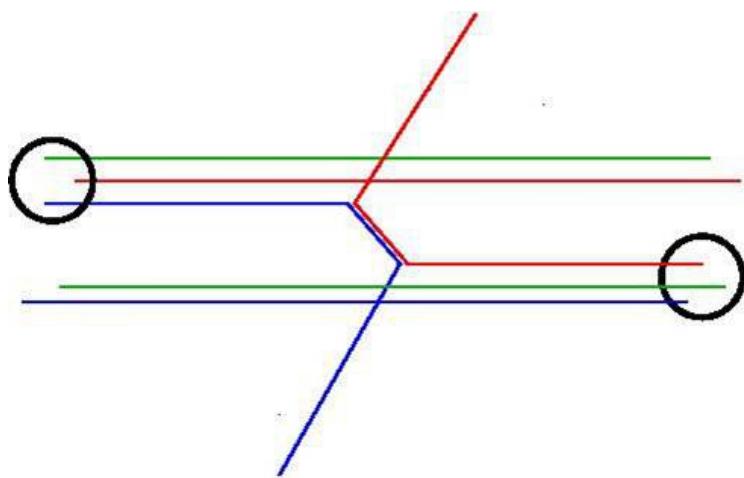


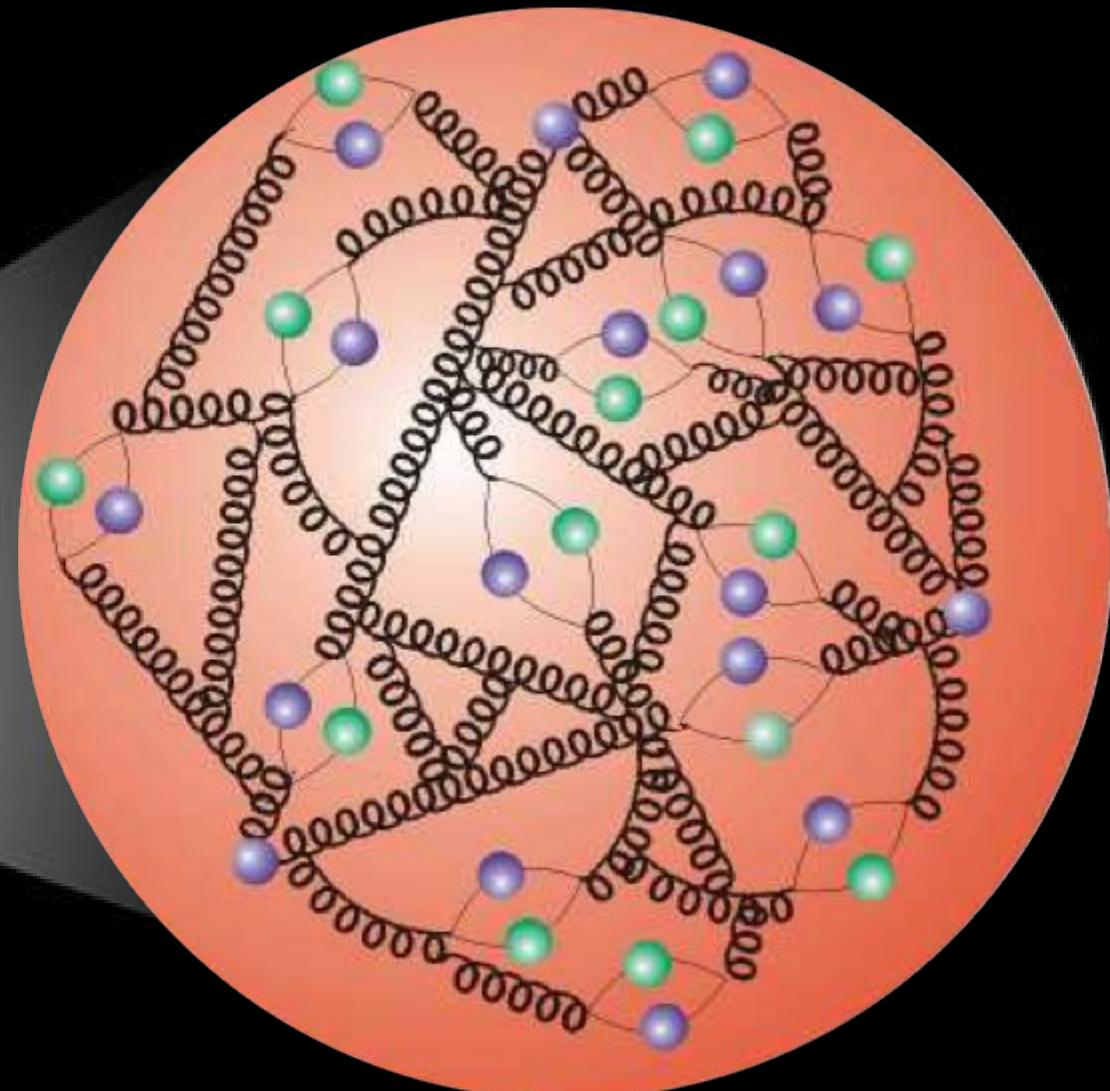
All you want to know
about proton
structure
... but are afraid to
ask



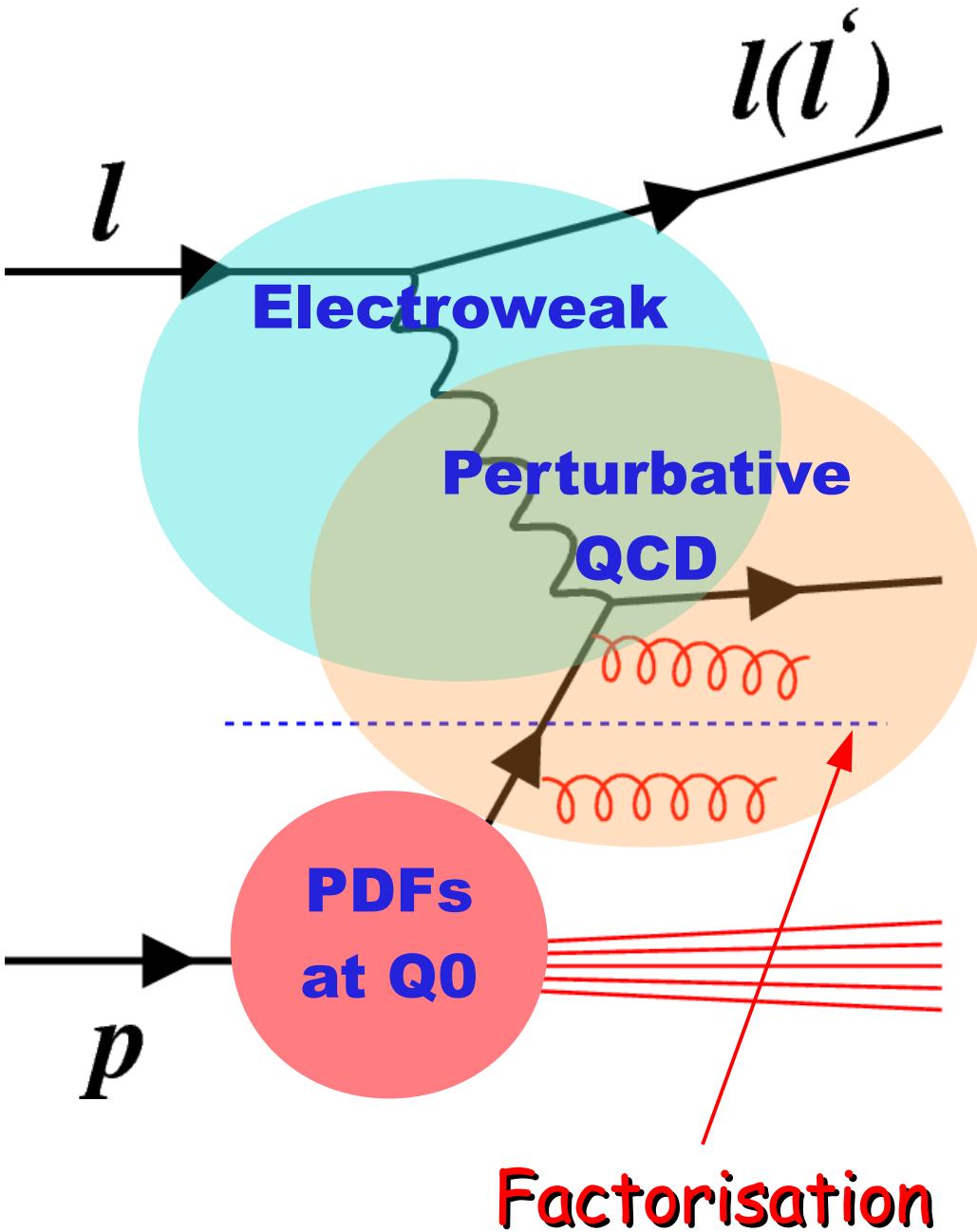
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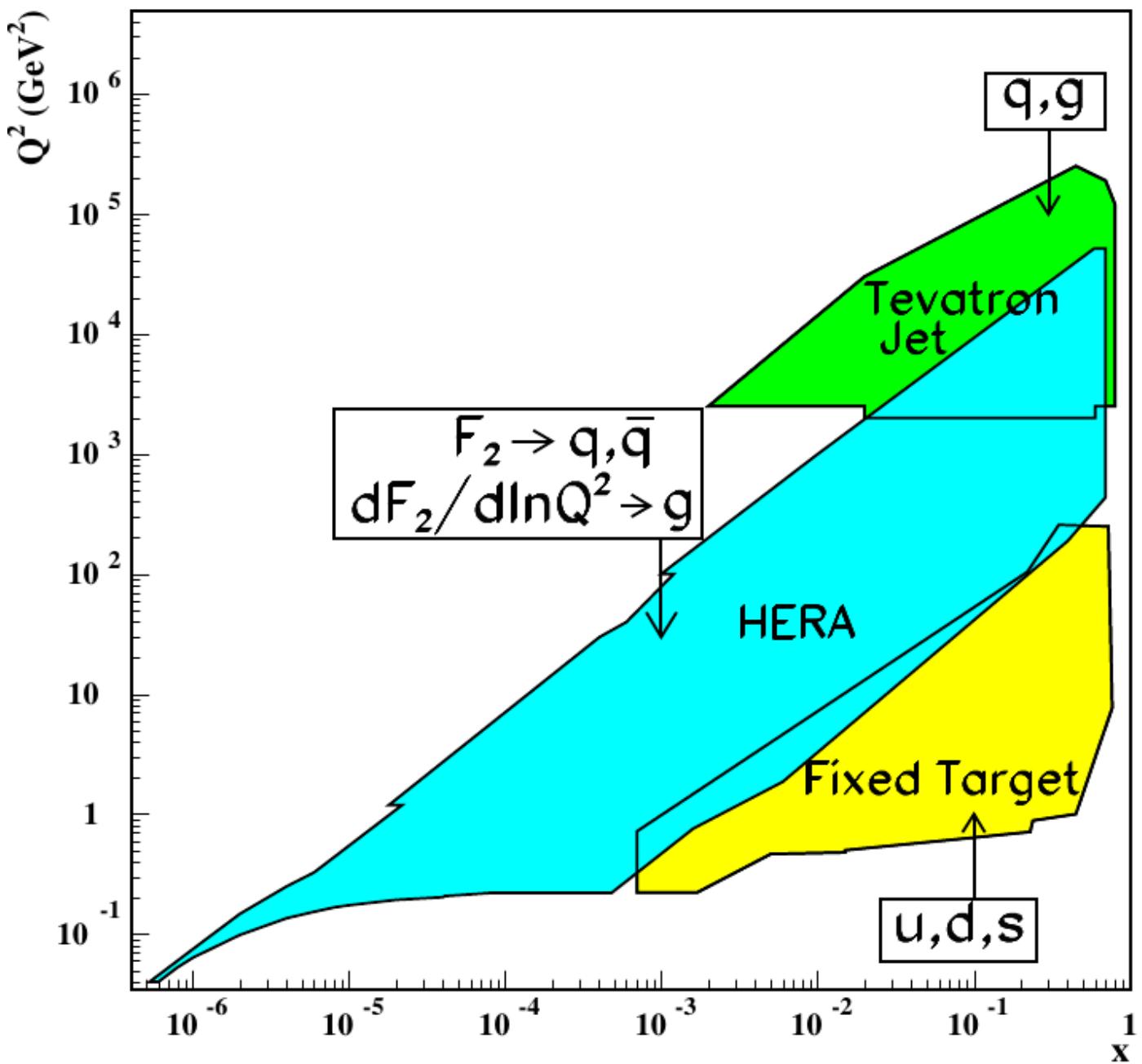


Determination of parton densities

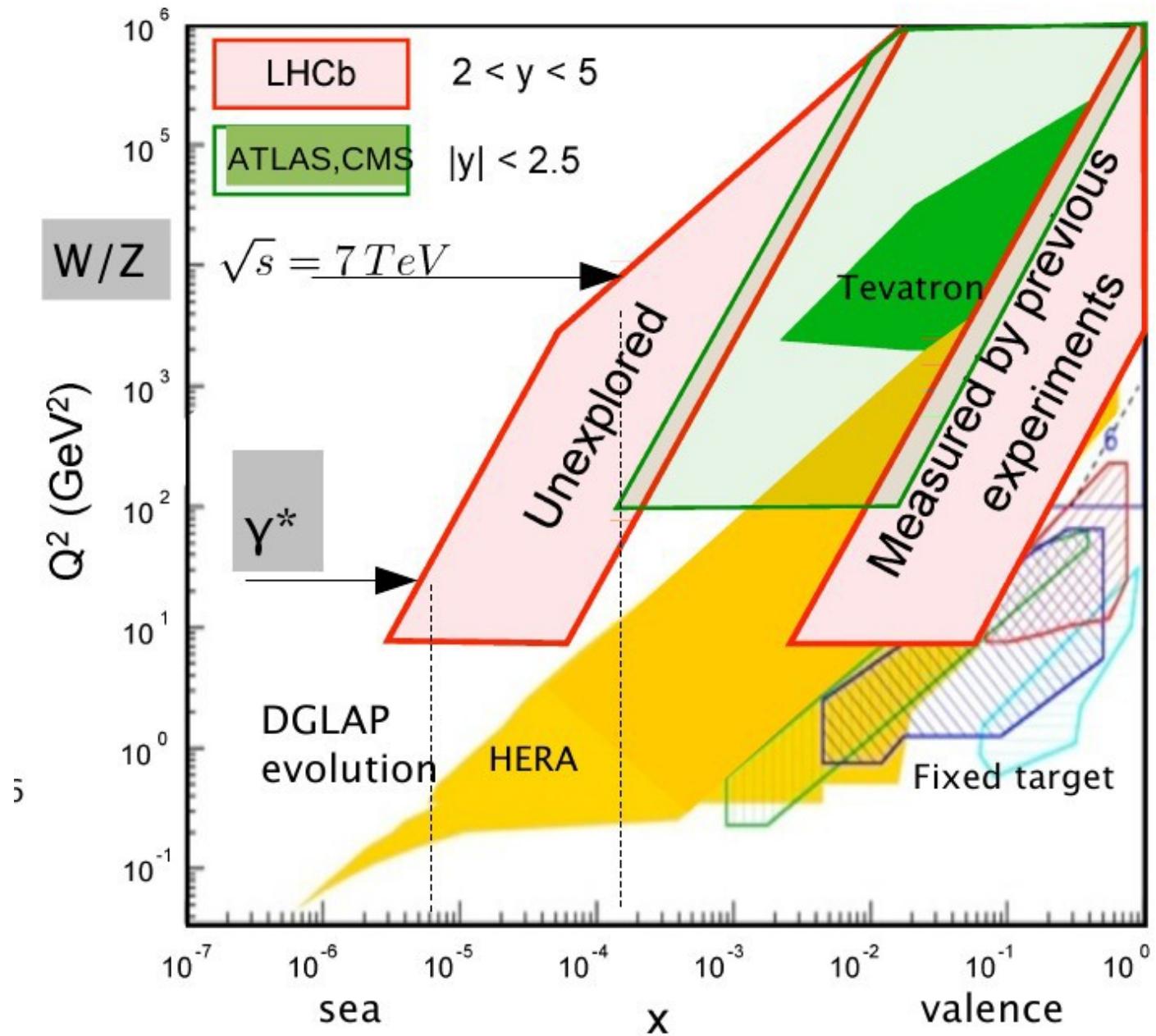


- Fix pQCD © PDFs
! Test Electroweak
 - Fix Electroweak
! Test pQCD © PDFs
 - Fix Electroweak & pQCD
! Determine PDFs
- ↓
- Discussed in this talk
- Use experimental data
 - Perform global QCD fit
 - Determin PDFs

Data for parton distributions: preLHC



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



Current global PDF groups Start including LHC data

ABM: Careful treatment of experimental correlations, nuclear and power corrections in DIS, FFNS

MSTW: negative input gluons at small- x , rather “large” $\alpha_s(M_Z^2)$, GMVNS

HERAPDF: Only HERA data, less negative gluons, GMVFS HERA data only

NNPDF: neural-network parametrization, Monte Carlo approach for error propagation, GMVFNS

CTEQ-TEA: parametrization with exponentials, substantially inflated uncertainties, GMVFNS

JR [with E. Reya]: detailed study of input scale dependence, dynamical (and “standard”) versions, FFNS

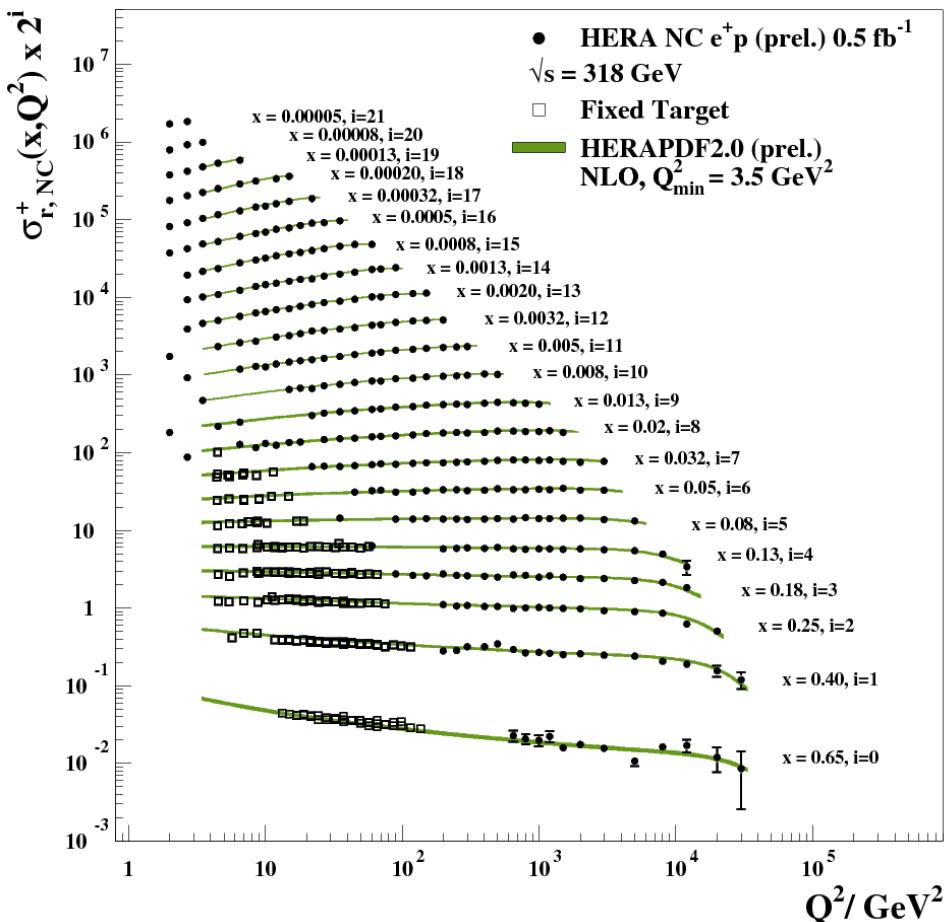
(there are more groups focused on particular aspects, e.g. CTEQ-JLab)

