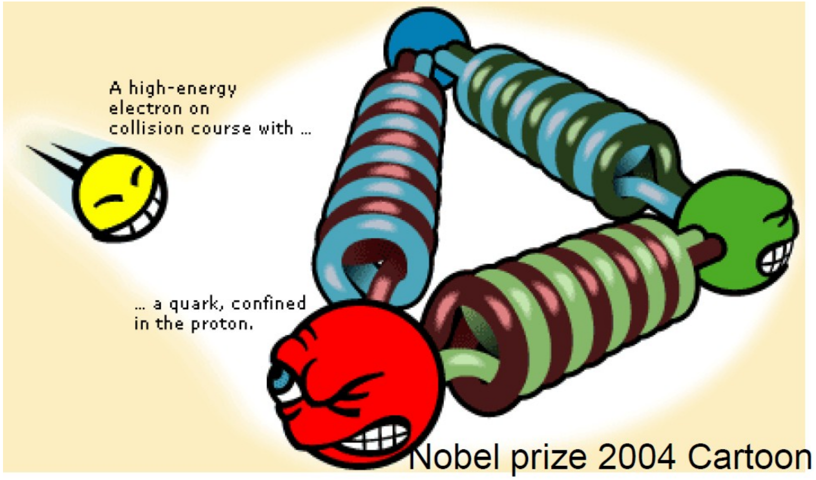
Nobel prize 2004

- **Theory:**
  - **Renormalisation group equation (RGE)**
  - **Solution of 1-loop equation**
  - **Running coupling constant**

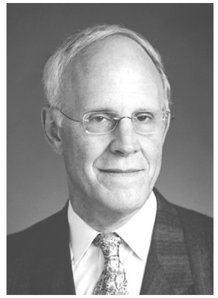
$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \ln\left(\frac{Q^2}{\mu^2}\right)}$$

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)}$$

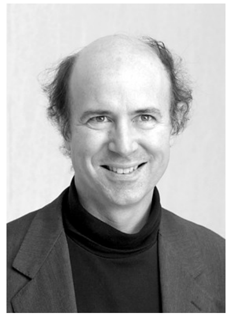
- **What happens at large distances?**
  - **$Q^2 \rightarrow 0$?**
  - **Cannot be answered here!**
    For $Q^2 \rightarrow \Lambda^2$ perturbation theory not applicable anymore!



Nobel prize 2004 Cartoon


D. Gross


D. Politzer


F. Wilczek

- **'Strong' coupling weak for $Q^2 \rightarrow \infty$, i.e. small distances**
- **Asymptotic freedom**
- **Perturbative methods usable**

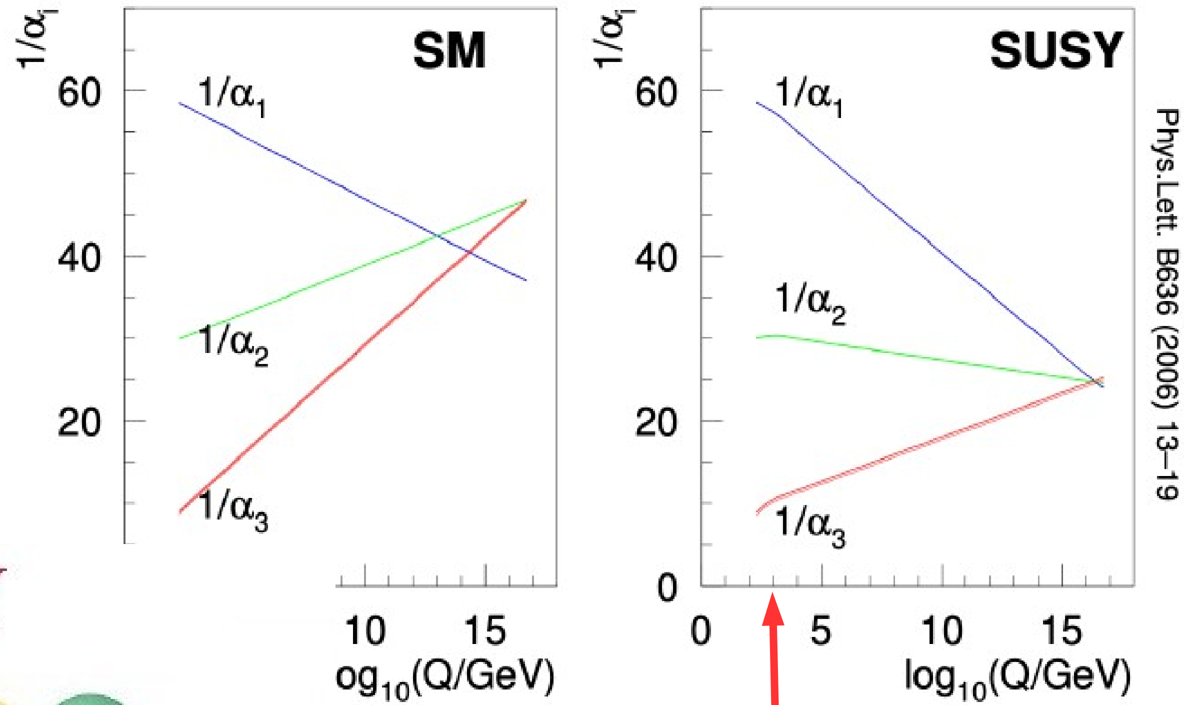
$$\beta_0 = \frac{33 - 2 \cdot N_f}{12\pi}$$

Physik Journal 3 (2004) Nr. 12

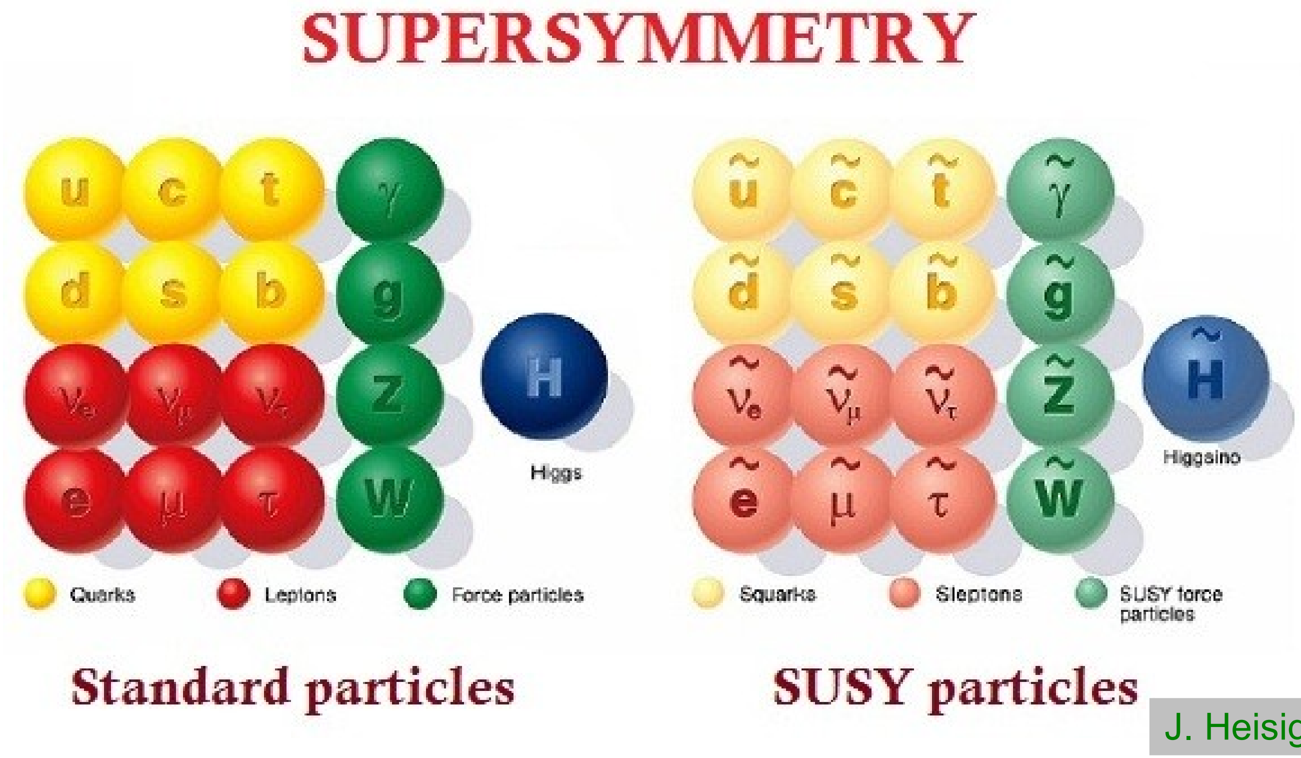
nobelprize.org

Unification of couplings?

Unification of couplings e.g. in Minimal Supersymmetric Standard Model (MSSM)?



We (LHC) are here

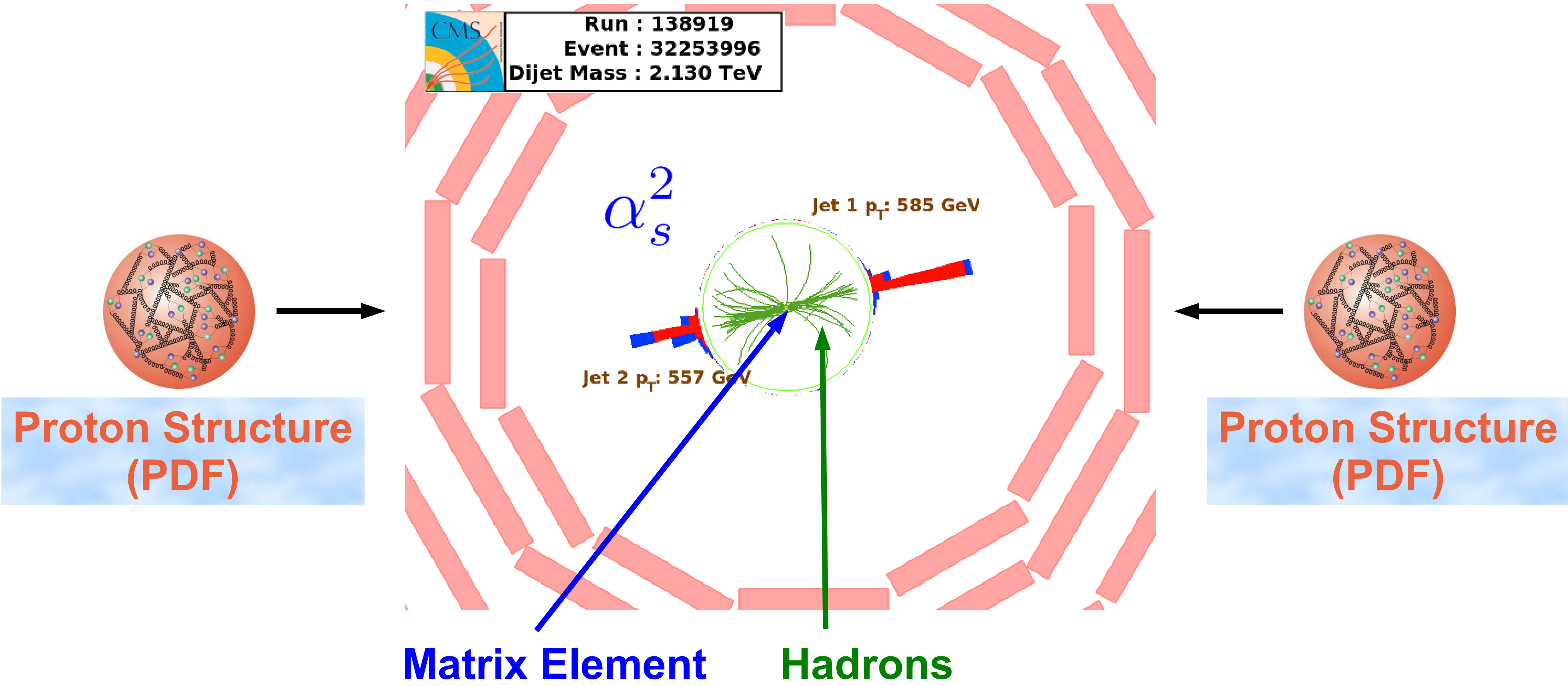


Need to test RUNNING even – in particular? – when no SUSY found!

Jets at the LHC

Abundant production of jets:

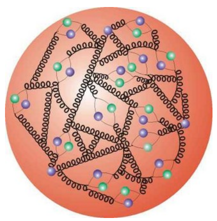
- Jets at hadron colliders provide the largest dynamic range ever for $\alpha_s(Q^2)$
- Plus insights into high-p_T QCD, the proton structure, non-perturbative and electroweak effects at high Q



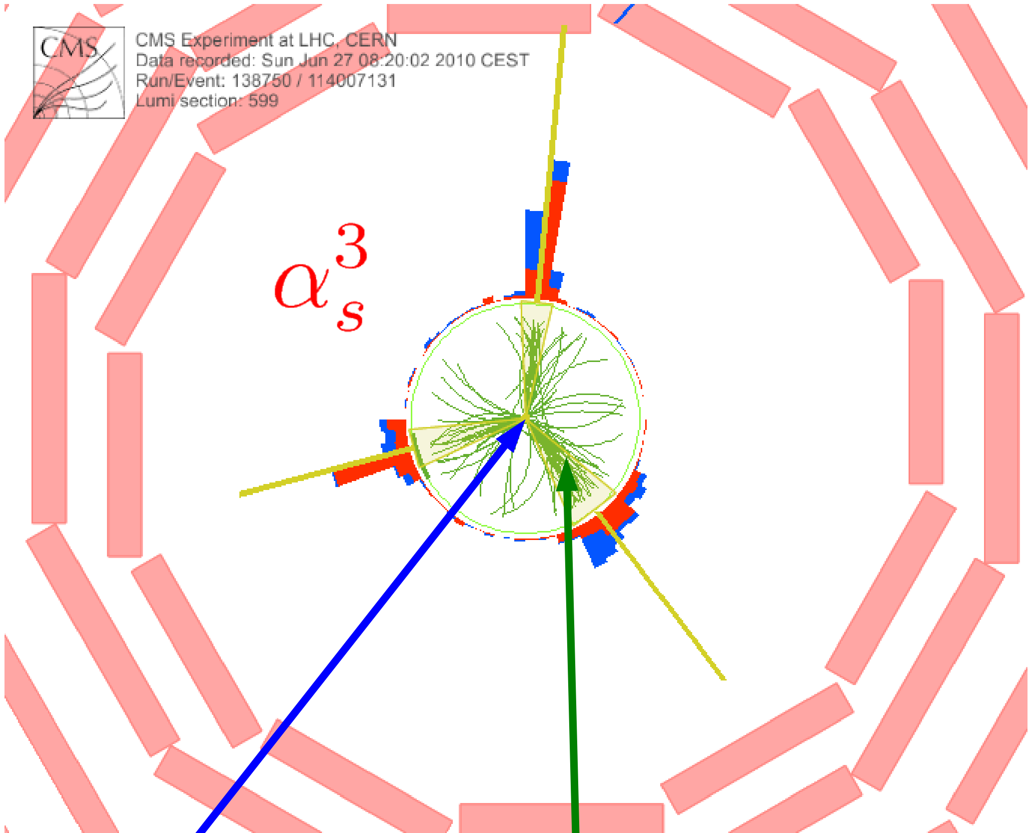
Jets at the LHC

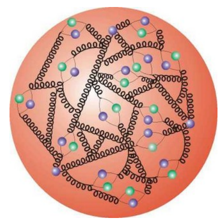
Abundant production of jets:

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



Proton Structure (PDF)



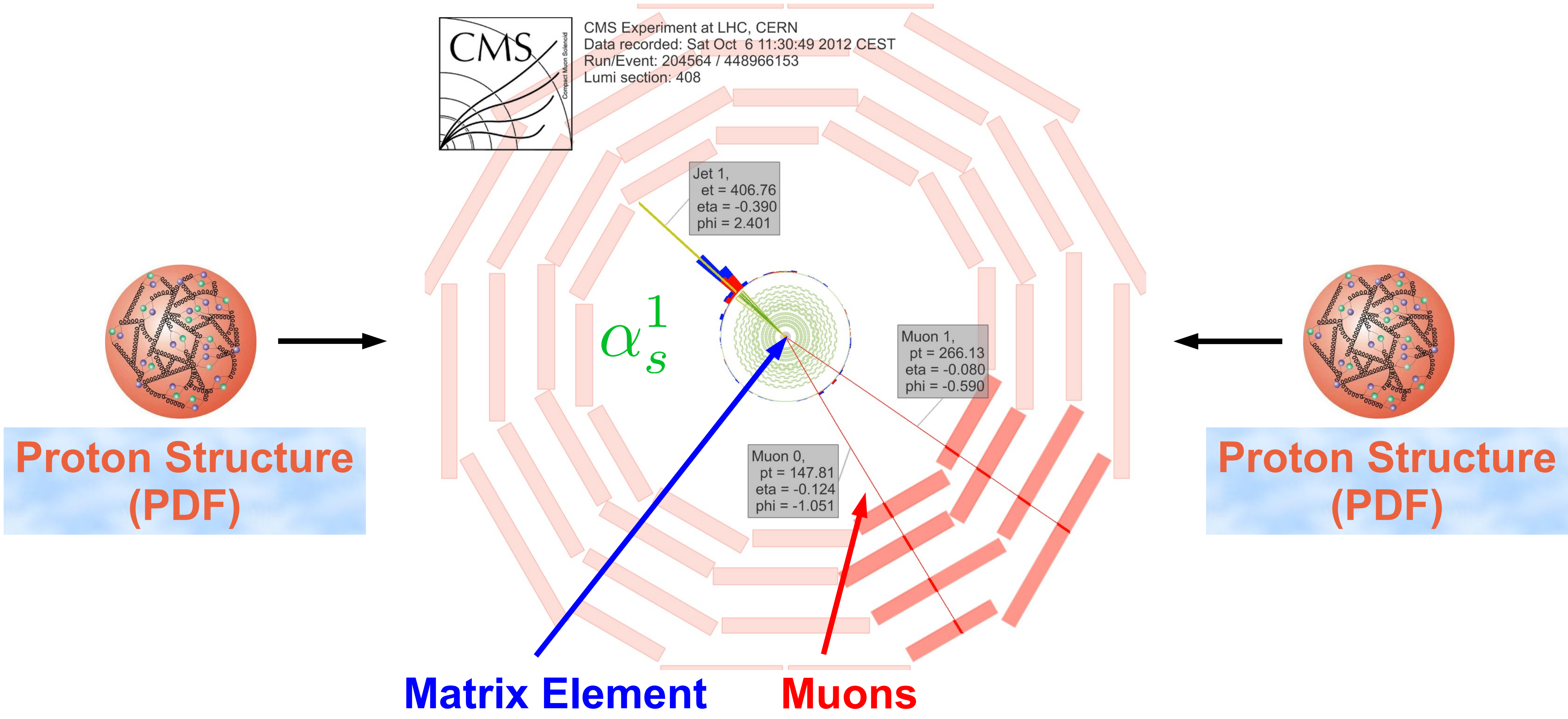


Proton Structure (PDF)

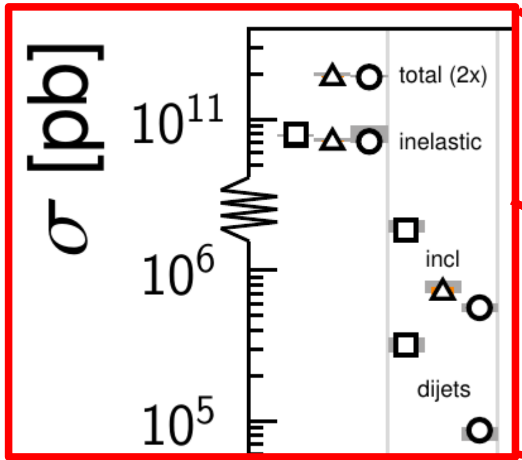
Matrix Element **Hadrons**

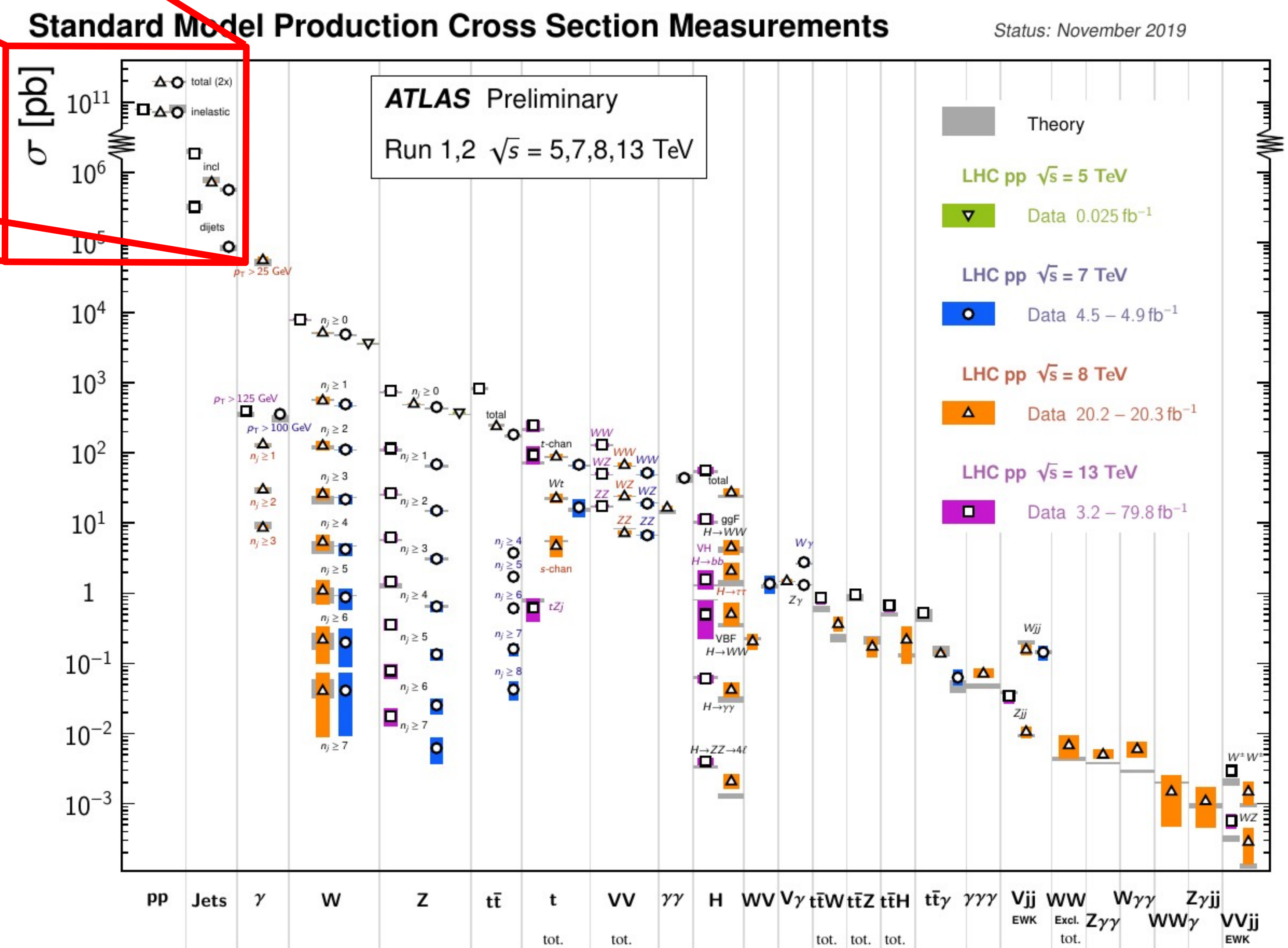
High-precision lepton measurements:

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



Jets at the LHC



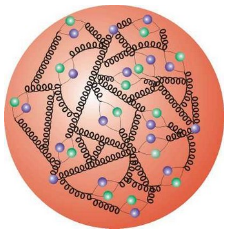


Jet cross sections ~ α_s^2

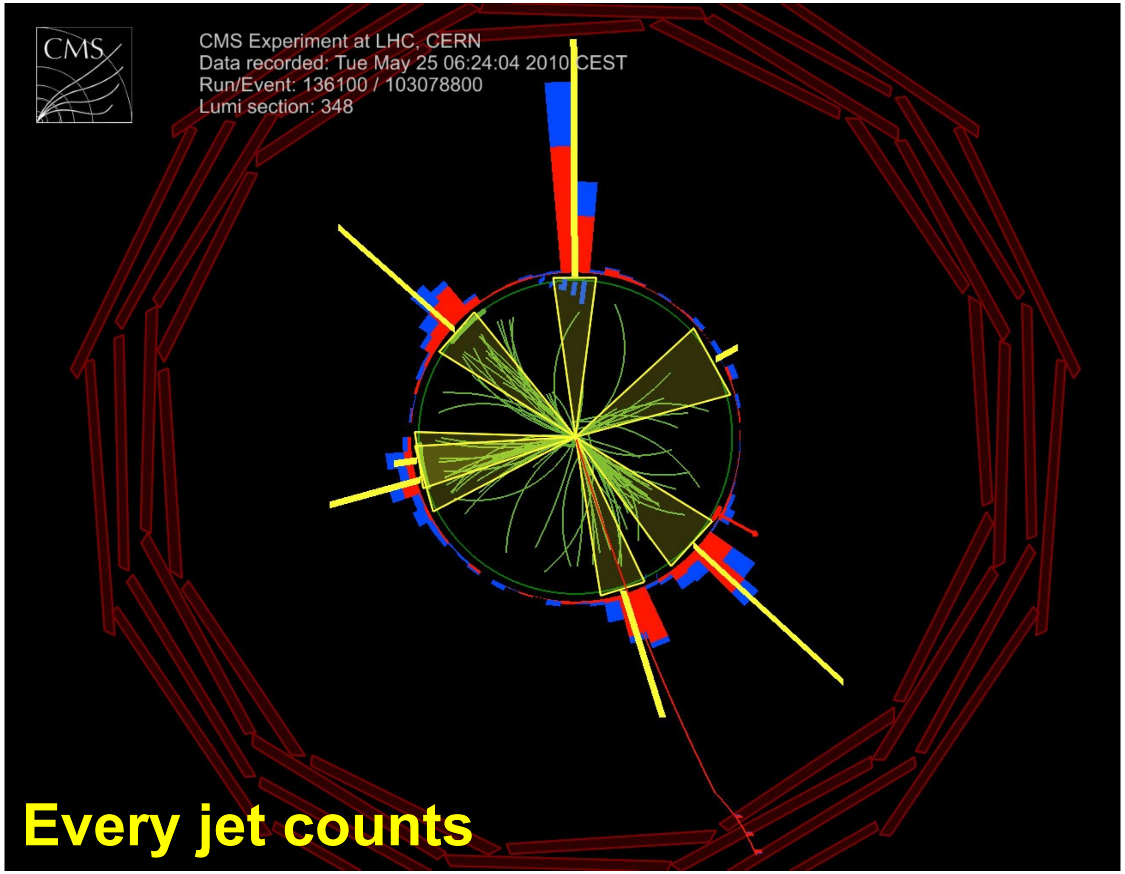
- **Determination of $\alpha_s(M_Z)$ in single-parameter fit**
- **Test consistency of running of $\alpha_s(Q)$**
- **Multi-parameter fit of $\alpha_s(M_Z)$ & PDFs**

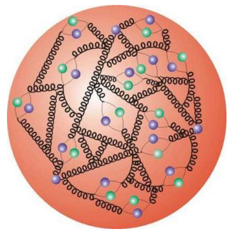
All inclusive

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.

