Precision QCD for New Physics Searches:

Working with heavy quarks at High Scales & High Orders

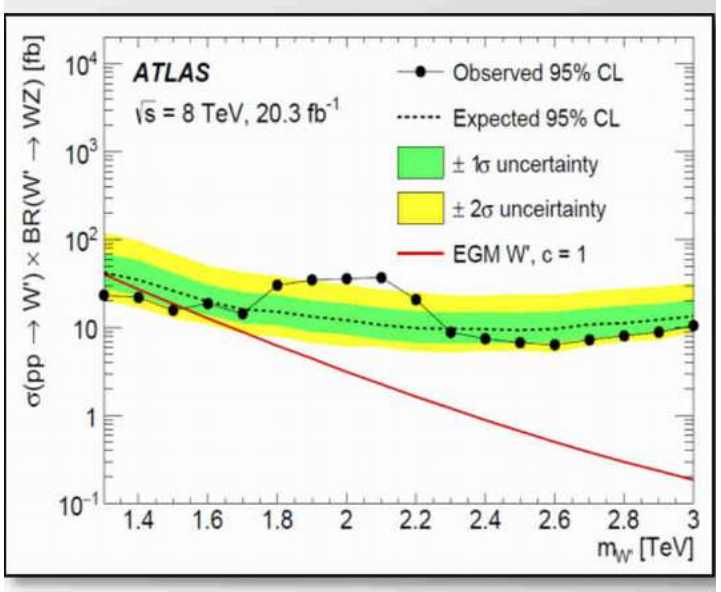
Fred Olness

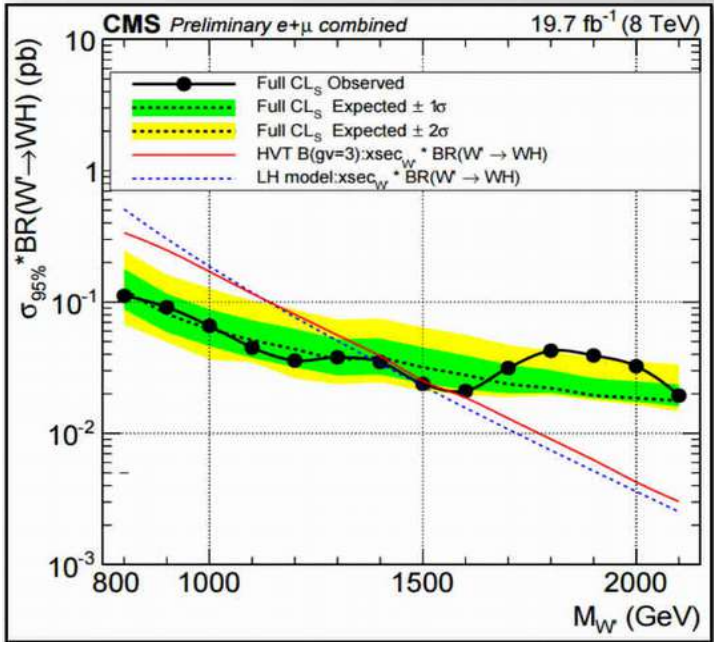
SMU

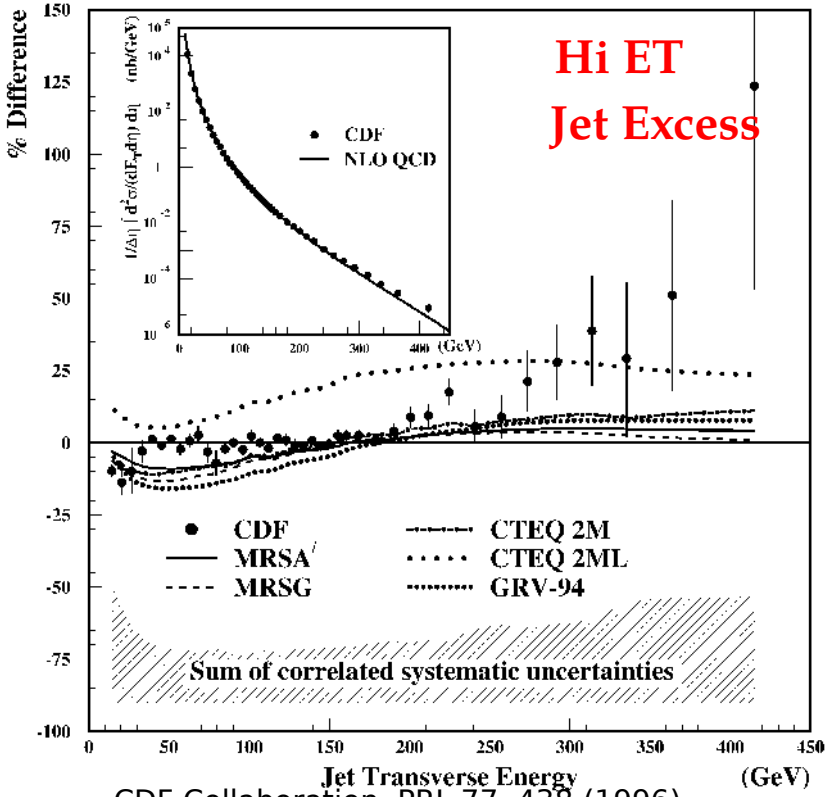
Thanks to:
F. Lyonnet, B. Clark, E. Godat, A. Kusina,, I. Schienbein, K. Kovarik, J.Y. Yu,
T. Jezo,J.G. Morfin, J.F. Owens, P. Nadolsky, M. Guzzi, V. Radescu, C. Keppel,

DPF 2015
4 August 2015

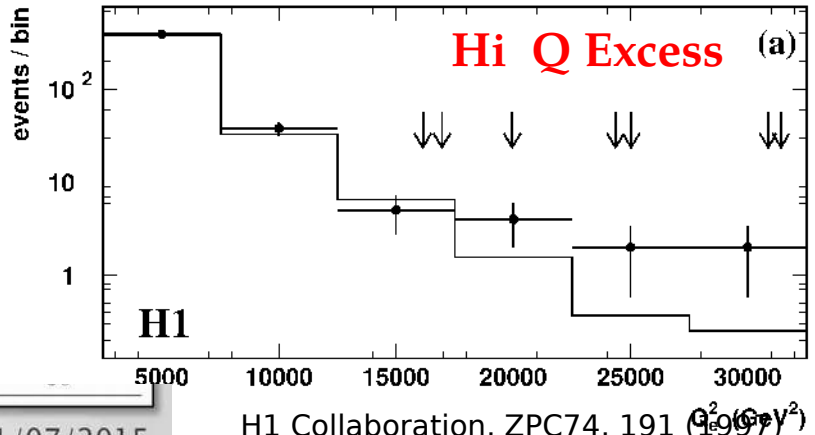
… things that go bump in the data …





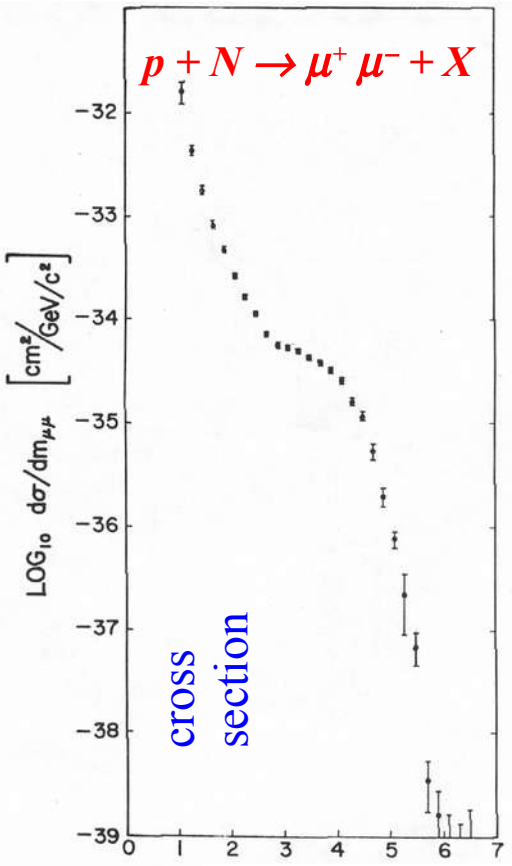


CDF Collaboration, PRL 77, 438 (1996)



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

Can you find the Nobel Prize???



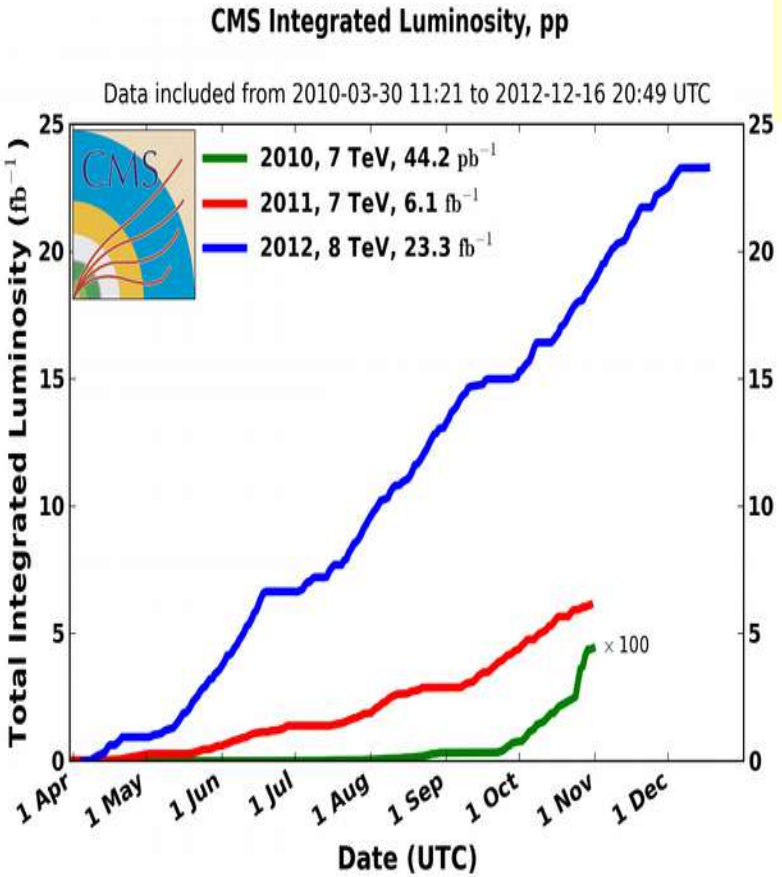
The Key to Discovery: The Parton Model and Factorization

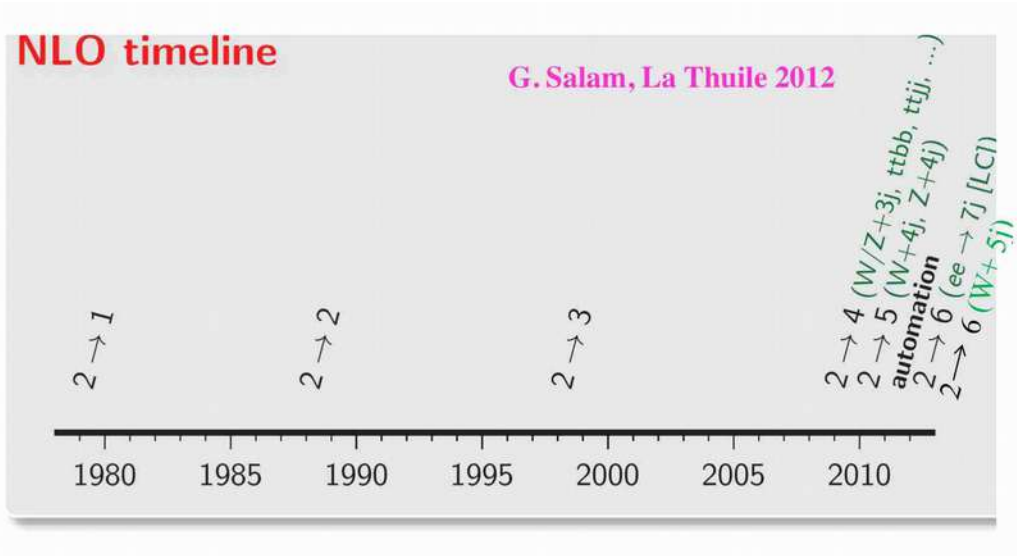
$$\sigma_{P\gamma \to c} = f_{P \to a} \otimes \hat{\sigma}_{a\gamma \to c}$$

Experimental Observables

Theoretical Calculations

WHAT ABOUT PDF'S ???





Issues we encounter:

1) Nuclear Corrections & Flavor Differentiation

2) Multi-Scale Problems: Heavy Quarks

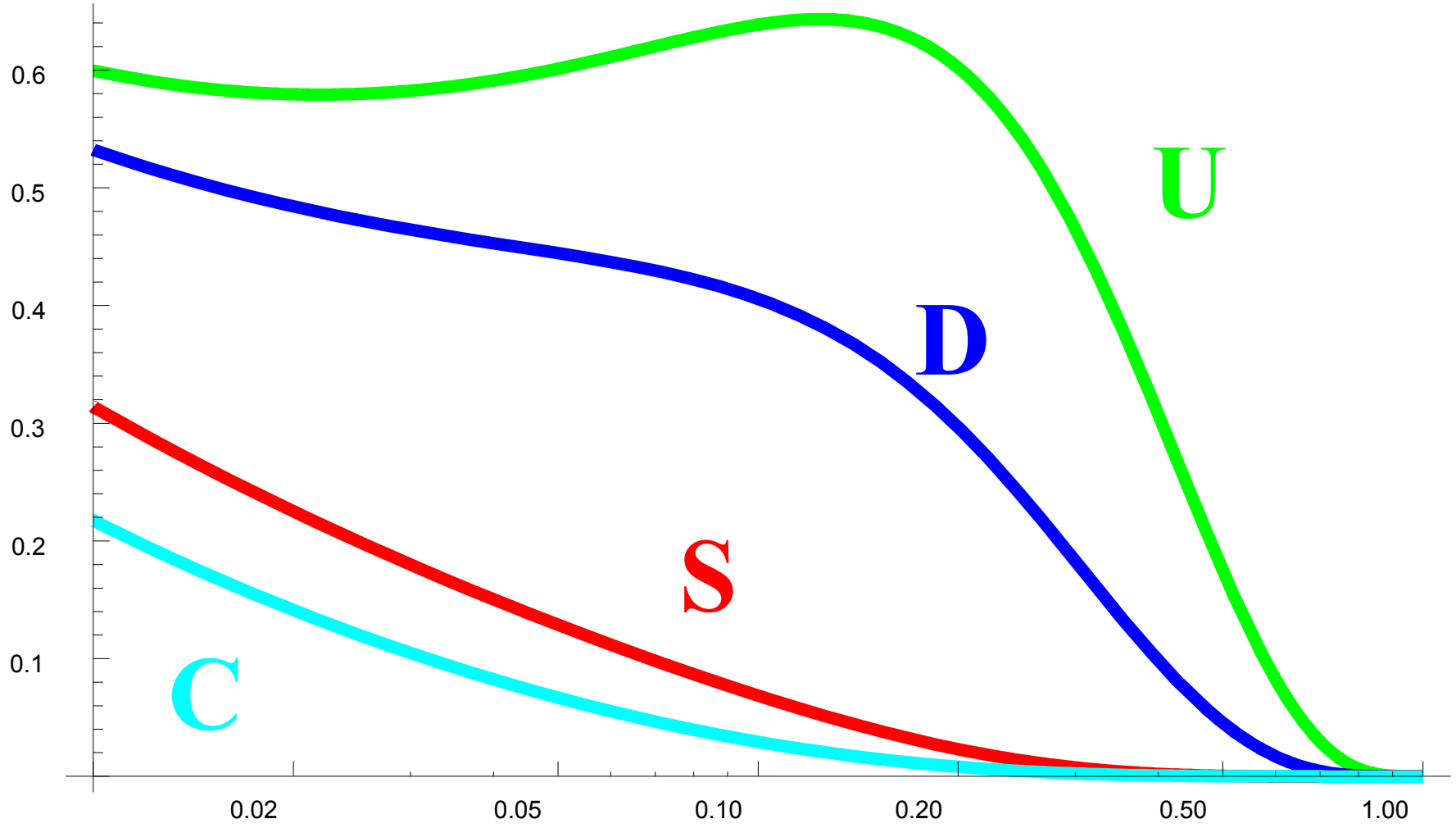
3) Higher Order Processes

nCTEQ-15

nuclear parton distribution functions

Without a good foundation ...

