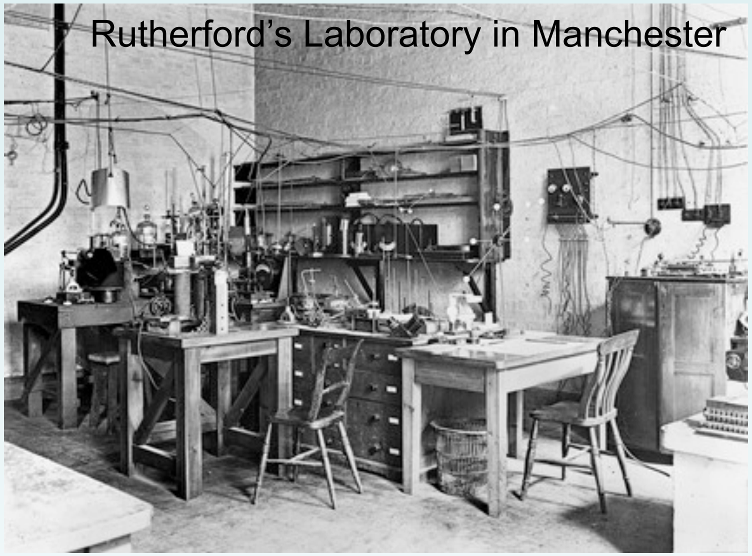
From PDFs and Heavy Quarks at HERA to the LHC

Katerina Lipka, DESY

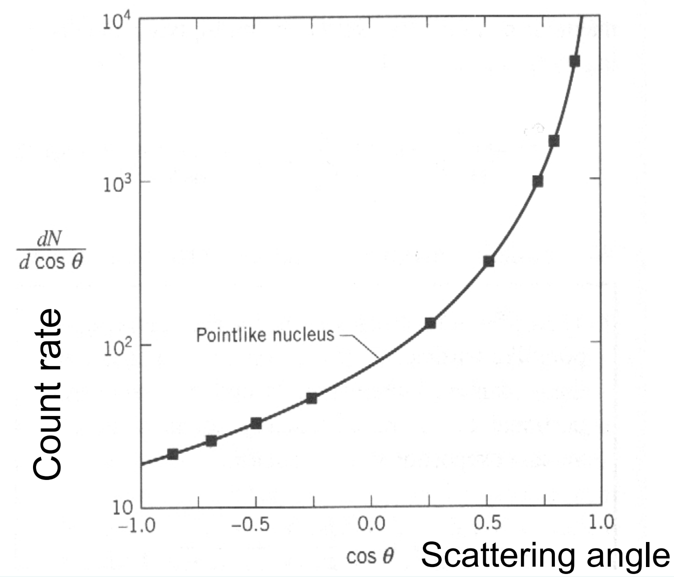
DESY Seminar February 2011

100 Years Ago...

Scattering experiments provide insight into the matter structure



α particle scattering off gold foil



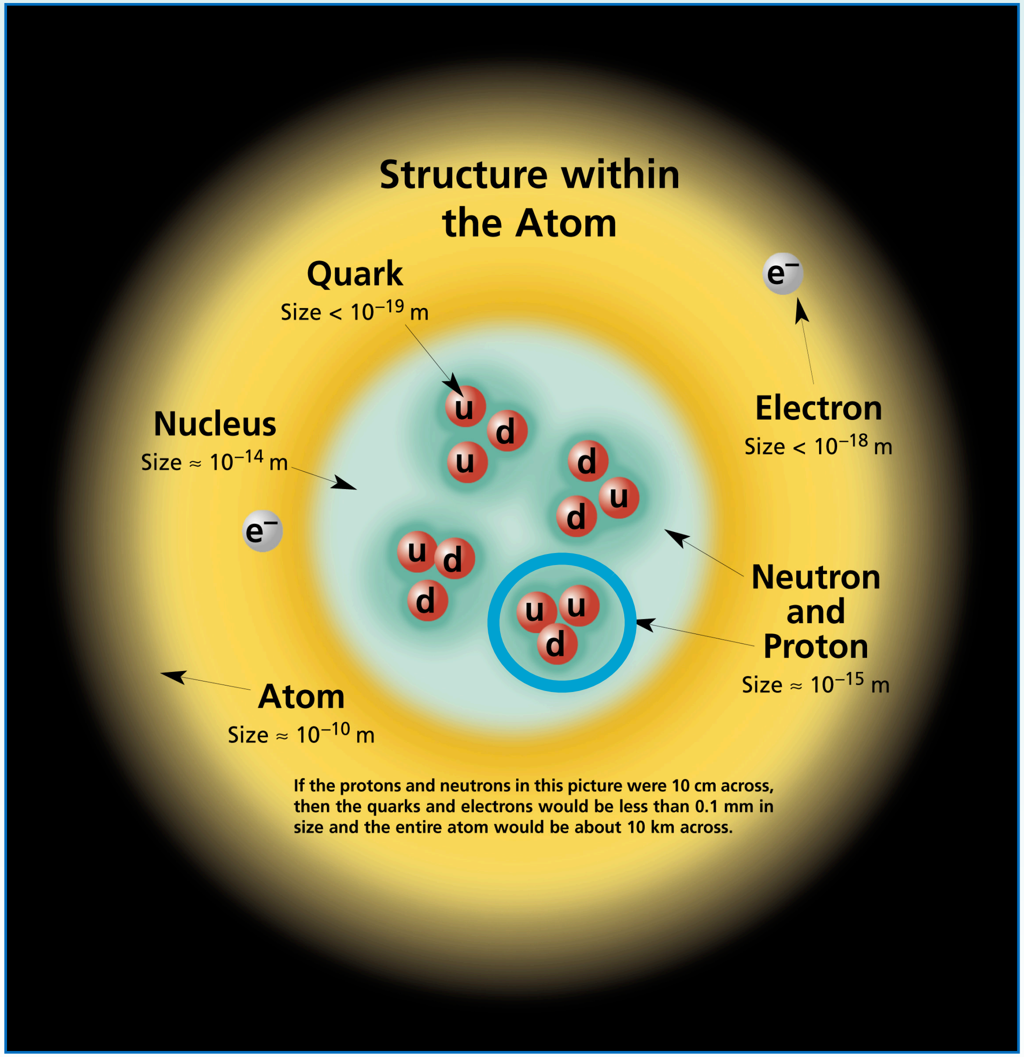
E. Rutherford, F.R.S.*
Philosophical Magazine
Series 6, vol. 21 May 1911, p. 669-688

The Scattering of α and β Particles by Matter and the Structure of the Atom

Considering the evidence as a whole, it seems simplest to suppose that the atom contains a central charge distributed through a very small volume, and that the large single deflexions are due to the central charge as a whole, and not to its constituents.

* Communicated by the Author. A brief account of this paper was communicated to the Manchester Literary and Philosophical Society in February, 1911.

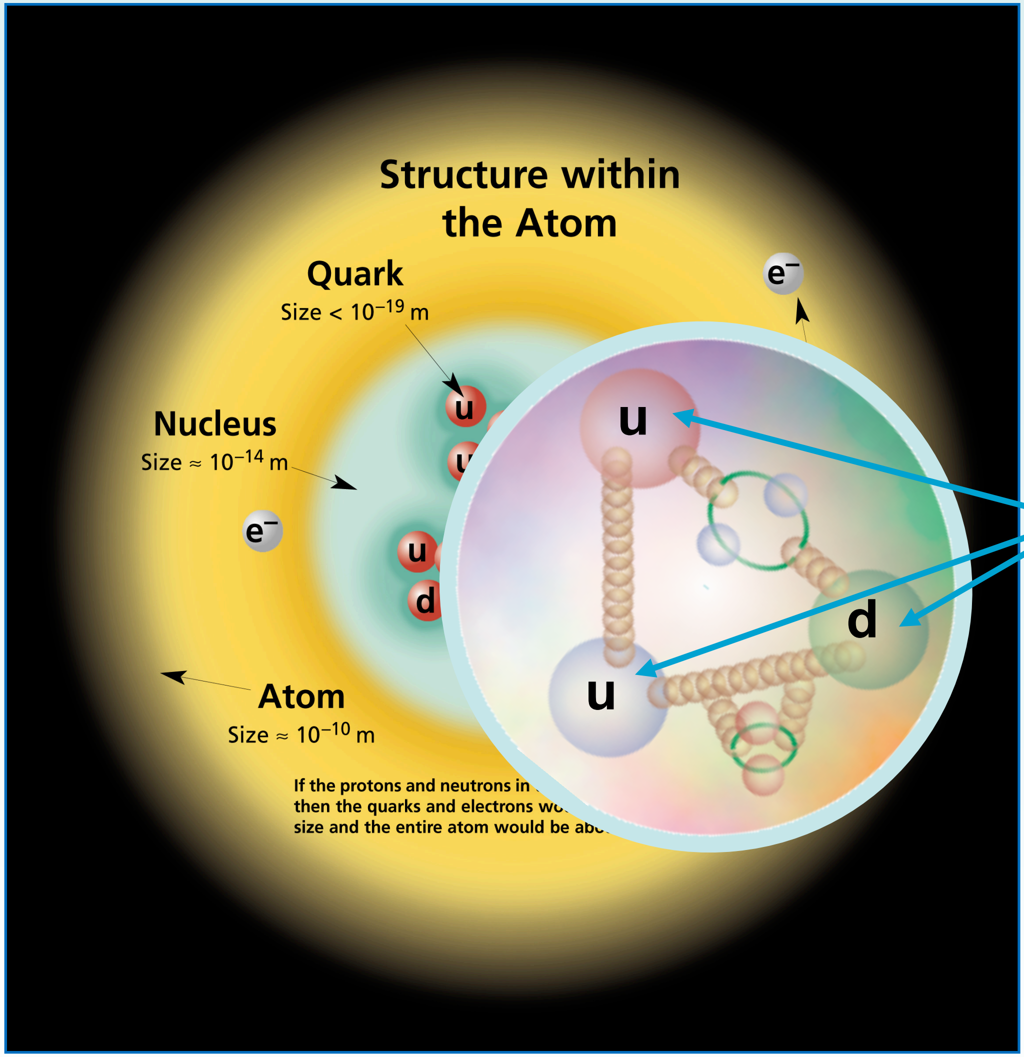
Atom : Electrons + Nucleus



nucleons: protons, neutrons

mass $M_N \sim 1$ GeV

Atom : Electrons + Nucleus



nucleons: protons, neutrons

mass M_N ~ 1 GeV

partons (quarks & qluons)

valence quarks (u, d)

→ most quantum properties

BUT:

M_u~0.003 M_N , M_d~0.006 M_N

Where does the mass of the nucleon comes from?

Feynman's Parton Model

- The nucleon is made up of point-like constituents (partons)
- Partons behave **incoherently**
- Probability $f(x)$ for a parton f to carry the fraction x of the nucleon momentum

is an intrinsic property of the nucleon, i.e. **process independent**

Learn about the nucleon structure via lepton-nucleon scattering

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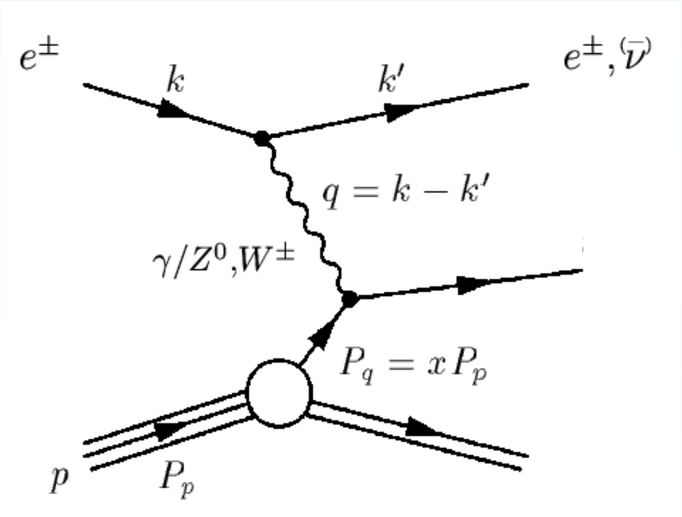
Learn about the nucleon structure via lepton-nucleon scattering

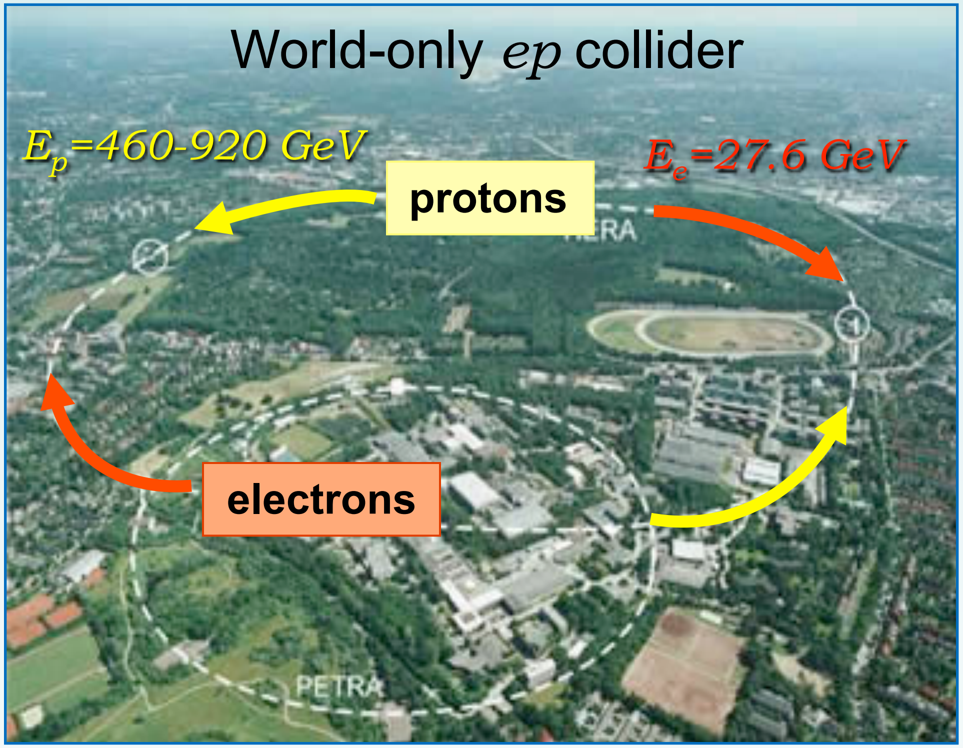
Electron-proton scattering in parton picture

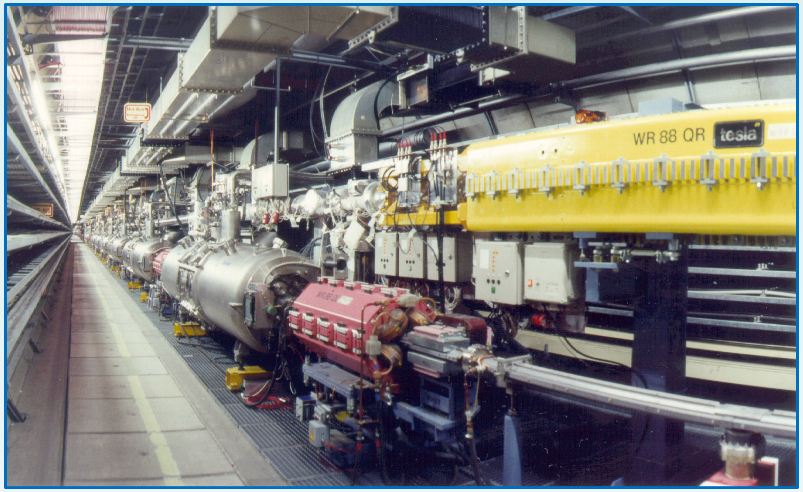


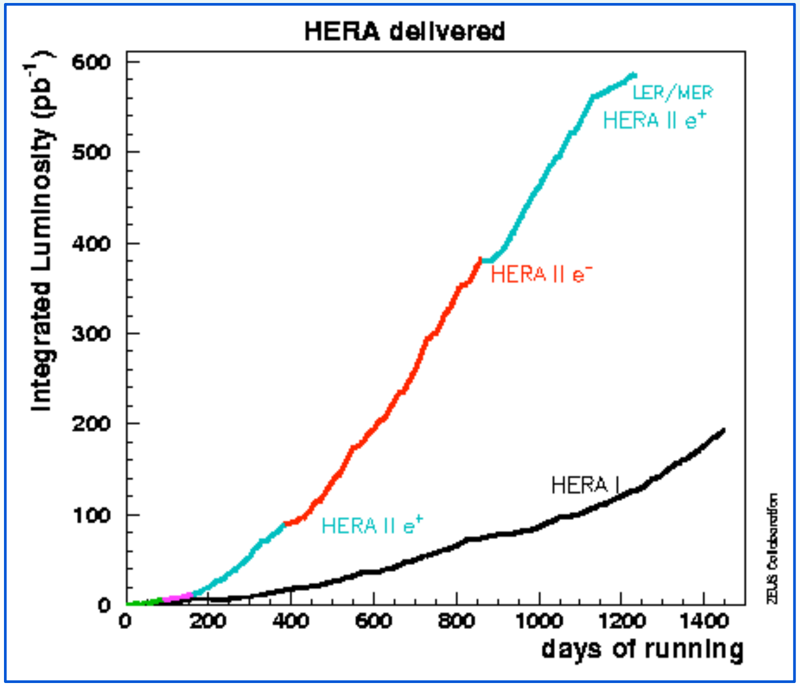
Electron scatters off a charged constituent (parton) of the proton

Identify the charged partons with quarks

Hadron - Electron Ring Accelerator





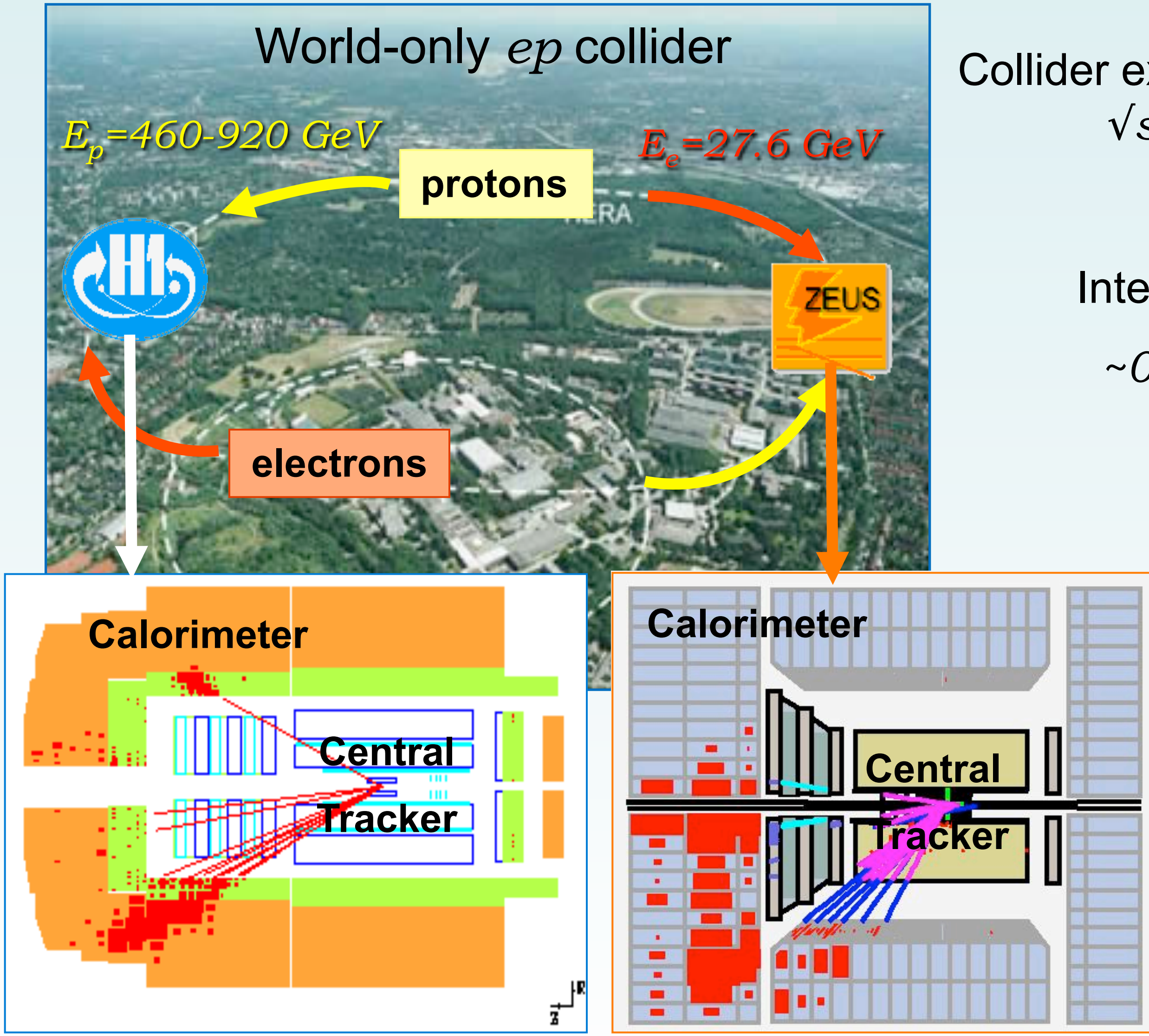


Unique tool to study proton structure

HERA: 6.3km circumference accelerator of electrons and protons.

End of running 30/6/07

HERA Collider Experiments



Collider experiments H1 & ZEUS

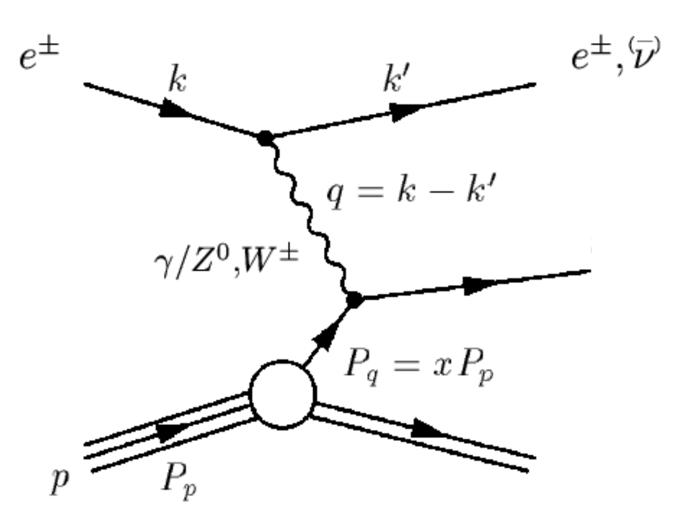
$\sqrt{s_{max}}$= 318 GeV

Integrated luminosity

~0.5 fb^{-1}/ experiment

ep Scattering at HERA

Deep Inelastic Scattering



Scatter both electron/positrons

Neutral Current: γ, Z^0 exchange

Charged Current: $W^\pm$ exchange

ep Scattering at HERA

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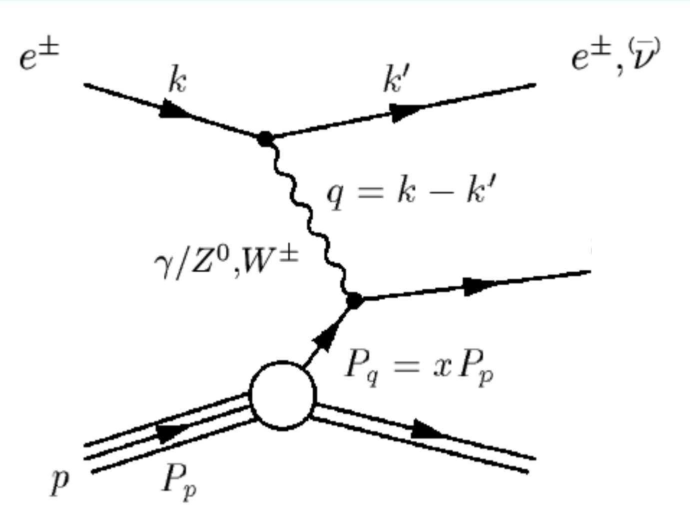
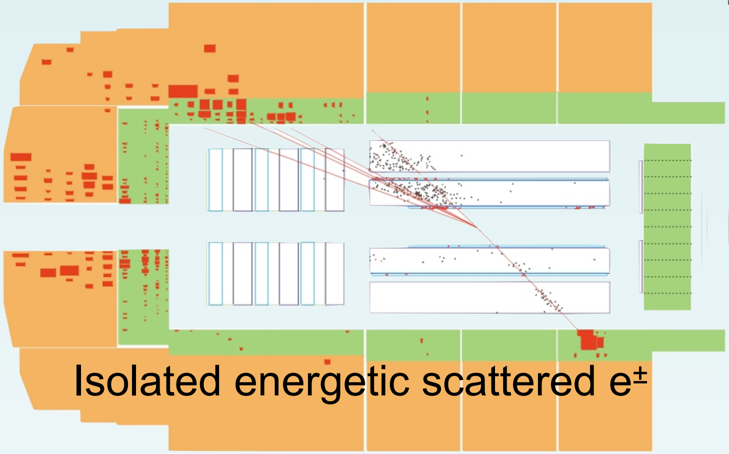


