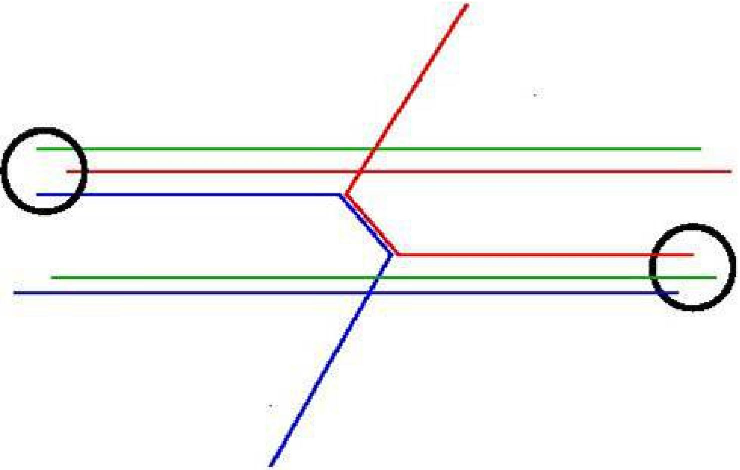
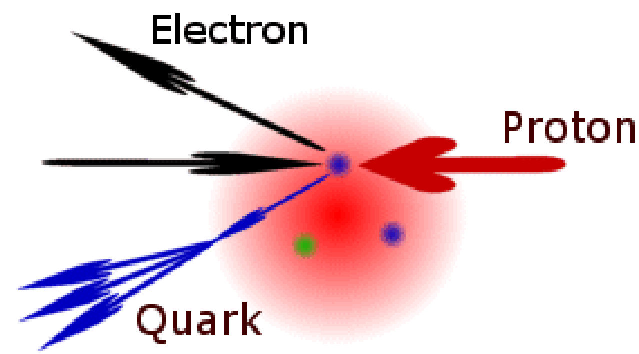
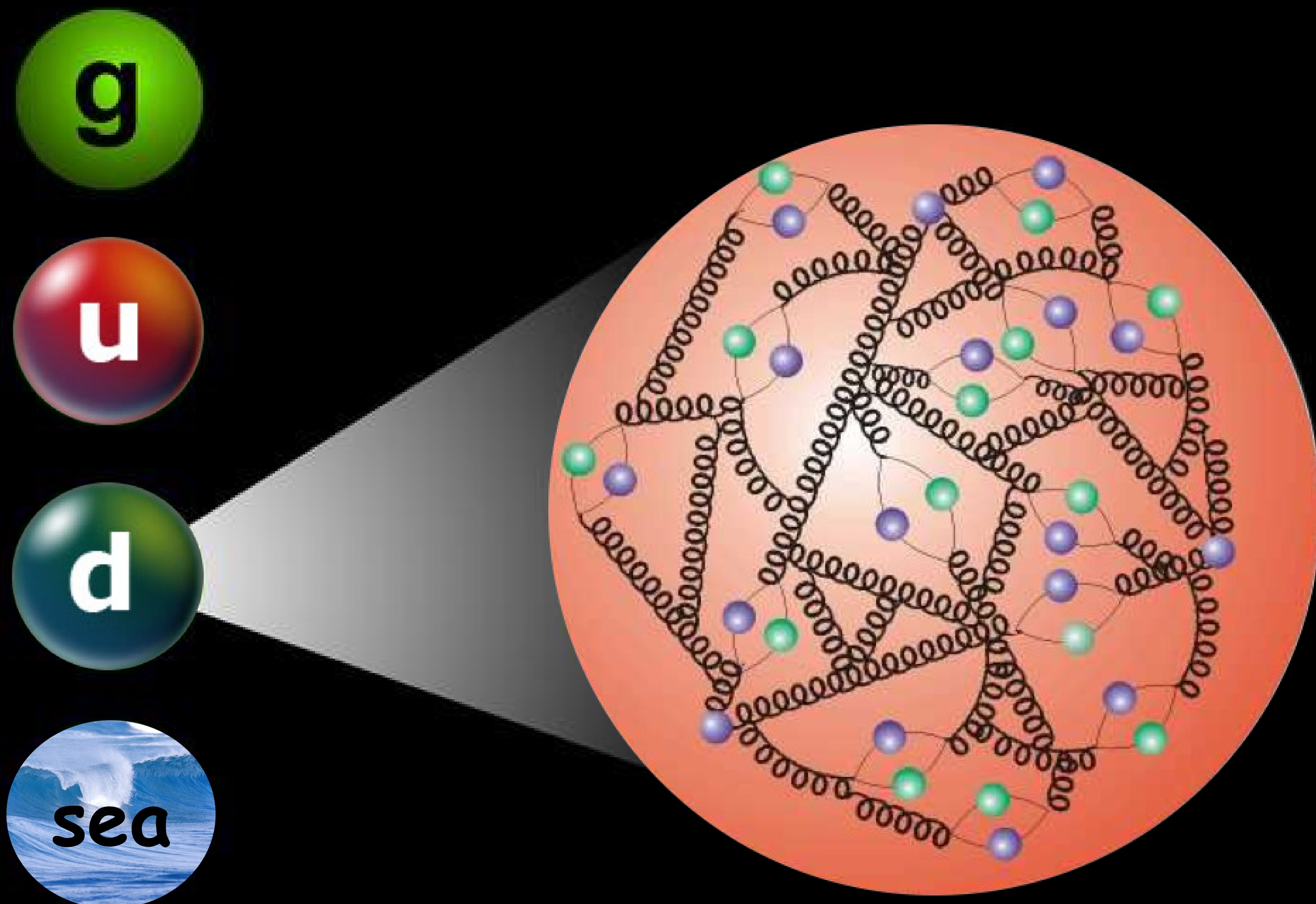




All you want to know about proton structure … but are afraid to ask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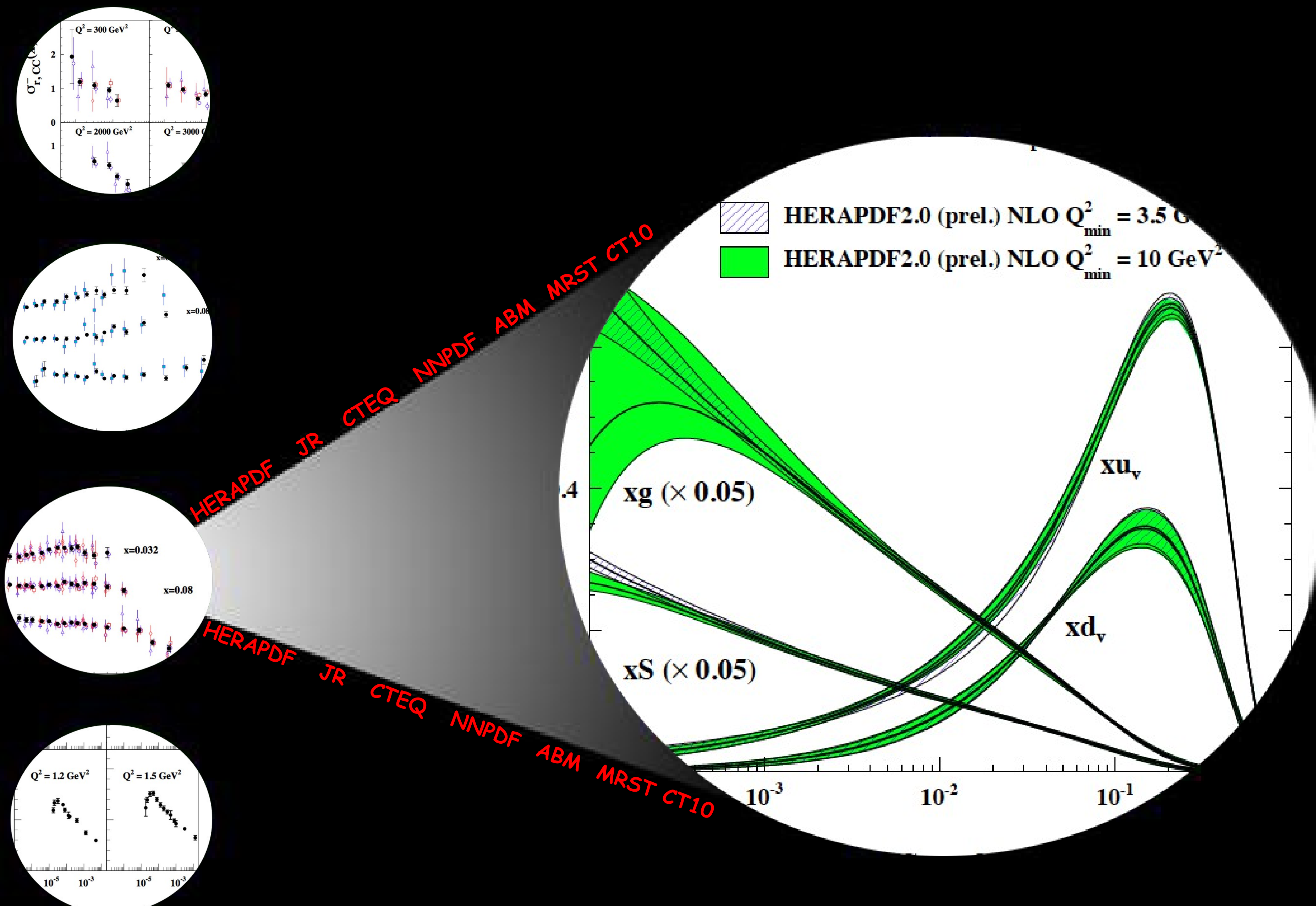


Q^2 = 300 GeV^2
Q^2 = 2000 GeV^2
x=0.032
x=0.08
Q^2 = 1.2 GeV^2
Q^2 = 1.5 GeV^2
HERAPDF JR CTEQ NNPDF ABM MRST CT10
HERAPDF JR CTEQ NNPDF ABM MRST CT10
HERAPDF2.0 (prel.) NLO Q^2_{min} = 10 GeV^2
xg (× 0.05)
xS (× 0.05)
xu_v
xd_v
10^{-3}
10^{-2}
10^{-1}

Global analysis of parton distributions

Goal: determination of the ***input distributions*** (for light quarks and gluons):

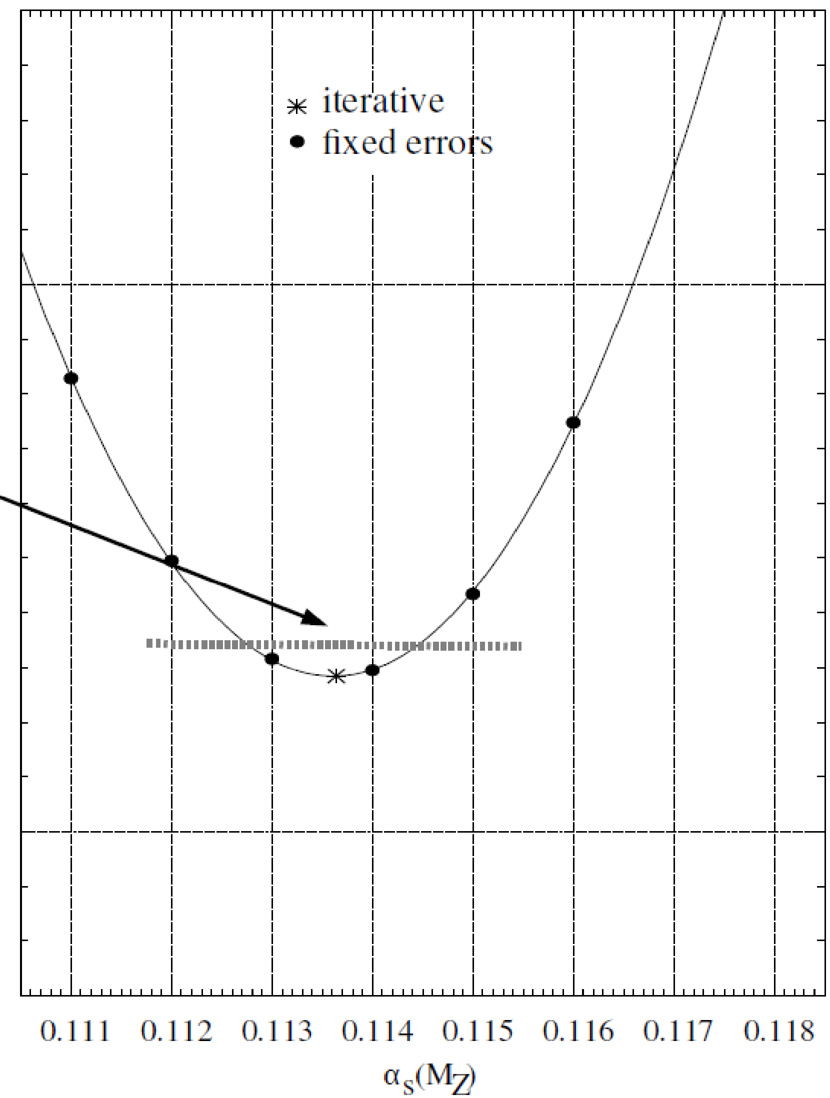
Method: Parametrizations $xf(x,Q_0^2) = Nx^a(1-x)^b \,\text{function}(x)$
and usual *statistical estimation* (fits):

$$\chi^2(p) = \sum_{i=1}^{N} \left(\frac{\text{data}(i) - \text{theory}(i,p)}{\text{error}(i)} \right)^2$$

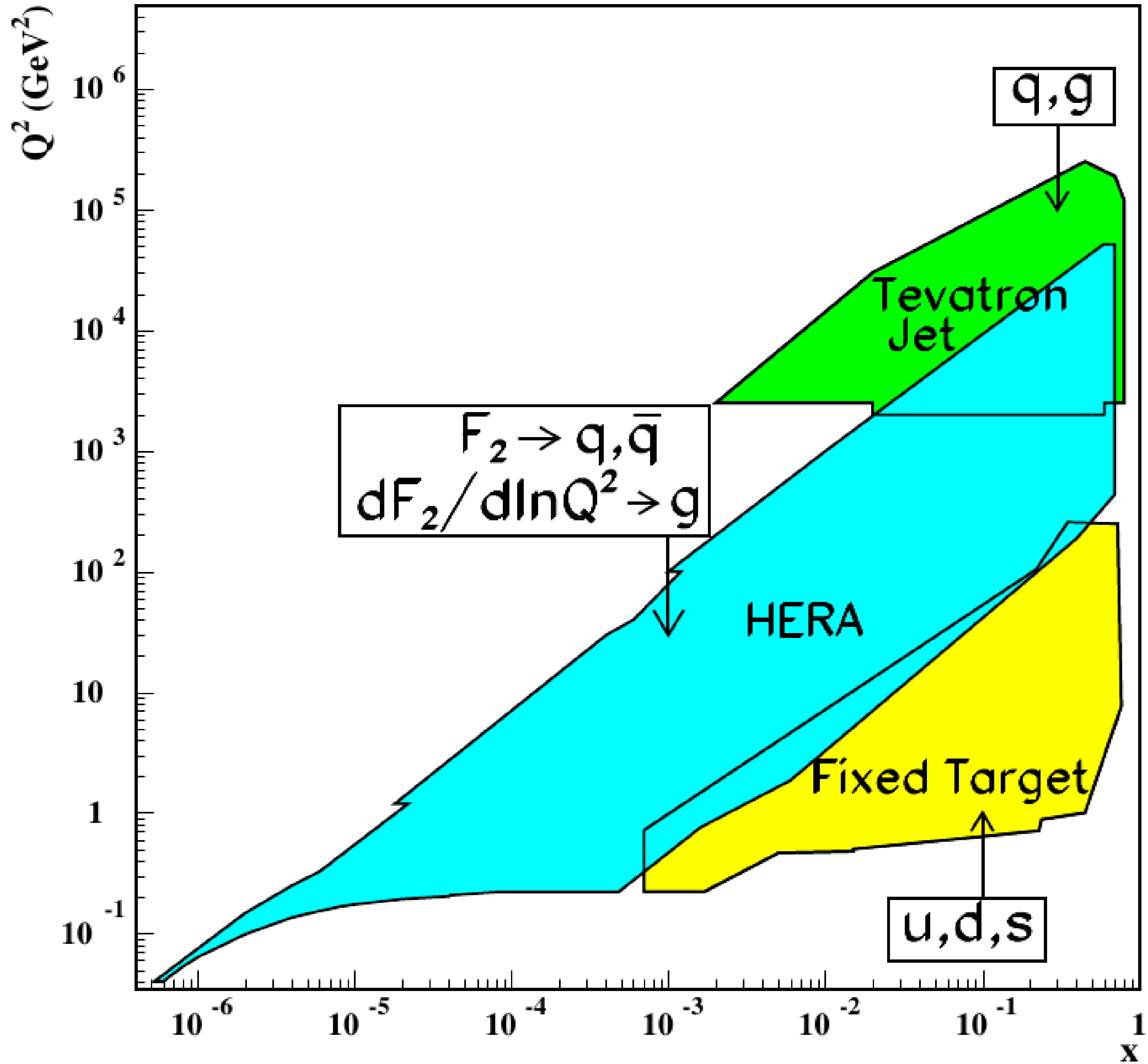
Position of minimum gives the value and curvature gives the error (region within a certain “tolerance” $\Delta\chi^2 = 1$)

(Monte Carlo methods can also be used)

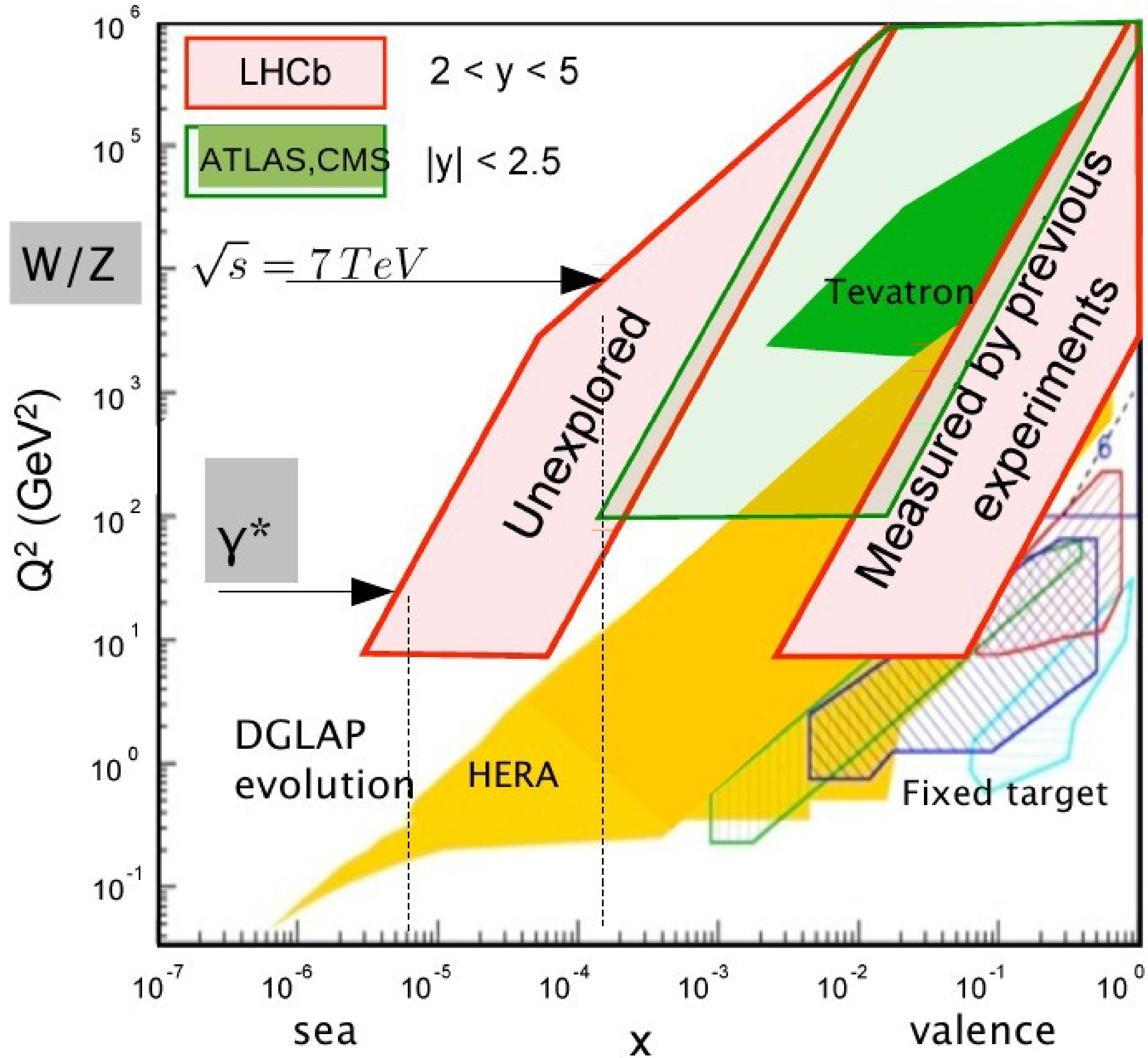
Usually the chi-square definition is more sophisticated, experimental correlations are also treated, etc.



