A Global Analysis of Nuclear PDFs and the Heavy Quark Components

Nuclear Corrections & Uncertainties
for LHC & Beyond

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SMU

LAPTH Workshop on NPDF
23 February 2010

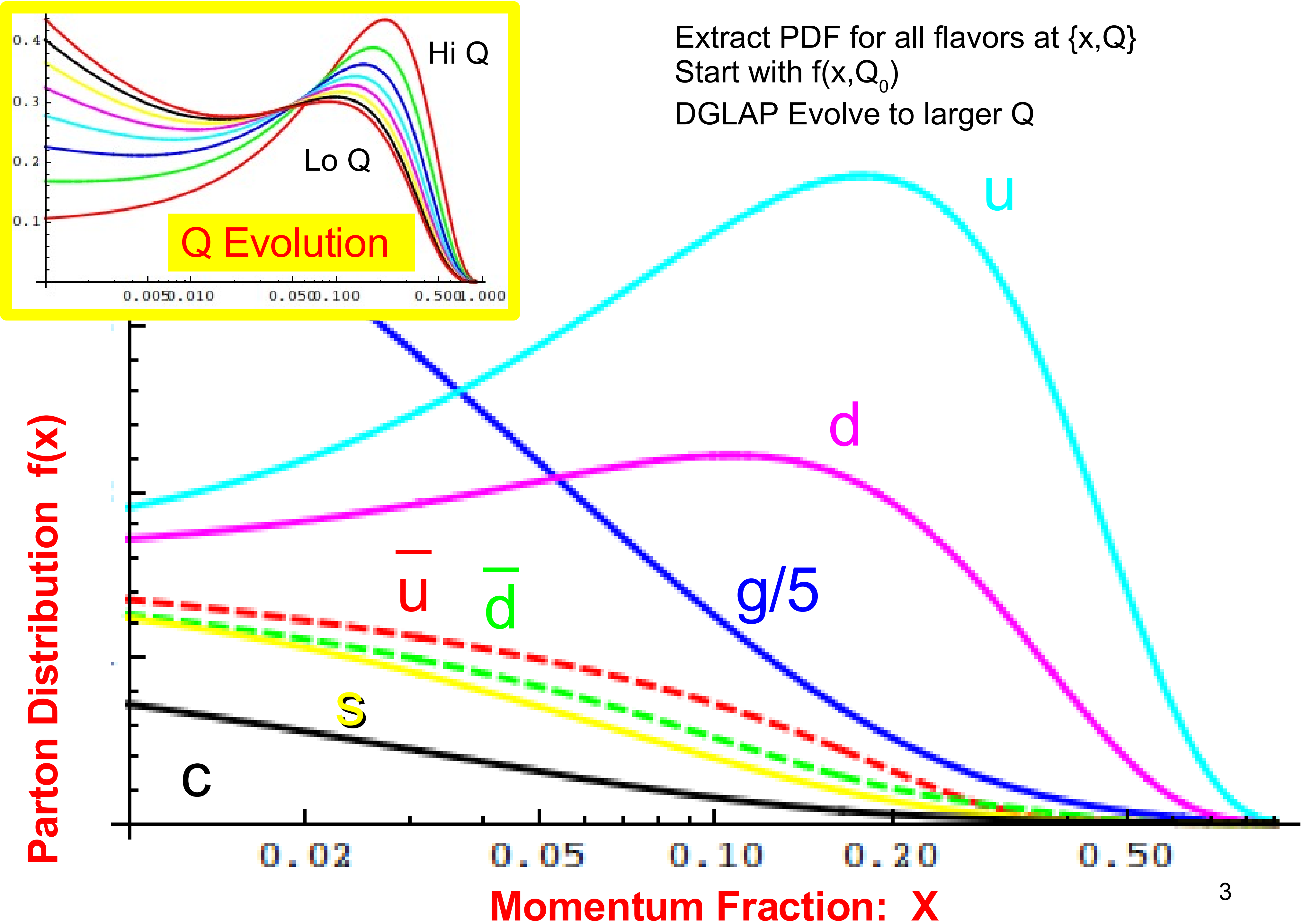
Conspirators:
I Schienbein, J.-Y. Yu,
Karol Kovarik, T.P. Stavreva
J. Owens, J. Morfin, C. Keppel, ...

Global Analysis of PDFs

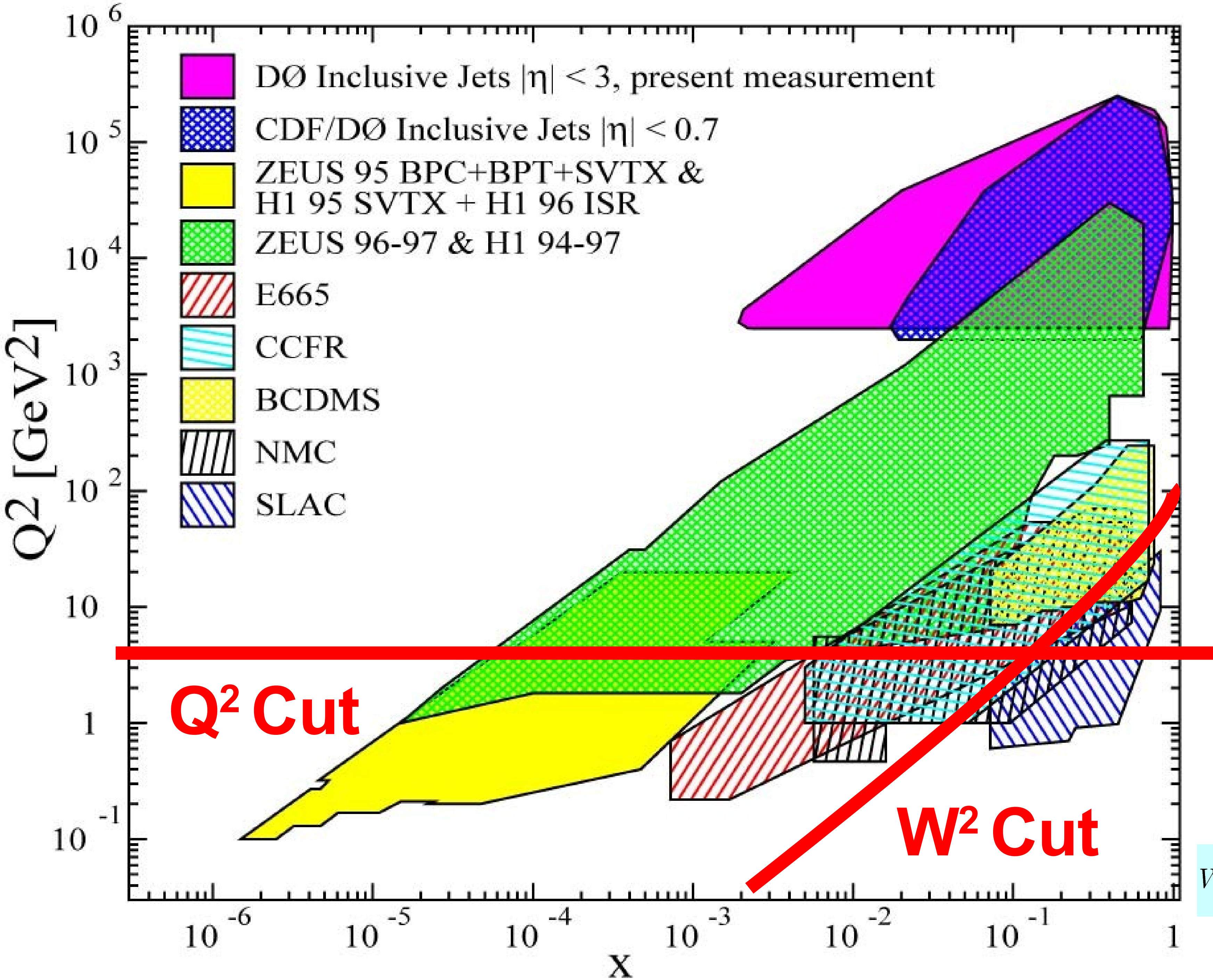
Definition of the Game

PDF Global Analysis: The Game

Extract PDF for all flavors at {x,Q}
Start with $f(x,Q_0)$
DGLAP Evolve to larger Q



Input Data for Global Analysis — *{x, Q^2} Kinematic Regions*



{Q^2,W^2} Cuts eliminate many data points

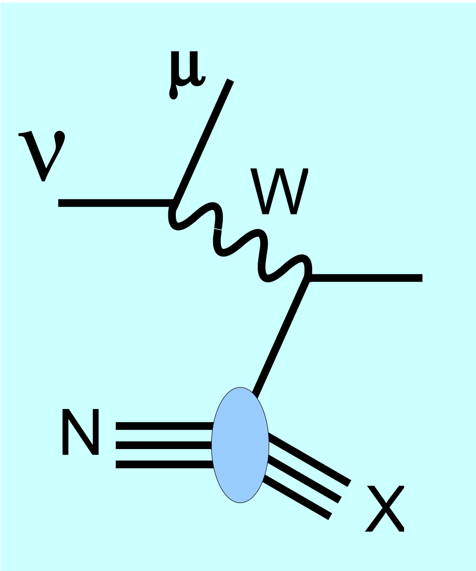
$$W^2 = Q^2\left(\frac{1}{x} - 1\right)$$

D0 Collaboration, *Inclusive jet production in ppbar collisions*, PRL 86, 1707 (2001).

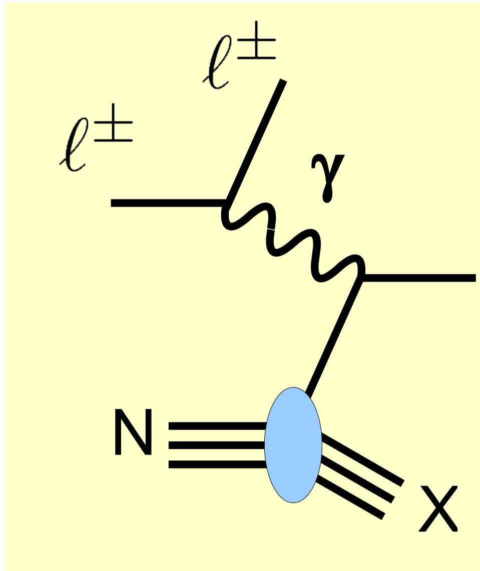
Global Analysis Data Sets

Deeply Inelastic Scattering

Neutrino DIS



Charged Lepton DIS



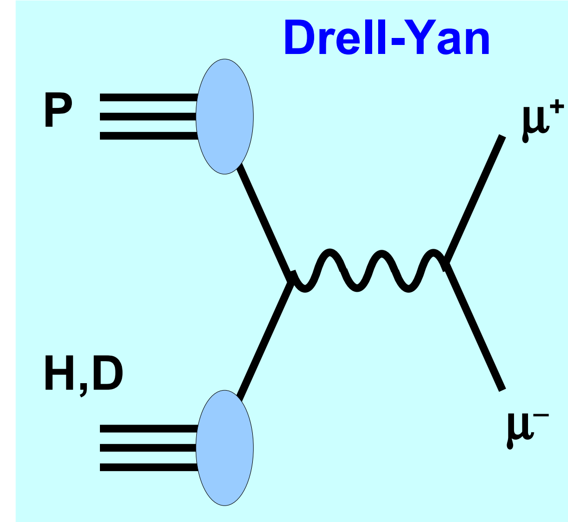
$$F_2^{\ell^{\pm}} \sim \left(\tfrac{1}{3}\right)^2 [d+s] + \left(\tfrac{2}{3}\right)^2 [u+c]$$

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

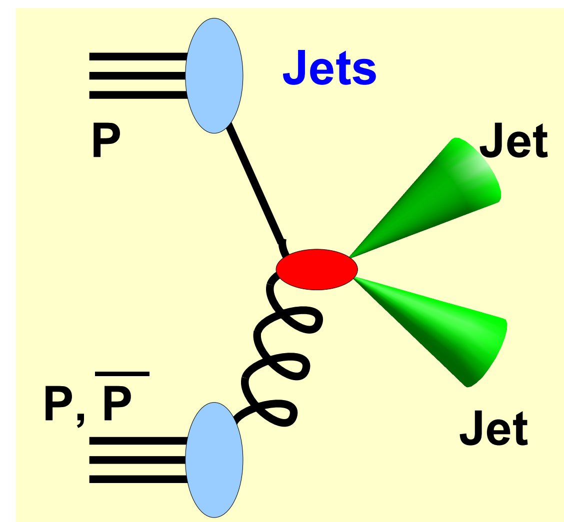
$$F_2^{\bar{\nu}} \sim [\bar{d}+\bar{s}+u+c]$$

$$F_3^{\bar{\nu}} \sim [(u-\bar{u})+(d-\bar{d})]$$

Neutrinos provide <u>different</u> linear combinations –
key for flavor differentiation



$$d\sigma_{DY} \sim [u\bar{u} + d\bar{d} + \ldots]$$

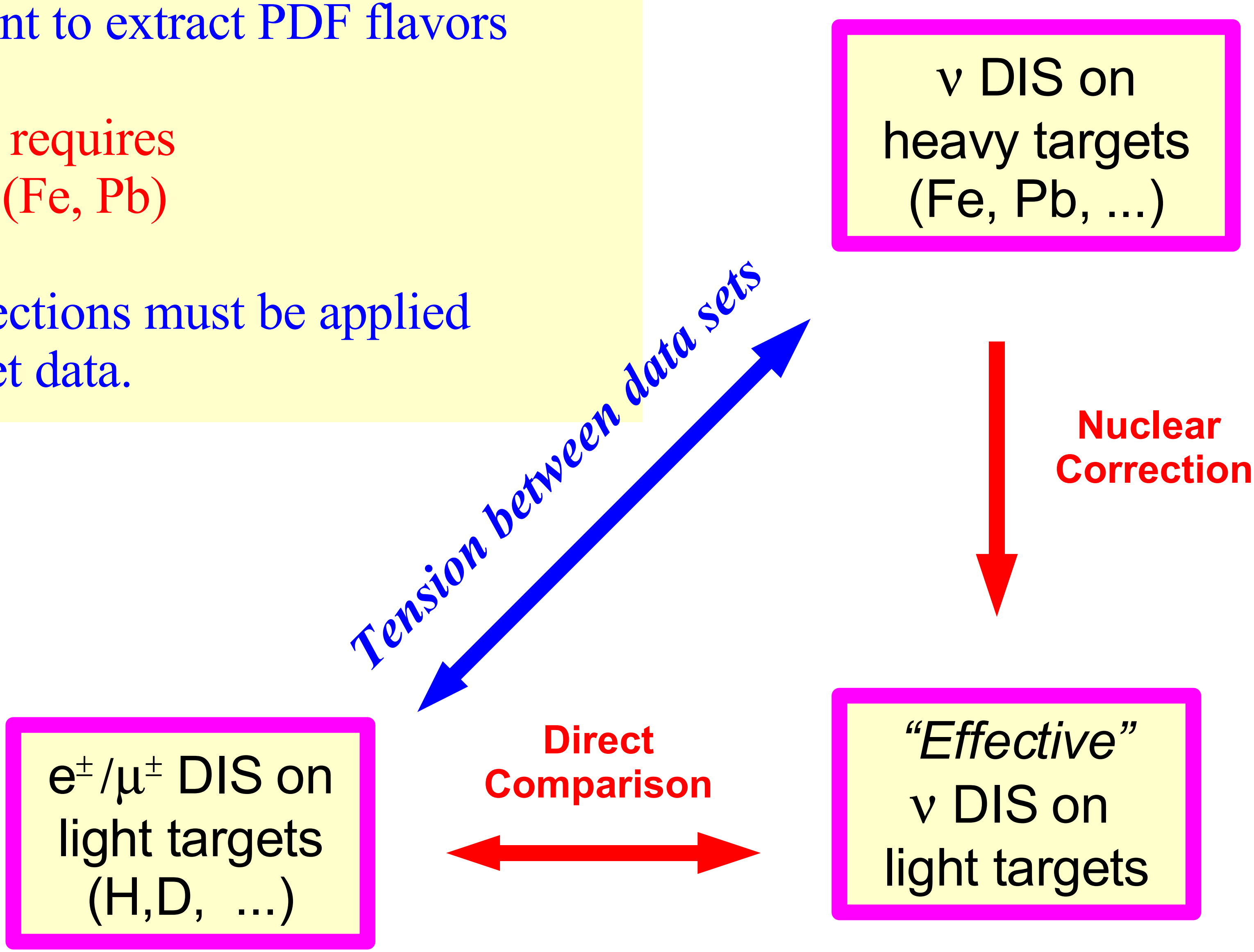


$$d\sigma \sim [gg + gq + q\bar{q} + \ldots]$$

Prompt γ, theoretical challenges in past

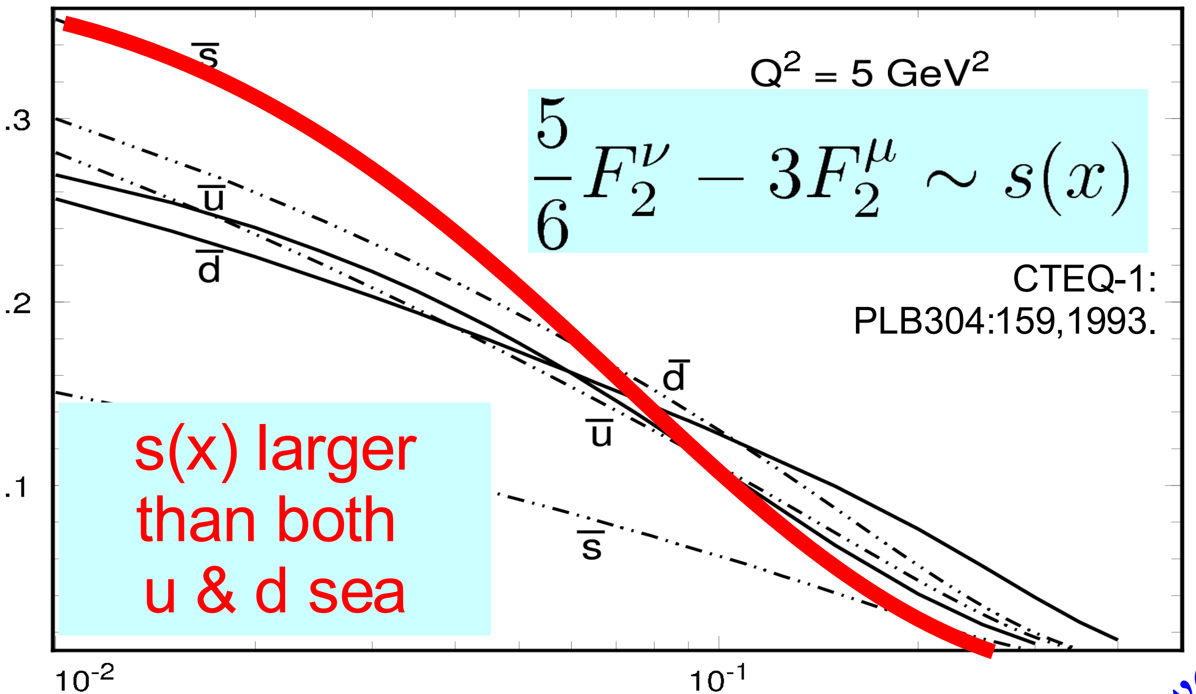
Heavy Target Data Essential for Determining Separate Parton Flavors

- Charged Current Neutrino data complement Neutral Current to extract PDF flavors
- Neutrino data requires heavy targets (Fe, Pb)
- Nuclear Corrections must be applied to heavy target data.



