nCTEQ15 Nuclear PDFs

... and related topics

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, V. Radescu, C. Keppel

xFitter Workshop: Dubna
18 February 2016

Challenges: … past, present,& future

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

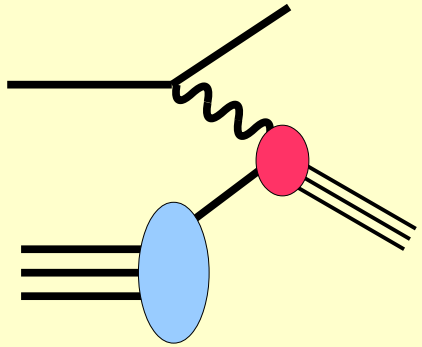
`http://www.hep.fsu.edu/~owens/qcd/QCD_list.html`

1) Flavor Differentiation & Nuclear Corrections

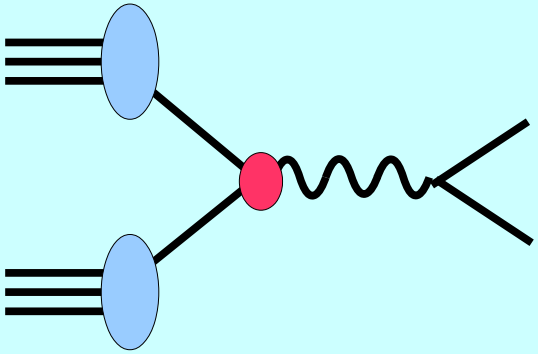
2) Multi-scale problems: Heavy Quarks

3) Hi-Order Corrections & ACOT

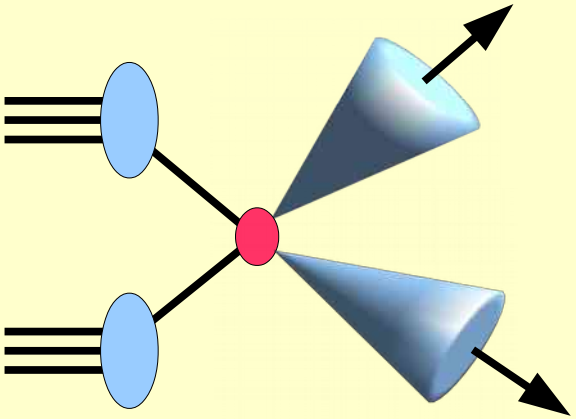
Key Data Sets for Global PDF Fits



DIS Production



Drell-Yan



Jet Production

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

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

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

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

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

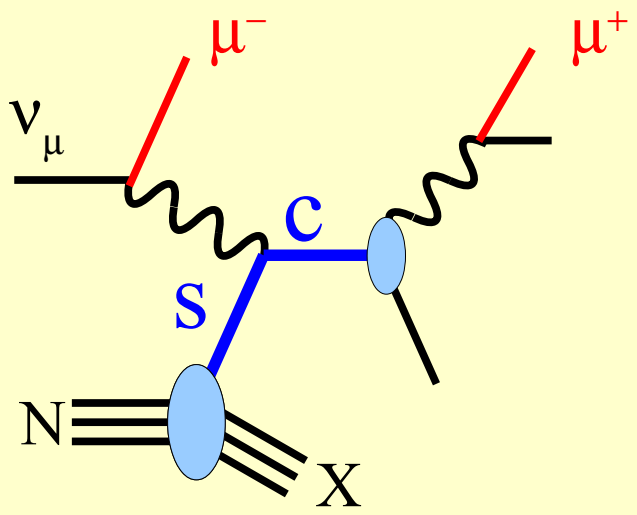
In particular, the DIS combinations have historically been particularly useful

Different linear combinations – key for flavor differentiation

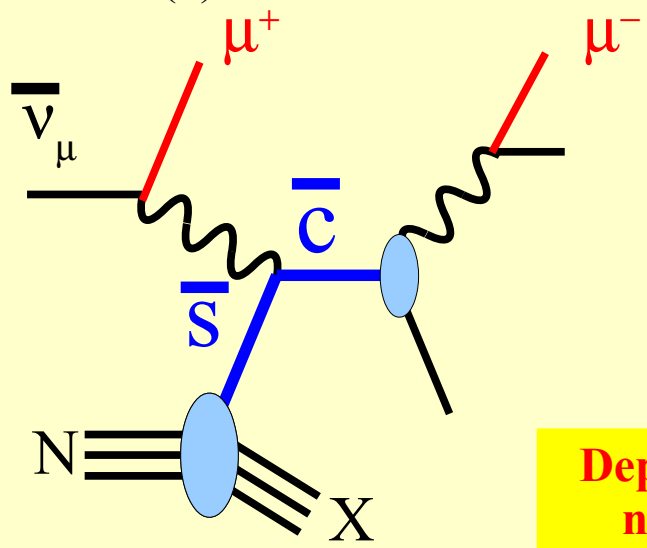
The ν-DIS data typically use heavy targets, and this requires the application of ***nuclear corrections***

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

Extract s(x)



Extract $\bar{s}(x)$



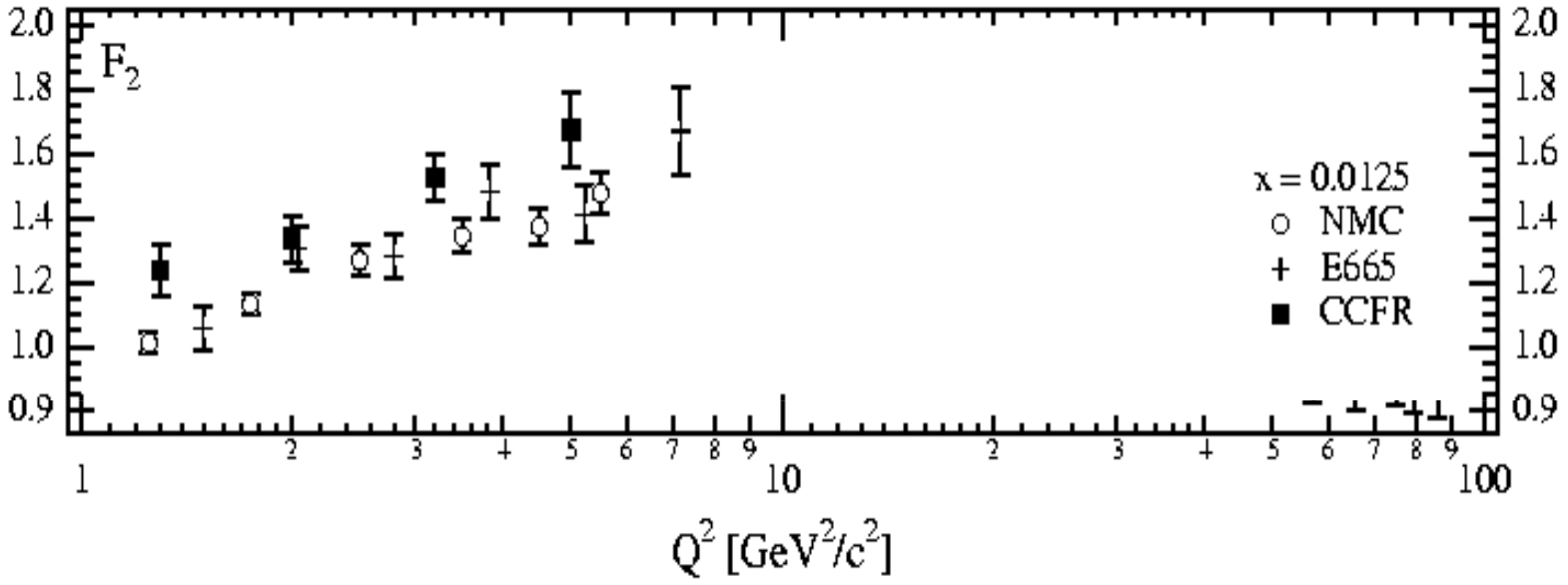
Depends on nuclear corrections

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

Used in CTEQ Fits

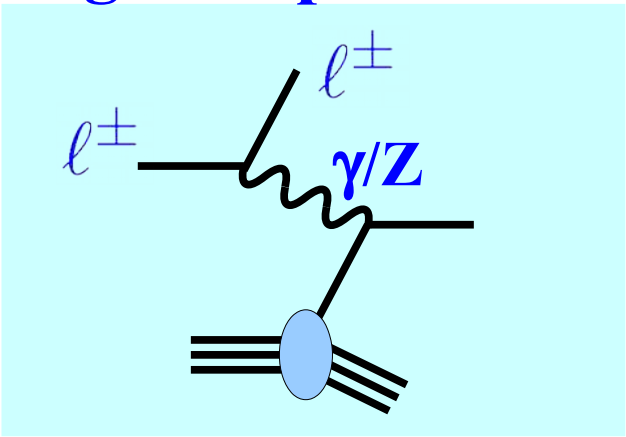
The CTEQ List of Challenges in Perturbative QCD

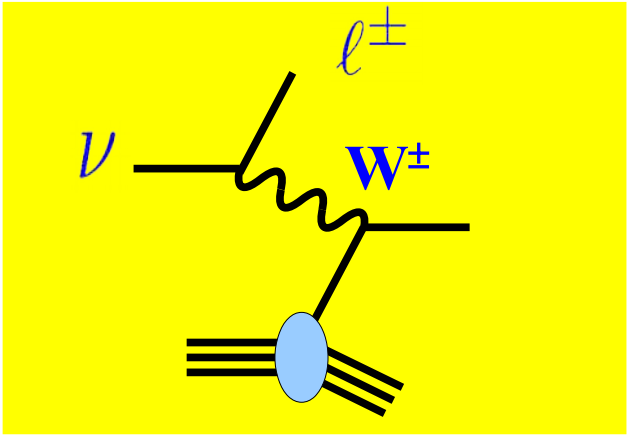
~1995



C T E Q

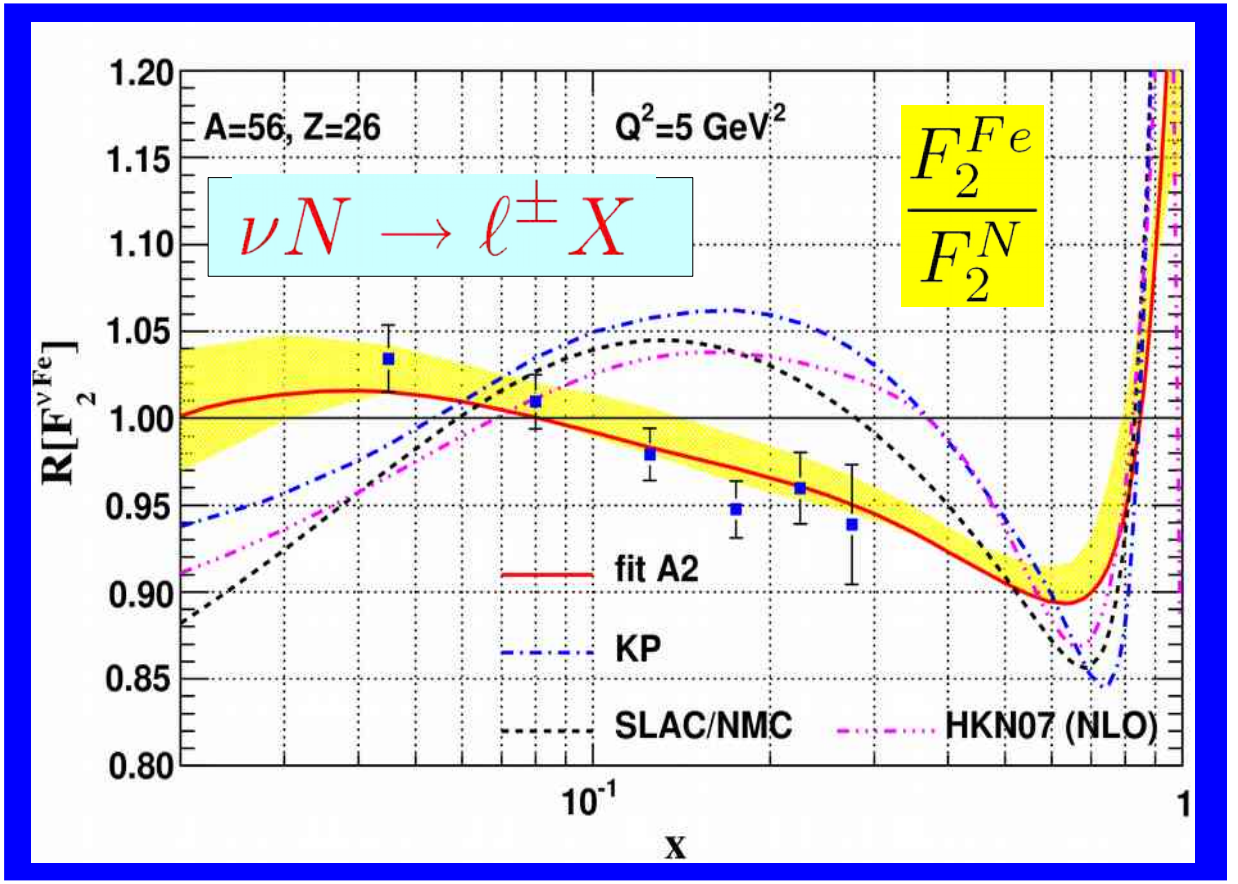
Charged Lepton DIS



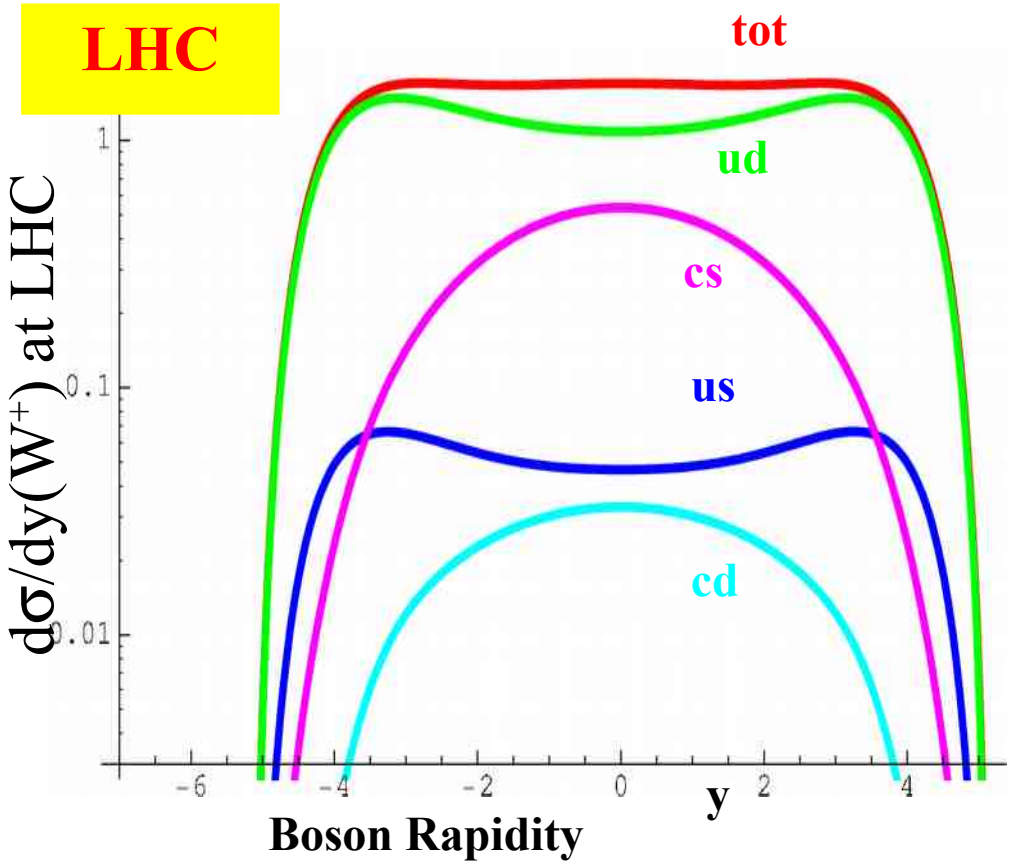


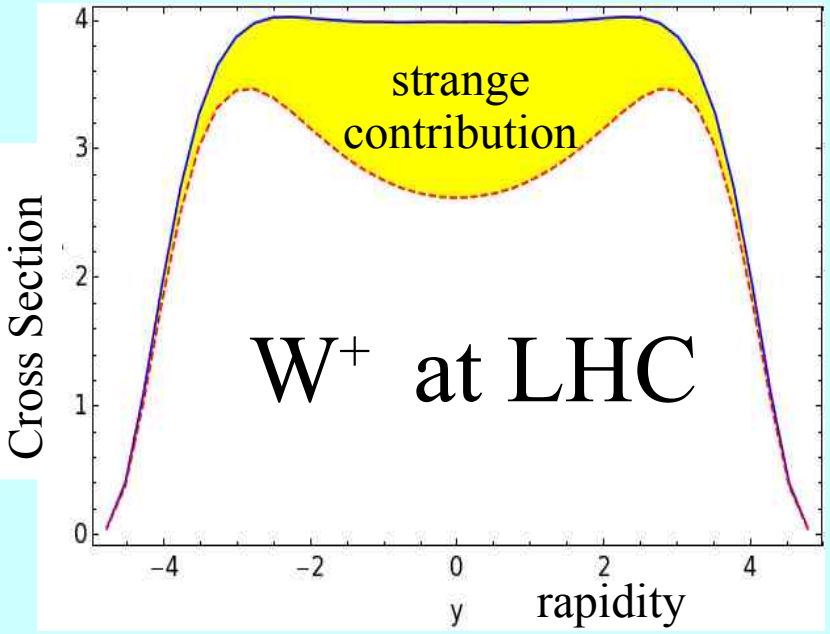
Neutrino DIS

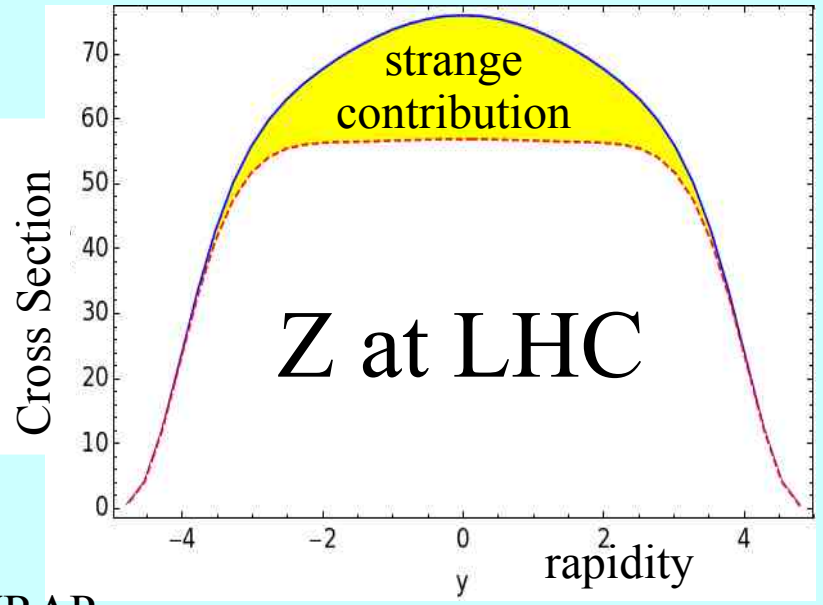
$$R = \frac{F_2^{Fe}}{F_2^N}$$



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







VRAP Code

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

CT14 strange quark PDF

- Conflicting results from experiments:

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

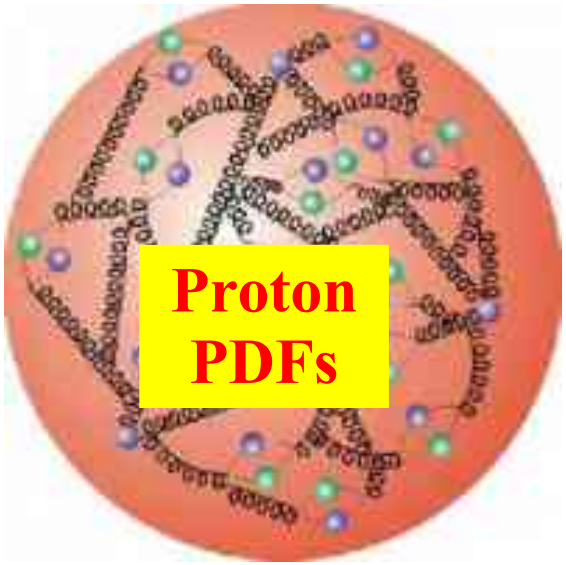
$$r^s_{\text{CT14NNLO}} = 0.53 \pm 0.20$$
$$r^s_{\text{CT10NNLO}} = 0.76 \pm 0.17$$

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

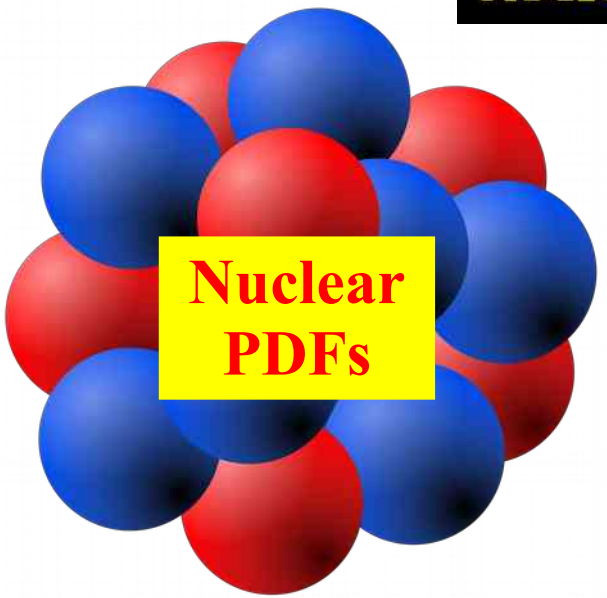
- NOMAD $$\kappa^s = 0.591 \pm 0.019$$

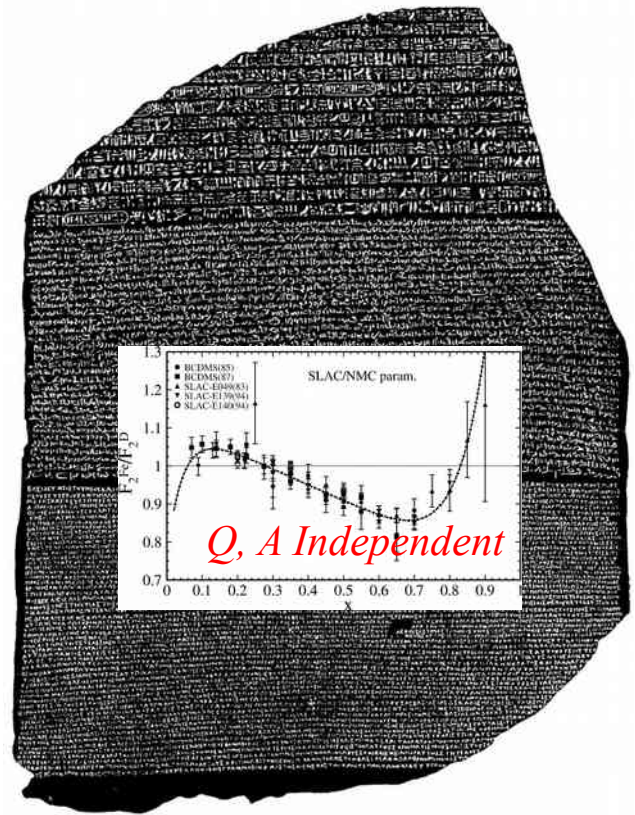
$$\kappa^s_{\text{CT14NNLO}} = 0.62 \pm 0.14$$
$$\kappa^s_{\text{CT10NNLO}} = 0.73 \pm 0.11$$