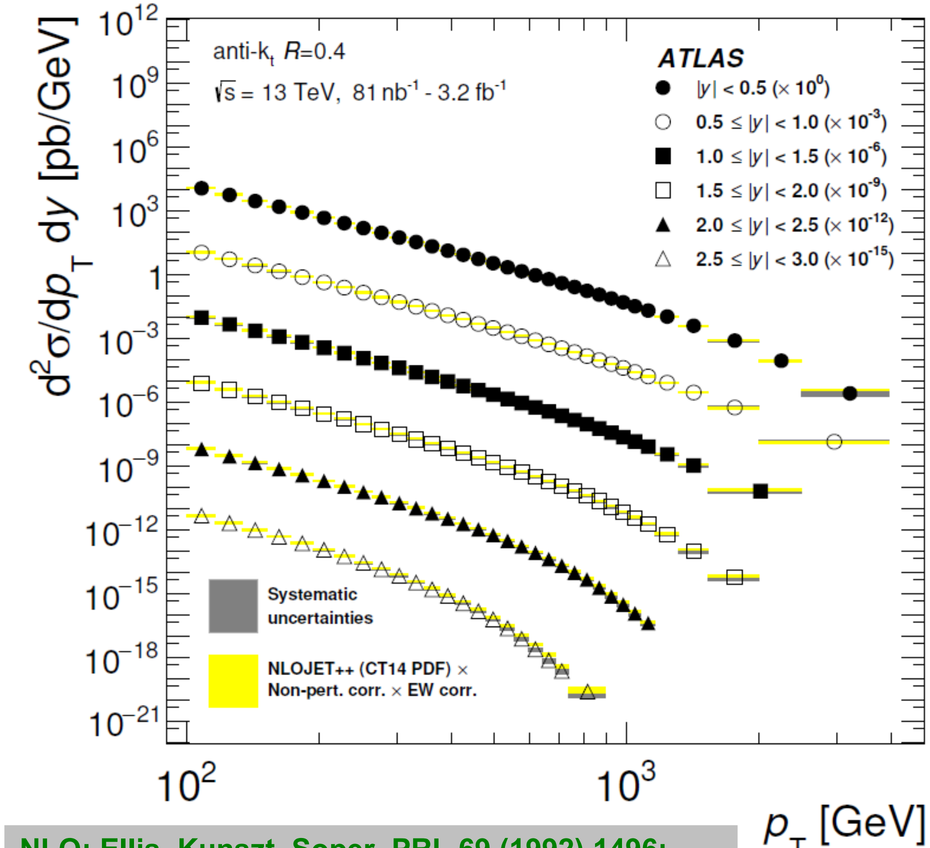
Inclusive jets: cross section

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.

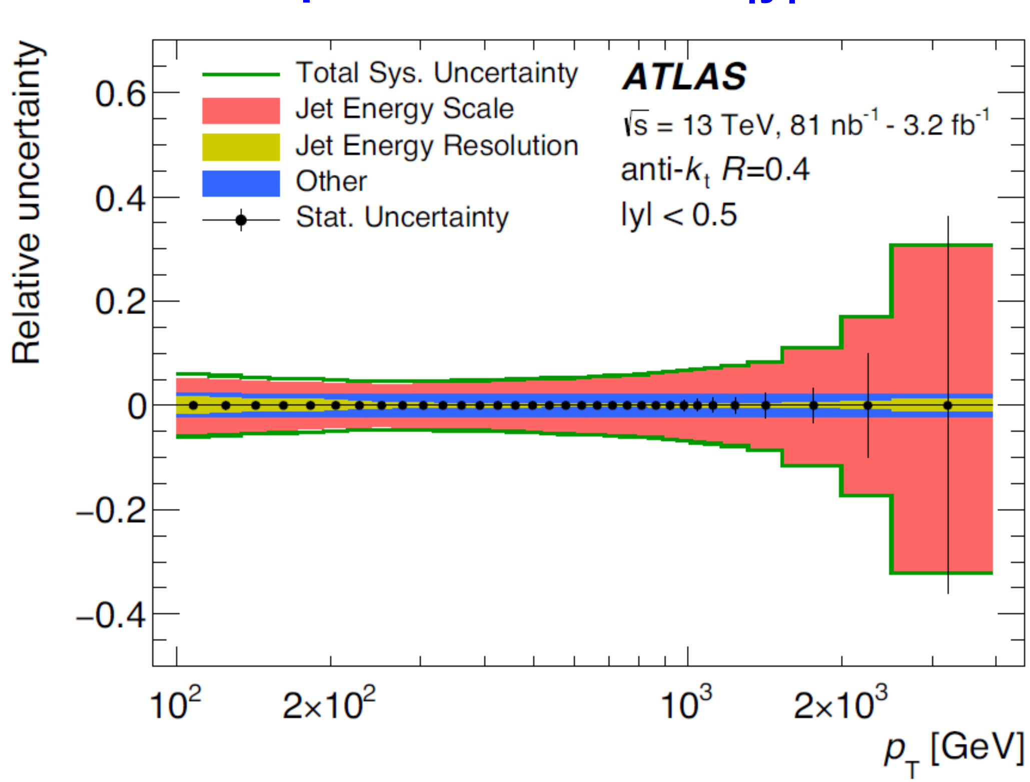
$$\frac{d^2\sigma}{dp_T dy} \propto \alpha_s^2$$

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



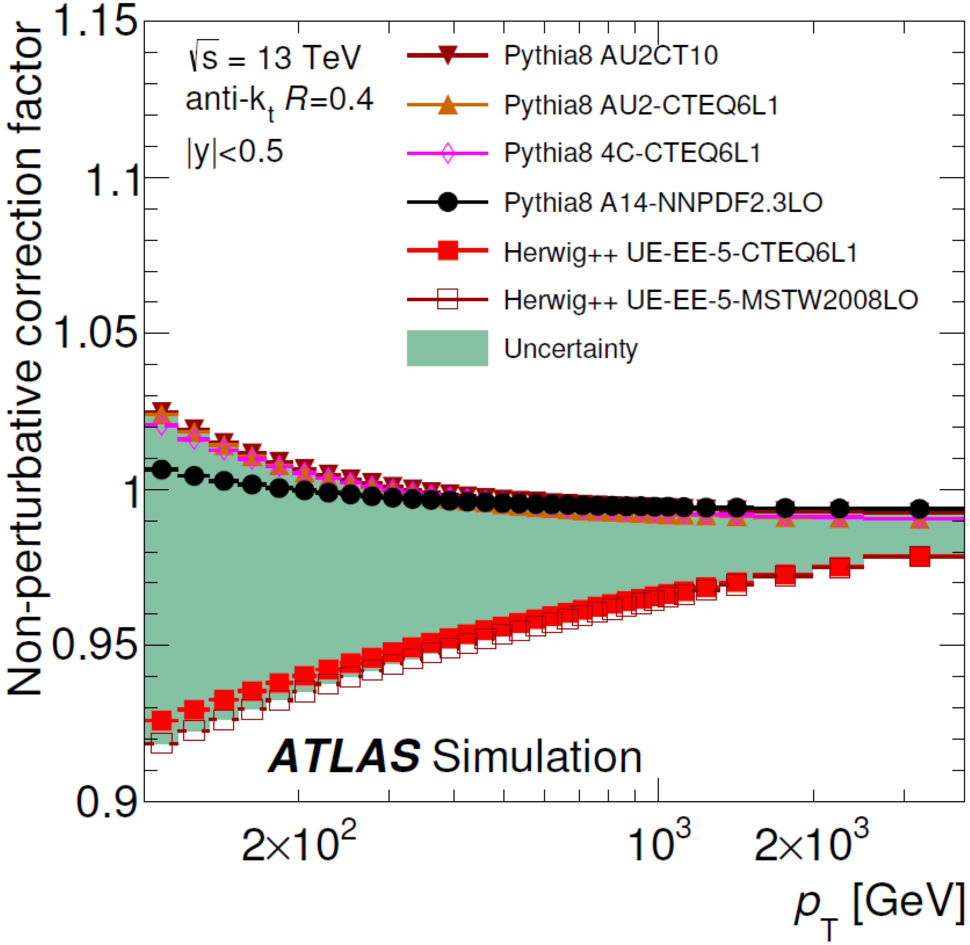
NLO: Ellis, Kunszt, Soper, PRL 69 (1992) 1496;
Giele, Glover, Kosower, NPB 403 (1993) 633;
Z. Nagy, PRD 68 (2003) 094002.

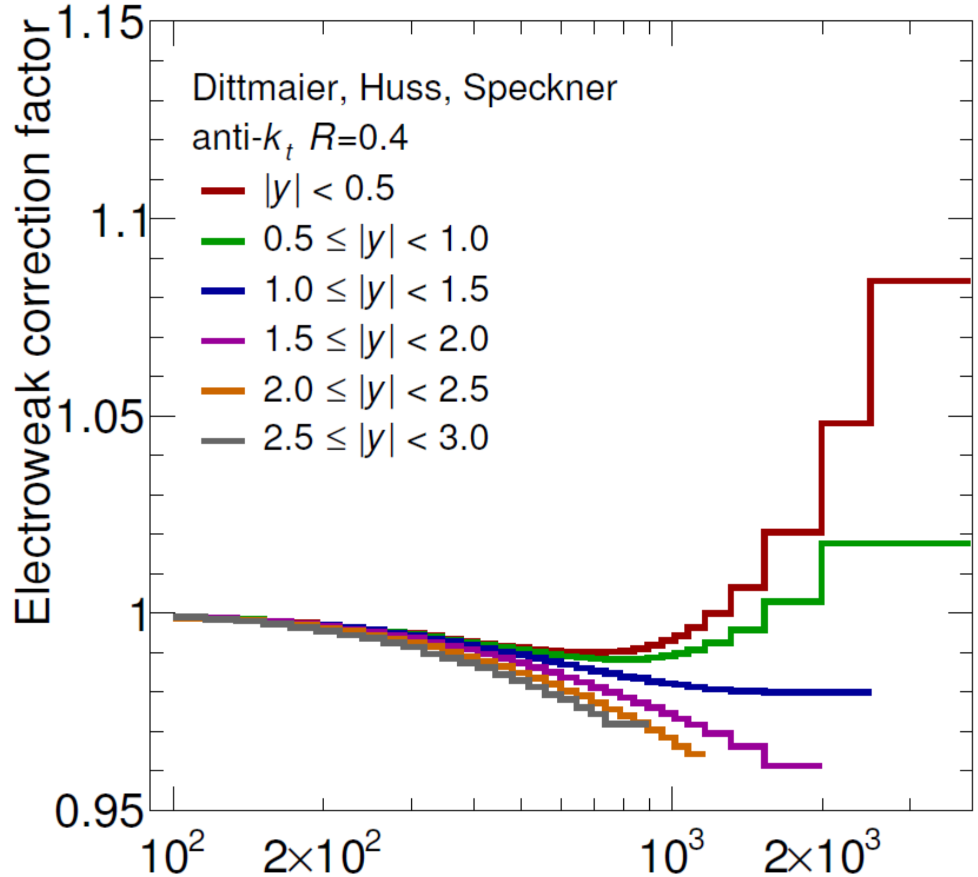
Inclusive jets: theory corrections

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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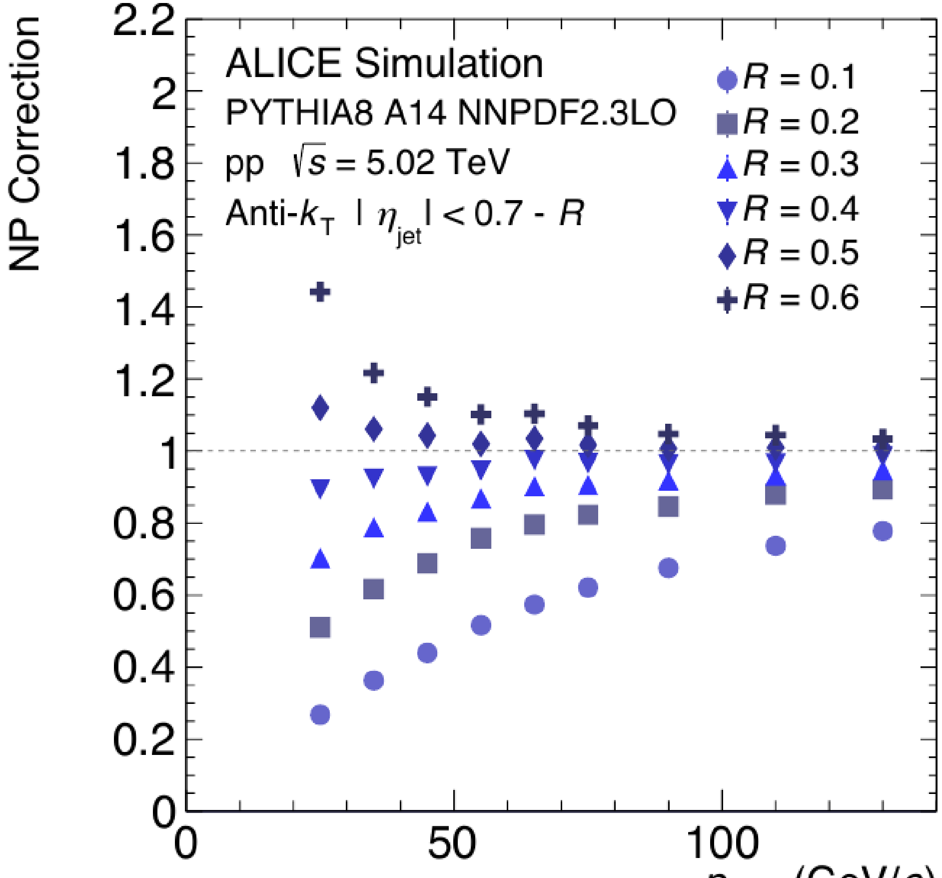

ALICE, arXiv:1909.09718.
See also CMS, SMP-19-003.

Electroweak correction factors:
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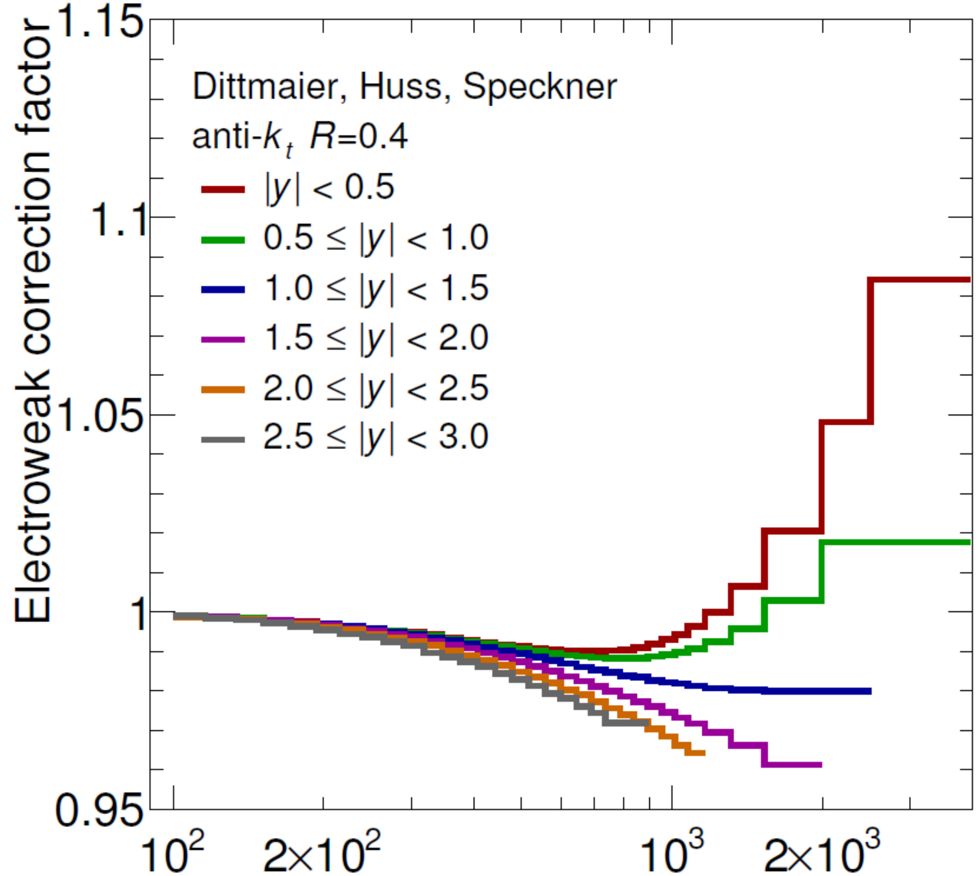
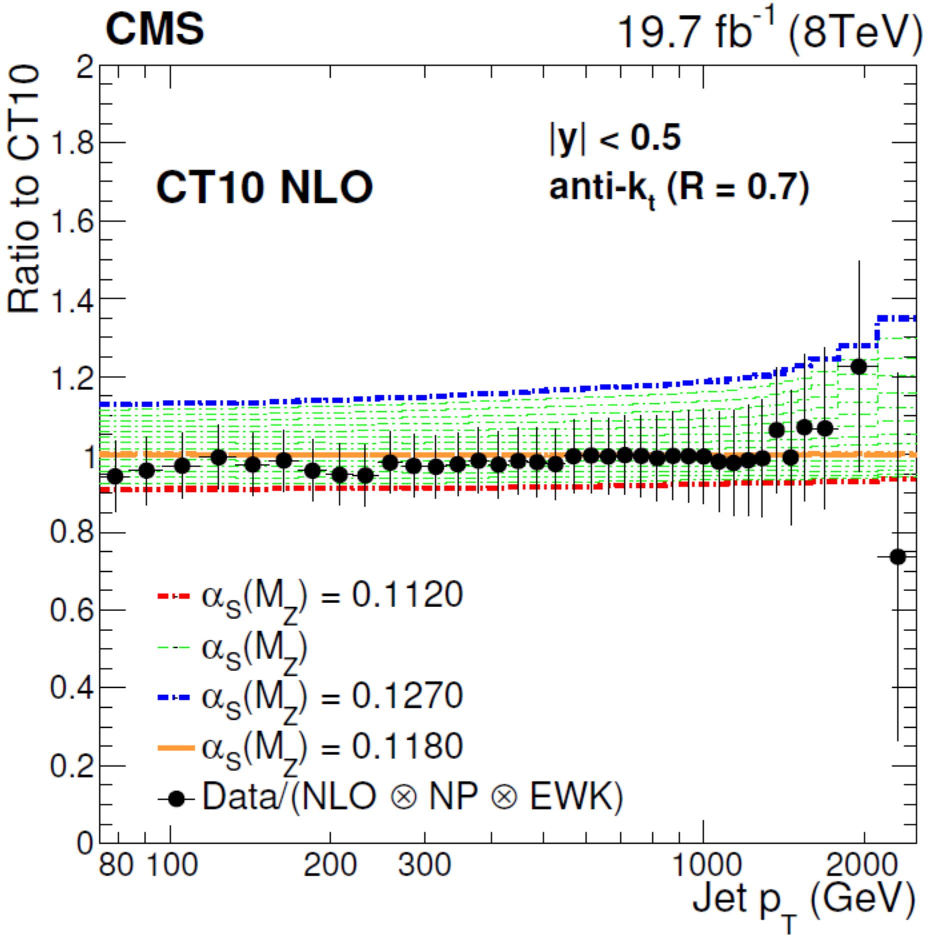


EW:
Dittmaier, Huss, Speckner, JHEP 11 (2012) 095.
Frederix et al., JHEP 04 (2017) 076.