PDF Nuclear Corrections for Charged and Neutral Current Processes.
I. Schienbein, J.Y. Yu, K. Kovarik, C. Keppel, J.G. Morfin, F. Olness, J.F. Owens, Phys.Rev.D80:094004,2009.

Heavy Target Data Essential for Determining Separate Parton Flavors



ν DIS on heavy targets (Fe, Pb, ...)

Tension between data sets

Nuclear Correction

$e^{\pm}/\mu^{\pm}$ DIS on light targets (H,D, ...)

Direct Comparison

"Effective" ν DIS on light targets

PDF Nuclear Corrections for Charged and Neutral Current Processes.
I. Schienbein, J.Y. Yu, K. Kovarik, C. Keppel, J.G. Morfin, F. Olness, J.F. Owens,
Phys.Rev.D80:094004,2009.

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Where are we going ???

"Tension" between neutrino and charged-lepton DIS data sets

Nuclear Correction for ν DIS data limit precision

Implications for Proton PDF

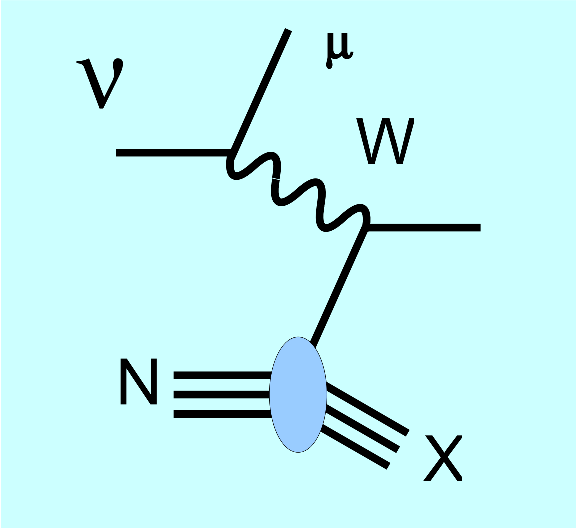
Implications for W/Z at LHC

Implications for Higgs at LHC

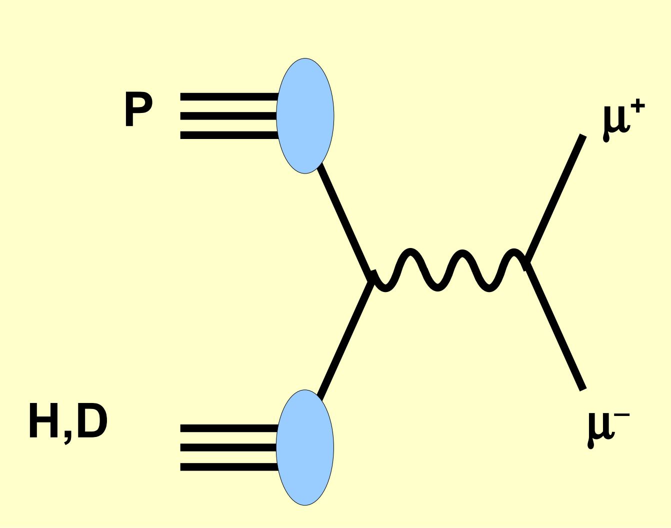
Study of
New & Updated
Data Sets

New & Updated Data Sets

ν Deeply Inelastic Scattering



Drell-Yan



NuTeV

Neutrinos on Iron

$\langle E_\nu \rangle$= 120 GeV

860K nu

230K nu-bar

1170+966 points

Chorus

Neutrinos on lead

0.01< x <0.7

10< E_ν <200 GeV

p_μ >5 GeV

412 points

E866 NuSea:

800 GeV proton beam on hydrogen & deuterium

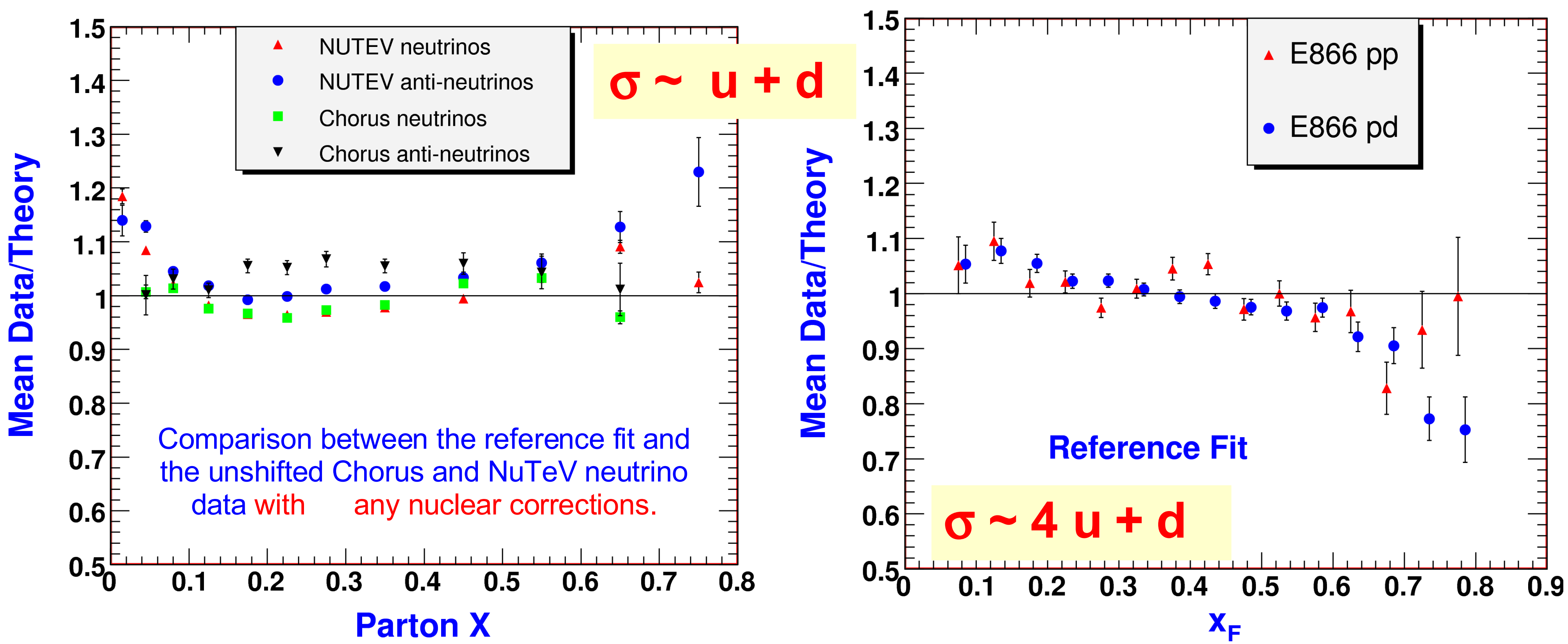
140K DY muon pairs

$M_{\mu\mu}$>4.5GeV *(Hi Mass)*

0.020 < x < 0.345

184+191 points

Could nuclear corrections be different for CC (W) or NC (γ,Z) processes???

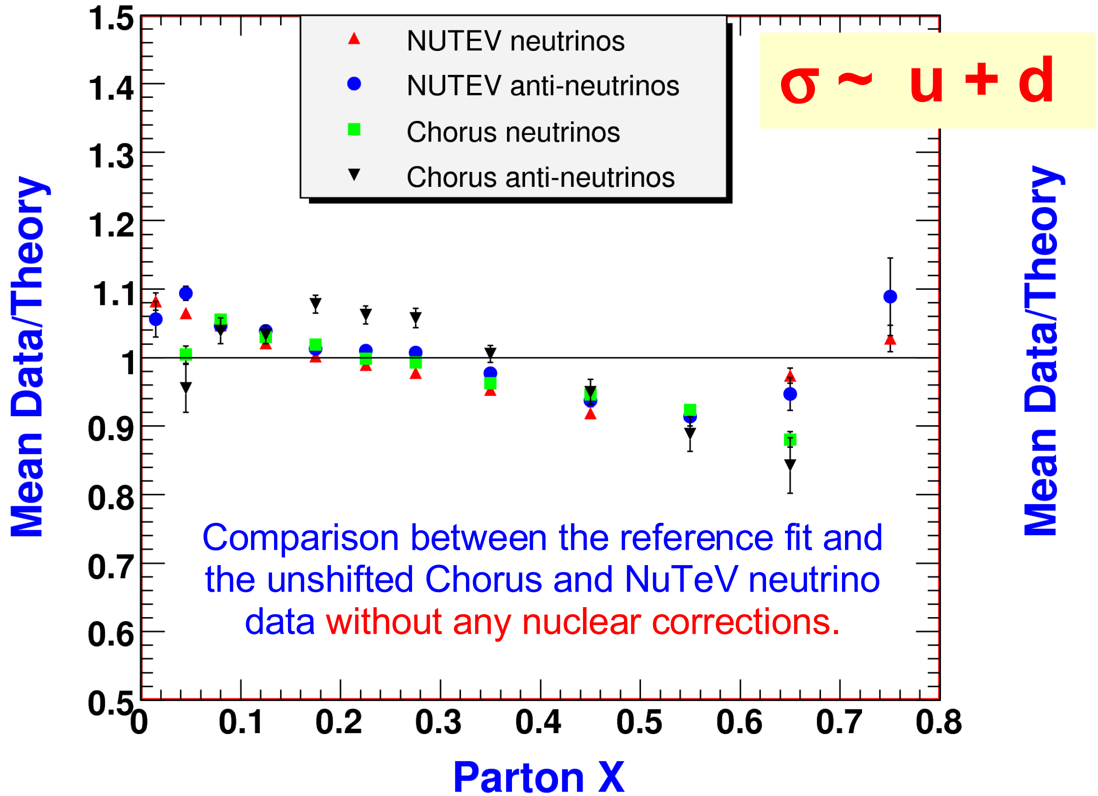


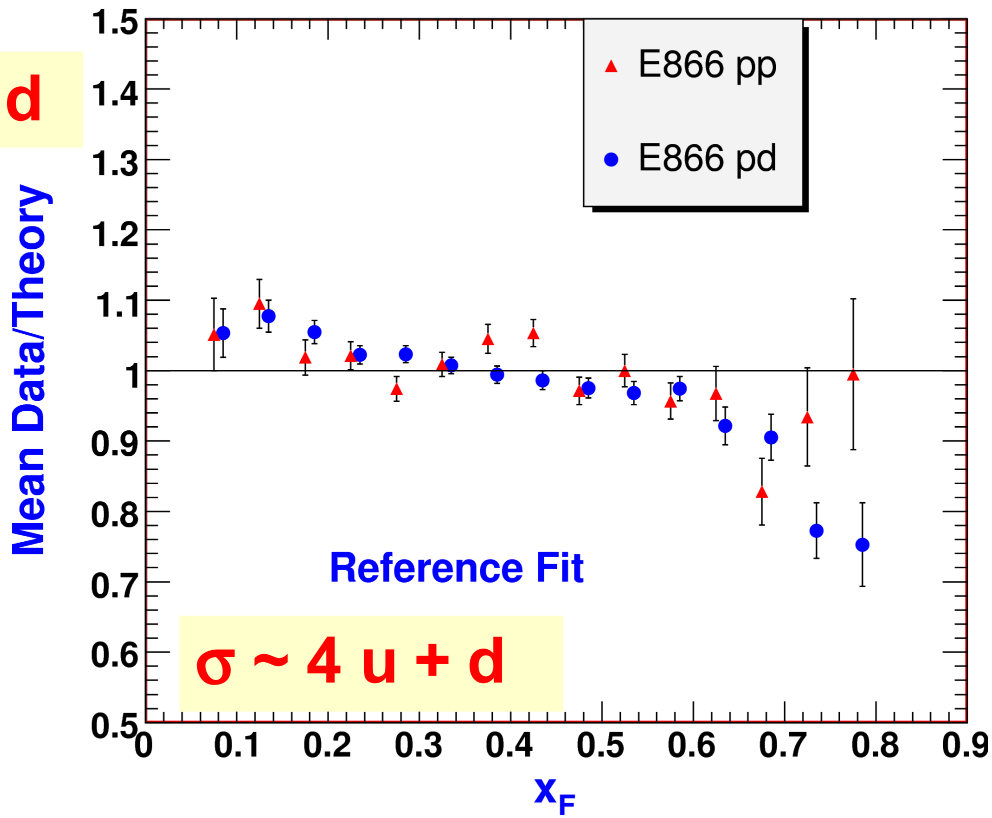
"Thus, these results suggest on a purely phenomenological level that the nuclear corrections may well be very similar for the nu and nubar cross sections and that the overall magnitude of the corrections may well be smaller than in the model used in this analysis."

χ=7453/5062 Reference Fit
χ=6606/5062 Mod Nuclear Fit

Owens, Huston, Keppel, Kuhlmann, Morfin, Olness, Pumplin, Stump. Phys.Rev.D75:054030,2007.

Could nuclear corrections be different for CC (W) or NC (γ,Z) processes???





"Thus, these results suggest on a purely phenomenological level that the nuclear corrections may well be very similar for the nu and nubar cross sections and that the overall magnitude of the corrections may well be smaller than in the model used in this analysis."

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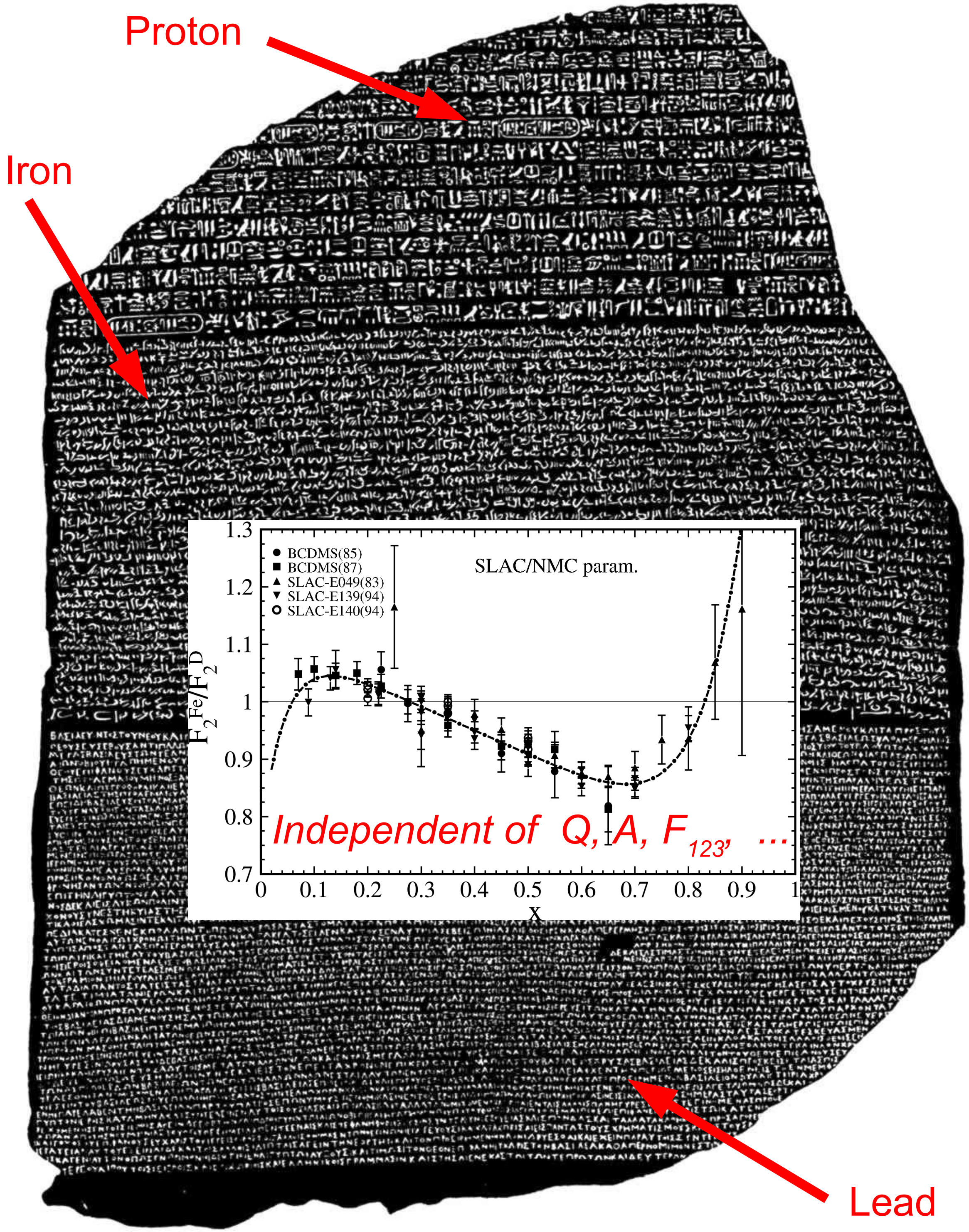
Where do nuclear corrections come from???

