LE

DISTRIBUZIONI PARTONICHE

DA HERA A LHC

STEFANO FORTE
UNIVERSITÀ DI MILANO

NAPOLI, 13 MAGGIO 2005

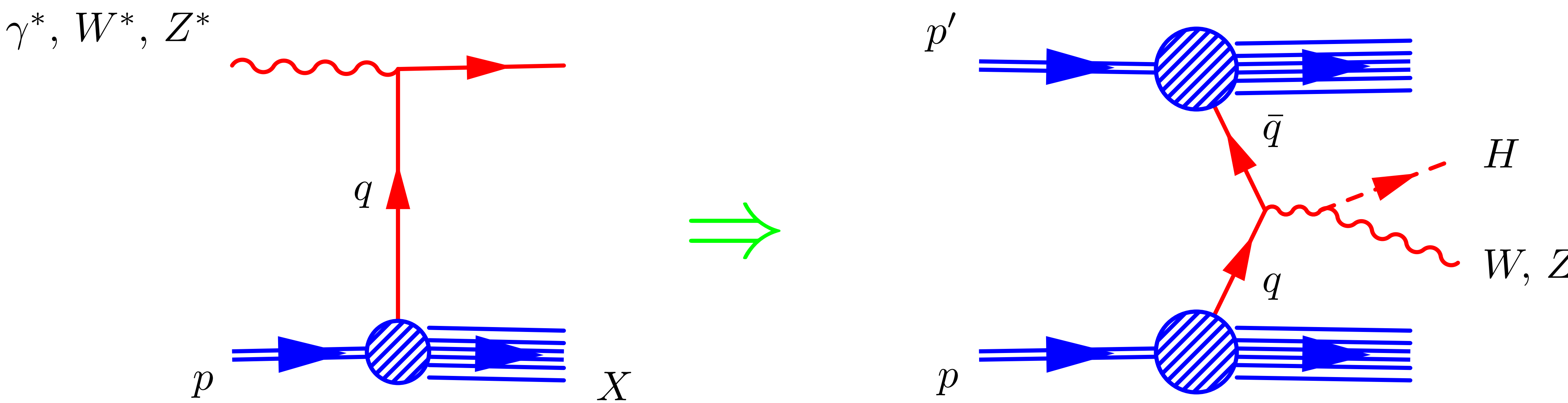
THE PARTON REVOLUTION:

The accurate computation of physical process at a hadron collider requires good knowledge of parton distributions of the nucleon

THE PARTON REVOLUTION:

THE ACCURATE COMPUTATION OF PHYSICAL PROCESS AT A HADRON COLLIDER REQUIRES GOOD KNOWLEDGE OF PARTON DISTRIBUTIONS OF THE NUCLEON

FACTORIZATION



IN ORDER TO EXTRACT THE RELEVANT PHYSICS SIGNAL,

WE NEED TO KNOW THE PARTON DISTRIBUTIONS AND THEIR UNCERTAINTY

PARTON DISTRIBUTIONS PROVIDE THE BRIDGE BETWEEN HADRONIC PHYSICS AND PHYSICS AT THE ENERGY FRONTIER

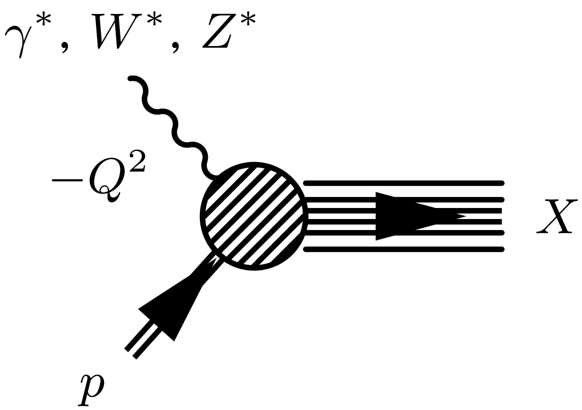
AN ONGOING EFFORT...

SUMMARY

- DETERMINING PARTON DISTRIBUTIONS:
  - PHENOMENOLOGY: FROM DEEP-INELASTIC STRUCTURE FUNCTIONS TO HADRON COLLIDERS
  - THEORY: HIGHER ORDER CORRECTIONS AND RESUMMATIONS
- AN INTERLUDE: THE NUTEV ANOMALY
  - PRECISION PHYSICS WITH PDFS COMES OF AGE
- THE UNCERTAINTY ON PARTON DISTRIBUTIONS
  - THE STATE OF THE ART: PDFS WITH ERRORS AND THEIR LIMITATIONS
  - THE FUTURE?: MONTECARLO PARTONS AND NEURAL PARTONS

DEEP-INELASTIC SCATTERING

STRUCTURE FUNCTIONS. . .



Lepton fractional energy loss: $y = \frac{p\cdot q}{p\cdot k}$;

Bjorken x: $x = \frac{Q^2}{2p\cdot q}$

lepton-nucleon CM energy: $s = \frac{Q^2}{xy}$;

virtual boson-nucleon CM energy $W^2 = Q^2 \frac{1-x}{x}$;

$$\frac{d^2\sigma^{\lambda_p \lambda_\ell}(x,y,Q^2)}{dxdy} = \frac{G_F^2}{2\pi(1+Q^2/m_W^2)^2} \frac{Q^2}{xy} \left\{ \left[-\lambda_\ell\, y \left(1-\frac{y}{2}\right) xF_3(x,Q^2) + (1-y)F_2(x,Q^2) \right. \right.$$

$$\left. \left. +y^2 x F_1(x,Q^2) \right] - 2\lambda_p \left[-\lambda_\ell\, y(2-y)x g_1(x,Q^2) - (1-y) g_4(x,Q^2) - y^2 x g_5(x,Q^2) \right] \right\}$$

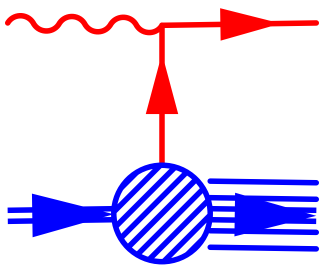
$\lambda_l \;\rightarrow$ lepton helicity

$\lambda_p \;\rightarrow$ proton helicity

	PARITY CONS.	PARITY VIOL.
UNPOL.	F_1, F_2	F_3
POL.	g_1	g_4, g_5

...AND PARTON DISTRIBUTIONS

STRUCTURE FUNCTION=HARD COEFF.⊗PARTON DISTN.



$$F_2^{\rm NC}(x,Q^2) = x\sum_{\text{flav. } i} e_i^2 (q_i+\bar q_i) + \alpha_s \left[C_i[\alpha_s]\otimes(q_i+\bar q_i) + C_g[\alpha_s]\otimes g\right]$$

q_i quark, $\bar q_i$ antiquark, g gluon

LEADING PARTON CONTENT (up to $O[\alpha_s]$ corrections)

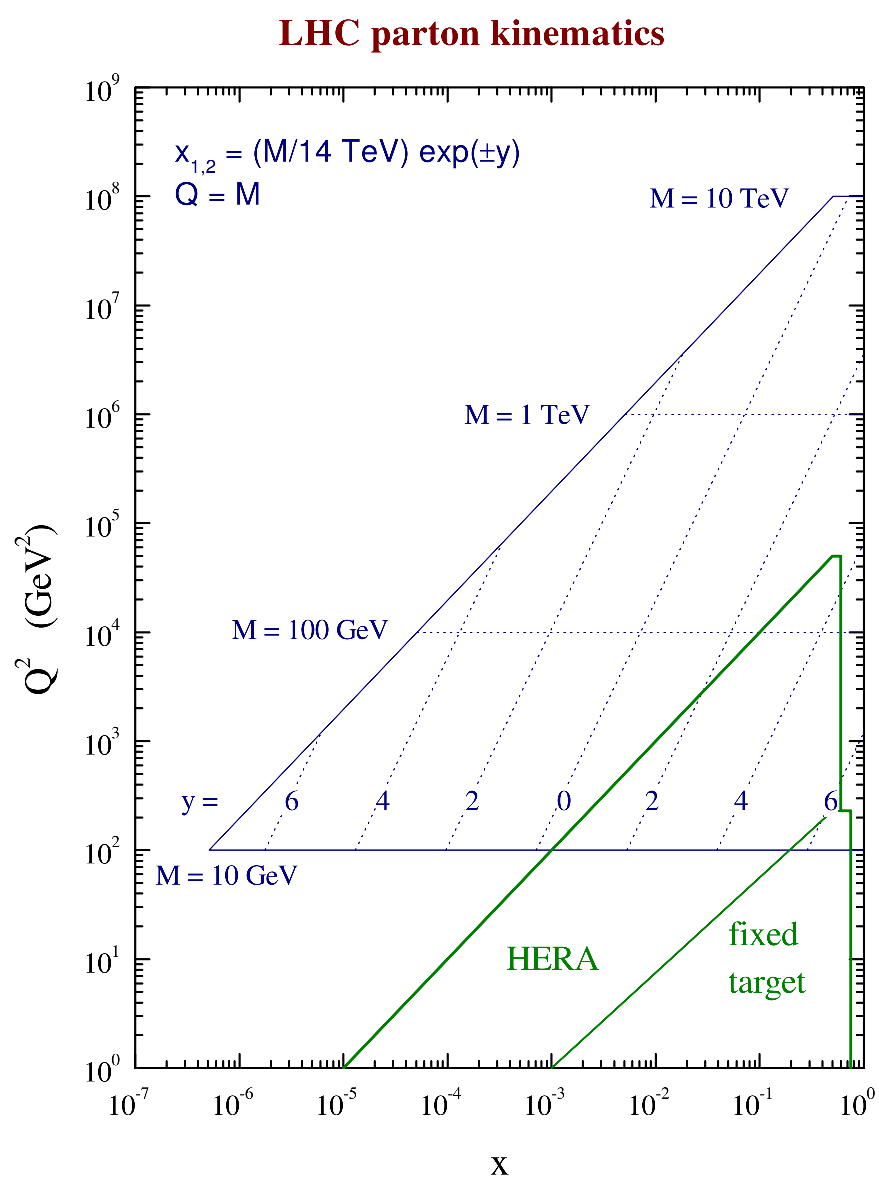
	$q_i \equiv q_i^{\uparrow\uparrow} + q_i^{\uparrow\downarrow}$	$\Delta q_i \equiv q_i^{\uparrow\uparrow} - q_i^{\uparrow\downarrow}$
NC	$F_1{}^{\gamma,\,Z} = \sum_i e_i^2\,(q_i+\bar q_i)$	$g_1{}^{\gamma,\,Z} = \sum_i e_i^2\,(\Delta q_i+\Delta\bar q_i)$
CC	$F_1^{W^+} = \bar u + d + s + \bar c$	$g_1^{W^+} = \Delta\bar u + \Delta d + \Delta s + \Delta\bar c$
CC	$-F_3^{W^+}/2 = \bar u - d - s + \bar c$	$g_5^{W^+} = \Delta\bar u - \Delta d - \Delta s + \Delta\bar c$
	$F_2 = 2xF_1$	$g_4 = 2xg_5$

$W^+ \to W^- \;\Rightarrow\; u\leftrightarrow d,\; c\leftrightarrow s$; more combinations using Isospin: $p\to n \;\Rightarrow\; u\leftrightarrow d$

FROM HERA TO LHC

AT A HADRON COLLIDER

- SCALE Q DETERMINED BY MASS OF FINAL STATE
- MOMENTUM FRACTIONS x_1 x_2 DETERMINED BY MASS & RAPIDITY OF FINAL STATE



FROM HERA TO LHC ⇒ EVOLUTION

AT A HADRON COLLIDER

- SCALE Q DETERMINED BY MASS OF FINAL STATE
- MOMENTUM FRACTIONS x_1 x_2 DETERMINED BY MASS & RAPIDITY OF FINAL STATE

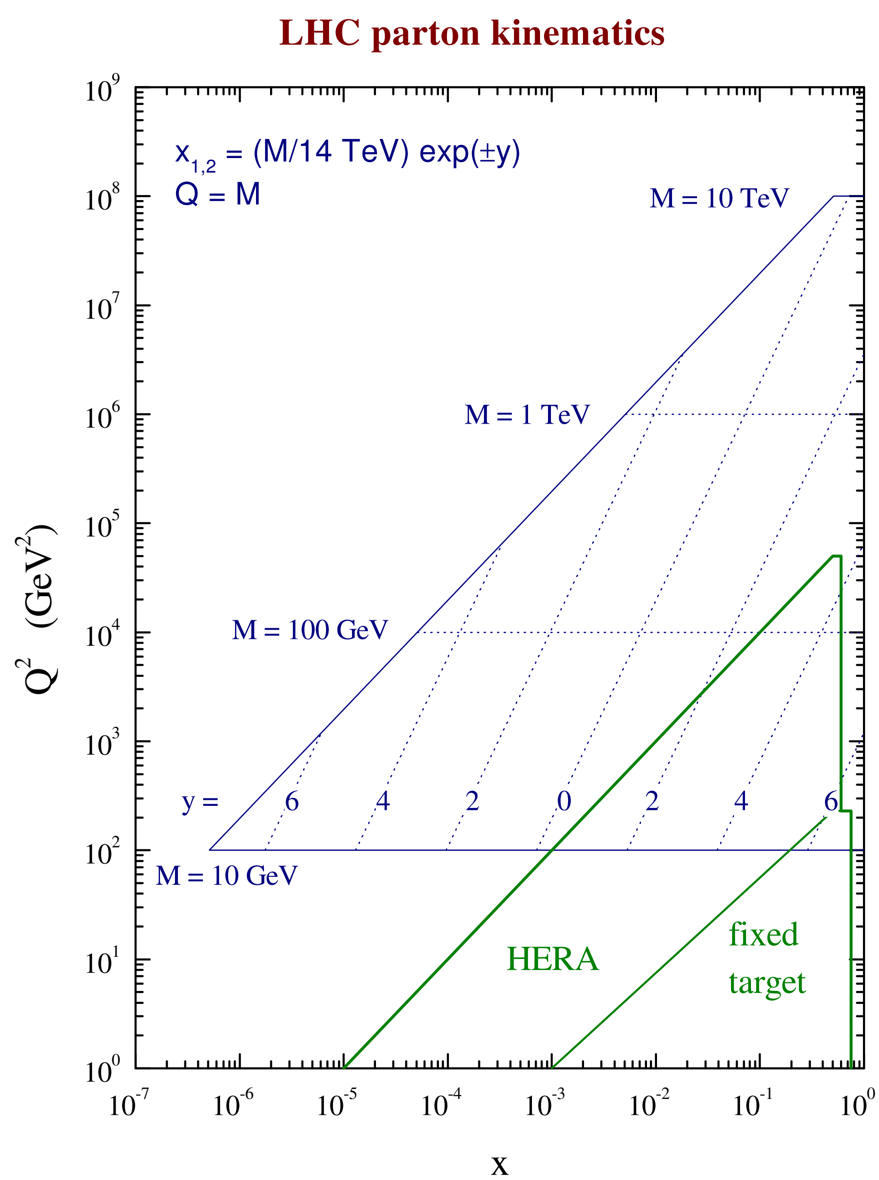
USE ALTARELLI-PARISI EQNS:

$$\frac{d}{dt}\Delta q_{NS} = \frac{\alpha_s(t)}{2\pi} P_{qq}^{NS} \otimes \Delta q_{NS},$$

$$\frac{d}{dt}\begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix} = \frac{\alpha_s(t)}{2\pi}\begin{pmatrix}P_{qq}^S & 2n_f P_{qg}^S \\ P_{gq}^S & P_{gg}^S\end{pmatrix} \otimes \begin{pmatrix}\Delta\Sigma \\ \Delta g\end{pmatrix}$$

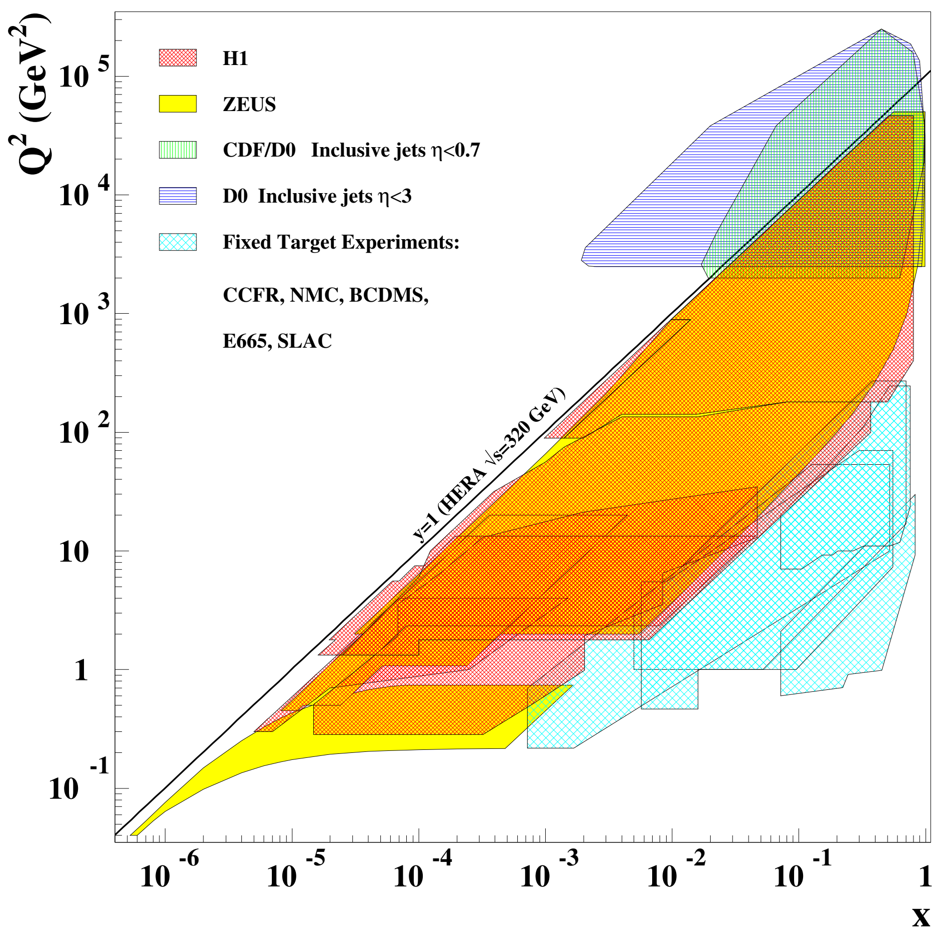
TO EVOLVE PARTONS

FROM DIS TO LHC KINEMATICS



THE NAME OF THE GAME

DIS DATA $\longrightarrow$ PARTON DISTRIBUTIONS



PROBLEMS:

- STRUCTURE FUNCTION (OR XSECT) IS A CONVOLUTION OVER x OF PARTON DISTNS. AND PERTURBATIVE CROSS SECTION $\longrightarrow$ MUST DECONVOLUTE