nCTEQ15 PDFs

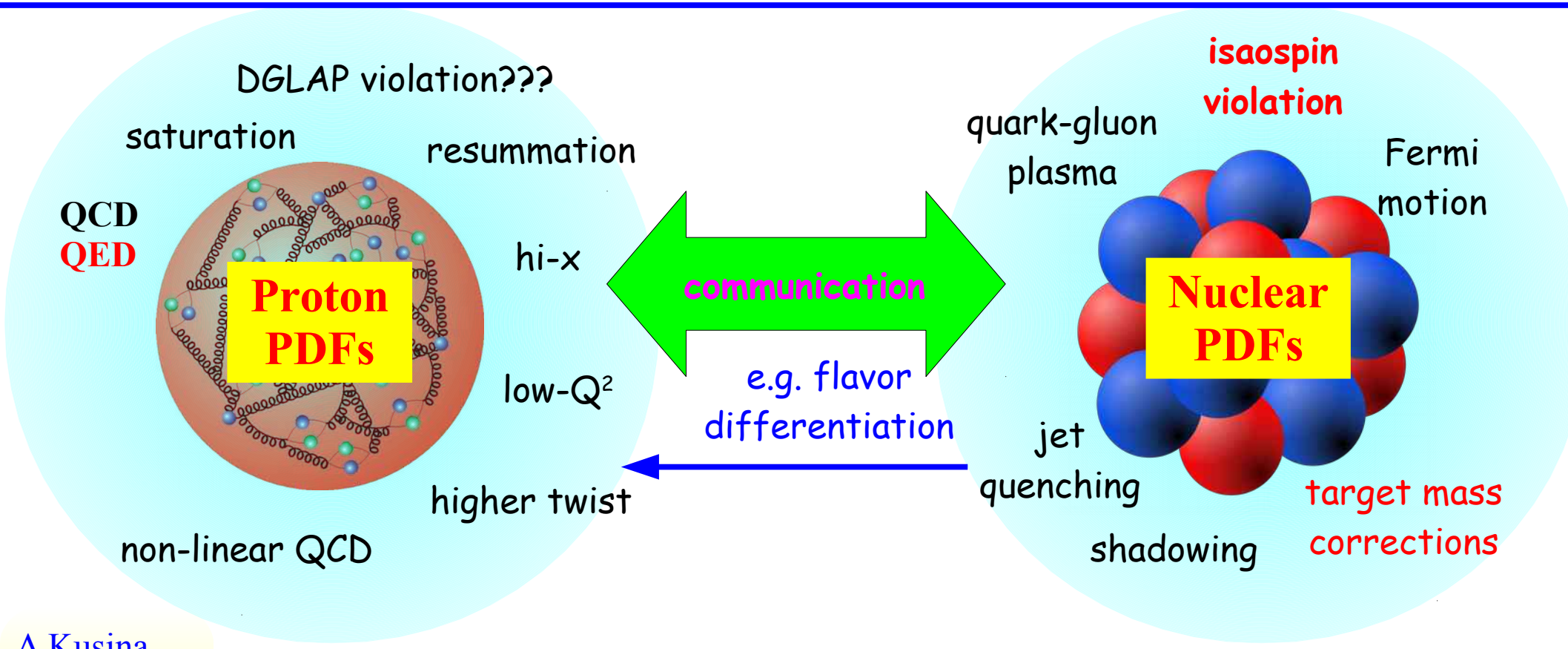


… there was a time when
nuclear corrections
were carved in stone …





Moving Into The 21st Century



A Kusina,
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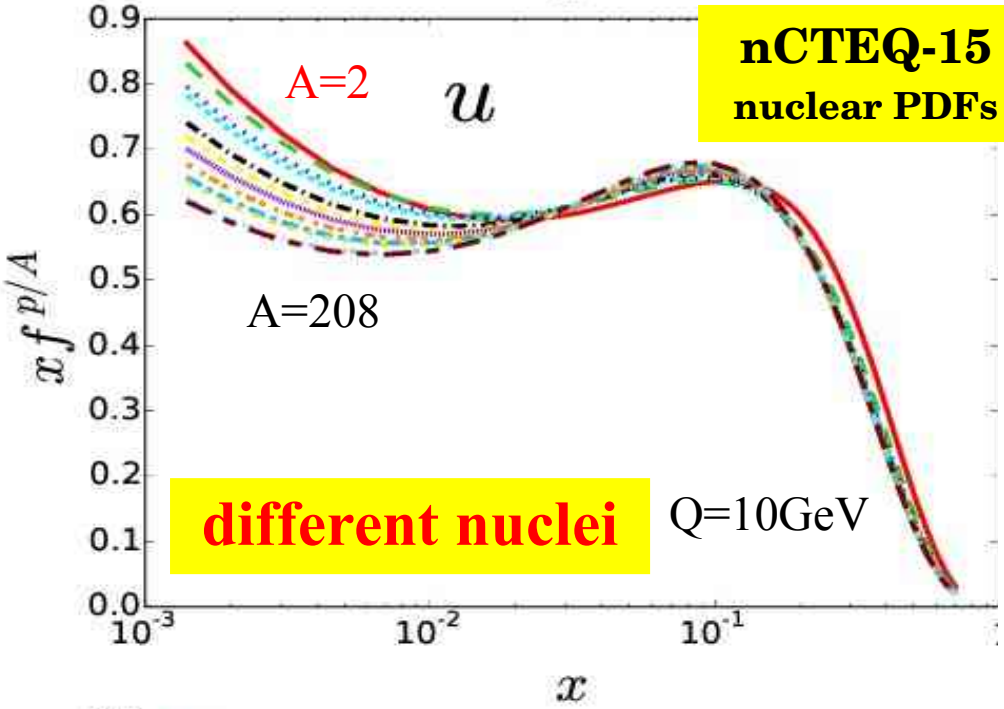
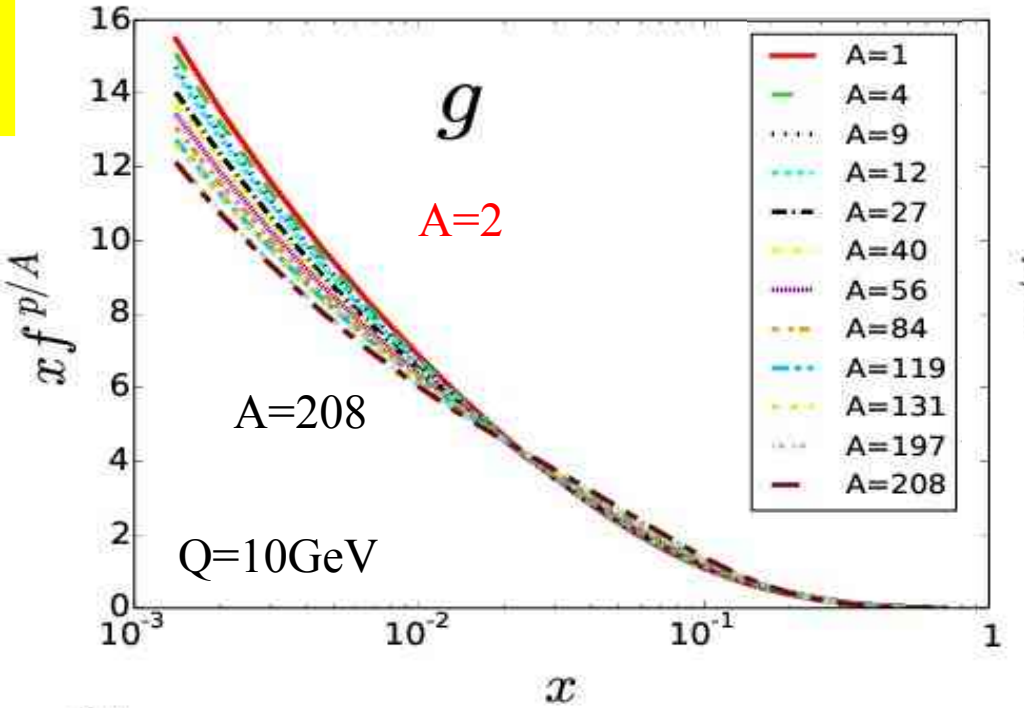
Data from nuclear targets play a key role in the flavor differentiation

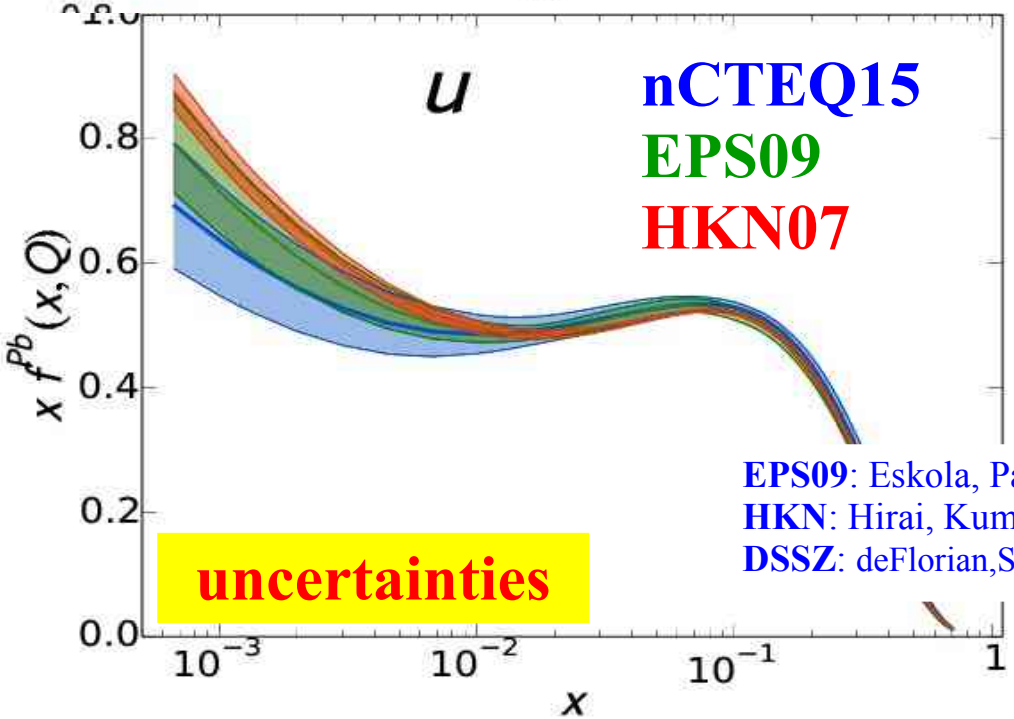
nCTEQ-15

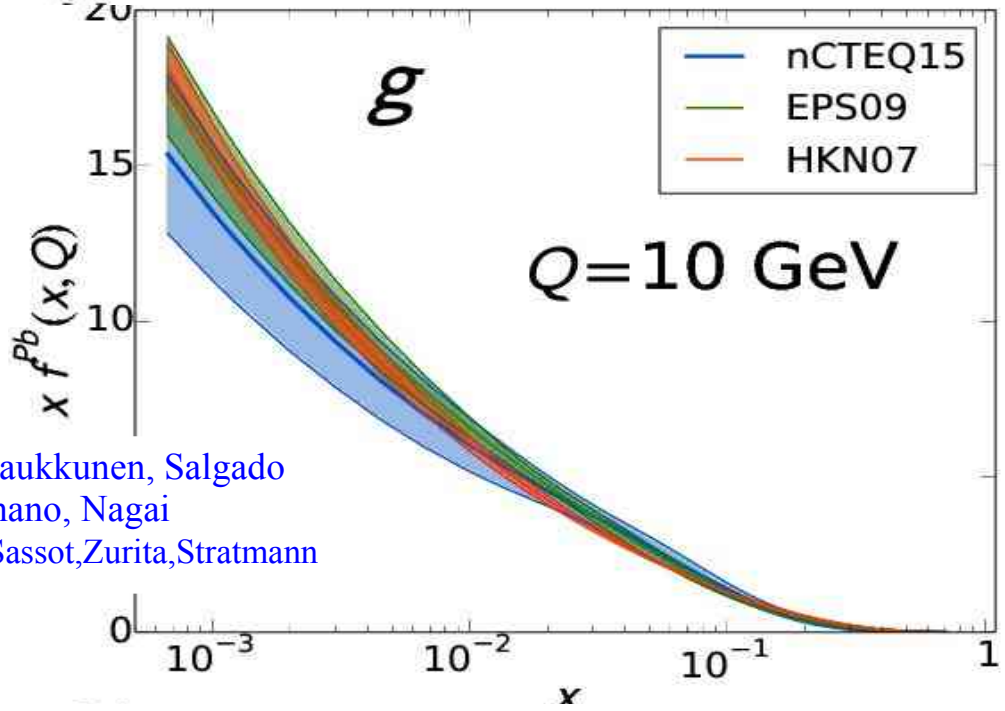
nuclear parton distribution functions

… the original motivation for nCTEQ15









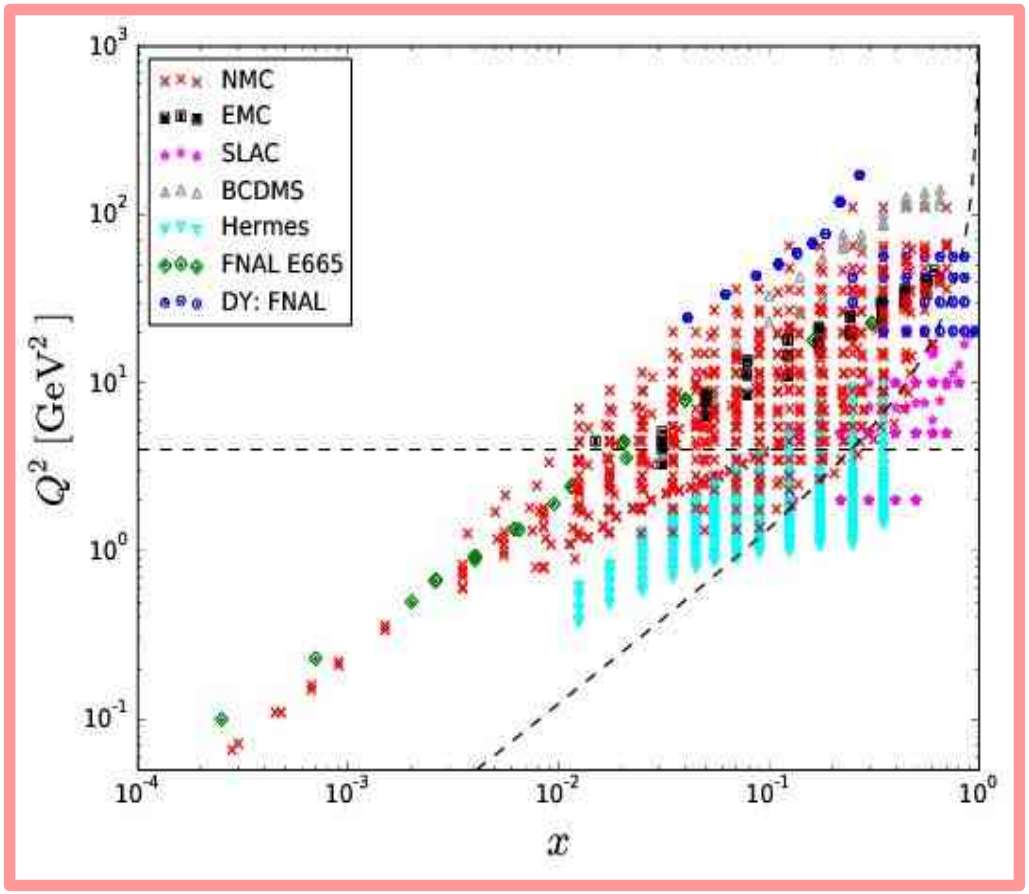
EPS09: Eskola, Paukkunen, Salgado
HKN: Hirai, Kumano, Nagai
DSSZ: deFlorian,Sassot,Zurita,Stratmann

DIS

III. EXPERIMENTAL DATA

F_2^A/F_2^D : Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
D	NMC-97	5160	48	292	201	247.73
He/D	Hermes	5156	49	182	17	13.45
	NMC-95,re	5124	50	18	12	9.78
	SLAC-E139	5141	51	18	3	1.42
Li/D	NMC-95	5115	52	24	11	6.10
Be/D	SLAC-E139	5138	51	17	3	1.37
C/D	FNAL-E665-95	5125	53	11	3	1.44
	SLAC-E139	5139	51	7	2	1.36
	EMC-88	5107	54	9	9	7.41
	EMC-90	5110	55	9	0	0.00
	NMC-95	5113	52	24	12	8.40
	NMC-95,re	5114	50	18	12	13.29
N/D	Hermes	5157	49	175	19	9.92
	BCDMS-85	5103	56	9	9	4.65
Al/D	SLAC-E049	5134	57	18	0	0.00
	SLAC-E139	5136	51	17	3	1.14
Ca/D	NMC-95,re	5121	50	18	12	11.54
	FNAL-E665-95	5126	53	11	3	0.94
	SLAC-E139	5140	51	7	2	1.63
	EMC-90	5109	55	9	0	0.00
Fe/D	SLAC-E049	5131	58	14	2	0.78
	SLAC-E139	5132	51	23	6	7.76
	SLAC-E140	5133	59	10	0	0.00
	BCDMS-87	5101	60	10	10	5.77
	BCDMS-85	5102	56	6	6	2.56
Cu/D	EMC-93	5104	61	10	9	4.71
	EMC-93(chariot)	5105	61	9	9	4.88
	EMC-88	5106	54	9	9	3.39
Kr/D						
Ag/D						
Sn/D						
Xe/D						
Au/D						
Pb/D						
Total:						

$F_2^A/F_2^{A'}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/Li	NMC-95,re	5123	50	25	7	5.56
Ca/Li	NMC-95,re	5122	50	25	7	1.11
Be/C	NMC-96	5112	63	15	14	4.08
Al/C	NMC-96	5111	63	15	14	5.39
Ca/C	NMC-95,re	5120	50	25	7	4.32
	NMC-96	5119	63	15	14	5.43
Fe/C	NMC-96	5143	63	15	14	9.78
Sn/C	NMC-96	5159	64	146	111	64.44
Pb/C	NMC-96	5116	63	15	14	7.74
Total:				296	202	107.85

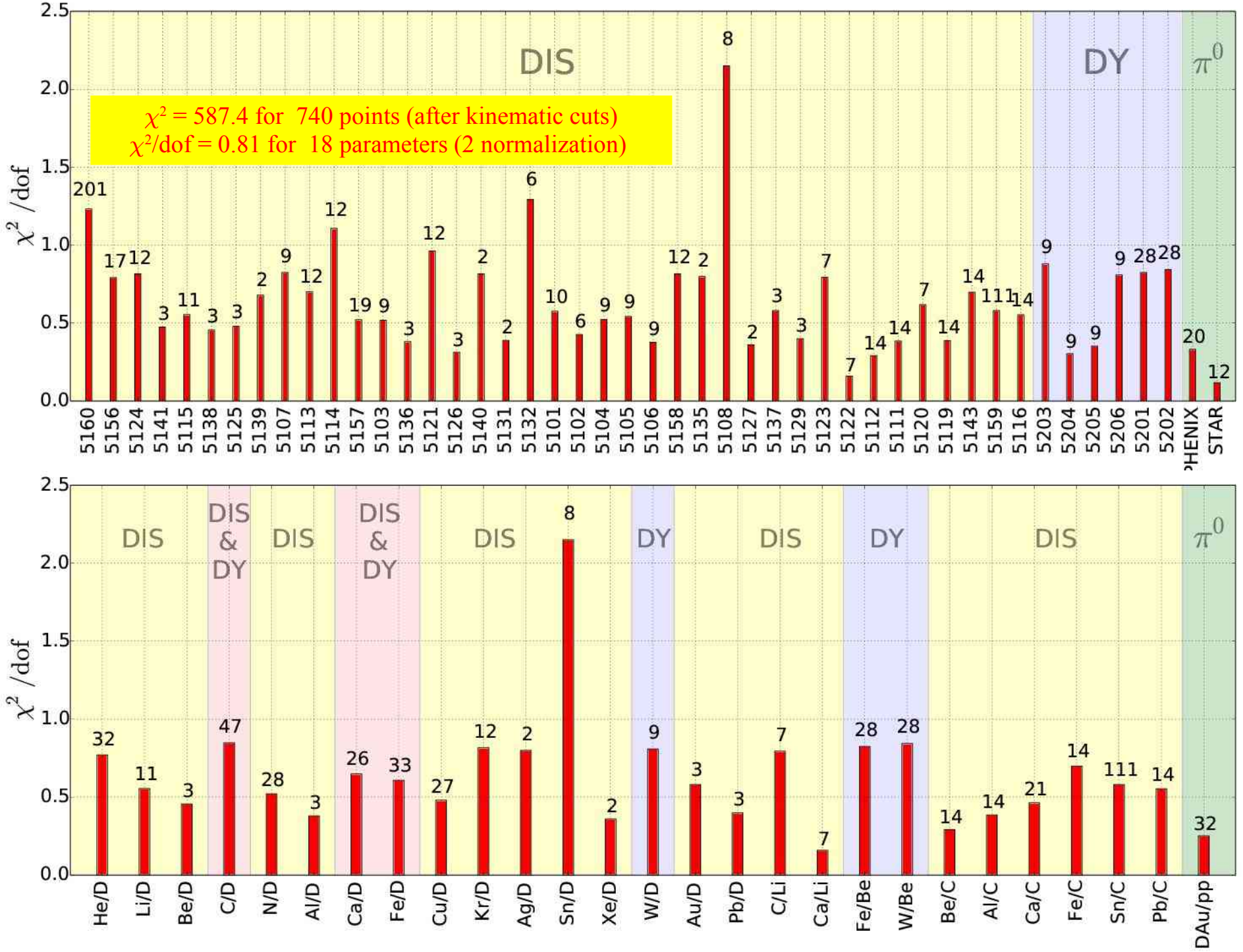


π Prod

$R^{\pi}_{dAu}/R^{\pi}_{pp}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
dAu/pp	PHENIX	PHENIX	67	21	20	6.63
	STAR-2010	STAR	68	13	12	1.41
Total:				34	32	8.04

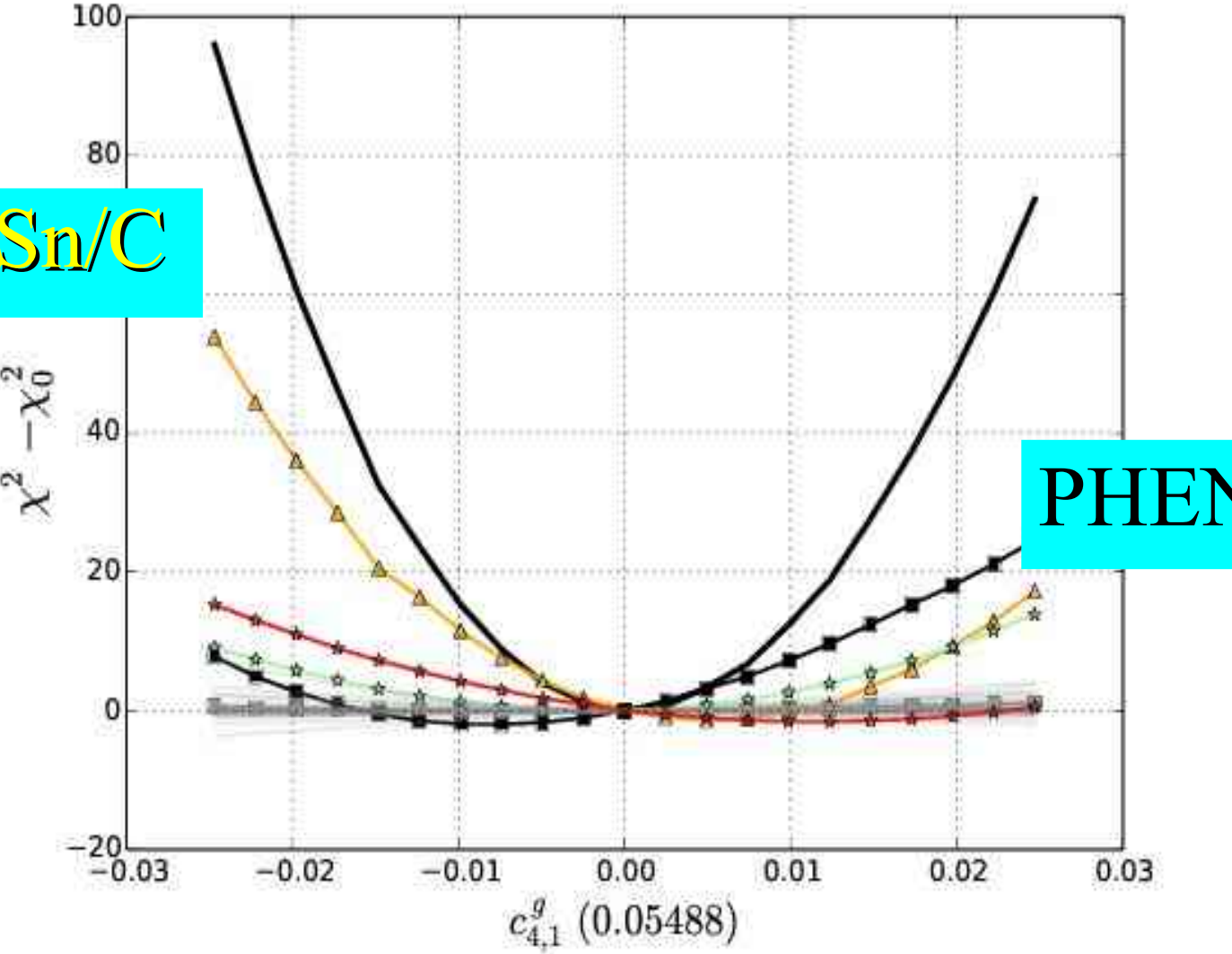
DY

$\sigma^{pA}_{DY}/\sigma^{pA'}_{DY}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/H2	FNAL-E772-90	5203	65	9	9	7.92
Ca/H2	FNAL-E772-90	5204	65	9	9	2.73
Fe/H2	FNAL-E772-90	5205	65	9	9	3.17
W/H2	FNAL-E772-90	5206	65	9	9	7.28
Fe/Be	FNAL-E886-99	5201	66	28	28	23.09
W/Be	FNAL-E886-99	5202	66	28	28	23.62
Total:				92	92	67.81