Inclusive jets: α_s

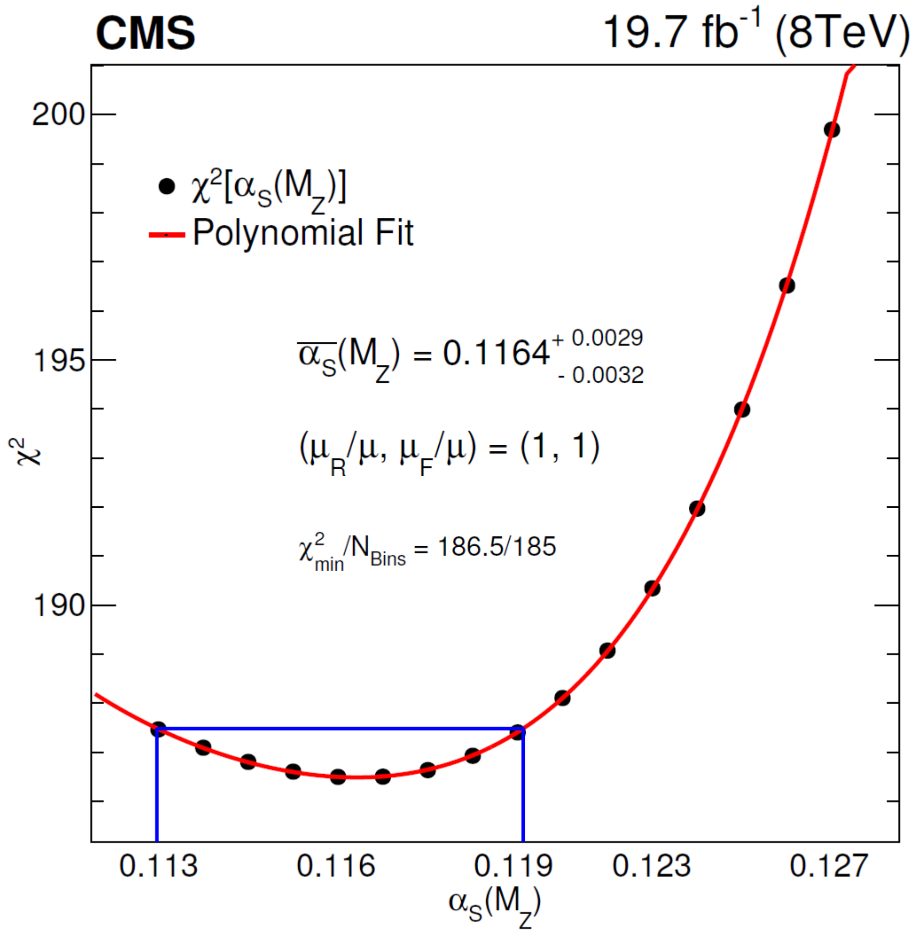
Sensitivity to $\alpha_s(M_Z)$ at NLO

- 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 $\alpha_s(M_Z)$



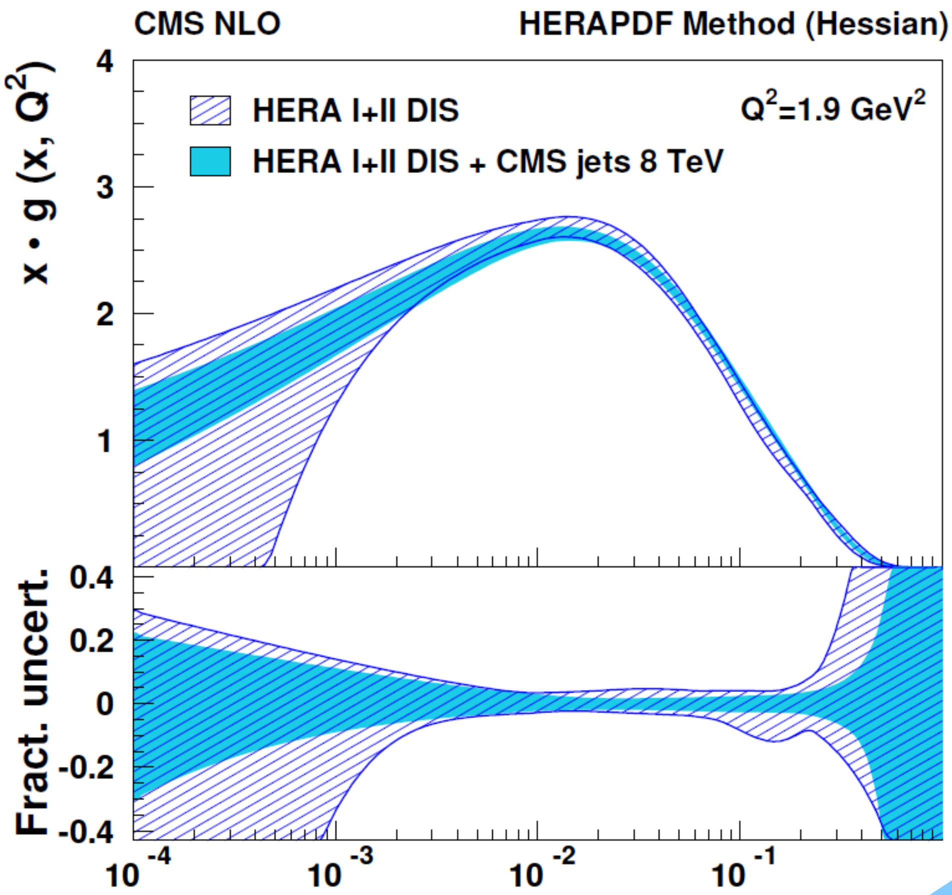
Jets @ NNLO not fully used yet in fits @ LHC → in progress

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

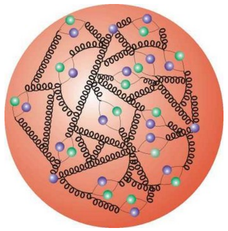
Question: How to deal with uncertainty of Missing higher orders (aka scale uncertainty) in PDF fits?

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

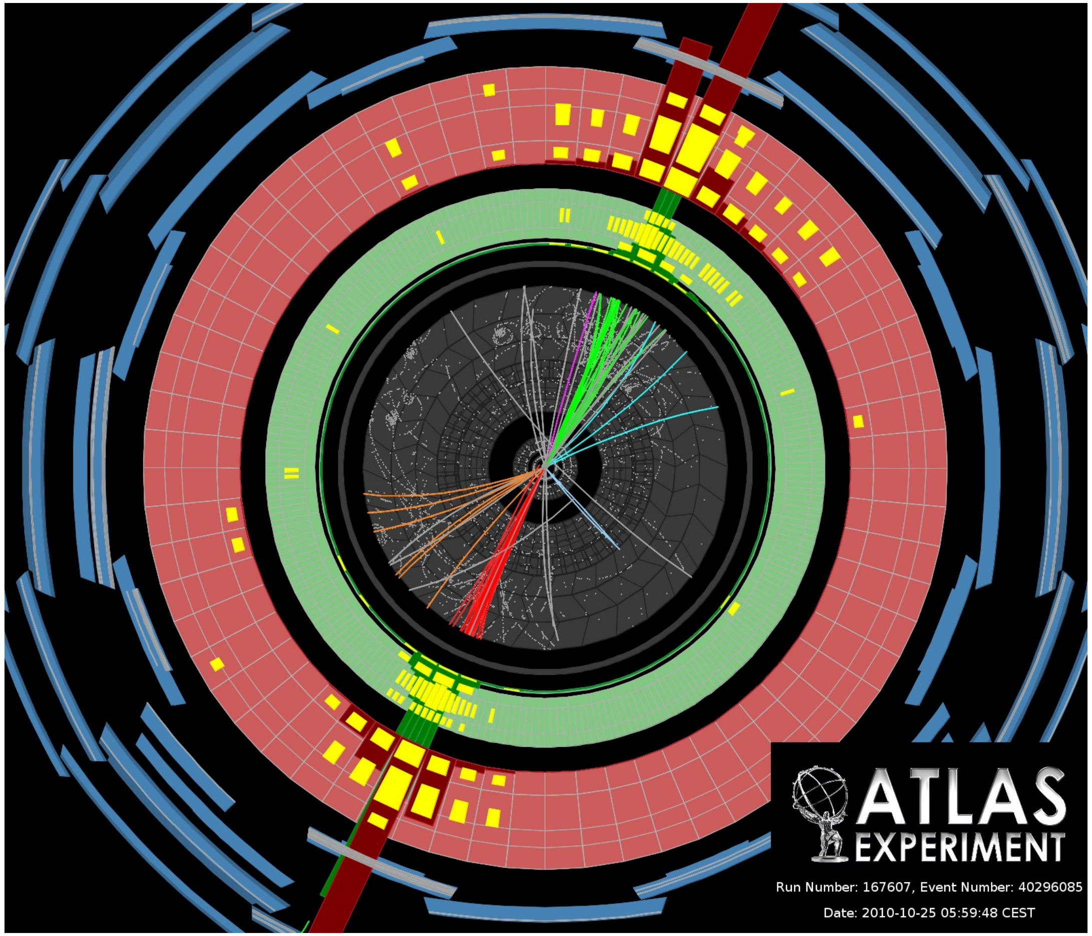
First progress → e.g. NNPDF, EPJC79 (2019) 931.

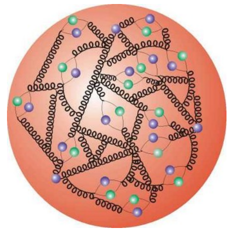
Dijets

Large masses



Proton





Proton

Relevant ATLAS & CMS measurements:

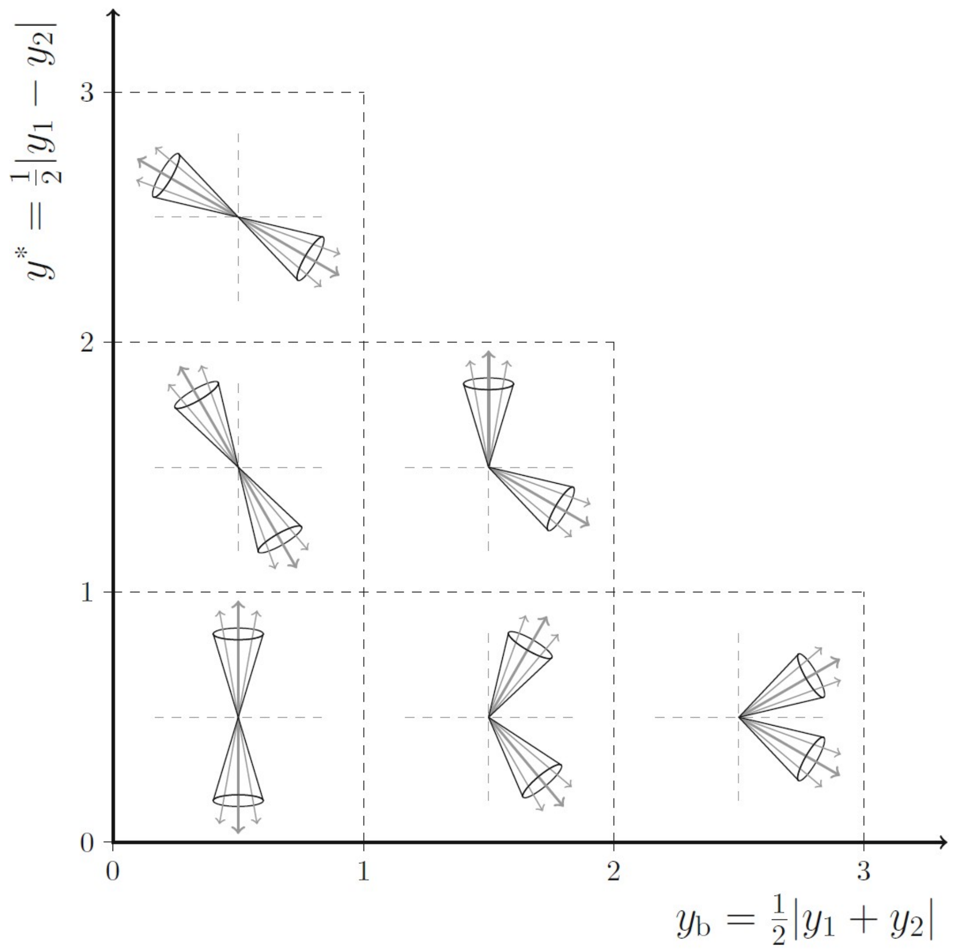
ATLAS:
JHEP 05 (2014) 059; JHEP 05 (2018) 195.
CMS:
PRD 87 (2013) 112002; EPJC 77 (2017) 746.

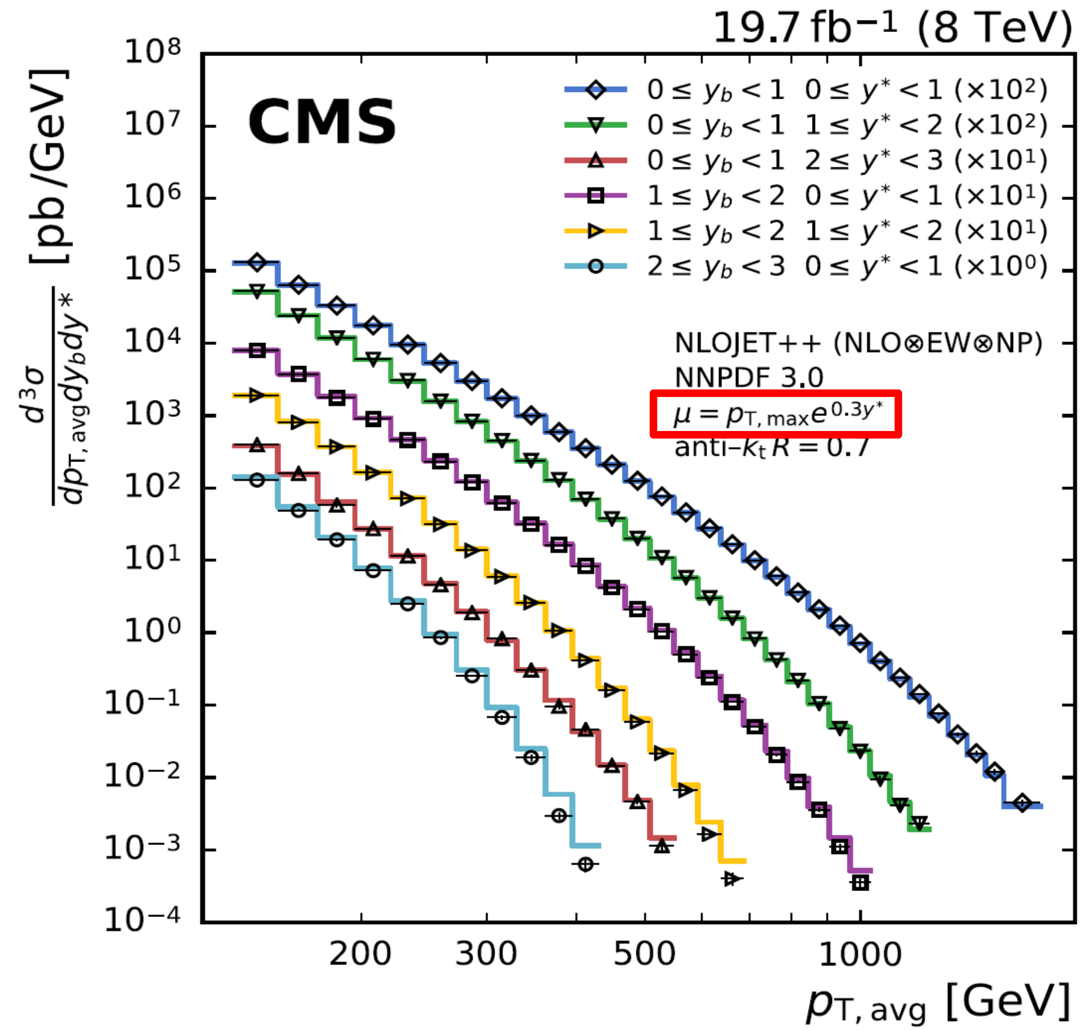
Triple-differential dijets

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

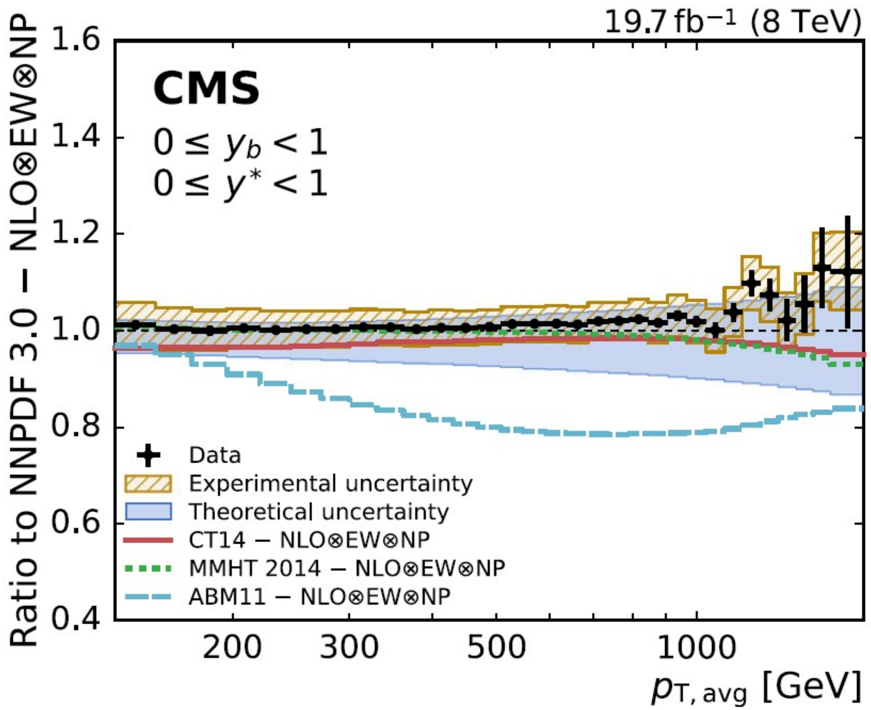




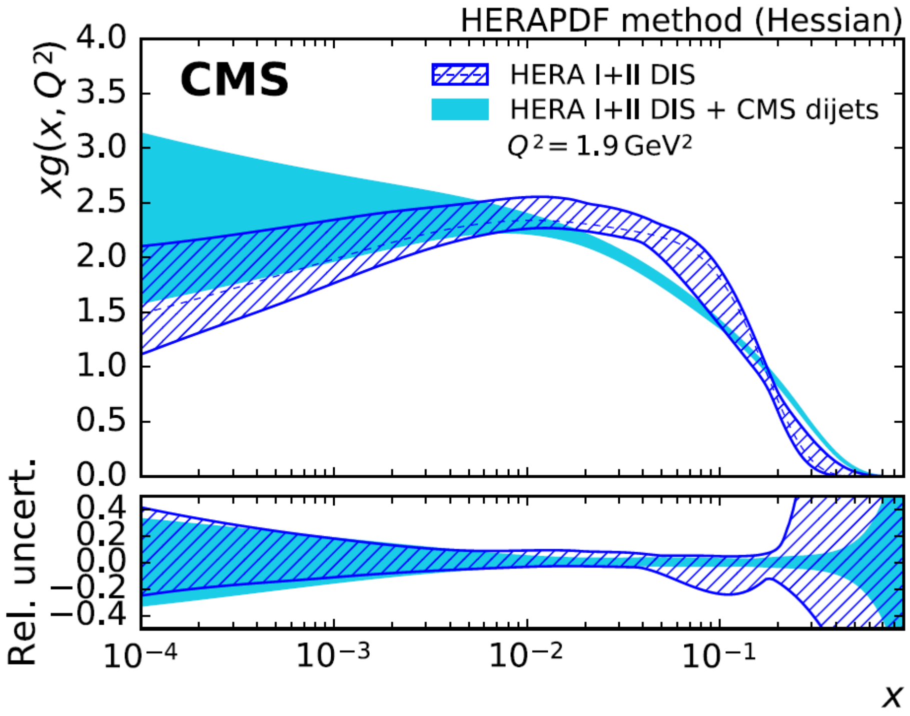
Triple-differential dijets

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

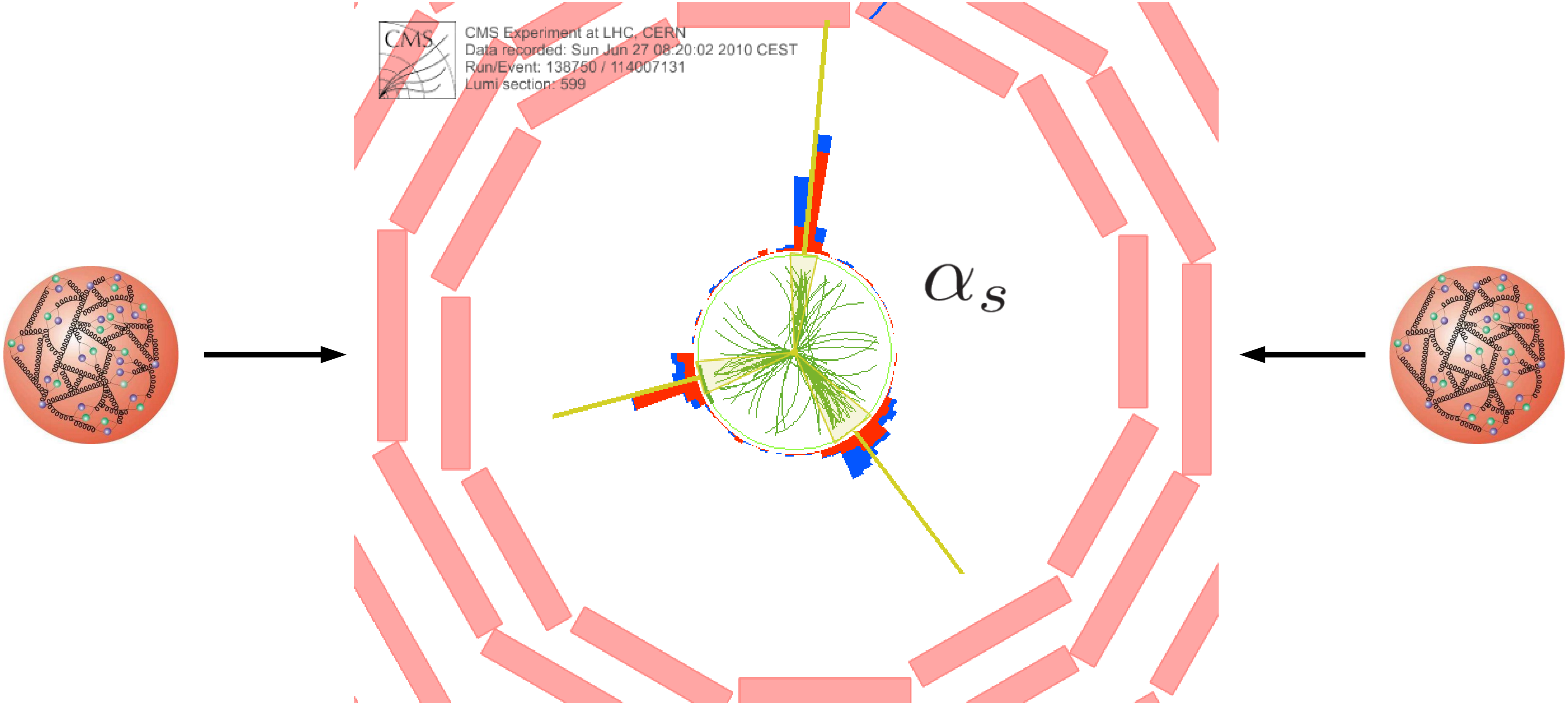


16-parameter fit

√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).

