QCD

AT THE DAWN OF THE LHC

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

Istituto Nazionale di Fisica Nucleare

L CRACOW SCHOOL OF TH. PHYSICS

ZAKOPANE, JUNE 10, 2010

Prologue: the discovery of the W

last time we looked for "new" physics at a hadron collider

theoretical prediction…

42 G. Altarelli et al. / Vector boson production

Table 2
Values (in nb) of the total cross sections for $W^{\pm}$ and Z^0 production

	$W^+ + W^-$	$W^+ + W^-$	$W^+ + W^-$	Z^0	Z^0	Z^0	$\frac{\sigma(W^+ + W^-)}{\sigma(Z^0)}$	$\frac{\sigma(W^+ + W^-)}{\sigma(Z^0)}$	$\frac{\sigma(W^+ + W^-)}{\sigma(Z^0)}$
$\sqrt{S}$ (GeV)	GHR	DO1	DO2	GHR	DO1	DO2	GHR	DO1	DO2
540	4.2	4.3	4.1	1.3	1.3	1.2	3.1	3.4	3.5
700	6.2	6.3	6.1	2.0	1.9	1.8	3.1	3.3	3.4
1000	9.5	9.5	9.6	3.1	3.0	2.9	3.1	3.2	3.3
1300	12.5	12.5	12.9	4.0	3.9	3.9	3.1	3.2	3.3
1600	15.5	15.6	16.5	5.0	4.8	5.0	3.1	3.2	3.3

Altarelli, Ellis, Greco, Martinelli, 1984

…and experimental discovery

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/85-108
11 July 1985

W PRODUCTION PROPERTIES AT THE CERN SPS COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

Aachen[1] – Amsterdam (NIKHEF)[2] – Annecy (LAPP)[3] – Birmingham[4] – CERN[5] – Harvard[6] – Helsinki[7] – Kiel[8] – London (Imperial College[9] and Queen Mary College[10]) – Padua[11] – Paris (Coll. de France)[12] – Riverside[13] – Rome[14] – Rutherford Appleton Lab.[15] – Saclay (CEN)[16] – Victoria[17] – Vienna[18] – Wisconsin[19] Collaboration

The corresponding experimental result for the 1984 data at $\sqrt{s}$ = 630 GeV is

$$(\sigma \cdot B)_W = 0.63 \pm 0.05\ (\pm 0.09)\ \text{nb}.$$

This is in agreement with the theoretical expectation [14] of $0.47^{+0.14}_{-0.08}$ nb. We note that the 15%

- agreement and uncertainties at 20% considered to be satisfactory
- results from different PDF sets differ by at least 5%
- no way to estimate dominant (PDF) uncertainties

QCD: THEN AND NOW

EXAMPLE: PARTON DISTRIBUTIONS

PDFs IN 1984

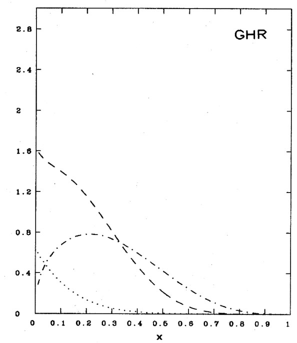


FIG. 25. Parton distributions of Glück, Hoffmann, and Reya (1982), at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and q_v (dotted line).

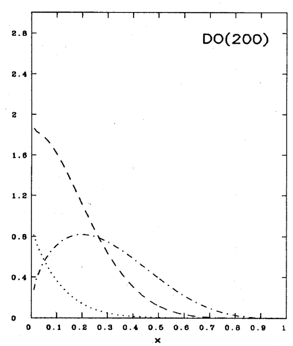


FIG. 27. "Soft-gluon" ($\Lambda=200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).

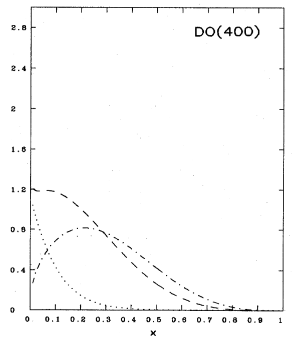
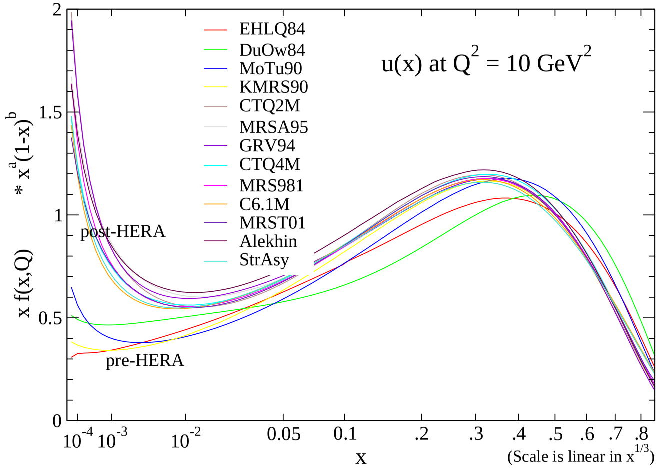


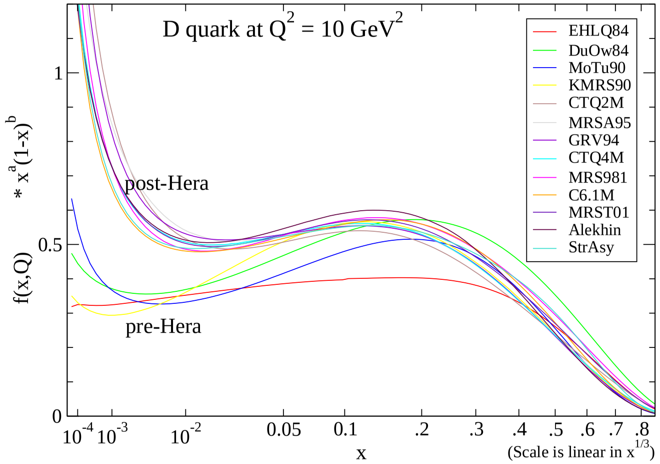
FIG. 26. "Hard-gluon" ($\Lambda=400$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).

Rev. Mod. Phys., Vol. 56, No. 4, October 1984

GHR VS DUKE-OWENS

20 YEARS OF VALENCE PDFs





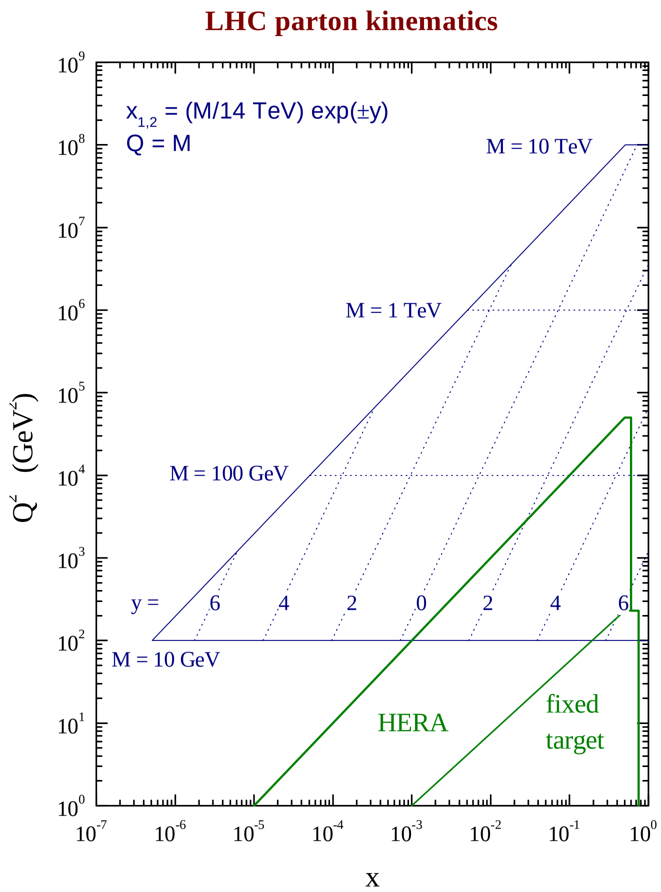
W.-K. TUNG, 2004

- HADRON COLLIDERS CIRCA 1985 ⇒ QUALITATIVE QCD: DISCOVERY PHYSICS
- DIS AT NMC AND HERA 1995-2005 ⇒ QUANTITATIVE QCD: PRECISION PHYSICS
- HADRON COLLIDERS CIRCA 2010 ⇒ PRECISION QCD ↔ NEW PHYSICS

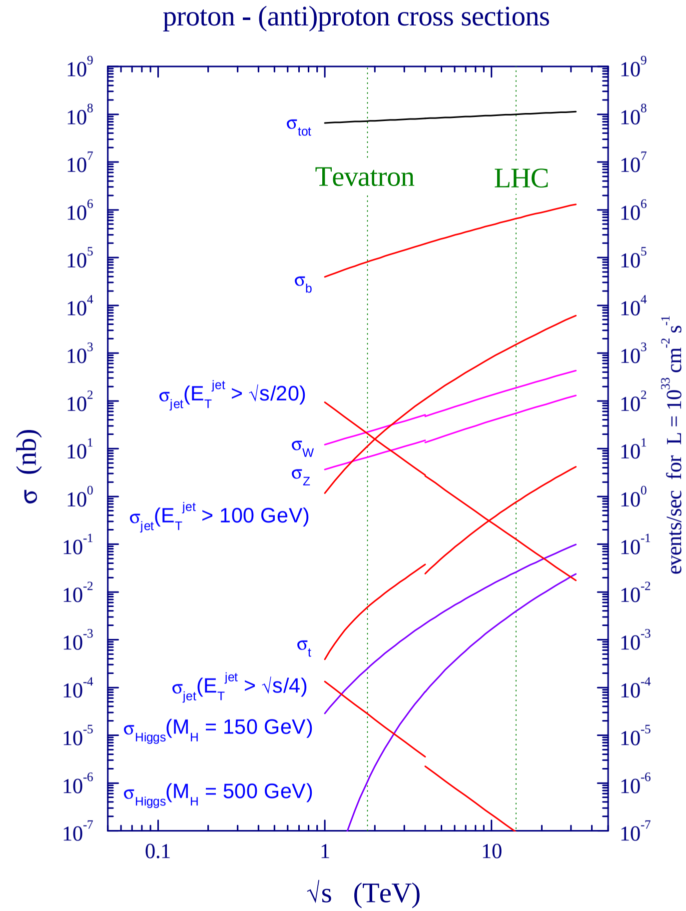
LHC: THE NAME OF THE GAME

$$\sigma_X(s, M_X^2) = \sum_{a,b} \int_{x_{\min}}^1 dx_1\, dx_2\, f_{a/h_1}(x_1) f_{b/h_2}(x_2) \hat{\sigma}_{q_a q_b \to X}\left(x_1 x_2 s, M_X^2\right)$$

LHC kinematics



LHC processes



- COMPUTE SIGNAL AND BACKGROUND PROCESSES IN AN UNEXPLORED KIEMATIC REGION
- SIGNAL TYPICALLY MUCH LOWER THAN BACKGROUND
- NEED PDFs BASED ON CURRENT THEORY AND PHENOMENOLOGY

SUMMARY

- LECTURE I: PARTON DISTRIBUTIONS
- LECTURE II: PERTURBATIVE CORRECTIONS
- LECTURE III:: RESUMMATION

APOLOGIES

- A PERSONAL SELECTION OF TOPICS
- FOCUS ON LHC PHENOMENOLOGY
- MANY THEORETICAL DEVELOPMENTS NOT COVERED
- PROGRESS IN JET PHYSICS NOT COVERED!

LECTURE I

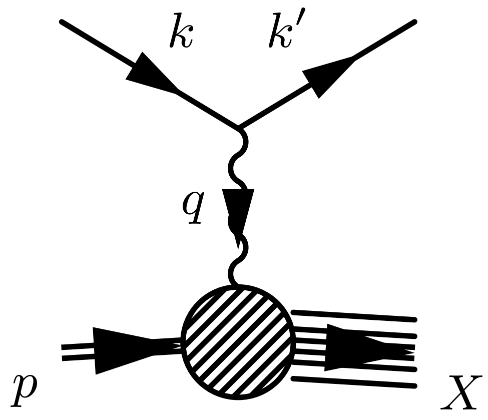
PARTON DISTRIBUTIONS

- FACTORIZATION: FROM PDFs TO OBSERVABLES AND BACK
- PDF DETERMINATION
- PDF UNCERTAINTIES
- LHC STANDARD CANDLES

FACTORIZATION

FACTORIZATION I: DEEP-INELASTIC SCATTERING

STRUCTURE FUNCTIONS. . .



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

gauge boson virtuality: $q^2 = -Q^2$

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

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

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

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

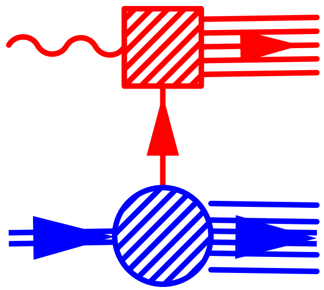
$$\left.\left. +y^2 xF_1(x,Q^2)\right] - 2\lambda_p\left[-\lambda_\ell\, y(2-y)xg_1(x,Q^2) - (1-y)g_4(x,Q^2) - y^2 xg_5(x,Q^2)\right] \right\}$$

$\lambda_l \rightarrow$ lepton helicity

$\lambda_p \rightarrow$ proton helicity

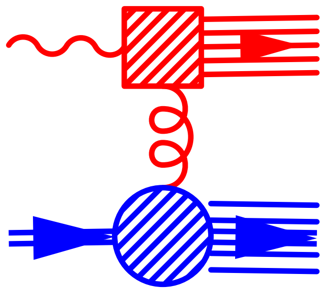
	PARITY CONS.	PARITY VIOL.
UNPOL.	$F_1,\ F_2$	F_3
POL.	g_1	$g_4,\ g_5$

...and Parton Distributions



Structure Function=Hard coeff. (partonic structure function)

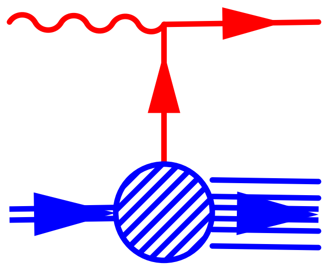
$\otimes$parton distn.



