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Measurements of α_s at ATLAS and CMS

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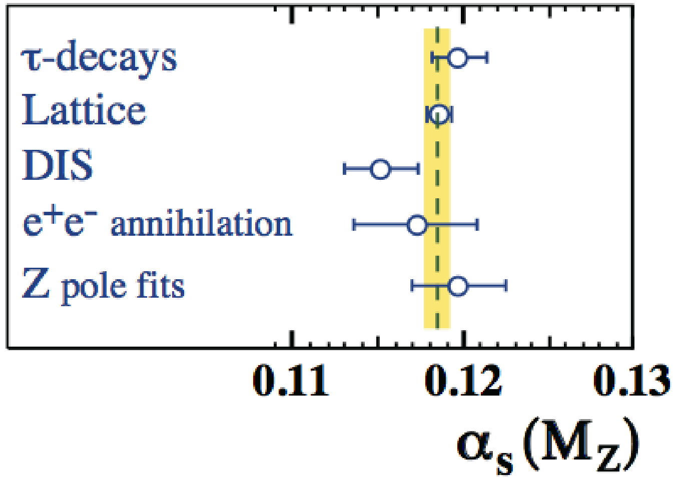
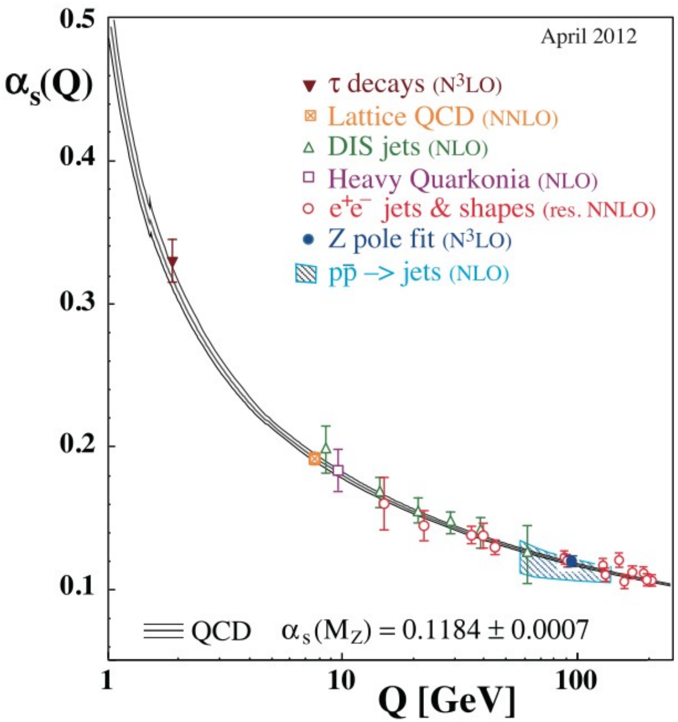
Motivation: Measuring α_s

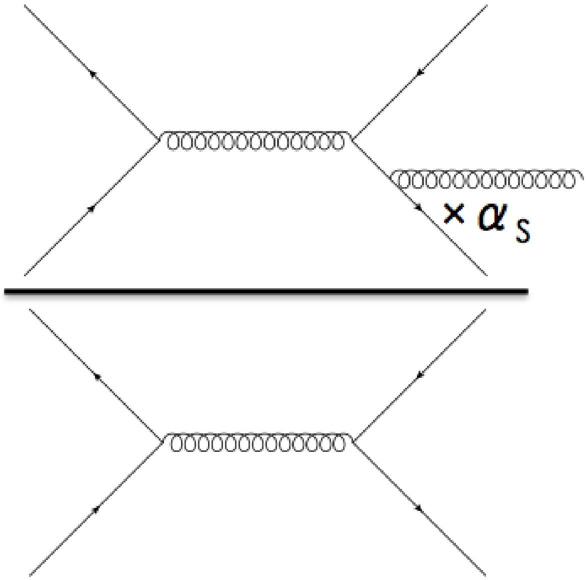
- Strong coupling constant α_s is the only free parameter in QCD
  - With quark masses
- Can be determined using many experimental observables
  - Different processes allow running behaviour to be observed
- Compatible values demonstrate
  - QCD, as a theory, is a good description of strong interactions
  - One universal coupling is sufficient to describe the strong interaction





Multijet ratios for α_s measurements

- Ratios of inclusive cross-sections for event with ≥ 3 jets and ≥ 2 jets
  - Sensitive to the value of α_s
  - Cancellation of systematic uncertainties (luminosity, PDFs, etc) for more precise test of QCD
- Cross-section can be measured relative to various quantities, typically jet transverse momenta
  - Collision energy at LHC means running of the coupling can be tested at new scales



Multijet ratios in 2010 ATLAS data

ATLAS-CONF-2013-041

- Two ratios of inclusive cross-sections for event with ≥ 3 jets and ≥ 2 jets were studied

