

# Determination of $\alpha_s(M_Z)$

## in a fit to inclusive jet data from multiple experiments

*QCD@LHC 2016*

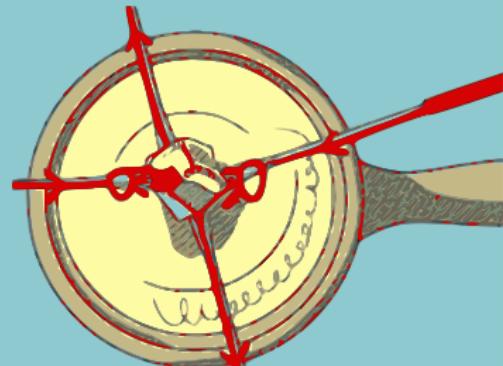
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(with contributions from G. Flouris and P. Kokkas)

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2016  
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# Introduction

- $\alpha_s(M_Z)$  among least well known fundamental physical parameters  
→ increased knowledge of  $\alpha_s(M_Z)$  needed for precision QCD
- inclusive jets in hadron-induced collisions  
← well defined observable for any process:

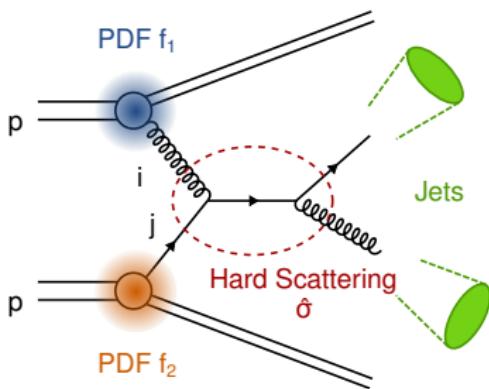
$$\sigma_{pp} = \sum_n \alpha_s^n(\mu_R^2) \sum_{i,j} \int dx_1 dx_2 f_i(x_1, \mu_F^2) f_j(x_2, \mu_F^2) \times \hat{\sigma}_{ij}(x_1 x_2 s, \mu_R^2, \mu_F^2)$$
[4]

## Main “ingredients” of calculation

- hard matrix element → depends on  $\alpha_s(M_Z)$
- convolution with PDFs → additional  $\alpha_s(M_Z)$  dependence?

?

$$\frac{\partial \sigma}{\partial [\alpha_s(M_Z)]} \leftrightarrow \frac{\partial f}{\partial [\alpha_s(M_Z)]}$$



# Experiments

- abundance of experimental data from:  
→ ATLAS, CMS, DØ, CDF, H1, ZEUS, ALICE, STAR, ...
- recent inclusive jet data used for  $\alpha_s$  extraction by CMS [3], DØ [1] and H1 [2] collaborations
  - + collaborations provide template for using their data
  - **large** differences in  $\alpha_s$  fit methodology  
→ methods, data compatible with each other?

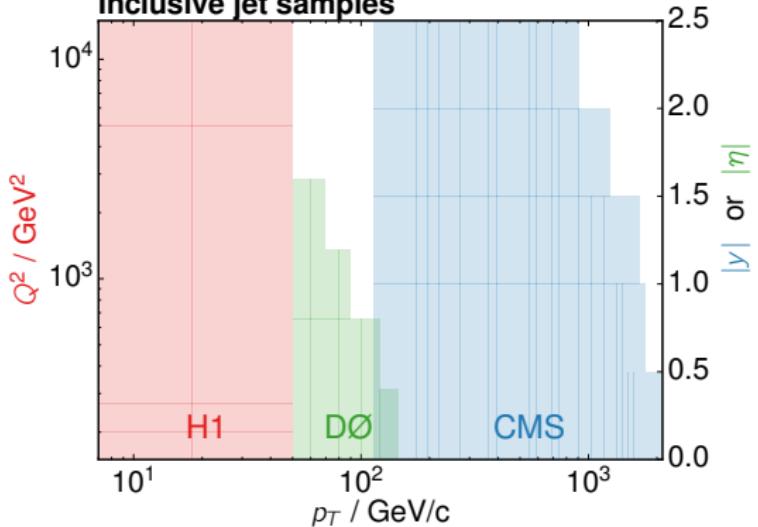
## Focus of this work

- **reproduce** fit results in CMS, DØ and H1 fit methodologies
- redo fits with a **unified** fit method
- extract  $\alpha_s(M_Z)$  from inclusive jet data from **multiple experiments**

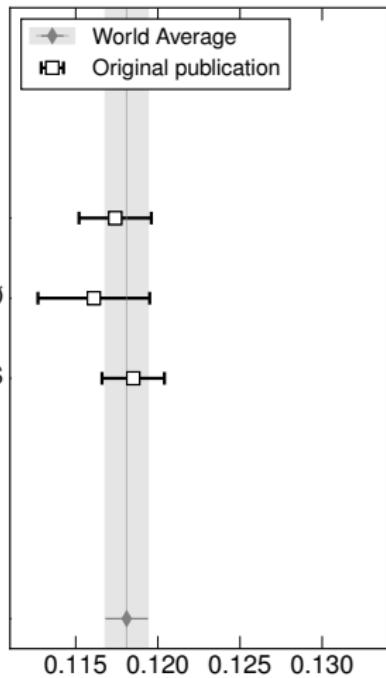
# $\alpha_s(M_Z)$ extraction from inclusive jet data