Data for parton distributions: preLHC



Now we go from predicting LHC measurements to using them for constraining parton distributions



Current global PDF groups

ABM: Careful treatment of experimental correlations, nuclear and power corrections in DIS, FFNS NEW! ABM12 arXiv:1310.3059

MSTW: negative input gluons at small-x, rather "large" $\alpha_s(M_Z^2)$, GMVNS Update expected soon

NEW! HERAPDF2.0 (prel.)

HERAPDF: Only HERA data, less negative gluons, GMVFS

NNPDF: neural-network parametrization, Monte Carlo approach for error propagation, GMVFNS NEW! NNPDF3.0 see M. Ubiali talk

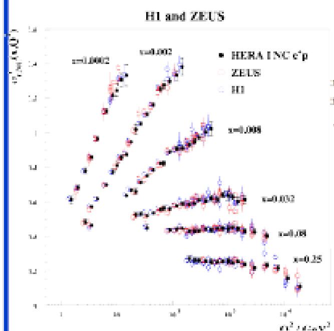
CTEQ-TEA: parametrization with exponentials, substantially inflated uncertainties, GMVFNS Constrains and impact on LHC results

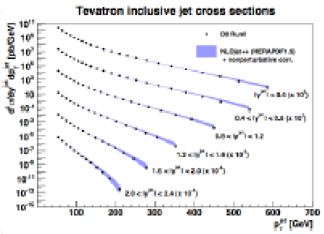
JR [with E. Reya]: detailed study of input scale dependence, dynamical (and "standard") versions, FFNS NEW! JR14 arXiv:1403.1852v

(there are more groups focused on particular aspects, e.g. CTEQ-JLab)

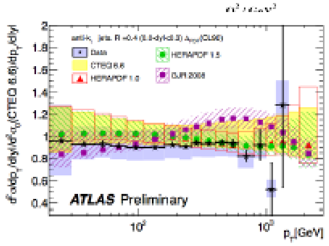
https://www.herafitter.org

experimental input





experiments:
HERA, Tevatron, LHC, fixed target



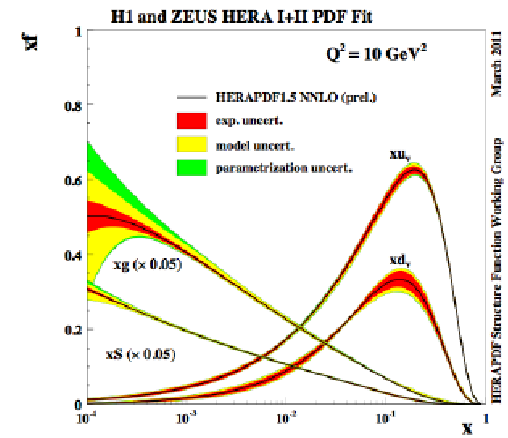
processes:
NC, CC DIS, jets, diffraction, heavy quarks (c,b,t)
Drell-Yan, W production

theoretical calculations/tools

Heavy quark schemes:	MSTW, CTEQ, ABM
Jets, W, Z production:	fastNLO, Applgrid
Top production	NNLO (Hathor)
QCD Evolution	DGLAP (QCDNUM)
	k_T factorisation
Alternative tools	NNPDF reweighting
Other models	Dipole model

+ Different error treatment models
+ Tools for data combination (HERAaverager)

HERAFitter



PDF or uPDF or DPDF

$\alpha_S(M_Z), m_c, m_b, m_t, f_s, ..$

Theory predictions

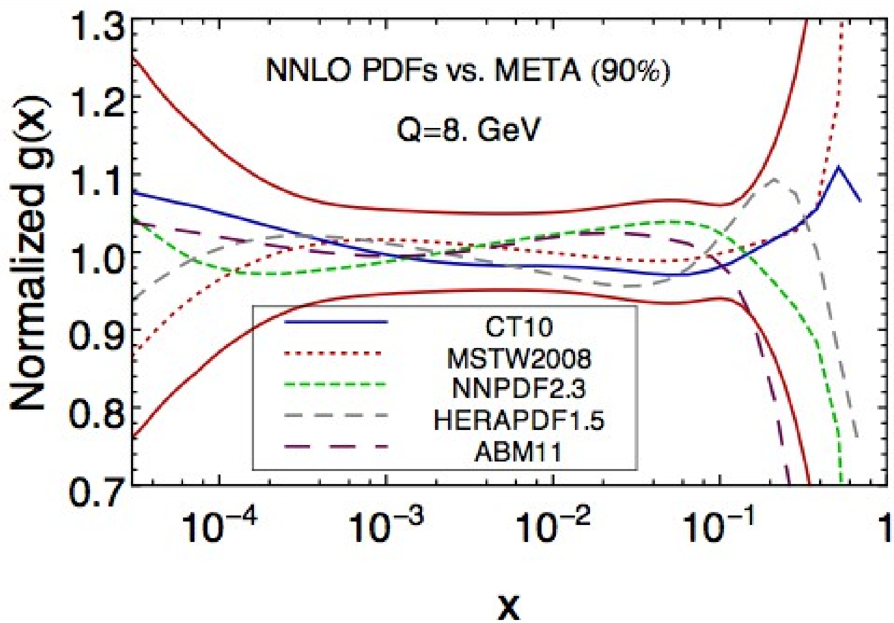
Benchmarking

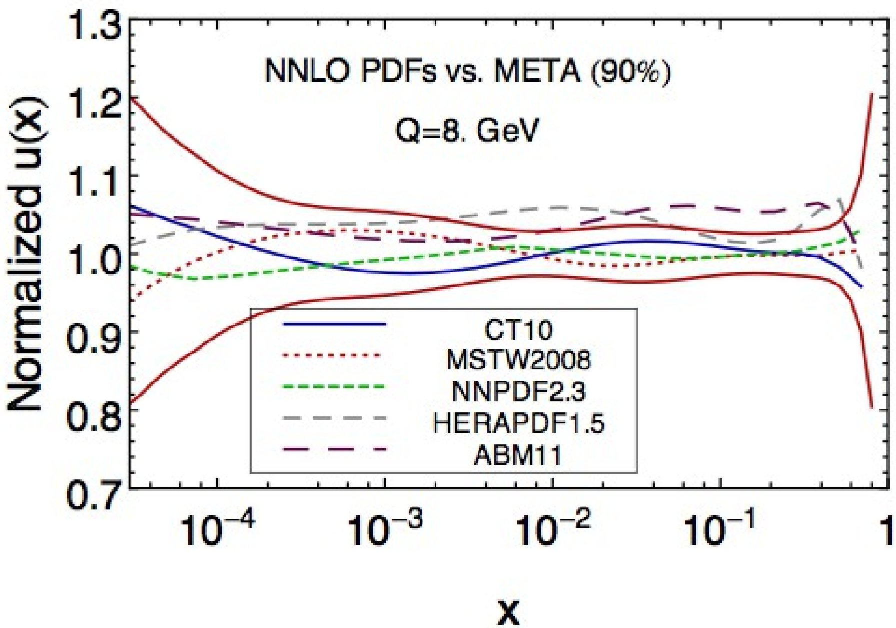
Comparison of schemes

For details see H. Priumov & M. Lisovyi talks

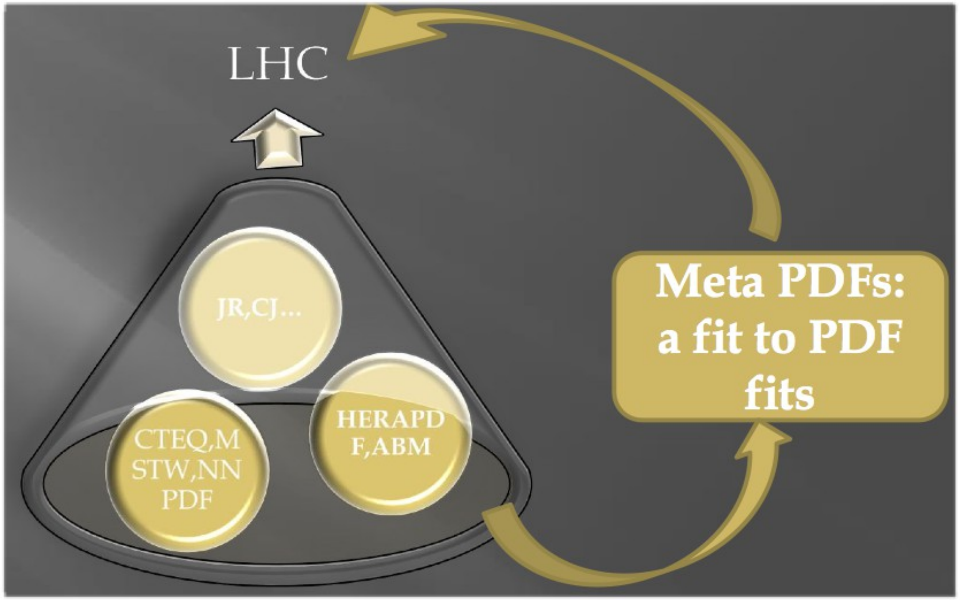
Combining various PDF sets – alternative approach: META PDFs

arXiv:1401.0013





- Alternative for PDF4LHC approach
- META PDFs serve as average of the chosen PDFs for central predictions
- Provide good estimation of total PDF uncertainties

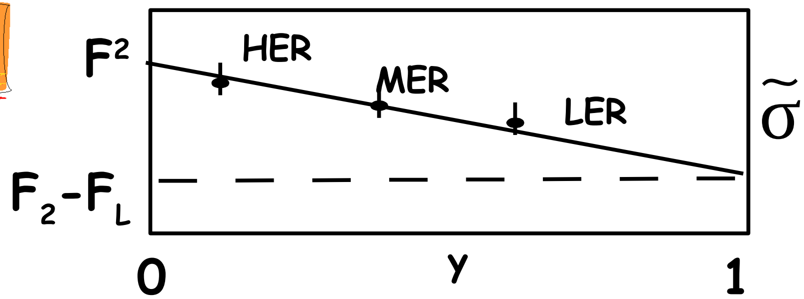


http://metapdf.hepforge.org

Moriond QCD 2014 J. Gao 6

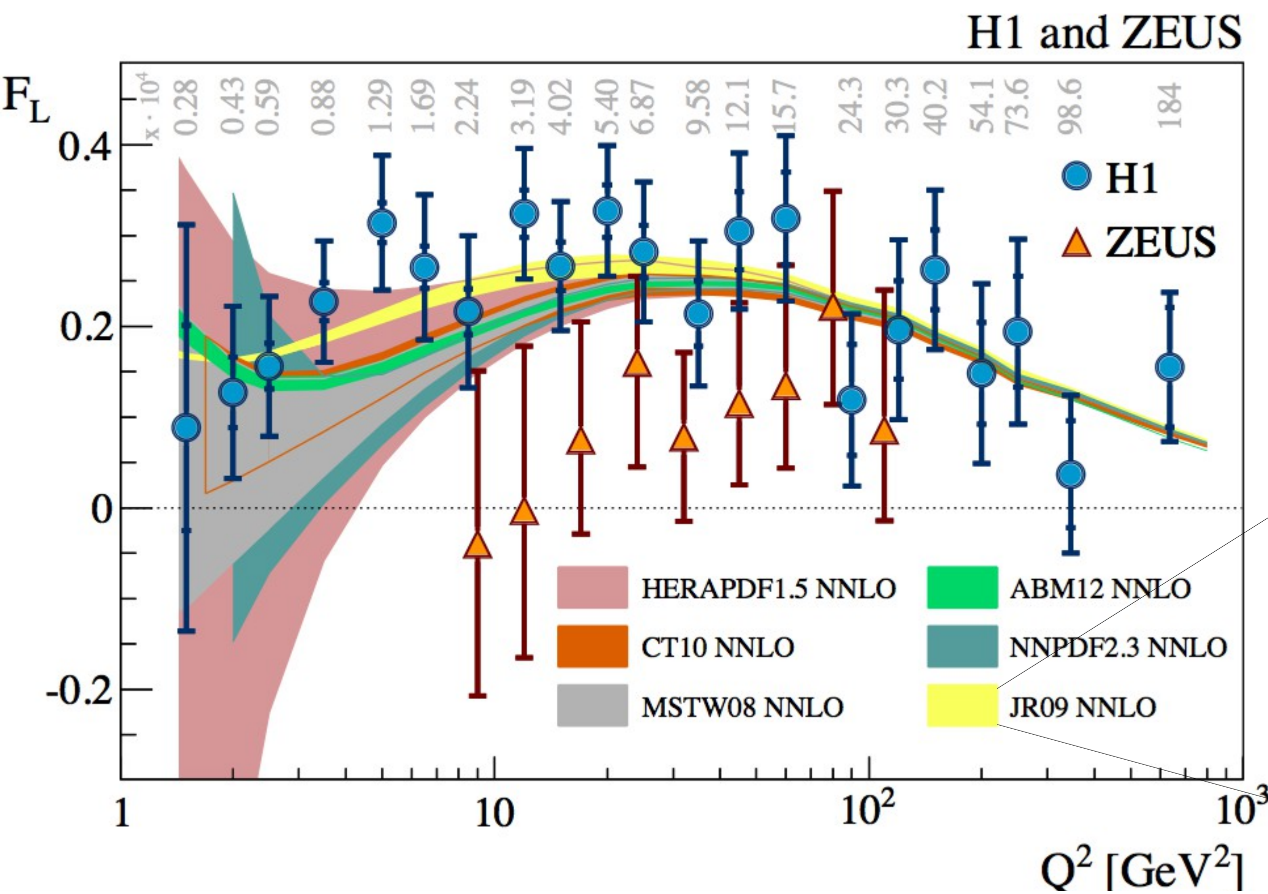
Inclusive measurements from HERA are core of every parton density extraction

$$\sigma^{\pm}_{r,\mathrm{NC}} = \frac{\mathrm{d}^2\sigma^{e^{\pm}p}_{\mathrm{NC}}}{\mathrm{d}x\mathrm{d}Q^2} \cdot \frac{Q^4 x}{2\pi\alpha^2 Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+} x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$



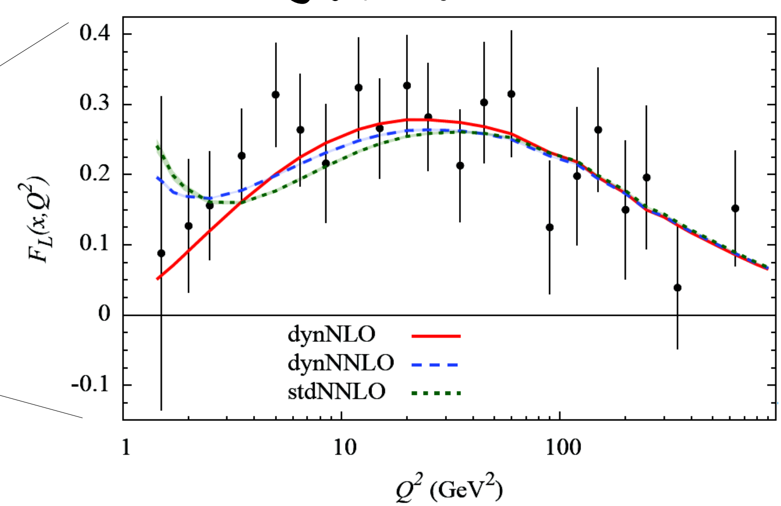
F_L structure function

- H1 & ZEUS published final F_L measurements including low-energy running data



Details in talks:
H1: S. Shushkevich
ZEUS: J. Grebenyuk

JR14

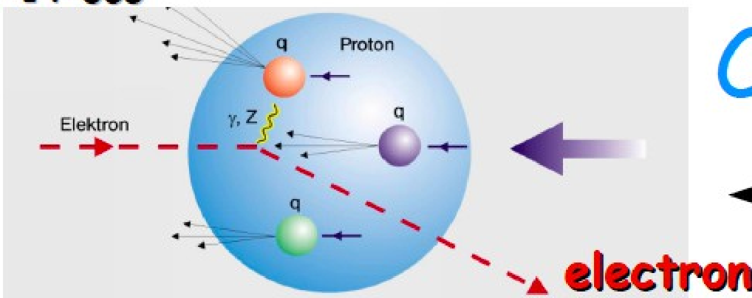


Consistent within ~ 1 sigma (sizeable point-to-point correlated uncertainties)

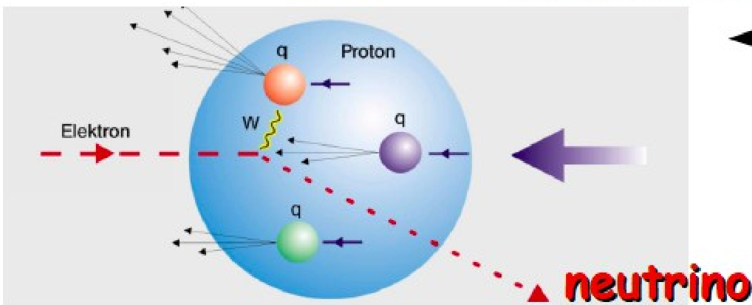
All H1 and ZEUS inclusive measurements FINAL

