Lecture on Deep Inelastic Scattering

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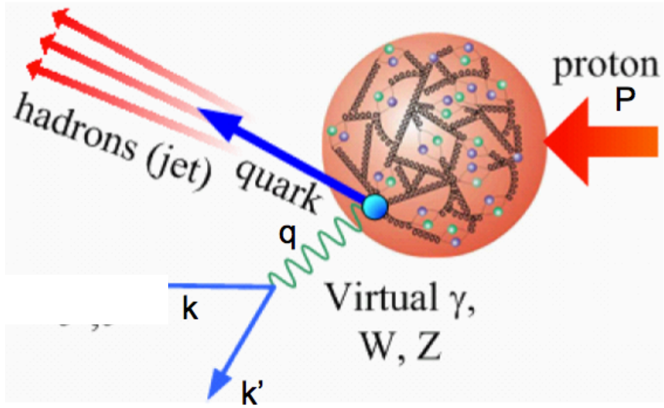
(DESY)



This lecture:

- Part I:
  - Introduction to DIS formalism
  - Physics Results from DIS experiments
- **Part II:**
  - **Relevance of DIS measurements for LHC physics**
  - **Example of QCD fits and impact of DIS data**

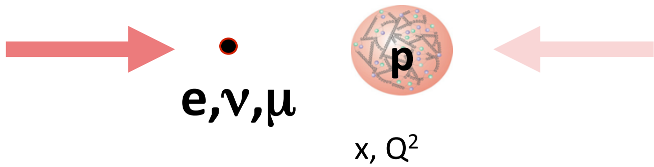
Outline

- Yesterday have presented the basis of DIS formalism:
  - Kinematic variables to describe the process
  - Differential Cross Section in terms of Structure Functions for different processes
  - Relation of Structure Functions to PDFs (factorisation theorem)
- Some Milestones of Experimental Results:
  - Discovery of gluon
  - Electroweak Unification

- **Today:**
  - **Will continue with more experimental results**
  - **Applicability of DIS measurements: determination of PDFs**
    - **importance of precision measurements and what does it involves**
  - **From Low x to High x**
  - **Relation between DIS to LHC**
    - **Most recent data sensitive to PDFs**
  - **Outlook**

Kinematics of DIS

- **Proton can be probed via elementary particles as:**
  - neutrinos (fixed target experiments) - interact only weakly
  - electrons (fixed target and collider experiments) - interact electroweakly



- **Deep Inelastic Scattering (DIS) is the cleanest probe to study the substructure of nucleon**
  - scattering of a lepton off the quarks within the proton resulting into a hadronic shower and a lepton

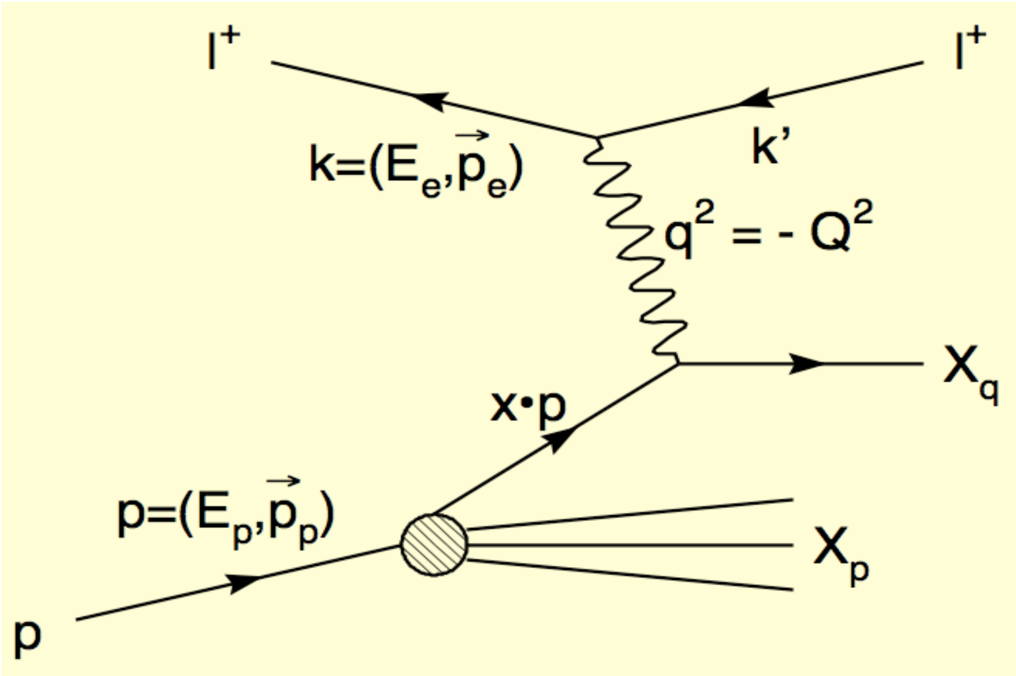
- **Kinematic Lorenz Invariant Variables:**

$$Q^2 = -q^2 = -(k-k')^2$$ Virtuality of the exchanged boson

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

$$y = \frac{p \cdot q}{p \cdot k}$$ Inelasticity parameter

$$s = (k+p)^2 = \frac{Q^2}{xy}$$ Invariant c.o.m.



For ep colider

$$s = 4E_eE_p$$

For fixed target

$$s = 2M_pE_l$$

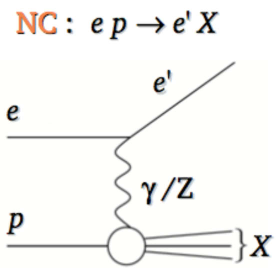
DIS Cross Section at HERA

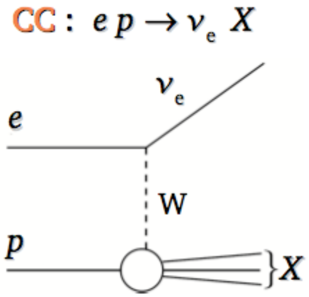
General Form for the Differential cross section:

$$\frac{d^2\sigma}{dxdQ^2} = A^i \left\{ (1 - y - \frac{x^2y^2M^2}{Q^2}) F_2^i + y^2 x F_1^i \mp (y - \frac{y^2}{2}) x F_3^i \right\}$$

A^i: process dependent

$$xF_3 \sim \sum (xq_i - x\bar{q}_i)$$
$$F_L \sim \alpha_S g$$
$$F_2 \sim \sum e_i^2 (xq_i + x\bar{q}_i)$$





NC:

$$\frac{d^2\sigma_{NC}^{\pm}}{dxdQ^2} = \frac{2\pi\alpha^2}{x} \left[\frac{1}{Q^2} \right]^2 \phi_{NC}^{\pm}(x, Q^2)$$

$$\phi_{NC} = Y_+ \tilde{F}_2^{\pm}(x, Q^2) - y^2 \tilde{F}_L^{\pm}(x, Q^2) \mp Y_- x\tilde{F}_3^{\pm}(x, Q^2),$$

$$\tilde{F}_2^{\pm} = F_2 - (v_e \pm P_e a_e)\kappa_Z F_2^{\gamma Z} + (v_e^2 + a_e^2 \pm 2P_e v_e a_e)\kappa_Z^2 F_2^Z, \quad \kappa_Z(Q^2) = \frac{1}{4sin^2(\theta_W)cos^2(\theta_W)} \frac{Q^2}{Q^2 + M_Z^2}$$

$$x\tilde{F}_3^{\pm} = -(a_e \pm P_e v_e)\kappa_Z xF_3^{\gamma Z} + (2v_e a_e \pm P_e(v_e^2 + a_e^2))\kappa_Z^2 xF_3^Z,$$

CC:

$$\frac{d^2\sigma_{CC}^{\pm}}{dxdQ^2} = (1 \pm P_e) \frac{G_F^2}{2\pi x} \left[\frac{M_W^2}{Q^2 + M_W^2} \right]^2 \phi_{CC}^{\pm}(x, Q^2).$$

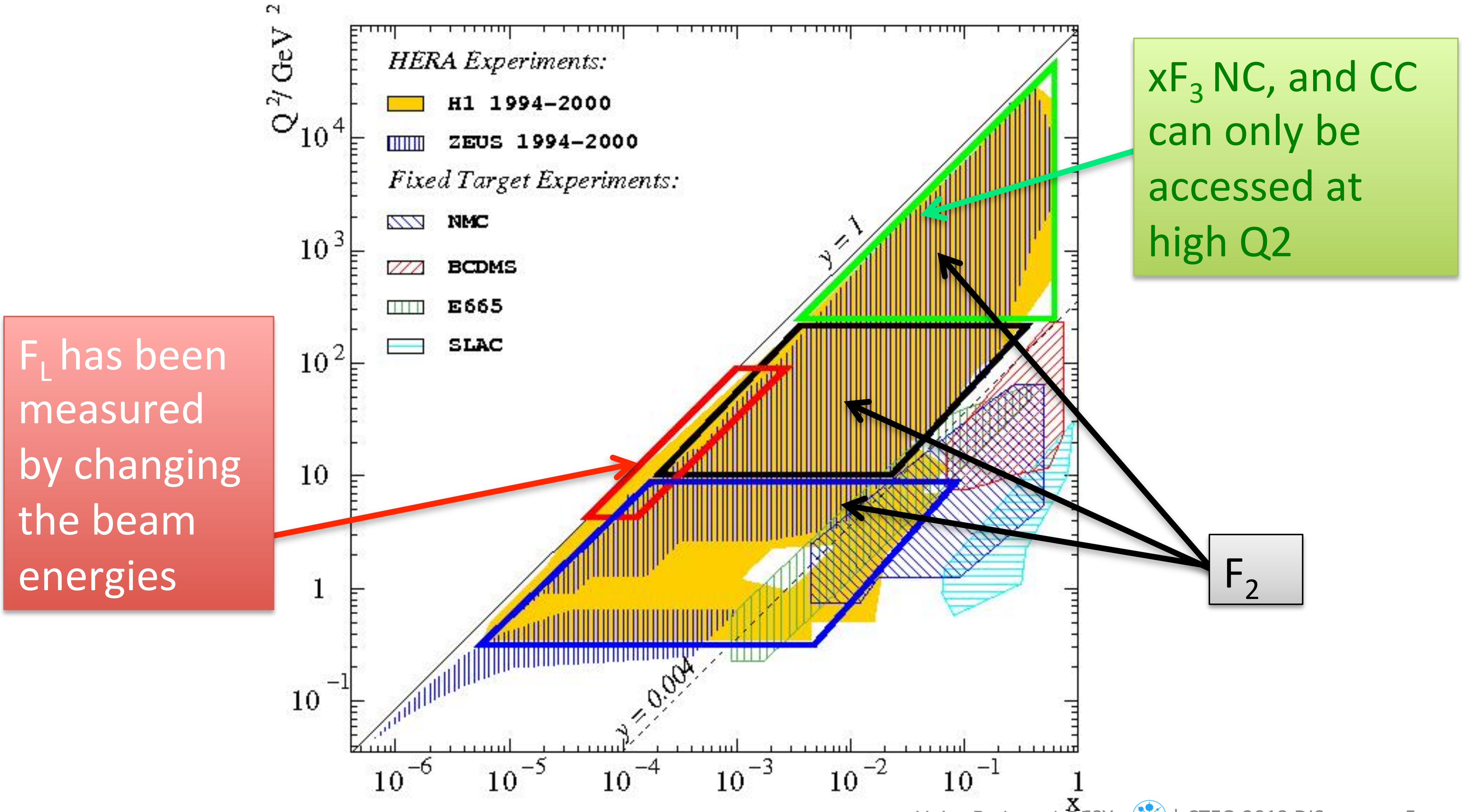
At LO

$$e^+ : \quad \phi_{CC}^+ = x[(\bar{u}(x) + \bar{c}(x)) + (1-y)^2(d(x) + s(x))]$$

$$e^- : \quad \phi_{CC}^- = x[(u(x) + c(x)) + (1-y)^2(\bar{d}(x) + \bar{s}(x))]$$

DIS Kinematic plane of HERA

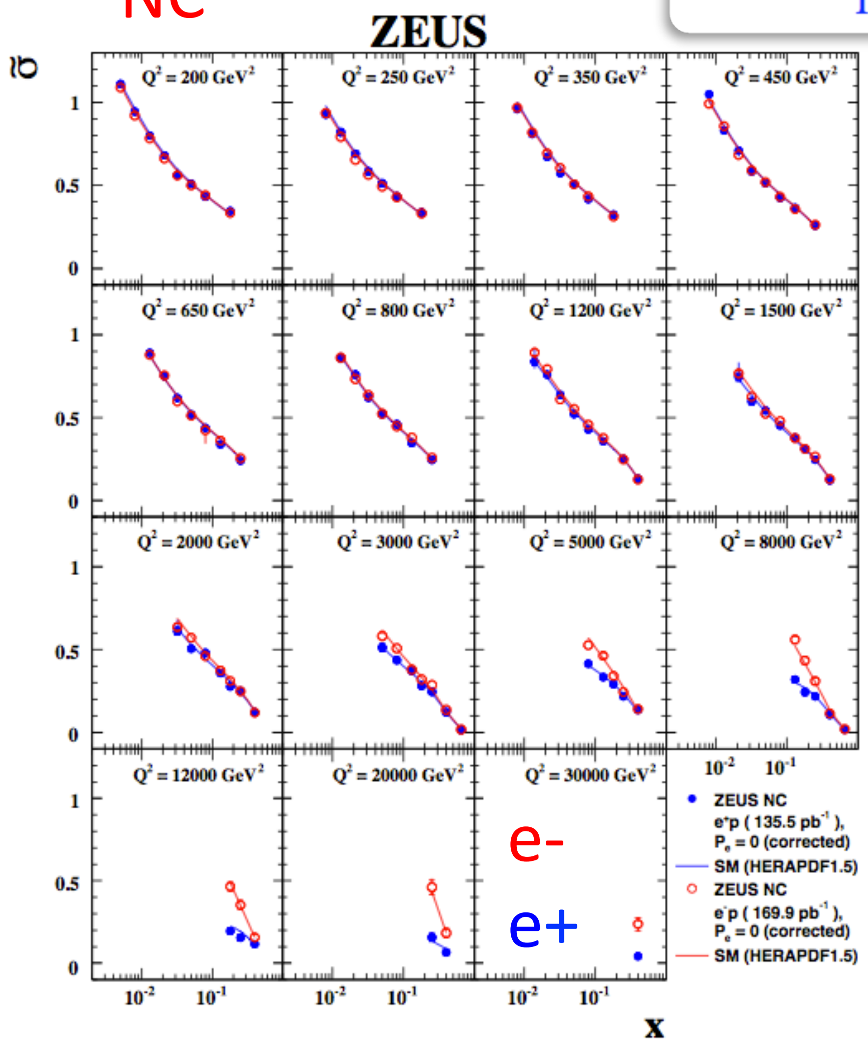
- A vast extension of the kinematic range: both to high Q2 and to low-x.



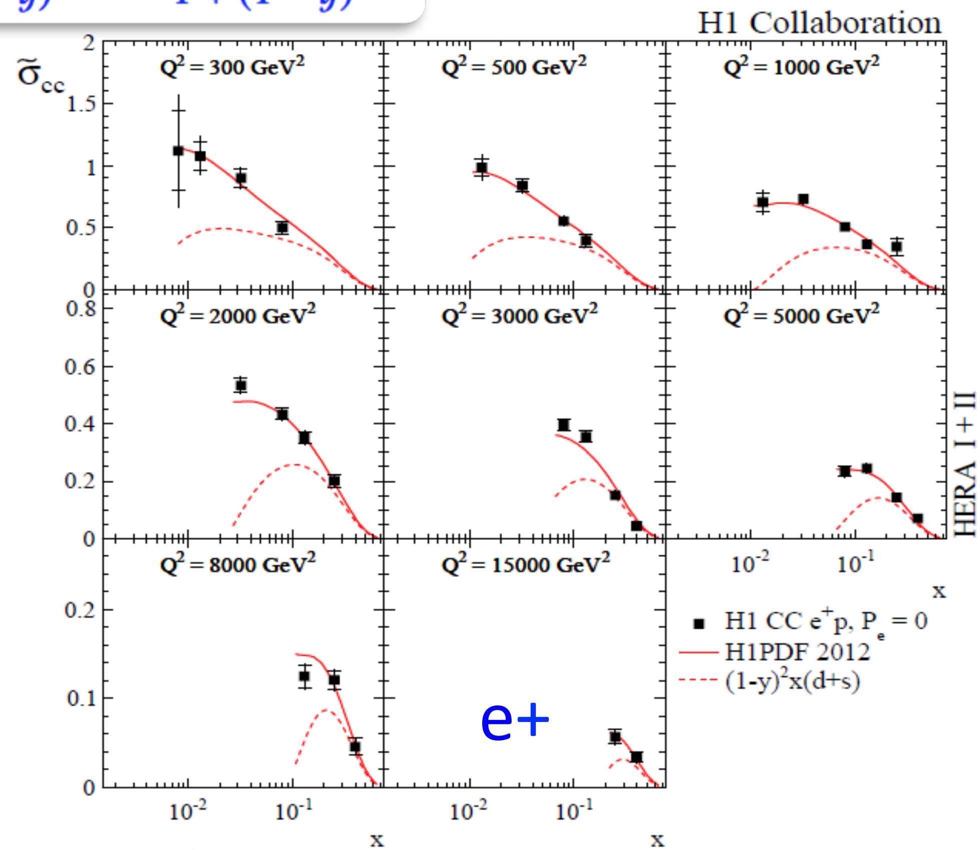
Inclusive Cross Sections

$$\sigma_r^{\pm} = \tilde{F}_2^{\pm} \mp \frac{1-(1-y)^2}{1+(1+y)^2} x\tilde{F}_3 - \frac{y^2}{1+(1-y)^2}\tilde{F}_L$$

NC



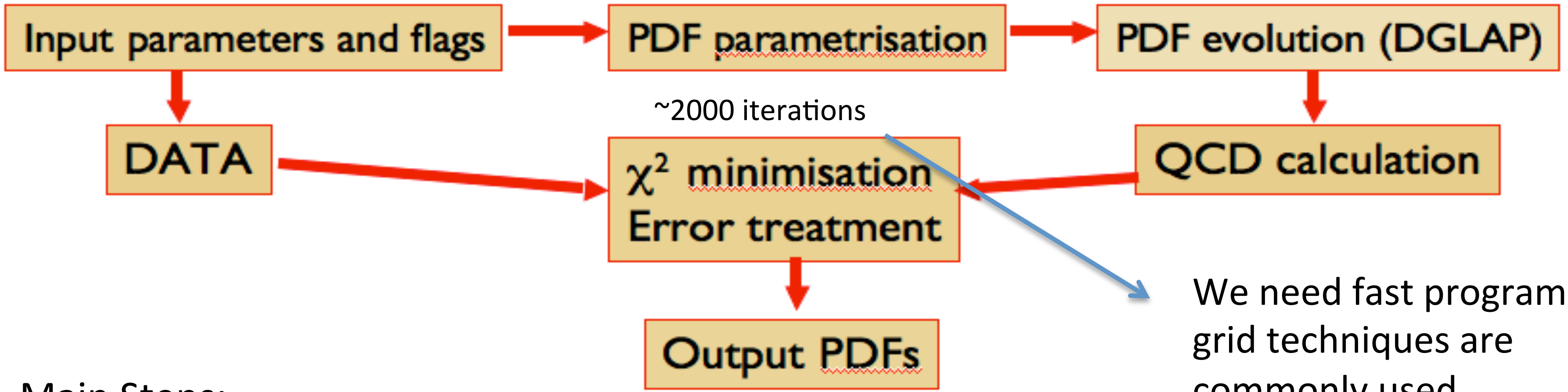
CC



Measurement of high-x d_v on a pure proton target **d** is not well known because **u** couples more strongly to the photon.

Historically information has come from deuterium targets assuming u in proton = d in neutron HERA doesnt need this assumption

Mechanism of extracting PDFs



We need fast programs! grid techniques are commonly used.

- Main Steps:
  - Parametrise PDFs at starting scale
    - Observables are sensitive to different linear combinations of PDFs
    - For the inclusive *ep* → *eX* scattering, the dominant contribution is given by the structure function *F2*
  - Evolve to the scale corresponding to data point
  - Calculate the cross section
  - Compare with data
  - Minimize with respect to PDF parameters

- a full coverage of kinematic plane in x is needed
- Fast calculations are needed (employ grid techniques)

➔ www.herafitter.org

PDF determination at HERA

- HERA PDFs are determined from QCD Fits to solely HERA data
  - NLO (and NNLO) DGLAP evolution equations, RT-VFNS (as for MSTW08) – for dealing with heavy quarks
    - Other schemes were investigated as well: RT (optimal), ACOT (full and χ), FFNS

- The QCD settings are optimised for HERA measurements of proton structure functions

$$F_2(x,Q^2) = \frac{4}{9}(xU + x\overline{U}) + \frac{1}{9}(xD + x\overline{D})$$

- PDF parametrised at the starting scale Q_0^2:

$$xg, xu_{val}, xd_{val}, x\bar{U} = x\bar{u}(+x\bar{c}), x\bar{D} = x\bar{d} + x\bar{s}(+x\bar{b})$$

- Simple Functional form: $xq_i(x) = A_i x^{B_i}(1-x)^{C_i} P_i(x)$

  - A - normalisation
  - B - low x behaviour
  - C - high x behaviour
  - D,E - medium x tuning

  - Where Pi(x) are polynomials in powers of x and only terms that bring significant improvement to the fit quality are retained
  - QCD sum rules:

$$\int_0^1 dx \cdot (xu_v + xd_v + x\bar{U} + x\bar{D} + xg) = 1$$

$$\int_0^1 dx \cdot 2u_v = 2 \qquad \int_0^1 dx \cdot d_v = 1$$

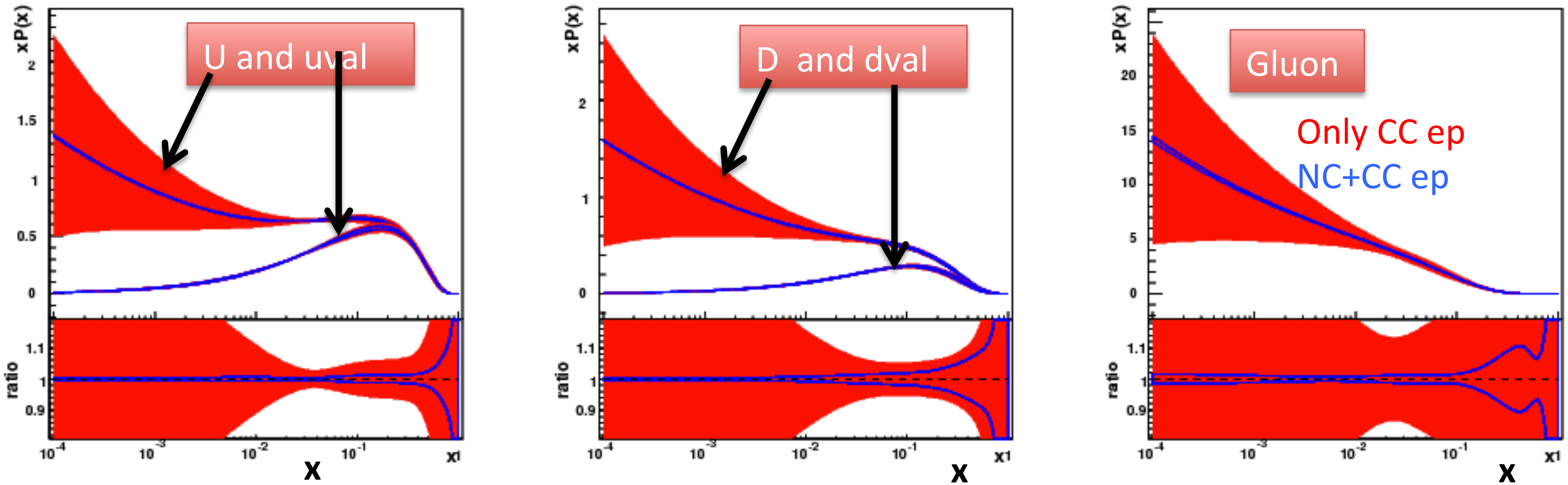
Additional Constraints:

$x\bar{s} = f_s x\bar{D}$ strange sea is a fixed fraction f_s of $\bar{D}$ at Q_0^2

$B_{Ubar} = B_{Dbar}$
sea = 2 x (Ubar +Dbar)
Ubar = Dbar at x=0

Impact of data on PDFs – simple exercise

- A visualisation of the impact of CC ep data is shown below (using HERA I data):
  (only size of uncertainties are relevant in this exercise)



  - **If ONLY CC ep data available: - can only constrain valence distributions**

- Errors assigned to the data points translate into errors assigned to the fit parameters and thus to errors on the parton distribution functions (PDFs)

Chi square definition

- Typical measurements sensitive to PDFs are precise, with statistical uncertainties < 10%, so it follows normal distribution which allows use of chi square minimization for determining optimal PDF parameters.

- The simplest situation is when the errors are Gaussian and there are no correlations among different data points:

$$\chi^2(p_k) = \sum_i \left(\frac{m_i(p_k) - \mu_i}{\Delta_i} \right)^2$$

p_k are parameters describing PDFs

$m_i(p_k)$ are predictions

- The measurements are, however, correlated with each other:
    - Bin-to-bin correlations due to systematic uncertainties are larger than statistical correlations
  - A convenient way to represent systematic correlations is by using nuisance parameters:
    - Influence of correlated uncertainty sources **j** on data points **i** can be described by a matrix **Γ_i^j** such that if a source moves up by **1σ** all data points move by **Γ_i^j**

$$\chi^2_{exp}(\mathbf{m}, \boldsymbol{b}) = \sum_i \frac{\left(m_i - \mu_i - \sum_j \Gamma_i^j b_j\right)^2}{\Delta_i^2} + \sum_j b_j^2.$$

b_j are nuisance parameters corresponding to correlated systematic

$\chi^2_{min}/N_{D.F} \approx 1$ if model is consistent with the data.