- data from H1, DØ and CMS cover large and complementary phase space

## Inclusive jet samples



- ✓ extracted  $\alpha_s(M_Z)$  values compatible with each other and with world average [4]
- ⚠ however, large differences in fit procedure



experimental uncertainty

 $\alpha_s(M_Z)$

# Comparison of $\alpha_s(M_Z)$ extraction methods

## H1 fit methodology

- iterative  $\chi^2$  minimization (*MINUIT*)

$$\chi_{\text{H1}}^2 \rightarrow \sum_{ij} (\ln m_i - \ln t_i) [\mathbf{V}_{(\text{rel})}^{-1}]_{ij} (\ln m_j - \ln t_j)$$

- determine central value with **experimental uncertainties** only
- assume PDF without  $\alpha_s(M_Z)$  dependence; use MSTW2008nlo with  $\alpha_s(M_Z) = 0.118$
- additional theory uncertainties: **NP corr.**, **PDF**, **PDF  $\alpha_s(M_Z)$** , **PDF set**,  $\mu_r$ ,  $\mu_f$ 
  - obtained through additional fits / linear error propagation

## D $\emptyset$ fit methodology

- iterative  $\chi^2$  minimization (*MINUIT*)

$$\chi_{\text{D}\emptyset}^2 \rightarrow \sum_i \left[ \frac{m_i - t_i}{\sqrt{\frac{1 + \sum_k \delta_{ik}^{(\text{NP})} (\alpha_k^{(\text{NP})}) + \sum_l \delta_{il}^{(\text{PDF})} (\alpha_l^{(\text{PDF})})}{1 + \sum_j \delta_{ij} (\epsilon_j)}}} \right]^2$$

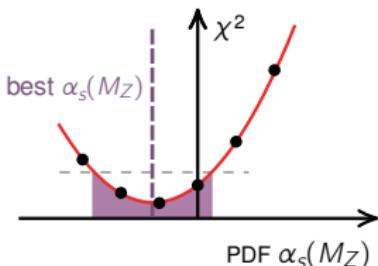
- one nuisance parameter for **each PDF eigenvector** and **each NP correction factor**
- interpolate cross section predictions obtained for PDFs assuming different values of  $\alpha_s(M_Z)$
- aNNLO (NLO predictions with threshold corrections + NNLO PDFs)
- 88 out of 110 data points excluded  $\leftarrow$  correlations with MSTW2008 PDFs

# Comparison of $\alpha_s(M_Z)$ extraction methods

CMS fit methodology

$$\chi^2_{\text{CMS}} \rightarrow \sum_{ij} (m_i - t_i) \left[ (\mathbf{V}_{\text{exp}} + \mathbf{V}_{\text{PDF}})^{-1} \right]_{ij} (m_j - t_j)$$

- $\chi^2$  is evaluated for each PDF in an  $\alpha_s(M_Z)$  series
  - resulting  $(\chi^2, \alpha_s(M_Z))$  points are assumed to lie on a parabola
  - fit of second-degree polynomial function → central value and uncertainty on  $\alpha_s(M_Z)$
- PDF: CT10nlo (results are also provided for MSTW2008 and NNPDF21)
- NP uncertainties obtained by performing additional fits with correlated variation of theory



Fit methods **differ significantly!**

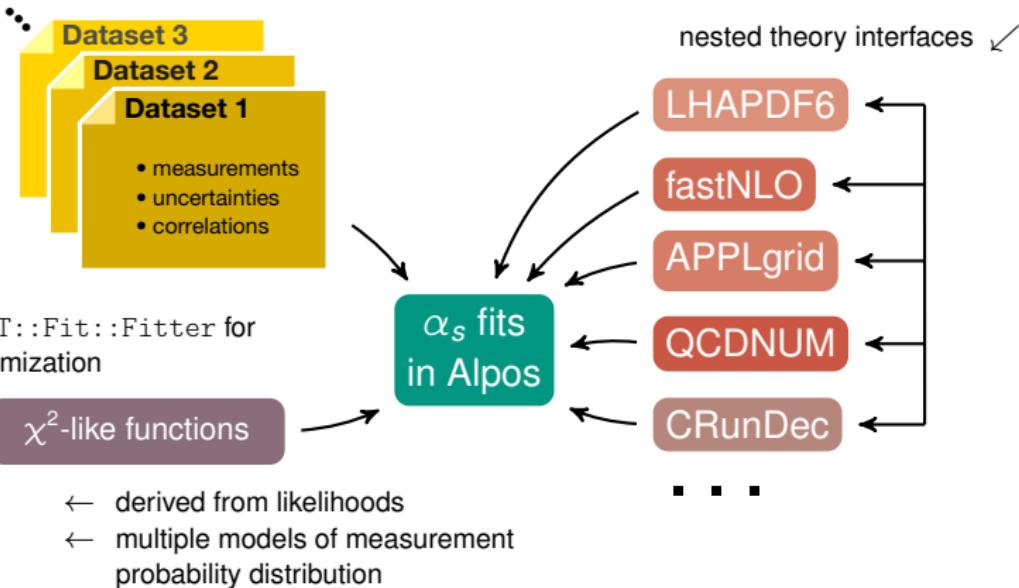
- “naive” combination of results (weighted average) not very conclusive
- need to extract  $\alpha_s(M_Z)$  using measurements from all experiments in a **unified** fit procedure

# Alpos setup for $\alpha_s$ fits

## ■ Alpos → new modular C++ based fitting framework

- used within H1 and CMS for PDF, electroweak and  $\alpha_s(M_Z)$  fits

→ input format: experience with xFitter/HERAFitter



[<https://ekptrac.physik.uni-karlsruhe.de/svn/Alpos>]