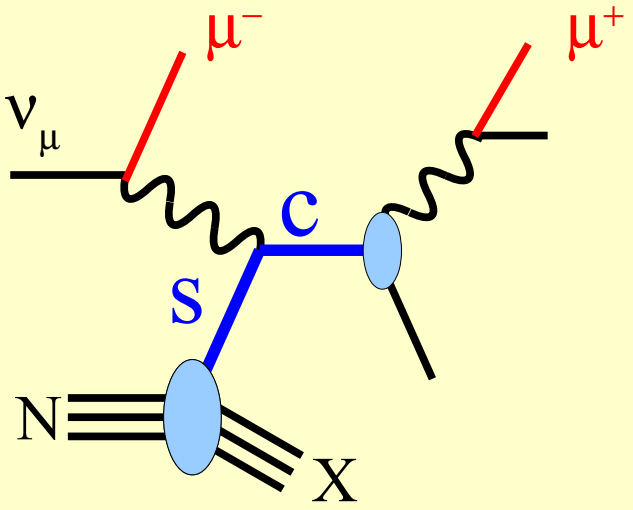
How do we differentiate flavors???



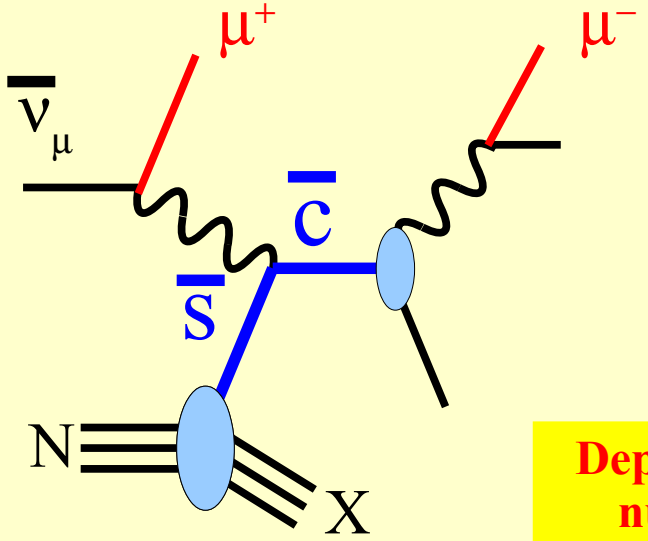
… why do we care about nuclear corrections

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

Extract s(x)



Extract $\bar{s}(x)$



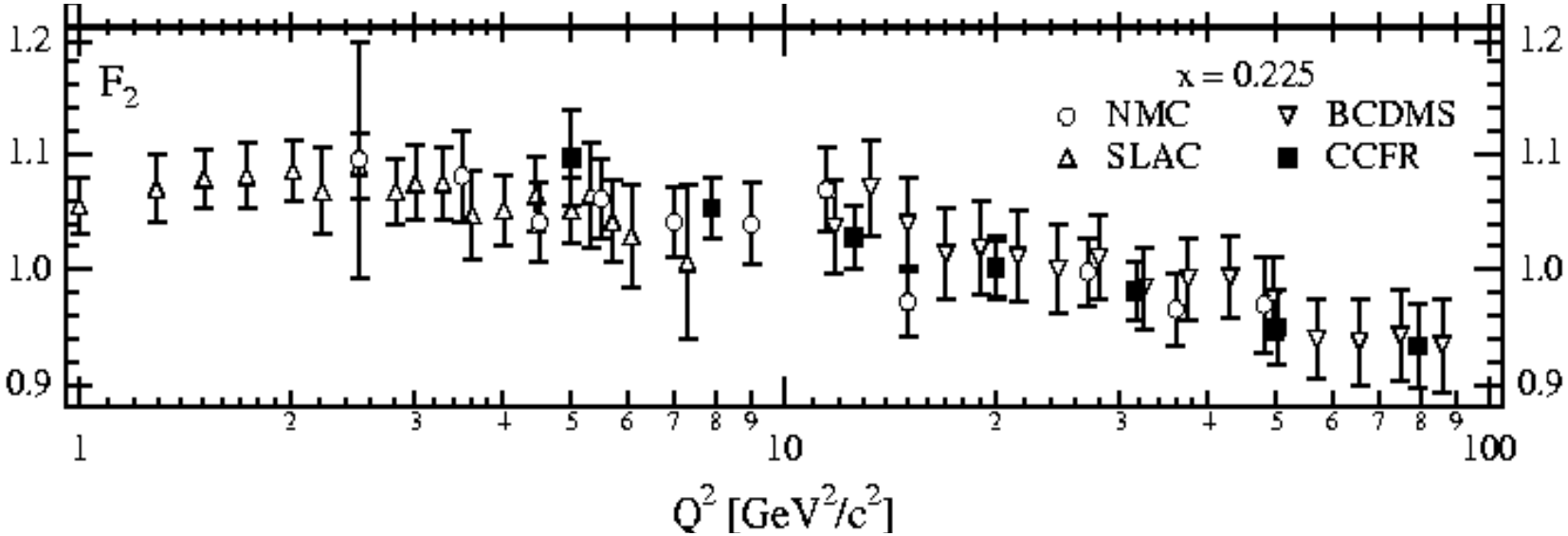
Depends on nuclear corrections

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

Used in CTEQ Fits

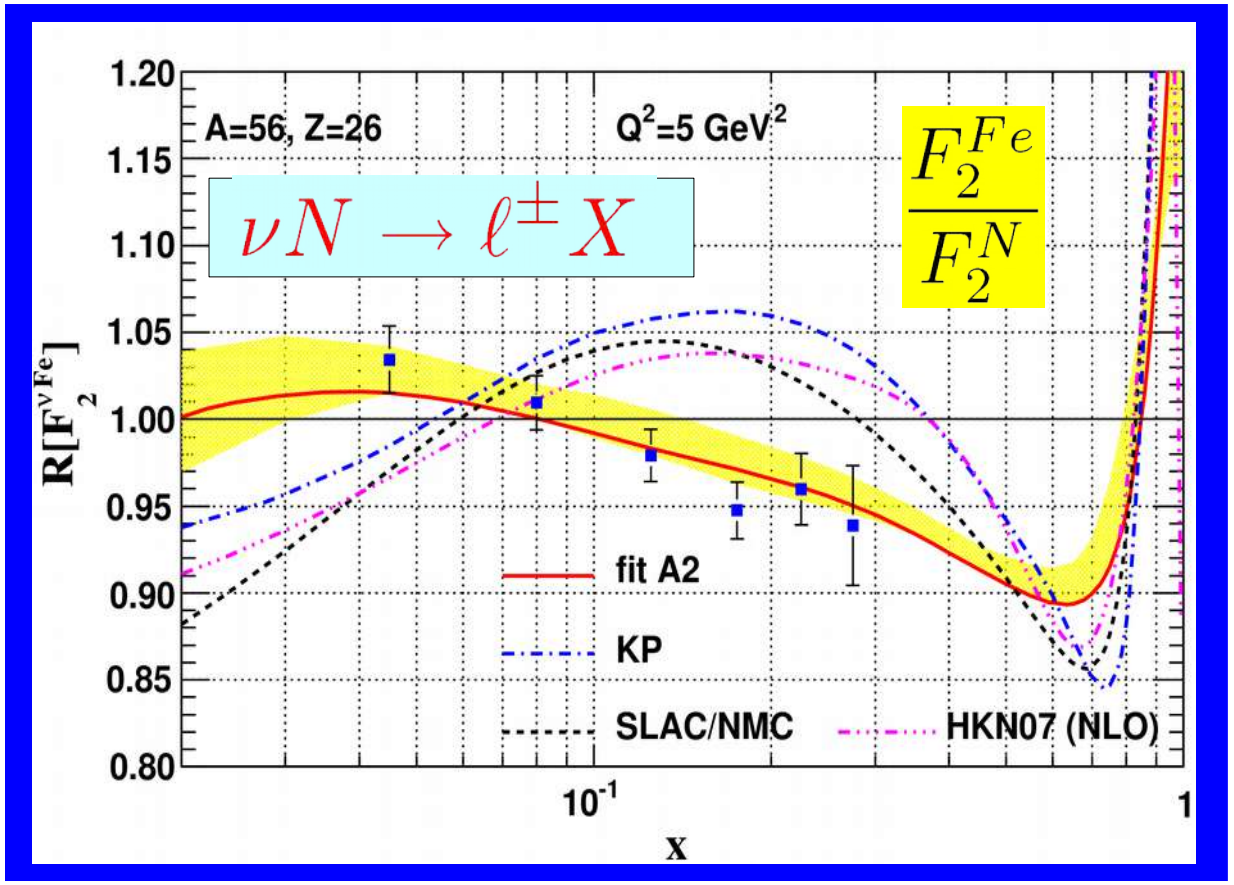
The CTEQ List of Challenges in Perturbative QCD

~1995

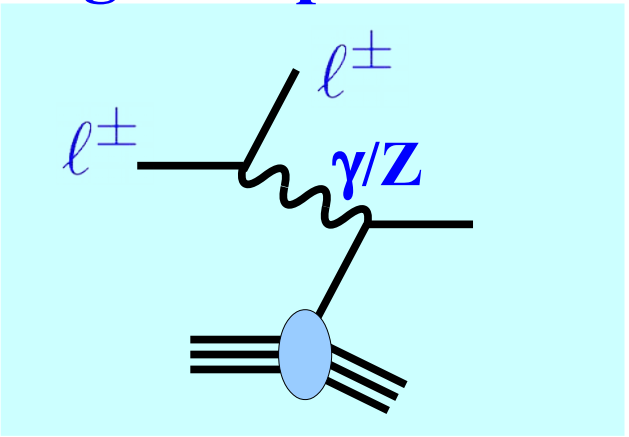


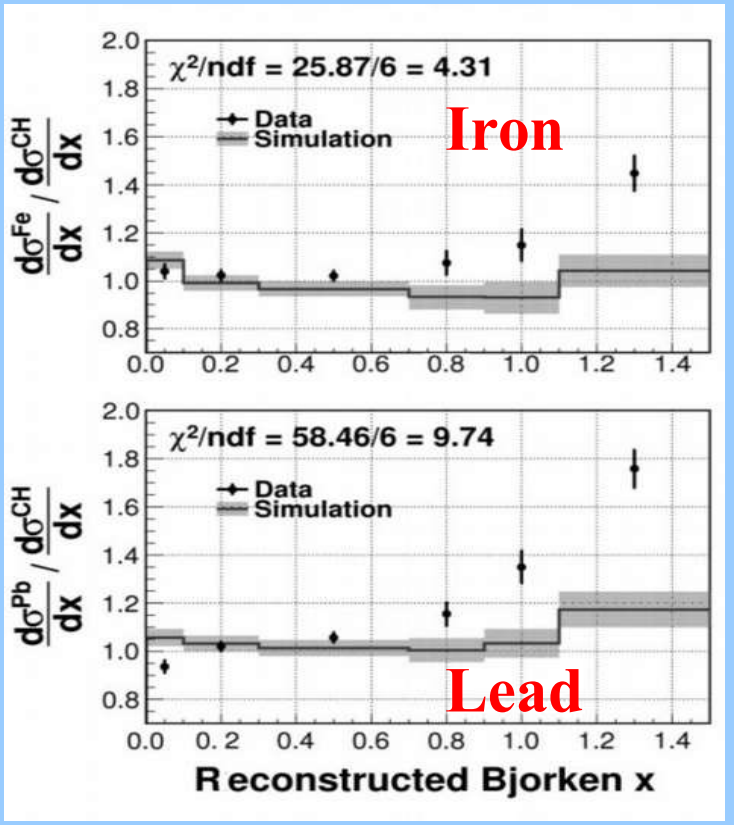
C T E Q

Nuclear Corrections: Compare Neutrino and Charged Lepton DIS

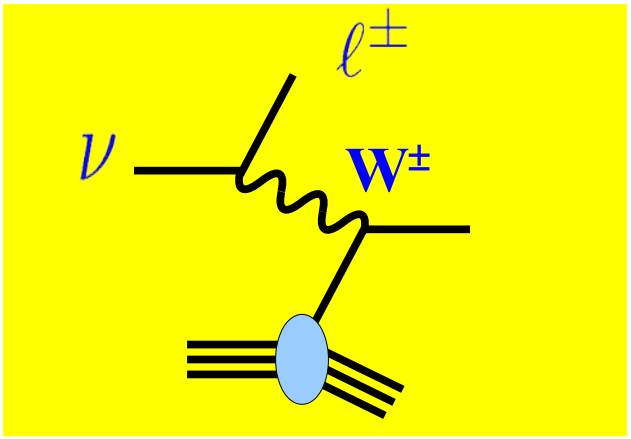


Charged Lepton DIS



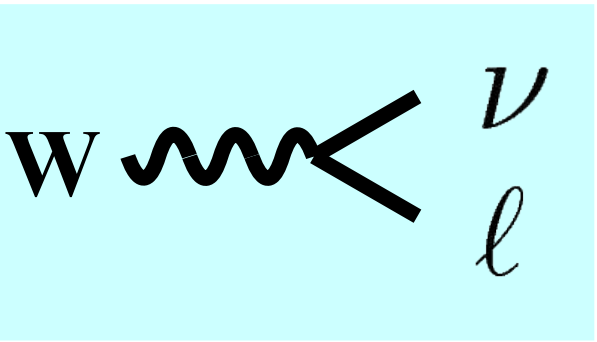


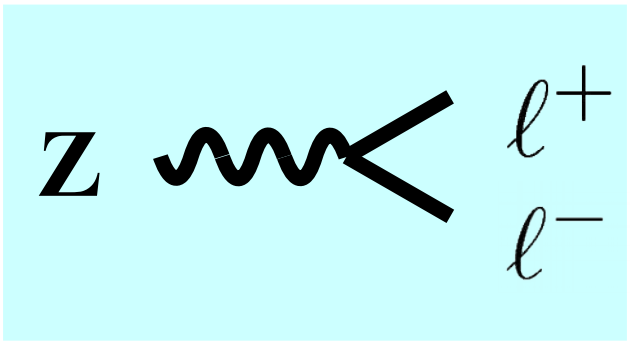
MINERvA: Phys.Rev.Lett. 112 (2014) 23, 231801



Neutrino DIS

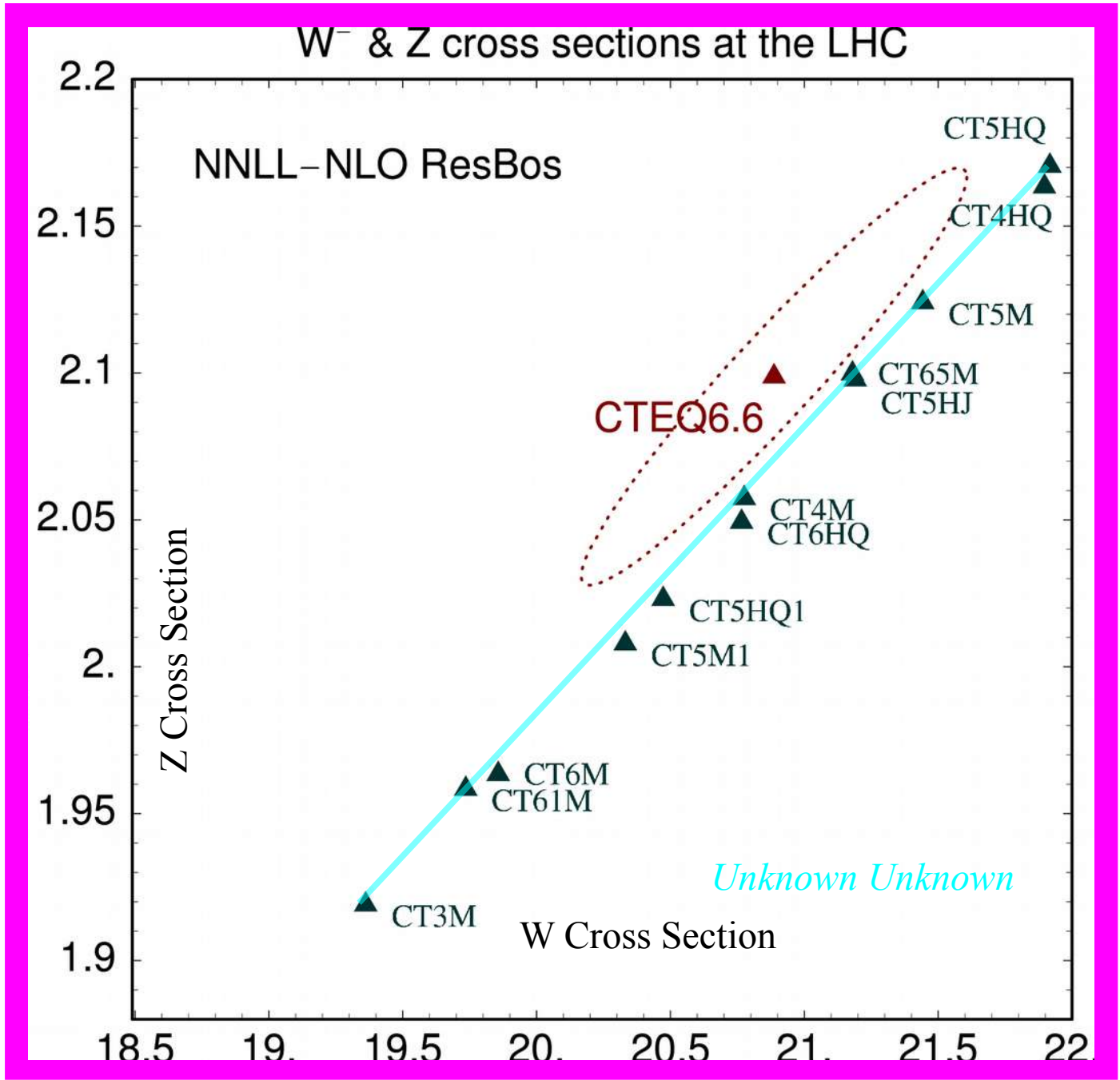
Strange Quark: Impact on LHC … W/Z correlation ⇒ M_W extraction