Inclusive measurements from HERA are core of every parton density extraction

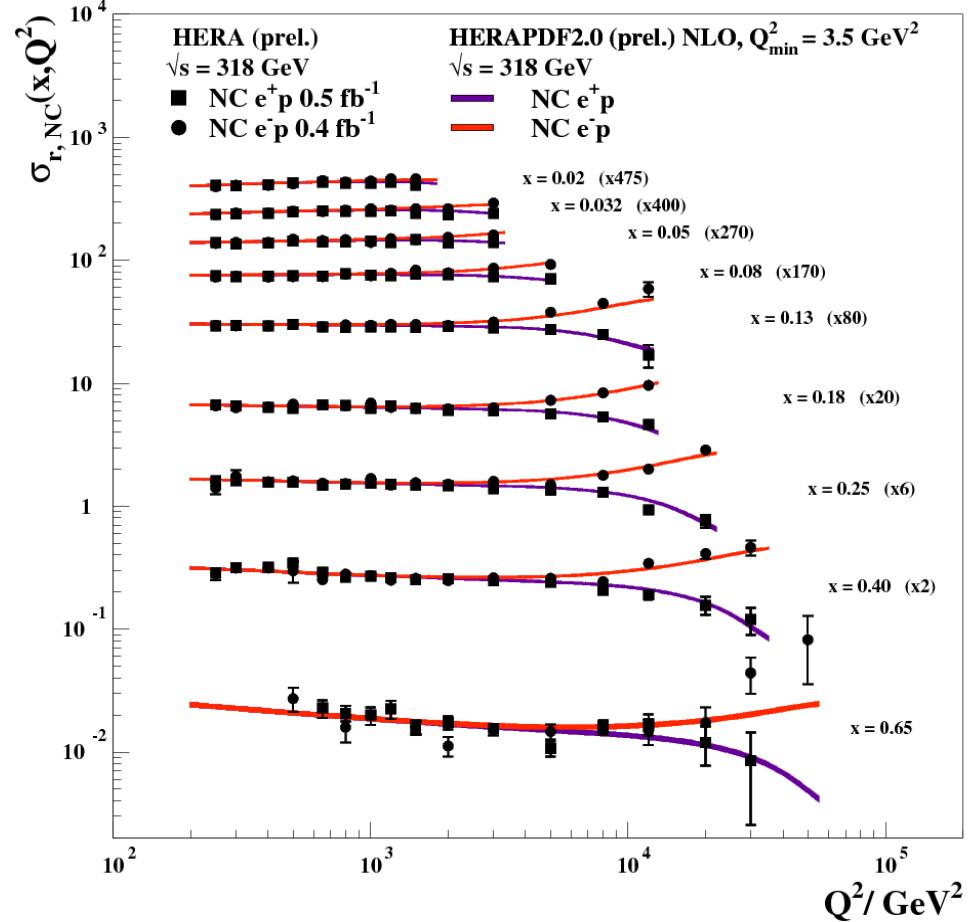


- NEW combined NC and CC cross sections - fantastic precision of data
 - QCD and EW effects beautifully seen

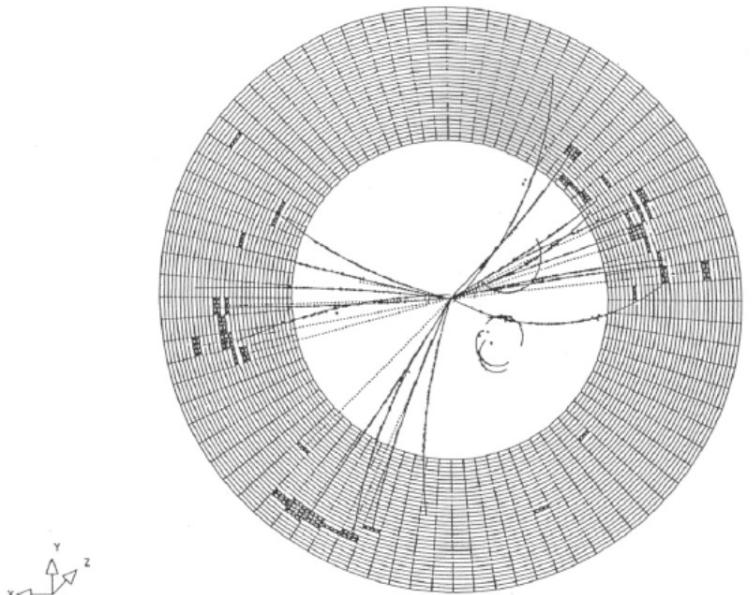
H1 and ZEUS preliminary



H1 and ZEUS preliminary



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



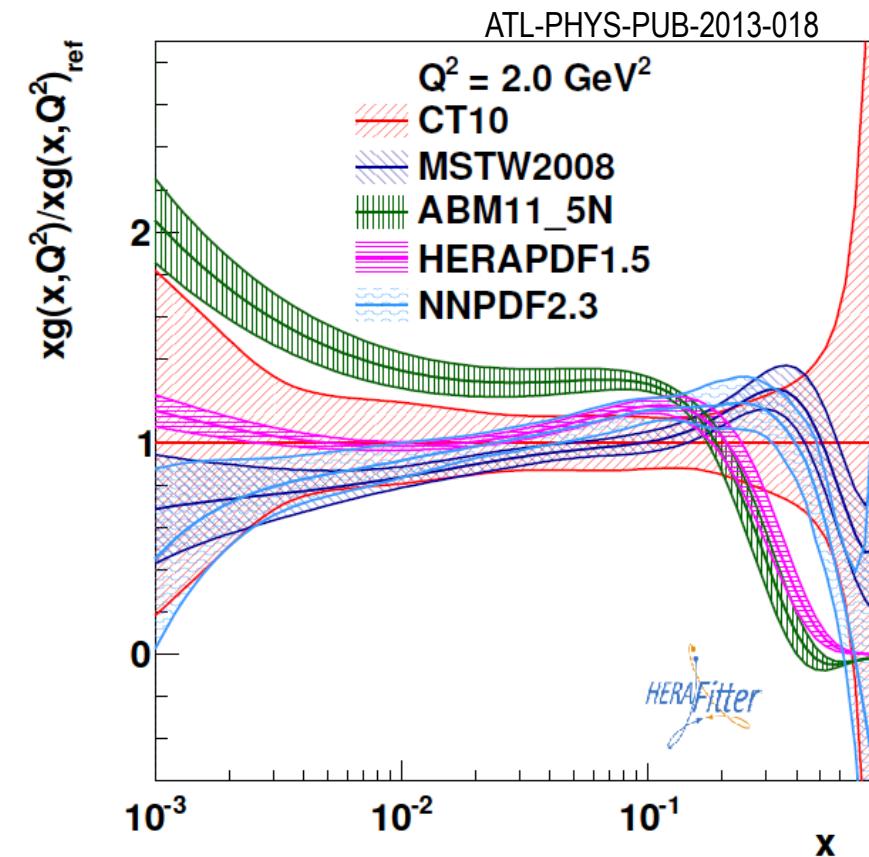
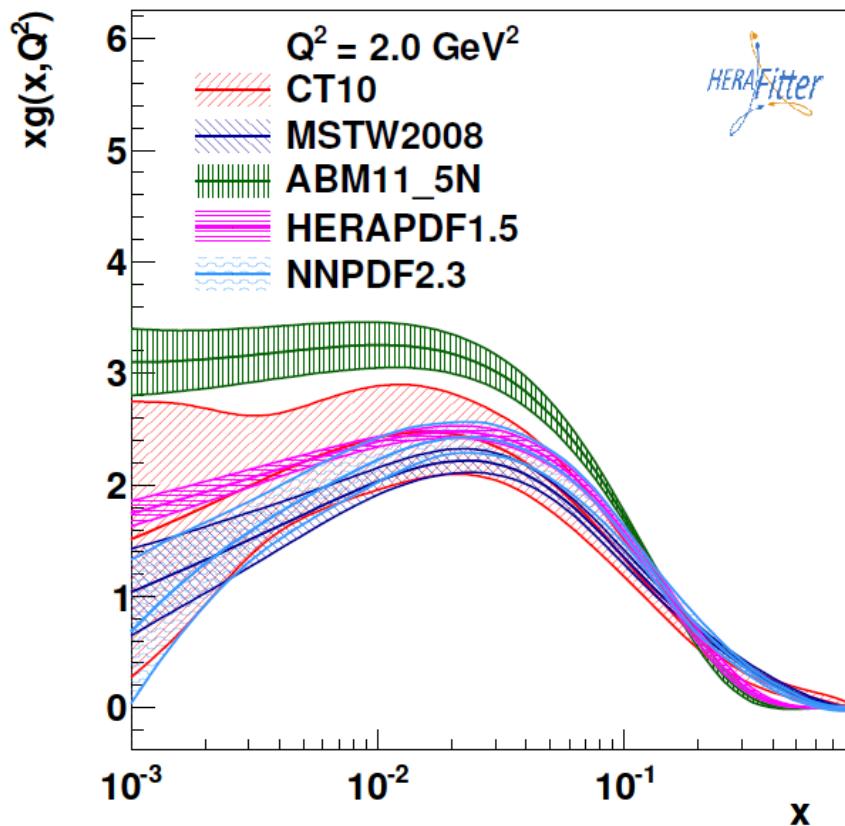
35th anniversary of GLUON

- PETRA, 1979

```
*** SUMS (GEV) *** PTOT 35.768 PTRANS 29.964 PLONG 15.768 CHARGE -2  
TOTAL CLUSTER ENERGY 15.169 PHOTON ENERGY 4.893 NR OF PHOTONS 11
```

Life starts after 35

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

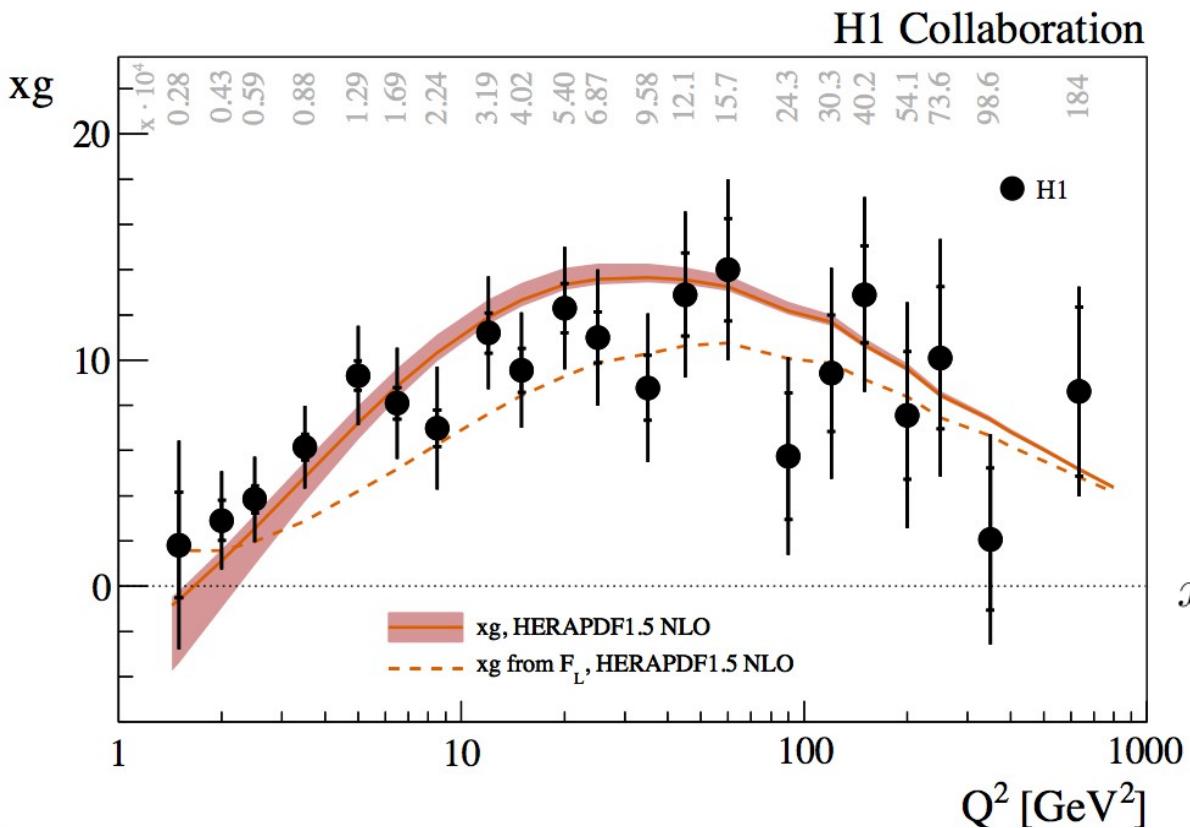


Gluon needs to be better constraint

- (In)direct constraints
 - scaling violation, collider jet data, prompt photon data, total $t\bar{t}$ cross sections

Gluon meets F_L

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

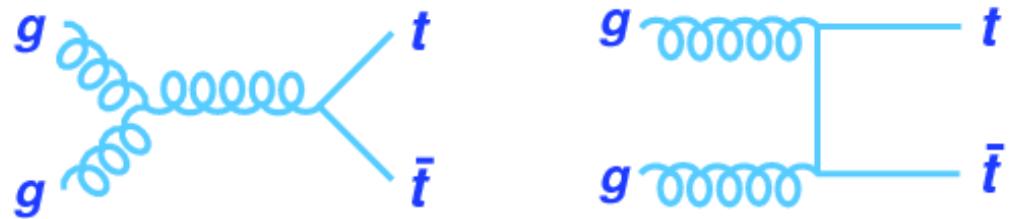


- Direct extraction of gluon density from F_L using approximation

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

Gluon approximated from F_L agrees with gluon determined from scaling violations

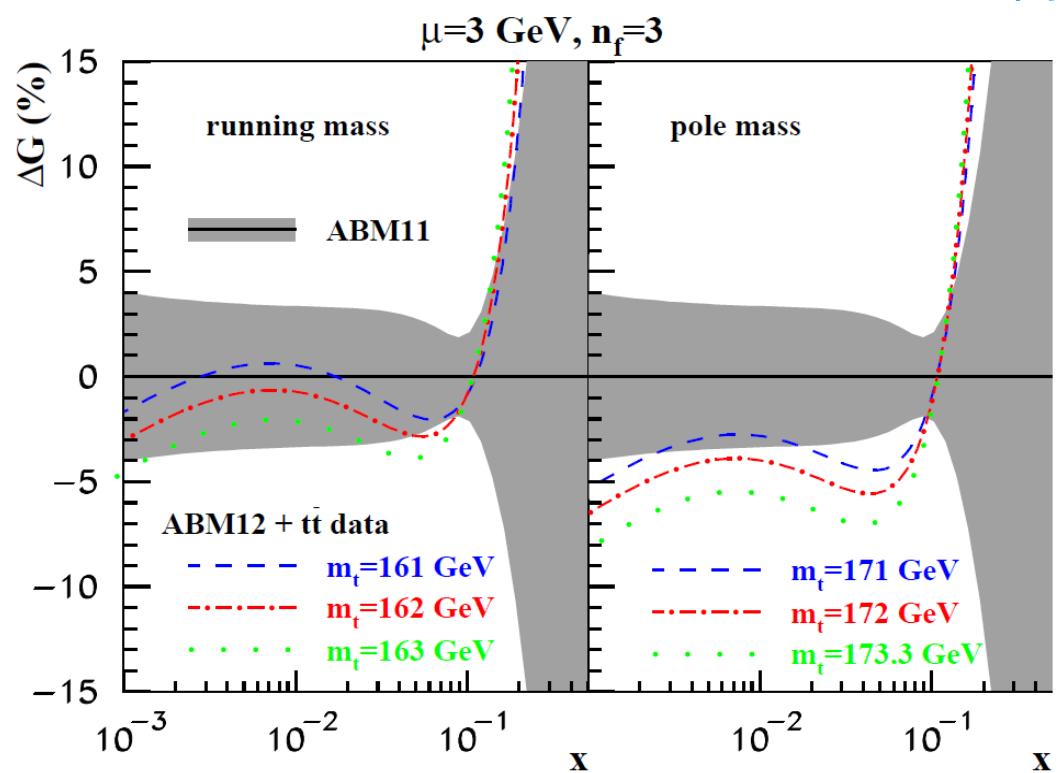
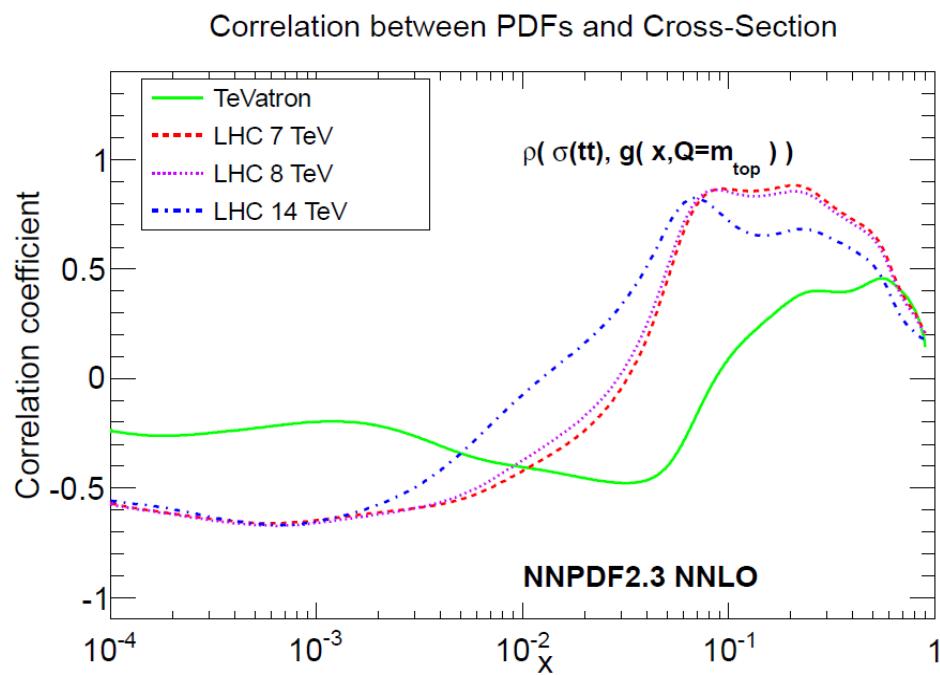
Gluon meets top quark



- Directly sensitive to large- x gluon PDF
- Recently computed in full NNLO QCD
 - For running and pole top mass
- X-section predictions from ABM and JR