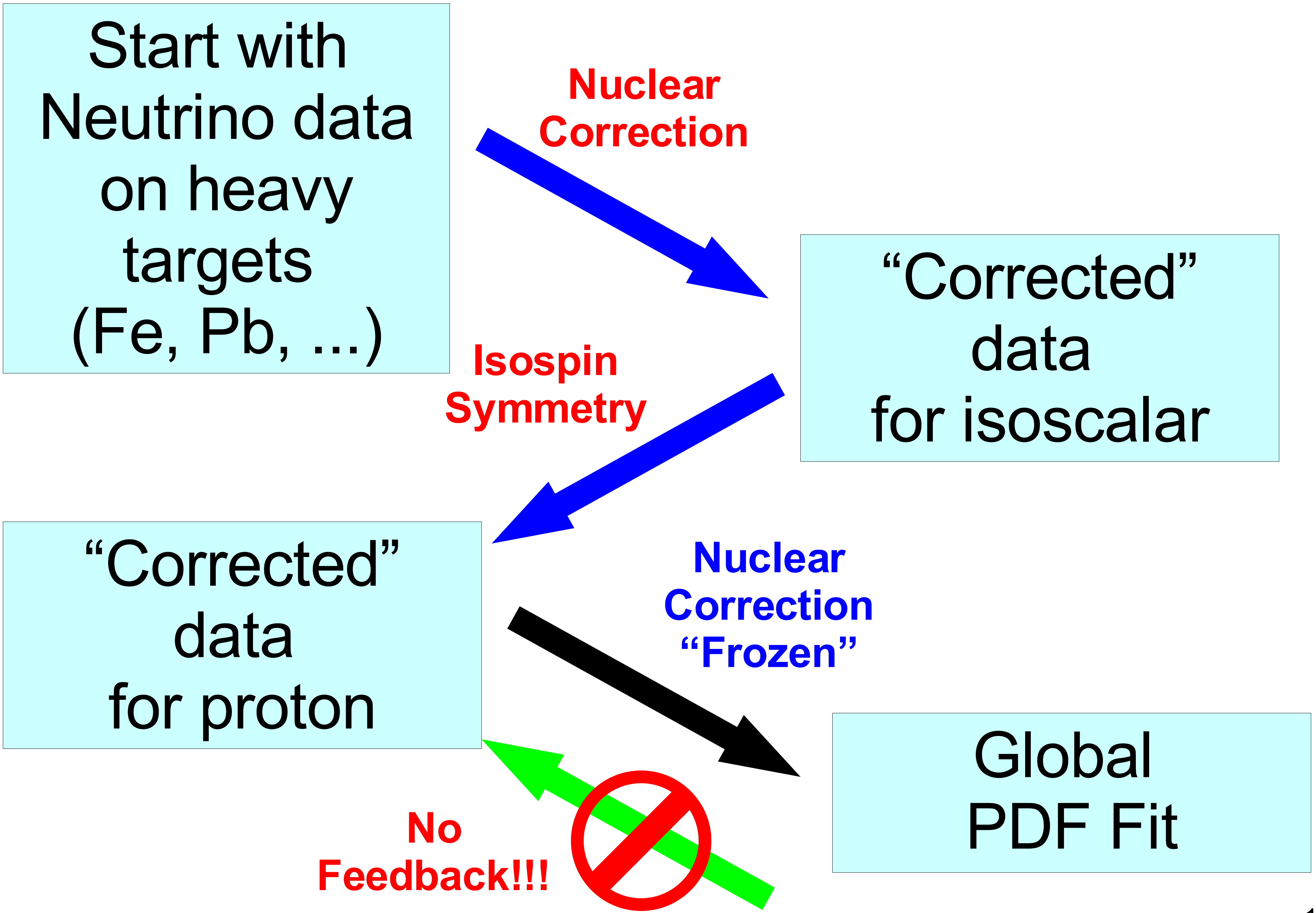
Where do Nuclear Corrections come from ???



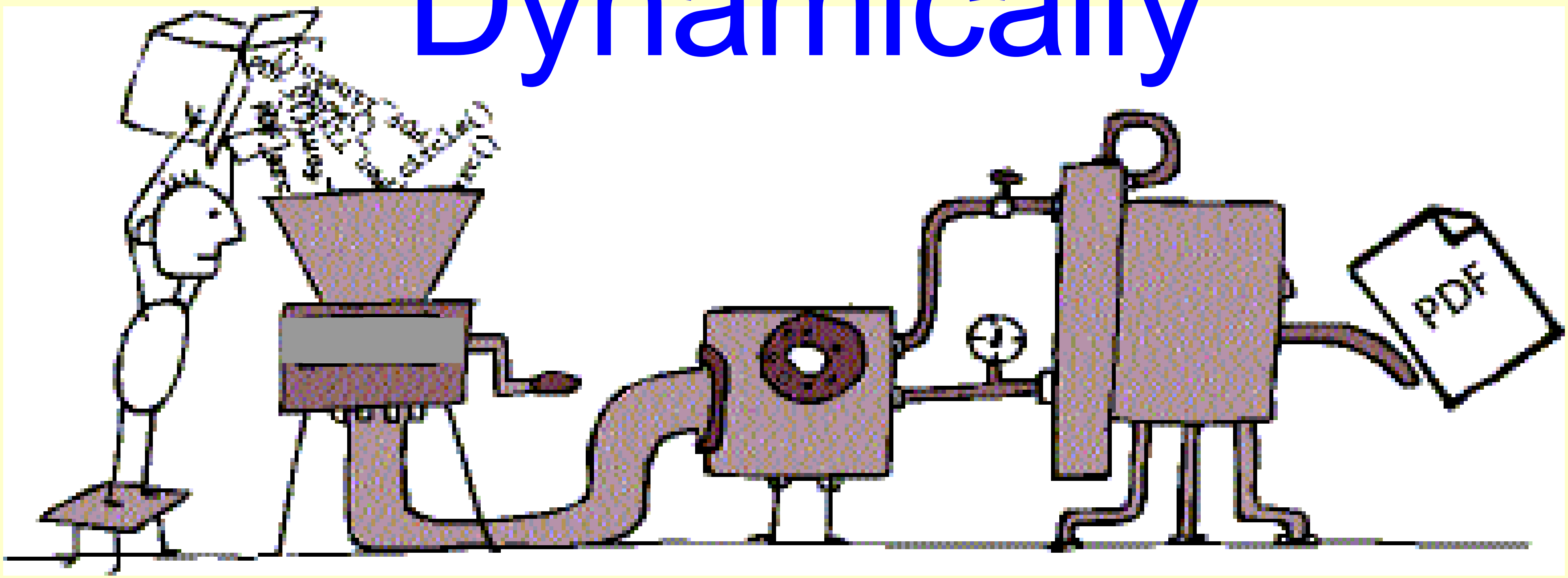
carved in stone

Discovered by the French in 1799 at Rosetta, a harbor on the Mediterranean coast in Egypt. Comparative translation of the stone assisted in understanding many previously undecipherable examples of hieroglyphics.

Traditional Input to Global PDF Fit



Include Nuclear Dimension Dynamically



Generalize PDF for Nuclear A

Allows CTEQ PDFs as a simple limit

Generalize PDF for Nuclear *A*

$$xf(x) = x^{c_1}(1-x)^{c_2}e^{c_3 x}(1+e^{c_4}x)^{c_5}$$

CTEQ6 parameterization

$$c_i \rightarrow c_i(A)$$

Generalize for Nuclear A

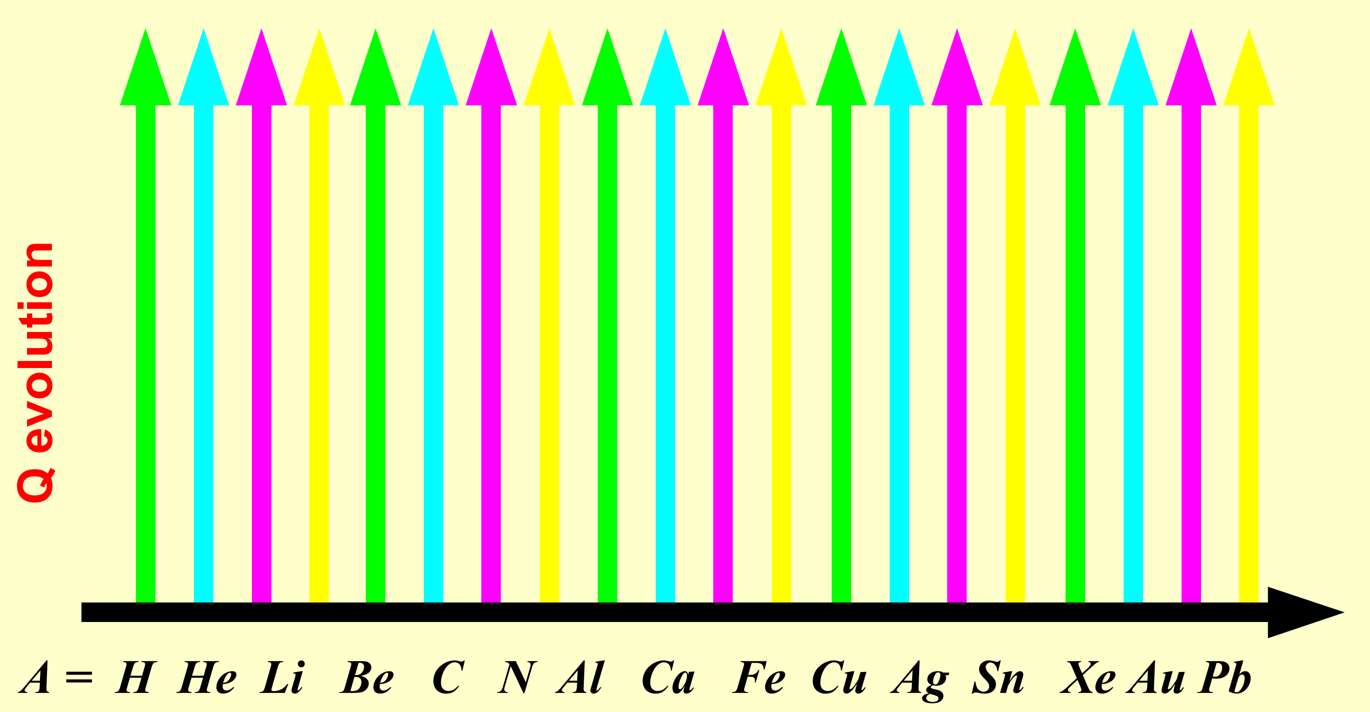
$$c_k = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$

Allows proton PDF as a simple limit

$A \rightarrow 1, \quad c_k(A) \rightarrow c_{k,0}$

$f(x,Q_0,A)$ given by above

Evolve each *A* with DGLAP evolution



Make Nuclear "A" Dependence an ***Dynamic*** Component of Fit

$$xf(x) = x^{c_1}(1-x)^{c_2} e^{c_3 x}(1+e^{c_4}x)^{c_5}$$

CTEQ6 parameterization

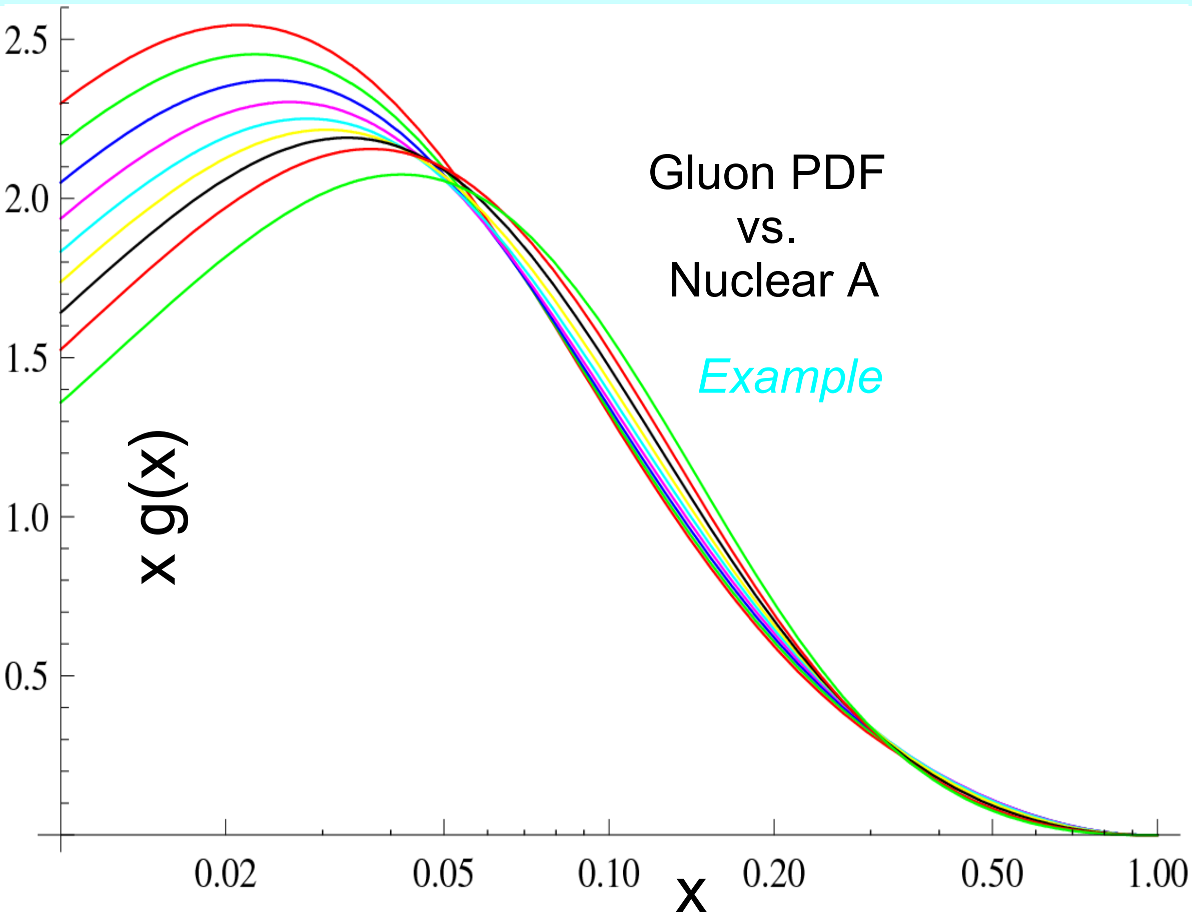
$$c_i \rightarrow c_i(A)$$

Generalize for Nuclear A

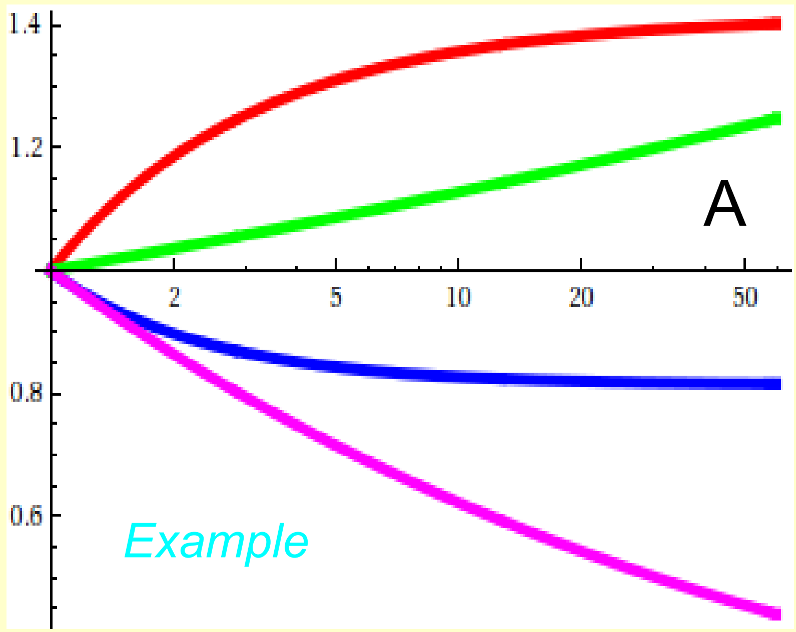
$$c_k = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$

