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

INT Program INT-15-3 Week 6
Intersections of BSM Phenomenology & QCD for New Physics Searches
September 14 - October 23, 2015

20 October 2015

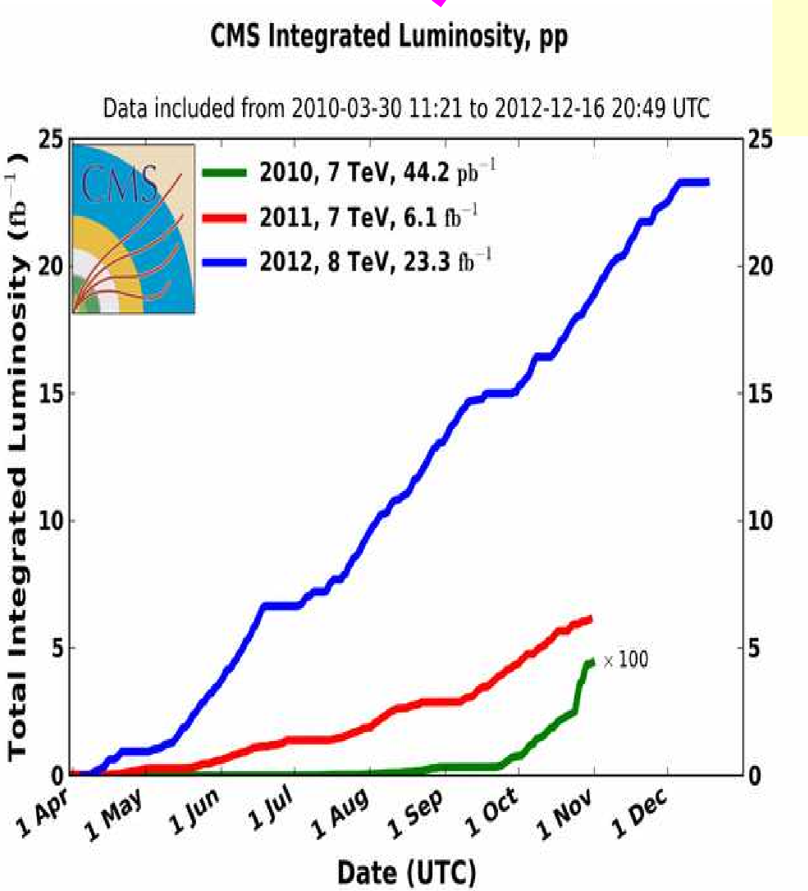
The Key to Discovery: The Parton Model and Factorization

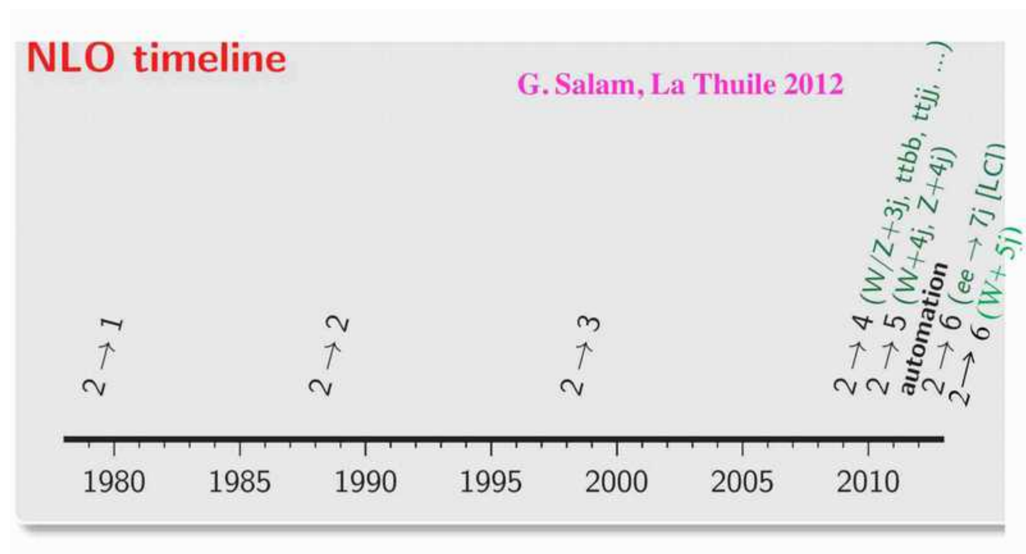
$$\sigma_{P\gamma \to c} = f_{P \to a} \otimes \hat{\sigma}_{a\gamma \to c}$$

Experimental Observables

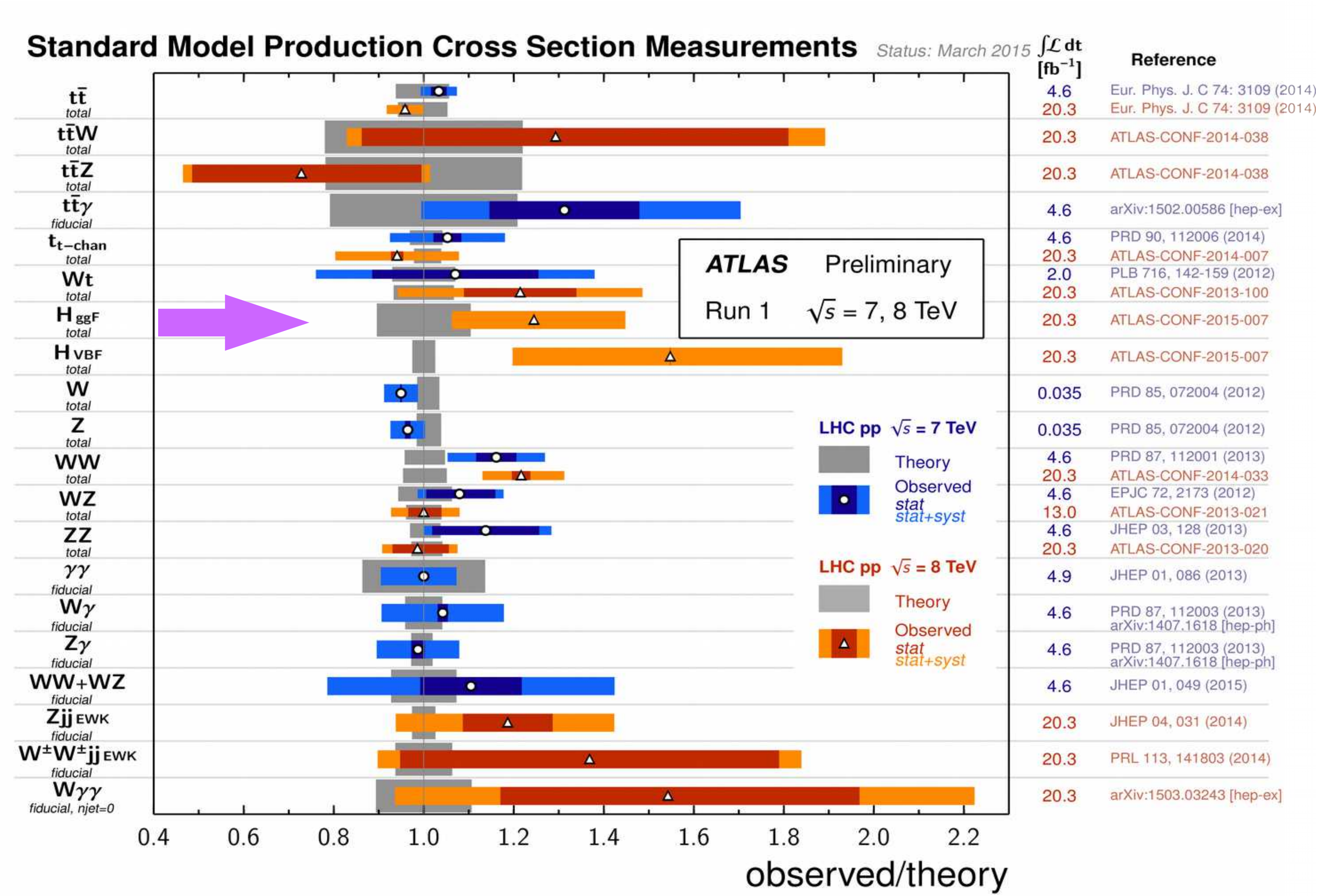
WHAT ABOUT PDF'S ???

Theoretical Calculations



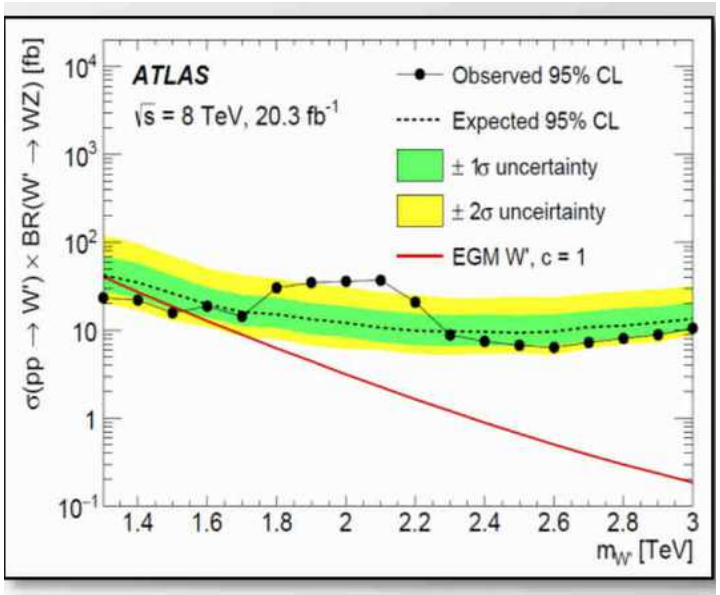


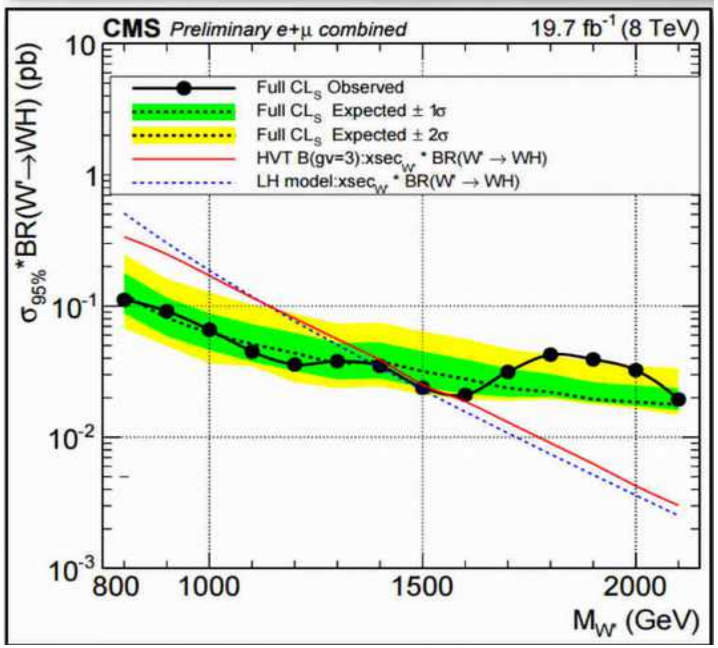
LHC Results: *Incredible Progress*

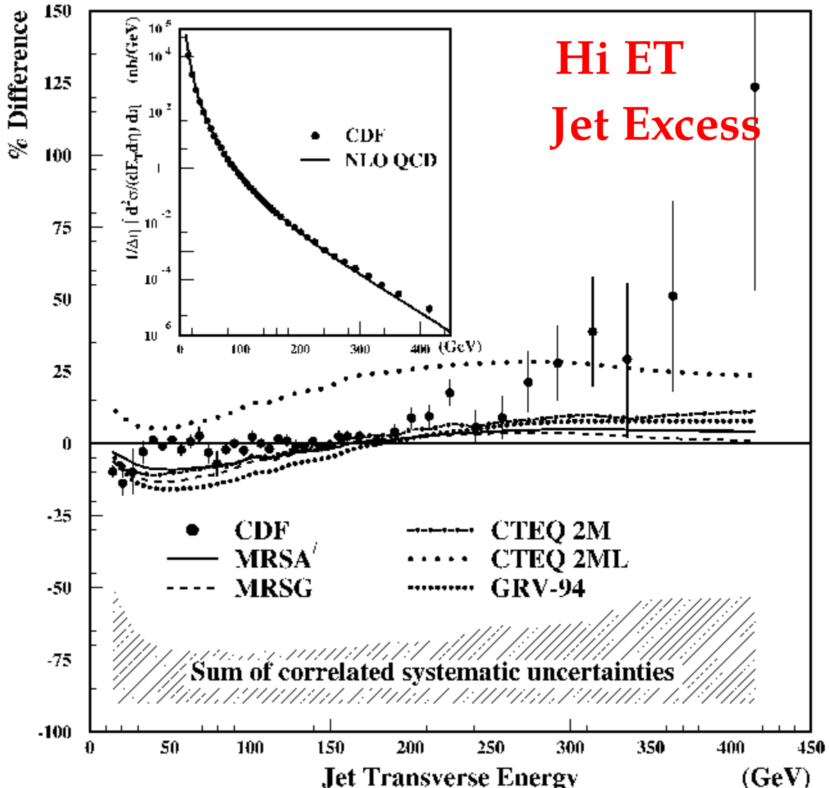


Much of theory error from PDFs N^{3}LO gg->H **PDF error 2x of Theory Error**

… things that go bump in the data …

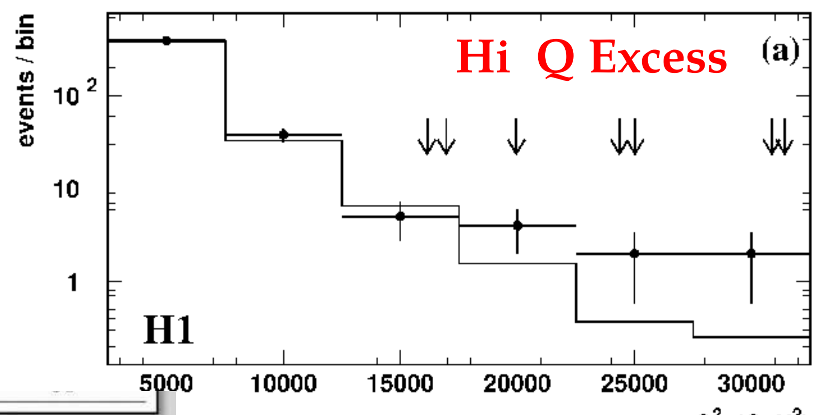




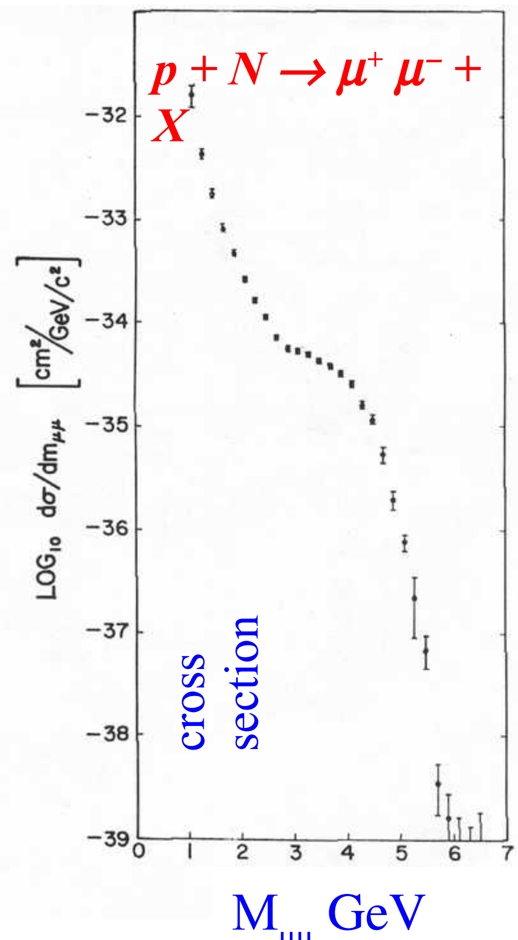


CDF Collaboration, PRL 77, 438 (1996)

Can you find the Nobel Prize???



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

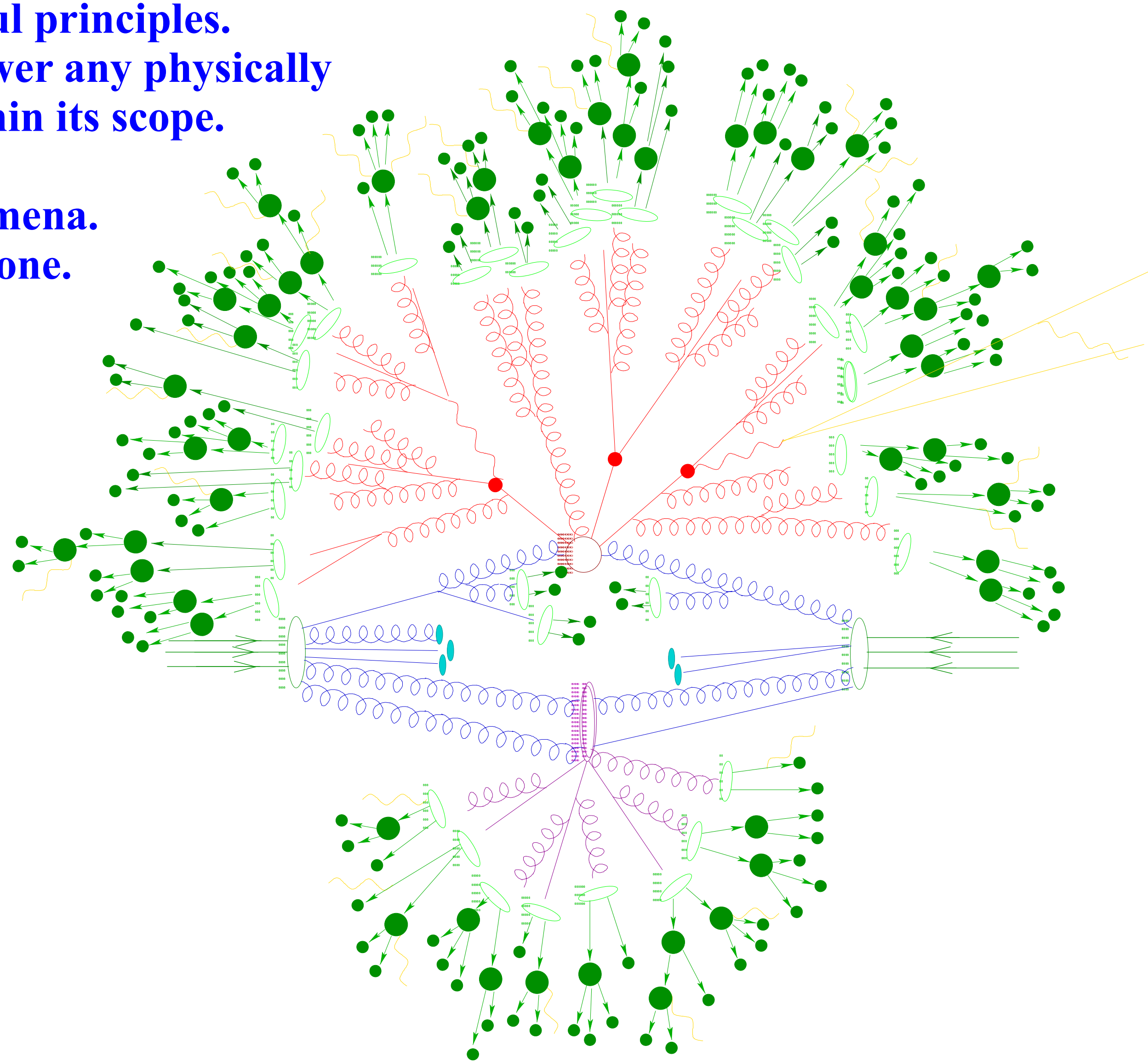


What QCD Tells Us About Nature – and Why We Should Listen

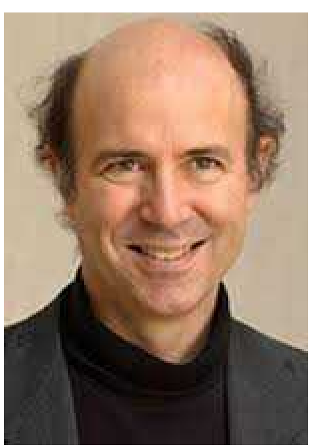
Frank Wilczek *(arXiv:hep-ph/9907340)*

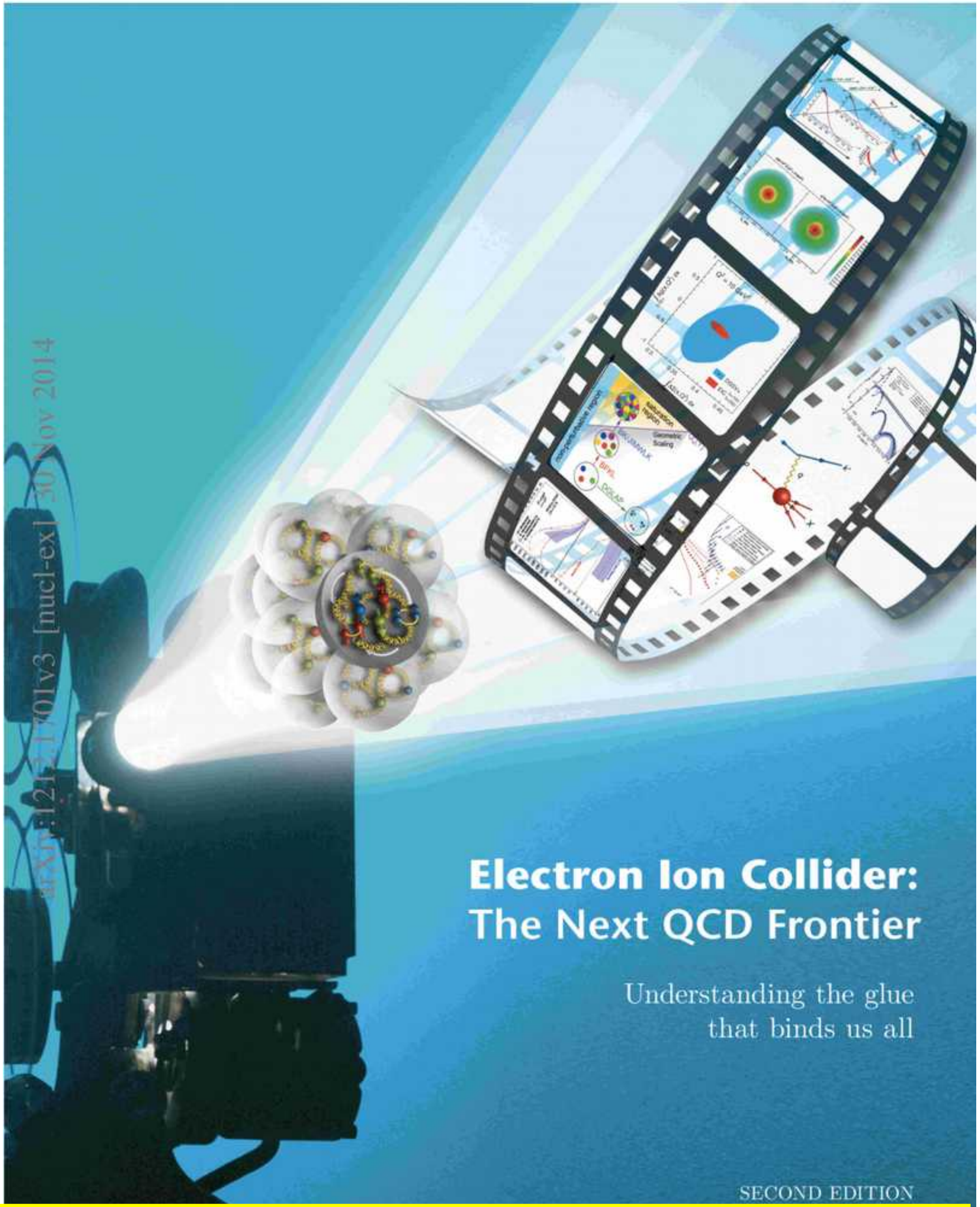
QCD is our most perfect physical theory

- It embodies deep and beautiful principles.
- It provides algorithms to answer any physically meaningful question within its scope.
- Its scope is wide.
- It contains a wealth of phenomena.
- It has few parameters … or none.
- It is true.
- It lacks flaws.



