# Recent QCD results from the xFitter project

## Demonstration of xFitter with FFNS/VFNS and multi-scale predictions

Fred Olness
SMU
*on behalf of the xFitter team*

xFitter Meeting: Minsk March 2019

*Thanks for the input from my xFitter friends & colleagues*

DIS2019 Workshop
Torino
8-12 April 2019

# xFitter Project

www.xFitter.org

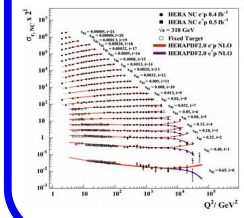
**Sample data files:**

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

DESY xFitter

xFitter/xFitterTalks » xFitter/../xFitterDevel.. » xFitter/../Meeting2017-.. » xFitter » xFitter/DownloadPage

**Experimental Data**



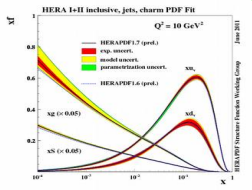
**Data:** HERA, Tevatron, LHC, fixed target experiments

**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<br>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:**

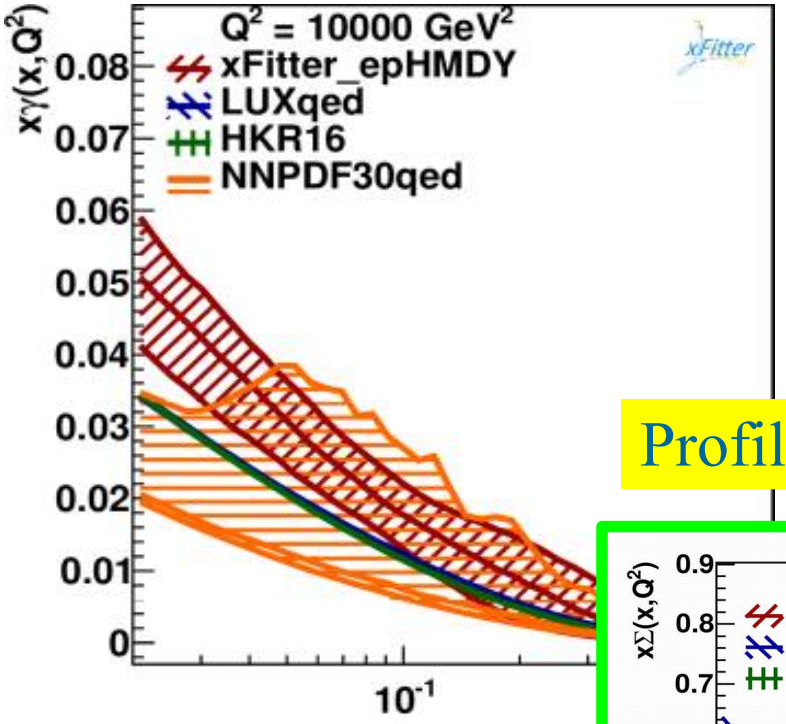
Photon PDF & QED
Pole & MS-bar masses
Profiling and Re-Weighting

Heavy Quark Variable Treshold
Improvements in $\chi^2$ and correlations
TMD PDFs (uPDFs)
*… and many other*

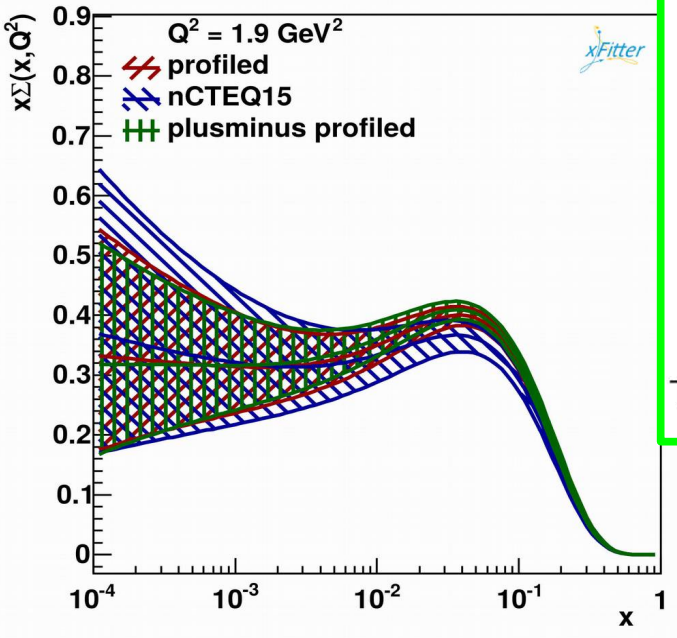
# xFitter Capabilities

www.xFitter.org

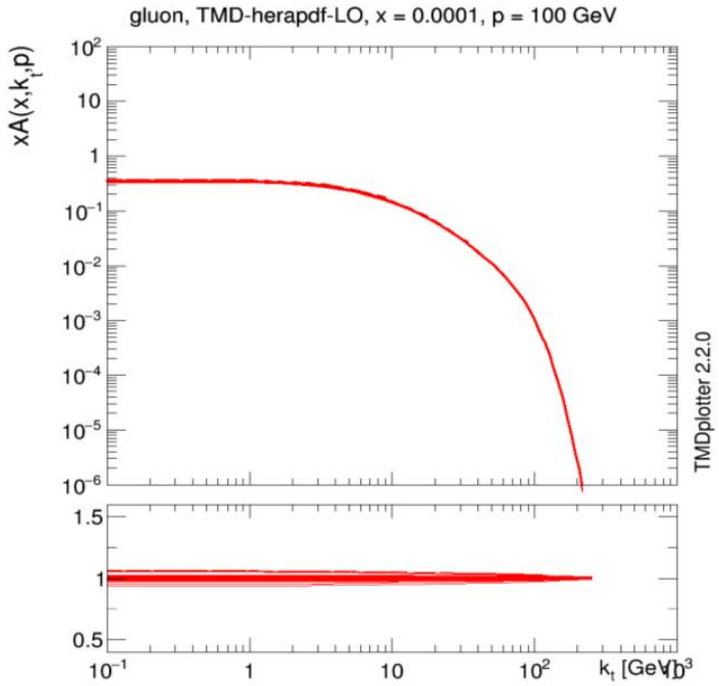
## Photon PDF




## Profiling Lead PDFs

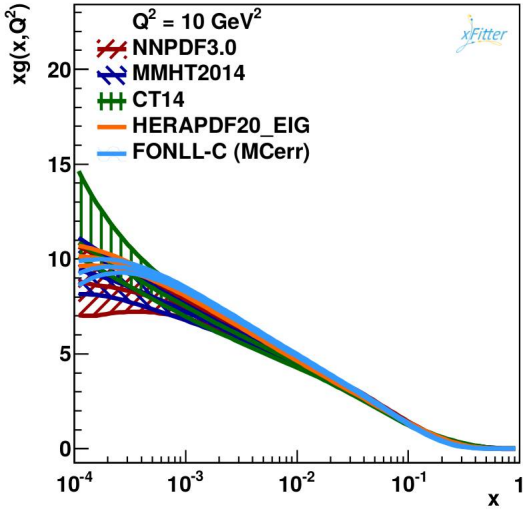



## TMD (uPDFs) in xFitter

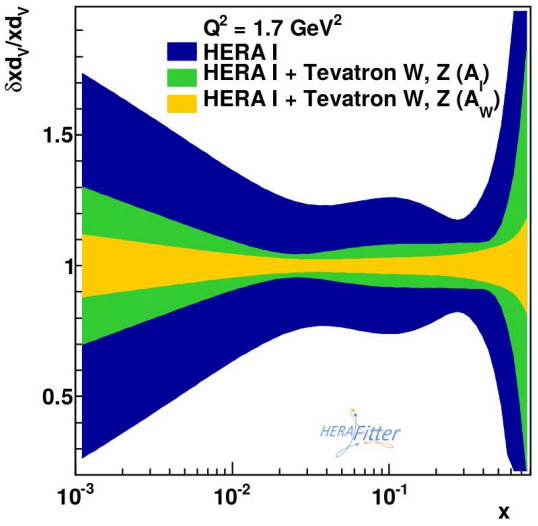


# *more* xFitter Capabilities

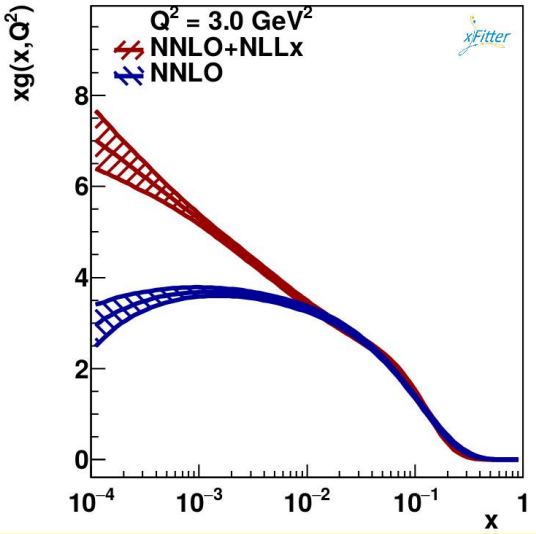
www.xFitter.org



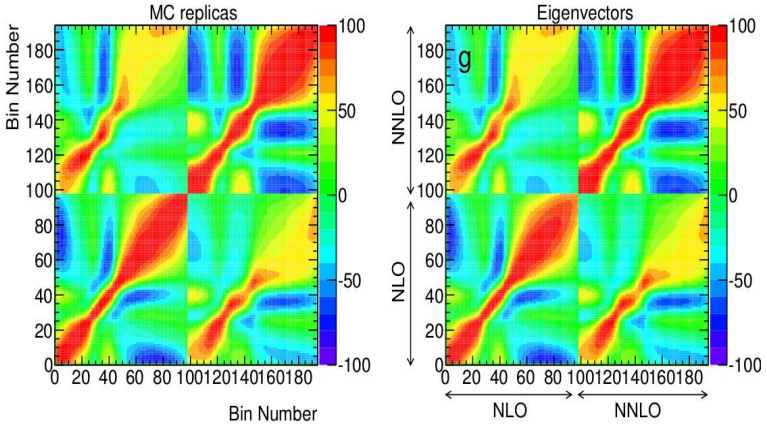

Multiple Heavy Quark Models



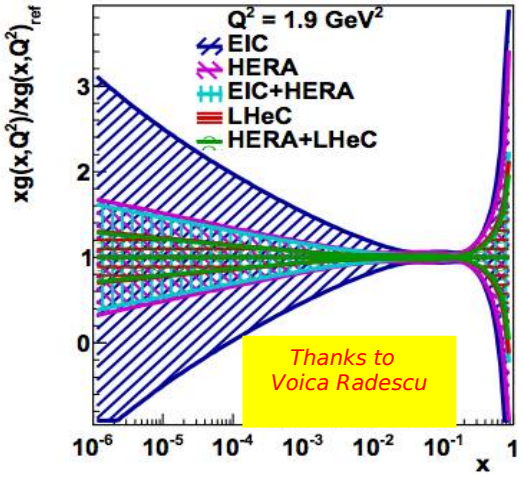

Profiling of W/Z Data



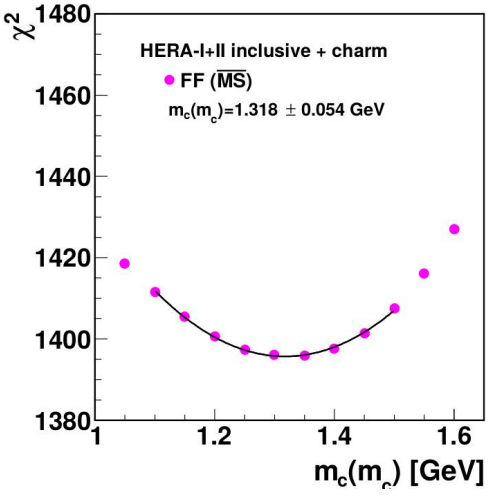

NNLx Resummation @ Small x




Correlation Coefficients



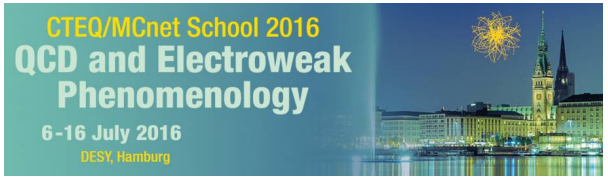

Sensitivity Studies




Pole & MS-Bar Running Mass

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 $\chi^2$ representations
→ understand different $\chi^2$ representations
nuisance parameters and covariance matrix χ2 formulas

