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Determination of $\alpha_s(M_Z)$

in a fit to inclusive jet data from multiple experiments

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D. Britzger, K. Rabbertz, **D. Savoiu**, G. Sieber, M. Wobisch

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INSTITUT FÜR EXPERIMENTELLE KERNPHYSIK

Introduction

Why $\alpha_s(M_Z)$?

- $\alpha_s(M_Z)$ among least well known fundamental physical parameters
  $\rightarrow$ increased knowledge of $\alpha_s(M_Z)$ needed for precision QCD

How?

- use **inclusive jet cross sections** in hadron-induced collisions
  $\leftarrow$ jets abundantly produced at hadron colliders
  $\leftarrow$ directly sensitive to $\alpha_s(M_Z)$
  $\leftarrow$ well defined observable for any process
- theory calculations standard: NLO
  $\rightarrow$ NNLO just around the corner

Objective

- develop a robust procedure to estimate $\alpha_s(M_Z)$
  $\rightarrow$ inclusion of more than one dataset
  $\rightarrow$ flexibile and consistent treatment of theory (preparation for NNLO)

Main "ingredients"

Data

- abundance of inclusive jet data from collider experiments:

  ATLAS, CDF, CMS, DØ, H1, STAR, ZEUS...

  → available for data/theory comparisons and α_s determinations

- inclusive jet measurement

  → phase space, experimental uncertainties

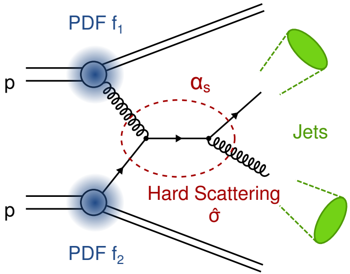
Theory

- hard matrix element $\hat{\sigma}$

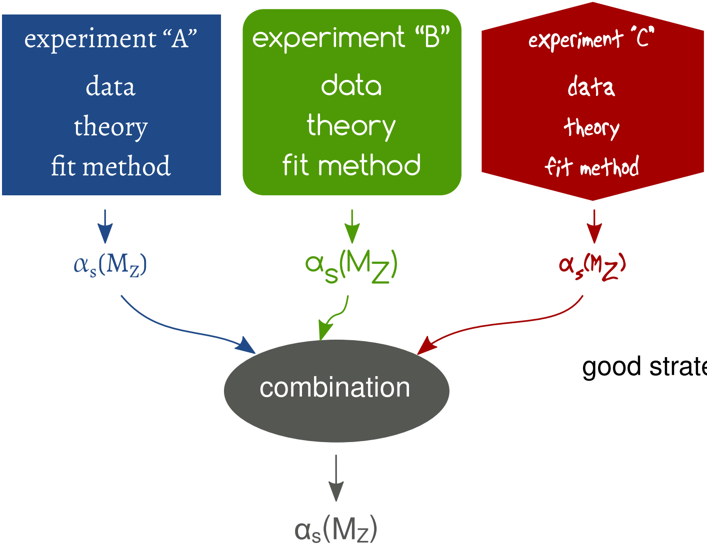
  → sensitive to $\alpha_s(M_Z)$

- convolution with PDFs

  → $\alpha_s(M_Z)$ dependence

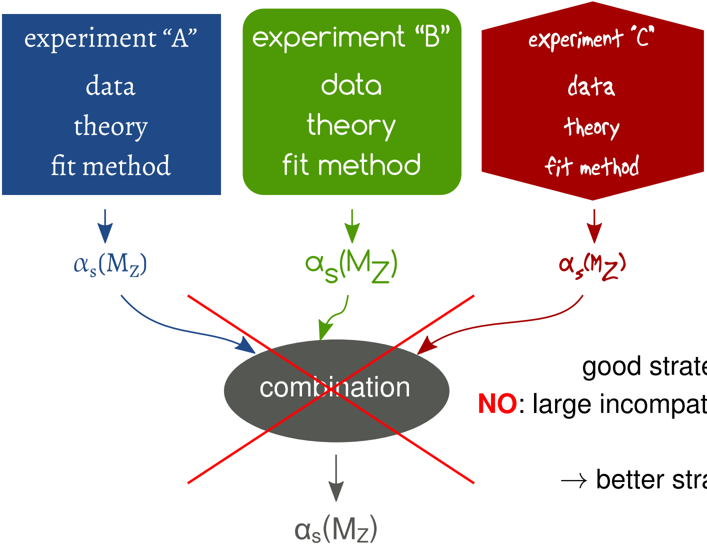


Strategy?



good strategy?