Benchmark measurement:

$$R_{3/2}(p_{\mathrm{T}}^{\mathrm{lead}}) = \frac{d\sigma_{N_{\mathrm{jet}}\geq 3}}{dp_{\mathrm{T}}^{\mathrm{lead}}} \Bigg/ \frac{d\sigma_{N_{\mathrm{jet}}\geq 2}}{dp_{\mathrm{T}}^{\mathrm{lead}}} \sim \alpha_s$$

"Probability that a 2-jet event has a third jet"

New observable:

$$N_{3/2}(p_{\mathrm{T}}^{(\mathrm{all\,jets})}) = \sum_{i}^{N_{\mathrm{jet}}} \frac{d\sigma_{N_{\mathrm{jet}}\geq 3}}{dp_{\mathrm{T},i}} \Bigg/ \sum_{i}^{N_{\mathrm{jet}}} \frac{d\sigma_{N_{\mathrm{jet}}\geq 2}}{dp_{\mathrm{T},i}} \sim f(\alpha_s)$$

- Comparable sensitivity to α_s, $N_{3/2}$ has smaller dependence on the choice of scale in the phase-space studied, used for α_s determination

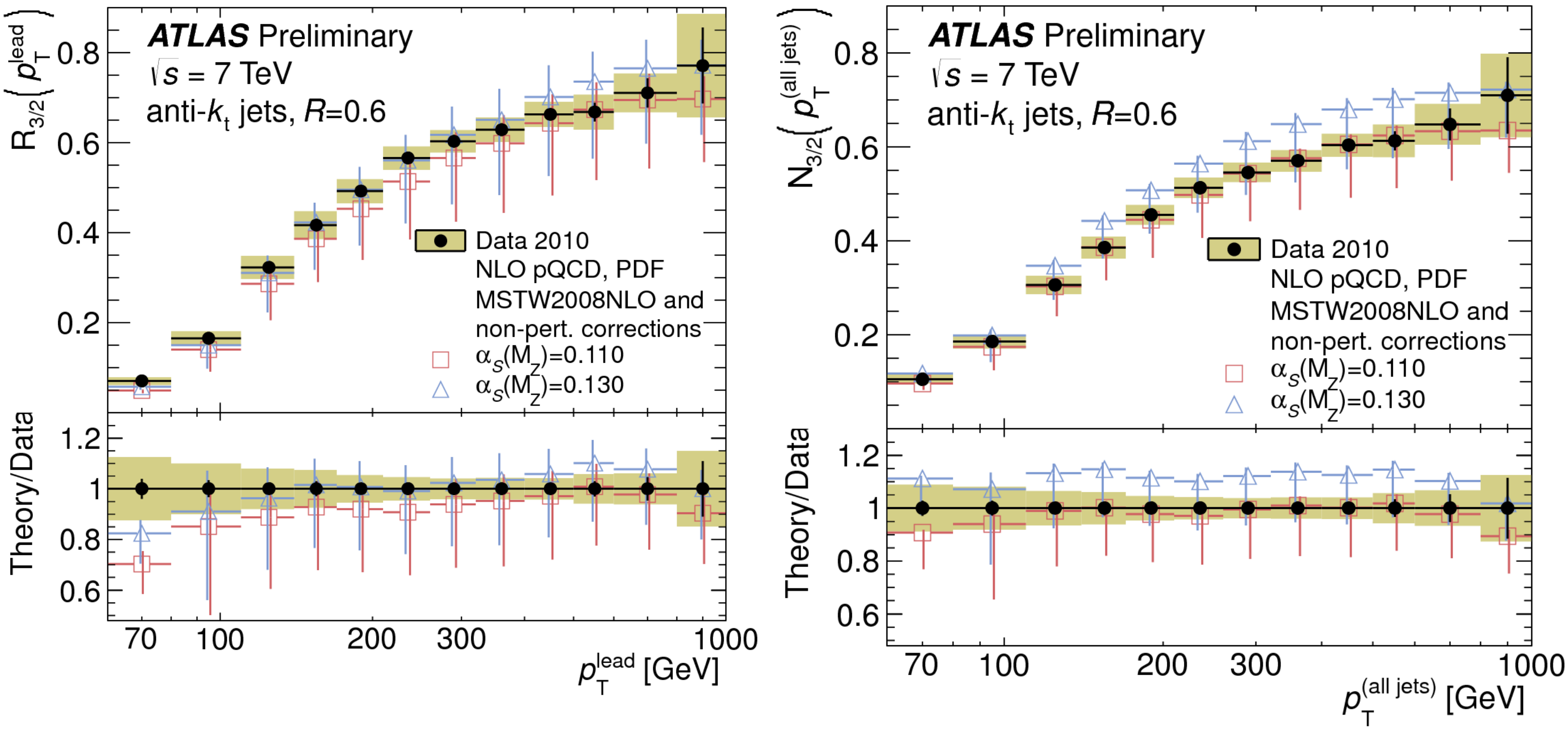
Jets at ATLAS in 2010

- Jets reconstructed with the anti-k_t algorithm with distance parameter R=0.6
  - Use jets in the region $|y|<2.8$ with $p_T>40$GeV
  - Leading jet must have $p_T>60$ GeV
- Use the highest p_T fully-efficient single-jet trigger to populate each p_T bin of the ratio measurement
- Experimental effects on data (detector inefficiency, resolution, etc) corrected for using bin-by-bin multiplicative factor
  - ALPGEN+HERWIG/JIMMY, correction up to ~7%