# Recent Work

# LAST YEAR ...

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

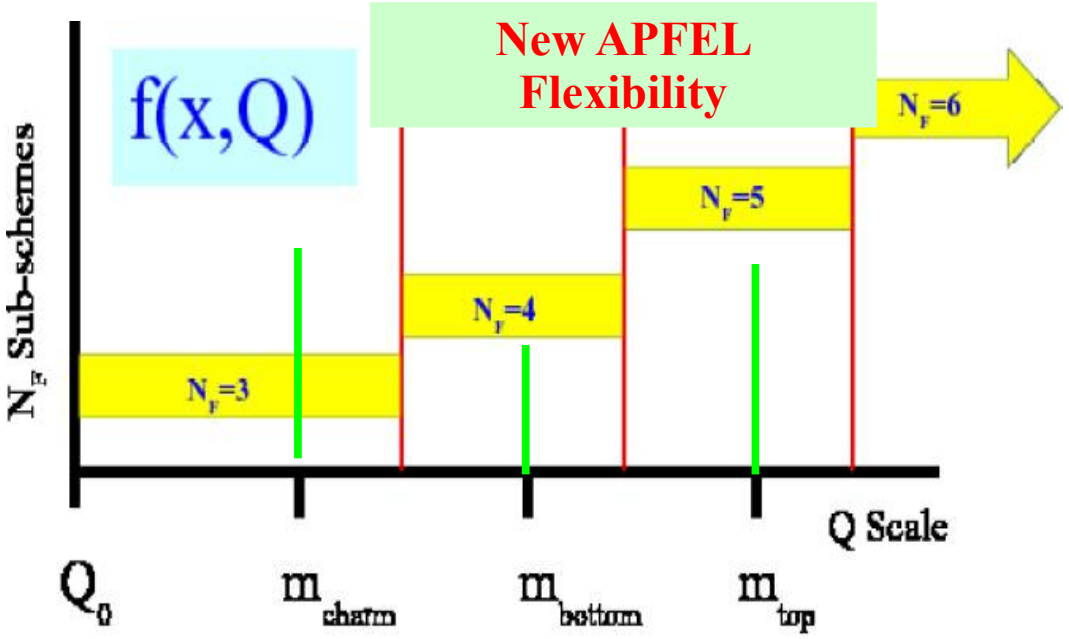
THE EUROPEAN PHYSICAL JOURNAL C

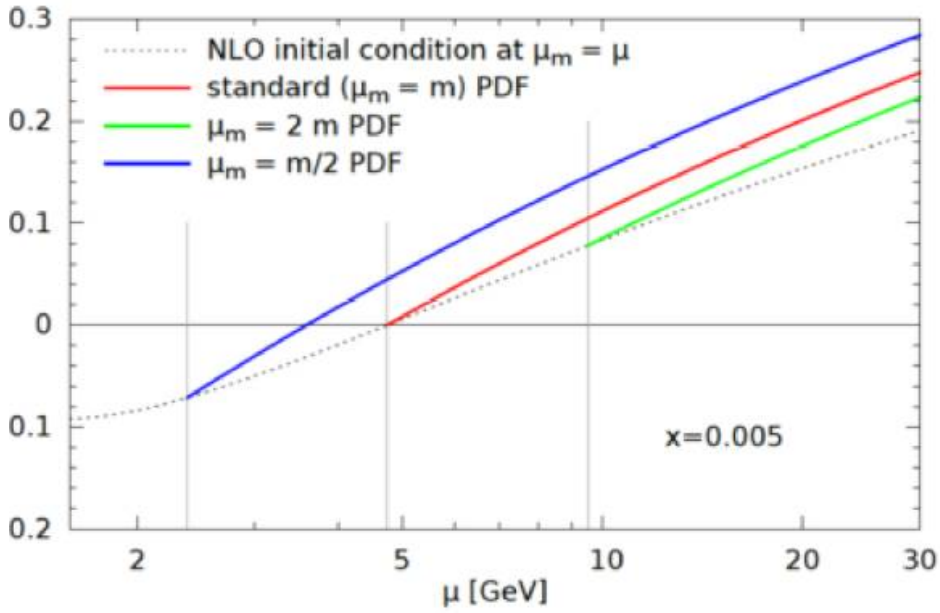
Regular Article - Theoretical Physics

## 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



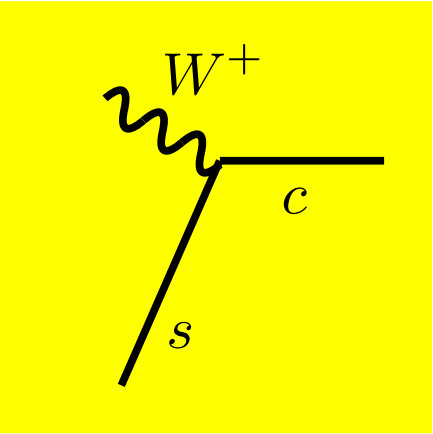



# In Progress

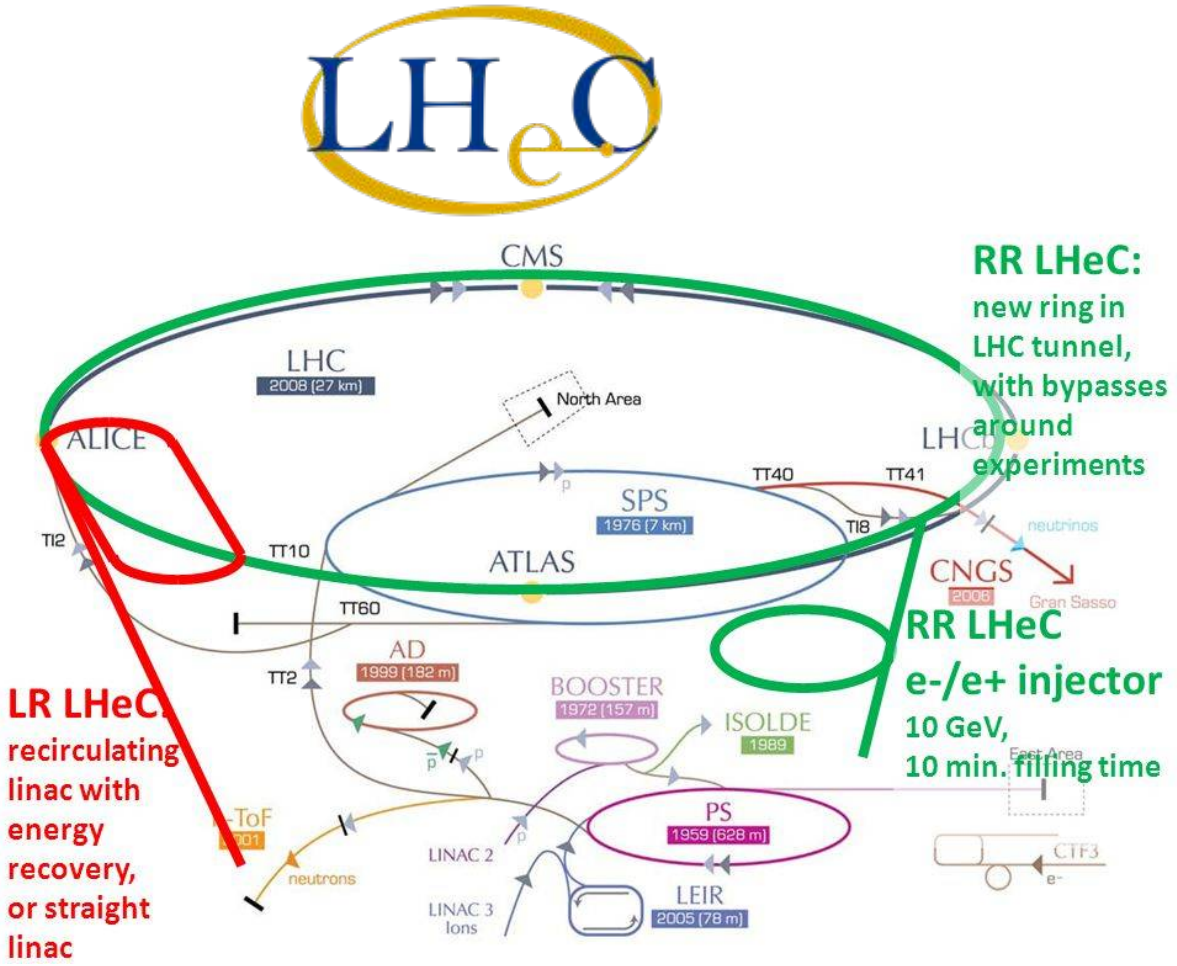
# The CC Charm Production

*with focus on **LHeC***

## *Measurement of strange PDF*



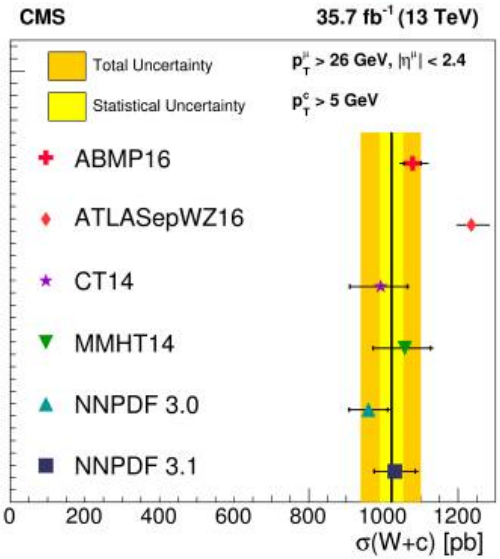

*Recent study led by Sasha[2], Valerio, Achim, ....*

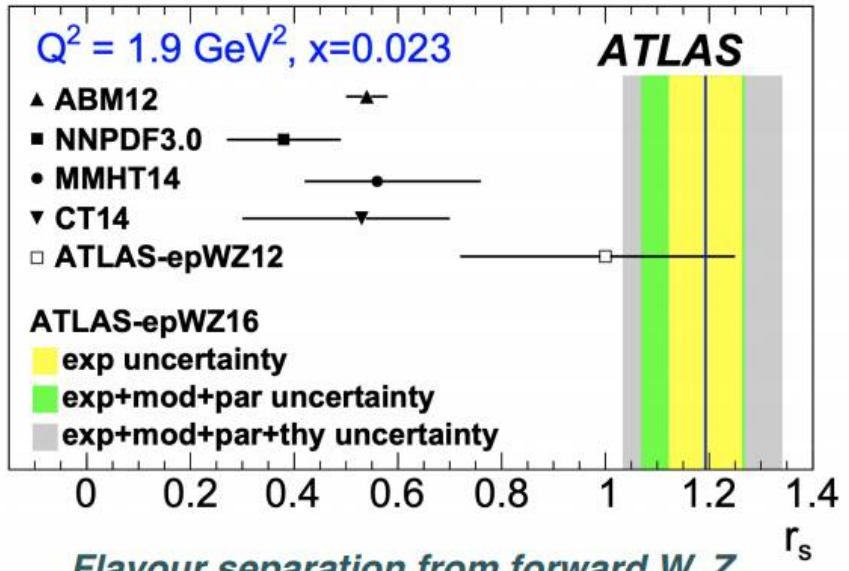


# Constraints from LHC data

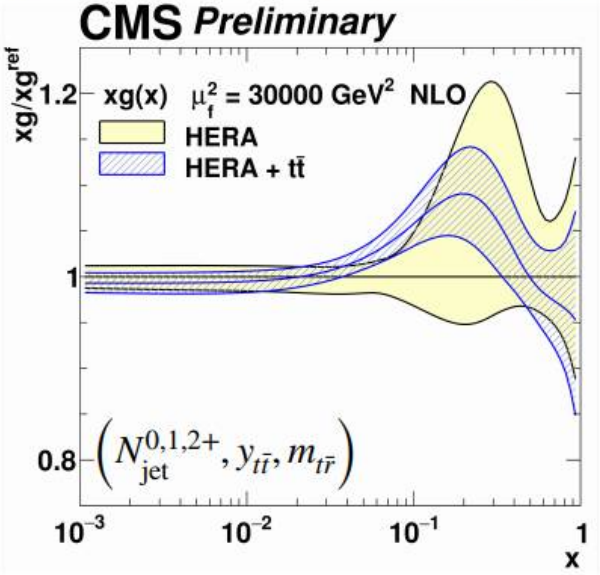
*Combined interpretation within global fit?*

## The strangeness conundrum: inclusive W,Z vs W+c

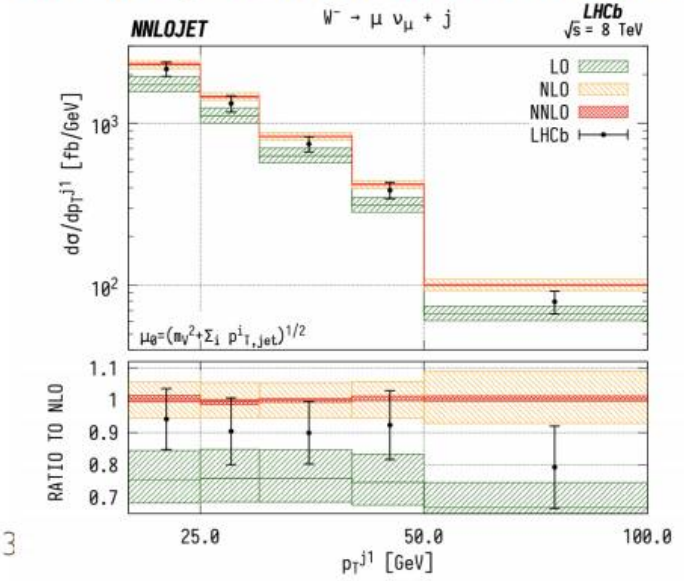



## Multi-differential top quark pairs




## Flavour separation from forward W, Z



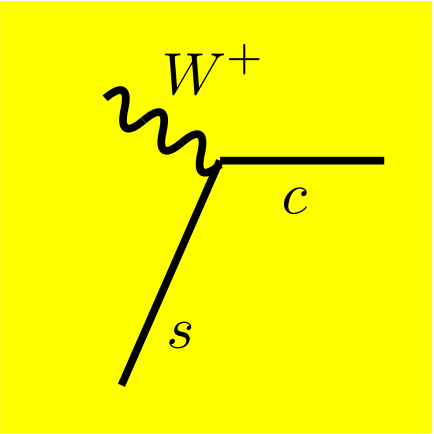

*Gehrmann-De Ridder et al 19*

Juan Rojo

# The CC Charm Production *with focus on LHeC*

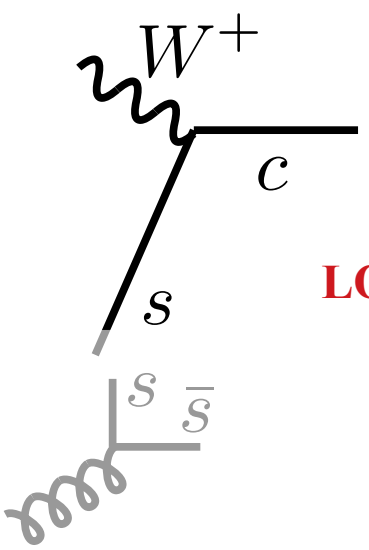
## *... A Case Study*

## *Highlights utility of xFitter*




- Measurement of strange PDF
- Compare/contrast FFNS and VFNS
- A multi-scale problem $\{m_s, m_c, Q\}$
- Variety of QCD Issues

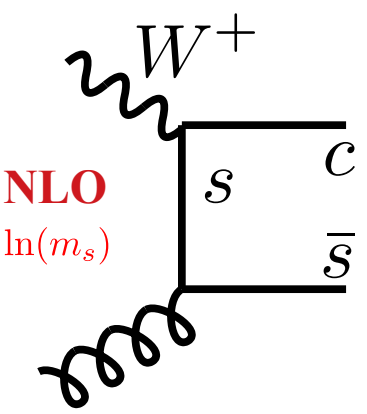
**t-channel**




**VFNS**

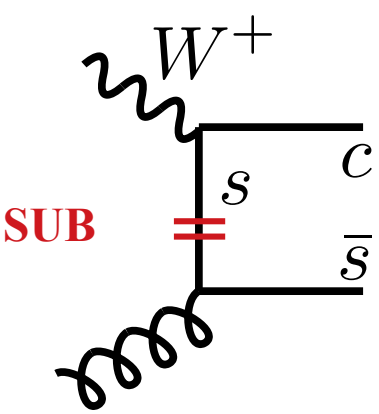
$f_s \otimes \sigma_{sW^+ \to c}$

gluon initiated




$f_s \otimes \sigma_{gW^+ \to c\bar{s}}$

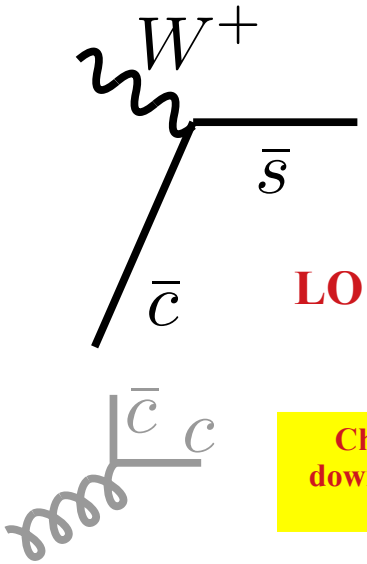
gluon initiated




$\mathcal{P} \sim \ln(m_s)$

$f_g \otimes \mathcal{P}_{g \to s} \otimes \sigma_{sW^+ \to c}$

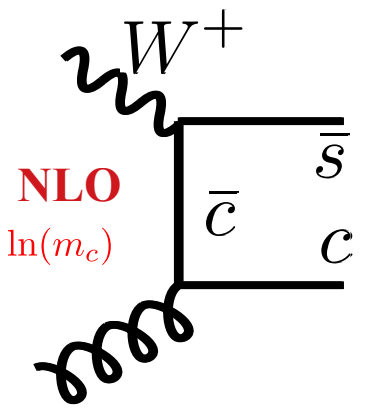
**u-channel**




**Charm goes down beam pipe**

$f_{\bar{c}} \otimes \sigma_{\bar{c}W^+ \to \bar{s}}$

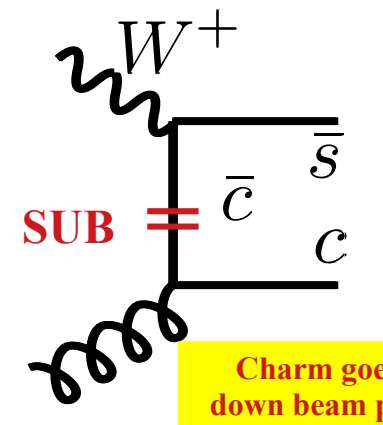
gluon initiated




**$F_2^c$ define carefully**

$f_g \otimes \sigma_{gW^+ \to \bar{s}c}$

gluon initiated

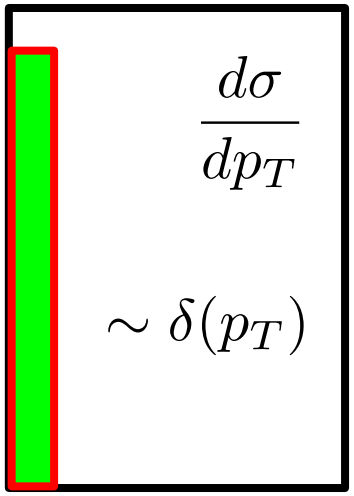


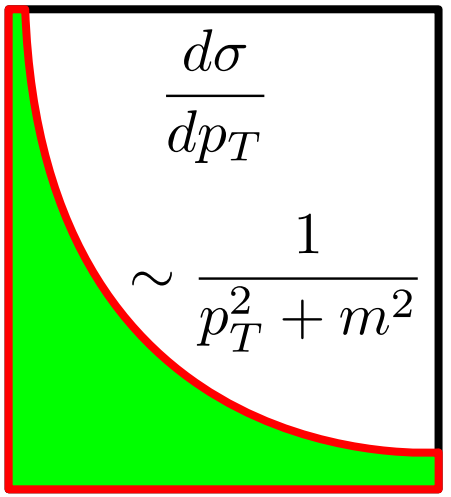

**Charm goes down beam pipe**

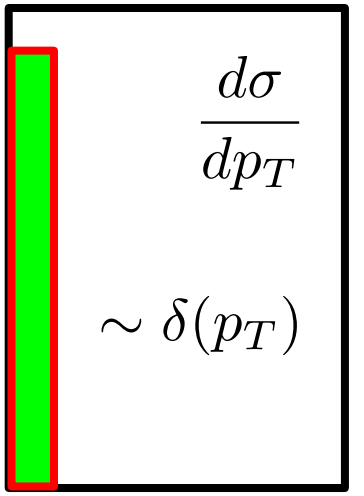
$\mathcal{P} \sim \ln(m_c)$

$f_g \otimes \mathcal{P}_{g \to \bar{c}} \otimes \sigma_{\bar{c}W^+ \to \bar{s}}$

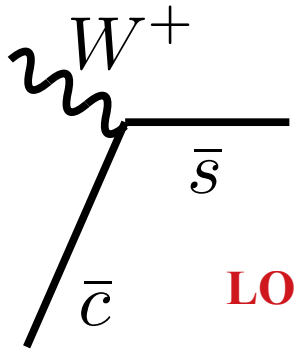
# Look in $P_T$ Space



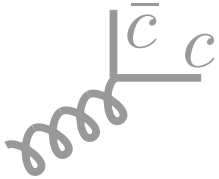




**u-channel**



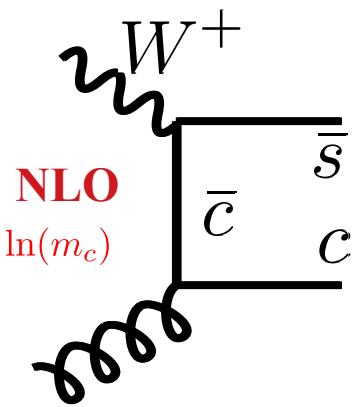

**LO**




**Charm goes down beam pipe**

$f_{\bar{c}} \otimes \sigma_{\bar{c}W^+ \to \bar{s}}$

gluon initiated



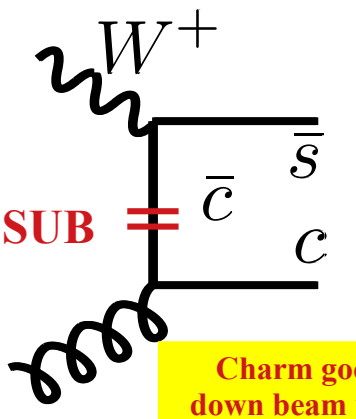

**NLO**

$\ln(m_c)$

$F_2^c$ **define carefully**

$f_g \otimes \sigma_{gW^+ \to \bar{s}c}$

gluon initiated




**SUB**

**Charm goes down beam pipe**

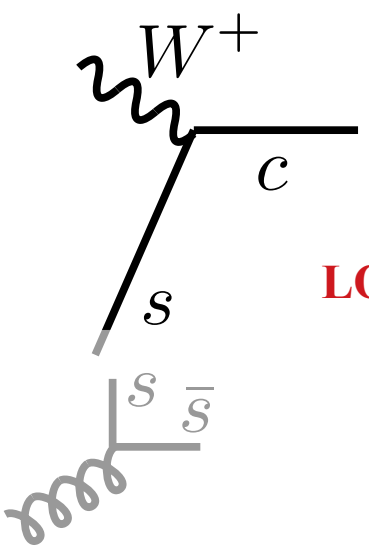
$\mathcal{P} \sim \ln(m_c)$

$f_g \otimes \mathcal{P}_{g \to \bar{c}} \otimes \sigma_{\bar{c}W^+ \to \bar{s}}$

# What if there is no Charm PDF ???



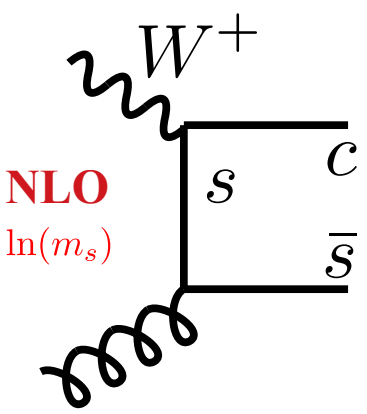
**t-channel**




**FFNS**

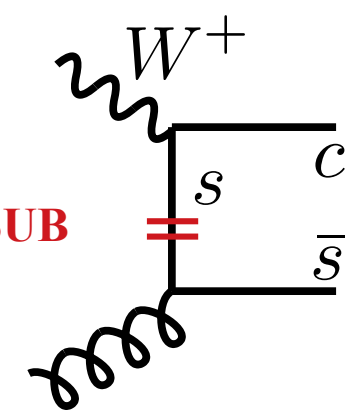
$f_s \otimes \sigma_{sW^+ \to c}$

gluon initiated




$f_s \otimes \sigma_{gW^+ \to c\bar{s}}$

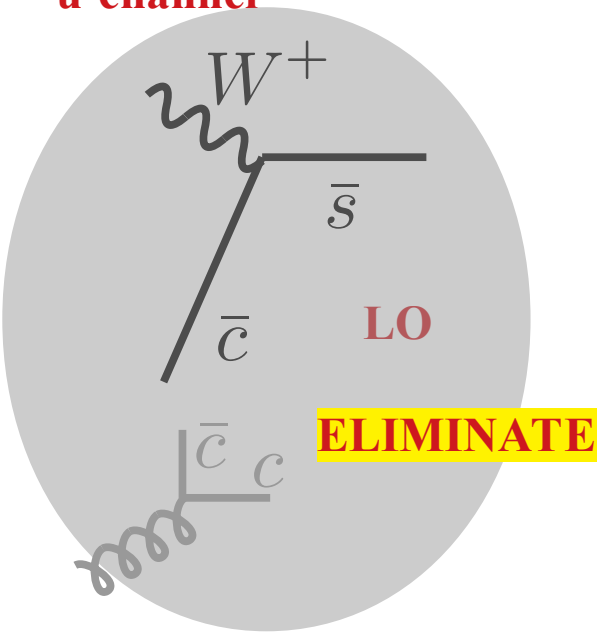
gluon initiated




$\mathcal{P} \sim \ln(m_s)$

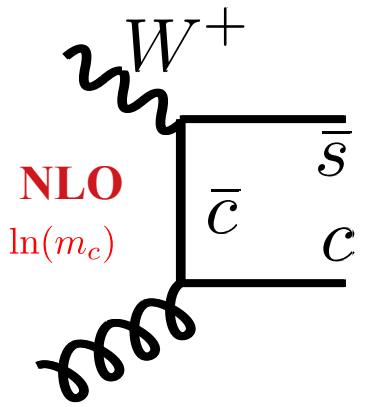
$f_g \otimes \mathcal{P}_{g \to s} \otimes \sigma_{sW^+ \to c}$