→ time to combine them

Combined inclusive DIS

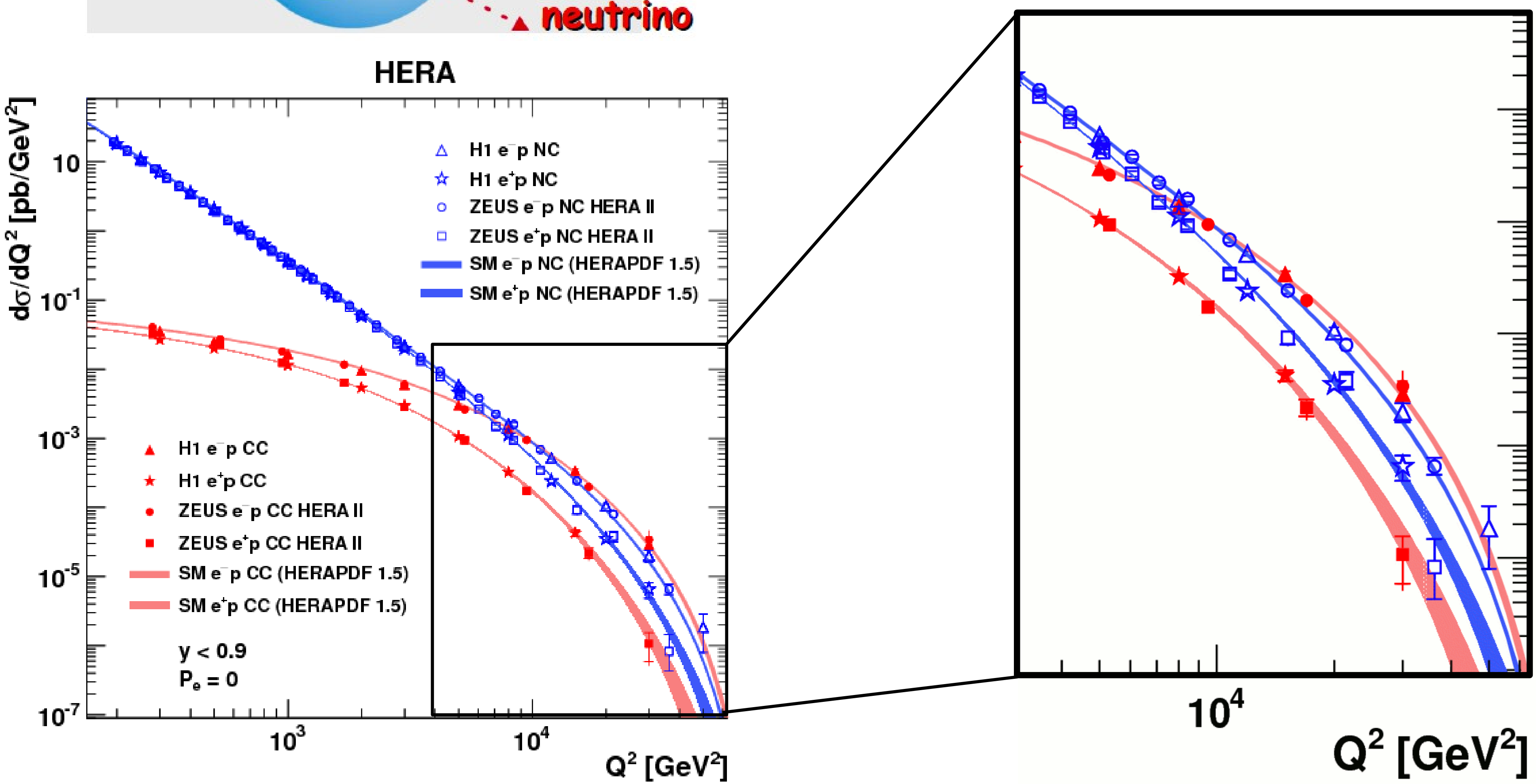


Neutral Current (NC)
γ, Z⁰ exchange



Charged Current (CC)
W± exchange

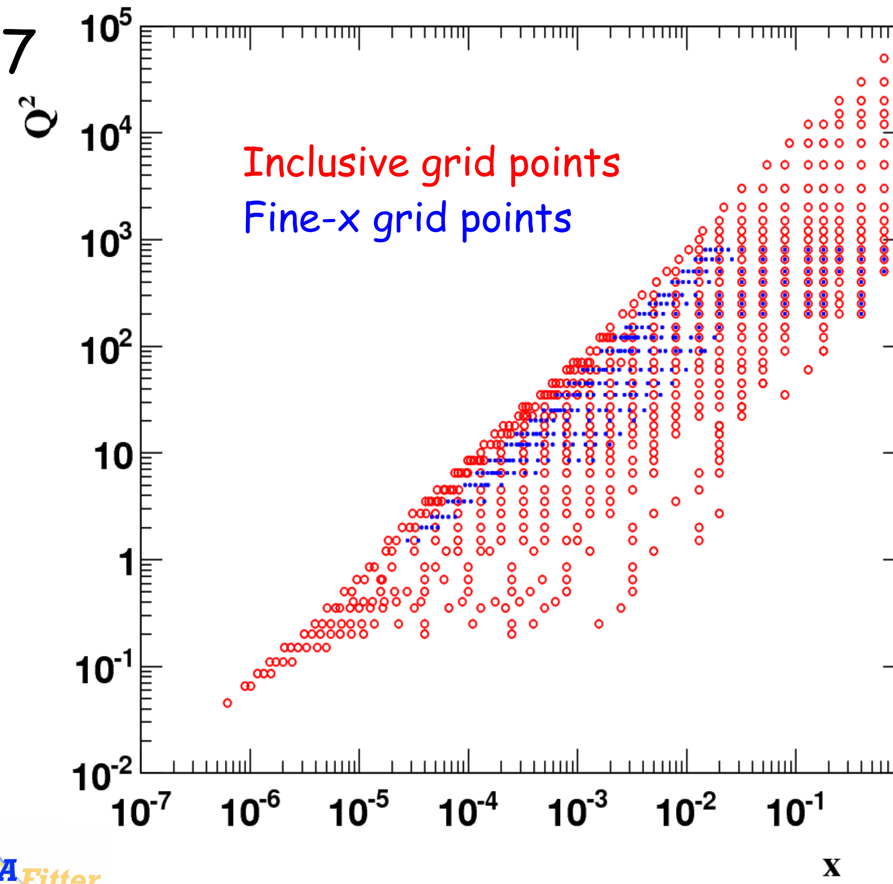
Fantastic precision of HERA final data



K. Klimek, 24.04.14, Structure functions and parton densities

Combined inclusive DIS

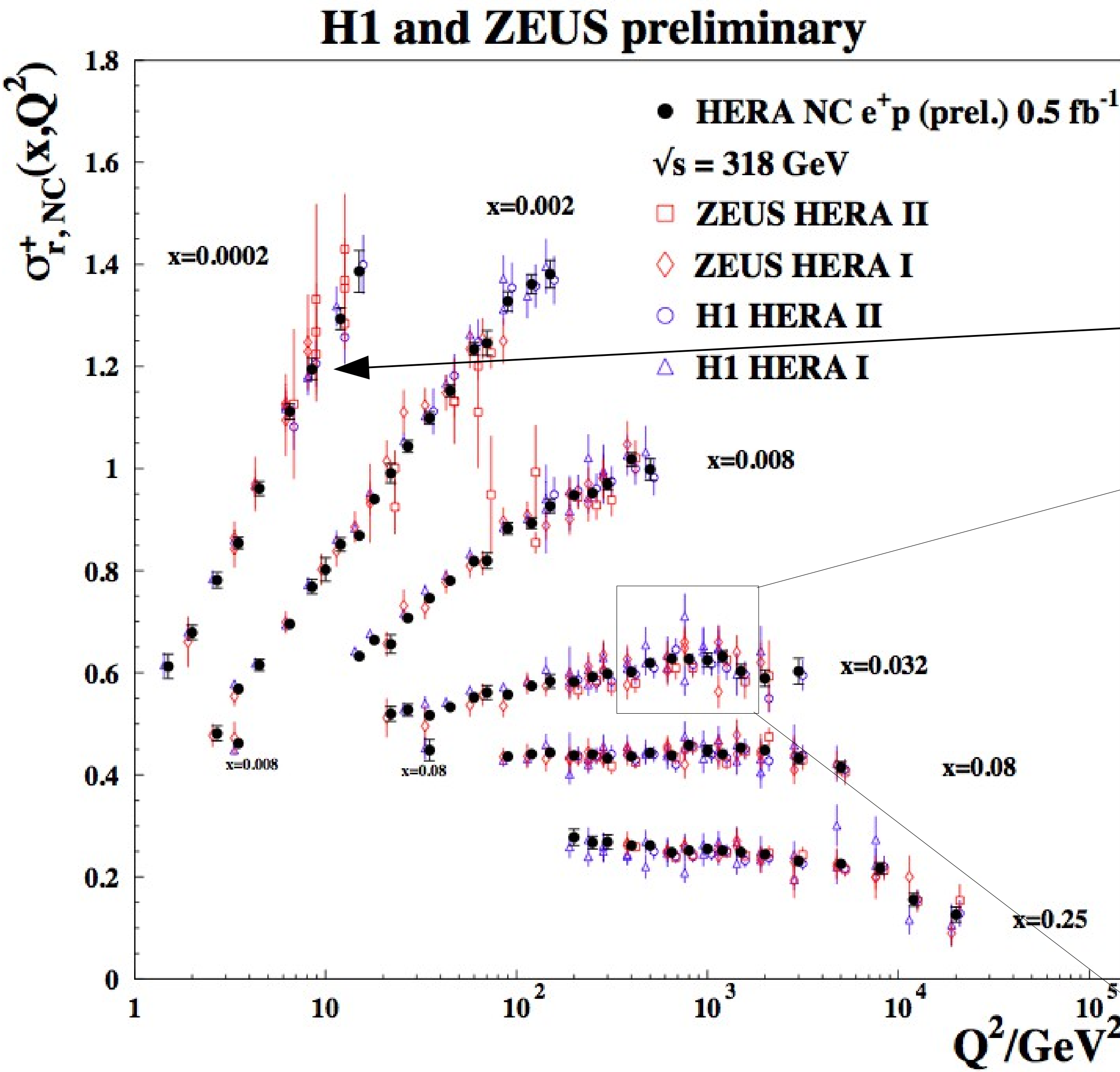
- <u>H1 and ZEUS published all HERA inclusive DIS measurements – 1 fb^{-1}</u>
- **Now we combine these measurements**
- 2927 data points combined into 1307
  - $0.045 < Q^2 < 50000$ GeV^2
  - $6\times10^{-07} < x < 0.65$
- Low energy running data included

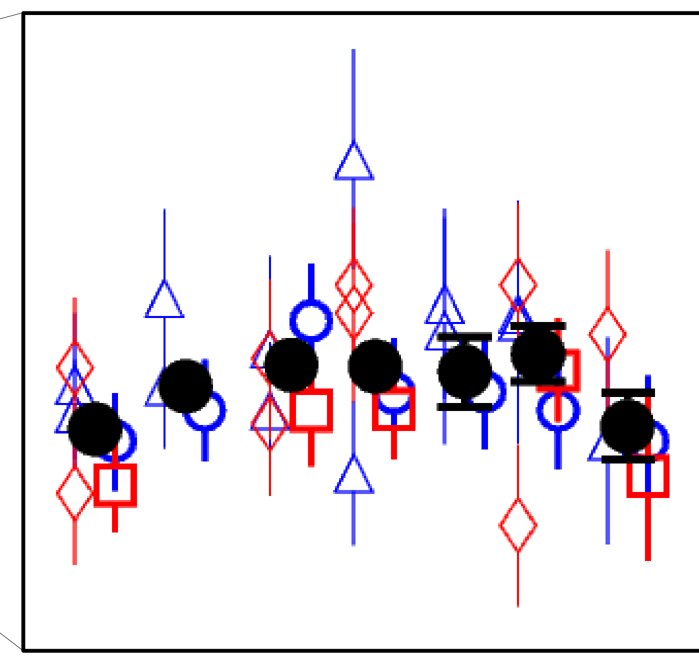


- HERAverager & HERAFitter used
  - Swimming done using our own full data

Impressive amount of data points combined

For details see O. Turkot talk

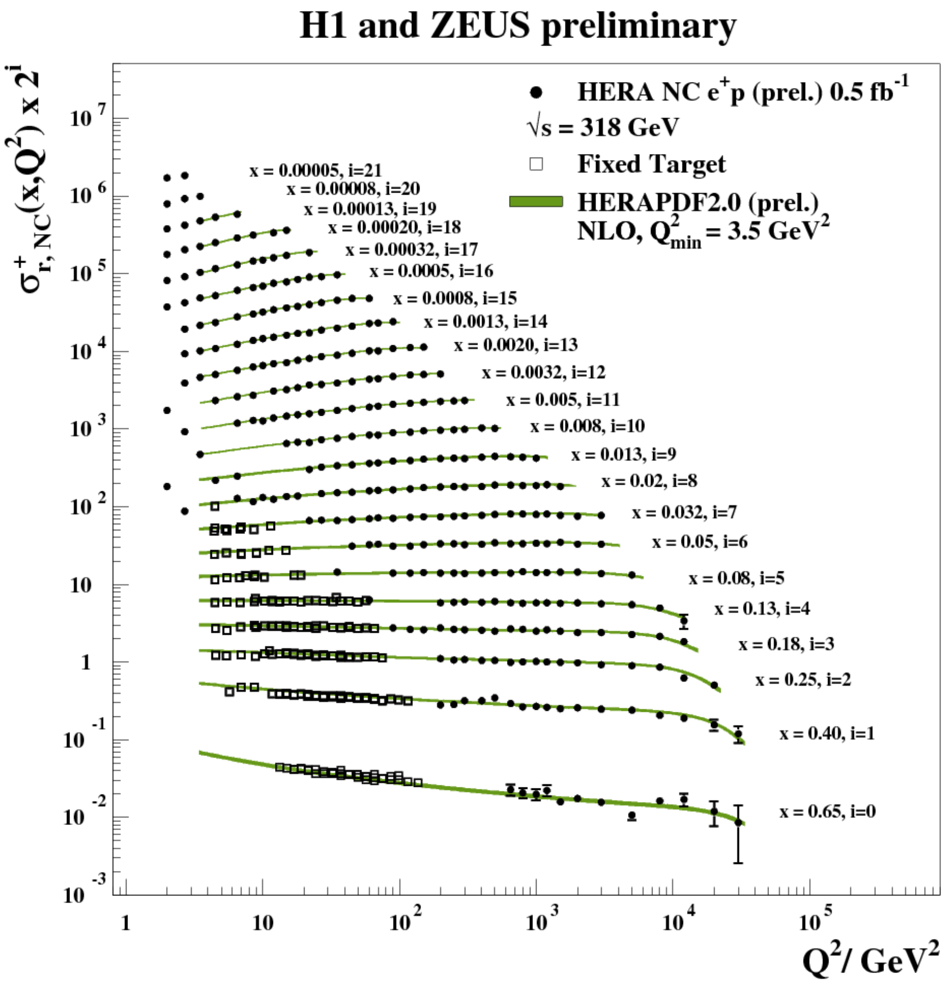


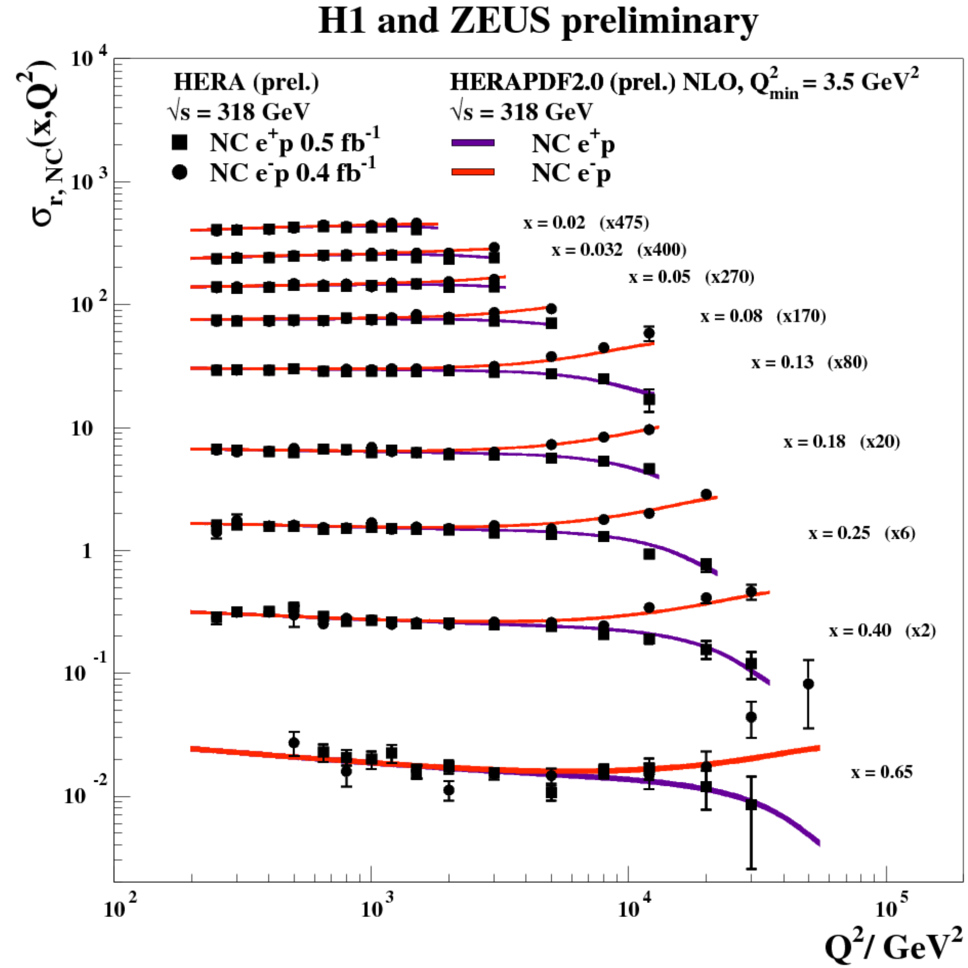


- 2927 data points combined to 1307
- 162 correlated systematic uncertainties
- Up to 6-8 data points combined to 1

Good consistency: χ^2/dof = 1685/1620

QCD scaling and EW effects beautifully seen

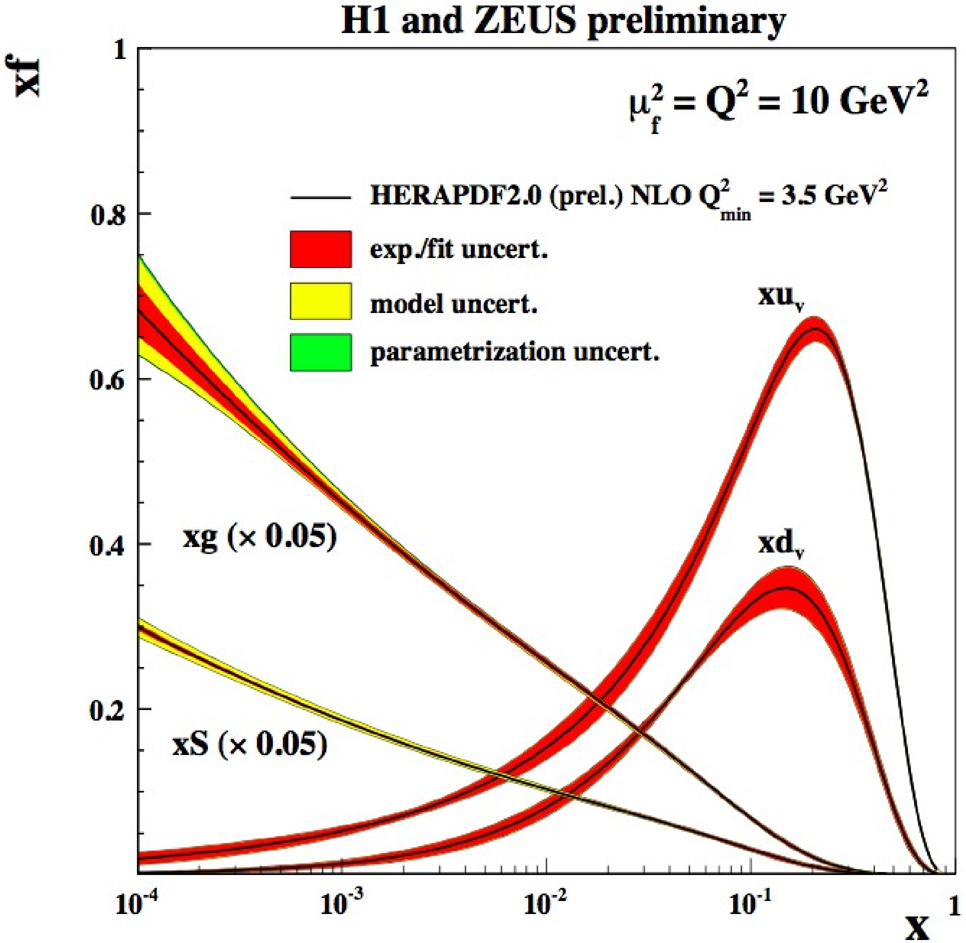




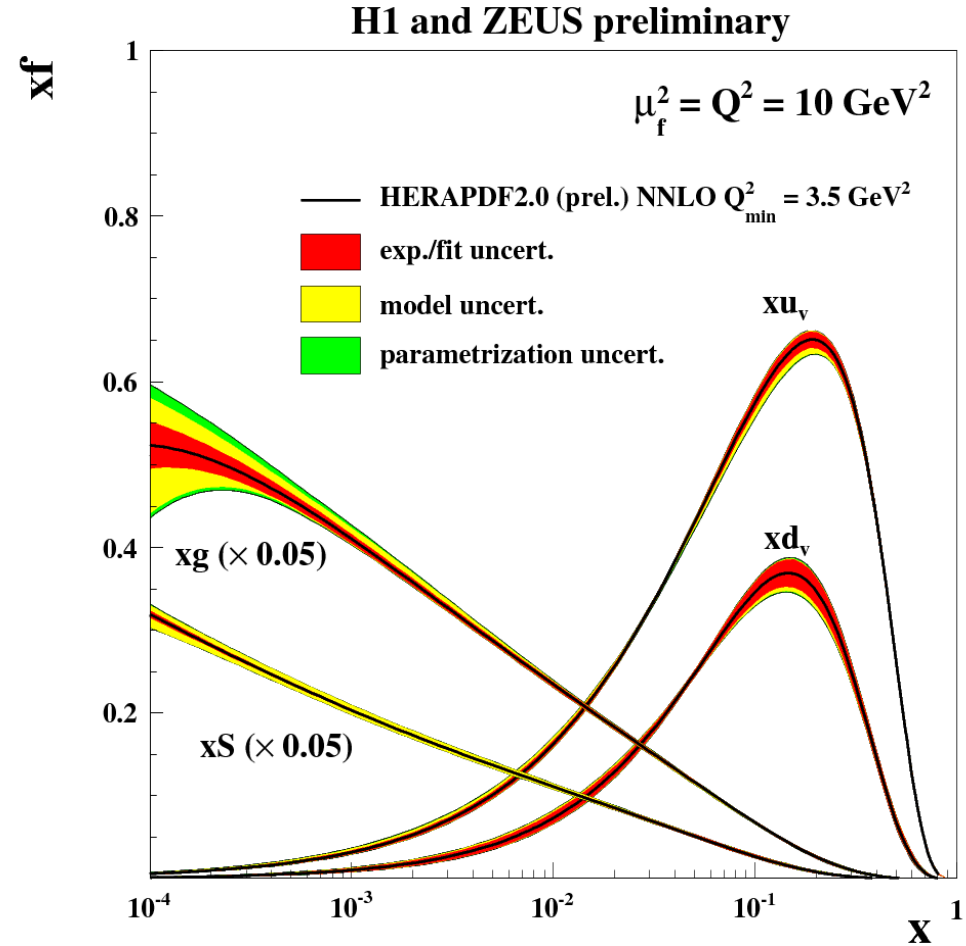
This data (exclusively!) used as input to global QCD fit HERAPDF2.0 (prel.)

