Determination of the strong coupling constant from inclusive jet cross sections

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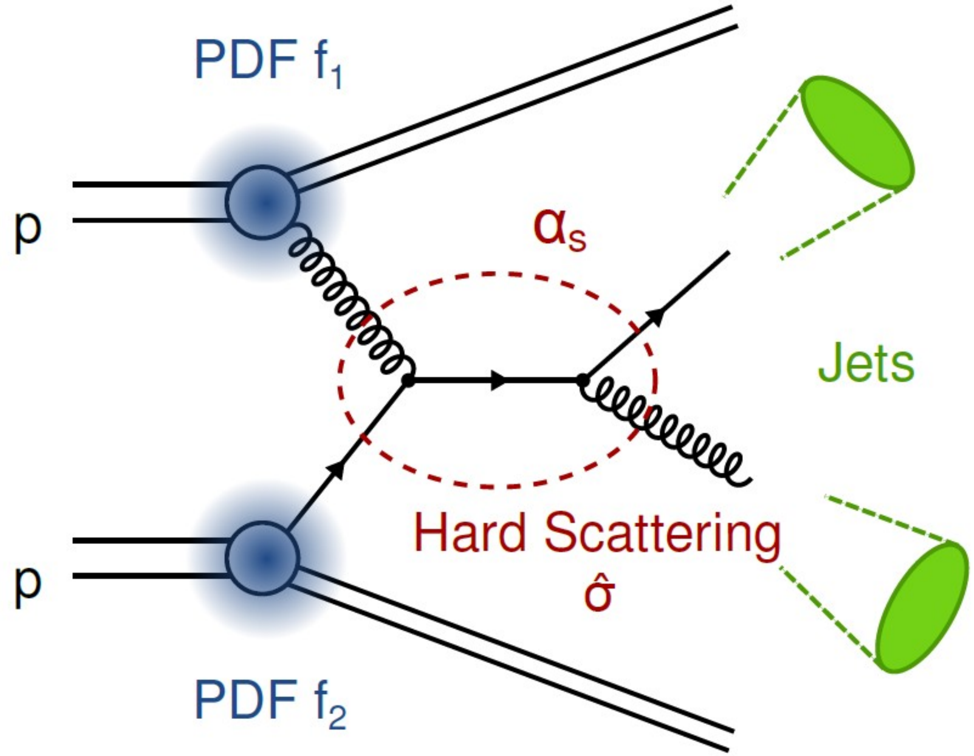
Motivation

- **Why $\alpha_s(M_Z)$?**
  - **Among least known parameters of the standard model**
  - **Important for all processes from hadron-induced collisions**
  - **Needed for QCD precision comparisons**
- **How?**
  - **Start with inclusive jet data**
    - **Wide kinematic range through abundant production of jets**
    - **Measured in many experiments**
    - **Well defined in fiducial volume of detectors**
  - **Compare to theoretical prediction**
    - **Directly sensitive to $\alpha_s(M_Z)$**
    - **Available at NLO in QCD+EW**
    - **QCD @ NNLO is under way**
    - **Less ambiguous with respect to scale choice**

Main ingredients

Data

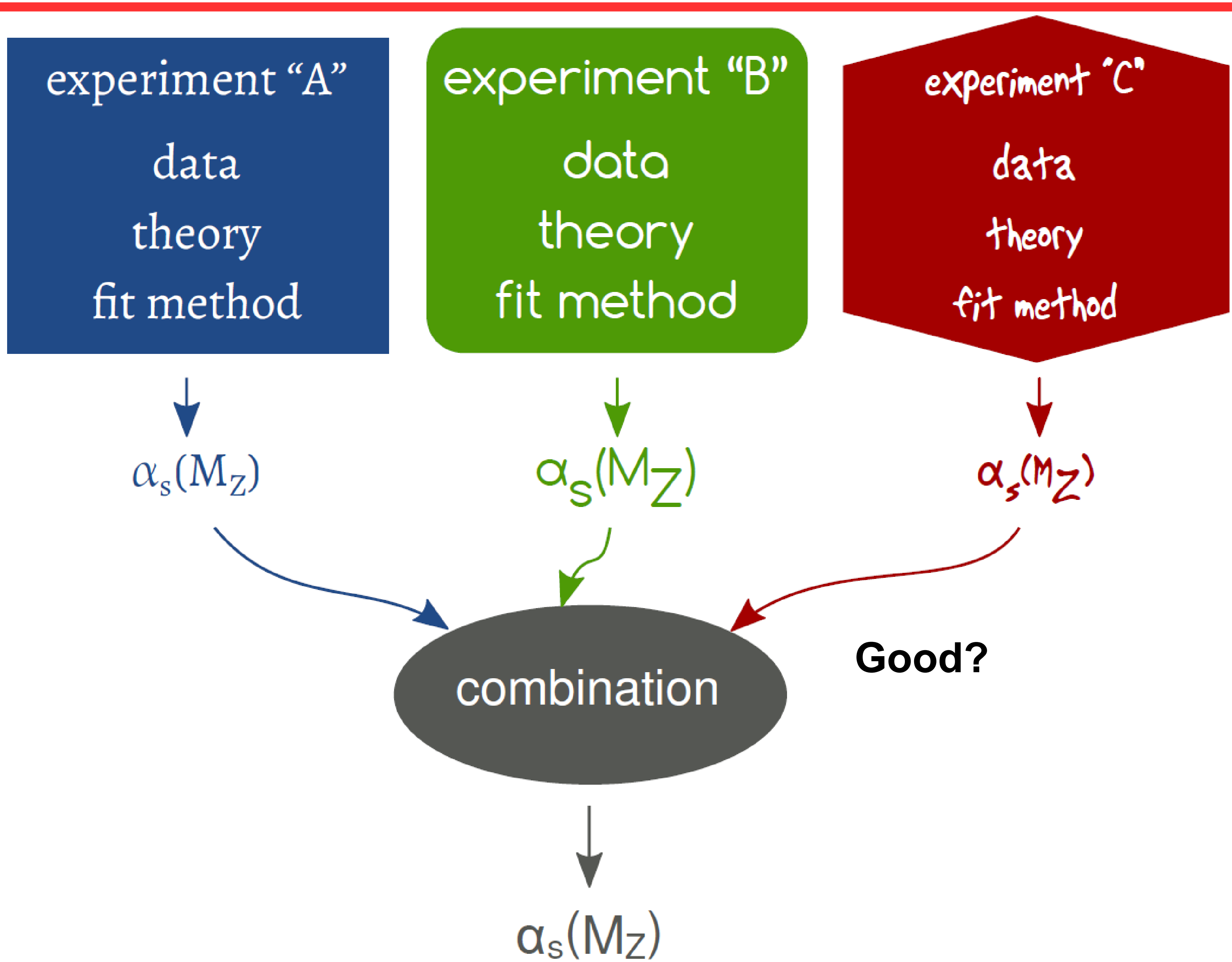
- Abundance of inclusive jet data from various experiments
  - ATLAS, CMS, CDF, D0, H1, ZEUS, STAR, …
- Inclusive jet measurement
  - Phase space, experimental uncertainties, correlations