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

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: $p \to n \Rightarrow u \leftrightarrow d$

FACTORIZATION II: HADRONIC PROCESSES

$$\sigma_X(s, M_X^2) = \sum_{a,b} \int_{x_{\min}}^1 dx_1\, dx_2\, f_{a/h_1}(x_1) f_{b/h_2}(x_2) \hat{\sigma}_{q_a q_b \to X}\left(x_1 x_2 s, M_X^2\right)$$

LEAD. ORD. $= \sigma_0 \sum_{a,b} \int_\tau^1 \frac{dx}{x} f_{a/h_1}(x) f_{b/h_2}(\tau/x) \equiv \sigma_0 \mathcal{L}(\tau) \Rightarrow \mathcal{L}$ PARTON LUMI

- Scaling variable $\tau = \frac{M_X^2}{s}$

EXAMPLE: DRELL-YAN $\sigma_X \to M^2 \frac{d\sigma}{dM^2}$; $\sigma_0 = \frac{4}{9}\pi\alpha\frac{1}{s}$

FACTORIZATION II: HADRONIC PROCESSES

$$\sigma_X(s, M_X^2) = \sum_{a,b} \int_{x_{\min}}^1 dx_1\, dx_2\, f_{a/h_1}(x_1) f_{b/h_2}(x_2) \hat\sigma_{q_a q_b \to X}\left(x_1 x_2 s, M_X^2\right)$$

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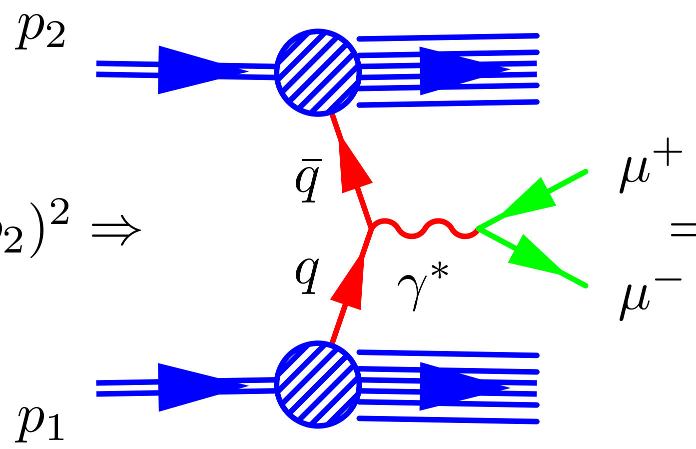
$s = (p_1 + p_2)^2 \Rightarrow$



$\Rightarrow M_X^2$

LEADING ORDER

DRELL-YAN

- Hadronic c.m. energy: $s = (p_1 + p_2)^2$
- Momentum fractions $x_{1,2} = \sqrt{\frac{\hat s}{s}} \exp \pm y$; Lead. Ord. $\hat s = M^2$
- Partonic c.m. energy: $\hat s = x_1 x_2 s$
- Invariant mass of final state X (dilepton, Higgs,...): $M_W^2 \Rightarrow$ scale of process
- Scaling variable $\tau = \frac{M_X^2}{s}$

- $\hat\sigma_{q_a q_b \to X} = \sigma_0 C\left(x, \alpha_s(M_H^2)\right)$; $\quad C\left(x, \alpha_s(M_H^2)\right) = \delta(1-x) + O(\alpha_s)$
- $\sigma_X(s, M^2) = \sigma_0 \sum_{a,b} \int_{x_{\min}}^1 dx_1\, dx_2\, f_{a/h_1}(x_1) f_{b/h_2}(x_2) \delta(x_1 x_2 x - \tau) C\left(x, \alpha_s(M_H^2)\right)$
  $= \sigma_0 \sum_{a,b} \int_{x_2}^1 \frac{dx_1}{x_1} \int_\tau^1 \frac{dx_2}{x_2} f_{a/h_1}(x_1) f_{b/h_2}(x_2) C\left(\frac{\tau}{x_1 x_2}, \alpha_s(M_H^2)\right)$

EXAMPLE: DRELL-YAN $\sigma_X \to M^2 \frac{d\sigma}{dM^2}$; $\sigma_0 = \frac{4}{9}\pi\alpha\frac{1}{s}$

EVOLUTION EQUATIONS

MUST EVOLVE FROM HERA TO LHC $\rightarrow$ USE DGLAP EQUATIONS (RG EQNS)

- DEFINE MELLIN MOMENTS OF PARTON DISTRIBUTIONS
  $f(N,Q^2) \equiv \int_0^1 dx\, x^{N-1} f_2(x,Q^2)$
  NOTE LARGE/SMALL $x \Leftrightarrow$ LARGE/SMALL N

- DEFINE LOGARITHMIC SCALE $t = \ln \frac{Q^2}{\Lambda^2}$: EVOLUTION GIVEN BY ORDINARY DIFFERENTIAL EQUATIONS (RG EQUATIONS)

- ANOMALOUS DIMENSIONS RELATED TO DGLAP SPLITTING FUNCTIONS
  $\gamma(N,\alpha_s(t)) \equiv \int_0^1 dx\, x^{N-1} P(x,\alpha_s(t))$

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

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

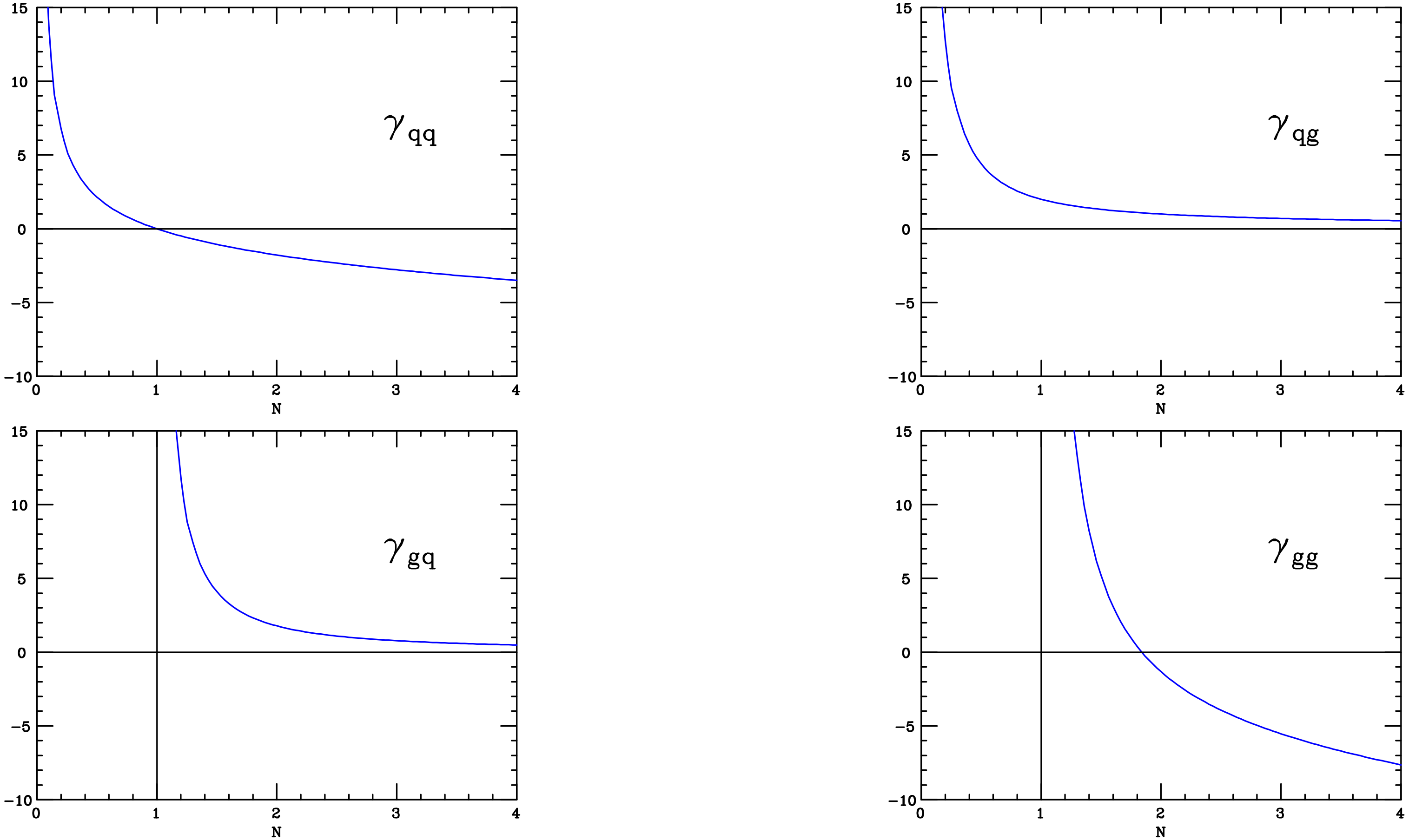
- EVOLUTION OF SINGLET $\Sigma(x,Q^2) = \sum_{i=1}^{n_f}\left(q_i(x,Q^2) + \bar{q}_i(x,Q^2)\right)$ COUPLED TO GLUON

- ALL “NONSINGLET” QUARK COMBINATIONS $q^{NS}(x,Q^2) = q_i(x,Q^2) - q_j(x,Q^2)$ EVOLVE INDEPENDENTLY

- ANOMALOUS DIMENSIONS COMPUTED IN PERTURBATION THEORY:
  $\gamma_i(N,\alpha_s(t)) = \gamma_i^{(0)}(N) + \alpha_s(t)\gamma_i^{(1)}(N) + \ldots$

PERTURBATIVE EVOLUTION

THE LEADING ORDER ANOMALOUS DIMENSIONS



QUALITATIVE FEATURES

- AS Q^2 INCREASES, PDFS DECREASE AT LARGE x & INCREASE AT SMALL x DUE TO RADIATION
- GLUON SECTOR SINGULAR AT $N = 1 \Rightarrow$ GLUON GROWS MORE AT SMALL x
- $\gamma_{qq}(1) = 0 \Rightarrow$ NUMBER OF QUARKS CONSERVED

SUM RULES

CONSTRUCT CONSERVED QUANTUM NUMBERS CARRIED BY PARTON DISTRIBUTIONS:

- BARYON NUMBER $\int_0^1 dx\,(u^p - \bar{u}^p) = 2 = 2\int_0^1 dx\left(d^p - \bar{d}^p\right)$
- MOMENTUM $\int_0^1 dx x\left[\sum_{i=1}^{N_f}\left(q^i(x) + \bar{q}_i(x)\right) + g(x)\right]=1$

CANNOT DEPEND ON SCALE

- BARYON NUMBER $\gamma_{qq}(1) - \gamma_{q\bar{q}}(1) = 0$; AT LO $\gamma_{q\bar{q}}(1) = 0$ SO $\gamma_{qq}(1) = 0$
- MOMENTUM $\gamma_{qq}(2) + \gamma_{qg}(2) = 0$, $\gamma_{gq}(2) + \gamma_{gg}(2) = 0$

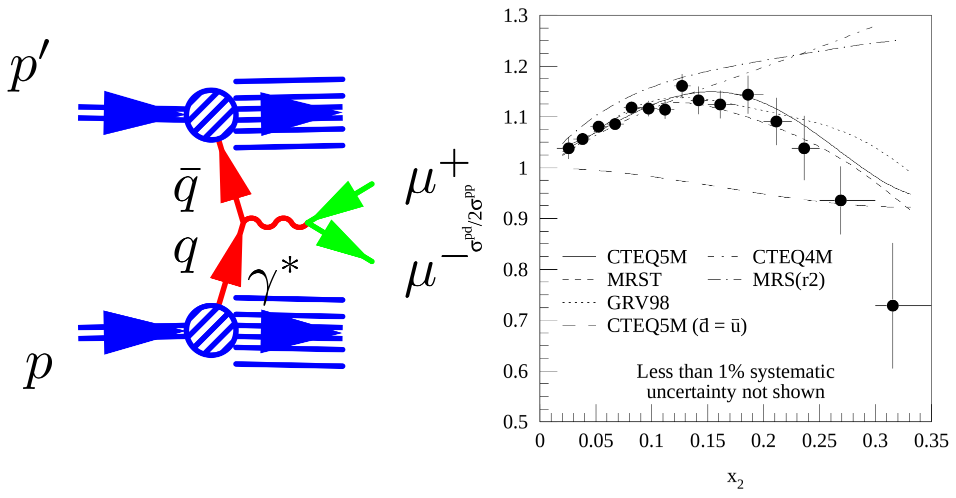
CAN EXTRACT FROM PHYSICAL OBSERVABLES: BARYON NUMBER

- GROSS–LLEWELLYN-SMITH SUM RULE $\frac{1}{2}\int_0^1 dx\,\left(F_3^{\nu p}(x,Q^2) + F_3^{\nu n}(x,Q^2)\right) =$
  $= C_{\rm GLS}(Q^2)\int_0^1 dx\,\left[u(x,Q^2) - \overline{u}(x,Q^2) + d(x,Q^2) - \overline{d}(x,Q^2)\right]$
- BJORKEN (UNPOLARIZED) SUM RULE $\frac{1}{2}\int_0^1 dx\,\left(F_1^{\nu p}(x,Q^2) - F_1^{\nu n}(x,Q^2)\right) =$
  $= C_{\rm BjU}(Q^2)\int_0^1 dx\,\left[u(x,Q^2) - \overline{u}(x,Q^2) - \left(d(x,Q^2) - \overline{d}(x,Q^2)\right)\right]$

DISENTANGLING QUARKS FROM ANTIQUARKS

γ^* DIS ONLY MEASURES $q+\bar{q}$ COMBINATION!

DRELL-YAN p/d ASYMMETRY

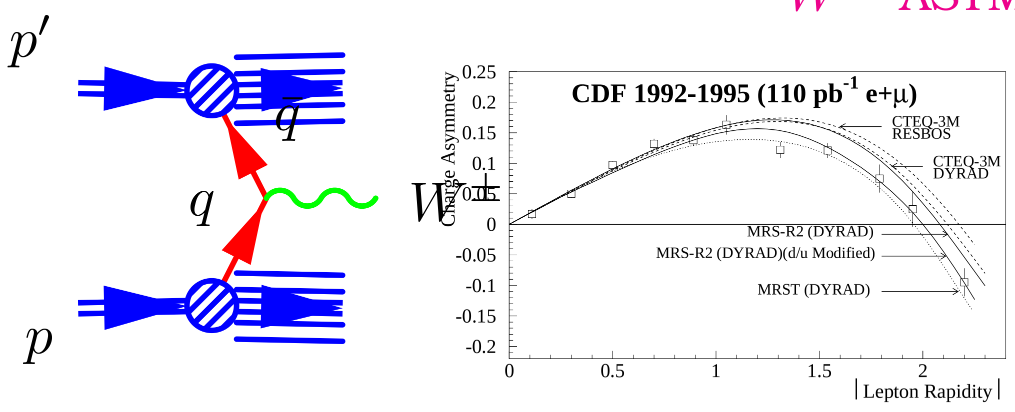


E866 (2001)

LIGHT ANTIQUARK ASYMMETRY

$$\frac{\sigma^{pn}}{\sigma^{pp}} \sim \left.\frac{\frac{4}{9}u^p\,\bar{d}^p + \frac{1}{9}d^p\,\bar{u}^p}{\frac{4}{9}u^p\,\bar{u}^p + \frac{1}{9}d^p\,\bar{d}^p}\right|_{\text{large } x} \approx \frac{\bar{d}}{\bar{u}}$$

$W^\pm$ ASYMMETRY



CDF (1998)

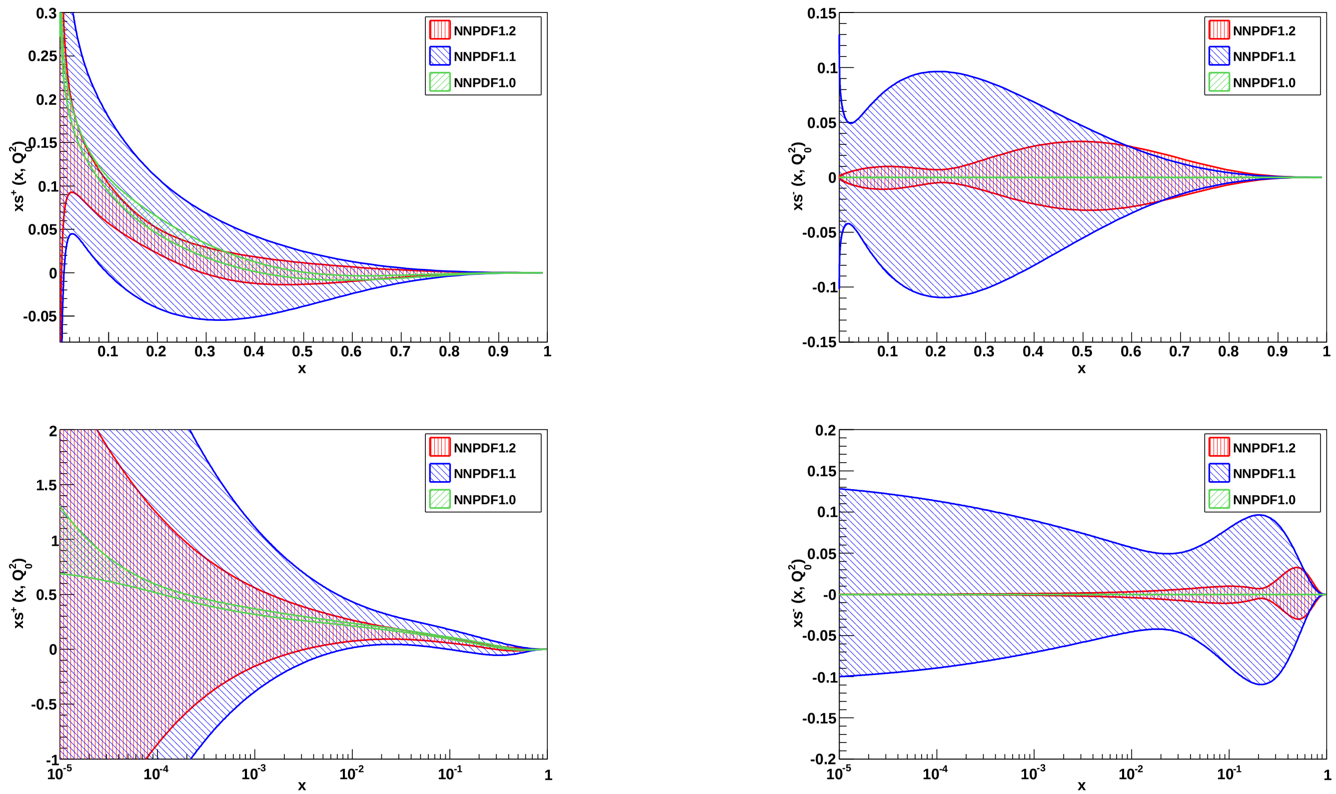
LIGHT QUARK ASYMMETRY

$$\frac{\sigma^{p\bar{p}}_{W+}}{\sigma^{p\bar{p}}_{W-}} \sim \frac{u^p\,d^p}{d^p\,u^p} \qquad (q^p = \bar{q}^{\bar{p}})$$