Theoretical Predictions

- NLO pQCD predictions from NLOJet++ using MSTW2008 NLO PDFs ($0.110<\alpha_s(M_Z)<0.130$)
- Distributions generated separately for events with ≥ 3 jets and ≥ 2 jets, then divided to get ratio prediction
- Renormalisation and factorisation scales for each observable is chosen to be the respective event variable (p_T^{lead}, $p_T^{all\ jets}$)
- Parton-level prediction from NLOJet++ corrected for non-perturbative effects (hadronisation, underlying event)
  - Pythia AMBT1 tune, correction <1% at high p_T and up to ~10% at p_T= 60 GeV

Ratio Measurements, ATLAS 2010



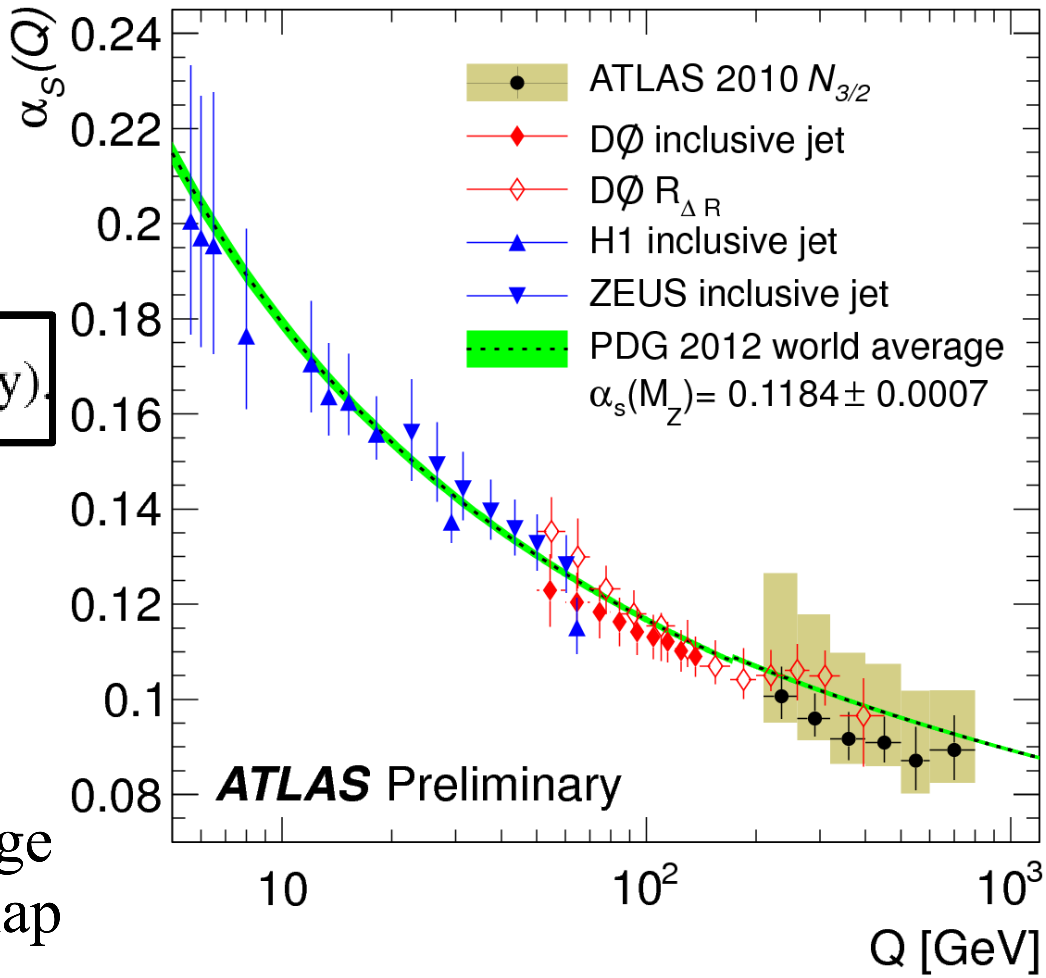
- Two ratio measurements sensitive to different event kinematics
- Total experimental uncertainty in yellow, dominated by jet energy scale
- Theoretical errors dominated by scale uncertainty and also include PDF uncertainty and non-perturbative correction uncertainty

Determination of α_s, ATLAS 2010

- Least-squares fit comparison to NLOJet++ predictions with different values of $\alpha_s(M_Z)$ in range 210 GeV < p_T < 800 GeV
- χ^2 function modified to take into account correlated systematic uncertainties using nuisance parameters and total statistical covariance matrix

$$\alpha_s(M_Z) = 0.111 \pm 0.006(\text{exp.}) \, {}^{+0.016}_{-0.003}(\text{theory})$$

- Test running behaviour by using RGE to evolve value of α_s from a scale of M_Z to the scale Q of different regions
- Good agreement with world average value as well as DØ result in overlap range