Data Combination

[JHEP01 (2010) 109]

- Typically several experiments provide their data in a similar kinematic phase space
  - One could combine them to gain ultimate precision
- The combination procedure is performed using χ^2 minimisation, in the same fashion as done when comparing data to theoretical models:

Constant term → tests consistency of combination

$$\chi^2_{exp,1}(\mathbf{m},\mathbf{b}) + \chi^2_{exp,2}(\mathbf{m},\mathbf{b}) \equiv \chi^2_0 + \chi^2_{ave}(\mathbf{m},\mathbf{b}')$$

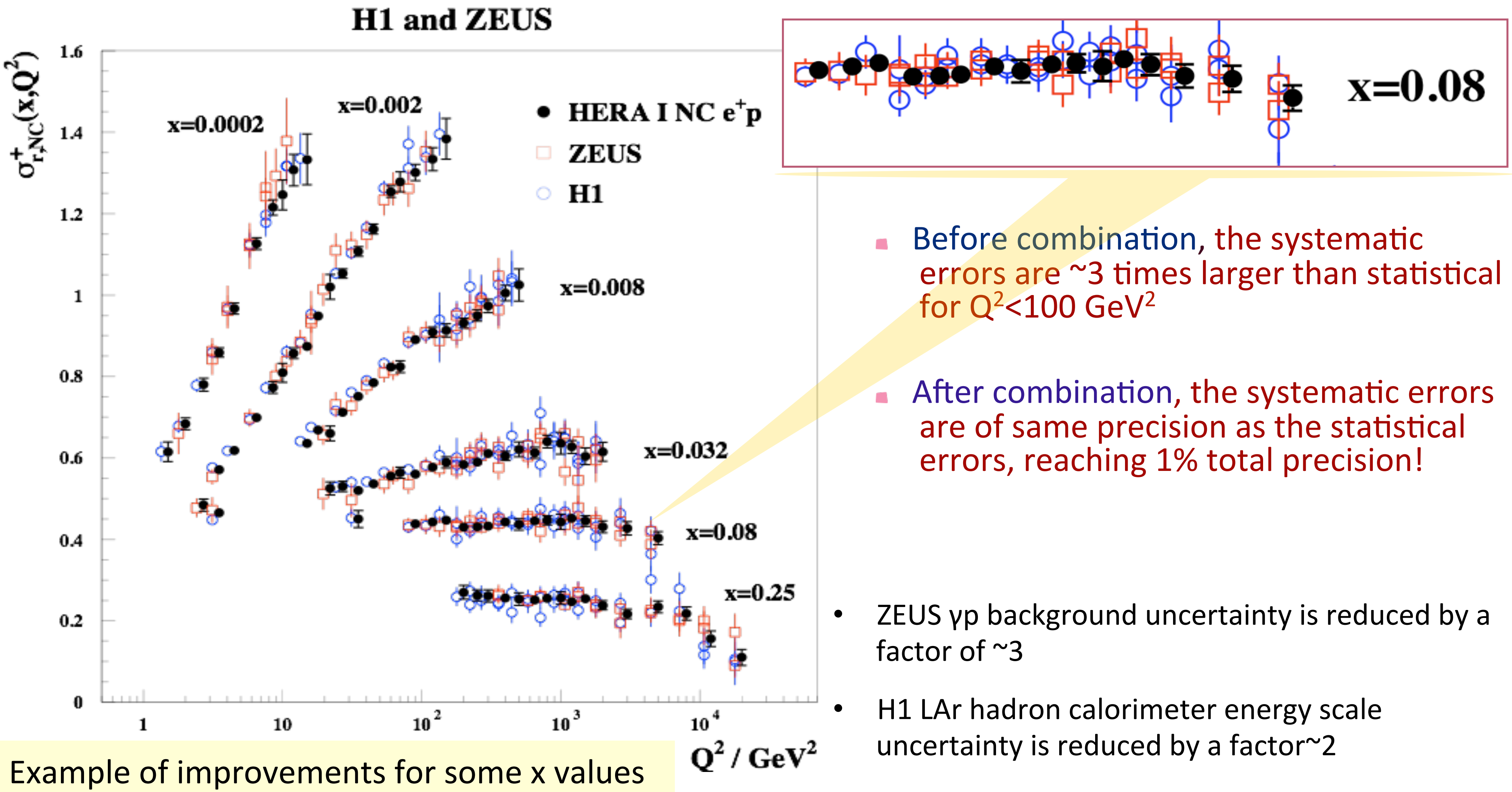
- Combination of measurements provides consistency check of the measurements in a model independent way.

  For example, at HERA:

  - Improvement of Statistical precision:
    - H1 and ZEUS collected similar amounts of physics data.
  - Improvement of Systematic precision:
    - H1 and ZEUS are different detectors and use different analysis techniques;
    - The H1 and ZEUS cross sections have different sensitivities to similar sources of correlated systematic uncertainty: can take best features from eachother

https://wiki-zeuthen.desy.de/HERAverager

Combined HERA-I Data



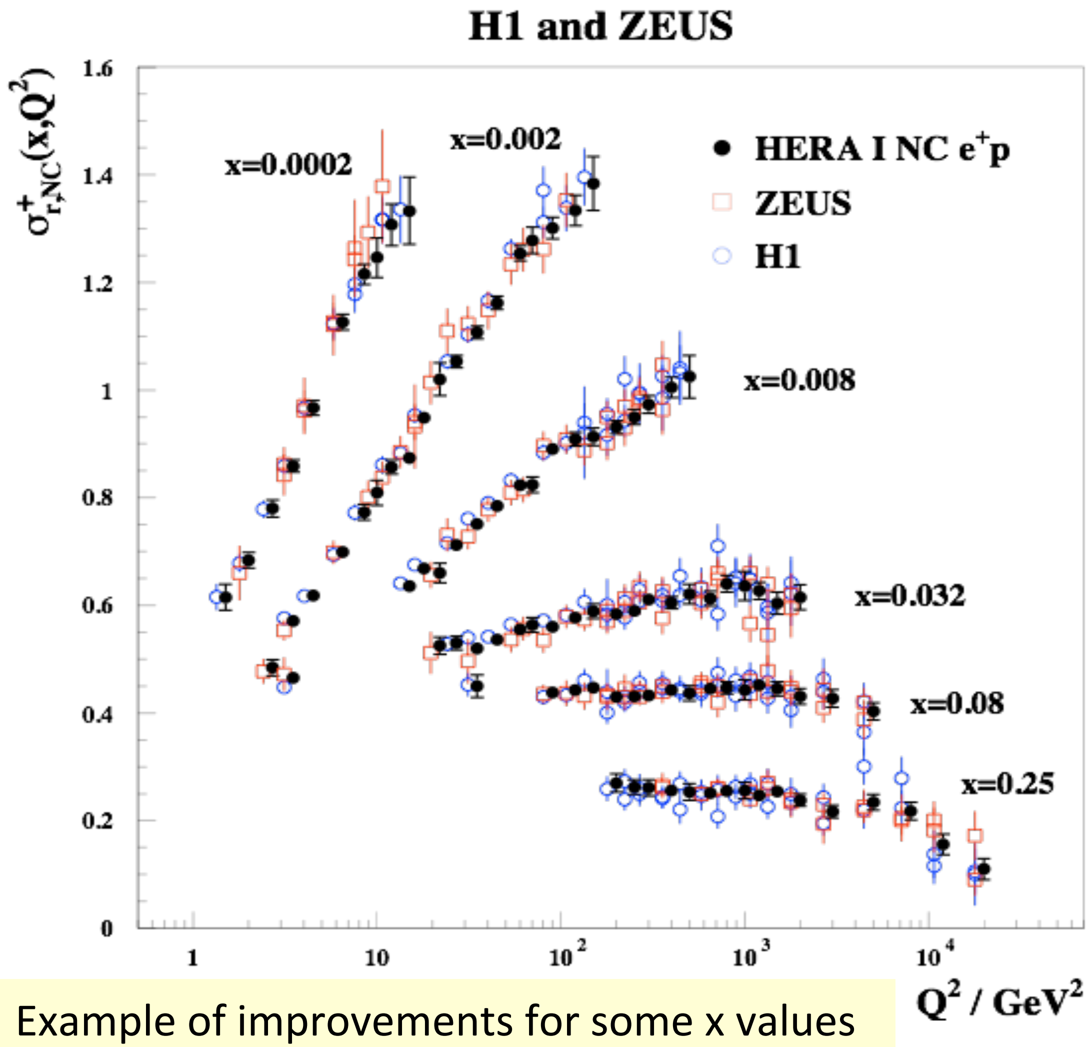
- Before combination, the systematic errors are ~3 times larger than statistical for Q^2<100 GeV^2
- After combination, the systematic errors are of same precision as the statistical errors, reaching 1% total precision!

Example of improvements for some x values

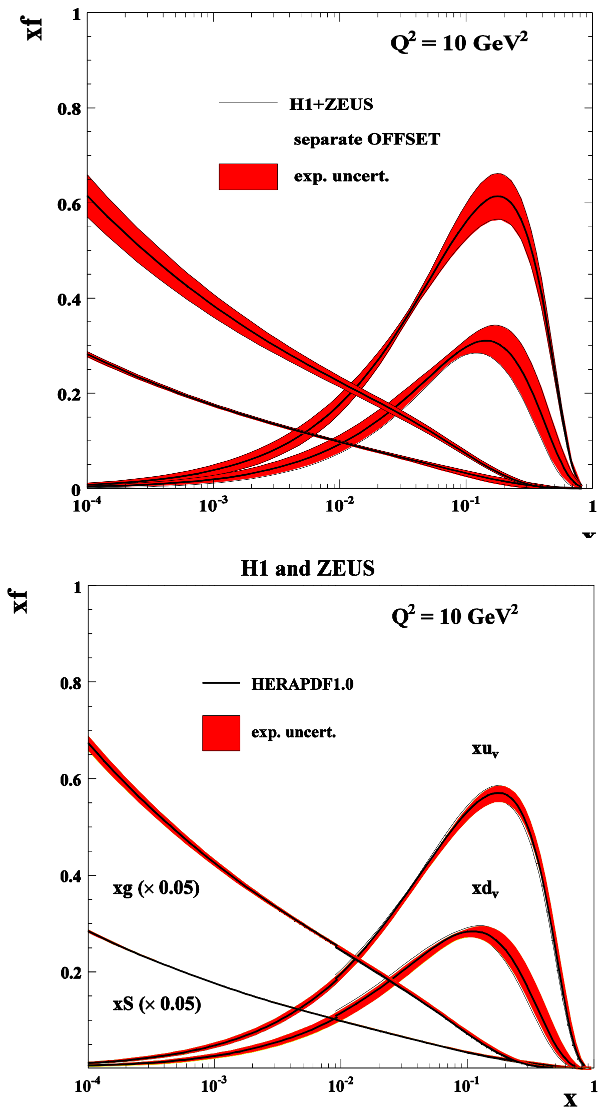
- ZEUS γp background uncertainty is reduced by a factor of ~3
- H1 LAr hadron calorimeter energy scale uncertainty is reduced by a factor~2

Combination of data is now actively used at LHC for ex W, Z for muon and electron channels

Combined HERA-I Data



Example of improvements for some x values



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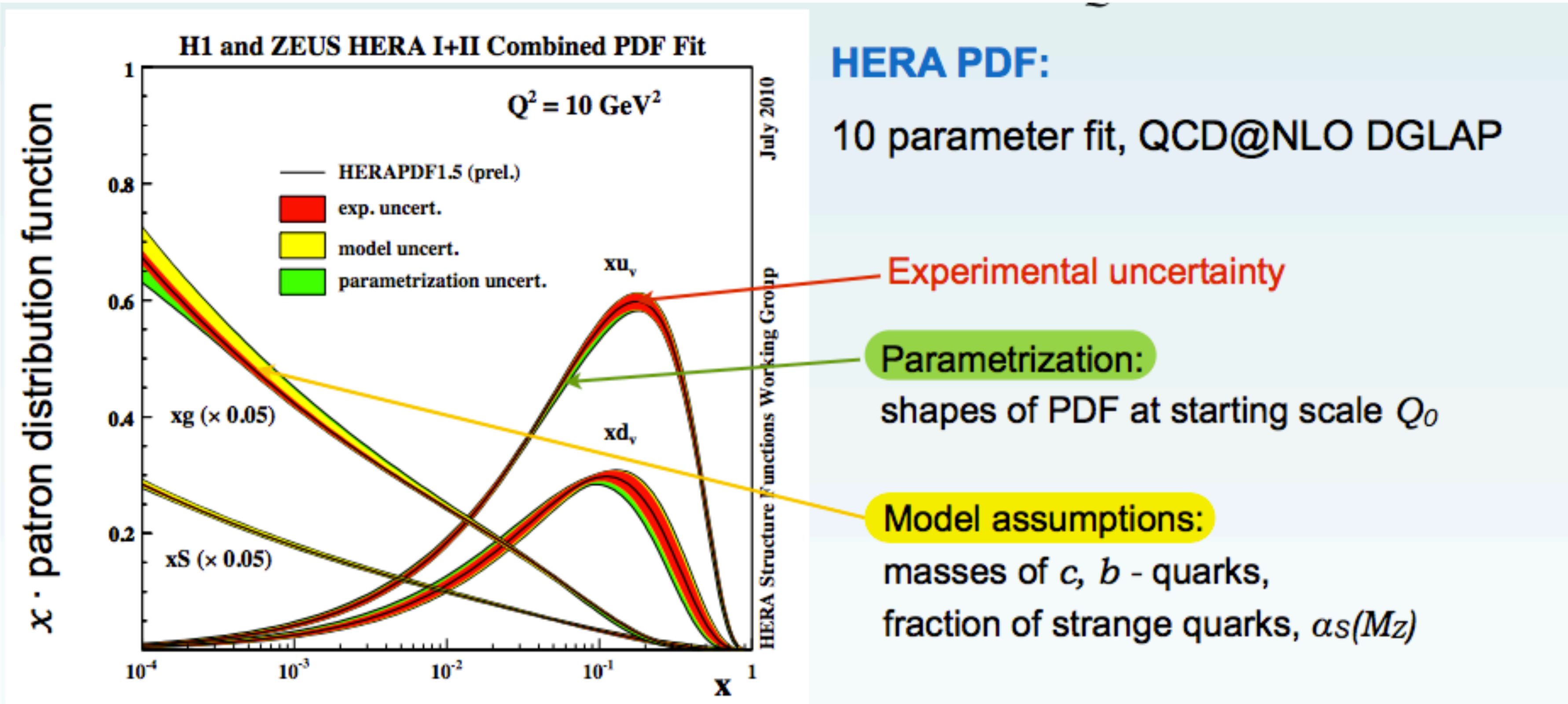
Modern Understanding of PDF

- At HERA PDF can be determined solely from HERA data:
  - use consistent data set: H1+ZEUS
  - proper treatment of error correlations



Gluons and sea quarks: dominant partons at low x

A summary of PDF sets

Table shows a summary of the current status of available PDFs (not included the high x PDFs)

	MSTW08	CTEQ6.6/CT10	NNPDF2.0/2.1	HERAPDF1.0/1.5	ABKM09/ABM11	GJR08/JR09
PDF order	LO, NLO, NNLO	LO, NLO, NNLO	LO, NLO, NNLO	NLO, NNLO	NLO, NNLO	NLO, NNLO
HERA DIS	✔ (old)	✔ (old/new)	✔ (new)	✔ (new/newest)	✔ (new)	✔ (new)
Fixed target DIS	✔	✔	✔	-	✔	✔
Fixed target DY	✔	✔	✔	-	✔	✔
Tevatron W, Z	✔	✔	✔	-	-	-
Tevatron jets	✔	✔	✔	-	✔	✔
HF Scheme	RTGMVF	SACOT GMVFN	FONLL GMVFN	RT GMVFN	BMSN FFNS/FFNS	FFNS
Alphas (NLO)	0.120	0.118(f)	0.119	0.1176(f)	0.1179	0.1145
Alphas (NNLO)	0.1171	0.118(f)	0.1174	0.1176(f)	0.1147	0.1124

The analyses differ in many areas:

- different treatment of heavy quarks
- inclusion of various data sets and account for possible tensions
- different alphas assumption

http://mstwpdf.hepforge.org/pdf4lhc/ Some commonly used plots from G. Watt

Additional Constraints to PDFs: on gluon

- Sensitivity to gluon PDF arise from the coupled singlet-gluon QCD evolution
  - scaling violation:

$$\frac{\partial F_2}{\partial \log Q^2} \sim \alpha_S\, xg(x). \qquad F_2 \sim (\sigma_T + \sigma_L),$$

- And it can be cross checked with other measurements:
  - From the inclusive structure function *FL*: pure QCD effect

$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3}\left[\frac{16}{3} F_2 + 8 \sum_q e_q^2 (1 - \frac{x}{z}) z g(z)\right] \qquad F_L \sim \sigma_L$$

quarks radiating a gluon — gluons splitting into quarks

→ Interesting case also for study physics at low Q2

- heavy flavour schemes, evolutions, higher twists

  - From the measurement of semi-inclusive structure function *Fc*

  - From the inclusive jet cross section (for ep and pp collisions) :
    - Able to decorrelate gluon and strong coupling

Measurement of Longitudinal Structure Function (1)

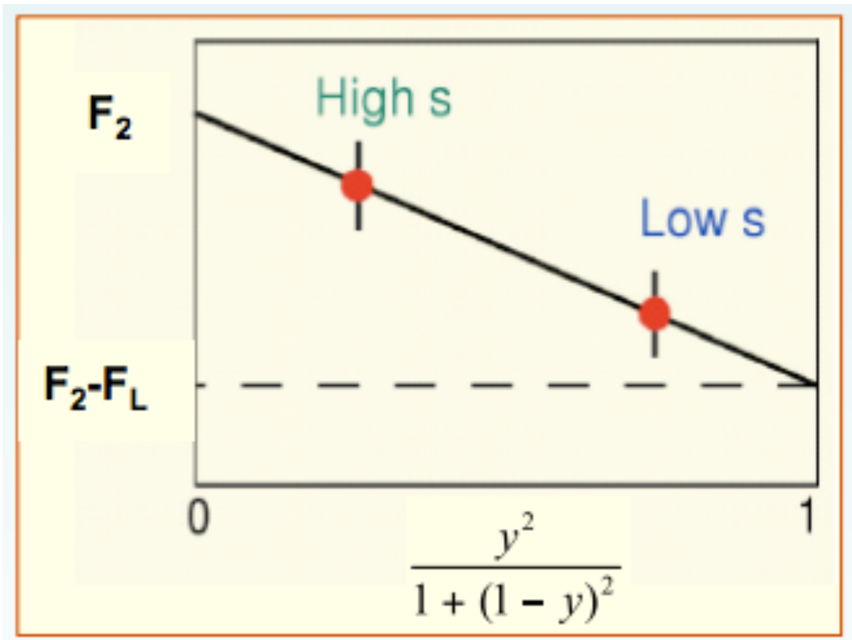
Direct measurement of F_L at HERA requires differential cross sections at same **x** and **Q²** but different **y**:

- larger difference in y, better sensitivity to F_L
- $Q^2=xys$ ➔ different y means different s(CME) → **different beam energies Ep = 460, 575, 920 GeV**

$$\sigma_{NC}(x,Q^2,y) \propto F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$

- Reduced proton beam energy runs at the end of HERA operation were dedicated to measure F_L.

At given x and Q^2:
→ F_2 is the intercept at y-axis
→ F_L is the negative slope



Measurement of Longitudinal Structure Function (2)

Direct measurement of F_L at HERA requires differential cross sections at same **x** and **Q²** but different **y**:

- larger difference in y, better sensitivity to F_L
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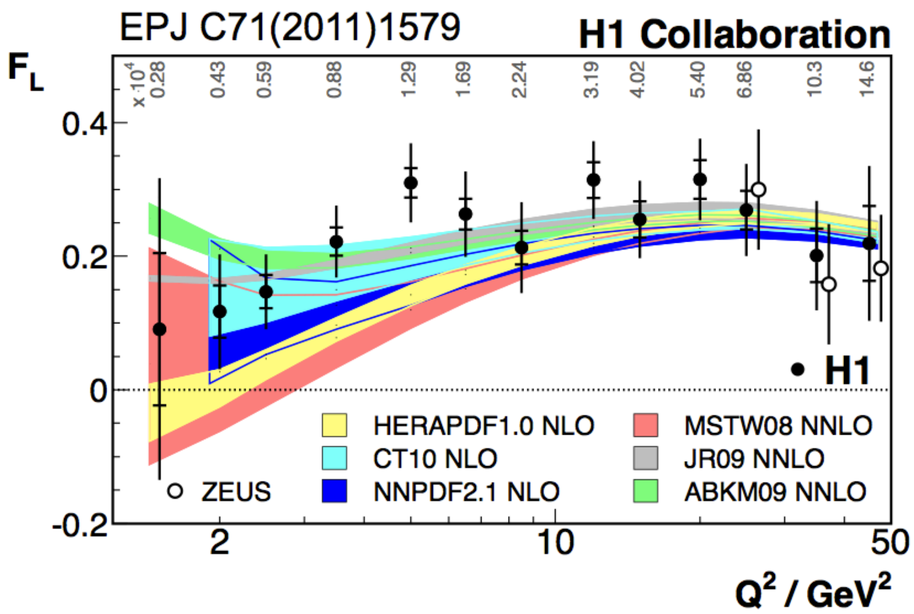
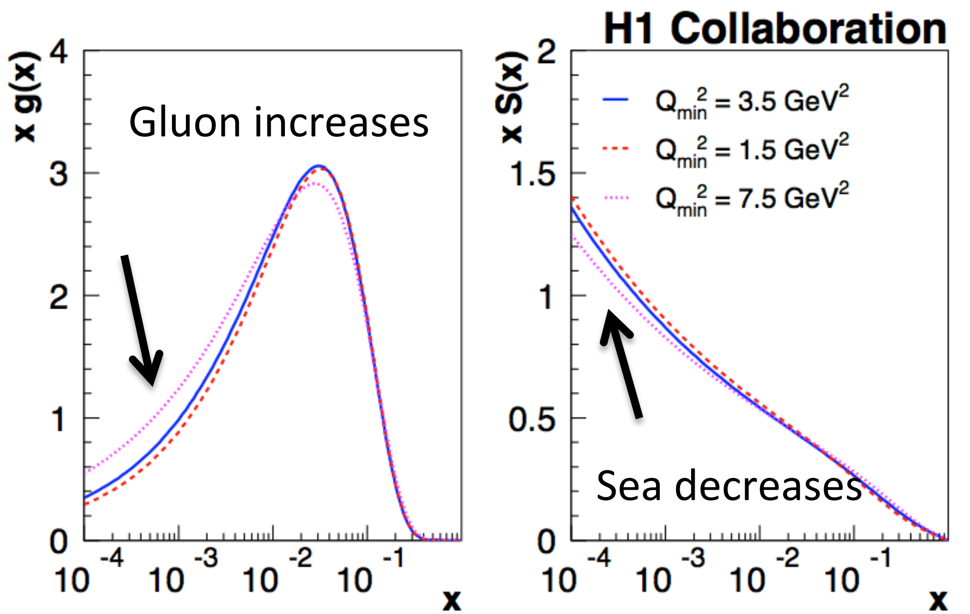




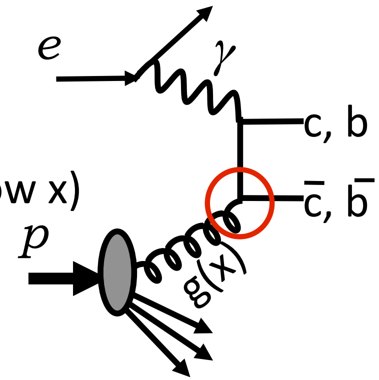
Observe sensitivity to the Q2 cut applied which triggers further explorations of DGLAP validity at low Q2.

