Parton Distribution Functions

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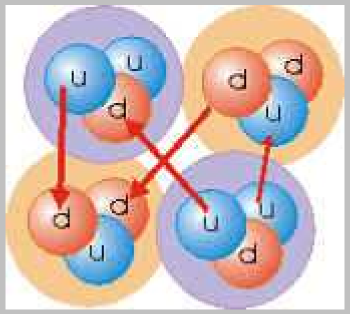
Outline

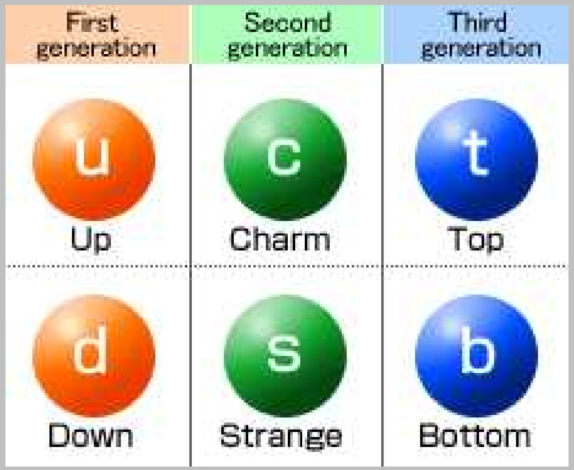
- QCD & Proton Structure
- Factorization
- Parton Distributions & Global Analysis
- Strange & Charm PDF
- nuclear PDFs

QCD in a Nutshell

Quantum Chromodynamics - The field theory of the strong interactions



The Actors: The quarks & gluons



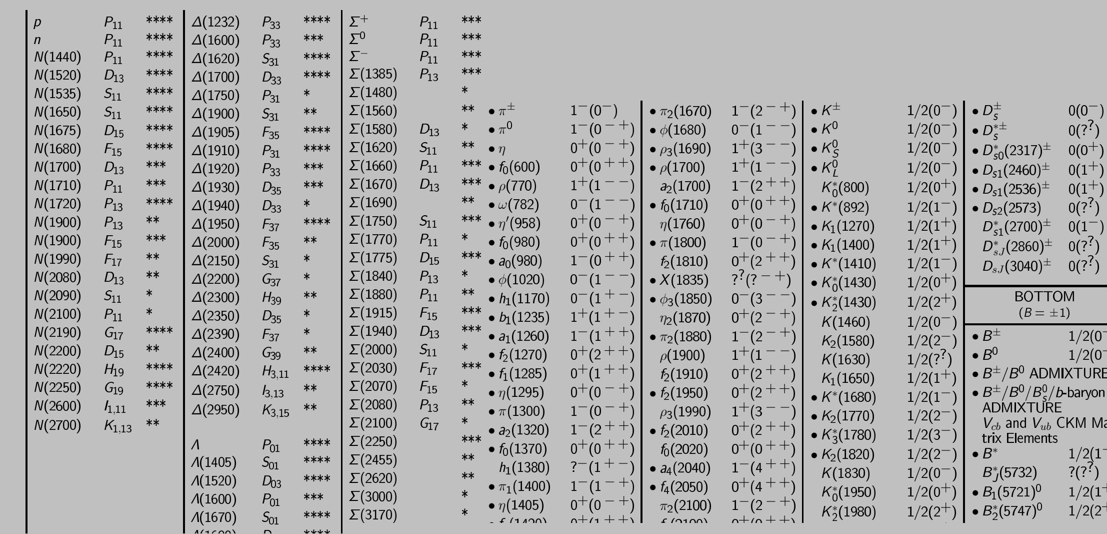
The Lagrangian:

$$\mathcal{L}_{QCD} = \bar{\psi}(\gamma^\mu D_\mu - m)\psi - \frac{1}{4}G_{\mu\nu}G^{\mu\nu}$$

The parameters:

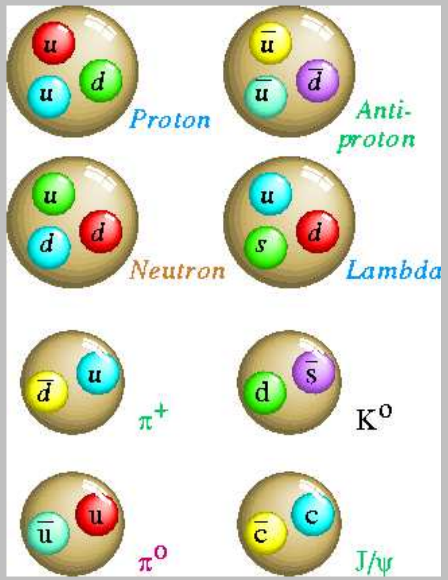
$$m_u, m_d, m_s, \Lambda, m_c, m_b, m_t, \Theta \ll 1$$

Proton Structure



The particle zoo-Too many hadrons discovered in ‘5o’s & 60’s to make sense of without further structure

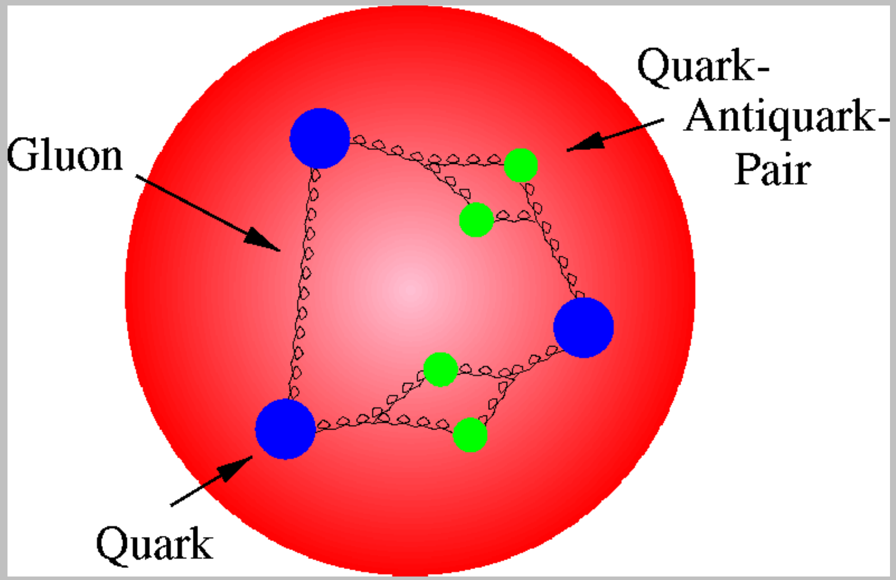
Hadrons -> composed of quarks



The valence quarks -> charge

$$e_{up} = \frac{2}{3} \;\&\; e_{down} = -\frac{1}{3}$$
$$e_{proton} = 2 \times \frac{2}{3} - \frac{1}{3} = +1$$
$$e_{neutron} = \frac{2}{3} - 2 \times \frac{1}{3} = 0$$

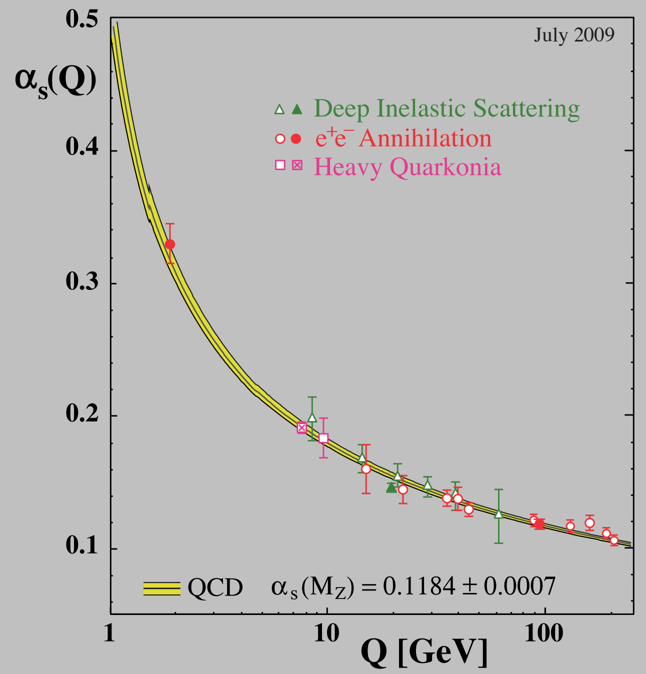
QFT: gluons keep quarks together
The gluons in turn can split in pairs of quarks - sea quarks



QCD in a Nutshell

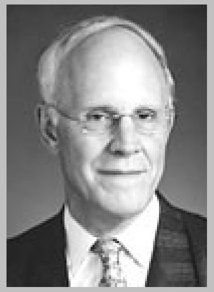
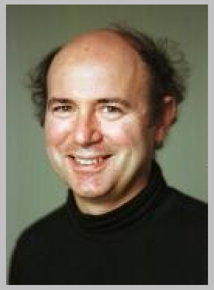
The running coupling constant

$$\alpha_s(\mu) = \frac{4\pi}{\beta_0 \ln(\mu^2/\Lambda^2)}$$

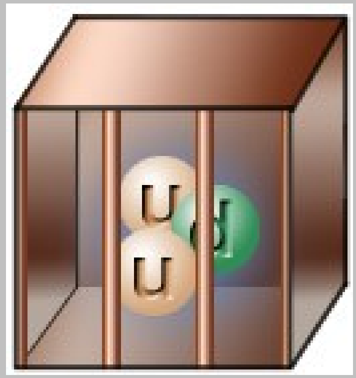


Asymptotic Freedom:
At high energies coupling constant -> small

Nobel Prize 2004: Gross Wilczek Politzer


Confinement:
No free quarks & gluons in nature



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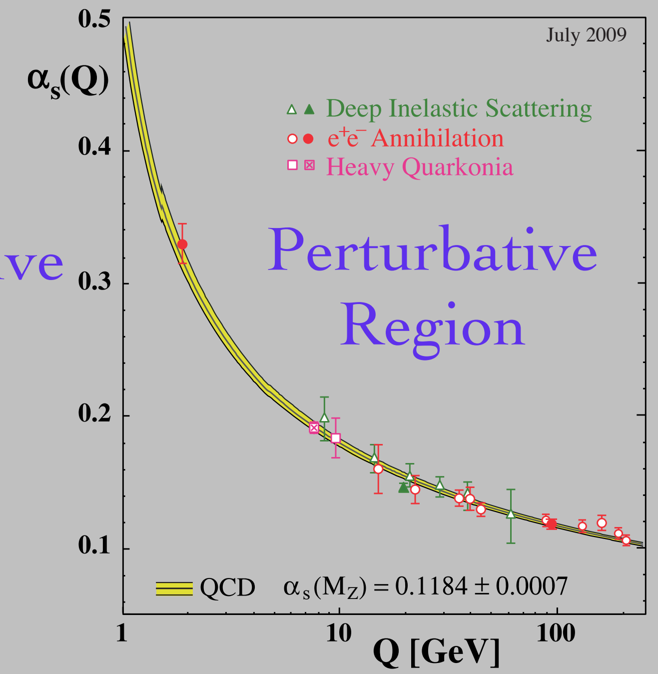
non Perturbative Region



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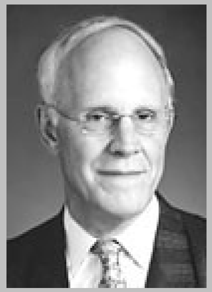

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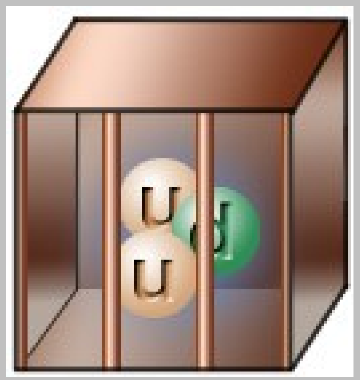
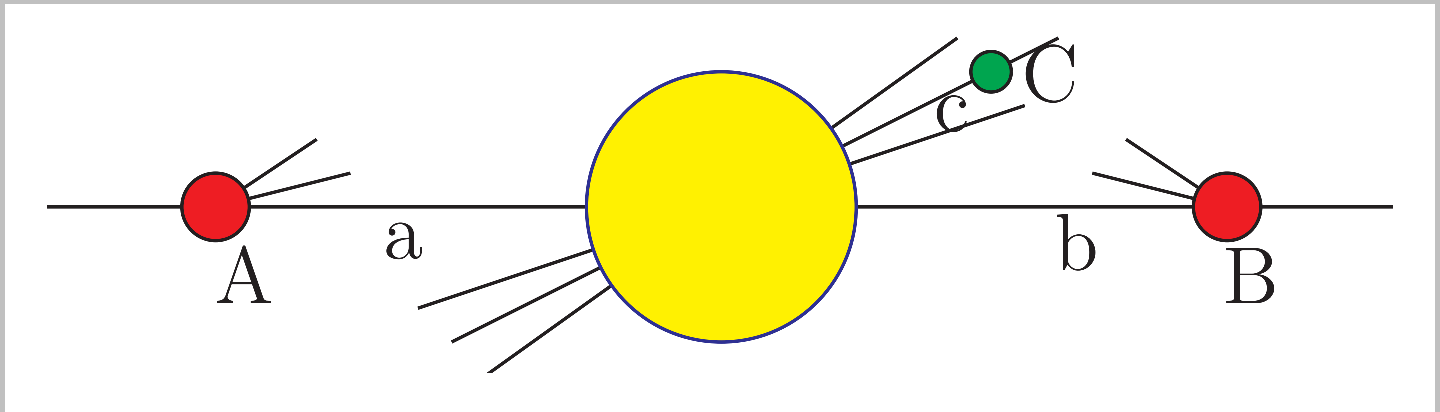


Factorization

From Theory to Measurement

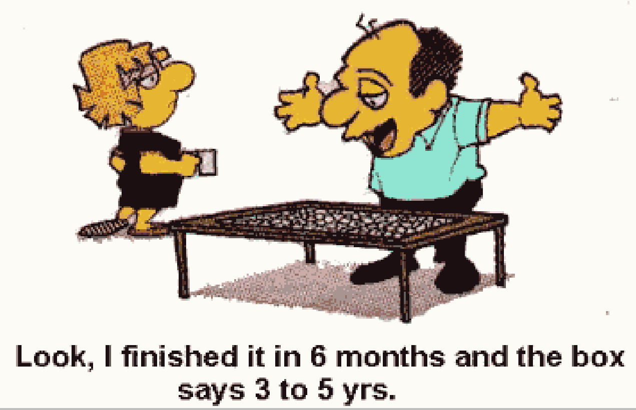


$$\sigma_{AB\to C} = PDF_{a/A} \otimes PDF_{b/B} \otimes \hat{\sigma}_{ab\to c} \otimes FF_{C/c}$$

The partonic cross-section:

- Calculable in perturbation theory (very time consuming!)
- Depends on the process

$$\hat{\sigma} = \sum_{n=0}^{\infty} \alpha_s^{n+1} \hat{\sigma}^{(n)}$$



The PDFs & FFs:

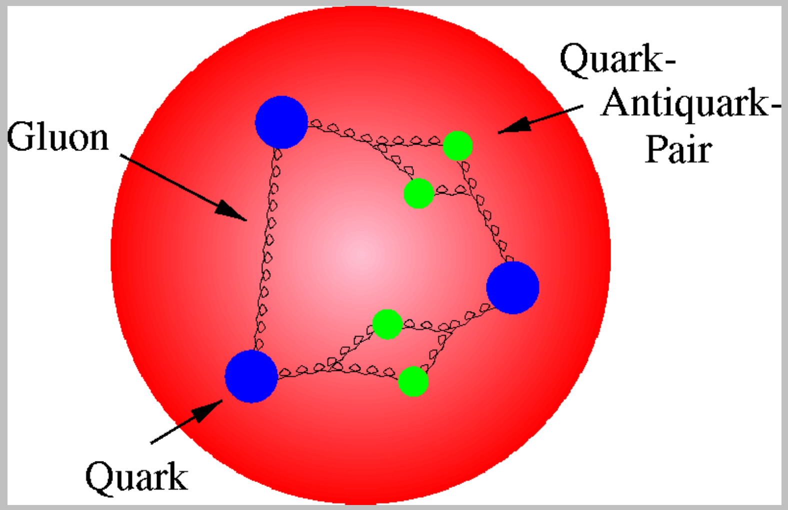
- NOT calculable via PT -> extracted via Global Fits
- Universal

PDFs

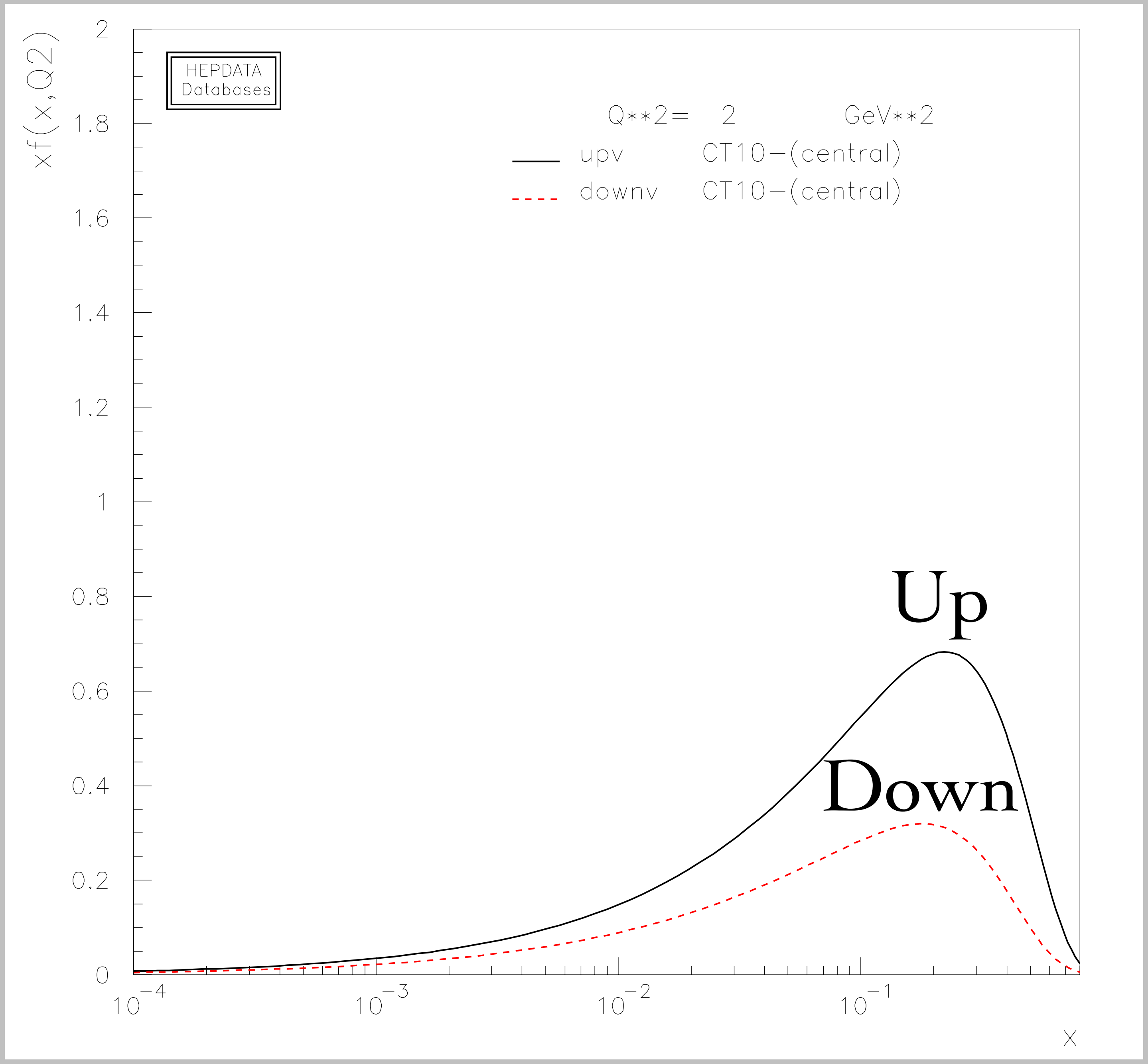
The PDFs provide the distributions of the partons in the proton

- x-dependence: $$x = \frac{p_z}{P_z}$$
  - fraction of proton's momentum carried by parton
  - (so far) not computable from first principles
- Q-dependence:
  - Q is the so-called factorization scale
  - Q dependence governed by RGE's (DGLAP evolution equations)