Theory

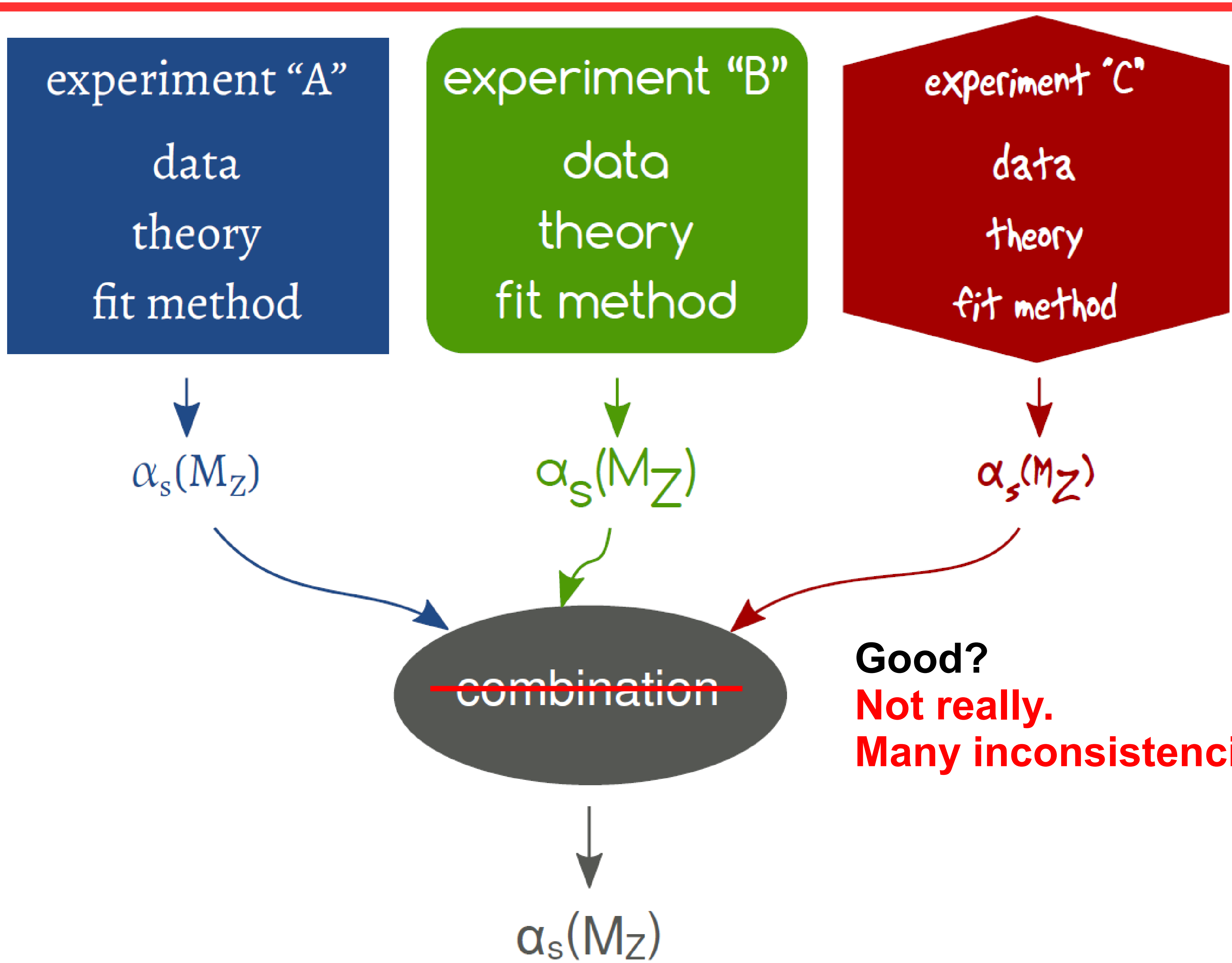
- Partonic matrix element $\hat{\sigma}$
  - Sensitive to $\alpha_s(M_Z)$
- Convolution with PDFs
  - Dependence on $\alpha_s(M_Z)$

Strategy?