Additional Constraints on PDFs: Charm at HERA

- Inclusive structure function *F2* is sensitive to

$$F_2 \sim \frac{4}{9}(U+\bar{U}) + \frac{1}{9}(D+\bar{D}), U = u + c; D = d + s + b$$

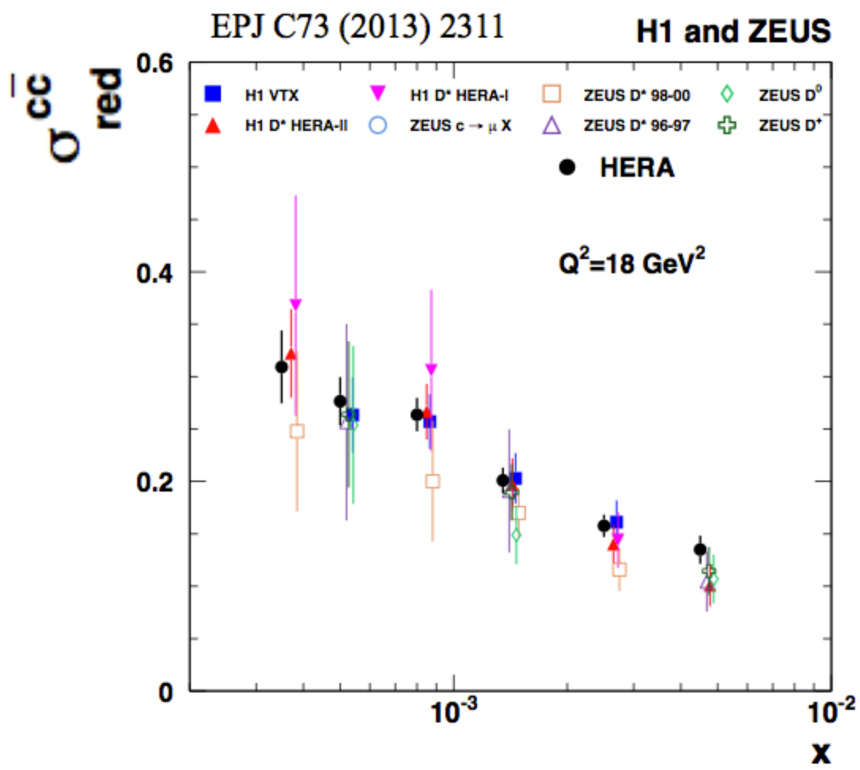
- Up to 30% of the inclusive cross section is related to charm production (at low x)



- F_2 charm data provides a complementary way
  - to impact gluon *
  - to decompose u from c and study the theoretical matching schemes

At HERA, different measurements available using various ways to tag the charm:

- reconstruction of D* and D decays
- inclusive analysis of tracks lifetime information
- muons from charm semi-leptonic decays



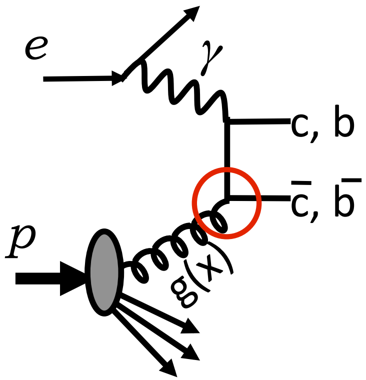
Eur. Phys. J. C 73:2311 (2013), [arXiv:1211.1182]

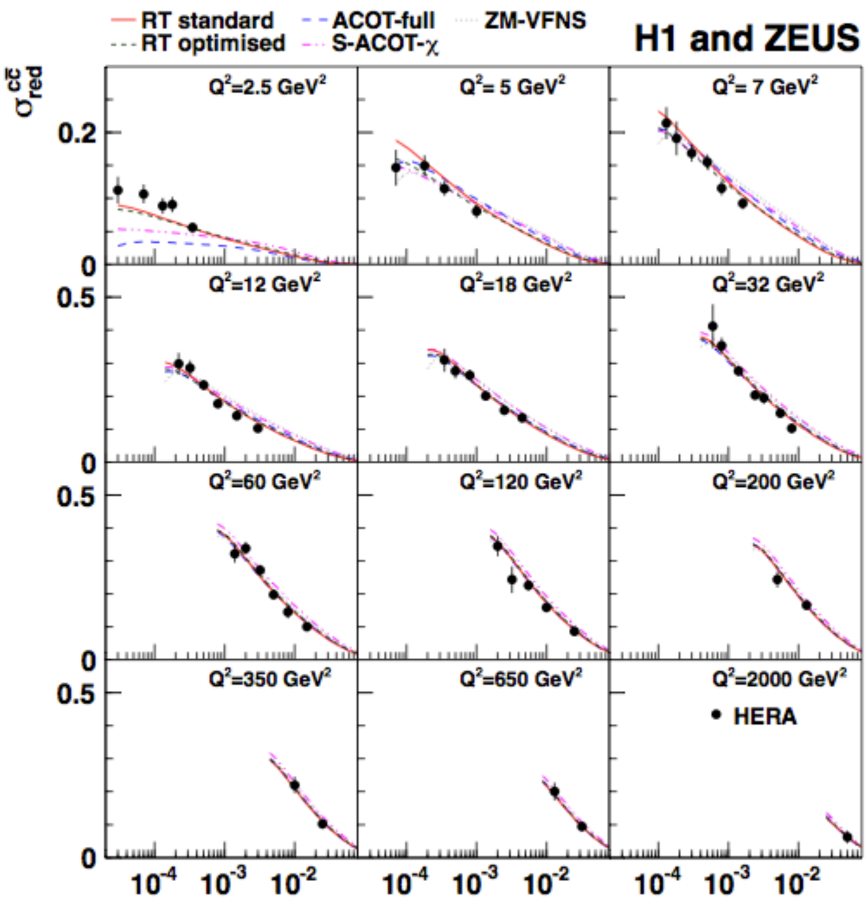
Additional Constraints on PDFs: Charm at HERA

Combined HERA *Fcc* data reaches 5 – 10% precision per point, can be used to study different HF models:

All models use a parameter mc related to the charm pole mass

→ can use it as a tuning parameter for different scheme

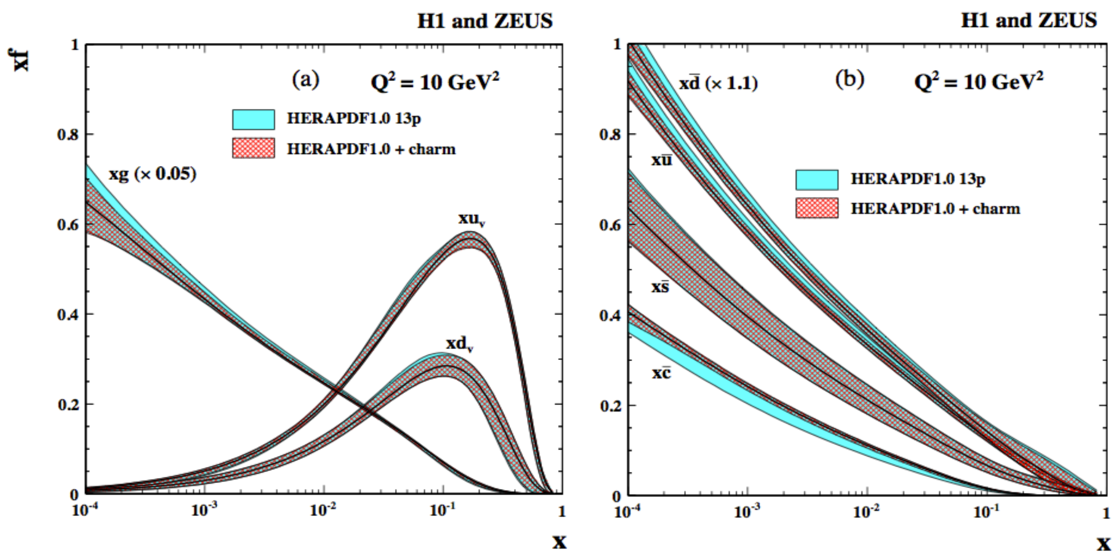




Eur. Phys. J. C 73:2311 (2013), [arXiv:1211.1182]

Inclusion of charm has impact on:

- gluon, charm and light sea:



From low x to high x

PDF flavour decomposition can be classified into regions:

- Low x (x<0.01)
  - Gluon density is determined with high accuracy from the *F2* scaling violation using QCD evolution
    - Indirect determination cross checked using direct measurement of *FL*
    - Results are consistent for Q2>10, however still open questions left for low Q2 and low x region
  - Accurate measurements on *F2* which probes linear combination of the quark distributions.
    - PDF decomposition is not so well constrained:

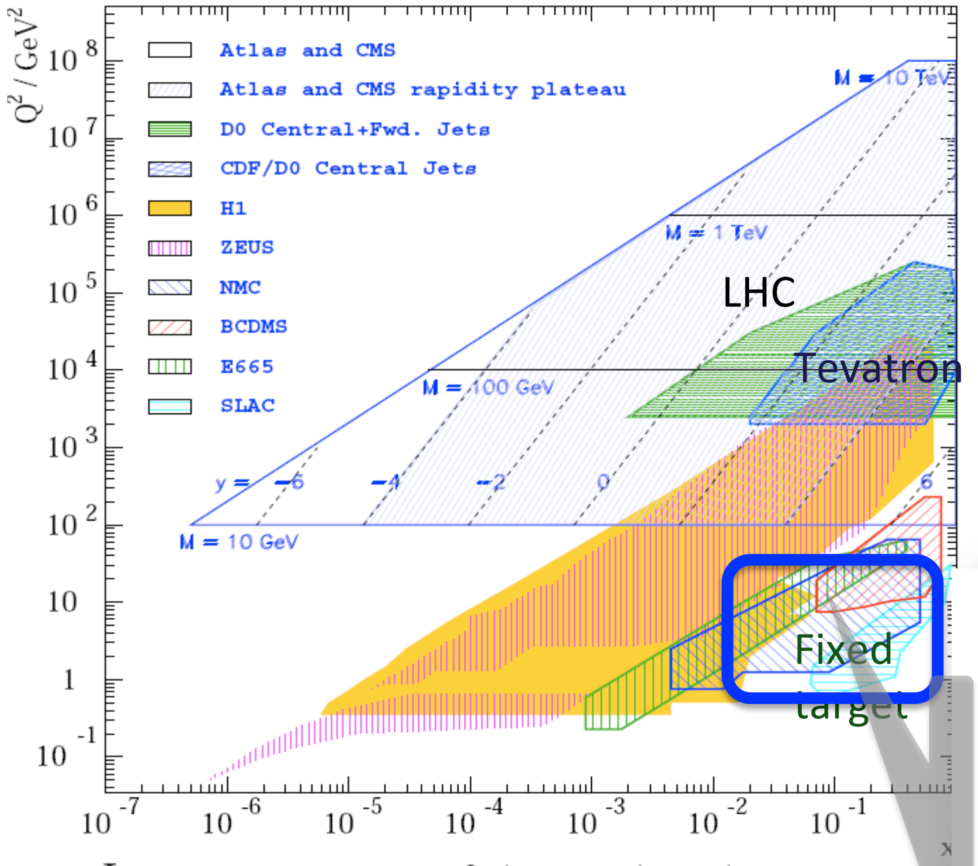
    Little is known experimentally about $\bar{u}/\bar{d}$ as well as $\bar{s}/\bar{d}$. (LHC can help further)

  Heavy *c* and *b* are determined using semi-inclusive scattering process with tagged heavy quarks.

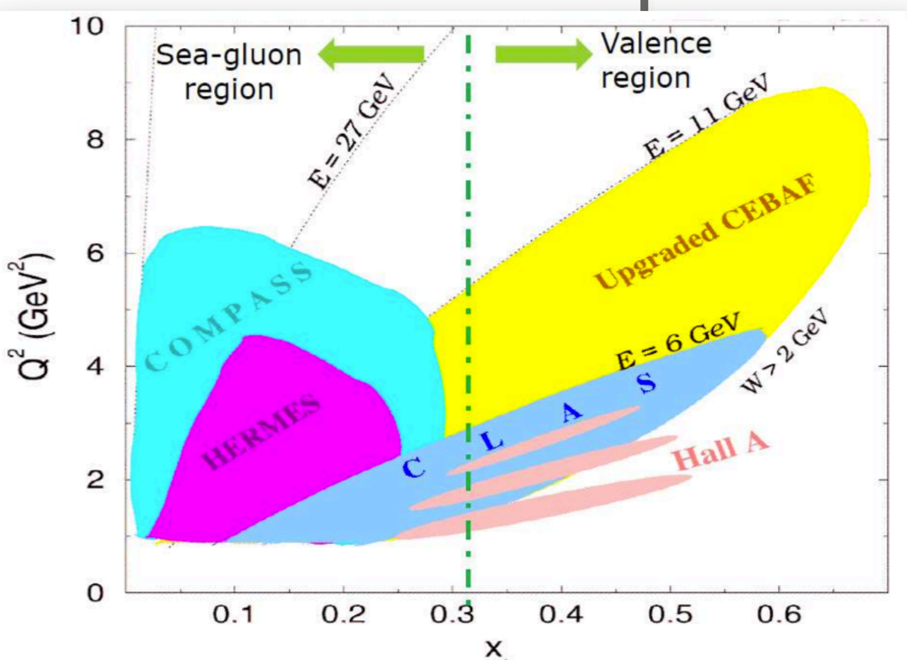
- High x (x>0.01)
  - Gluon at high x is very sensitive to Higgs Production, hence improvement is crucial for precision measurements of properties of Higgs
    - scaling violation, pp jets
  - Light quarks:
    - HERA's CC helps provide clean constraints on u and d at high x
    - Separation of *s* from neutrino scattering, however with large theoretical uncertainties.
    - Separation of $\bar{u}$, $\bar{d}$ using *p p, pd* experiments.

    Another handle on *u/d:* measurement of *F2d.*

Constraints from High x Measurements



- Structure functions sensitive:
  - to gluon density
  - to power corrections in Q2
  - to higher twist contributions
  - to high x pdfs
- Exploit the difference between proton and deuteron structure functions:
  - sensitive to d/u.



JLAB has an intense program on polarised and unpolarised structure functions and more is to come with JLAB@12GeV

Halls A,C: dedicated small angle spectrometers.
Hall B: large acceptance spectrometer CLAS.

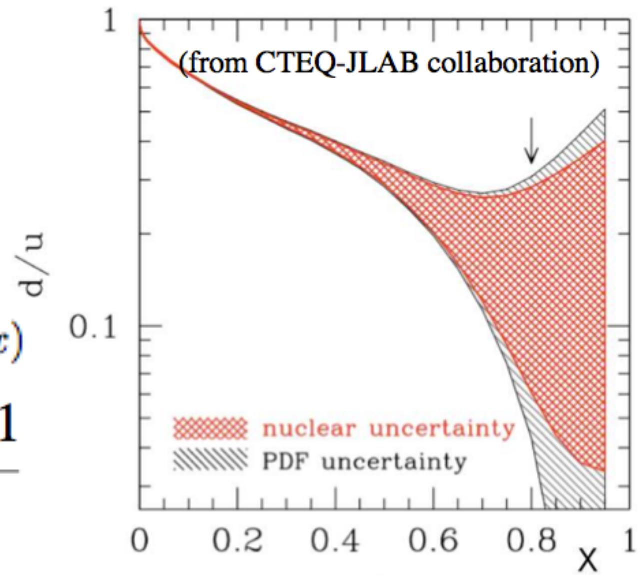
Hall D: under construction for photon beam experiments.

Measurements at JLAB (hall B)

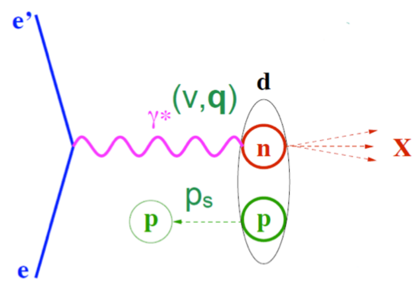
- Measurements of the neutron structure proton
  - Provides handle of d/u at high x:
    - Important for high energy predictions
  - Measured using F2n/F2p (assuming isospin symmetry)

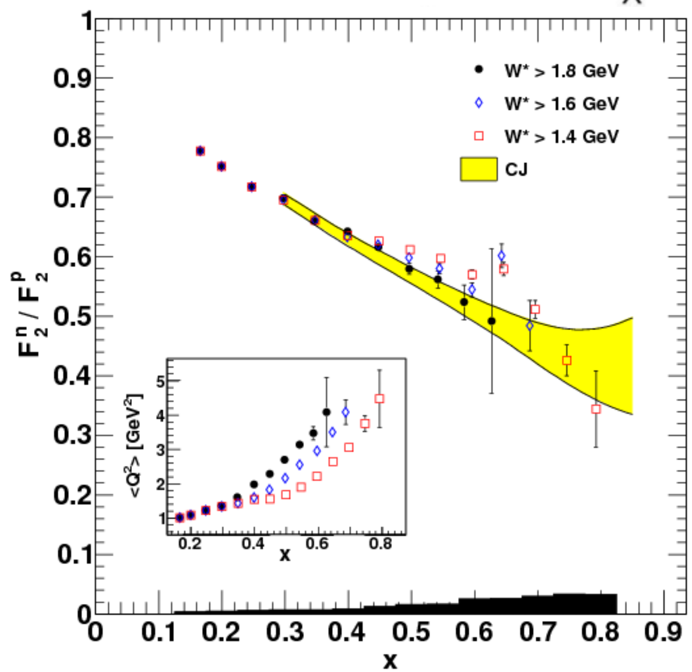
$$u^p(x) = d^n(x) \equiv u(x),\ d^p(x) = u^n(x) \equiv d(x),\ s^p(x) = s^n(x) \equiv s(x)$$

$$\frac{F_2^n}{F_2^p} = \frac{u + u + 4(d + d) + s + s}{4(u + u) + d + d + s + s} \longrightarrow \frac{d}{u} \approx \frac{4F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}}$$



  - BONUS experiment at JLAB extracts F2n in a model independent way using tagging spectator proton approach:
    - detect a low momentum, backward moving proton to emulate a quasi-free neutron target





  - Results are in good agreement with CJ prediction (will hear more on that on PDF lecture), but higher precision on data is desirable
    - Sensitive to nuclear medium effects (referred to as EMC)

Future Measurement at JLAB (hall A)

- MARATHON will measure with *Ee* = 12 GeV F2n/F2p taking into account Fermi-motion and binding effects in deuterium

Using of Super-Ratio method:

$$\frac{\sigma^{He^3}}{\sigma^{H^3}} \approx \frac{F_2^{He^3}}{F_2^{H^3}} = R^* \frac{2F_2^P + F_2^n}{F_2^p + 2F_2^n}$$

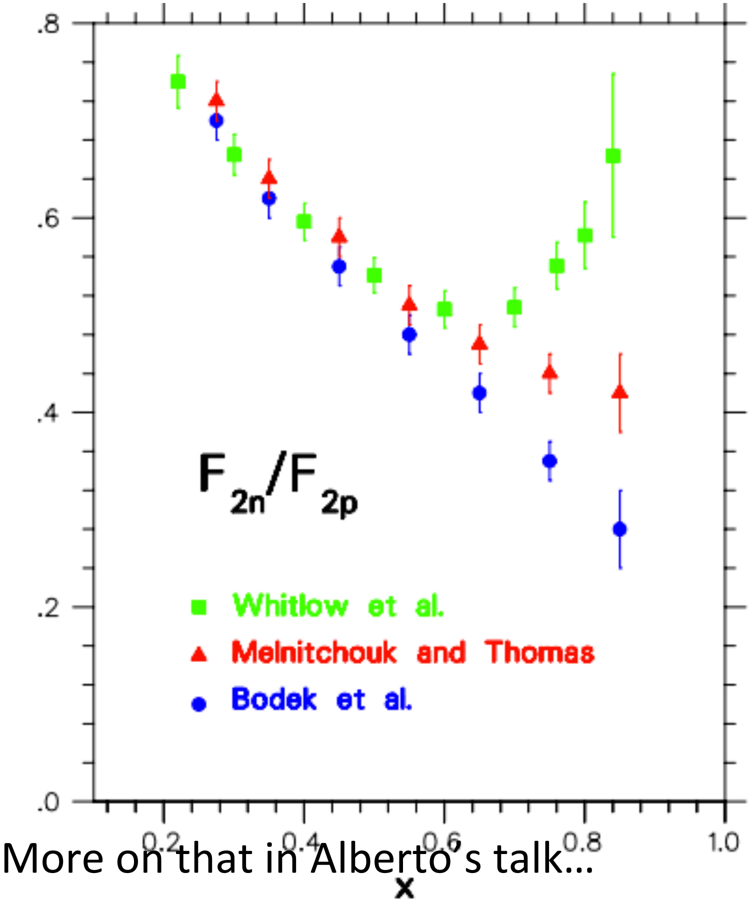
$$\mathcal{R} = \frac{R(^3\mathrm{He})}{R(^3\mathrm{H})} .$$

$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n} , \qquad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n} ,$$

In terms of the proton and neutron momentum distributions:

$$F_2^{^3\mathrm{H}} = f_{p/^3\mathrm{H}} \otimes F_2^p + 2\, f_{n/^3\mathrm{H}} \otimes F_2^n .$$

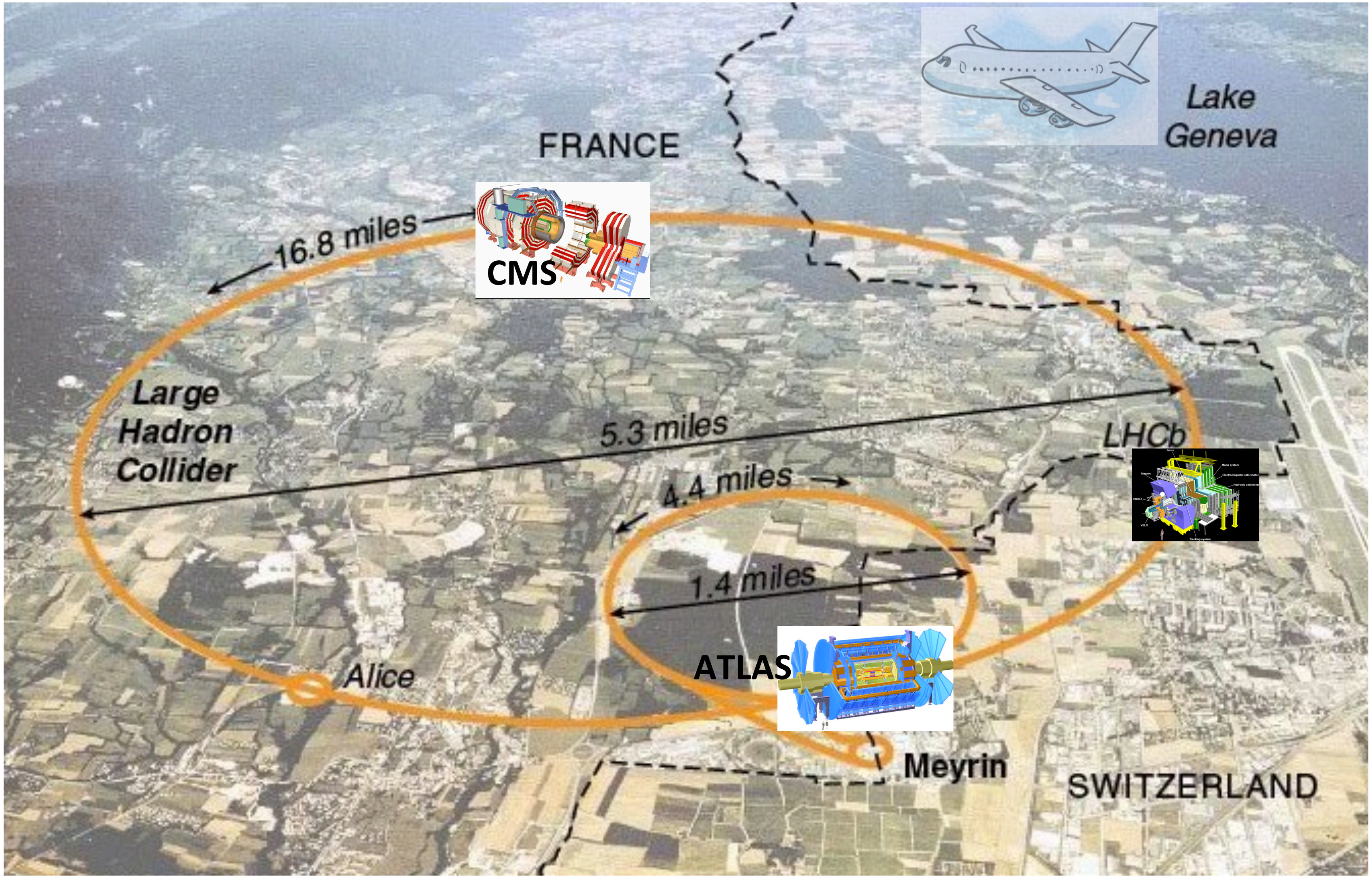
$$F_2^{^3\mathrm{He}} = 2\, f_{p/^3\mathrm{He}} \otimes F_2^p + f_{n/^3\mathrm{He}} \otimes F_2^n$$



More on that in Alberto's talk…

F2n/2Fp from above does not depend on the size of the EMC effect in 3He or 3H, but rather on the ratio of the EMC effects in 3He and 3H.

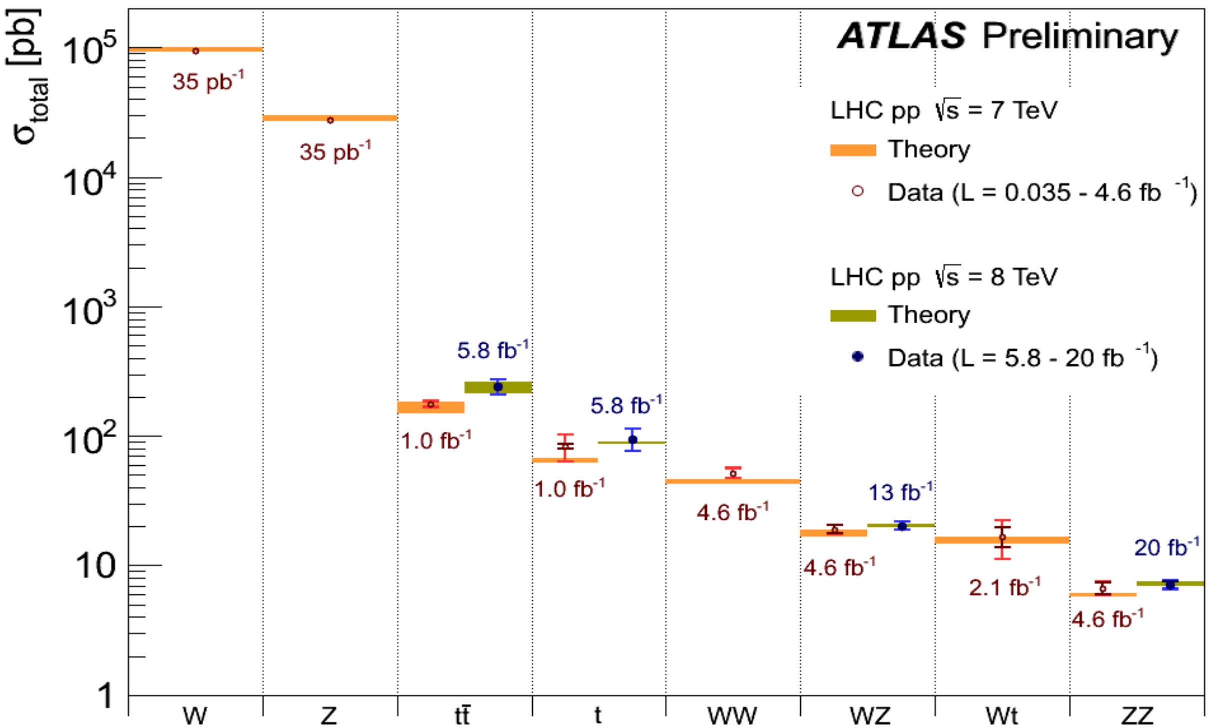
From DIS to LHC



Pushing Energy Frontier

- LHC can provide with its multitude of new measurements

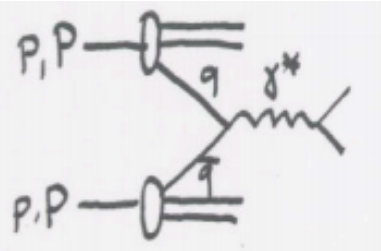
- PDF discrimination by confronting theory with data
- PDF improvement by using LHC data for more accurate



1. **W and Z production**
2. **W+c production**
3. **Inclusive Jet and Di-Jet production**
4. **Drell-Yan: low and high invariant mass**
5. **Top, ttbar**
6. **Prompt Photon, + Jets**
7. **W,Z+b**

Drell-Yan kinematics

- At the pp coliders



- Consider x1 and x2 be fractions of the proton momenta carried by the partons participating in pp collision
- Kinematic variables

$$P^2 = M_p^2 = E_p^2 - \vec{p}^{\,2} \qquad m_{12}^2 = (p_1 + p_2)^2 = s x_1 x_2$$

$$s = (P_1 + P_2)^2 = 4E_p^2 \qquad y = \frac{1}{2}\ln\left(\frac{x_1}{x_2}\right)$$ is rapidity!

