Precision QCD for New Physics Searches:

Working with heavy quarks at High Scales & High Orders

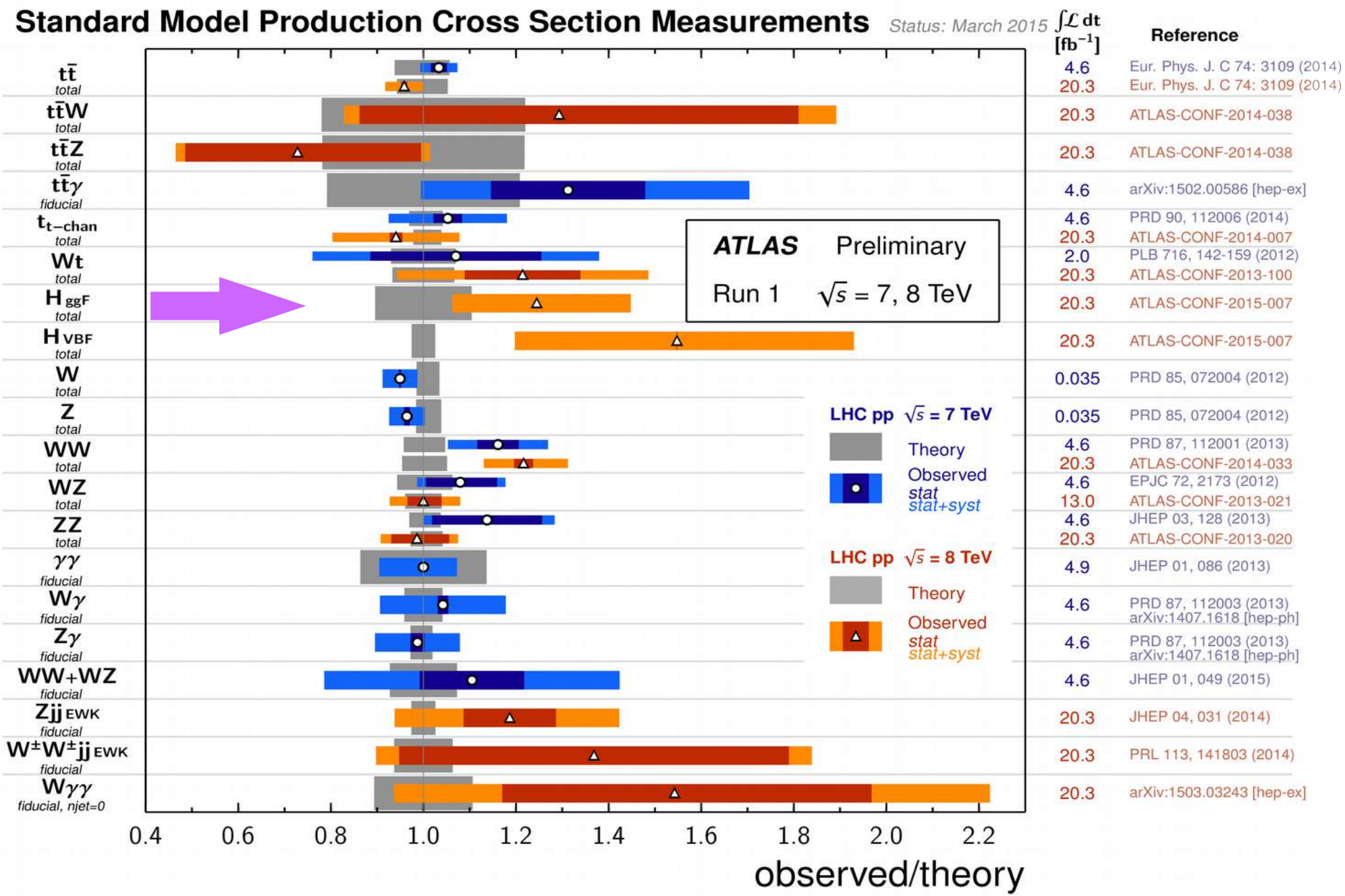
Fred Olness

SMU

Thanks to:
F. Lyonnet, E. Godat, A. Kusina,, I. Schienbein, K. Kovarik, J.Y. Yu, T. Jezo, J.G. Morfin, J.F. Owens, P. Nadolsky, M. Guzzi, V. Radescu, C. Keppel, B. Clark

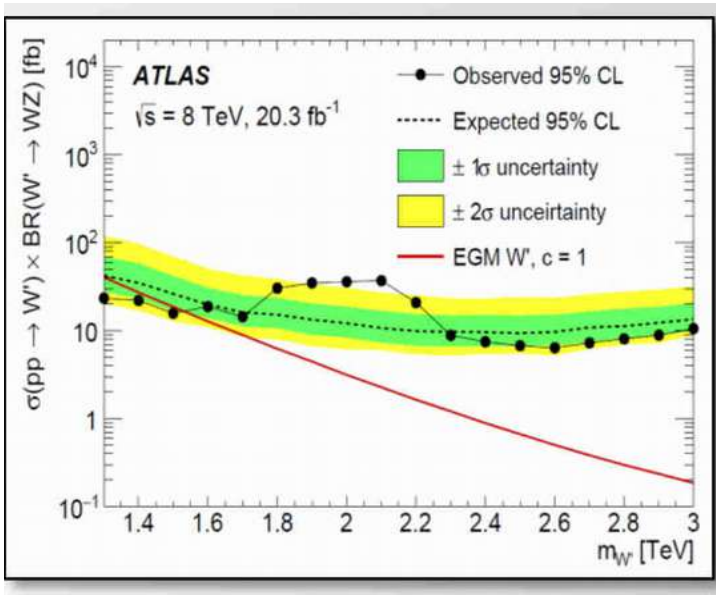
Fermilab
30 July 2015

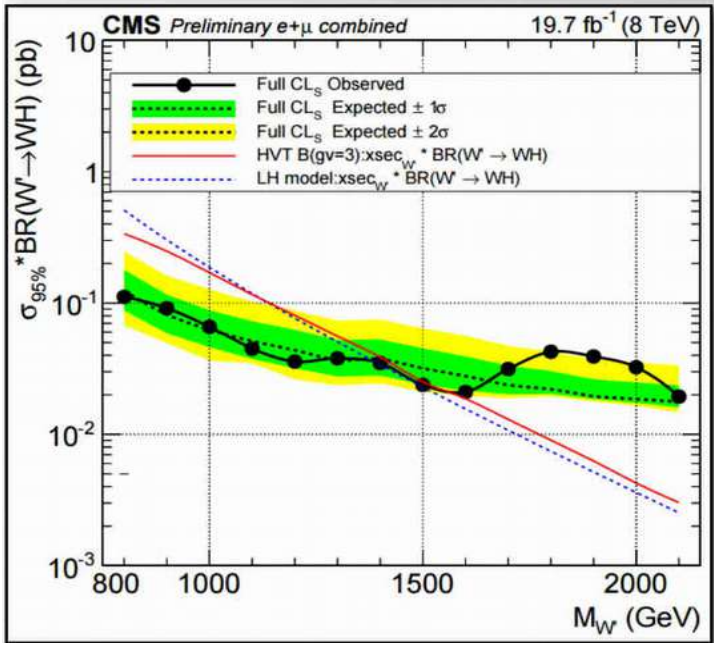
LHC Results: *Incredible Progress*

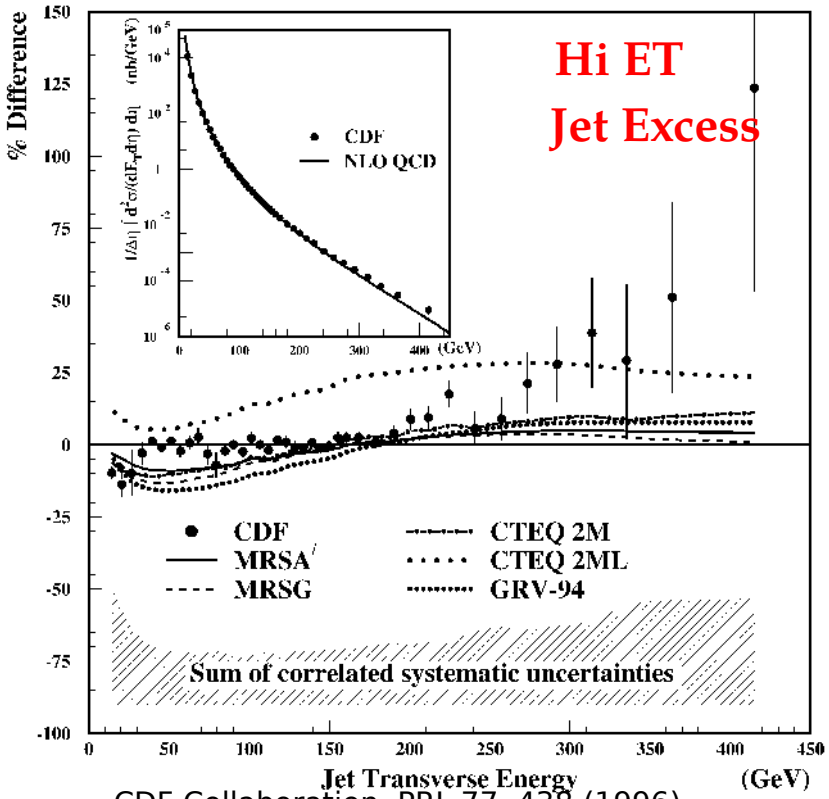


Much of theory error from PDFs N^{3}LO gg->H **PDF error 2x of Theory Error**

… things that go bump in the data …

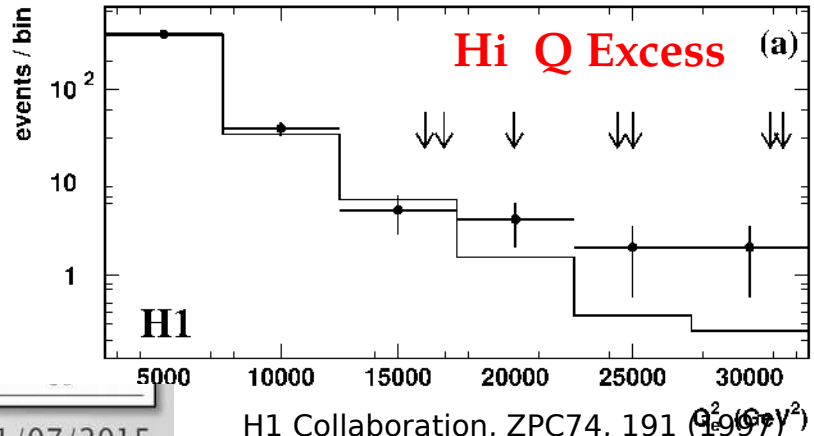




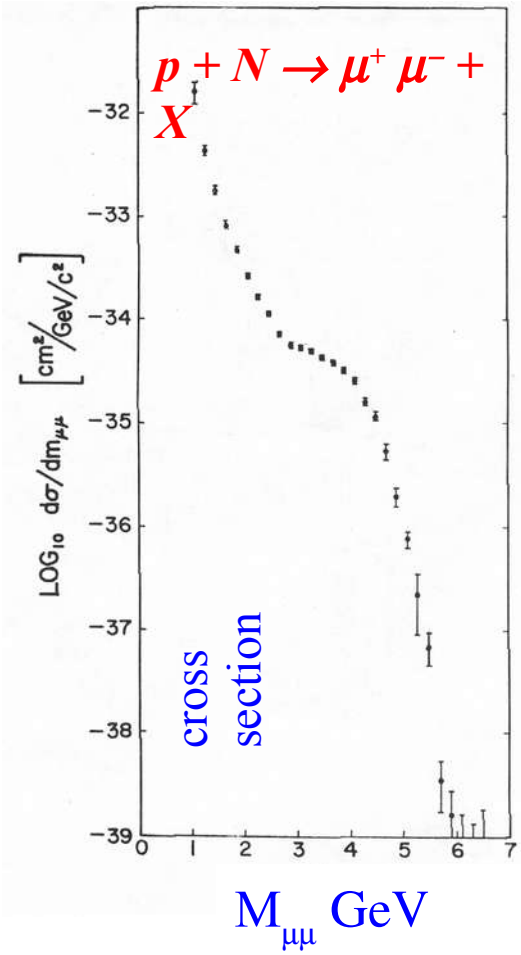


CDF Collaboration, PRL 77, 438 (1996)

Can you find the Nobel Prize???



H1 Collaboration, ZPC74, 191 (1997)
ZEUS Collaboration, ZPC74, 207 (1997)



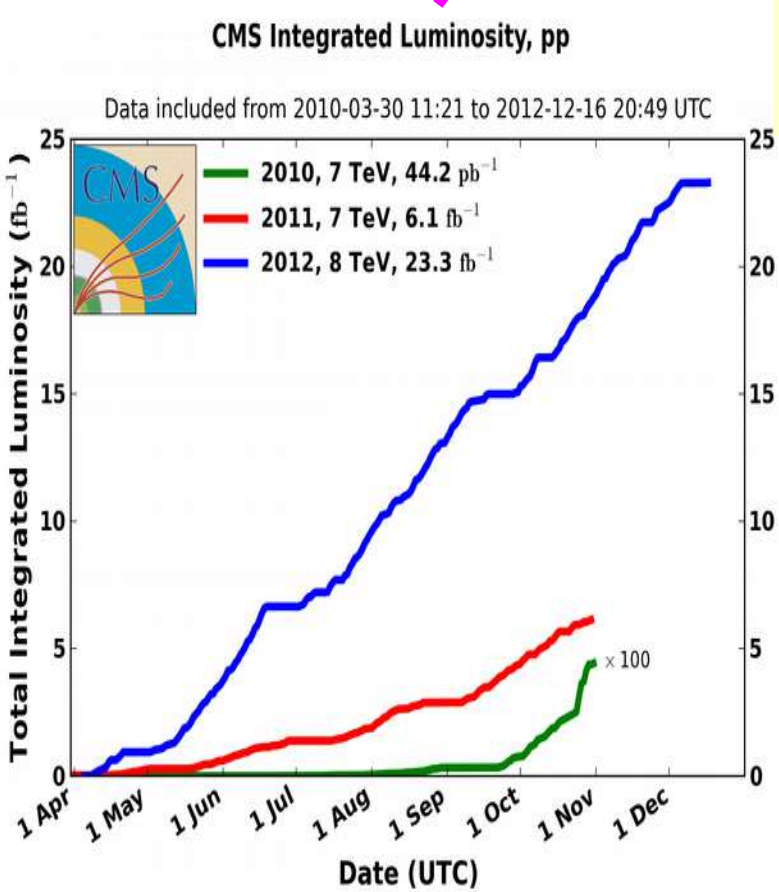
The Key to Discovery: The Parton Model and Factorization

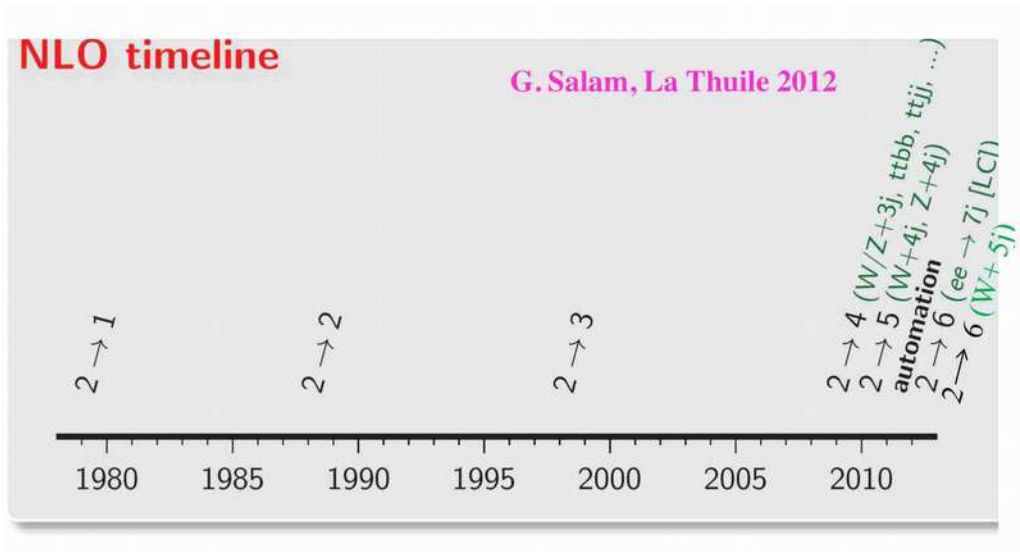
$$\sigma_{P\gamma\to c} = f_{P\to a} \otimes \hat{\sigma}_{a\gamma\to c}$$

Experimental Observables

WHAT ABOUT PDF'S ???

Theoretical Calculations





Challenges: … past, present,& future

C T E Q

The CTEQ List of Challenges in Perturbative QCD

~1995

Welcome to the CTEQ List of Challenges in Perturbative QCD! Although QCD has successfully passed many tests, there are still areas where there are problems when comparing theory and experiment or where additional data or calculations are needed. Here is our current list of Challenges in Perturbative QCD. This is expected to be a dynamic list, so check back often. It is expected that existing entries will be periodically updated and that new entries will be added.

1. Direct photon production
2. Heavy quark production cross sections
3. Jet cross sections and xt scaling
4. Determining the gluon distribution
5. Large-x behavior of parton distributions
6. Determining the flavor dependence of pdf's
7. Extracting Charged & Neutral Current Cross Sections

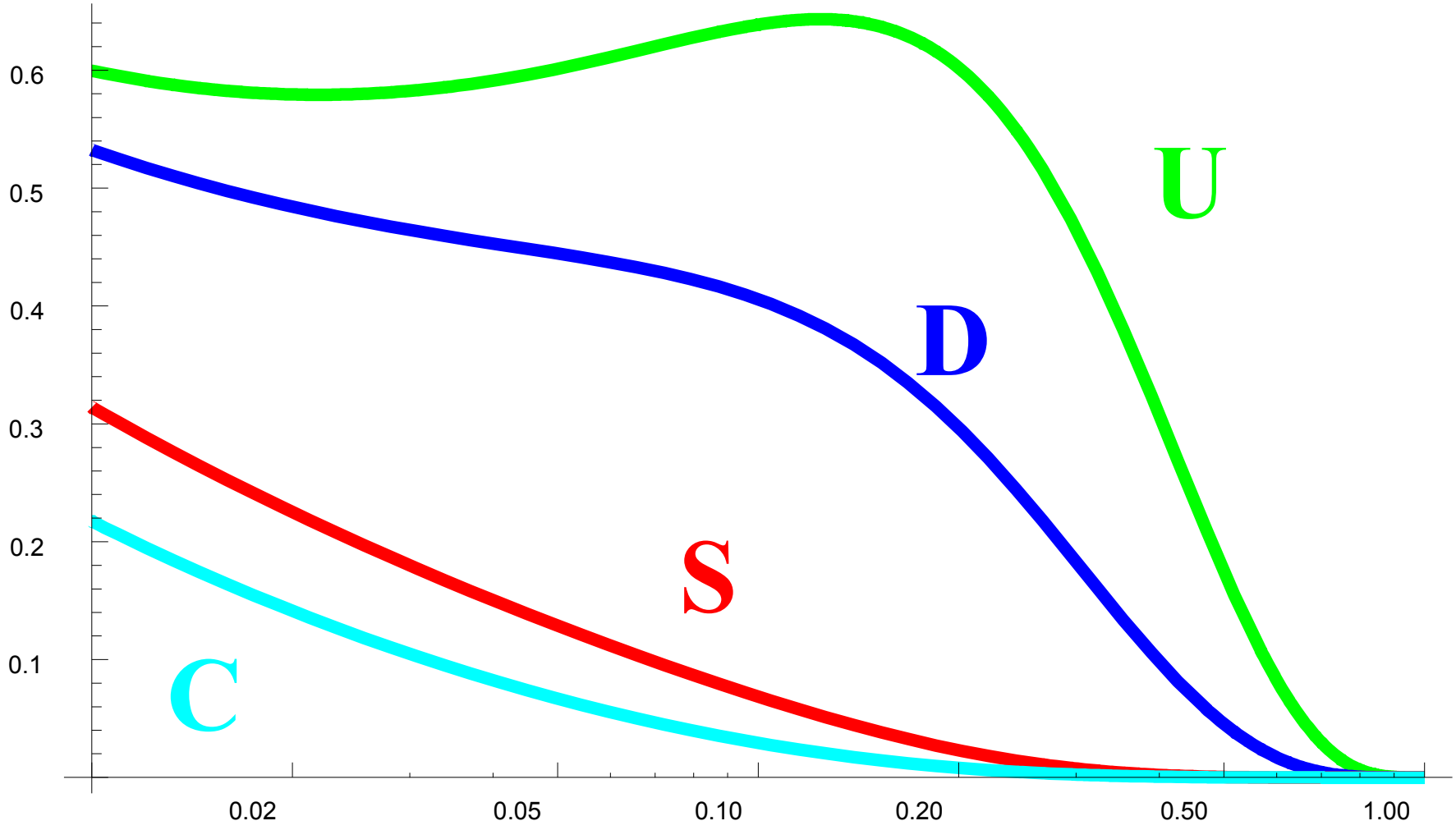
http://www.hep.fsu.edu/~owens/qcd/QCD_list.html

1) Flavor Differentiation & Nuclear Corrections

2) Multi-scale problems: Heavy Quarks

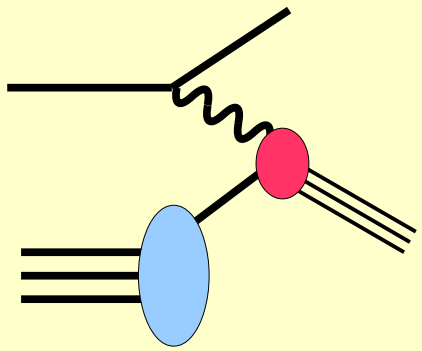
3) Hi-Order Corrections & ACOT

How do we differentiate flavors???