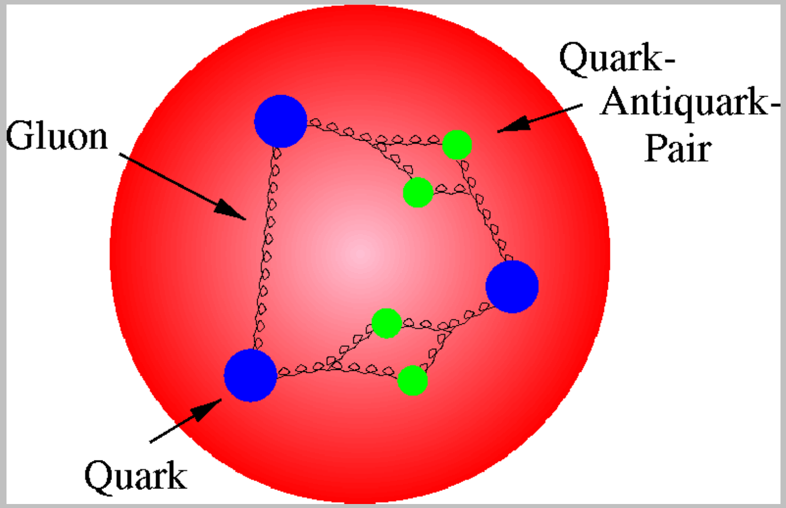
Parton Distributions



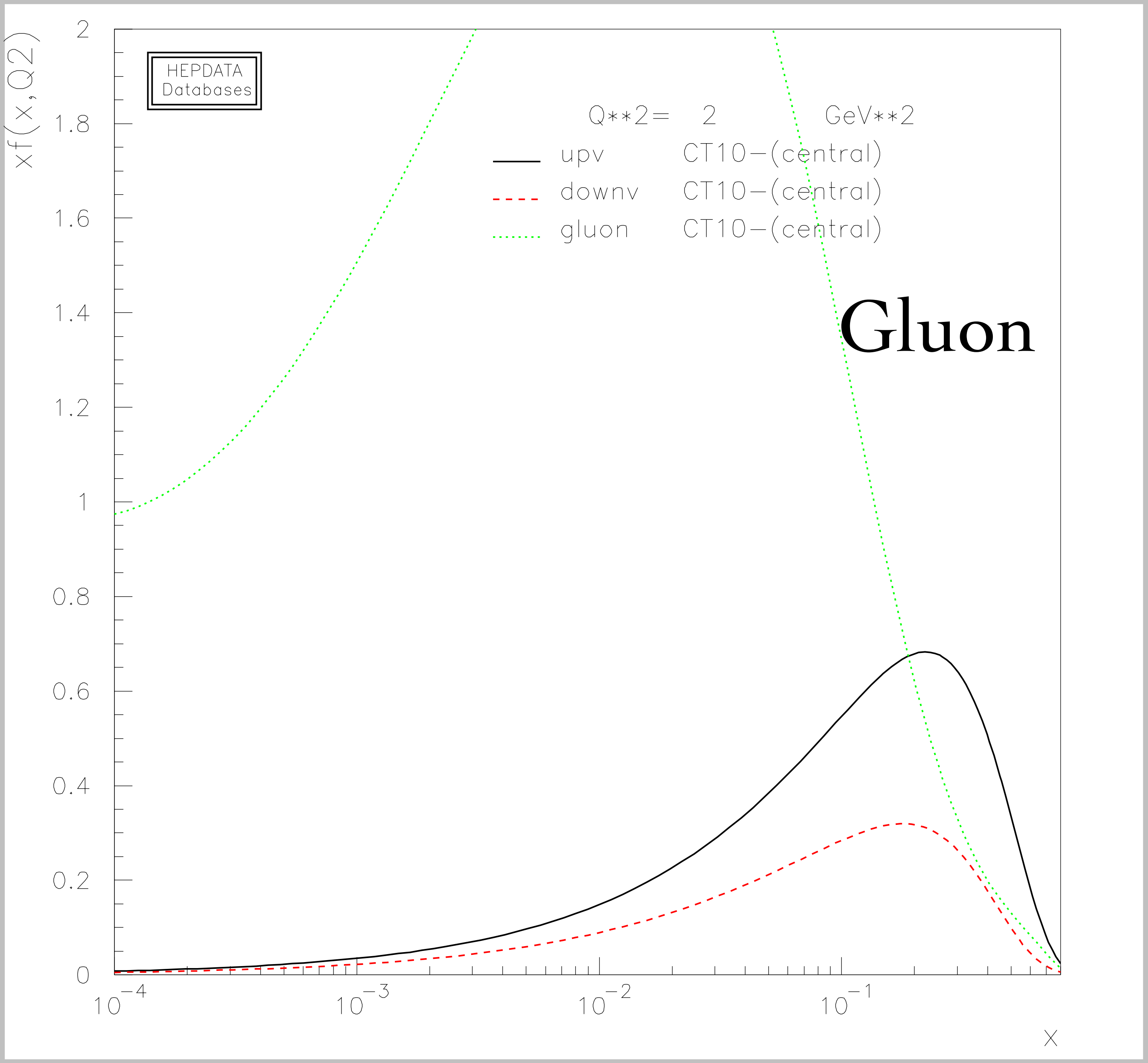
- Valence quarks
  p=|uud>



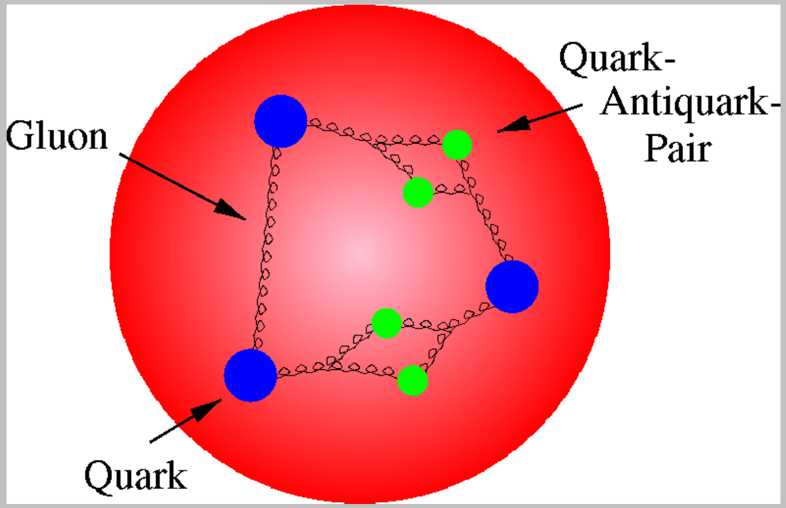
Parton Distributions



- **Gluons**
  carry about 40%
  of the momentum!



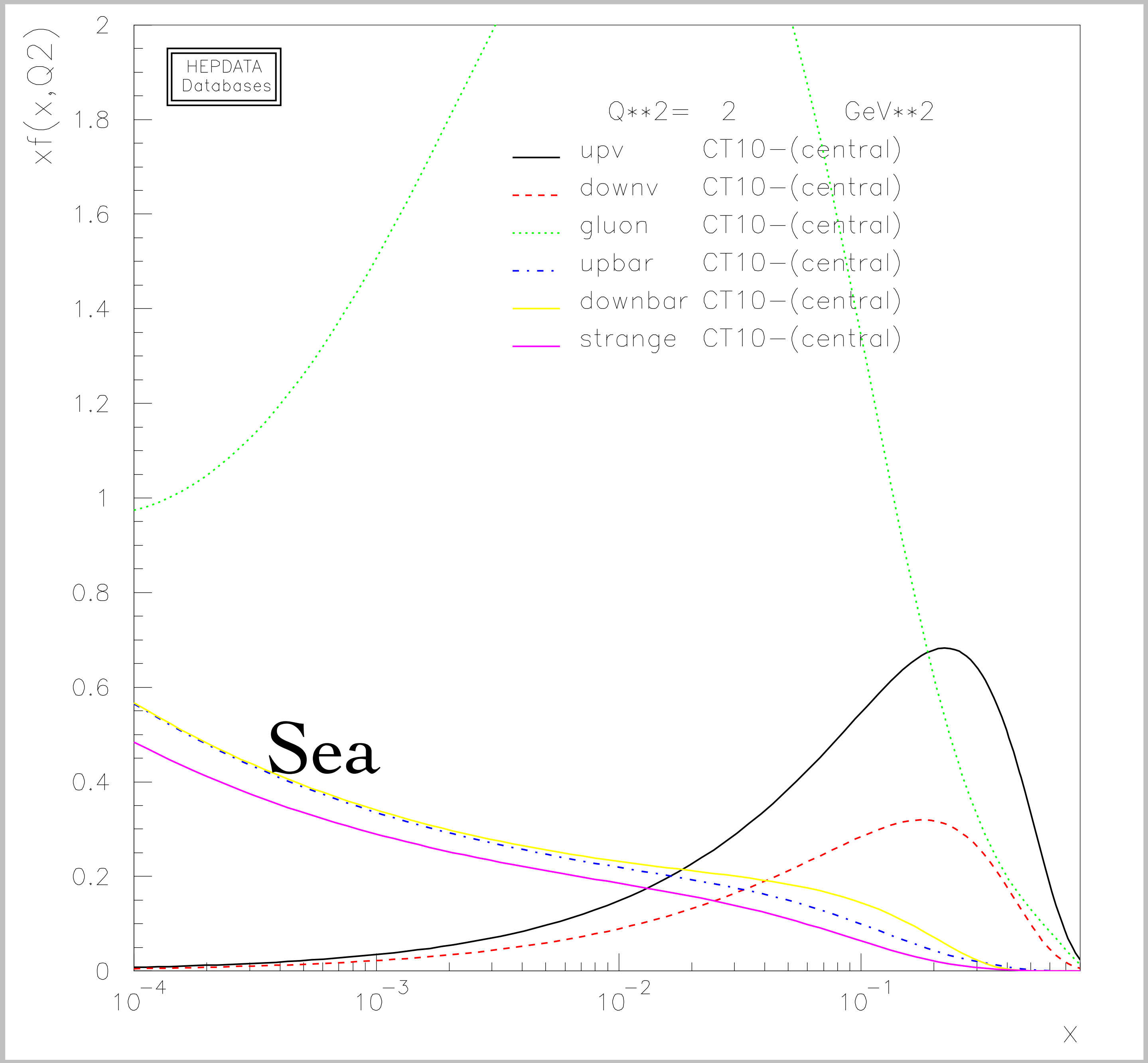
Parton Distributions



- **Sea quarks**

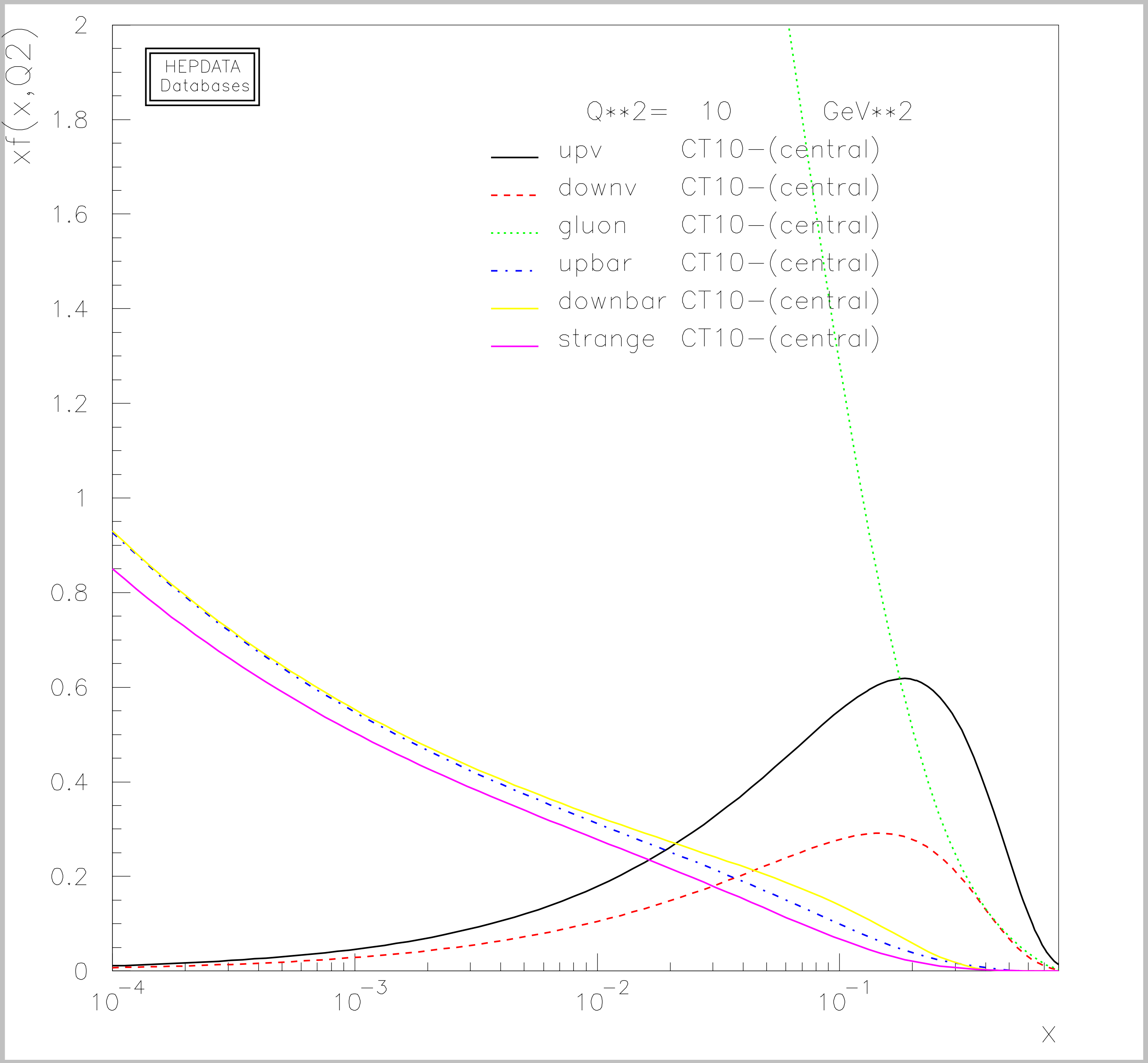
  light quark sea,

  strange quark sea



Q² dependence

- RGE's (DGLAP)
- integro-differential equations
- known to NNLO



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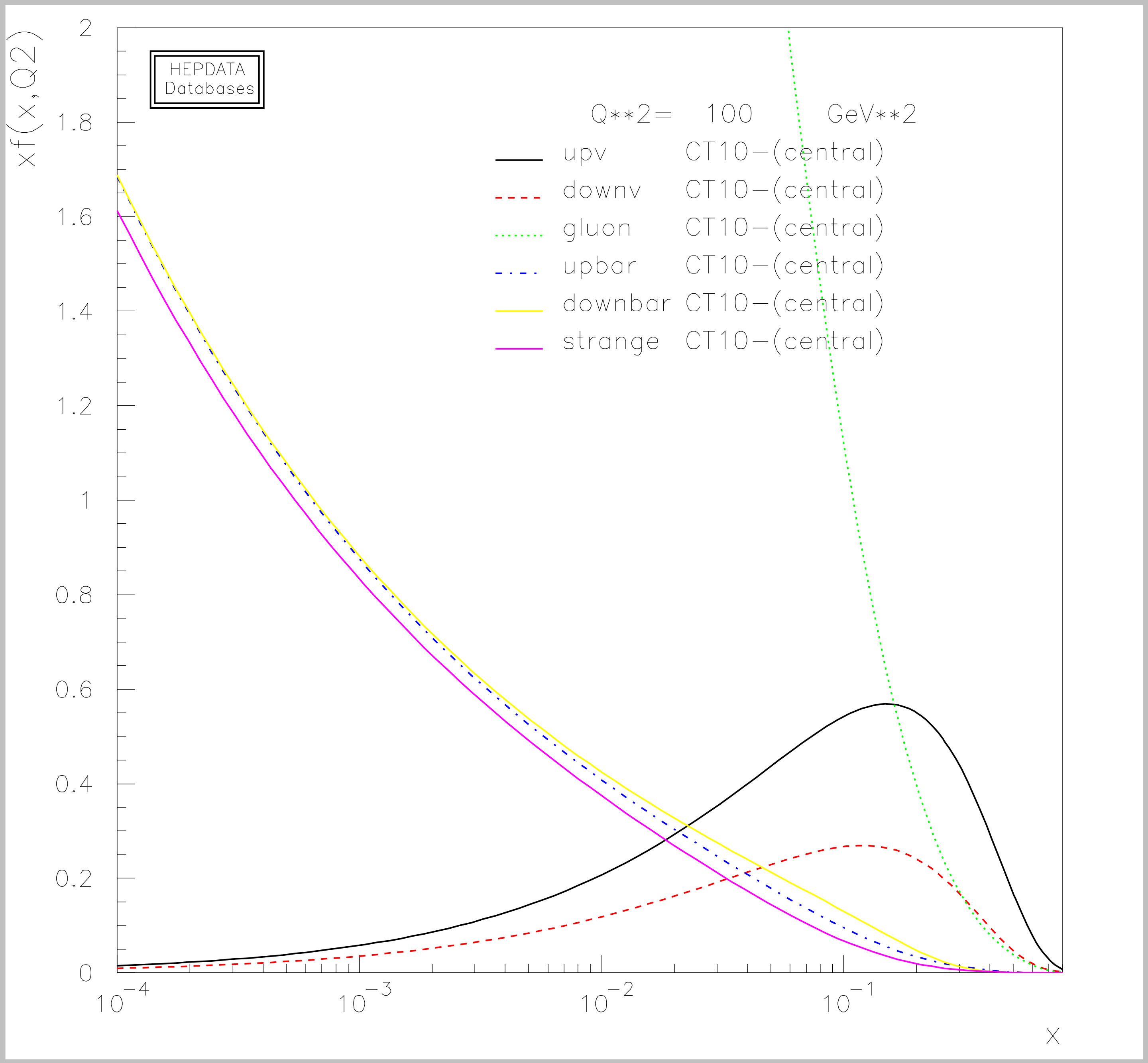

Q^2 dependence

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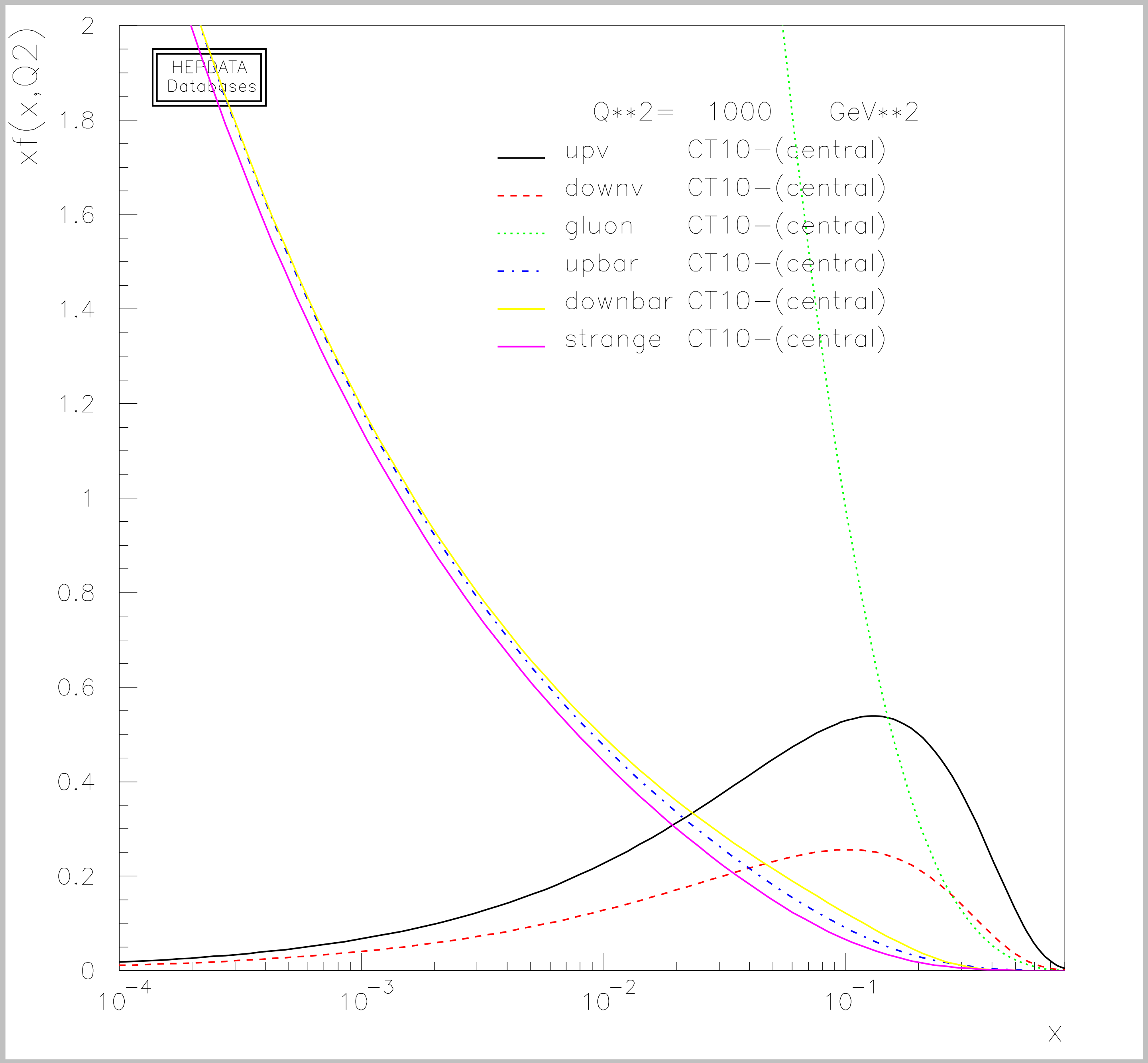