$$E_p = \left|\overrightarrow{p_{1,2}}\right| = \frac{\sqrt{s}}{2}$$

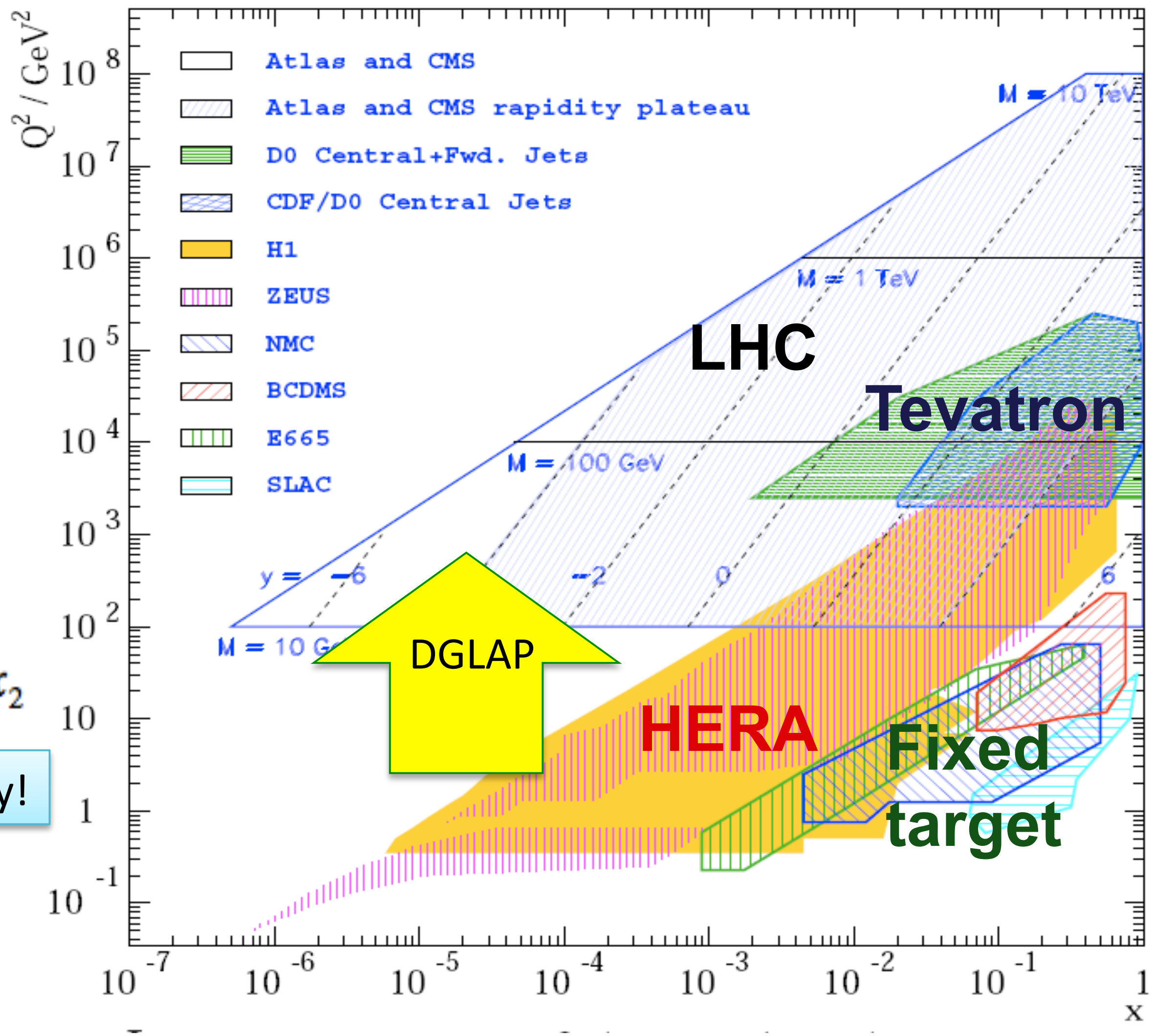
$$x_1 = \frac{M}{\sqrt{s}} e^{+y}$$

$$p_1 = \frac{\sqrt{s}}{2}(x_1, 0, 0, x_1)$$

$$x_2 = \frac{M}{\sqrt{s}} e^{-y}$$

$$p_2 = \frac{\sqrt{s}}{2}(x_2, 0, 0, -x_2)$$

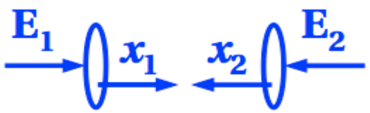
Low and high x are linked together at the LHC



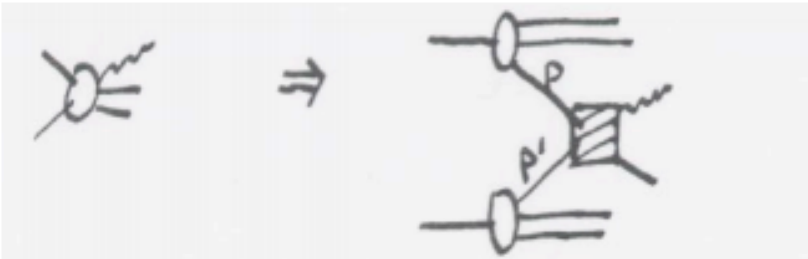
So we can relate DY kinematica variables and to Q2 and x in DIS

Probing the Proton Structure: Drell Yan

Proton-proton collisions:



Factorisation in pp DY process:

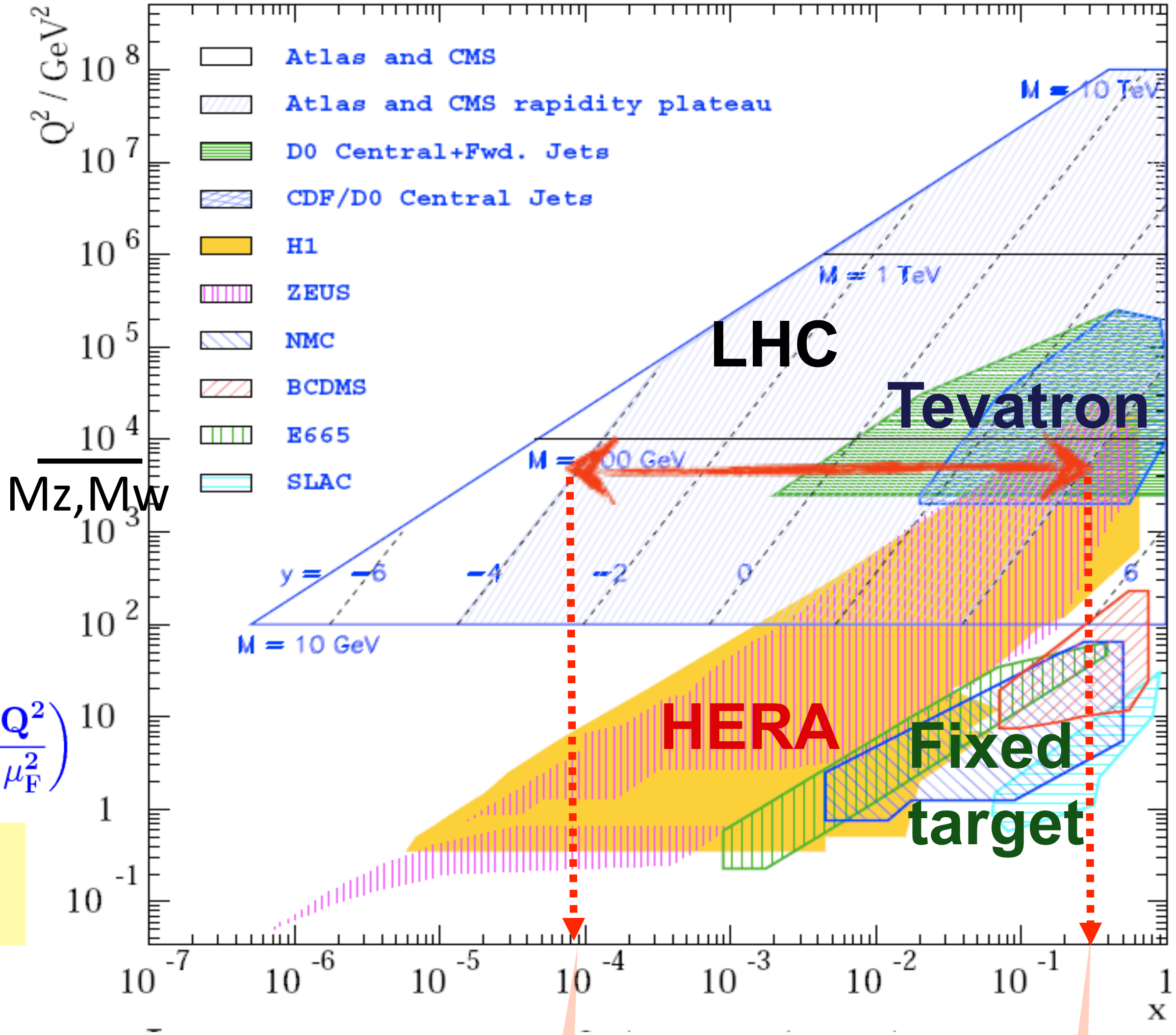


$$\sigma_X = \sum_{a,b} \int_0^1 dx_1 dx_2\, f_a(x_1, \mu_F^2)\, f_b(x_2, \mu_F^2)$$
$$\times\ \hat{\sigma}_{ab\to X}\left(x_1, x_2, \{p_i^\mu\}; \alpha_S(\mu_R^2), \alpha(\mu_R^2), \frac{Q^2}{\mu_R^2}, \frac{Q^2}{\mu_F^2}\right)$$

hadronic cross section

Partonic cross section

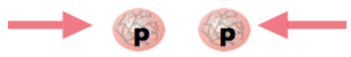
So, to predict Z or W production at LHC with a rapidity y=-4, it is needed:



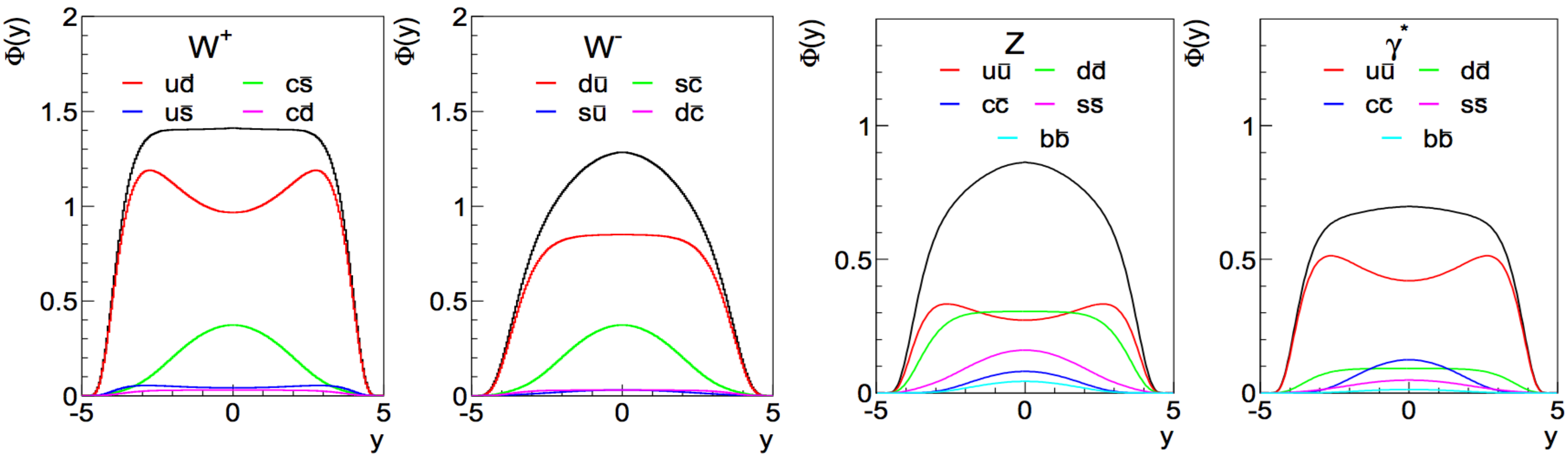
$f(x_1=10^{-4}, Q^2=M^2_{W,Z})$ $f(x_1=0.3, Q^2=M^2_{W,Z})$

Flavour decomposition of W and Z and the LHC

- Additional constraints on PDFs come from DY and jet data at the LHC
  probe a bi-linear combination of quarks



$$W^+ \sim 0.95(u\bar{d} + c\bar{s}) + 0.05(u\bar{s} + c\bar{d})$$
$$W^- \sim 0.95(d\bar{u} + s\bar{c}) + 0.05(d\bar{c} + s\bar{u})$$
$$Z \sim 0.29(u\bar{u} + c\bar{c}) + 0.37(d\bar{d} + s\bar{s} + b\bar{b})$$
$$\gamma^* \sim 0.44(u\bar{u} + c\bar{c}) + 0.11(d\bar{d} + s\bar{s} + b\bar{b})$$



Measurements of W, Z production differentially in y_Z and η_ℓ provide information on light sea decomposition and can constrain better the strange distribution

Measurements at LHC sensitive to PDFs

- Standard Model LHC measurements can add PDF discrimination and PDF improvement:
  - W, Z inclusive:light quark sea is flavour symmetric:
    - Confirmed by preliminary W+c
    - High mass, low mass DY → feedback on dbar-ubar
  - Exploiting different energy beams for inclusive jets brings forward sensitivity to the gluon PDFs.
    - Photon-jet measurements → gluon PDF
    - First alphas from ATLAS from 3/2 jets 2010 → consistent with world average
  - Top measurement is becoming a valuable player in the impact on PDFs (and alphas)

- More precision measurements from LHC are to come also with 2012 data:
  - Top, W,Z+ c,b, W,Z+jets, …

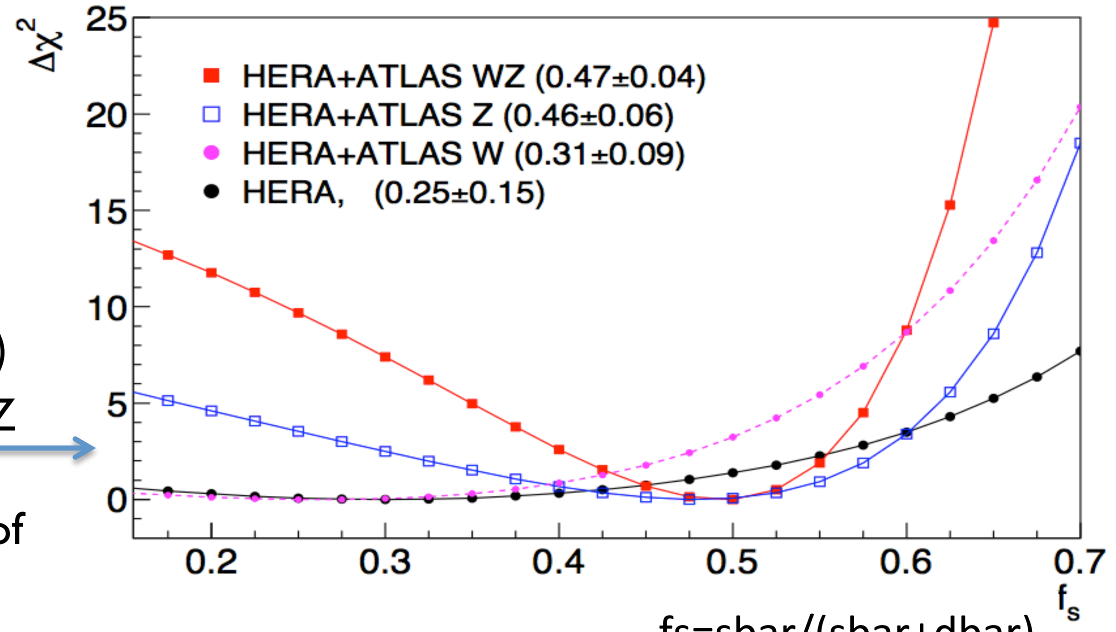
- It is crucial to match data precision to available theoretical calculation:
  - require sometimes tedious work to interface/validate different packages to allow for a consistent QCD interpretation of the measurements:
    - Ex: APPLGRID interface to aMC@NLO, SHERPA, JetPHOX, FEWZ vs DYNNLO (@NNLO), FEWZ vs SANC (EW NLO), FEWZ vs MCFM (NLO), aMC@NLO vs MCFM, HATHOR vs TOP++.. Etc..

Importance of correlation information

$$\chi^2(\mathbf{T},\mathbf{b}) = \sum_i \frac{\left[T^i(1-\sum_j \gamma^i_j b_j)_{corr} - D^i\right]^2}{\Delta^2_{uncorr}} + \sum_j b_j^2$$

→ By providing also correlations (b) allows for more flexibility to theory (T) to describe data (D)

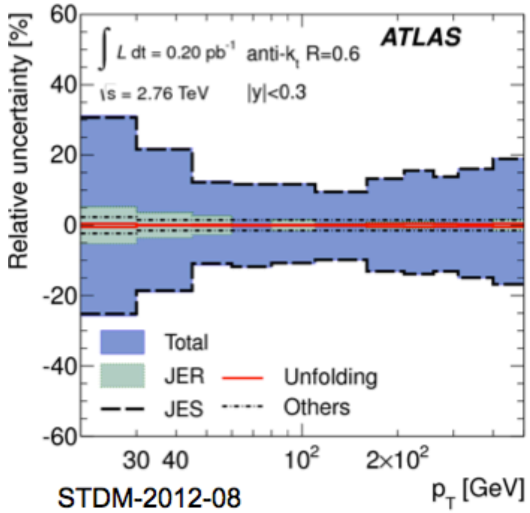
- For **s/d:** most constraints comes from the Z data, however addition of the W data brings further constraint due to common sources of correlations cancelling out
  - Equivalent to taking ratio of measurements

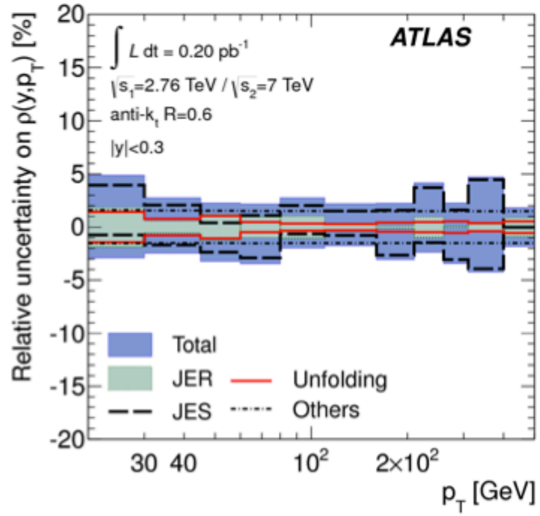


fs=sbar/(sbar+dbar)

- Similarly for 2.76 vs 7 TeV jets measurements:
  - Impressive error reductions

- Future measurements can benefit from careful identification of common correlated sources

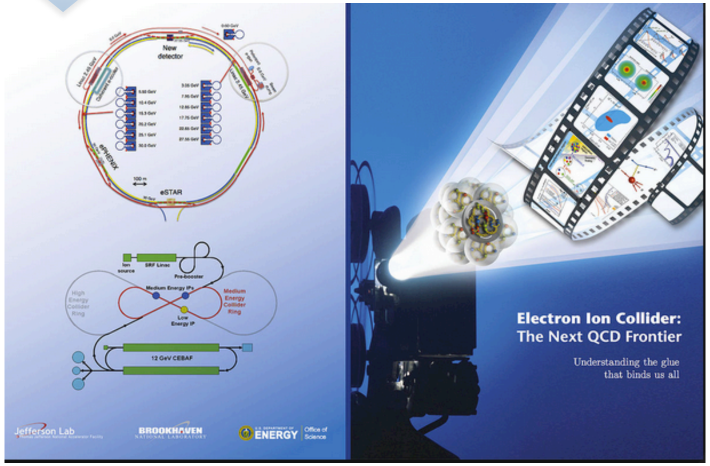




Future ep colliders

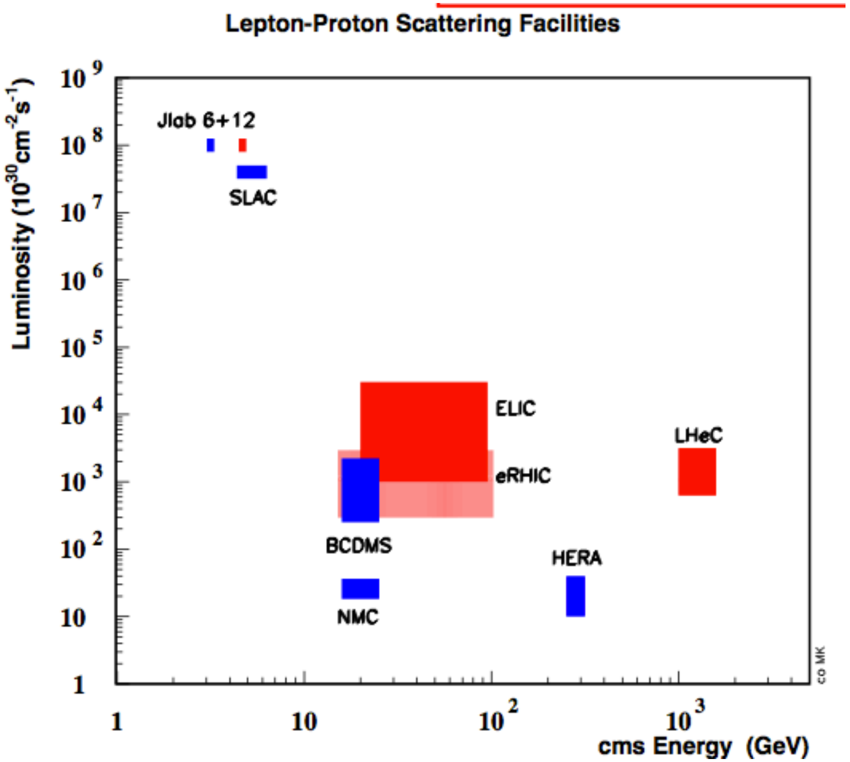
LHeC (ep collider to complement LHC at CERN), EIC

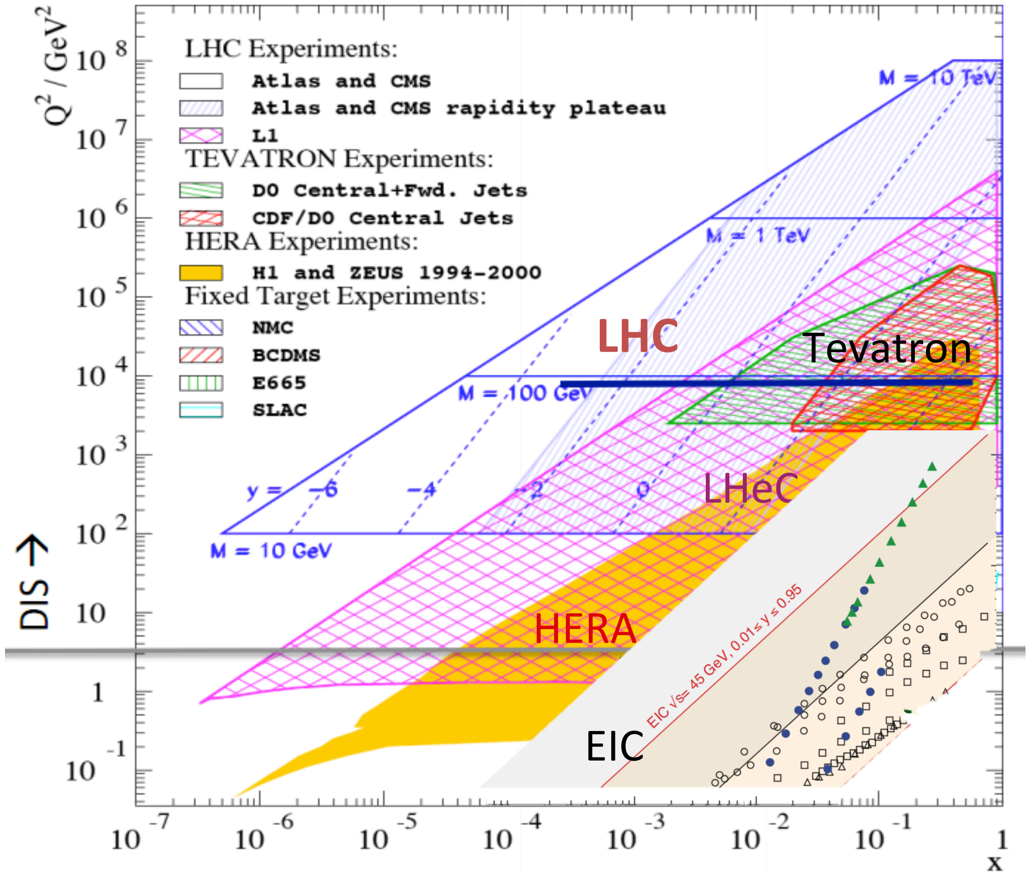
arXiv:1206.2913



LHeC kinematic plane

LHeC (ep collider to complement LHC at CERN), EIC





- LHeC sensitivity extends to $x=10^{-6}$
- Much increased luminosity for EIC

and LHeC colliders compared to HERA.

Motivation for LHeC

- What HERA could/did not do:

Test of the isospin symmetry (u-d) with eD	no deuterons
Investigation of the q-g dynamics in nuclei	no time for eA
Verification of saturation prediction at low x	too low c.o.m energy
Measurement of the strange quark distribution	too low Luminosity
Discovery of Higgs in WW fusion in CC	too low cross section
Study of top quark distribution in the proton	too low c.o.m energy
Precise measurement of FL	too short running time with low energy runs
Resolving d/u question at large Bjorken x	too low Luminosity
Determination of gluon distribution at hi/lo x	too small range
High precision measurement of α_s	overall not precise enough

HEP needs a TeV energy scale machine with 100 times higher luminosity than HERA to develop DIS physics further and to complement the physics at the LHC. The Large Hadron Collider p and A beams offer a unique opportunity to build a second ep and first eA collider at the energy frontier.

(M. Klein)

Summary

DIS provided us with most valuable information on the proton substructure

- Low x and high x are exploited at HERA (the only ep collider) or at JLAB (fixed target experiments)

… Many more valuable measurements are already available, but not covered in this talk …

PDFs still limit our knowledge of cross sections whether SM or BSM.