Allows proton PDF as a simple limit

$A \rightarrow 1, \quad c_k(A) \rightarrow c_{k,0}$



$c_i(A)/c_i(A=1)$ coefficients vs. Nuclear A



Nuclear PDFs

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

$$xf(x) = x^{c_1}(1-x)^{c} \ldots + e^{c_4}x)^{c_5}$$

$$c_i \to c_i(A)$$

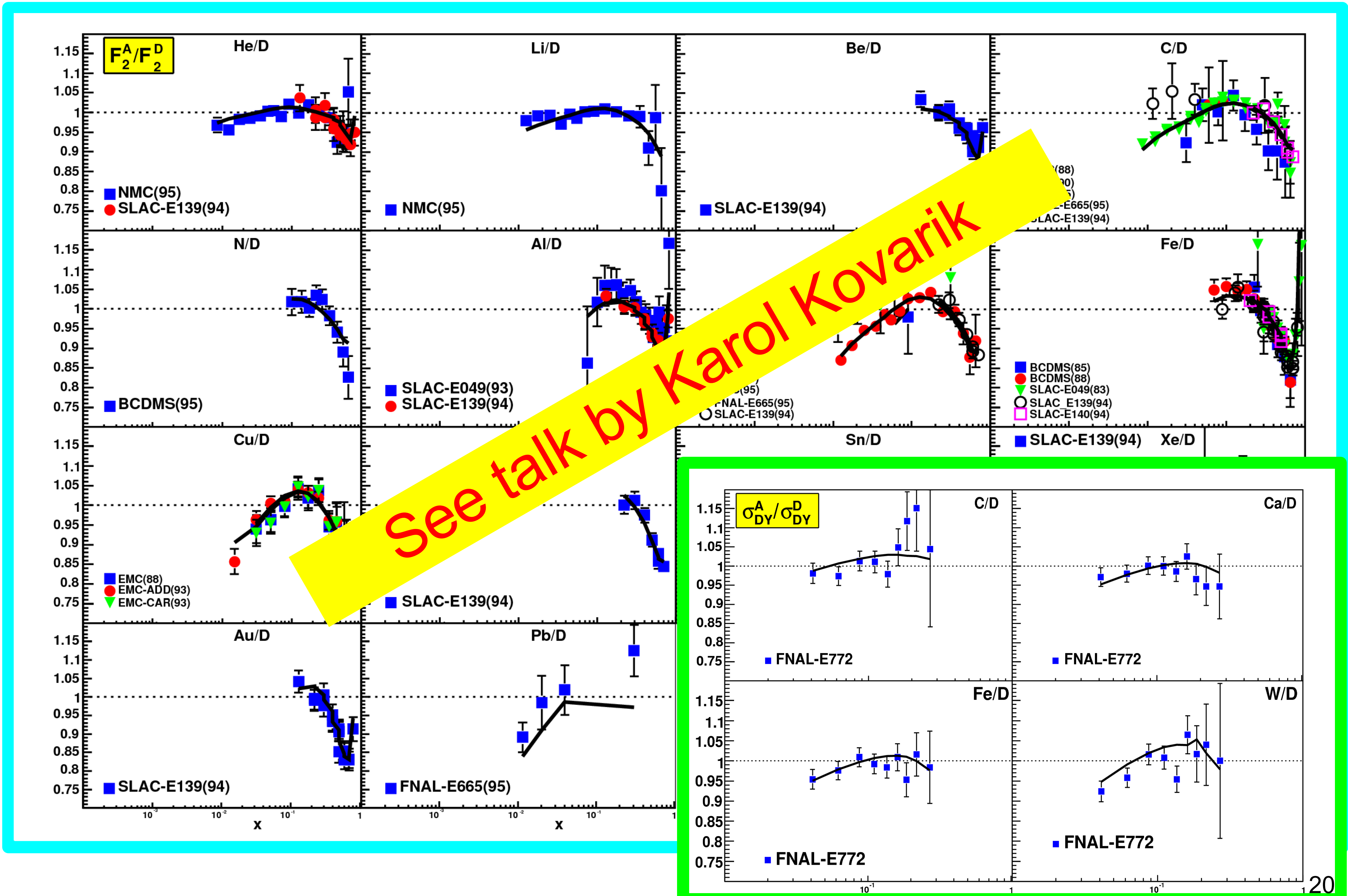
$$c_k = c_{k,0} + c_{k,1}(1 - A^{-c_{k,2}})$$

See talk by Karol Kovarik

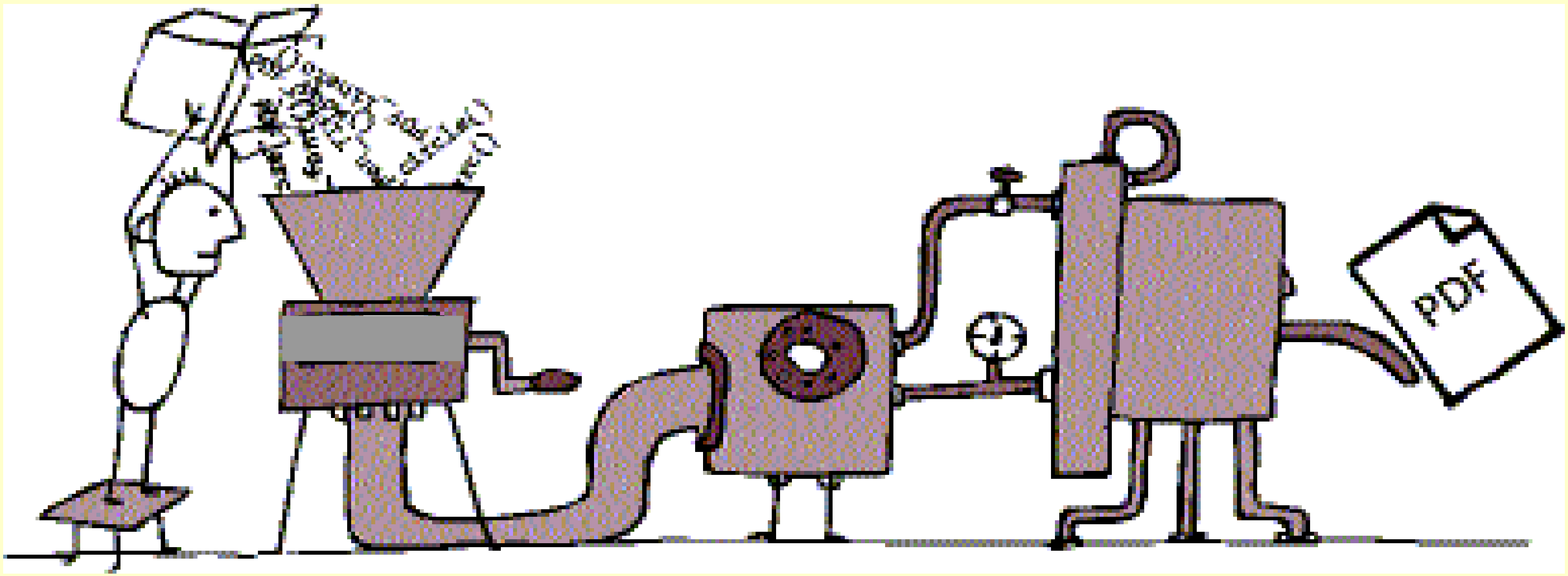
Observable	Experiment	Ref.	# data	χ^2 A1L	χ^2 A1M	χ^2 A1A	ID
F_2^A/F_2^D :							
He/D	SLAC-E139	[18]	18	9.8	6.82	6.28	5141
	NMC-95,re	[19]	16	35.6	16.91	18.31	5124
	Hermes	[20]	92	134.0	72.14	71.05	5156
Li/D	NMC-95	[21]	15	45.0	18.80	19.68	5115
Be/D	SLAC-E139	[18]	17	52.7	21.48	20.75	5138
C/D	EMC-88	[22]	9	10.3	7.29	7.11	5107
	EMC-90	[23]	2	0.2	0.14	0.11	5110
	SLAC-E139	[18]	7	31.3	4.06	4.51	5139
	NMC-95,re	[19]	16	13.9	16.12	16.62	5114
	NMC-95	[21]	15	13.9	7.13	7.26	5113
	FNAL-E665-95	[illegible]	[illegible]	23.4	8.81	8.29	5125
N/D	BCDMS-85	[illegible]	[illegible]	12.1	6.94	7.26	5103
	Hermes	[illegible]	[illegible]	94.5	62.42	58.94	5157
Al/D	[illegible]	[illegible]	[illegible]	32.2	20.42	20.38	5134
	[illegible]	[illegible]	17	22.12	6.50	8.05	5136
Ca/D	[illegible]	[23]	2	5.5	1.47	1.37	5109
	[illegible]	[18]	7	14.2	2.07	1.53	5140
	[illegible]	[19]	15	48.6	12.75	13.74	5121
[illegible]	[illegible]	[24]	4	16.2	7.88	7.67	5126
[illegible]	[illegible]	[25]	6	5.3	3.91	4.39	5102
[illegible]	[illegible]	[27]	10	35.0	8.58	9.81	5101
	SLAC-E049	[28]	14	8.8	10.39	6.24	5131
	SLAC-E139	[18]	23	43.4	35.14	35.31	5132
	SLAC-E140	[29]	6	16.8	2.93	4.87	5133
Cu/D	EMC-88	[22]	9	7.1	4.24	4.47	5106
	EMC-93(addendum)	[30]	10	14.4	6.13	6.89	5104
	EMC-93(chariot)	[30]	9	9.8	6.18	6.53	5105
Kr/D	Hermes	[20]	84	120.7	64.53	62.98	5158
Ag/D	SLAC-E139	[18]	7	22.5	4.04	2.88	5135
Sn/D	EMC-88	[22]	8	28.3	19.82	20.09	5108
Xe/D	FNAL-E665-92(em cut)	[31]	4	4.0	0.65	0.61	5127
Au/D	SLAC-E139	[18]	18	48.6	8.22	7.89	5137
Pb/D	FNAL-E665-95	[24]	4	20.3	7.77	7.46	5129
$F_2^A/F_2^{A'}$:							
Be/C	NMC-96	[32]	15	14.3	5.87	5.82	5112
Al/C	NMC-96	[32]	15	14.1	5.17	5.19	5111
Ca/C	NMC-95	[19]	20	21.7	31.47	35.73	5120
	NMC-96	[32]	15	19.8	5.39	5.31	5119
Fe/C	NMC-95	[32]	15	25.9	9.54	9.35	5143
Sn/C	NMC-96	[33]	144	312.5	102.82	96.29	5159
Pb/C	NMC-96	[32]	15	13.4	7.31	8.09	5116
C/Li	NMC-95	[19]	20	49.7	21.82	20.37	5123
Ca/Li	NMC-95	[19]	20	38.3	24.62	23.53	5122
$\sigma_{DY}^{pA}/\sigma_{DY}^{pA'}$:							
C/D	FNAL-E772-90	[34]	9	14.3	7.26	6.88	5203
Ca/D	FNAL-E772-90	[34]	9	14.1	3.81	3.33	5204
Fe/D	FNAL-E772-90	[34]	9	21.7	3.71	3.15	5205
W/D	FNAL-E772-90	[34]	9	49.7	11.07	11.27	5206
Fe/Be	FNAL-E866-99	[35]	28	38.3	29.95	29.33	5201
W/Be	FNAL-E866-99	[35]	28	38.3	25.54	25.30	5202
Total:			958	1514.4	777.0	768.3	

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.

Fit to Nuclear DIS Data

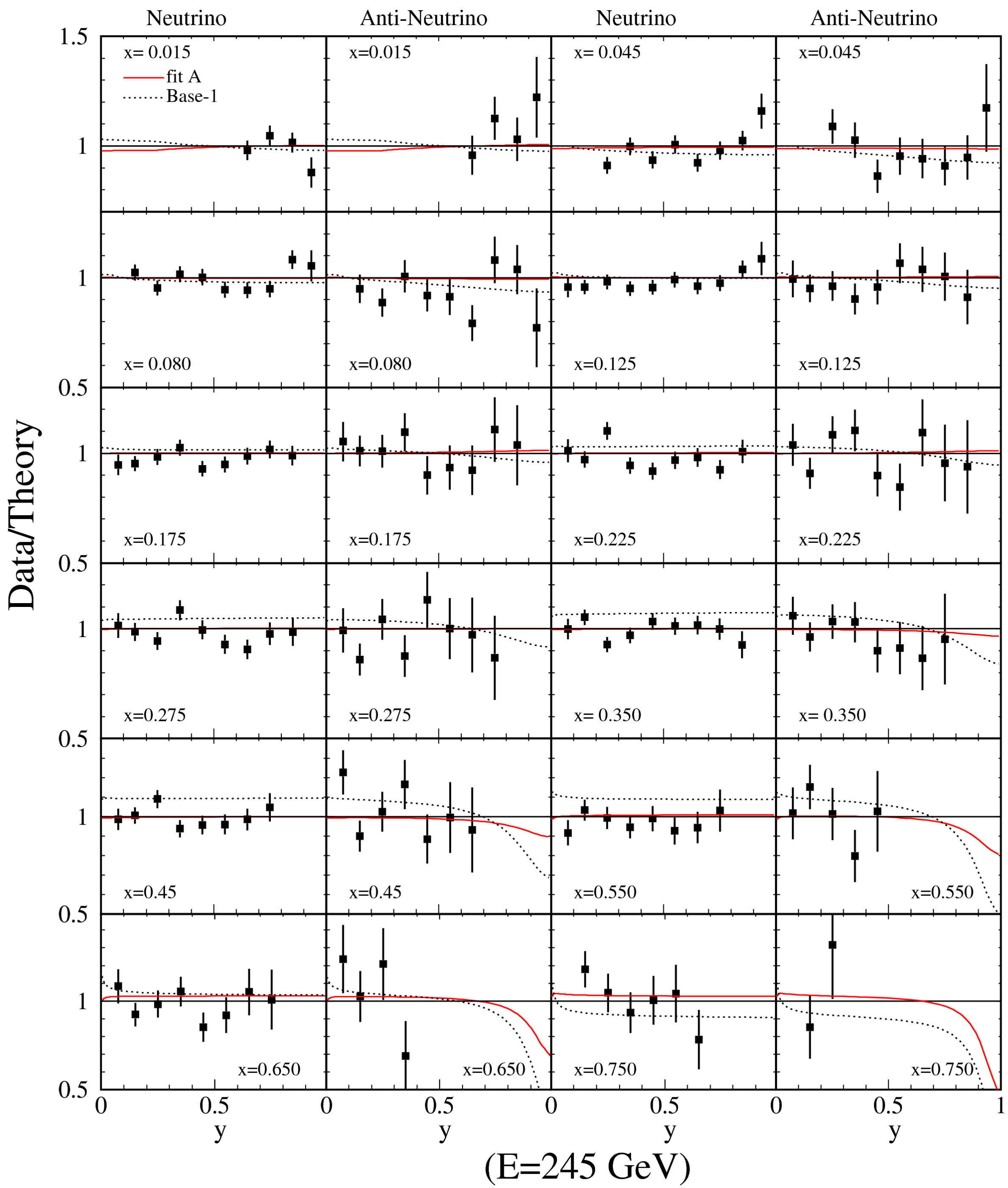


Use νFe CC Data

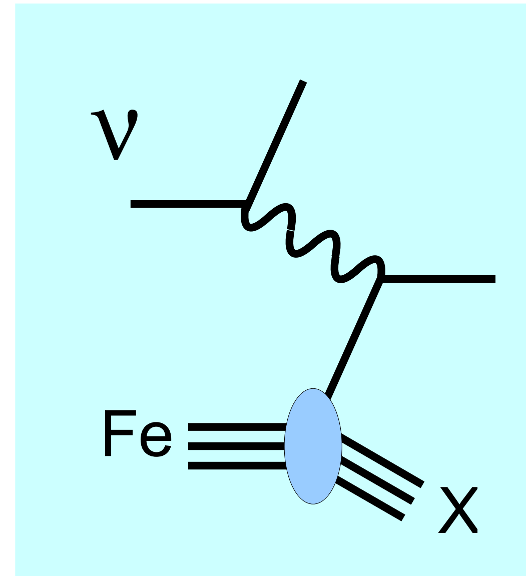


Extract **Fe** nPDFs: A=56

Use Nuclear Data to Extract Nuclear PDFs Directly: *(Model Independent)*



(E=245 GeV)



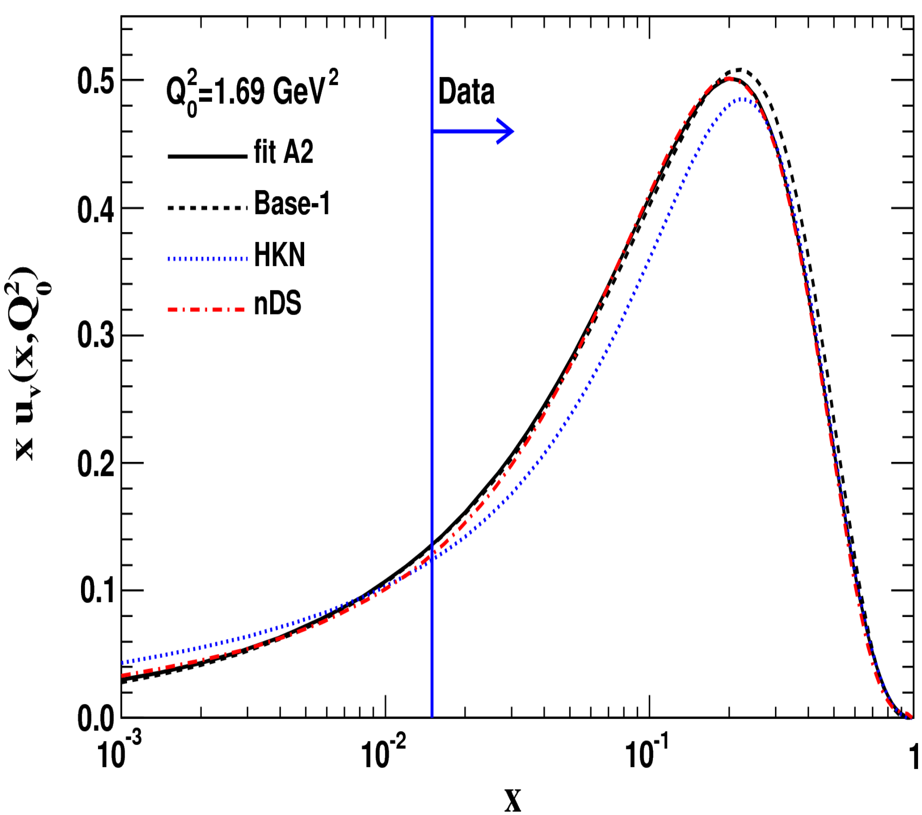
Comparison of
NuTeV Iron data
with
Nuclear PDF Fit