Q^2 dependence

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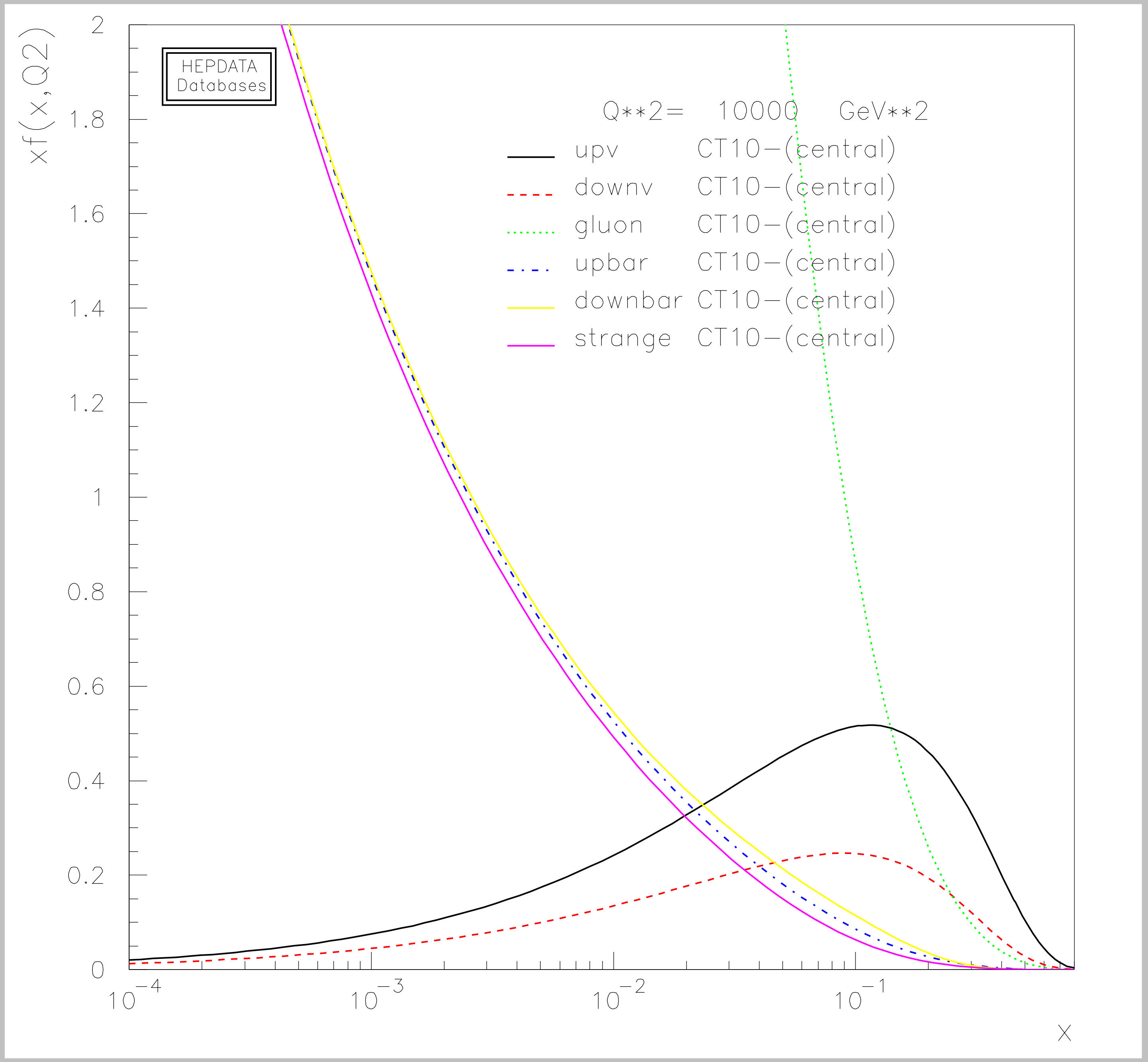
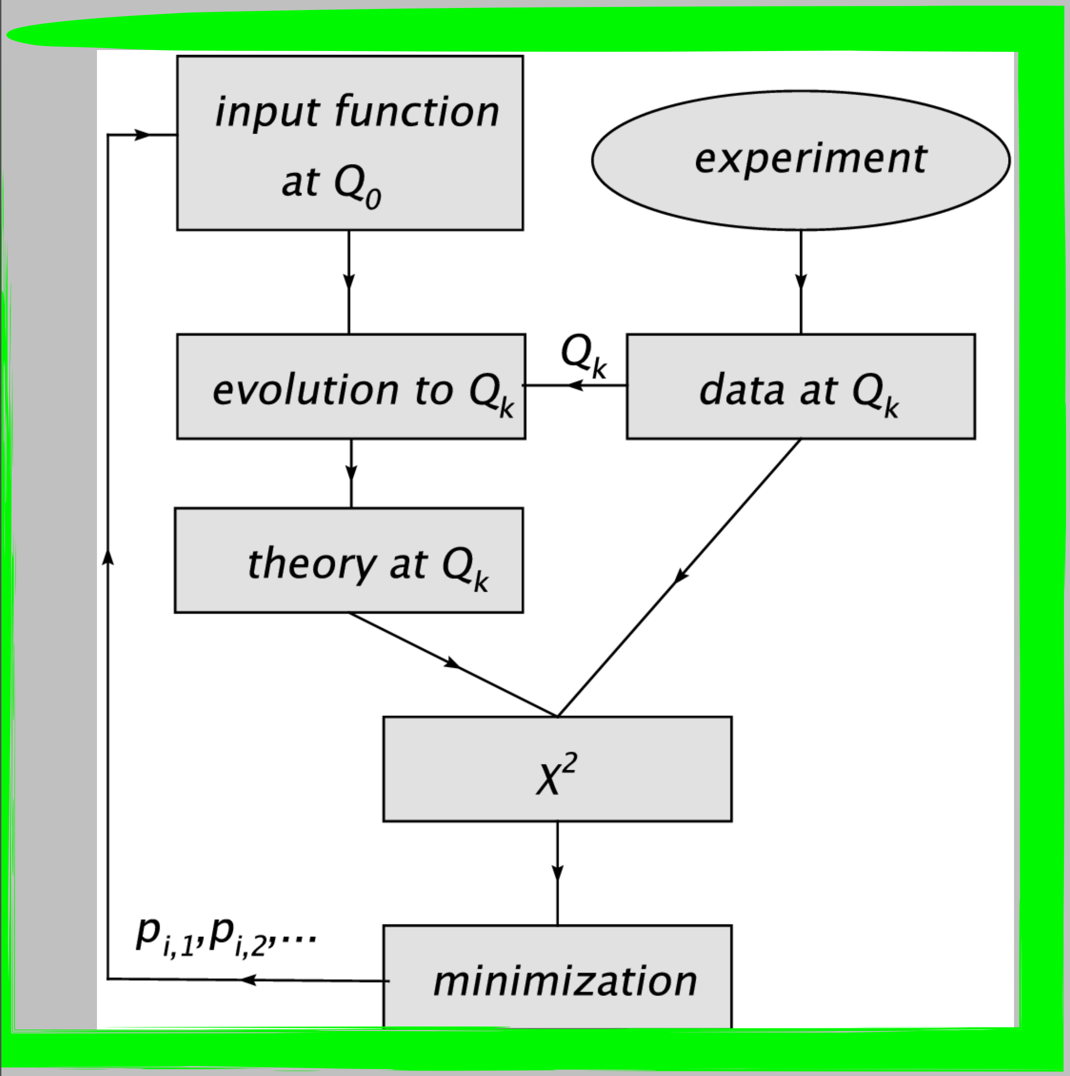


Global Analysis of PDFs

- So how does one obtain the PDFs?



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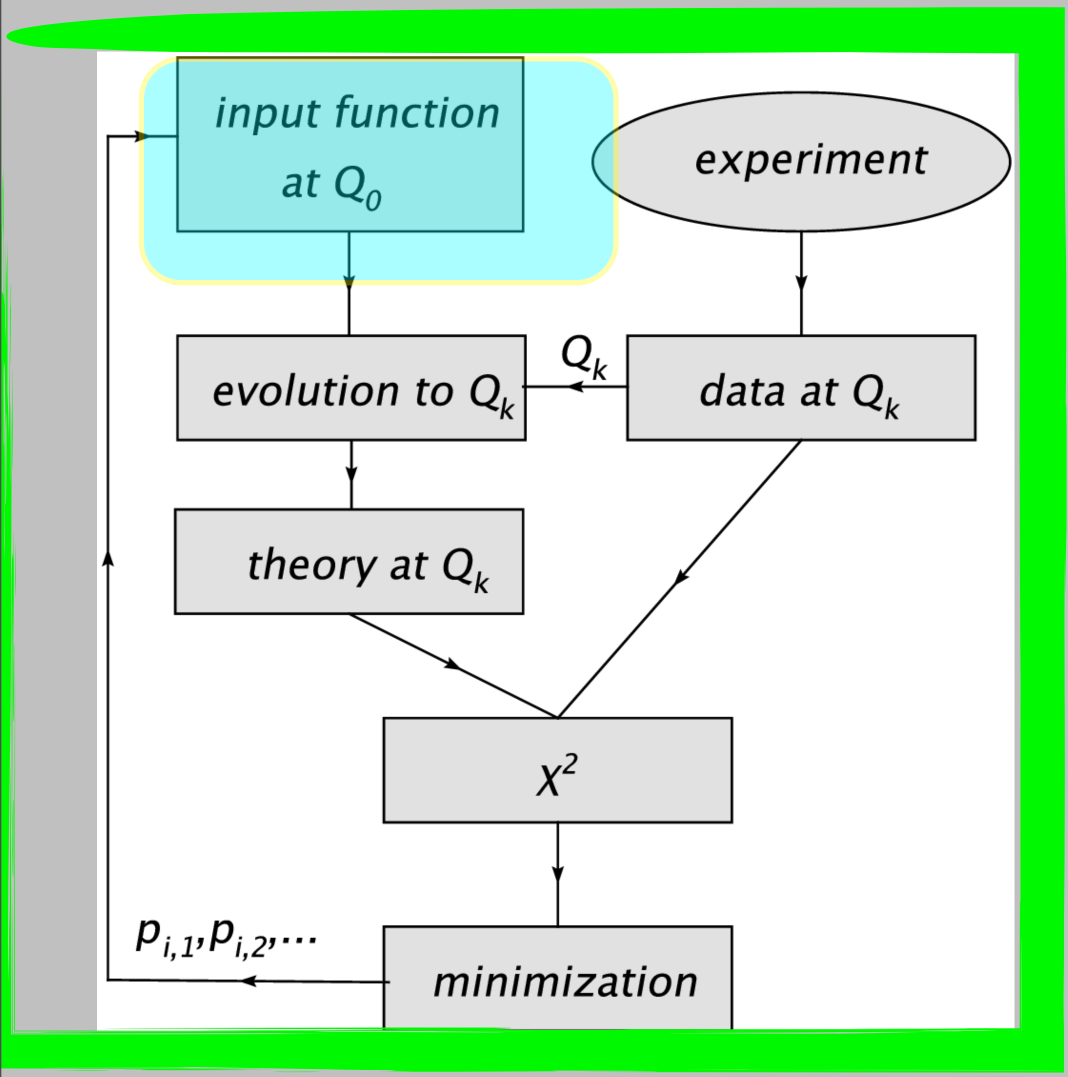

Parameter Dependent Functional Form

$$x\, f_k^{p/A}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} e^{c_3 x} (1 + e^{c_4} x)^{c_5}, \quad k = u_v, d_v, g, \bar{u}+\bar{d}, s, \bar{s},$$

$$\bar{d}(x, Q_0)/\bar{u}(x, Q_0) = c_0 x^{c_1} (1-x)^{c_2} + (1 + c_3 x)(1-x)^{c_4}$$

CTEQ

Global Analysis of PDFs

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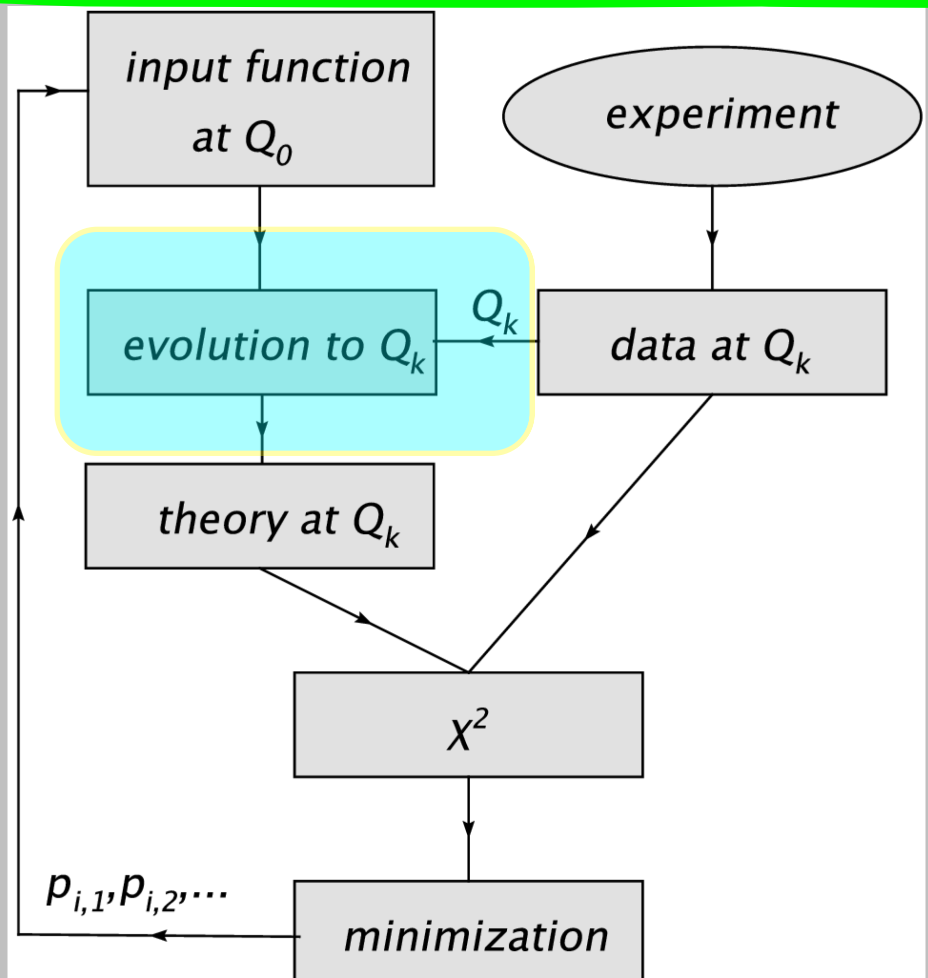

DGLAP Evolution Equations

$$\frac{\partial q_S(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[\int_x^1 \left(P_{qq}(\frac{x}{x_1})q_s(x_1,Q^2) + P_{qg}(\frac{x}{x_1})g(x,Q^2)\right)\right], \quad (6)$$

$$\frac{\partial g(x,Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi}\left[\int_x^1 \left(P_{gq}(\frac{x}{x_1})q_s(x_1,Q^2) + P_{gg}(\frac{x}{x_1})g(x,Q^2)\right)\right]. \quad (7)$$

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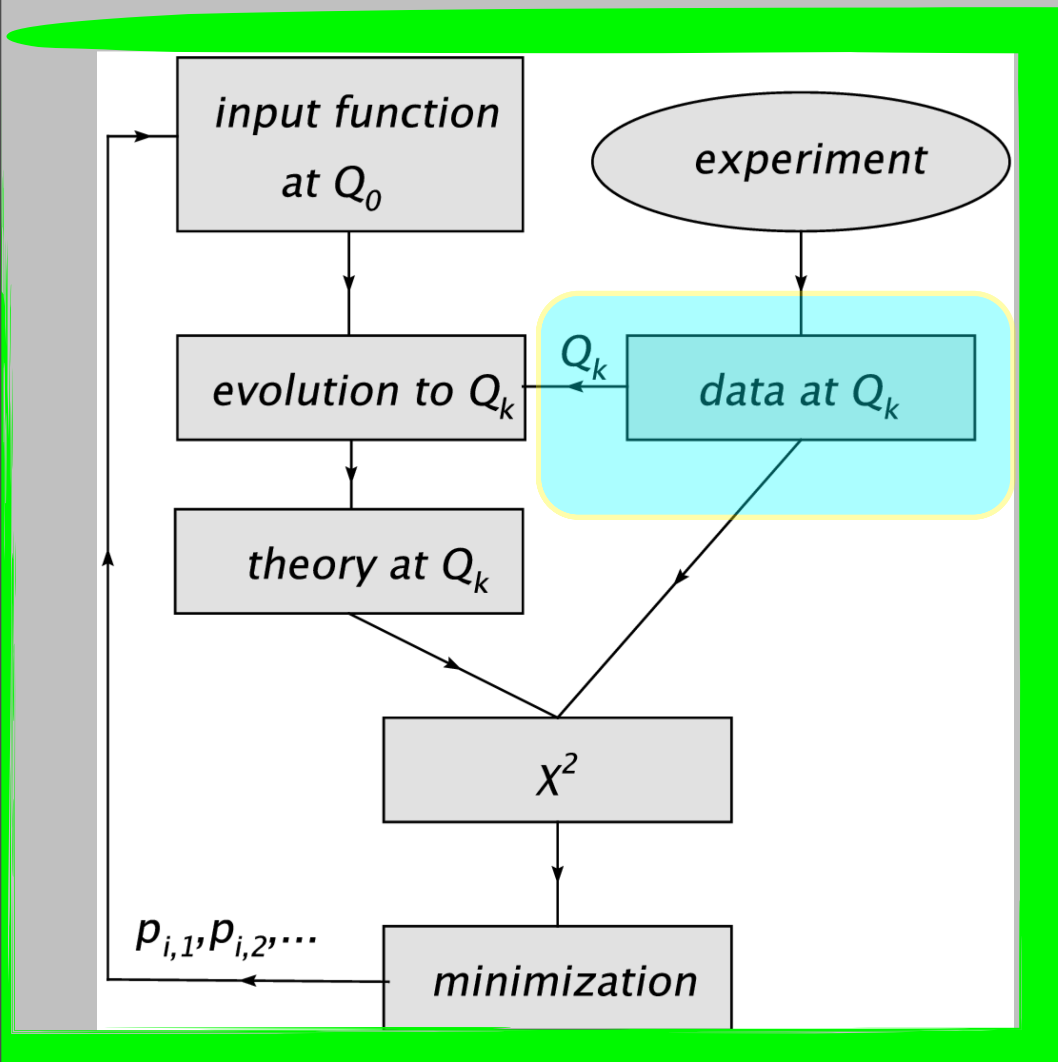

Data

Data sets fitted in MSTW 2008 NLO analysis [arXiv:0901.00

Data set	χ^2 / $N_{\text{pts.}}$
H1 MB 99 e^+p NC	9 / 8
H1 MB 97 e^+p NC	42 / 64
H1 low Q^2 96–97 e^+p NC	44 / 80
H1 high Q^2 98–99 e^-p NC	122 / 126
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ZEUS SVX 95 e^+p NC	35 / 30
ZEUS 96–97 e^+p NC	86 / 144
ZEUS 98–99 e^-p NC	54 / 92
ZEUS 99–00 e^+p NC	63 / 90
H1 99–00 e^+p CC	29 / 28
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H1/ZEUS $e^{\pm}p$ F_2^{charm}	107 / 83
H1 99–00 e^+p incl. jets	19 / 24
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DØ II $p\bar{p}$ incl. jets	114 / 110
CDF II $p\bar{p}$ incl. jets	56 / 76
CDF II $W \to l\nu$ asym.	29 / 22
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BCDMS μp F_2	182 / 163
BCDMS μd F_2	190 / 151
NMC μp F_2	121 / 123
NMC μd F_2	102 / 123
NMC $\mu n/\mu p$	130 / 148
E665 μp F_2	57 / 53
E665 μd F_2	53 / 53
SLAC ep F_2	30 / 37
SLAC ed F_2	30 / 38
NMC/BCDMS/SLAC F_L	38 / 31
E866/NuSea pp DY	228 / 184
E866/NuSea pd/pp DY	14 / 15
NuTeV νN F_2	49 / 53
CHORUS νN F_2	26 / 42
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CCFR $\nu N \to \mu\mu X$	66 / 86
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All data sets	**2543 / 2699**

- Red = New w.r.t. MRST 2006 fit.

G. Watt

Global Analysis of PDFs

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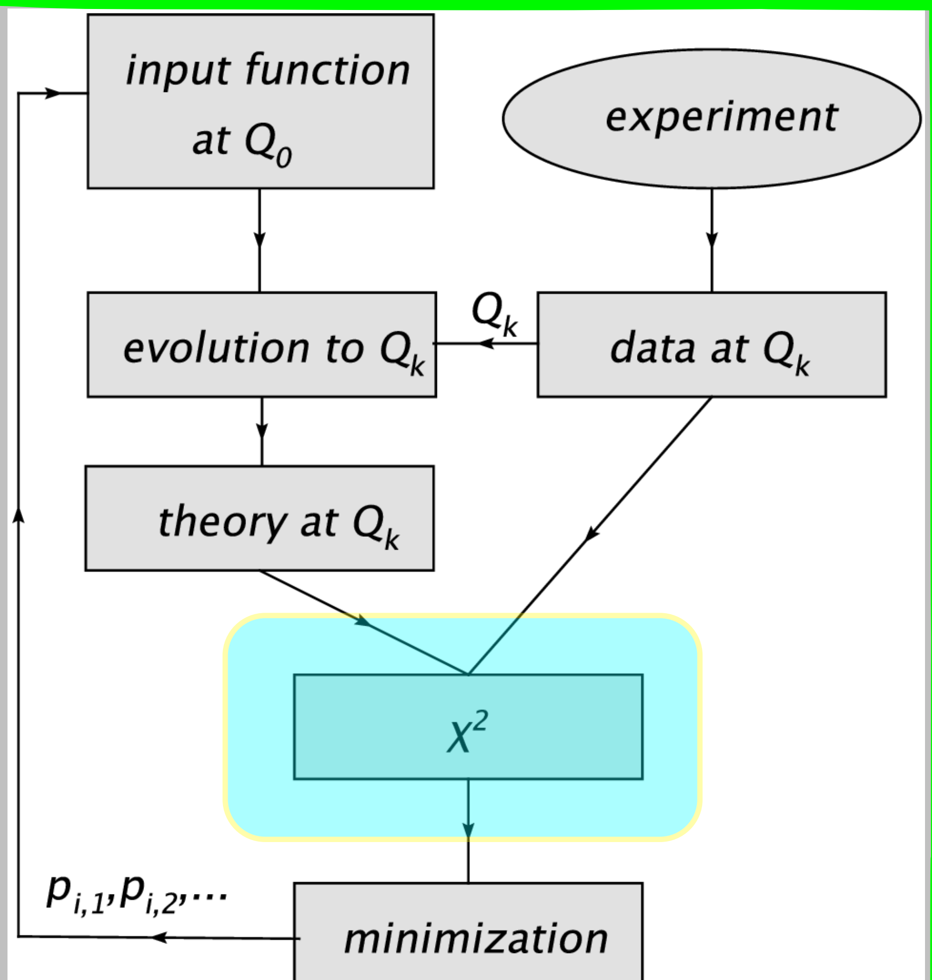

minimize χ^2 function

$$\chi^2_{global}[A_i] = \sum_n w_n \chi^2_n ; \chi^2_n = \sum_I \left(\frac{D_{nI} - T_{nI}}{\sigma_{nI}}\right)^2$$