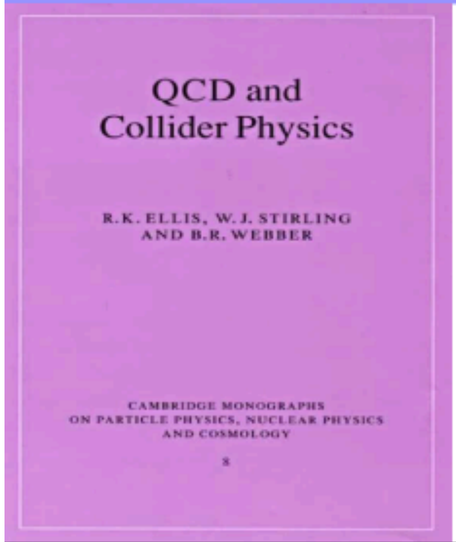
- Standard Model LHC measurements can themselves contribute to PDF discrimination and PDF improvement:
  - LHC data suggest that the light quark sea is flavour symmetric:
    - W,Z inclusive cross check against W+c
  - Exploiting different energy beams for inclusive jets brings forward sensitivity to the gluon PDFs.
    - gluon PDF can also be improved through Photon-jet measurements [see P. Lenzi]
  - Top measurement is becoming a valuable player in the impact on PDFs (and alphas)

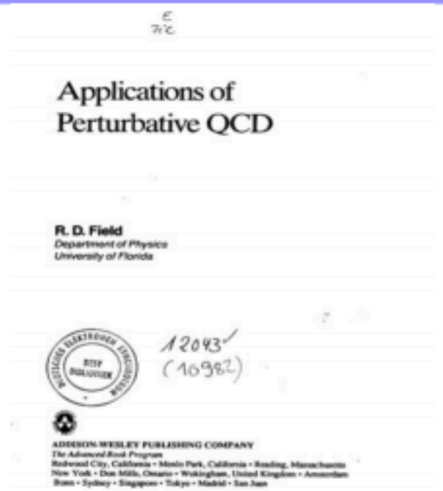
  … Many more valuable measurements are already available, but not covered in this talk …

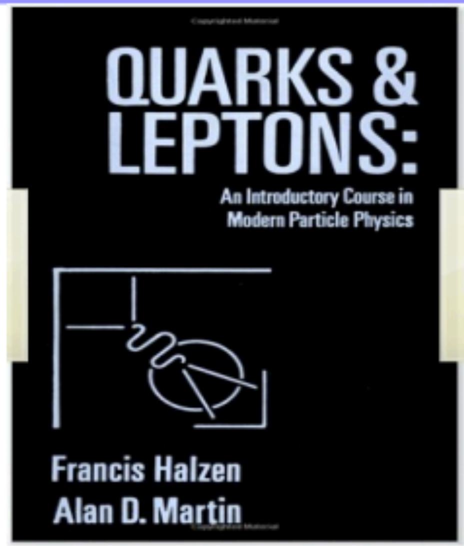
- More precision measurements from LHC to come from Run I and in future from Run 2

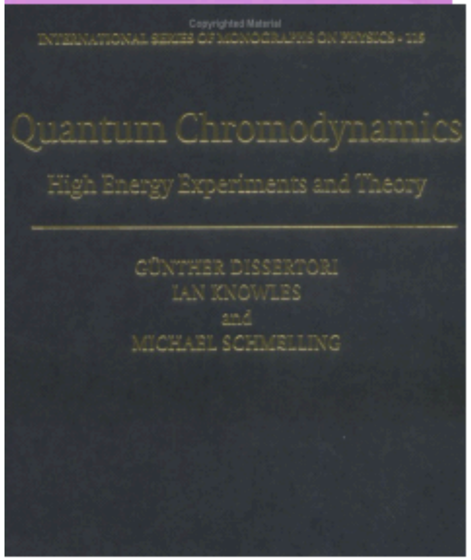
LHeC can represent a natural extension to LHC by providing an accurate and complete PDF set

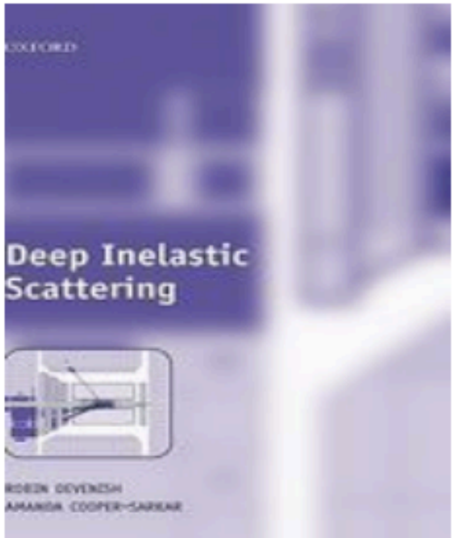
Literature











Add to that:
Quantum Chromodynamics: High energy experiments and theory: G. Dissertori, I. Knowles, M. Schmelling
CTEQ lectures

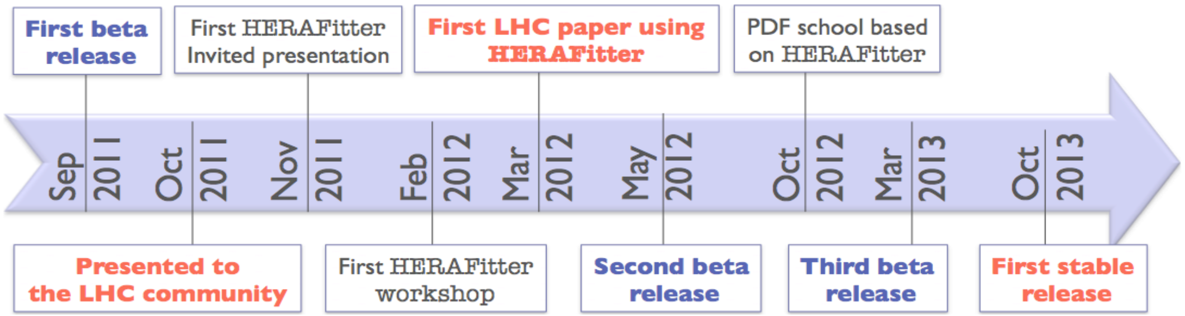

Back up slides

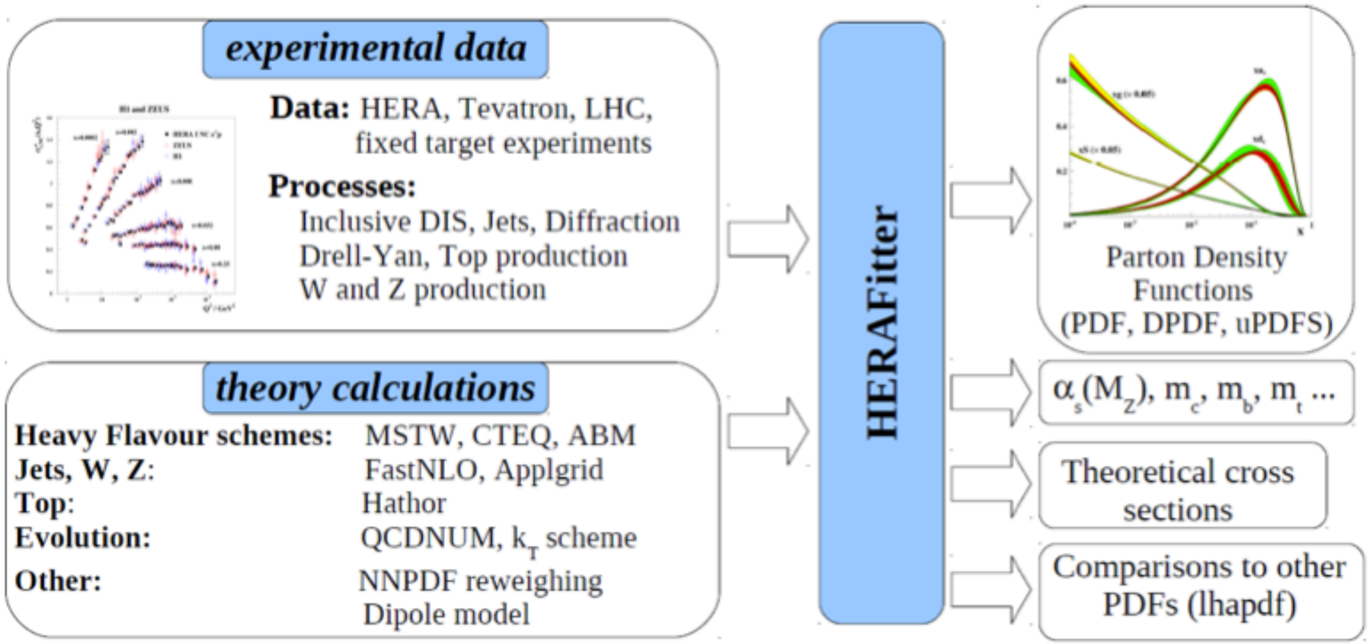

Not necessarily useful

HERAFitter QCD platform

Heritage of HERA transferred to LHC:

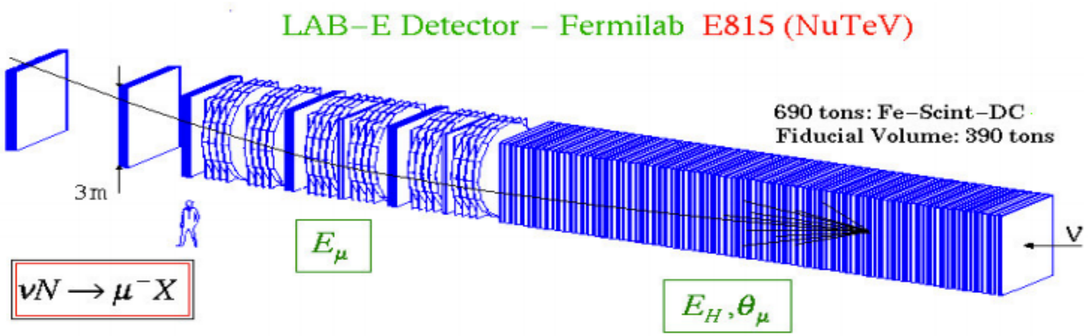
Open Source QCD Framework freely available at https://www.herafitter.org



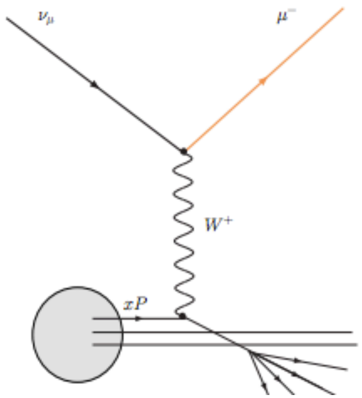


νN scattering (fixed target)

- Features: dense detector to facilitate the interaction rate:



- NuTeV is a precision neutrino DIS experiment
- Data taking: 1996-97 FermiLab fi xed target run $E_\nu \in (30\ ,\ 400)$ GeV and $Q^2 \in (1\ ,\ 600)$ GeV^2
- Charged Current events: $8.0 \times 10^5\ \nu$ and $2.2 \times 10^5\ \overline{\nu}$



- Lorentz-invariant quantities in terms of measured $E_\mu,\ \theta_\mu,\ E_{had}$:

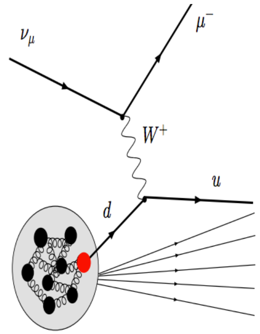
$$\begin{cases} Q^2 = 4(E_\mu + E_{had})E_\mu sin^2\frac{\theta_\mu}{2} & \longrightarrow \text{negative square 4-momentum transfer} \\ x = \frac{Q^2}{2ME_{had}} & \longrightarrow \text{Bjorken scaling variable} \\ y = \frac{E_{had}}{E_\mu + E_{had}} & \longrightarrow \text{inelasticity} \\ \nu = E_{had} & \longrightarrow \text{energy transfered to hadronic system} \end{cases}$$

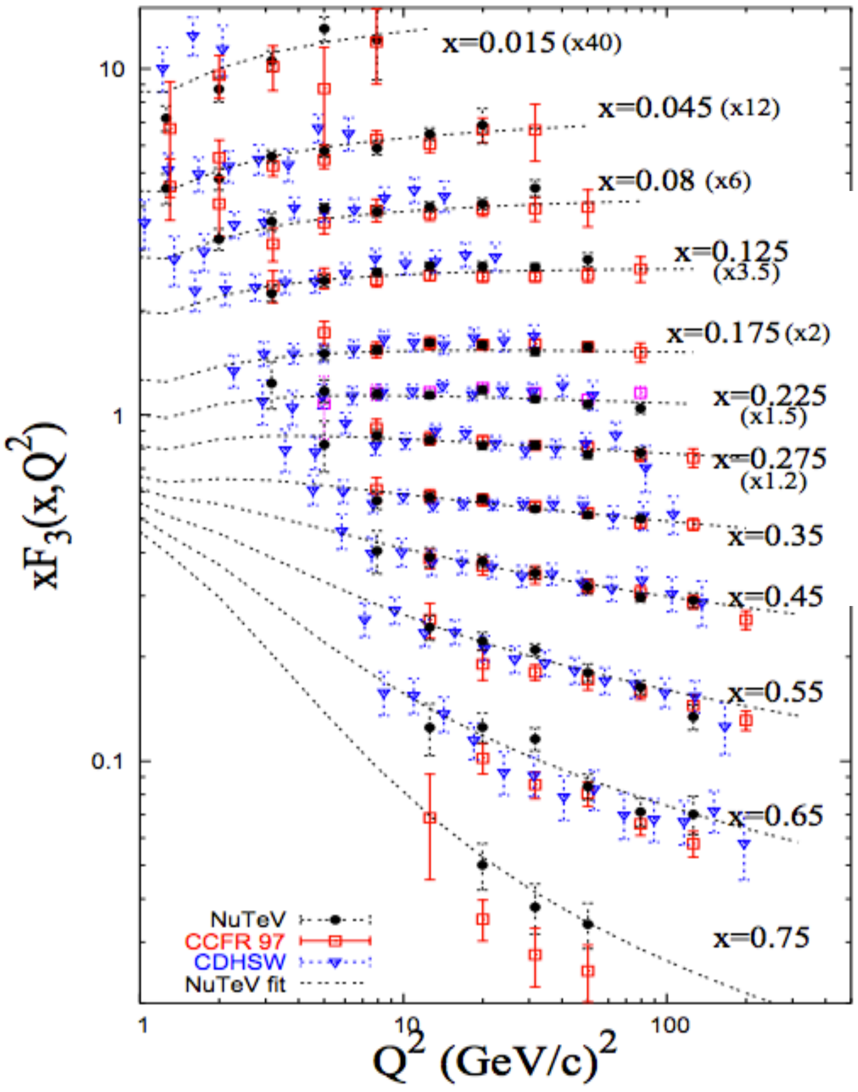
Measurement of F2 and xF3 at NuTeV is extracted from a linear combination of cross sections:

$$\left[\frac{d^2\sigma^\nu}{dxdy} + \frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right]\frac{\pi}{2MG^2E_\nu} = \left(1 - y - \frac{Mxy}{2E} + \frac{1+\left(\frac{2Mx}{Q}\right)^2}{1+R_L}\frac{y^2}{2}\right)F_2^{avg} + y\left(1-\frac{y}{2}\right)\Delta xF_3$$

$$\left[\frac{d^2\sigma^\nu}{dxdy} - \frac{d^2\sigma^{\overline{\nu}}}{dxdy}\right]\frac{\pi}{2MG^2E_\nu} = \Delta F_2\left(1 - y - \frac{Mxy}{2E} + \frac{1+\left(\frac{2Mx}{Q}\right)^2}{1+R_L}\frac{y^2}{2}\right) + \left(y - \frac{y^2}{2}\right)xF_3^{avg} \approx \left(y - \frac{y^2}{2}\right)xF_3^{avg}$$

Structure functions from νN data



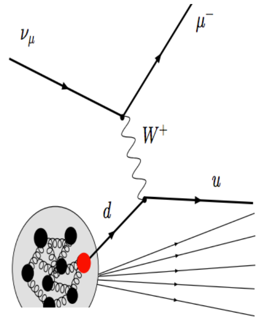


- Fit for $F_2^{avg}(x, Q^2)$ input model for
  - $R_L(x, Q^2)$ [L.W.Whitlow $et.al.$ Phys.Lett. B250(1990)]
  - $\Delta xF_3(x, Q^2)$ [R.Thorne and R.Roberts, Phys.Lett. B 421 (1998)]
- Fit for $xF_3^{avg}(x, Q^2)$ no inputs required

- Theory curves corrected for:
  - Target Mass(H.Georgi& H.D.Politzer, Phys.Rev D14 1829)
  - Nuclear Effects:
    - correction measured in charged-lepton experiments from nuclear targets
    - standard way: apply the same correct. to neutrino scattering

Can determine alphas without gluon!

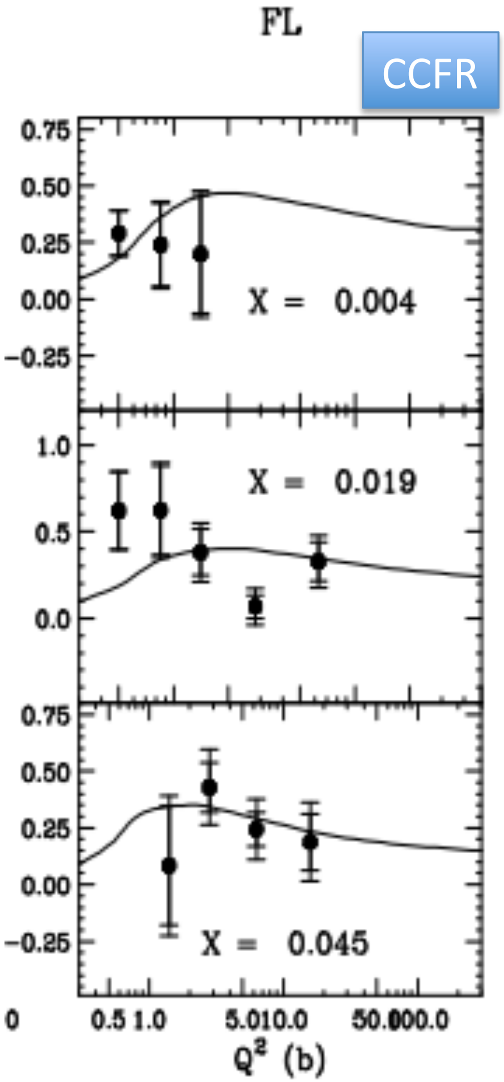
FL from νN data

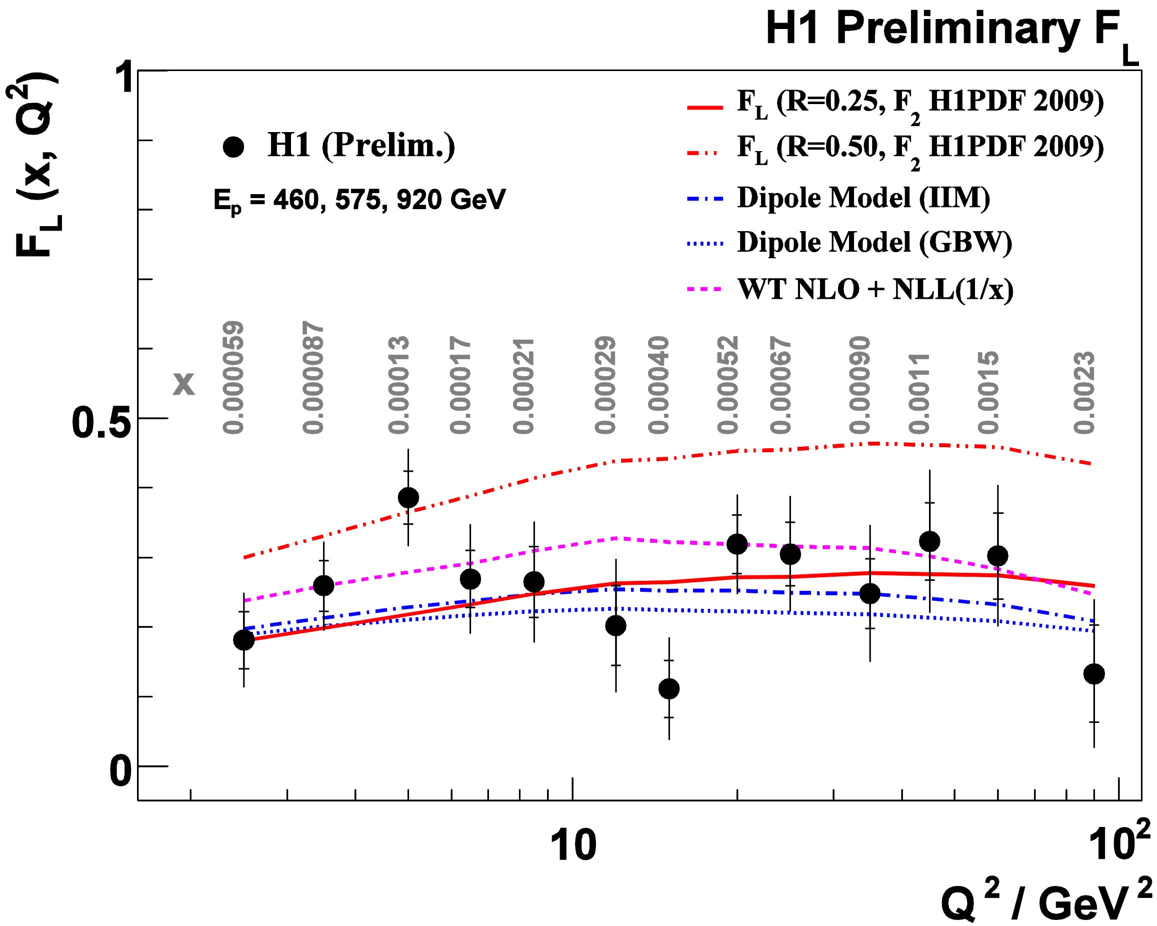


Also FL is possible to be extracted from a 3 parameter fit:

complementary to the x region accessed by HERA

CCFR

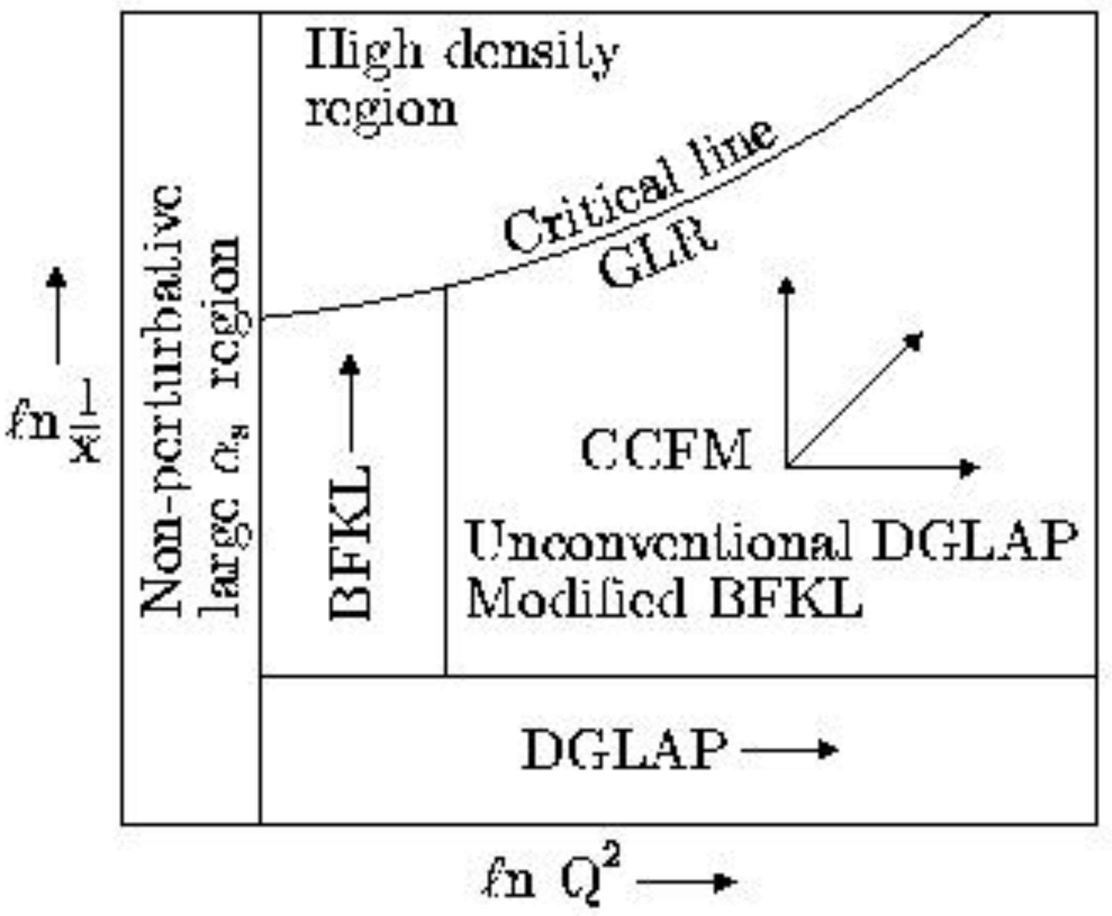




U.K. Yang, PhD thesis 2001

pQCD and DGLAP formalism

- The kinematic region of data must sometimes be adjusted in order to stay in the validity region of the pQCD, where DGLAP evolution equations are valid

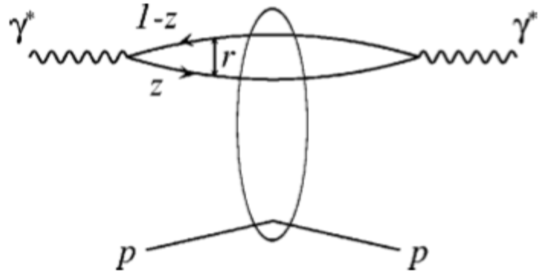


1. Q^2 cut : Q^2 > few GeV^2 so that perturbative QCD is applicable- $\alpha_s(Q^2)$ small
2. W^2 cut: to avoid higher twist terms- usual formalism is leading twist
3. x cut: to avoid regions where ln(1/x) resummation (BFKL) and non-linear effects may be necessary

Low x phenomenology with Dipole Models

Eur.Phys.J.C71 (2011)

- At low x and Q^2 the virtual photon-proton scattering can be described using the color dipole model:
  - Fluctuation of the photon into a quark-antiquark pair (dipole) interacting with proton
  - Dipole has built-in saturation assumption
- Following models have been considered:



$$\sigma_{T,L}(x,Q^2) = \int d^2\mathbf{r} \int_0^1 dz |\Psi_{T,L}(z,\mathbf{r})|^2 \sigma(x,r^2)$$

- **GBW dipole model:**

$$\sigma(x,r^2) = \sigma_0 \left(1 - \exp[-\frac{r^2}{4R_0^2(x)}]\right) \qquad R_0^2(x) = \left(\frac{x}{x_0}\right)^\lambda$$

Fitting parameters: σ_0, λ, x_0.