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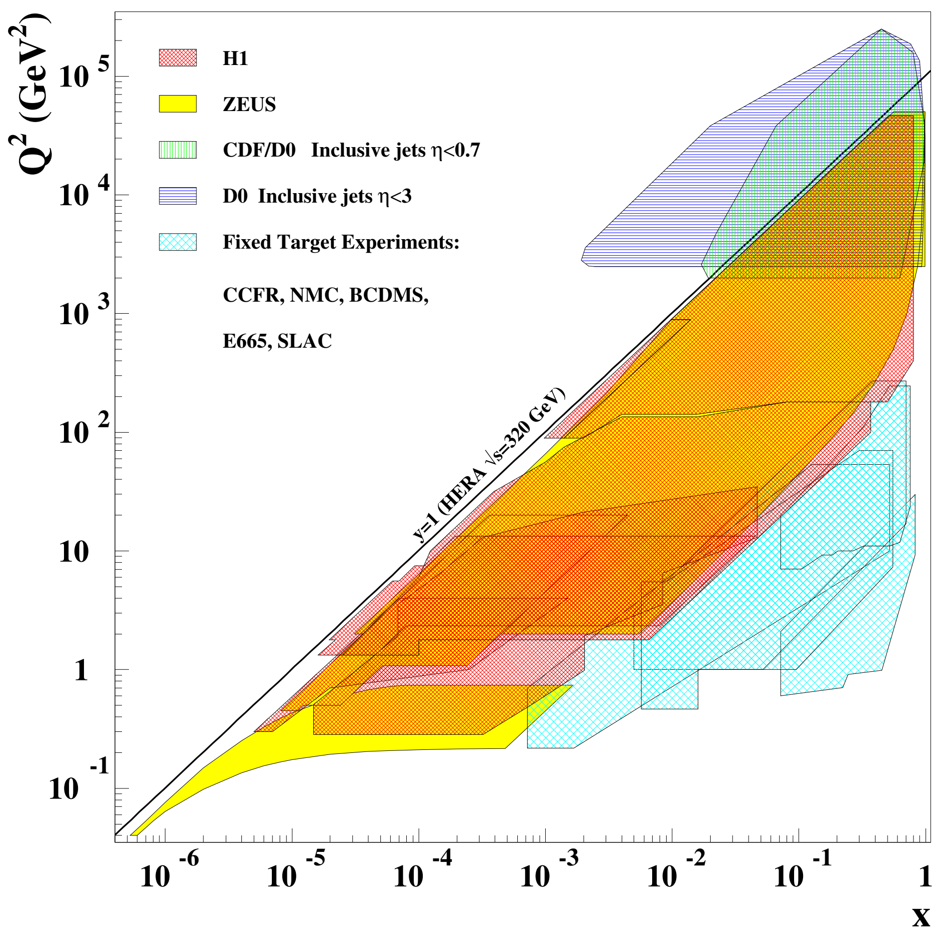

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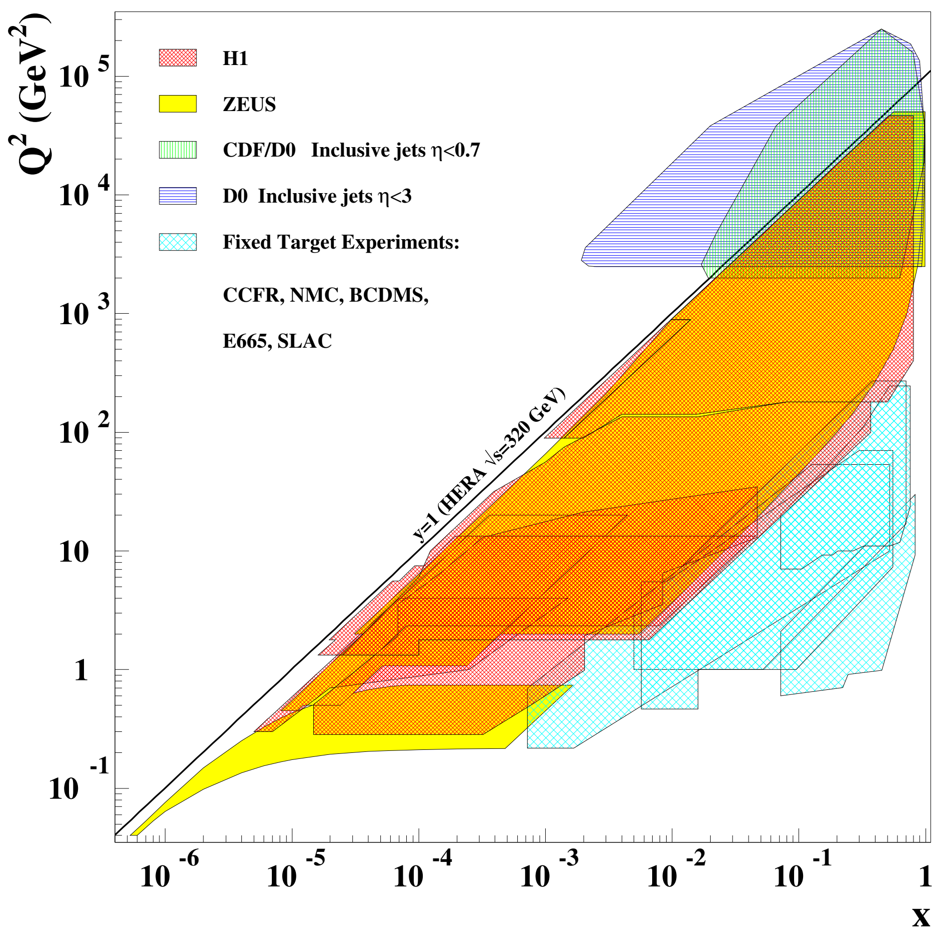

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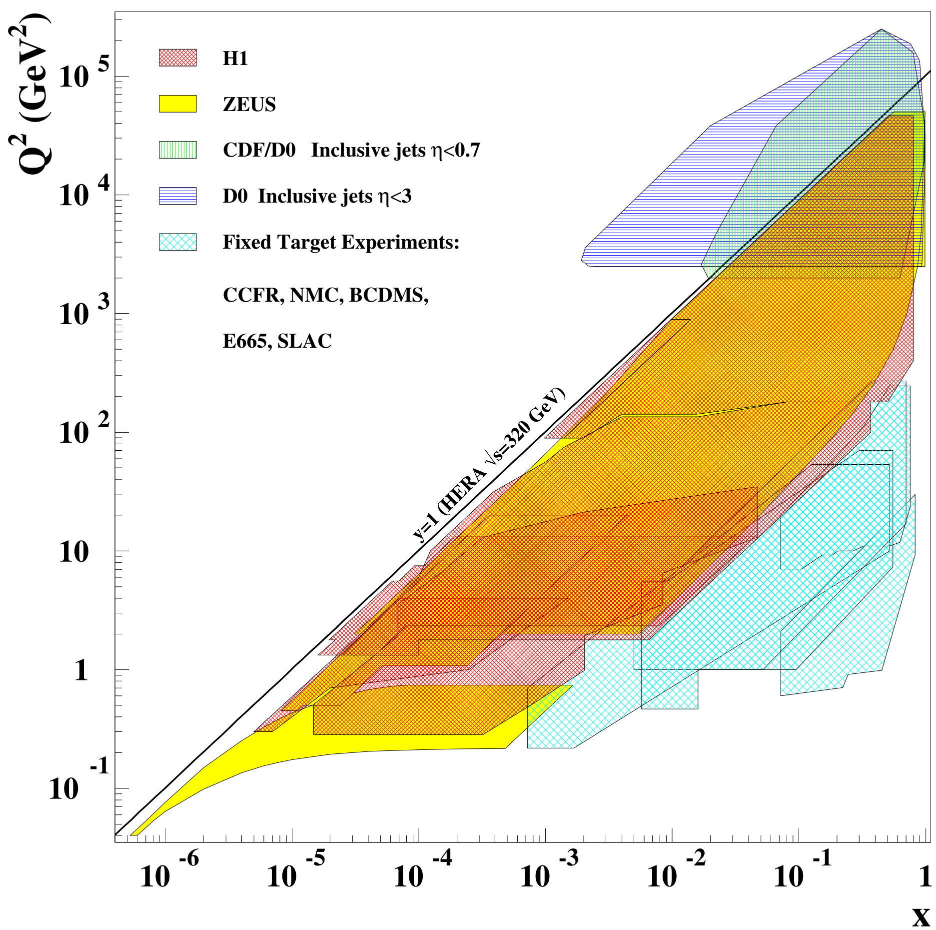

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- TH UNCERTAINTIES: HIGHER PERTURBATIVE ORDERS, RESUMMATION, NUCLEAR CORRECTIONS, HIGHER TWIST, HEAVY QUARK THRESHOLDS. . .

PHENOMENOLOGY: DETERMINING THE GLUON

EVOLUTION:

SINGLET SCALING VIOLATIONS

$$\frac{d}{dt}F_2^s(N,Q^2) = \frac{\alpha_s(Q^2)}{2\pi}\left[\gamma_{qq}(N)F_2^s + 2\,n_f\gamma_{qg}(N)g(N,Q^2)\right] + O(\alpha_s^2)$$

$$F_2(N,Q^2) \equiv \int_0^1 dx\, x^{N-1}F_2(x,Q^2); \qquad \gamma_{ij}(N) \equiv \int_0^1 dx\, x^{N-1}P_{ij}(x,Q^2)$$

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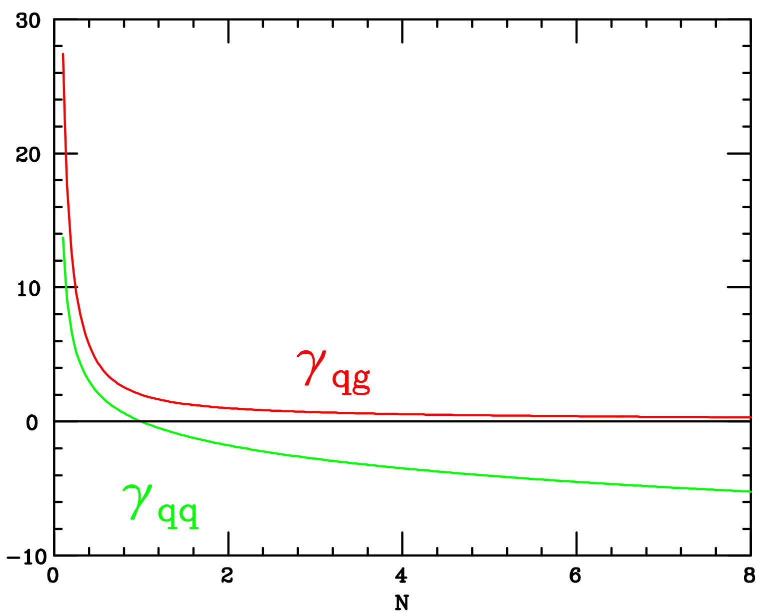
LARGE/SMALL X $\Leftrightarrow$ LARGE/SMALL N

AT LARGE N

$\gamma_{qg} << \gamma_{qq}$



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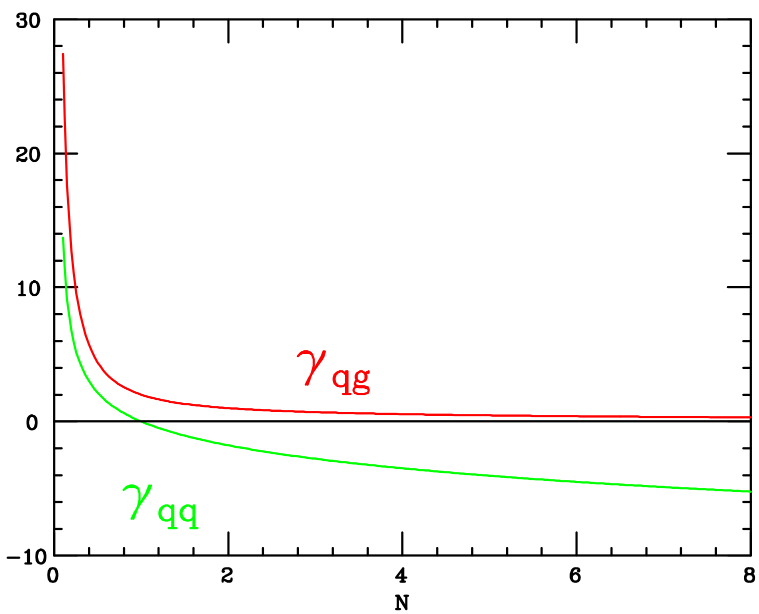
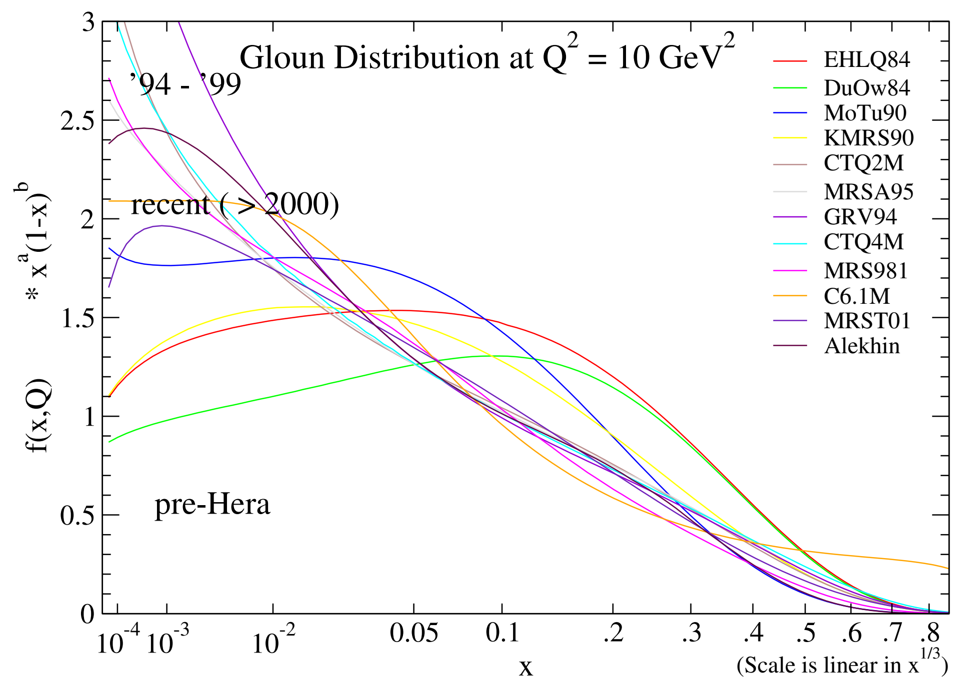


AT LARGE x

$\Rightarrow$ GLUON HARD TO DETERMINE



W.K. Tung, 2004

PHENOMENOLOGY: DISENTANGLING THE QUARK SEA

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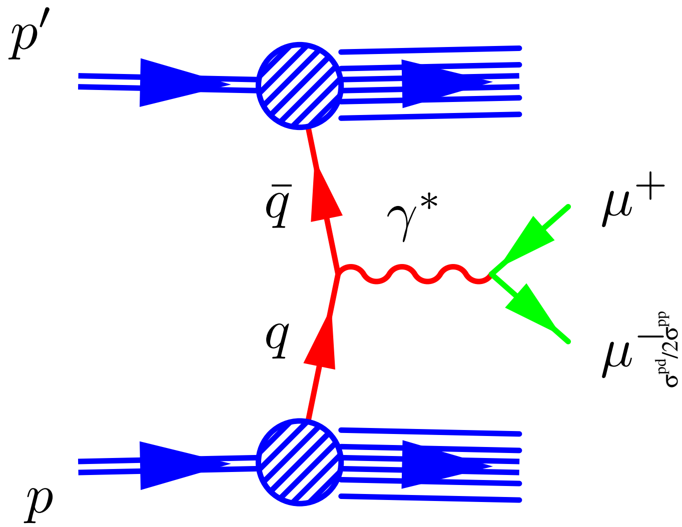
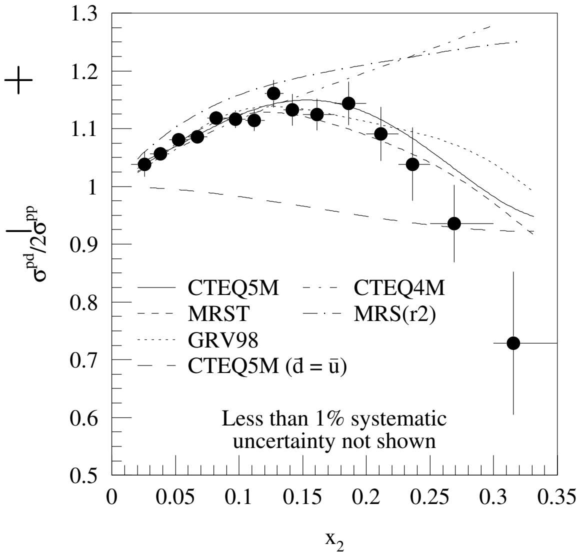
DRELL-YAN p/d ASYMMETRY





$$\left.\frac{\sigma^{pd}}{\sigma^{pp}}\right|_{x_1 >> x_2} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right)$$

E866

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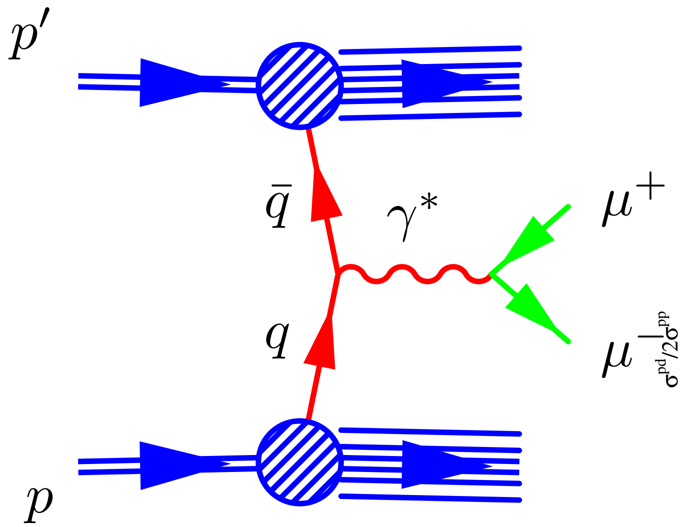

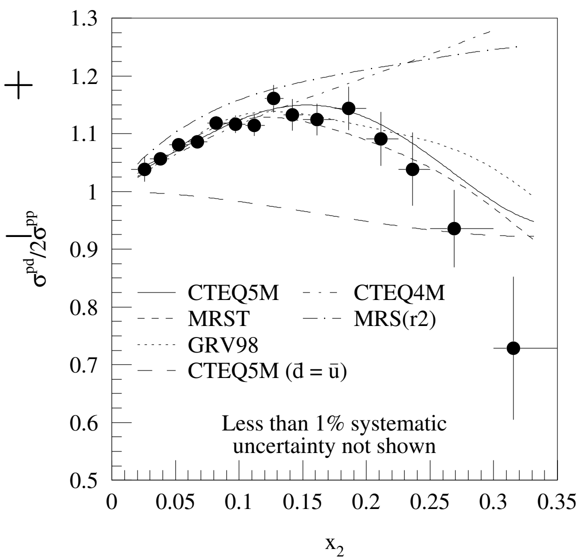

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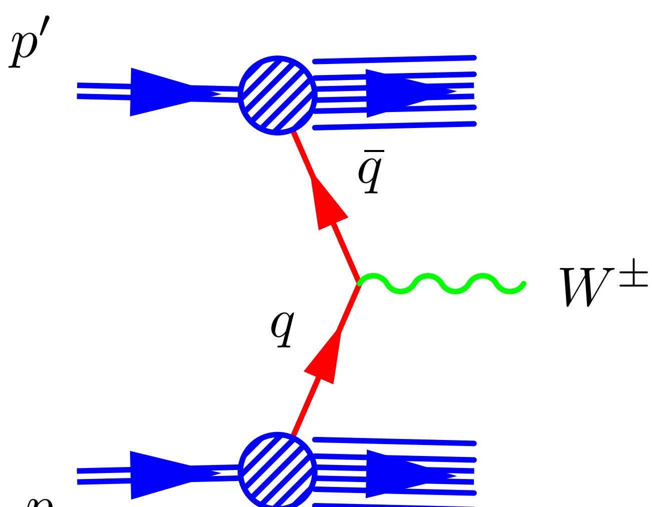
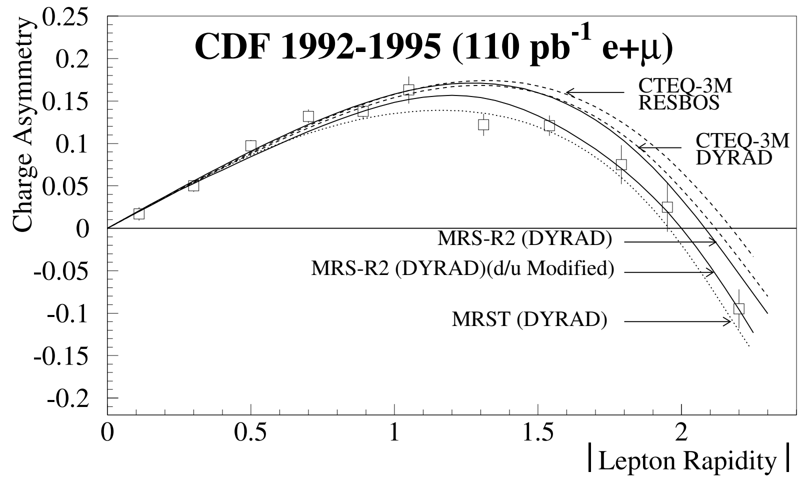
E866

$W^{\pm}$ ASYMMETRY





CDF

PHENOMENOLOGY: DISENTANGLING STRANGENESS

γ^* SCATTERING VS. $W^\pm$ SCATTERING:

IN NC, CHARGED LEPTON DIS, ONLY MEASURE COMBINATION $\sum_i e_i^2 (q_i + \bar{q}_i)$

- CANNOT DETERMINE STRANGENESS
- CAN ONLY DETERMINE C-EVEN COMBINATION $q_i + \bar{q}_i$

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IN NEUTRINO DIS, CAN DISENTANGLE INDIVIDUAL PDFS BY LINEAR COMBINATION: AT LO

$$\frac{1}{2}\left(F_1^{W^-} + \frac{1}{2}F_3^{W^-}\right) = u + c; \qquad \frac{1}{2}\left(F_1^{W^+} - \frac{1}{2}F_3^{W^+}\right) = \bar{u} + \bar{c}$$

$$\frac{1}{2}\left(F_1^{W^+} + \frac{1}{2}F_3^{W^+}\right) = d + s; \qquad \frac{1}{2}\left(F_1^{W^-} - \frac{1}{2}F_3^{W^-}\right) = \bar{d} + \bar{s}$$

c, $\bar{c}$, s, $\bar{s}$ only present above charm threshold

Theoretical Issues: NNLO corrections

how big is the impact of higher order perturbative corrections?

