Precision QCD:

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

Santa Fe Jets and Heavy Flavor Workshop
11-January 13, 2016

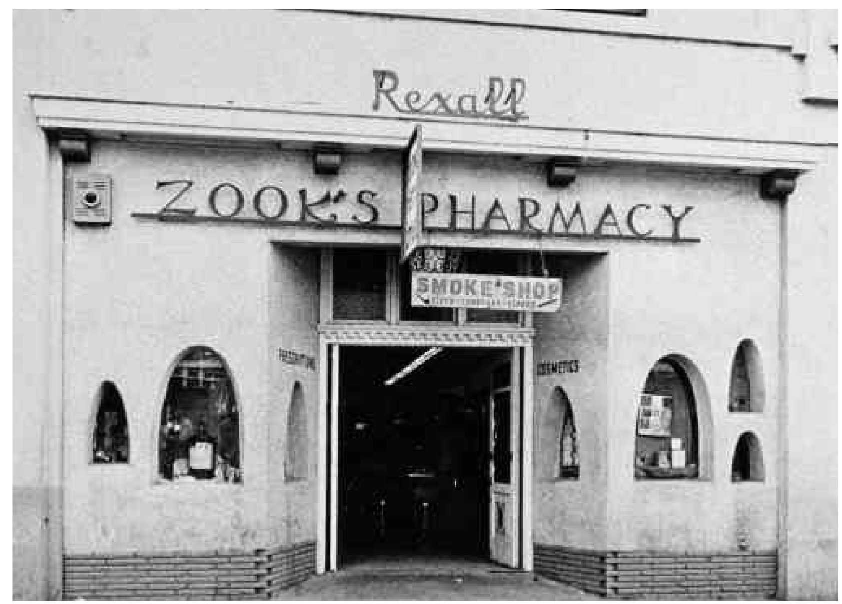
An exciting PLACE for physics

109 East Palace
Dorothy Scarritt McKibbin
Gateway to Los Alamos

P.O. Box 1663

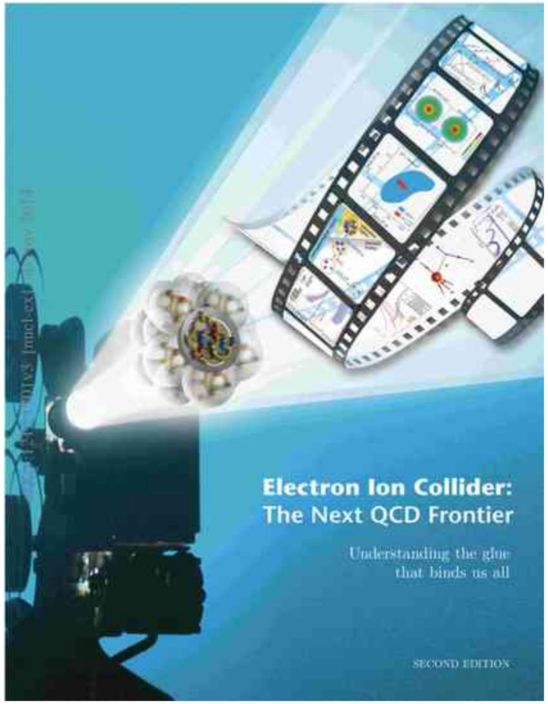
La Fonda Hotel:

a favorite watering hole for the scientists and their wives who ventured down from the Hill for a taste of civilization during the Manhattan Project.



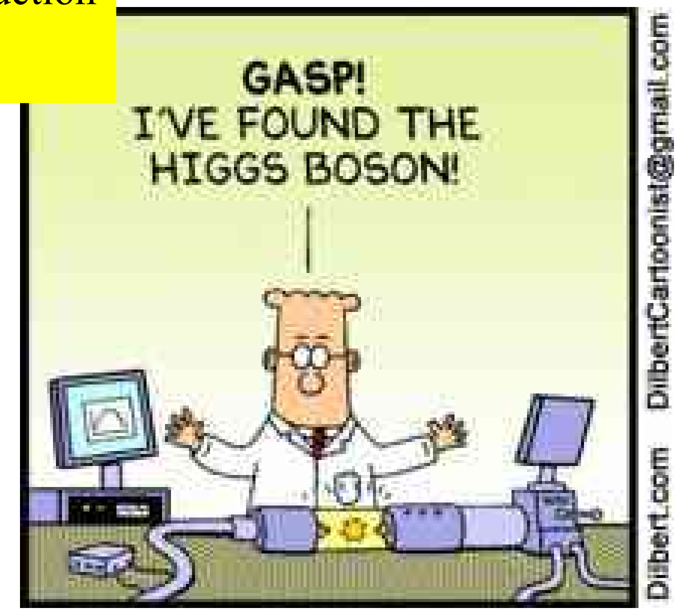
'Book links Trotsky assassin to Plaza pharmacy, now Haagen-Dazs shop

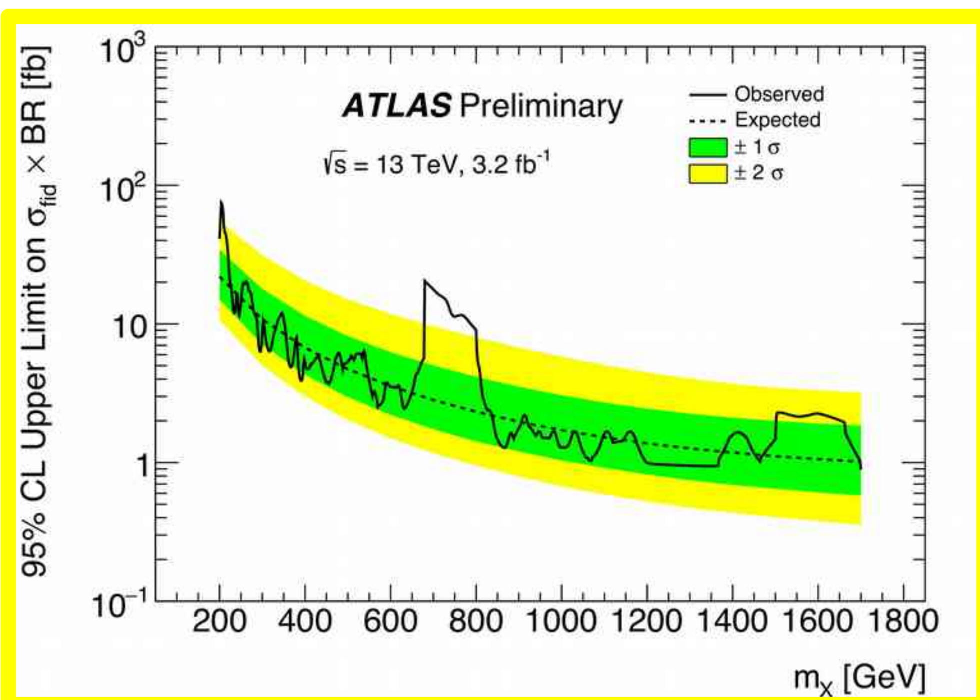
An exciting time for physics



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.





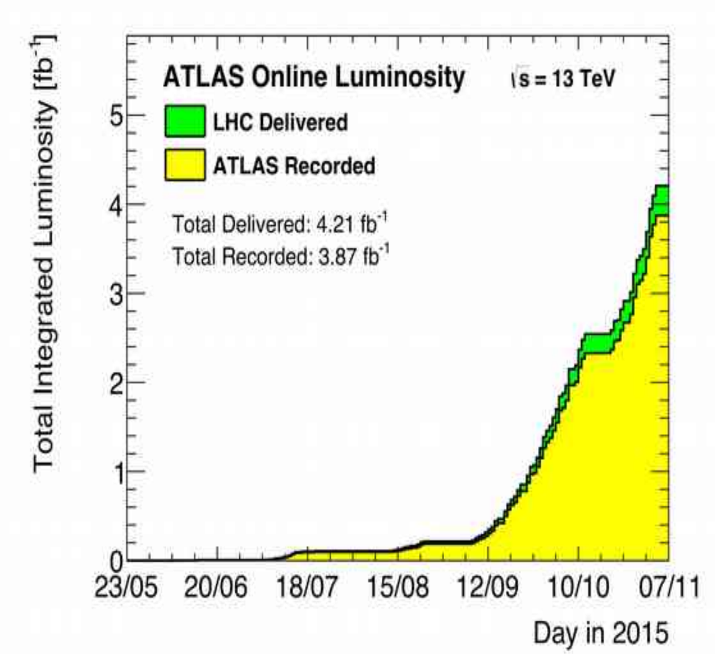
The Key to Discovery: The Parton Model and Factorization

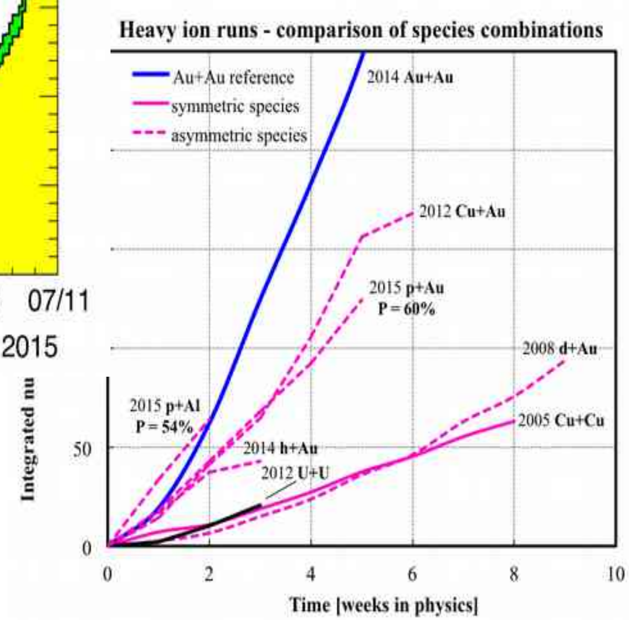
$$\sigma_{P\gamma\to c} = f_{P\to a} \otimes \hat{\sigma}_{a\gamma\to c}$$

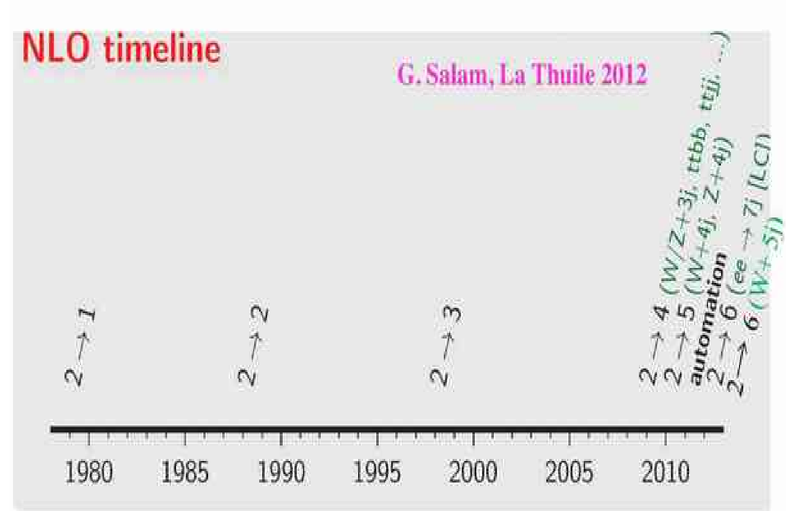
Experimental Observables

WHAT ABOUT PDF'S ???

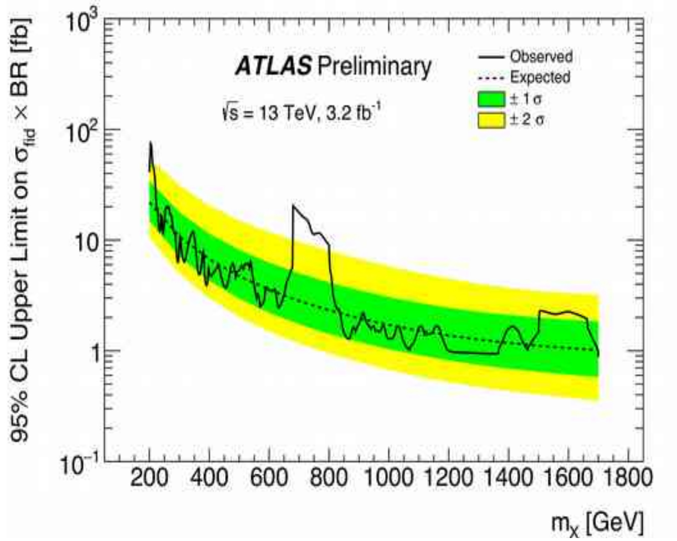
Theoretical Calculations

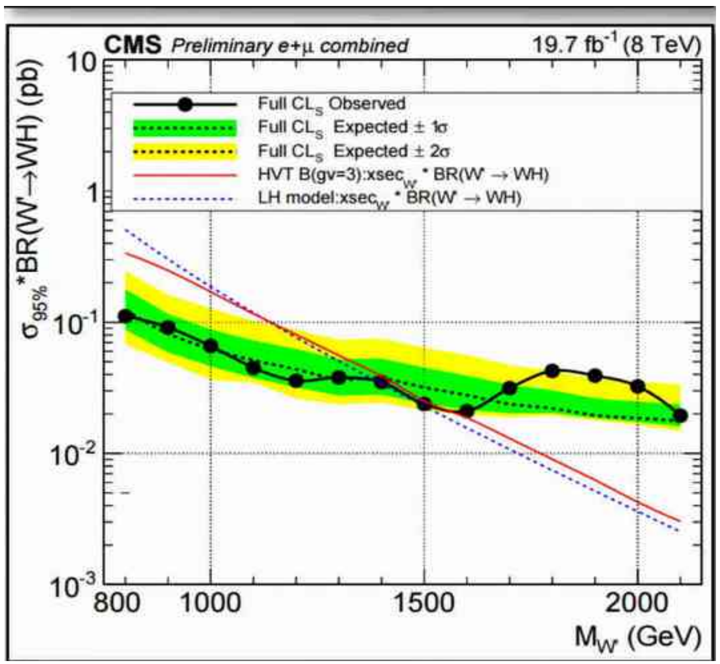


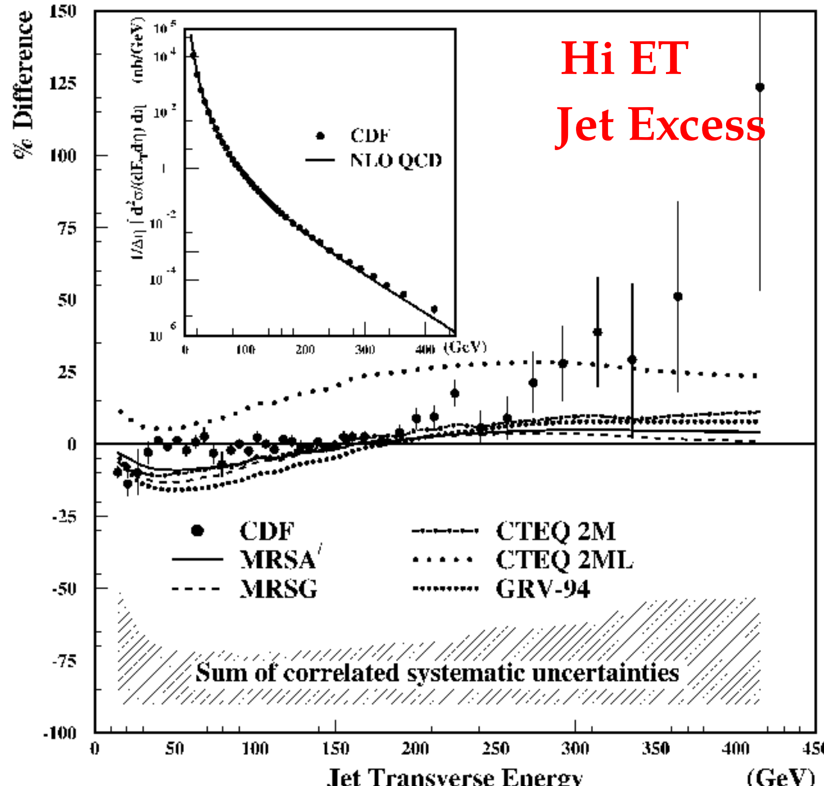




… things that go bump in the data ...

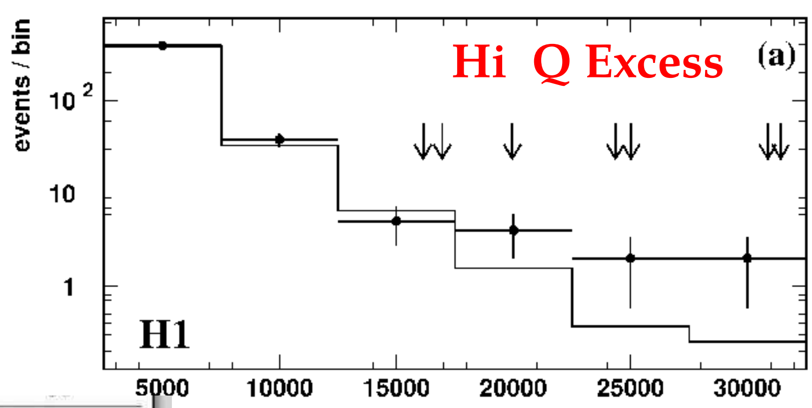




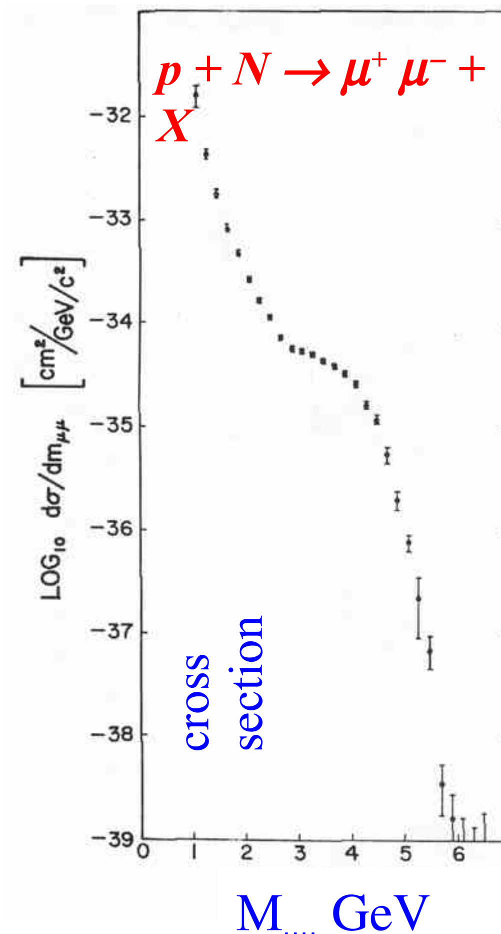


CDF Collaboration, PRL 77, 438 (1996)

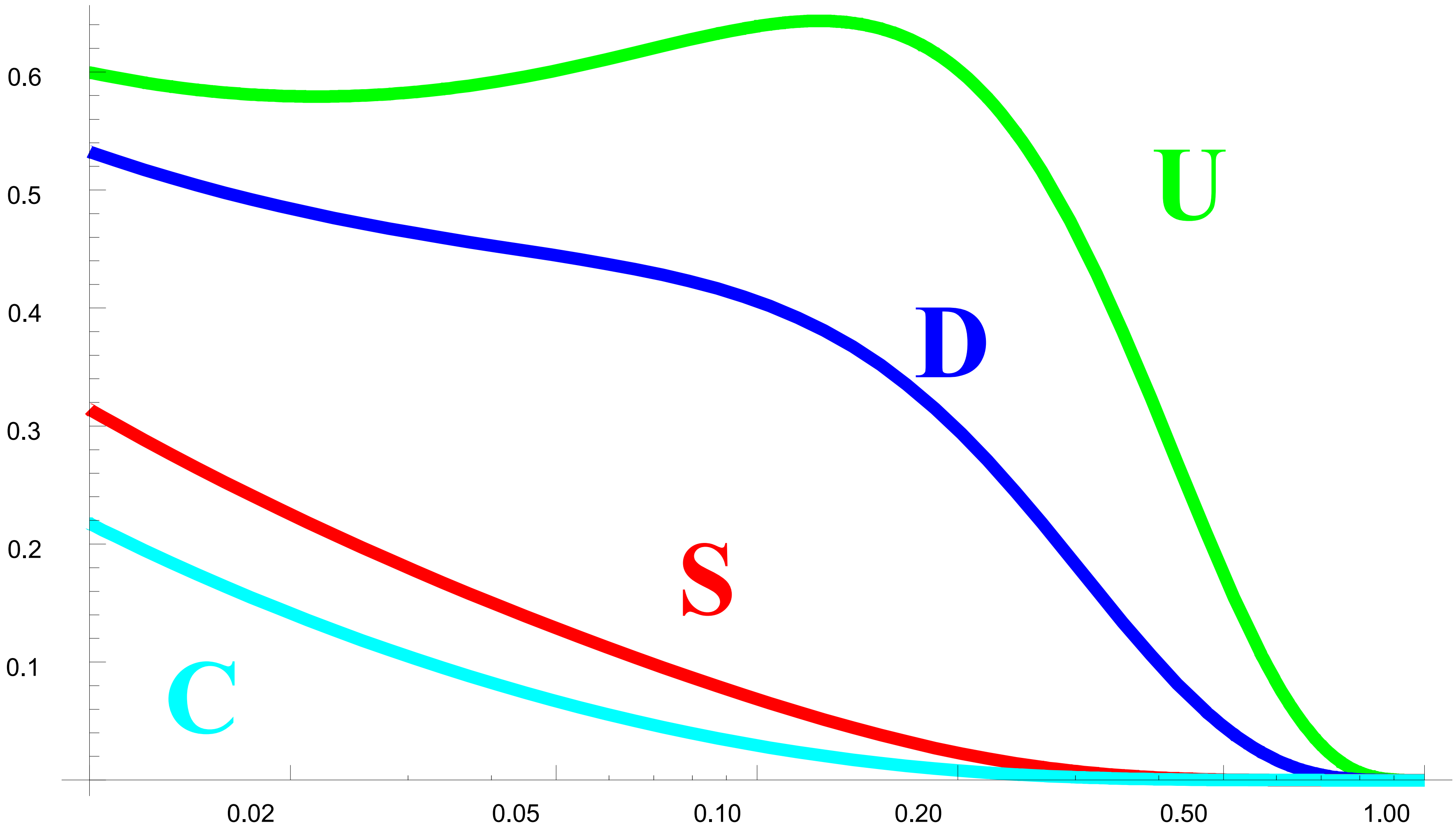
Can you find the Nobel Prize???