Multijet Ratio in 2011 CMS data

CMS-QCD-11-003, submitted to EPJC

- Ratio studied by CMS in 2011 data (5.0 fb^{-1}) is given by

$$R_{32} = \frac{d\sigma_{N_{\mathrm{jet}}\geq 3}}{d\langle p_{\mathrm{T}1,2}\rangle} \Big/ \frac{d\sigma_{N_{\mathrm{jet}}\geq 2}}{d\langle p_{\mathrm{T}1,2}\rangle}$$

- where $\langle p_{T1,2} \rangle$ is the average of the transverse momentum of the two leading jets: $(p_{T1}+p_{T2})/2$
- Trigger strategy uses 3 single jet triggers in the $\langle p_{T1,2} \rangle$ range where each is fully efficient

Jets at CMS in 2011

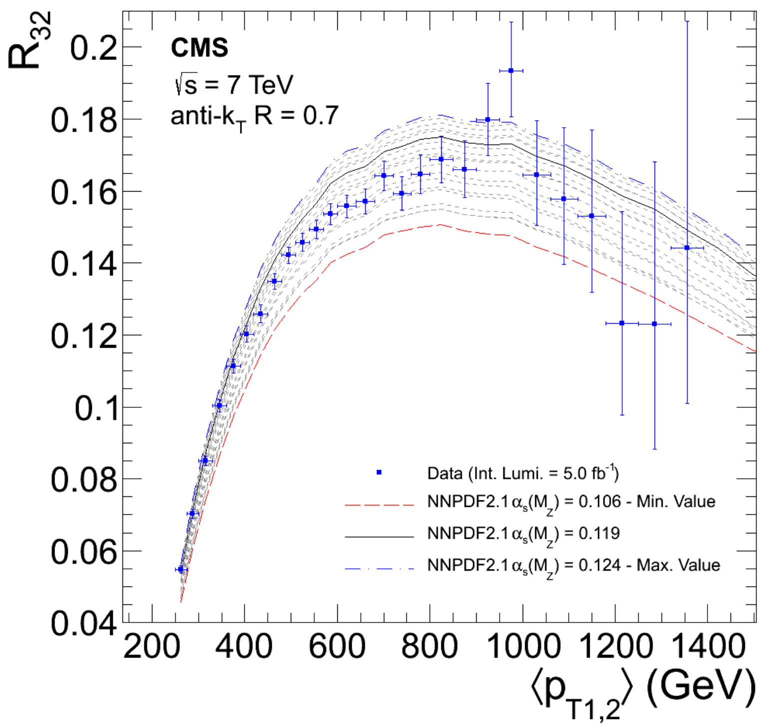
- Jets reconstructed with the anti-k_t algorithm with distance parameter R=0.7
  - Use jets in the region |y|<2.5 with p_T>150GeV
  - Select events with at least 2 such jets and reject events with either or both leading jets beyond |y|=2.5
- Experimental effects on data (detector inefficiency, resolution, etc) using the iterative Bayesian method as implemented in ROOUNFOLD
  - Pythia 6 tune Z2 used to create response matrix