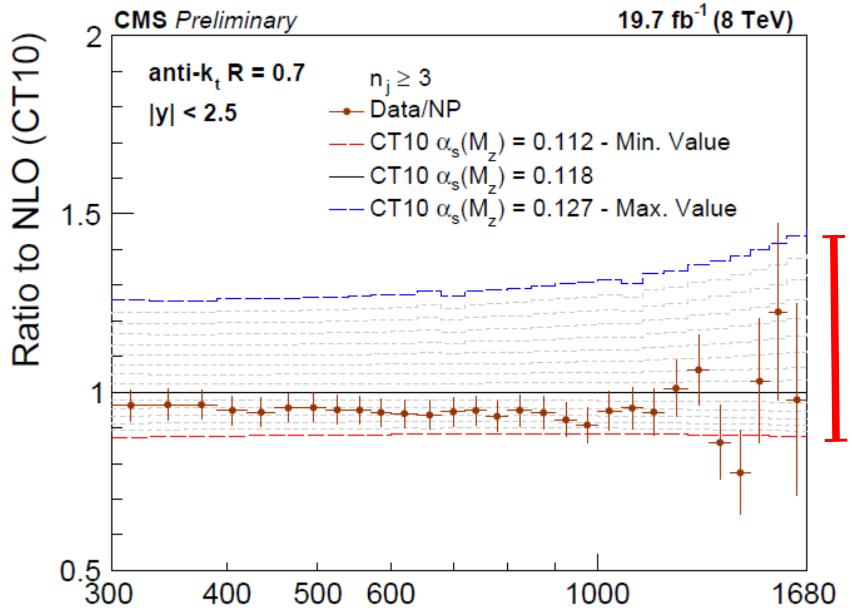
Jet cross section ratios

- **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

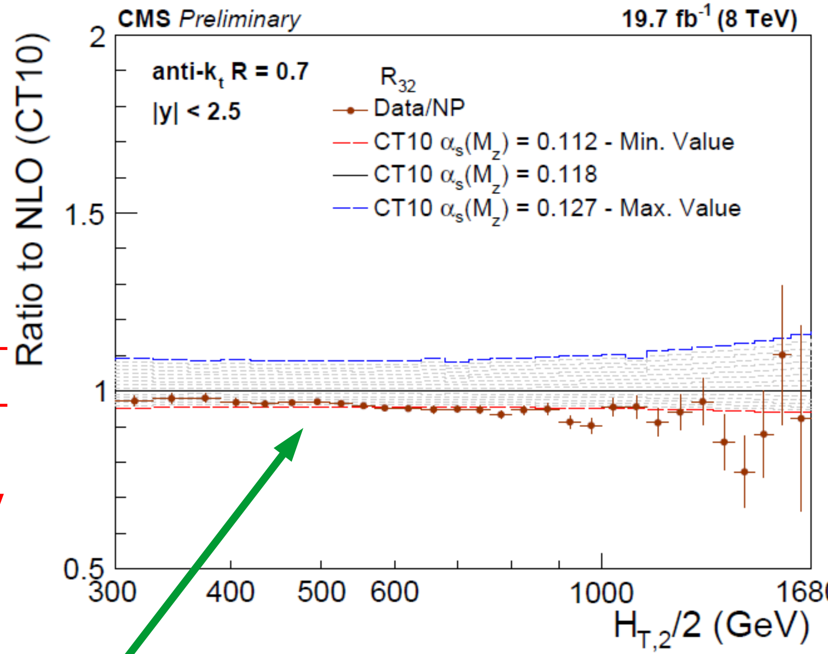
Inclusive 3-jet cross section

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



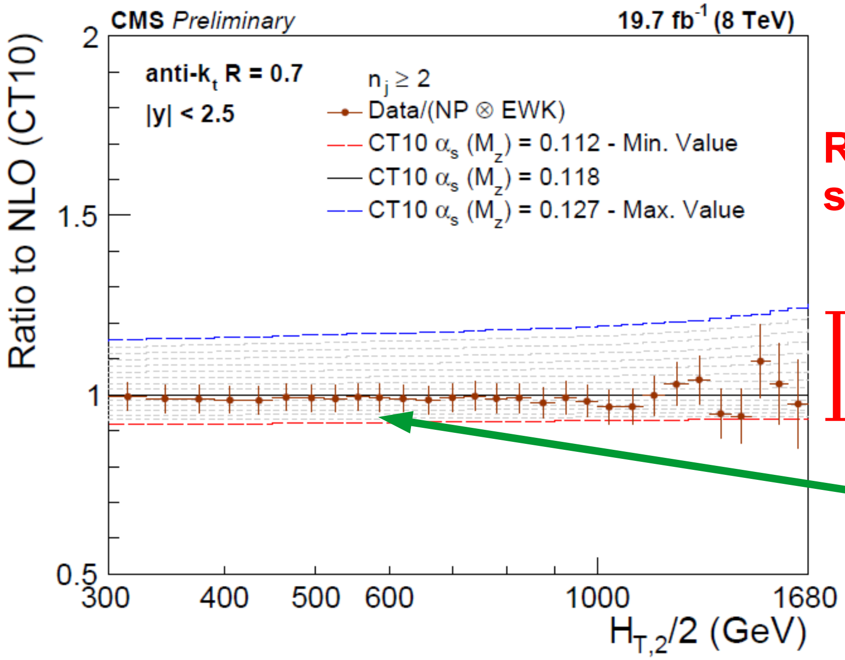
Inclusive 3-jet to inclusive 2-jet cross section ratio

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



Inclusive 2-jet cross section

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

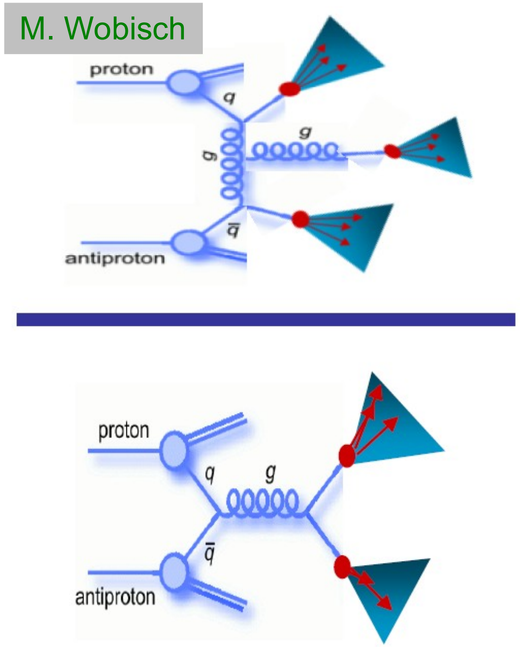


Reduced sensitivity

Much reduced systematic uncertainty

3- to 2-jet ratios

M. Wobisch

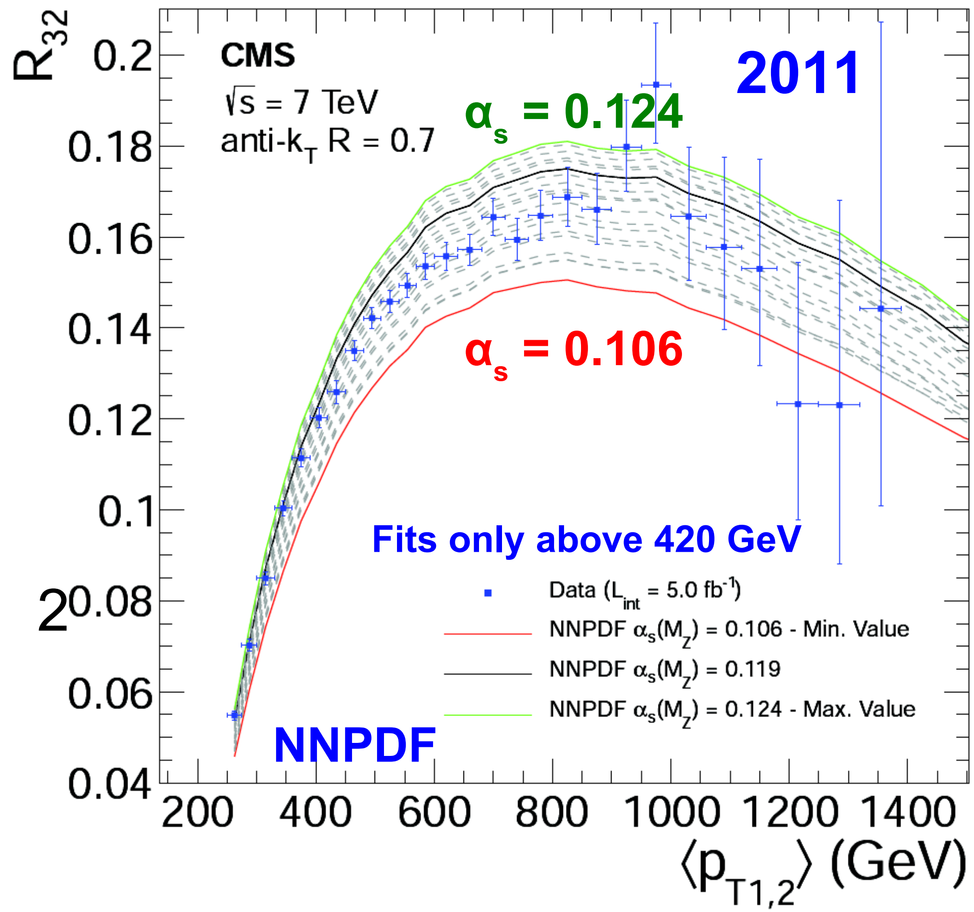


$R_{3/2}$

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.**

$\rightarrow \alpha_s$

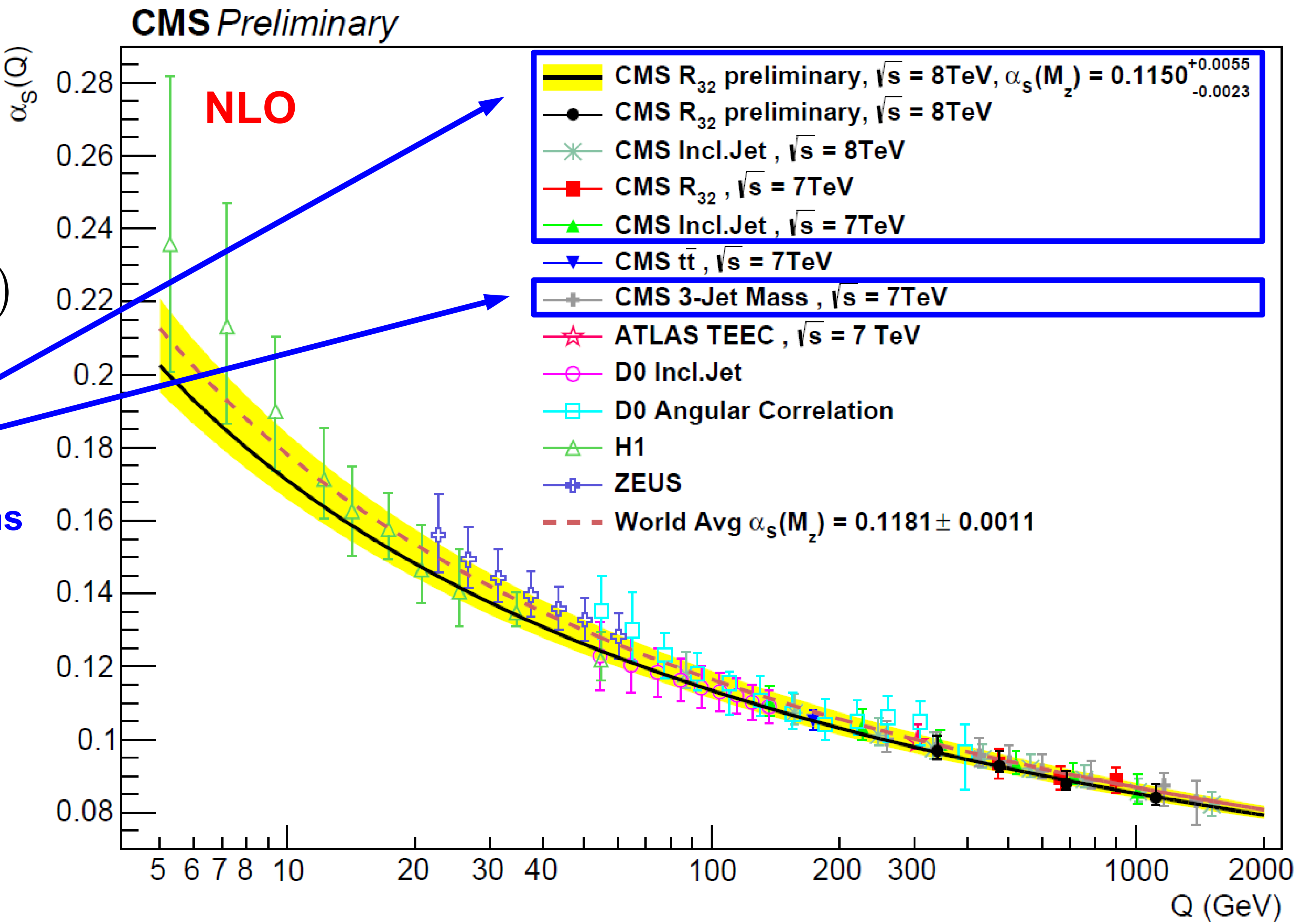
√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1148	23	50
8	19.7	0.1150	22	+50

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

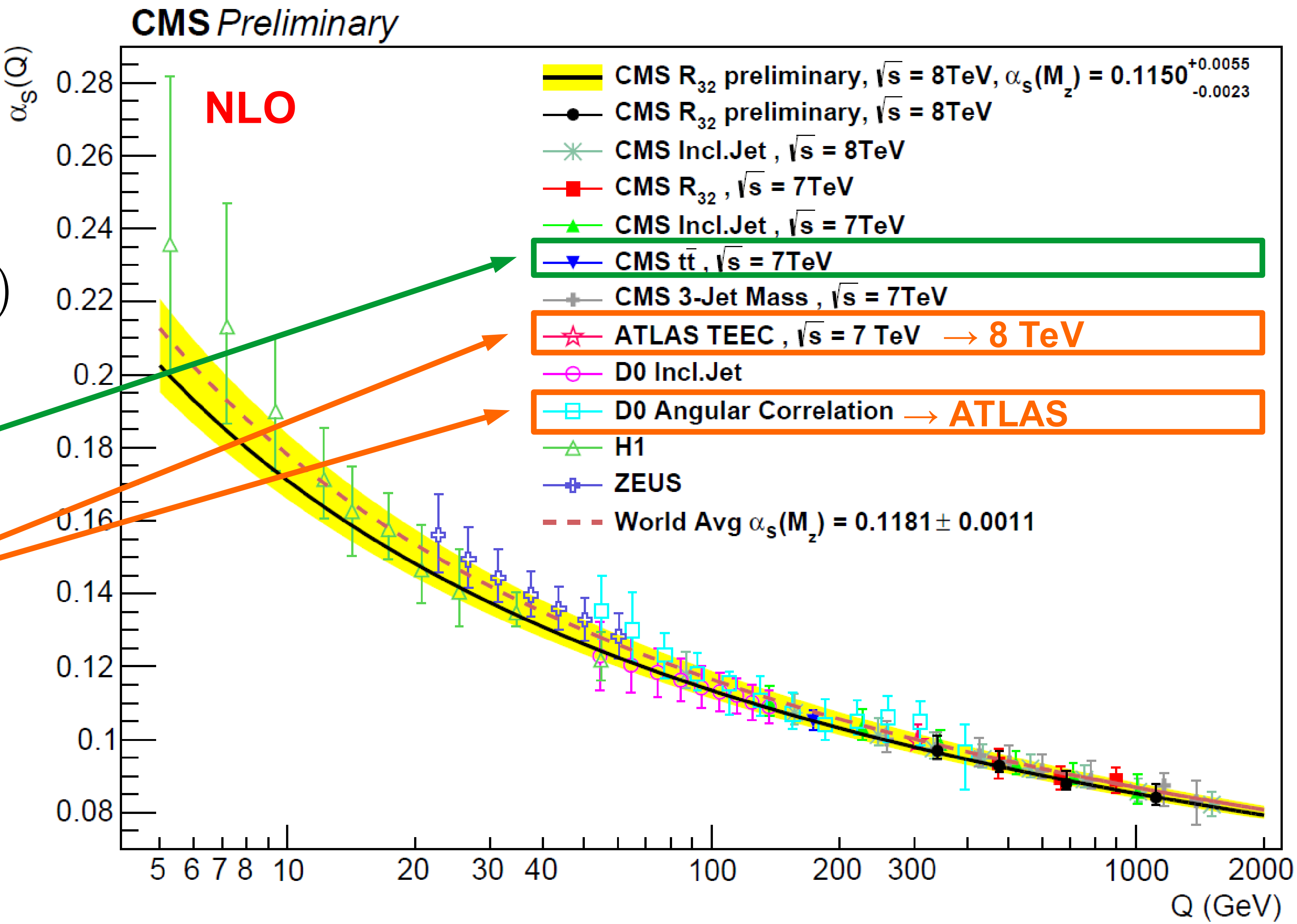
Running of $\alpha_s(Q)$

Perform fits in fixed intervals of the chosen scale Q

$\alpha_s(Q)$

ttbar NNLO

Normalised distributions

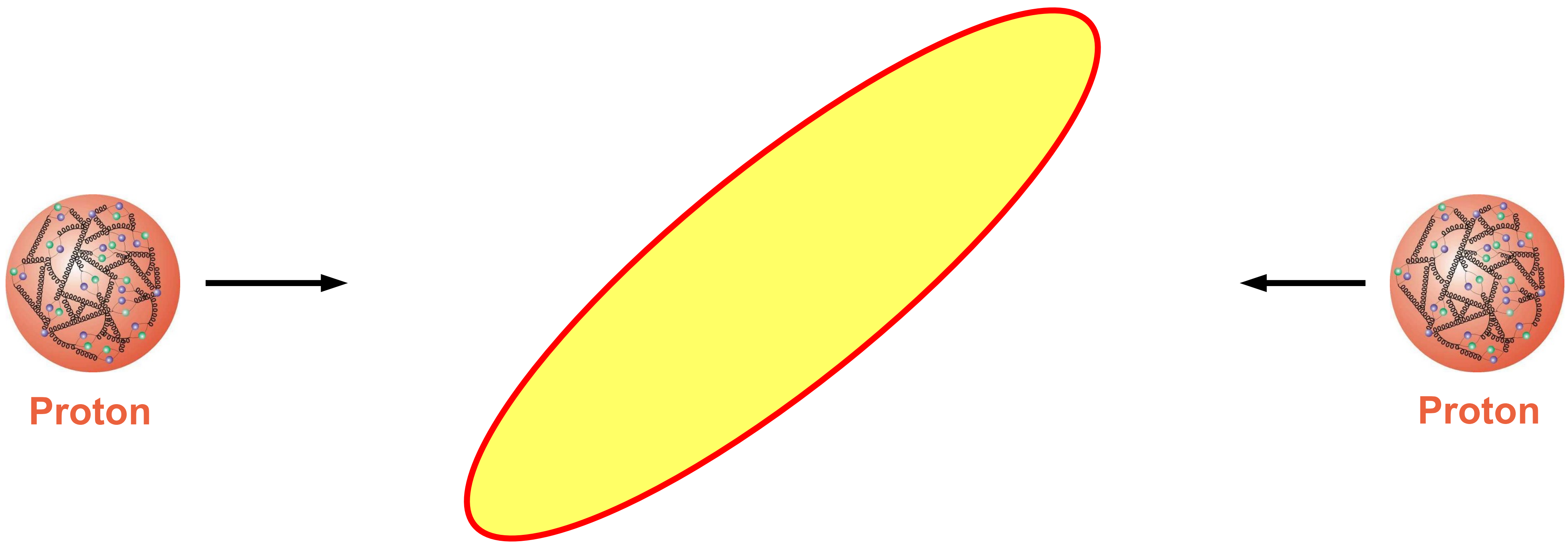


Needs an update for latest ATLAS, CMS, & H1 points ...

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

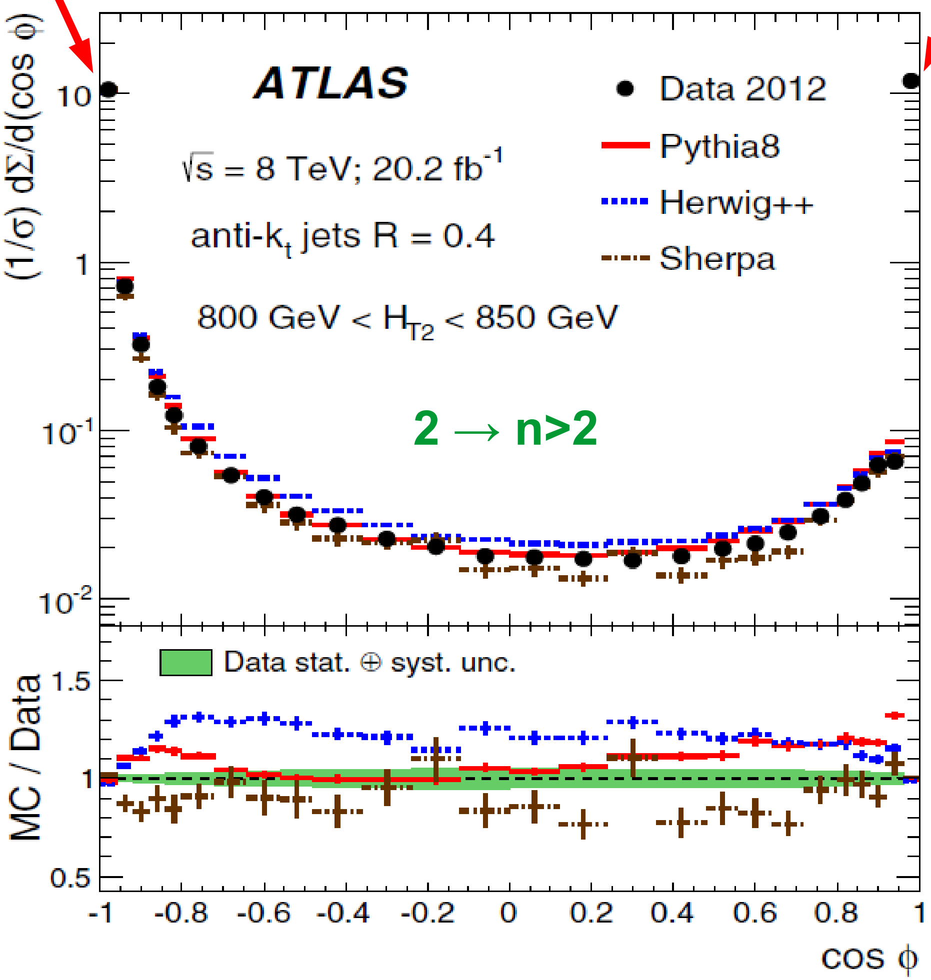
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E_{\mathrm{T}i}^{A}E_{\mathrm{T}j}^{A}}{\left(\sum_k E_{\mathrm{T}k}^{A}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