γ, Z : Neutral Current $ep \rightarrow e\,X$



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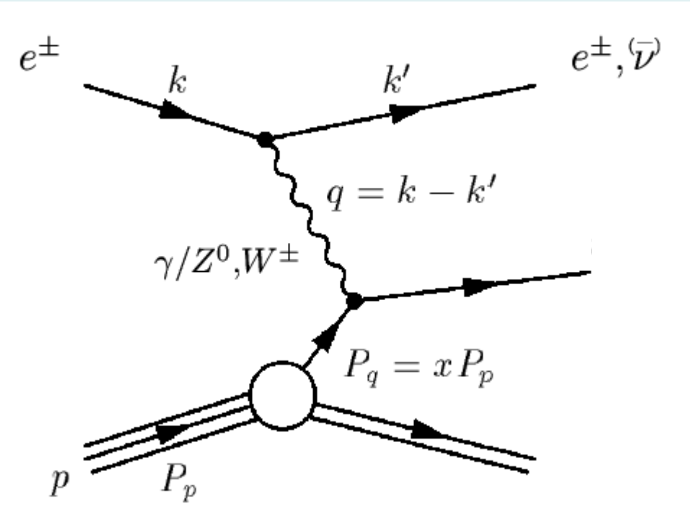

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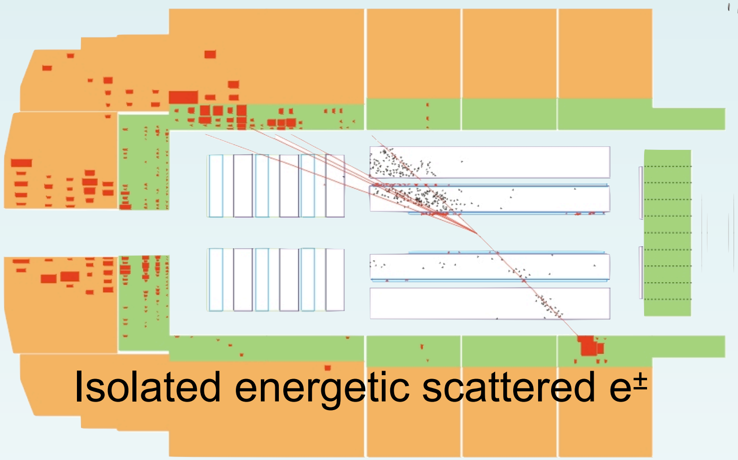
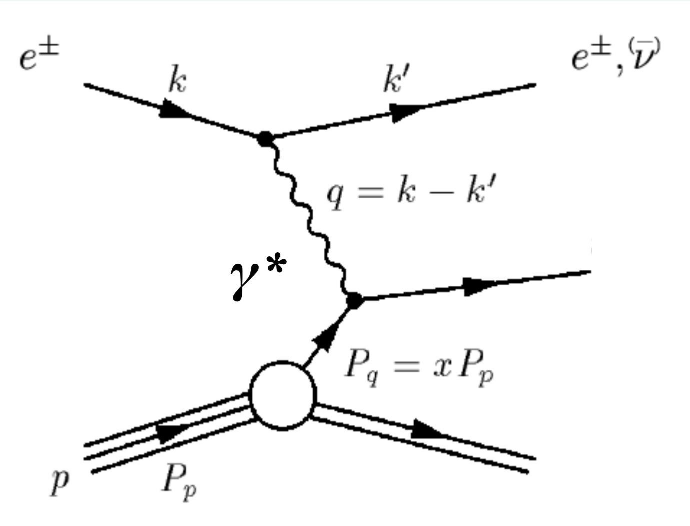


$W^{\pm}$: Charged Current $ep \rightarrow \nu\,X$

Kinematics of *ep* Scattering in Parton Model

γ exchange



Kinematics:

x=-q^2/ 2p·q Bjorken scaling

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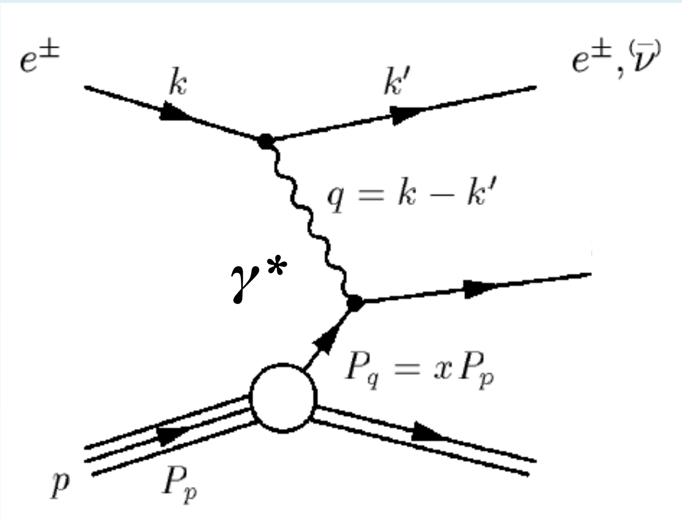
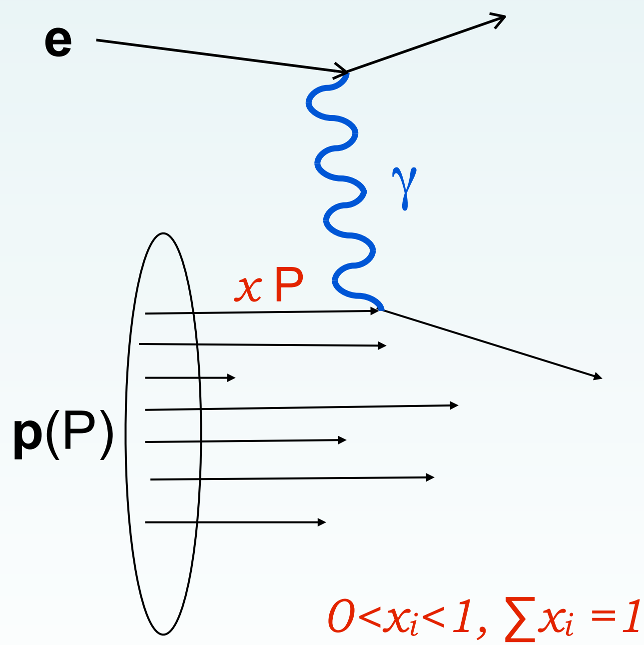


Infinite proton momentum frame:

partons do not interact,
move parallel to the proton,
massless, no transverse momentum
parton i carries fraction x_i of P_p



$0<x_i<1, \sum x_i = 1$

Kinematics:

$x=-q^2/2p\cdot q$ *Bjorken scaling*

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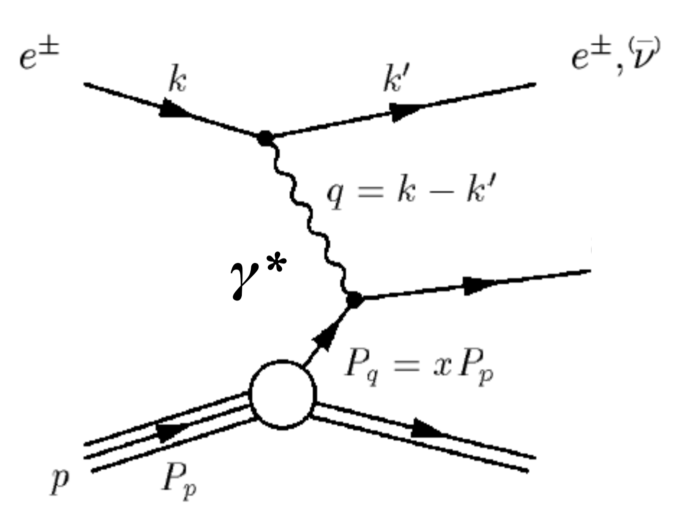

Kinematics:

x=-q^2/ 2p·q *Bjorken scaling*

Q^2 =-q^2 *photon virtuality*

Kinematics of *ep* Scattering in Parton Model

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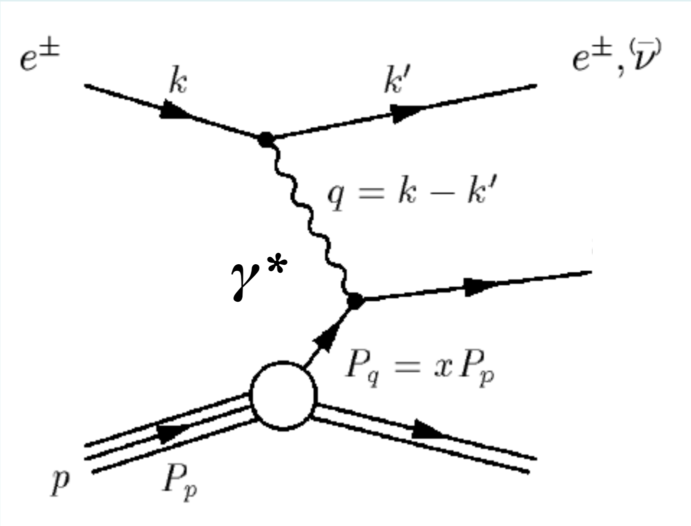
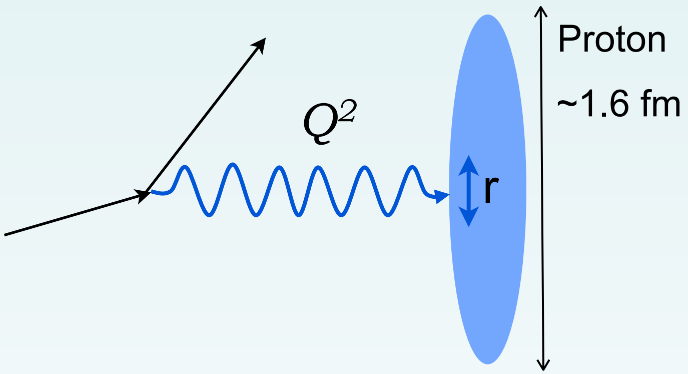


4-momentum transfer Q^2 defines distance scale r at which proton is probed



$r \approx \hbar c / Q = 0.2[fm] / Q[GeV]$

Kinematics:

$x = -q^2 / 2p \cdot q$ *Bjorken scaling*

$Q^2 = -q^2$ *photon virtuality*

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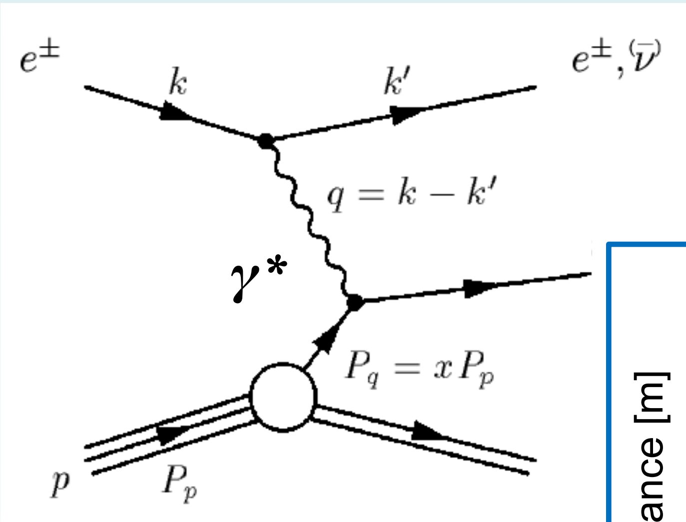
γ exchange



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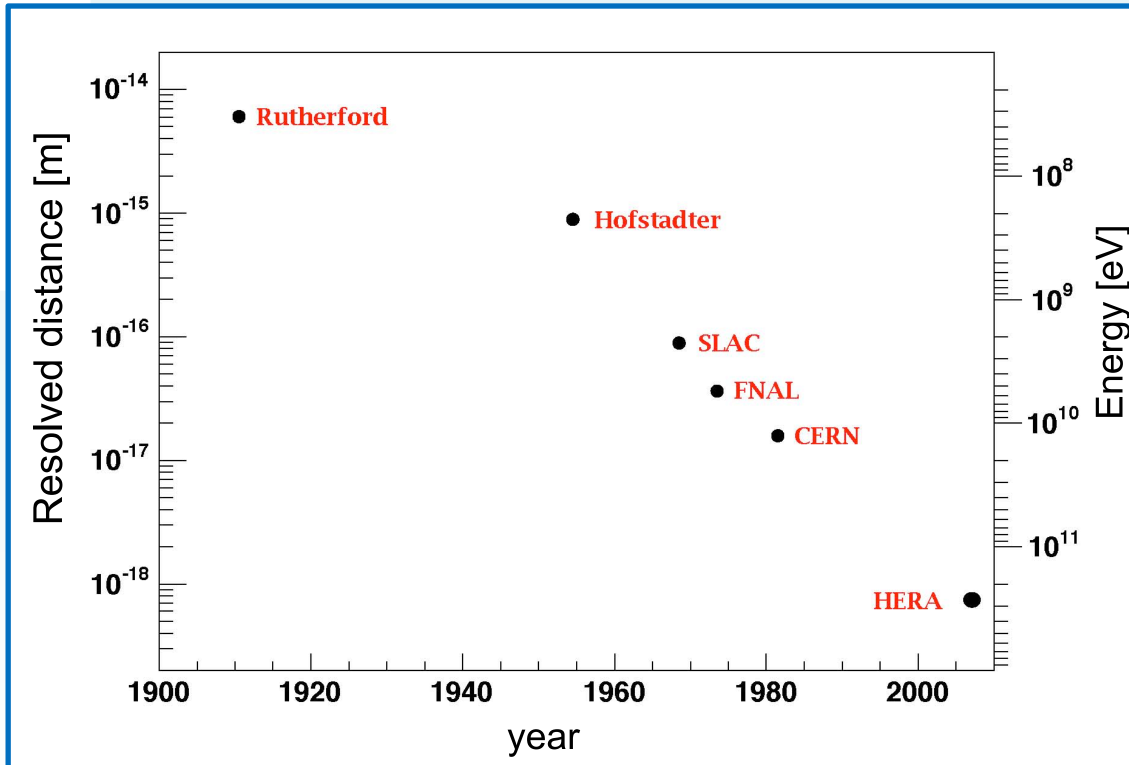
HERA collider: $r_{min} \approx R_p/1000$



Kinematics:

$x = -q^2 / 2p \cdot q$ *Bjorken scaling*

$Q^2 = -q^2$ *photon virtuality*

DIS Cross Section and Proton Structure

E.g. for Neutral Current: $e^{\pm}p \rightarrow e^{\pm} X$

measured

dominant contribution

$$\frac{d^2\sigma^{e^{\pm}p}}{dx dQ^2} \propto \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2 - y^2 F_L \mp xF_3\right]$$

y : transferred photon energy fraction

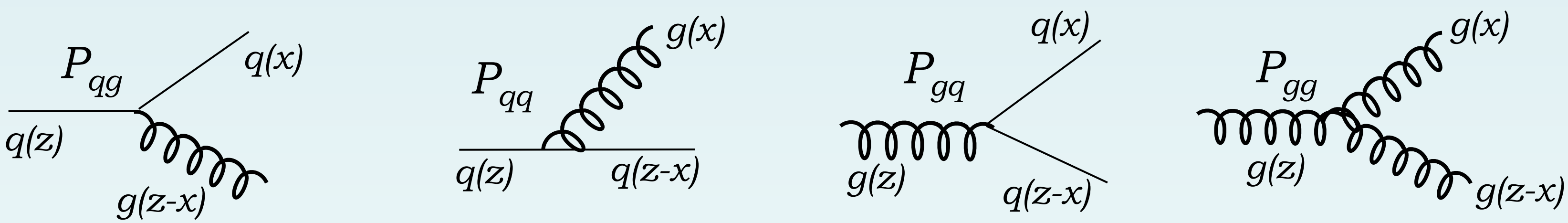
Quark-Parton Model: $F_2 \propto x \sum_f q_f + \bar{q}_f$

Parton Distribution Functions (PDFs):
probability to find a parton q in a proton carrying fraction x of it's momentum

Bjorken scaling: if partons do not interact, $q=q(x)$; $F_2=F_2(x)$

QuantumChromoDynamics Picture

Quarks do interact via gluon exchange. Probability via splitting functions:



Interpretation of PDFs: number of partons in the proton, carrying momentum between xP and $(x+dx)P$, as resolved at Q^2. $F_2(x) \rightarrow F_2(x,Q^2)$, $q(x) \rightarrow q(x,Q^2)$

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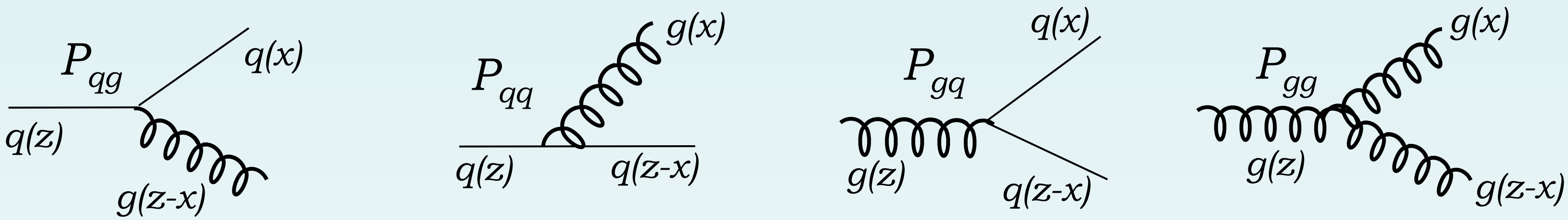

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Additional dependence on Q^2 quantitatively described in perturbative QCD via Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) Evolution Equations

$$\frac{\partial q(x,Q^2)}{\partial lnQ^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{qq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{qg}\left(\frac{x}{z}\right)\right]$$

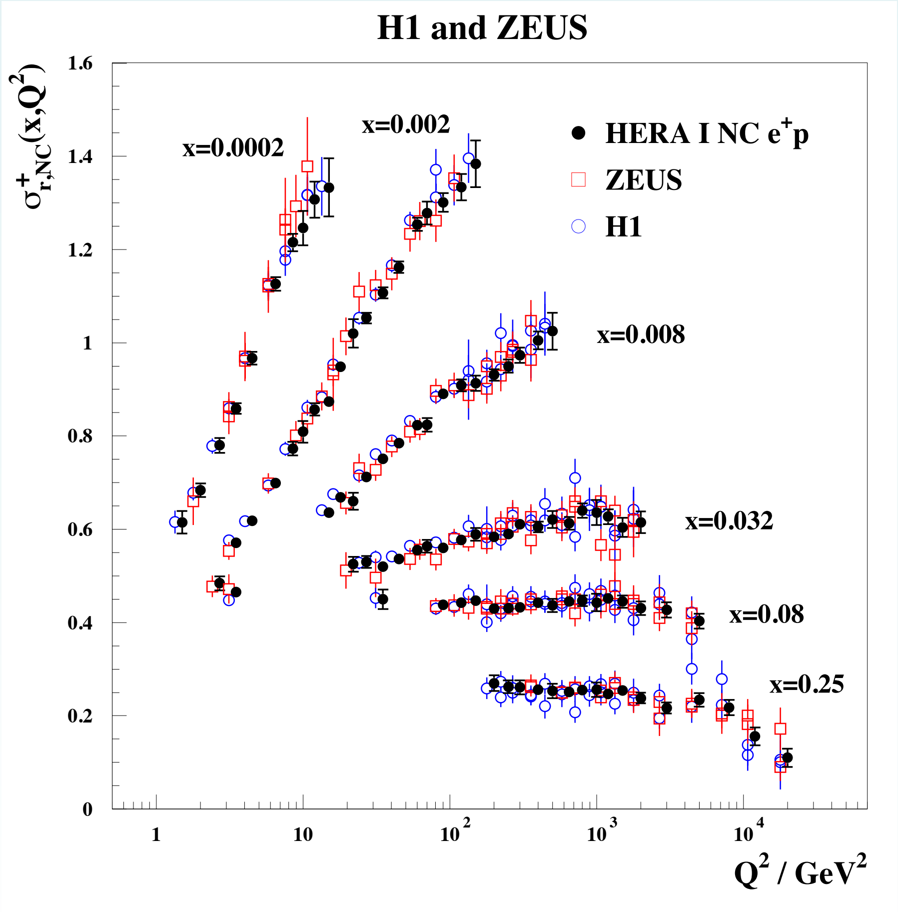
$$\frac{\partial g(x,Q^2)}{\partial lnQ^2} \propto \int_x^1 \frac{dz}{z}\left[q(z,Q^2)P_{gq}\left(\frac{x}{z}\right) + g(z,Q^2)P_{gg}\left(\frac{x}{z}\right)\right]$$

Quark and gluon distributions coupled in DGLAP equations

Scaling Violations at Highest Precision

JHEP 01 (2010) 109: combined H1 and ZEUS data from HERA I, $\mathcal{L}$~115 pb^{-1}

$$\sigma_r = F_2(x,Q^2) - \frac{y^2}{1+(1-y)^2} F_L(x,Q^2)$$



H1 and ZEUS data averaged:

- global fit of 1402 measurements
- 110 sources of systematic errors
- account for systematic correlations (cross calibration of experiments)
- total uncertainty: *1-2%* for *Q^2<500 GeV^2*
- covered kinematics:

  10^{-7}<x<0.65

  0.05<Q^2<30000 GeV^2

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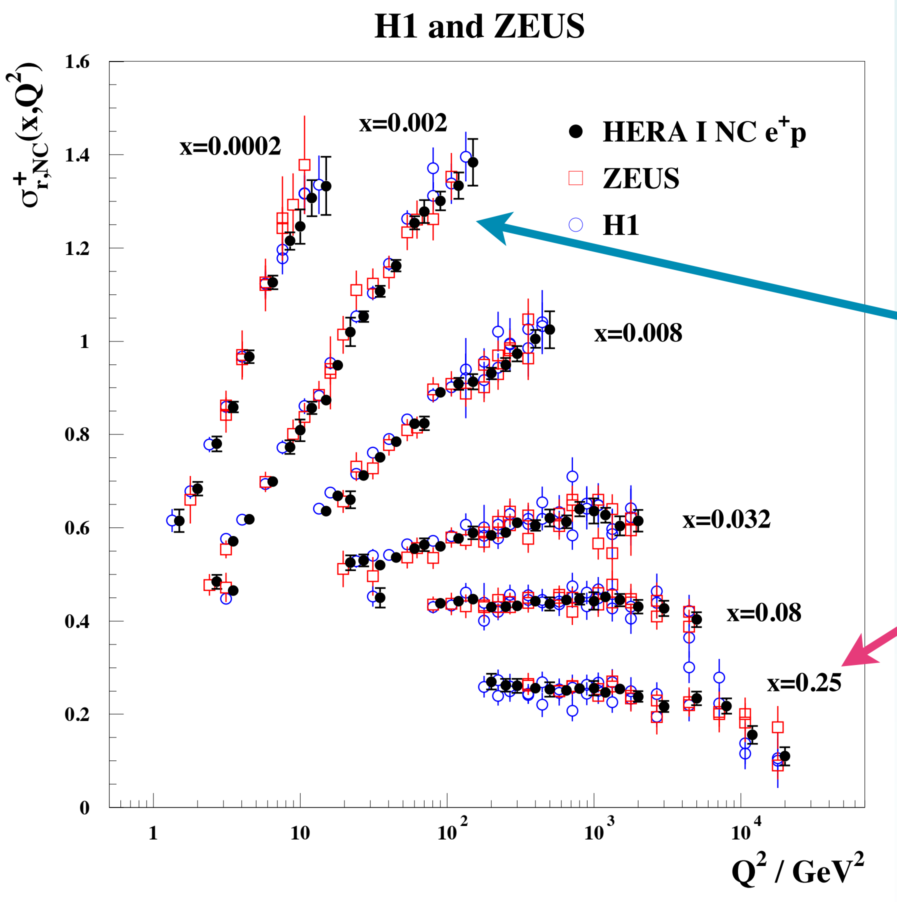
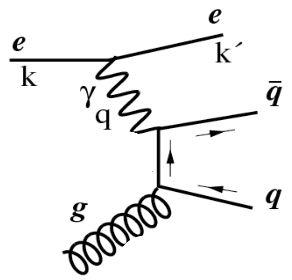


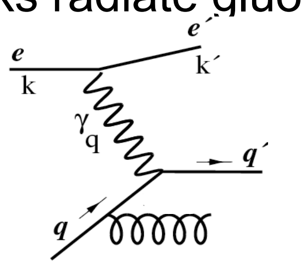
small x : F_2 rises with Q^2

gluon splits into quark pair



large x : F_2 falls with Q^2

quarks radiate gluons



Determination of Parton Density Functions

Structure function factorization: for an exchange-Boson V (γ, Z, $W^{\pm}$)

$$F_2^V(x, Q^2) = \sum_{i=q,\bar{q},g} \int_x^1 dz \times C_2^{V,i}(\frac{x}{z}, Q^2, \mu_F, \mu_R, \alpha_S) \times f_i(z, \mu_F, \mu_R)$$

determined using measured cross sections

calculable in pQCD

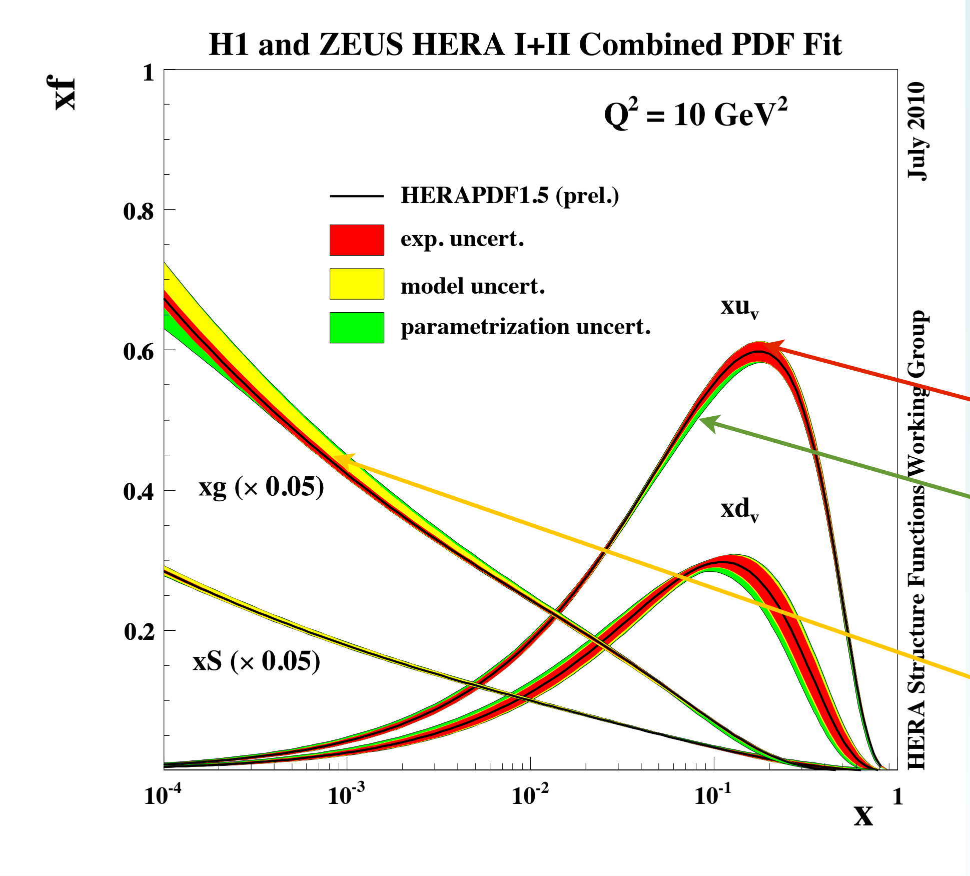
PDF

x-dependence of PDFs is not calculable in perturbative QCD:

- parameterize at a starting scale Q^2_0 : $f(x)=Ax^B(1-x)^C(1+Dx+Ex^2)$
- evolve these PDFs using DGLAP equations to $Q^2>Q^2_0$
- construct structure functions from PDFs and coefficient functions: predictions for every data point in (x, Q^2) – plane
- χ^2- fit to the experimental data

HERA Parton Density Functions

PDFs determined from the QCD fit to the NC and CC cross sections



HERAPDF1.5 (prel.)