# Reproduction of published values in Alpos

## H1

- method as outlined in publication
- exact reproduction of published results

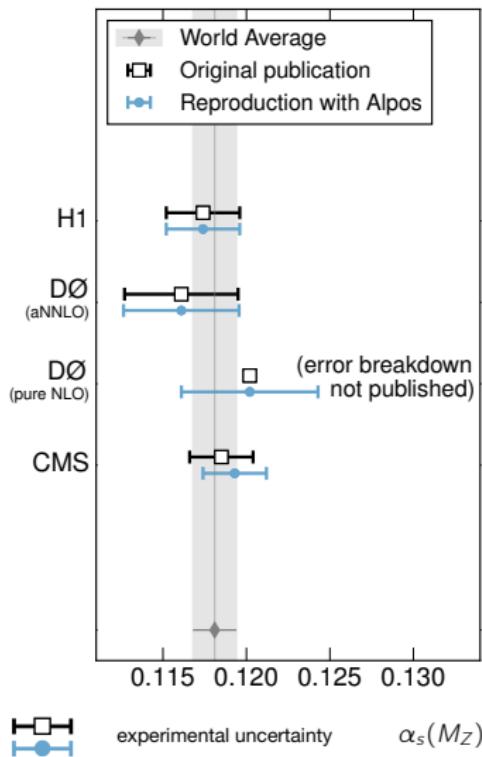
## DØ

- two results: aNNLO and pure NLO
- exp. uncertainties only provided by DØ for aNNLO

## CMS

- original publication → PDF uncertainties **constant** in  $V_{\text{PDF}}$
- Alpos** → PDF uncertainties are **rescaled** with theory predictions  
→ original CMS code used for checks

Published  $\alpha_s(M_Z)$  results are reproduced within our framework



# Unified fitting procedure

Define fitting procedure for refitting all datasets:

- use iterative  $\chi^2$  minimization method
  - assume log-normal distribution of measurements → relative uncertainties
  - central result with experimental, PDF and non-perturbative uncertainties

$$\chi_{\text{unified}}^2 = \sum_{ij} (\ln m_i - \ln t_i) \left[ \left( V_{\text{exp}}^{(\text{rel})} + V_{\text{PDF}}^{(\text{rel})} + V_{\text{NP}}^{(\text{rel})} \right)^{-1} \right]_{ij} (\ln m_j - \ln t_j)$$

- $\chi^2$  is expressed in terms of nuisance parameters for PDF uncertainties
  - ← study compatibility of PDFs with data
  - ⚠️ nuisance parameter representation not possible for NNPDF
- keep restricted dataset for DØ (22/110 points)
- scale choice: **pp**, **p̄p**:  $\mu_R = \mu_F = p_T$       **ep**:  $\mu_R^2 = (Q^2 + p_T^2)/2$ ;  $\mu_F^2 = Q^2$
- PDF sets studied: MSTW2008, MMHT2014, CT10, CT14
  - ABM11 and HERAPDF20 also studied
  - both sets exhibit issues describing data, in particular for CMS

# PDF $\alpha_s(M_Z)$ dependence

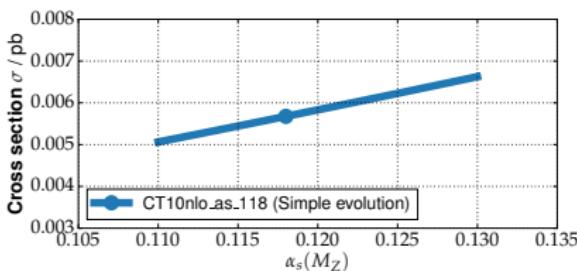
How to express the  $\alpha_s(M_Z)$  dependence of the cross section?

- ② how to account for  $\alpha_s(M_Z)$  dependence in PDFs?

Two methods are studied:

## “Fixed PDF” ( $\circ$ )

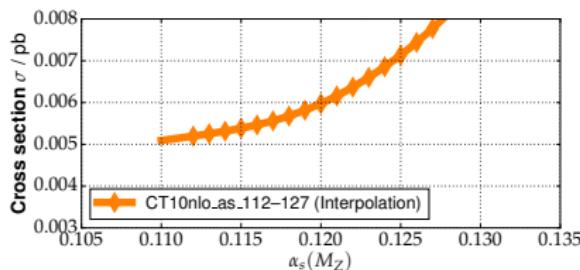
(method used in H1 publication)



- calculate cross section using PDF for **one** chosen  $\alpha_s(M_Z)$
- prediction  $\sigma(\alpha_s(M_Z))$  directly from fastNLO

## “PDF Interpolation” ( $\diamond$ )

(method used in DØ publication)



- calculate cross section using PDF for **each** available  $\alpha_s(M_Z)$
- prediction  $\sigma(\alpha_s(M_Z))$  from **interpolation** between the points

# Method comparison

## “Fixed PDF”

- ⊕  $\alpha_s(M_Z)$  dependence is **quadratic**, as expected for inclusive jet cross sections
- ⊕ well-defined theory
- ⊕ clear breakdown of PDF uncertainties
- ⊖ introduces an additional procedural uncertainty due to  $\alpha_s(M_Z)$  used in PDF fit
- ⊖ possible bias towards assumed PDF  $\alpha_s(M_Z)$

## “PDF Interpolation”

- ⊕ provides a way to include the uncertainty due to the choice of PDF  $\alpha_s(M_Z)$  **in the fit**
- ⊕ interpolation method needs to be defined (e.g. fit or splines)
  - ⚠ spline interpolation not well suited for some PDFs (e.g. NNPDF)
- ⊖ spline extrapolation may give unphysical results
- ⌚ does procedure reproduce PDF  $\alpha_s$  dependence?