Sum over experiments

Sum over data points

weights: default=1, allows to emphasize certain data sets

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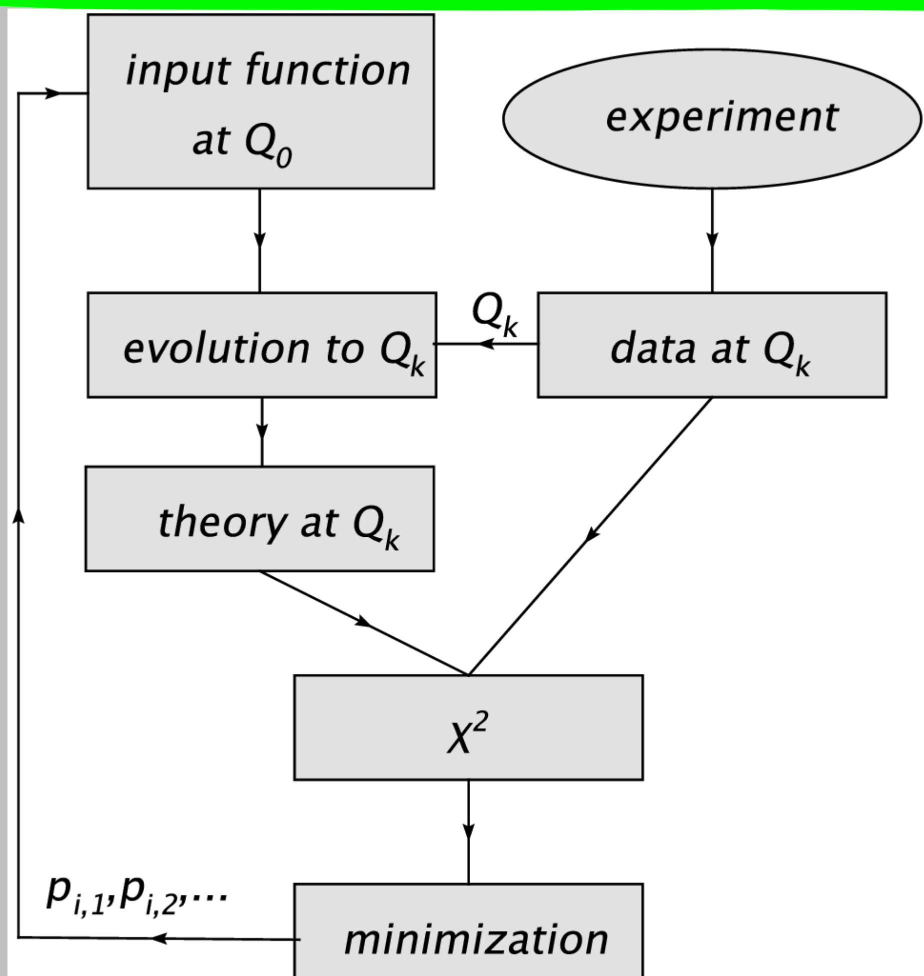

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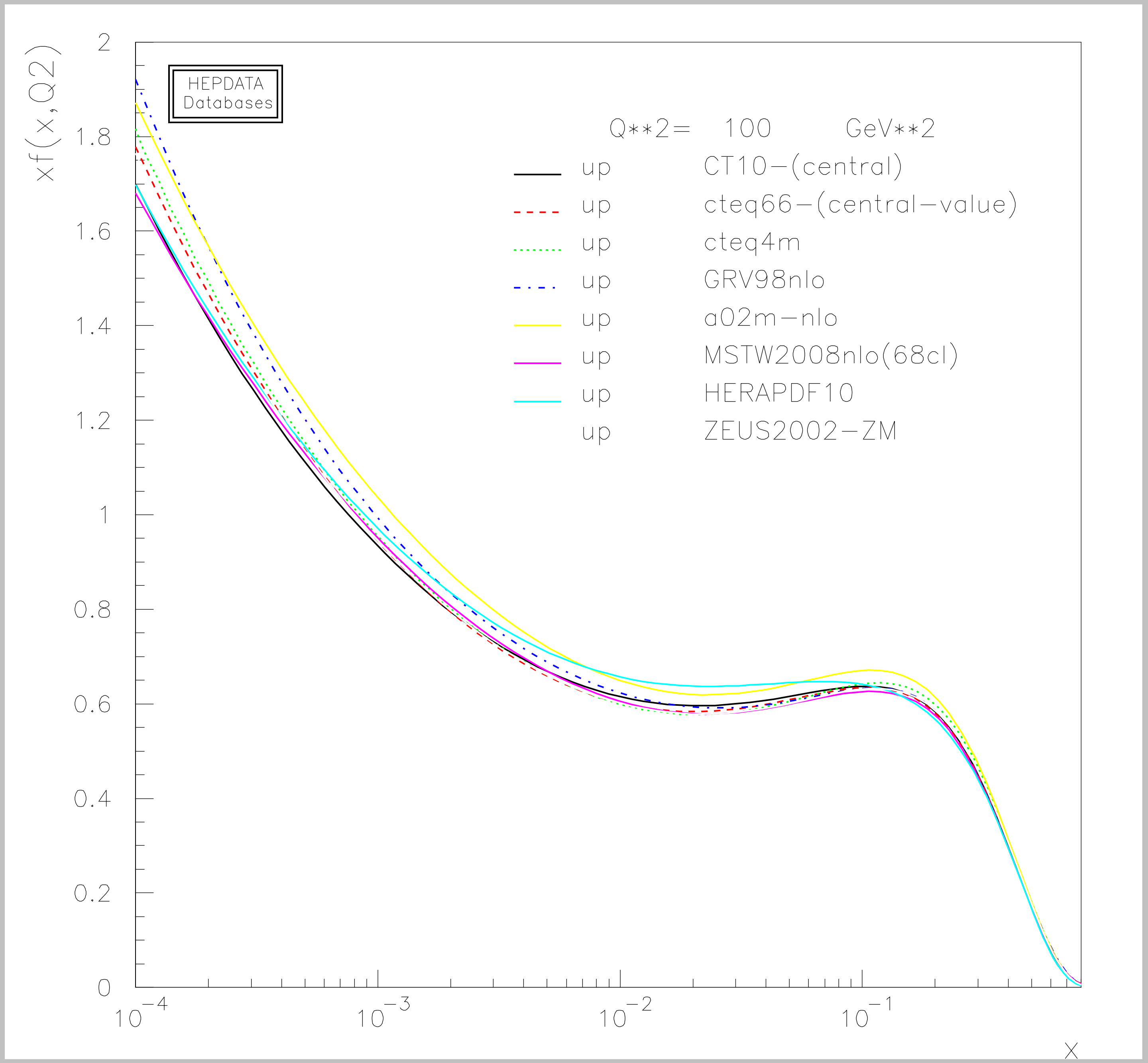
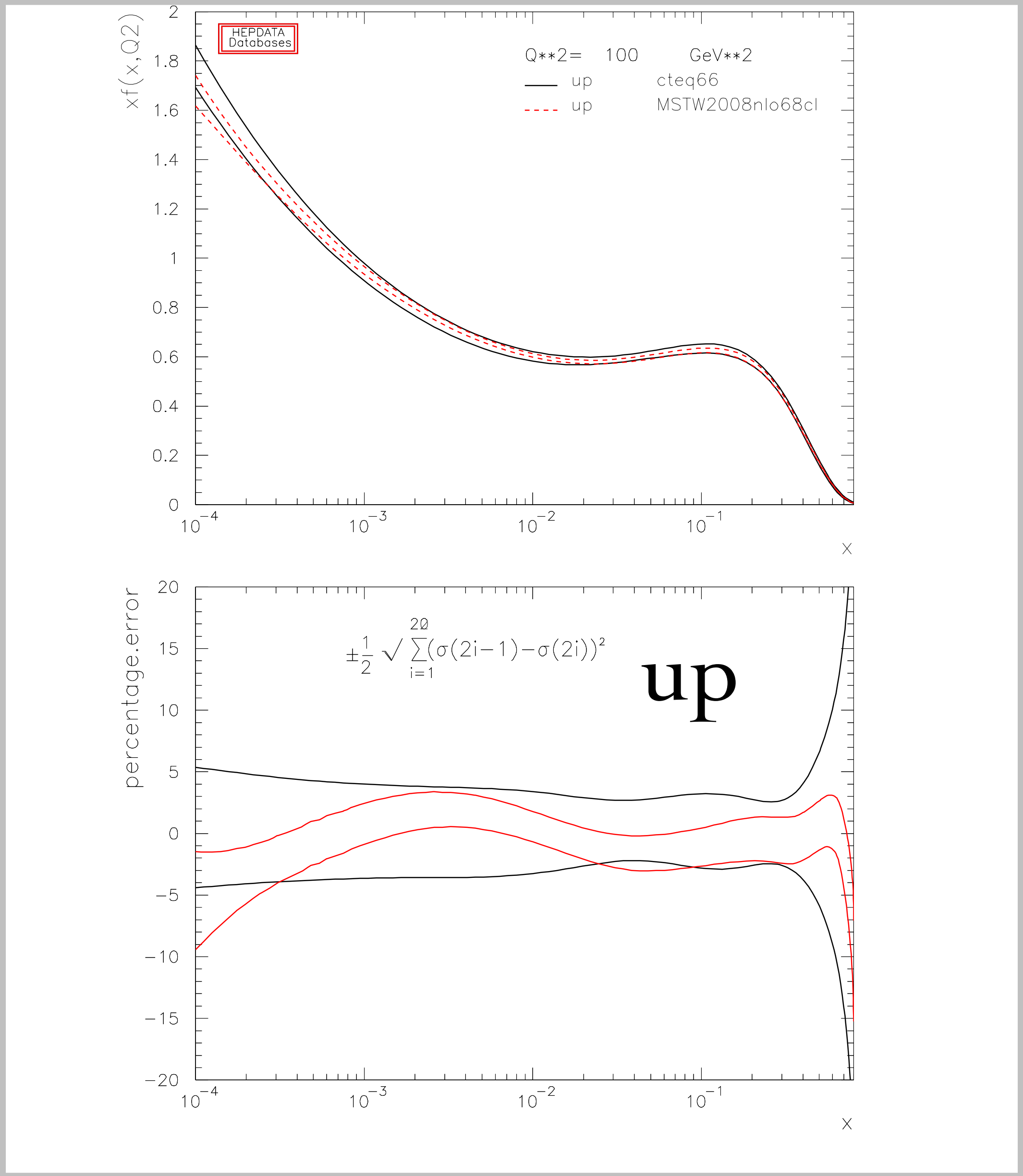
PDFs

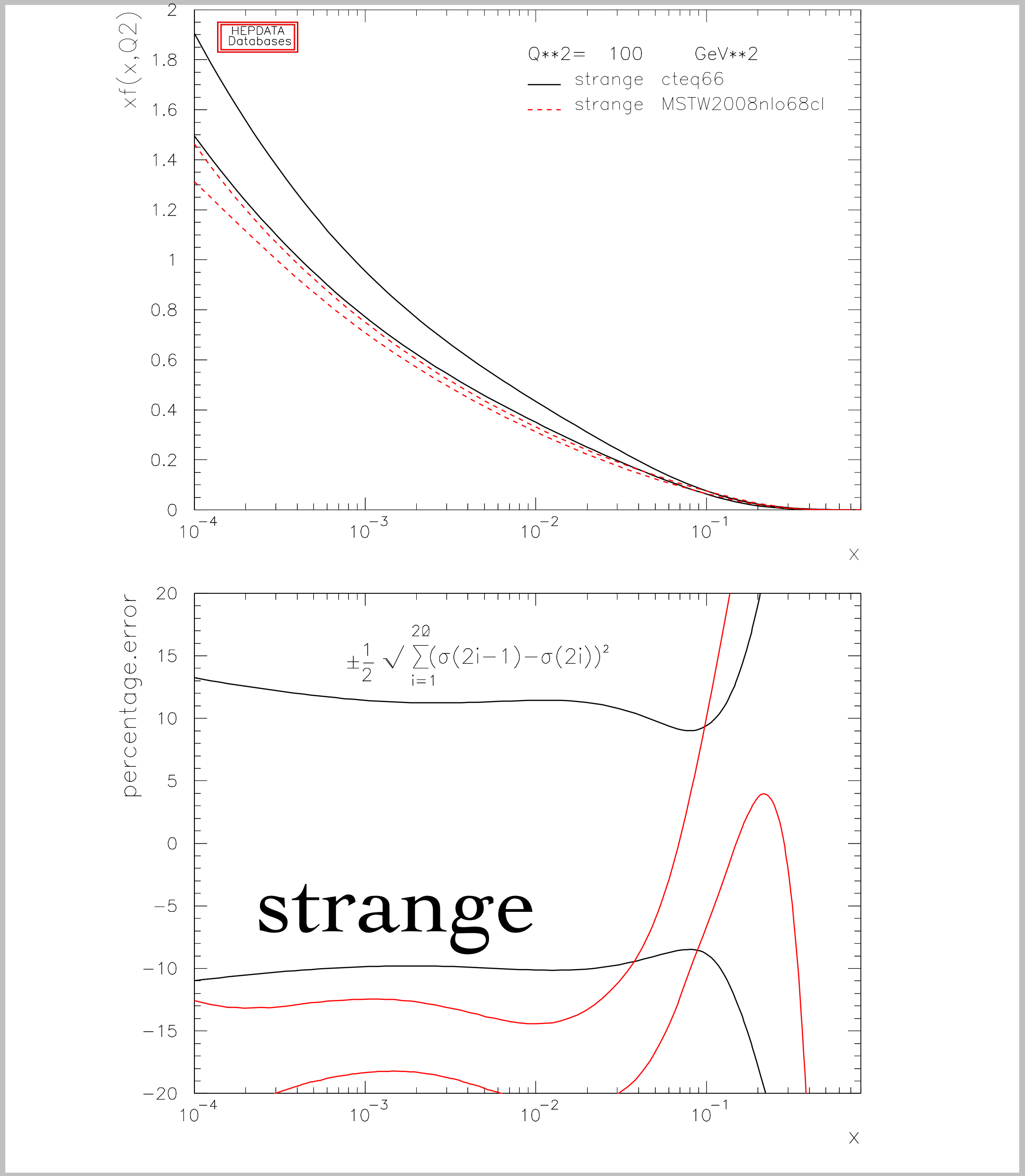
Many Different groups fitting PDFs in last 2-3 decades

- CTEQ,MSTW,GRV,ABSM,HERAPDF, ZEUS,NNPDFs ...
- Differ in functional forms, data used, etc.



PDF Uncertainty





Decreasing PDF Uncertainty:

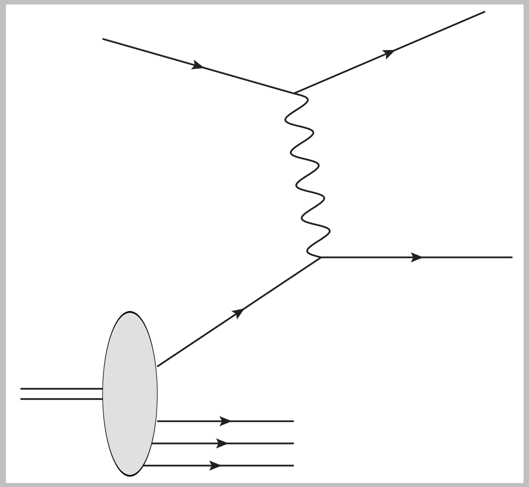
- More data with reduced error
- Improved theory precision -> higher orders calculations

Structure Functions

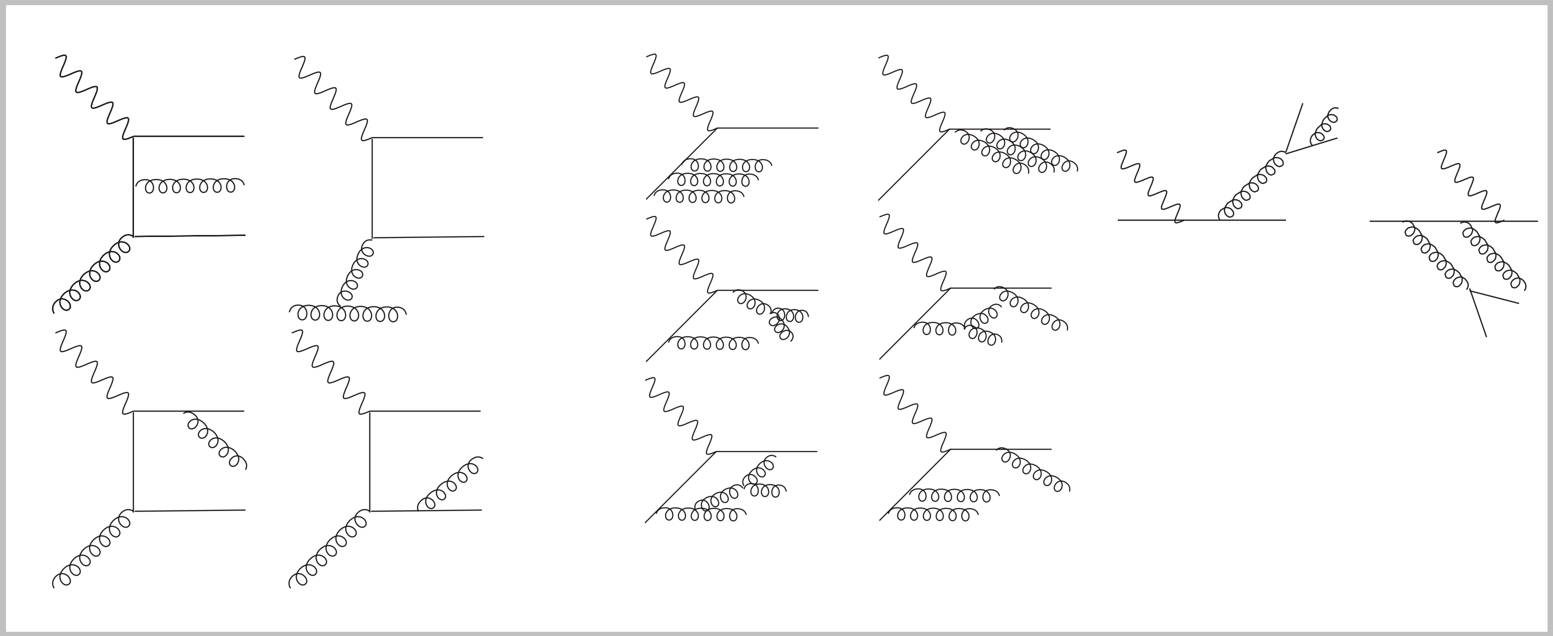
$$F_2(x,Q^2) = \sum_q e_q^2 x(q+\bar{q})(x,Q^2)$$

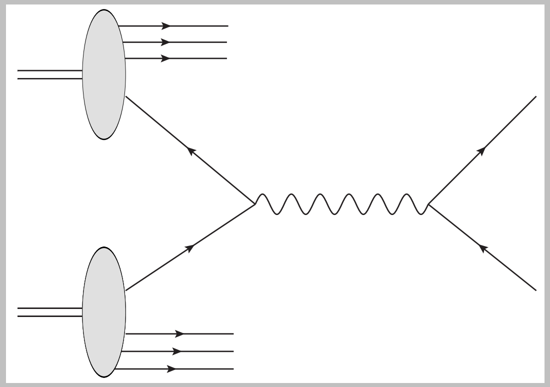
$$F_L(x,Q^2) \doteq 0 + \mathcal{O}(\alpha_s)$$