χ^2 = 587.4 for 740 points (after kinematic cuts)
χ^2/dof = 0.81 for 18 parameters (2 normalization)
χ^2 /dof
DIS
DY
π^0
5160 5156 5124 5141 5115 5138 5125 5139 5107 5113 5114 5157 5103 5136 5121 5126 5140 5131 5132 5101 5102 5104 5105 5106 5158 5135 5108 5127 5137 5129 5123 5122 5112 5111 5120 5119 5143 5159 5116 5203 5204 5205 5206 5201 5202 PHENIX STAR
DIS
DIS & DY
DIS
DIS & DY
DIS
DY
DIS
DY
DIS
π^0
He/D Li/D Be/D C/D N/D Al/D Ca/D Fe/D Cu/D Kr/D Ag/D Sn/D Xe/D W/D Au/D Pb/D C/Li Ca/Li Fe/Be W/Be Be/C Al/C Ca/C Fe/C Sn/C Pb/C DAu/pp

DIS Sn/C

PHENIX



nCTEQ Nuclear PDF's

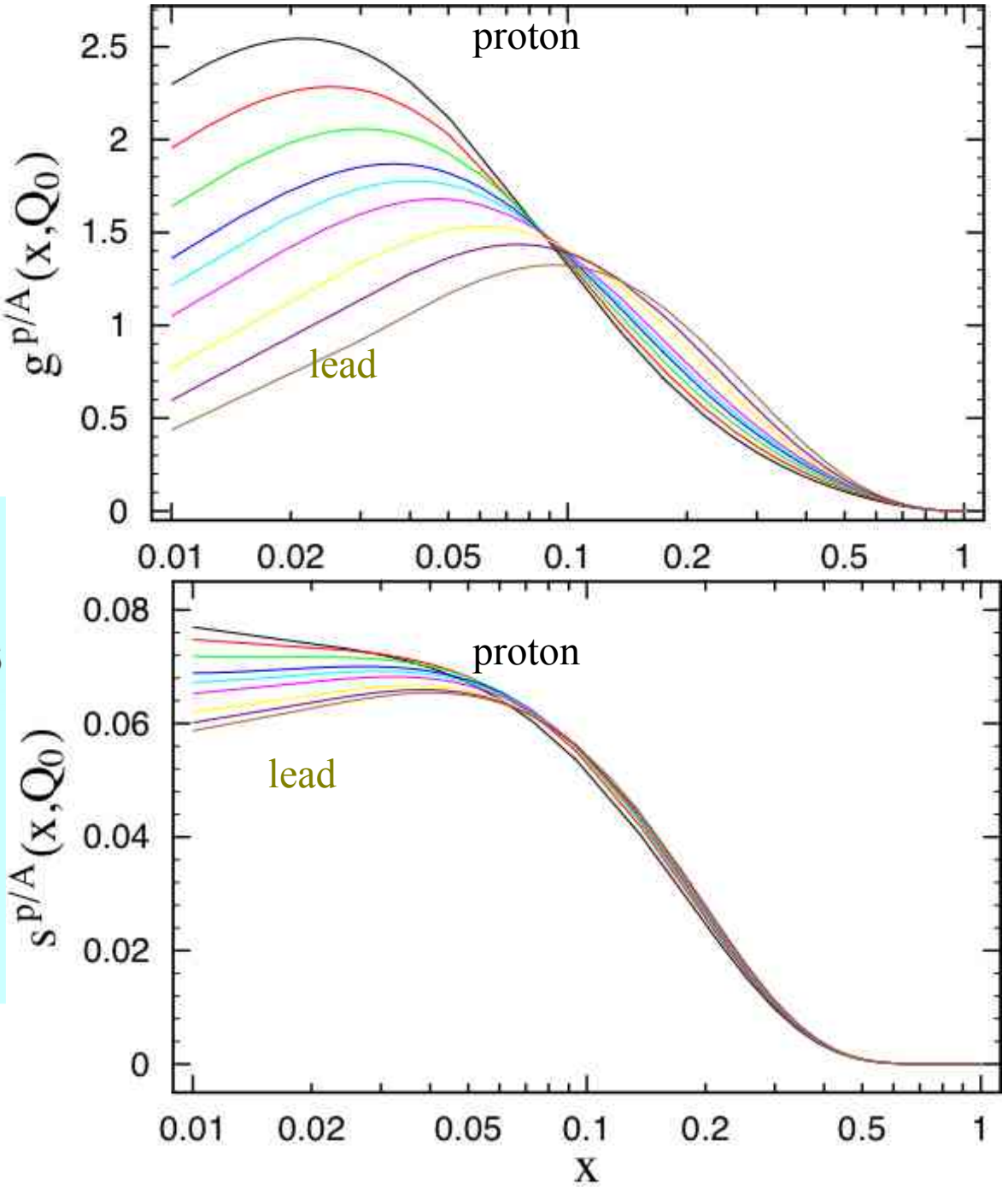
- ✔ CTEQ style global fit extended
  handle various nuclear targets
- ✔ CTEQ Data + nuclear DIS & DY
  [~15 targets; ~2000+ data]
- ✔ A-dependence modeled;
  NLO fits work well

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.

A-Dependent PDFs

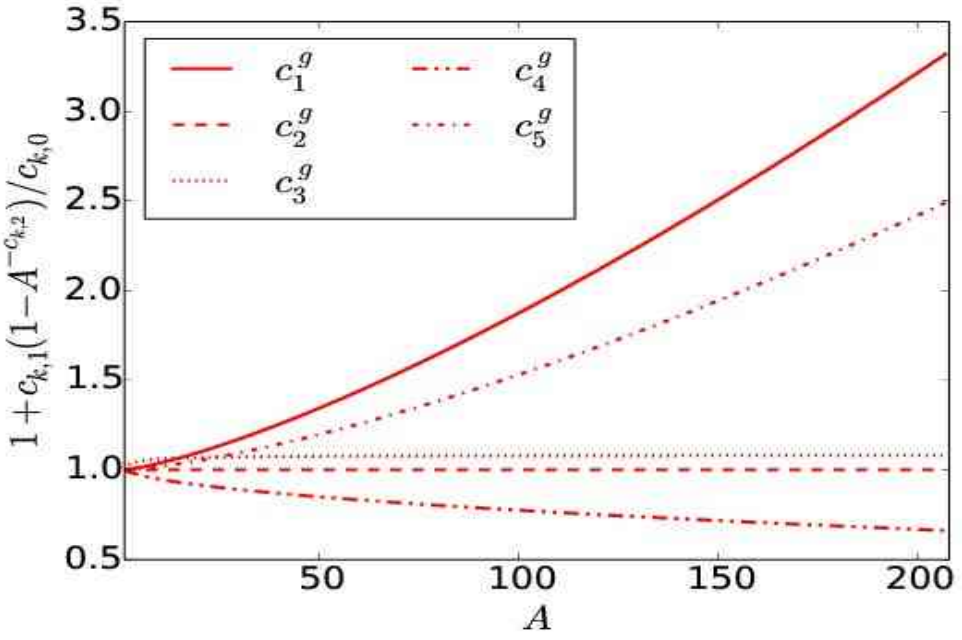
$$xf(x) = x^{a_1}(1-x)^{a_2}e^{a_3 x}(1+e^{a_4}x)^{a_5}$$

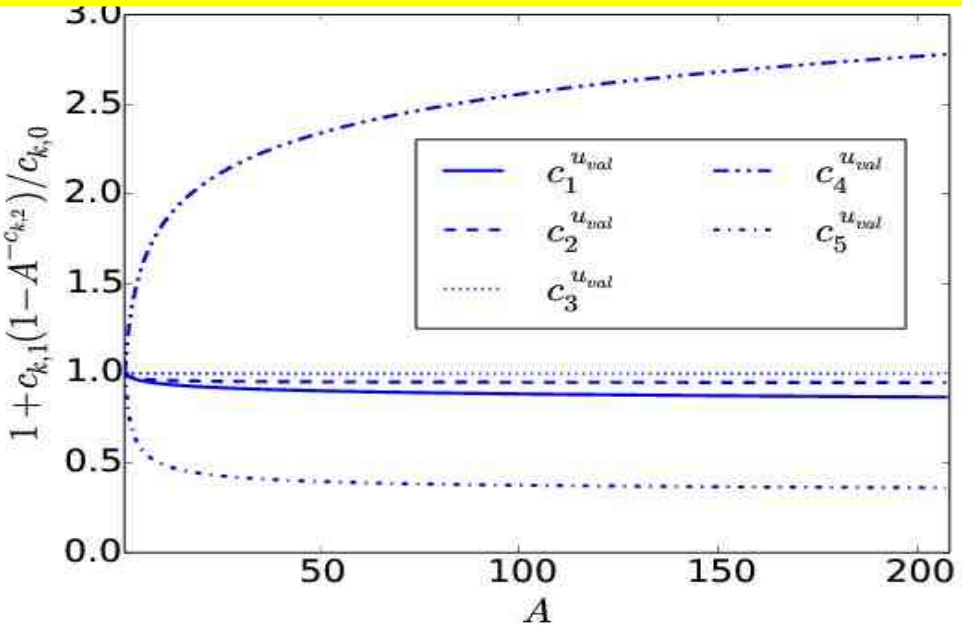
$$a_i \rightarrow a_i(A)$$

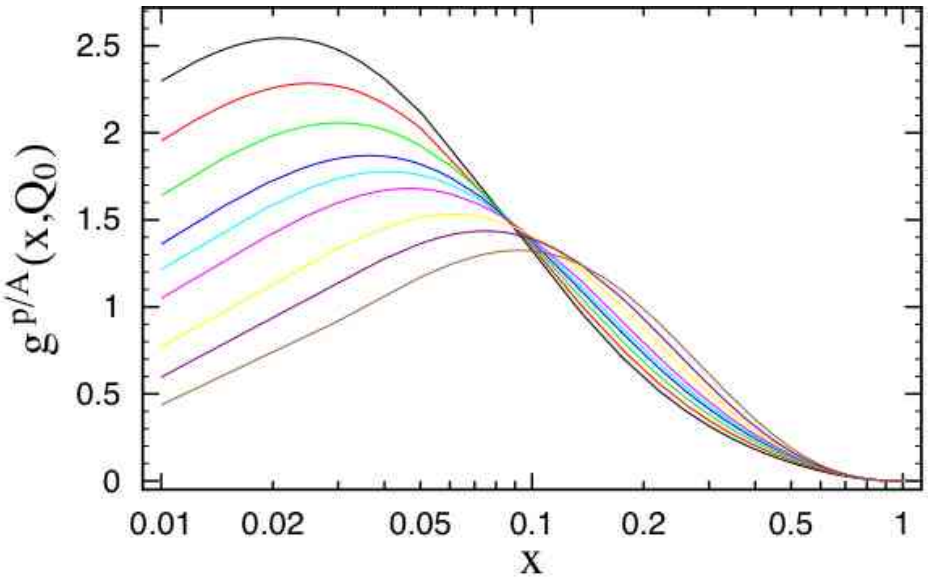
$$a_k = a_{k,0} + a_{k,1}\,(1-A^{-ak,2})$$

Set by proton

Nuclear dof







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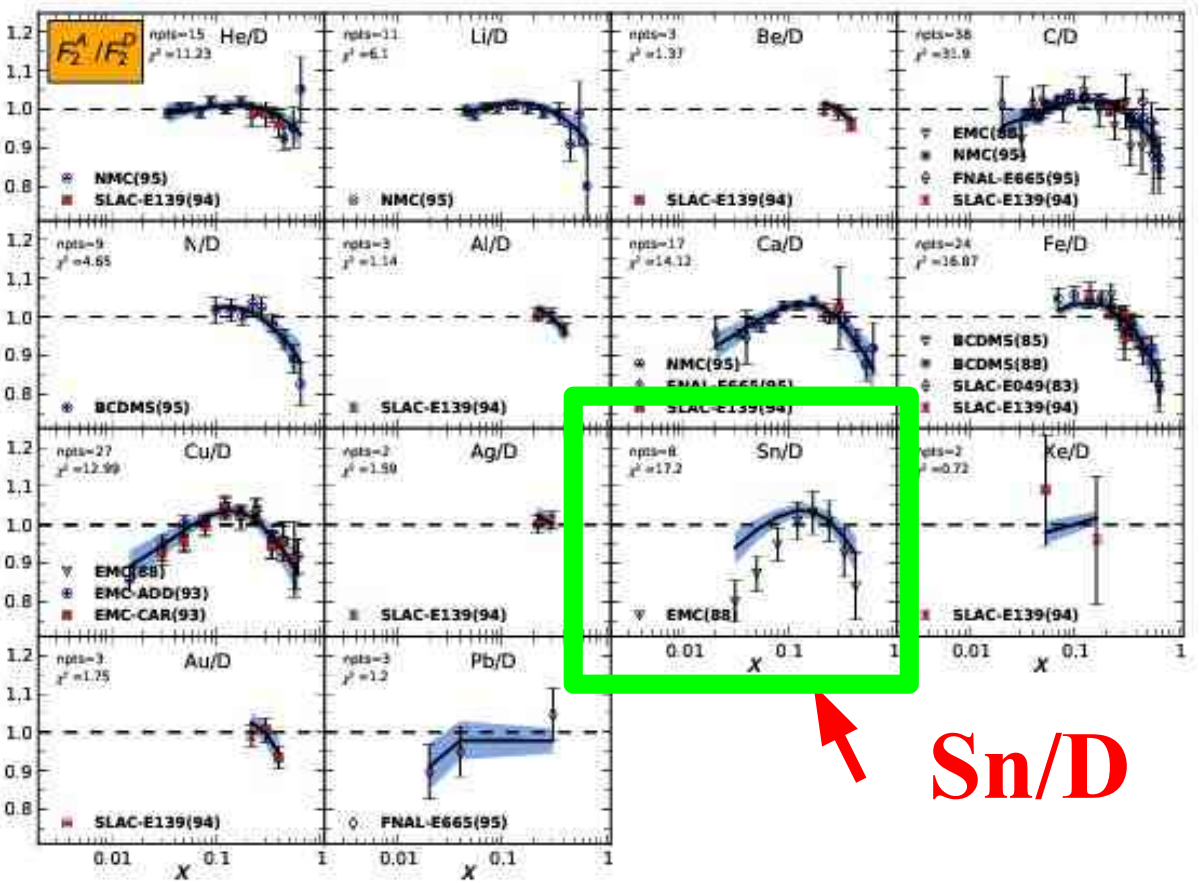
	EMC-88	5106	54	9	9	3.39
Kr/D	Hermes	5158	49	167	12	9.79
Ag/D	SLAC-E139	5135	51	7	2	1.60
Sn/D	EMC-88	5108	54	8	8	17.20
Xe/D	FNAL-E665-92	5127	62	10	2	0.72
Au/D	SLAC-E139	5137	51	18	3	1.74
Pb/D	FNAL-E665-95	5129	53	11	3	1.20
Total:				1205	414	403.70



Sn/D

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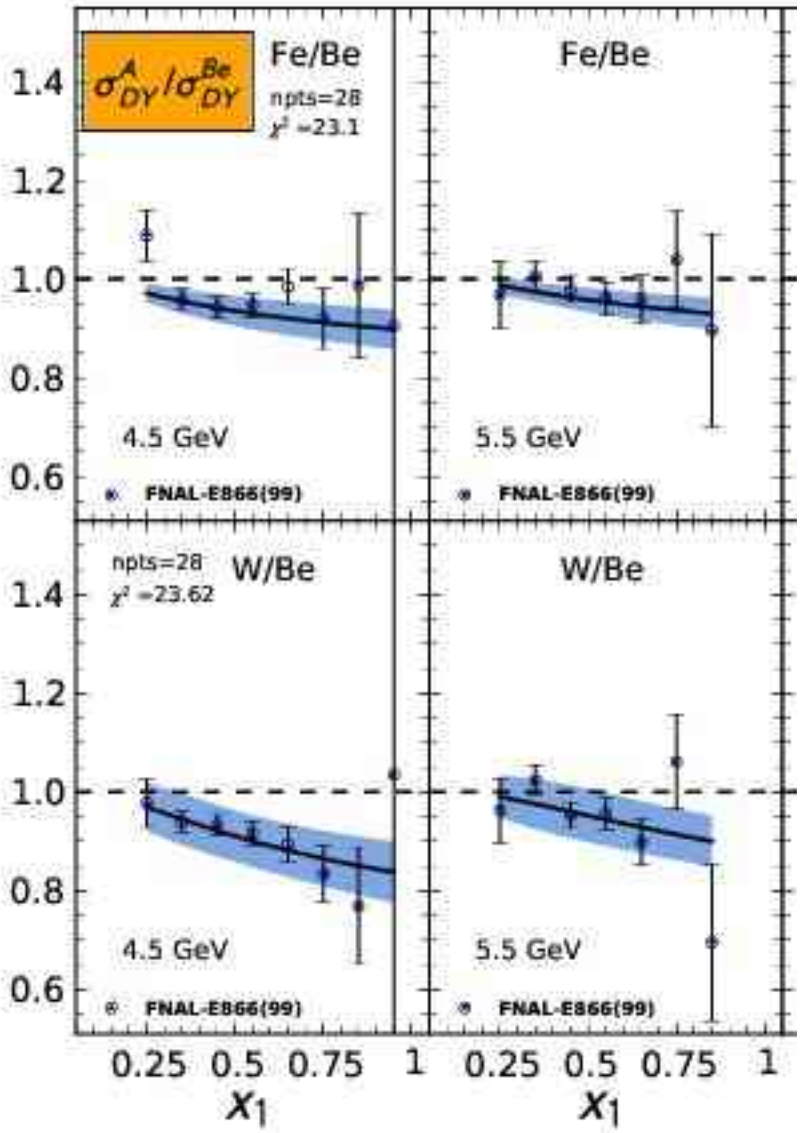
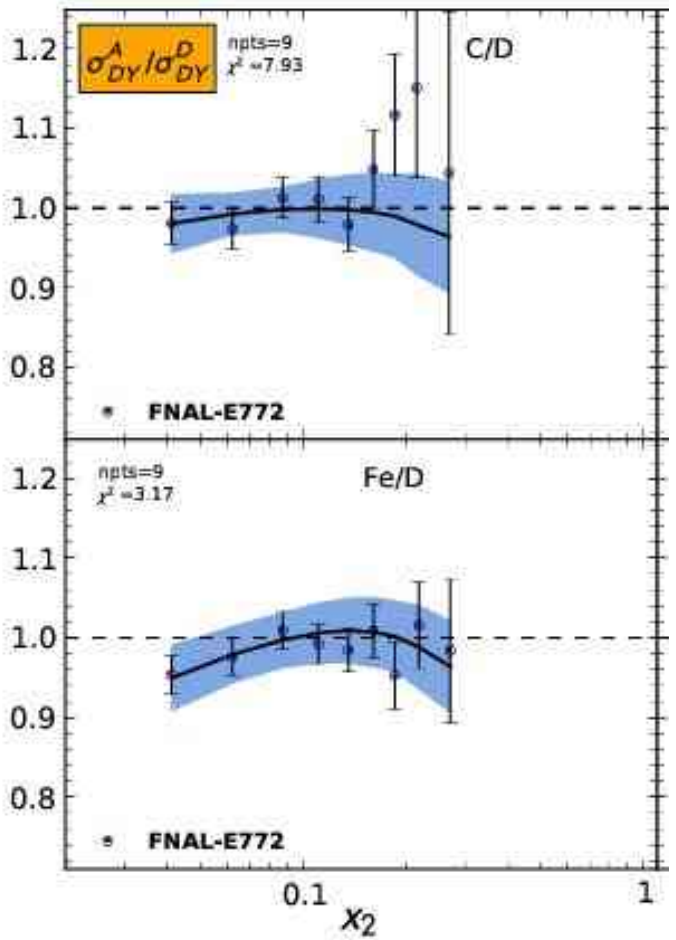
DY



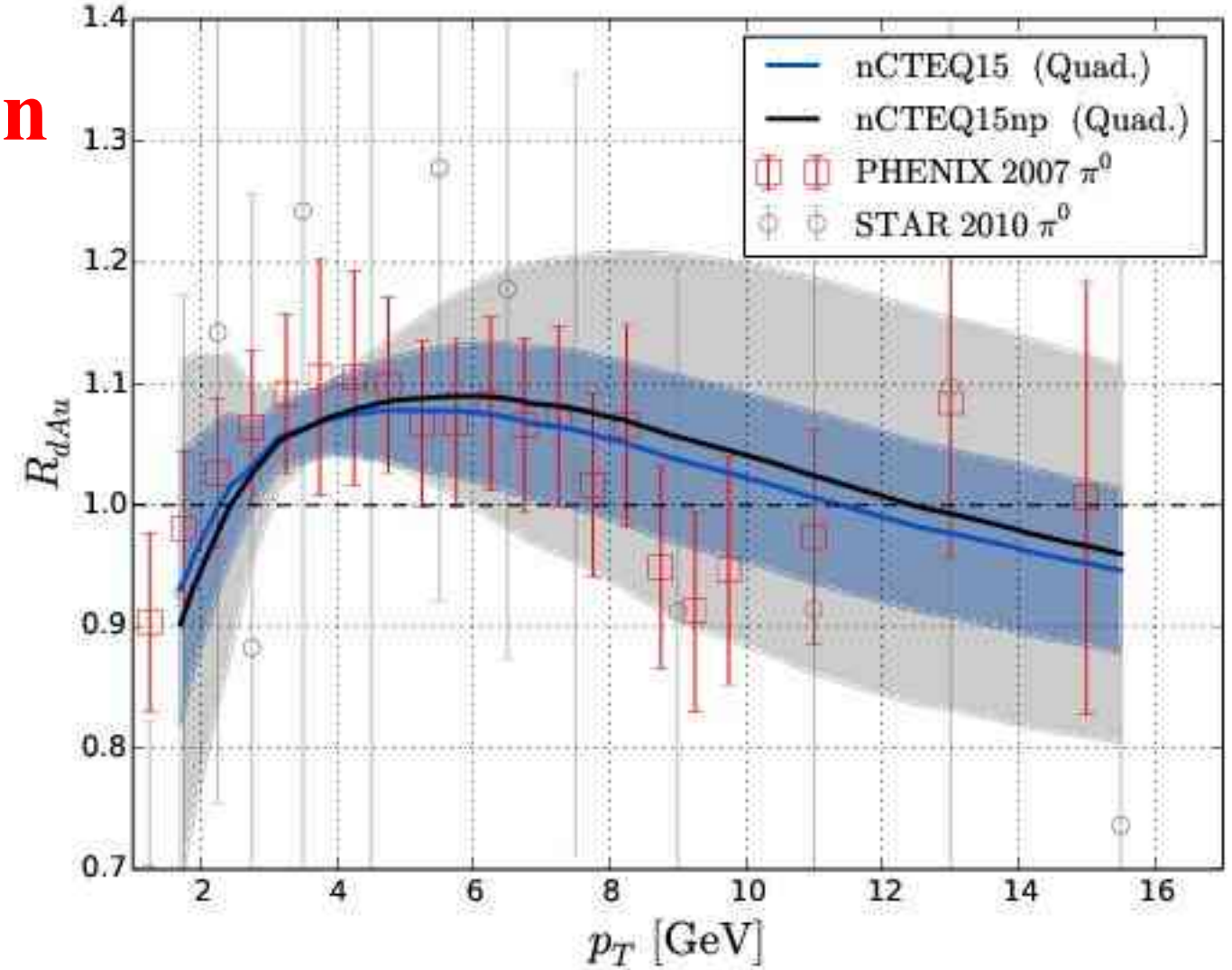


$\sigma^{pA}_{DY}/\sigma^{pA'}_{DY}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
C/H2	FNAL-E772-90	5203	65	9	9	7.92
Ca/H2	FNAL-E772-90	5204	65	9	9	2.73
Fe/H2	FNAL-E772-90	5205	65	9	9	3.17
W/H2	FNAL-E772-90	5206	65	9	9	7.28
Fe/Be	FNAL-E886-99	5201	66	28	28	23.09
W/Be	FNAL-E886-99	5202	66	28	28	23.62
Total:				92	92	67.81

