Recent QCD results from the xFitter project

Focus: Heavy Flavor PDF Matching Scales

xFitter Project

Open Source QCD Fit framework

DIS2017 April 3 - 7, 2018

Fredrick Olness

SMU

on behalf of the xFitter team

xFitter Meeting: Krakow March 2018

xFitter Project *Overview*

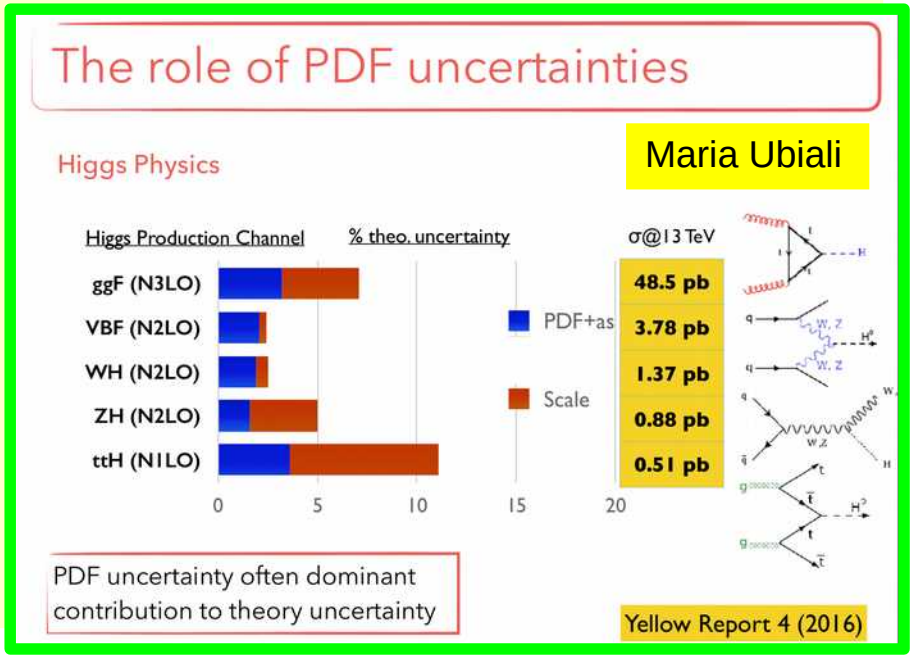
www.xfitter.org

The xFitter project is an open source QCD fit framework ready to extract PDFs and assess the impact of new data.

The framework includes modules allowing for a various theoretical and methodological options, capable to fit a large number of relevant data sets from HERA, Tevatron and LHC.

This framework is already used in many analyses at the LHC.

Proton parton distribution functions (PDFs) are essential for precision physics at the LHC and other hadron colliders. The determination of the PDFs is a complex endeavor involving several physics process. … In particular, the precise measurements obtained or to come from LHC will continue to improve the knowledge of the PDF.



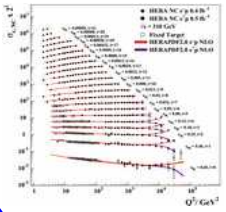
xFitter release xfitter-2.0.0

www.xFitter.org

Sample data files:

LHC: ATLAS, CMS, LHCb
Tevatron: CDF, D0
HERA: H1, ZEUS, Combined
Fixed Target: …
User Supplied: ...

Experimental Data



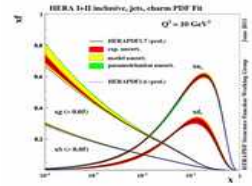
Data: HERA, Tevatron, LHC, fixed target experiments

Processes:
Inclusive DIS, Jets, Drell-Yan, Diffraction, Top production W and Z production

Theory Calculations

HQ Schemes:	MSTW, NNPDF, ABM, ACOT
Jets, W, Z:	FastNLO, ApplGrid
Top:	Hathor
Evolution:	QCDNUM, APFEL, k_T
Other:	NNPDF reweighting TMDs, Dipole Model, ...

xFitter



Parton Distribution Functions: PDF, Updf, TMD

$\alpha_S(M_Z)$, m_c,m_b,m_t ...

Theoretical Cross Sections

Comparisons to other PDFs (LHAPDF)

xFitter 2.0.0 FrozenFrog

Features & Recent Updates:

Photon PDF & QED
Pole & MS-bar masses
Profiling and Re-Weighting

Heavy Quark Variable Treshold
Improvements in χ^2 and correlations
TMD PDFs (uPDFs)
... and many other

NEW xfitter examples *(CTEQ school)*

http://xfitter.org

Stefano Camarda
Ringailė Plačakytė
Voica Radescu

A list of educational examples are provided in the package

Exercise 1: PDF fit
→ learn the basic settings of a QCD analysis, based on HERA data only

Exercise 2: Simultaneous PDF fit and αs
→ learn the basic of an αs extraction using H1 jet data

Exercise 3: LHAPDF analysis
→ how to estimate impact of a new data without fitting:
→ profiling and reweighting techniques

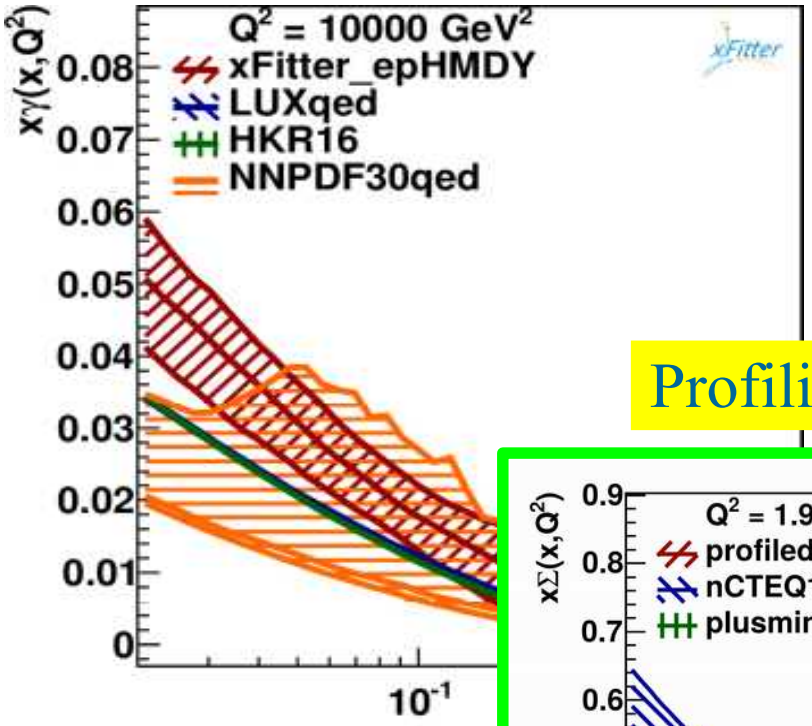
Exercise 4: Plotting LHAPDF files
→ direct visualisation of PDFs from LHAPDF6 using simple python scripts

Exercise 5: Equivalence of χ^2 representations
→ understand different χ^2 representations
nuisance parameters and covariance matrix χ2 formulas