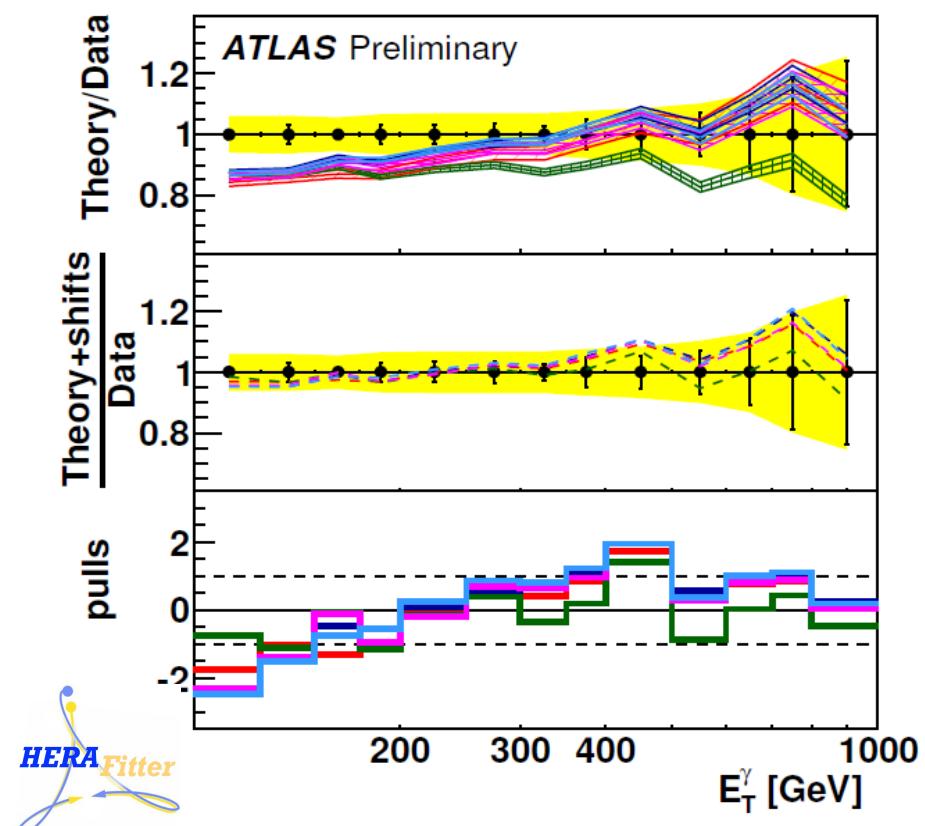
- ABM12 added combined $t\bar{t}$ cross sections from LHC and Tevatron to test impact on
 - gluon PDF
 - strong coupling α_s
 - value and scheme choice for m_t

K. Klimek, 23.05.14, Parton

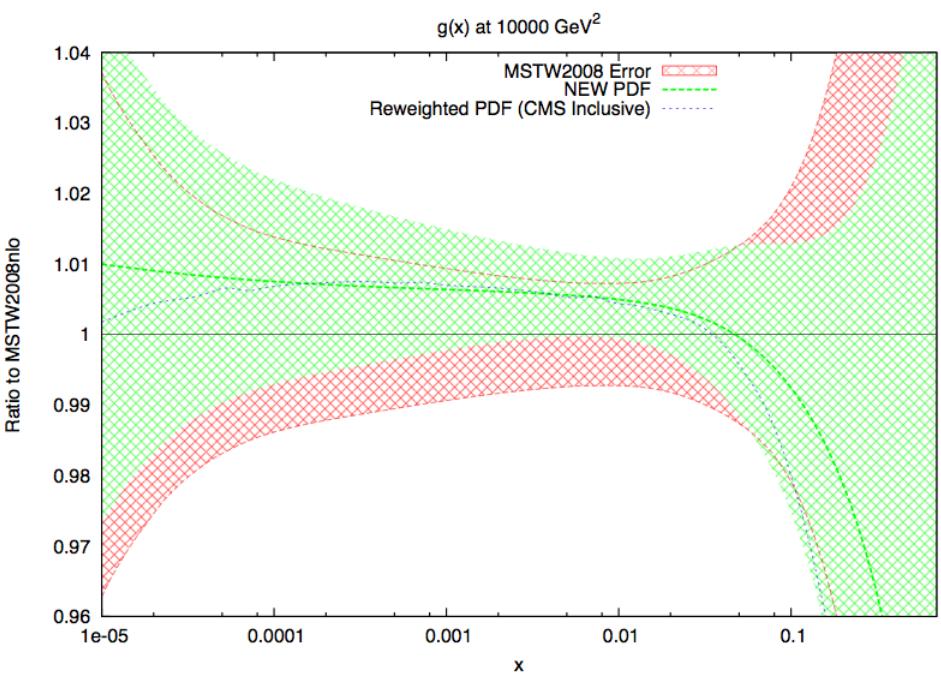


Gluon meets prompt photons and jets

- Prompt γ data help constrain gluon

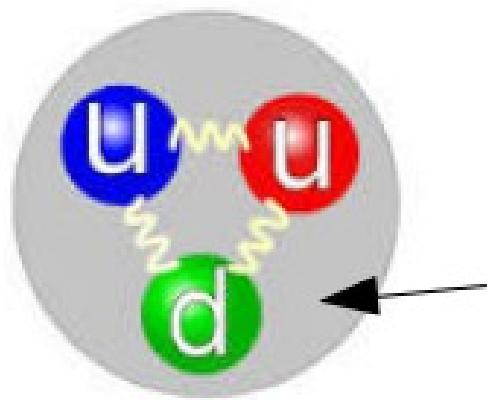


- LHC jet data included directly in the framework of MSTW PDF
- Good agreement between ATLAS and CMS data sets

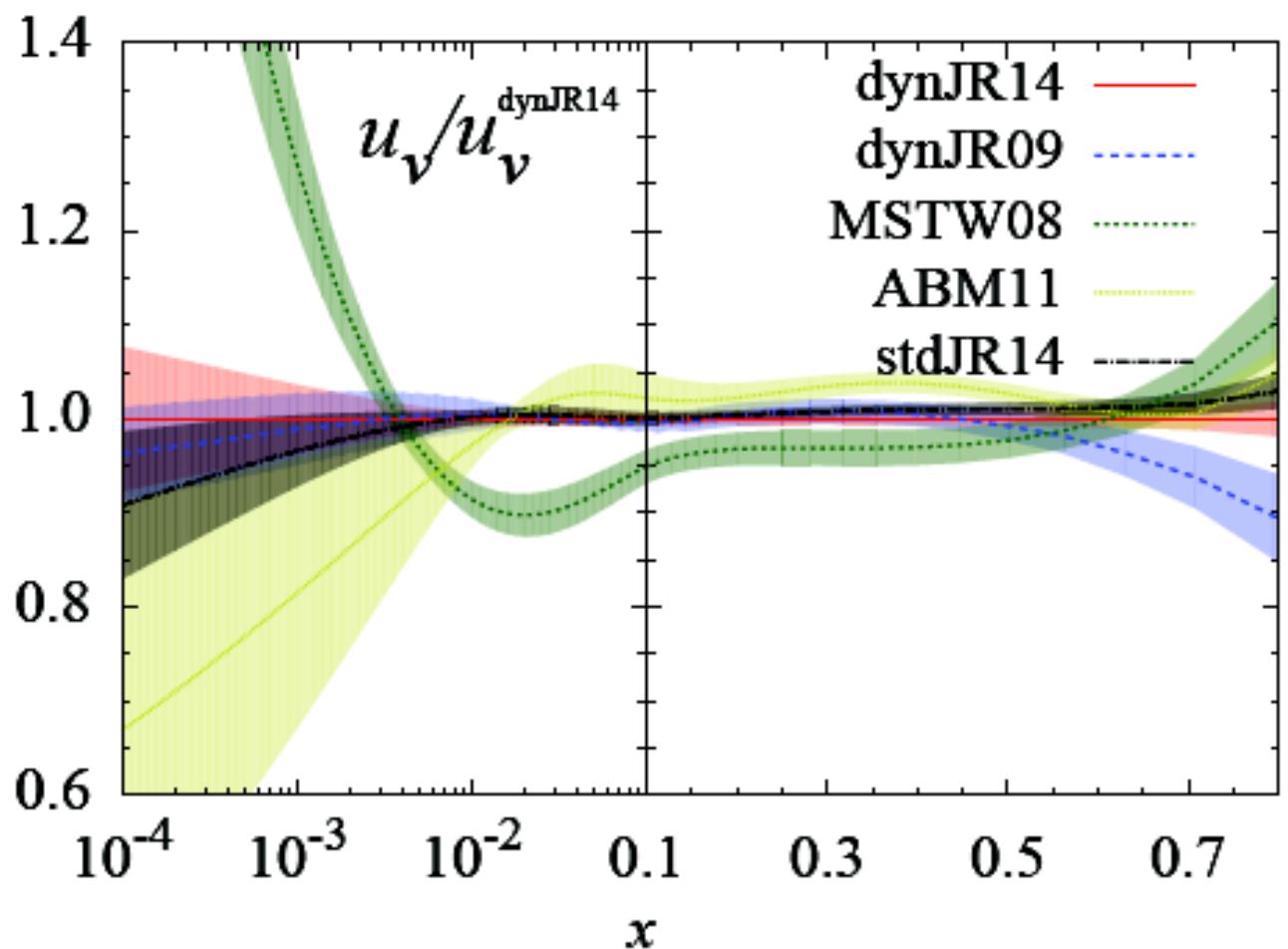


- Precise data - scale uncertainty dominant - for both kinds of measurements

NNLO calculations necessary to fully exploit PP and jet measurements

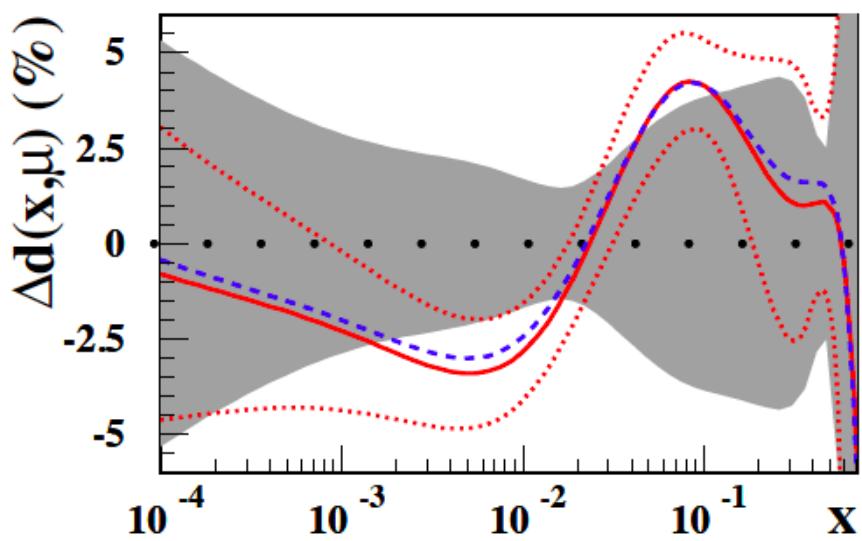


What's
that?!



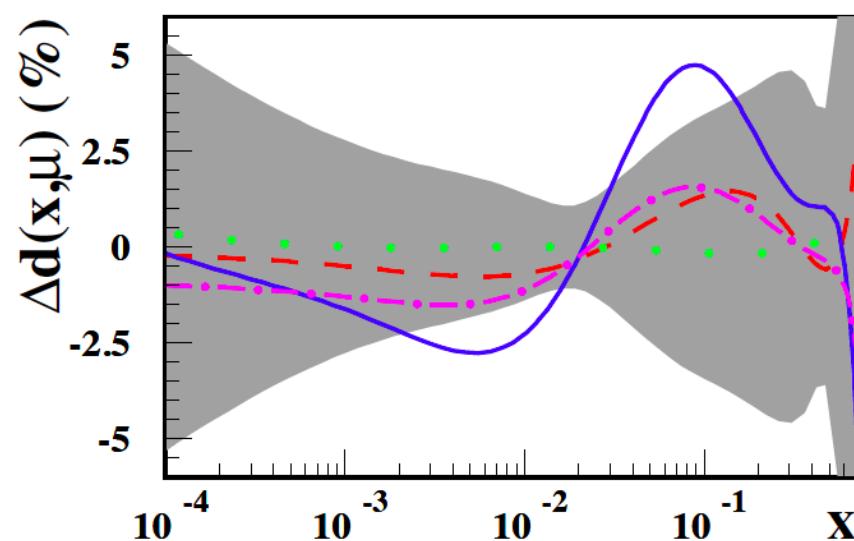
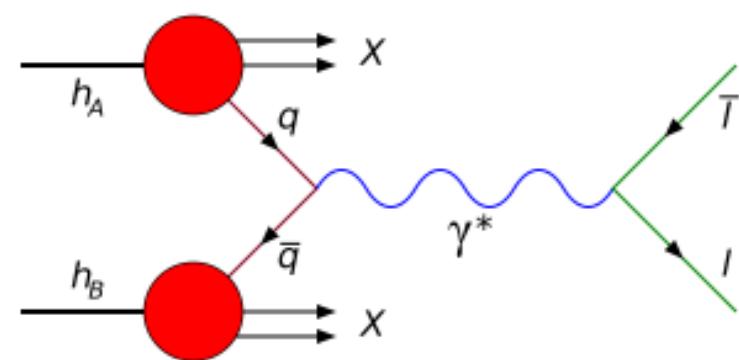
What DY can teach us?

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



• • • ABM12 (no LHC)
• • • + LHC (1 iter.)
— — — + LHC (2 iter.)

- Improved determination of quark distribution at $x \sim 0.1$
- Better constraint on d-quark



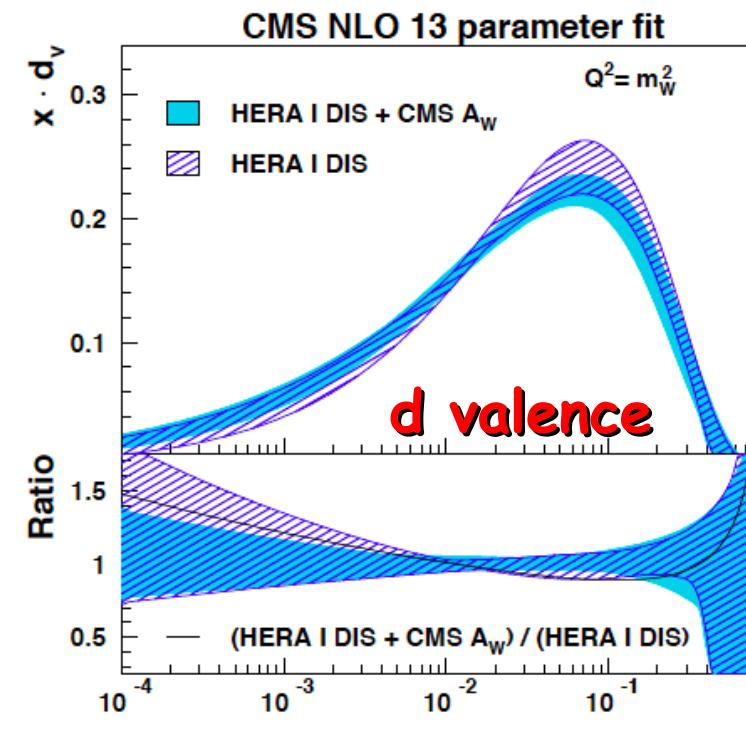
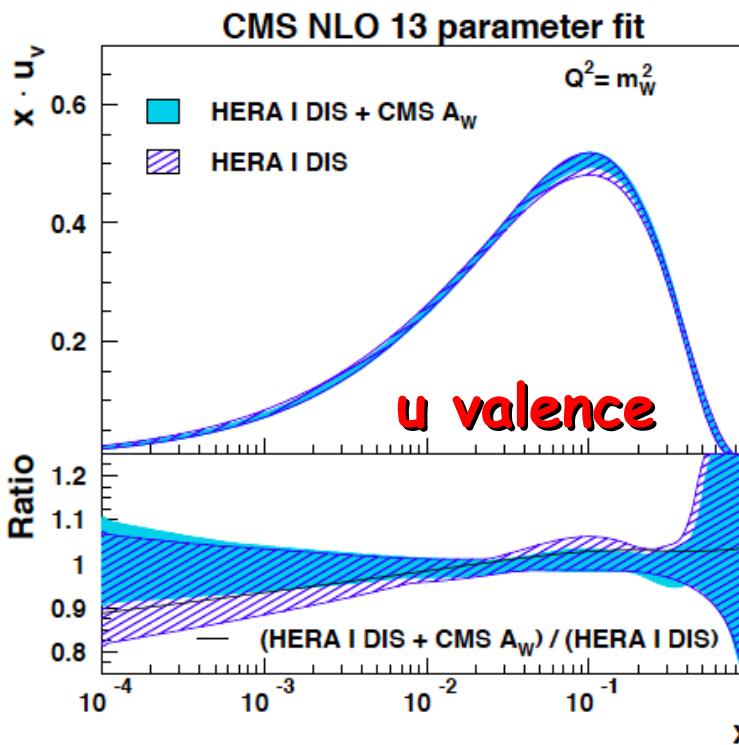
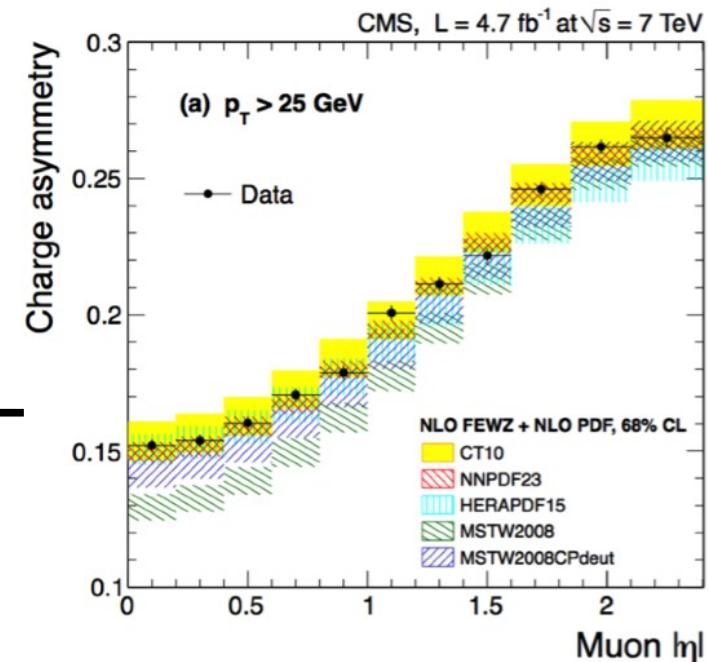
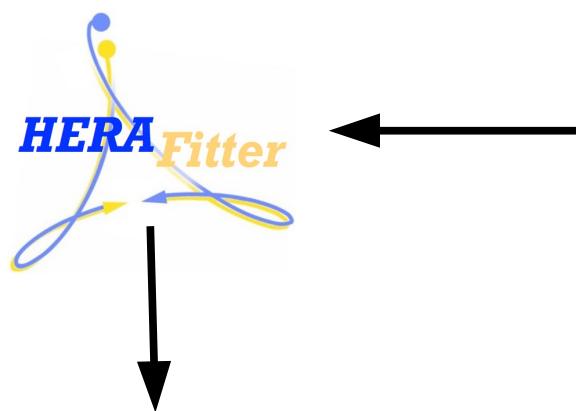
— + LHCb (W^+, W^-)
• • • + LHCb (Z)
— — — + CMS (W^+/W^-)
- - - - + ATLAS (W^+, W^-, Z)



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



Valence
uncertainties
significantly
improved



A SMOOTH SEA
NEVER MADE A SKILLED SAILOR.