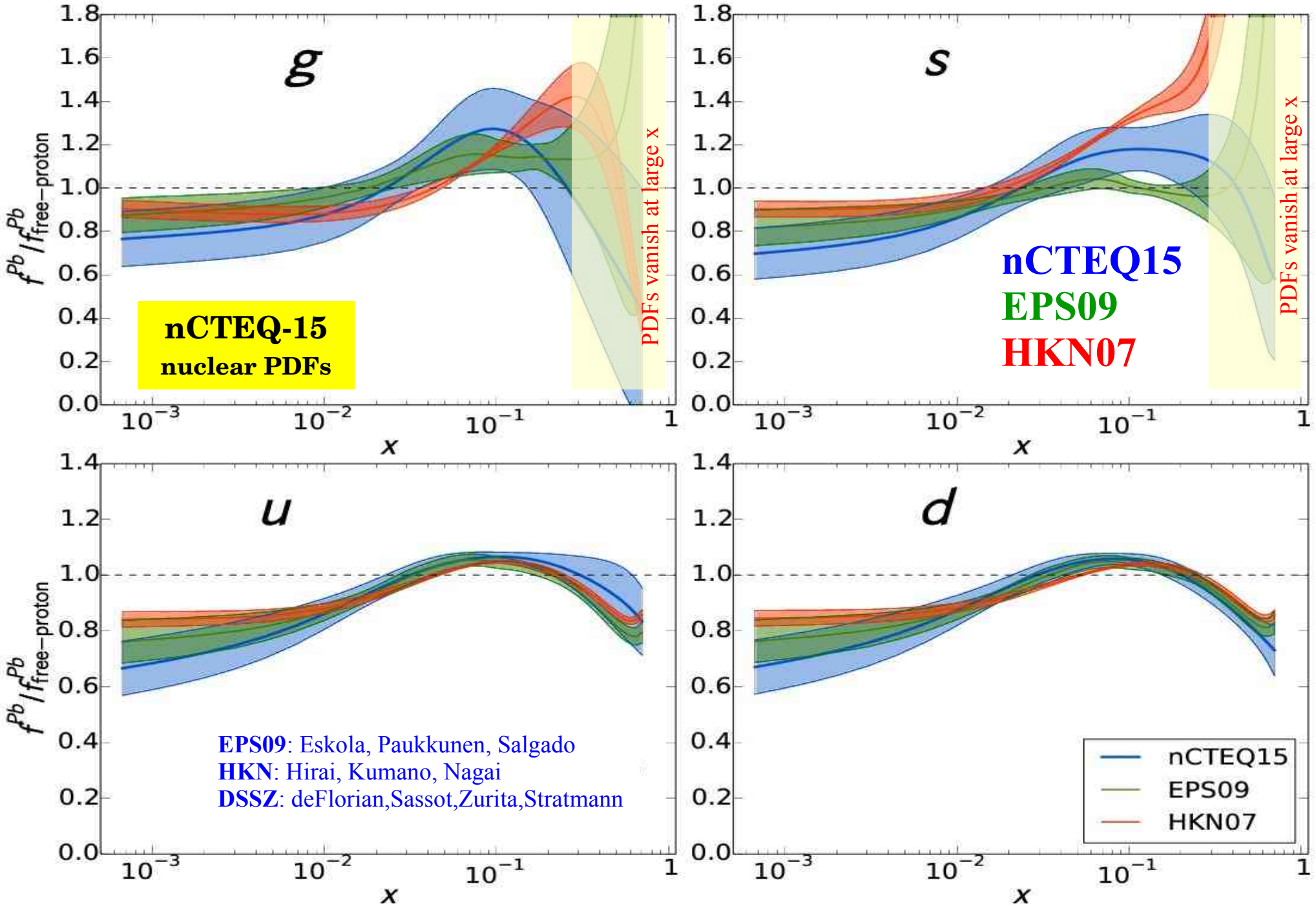
$\mathbf{R^{\pi}_{dAu}/R^{\pi}_{pp}}$: Observable	Experiment	ID	Ref.	# data	# data after cuts	χ^2
dAu/pp	PHENIX	PHENIX	67	21	20	6.63
	STAR-2010	STAR	68	13	12	1.41
Total:				34	32	8.04

π Production

Results with & without

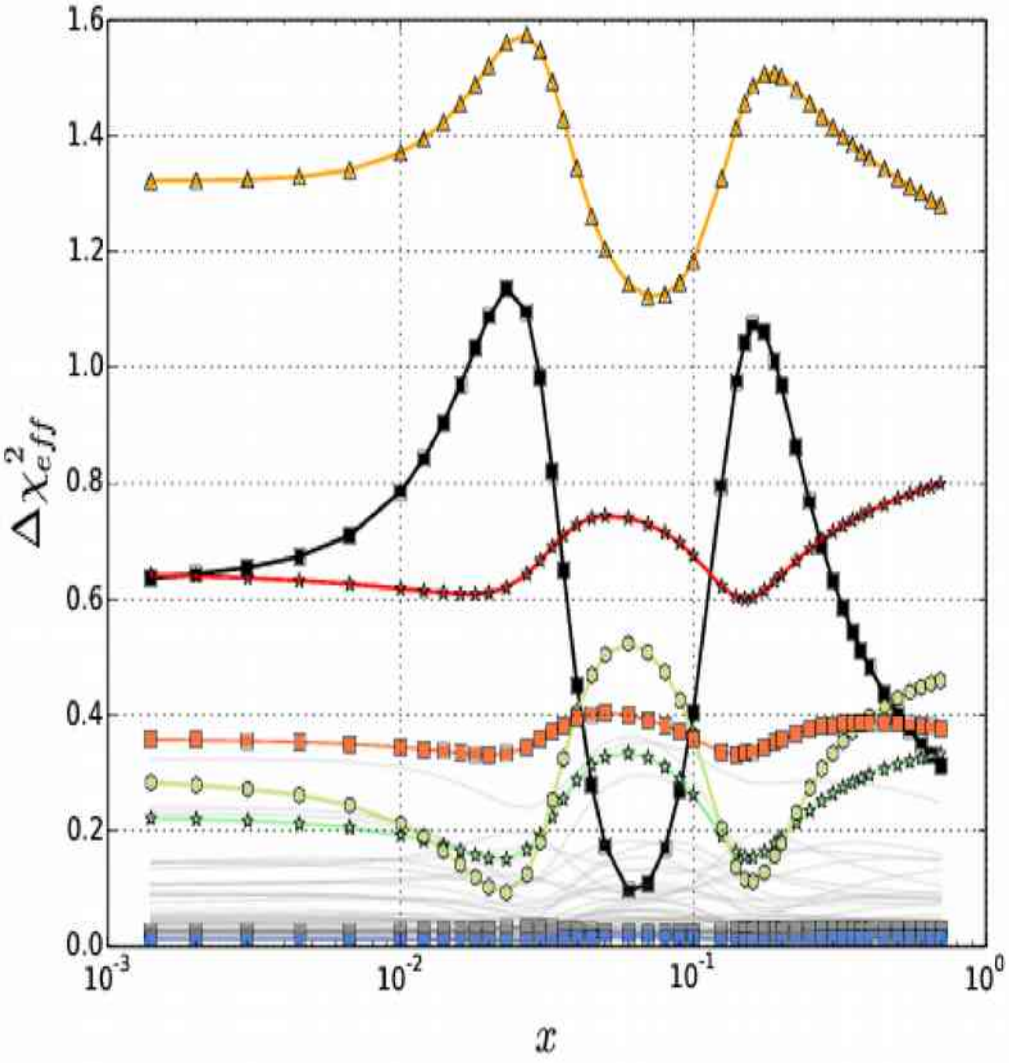


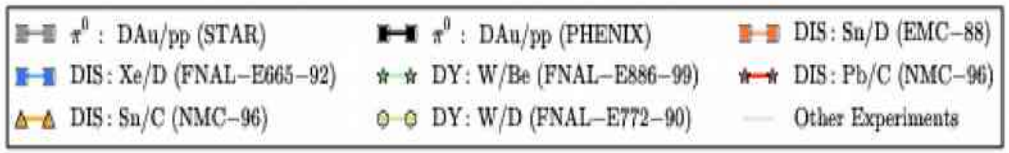
Ratio to Proton for Lead … *with Uncertainty*



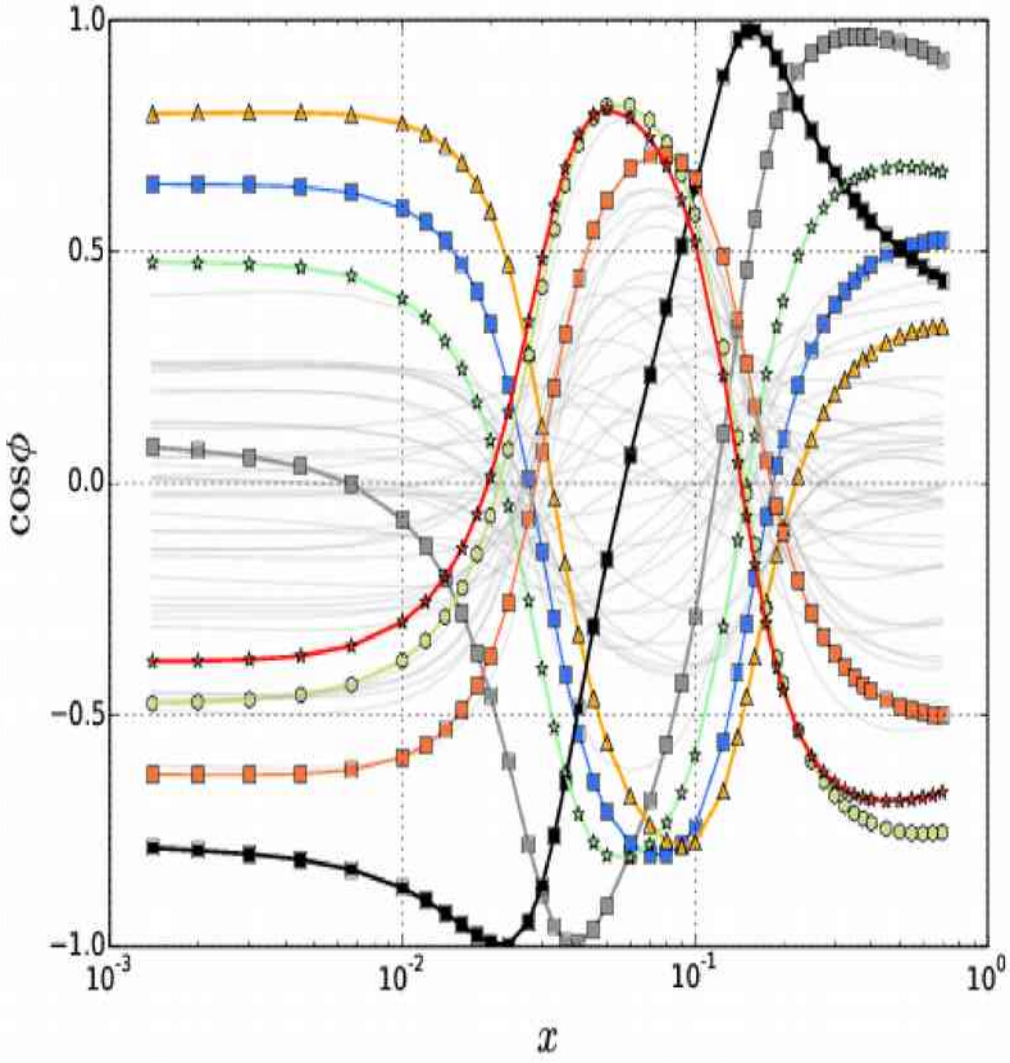
What data are influencing Gluon $Q=10\ GeV$

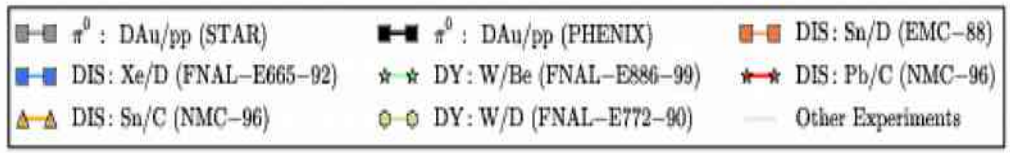
Effective $\chi 2$



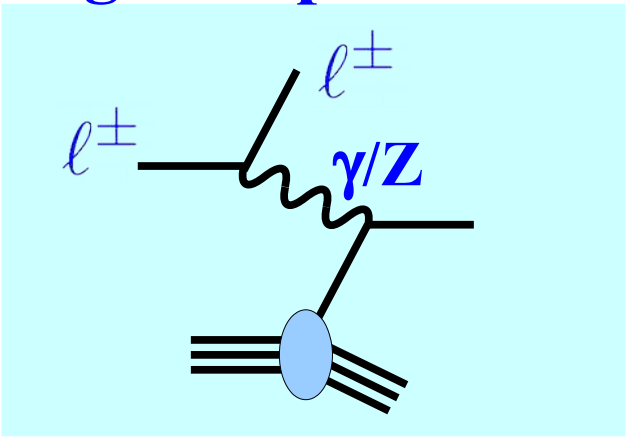


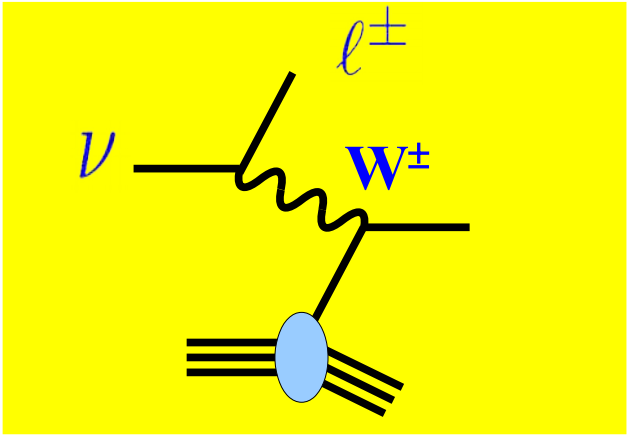
Correlation $\cos\phi$





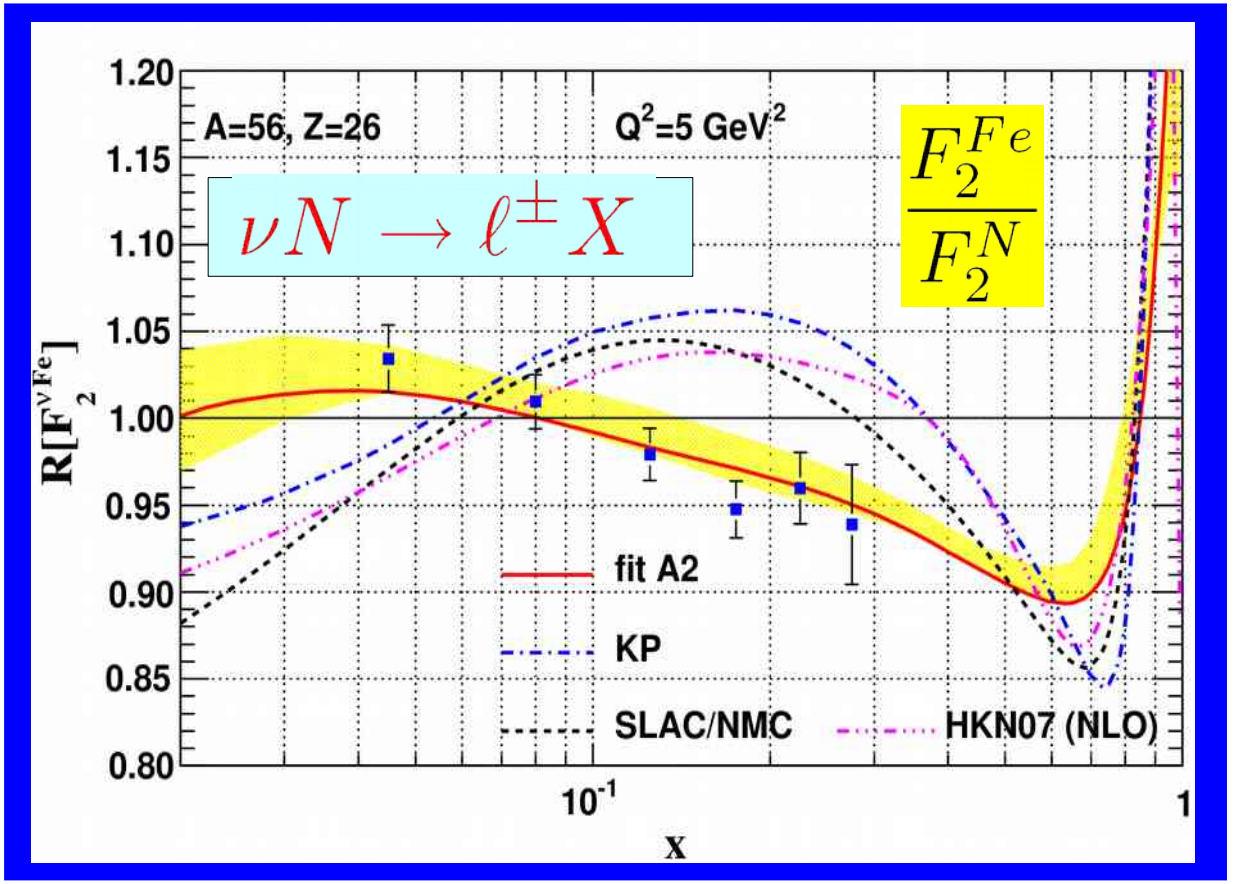
Charged Lepton DIS



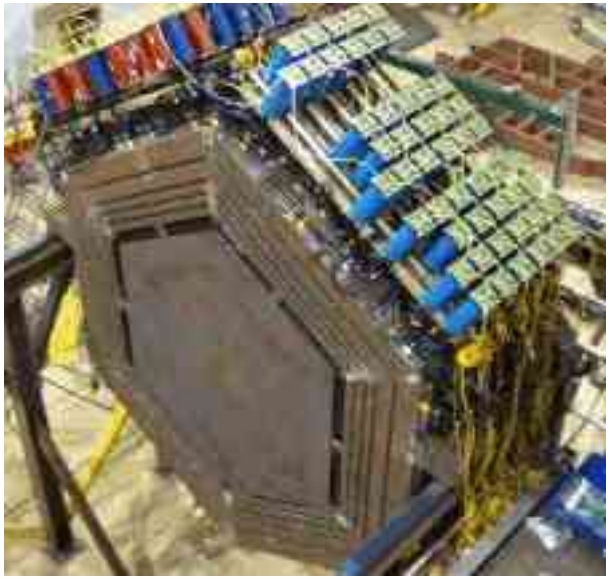


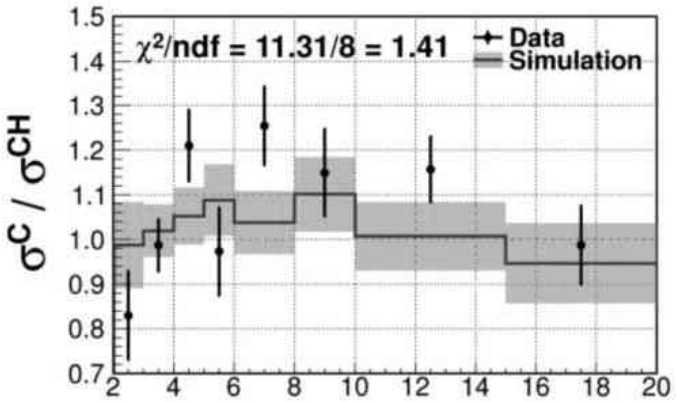
Neutrino DIS

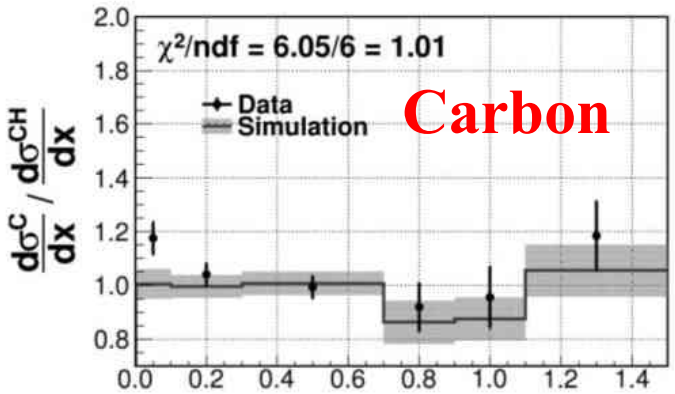
$$R = \frac{F_2^{Fe}}{F_2^N}$$

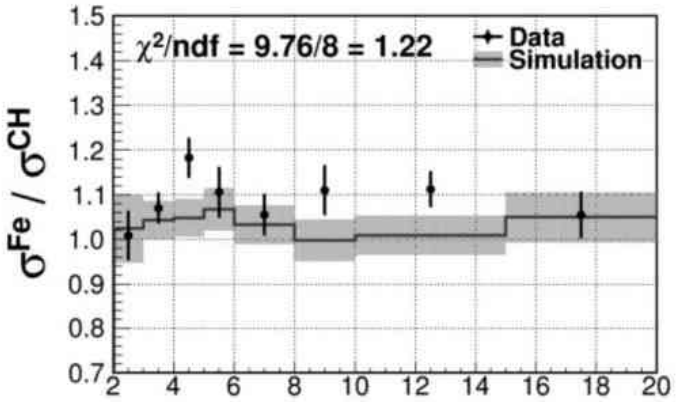


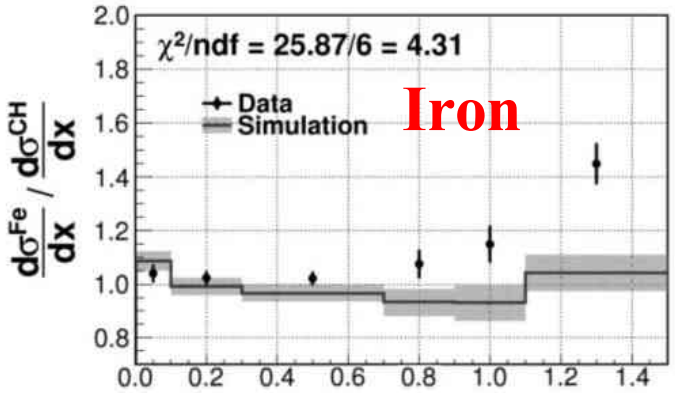
MINERvA: nu-DIS data on nuclear targets

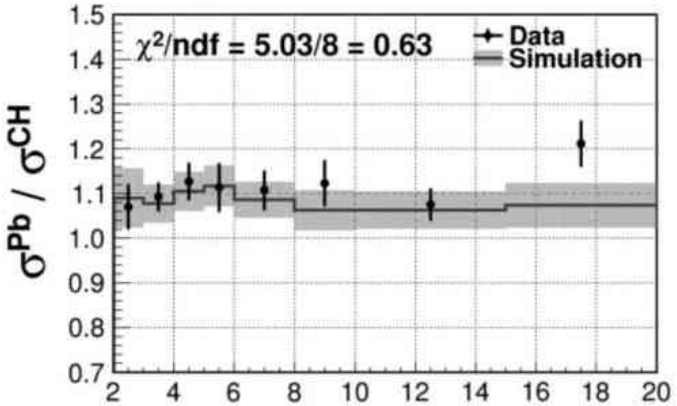


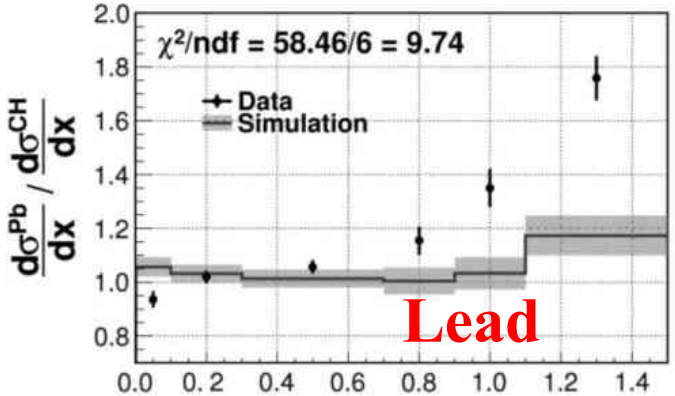










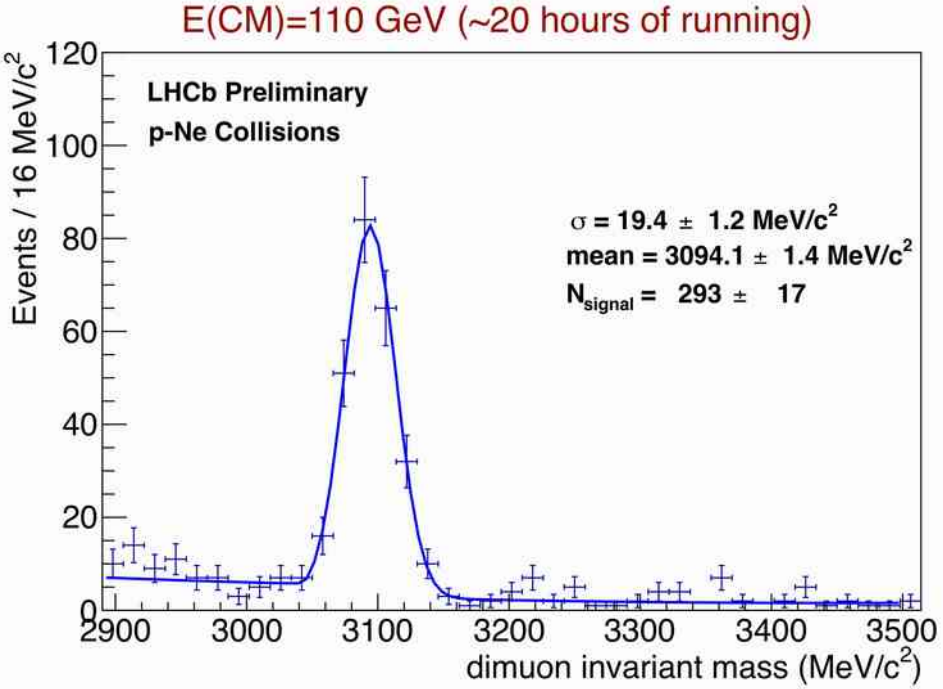


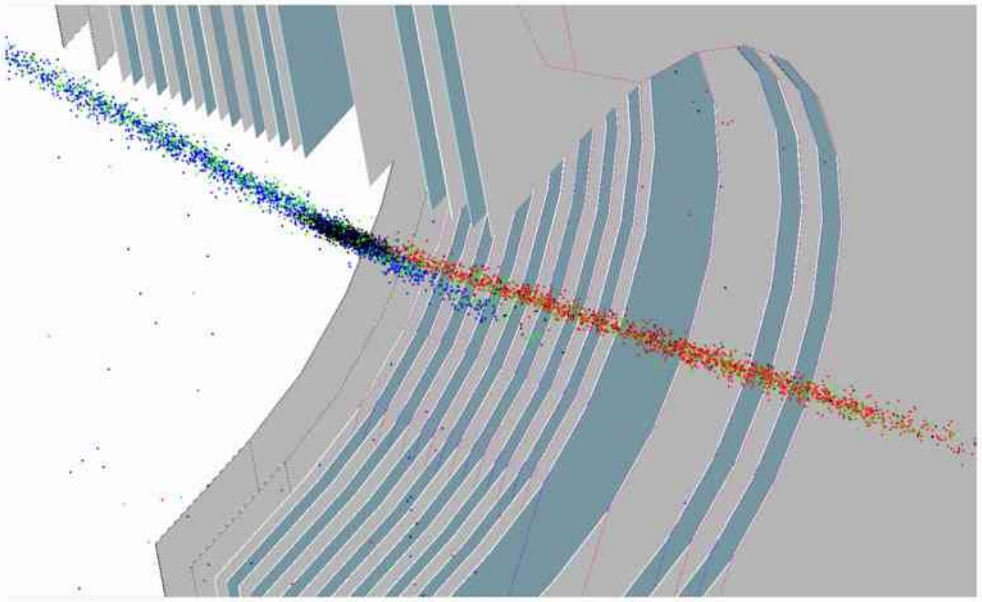
MINERvA Collaboration
Measurement of Ratios of νμ Charged-Current Cross Sections on C, Fe, and Pb to CH at Neutrino Energ
2-20 GeV Phys.Rev.Lett. 112 (2014) 23, 231801

SMOG

Mike Williams for LHCb
Santa Fe Jets and Heavy Flavor Workshop
12 January 2016

LHCb developed the System for Measuring the Overlap with Gas to obtain a high-precision (1%) luminosity measurement by injecting a noble gas into the VELO to profile the beams -- but also permits running in fixed-target mode!