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

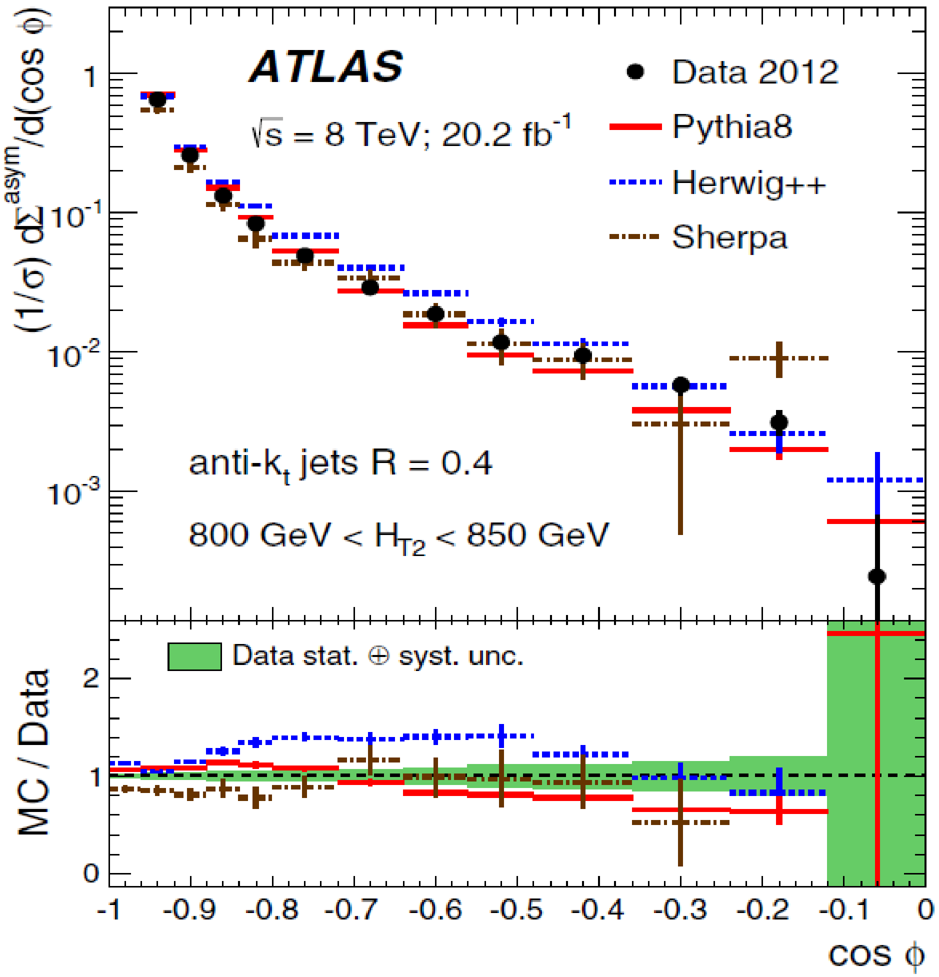
$\mathrm{TEEC} \propto \alpha_s$

$2 \to 2$

$2 \to 2$



$\mathrm{ATEEC} \propto \alpha_s$



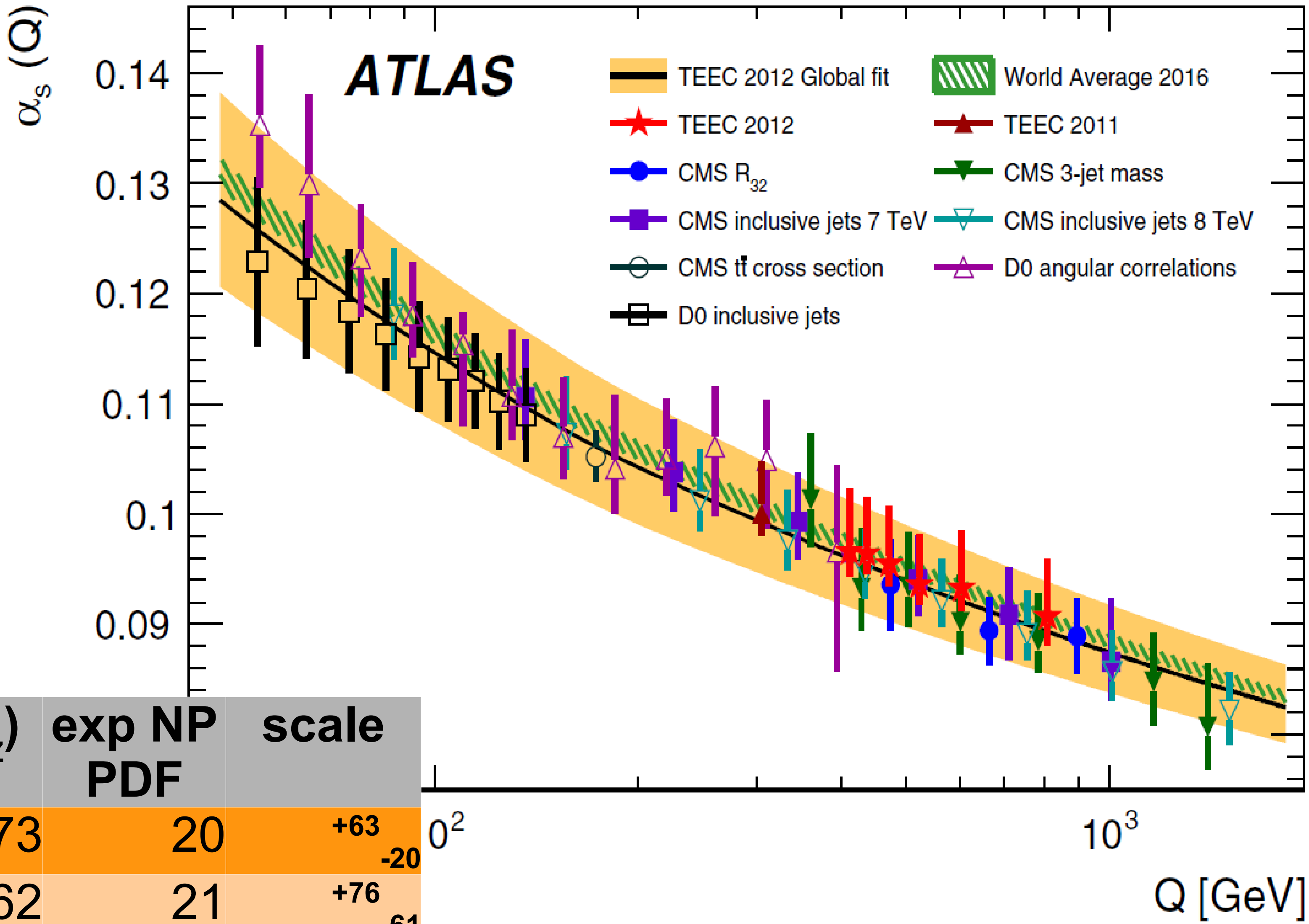
(A)TEEC in bins of $Q = (p_{T1}+p_{T2})/2$

Theory:
3-jet NLOJet++

Scale choice:

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

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



√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	$^{+61}_{-13}$

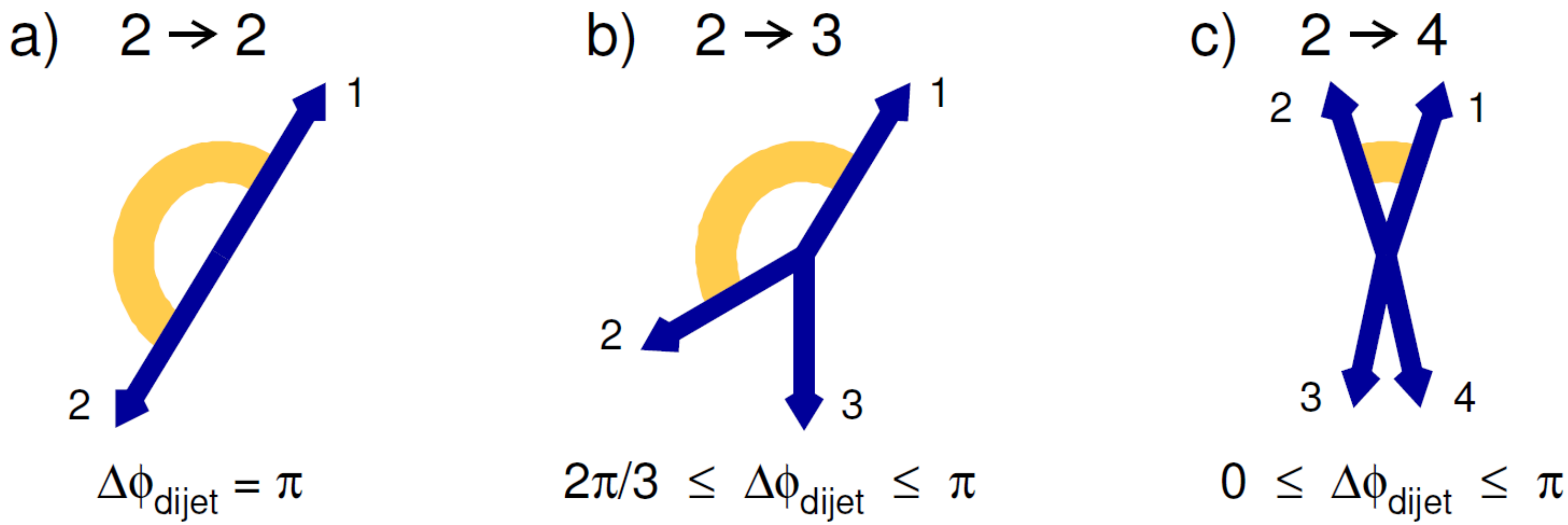
Orange: TEEC
Blue: ATEEC

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^*.

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

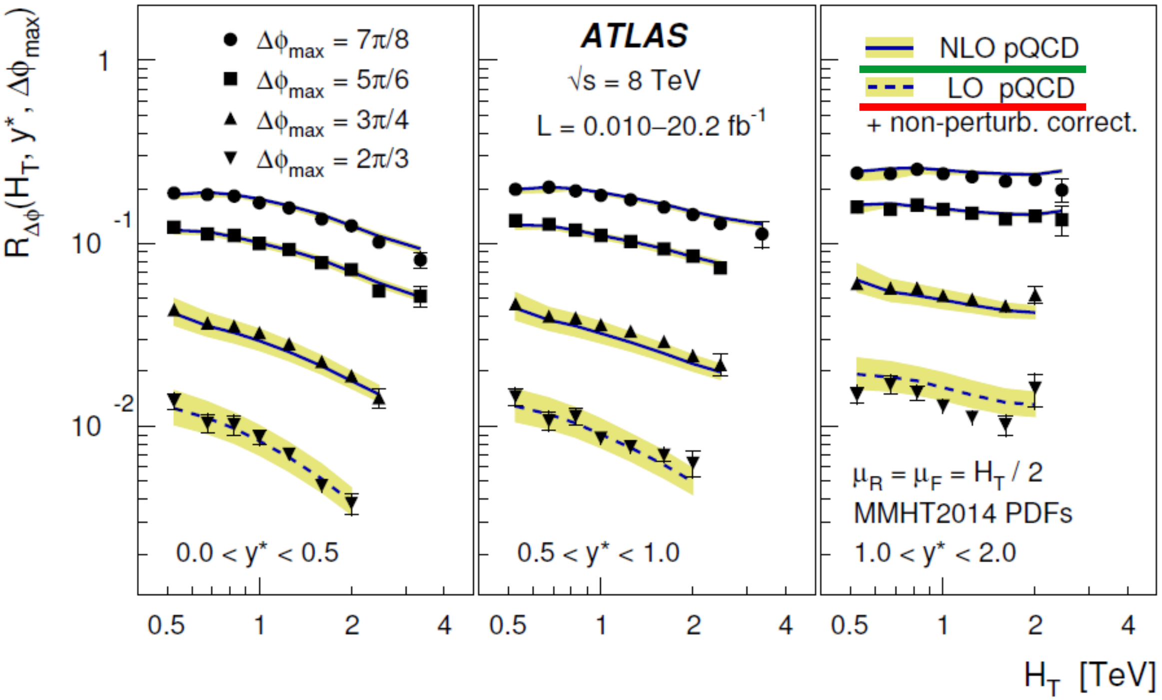
$$R_{\Delta\phi} \propto \alpha_s$$



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

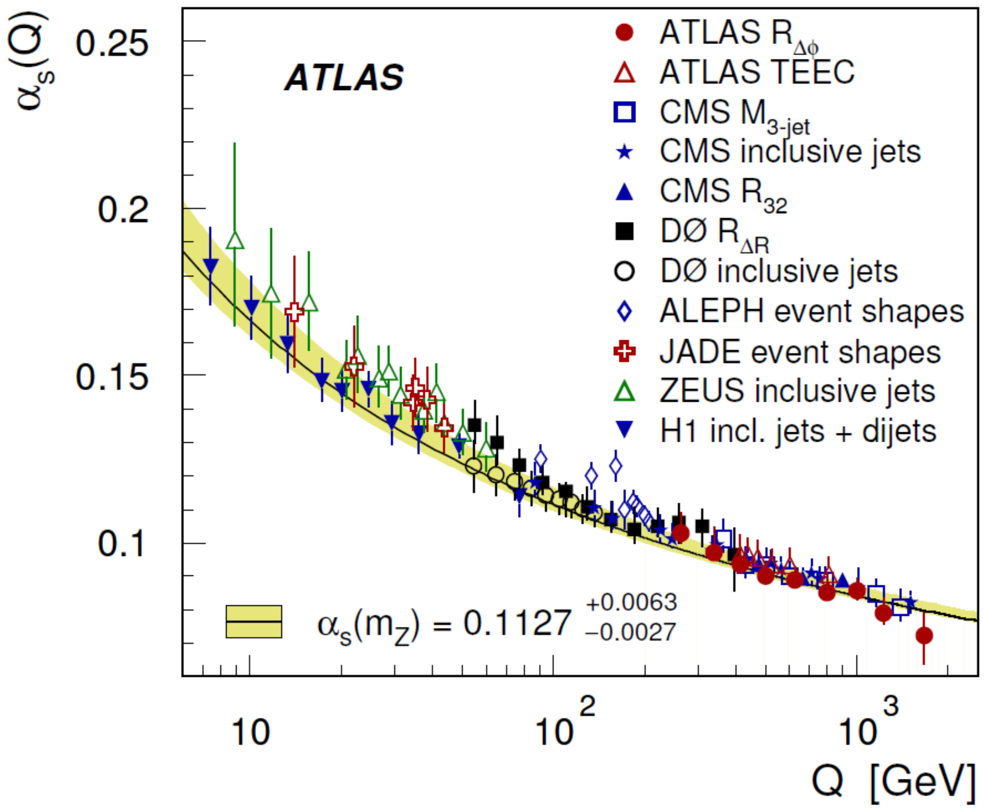
Wobisch et al., JHEP 01 (2013) 172;
KR, M. Wobisch, JHEP 12 (2015) 024.

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



Theory:
3-jet NLOJet++

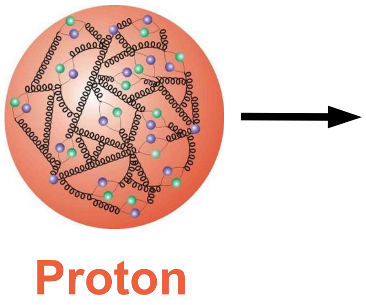
Scale choice: $\mu_R = \mu_F = H_T/2$

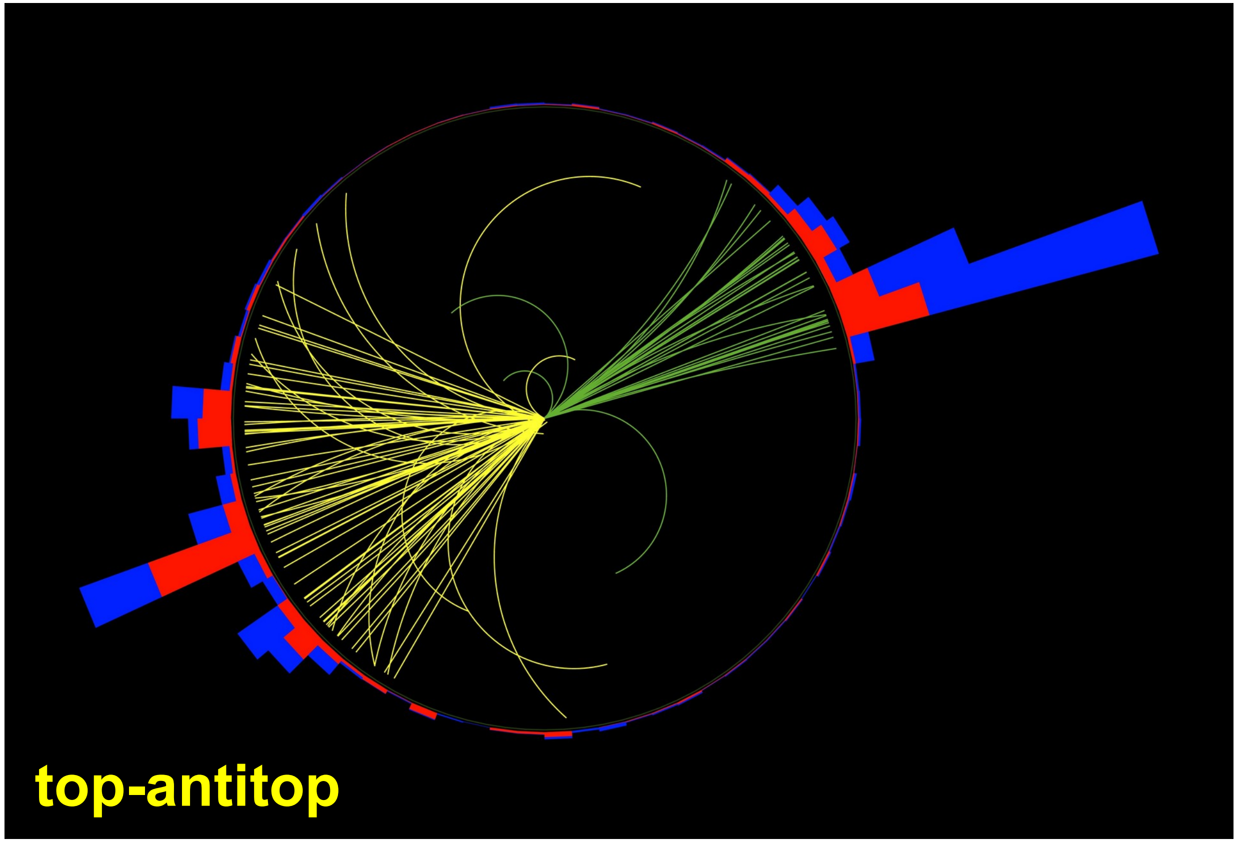


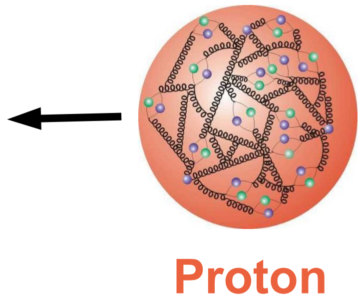
From more precise results with
$\Delta\varphi_{max} = 7\pi/8$ in the two y* regions below 1.0:

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

Heavy quarks



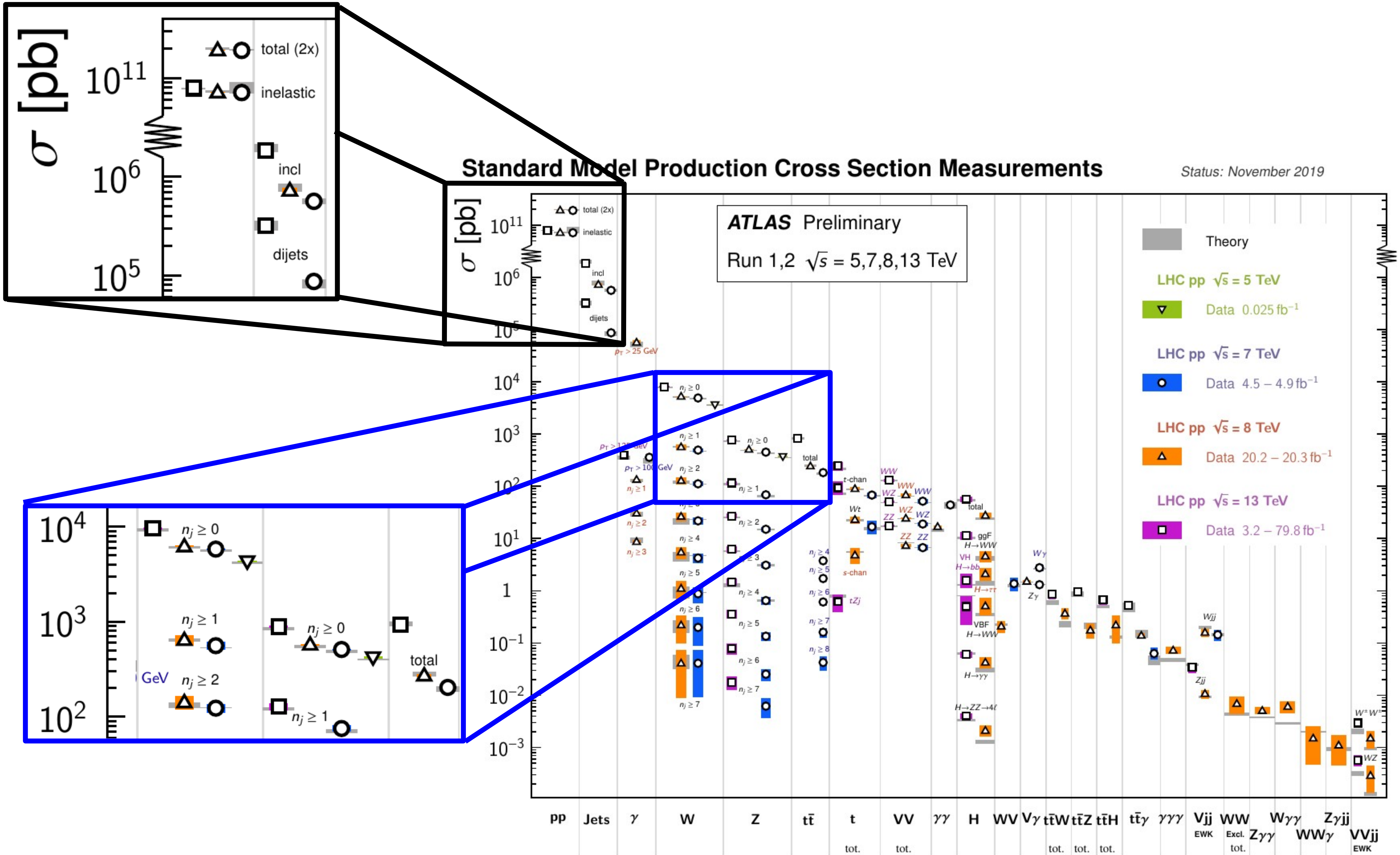




Relevant CMS measurements:

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.

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
- What top mass? Pole? MS_{bar}?
- Top measurements already in PDF?
- Theory at NNLO or NNLO+NNLL

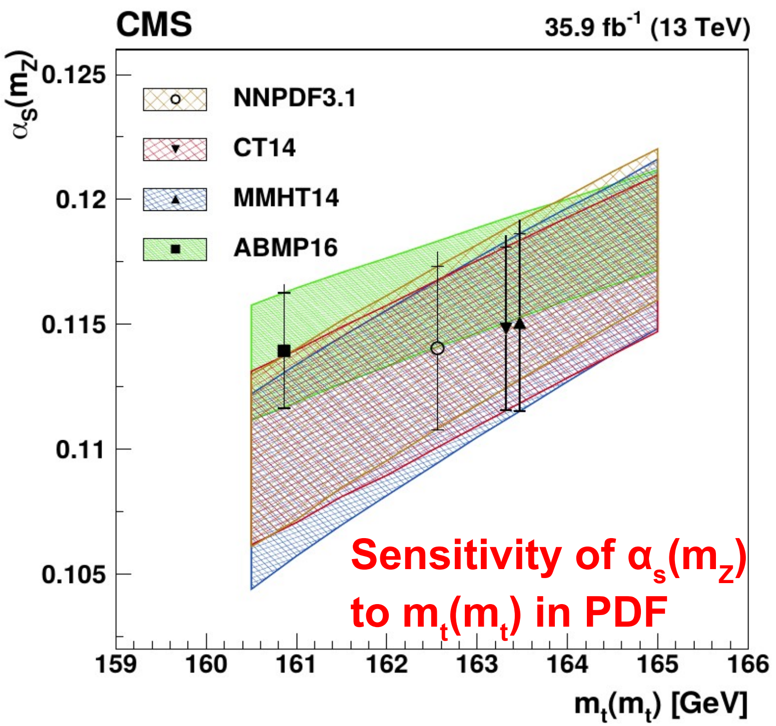
Fits with tt production cross section

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 →

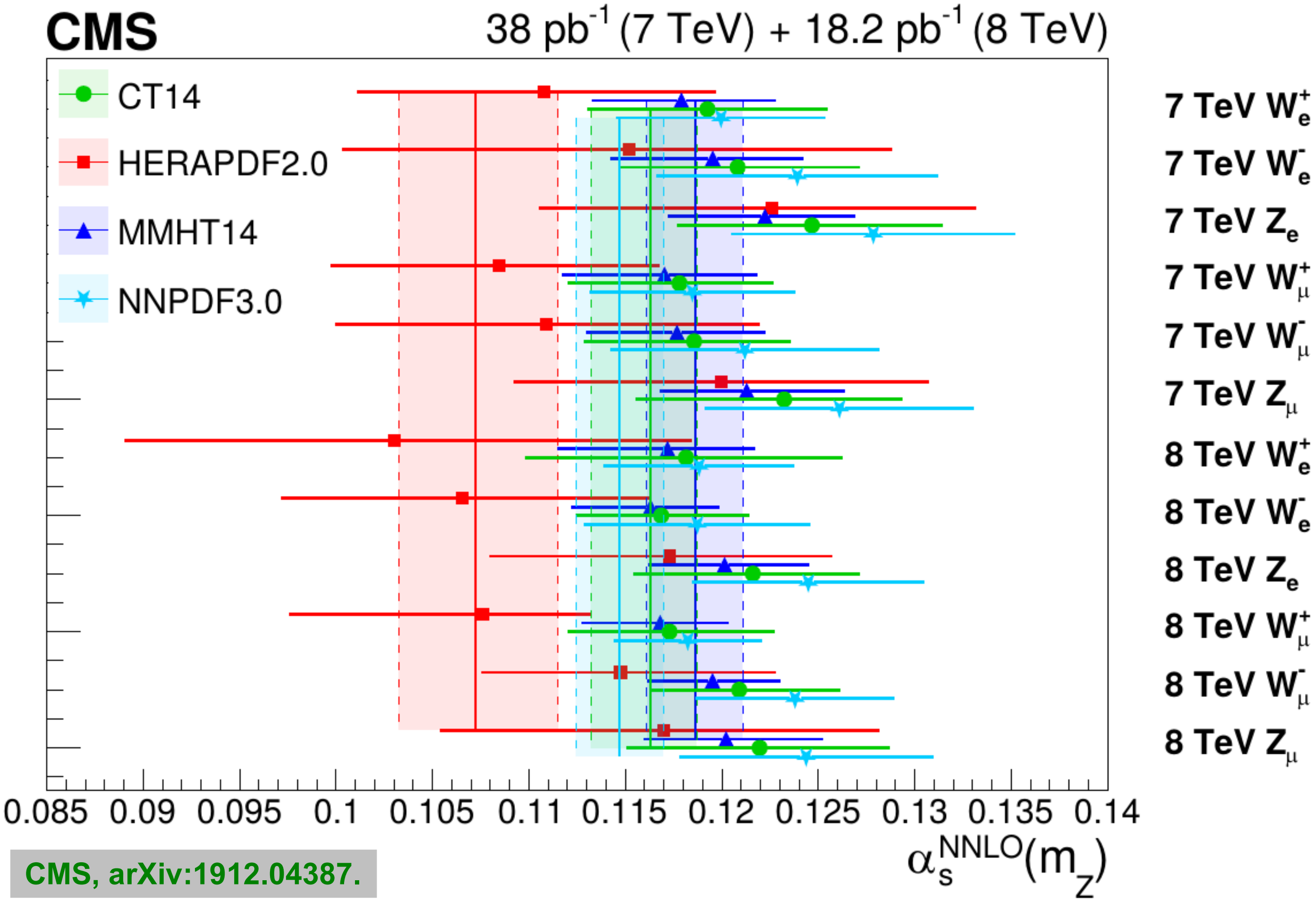
√s [TeV]	lum [fb^{-1}]	$\alpha_s(M_Z)$	exp m_t PDF ...	scale
7	2.3	0.1151	$^{+27}_{-26}$	$^{+9}_{-8}$
13	35.9	**0.1139**	23	$^{+14}_{-1}$

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

Inclusive W,Z production

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

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



CMS, arXiv:1912.04387.