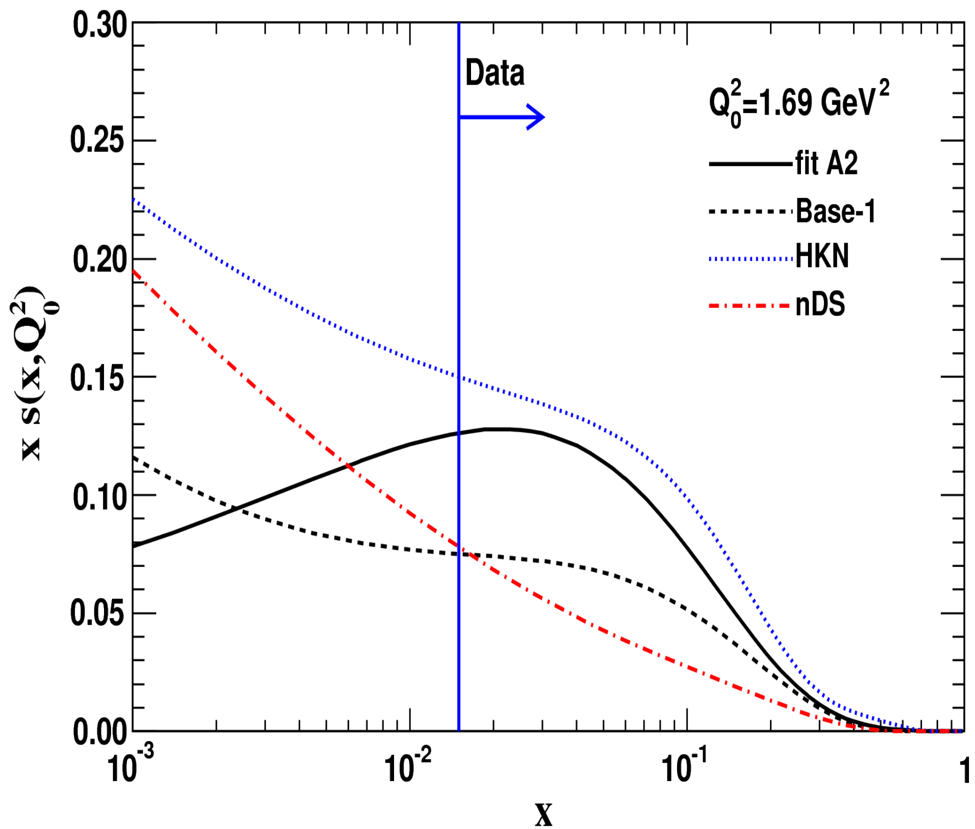
using CTEQ values
fix $g(x)$ & $\bar{d}/\bar{u}$

Schienbein, Yu, Keppel, Morfin, Olness, Owens,
Phys.Rev.D77:054013,2008

Use Nuclear Data to Extract Nuclear PDFs Directly:

$u_{Fe}(x,Q)$ $s_{Fe}(x,Q)$



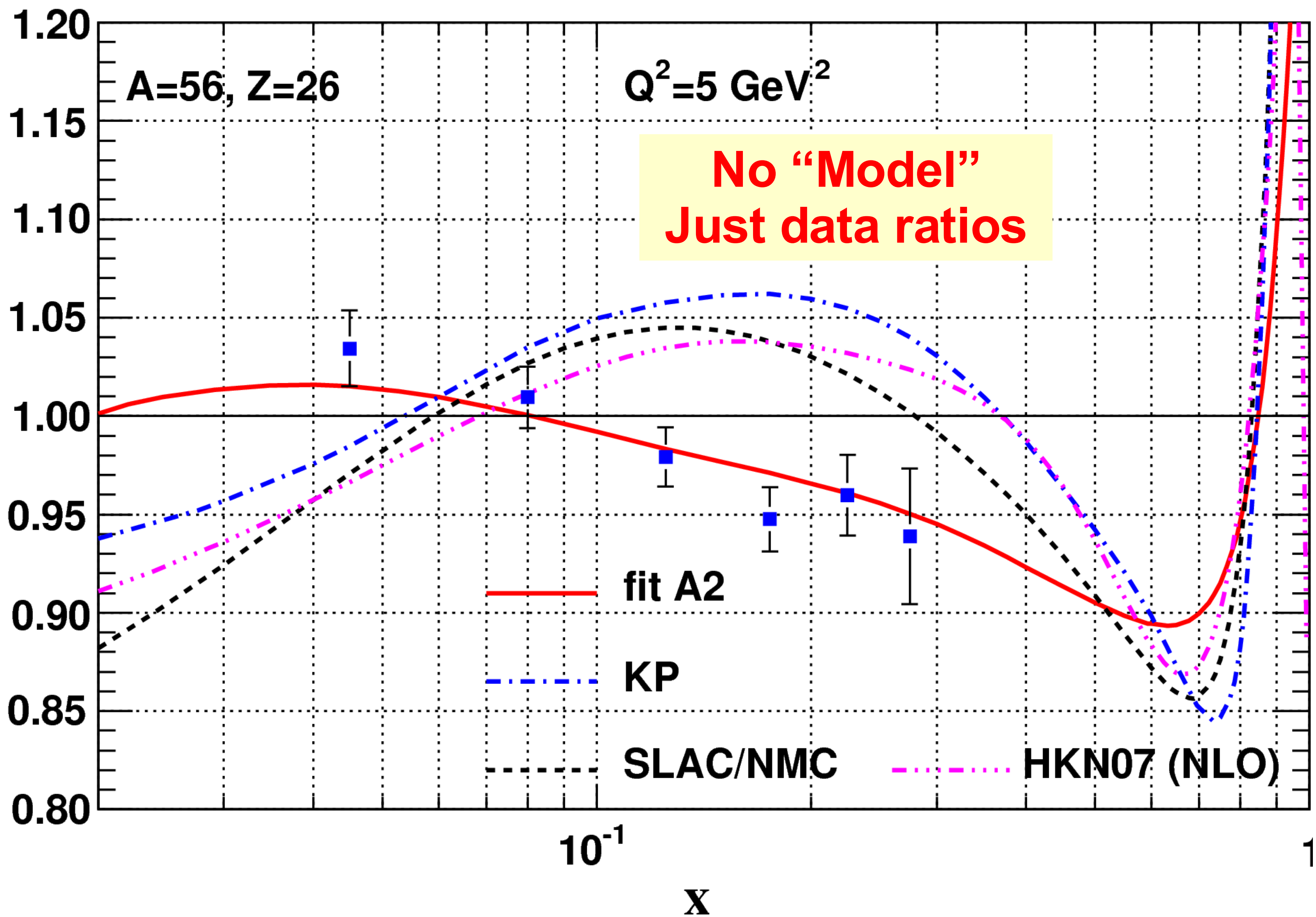


Model Independent -- Extract Phenomenologically

Schienbein, Yu, Keppel, Morfin, Olness, Owens, Phys.Rev.D77:054013,2008

Nuclear Correction Factors from neutrino-Nucleon CC Data

$$\frac{F_2^{\nu Fe}}{F_2^D}$$

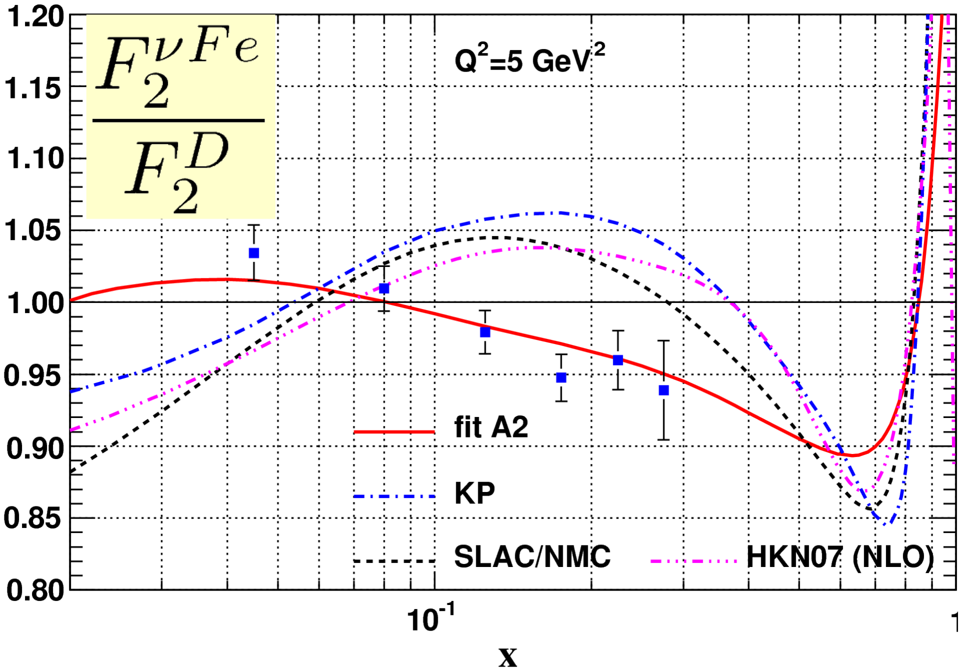


CTEQ 6.5+ removes νFe data*

Implications???

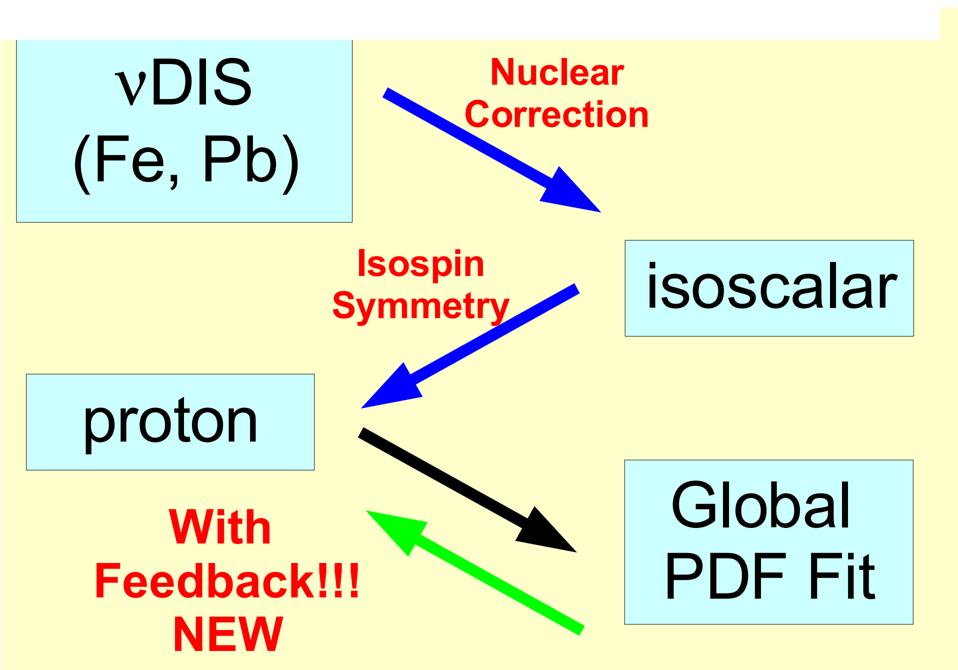
Schienbein, Yu, Keppel, Morfin, Olness, Owens, Phys.Rev.D77:054013,2008

... the smoking gun!!!



We have unambiguously identified the source of the "tension" between the neutrino and charged lepton DIS data

For the first time, we have an integrated environment were we can investigate these effects in an unbiased comparison



No "Model" Just data ratios

CTEQ 6.5, 6.6, ... removes νFe data*

Implications???

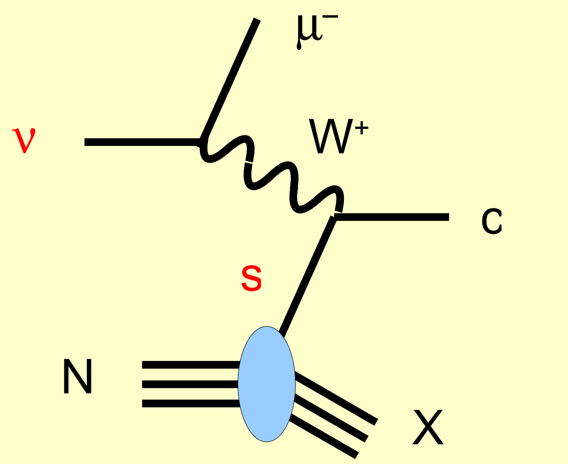
Schienbein, Yu, Keppel, Morfin, Olness, Owens, Phys.Rev.D77:054013,2008

Important connection between

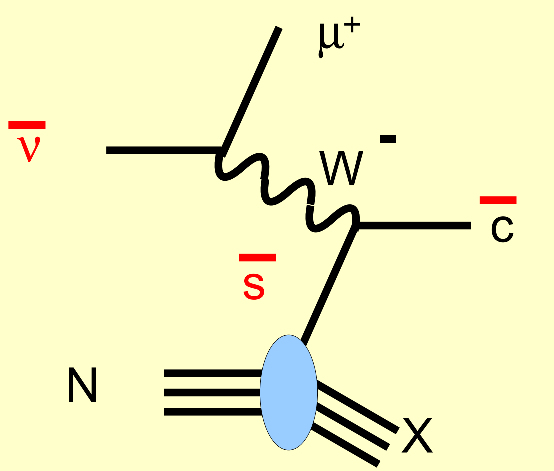
νDIS
and
Heavy Quarks

What observables are sensitive to heavy quark components?

νN Fixed Target DIS

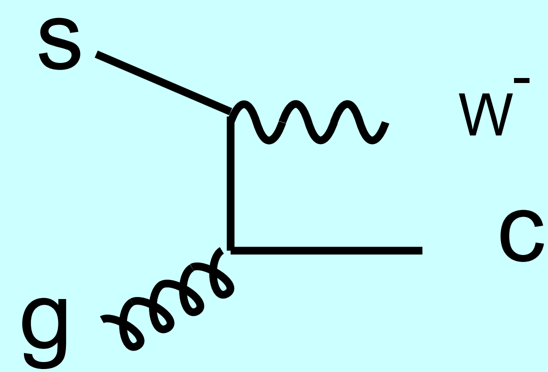


s(x) proportional to ν

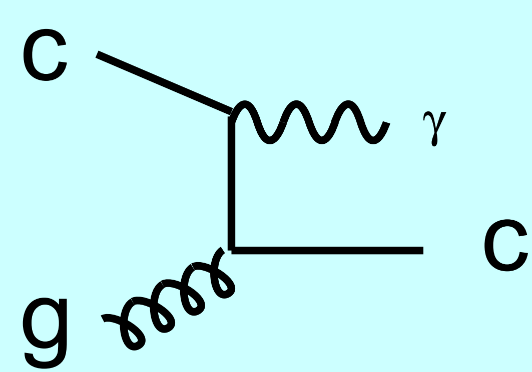


$\bar{s}$(x) proportional to $\bar{\nu}$

Tevatron & LHC



Wc final state

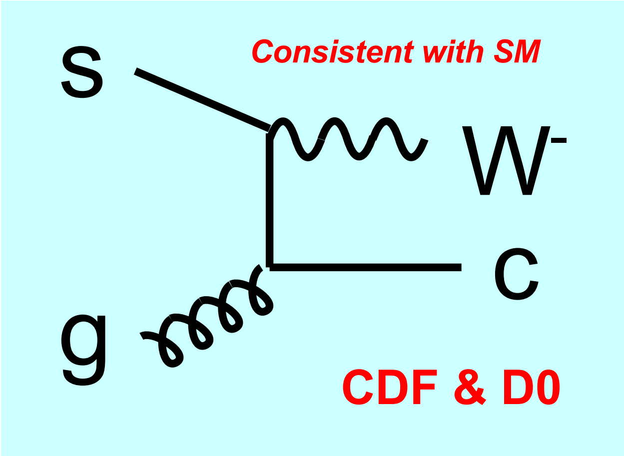


γc final state

See talk by T.P. Stavreva

What constrains the Strange PDF

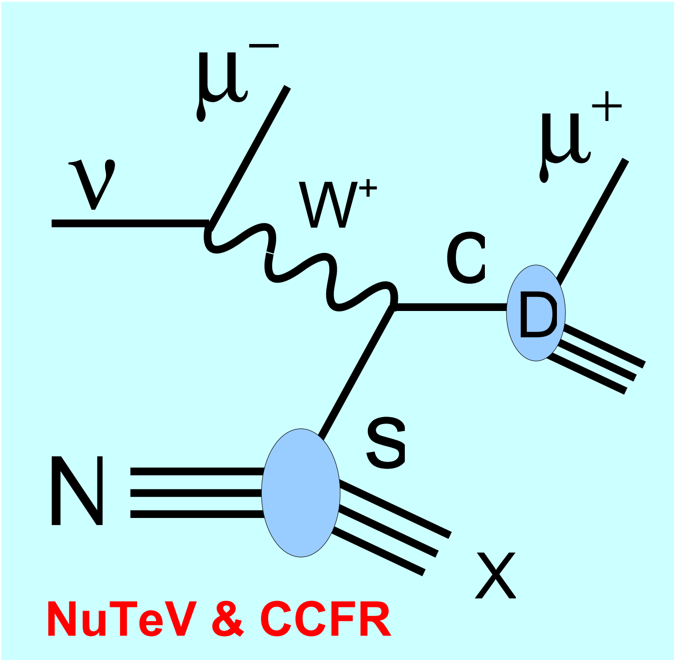
s g→Wc at the Tevatron



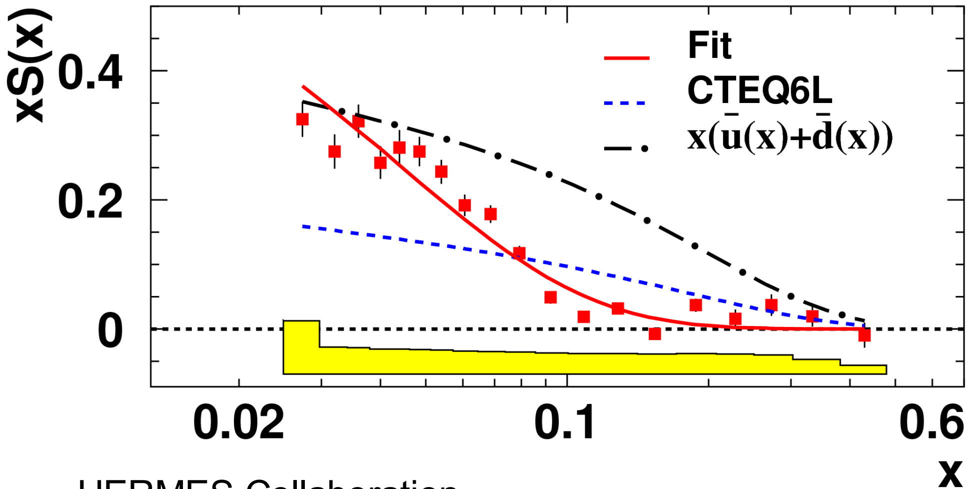
CDF Collaboration
Phys.Rev.Lett.100:091803,2008.