Strategy?



good strategy?

NO: large incompatibilities

→ better strategy?

Better Strategy

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experiment "A"
data

experiment "B"
data

experiment "C"
data

unified theory

(N)NLO calculation ... non-perturbative corrections ... PDFs ... α_s evolution

common fit method

χ^2 definition ... treatment of uncertainties on data, theory ... estimation of uncertainties on α_s

$$\alpha_s(M_Z)$$

Better Strategy

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experiment "A" data	experiment "B" data	experiment "C" data

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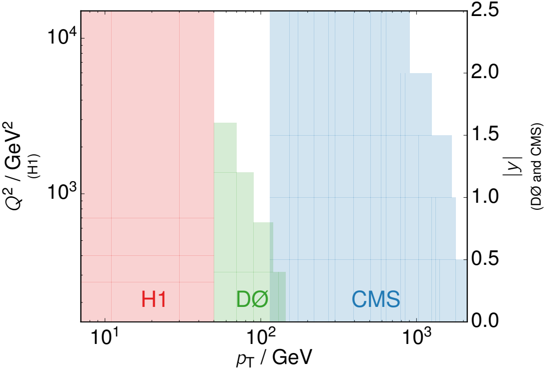
χ^2 definition ... treatment of uncertainties on data, theory ... estimation of uncertainties on α_s

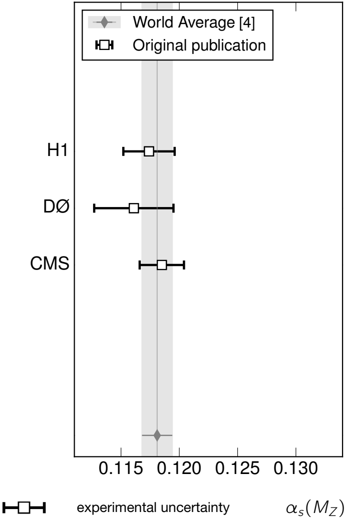
$$\alpha_s(M_Z)$$

- ✔ clean
- ✔ consistent
- ✔ convincing

First look: $\alpha_s(M_Z)$ at CMS, DØ and H1

- recent α_s extractions by CMS [3], DØ [1] and H1 [2]
- data from cover large and complementary phase space





Comparison of fit setups

	H1	DØ	CMS
theory predictions	NLO	approximate NNLO	NLO
$\alpha_s(M_Z)$ extraction procedure	direct χ^2 minimization	direct χ^2 minimization	"indirect" χ^2 minimization (fit of parabola to discrete χ^2 points)
χ^2 definition	conventional χ^2 (**log** data – **log** theory) + relative uncertainties	modified χ^2 + nuisance parameters	conventional χ^2 (data – theory) + absolute uncertainties
uncertainty estimation	linear error propagation	nuisance parameters	• "$\Delta\chi^2 = +1$" • subtraction in quadrature • "offset" method

...

Fit methods **differ significantly**!

→ "naive" combination of results (weighted average) not conclusive

→ need to extract $\alpha_s(M_Z)$ using measurements from all experiments in a **unified** fit procedure

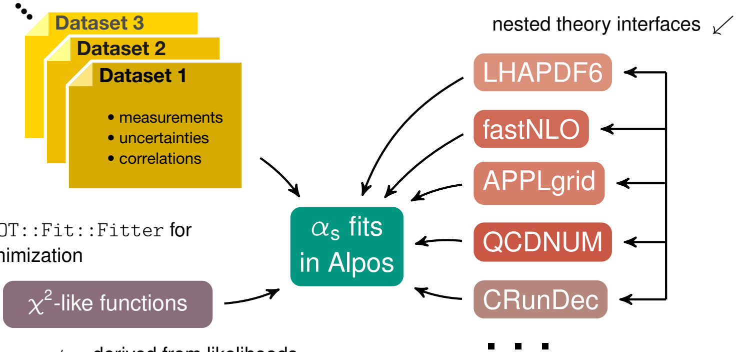
New fitting tool – Alpos

- **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

nested theory interfaces ↙

↘ `ROOT::Fit::Fitter` for minimization



← derived from likelihoods
← multiple models of measurement probability distribution