QCD@NLO DGLAP

combined H1 and ZEUS data

Experimental uncertainty

Parametrization:

shapes of PDF at starting scale Q_0

Model assumptions:

masses of c, b - quarks,

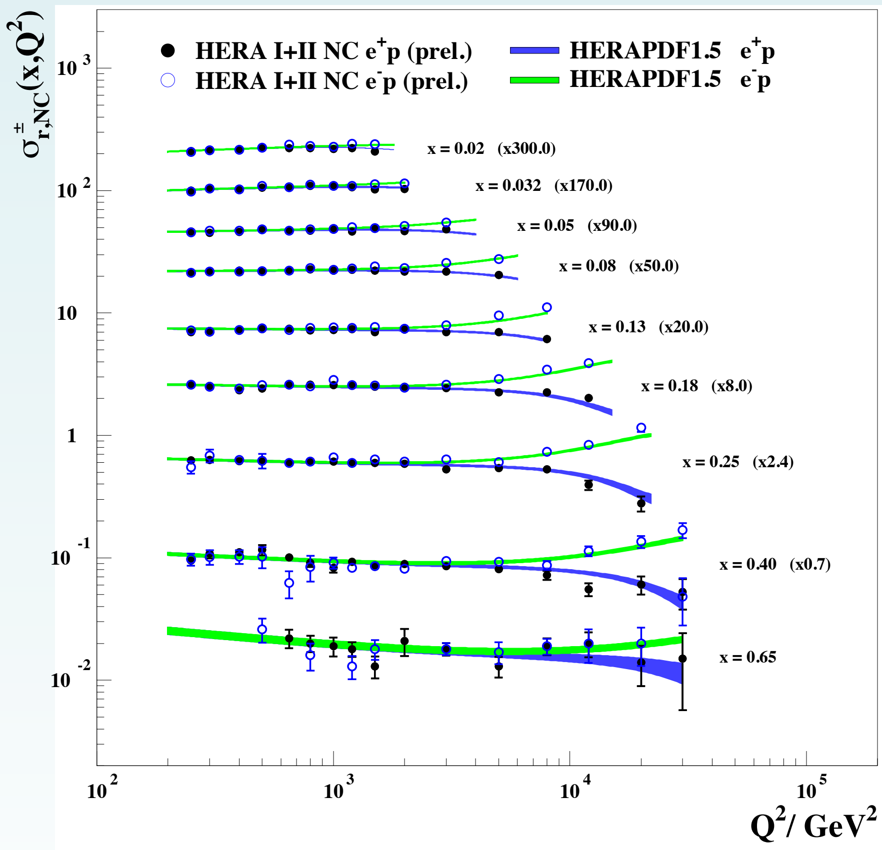
fraction of strange quarks, $\alpha_S(M_Z)$

Gluons and sea quarks: dominant partons at low x

HERA DIS Cross Sections vs HERAPDF

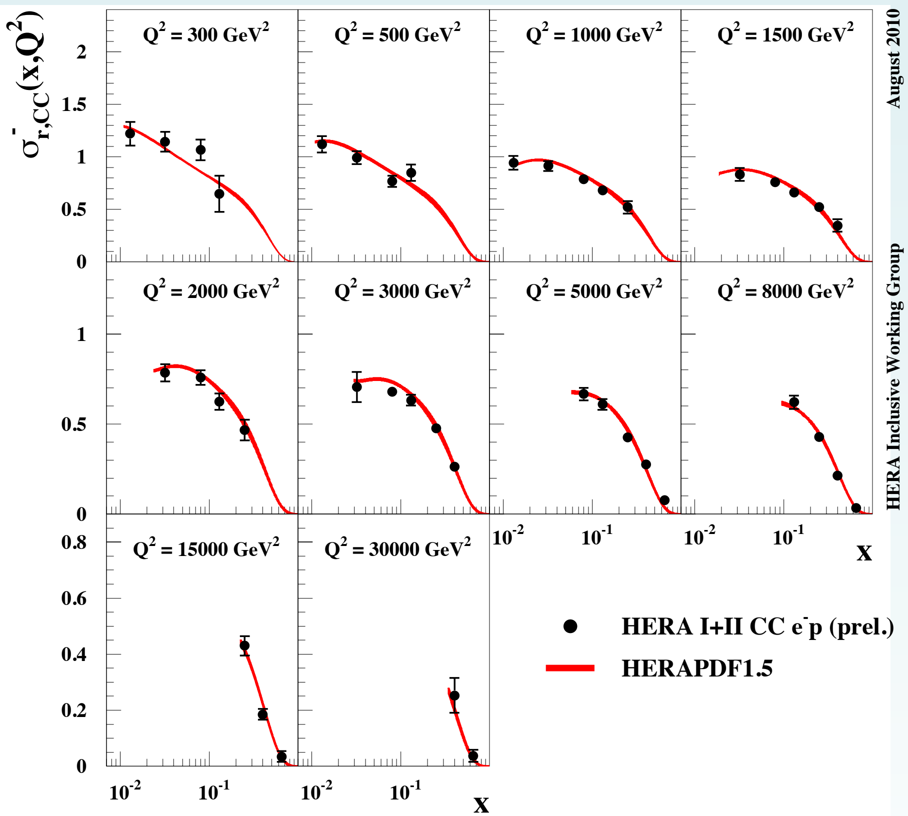
Neutral Current

H1 and ZEUS



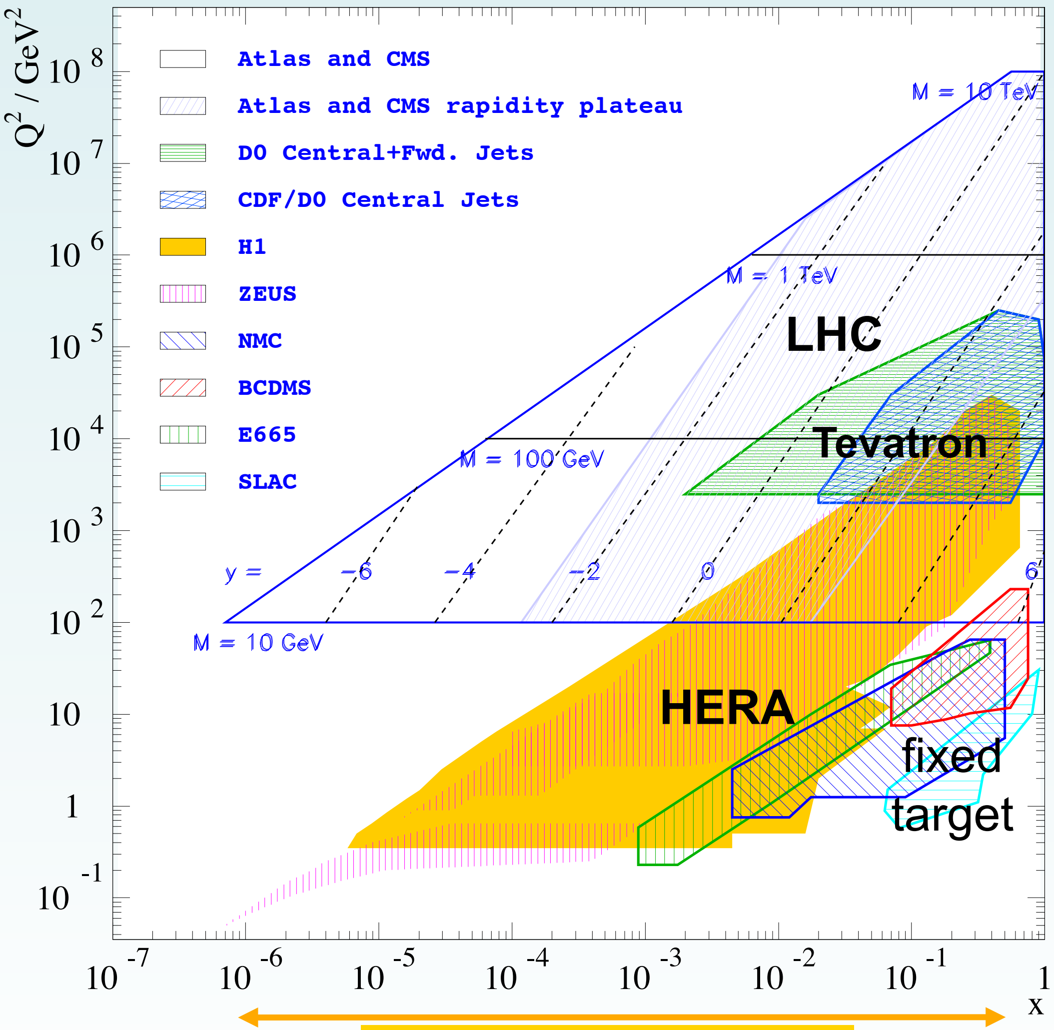
Charged Current

H1 and ZEUS



QCD using HERAPDF describes HERA NC and CC data very well

PDFs From HERA to Tevatron and the LHC



HERA coverage in x

PDFs obtained from data of fixed target, HERA, Tevatron

HERA measurements:

covers most of the (x,Q^2) plane, best constrain at low, medium x

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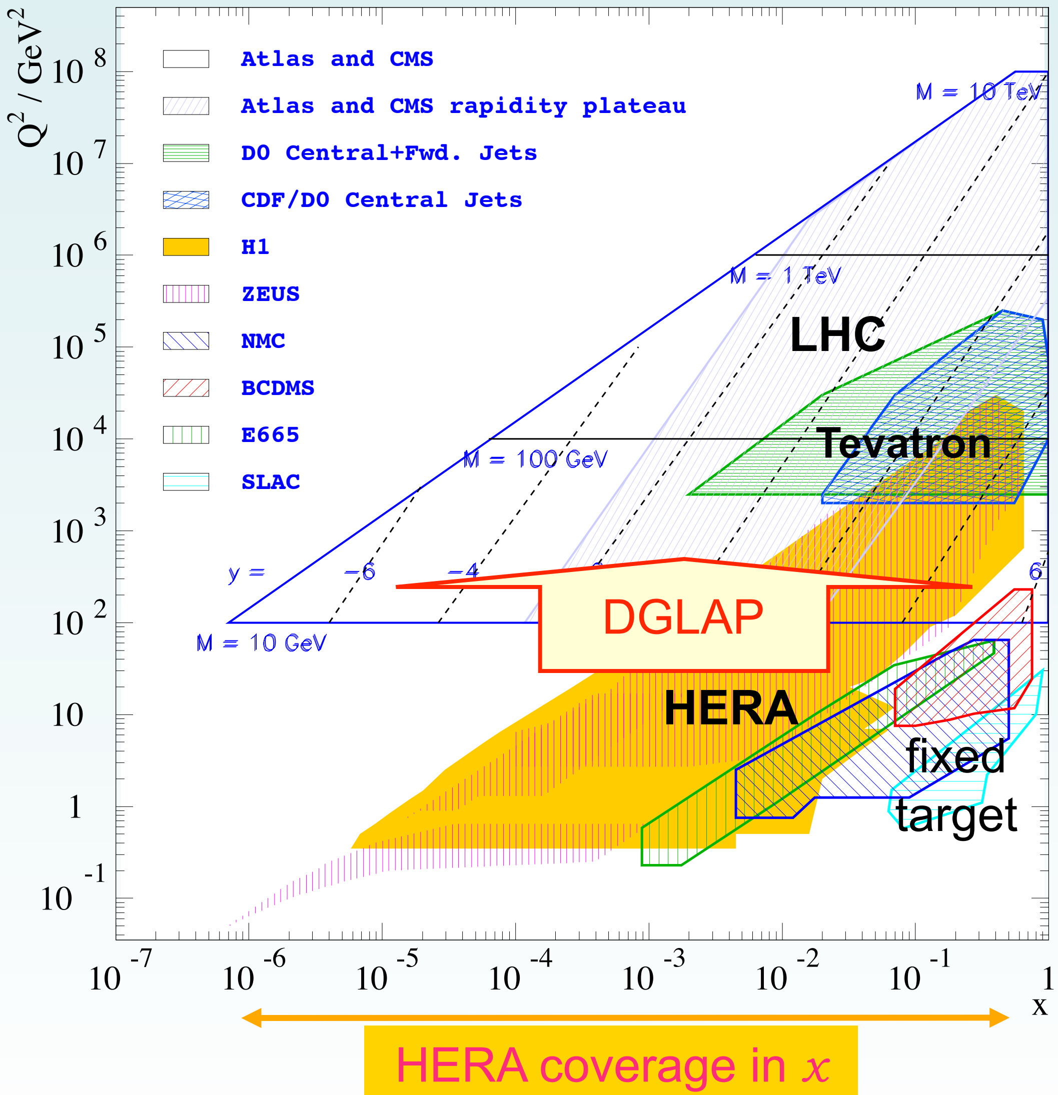

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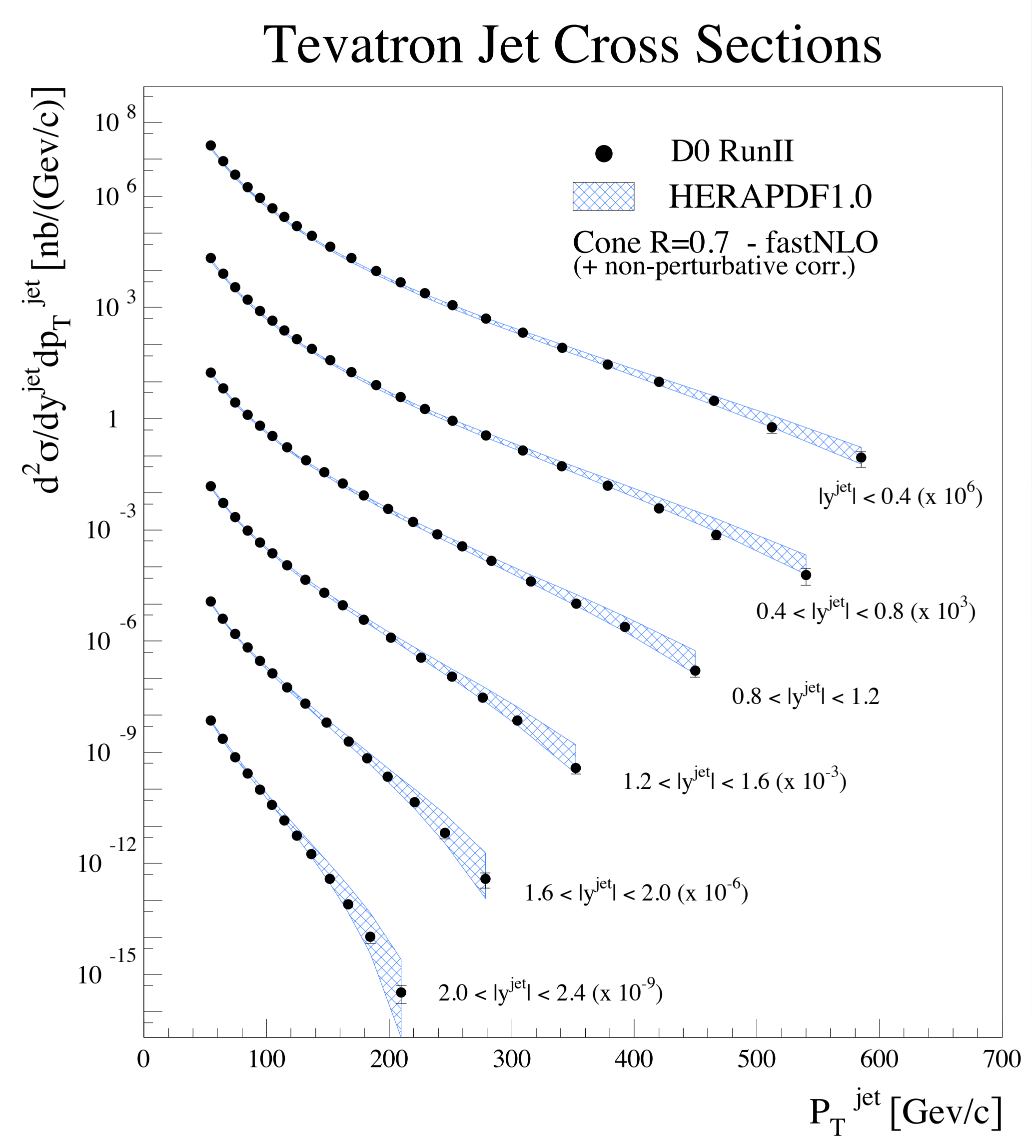
From HERA to kinematics of Tevatron, LHC:

evolution in Q^2 via DGLAP

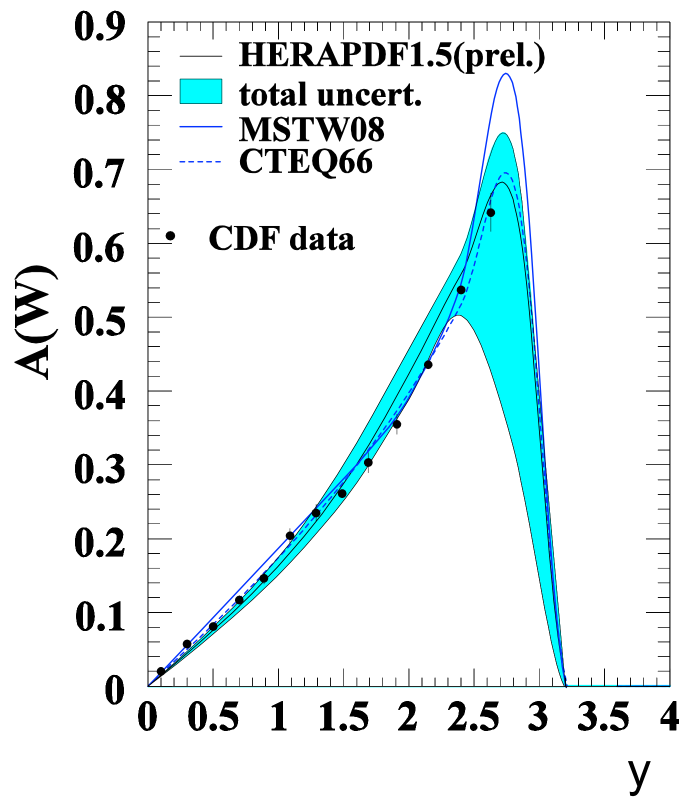
HERAPDF vs Jets at Tevatron

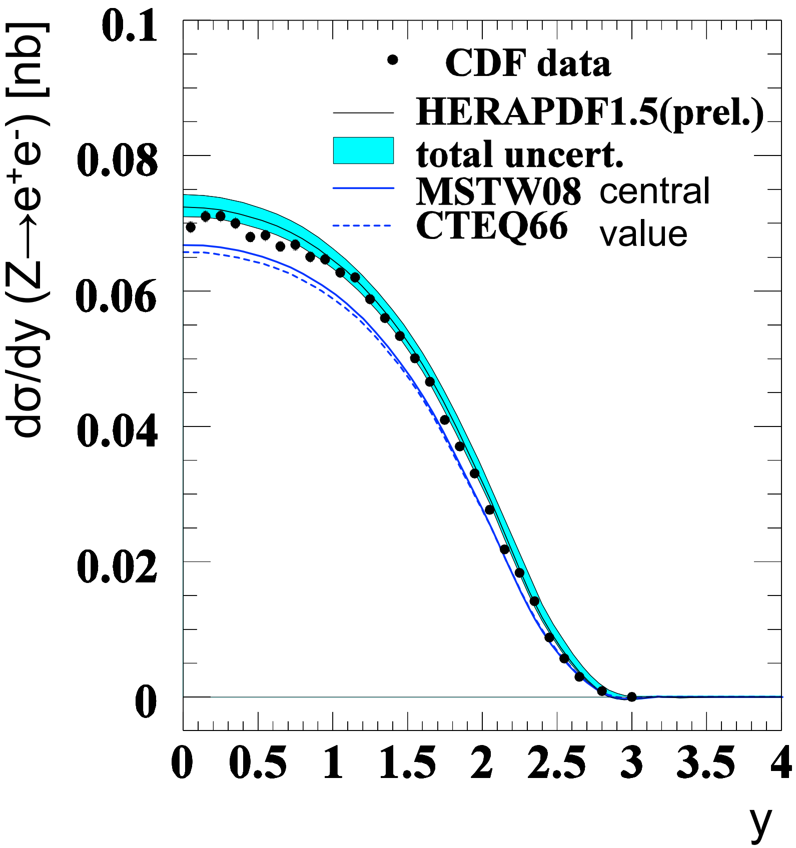


Prediction based on HERAPDF

in agreement with Tevatron

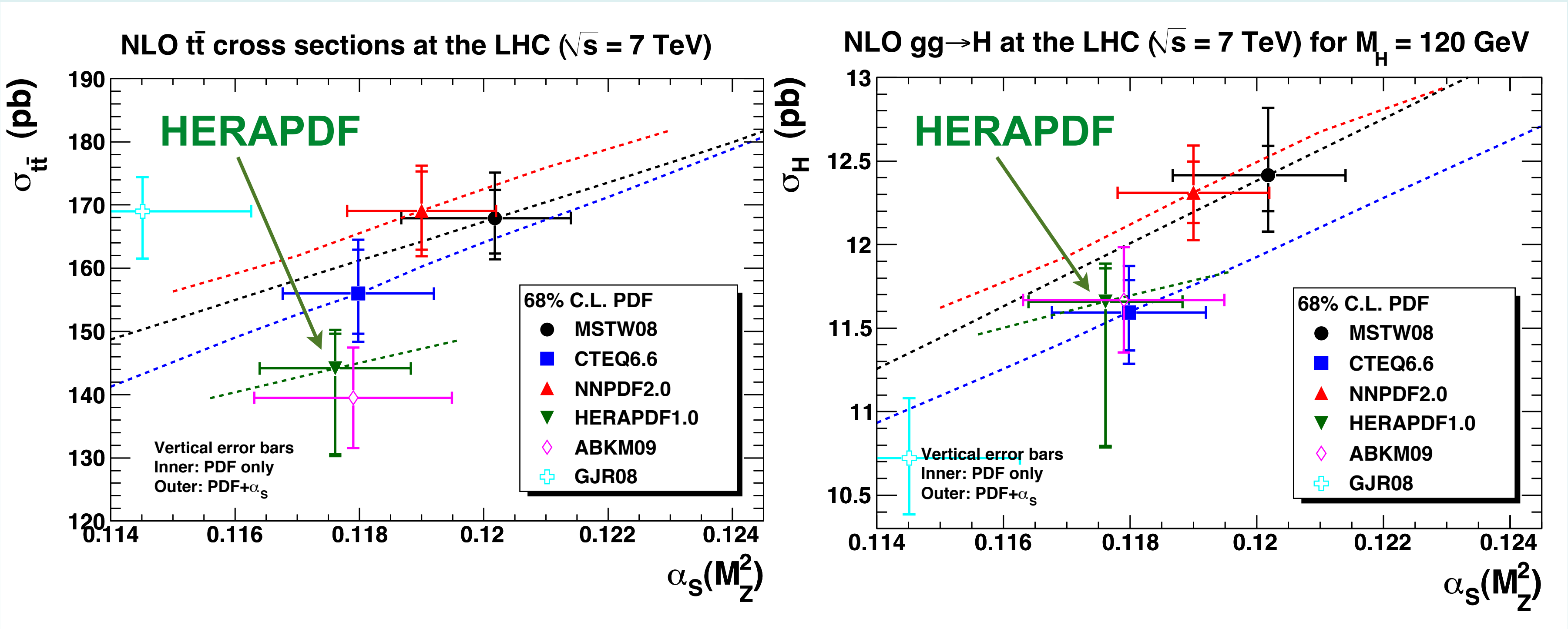
W and Z Production at Tevatron





Prediction based on HERAPDF agrees very well with Tevatron data

Benchmarking PDFs: LHC Cross Sections



Dominant uncertainty on HERAPDF1.0 (parameterization) not accounted for in most PDFs