DISENTANGLING STRANGENESS

- STRANGENESS ALMOST UNCONSTRAINED BY INCLUSIVE DIS DATA
  NNPDF1.1: s, $\bar{s}$ (actually $s^{\pm}$) indep. parametrized, no dimuon data
- IN PARTON FITS UP TO 2009 $\rightarrow$ STRANGENESS FIXED BY ASSUMPTION
  NNPDF1.0: $s(x, Q_0^2) = \bar{s}(x, Q_0^2)$, $s + \bar{s} = \frac{1}{2}(\bar{u} + \bar{d})$
- IN CURRENT PARTON FITS $\rightarrow$ STRANGENESS FIXED BY DIS DIMUON PRODUCTION $\nu + s \rightarrow c$
  NNPDF1.2: s, $\bar{s}$ (actually $s^{\pm}$) indep. parametrized, dimuon data

STRANGE PDFS



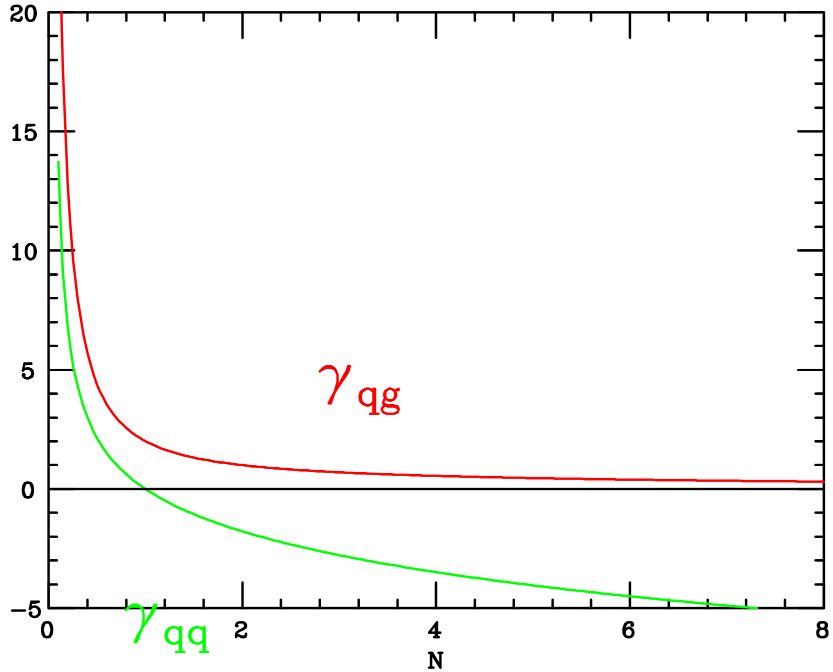
DETERMINING THE GLUON

SMALL x (SMALL N):

SINGLET SCALING VIOLATIONS (HERA)

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

ANOMALOUS DIMENSIONS

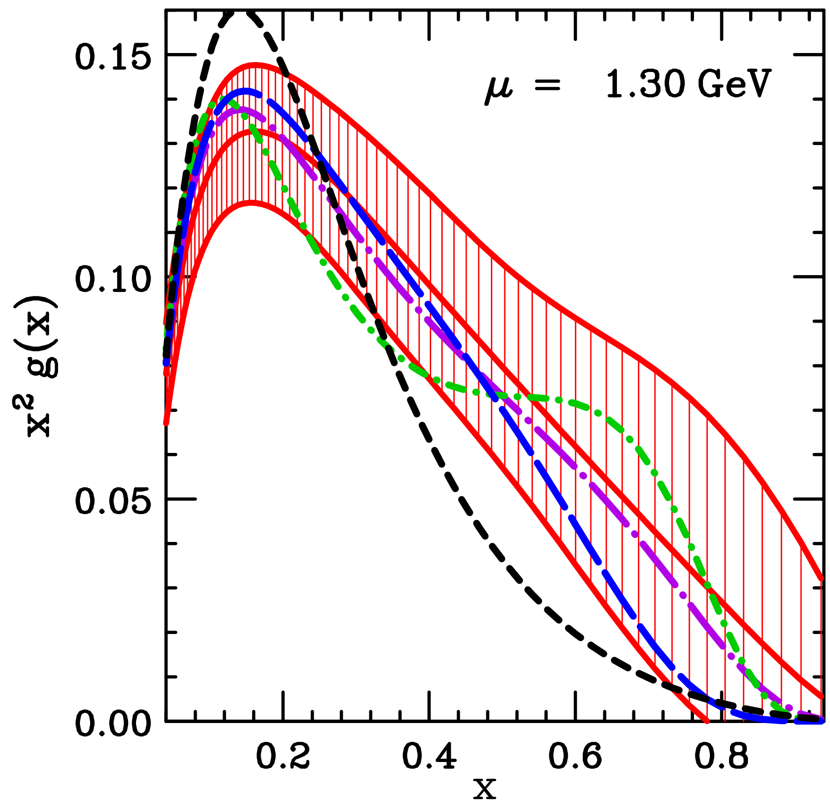


LARGE x:

HIGH p_T JETS (TEVATRON)

CTEQ6.6 GLUON

(DASHED: NO JET DATA)



PRESENT

- SMALL x GLUON & SINGLET $\Leftrightarrow$ PRECISE HERA DATA
- SMALL x FLAVOUR SEPARATION $\Leftrightarrow$ TEVATRON W ASYMMETRY DATA
- MEDIUM x FLAVOUR SEPARATION $\Leftrightarrow$ FIXED TARGET p/d DIS DATA, DRELL YAN, NEUTRINO INCLUSIVE
- STRANGENESS $\Leftrightarrow$ NEUTRINO DIMUON
- LARGE x GLUON $\Leftrightarrow$ TEVATRON JETS

PRESENT

- SMALL x GLUON & SINGLET $\Leftrightarrow$ PRECISE HERA DATA
- SMALL x FLAVOUR SEPARATION $\Leftrightarrow$ TEVATRON W ASYMMETRY DATA
- MEDIUM x FLAVOUR SEPARATION $\Leftrightarrow$ FIXED TARGET p/d DIS DATA, DRELL YAN, NEUTRINO INCLUSIVE
- STRANGENESS $\Leftrightarrow$ NEUTRINO DIMUON
- LARGE x GLUON $\Leftrightarrow$ TEVATRON JETS

FUTURE

- W ASYMMETRY $\Leftrightarrow$ FULL FLAVOUR SEPARATION AT MEDIUM/SMALL x
- HIGH p_T JETS $\Leftrightarrow$ PRECISE GLUON AT INTERMEDIATE x
- HQ PRODUCTION $\Leftrightarrow$ INDIVIDUAL QUARK FLAVOURS & GLUON AT SMALL x
- HIGGS PRODUCTION $\Leftrightarrow$ MEDIUM x GLUON

PDF DETERMINATION

THE "STANDARD" APPROACH (MSTW, CTEQ):

FUNCTIONAL PARTON FITTING

- CHOOSE A FIXED FUNCTIONAL FORM:
  - MSTW: 20 PARMS.

    $$xq(x,Q_0^2) = A(1-x)^{\eta}(1+\epsilon x^{0.5}+\gamma x)x^{\delta}, (5\ \text{indep. fns.}); x[\bar{u}-\bar{d}](x,Q_0^2) = A(1-x)^{\eta}(1+\gamma x+\delta x^2)x^{\delta};$$

    $$x[s-\bar{s}](x,Q_0^2) = A_-(1-x)^{\eta_s}x^{\delta_-}(1-x/x_0); xg(x,Q_0^2) = A_g(1-x)^{\eta_g}(1+\epsilon_g x^{0.5}+\gamma_g x)x^{\delta_g}+A_{g'}(1-x)$$

  - CTEQ6: 22 PARMS.

    $$x\,f(x,Q_0) = A_0\,x^{A_1}\,(1-x)^{A_2}\,e^{A_3 x}\,(1+e^{A_4}\,x)^{A_5}, \quad (7\ \text{indep. functions})$$

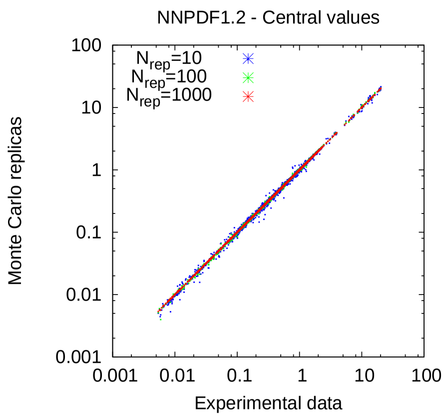
  - BASIS FUNCTIONS: $u_v \equiv u-\bar{u}$, $d_v \equiv d-\bar{d}$, $\bar{u}-\bar{d}$ (MSTW) OR $\bar{u}/\bar{d}$ (CTEQ), $s^{\pm} \equiv s \pm \bar{s}$, g.
- EVOLVE TO DESIRED SCALE & COMPUTE PHYSICAL OBSERVABLES
- DETERMINE BEST-FIT VALUES OF PARAMETERS
- DETERMINE ERROR BY PROPAGATION OF ERROR ON PARMS ('HESSIAN METHOD') OR BY PARM. SCANS ('LAGRANGE MULTIPLIER METHOD')

THE NNPDF APPROACH:
THE NEURAL MONTE CARLO

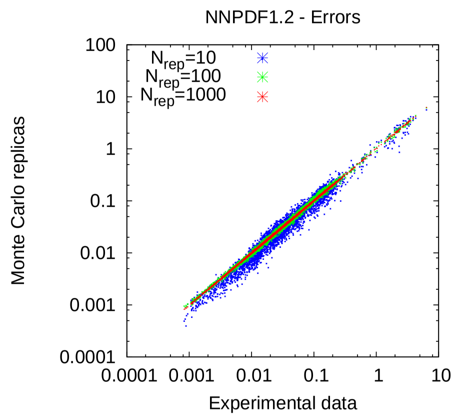
BASIC IDEA: MONTE CARLO SAMPLING OF THE PROBABILITY MEASURE IN THE (FUNCTION) SPACE OF PDFs

- START FROM MONTE CARLO SAMPLING OF DATA SPACE
- SPACE OF FUNCTIONS HUGE
  5 BINS FOR 10 PTS$\times$ 7 FCTNS $\rightarrow 5^{70} \sim 10^{49}$ BINS
- IMPORTANCE SAMPLING: DATA TELL US WHICH BINS ARE POPULATED

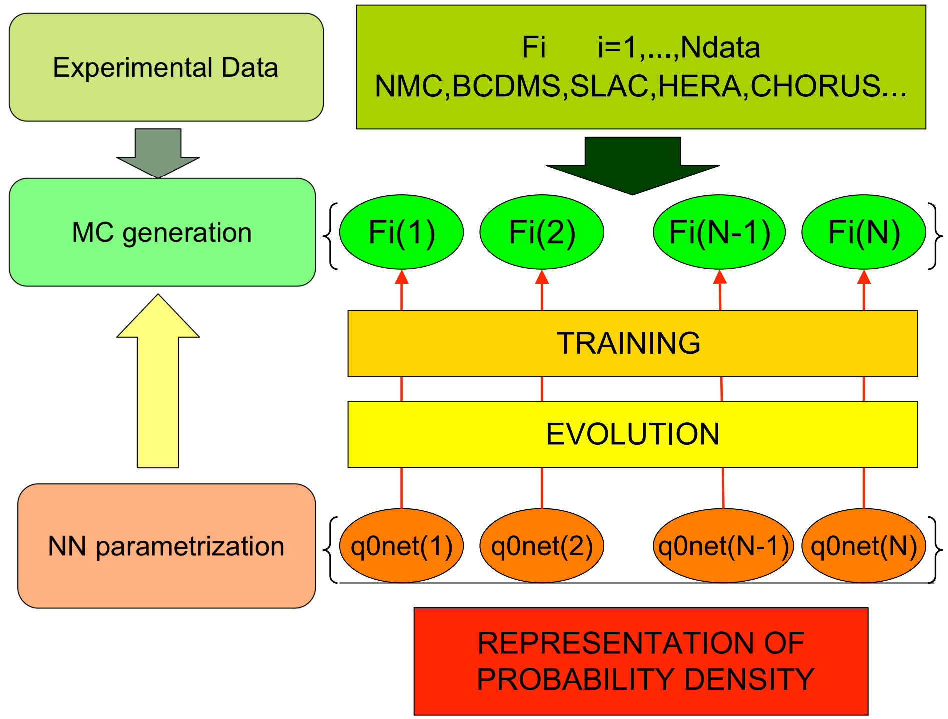
replica averages vs. central values



replica standard dev. vs. uncertainties

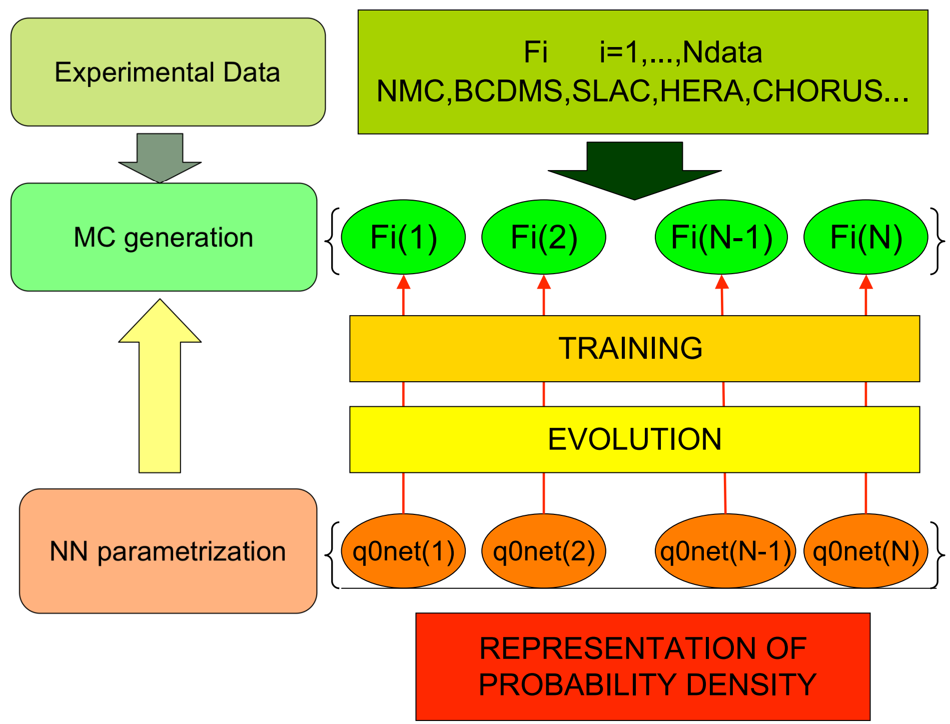


10 REPLICAS ENOUGH FOR CENTRAL VALS, 100 FOR UNCERTAINTIES, 1000 FOR CORRELNS



DATA MONTE CARLO ⇒ PDF MONTE CARLO
NEURAL NETWORK PARM+ CROSS-VALIDATION METHOD

- EACH PDF↔ NEURAL NETWORK PARAMETRIZED BY 37 PARAMETERS
- NNPDF1.2: $37 \otimes 7 = 259$ PARMS (RECALL MSTW, CTEQ → 20 FREE PARAMETERS)
  "INFINITE" NUMBER OF PARAMETERS⇒ CAN REPRESENT ANY FUNCTION
- COMPLEX SHAPES (LARGE NO.OF PARAMETERS) REQUIRE LONGER FITTING
- FIT STOPS WHEN QUALITY OF FIT TO RANDOMLY SELECTED "VALIDATION" DATA (NOT FITTED) STOPS IMPROVING
- CAN OBTAIN A FIT WITH χ^2 LOWER THAN BEST FIT ("OVERLEARNING")