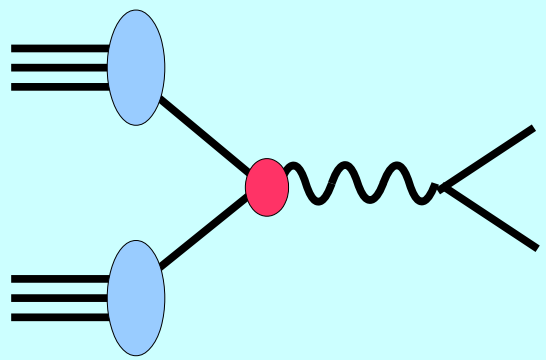


... why do we care about nuclear corrections

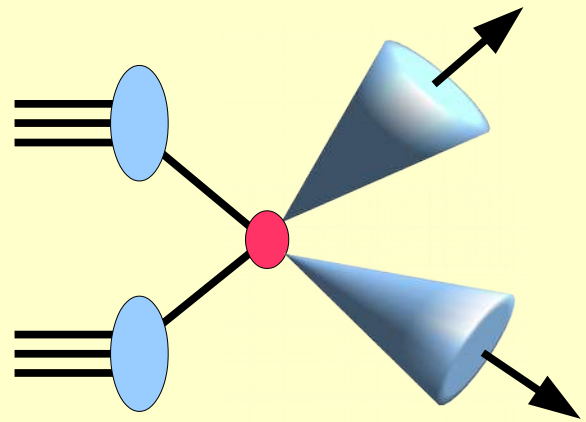
Key Data Sets for Global PDF Fits



DIS Production



Drell-Yan



Jet Production

$$F_2^{\nu} \sim [d + s + \bar{u} + \bar{c}]$$

$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$

$$F_3^{\nu} = 2\,[d + s - \bar{u} - \bar{c}]$$

$$F_3^{\bar{\nu}} = 2\,[u + c - \bar{d} - \bar{s}]$$

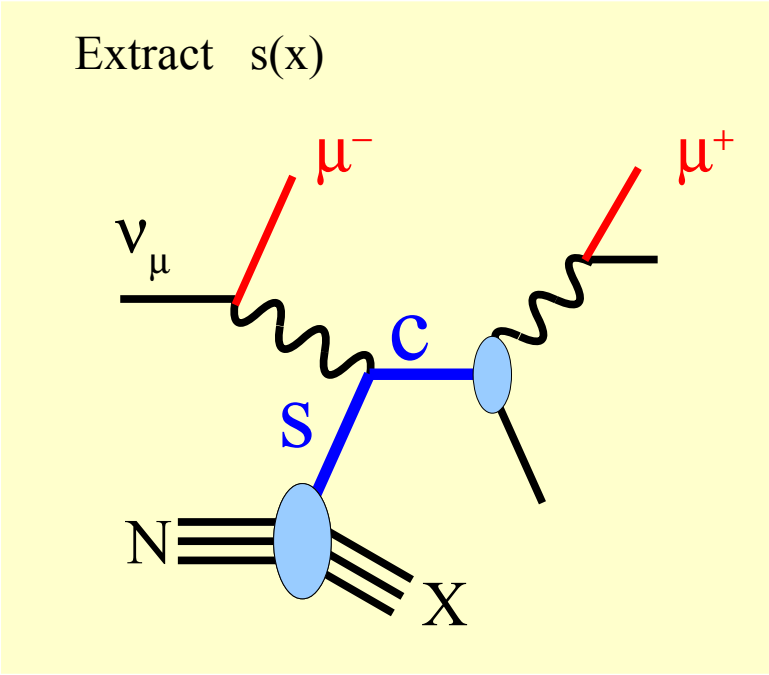
$$F_2^{\ell^\pm} \sim \left(\tfrac{1}{3}\right)^2 [d + s] + \left(\tfrac{2}{3}\right)^2 [u + c]$$

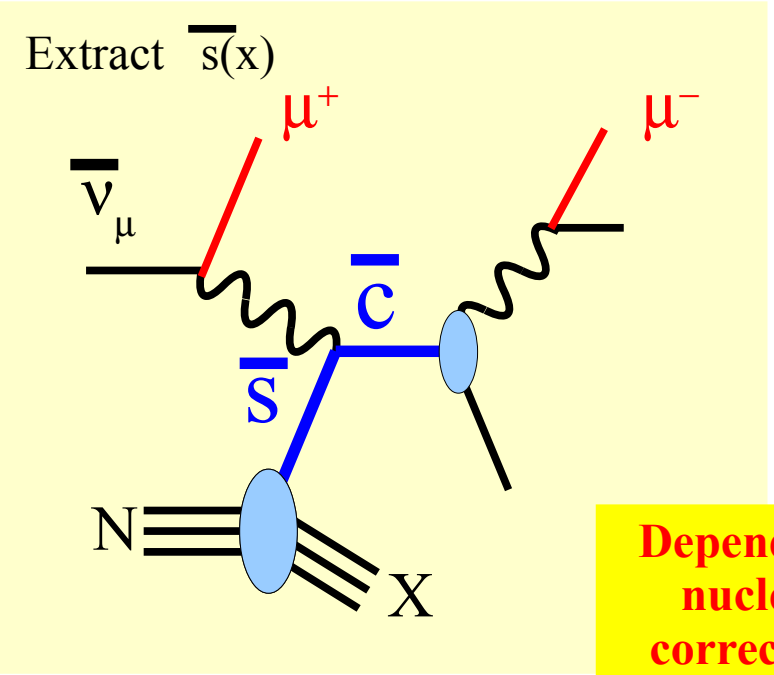
In particular, the DIS combinations have historically been particularly useful

<u>Different</u> linear combinations – key for flavor differentiation

The ν-DIS data typically use heavy targets, and this requires the application of ***<u>nuclear corrections</u>***

Di-muon production ⇒ Extract s(x) Parton Distribution





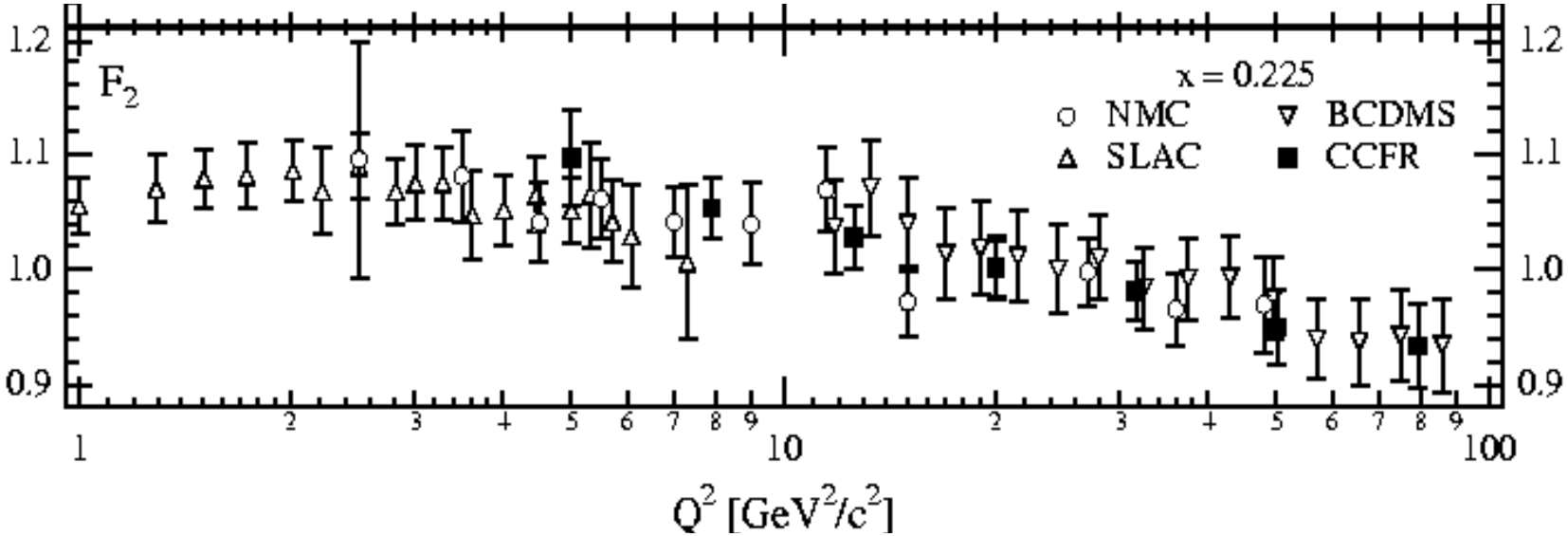
Depends on nuclear corrections

Can extract s(x) and $\bar{s}(x)$ separately

Used in CTEQ Fits

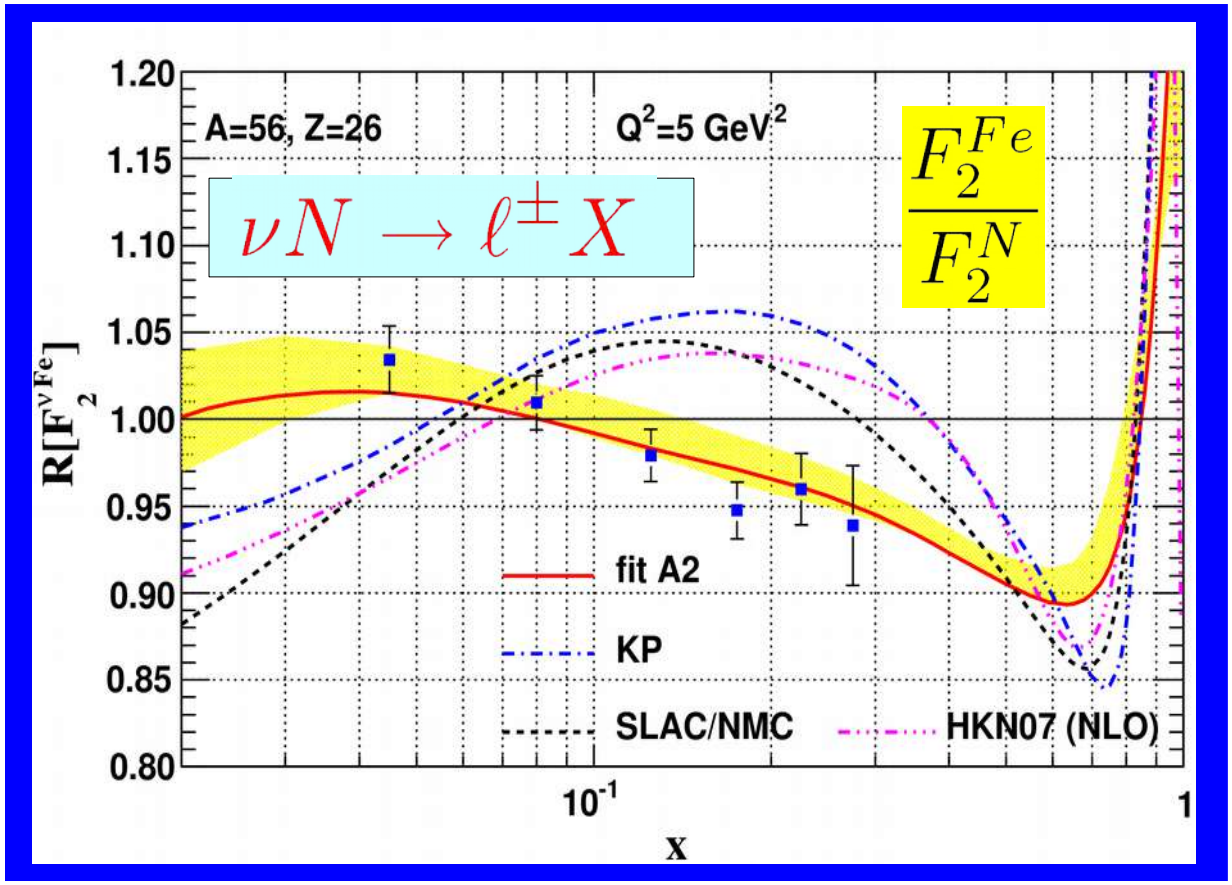
The CTEQ List of Challenges in Perturbative QCD

~1995

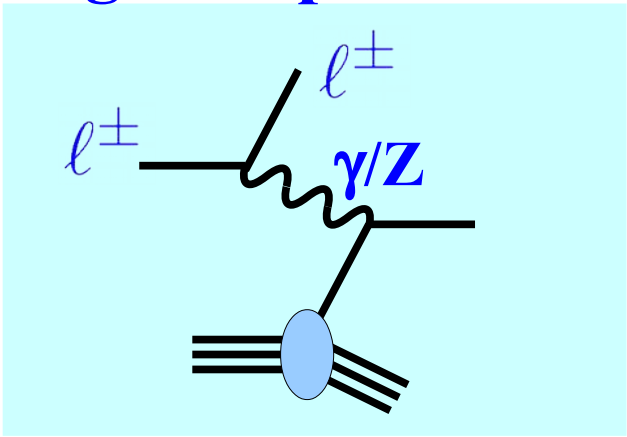


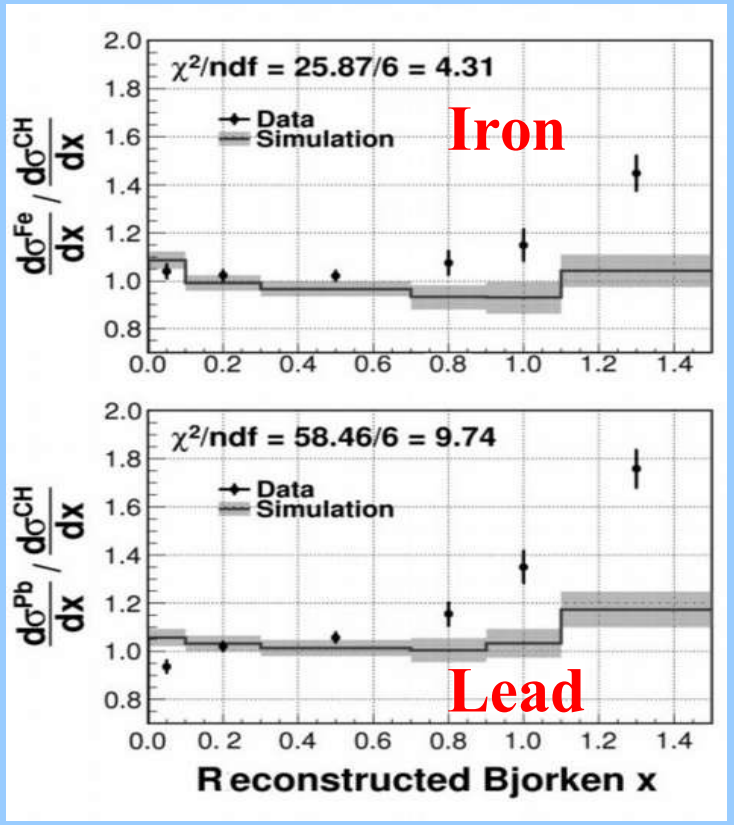
C T E Q

Nuclear Corrections: Compare Neutrino and Charged Lepton DIS

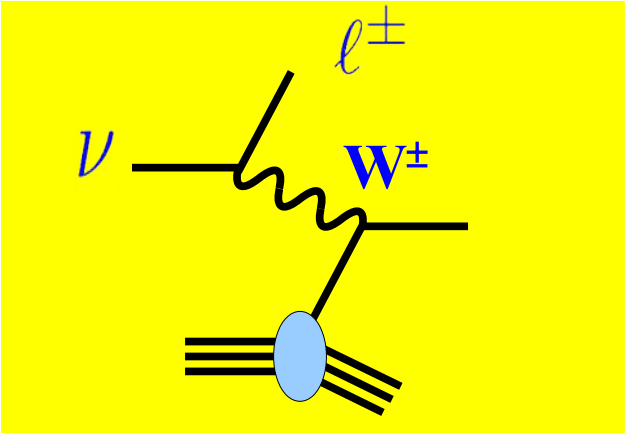


Charged Lepton DIS



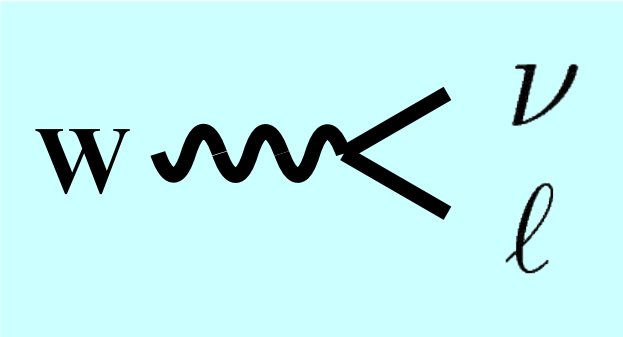


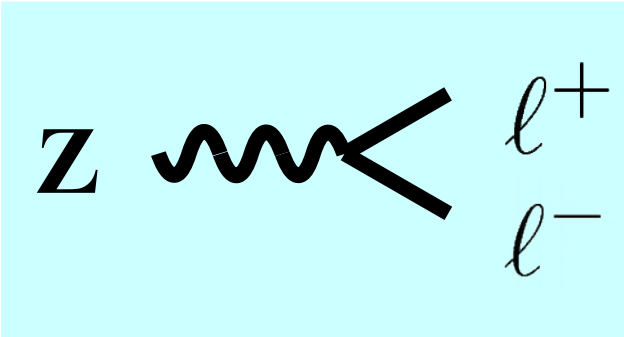
MINERvA: Phys.Rev.Lett. 112 (2014) 23, 231801



Neutrino DIS

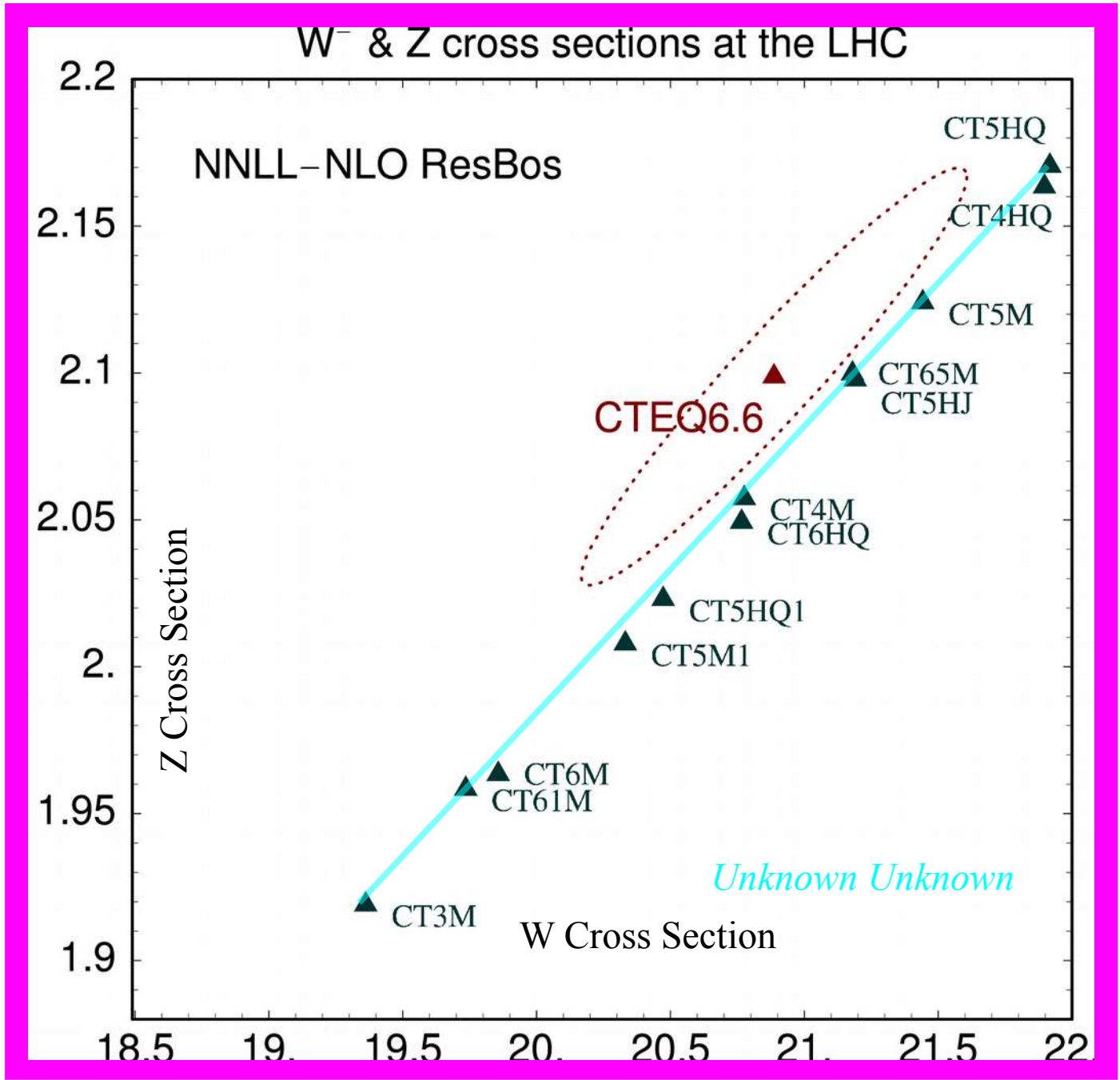
Strange Quark: Impact on LHC … W/Z correlation ⇒ MW extraction