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

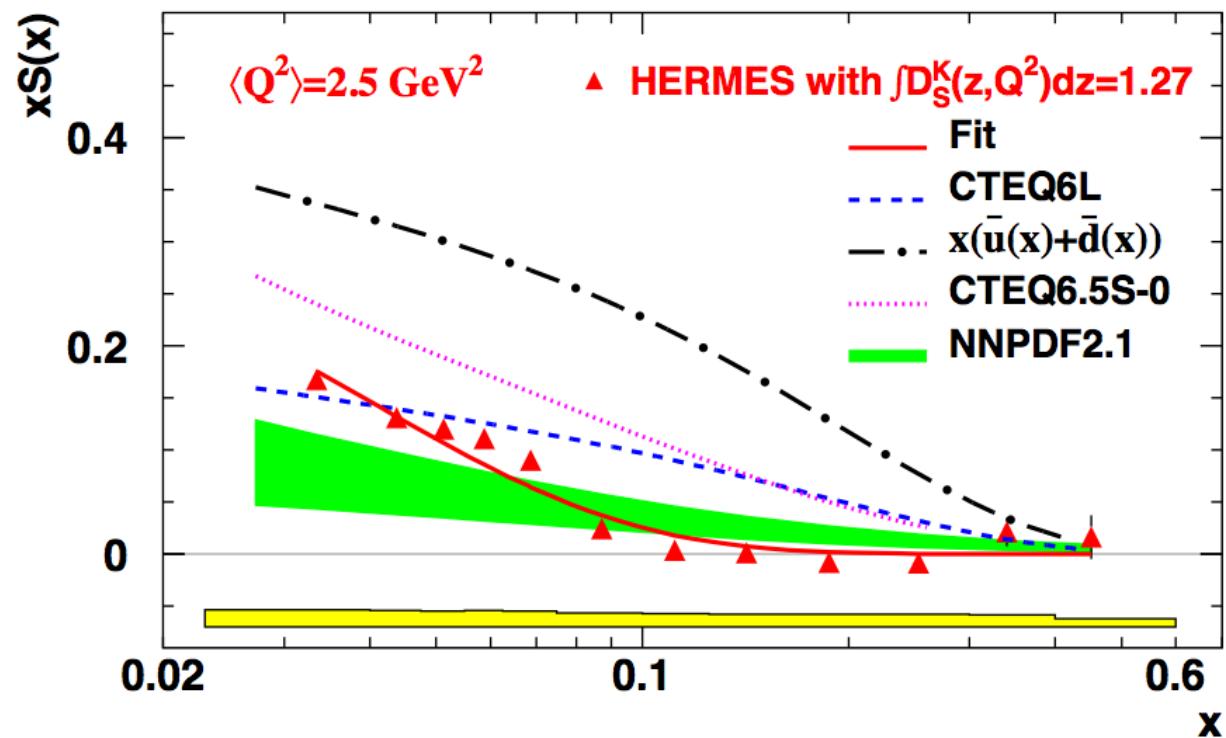
Is light-quark sea symmetric as SU(3) suggests?

Is strangeness suppressed due to s-quarks large masses?

Strange sea @ LO from HERMES

- Inclusive data only have no sensitivity to strange sea
- Direct measurements of strange particles can help constraining sea
- HERMES extracted strange PDF@LO using newest K^+K^- multiplicities

- $xS(x;Q^2)$ shape
- strikingly different from CTEQ6L and other global LO PDFs
 - strikingly different from sum of light antiquarks
 - absence of strength above $x \sim 0.1$ discrepant with CTEQ6L

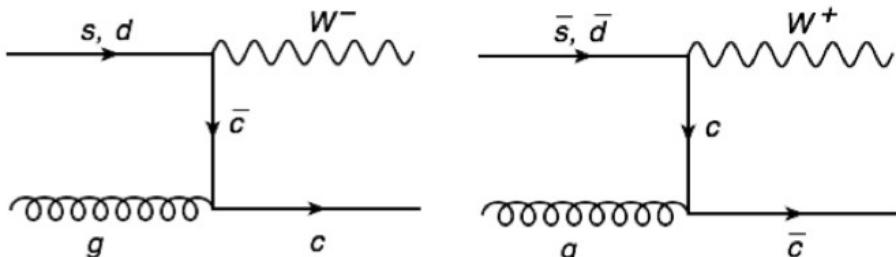


Distribution softer than that determined by other analysis



Prince Charming helps strangers

- PDFs with different strange sea assumptions
- $W + \text{charm}$ measurements

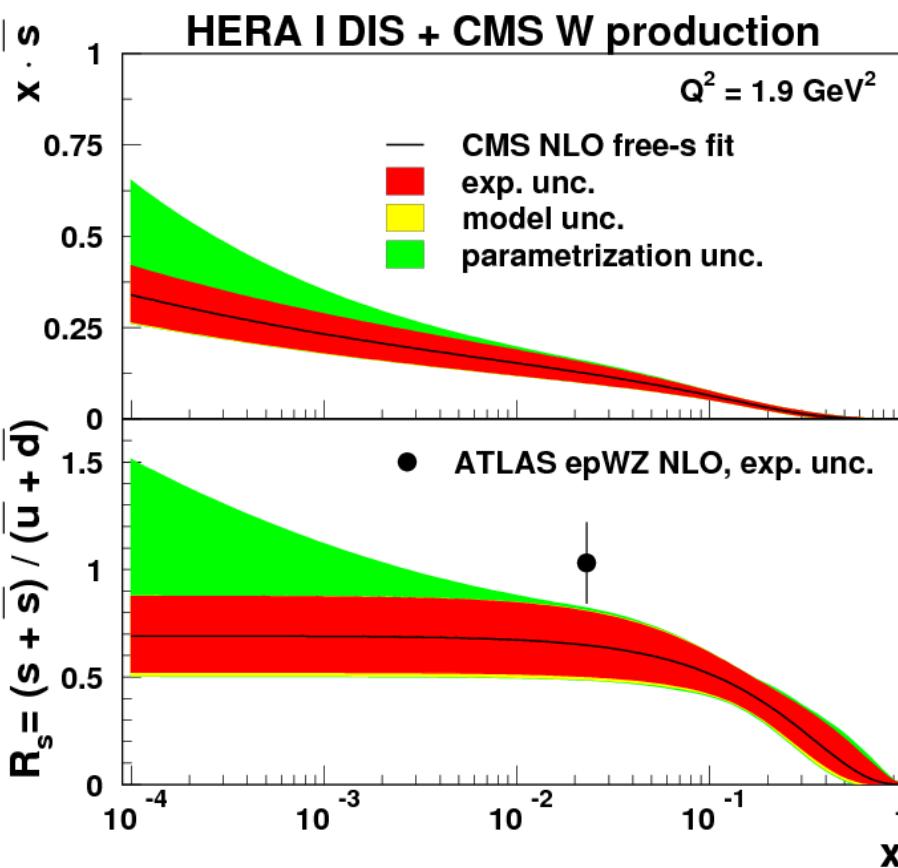
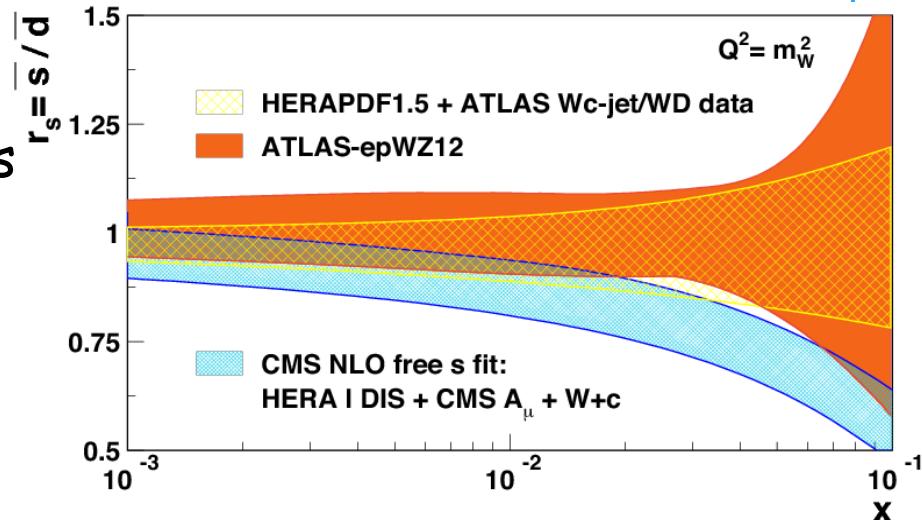


- ATLAS results

Supports SU(3)-symmetric light-quark sea

- CMS results

Agreement with NOMAD [Nucl.Phys. B876 (2013) 339]



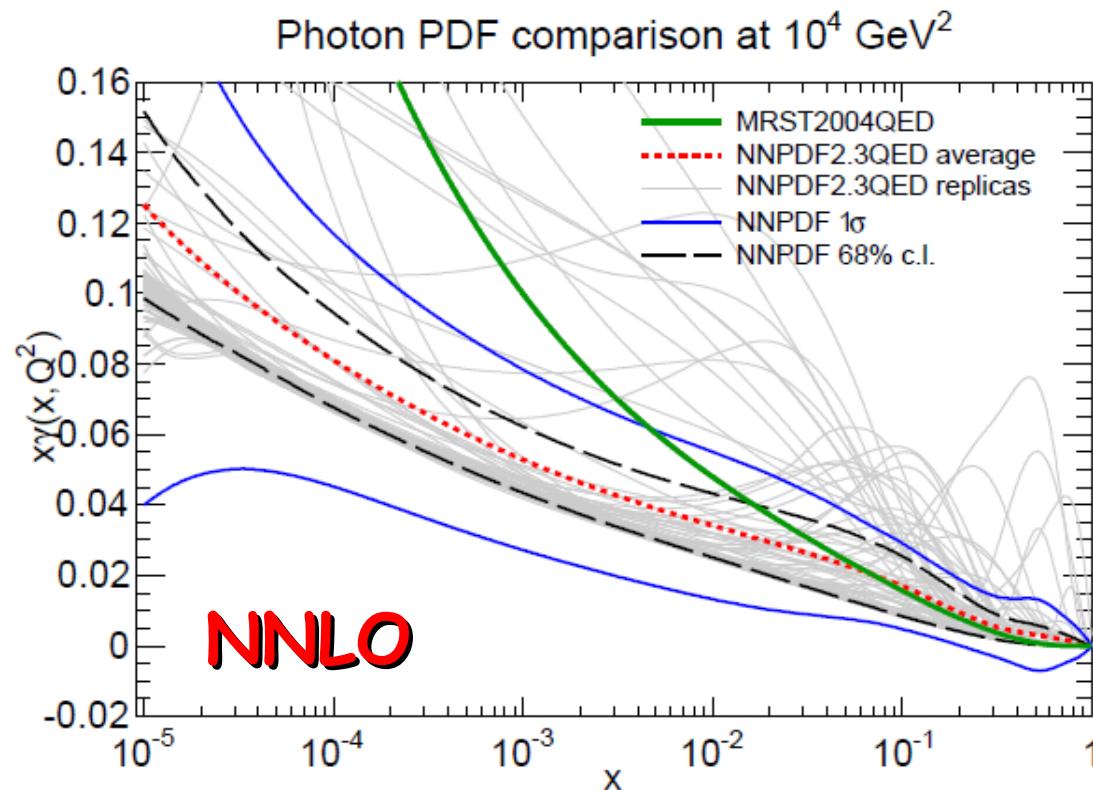
Yet another one - please meet photon PDF



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 $x > 0.3$

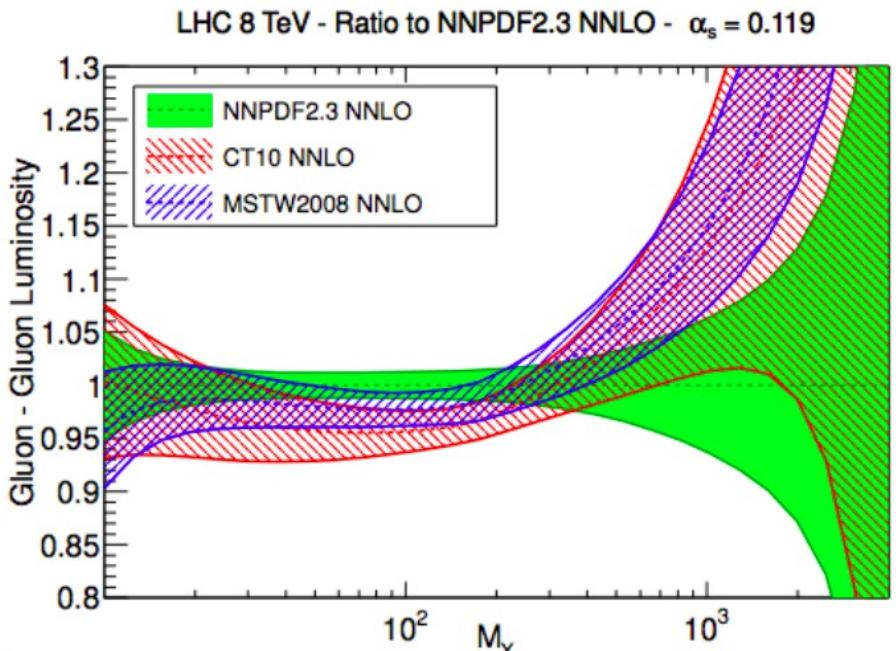


- Another approach to be implemented into HERAFitter and used for QED fits of LHC data: arXiv:1401.1133 (R. Sadykov)

Summary

V. Radescu's DIS14 talk

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



Large uncertainties at large masses degrade the prospects for eventual characterization of new BSM heavy particles

Volk

What is mid/long-term perspective?

Experimental long-term perspective

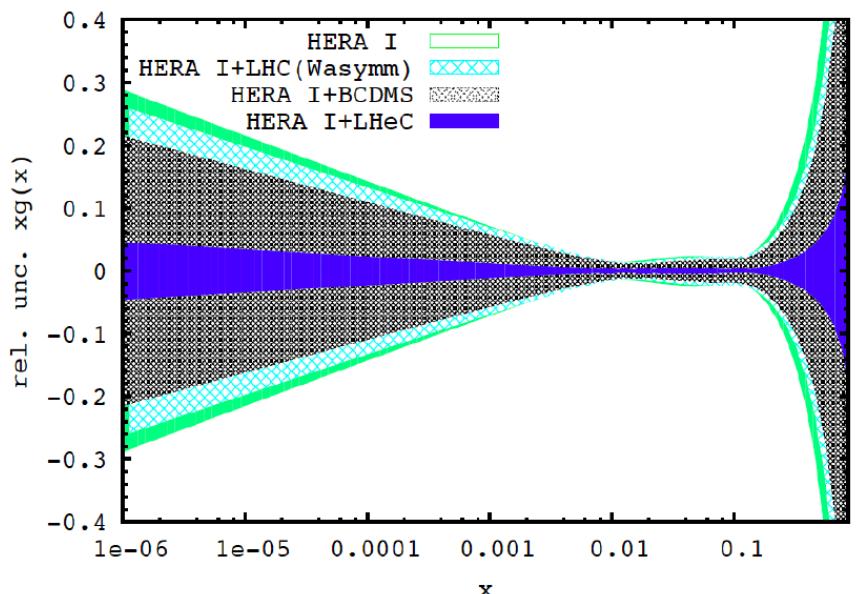
Measurements

- Nomad & Chorus give strange sea
- LHC data - so far rather limited impact on global PDFs
- LHC data needed with highest precision
 - Statistics generally not an issue
 - Detailed data understanding crucial
- Comparison and understanding between ATLAS, CMS & LHCb needed
- W, Z rapidity data needed at <1%
 - Understanding of systematics!
- Jets cross sections
 - Jet energy scale!
- W+charm
 - Total uncertainty aimed at 3%

New machines/experiments

LHeC

- better low- x , Q2 knowledge
- OK for all scales: low- x , Q2 knowledge improves high- x , Q2 knowledge



EIC - electron-ion collider

- all x and Q
 - access to gluon and sea quarks
- High luminosity LHC - problematic

Theoretical long-term perspective

- Various opinions BUT one is very obvious for everybody
- **NNLO calculations necessary**
 - Existing for some processes: total ttbar cross section
 - Missing for most of the others
- Precision of the data so high that NNLO calculations are crucial for reducing PDF uncertainties
 - NNLO predictions for jets a long-standing issue
 - Massive work right now for pp collisions
 - Maybe final results within 2 years
- Open issues
 - Heavy flavor scheme - GMVFNS & FFNS
 - W+charm @ NNLO
 - Higher-twist contributions to DIS F_2/F_L data

Additional material

Global analysis of parton distributions

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

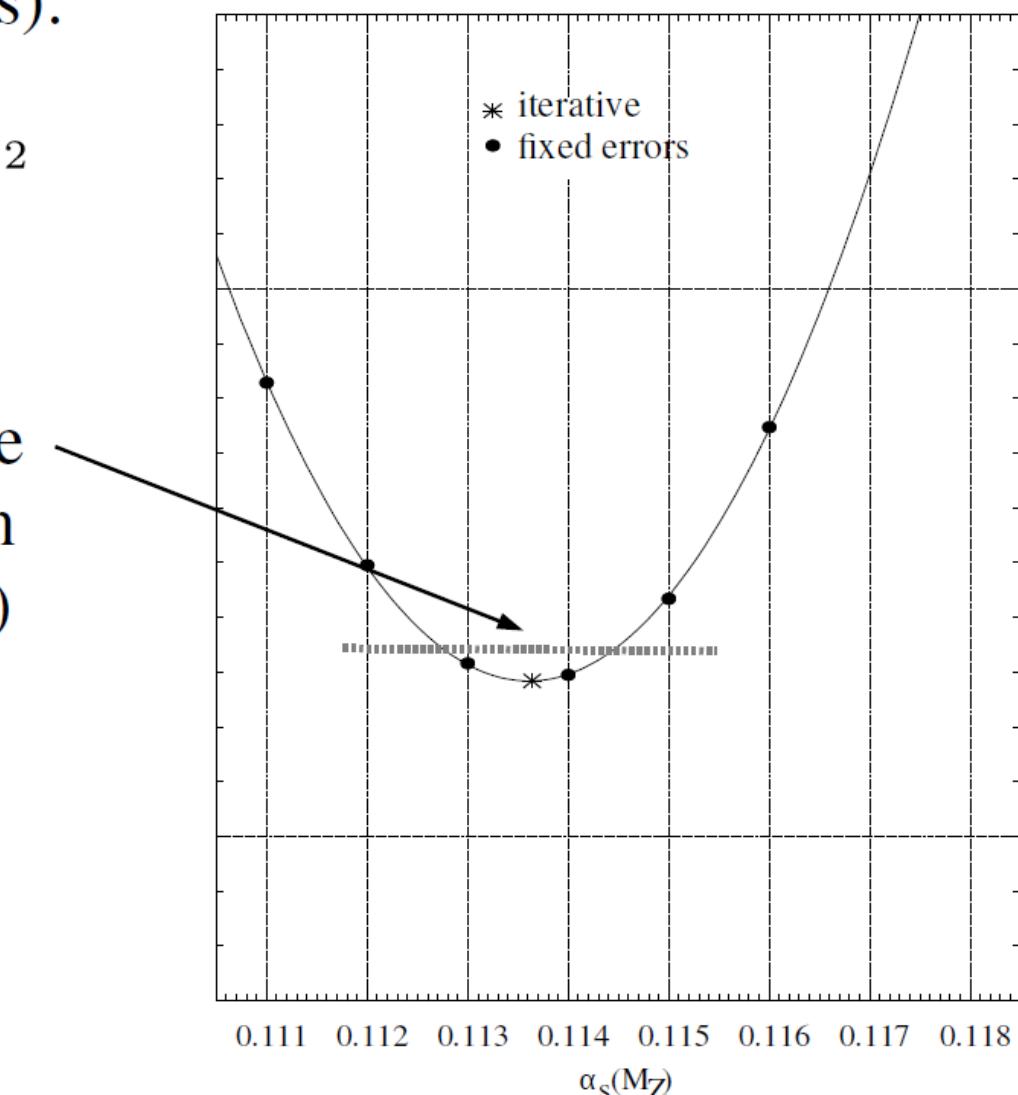
Method: Parametrizations $xf(x, Q_0^2) = Nx^a(1-x)^b$ function(x)
and usual *statistical estimation* (fits):

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

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.