D0 Collaboration
Phys.Lett.B666:23-30,2008.

Neutrino DIS
Charm Production



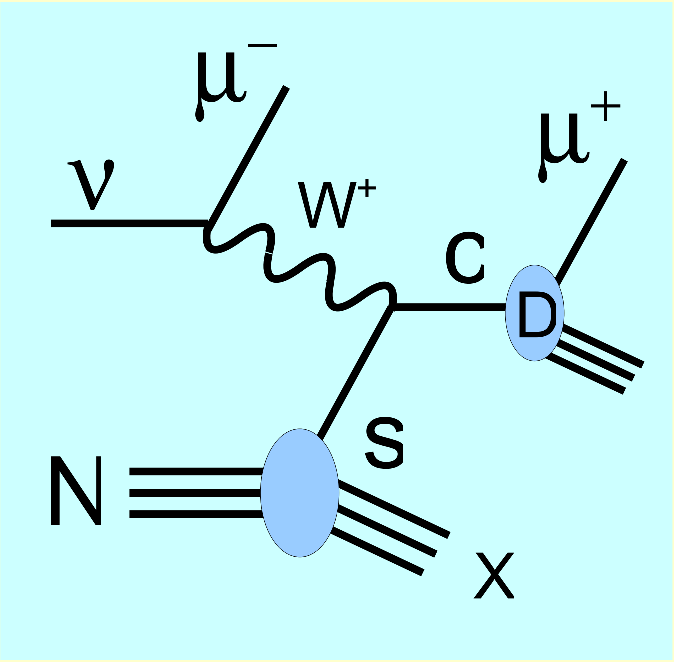
HERMES: DIS K± Production



HERMES Collaboration
Phys.Lett.B666:446-450,2008.

ν Fe provides best constraint on s(x)

Heavy Quarks & PDF's



Heavy Quarks: How do we deal with multiple scales???

Problem:

Heavy Quark introduces new scale: $\log\left(\frac{Q^2}{\mu^2}\right) \quad \log\left(\frac{M_H^2}{\mu^2}\right)$

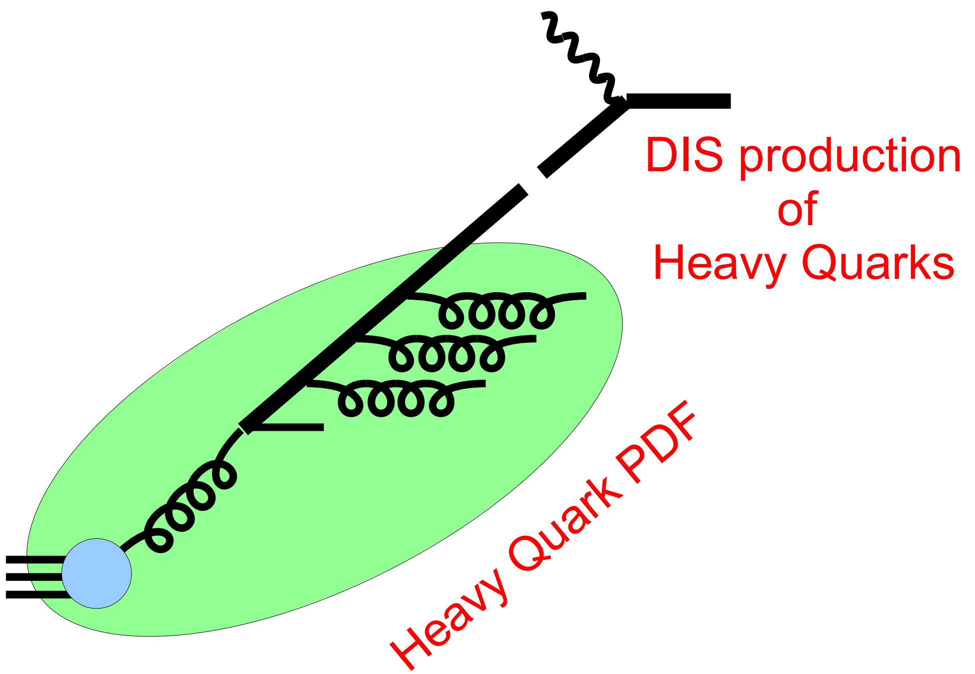
... life gets interesting.

Solution:

Resum *$Log(M_H)$* in the Heavy Quark PDF's:

...include charm and bottom in the PDFs

DGLAP equation
Resums iterative splittings
inside the proton



Result:

We can describe the full kinematic range from low to high

this is the essence of the ACOT renormalization scheme

ACOT, PRD 50, 3102

Effect of Kinematic Mass and Scaling

ACOT (Aivazis, Collins, Olness, Tung) A general framework for including the heavy quark components.

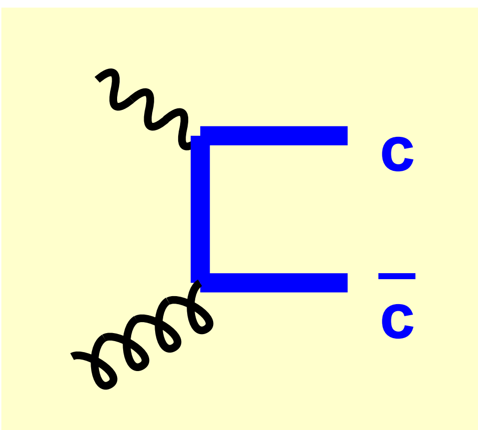
Phys.Rev.D50:3102-3118,1994.

S-ACOT (Simplified-ACOT) ACOT with the initial-state heavy quark masses set to zero.

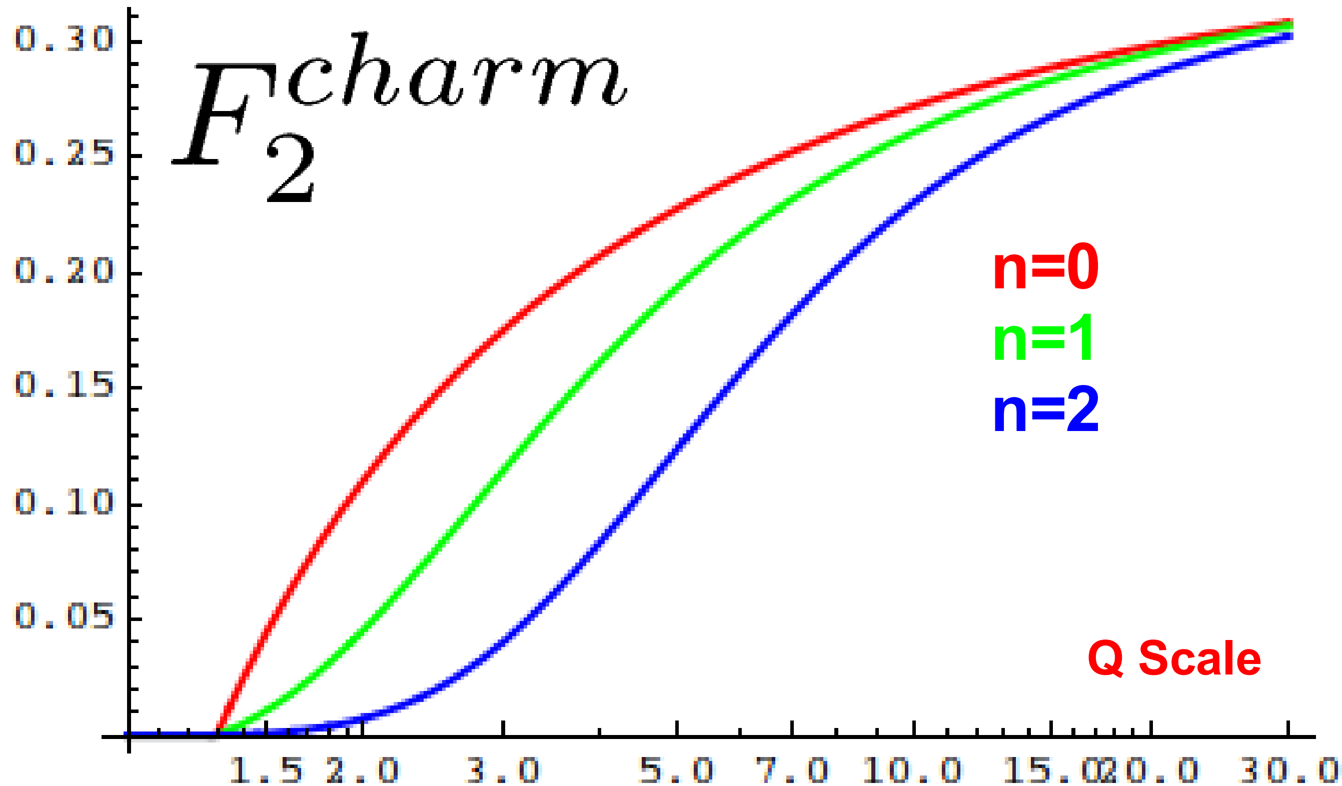
Phys.Rev.D62:096007,2000.

ACOT-χ & **S-ACOT-χ:** As above with a generalized slow-rescaling

Phys.Rev.D62:096007,2000.

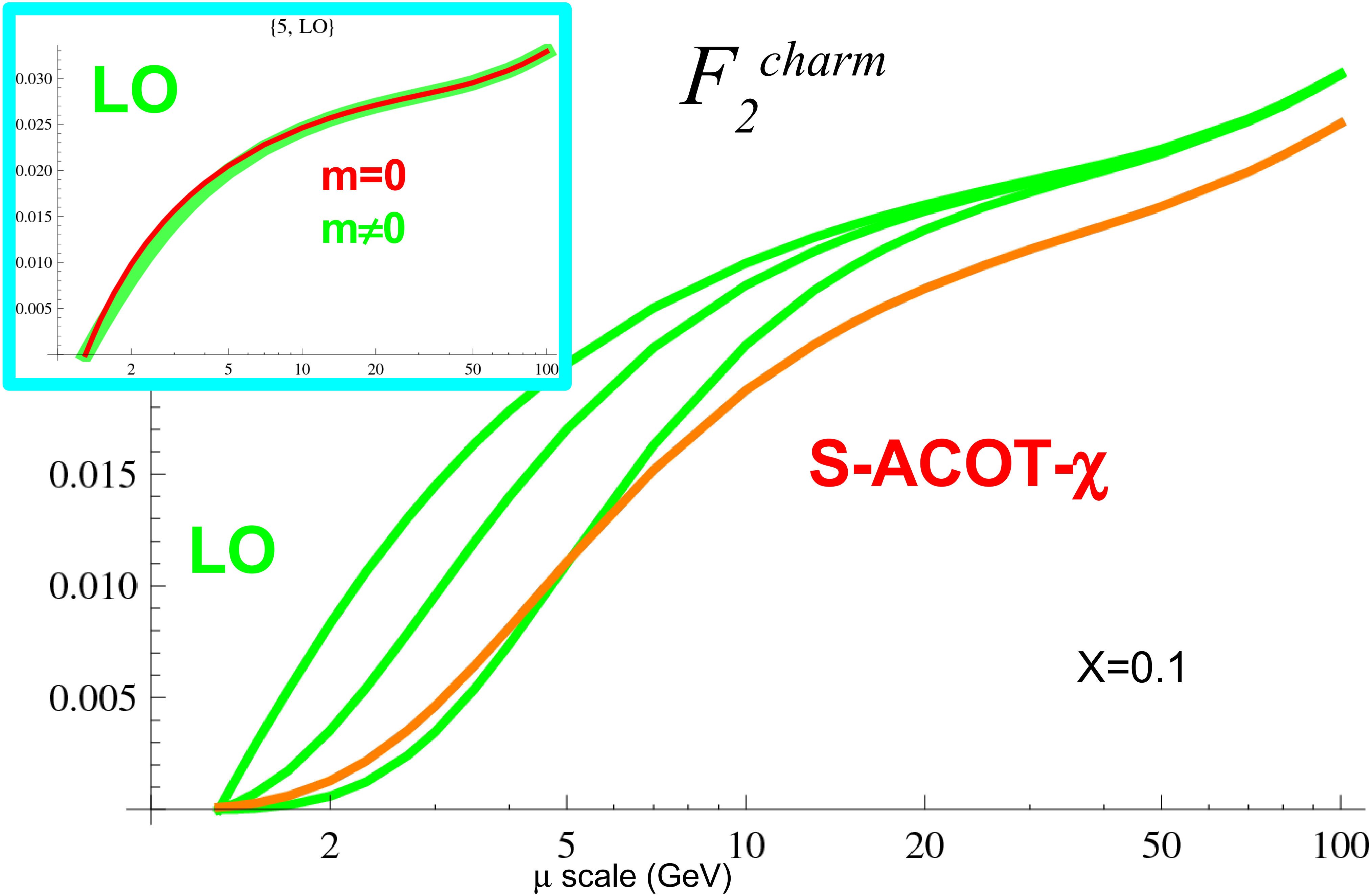


$$\chi = x\left[1+\frac{(\mathbf{n} m_c)^2}{Q^2}\right]$$



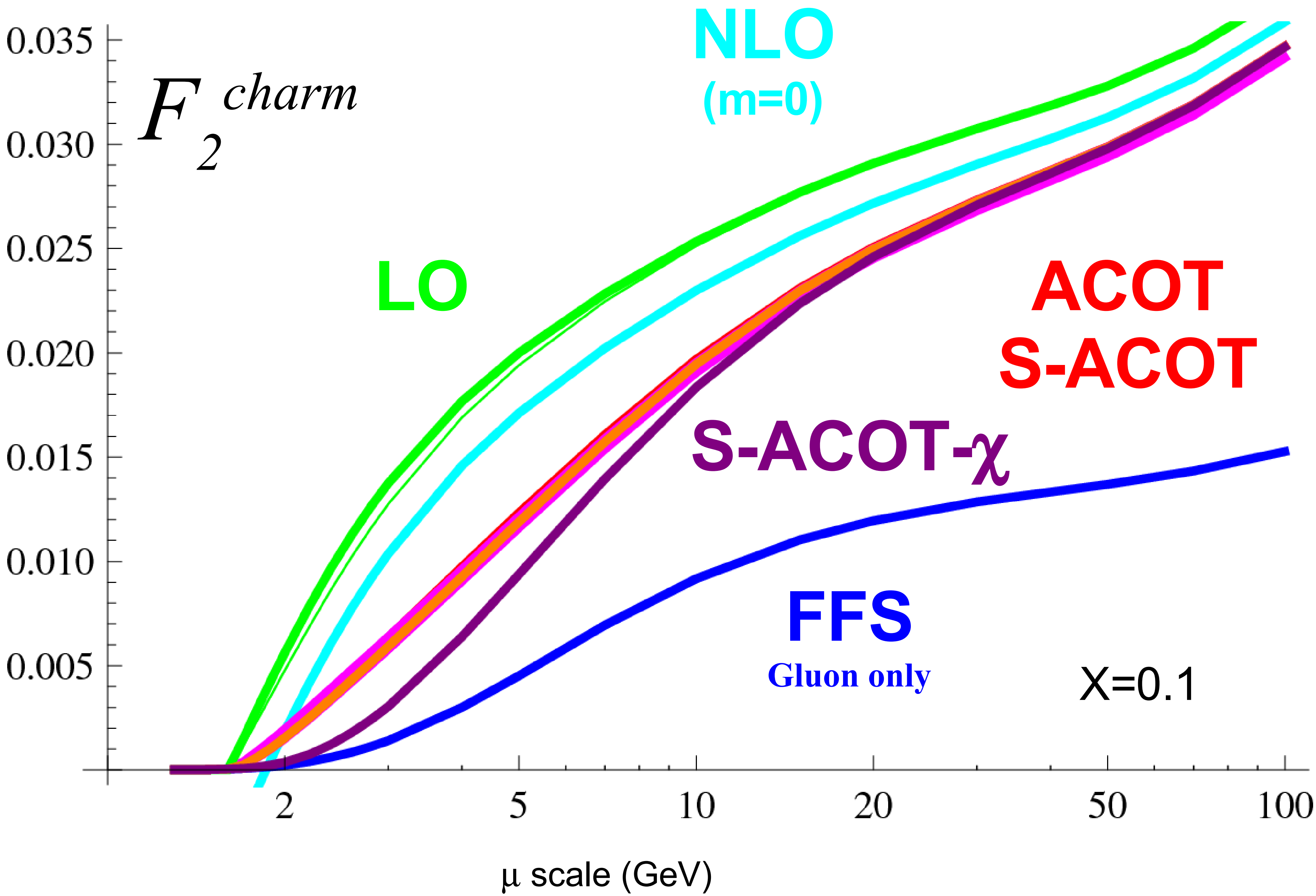
***Kinematic Masses are more important than Dynamical Masses** (in general)*

F_2 Charm in the threshold region



***Kinematic Masses are more important than Dynamical Masses** (in general)*

F_2 Charm in the threshold region



A man with one watch knows what time it is; a man with two is never sure.