In most cases, both methods yield comparable results

# Method comparison

## “Fixed PDF”

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choose this as main method

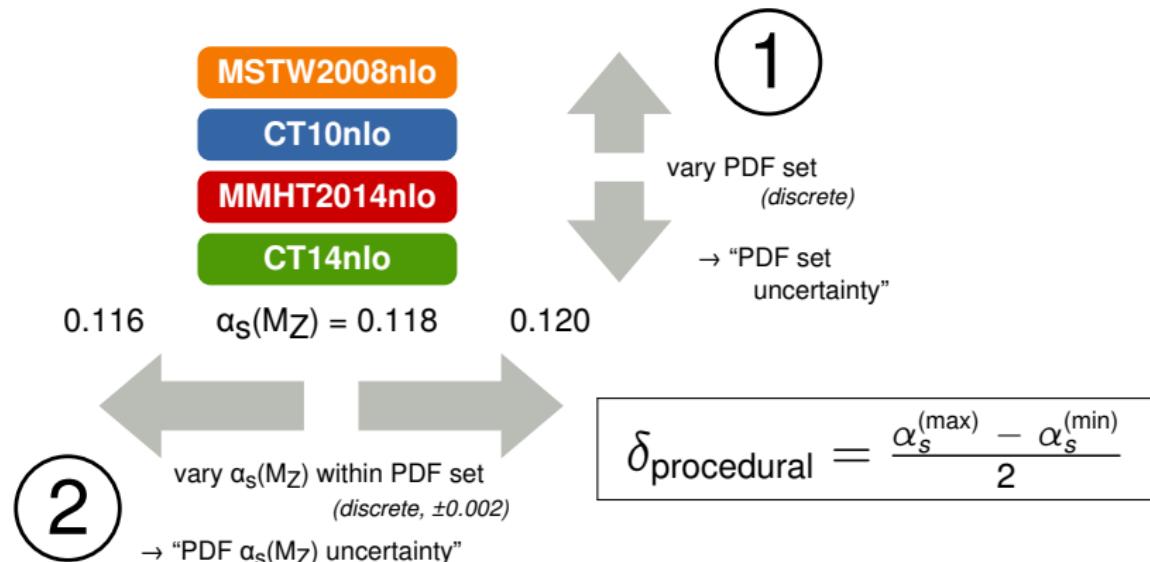
## “PDF Interpolation”

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- ⁇ does procedure reproduce PDF  $\alpha_s$  dependence?

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# Procedural PDF uncertainties

- additional PDF-related procedural uncertainties arise in addition to “PDF uncertainties” themselves:
  - choice of PDF set
  - choice of  $\alpha_s(M_Z)$  assumed when fitting PDF



# Refits with unified procedure

## Refit results

- all refits have reasonable  $\chi^2/\text{ndf}$  and compatible with each other
- $\chi^2/\text{ndf}$  values at minimum:

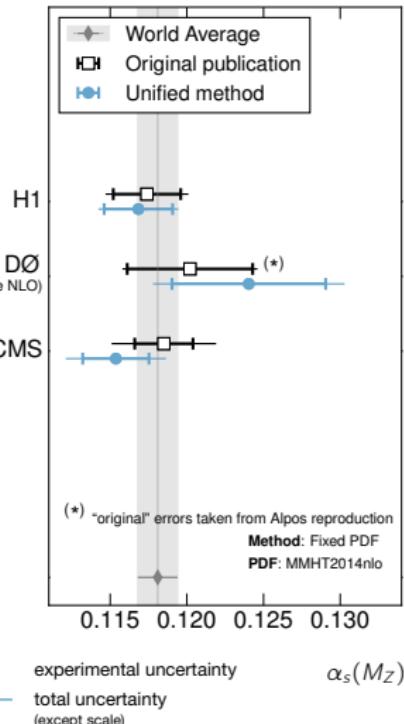
$$\begin{aligned} \text{H1 } \chi^2/\text{ndf} &= 23.1/23 = 1.004 \\ \text{D}\emptyset \quad \chi^2/\text{ndf} &= 17.2/21 = 0.819 \\ \text{CMS } \chi^2/\text{ndf} &= 110/132 = 0.832 \end{aligned}$$

## Comparison to published values

- good agreement

H1 method similar, but  $V_{\text{PDF}}$  and  $V_{\text{NP}}$  in  $\chi^2$   
CMS, D $\emptyset$  change of fitting method → changes of fit values and uncertainties

Final results remain comparable with each other and with original publication  
→ Can proceed with combination



# Combined fit

## Input to combined fit

- choose H1, DØ (pure NLO) and CMS
  - no correlations assumed for exp. uncertainties across experiments
- PDF choice: MMHT2014nlo (others very similar)