The W-Z correlation is limited by the uncertainty coming from the strange quark distribution

Key for M_W determination



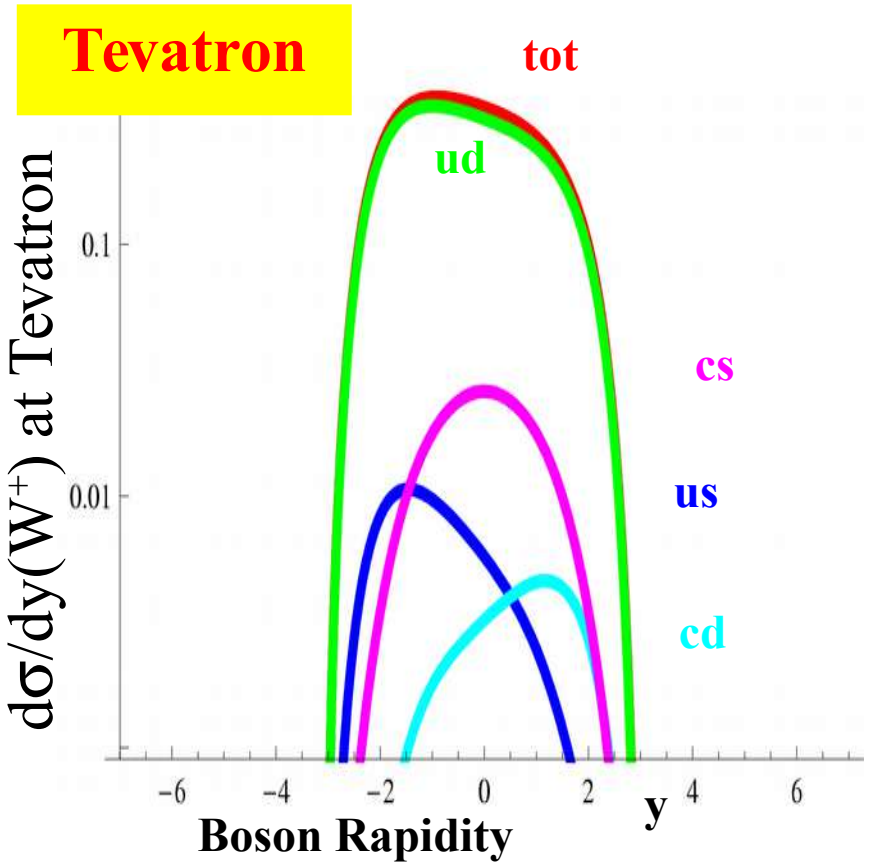
W/Z Production

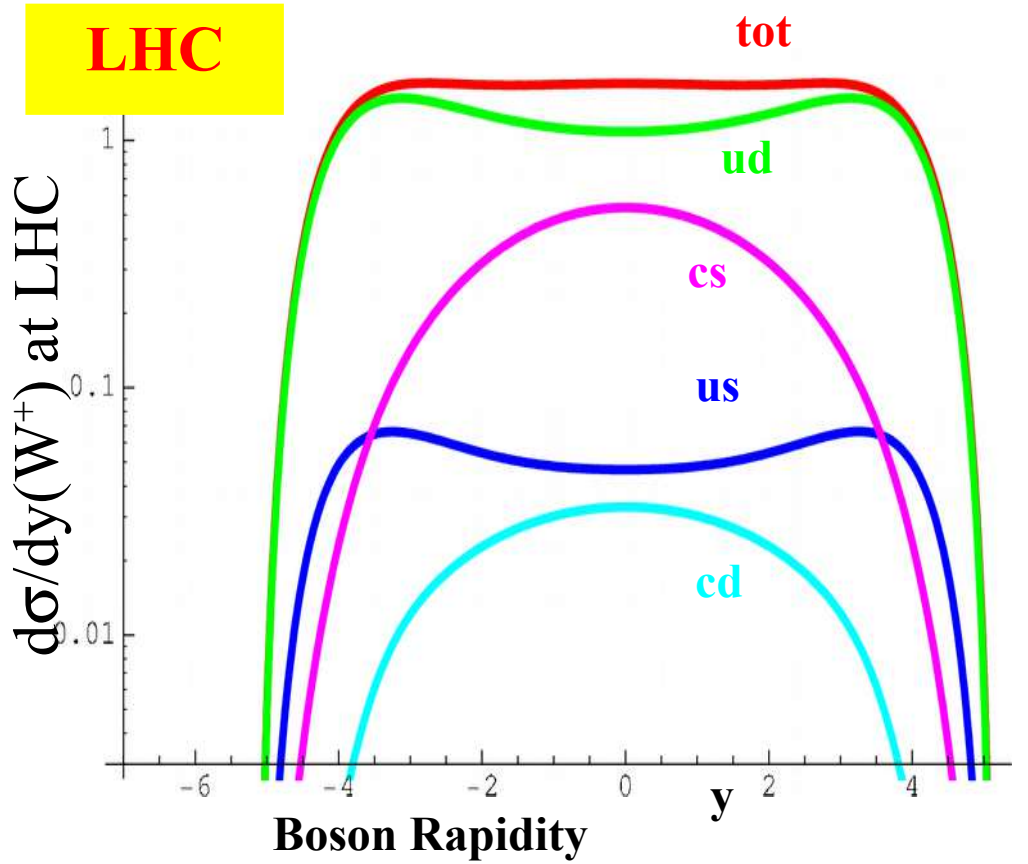
“Benchmark Calculations”

... things are different at the LHC

... the fine print:
Surprisingly, the LHC analysis depends on many other data sets

W Production at LHC: *... things are very different*

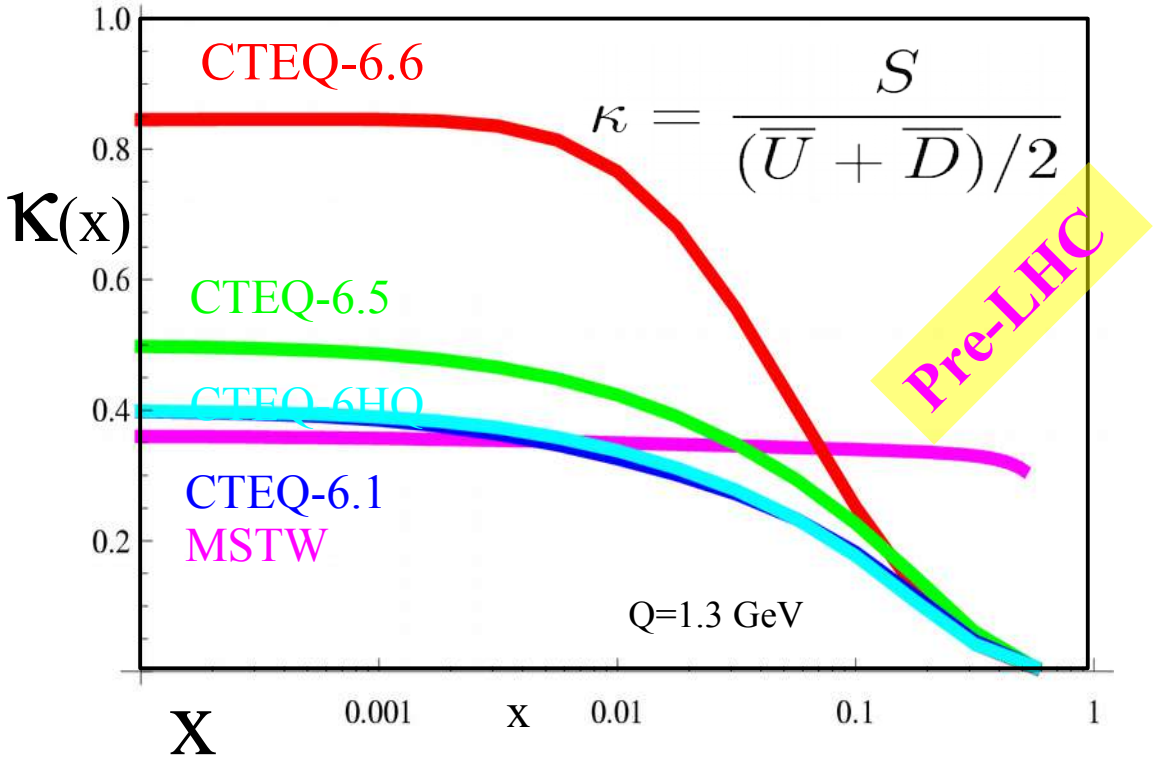


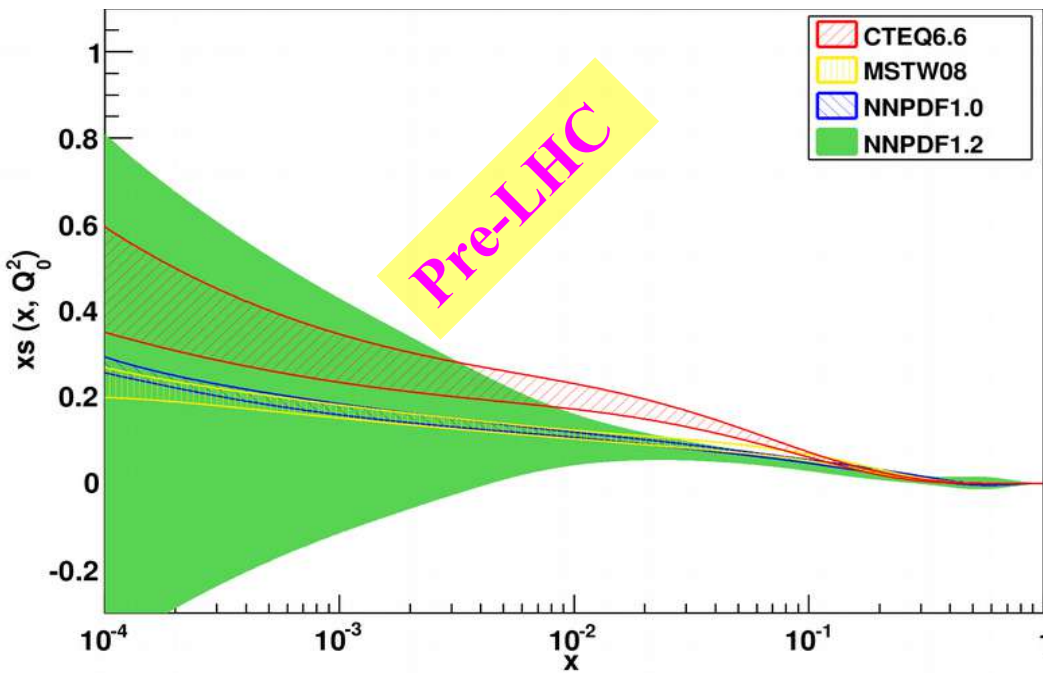


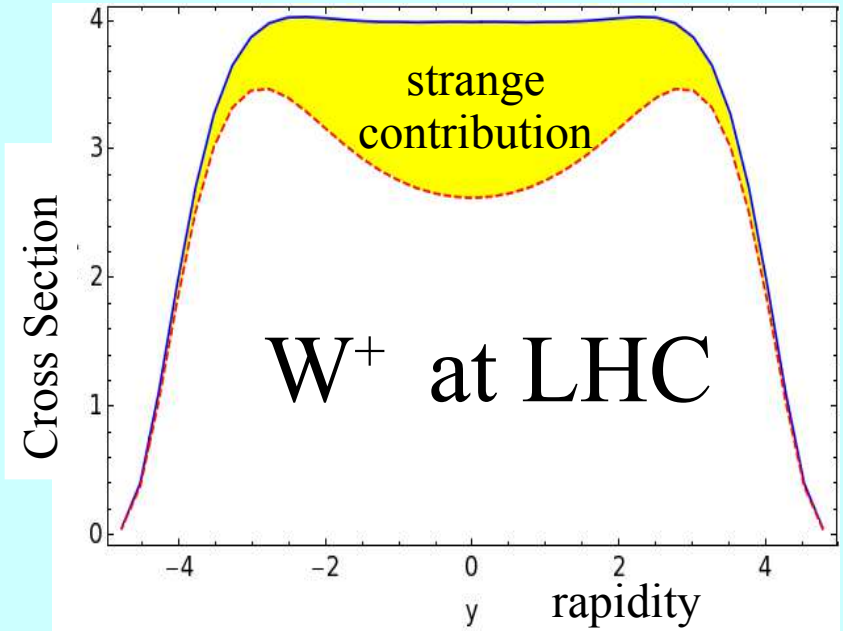
- Larger Energy ⇒ probes PDFs to small momentum fraction x
- Larger Rapidity **(y)** ⇒ probes PDFs to ***really*** small x
- Larger fraction of heavy quarks

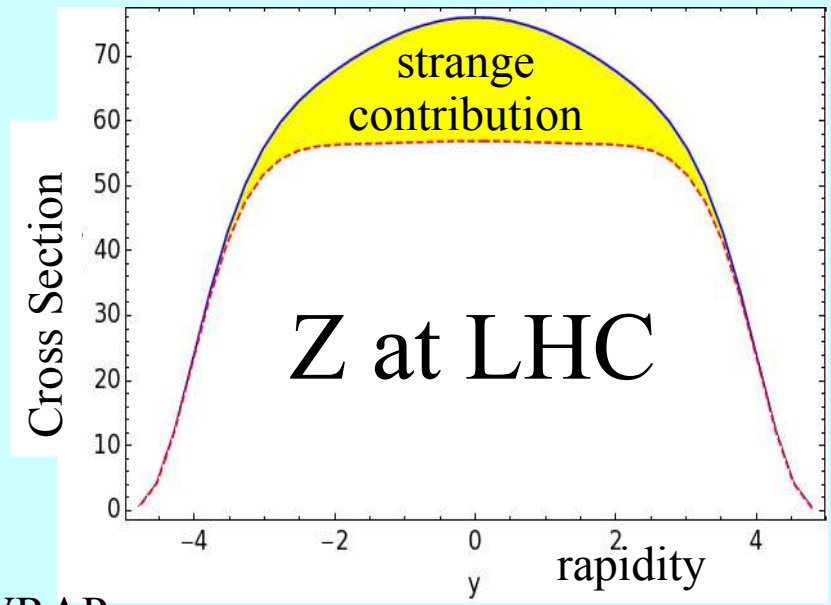
Heavy Quark components play an increasingly important role at the LHC

Large PDF Uncertainties ⇒ S(x) PDF ⇒ W/Z at LHC





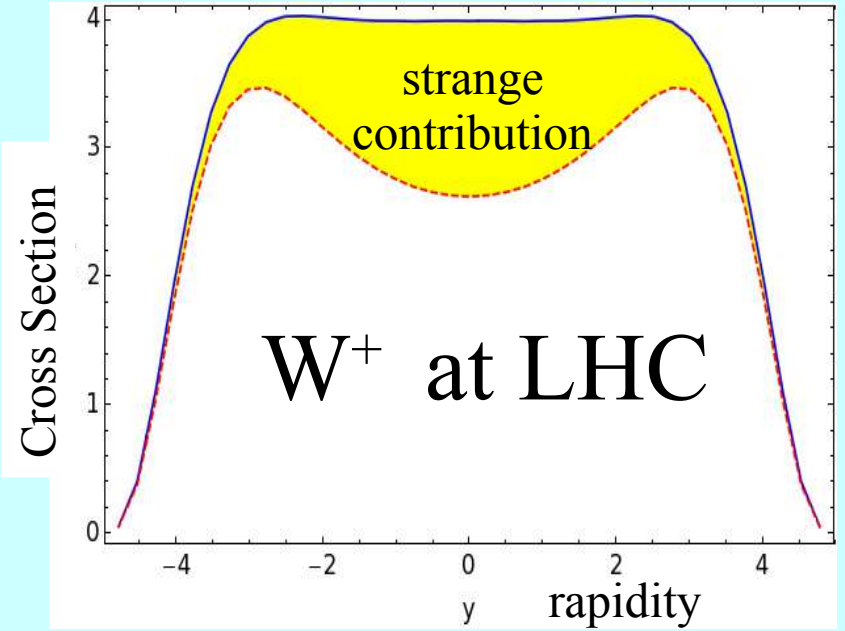


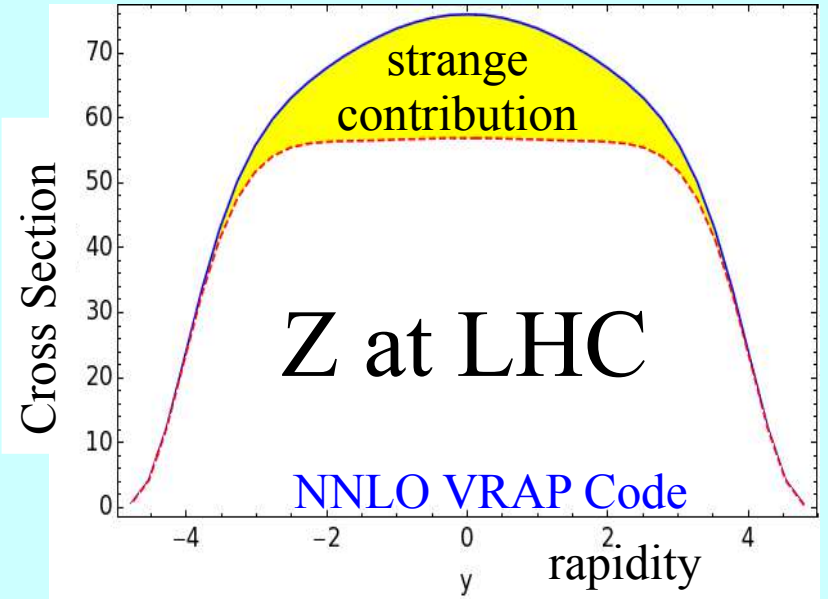


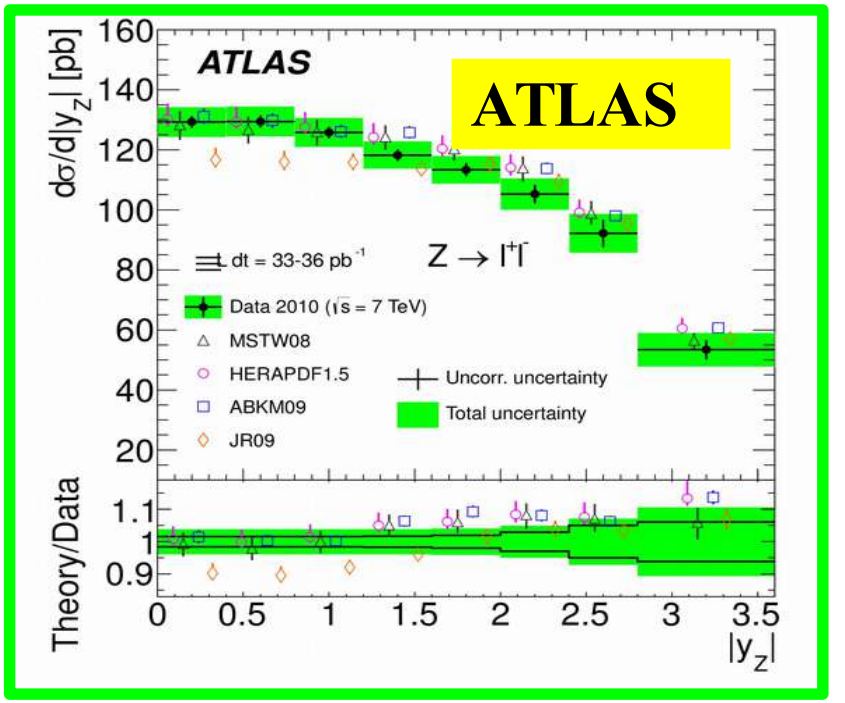
VRAP Code

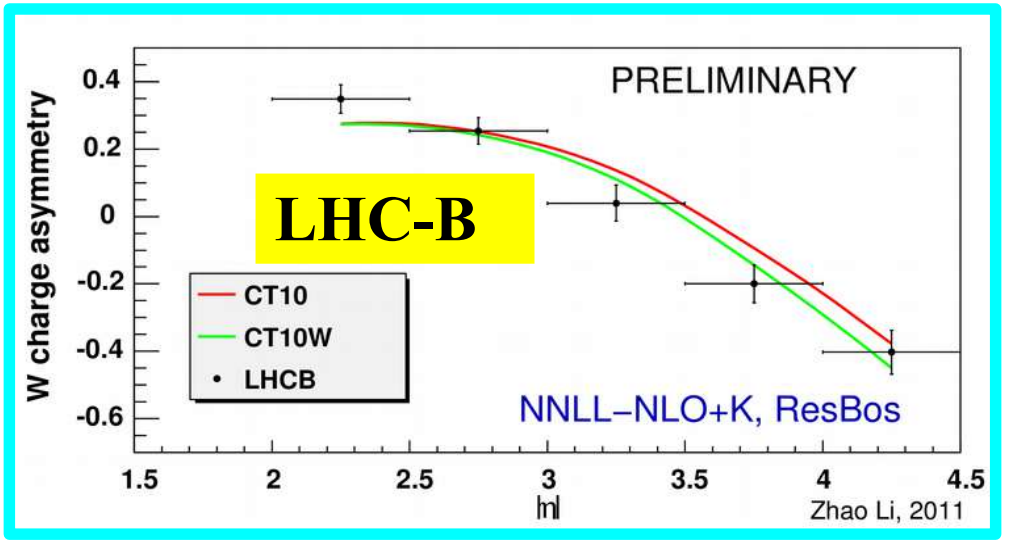
Anastasiou, Dixon, Melnikov, Petriello, Phys.Rev.D69:094008,2004.