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

Key for M_W determination



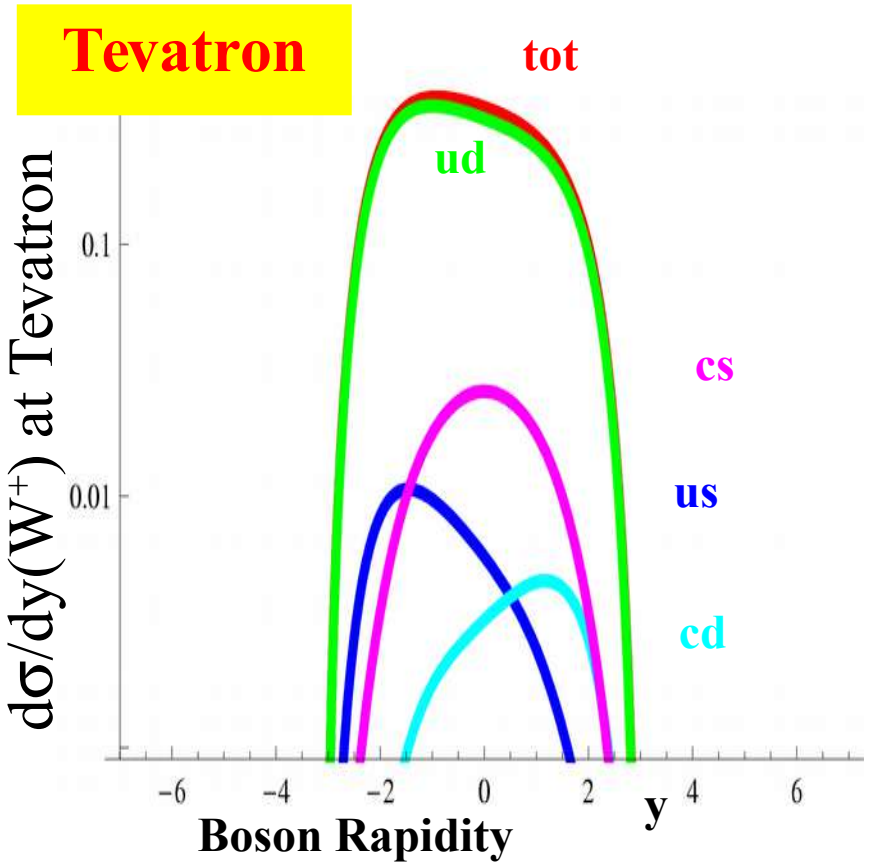
W/Z Production

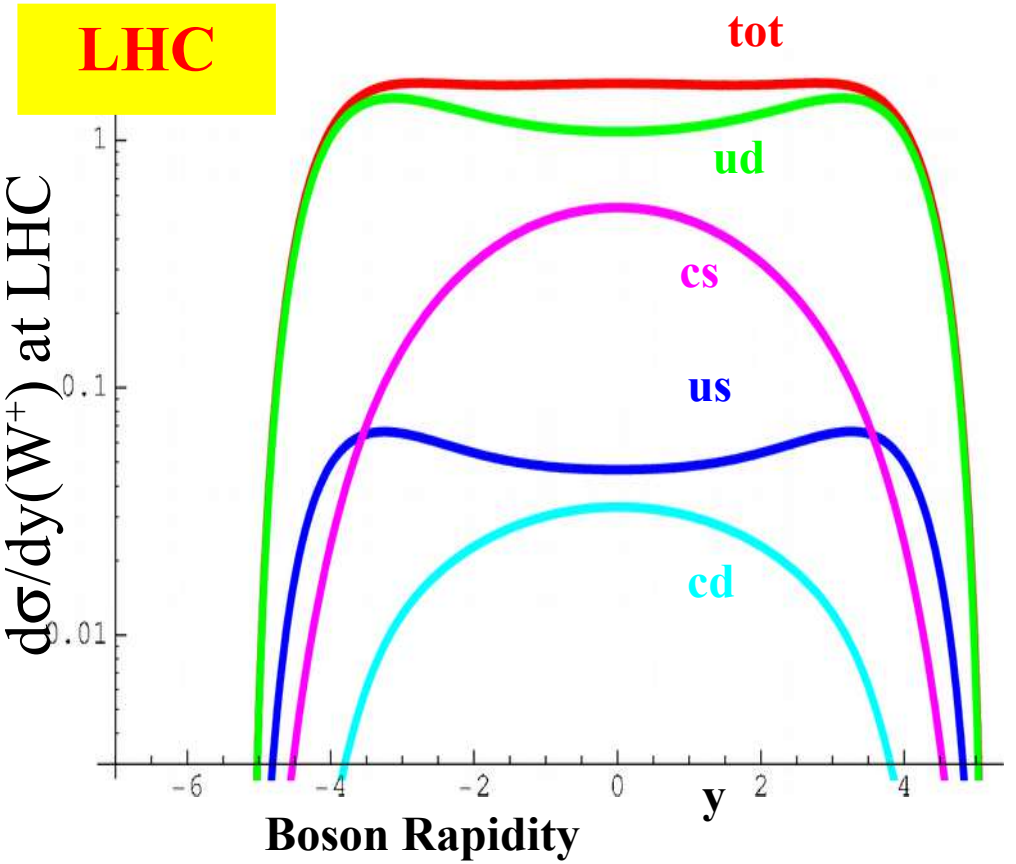
"Benchmark Calculations"

... 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*

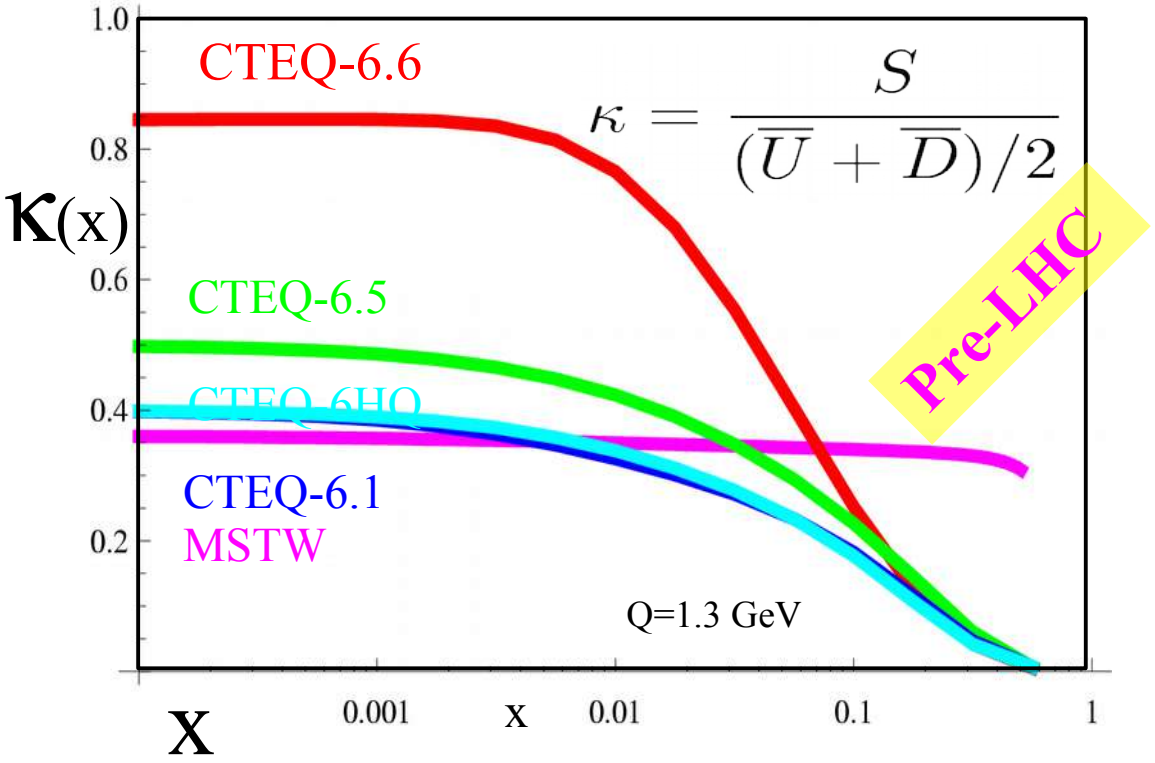


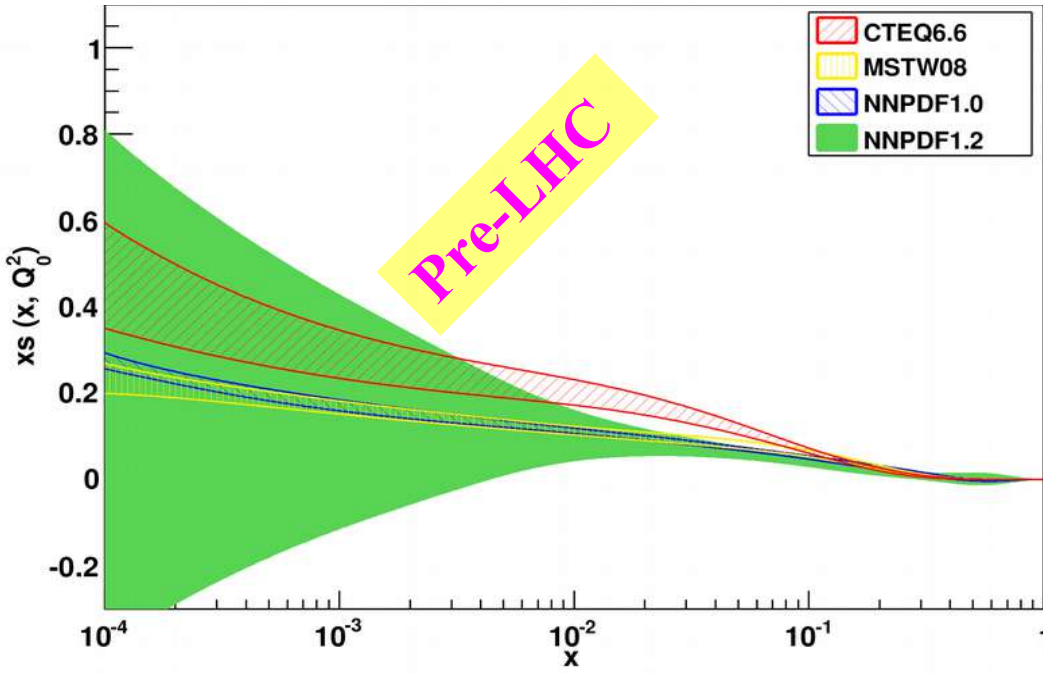


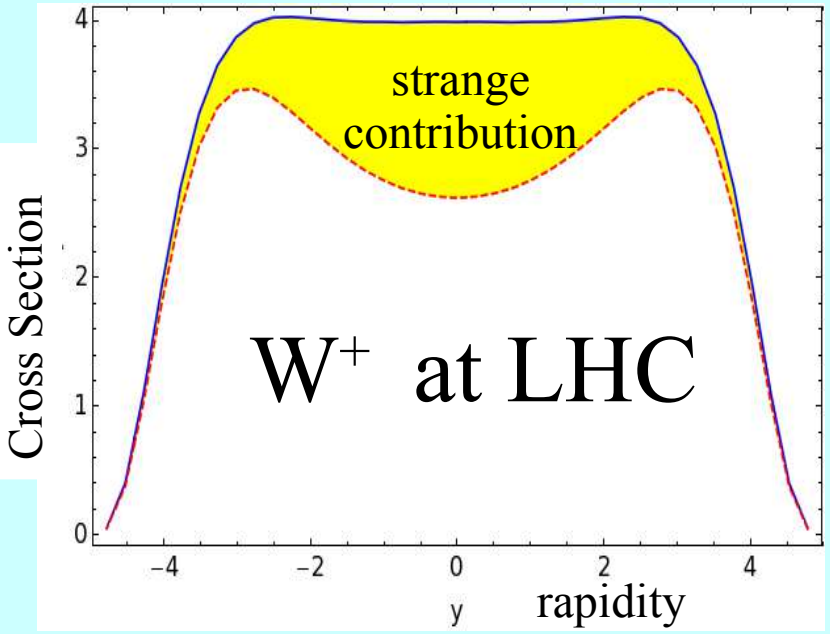
- Larger Energy ⇒ probes PDFs to small momentum fraction x
- Larger Rapidity **(y)** ⇒ probes PDFs to ***really*** small x
- Larger fraction of heavy quarks

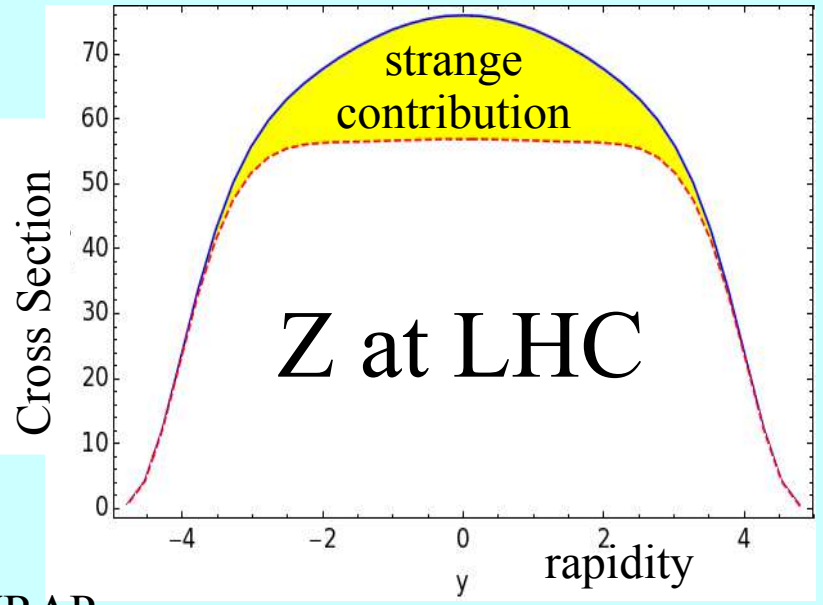
Heavy Quark components play an increasingly important role at the LHC

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









VRAP Code

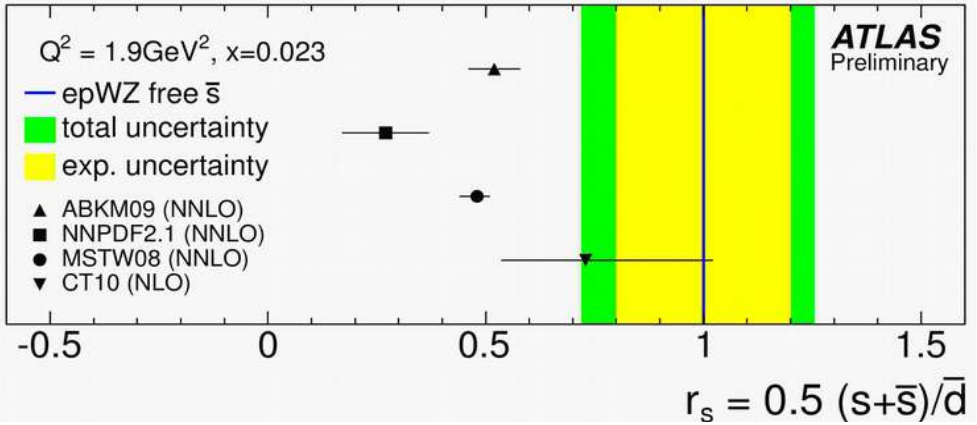
Anastasiou, Dixon, Melnikov, Petriello, Phys.Rev.D69:094008,2004.