Les Houches 2009

Comparative Studies

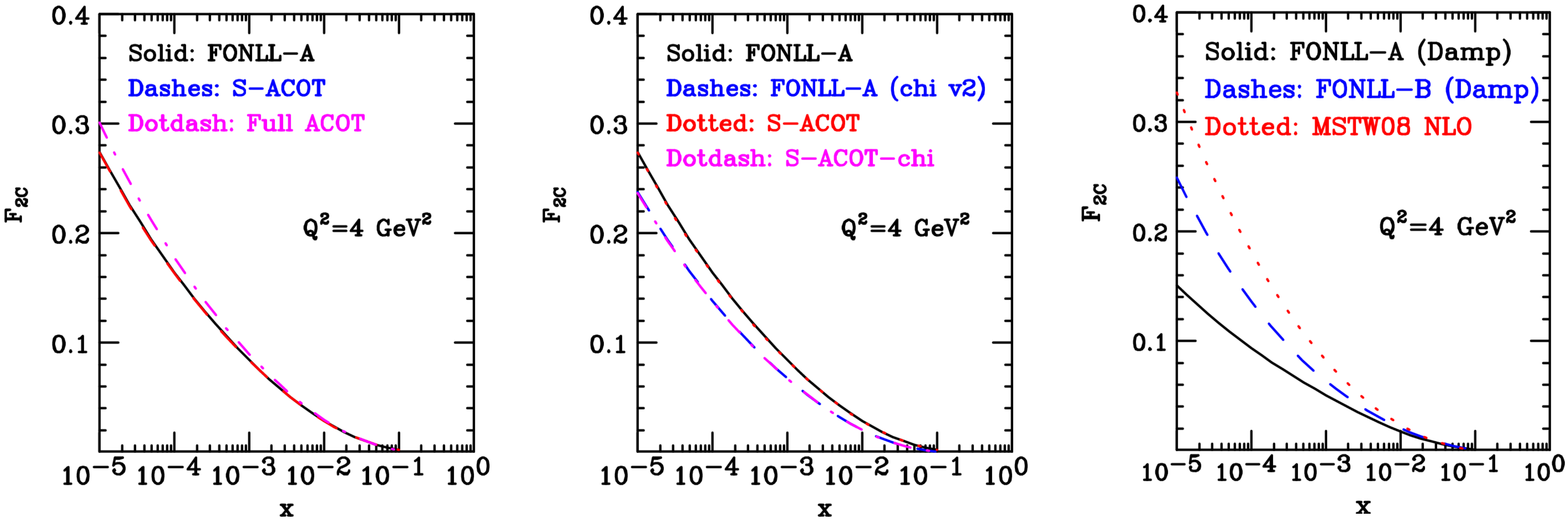
Physics at TeV Colliders

Les Houches 8-26 June 2009

LES HOUCHES

centre de physique

Les Houches Comparative Study



ACOT & S-ACOT essentially identical

... it's all in the kinematics

FONNL & S-ACOT essentially identical

chi(χ) prescription enforces threshold

MSTW09 uses different threshold definition

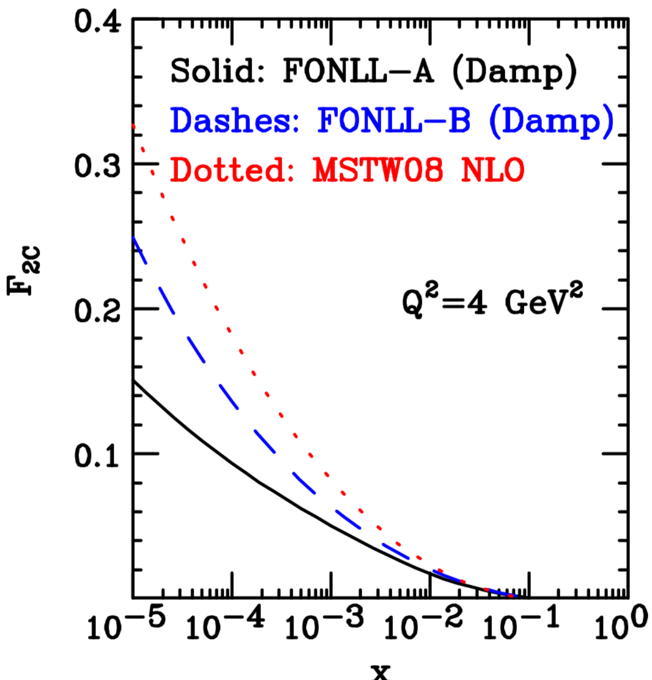
different scheme different intermediate result

Essential to match PDF with (hard) cross section in proper schemes!!!

		Consistent Schemes		Mixed Schemes	
Set	# pts	6HQ	6M	6M⊗GM	6HQ⊗ZM
ZEUS	104	0.91	0.98	2.84	3.72
H1	484	1.02	1.04	1.50	1.22
TOTAL	1925	1.04	1.06	1.26	1.30

χ^2/DOF

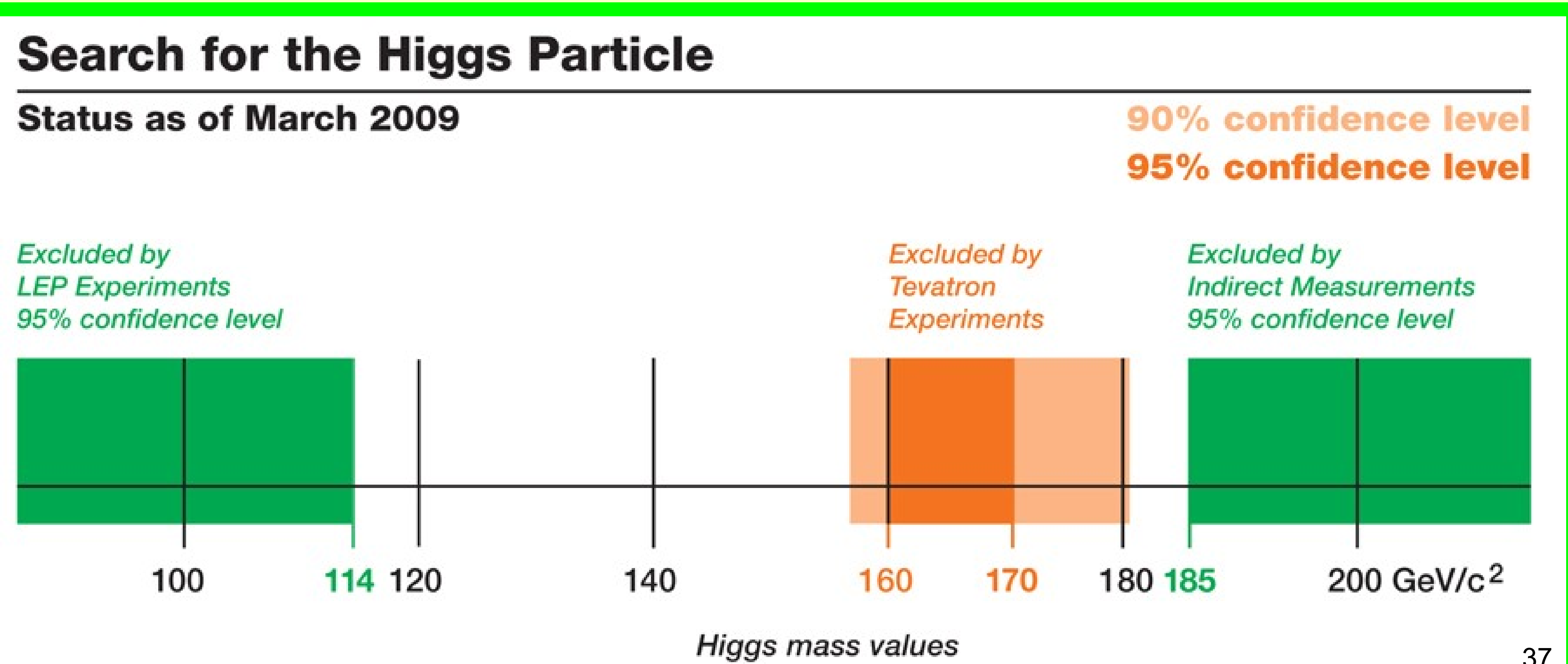
$\delta\chi^2 \approx 420$ $\delta\chi^2 \approx 500$



Just because the PDFs or (hard) cross sections do not match, for a consistent scheme, the physical observable should be invariant to $O(\alpha_s^{N+1})$

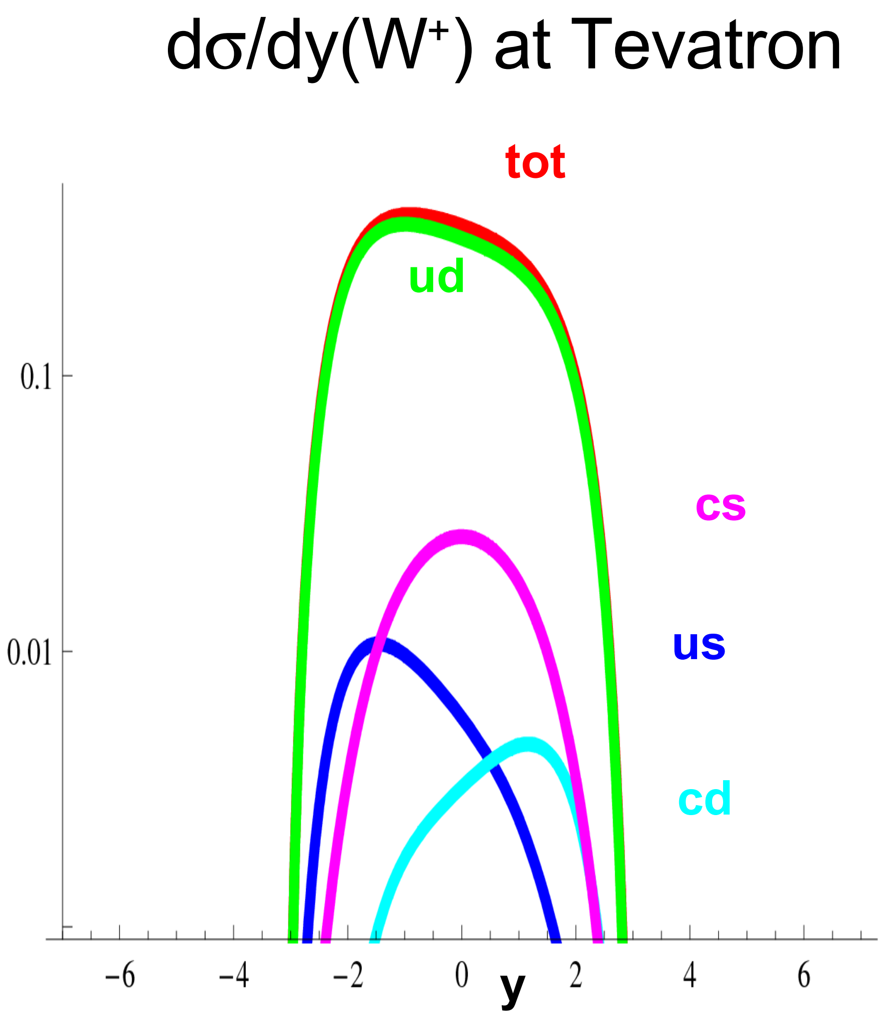
W/Z at LHC

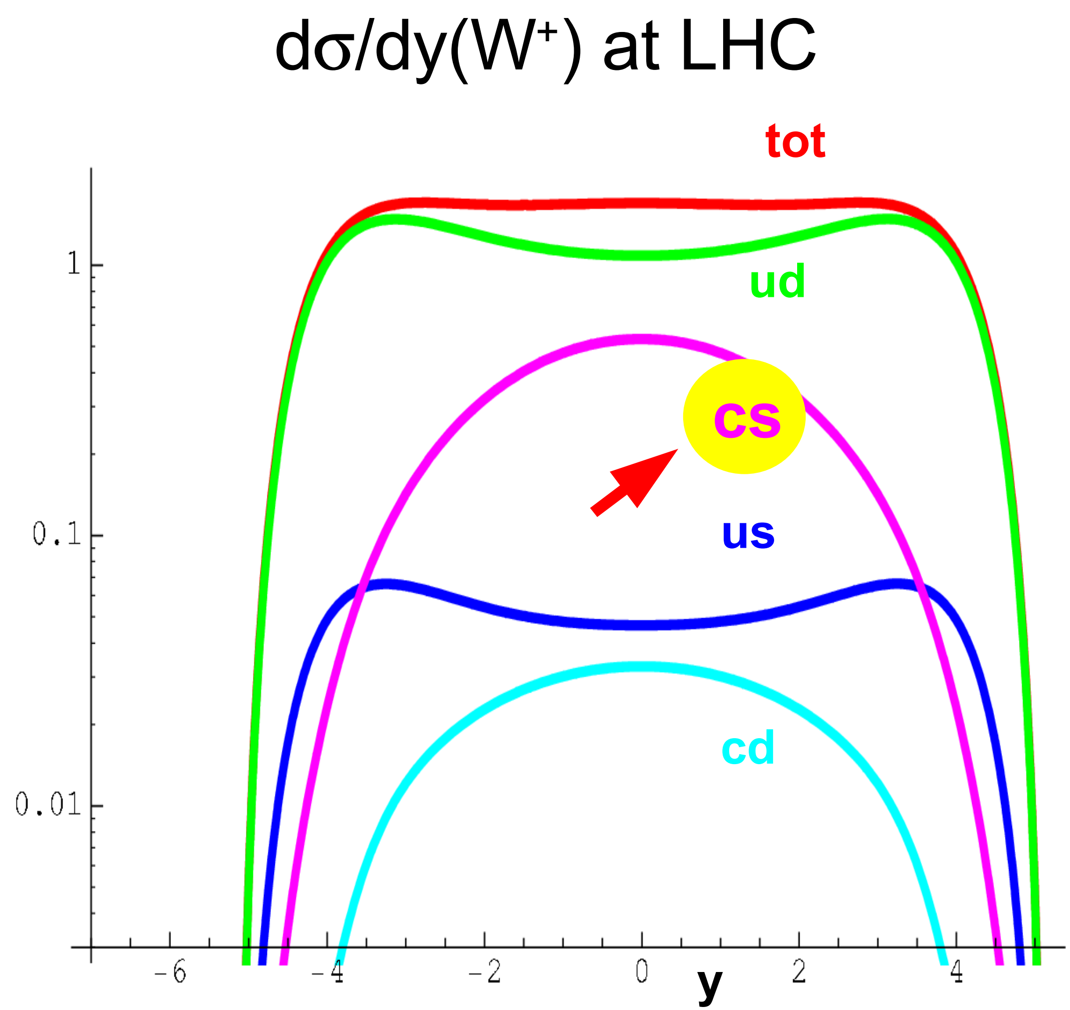
& the race for the Higgs



LHC started up in November 2009

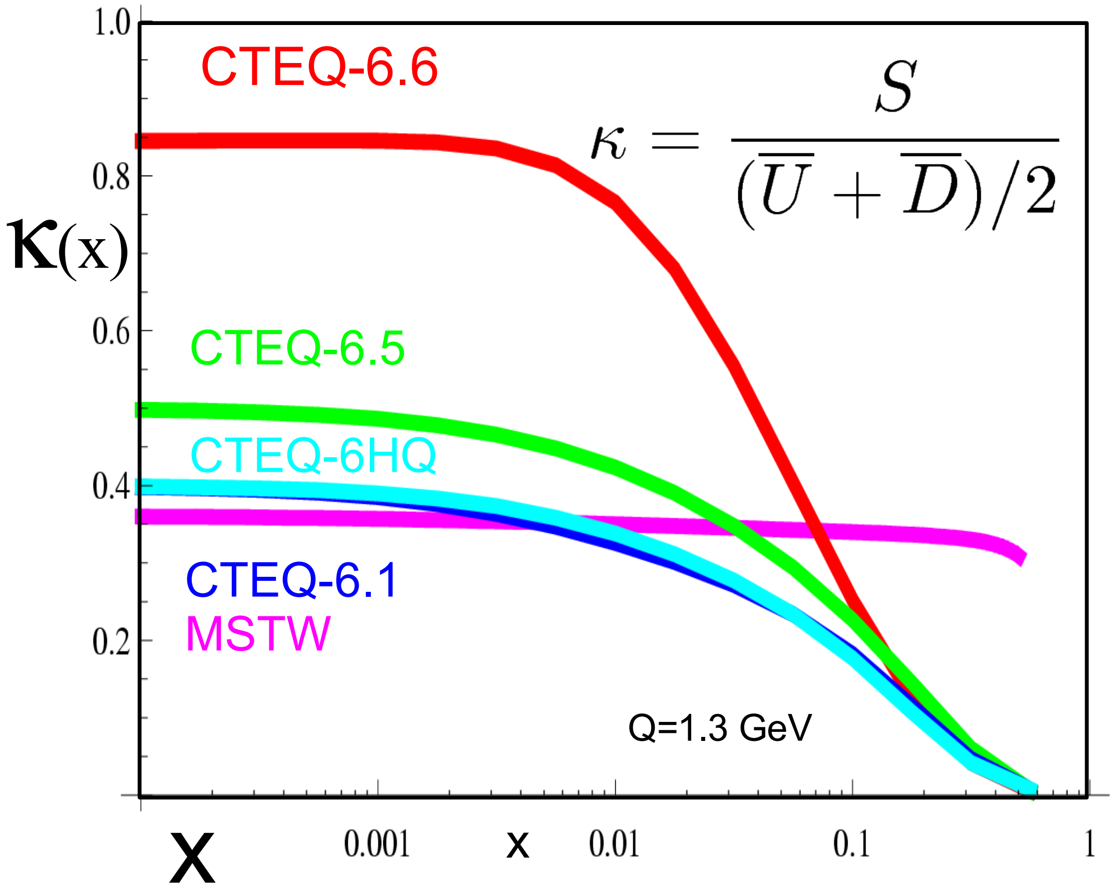
"Old" is "New" --- Re-discovering W & Z

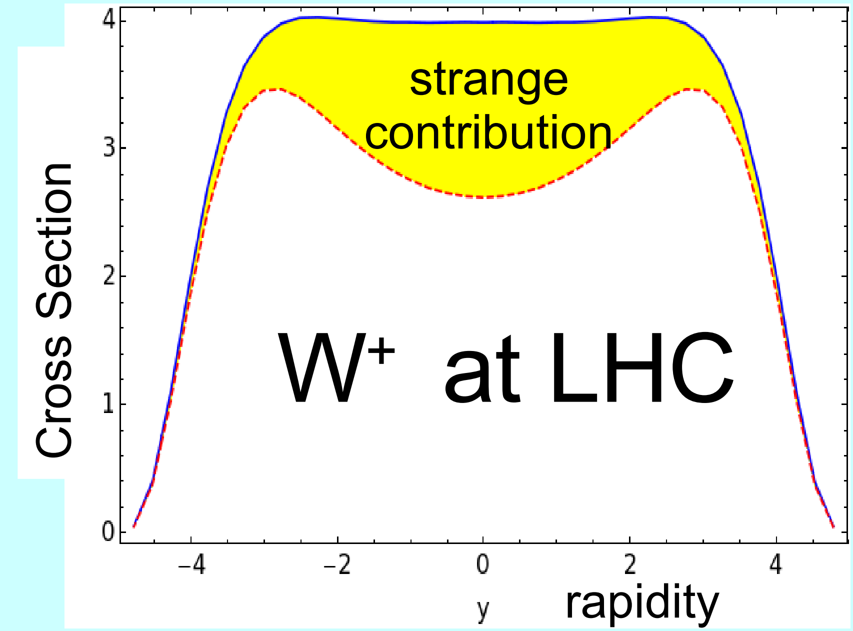


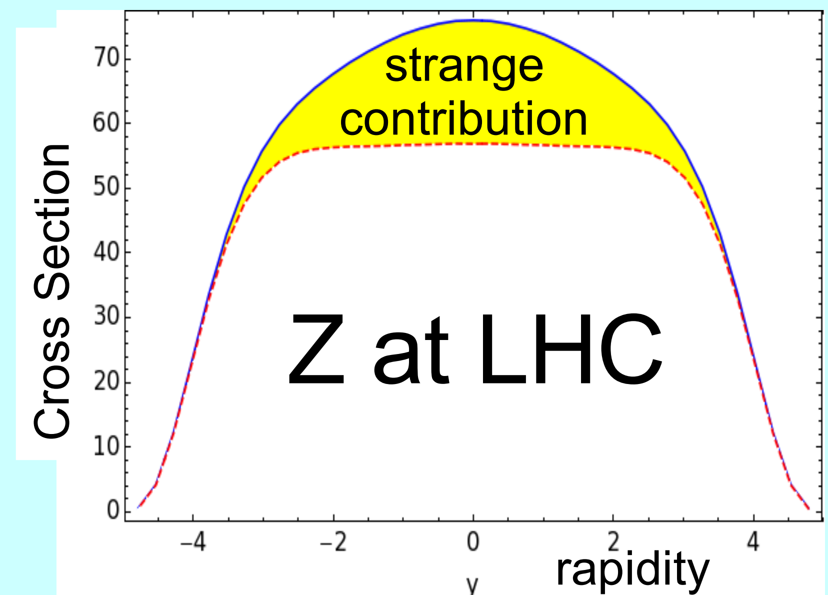


- Larger E $\Rightarrow$ probes PDFs to small x
- Larger Rapidity $\Rightarrow$ probes PDFs to really small x
- **Larger fraction of heavy quarks**