Good?

Strategy?



Good?
Not really.
Many inconsistencies!

Better strategy

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

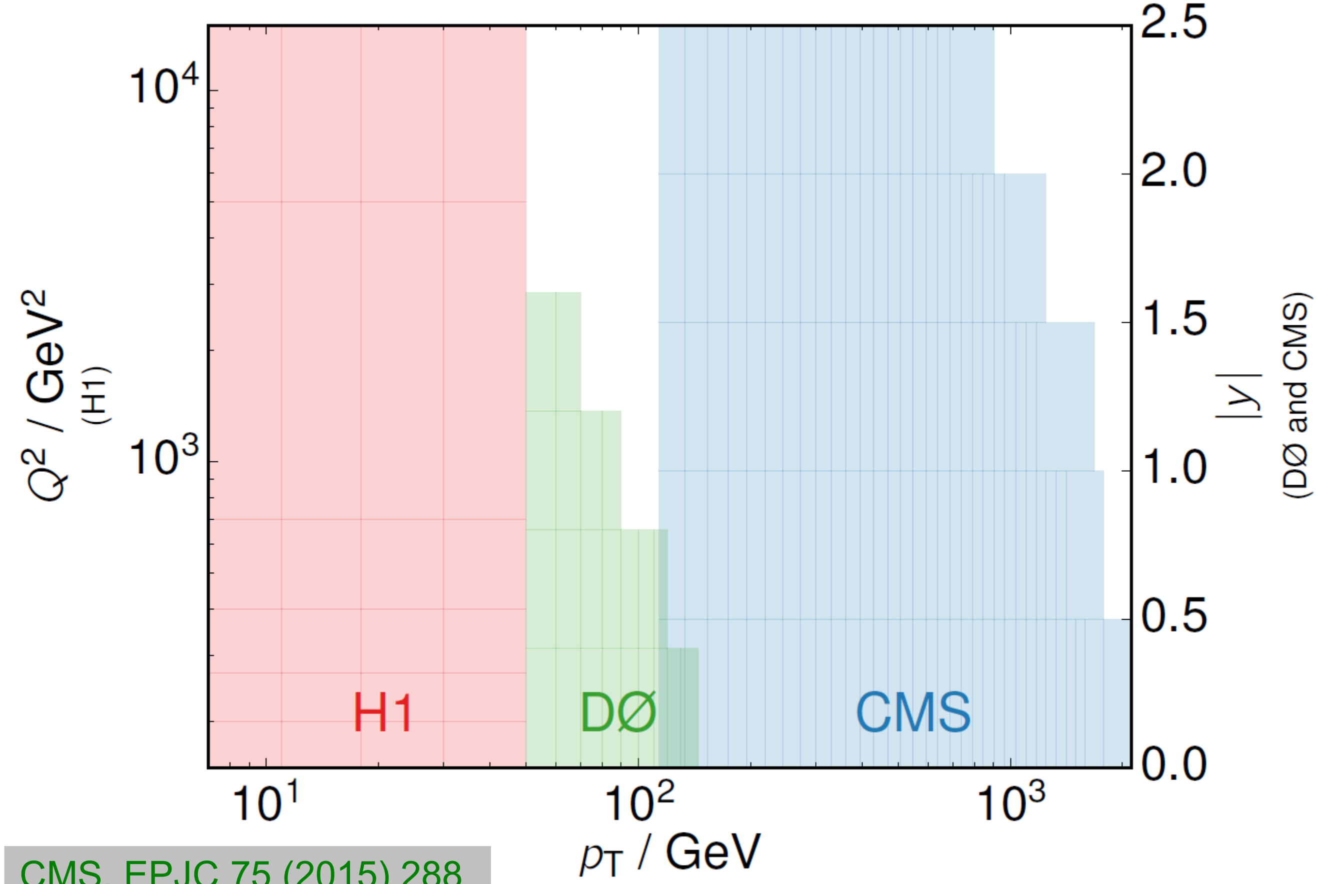
↓

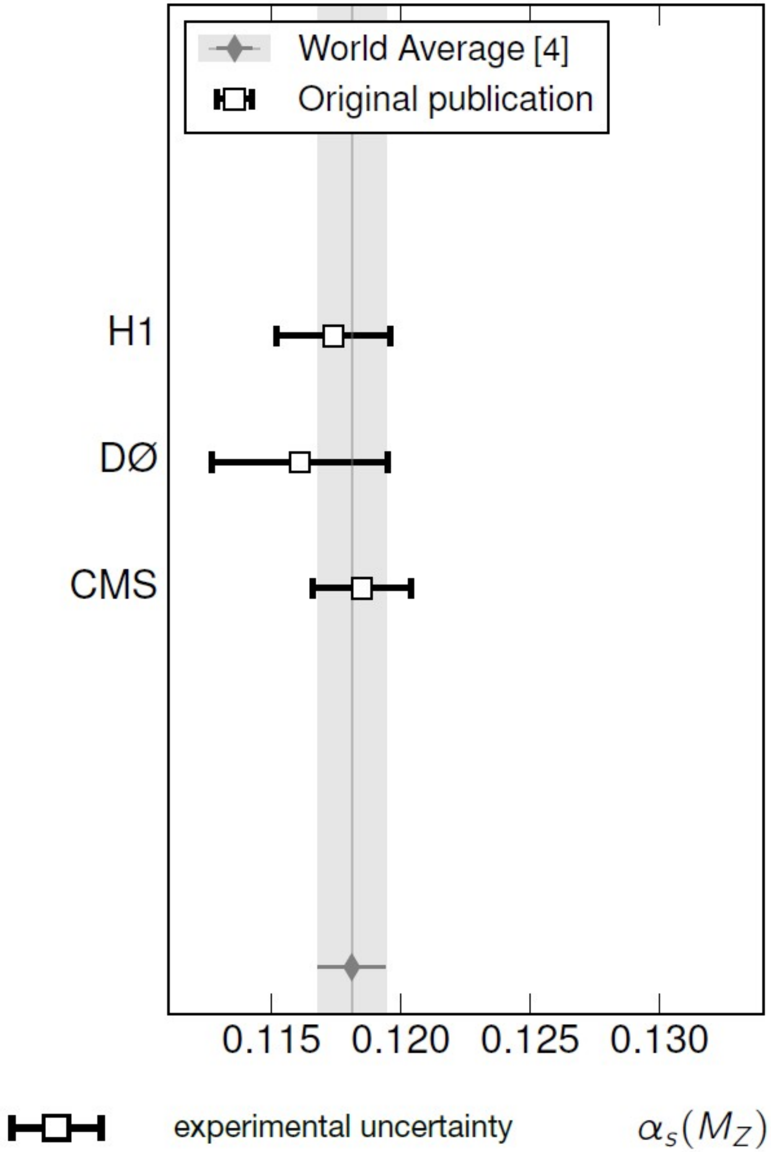
$\alpha_s(M_Z)$

First look: $\alpha_s(M_Z)$ at CMS, D0, H1

Data