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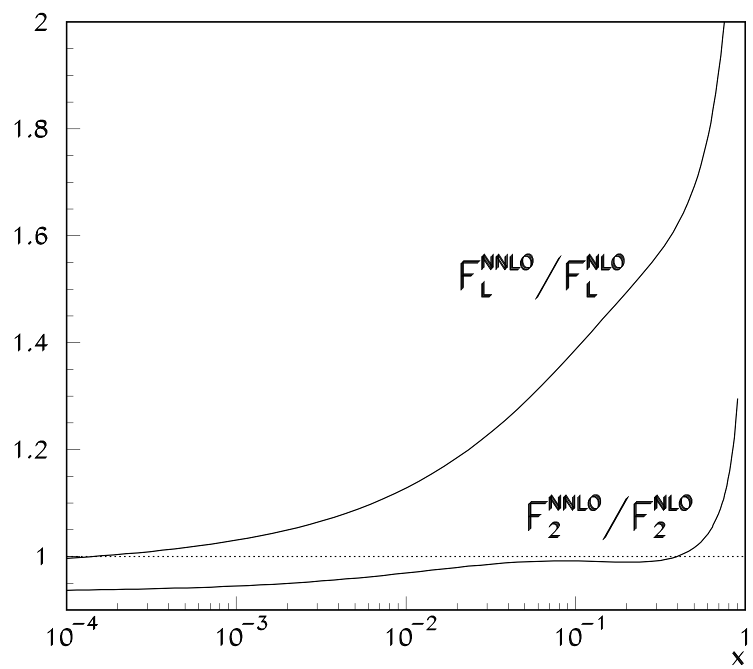
how big is the impact of higher order perturbative corrections?

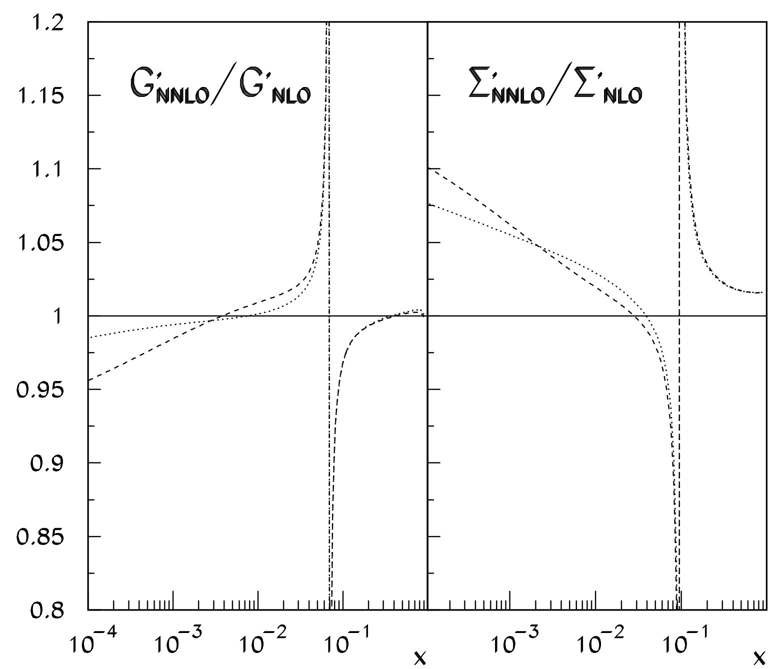
FULL NNLO splitting functions computed recently!

(Moch, Vermaseren and Vogt, April 2004)

perturbative coefficients



evolution



Alekhin

The Results

Anomalous dimensions in Mellin space

– One-loop : Gross, Wilczek ’73

$$\gamma_{\rm ns}^{(0)}(N) \quad = \quad C_F\Big(2(\mathbf{N}_- + \mathbf{N}_+)S_1 - 3\Big)$$

– Two-loop : Floratos, Ross, Sachrajda ‘79 ; Gonzalez-Arroyo, Lopez, Ynduráin ‘79

$$\gamma_{\rm ns}^{(1)+}(N) \; = 4C_AC_F\Bigg(2\mathbf{N}_+S_3 - \frac{17}{24} - 2S_{-3} - \frac{28}{3}S_1 + (\mathbf{N}_- + \mathbf{N}_+)\Bigg[\frac{151}{18}S_1 + 2S_{1,-2} - \frac{1}{6}$$

$$+4C_Fn_f\Bigg(\frac{1}{12} + \frac{4}{3}S_1 - (\mathbf{N}_- + \mathbf{N}_+)\Bigg[\frac{11}{9}S_1 - \frac{1}{3}S_2\Bigg]\Bigg) + 4{C_F}^2\Bigg(4S_{-3} + 2S_1 + 2S_2 - \frac{3}{8}$$

$$+\mathbf{N}_-\Bigg[S_2 + 2S_3\Bigg] - (\mathbf{N}_- + \mathbf{N}_+)\Bigg[S_1 + 4S_{1,-2} + 2S_{1,2} + 2S_{2,1} + S_3\Bigg]\Bigg)$$

$$\gamma_{\rm ns}^{(1)-}(N) \; = \; \gamma_{\rm ns}^{(1)+}(N) + 16C_F\Bigg(C_F - \frac{C_A}{2}\Bigg)\Bigg((\mathbf{N}_- - \mathbf{N}_+)\Bigg[S_2 - S_3\Bigg] - 2(\mathbf{N}_- + \mathbf{N}_+ - 2)$$

– Compact notation : $\mathbf{N}_{\pm} f(N) \, = \, f(N \pm 1)$, $\quad \mathbf{N}_{\pm\mathbf{i}} f(N) \, = \, f(N \pm i)$

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THE ONE THEY LIKE IN STOCKHOLM: $\Rightarrow$

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– Three-loop :

S.M., Vermaseren, Vogt ‘04

$$\gamma_{\rm ns}^{(2)+}(N) = 16 C_A C_F n_f \Big(\frac{3}{2}\zeta_3 - \frac{5}{4} + \frac{10}{9}S_{-3} - \frac{10}{9}S_3 + \frac{4}{3}S_{1,-2} - \frac{2}{3}S_{-4} + 2S_{1,1} - \frac{25}{9}S_2 + \frac{257}{27}S_1 - \frac{2}{3}S_{-3,1} - \mathbf{N}_+\Big[S_{2,1} - \frac{2}{3}S_{3,1} -$$

$$- (\mathbf{N}_+ - 1)\Big[\frac{23}{18}S_3 - S_2\Big] - (\mathbf{N}_- + \mathbf{N}_+)\Big[S_{1,1} + \frac{1237}{216}S_1 + \frac{11}{18}S_3 - \frac{317}{108}S_2 + \frac{16}{9}S_{1,-2} - \frac{2}{3}S_{1,-2,1} - \frac{1}{3}S_{1,-3} - \frac{1}{2}S_{1,3} - \frac{1}{2}S_{2,1}$$

$$- \frac{1}{3}S_{2,-2} + S_1\zeta_3 + \frac{1}{2}S_{3,1}\Big]\Big) + 16 C_F {C_A}^2 \Big(\frac{1657}{576} - \frac{15}{4}\zeta_3 + 2S_{-5} + \frac{31}{6}S_{-4} - 4S_{-4,1} - \frac{67}{9}S_{-3} + 2S_{-3,-2} + \frac{11}{3}S_{-3,1} + \frac{3}{2}S_{-2}$$

$$- 6S_{-2}\zeta_3 - 2S_{-2,-3} + 3S_{-2,-2} - 4S_{-2,-2,1} + 8S_{-2,1,-2} - \frac{1883}{54}S_1 - 10S_{1,-3} - \frac{16}{3}S_{1,-2} + 12S_{1,-2,1} + 4S_{1,3} - 4S_{2,-2} - \frac{5}{2}S_4 +$$

$$+ \frac{176}{9}S_2 + \frac{13}{3}S_3 + (\mathbf{N}_- + \mathbf{N}_+ - 2)\Big[3S_1\zeta_3 + 11S_{1,1} - 4S_{1,1,-2}\Big] + (\mathbf{N}_- + \mathbf{N}_+)\Big[\frac{9737}{432}S_1 - 3S_{1,-4} + \frac{19}{6}S_{1,-3} + 8S_{1,-3,1} + \frac{91}{9}S_{1,}$$

$$- 6S_{1,-2,-2} - \frac{29}{3}S_{1,-2,1} + 8S_{1,1,-3} - 16S_{1,1,-2,1} - 4S_{1,1,3} - \frac{19}{4}S_{1,3} + 4S_{1,3,1} + 3S_{1,4} + 8S_{2,-2,1} + 2S_{2,3} - S_{3,-2} + \frac{11}{12}S_{3,1} - S_{4,}$$

$$+ \frac{1}{6}S_{2,-2} - \frac{1967}{216}S_2 + \frac{121}{72}S_3\Big] - (\mathbf{N}_- - \mathbf{N}_+)\Big[3S_2\zeta_3 + 7S_{2,1} - 3S_{2,1,-2} + 2S_{2,-2,1} - \frac{1}{4}S_{2,3} - \frac{3}{2}S_{3,-2} - \frac{29}{6}S_{3,1} + \frac{11}{4}S_{4,1} + \frac{1}{2}S_{2,}$$

$$+ \mathbf{N}_+\Big[\frac{28}{9}S_3 - \frac{2376}{216}S_2 - \frac{8}{3}S_4 - \frac{5}{2}S_5\Big]\Big) + 16 C_F n_f^2 \Big(\frac{17}{144} - \frac{13}{27}S_1 + \frac{2}{9}S_2 + (\mathbf{N}_- + \mathbf{N}_+)\Big[\frac{2}{9}S_1 - \frac{11}{54}S_2 + \frac{1}{18}S_3\Big]\Big) + 16 {C_F}^2 C_A \Big(\frac{45}{4}$$

$$- \frac{151}{64} - 10S_{-5} - \frac{89}{6}S_{-4} + 20S_{-4,1} + \frac{134}{9}S_{-3} - 2S_{-3,-2} - \frac{31}{3}S_{-3,1} + 2S_{-3,2} - \frac{9}{2}S_{-2} + 18S_{-2}\zeta_3 + 10S_{-2,-3} - 6S_{-2,-2}$$

$$+ 8S_{-2,-2,1} - 28S_{-2,1,-2} + 46S_{1,-3} + \frac{26}{3}S_{1,-2} - 48S_{1,-2,1} + \frac{28}{3}S_{1,2} - \frac{185}{6}S_3 - 8S_{1,3} + 2S_{3,-2} - 4S_5 - (\mathbf{N}_- + \mathbf{N}_+ - 2)\Big[9S_1\zeta_3$$

$$+ \frac{209}{6}S_{1,1} - 14S_{1,1,-2} - \frac{242}{18}S_2 + 9S_{2,-2} + \frac{33}{4}S_4 - 3S_{3,1} + \frac{14}{3}S_{2,1}\Big] + (\mathbf{N}_- + \mathbf{N}_+)\Big[17S_{1,-4} - \frac{107}{6}S_{1,-3} - 32S_{1,-3,1} - \frac{173}{9}S_{1,-}$$

$$+16S_{1,-2,-2}+\frac{103}{3}S_{1,-2,1}-2S_{1,-2,2}-36S_{1,1,-3}+56S_{1,1,-2,1}+8S_{1,1,3}-\frac{109}{9}S_{1,2}-4S_{1,2,-2}+\frac{43}{3}S_{1,3}-8S_{1,3,1}-11S_{1}$$

$$+21S_{2,-3}-30S_{2,-2,1}-4S_{2,1,-2}-5S_{2,3}-S_{4,1}+\frac{31}{6}S_{2,-2}-\frac{67}{9}S_{2,1}\Big]+(\mathbf{N}_{-}-\mathbf{N}_{+})\Big[9S_2\zeta_3+2S_{2,-3}+4S_{2,-2,1}-12S_{2,1,}$$

$$+13S_{4,1}+\frac{1}{2}S_{2,-2}+\frac{11}{2}S_4-\frac{33}{2}S_{3,1}+\frac{59}{9}S_3+\frac{127}{6}S_{2,1}-\frac{1153}{72}S_2\Big]+\mathbf{N}_{+}\Big[8S_{3,-2}+\frac{4}{3}S_{3,1}-2S_{3,2}+14S_5+\frac{23}{6}S_4+\frac{73}{3}S_3$$

$$+16{C_F}^2n_f\Big(\frac{23}{16}-\frac{3}{2}\zeta_3+\frac{4}{3}S_{-3,1}-\frac{59}{36}S_2+\frac{4}{3}S_{-4}-\frac{20}{9}S_{-3}+\frac{20}{9}S_1-\frac{8}{3}S_{1,-2}-\frac{8}{3}S_{1,1}-\frac{4}{3}S_{1,2}+\mathbf{N}_{+}\Big[\frac{25}{9}S_3-\frac{4}{3}S_{3,1}-\frac{1}{3}S$$

$$-(\mathbf{N}_{+}-1)\Big[\frac{67}{36}S_2-\frac{4}{3}S_{2,1}+\frac{4}{3}S_3\Big]+(\mathbf{N}_{-}+\mathbf{N}_{+})\Big[S_1\zeta_3-\frac{325}{144}S_1-\frac{2}{3}S_{1,-3}+\frac{32}{9}S_{1,-2}-\frac{4}{3}S_{1,-2,1}+\frac{4}{3}S_{1,1}+\frac{16}{9}S_{1,2}-\frac{4}{3}S$$

$$+\frac{11}{18}S_2-\frac{2}{3}S_{2,-2}+\frac{10}{9}S_{2,1}+\frac{1}{2}S_4-\frac{2}{3}S_{2,2}-\frac{8}{9}S_3\Big]\Big)+16{C_F}^3\Big(12S_{-5}-\frac{29}{32}-\frac{15}{2}\zeta_3+9S_{-4}-24S_{-4,1}-4S_{-3,-2}+6S_{-3}$$

$$-4S_{-3,2}+3S_{-2}+25S_3-12S_{-2}\zeta_3-12S_{-2,-3}+24S_{-2,1,-2}-52S_{1,-3}+4S_{1,-2}+48S_{1,-2,1}-4S_{3,-2}+\frac{67}{2}S_2-17S_4$$

$$+(\mathbf{N}_{-}+\mathbf{N}_{+}-2)\Big[6S_1\zeta_3-\frac{31}{8}S_1+35S_{1,1}-12S_{1,1,-2}+S_{1,2}+10S_{2,-2}+S_{2,1}+2S_{2,2}-2S_{3,1}-3S_5\Big]+(\mathbf{N}_{-}+\mathbf{N}_{+})\Big[23S$$

$$-22S_{1,-4}+32S_{1,-3,1}-2S_{1,-2}-8S_{1,-2,-2}-30S_{1,-2,1}-6S_{1,3}+4S_{1,-2,2}+40S_{1,1,-3}-48S_{1,1,-2,1}+8S_{1,2,-2}+4S_{1,2,2}$$

$$+4S_{1,4}+28S_{2,-2,1}+4S_{2,1,2}+4S_{2,2,1}+4S_{3,1,1}-4S_{3,2}+8S_{2,1,-2}-26S_{2,-3}-2S_{2,3}-4S_{3,-2}-3S_{2,-2}-3S_{2,2}+\frac{3}{2}S_4\Big]$$

$$+(\mathbf{N}_{-}-\mathbf{N}_{+})\Big[12S_{2,1,-2}-6S_2\zeta_3-2S_{2,-3}+3S_{2,3}+2S_{3,-2}-\frac{81}{4}S_{2,1}+14S_{3,1}-5S_{2,-2}-\frac{1}{2}S_{2,2}+\frac{15}{8}S_2+\frac{1}{2}S_3-13S_{4,1}$$

$$+\mathbf{N}_{+}\Big[14S_4-\frac{265}{8}S_2-\frac{87}{4}S_3-4S_{4,1}-4S_5\Big]\Big)$$

THEORETICAL ISSUES: RESUMMATION

AT $O(\alpha_s^n)$, $O\left[ln(\frac{1}{x})^n\right]$ AND $O\left[(ln(1-x))^{2n-1}\right]$ CONTRIBUTIONS ARISE:

IS A FIXED-ORDER PERTURBATIVE CALCULATION SUFFICIENT?

$x_{\rm cut}$:	0	0.0002	0.001	0.0025	0.005	0.01
# DATA POINTS	2097	2050	1961	1898	1826	1762
$\chi^2(x>0)$	2267					
$\chi^2(x>0.0002)$	2212	2203				
$\chi^2(x>0.001)$	2134	2128	2119			
$\chi^2(x>0.0025)$	2069	2064	2055	2040		
$\chi^2(x>0.005)$	2024	2019	2012	1993	1973	
$\chi^2(x>0.01)$	1965	1961	1953	1934	1917	1916
Δ_i^{i+1}	0.19 0.10 0.24 0.28 0.02					

DATA-THEORY AGREEMENT FOR EVOLUTION OF F_2 IMPROVES IF SMALL x DATA REMOVED (MRST 2003)

χ^2 improves with fixed # of pts (same row)

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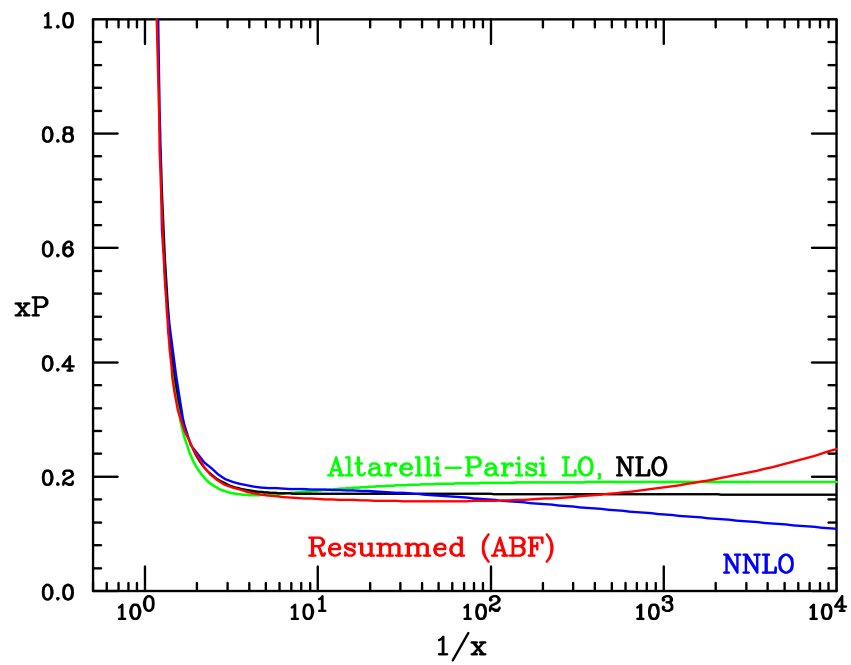
RESUMMED SPL. FCTN.