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

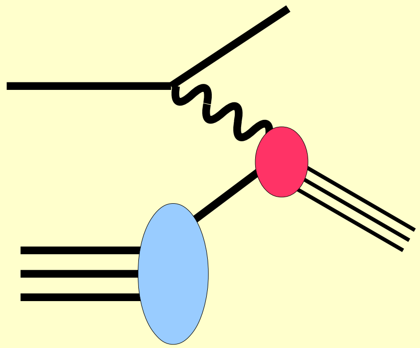


How do we differentiate flavors???

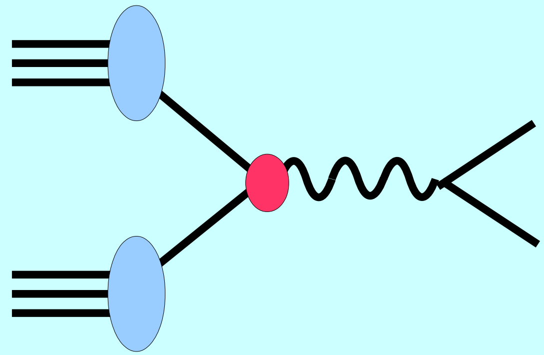


... why do we care about nuclear corrections

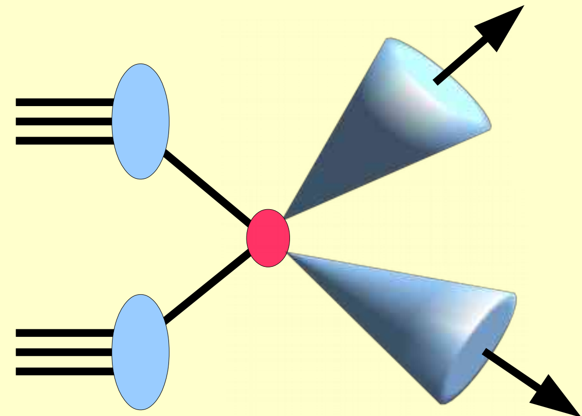
Key Data Sets for Global PDF Fits



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

Different linear combinations – key for flavor differentiation

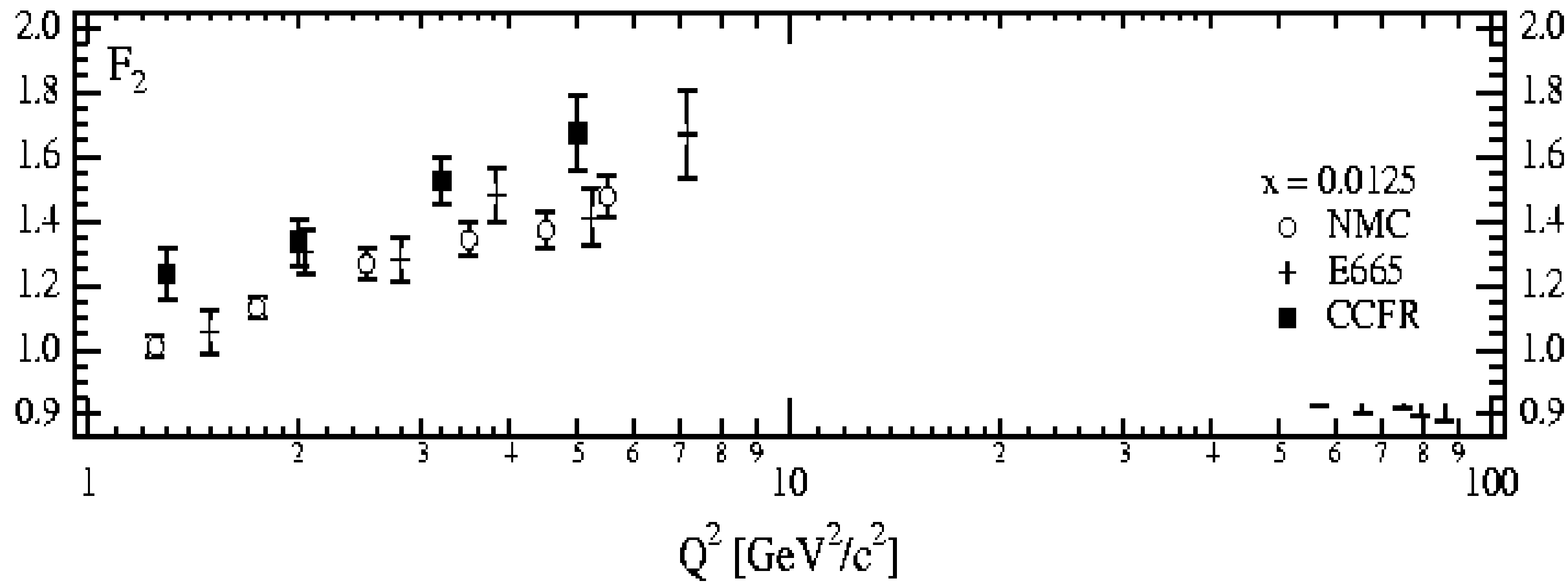
*The ν-DIS data typically use heavy targets, and this requires the application of **nuclear corrections***

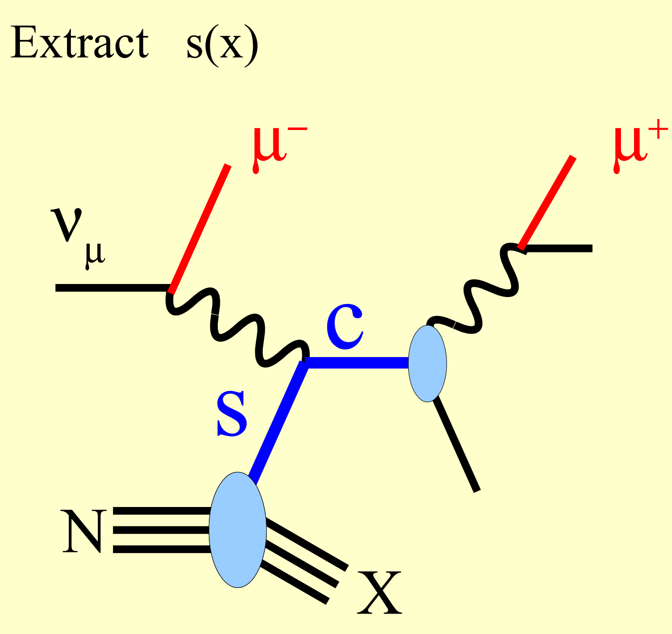
Di-muon production ⇒ Extract s(x) Parton Distribution

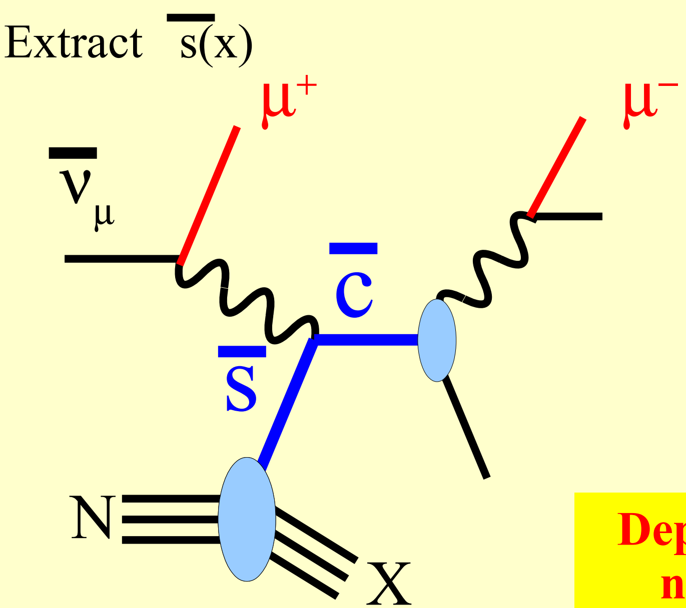
The CTEQ List
of Challenges in
Perturbative QCD

~1995

CTEQ





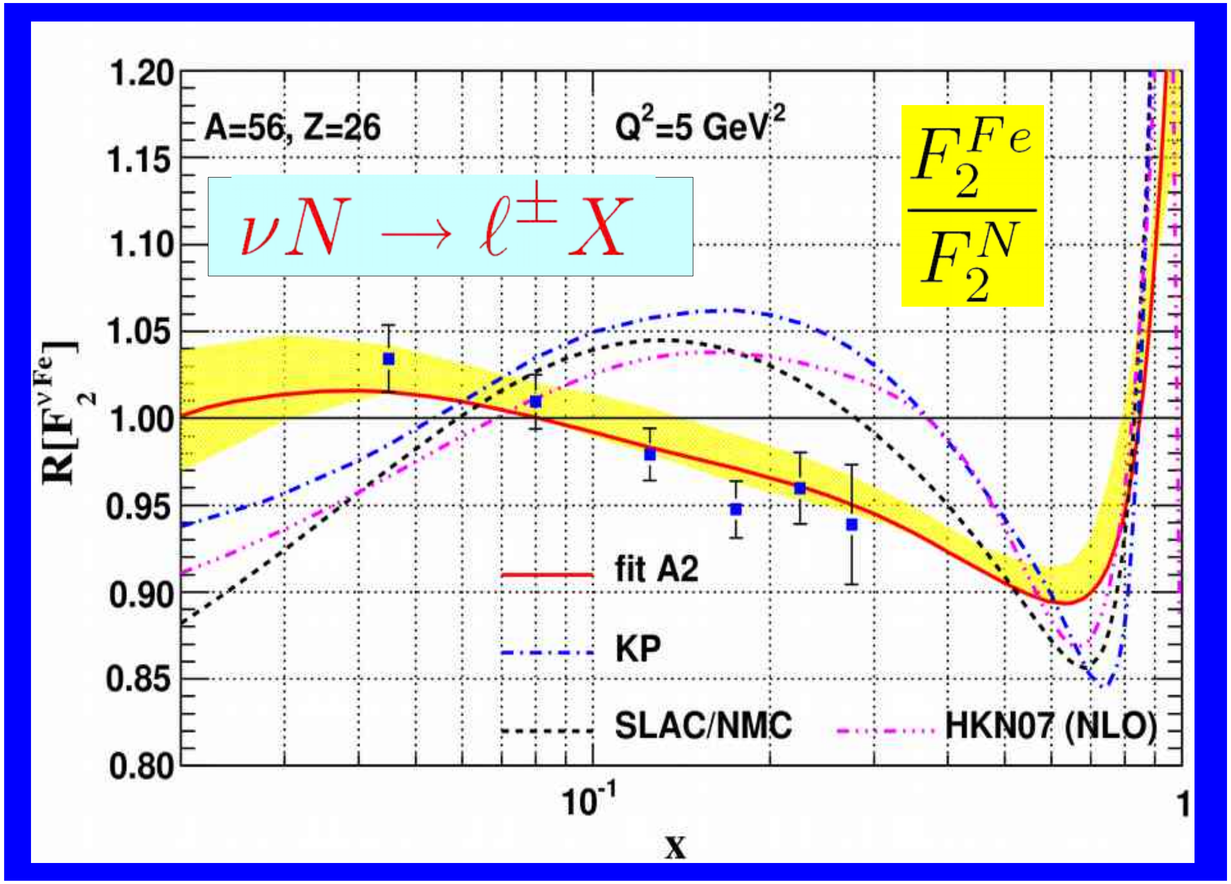


Depends on nuclear corrections

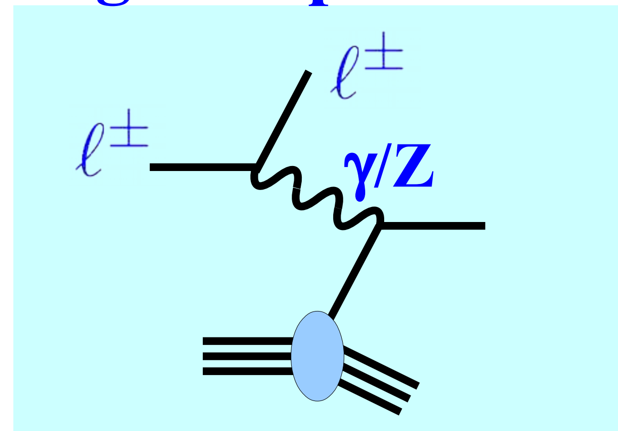
Can extract s(x) and s̄(x) separately

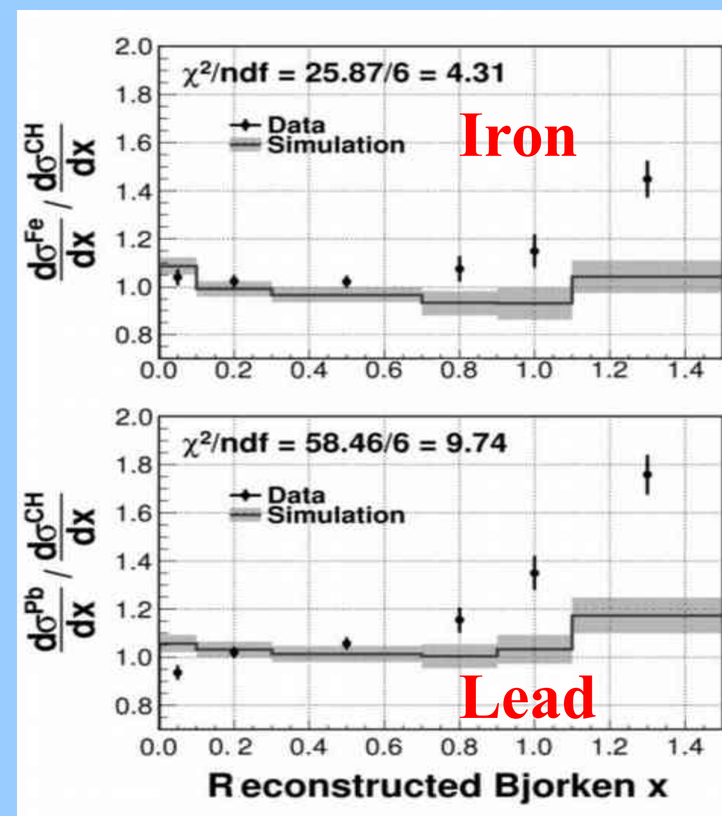
Used in CTEQ Fits

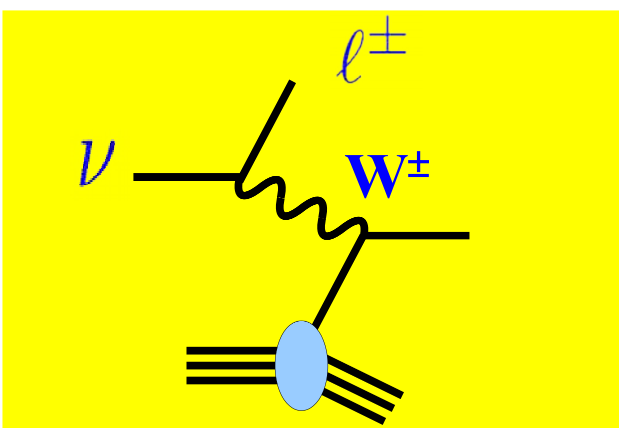
Nuclear Corrections: Compare Neutrino and Charged Lepton DIS



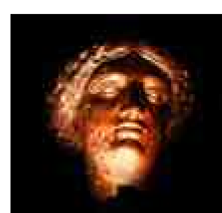
Charged Lepton DIS





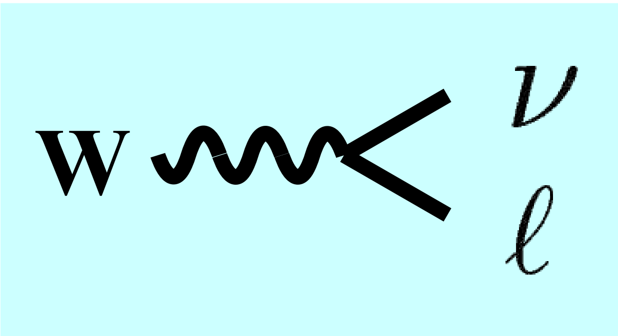


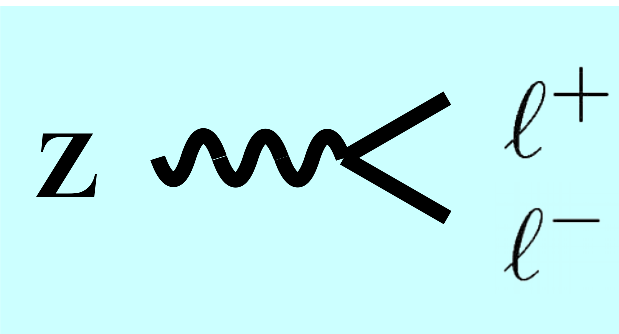
Neutrino DIS



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

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

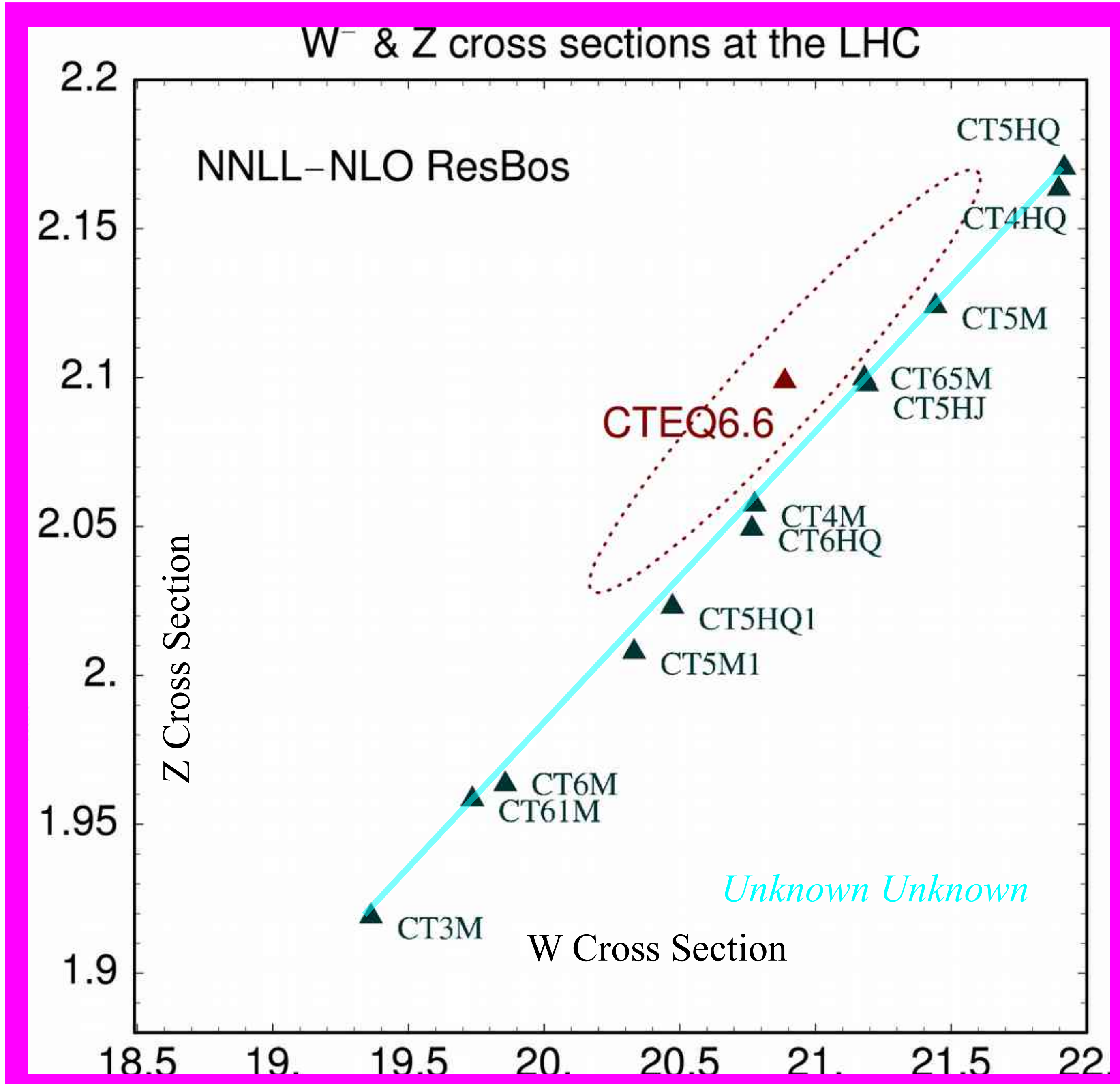




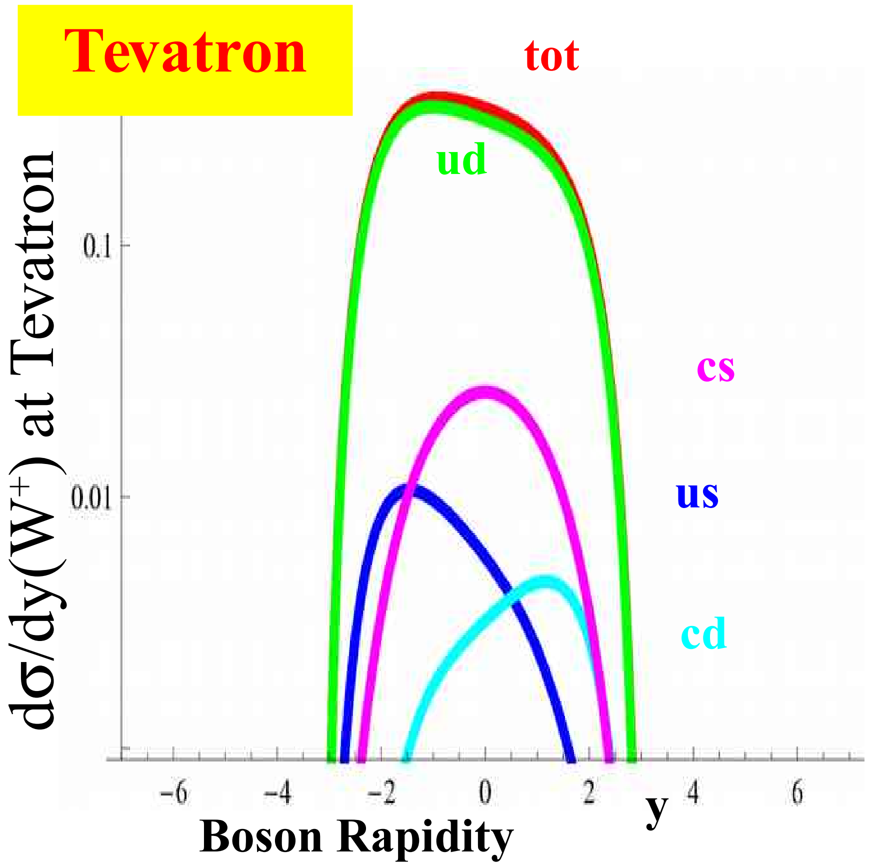
The W-Z correlation is limited by the uncertainty coming from the strange quark distribution