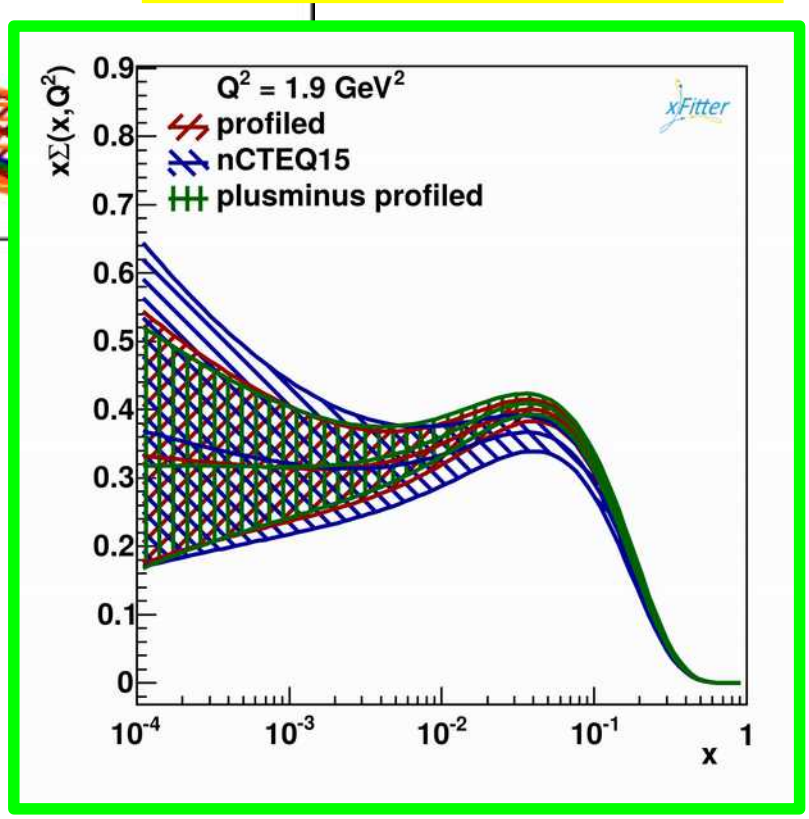
xFitter Capabilities

www.xFitter.org

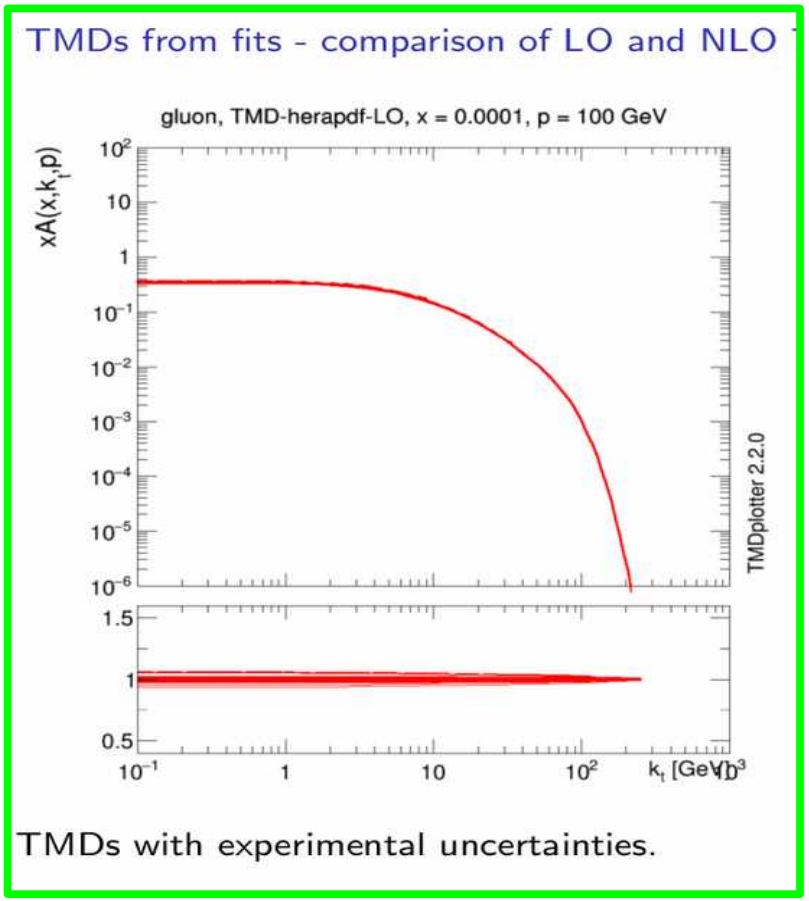
Photon PDF



Profiling Lead PDFs

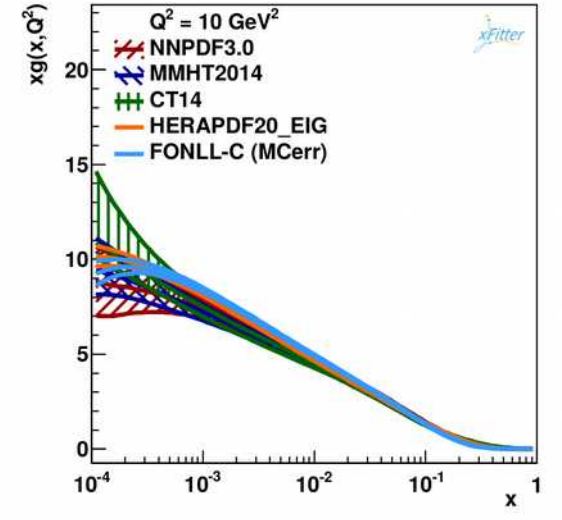


TMD (uPDFs) in xFitter

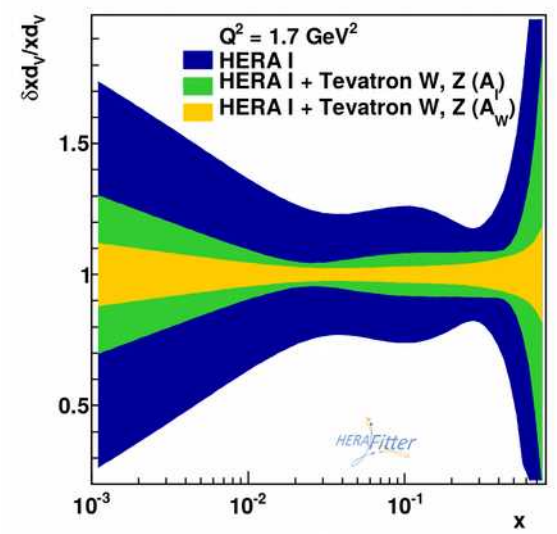


more xFitter Capabilities

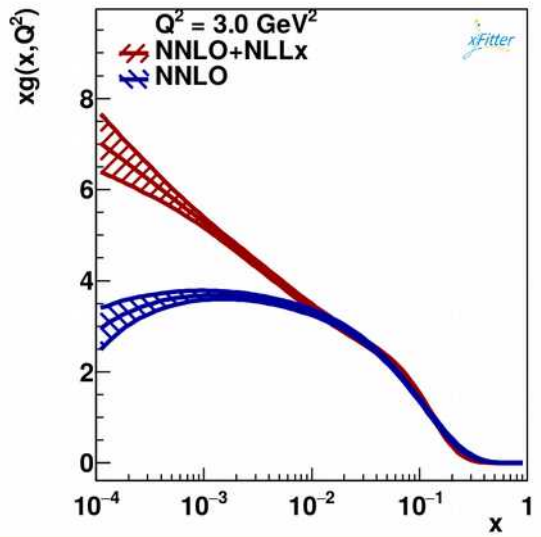
www.xFitter.org



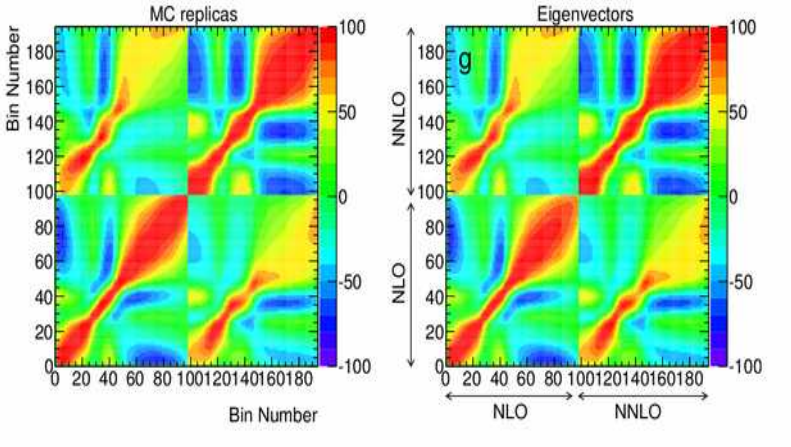
Multiple Heavy Quark Models



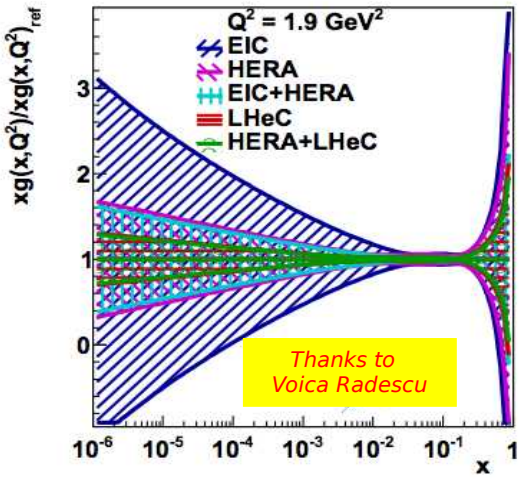
Profiling of W/Z Data



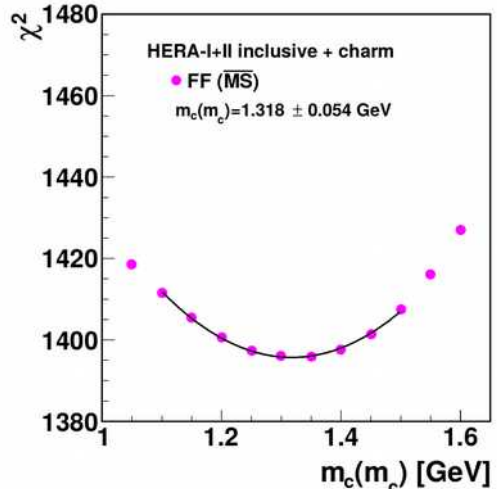
NNLx Resummation @ Small x



Correlation Coefficients



Sensitivity Studies



Pole & MS-Bar Running Mass

Displacement of Heavy Quark Matching Scales in xFitter¶

Eur. Phys. J. C (2017) 77:837
https://doi.org/10.1140/epjc/s10052-017-5407-3

THE EUROPEAN PHYSICAL JOURNAL C

CrossMark

Regular Article - Theoretical Physics

Impact of the heavy-quark matching scales in PDF fits

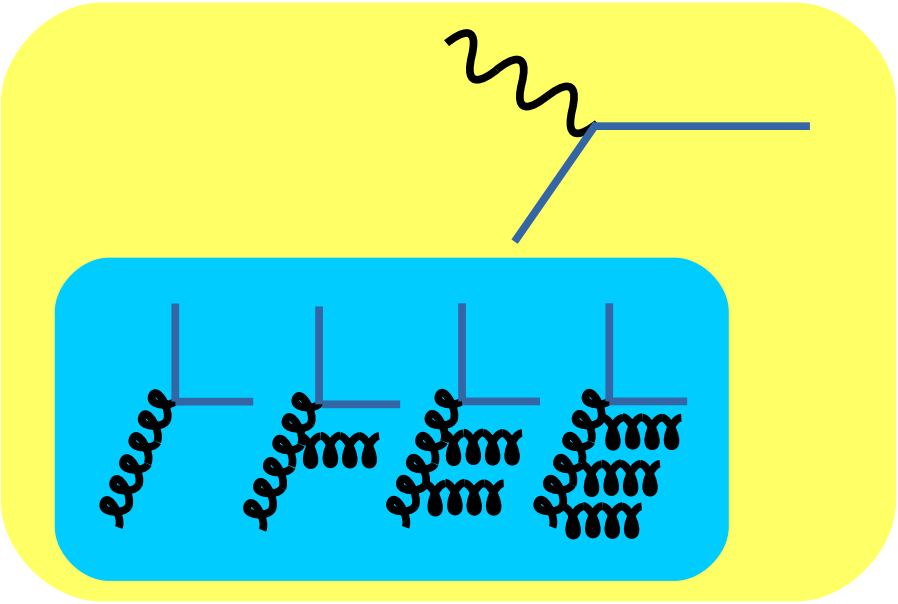
The xFitter Developers' Team:, V. Bertone[1,2], D. Britzger[3], S. Camarda[4], A. Cooper-Sarkar[5], A. Geiser[3], F. Giuli[5], A. Glazov[3], E. Godat[6], A. Kusina[7,8], A. Luszczak[9], F. Lyonnet[6], F. Olness[6,a], R. Plačakytė[10], V. Radescu[3,4], I. Schienbein[7], O. Zenaiev[3]

[1] Department of Physics and Astronomy, VU University, 1081 HV Amsterdam, The Netherlands
[2] Nikhef Theory Group Science Park 105, 1098 XG Amsterdam, The Netherlands

Impact of the heavy quark matching scales in PDF fits
The xFitter Developers Team: V. Bertone, et al.,
Eur.Phys.J. C77 (2017) no.12, 837

Compare: VFNS vs. FFNS e.g. 4-Flavor vs. 5-Flavor

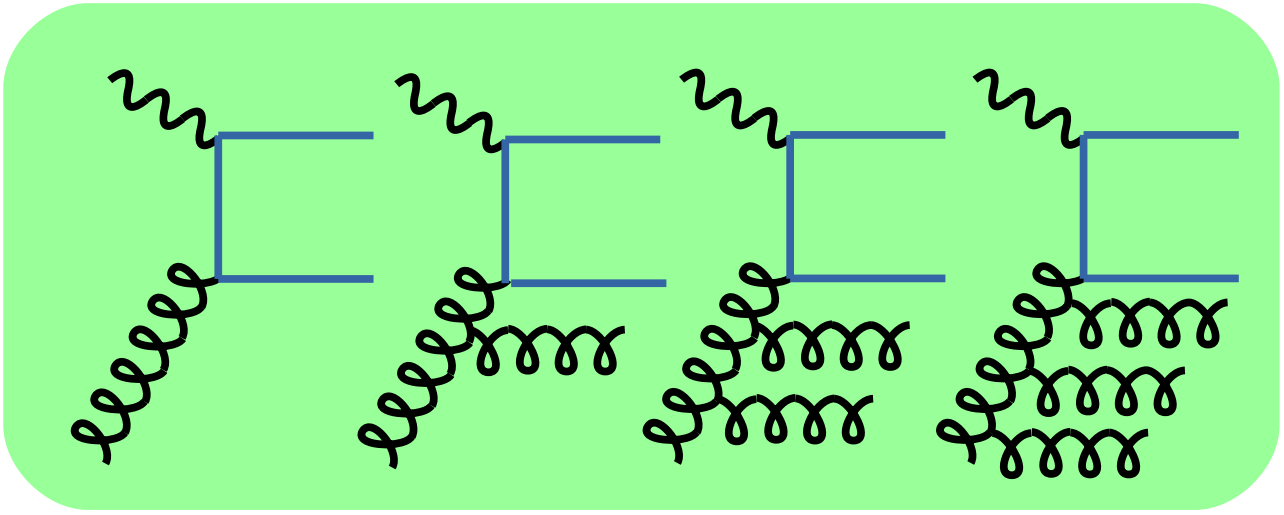
Varible Flavor Number Scheme (VFNS)



+ Use DGLAP to resum higher orders
- Subtraction (Double Counting) delicate

Fixed Flavor Number Scheme (FFNS)

+ No HQ PDFs
- Must calculate explicitly



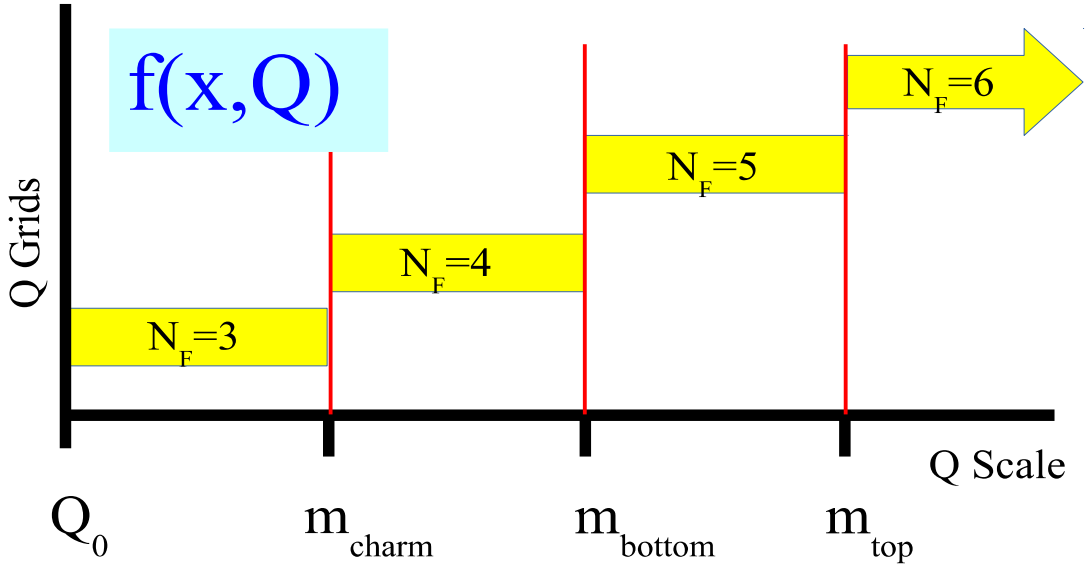
Previously: **HQ Evolution initiated at $\mu = m$**

Traditional VFNS

What are the benefits?

1) **Boundary Conditions are simple**

2) **use DGLAP to resum logs**

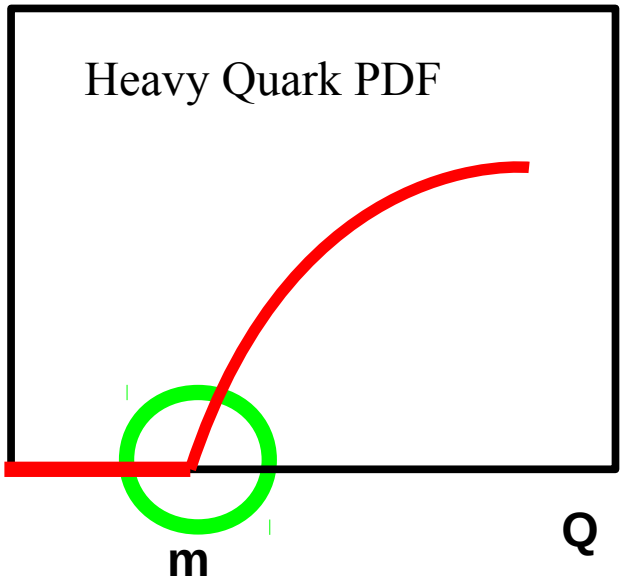


NLO Matching Condition

$$f_b^5(x,\mu) = \left(\frac{\alpha_S}{2\pi}\right)\left[P_{1,0} + P_{1,1}\log\left(\frac{\mu^2}{m_b^2}\right)\right] \otimes f_g^4(x,\mu)$$

Zero at NLO

DGLAP kernel

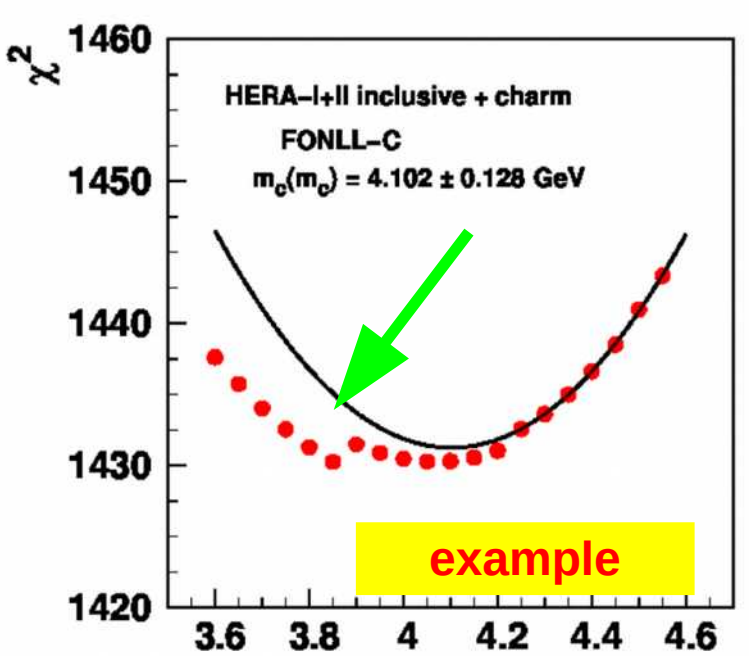


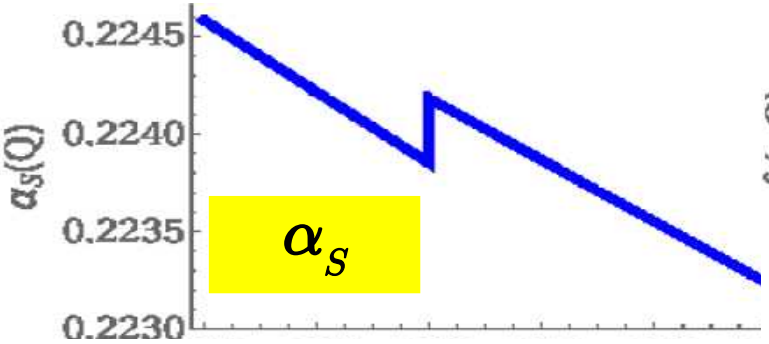
Beyond NLO Matching Condition

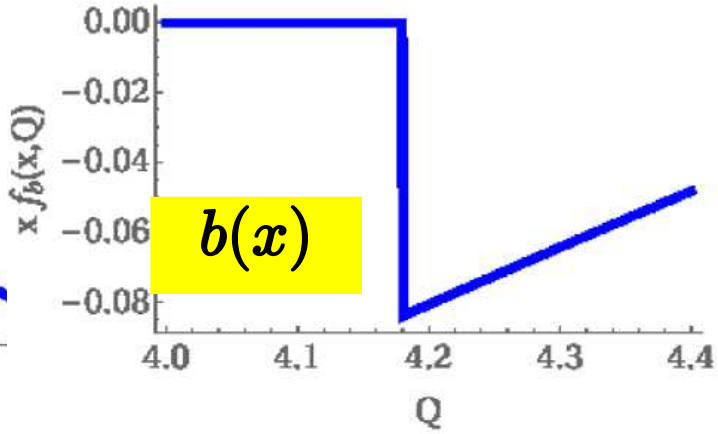
$$f_b^5(x,\mu) = \left(\frac{\alpha_S}{2\pi}\right)^{\mathbf{N}} \left[P_{1,0} + P_{1,1}\log\left(\frac{\mu^2}{m_b^2}\right)\right] \otimes f_g^4(x,\mu)$$

