FROM DIS

TO

FIRST LHC MEASUREMENTS

STEFANO FORTE
UNIVERSITÀ DI MILANO & INFN

UNIVERSITÀ DEGLI STUDI DI MILANO
DIPARTIMENTO DI FISICA

DIS 2010

FLORENCE, APRIL 19, 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

$\sqrt{S}$ (GeV)	$W^+ + W^-$ GHR	$W^+ + W^-$ DO1	$W^+ + W^-$ DO2	Z^0 GHR	Z^0 DO1	Z^0 DO2	$\frac{\sigma(W^+ + W^-)}{\sigma(Z^0)}$ GHR	$\frac{\sigma(W^+ + W^-)}{\sigma(Z^0)}$ DO1	$\frac{\sigma(W^+ + W^-)}{\sigma(Z^0)}$ 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 PDF uncertainties

PDFs: THEN AND NOW

PDFs IN 1984

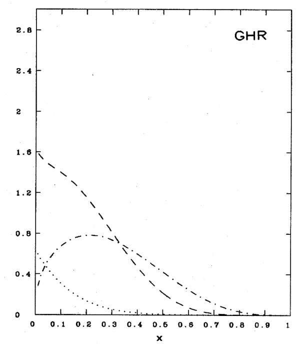


FIG. 25. Parton distributions of Glück, Hoffmann, and Reya (1982), at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and q_v (dotted line).

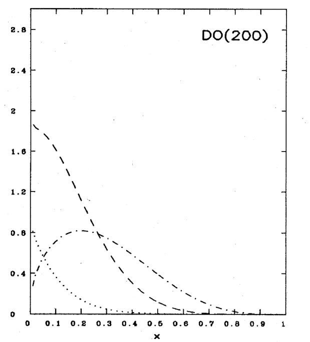


FIG. 27. "Soft-gluon" ($\Lambda=200$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).

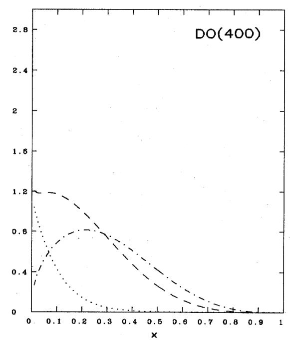
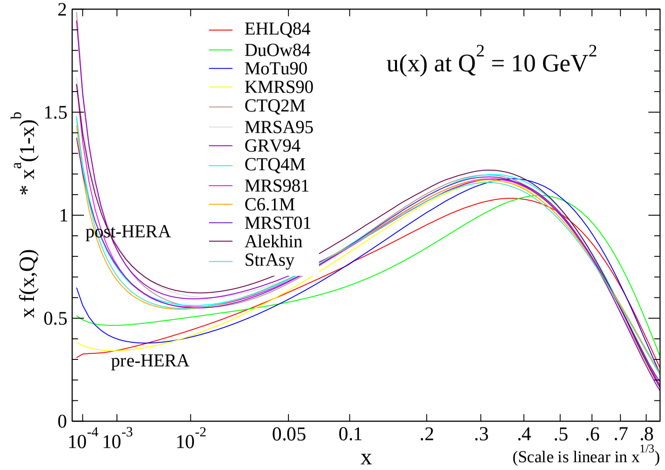


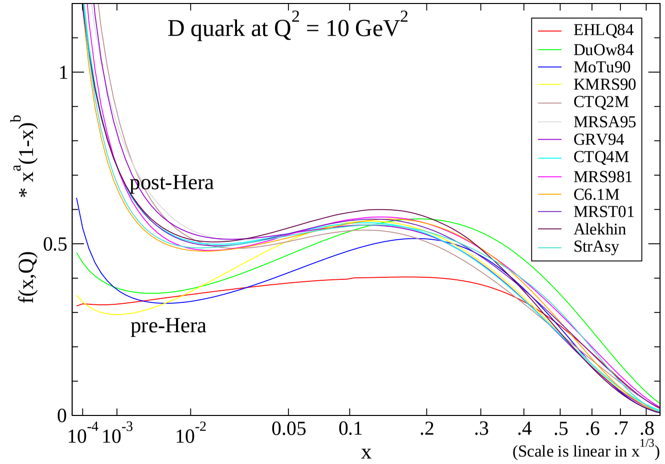
FIG. 26. "Hard-gluon" ($\Lambda=400$ MeV) parton distributions of Duke and Owens (1984) at $Q^2=5$ GeV^2: valence quark distribution $x[u_v(x)+d_v(x)]$ (dotted-dashed line), $xG(x)$ (dashed line), and $q_v(x)$ (dotted line).

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 $\Rightarrow$ QUALITATIVE QCD: DISCOVERY PHYSICS
- DIS AT NMC AND HERA 1995-2005 $\Rightarrow$ QUANTITATIVE QCD: PRECISION PHYSICS
- HADRON COLLIDERS CIRCA 2010 $\Rightarrow$ PRECISION QCD $\leftrightarrow$ NEW PHYSICS

SUMMARY

- PDFs: THE STATE OF THE ART
  - PDF determination
  - the origin of PDF uncertainties
  - standard candles now
- PERTURBATIVE CORRECTIONS
  - the problem of heavy quarks
  - beyond NLO: problems and tools
  - the value of α_s
- RESUMMATION
  - soft gluons beyond the eikonal: theory and phenomenology
  - small x resummation: progress and phenomenological impact
  - beyond fixed order?

APOLOGIES: progress in jet physics not covered & MORE

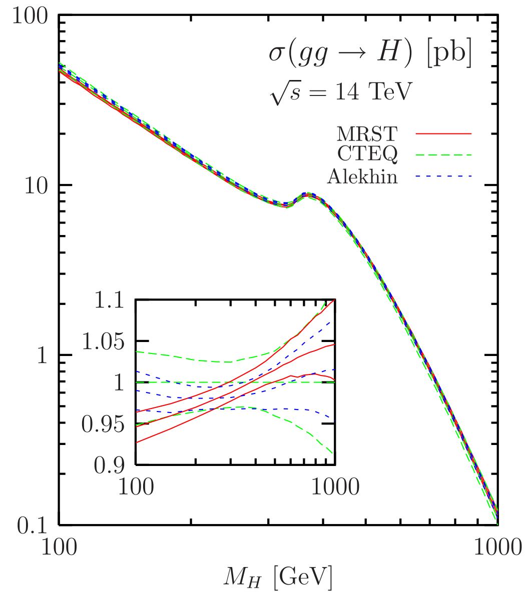
PDFs

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)

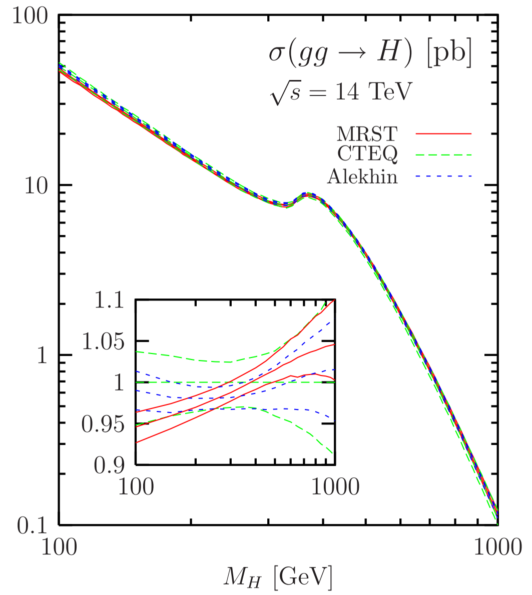
- WIDELY DIFFERENT UNCERTAINTY ESTIMATES
- UNSATISFACTORY AGREEMENT WITHIN UNCERTAINTIES
- $\Delta\chi^2 = 100$ (CTEQ); 50 (MRST); 1 (ALEKHIN)

PDFs: THE STATE OF THE ART

THE HIGGS CROSS SECTION

CAN WE CALCULATE IT?

PDF WITH ERRORS: DO THEY AGREE?



(Djouadi, Ferrag, 2004)

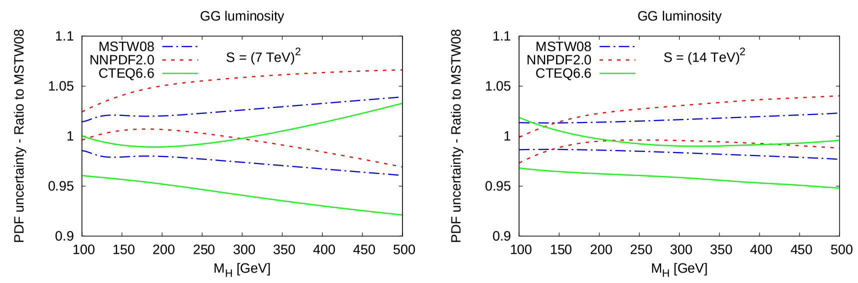
FIRST PDF SETS WITH ERROR (2002-2003)

CTEQ, MRST (global); Alekhin (DIS)

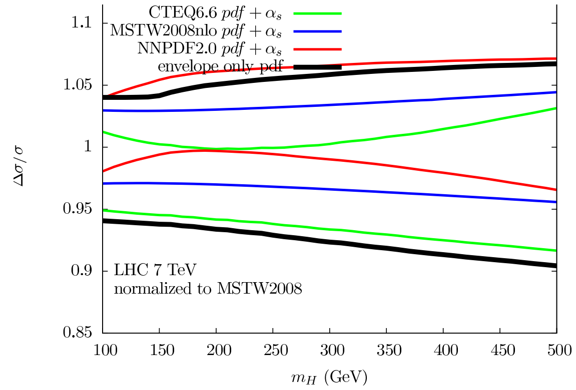
- WIDELY DIFFERENT UNCERTAINTY ESTIMATES
- UNSATISFACTORY AGREEMENT WITHIN UNCERTAINTIES
- $\Delta\chi^2 = 100$ (CTEQ); 50 (MRST); 1 (ALEKHIN)

CURRENT GLOBAL PDF SETS

gluon luminosities



gg→H cross section



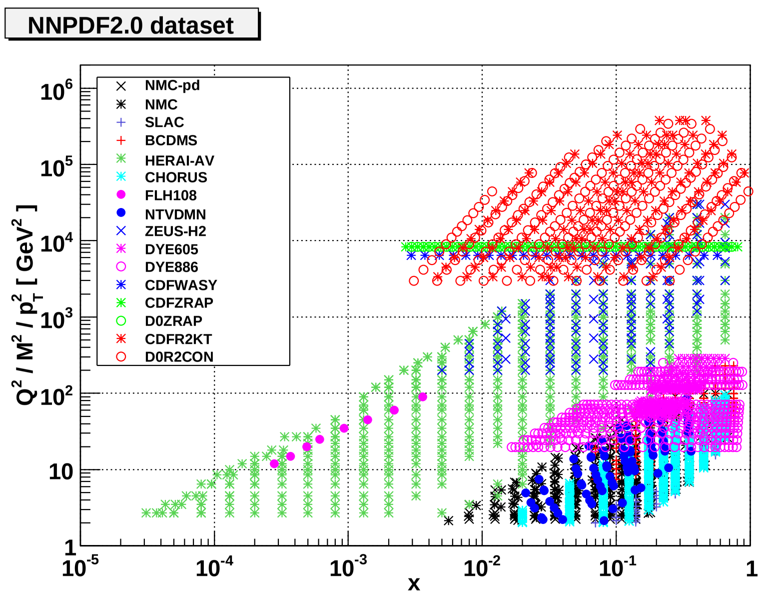
(Demartin et al., 2010)

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

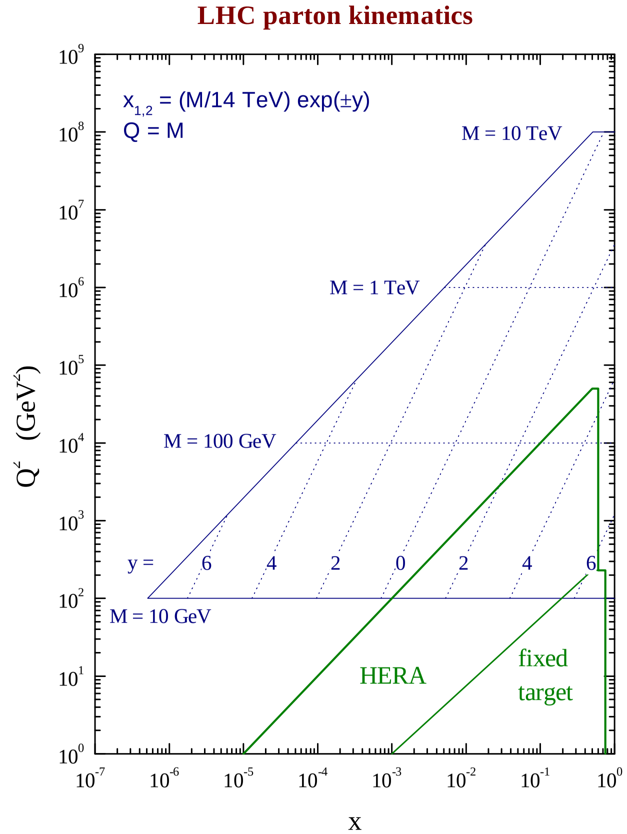
CURRENT PDF SETS

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

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,...)

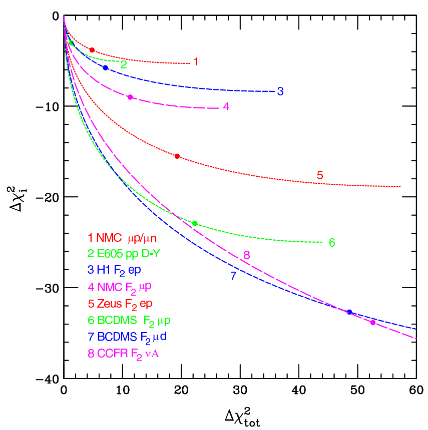
PDF UNCERTAINTIES: HOW ARE THEY DETERMINED?

"estimates of PDF uncertainties follow and ad-hoc recipe defined by the fitters" (C. Hays, 09)

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

MINIMUM χ_i^2

VS GLOBAL χ^2



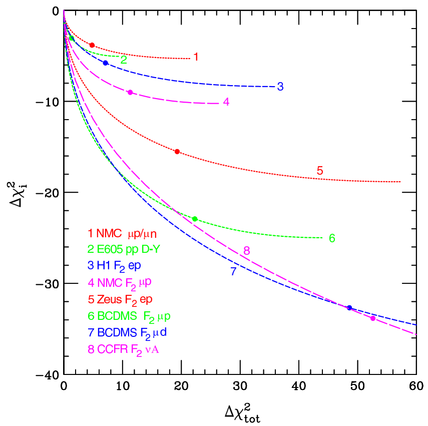
Collins, Pumplin 2001

PDF UNCERTAINTIES: HOW ARE THEY DETERMINED?

"estimates of PDF uncertainties follow and ad-hoc recipe defined by the fitters" (C. Hays, 09) CTEQ TOLERANCE CRITERION &

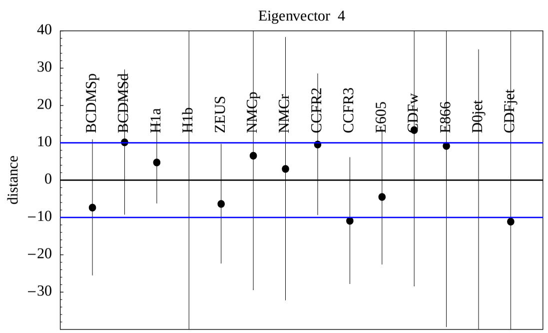
- STANDARD $\Delta\chi^2 = 1$ BANDS TOO NARROW $\Rightarrow$ LARGE DISCREPANCIES FOR INDIVIDUAL EXPERIMENTS
- TOLERANCE $\Rightarrow$ ENVELOPE OF UNCERTAINTIES OF EXPERIMENTS

MINIMUM χ_i^2 VS GLOBAL χ^2



Collins, Pumplin 2001

CTEQ TOLERANCE PLOT FOR 4TH EIGENVEC.

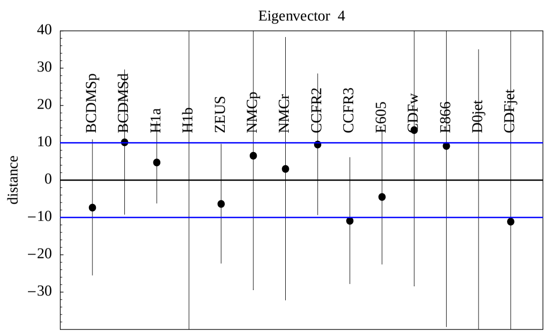


PDF UNCERTAINTIES: HOW ARE THEY DETERMINED?