PDF Uncertainties ⇐ S(x) PDF ⇐ W/Z at LHC









NNLO VRAP Code
Anastasiou, Dixon, Melnikov, Petriello,
Phys.Rev.D69:094008,2004.

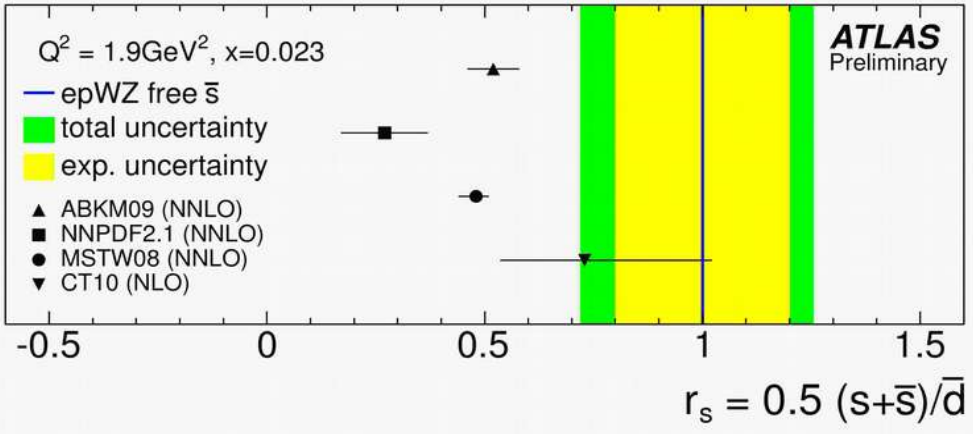
Kusina, Stavreva, Berge, Olness,
Schienbein, Kovarik, Jezo, Yu, Park
Phys.Rev. D85 (2012) 094028

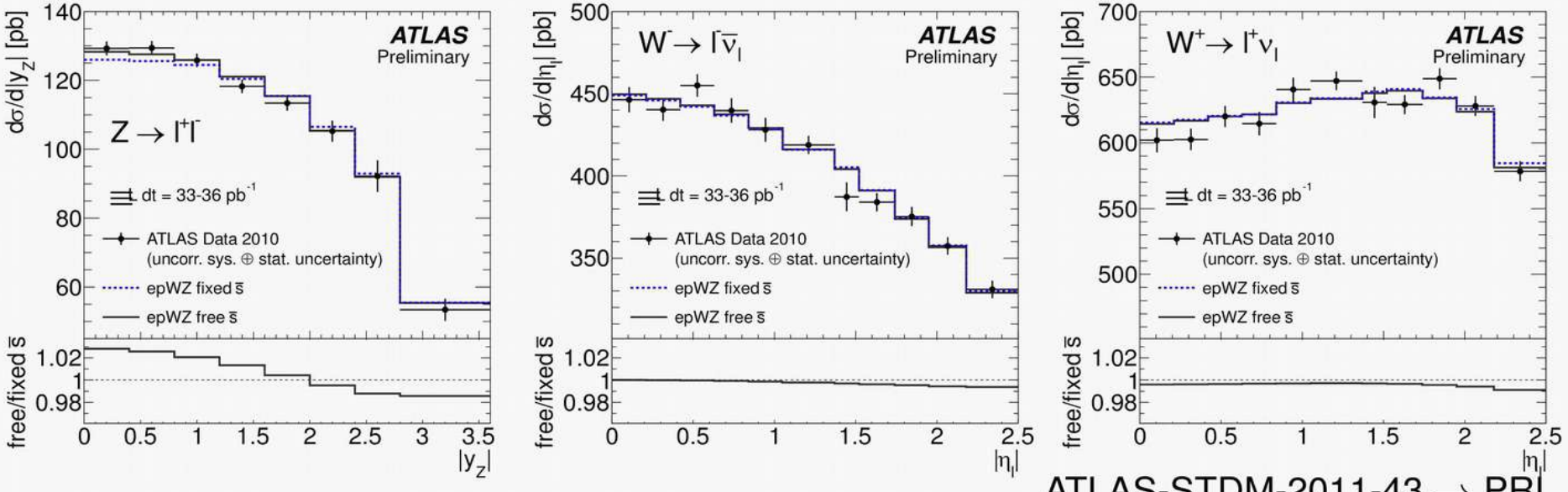
y distribution shape can constrain s(x) PDF

W, Z data sensitivity to strange sea

- ATLAS performed NNLO QCD fit to Z, W^+, W^- + HERA ep DIS cross sections: significant tension for Z observed when suppressing strange by 50% at low scale $1.9\,\mathrm{GeV}^2$
- Fit with free strange sea gives no supression

$$r_s = 1.00 \pm 0.20_{\mathrm{exp}}\,{}^{+0.16}_{-0.20}\,{}_{\mathrm{sys}}$$





ATLAS-STDM-2011-43 → PRL

DIY: Do It Yourself: Strange Quark from LHC Data

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HERAFitter

Welcome to HERAFitter Project

HERAFitter is a QCD Fit Package used to determine HERAPDFs and it is part of the HERAPDF project https://www.desy.de/h1zeus.

Downloads of HERAFItter software package

New HERAFitter
HERE upon registra

Registration

To register, please l
(firstnamelastname
<herafitter-help

HERAFitter M

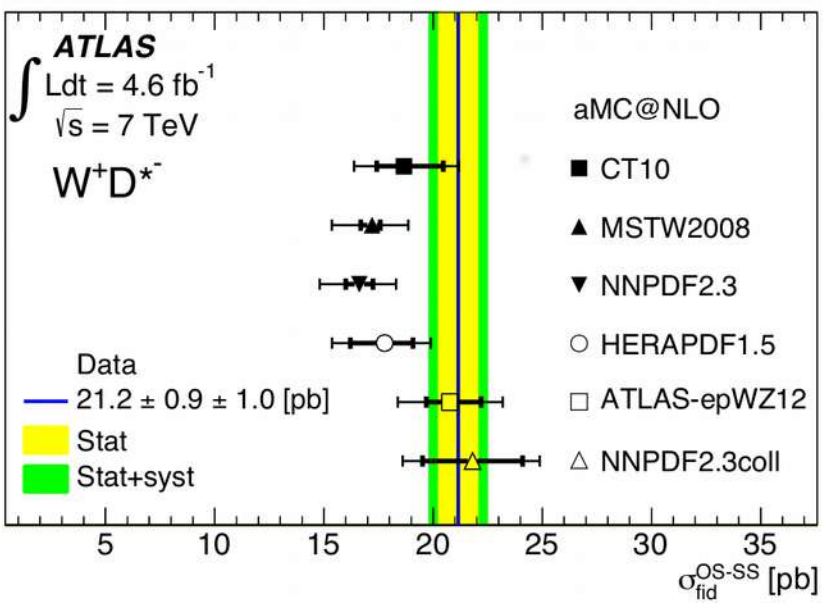
- User's Meeti
and develop

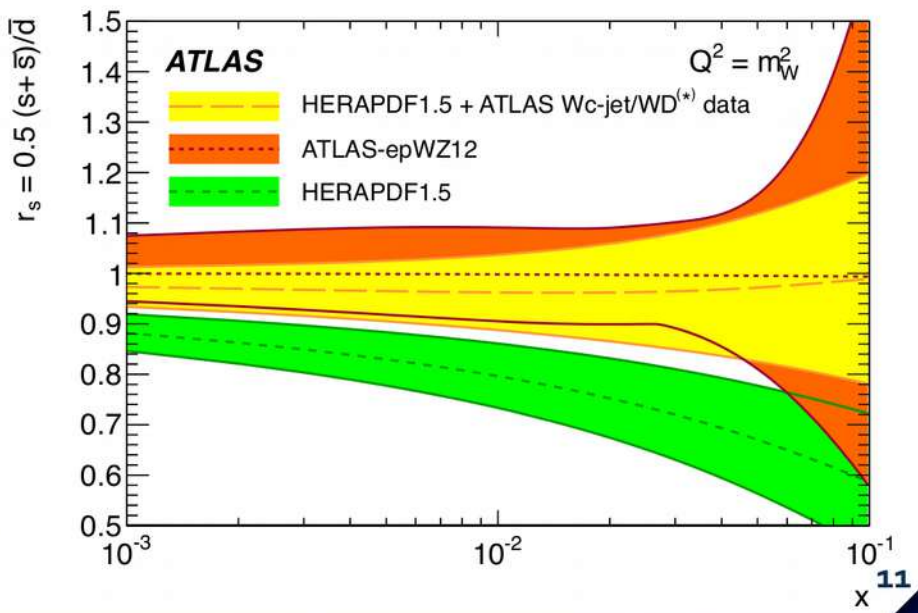
Other LHC processes also favor Strange enhancement

W + c / D production

JHEP 05 (2014) 068

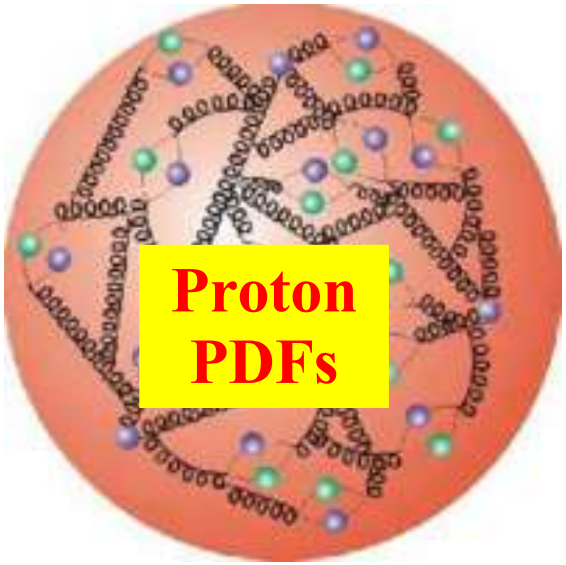
- Further sensitivity to s-quark content of the PDF from W+c studies
- Two measurements strategies: tag the c-jet vs reconstruct D-meson
- Consistently with W/Z inclusive measurements, ATLAS data favor s-quark enhancement against ½ suppression wrt d-quark PDF
  - Substantial reductions of uncertainty



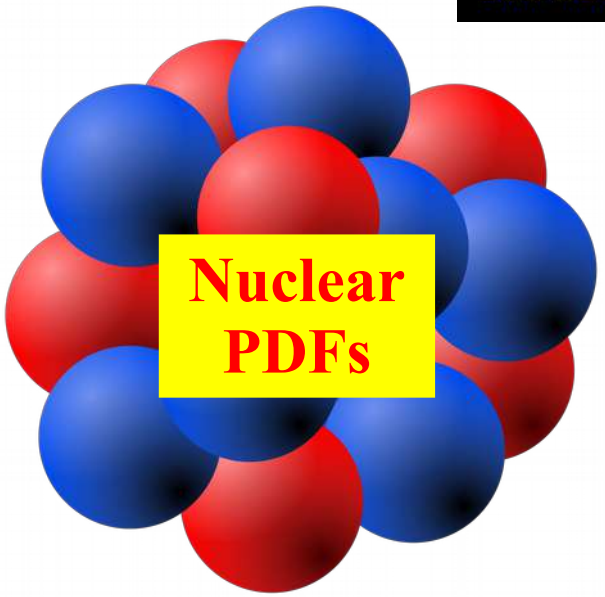


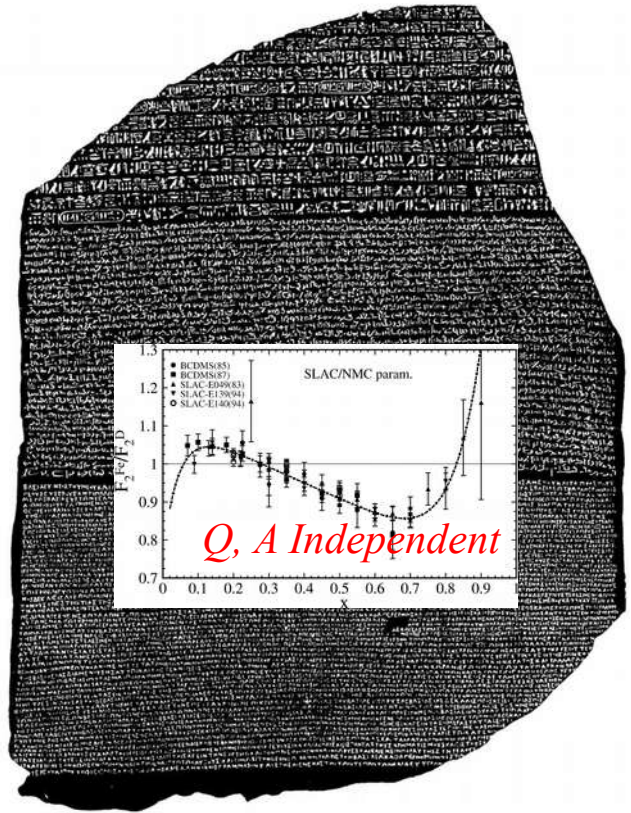
favors s-quark enhancement, not k=1/2 suppression

nCTEQ15 PDFs

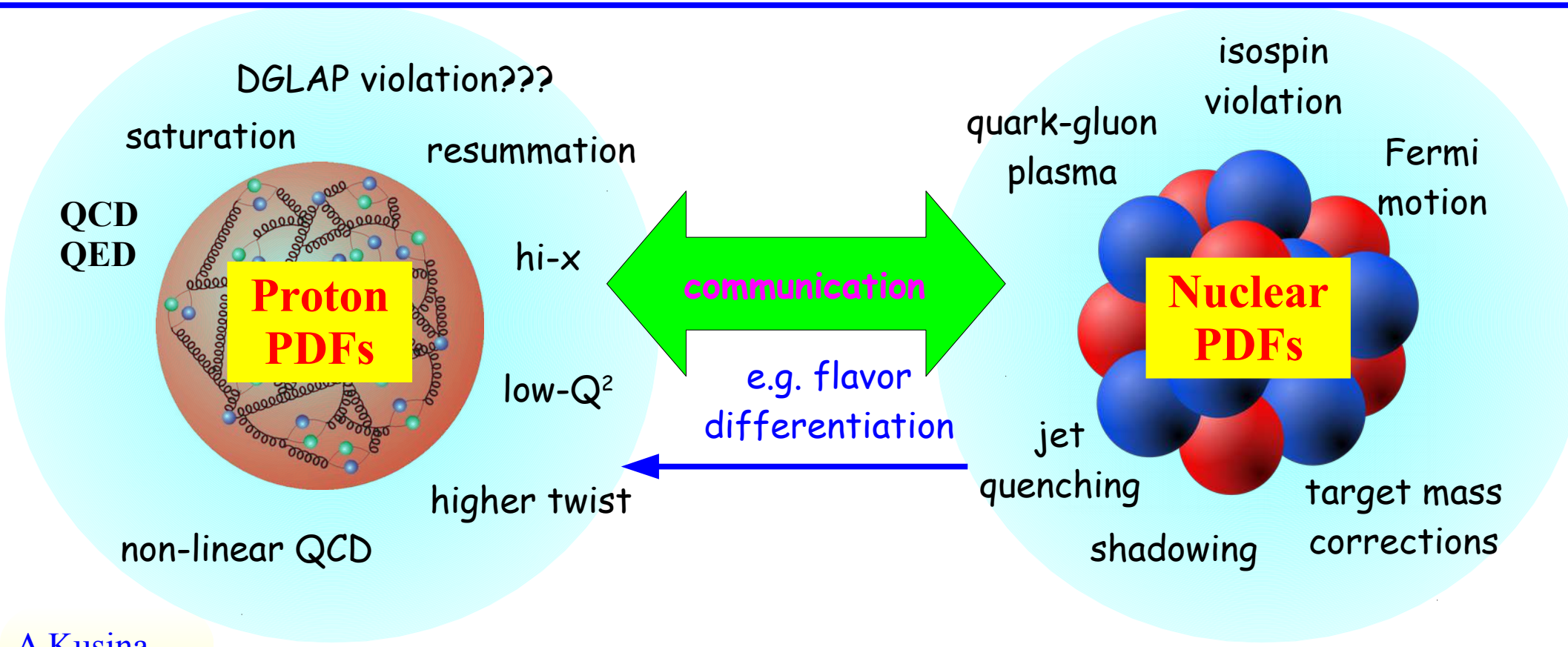


… there was a time when
nuclear corrections
were carved in stone …





Moving Into The 21st Century



A Kusina,
K. Kovarik
T. Jezo,
D. Clark,
C. Keppel,
F. Lyonnet,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein,
J. Yu
E. Godat

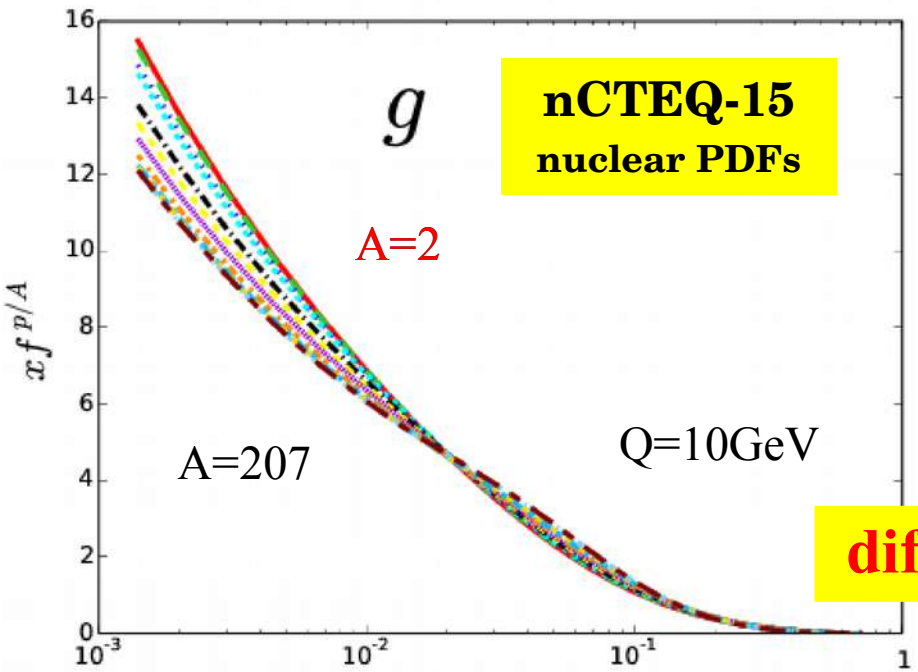
Data from nuclear targets is play a key role in the flavor differentiation