[https://ekptrac.ekp.kit.edu/svn/Alpos]

Common fit method

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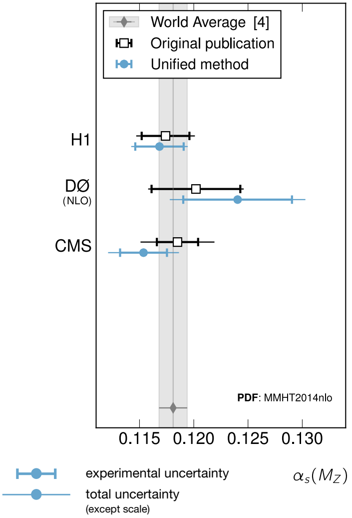
theory predictions	consistent (N)NLO
$\alpha_s(M_Z)$ extraction procedure	direct χ^2 minimization
χ^2 definition	conventional χ^2 (**log** data – **log** theory) + relative uncertainties
PDF and non-perturbative uncertainties	included in χ^2 definition
PDF $\alpha_s(M_Z)$ dependence	additional uncertainty on $\alpha_s(M_Z)$

- applying common method yields different $\alpha_s(M_Z)$ for the same dataset
- results remain in agreement with original publication

  $\rightarrow \alpha_s(M_Z)$ values consistent due to common method



Common fit method

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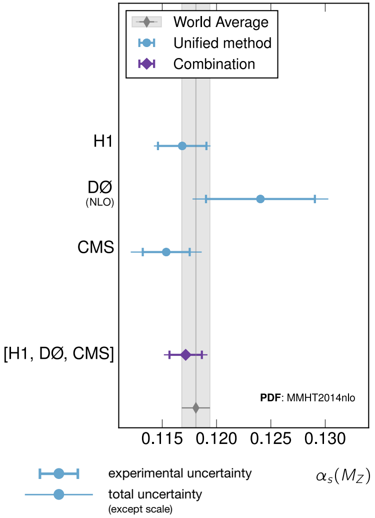


Result

$$\alpha_s(M_Z) = 0.1172\,(15)_{\text{exp}}\,(14)_{\text{theo (except scale)}}\,(50)_{\text{scale}}$$

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

Conclusions

- developed method of extracting $\alpha_s(M_Z)$ from multiple inclusive jet data sets
- **Alpos**: recently developed, public fitting code
- applied to data from the H1, CMS and DØ experiments
  - $\rightarrow$ consistent results
  - $\rightarrow$ agreement with world average for $\alpha_s(M_Z)$
  - $\rightarrow$ reduced experimental uncertainties
- scale uncertainties remain the largest single contribution to the total uncertainty

Outlook

- switch to NNLO accuracy
- include data from ATLAS, CDF, STAR, ZEUS. . .
- use insights gained for more complex QCD studies with data from multiple experiments

References I

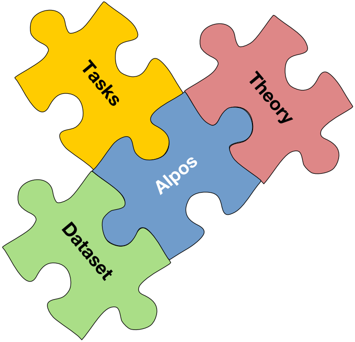
[1] V.M. Abazov et al. “Determination of the strong coupling constant from the inclusive jet cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV”. In: *Phys. Rev. D* 80 (2009), p. 111107. DOI: 10.1103/PhysRevD.80.111107. arXiv: 0911.2710 [hep-ex].

[2] V. Andreev et al. “Measurement of multijet production in *ep* collisions at high Q^2 and determination of the strong coupling α_s”. In: *Eur. Phys. J. C* 75 (2015), p. 65. DOI: 10.1140/epjc/s10052-014-3223-6. arXiv: 1406.4709 [hep-ex].