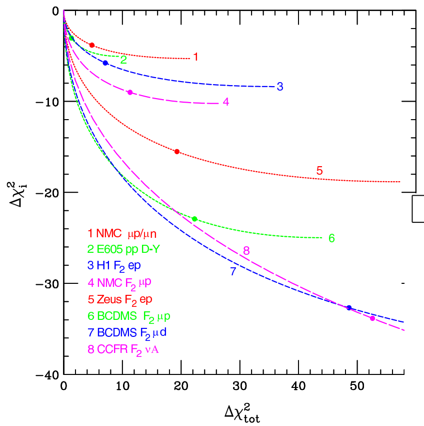
"estimates of PDF uncertainties follow and ad-hoc recipe defined by the fitters" (C. Hays, 09) CTEQ TOLERANCE CRITERION & MSTW DYNAMICAL TOLERANCE

- 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

CTEQ TOLERANCE PLOT FOR 4TH EIGENVEC.

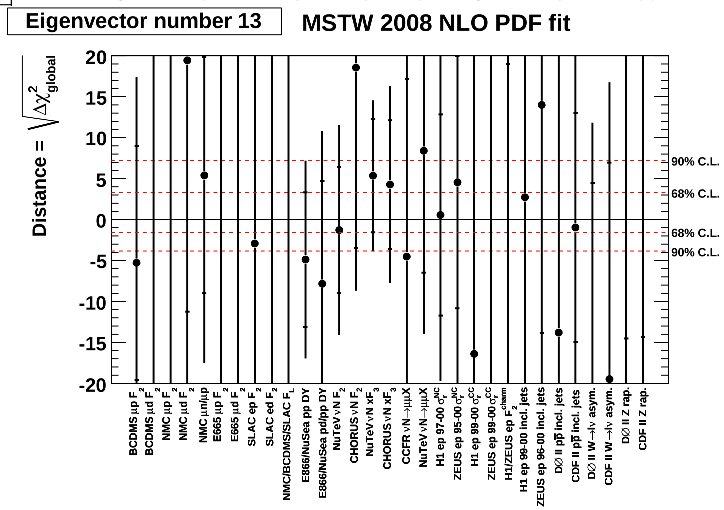


MINIMUM χ_i^2 VS GLOBAL χ^2

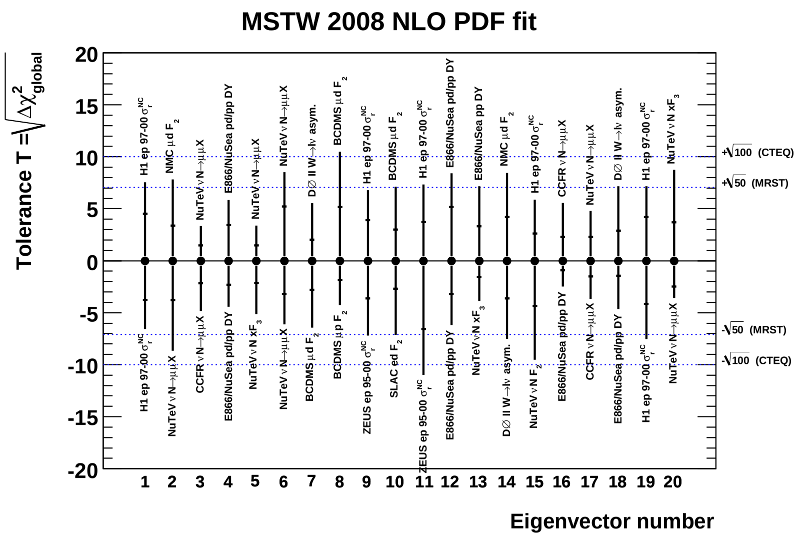


Collins, Pumplin 2001

MSTW TOLERANCE PLOT FOR 13TH EIGENVEC.



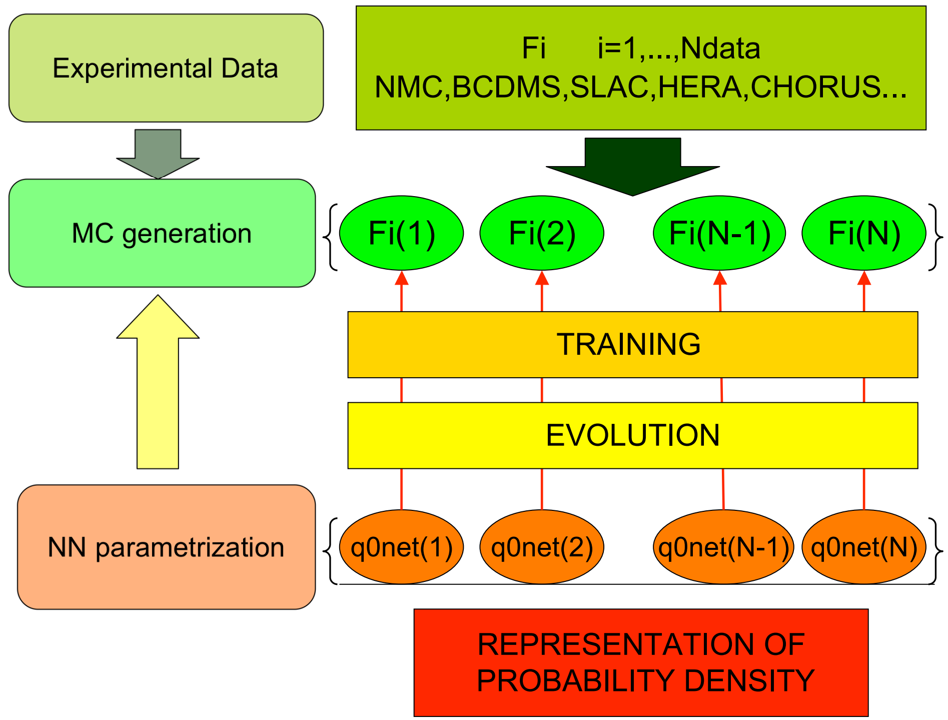
GLOBAL MSTW TOLERANCE



PDF UNCERTAINTIES: HOW ARE THEY DETERMINED?
THE MONTE CARLO APPROACH (NNPDF)

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

- START FROM MONTE CARLO SAMPLING OF DATA SPACE
- EACH PDF$\leftrightarrow$ NEURAL NETWORK PARAMETRIZED BY 37 PARAMETERS (NNPDF2.0: $37 \otimes 7 = 259$ PARMS)
  "INFINITE" NUMBER OF PARAMETERS$\Rightarrow$ CAN REPRESENT ANY FUNCTION
- FIT STOPS WHEN QUALITY OF FIT TO RANDOMLY SELECTED "VALIDATION" DATA (NOT FITTED) STOPS IMPROVING



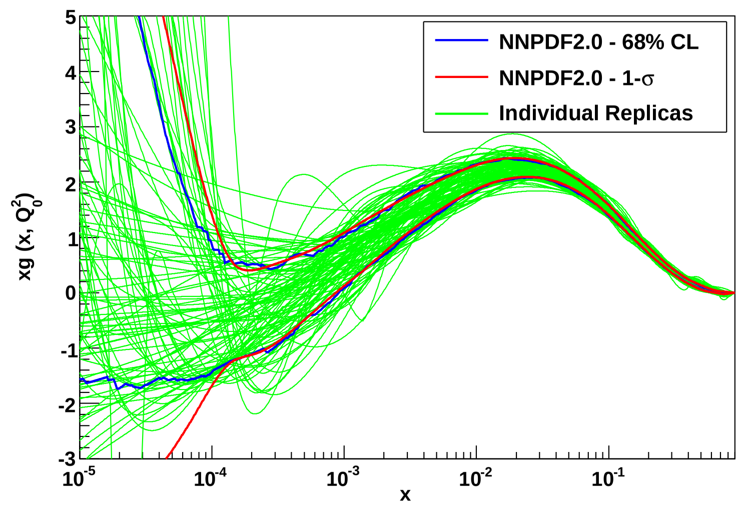
PDF UNCERTAINTIES: HOW ARE THEY DETERMINED?

THE MONTE CARLO APPROACH (NNPDF)

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

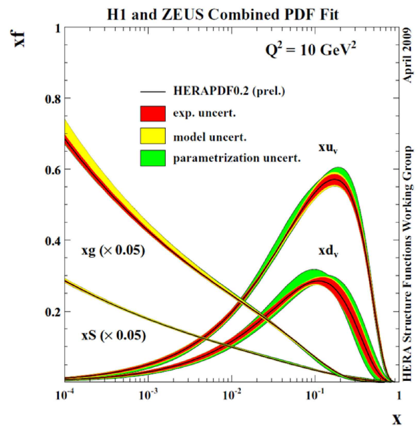
- START FROM MONTE CARLO SAMPLING OF DATA SPACE
- EACH PDF$\leftrightarrow$ NEURAL NETWORK PARAMETRIZED BY 37 PARAMETERS (NNPDF2.0: $37 \otimes 7 = 259$ PARMS)
  "INFINITE" NUMBER OF PARAMETERS$\Rightarrow$ CAN REPRESENT ANY FUNCTION
- FIT STOPS WHEN QUALITY OF FIT TO RANDOMLY SELECTED "VALIDATION" DATA (NOT FITTED) STOPS IMPROVING

CAN DETERMINE BOTH 68C.L.& 1-σ



PARAMETRIZATION UNCERTAINTIES
EXPLORING THE SPACE OF PARAMETERS

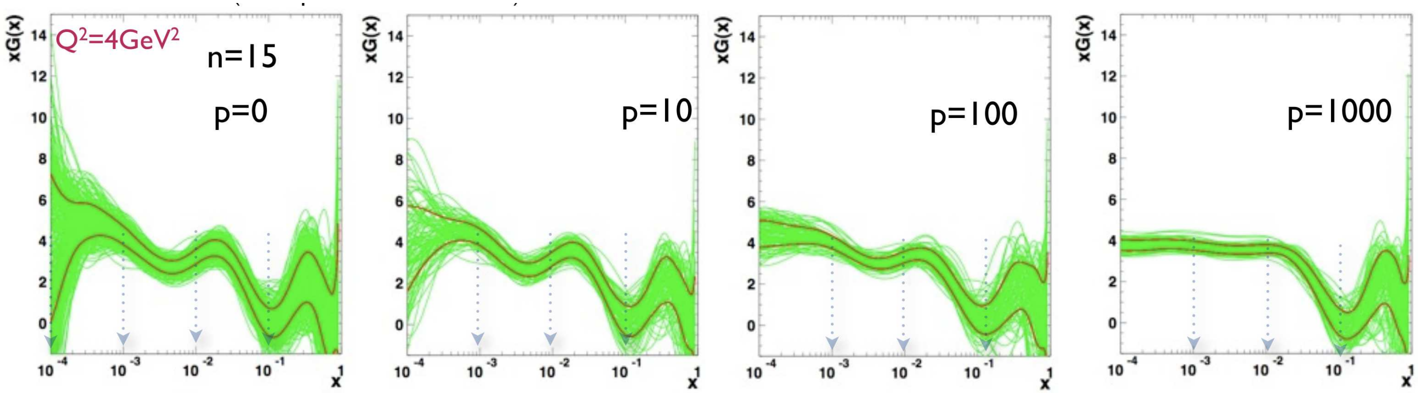
- IN HESSIAN APPROACH CAN VARY THE FUNCTIONAL FORM, ASSUMPTIONS, STARTING SCALE
- DONE IN THE HERAPDF1.0 FIT: VARIATION OF STRANGENESS FRACTION, LARGE x BEHAVIOUR, HIGHER ORDER POLYNOMIAL TERMS
- NO TOLERANCE ($\Delta\chi^2 = 1$), UNCERTAINTY DOUBLED



- Red: experimental uncertainties
- Yellow: model uncertainties
- Green: pdf parametrization uncertainties

ORTHOGONAL POLYNOMIALS

- OLD IDEA (PARISI, SOURLAS, 1978; ZOMER 1996): EXPAND PDFS OVER BASIS OF ORTHOGONAL POLYNOMIALS
- GLAZOV, RADESCU, 2009: COUPLED TO MONTE CARLO METHOD
- LENGTH PENALTY TO STABILIZE THE FIT



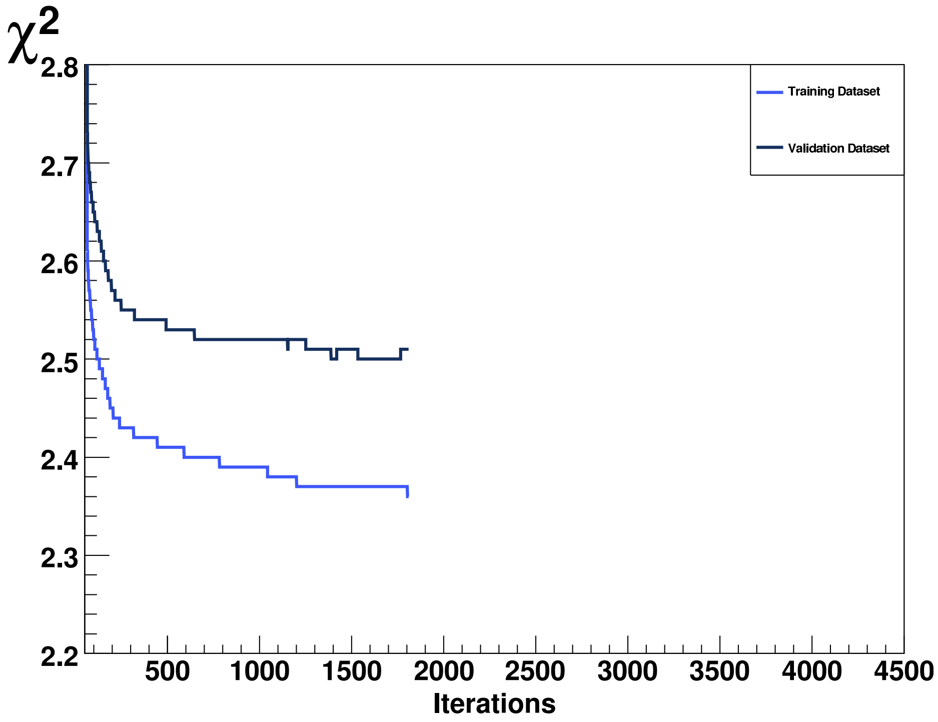
(Glazov, Radescu, 2009)

PARAMETRIZATION UNCERTAINTIES
CROSS-VALIDATION

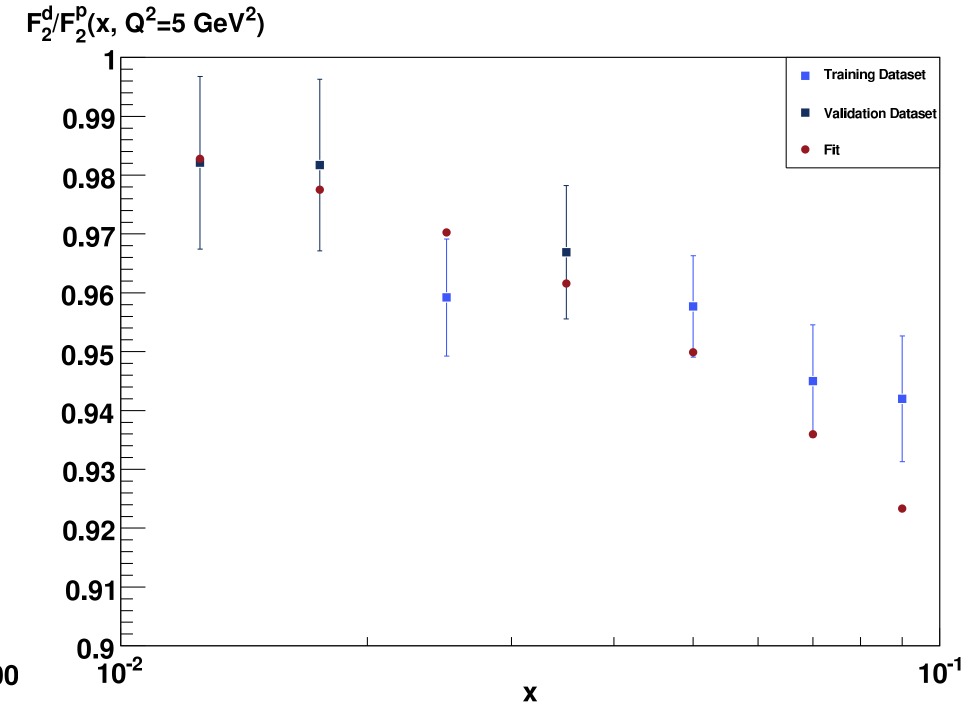
- REPLICAS ARE FITTED TO A DATA SUBSET
- A DIFFERENT SUBSET OF DATA USE FOR EACH REPLICA
- OPTIMAL FIT WHEN FIT TO VALIDATION (CONTROL) DATA STOPS IMPROVING
-