Structure Functions
Backbone of Global Analysis



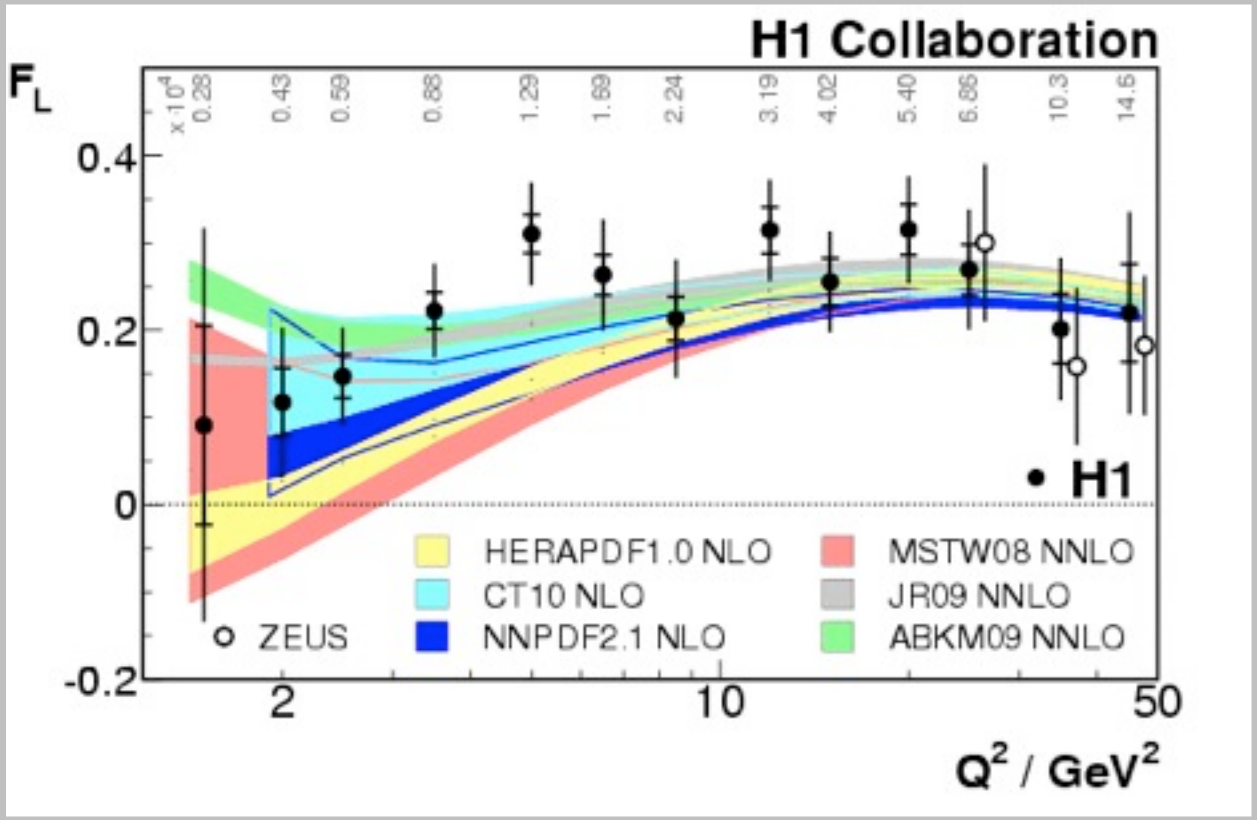
DIS
deep inelastic scattering

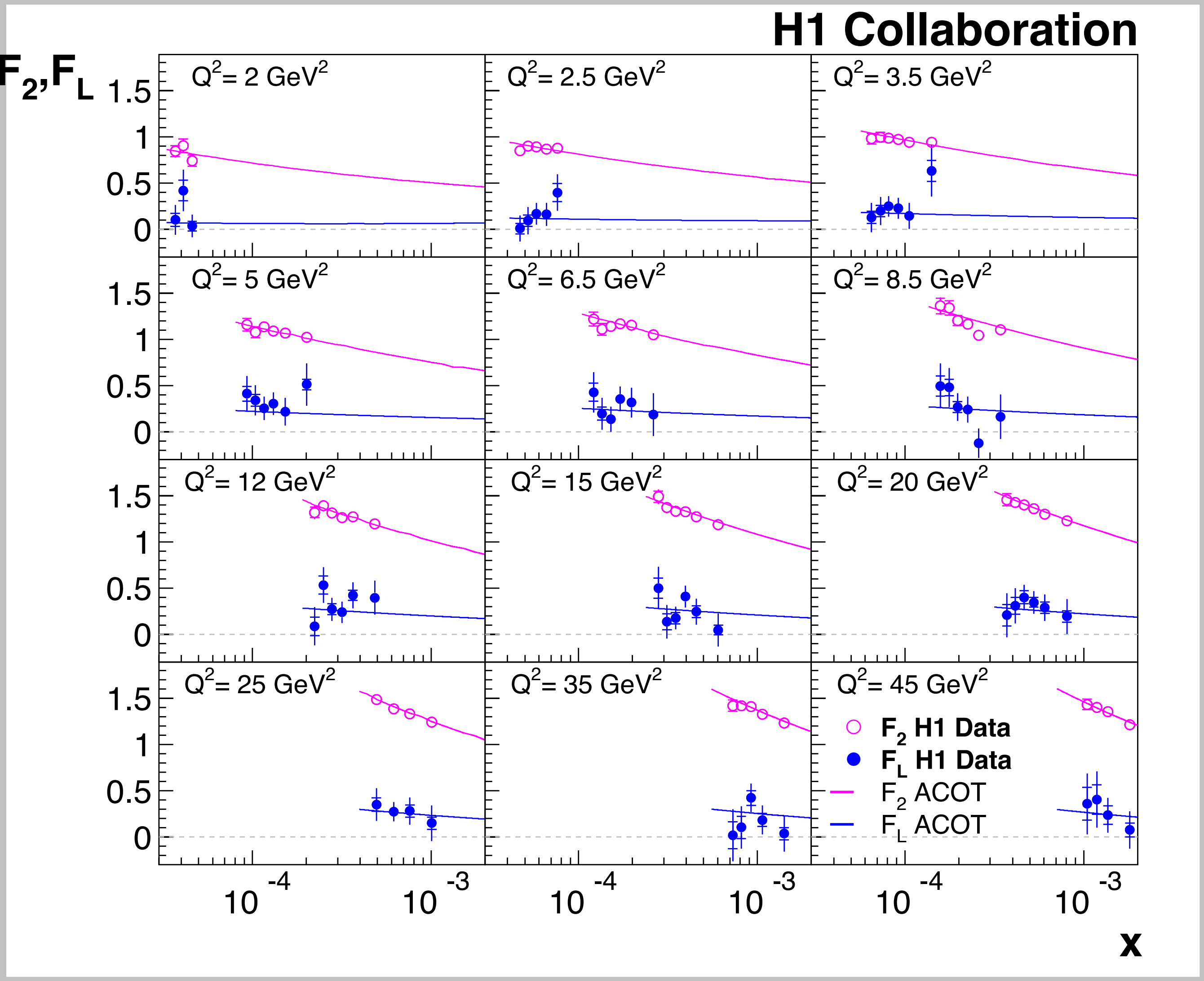




DY
Drell-Yan

Structure Functions

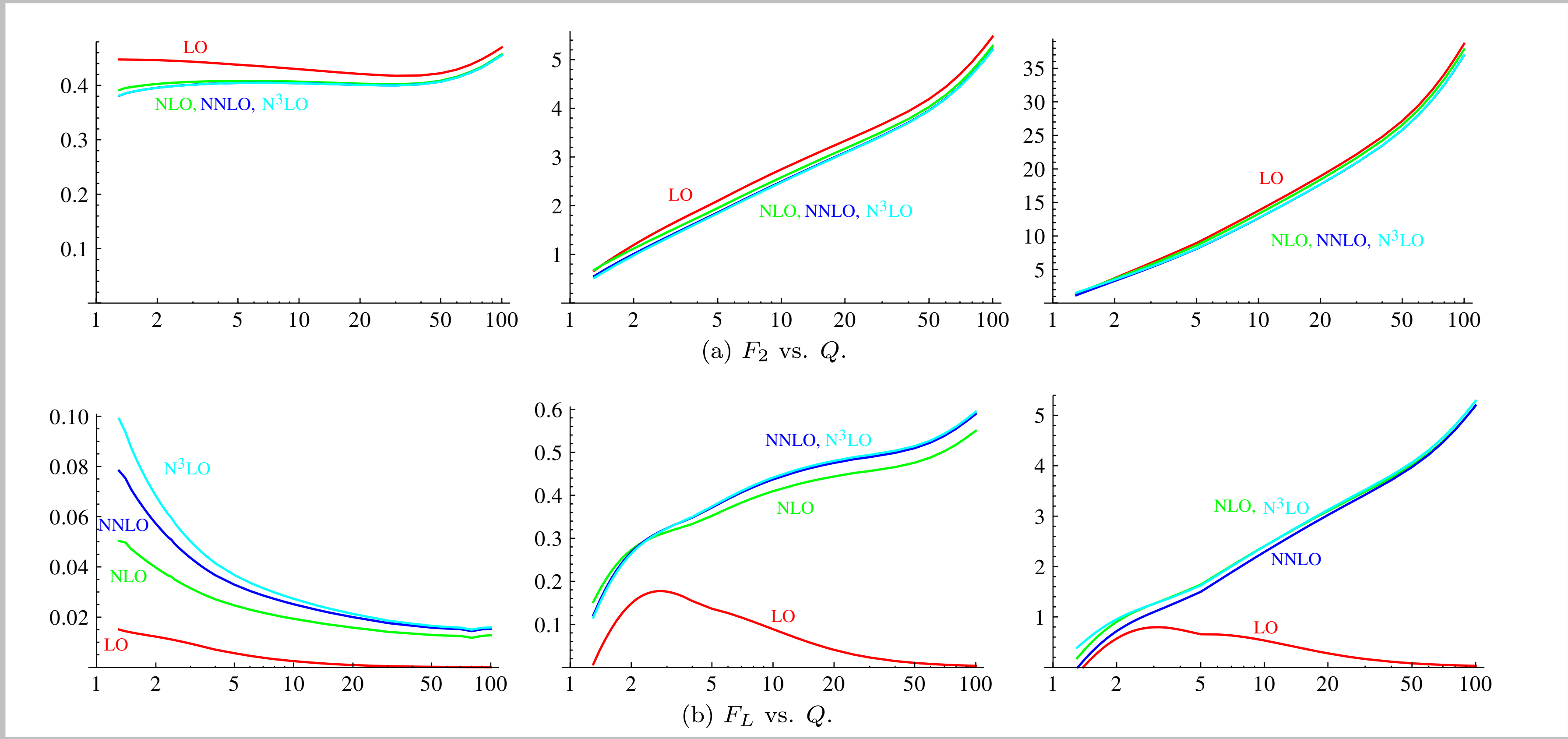




Striving toward increased precision in both data and theory!

Structure Functions to N3LO

I.Schienbein F. Olness K.Kovarik T.Jezo A.Kusina J.Yu TS arXiv:1203.0282

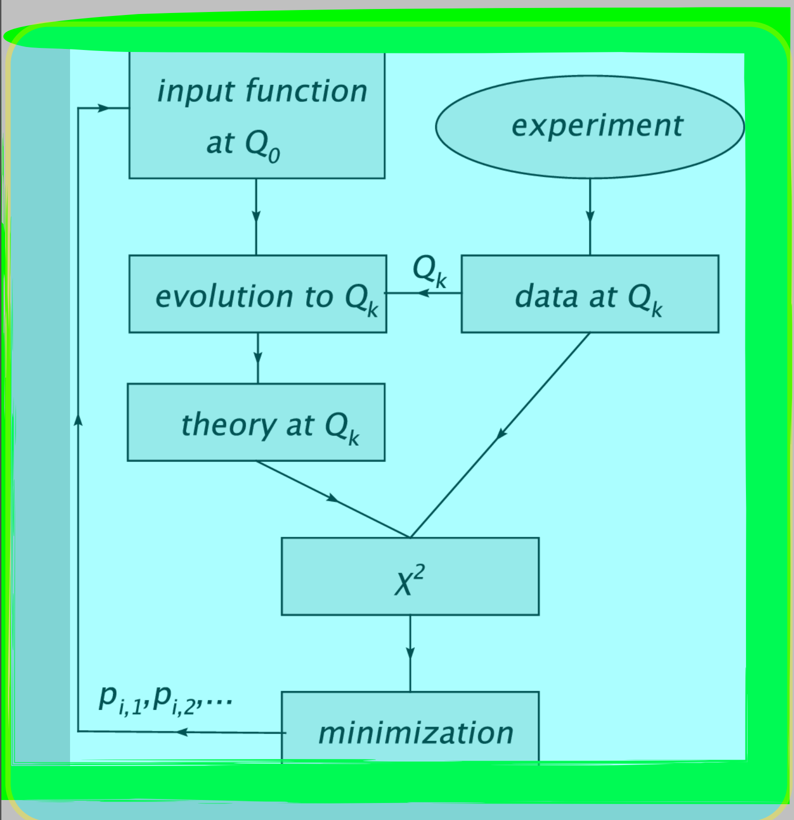


(a) F_2 vs. Q.
(b) F_L vs. Q.

$x = \{10^{-1}, 10^{-3}, 10^{-5}\}$ (left to right)

- F_2 - the higher order corrections converge quickly
- F_L - difference noticeable at each order - obvious need for higher order corrections

Precision PDFs → BSM Searches



$$\sigma_{AB\to C} = PDF_{a/A} \otimes PDF_{b/B} \otimes \hat{\sigma}_{ab\to c} \otimes FF_{C/c}$$

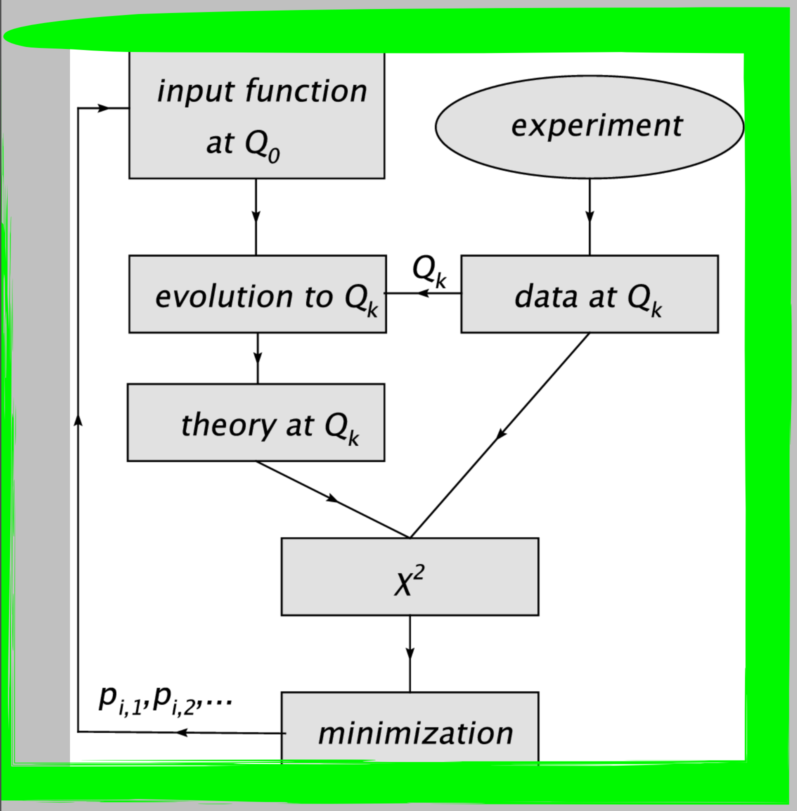
Susy, Dark Matter, GUTs, X-Dims

DATA + Higher Order F_2&F_L → Precision PDFs

Precision PDFs + Higher Order SM Calculation → Precision SM Observables

Precision SM Observables → Background for BSM searches under control → Akin&Suchita's Talks

Precision PDFs → BSM Searches



$$\sigma_{AB\to C} = PDF_{a/A} \otimes PDF_{b/B} \otimes \hat{\sigma}_{ab\to c} \otimes FF_{C/c}$$

Susy, Dark Matter, GUTs, X-Dims

DATA + Higher Order F_2&F_L → Precision PDFs

Precision PDFs + Higher Order SM Calculation → Precision SM Observables

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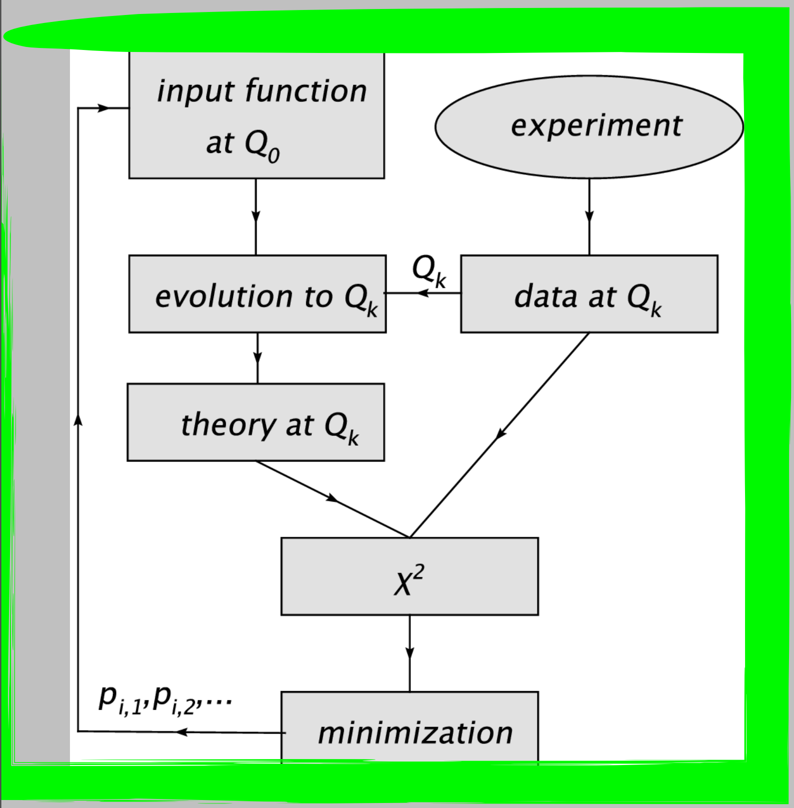

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PDF Expectations

Early parametrizations by Duke-Owens

$$x\bar{u} = x\bar{d} = x\bar{s} = A_S(1-x)^{\eta_S} S/6$$

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S.Berge I.Schienbein F. Olness K.Kovarik T.Jezo A.Kusina J.Yu TS K.Park

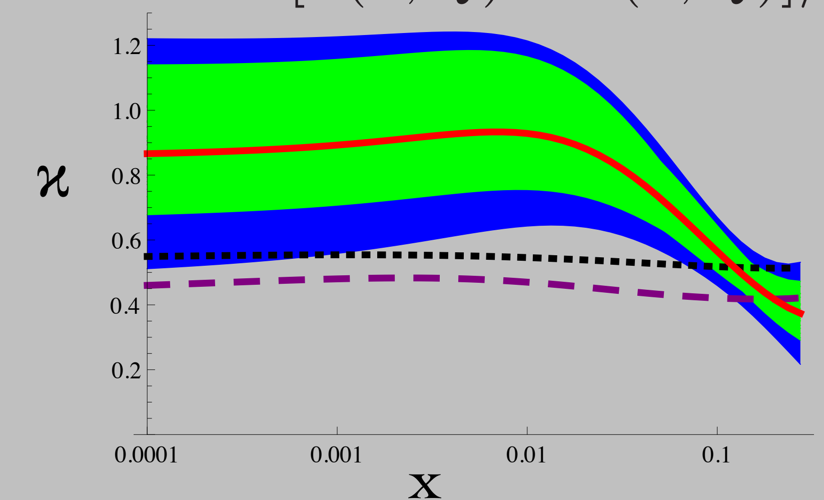
arXiv:1203.1290

The SU(3) symmetry is broken:

$$\bar{s} \neq \bar{u}$$

$$\bar{s} \neq \bar{d}$$

$$\kappa(x,Q) = \frac{s(x,Q)}{[\bar{u}(x,Q)+\bar{d}(x,Q)]/2}$$



bands CTEQ6.6

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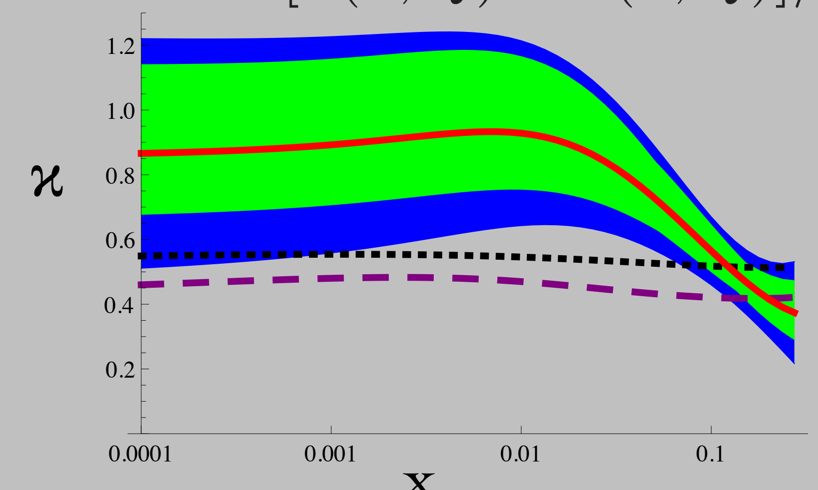

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The SU(3) symmetry is broken:

$$\bar{s} \neq \bar{u}$$

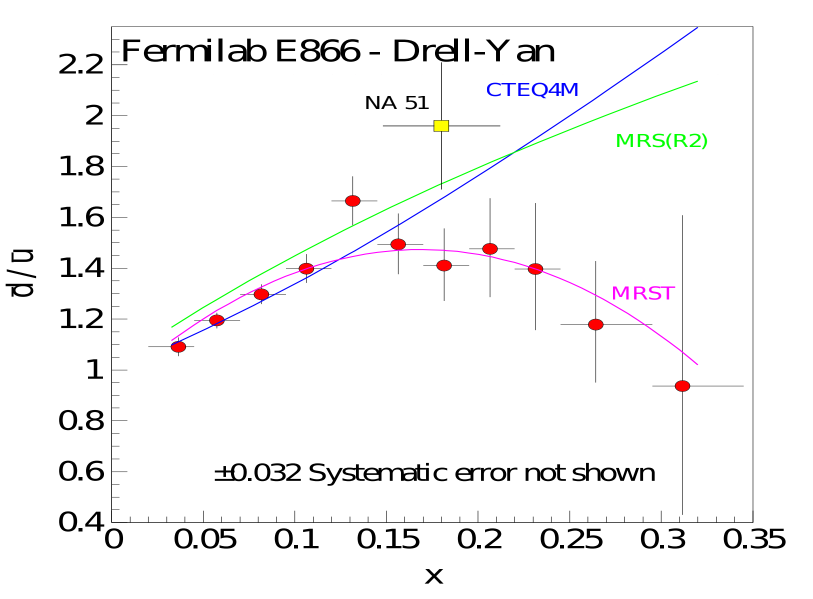
$$\bar{s} \neq \bar{d}$$

$\bar{d} = \bar{u}$ also doesn't hold

The SU(2) $\begin{pmatrix} u \\ d \end{pmatrix}$ symmetry is also broken:

$$\bar{d} > \bar{u}$$

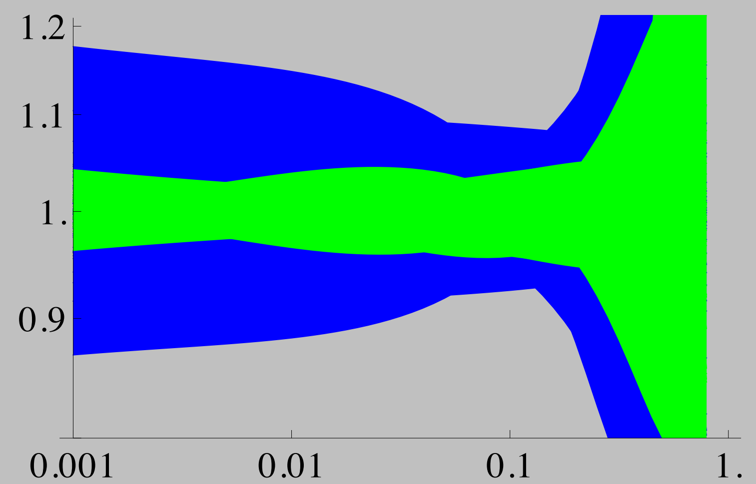
Isospin asymmetry in the nucleon light sea: $\bar{d}(x) \neq \bar{u}(x)$



Still assumed $\begin{pmatrix} p \\ n \end{pmatrix}$

The Strange PDF

- ✦Very Important for W&Z benchmark LHC processes



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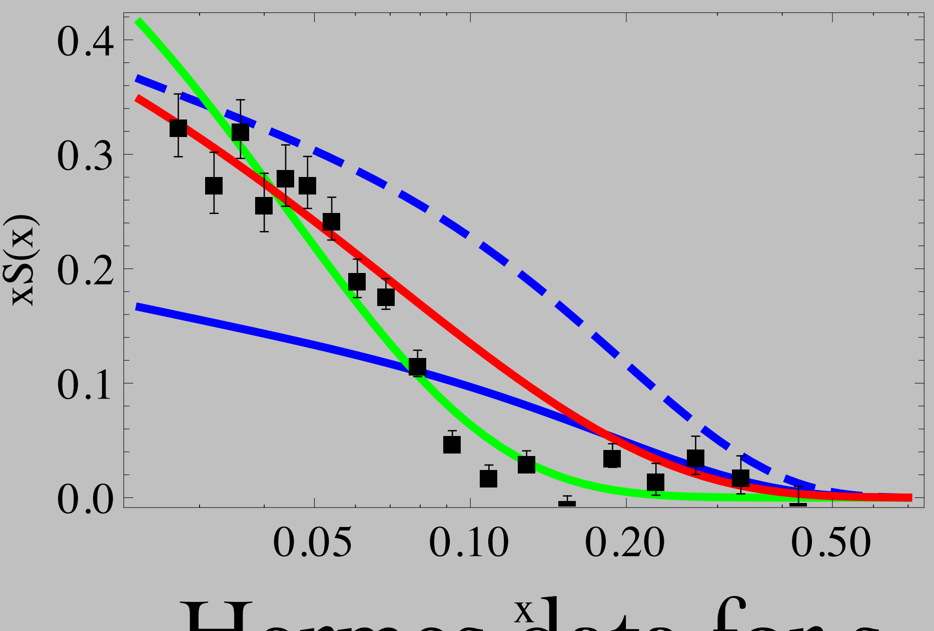