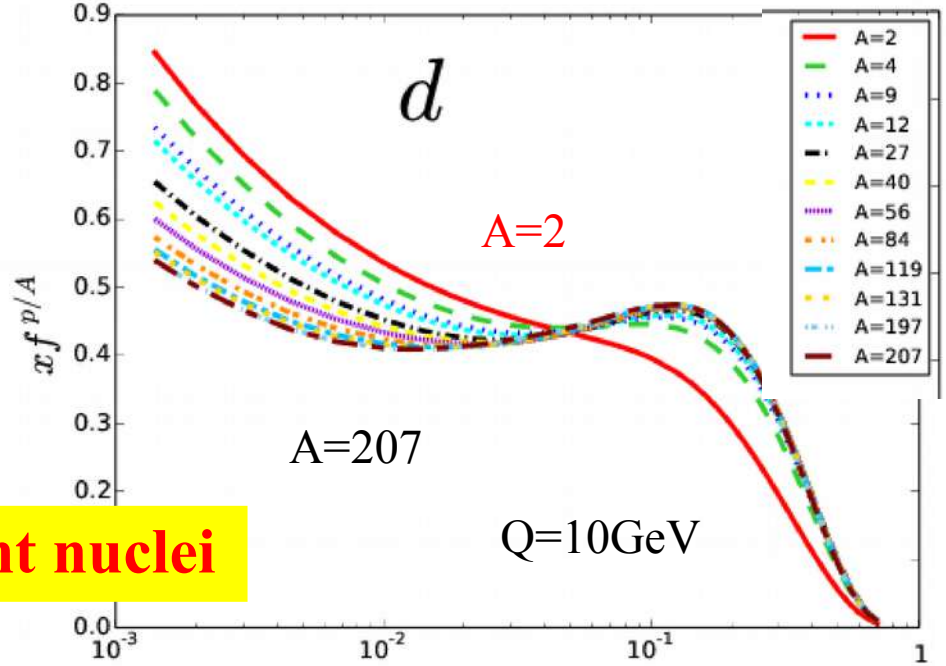
nCTEQ-15

nuclear parton distribution functions

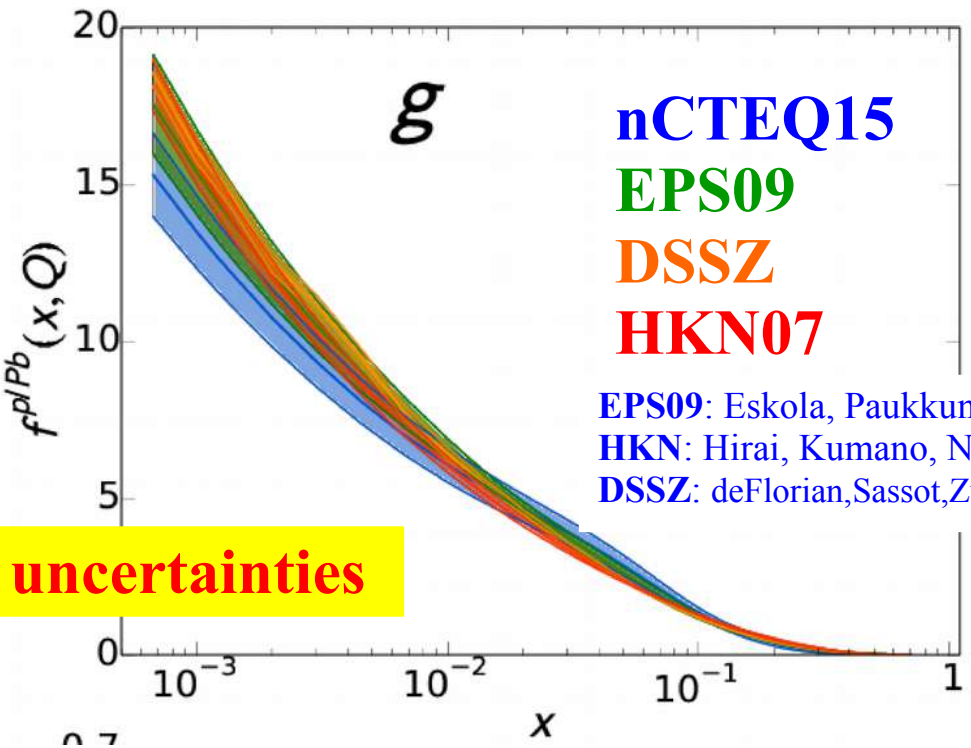
… the original motivation for nCTEQ15

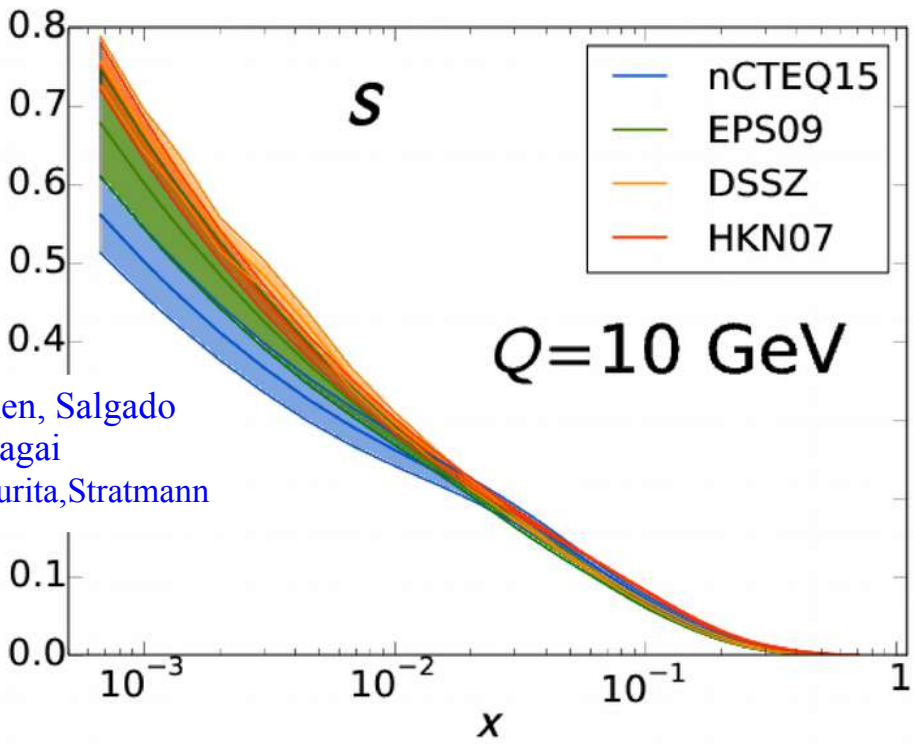
nCTEQ15 PDFs … *from A to Z* … *with Uncertainties*





different nuclei



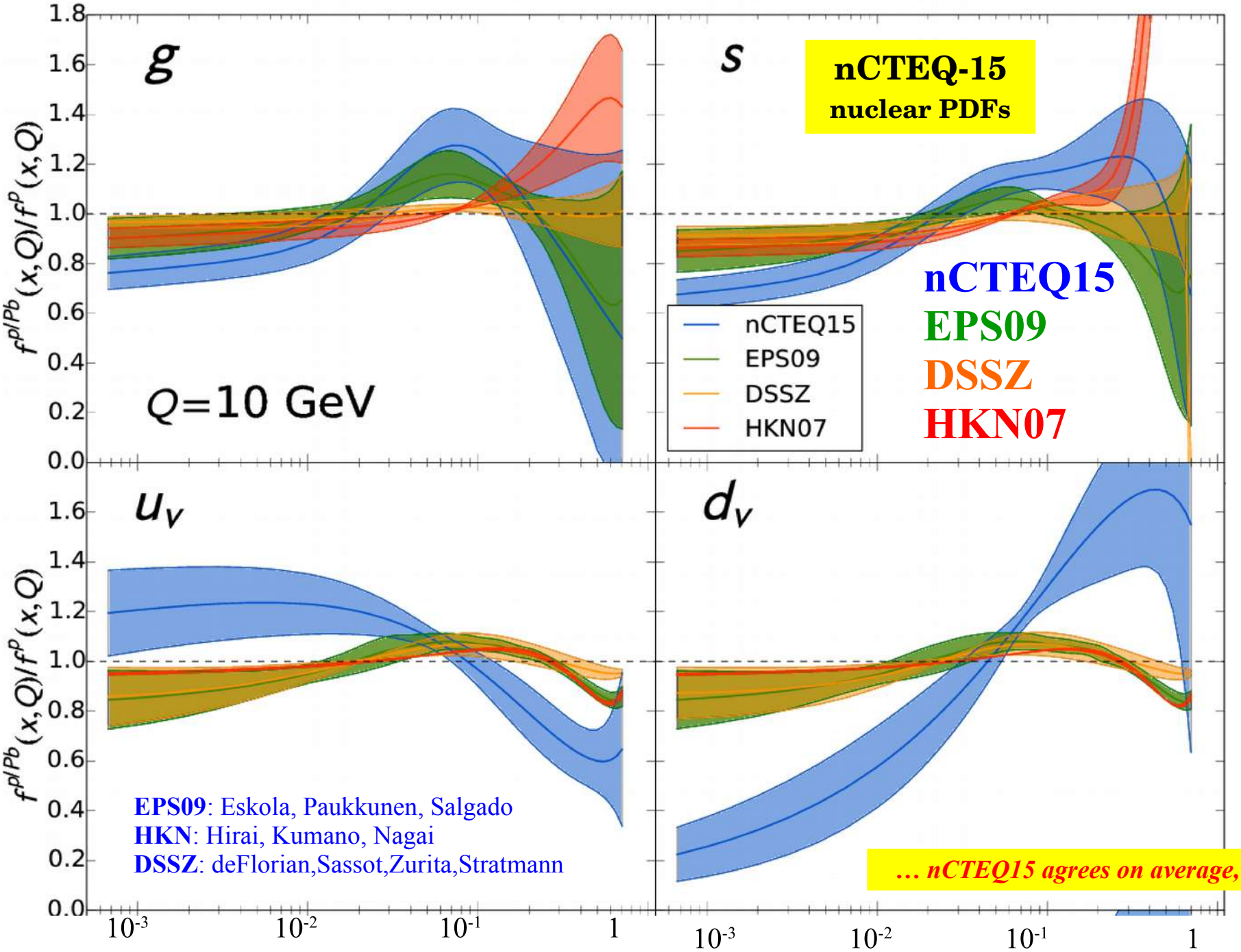


nCTEQ15
EPS09
DSSZ
HKN07

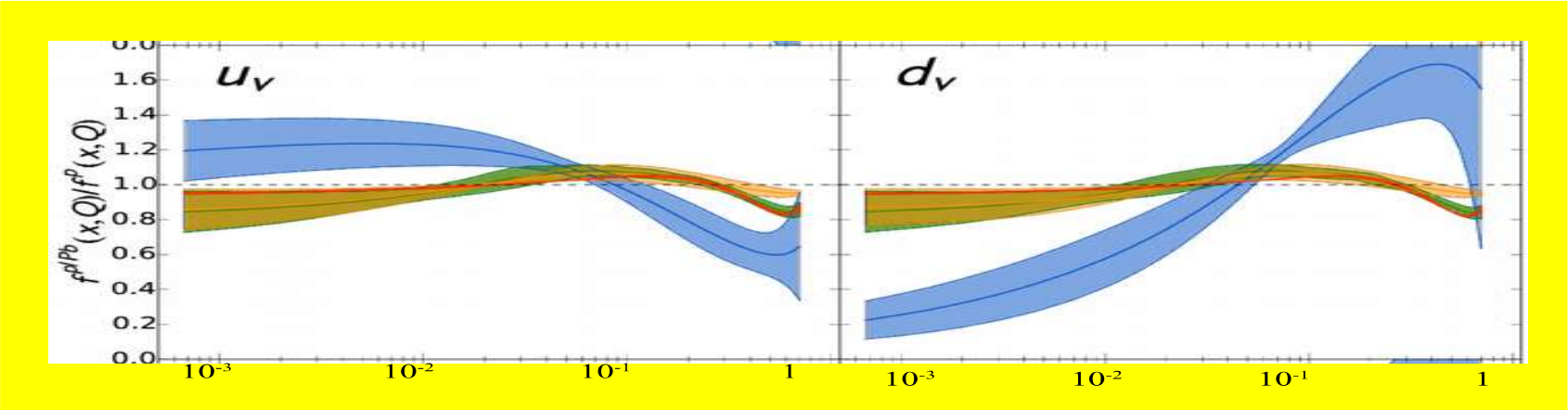
EPS09: Eskola, Paukkunen, Salgado
HKN: Hirai, Kumano, Nagai
DSSZ: deFlorian,Sassot,Zurita,Stratmann

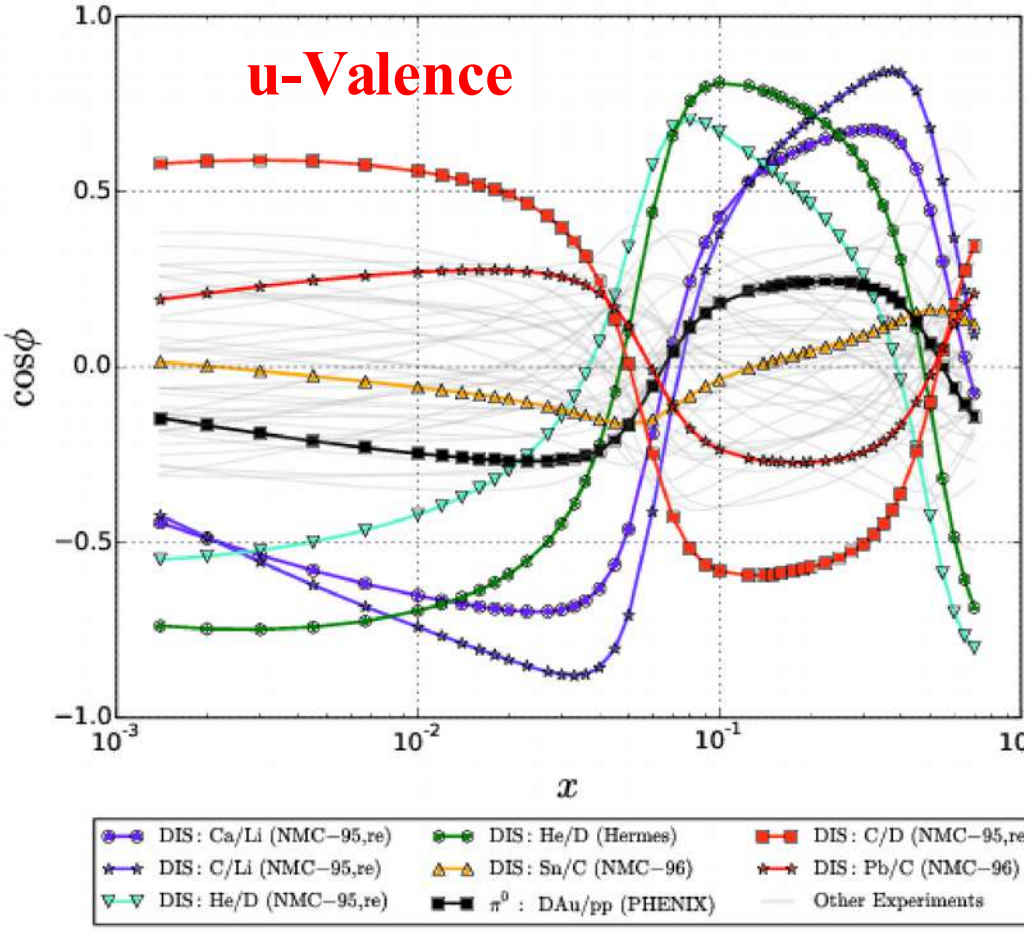
uncertainties

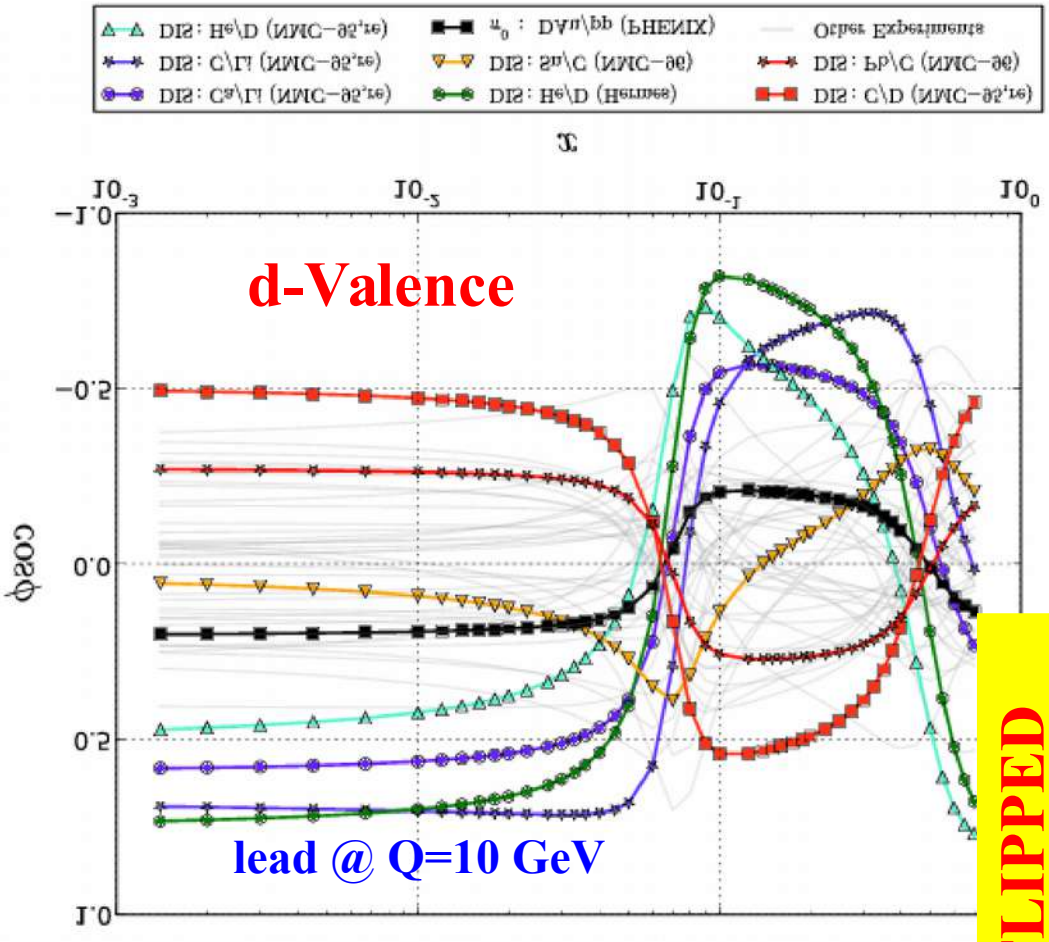
Ratio to Proton for Lead … *with Uncertainty*