- $\alpha_s(M_Z)$ extractions by CMS, D0, and H1
- cover large and complementary phase space





CMS, EPJC 75 (2015) 288.
D0, PRD 80 (2009) 111107.
H1, EPJC 75 (2015) 65.

[4] PDG, ChPC 40 (2016) 100001.

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

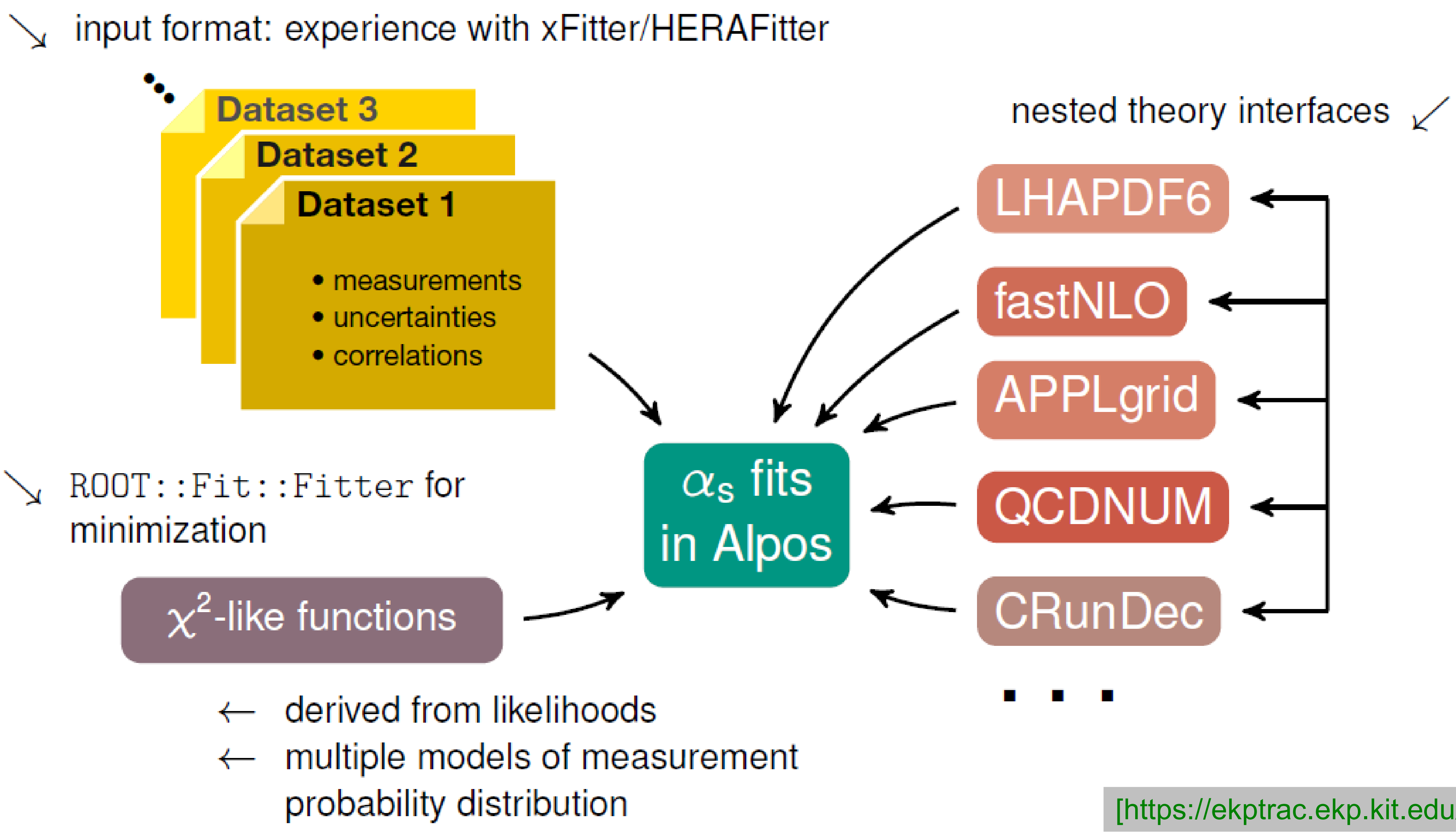
Significant differences!