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

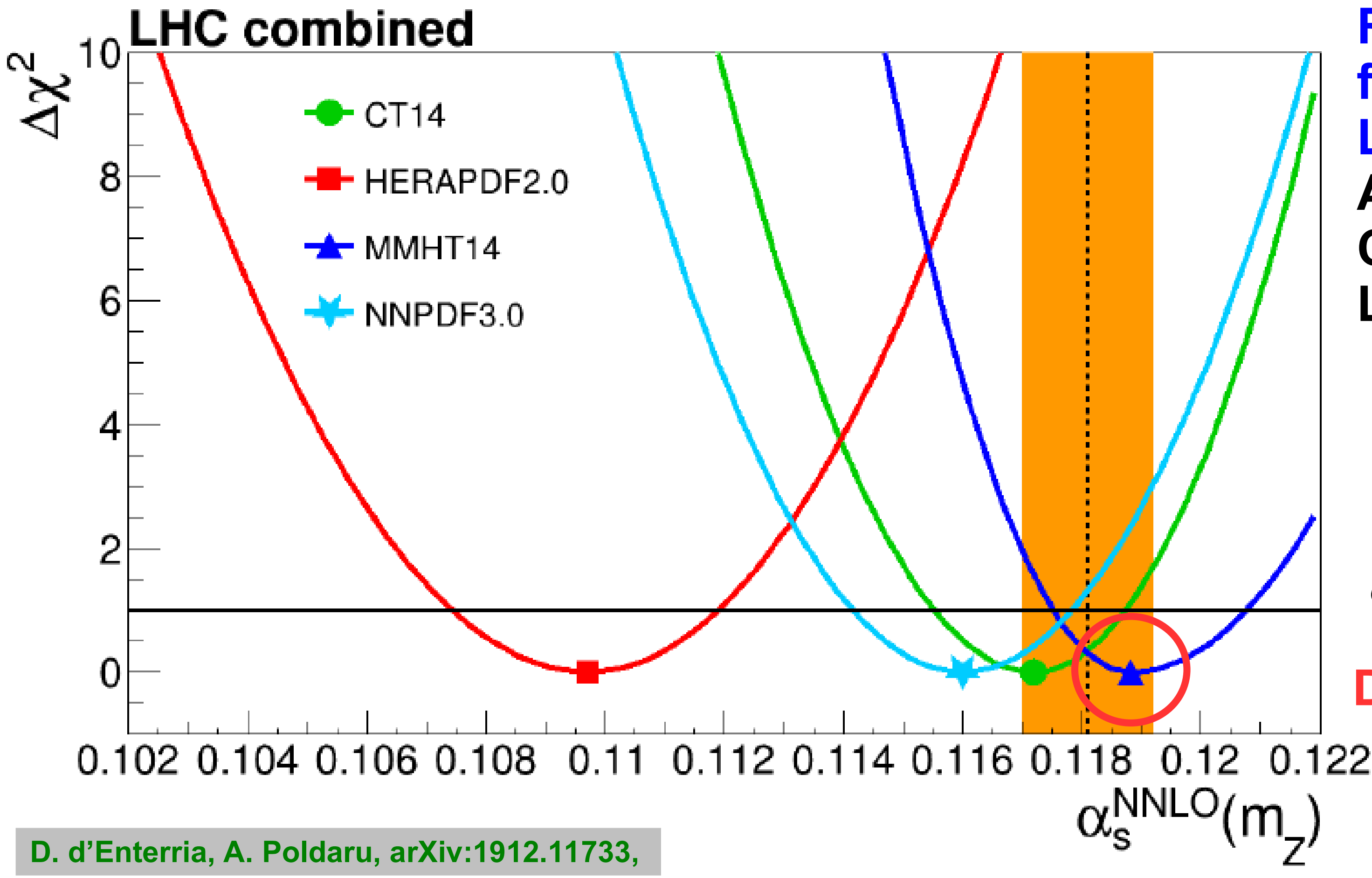
In total data from ATLAS, CMS, LHCb and Tevatron are investigated in separate publication!

D. d'Enterria, A. Poldaru, arXiv:1912.11733,

Inclusive W,Z production

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

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



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

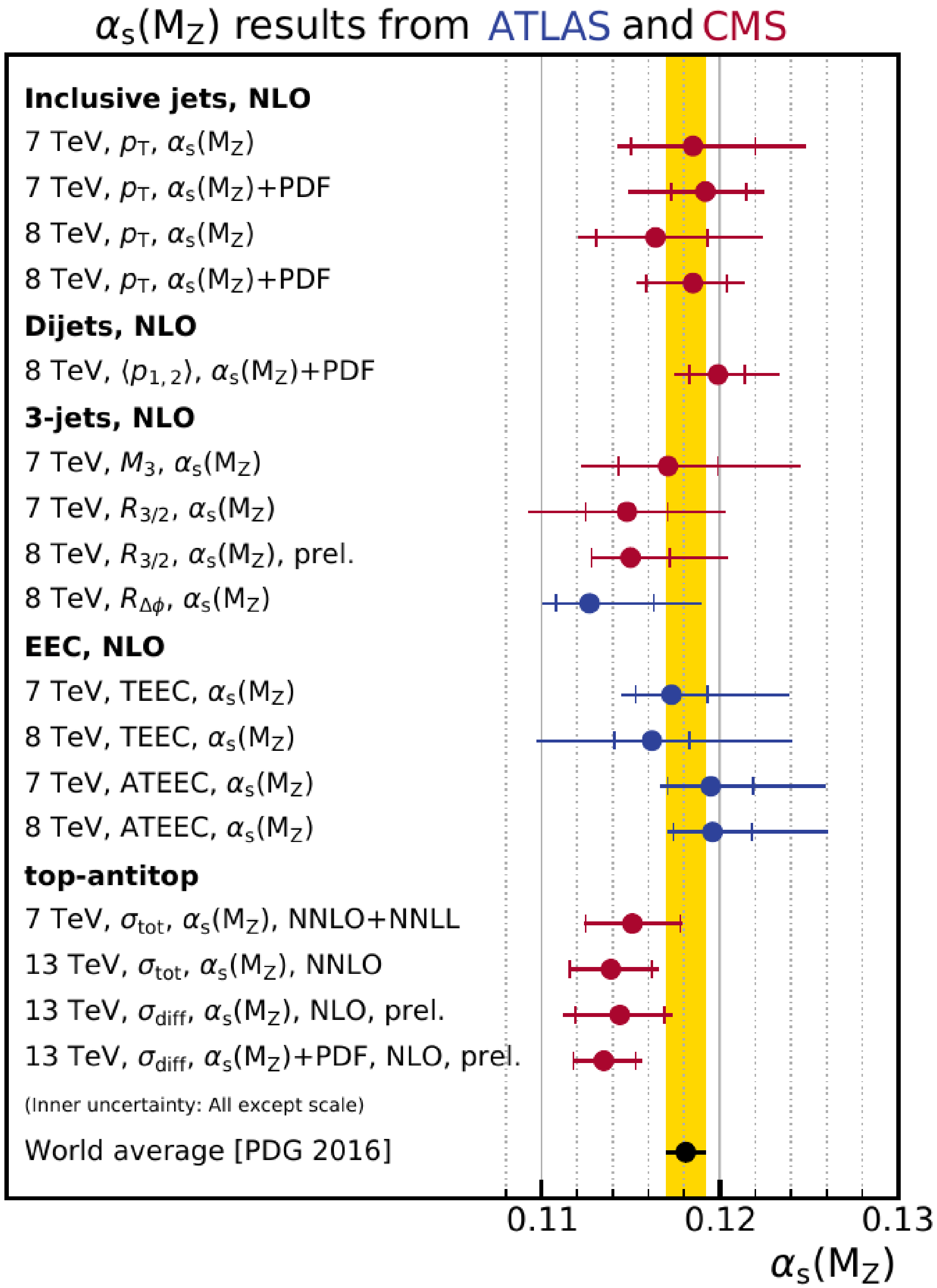
ATLAS 7
CMS 12
LHCb 9

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

Derived from MMHT14 only!

D. d'Enterria, A. Poldaru, arXiv:1912.11733,

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

$\mu_0 = p_{\mathrm{T},3}, \quad \left(p_{\mathrm{T},1} + p_{\mathrm{T},2}\right)/2, \quad m_{jjj}/2?$

Perspectives & educated guesses

- **Experiment:**
  - **Done: Observables $\sigma \sim \alpha_s^2$, α_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 2019

PDG2019

All except lattice

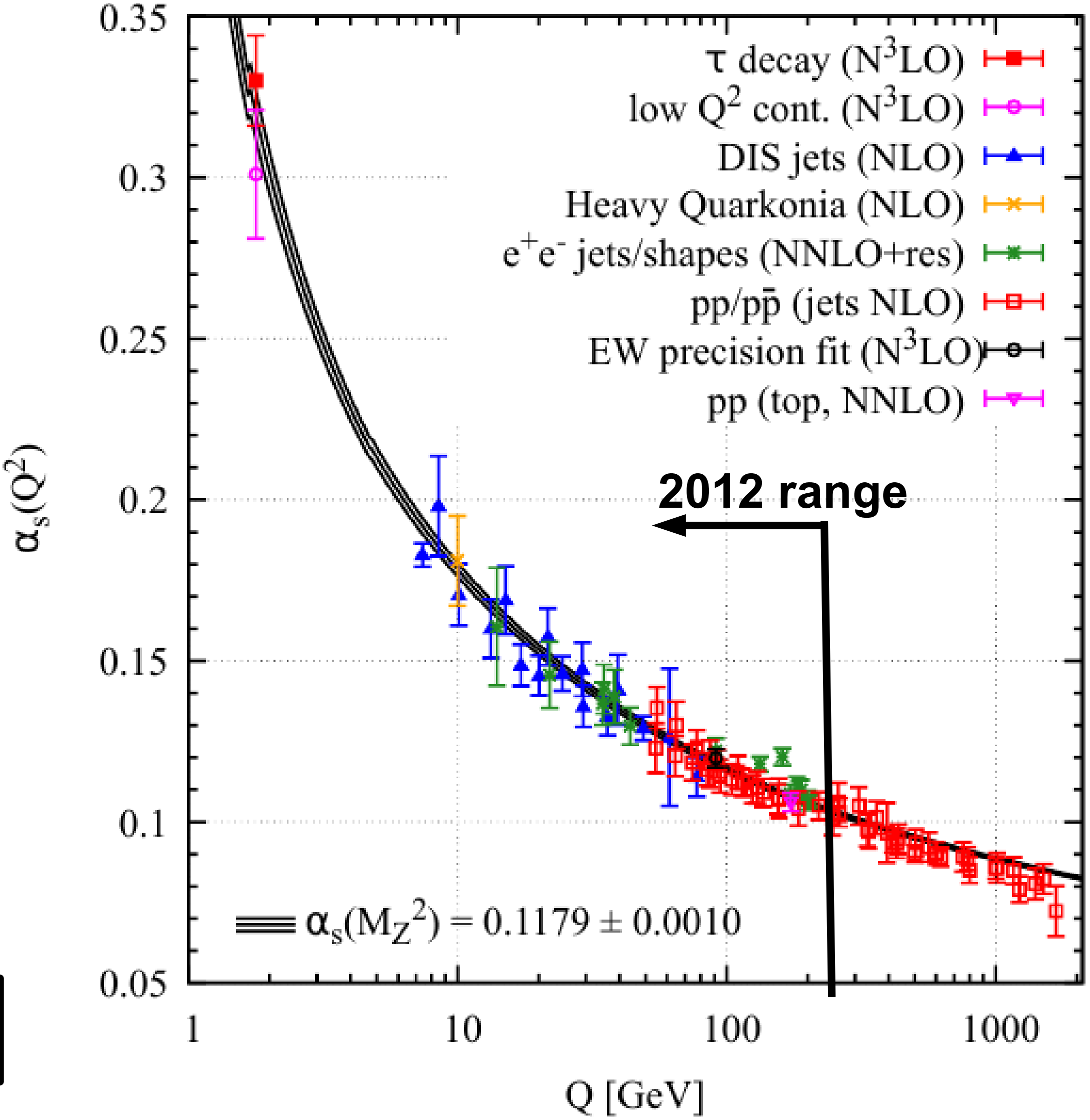
$$\alpha_S(M_Z) = 0.1176 \pm 0.0011$$

Lattice FLAG 2019

$$\alpha_S(M_Z) = 0.1182 \pm 0.0008$$

Final PDG average

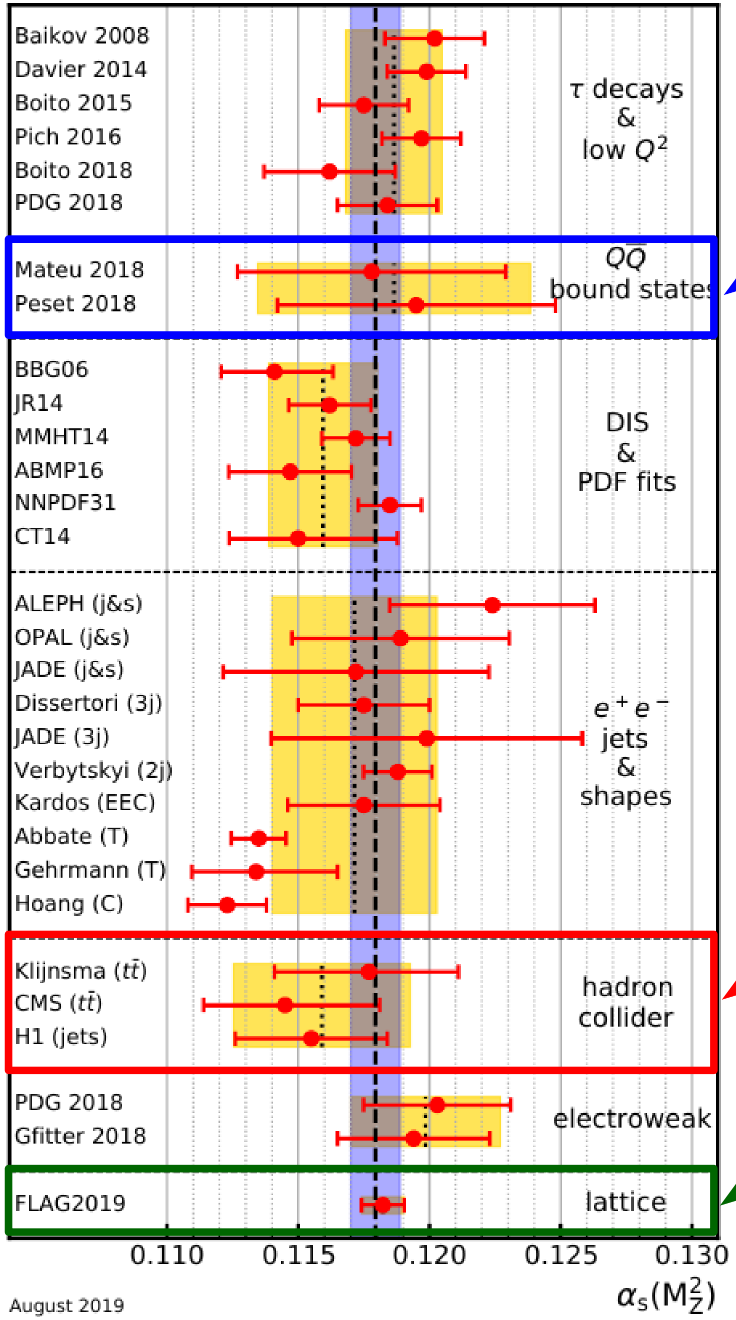
$$\alpha_S(M_Z) = 0.1179 \pm 0.0010$$



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

PDG´92: 2.4%

PDG Summary 2019

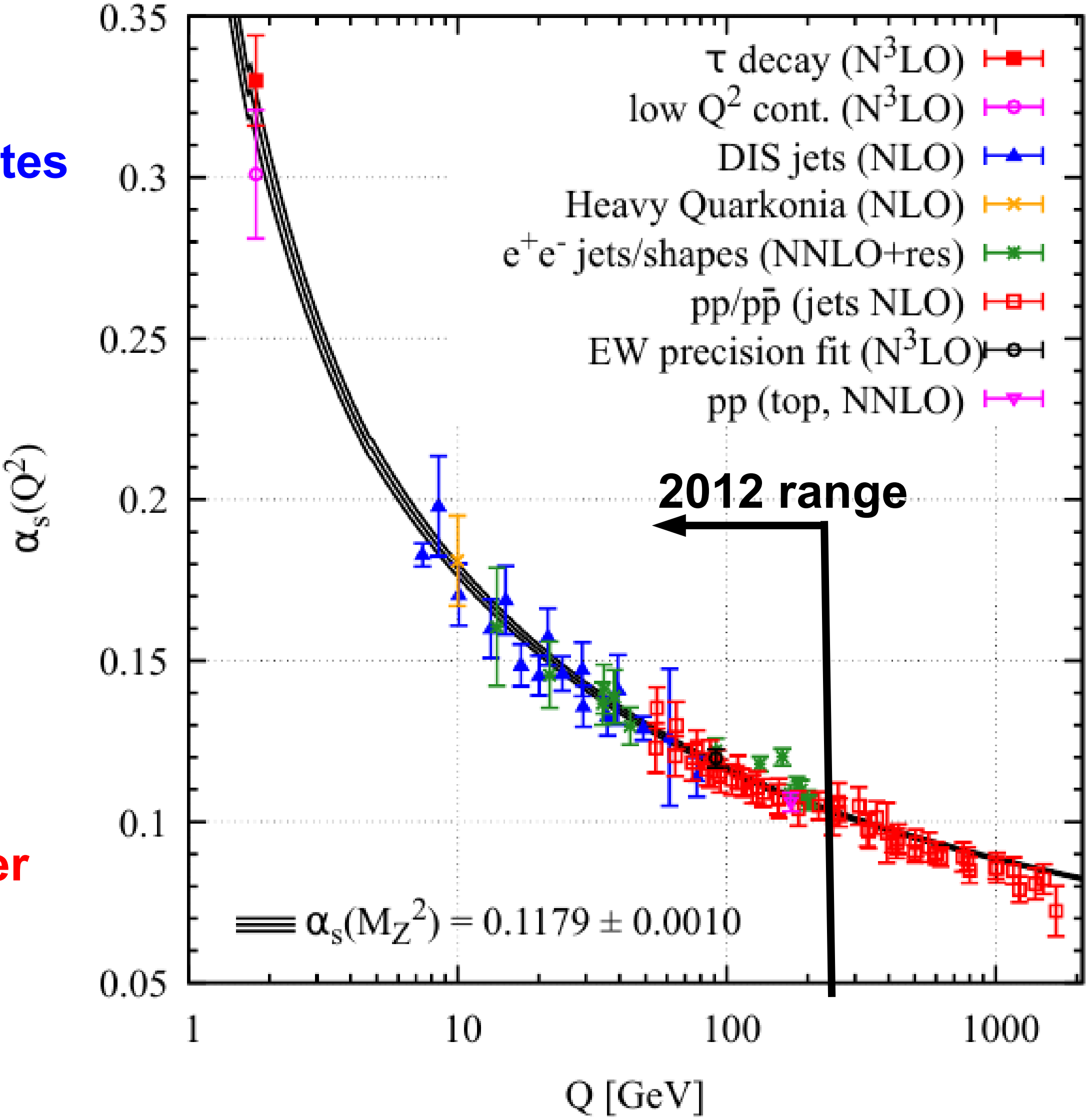


PDG2019

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(?) 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!