Hermes data for s

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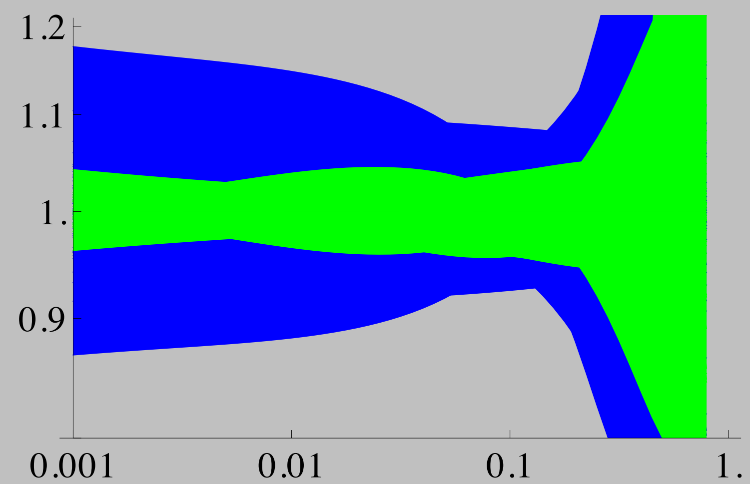

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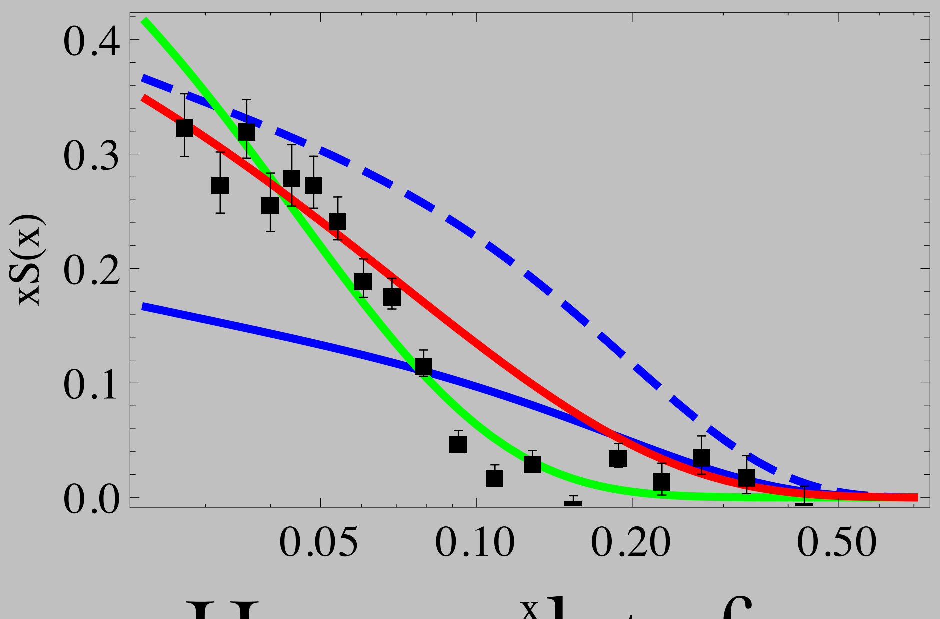

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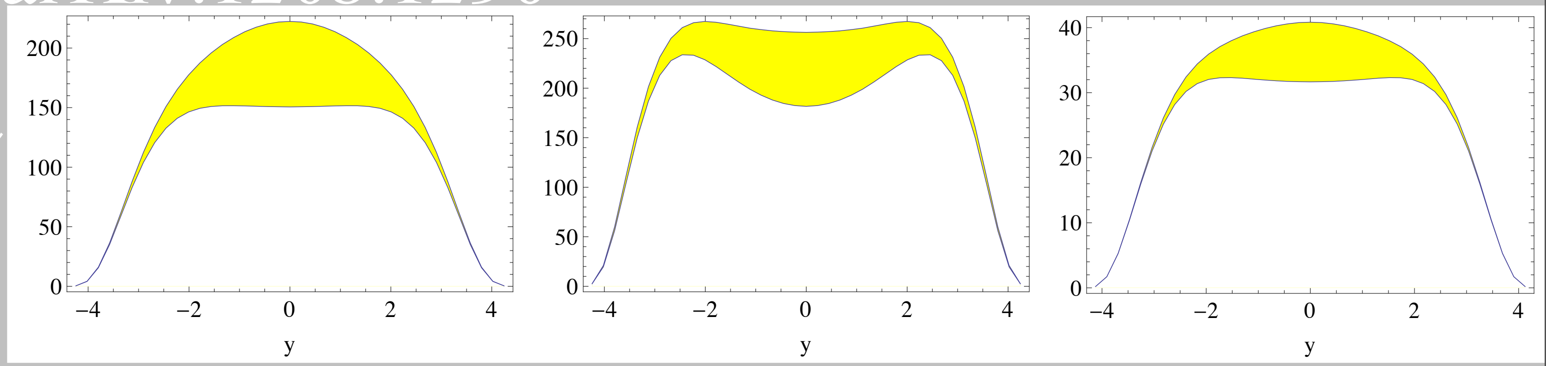
Contributions ~ to s PDF of the W^+,W^-,Z cross-sections at the LHC



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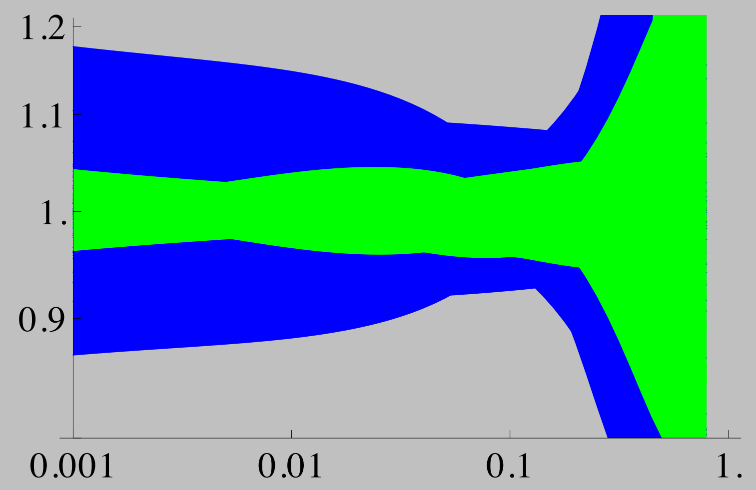

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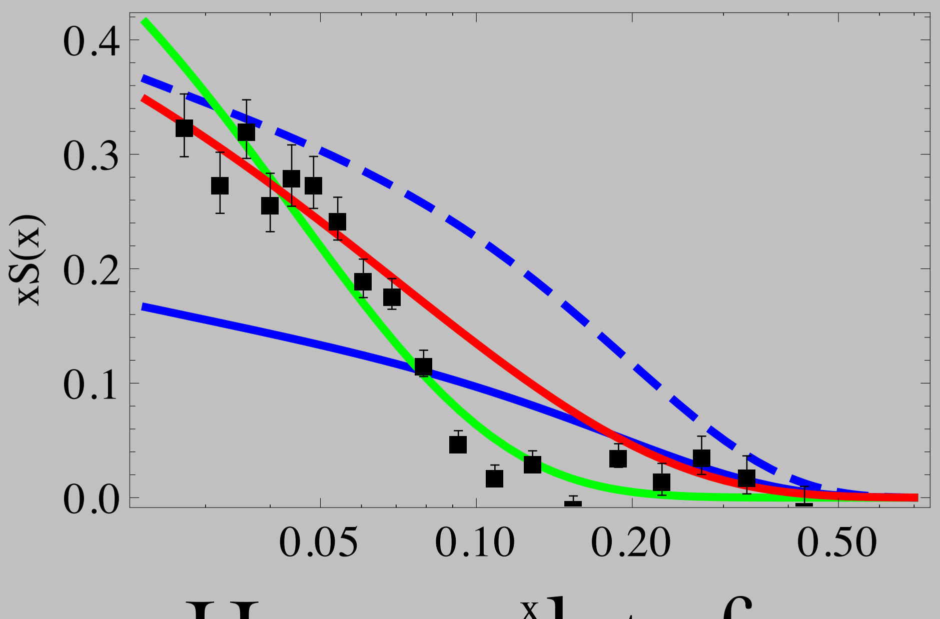

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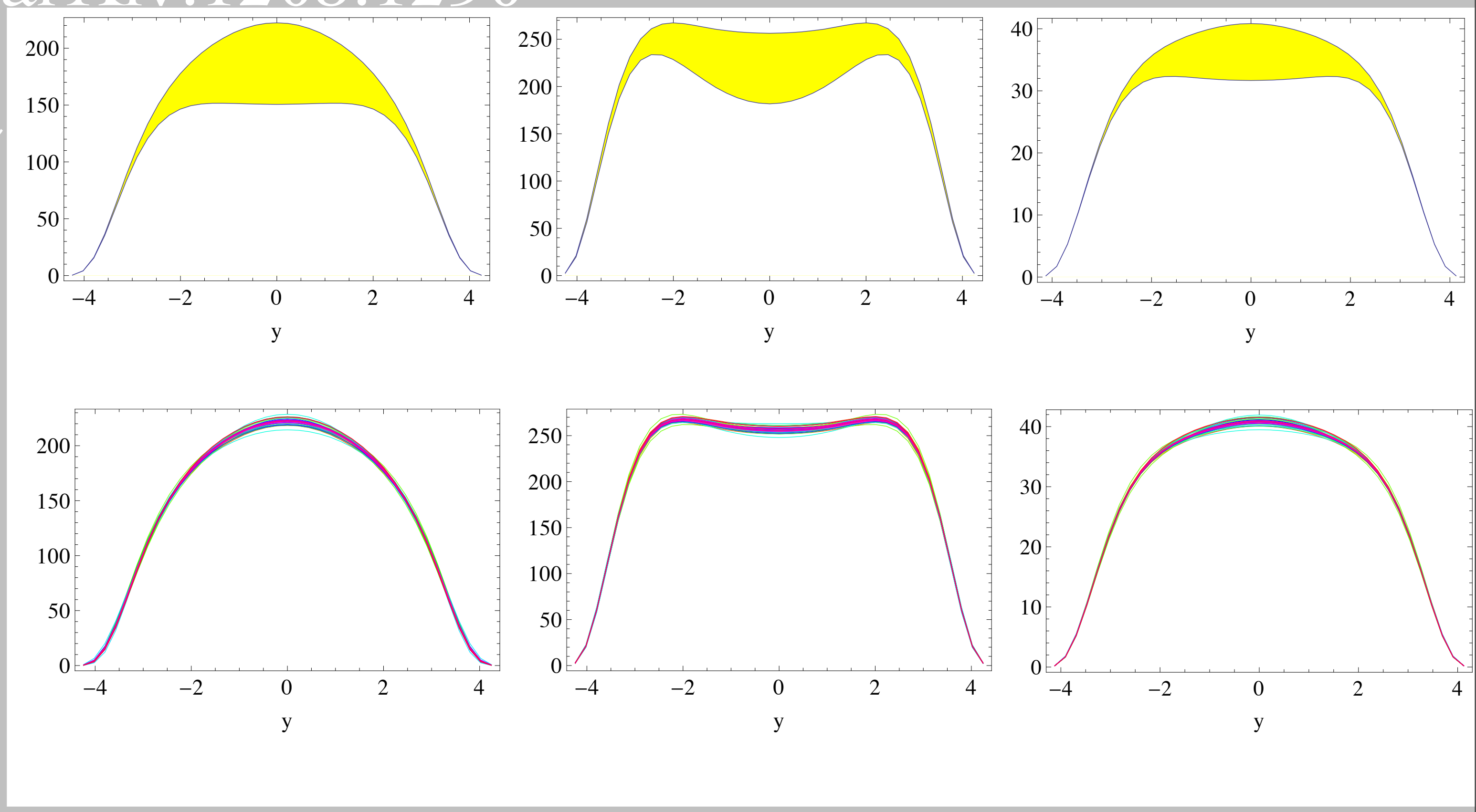

strange PDF uncertainty dominant uncertainty to W cross-section

Intrinsic Charm

Possible intrinsic contribution to the charm pdf, just like s, $\bar{d}$, $\bar{u}$

$$c(x, \mu) \neq 0 \text{ at } \mu = m_c$$

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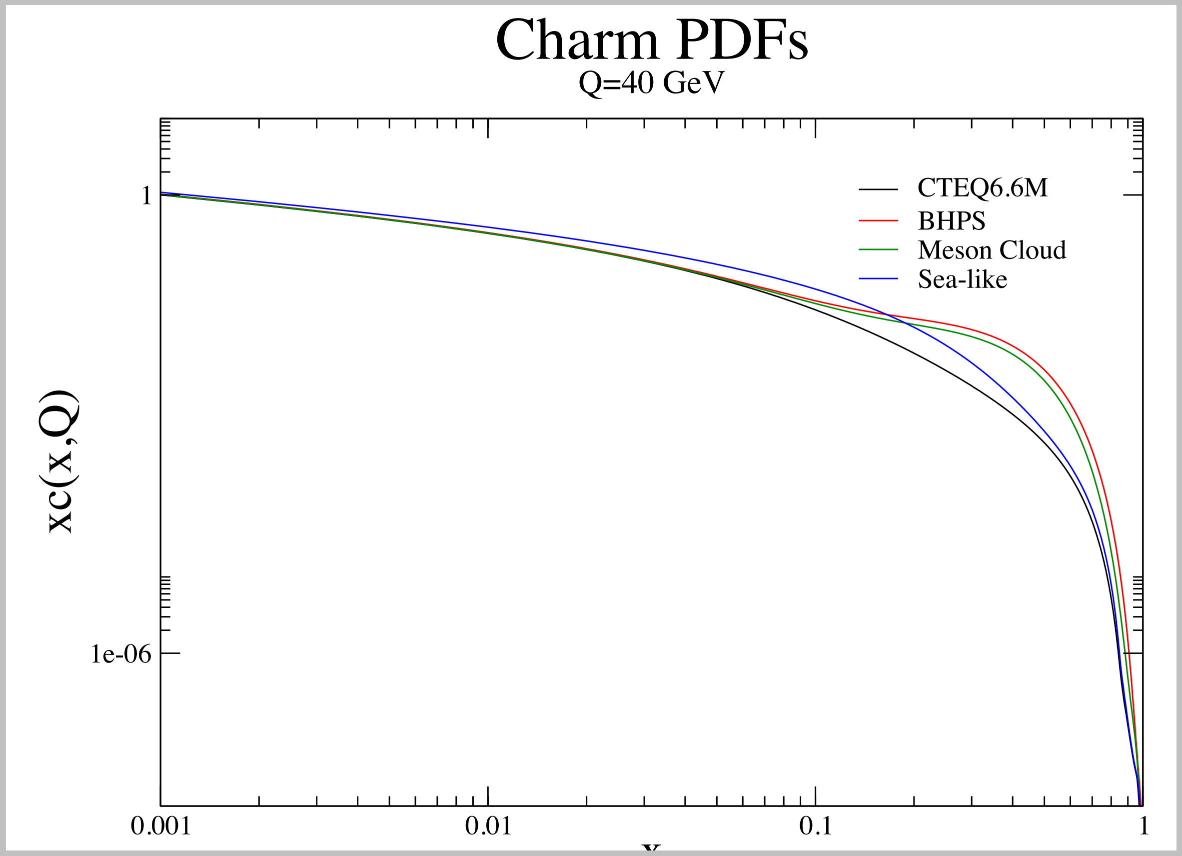
This idea incorporated in global fit -> IC PDFs



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Possible intrinsic contribution to the charm pdf, just like s, $\bar{d}$, $\bar{u}$

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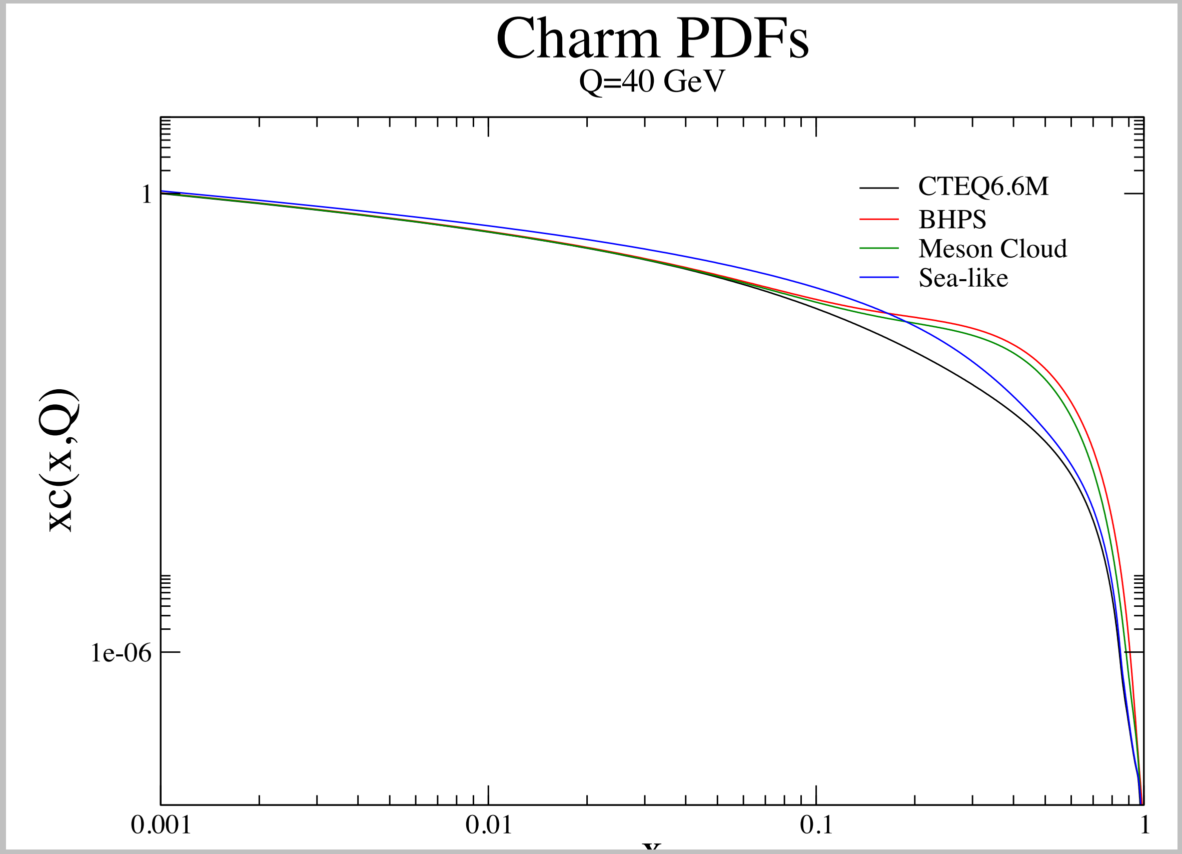
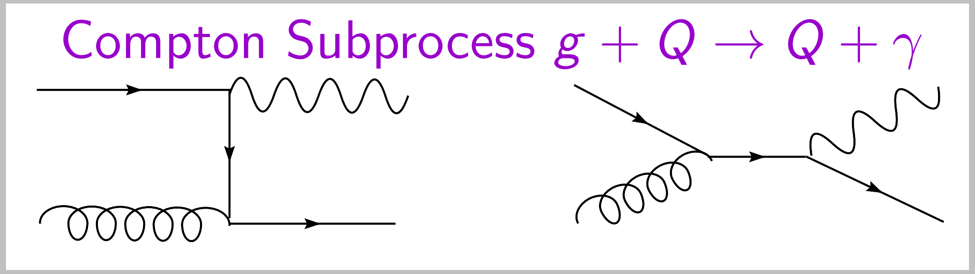
This idea incorporated in global fit -> IC PDFs