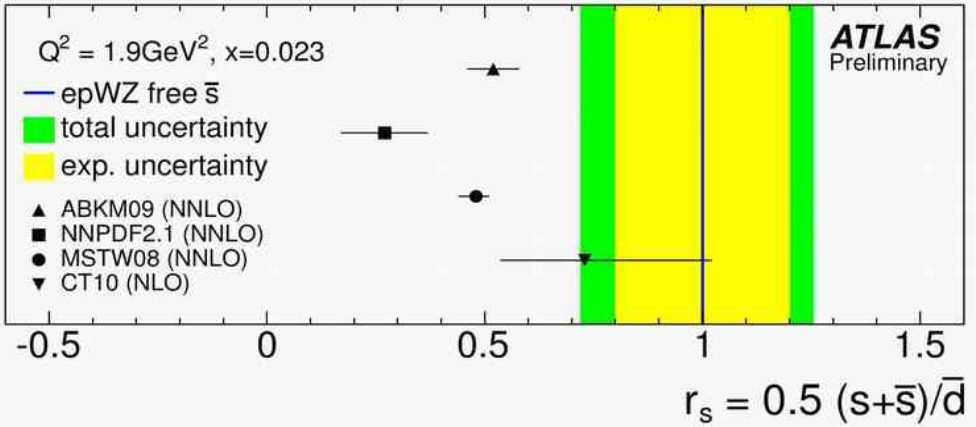
In fixed-target mode, LHCb is a central-backward detector that probes energy densities between that of the SPS and RHIC. Data collected: p-He, p-Ne, p-Ar and Pb-Ne, Pb-Ar.

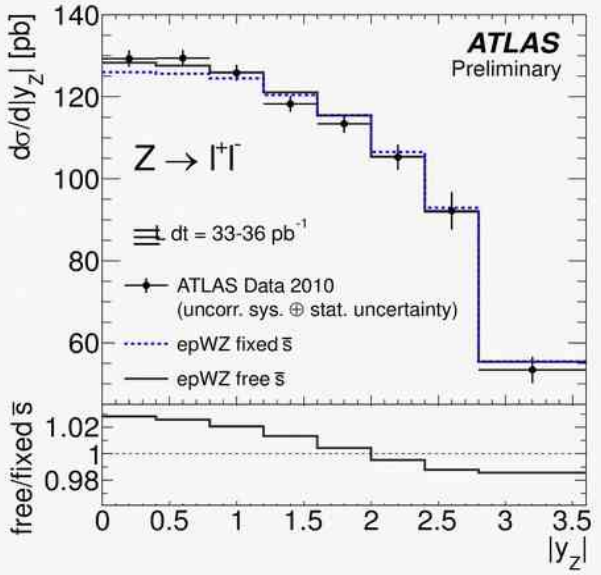
Use LHC data to constrain Strange Quark

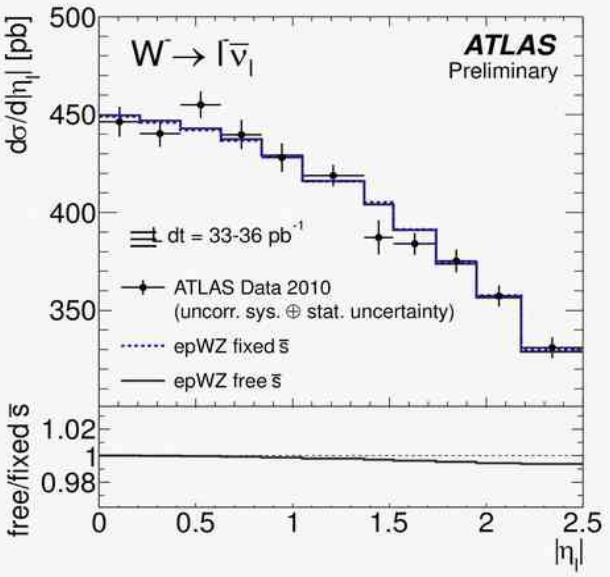
W, Z data sensitivity to strange sea

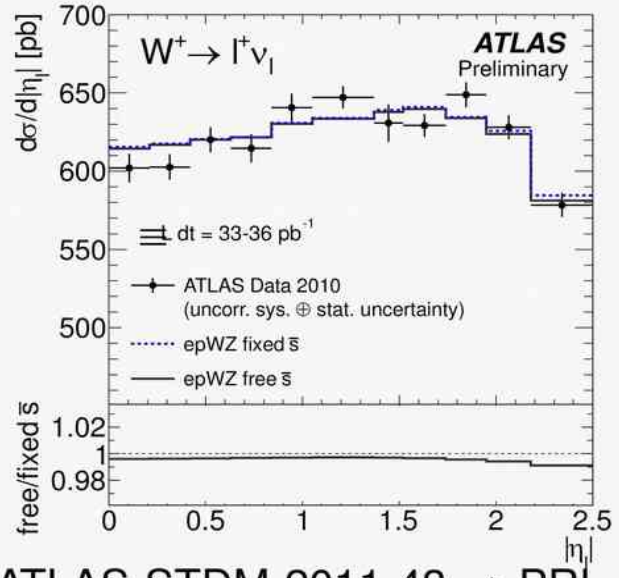
- ATLAS performed NNLO QCD fit to Z, W^+, W^- + HERA ep DIS cross sections: significant tension for Z observed when suppressing strange by 50% at low scale $1.9\,\mathrm{GeV}^2$
- Fit with free strange sea gives no supression

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



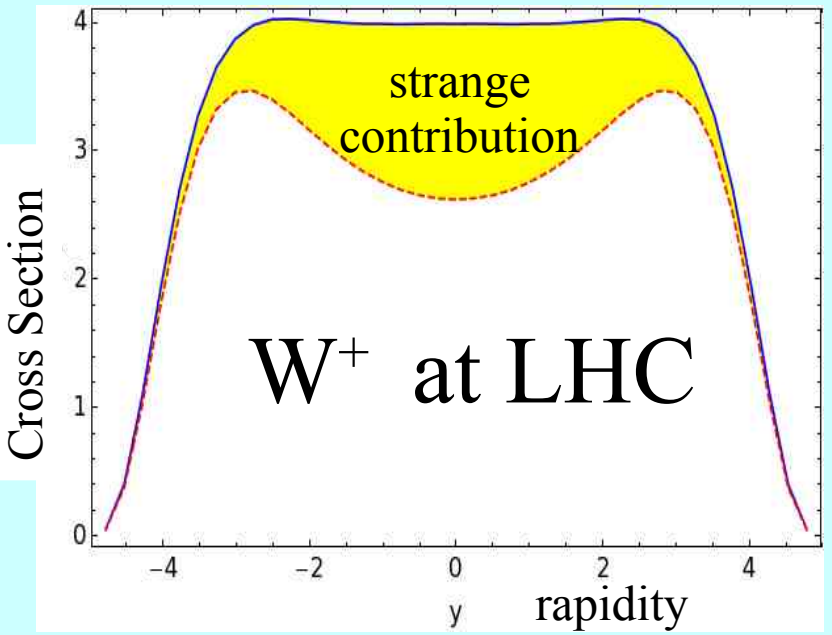


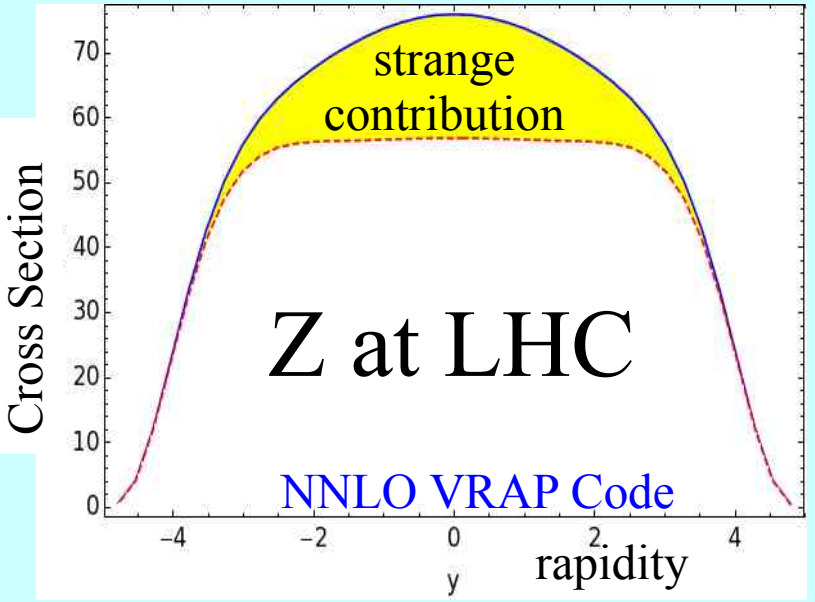


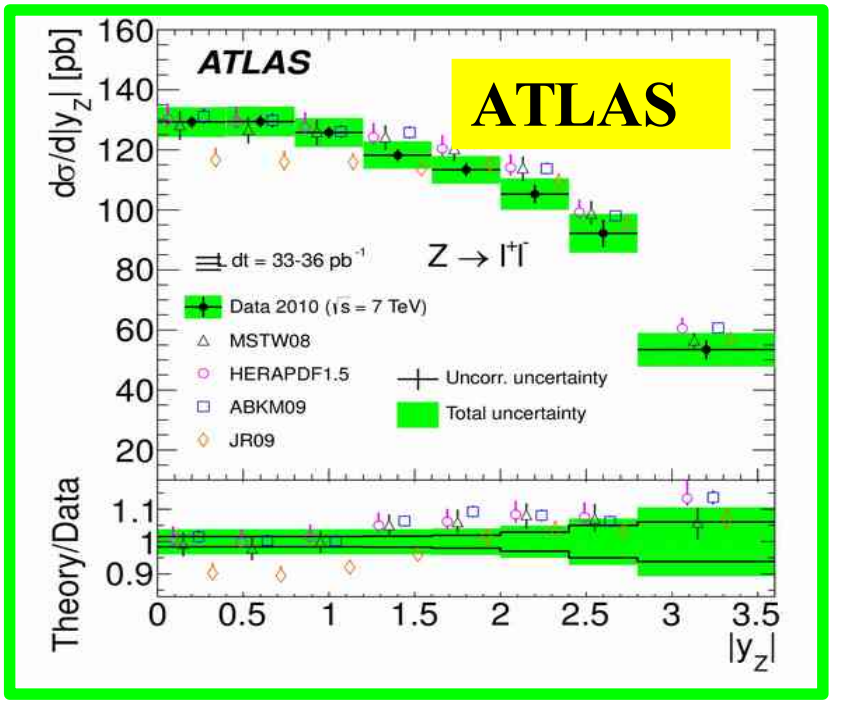


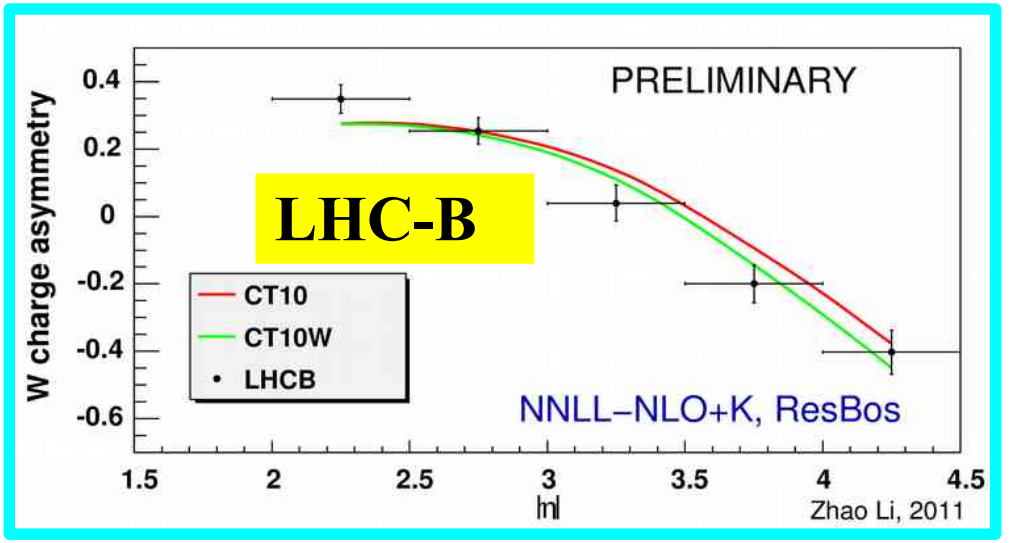
ATLAS-STDM-2011-43 → PRL

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









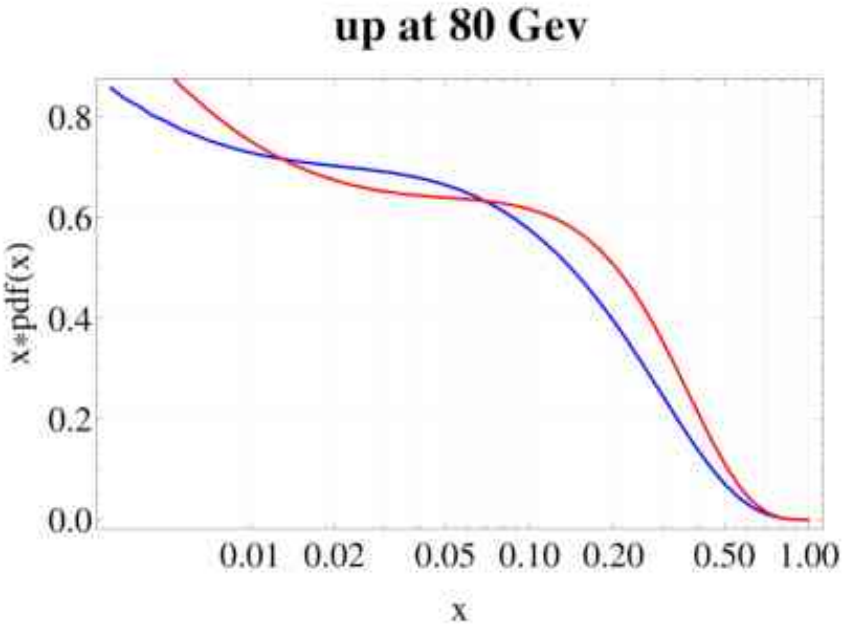
NNLO VRAP Code
Anastasiou, Dixon, Melnikov, Petriello,
Phys.Rev.D69:094008,2004.

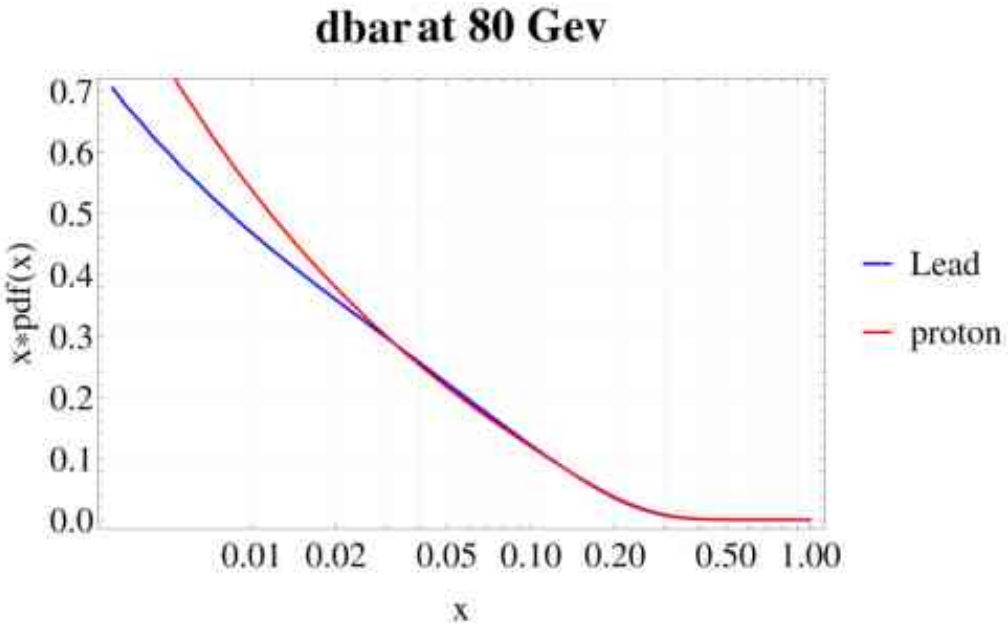
Kusina, Stavreva, Berge, Olness,
Schienbein, Kovarik, Jezo, Yu, Park
Phys.Rev. D85 (2012) 094028

y distribution shape can constrain s(x) PDF

Nuclear Modifications

Slides stolen from Ben Clark

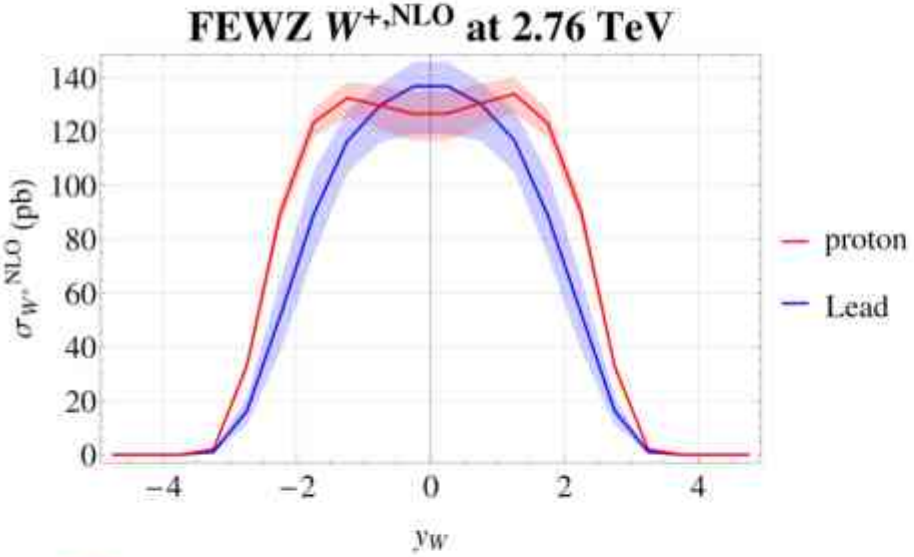


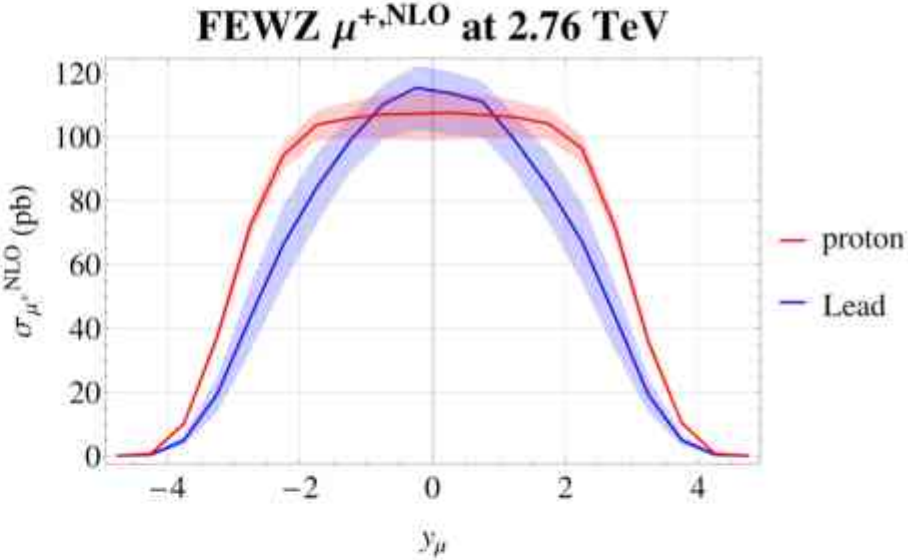


- The nuclear modifications are present in the PDFs and vary with A as well as x and Q.
- We expect modifications to any hadronic observable involving heavy nuclei.

Pb-Pb vs. p-p rapidity

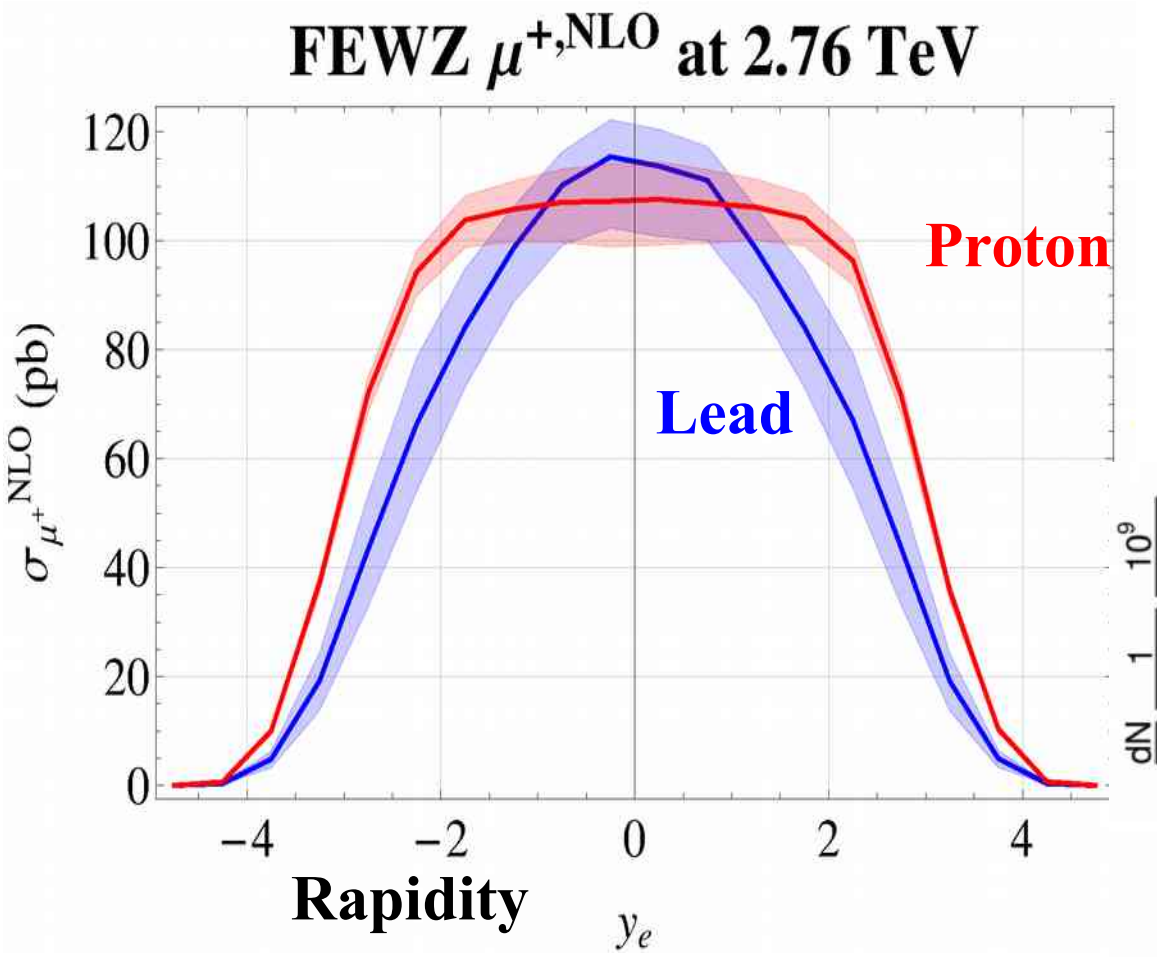
- There is an observable shape change for on-shell W^+ production. The difference is up to 20 % in some regions of parameter space.