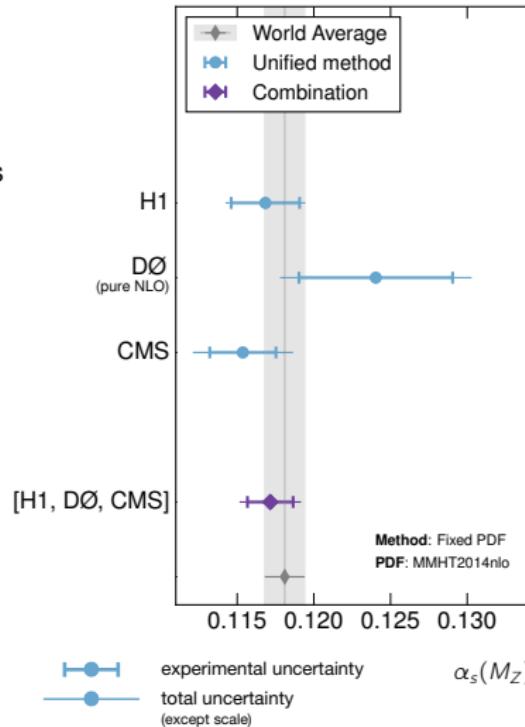
## Result

$$\begin{aligned}\alpha_s(M_Z) &= 0.1172(15)_{\text{exp}}(5)_{\text{NP}}(9)_{\text{PDF, MMHT}} \\ &\quad (8)_{\text{PDF set}}(5)_{\text{PDF }}\alpha_s(50)_{\text{scale}} \\ &= 0.1172(15)_{\text{exp}}(14)_{\text{theo (except scale)}}(50)_{\text{scale}}\end{aligned}$$

$$\chi^2_{\min}/\text{ndf} = 152.2/178 = 0.855$$

## Conclusions

- combined fit shows reasonable  $\chi^2/\text{ndf}$
- combined result compatible with individual fits
- uncertainties reduced



# Beyond the first combination

## Additional studies with available data

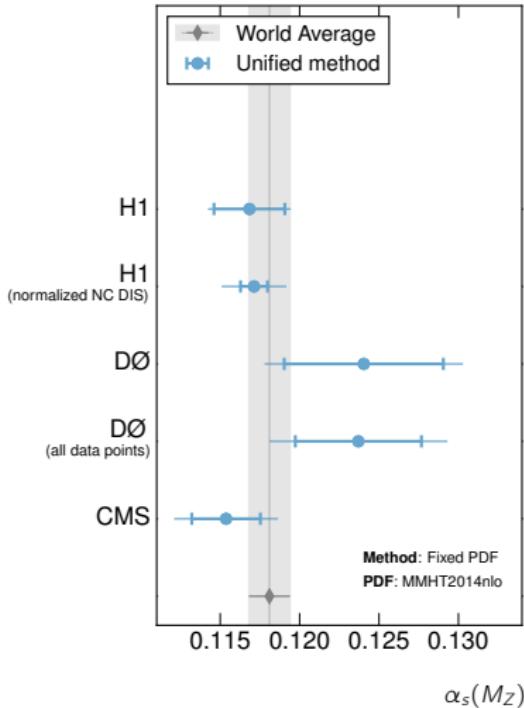
- H1 inclusive jets, normalized to NC DIS
  - reduced overall uncertainty
- DØ unrestricted dataset
  - ? necessary to remove 88 data points?

## Data from other experiments

- data available (ATLAS, CDF, ZEUS, ...)
- no template provided how to use data in fit
- experimental correlations important

## Fit of PDFs together with $\alpha_s(M_Z)$

- ⊕ correlation of PDF parameters with  $\alpha_s(M_Z)$
- ⊖ observed issues with HERA DIS + CMS jets



# Conclusions

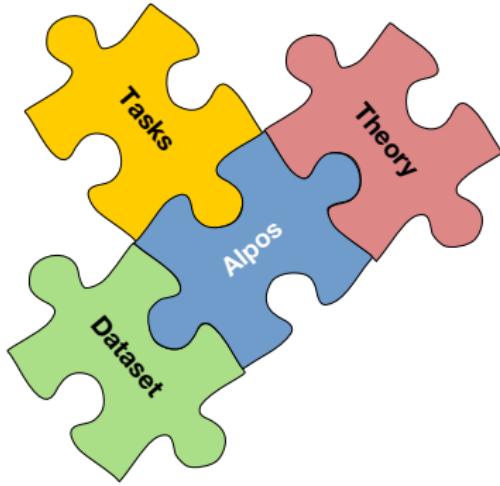
- $\alpha_s(M_Z)$  was determined from a fit to inclusive jet data from the H1, CMS and DØ experiments
- **Alpos**: recently developed, public fitting code
- results consistent among themselves and with the current world average for  $\alpha_s(M_Z)$
- experimental uncertainties are reduced
- scale uncertainties remain the largest single contribution to the total uncertainty

$\alpha_s(M_Z)$  fits ideally suited to deepen understanding of jet data and prepare them for PDF fits