Use LHC data to constrain Strange Quark

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

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



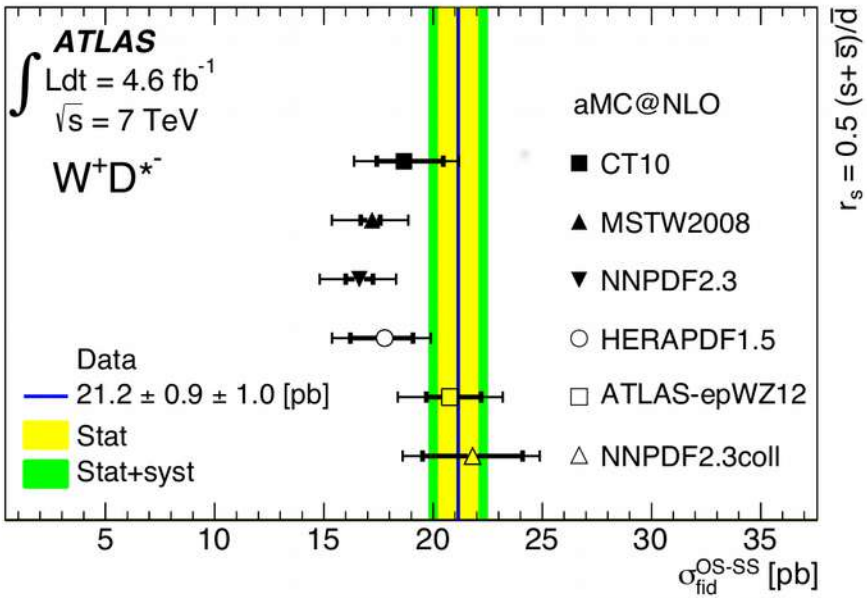
DIY: Do It Yourself: Strange Quark from LHC Data

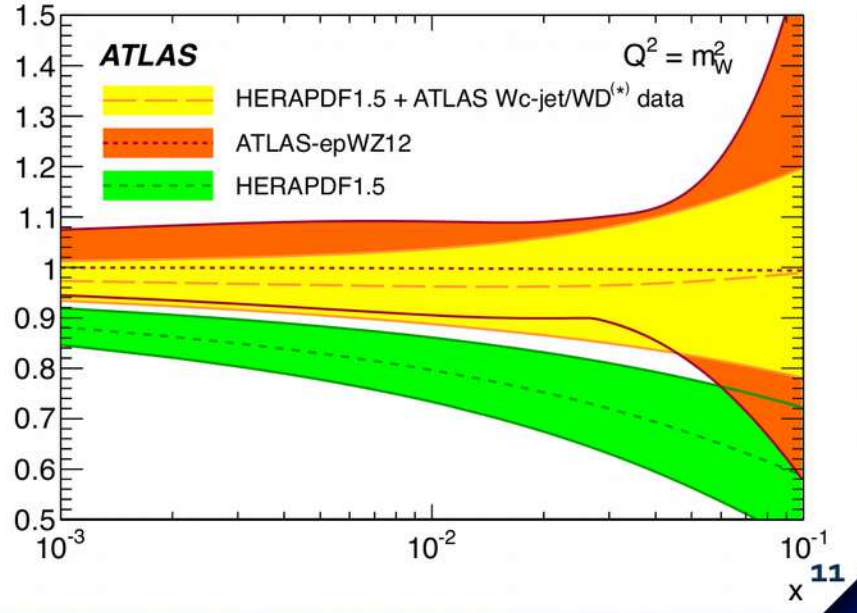
Other LHC processes also favor Strange enhancement

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





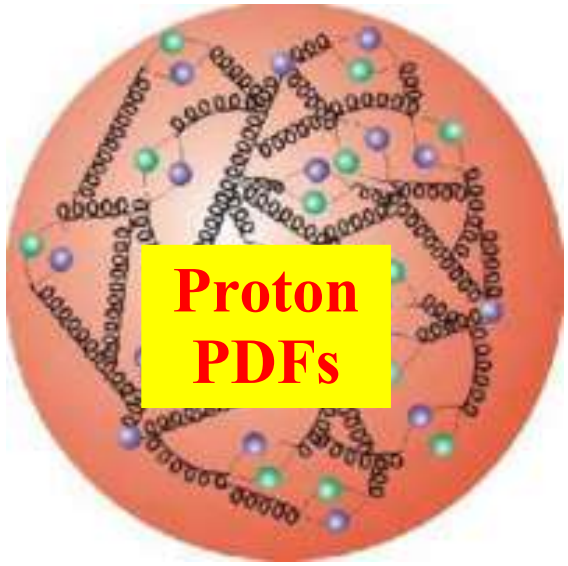
favors s-quark enhancement, not k=1/2 suppression

now that we see necessity
of nuclear corrections ...

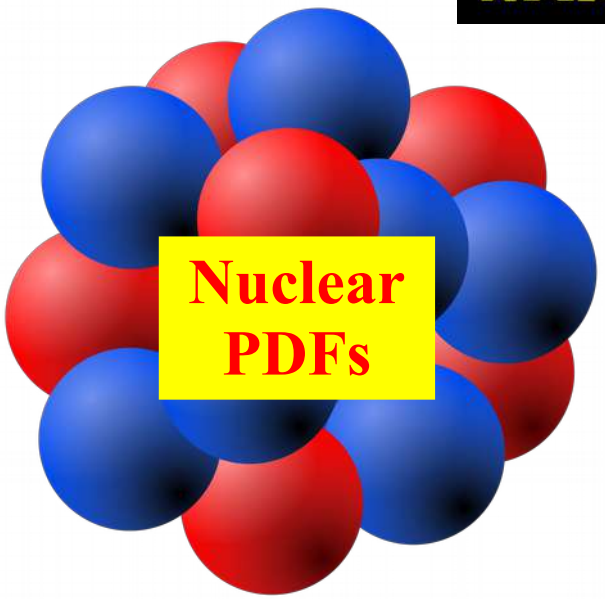
nCTEQ-15

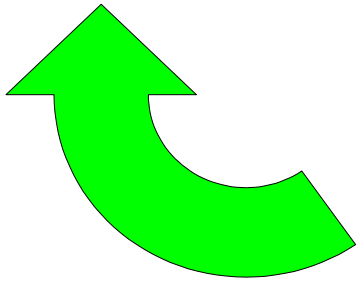
nuclear parton distribution functions

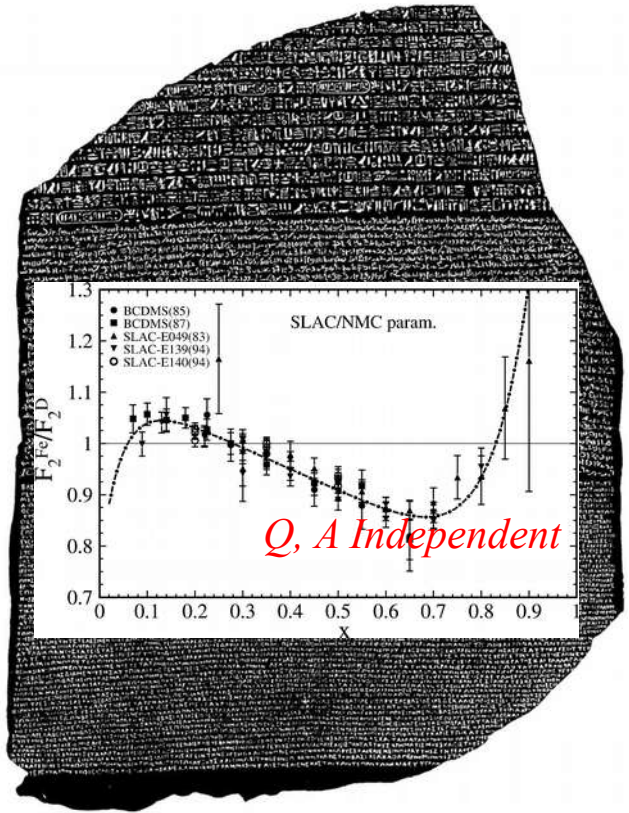
A long time ago in a galaxy far, far away ...

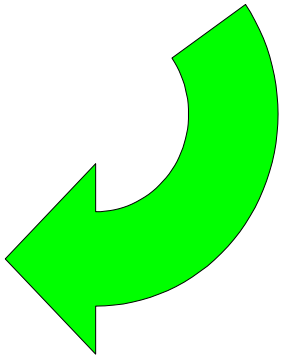


… there was a time when
nuclear corrections
were carved in stone …



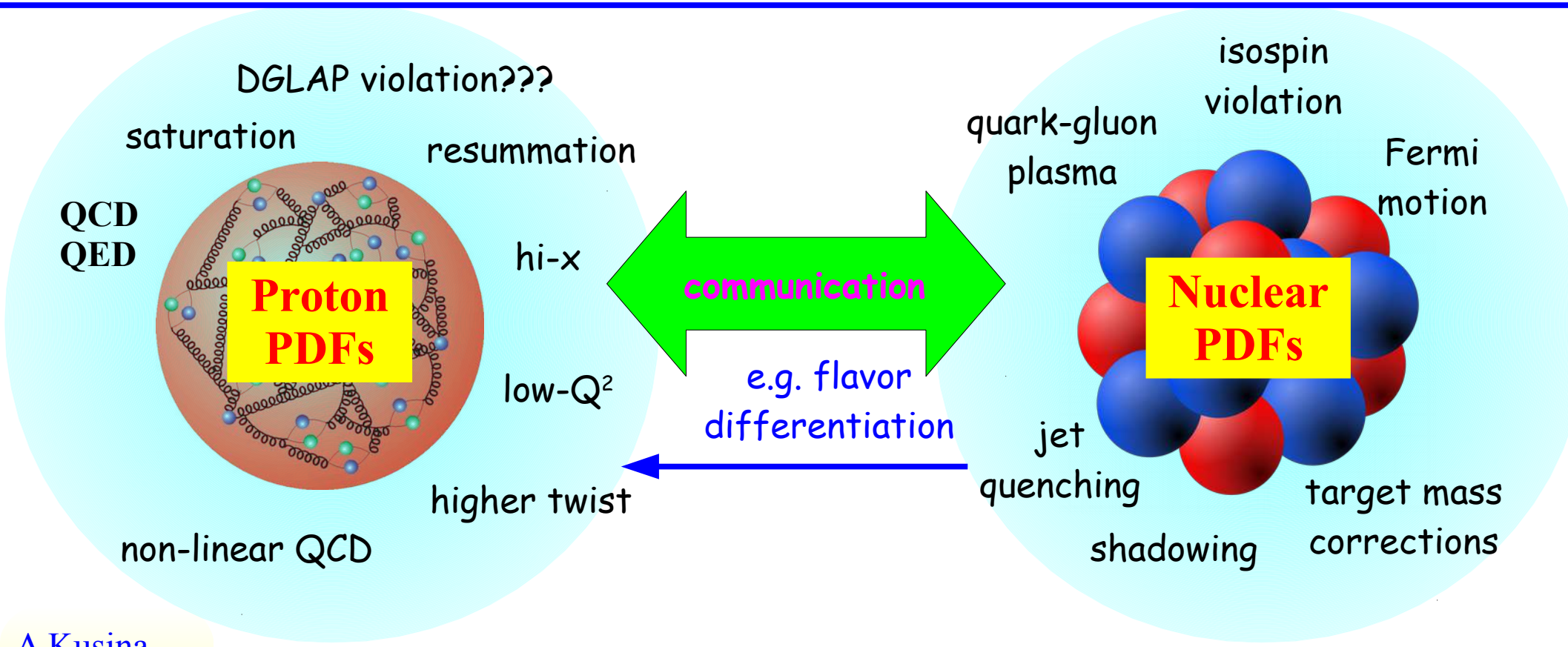






… the original motivation for nCTEQ15

Moving Into The 21st Century



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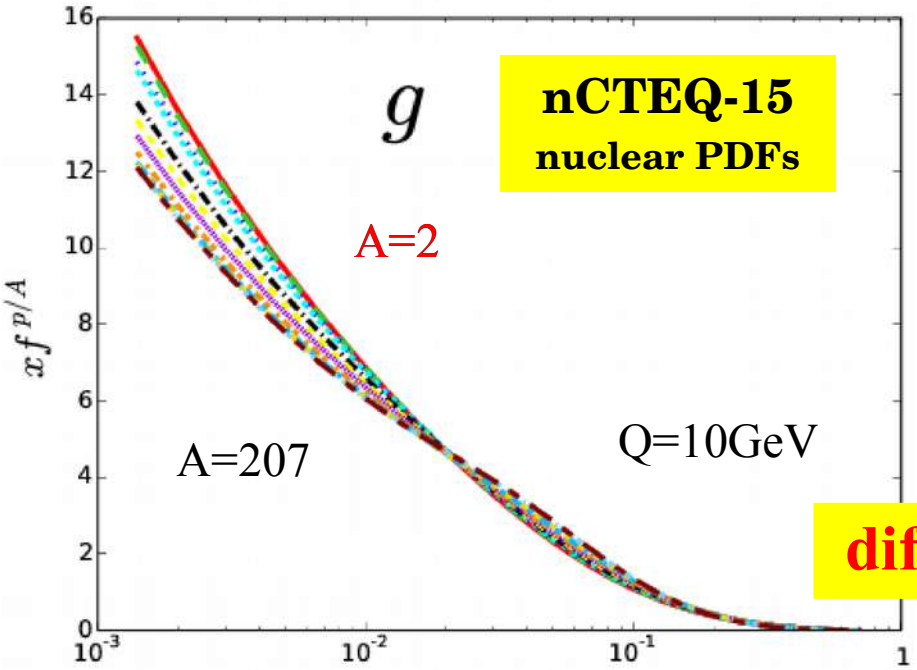
C. Keppel,
F. Lyonnet,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein,
J. Yu
E. Godat