CLOSER TO LO THAN TO NNLO

Altarelli, Ball, S.F.

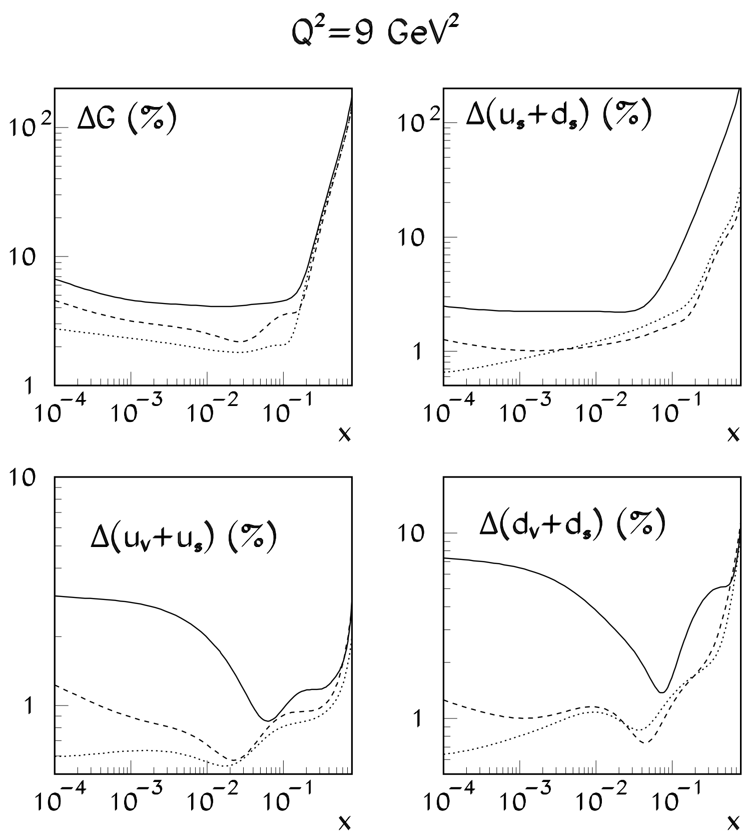
(see also Ciafaloni, Salam et al.)



DOES IT ALL MATTER?

IMPACT OF HADR. COLL. DATA

PDF UNCERTAINTIES



top → DIS only

middle → DIS + Drell-Yan E866

bottom → DIS+DY (E866+LHC)

Alekhin 2004 prelim.

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IMPACT OF HADR. COLL. DATA

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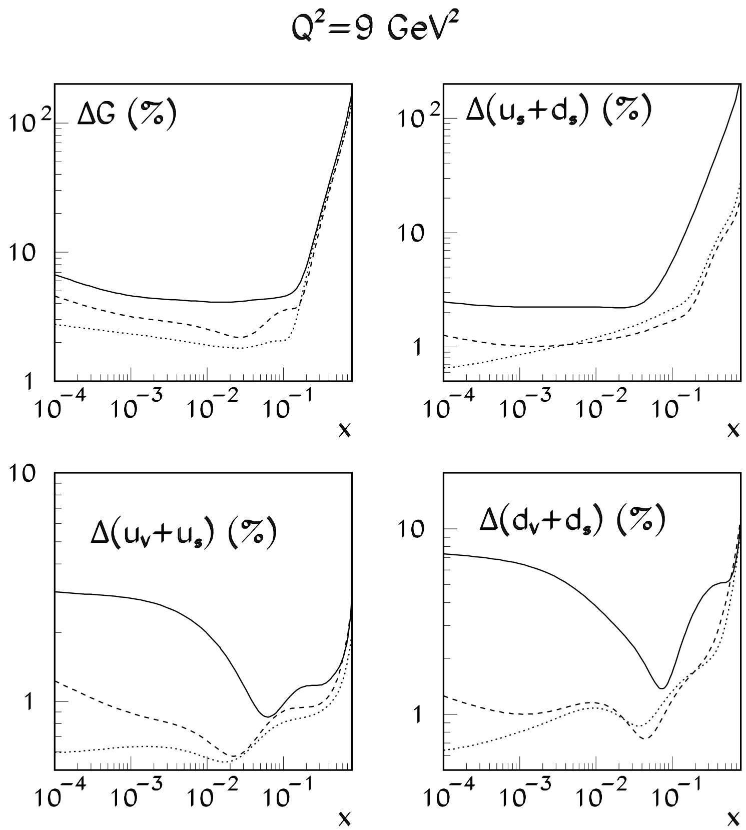

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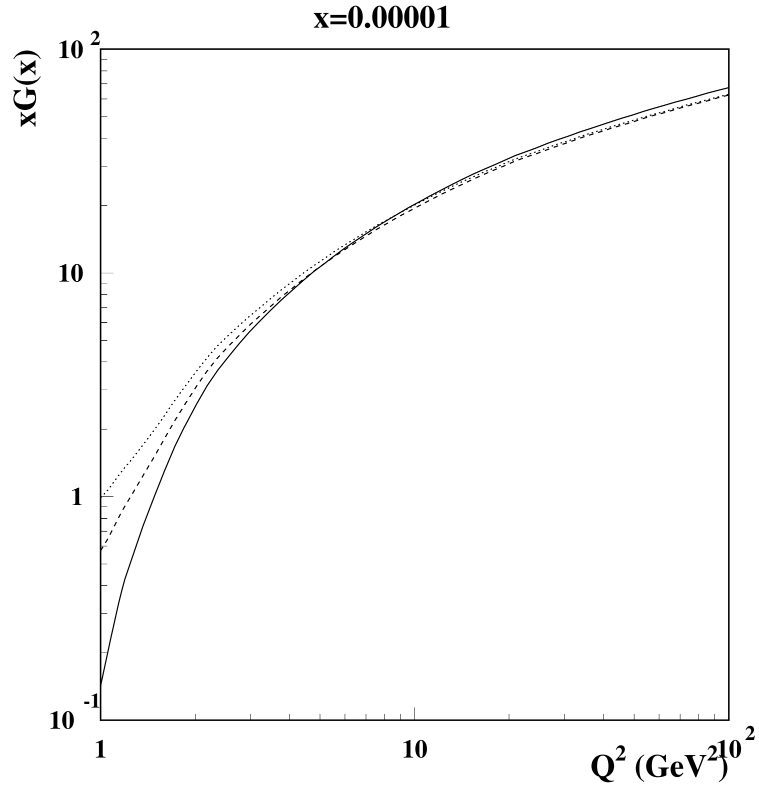
IMPACT OF NNLO CORRECTIONS

GLUON DISTRIBUTION



bottom → NLO best fit

middle → NNLO best fit

top → NNLO evoln. of NLO best fit

NOTE LOG SCALE!

Alekhin 2004 prelim.

PDFs for precision physics: the NuTeV anomaly

PW Ratio: Data...

NuTeV 2001 $\sin^2\theta_W(\text{OS}) = 0.2272 \pm 0.0013(\text{stat}) \pm 0.0009(\text{syst}) \pm 0.0002(M_t, M_H)$

Global Fit 2003 $\sin^2\theta_W(\text{OS}) = 0.2229 \pm 0.0004$

...vs. Theory

$$R^- = \frac{\sigma_{NC}(\nu) - \sigma_{NC}(\bar{\nu})}{\sigma_{CC}(\nu) - \sigma_{CC}(\bar{\nu})} = \left(\frac{1}{2} - \sin^2\theta_W\right)$$

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$$+ O(\delta(u-d)^2 \quad)$$

u,d...denote momentum fractions carried by corresp. quark flavors

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$s - \bar s \approx 0.004$ (or 2% isospin vln.) enough to remove anomaly: can we test it?

Disentangling strangeness

Charm is copiously produced in $W^+ + s \to c$

easily tagged through dimuon signal, 2nd muon from subsequent c decay

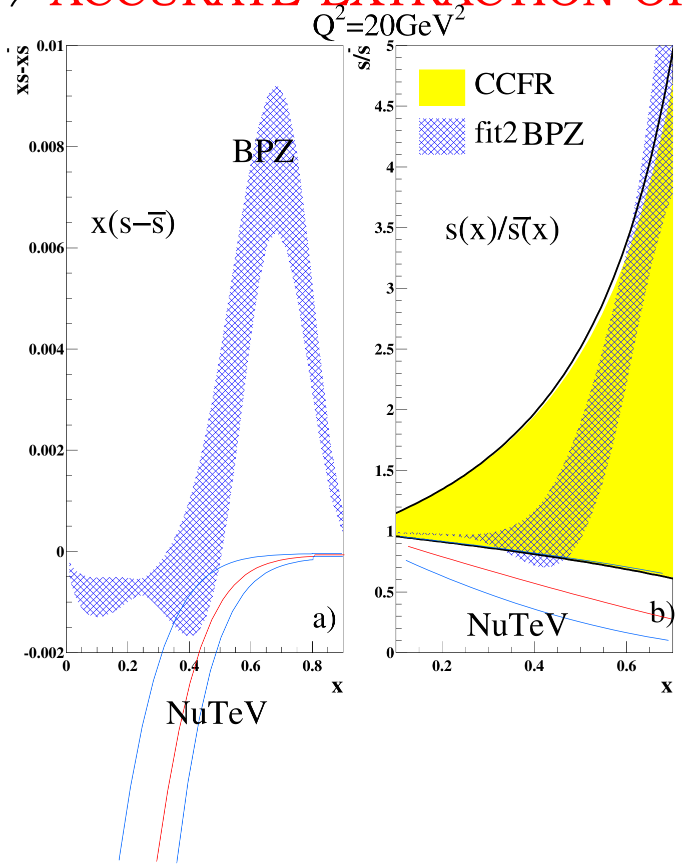
$\Rightarrow$ accurate extraction of the strange distribution

DISENTANGLING STRANGENESS

CHARM IS COPIOUSLY PRODUCED IN $W^+ + s \to c$

easily tagged through dimuon signal, 2nd muon from subsequent c decay

$\Rightarrow$ ACCURATE EXTRACTION OF THE STRANGE DISTRIBUTION



CCFR/NUTEV $s - \bar{s}$ DETERMINATION

5000 ν & 1500 $\bar{\nu}$ DIMUON EVENT SAMPLE:

ASSUMED PARM.: $s(x) = \kappa \frac{\bar{u}(x)+\bar{d}(x)}{2}(1-x)^\alpha$

NEGATIVE $s - \bar{s}$ AT SMALL x

$\Rightarrow$ MOM. FRACT. $s - \bar{s} = -0.003 \pm 0.001$

NUTEV ANOMALY WORSE!

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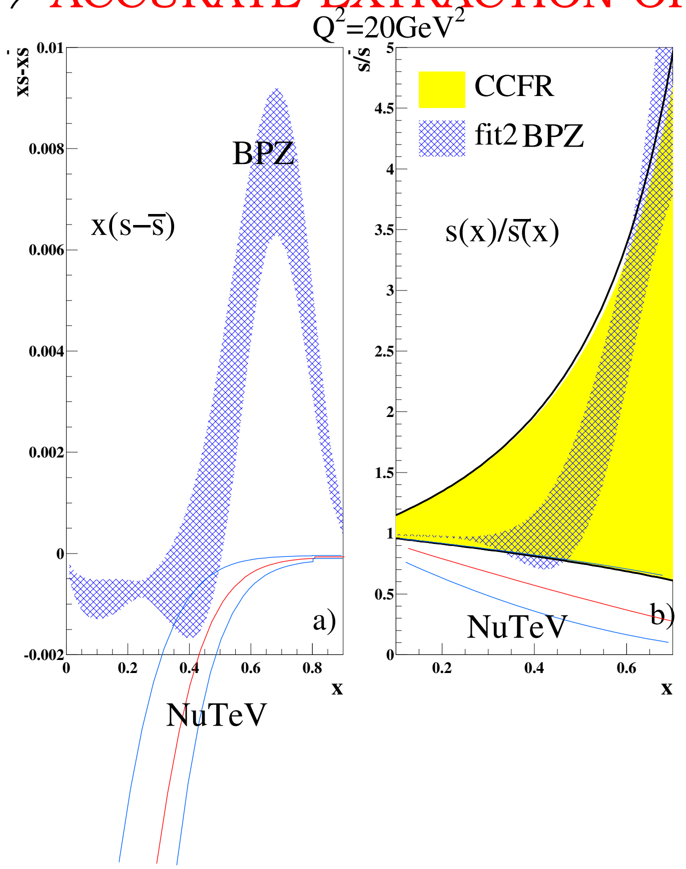

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NUTEV ANOMALY WORSE!

HOWEVER, BPZ GLOBAL FIT TO NEUTRINO INCLUSIVE DIS (Barone et al 2003) $\Rightarrow$ POSITIVE (TINY) ASYMMETRY

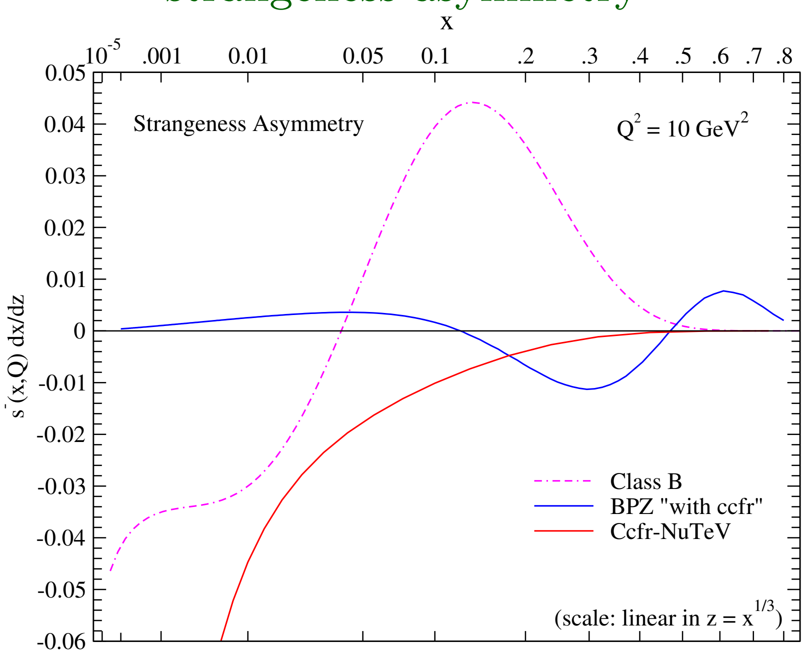
COMBINING INCLUSIVE AND EXCLUSIVE INFORMATION

CTEQ DEDICATED DIMUON ANALYSIS (April 2004)

- $\int_0^1 (s(x) - \bar{s}(x))dx = 0$ IN PROTON
  $\Rightarrow$ EITHER $s(x) - \bar{s}(x)$ HAS A NODE OR IT VANISHES EVERYWHERE

- $[s(x) - \bar{s}(x)] < 0$ FOR SMALL $x \lesssim 0.05$ CONSTRAINED BY DIMUON

strangeness asymmetry



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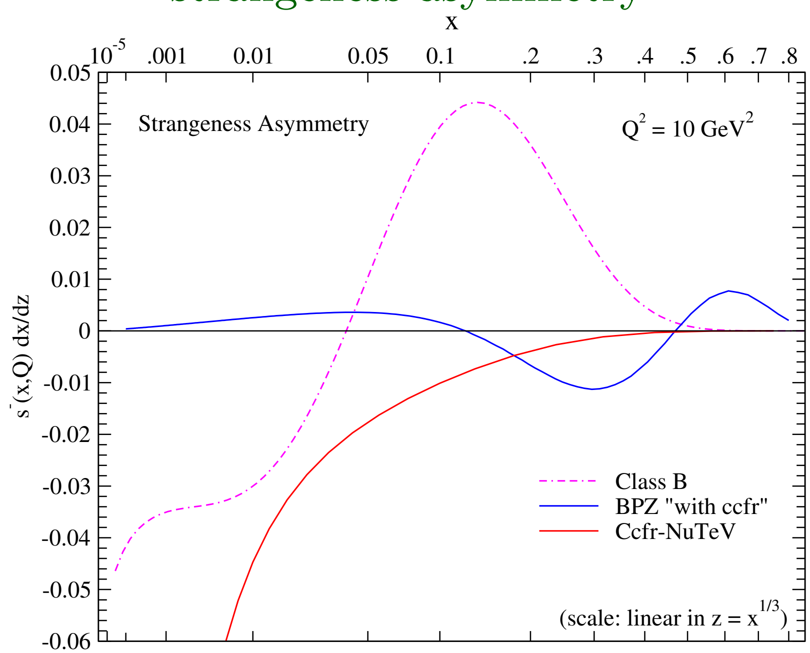
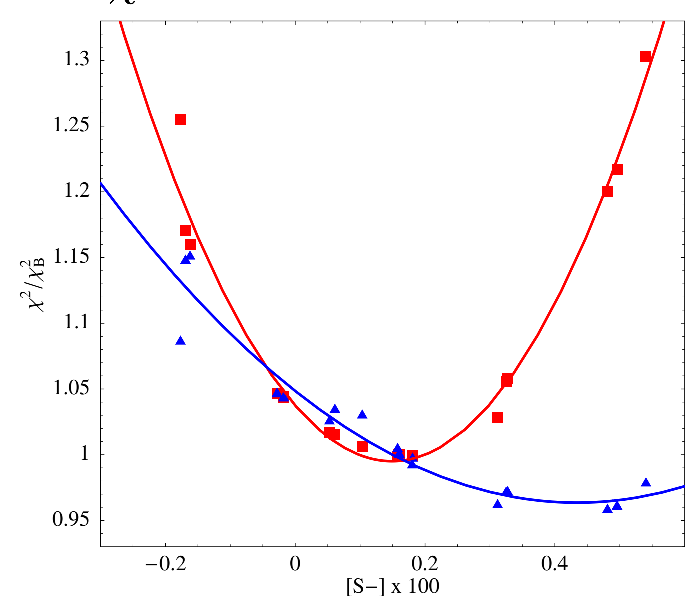
- $[s(x) - \bar{s}(x)] < 0$ FOR SMALL $x \lesssim 0.05$ CONSTRAINED BY DIMUON
- LARGE x REGION WEIGHS MORE IN MOMENTUM FRACTION
- POSITIVE MOM. FRACTION $s - \bar{s} \approx 0.02$: THE END OF THE NUTEV ANOMALY

strangeness asymmetry



χ^2 dimuon vs. inclusive



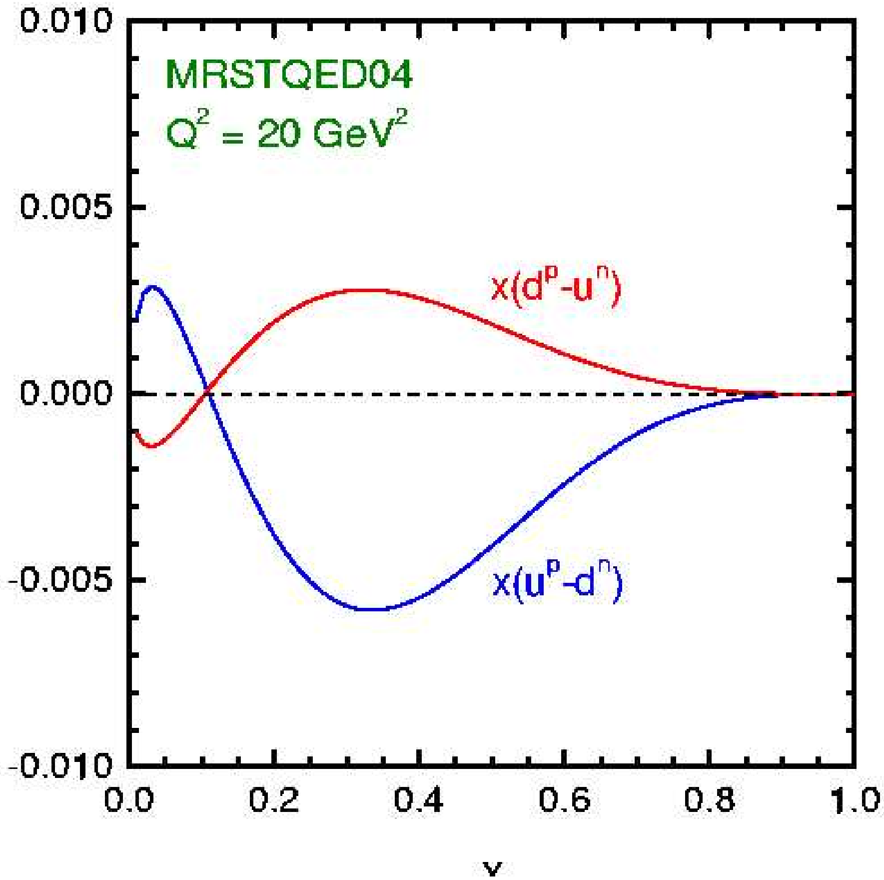
ISOSPIN VIOLATION

QED EFFECTS LEAD TO ISOSPIN VIOLATION:

$u - \bar{u}$ radiate more photons than $d - \bar{d}$: $\frac{d}{dt} q_i \propto e_i^2 q_i$

$\Rightarrow$ MORE PHOTON MOMENTUM IN PROTON THAN NEUTRON

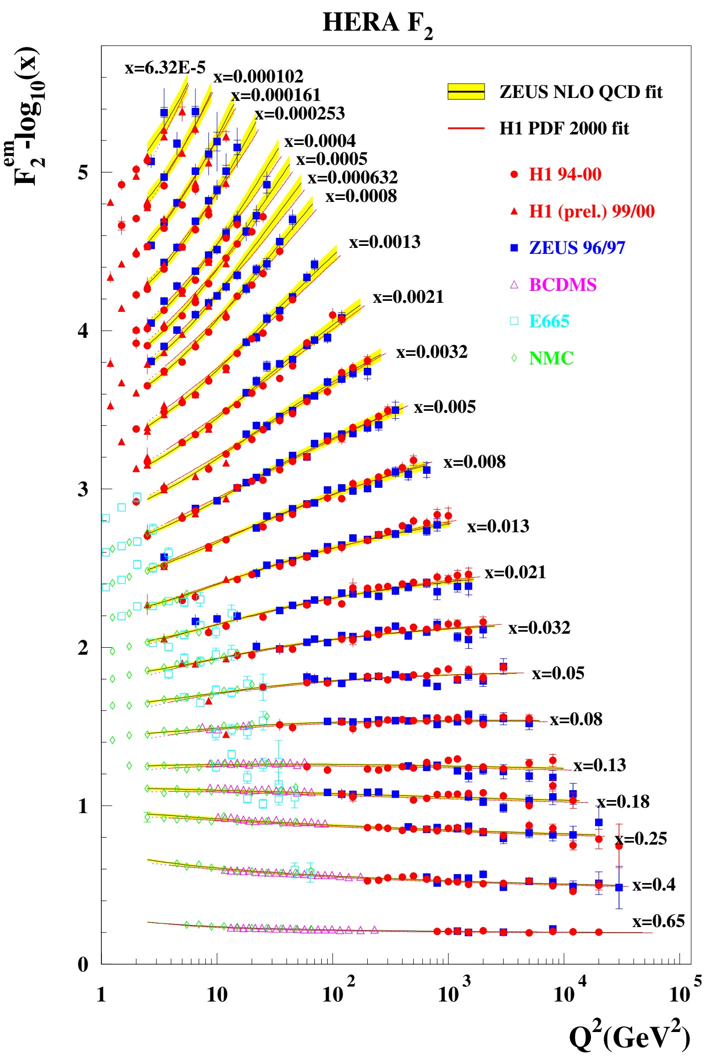
$\Rightarrow |u(x) - \bar{u}(x)| < |d(x) - \bar{d}(x)|$ AT LARGE x



- SIGN OF EFFECT AS REQUIRED TO EXPLAIN NUTEV
- SIZE OF EFFECTS WITH REASONABLE ASSUMPTIONS ABOUT 1/2 OF NUTEV ANOMALY
- THEORETICAL RESULTS AGREES WITH FIT IF ISOSPIN VIOLATION ALLOWED

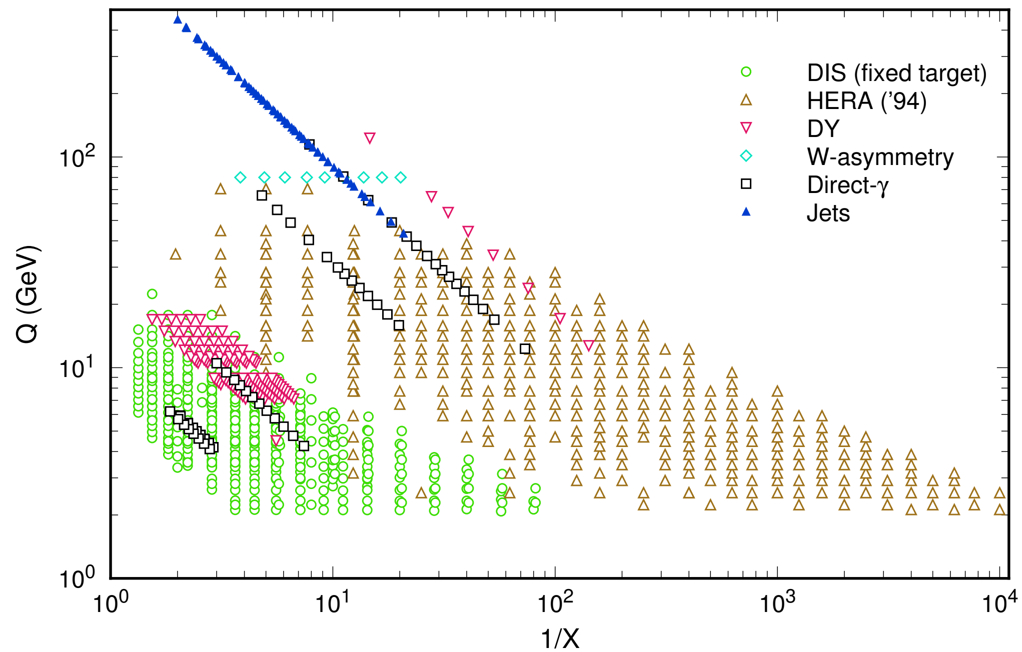
MRST 2005

PARTONS WITH ERRORS



GIVEN A SET OF DATA POINTS MUST DETERMINE A SET OF FUNCTIONS WITH ERRORS

DATA INCLUDED IN CTEQ5 PARTON FIT



WHAT'S THE PROBLEM? D. Kosower, 1999

- FOR A SINGLE QUANTITY, WE QUOTE 1 SIGMA ERRORS: VALUE± ERROR
- FOR A PAIR OF NUMBERS, WE QUOTE A 1 SIGMA ELLIPSE
- FOR A FUNCTION, WE NEED AN "ERROR BAR" IN A SPACE OF FUNCTIONS

MUST DETERMINE THE PROBABILITY DENSITY (MEASURE) $\mathcal{P}[f_i(x)]$ IN THE SPACE OF PARTON DISTRIBUTION FUNCTIONS $f_i(x)$ (i=quark, antiquark, gluon)

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$$\left\langle \sigma\left[f_i(x)\right] \right\rangle = \int \mathcal{D}f_i\, \sigma\left[f_i(x)\right]\, \mathcal{P}[f_i],$$

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MUST DETERMINE AN INFINITE–DIMENSIONAL OBJECT FROM A FINITE SET OF DATA POINTS

THE STANDARD SOLUTION:

FUNCTIONAL PARTON FITTING

- CHOOSE A FIXED FUNCTIONAL FORM:
  - MRST: 24 PARMS., SOME FIXED $\to$ 15 PARMS.

$$xq(x,Q_0^2) = A(1-x)^\eta(1+\epsilon x^{0.5}+\gamma x)x^\delta, \quad x[\bar{u}-\bar{d}](x,Q_0^2) = A(1-x)^\eta(1+\gamma x+\delta x^2)x^\delta.$$

$$xg(x,Q_0^2) = A_g(1-x)^{\eta_g}(1+\epsilon_g x^{0.5}+\gamma_g x)x^{\delta_g} - A_-(1-x)^{\eta_-}x^{-\delta_-},$$

  - CTEQ: 20 PARMS.

$$x\,f(x,Q_0) = A_0\,x^{A_1}\,(1-x)^{A_2}\,e^{A_3 x}\,(1+e^{A_4}\,x)^{A_5}$$

with independent params for combinations $u_v \equiv u-\bar{u}$, $d_v \equiv d-\bar{d}$, g, and $\bar{u}+\bar{d}$, $s=\bar{s}=0.2\,(\bar{u}+\bar{d})$ at Q_0; NORM. FIXED BY SUM RULES

  - ALEKHIN: 17 PARMS.

$$xu_{\rm V}(x,Q_0) = \frac{2}{N_{\rm u}^{\rm V}}x^{a_{\rm u}}(1-x)^{b_{\rm u}}(1+\gamma_2^{\rm u}x); \quad xu_{\rm S}(x,Q_0) = \frac{A_{\rm S}}{N_{\rm S}}\eta_{\rm u}x^{a_{\rm s}}(1-x)^{b_{\rm su}}$$

$$xd_{\rm V}(x,Q_0) = \frac{1}{N_{\rm d}^{\rm V}}x^{a_{\rm d}}(1-x)^{b_{\rm d}}; \quad xd_{\rm S}(x,Q_0) = \frac{A_{\rm S}}{N^{\rm S}}x^{a_{\rm s}}(1-x)^{b_{\rm sd}},$$

$$xs_{\rm S}(x,Q_0) = \frac{A_{\rm S}}{N^{\rm S}}\eta_{\rm s}x^{a_{\rm s}}(1-x)^{(b_{\rm su}+b_{\rm sd})/2}; \quad xG(x,Q_0) = A_{\rm G}x^{a_{\rm G}}(1-x)^{b_{\rm G}}(1+\gamma_1^{\rm G}\sqrt{x}+\gamma_2^{\rm G}x),$$

THE STANDARD SOLUTION:

FUNCTIONAL PARTON FITTING

- CHOOSE A FIXED FUNCTIONAL FORM:
  - MRST: 24 PARMS., SOME FIXED → 15 PARMS.

$$xq(x,Q_0^2) = A(1-x)^\eta(1+\epsilon x^{0.5}+\gamma x)x^\delta, \quad x[\bar u - \bar d](x,Q_0^2) = A(1-x)^\eta(1+\gamma x+\delta x^2)x^\delta.$$

$$xg(x,Q_0^2) = A_g(1-x)^{\eta_g}(1+\epsilon_g x^{0.5}+\gamma_g x)x^{\delta_g} - A_-(1-x)^{\eta_-}x^{-\delta_-},$$

  - CTEQ: 20 PARMS.

$$x\, f(x,Q_0) = A_0\, x^{A_1}\,(1-x)^{A_2}\, e^{A_3 x}\,(1+e^{A_4}\, x)^{A_5}$$

with independent params for combinations $u_v \equiv u-\bar u$, $d_v \equiv d-\bar d$, g, and $\bar u + \bar d$, $s = \bar s = 0.2\,(\bar u + \bar d)$ at Q_0; NORM. FIXED BY SUM RULES

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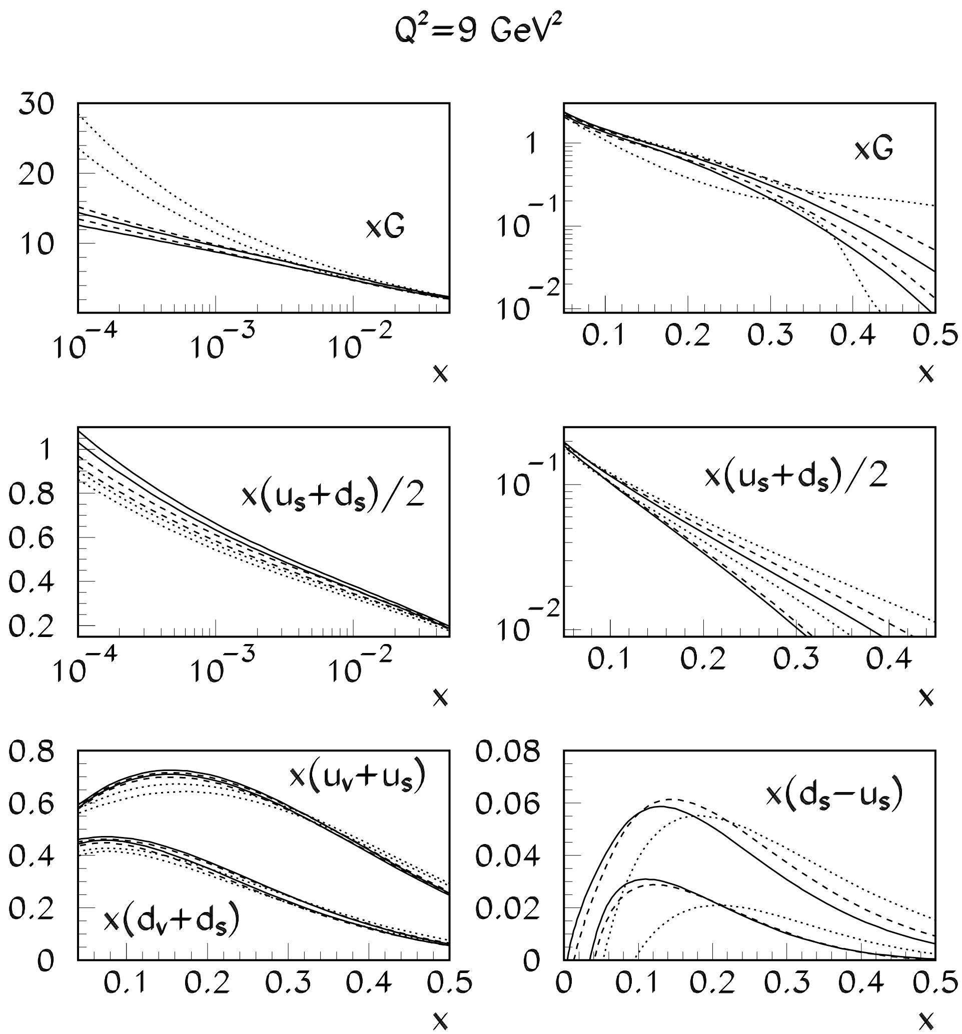
- EVOLVE TO DESIRED SCALE & COMPUTE PHYSICAL OBSERVABLES
- DETERMINE BEST-FIT VALUES OF PARAMETERS
- DETERMINE ERROR BY PROPAGATION OF ERROR ON PARMS ('HESSIAN METHOD') OR BY PARM. SCANS ('LAGRANGE MULTIPLIER METHOD')

PROBLEM PROJECTED ONTO THE FINITE–DIMENSIONAL SPACE OF PARAMETERS

HOW WELL DOES IT WORK?

ALEKHIN 2003 PARTONS (DIS only)



TOTAL ERROR BANDS FOR LO (DOTS), NLO (DASHES), NNLO (SOLID) PARTON DISTRIBUTIONS

valence $u^v \equiv u - \bar{u}$, $d^v \equiv d - \bar{d}$,
sea $u^s = \bar{u}^s = d^s = \bar{d}^s$

BUT CAN WE TRUST THESE ERRORS?

PDF ERRORS COMPARABLE TO OR EVEN LARGER THAN THEORY ERRORS

W PRODUCTION CROSS-SECTION
TEVATRON

PDF SET	XSEC [NB]	PDF UNCERTAINTY
ALEKHIN	2.73	$\pm$ 0.05 (TOT)
MRST2002	2.59	$\pm$ 0.03 (EXPT)
CTEQ6	2.54	$\pm$ 0.10 (EXPT)

THORNE 2003

- ALEKHIN VS. MRST/CTEQ $\rightarrow$ W PRODUCTION XSECT AT TEVATRON DO NOT AGREE WITHIN RESPECTIVE ERRORS

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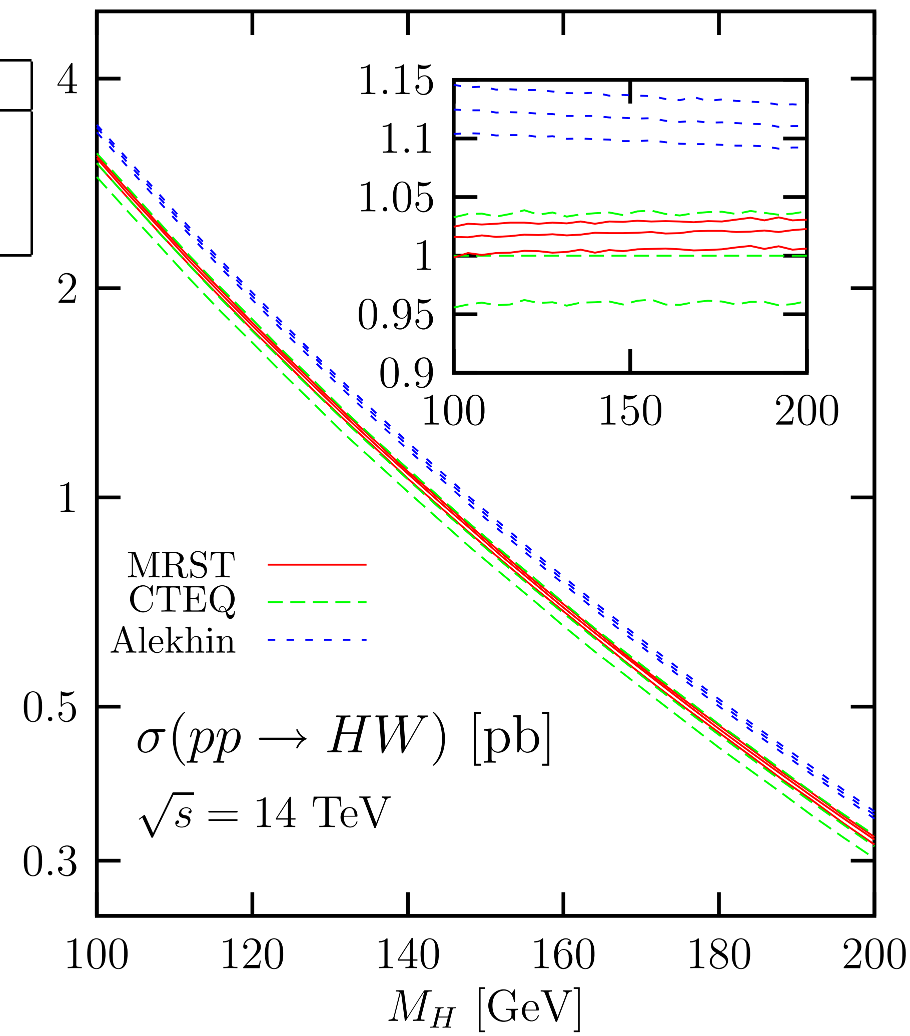
- ALEKHIN VS. MRST/CTEQ → PREDICTIONS FOR ASSOCIATE HIGGS W PRODUCTION LHC DO NOT AGREE WITHIN RESPECTIVE ERRORS