Lessons: The Nature of Nature
… alien, simple, beautiful, weird,
& comprehensible





2015 Long Range Plan for Nuclear Science *15 Oct 2015*

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Expect the Unexpected

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`

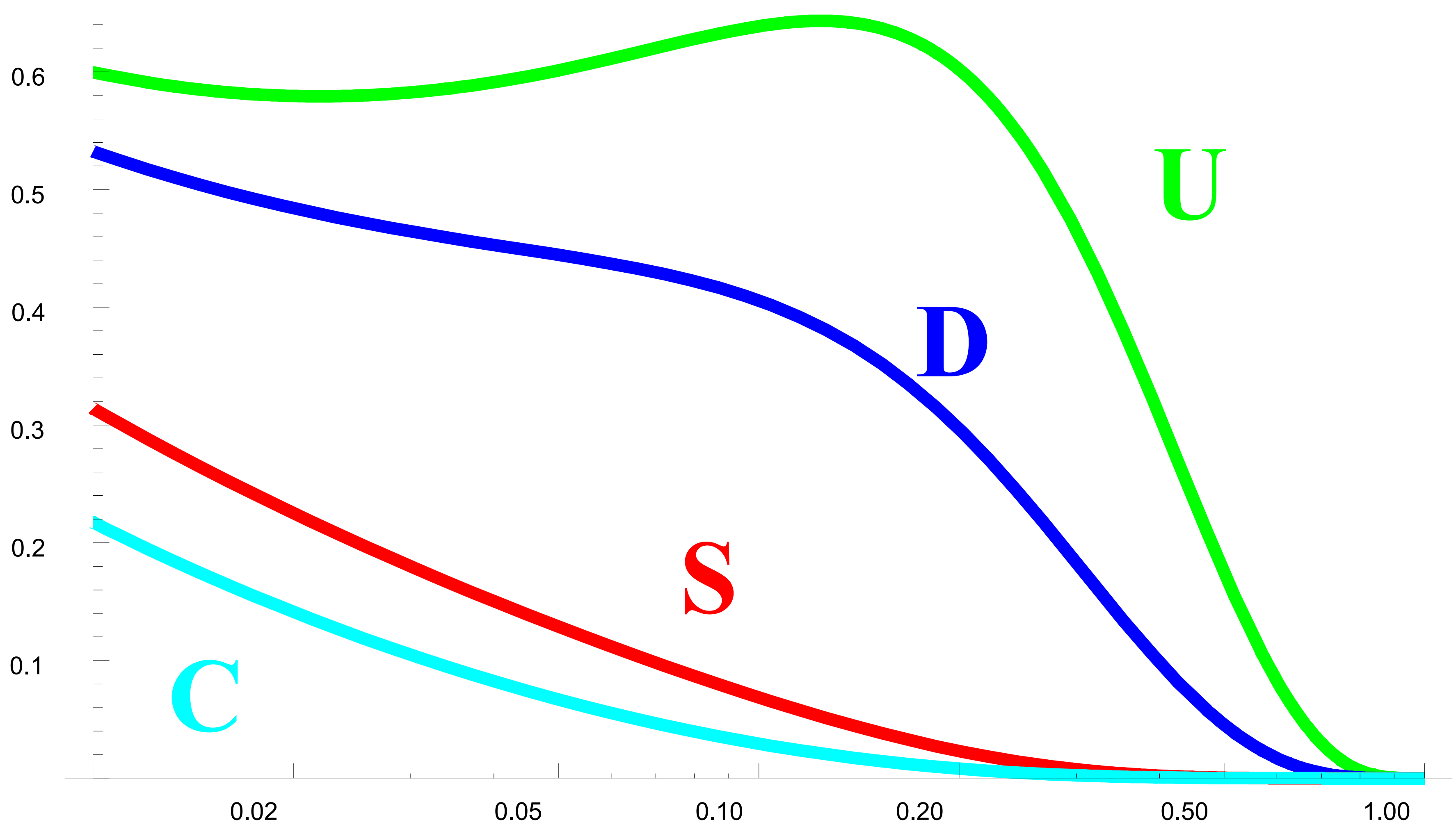
1) Flavor Differentiation
& Nuclear Corrections

2) Multi-scale problems:
Heavy Quarks

3) Hi-Order Corrections
& ACOT

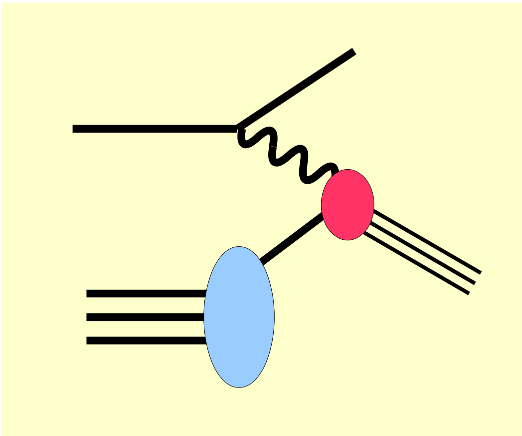
SEC reminds us that past performance does not guarantee future results

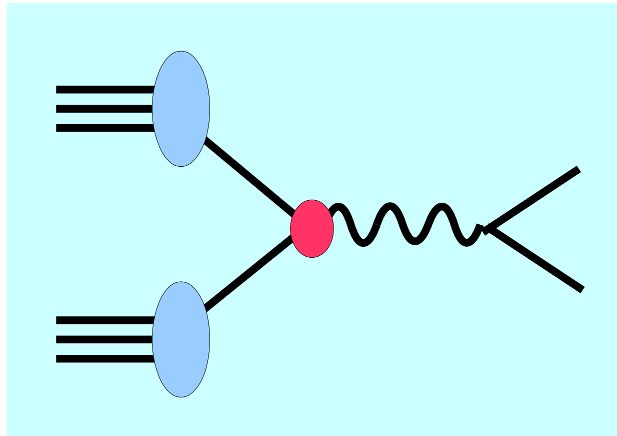
How do we differentiate flavors???

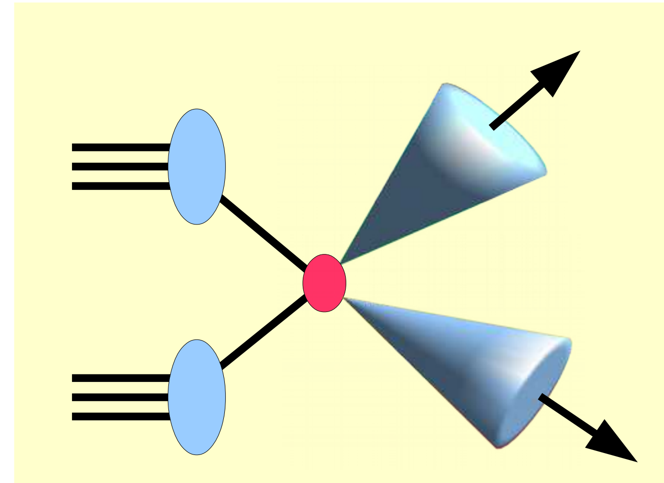


... why do we care about nuclear corrections

Key Data Sets for Global PDF Fits







$$F_2^{\nu} \sim [d + s + \bar{u} + \bar{c}]$$
$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$
$$F_3^{\nu} = 2\,[d + s - \bar{u} - \bar{c}]$$
$$F_3^{\bar{\nu}} = 2\,[u + c - \bar{d} - \bar{s}]$$

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

In particular, the DIS combinations have historically been particularly useful

Different linear combinations – key for flavor differentiation

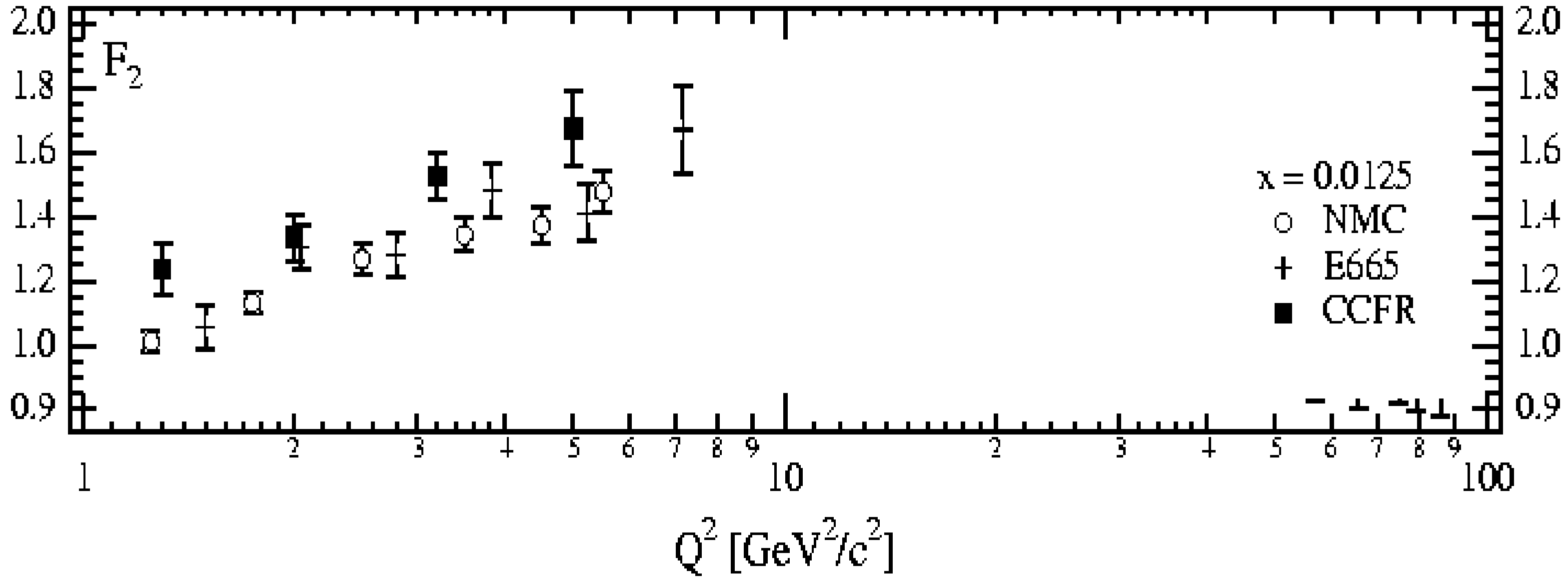
*The ν-DIS data typically use heavy targets, and this requires the application of **nuclear corrections***

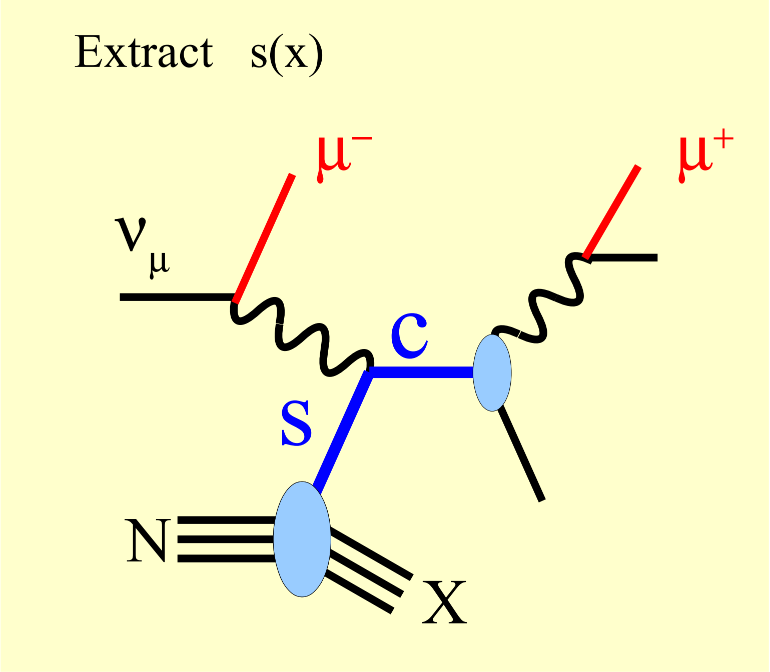
Di-muon production ⇒ Extract s(x) Parton Distribution

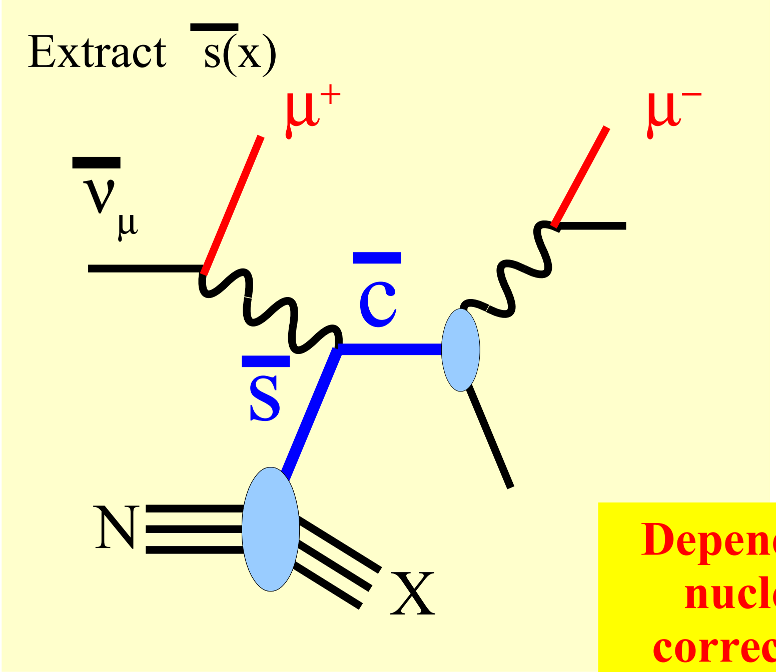
The CTEQ List of Challenges in Perturbative QCD

~1995

C T E Q





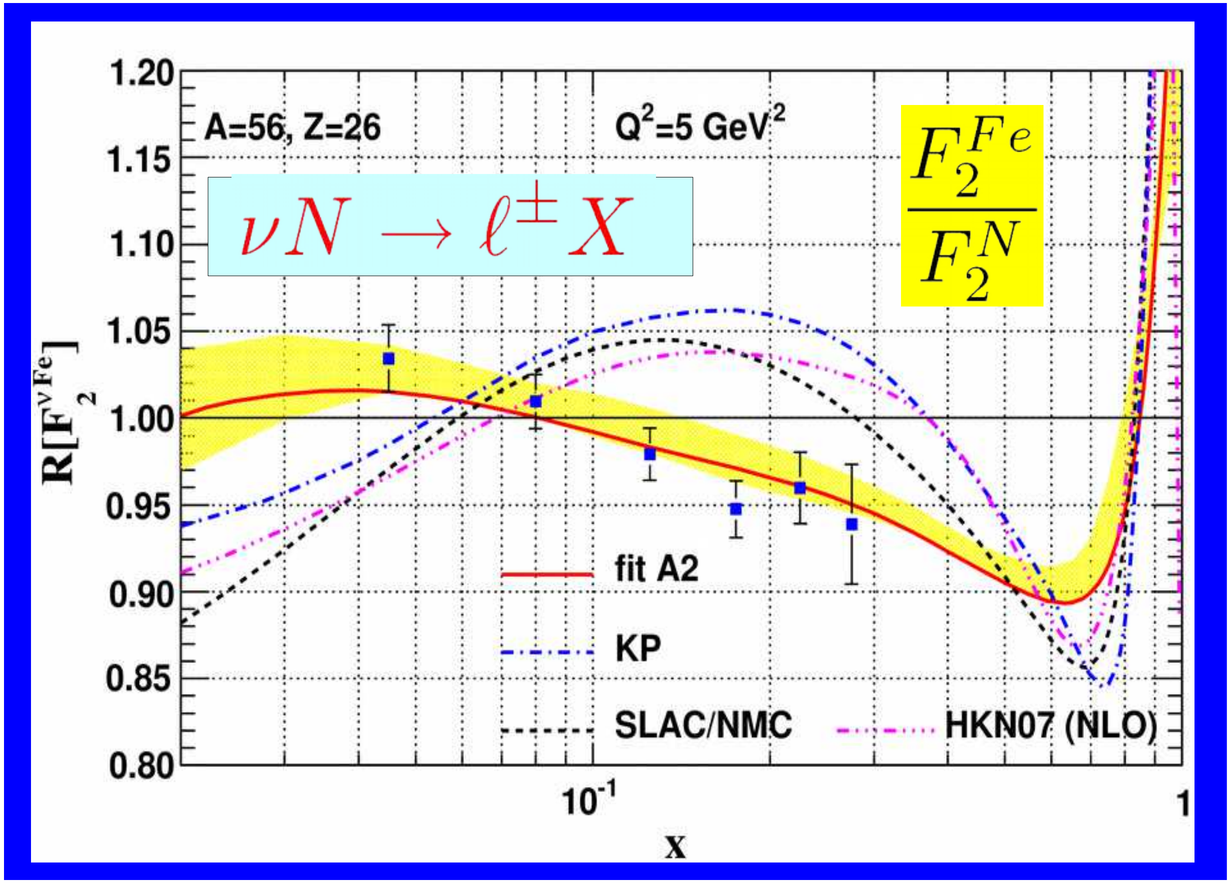


Depends on nuclear corrections

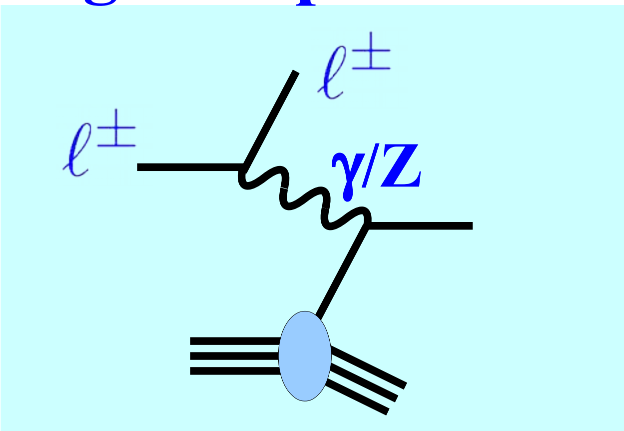
Can extract s(x) and $\bar{s}$(x) separately

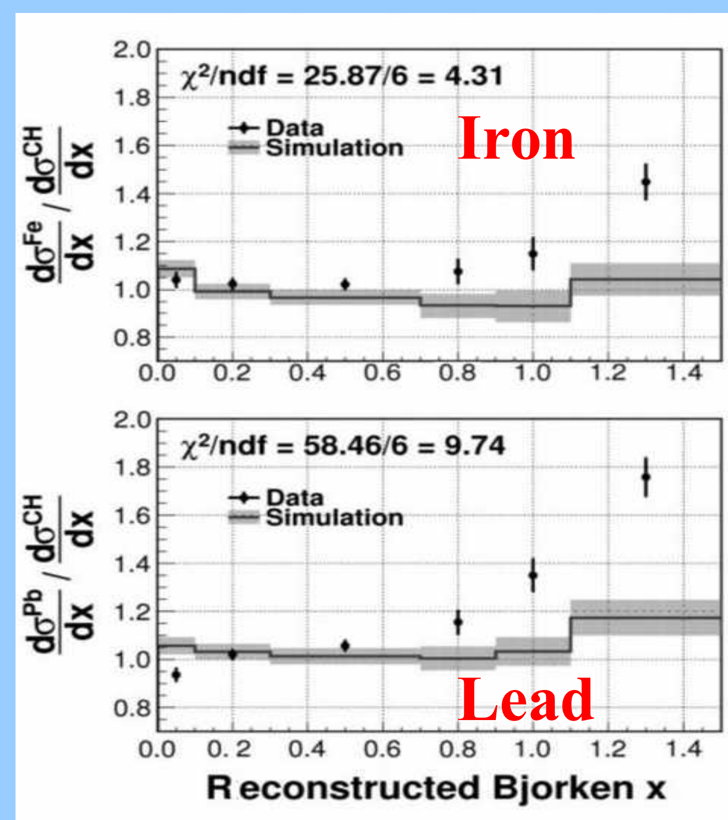
Used in CTEQ Fits

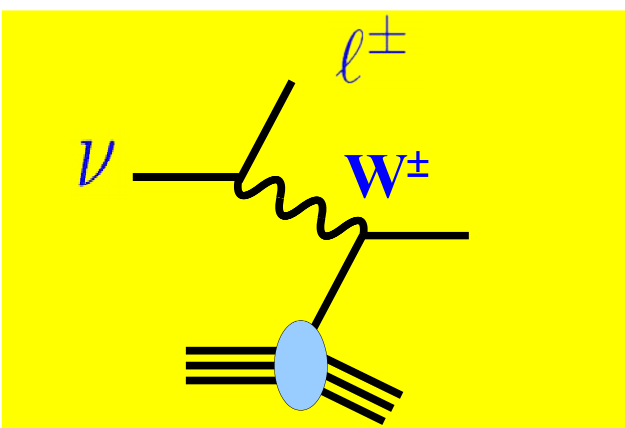
Nuclear Corrections: Compare Neutrino and Charged Lepton DIS



Charged Lepton DIS



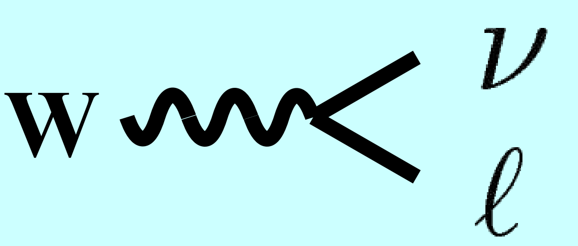


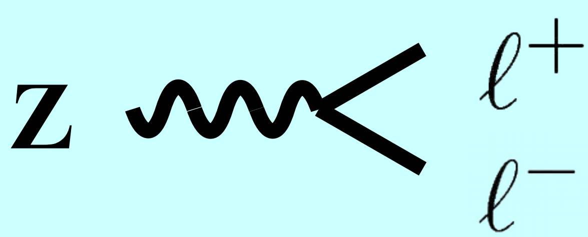


Neutrino DIS

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

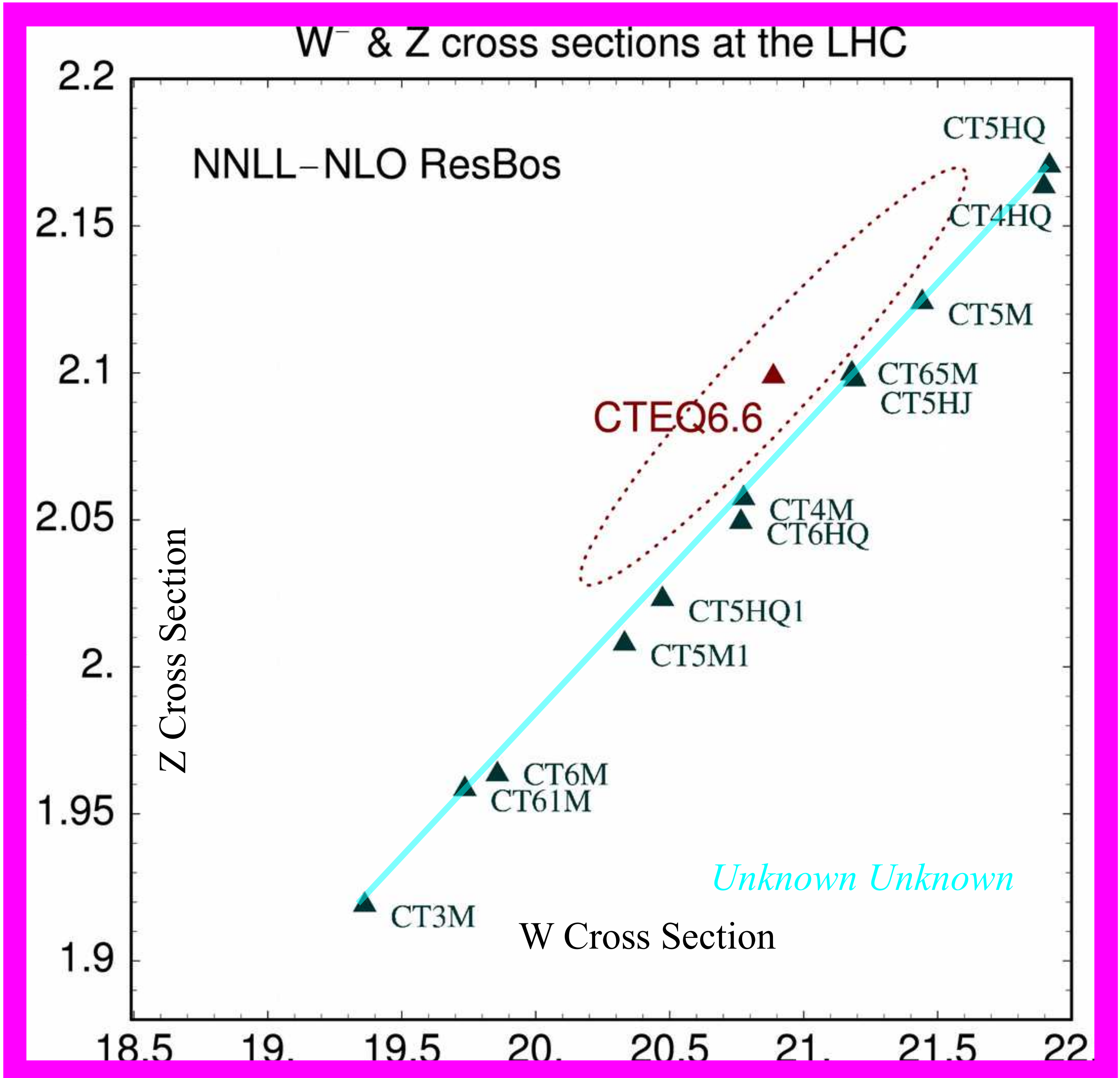
Strange Quark: Impact on LHC … W/Z correlation ⇒ MW extraction





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

Key for M_W determination



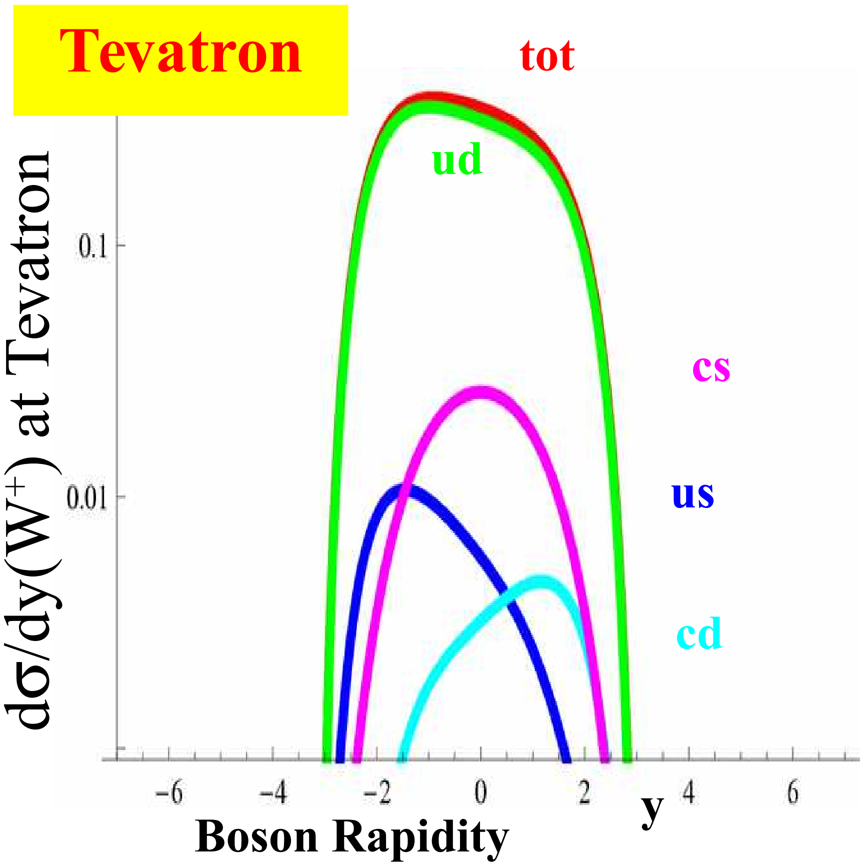
W/Z Production

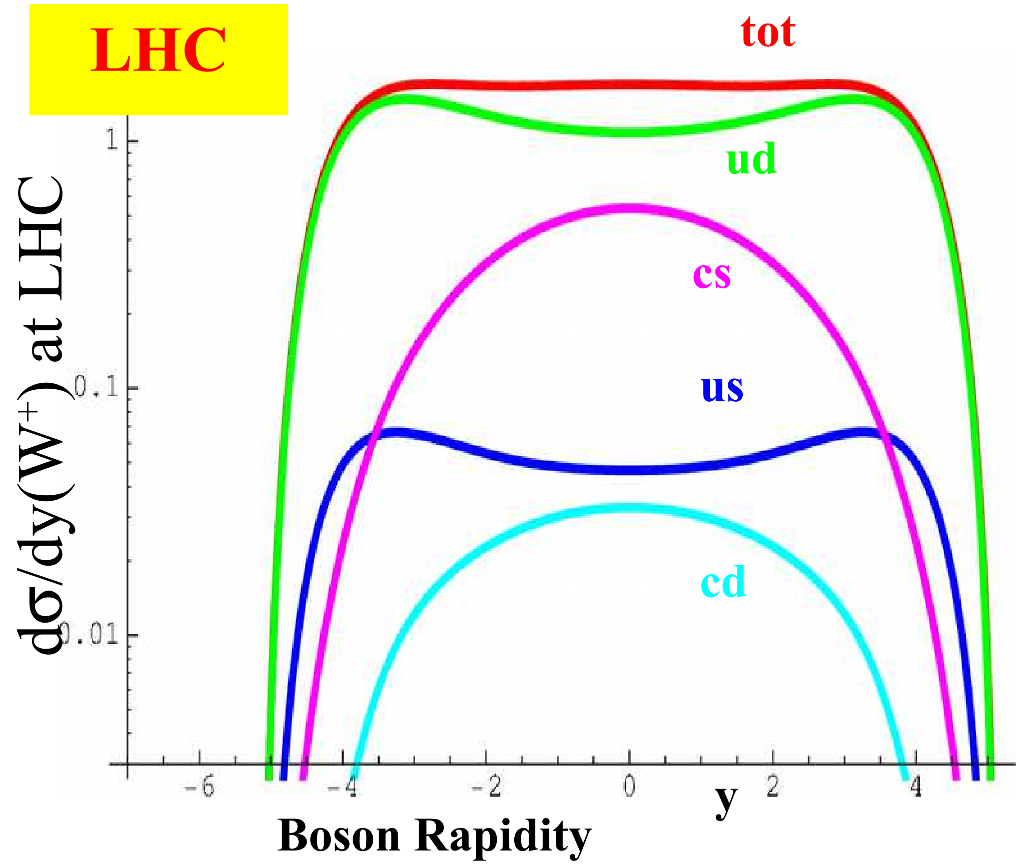
“Benchmark Calculations”