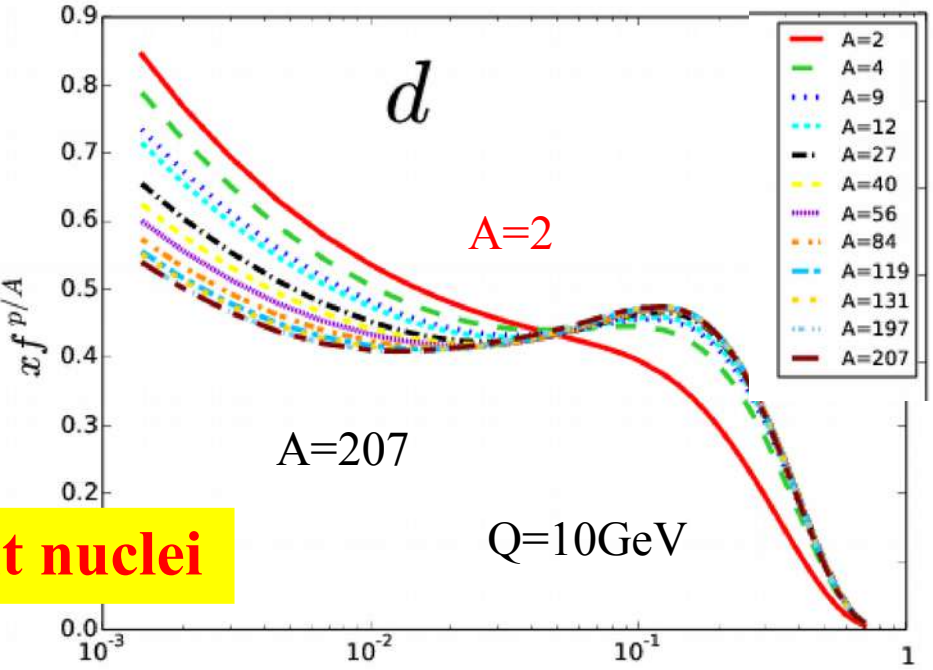
Data from nuclear targets is play a key role in the flavor differentiation

nCTEQ-15

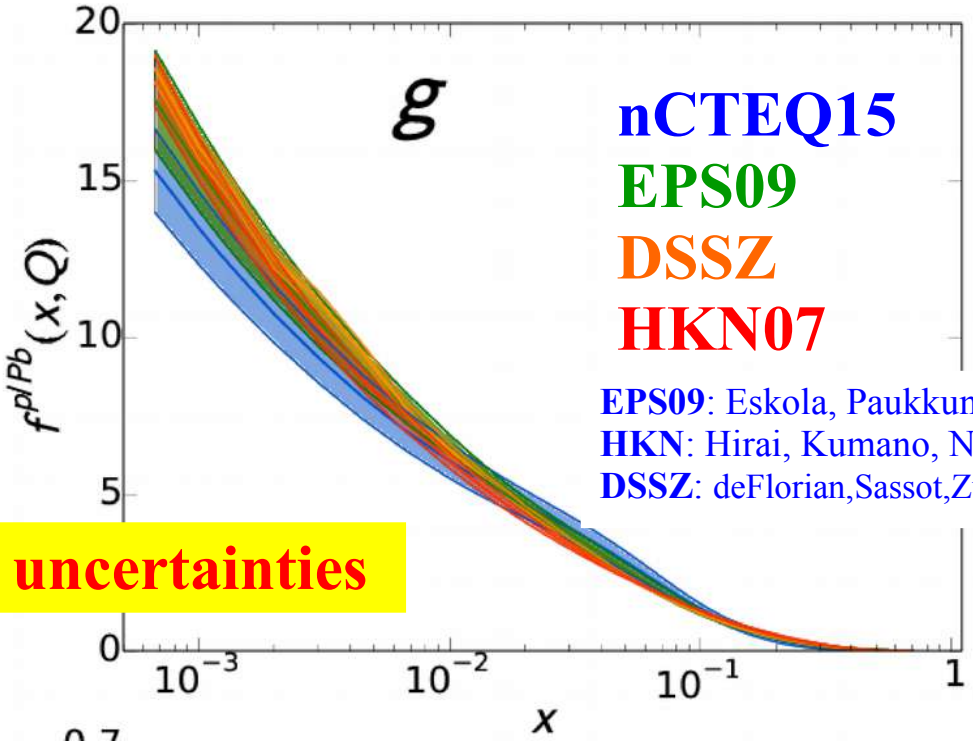
nuclear parton distribution functions

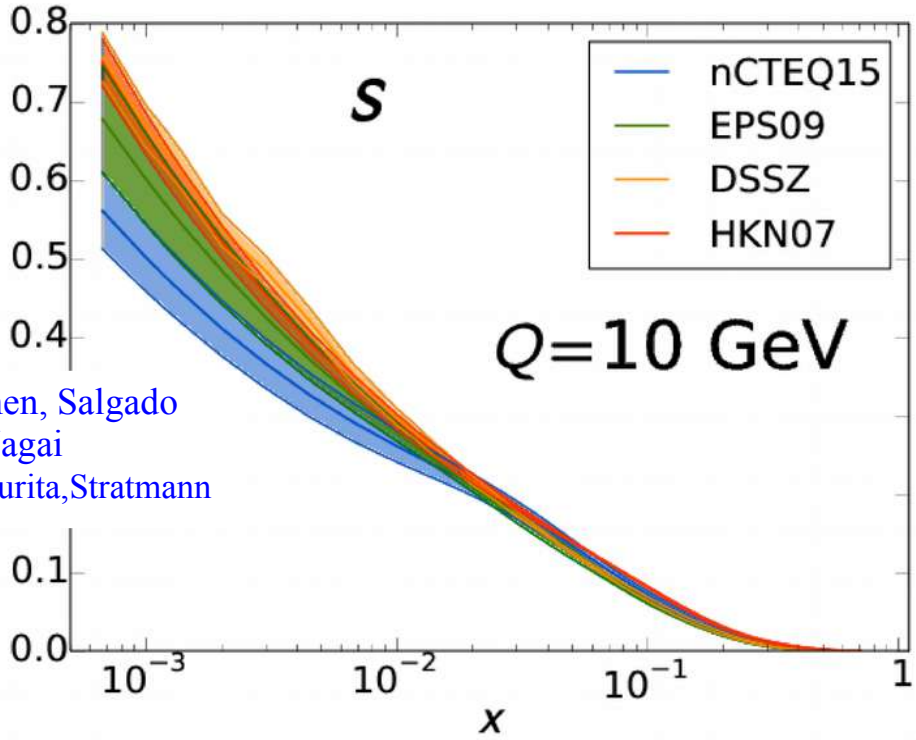
… the original motivation for nCTEQ15





different nuclei

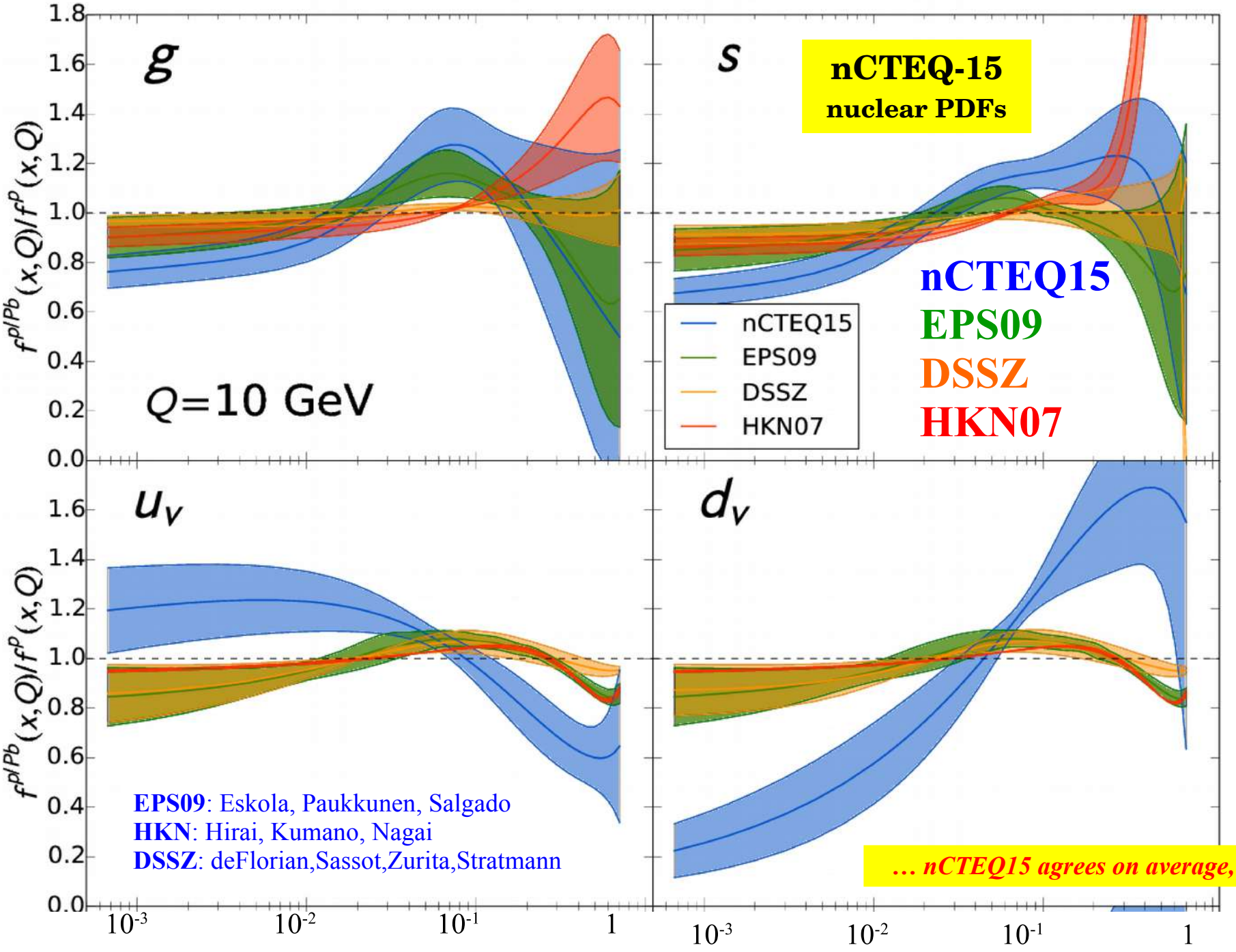




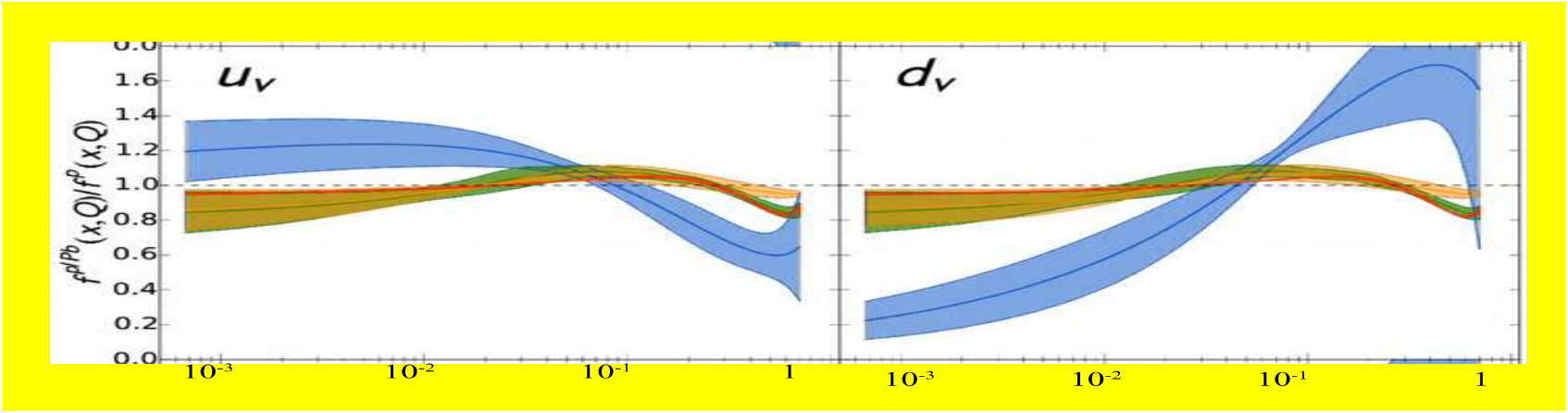
EPS09: Eskola, Paukkunen, Salgado
HKN: Hirai, Kumano, Nagai
DSSZ: deFlorian,Sassot,Zurita,Stratmann

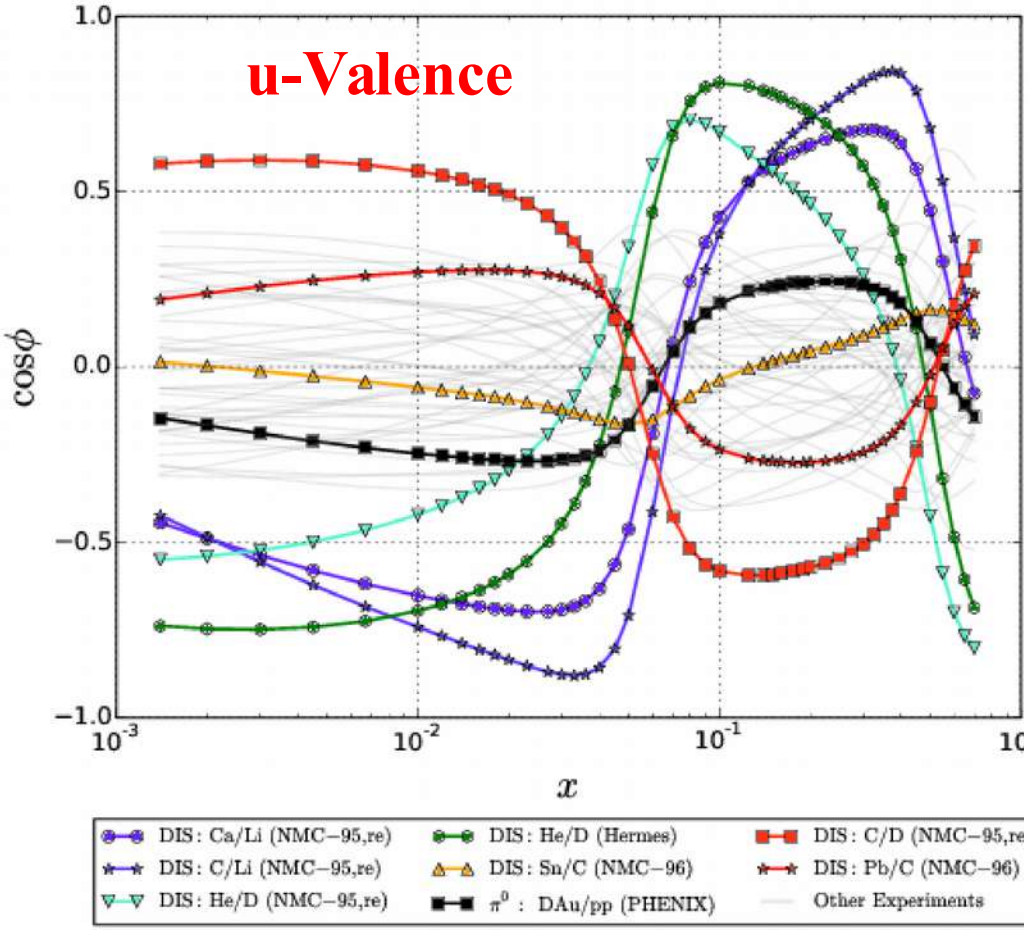
uncertainties

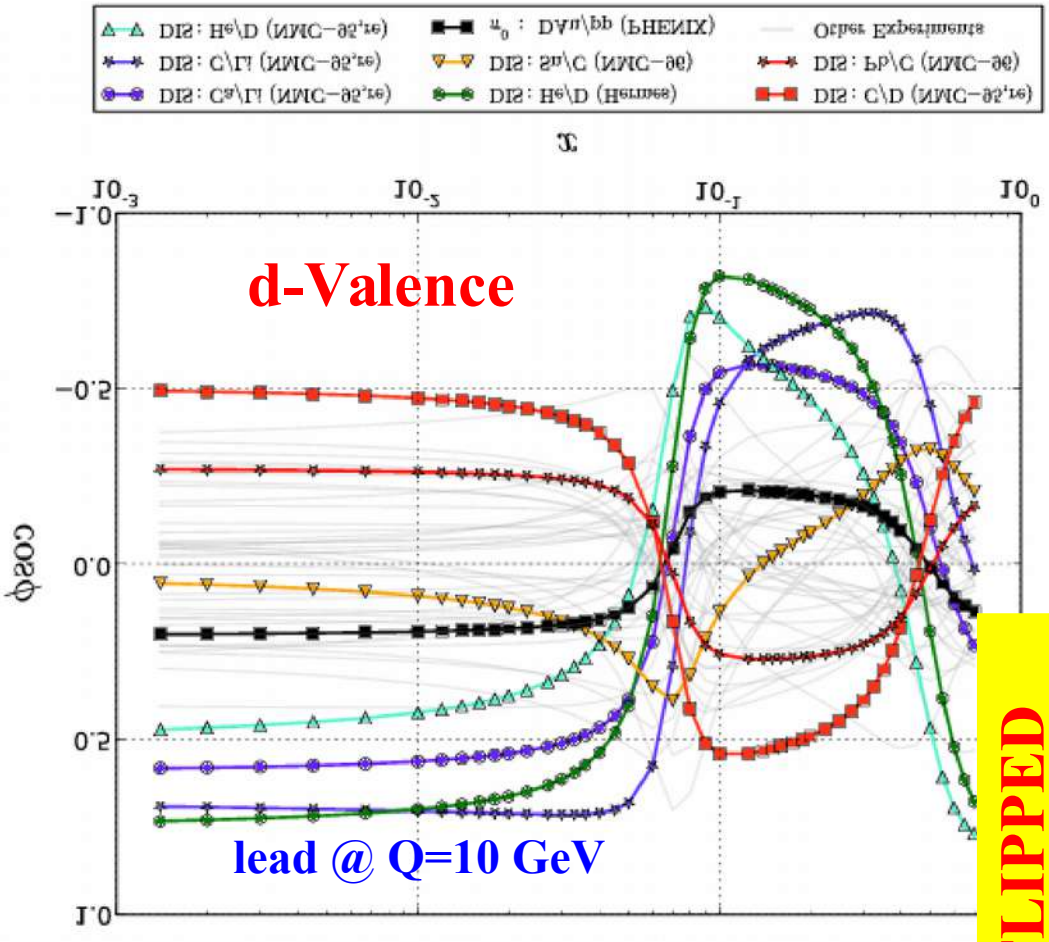
Ratio to Proton for Lead … *with Uncertainty*