Current global PDF groups

ABM: Careful treatment of experimental correlations, nuclear and power corrections in DIS, FFNS **NEW! ABM12** [arXiv:1310.3059](https://arxiv.org/abs/1310.3059)

MSTW: negative input gluons at small- x , rather “large” ^{Update}
 $\alpha_s(M_Z^2)$, GMVNS ^{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

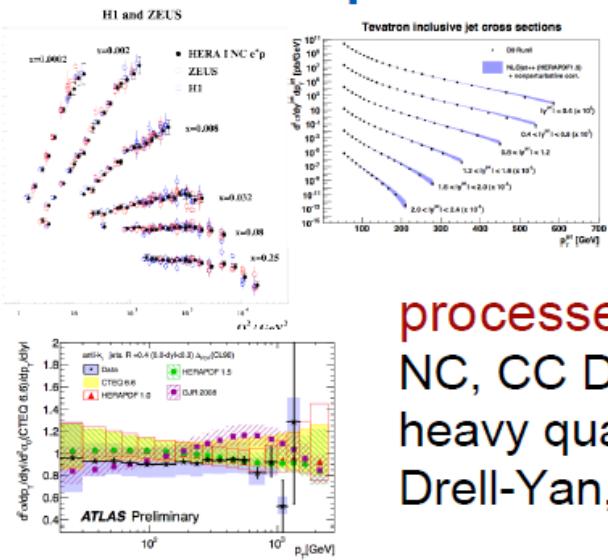
CTEQ-TEA: parametrization with exponentials, substantially inflated uncertainties, GMVFNS **Constraints and impact on LHC results**

JR [with E. Reya]: detailed study of input scale dependence, dynamical (and “standard”) versions, FFNS
(there are more groups focused on particular aspects, e.g. CTEQ-JLab)

NEW! JR14

[arXiv:1403.1852v](https://arxiv.org/abs/1403.1852v)

experimental input



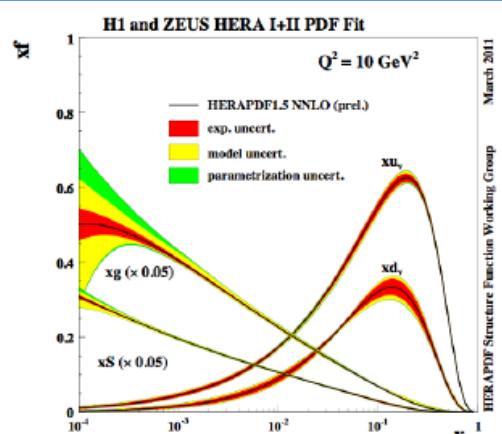
experiments:
HERA, Tevatron,
LHC, fixed target

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

$\alpha_s(M_Z), m_c, m_b, m_t, f_s, \dots$

Theory predictions

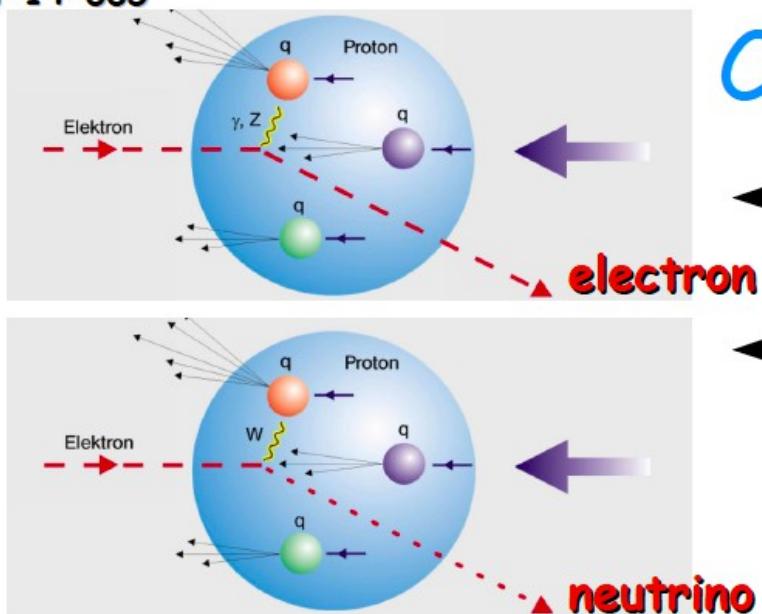
Benchmarking

Comparison of schemes

Inclusive measurements from HERA are core of every parton density extraction



ZEUS-prel-14-005



Combined inclusive DIS



H1prelim-14-041

Neutral Current (NC)

γ, Z^0 exchange

Charged Current (CC)

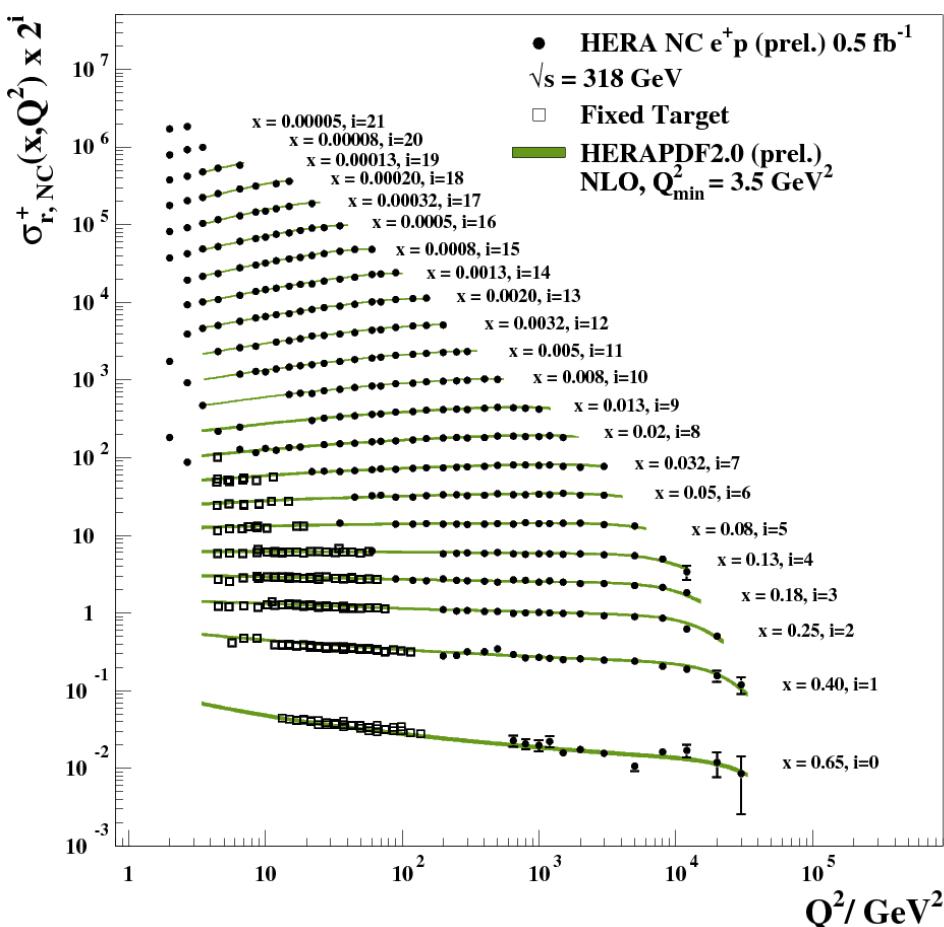
W^\pm exchange

HERA combined inclusive cross sections

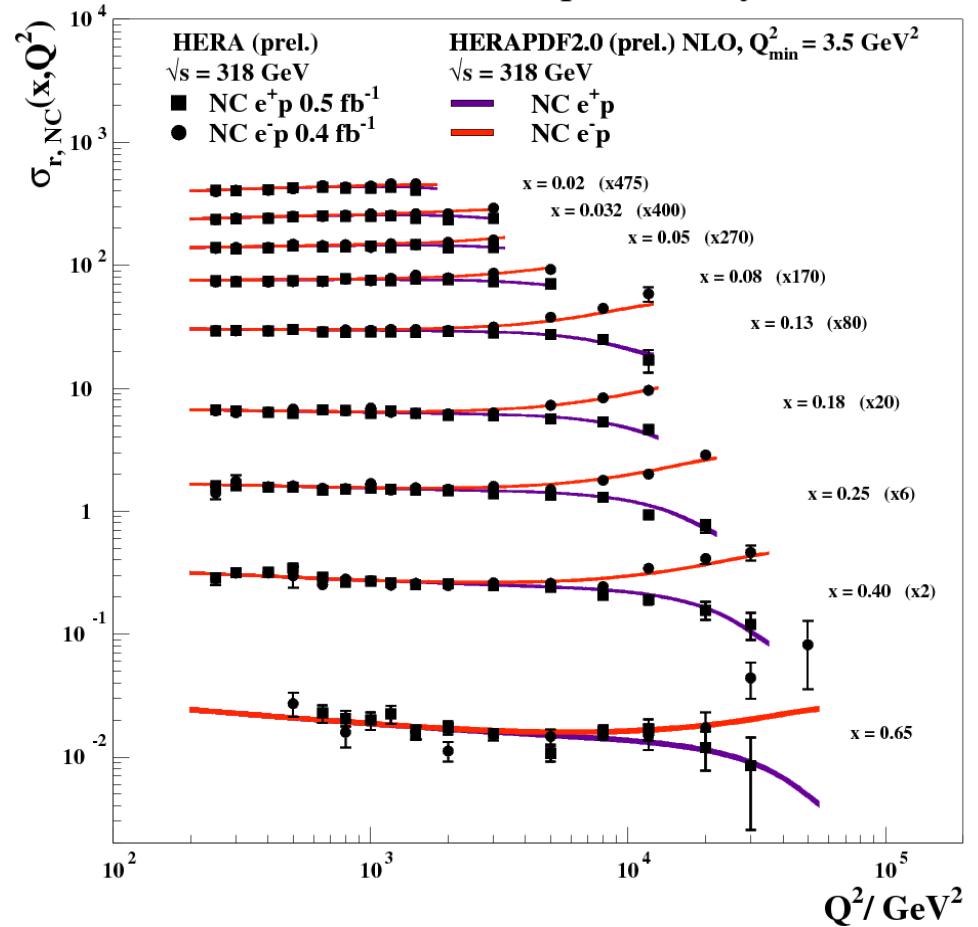
- Combined NC and CC cross sections
 - Fantastic precision of data
 - QCD and EW effects beautifully seen



H1 and ZEUS preliminary



H1 and ZEUS preliminary

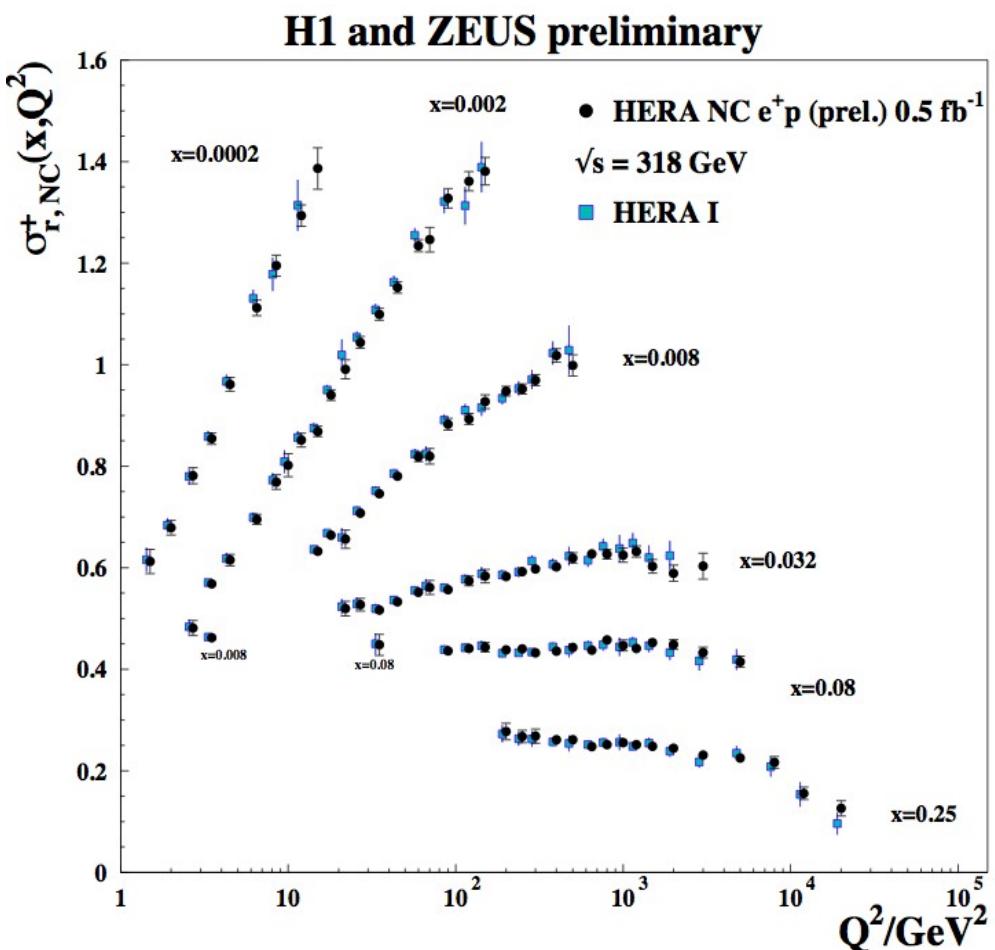


This data (exclusively!) used as input to global QCD fit HERAPDF2.0 (prel.)

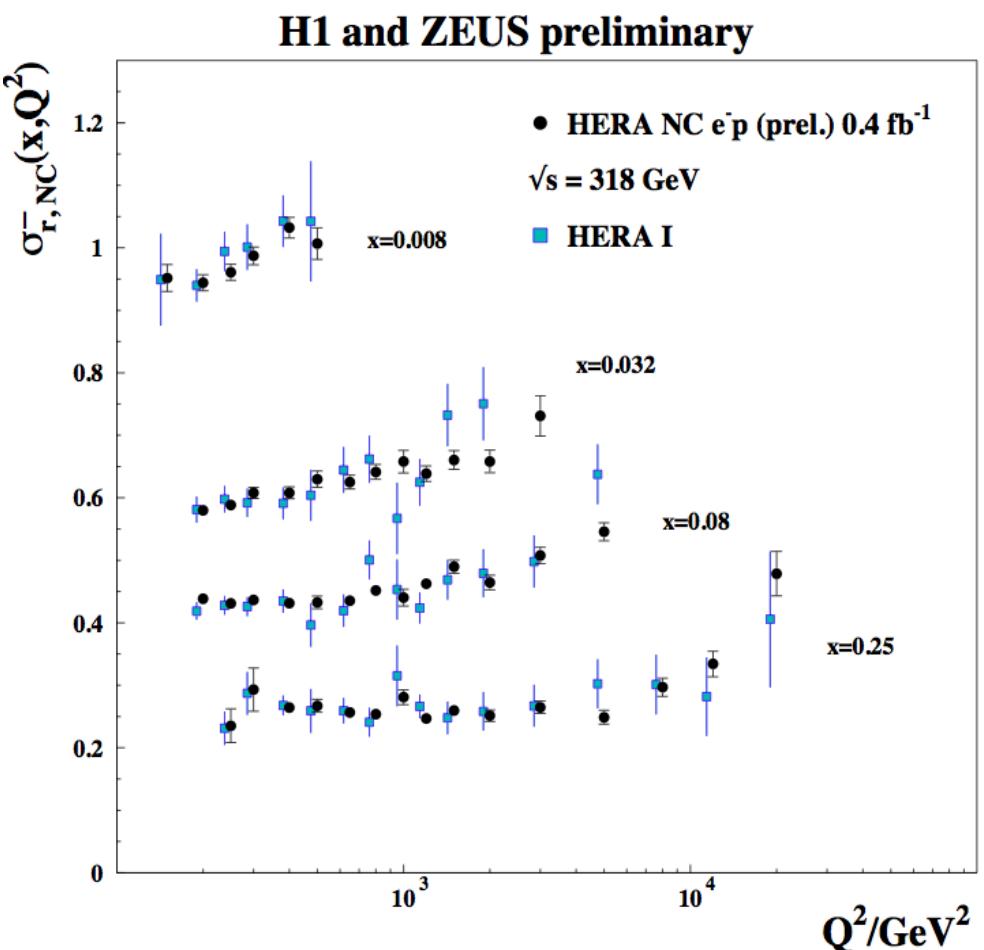
Comparison with HERAI combination

- Significant reduction of systematic uncertainties
- Significant increase of statistics

NCe⁺p: 3 times HERAI luminosity



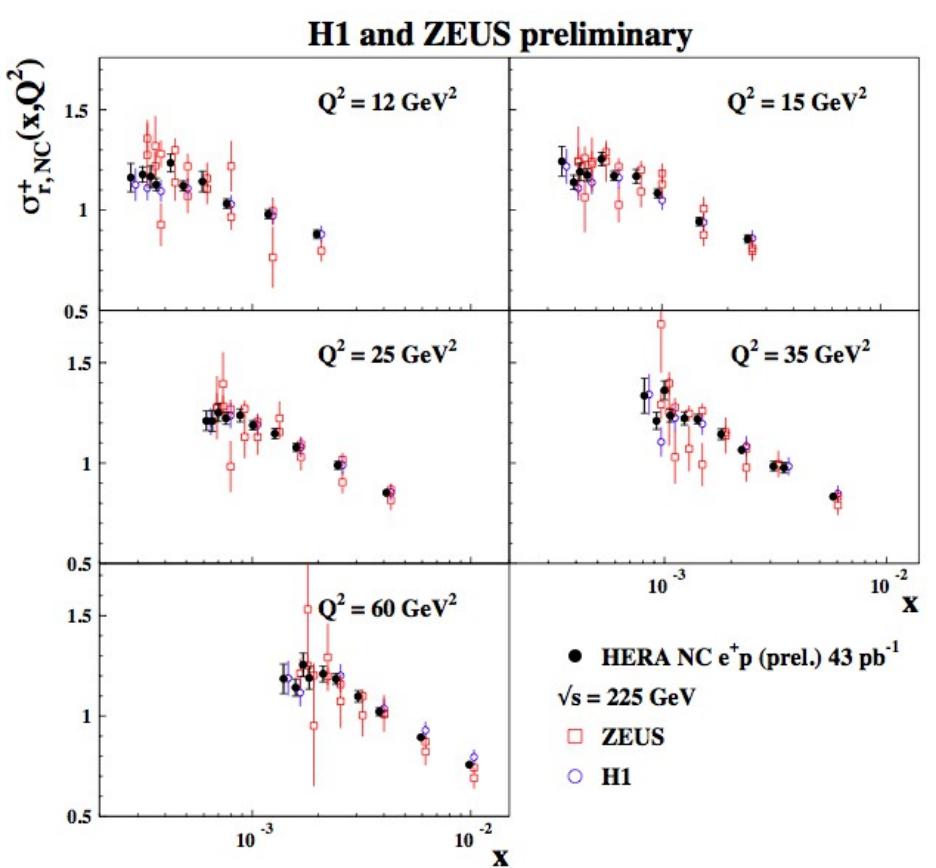
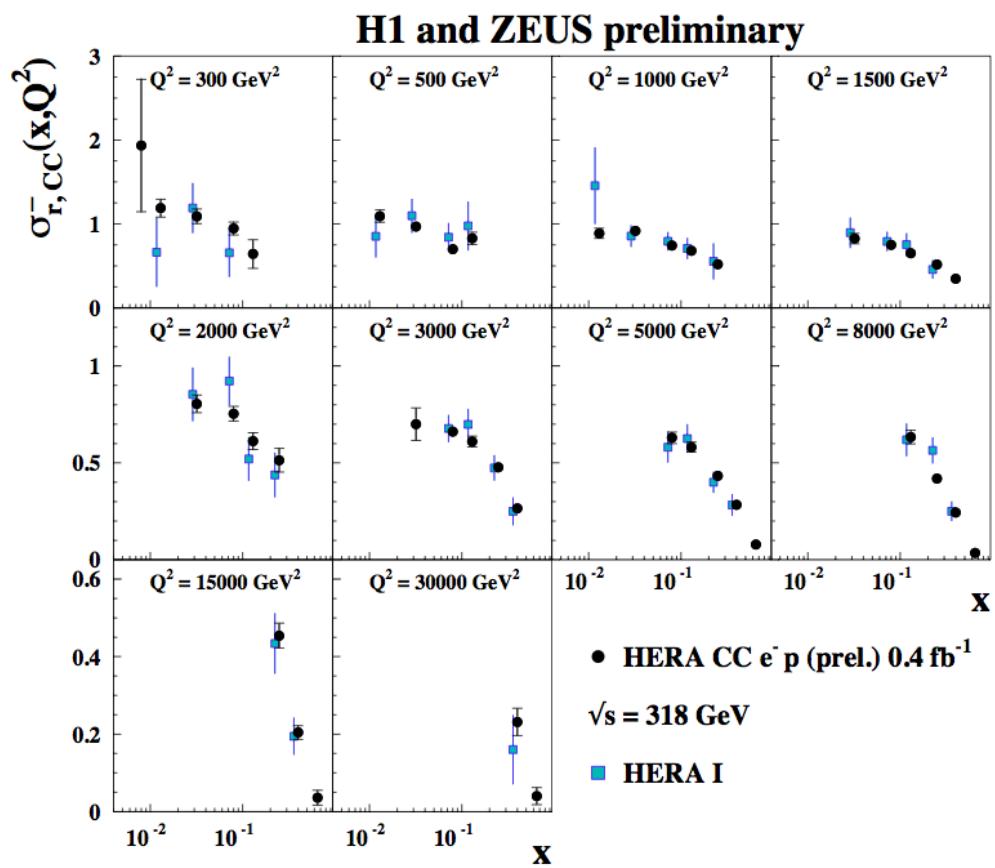
NCe⁻p: 10 times HERAI luminosity