NLO & NNLO parton densities

NLO



NNLO

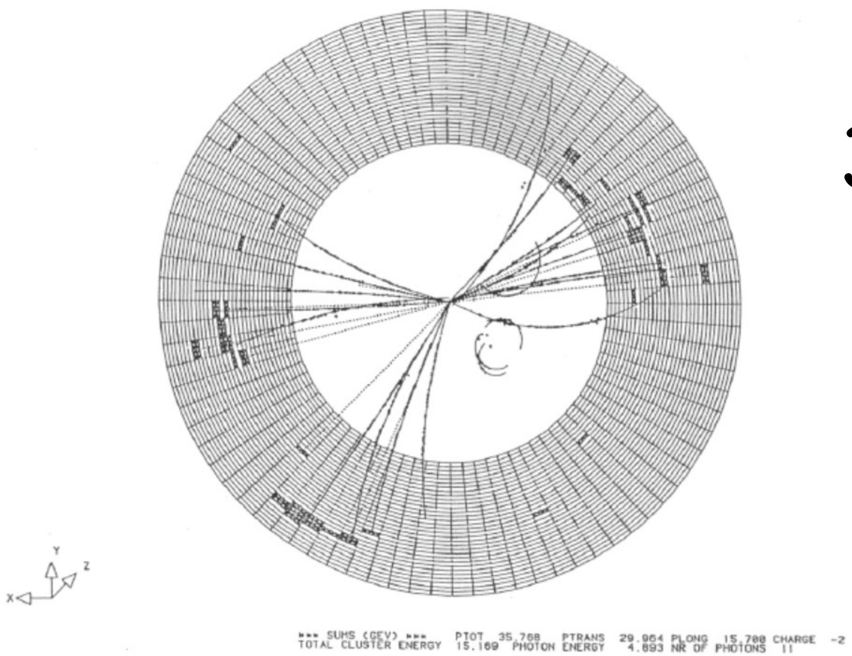


For details see V. Radescu talk

HERAPDF2.0 (prel.) extracted

with experimental, model and parametrization uncertainties

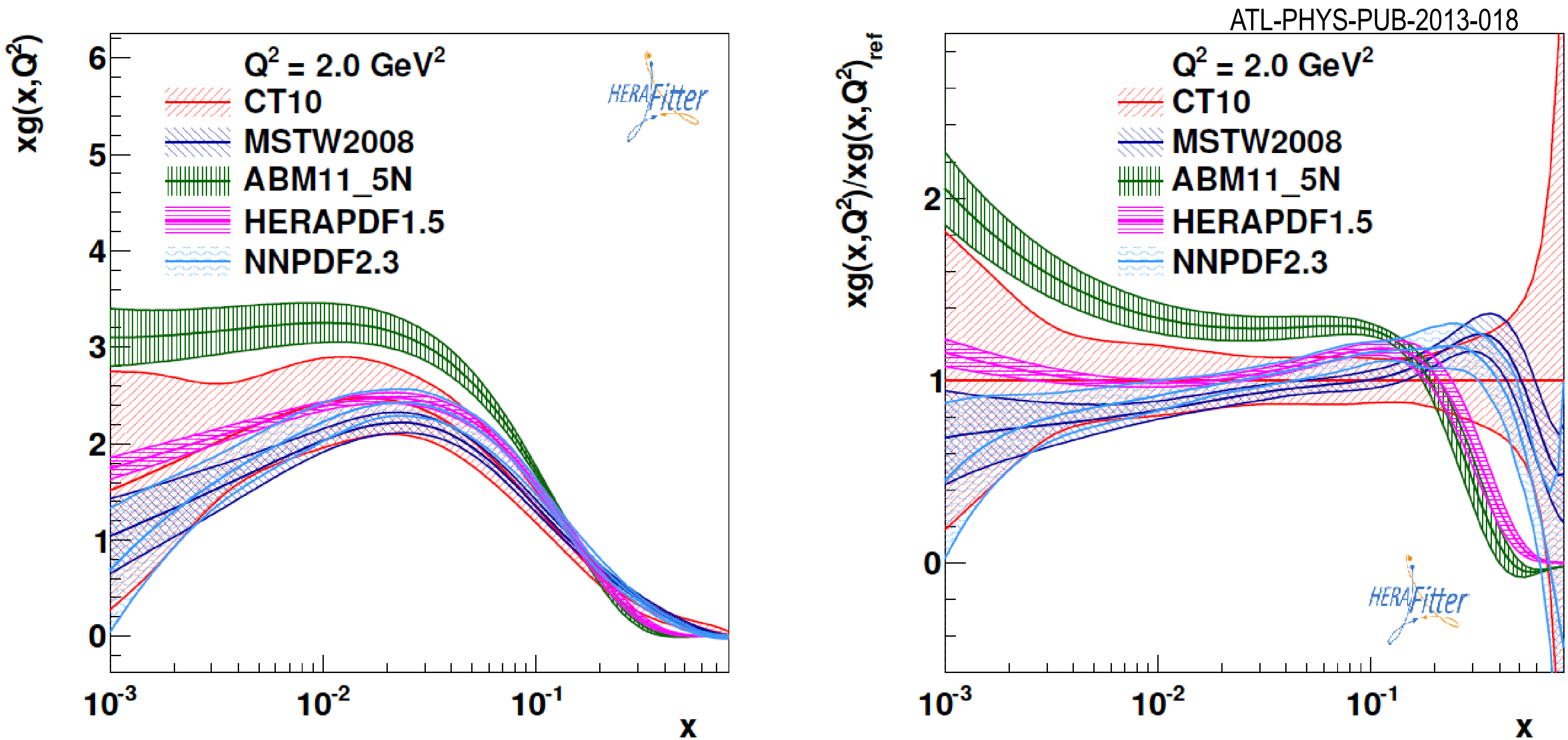
35th anniversary of GLUON



- PETRA, 1979

Life starts after 35

- Gluon PDF at large x → significant uncertainties for LHC important processes
- Gluons from different PDF groups differ outside PDF uncertainties

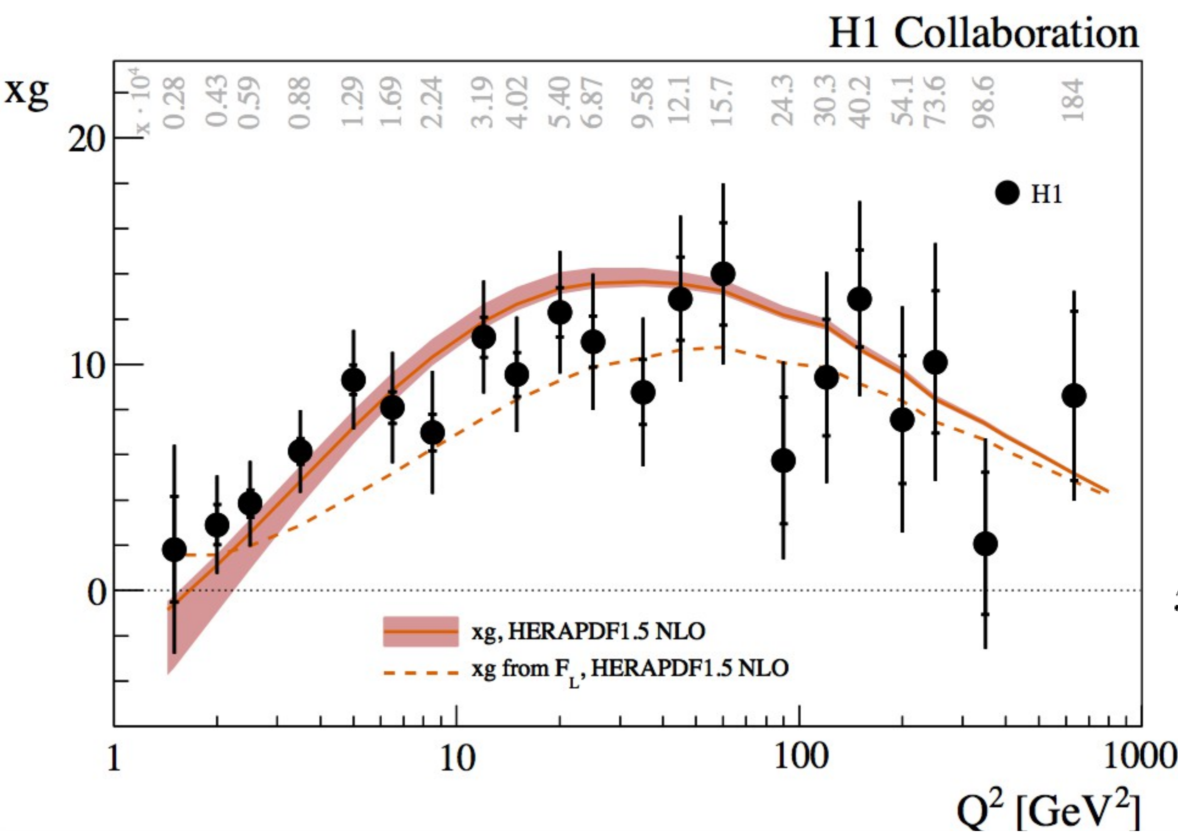


Gluon needs to be better constraint

- (In)direct constrains
  - scaling violation, collider jet data, prompt photon data, total ttbar cross sections

Gluon meets F_L

- H1 performed direct extraction of gluon density from F_L measurement @NLO

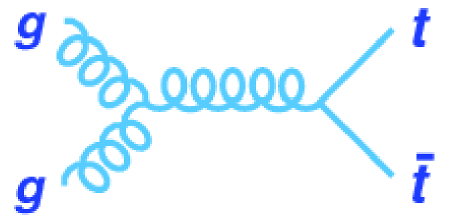


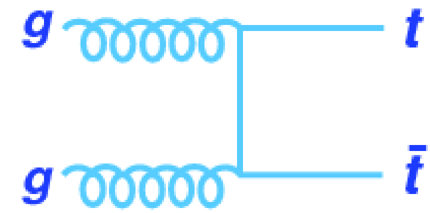
- Direct extraction of gluon density from F_L using approximation

$$xg(x, Q^2) \approx 1.77 \frac{3\pi}{2\alpha_S(Q^2)} F_L(ax, Q^2)$$

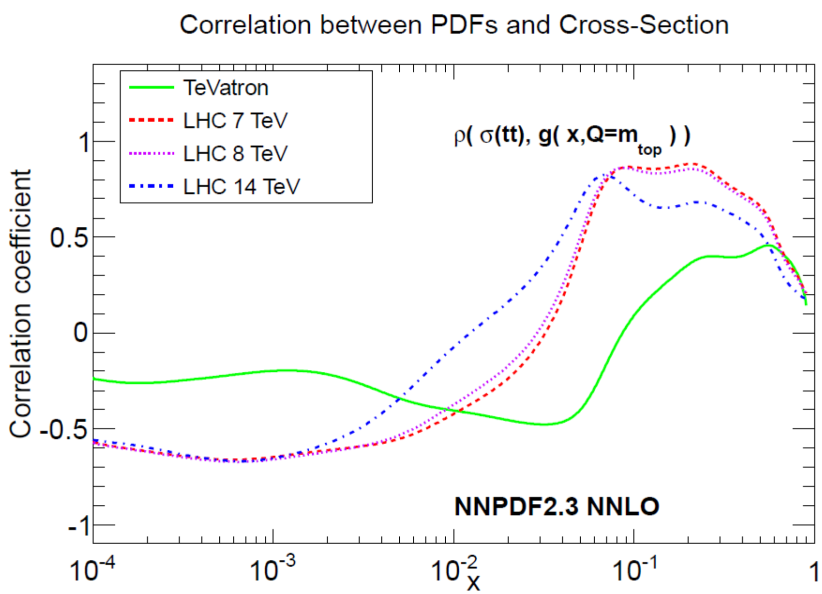
Gluon approximated from F_L agrees with gluon determined from scaling violations

Gluon meets top quark





- Directly sensitive to large-x gluon PDF
- Recently computed in full NNLO QCD
  - For running and pole top mass



Measurement	total (pb)
Tevatron CDF+D0	7.65 ± 0.42 (5.5%)
Atlas 7 TeV	177^{+10}_{-11} $(^{+5.6\%}_{-6.2\%})$
CMS 7 TeV	160.9 ± 6.6 (4.0%)
Atlas 8 TeV	241 ± 32 (13.0%)
CMS 8 TeV	227 ± 15 (6.7%)

JR14: pole mass 173 GeV²

at $\sqrt{s} = 7$ TeV

$$\sigma^{\rm dyn}_{t\bar{t}} = 143.2^{+5.4}_{-5.8} \pm 2.4\,{\rm pb}$$
$$\sigma^{\rm std}_{t\bar{t}} = 154.1^{+6.1}_{-6.5} \pm 3.0\,{\rm pb}$$

TeVatron

$$\sigma^{\rm dyn}_{t\bar{t}} = 7.07^{+0.22}_{-0.19} \pm 0.06\,{\rm pb}$$
$$\sigma^{\rm std}_{t\bar{t}} = 7.37^{+0.25}_{-0.21} \pm 0.07\,{\rm pb}$$

arXiv:1403.1852v

ABM12: top data INCLUDED in fit, m_t FITTED

Pole mass 171GeV²	Running mass 162GeV²
$143.0\ ^{+5.6}_{-8.8}\ ^{+6.5}_{-6.5}$	$150.2\ ^{+0.1}_{-4.6}\ ^{+6.1}_{-6.1}$
$209.1\ ^{+7.9}_{-12.6}\ ^{+8.7}_{-8.7}$	$219.3\ ^{+0.1}_{-6.6}\ ^{+8.2}_{-8.2}$

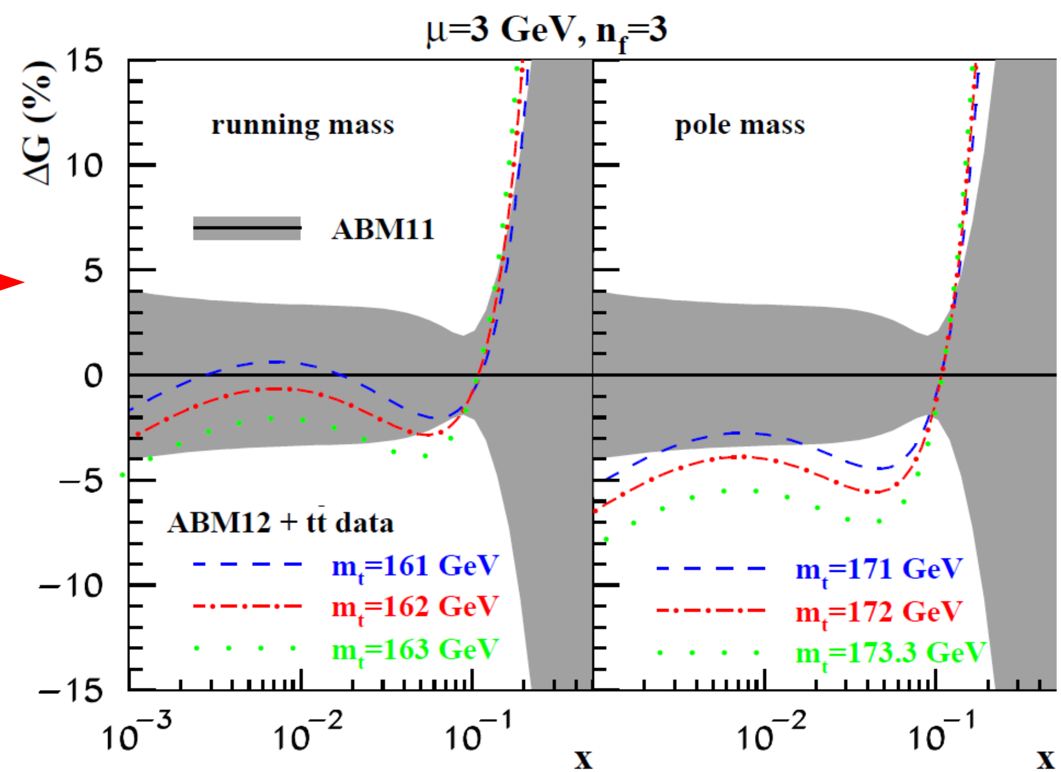
arXiv:1310.3059

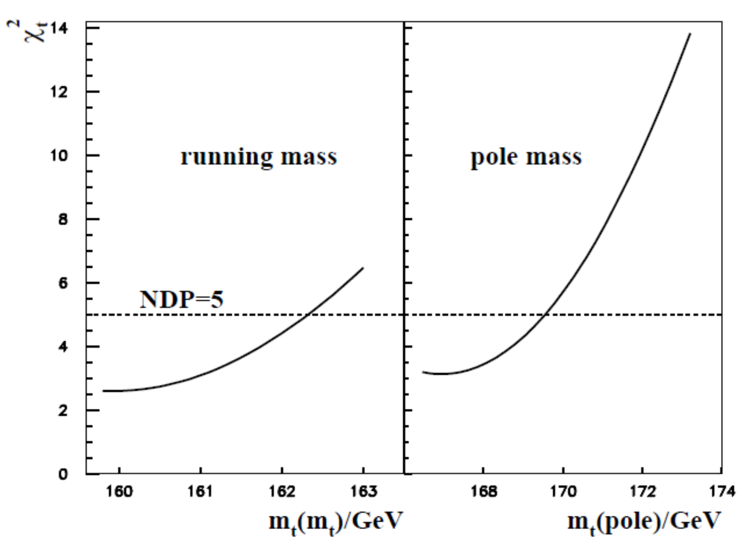
ABM12 meets top quark

- ABM12 added combined tt cross sections from LHC and Tevatron to test impact on
  - gluon PDF
  - strong coupling α_s
  - value and scheme choice for m_t

$$m_t(m_t) = 162.3 \pm 2.3 \text{ GeV}$$

$$m_t(\text{pole}) = 171.2 \pm 2.4 \text{ GeV}$$

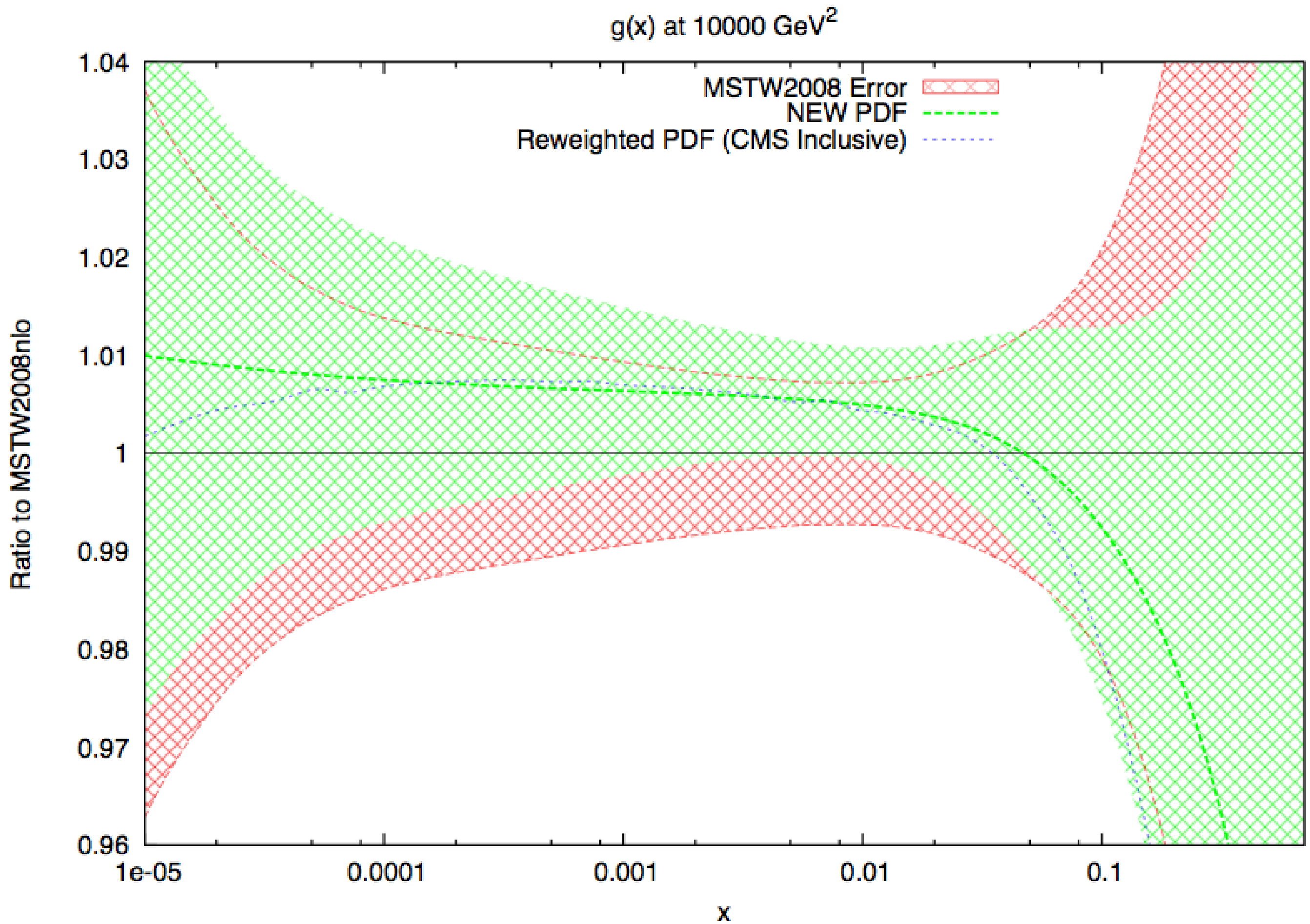




stability of ABM analysis
provided all correlations are accounted for

Gluon meets LHC jets

- LHC jet data included directly in the framework of MSTW PDF
  - highest precision inclusive jet cross sections from ATLAS and CMS
- Good agreement between ATLAS and CMS data sets
- Good agreement with reweighting method