**u-channel**




$f_{\bar{c}} \otimes \sigma_{\bar{c}W^+ \to \bar{s}}$

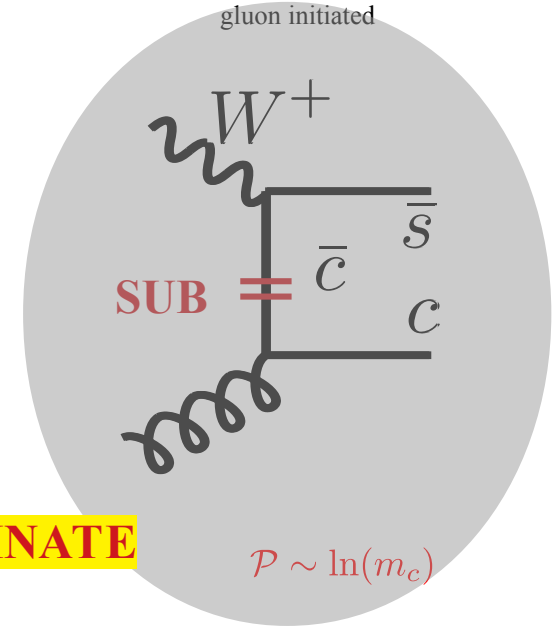
gluon initiated




**Divergent**
**$\alpha_s \ln(\mu/m)$**

$f_g \otimes \sigma_{gW^+ \to \bar{s}c}$

gluon initiated

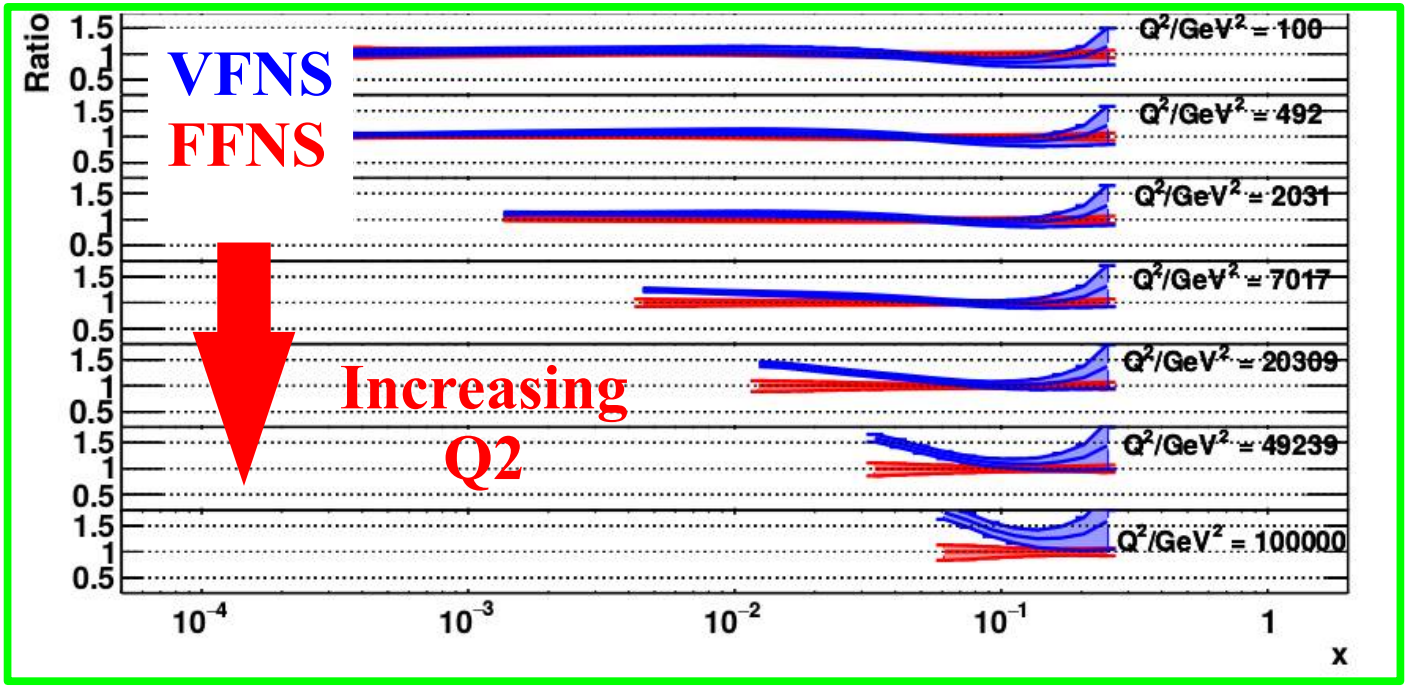


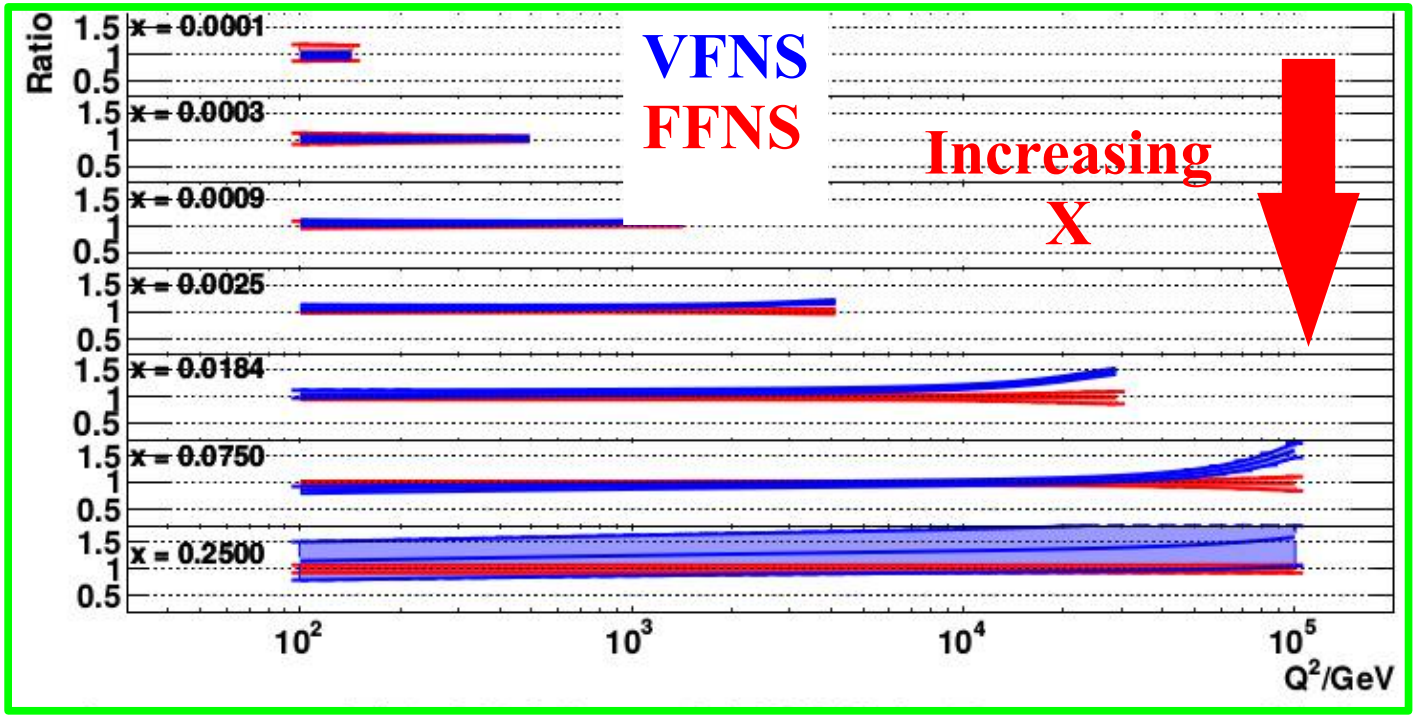

$f_g \otimes \mathcal{P}_{g \to \bar{c}} \otimes \sigma_{\bar{c}W^+ \to \bar{s}}$

# xFitter incorporates both FFNS & VFNS

Let's compare
FFNS & VFNS
across kinematic limits…

… special interest at:
Hi $Q^2$, Hi x




# Ratio Plot:
# VFNS
# FFNS

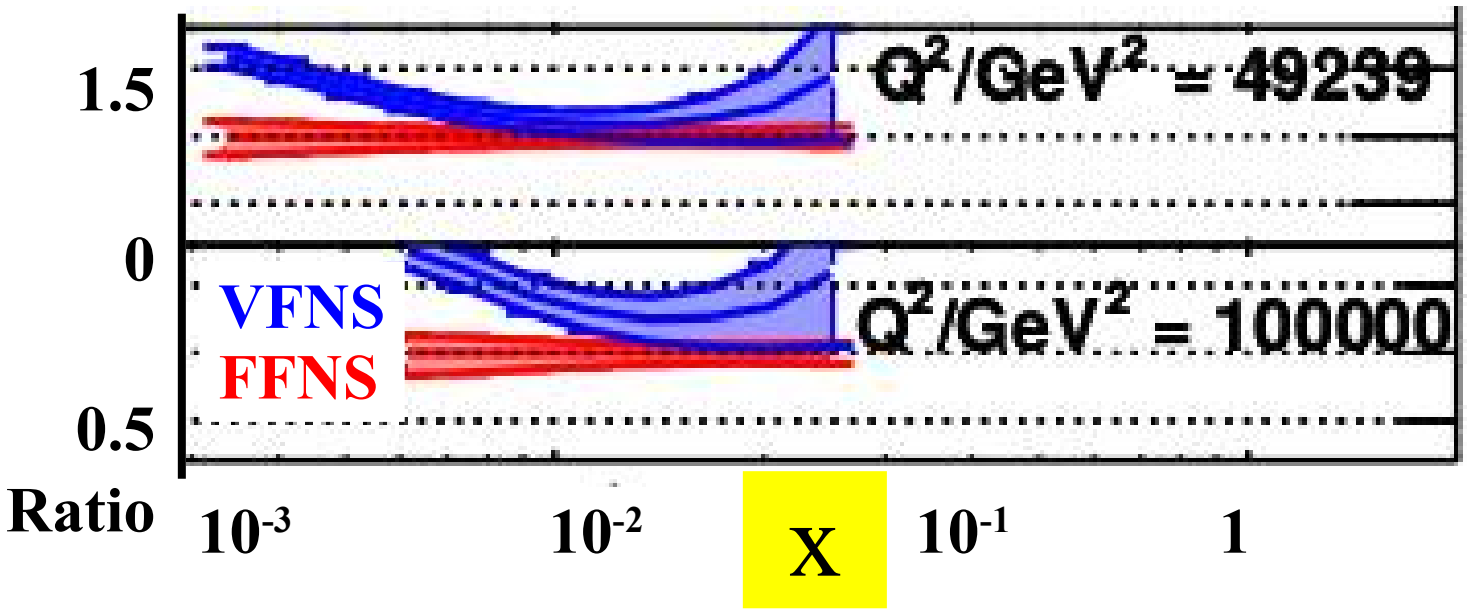
**Observations:**

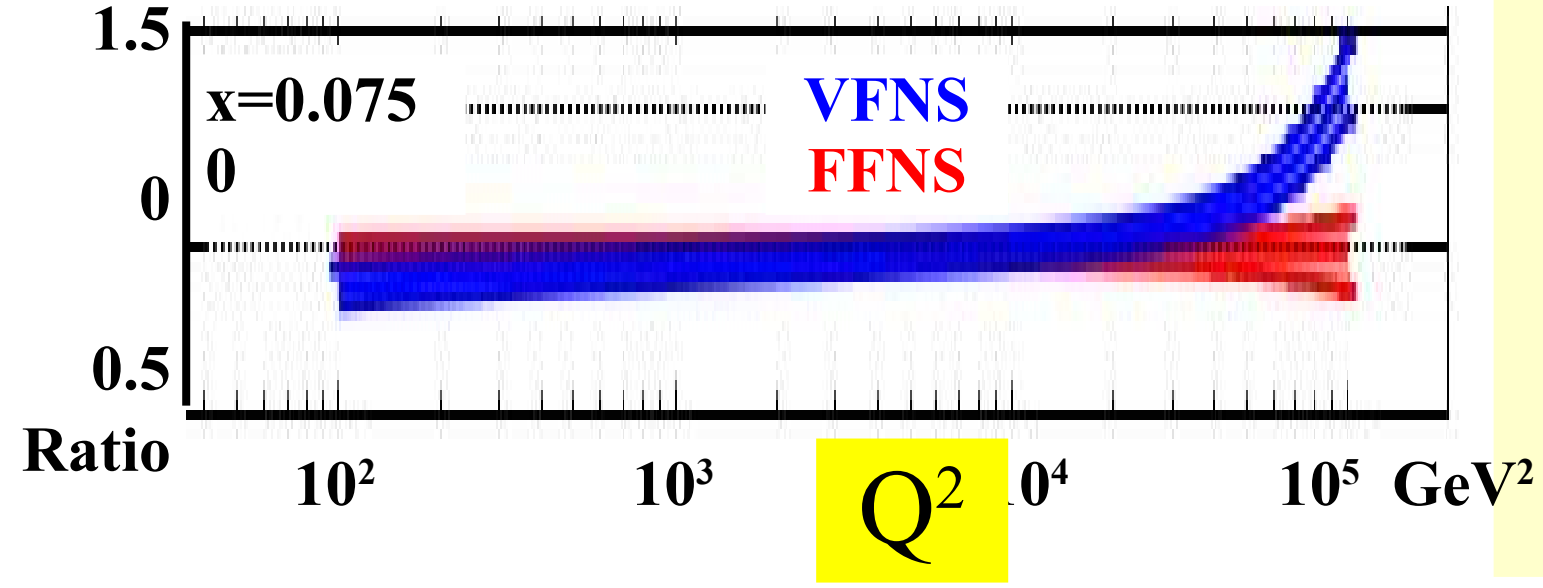
**They differ at**

**i) large $Q^2$**

**ii) large X**

## Ratio Plot:
VFNS
FFNS




**Observations:**

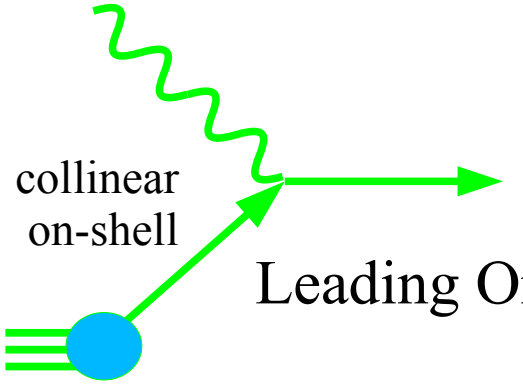
**They differ at**

**i) large $Q^2$**

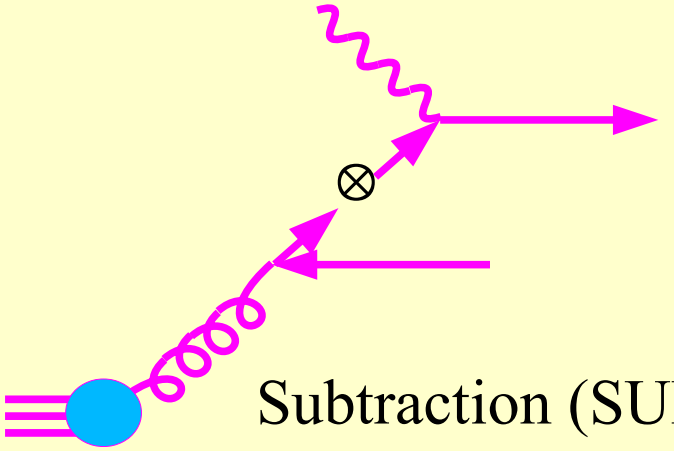
**ii) large X**

# Source of the large Q difference

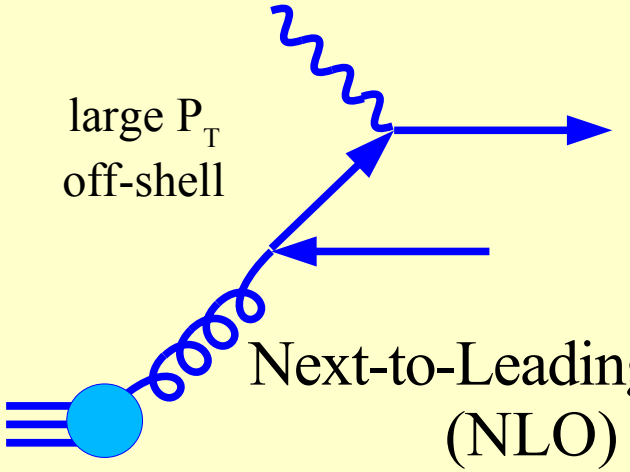
**TOT = LO + NLO - SUB**



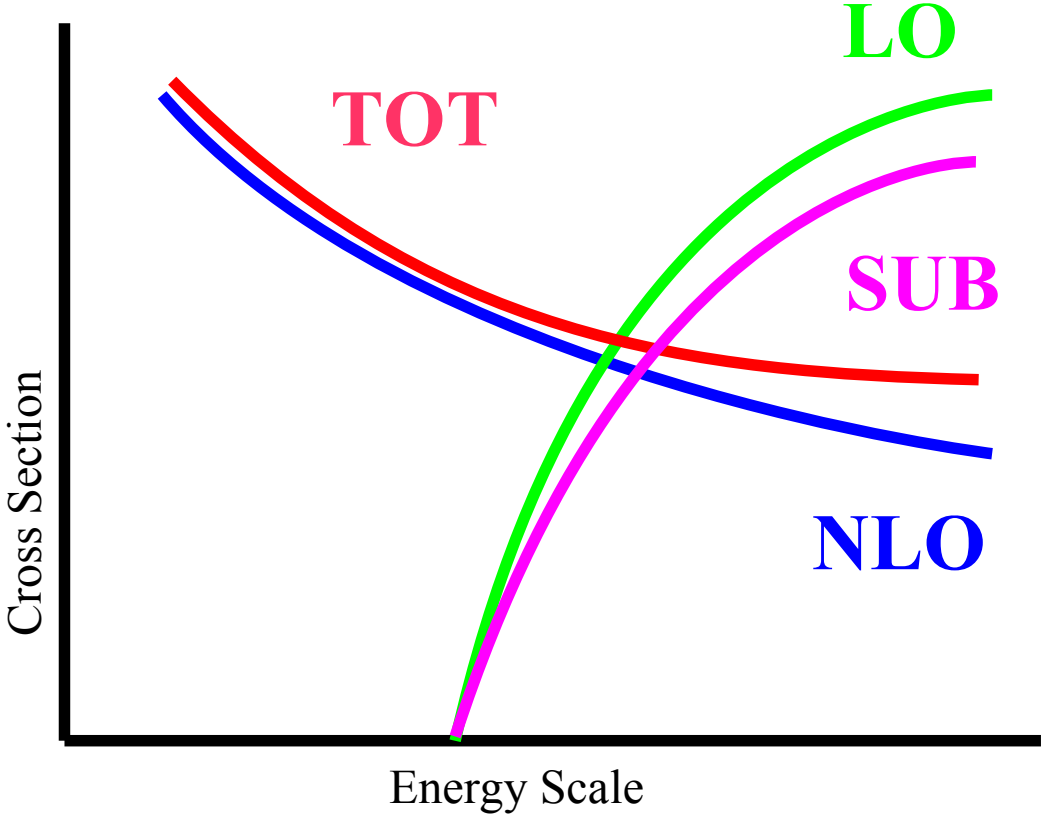

Leading Order (LO)



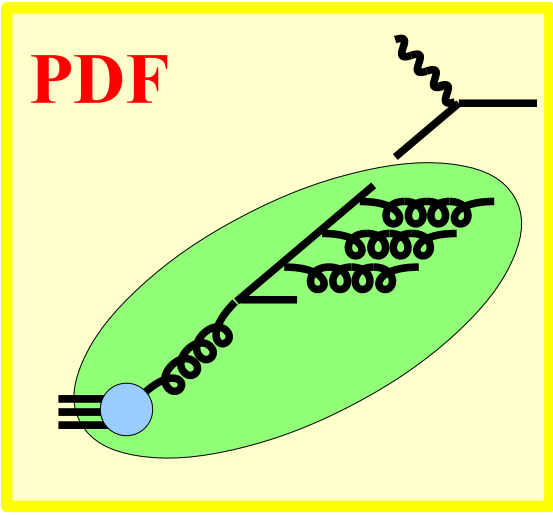
Subtraction (SUB)