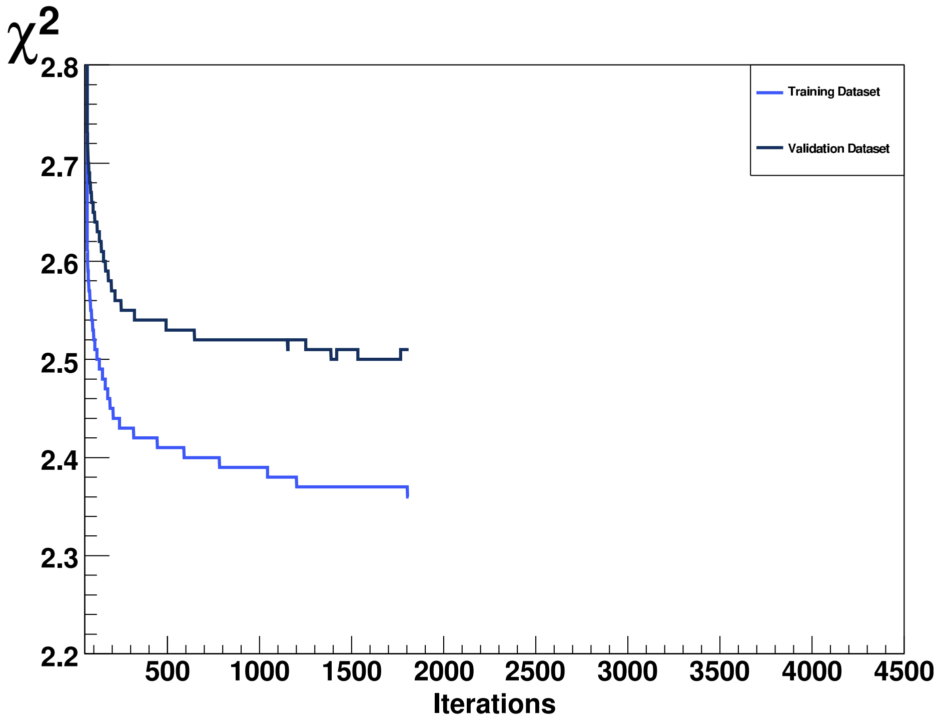


DATA MONTE CARLO ⇒ PDF MONTE CARLO
CROSS-VALIDATION

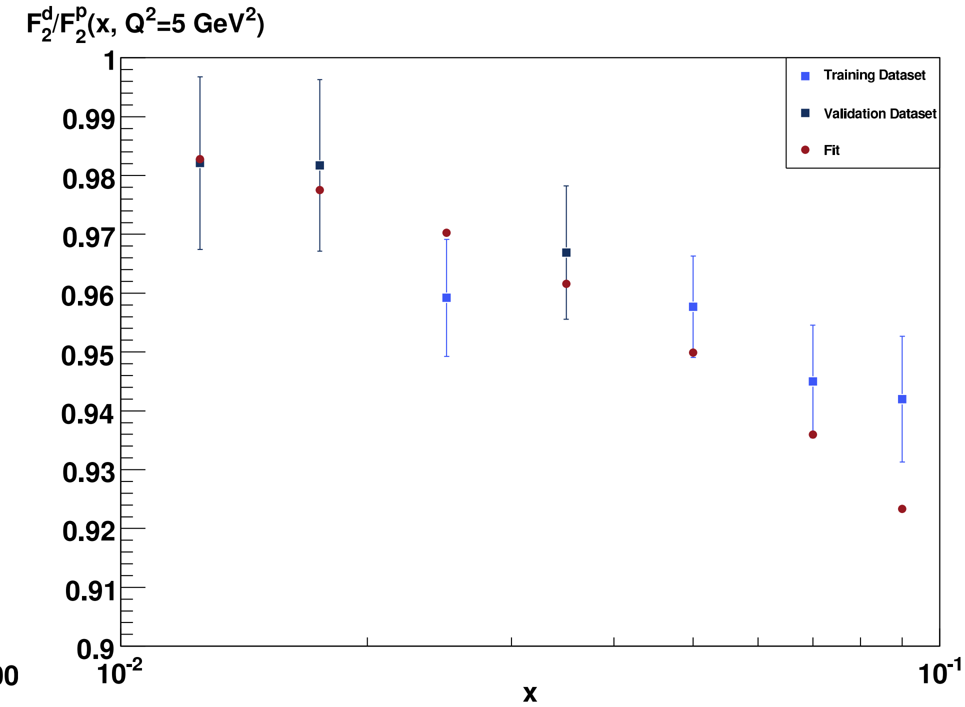
- REPLICAS ARE FITTED TO A DATA SUBSET
- A DIFFERENT SUBSET OF DATA USE FOR EACH REPLICA
- OPTIMAL FIT WHEN FIT TO VALIDATION (CONTROL) DATA STOPS IMPROVING
-

OPTIMAL FITTING

χ^2



FIT TO DATA

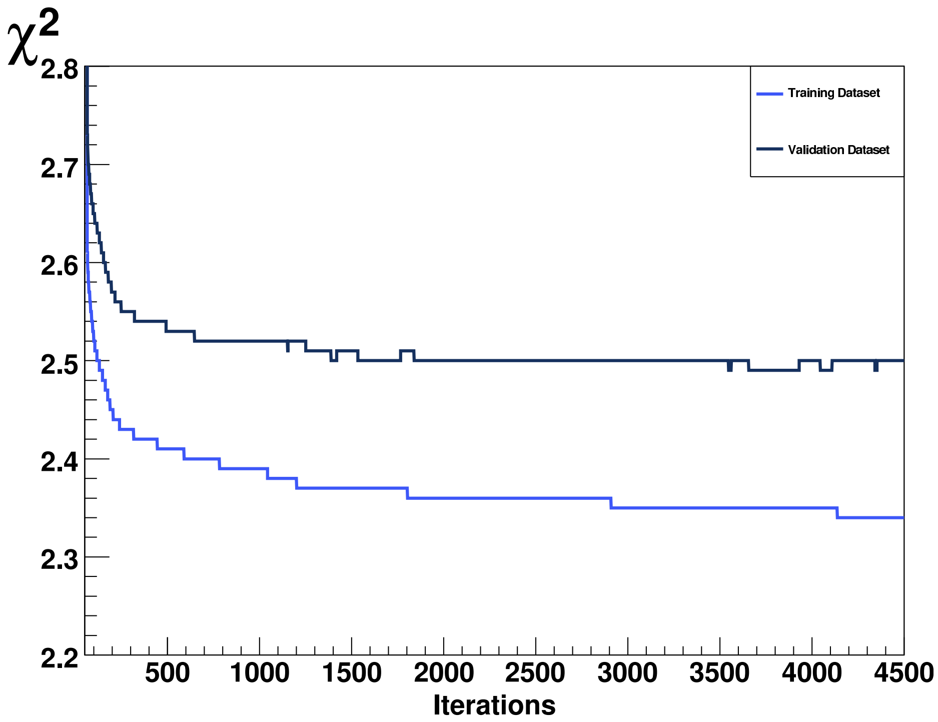


DATA MONTE CARLO ⇒ PDF MONTE CARLO
CROSS-VALIDATION

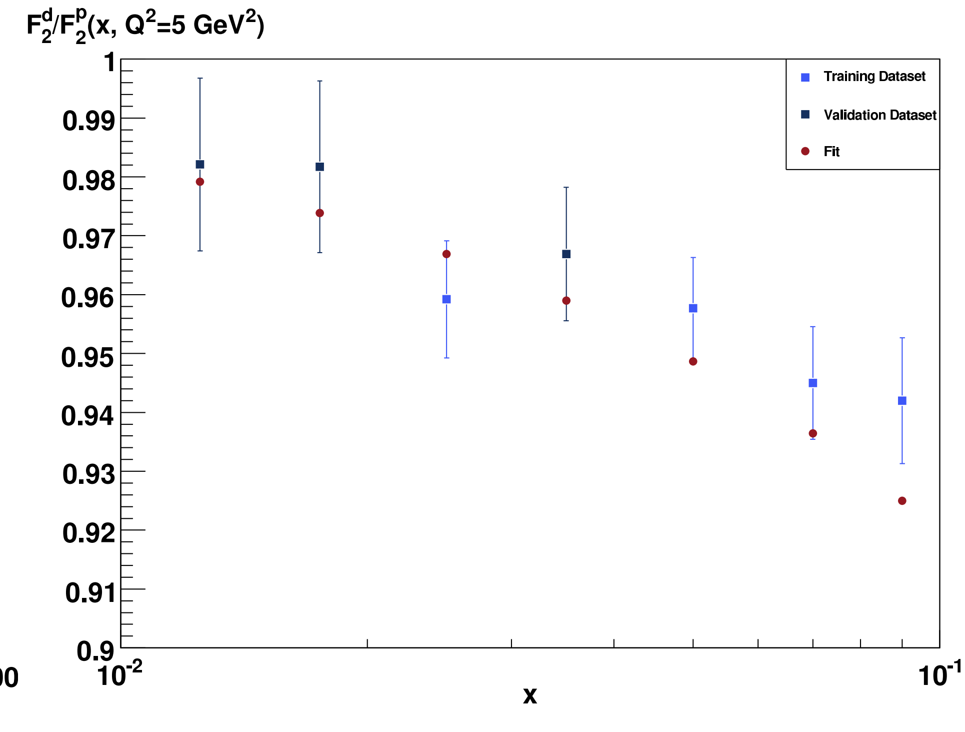
- REPLICAS ARE FITTED TO A DATA SUBSET
- A DIFFERENT SUBSET OF DATA USE FOR EACH REPLICA
- OPTIMAL FIT WHEN FIT TO VALIDATION (CONTROL) DATA STOPS IMPROVING
- THE BEST FIT IS NOT AT THE MINIMUM OF THE χ^2

OVERFITTING

χ^2



FIT TO DATA

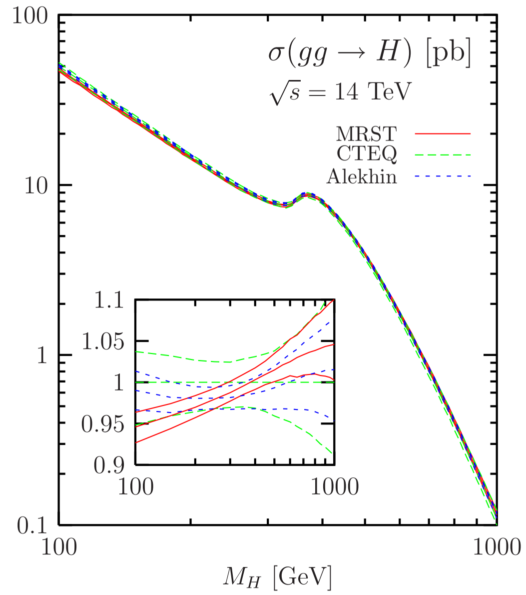


PDFs: THE STATE OF THE ART

THE HIGGS CROSS SECTION

CAN WE CALCULATE IT?

PDF WITH ERRORS: DO THEY AGREE?



(Djouadi, Ferrag, 2004)

FIRST PDF SETS WITH ERROR
(2002-2003)
CTEQ, MRST (global); Alekhin (DIS)

- WIDELY DIFFERENT UNCERTAINTY ESTIMATES
- UNSATISFACTORY AGREEMENT WITHIN UNCERTAINTIES
- $\Delta\chi^2 = 100$ (CTEQ); 50 (MRST); 1 (ALEKHIN)

PDFs: THE STATE OF THE ART

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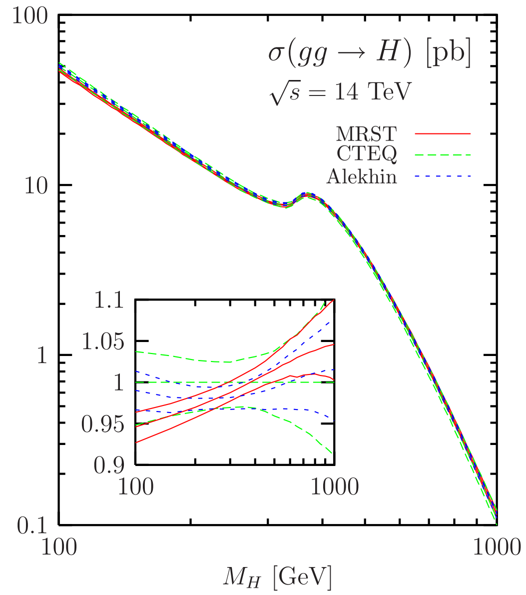

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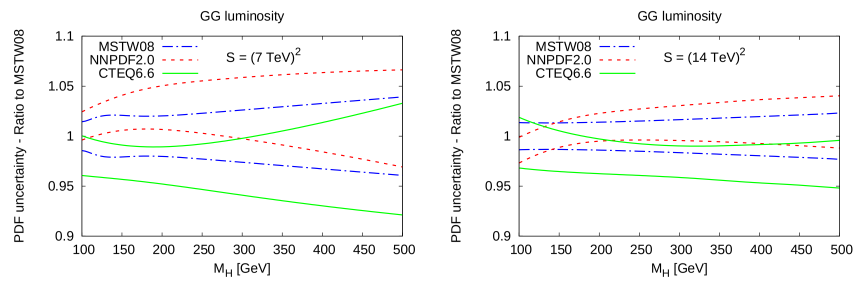
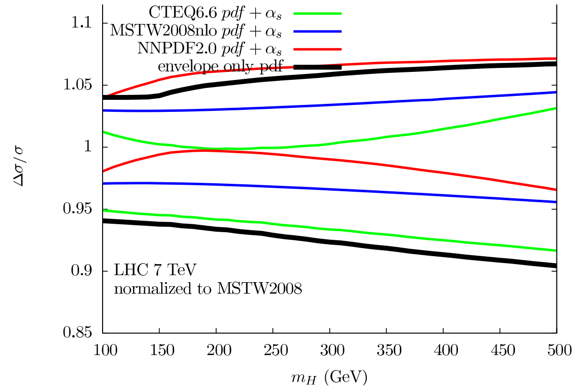
CURRENT GLOBAL PDF SETS

gluon luminosities



gg→H cross section



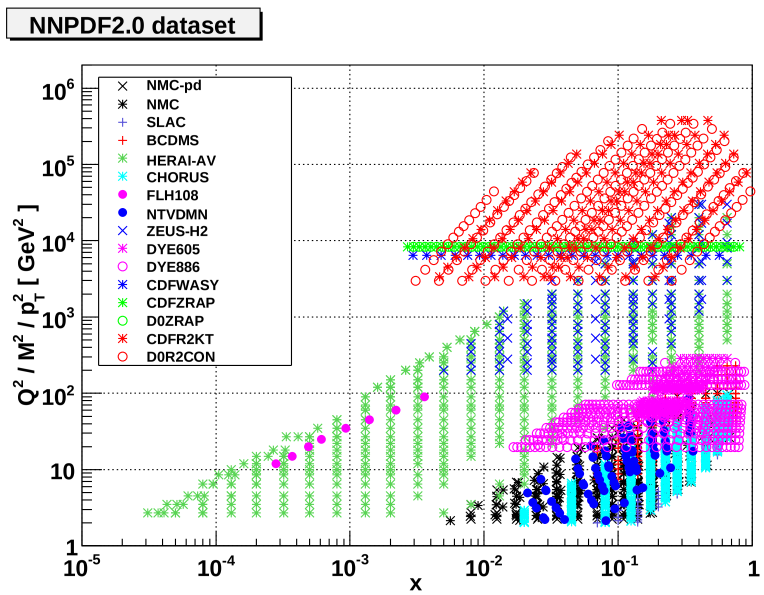
(Demartin et al., 2010)

- THREE GLOBAL (DIS+HADRONIC) PDF SETS AVAILABLE
- REASONABLE AGREEMENT OF CENTRAL VALUES & UNCERTAINTIES

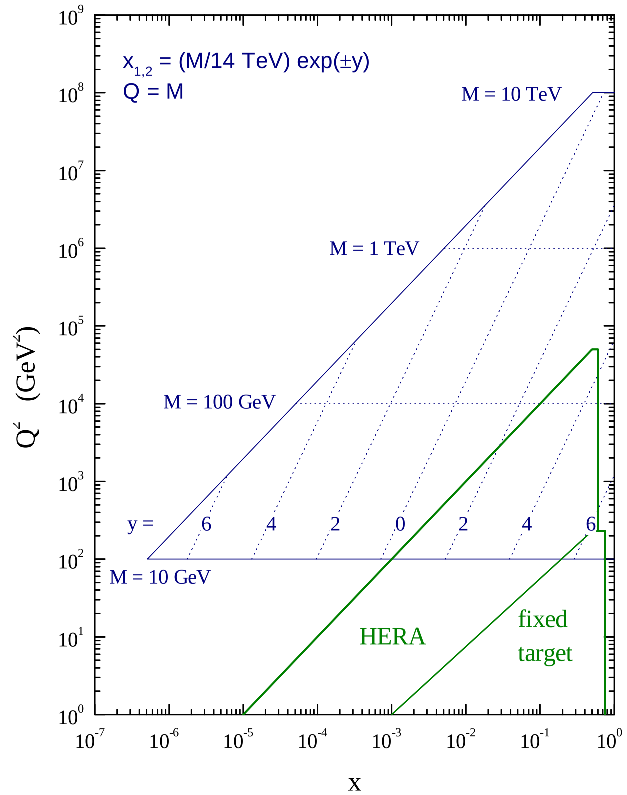
CURRENT PDF SETS

$$\sigma_X(s, M_X^2) = \sum_{a,b} \int_{x_{\min}}^{1} dx_1\, dx_2\, f_{a/h_1}(x_1) f_{b/h_2}(x_2) \hat{\sigma}_{q_a q_b \to X}\left(x_1 x_2 s, M_X^2\right)$$

data for a global fit (NNPDF2.0)



LHC kinematics



- CTEQ6.6: GLOBAL, NLO, VFN WITH HQ MASS, SEVERAL α_s VALUES
- MSTW08: GLOBAL, NLO & NNLO, VFN WITH HQ MASS, SEVERAL α_s VALUES
- NNPDF2.0: GLOBAL, NLO, VFN WITHOUT HQ MASS, SEVERAL α_s VALUES
- ALEKHIN ABKM: DIS+SOME DY, NLO & NNLO, BMSN (FFN), SINGLE α_s VALUE
- HERAPDF1.0: ONLY HERA DATA, NLO, VFN WITH HQ MASS, SEVERAL α_s VALS.
- SETS BASED ON MODEL ASSUMPTIONS (GRV/GJR, STATISTICAL PDFS,...)