Large gain in precision

New kinematic ranges explored

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

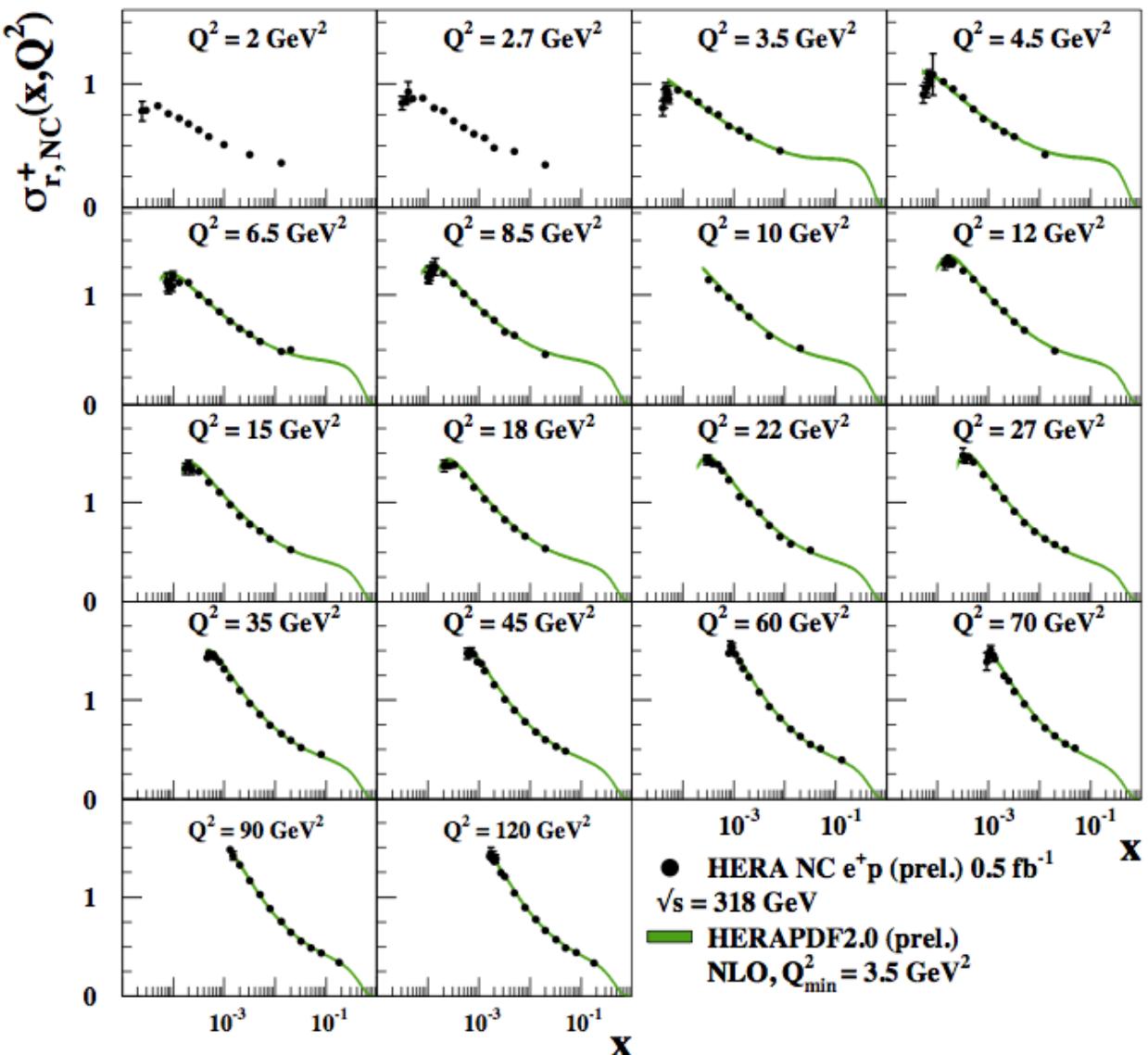


HERAPDF2.0 (prel.)

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

HERAPDF2.0 (prel.) @ NLO

H1 and ZEUS preliminary



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

$$\chi^2/\text{dof} = 1386/1130$$

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

$$\chi^2/\text{dof} = 1156/1003$$

Situation somewhat improved

- Similar results for NNLO

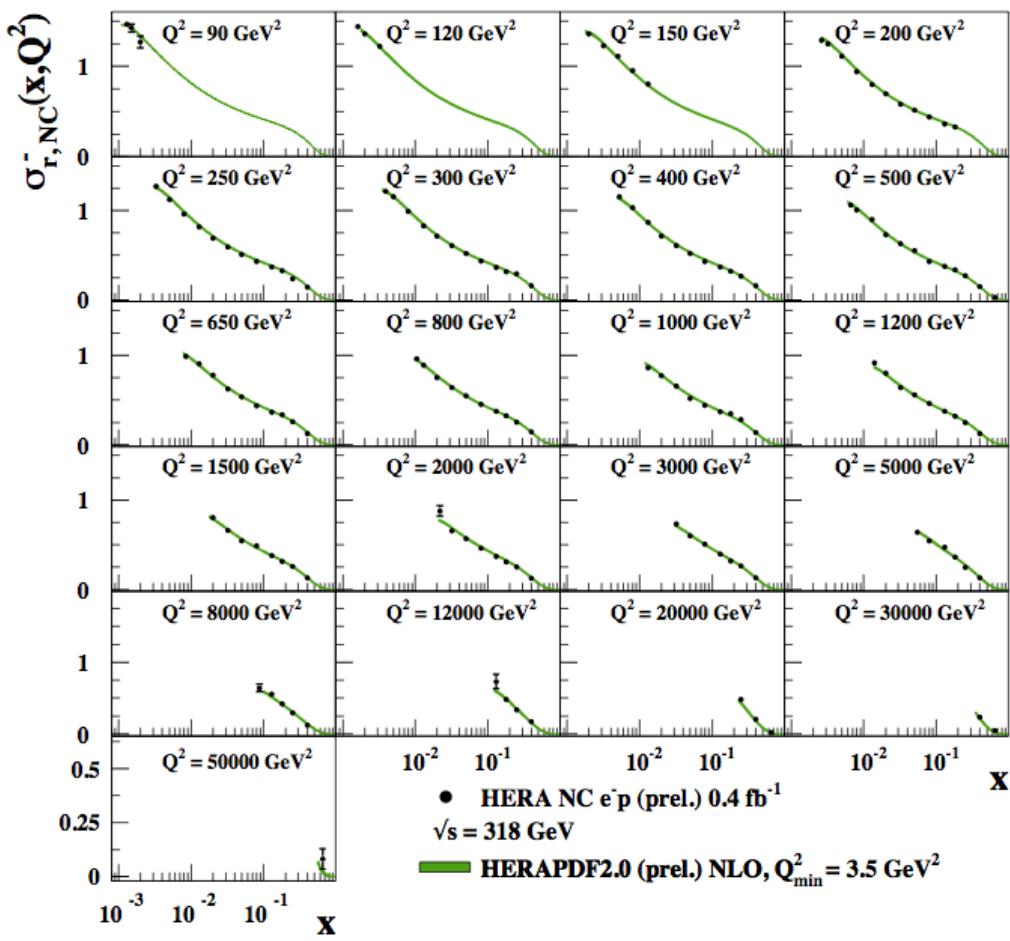
Reasonable description of NC, CC and low energy data for NLO and NNLO

HERAPDF2.0 (prel.) @ NNLO

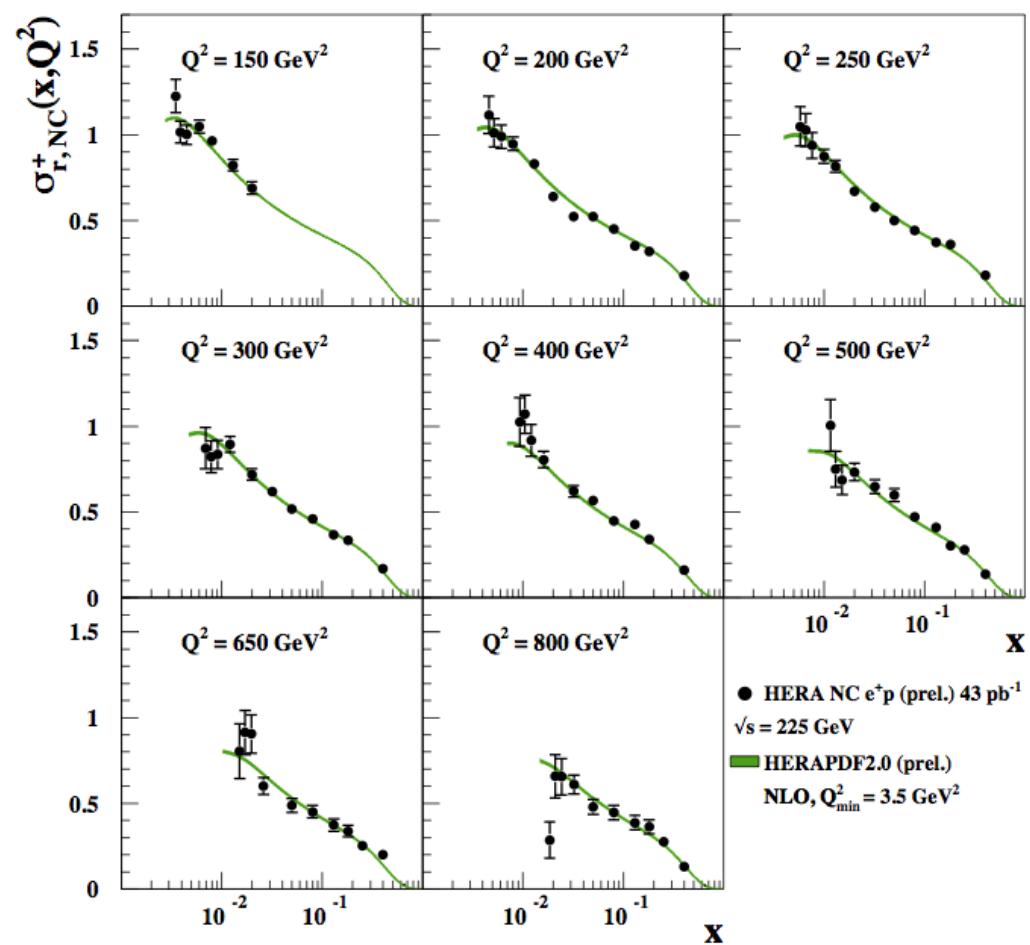
K. Klimek

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

H1 and ZEUS preliminary



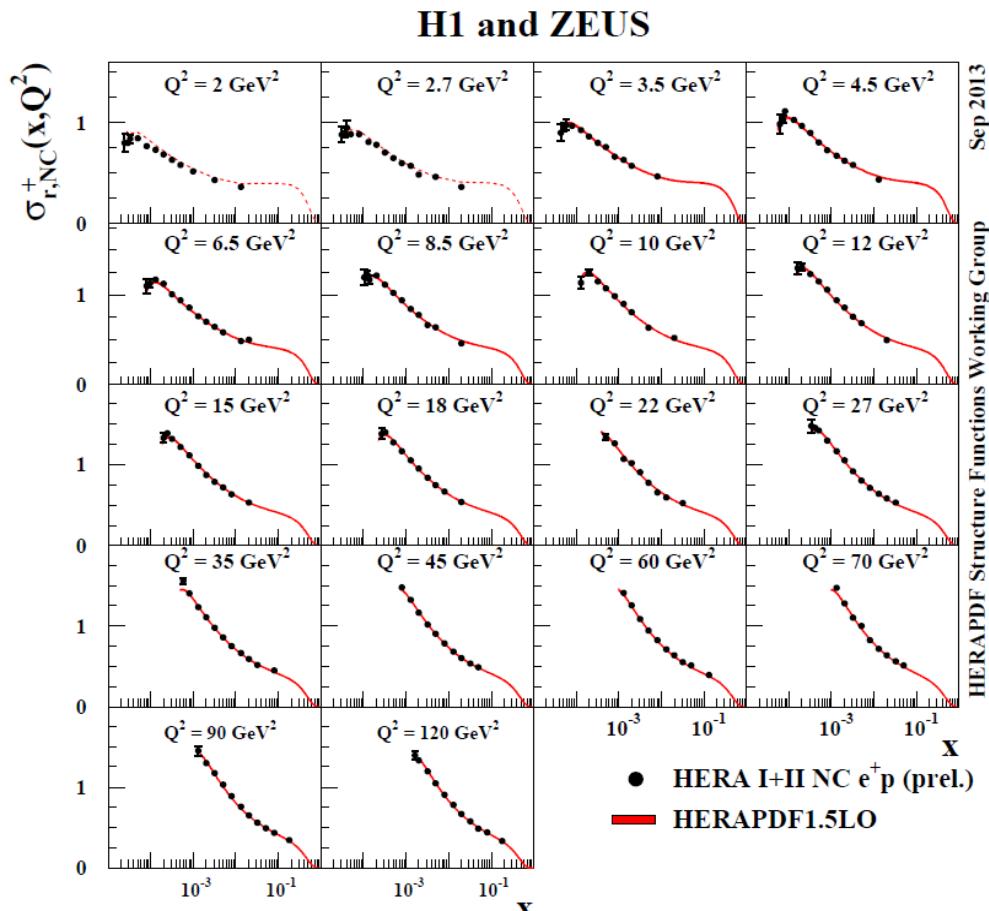
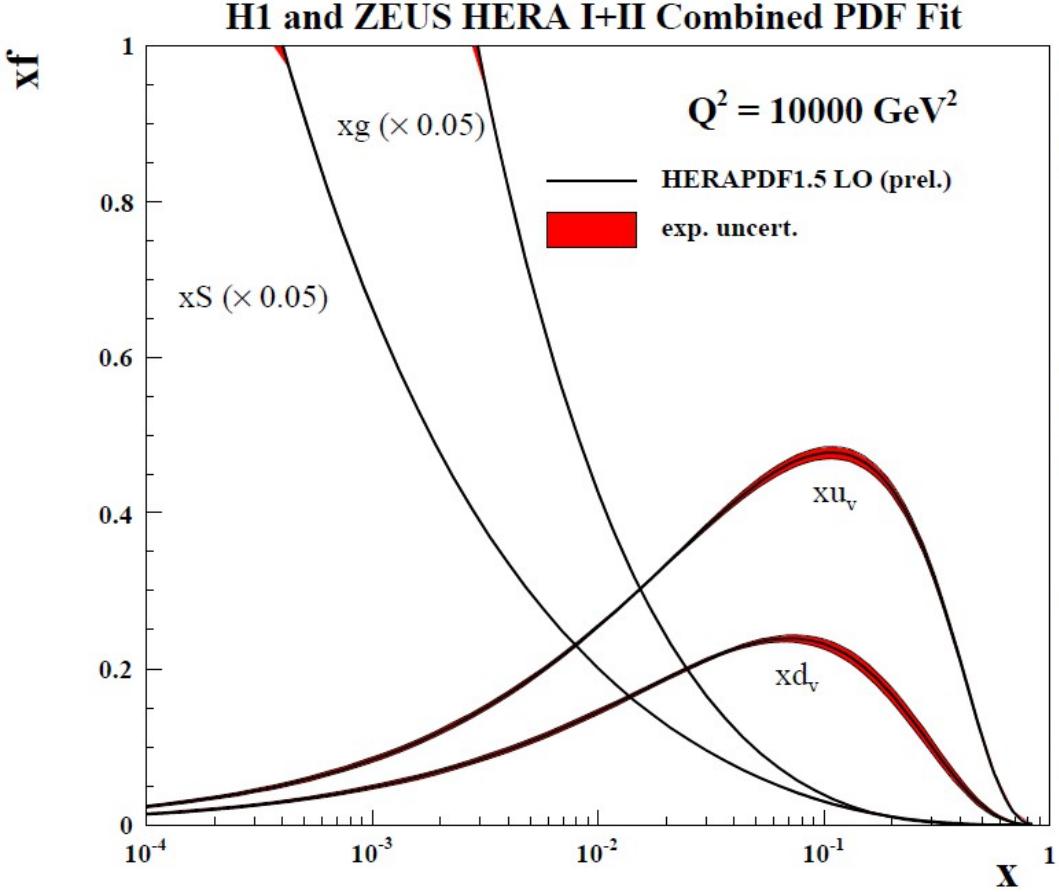
H1 and ZEUS preliminary



HERAPDF1.5LO (prel.)