- **neglected in naïve combination of results**
- **develop unified fit procedure**

Fitting framework: Alpos

New modular C++ based fitting framework

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



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

Fitting framework: Alpos

New modular C++ based fitting framework

→ **E. Eren: CMS jet results, next talk**

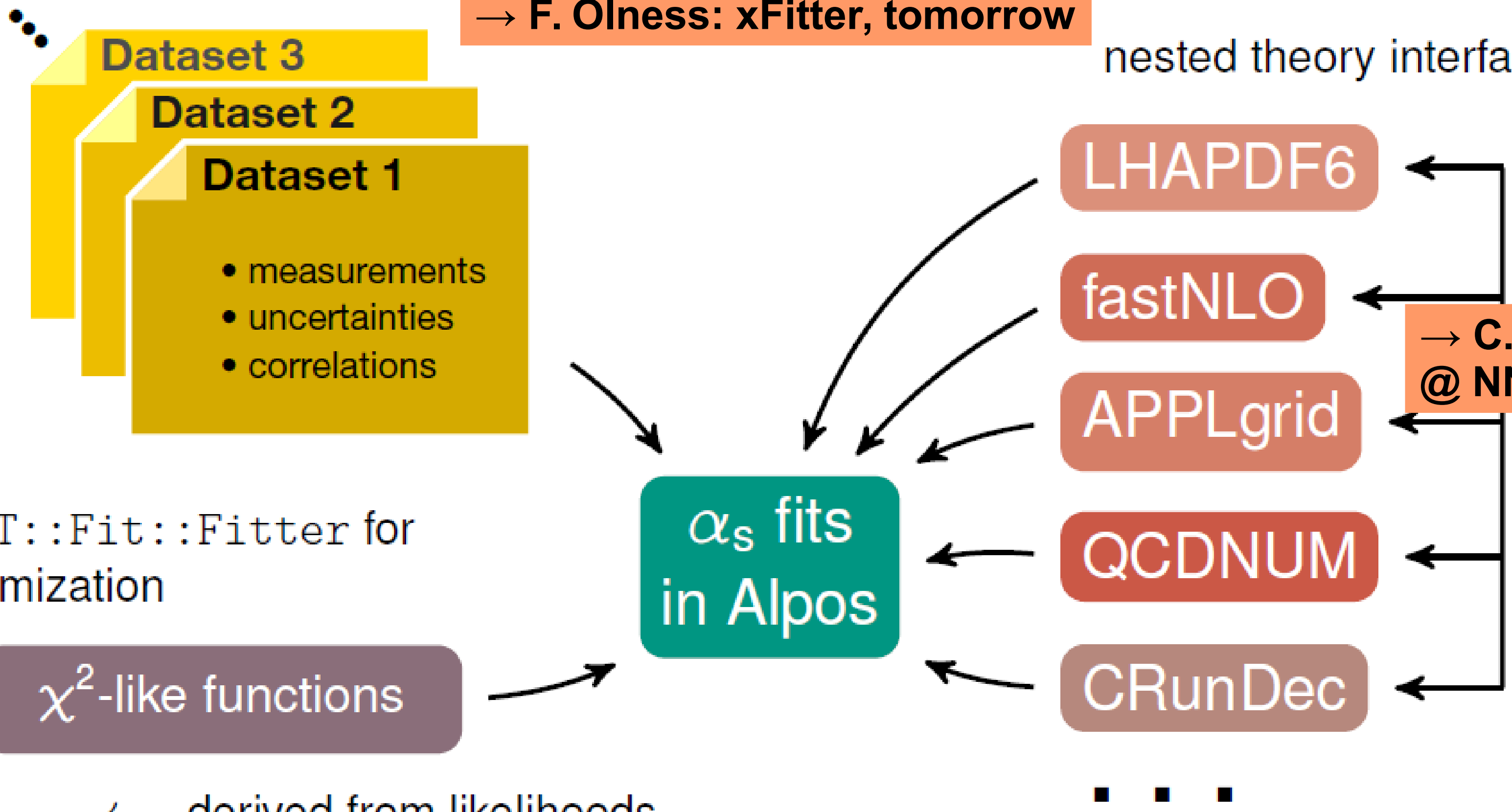
- **used for $\alpha_s(M_Z)$, PDF, and electroweak fits within H1 and CMS**