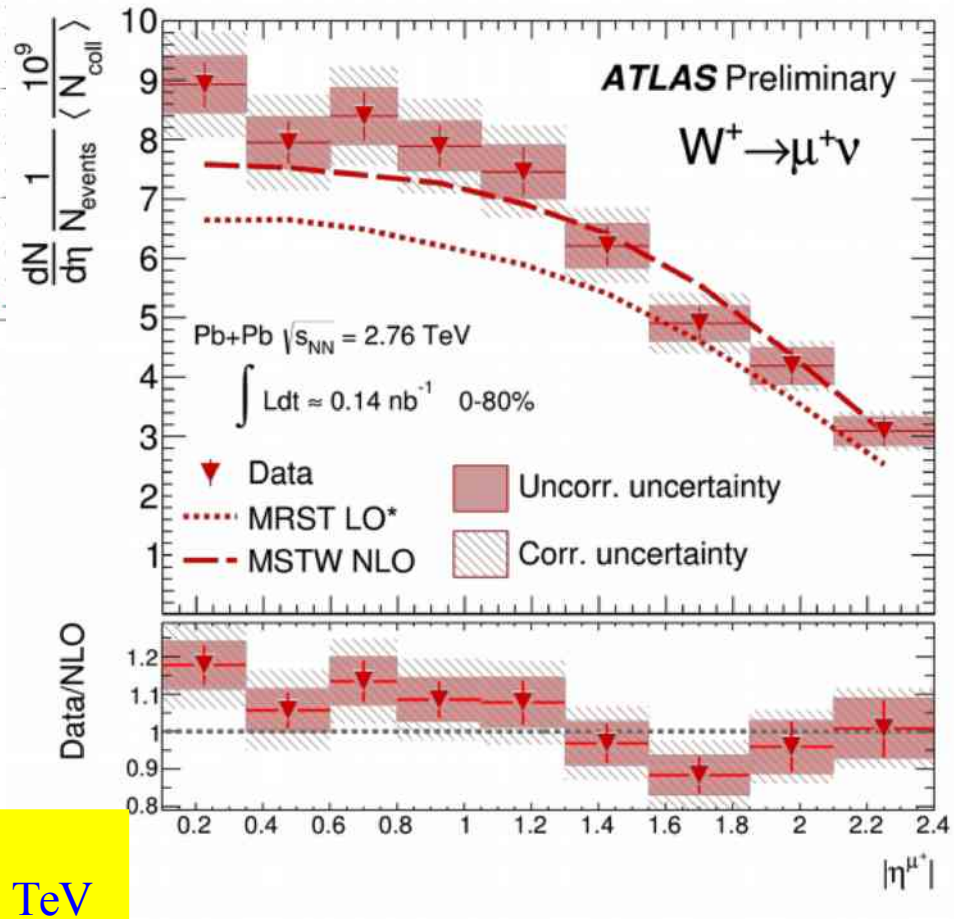


- These differences should be seen with a higher integrated luminosity for Pb-Pb collisions.

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

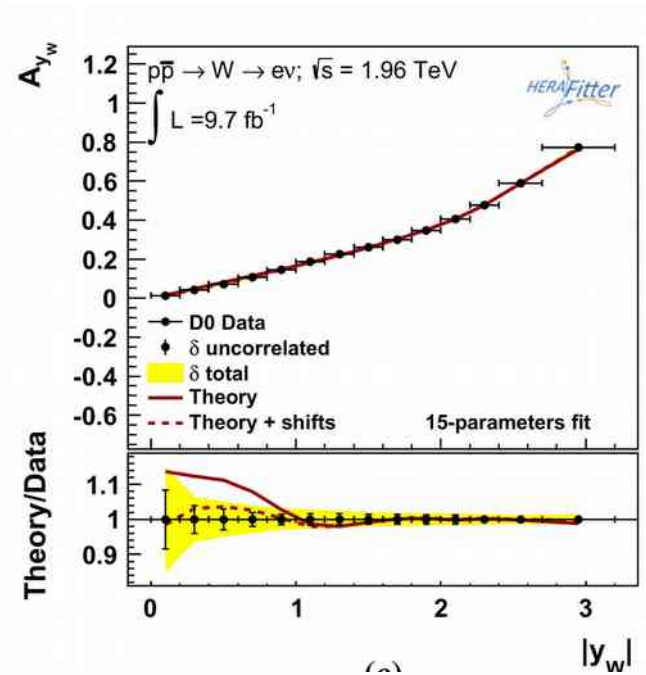


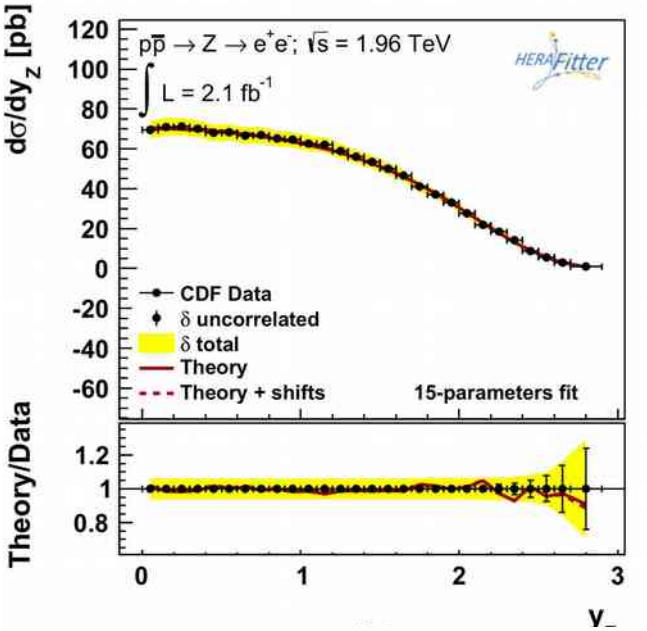
$$W^+ \rightarrow \mu^+ \nu$$

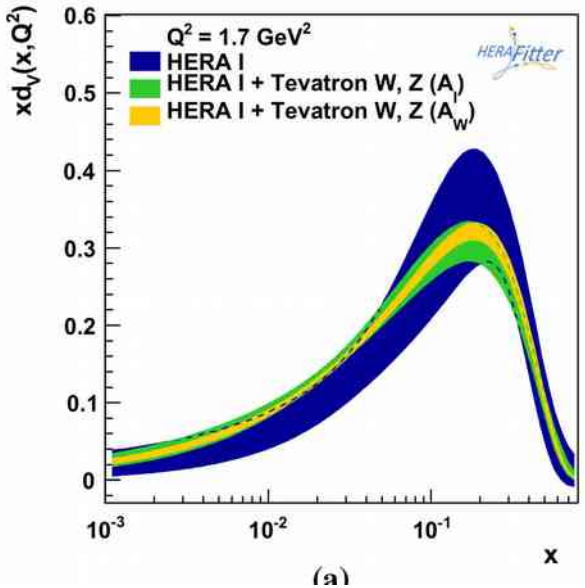


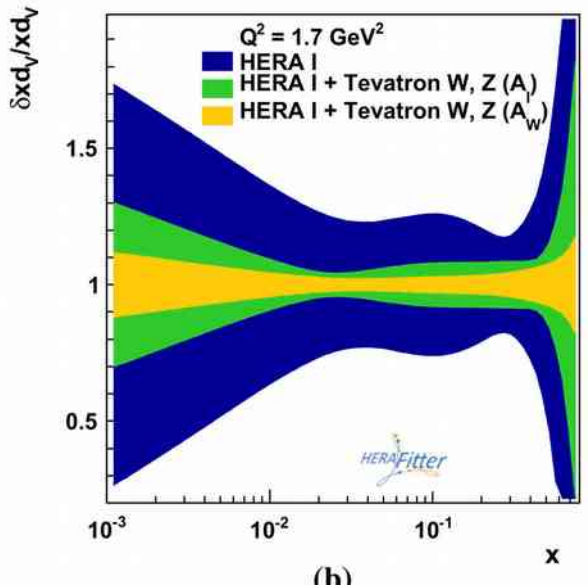
This is a shape measurement

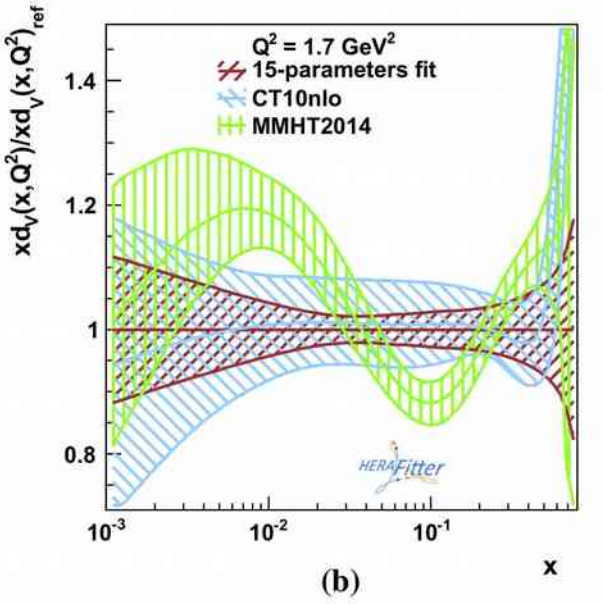
Similar studies with Z:
ATLAS just released 2013 Z data for p-Pb at 5.02 TeV









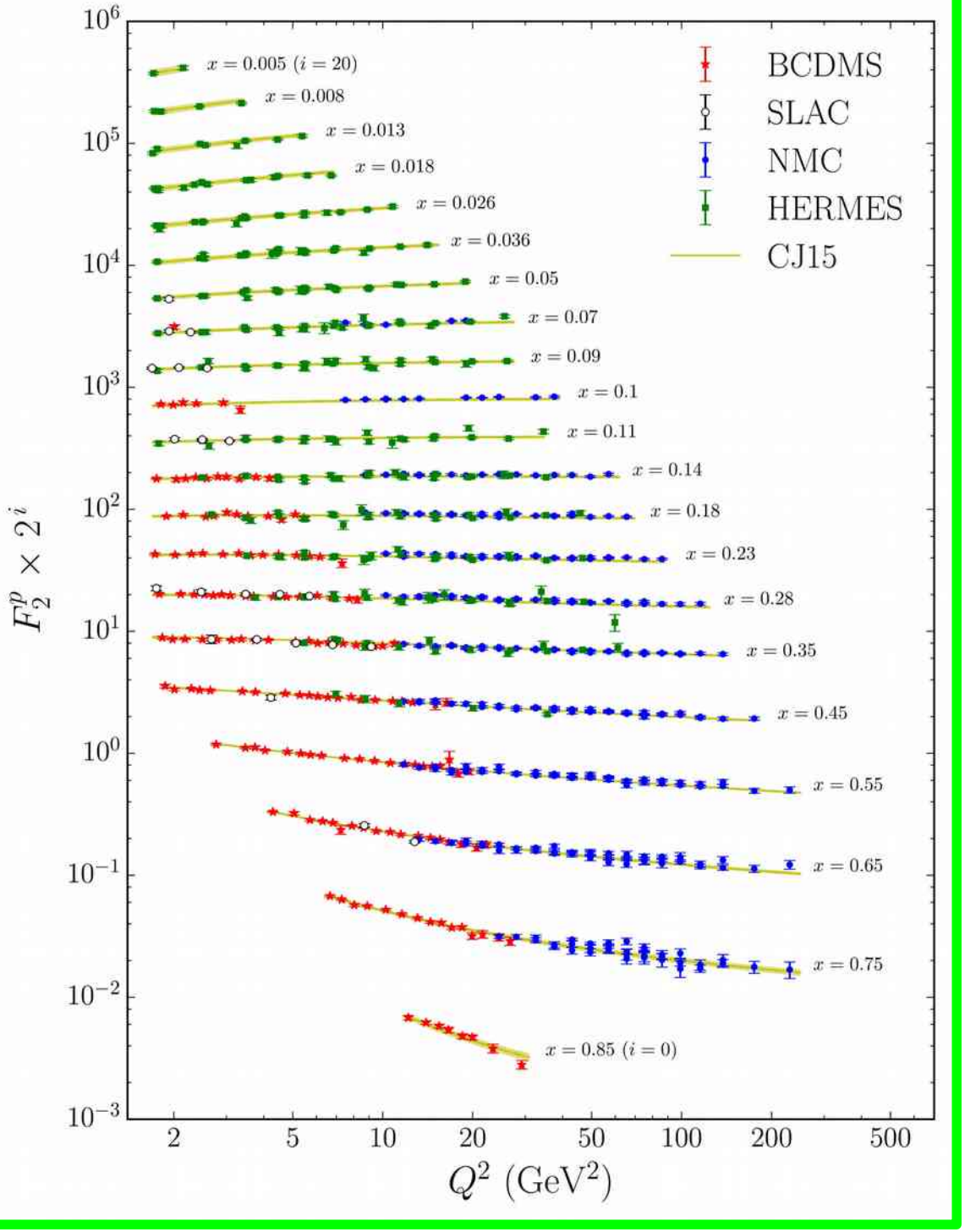


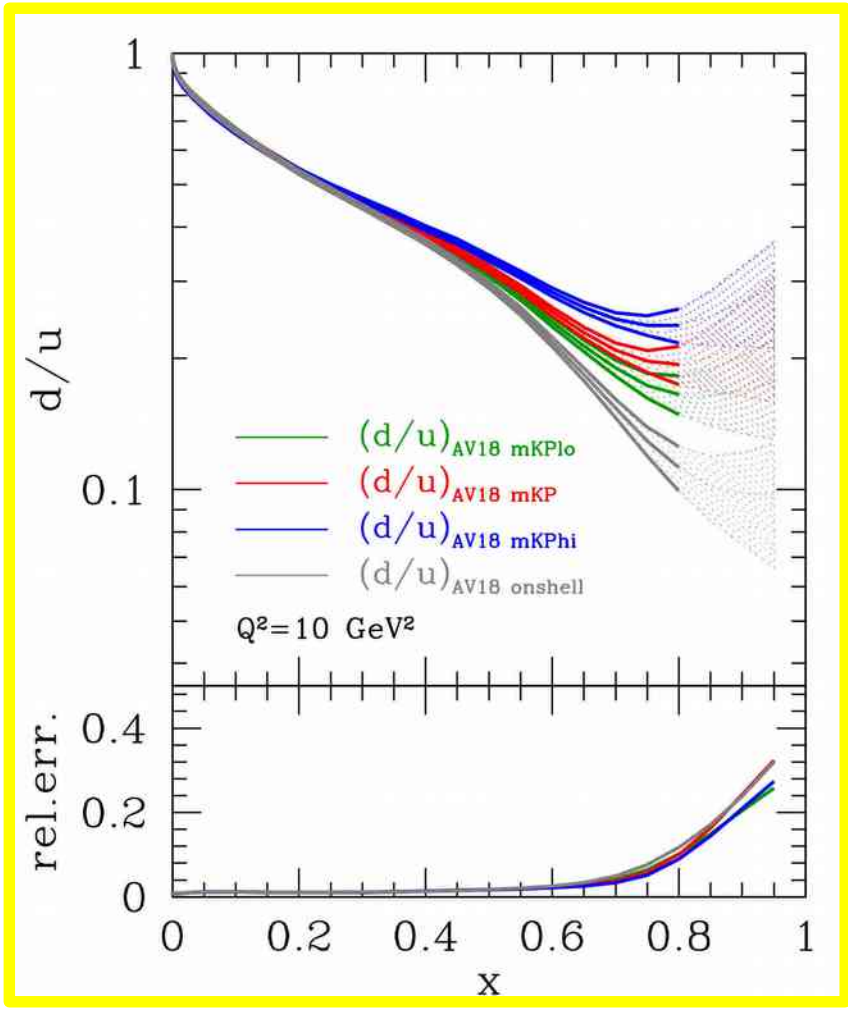
EPJC 75:458 (2015)
QCD Analysis of W- and Z-boson production at Tevatron