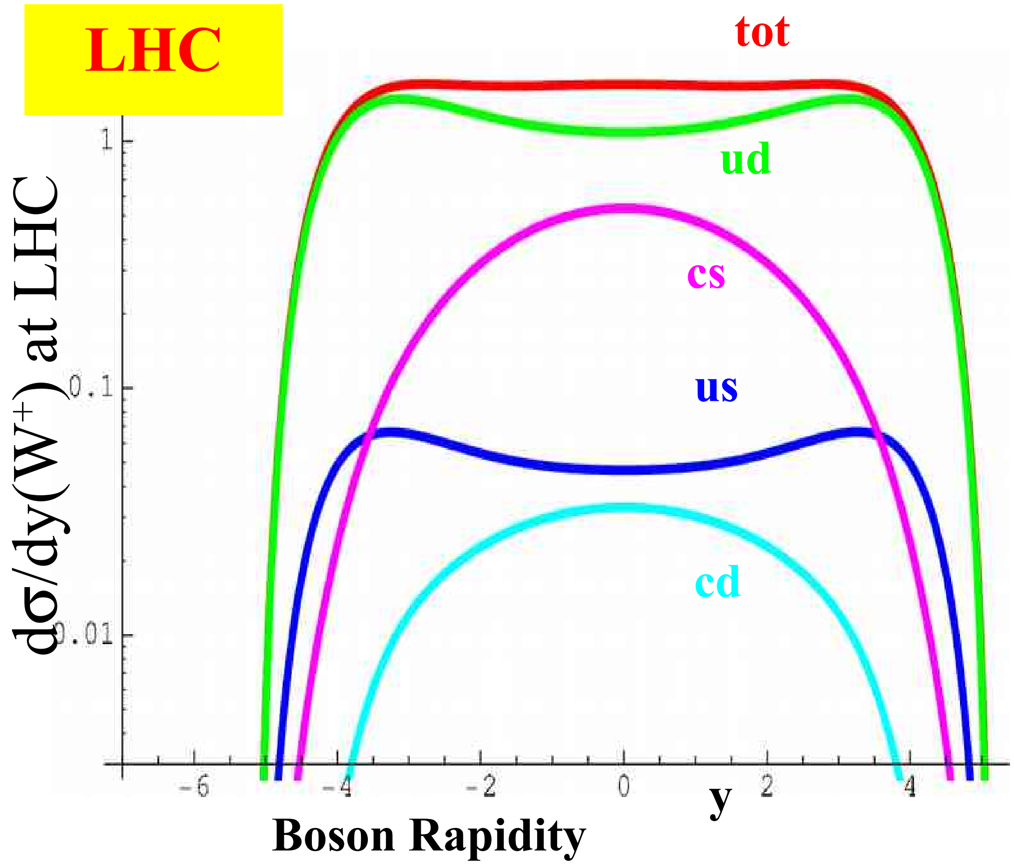
Key for M_W determination

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



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

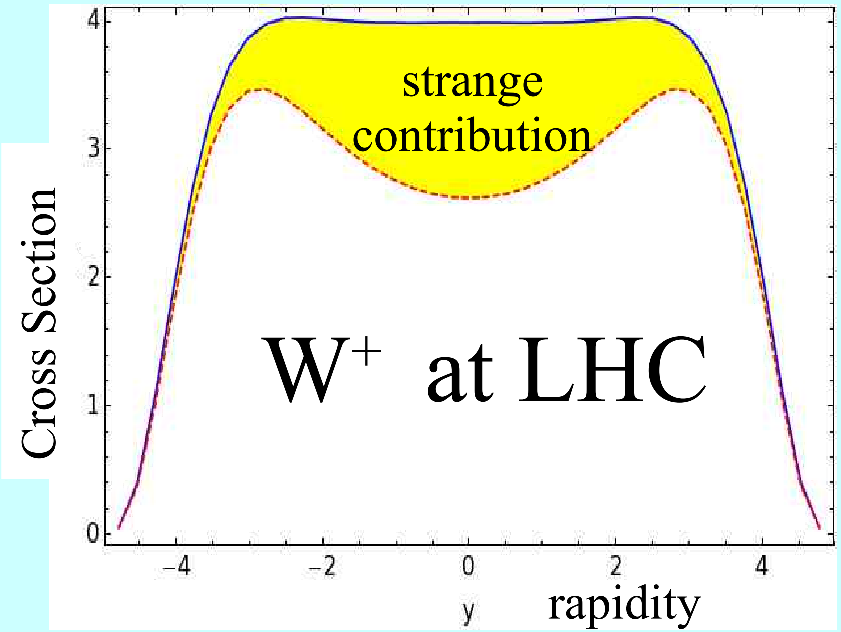


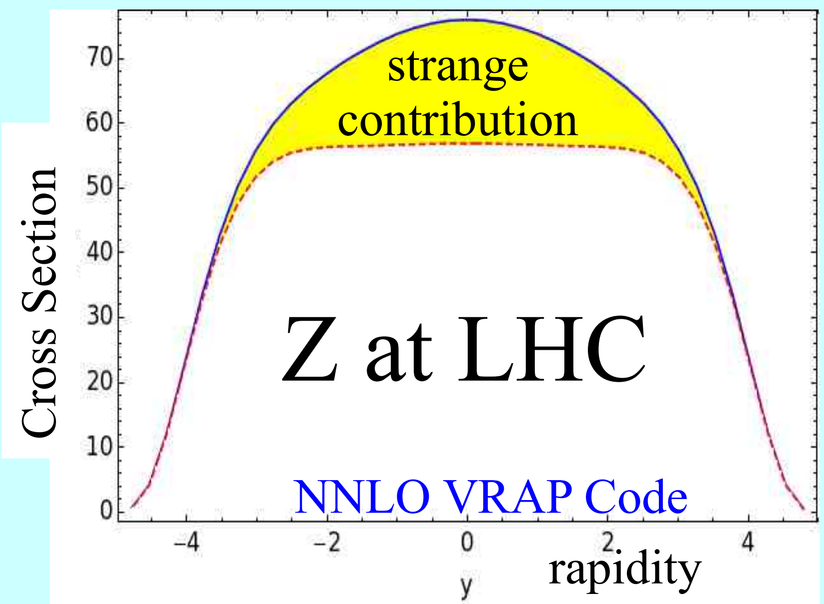


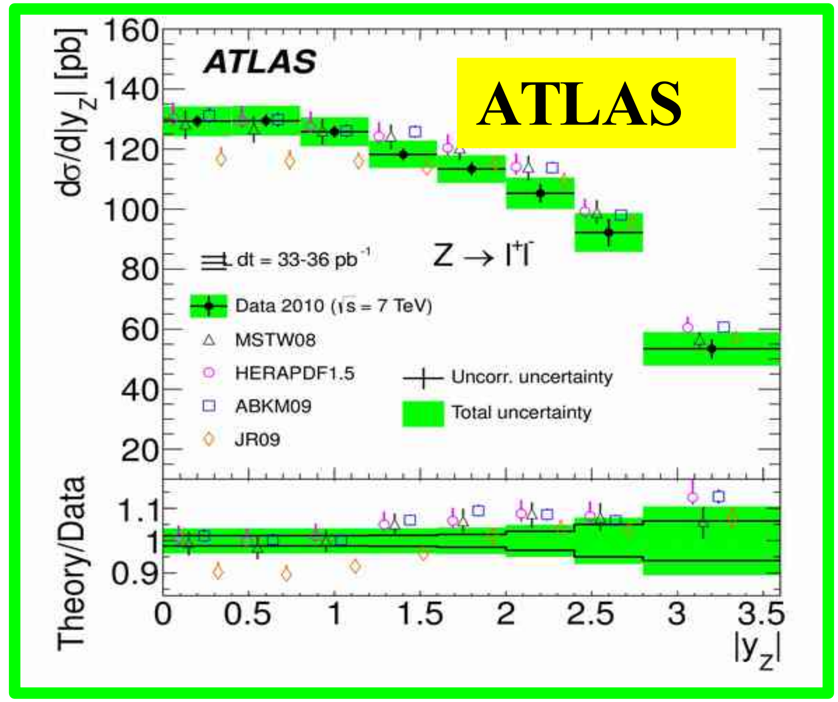
- Larger Energy ⇒ probes PDFs to small momentum fraction x
- Larger Rapidity (y) ⇒ probes PDFs to ***really*** small x
- Larger fraction of heavy quarks

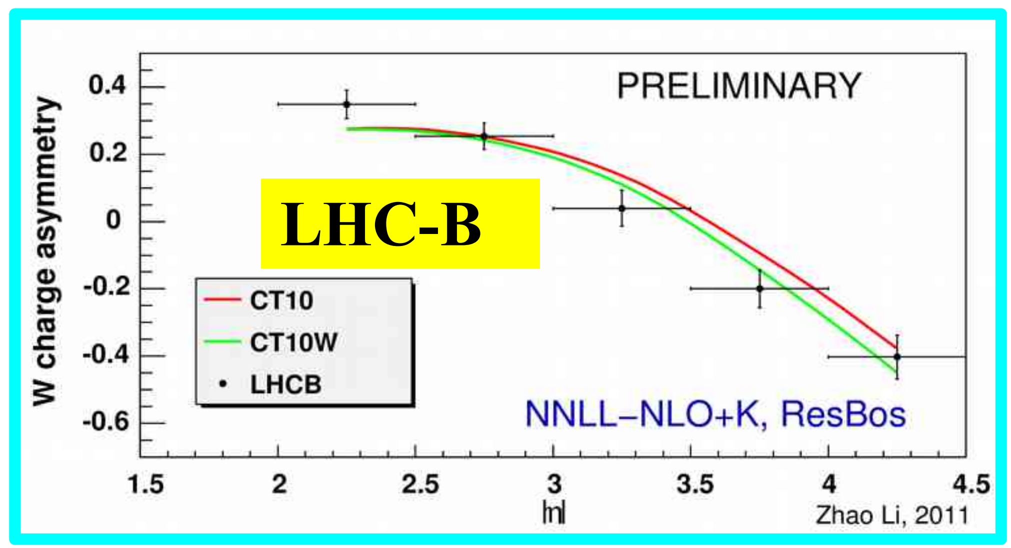
Heavy Quark components play an increasingly important role at the LHC

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

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

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

- 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

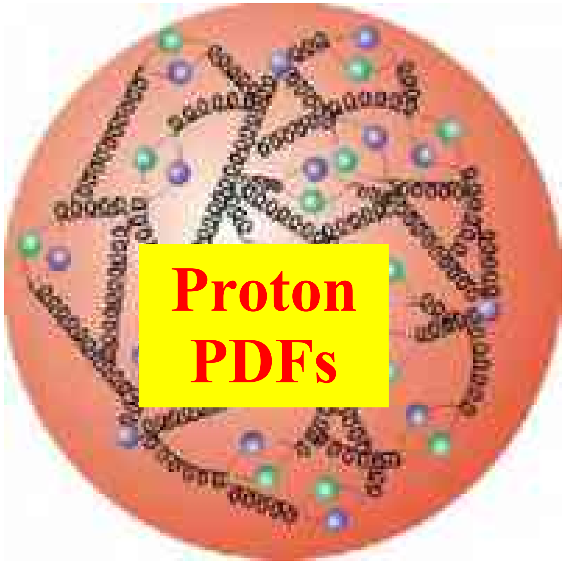
- NOMAD $\kappa^s = 0.591 \pm 0.019$

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

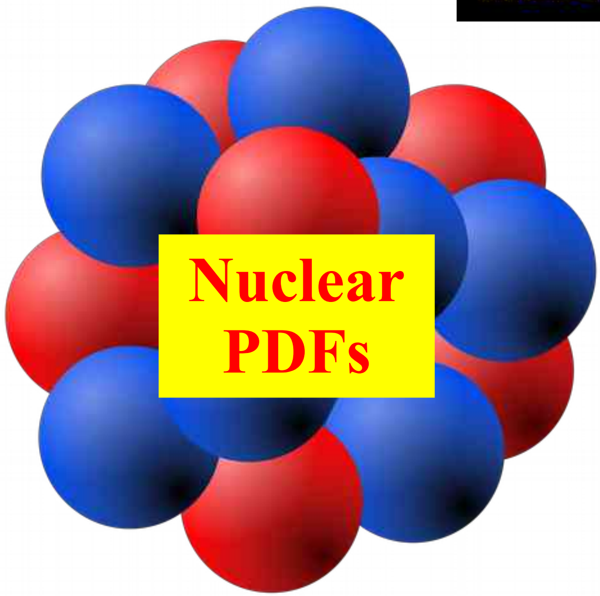
A man with one watch ...

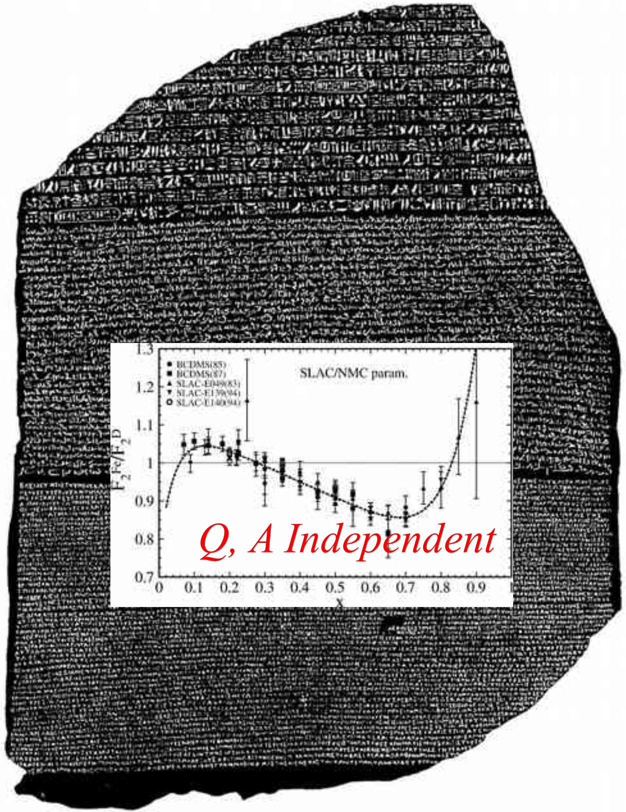
nCTEQ15 PDFs

STAR WARS

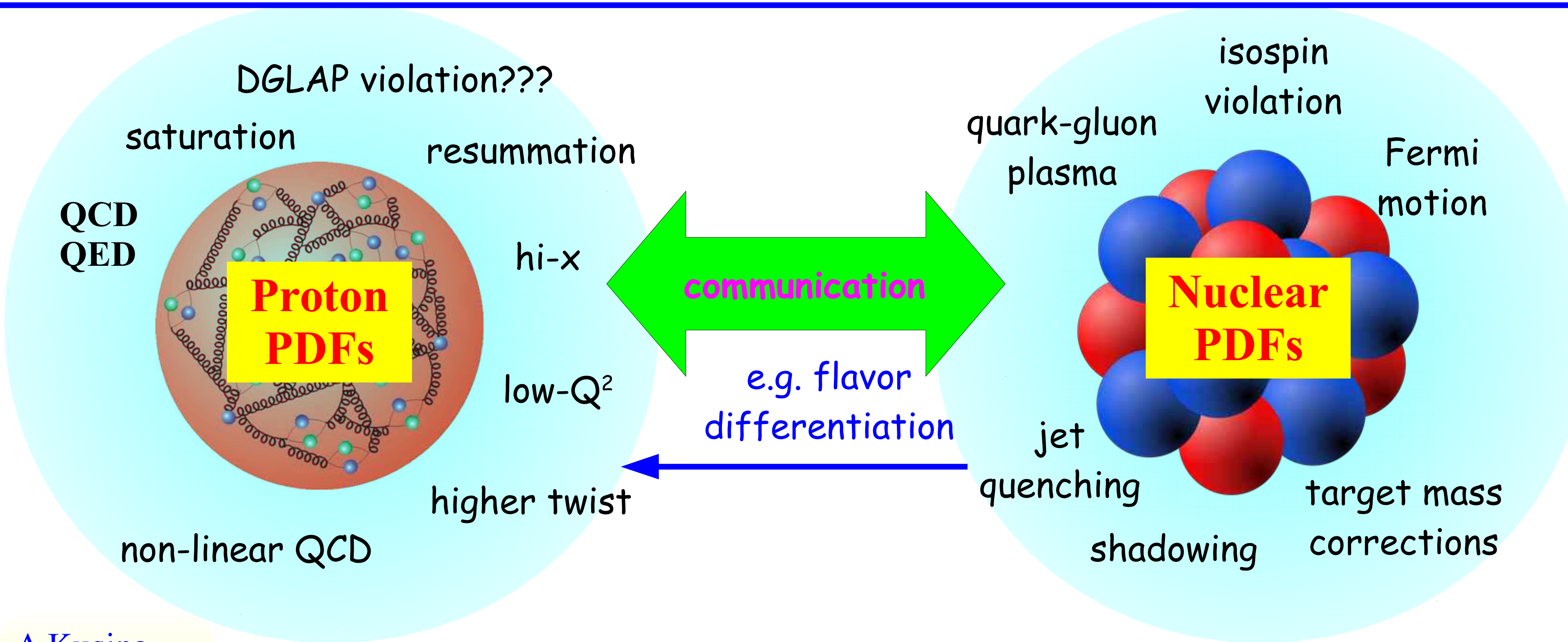


… there was a time when
nuclear corrections
were carved in stone …





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

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

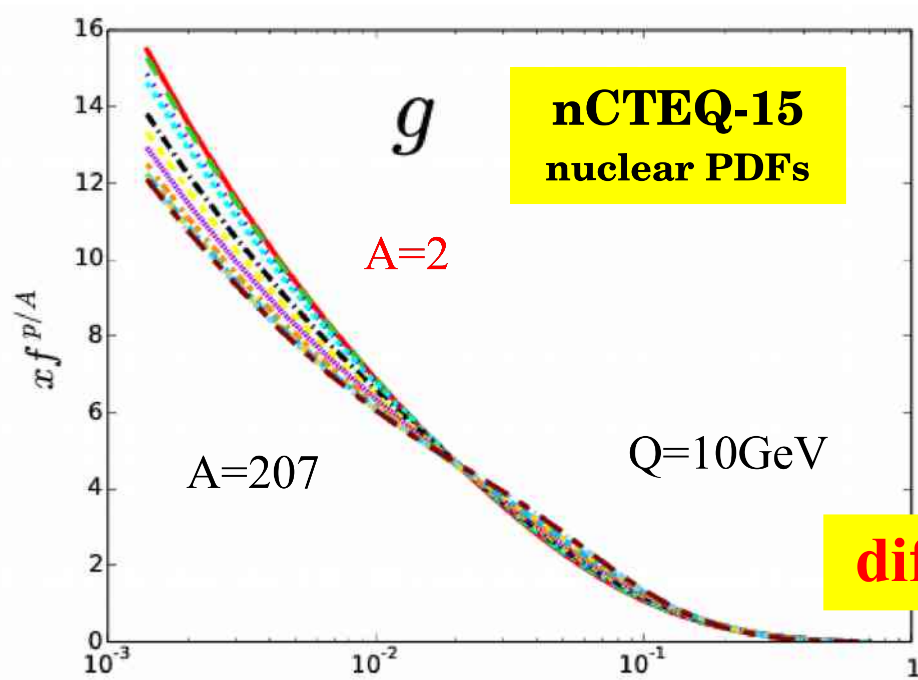
Table II: The DIS $F_2^A/F_2^{A'}$ data sets used in the `nCTEQ15` fit. We list the same details for each data set as in Tab. [I].