Differences between the PDF groups:

- data used in the fit and estimation of uncertainties
- different treatment of heavy quarks

Heavy Quarks and PDF Fits

Factorization: $F_2^V(x,Q^2) = \sum_{i=q,\bar{q},g} \int_x^1 dz \times C_2^{V,i}(\frac{x}{z},Q^2,\mu_F,\mu_R,\alpha_S) \times f_i(z,\mu_F,\mu_R)$

i - number of active flavours in the proton: defines the factorization (HQ) scheme

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- i fixed : Fixed Flavour Number Scheme (FFNS)

  only light flavours in the proton: i = *3 (4)*

  c- (b-) quarks massive, produced in boson-gluon fusion

  $Q^2 \gg m_{HQ}{}^2$: can be less precise, NLO coefficients contain terms ~ $ln(\frac{Q}{m_{HQ}})$

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- i variable: Variable Flavour Number Scheme (VFNS)

- Zero Mass VFNS: all flavours massless. Breaks down at $Q^2 \sim m_{HQ}^2$

- Generalized Mass VFNS: different implementations provided by PDF groups

  smooth matching with FFNS for $Q^2 \rightarrow m_{HQ}^2$ must be assured

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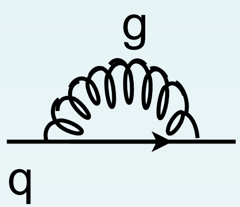
QCD analysis of the proton structure: treatment of heavy quarks essential

Heavy Quark Mass Definition in PDFs

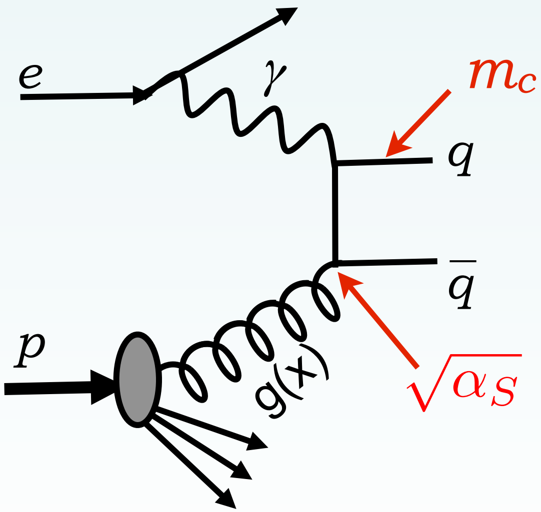
Usually HQ coefficient functions use a pole mass definition

BUT: pole mass defined for free quarks
Corrections due to loop integrals receive large contributions ~ O(Λ_{QCD})



large higher order corrections
bad convergence of perturbative series

Another way of defining quark mass: via renormalization



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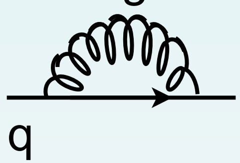

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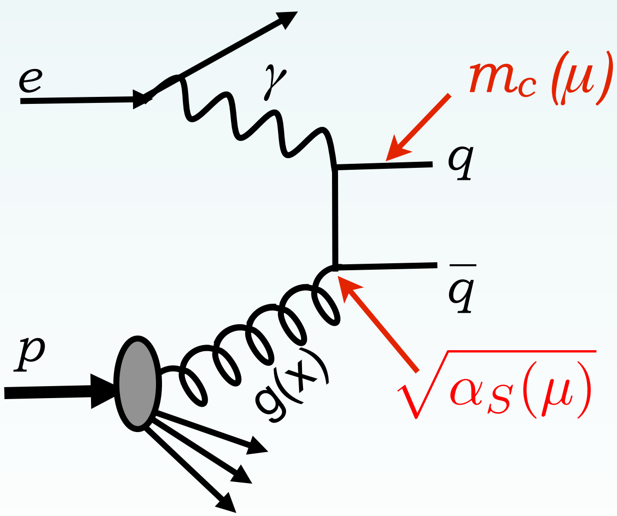
bad convergence of perturbative series

Another way of defining quark mass: via renormalization



running coupling

running mass

Heavy Quark Mass Meaning in PDFs

Massive HQ coefficient functions are calculated at NLO using pole mass

Smith. et al NPB 395,162 (1993)

Used by the global fit groups: MSTW, CTEQ, ABKM, GJR, HERAPDF

ZMVFNS: m_{HQ} defines a threshold at which HQ appears as an active flavour

GMVFNS: m_{HQ} is also used as a parameter at which FFNS turns into VFNS

Heavy Quark Mass Values in PDFs

Massive HQ coefficient functions are calculated at NLO using pole mass

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PDF group	m_c / m_b	HQ scheme
MSTW	1.4 / 4.75	GMVFNS
CTEQ	1.3 / 4.5	GMVFNS
JR	1.3 / 4.2	FFNS
ABKM	1.5 / 4.5	FFNS
HERAPDF	$1.4^{-0.05}_{+0.25}$ / 4.75	GMVFNS

PDG values: 1.66±0.18 / 4.79

PDF fits assume pole mass definition for heavy quarks

Values of m_c as used by most PDF groups too low wrt. PDG

Heavy Quark Mass Values in PDFs

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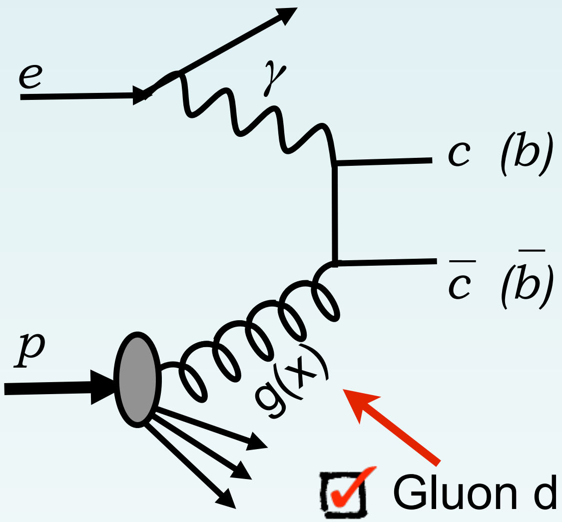
Values of m_c as used by most PDF groups too low wrt. PDG

HQ treatment in PDF fits, meaning and values of HQ masses non trivial..

Heavy quark data can help!

Heavy Quark Production at HERA

Heavy quarks in *ep* scattering produced in boson-gluon fusion



Contribution to total DIS cross section:

charm: ~ 30% at large Q^2

beauty: at most 1%

☑ Gluon directly involved:
cross-check of *g(x)* from NC and CC DIS cross sections

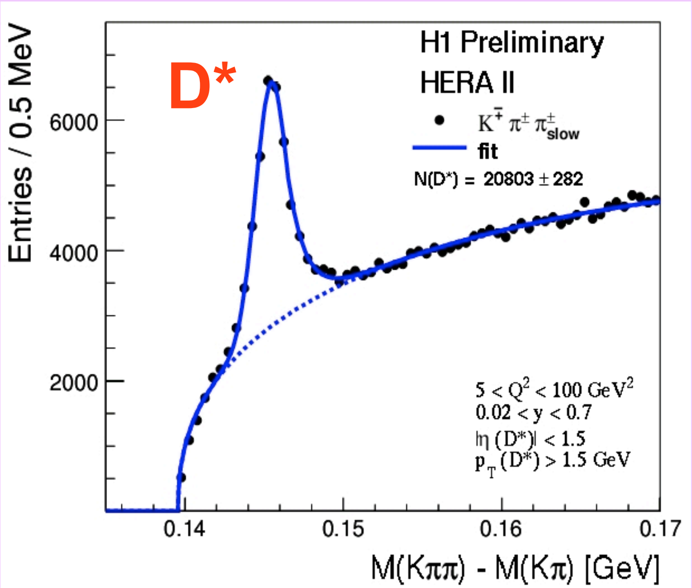
☑ HQ contributions to the proton structure function F_2: (e.g. charm)

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

→ Direct test of HQ schemes in PDF fits

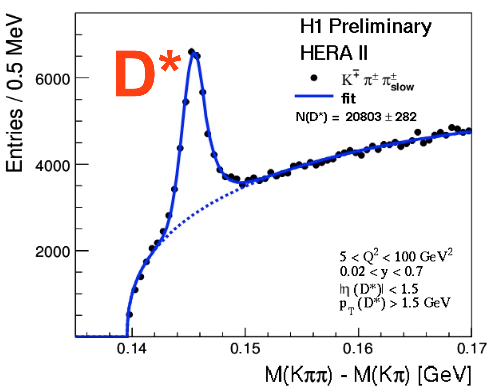
Heavy Quark Tagging Methods at HERA

charmed mesons

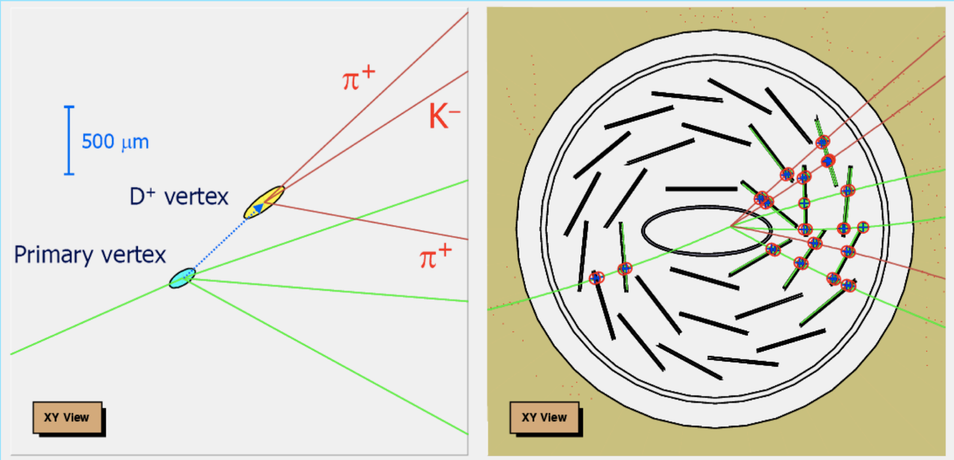


Heavy Quark Tagging Methods at HERA

charmed mesons

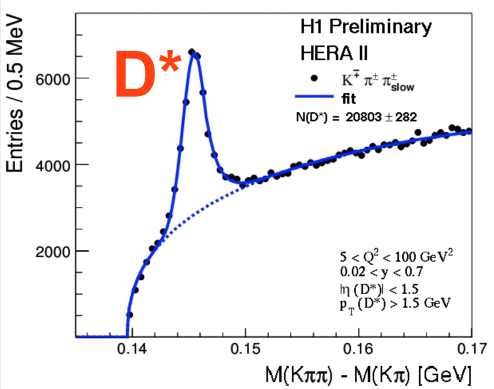


+ vertex reconstruction



Heavy Quark Tagging Methods at HERA

charmed mesons



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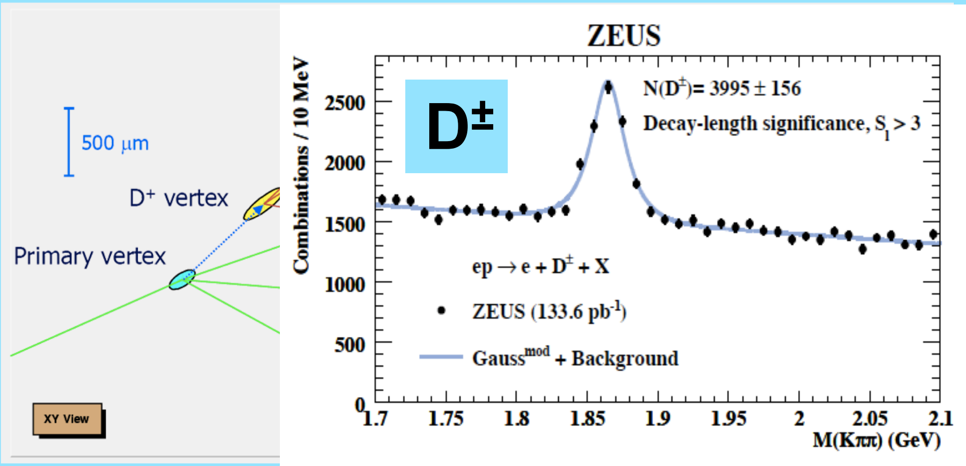
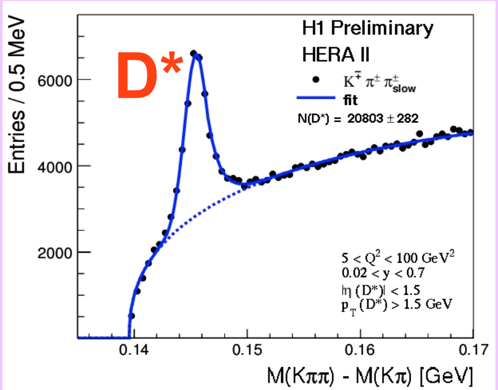
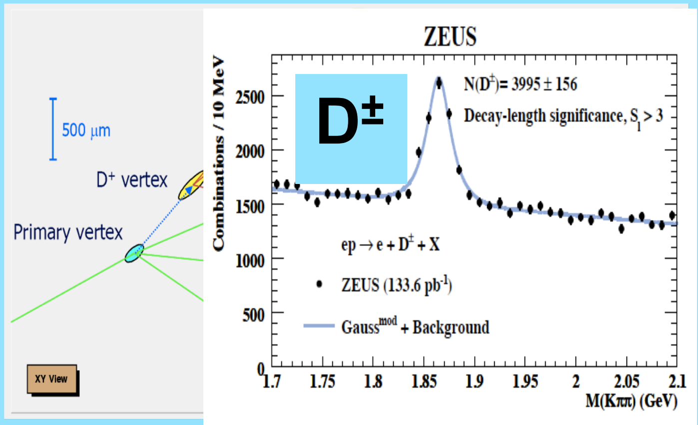


Heavy Quark Tagging Methods at HERA

charmed mesons

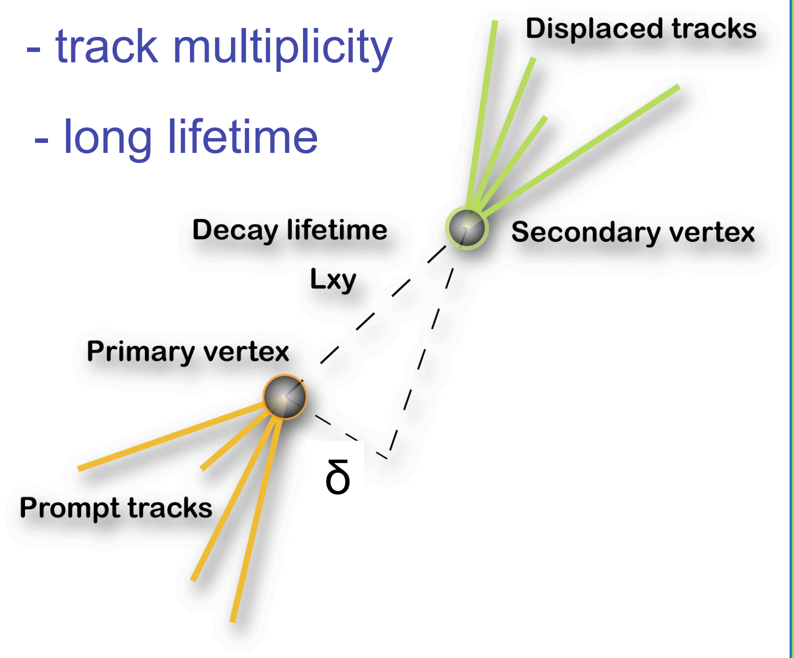


+ vertex reconstruction



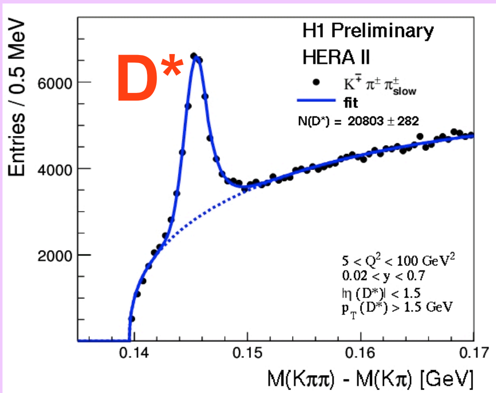
properties of c-,b- hadrons:

- track multiplicity
- long lifetime



Heavy Quark Tagging Methods at HERA

charmed mesons



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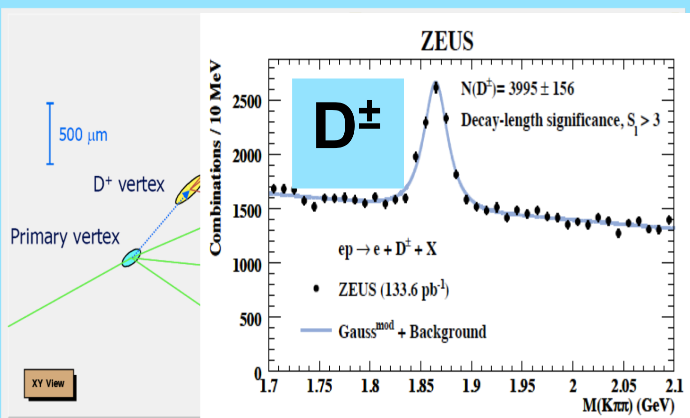
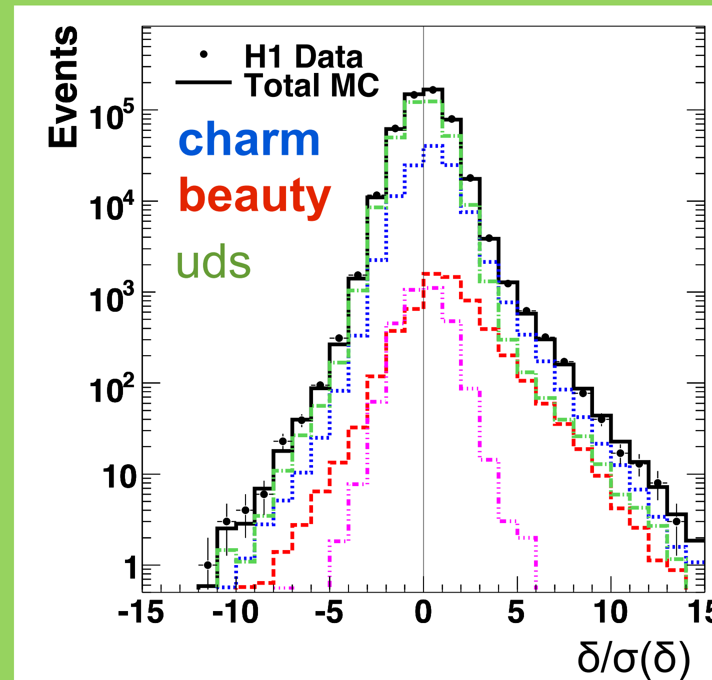
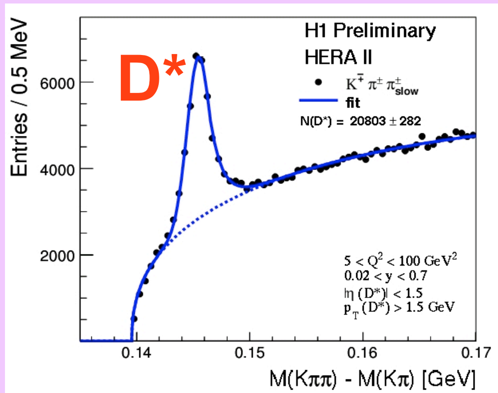