OPTIMAL FITTING

χ^2



FIT TO DATA

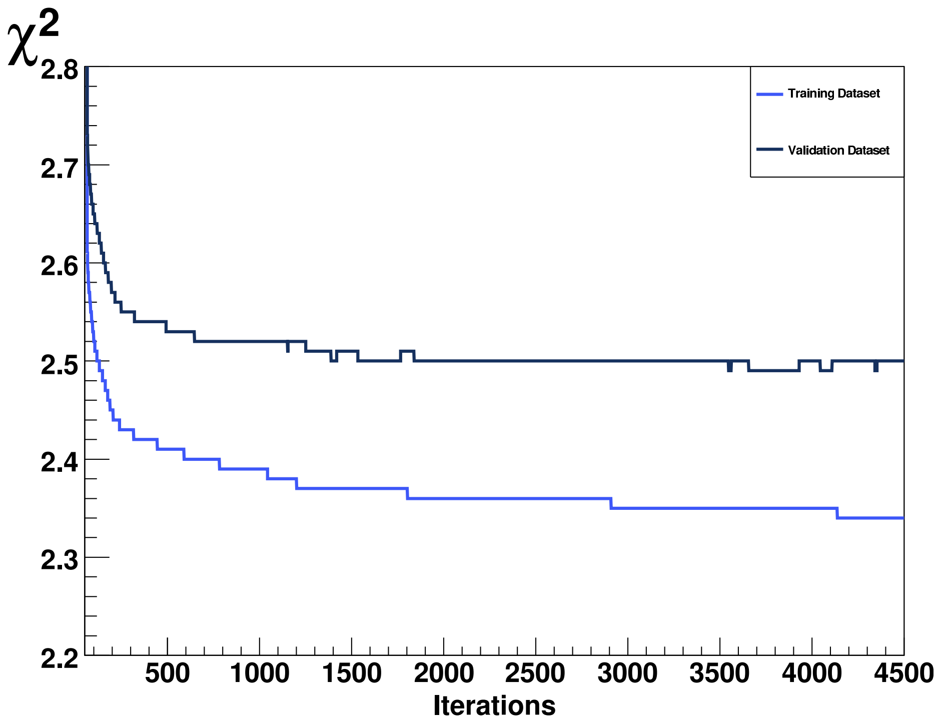


PARAMETRIZATION UNCERTAINTIES
CROSS-VALIDATION

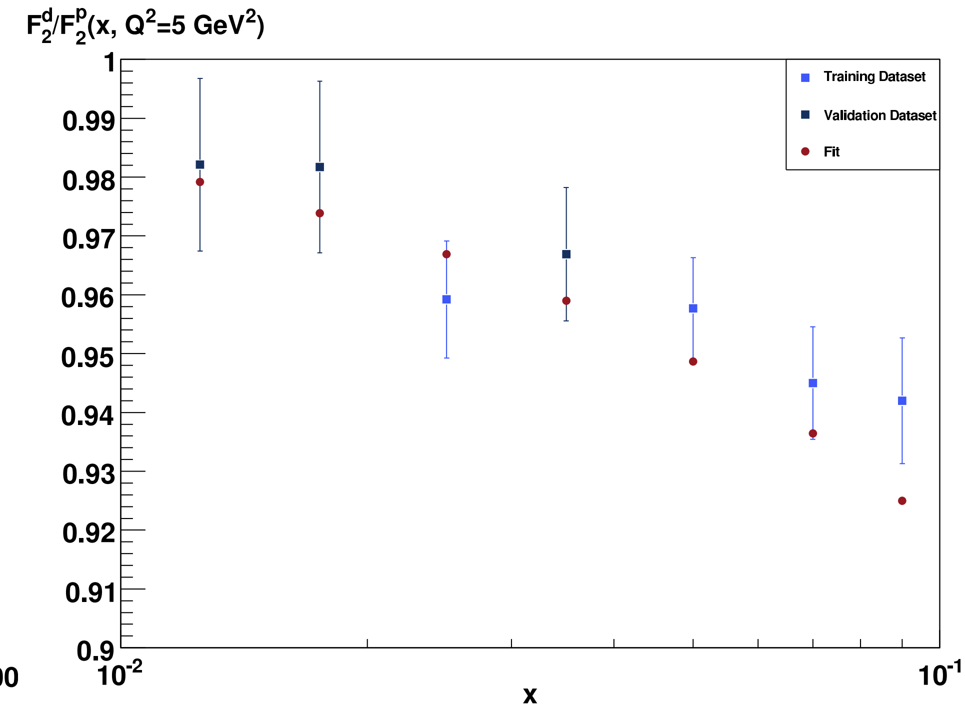
- REPLICAS ARE FITTED TO A DATA SUBSET
- A DIFFERENT SUBSET OF DATA USE FOR EACH REPLICA
- OPTIMAL FIT WHEN FIT TO VALIDATION (CONTROL) DATA STOPS IMPROVING
- THE BEST FIT IS NOT AT THE MINIMUM OF THE χ^2

OVERFITTING

χ^2



FIT TO DATA

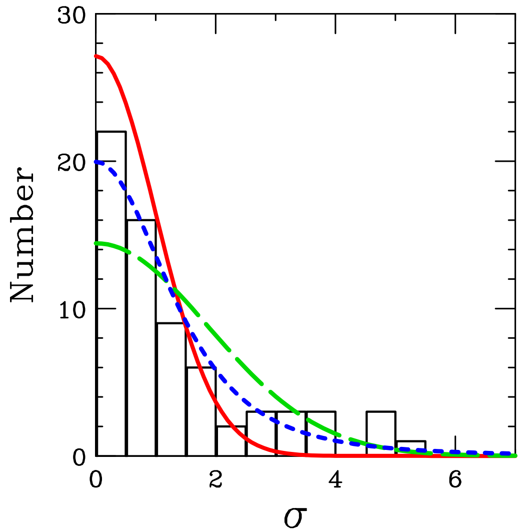


WHERE IS THE HESSIAN UNCERTAINTY COMING FROM?

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.

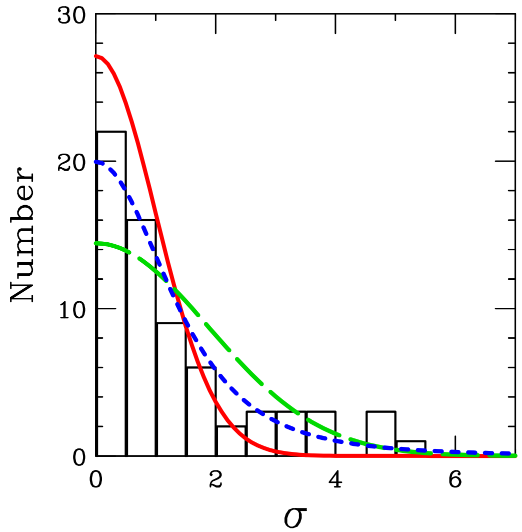


WHERE IS THE HESSIAN UNCERTAINTY COMING FROM?

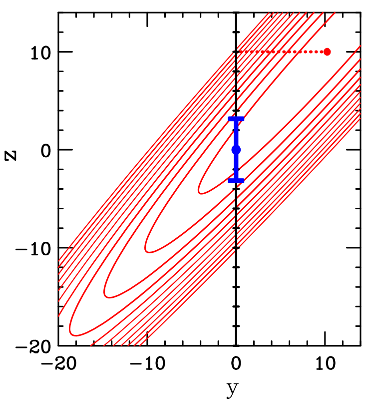
WHY DOES ONE NEED LARGE TOLERANCES?

DATA INCOMPATIBILITY (Pumplin, 2009)

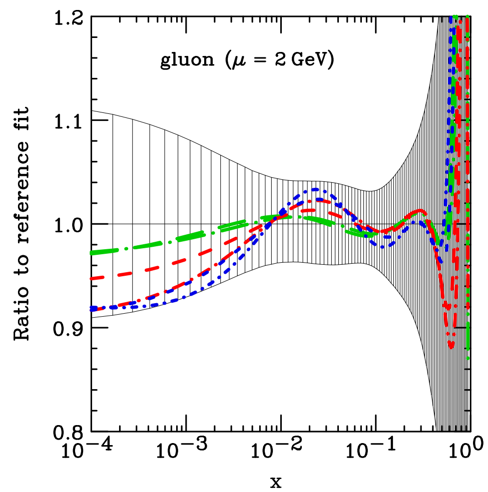
- CAN "REDIAGONALIZE": DIAGONALIZE SIMULTANEOUSLY χ^2 FOR TOTAL AND i–TH EXPT $\Rightarrow$ COMPATIBILITY OF EACH EXPT WITH GLOBAL FIT
- STUDY DISTRIBUTION OF DISCREPANCIES
- APPROX. GAUSSIAN WITH UNCERTAINTIES RESCALED BY 2 $\Rightarrow$ $\Delta\chi^2 \sim 10$ FOR 90%C.L.



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.



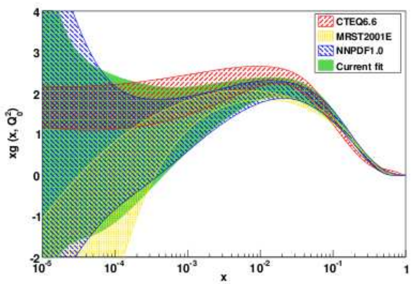
WHERE IS THE MONTE CARLO UNCERTAINTY COMING FROM?

FIT TO REPLICAS VS RANDOM SUBSET OF CENTRAL VAL.S

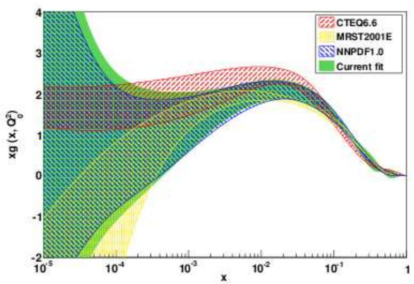
	REPLICAS	CENTRAL V.
χ^2	1.32	1.32
$\langle\chi^2\rangle_{\rm rep}$	2.79 ± 0.24	1.65 ± 0.20
$\langle\sigma^{\rm dat}\rangle$	0.039	0.035

GLUE

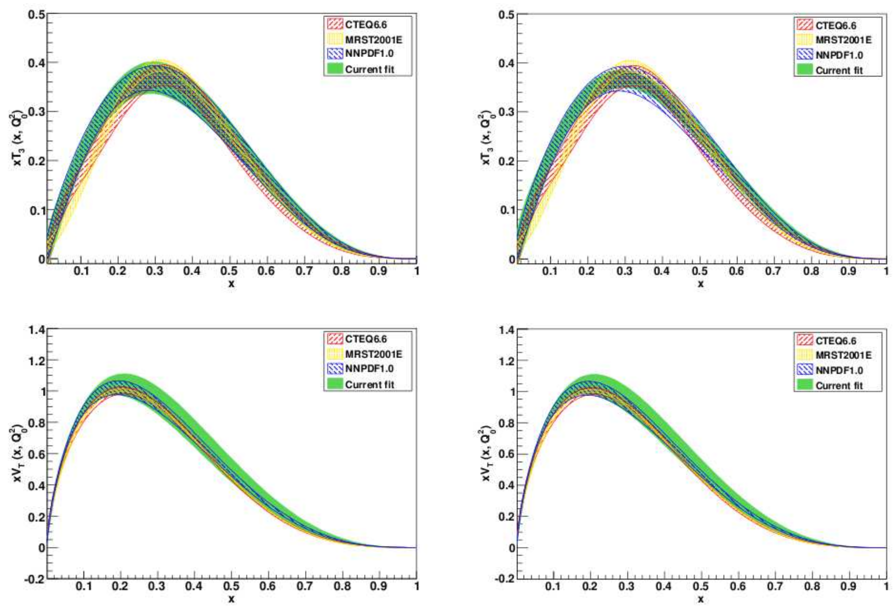
replicas



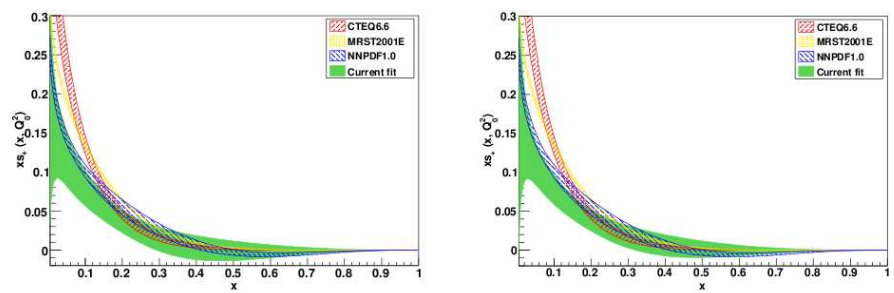
c. vals.



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

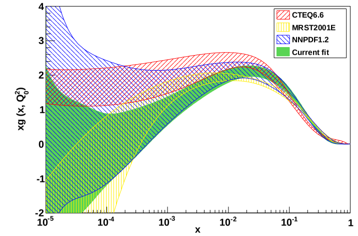
WHERE IS THE MONTE CARLO UNCERTAINTY COMING FROM?

CENTRAL VALUES: VARYING PARTITION VS FIXED PARTITION

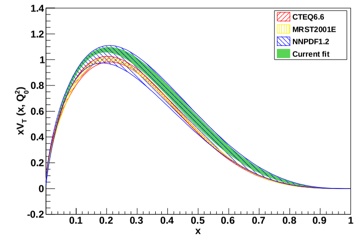
	REPLICAS	CENTRAL VALUE	FIXED PARTITION
χ^2	1.32	1.32	$\sim$1.3
$\langle\chi^2\rangle_{\rm rep}$	2.79 ± 0.24	1.65 ± 0.20	$\sim 1.6 \pm 0.2$
$\langle\sigma^{\rm dat}\rangle$	0.039	0.035	$\sim$0.03

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

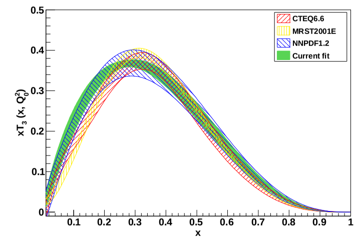
GLUE



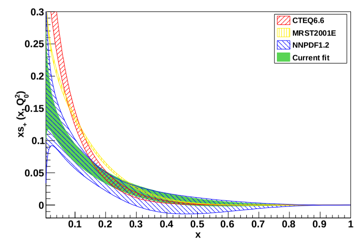
VALENCE



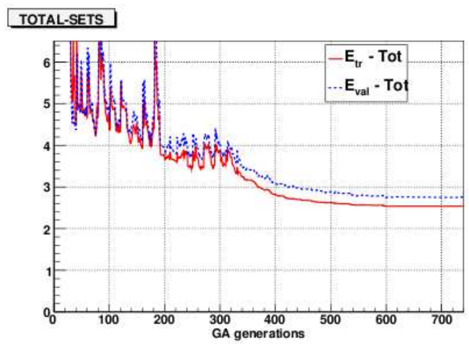
TRIPLET

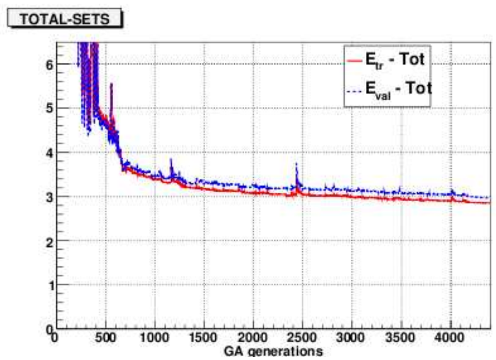


STRANGE



- 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.