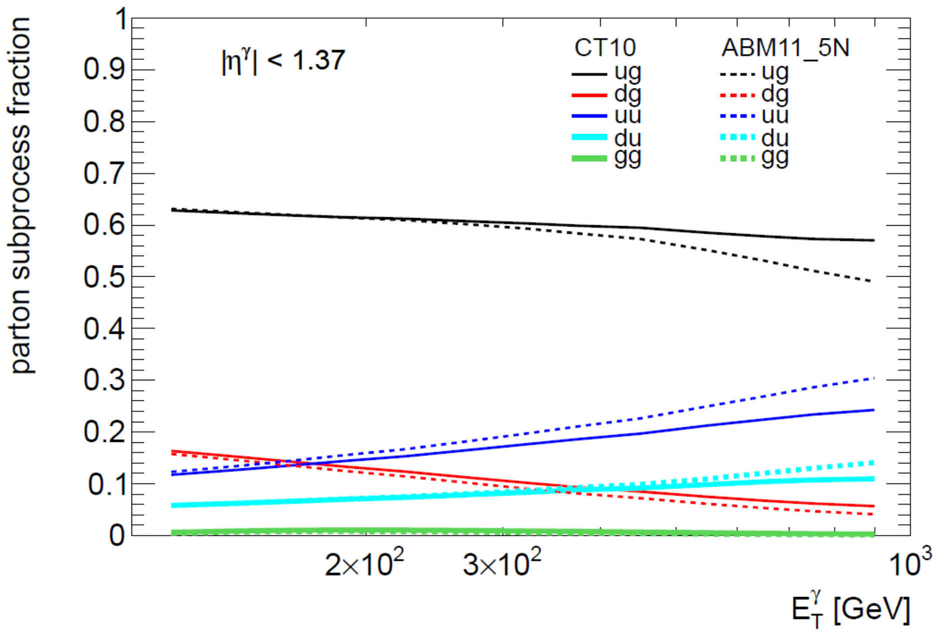
For details see R. Thorne

ATLAS EXPERIMENT

ATL-PHYS-PUB-2013-018

Gluon meets prompt photons

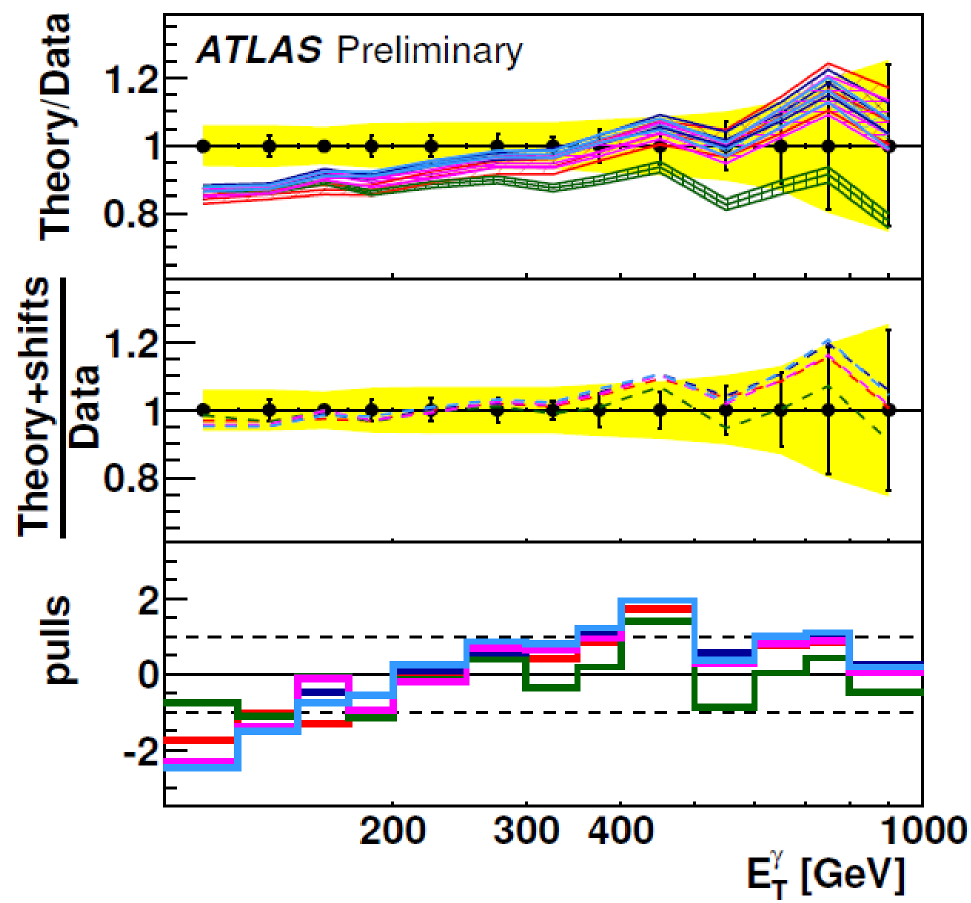
- Prompt γ data help constrain gluon



- At intermediate E_T - most precise data - scale uncertainty dominant

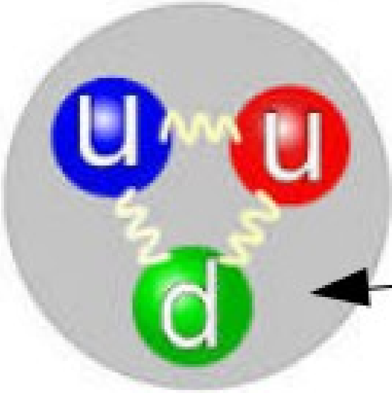
NNLO calculations necessary to fully exploit this measurement

- Asses data sensitivity to PDF using HERAFitter platform

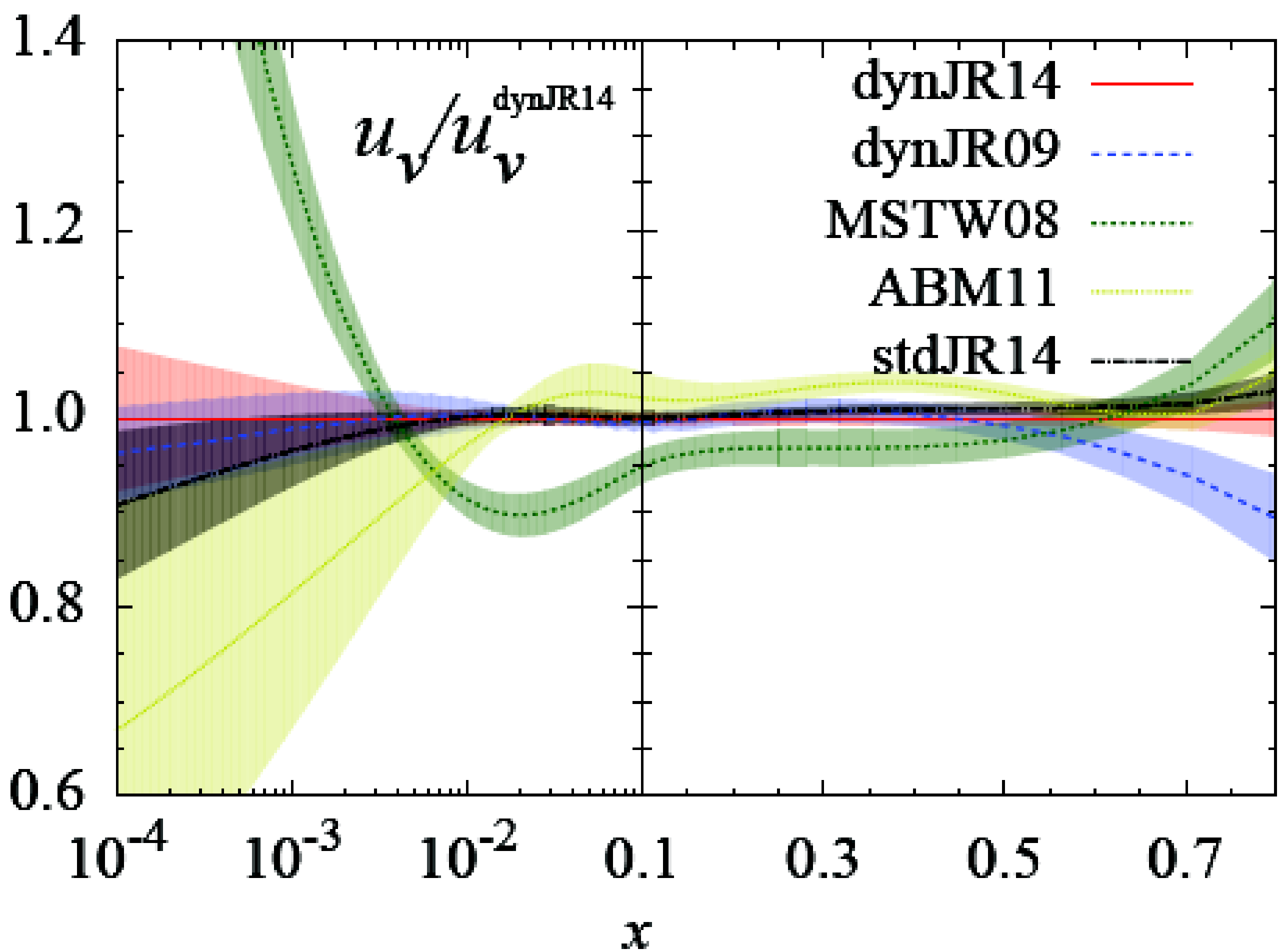


More prompt γ measurements from HERA – see O. Kuprash talk

K. Klimek, 28.04.14, Structure functions and parton densities



What's that?!

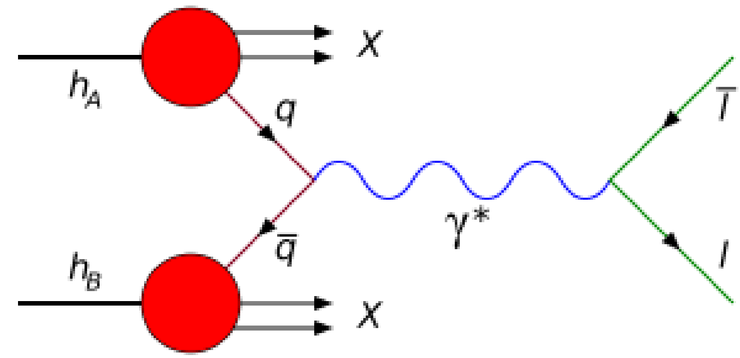


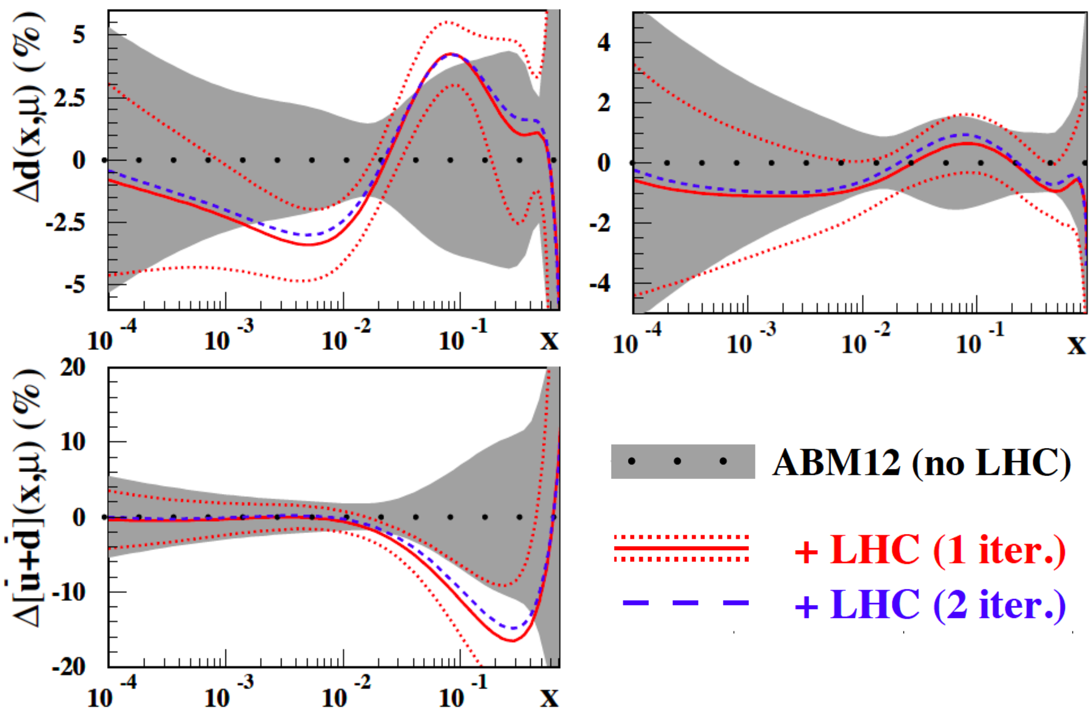
More about high-x measurements from HERA - see A. Levy talk

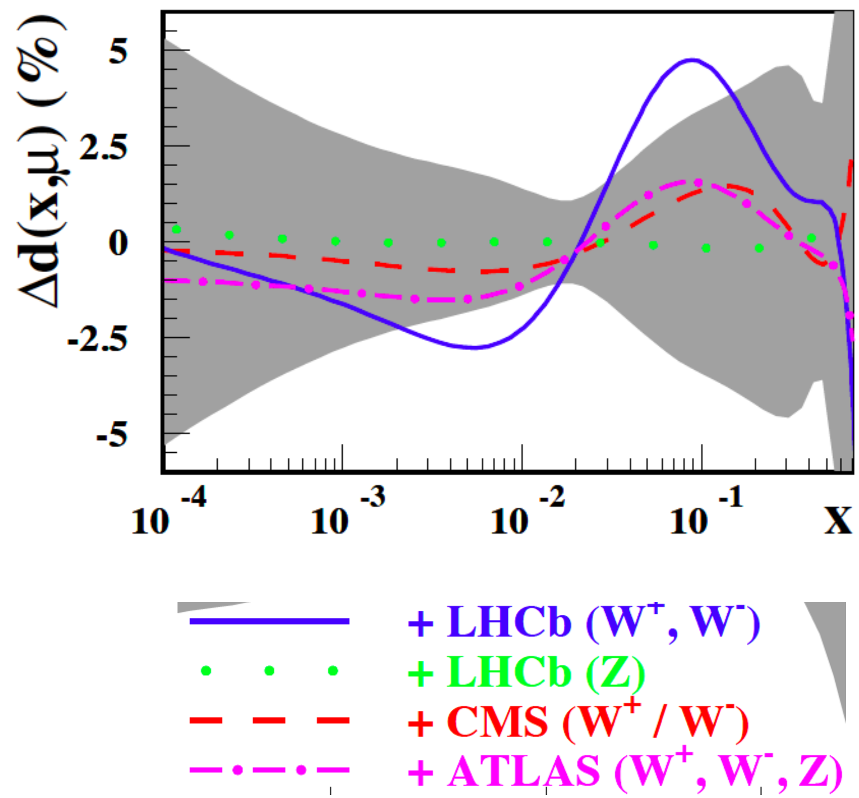
More about disentangling quark distributions - see S. Alekhin talk

What DY can teach us?

- ABM12 included LHC Drell-Yan data from ATLAs, CMS and LHCb





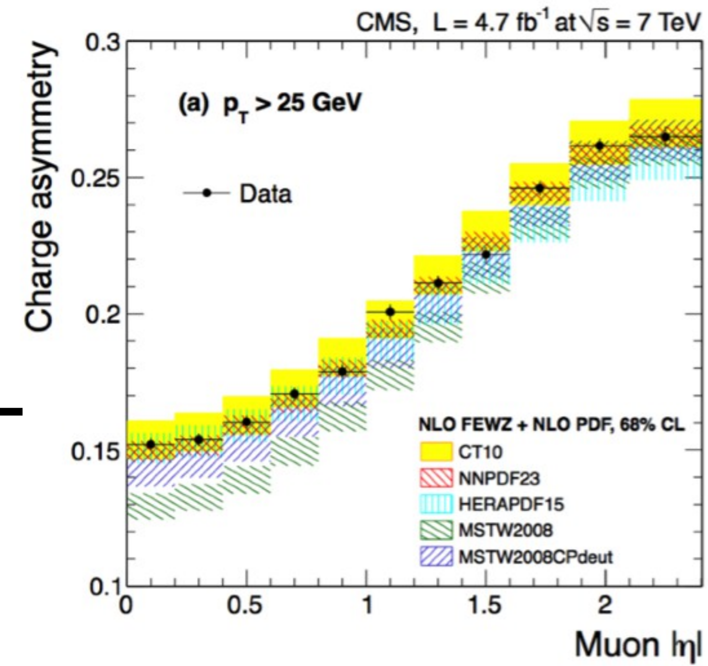


- Improved determination of quark distribution at x ~ 0.1
- Better constraint on d-quark

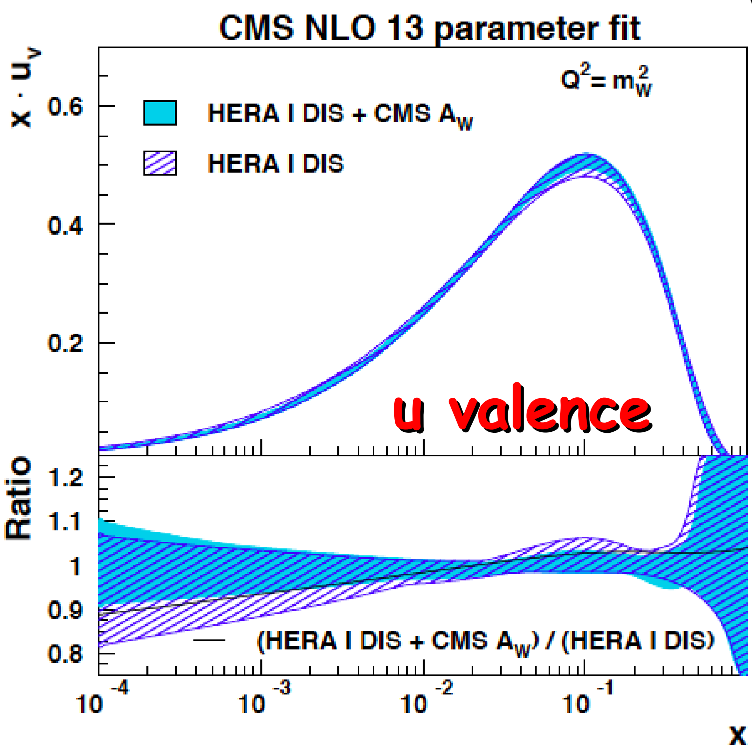
arXiv:1312.6283v2

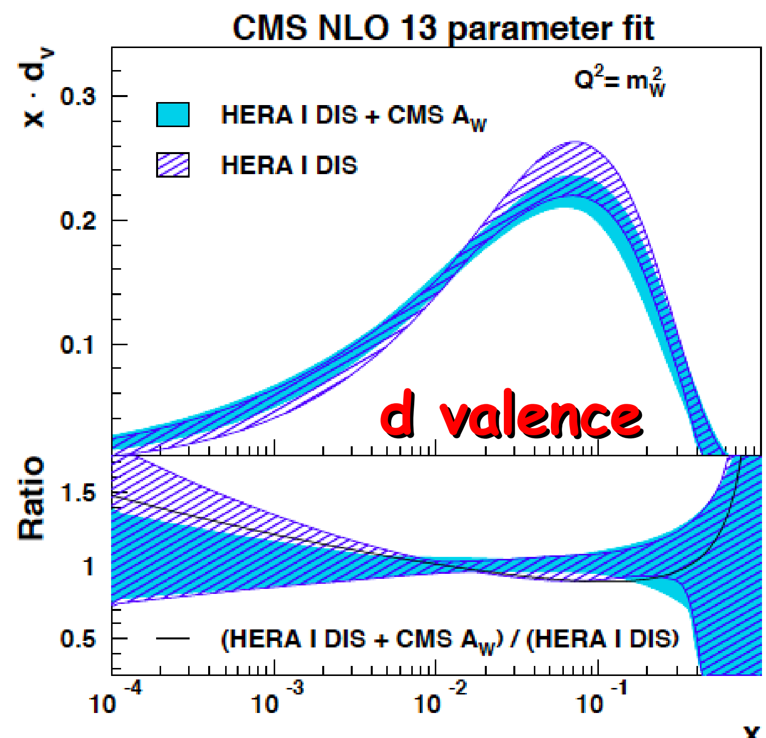
What can W asymmetry teach us?

$$A_W = \frac{W^+ - W^-}{W^+ + W^-} \approx \frac{u_v - d_v}{u_v + d_v + 2u_{sea}}$$