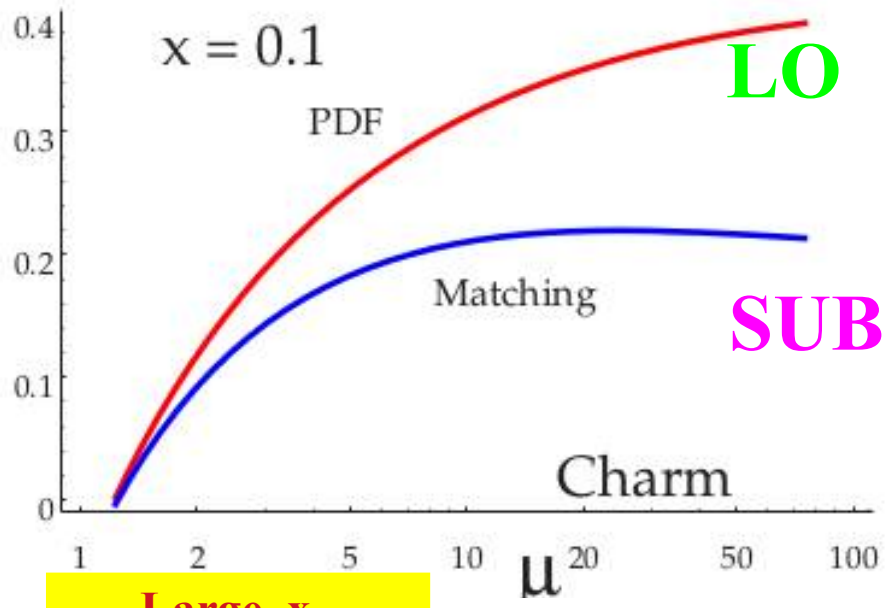

Next-to-Leading Order (NLO)

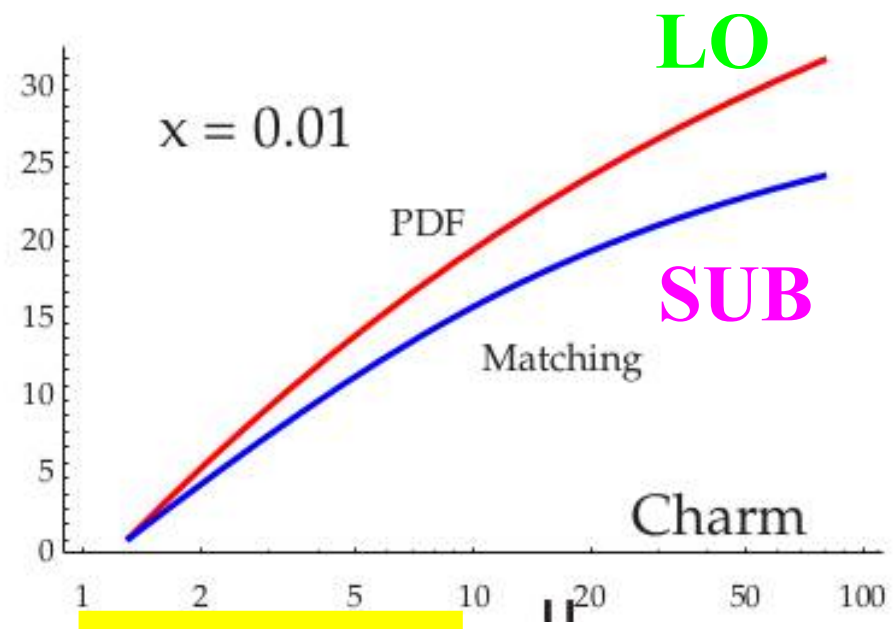



**At large scales, PDF resummation becomes important!!!**

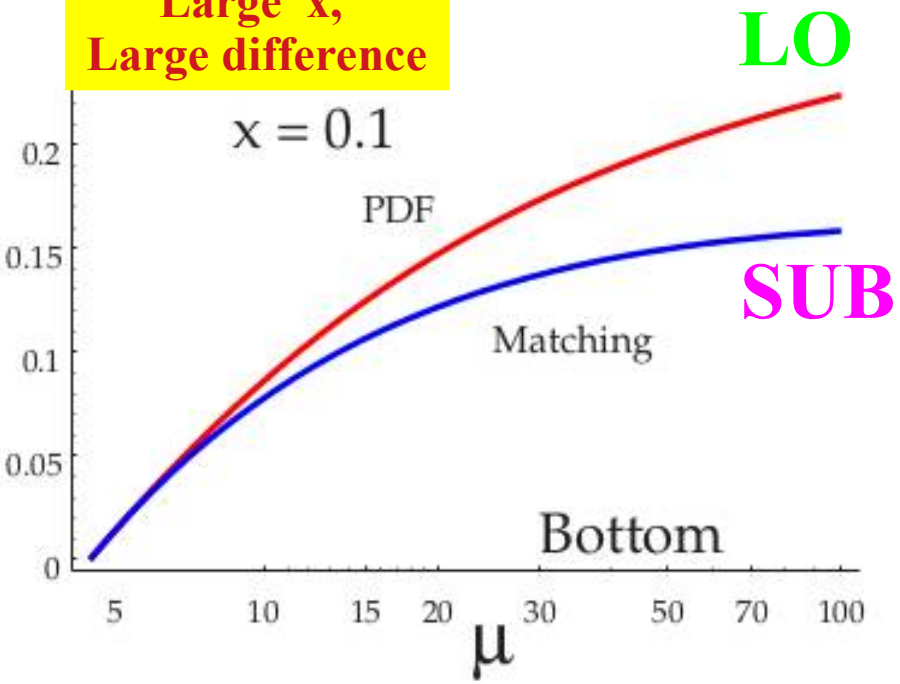


# Source of the large X difference

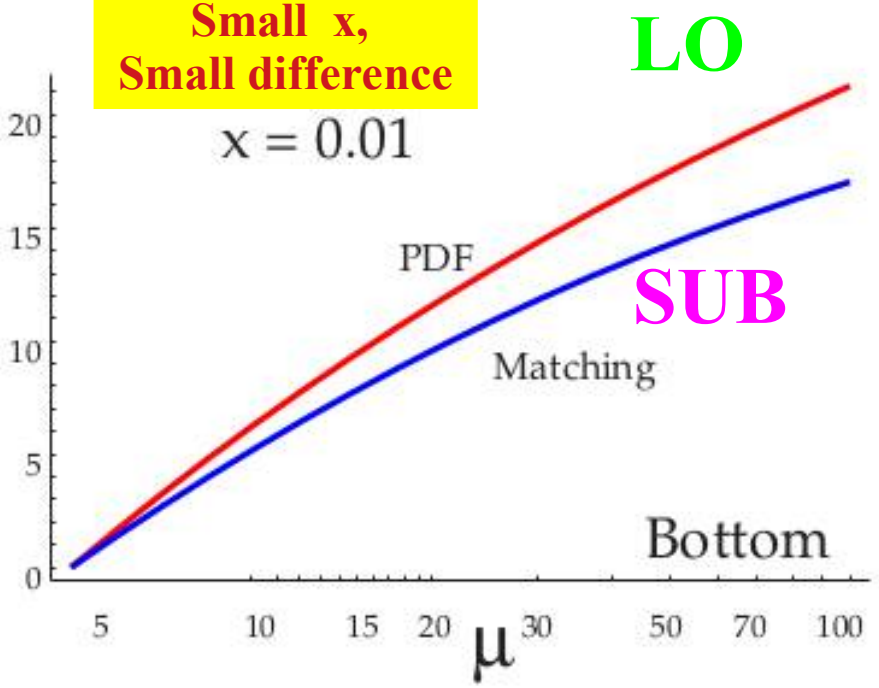



**Large x, Large difference**



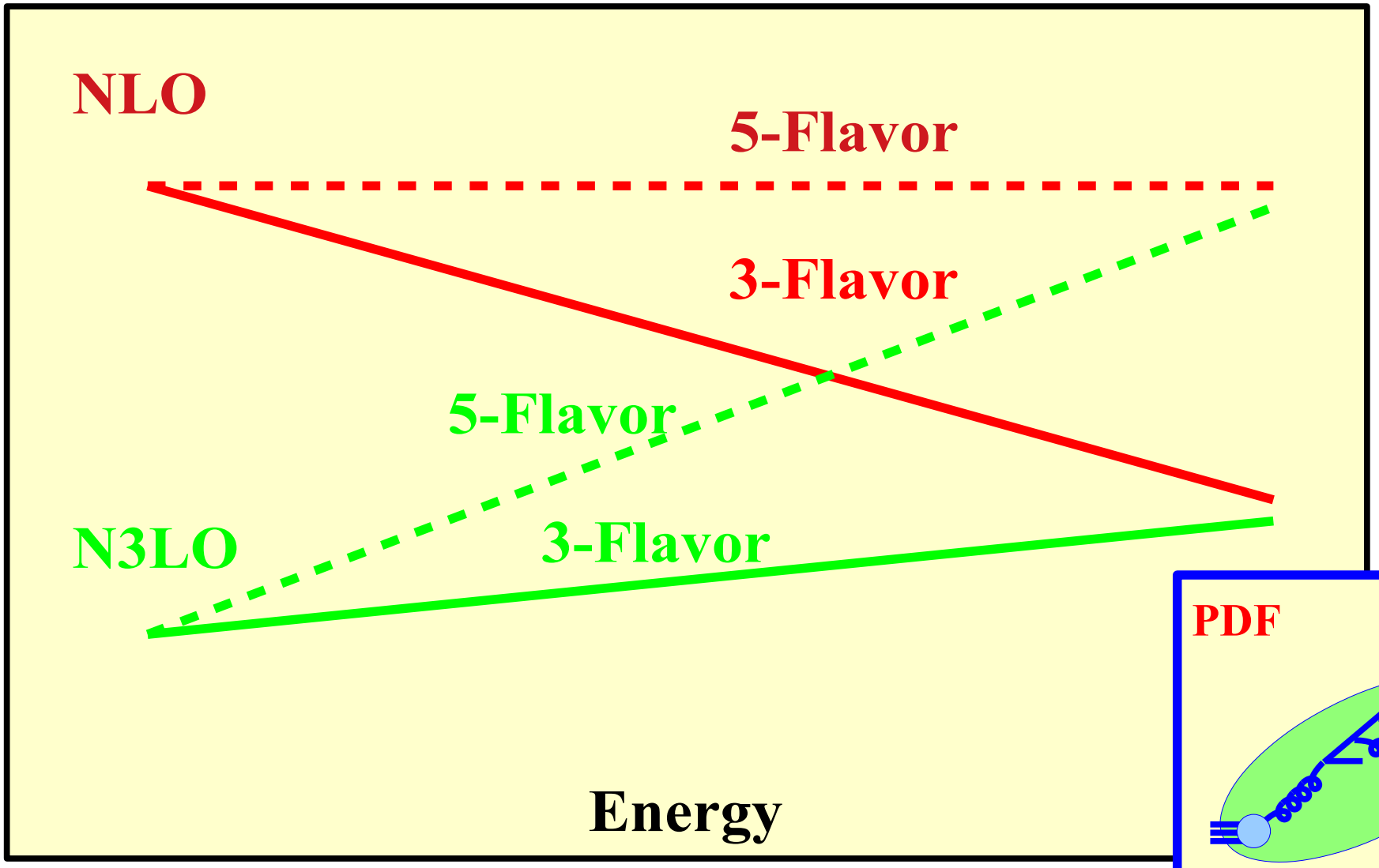

**Small x, Small difference**

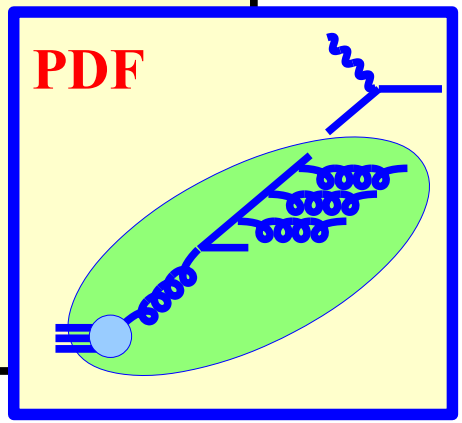


# When should we switch to VFNS?

One measure, when the difference between FFNS and VFNS is larger than the higher order correction.

Some observations on Charm CC:
... based on work by Fred & Aleksander (Olek) Kusina et al.,
arXiv:1306.6553 Phys.Rev. D88 (2013) no.7, 074032

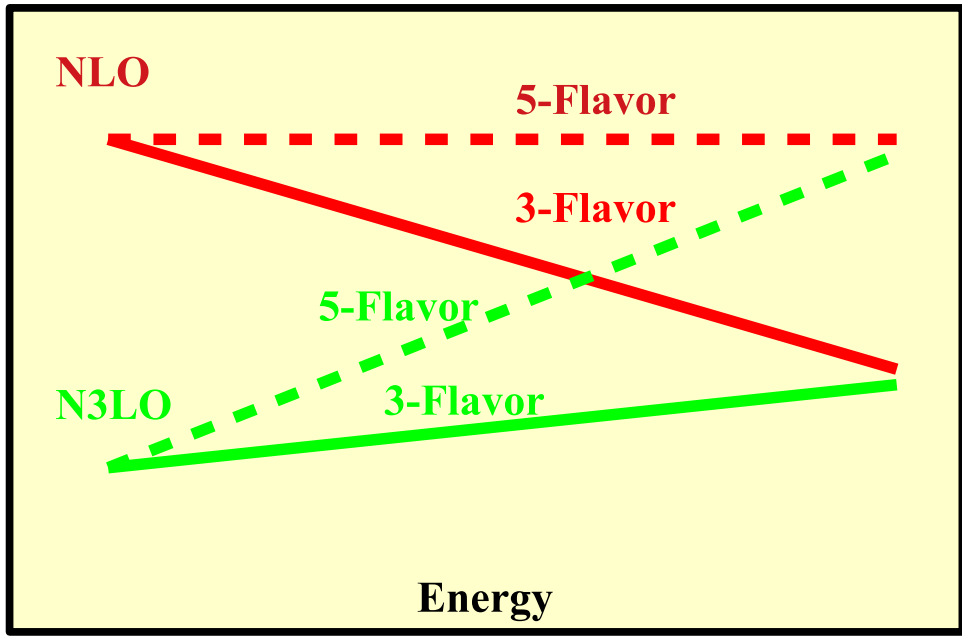


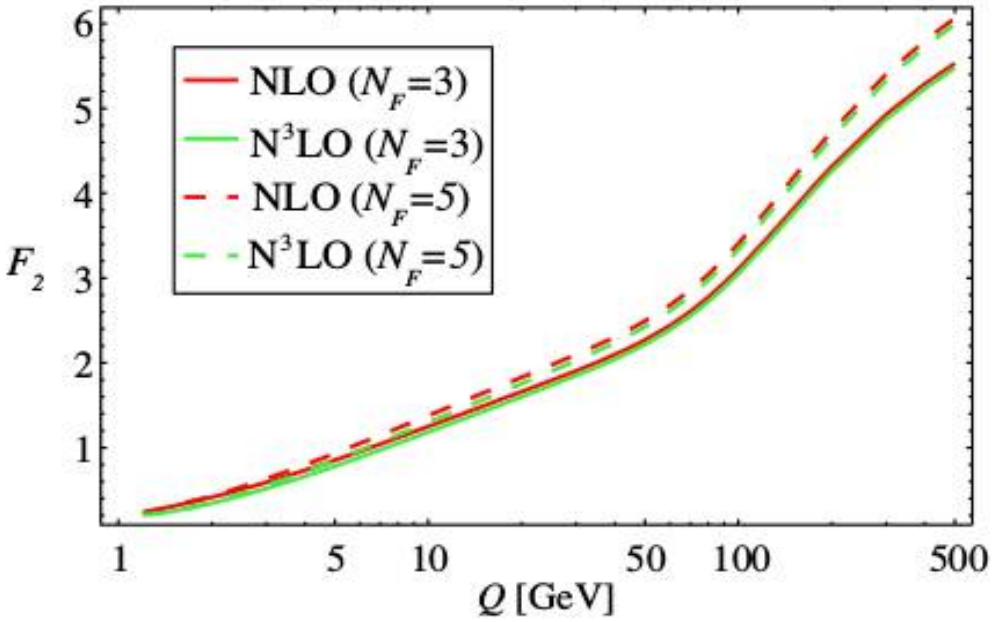

**Low Energy:**
3 & 5 Flavor match
(c & b PDFs = 0)

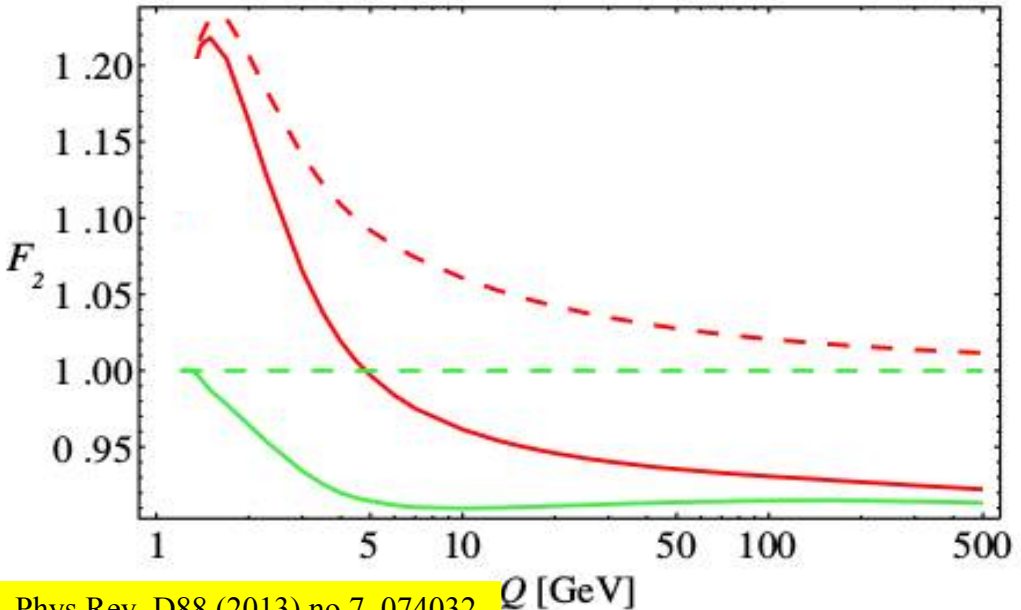
**Hi Energy:**
NLO & N3LO match
($\alpha_s \sim 0$)