WHY UNCERTAINTIES ARE IMPORTANT: 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 $\Rightarrow$ THREE σ DISCREPANCY WITH GLOBAL FIT

WHY UNCERTAINTIES ARE IMPORTANT: THE NUTEV ANOMALY...

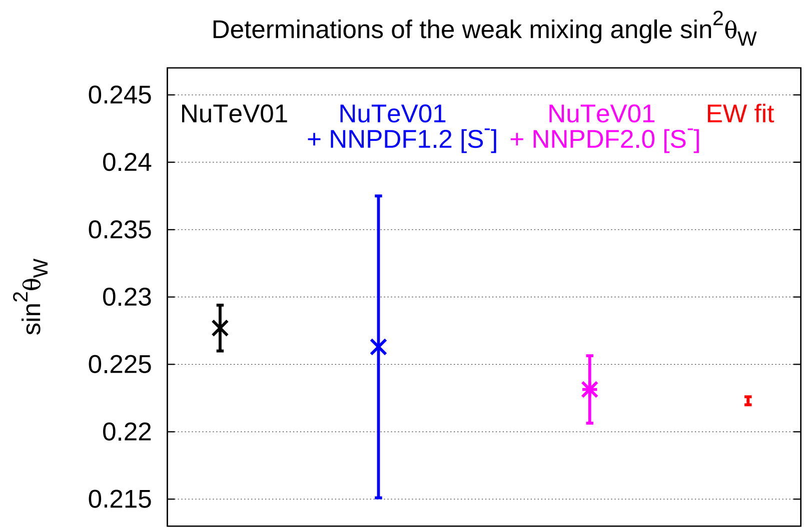
$$R_{\rm PW} \equiv \frac{\sigma(\nu\mathcal{N}\to\nu X)-\sigma(\bar\nu\mathcal{N}\to\bar\nu X)}{\sigma(\nu\mathcal{N}\to\ell X)-\sigma(\bar\nu\mathcal{N}\to\bar\ell X)}$$

$$= \frac{1}{2}-\sin^2\theta_{\rm W}+\left(\frac{(U^- - D^-)+(C^- - S^-)}{\mathcal{Q}^-}\frac{1}{6}\left(3-7\sin^2\theta_{\rm W}\right)\right),$$

- 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 $\Rightarrow$ THREE σ DISCREPANCY WITH GLOBAL FIT

...IS GONE

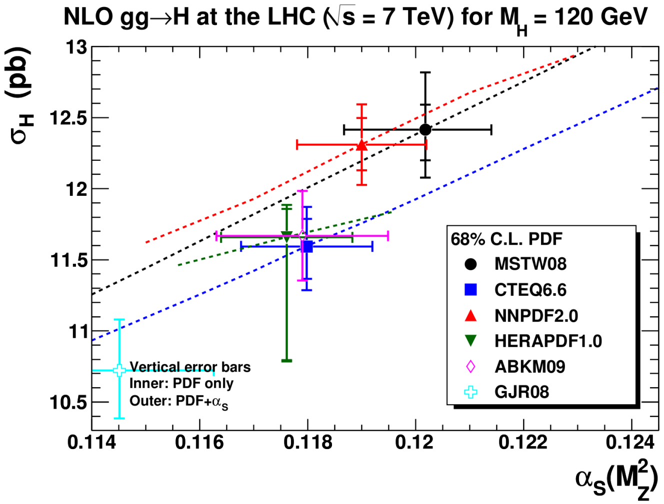
- ONCE UNCERTAINTY ON STRANGENESS ASYMMETRY KEPT INTO ACCOUNT (DIS ONLY FIT: NNPDF1.2) THE EFFECT LOSES STATISTICAL SIGNIFICANCE
- IF HADRONIC DATA INCLUDED (NNPDF2.0 GLOBAL FIT), STRANGENESS ASYMMETRY DETERMINED QUITE ACCURATELY $\longrightarrow$ CORRECTED RESULT IN IMPRESSIVE AGREEMENT WITH SM GLOBAL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



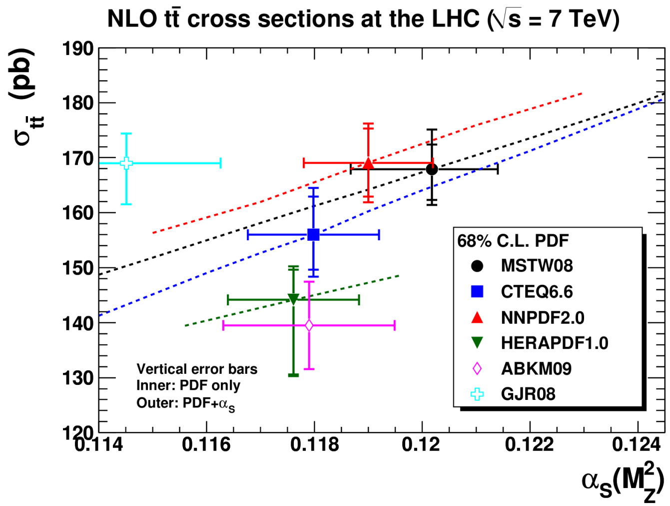
(NNPDF2.0, 2010)

STANDARD CANDLES: WHERE DO WE STAND?

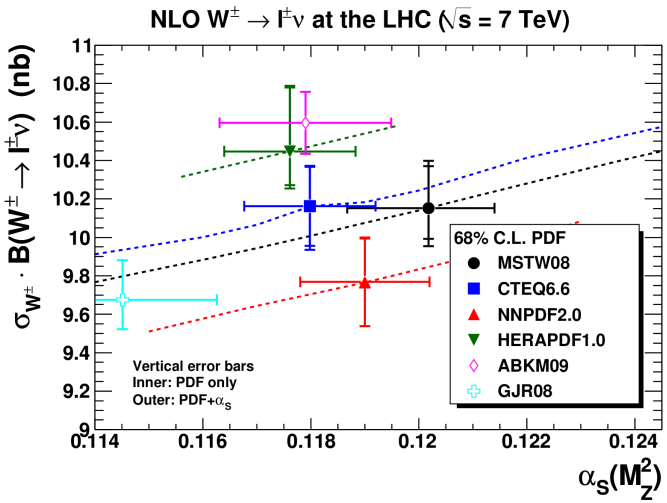
HIGGS



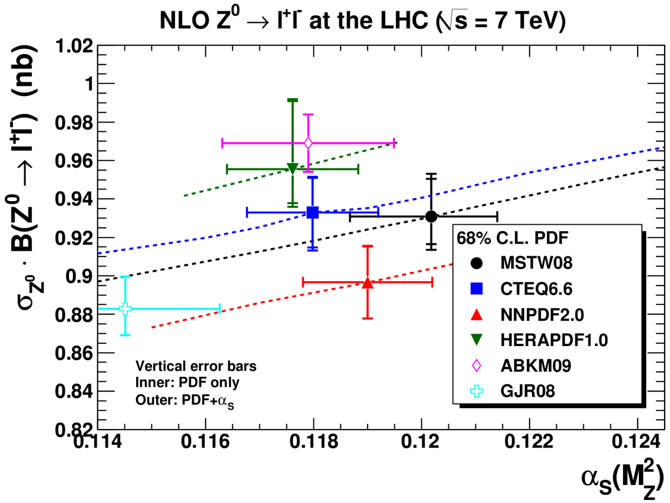
TOP



$W^{\pm}$



Z



(G. Watt, 2010)

- GLOBAL FITS (MSTW, NNPDF, CTEQ) IN GOOD MUTUAL AGREEMENT (CENTRAL VALUE & UNCERTAINTY
- CHOICE OF α_s VALUE IMPORTANT

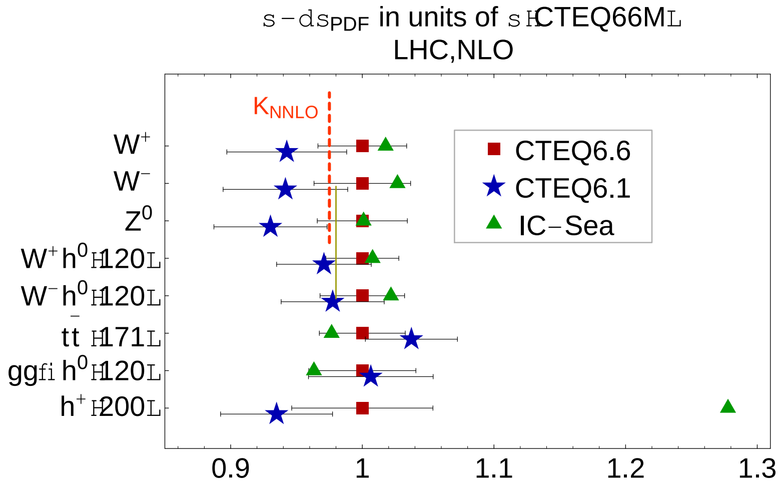
PERTURBATIVE CORRECTIONS

HEAVY QUARKS:
OLD PROBLEM, OLD SOLUTIONS

- MANY FITS (CTEQ<6, NNPDF, ALEKHIN<09) TREAT CHARM AS MASSLESS ABOVE THRESHOLD $\Rightarrow$ "ZMVFN" SCHEME
- COMBINED MATCHED SCHEMES AVAILABLE SINCE LONG (ACOT94, FONLL98) INCLUDING CHARM MASS ALONG WITH LL RESUMMATION; ALTERNATIVE TR/TR' PROCEDURE IMPLEMENTED SINCE '98 IN MRST

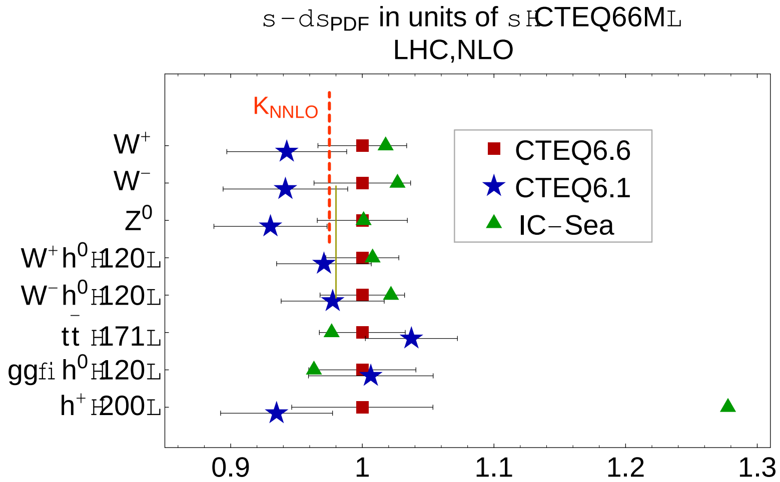
HEAVY QUARKS:
OLD PROBLEM, OLD SOLUTIONS

- MANY FITS (CTEQ<6, NNPDF, ALEKHIN<09) TREAT CHARM AS MASSLESS ABOVE THRESHOLD $\Rightarrow$ "ZMVFN" SCHEME
- COMBINED MATCHED SCHEMES AVAILABLE SINCE LONG (ACOT94, FONLL98) INCLUDING CHARM MASS ALONG WITH LL RESUMMATION; ALTERNATIVE TR/TR' PROCEDURE IMPLEMENTED SINCE '98 IN MRST
- WHEN CTEQ IMPLEMENTED ACOT IN 2008, SURPRISING CHANGE CTEQ61$\rightarrow$CTEQ6.5 IN σ_W, & AGREEMENT WITH MRST SPOILED (LATER RESTORED)



(Nadolsky et al., 2008)

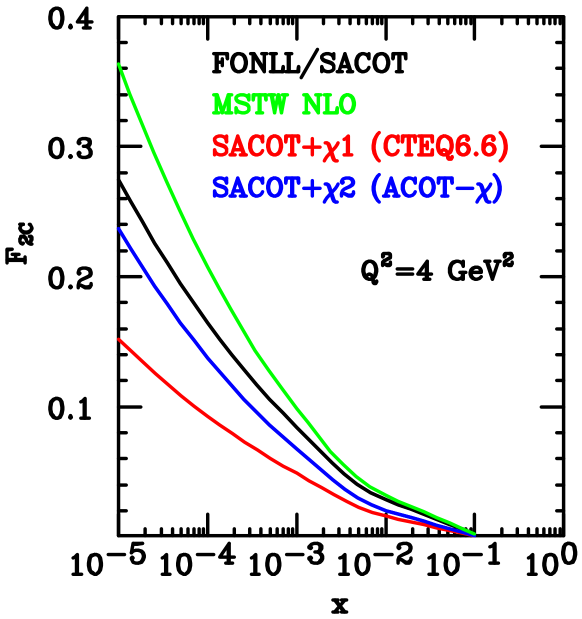
HEAVY QUARKS:
OLD PROBLEM, OLD SOLUTIONS



(Nadolsky et al., 2008)

- MANY FITS (CTEQ<6, NNPDF, ALEKHIN<09) TREAT CHARM AS MASSLESS ABOVE THRESHOLD ⇒ "ZMVFN" SCHEME
- COMBINED MATCHED SCHEMES AVAILABLE SINCE LONG (ACOT94, FONLL98) INCLUDING CHARM MASS ALONG WITH LL RESUMMATION; ALTERNATIVE TR/TR' PROCEDURE IMPLEMENTED SINCE '98 IN MRST
- WHEN CTEQ IMPLEMENTED ACOT IN 2008, SURPRISING CHANGE CTEQ61→CTEQ6.5 IN σ_W, & AGREEMENT WITH MRST SPOILED (LATER RESTORED)

OLD SOLUTION, RECENT PROGRESS:
THE LES HOUCHES 2009 BENCHMARKS

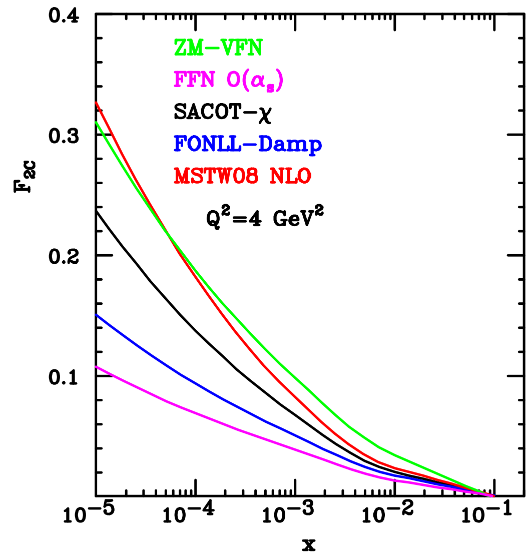


(Rojo et al., 2010)

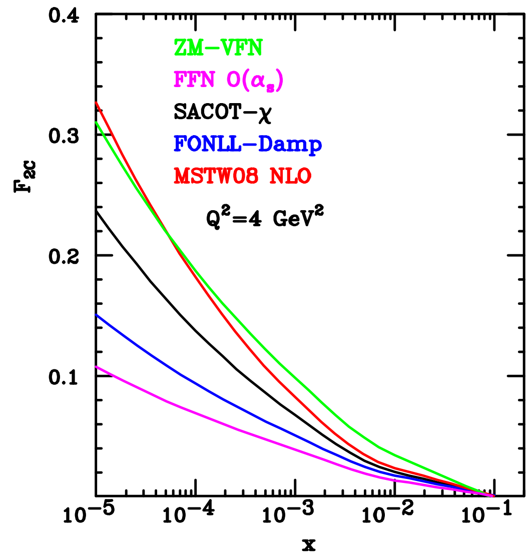
- FONLL PRESCRIPTION RECENTLY ALSO IMPLEMENTED FOR DIS, AVAILABLE TO $O(\alpha_s^2)$ (LIKE TR/TR', ACOT ONLY TO $O(\alpha_s)$)
- $O(\alpha_s)$ FONLL, ACOT COINCIDE EXACTLY, TR' DIFFERS BY SUBLEADING $O(\alpha_s^2(m_c))$ Q^2–INDEP. TERM
- VARIOUS PRESCRIPTIONS FOR HANDLING SUBLEADING TERMS ("χ–SCALING"): DIFFERENCES SIZABLE

HEAVY QUARKS:
OLD SOLUTION, NEW PROBLEMS

- IMPACT OF SUBLEADING TERMS SIZABLE CLOSE TO THRESHOLD
- DIFFERENCE BETWEEN DIFFERENT PRESCRIPTIONS (ACOT-χ–SCALING, FONLL-DAMPING, MSTW-MATCHING) AS LARGE AS DIFFERENCE BETWEEN FFN (NO DGLAP RESUMMATION FOR CHARM) AND ZMVFN (NO CHARM MASS)