Processes sensitive to IC

$pp \to D + X \quad pp \to \gamma + Q$





$g + g \to Q + \bar{Q} + \gamma$

$g + Q \to g + Q + \gamma$

$Q + q \to q + Q + \gamma$

$Q + \bar{q} \to Q + \bar{q} + \gamma$

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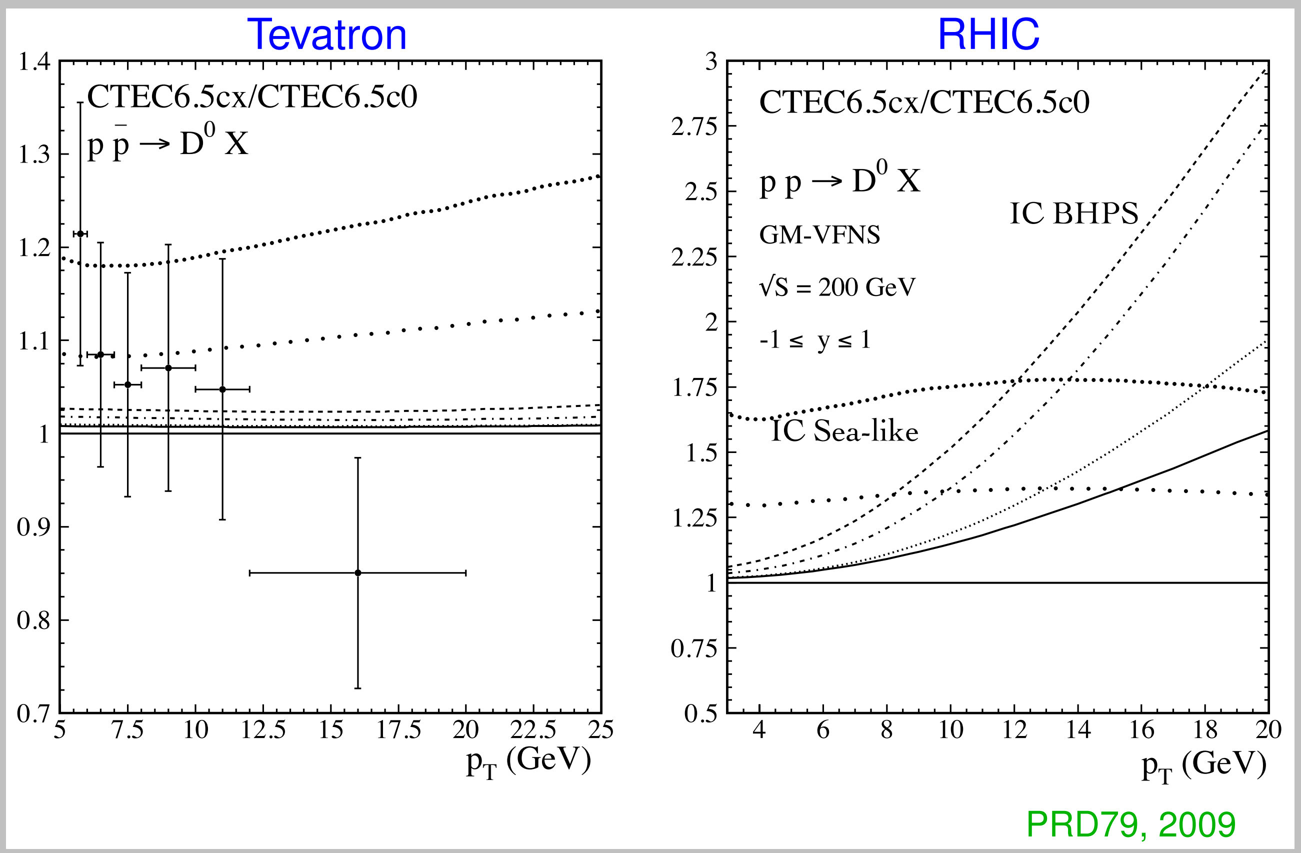
$Q + \bar{Q} \to Q + \bar{Q} + \gamma$

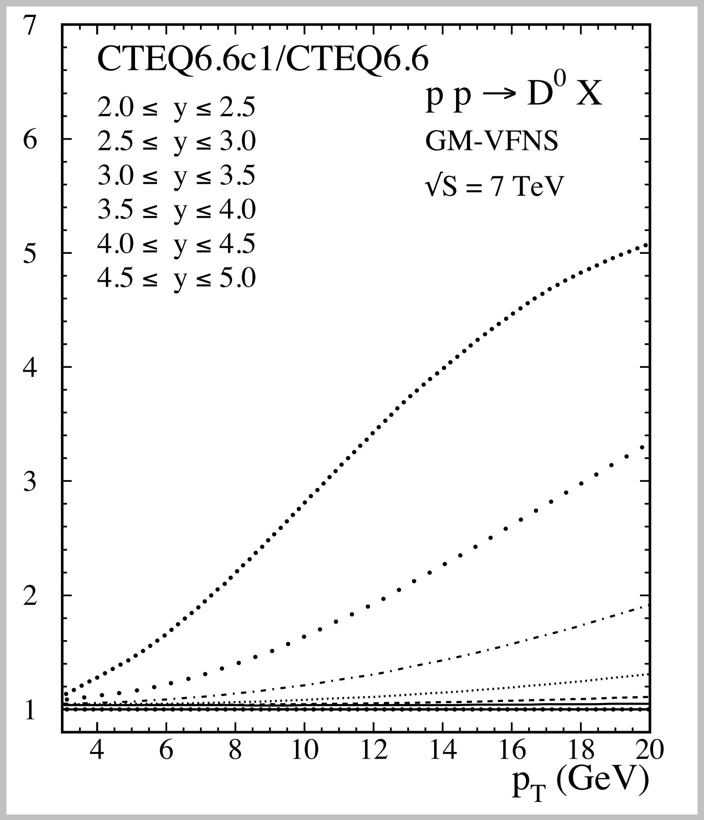
$q + \bar{q} \to Q + \bar{Q} + \gamma$

D Meson Production

$$pp \rightarrow D + X$$

LHCb



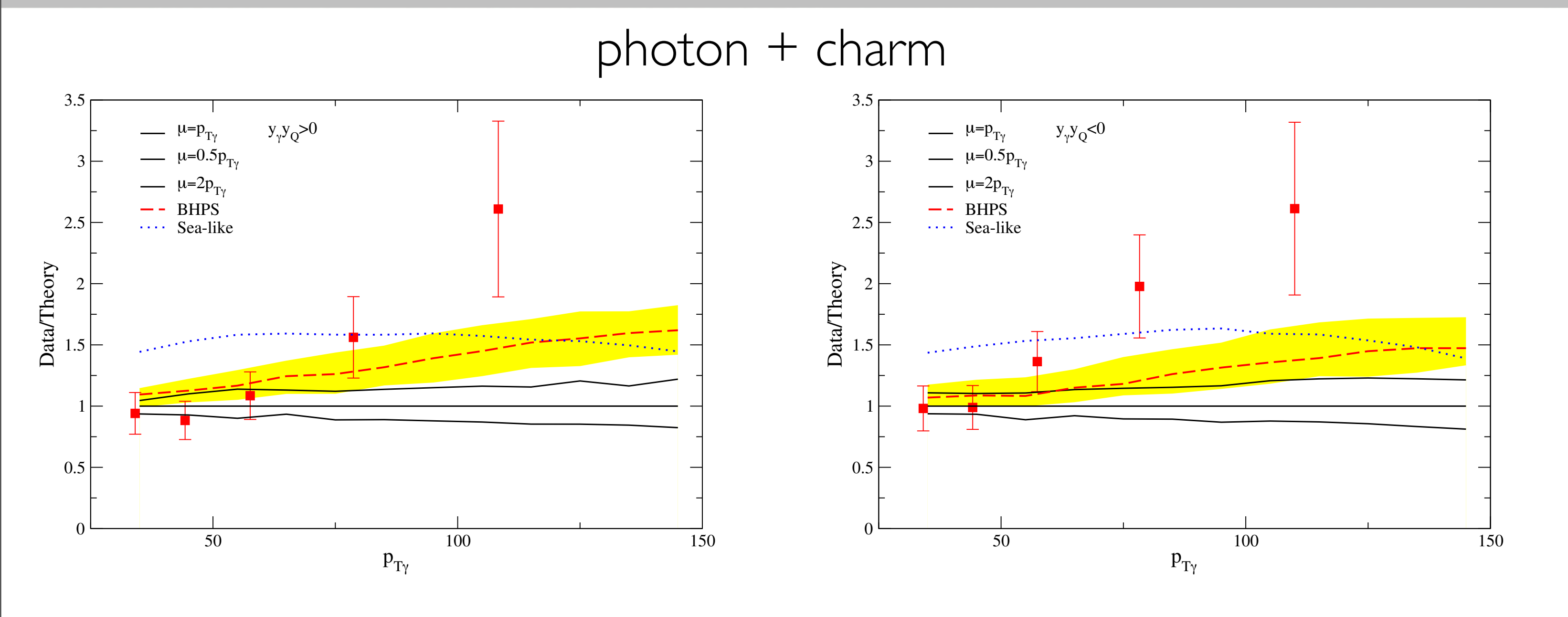


LHCb measurements extremely sensitive to IC

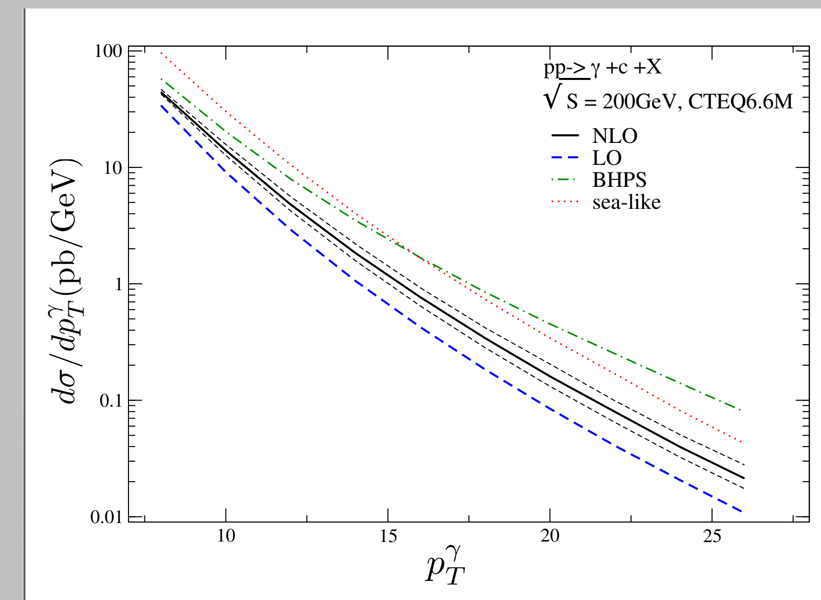
Photon + Q Production

J.Owens TS arXiv:0901.3791

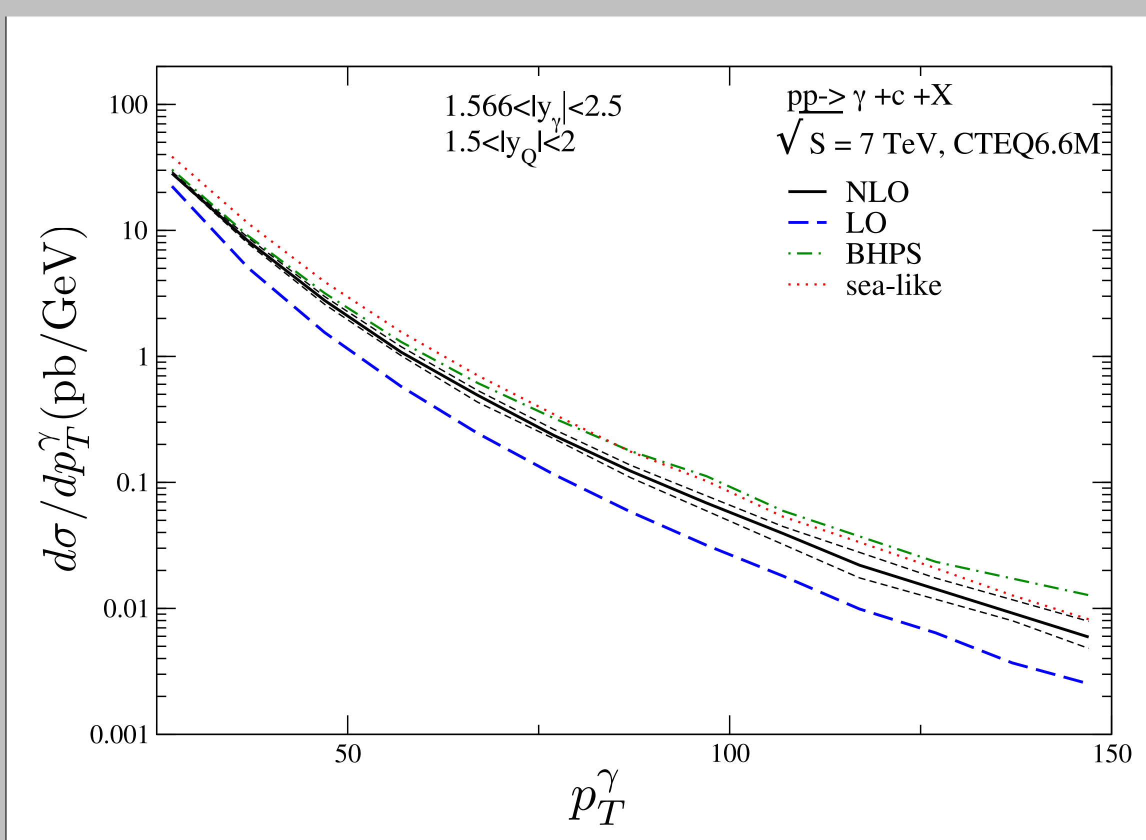
Tevatron

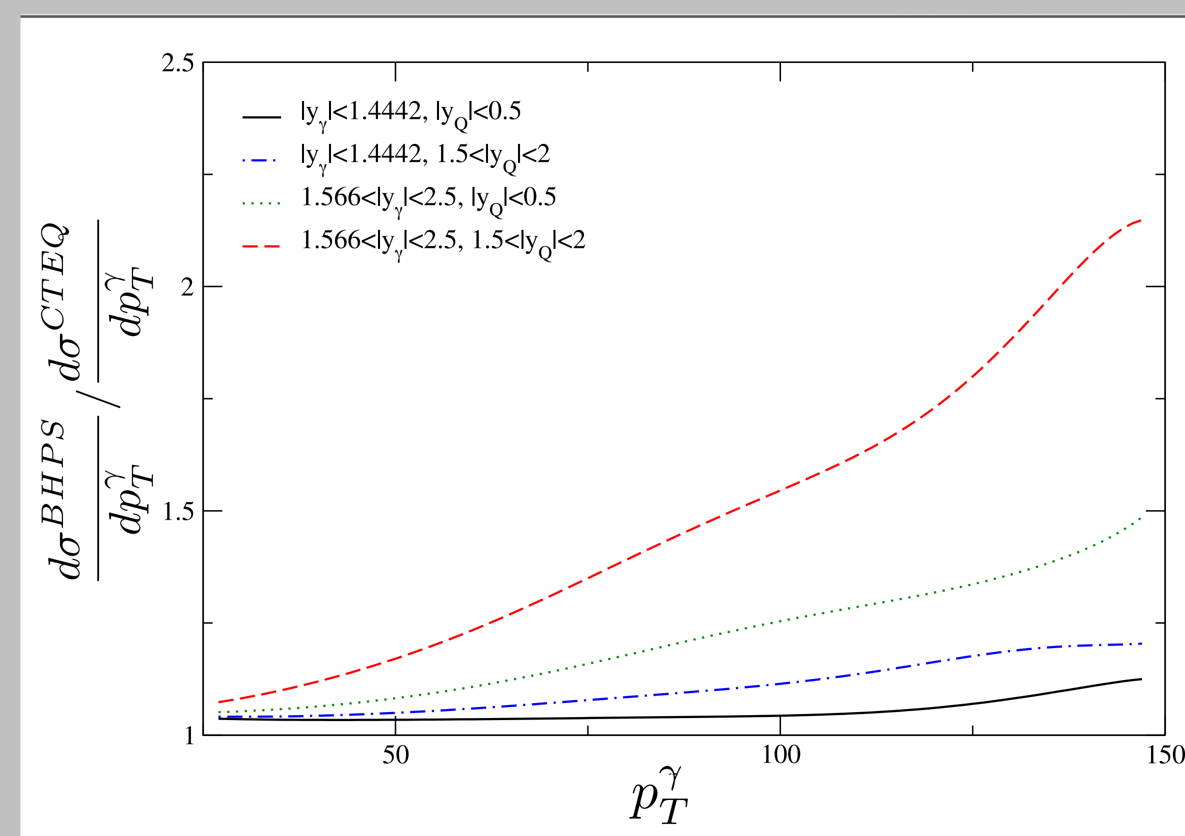


RHIC

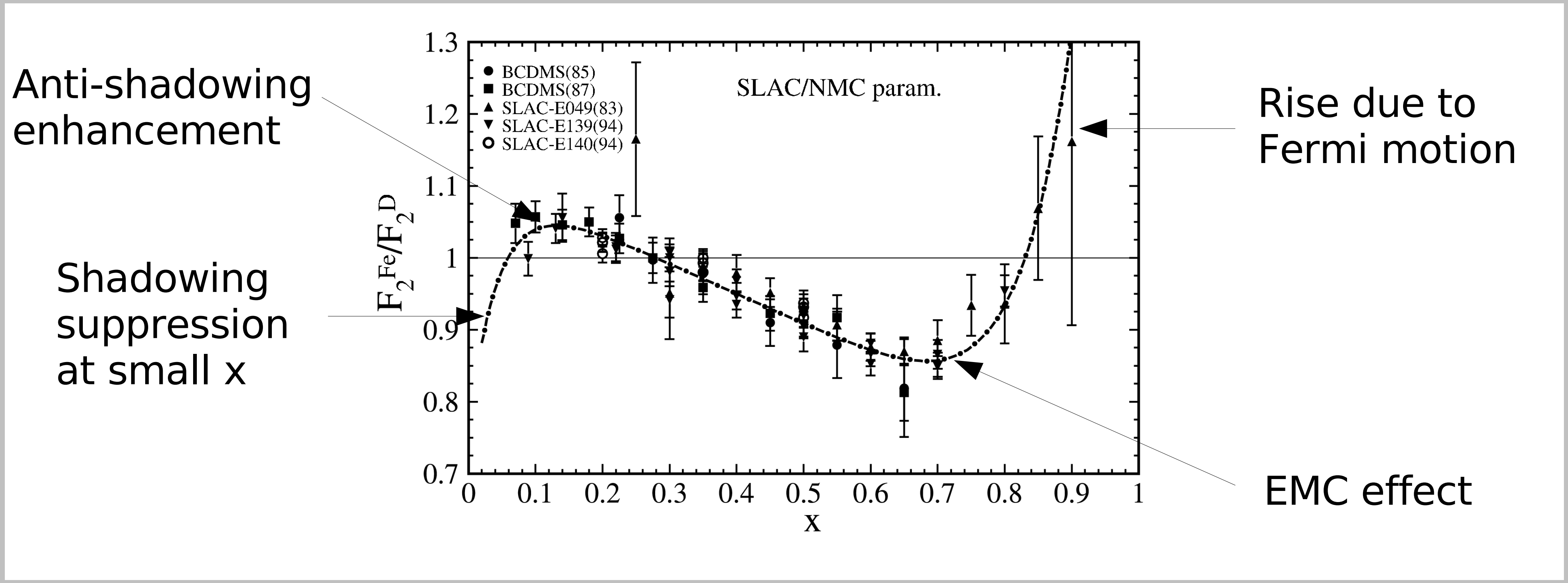


CMS





nuclear PDFs



- ✦Needed in ion collisions and for global fits of proton PDFs
- ✦Can constrain them with various processes sensitive to g in pA collisions, end of 2012 at LHC
- ✦Cannot be obtained from free PDFs

nuclear PDFs

Different nPDF groups, different analysis

Functional Form

- Convolution Relation - DS'04:
  $f_i^{p/A}(x_N, Q_0^2) = \int_{x_N}^{A} \frac{dy}{y} W_i(y, A, Z) f_i^p(x_N/y, Q_0^2)$

$$W_v(y, A, Z) = A[a_v \delta(1 - \epsilon_v - y) + (1 - a_v)\delta(1 - \epsilon_{v'} - y)] + n_v (y/A)^{\alpha_v}(1 - y/A)^{\beta_v} + n_s (y/A)^{\alpha_s}(1 - y/A)^{\beta_s}$$

- Multiplicative Factor - EPS'09, HKN'07:
  $f_i^{p/A}(x_N, Q_0^2) = R_i(x_N, Q_0, A, Z) f_i^p(x_N, Q_0^2)$
  $R_i^{HKN}(x, A, Z) = 1 + (1 - \frac{1}{A^\alpha}) \frac{a_i + b_i x + c_i x^2 + d_i x^3}{(1-x)^{\beta_i}} \qquad (i = u_v, d_v, \bar{q}, g)$

$$R_i^{EPS}(x, A, Z) = \begin{cases} a_0 + (a_1 + a_2 x)(e^{-x} - e^{-x_a}) & x \le x_a \\ b_0 + b_1 x + b_2 x^2 + b_3 x^3 & x_a \le x \le x_e \\ c_0 + (c_1 - c_2 x)(1 - x)^{-\beta} & x_e \le x \le 1 \end{cases}$$

- A-Dependant Functional Form - nCTEQ:

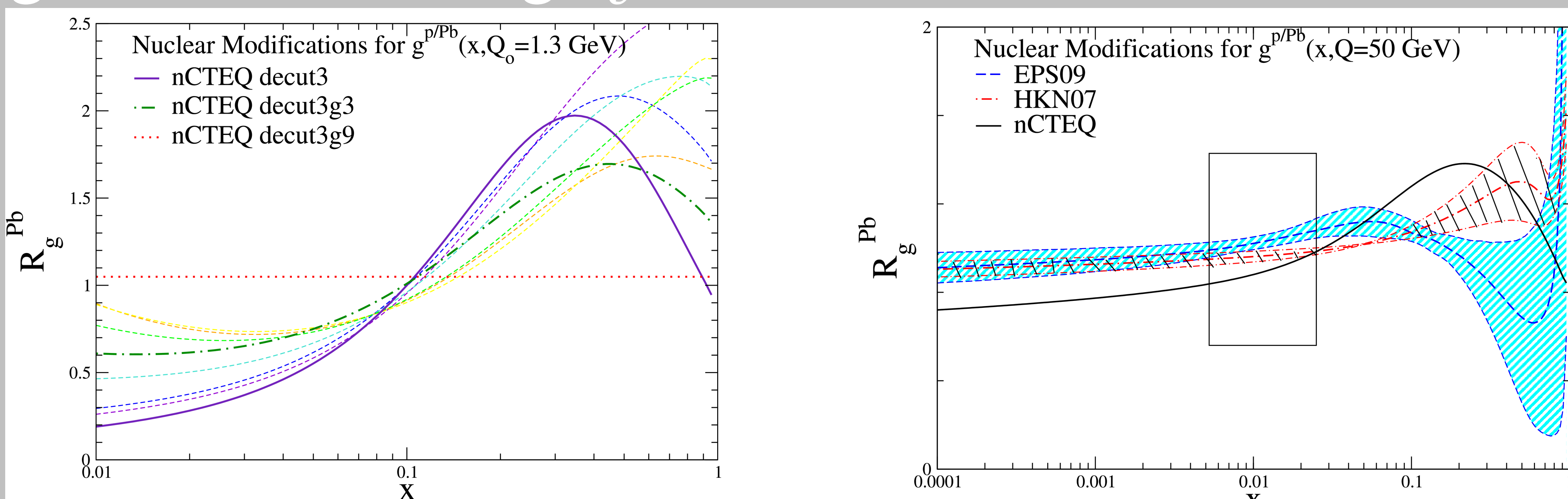
Data

	R	Nucleus	Experiment	EPS09	HKN07	DS04
DIS		D/p	NMC		O	
	A/D	4He	SLAC E139	O	O	O
			NMC95	O (5)	O	O
		Li	NMC95	O	O	
		Be	SLAC E139	O	O	O
		C	EMC-88, 90		O	
			NMC 95	O	O	O
			SLAC E139	O	O	O
			FNAL-E665		O	
		N	BCDMS 85		O	
			HERMES 03		O	
		Al	SLAC E49		O	
			SLAC E139	O	O	O
		Ca	EMC 90		O	
			NMC 95	O	O	O
			SLAC E139	O	O	O
			FNAL-E665		O	
		Fe	SLAC E87		O	
			SLAC E139	O (15)	O	O
			SLAC E140		O	
			BCDMS 87		O	
		Cu	EMC 93	O	O	
		Kr	HERMES 03		O	
		Ag	SLAC E139	O	O	O
		Sn	EMC 88		O	
		Au	SLAC E139	O	O	O
			SLAC E140		O	
		Pb	FNAL-E665		O	
	A/C	Be	NMC 96	O	O	O
		Al	NMC 96	O	O	O
		Ca	NMC 95		O	
			NMC 96	O	O	O
		Fe	NMC 96	O	O	O
		Sn	NMC 96	O (10)	O	O
		Pb	NMC 96	O	O	O
	A/Li	C	NMC 95	O	O	
		Ca	NMC 95	O	O	
DY	A/D	C	FNAL-E772	O	O	O
		Ca		O (15)	O	O
		Fe		O (15)	O	O
		W		O (10)	O	O
	A/Be	Fe	FNAL E866	O	O	
		W		O	O	
π pro	dA/pp	Au	RHIC-PHENIX	O (20)		

gluon nPDF

F.Arleo F. Olness J.Owens I.Schienbein K.Kovarik J.Yu TS arXiv:1012.1178

gluon nPDF largely unconstrained

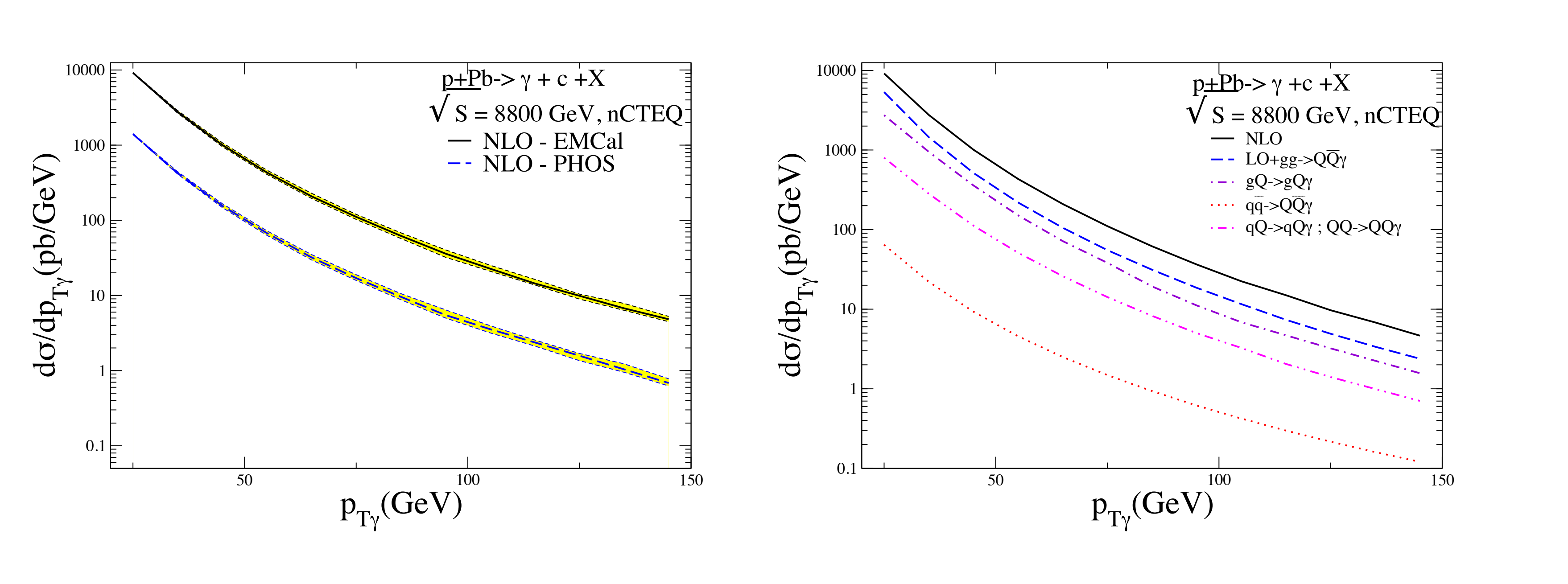


Processes helpful for constraining g nPDF

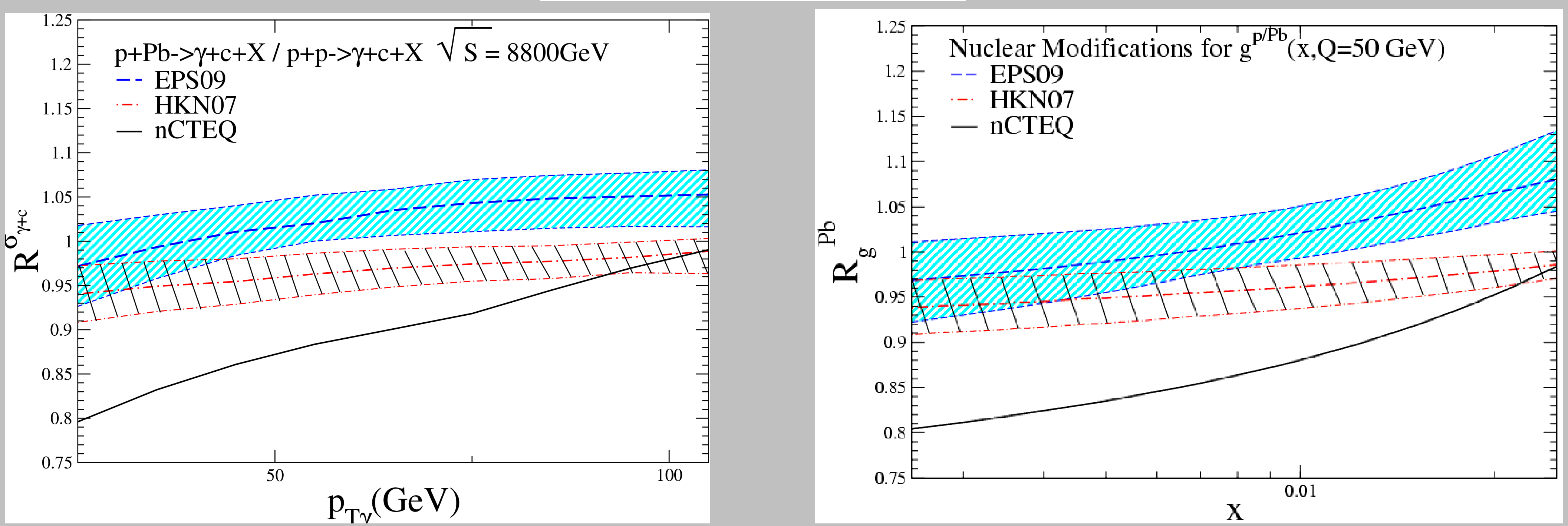
- Inclusive jet data (like Tevatron for free gluon)
- Inclusive hadron production
- Heavy quark ; Quarkonium production
- Isolated direct photons
- Direct Photons + jet
- **Direct Photon + Heavy Quark Jet**

gluon nPDF

F.Arleo F. Olness J.Owens I.Schienbein K.Kovarik J.Yu TS arXiv:1203.0282



$$R_{pA}^{\gamma Q} = \frac{\sigma(pA \to \gamma\ Q\ X)}{A\ \sigma(pp \to \gamma\ Q\ X)}$$



The cross-section ratio follows the gluon ratio

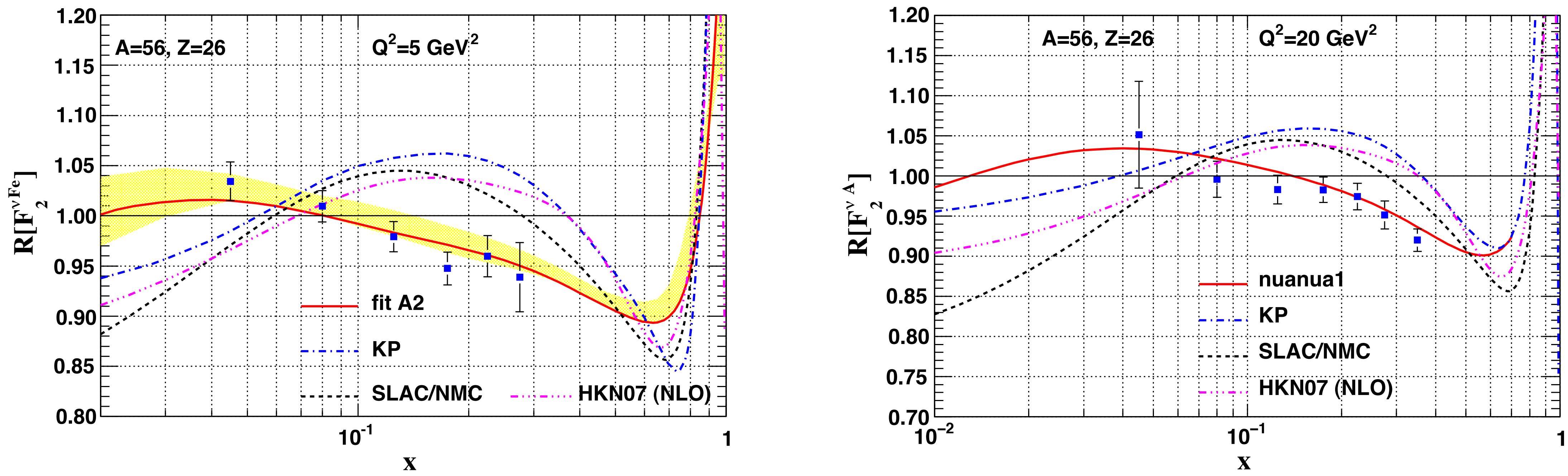
Conclusions

- PDFs an indispensable part of hadronic cross-section calculations
- Universal -> obtained through global analysis
- Reduced PDF error -> controlled SM background for BSM searches
- Focus on strange quark PDF and Intrinsic Charm existence
- nPDFs -> need to have own global analysis
- gluon nPDF -> constrain through γ+Q in our case

neutrino DIS fits

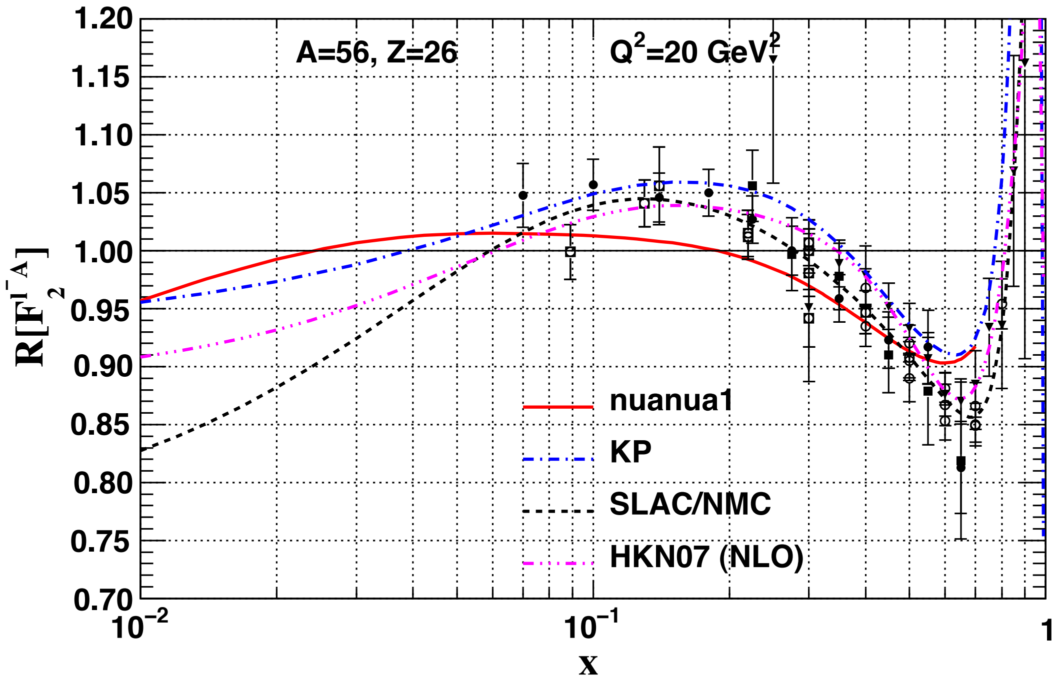
νA data

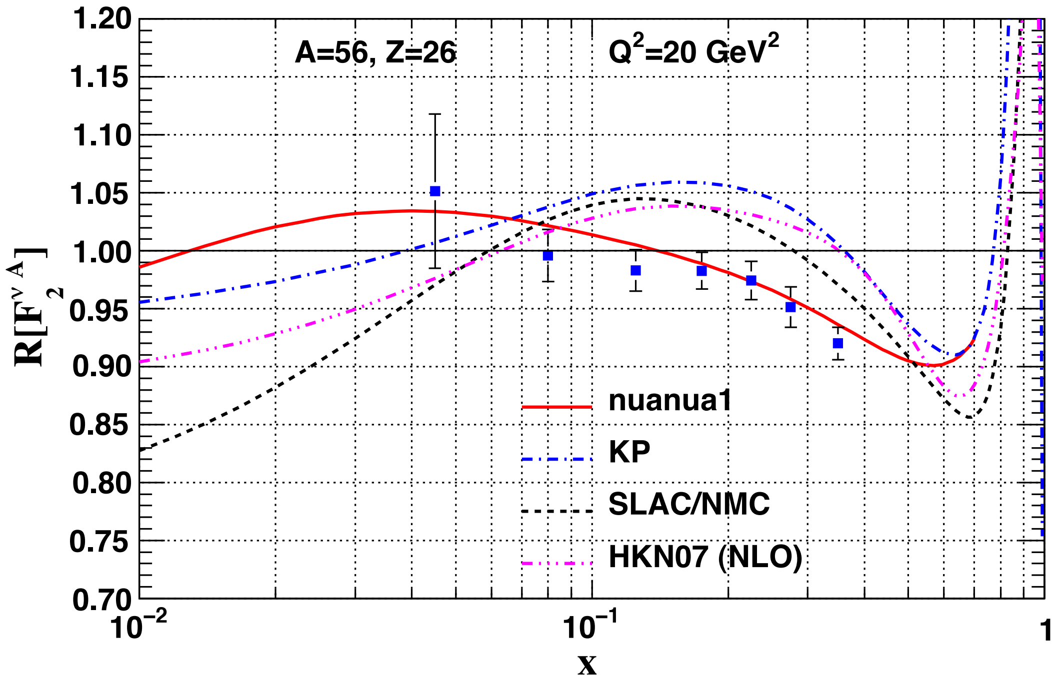
ID	$\mathbf{d\sigma^{\nu A}/dxdy}$: Observable	Experiment	# data
33	Pb	CHORUS ν	607 (412)
34	Pb	CHORUS $\bar{\nu}$	607 (412)
35	Fe	NuTeV ν	1423 (1170)
36	Fe	NuTeV $\bar{\nu}$	1195 (966)
37	Fe	CCFR ν di-muon	44 (44)
38	Fe	NuTeV ν di-muon	44 (44)
39	Fe	CCFR $\bar{\nu}$ di-muon	44 (44)
40	Fe	NuTeV $\bar{\nu}$ di-muon	42 (42)
	Total:		4006 (3134)



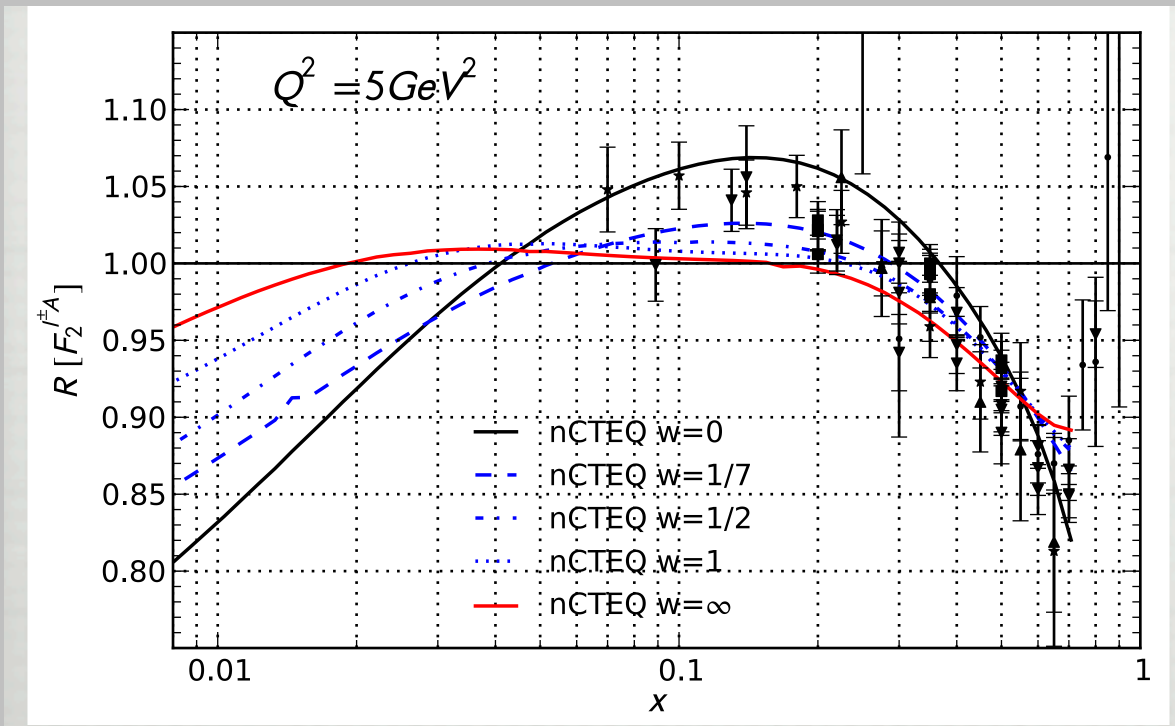
- Left: Fit to only νFe data (arXiv:0710.4897)
- Right: New fit to all νA data in A-dependent nPDF framework (arXiv:0907.2357)
- These fits describe $R[F_2^{\nu A}]$ very well

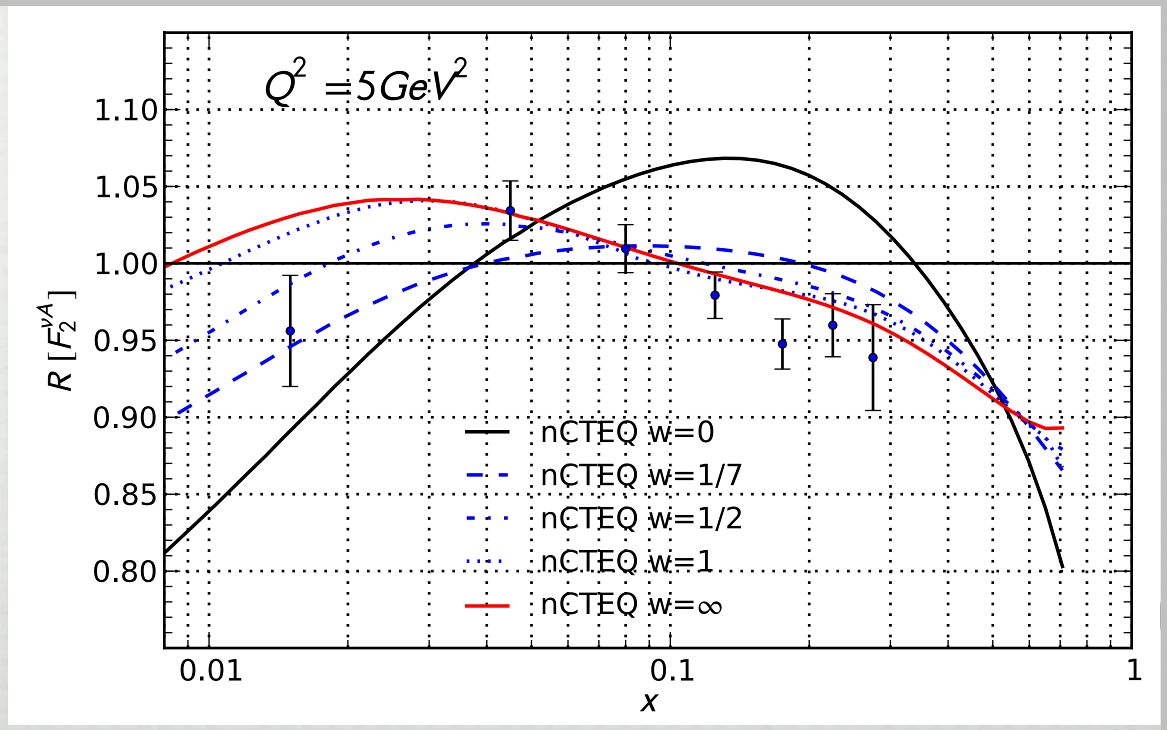
Are there inconsistencies between νA and $l^{\pm}A$?





- The neutrino fit does not describe the DY and $l^{\pm}A$ data
- Can a global fit combining the two data sets help?
- DY, $l^{\pm}A$ (708 data points) with νA (3134 data points)
- Use different weights to make up for data imbalance





- No single compromise fit between charged lepton and neutrino data [PRL106(2011)122301]
- Different nuclear correction factors preferred
- Implications for free and bound PDFs extraction
- Further experimental measurements and theoretical study needed to explain this behavior