What data are influencing up & down



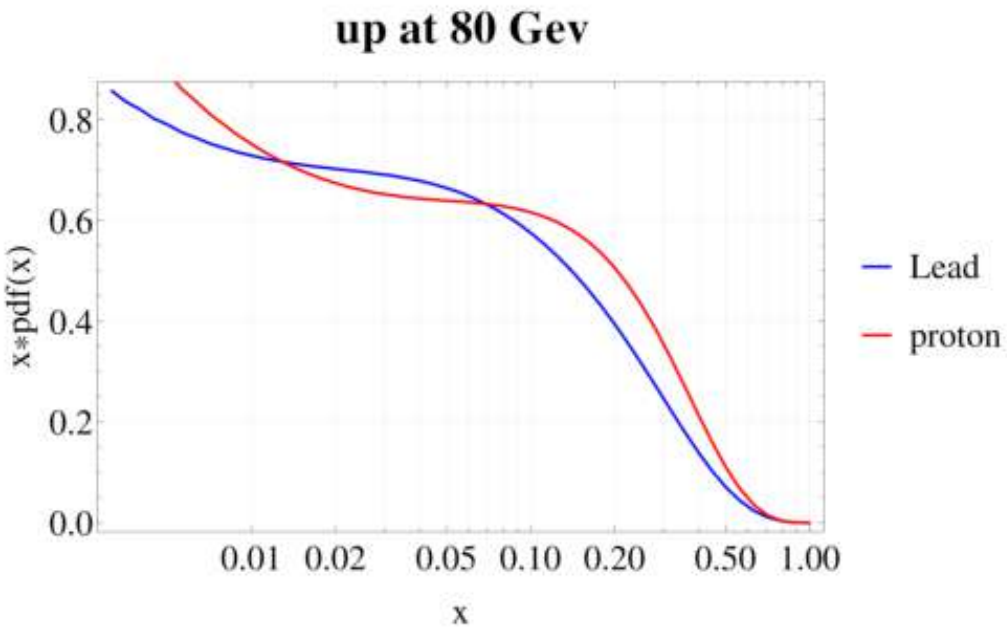


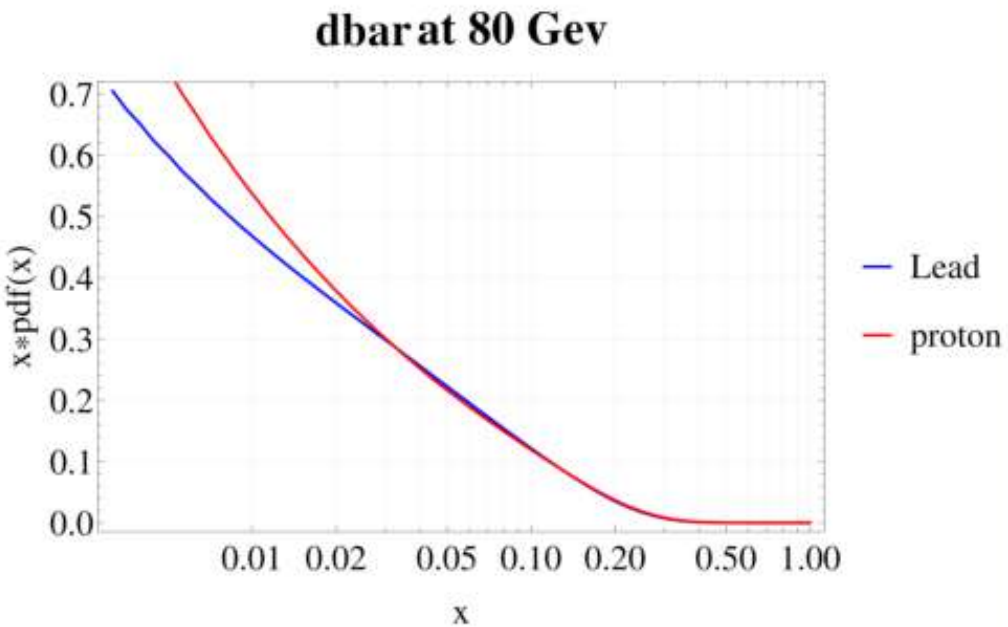


FLIPPED

Nuclear Modifications

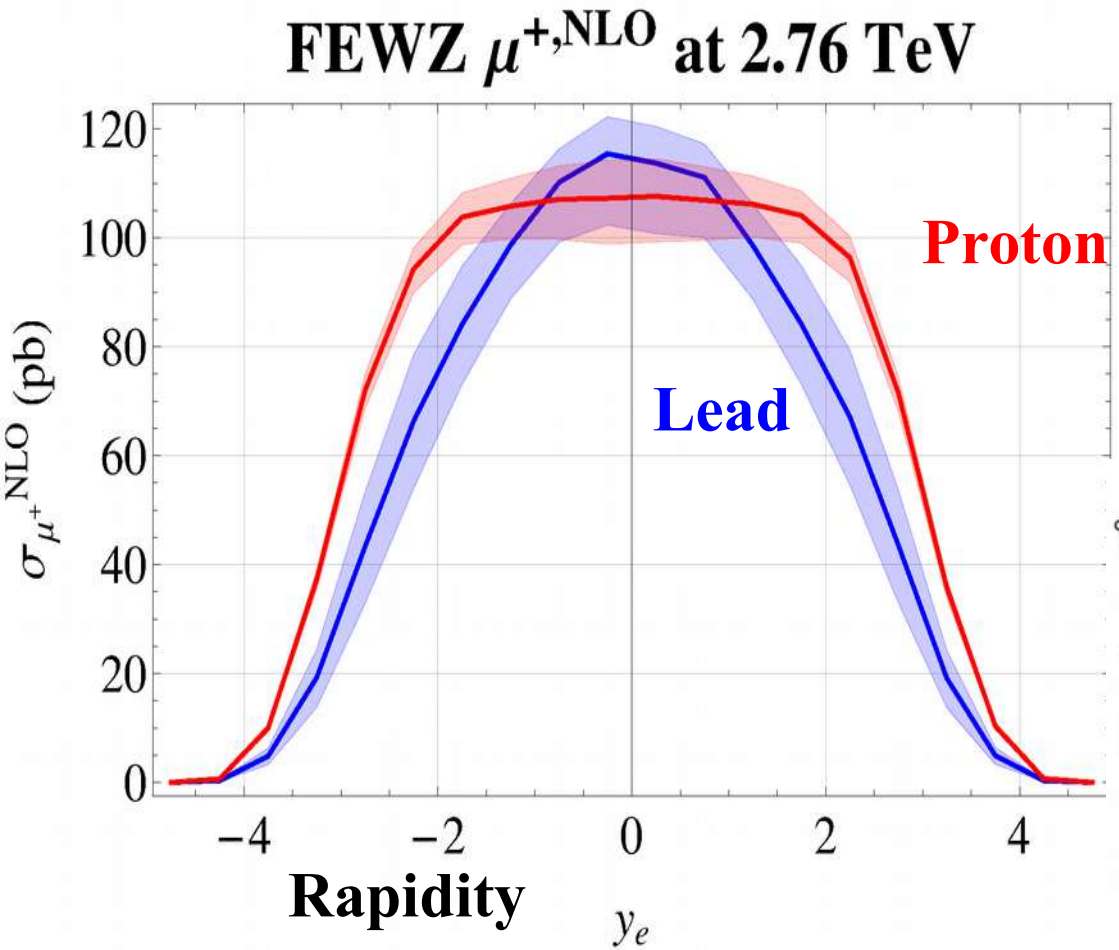
Slides stolen from Ben Clark



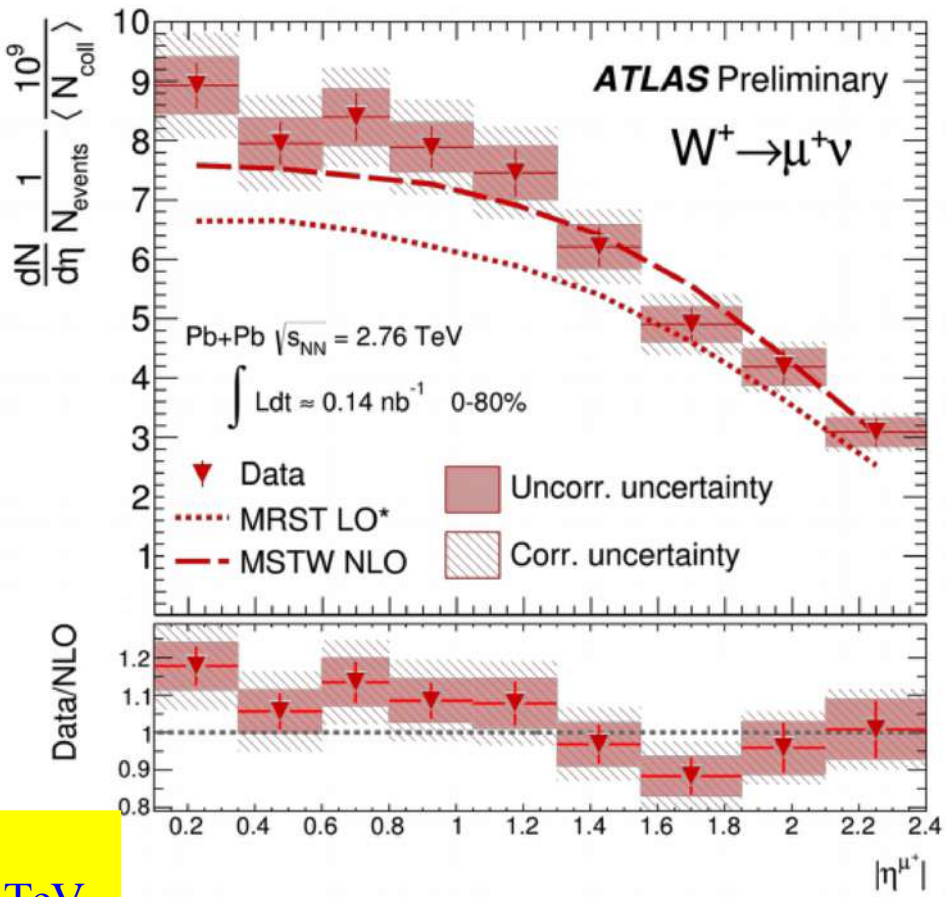


- The nuclear modifications are present in the PDFs and vary with A as well as x and Q.
- We expect modifications to any hadronic observable involving heavy nuclei.

W^+ Production at LHC Pb-Pb vs. Proton



$$W^+ \rightarrow \mu^+ \nu$$



This is a shape measurement

Similar studies with Z:
ATLAS just released 2013 Z data for p-Pb at 5.02 TeV

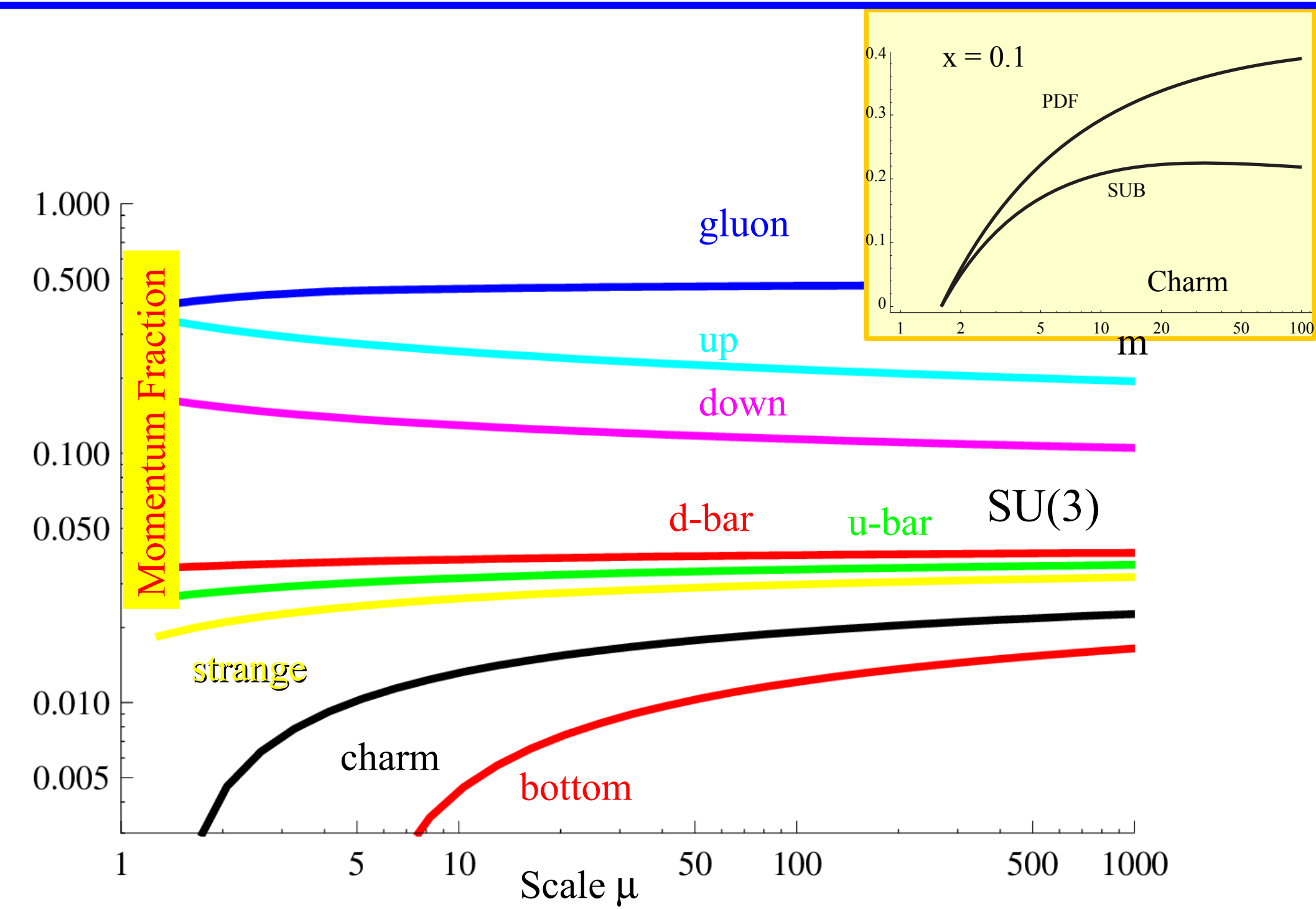
... what about the

Heavy Quarks

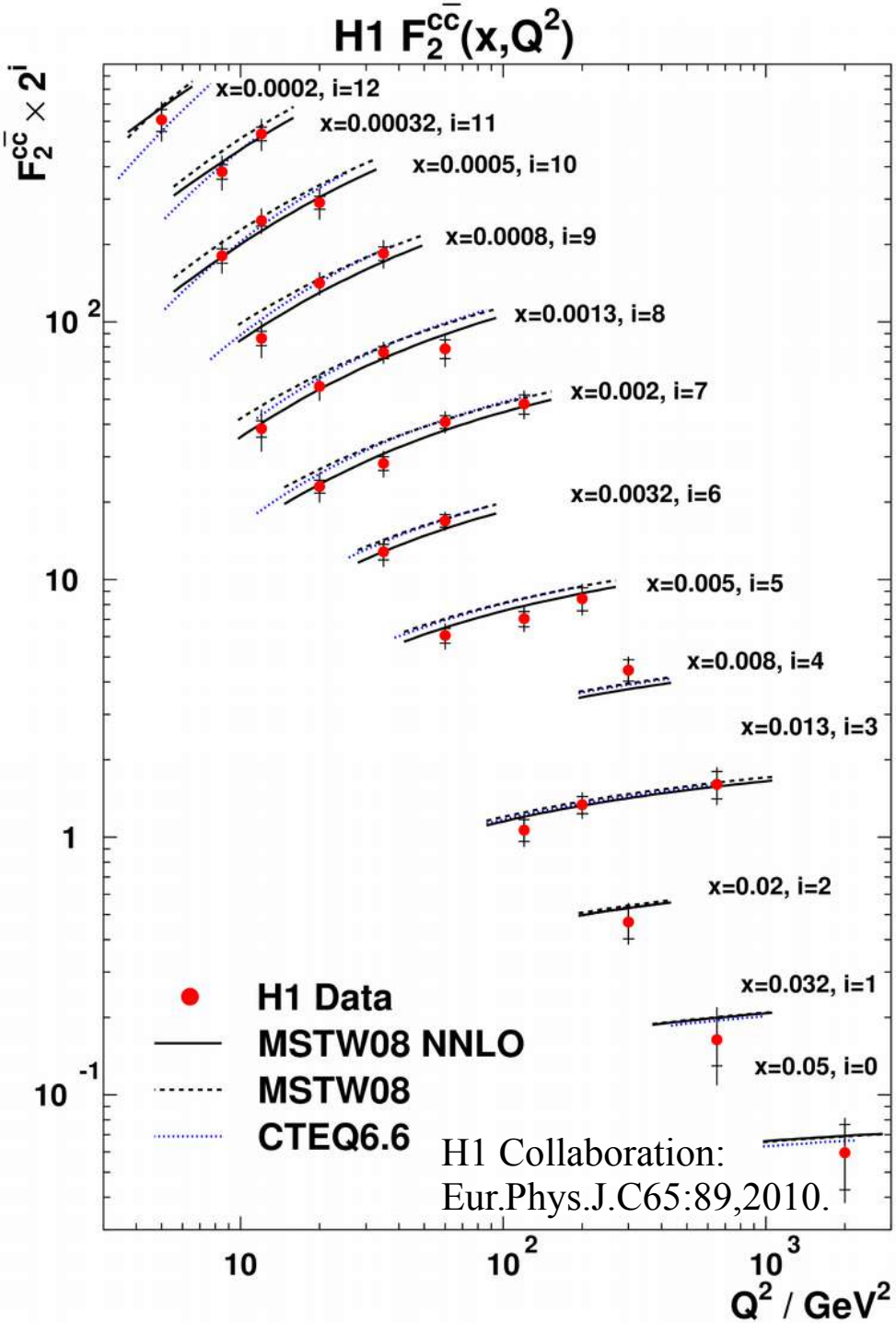
c & b: Extrinsic & Intrinsic

Historically, these have been a challenge because $Q \sim m_{c,b}$

When should we use Charm & Bottom PDFs???

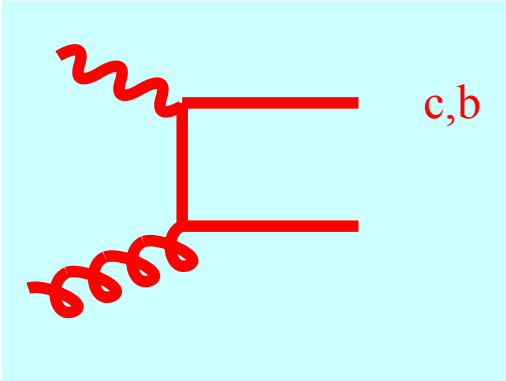


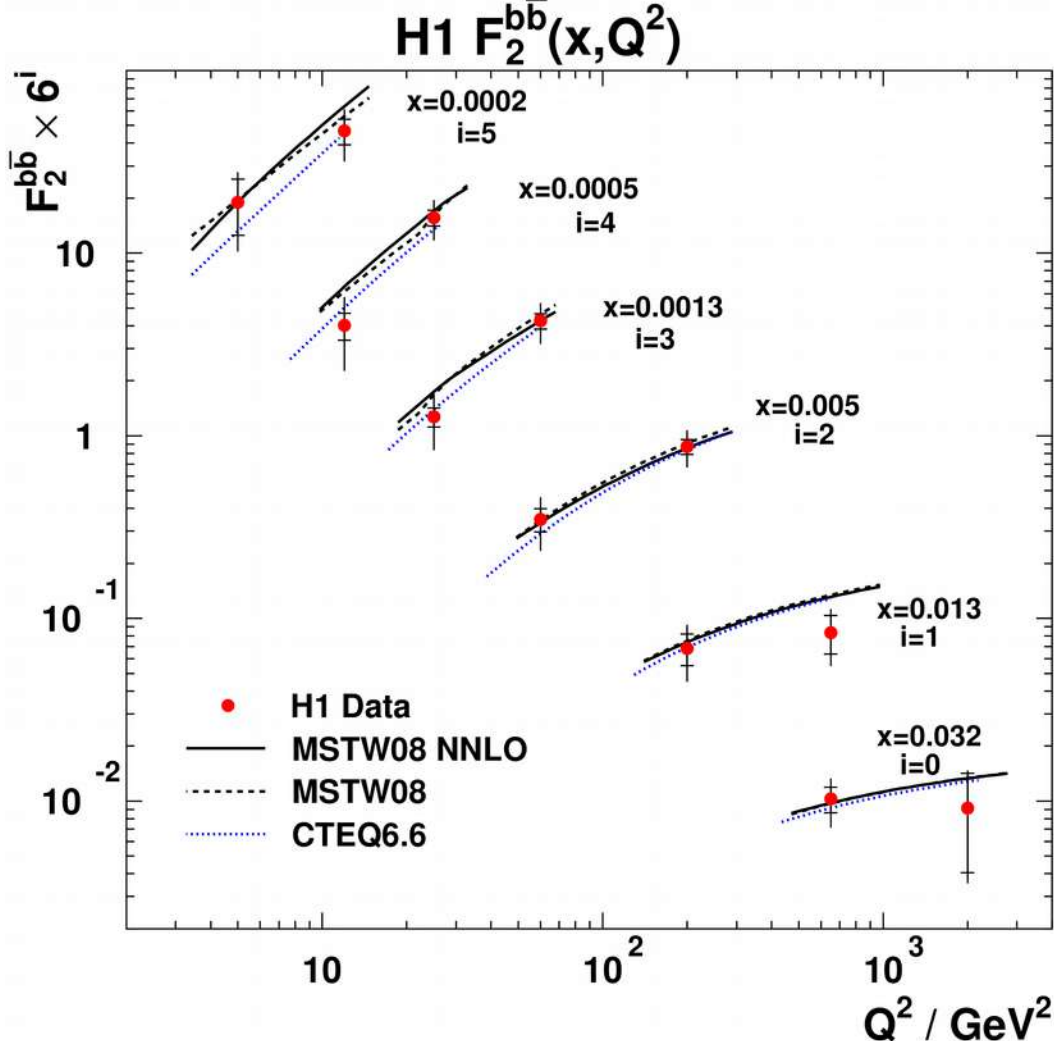
Heavy Flavor Components will play a MORE prominent role at LHC



H1 Collaboration:
Eur.Phys.J.C65:89,2010.