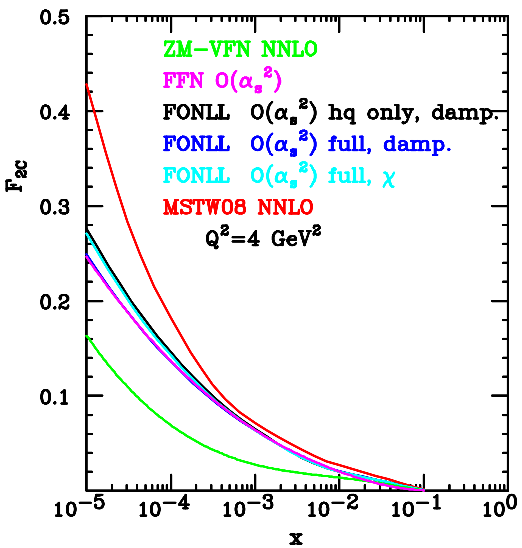


HEAVY QUARKS:
OLD SOLUTION, NEW PROBLEMS



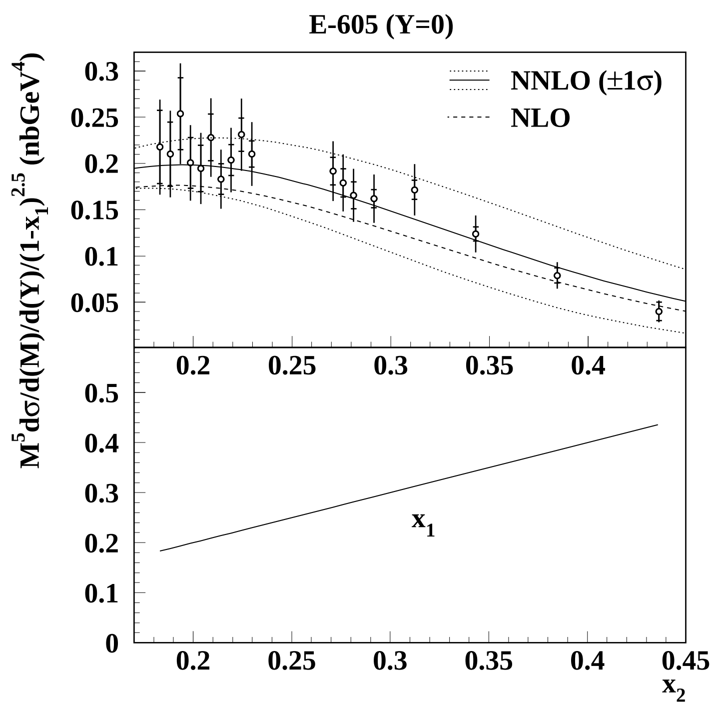
- IMPACT OF SUBLEADING TERMS SIZABLE CLOSE TO THRESHOLD
- DIFFERENCE BETWEEN DIFFERENT PRESCRIPTIONS (ACOT-χ–SCALING, FONLL-DAMPING, MSTW-MATCHING) AS LARGE AS DIFFERENCE BETWEEN FFN (NO DGLAP RESUMMATION FOR CHARM) AND ZMVFN (NO CHARM MASS)

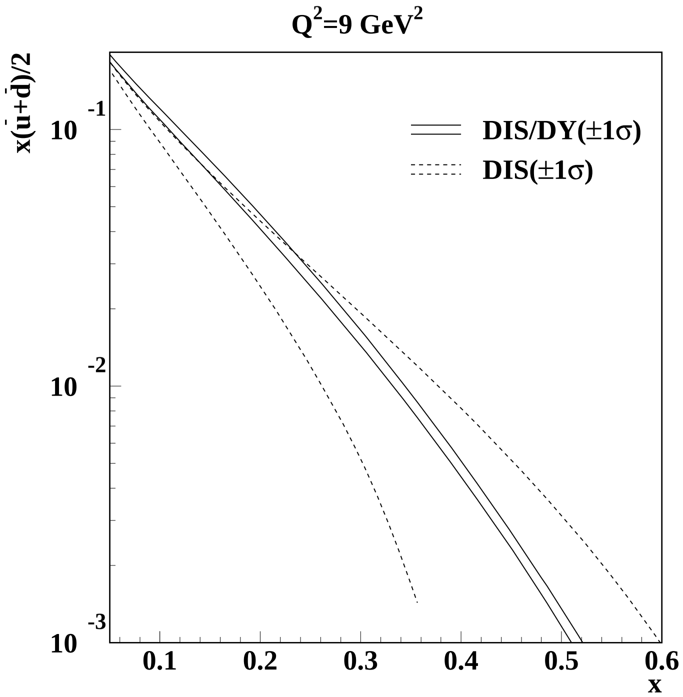
THE SOLUTION:
GO UP ONE ORDER



- IF EVERYTHING AT ONE EXTRA ORDER IN α_s, DIFFERENCES MINOR
- IN FONLL, CAN COMBINE $O(\alpha_s^2)$ TREATMENT OF HQ WITH STANDARD NLO $O(\alpha_s)$ TREATMENT OF LIGHT QUARKS $\Rightarrow$ EXCELLENT APPROX TO FULL RESULT (s.f., Laenen, Nason, Rojo 2010)
- RECENT PROGRESS: $O(\alpha^3)$ MASSLESS LIMIT OF HQ PRODUCTION COEFF. FCTNS. COMPUTED (Bierenbaum, Blümlein, Klein, 2009)

NNLO CORRECTIONS



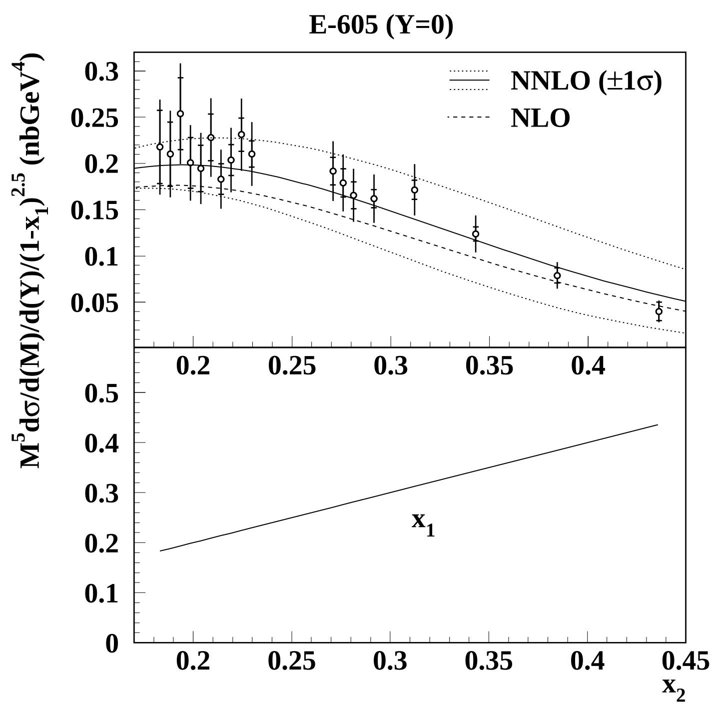


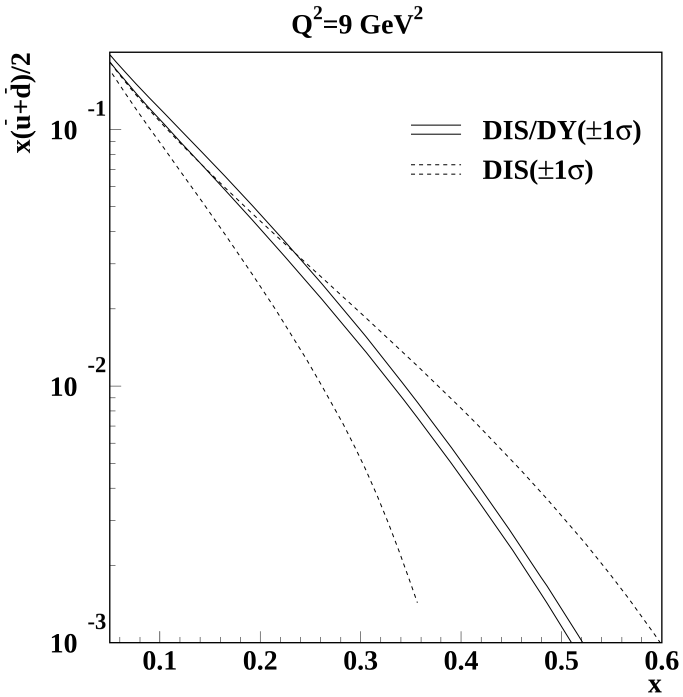
Alekhin, Melnikov, Petriello, 2006

- CURRENT GLOBAL PDF FITS ARE NLO
- MSTW08 NNLO TREATS DIS AT NNLO, JETS AT NLO, DRELL-YAN AT LO+K–FACTORS
- ALEKHIN-SERIES FITS GENUINELY NNLO, BUT ONLY DIS+ TWO FIXED–TARGET DY EXPERIMENTS INCLUDED
- BUT IMPACT NOT NEGLIGIBLE...

WHY NOT INCLUDED?

NNLO CORRECTIONS



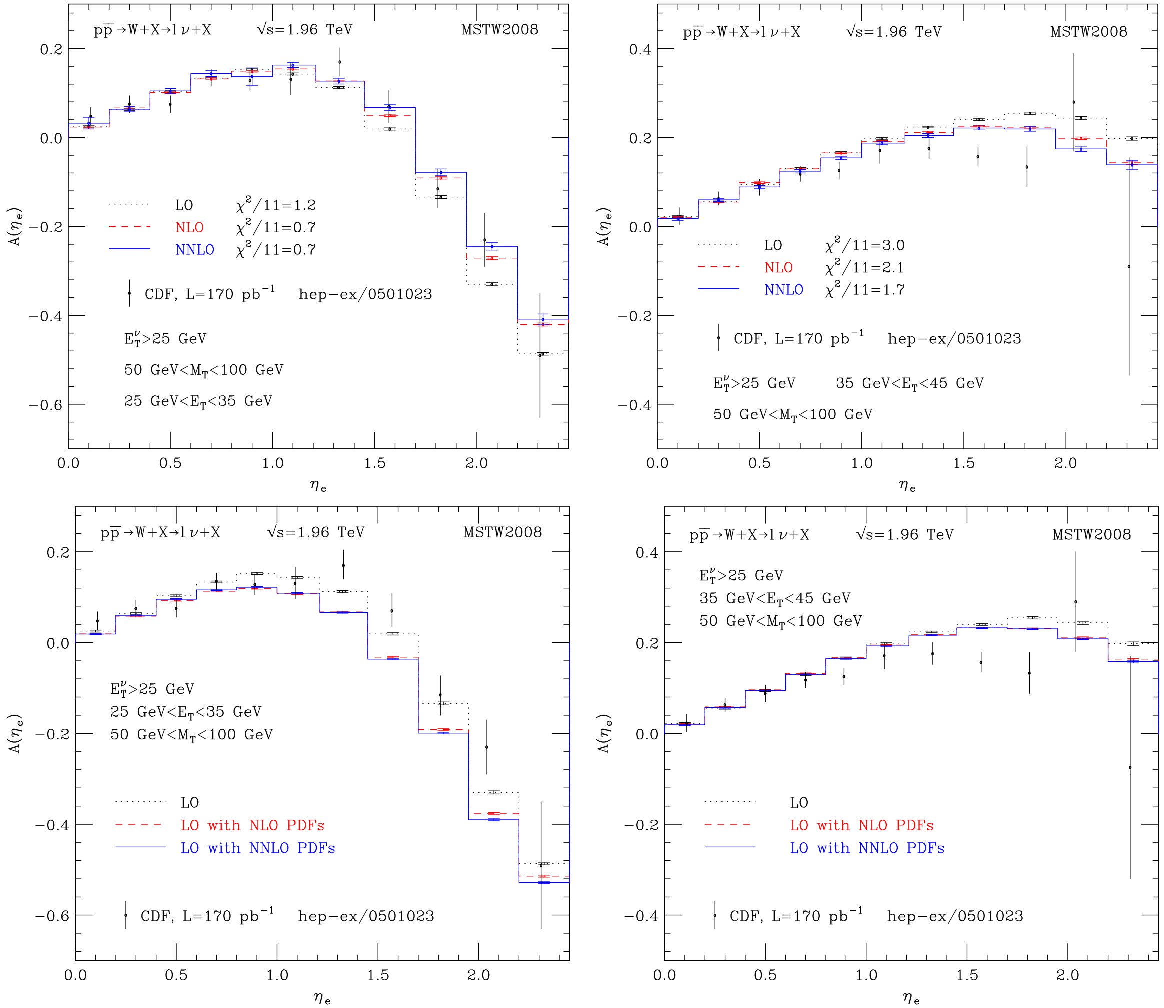


Alekhin, Melnikov, Petriello, 2006

- CURRENT GLOBAL PDF FITS ARE NLO
- MSTW08 NNLO TREATS DIS AT NNLO, JETS AT NLO, DRELL-YAN AT LO+K–FACTORS
- ALEKHIN-SERIES FITS GENUINELY NNLO, BUT ONLY DIS+ TWO FIXED–TARGET DY EXPERIMENTS INCLUDED
- BUT IMPACT NOT NEGLIGIBLE...

WHY NOT INCLUDED? CONVOLUTIONS ARE HARD!

PROBLEM: NNLO NEEDED FOR STANDARD CANDLES
EXAMPLE: THE W CHARGE ASYMMETRY



Catani, Ferrera, Grazzini, 2010

- NNLO CORRECTIONS VISIBLY IMPROVE AGREEMENT WITH DATA
- EFFECT ON MATRIX ELEMENT COMPARABLE TO EFFECT ON PDFs, BUT IN DIFFERENT REGIONS

TOWARDS NNLO TOOLS:

GRID–BASED METHODS AT NLO

ORIGINAL IDEA

EXPANSION OF PDFS ON BASES OF POLYNOMIALS (PASCAUD, ZOMER, 2001

- PRECOMPUTE CONVOLUTION WITH BASIS FUNCTIONS
- EXPAND PDF OVER BASIS
- CONVOLUTIONS REDUCED TO LINEAR COMBINATIONS $\longrightarrow$ MATRIX MULTIPLICATION

THE GRID IDEA

(CARLI, SALAM, SIEGERT 2005)

- REPRESENT PDFS ON INTERPOLATED GRID
- BASIS FCTNS $\leftrightarrow$ INTERPOLATING FCTNS
- DO CONVOLUTIONS OVER BASIS FUNCTIONS (IF MONTE CARLO USED, BASIS FCTNS $\longrightarrow$ WEIGHTS FOR MC INTEGRAL)
- GRID CAN BE OPTIMIZED

SOME IMPLEMENTATIONS:

- FASTNLO: FAST INTERFACE FOR JET CROSS SECTIONS (Kluge, Rabbertz, Wobisch 2006)

TOWARDS NNLO TOOLS:

GRID–BASED METHODS AT NLO

ORIGINAL IDEA

EXPANSION OF PDFS ON BASES OF POLYNOMIALS (PASCAUD, ZOMER, 2001

- PRECOMPUTE CONVOLUTION WITH BASIS FUNCTIONS
- EXPAND PDF OVER BASIS
- CONVOLUTIONS REDUCED TO LINEAR COMBINATIONS $\longrightarrow$ MATRIX MULTIPLICATION

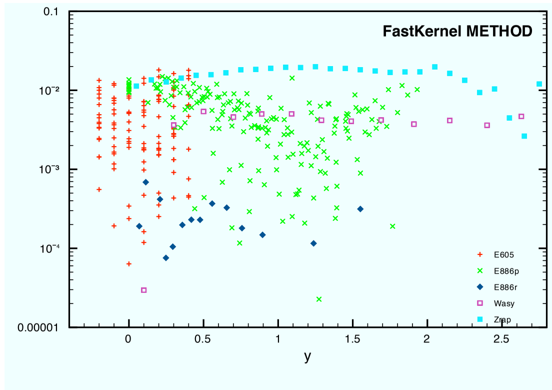
THE GRID IDEA

(CARLI, SALAM, SIEGERT 2005)