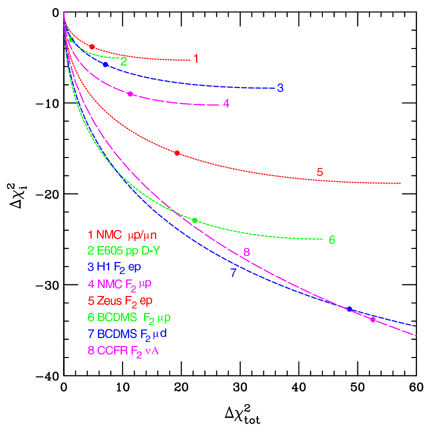
PDF UNCERTAINTIES

WHAT IS A ONE-σ UNCERTAINTY?

MSTW/CTEQ: THE SPREAD OF PDFs WITHIN AN ACCEPTABLE TOLERANCE

- STANDARD $\Delta\chi^2 = 1$ BANDS TOO NARROW $\Rightarrow$ LARGE DISCREPANCIES FOR INDIVIDUAL EXPERIMENTS

MINIMUM χ_i^2
VS GLOBAL χ^2



Collins, Pumplin
2001

WHAT IS A ONE-σ UNCERTAINTY?

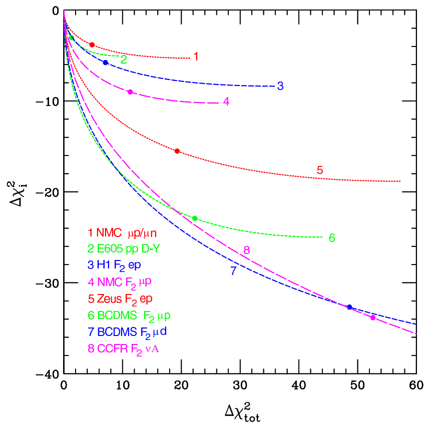
MSTW/CTEQ: THE SPREAD OF PDFS WITHIN AN ACCEPTABLE TOLERANCE

CTEQ TOLERANCE CRITERION &

- STANDARD $\Delta\chi^2 = 1$ BANDS TOO NARROW $\Rightarrow$ LARGE DISCREPANCIES FOR INDIVIDUAL EXPERIMENTS
- TOLERANCE $\Rightarrow$ ENVELOPE OF UNCERTAINTIES OF EXPERIMENTS

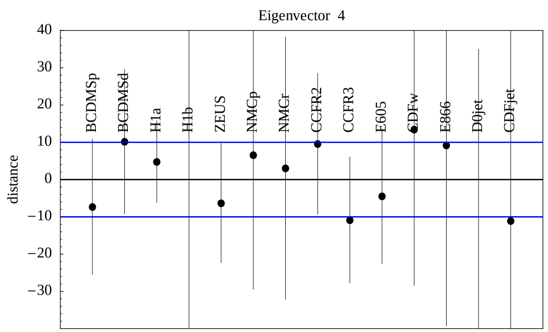
MINIMUM χ_i^2

VS GLOBAL χ^2



Collins, Pumplin
2001

CTEQ TOLERANCE PLOT FOR 4TH EIGENVEC.

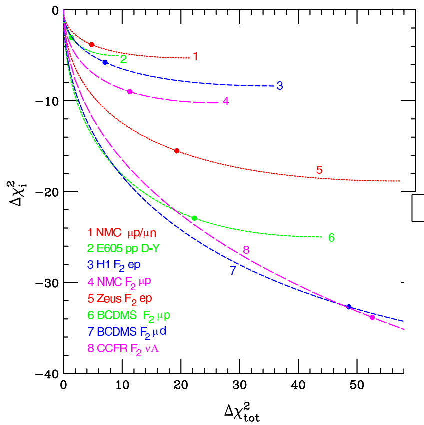


WHAT IS A ONE-σ UNCERTAINTY?

MSTW/CTEQ: THE SPREAD OF PDFS WITHIN AN ACCEPTABLE TOLERANCE
CTEQ TOLERANCE CRITERION & MSTW DYNAMICAL TOLERANCE

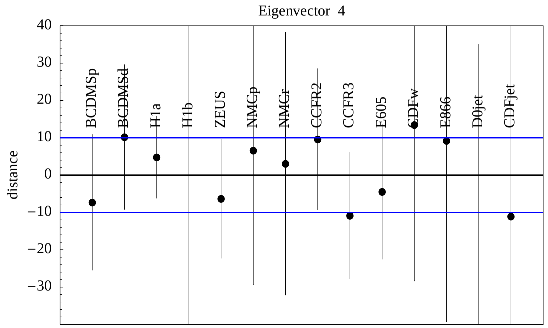
- STANDARD $\Delta\chi^2 = 1$ BANDS TOO NARROW $\Rightarrow$ LARGE DISCREPANCIES FOR INDIVIDUAL EXPERIMENTS
- TOLERANCE $\Rightarrow$ ENVELOPE OF UNCERTAINTIES OF EXPERIMENTS
- DYNAMICAL $\Rightarrow$ SEPARATELY DETERMINED FOR EACH HESSIAN EIGENVECTOR

MINIMUM χ_i^2 VS GLOBAL χ^2

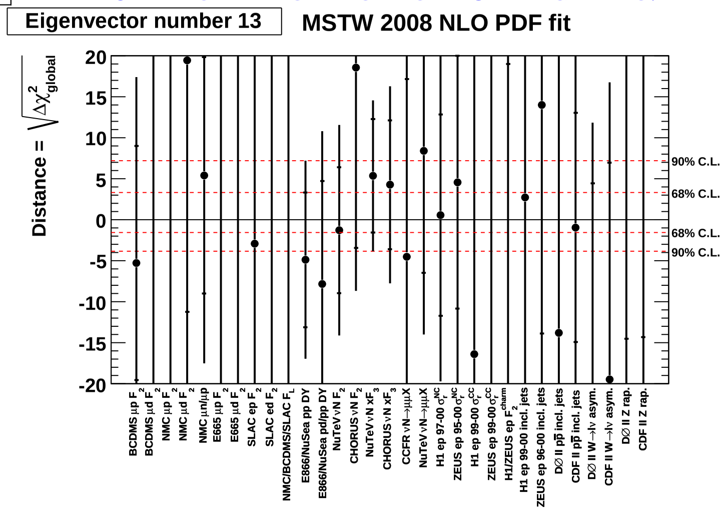


Collins, Pumplin 2001

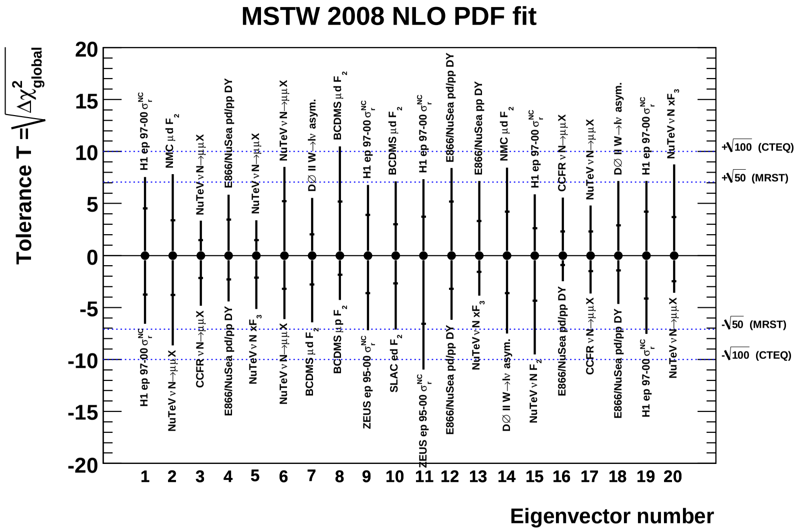
CTEQ TOLERANCE PLOT FOR 4TH EIGENVEC.



MSTW TOLERANCE PLOT FOR 13TH EIGENVEC.



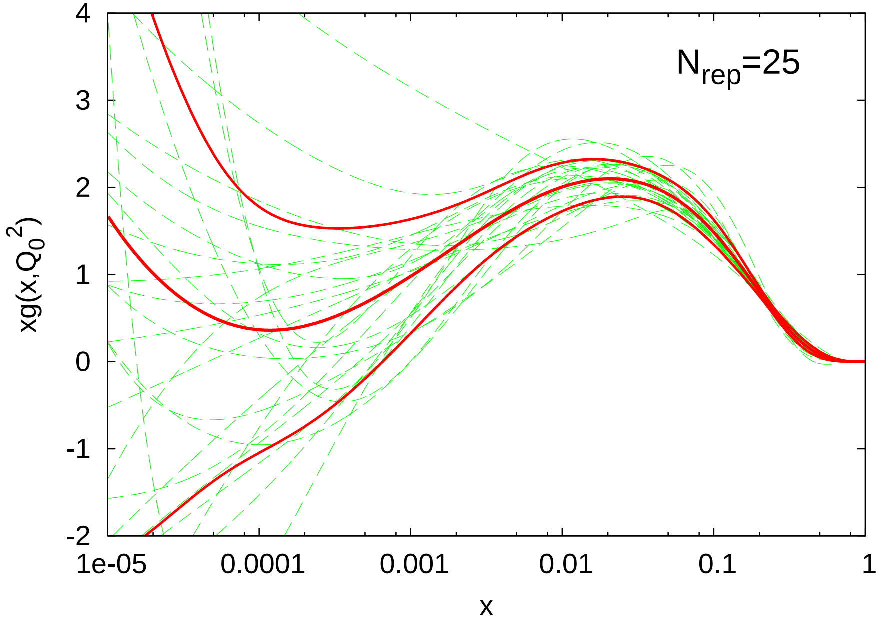
GLOBAL MSTW TOLERANCE

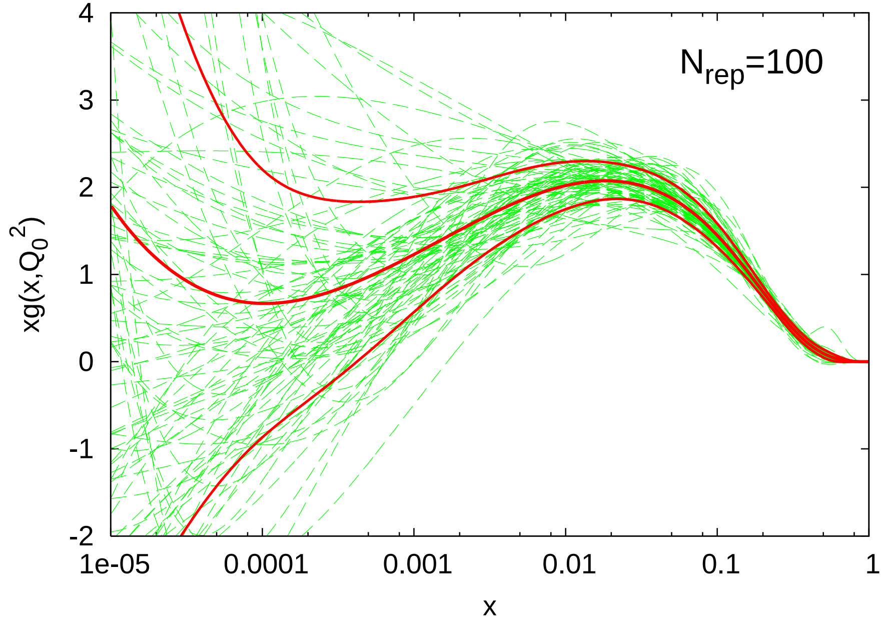


WHAT IS A ONE-σ UNCERTAINTY?

NNPDF: THE CENTRAL 68% OF THE MC DISTRIBUTION OF PDFS

Example: the gluon distribution in the NNPDF1.0 set



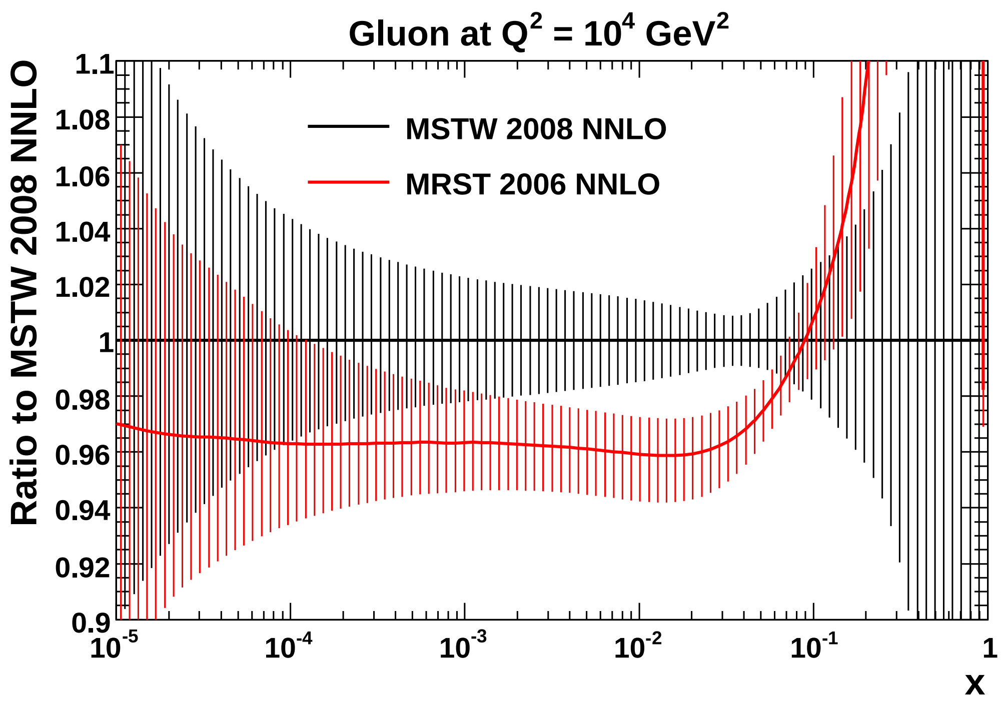


- ENSEMBLE OF REPLICAS $\leftrightarrow$ PROBABILITY DISTRIBUTION OF PDFS
- EXPECTED CENTRAL VALUE $\leftrightarrow$ MEAN; UNCERTAINTY $\leftrightarrow$ STANDARD DEVIATION
- ANY FEATURES OF DISTRIBUTION CAN BE DETERMINED (C.L. INTERVALS, CORRELATIONS...)