# References I

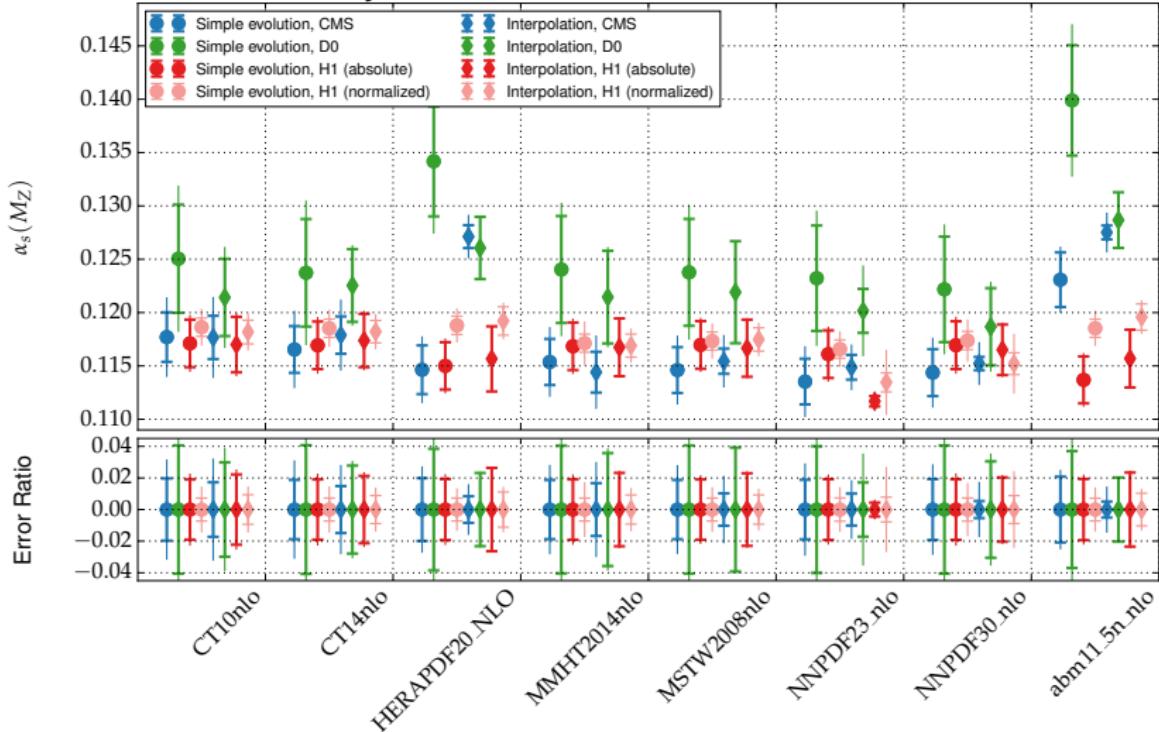
- [1] V.M. Abazov et al. "Determination of the strong coupling constant from the inclusive jet cross section in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV". In: *Phys. Rev. D* 80 (2009), p. 111107. DOI: 10.1103/PhysRevD.80.111107. arXiv: 0911.2710 [hep-ex].
- [2] V. Andreev et al. "Measurement of multijet production in  $ep$  collisions at high  $Q^2$  and determination of the strong coupling  $\alpha_s$ ". In: *Eur. Phys. J. C* 75 (2015), p. 65. DOI: 10.1140/epjc/s10052-014-3223-6. arXiv: 1406.4709 [hep-ex].
- [3] Vardan Khachatryan et al. "Constraints on parton distribution functions and extraction of the strong coupling constant from the inclusive jet cross section in  $pp$  collisions at  $\sqrt{s} = 7$  TeV". In: *Eur. Phys. J. C* 75 (2015), p. 288. DOI: 10.1140/epjc/s10052-015-3499-1. arXiv: 1410.6765 [hep-ex].
- [4] K.A. Olive and others (Particle Data Group). "Review of Particle Physics". In: *Chin. Phys. C* 38 (2014). (2015 update), p. 090001. DOI: 10.1088/1674-1137/38/9/090001.

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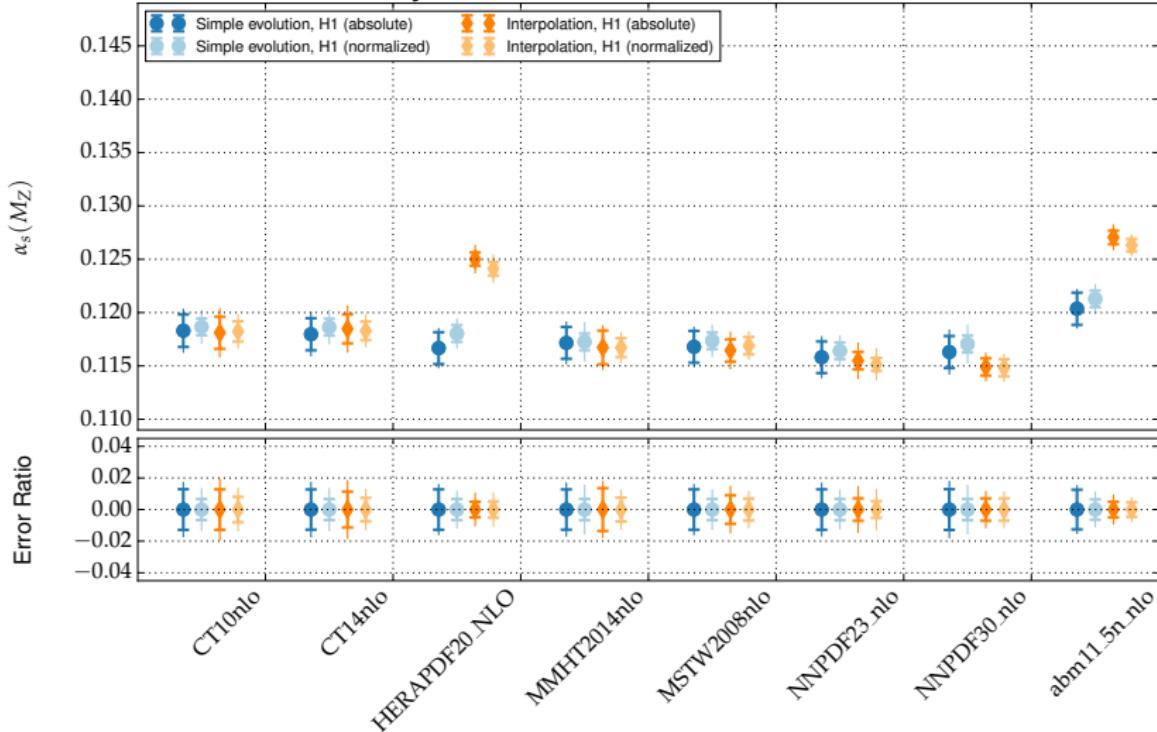
# Backup