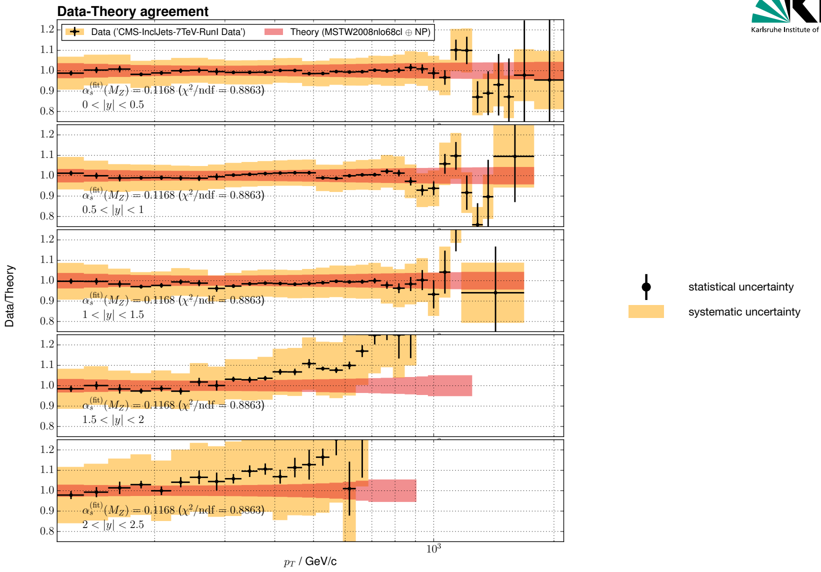
[3] Vardan Khachatryan et al. “Constraints on parton distribution functions and extraction of the strong coupling constant from the inclusive jet cross section in pp collisions at $\sqrt{s}$ = 7 TeV”. In: *Eur. Phys. J. C* 75 (2015), p. 288. DOI: 10.1140/epjc/s10052-015-3499-1. arXiv: 1410.6765 [hep-ex].

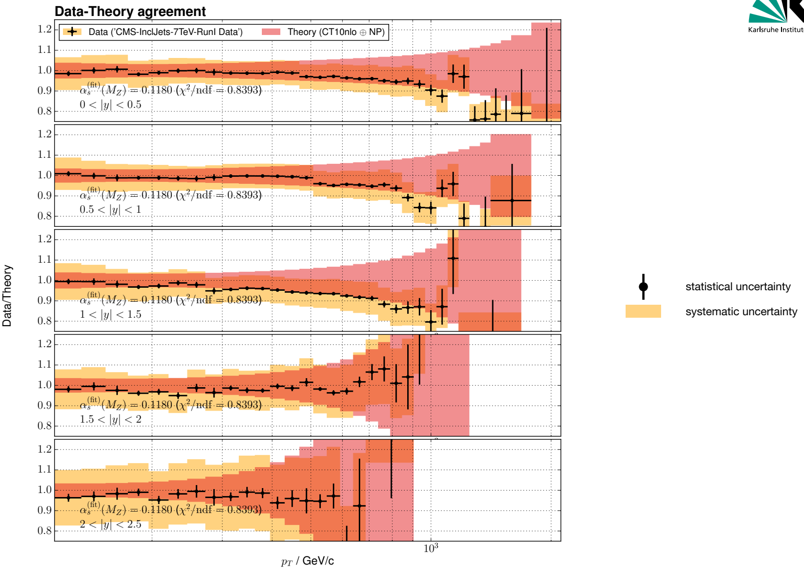
[4] K.A. Olive and others (Particle Data Group). “Review of Particle Physics”. In: *Chin. Phys. C* 38 (2014). (2015 update), p. 090001. DOI: 10.1088/1674-1137/38/9/090001.

Many thanks to G. Flouris and P. Kokkas for their insights, as well as for providing the original CMS fitting code