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







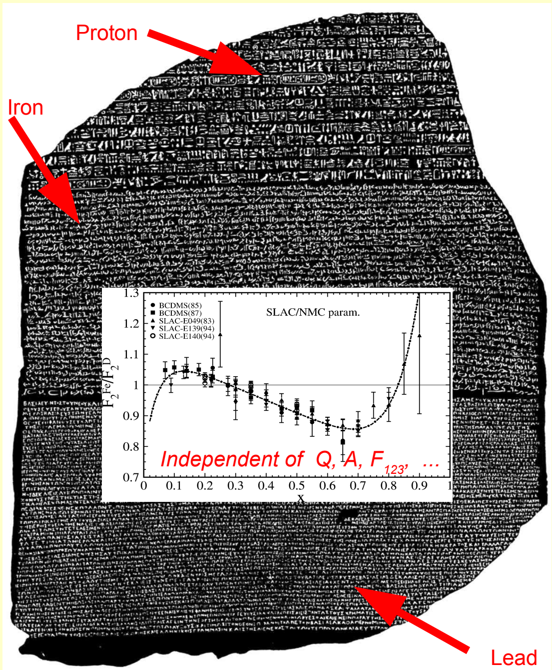
PDF Uncertainties will feed into LHC "Benchmark" processes

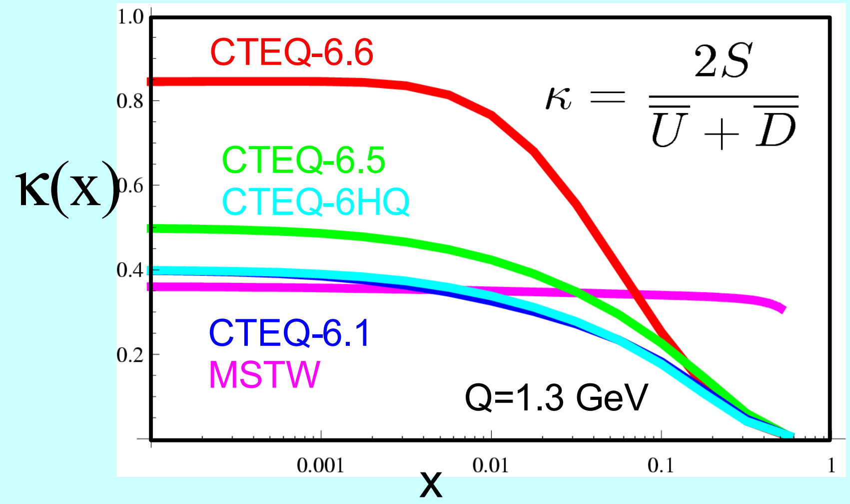
VRAP Code

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

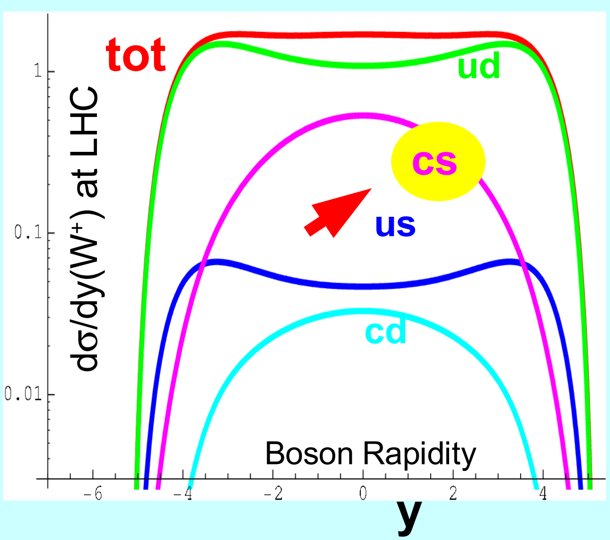
Conclusions

Implications of Nuclear PDF uncertainties

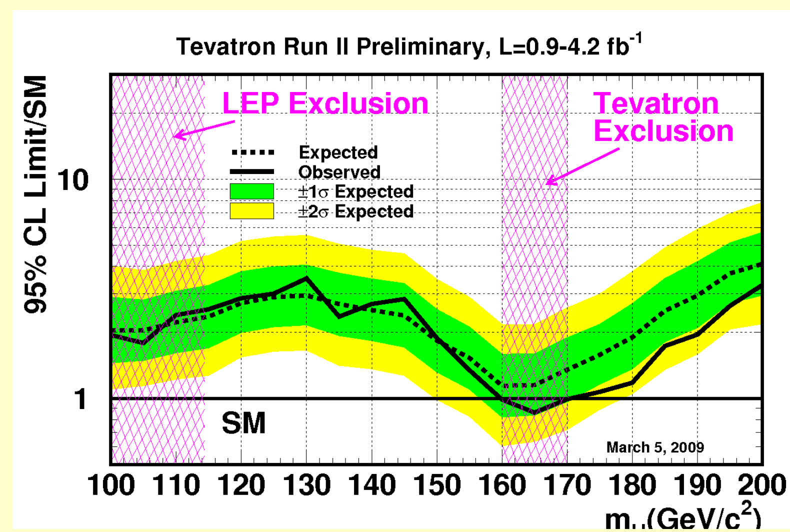




We're not sure how strange is the proton



Uncertainty in W/Z



Benchmark for Higgs

Conclusions

Nuclear Corrections: Important uncertainty of PDFs

At LHC, nuclear corrections play a prominent role: ⇒ *{s,c,b...},*

... key in W/Z production ⇒ Higgs Discovery

{Q,W} Cuts eliminate large region of data

Tensions between various data sets:

Historically, neutrino DIS and charged-lepton DIS

New global fitting program includes heavy target effects **DYNAMICALLY**

Nuclear corrections are not "carved in stone"

Incorporates proper errors and systematics

Extensible to all nuclear A values

Yields NLO nuclear PDFs: $f_i(x,Q,A)$

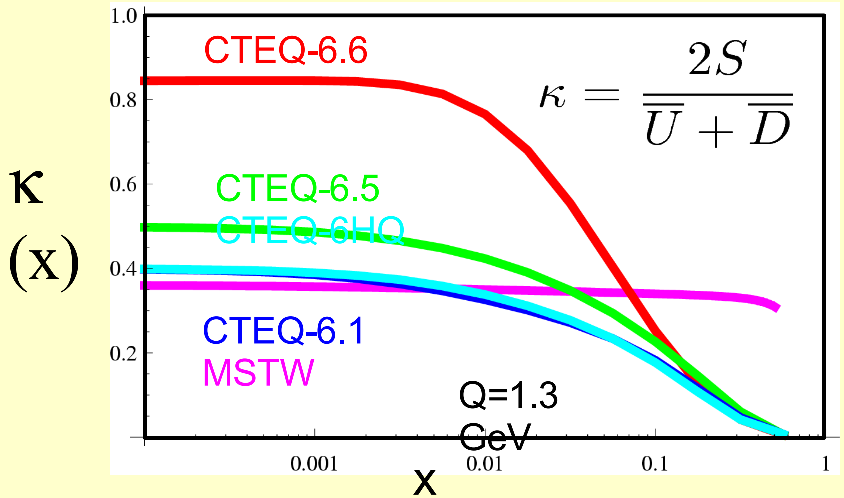
Room for future measurements & analysis

.

Important ingredient for standard CTEQ fits

Conclusions

How well do we know the Strange PDF???



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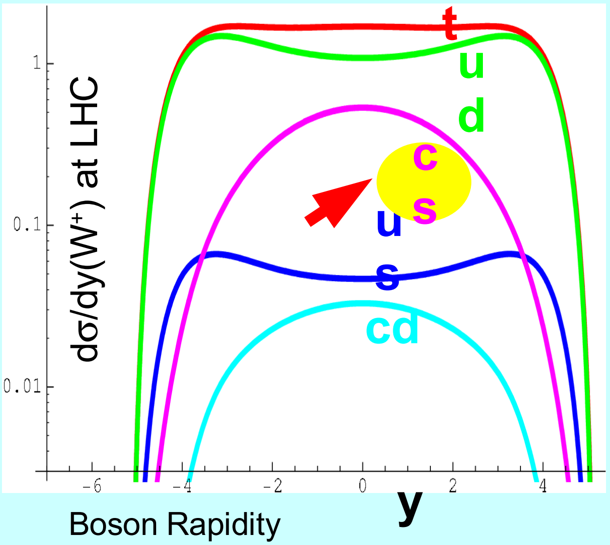
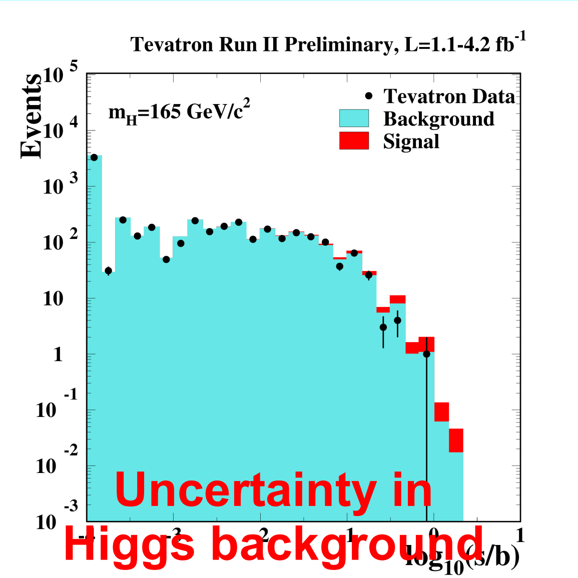
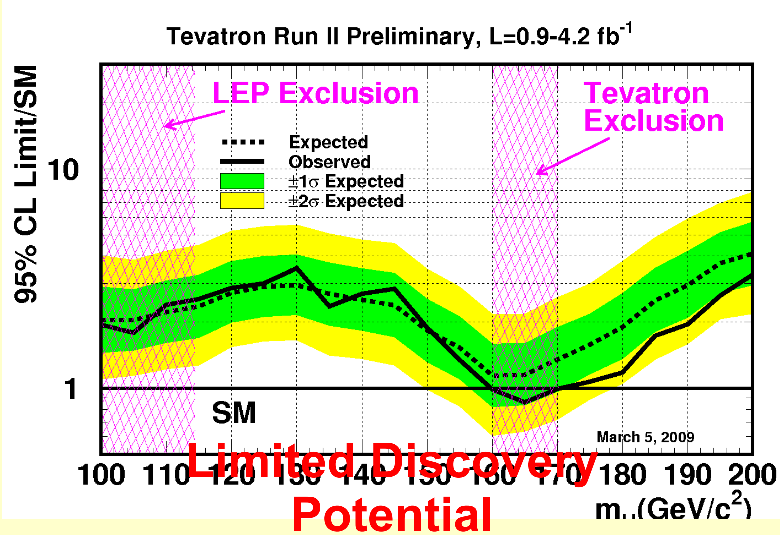


Uncertainty in W/Z

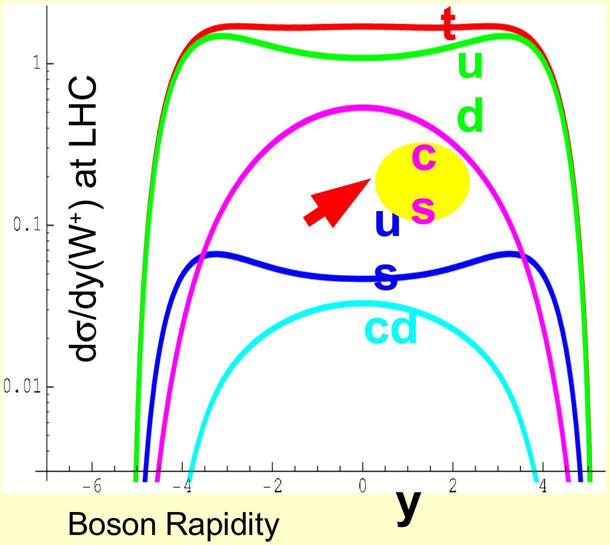


Uncertainty in Higgs background

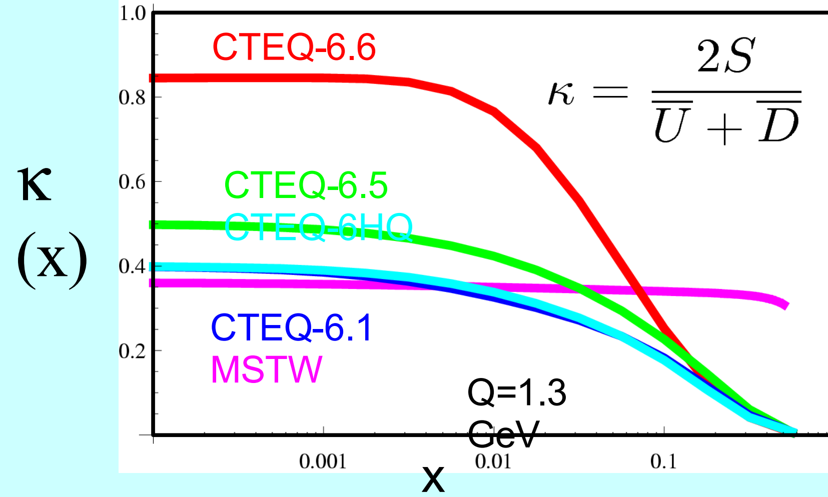


Limited Discovery Potential

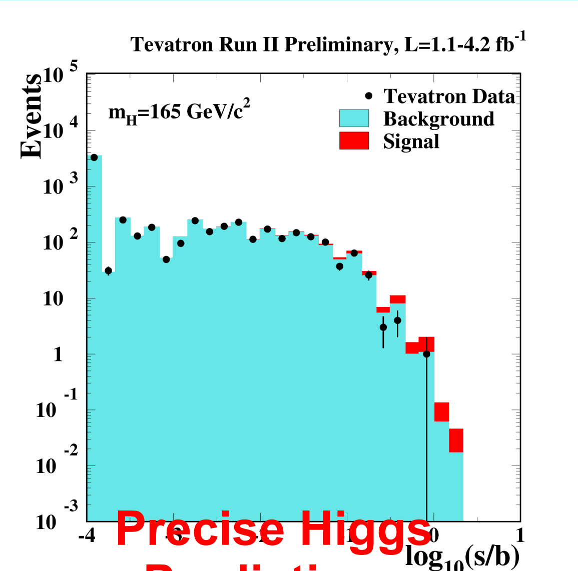
How do we get the most out of the LHC Data???



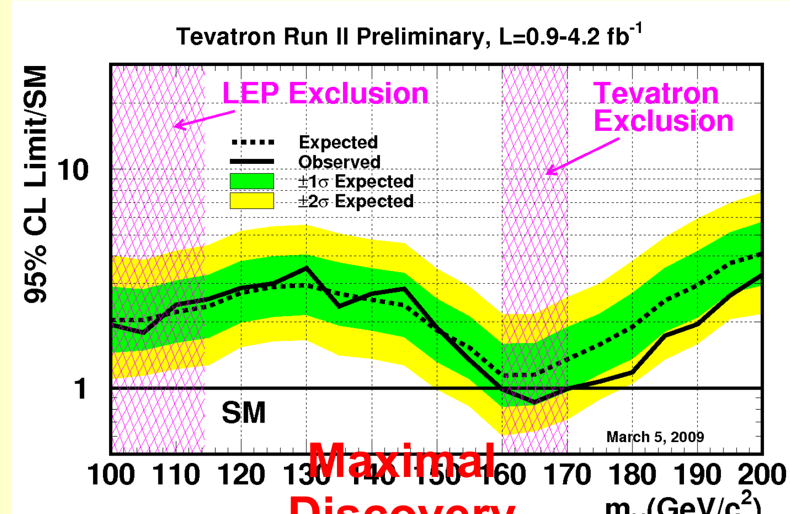
Use LHC data



Tune up PDFs and Benchmarks



Precise Higgs Predictions



Maximal Discovery Potential