WHAT DETERMINES PDF UNCERTAINTIES?

UNCERTAINTIES IN MSTW/CTEQ FITS OFTEN GO UP WHEN DATA ARE ADDED, BECAUSE OF THE NEED TO ADD PARAMETERS

Smaller high-x gluon (and slightly smaller α_S) results in larger small-x gluon – now shown at NNLO.



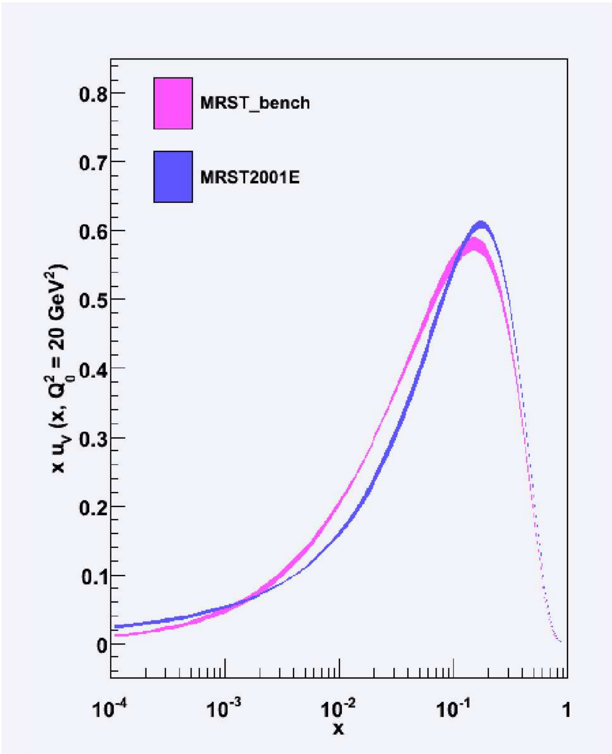
R. THORNE, HERALHC2008

Larger small-x uncertainty due to extrat free parameter.

WHAT DETERMINES PDF UNCERTAINTIES?

THE PROBLEM OF BENCHMARK FITS (HERALHC 2005-2008)

- PERFORM A MRST (MRSTBENCH) FIT TO A CONSISTENT SUBSET OF DATA, USE $\Delta\chi^2 = 1$
  $\Rightarrow$ RESULTS NOT CONSISTENT, UNCERTAINTY DOES NOT GROW AS DATASET DECREASES



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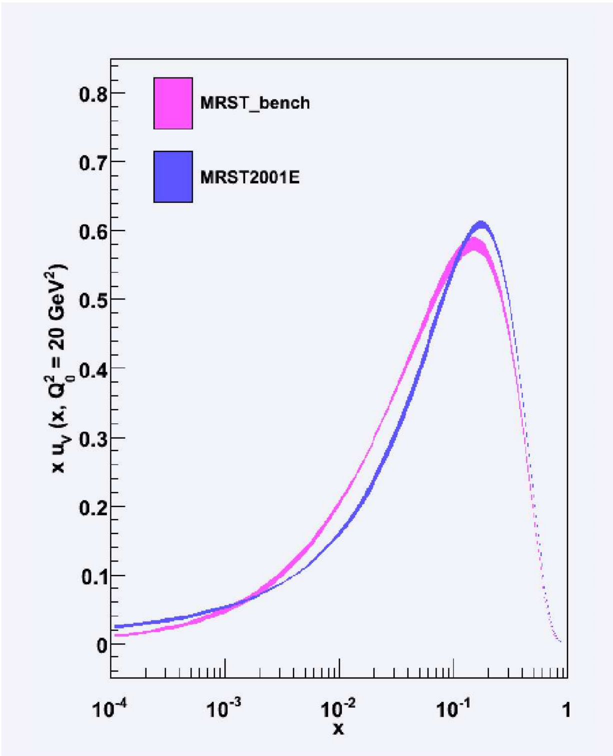
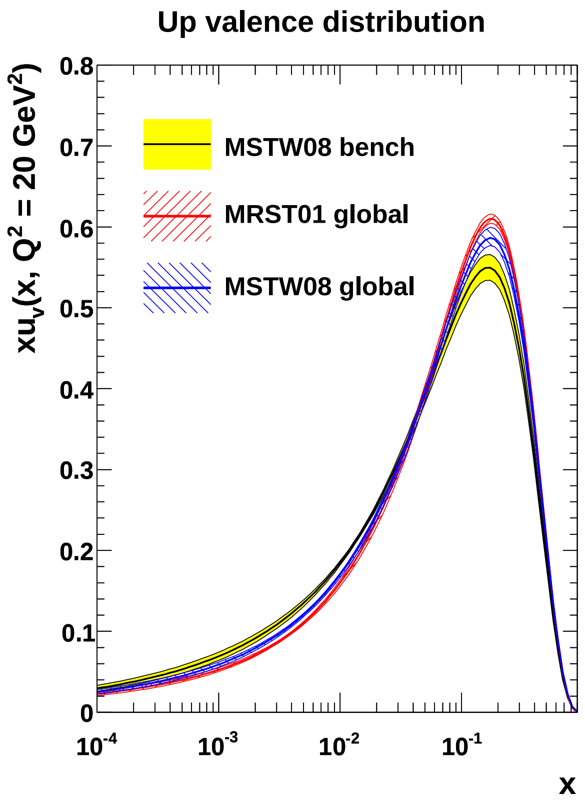
- ...BUT MRST WAS DONE WITH TOLERANCE 50: REPEAT WITH DYNAMICAL TOLERANCE (MSTW08BENCH)
- IMPROVEMENT, BUT PROBLEM NOT SOLVED
  $\Rightarrow$ MUST TUNE PARAMETRIZATION AND STATISTICAL TREATMENT TO DATASET

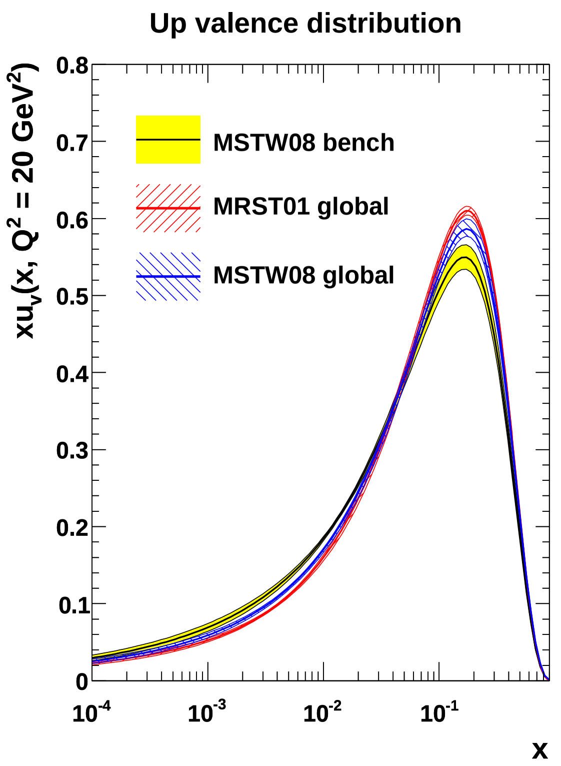




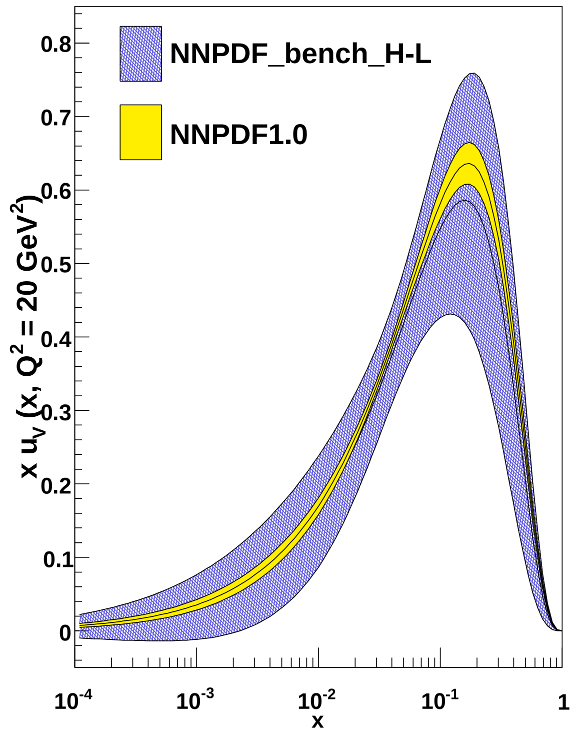
WHAT DETERMINES PDF UNCERTAINTIES?

THE NNPDF SOLUTION (HERALHC 2008)

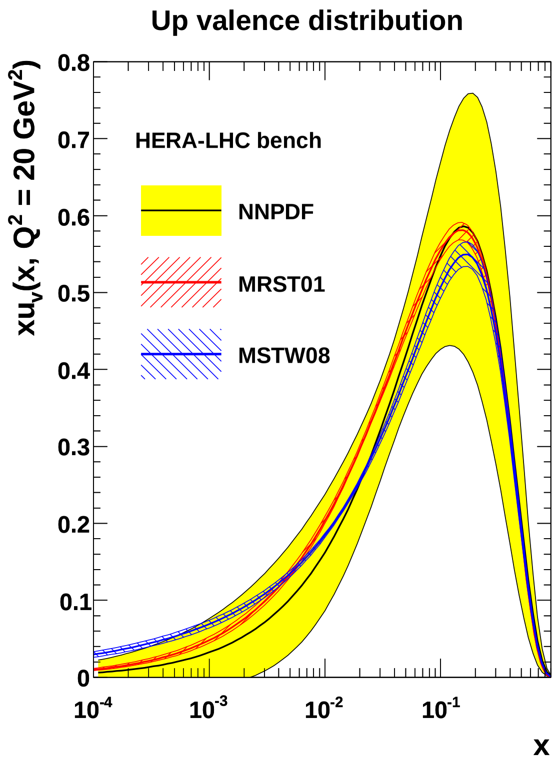
MRST/MSTW: BENCH VS REF



NNPDF: BENCH VS REF



NNPDF BENCH VS MRST/MSTW BENCH

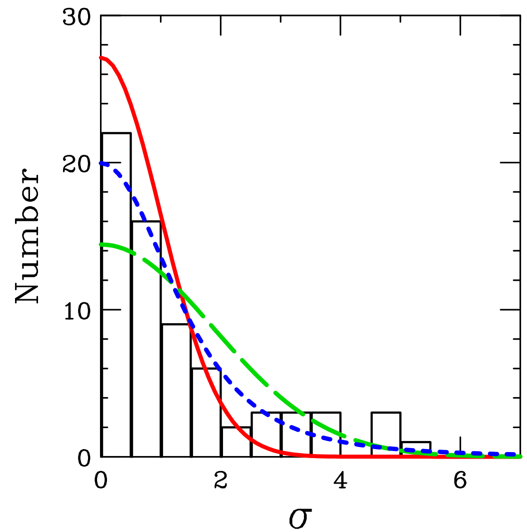


- SINGLE PARAMETRIZATION AND STAT. TREATMENT CAN ACCOMMODATE DIFFERENT DATASETS
- IMPACT OF DATA CAN BE STUDIED INDEPENDENT OF THEORETICAL FRAMEWORK

WHERE IS THE HESSIAN UNCERTAINTY COMING FROM?
WHY DOES ONE NEED LARGE TOLERANCES?

DATA INCOMPATIBILITY (Pumplin, 2009)

- CAN "REDIAGONALIZE": DIAGONALIZE SIMULTANEOUSLY χ^2 FOR TOTAL AND i–TH EXPT $\Rightarrow$ COMPATIBILITY OF EACH EXPT WITH GLOBAL FIT
- STUDY DISTRIBUTION OF DISCREPANCIES
- APPROX. GAUSSIAN WITH UNCERTAINTIES RESCALED BY 2 $\Rightarrow$ $\Delta\chi^2 \sim 10$ FOR 90%C.L.



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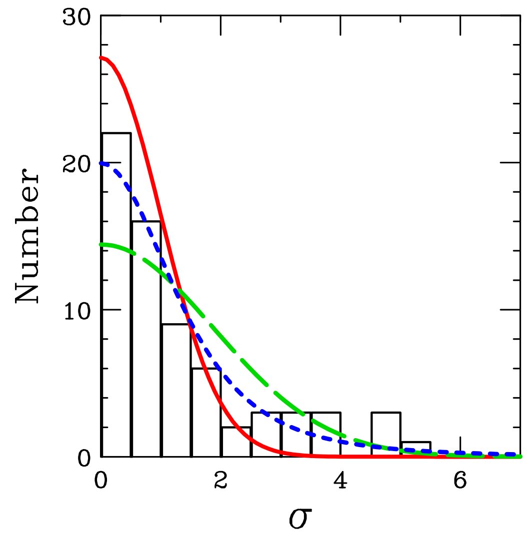
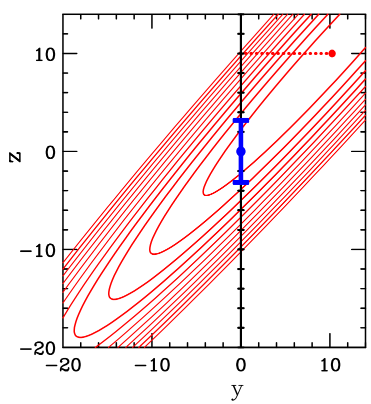
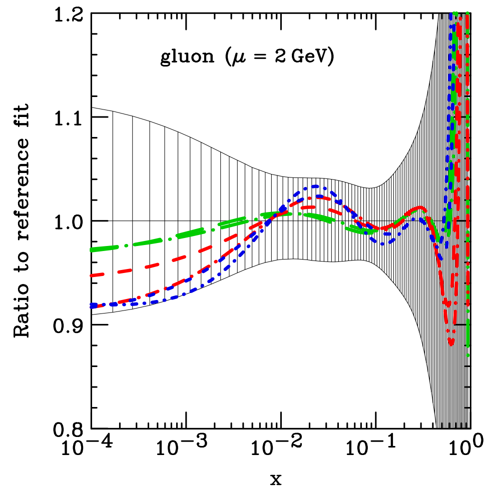


FUNCTIONAL BIAS (Pumplin, 2009)



- IF PARM. NOT GENERAL ENOUGH, GLOBAL MIN. IS NOT TRUE MIN.
- ONE-σ VARIATION ABOUT FAKE MIN CORRESP. TO LARGE χ^2 VARIATION
- USE OF CHEBYSHEV POLYNOMIALS SUGGESTS "MOST GENERAL" PARM. WITHIN $\Delta\chi^2 = 10$ OF CTEQ6.6 PARM.



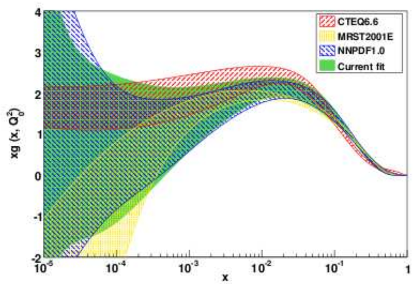
WHERE IS THE MONTE CARLO UNCERTAINTY COMING FROM?