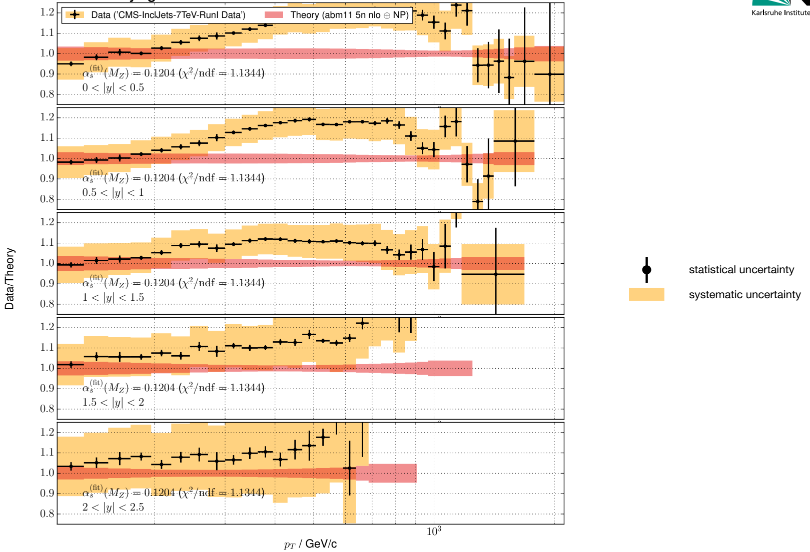


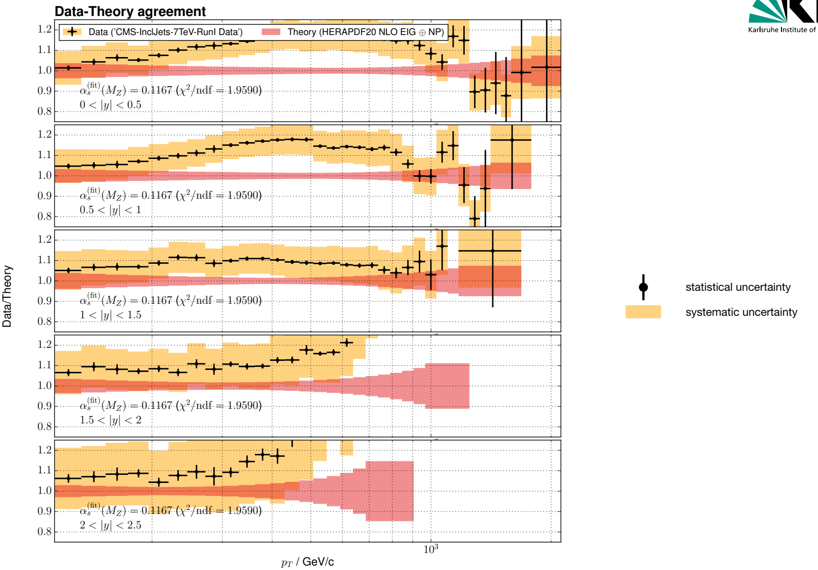
Backup


Data-Theory agreement
Data ('CMS-InclJets-7TeV-RunI Data')
Theory (MSTW2008nlo68cl ⊕ NP)
$\alpha_s^{(\mathrm{fit})}(M_Z) = 0.1168$ (χ^2/ndf = 0.8863)
$0 < |y| < 0.5$
$0.5 < |y| < 1$
$1 < |y| < 1.5$
$1.5 < |y| < 2$
$2 < |y| < 2.5$
Data/Theory
p_T / GeV/c
statistical uncertainty
systematic uncertainty


Data-Theory agreement
Data ('CMS-InclJets-7TeV-RunI Data')
Theory (CT10nlo ⊕ NP)
$\alpha_s^{(\mathrm{fit})}(M_Z) = 0.1180$ ($\chi^2/\mathrm{ndf} = 0.8393$)
$0 < |y| < 0.5$
$0.5 < |y| < 1$
$1 < |y| < 1.5$
$1.5 < |y| < 2$
$2 < |y| < 2.5$
Data/Theory
p_T / GeV/c
10^3
statistical uncertainty
systematic uncertainty

Data-Theory agreement




Data-Theory agreement
Data ('CMS-InclJets-7TeV-RunI Data')
Theory (HERAPDF20 NLO EIG ⊕ NP)
$\alpha_s^{(\mathrm{fit})}(M_Z) = 0.1167$ (χ^2/ndf = 1.9590)
$0 < |y| < 0.5$
$0.5 < |y| < 1$
$1 < |y| < 1.5$
$1.5 < |y| < 2$
$2 < |y| < 2.5$
Data/Theory
p_T / GeV/c
10^3
statistical uncertainty
systematic uncertainty

References

Comparison of $\alpha_s(M_Z)$ extraction methods

H1 fit methodology

$$\chi^2_{\rm H1} \to \sum_{ij} (\ln m_i - \ln t_i) \left[\mathbf{V}^{-1}_{\rm (rel)} \right]_{ij} (\ln m_j - \ln t_j)$$