- REPRESENT PDFS ON INTERPOLATED GRID
- BASIS FCTNS $\leftrightarrow$ INTERPOLATING FCTNS
- DO CONVOLUTIONS OVER BASIS FUNCTIONS (IF MONTE CARLO USED, BASIS FCTNS $\longrightarrow$ WEIGHTS FOR MC INTEGRAL)
- GRID CAN BE OPTIMIZED

SOME IMPLEMENTATIONS:

- FASTNLO: FAST INTERFACE FOR JET CROSS SECTIONS (Kluge, Rabbertz, Wobisch 2006)
- FASTKERNEL: GRID METHOD INTERFACED TO N-SPACE COMPUTATION OF GLAP GREEN FUNCTIONS, INTERFACED TO FASTNLO FOR JETS AND TO SUITABLE FAST-DY (NNPDF, 2010)



TOWARDS NNLO TOOLS:

GRID–BASED METHODS AT NLO

ORIGINAL IDEA

EXPANSION OF PDFS ON BASES OF POLYNOMIALS (PASCAUD, ZOMER, 2001

- PRECOMPUTE CONVOLUTION WITH BASIS FUNCTIONS
- EXPAND PDF OVER BASIS
- CONVOLUTIONS REDUCED TO LINEAR COMBINATIONS $\longrightarrow$ MATRIX MULTIPLICATION

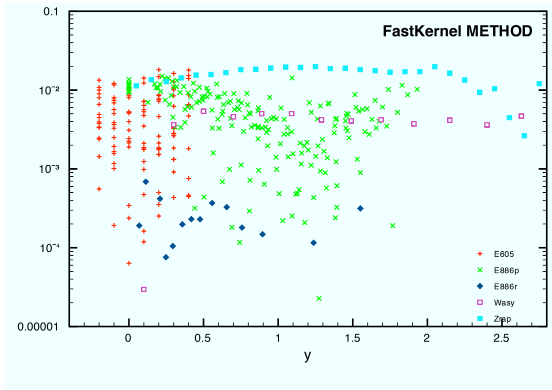
THE GRID IDEA

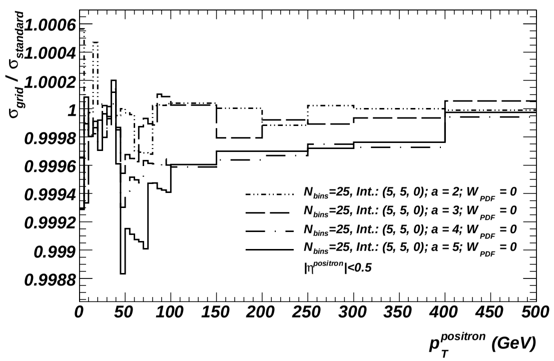
(CARLI, SALAM, SIEGERT 2005)

- REPRESENT PDFS ON INTERPOLATED GRID
- BASIS FCTNS $\leftrightarrow$ INTERPOLATING FCTNS
- DO CONVOLUTIONS OVER BASIS FUNCTIONS (IF MONTE CARLO USED, BASIS FCTNS $\longrightarrow$ WEIGHTS FOR MC INTEGRAL)
- GRID CAN BE OPTIMIZED

SOME IMPLEMENTATIONS:

- FASTNLO: FAST INTERFACE FOR JET CROSS SECTIONS (Kluge, Rabbertz, Wobisch 2006)
- FASTKERNEL: GRID METHOD INTERFACED TO N-SPACE COMPUTATION OF GLAP GREEN FUNCTIONS, INTERFACED TO FASTNLO FOR JETS AND TO SUITABLE FAST-DY (NNPDF, 2010)
- APPLGRID: OPTIMIZED GRID, POTENTIALLY UNIVERSAL INTERFACE, IMPLEMENTED FOR JETS, W AND Z PRODUCTION (Carli et al., 2010)





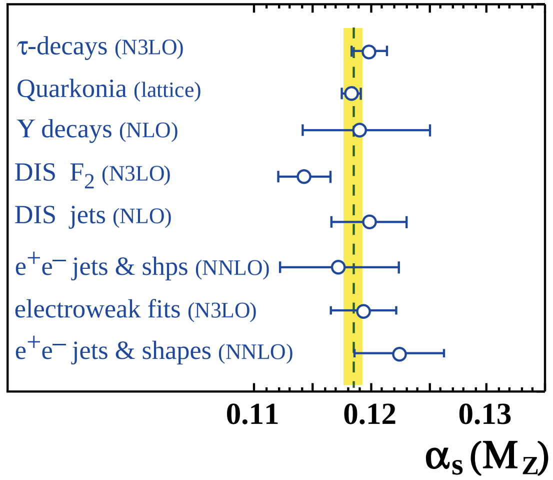
THE SCANDAL OF α_s:

NEW GLOBAL α_s DETERMINATION BY BETHKE (2009):

$$\alpha_s = 0.1184 \pm 0.0007$$

ADOPTED BY PDG WEB UPDATE (2009)

"older measurements not included because [of]...their large ... uncertainties"



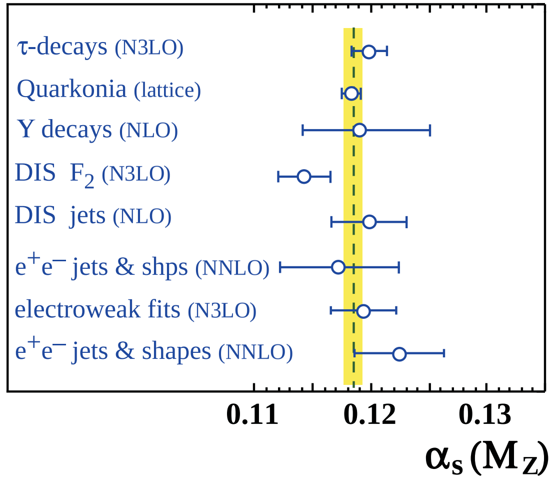
THE SCANDAL OF α_s:

NEW GLOBAL α_s DETERMINATION BY BETHKE (2009):

$$\alpha_s = 0.1184 \pm 0.0007$$

ADOPTED BY PDG WEB UPDATE (2009)

"older measurements not included because [of]...their large ... uncertainties"



WHAT'S THE PROBLEM?

- N^3LO DETERMINATION (Blümlein, Böttcher, Guffanti, 2006) FROM NONSINGLET SCALING VIOLATIONS: $\alpha_s = 0.114 \pm 0.002$ (NLO: $\alpha_s = 0.115 \pm 0.002$) AT THREE σ FROM AVERAGE
- DO WE UNDERSTAND HIGHER ORDERS?
  MSTW (2010) SEE A CHANGE OF 2 SIGMA FROM NLO TO NNLO
  $\alpha_s = 0.1202^{+0.0012}_{-0.0015}$ TO $\alpha_s = 0.1171 \pm 0.0014$
- DO WE UNDERSTAND EXTRAPOLATION? IF TRUNCATED MOMENTS ARE USED (NO ASSUMPTIONS) NLO RESULT FROM NONSINGLET SCALING VIOLATIONS IS (s.f. et al., 2002) $\alpha_s = 0.124^{+0.005}_{-0.008}$

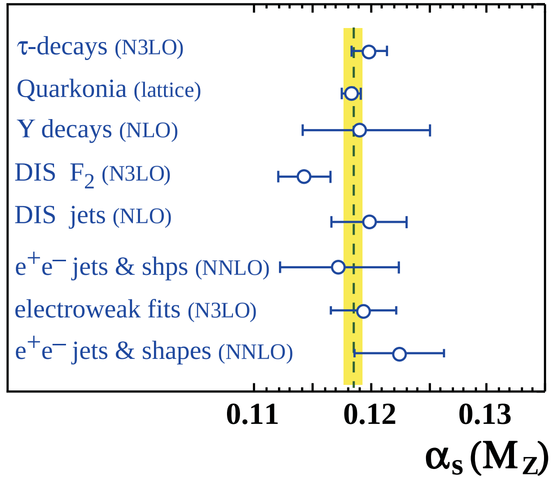
THE SCANDAL OF α_s:

NEW GLOBAL α_s DETERMINATION BY BETHKE (2009):

$$\alpha_s = 0.1184 \pm 0.0007$$

ADOPTED BY PDG WEB UPDATE (2009)

"older measurements not included because [of]...their large ... uncertainties"



WHAT'S THE PROBLEM?

- N^{3}LO DETERMINATION (Blümlein, Böttcher, Guffanti, 2006) FROM NONSINGLET SCALING VIOLATIONS: $\alpha_s = 0.114 \pm 0.002$ (NLO: $\alpha_s = 0.115 \pm 0.002$) AT THREE σ FROM AVERAGE
- DO WE UNDERSTAND HIGHER ORDERS?
  MSTW (2010) SEE A CHANGE OF 2 SIGMA FROM NLO TO NNLO
  $\alpha_s = 0.1202^{+0.0012}_{-0.0015}$ TO $\alpha_s = 0.1171 \pm 0.0014$
- DO WE UNDERSTAND EXTRAPOLATION? IF TRUNCATED MOMENTS ARE USED (NO ASSUMPTIONS) NLO RESULT FROM NONSINGLET SCALING VIOLATIONS IS (s.f. et al., 2002) $\alpha_s = 0.124^{+0.005}_{-0.008}$

SOLUTIONS?

- AN LHEC WITH DEUTERON WOULD SOLVE THE ISSUE EXPERIMENTALLY (PERMILLE ACCURACY ON α_s)
- WE NEED A BELIEVABLE CONSERVATIVE α_s AVERAGE FOR PHENOMENOLOGY

RESUMMATION

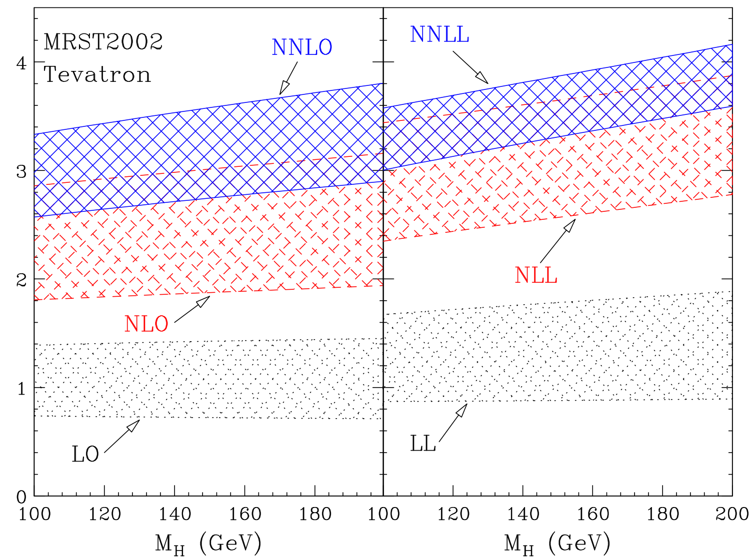
SOFT GLUONS

IMPORTANT WHENEVER PARTONIC CM ENERGY RELATIVELY CLOSE TO FINAL STATE MASS
NEEDED FOR PERCENT ACCURACY IN

SOFT GLUONS

IMPORTANT WHENEVER PARTONIC CM ENERGY RELATIVELY CLOSE TO FINAL STATE MASS
NEEDED FOR PERCENT ACCURACY IN HIGGS

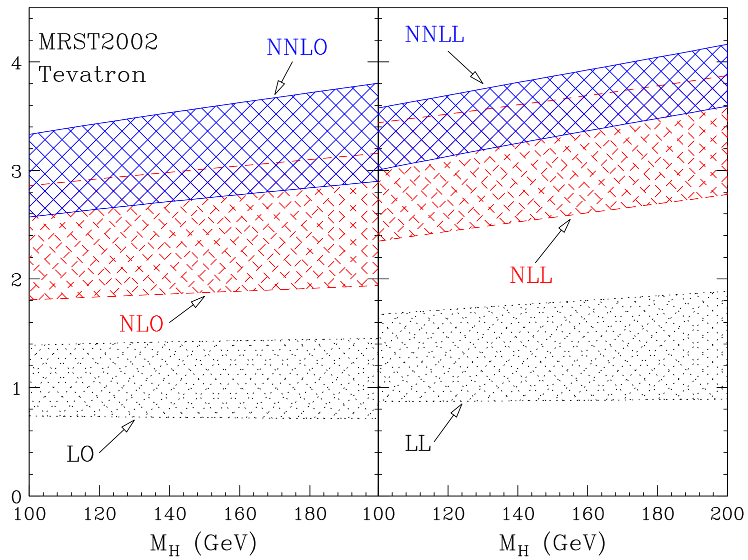
HIGGS (Catani et al., 2002)



SOFT GLUONS

IMPORTANT WHENEVER PARTONIC CM ENERGY RELATIVELY CLOSE TO FINAL STATE MASS
NEEDED FOR PERCENT ACCURACY IN HIGGS & TOP PRODUCTION

HIGGS (Catani et al., 2002)



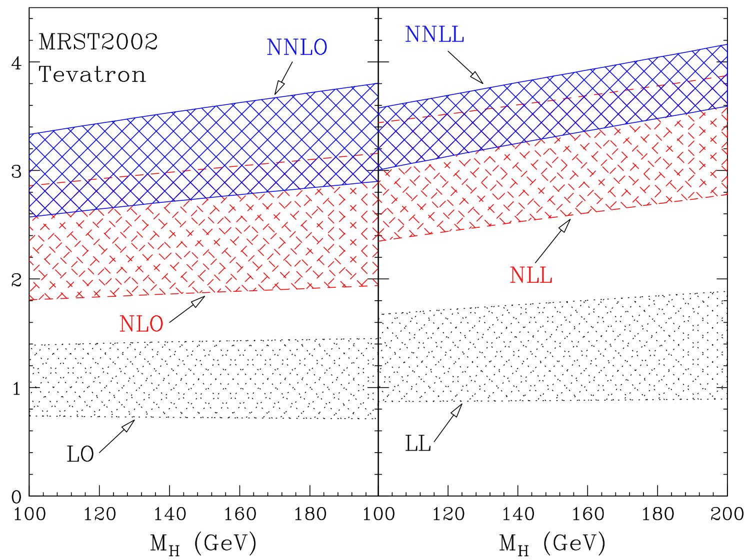
TOP (Cacciari et al, 2008)

$$\Delta\sigma_{t\bar{t}}^{NLO}(LHC14) = 11.6\%$$
$$\Delta\sigma_{t\bar{t}}^{NLO+NLL}(LHC14) = 9.3\%$$

SOFT GLUONS

IMPORTANT WHENEVER PARTONIC CM ENERGY RELATIVELY CLOSE TO FINAL STATE MASS
NEEDED FOR PERCENT ACCURACY IN HIGGS & TOP PRODUCTION

HIGGS (Catani et al., 2002)



TOP (Cacciari et al, 2008)

$\Delta\sigma_{t\bar{t}}^{NLO}(LHC14) = 11.6\%$

$\Delta\sigma_{t\bar{t}}^{NLO+NLL}(LHC14) = 9.3\%$

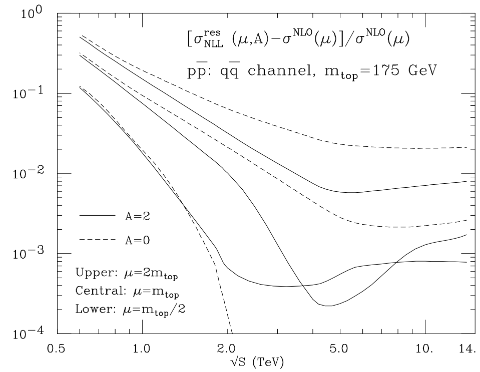
THEORETICAL PROGRESS

- IR SINGULARITIES TO ALL ORDERS FOR ANY NUMBER OF LEGS CONJECTURED TO BE DETERMINED BY THREE UNIVERSAL ANOMALOUS DIMENSIONS (Becher, Neubert; Gardi, Magnea, 2009)
  PROVEN IN PLANAR LIMIT(Magnea, Dixon, Sterman, 2010) , EXACT RESULTS AVAILABLE IN $\mathcal{N} = 4$ CASE (Alday, 2009)
- TWO LOOP SOFT ANOMALOUS DIMENSIONS COMPUTED $\Rightarrow$ NNLL TOP PRODUCTION (Beneke, Falgari, Schiwnn, 2010)
- CLASS OF $1 - x$ POWER-SUPPRESSED TERMS EXPONENTIATED (Laenen, Magnea, Stavenga 2008), CHECKED AT LL (Grunberg, Ravindran, 2009), BASED ON MODIFIED EVOLUTION EQN. $\alpha_s(Q^2(1-x)/x)$) (Dokshitzer, Marchesini, Salam, 2006)
- CONJECTURED EXPONENTIATION OF POWER-SUPPRESSED TERMS FOR PHYSICAL ANOMALOUS DIMENSION (Moch, Vogt 2009)