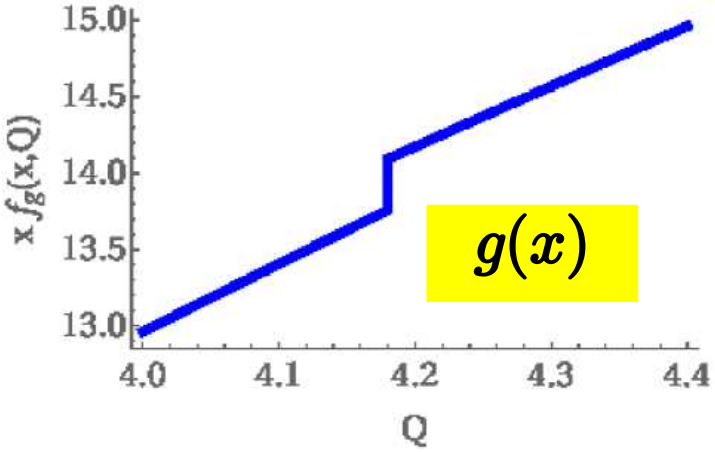
Non-Zero at +NLO

Discontinuities are Unavoidable



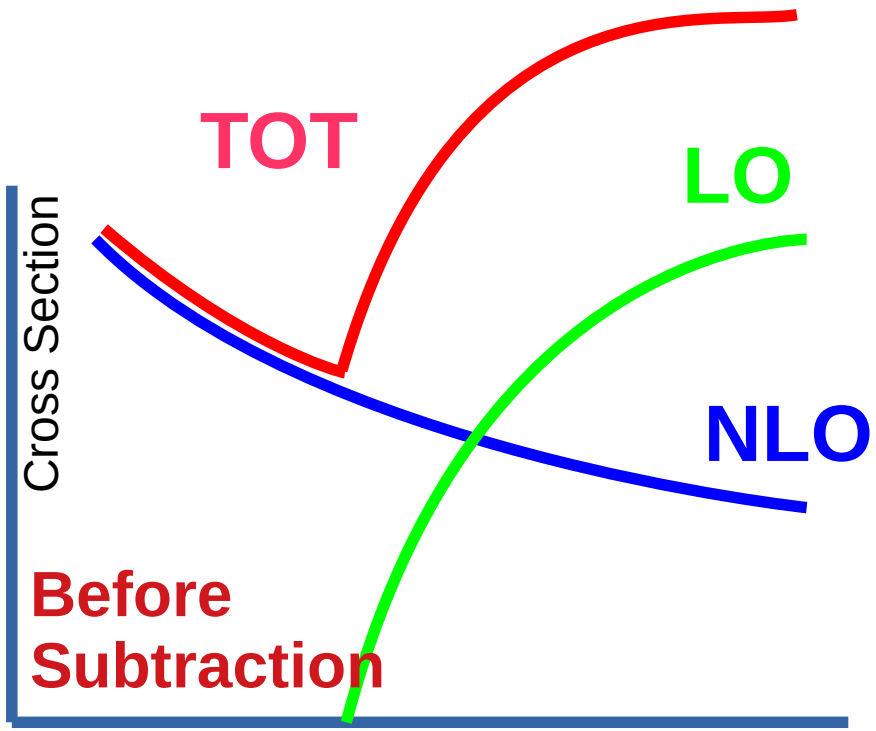


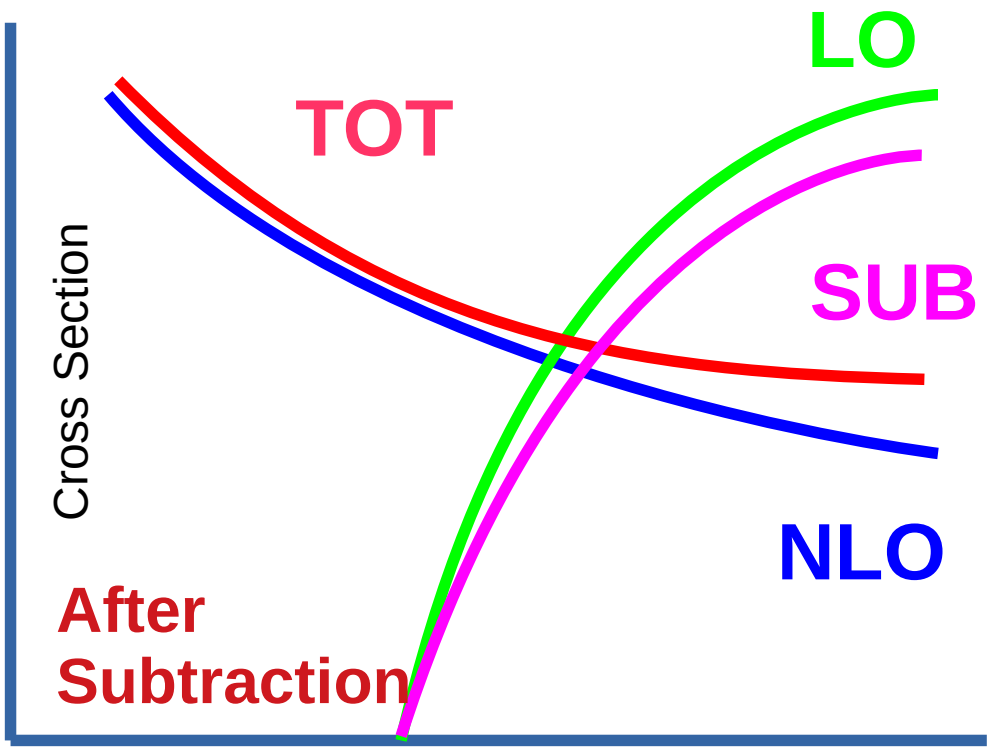


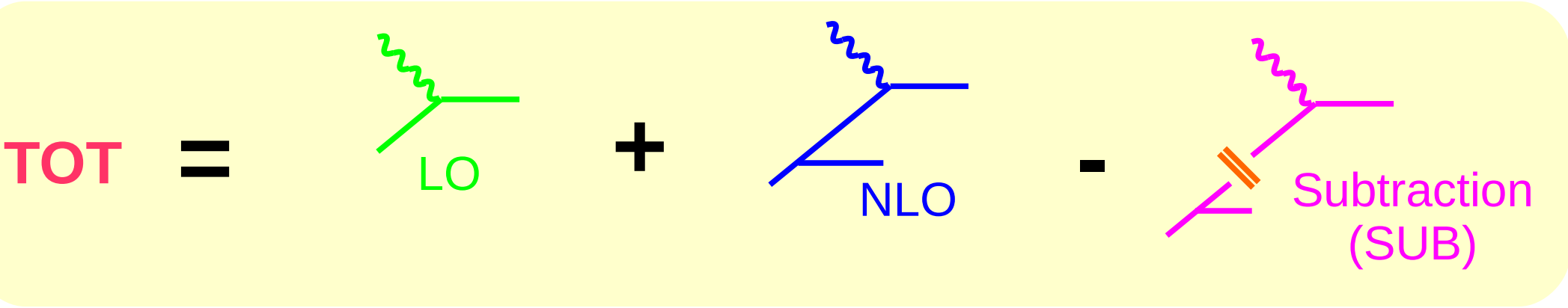


$\mu=m$ … is no longer a special B.C.

VFNS addresses "Double Counting" via the elegance of QCD







SOLUTION: shift heavy quark matching scale

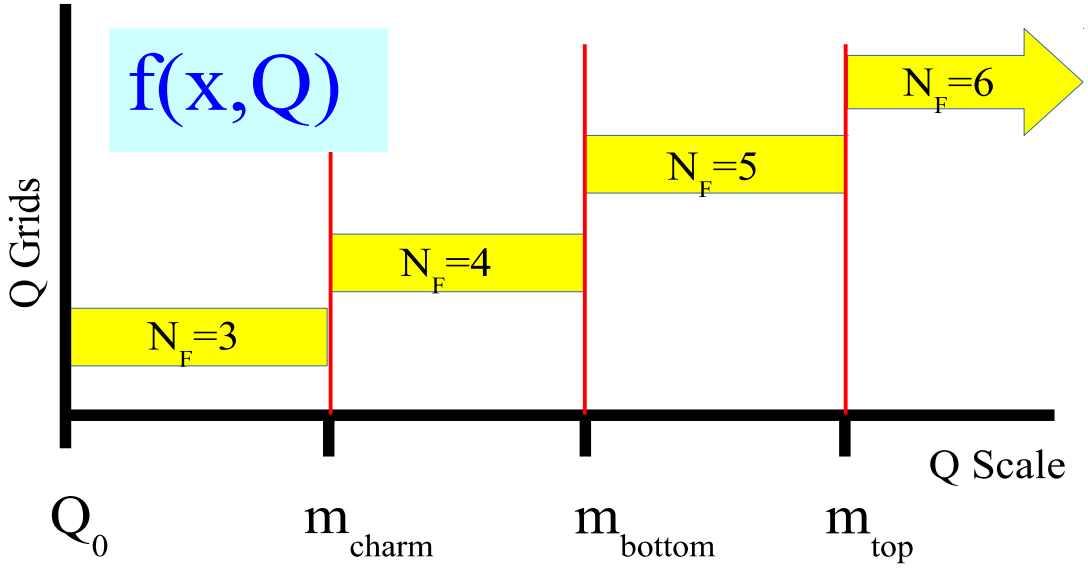
We can adjust the matching scale for the heavy quark PDF transition

APFEL Features

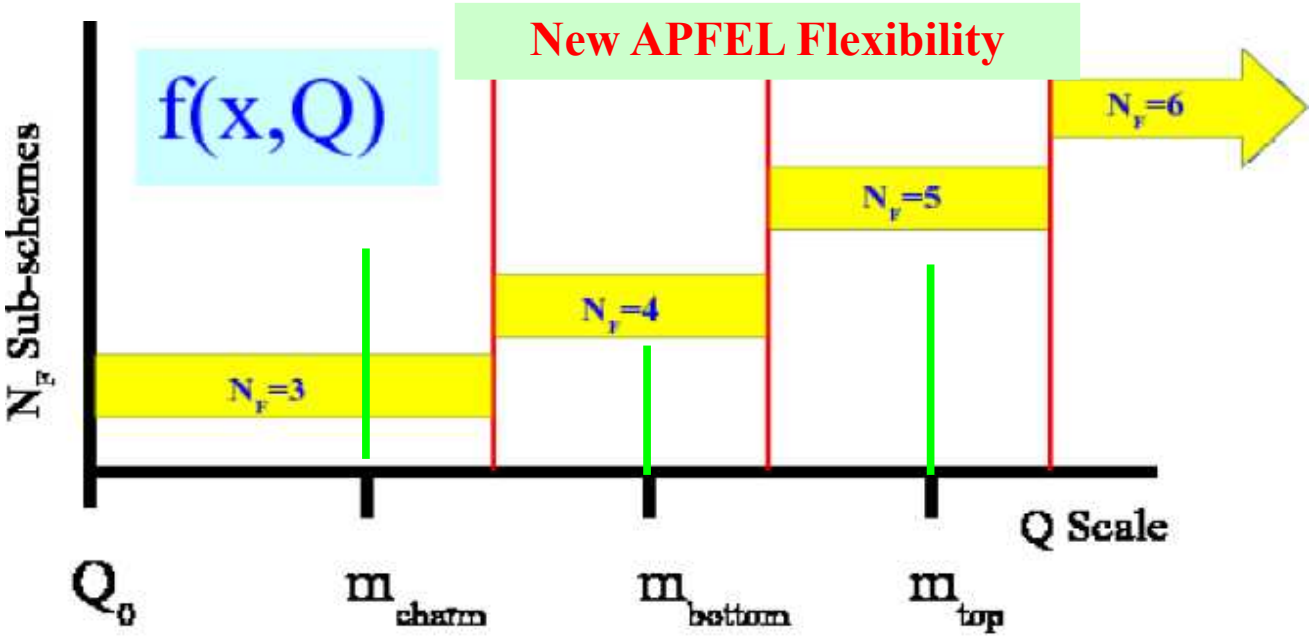
Ability to adjust matching scale $\mu_{c,b}$