track displacement significance

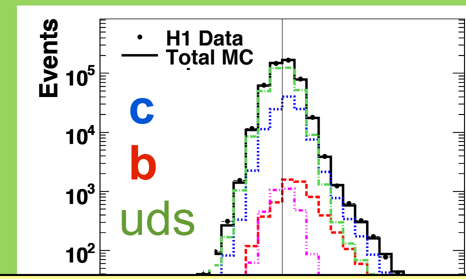


Heavy Quark Tagging Methods at HERA

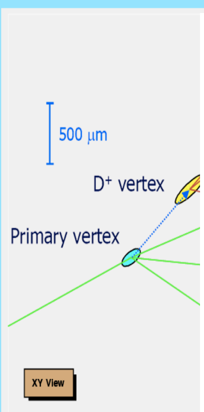
charmed mesons

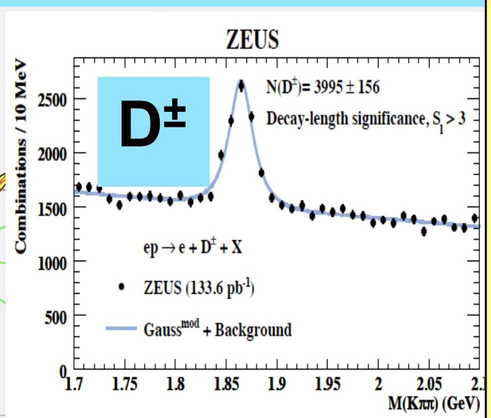


track displacement

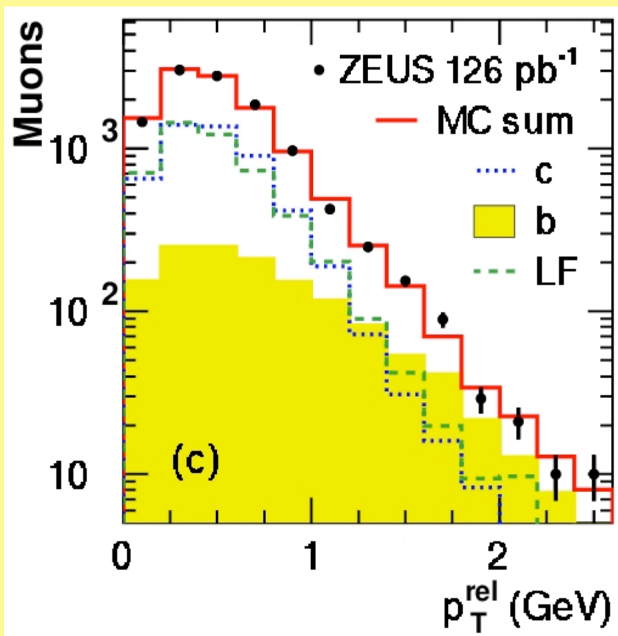


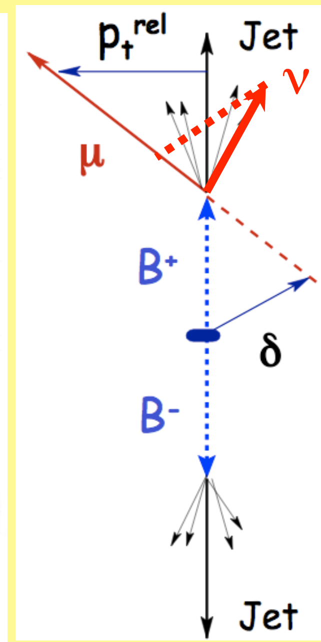
+ vertex reconstruction





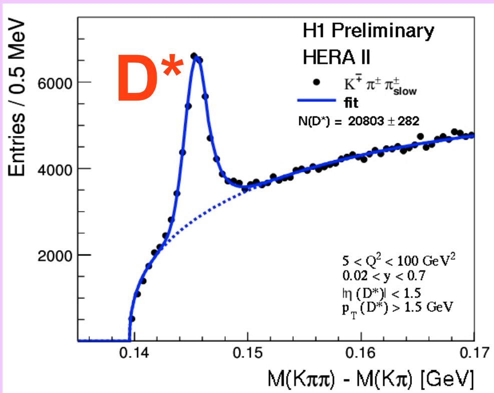
semi-leptonic decays of c and b





Heavy Quark Tagging Methods at HERA

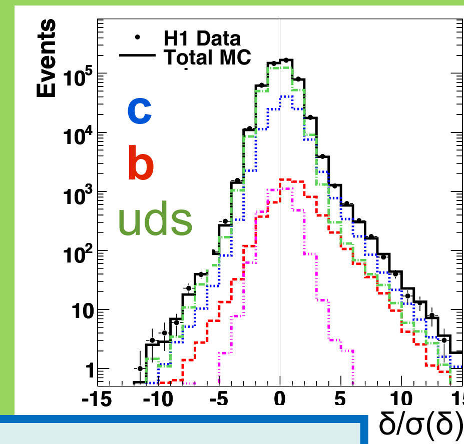
charmed mesons



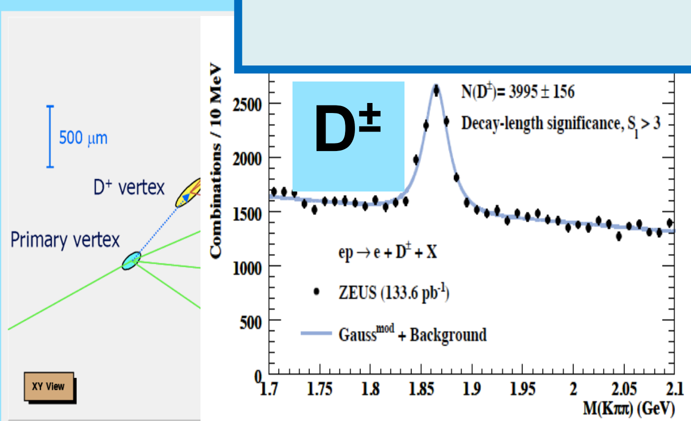
different tag methods

orthogonal systematics

track displacement

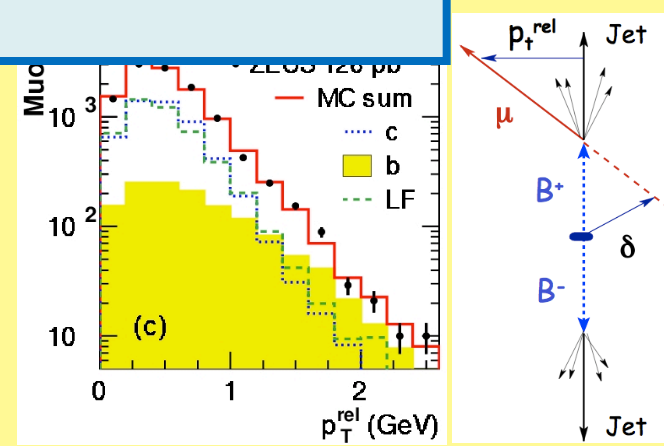


+ ver



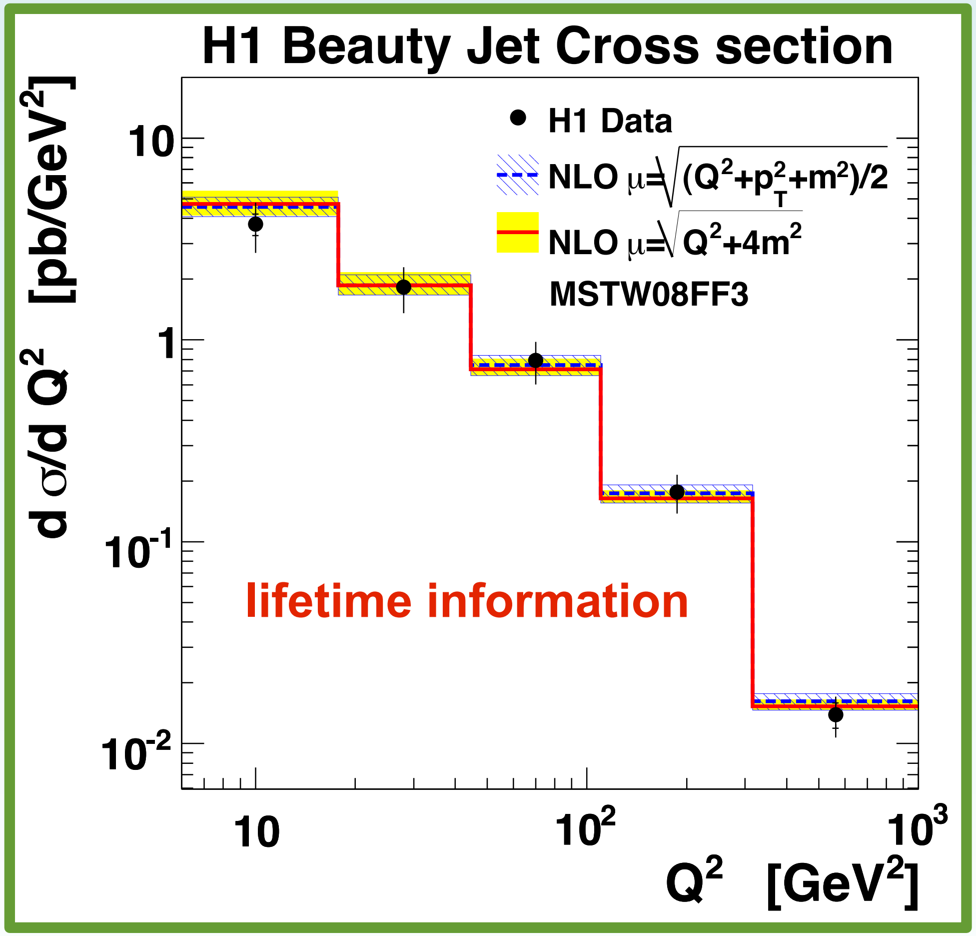
Combination of all measurements

ys of c, b



Understanding Beauty Production

Beauty production in DIS



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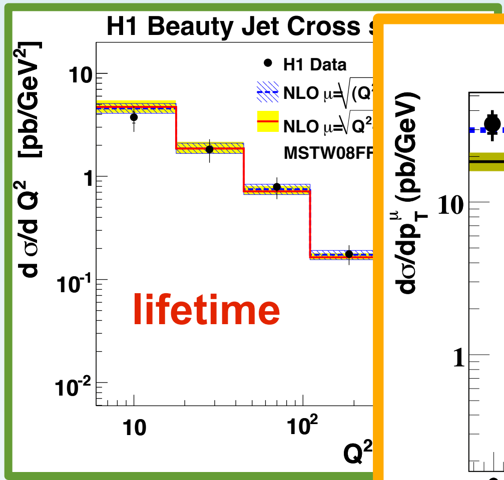

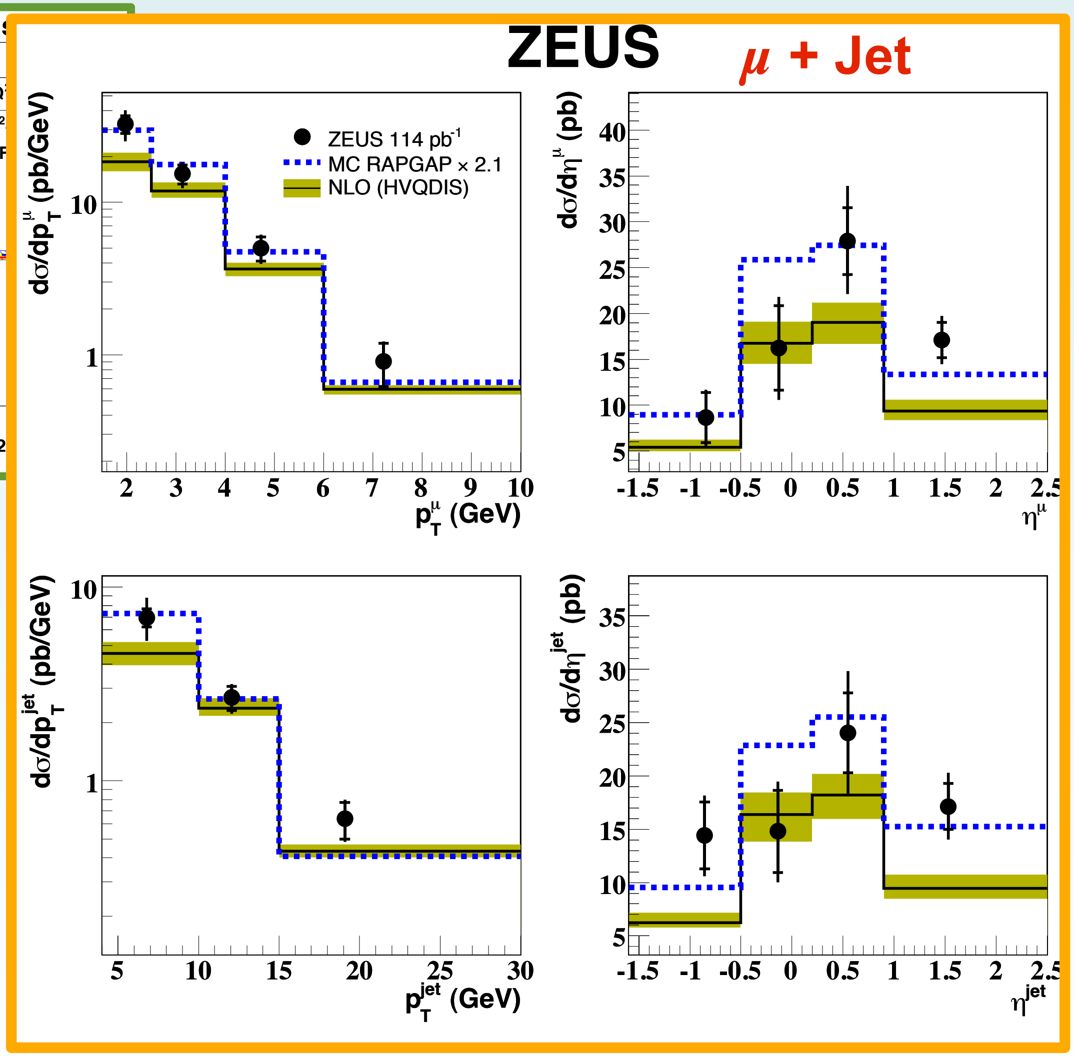

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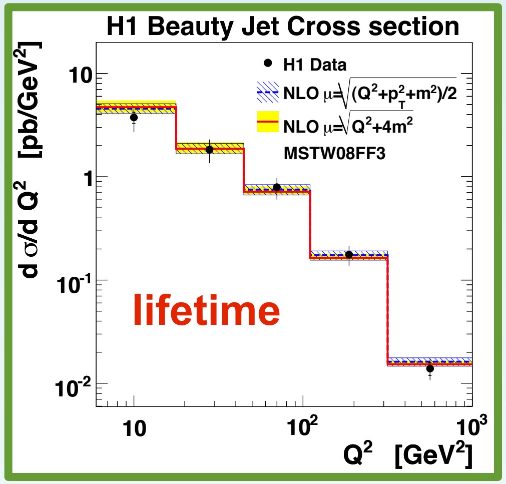

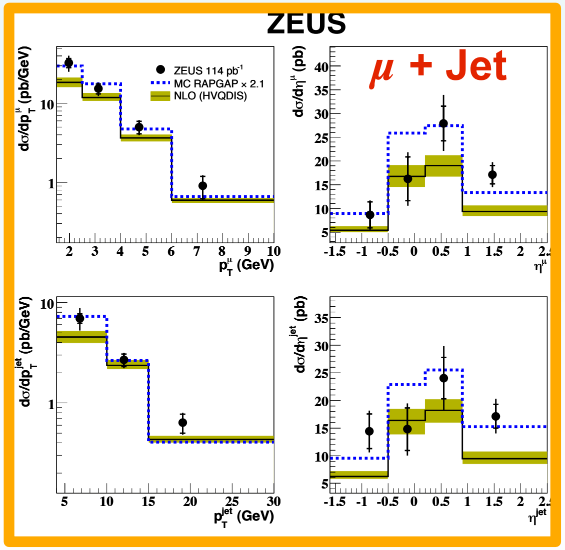

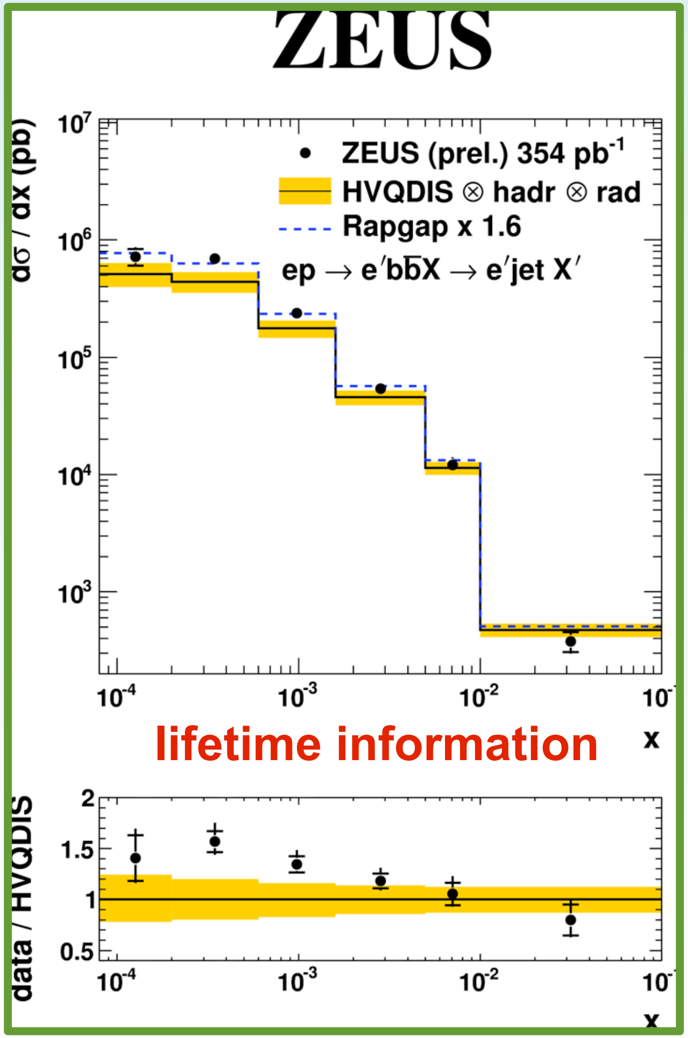

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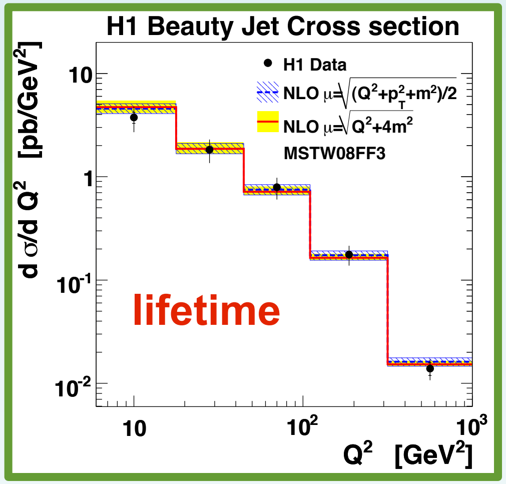
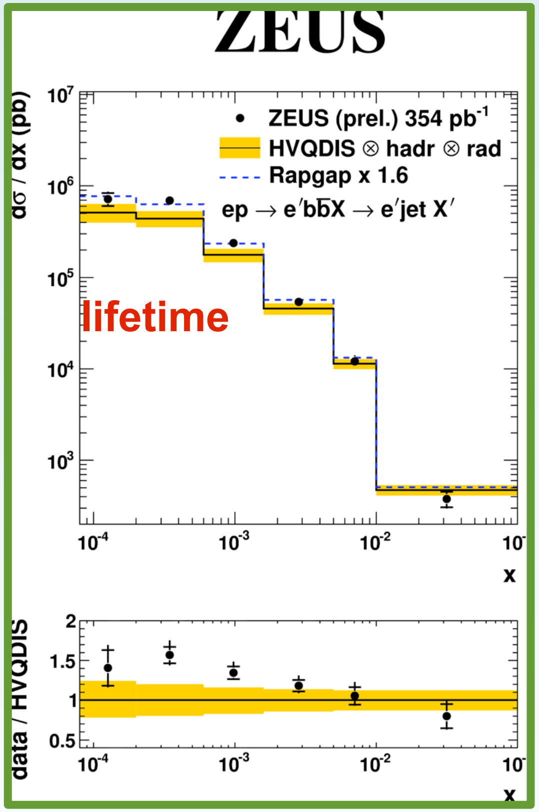
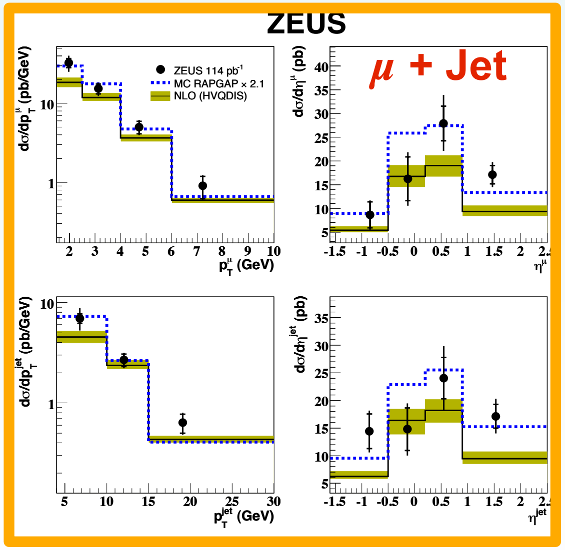


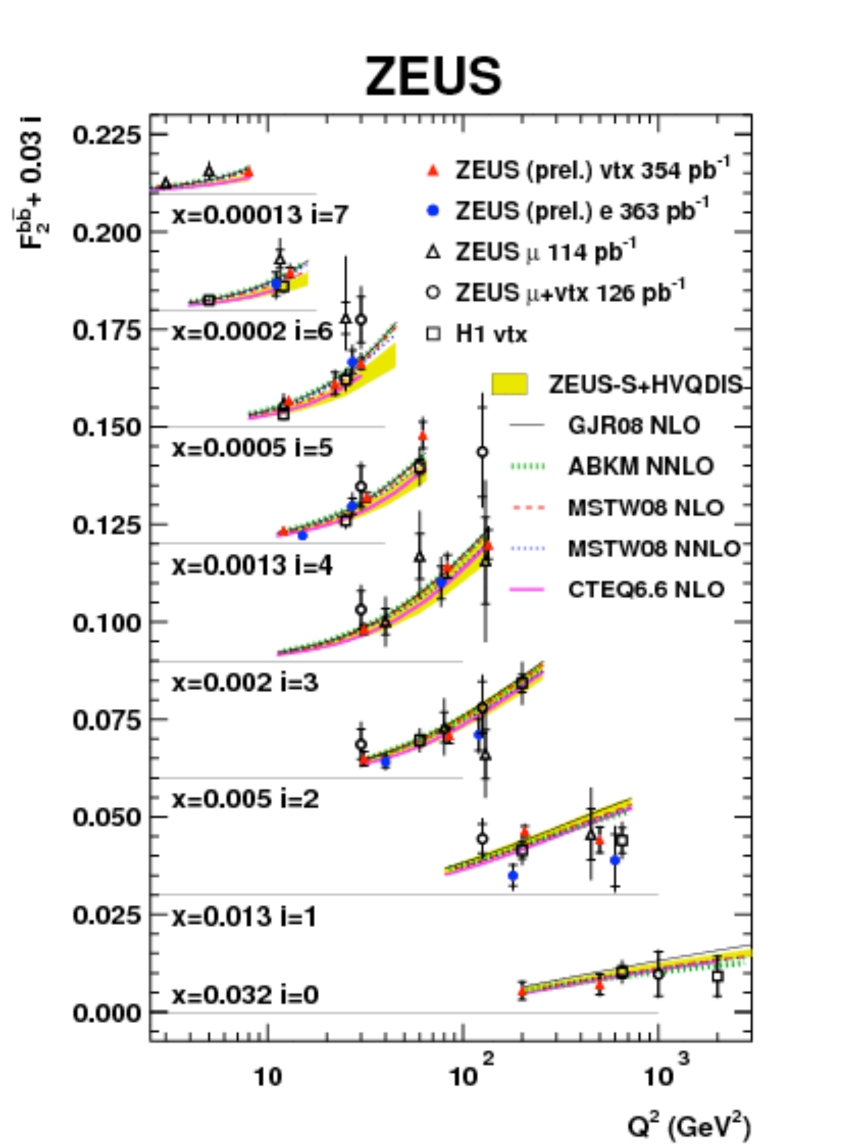




HERA measurements of beauty in DIS

described well by NLO QCD

Beauty Contribution to Proton Structure



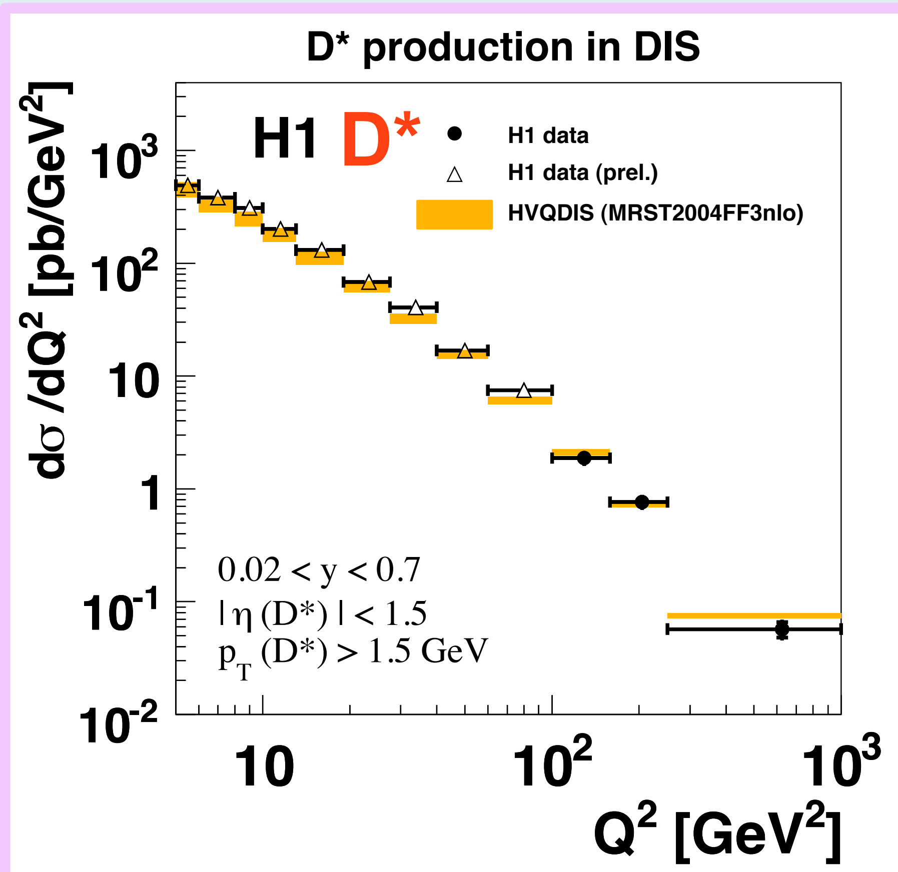
Beauty contribution F^b_2
to the proton structure function F_2:

- well described by NLO and NNLO using different HQ schemes

- large statistical uncertainties

Understanding of HQ Production Mechanism

Open charm production in DIS



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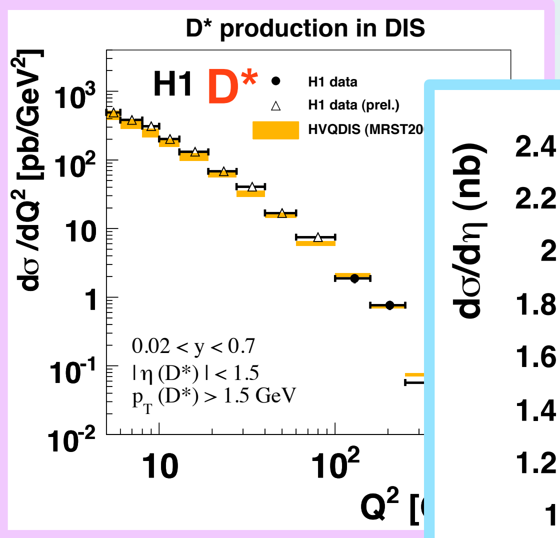