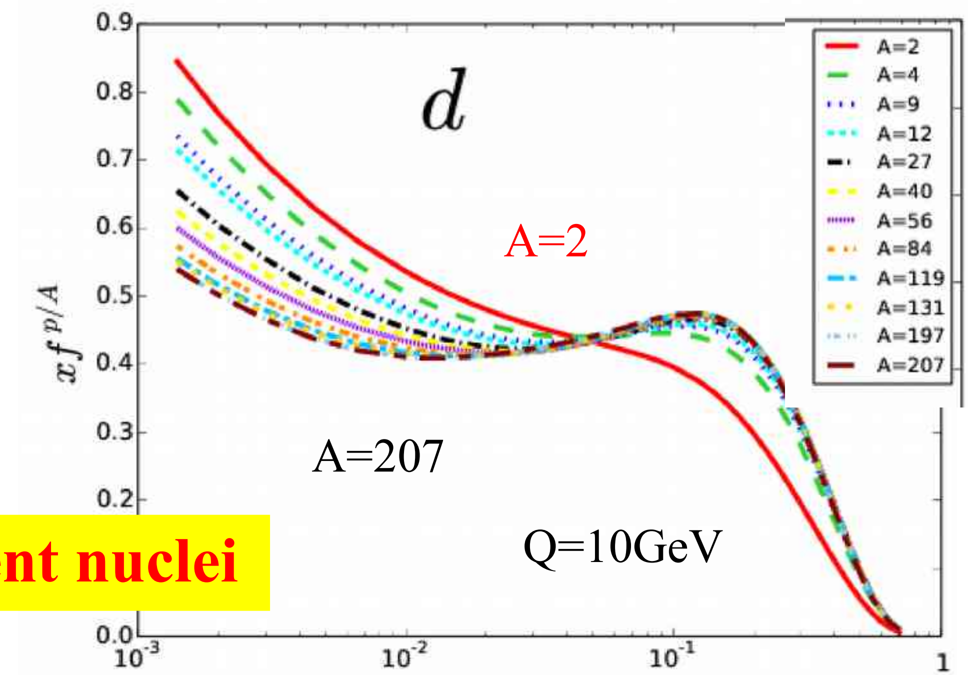
$\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/H2	FNAL-E772-90	5203	[64]	9	9	11.10
Ca/H2	FNAL-E772-90	5204	[64]	9	9	3.11
Fe/H2	FNAL-E772-90	5205	[64]	9	9	3.33
W/H2	FNAL-E772-90	5206	[64]	9	9	7.30
Fe/Be	FNAL-E886-99	5201	[65]	28	28	26.09
W/Be	FNAL-E886-99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

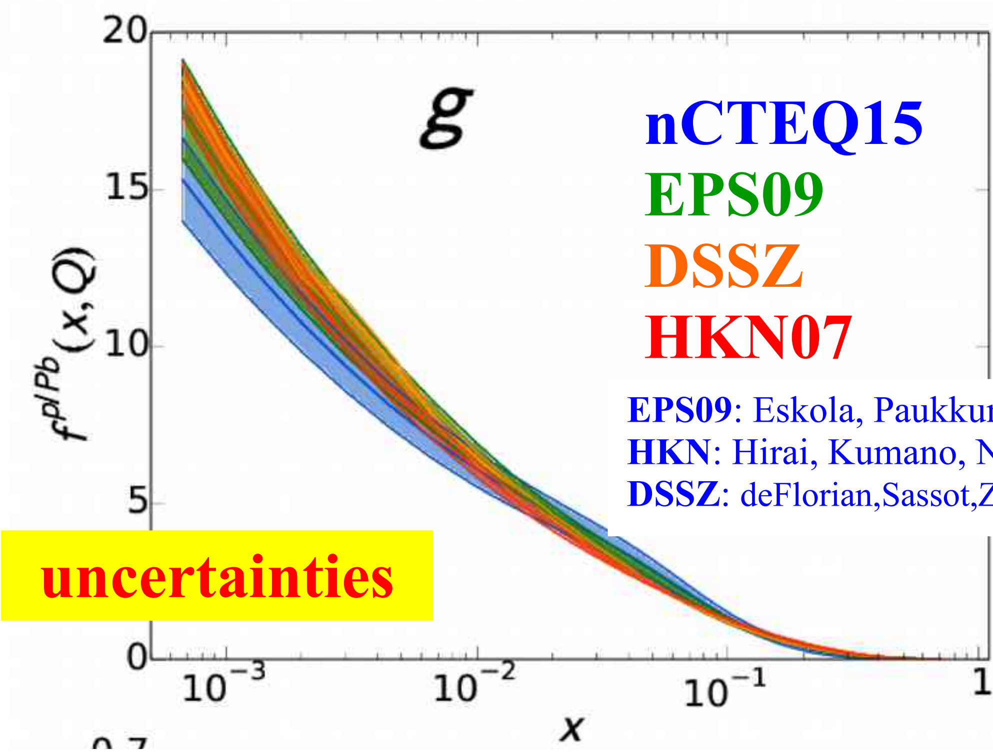
$R_{dAu}^{\pi}/R_{pp}^{\pi}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
dAu/pp	PHENIX	PHENIX	[66]	21	20	5.07
	STAR-2010	STAR	[67]	13	12	1.30
Total:				34	32	6.37

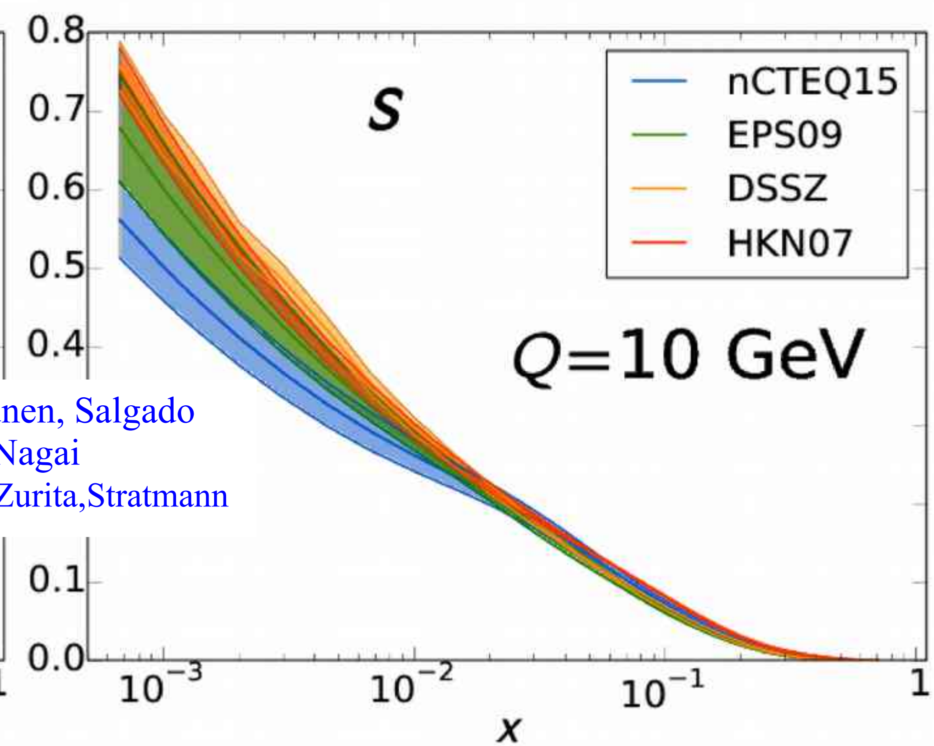
nCTEQ15 PDFs *… from A to Z … with Uncertainties*





different nuclei





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

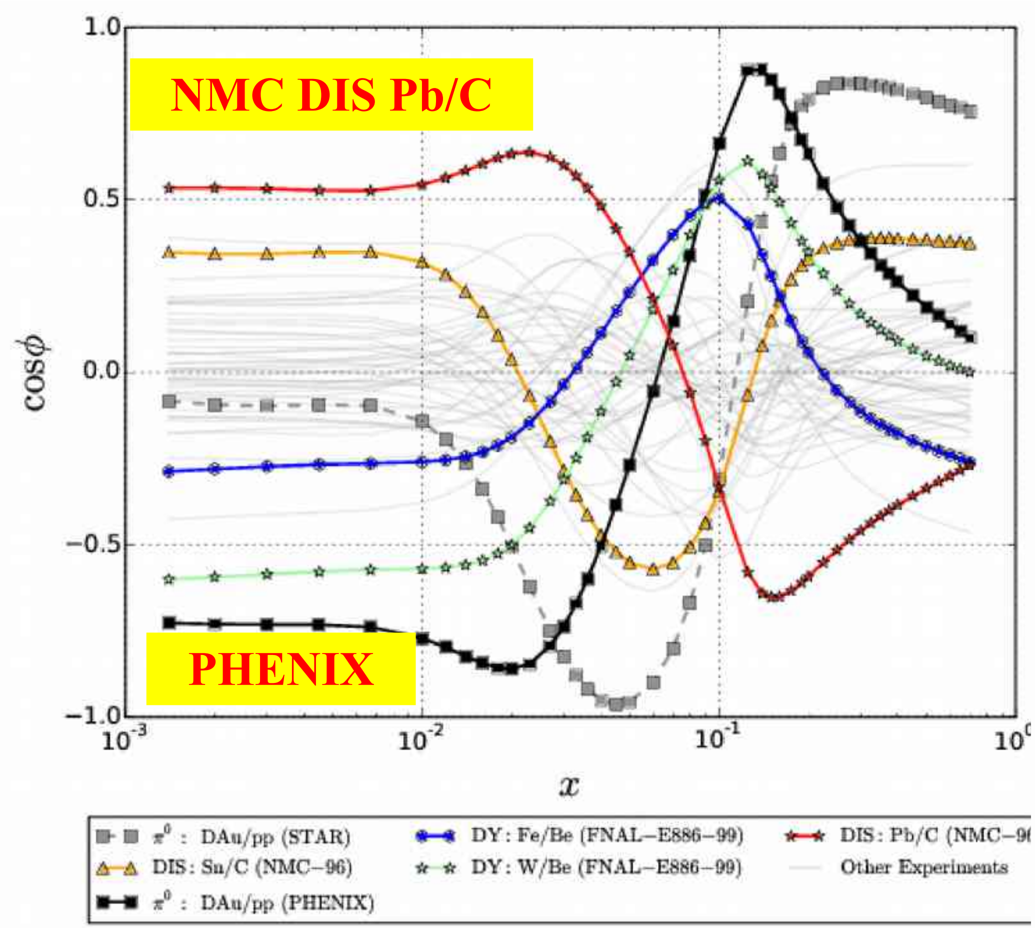
uncertainties

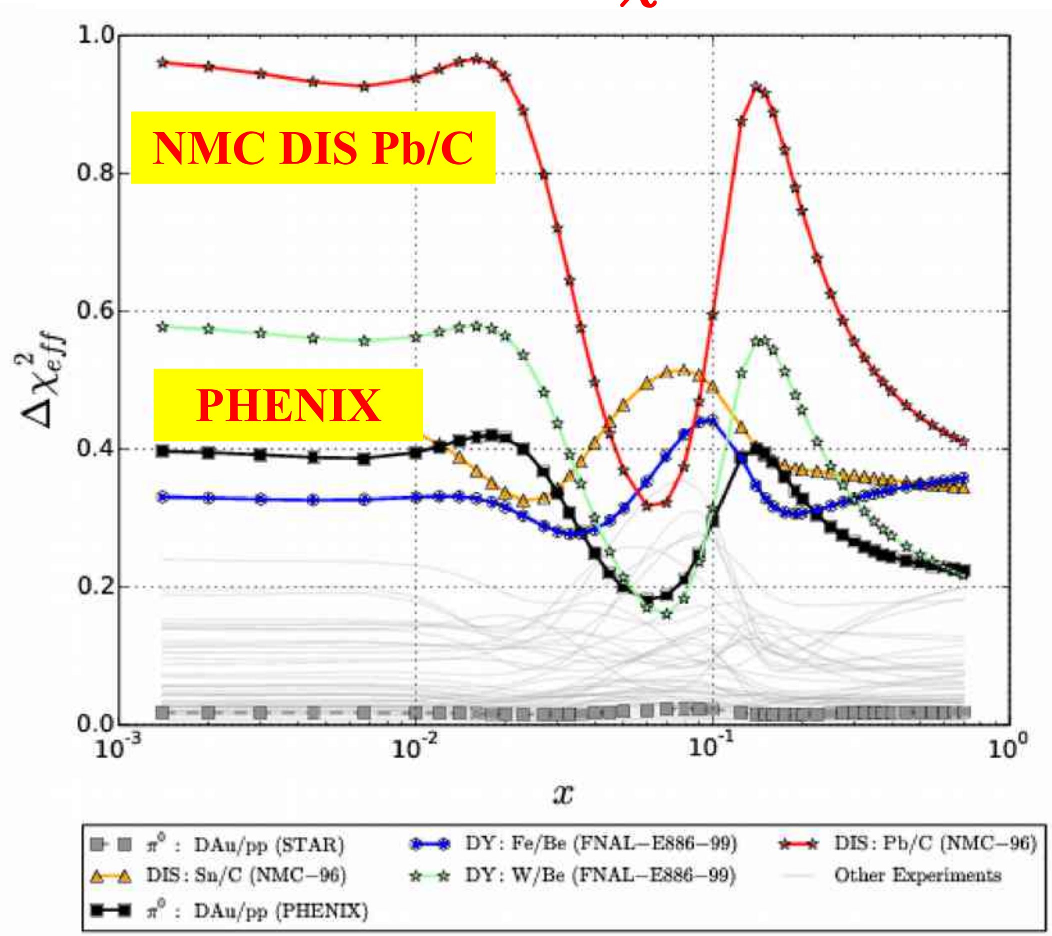
What is driving the Gluon PDF ???

Correlation Cos

lead @ Q=10 GeV

Effective χ^2



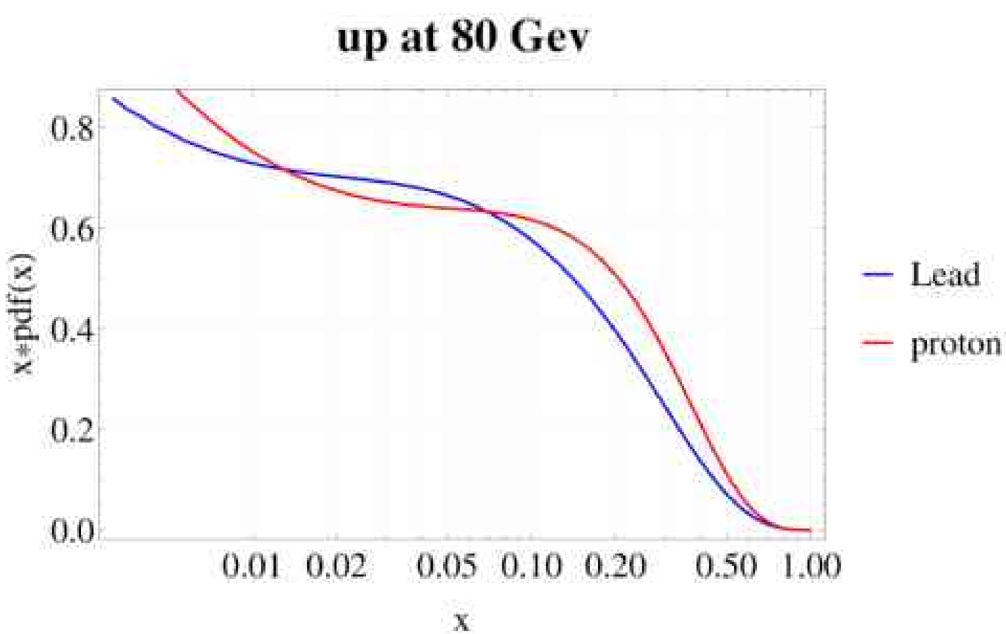


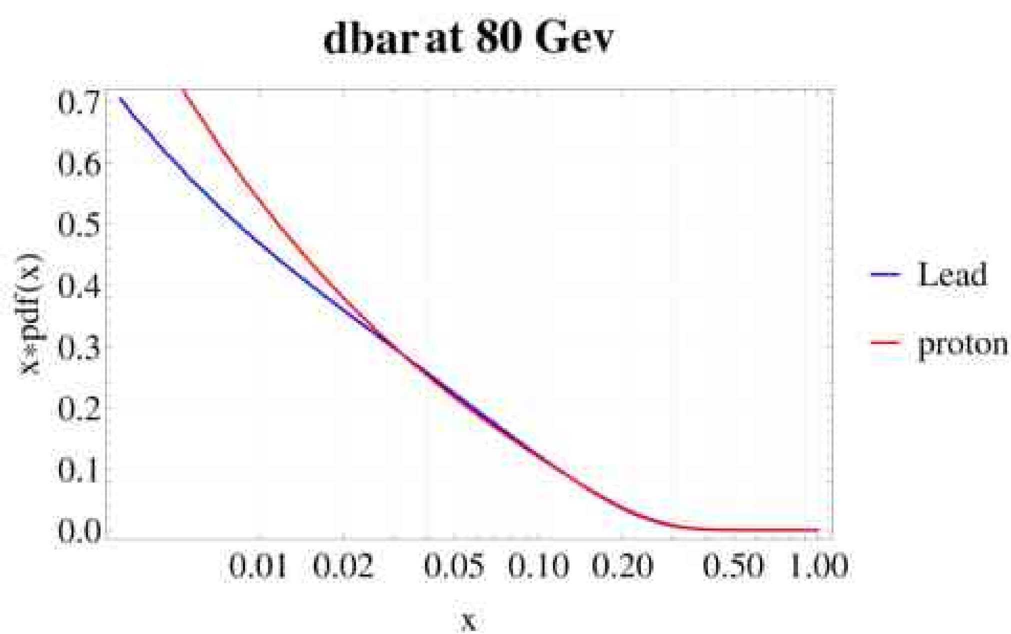
PHENIX: dAu π^0 Production

… can use more data

Nuclear Modifications

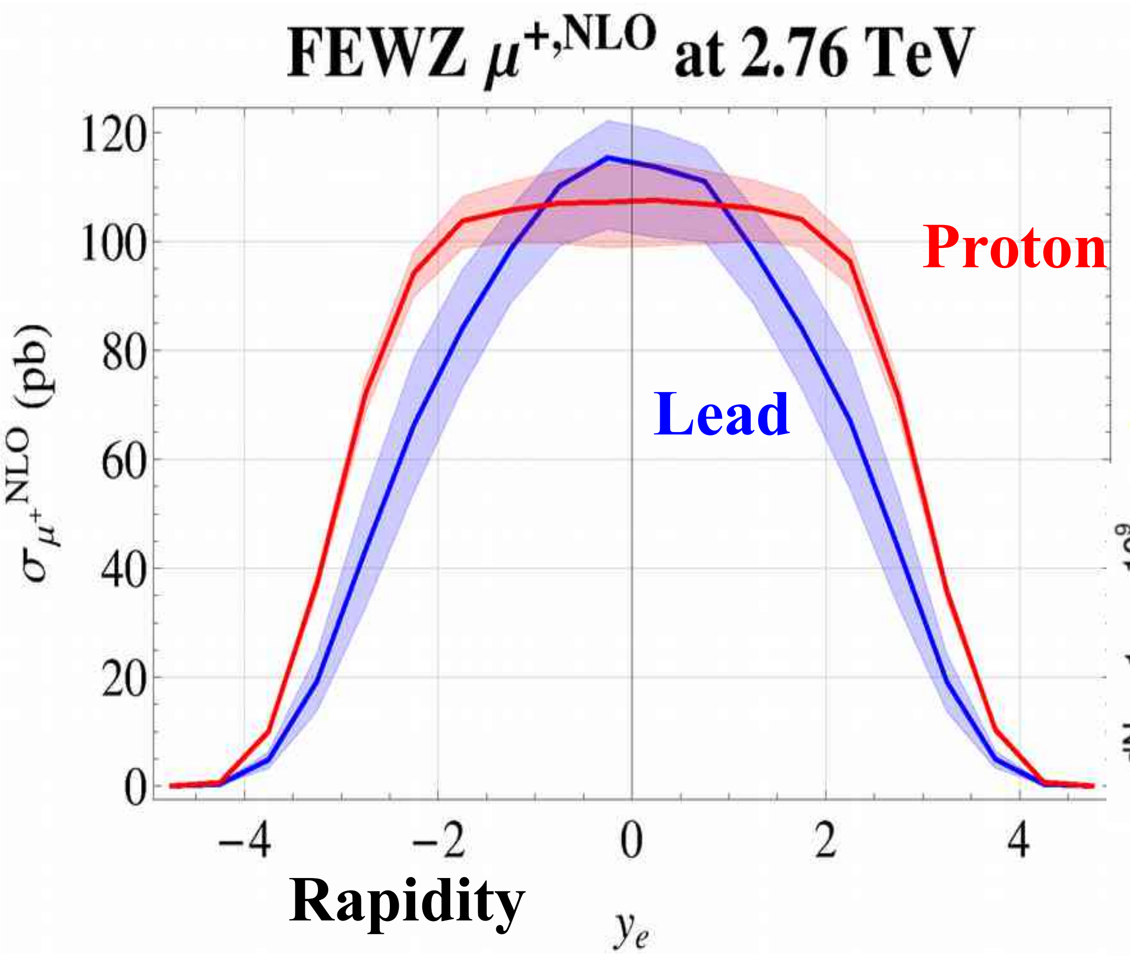
Slides stolen from Ben Clark



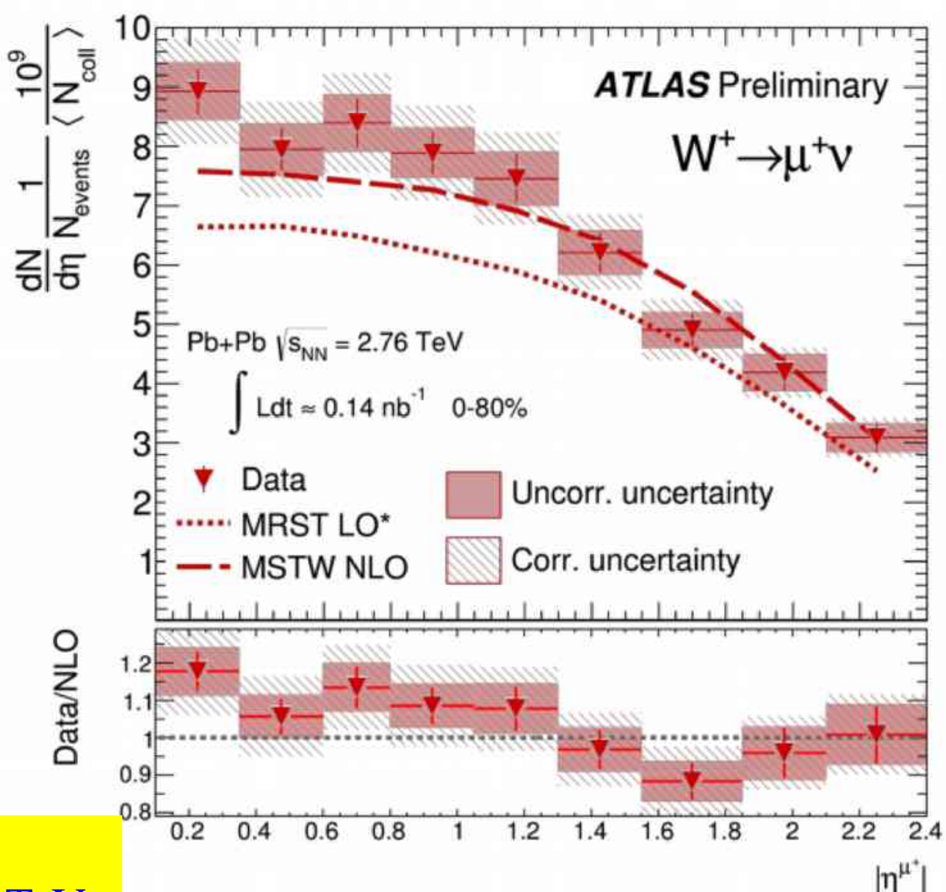


- The nuclear modifications are present in the PDFs and vary with A as well as x and Q.
- We expect modifications to any hadronic observable involving heavy nuclei.