- **IIM (CGC) dipole model:**

$$\sigma(x,r^2) = \sigma_0 \begin{cases} N_0 \quad (\tau^2)^{\gamma_s + \frac{\ln(\tau)}{\kappa\lambda \ln(x)}} & \text{if } \tau \le 1 \\ \left(1 - \exp[-a \ln^2(2b\ \tau)]\right) & \text{if } \tau > 1 \end{cases}$$

$$\tau = r/2R_0(x)$$

Fitting parameters: σ_0, λ, x_0.

- **B-SAT dipole model:**

$$\sigma(x,r^2) = \sigma_0 \left(1 - \exp\left[-\frac{\pi^2 r^2 \alpha_s(\mu^2) xg(x,\mu^2)}{3\sigma_0}\right]\right)$$

$$xg(x,Q_0^2) = A_g x^{-\lambda_g}(1-x)^{5.6}$$

$$\mu^2 = \frac{C}{r^2} + \mu_0^2$$

Fitting parameters: A_g, λ_g, Q_0.
Fixed parameters: $\sigma_0 = 23.8$(mb), $C = 1.0$, $\mu_0^2 = 4.0$.

Schemes for Heavy Quarks

- Heavy Quarks introduce an additional scale: Q^2, M_H

$$F = \sum_a \int \frac{dy}{y} f_N^a(x,\mu_F) \otimes \omega_{h/a}\left(\frac{x}{y}, \frac{Q}{\mu_F}, \frac{M_H}{\mu_F}, \alpha_S(\mu_R)\right) + O\left(\frac{\Lambda_{QCD}}{Q}\right)$$

  - 3 regions of interests are observed:
    - $Q^2 << M_H^2$ ⟶ decoupling
    - $Q^2 \sim M_H^2$ ⟶ transition region
    - $Q^2 >> M_H^2$ ⟶ heavy quarks treated as light quarks

Fixed Flavour Number Scheme (FFNS)

- it sums over fixed number of active parton flavours: u, d, s
- heavy quarks only in the final state, massive: nf=3 for charm, nf=4 for bottom
- Returns an efficient organisation of the perturbative series at $M_H^2 \sim Q^2$
  - at $Q^2 >> M_H^2$ large logarithms spoil the perturbative series

Zero-Mass Variable Flavour Number Scheme (ZM-VFNS)

- introduces a PDF for heavy quarks and the number of active flavours increases by one unit when a heavy quark threshold is crossed
- heavy quarks omitted entirely below M_H^2 and included as massless partons above thresholds

General-Mass Variable Flavour Number Scheme (GM-VFNS)

- interpolating scheme combining the best feature from FFNS and VFNS with matching scale of order M_H^2 for each of the heavy quark thresholds:

Monte Carlo Method

[benchmark exercise with NNPDF - PDF4LHC Interim Report arXiv:1101:0536]

- Method consists in preparing replicas of data sets allowing the central values of the cross sections to fluctuate within their systematic and statistical uncertainties taking into account all point to point correlations
  - Shift central values randomly within the uncorrelated errors assuming Gauss distribution of the errors:

$$\sigma_i = \sigma_i(1 + \delta_i^{uncorr} RAND_i)$$

  - Shift central values with the same probability of the corresponding correlated systematic shift assuming Gauss distribution of the errors:

$$\sigma_i = \sigma_i(1 + \delta_i^{uncorr} RAND_i + \sum_j^{N_{sys}} \delta_{ij}^{corr} RAND_j)$$

- Preparation of the data is repeated for N times (N>100)
  - For each MC replica, NLO QCD fit is performed to extract the N PDF sets

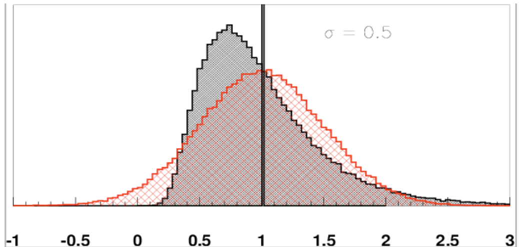
- Errors on the PDFs are estimated from the RMS of the spread of the N curves corresponding to the N individual extracted PDFs

Results of the MC method

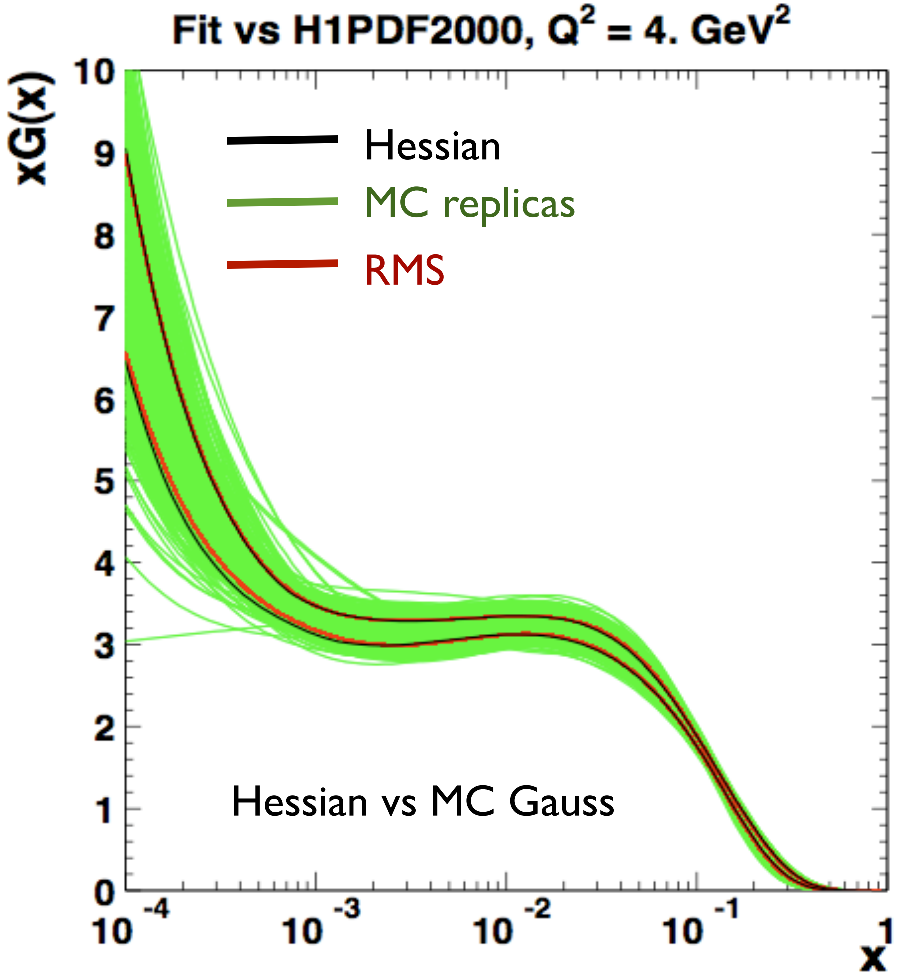
- Standard error estimation of PDFs relies on the assumption that all errors follow Gauss statistics

- MC method can provide an independent cross check of it
  - Hessian Method and MC method give the same results in the linear error propagation approximation

- MC method allows to test various assumptions for error distributions
  - some systematic uncertainties follow Log-Normal distribution (i.e., lumi, detector acceptance, ...)

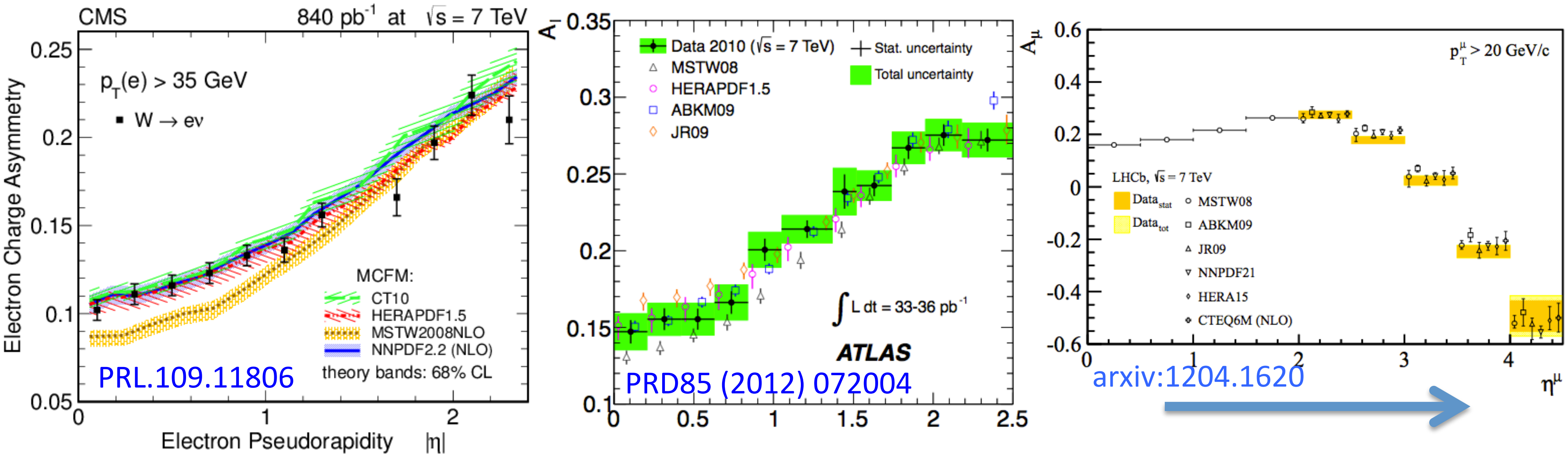


  - does this affect the PDF uncertainty?
    - Similar results to Gauss distributions when using Log-Normal assumptions



W Charge Asymmetry

- The interplay between the flavour asymmetries can be enhanced via ratio measurements:
  - W-asymmetry $\mathbf{A_W = [\sigma(W^+) - \sigma(W^-)]/ [\sigma(W^+) + \sigma(W^-)]=(u_v - d_v) /(u_v + d_v + 2\ qbar\ )}$ at x1=x2



- CMS measures directly the electron asymmetry data from 2011 and clearly disfavour MSTW2008:
  - MSTW have addressed this in more recent versions of their PDFs [see J. Rojo's talk].

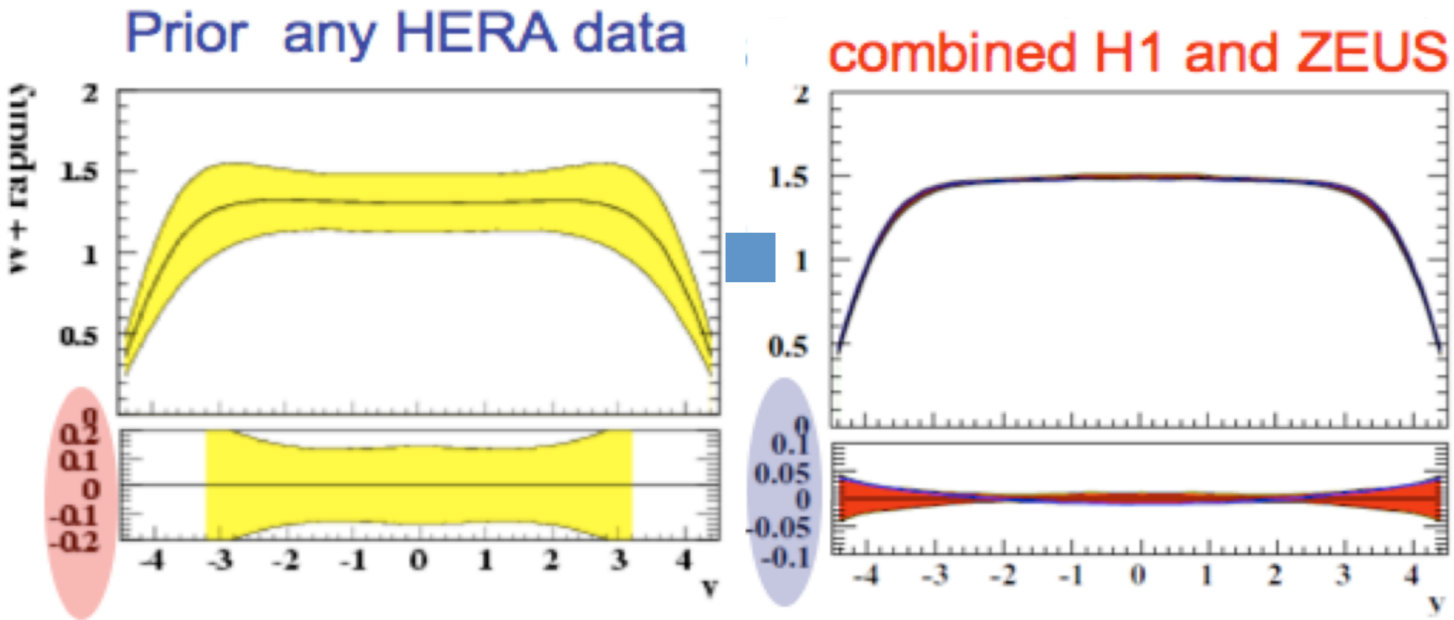
- ATLAS differential measurements of W^+ and W^- (combined muon and electron) based on 2010 data translated into charge asymmetry *Al* as long as proper treatment of correlations are accounted for.

- LHCb extends the measurement (muon channel) to forward region and provides a comparison with various predictions (interesting region where distribution changes sign due to V-A structure)

NOTE: Selection criteria are optimized for each experiment

Impact of HERA on the LHC predictions

- Impressive precision of HERAPDF sea and gluon is relevant for W, Z production at the LHC:



exp errors only

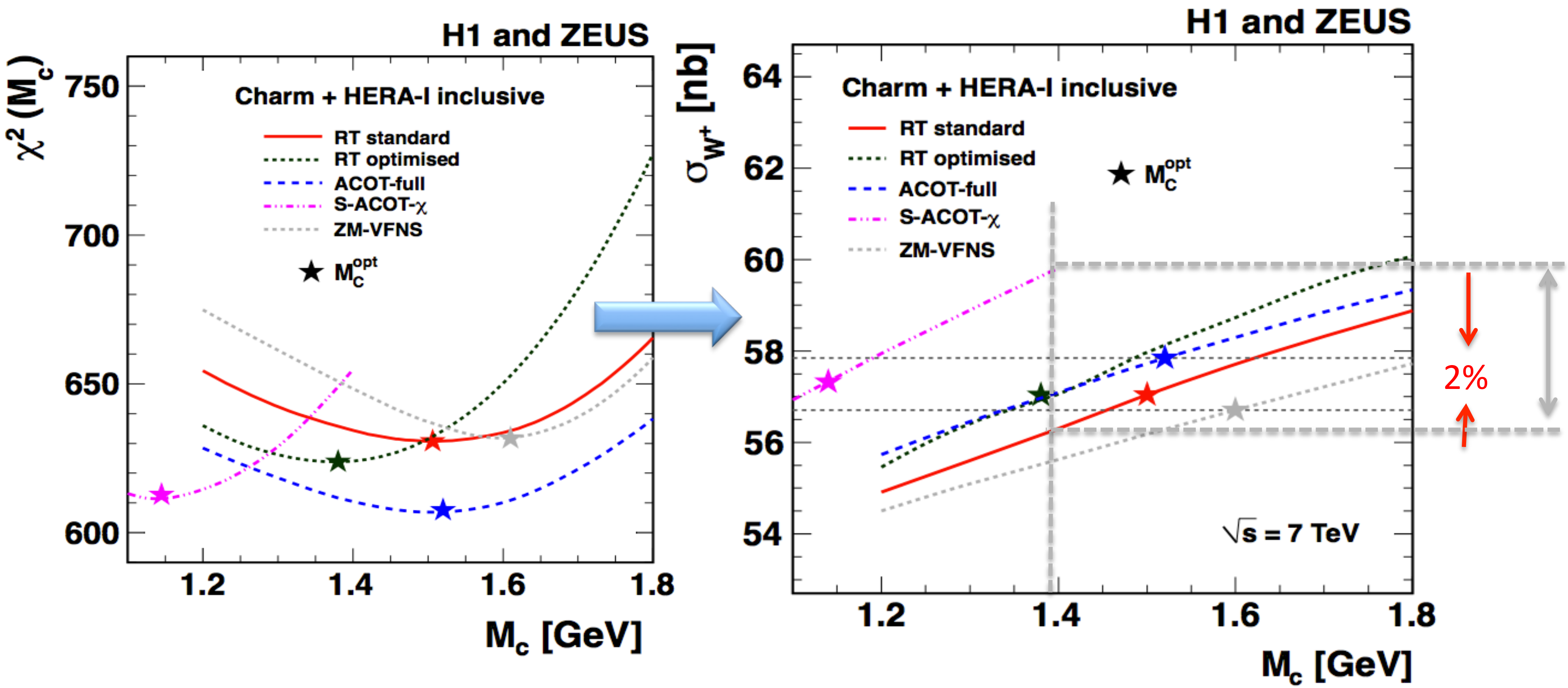
➡ this assumes that DGLAP worked which was confirmed at HERA

- Inclusion of HERA data shows tremendous improvement on the predictions for W and Z production at the central rapidity:
  - such an improvement is due to improvement in the low-x gluon and sea:
    - remember that at the LHC the W, Z bosons are made mostly of sea-sea partons at low x and the the scale of M_Z^2 the sea is driven by the gluon.

Impact of F_2 charm on W,Z cross sections

- F_2 charm data helps constrain charm-quark by studying m_c -choice in variable flavor number schemes

Eur. Phys. J. C 73:2311 (2013), [arXiv:1211.1182]

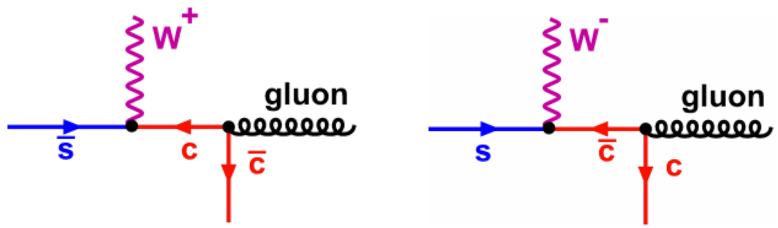


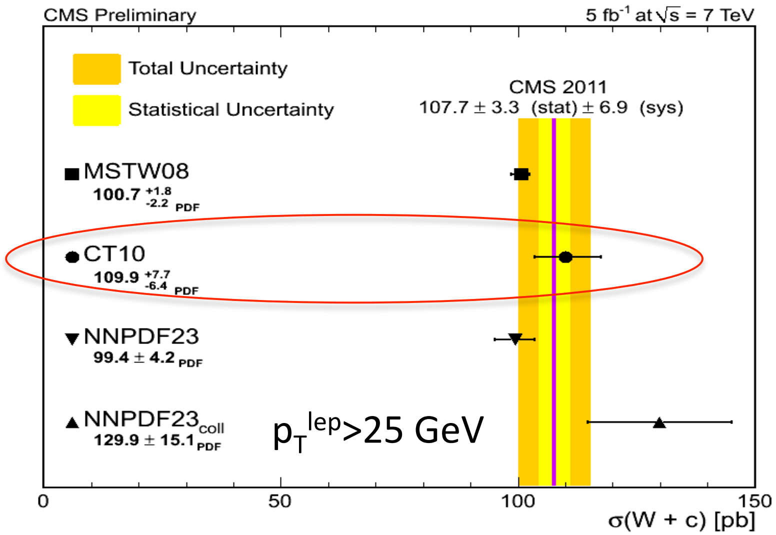
- Large spread of the total cross section predictions at the LHC for W+, W-, Z:
  - The spread is reduced significantly when predictions are evaluated at the m_c determined from F_2 charm

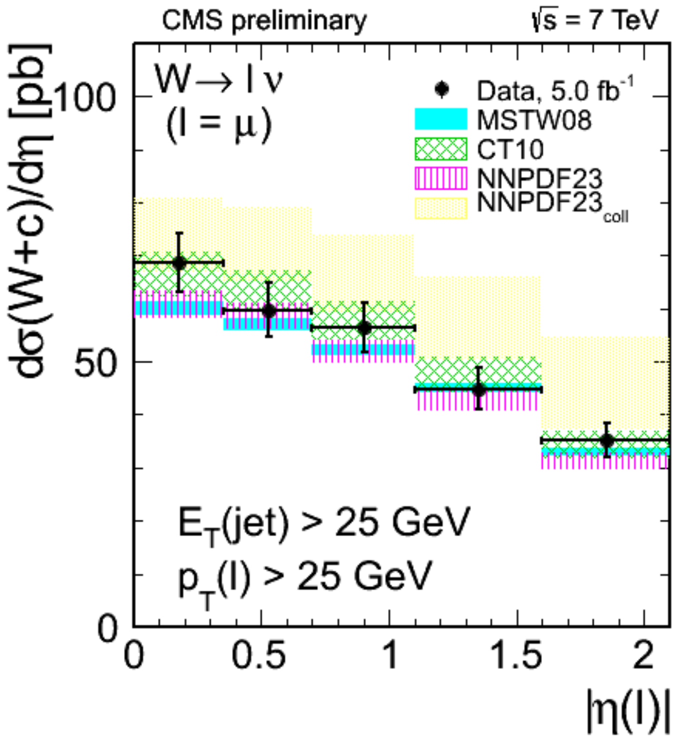
W+c sensitivity to Strange from CMS

Question: would other measurements confirm ATLAS favour of sbar=dbar?

- CMS has released a preliminary W+c measurement directly sensitive to strange:



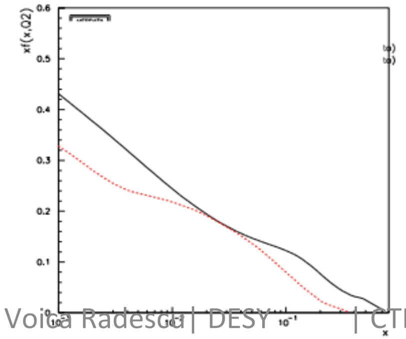




[CMS-SMP-12-002]

Very good agreement with CT10 and not in such good agreement with NNPDF2.3 (Coll):

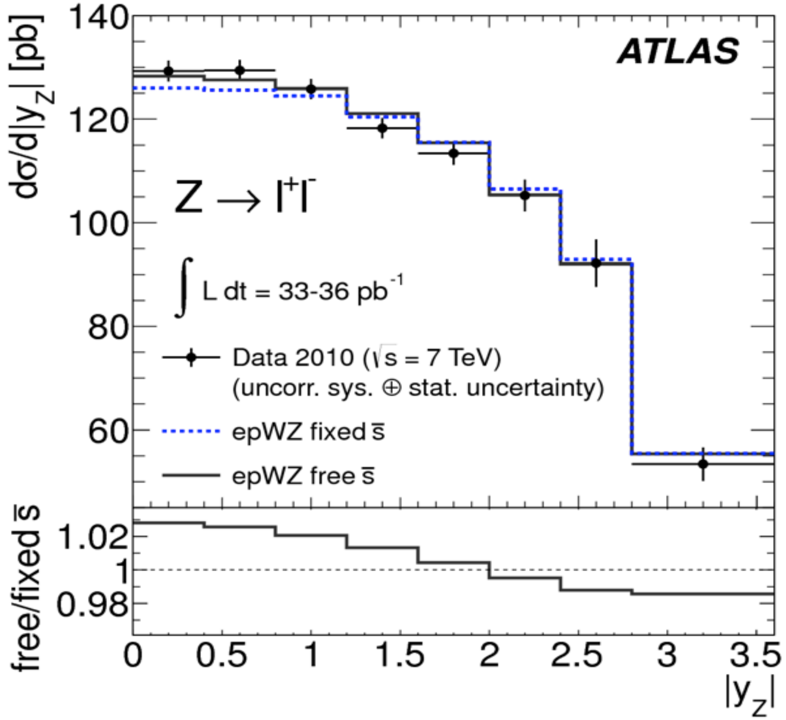
- has large strangeness

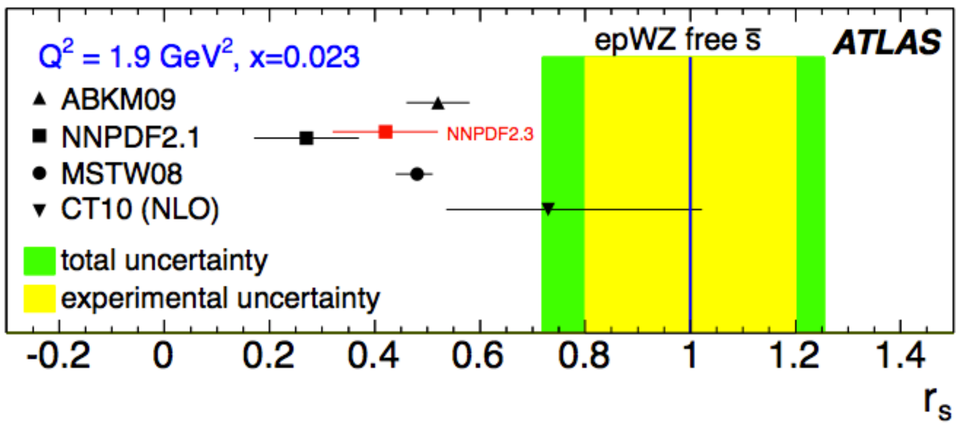


Q²=2 GeV²
NNPDF23(Coll)
Strange
Downsea

Strange quark from W, Z measurements at ATLAS

- Strange quark is not so well constrained:
  - Neutrino dimuon data favours suppressed strange
- At LHC, Z cross sections together with y_Z shape may provide a constraint on **s**-quark density and it can be cross checked by W+charm data.
  - The results for NNLO fits to inclusive W, Z differential data with free and fixed **s:**
    - For W+ and W- there is little difference, helps to fix the normalisation.
    - For Z, the cross section is increased and the shape is modified.