Need to compute proper boundary conditions at NLO/NNLO

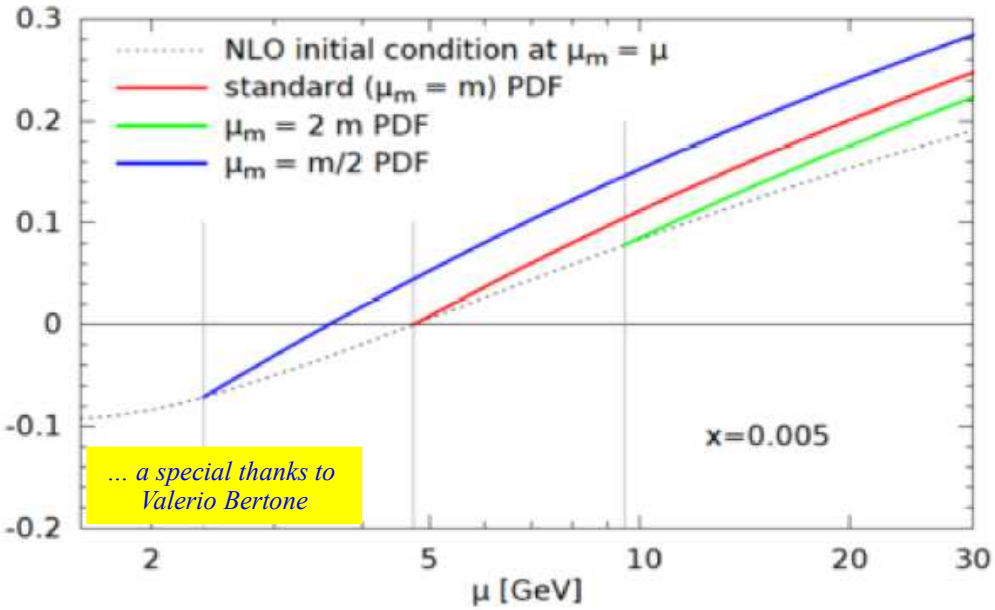
Traditional VFNS



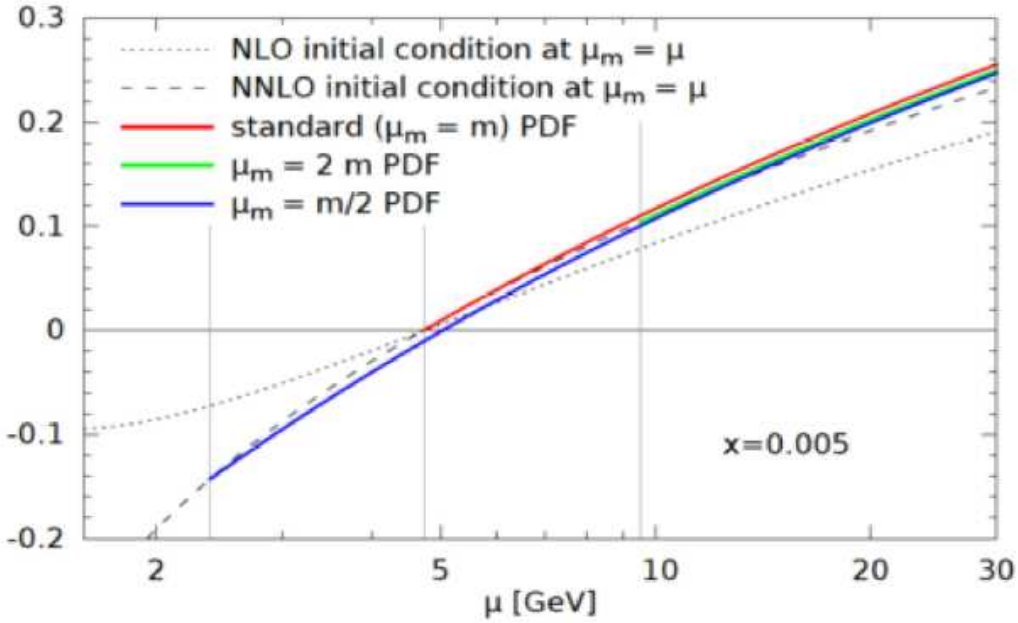
New APFEL Flexibility



The matching conditions are non-trivial



... a special thanks to Valerio Bertone



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Zero at NLO

DGLAP kernel

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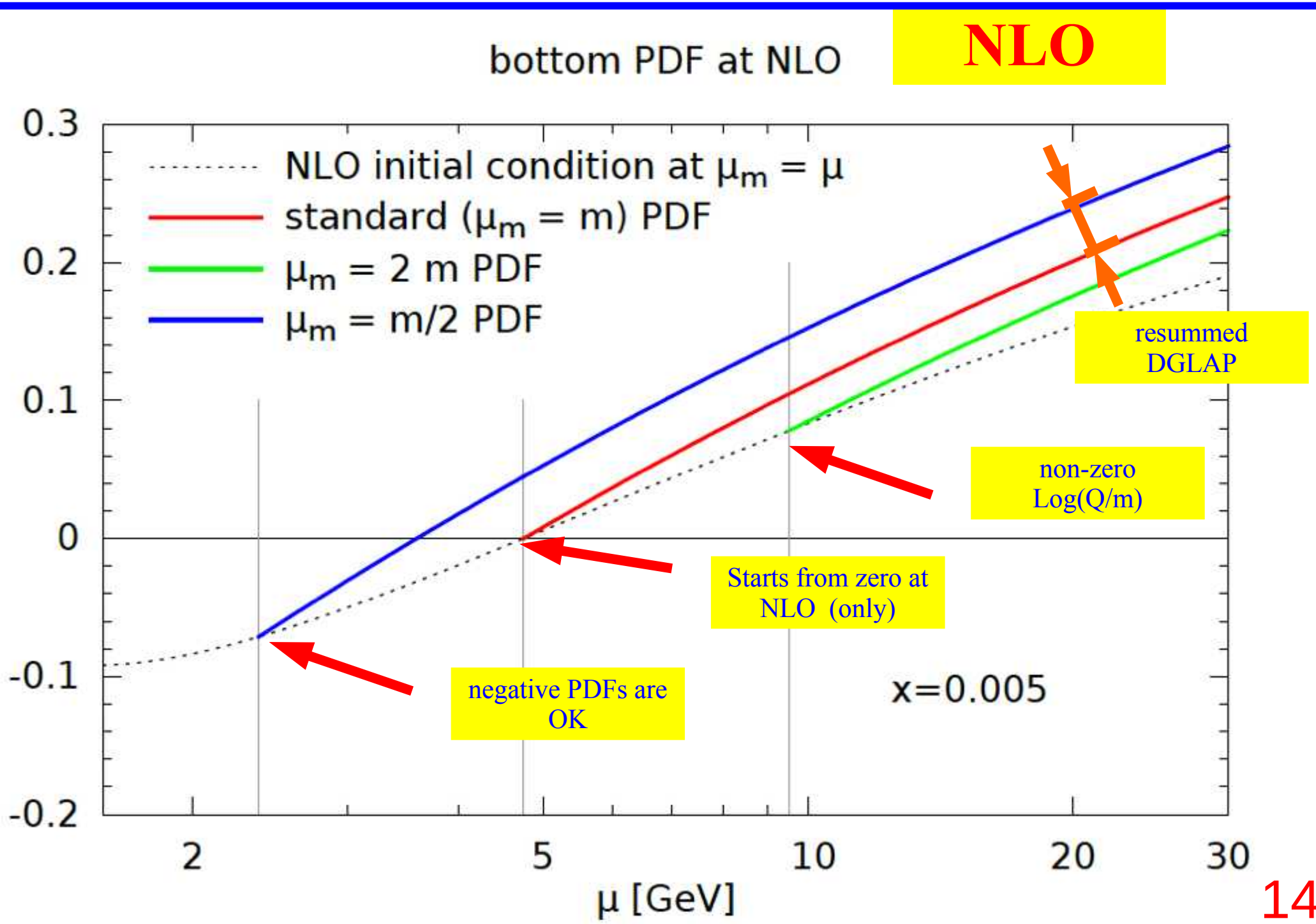
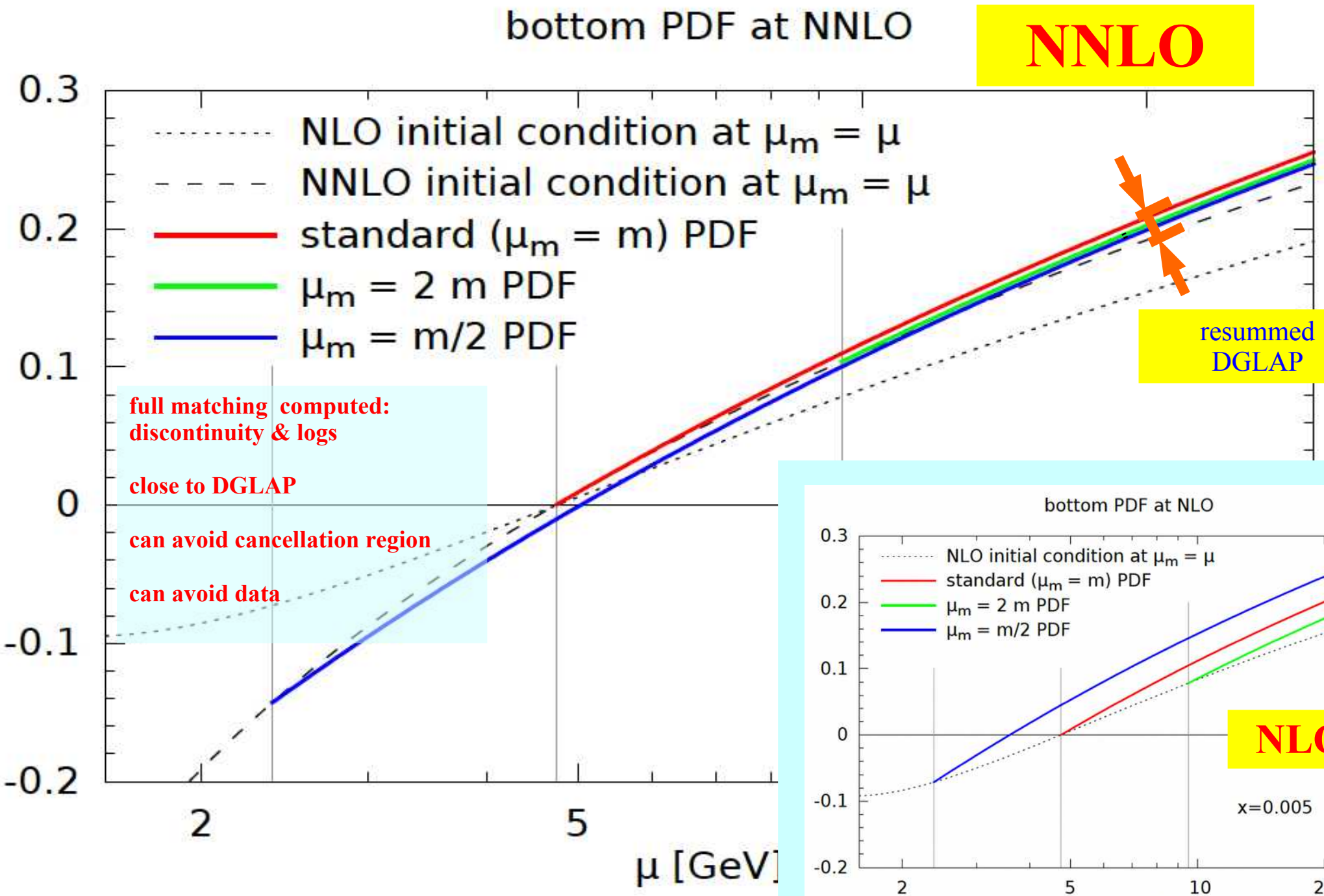
The matching conditions are non-trivial

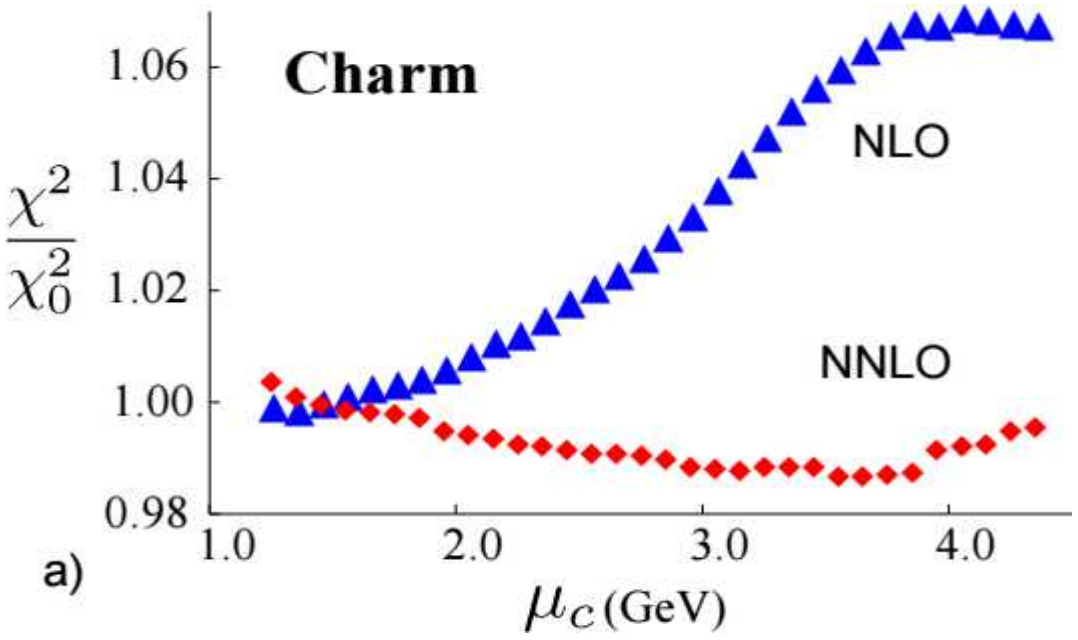


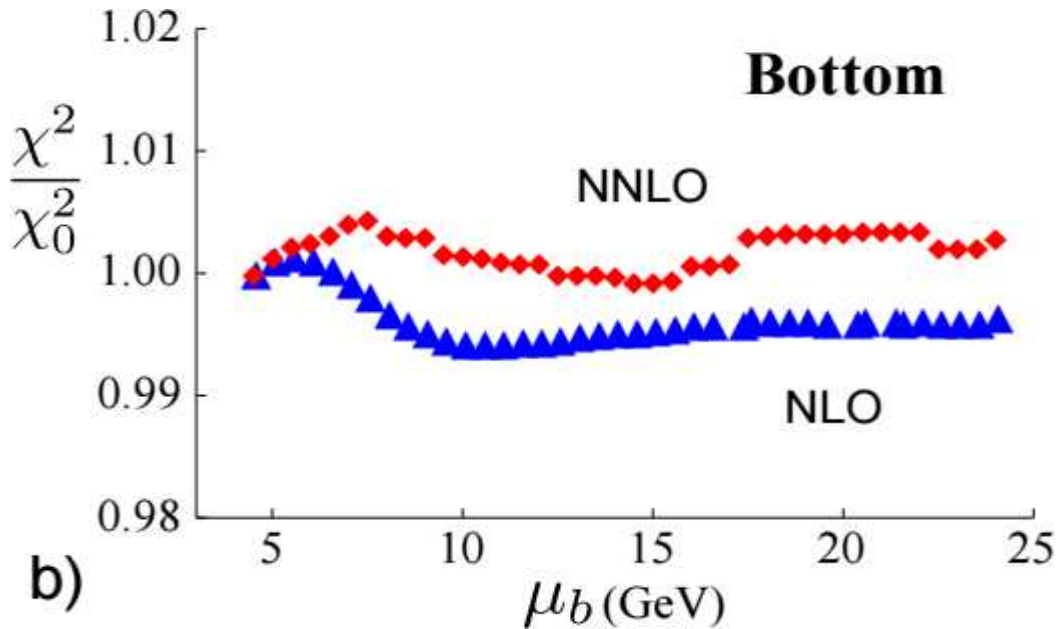
The matching conditions are non-trivial, especially at NNLO



Let's try with a real fit: Focus on HERA Data

Charm NLO $\mu_c =$	$1\,m_c$	$2\,m_c$	$3\,m_c$
Charm cross section H1-ZEUS combined [36]	46 / 47	61 / 47	54 / 47
H1 F2 Beauty Vertex [35]	3.1 / 12	2.8 / 12	2.7 / 12
Beauty cross section ZEUS Vertex [37]	12 / 17	12 / 17	12 / 17
HERA1+2 CCep [34]	44 / 39	44 / 39	45 / 39
HERA1+2 CCem [34]	52 / 42	47 / 42	48 / 42
HERA1+2 NCem [34]	220 / 159	228 / 159	227 / 159
HERA1+2 NCep 820 [34]	65 / 70	70 / 70	68 / 70
HERA1+2 NCep 920 [34]	414 / 377	433 / 377	471 / 377
HERA1+2 NCep 460 [34]	221 / 204	217 / 204	225 / 204
HERA1+2 NCep 575 [34]	216 / 254	224 / 254	222 / 254
Correlated χ^2 total (charm)	86 (10.5)	91 (12.5)	105 (11.3)
Log penalty χ^2 total (charm)	+6.7 (+0.1)	-0.7 (-0.4)	-1.2 (-0.2)
Total χ^2 / dof	1386 / 1207	1430 / 1207	1479 / 1207





Lessons so far ….