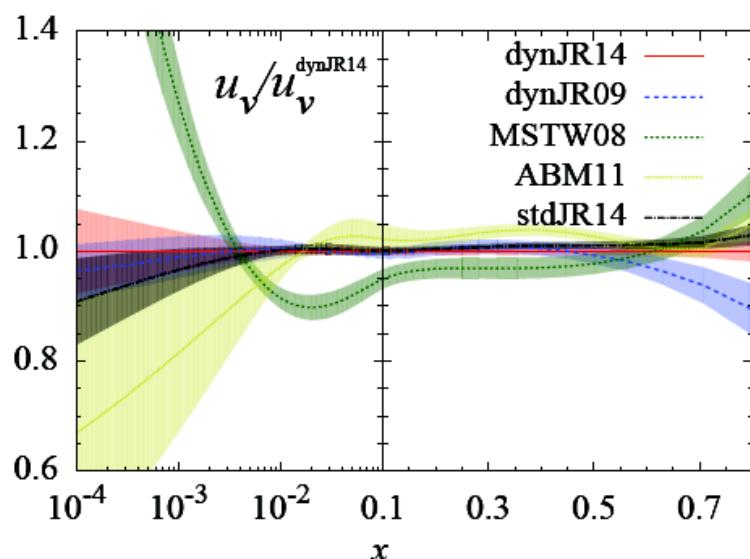
- Parton densities @LO are essential for proper simulation of parton showers and underlying event properties in LO+PS Monte Carlo event generators
- HERAPDF1.5 LO set based on HERAPDF1.5 NLO PDF settings
- Includes experimental uncertainties
- Available in LHAPDF library

For details see M. Cooper-Sarkar talk

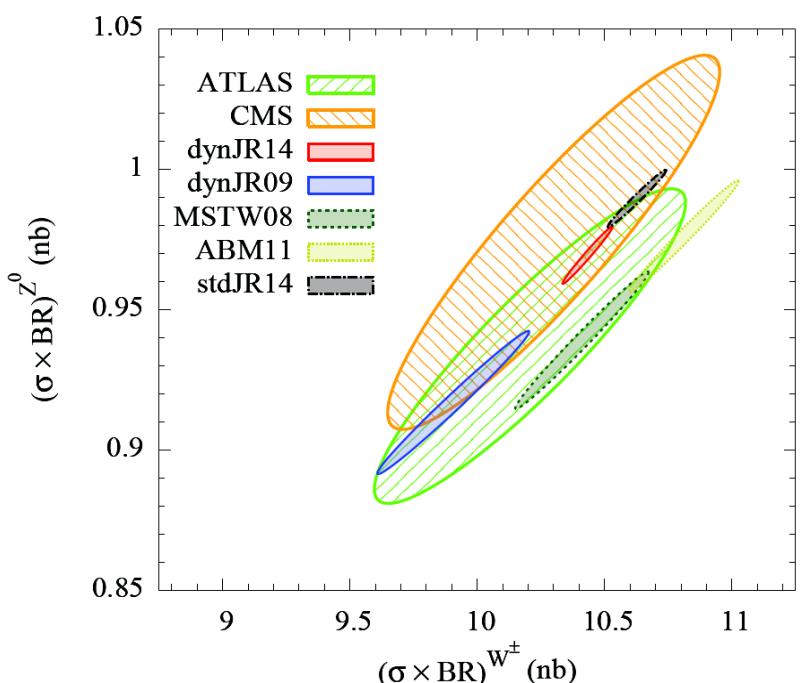
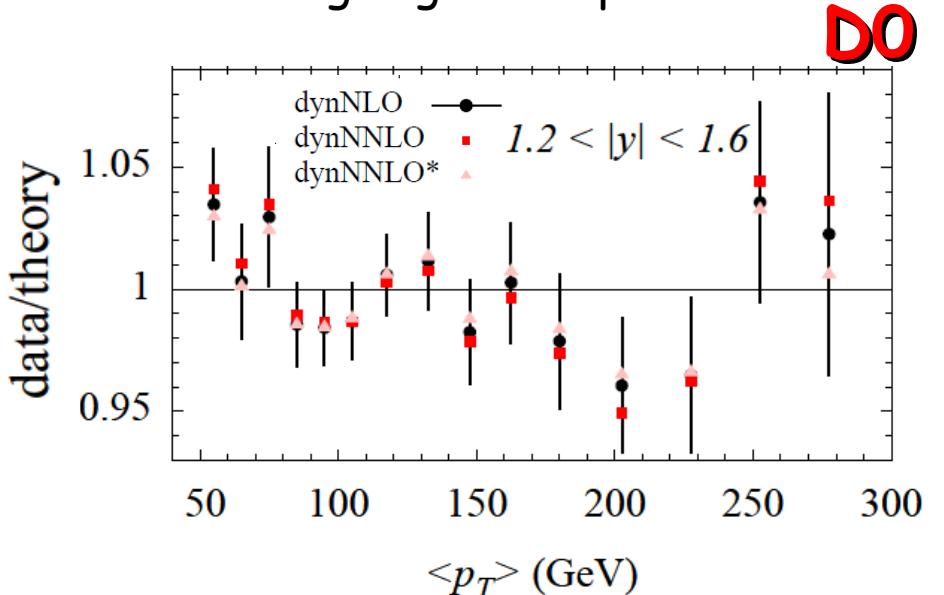


JR14 dynamical & standard

- 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
 - HERA I inclusive & charm, H1 F_L
 - HERA jets (not for NNLO)



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



NNPDF3.0

Slide from J. Rojo

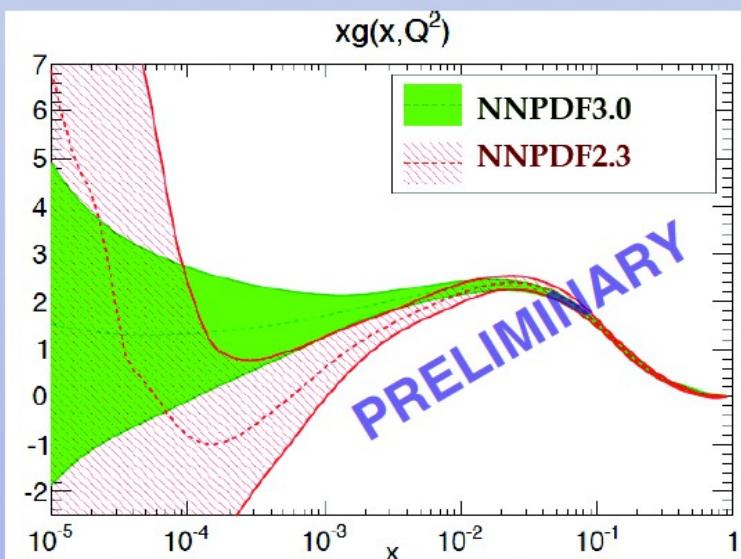
PDF
updates

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.....

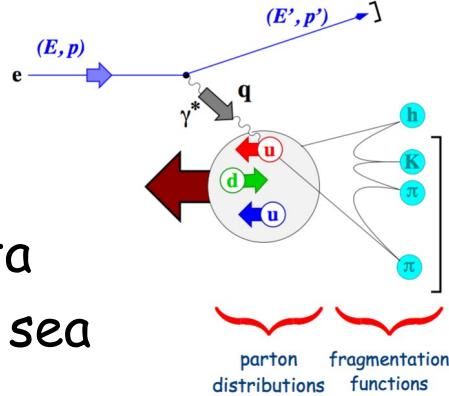


- ⌚ Completely redesigned fitting methodology based on **closure tests** with known underlying physical laws (S. Forte, PDF4LHC, 12/2014)
- ⌚ Substantially improved **Genetic Algorithms** minimization with new **Weight Penalty method** for fitting (iterative Bayesian regularization)

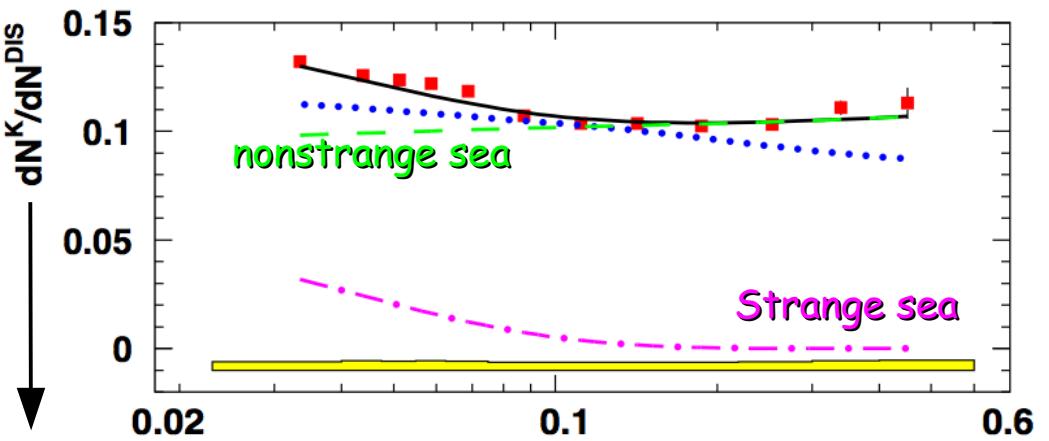
Experiment	Dataset	DOF
NMC	NMCPD	356
	NMC	132
	224	
SLAC	SLACP	74
	SLACD	37
	37	
BCDMS	BCDMSP	581
	BCDMSD	333
	248	
CHORUS	CHORUSNU	862
	CHORUSNB	431
	431	
NTVDMN	NTVNUDMN	79
	NTVNBDMN	41
	38	
HERA1AV	HERA1NCEP	592
	HERA1NCEM	379
	HERA1CCEP	145
	HERA1CCEM	34
	34	
ZEUSHERA2	Z06NC	252
	Z06CC	90
	ZEUSHERA2NCP	37
	ZEUSHERA2CCP	90
	35	
H1HERA2	H1HERA2NCEM	511
	H1HERA2NCEP	139
	H1HERA2CCEM	138
	H1HERA2CCEP	29
	H1HERA2LOWQ2	29
	H1HERA2HIGHY	124
	52	
HERAF2CHARM	DYE886	47
	DYE886R	199
	DYE886P	15
	184	
DYE605	CDF	119
	CDFZRAP	105
	CDFR2KT	29
	76	
D0	D0ZRAP	138
	D0R2CON	28
	110	
ATLAS	ATLASWZRAP36PB	179
	ATLASR04JETS36PB	30
	ATLASR04JETS2P76TEV	90
	50	
CMS	CMSWEASY840PB	95
	CMSWMASY47FB	11
	CMSJETS11	63
	CMSWCHARMTOT	5
	CMSWCHARMRAT	5
	CMSDY2D11	132
LHCb	LHCBW36PB	19
	LHCBBZ940PB	10
	9	
TOP	Total (exps)	6
		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 strange quark distribution (2008))
 - Newest K^+K^- multiplicities on deuteron used: PR D87, 074029 (2013)



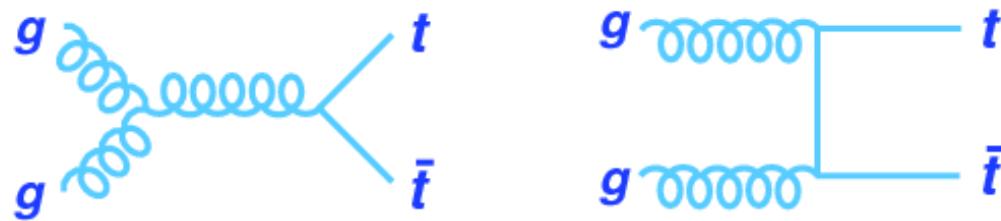
nek, 23.05.14, Parton densities



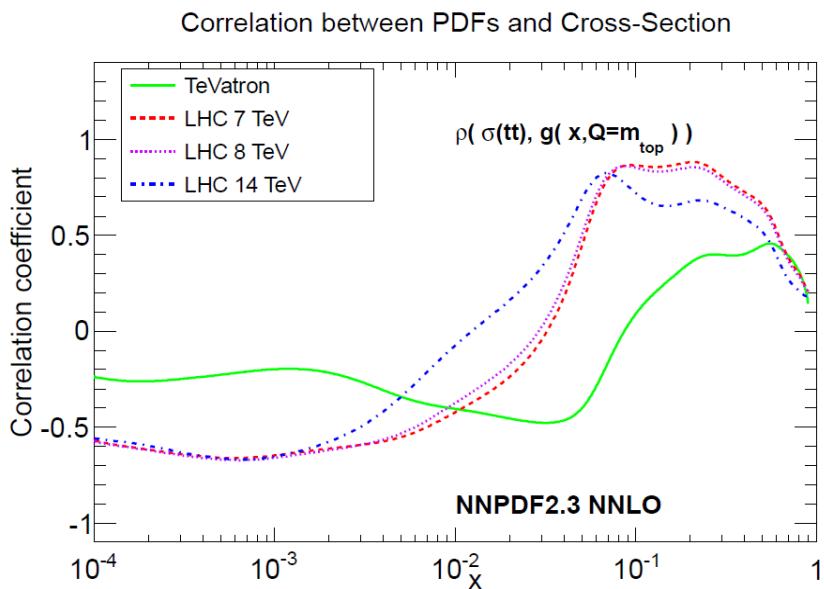
$$s(x) + \bar{s}(x) \quad S(x) \int \mathcal{D}_S^K(z) dz \simeq Q(x) \left[5 \frac{d^2 N^K(x)}{d^2 N^{DIS}(x)} - \int \mathcal{D}_Q^K(z) dz \right]$$

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

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 GeV^2

at $\sqrt{s} = 7 \text{ TeV}$

$$\begin{aligned}\sigma_{t\bar{t}}^{\text{dyn}} &= 143.2^{+5.4}_{-5.8} \pm 2.4 \text{ pb} \\ \sigma_{t\bar{t}}^{\text{std}} &= 154.1^{+6.1}_{-6.5} \pm 3.0 \text{ pb}\end{aligned}$$

TeVatron

$$\begin{aligned}\sigma_{t\bar{t}}^{\text{dyn}} &= 7.07^{+0.22}_{-0.19} \pm 0.06 \text{ pb} \\ \sigma_{t\bar{t}}^{\text{std}} &= 7.37^{+0.25}_{-0.21} \pm 0.07 \text{ pb}\end{aligned}$$

arXiv:1403.1852v

ABM12: top data INCLUDED in fit, m_t , FITTED

Pole mass 171 GeV^2	Running mass 162 GeV^2
$143.0^{+5.6}_{-8.8} {}^{+6.5}_{-6.5}$	$150.2^{+0.1}_{-4.6} {}^{+6.1}_{-6.1}$
$209.1^{+7.9}_{-12.6} {}^{+8.7}_{-8.7}$	$219.3^{+0.1}_{-6.6} {}^{+8.2}_{-8.2}$

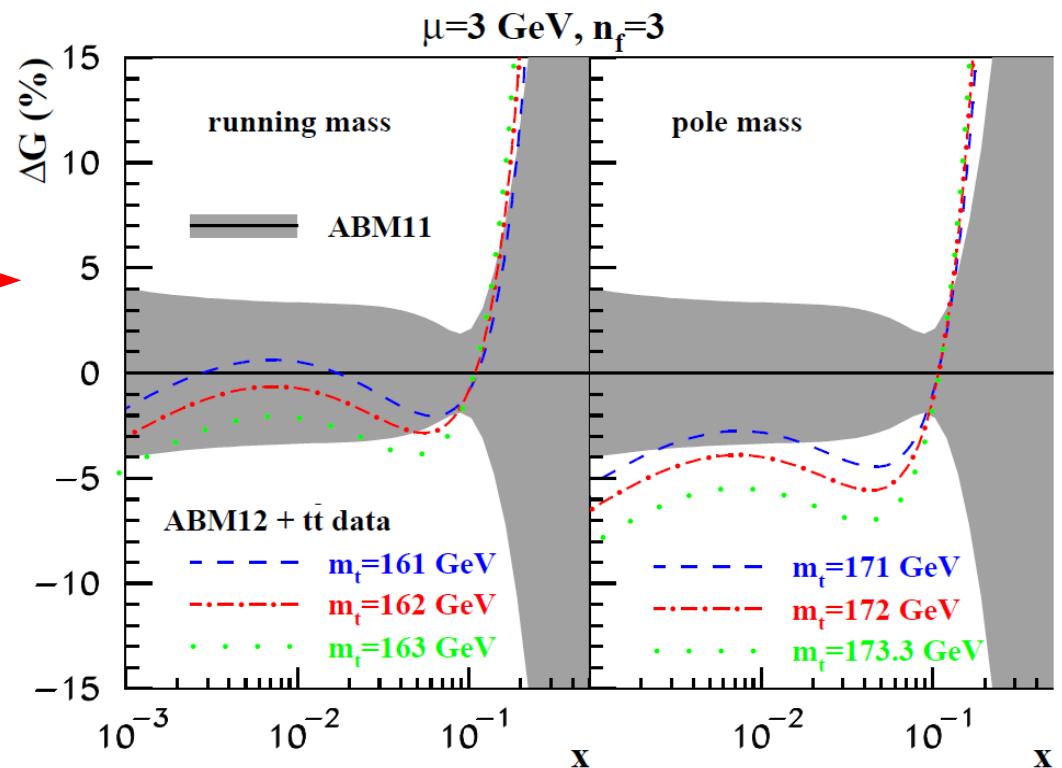
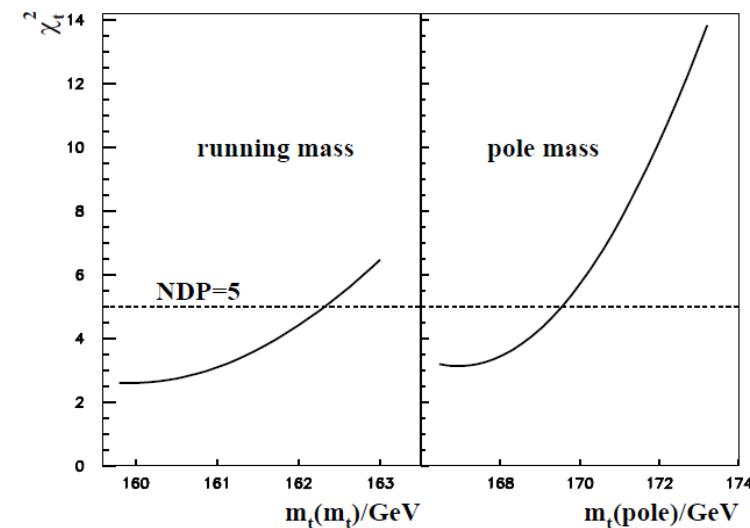
arXiv:1310.3059

ABM12 meets top quark

- ABM12 added combined $t\bar{t}$ cross sections from LHC and Tevatron to test impact on
 - gluon PDF
 - strong coupling α_s
 - value and scheme choice for m_t