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



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



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

Focus: c & b:

Extrinsic & Intrinsic

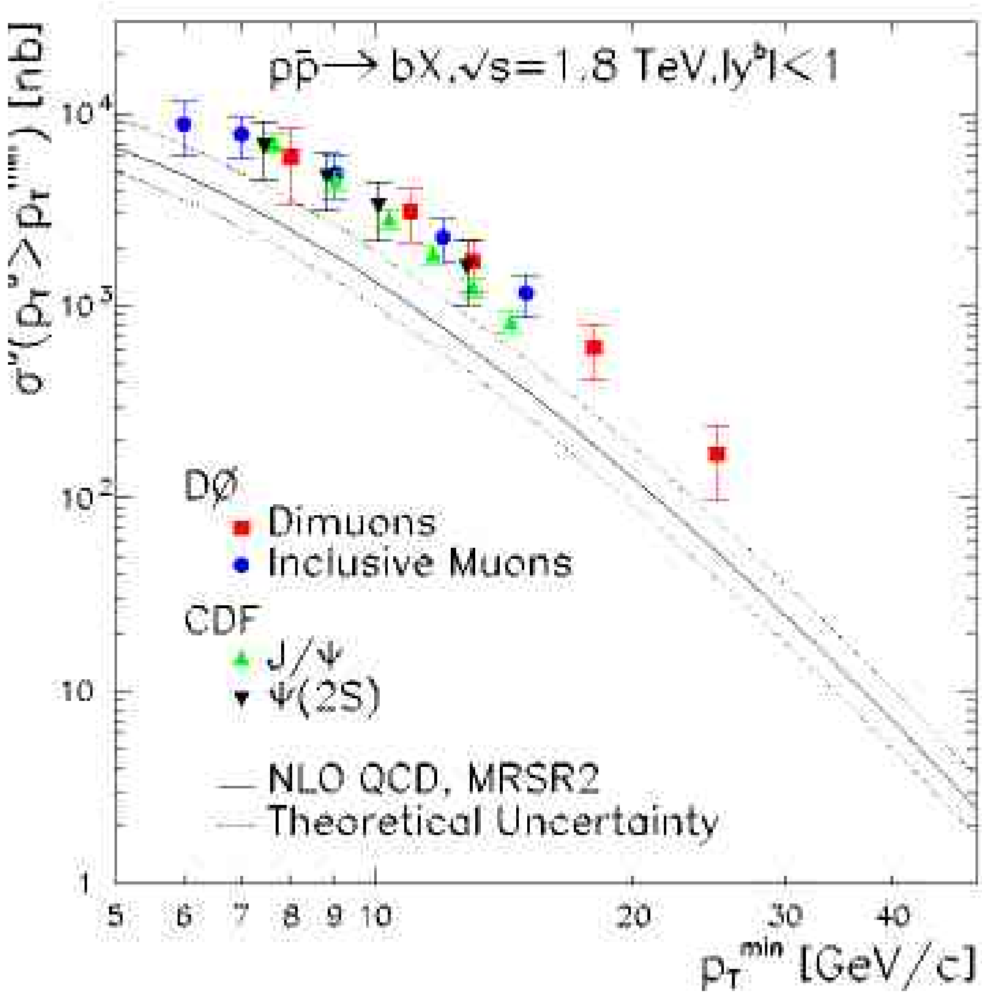
Historically, these have been a challenge because $Q \sim m_{c,b}$

Heavy Quarks : … past challenges

The CTEQ List of Challenges in Perturbative QCD

C T E Q

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



~1995

Multi-Scale Problems are Challenging

Two-Loop Total Cross Section: One Scale

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

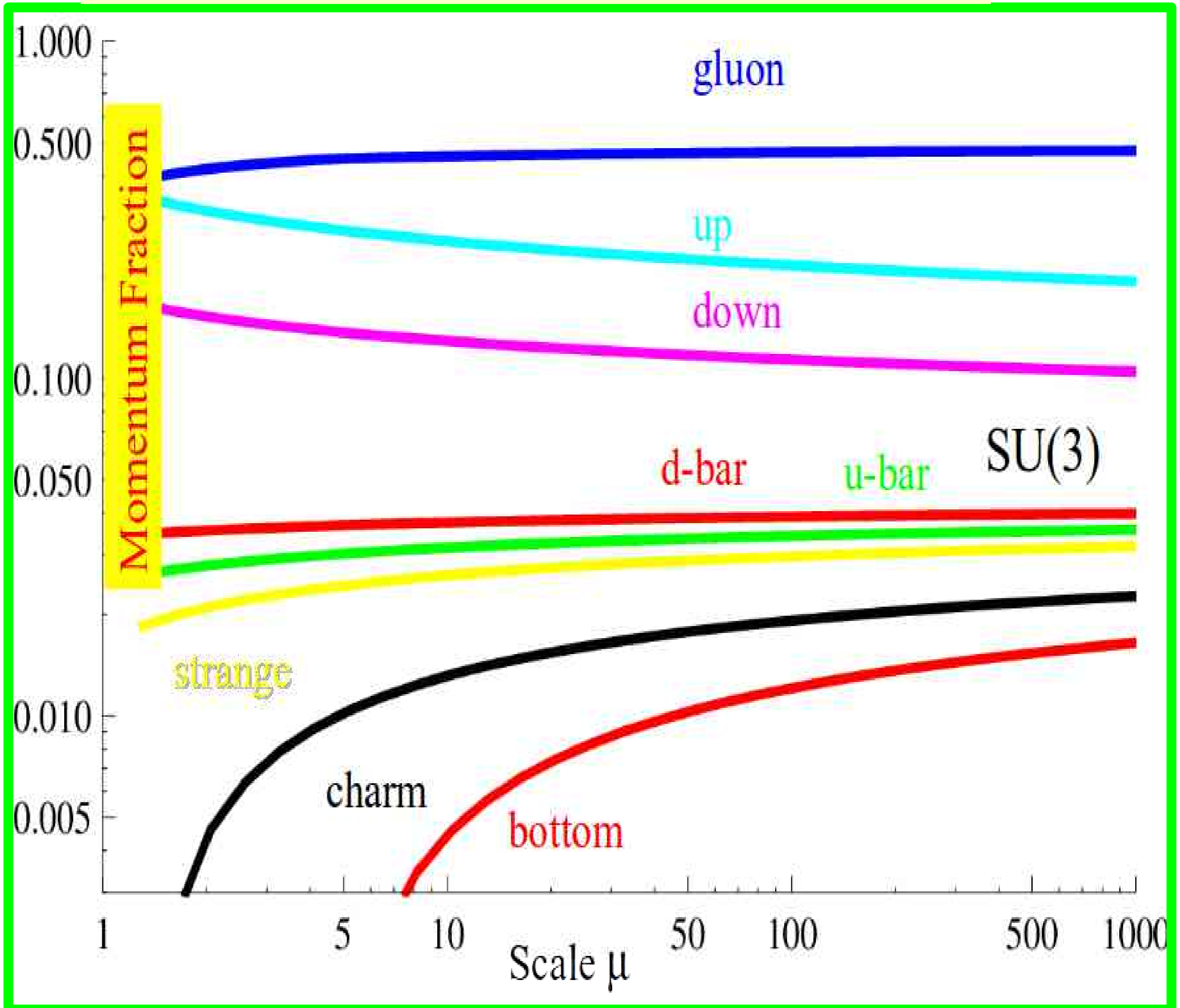
Two-Loop Drell-Yan Cross Section: Two Scales

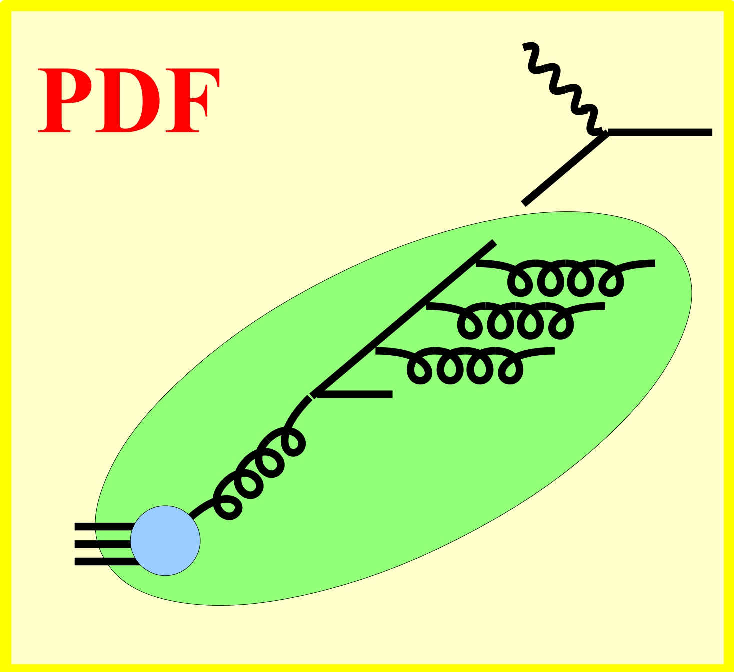
Ref: CTEQ Handbook

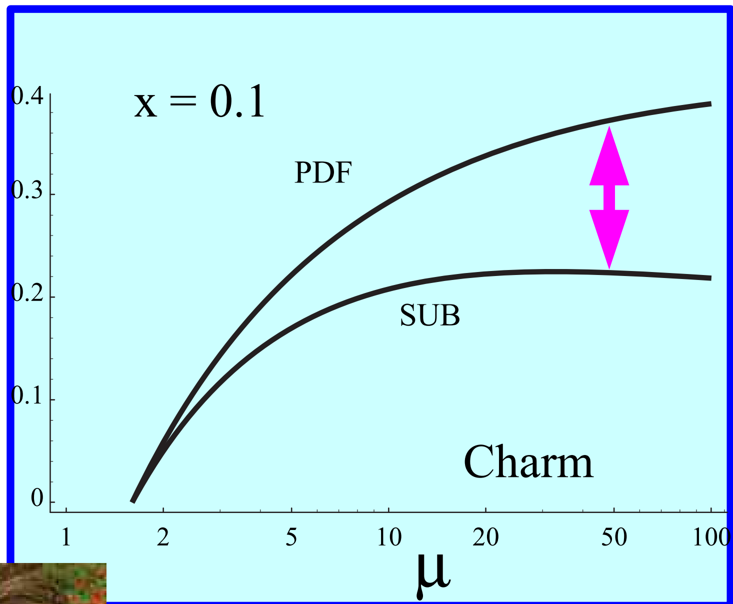
$$\begin{aligned}
H_{q\bar q}^{(2),S+V}(z)=&\left[\frac{\alpha_s}{4\pi}\right]^2\delta(1-z)\left\{C_AC_F\left[\left[\tfrac{193}{3}-24\zeta(3)\right]\ln\left[\frac{Q^2}{M^2}\right]-11\ln^2\left[\frac{Q^2}{M^2}\right]-\tfrac{12}{5}\zeta(2)^2+\tfrac{592}{9}\zeta(2)+28\zeta(3)-\tfrac{1535}{12}\right]\right.\\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

Charm & Bottom PDFs   Resum Logs

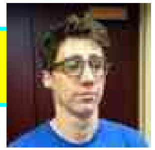
Resum $\alpha_s \ln(m/Q)$





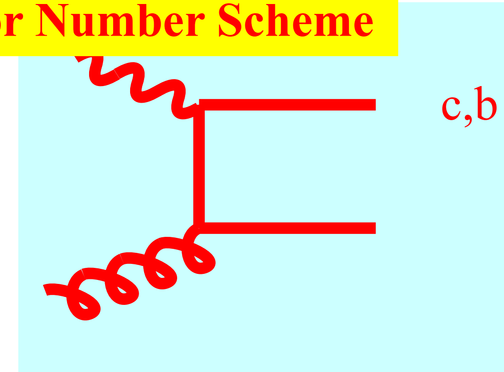


Plots made with ManeParse Mathematica package

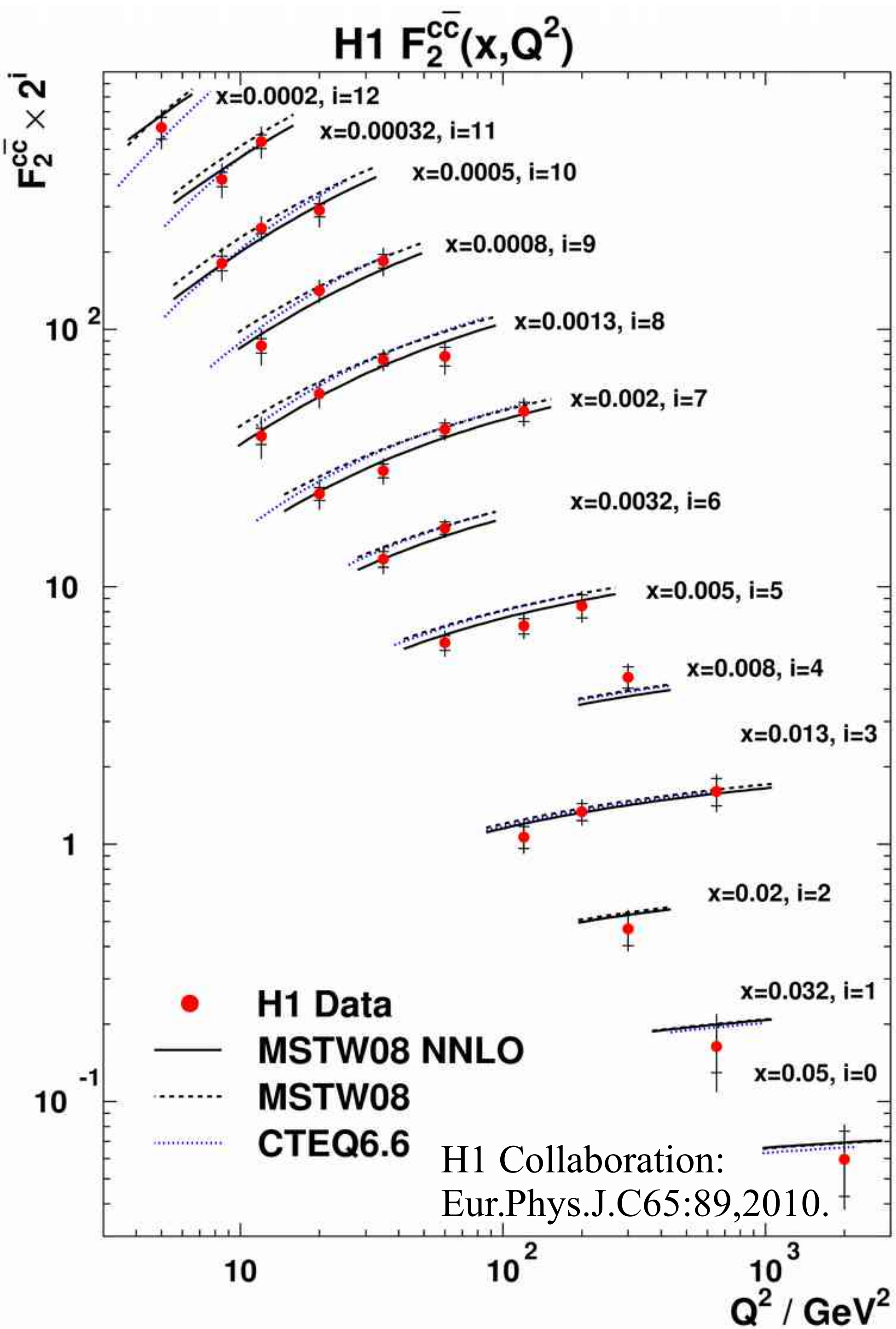


How to include the Heavy Flavor Component???

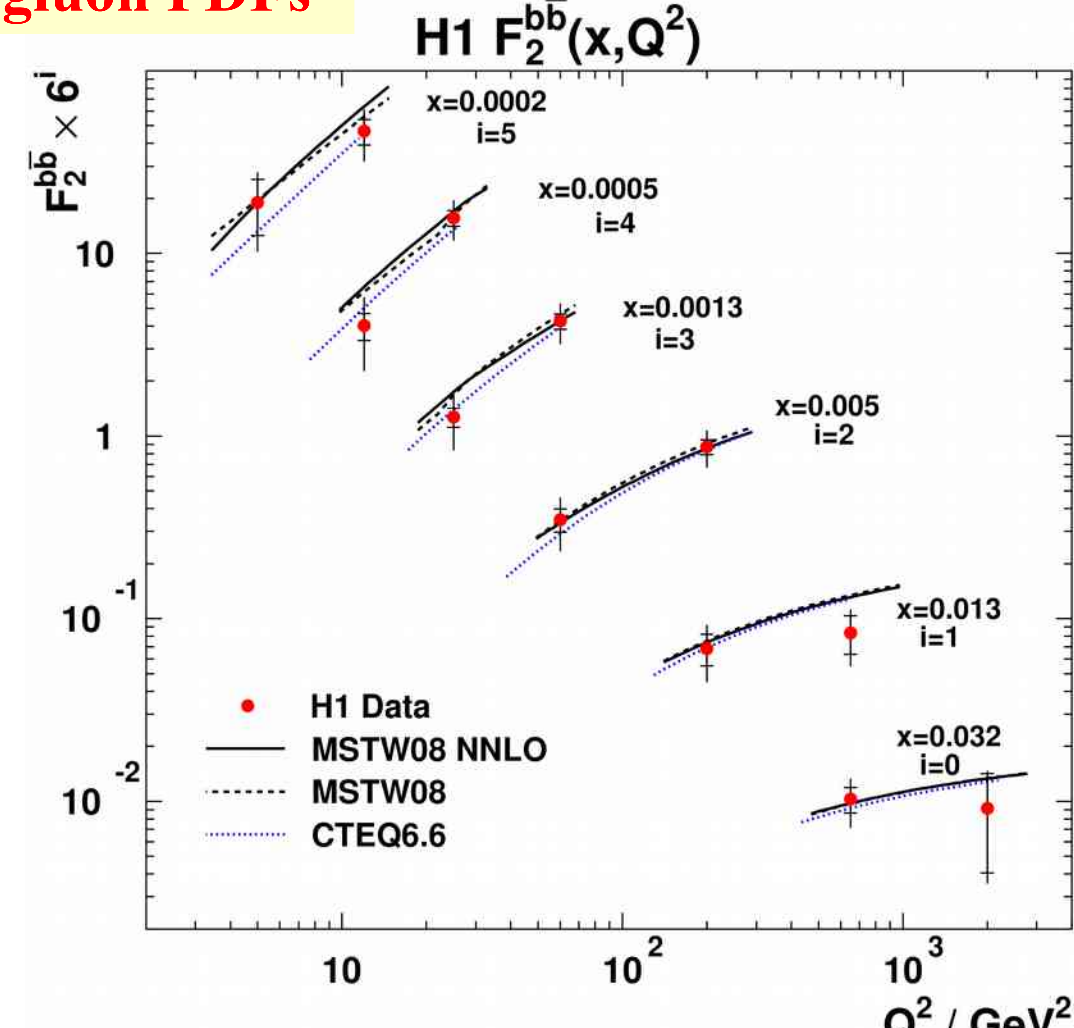
FFNS: Fixed Flavor Number Scheme



c & b tied to gluon PDFs

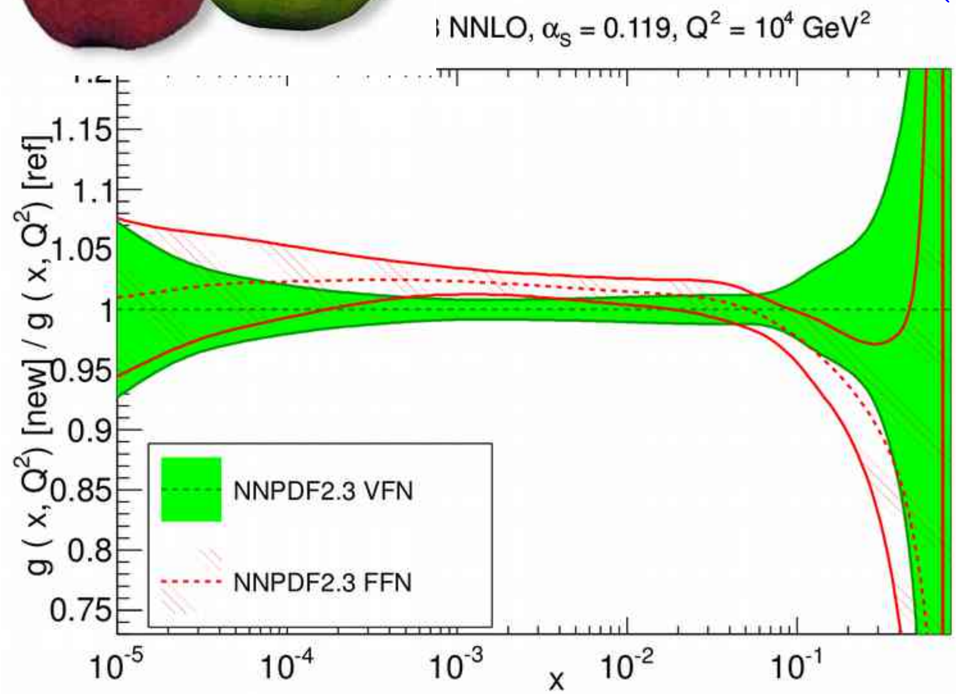


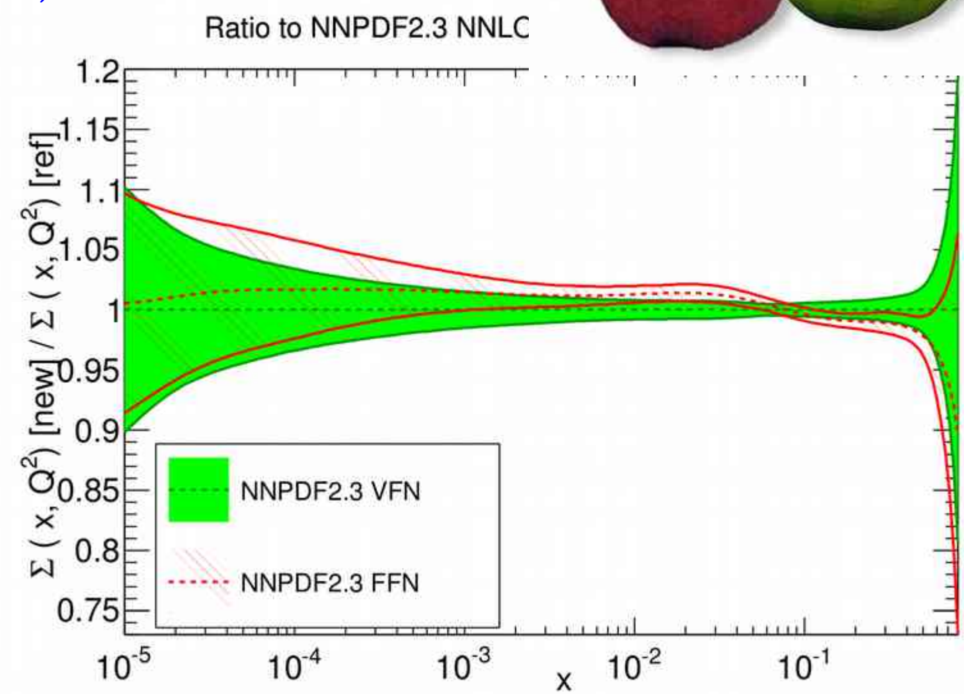
H1 Collaboration:
Eur.Phys.J.C65:89,2010.