If we have data/constraints across a wide Q range:

At NLO, need to match near $\mu_c \sim m_c$ for charm

VFNS w/ DGLAP resums higher logs; these are important

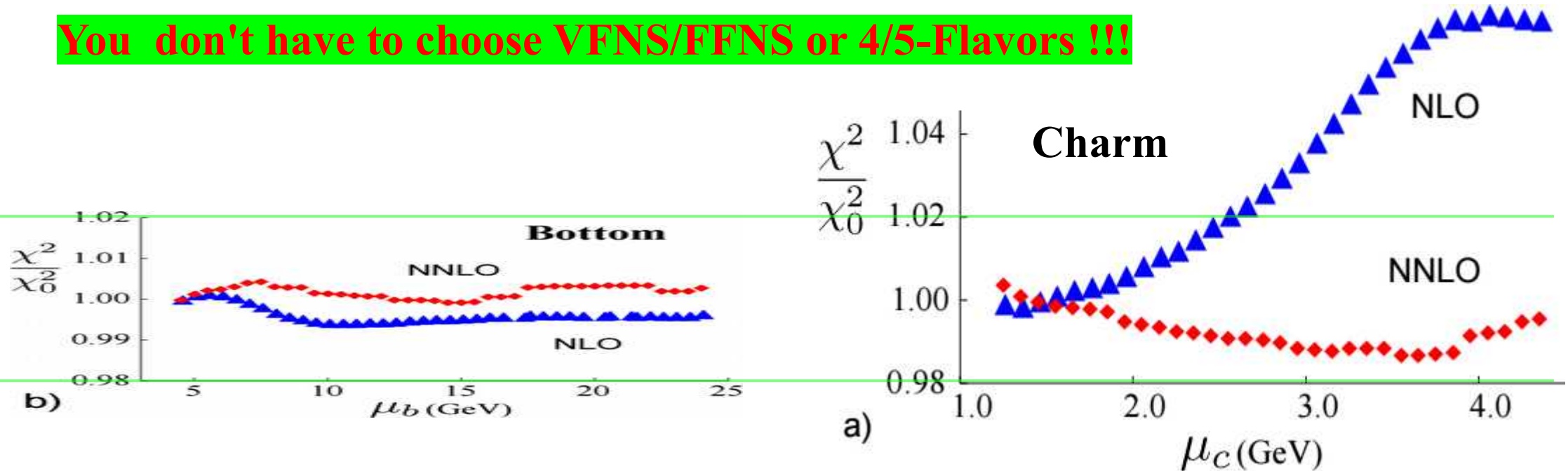
At NNLO, we have greater freedom where to match both $\mu_{c,b}$

We can use this freedom to avoid

i) discontinuities in the middle of data sets

ii) delicate cancellations near $\mu_{c,b} \sim m_{c,b}$

You don't have to choose VFNS/FFNS or 4/5-Flavors !!!



One more idea

A proposal: Consider N_F dependent PDF

Builds upon the previous...

Simplification:

Match at $\mu_{c,b} \sim m_{c,b}$,

but switch at arbitrary scale

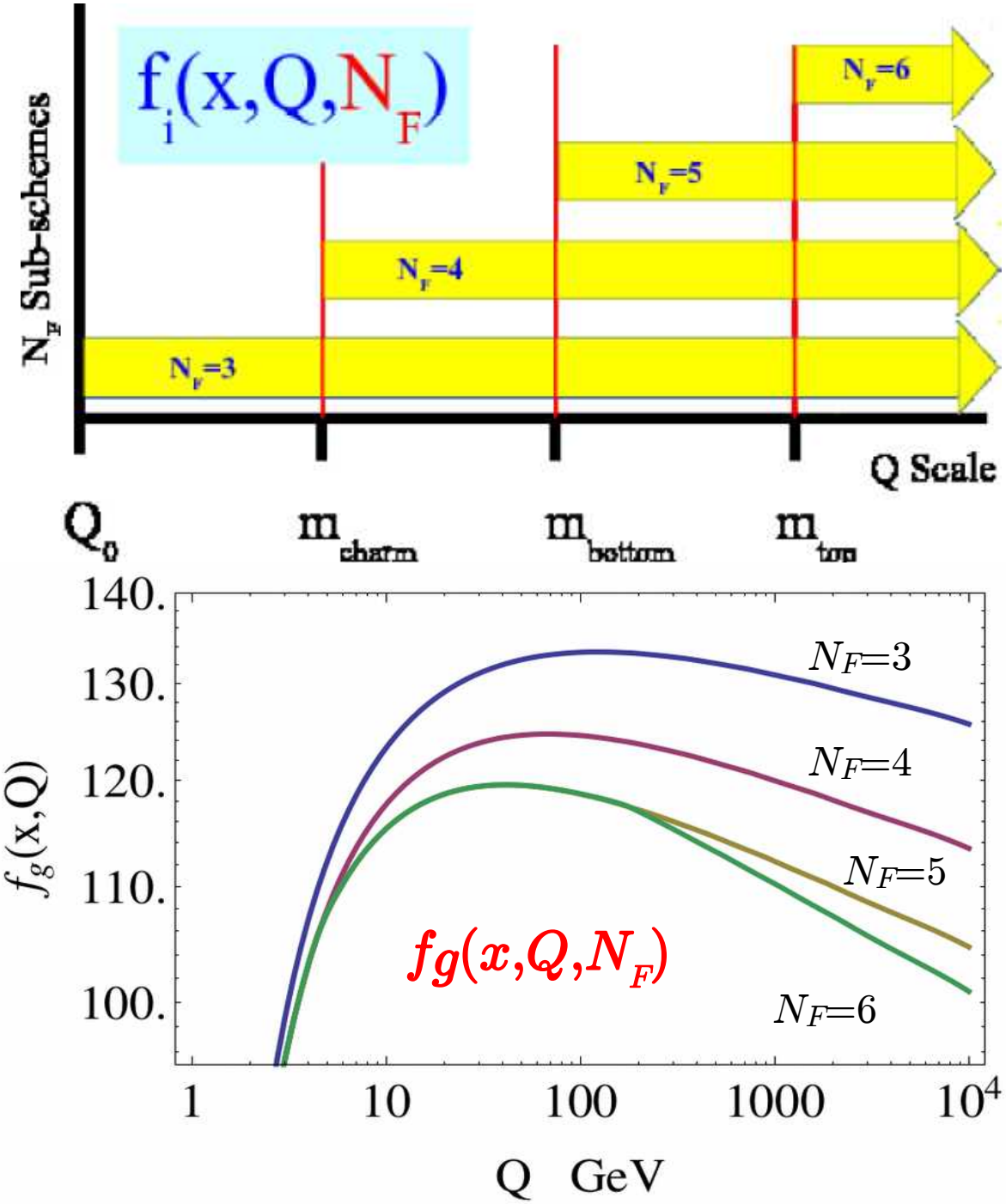
Advantages:

* avoid discontinuities in data
* avoid delicate cancellations

and

* minimal set of PDF grids

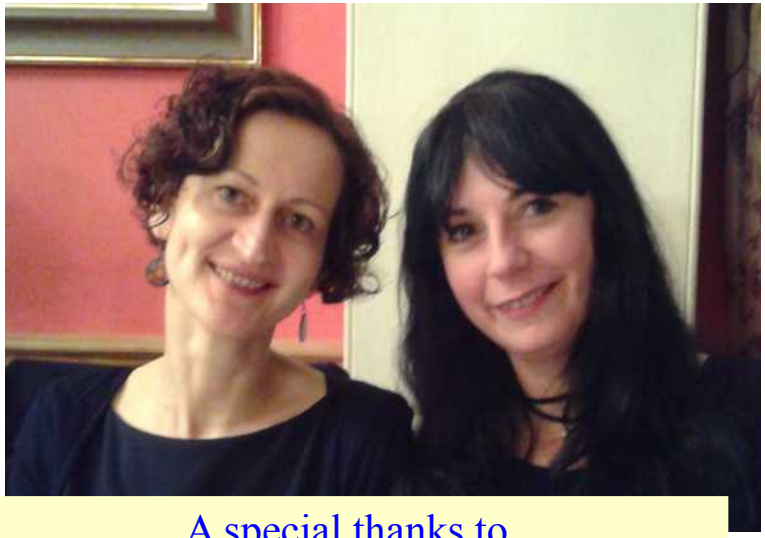
New tool opens up many possibilities



Summary

Thanks to my xFitter colleagues

xFitter Meeting: Krakow March 2018



A special thanks to
former xFitter conveners:
Ringaile Placakyte & Voica Radescu

Summary

xFitter project - a multi-functional QCD framework well integrated into the high energy community (both, experimental and theory) www.xFitter.org

→ many active developments thanks to the close collaboration with experiments and theory groups

→ technical updates include usage of GitLab and HEPFORGE

→ **xfitter-2.0.0** is latest release *(many ongoing developments)* **Frozen Frog**

→ over 30+ public results obtained using xFitter (main applications are from LHC)

→ several published dedicated physics studies (developers team publications), more studies are ongoing

→ foreseen future physic (low-x phenomenology, nuclear PDF, etc...) and technical developments (improved user interface for parametrisation, data cards, python interface, etc...)

→ useful for future projects, and room for suggestions and contributions

→ Heavy Flavor Thresholds Study: valuable insight on VFNS/FFNS issues

we welcome new ideas and developers :)

www.xfitter.org

Back-up Slides

BACKUP

Charm NNLO $\mu_c =$	$1\,m_c$	$2\,m_c$	$3\,m_c$
Charm cross section H1-ZEUS combined	45 / 47	50 / 47	50 / 47
H1 F2 Beauty Vertex	3.5 / 12	3.5 / 12	3.3 / 12
Beauty cross section ZEUS Vertex	13 / 17	13 / 17	13 / 17
HERA1+2 CCep	43 / 39	43 / 39	43 / 39
HERA1+2 CCem	55 / 42	55 / 42	54 / 42
HERA1+2 NCem	217 / 159	217 / 159	217 / 159
HERA1+2 NCep 820	66 / 70	64 / 70	66 / 70
HERA1+2 NCep 920	444 / 377	433 / 377	442 / 377
HERA1+2 NCep 460	218 / 204	219 / 204	216 / 204
HERA1+2 NCep 575	220 / 254	218 / 254	219 / 254
Correlated χ^2 total (charm)	111 (10.8)	109 (11.3)	110 (14.5)
Log penalty χ^2 total (charm)	+18 (-1.1)	+18 (-1.8)	+15 (-1.8)
Total χ^2 / dof	1453 / 1207	1439 / 1207	1447 / 1207

Bottom NNLO $\mu_b =$	$1\,m_b$	$3\,m_b$	$5\,m_b$	$10\,m_b$	$14\,m_b$
Charm cross section H1-ZEUS combined	45 / 47	45 / 47	45 / 47	45 / 47	45 / 47
H1 F2 Beauty Vertex	3.5 / 12	3.7 / 12	3.7 / 12	3.6 / 12	3.6 / 12
Beauty cross section ZEUS Vertex	13 / 17	13 / 17	13 / 17	13 / 17	14 / 17
HERA1+2 CCep	43 / 39	43 / 39	43 / 39	42 / 39	42 / 39
HERA1+2 CCem	55 / 42	55 / 42	55 / 42	55 / 42	56 / 42
HERA1+2 NCem	217 / 159	216 / 159	220 / 159	218 / 159	218 / 159
HERA1+2 NCep 820	66 / 70	66 / 70	66 / 70	66 / 70	66 / 70
HERA1+2 NCep 920	444 / 377	445 / 377	445 / 377	451 / 377	453 / 377
HERA1+2 NCep 460	218 / 204	219 / 204	219 / 204	217 / 204	218 / 204
HERA1+2 NCep 575	220 / 254	219 / 254	219 / 254	219 / 254	219 / 254
Correlated χ^2 total (bottom)	111 (0.9)	112 (0.9)	112 (0.9)	114 (0.9)	116 (0.9)
Log penalty χ^2	+18	+17	+15	+18	+18
Total χ^2 / dof	1453 / 1207	1453 / 1207	1457 / 1207	1463 / 1207	1470 / 1207

Introduction

Precise knowledge of the PDFs are essential for predictions at hadron colliders

QCD factorisation:

$$\sigma \approx \hat{\sigma} \otimes PDF$$

Experimental Data:

→ a large variety of data from fixed-target and collider experiments

Theory:

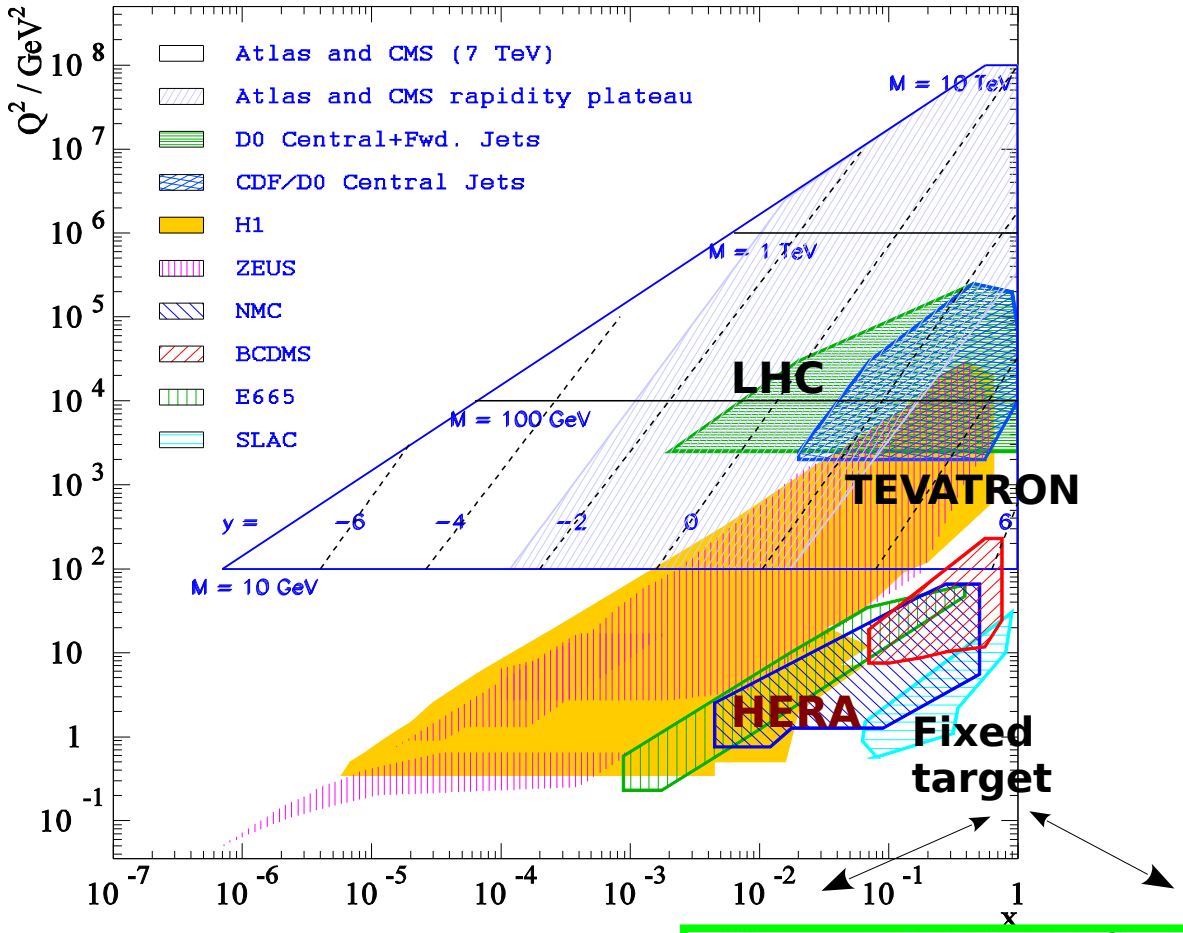
→ intense theoretical developments

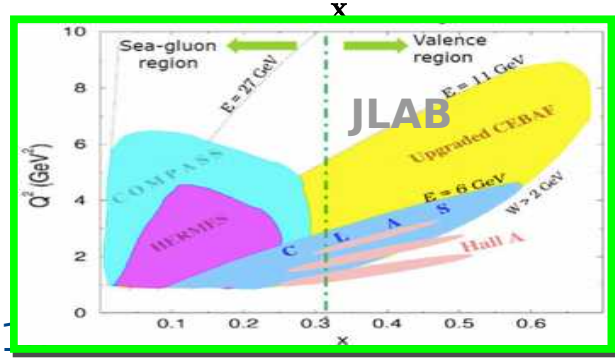
QCD Analysis:

→ available PDFs: CT/CJ, MMHT, NNPDF, ABM, HERAPDF, JR

… and **Tools**

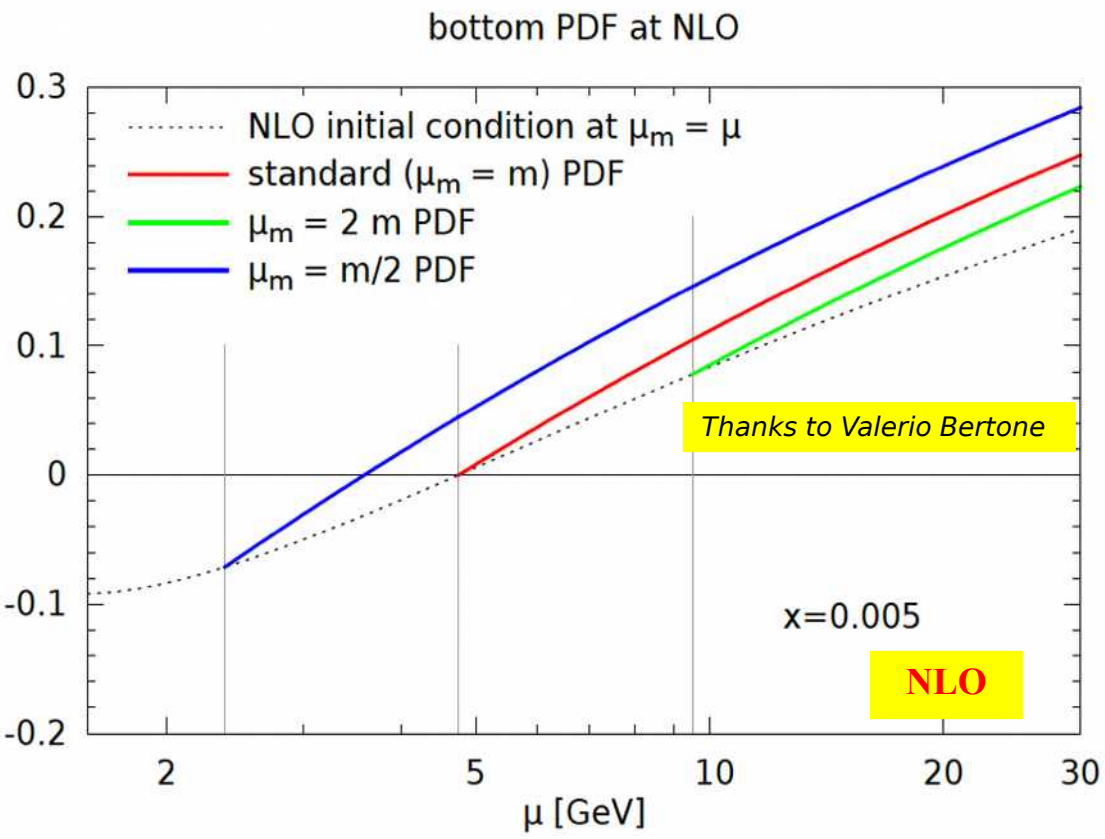
kinematic plane of the experimental data (in x,Q^2)



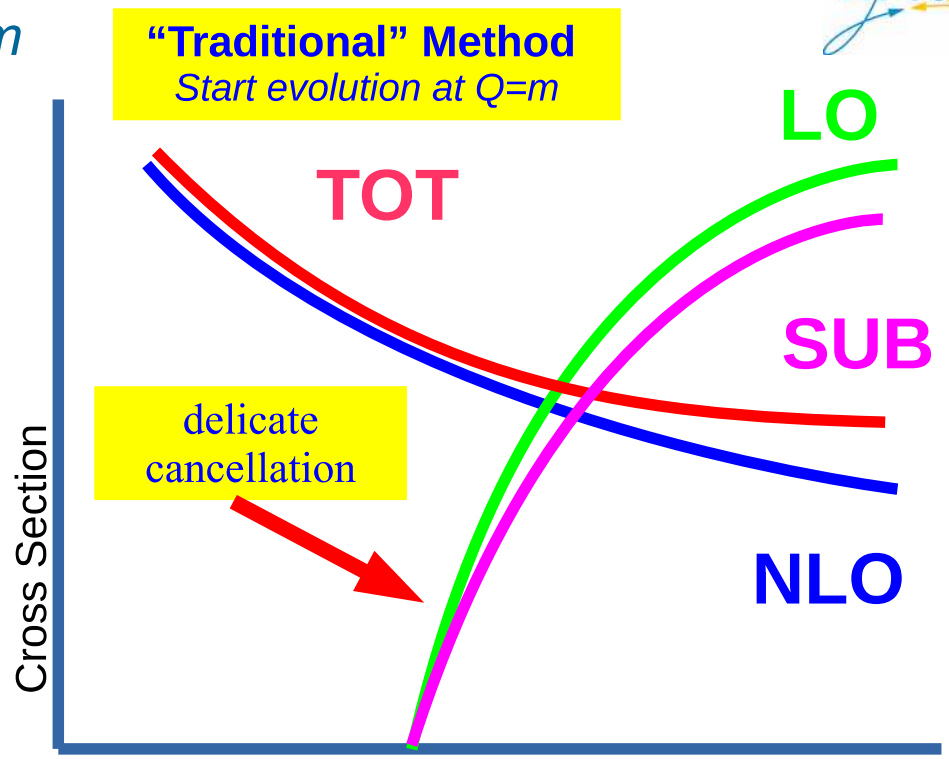


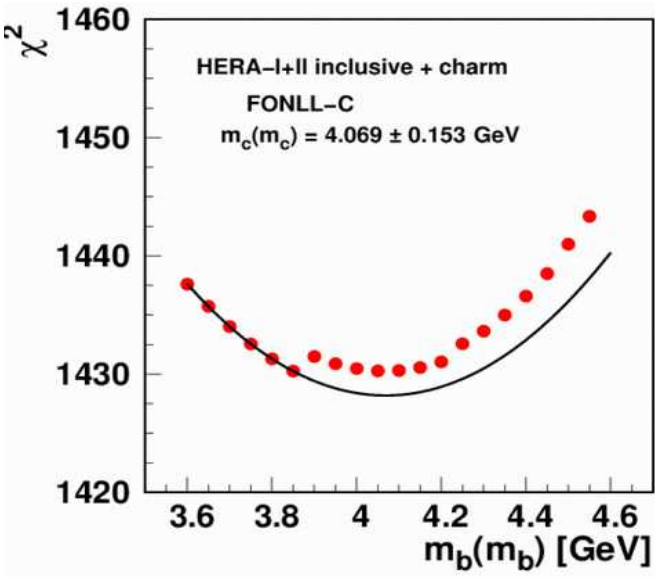
Variable Matching Scale μ_m

→ Freedom to Choose Matching Scale μ_m
→ Avoid delicate cancellations
→ Select scale “away” from data



A theoretical laboratory ...
1) flexibly interpolate between VFNS and FFNS
2) answer many outstanding theoretical debates with numerical results!!!





Variable Matching Scale μ_m

APFEL has a new feature

We can adjust the matching scale for the heavy quark PDF transition

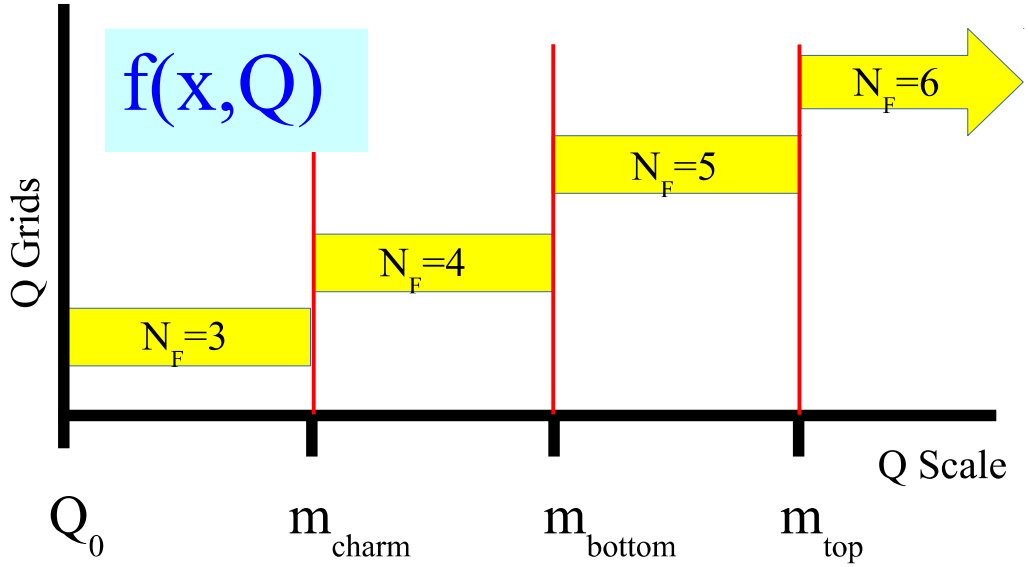
What are the benefits?

1) **avoid discontinuities in the middle of data sets**

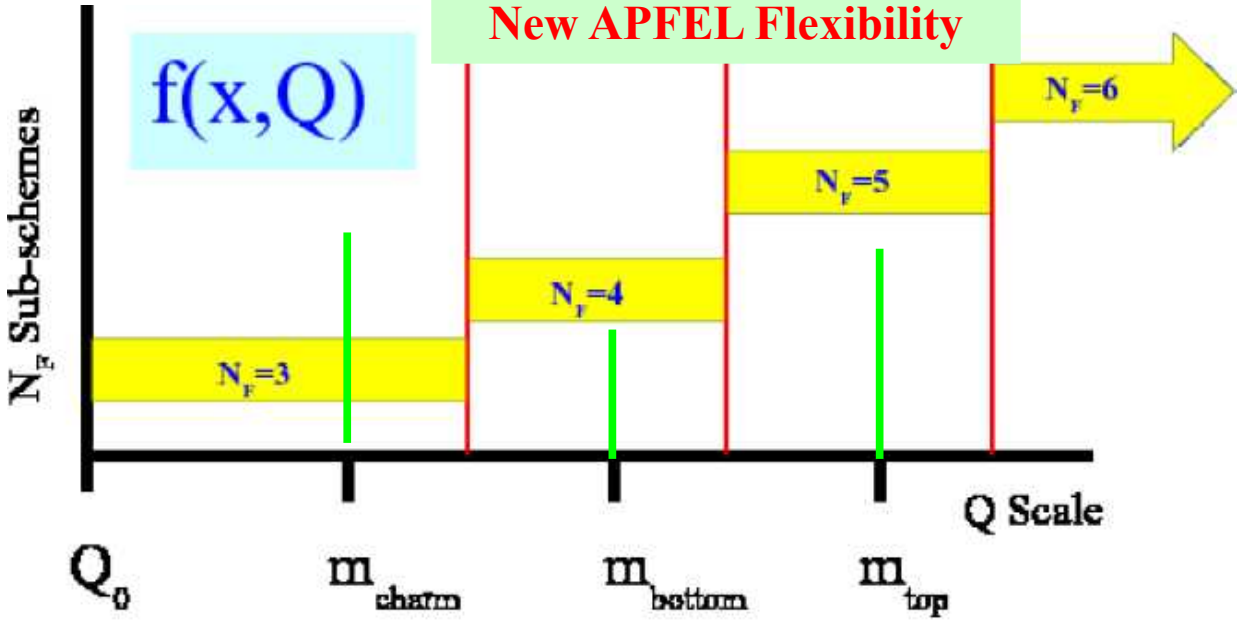
2) **avoid delicate matching**

in region $\mu \sim m_{c,b}$

Traditional VFNS



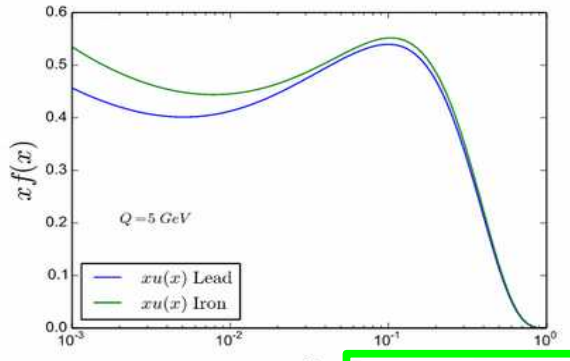
New APFEL Flexibility

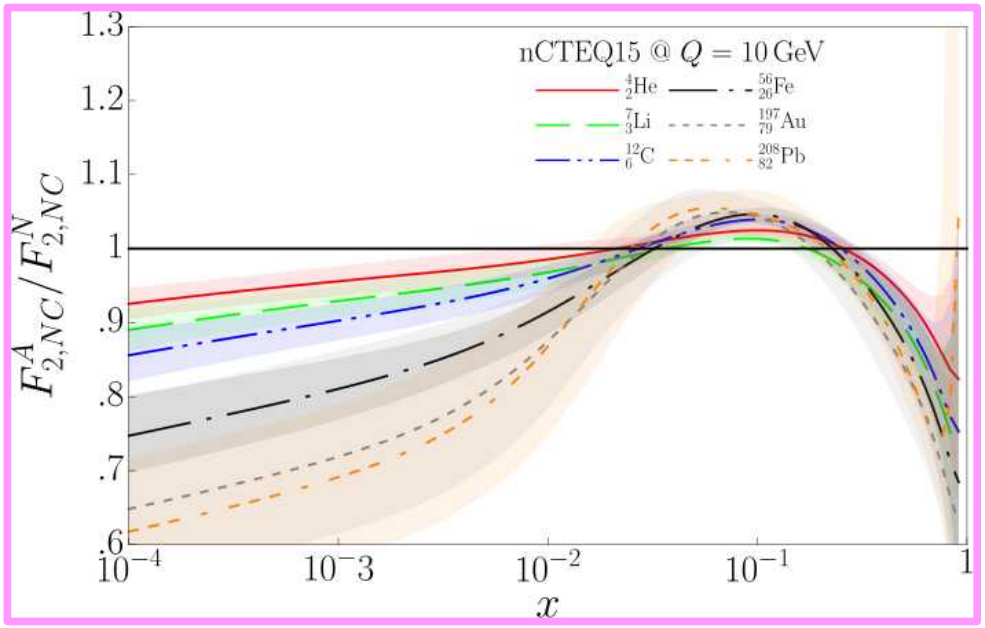


Tools for PDF Analysis

- → LHAPDF Standard
- → Interface to Python
- → ManeParse Mathematica Package

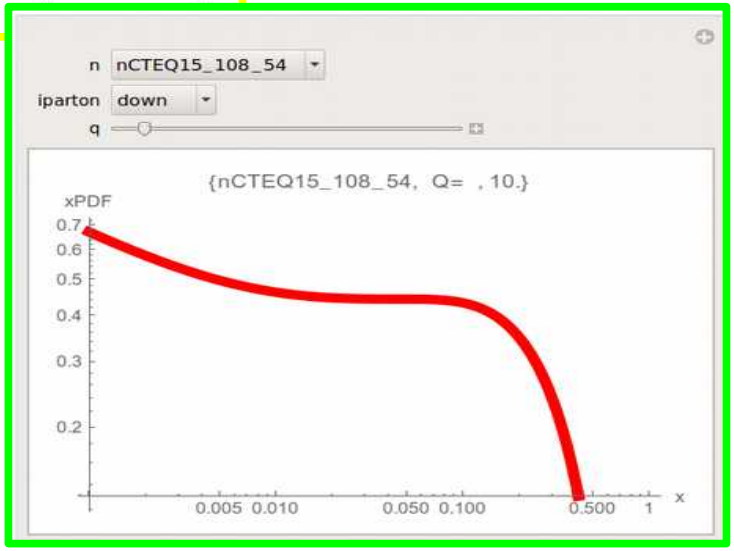
```
# loop over Q values
for iq,qq in enumerate(Qval):
    # divide it into two subplot vertically
    subplot2grid((1,2),(0,iq))
    semilogx(xvalues, fulllead_x_vals[qq], label='$xu(x)\ \
    semilogx(xvalues, fulliron_x_vals[qq], label='$xu(x)\ \
    legend(loc=3)
    text(2e-3,0.2, "$Q={}\ GeV$".format(qq))
    xlabel('$x$',fontsize=18)
    ylabel('$xf(x)$',fontsize=18)
```