→ **D. Britzger: DIS jet fits @ NNLO, yesterday**

↘ input format: experience with xFitter/HERAFitter

→ **F. Olness: xFitter, tomorrow**

nested theory interfaces ↙



→ **C. Gwenlan: Usage @ NNLO, yesterday**

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

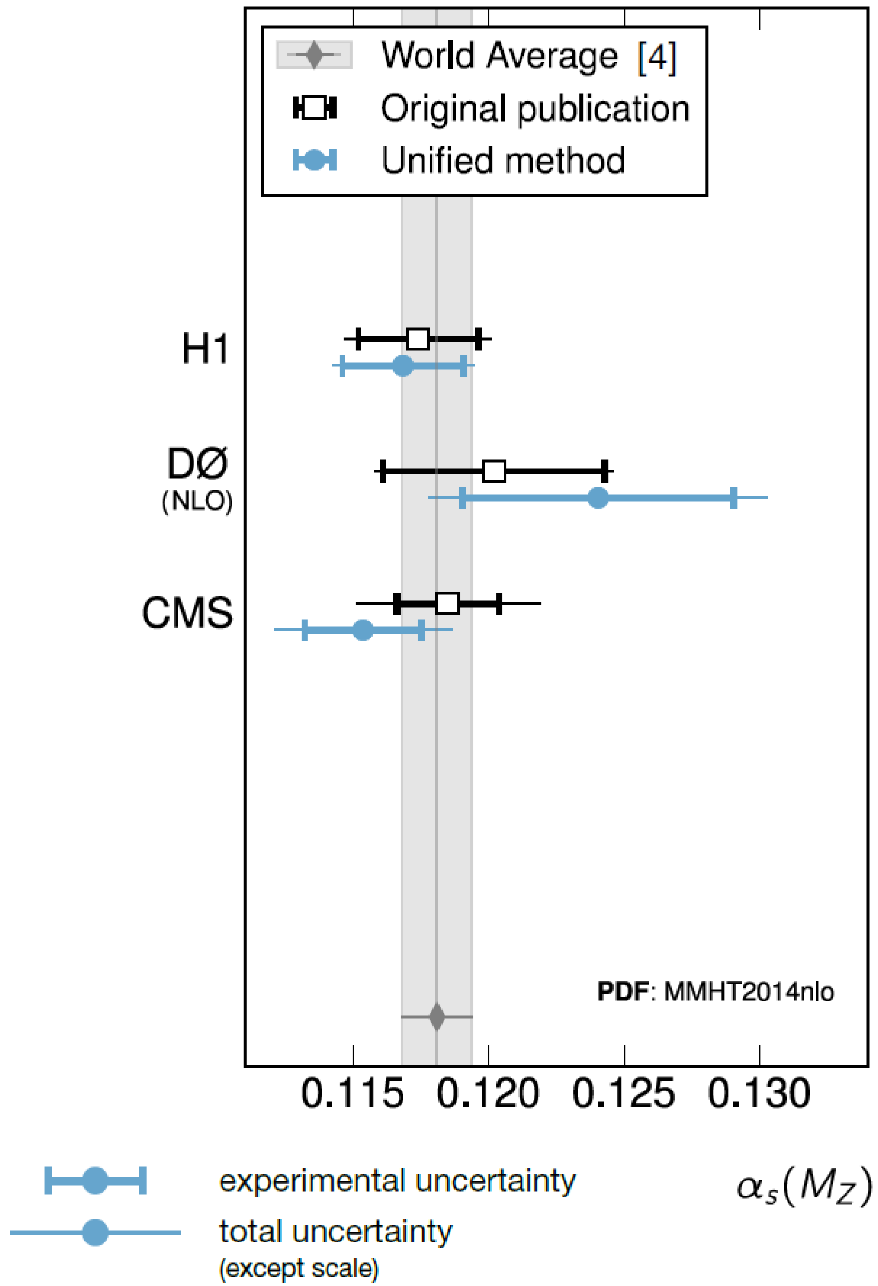
← derived from likelihoods

← multiple models of measurement probability distribution

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

Unified fit method

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 $\alpha_s(M_Z)$



Unified approach:

- **slight differences wrt. original**
- **compatible within uncertainties**
- **more consistent comparison**
- **simultaneous fit**

Unified fit result

theory predictions	consistent (N)NLO
$\alpha_s(M_Z)$ extraction procedure	direct χ^2 minimization
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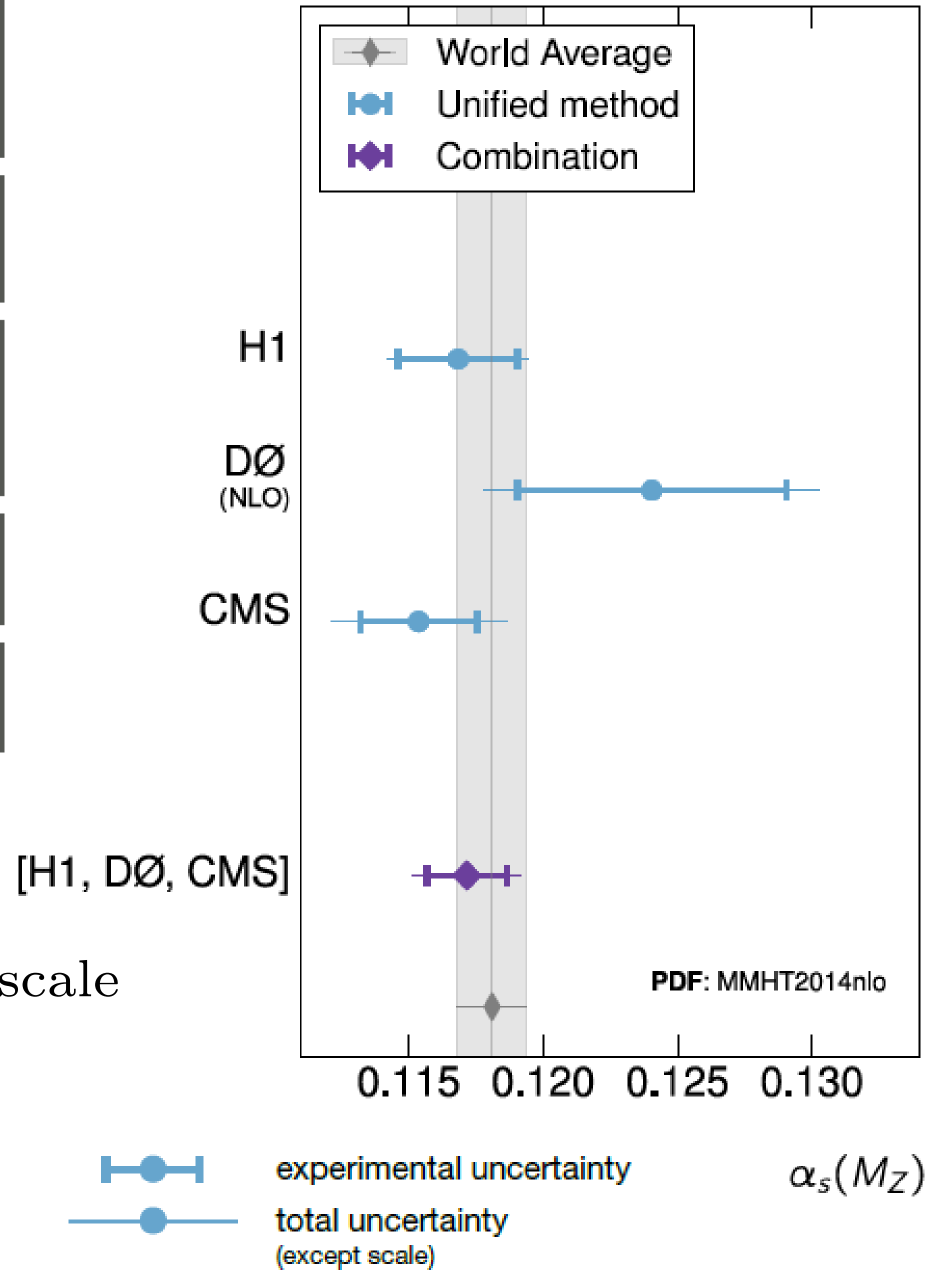