THE ROLE OF SUBLEADING TERMS

EXAMPLE 1 (OLD): TOP

- SUBLEADING TERMS HELP IN IMPROVING THE RESUMMED-FIXED ORDER MATCHING (CAN CHECK WITH KNOWN FIXED ORDERS)
- IF $\mu_R = \mu_F$ VARIED TOGETHER, NLL UNCERTAINTY ON σ_t
  2% W/O MATCHING TERMS $(A = 0)$,
  7% WITH MATCHING TERMS $(A = 2)$;
  9% UNCERTAINTY IF SCALES VARIED INDEPENDENTLY
  (Cacciari, Frixione, Mangano, Nason, Ridolfi, 1998)

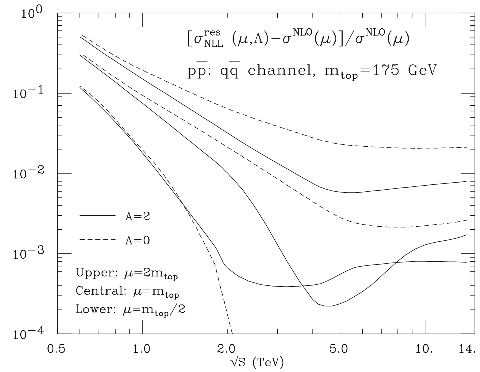


(Bonciani, Catani, Mangano, Nason, 1998)

THE ROLE OF SUBLEADING TERMS

EXAMPLE 1 (OLD): TOP

- SUBLEADING TERMS HELP IN IMPROVING THE RESUMMED-FIXED ORDER MATCHING (CAN CHECK WITH KNOWN FIXED ORDERS)
- IF $\mu_R = \mu_F$ VARIED TOGETHER, NLL UNCERTAINTY ON σ_t
  2% W/O MATCHING TERMS ($A = 0$),
  7% WITH MATCHING TERMS ($A = 2$);
  9% UNCERTAINTY IF SCALES VARIED INDEPENDENTLY
  (Cacciari, Frixione, Mangano, Nason, Ridolfi, 1998)



(Bonciani, Catani, Mangano, Nason, 1998)

EXAMPLE 2 (NEW): HIGGS

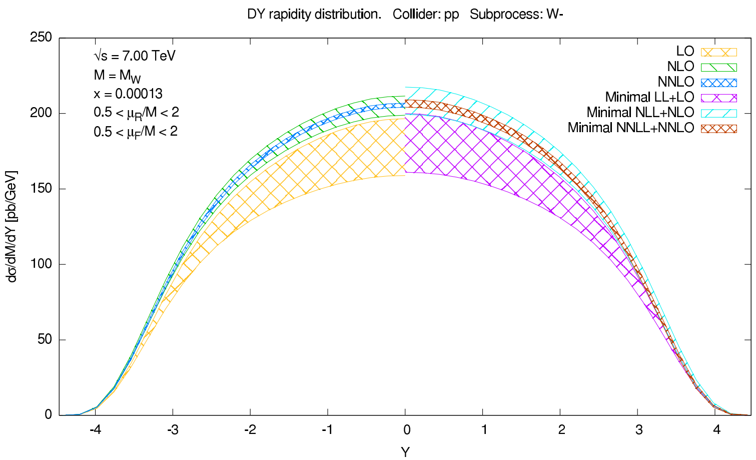
$m_H = 120\ GeV$, LHC 14 TeV, MSTW08NNLO PDFs

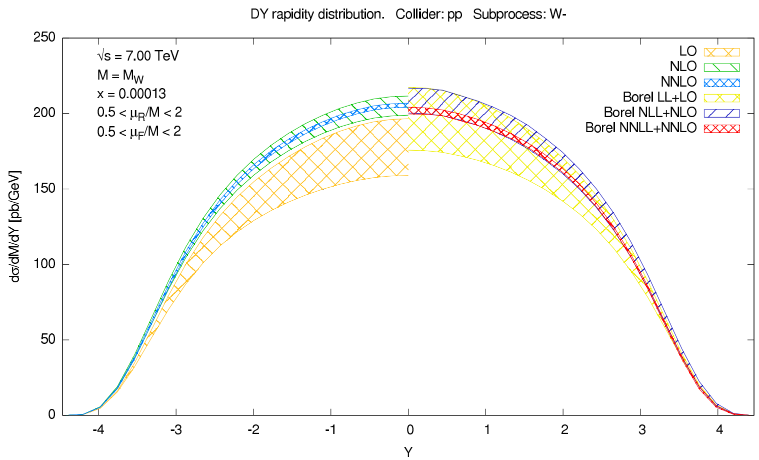
$\sigma^{NNLO+NNLL} - \sigma^{NNLO} = 3.4pb$ (6.8%) (de Florian, Grazzini 2009)
$\sigma^{NNLO+NNLL} - \sigma^{NNLO} = .9pb$ (1.8%) (Ahrens, Becher, Neubert, Yang 2009)
RESULT FOR DFG OBTAINED USING http://theory.fi.infn.it/grazzini/hcalculators.html

- ALMOST ALL THE DIFFERENCE DUE TO POWER SUPPRESSED TERMS
- RESUMMATION OF π^2 TERMS DONE BY AHRENS ET AL. (Parisi, 1980, Eynck, Laenen, Magnea, 2003)$\Rightarrow$ $\sigma^{NNLO+NNLL+\pi^2} - \sigma^{NNLO+NNLL} = 2.9pb$ (5.8%)

EXAMPLE 3 (NEW): DRELL-YAN, W Z

- RESUMMED SERIES DIVERGES, PRESCRIPTION NEEDED TO SUM IT
- STANDARD (MINIMAL) PRESCRIPTION INVOLVES CANCELLATION WITH CONTRIBUTION FROM UNPHYSICAL REGION; OTHER PRESCRIPTIONS AVAILABLE (E.G. BOREL SUM) (Ridolfi, S.F. et al, 2006-2009), DIFFERENT HO AND MATCHING
- IMPACT OF RESUMMATION COMPARABLE TO NNLO, BUT AMBIGUITY LARGE

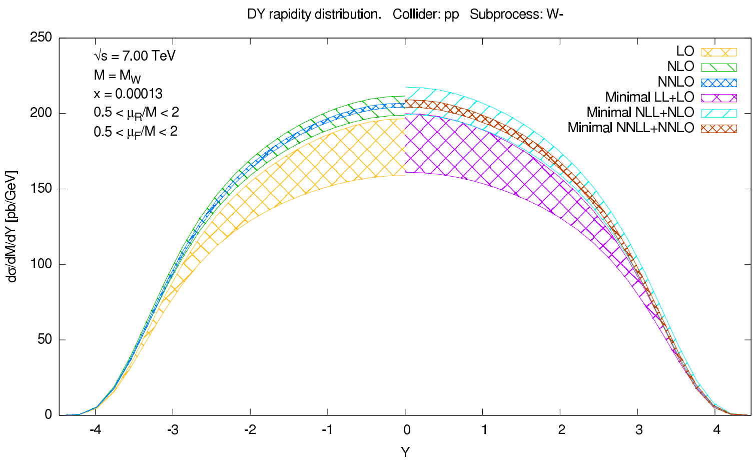


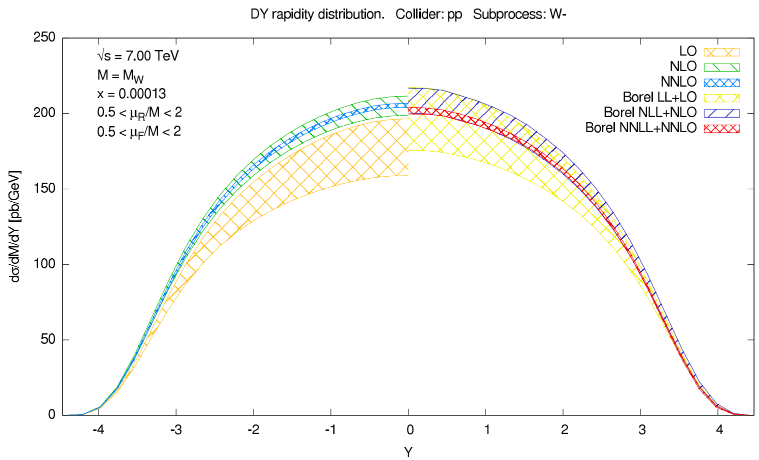


(Bonvini, s.f., Ridolfi, prelim)

EXAMPLE 3 (NEW): DRELL-YAN, W Z

- RESUMMED SERIES DIVERGES, PRESCRIPTION NEEDED TO SUM IT
- STANDARD (MINIMAL) PRESCRIPTION INVOLVES CANCELLATION WITH CONTRIBUTION FROM UNPHYSICAL REGION; OTHER PRESCRIPTIONS AVAILABLE (E.G. BOREL SUM) (Ridolfi, S.F. et al, 2006-2009), DIFFERENT HO AND MATCHING
- IMPACT OF RESUMMATION COMPARABLE TO NNLO, BUT AMBIGUITY LARGE





(Bonvini, s.f., Ridolfi, prelim)

DESIDERATA

- EXPLORE THE PHENOMENOLOGICAL IMPLICATIONS OF PRESCRIPTIONS, SUBLEADING TERMS, MATCHING
- TEST AND IMPLEMENT SUBLEADING RESUMMATION ASAP
- NEED RESUMMED PDFS!

CAVEAT

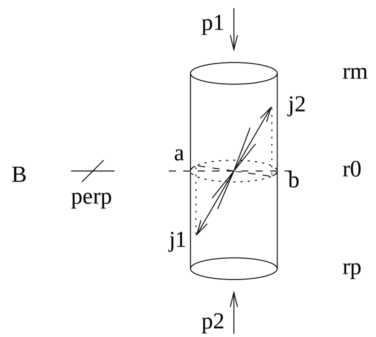
AT THE PERCENT LEVEL, NOT ONLY QCD CORRECTIONS ARE RELEVANT
EXAMPLE: NNLO HIGGS XSECT ($m_H = 120$ GEV, LHC14):
$\sigma^{NNLO} = 47.6pb$ (ABNY) OR $\sigma^{NNLO} = 51.1pb$ (DEFG),
6% DIFFERENCE LIKELY DUE TO EW CORRECTIONS (NOT INCLUDED IN ABNY)

SMALL x RESUMMATION
WHERE IS IT?

- HERA DATA HAVE TAUGHT US THAT THE EFFECT OF HIGH-ENERGY LOGS IS SMALL
- WE ARE SLOWLY REALIZING THAT THIS MIGHT BE ALWAYS THE CASE

MUELLER-NAVELET JETS

- CLASSIC PROCESS TO SEARCH FOR ENERGY (BFKL) LOGS
- AS RAPIDITY GAP GROWS, EXPECT XSECT TO GROW AND AZIMUTHAL CORRELATION TO DECORRELATE DUE TO GLUON RADIATION

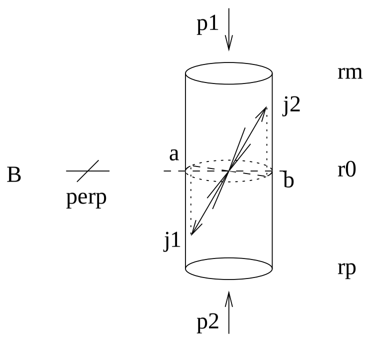


SMALL x RESUMMATION
WHERE IS IT?

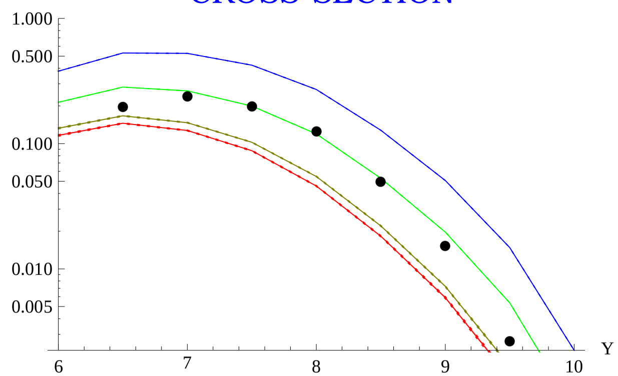
- HERA DATA HAVE TAUGHT US THAT THE EFFECT OF HIGH-ENERGY LOGS IS SMALL
- WE ARE SLOWLY REALIZING THAT THIS MIGHT BE ALWAYS THE CASE

MUELLER-NAVELET JETS

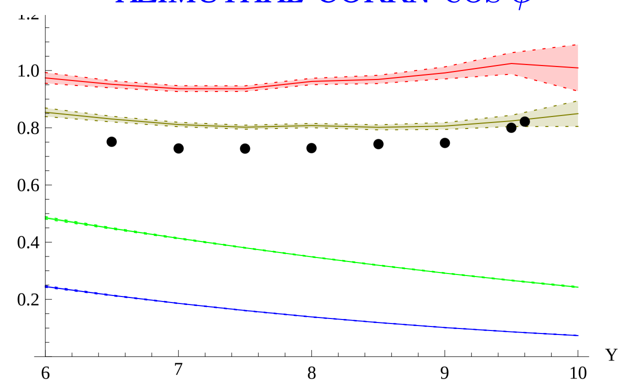
- CLASSIC PROCESS TO SEARCH FOR ENERGY (BFKL) LOGS
- AS RAPIDITY GAP GROWS, EXPECT XSECT TO GROW AND AZIMUTHAL CORRELATION TO DECORRELATE DUE TO GLUON RADIATION
- PROCESS COMPUTED RECENTLY TO FULL NLLx
(Colferai, Schwennsen, Szymanowski, Wallon, 2010)
NLO CORRECTIONS VERY LARGE,
BRING NLLx "BFKL" & NLLQ^2 "DGLAP" RESULTS FOR CROSS SECTION TOWARDS AGREEMENT & RESTORE AZIMUTHAL CORRELATIONS $\Rightarrow$ NO LARGE NFKL EFFECTS



CROSS SECTION



AZIMUTHAL CORRN $\cos\phi$



LLx BFKL NLLx BFKL LLx vert+ NLL NLxvert+NLL NLO

DGLAP

MATCHED CALCULATIONS
& WHAT THEY ARE GOOD FOR

- MATCHED NLLQ^2+NLLx EVOLUTION EQUATION AVAILABLE SINCE SEVERAL YEARS WITH $n_f = 0$ (Ciafaloni, Colferai, Salam, Stasto, 2003; Altarelli, Ball, S.F., 2005)
- FIRST RESUMMED STRUCTURE FUNCTIONS (THORNE, WHITE, 2007)
- GENERAL FORMALISM FOR COEFFICIENT FUNCTION RESUMMATION (Ball 2008)

MATCHED CALCULATIONS
& WHAT THEY ARE GOOD FOR

- MATCHED NLLQ^2+NLLx EVOLUTION EQUATION AVAILABLE SINCE SEVERAL YEARS WITH $n_f = 0$ (Ciafaloni, Colferai, Salam, Stasto, 2003; Altarelli, Ball, S.F., 2005)

- FIRST RESUMMED STRUCTURE FUNCTIONS (THORNE, WHITE, 2007)

- GENERAL FORMALISM FOR COEFFICIENT FUNCTION RESUMMATION (Ball 2008)

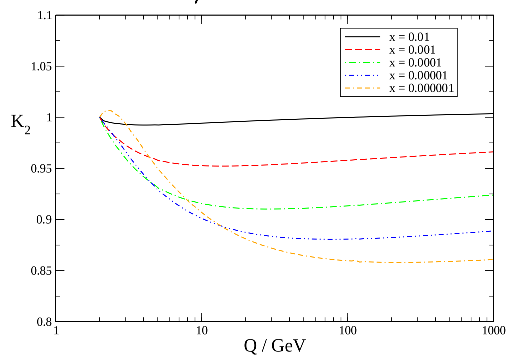
- FULLY CONSISTENT RESUMMED NLL DIS STRUCTURE FUNCTIONS (ALTARELLI, BALL, S.F. 2008)
NLL RESUMMATION EFFECTS ABOUT SAME SIZE AS NNLO, BUT OPPOSITE SIGN IN HERA REGION: NNLO $\leftrightarrow$ MORE SCALE DEP. THAN NLO, NLL $\leftrightarrow$ LESS SCALE DEP. THAN NLO