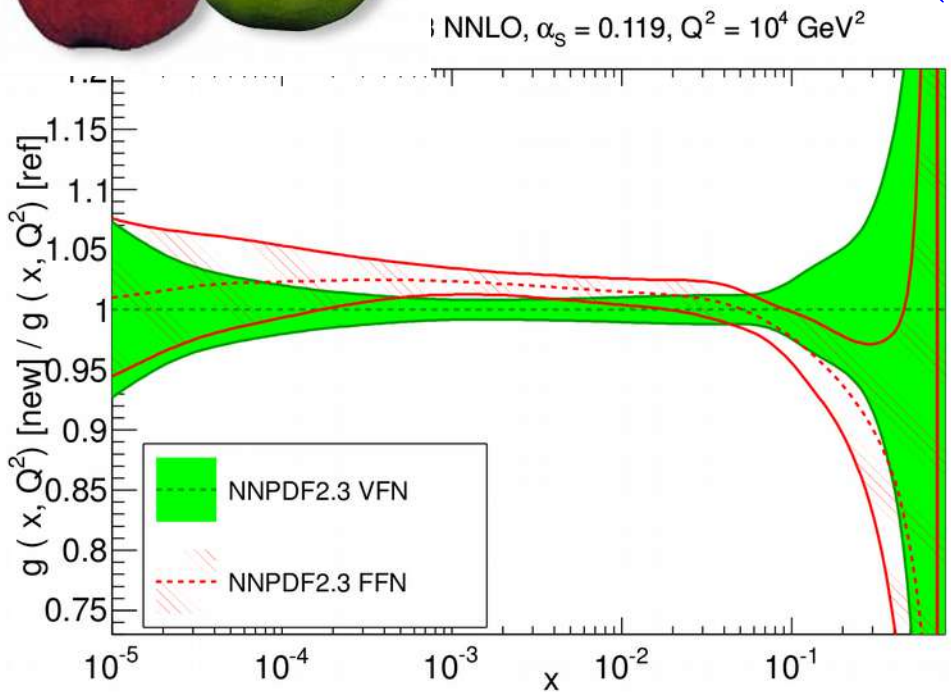
c & b tied to gluon PDFs

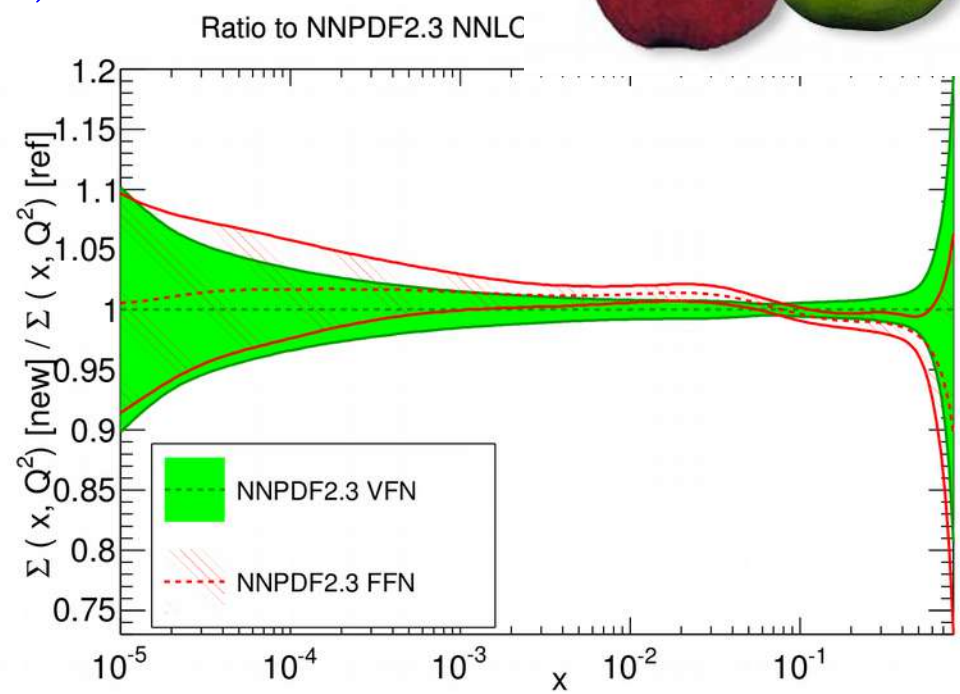




Compare VFN & FFN Schemes

Resum: $\alpha \ln(m/Q)$





$$\Delta\chi^2 \equiv \chi^2_{FFN} - \chi^2_{VFN} \quad > 0$$

$x_{\rm min}$	$x_{\rm max}$	$Q^2_{\rm min}$ (GeV)	$Q^2_{\rm max}$ (GeV)	$\Delta\chi^2$ (DIS)	$N_{\rm dat}^{\rm DIS}$	$\Delta\chi^2$ (HERA-I)	$N_{\rm dat}^{\rm hera-I}$
$4\cdot10^{-5}$	1	3	10^6	72.2	2936	77.1	592
$4\cdot10^{-5}$	0.1	3	10^6	87.1	1055	67.8	405
$4\cdot10^{-5}$	0.01	3	10^6	40.9	422	17.8	202
$4\cdot10^{-5}$	1	10	10^6	53.6	2109	76.4	537
$4\cdot10^{-5}$	1	100	10^6	91.4	620	97.7	412
$4\cdot10^{-5}$	0.1	10	10^6	84.9	583	67.4	350
$4\cdot10^{-5}$	0.1	100	10^6	87.7	321	87.1	227

The NNPDF Collaboration, PLB723 (2013) 330

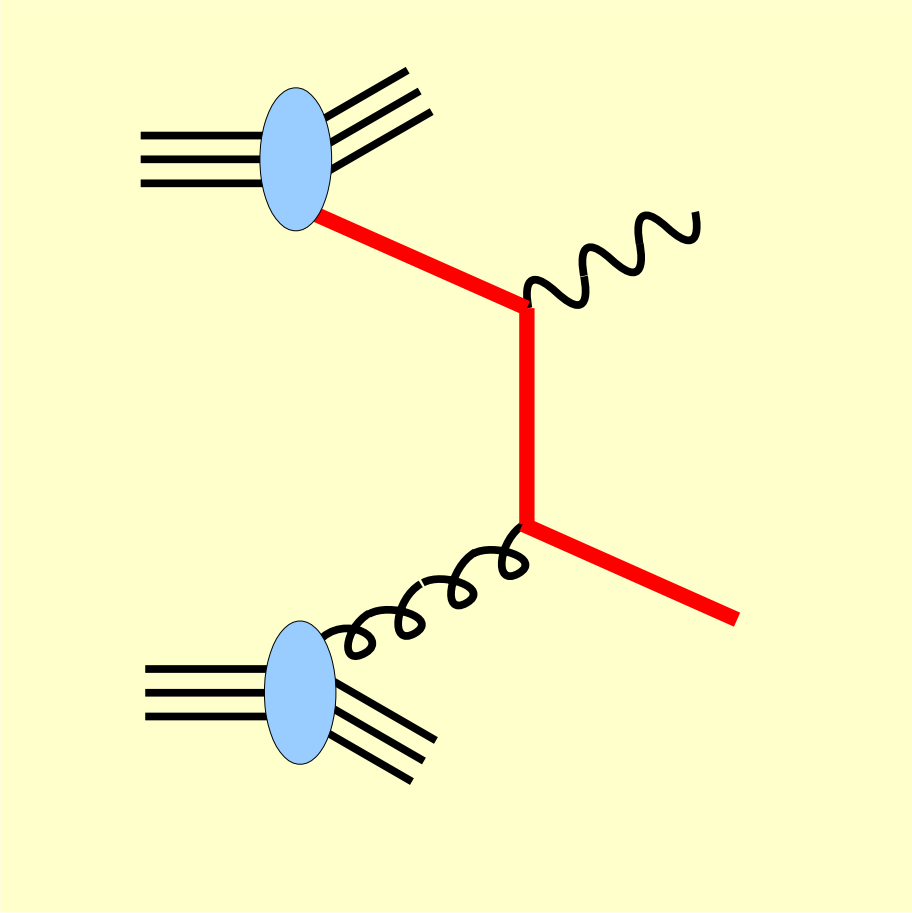
... what about the

Heavy Quarks

at high energies

Tevatron & LHC

Tevatron & LHC can Access Heavy Flavor Components Directly



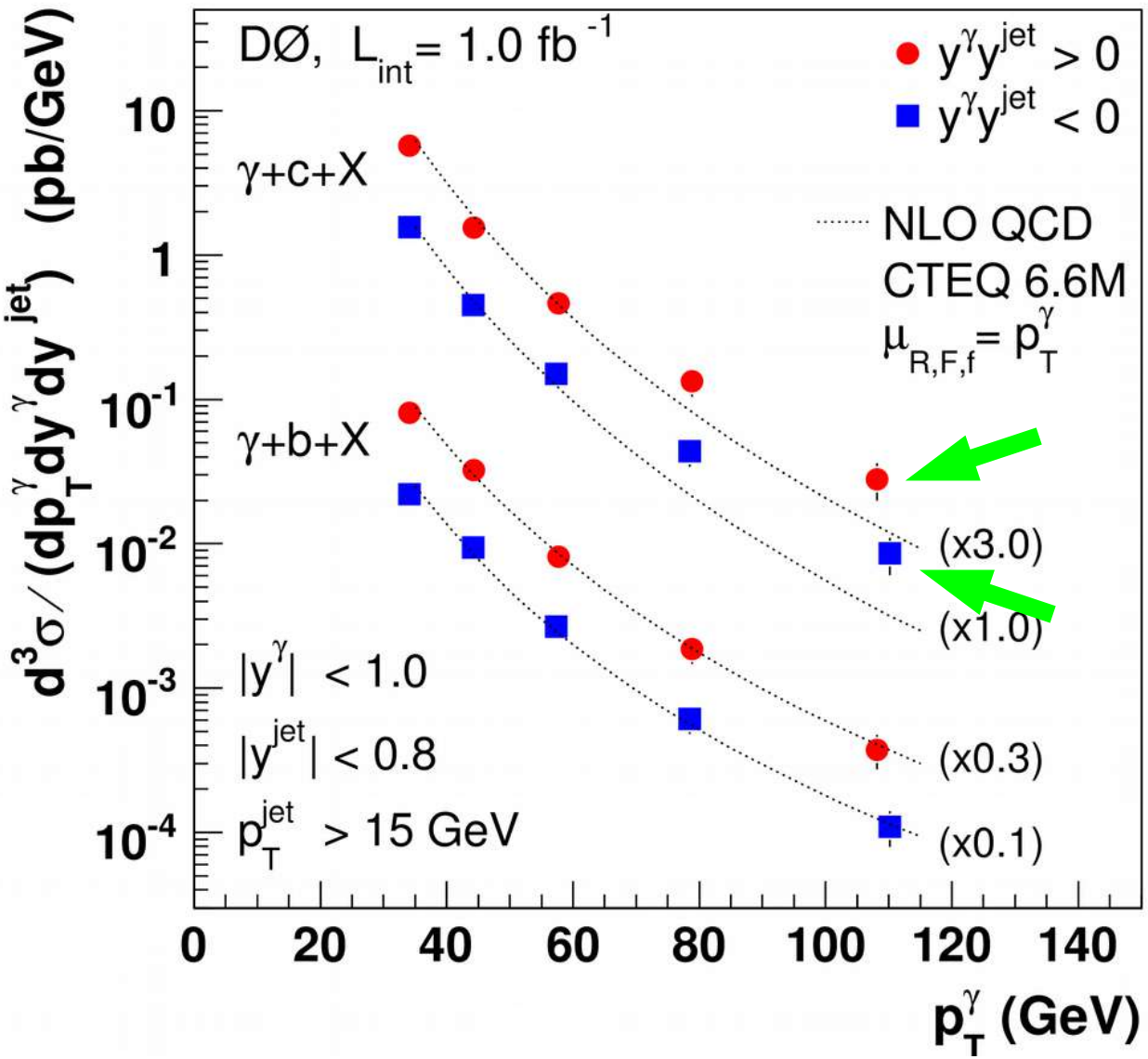
$$c\ g \rightarrow c\ \gamma$$

$$b\ g \rightarrow b\ \gamma$$

$$s\ g \rightarrow c\ W$$

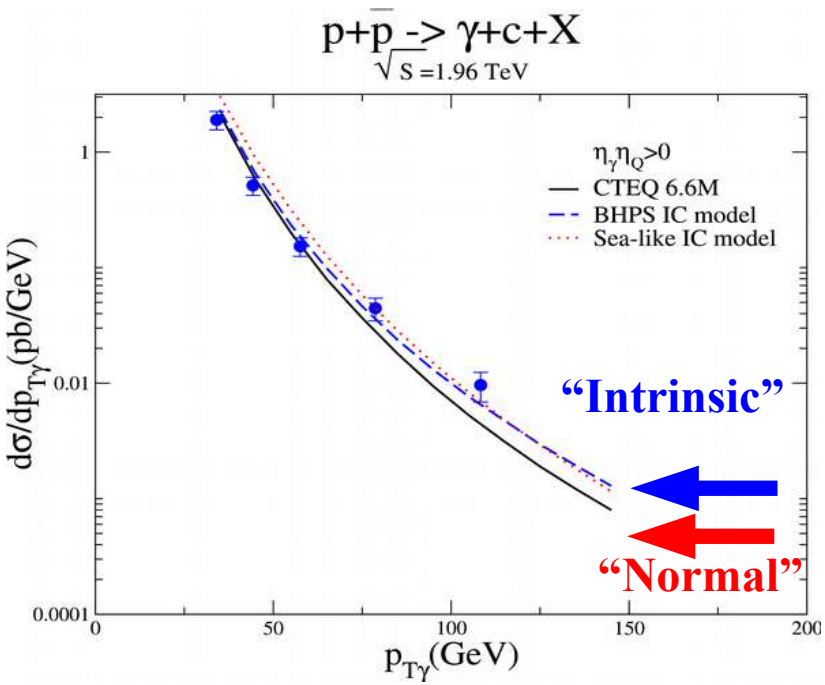
$$c\ g \rightarrow b\ W$$

Heavy Quarks at the Tevatron: … "intrinsic" charm???



Excess in Charm,
NOT Bottom

only at high PT



D. Duggan (D0) arXiv:0906.0136

T. Stavreva, I. Schienbein, F. Arleo, K. Kovarik, F. Olness, J.Y. Yu, J.F. Owens, JHEP 1101 (2011) 152

Heavy Quarks at the Tevatron: … "intrinsic" charm???

DGLAP Evolution equations …
including **ordinary Q_0** and **intrinsic Q_1** heavy quark

$$\dot{g} = P_{gg} \otimes g + P_{gq} \otimes q + P_{gQ} \otimes Q_0 + \cancel{P_{gQ} \otimes Q_1},$$
$$\dot{q} = P_{qg} \otimes g + P_{qq} \otimes q + P_{qQ} \otimes Q_0 + \cancel{P_{qQ} \otimes Q_1},$$
$$\dot{Q}_0 + \dot{Q}_1 = P_{Qg} \otimes g + P_{Qq} \otimes q + P_{QQ} \otimes Q_0 + P_{QQ} \otimes Q_1 .$$

neglect

Equations decouple:
- Intrinsic component evolves independently
- Scale set by m_Q
- Adjust normalization by simple rescaling

$$\dot{Q}_1 = P_{QQ} \otimes Q_1 .$$

$$c_1(x) = \bar{c}_1(x) \propto x^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$$

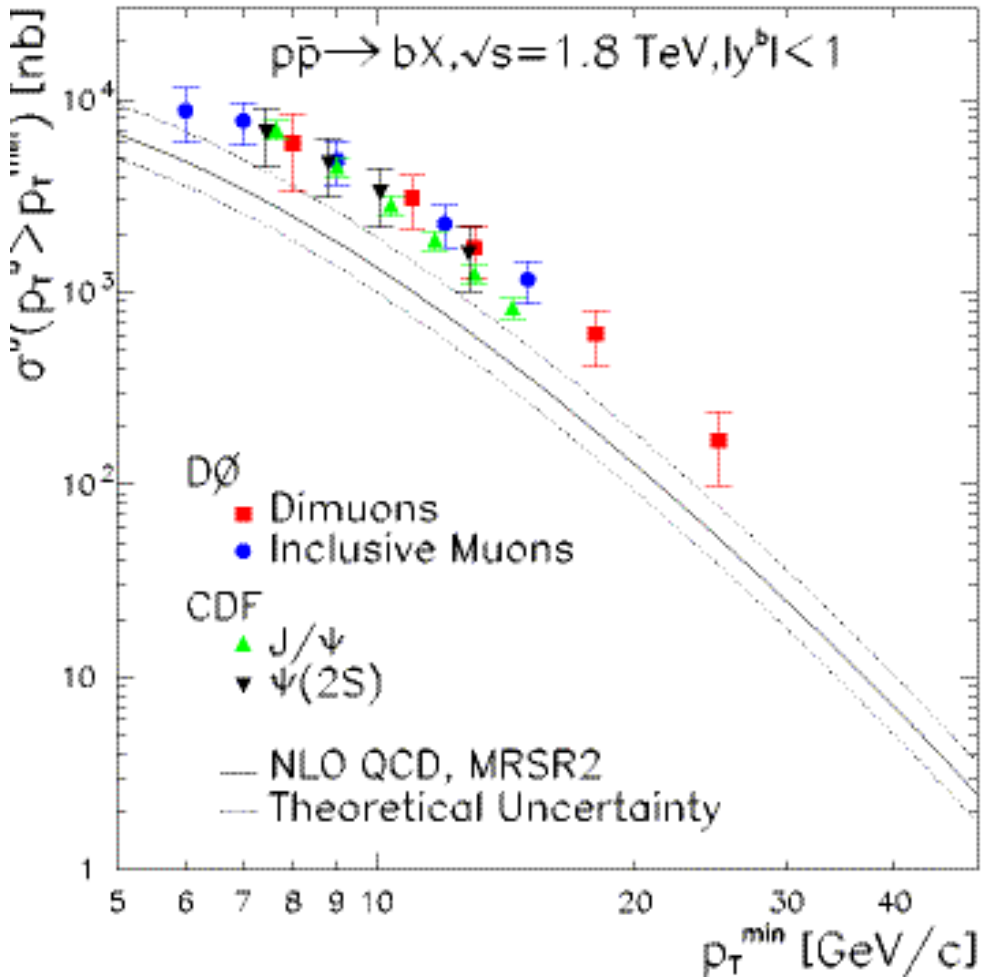
arXiv:1504.05156: On the intrinsic bottom content of the nucleon and its impact on heavy new physics at the LHC
F. Lyonnet, A. Kusina, T. Ježo, K. Kovařík, F. Olness, I. Schienbein, J.Y. Yu

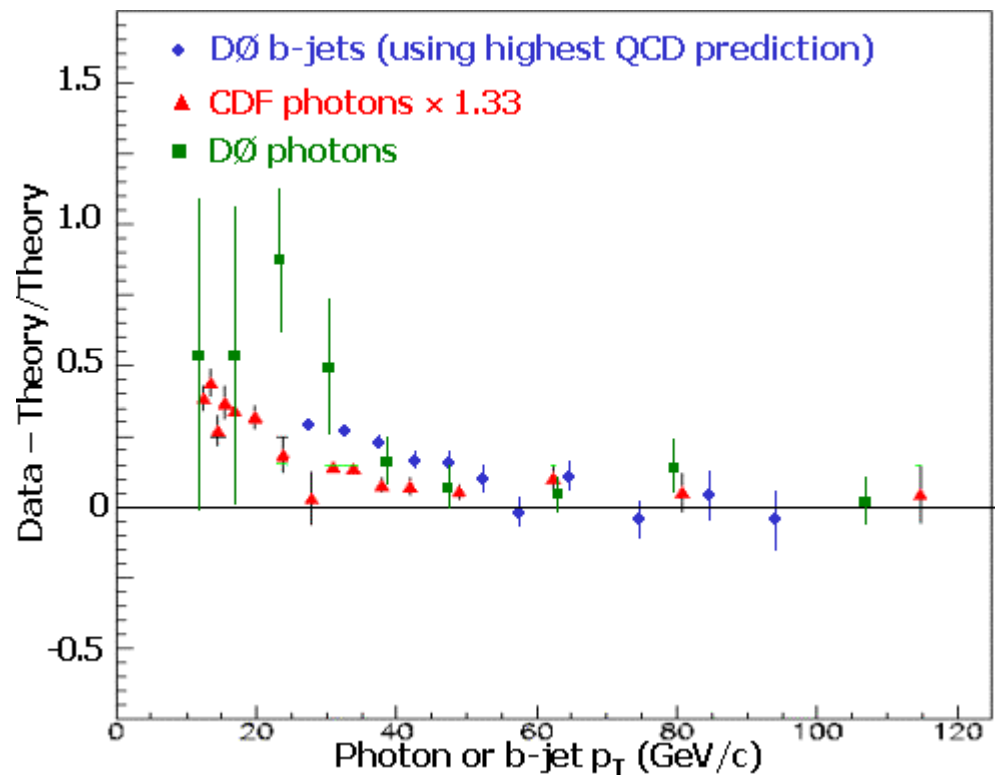
Heavy Quarks : … past challenges

The CTEQ List of Challenges in Perturbative QCD

Calculating b-quark production cross sections at hadron-hadron colliders

C T E Q



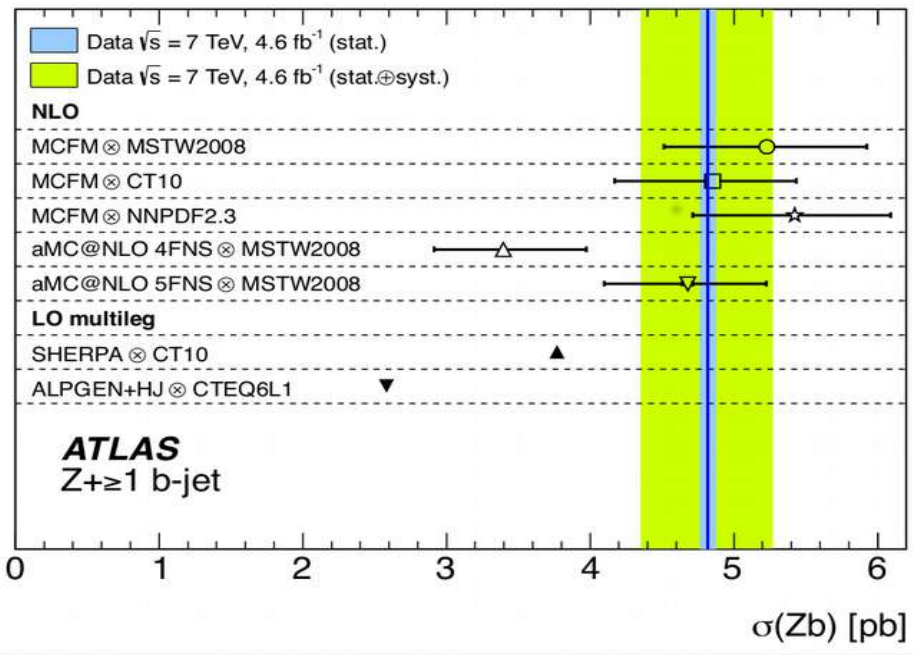


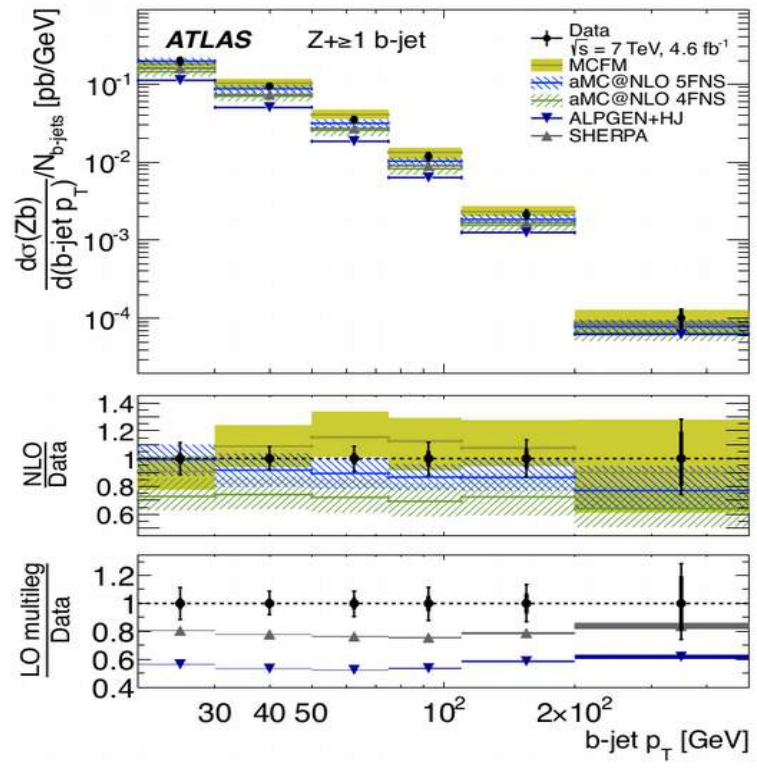
~1995

Heavy flavor: Z+b-jets

JHEP 10 (2014) 141

- Good agreement with NLO MCFM and aMC@NLO
  - Seems to favor scheme where b-quark is taken from PDF (5 FNS)
  - LO+PS generators are underestimating the cross section
  - Can't constrain PDF yet due to too large uncertainty
- Good description of b-jet p_T shape
  - Normalization is off