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

Backup Slides

Inclusive jets: NNLO & scale choice

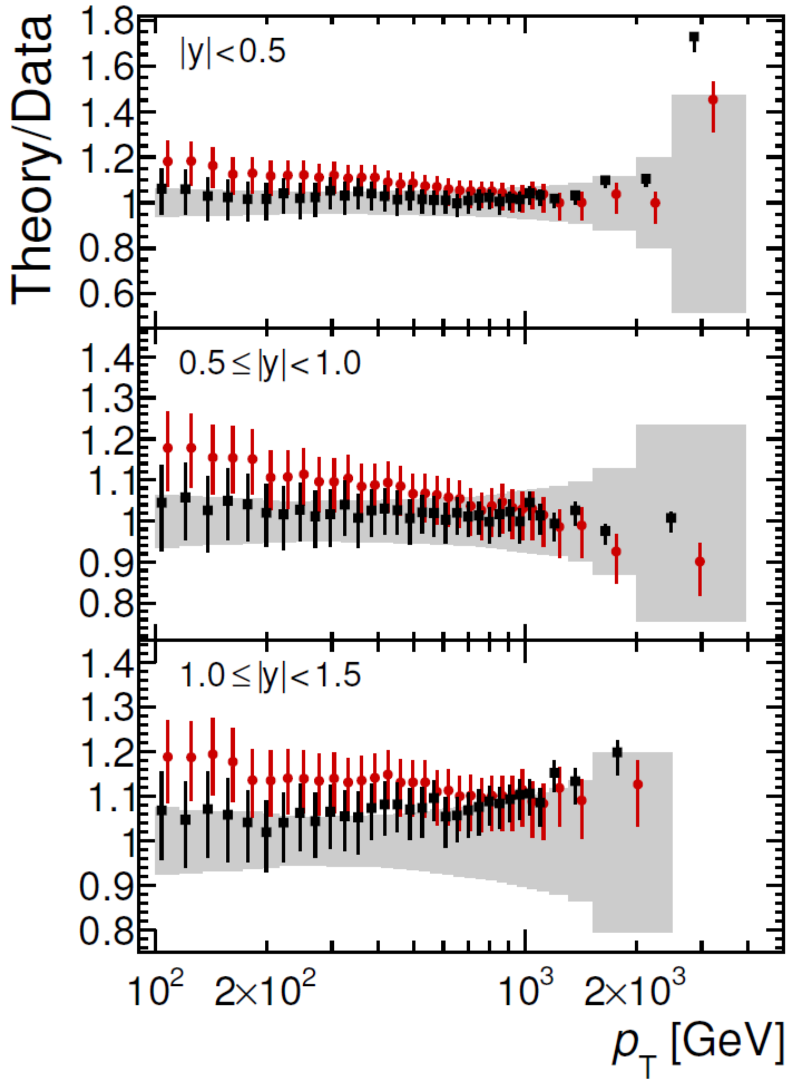
anti-kt, R=0.4, 13 TeV

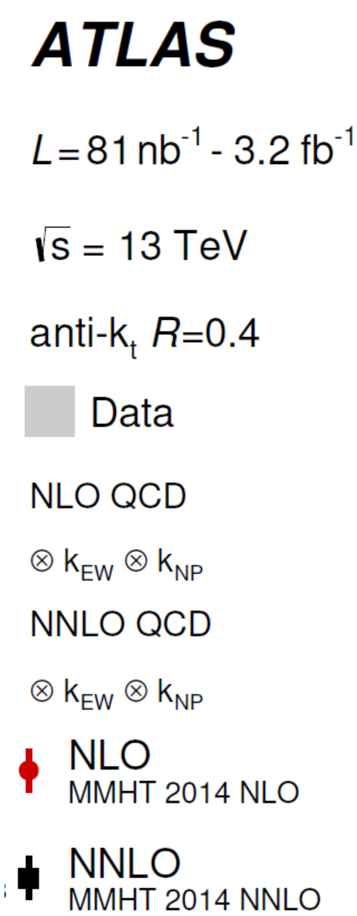
QCD scale choice: $\mu_R = \mu_F = p_{T,jet}$

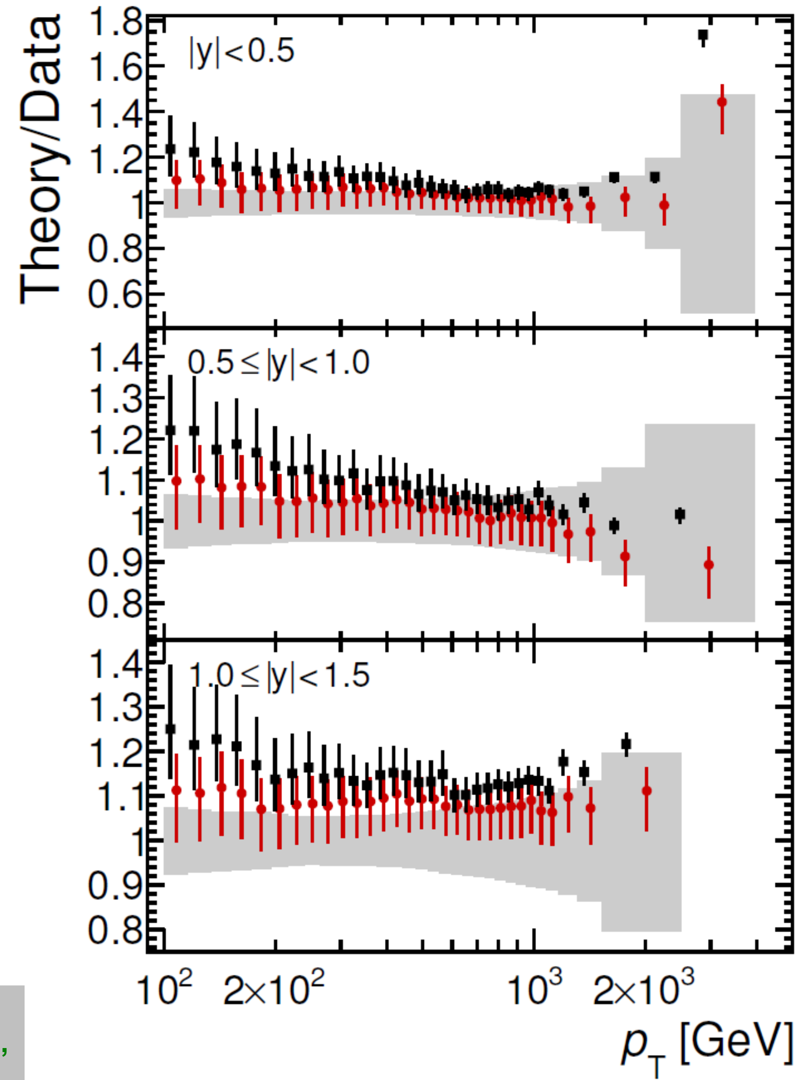
- close to recommended one

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.

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

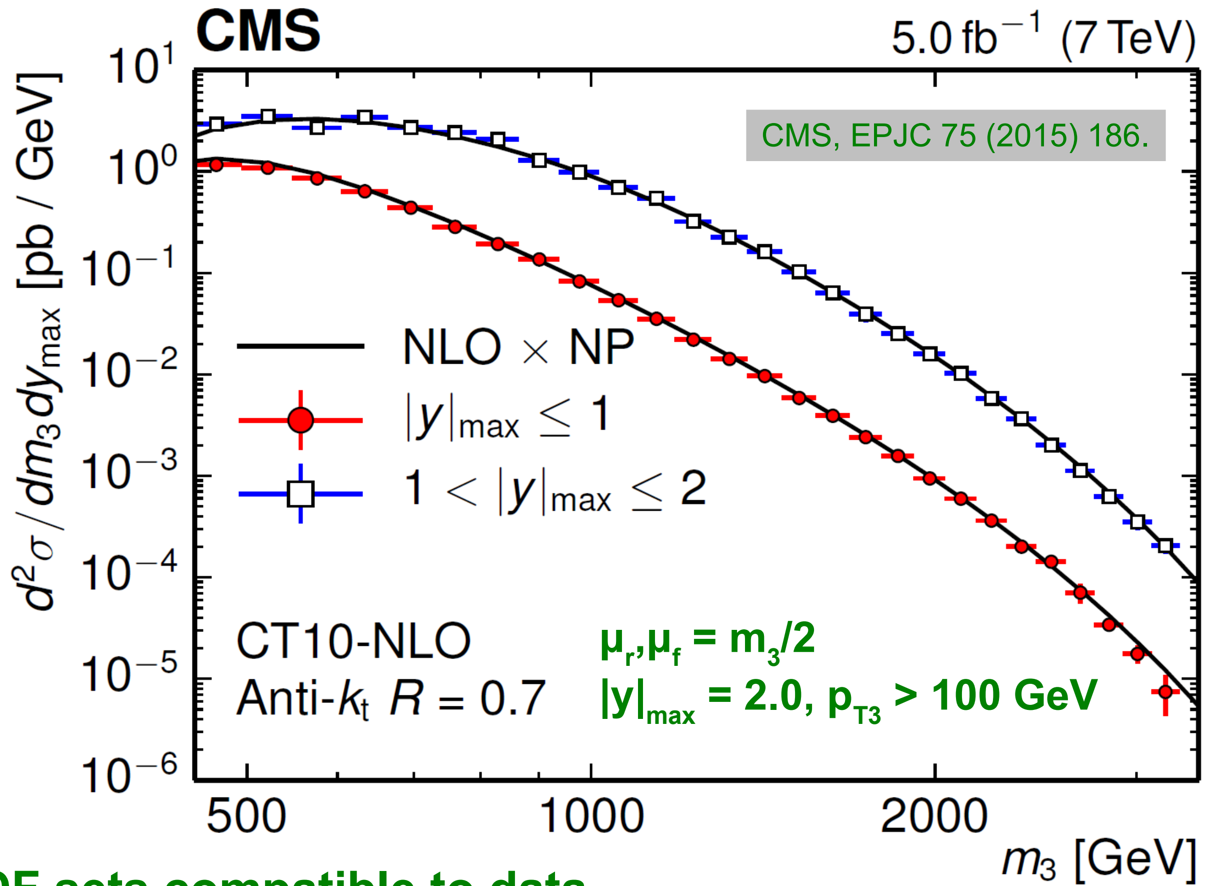
3-jet mass

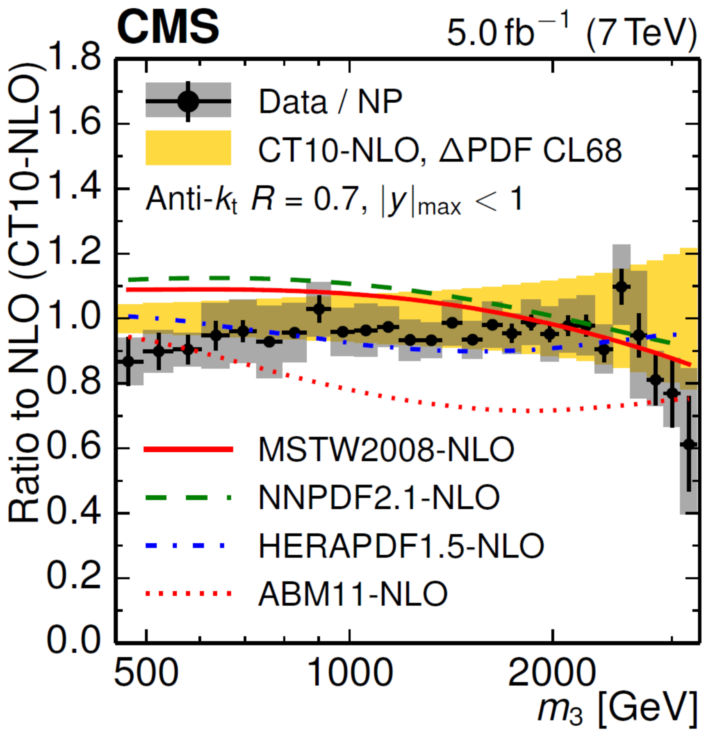
Sensitive to α_s beyond 2→2 process

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 $\alpha_s(M_Z)$: $\rightarrow \alpha_s$

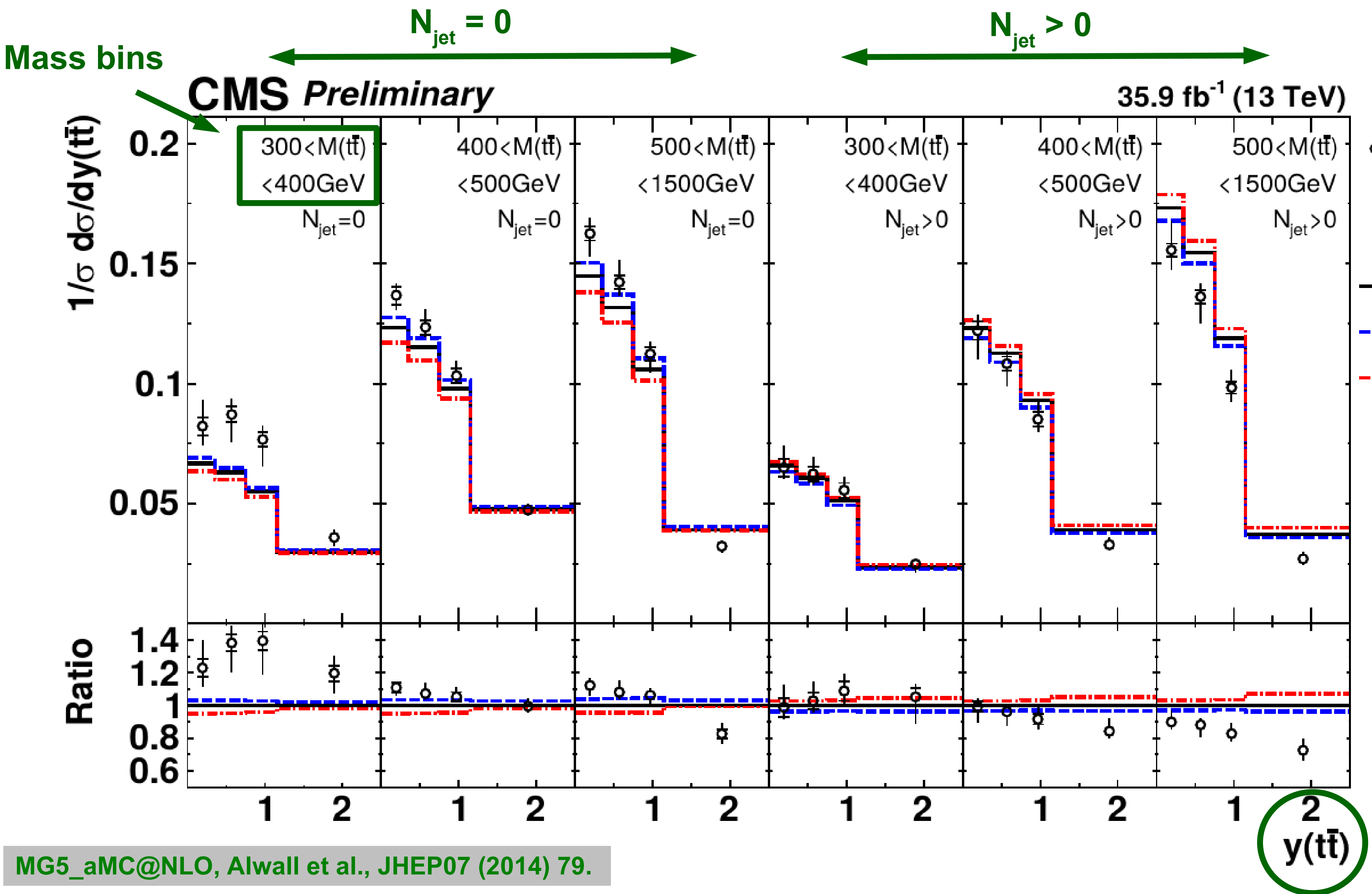
√s [TeV]	lum [fb⁻¹]	$\alpha_s(M_Z)$	exp NP PDF	scale
7	5.0	0.1171	28	$^{+69}_{-40}$

Sensitivity of differential cross section

NLO

Normalised

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



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

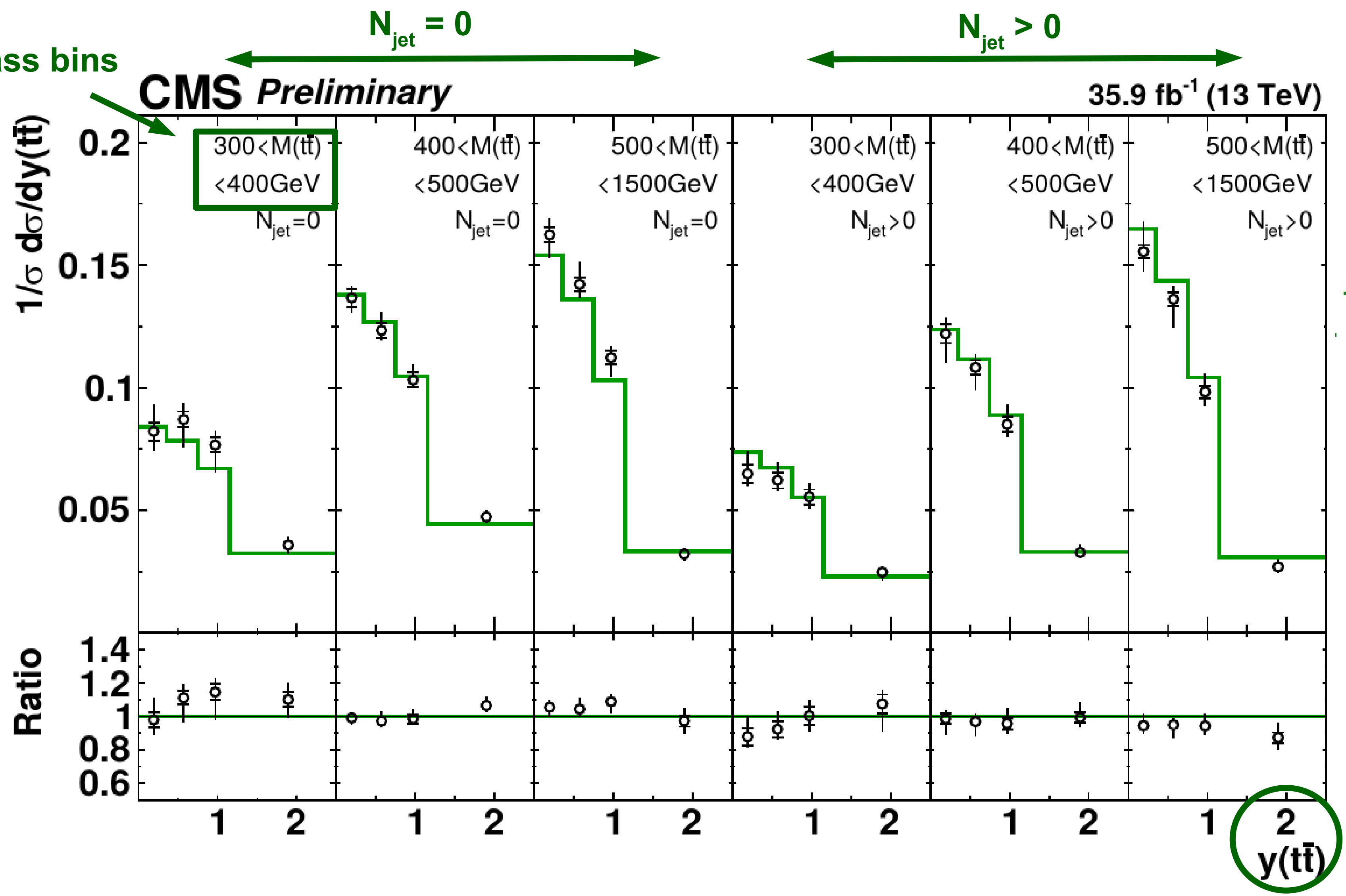
Initial description of data at NLO with CT14 PDFs for 3 values of $\alpha_s(M_Z)$

Fits using tt differential distributions

NLO

Normalised

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



Partial χ^2 of tt only

M(tt),y(tt) → PDFs

N_{jet} → m_t^{pole}, α_s

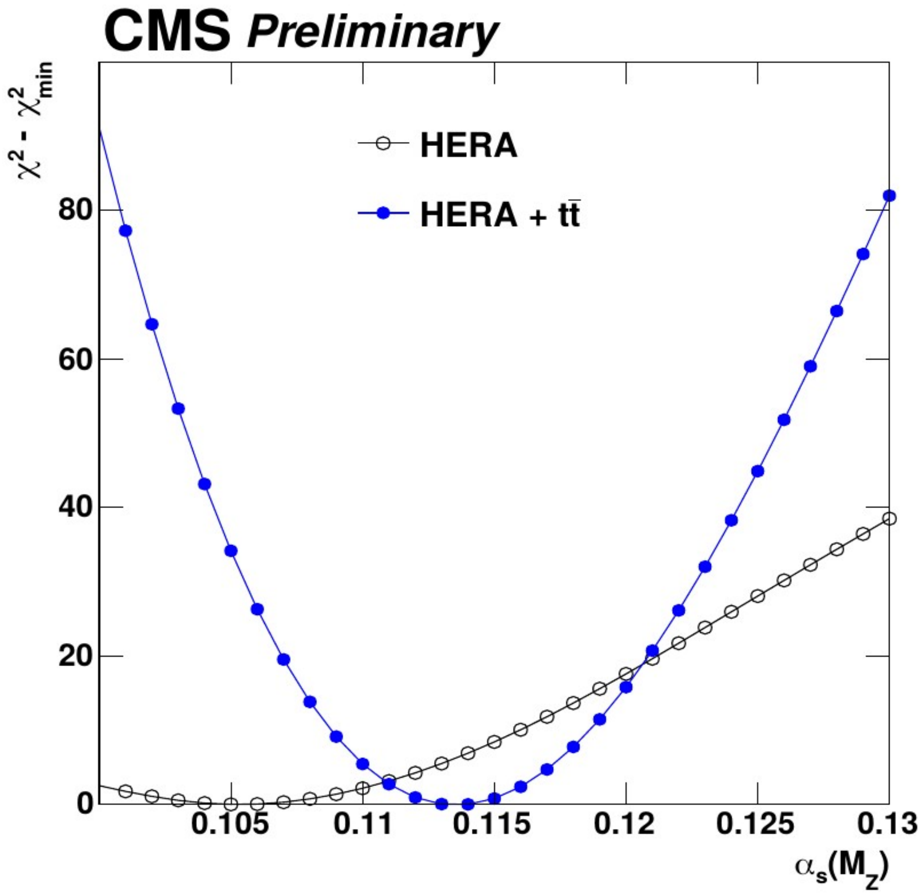
Description of data after fit of $\alpha_s(M_Z)$, m_t^{pole}, PDFs to HERA + tt data

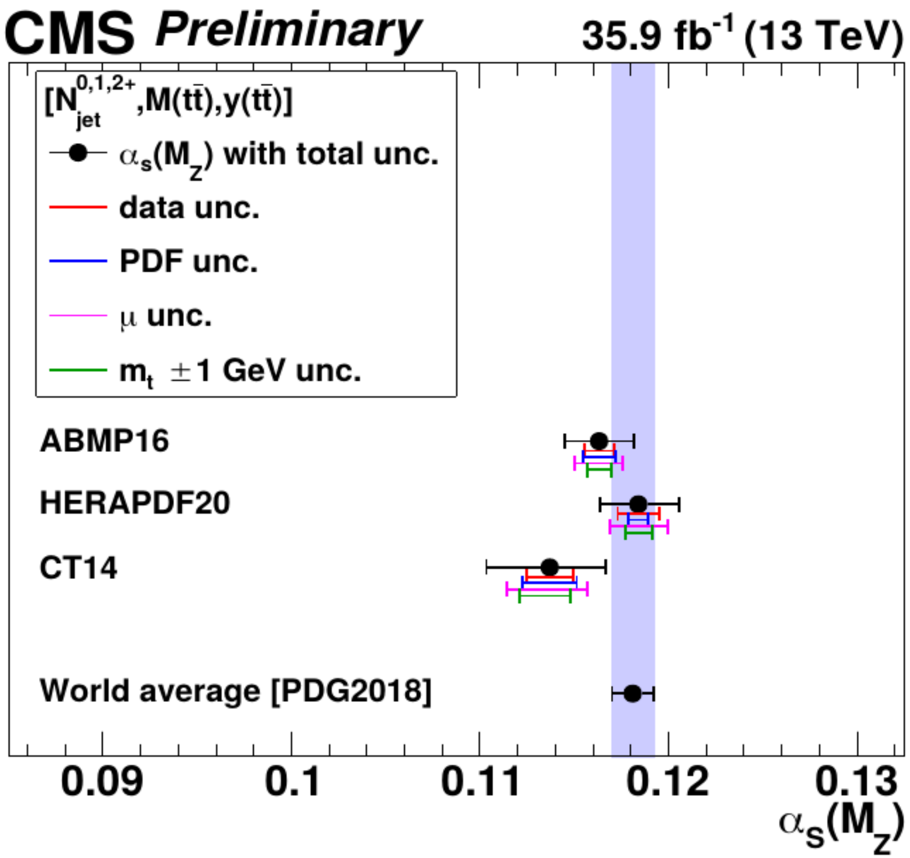
Fits using tt differential distributions