HIGGS PRODUCTION AT LHC



DJOUADI AND FERRAG, 2004

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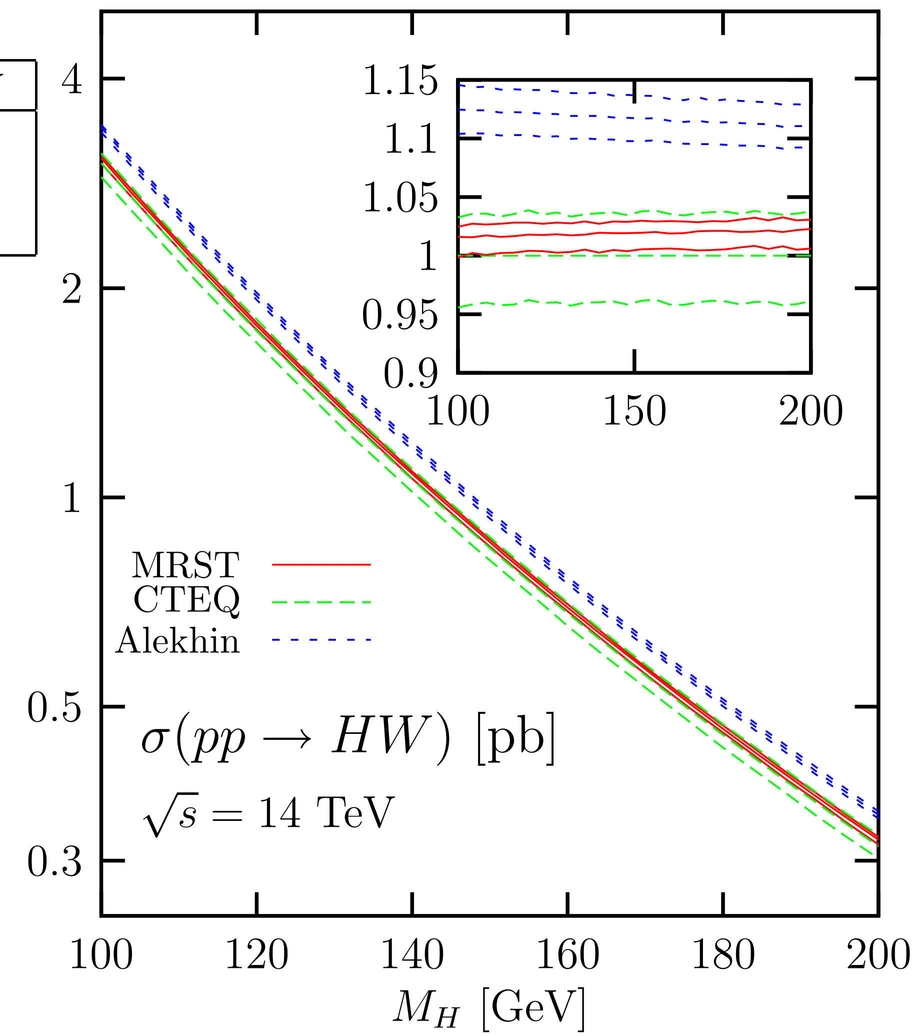
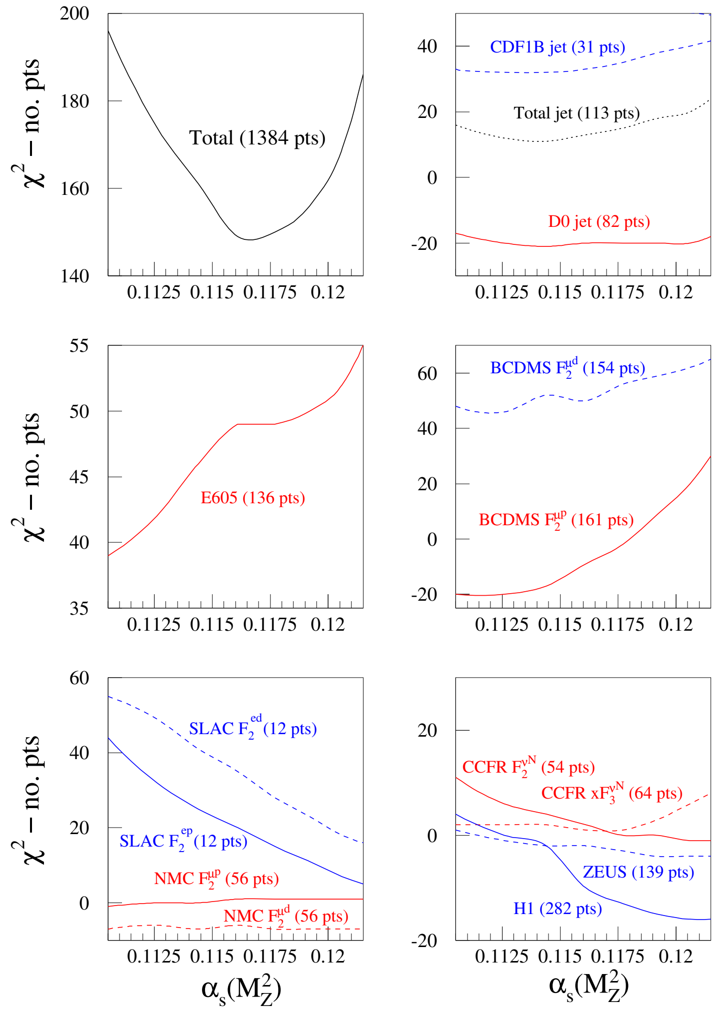


DJOUADI AND FERRAG, 2004

PARTON SETS DO NOT AGREE WITHIN RESPECTIVE ERRORS

HOW ARE PDF ERRORS DETERMINED?

GLOBAL χ^2 MINIMUM DOES NOT CORRESPOND TO LOCAL MINIMA



MRST 2003

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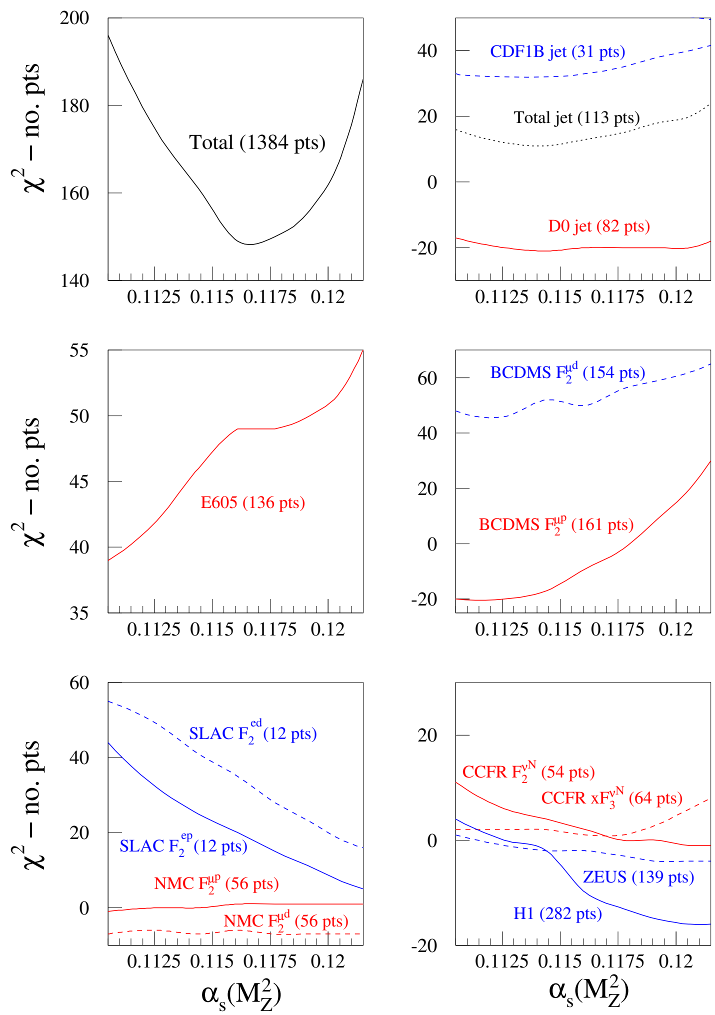
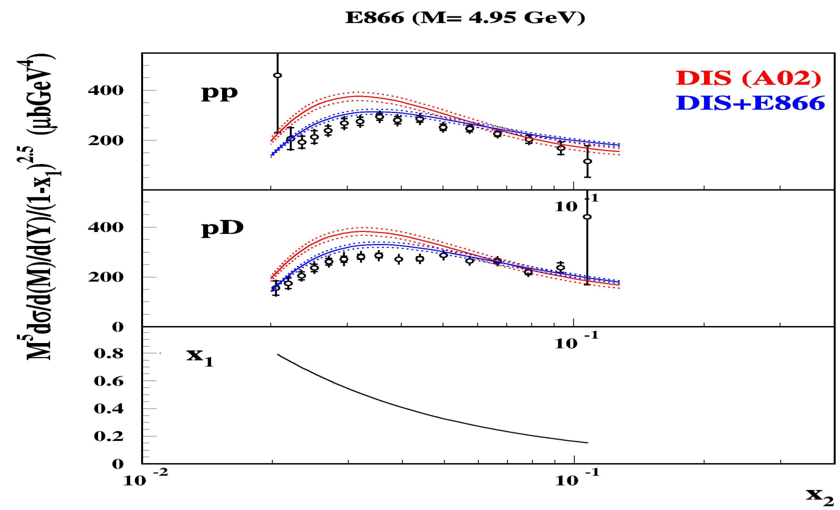


MRST 2003

E866 DY DATA DISAGREE WITH DIS DATA:

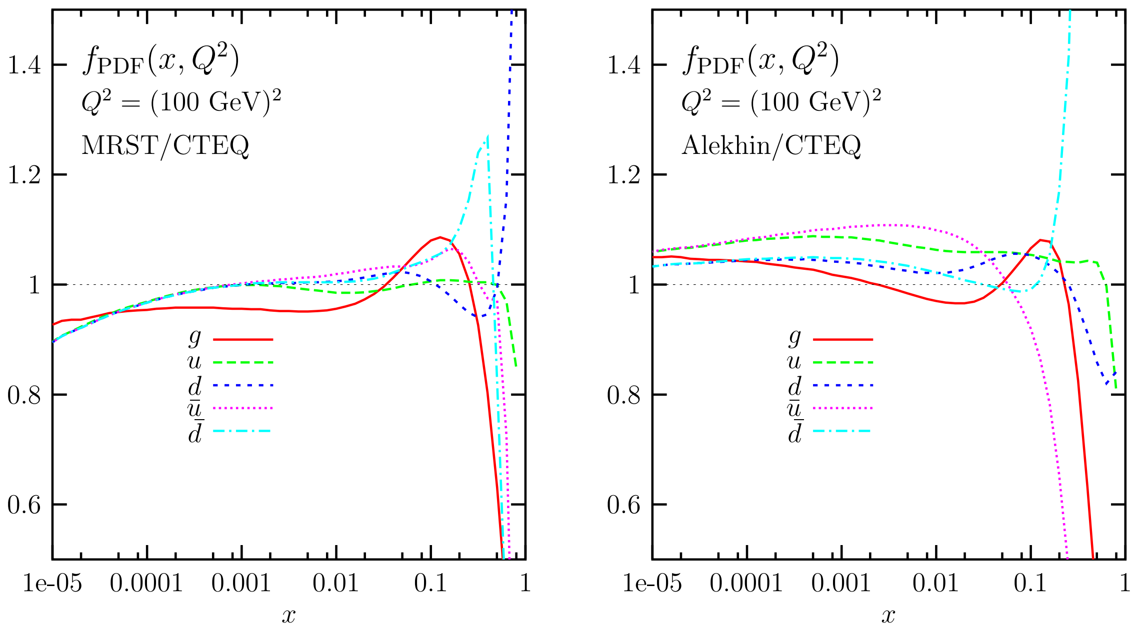
$\sigma_{DY} \sim q(x_1)q(x_2)$ DISAGREES WITH DIS QUARK AT SAME x AND Q^2



ALEKHIN 2005

PROBLEM: INCONSISTENT EXPERIMENTS

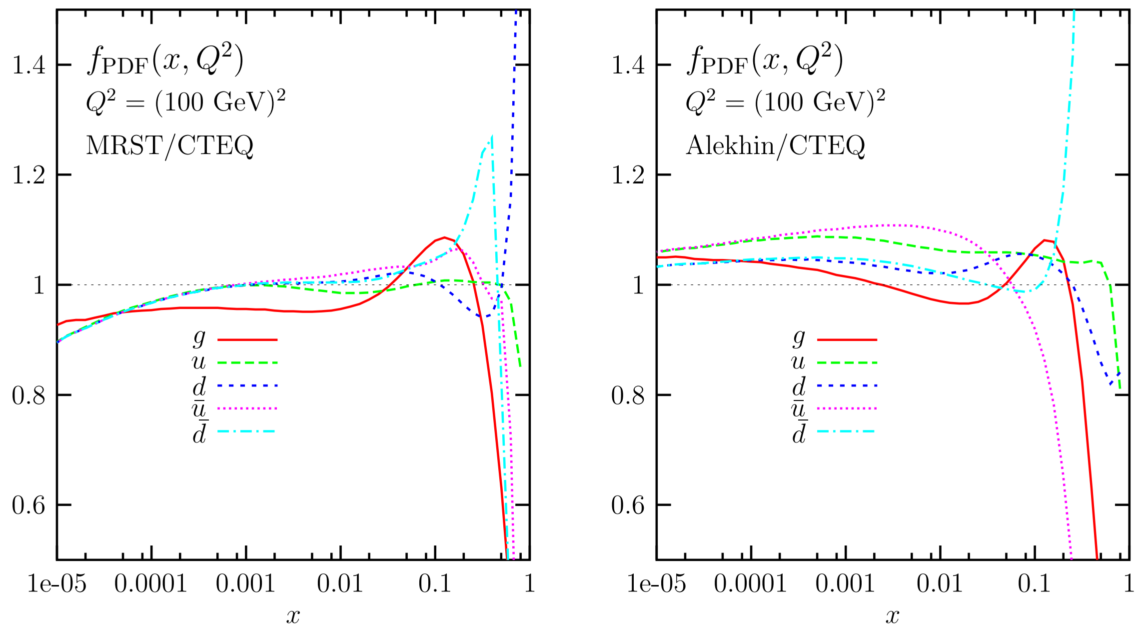
PARAMETRIZATION BIAS?



MRST & CTEQ
$\longrightarrow$ SIMILAR PARTONS

Djouadi and Ferrag 2003

PARAMETRIZATION BIAS?



MRST & CTEQ

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Djouadi and Ferrag 2003

SIMILAR PARTONS

$\longrightarrow$ SIMILAR RESULTS

THE W XSECT. AGAIN...

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ALEKHIN	LHC	215	$\pm$ 6 (TOT)
MRST2002	LHC	204	$\pm$ 4 (EXPT)
CTEQ6	LHC	205	$\pm$ 8 (EXPT)

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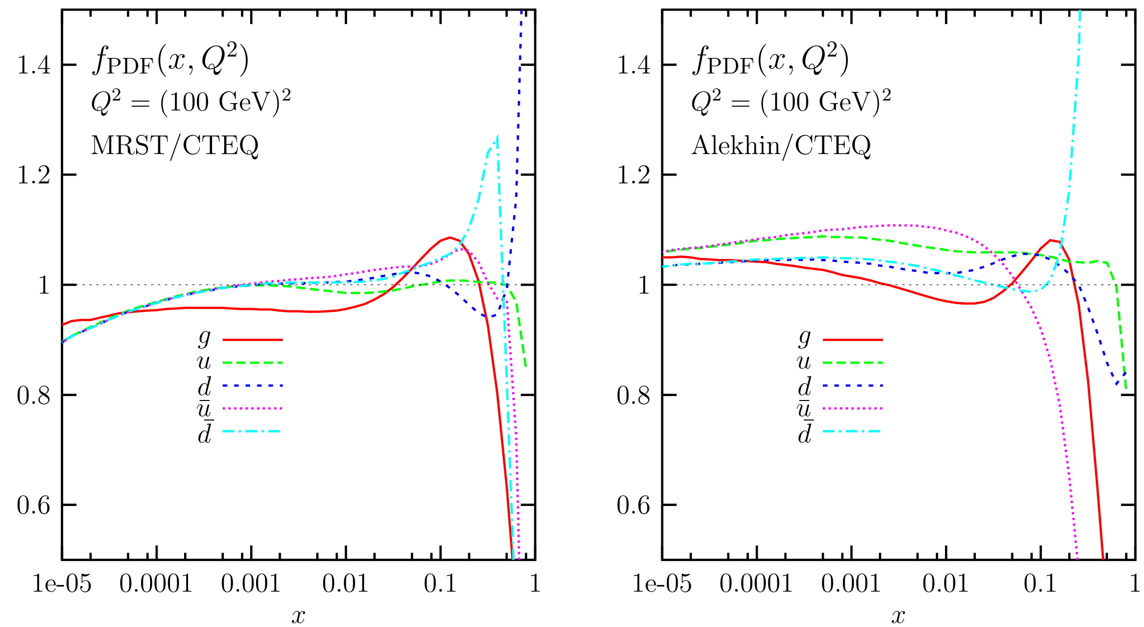

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We do not seem to have the optimum parameterization for both finding the best fit and also investigating fluctuations about this best fit (...) This might then influence our error analysis...(MRST 2004)

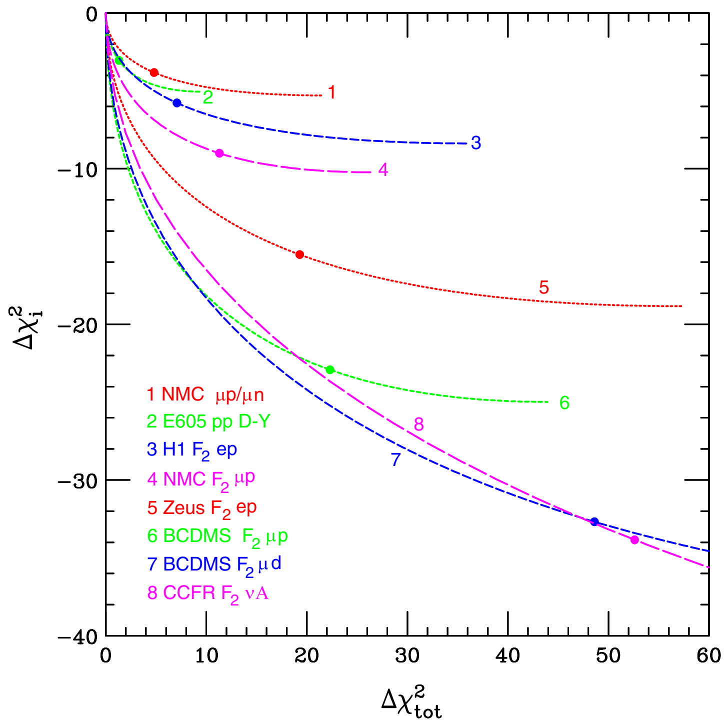
CONSERVATIVE SOLUTIONS

CTEQ TOLERANCE CRITERION

SINGLE OUT INCONSISTENT DATA

- how many parameters are significantly determined by each dataset?
- how consistent are the data from one set with the rest?