... 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*

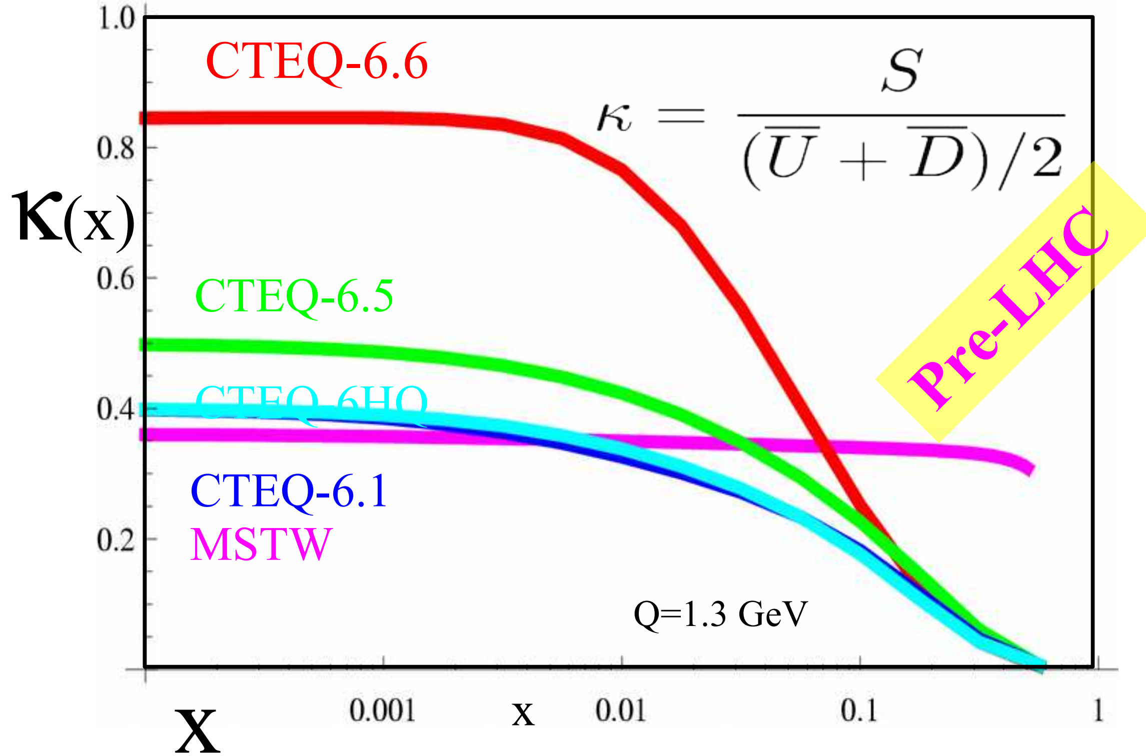


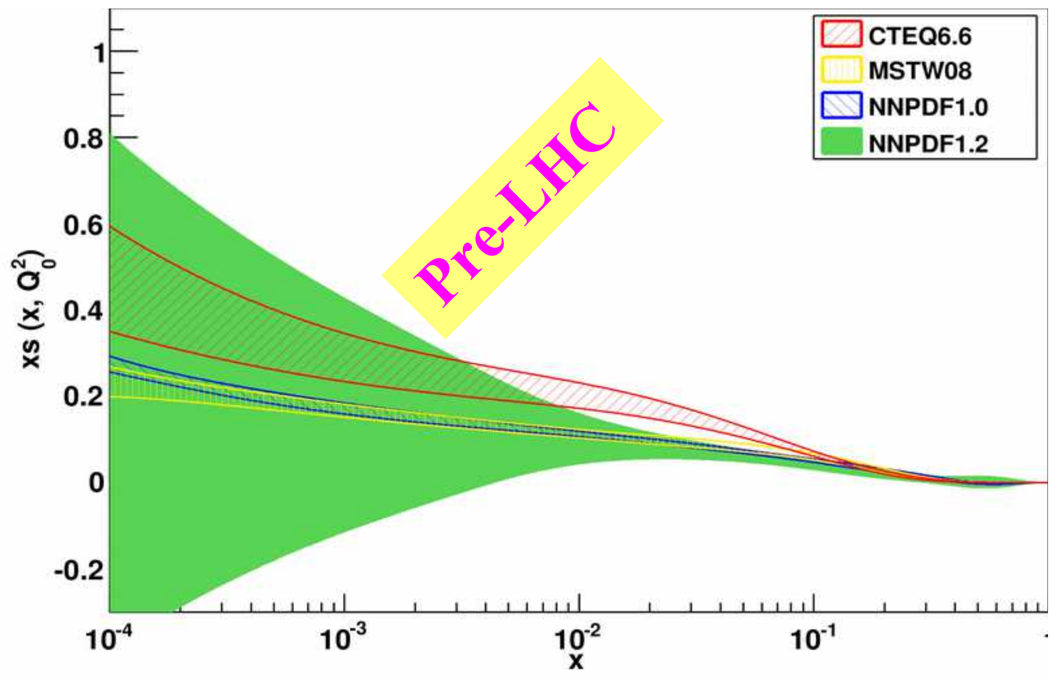


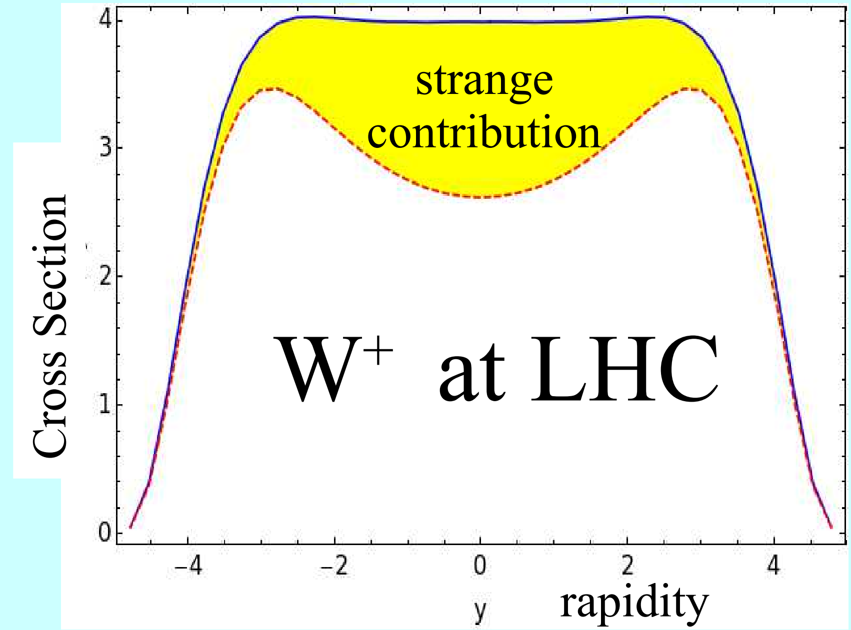
- Larger Energy ⇒ probes PDFs to small momentum fraction x
- Larger Rapidity **(y)** ⇒ probes PDFs to ***really*** small x
- Larger fraction of heavy quarks

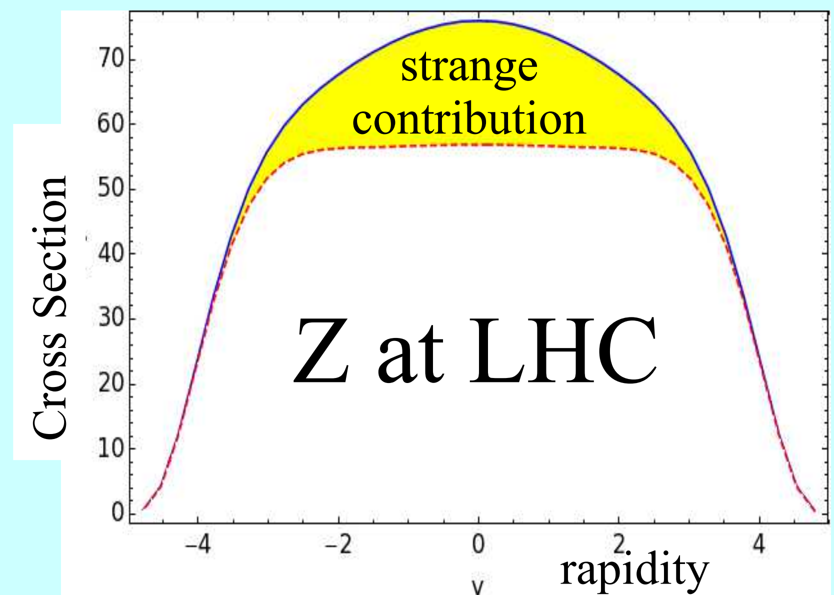
Heavy Quark components play an increasingly important role at the LHC

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





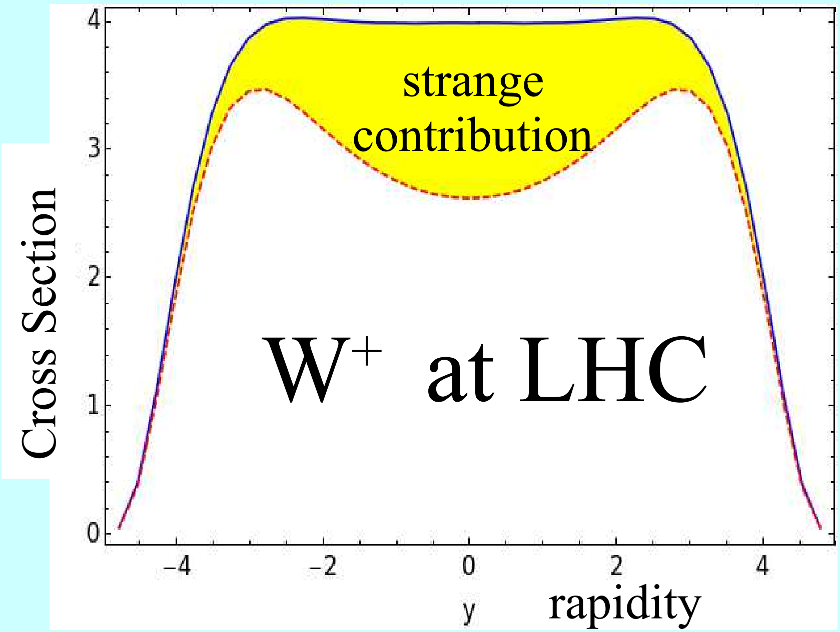


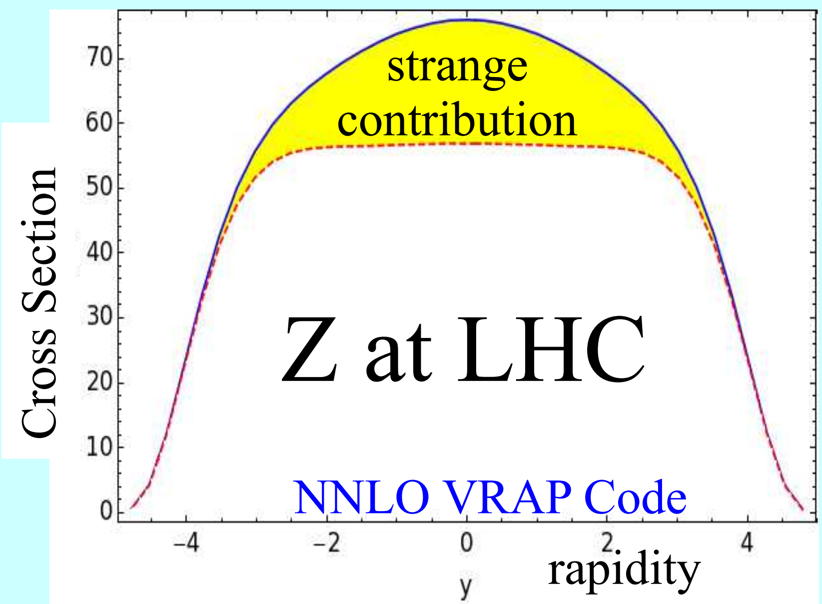


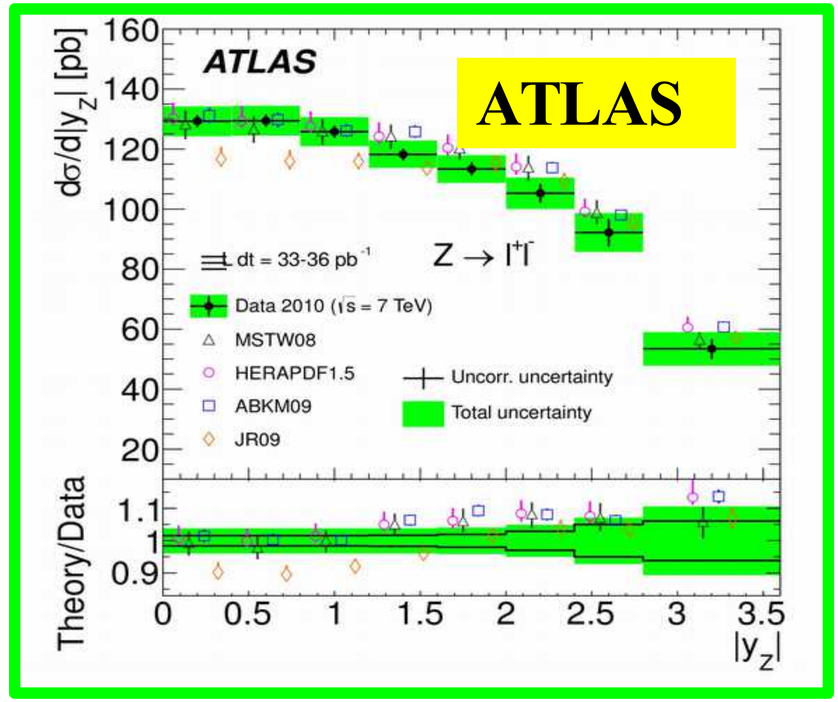
VRAP Code

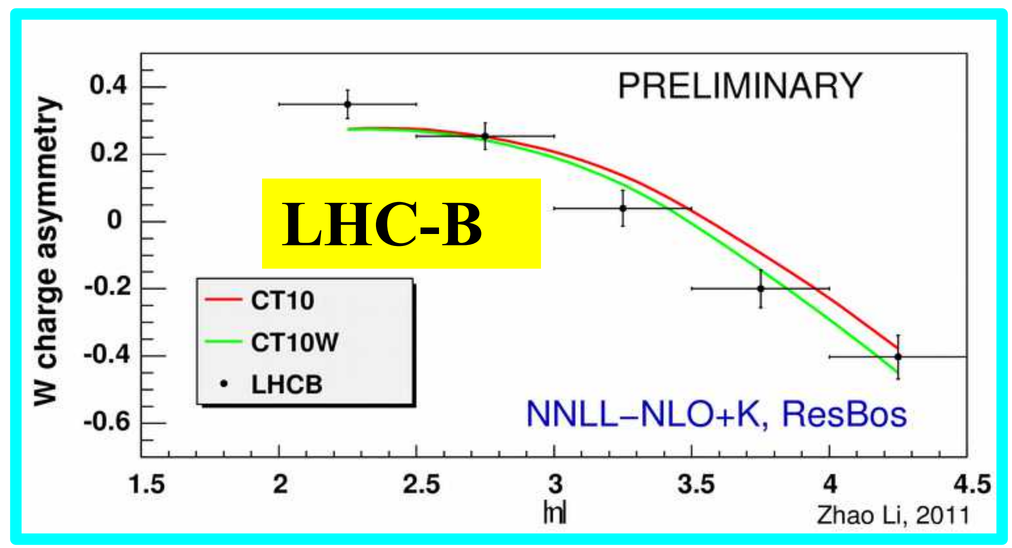
Anastasiou, Dixon, Melnikov, Petriello, Phys.Rev.D69:094008,2004.

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

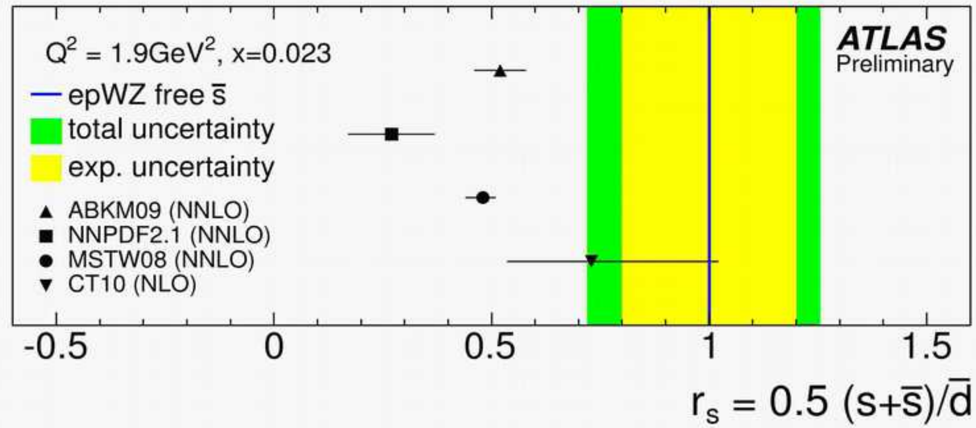
Use LHC data to constrain Strange Quark

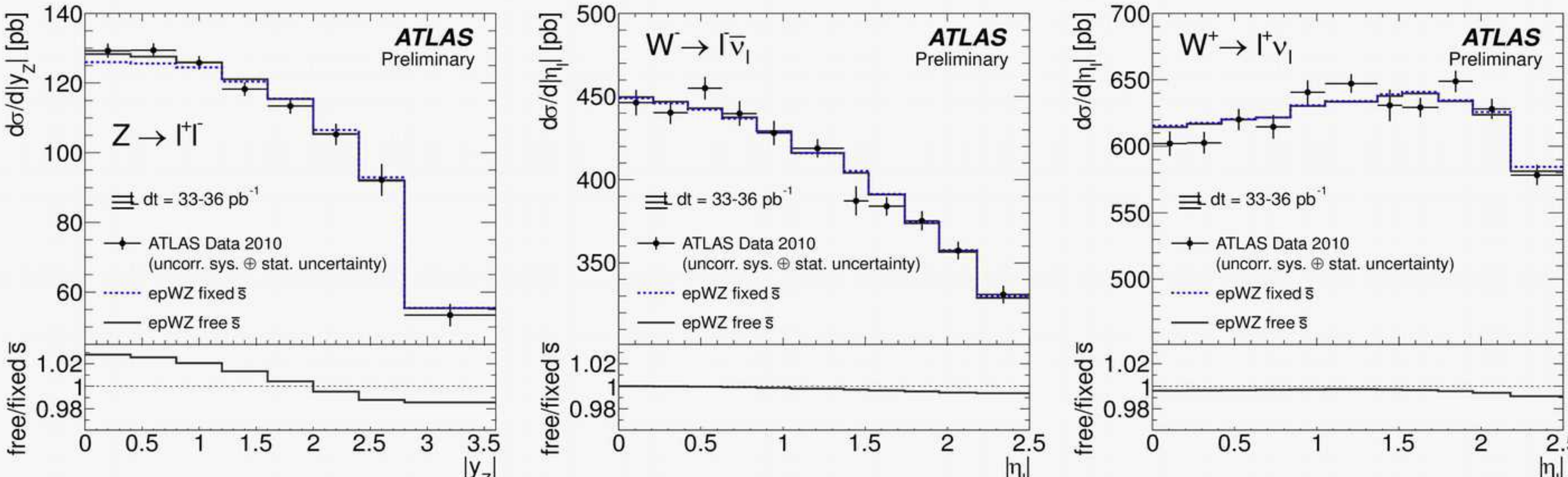
W, Z data sensitivity to strange sea

- 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

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





ATLAS-STDM-2011-43 → PRL

Jan Kretzschmar, 7.3.2012 – p.7

Slide from Carl Schmidt 19 October 2015: INT Workshop

CT14 strange quark PDF

- Conflicting results from experiments:
- ATLAS $r^s = \frac{\bar{s}(x,Q)}{\bar{d}(x,Q)} = 0.96^{+0.26}_{-0.30}$ at $x = 0.023, \quad Q = 1.4$ GeV

$$r^s_{\text{CT14NNLO}} = 0.53 \pm 0.20$$
$$r^s_{\text{CT10NNLO}} = 0.76 \pm 0.17$$

- CMS $\kappa^s = \frac{\int_0^1 x\left[s(x,Q)+\bar{s}(x,Q)\right]dx}{\int_0^1 x\left[\bar{u}(x,Q)+\bar{d}(x,Q)\right]dx} = 0.52^{+0.18}_{-0.15}$ at $Q^2 = 20$ GeV^2
- NOMAD $\kappa^s = 0.591 \pm 0.019$

$$\kappa^s_{\text{CT14NNLO}} = 0.62 \pm 0.14$$
$$\kappa^s_{\text{CT10NNLO}} = 0.73 \pm 0.11$$

A man with one watch ...

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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

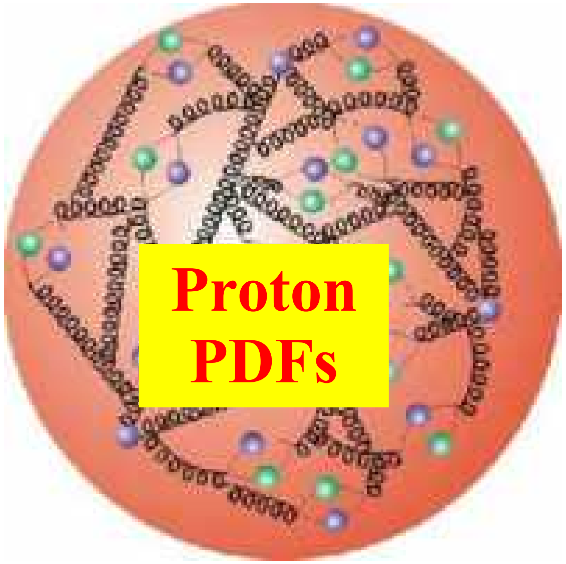
To register, please l
(firstnamelastname
<herafitter-help

HERAFitter M

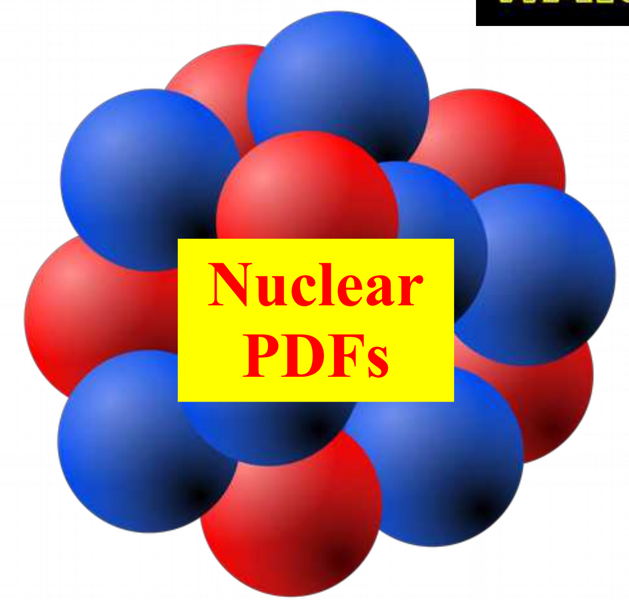
- User's Meeti
and develop

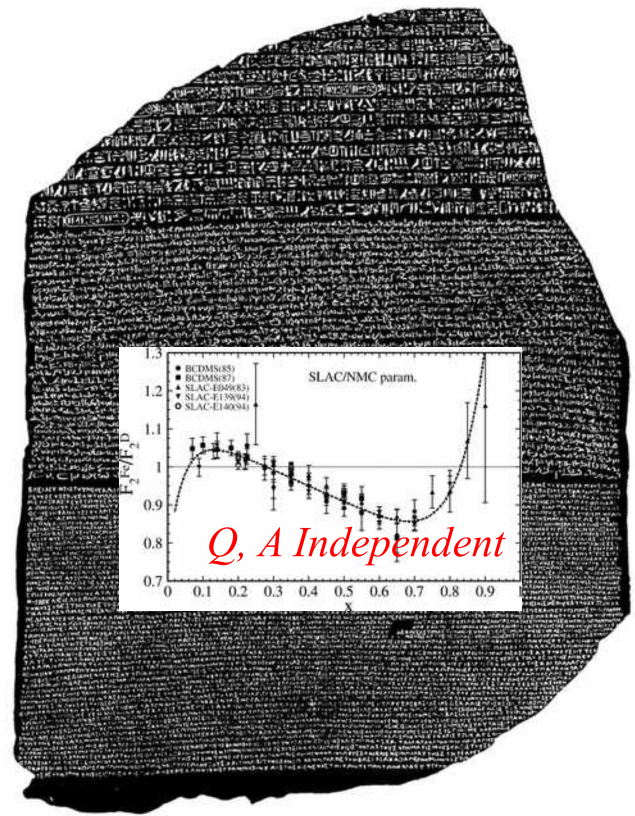
nCTEQ15 PDFs

now that we see necessity of nuclear corrections … **A long time ago in a galaxy far, far away …**