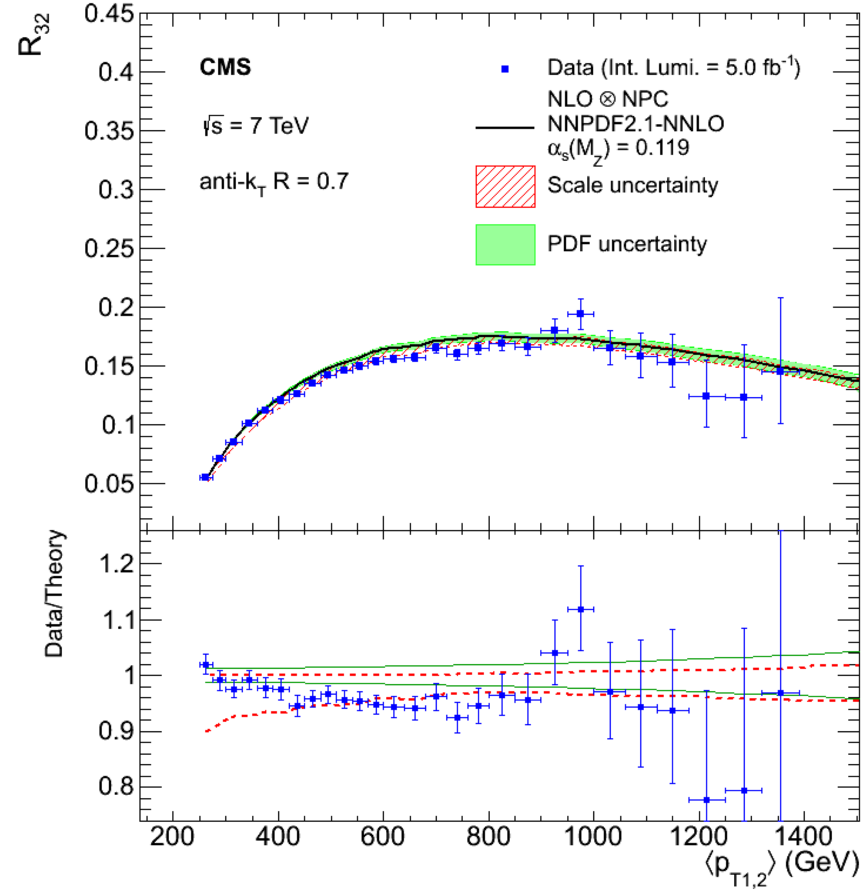
Theoretical Predictions

- NLO pQCD predictions from NLOJet++/FASTNLO using 4 PDFs sets: NNPDF 2.1, ABM11, MSTW2008 and CT10, each with NNLO evolution code
- Renormalisation and factorisation scales chosen to be equal to $\langle p_{T1,2} \rangle$
- Parton-level prediction from NLOJet++ corrected for non-perturbative effects (hadronisation, underlying event, etc)
- Pythia 6 tune Z2 and Herwig++ tune 2.3, correction factor 1.02 at $\langle p_{T1,2} \rangle$=250 GeV decreasing to 1.0 for higher $\langle p_{T1,2} \rangle$

Ratio Measurement, CMS 2011

- Ratio is measured and compared to a range of values for the strong coupling constant





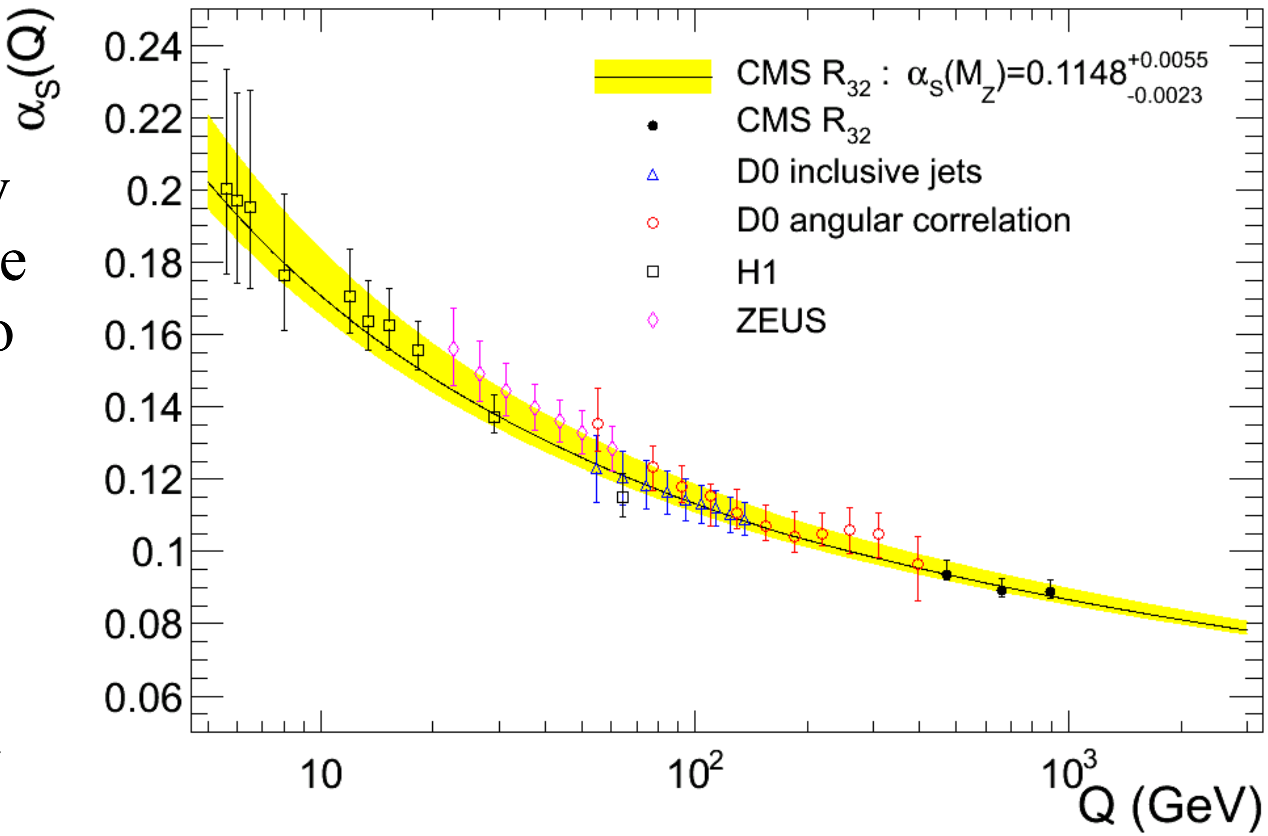
- NNPDF 2.1 used as reference PDF set
- Jet energy scale and unfolding the main sources of experimental systematic uncertainties

Determination of α_s, CMS 2011

- Least-squares fit comparison to NLOJet++ predictions with different values of $\alpha_s(M_Z)$ in range 420 GeV < $\langle p_{T1,2} \rangle$ < 1390 GeV

$$\alpha_S(M_Z) = 0.1148 \pm 0.0014\,(\text{exp.}) \pm 0.0018\,(\text{PDF})^{+0.0050}_{-0.0000}\,(\text{scale})$$