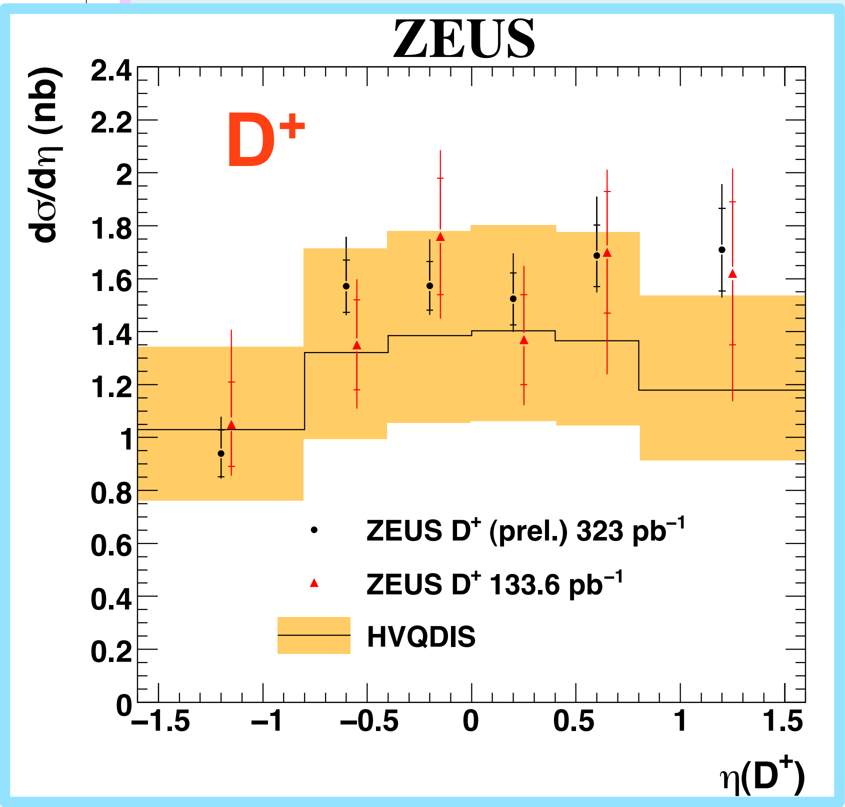

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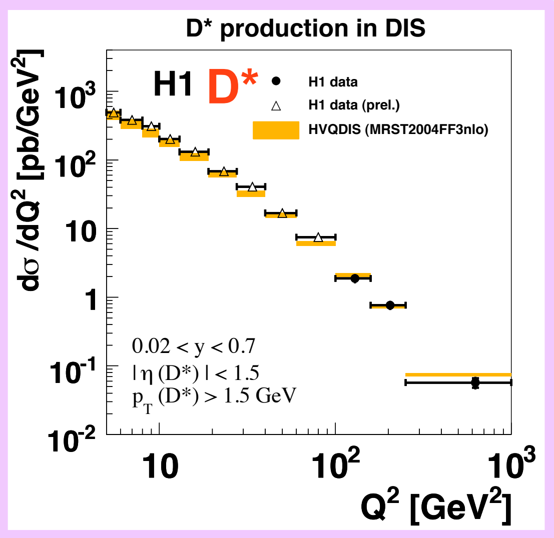
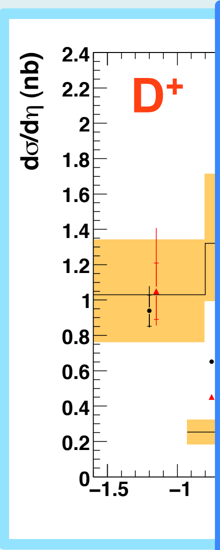
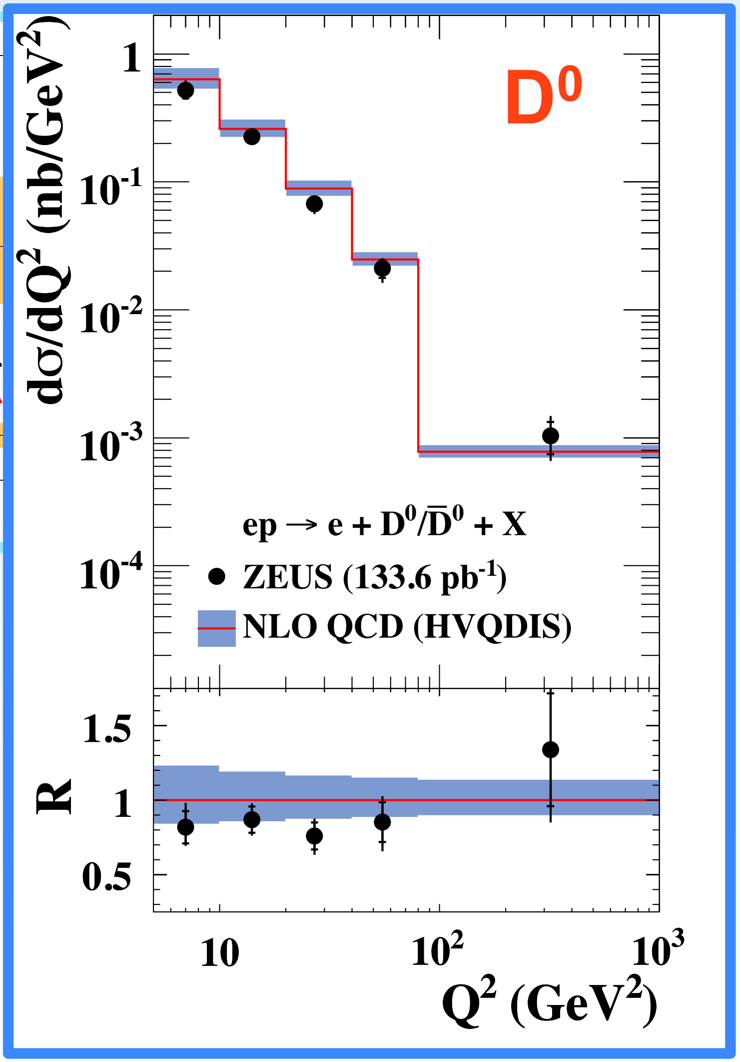
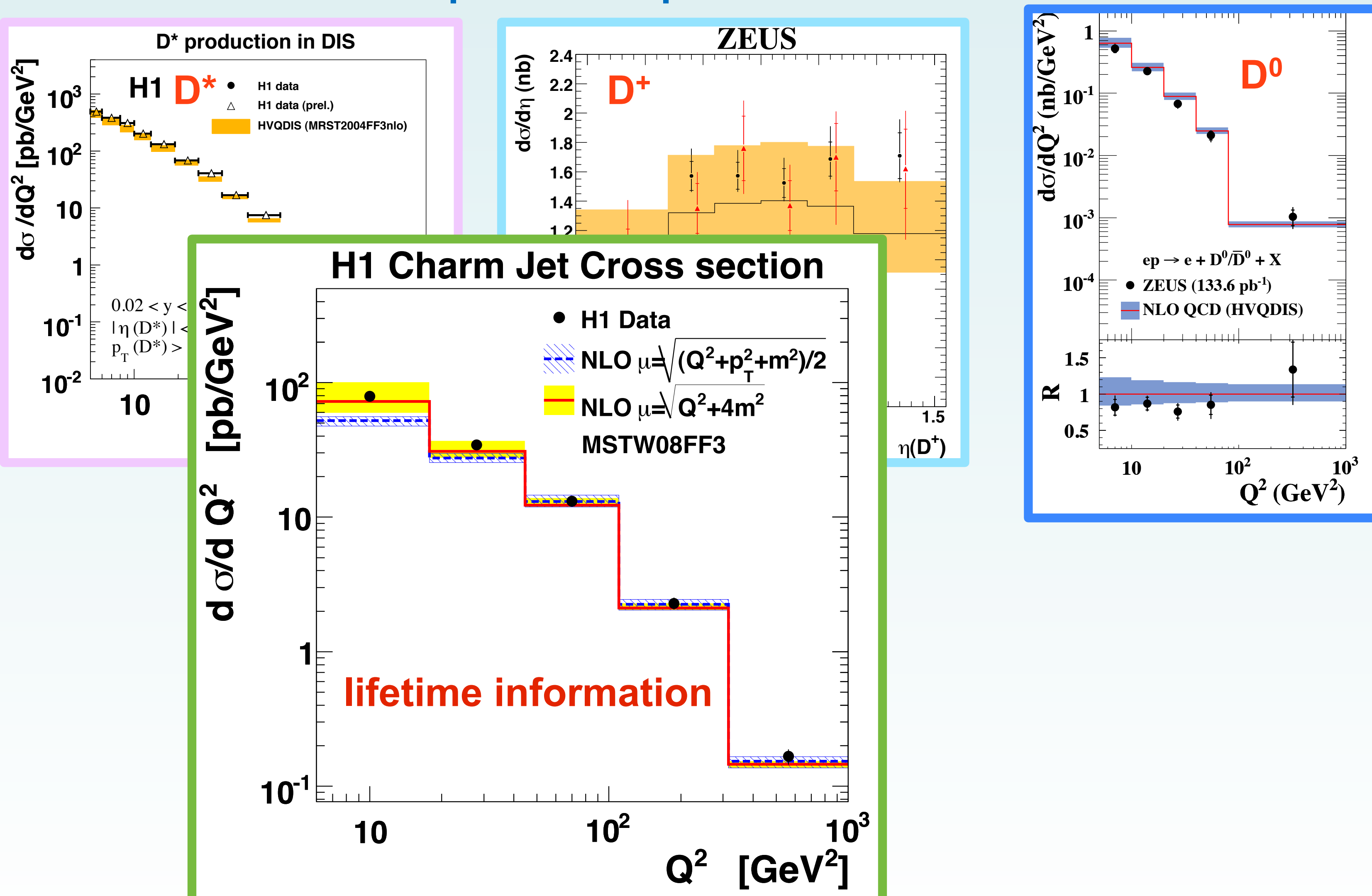






Understanding of HQ Production Mechanism

Open charm production in DIS



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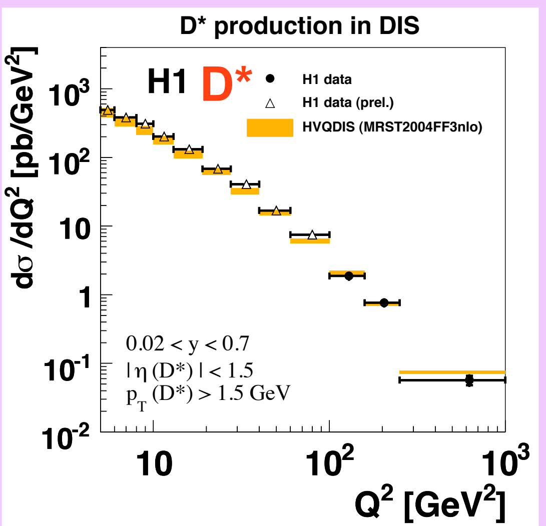
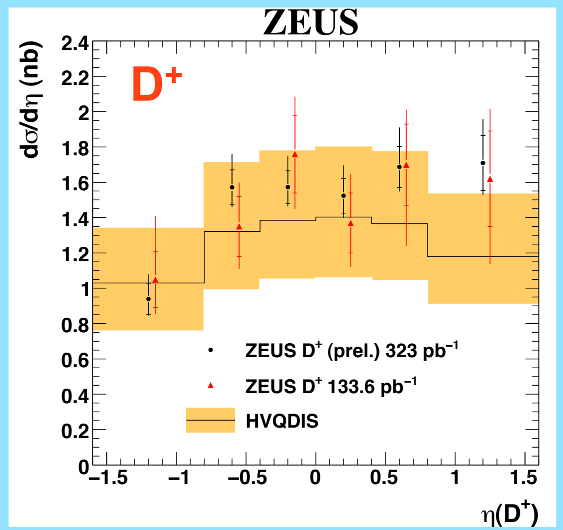
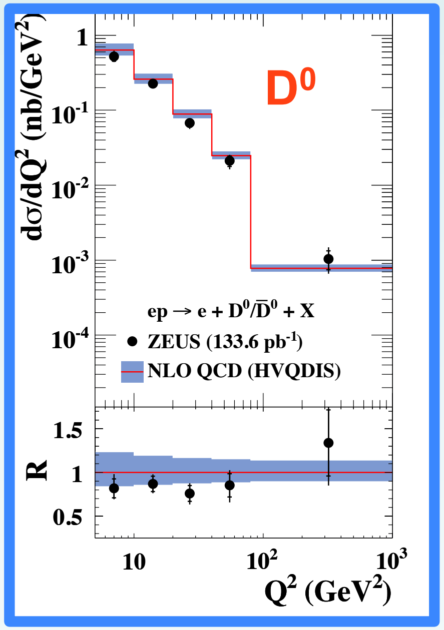
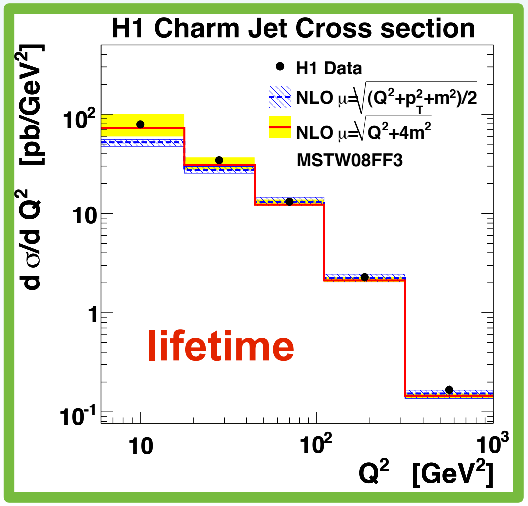
Open charm production in DIS







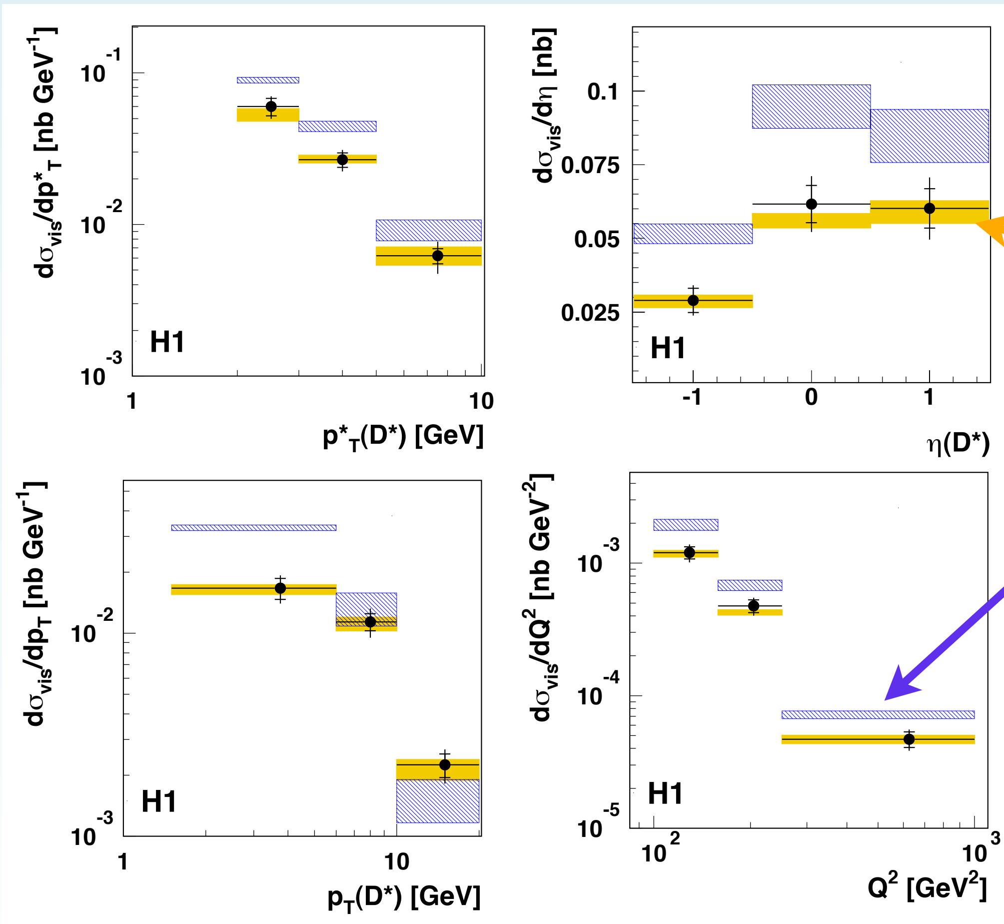


HERA measurements of charm in DIS

described well by NLO QCD

Massive or Massless Scheme?

100 GeV^2<Q^2<1000 GeV^2



Open charm at high Q^2

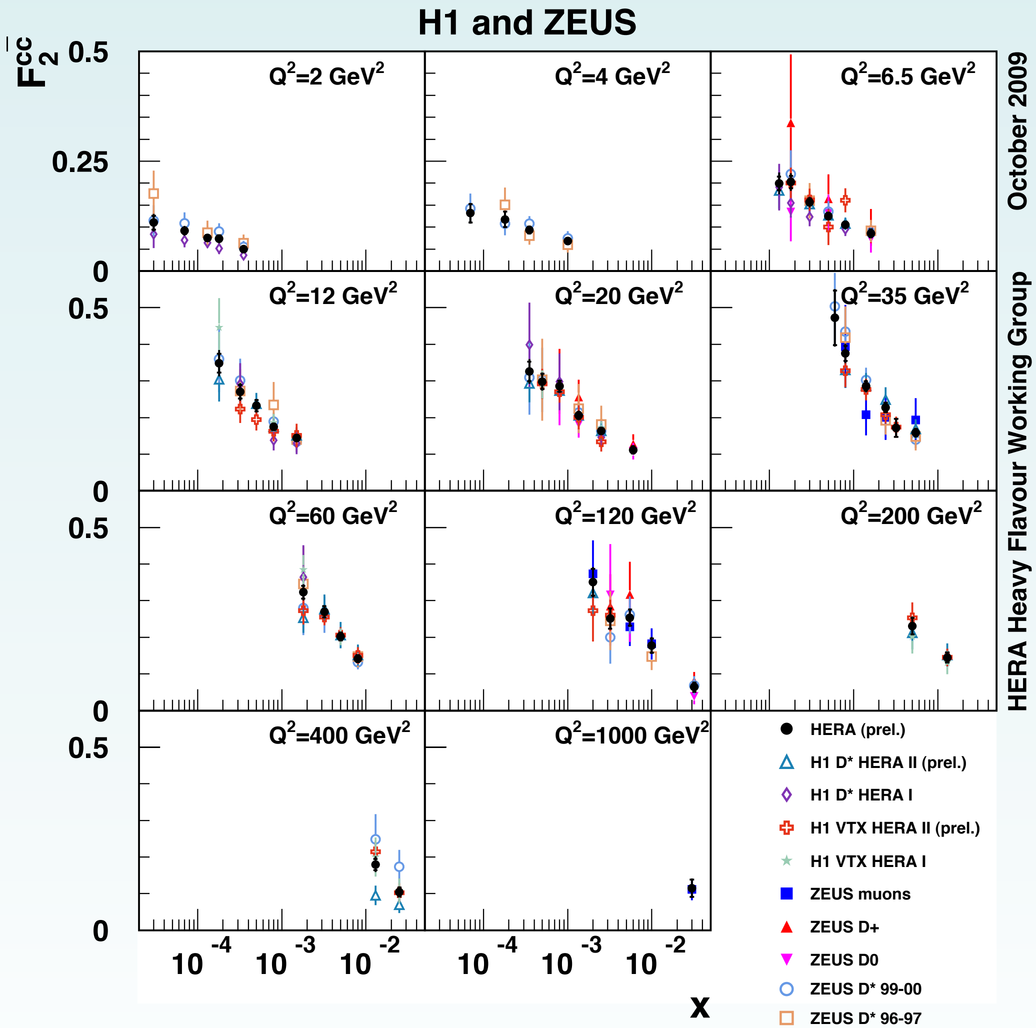
vs

FFNS NLO

ZMVFNS NLO

Charm at $Q^2 >> m_c^2$: FFNS describes data well, ZMVFNS does not

Charm Structure Function at HERA



HERA Charm Measurement:

H1 + ZEUS

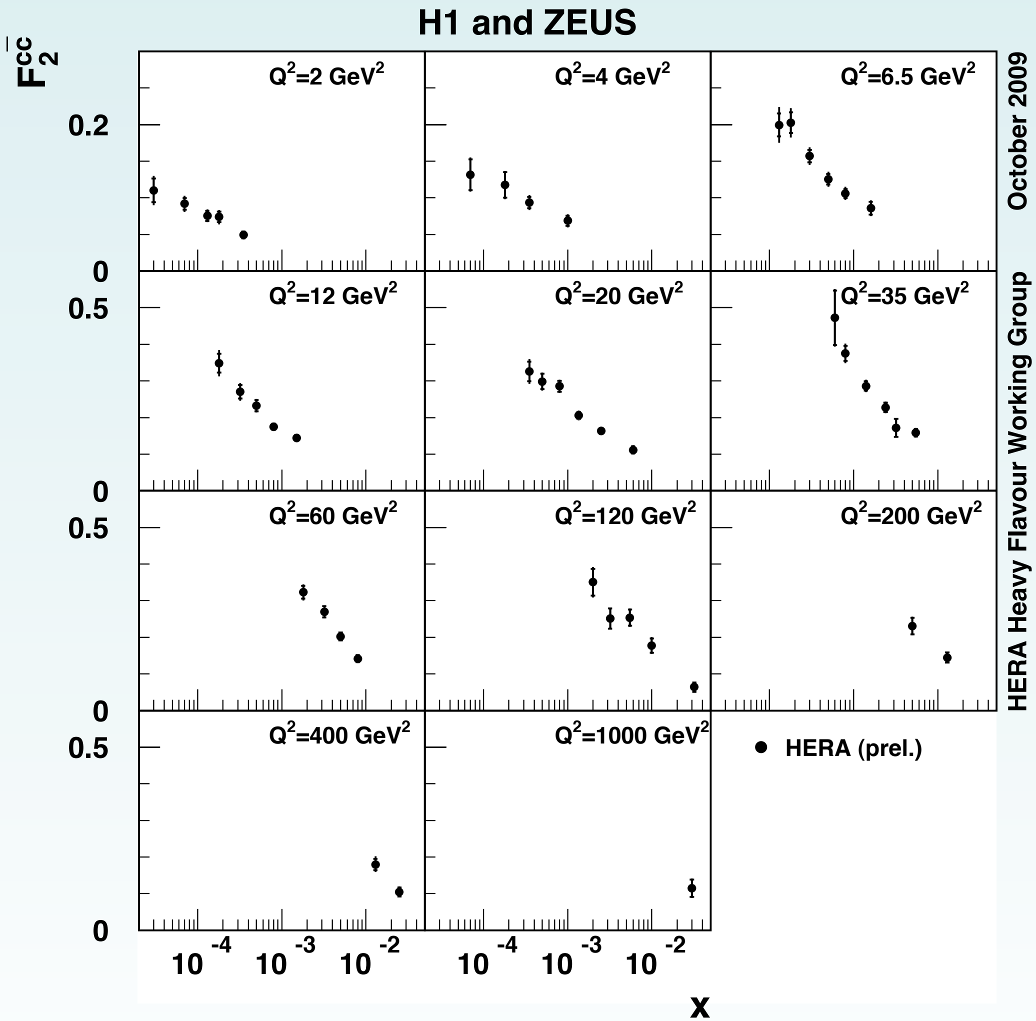
9 measurements

different charm tag methods

51 systematic error sources

correlations accounted for

Combined Charm Data of HERA



HERA Charm Measurement:

H1 + ZEUS

9 measurements

different charm tag methods

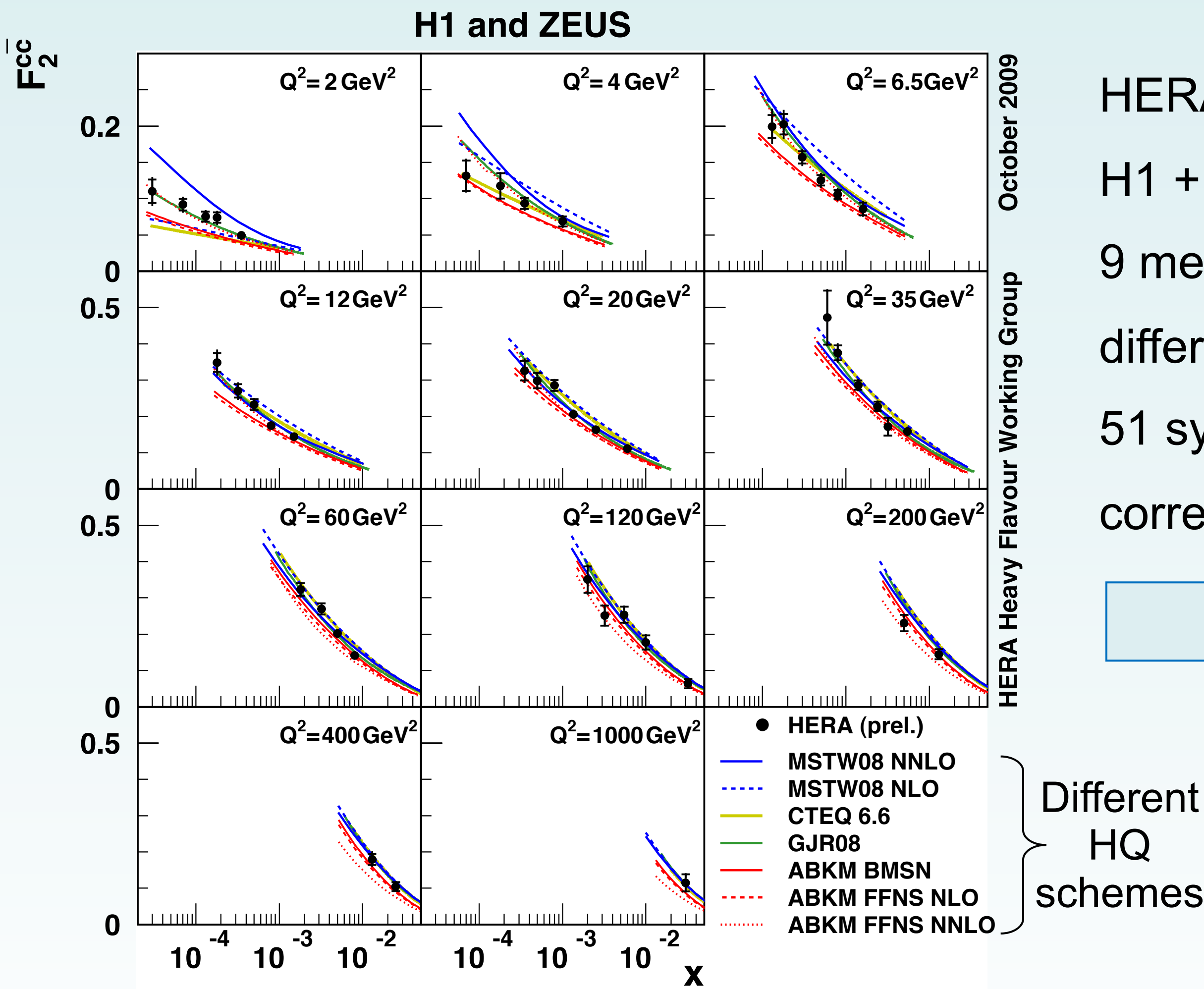
51 systematic error sources

correlations accounted for

Precision 5 - 10%

Very precise F_2^{cc} measurement

Charm at HERA: Test HQ Schemes in PDFs



HERA Charm Measurement:

H1 + ZEUS

9 measurements

different charm tag methods

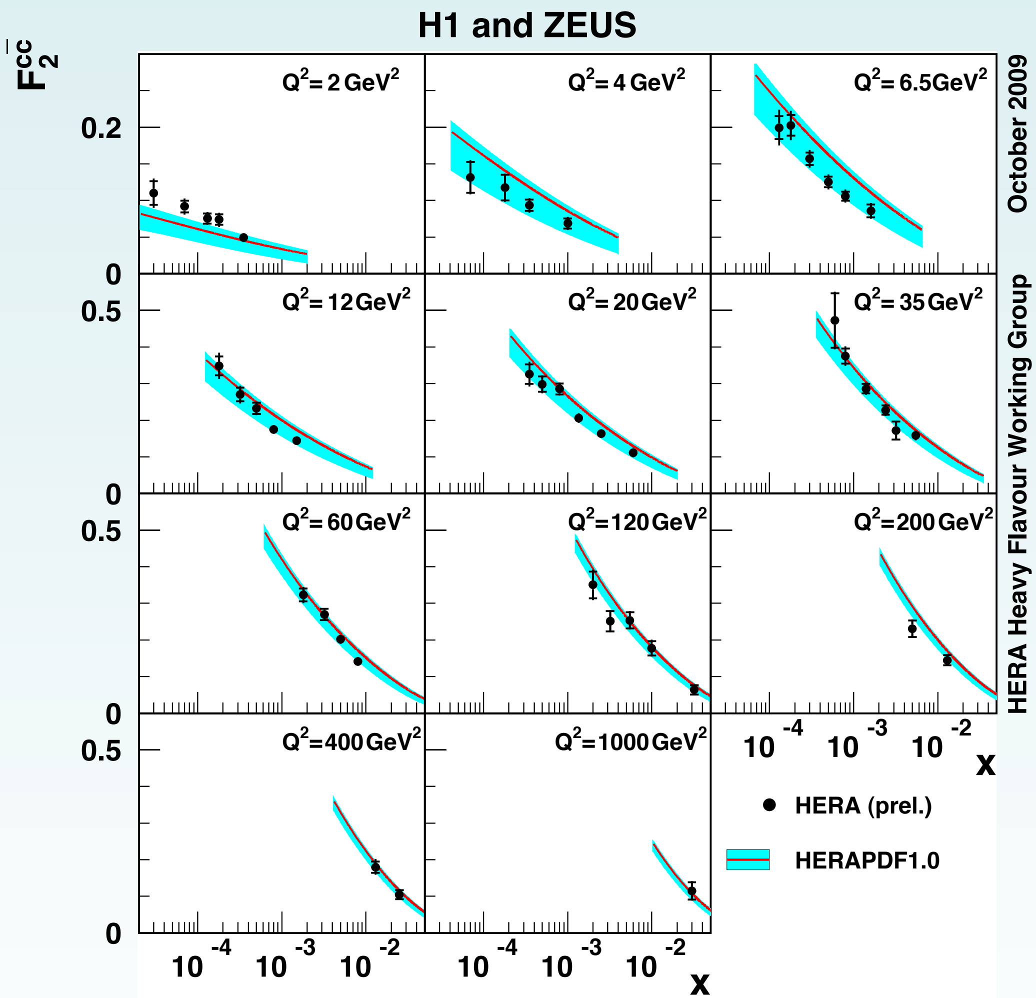
51 systematic error sources

correlations accounted for

Precision 5 - 10%

Data help understanding differences in HQ schemes

Charm at HERA: Test Choice of m_c in PDF



F^c_2 not included in HERAPDF1.0

but is well described

charm quark mass value varied

in the PDF Fit:

m_c=1.4 GeV

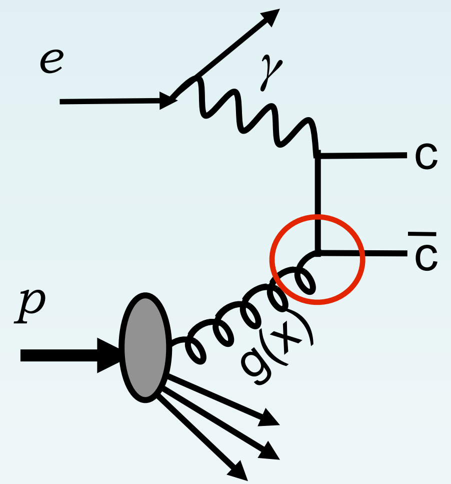
m_c=1.35 vs 1.65 GeV

PDG pole mass

PDFs obtained from inclusive data sensitive to the choice of m_c

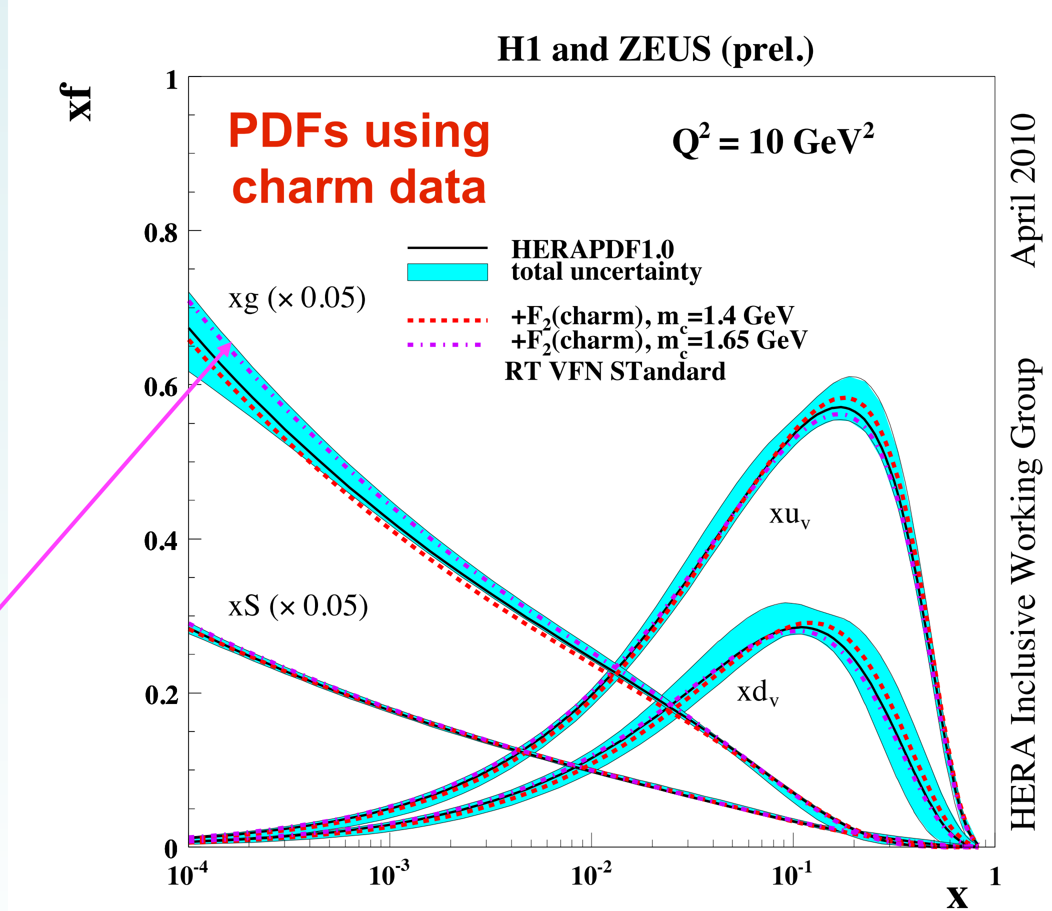
Charm Data in the PDF Fit

Charm production probes gluon directly. **Do charm data influence the gluon?**



Consider 2 values of m_c

m_c=1.65 GeV: **better fit**
steeper gluon distribution

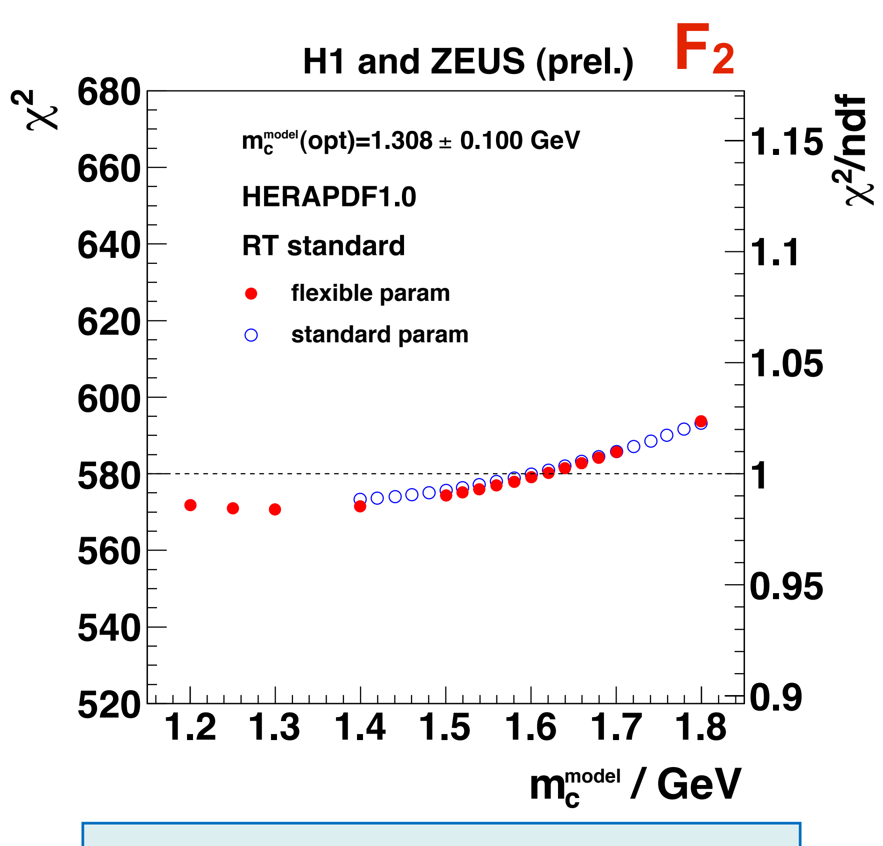


PDFs and PDF fit using charm data is sensitive to the value of m_c

Charm Mass as a Model Parameter in PDF

Study the sensitivity of the PDF fit to the value of m_c

PDF fit to inclusive DIS

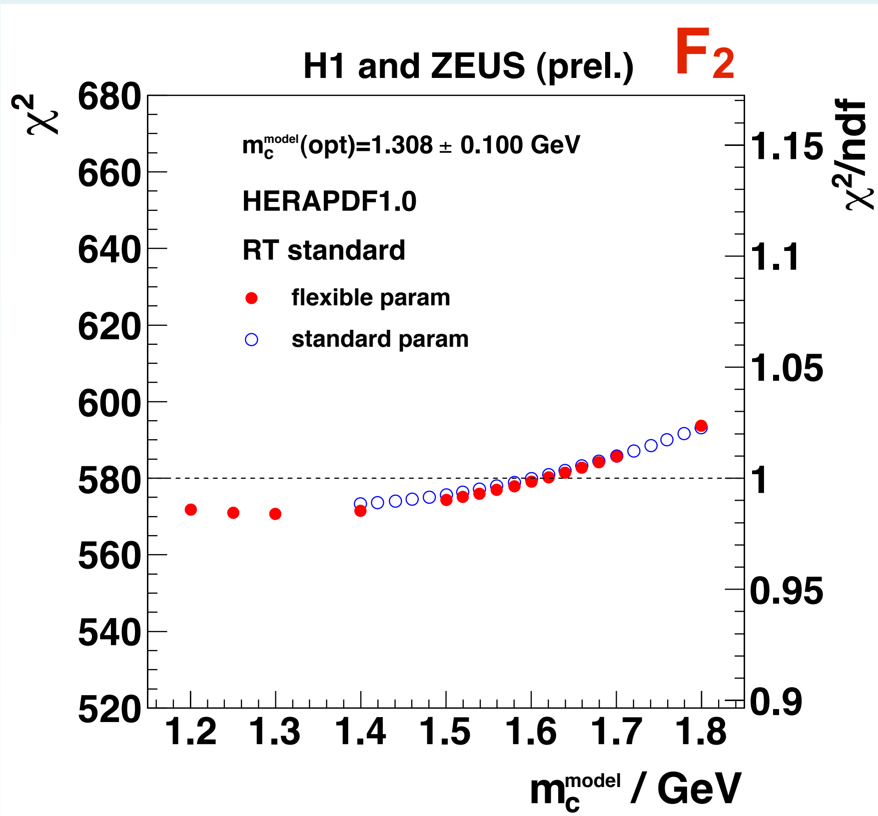


Weak dependence on m_c

Charm Mass as a Model Parameter in PDF

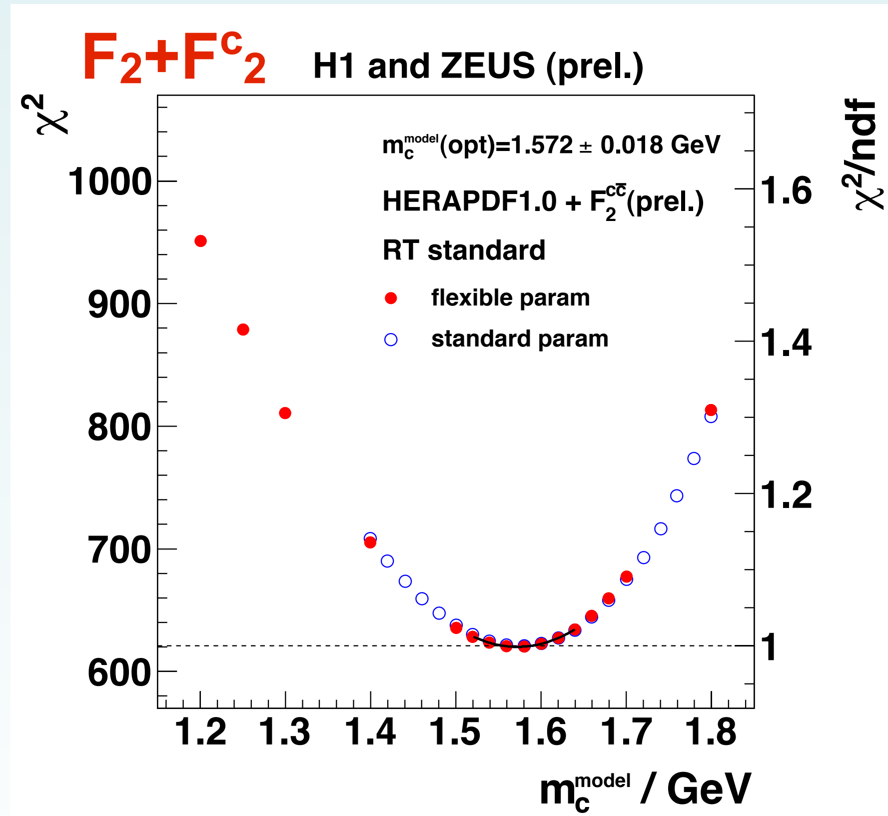
Study the sensitivity of the PDF fit to the value of m_c

PDF fit to inclusive DIS



Weak dependence on m_c

PDF fit to inclusive DIS **+ charm data**



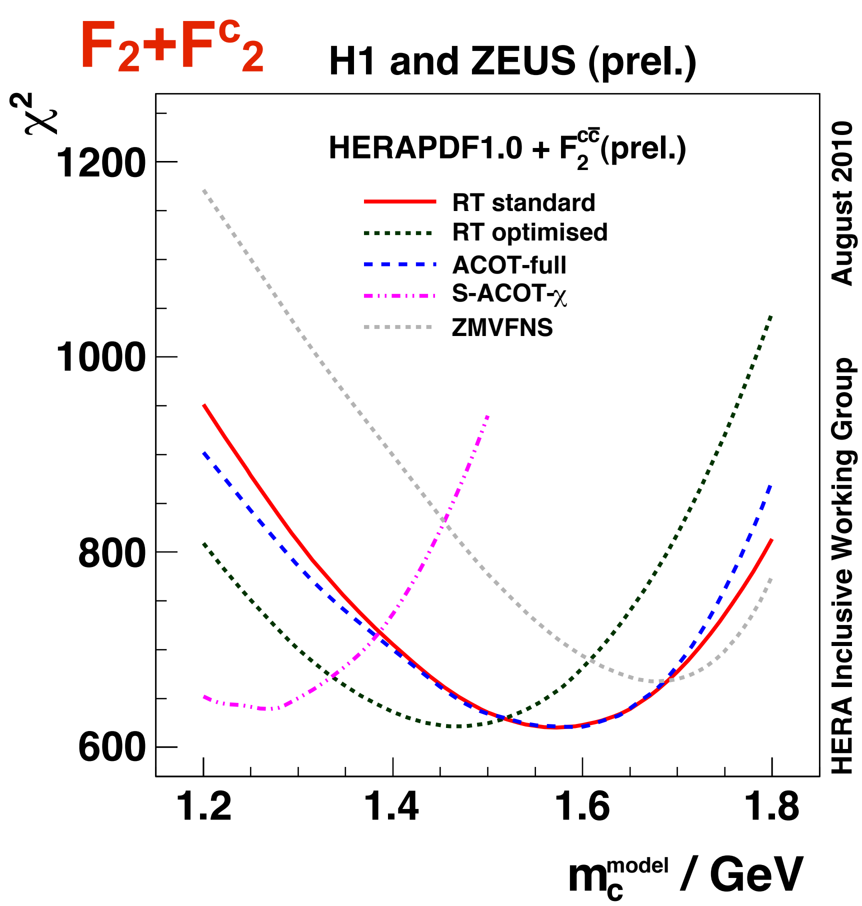
Strong dependence on m_c

Different HQ Schemes in PDFs

Value of m_c : how different for various HQ schemes in PDF Fits?

Test different HQ schemes

(used by different PDF groups)



Different HQ Schemes in PDFs

Value of m_c : how different for various HQ schemes in PDF Fits?

Test different HQ schemes

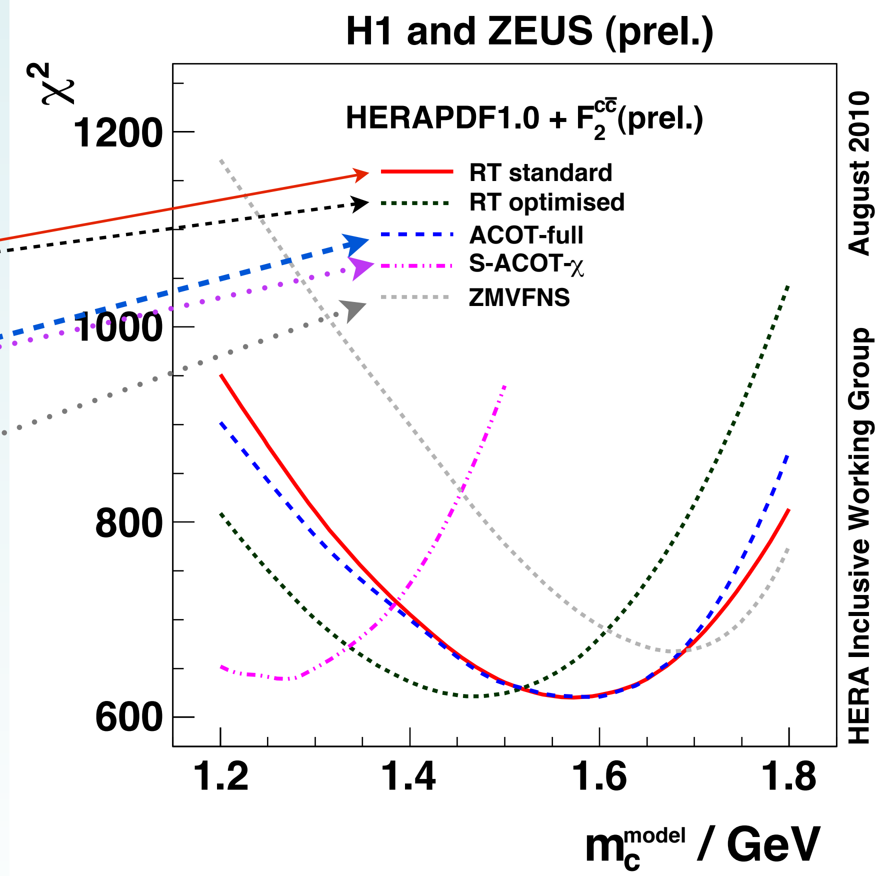
(used by different PDF groups)

RT : MSTW PDFs

ACOT: CTEQ PDFs

ZMVFNS: NNPDF

NB: ZMVFNS does not describe charm data even at $Q^2 >> m_c^2$



Different HQ Schemes in PDFs

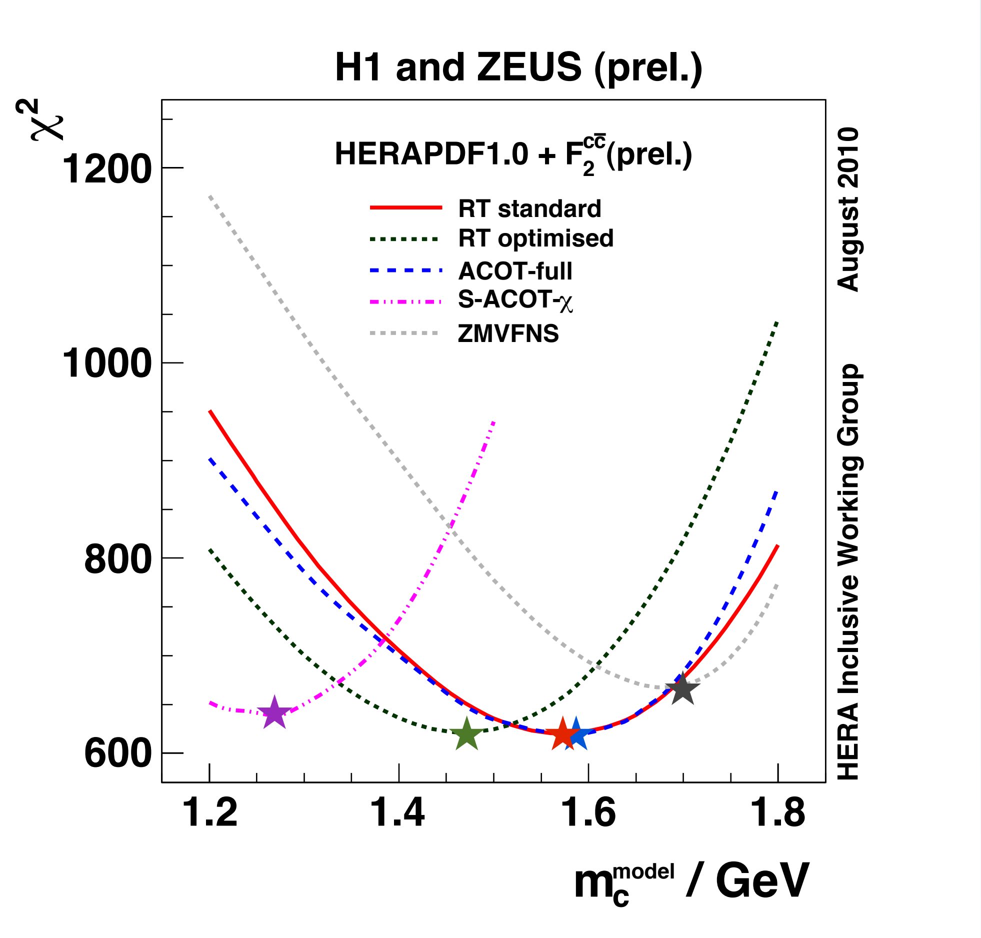
Value of m_c : how different for various HQ schemes in PDF Fits?

Test different HQ schemes

(used by different PDF groups)

Different HQ schemes prefer

different optimal★ m_c



Different HQ Schemes in PDFs

Value of m_c : how different for various HQ schemes in PDF Fits?