## Individual refits by PDF

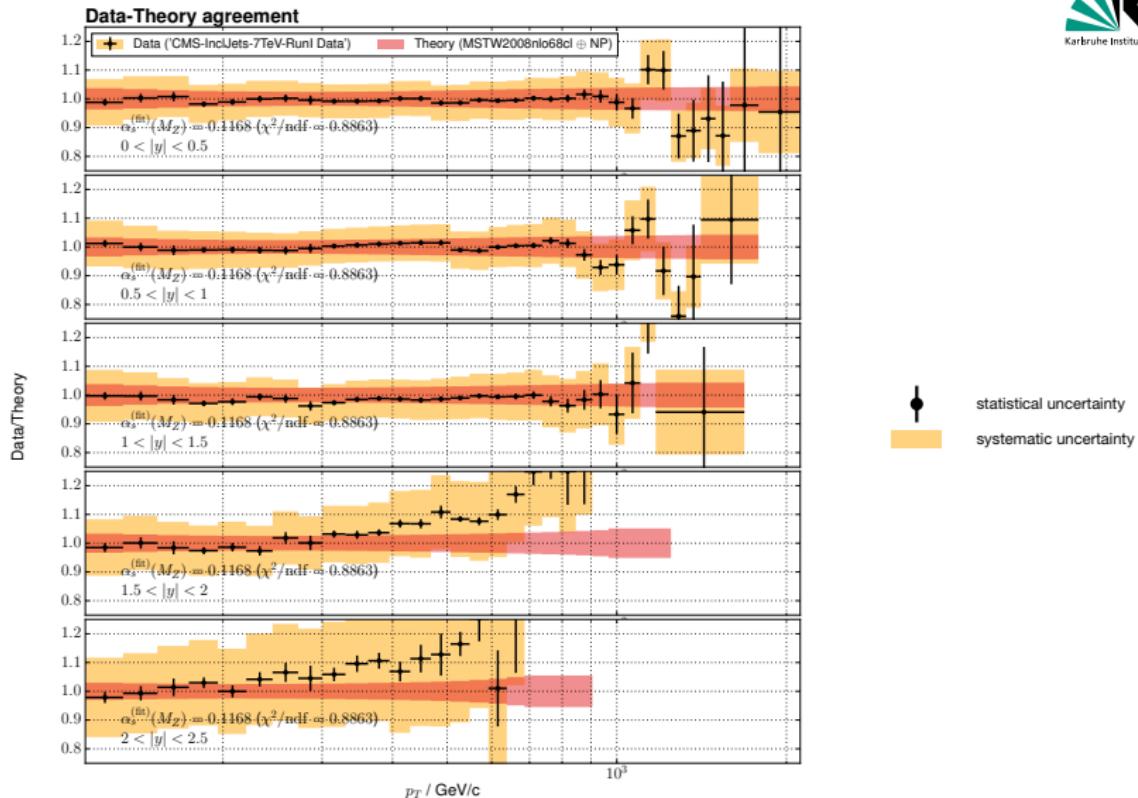


## References

## Combination result by PDF



## References

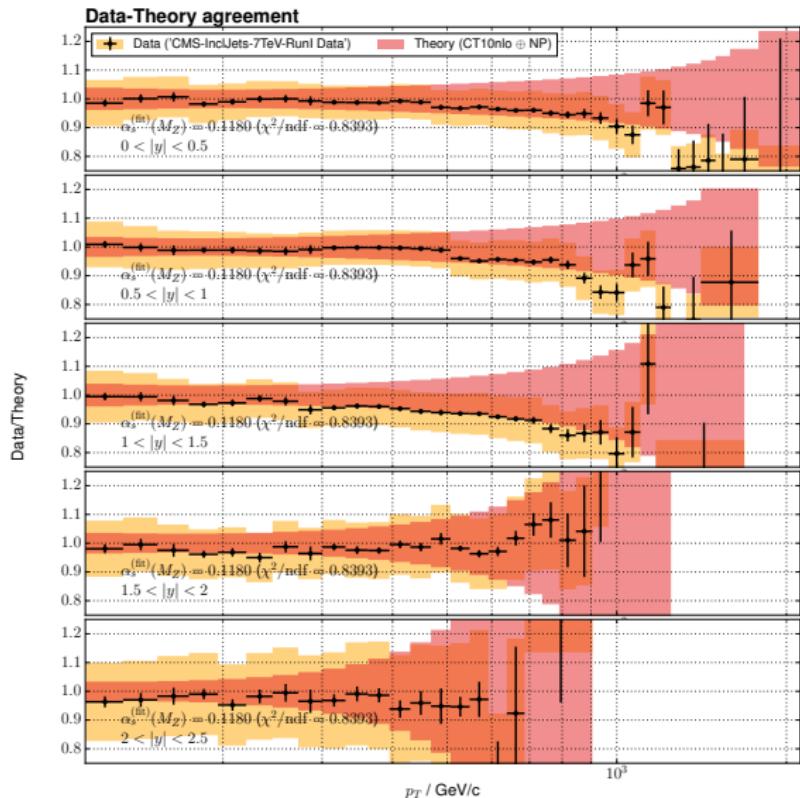


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