NNPDF: 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)	$N_{\rm dat}^{\rm hera-I}$
$4 \cdot 10^{-5}$	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

Higher Orders

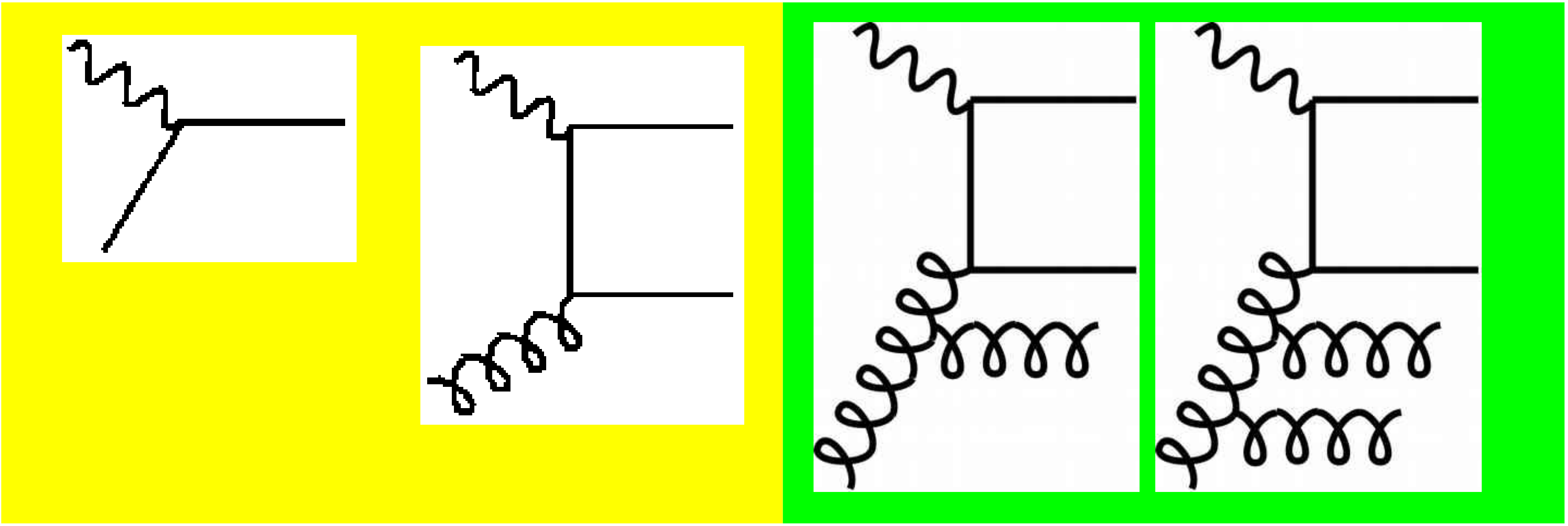
An example...

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

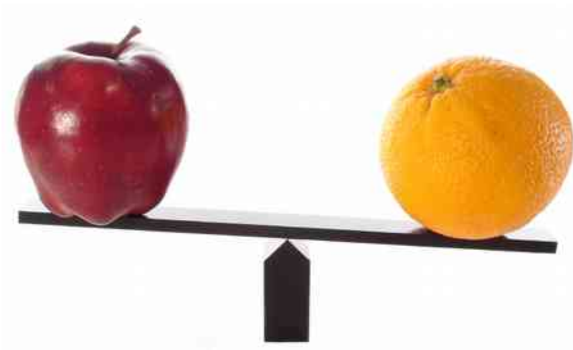
Based on the Collins-Wilczek-Zee (CWZ) Renormalization Scheme
... hence, extensible to all orders

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

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

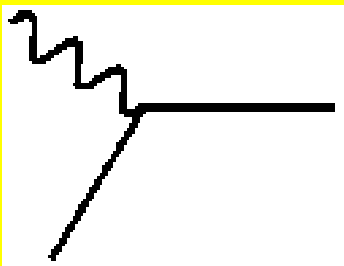
PDFs Discontinuous at N2LO

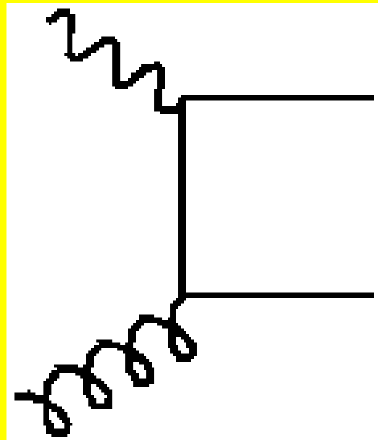
α_s Discontinuous at α_s^3

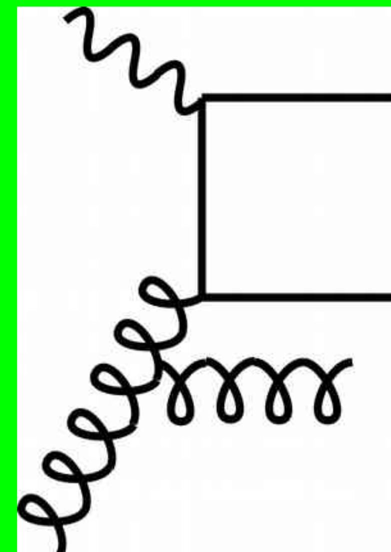


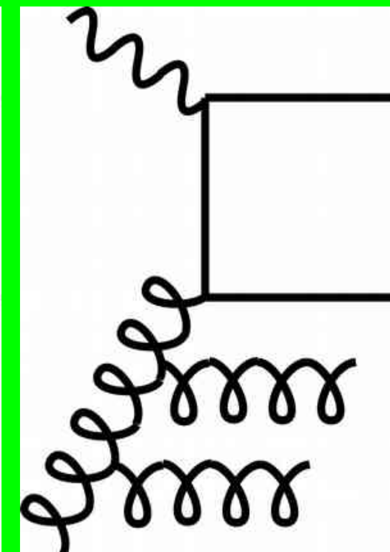
ACOT Extension to Higher Orders

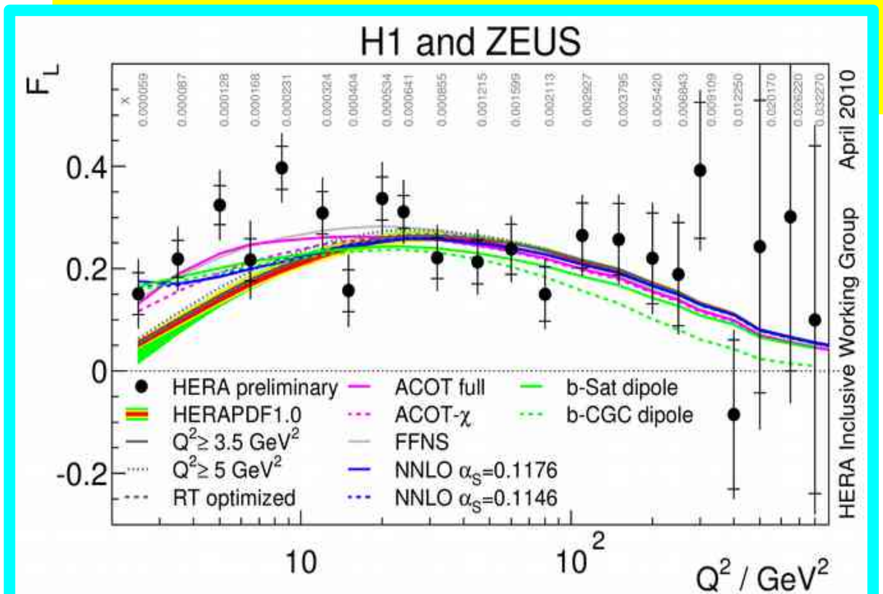
LO **NLO** **N2LO** **N3LO**









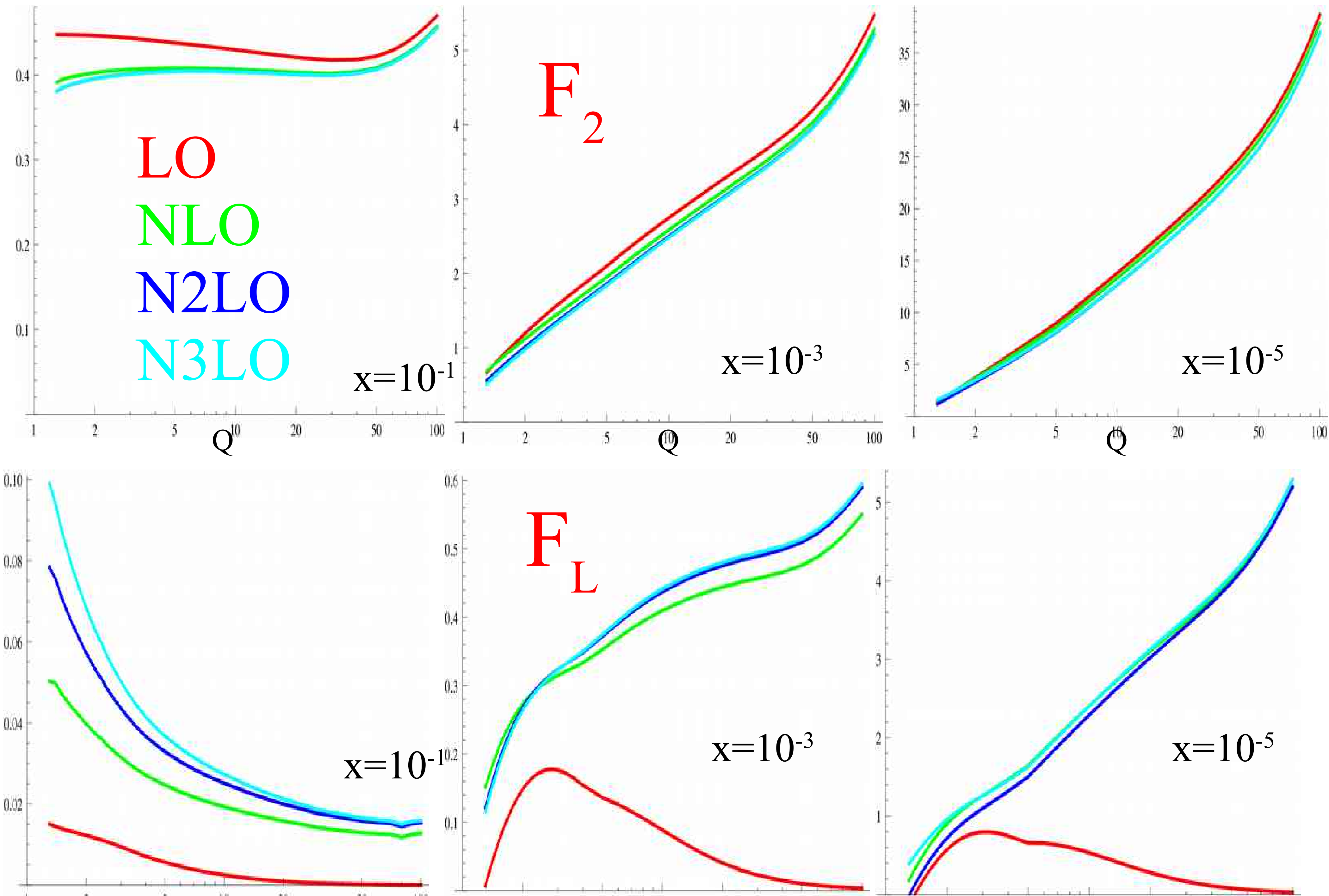


Masses are important

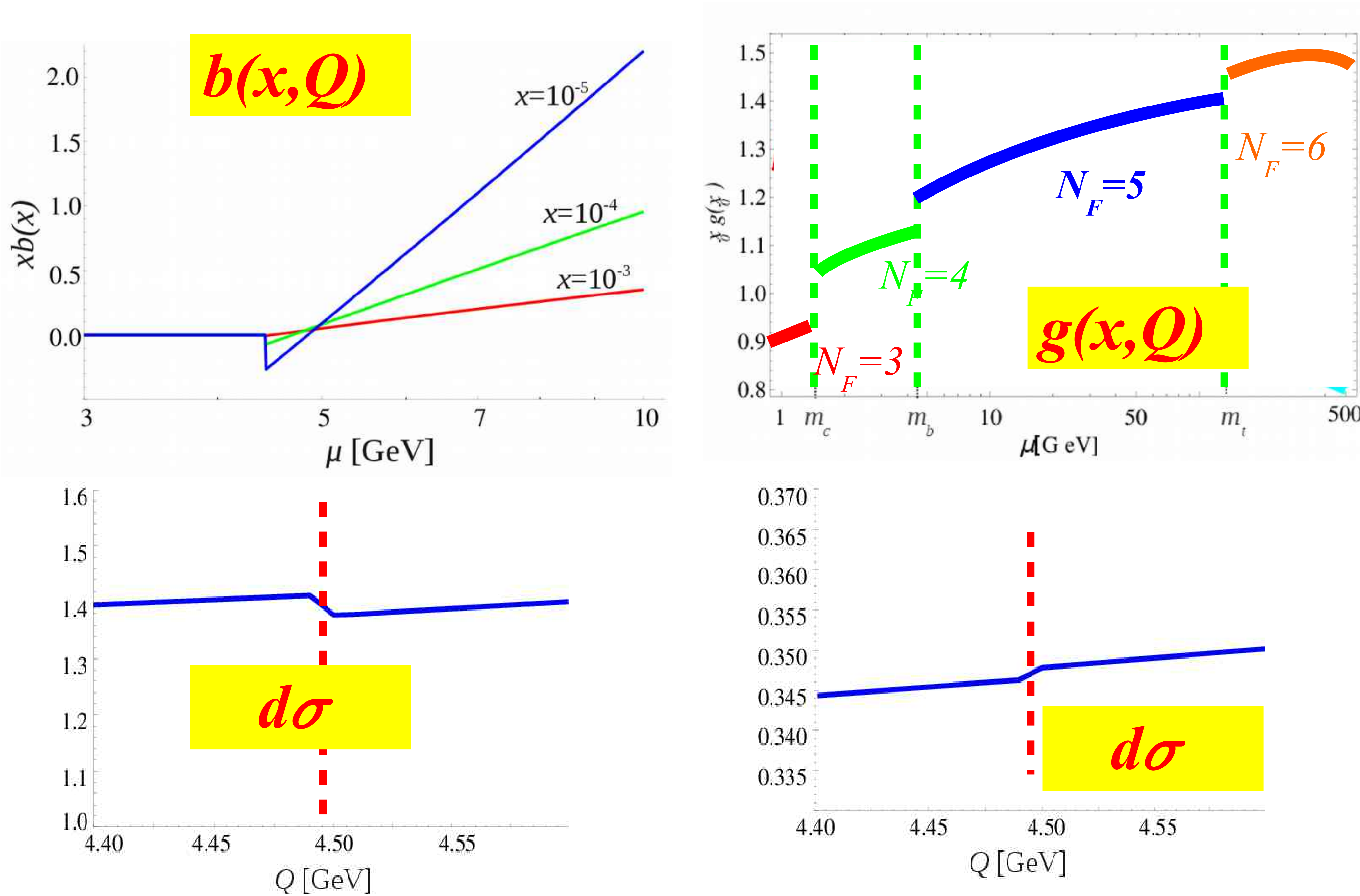
Higher Orders are important

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

$F_{2,L}$ @ N3LO



At higher orders: f(x,Q) & α_s(Q) are discontinuous



Would you buy a one-gear car? Hybrid-VFNS

FFNS: Fixed Flavor Number Scheme
VFNS: Variable Flavor Number Scheme

Car with a single gear (**FFNS**)

✓ don’t have to shift
✓ drive around city
✗ won’t work on highway

automatic transmission changing at fixed speed: 30, 40 ... (**VFNS**)

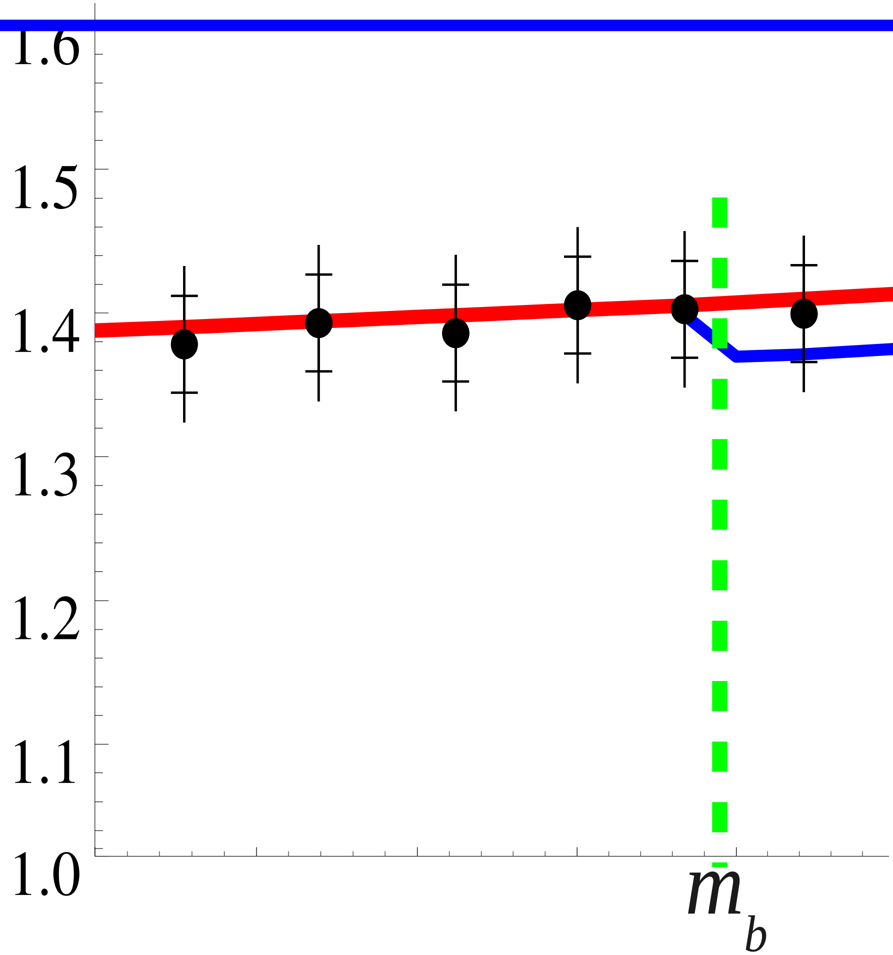
✓ shifts automatically
✓ you decide what to do
✓ can go to highway
✗ somethimes can shift when you don’t want

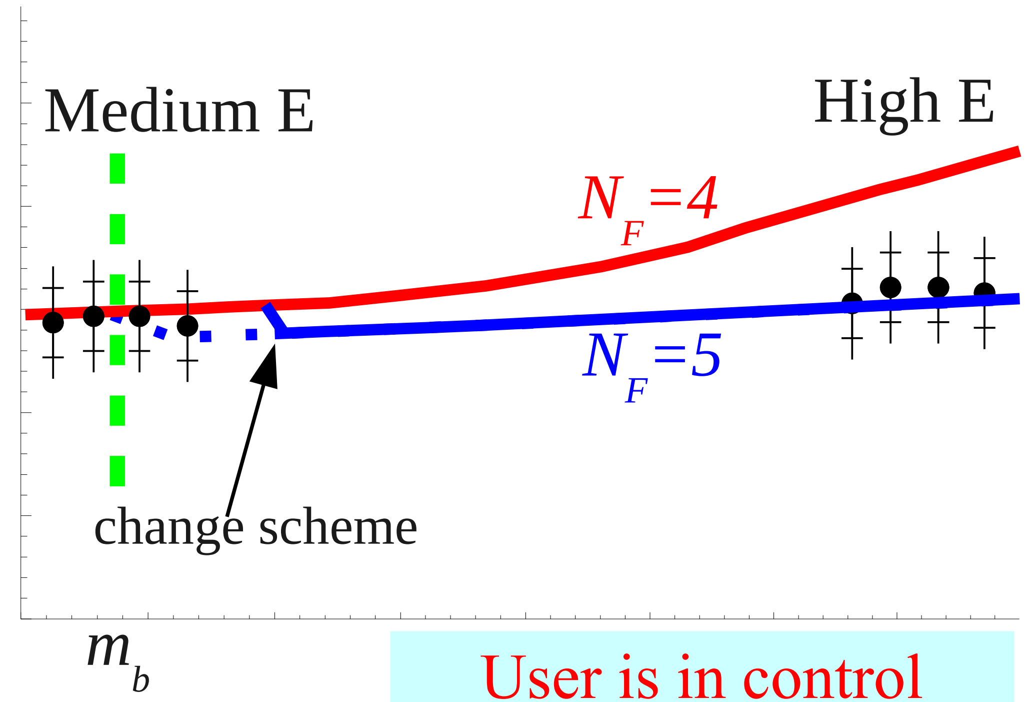
manual transmition (**Hybrid VFNS**)