- Result dominated by theoretical uncertainties
- Test running behaviour by using RGE to evolve value of α_s from a scale of M_Z to the scale Q of different regions
- Energy-dependence measurement extended to the TeV range for the first time



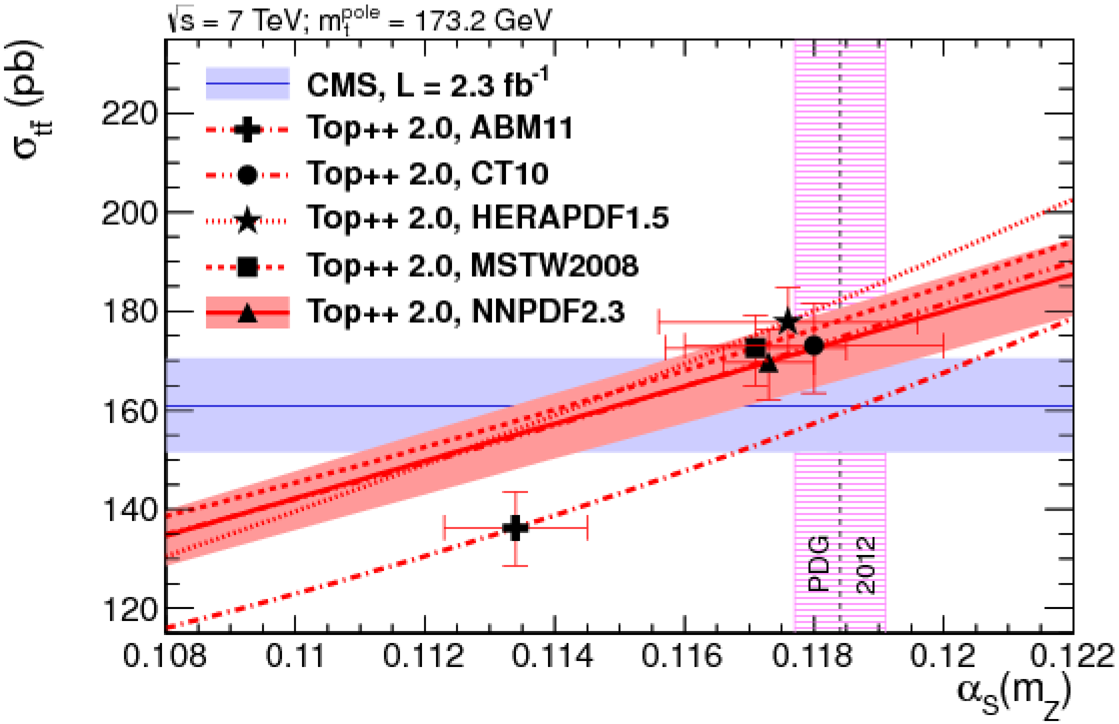
Top pair production, CMS 2011

CMS-TOP-12-022, submitted to PLB

- NNLO calculations now available for top pair production cross-section
  - m_t, α_s and gluon PDF the main inputs for calculation
- Dependence of the cross-section result on these inputs allows determination of one of them when fixing the other two.
- *The top quark pole ("on-shell") mass* m_t^{pole}*, which could be up to 1 GeV higher than the top mass used in current Monte Carlo event generators is used throughout this analysis*

Predicted top pair cross-section, sensitivity to α_s

- NNLO prediction calculated with Top++2.0 for all production channels with the renormalisation and factorisation scales set to m_t^{pole} and using NNPDF2.3
- Well-described by 2nd-order polynomial



Measured cross-section

- Use most precise individual cross-section result (dilepton), JHEP **11** (2012) 067: 161.9 ± 6.7 pb
  - assuming m_t=172.5 GeV and $\alpha_s(M_Z)$=0.1180
- Parametrize the dependence of the event kinematics and thus acceptance corrections as in reference.
- Additional 1% uncertainty due to dependence of the acceptance correction on the value of $\alpha_s(M_Z)$ used in the simulation from which the correction is derived

Derivation of $\alpha_s(M_Z)$

- Combine the theoretical probability distribution f_{th} with the experimental result+uncertainty f_{exp} to form a Bayesian posterior probability distribution:

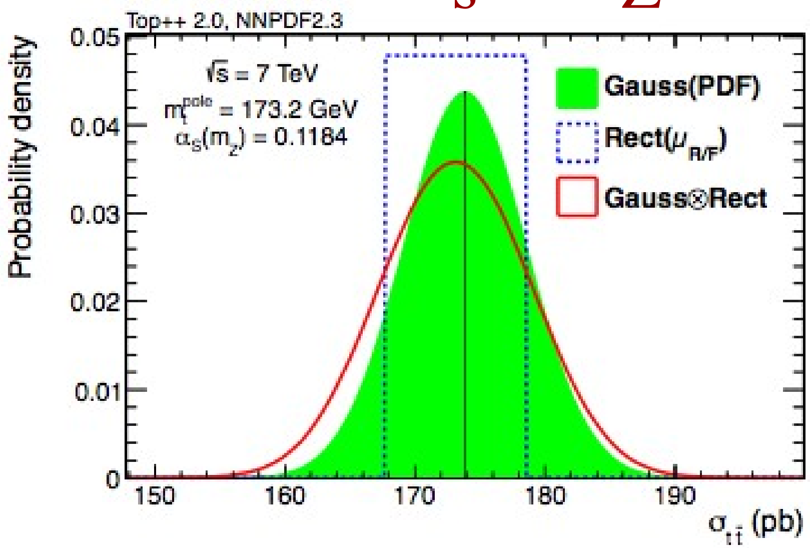
$$P(\alpha_s) = \int f_{exp}(\sigma_{t\bar{t}}|\alpha_s)\, f_{th}(\sigma_{t\bar{t}}|\alpha_s)\, d\sigma_{t\bar{t}}$$

taking m_t^{pole}=173.2±1.4 GeV

- Probability function for the predicted cross-section is used as a Bayesian prior:

$$f_{th}(\sigma_{t\bar{t}}) = \frac{1}{2\left(\sigma_{t\bar{t}}^{(h)} - \sigma_{t\bar{t}}^{(l)}\right)} \left(\text{erf}\left[\frac{\sigma_{t\bar{t}}^{(h)} - \sigma_{t\bar{t}}}{\sqrt{2}\,\delta_{PDF}}\right] - \text{erf}\left[\frac{\sigma_{t\bar{t}}^{(l)} - \sigma_{t\bar{t}}}{\sqrt{2}\,\delta_{PDF}}\right]\right)$$

Derivation of $\alpha_s(M_Z)$



- Probability function for the predicted cross-section is used as a Bayesian prior:

$$f_{\mathrm{th}}(\sigma_{t\bar{t}}) = \frac{1}{2\left(\sigma_{t\bar{t}}^{(h)} - \sigma_{t\bar{t}}^{(l)}\right)} \left(\mathrm{erf}\left[\frac{\sigma_{t\bar{t}}^{(h)} - \sigma_{t\bar{t}}}{\sqrt{2}\,\delta_{\mathrm{PDF}}}\right] - \mathrm{erf}\left[\frac{\sigma_{t\bar{t}}^{(l)} - \sigma_{t\bar{t}}}{\sqrt{2}\,\delta_{\mathrm{PDF}}}\right] \right)$$

Highest and lowest prediction within scale uncertainty

The error function

Width of the Gaussian used to describe the PDF uncertainty

Derivation of $\alpha_s(M_Z)$

- Combine theoretical probability distribution f_{th} with the experimental result+uncertainty f_{exp} to form a Bayesian posterior probability distribution:

$$P(\alpha_s) = \int f_{\text{exp}}(\sigma_{t\bar{t}}|\alpha_s)\, f_{\text{th}}(\sigma_{t\bar{t}}|\alpha_s)\, \mathrm{d}\sigma_{t\bar{t}}$$

taking m_t^{pole}=173.2±1.4 GeV

- Probability function for the predicted cross-section is used as a Bayesian prior:

$$f_{\text{th}}(\sigma_{t\bar{t}}) = \frac{1}{2\left(\sigma_{t\bar{t}}^{(h)} - \sigma_{t\bar{t}}^{(l)}\right)} \left(\text{erf}\left[\frac{\sigma_{t\bar{t}}^{(h)} - \sigma_{t\bar{t}}}{\sqrt{2}\,\delta_{\text{PDF}}}\right] - \text{erf}\left[\frac{\sigma_{t\bar{t}}^{(l)} - \sigma_{t\bar{t}}}{\sqrt{2}\,\delta_{\text{PDF}}}\right]\right)$$

- Result: $\alpha_S(m_Z) = 0.1151^{+0.0033}_{-0.0032}$

Uncertainty is the sum in quadrature of the 68% CL of the posterior probability, the effect of varying m_t^{pole} within its uncertainty and the uncertainty on the LHC beam energies

3-jet mass cross-section, CMS 2011

CMS-PAS-SMP-12-027

- Double differential 3-jet mass cross-section is measured as a function of the mass m_3 and the maximum rapidity y_{max}

$$m_3^2 = (p_1 + p_2 + p_3)^2$$

$$y_{\mathrm{max}} = \mathrm{sign}(|\max(y_1, y_2, y_3)| - |\min(y_1, y_2, y_3)|) \cdot \max(|y_1|, |y_2|, |y_3|)$$

- The cross-section is defined to be

$$\frac{d^2\sigma}{dm_3 dy_{\mathrm{max}}} = \frac{1}{\epsilon \mathcal{L}_{\mathrm{eff}}} \frac{N}{\Delta m_3 (2 \cdot \Delta |y|_{\mathrm{max}})}$$