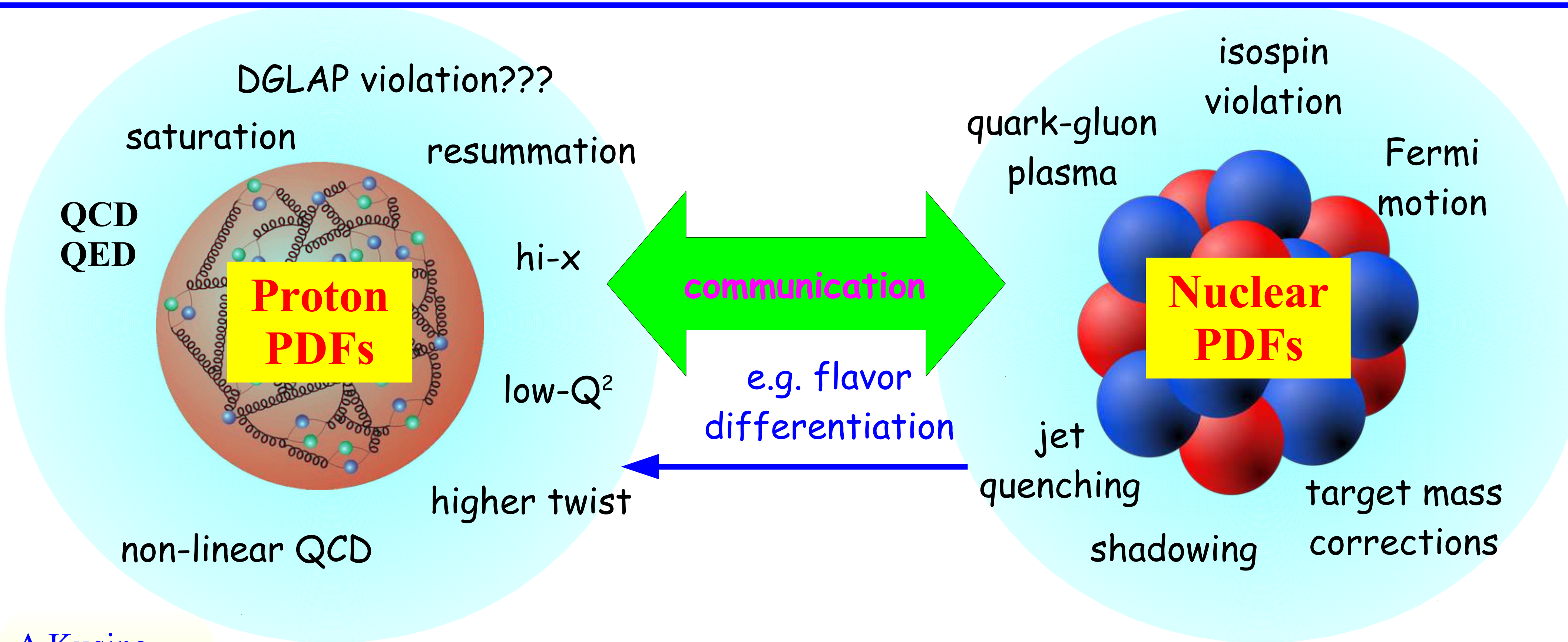


… there was a time when
nuclear corrections
were carved in stone …





Moving Into The 21st Century



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

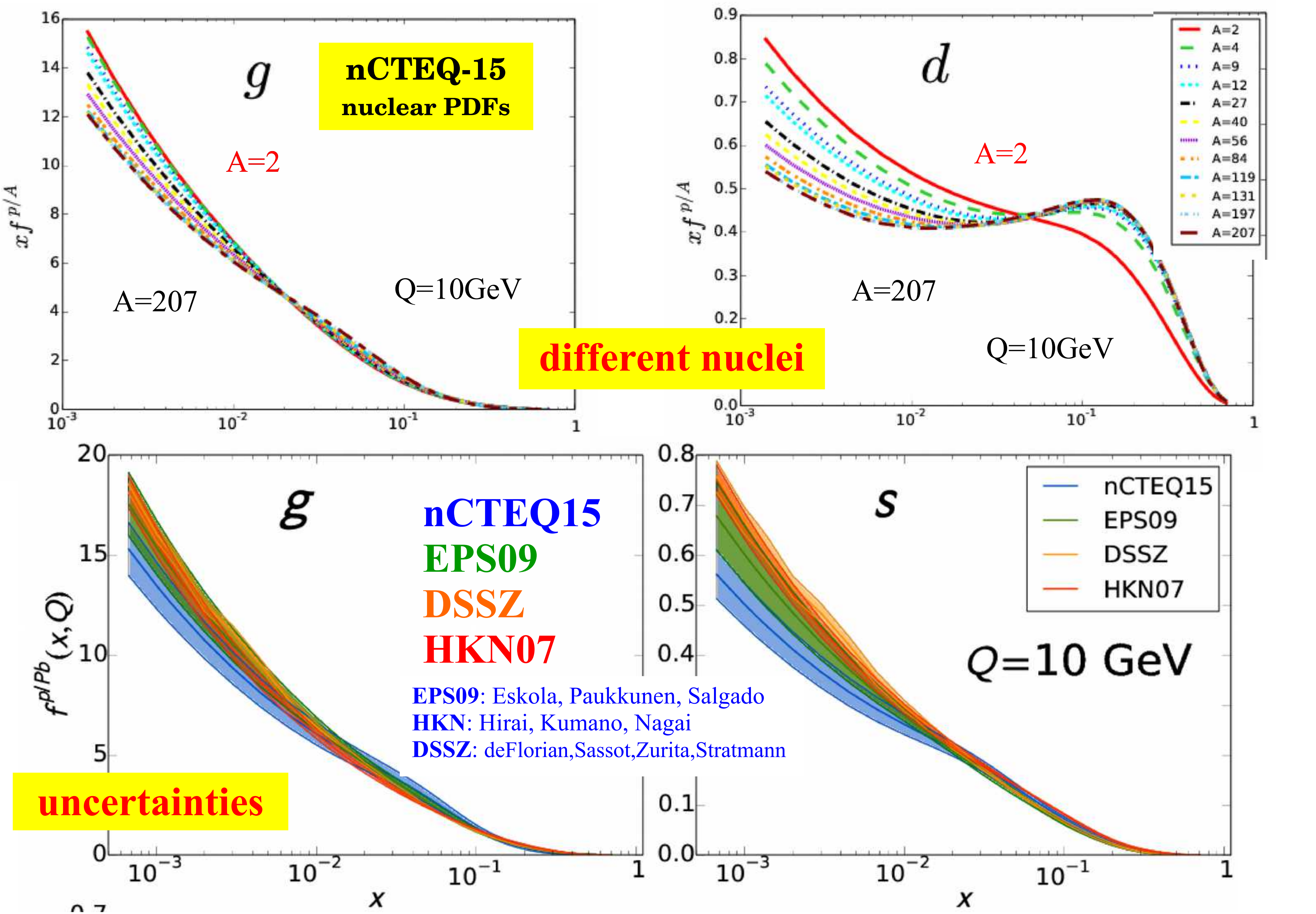
nCTEQ-15

nuclear parton distribution functions

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

… the original motivation for nCTEQ15

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



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

nCTEQ Nuclear PDF's

F_2^A/F_2^D : Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
D	NMC-97	5160	[47]	292	201	247.73
He/D	Hermes	5156	[48]	182	17	18.02
	NMC-95,re	5124	[49]	18	12	10.64
	SLAC-E139	5141	[50]	18	3	1.04
Li/D	NMC-95	5115	[51]	24	11	3.94
Be/D	SLAC-E139	5138	[50]	17	3	0.44
C/D	FNAL-E665-95	5125	[52]	11	3	3.53
	SLAC-E139	5139	[50]	7	2	1.15
	EMC-88	5107	[53]	9	9	7.06
	EMC-90	5110	[54]	9	0	0.00
	NMC-95	5113	[51]	24	12	7.39
	NMC-95,re	5114	[49]	18	12	13.36
N/D	Hermes	5157	[48]	175	19	10.46
	BCDMS-85	5103	[55]	9	9	4.66
Al/D	SLAC-E049	5134	[56]	18	0	0.00
	SLAC-E139	5136	[50]	17	3	0.66
Ca/D	NMC-95,re	5121	[49]	18	12	12.24
	FNAL-E665-95	5126	[52]	11	3	4.87
	SLAC-E139	5140	[50]	7	2	1.43
	EMC-90	5109	[54]	9	0	0.00
Fe/D	SLAC-E049	5131	[57]	14	2	0.67
	SLAC-E139	5132	[50]	23	6	8.20
	SLAC-E140	5133	[58]	10	0	0.00
	BCDMS-87	5101	[59]	10	10	6.47
	BCDMS-85	5102	[55]	6	6	2.83
Cu/D	EMC-93	5104	[60]	10	9	4.31
	EMC-93(chariot)	5105	[60]	9	9	5.72
	EMC-88	5106	[53]	9	9	3.97
Kr/D	Hermes	5158	[48]	167	12	9.68
Ag/D	SLAC-E139	5135	[50]	7	2	1.36
Sn/D	EMC-88	5108	[53]	8	8	17.88
Xe/D	FNAL-E665-92	5127	[61]	10	2	0.74
Au/D	SLAC-E139	5137	[50]	18	3	1.55
Pb/D	FNAL-E665-95	5129	[52]	11	3	5.91
Total:				1205	414	417.92

$F_2^A/F_2^{A'}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/Li	NMC-95,re	5123	[49]	25	7	5.22
Ca/Li	NMC-95,re	5122	[49]	25	7	1.49
Be/C	NMC-96	5112	[62]	15	14	7.25
Al/C	NMC-96	5111	[62]	15	14	4.98
Ca/C	NMC-95,re	5120	[49]	25	7	3.31
	NMC-96	5119	[62]	15	14	5.18
Fe/C	NMC-96	5143	[62]	15	14	10.38
Sn/C	NMC-96	5159	[63]	146	111	62.95
Pb/C	NMC-96	5116	[62]	15	14	9.09
Total:				296	202	109.85

Table II: The DIS $F_2^A/F_2^{A'}$ data sets used in the nCTEQ15 fit. We list the same details for each data set as in Tab. I.

$\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/H2	FNAL-E772-90	5203	[64]	9	9	11.10
Ca/H2	FNAL-E772-90	5204	[64]	9	9	3.11
Fe/H2	FNAL-E772-90	5205	[64]	9	9	3.33
W/H2	FNAL-E772-90	5206	[64]	9	9	7.30
Fe/Be	FNAL-E886-99	5201	[65]	28	28	26.09
W/Be	FNAL-E886-99	5202	[65]	28	28	25.61
Total:				92	92	76.54

Table III: The Drell-Yan process data sets used in the nCTEQ15 fit. We list the same details for each data set as in Tab. I.

$R_{dAu}^{\pi}/R_{pp}^{\pi}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
dAu/pp	PHENIX	PHENIX	[66]	21	20	5.07
	STAR-2010	STAR	[67]	13	12	1.30
Total:				34	32	6.37

nCTEQ Nuclear PDF's

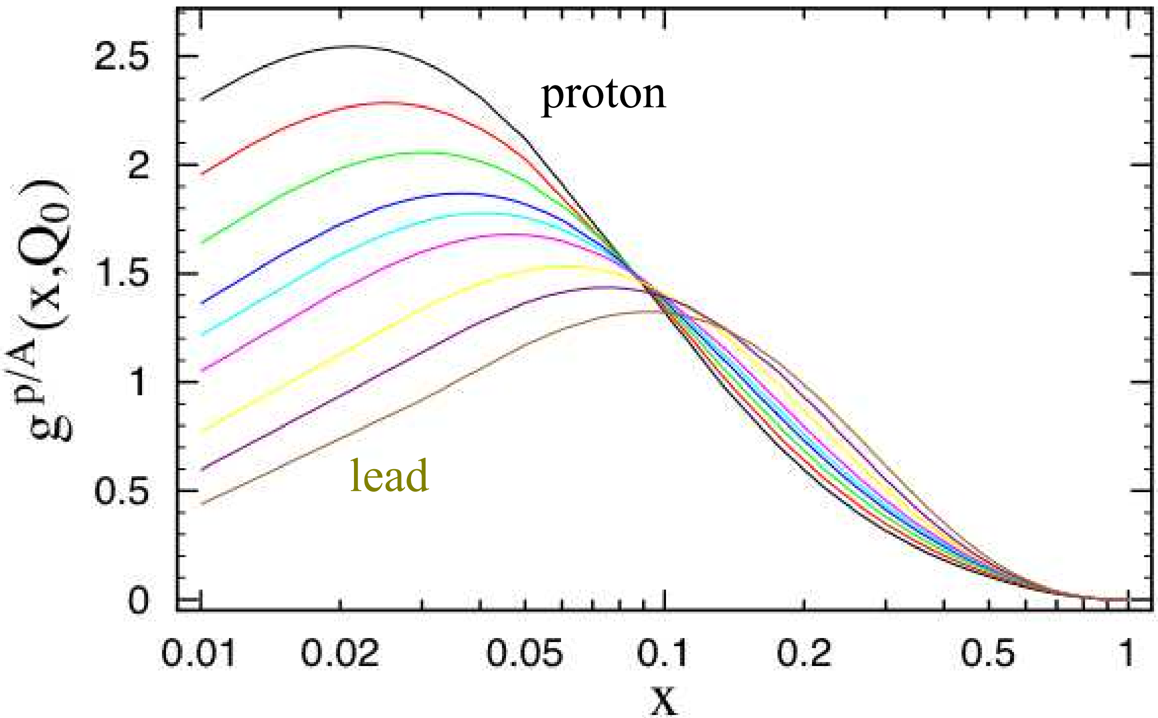
- ✔ CTEQ style global fit extended
  handle various nuclear targets
- ✔ CTEQ Data + nuclear DIS & DY
  [~15 targets; ~2000+ data]
- ✔ A-dependence modeled;
  NLO fits work well

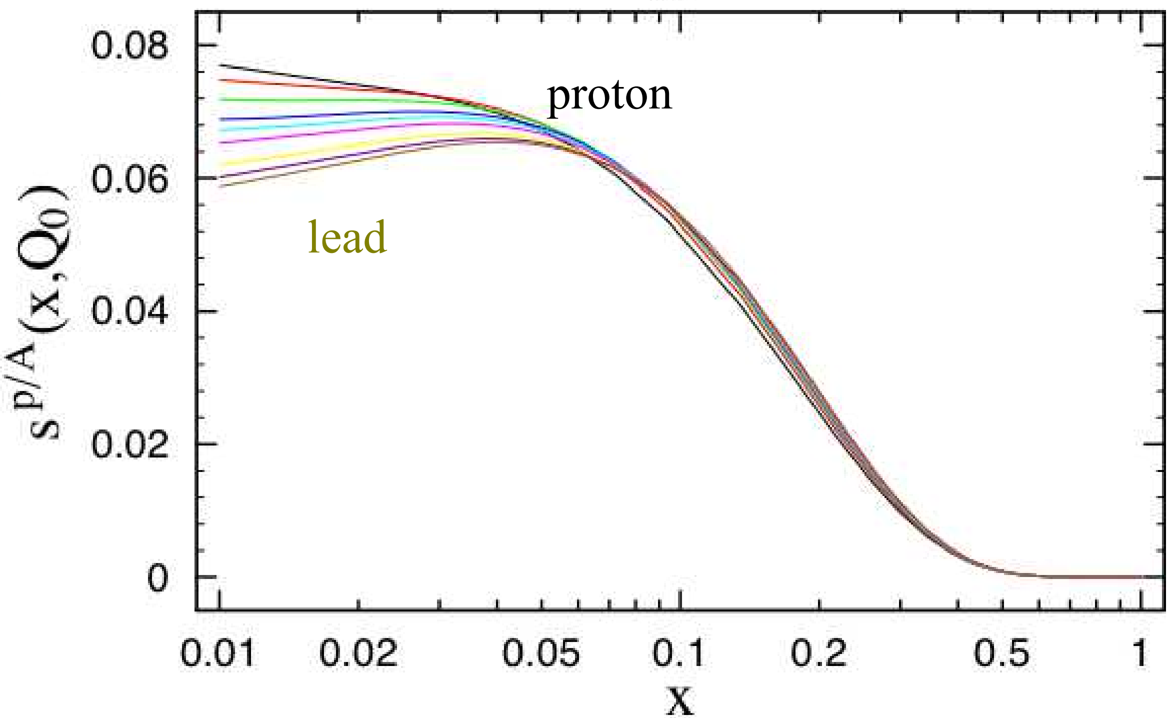
A-Dependent PDFs

$$xf(x) = x^{a_1}(1-x)^{a_2} e^{a_3 x}(1+e^{a_4}x)^{a_5}$$

$$a_i \rightarrow a_i(A)$$

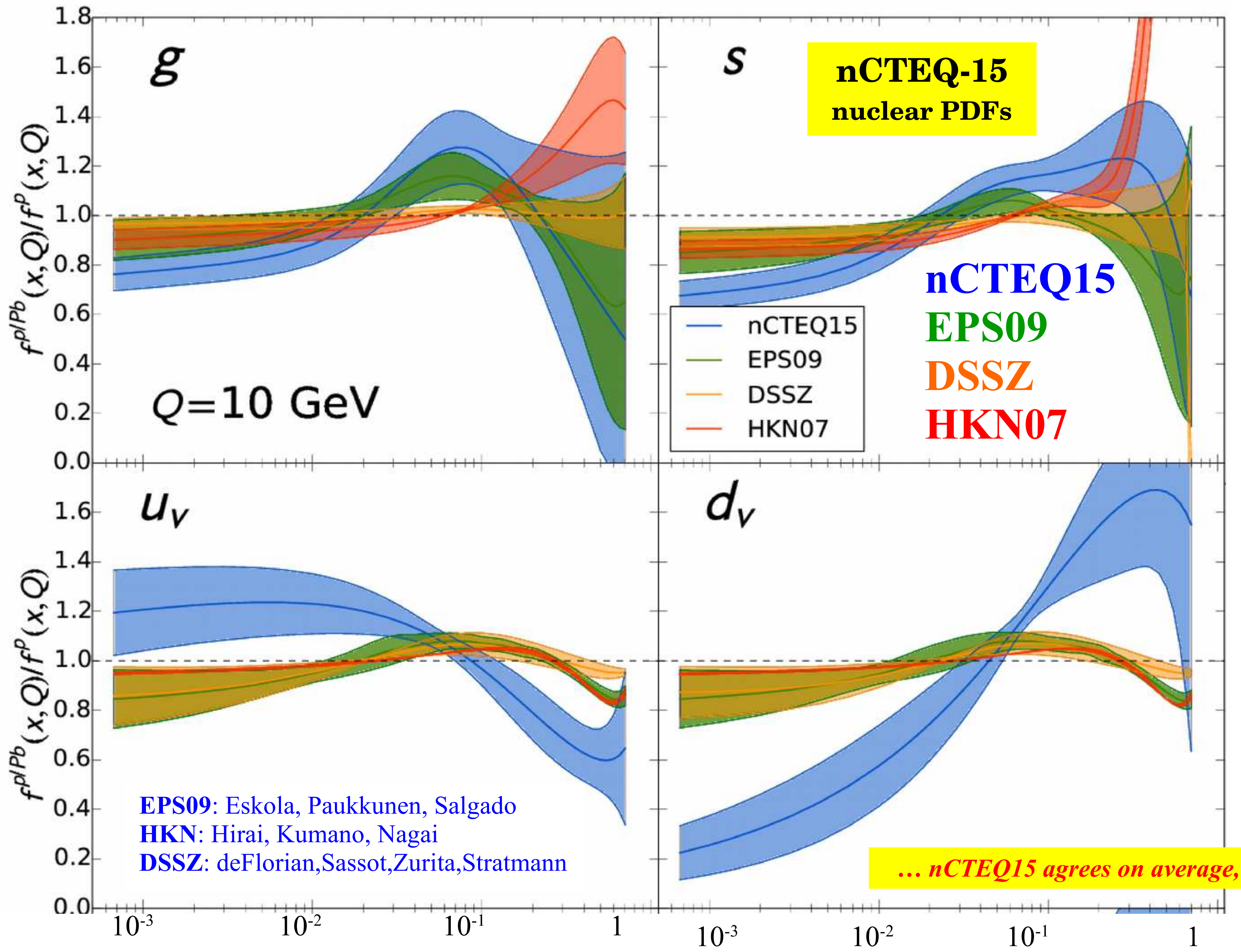
$$a_k = a_{k,0} + a_{k,1}\left(1 - A^{-a_{k,2}}\right)$$





Nuclear PDFs from neutrino deep inelastic scattering.
I. Schienbein, J.Y. Yu, C. Keppel, J.G. Morfin,
F. Olness, J.F. Owens. Phys.Rev.D77:054013,2008.

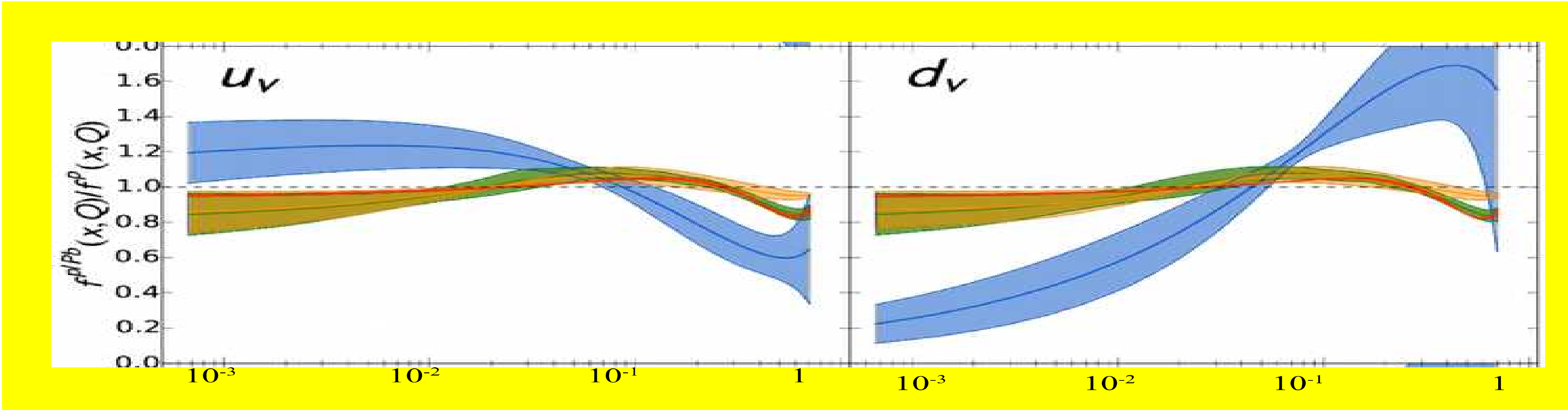
Ratio to Proton for Lead … *with Uncertainty*

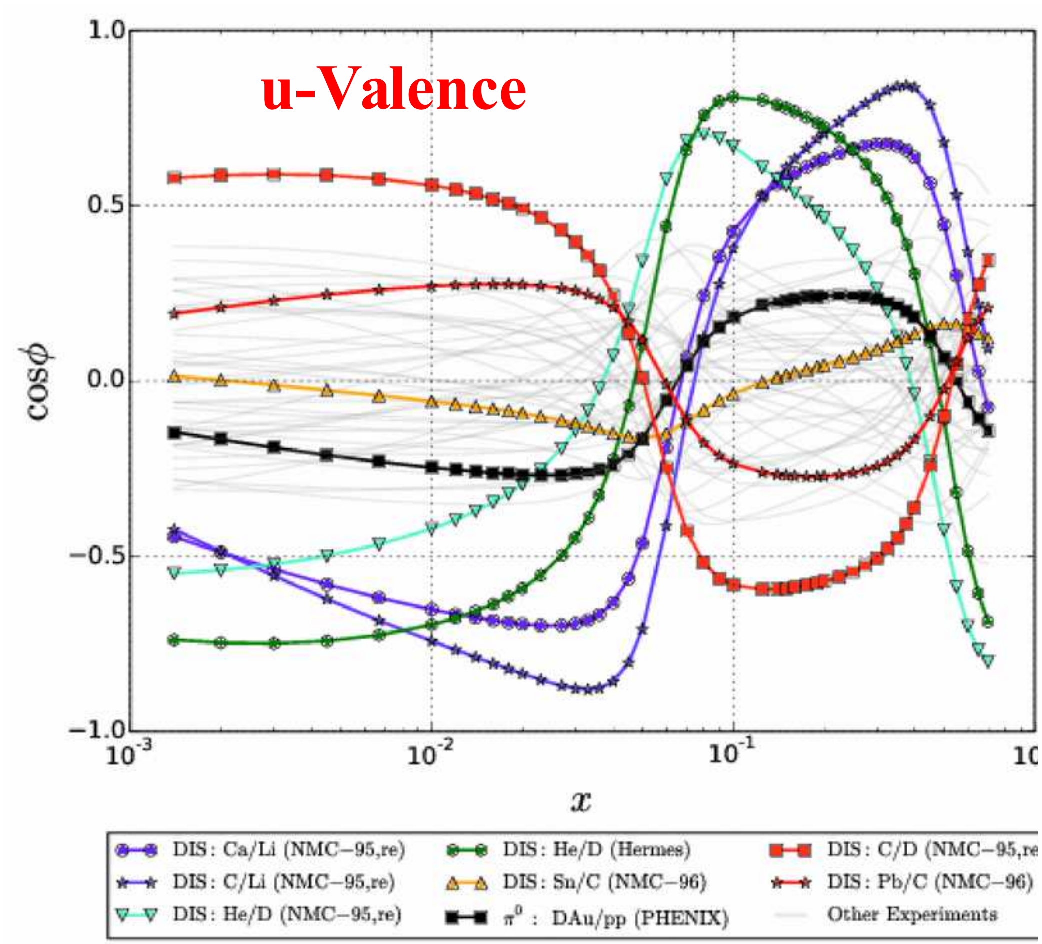


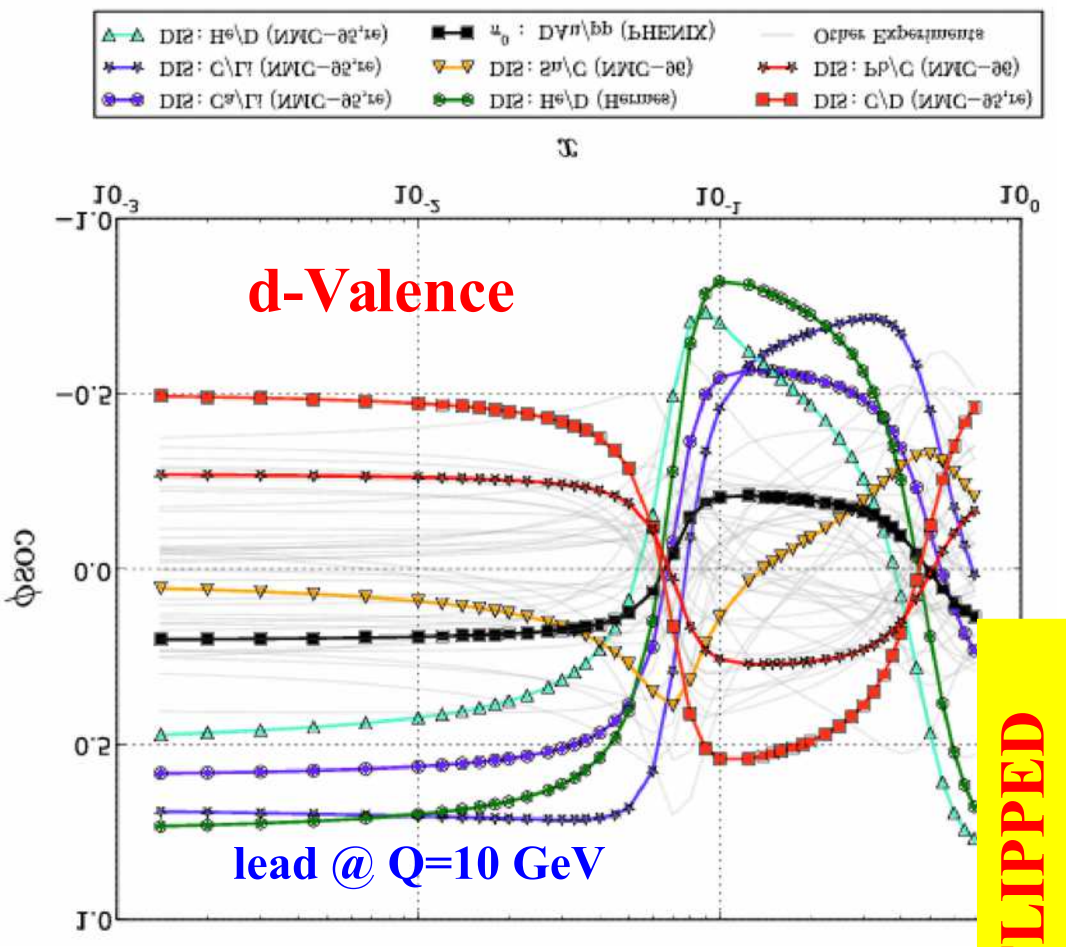
EPS09: Eskola, Paukkunen, Salgado
HKN: Hirai, Kumano, Nagai
DSSZ: deFlorian,Sassot,Zurita,Stratmann

… nCTEQ15 agrees on average, but ...