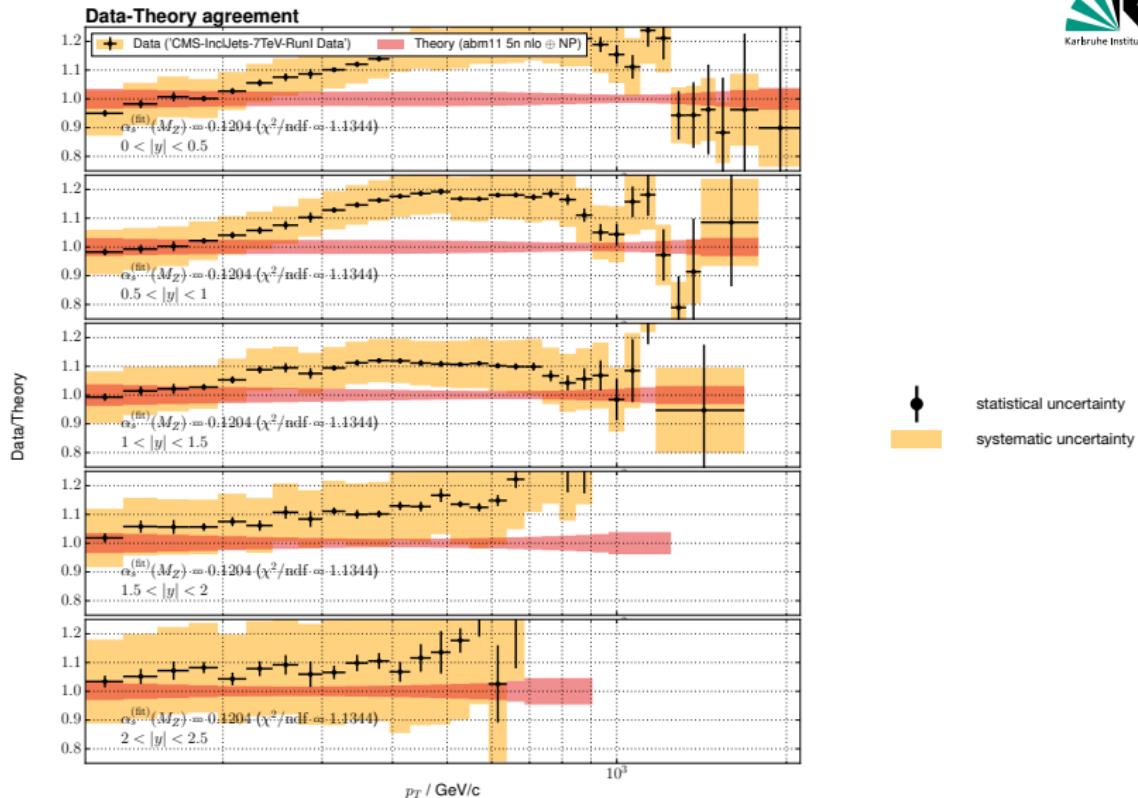


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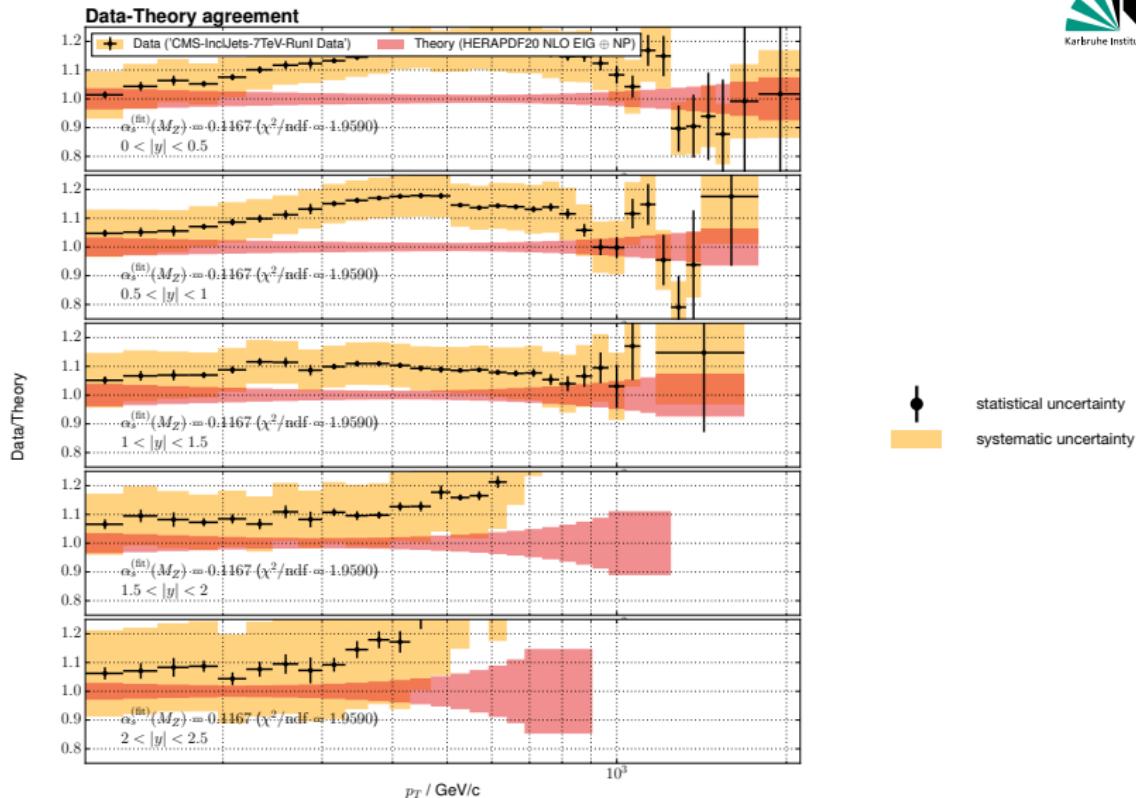


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