What data are influencing up & down



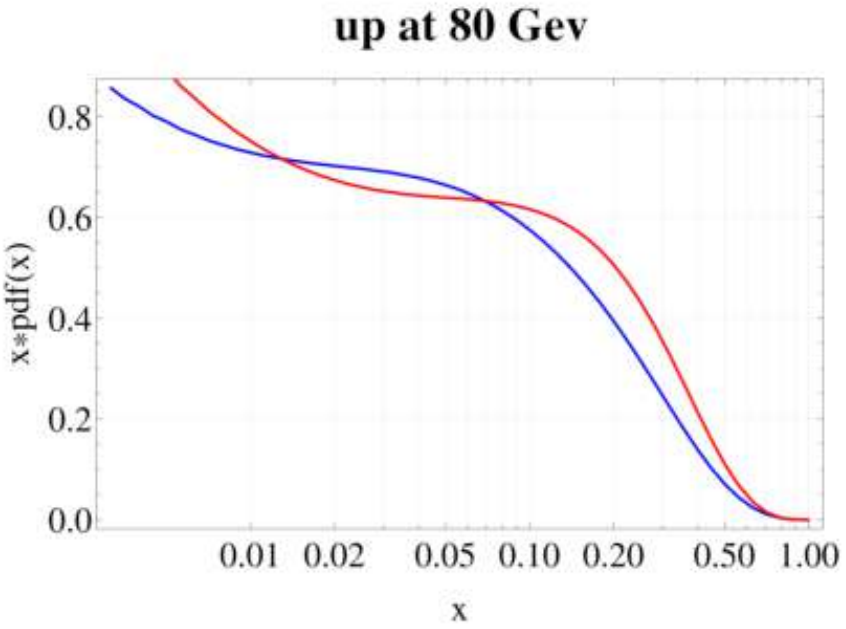


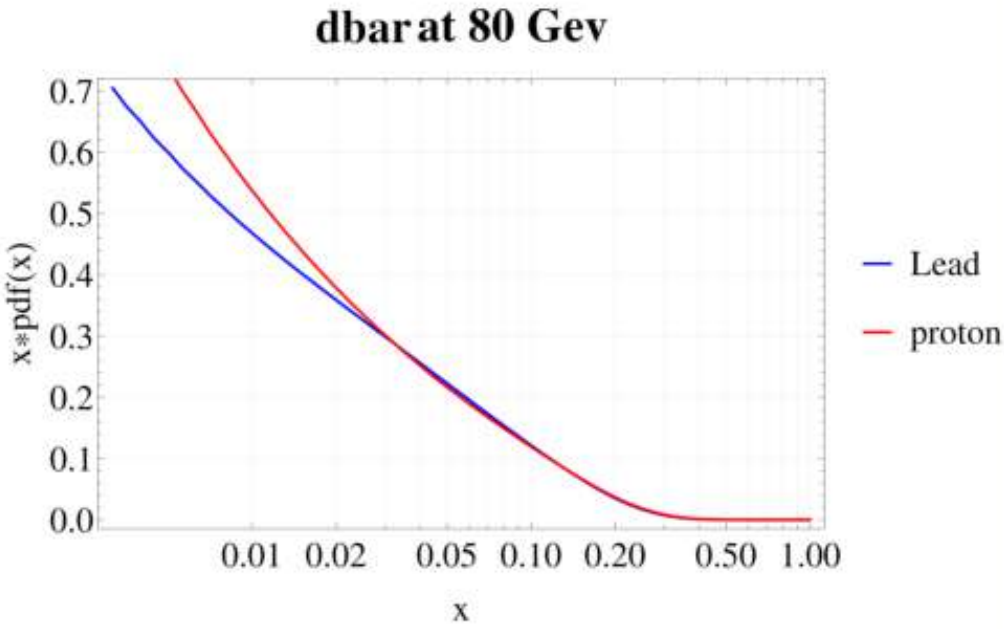


FLIPPED

Nuclear Modifications

Slide 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.

... what about the

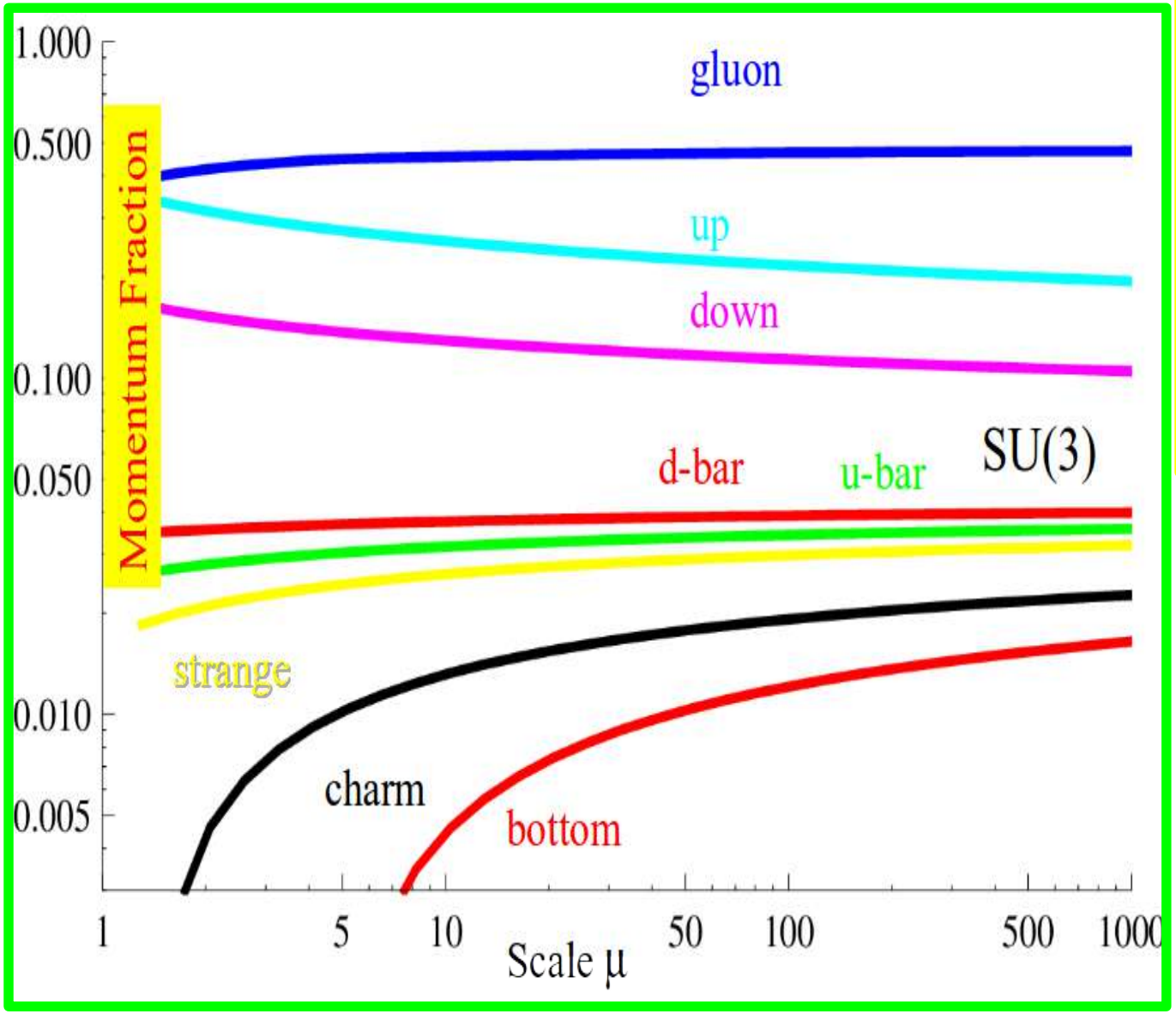
Heavy Quarks

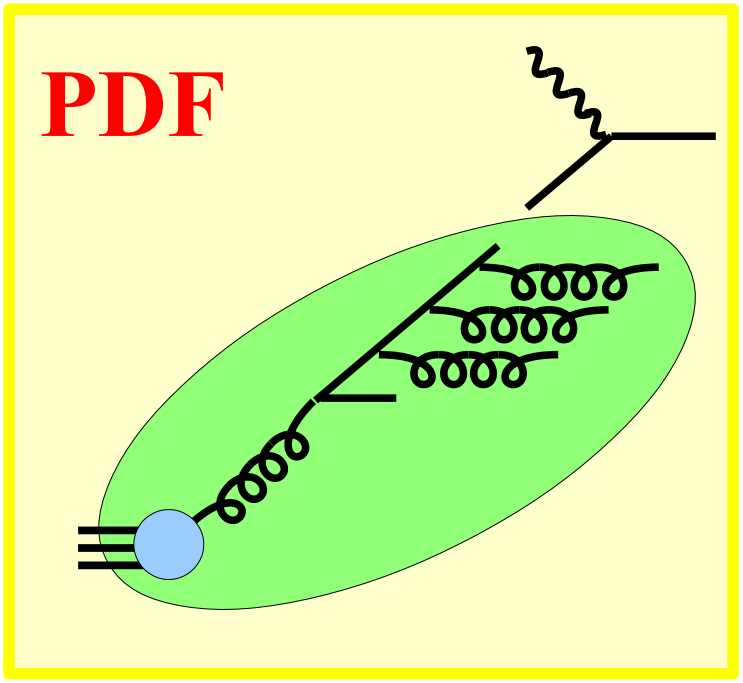
c & b: Extrinsic & Intrinsic

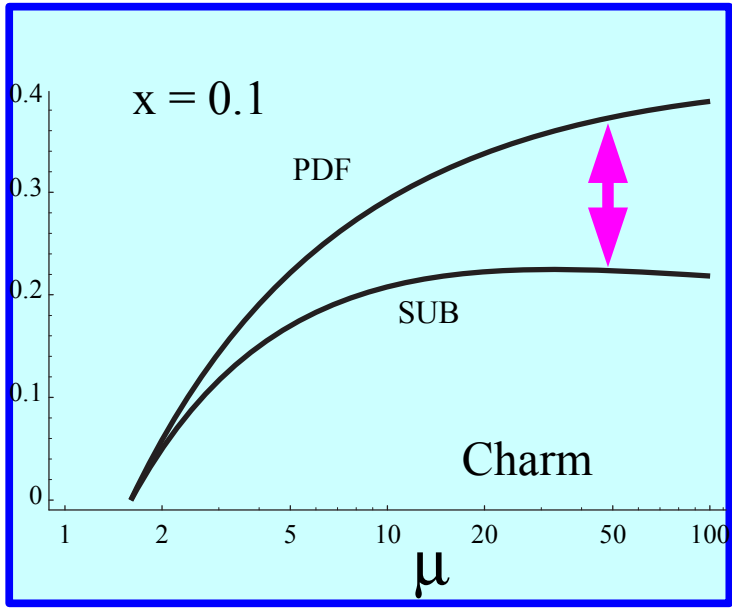
Historically, these have been a challenge because $Q \sim m_{c,b}$

When should we use Charm & Bottom PDFs???

Resum $\alpha_s \ln(m/Q)$

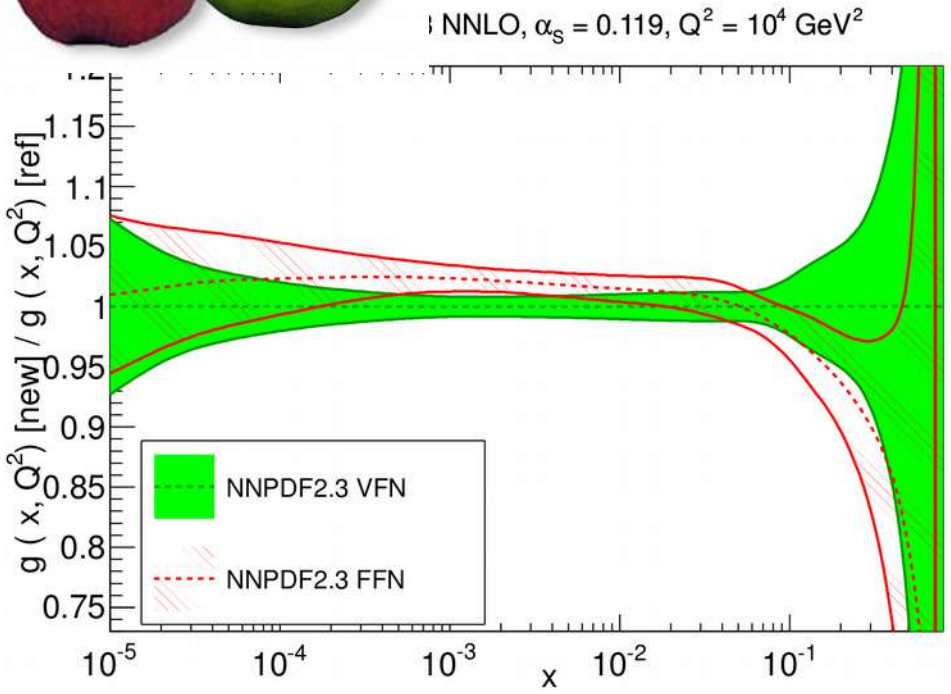


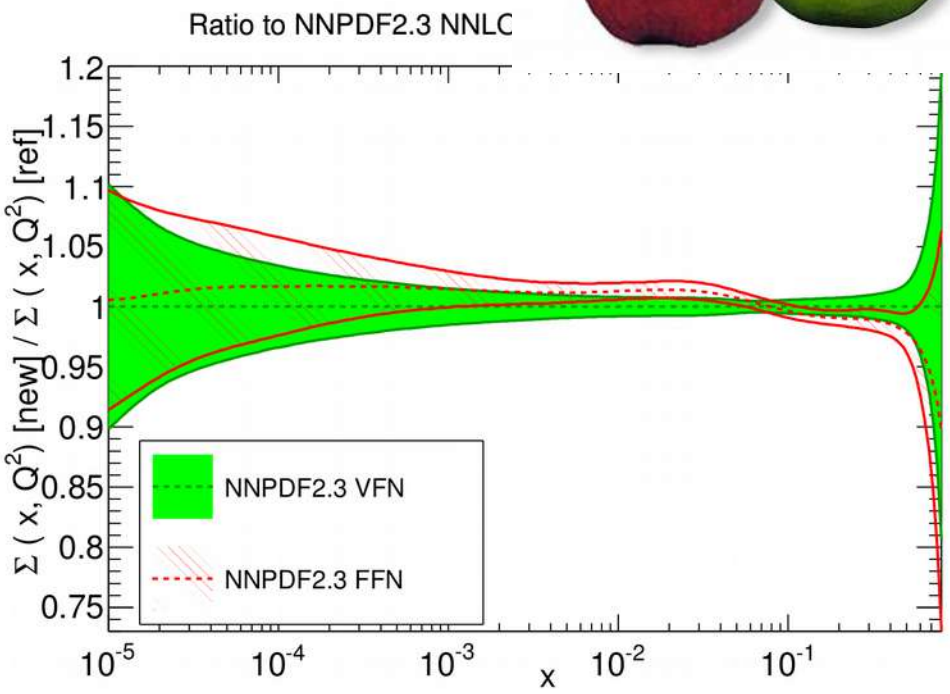




Compare VFN & FFN Schemes

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



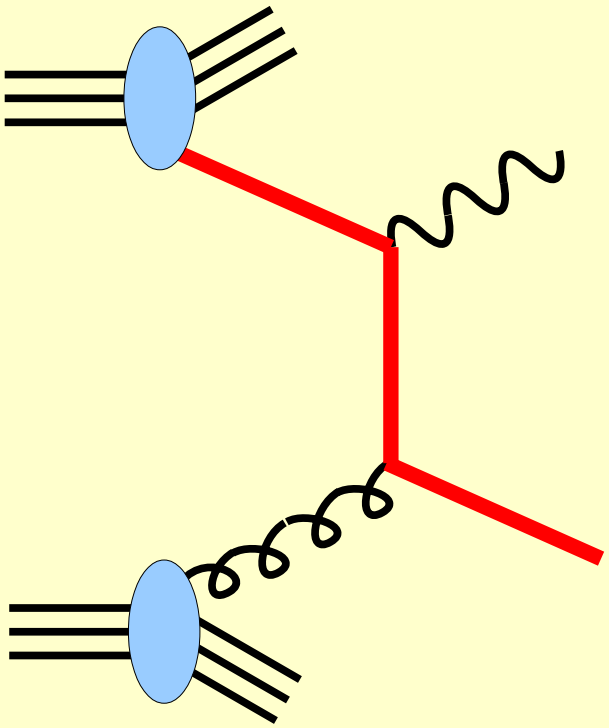


$$\Delta\chi^2 \equiv \chi^2_{FFN} - \chi^2_{VFN} > 0$$

$x_{\min}$	$x_{\max}$	$Q^2_{\min}$ (GeV)	$Q^2_{\max}$ (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