NLO QCD fit with HERAI data using HERAFitter framework

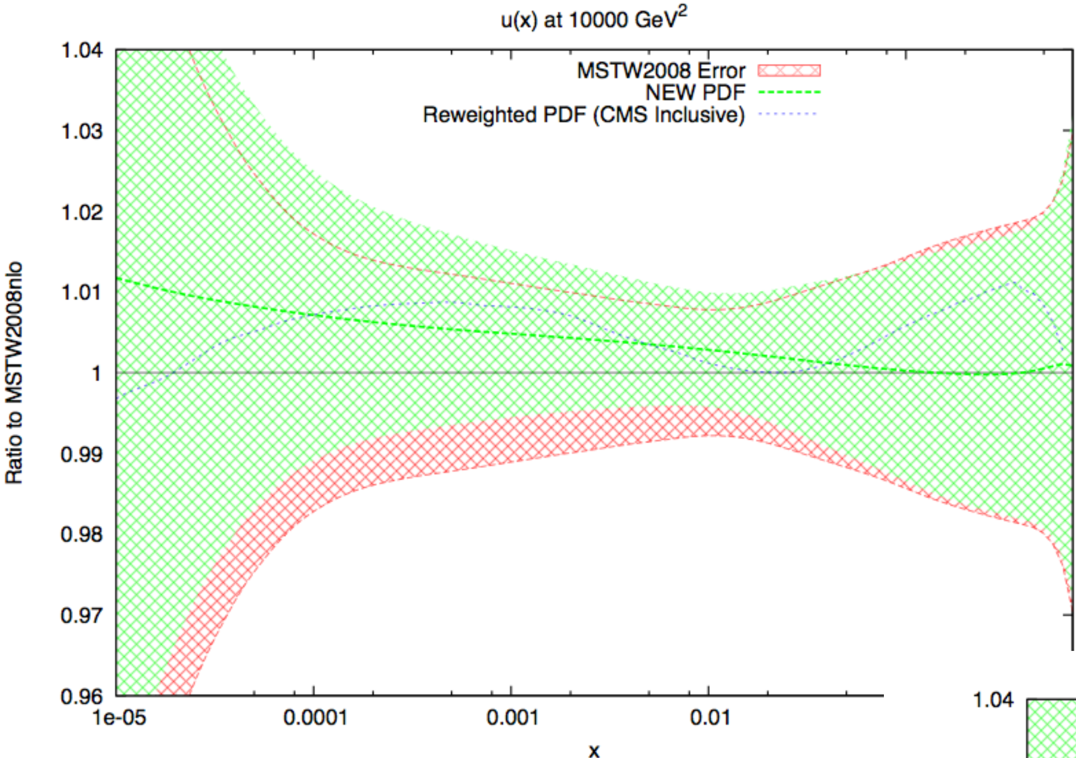




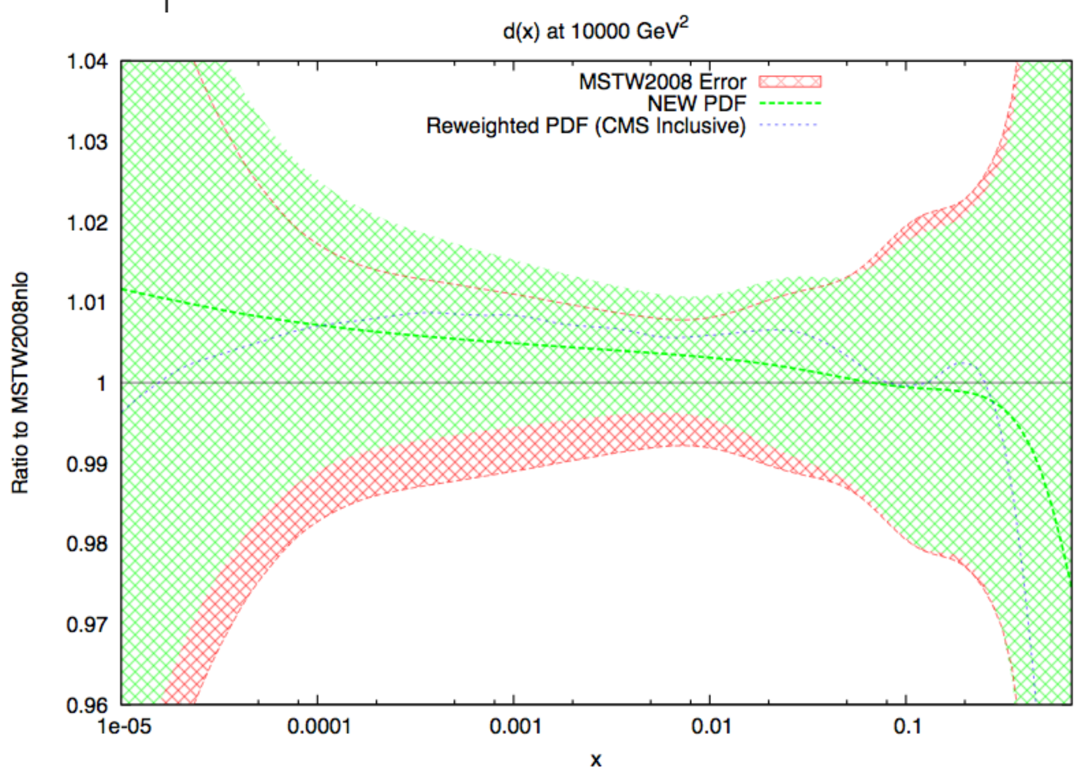
Valence uncertainties significantly improved

For details see A. Khukhunaishvili talk

What can jets teach us?



- MSTW2008 fit with CMS jet data
  - Clear indication of fit sensitivity to jet data



For details see R. Thorne talk


A SMOOTH SEA
NEVER MADE A SKILLED SAILOR.

Little is known about the strange quark distribution in the proton (1312.6283)

Is light-quark sea symmetric as SU(3) suggests?

Is strangeness suppressed due to s-quarks large masses?

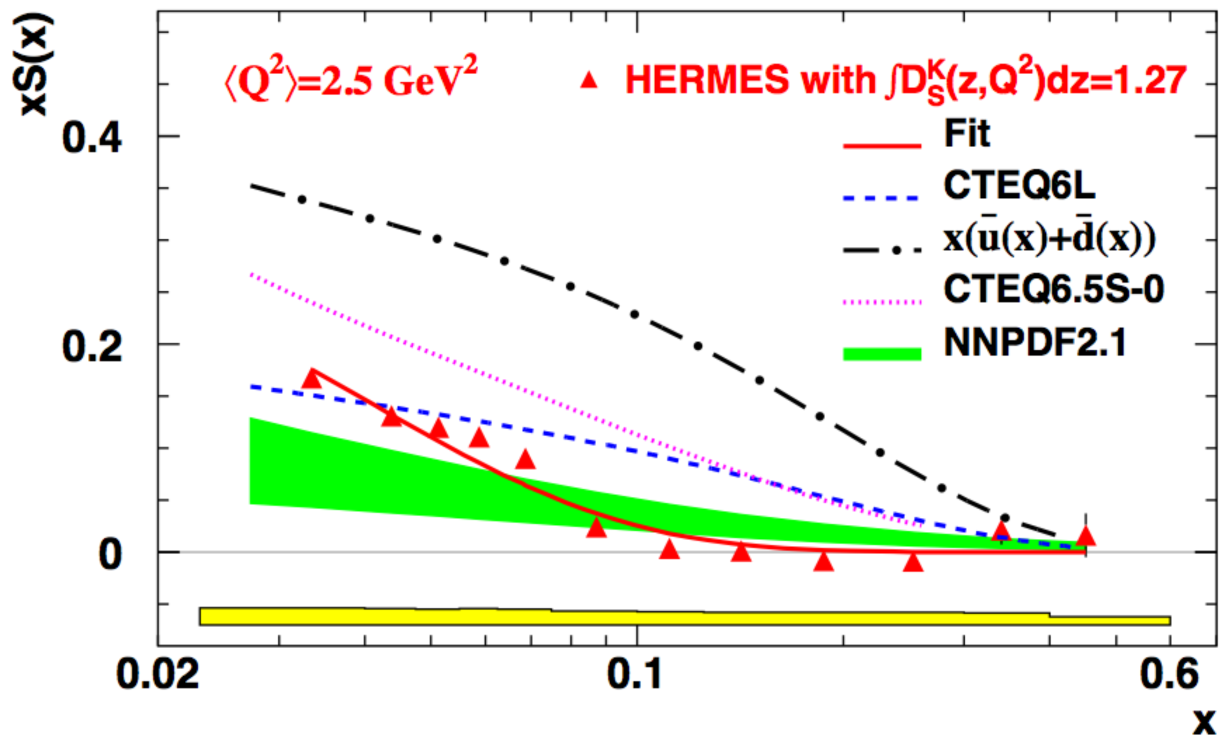
Strange sea @ LO from HERMES

DESY-13-246

- Direct measurements of strange particles can help constraining sea
  - Strangeness tagging via kaons very promising
- HERMES extracted strange PDF@LO using newest K^+K^- multiplicities

<u>xS(x;Q2) shape</u>

- strikingly different from CTEQ6L and other global LO PDFs
- strikingly different from sum of light antiquarks
- absence of strength above x ~ 0.1 discrepant with CTEQ6L



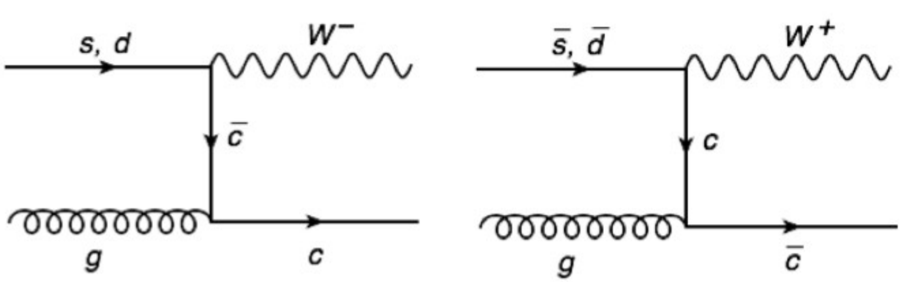
Distribution softer than that determined by other analysis

arXiv:1402.6263v1

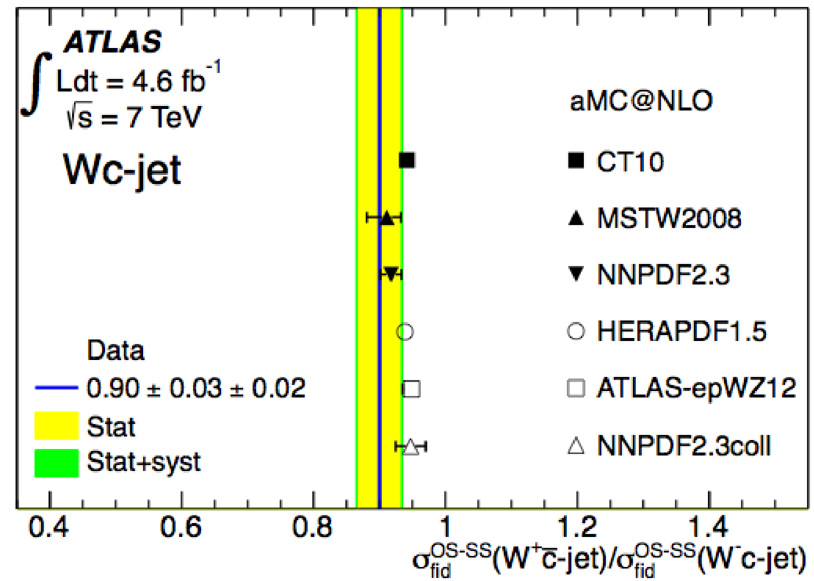
Prince Charming helps strangers

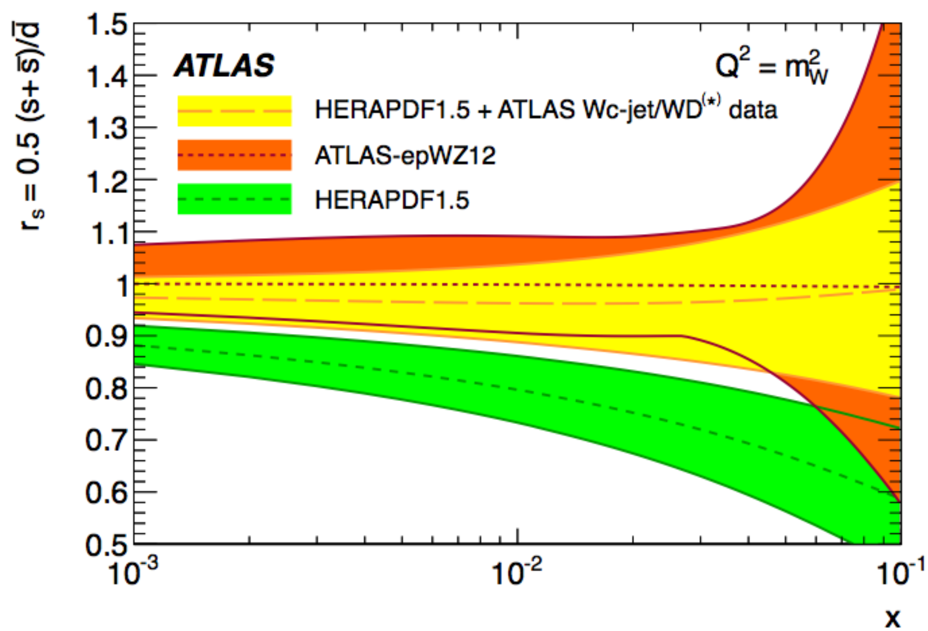
For details see G. Aad talk

- PDFs with different strange see assumptions
- Differential W and Z cross sections at LHC
  - constraints on strange sea at $Q^2 \sim M^2_{Z/W}$
  - ATLAS-epWZ12 PDF based on ATLAS W and Z cross-section + HERAI data
- W + charm measurements



SU(3)-symmetric light-quark sea hypothesis supported





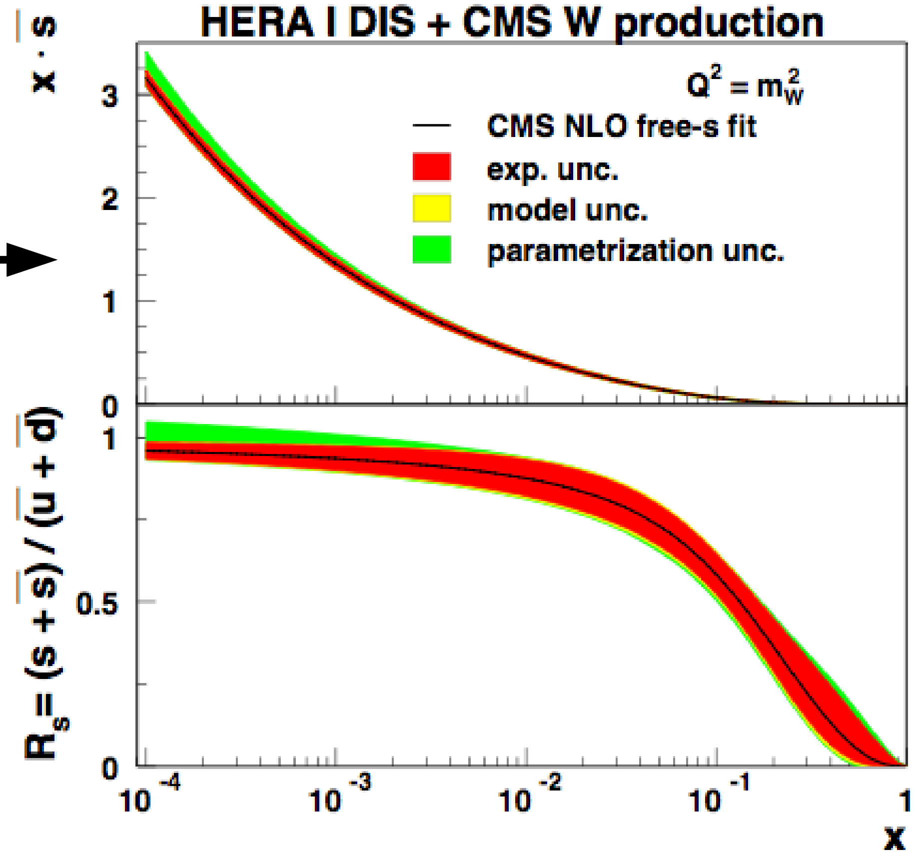
$$r_s \equiv 0.5(s+\bar{s})/\bar{d} = 0.96\,^{+0.16}_{-0.18}\,^{+0.21}_{-0.24}$$

arXiv:1312.6283v2

Prince Charming helps strangers

For details see R. Placakyte and A. Khukhunaishvili talks

NLO QCD fit with HERAI data And CMS A_W using HERAFitter framework



$$\kappa_s(Q^2) = \frac{\int_0^1 x\left[\bar{s}(x,Q^2) + s(x,Q^2)\right] dx}{\int_0^1 x\left[\bar{u}(x,Q^2) + \bar{d}(x,Q^2)\right] dx}$$

$$0.52^{+0.12}_{-0.10}\,(\text{exp.})^{+0.05}_{-0.06}\,(\text{model})^{+0.13}_{-0.10}\,(\text{parametrization})$$

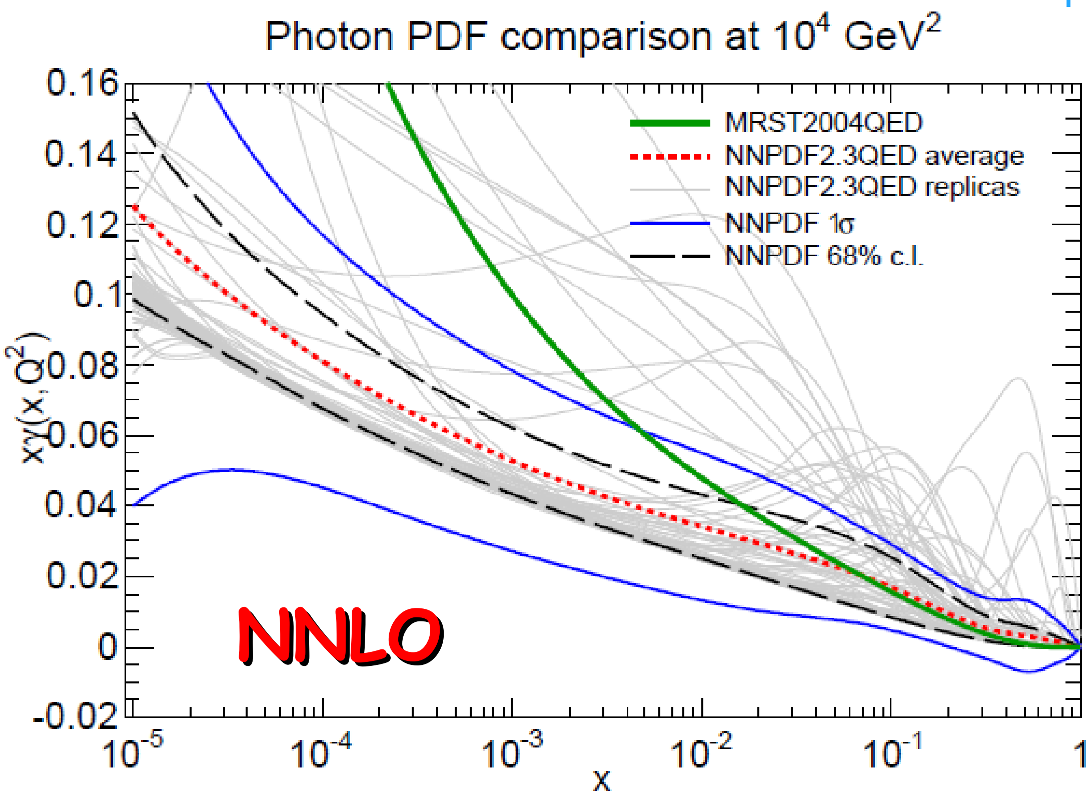
Good agreement with NOMAD [Nucl.Phys. B876 (2013) 339, $\kappa_s = 0.59 \pm 0.019$]

Yet another one
- please meet photon PDF

Precision of LHC data requires inclusion of higher order electroweak effects

PDFsetQED

- Two existing photon PDF sets with QED corrections included
    - MRST2008QED
    - new NNPDF2.3QED arXiv:1308.0598
- Photon PDF determined by DIS and Drell-Yan LHC data
- Good agreement with MRST2004QED result for x > 0.3



→ More about QED effect in PDFs – see C. Schmidt talk

- Another approach to be implemented into HERAFitter and used for QED fits of LHC data: arXiv:1401.1133 (R. Sadykov)
    - QED-modified evolution equations are implemented into β version of release of QCDNUM program
    - APPLGRID interface to SANC MC generator created for fast evaluation of LO photon-induced cross-sections