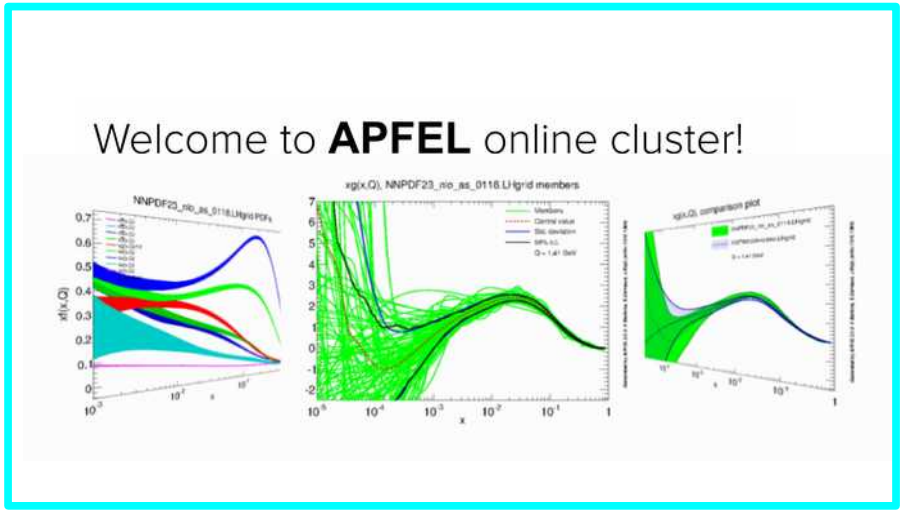




Thanks to Florian Lyonnet & Eric Godat

PDF Set
MSTW2008nnlo68cl [7]
CT14nnlo [8]
NNPDF30_nnlo_as_0118_nf_6 [9]
HERAPDF20_NLO_VAR [10]
abm12lhc_5_nnlo [11]
CJ15nlo [12]
nCTEQ15_1_1 [13]
nCTEQ15_208_82 [13]
ct10.pds [14]
ctq66m.pds [2]





Data Available at HEPforge

http://xfitter.hepforge.org/data.html

This page contains the list of publicly available experimental data sets (with corresponding theory grids if available) in the xFitter package.

To download data set please click on the arXiv link (and open/save tar.gz file).

No	Collider	Experiment	Reaction	arXiv	Readme
1	fixedTarget	bcdms	inclusiveDis	cern-ep-89-06	README
2	hera	h1	beautyProduction	0907.2643	
3	hera	h1	inclusiveDis	1012.4355	
4	hera	h1	jets	0706.3722	README
5	hera	h1	jets	0707.4057	README
6	hera	h1	jets	0904.3870	README
7	hera	h1	jets	0911.5678	README
8	hera	h1	jets	1406.4709	README
9	hera	h1zeusCombined	charmProduction	1211.1182	
10	hera	h1zeusCombined	inclusiveDis	0911.0884	
11	hera	h1zeusCombined	inclusiveDis	1506.06042	
12	hera	zeus	beautyProduction	1405.6915	
13	hera	zeus	diffractiveDis	0812.2003	
14	hera	zeus	jets	0208037	
15	hera	zeus	jets	0608048	
16	hera	zeus	jets	1010.6167	
17	lhc	atlas	drellYan	1305.4192	
18	lhc	atlas	drellYan	1404.1212	
19	lhc	atlas	jets	1112.6297	
20	lhc	atlas	jets	1304.4739	
21	lhc	atlas	topProduction	1406.5375	
22	lhc	atlas	topProduction	1407.0371	
23	lhc	atlas	wzProduction	1203.4051	
24	lhc	atlas	wzProduction	1612.03016	README
25	lhc	cms	jets	1212.6660	
26	lhc	cms	topProduction	1208.2671	
27	lhc	cms	topProduction	1211.2220	
28	lhc	cms	topProduction	cms-pas-top-11-024	
29	lhc	cms	wzProduction	1110.4973	
30	lhc	cms	wzProduction	1206.2598	
31	lhc	cms	wzProduction	1312.6283	
32	lhc	cms	wzProduction	1603.01803	
33	lhc	lhcb	beautyProduction	1306.3663	
34	lhc	lhcb	charmProduction	1302.2864	
35	lhc	lhec	inclusiveDis	1206.2913	README
36	lhc	lhec	inclusiveDis	1605.08579	README
37	tevatron	cdf	jets	0807.2204	
38	tevatron	cdf	wzProduction	0901.2169	
39	tevatron	cdf	wzProduction	0908.3914	
40	tevatron	d0cdfCombined	topProduction	1309.7570	
41	tevatron	d0	jets	0802.2400	
42	tevatron	d0	wzProduction	0702025	
43	tevatron	d0	wzProduction	1309.2591	
44	tevatron	d0	wzProduction	1312.2895	
45	tevatron	d0	wzProduction	1412.2862	

Tools for PDF determination

Available (open-source) tools for the PDF determination:

xFitter (former HERAFitter): an open-source package that provides a framework for the determination of the PDFs of the proton and for many different kinds of analyses in QCD

EPJC (2015), 75: 304, *xfitter.org*

OPENQCDRAD (ABM collaboration: numerical computation of all hard scattering cross sections (DIS structure function calculation including heavy quark contributions, W and Z production)

PRD86 (2012) 054009, *www-zeuthen.desy.de/˜alekhin/OPENQCDRAD*

APFEL (used by NNPDF): a PDF evolution library, is a computer library specialized in the solution of DGLAP evolution equations up to NNLO in QCD and to LO in QED

arXiv.1310.1394, *apfel.hepforge.org*

QCDNUM: Fast QCD Evolution and Convolution (numerically solves the evolution equations for parton densities and fragmentation functions in pQCD)

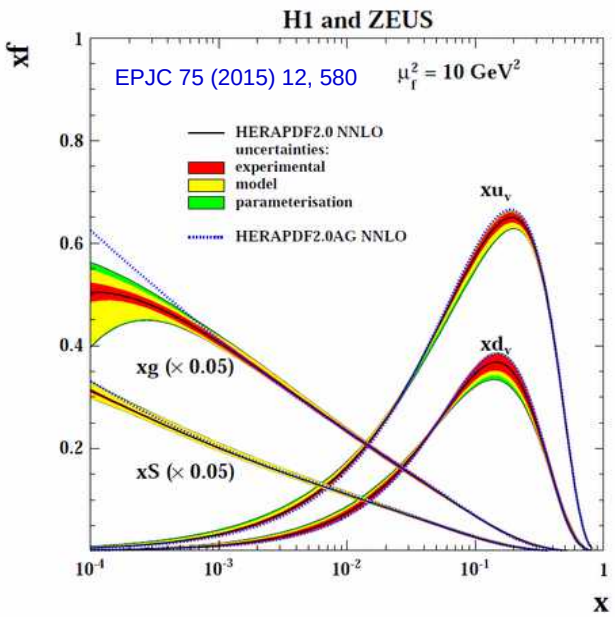
Comp.Phys.Com.182:490,2011

ALPOS: an object-oriented data to theory comparison and fitting tool (profit from and exchange with xFitter experience)
→ access from a public svn repository (via request)

http://desy.de/~britzger/alpos/

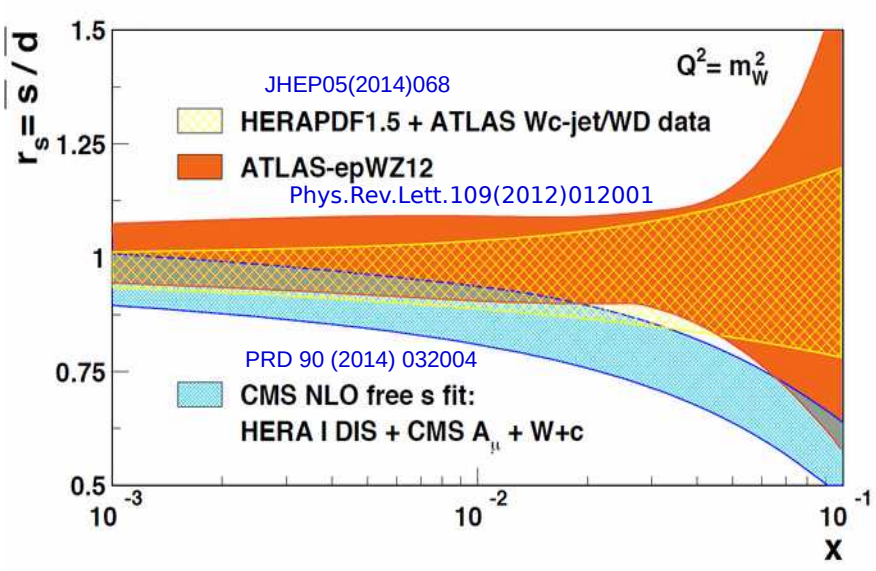
Results Obtained with xFitter: Examples

DIS inclusive processes in *ep*

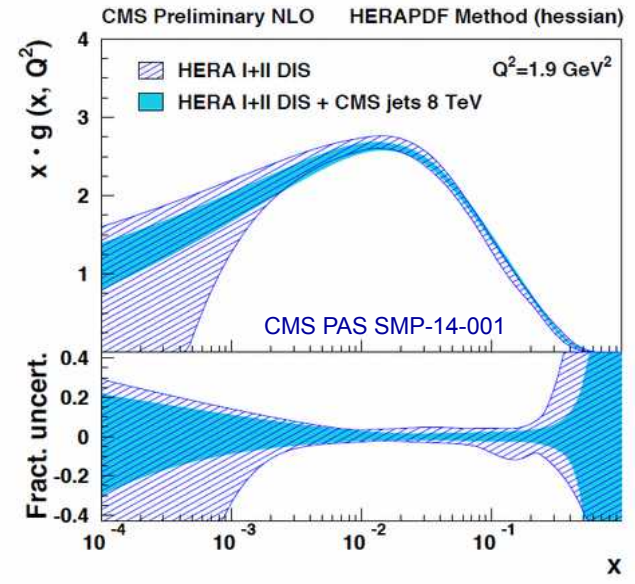


Drell-Yan processes (*pp, ppbar*)

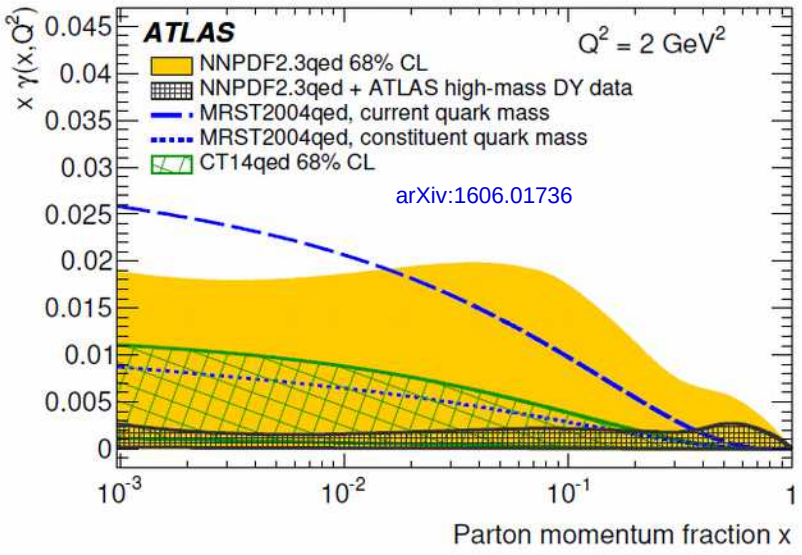
→ strange quark density determination



Jet production (*ep, pp, ppbar*)

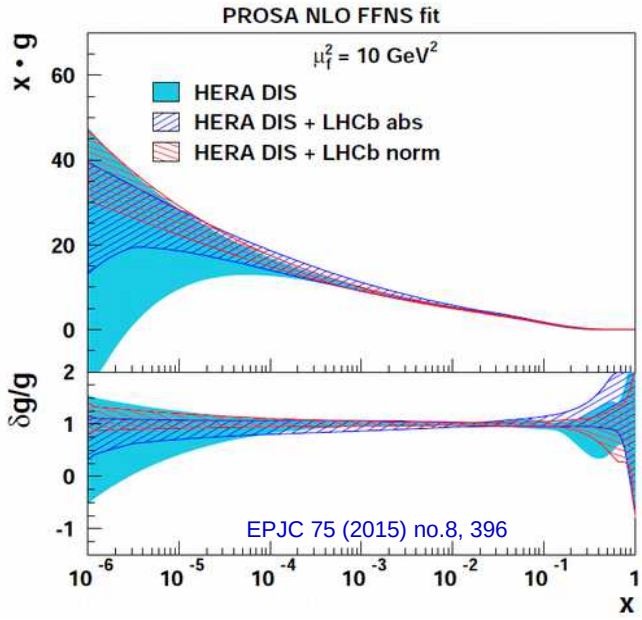


DY data sensitivity to photon PDF

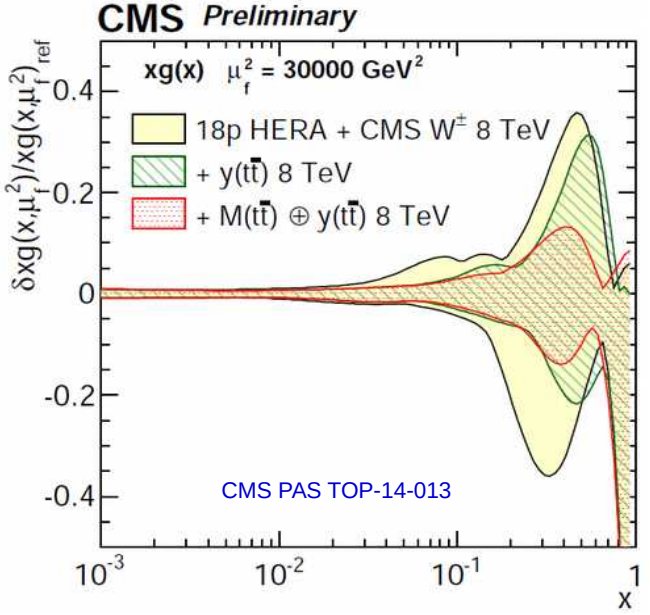


Results Obtained with xFitter: Examples

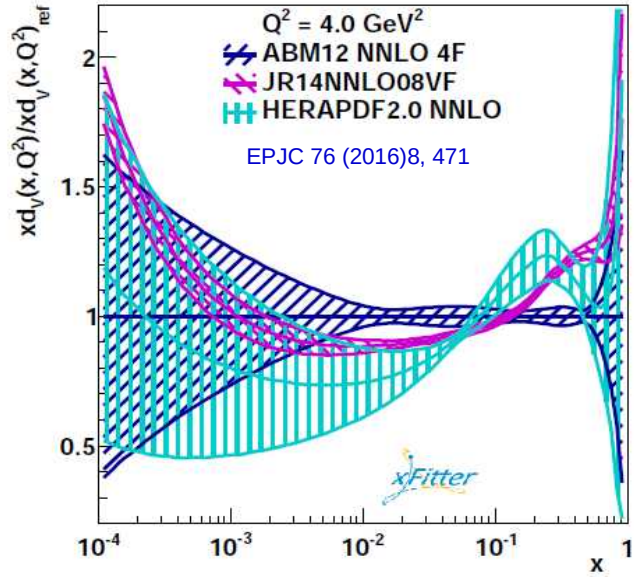
Heavy Quark production (*ep, pp, ppbar*)