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

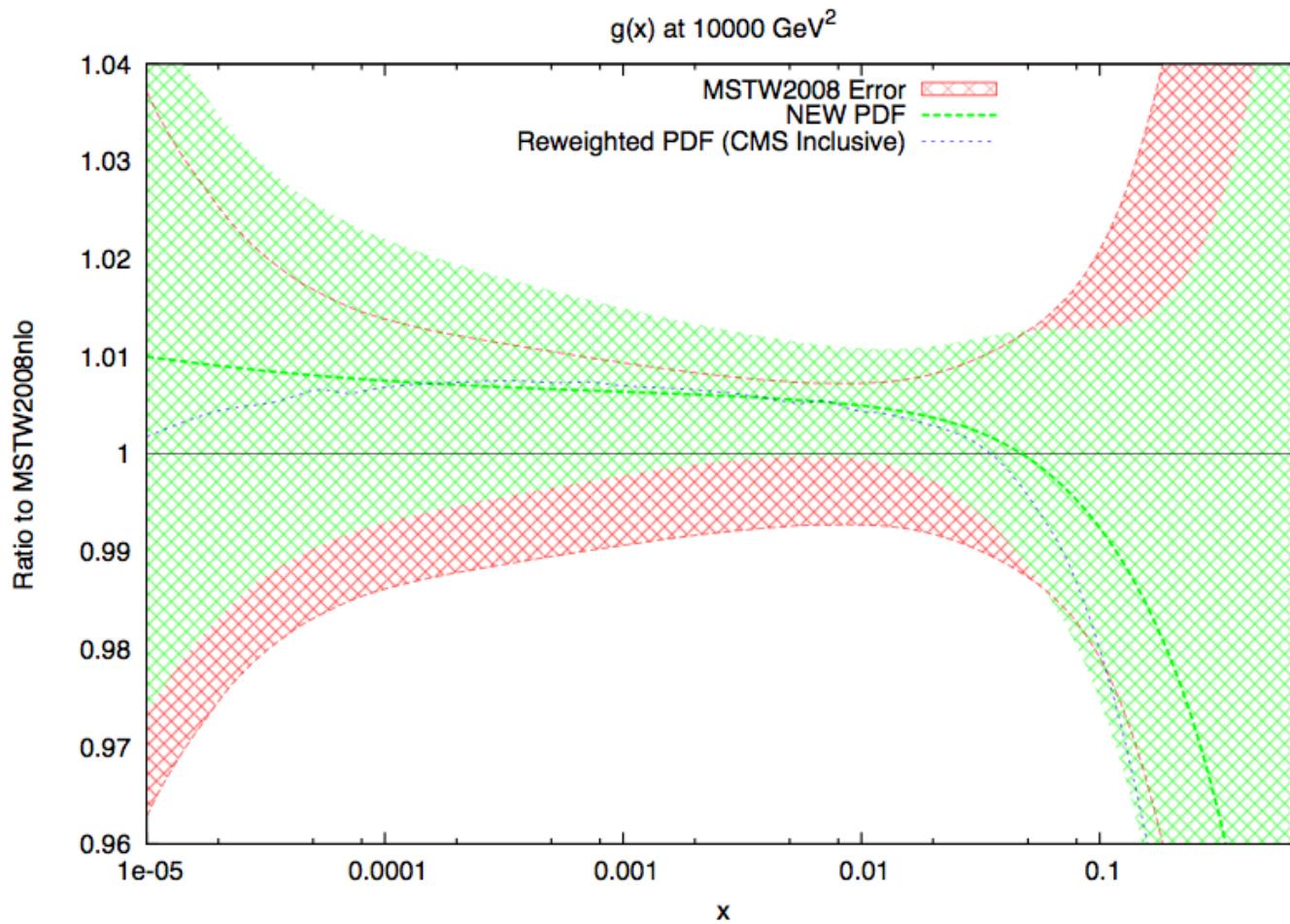
$$m_t(\text{pole}) = 171.2 \pm 2.4 \text{ GeV}$$



stability of ABM analysis
provided all correlations are accounted for

Gluon meets LHC jets

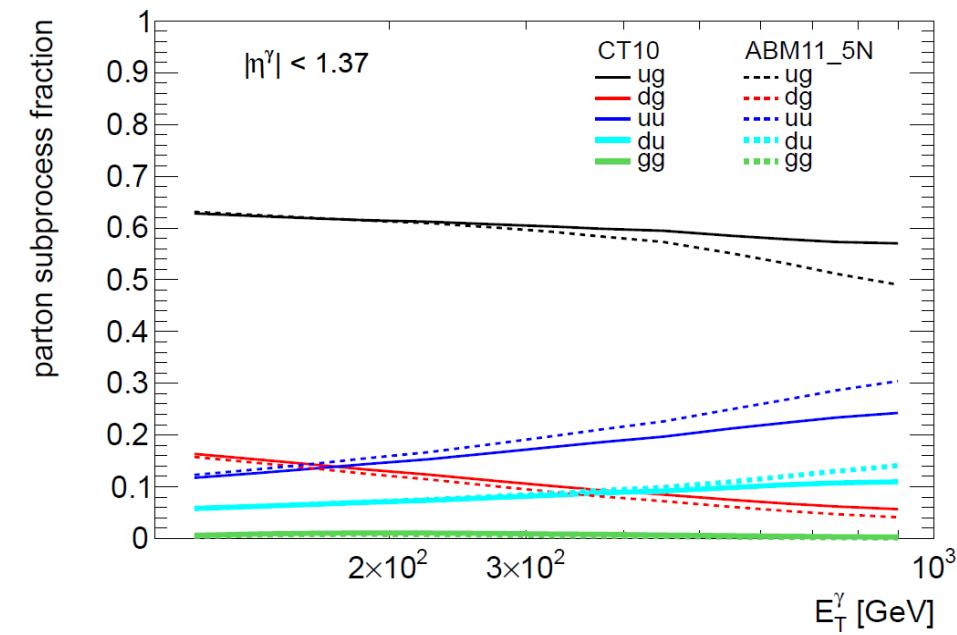
- LHC jet data included directly in the framework of MSTW PDF
 - highest precision inclusive jet cross sections from ATLAS and CMS
- Good agreement between ATLAS and CMS data sets
- Good agreement with reweighting method



For details see R. Thorne

Gluon meets prompt photons

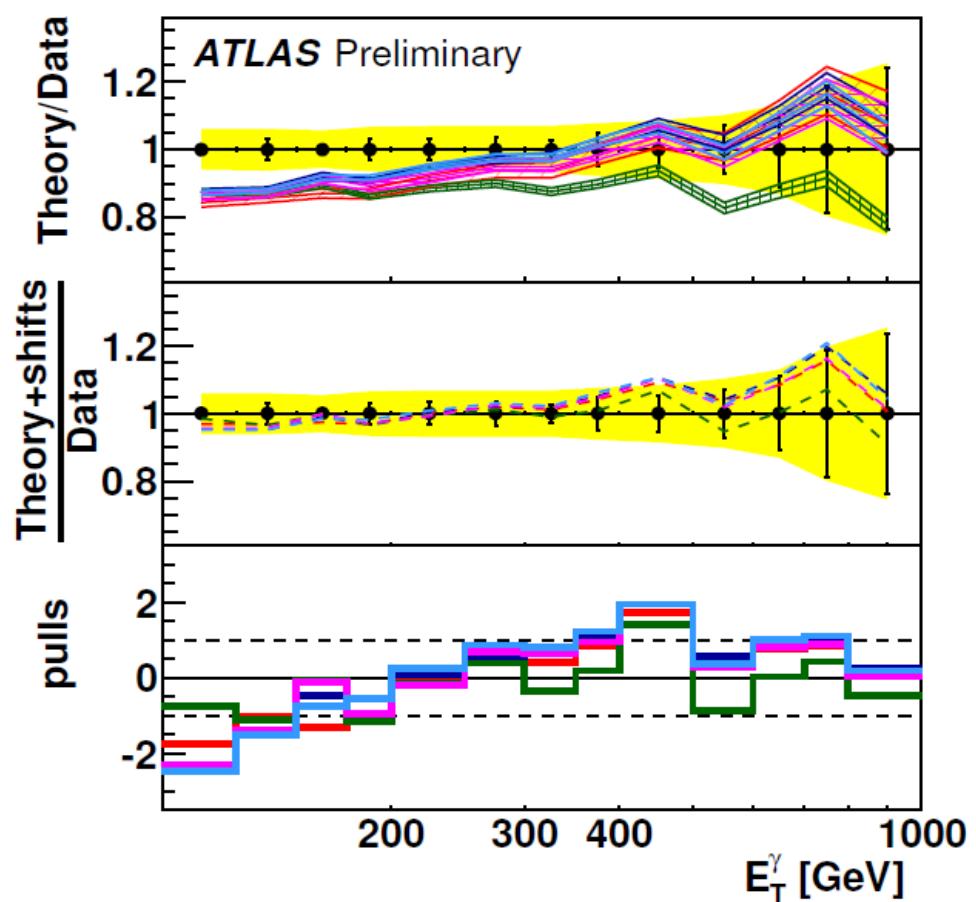
- Prompt γ data help constrain gluon



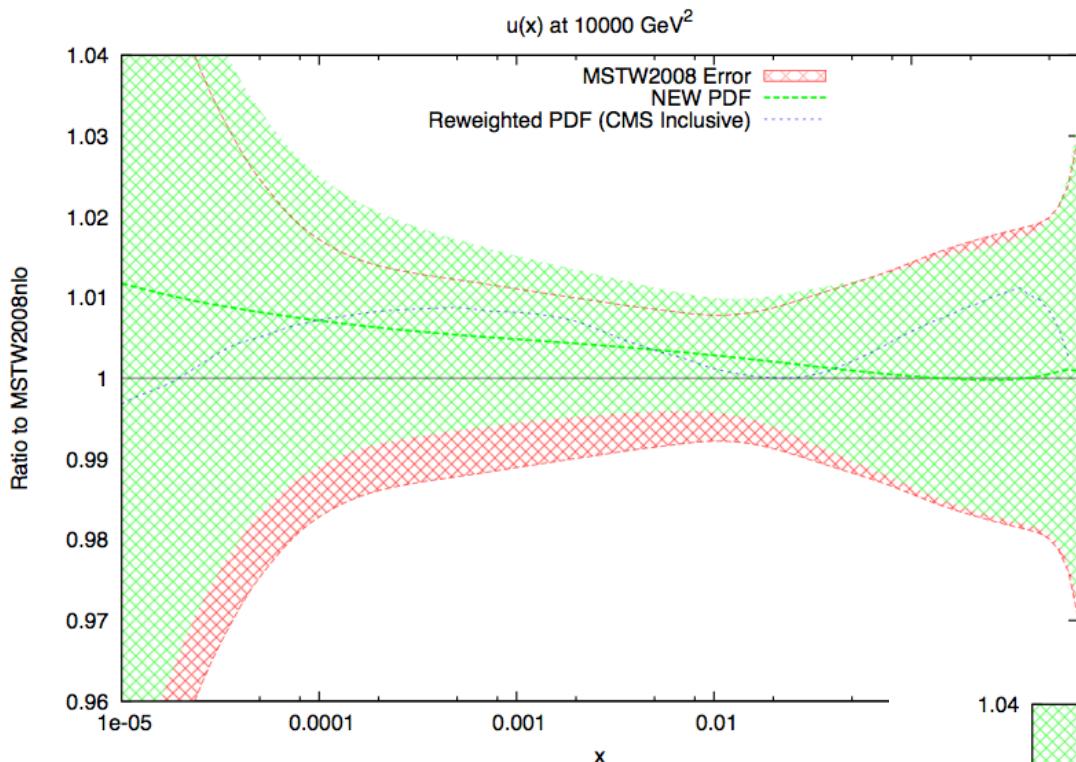
- At intermediate E_T - most precise data - scale uncertainty dominant

NNLO calculations necessary to fully exploit this measurement

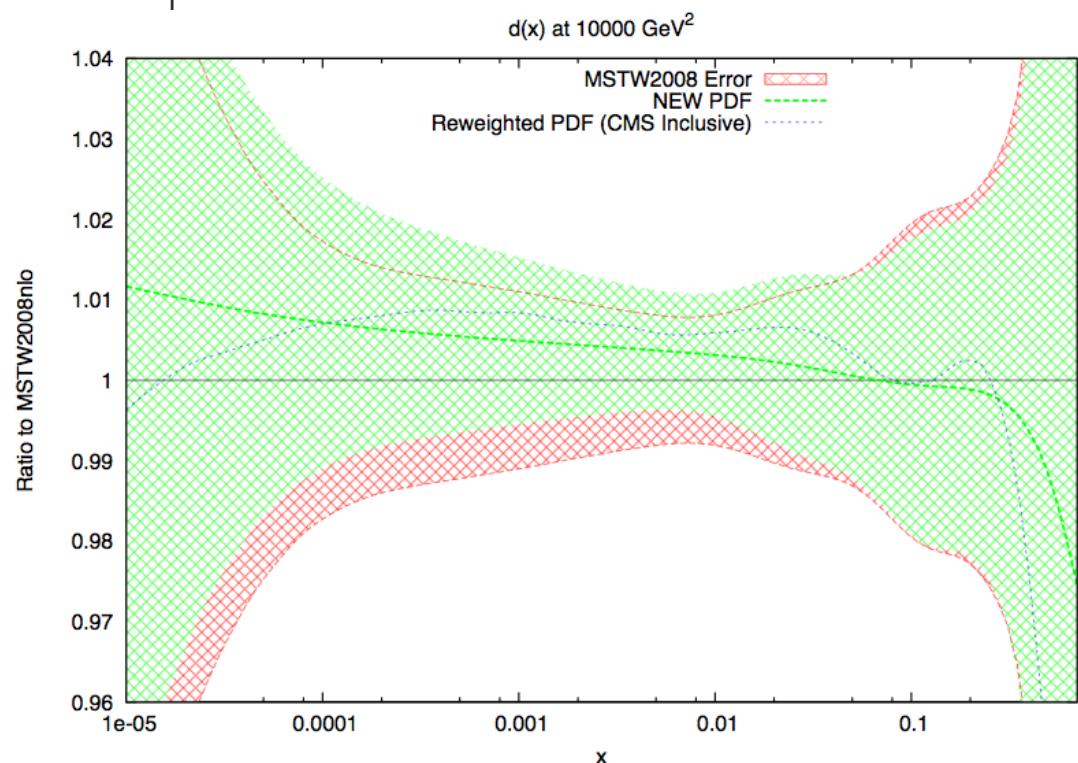
- Asses data sensitivity to PDF using HERAFitter platform



What can jets teach us?



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



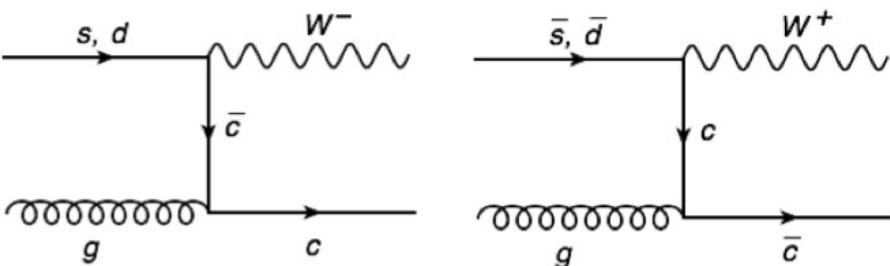


Prince Charming helps strangers

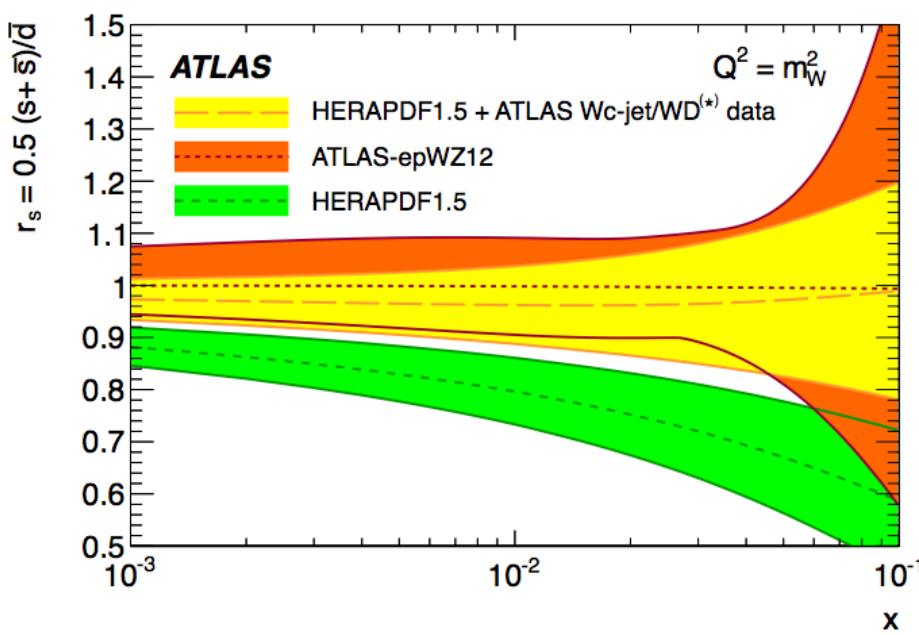
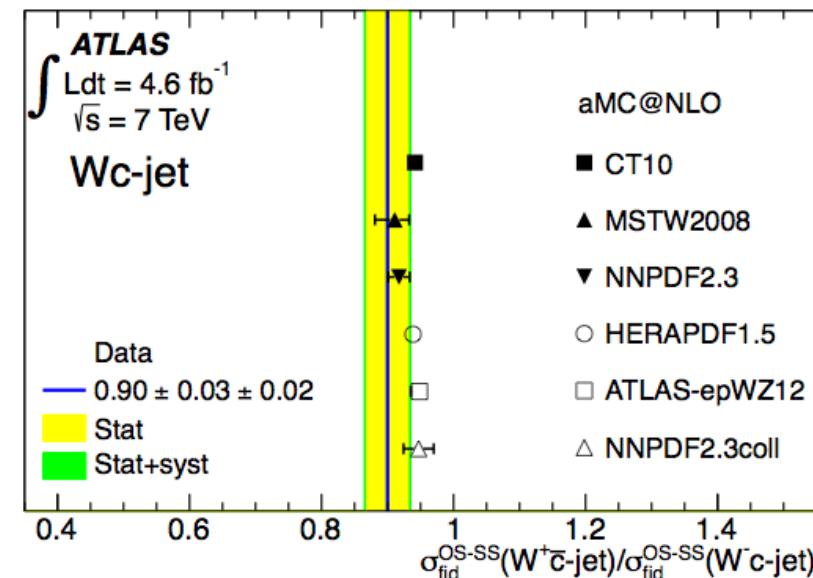


For details see G. Aad talk

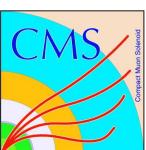
- PDFs with different strange sea assumptions
- Differential W and Z cross sections at LHC
 - constraints on strange sea at $Q^2 \sim M_{Z/W}^2$
 - ATLAS-epWZ12 PDF based on ATLAS W and Z cross-section + HERAI data
- W + charm measurements



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



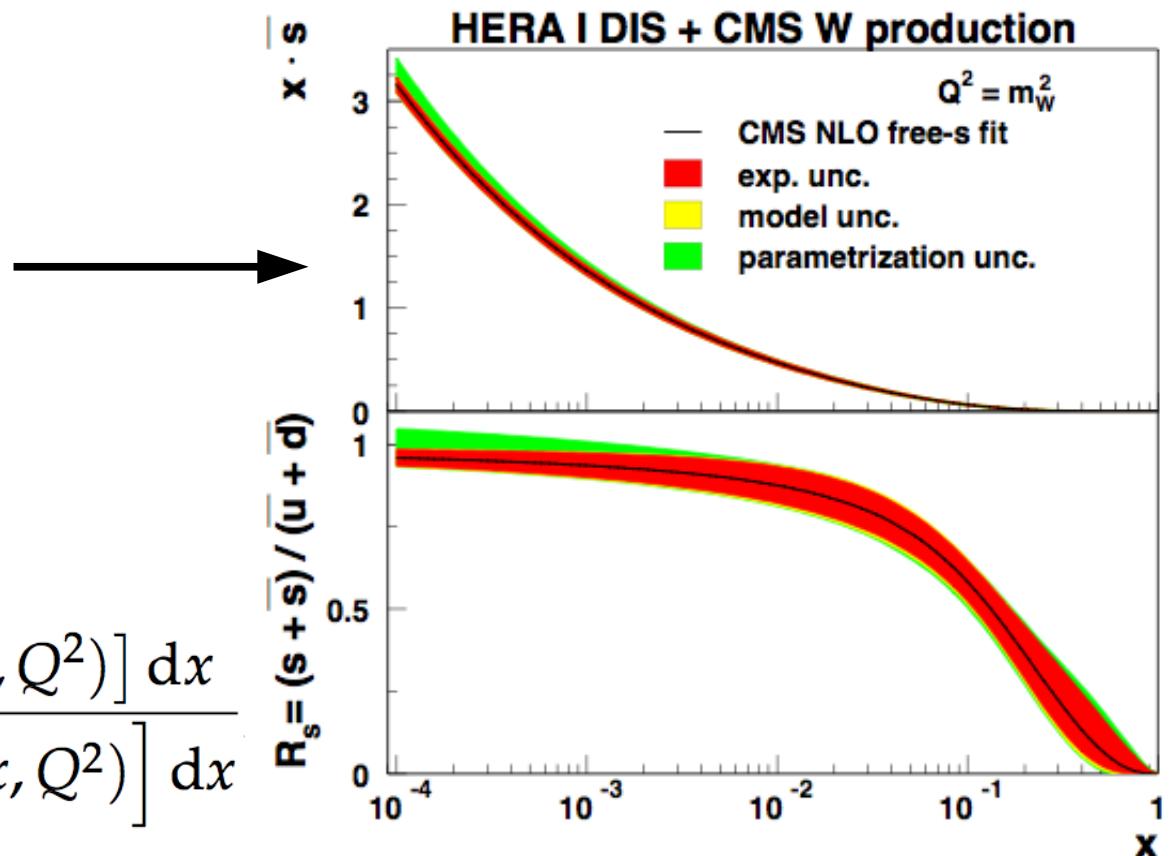
$$r_s \equiv 0.5(s + \bar{s})/\bar{d} = 0.96^{+0.16}_{-0.18}{}^{+0.21}_{-0.24}$$



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



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

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

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