What data are influencing up & down



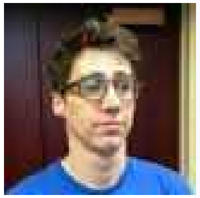


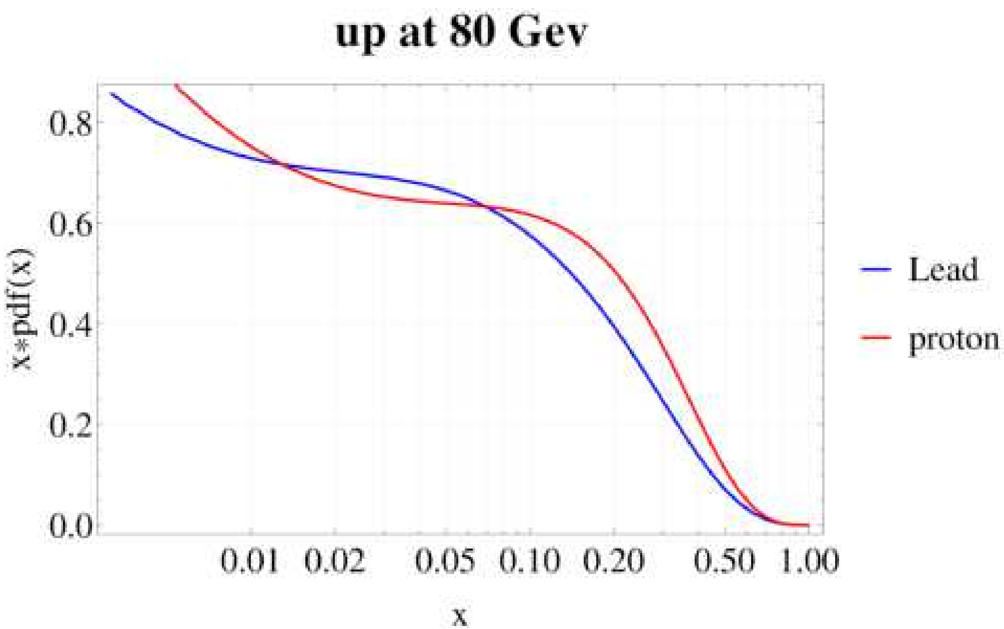


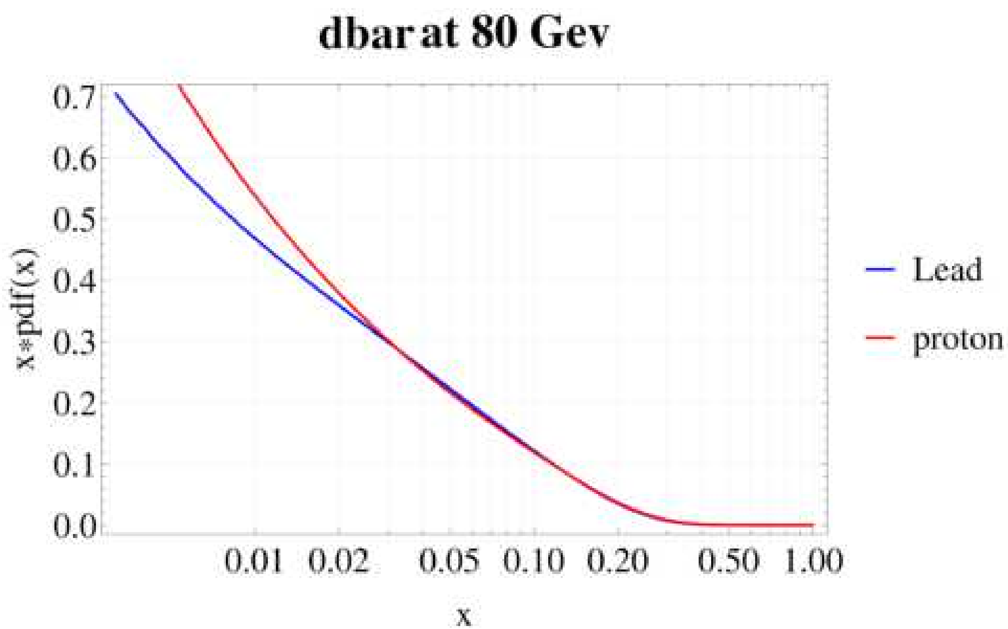
Heavy Ion @ LHC

Nuclear Modifications

Slides stolen from Ben Clark



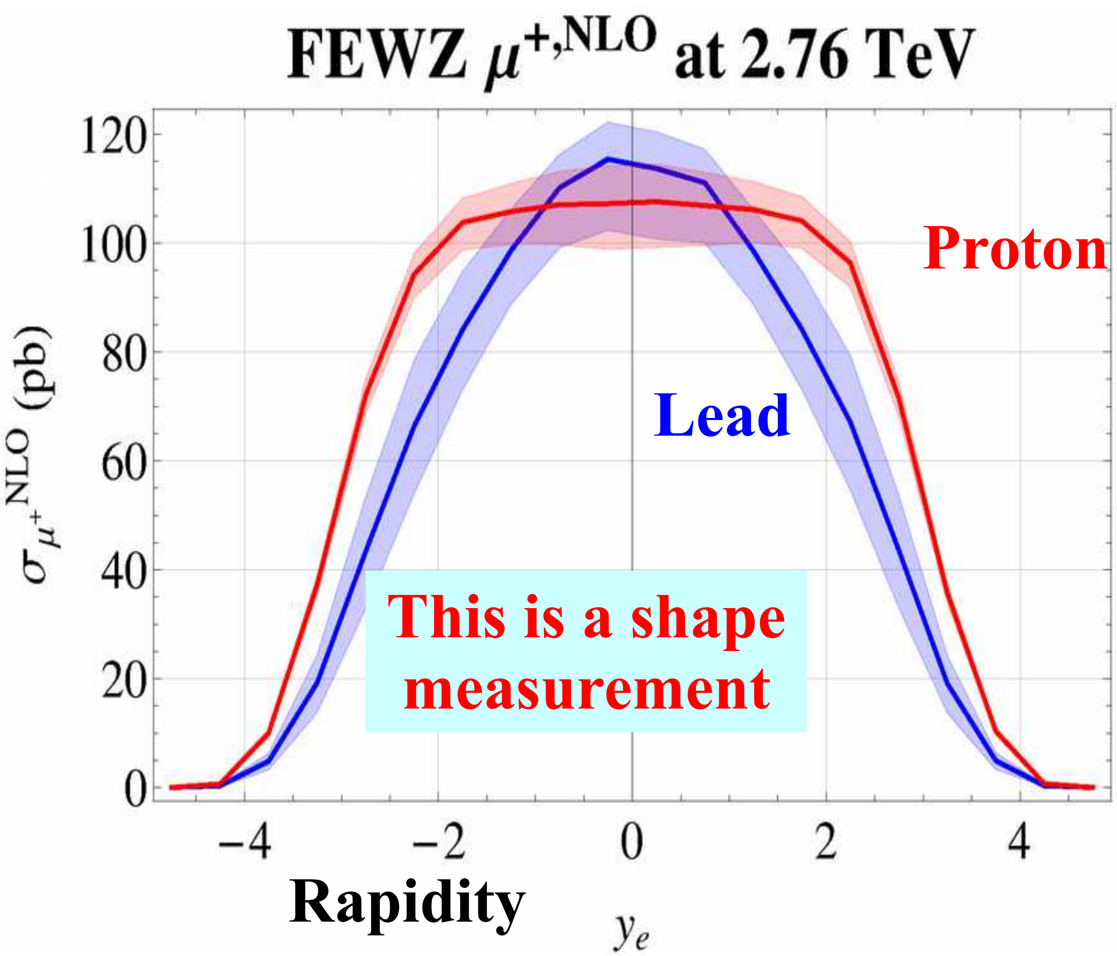


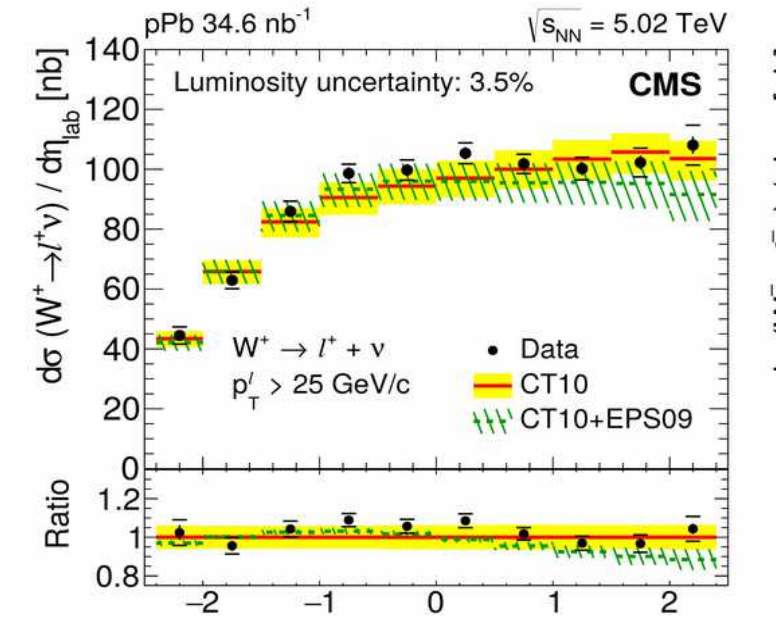


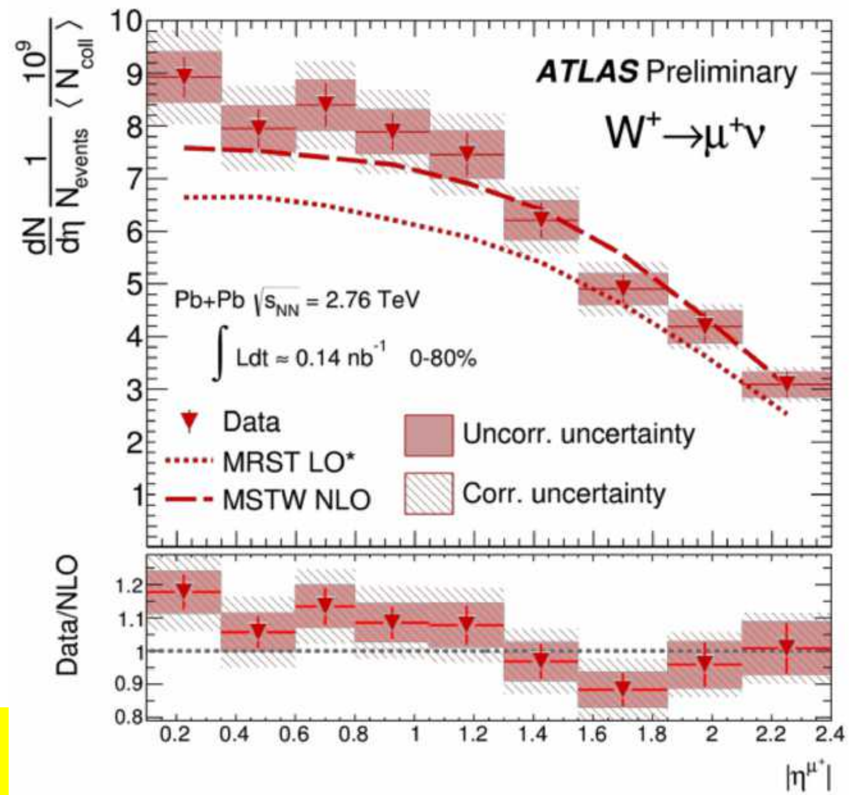
- The nuclear modifications are present in the PDFs and vary with A as well as x and Q.
- We expect modifications to any hadronic observable involving heavy nuclei.

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

$$W^+ \to \mu^+ \nu$$







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

... what about

Heavy Quarks

...

charm

&

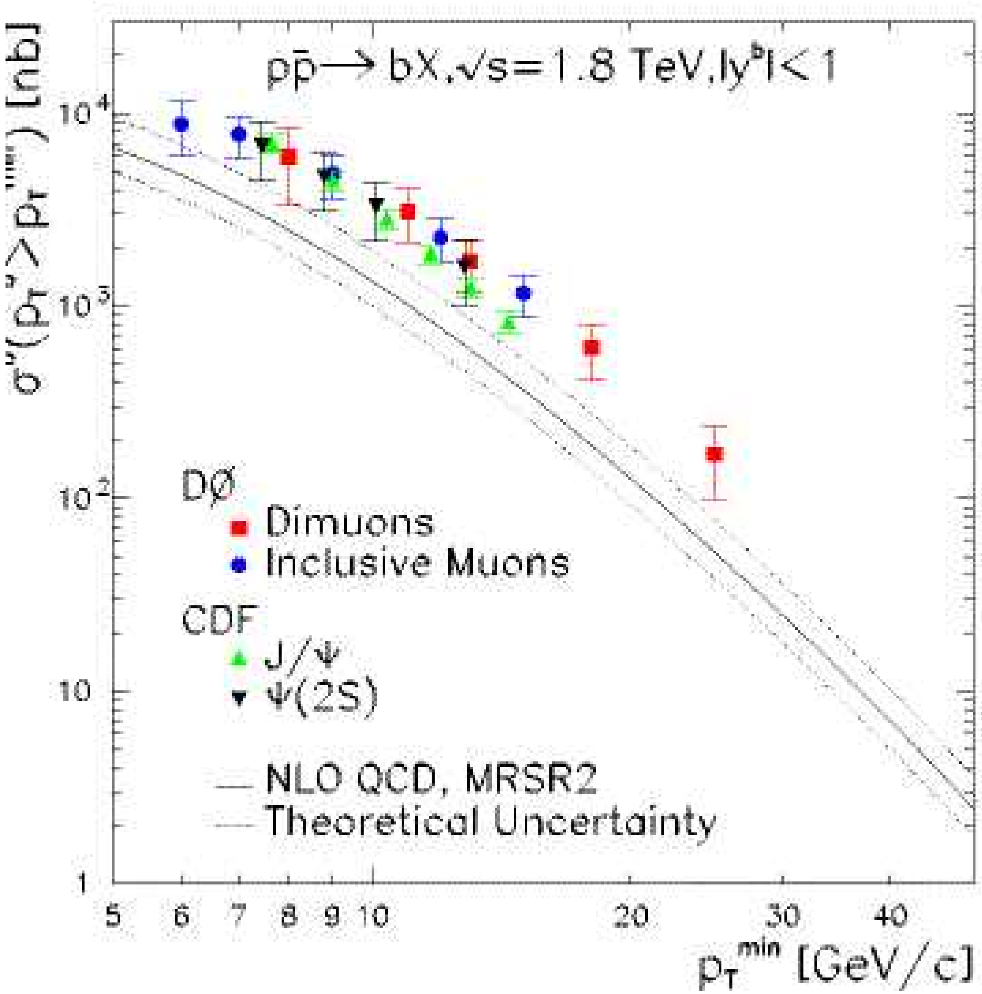
bottom

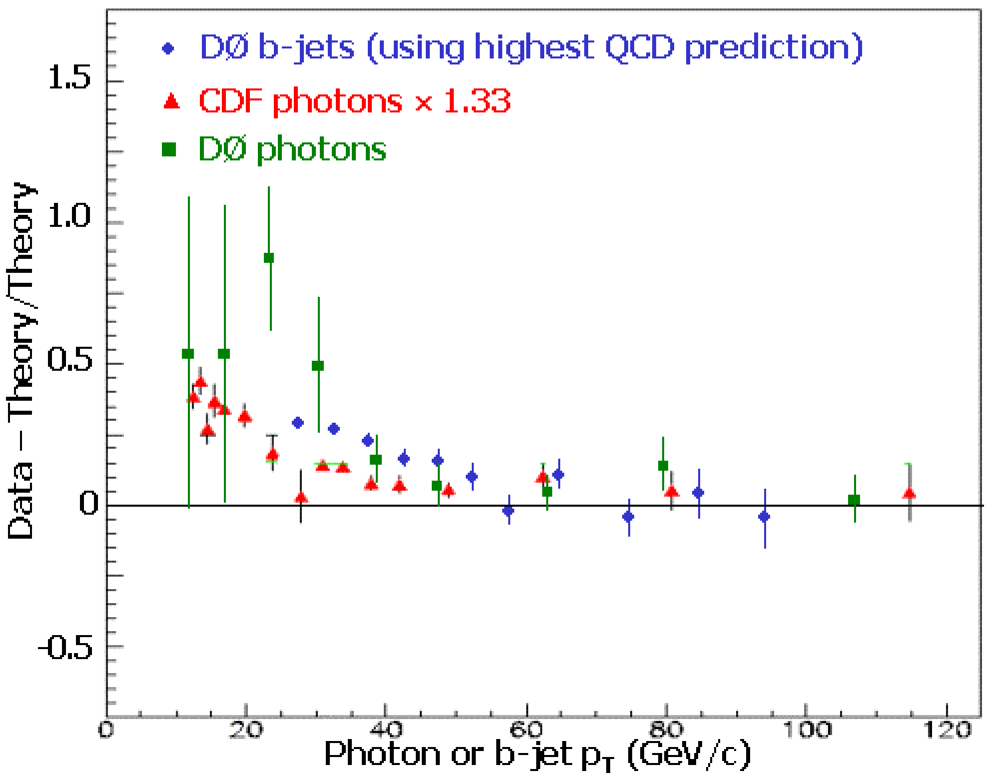
Heavy Quarks : … past challenges

The CTEQ List of Challenges in Perturbative QCD

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

C T E Q





~1995

Multi-Scale Problems are Challenging

Two-Loop Total Cross Section: One Scale

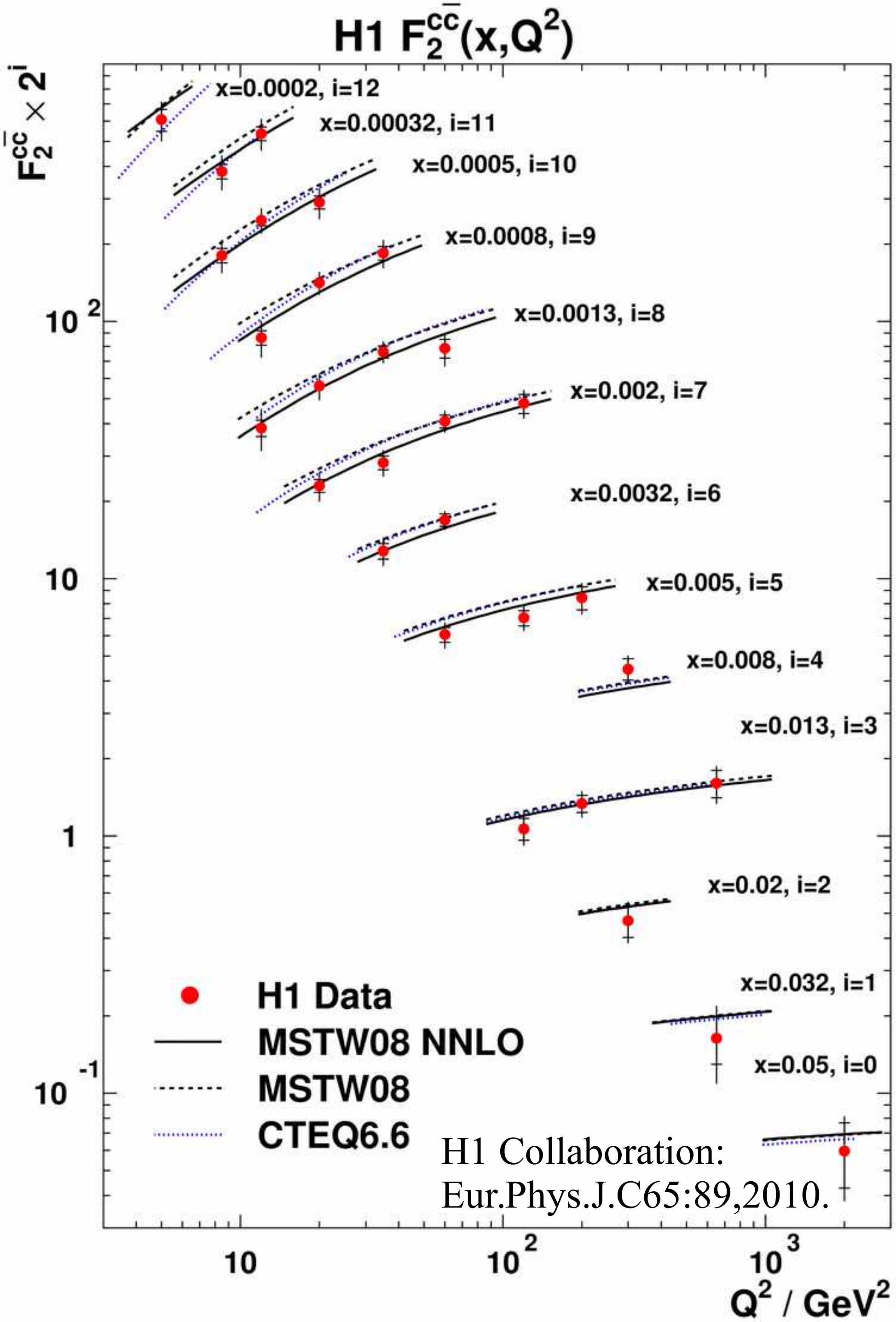
$$\sigma(Q^2)=\sigma_0\left\{1+\frac{\alpha_s(Q^2)}{4\pi}(3C_F)+\left[\frac{\alpha_s(Q^2)}{4\pi}\right]^2\left[-C_F^2\left[\frac{3}{2}\right]+C_FC_A\left[\frac{123}{2}-44\zeta(3)\right]+C_FTn_f(-22+16\zeta(3))\right]\right.$$

Two-Loop Drell-Yan Cross Section: Two Scales

$$\begin{aligned}
H_{q\bar{q}}^{(2),S+V}(z)=&\left[\frac{\alpha_s}{4\pi}\right]^2\delta(1-z)\Bigg\{C_AC_F\left[[\tfrac{193}{3}-24\zeta(3)]\ln\left[\frac{Q^2}{M^2}\right]-11\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{12}{5}\zeta(2)^2+\tfrac{592}{9}\zeta(2)+28\zeta(3)-\tfrac{1535}{12}\right]\\
&+C_F^2\left[[18-32\zeta(2)]\ln^2\left[\frac{Q^2}{M^2}\right]+[24\zeta(2)+176\zeta(3)-93]\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.+\tfrac{8}{5}\zeta(2)^2-70\zeta(2)-60\zeta(3)+\tfrac{511}{4}\right]\\
&+n_fC_F\left[2\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{34}{3}\ln\left[\frac{Q^2}{M^2}\right]+8\zeta(3)-\tfrac{112}{9}\zeta(2)+\tfrac{127}{6}\right]\Bigg\}\\
&+C_AC_F\left[-\tfrac{44}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+\{[\tfrac{536}{9}-16\zeta(2)]\mathcal{D}_0(z)-\tfrac{176}{3}\mathcal{D}_1(z)\}\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.-\tfrac{176}{3}\mathcal{D}_2(z)+[\tfrac{1072}{9}-32\zeta(2)]\mathcal{D}_1(z)+[56\zeta(3)+\tfrac{176}{3}\zeta(2)-\tfrac{1616}{27}]\mathcal{D}_0(z)\right]\\
&+C_F^2\left[[64\mathcal{D}_1(z)+48\mathcal{D}_0(z)]\ln^2\left[\frac{Q^2}{M^2}\right]+\{192\mathcal{D}_2(z)+96\mathcal{D}_1(z)-[128+64\zeta(2)]\mathcal{D}_0(z)\}\ln\left[\frac{Q^2}{M^2}\right]\right.\\
&\left.+128\mathcal{D}_3(z)-(128\zeta(2)+256)\mathcal{D}_1(z)+256\zeta(3)\mathcal{D}_0(z)\right]\\
&+n_fC_F\left[\tfrac{8}{3}\mathcal{D}_0(z)\ln^2\left[\frac{Q^2}{M^2}\right]+[\tfrac{32}{3}\mathcal{D}_1(z)-\tfrac{80}{9}\mathcal{D}_0(z)]\ln\left[\frac{Q^2}{M^2}\right]+\tfrac{32}{3}\mathcal{D}_2(z)-\tfrac{160}{9}\mathcal{D}_1(z)+[\tfrac{224}{27}-\tfrac{32}{3}\zeta(2)]\mathcal{D}_0(z)\right].
\end{aligned}$$