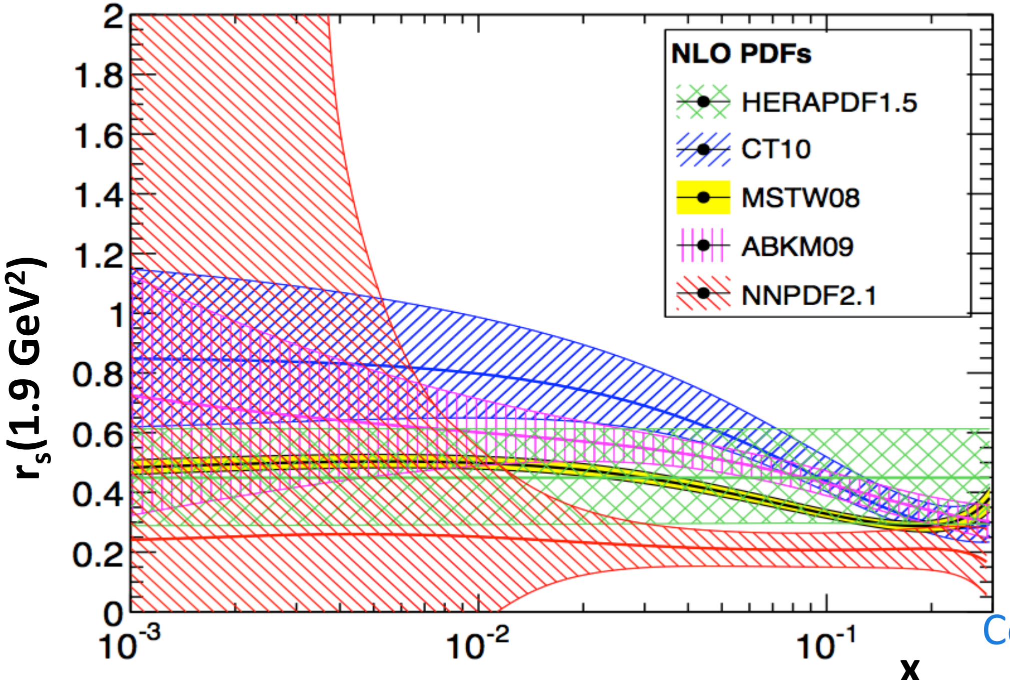
$$r_s = 1.00 \pm 0.20_{\mathrm{exp}} \pm 0.07_{\mathrm{mod}}{}^{+0.10}_{-0.15}{}_{\mathrm{par}}{}^{+0.06}_{-0.07}\alpha_S \pm 0.08_{\mathrm{th.}}$$

ATLAS result is the kinematic region probed by LHC data at x~0.01 and indicates a flavour symmetric sea with an enhanced strangeness, in agreement with the CT10 (s/d~0.75)

- It is above of MSTW08, ABKM09, NNPDF2.3 (s/d~0.5)

Strange quark content of the proton

Strange quark is not so well constrained:



Courtesy of G. Watt

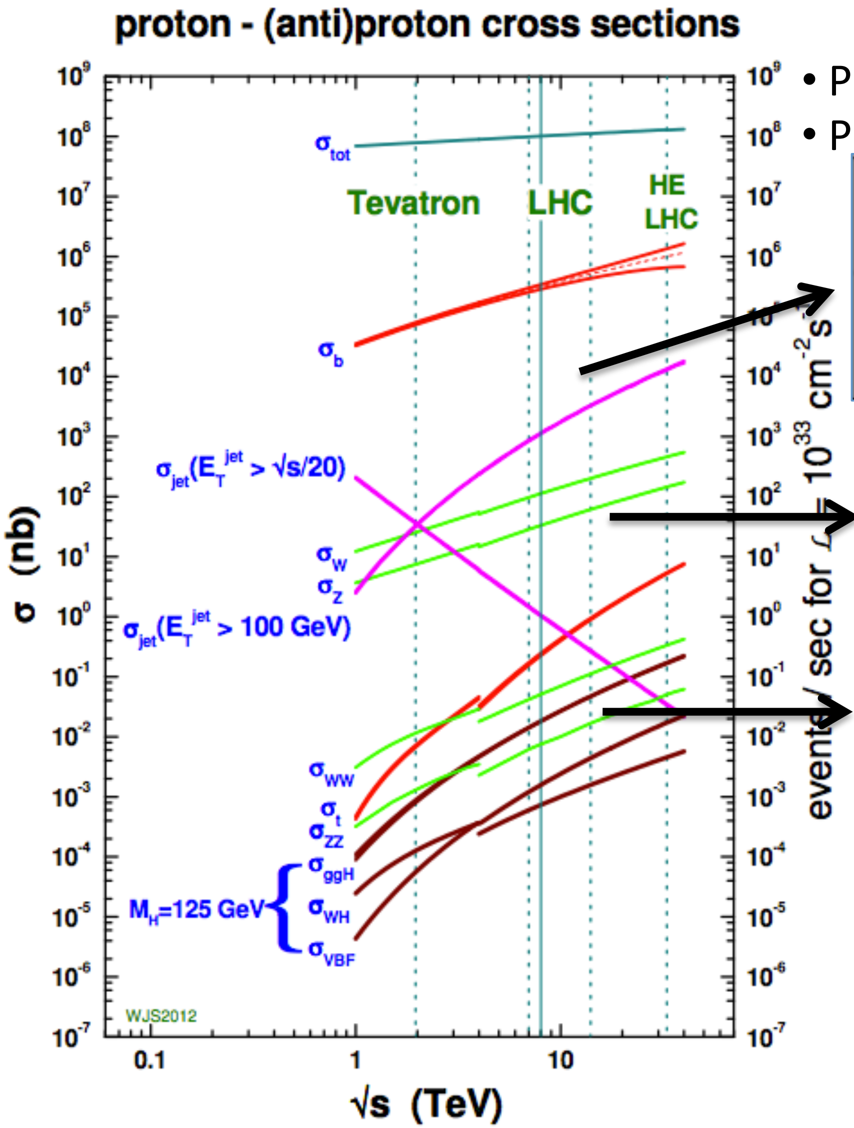
- Flavour SU(3) symmetry: three light quark distributions are equal:
  - Strange quark density may be suppressed due to their larger mass as favored by Neutrino dimuon data.
  - Often it is assumed that s=sbar and rs=0.5 $r_s(x) = 0.5(s(x) + \bar{s}(x))/\bar{d}(x)$

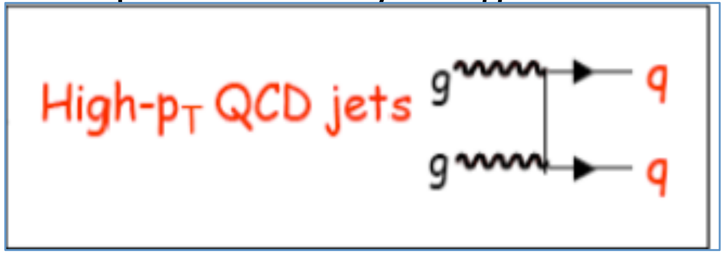
- At LHC, Z cross sections together with y_Z shape may provide a constraint on **s**-quark density and cross checked against its W+charm data.

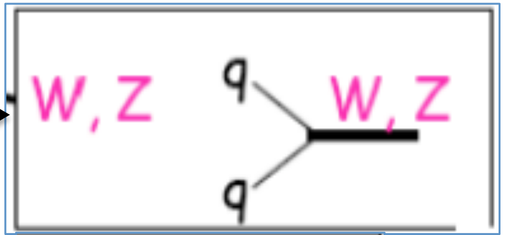
Pushing Energy Frontier

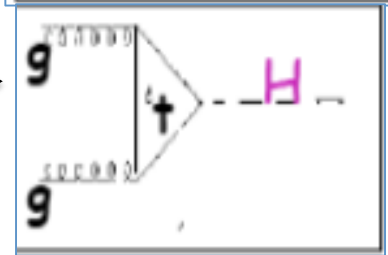
LHC can provide with its multitude of new measurements

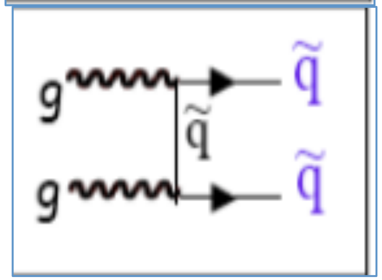
- PDF discrimination by confronting theory with data
- PDF improvement by using LHC data for more accurate











Factorisation schemes

- Basically factorisation scheme tells us which part are absorbed by PDFs and which by Hard Scattering coefficients:

$$F_2^{(Vh)}(x,Q^2) = \sum_{i=f,\bar{f},G} \int_0^1 d\xi C_2^{(Vi)}\left(\frac{x}{\xi},\frac{Q^2}{\mu^2},\frac{\mu_f^2}{\mu^2},\alpha_s(\mu^2)\right) \otimes f_{i/h}(\xi,\mu_f^2,\mu^2)$$

Hard scattering coefficients

PDFs

- Two sort of extreme prescriptions are generally used:
  - **MS bar scheme**: absorb as little as possible into pdfs

$$F_2^{\overline{MS}}(x,Q^2) = x\sum e_q^2 \int \frac{dx_2}{x_2} q^{\overline{MS}}(x,Q^2)\left[\delta\left(1-\frac{x}{x_2}\right)+\frac{\alpha_s}{2\pi}C^{\overline{MS}}\left(\frac{x}{x_2}\right)+...\right]$$

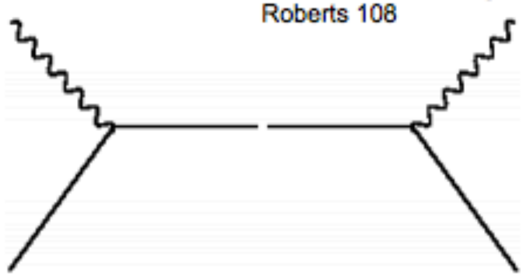
  - **DIS scheme**: absorb as much as possible into pdfs

$$F_2^{DIS}(x,Q^2) = x\sum e_q^2 q(x,Q^2)$$

Higher Twist

- So far considered only *"leading twist"*

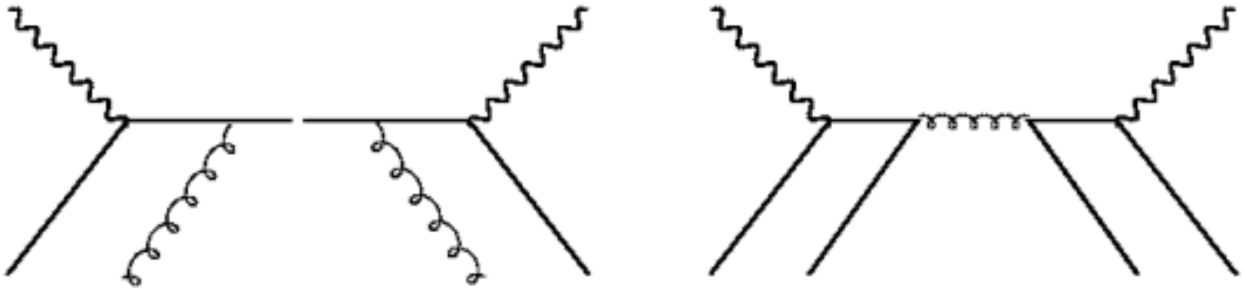
Ellis, Webber, Stirling, 123
Roberts 108



twist = dimension (spin) of operators in Operator Product Expansion (OPE)

$$F_2(x, Q^2) = \sum_i C_{2\,i} \otimes f_i + \text{non-leading power of } Q$$

- Factorization theorem (Collins hep-ph/9709499):
- in general:



$$F_2(x, Q^2) = \sum_n \frac{B_n(x, Q^2)}{Q^{2n}}$$

n>0 higher twists
non-leading powers ...

- NOT covered by factorization theorem.... but contributions can be large ?!?

Slide from Hannes Jung: http://www.desy.de/~jung/qcd_and_mc_2012

Scale dependence

- A hard scattering calculation introduces a renormalization scale to remove UV divergencies and a factorization scale that separates the hard from soft physics:
  - Scale dependence usually represent largest theoretical uncertainties
- Factorization and renormalization scales are both usually chosen to be the characteristic energy scale in the process.
  - This was in the standard convention various logarithms in the calculations vanish.

$$F(x, Q^2) = \sum_i C_i(\mu_R, \mu_F, Q^2, y) \otimes f_i(z, \mu_F)$$

i - number of active flavours in the proton, what about heavy c and b ?

m_c=1.5 M_p, m_b=4.7 M_p

QCD analysis of the proton structure: treatment of heavy quarks essential

Different prescriptions how to treat Heavy Quarks in PDF Fits (HQ schemes):

c, b - massless particles in the proton

c, b - massive, produced in hard scattering

Scale dependence -- continuation

- The physical structure functions should not depend on the choices made for muF and muR
- For calculations carried to the order NLO in alphas:

$$\mu_R \frac{\partial F}{\partial \mu_R} = 0 \text{ up to } \mathrm{O}(\alpha_S^2);$$
$$\mu_F \frac{\partial F}{\partial \mu_F} = 0 \text{ up to } \mathrm{O}(\alpha_S^2).$$

- Then performing the expansion in NLO of the structure function:

$$F(x,Q^2) = \sum_i \left[C_i^0(\mu_R,\mu_F,Q^2,y) + \alpha_S(\mu_R) C_i^1(\mu_R,\mu_F,Q^2,y)\right] \otimes f_i(z,\mu_F).$$

$$\mu_R \frac{\partial F}{\partial \mu_R} = \sum_i \left[\underbrace{\mu_R \frac{\partial C_i^0}{\partial \mu_R}}_{O(\alpha_s^0)} + \underbrace{\mu_R \frac{\partial \alpha_S}{\partial \mu_R} C_i^1}_{O(\alpha_s^2)} + \underbrace{\alpha_S \frac{\partial C_i^1}{\partial \mu_R}}_{O(\alpha_s^1)} \right] \otimes f_i = 0 \Longrightarrow \alpha_S \frac{\partial C_i^1}{\partial \mu_R} = 0,$$

DIS Cross Section

General Form for the Differential cross section:

$$\frac{d^2\sigma}{dx dQ^2} = A^i \left\{ (1 - y - \frac{x^2 y^2 M^2}{Q^2}) F_2^i + y^2 x F_1^i \mp (y - \frac{y^2}{2}) x F_3^i \right\}$$

A^i: process dependent

$$\eta_\gamma = 1; \qquad \eta_{\gamma Z} = \left(\frac{G_F M_Z^2}{2\sqrt{2}\pi\alpha}\right)\left(\frac{Q^2}{Q^2 + M_Z^2}\right); \qquad \eta_Z = \eta_{\gamma Z}^2;$$

$$\eta_W = \frac{1}{2}\left(\frac{G_F M_W^2}{4\pi\alpha}\frac{Q^2}{Q^2 + M_W^2}\right)^2,$$

structure functions express the dependence of cross-section on the constituents of the nucleon

At HERA four processes give access to proton substructure: CC e+p, CC e-p, NC e+p, NCe-p

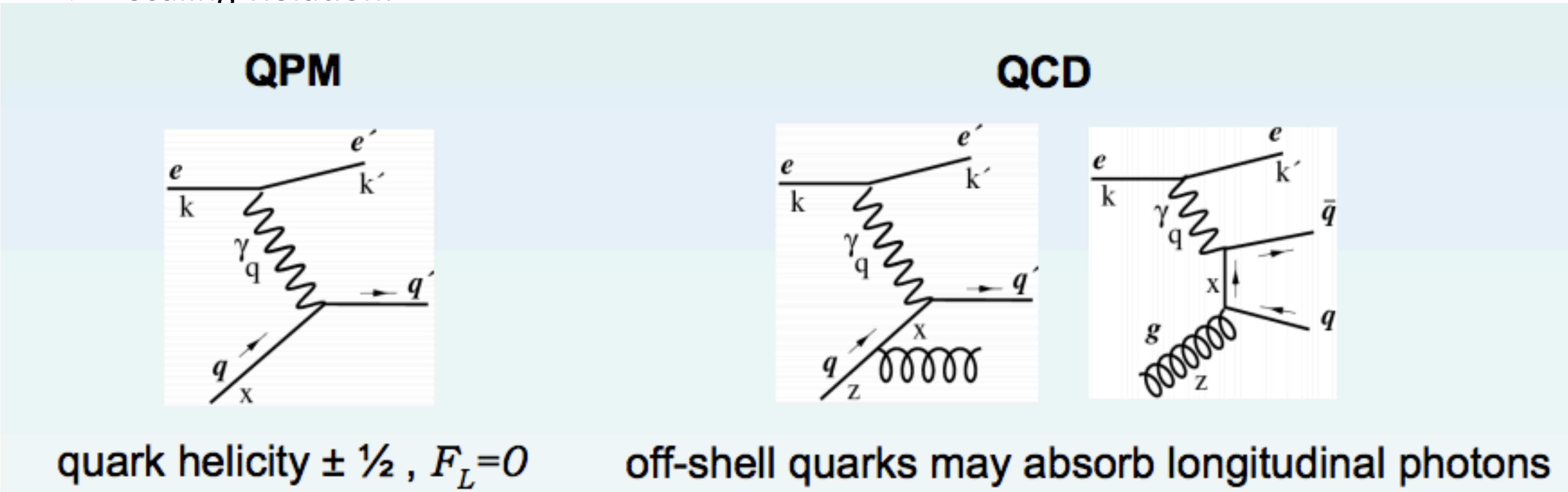
(convenient to introduce reduced cross section to better single out the effect of PDFs)

$$\tilde{\sigma}(x, Q^2) = \frac{x Q^4}{2\pi\alpha^2}\frac{1}{Y_+}\frac{d^2\sigma}{dx dQ^2} = \tilde{F}_2(x, Q^2) \mp \frac{Y_-}{Y_+} \cdot x\tilde{F}_3(x, Q^2) - \frac{y^2}{Y_+} \cdot \tilde{F}_L(x, Q^2).$$

$$Y_\pm = 1 \pm (1 - y)^2,$$

Additional Constraints to PDFs: on gluon

- Sensitivity to gluon PDF arise from the coupled singlet-gluon QCD evolution
  - scaling violation:



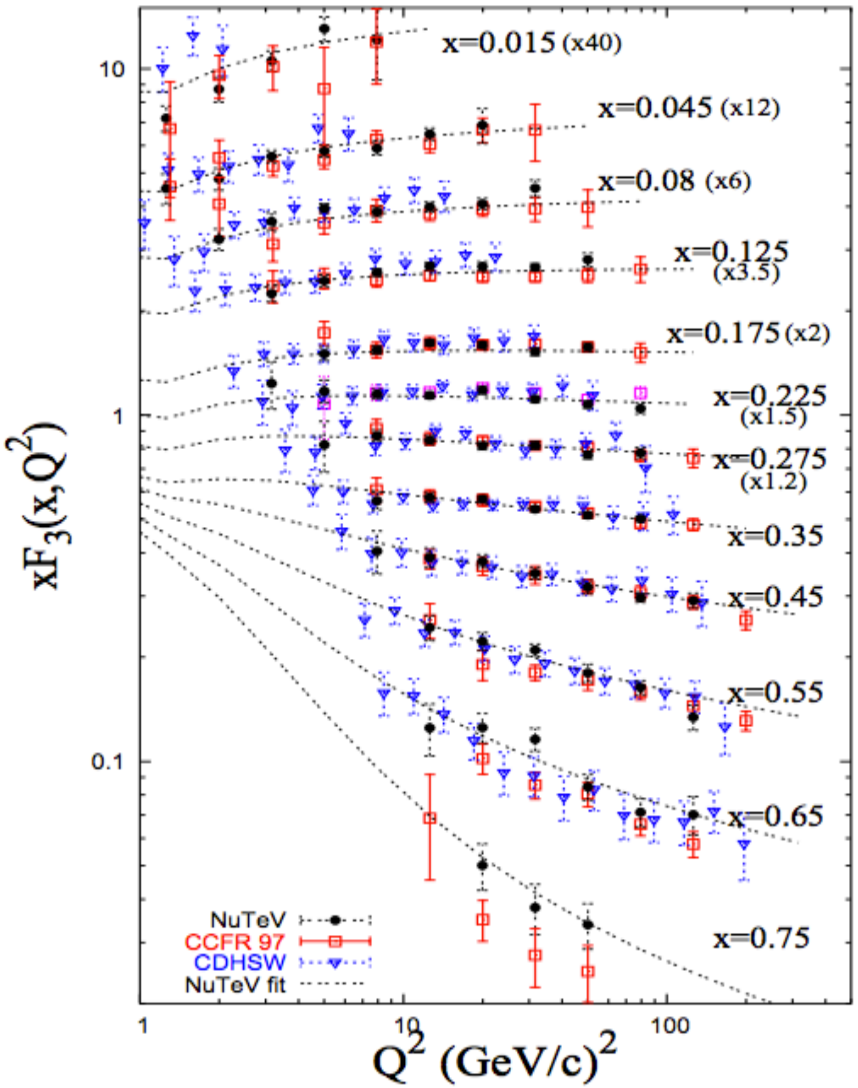
→ Interesting case also for study physics at low Q2

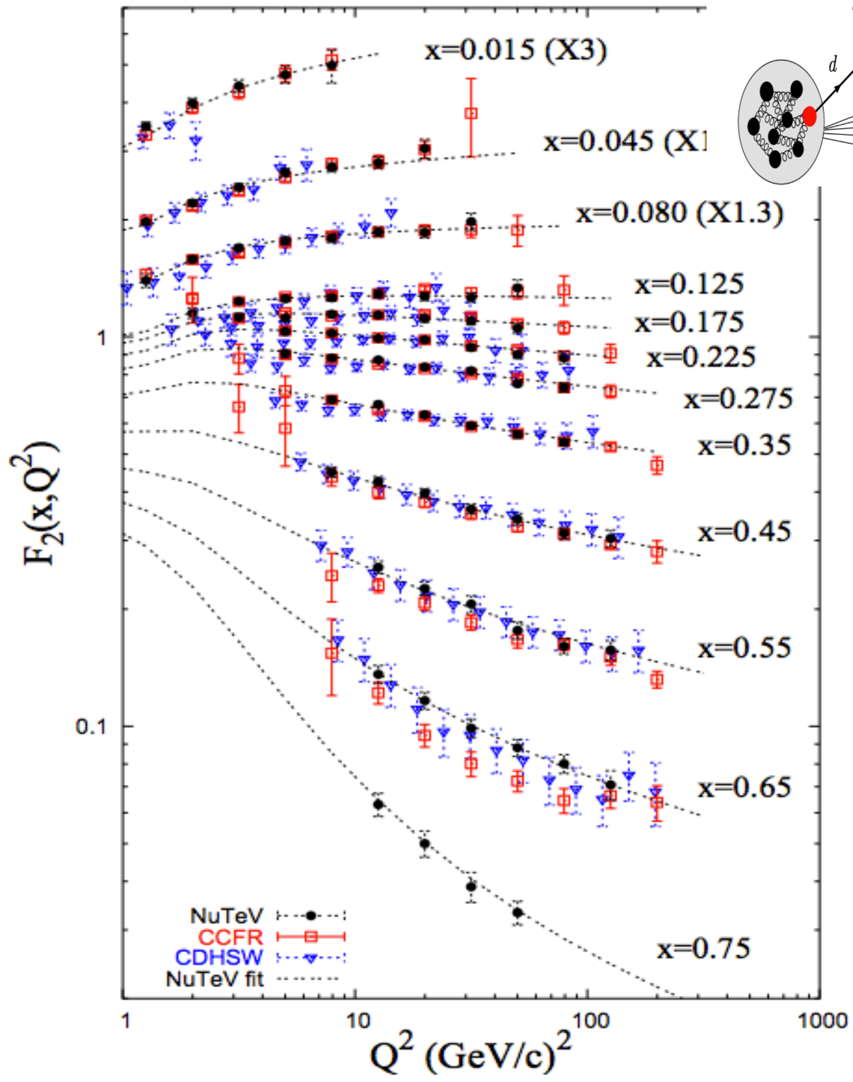
- heavy flavour schemes, evolutions, higher twists

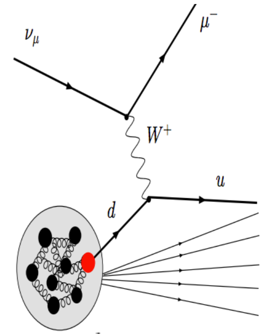
- From the measurement of semi-inclusive structure function *Fc*

- From the inclusive jet cross section (for ep and pp collisions) :
  - Able to decorrelate gluon and strong coupling