FIT TO REPLICAS VS RANDOM SUBSET OF CENTRAL VAL.S

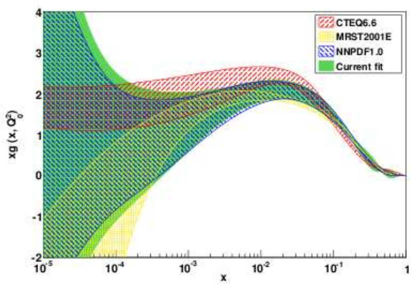
	REPLICAS	CENTRAL V.
χ^2	1.32	1.32
$\langle\chi^2\rangle_{\rm rep}$	2.79 ± 0.24	1.65 ± 0.20
$\langle\sigma^{\rm dat}\rangle$	0.039	0.035

GLUE

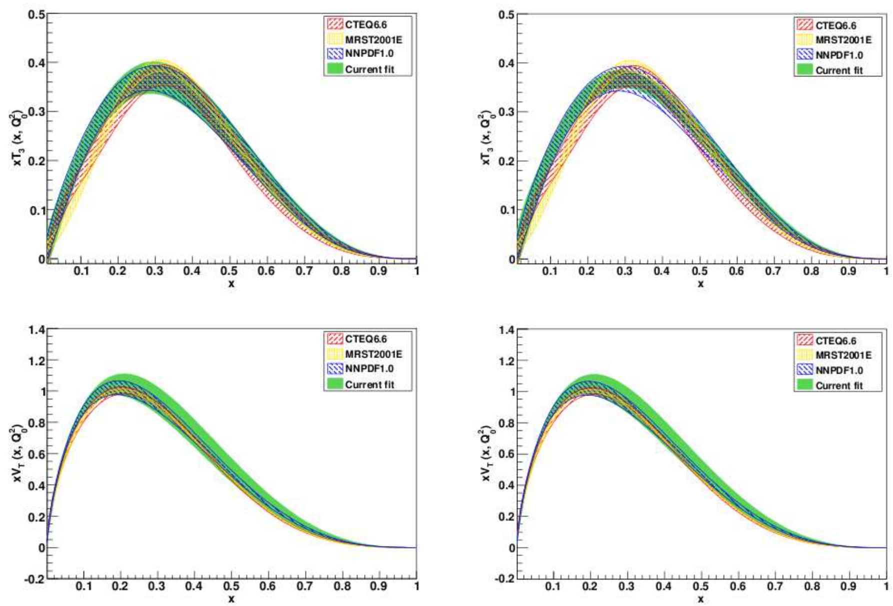
replicas



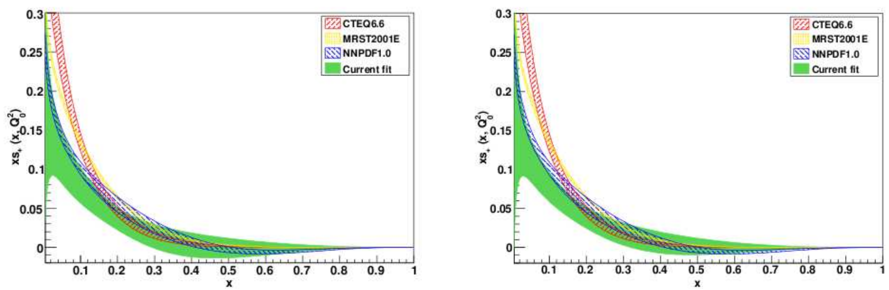
c. vals.



LIGHT QUARKS



STRANGE



- QUALITY OF FIT &PDFS UNCHANGED
- REDUCTION OF $\langle\chi^2\rangle_{\rm rep}$ BY FACTOR $\sim 2 \Rightarrow$ FLUCTUATIONS ABOUT TRUE VALUE HALVED
- UNCERTAINTY ON DATA ONLY REDUCED BY 1.1 $\Rightarrow$ EXPT. UNCERTAINTIES UNDERESTIMATED OR UNDERLYING INCOMPRESSIBLE UNCERTAINTY

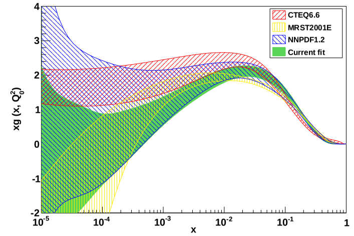
WHERE IS THE MONTE CARLO UNCERTAINTY COMING FROM?

CENTRAL VALUES: VARYING PARTITION VS FIXED PARTITION

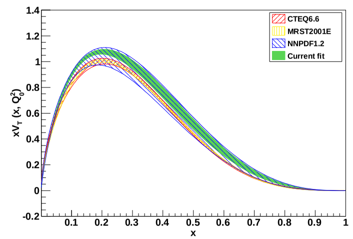
	REPLICAS	CENTRAL VALUE	FIXED PARTITION
χ^2	1.32	1.32	$\sim$1.3
$\langle\chi^2\rangle_{\rm rep}$	2.79 ± 0.24	1.65 ± 0.20	$\sim 1.6 \pm 0.2$
$\langle\sigma^{\rm dat}\rangle$	0.039	0.035	$\sim$0.03

fixed partition results obtained averaging over 5 different choices of partition (100 replicas each); more partitions needed for accurate results

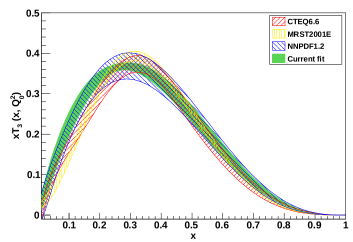
GLUE



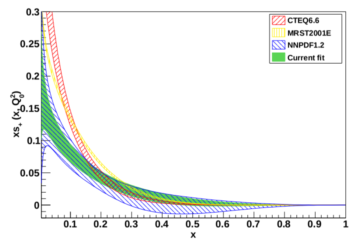
VALENCE



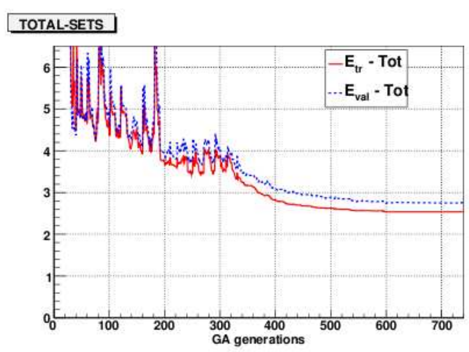
TRIPLET

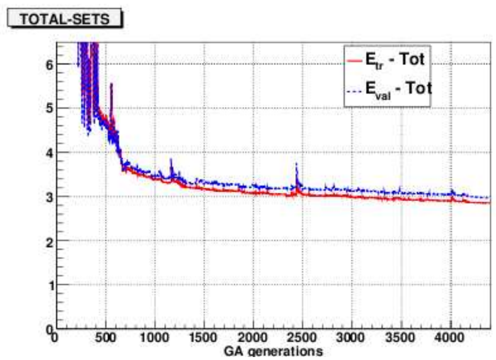


STRANGE



- QUALITY OF FIT UNCHANGED
- $\langle\chi^2\rangle_{\rm rep}$ UNCHANGED $\Rightarrow$ CENTRAL FIT UNCHANGED
- UNCERTAINTY ON PREDICTION (I.E. ON PDFS) REDUCED





FUNCTIONAL UNCERTAINTY

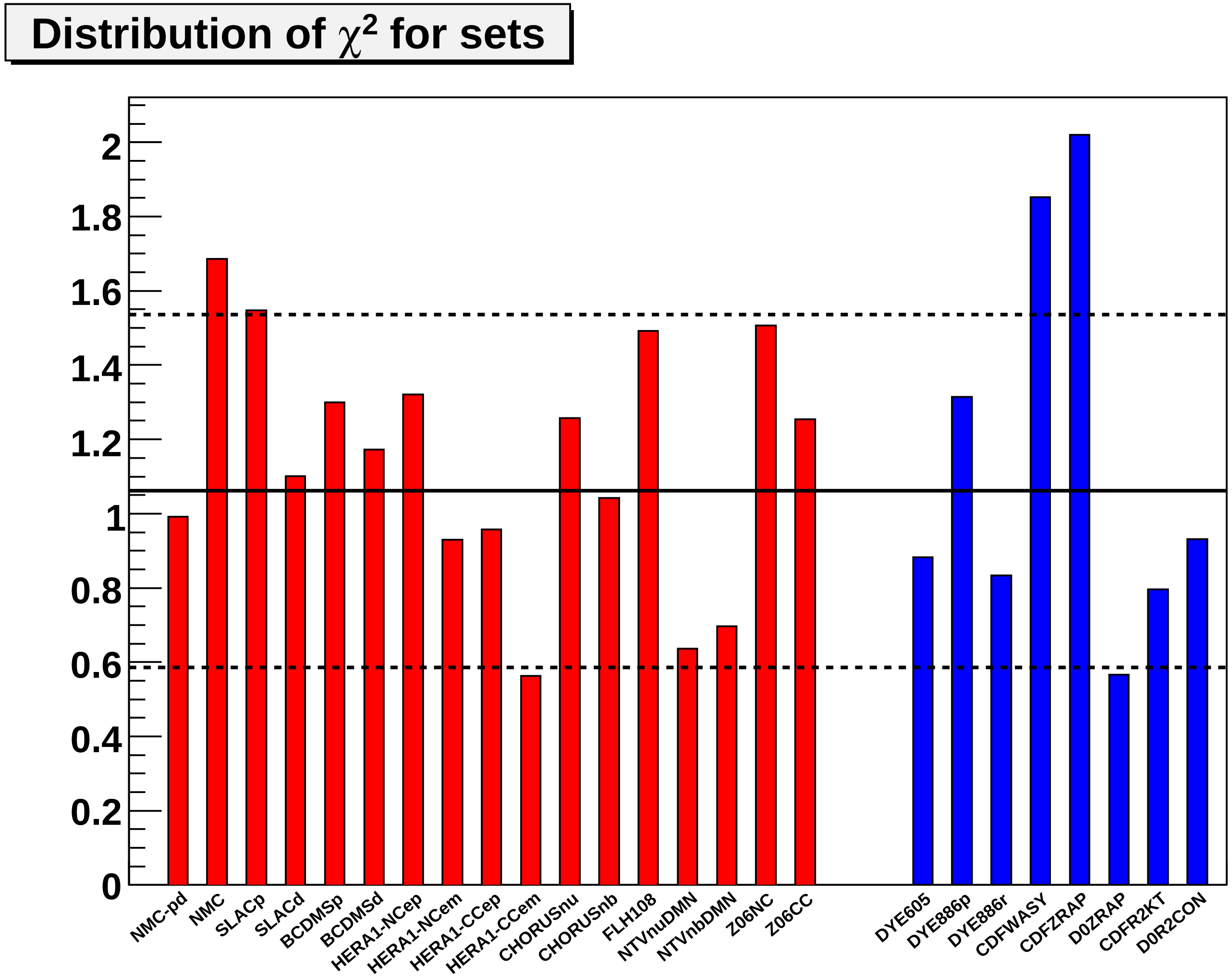
- MORE THAN HALF OF UNCERTAINTY DUE TO "FUNCTIONAL FORM": $\langle\sigma^{\rm dat}\rangle = \sim 0.03$ SMALLER FOR HERA DATA
- REMAINING UNCERTAINTY ROUGHLY SCALES WITH DATA UNCERTAINTY: $\langle\sigma^{\rm dat}\rangle = \sim 0.005$ CENT.; $\langle\sigma^{\rm dat}\rangle = \sim 0.009$ REP.

LHC STANDARD CANDLES

HOW WELL DOES IT WORK?

DIS DATA VS. HADRONIC DATA

NNPDF2.0



- NO OBVIOUS MUTUAL TENSION BETWEEN DIS AND HADRONIC DATA
- SOME INTERNAL DATA INCONSISTENCIES (NMC DIS DATA, CDF Z AND W RAPIDITY DISTRIBUTIONS)
- REASONABLE DISTRIBUTION OF χ^2 VALUES

DATA VS. THEORY:
DETAILED TESTS

- GLOBAL FITS INCLUDE DATASETS IN DISPARATE KINEMATIC REGIONS
- MUTUAL CONSISTENCY $\Rightarrow$ TEST OF DGLAP EVOLUTION
- INCONSISTENT DATA $\Rightarrow$ NO IMPROVEMENT IN PDF ACCURACY
- CAN TEST BY COMPARING FITS TO DIFFERENT DATA SUBSETS

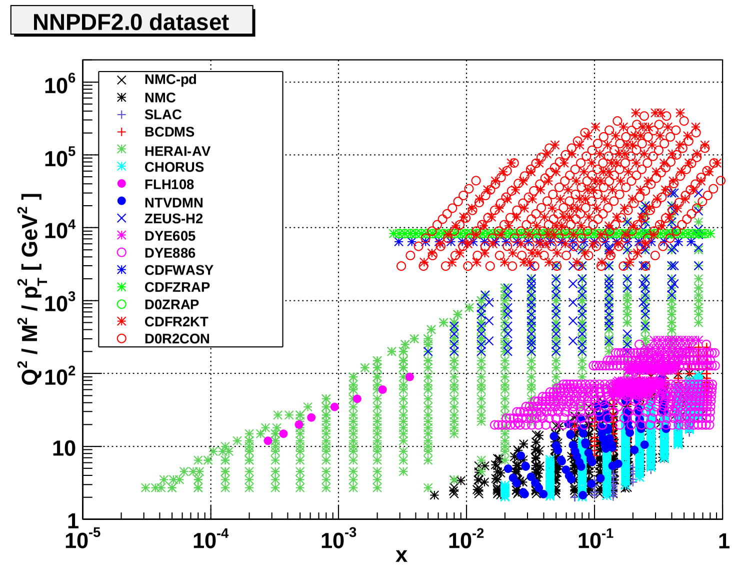
A USEFUL TOOL:
DISTANCE BETWEEN PDF SETS

$$d^2\left(\langle q^{(1)}\rangle, \langle q^{(2)}\rangle\right) = \frac{\left(\langle q^{(1)}\rangle_{(1)} - \langle q^{(2)}\rangle_{(2)}\right)^2}{\sigma^2_{(1)}[\langle q^{(1)}\rangle] + \sigma^2_{(2)}[\langle q^{(2)}\rangle]}; \quad \sigma^2_{(i)}[\langle q^{(i)}\rangle] = \frac{1}{N^{(i)}_{\rm rep}}\sigma^2_{(i)}[q^{(i)}]$$

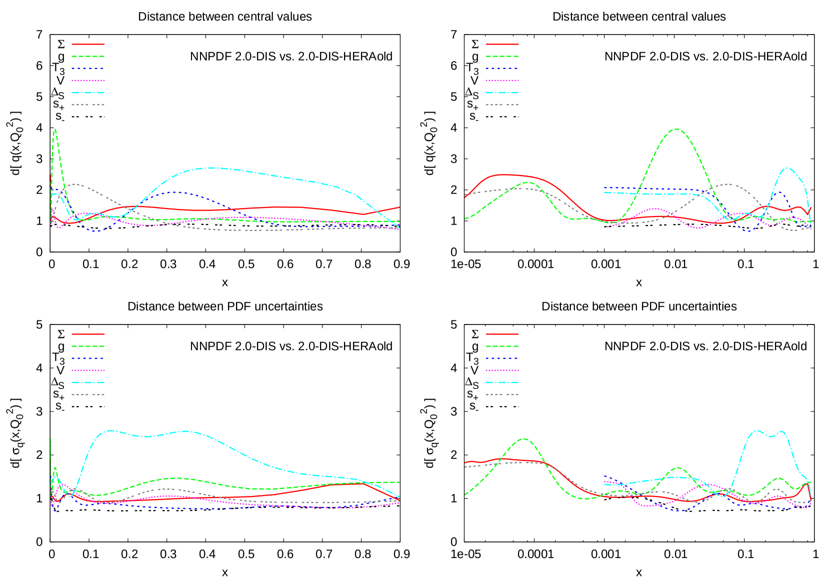
- MEAN PDF EXTRACTED FROM MONTECARLO SET OF SIZE $N_{\rm rep}$ FLUCTUATES WITH STANDARD DEVIATION $\frac{\sigma}{N_{\rm rep}}$
- IF TWO MC SETS EXTRACTED FROM SAME UNDERLYING DISTRIBUTION, THEN $d \sim 1$

STABILITY:
OLD HERA DATA VS. COMBINED HERA DATA

	DIS-HERAold	DIS	NNPDF2.0
χ^2_{tot}	1.12	1.20	1.21
NMC-pd	0.87	0.85	0.99
NMC	1.65	1.69	1.69
SLAC	1.33	1.37	1.34
BCDMS	1.25	1.26	1.27
HERAI	**0.96**	**1.13**	1.14
CHORUS	1.12	1.13	1.18
FLH108	1.53	1.51	1.49
NTVDMN	0.71	0.71	0.67
ZEUS-H2	1.49	1.50	1.51
CDFR2KT	0.78	0.91	0.80
D0R2CON	0.94	1.00	0.93
DYE605	8.21	7.32	0.88
DYE866	2.46	2.24	1.28
CDFWASY	20.32	13.06	1.85
CDFZRAP	3.13	3.12	2.02
D0ZRAP	0.65	0.65	0.47