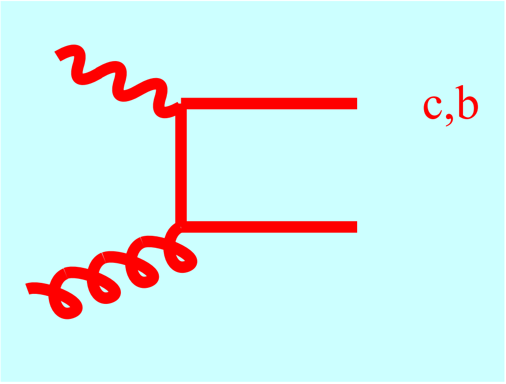
Ref: CTEQ Handbook

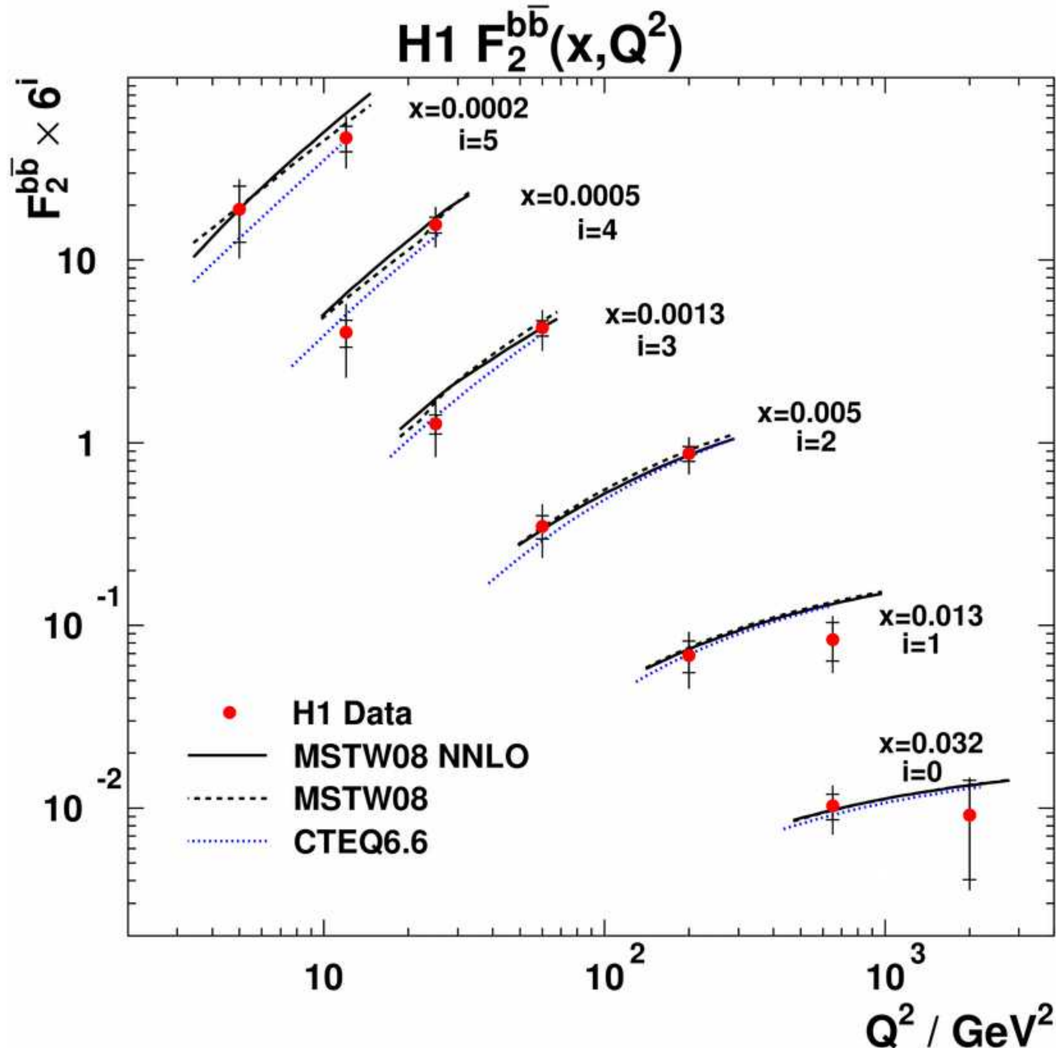
Heavy Flavor Components will play a MORE prominent role at LHC



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

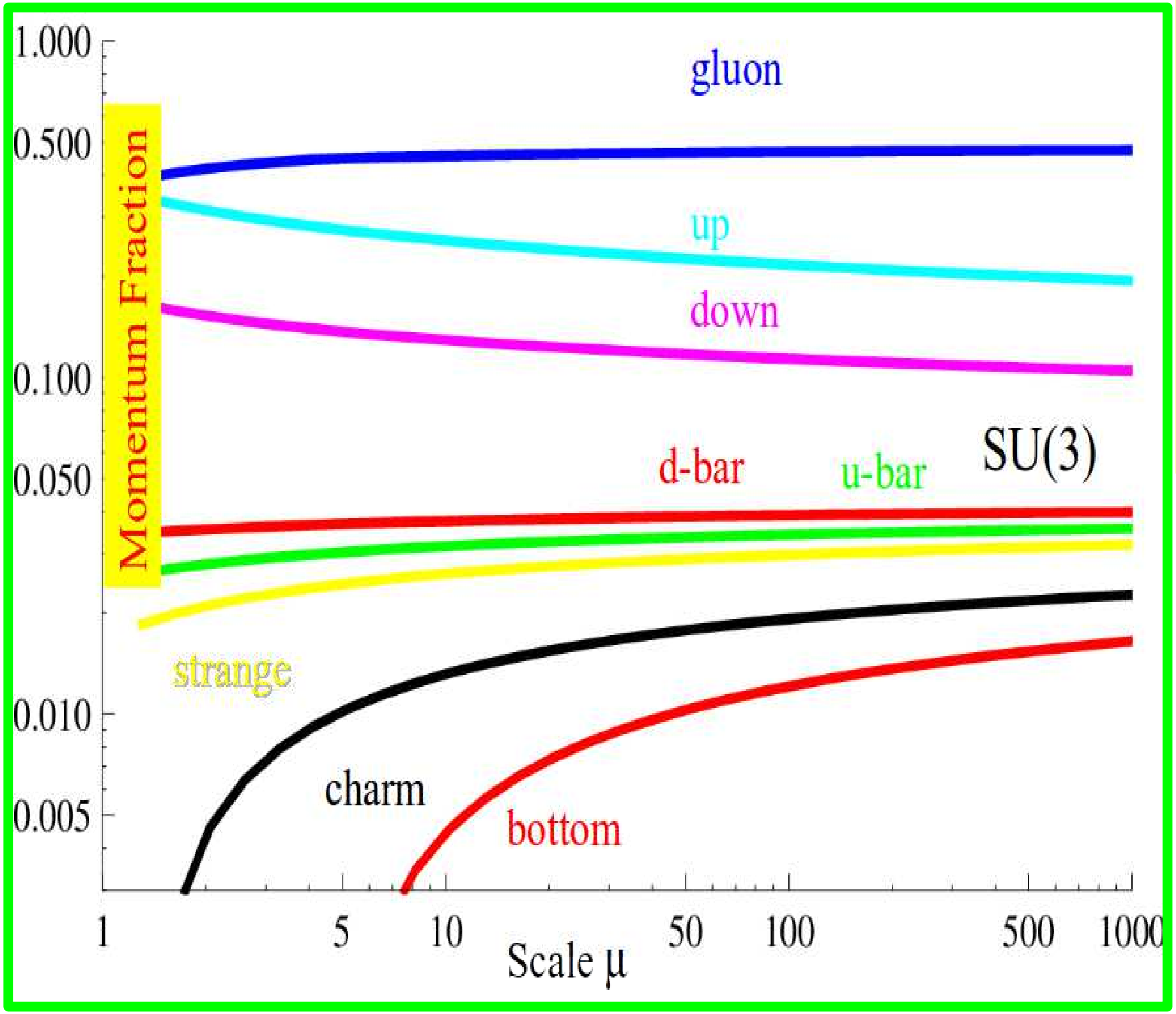
c & b tied to gluon PDFs

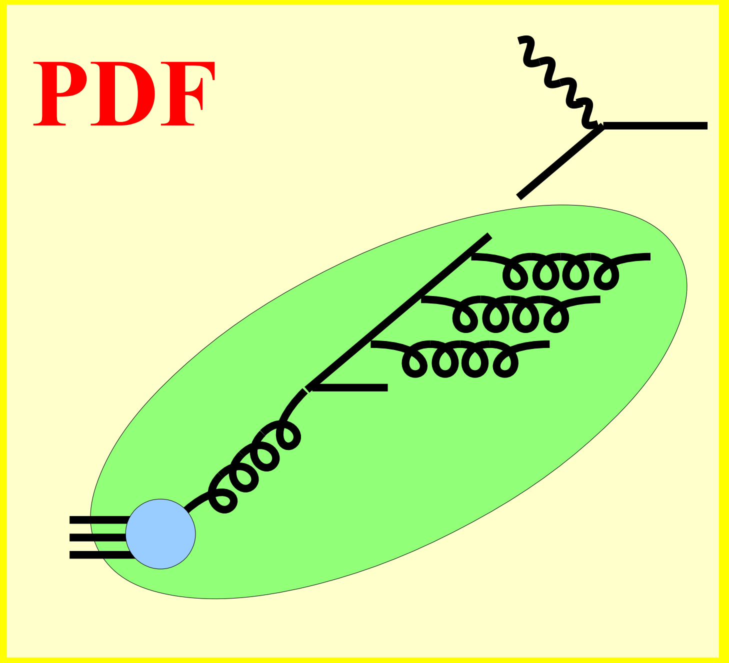


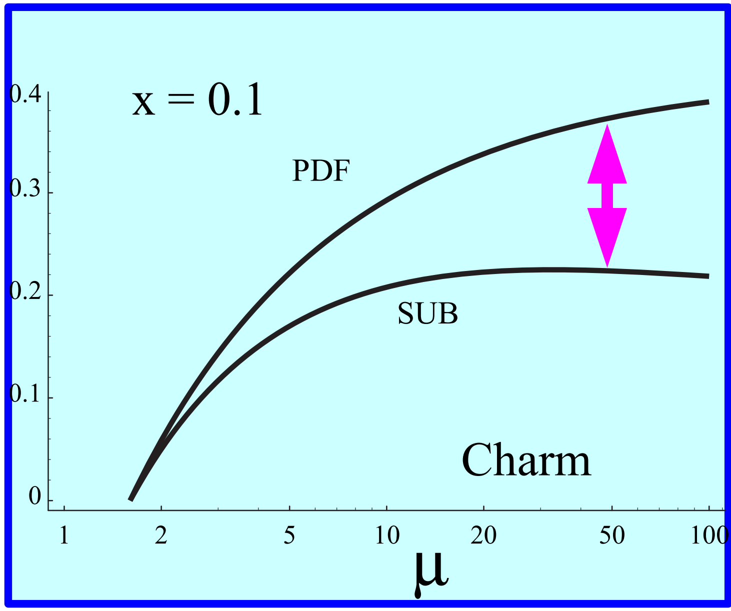


Charm & Bottom PDFs Resum Logs

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

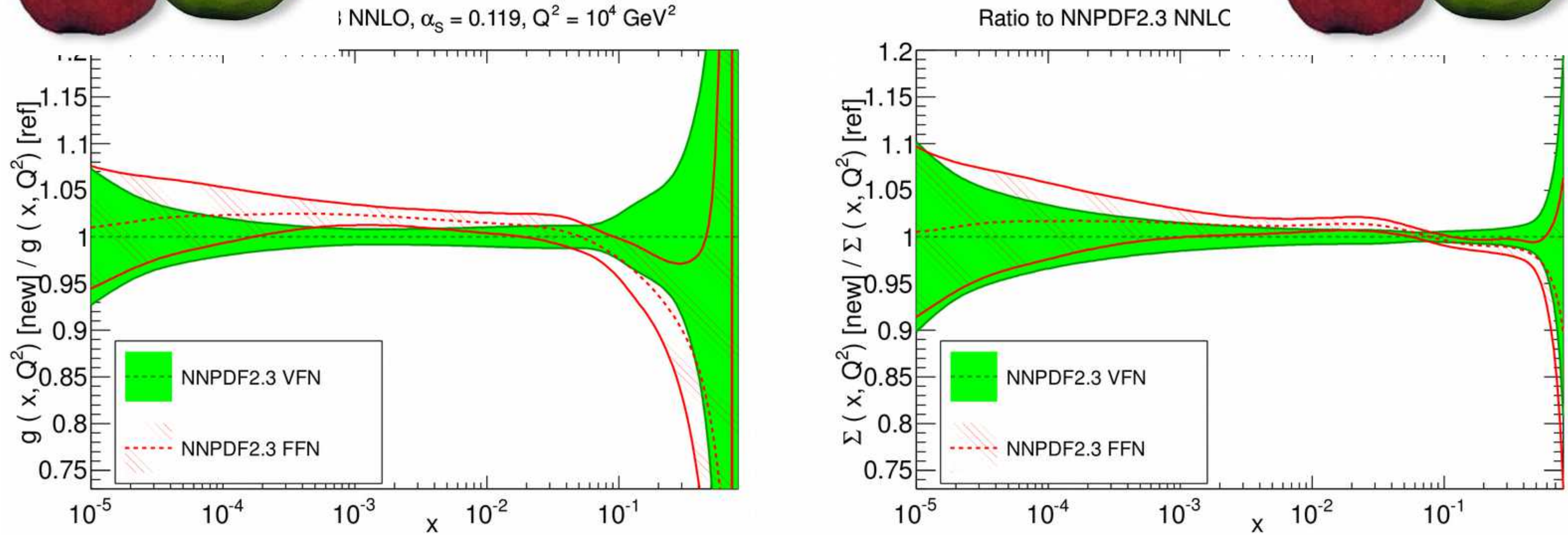






Compare VFN & FFN Schemes

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



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

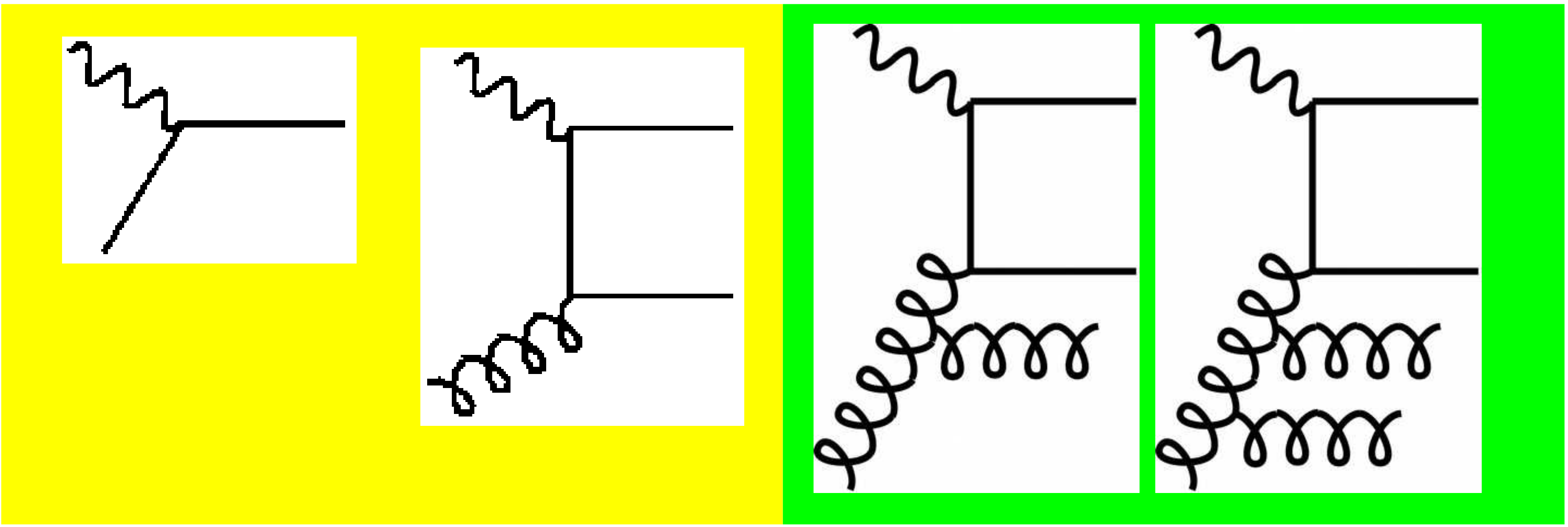
VFN Wins

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

The NNPDF Collaboration, PLB723 (2013) 330

ACOT Extension to Higher Orders

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



Full ACOT

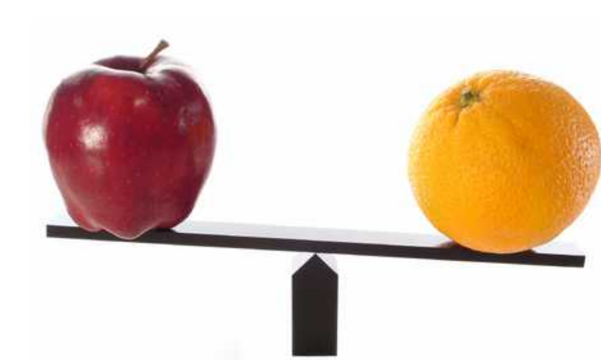
Based on the Collins-Wilczek-Zee (CWZ) Renormalization Scheme
... hence, extensible to all orders

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



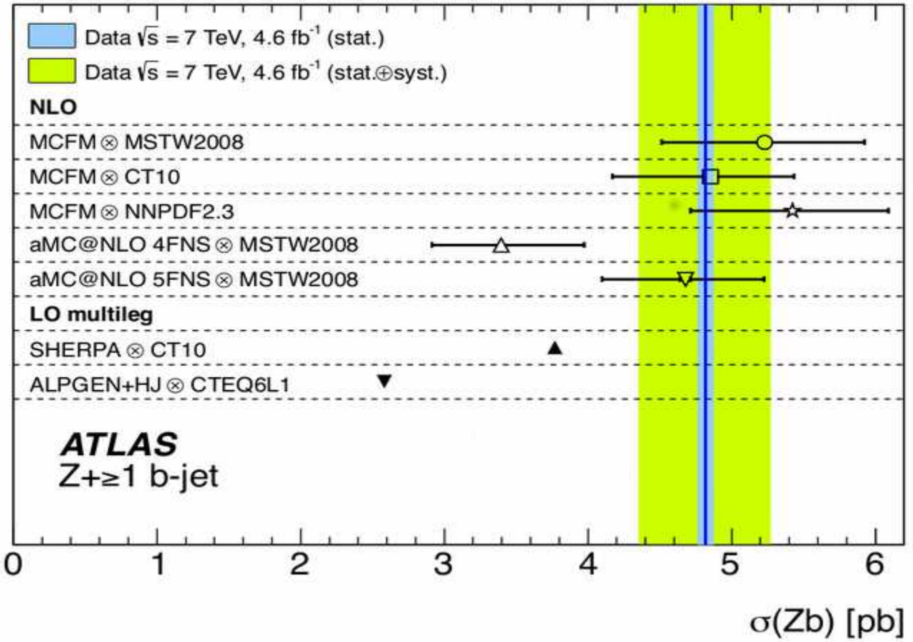
Heavy Quarks : … *current example*

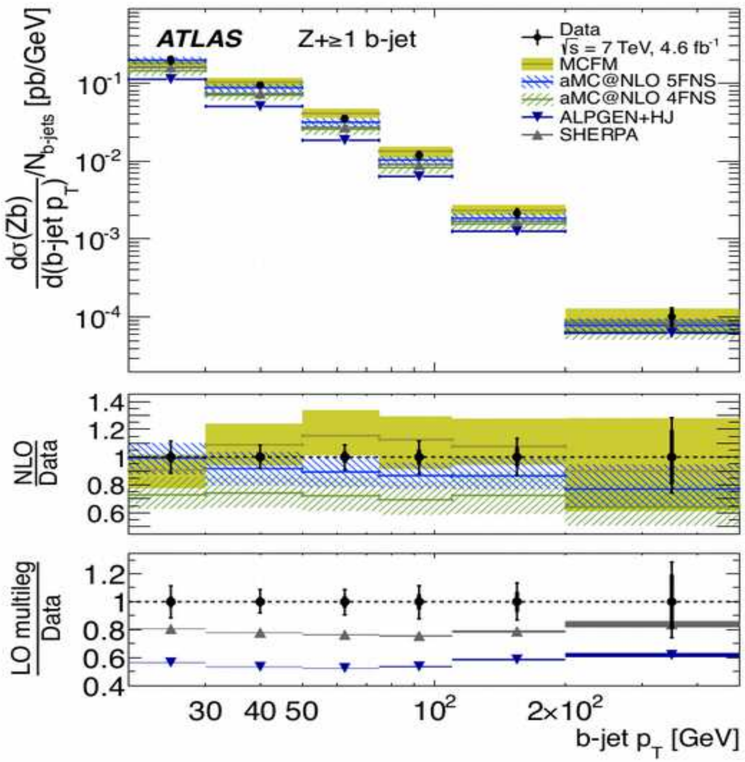
Heavy flavor: Z+b-jets

JHEP 10 (2014) 141

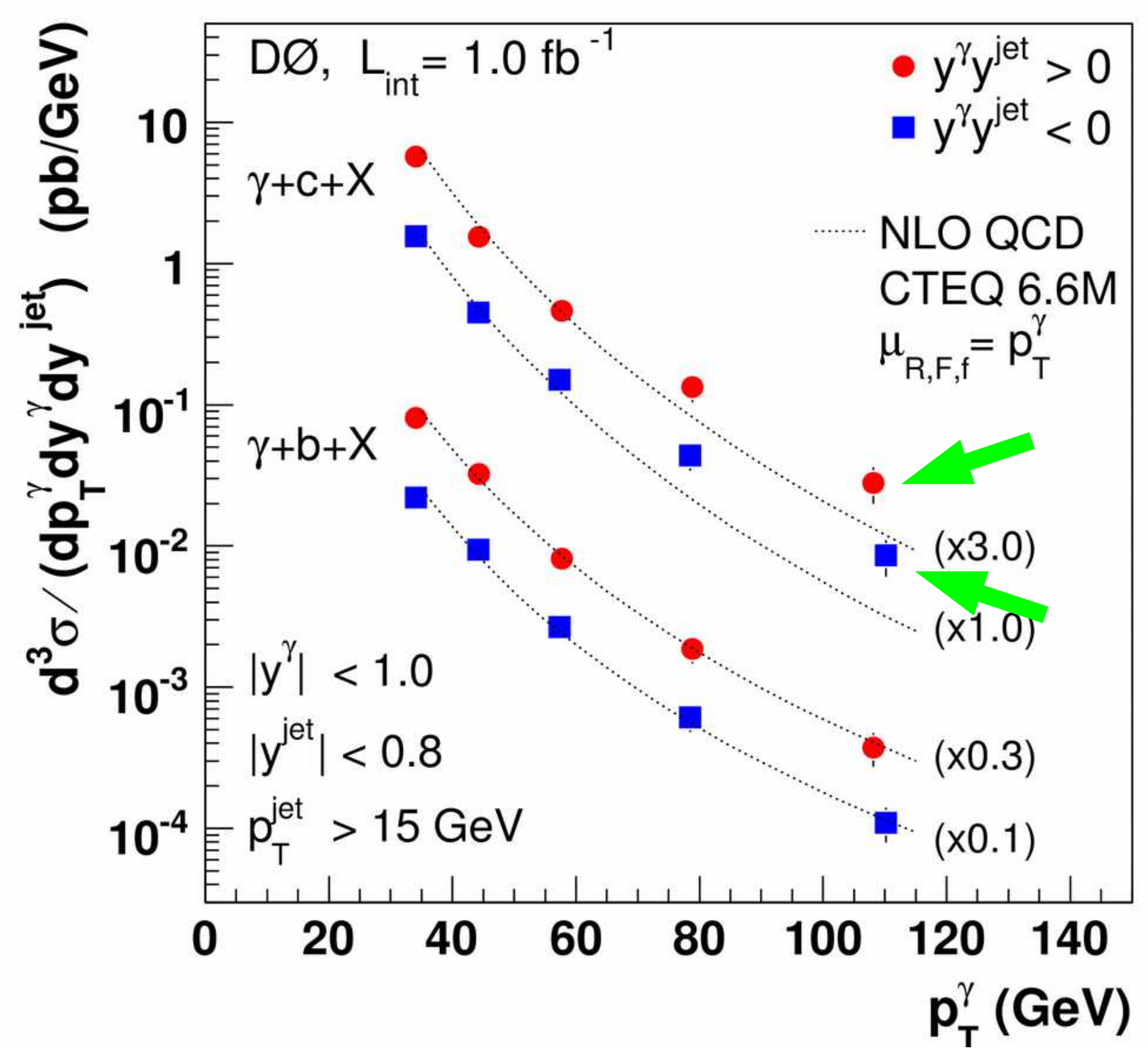
- Good agreement with NLO MCFM and aMC@NLO
  - Seems to favor scheme where b-quark is taken from PDF (5 FNS)
  - LO+PS generators are underestimating the cross section
  - Can't constrain PDF yet due to too large uncertainty

- Good description of b-jet p_T shape
  - Normalization is off





... what about the *Intrinsic* Heavy Quarks

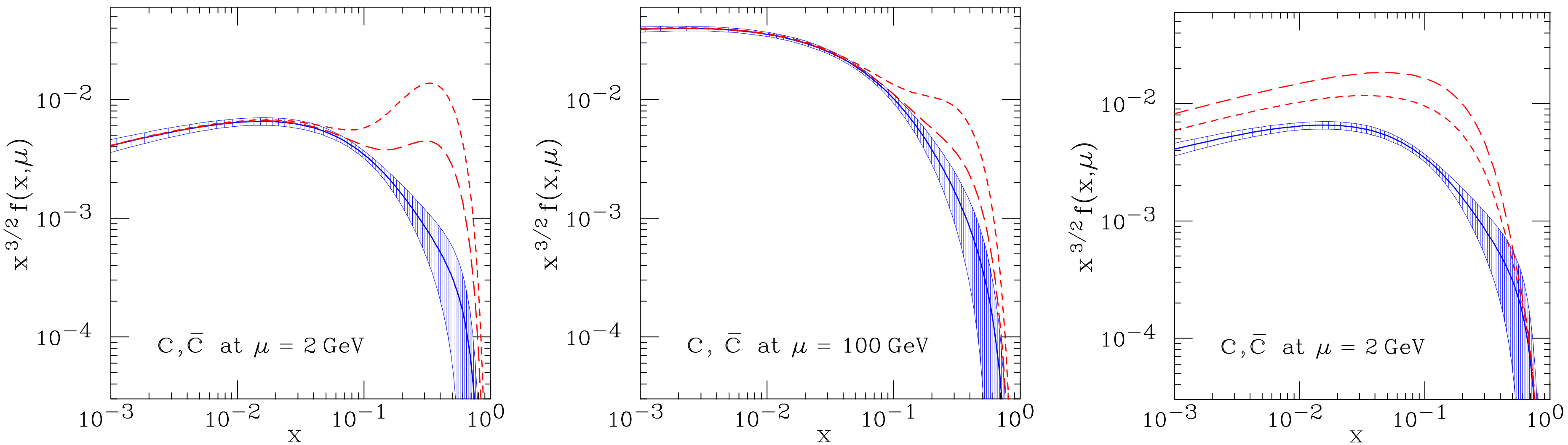


Excess in Charm,
NOT Bottom

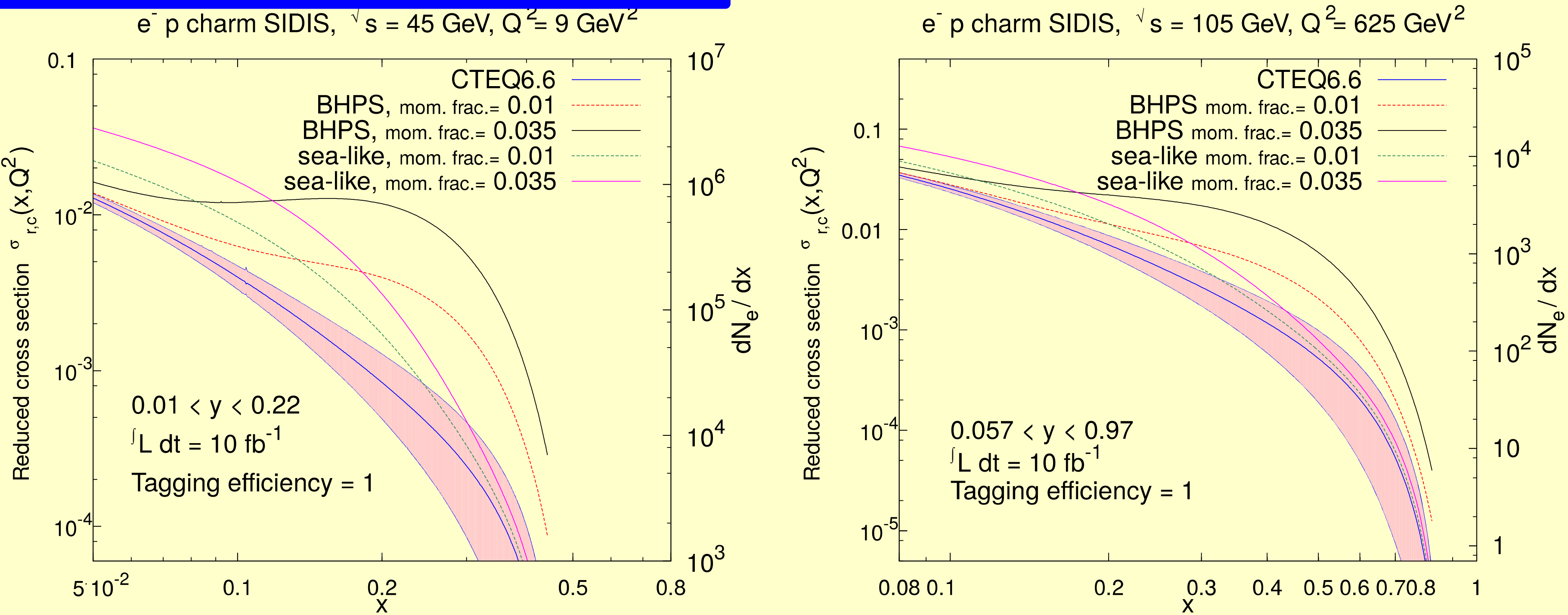
only at high PT

D. Duggan (D0) arXiv:0906.0136

Intrinsic Charm PDFs



Gluons and the quark sea at high-energies
Institute for Nuclear Theory in Seattle in Fall 2010.