Summary

- Our knowledge of parton distributions in proton is growing
- More precise measurements require more precise PDFs
- We entered PDF-LHC era
  - From predicting LHC measurements we use them in PDF determination
- Still long way to full and precise understanding of proton

… still so much to learn

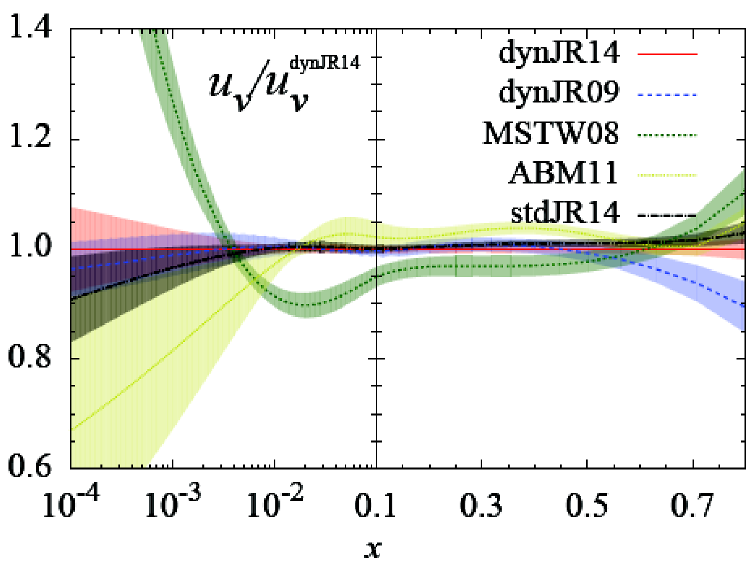
My personal thanks to my PDF teachers (in general and for this talk)

A. Cooper-Sarkar, P. Jimenez-Delgado, R. Placakyte, V. Radescu, S-O. Moch, J. Rojo, P. Nadolsky, R. Thorne

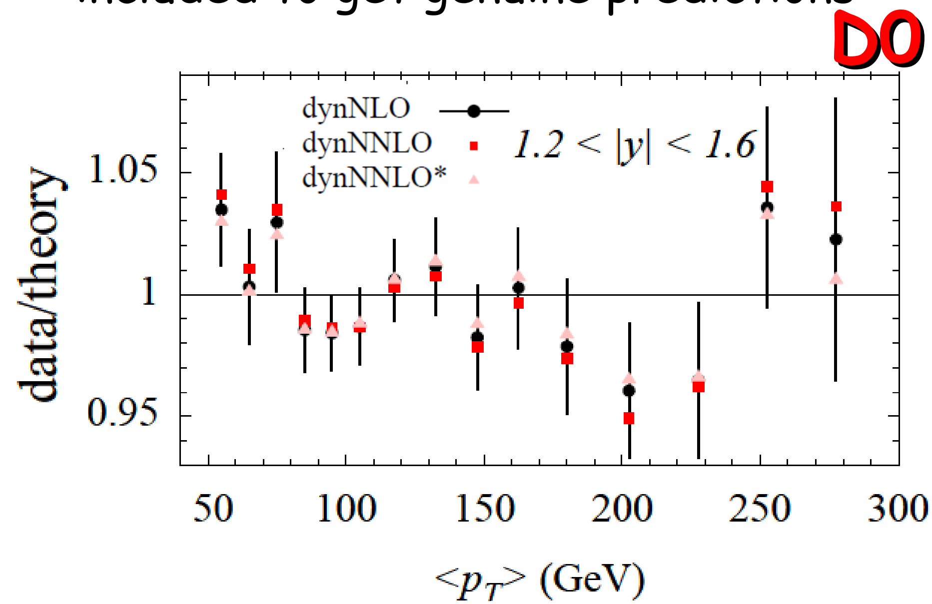
Additional material

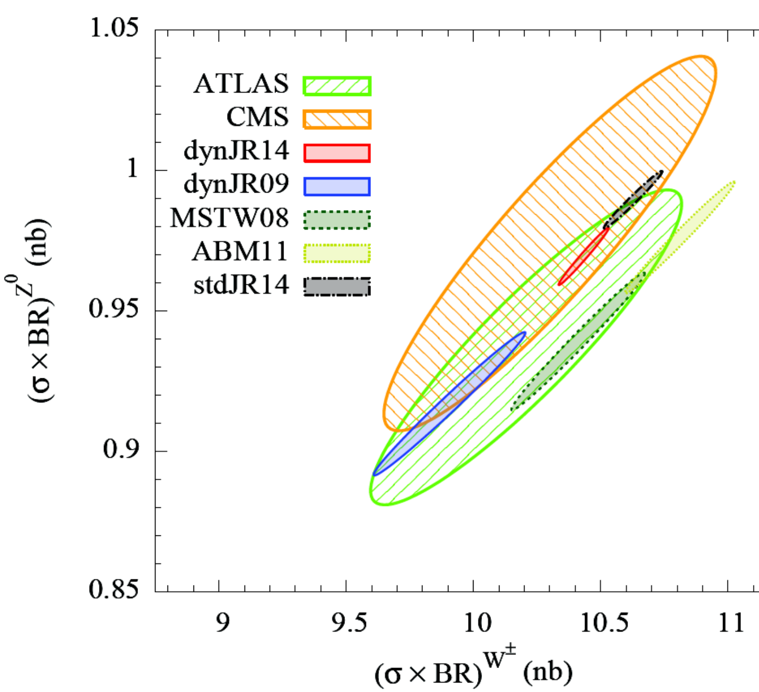
JR14 dynamical & standard

- New dynamical and standard JR14 PDFs
- Improved calculations
  - nonperturbative higher-twist terms
  - nuclear corrections,target mass corrections
  - running mass in DIS charm & beauty production
  - complete treatment of syst. uncertainties of data including experimental correlations
- More/updated data included
  - HERAI inclusive & charm, H1 F_L
  - HERA jets (not for NNLO)
  -



- No Tevatron gauge bosons & LHC data included to get genuine predictions

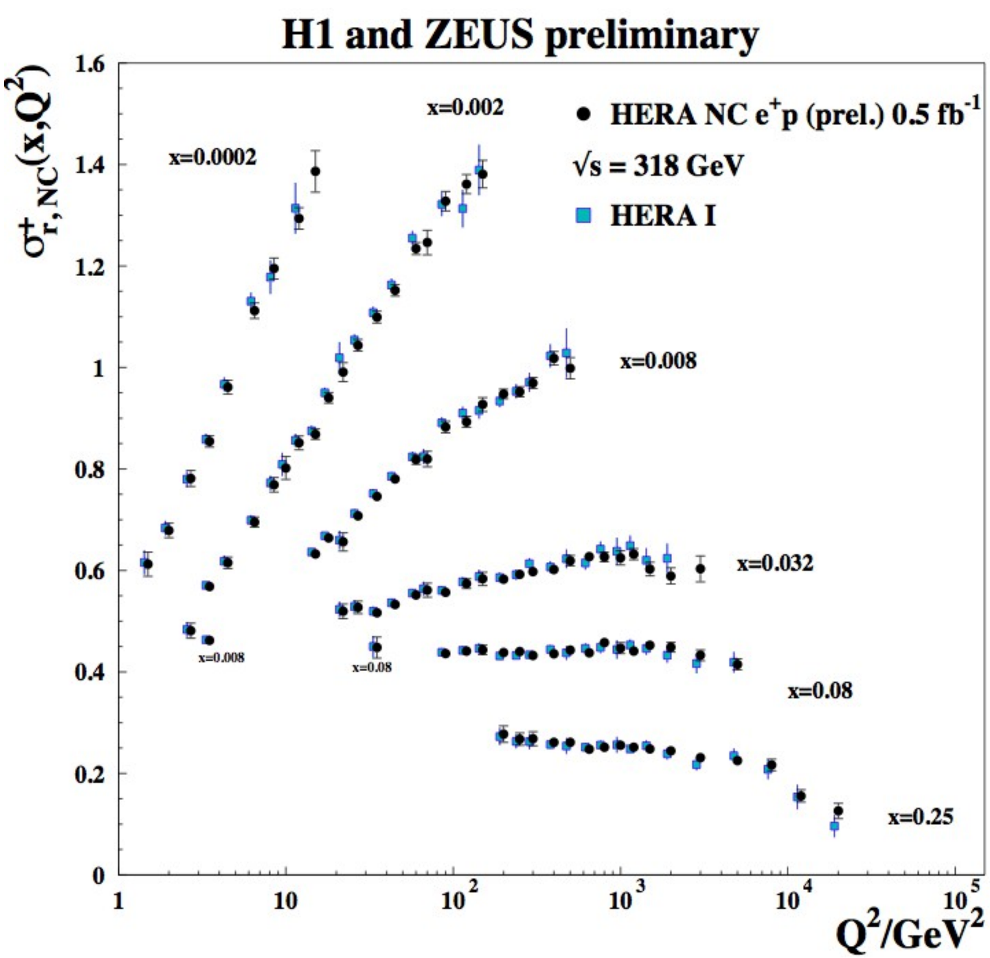




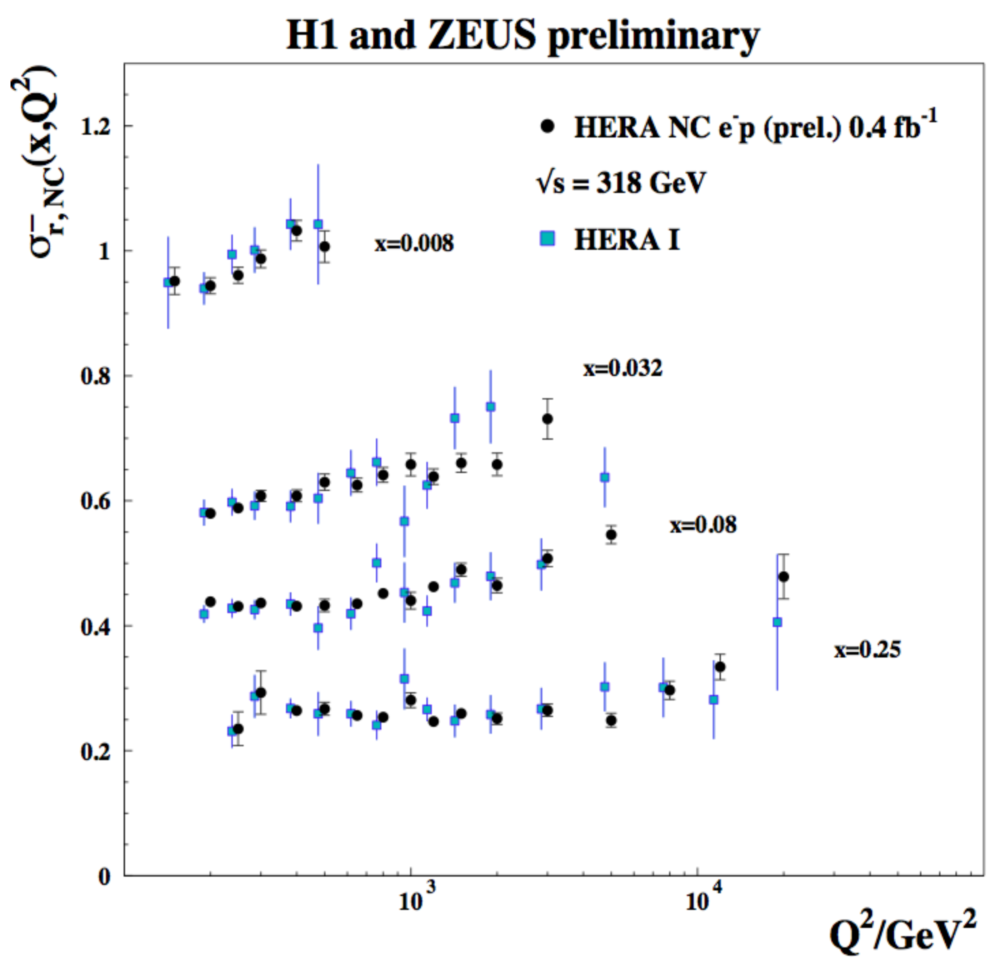
Comparison with HERAI combination

- Significant reduction of systematic uncertainties
- Significant increase of statistics

NCe⁺p: 3 times HERAI luminosity



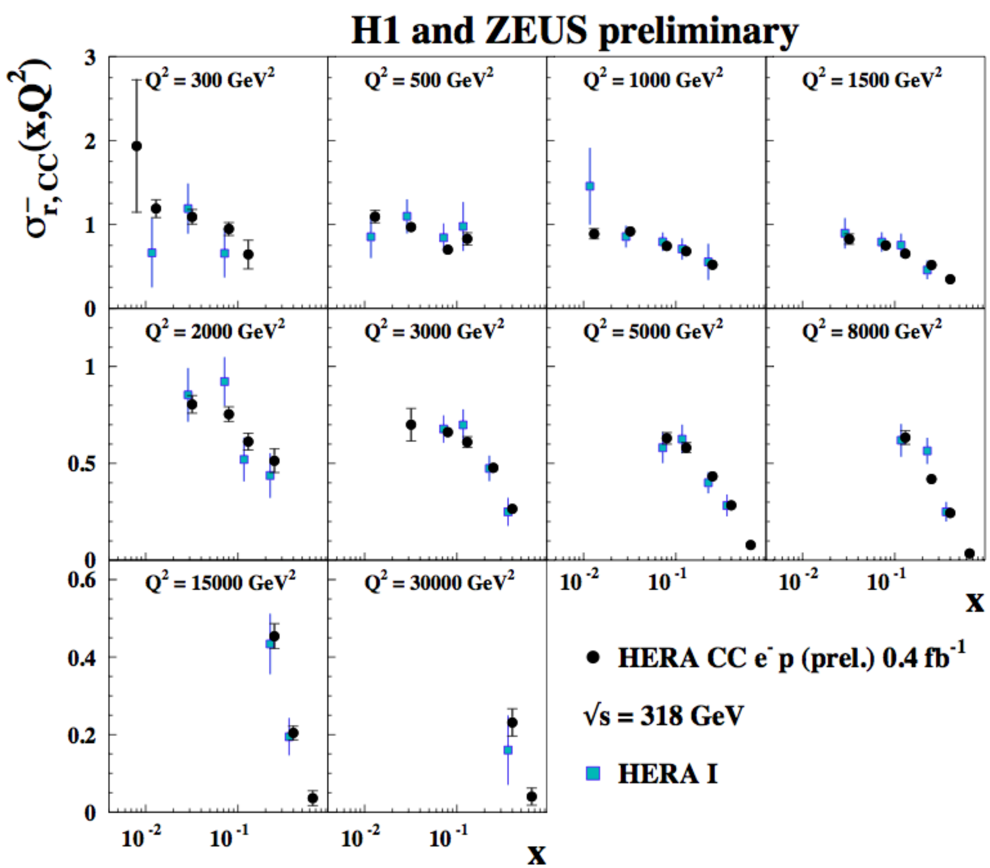
NCe⁻p: 10 times HERAI luminosity

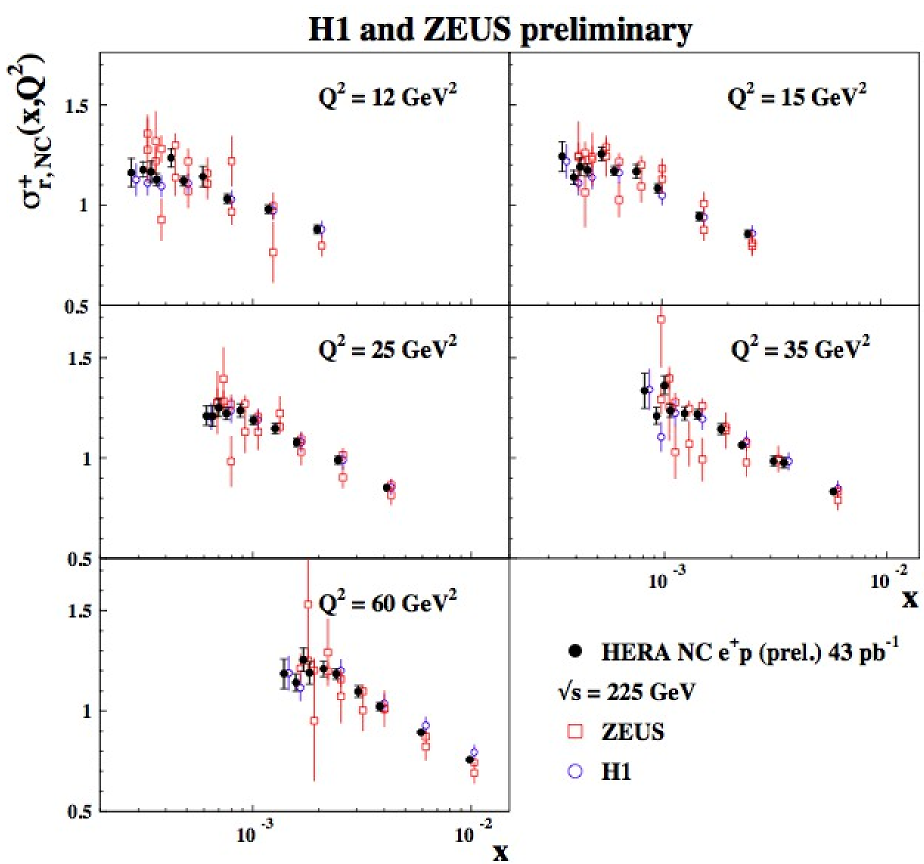


Large gain in precision

New kinematic ranges explored

- Kinematic range extended for existing data samples
- Low energies added: CME = 225 GeV and 251 GeV

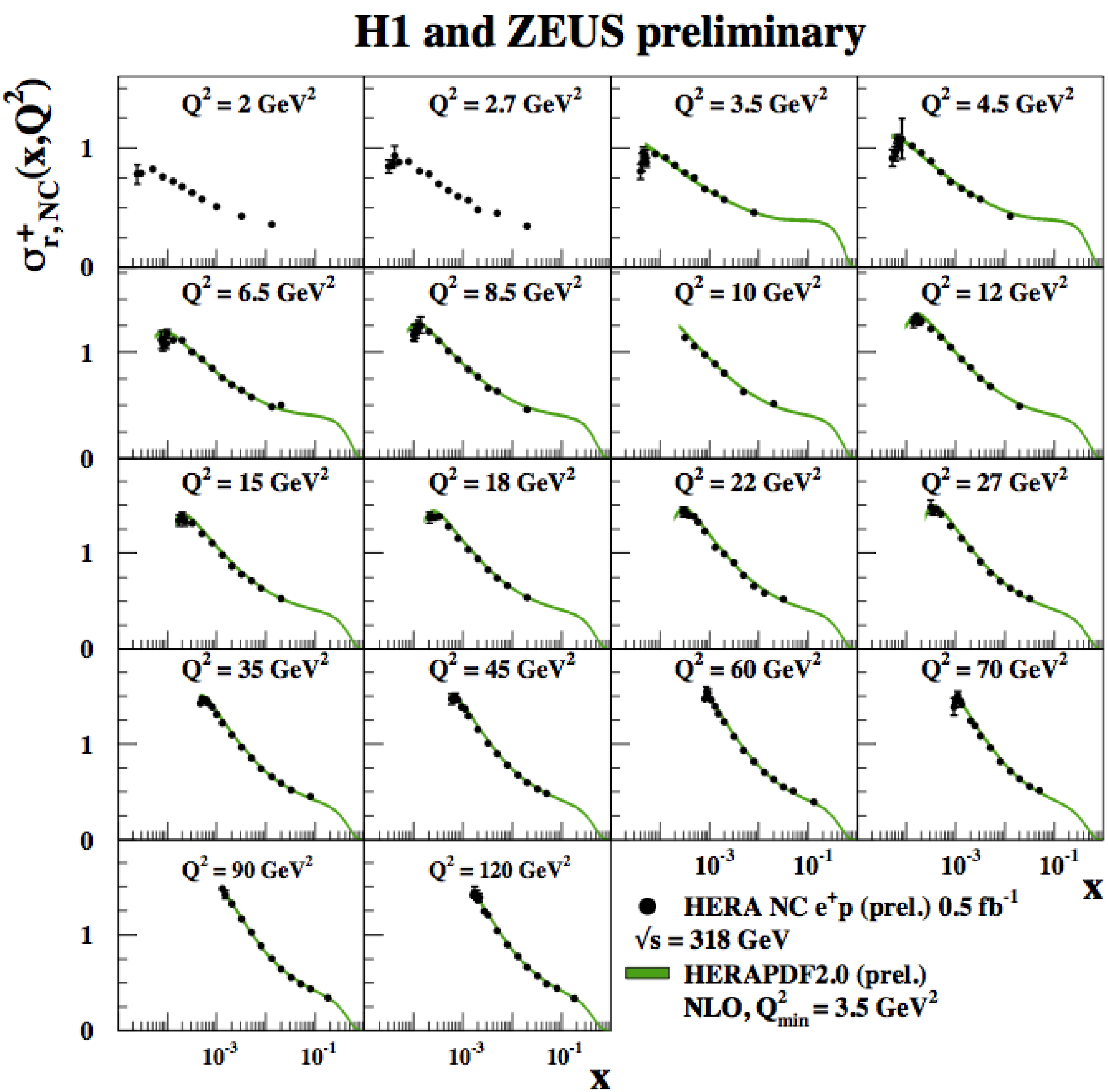




HERAPDF2.0 (prel.)