- LL RESUMMATION FOR HIGGS C.F. AT FINITE m_t (Marzani, Ball, Del Duca, s.f., Vicini, 2008)
ACCURATE APPROXIMATE NNLO HIGGS PRODUCTION (Harlander, Mantler, Marzani, Ozeren, 2010) $\longrightarrow$ HIGGS-MEDIATED DIS (Soar, Moch, Vermaseren, Vogt, 2010)

- NLL RESUMMATION FOR DRELL-YAN (Marzani, Ball, 2009)
SIZABLE ENHANCEMENT IN COMPARISON TO NNLO

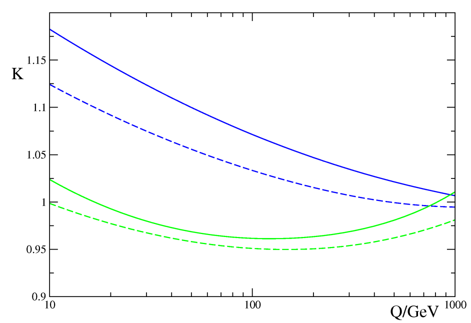
- NLL RESUMMATION FOR PROMPT PHOTON PRODUCTION (Diana, 2009)

F_2 res/NLO K fact



(ABF 2008)

DY res/NLO & NNLO/LO



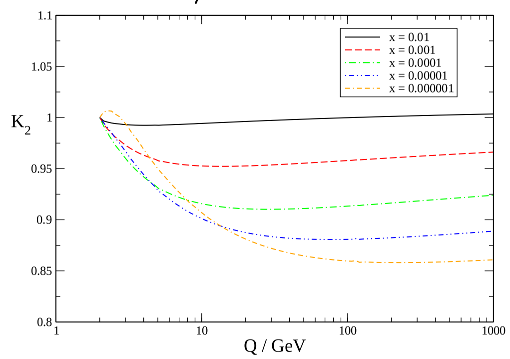
(Marzani, Ball, 2009)

MATCHED CALCULATIONS
& WHAT THEY ARE GOOD FOR

- MATCHED NLLQ^2+NLLx EVOLUTION EQUATION AVAILABLE SINCE SEVERAL YEARS WITH $n_f = 0$ (Ciafaloni, Colferai, Salam, Stasto, 2003; Altarelli, Ball, S.F., 2005)
- FIRST RESUMMED STRUCTURE FUNCTIONS (THORNE, WHITE, 2007)
- GENERAL FORMALISM FOR COEFFICIENT FUNCTION RESUMMATION (Ball 2008)
- FULLY CONSISTENT RESUMMED NLL DIS STRUCTURE FUNCTIONS (ALTARELLI, BALL, S.F. 2008)
  NLL RESUMMATION EFFECTS ABOUT SAME SIZE AS NNLO, BUT OPPOSITE SIGN IN HERA REGION: NNLO $\leftrightarrow$ MORE SCALE DEP. THAN NLO, NLL $\leftrightarrow$ LESS SCALE DEP. THAN NLO
- LL RESUMMATION FOR HIGGS C.F. AT FINITE m_t (Marzani, Ball, Del Duca, s.f., Vicini, 2008)
  ACCURATE APPROXIMATE NNLO HIGGS PRODUCTION (Harlander, Mantler, Marzani, Ozeren, 2010) $\longrightarrow$ HIGGS-MEDIATED DIS (Soar, Moch, Vermaseren, Vogt, 2010)
- NLL RESUMMATION FOR DRELL-YAN (Marzani, Ball, 2009)
  SIZABLE ENHANCEMENT IN COMPARISON TO NNLO
- NLL RESUMMATION FOR PROMPT PHOTON PRODUCTION (Diana, 2009)

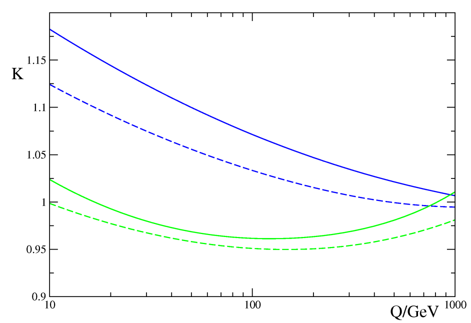
- RESUMMATION MANDATORY TO STABILIZE NNLO
- RELEVANT AT $\sim 5\%$ LEVEL

F_2 res/NLO K fact



(ABF 2008)

DY res/NLO & NNLO/LO

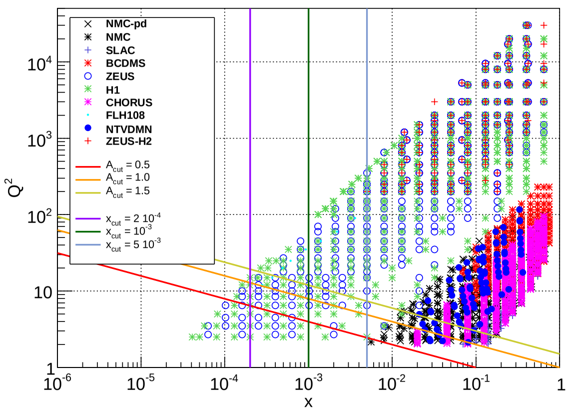


(Marzani, Ball, 2009)

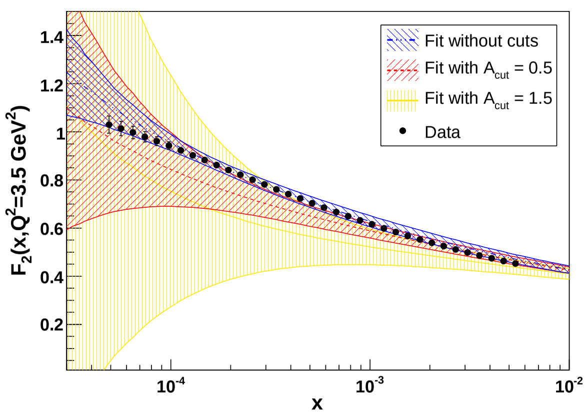
BEYOND FIXED ORDER?

IS THERE EVIDENCE FOR DEVIATION FROM FIXED–ORDER EVOLUTION IN THE DATA?
CUT PDF FITS, THE IDEA: EVOLVE BACKWARDS INTO LOW x, Q^2 REGION
CHECK WHETHER DATA DEVIATE FROM EVOLVED SOLUTION:

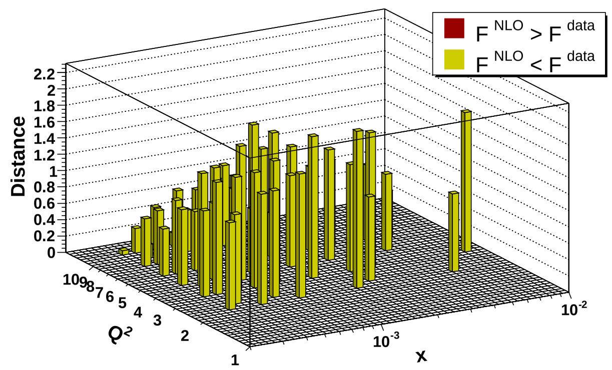
the cut



the effect on F_2



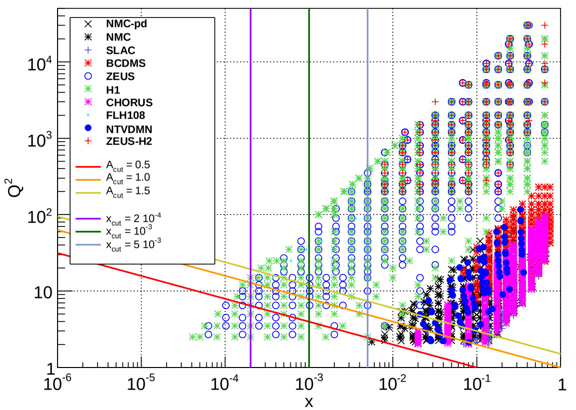
data-th. distance



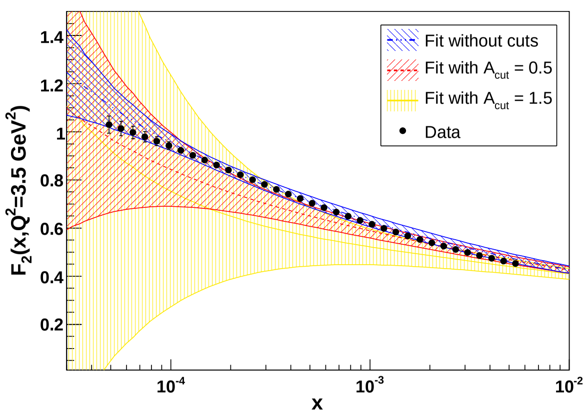
BEYOND FIXED ORDER?

IS THERE EVIDENCE FOR DEVIATION FROM FIXED–ORDER EVOLUTION IN THE DATA?
CUT PDF FITS, THE IDEA: EVOLVE BACKWARDS INTO LOW x, Q^2 REGION
CHECK WHETHER DATA DEVIATE FROM EVOLVED SOLUTION:

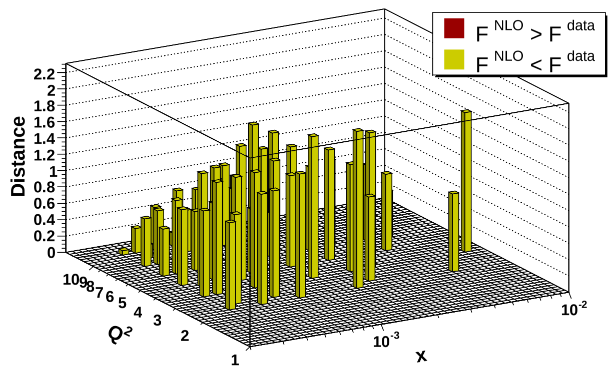
the cut



the effect on F_2



data-th. distance



YES! (Caola, s.f., 2009)

- DATA AT LOW x AND Q^2 SHOW LESS EVOLUTION THAN PREDICTED BY NLO DGLAP
- NNLO WOULD MAKE THIGS WORSE, WHILE RESUMMATION MIGHT EXPLAIN THE EFFECT
- THIS MAY BIAS DOWNWARDS NNLO α_s FROM SCALING VIOLATION

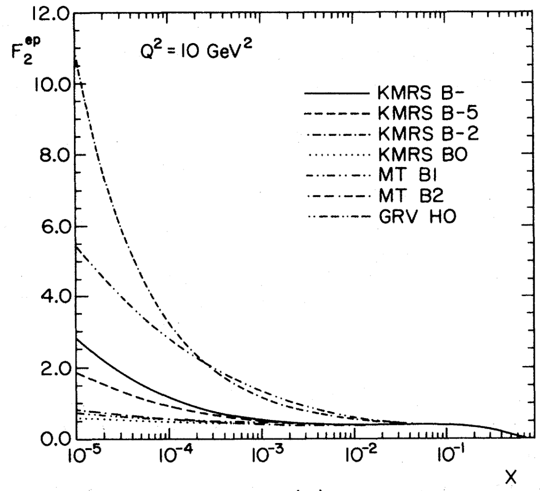
FURTHER PROGRESS?

- HERA II VERY PRECISE COMBINATION DATA
- LHEC!

WHAT'S BEHIND THE CORNER?

YESTERDAY

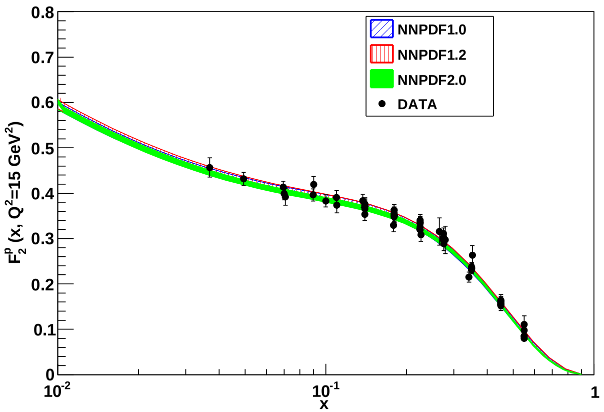
F_2 JUST BEFORE THE HERA START (1991)



(a)

TODAY

F_2 AND PDF UNCERTAINTIES

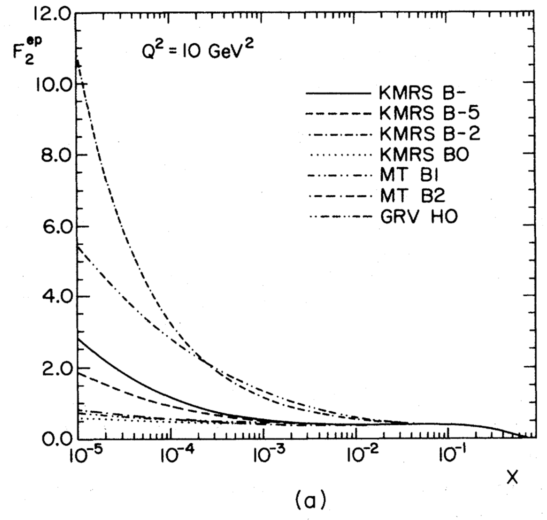


- PERTURBATIVE QCD IS READY FOR PRECISION PHYSICS

WHAT'S BEHIND THE CORNER?

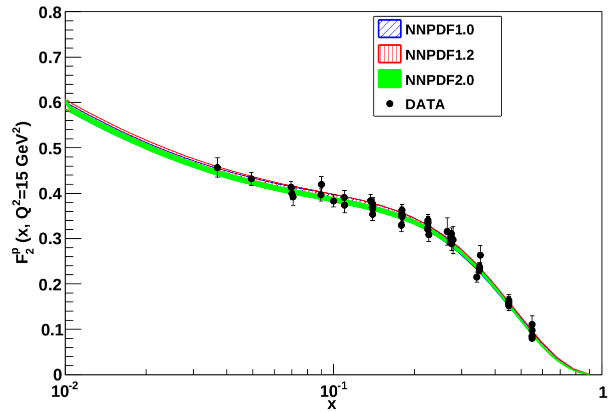
YESTERDAY

F_2 JUST BEFORE THE HERA START (1991)



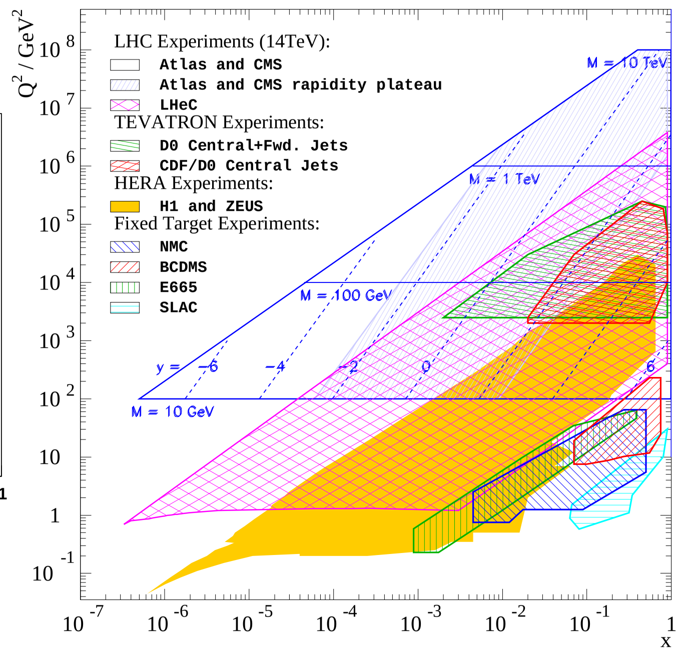
TODAY

F_2 AND PDF UNCERTAINTIES



TOMORROW

THE LHC AND LHEC KINEMATICS



- PERTURBATIVE QCD IS READY FOR PRECISION PHYSICS
- WHAT LIES BEYOND?
  - WE ARE READY TO DISCOVER NEW PHYSICS AT THE LHC
  - WE WILL LIKELY NEED AN LHEC TO STRETCH THE LIMITS OF QCD & EXPLOIT FULLY THE DISCOVERY POTENTIAL OF LHC

CONCLUSION

THIS IS JUST THE BEGINNING!