New & Improved!!! ... "intrinsic" PDFs

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

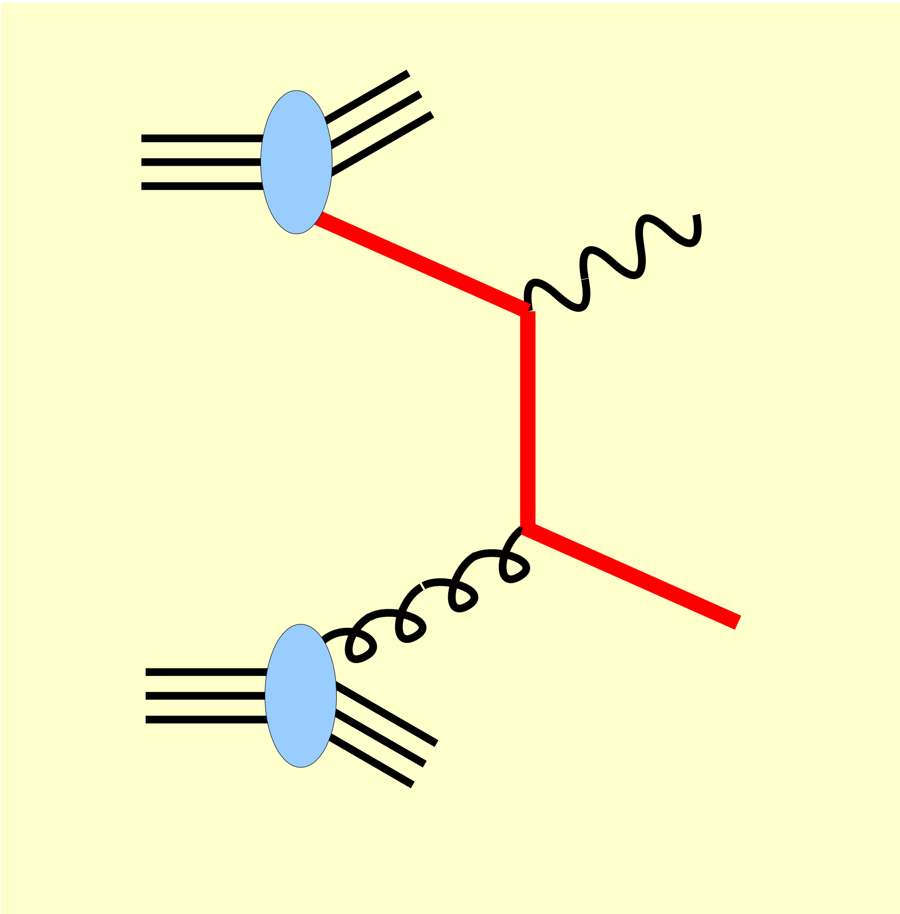
Equations decouple:
- Intrinsic component evolves independently
- Scale set by m_Q
- Adjust normalization by simple rescaling

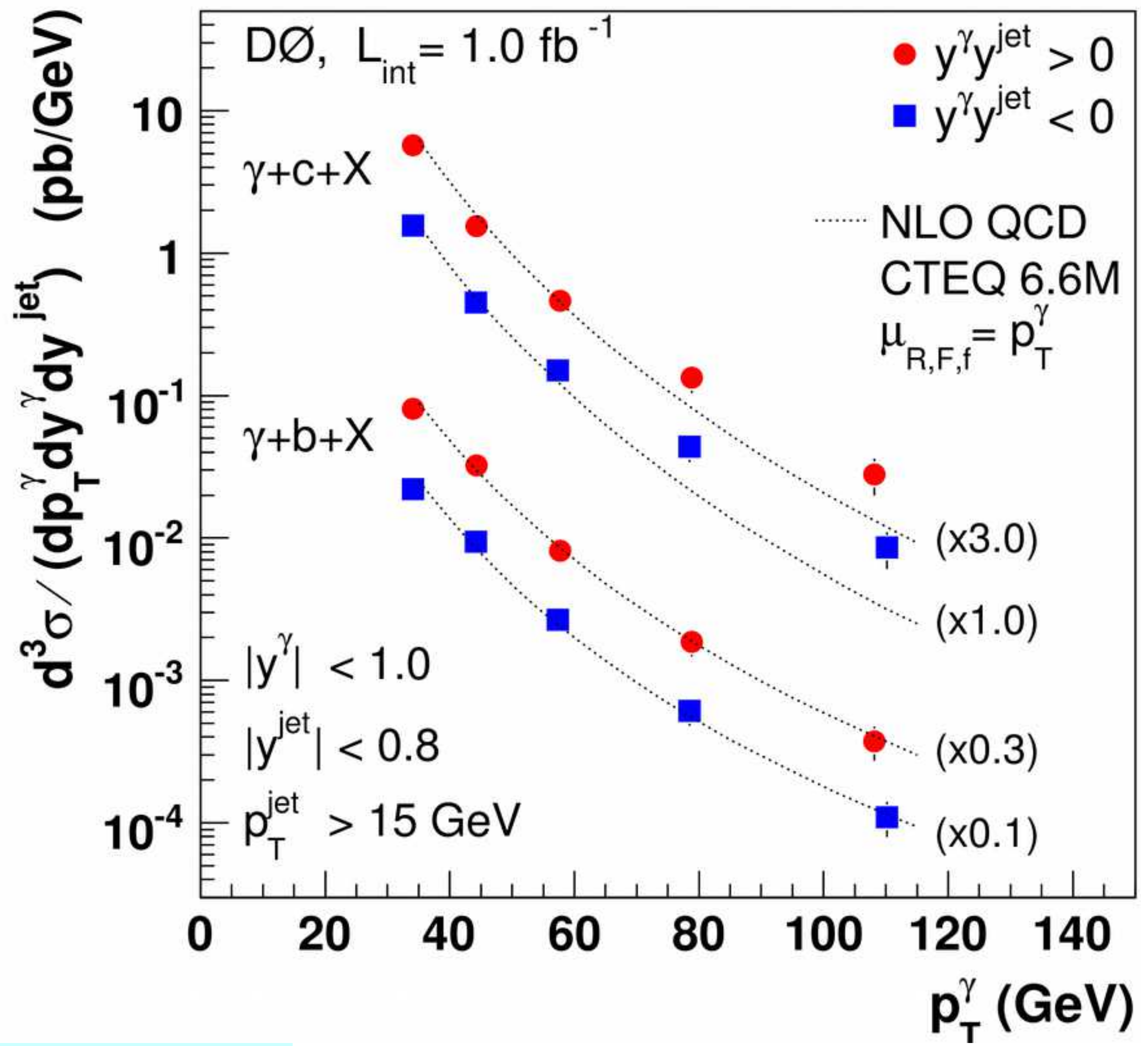
$$\dot{Q}_1 = P_{QQ} \otimes Q_1 .$$

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

JHEP 1507 (2015) 141 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 *arXiv:1504.05156:*

Tevatron & LHC can Access Heavy Flavor Components Directly





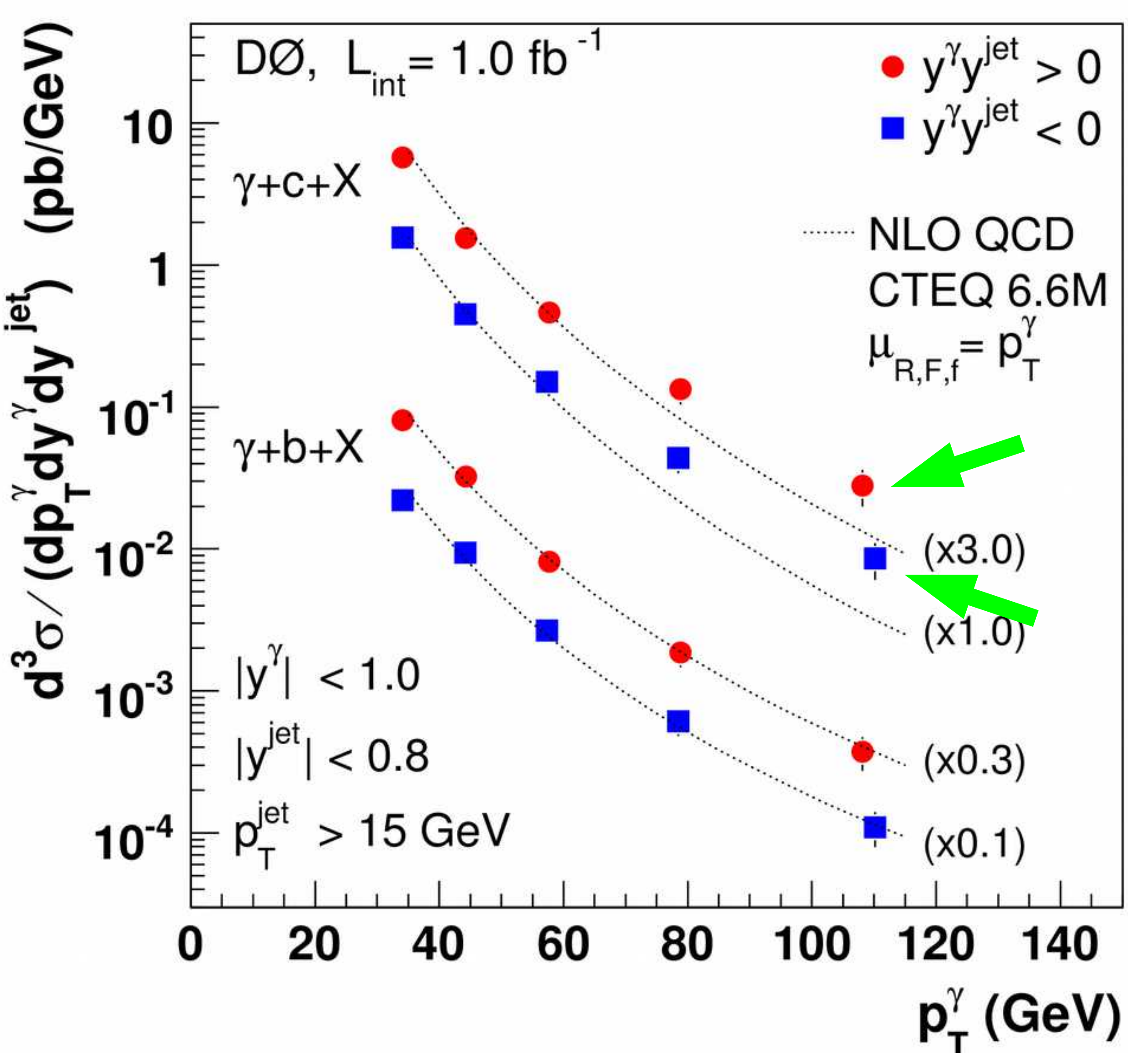
$c\ g \to c\ \gamma$

$b\ g \to b\ \gamma$

$s\ g \to c\ W$

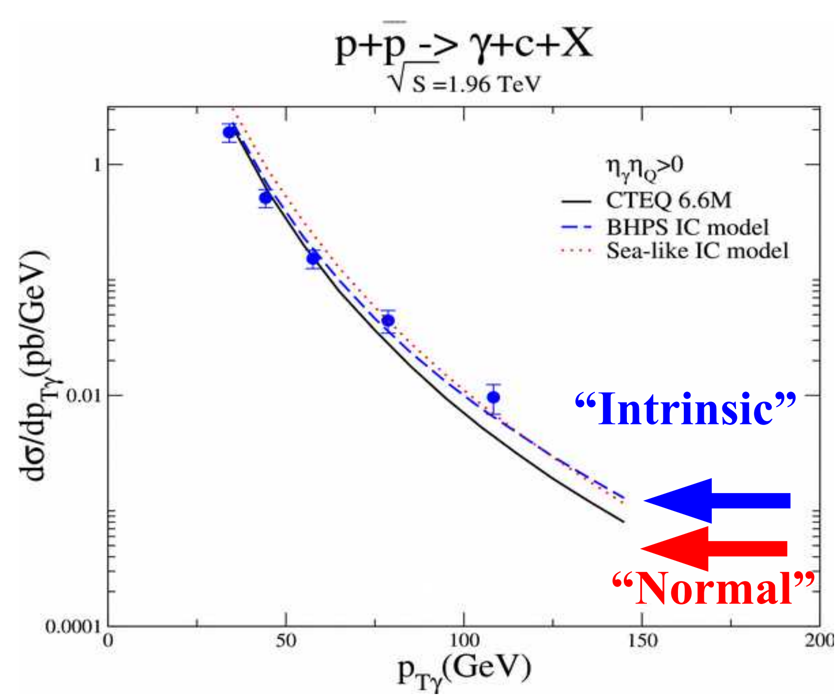
$c\ g \to b\ W$

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



Excess in Charm, NOT Bottom

only at high PT

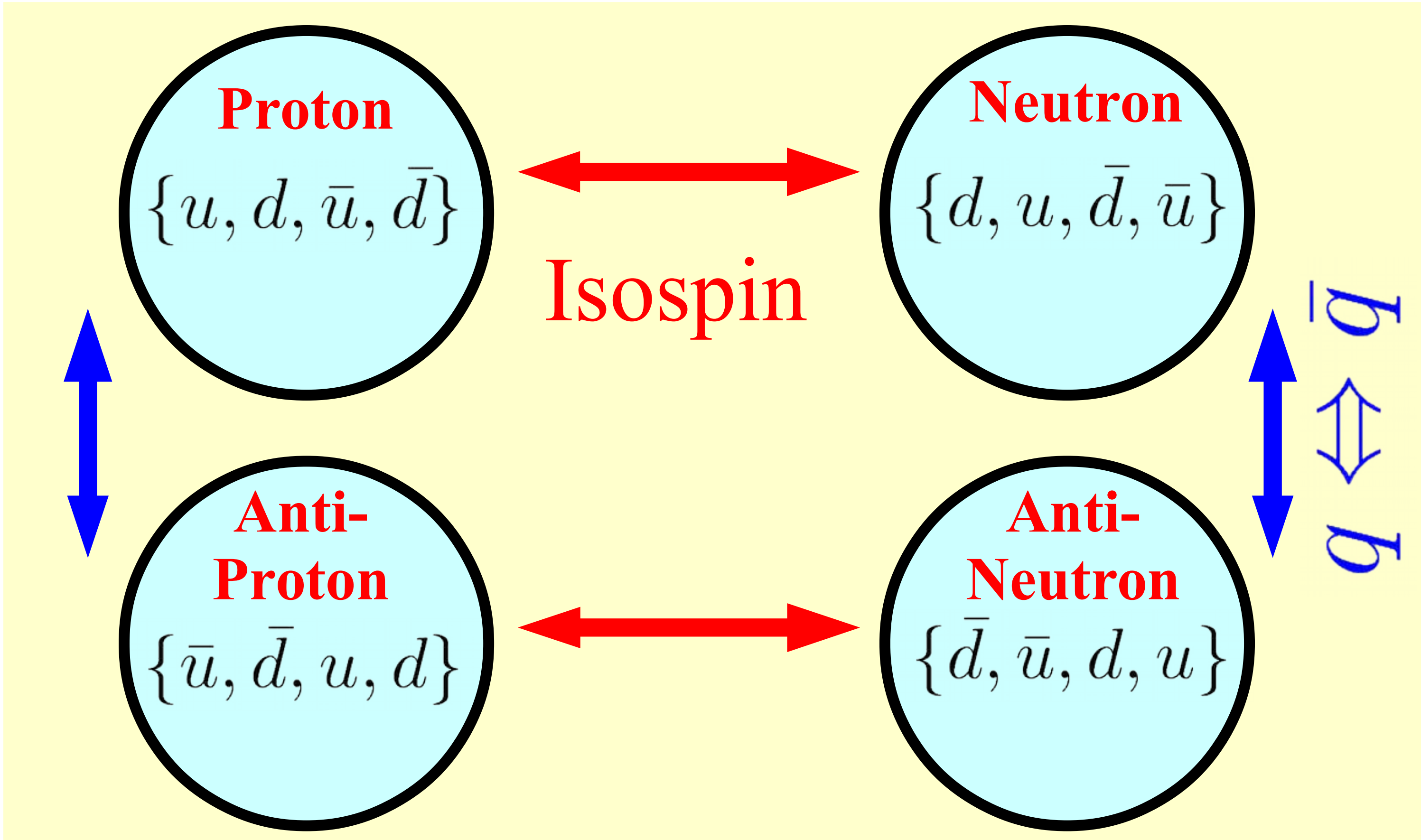


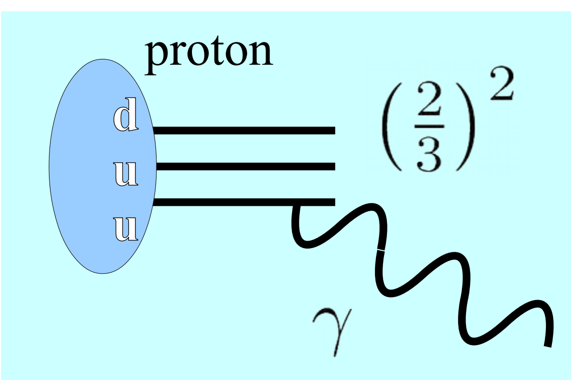
D. Duggan (D0) arXiv:0906.0136

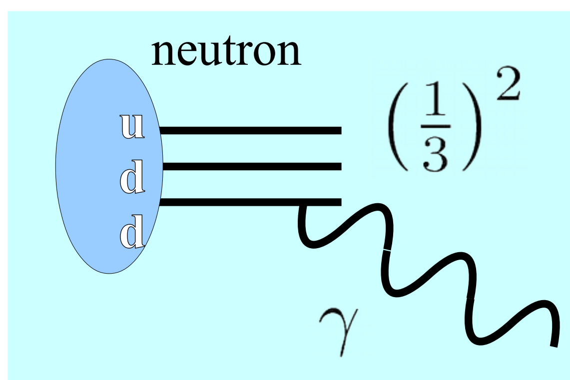
T. Stavreva, I. Schienbein, F. Arleo, K. Kovarik, F. Olness, J.Y. Yu, J.F. Owens, JHEP 1101 (2011) 152

Things I won't have time to discuss

Isospin Symmetry used to relate PDFs





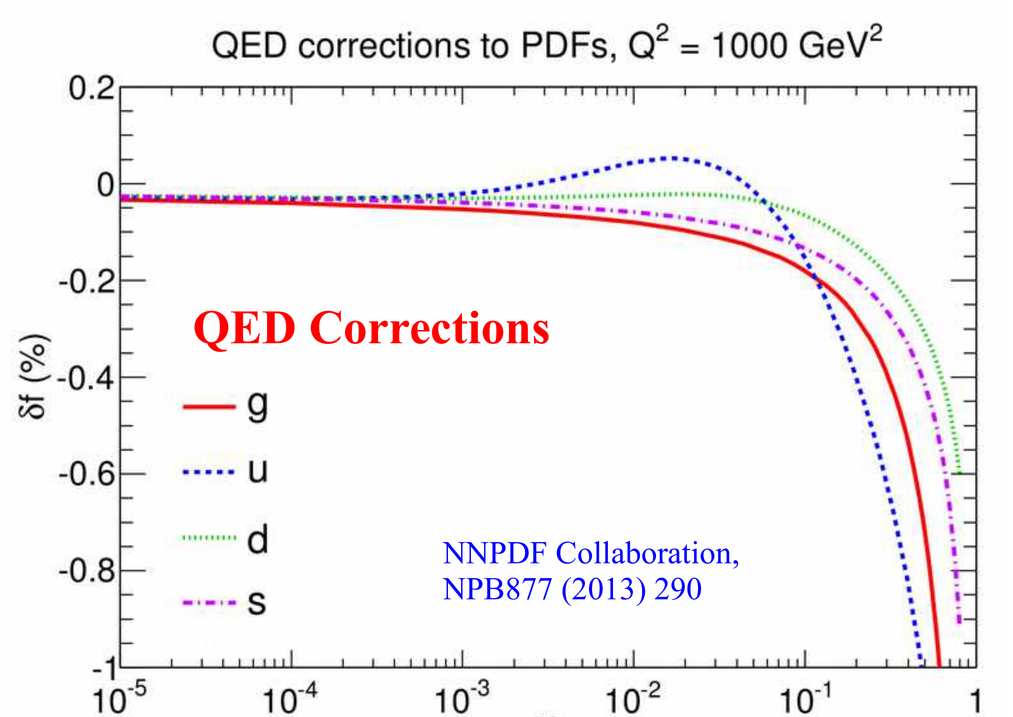


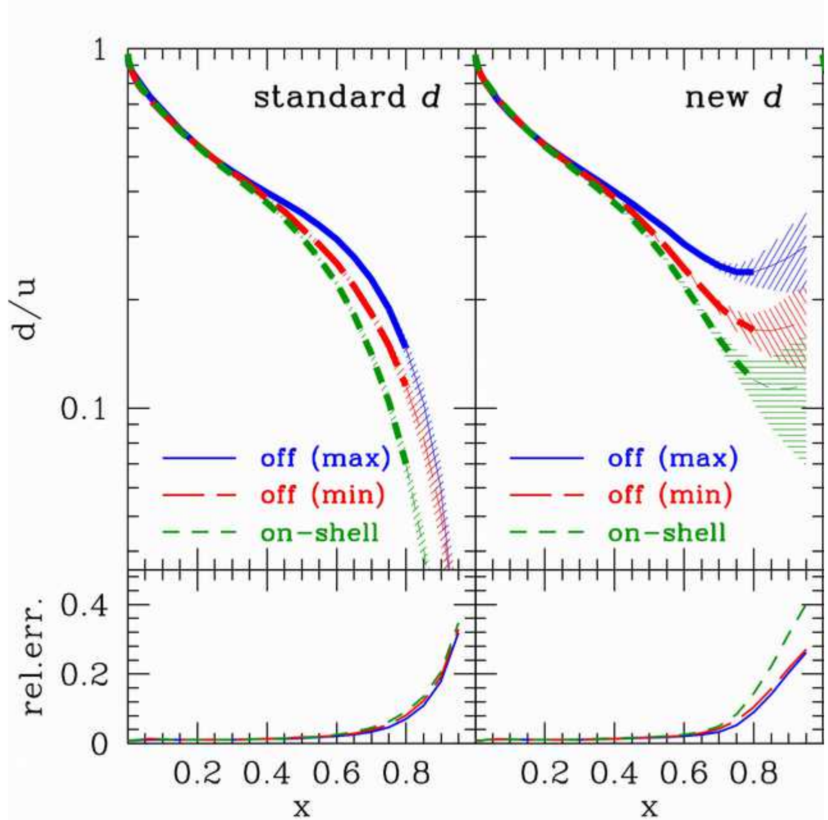
Isospin terms are comparable to NNLO QCD

QCD & EW Corrections do NOT factorize

A Review of Target Mass Corrections.
Ingo Schienbein et al,
J.Phys.G35:053101,2008.

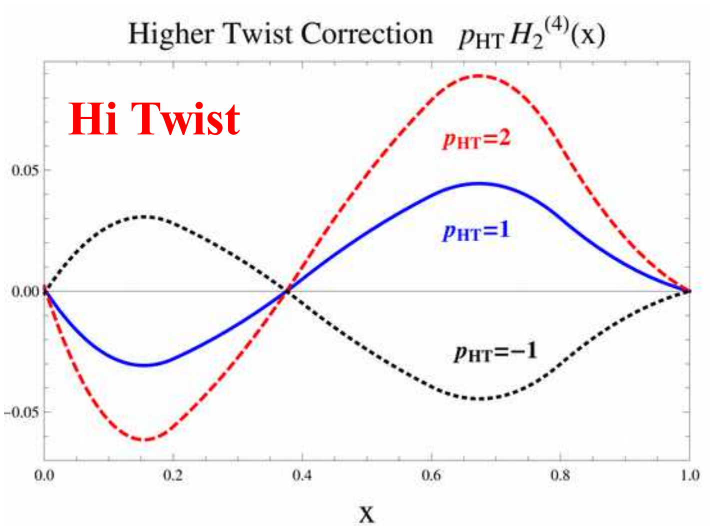
Hi-x Issues: Isospin Symmetry Violation, Higher Twist, ...