Tevatron & LHC can Access Heavy Flavor Components Directly



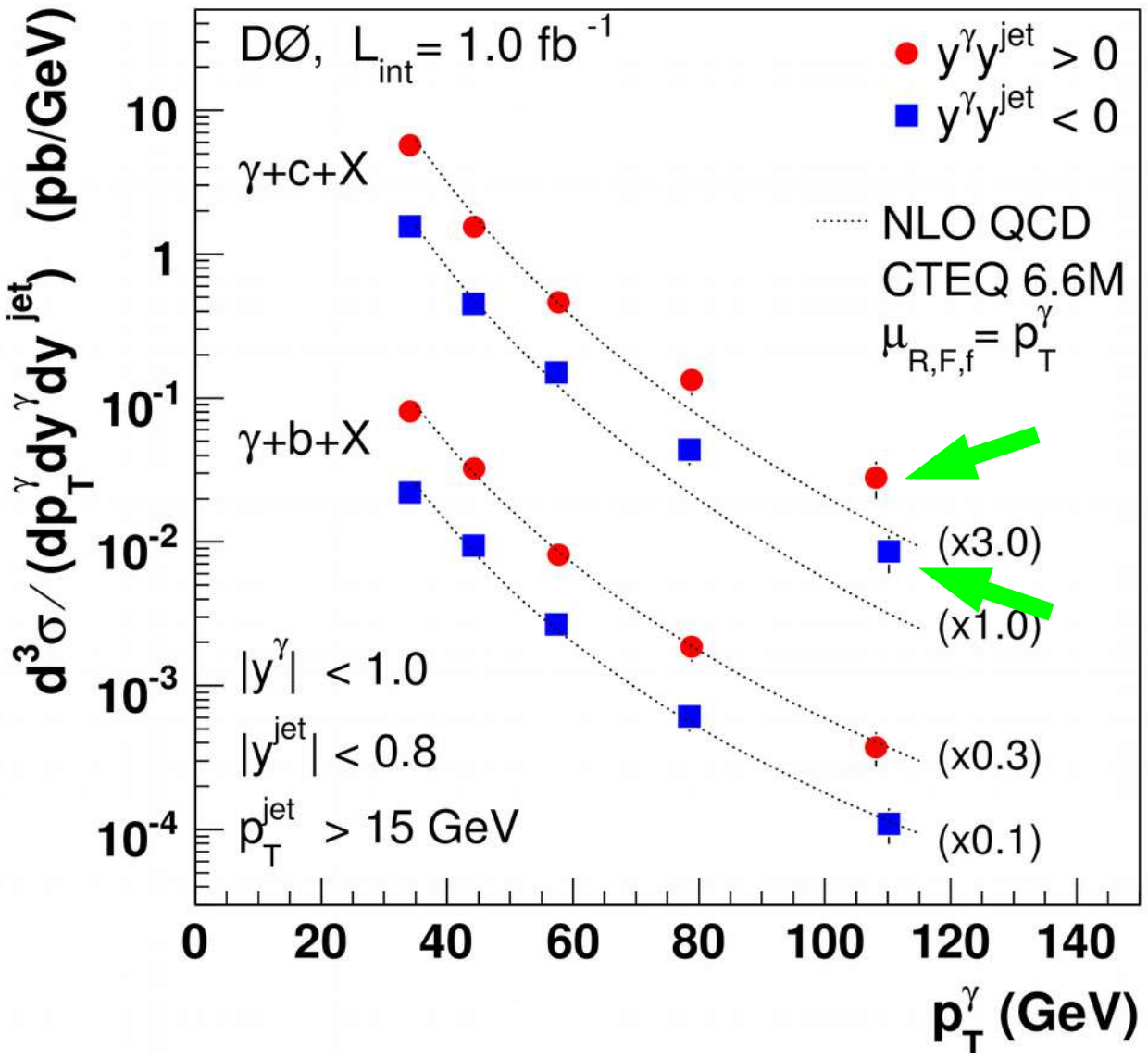
$$c\ g \rightarrow c\ \gamma$$

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

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

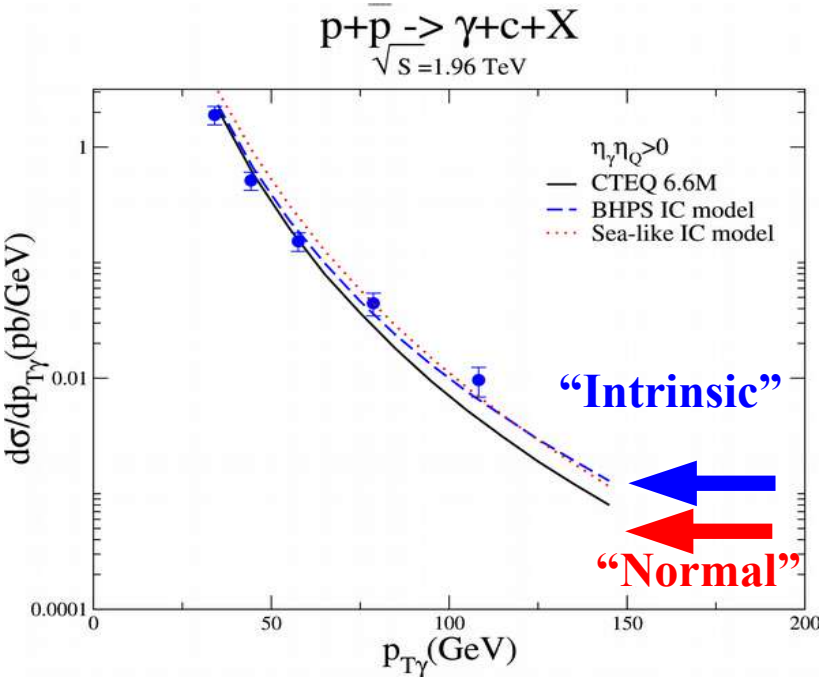
$$c\ g \rightarrow b\ W$$

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

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

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

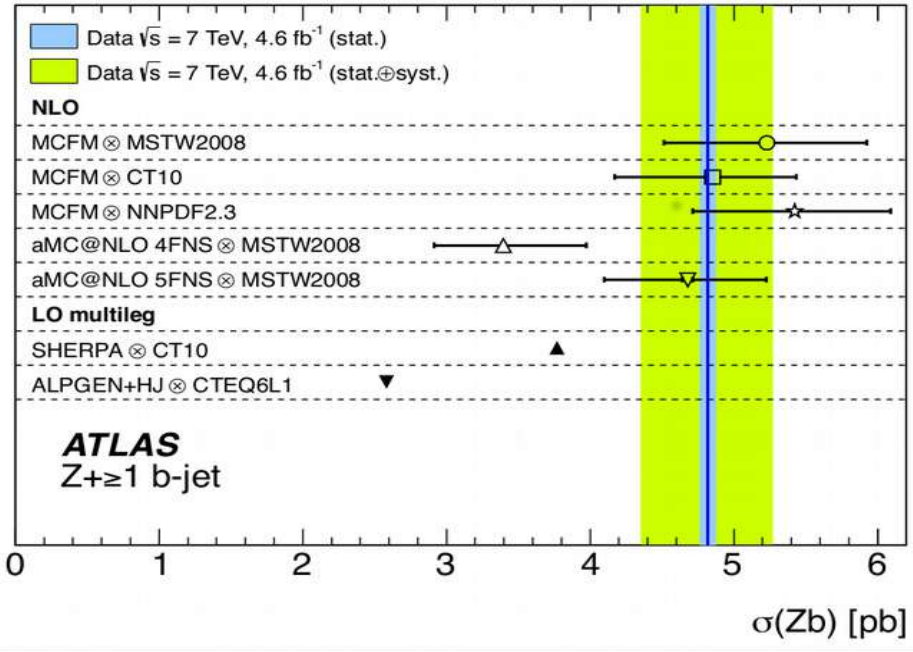
… see talk by Eric Godat this afternoon

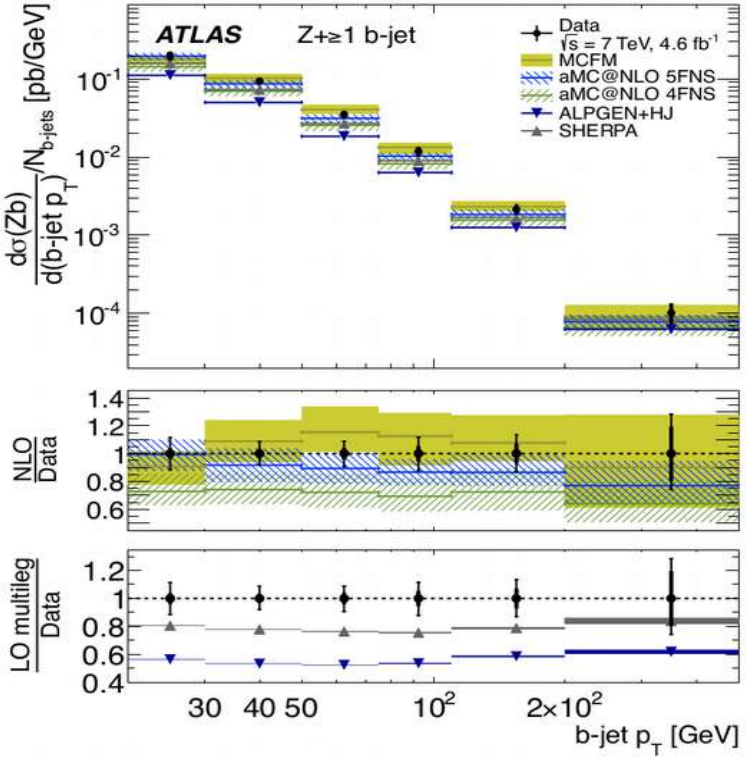
arXiv:1504.05156: On the intrinsic bottom content of the nucleon and its impact on heavy new physics at the LHC
F. Lyonnet, A. Kusina, T. Ježo, K. Kovařík, F. Olness, I. Schienbein, J.Y. Yu

Heavy 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

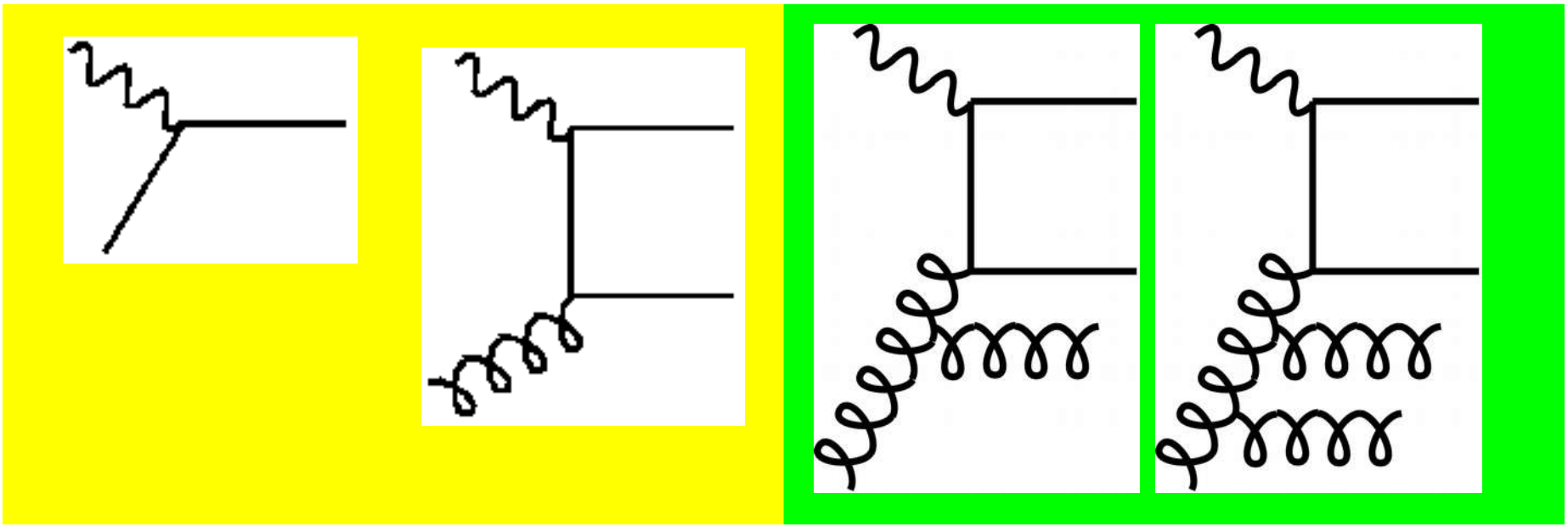
An example...

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

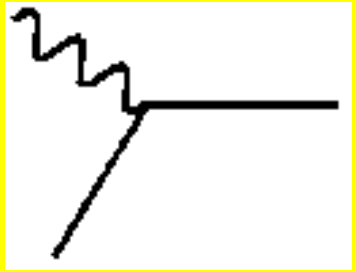
DGLAP kernels & PDF evolution are pure MS-Bar
Subtractions are MS-Bar

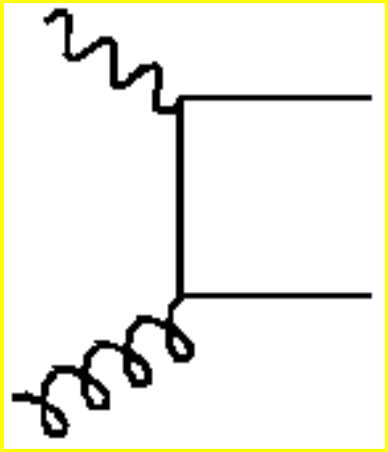
ACOT: $m \to 0$ limit yields MS-Bar
with no finite renormalization