**Low Energy:**
3 & 5 Flavor match
(c & b PDFs = 0)

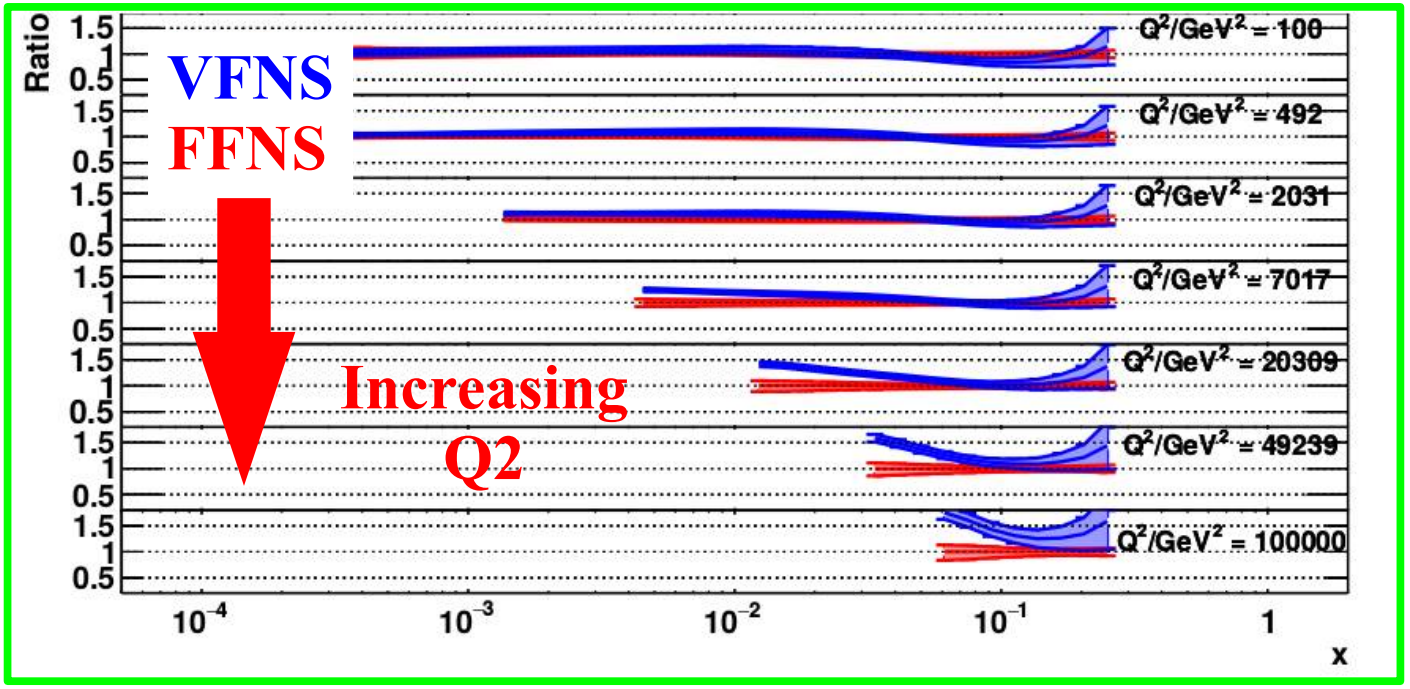


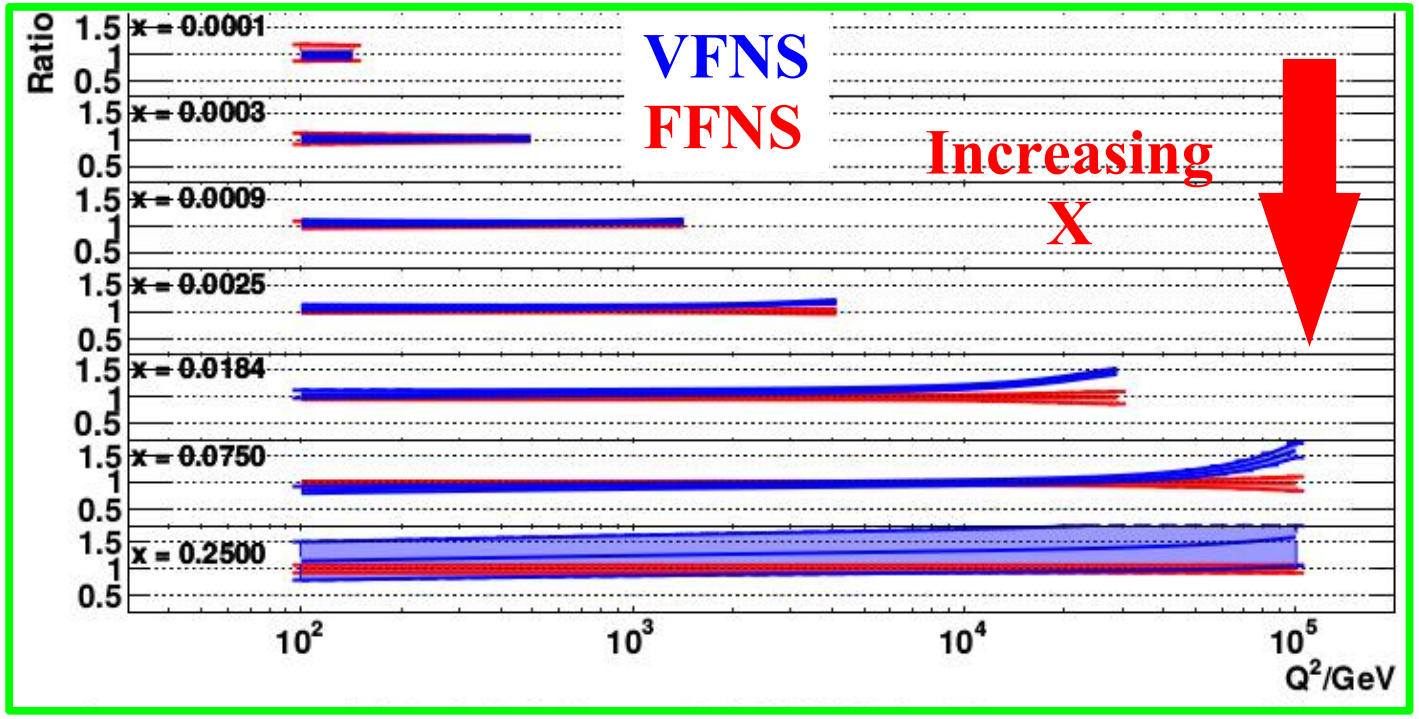

**Hi Energy:**
NLO & N3LO match
($\alpha_s \sim 0$)




Phys.Rev. D88 (2013) no.7, 074032




# Ratio Plot:
# VFNS
# FFNS

**Observations:**

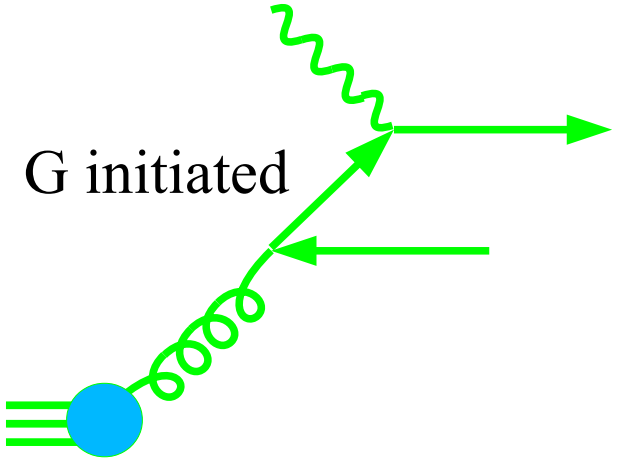
**They differ at**

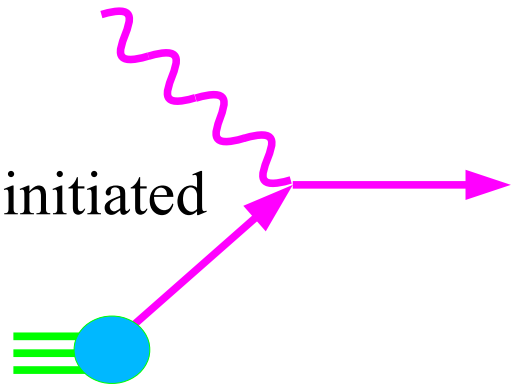
**i) large $Q^2$**

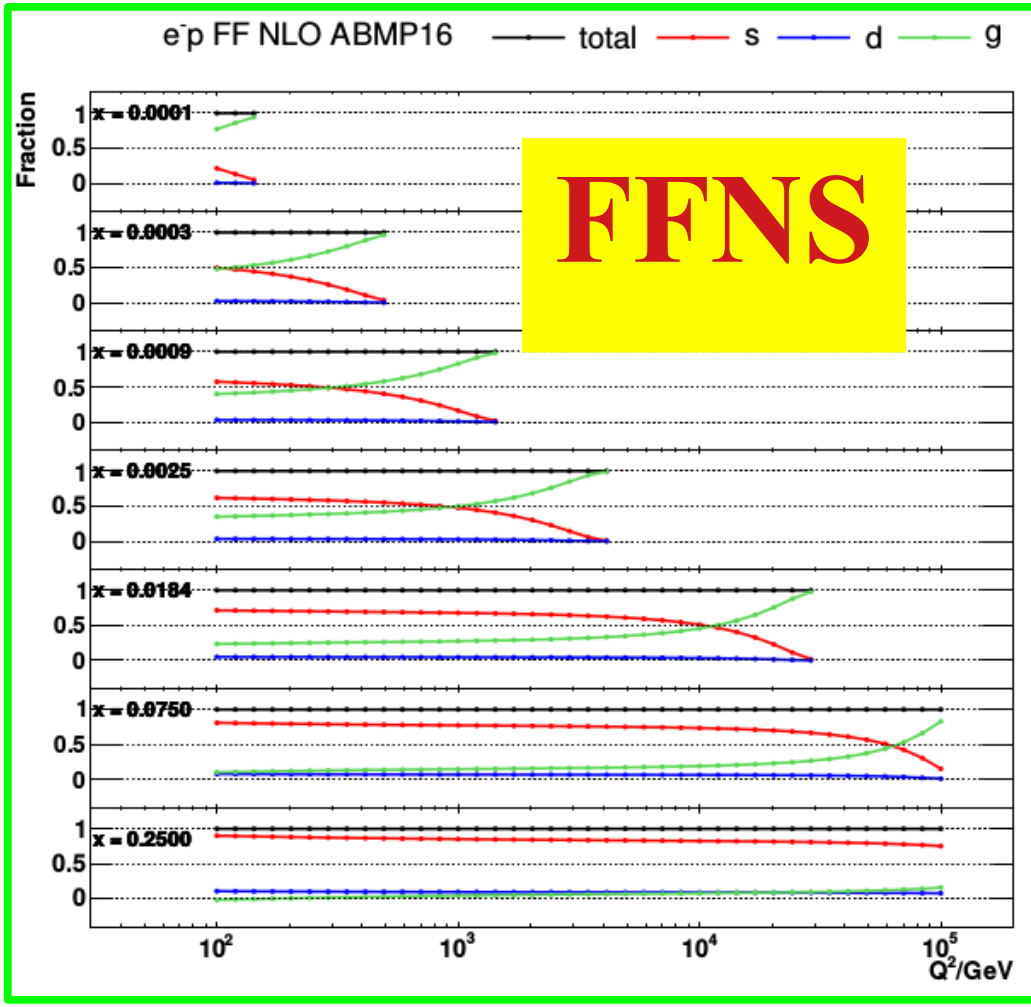
**ii) large X**

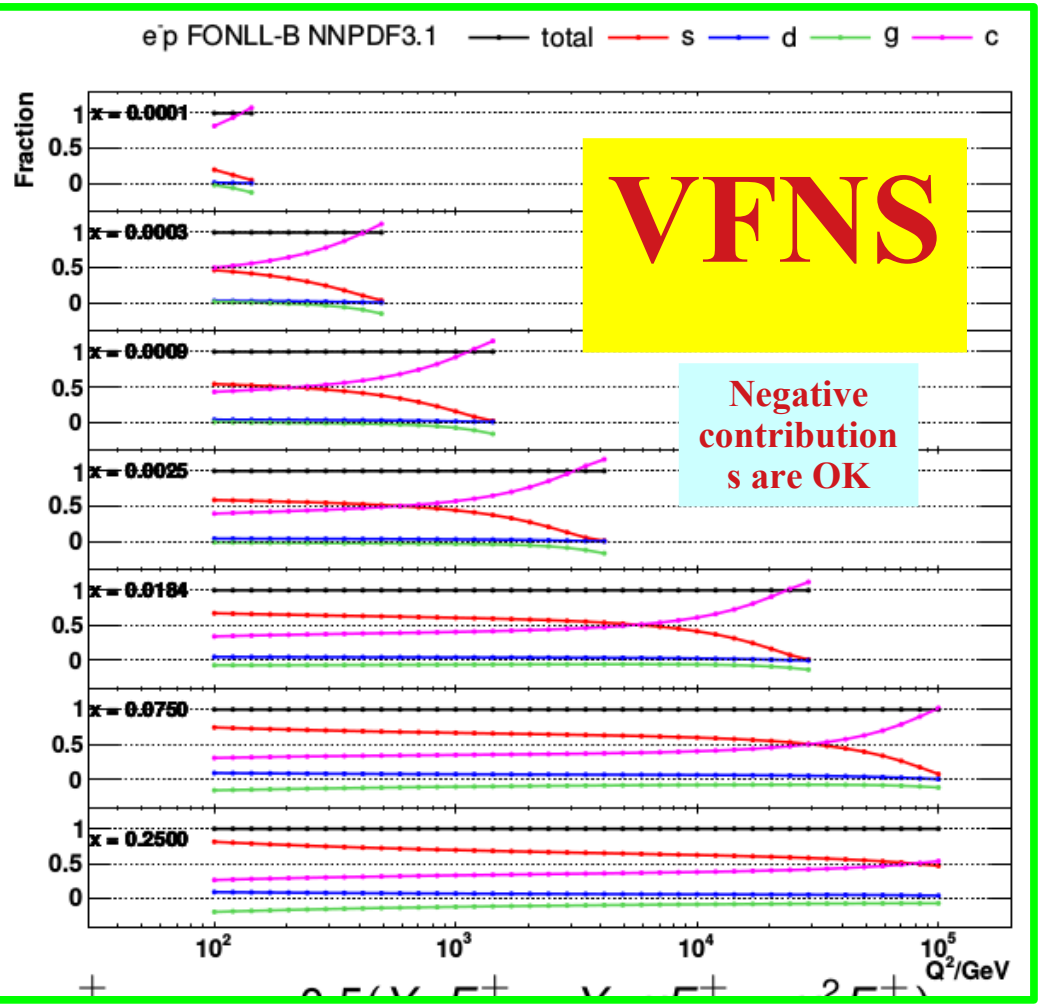
# Gluon & Charm Initiated Contributions

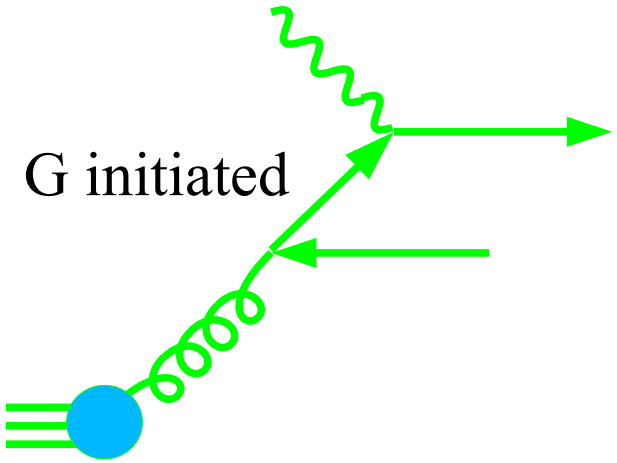
# Flavor Decomposition

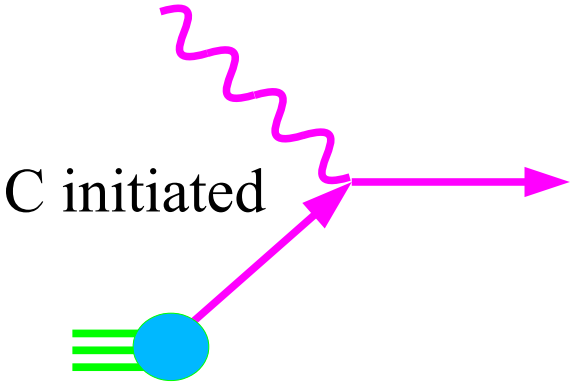


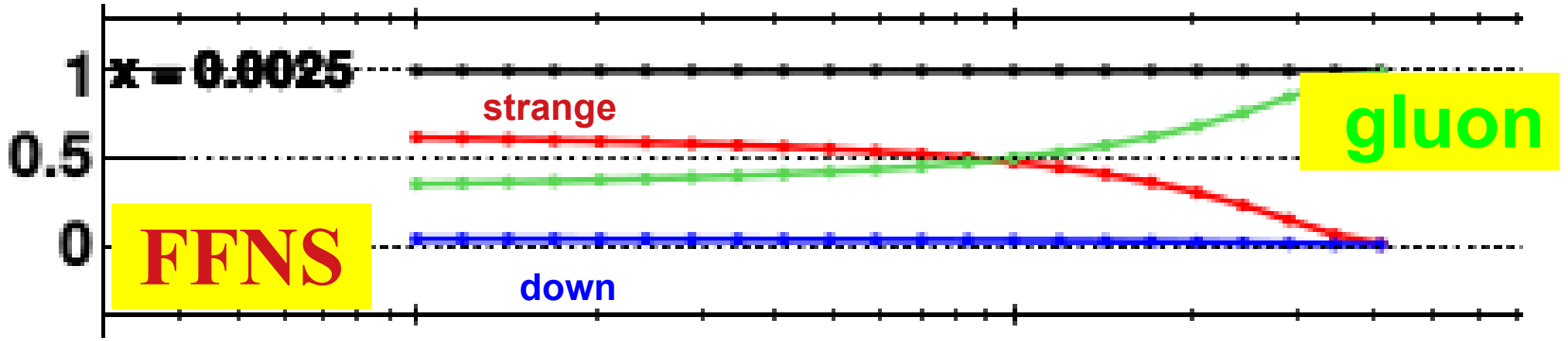



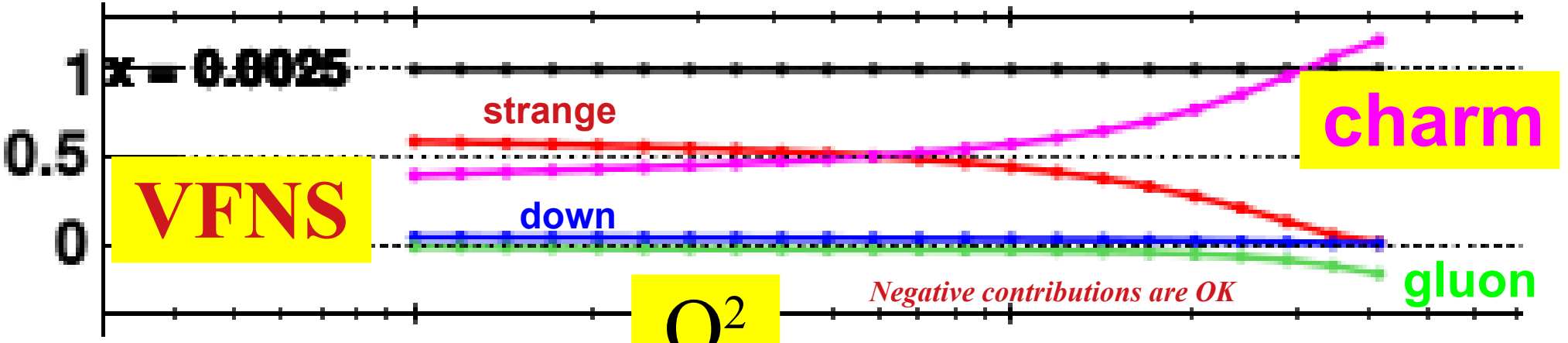




G initiated


C initiated


1
0.5
0
x = 0.0025
strange
gluon
FFNS
down


1
0.5
0
x = 0.0025
strange
charm
VFNS
down
gluon
Negative contributions are OK
Q²
10²
10³ GeV²

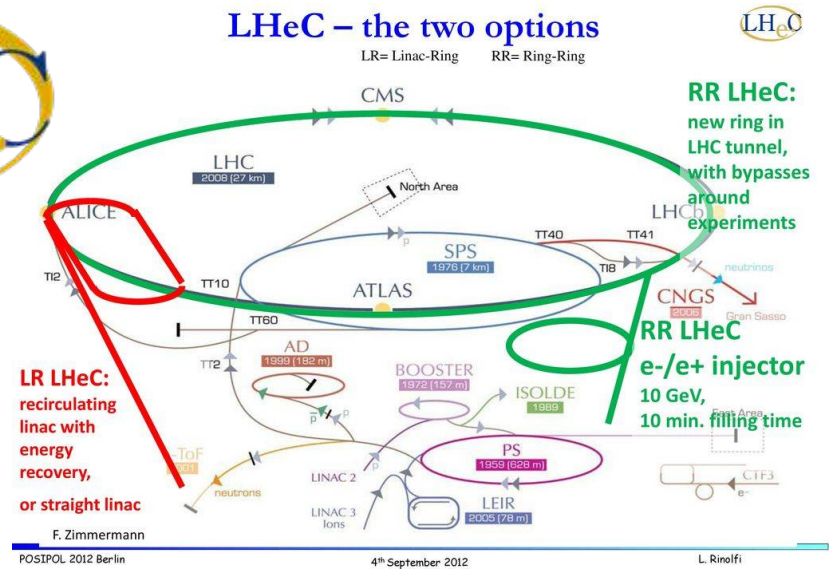
# The bottom line:

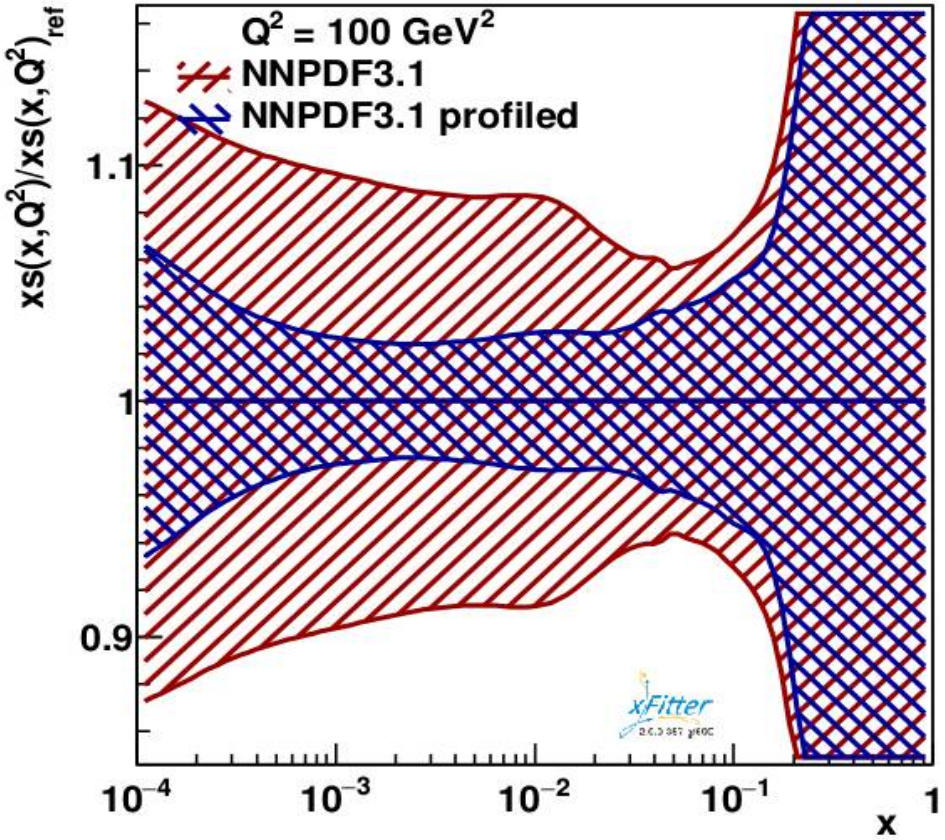
Can we improve the PDFs???