✓you decide what to do
✗ do it responsibly

Hybrid scheme for heavy flavors:
A. Kusina, F.I. Olness, I. Schienbein, T. Jezo,
K. Kovarik, T. Stavreva, J.Y. Yu.
Phys.Rev. D88 (2013) 7, 074032

Hybrid scheme for heavy flavors:





Solution:

$f(x,Q) \longrightarrow f(x,Q,N_F)$

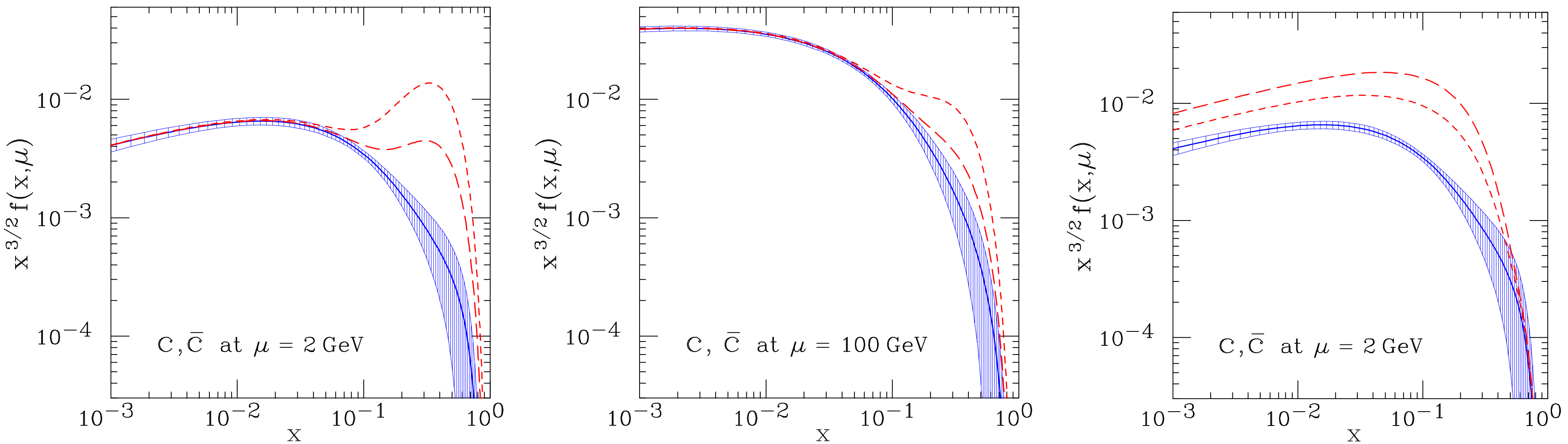
User is in control
Must use responsibly

Hybrid scheme for heavy flavors:
A. Kusina, F.I. Olness, I. Schienbein, T. Jezo, K. Kovarik, T. Stavreva, J.Y. Yu.
Phys.Rev. D88 (2013) 7, 074032

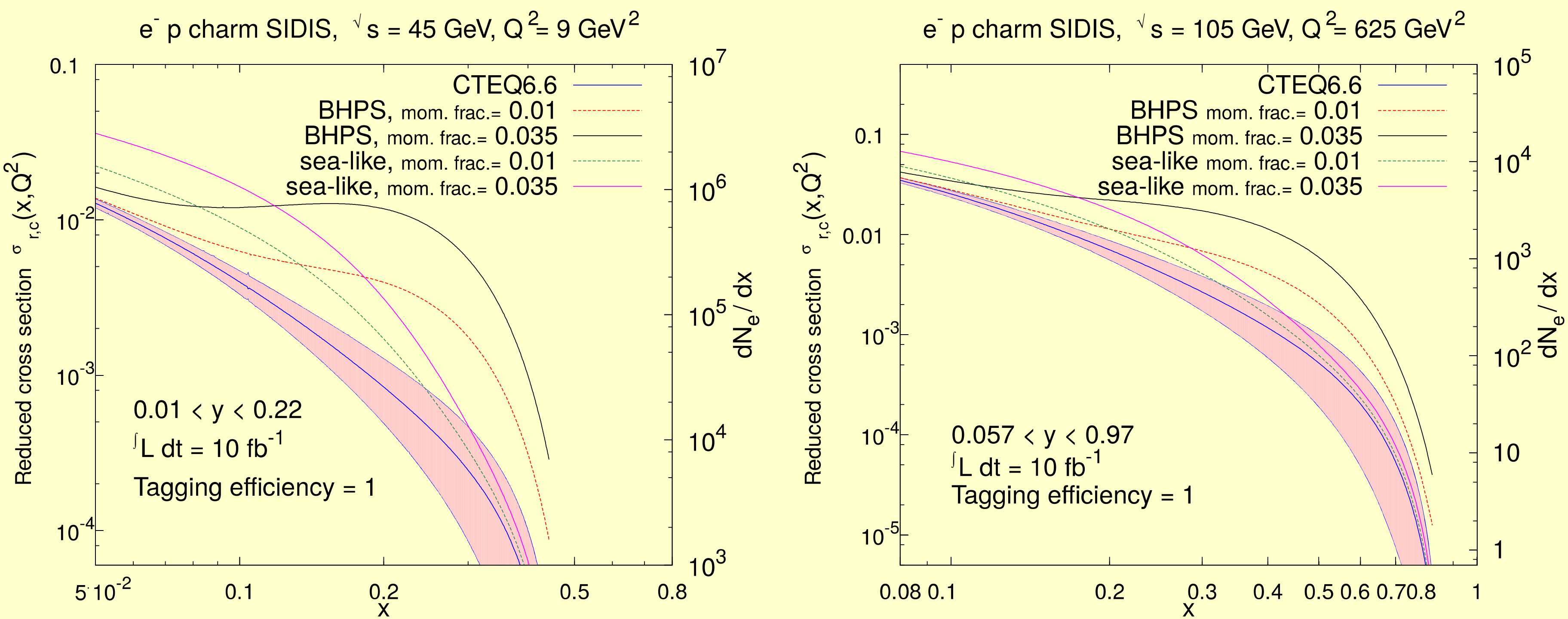
... what about

Intrinsic
Heavy Quarks

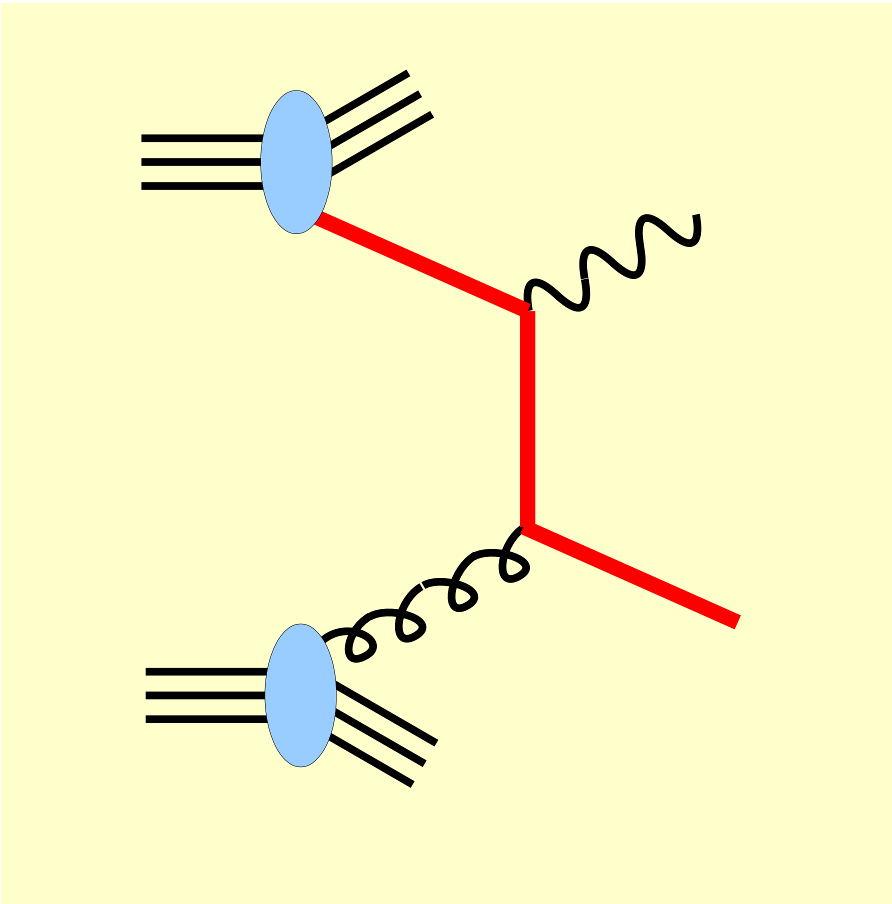
Intrinsic Charm PDFs

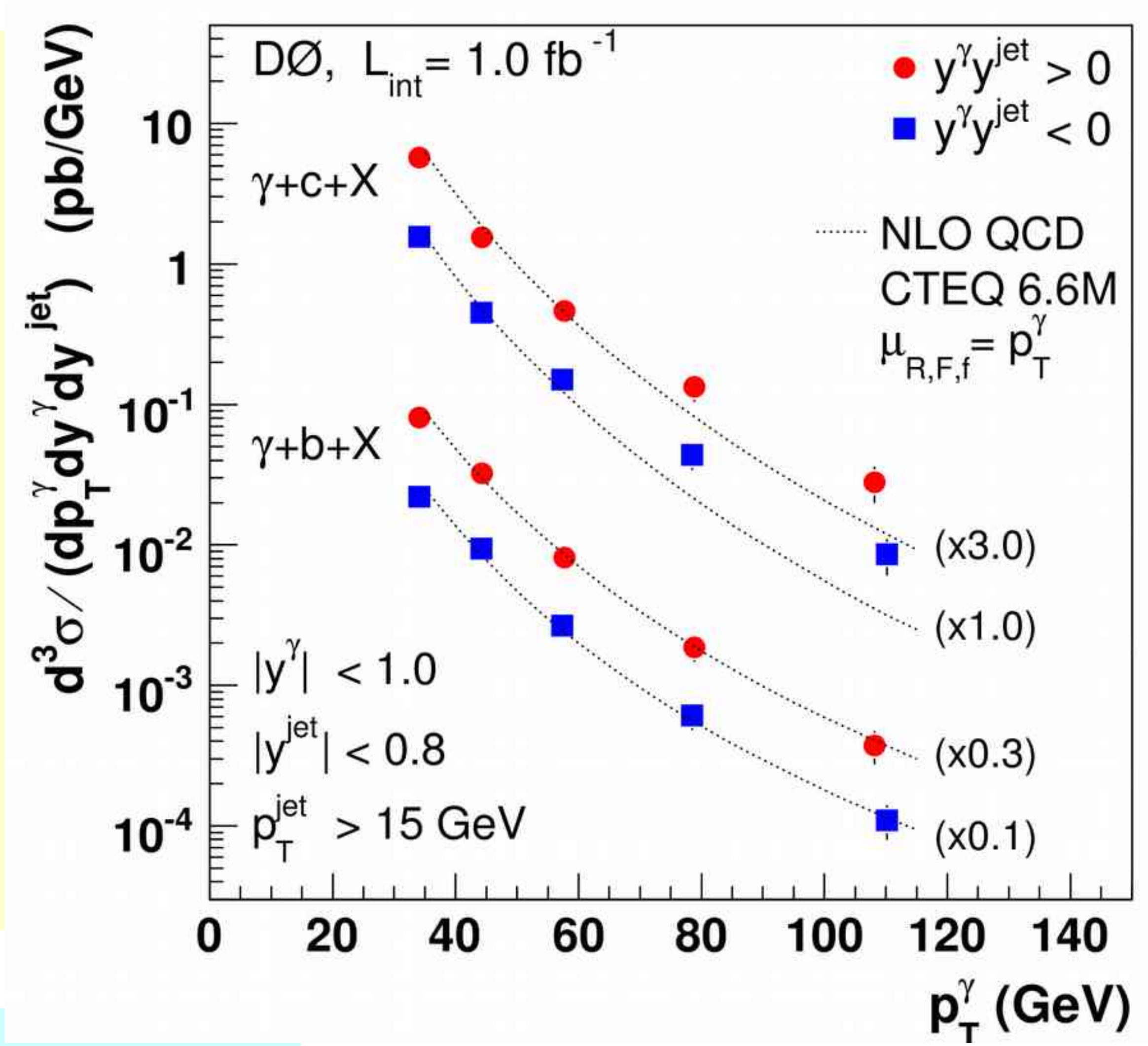


Gluons and the quark sea at high-energies



Tevatron & LHC can Access Heavy Flavor Components Directly





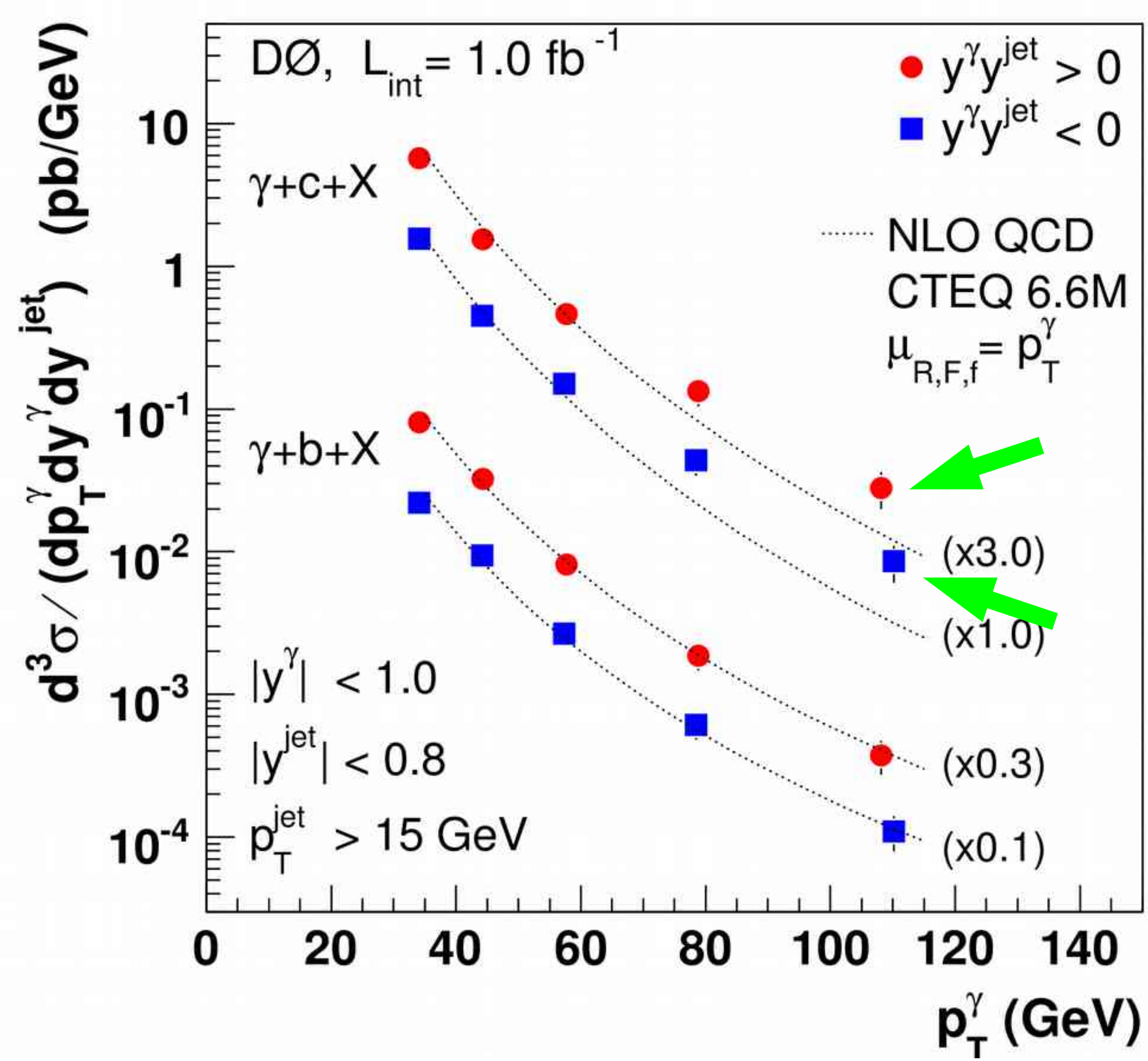
$c\ g \rightarrow c\ \gamma$

$b\ g \rightarrow b\ \gamma$

$s\ g \rightarrow c\ W$

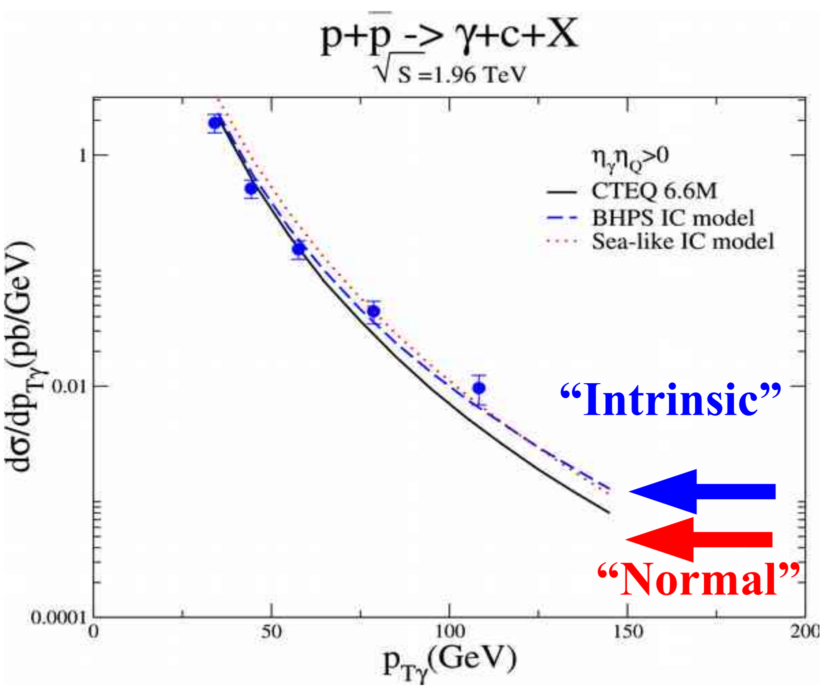
$c\ g \rightarrow b\ W$

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

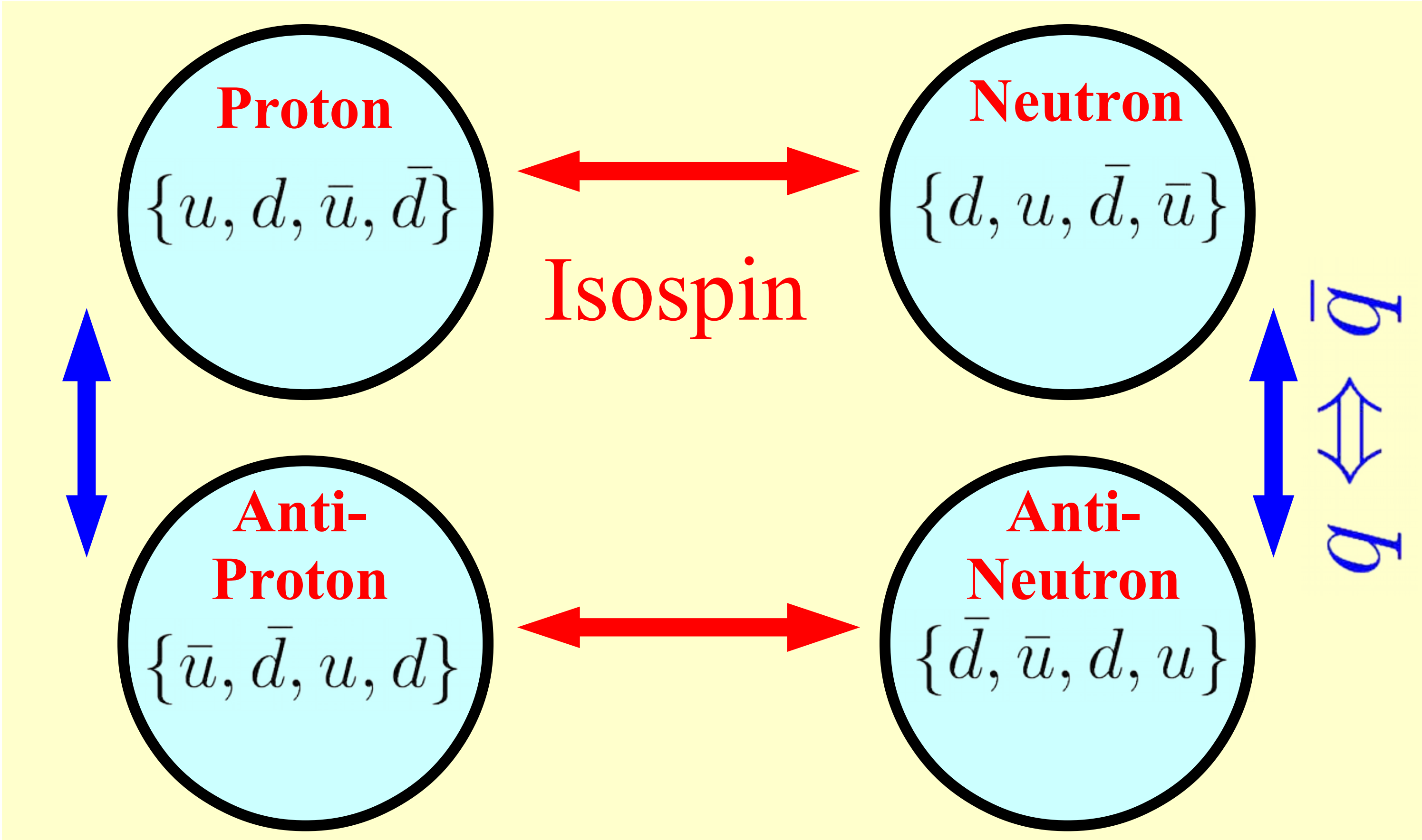
$$\dot{Q}_1 = P_{QQ} \otimes Q_1 .$$

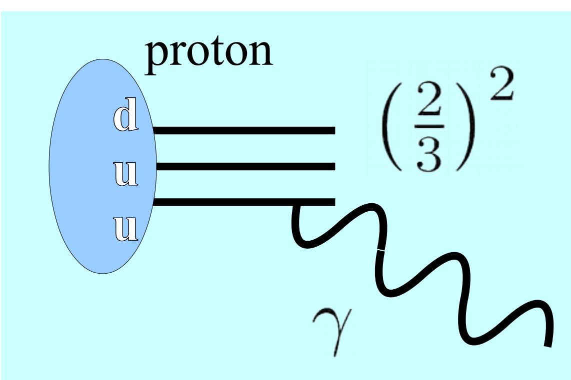
$$c_1(x) = \bar{c}_1(x) \propto x^2[6x(1+x)\ln x + (1-x)(1+10x+x^2)]$$