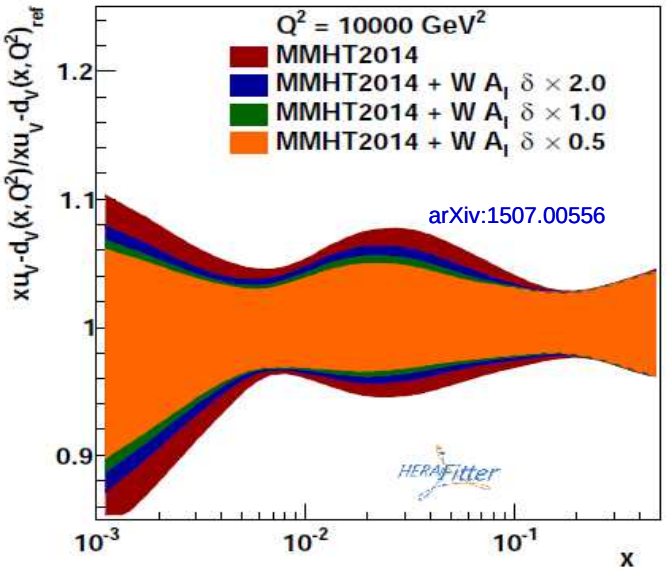
Top-quark production (*pp, ppbar*)



Evaluation of modern PDFs (benchmarking)

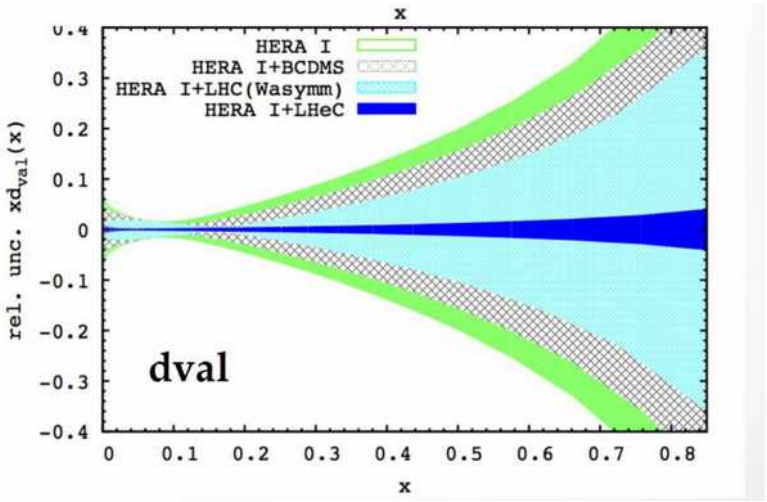


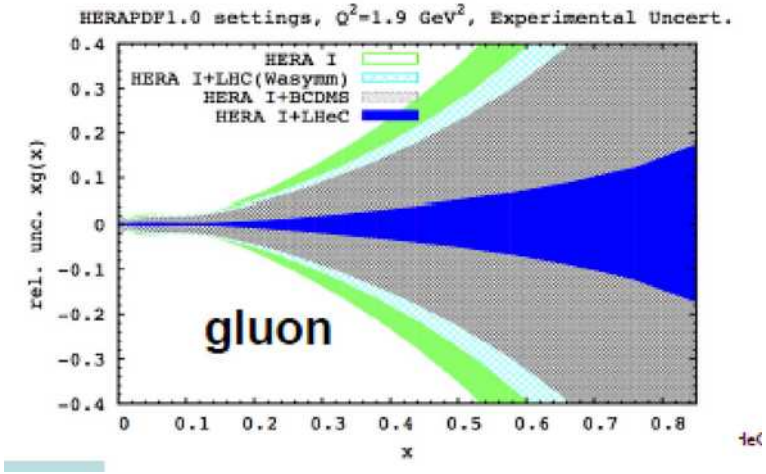
PDF4LHC report (benchmarking)



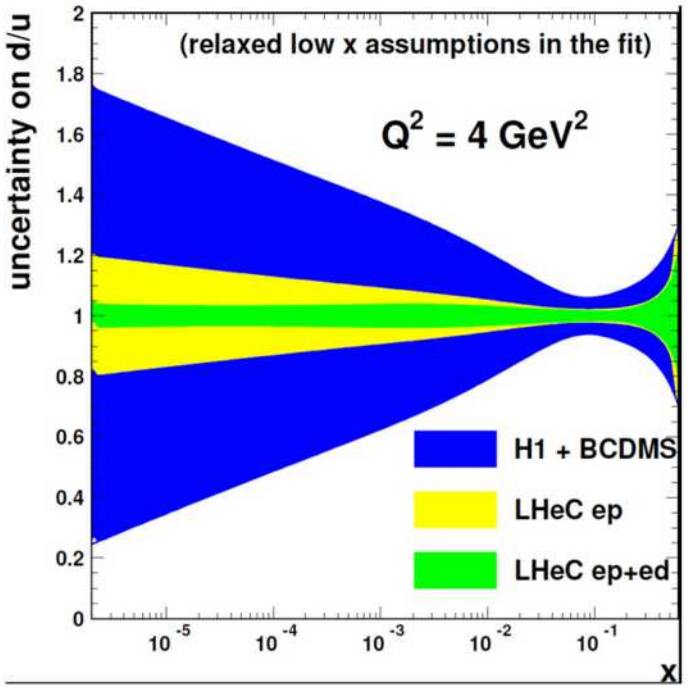
LHeC & FCCeh Studies

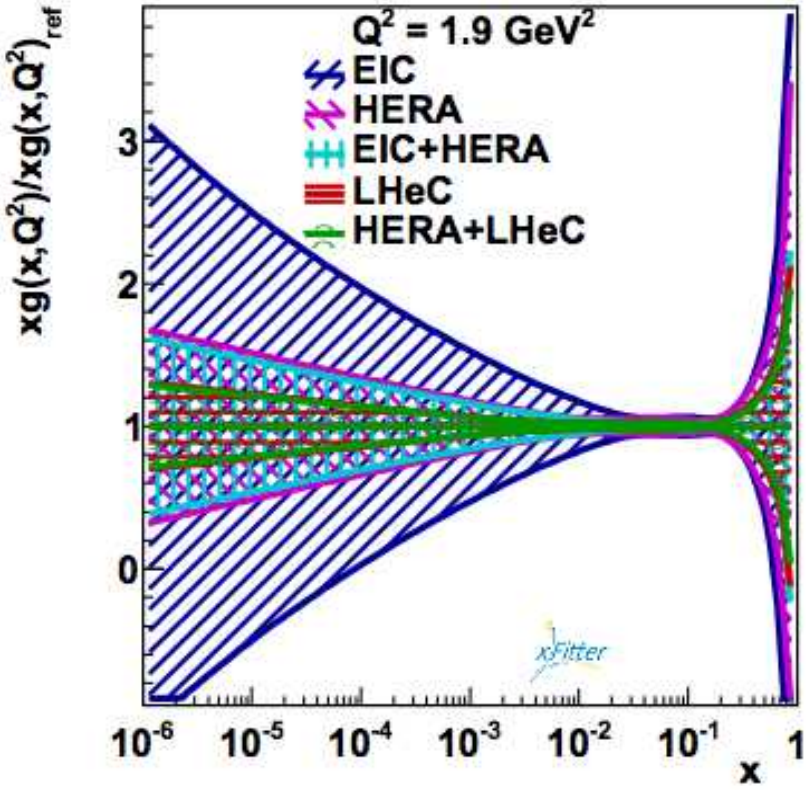
→ Compute PDFs for future facilities
→ Determine discovery reach





pseudo data available





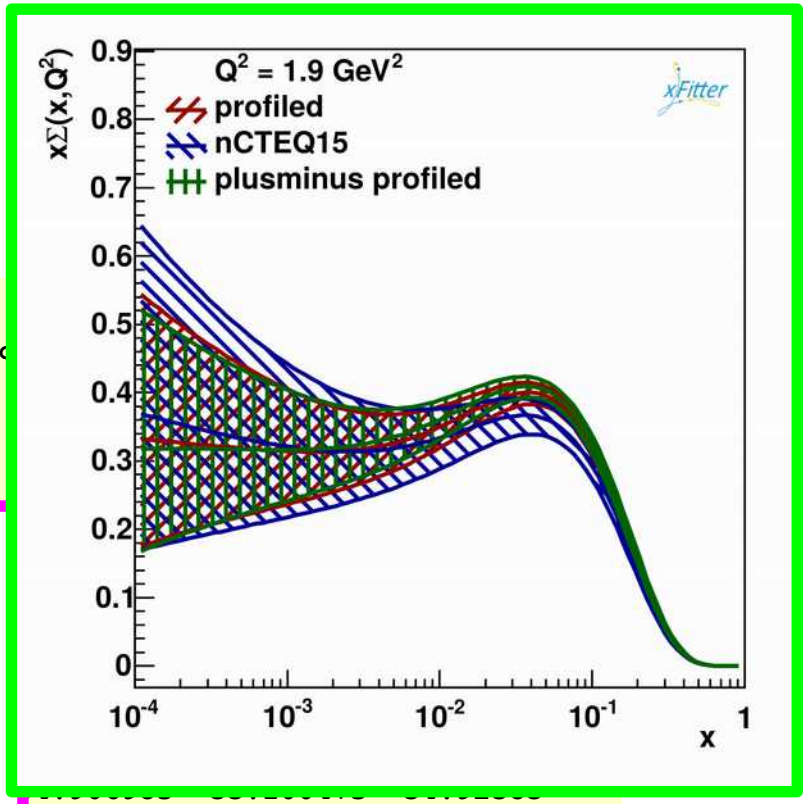
Thanks to Voica Radescu

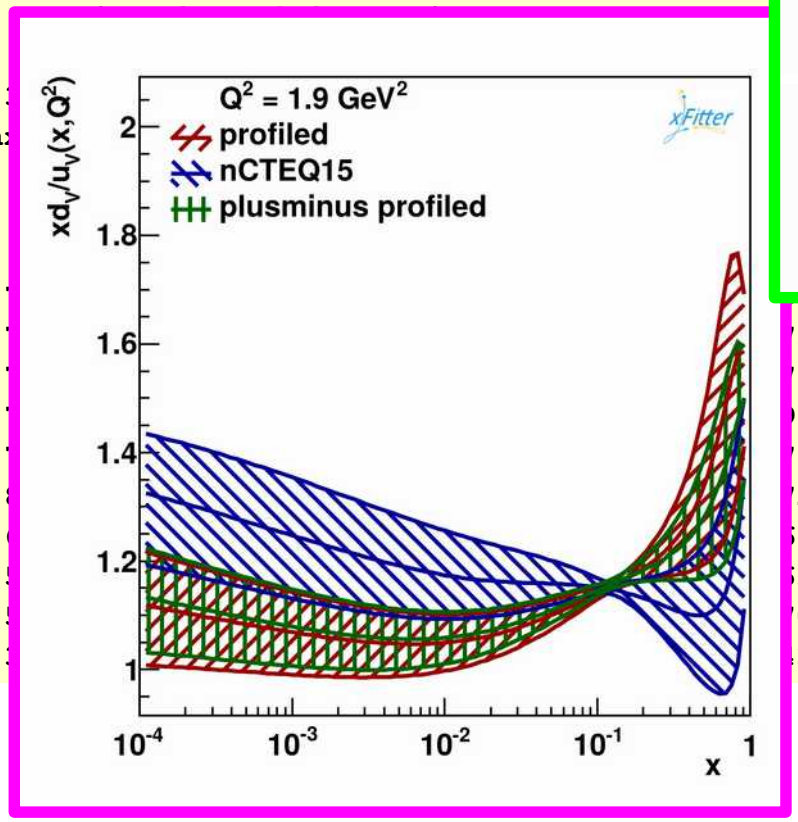
Profiling $W^{\pm}$ in Proton-Lead Collisions

→ Use nCTEQ15 LHAPDF grids
→ Use FEWZ for W cross section calculations
→ Input LHC pPb data
→ Use xFitter Profiling utilities

```
! This theory file a test file
! generated from cms_Wm_pPb/tab1_NLO_nCTEQ15/0-NLO.w.output_FEWZextractor.pic
!
&Data
   Name  = 'cms_wm_fig3b_rew_theory'
   NData =  10
   NColumn =  35
   ColumnType = 2*'Bin','Theory',1
   ColumnName = 'bin_min','bin_max

   Percent = 35*false
&End
-3.210000  -2.210000  68.741530
-2.710000  -1.710000  73.166300
-2.210000  -1.210000  77.117926
-1.710000  -0.710000  76.802215
-1.210000  -0.210000  74.028980
-0.710000   0.290000  71.703561
-0.210000   0.790000  66.724986
 0.290000   1.290000  60.784235
 0.790000   1.790000  55.089179
 1.290000   2.290000  50.663899
```






```
                                                  3.155551  73.195358  72.75966
                                                  7.284879  96.182211  95.26098
                                                  6.491652  76.373931  75.46185
                                                  4.670278  73.321801  72.60121
                                                  2.562872  70.763443  70.600849
                                                  7.724555  65.643148  66.244718
                                                  1.834261  7
                                                  0.149144  5
                                                  1.320199  3
```

Both profiling & reweighting available

Thanks to Eric Godat & Voica Radescu

xFitter Workshops

www.xfitter.org

xFitter Meeting in Oxford, UK