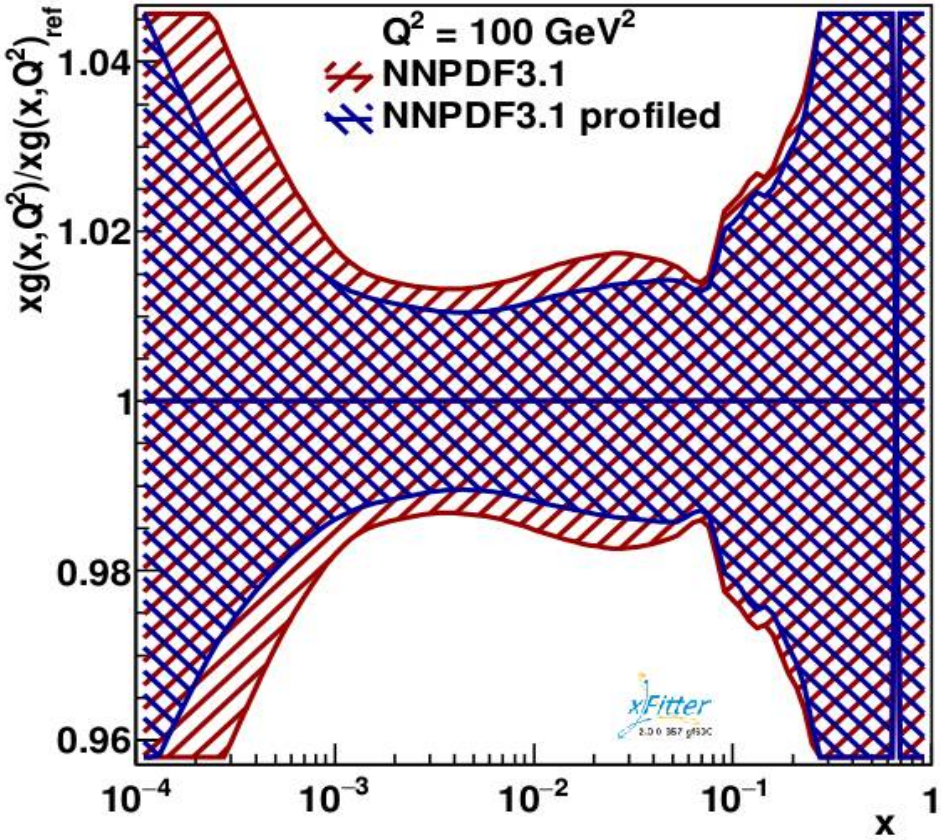
# Can we improve the PDFs: … YES!!!

**Excellent improvement on s(x)**

**Additional improvement on g(x)**



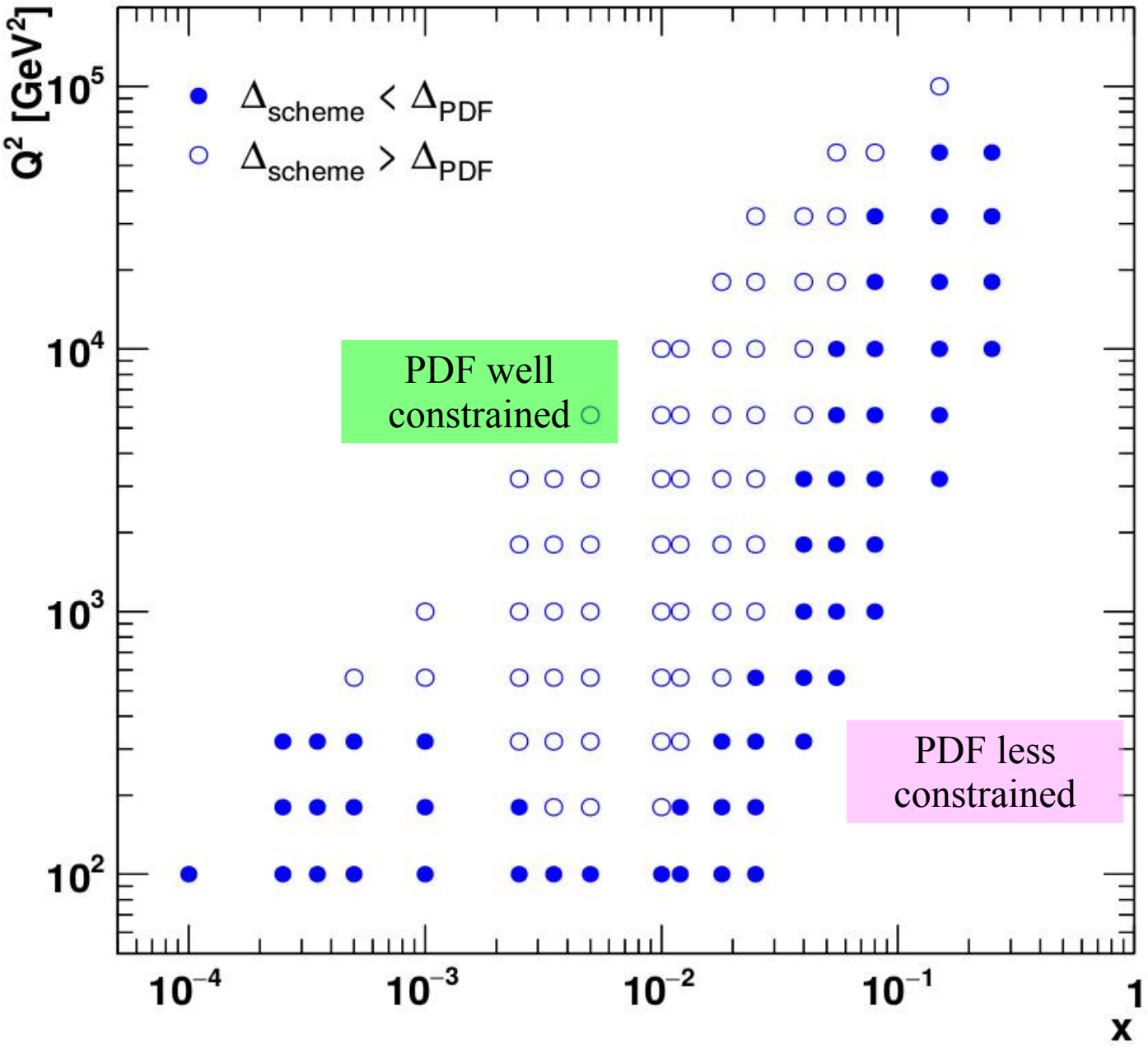



# Scheme Differences:

*FFNS & VFNS*
*What is impact?*

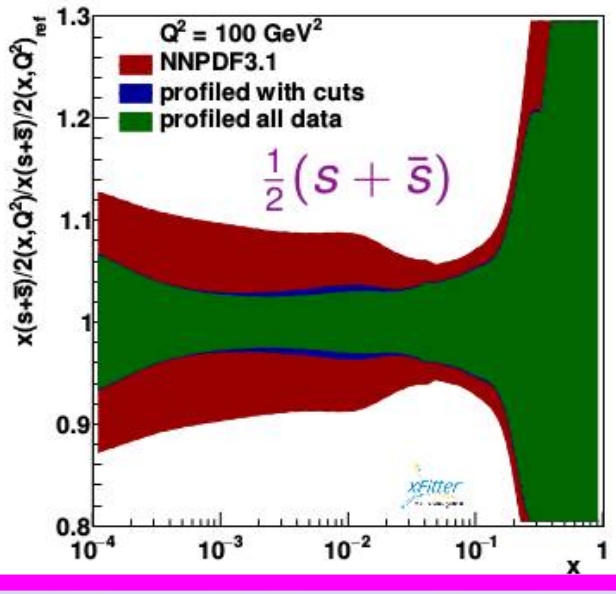
# Scheme Differences: Where FFNS & VFNS differ

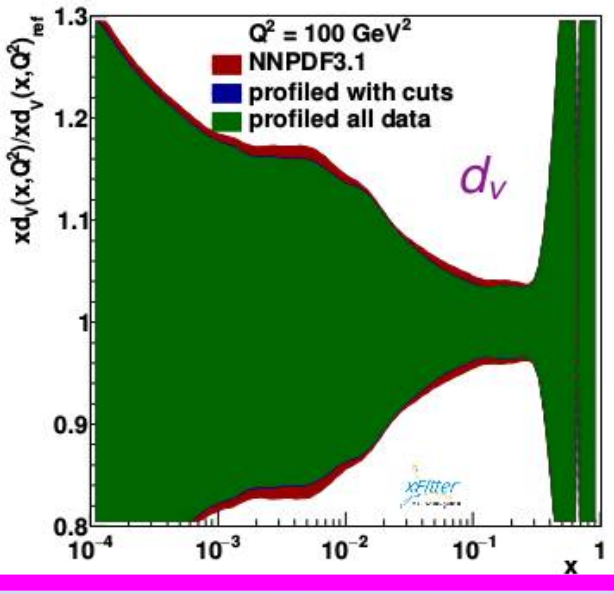


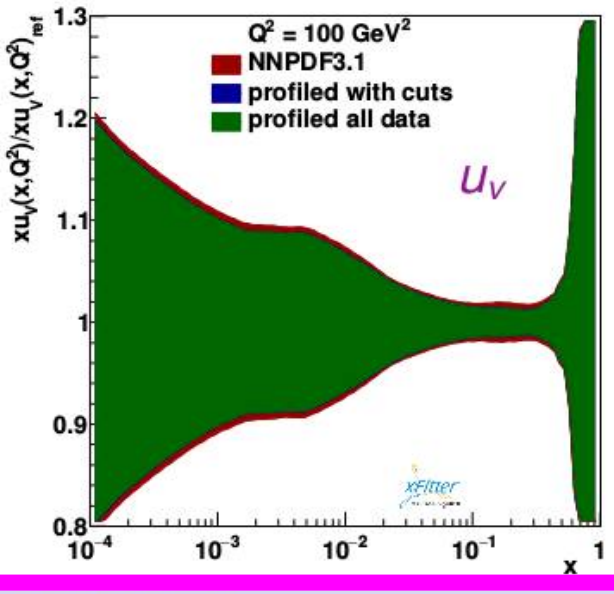

Let's cut out points where PDF Δ is larger than Scheme Δ

Reflects PDF uncertainty larger at kinematic "edges"

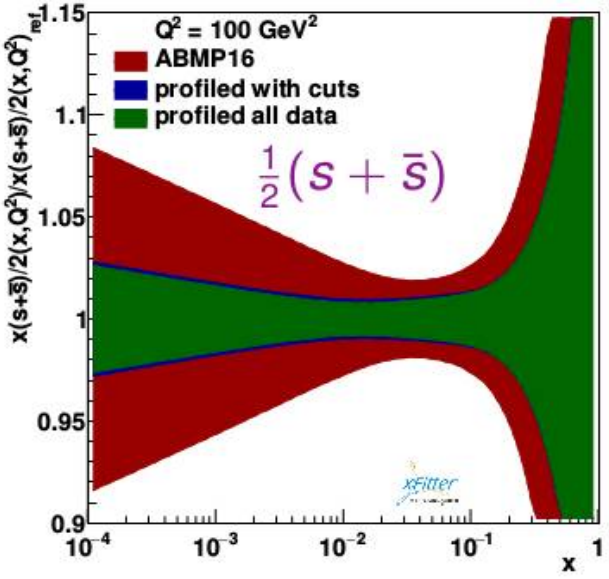
# PDF profiling with cuts: PDF profiling with cuts [NNPDF]