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g} - A'_g x^{B'_g}(1-x)^{C'_g}, \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}\left(1 + D_{u_v}x + E_{u_v}x^2\right), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\bar{U}(x) &= A_{\bar{U}} x^{B_{\bar{U}}}(1-x)^{C_{\bar{U}}}\,(1 + D_{\bar{U}}x), \\
x\bar{D}(x) &= A_{\bar{D}} x^{B_{\bar{D}}}(1-x)^{C_{\bar{D}}}.
\end{aligned}
$$

HERAPDF2.0 (prel.) @ NLO



- NLO fit for $Q^2_{min} = 3.5\ GeV^2$

  $\chi^2/dof = 1386/1130$

- Additional fit performed with $Q^2_{min} = 10\ GeV^2$

  $\chi^2/dof = 1156/1003$

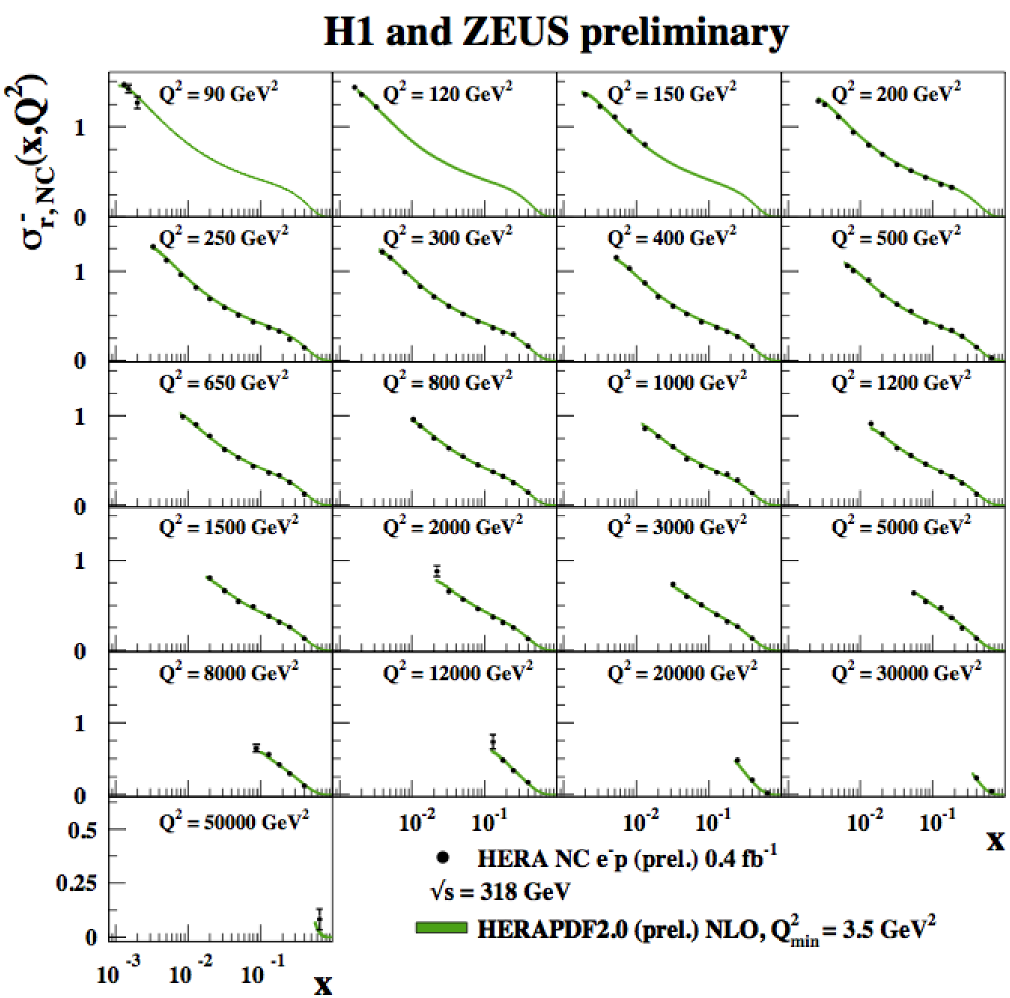
  Situation somewhat improved

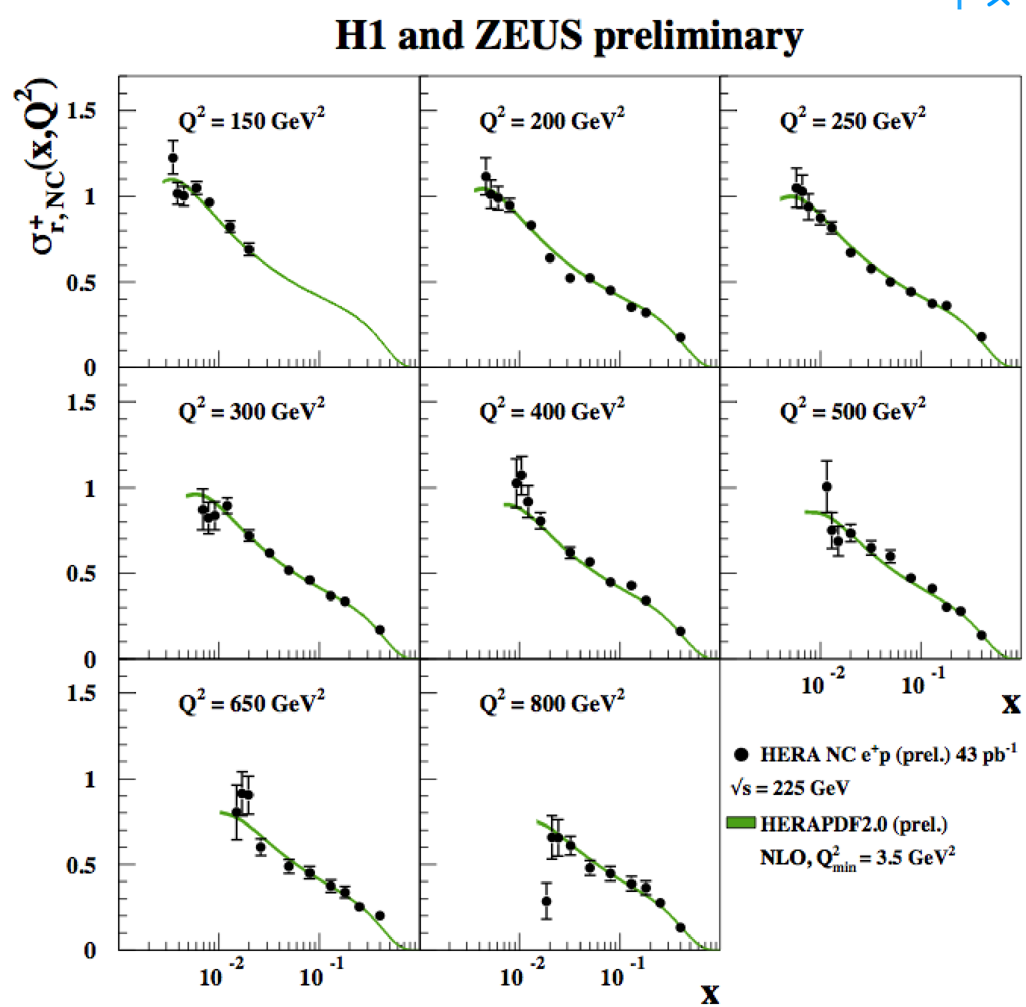
- **Similar results for NNLO**

Reasonable description of NC, CC and low energy data for NLO and NNLO

HERAPDF2.0 (prel.) @ NNLO

- High-Q^2 region well described for NCep and CCep and low energy data for NLO and NNLO



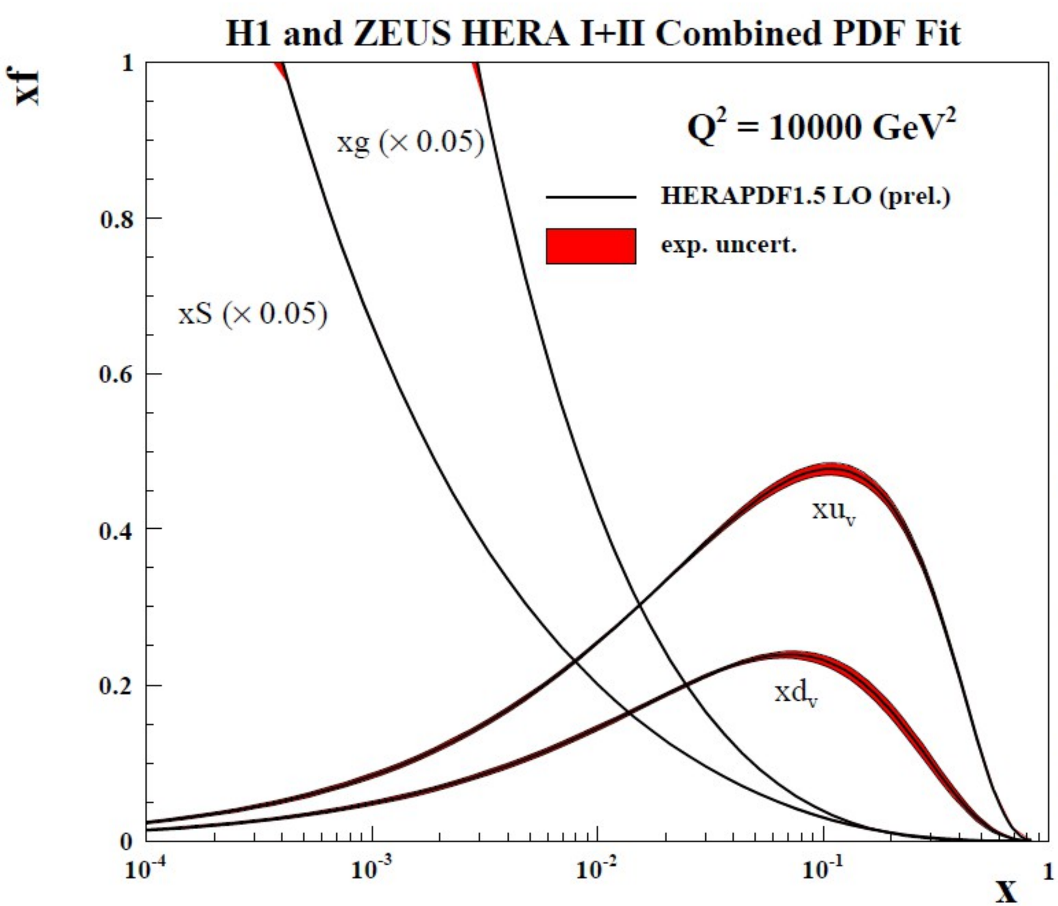


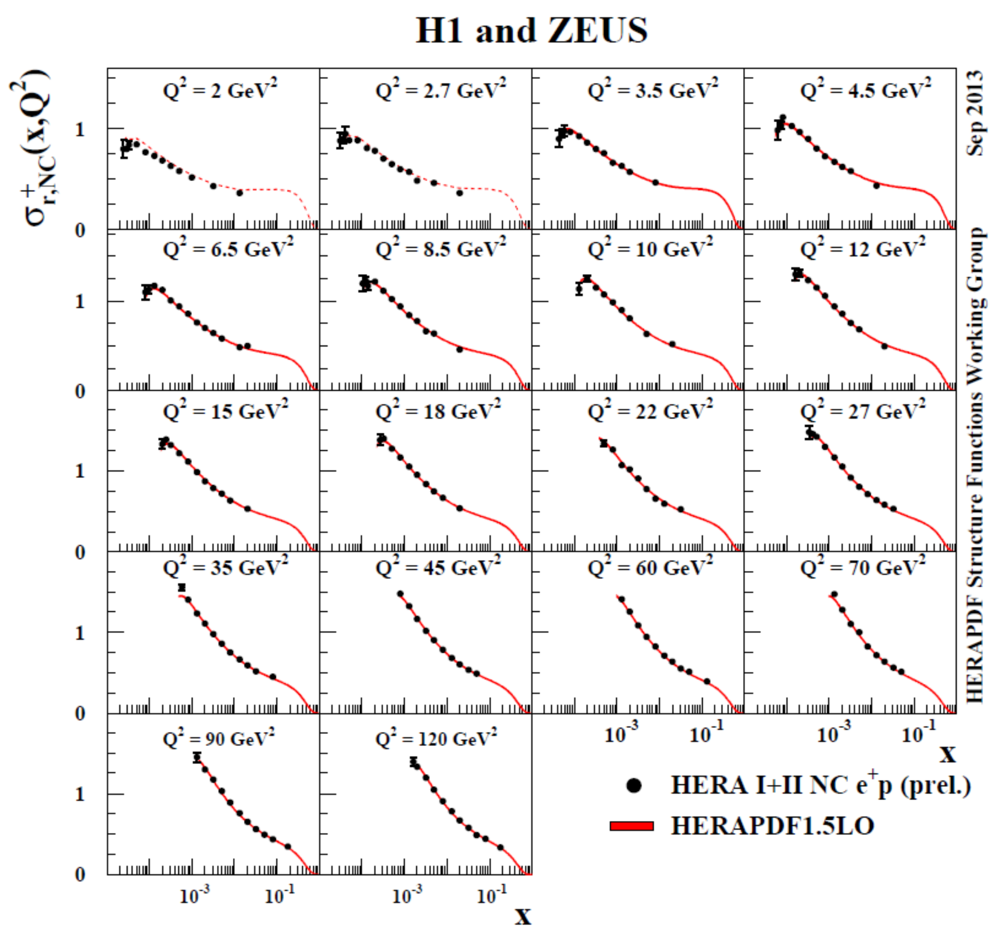
K. Klimek

HERAPDF1.5LO (prel.)

- Parton densities @LO are essential for proper simulation of parton showers and underlying event properties in LO+PS Monte Carlo event generators
- HERAPDF1.5 LO set based on HERAPDF1.5 NLO PDF settings
- Includes experimental uncertainties
- Available in LHAPDF library

For details see M. Cooper-Sarkar talk





NNPDF3.0

Slide from J. Rojo

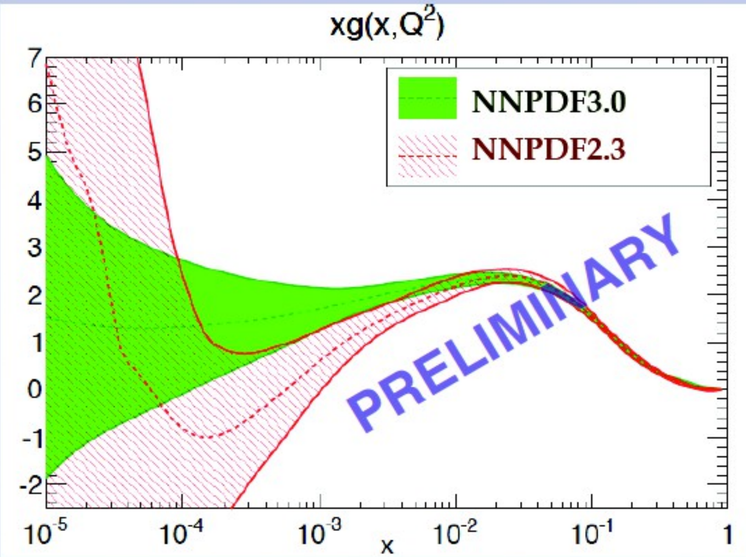
PDF updates

NNPDF updates

- Next release will be **NNPDF3.0,** based on a complete rewriting of the NNPDF framework in C++ (more than **70K** lines of code)

For details see M. Ubiali talk

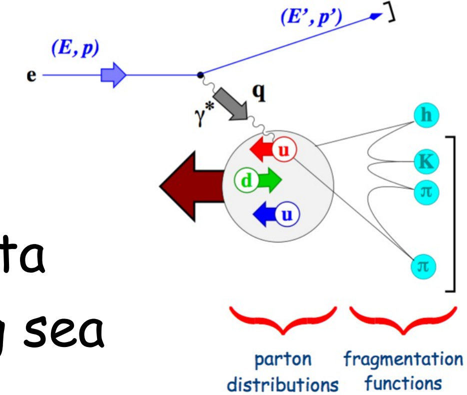
- More than **1000 new data points** from **HERA-II and the LHC**, including jet cross-sections, W+charm production, top quark data, low and high mass Drell-Yan, W lepton asymmetries.....



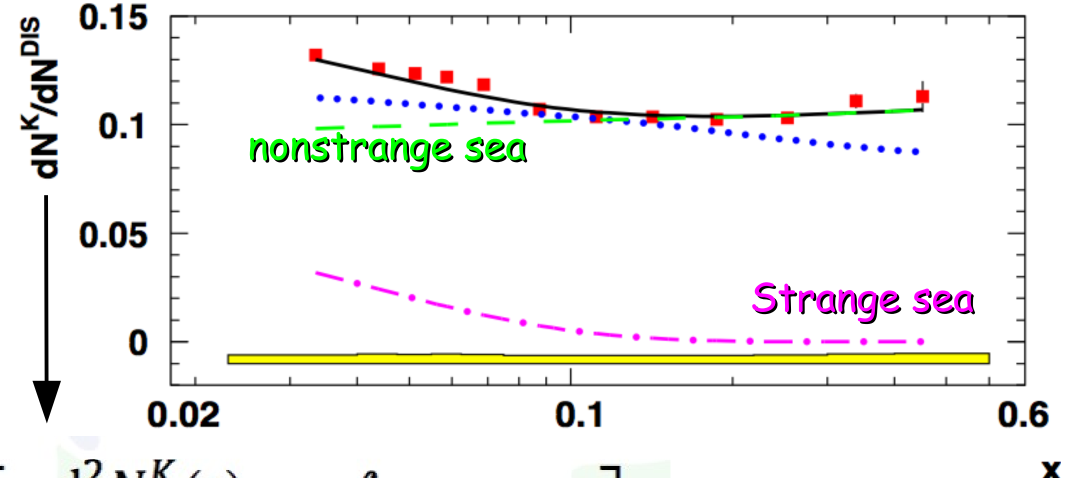
- Completely redesigned fitting methodology based on **closure tests** with known underlying physical laws **(S. Forte, PDF4LHC, 12/2014)**
- Substantially improved **Genetic Algorithms minimization** with new **Weight Penalty method** for fitting (iterative Bayesian regularization)

Experiment	Dataset	DOF
NMC		356
	NMCPD	132
	NMC	224
SLAC		74
	SLACP	37
	SLACD	37
BCDMS		581
	BCDMSP	333
	BCDMSD	248
CHORUS		862
	CHORUSNU	431
	CHORUSNB	431
NTVDMN		79
	NTVNUDMN	41
	NTVNBDMN	38
HERA1AV		592
	HERA1NCEP	379
	HERA1NCEM	145
	HERA1CCEP	34
	HERA1CCEM	34
ZEUSHERA2		252
	Z06NC	90
	Z06CC	37
	ZEUSHERA2NCP	90
	ZEUSHERA2CCP	35
H1HERA2		511
	H1HERA2NCEM	139
	H1HERA2NCEP	138
	H1HERA2CCEM	29
	H1HERA2CCEP	29
	H1HERA2LOWQ2	124
	H1HERA2HGHY	52
HERAF2CHARM		47
DYE886		199
	DYE886R	15
	DYE886P	184
DYE605		119
CDF		105
	CDFZRAP	29
	CDFR2KT	76
D0		138
	D0ZRAP	28
	D0R2CON	110
ATLAS		179
	ATLASWZRAP36PB	30
	ATLASR04JETS36PB	90
	ATLASR04JETS2P76TEV	59
CMS		95
	CMSWEASY840PB	11
	CMSWMASY47FB	11
	CMSJETS11	63
	CMSWCHARMTOT	5
	CMSWCHARMRAT	5
	CMSDY2D11	132
LHCB		19
	LHCBW36PB	10
	LHCBZ940PB	9
TOP		6
Total (exps)		4214

PDF determination @ HERMES



- Strange contribution to sea cannot be constrain by inclusive data
- Direct measurements of strange particles can help constraining sea
  - Strangeness tagging via kaons very promising
- Extract <u>strange quark distribution</u> (2008),)
  - Newest K^+K^- multiplicities on deuteron used: PR **D87**, 074029 (2013)



s(x) + s̄(x)

$$S(x)\int \mathcal{D}_S^K(z)\,\mathrm{d}z \simeq Q(x)\left[5\,\frac{\mathrm{d}^2N^K(x)}{\mathrm{d}^2N^{\mathrm{DIS}}(x)} - \int \mathcal{D}_Q^K(z)\,\mathrm{d}z\right]$$

- Assume $S(x,Q^2)$ 0 at high x → extract non-strange fragmentation
- Strange fragmentation measured before (PR D75,114010 (2007)) → **extract xS(x)**