Higher Orders

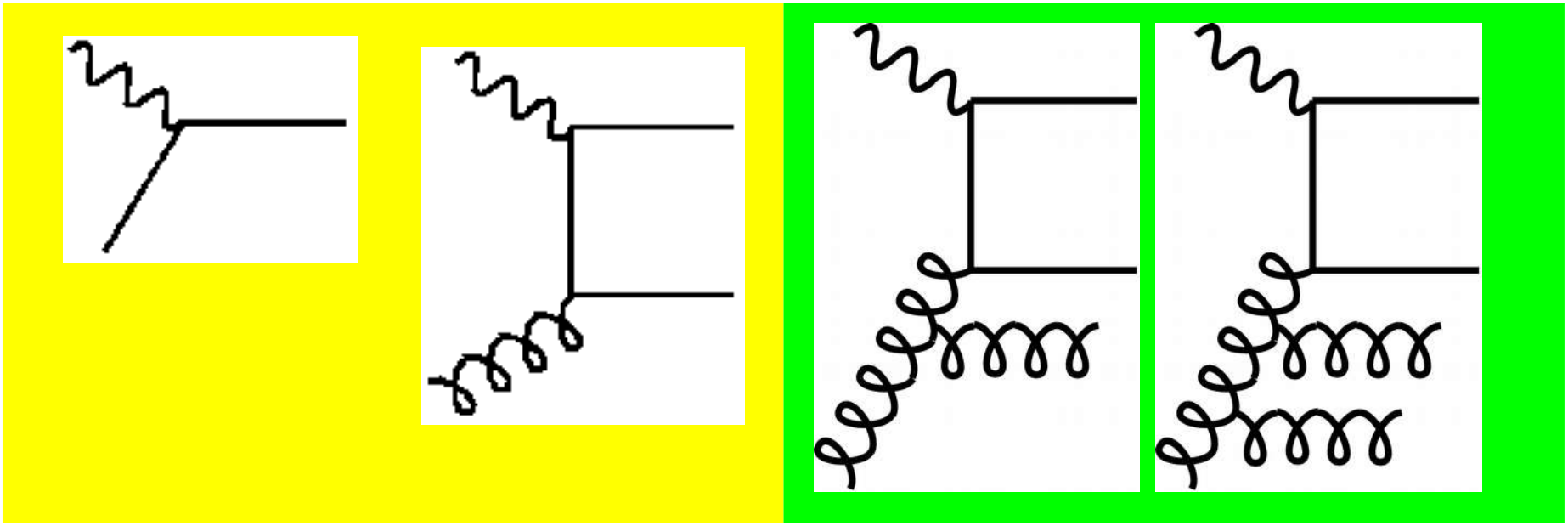
An example...

ACOT@ NNLO + N^3LO

Stavreva, Olness, Schienbein, Jezo, Kusina, Kovarik, Yu
Phys.Rev. D85 (2012) 114014

ACOT Extension to Higher Orders

LO **NLO** **N2LO** **N3LO**



Full ACOT

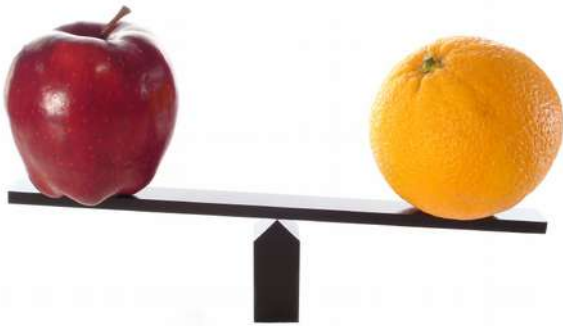
Based on the Collins-Wilczek-Zee (CWZ) Renormalization Scheme
... hence, extensible to all orders

DGLAP kernels & PDF evolution are pure MS-Bar
Subtractions are MS-Bar

ACOT: $m \rightarrow 0$ limit yields MS-Bar
with no finite renormalization

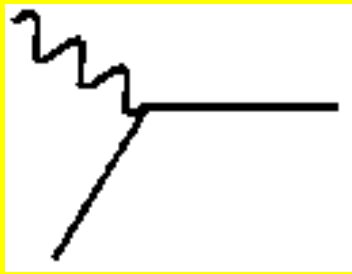
PDFs Discontinuous at N2LO

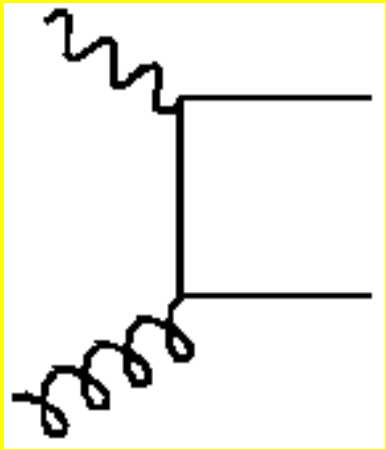
α_s Discontinuous at α_s^3

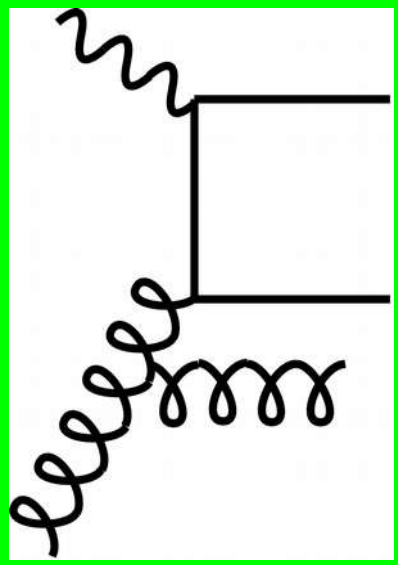


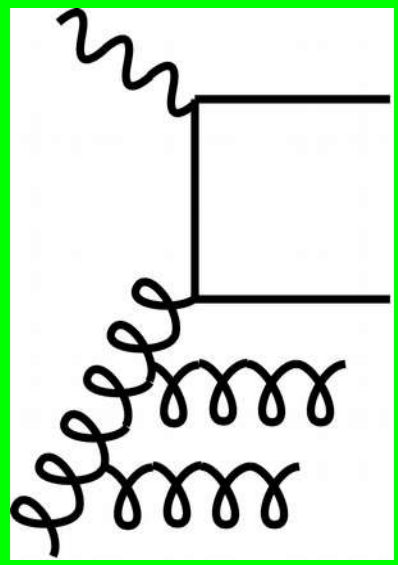
ACOT Extension to Higher Orders

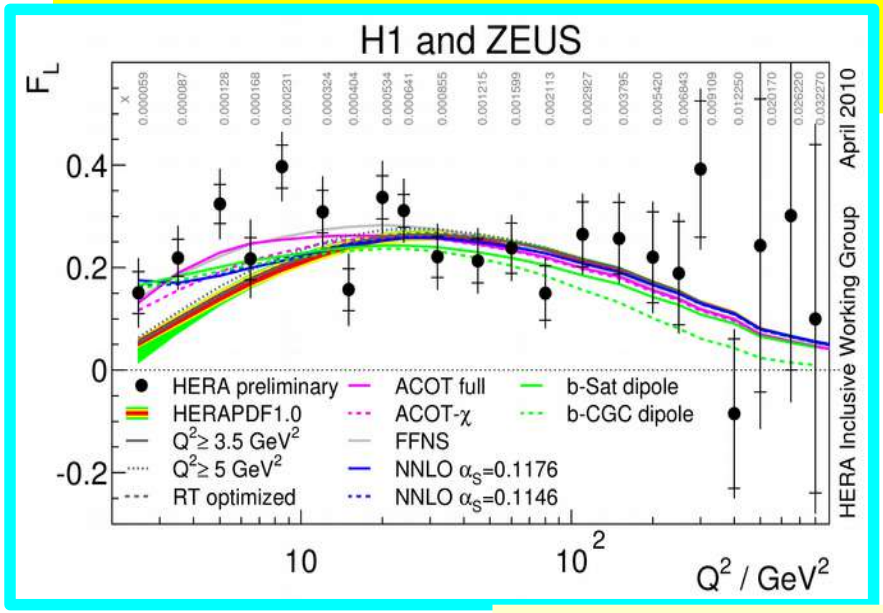
LO **NLO** **N2LO** **N3LO**









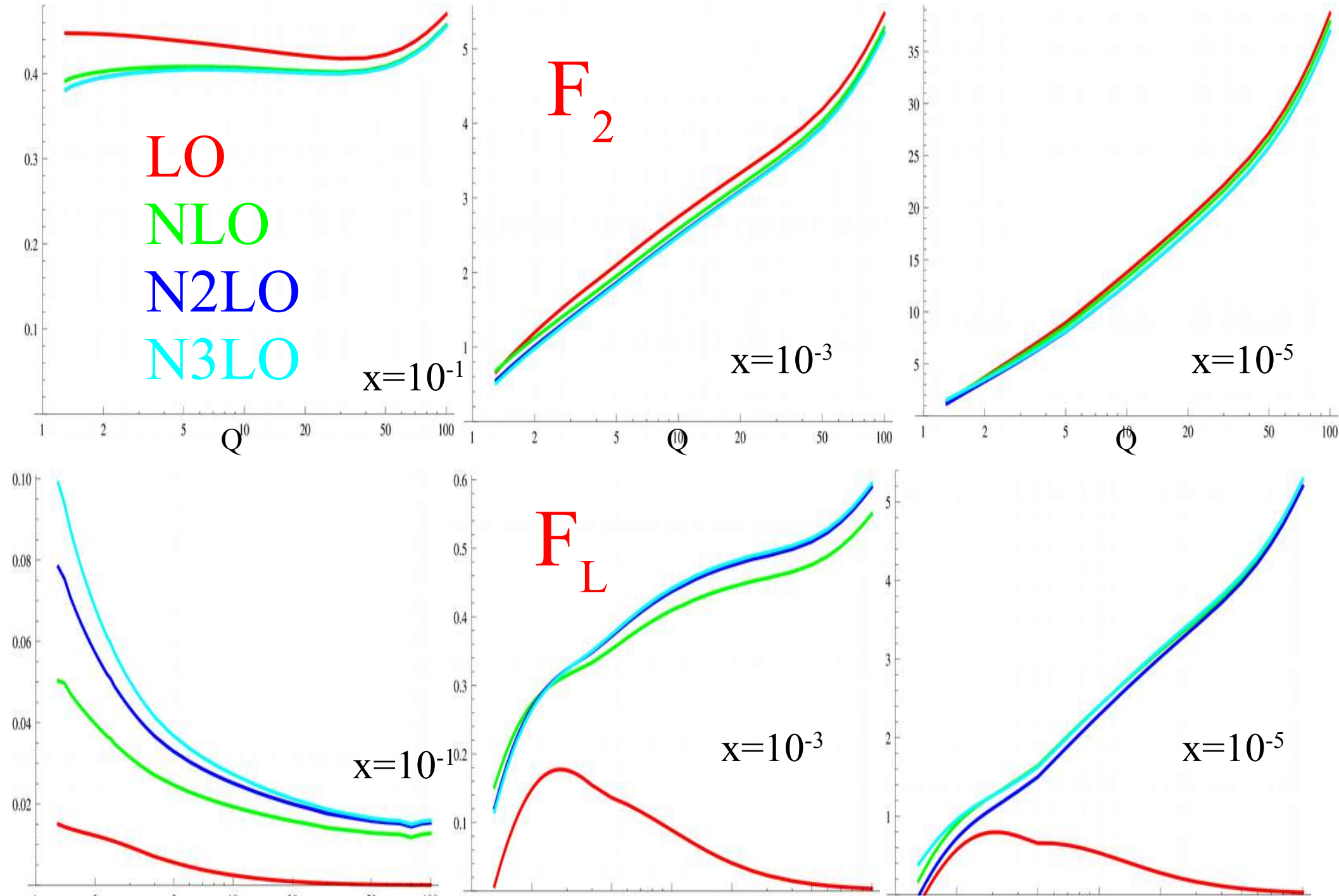


Masses are important

Higher Orders are important

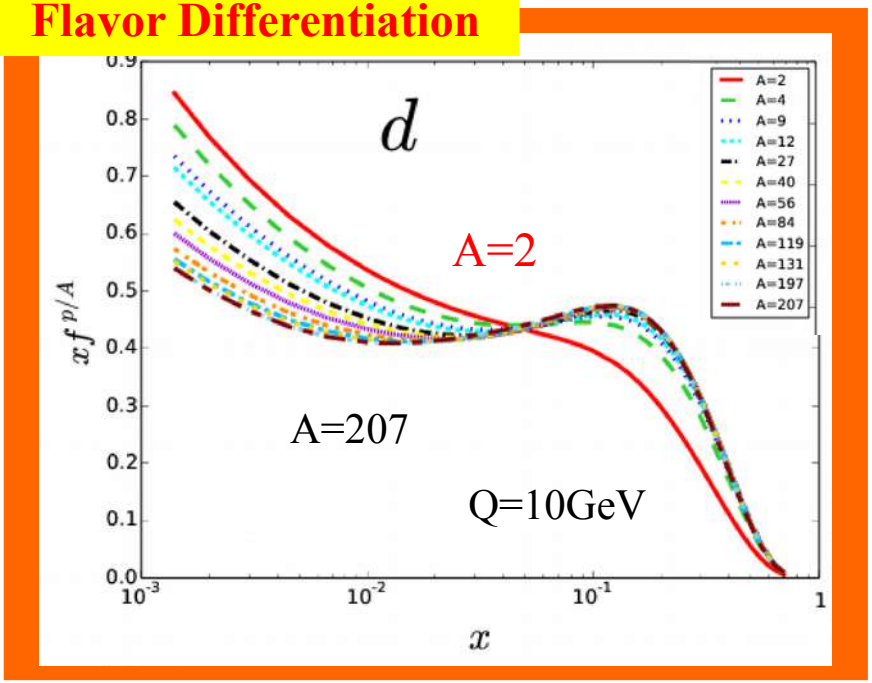
$$F_L \sim \frac{m^2}{Q^2} q(x) + \alpha_S \{c_g \otimes g(x) + c_q \otimes q(x)\}$$

$F_{2,L}$ @ N3LO

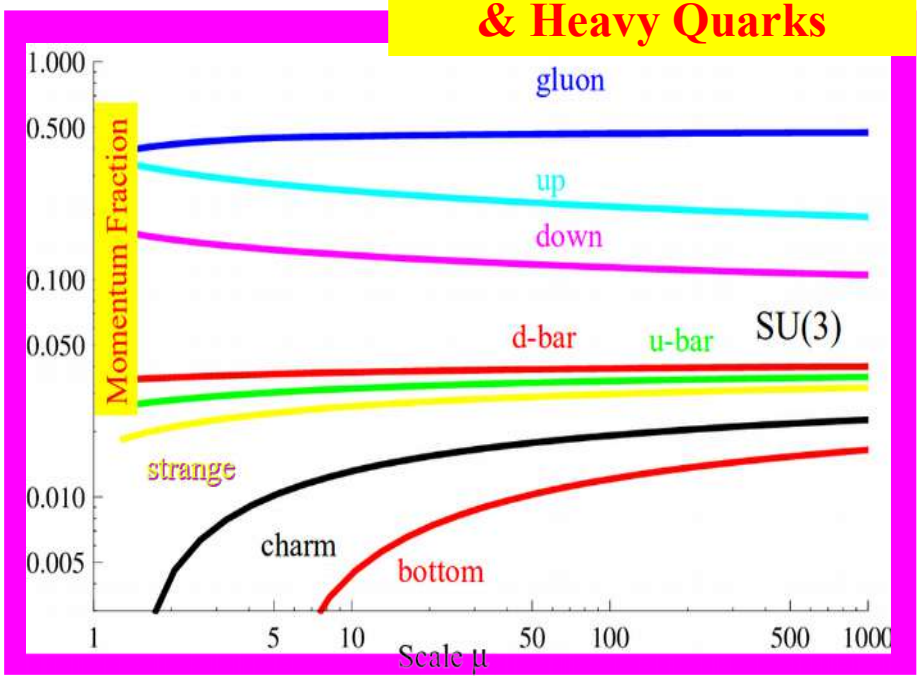


Conclusion

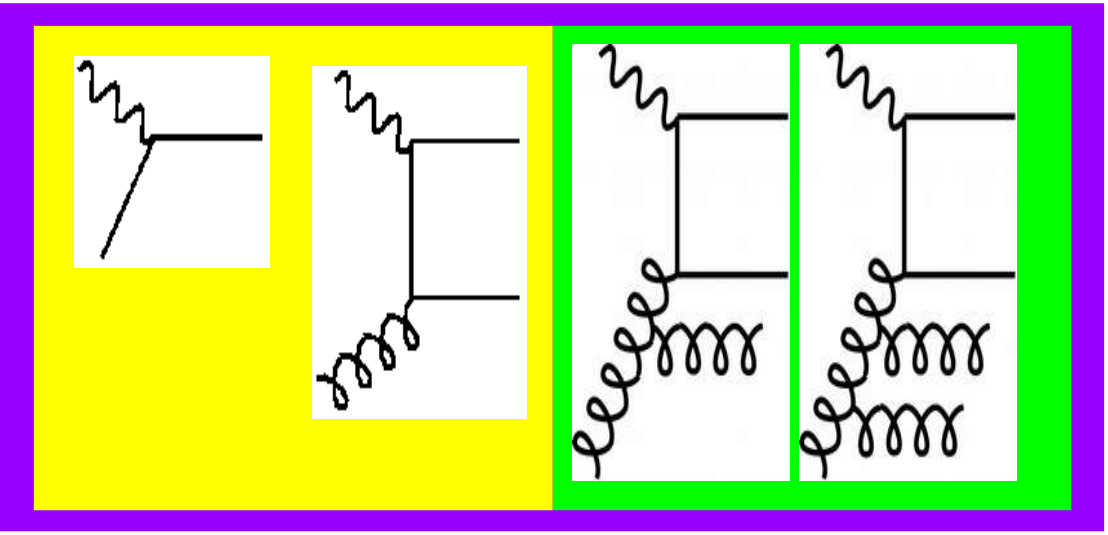
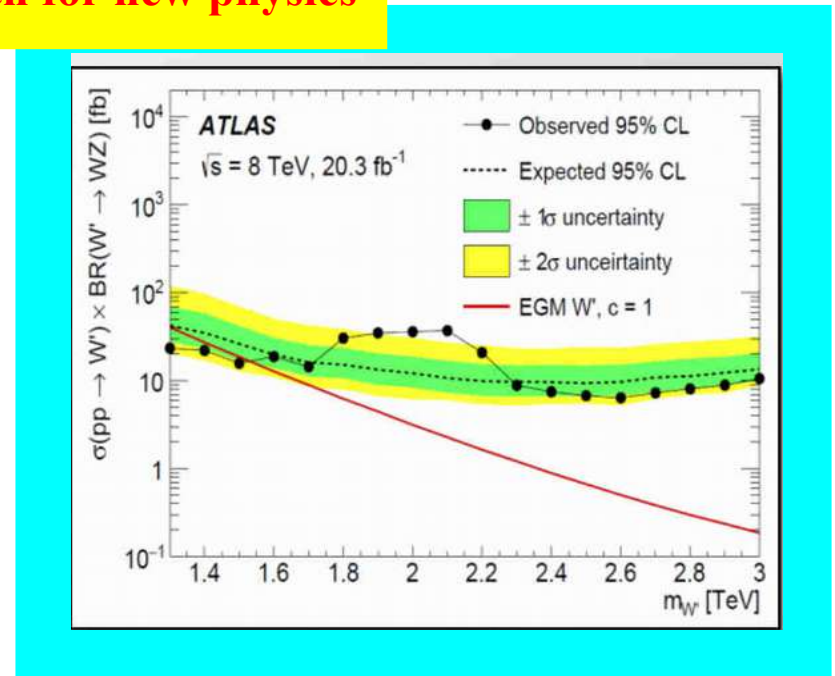
Nuclear Corrections & Flavor Differentiation



Multi-Scale Processes & Heavy Quarks



Higher Order Processes



Search for new physics