Structure functions from νN data

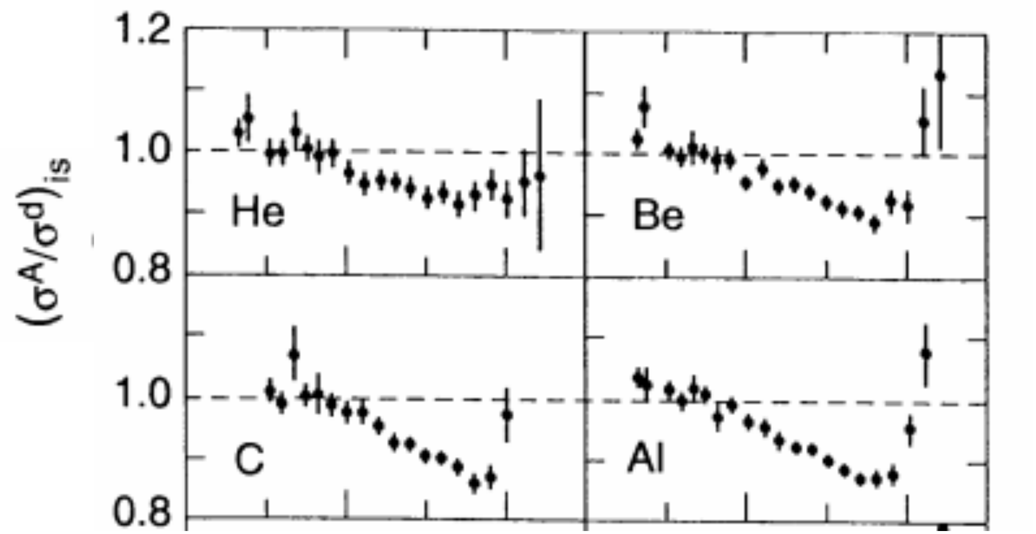


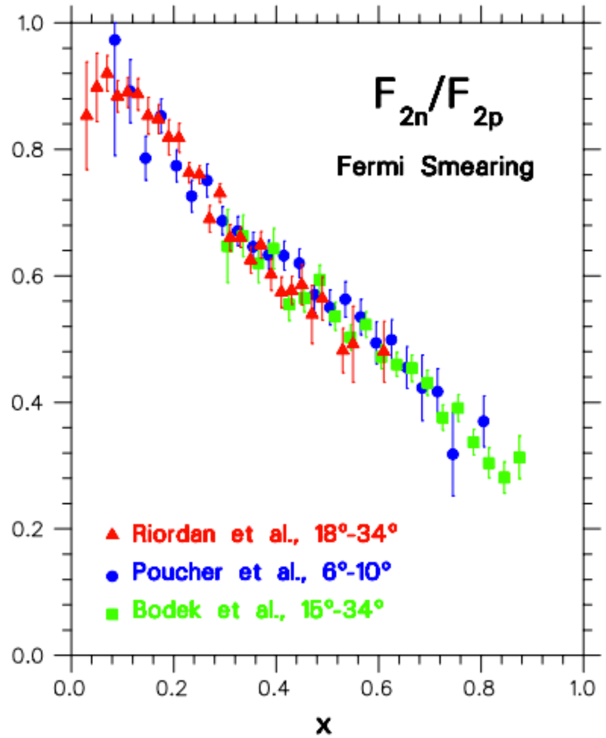




Nuclear Corrections at high x

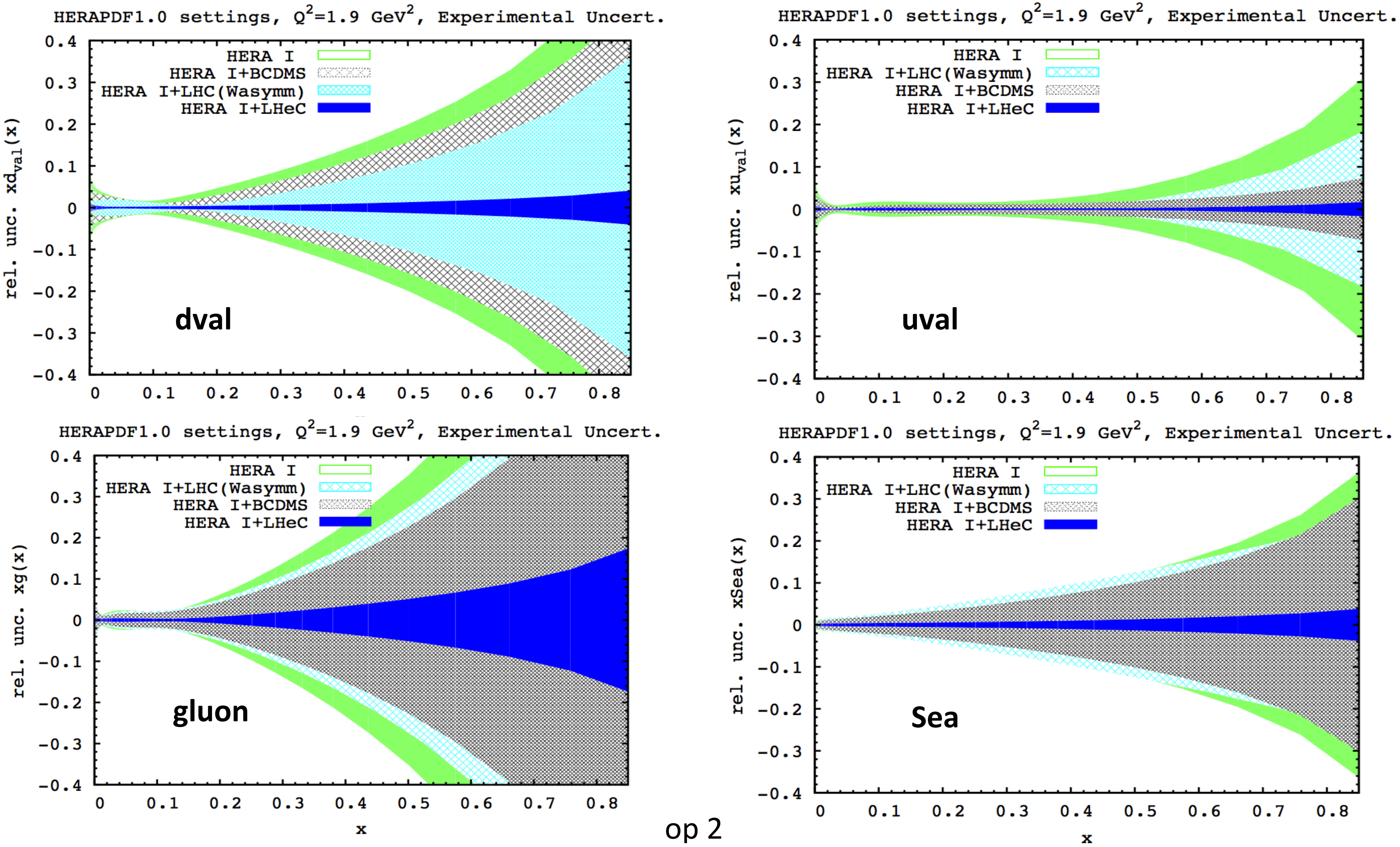
- The nuclear environment in which a struck quark is embedded could modify the x distribution of the quarks inside the nucleon
- To extract F2n/F2p ratio experimentaly from DIS measurements off the proton and deuteron, a smearing model to account for the Fermi-motion of the nucleons in the deuteron was taken into account [SLAC-MIT]
  - At low x: ratio close to 1→ no valence
  - At high x: ratio close to ¼ → high momentum partons in the proton are mainly up PDFs
- European Muon Collaboration (EMC) observed dependence on nuclear medium:





Impact of LHeC on PDFs: zoom on high x

* Experimental uncertainties are shown at the starting scale Q^2=1.9 GeV^2



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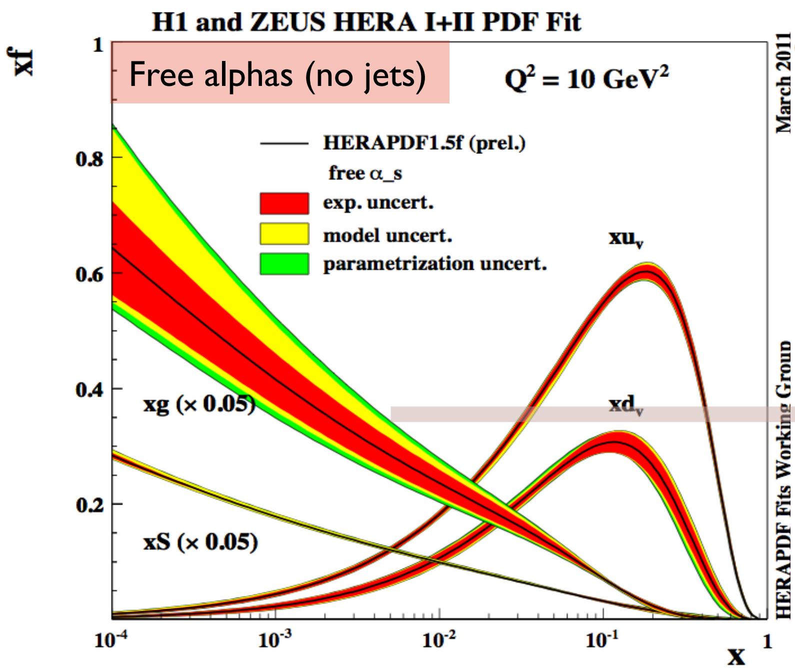
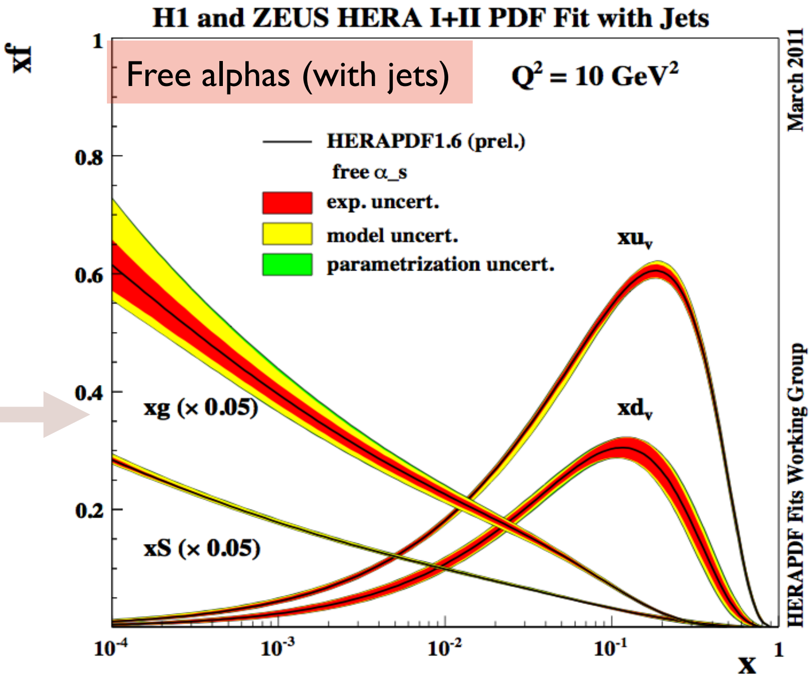
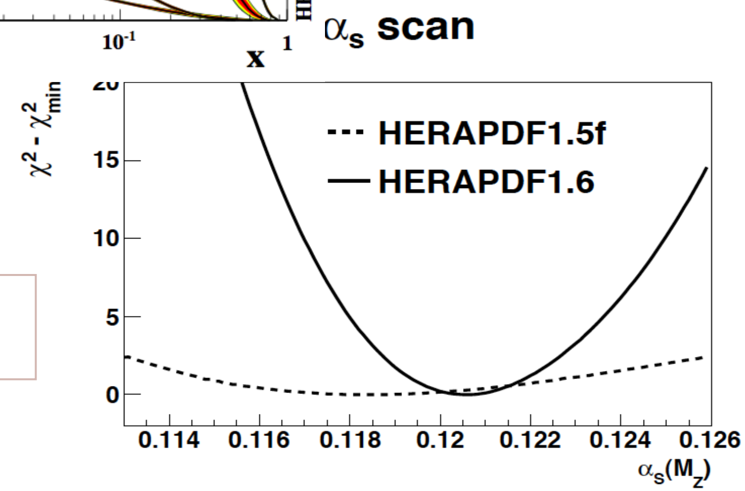
Alphas from HERA

- Addition of the HERA Jet cross section data (NLOJet++/fastNLO) into the fits allows to constrain simultaneously alphas and gluon
- Comparison of the PDFs with free alphas fit with and without Jet data





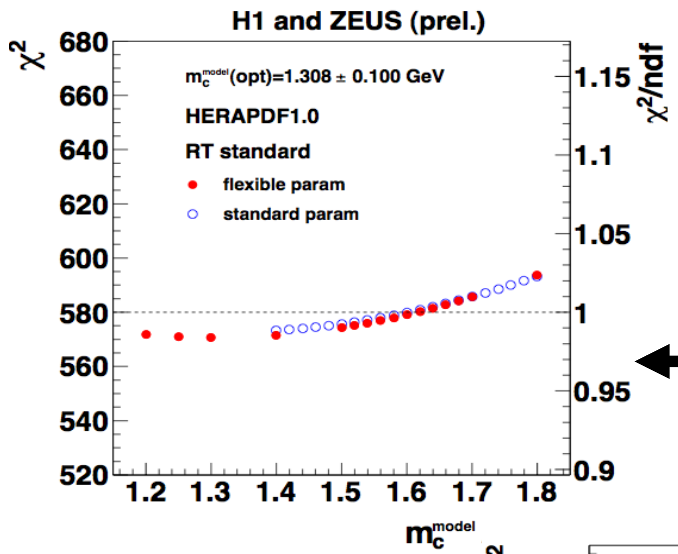


- HERA data prefer larger value for strong coupling:

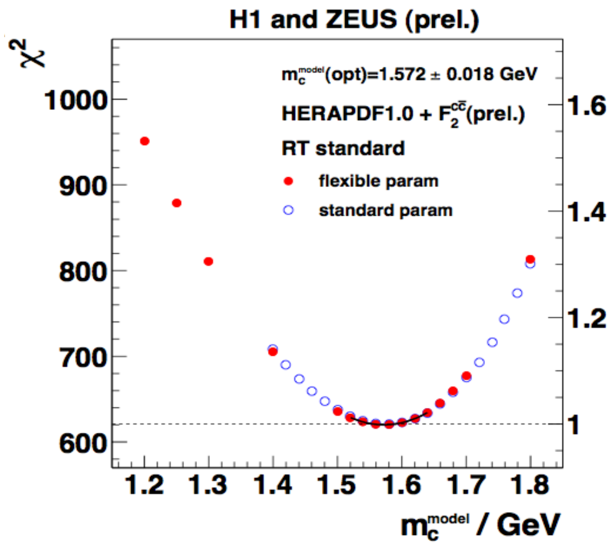
$$\alpha_s = 0.1202 \pm 0.0013\,(\exp) \pm 0.0007\,(mod) \pm 0.0012\,(had)^{+0.0045}_{-0.0036}\,(th)$$

Effect of the charm data

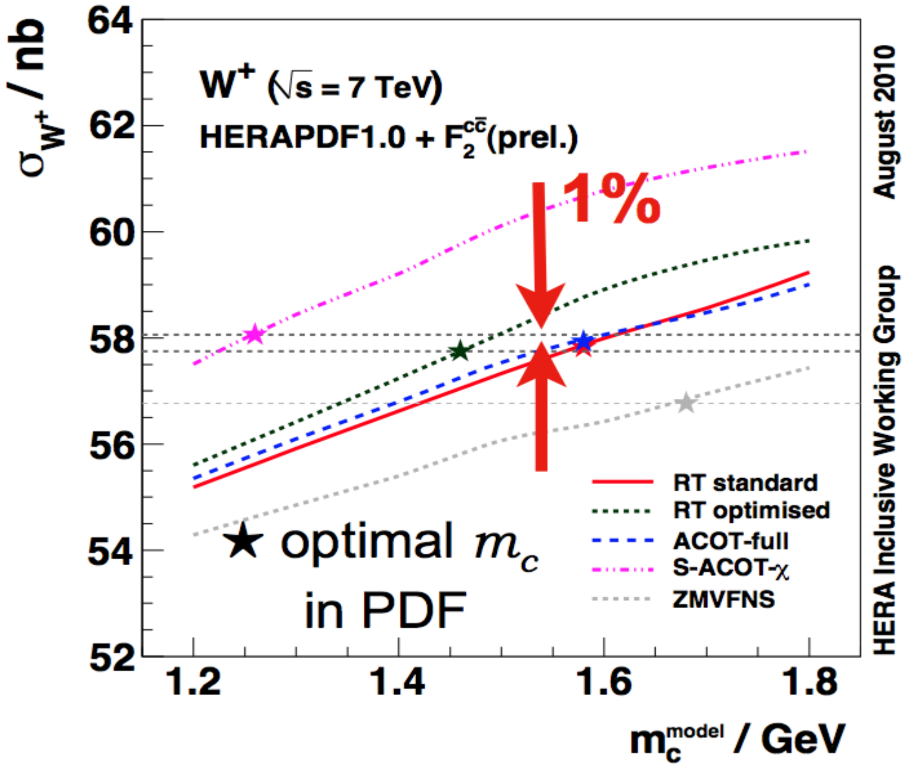
- Addition of the HERA combined F_2 charm data can help reduce model uncertainty of m_c(1.35-1.65):
  - Inclusive data show low sensitivity, addition of the charm data have strong constraining power



without charm data



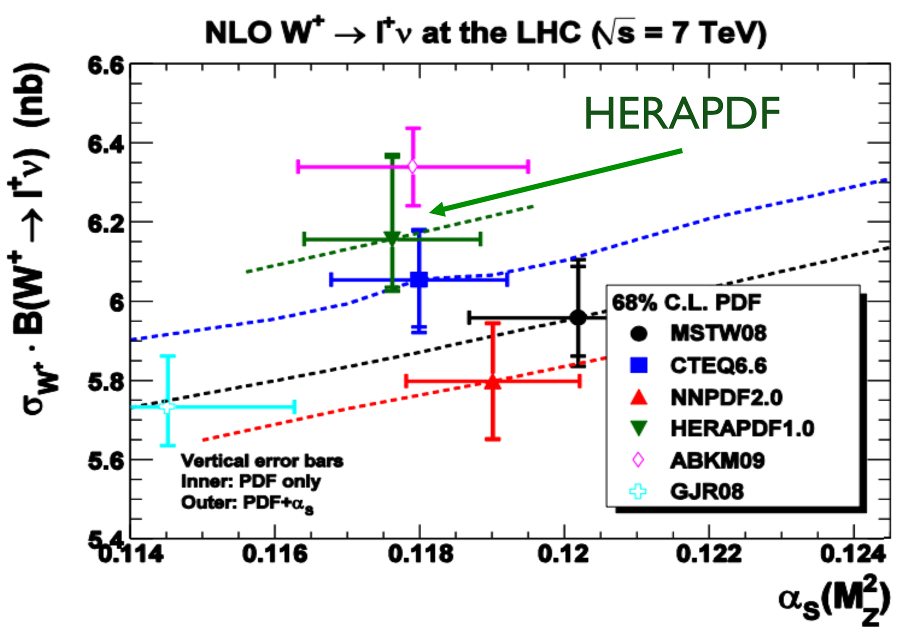
Including charm data



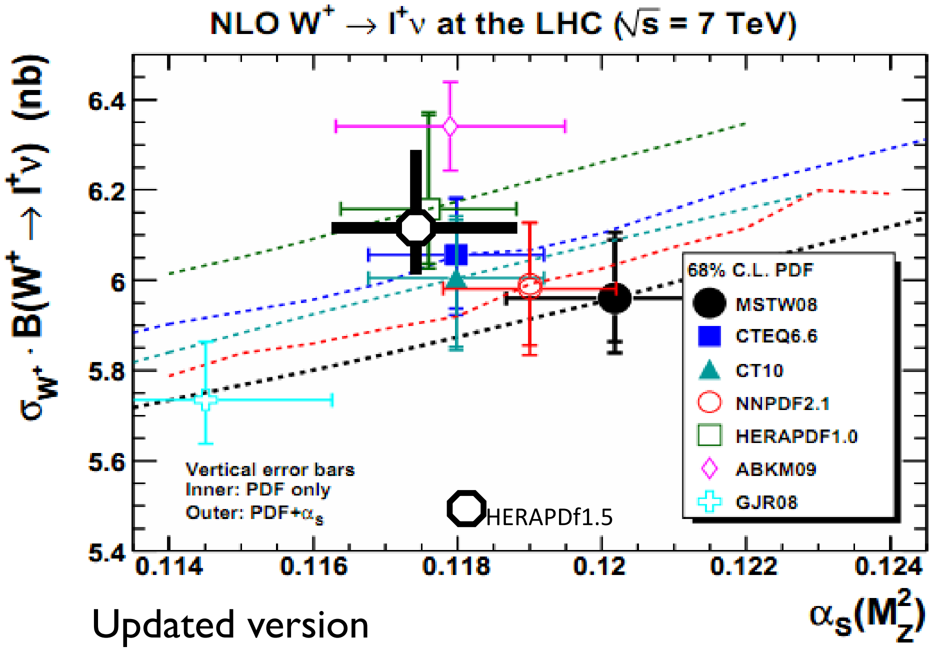
- 11% error due to different schemes
- Uncertainty on σW prediction due to HF treatment in PDFs reduced to 1 %

Level of PDF agreement

- Overall disagreement in W, Z cross sections was found ~8%

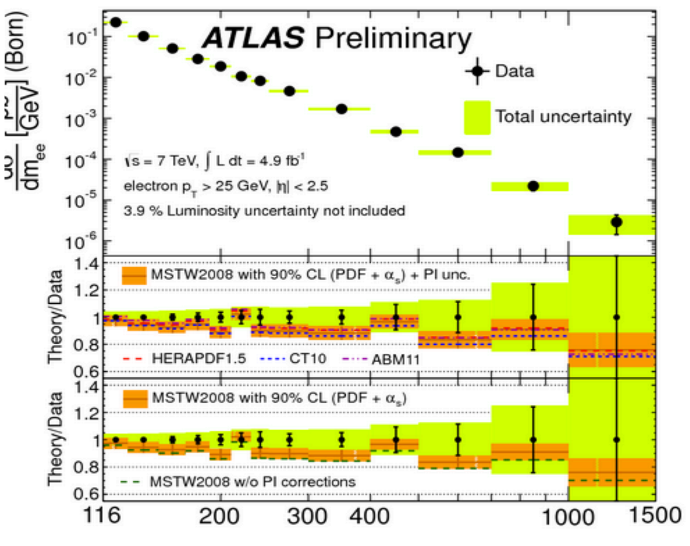


(Plots from G.Watt -68%CL)



Updated version

Measurements at LHC sensitive to PDFs



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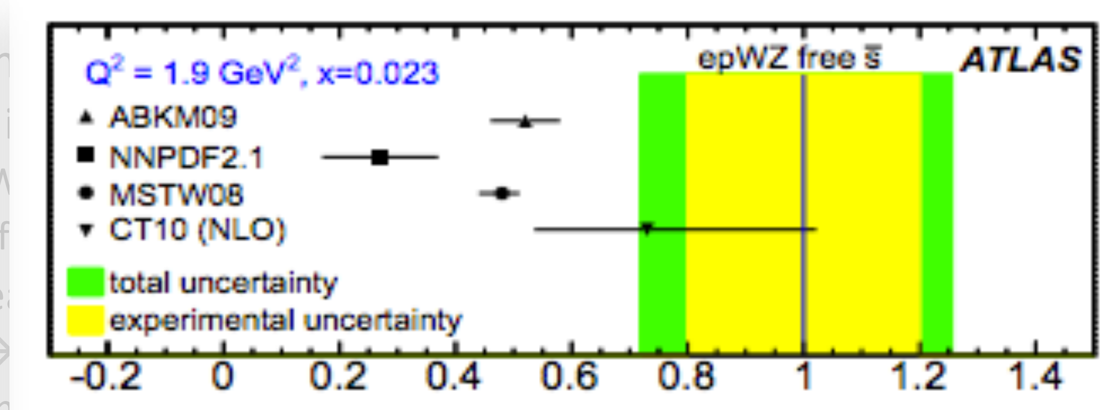
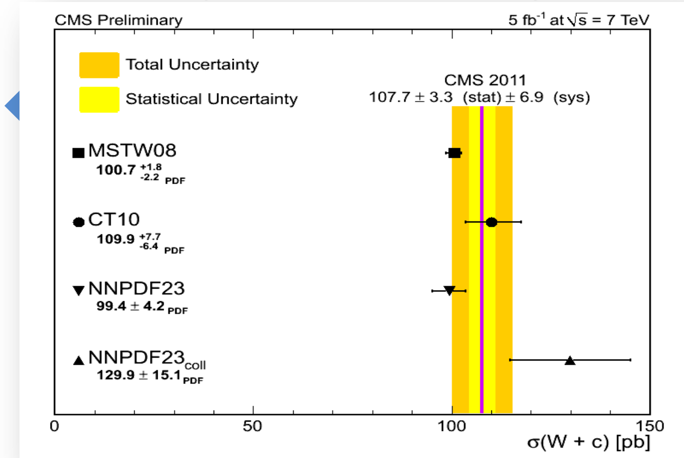
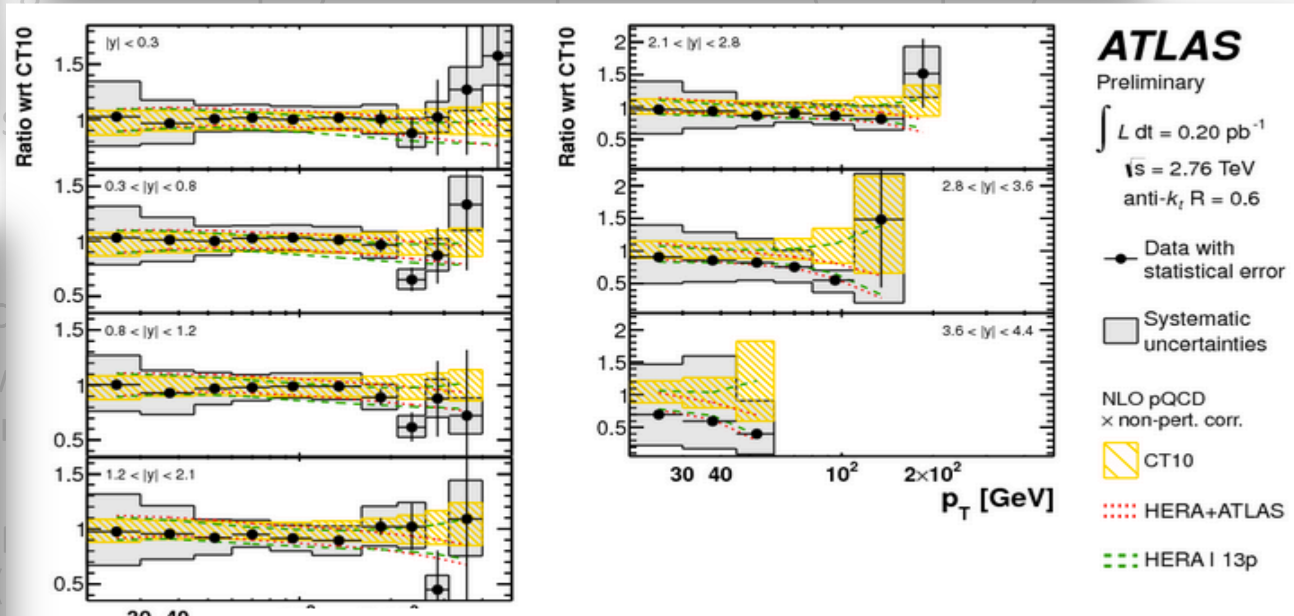


CERN-PH-EP-2012-030

- Top, W,Z+ c,b, W,Z+jets, …





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