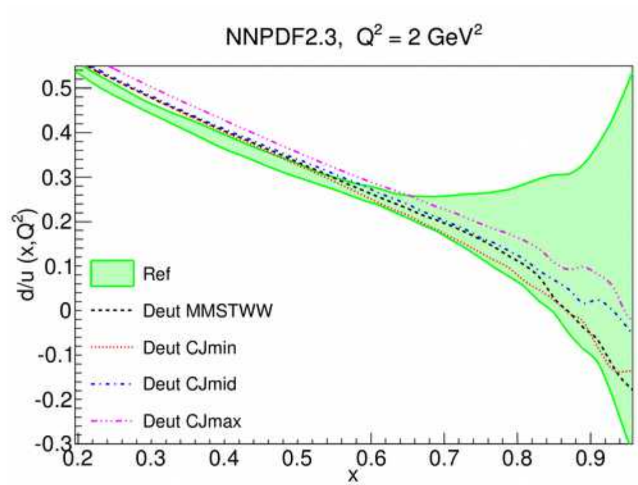


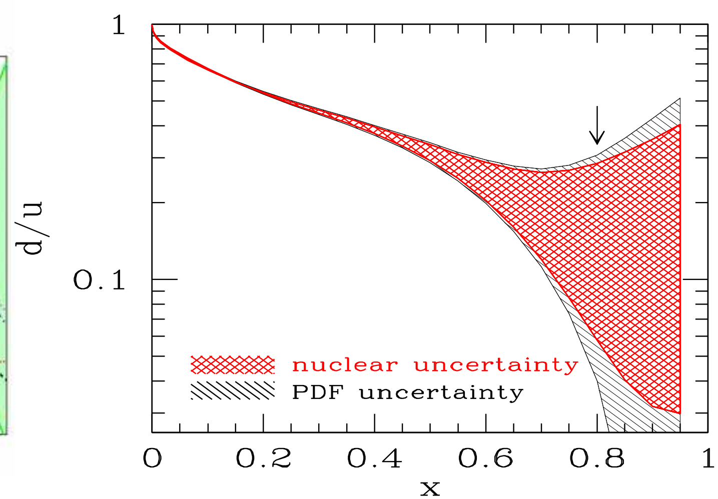


Nuclear Corrections or Parameterization???

Hi-x is a "Gold Mine" for EIC







The NNPDF Collaboration, PLB723 (2013) 330

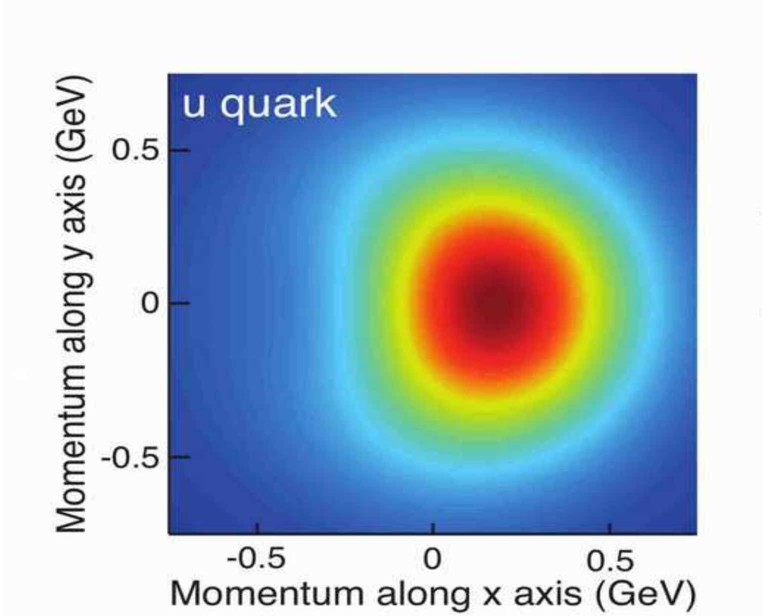
CTEQ-CJ: Phys.Rev. D84 (2011) 014008

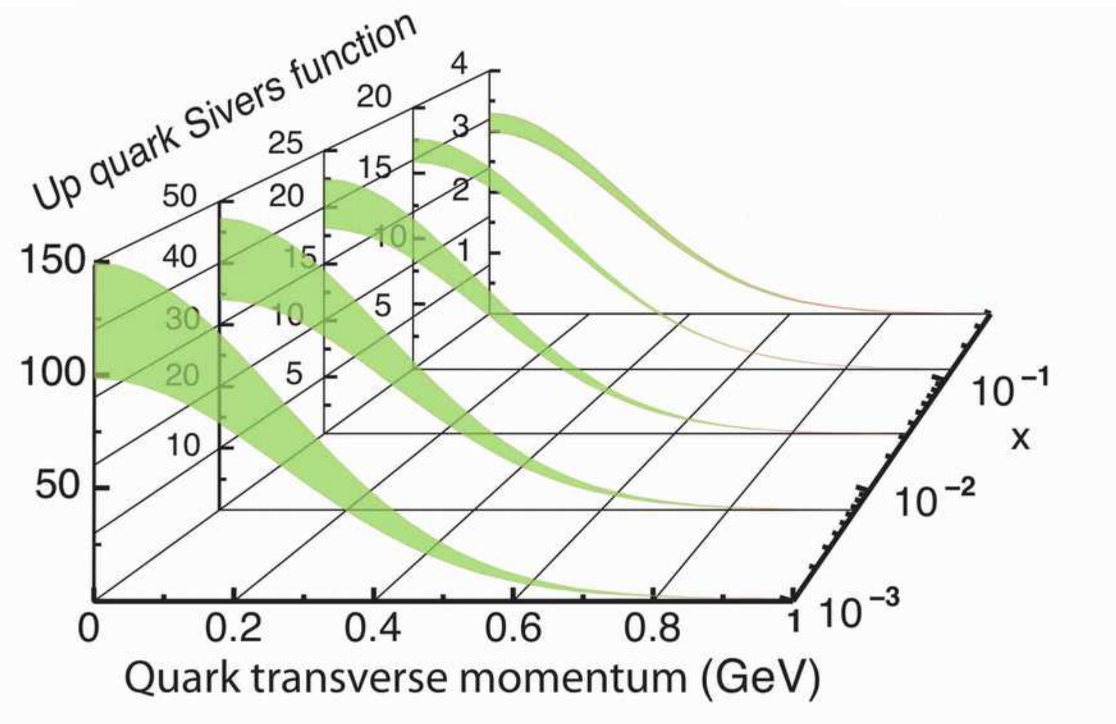
TMD & Generalized PDFs

previously discussed by: Rolf Ent & Michael Engelhardt

Kresimir Kumericki
Curse of dimensionality

Lattice Calculations





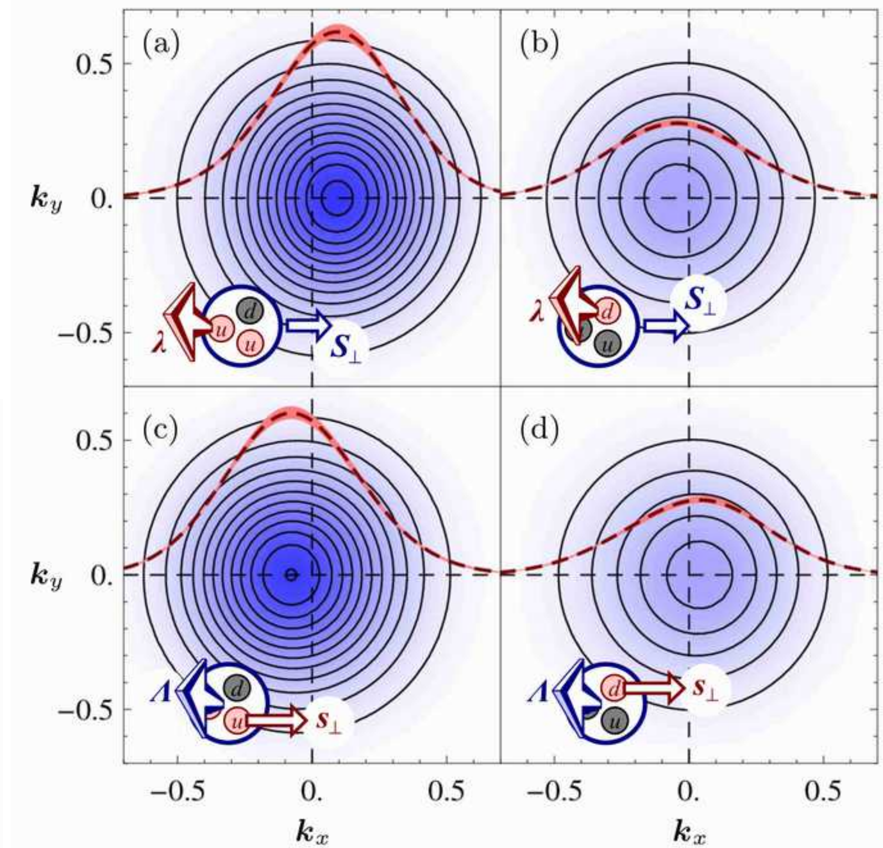


FIG. 3: Quark densities in the $k_\perp$-plane, for $m_\pi \approx 500$ MeV. (a) ρ_L for u-quarks and $\lambda = 1$, $S_\perp = (1, 0)$, (b) the same for d-quarks, (c) ρ_T for u-quarks and $\Lambda = 1$, $s_\perp = (1, 0)$, (d) the same for d-quarks. The error bands show the density profile at $k_y = 0$ as a function of k_x (scale not shown).

Intrinsic quark transverse momentum in the nucleon from lattice QCD
Hagler et al., TUM/T39-09-08

Two Particle Correlations

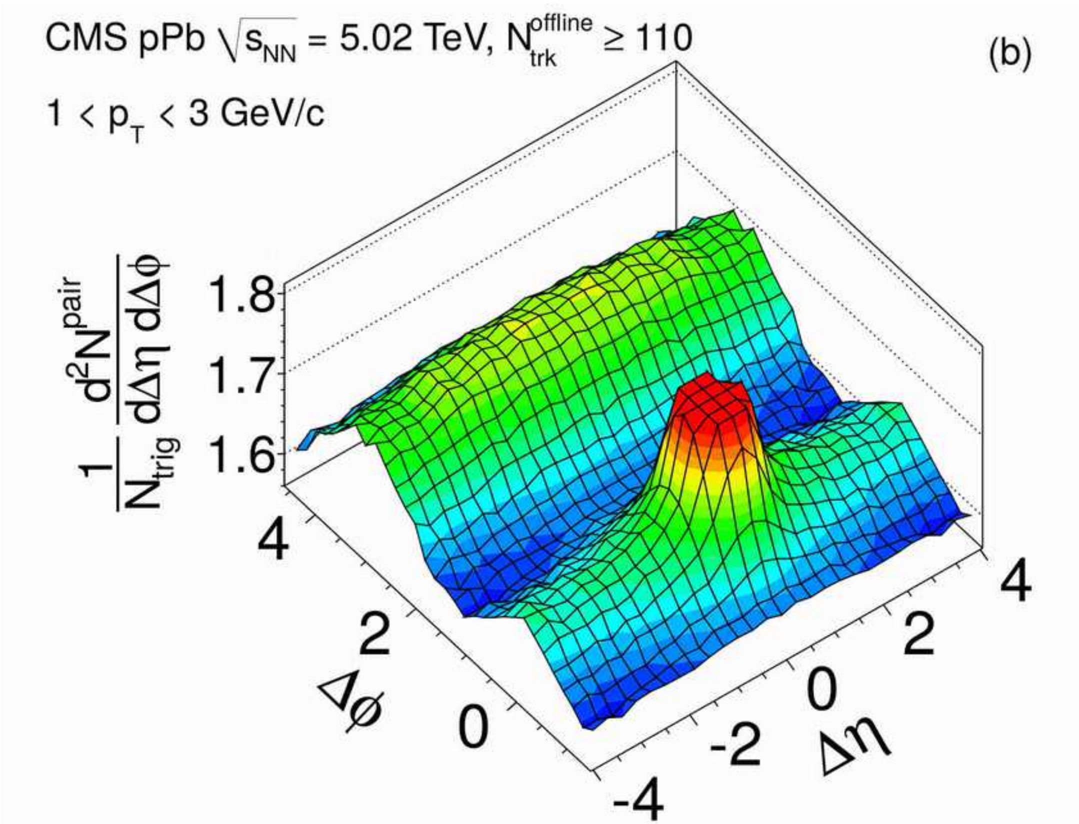
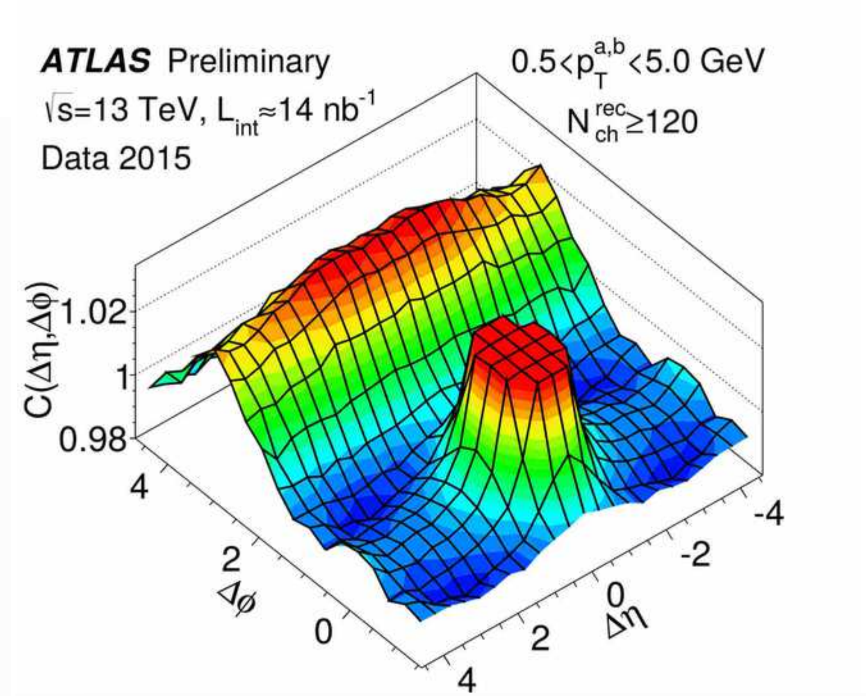
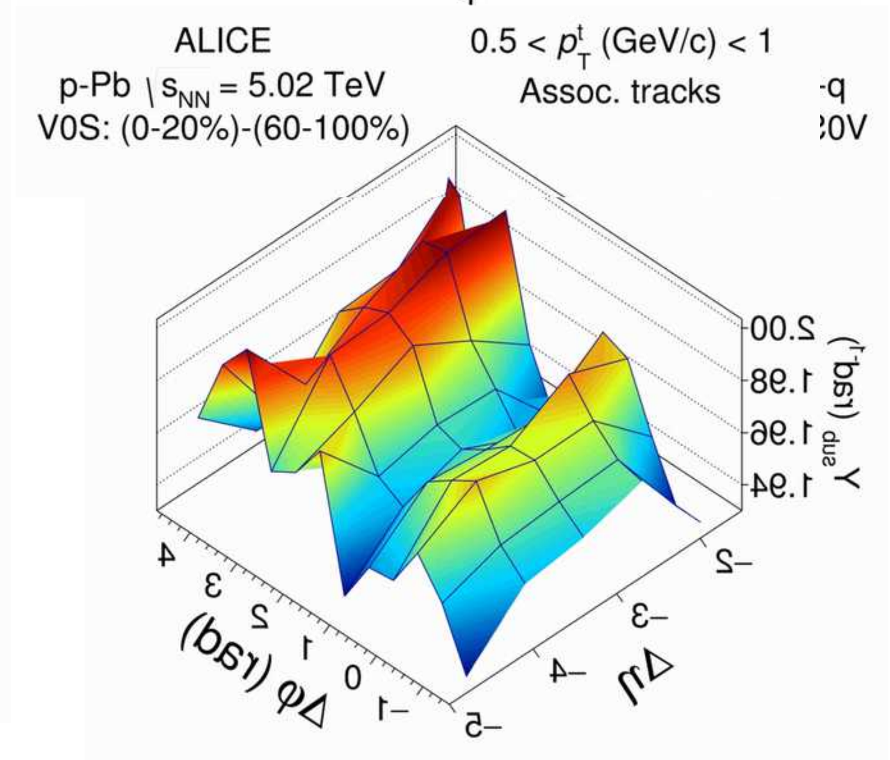


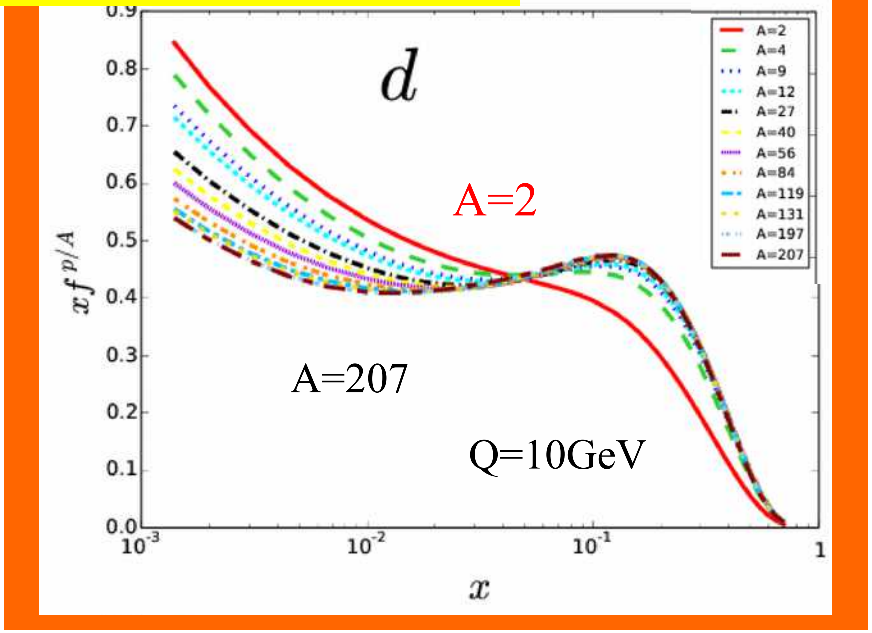
Figure 3.33: The two-particle correlation function in high-multiplicity p+Pb collisions as a function of $\Delta\phi$ and $\Delta\eta$ reported by the CMS collaboration [252]. The 'ridge' structure is seen as a correlation near $\Delta\phi = 0$ stretching over many units of rapidity $\Delta\eta$.



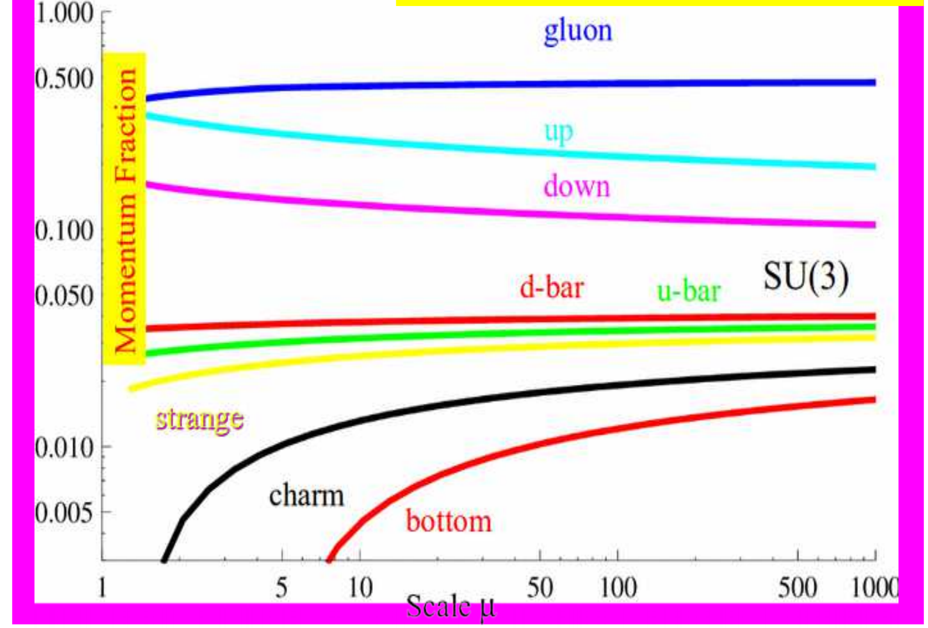


Conclusion

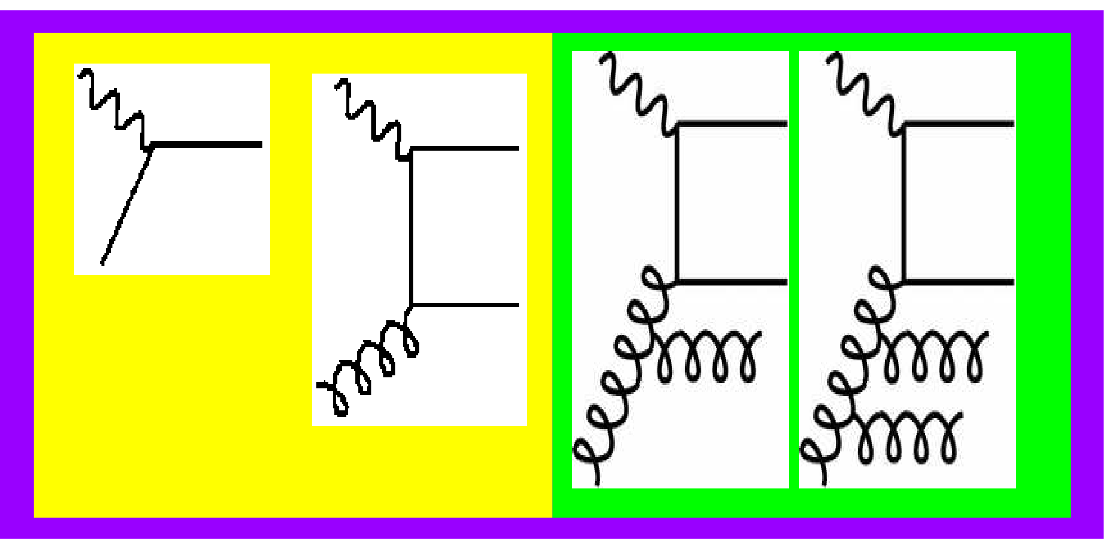
Nuclear Corrections & Flavor Differentiation



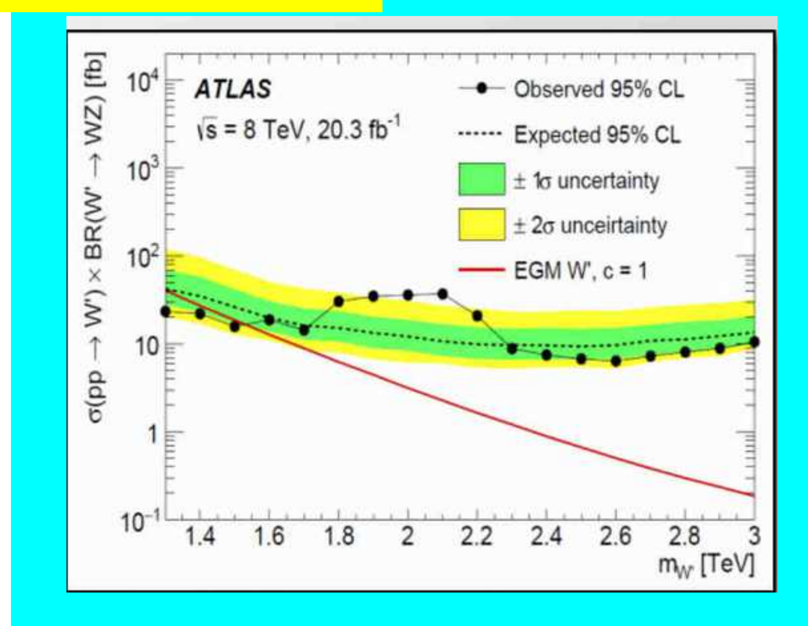
Multi-Scale Processes & Heavy Quarks



Higher Order Processes



Search for new physics



Thinking Outside the PDF

"QCD is our most perfect physical theory"

DGLAP violation???

saturation

resummation

QCD

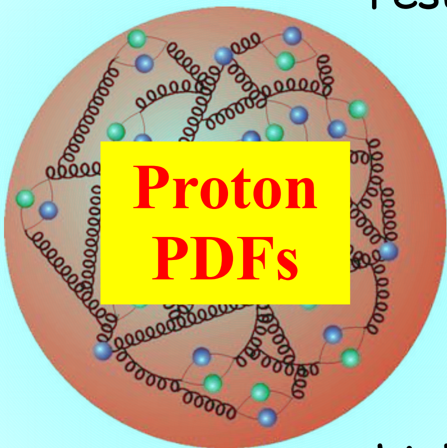
QED

hi-x

low-Q^2

higher twist

non-linear QCD



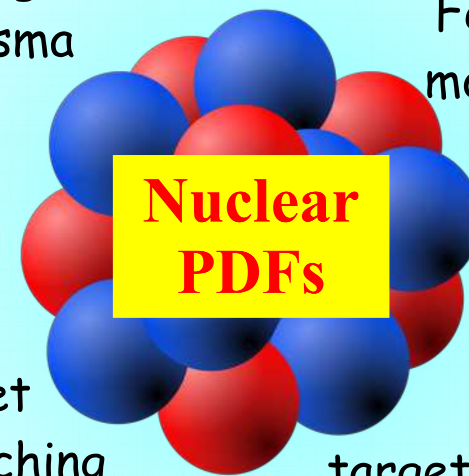
communication

e.g. flavor differentiation

isospin violation

quark-gluon plasma

Fermi motion

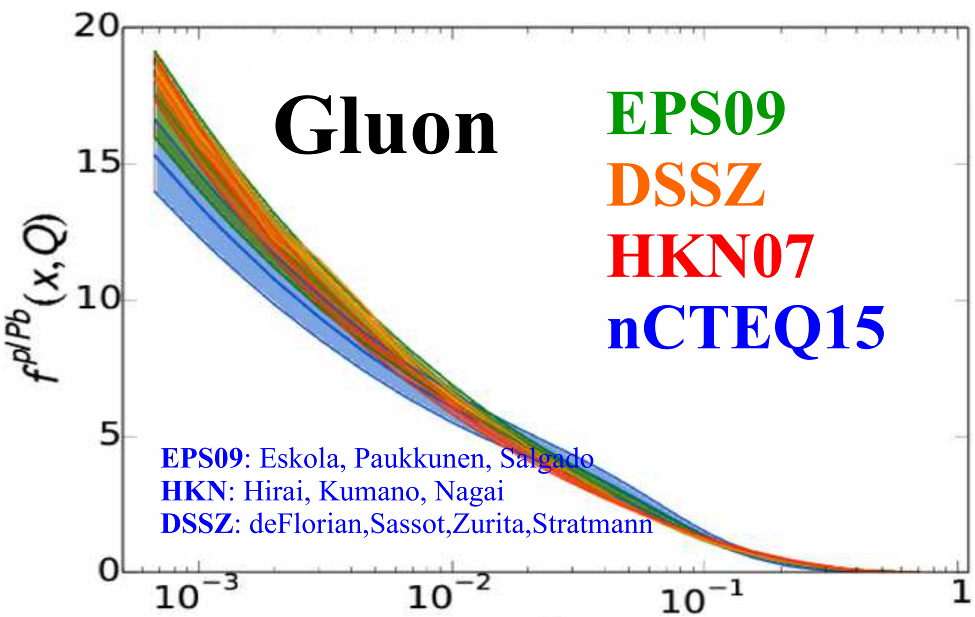


jet quenching

shadowing

target mass corrections

1) Flavor Differentiation & Nuclear Corrections
2) Multi-scale problems: Heavy Quarks Resummation
3) Hi-Order Corrections



Lessons: The Nature of Nature
… alien, simple, beautiful, weird, & comprehensible