Result of simultaneous fit:

$$\alpha_s(M_Z) = 0.1172(15)_{\rm exp}\,(14)_{\rm theo\ w/o\ scale}\,(50)_{\rm scale}$$

$$[\chi^2_{\rm min}/{\rm ndf} = 152/178 = 0.86]$$

D. Savoiu, Master's thesis, IEKP-KA/2016-25, KIT

More datasets

Objective

- **Develop a robust procedure to determine $\alpha_s(M_Z)$**
  - **Include more than one dataset**
  - **Consistent treatment of theory**
  - **Extensible to additional observables**
  - **Unique**
  - **Flexibility**
- **How?**
  - **Start with inclusive jet data**
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Outlook

- NNLOJET provides NNLO in common interface for:
  - Z incl., Z+jet, W incl., pp jet+dijets, H incl., H+jet, DIS jet+dijets, e+e- 3jets
  - W+jet almost ready; more to come
- APPLgrid+fastNLO interface (NNLO-Bridge) is working
- Numerous adaptations implemented by all sides
- Large-scale productions tested for Z+jet and DIS jet
- Work in progress: Implementation of final combination procedure for interpolation grids
- Looking forward to many new NNLO interpolation grids in 2017

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Backup

α_s

Method comparison

H1 fit methodology

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

- 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

$$\chi^2_{\mathrm{DØ}} \to \sum_i \frac{\left[m_i - t_i \frac{1 + \sum_k \delta_{ik}^{(\mathrm{NP})}\left(\alpha_k^{(\mathrm{NP})}\right) + \sum_l \delta_{il}^{(\mathrm{PDF})}\left(\alpha_l^{(\mathrm{PDF})}\right)}{1 + \sum_j \delta_{ij}(\epsilon_j)} \right]^2}{\sigma^2_{i,\mathrm{stat}} + \sigma^2_{i,\mathrm{uncorr}}}$$

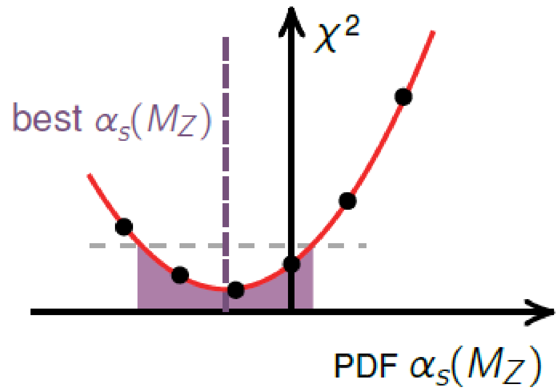
- iterative χ^2 minimization (*MINUIT*)
  - one nuisance parameter for each PDF eigenvector and each NP correction factor
  - interpolate cross section predictions obtained for PDFs assuming different values of $\alpha_s(M_Z)$
- aNNLO (NLO predictions with threshold corrections + NNLO PDFs)
- 88 out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

Method comparison

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

CMS fit methodology

- χ^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 $\rightarrow$ 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**!

$\rightarrow$ "naive" combination of results (weighted average) not very conclusive

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

PDF $\alpha_s(M_Z)$ dependence

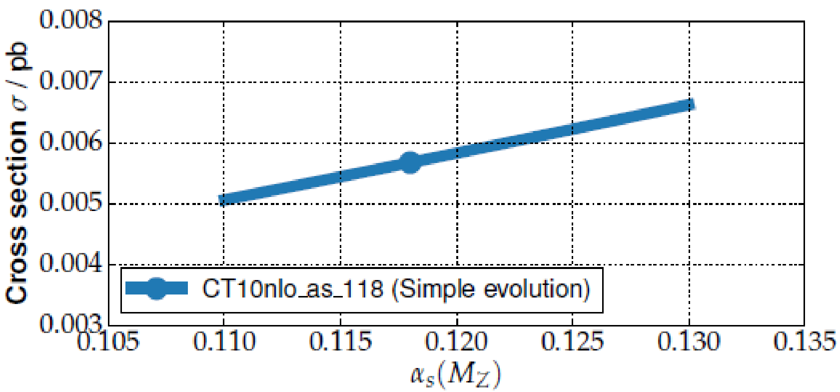
How to express the $\alpha_s(M_Z)$ dependence of the cross section?