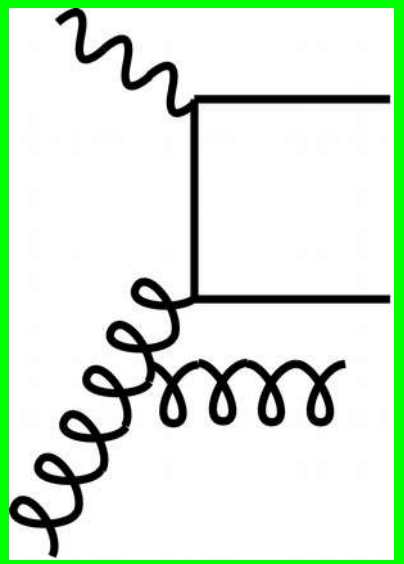
PDFs Discontinuous at N2LO

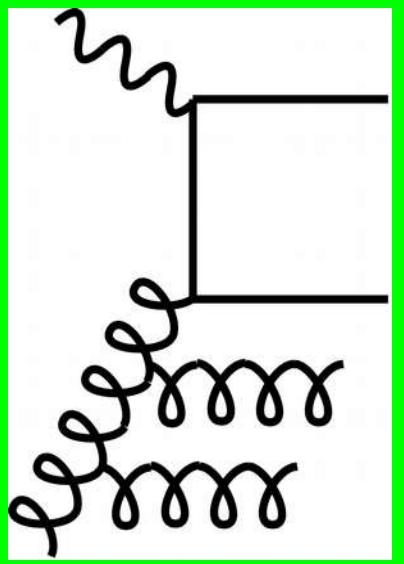
α_s Discontinuous at α_s^3

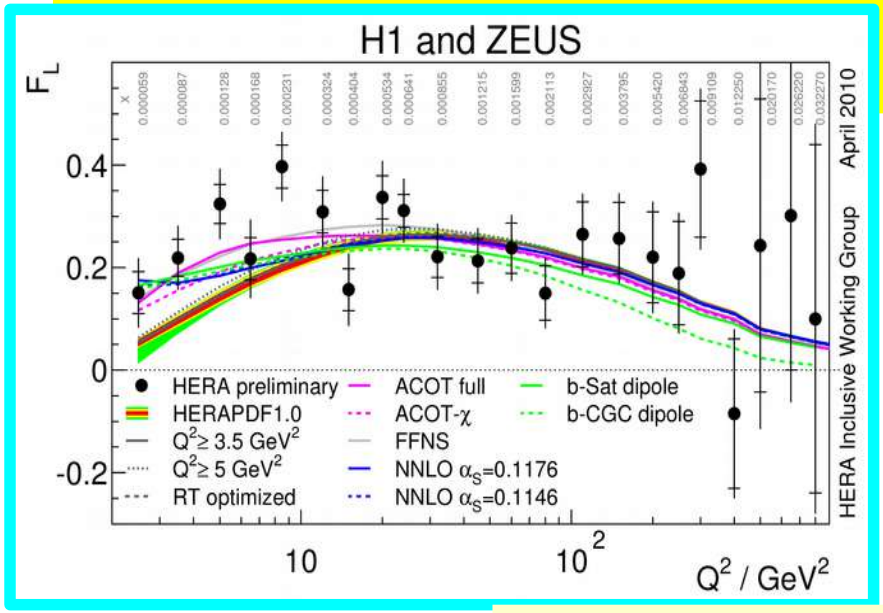
LO **NLO** **N2LO** **N3LO**









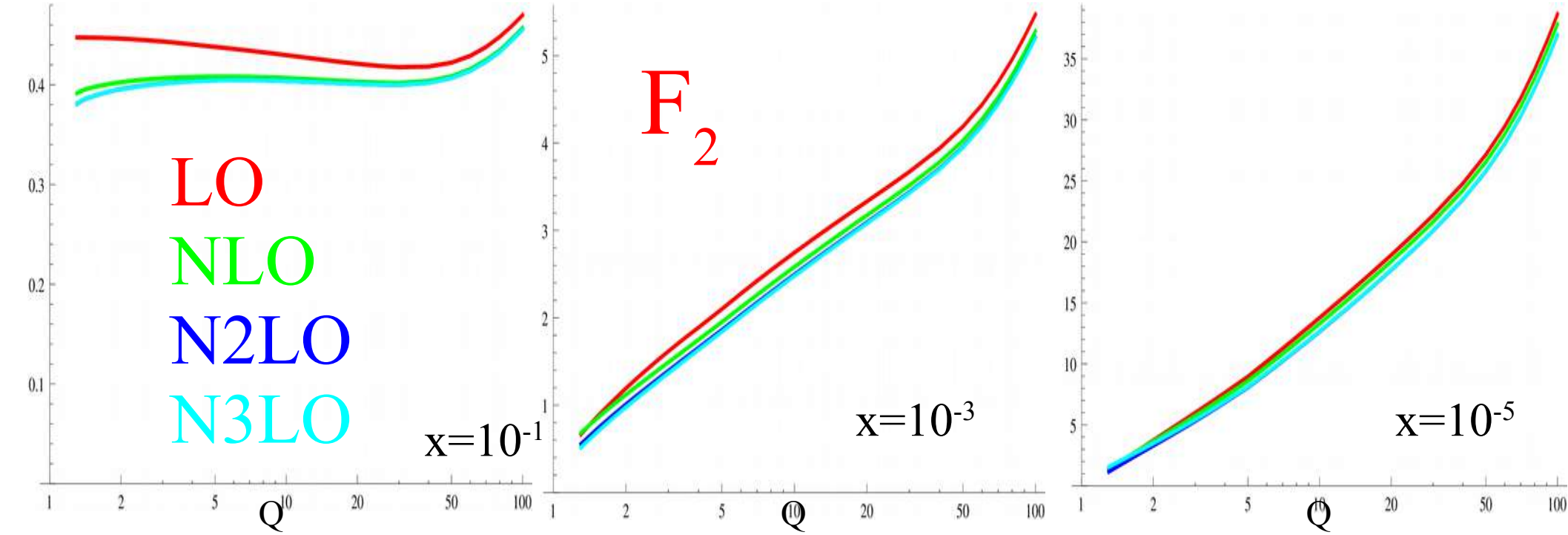


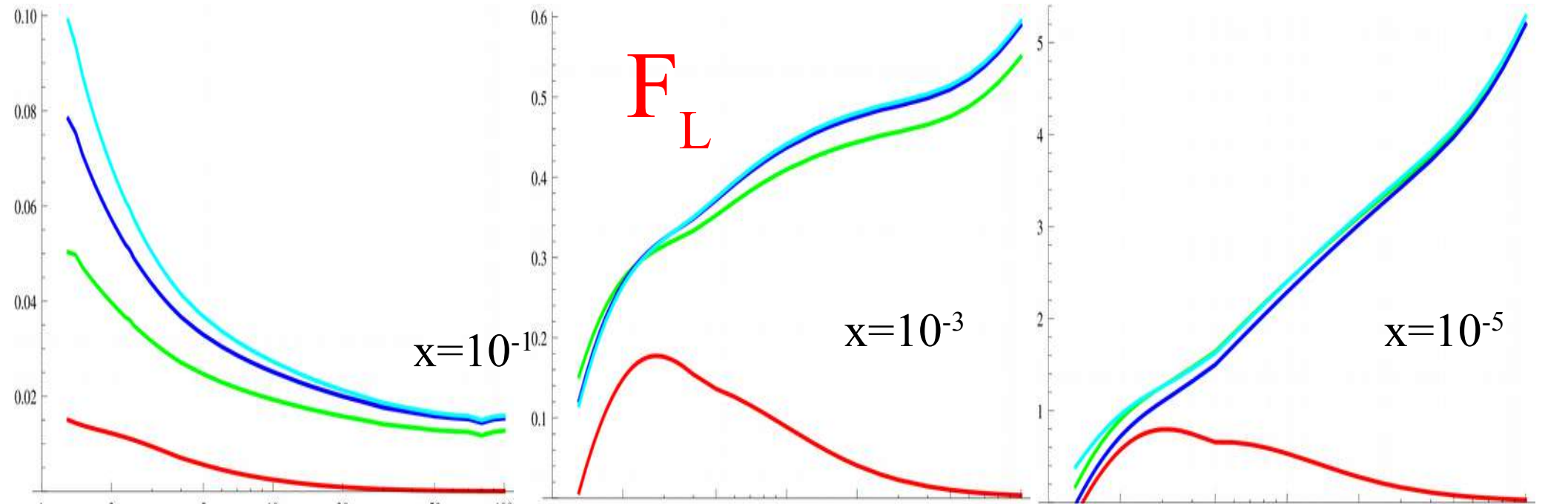
Masses are important

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

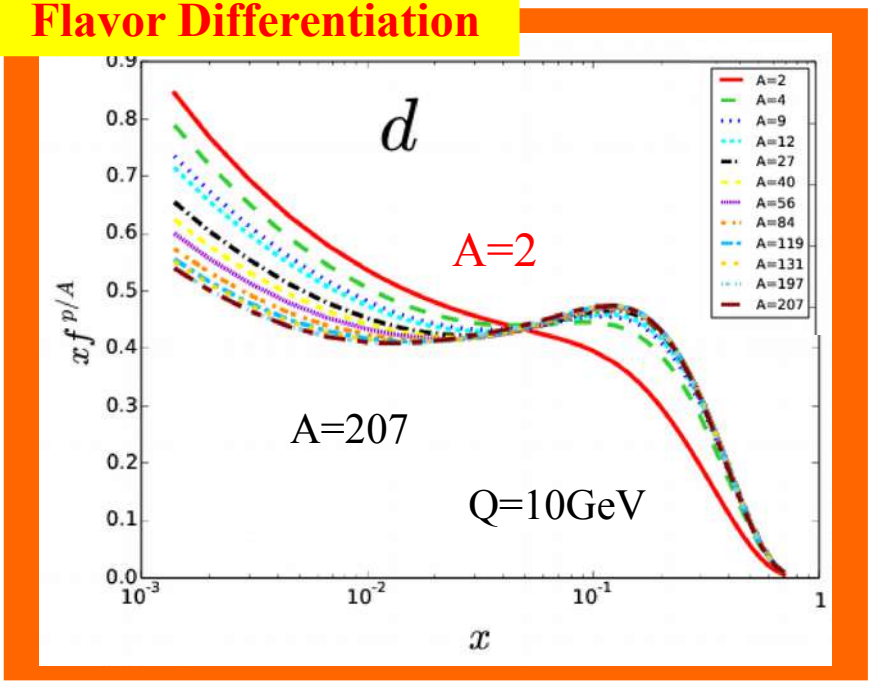




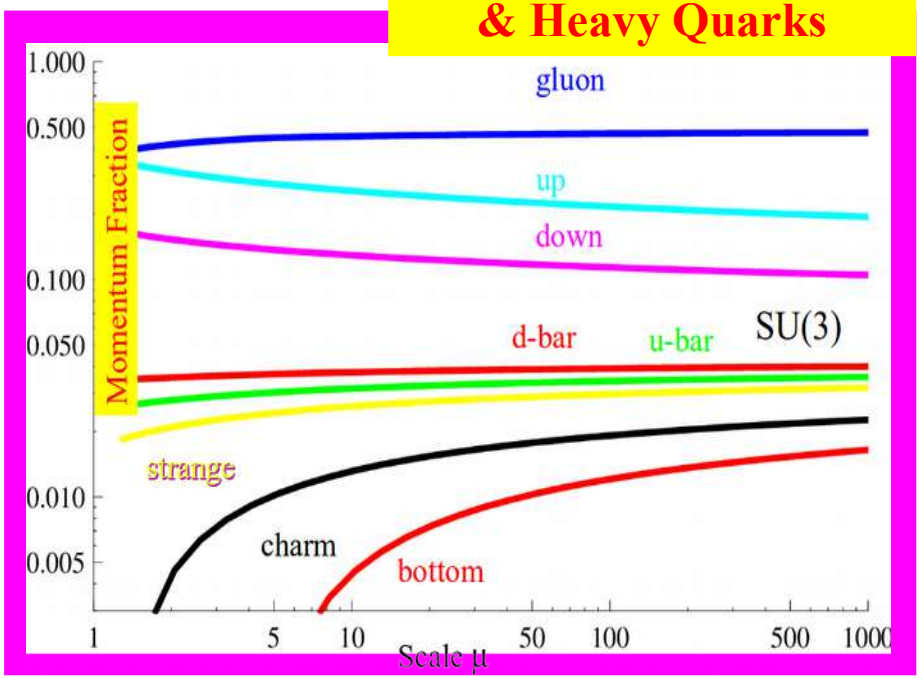
Conclusion

PDF Tools for Precision Physics

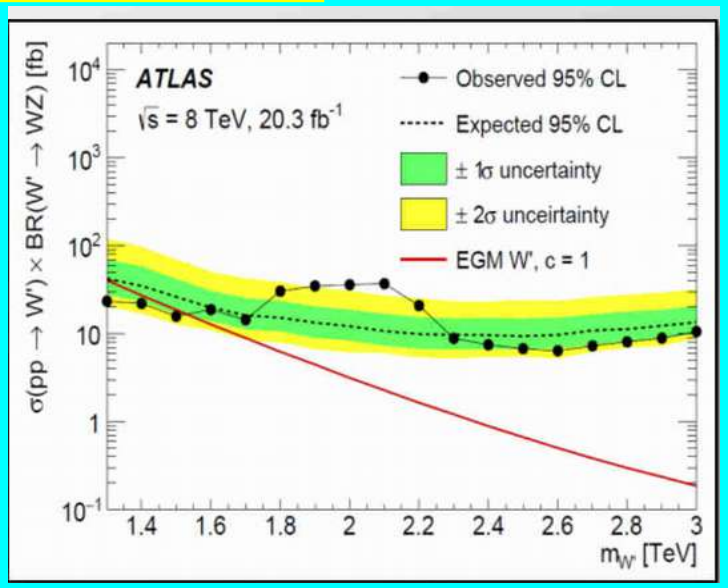
Nuclear Corrections & Flavor Differentiation



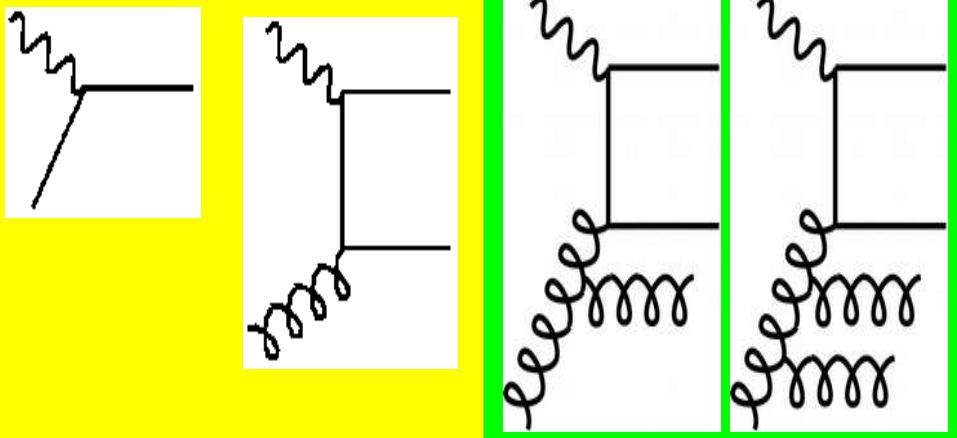
Multi-Scale Processes & Heavy Quarks



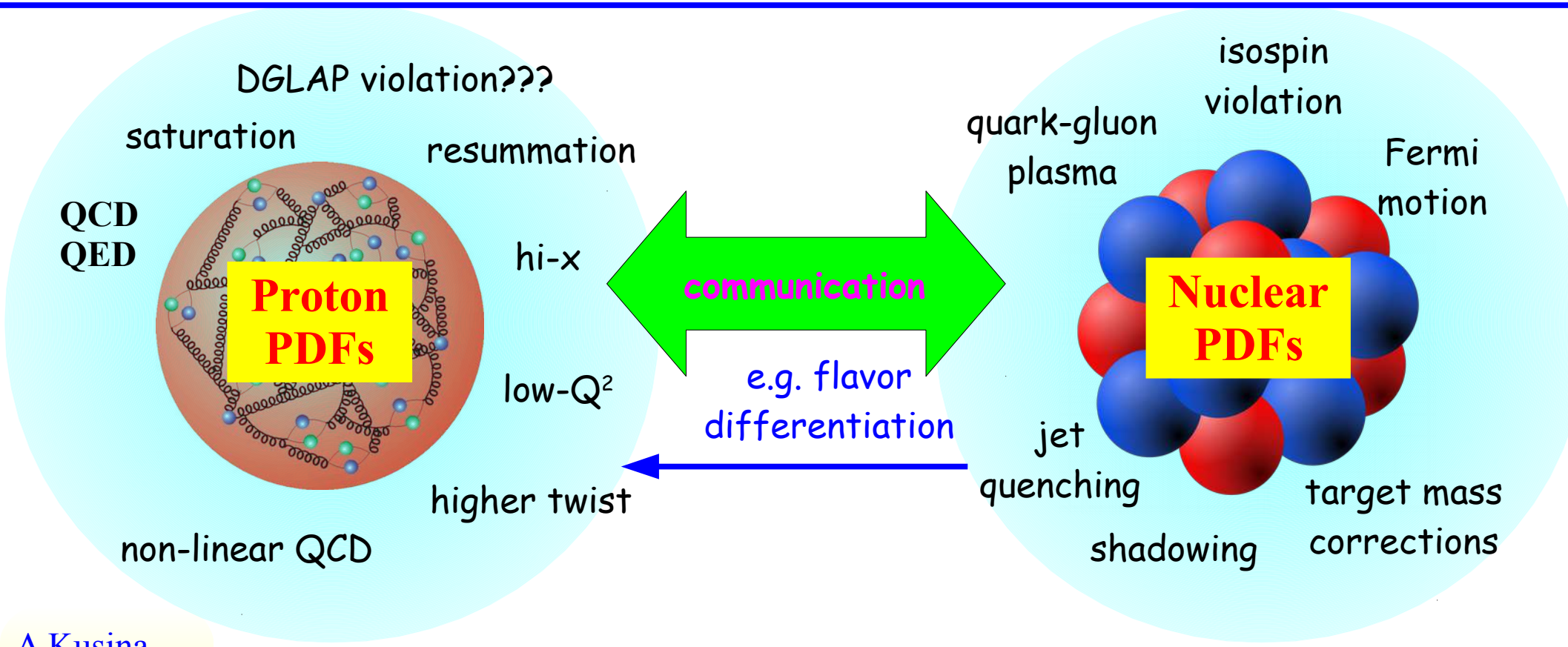
Search for new physics



Higher Order Processes



Moving Into The 21st Century



A Kusina,
K. Kovarik
T. Jezo,
D. Clark,
C. Keppel,
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J. Morfin,
F. Olness
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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

will be available at HEPForge.org