NLO

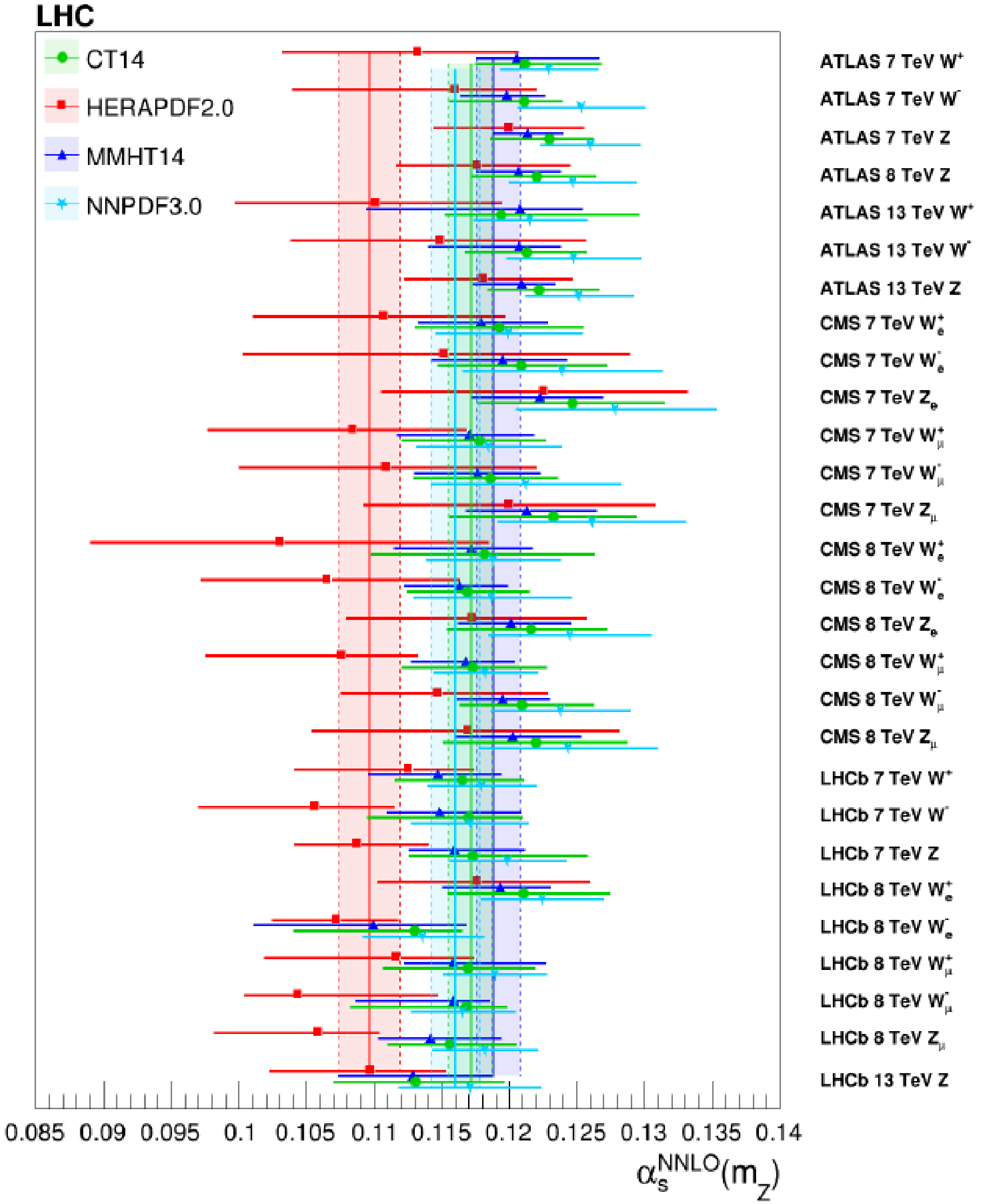
Comparison of χ^2 for $\alpha_s(M_Z)$ with HERA only and with additional tt data

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





Inclusive W,Z production



D. d'Enterria, A. Poldaru, arXiv:1912.11733,
CMS, arXiv:1912.04387.

Combining LHC & Tevatron tt data

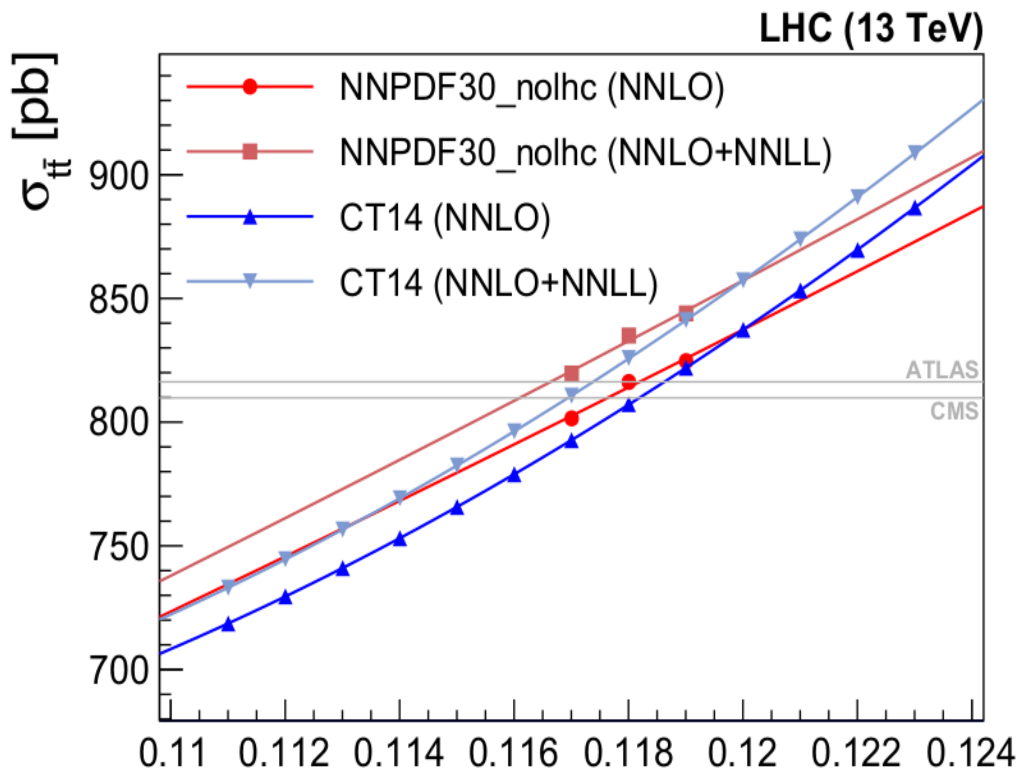
- fitting procedure similar to CMS; more conservative scale dependence treatment
- combines results using NNLO or NNLO+NNLL for theory prediction
- updated and complemented set of ttbar cross section measurements from LHC
- includes Tevatron results
- consideration of correlations among measurements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

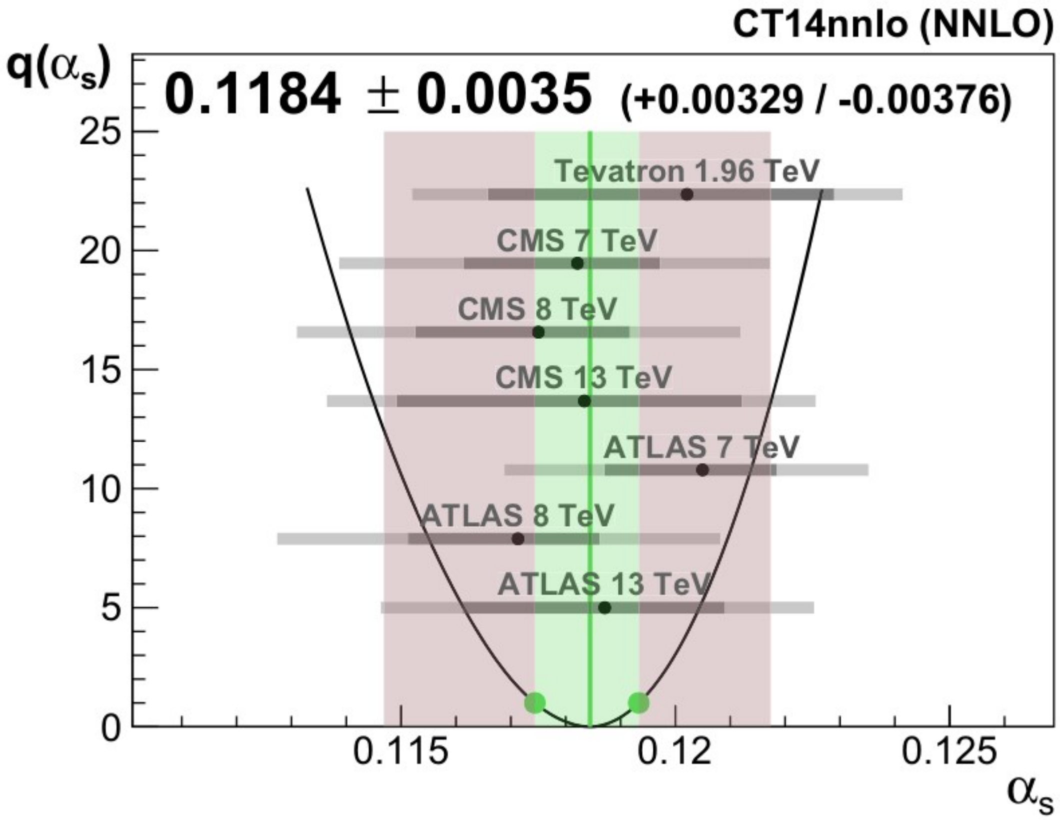
Datasets:

	$\sigma_{t\bar{t}}$ (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.

Combining LHC & Tevatron $t\bar{t}$ 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 $\alpha_s(M_Z)$!

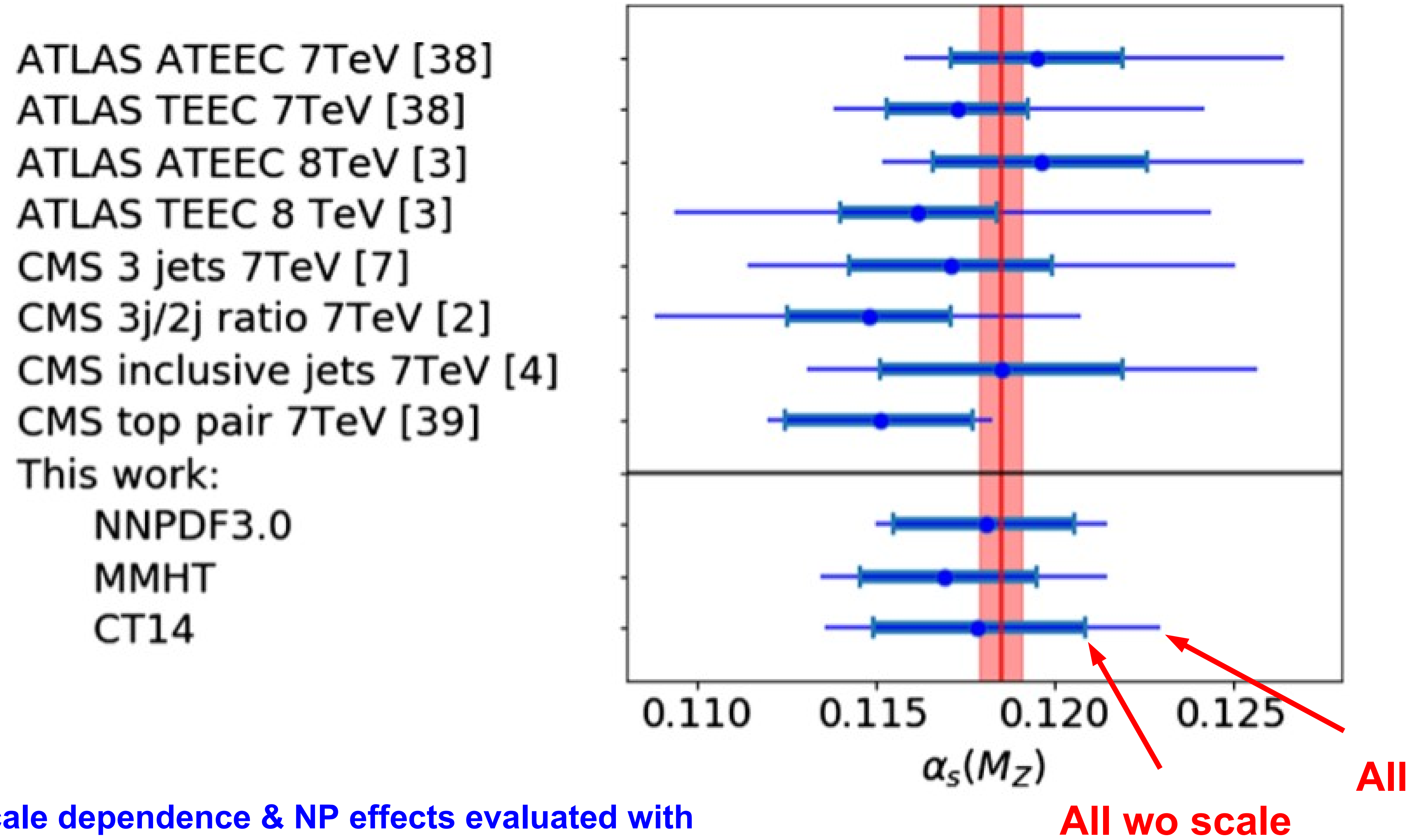
(No ratios [n+1]/n though ...)

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

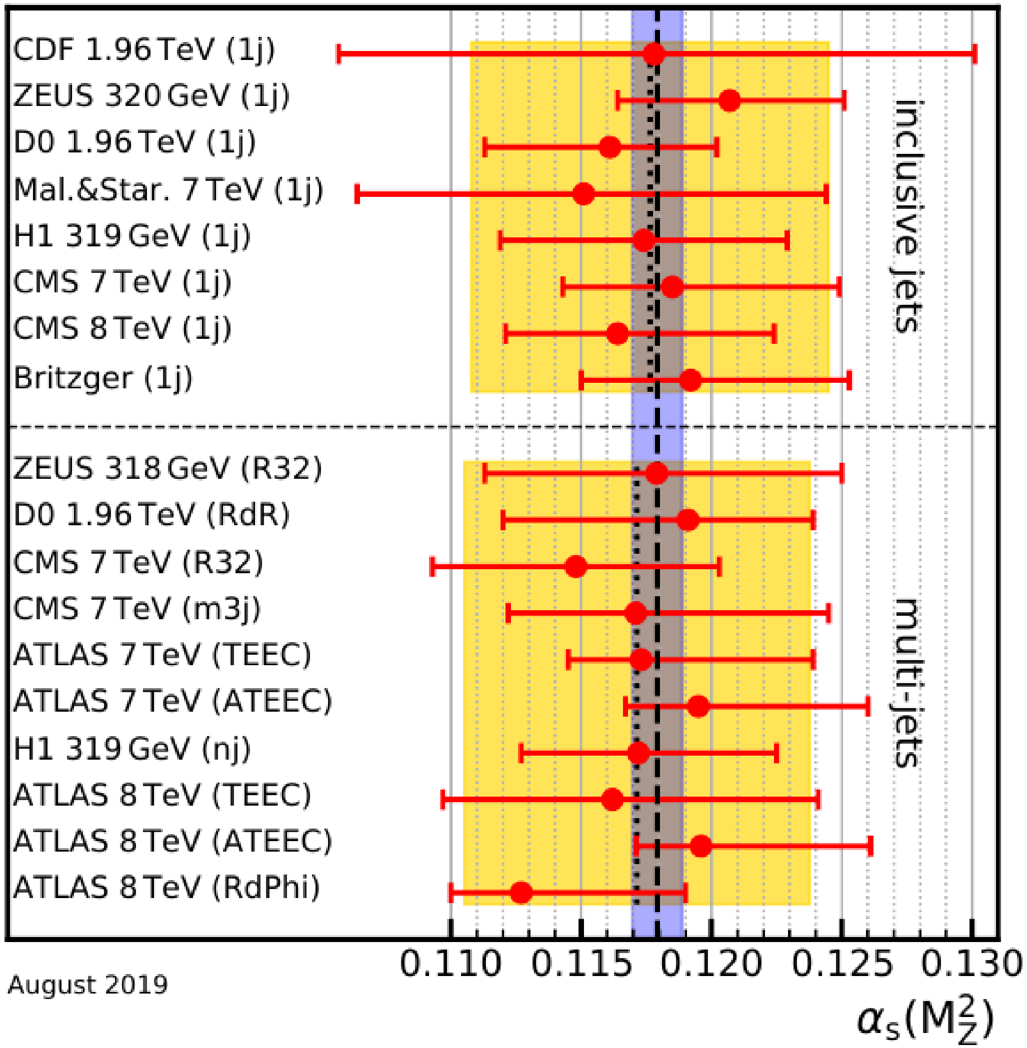


Scale dependence & NP effects evaluated with "standard" method & profile X2 resp. nuisance parameter

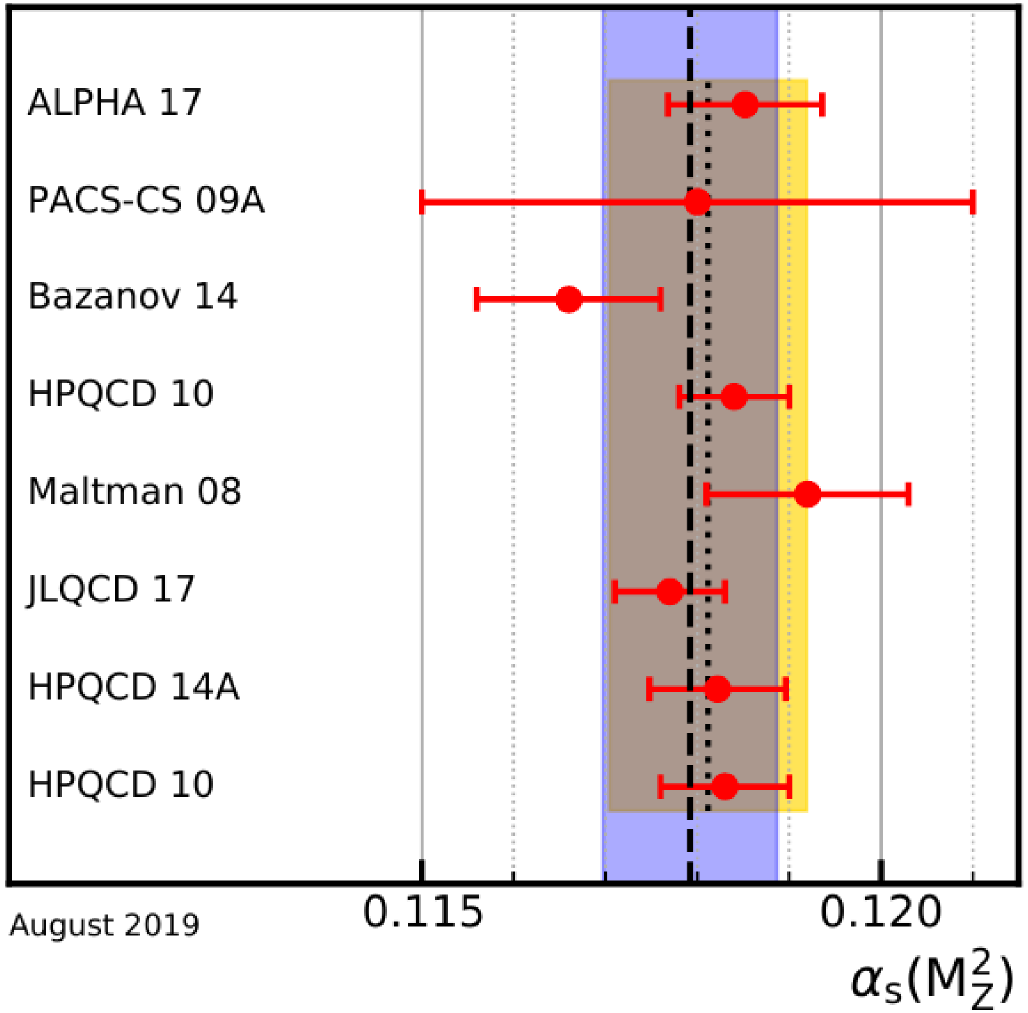
M. Johnson, D. Maitre, PRD 97 (2018) 054013.

PDG 2019 Comparison

α_s at NLO from jet production



α_s from lattice groups



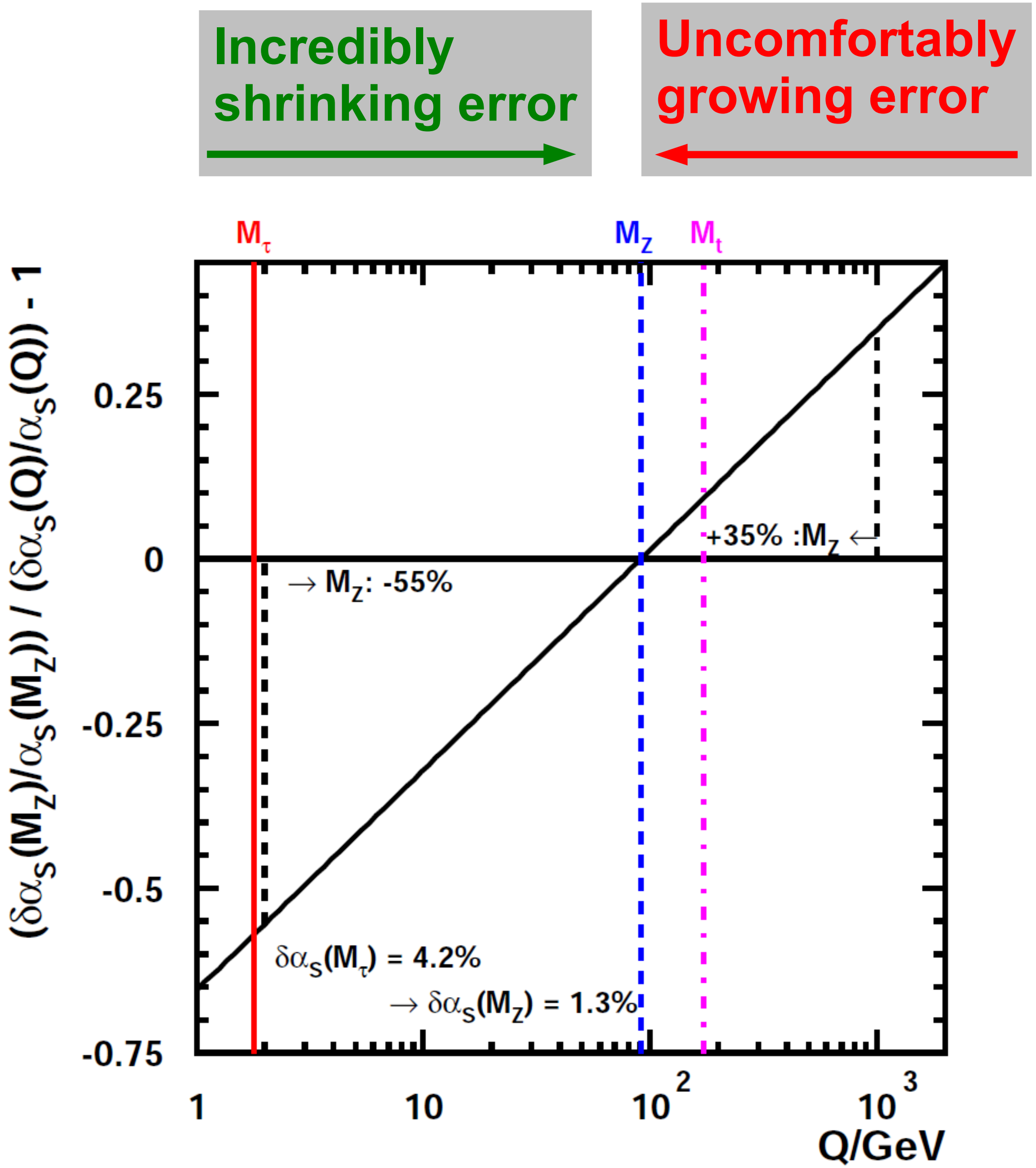
Jet energy scale and α_s

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



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 ~ 1% (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	< 1% possible (ILC/TLEP) ~ 1% (control n.p. via Q^2-dep.)	~1%
e^+e^- jet rates	expt ~ 2% (LEP) thry ~ 1% (NNLO, n.p. moderate) [28]	< 1% possible (ILC/TLEP) ~ 0.5% (NLL missing)	
precision EW	expt ~ 3% (R_Z, LEP) thry ~ 0.5% (N^{3}LO, n.p. small) [9, 29]	0.1% (TLEP [10]), 0.5% (ILC [11]) ~ 0.3% (N^{4}LO feasible, ~ 10 yrs)	<1%
τ decays	expt ~ 0.5% (LEP, B-factories) thry ~ 2% (N^{3}LO, n.p. small) [8]	< 0.2% possible (ILC/TLEP) ~ 1% (N^{4}LO feasible, ~ 10 yrs)	
ep colliders	~ 1–2% (pdf fit dependent) [30, 31], (mostly theory, NNLO) [32, 33]	0.1% (LHeC + HERA [23]) ~ 0.5% (at least N^{3}LO required)	<1%
hadron colliders	~ 4% (Tev. jets), ~ 3% (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17, 21, 34]	< 1% challenging (NNLO jets imminent [22])	~1%
lattice	~ 0.5% (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	~ 0.3% (~ 5 yrs [38])	<0.5%

Snowmass QCD Report, arXiv:1310.5189.