STUDY MINIMUM ALLOWED χ_i^2
FOR i-TH EXP. AS
GLOBAL χ^2 ALLOWED TO INCREASE



Collins, Pumplin 2001

CCFR, BCDMS

INCOMPATIBLE WITH THE REST

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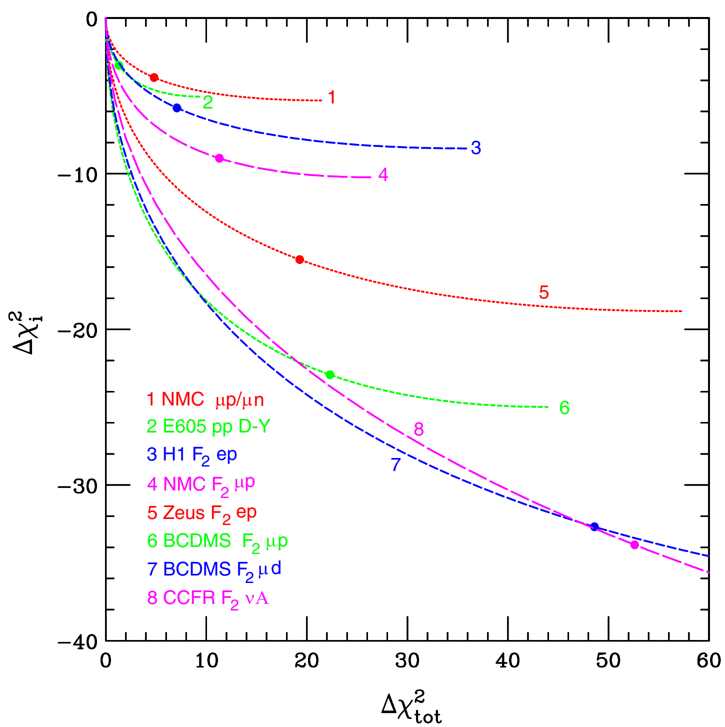

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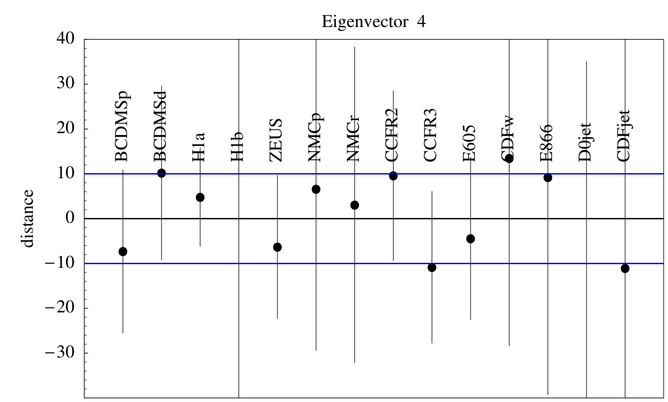
INCOMPATIBLE WITH THE REST

OPTIONS

- discard incompatible experiments
- reweight individual contributions
- INCORPORATE IN ERROR, TOLERATING FIXED MAX DEVIATION FOR EACH EXPERIMENT & EACH FIT PARAMETER



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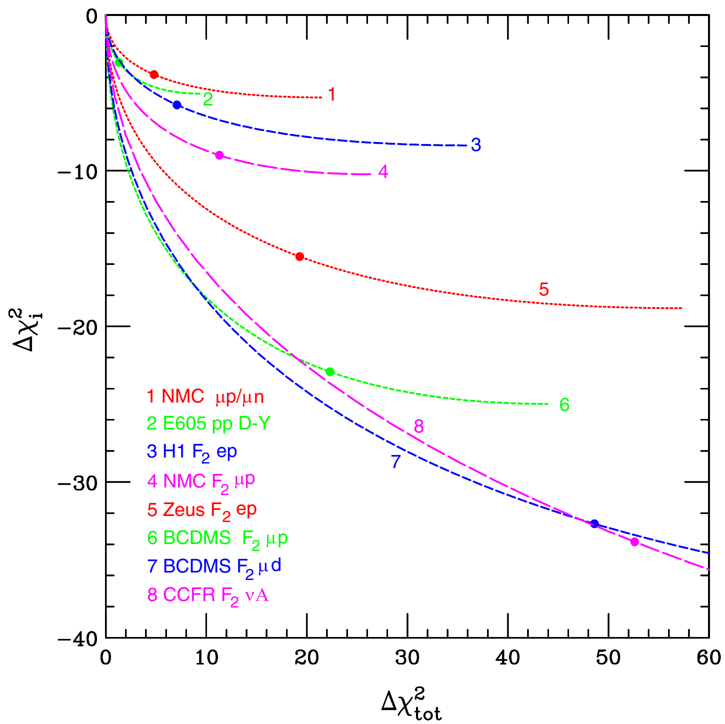

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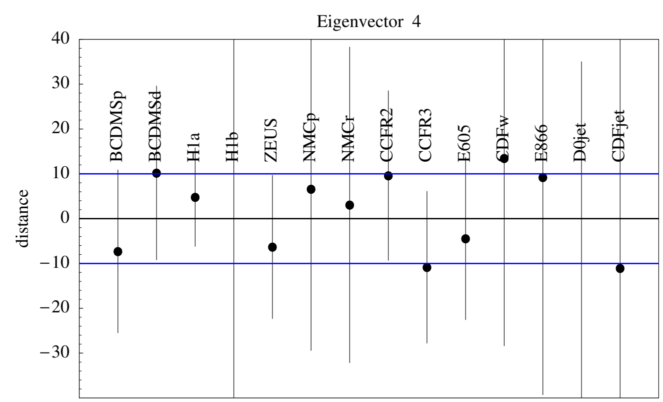


$\Delta\chi^2 = 100$ (CTEQ6)

CONSERVATIVE SOLUTIONS

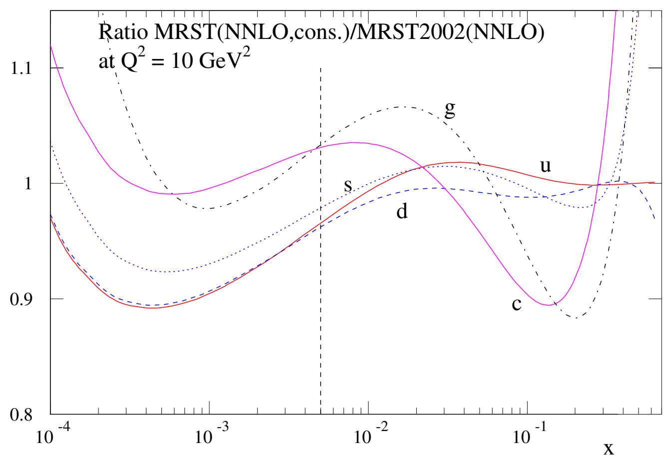
IMPOSE RESTRICTIVE KINEMATIC CUTS

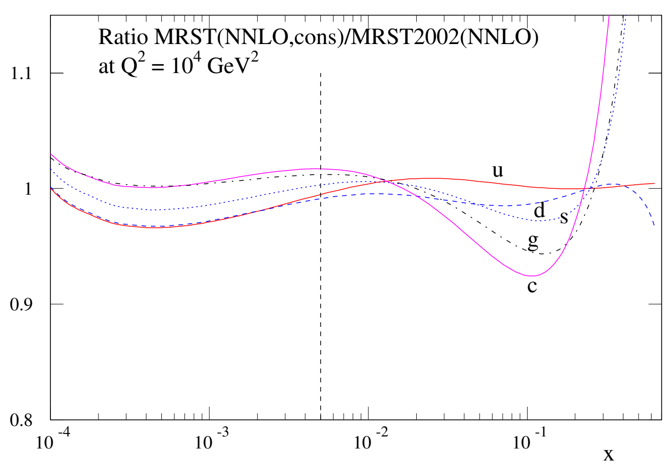
cut in Q^2 raised from 2 to 10 GeV^2; cut off $x < 0.005$; cut in W^2 raised from 12.5 to 15 GeV^2

MRST 2003 CONSERVATIVE PARTONS

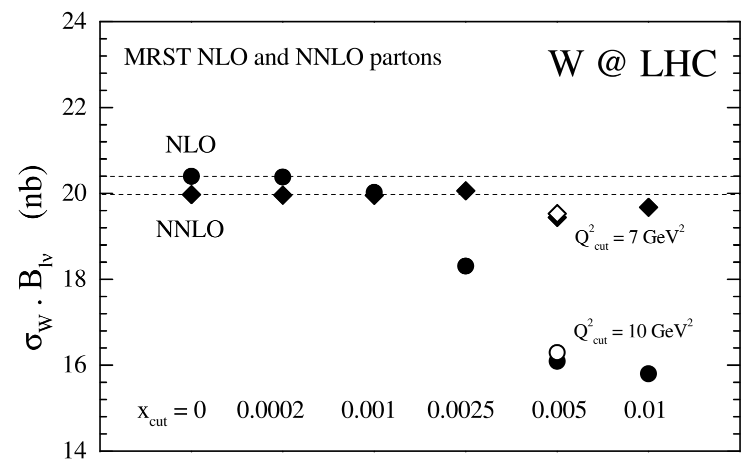
- ABOUT 800 DATAPOINTS REMOVED OUT OF ABOUT 2000
- $\Delta\chi^2 = 5$ SUFFICIENT FOR REASONABLE 1-σ

CONSERVATIVE/PLAIN





VARIATION OF THE W XSECT.



conservative partons unreliable for total xsect.
because small x region important
partly stabilized by NNLO

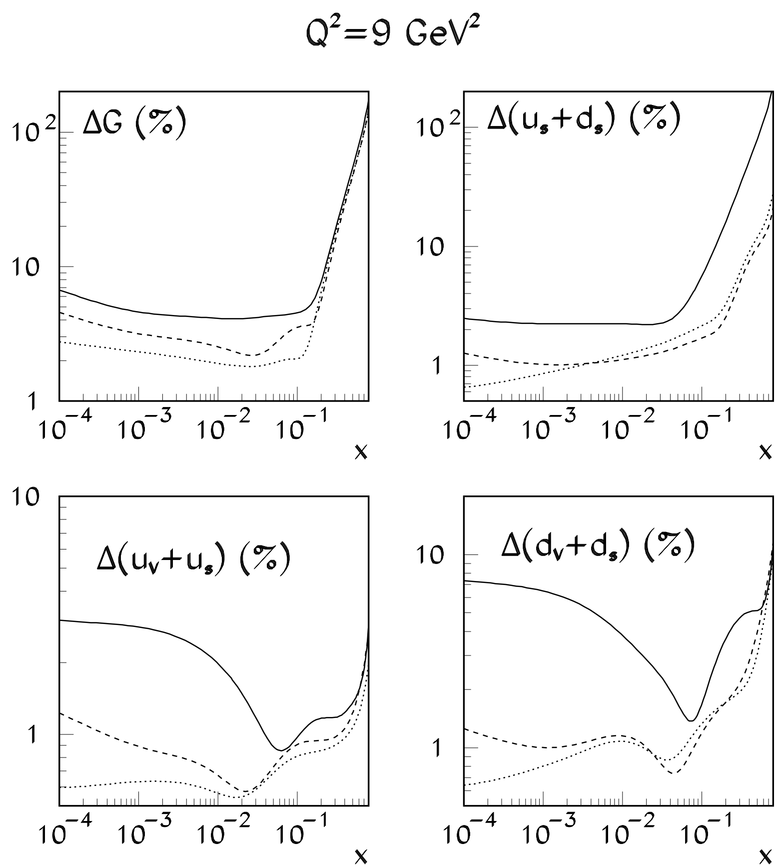
CONSERVATIVE SOLUTIONS

SELECT COHERENT SET OF DATA

ALEKHIN PARTONS

- ONLY DIS DATA INCLUDED
- $\Delta\chi^2 = 1$ PROVIDES GOOD 1-σ CURVES

PERCENTAGE ERRORS

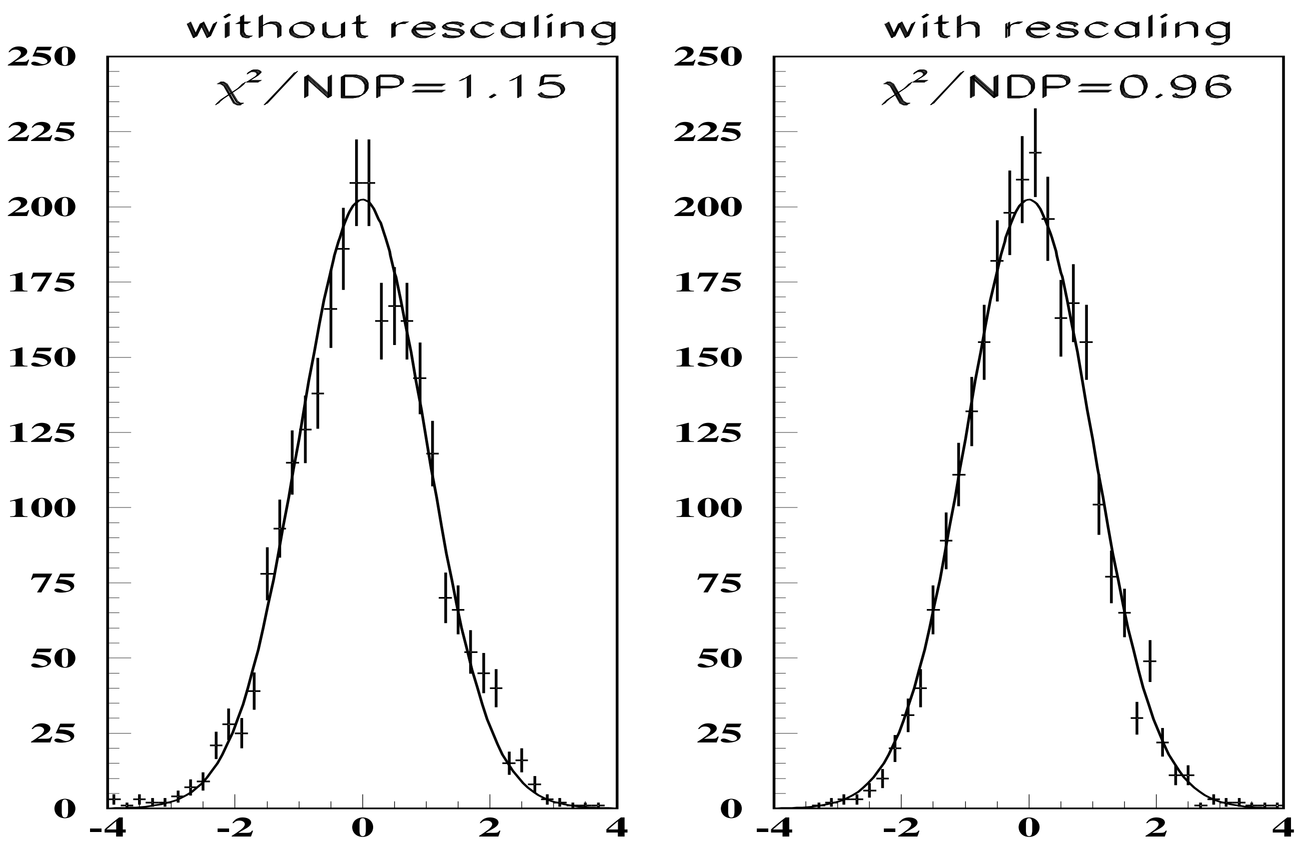


- ALEKHIN 2003 PARTON UNCERTAINTIES (SOLID, DASHED) COMPARABLE TO CTEQ6 (DOTTED)
- CANNOT SEPARATE ACCURATELY ANTIQUARK DISTNS.
- ERROR ON σ_W COMPARABLE TO CTEQ, MRST

ERROR RESCALING

HOW CAN DATA FROM INCONSISTENT SETS BE INCLUDED?

ASSUME INCONSISTENCY DUE TO UNDERESTIMATED (SYST.) ERROR:



For the experiments with $\chi^2 > 1$ the statistical errors in data were rescaled in order to get $\chi^2 = 1$

ALEKHIN 2005 (PRELIM.)

NEW SOLUTIONS

THE BAYESIAN MONTE CARLO APPROACH (GIELE, KOSOWER, KELLER 2001)

- generate a Monte-Carlo sample of fcts. with "reasonable" prior distn. (e.g. an available parton set) $\longrightarrow$ representation of probability functional $\mathcal{P}[f_i]$
- calculate observables with functional integral
- update probability using Bayesian inference on MC sample: better agreement with data $\longrightarrow$ more functions in sample
- iterate until convergence achieved

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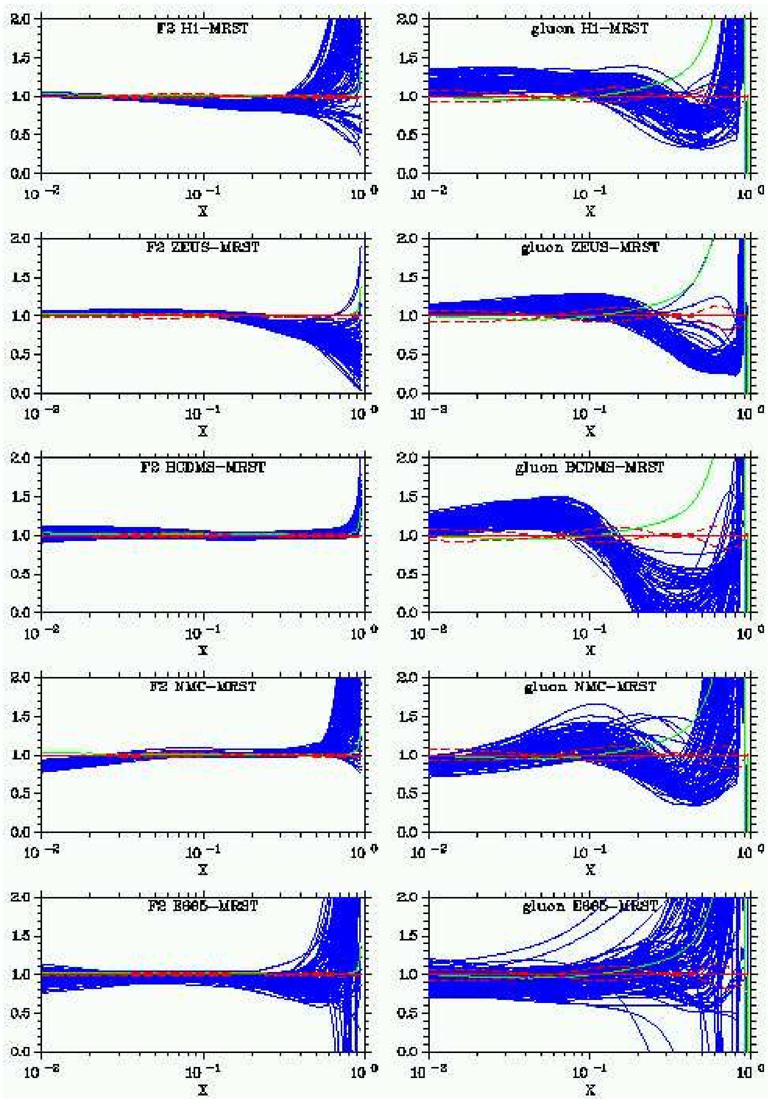
PROBLEM IS MADE FINITE-DIMENSIONAL BY THE CHOICE OF PRIOR, BUT RESULT DO NOT DEPEND ON THE CHOICE IF SUFFICIENTLY GENERAL
HARD TO HANDLE "FLAT DIRECTIONS"
(Monte Carlo replicas which lead to same agreement with data);
COMPUTATIONALLY VERY INTENSIVE;
DIFFICULT TO ACHIEVE INDEP. FROM PRIOR

Result: Fermi partons



F_2^{singlet} and gluon ratios Fermi/MRST

only subset of data fitted (H1, E665, BCDMS DIS data)

good agreement with Tevatron W xsect

trouble with value of α_s

NEW SOLUTIONS

THE NEURAL MONTE CARLO APPROACH (S.F., GARRIDO, LATORRE, PICCIONE 2002)

BASIC IDEA: USE NEURAL NETWORKS AS UNIVERSAL UNBIASED INTERPOLANTS

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BASIC IDEA: USE NEURAL NETWORKS AS UNIVERSAL UNBIASED INTERPOLANTS

- GENERATE A SET OF MONTE CARLO REPLICAS $\sigma^{(k)}(p_i)$ OF THE ORIGINAL DATASET $\sigma^{(\mathrm{data})}(p_i)$ (p_i values of the kin. variables where σ is measured)
  $\Rightarrow$ REPRESENTATION OF $\mathcal{P}[\sigma(p_i)]$ AT DISCRETE SET OF POINTS p_i
- TRAIN A NEURAL NET FOR EACH PDF ON EACH REPLICA, THUS OBTAINING A NEURAL REPRESENTATION OF THE PDFS $f_i^{(net),(k)}$
- THE SET OF NEURAL NETS IS A REPRESENTATION OF THE PROBABILITY DENSITY:

$$\left\langle \sigma\left[f_i\right]\right\rangle = \frac{1}{N_{rep}}\sum_{k=1}^{N_{rep}} \sigma\left[{f_i}^{(net)(k)}\right]$$

- CHECK GOODNESS OF FIT THROUGH STATISTICAL INDICATORS (χ^2, CORRELATION,. . .)