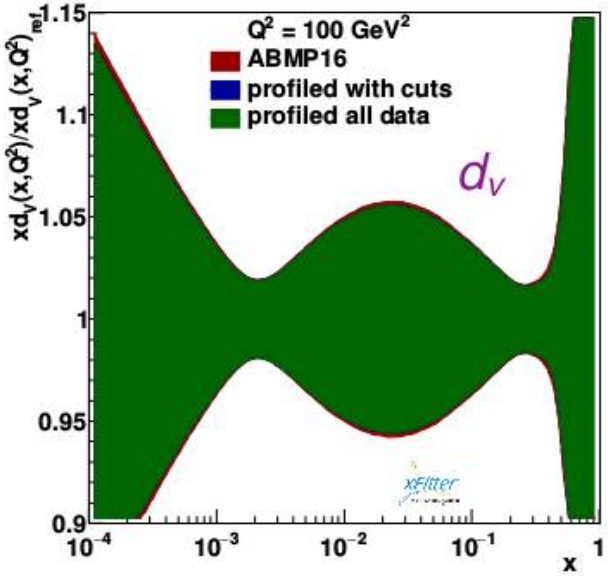


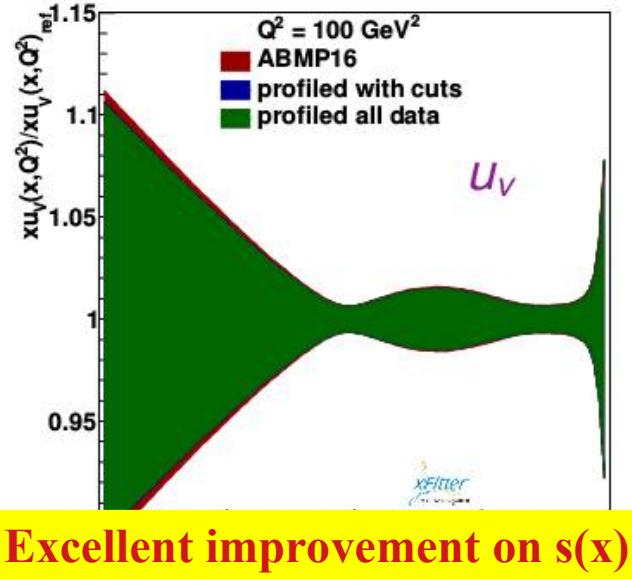




# PDF profiling with cuts: PDF profiling with cuts [ABMP]



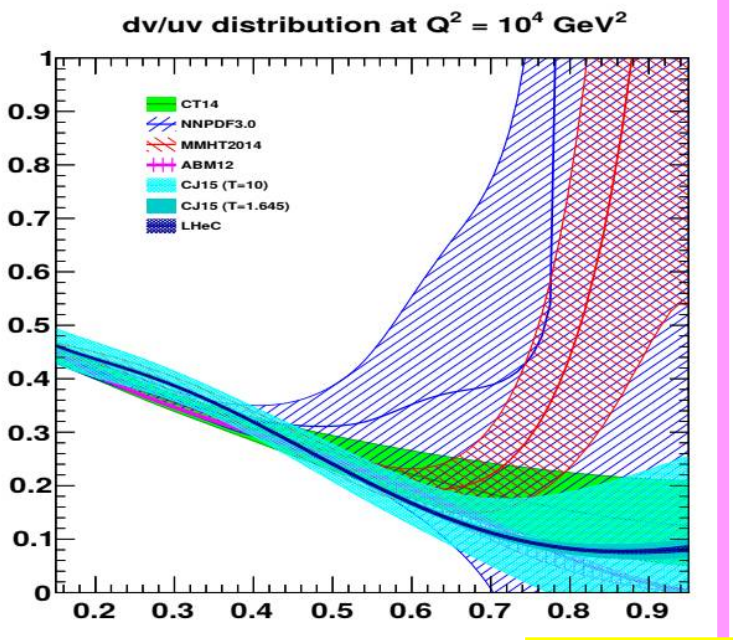




**Excellent improvement on s(x)**

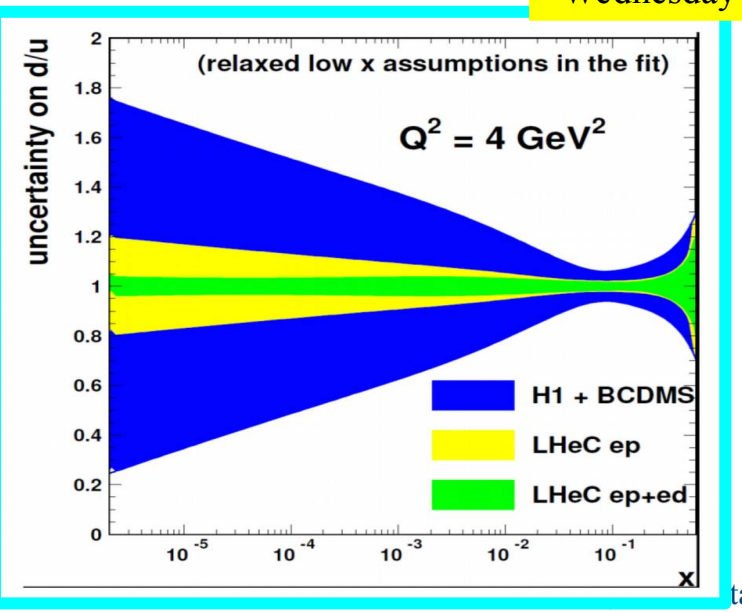
**Additional improvement on g(x)**

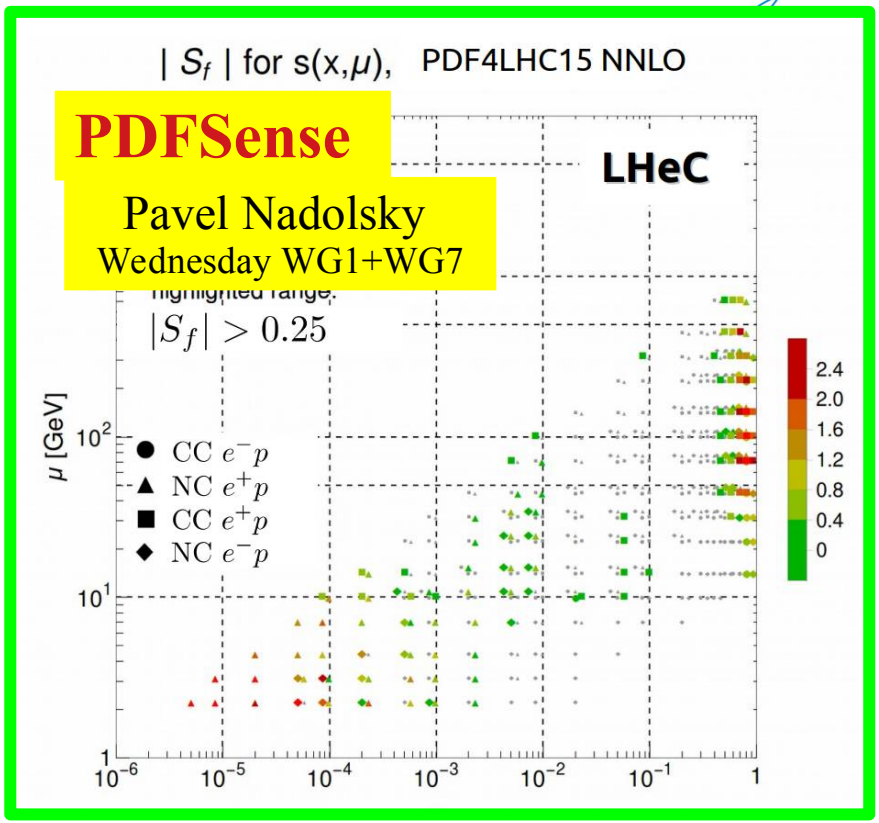
# LHeC & FCCeh Studies

***Note: This is just one LHeC channel***




Claire Gwenlan
Wednesday WG1+WG7




**PDFSense**

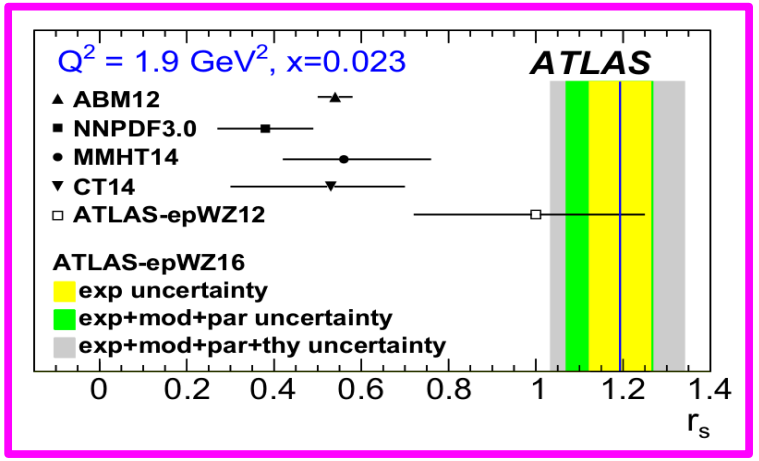
Pavel Nadolsky
Wednesday WG1+WG7


***possibly***
**24-25 October 2019**
**… near CERN**

# Conclusions

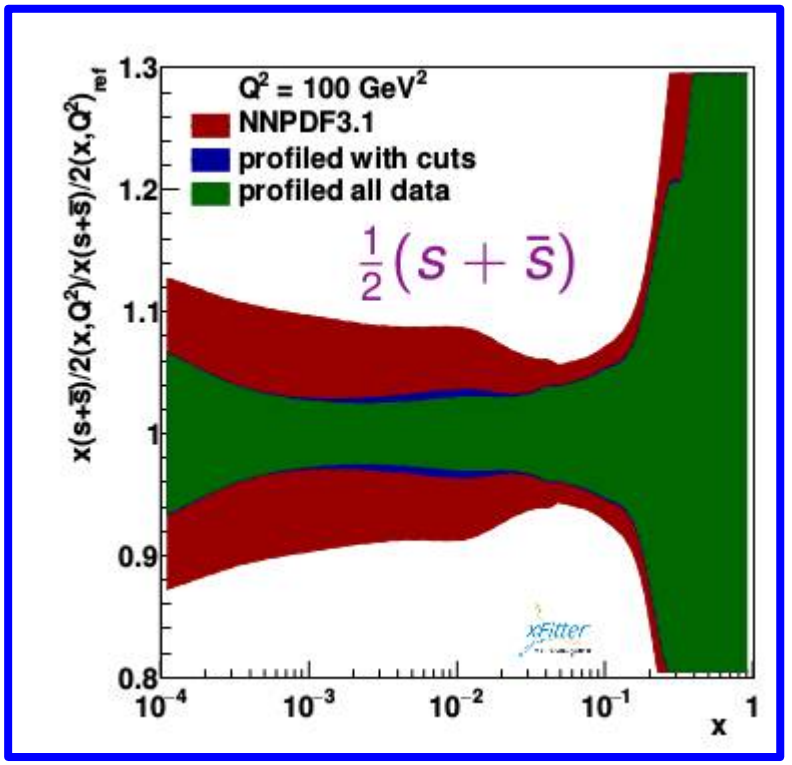
# Summary: Versatility of xFitter

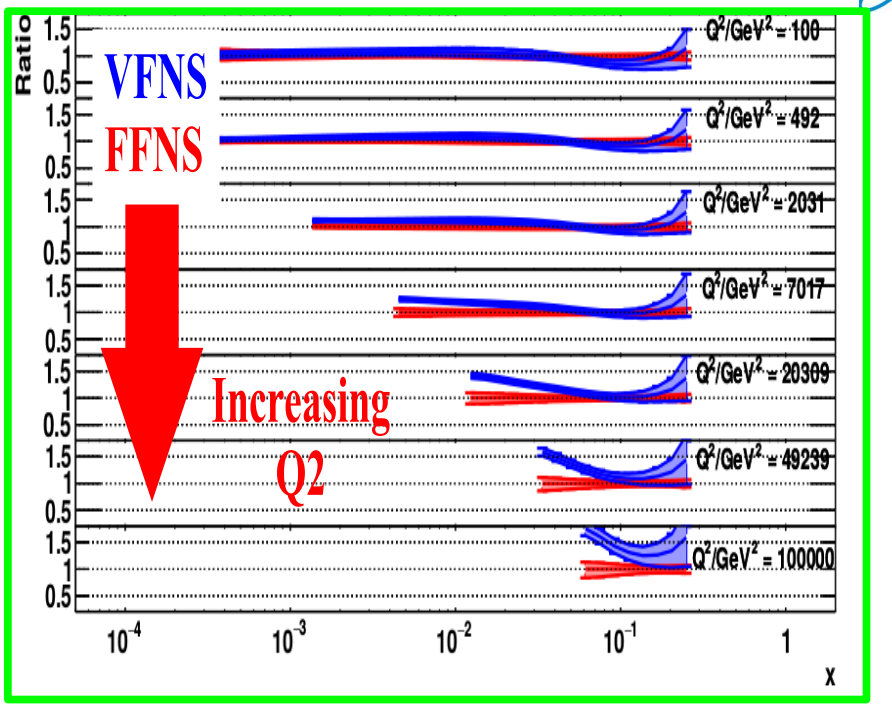


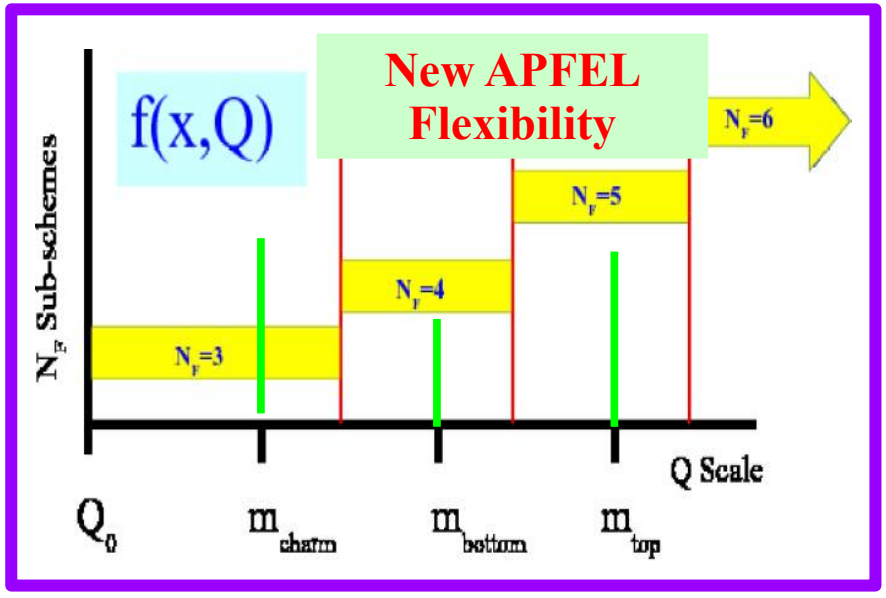



xFitter.org

xFitter




**PDF Uncertainty, heavy quarks, FFNS & VFNS, C & G initiated, s(x) extraction, resummation...**

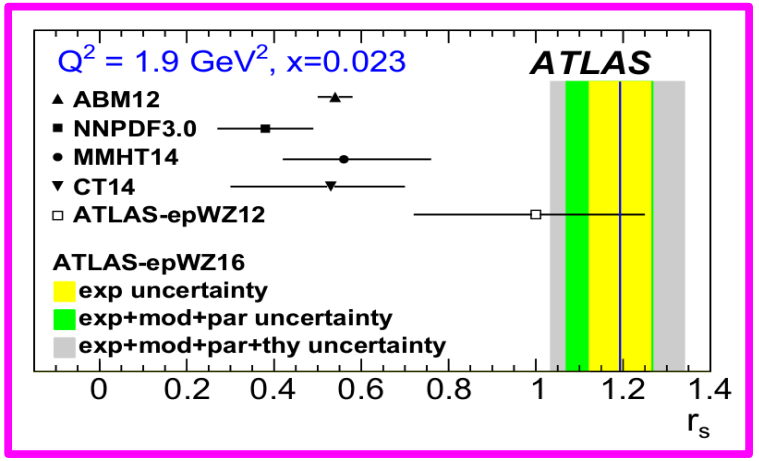
# *... a toast to the xFitter developers*