other activities

CJ-15

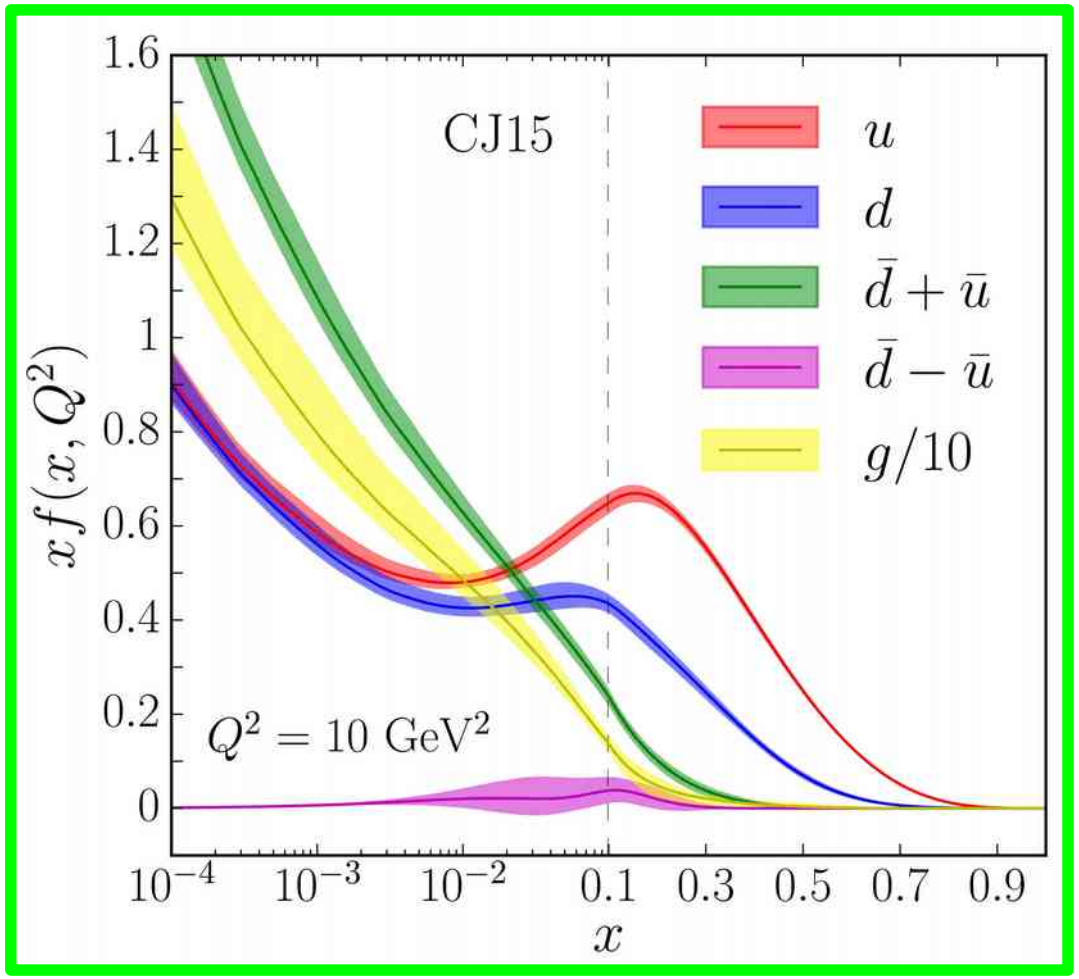
arXiv: 1602.03154

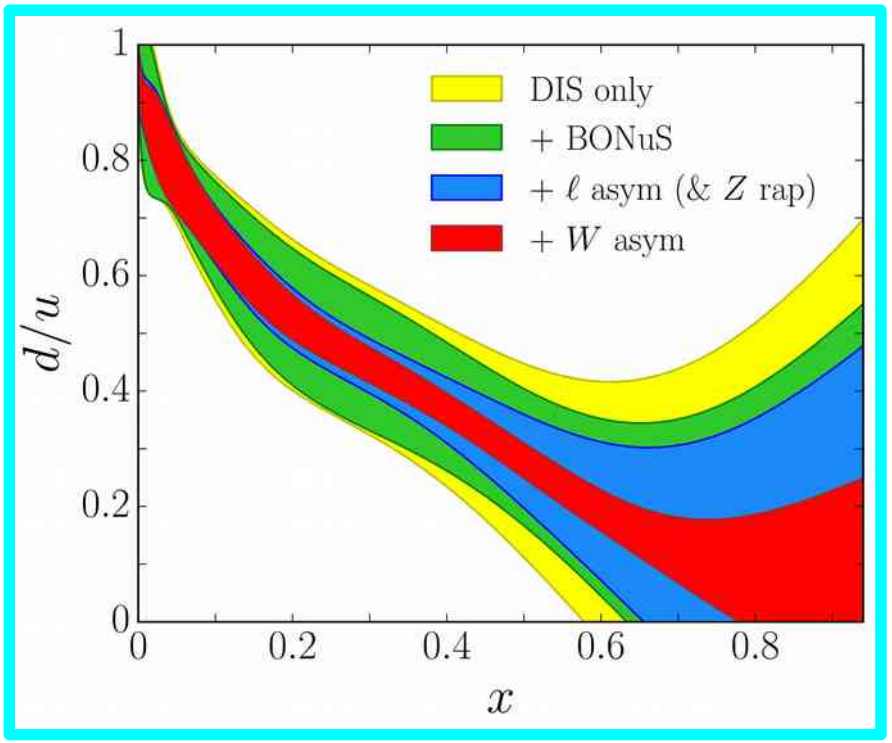


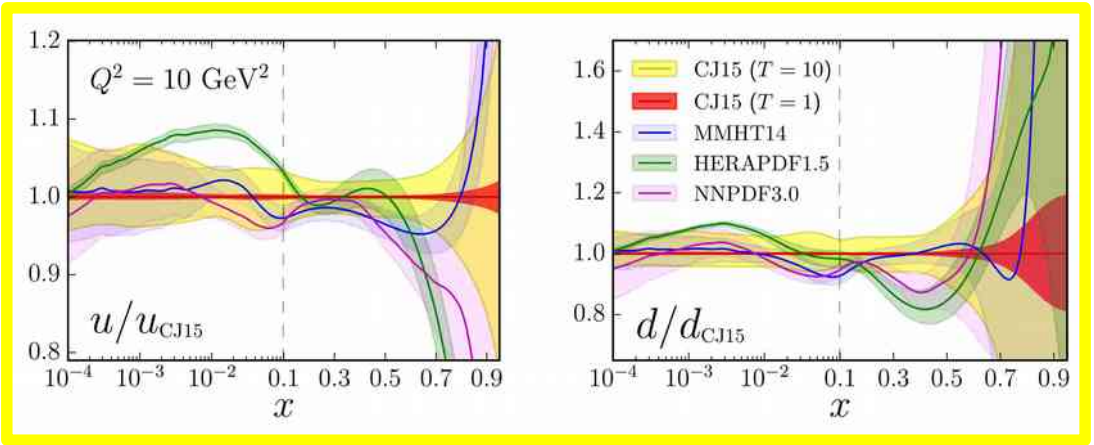


CJ-15

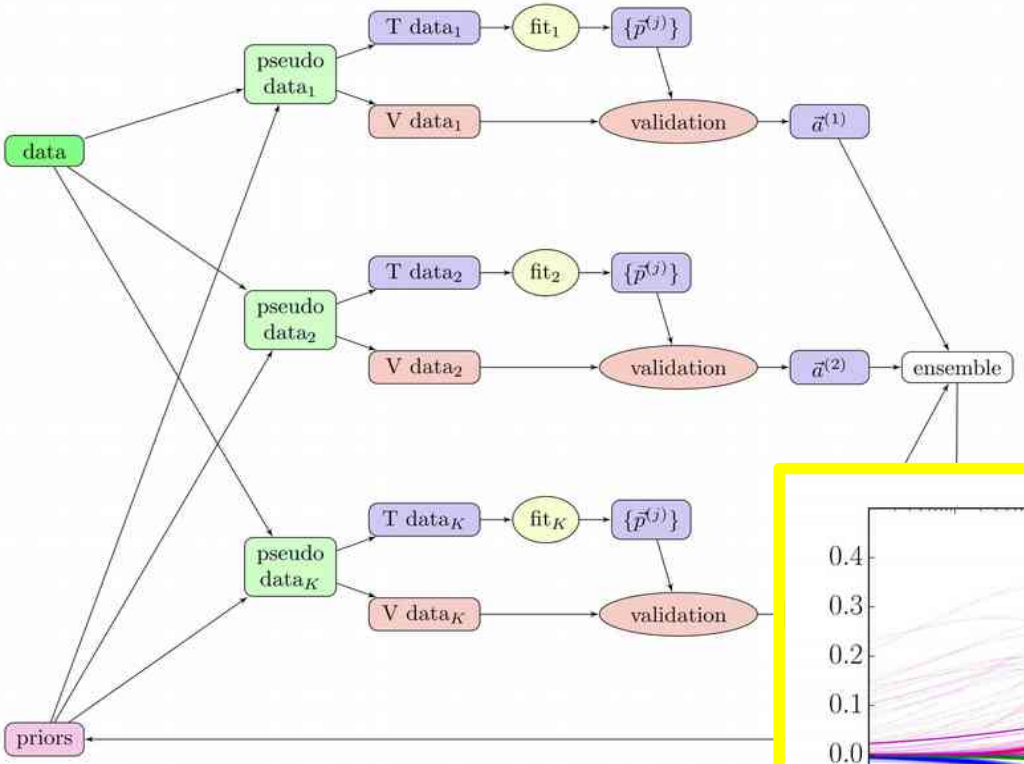
arXiv: 1602.03154

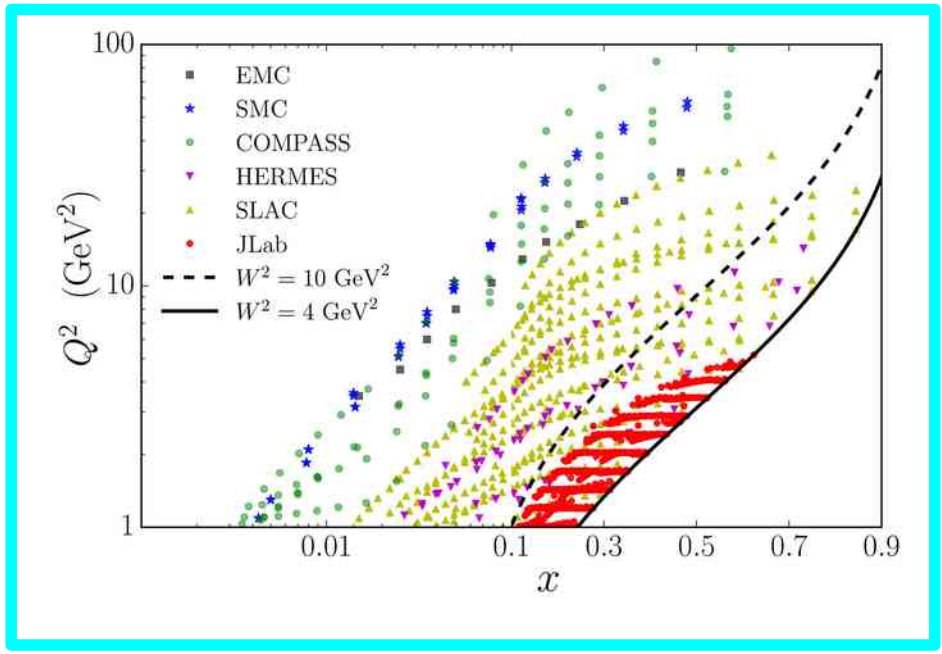


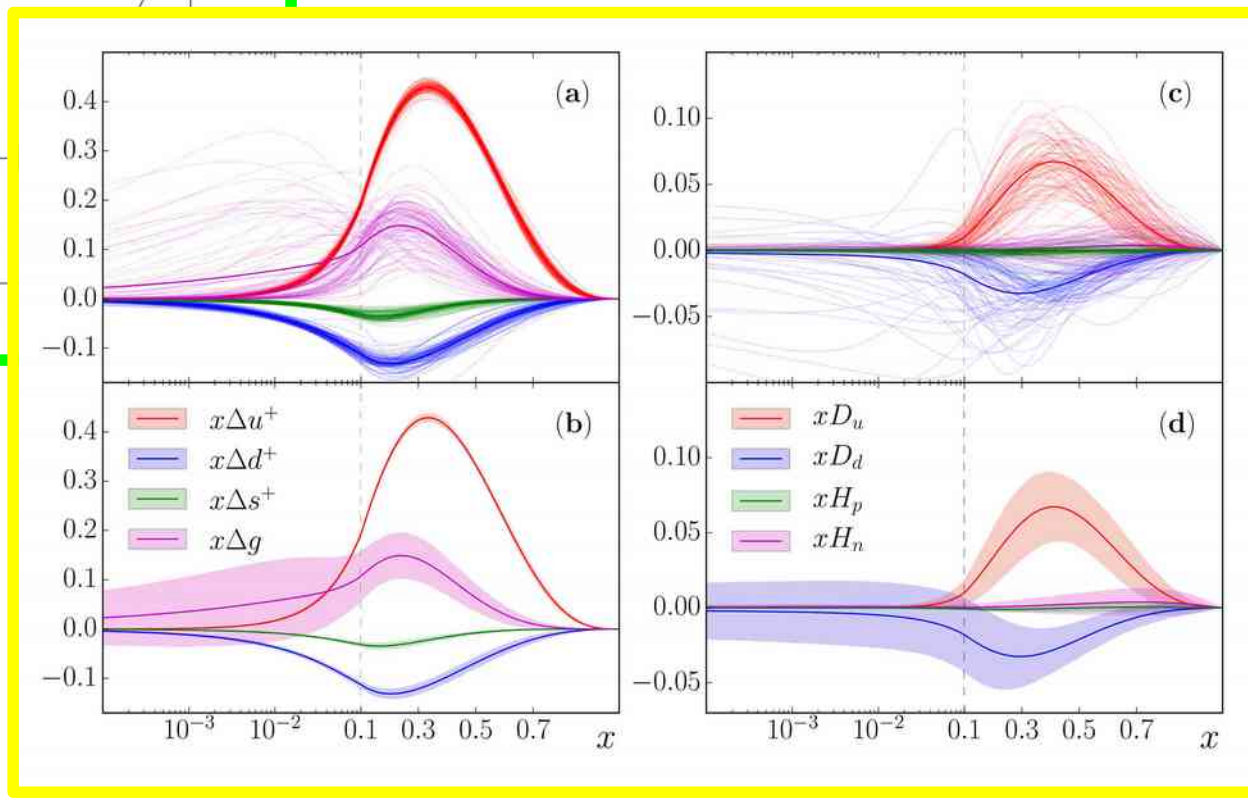




JAM (JLab Angular Momentum) Collaboration arXiv:1601.07782



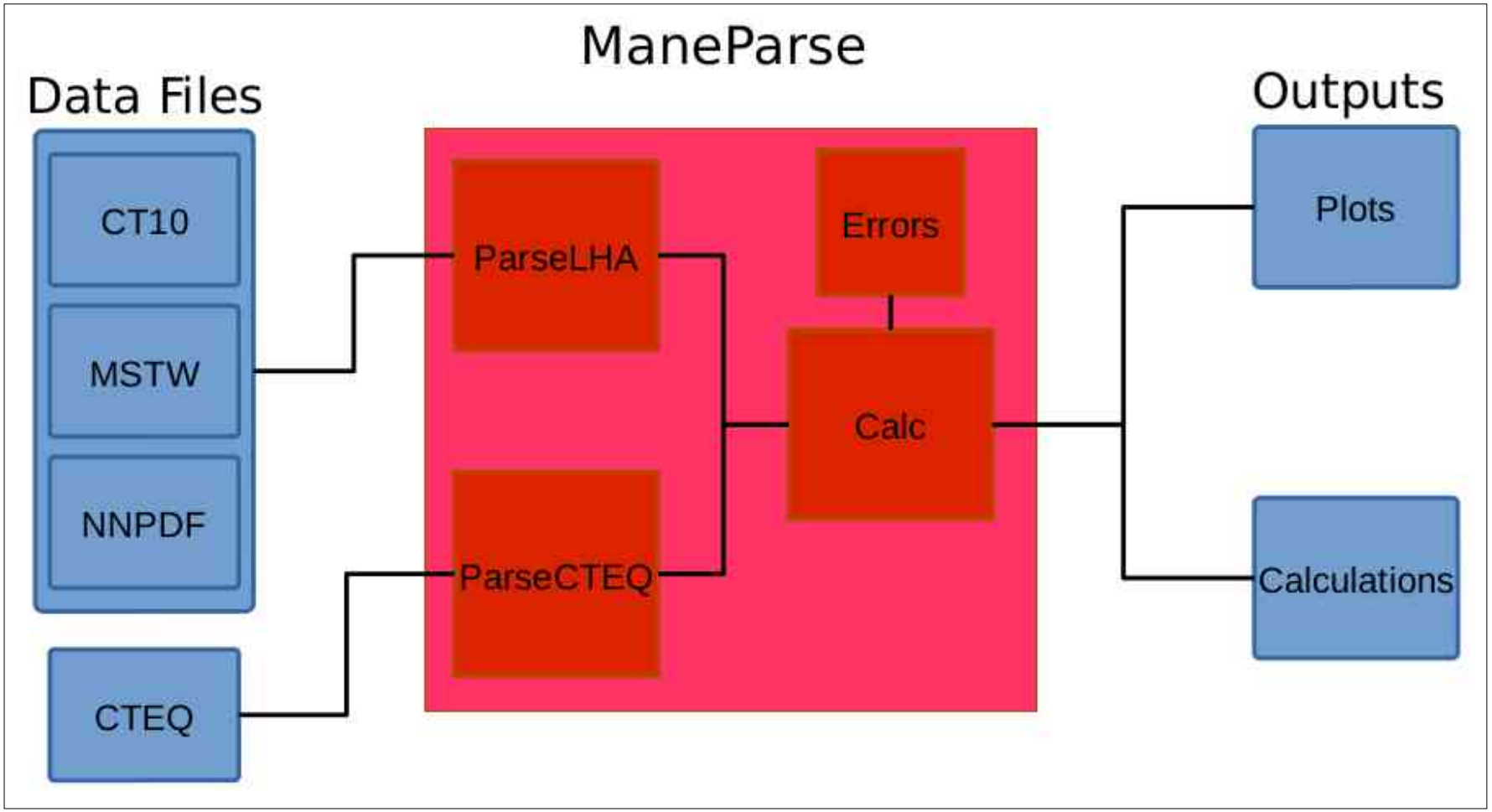




Iterative Monte Carlo analysis of spin-dependent parton distributions

other activities

ManeParse



Download data sets

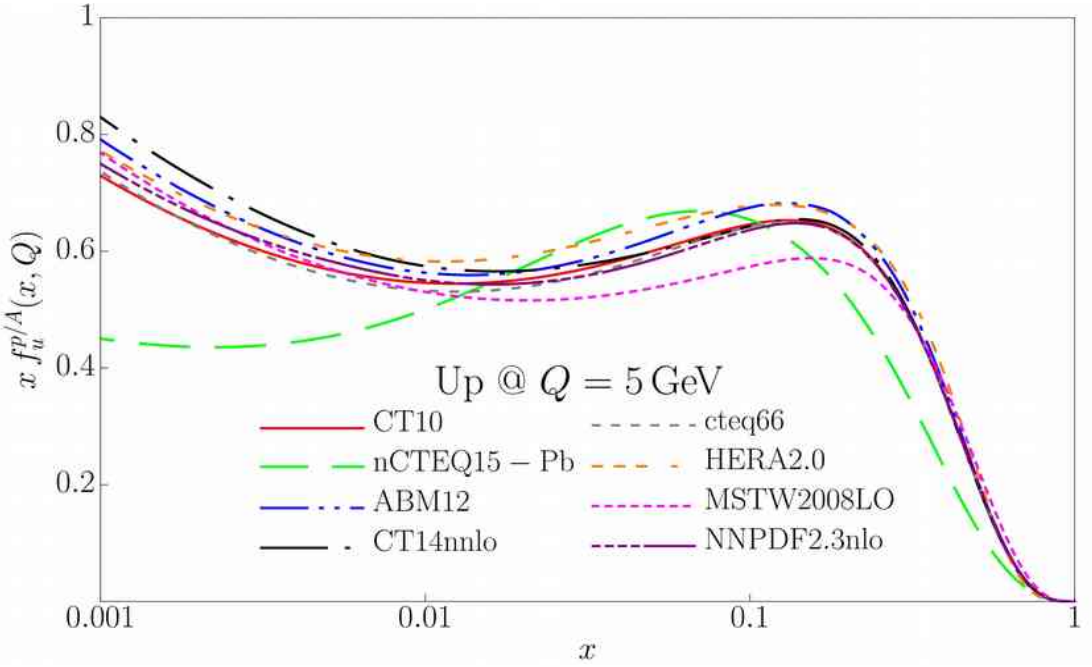
Load parser that matches your files

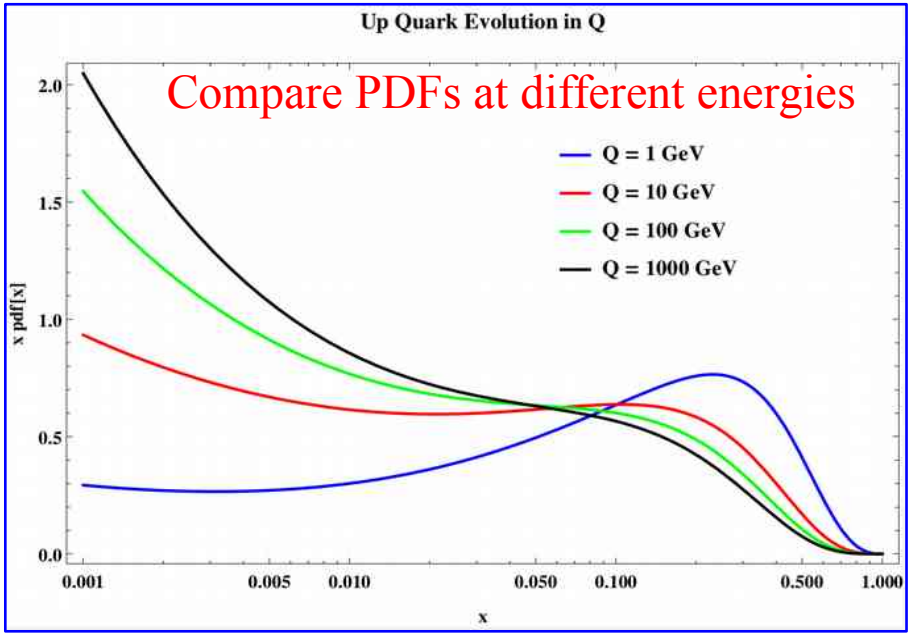
Interpolate and

Error functions

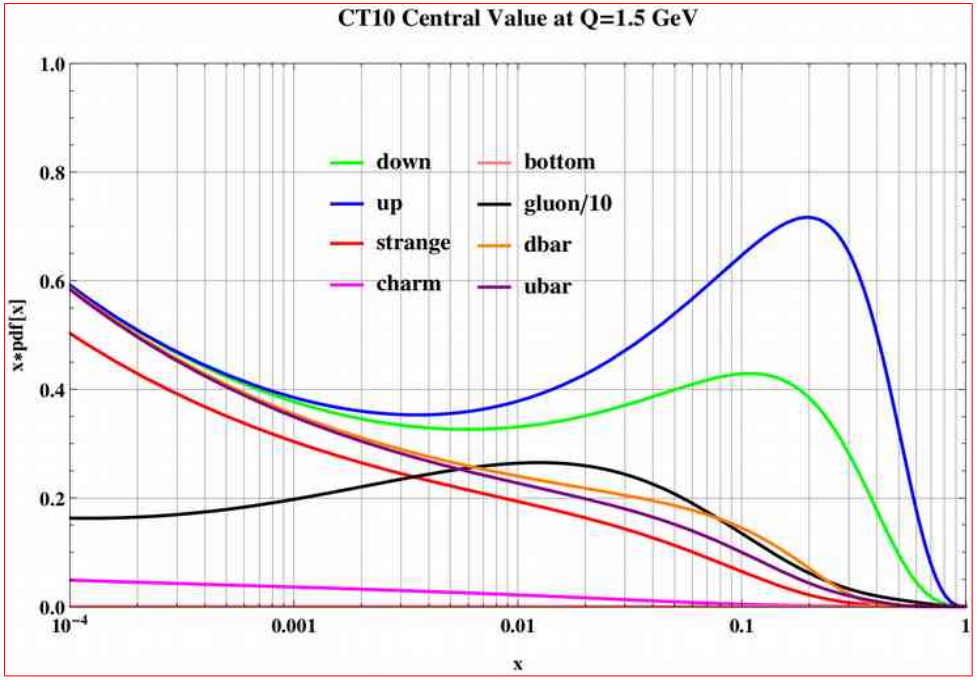
Mathematica provides plotting and integration

Examples: I

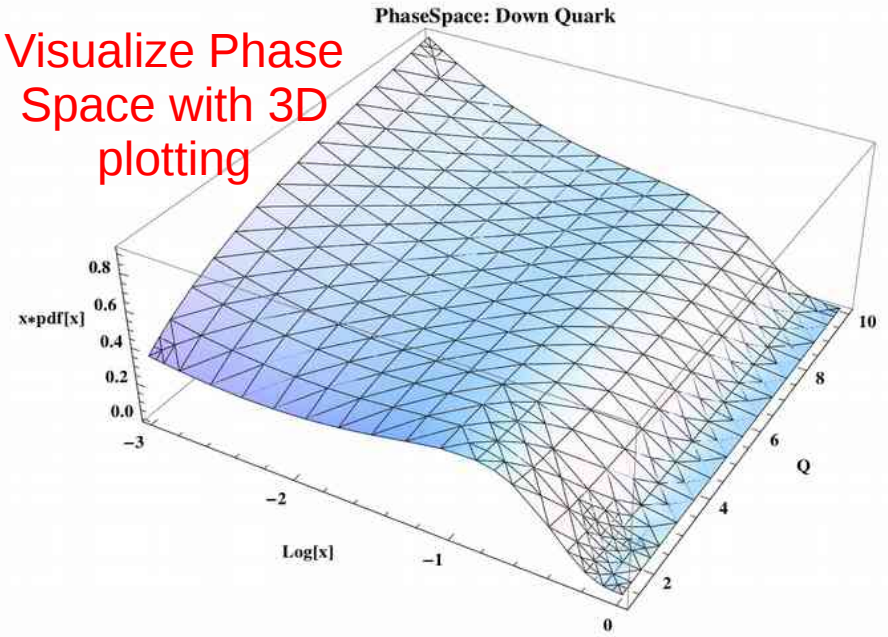




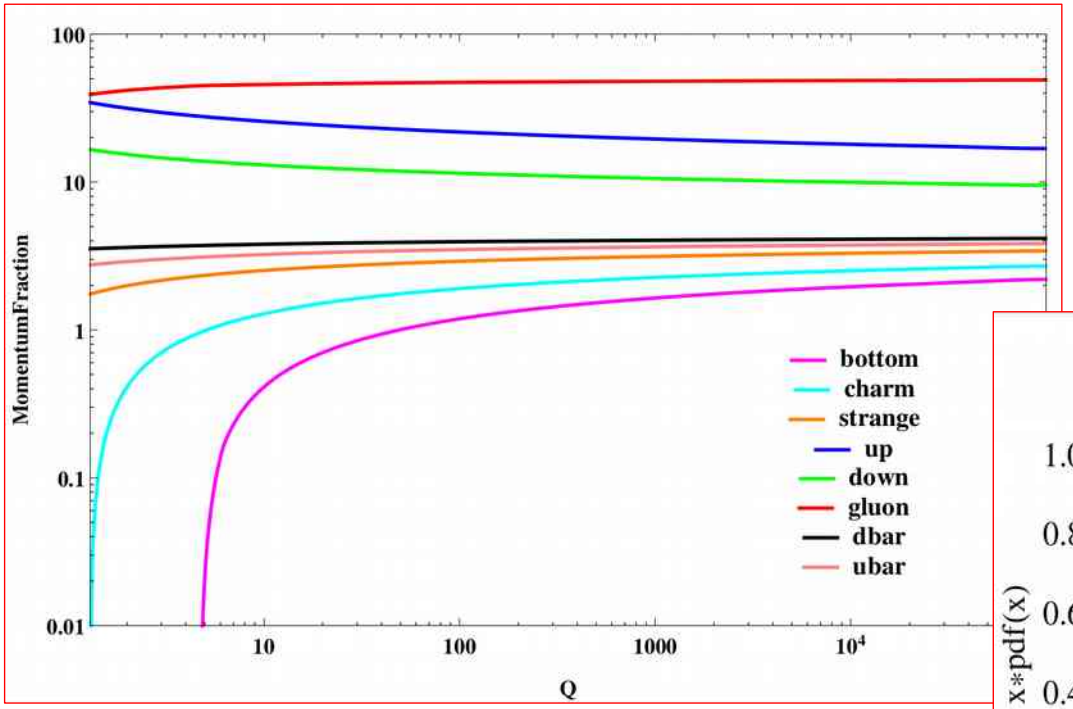
Plot of Multiple Partons for a Single PDF



Visualize Phase Space with 3D plotting

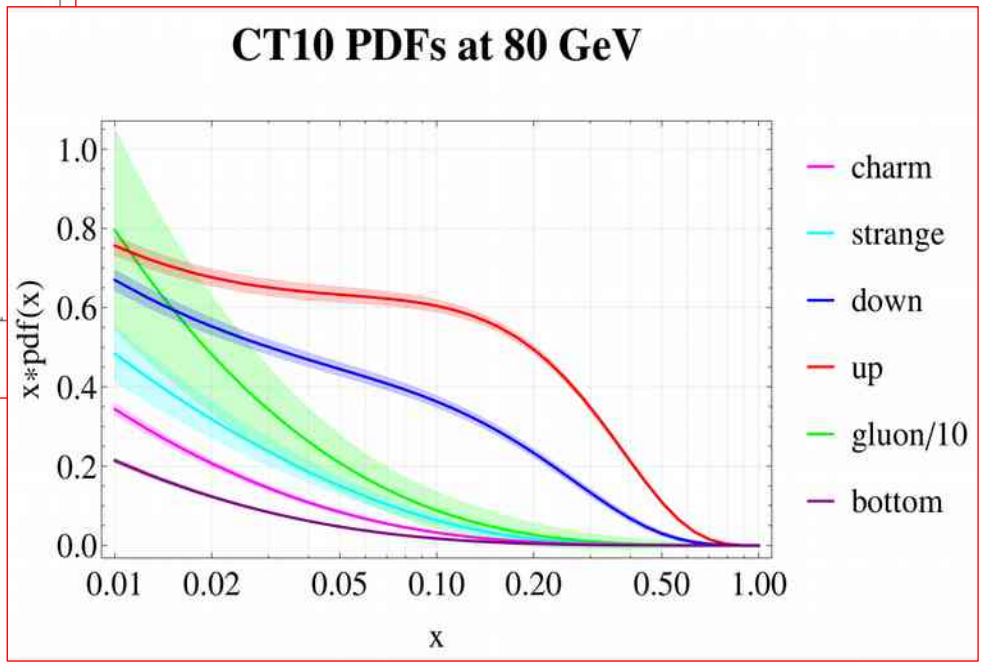


Examples: II



Full sets of PDFs inside Mathematica

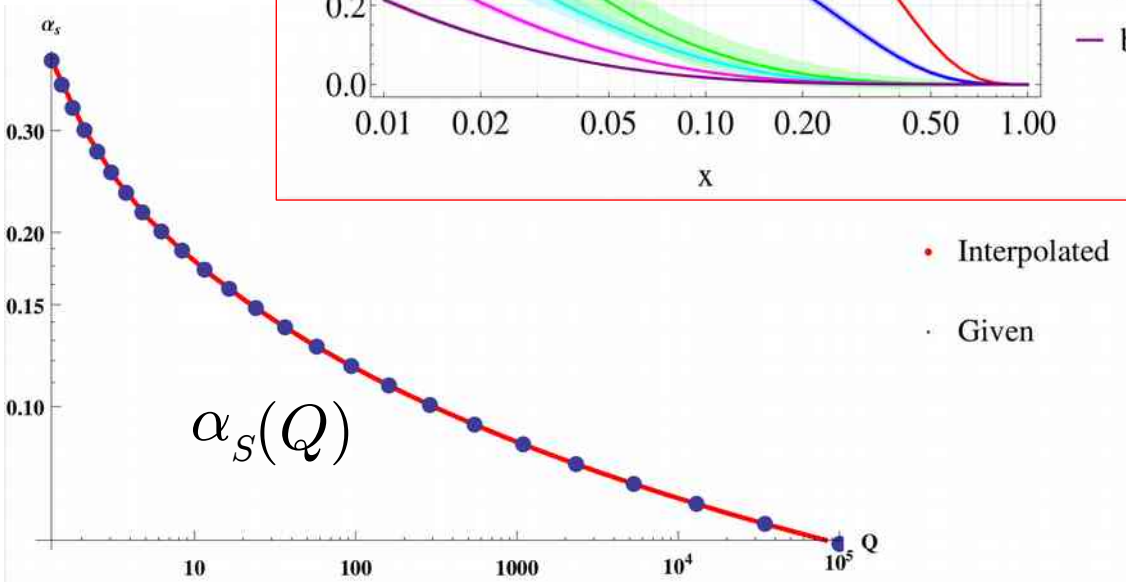
Easy to manipulate



Momentum Sum Rule provides a good check for interpolation errors

$$1 = \sum_i \int_0^1 x \cdot pdf_i(x, Q)\, dx$$

Proper α_s is essential for NLO+ calculations



Conclusion

nCTEQ-15

nuclear PDFs

DGLAP violation???