- Use only jets with $p_T > 100$ GeV within $|y| < 3$

Prediction and Measurement

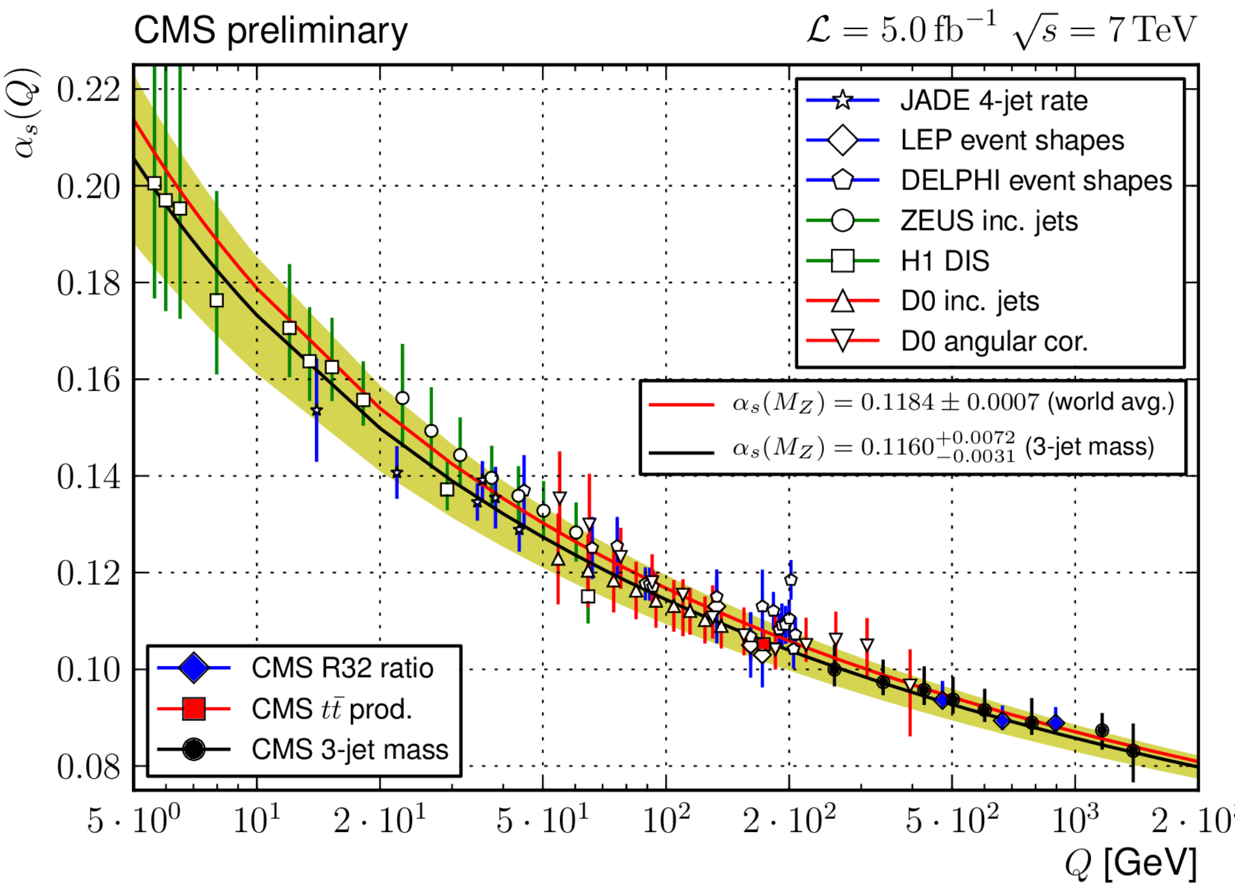
- NLO pQCD prediction from NLOJet++/FASTNLO using MSTW2008, factorisation and renormalisation scales set to $m_3/2$
  - Non-perturbative corrections go from 8% to 1% with increasing m_3 from SHERPA and MADGRAPH+PYTHIA8
- Data measurement for α_s determination limited to region $|y|_{max}<1$
  - Unfolded to particle level with the D'Agostini unfolding algorithm with 4 iterations using Pythia 6 tune Z2 and Herwig++ simulated events
- Jet energy scale uncertainty is dominant, up to 20% at high m_3

3-jet mass result, CMS 2011

- Determination of α_s in the region $445 < m_3 < 3092$ GeV from least-squares fit:

$$\alpha_S(M_Z) = 0.1160 \pm^{0.0025}_{0.0023} \,(\text{exp, PDF, NP}) \pm^{0.0068}_{0.0021} \,(\text{scale})$$

- Observation of running behaviour in 8 bins of m_3



Summary

- Measurement of the value of the strong coupling constant via multiple experimental observables and across a wide range of energy scales reinforce the position of QCD as a theory of the strong nuclear force
- All LHC-era results are consistent with the current world average from the Particle Data Group, $\alpha_s(M_Z)=0.1184\pm0.0007$

	$\alpha_s(M_Z)$		
ATLAS $N_{3/2}$, 2010	0.111	+0.017	-0.007
CMS R_{32}, 2011	0.1148	+0.0055	-0.0023
CMS top quark, 2011	0.1151	+0.0033	-0.0032
CMS 3-jet mass, 2011	0.1160	+0.0072	-0.0031