- iterative χ^2 minimization (*MINUIT*)
  - 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, μ_r, μ_f
  - obtained through additional fits / linear error propagation

DØ fit methodology

$$\chi^2_{\rm DØ} \to \sum_i \frac{\left[m_i - t_i \frac{1+\sum_k \delta^{\rm (NP)}_{ik}\left(\alpha^{\rm (NP)}_k\right) + \sum_l \delta^{\rm (PDF)}_{il}\left(\alpha^{\rm (PDF)}_l\right)}{1+\sum_j \delta_{ij}(\varepsilon_j)} \right]^2}{\sigma^2_{i,\rm stat} + \sigma^2_{i,\rm uncorr}}$$

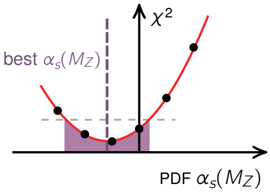
- iterative χ^2 minimization (*MINUIT*)
  - one nuisance parameter for each PDF eigenvector and each NP correction factor
  - interpolate cross section predictions obtained for PDFs assuming different values of $\alpha_s(M_Z)$
- aNNLO (NLO predictions with threshold corrections + NNLO PDFs)
- 88 out of 110 data points excluded ← correlations with MSTW2008 PDFs

Comparison of $\alpha_s(M_Z)$ extraction methods

CMS fit methodology

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

- χ^2 is evaluated for each PDF in an $\alpha_s(M_Z)$ series
  - resulting $\left(\chi^2, \alpha_s(M_Z)\right)$ points are assumed to lie on a parabola
  - fit of second-degree polynomial function $\to$ 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



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References

PDF $\alpha_s(M_Z)$ dependence

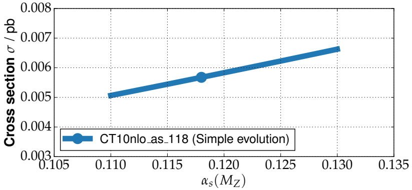
How to express the $\alpha_s(M_Z)$ dependence of the cross section?

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

Two methods are studied:

"Fixed PDF" (○)

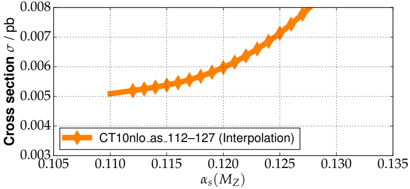
(method used in H1 publication)



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

"PDF Interpolation" (◊)

(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 α_s dependence?

In most cases, both methods yield comparable results

Method comparison

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choose this as main method

“PDF Interpolation”

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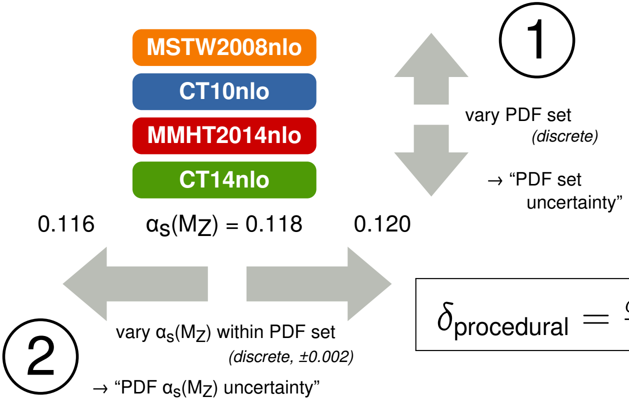
- ? does procedure reproduce PDF α_s dependence?

In most cases, both methods yield comparable results

Procedural PDF uncertainties

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



$$\delta_{\text{procedural}} = \frac{\alpha_s^{(\text{max})} - \alpha_s^{(\text{min})}}{2}$$

Refits with unified procedure

Refit results

- all refits have reasonable χ^2/ndf and compatible with each other
- χ^2/ndf values at minimum:

H1	$\chi^2/\text{ndf} = 23.1/23 = 1.004$
DØ	$\chi^2/\text{ndf} = 17.2/21 = 0.819$
CMS	$\chi^2/\text{ndf} = 110/132 = 0.832$

Comparison to published values

- good agreement

H1	method similar, but V_{PDF} and V_{NP} in χ^2
CMS, DØ	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