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

Two methods are studied:

"Fixed PDF" (○)

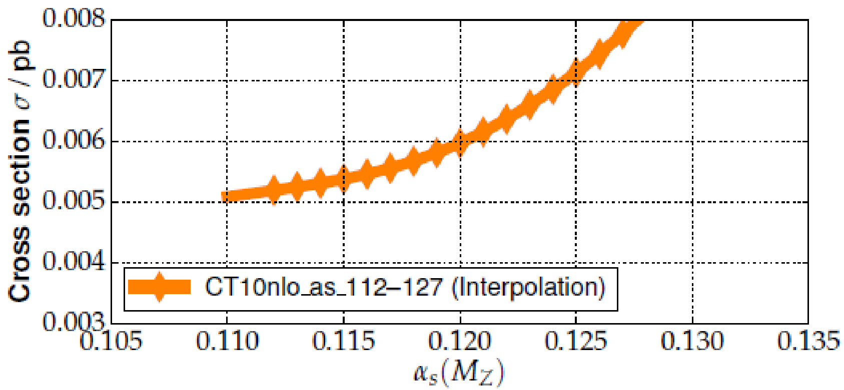
(method used in H1 publication)



- 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 $\alpha_s(M_Z)$

choose this as main method

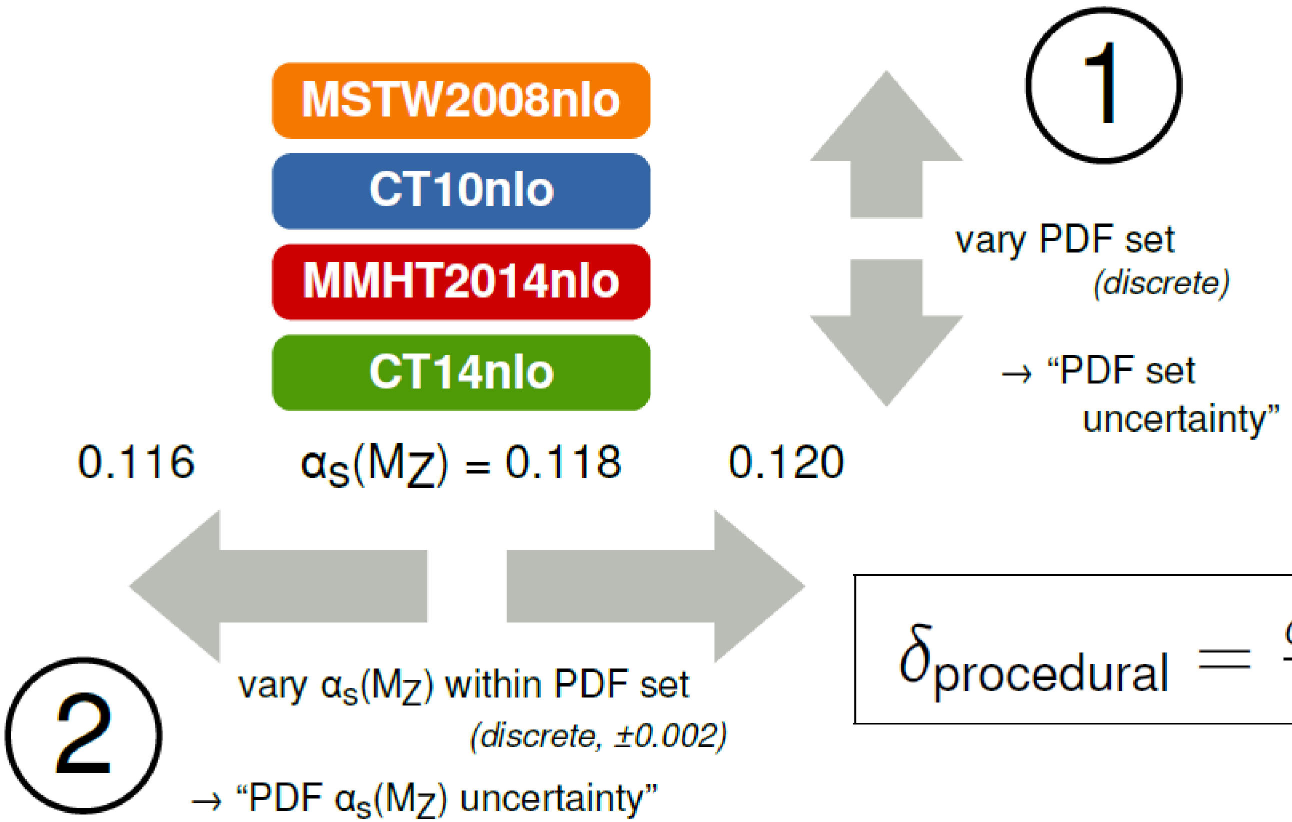
"PDF Interpolation"

- (+) provides a way to include the uncertainty due to the choice of PDF $\alpha_s(M_Z)$ **in the fit**
- (o) 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

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



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