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THE NNPDF COLLABORATION

L. DEL DEBBIO, S.F. J. LATORRE, A. PICCIONE, J. ROJO

Neural networks as interpolators

- start with random network & compute output for given input (F_2 for given (x, Q^2))
- compare computed output to desired output by means of energy function ($e.g.\ \chi^2$)
- vary weights and thresholds (back-propagation or genetic algorithm)
- iterate

as training progresses, smoothness of net decreases

NEURAL NETWORKS AS INTERPOLATORS

- START WITH RANDOM NETWORK & COMPUTE OUTPUT FOR GIVEN INPUT (F_2 FOR GIVEN (x, Q^2))
- COMPARE COMPUTED OUTPUT TO DESIRED OUTPUT BY MEANS OF ENERGY FUNCTION ($e.g.\ \chi^2$)
- VARY WEIGHTS AND THRESHOLDS (BACK-PROPAGATION OR GENETIC ALGORITHM)
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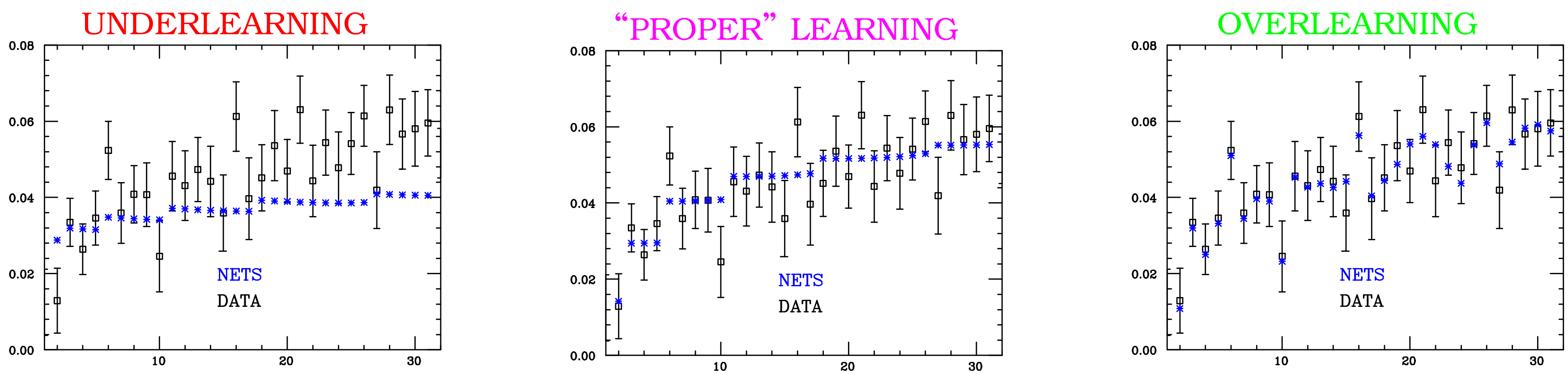
AS TRAINING PROGRESSES, SMOOTHNESS OF NET DECREASES

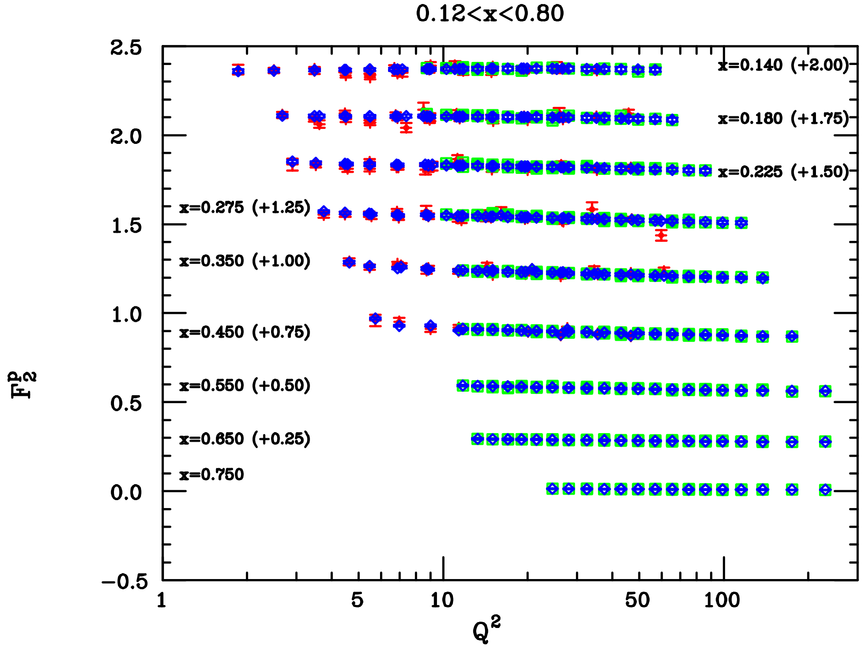


TRAINING CAN BE STOPPED BEFORE OVERLEARNING
ON THE BASIS OF STATISTICAL CRITERIA

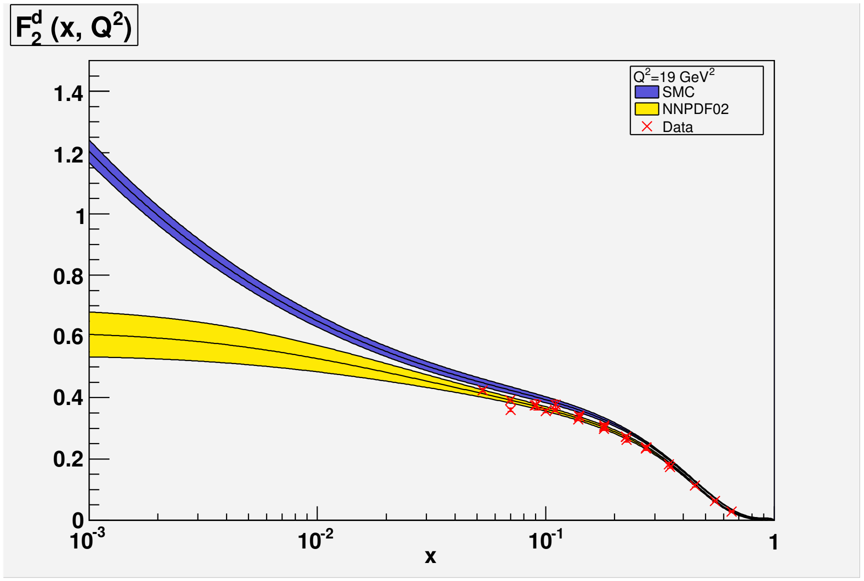
Preliminary Result: Neural Structure Functions

SET ASIDE INTRICACIES OF FULL THE PARTON FIT & FIT STRUCTURE FUNCTION...

NEURAL F_2 VS p DATA



NEURAL DEUTERON F_2



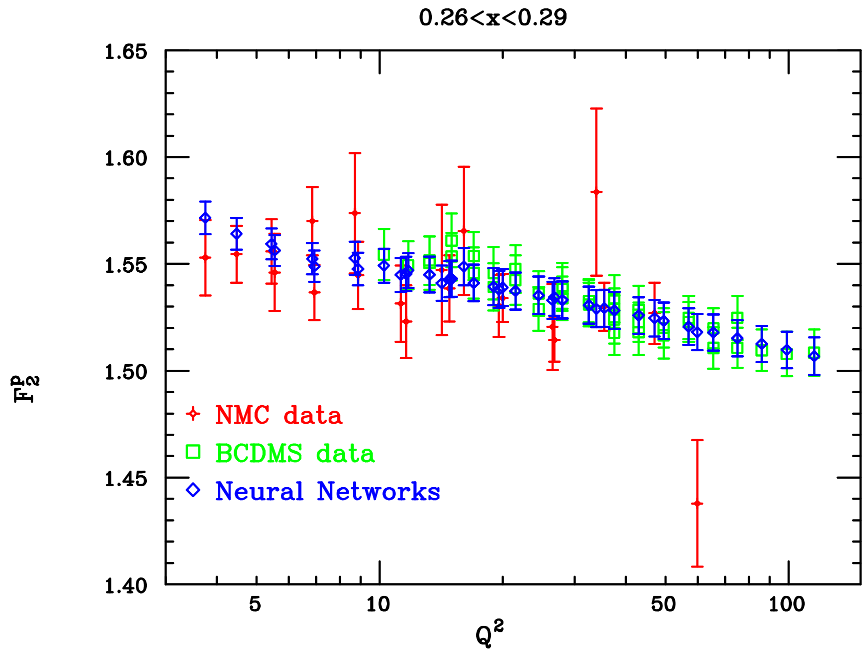
- FULL NEURAL FIT TO WORLD DATA F_2 FOR PROTON, DEUTERON & NONSINGLET AVAILABLE
- ERRORS AND CORRELATIONS FAITHFULLY REPRODUCED, BUT STAT. UNCERTAINTIES OPTIMALLY COMBINED
  $\Rightarrow$ FIT CAN BE USED IN LIEU OF DATA, BUT BETTER THAN THEM
- FITS WITH FIXED FUNCTIONAL FORM UNDERESTIMATE ERROR ON EXTRAPOLATION

NEURAL HANDLING OF INCOMPATIBLE DATA

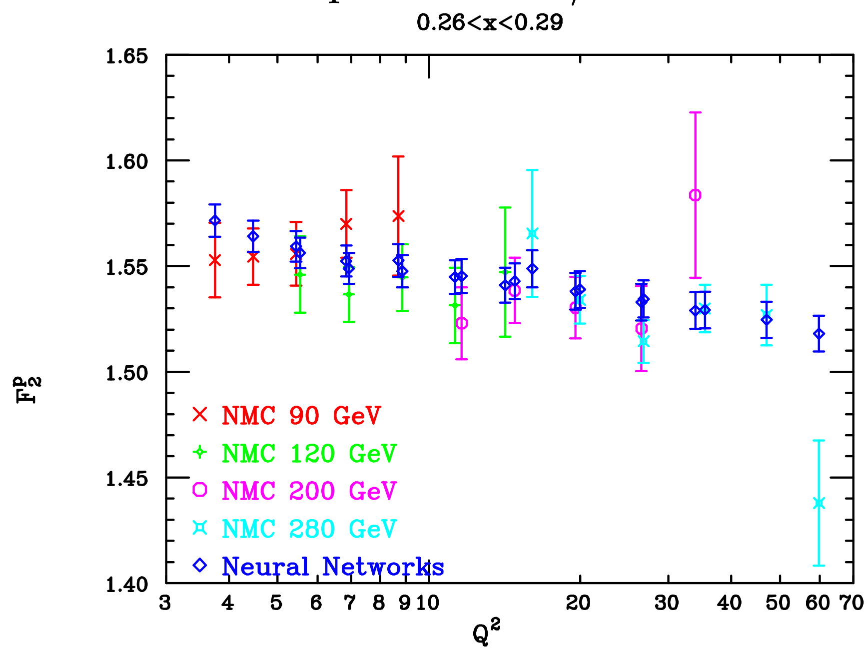
- FOR PROTON FITS (PRE-HERA DATA), CONVERGENCE ACHIEVED, BUT $E^{(0)} \gtrsim 1.4$ EVEN W. VERY LONG TRAINING
- for NMC data $E^{(0)} \gtrsim 1.6$ (training with all data)
- for NMC data $E^{(0)} \gtrsim 2.2$ (training with NMC only)
- ALL OTHER STATISTICAL INDICATORS OK

SOME NMC DATA ARE INCOMPATIBLE WITH OTHER DATA

Blow-up of proton data/nets



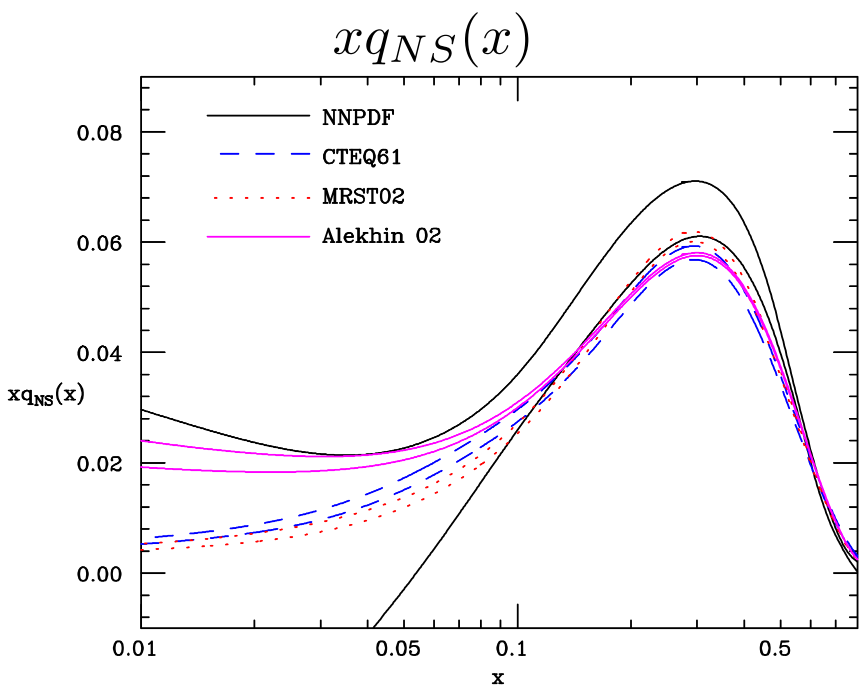
NMC proton data/nets

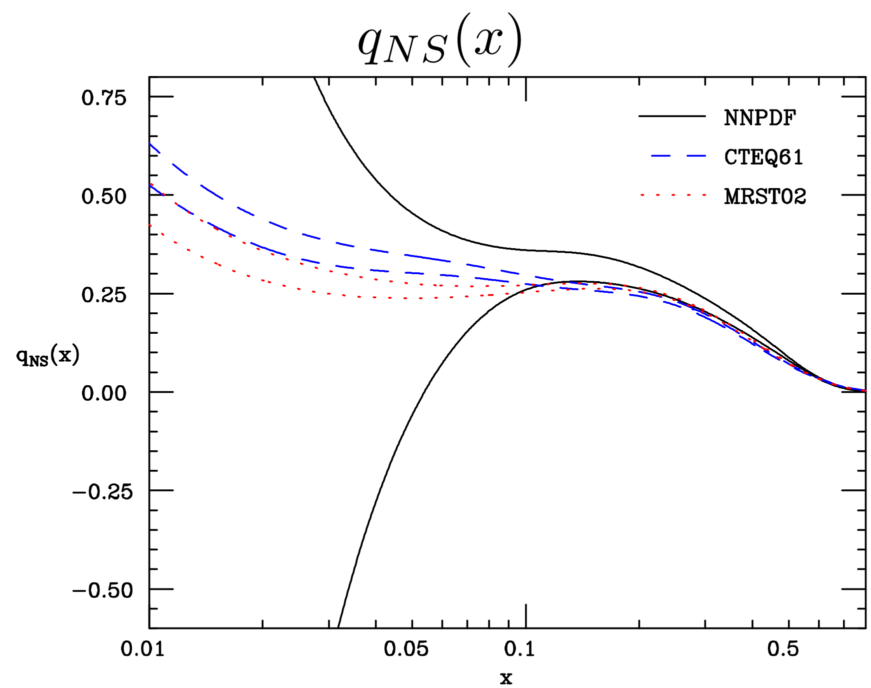


NEURAL NET DISCARDS INCONSISTENT DATA & PROVIDES GOOD FIT TO THE REST

TOWARDS NEURAL PARTONS:
THE NONSINGLET CASE (NNPDF 05)

- x SPACE PARTONS, N SPACE EVOLUTION: DETERMINE INTERPOLATED EVOLUTION KERNELS
- FULL NNLO EVOLUTION IMPLEMENTED, PRELIMINARY NLO FITS AVAILABLE





- FITS WITH FIXED FUNCTIONAL FORM SUBSTANTIALLY UNDERESTIMATE ERROR ON EXTRAPOLATION
- NO EVIDENCE FOR "WELL-KNOWN" SMALL x RISE OF NONSINGLET

CONCLUSIONS

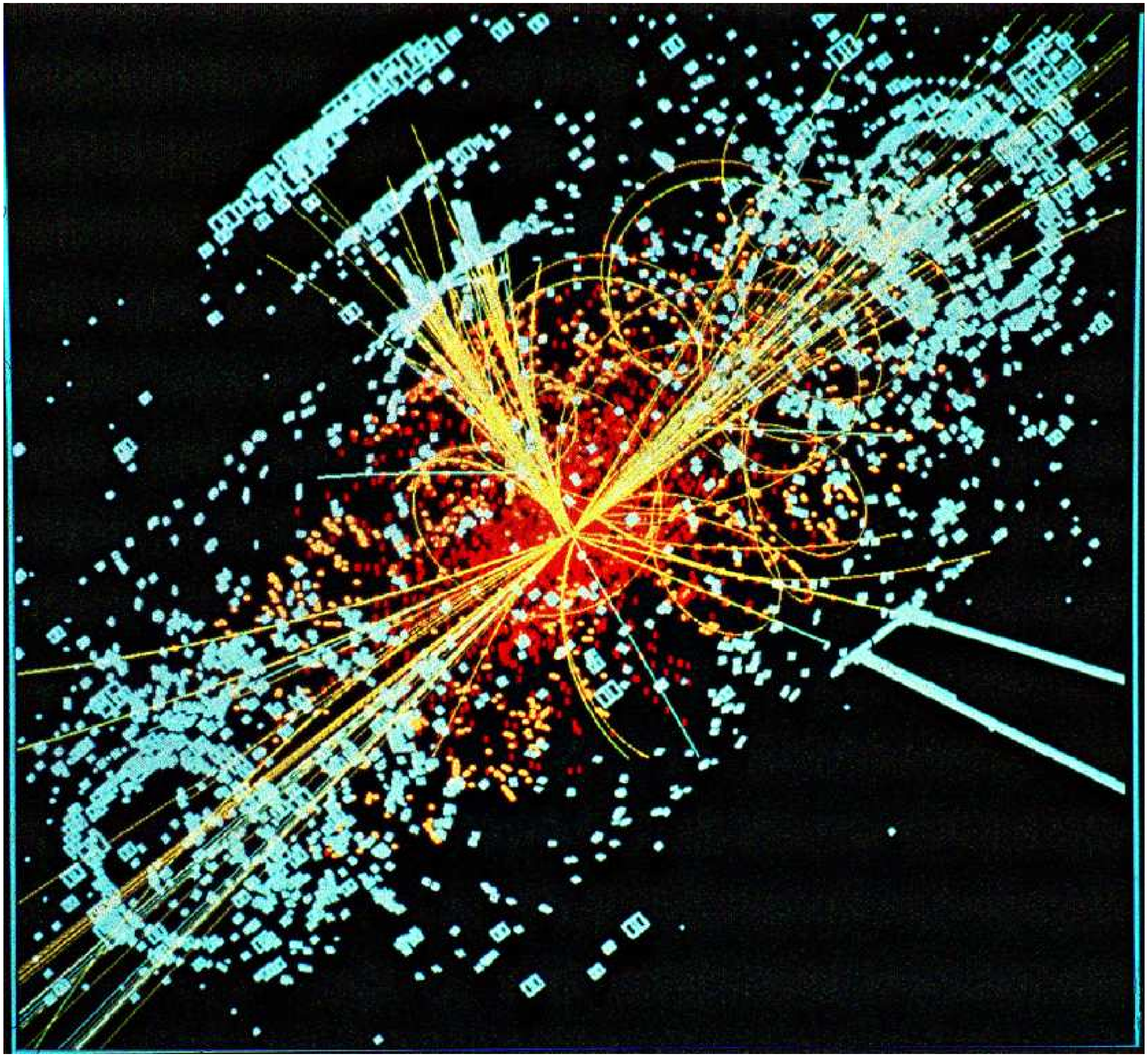
- The needs of precision phenomenology at the LHC has stimulated dramatic progress in the physics of structure functions

- Parton distributions with errors are now being developed thanks to the availability of a wide variety of data and of rapid theoretical progress in perturbative QCD

- "Standard" methods of PDF determination are stretched to their limit and motivate the development of new techniques

- neural parton distributions are behind the corner

HIGGS PRODUCTION AT THE LHC



Higgs decay in $e^+e^- + 2$ jets at CMS