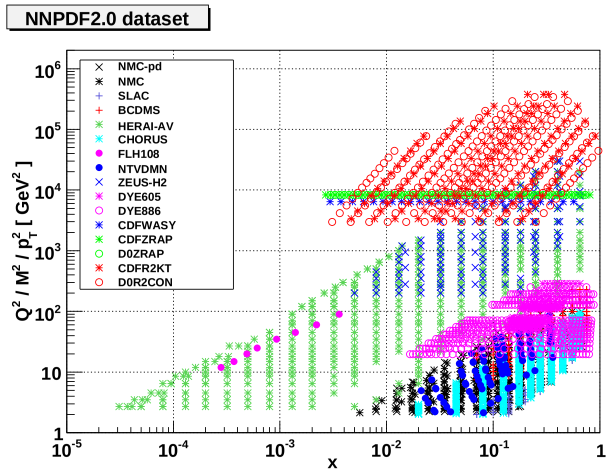


- PDFs UNCHANGED, MARGINAL IMPROVEMENT IN GLUON
- QUALITY OF FIT TO FIXED-TARGET DIS UNCHANGED
- SLIGHT DETERIORATION IN QUALITY OF FIT TO HERA DATA
- ⇒ COULD BE EVIDENCE FOR (MARGINALLY) INADEQUATE THEORY

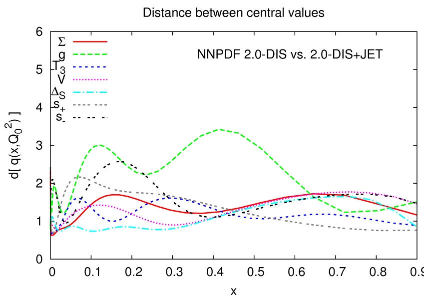


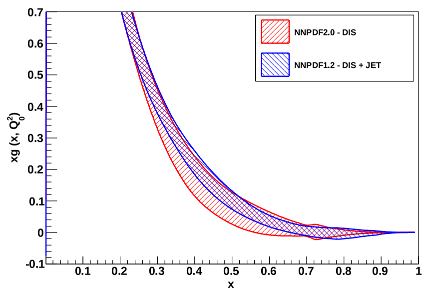
PREDICTIVITY:
DIS DATA VS. JET DATA

	DIS	DIS+JET	NNPDF2.0
χ^2_{tot}	1.20	1.18	1.21
NMC-pd	0.85	0.86	0.99
NMC	1.69	1.66	1.69
SLAC	1.37	1.31	1.34
BCDMS	1.26	1.27	1.27
HERAI	1.13	1.13	1.14
CHORUS	1.13	1.11	1.18
FLH108	1.51	1.49	1.49
NTVDMN	0.71	0.75	0.67
ZEUS-H2	1.50	1.49	1.51
CDFR2KT	**0.91**	**0.79**	0.80
D0R2CON	**1.00**	**0.93**	0.93
DYE605	7.32	10.35	0.88
DYE866	2.24	2.59	1.28
CDFWASY	13.06	14.13	1.85
CDFZRAP	3.12	3.31	2.02
D0ZRAP	0.65	0.68	0.47



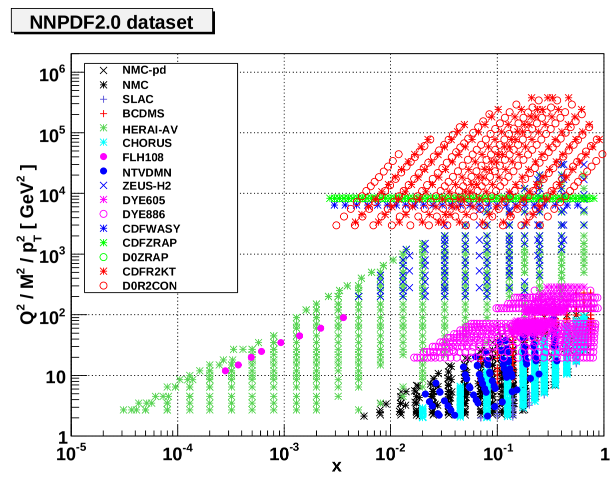
- HIGH E_T JET DATA WELL REPRODUCED EVEN WHEN NOT FITTED $\Rightarrow$ LARGE x GLUON WELL DETERMINED BY SCALING VIOLATIONS!
- SIGNIFICANT IMPROVEMENT IN LARGE x GLUON ACCURACY
- OTHER PDFs UNCHANGED



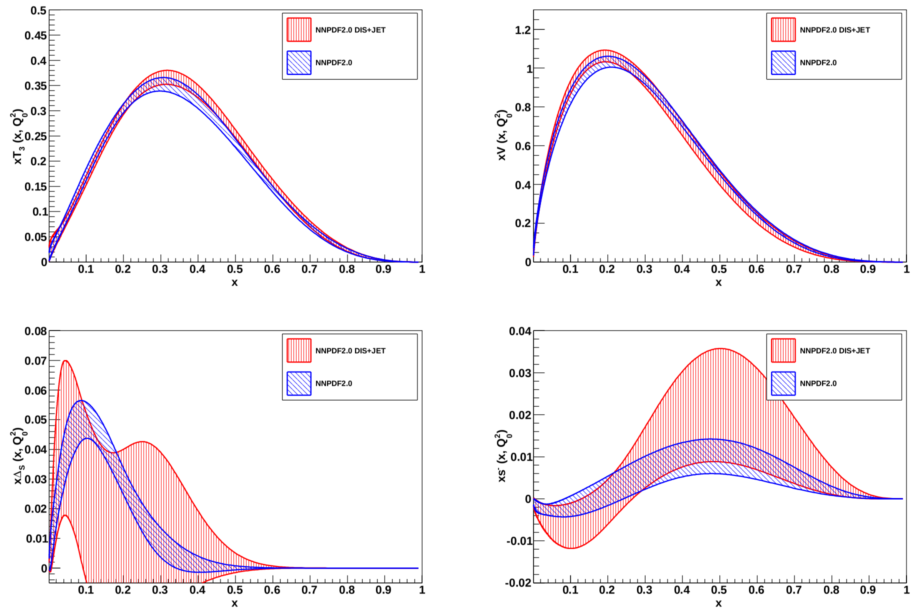


GLOBAL FITTING: DIS+JETS VS. DRELL-YAN (AND W, Z) DATA

	DIS	DIS+JET	NNPDF2.0
$\chi^2_{\rm tot}$	1.20	1.18	1.21
NMC-pd	0.85	0.86	0.99
NMC	1.69	1.66	1.69
SLAC	1.37	1.31	1.34
BCDMS	1.26	1.27	1.27
HERAI	1.13	1.13	1.14
CHORUS	1.13	1.11	1.18
FLH108	1.51	1.49	1.49
NTVDMN	0.71	0.75	0.67
ZEUS-H2	1.50	1.49	1.51
CDFR2KT	0.91	0.79	0.80
D0R2CON	1.00	0.93	0.93
DYE605	7.32	**10.35**	**0.88**
DYE866	2.24	**2.59**	**1.28**
CDFWASY	13.06	**14.13**	**1.85**
CDFZRAP	3.12	**3.31**	**2.02**
D0ZRAP	0.65	**0.68**	**0.47**



- VERY SUBSTANTIAL IMPROVEMENT IN FIT QUALITY WHEN DATA INCLUDED $\Rightarrow$ SOME PDF COMBINATIONS POORLY DETERMINED WITHOUT THESE DATA
- HUGE IMPROVEMENT IN SEA ASYM $\bar{u}-\bar{d}$ & STRANGENESS $s-\bar{s}$
- SIGNIFICANT IMPROVEMENT IN TOTAL VALENCE $(\sum_i(q_i-\bar{q}_i))$ & ISOTRIPLET $(u+\bar{u}-(d+\bar{d}))$



WHY IT ALL MATTERS: THE NUTEV ANOMALY...

$$
\begin{aligned}
R_{\mathrm{PW}} &\equiv \frac{\sigma(\nu\mathcal{N}\to\nu X)-\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\nu\mathcal{N}\to\ell X)-\sigma(\bar\nu\mathcal{N}\to\bar\ell X)} \\
&= \frac{1}{2}-\sin^2\theta_{\mathrm{W}}+\left(\frac{(U^- - D^-)+(C^- - S^-)}{\mathcal{Q}^-}\frac{1}{6}\left(3-7\sin^2\theta_{\mathrm{W}}\right)\right) ,
\end{aligned}
$$

- PASCHOS-WOLFENSTEIN RATIO CAN BE MEASURED IN NEUTRINO DIS
- RESULT DEPENDS ON EW MIXING ANGLE, VALENCE ISOSPIN BREAKING (WITH ISOSINGLET TARGET), STRANGENESS VALENCE MOMENTUM ASYMMETRY
- STRANGENESS VALENCE MOMENTUM
  ASSUMED BY NUTEV TO VANISH $\Rightarrow$ THREE σ DISCREPANCY WITH GLOBAL FIT

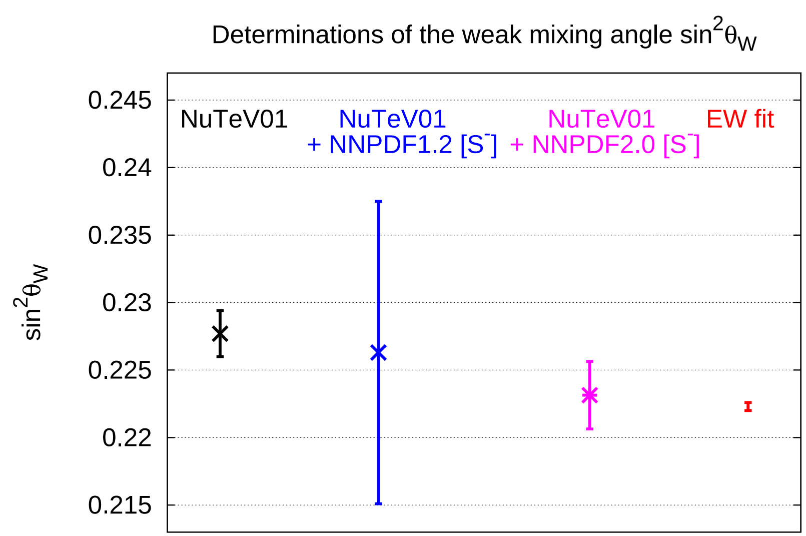
WHY IT ALL MATTERS:
THE NUTEV ANOMALY...

$$R_{\rm PW} \equiv \frac{\sigma(\nu\mathcal{N}\to\nu X)-\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\nu\mathcal{N}\to\ell X)-\sigma(\bar\nu\mathcal{N}\to\bar\ell X)}$$
$$= \frac{1}{2}-\sin^2\theta_{\rm W}+\left(\frac{(U^- - D^-)+(C^- - S^-)}{\mathcal{Q}^-}\frac{1}{6}\left(3-7\sin^2\theta_{\rm W}\right)\right),$$

- PASCHOS-WOLFENSTEIN RATIO CAN BE MEASURED IN NEUTRINO DIS
- RESULT DEPENDS ON EW MIXING ANGLE, VALENCE ISOSPIN BREAKING (WITH ISOSINGLET TARGET), STRANGENESS VALENCE MOMENTUM ASYMMETRY
- STRANGENESS VALENCE MOMENTUM ASSUMED BY NUTEV TO VANISH ⇒ THREE σ DISCREPANCY WITH GLOBAL FIT

...IS GONE

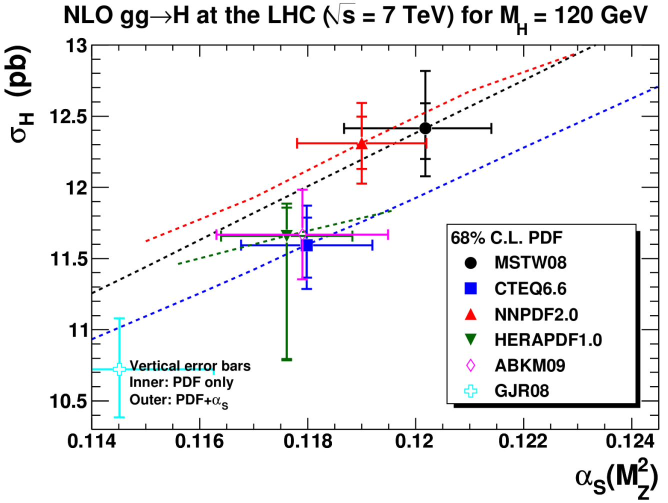
- ONCE UNCERTAINTY ON STRANGENESS ASYMMETRY KEPT INTO ACCOUNT (DIS ONLY FIT: NNPDF1.2) THE EFFECT LOSES STATISTICAL SIGNIFICANCE
- IF HADRONIC DATA INCLUDED (NNPDF2.0 GLOBAL FIT), STRANGENESS ASYMMETRY DETERMINED QUITE ACCURATELY → CORRECTED RESULT IN IMPRESSIVE AGREEMENT WITH SM GLOBAL FIT



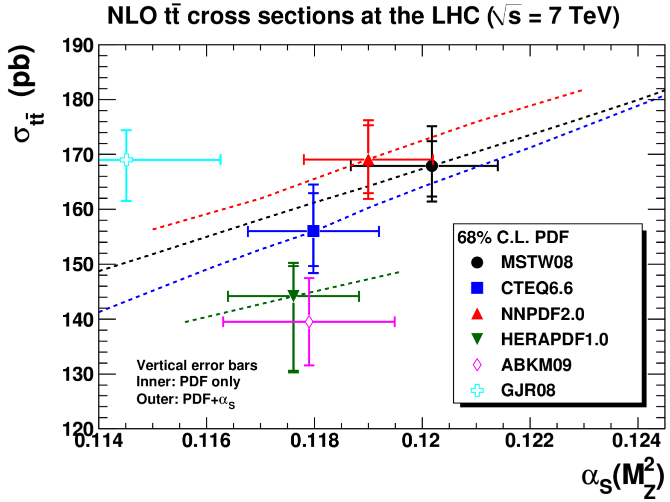
(NNPDF2.0, 2010)

LHC STANDARD CANDLES: WHERE DO WE STAND?

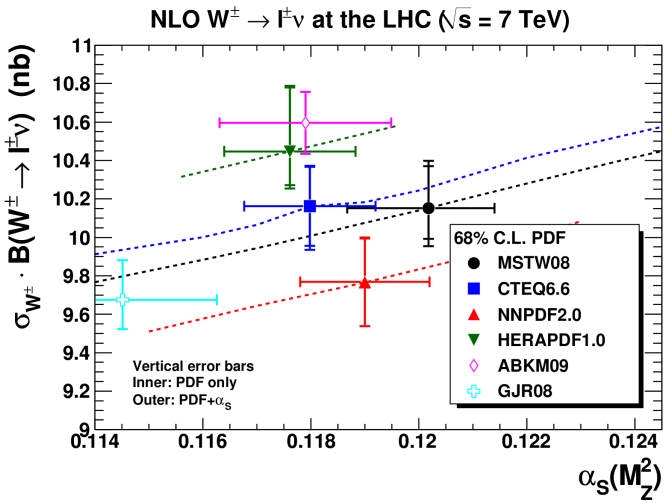
HIGGS



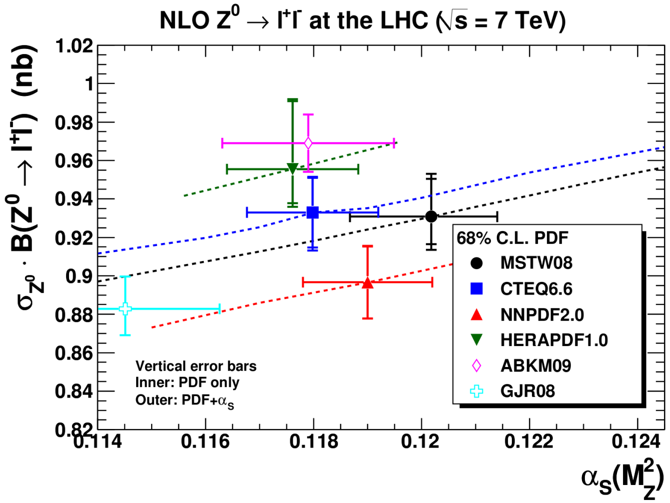
TOP



$W^{\pm}$



Z



(G. Watt, 2010)

- GLOBAL FITS (MSTW, NNPDF, CTEQ) IN GOOD MUTUAL AGREEMENT (CENTRAL VALUE & UNCERTAINTY $\Rightarrow$ WELL, BUT ROOM FOR IMPROVEMENT
- CHOICE OF α_s VALUE IMPORTANT $\Rightarrow$ HOW WELL DO WE CONTROL OUR THEORY?