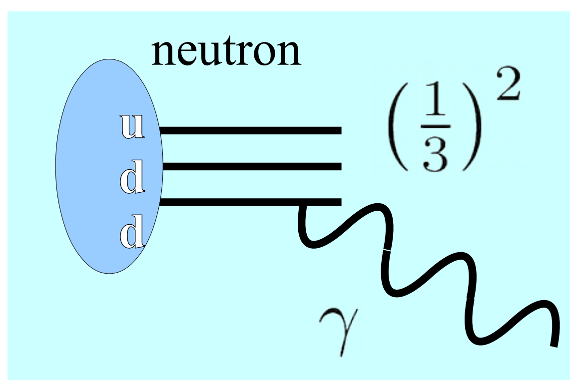
arXiv:1504.05156: On the intrinsic bottom content of the nucleon and its impact on heavy new physics at the LHC
F. Lyonnet, A. Kusina, T.Ježo, K. Kovařík, F. Olness, I. Schienbein, J.Y. Yu

More interesting things, particularly at large-x

Isospin Symmetry used to relate PDFs





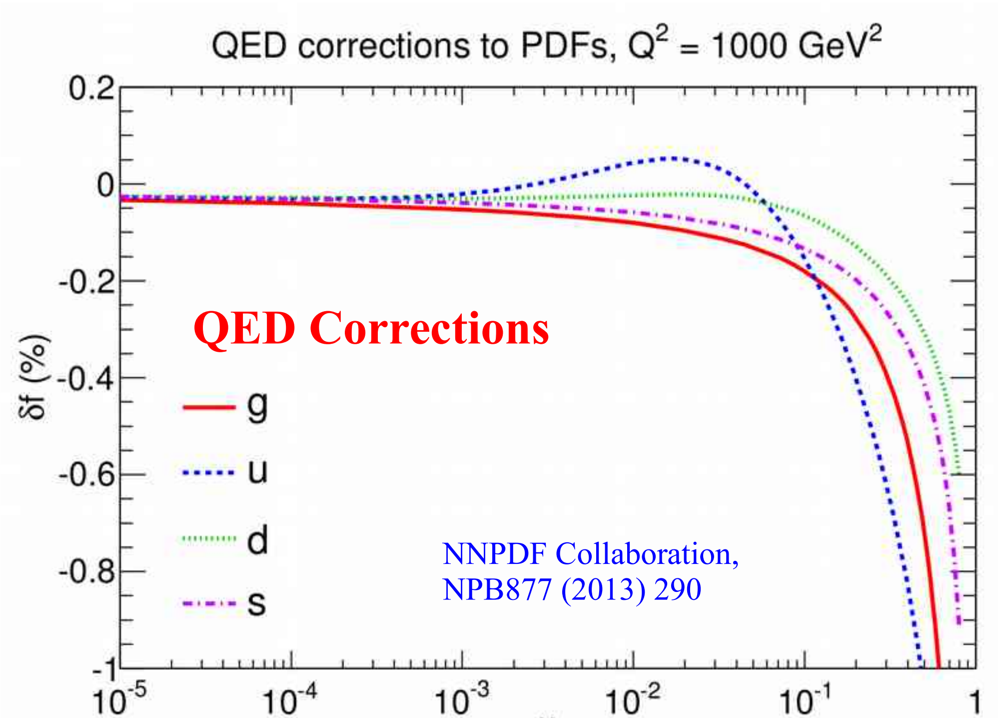


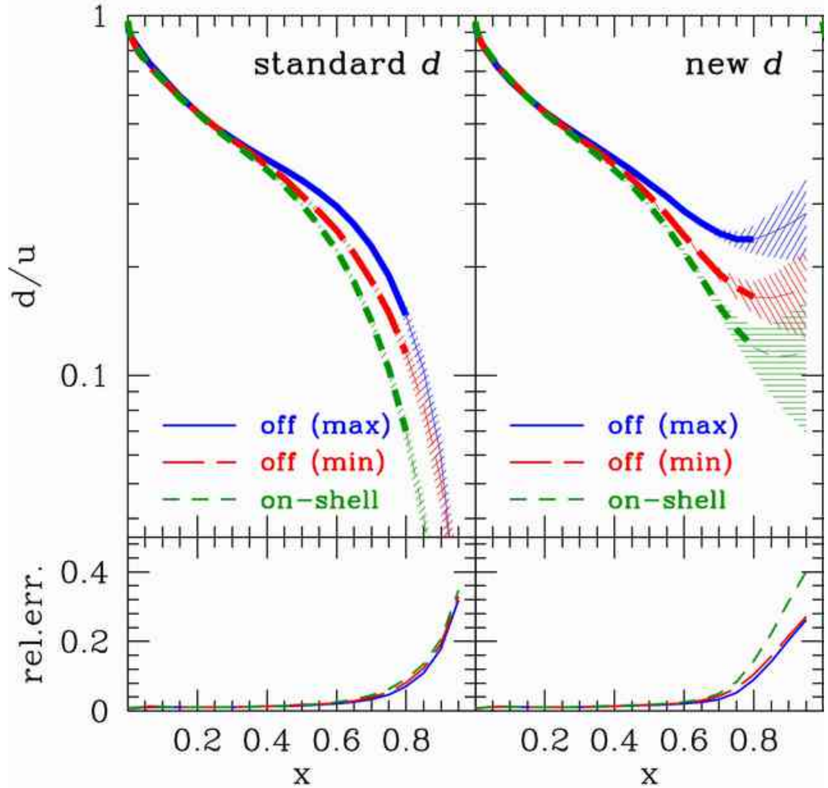
Isospin terms are comparable to NNLO QCD

QCD & EW Corrections do NOT factorize

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

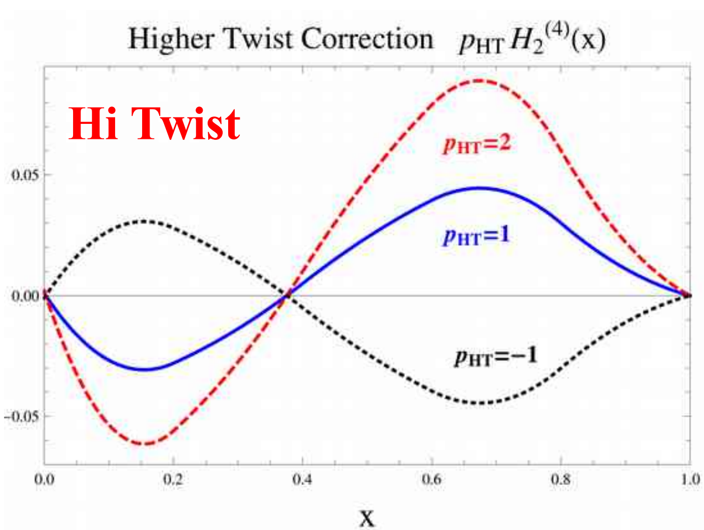
Hi-x Issues: Isospin Symmetry Violation, Higher Twist, ...

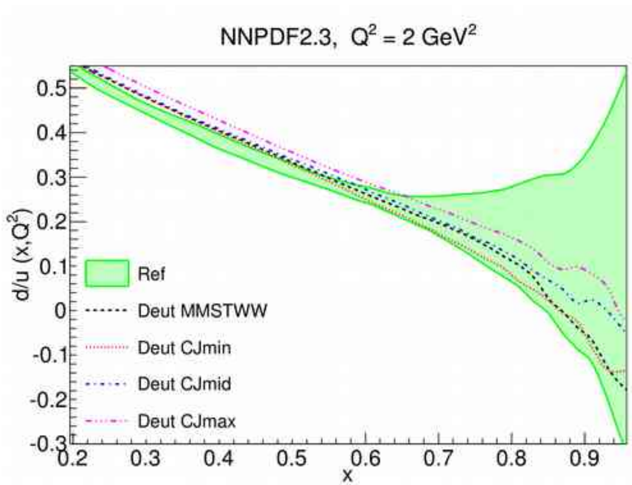


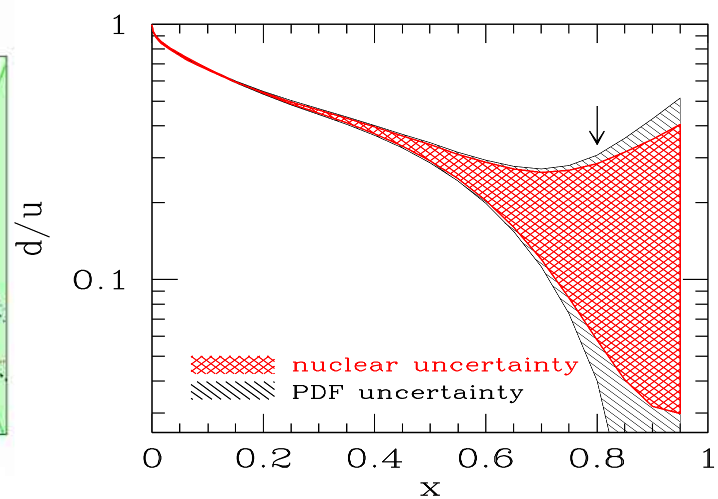


Hi-x is a “Gold Mine” for EIC

Nuclear Corrections or Parameterization???





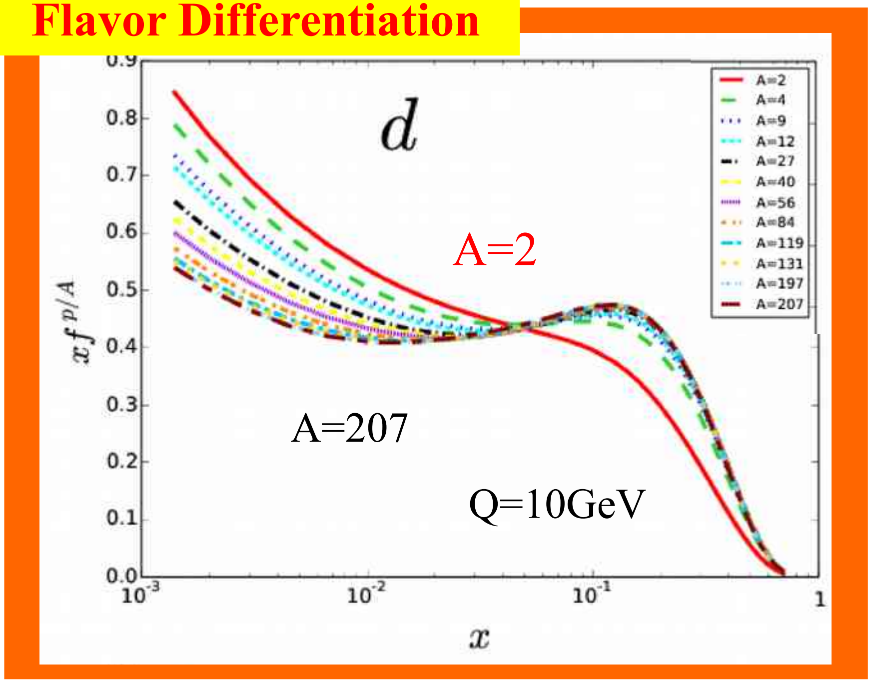


The NNPDF Collaboration, PLB723 (2013) 330

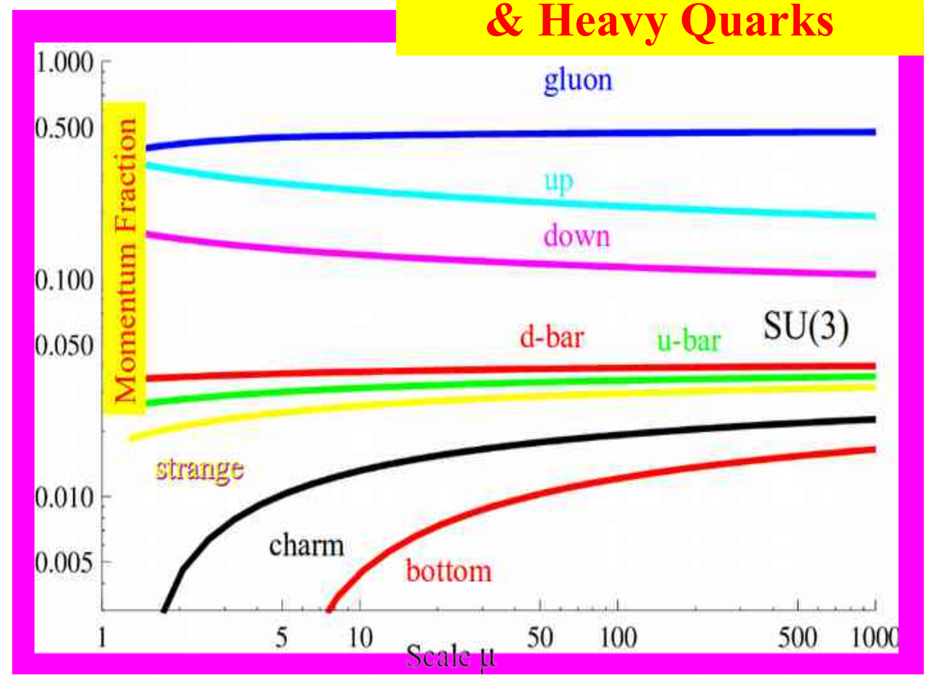
CTEQ-CJ: Phys.Rev. D84 (2011) 014008

Conclusion

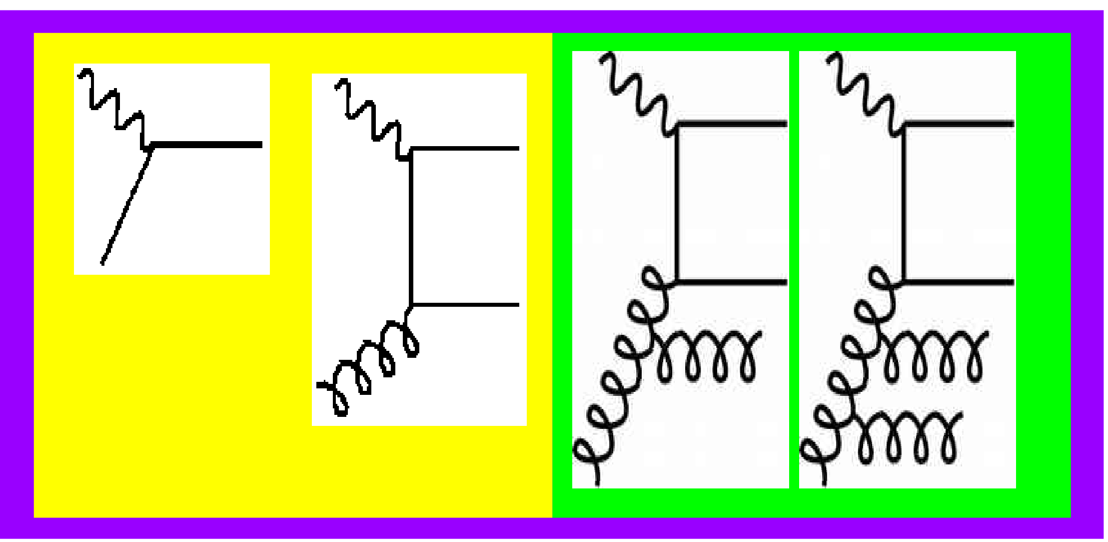
Nuclear Corrections & Flavor Differentiation



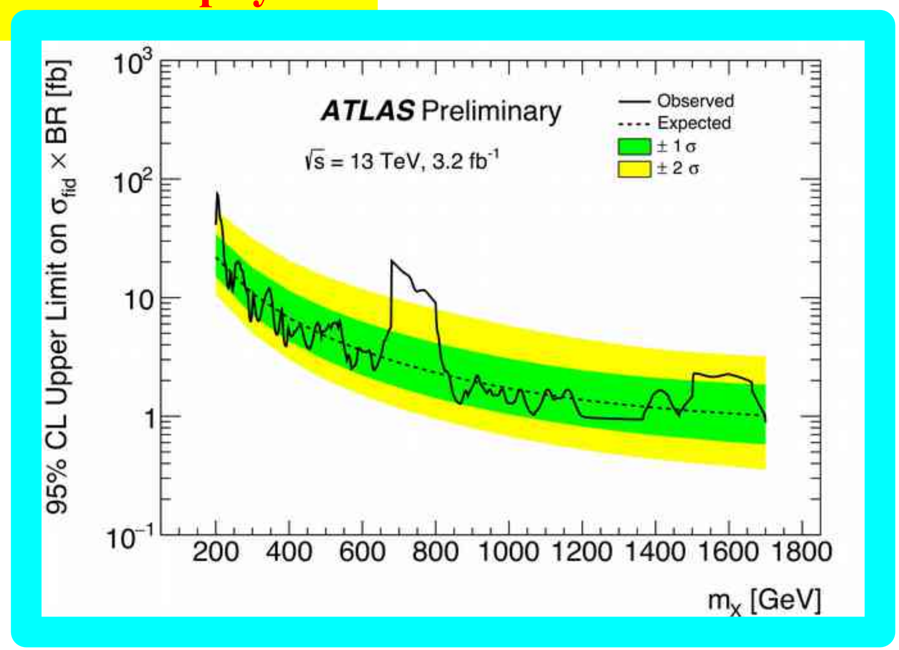
Multi-Scale Processes & Heavy Quarks



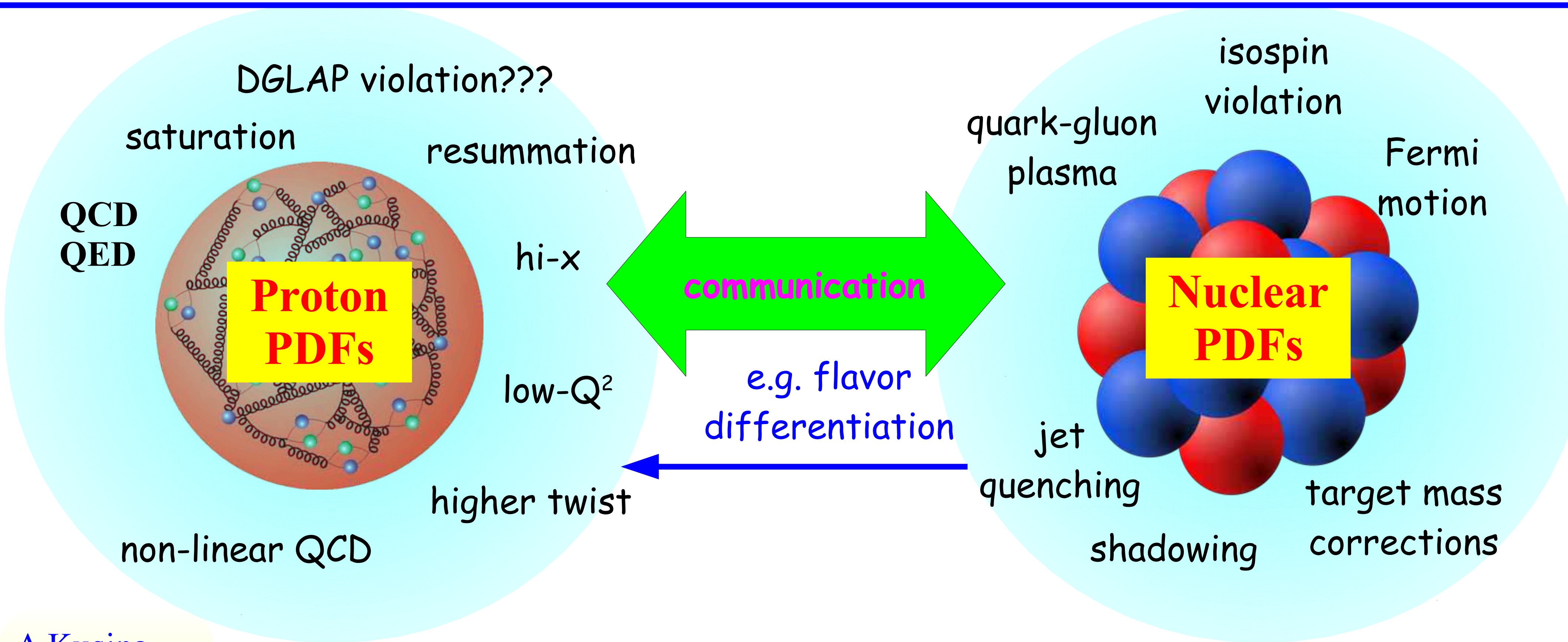
Higher Order Processes



Search for new physics



Moving Into The 21st Century



hi precision requires addressing the above details

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