*a very useful tool*

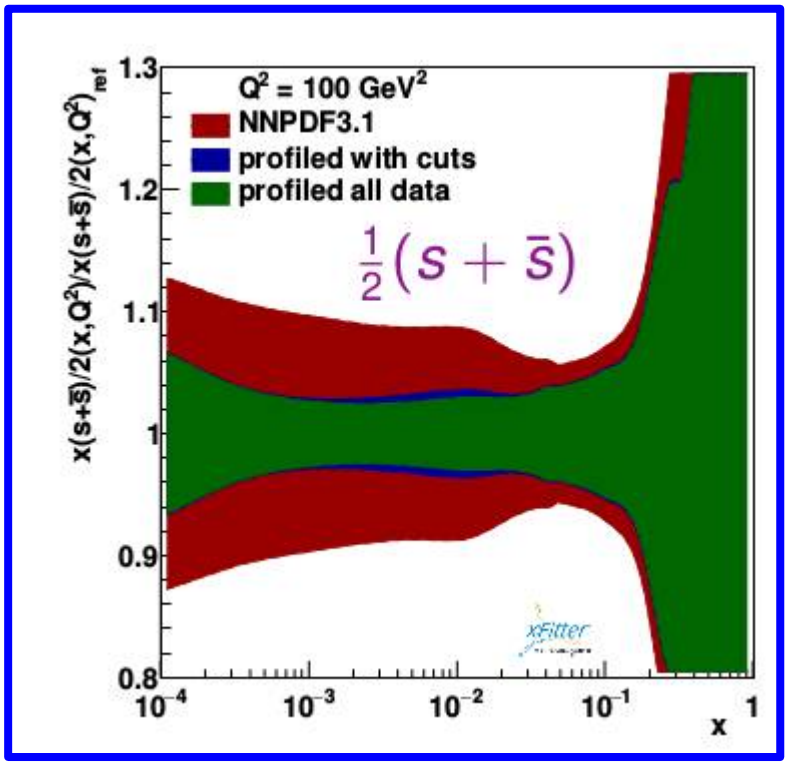
xFitter Meeting: Minsk March 2019

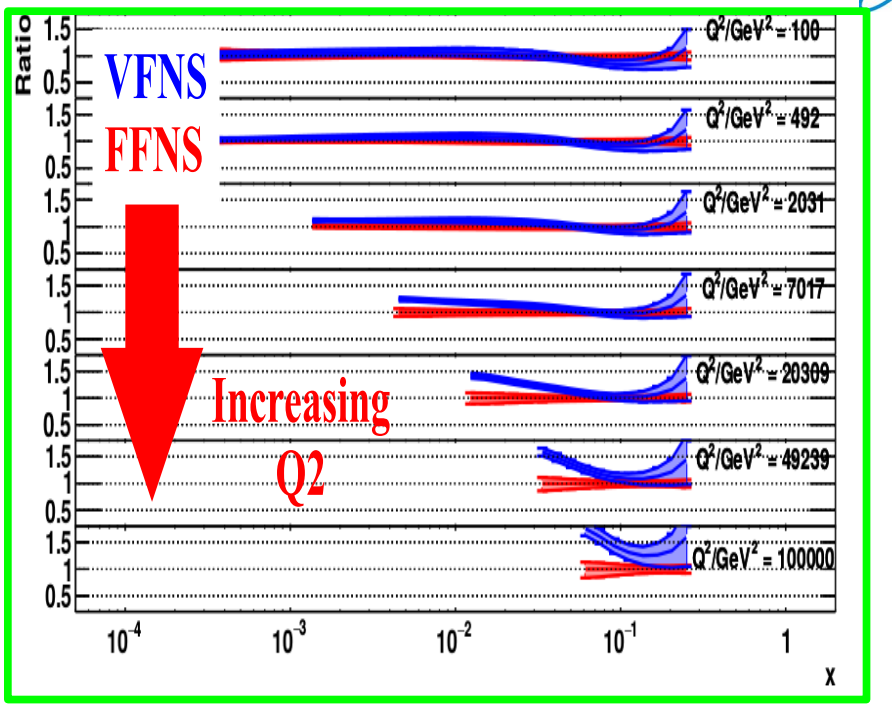
# Summary: Versatility of xFitter

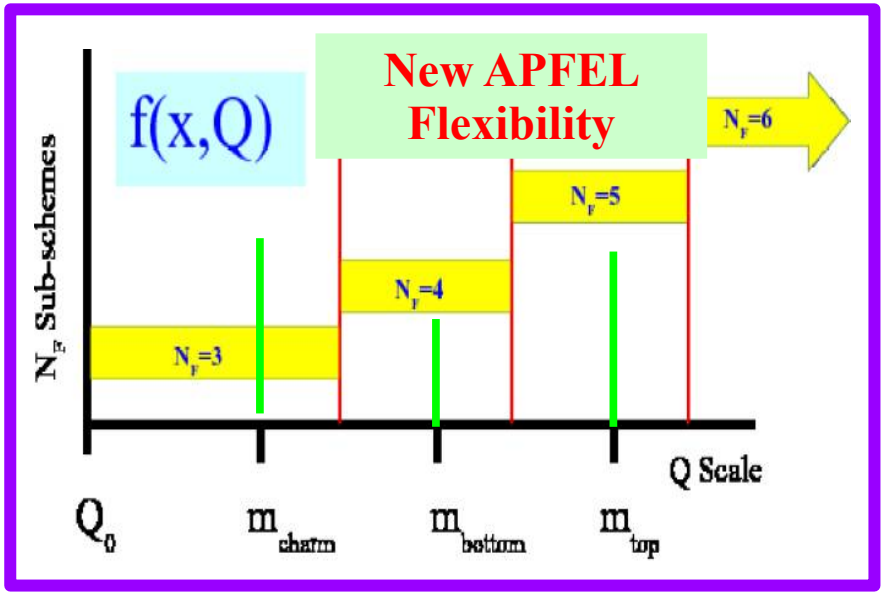





xFitter.org



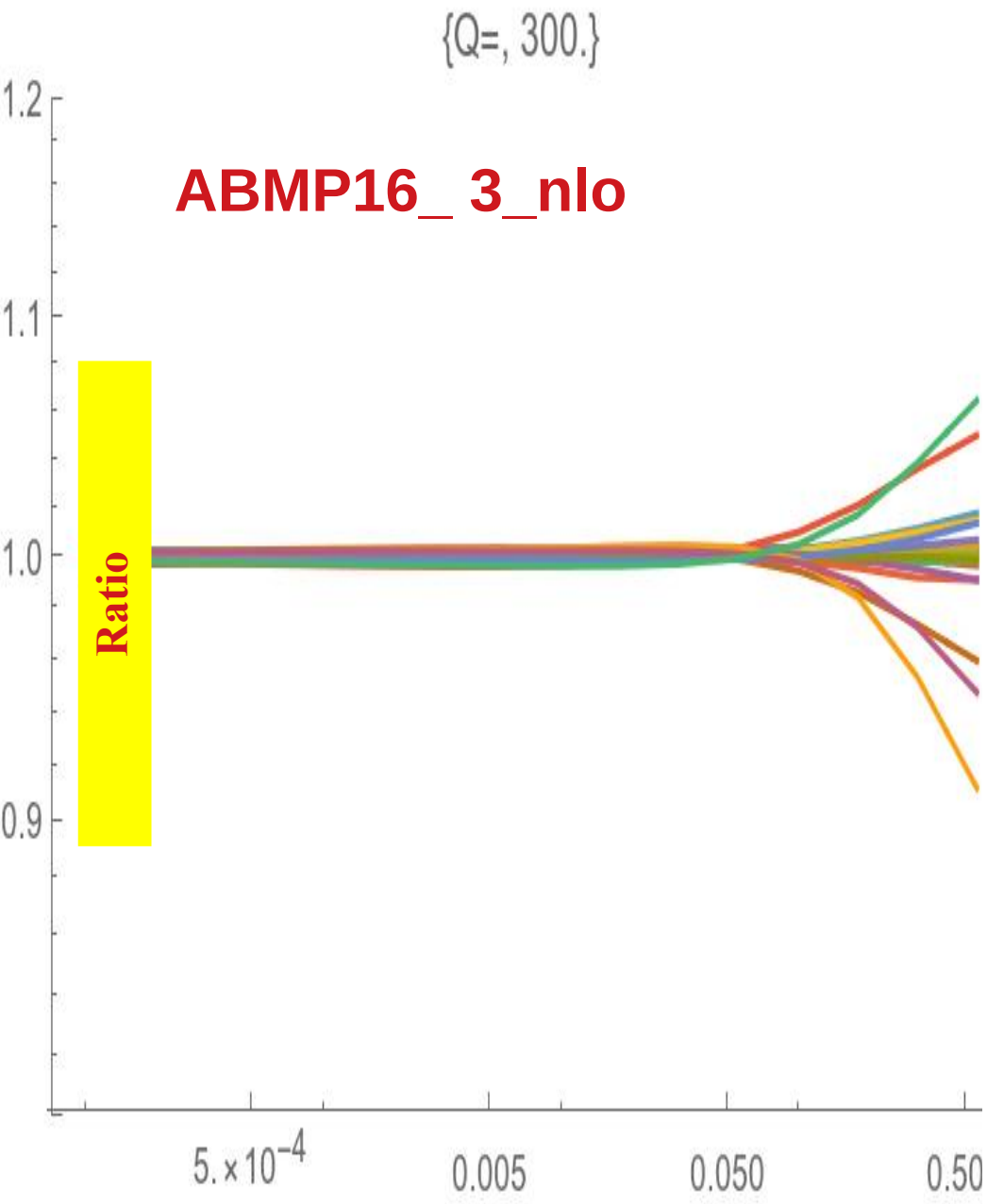

**PDF Uncertainty, heavy quarks, FFNS & VFNS, C & G initiated, s(x) extraction, resummation...**

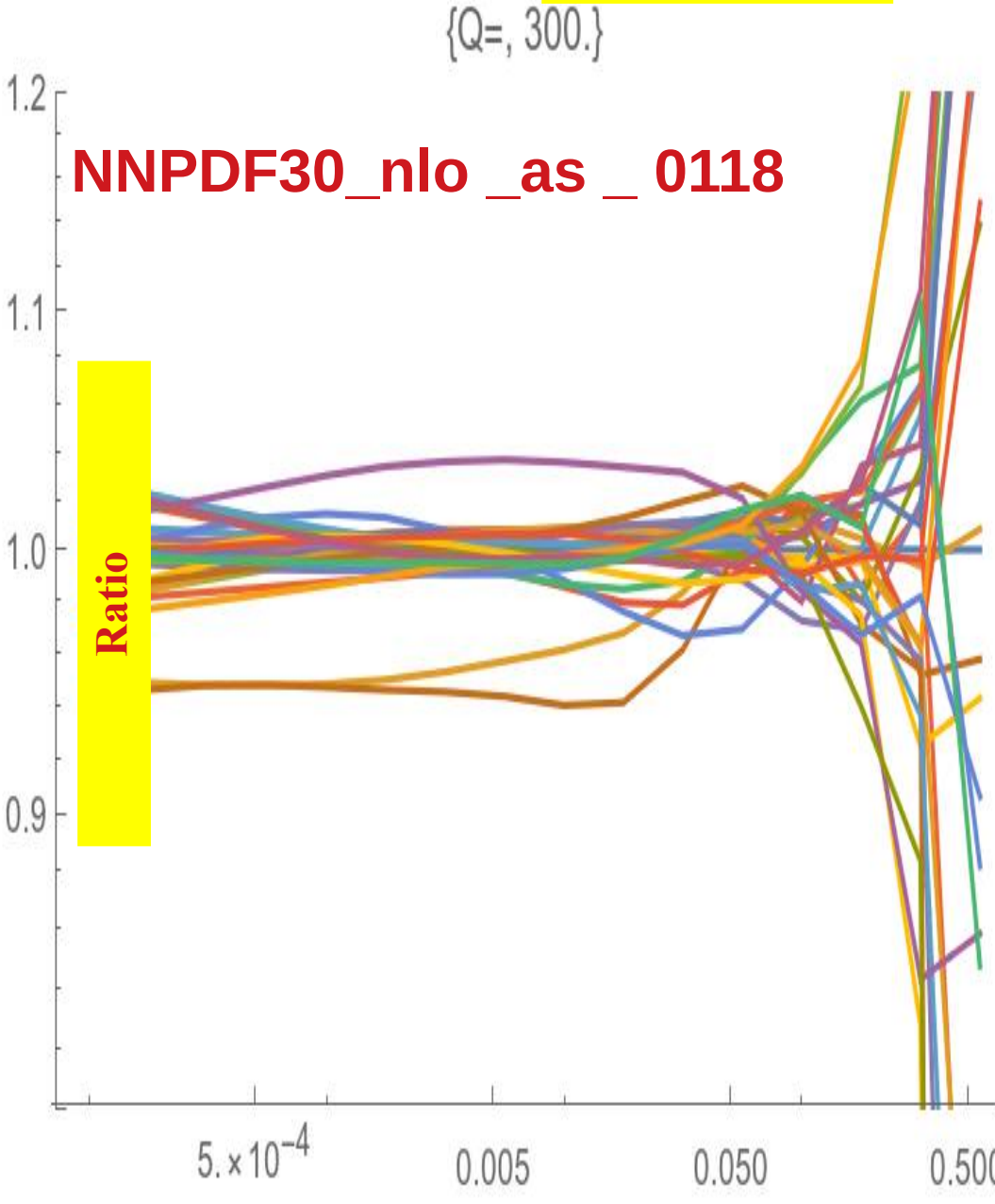
# EXTRA

# Uncertainties: PDF & $\mu$

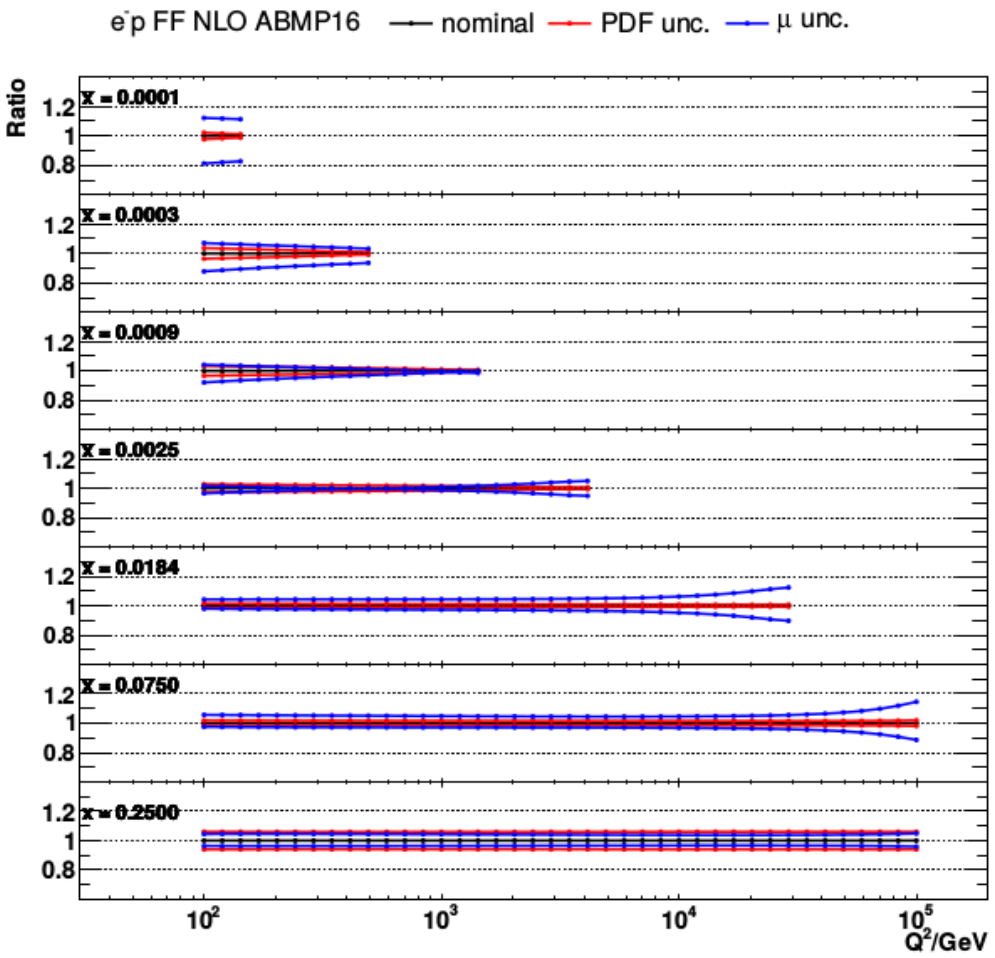
*variations*

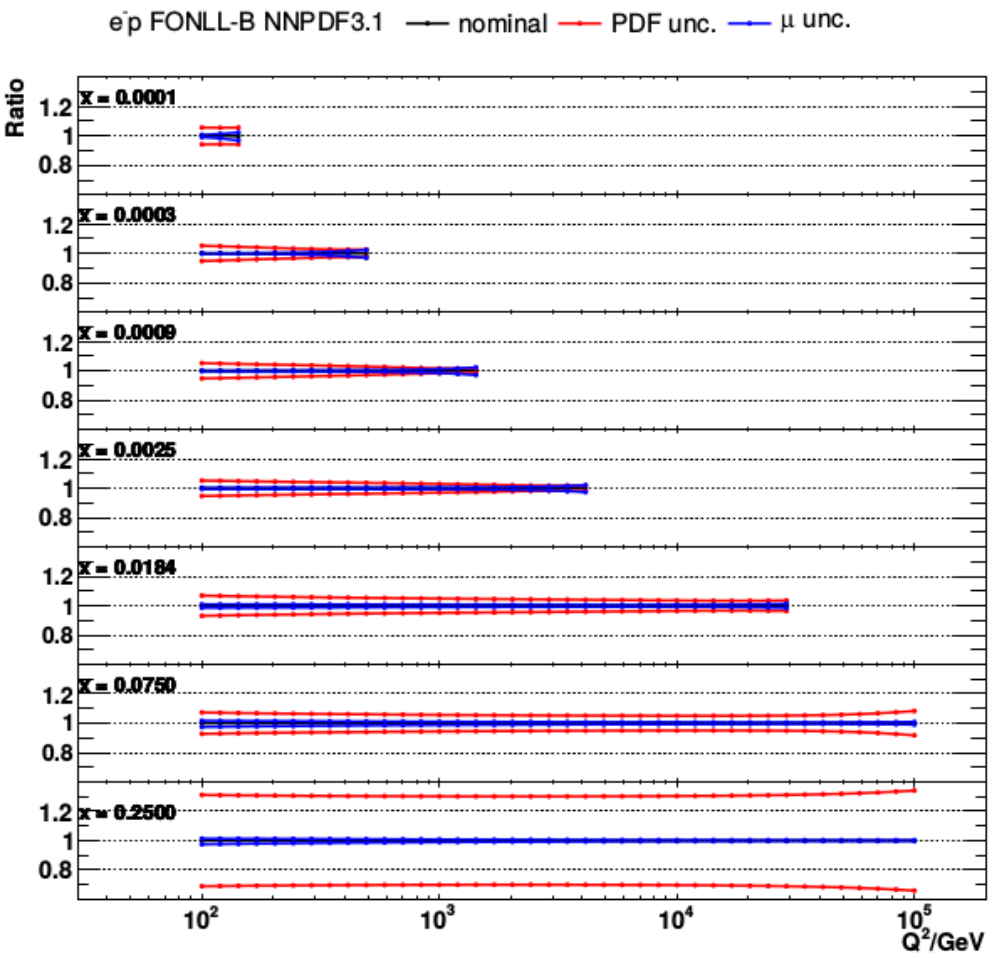
Q=300


{Q=, 300.}
ABMP16_ 3_nlo
Ratio
1.2
1.1
1.0
0.9
5. x 10^-4
0.005
0.050
0.50


{Q=, 300.}
NNPDF30_nlo _as _ 0118
Ratio
1.2
1.1
1.0
0.9
5. x 10^-4
0.005
0.050
0.500

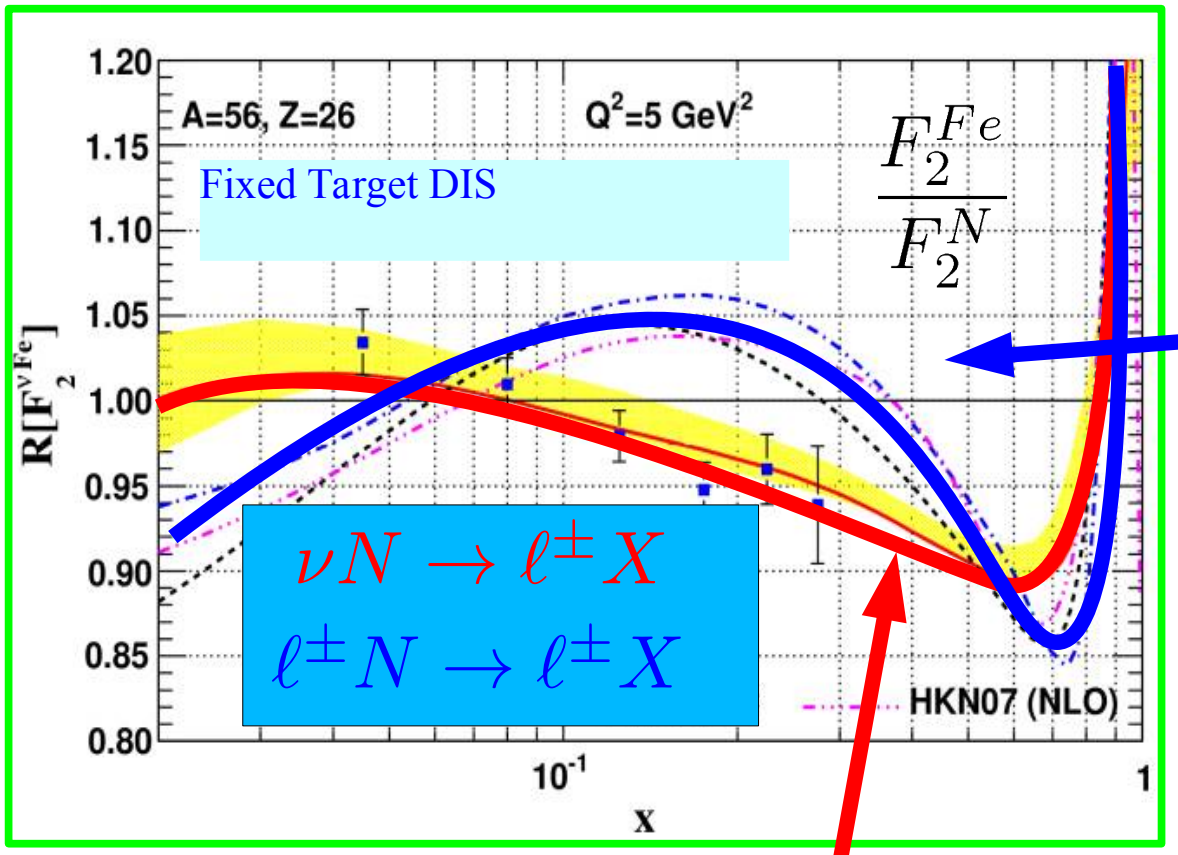
# Theoretical uncertainties: $Q^2$



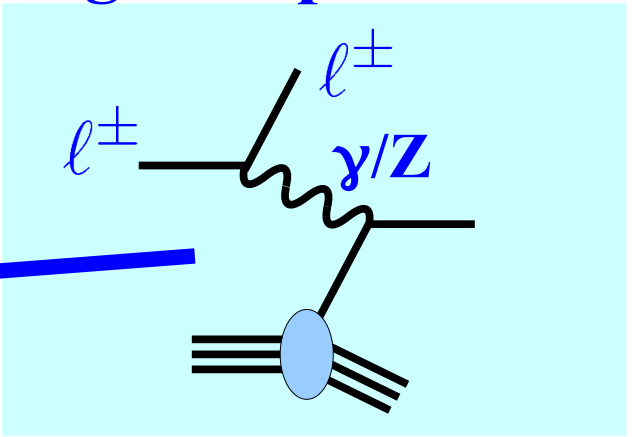




- Scale uncertainties: FF ABM > FONLL-B [to be checked]
- PDF uncertainties: FONLL-B [NNPDF] > FF ABM [ABMP16], especially at low $y$ ($s$ contribution)

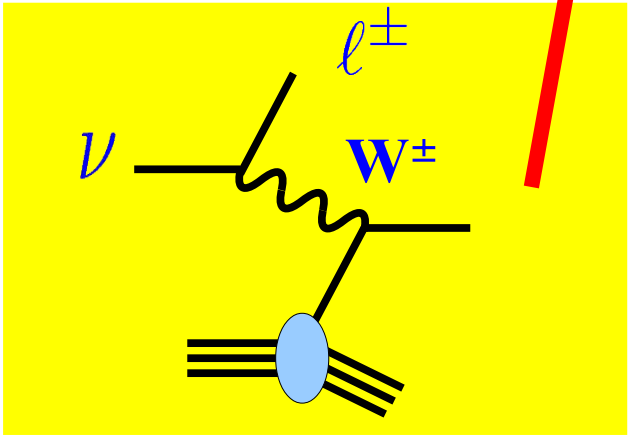
# Age Old Puzzle: What is the strange quark PDF ???




## Charged Lepton DIS

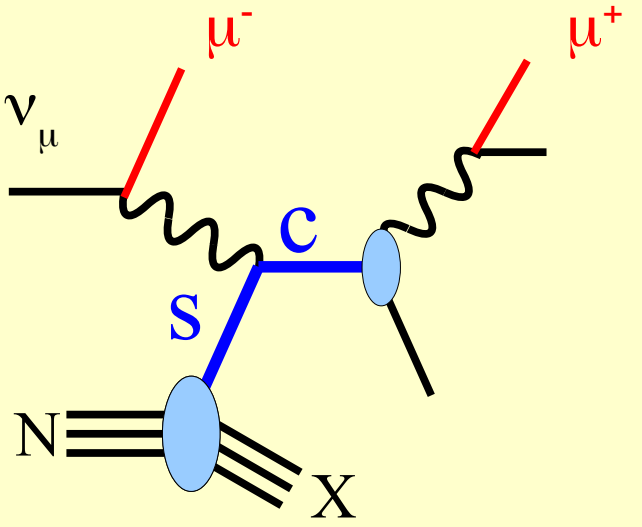



*some caveats*
*... correlated errors*




## Neutrino DIS

Extract s(x)



# 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).**

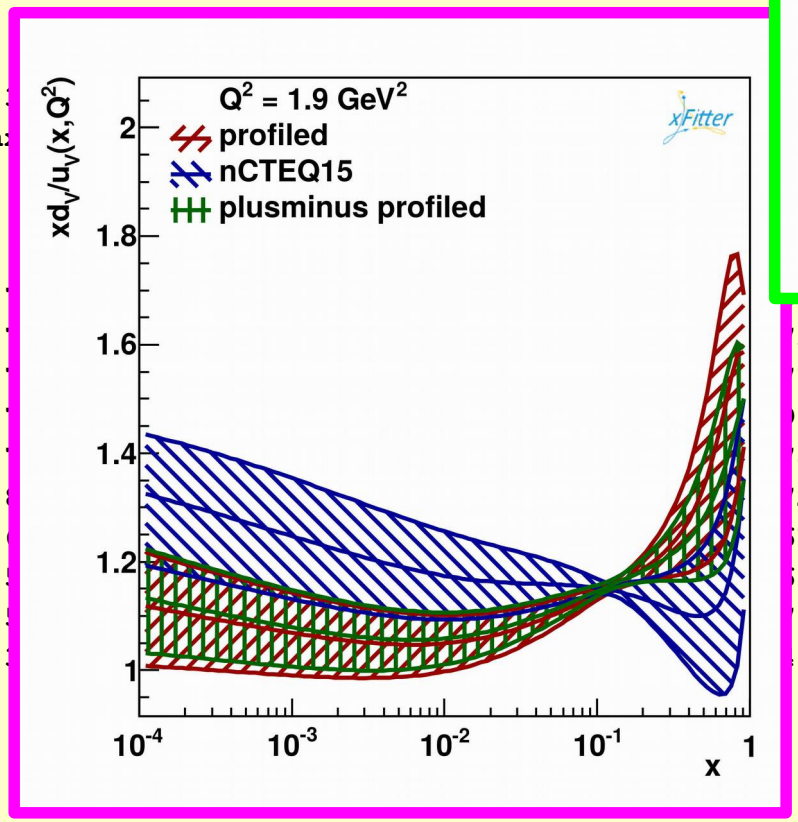
| No | Collider | Experiment | Reaction | arXiv | Readme |
|---|---|---|---|---|---|
| 1 | fixedTarget | bcdms | inclusiveDis | cern-ep-89-06 | README |
| 2 | hera | h1 | beautyProduction | 0907.2643 | |
| 3 | hera | h1 | inclusiveDis | 1012.4355 | |
| 4 | hera | h1 | jets | 0706.3722 | README |
| 5 | 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 | |

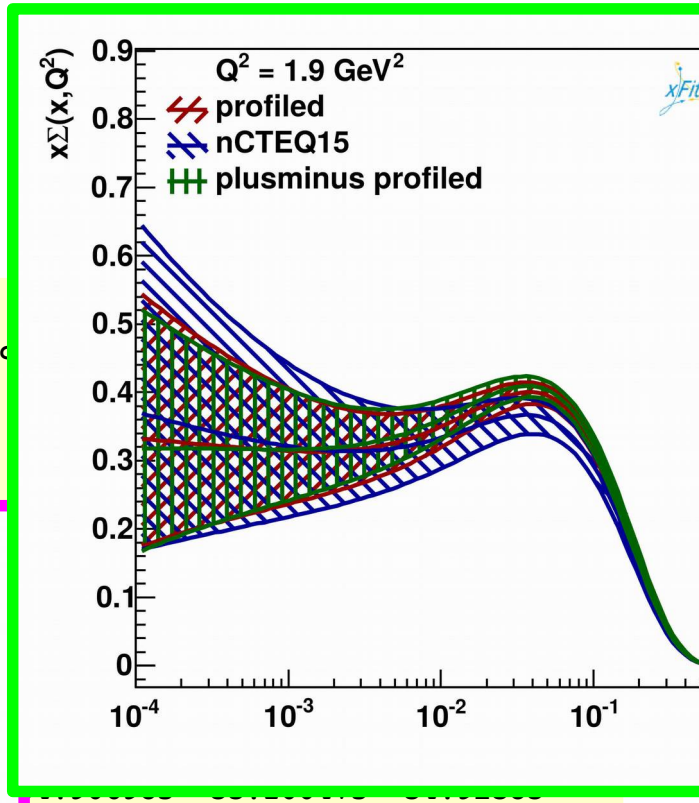
# Profiling $W^{\pm}$ in Proton-Lead Collisions

→ 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',
   ColumnName = 'bin_min','bin_ma

   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 Rad*

# xFitter Workshops

www.xfitter.org


xFitter Meeting in Oxford, UK


# Thanks to my xFitter colleagues


xFitter Meeting: Krakow March 20

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

xFitter