saturation

resummation

QCD

QED

Proton PDFs

hi-x

low-Q^2

higher twist

non-linear QCD

communication

isaospin violation

quark-gluon plasma

Fermi motion

Nuclear PDFs

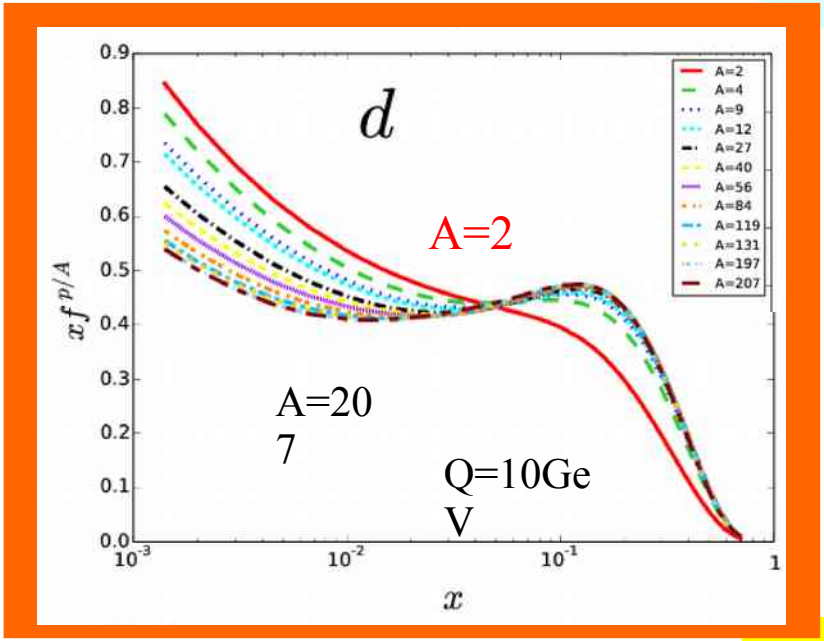
jet quenching

target mass corrections

shadowing

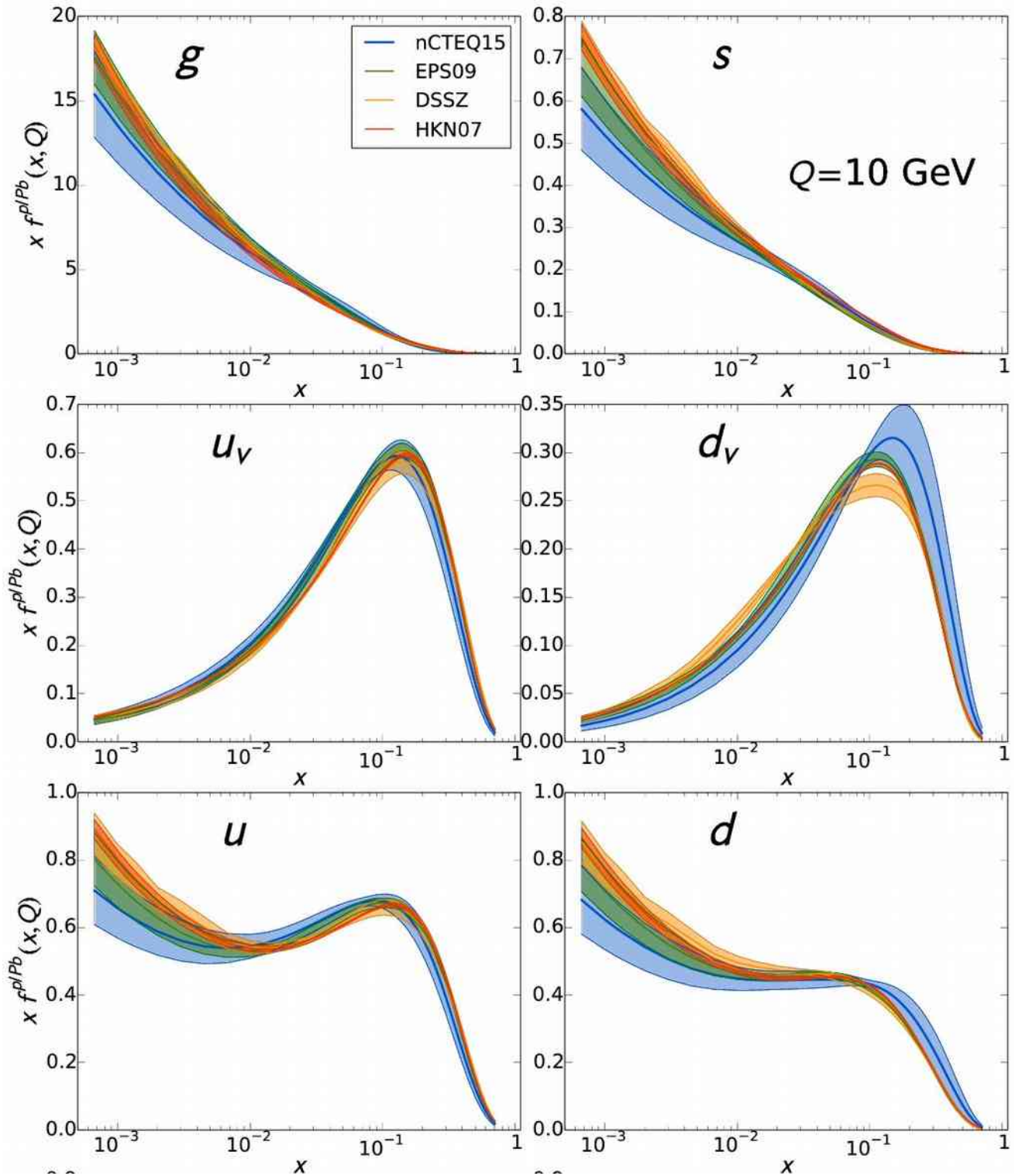
Nuclear Corrections & Flavor Differentiation

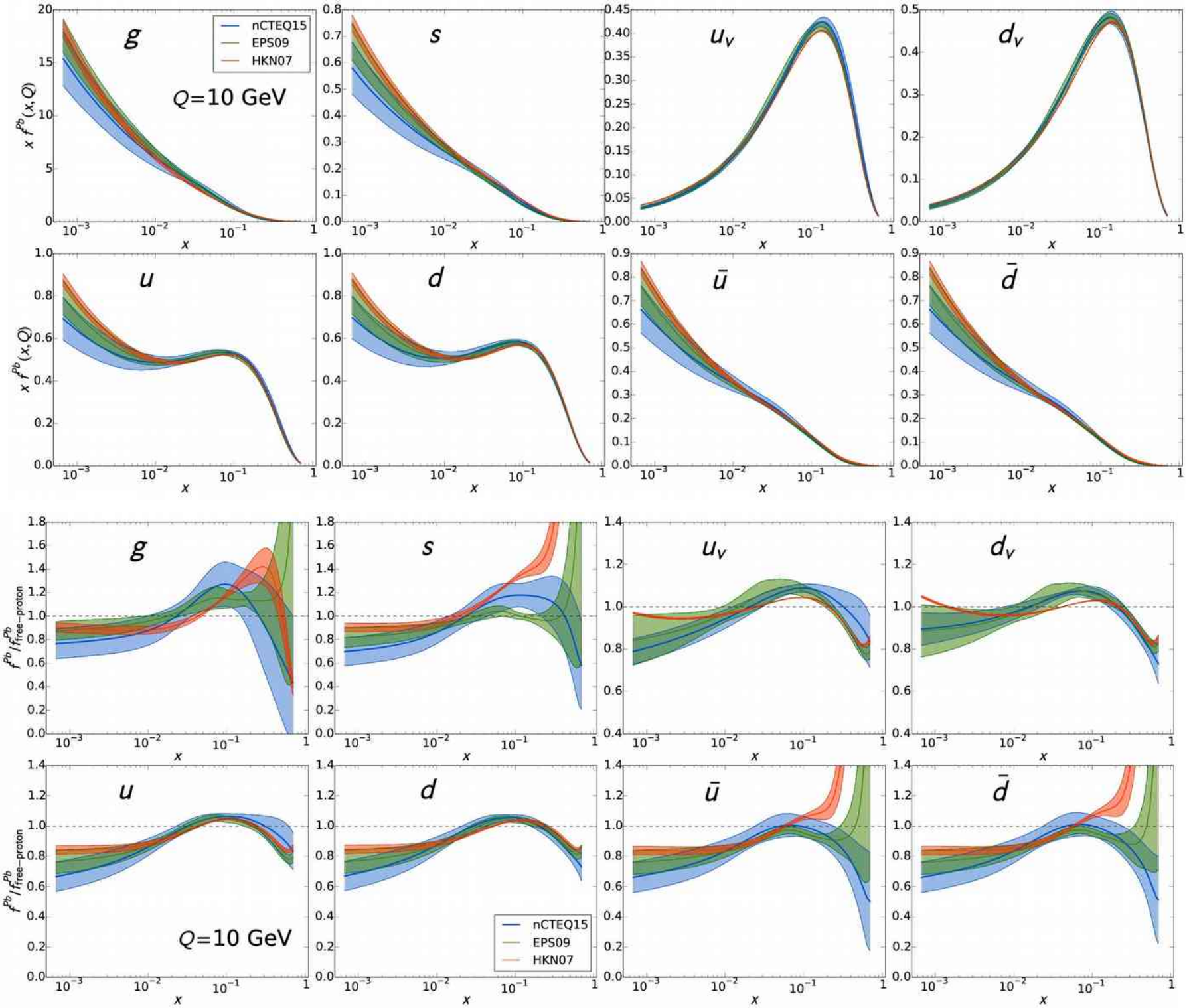
A Kusina,
K. Kovarik
T. Jezo,
D. Clark,
C. Keppel,
F. Lyonnet,
J. Morfin,
F. Olness
J. Owens,
I. Schienbein,
J. Yu
E. Godat

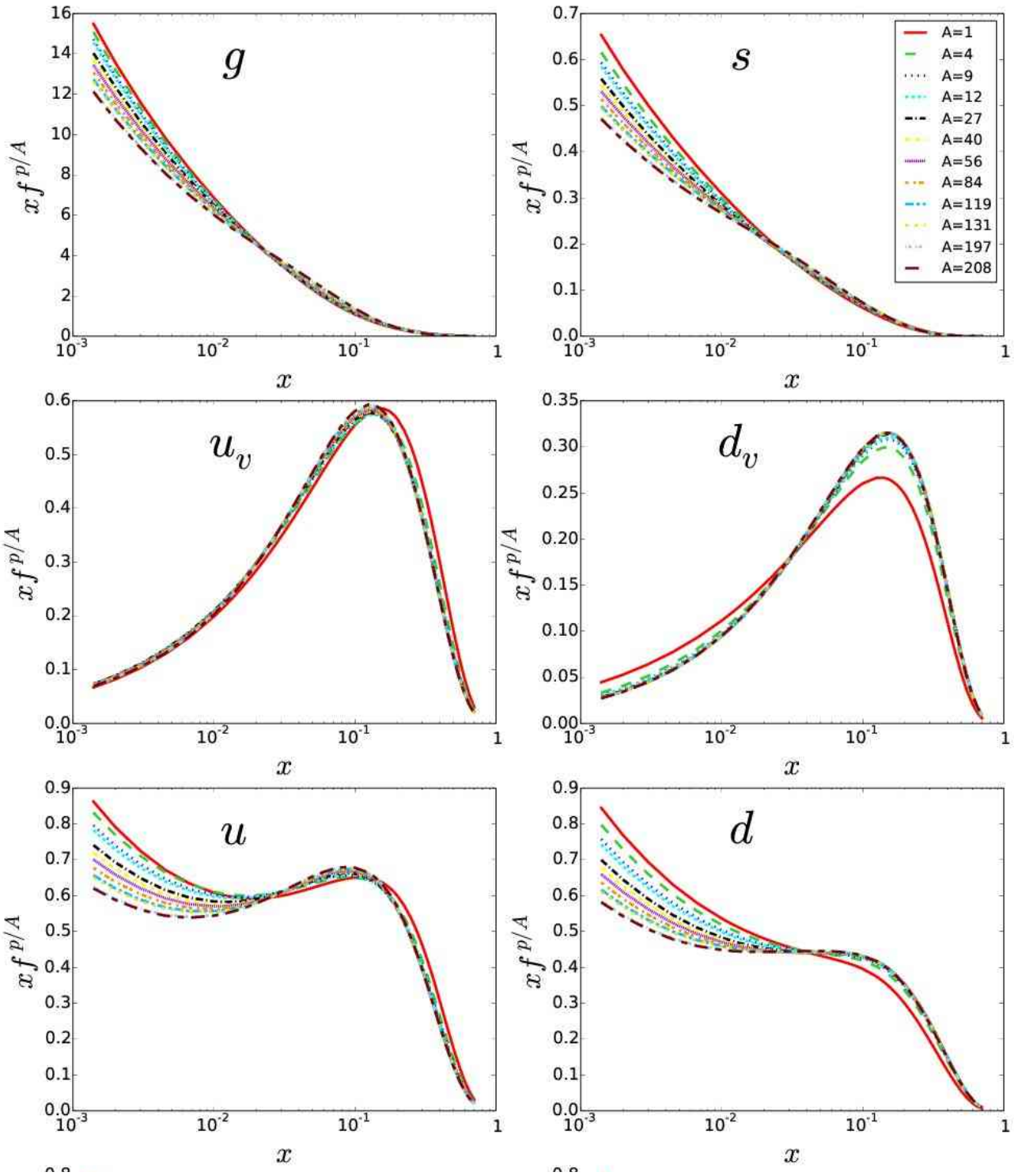


… the original motivation for nCTEQ15

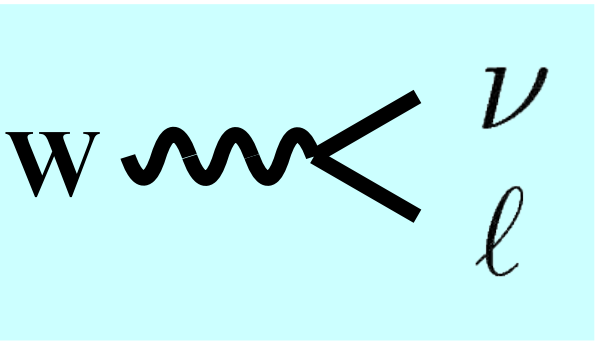
Leftover

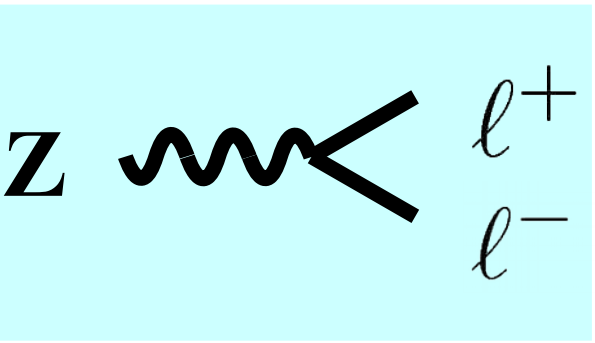

g
s
u_V
d_V
u
d
nCTEQ15
EPS09
DSSZ
HKN07
Q=10 GeV
$x\, f^{p/Pb}(x,Q)$
x


g
s
u_v
d_v
u
d
$\bar{u}$
$\bar{d}$
nCTEQ15
EPS09
HKN07
Q=10 GeV
$x\, f^{Pb}(x,Q)$
$f^{Pb}/f^{Pb}_{free-proton}$
x


g
s
u_v
d_v
u
d
$x f^{p/A}$
x
A=1
A=4
A=9
A=12
A=27
A=40
A=56
A=84
A=119
A=131
A=197
A=208

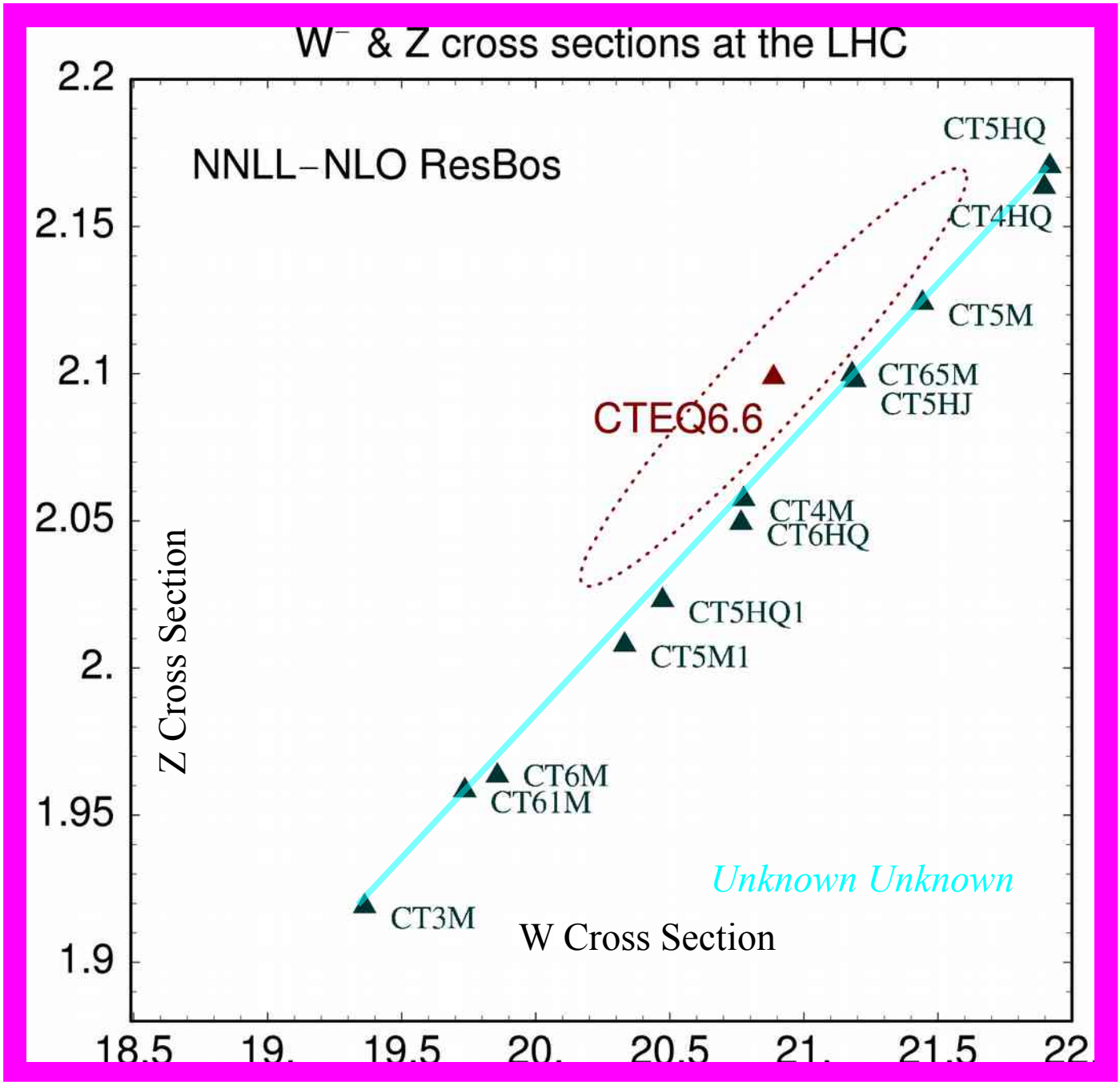
Strange Quark: Impact on LHC … W/Z correlation ⇒ MW extraction



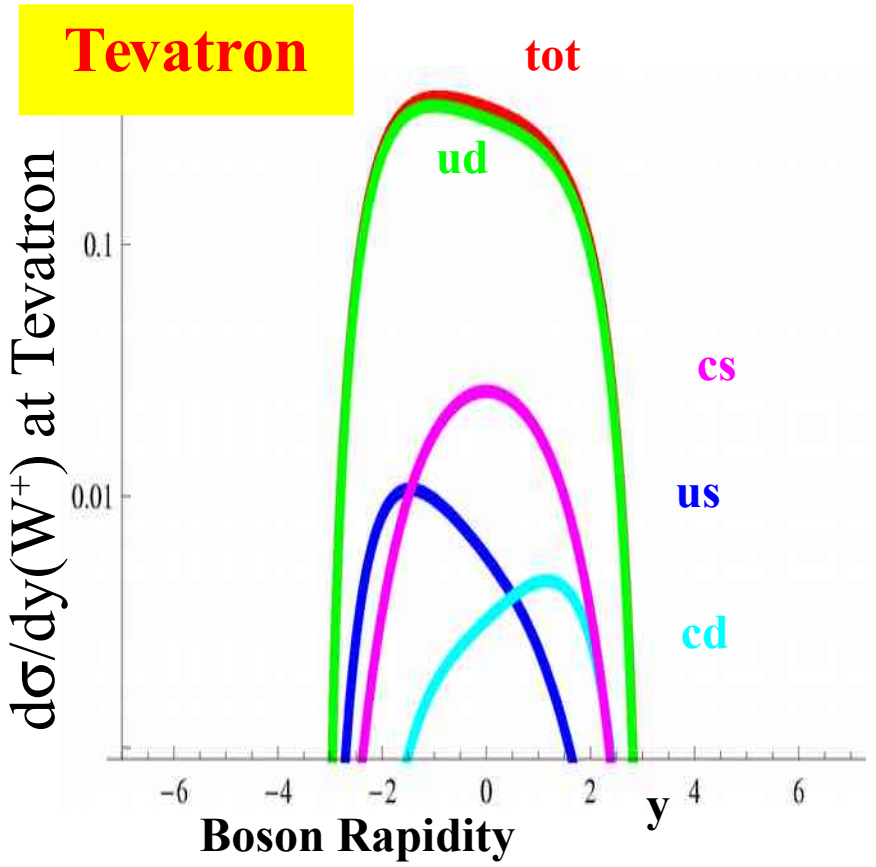


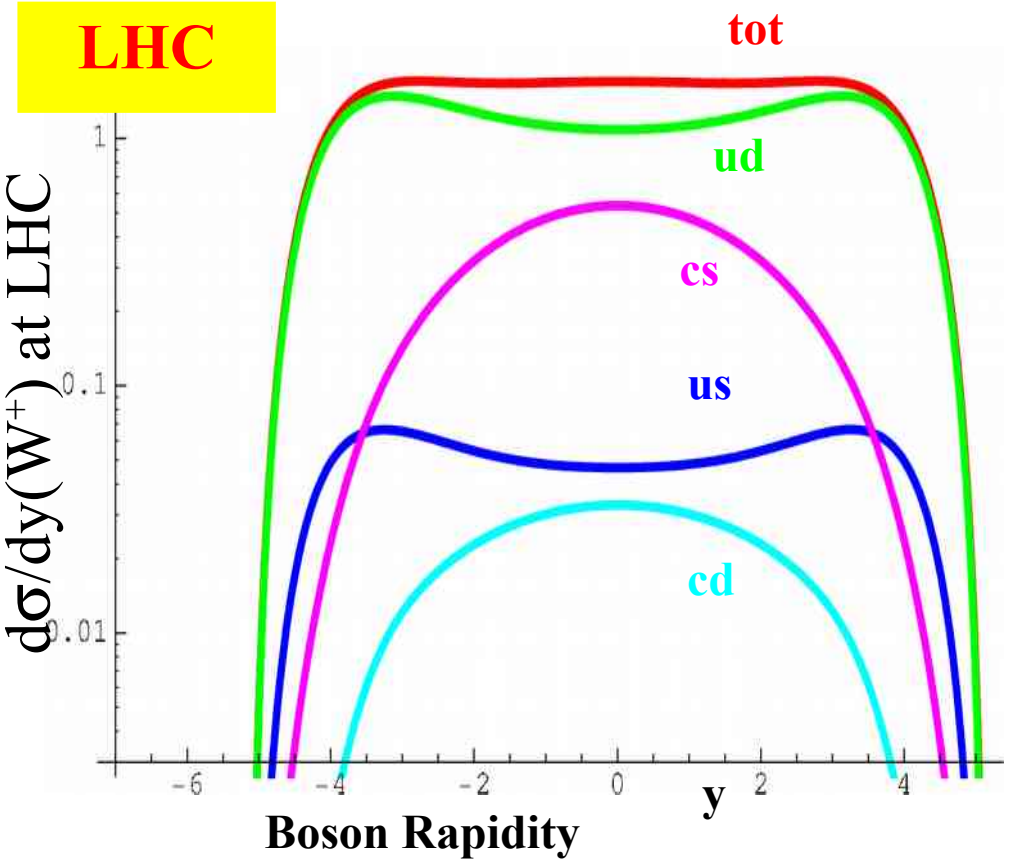
The W-Z correlation is limited by the uncertainty coming from the strange quark distribution

Key for M_W determination



W 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