Test different HQ schemes

(used by different PDF groups)

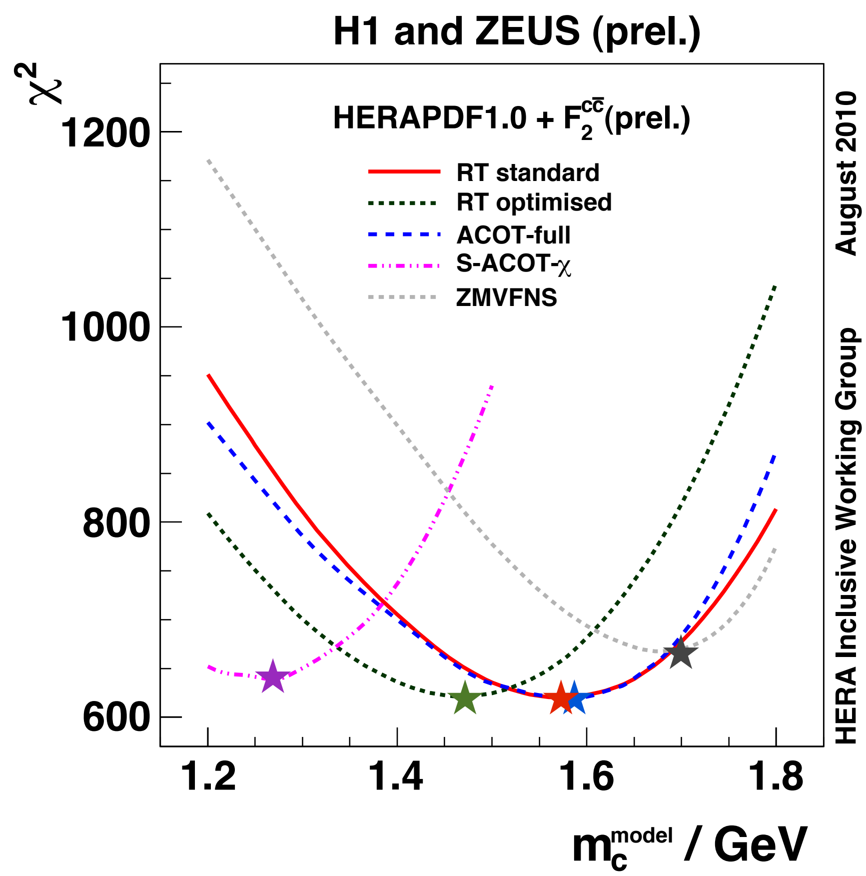
Different HQ schemes prefer

different optimal★ m_c

↓

parameter of a specific

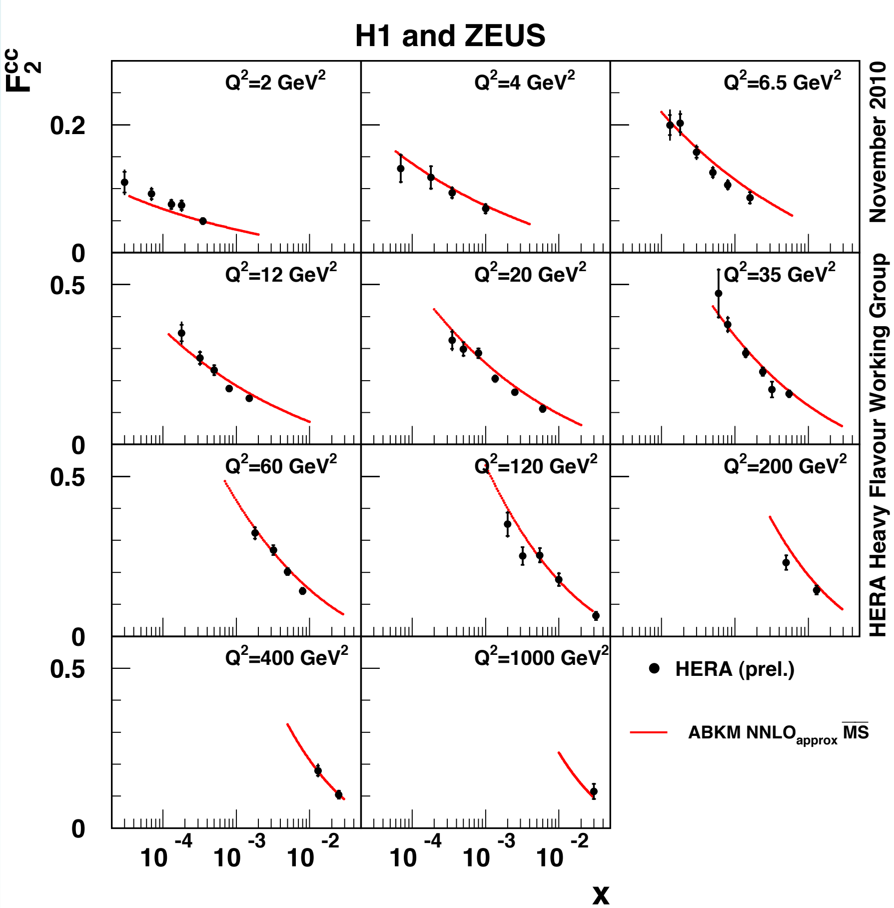
HQ scheme in PDF fits



What is the Meaning of m_c in PDF Fits?

Recent theory developments: (ABKM group, DESY, *arXiv:1011.5790*)

HQ coefficient functions provided in $\overline{\text{MS}}$ scheme using running m_{HQ}



Perturbative series converge better

Consistent treatment of HQ in PDF fits

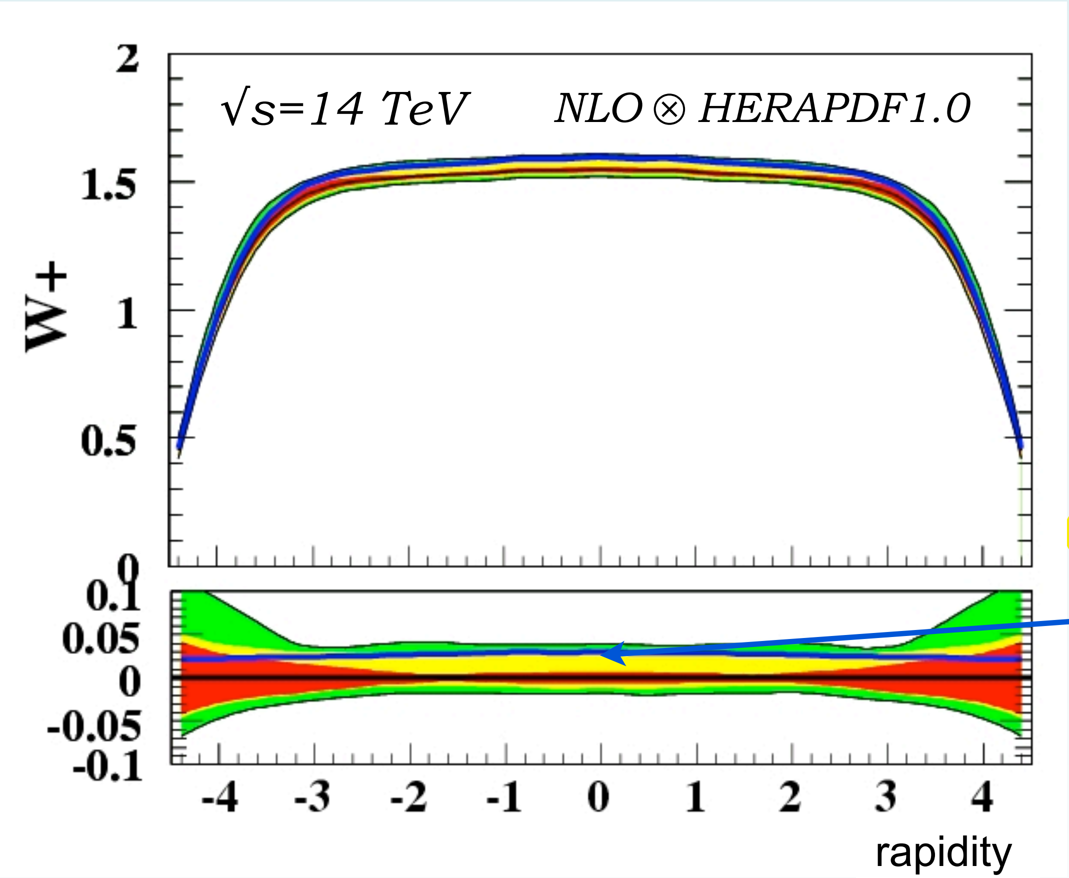
$m_c(m_c)$ determined using DIS data

What happens if HERA charm data are included?

Work in progress…

Heavy Quarks in PDFs and W/Z at LHC

Prediction of W± cross section @ LHC: dominant uncertainty due to PDF



Prediction using m_c=1.4 GeV

Error band: PDF uncertainty

Experimental error

Parametrization variation

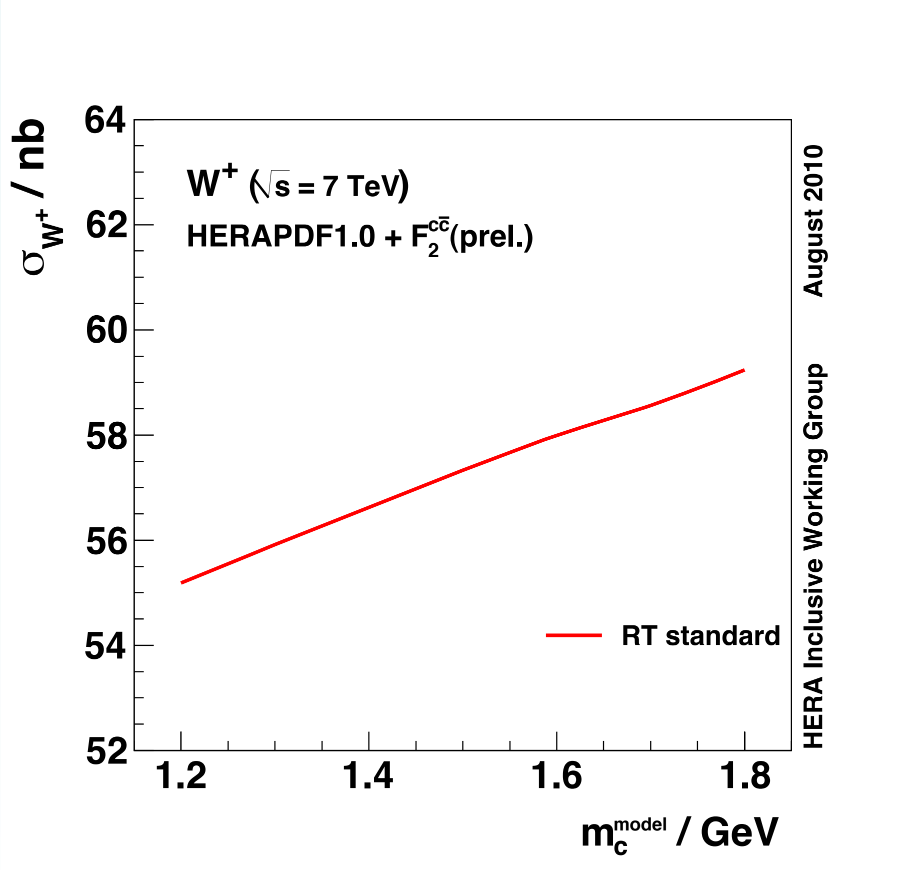
Model assumptions

including m_c variation

m_c variation in PDF: significant uncertainty on W@LHC in central region

Heavy Quarks in PDFs and W/Z at LHC

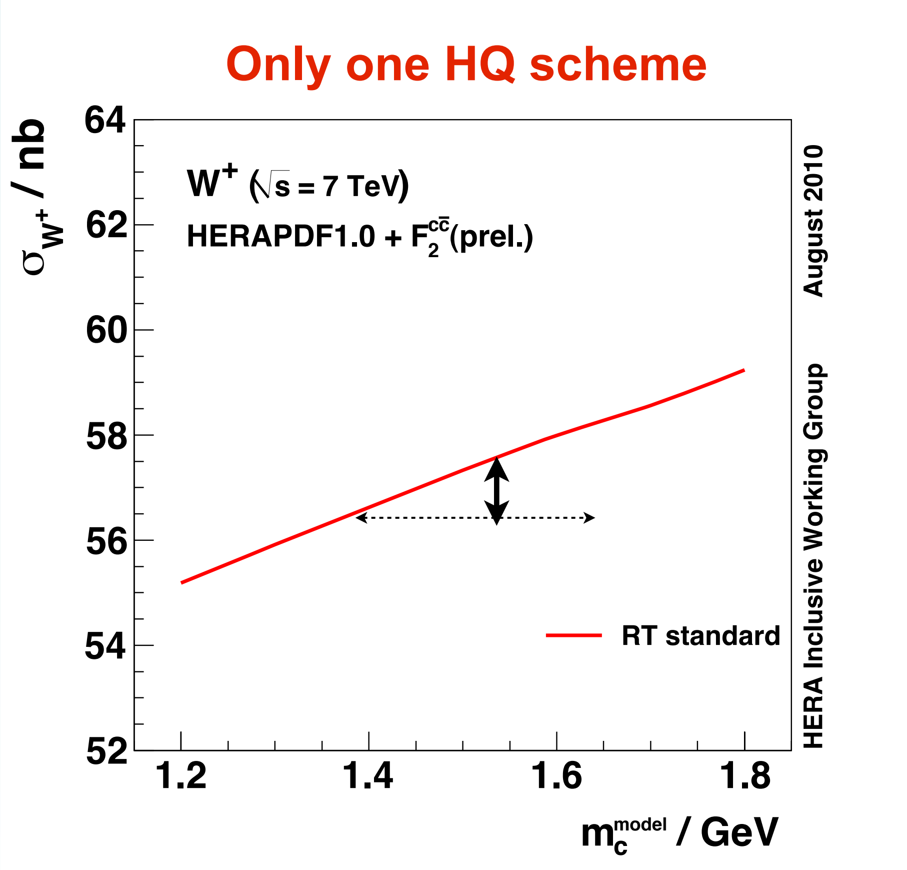
Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions



Larger $m_c \rightarrow$ more gluons, less charm $\rightarrow$ more light quarks $\rightarrow$ larger σ_W

Heavy Quarks in PDFs and W/Z at LHC

Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions



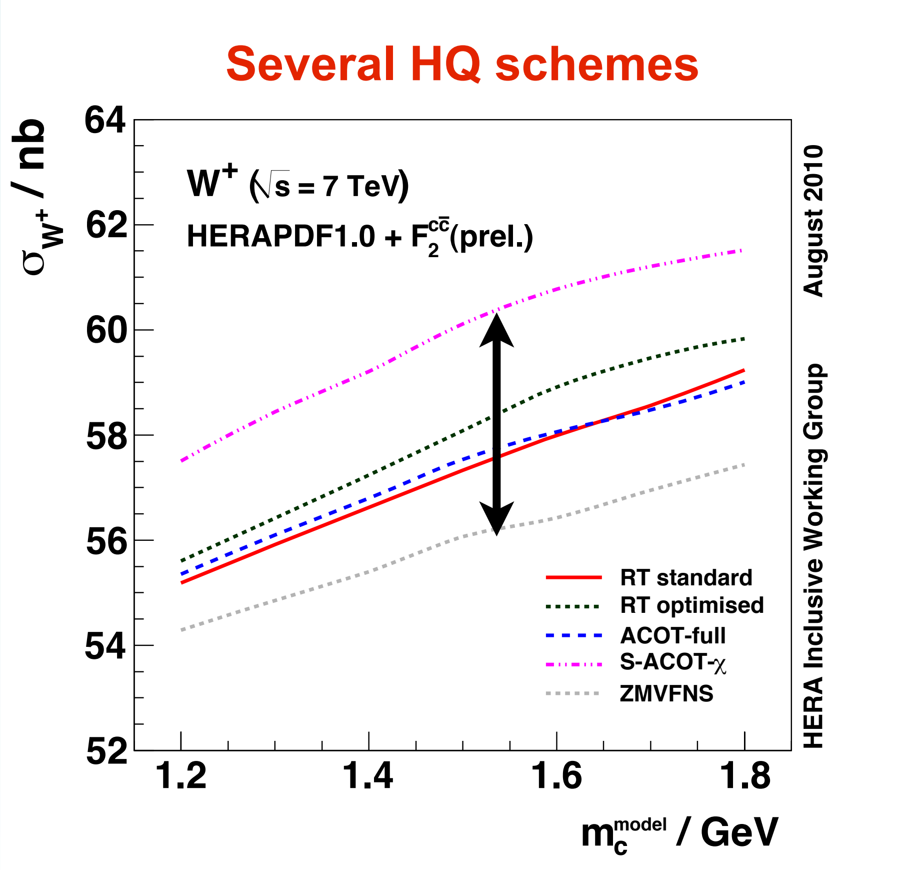
m_c variation in PDF

1.4 < m_c < 1.65 GeV

3% uncertainty on W prediction

Heavy Quarks in PDFs and W/Z at LHC

Vary the charm mass in the PDF. Use resulting PDFs for LHC predictions



m_c variation in PDF

$1.4 < m_c < 1.65$ GeV

3% uncertainty on W prediction

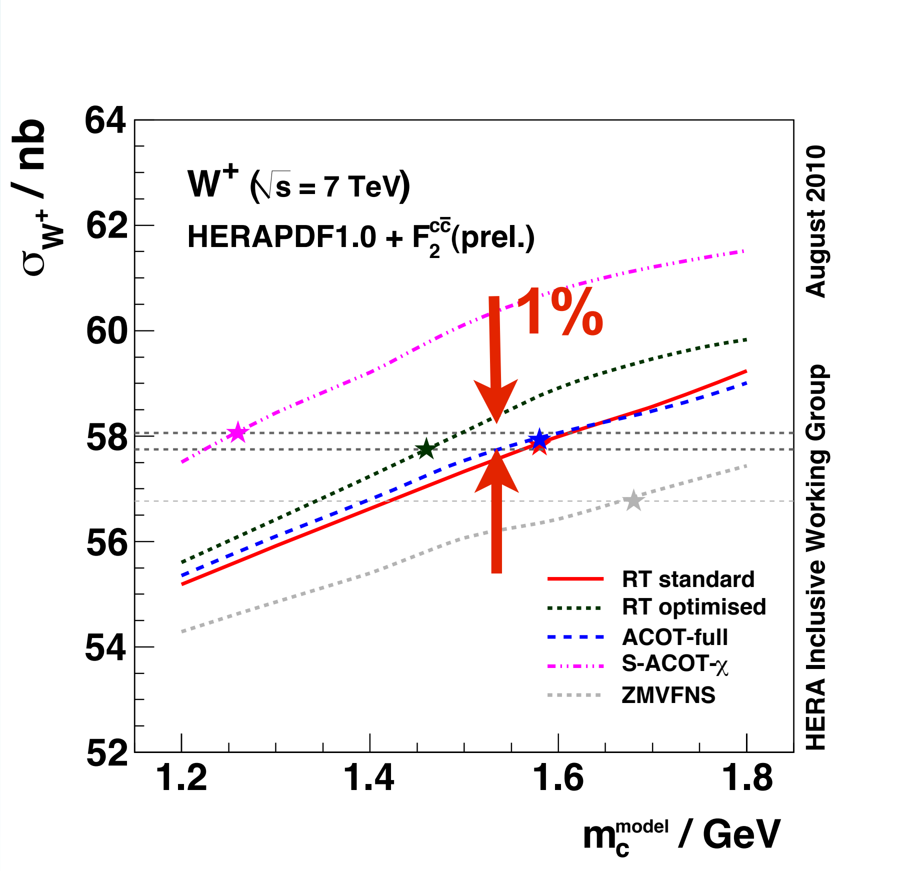
Using different HQ schemes:

+ 7% uncertainty

Large uncertainty on σ_W prediction due to HQ treatment in PDFs

Charm at HERA and W/Z at LHC

Use the optimal m_c for HQ schemes in PDFs fixed by HERA charm data

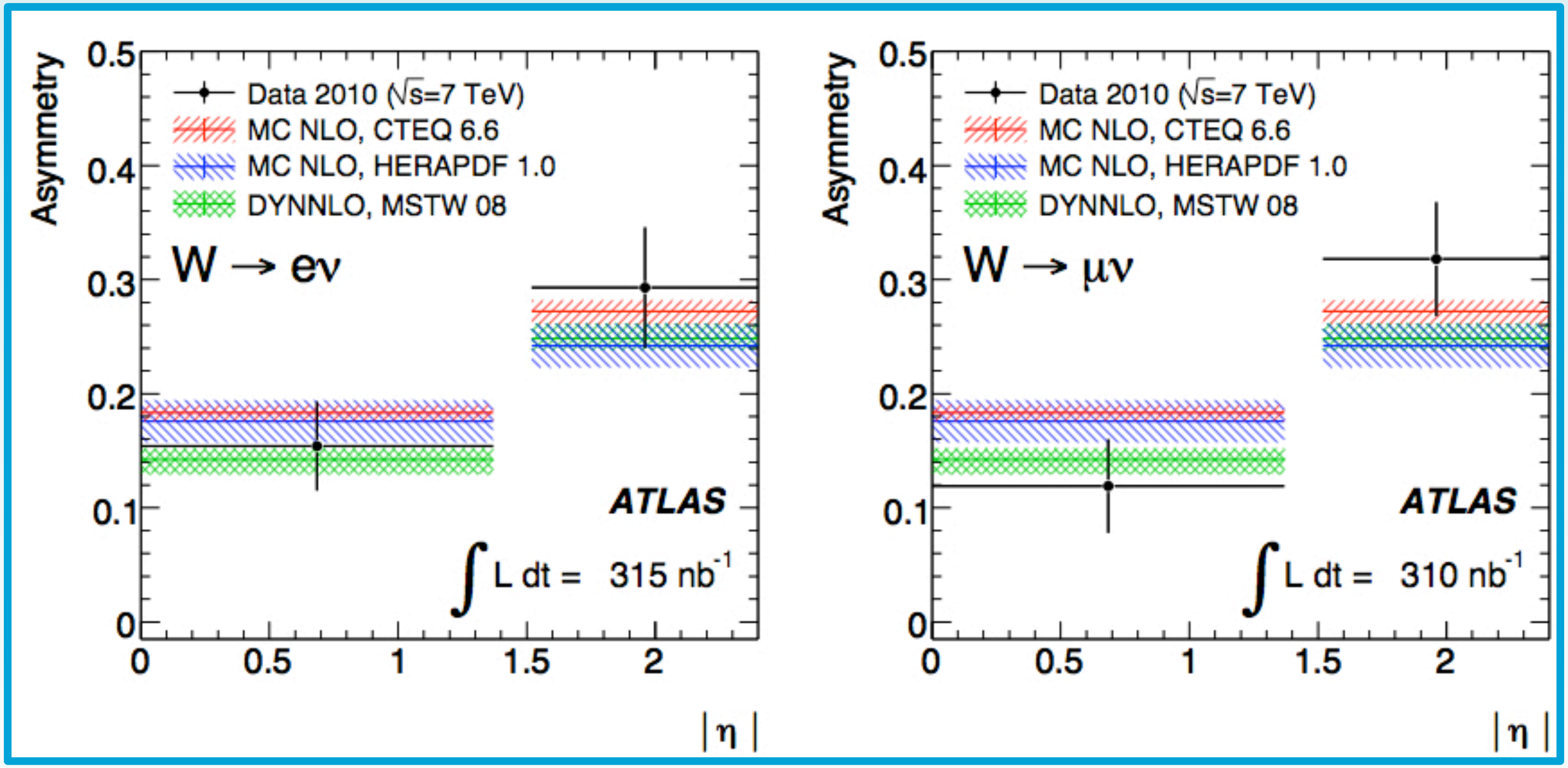


★ Optimal m_c using F_2+F_2^c

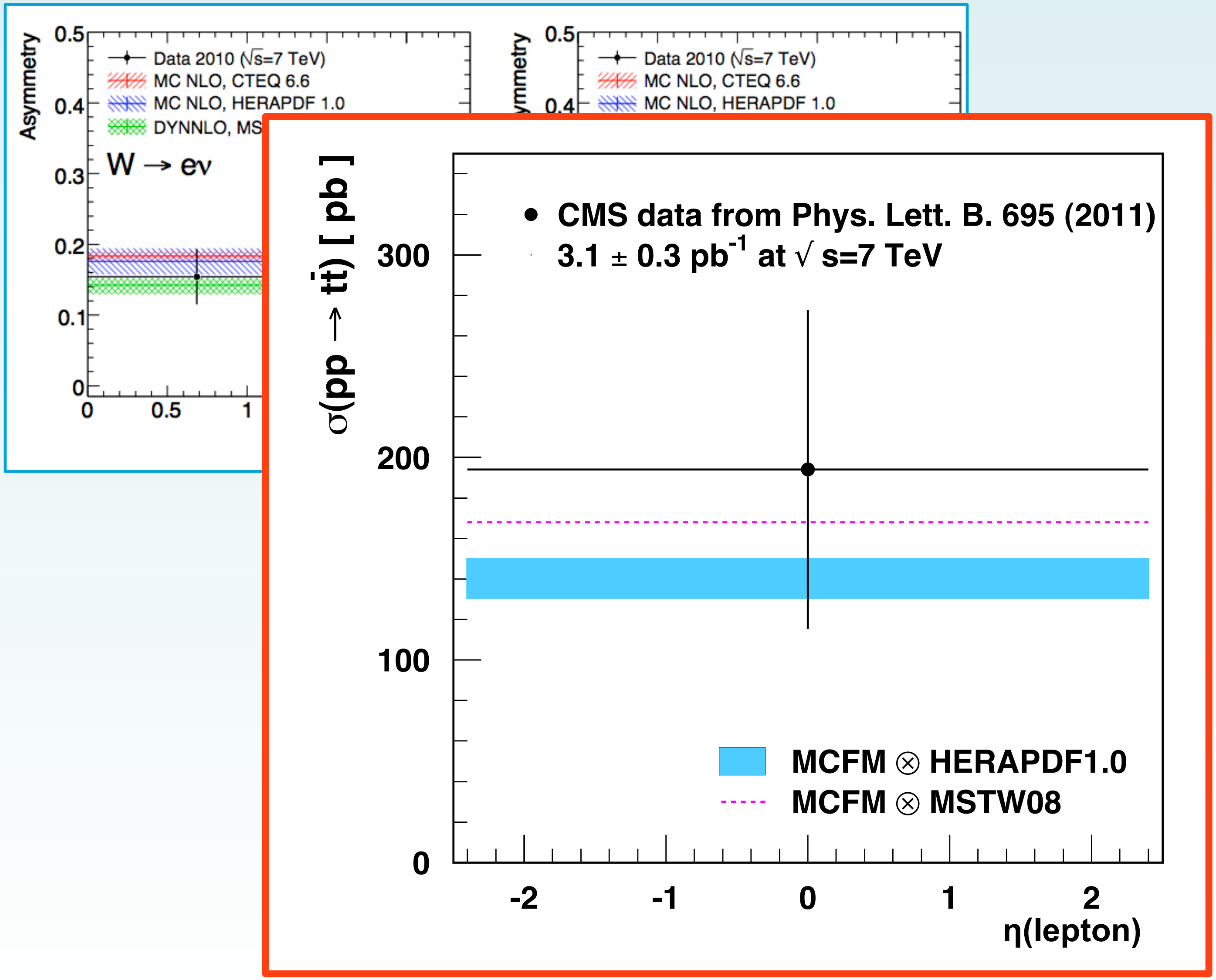
ZMVFNS not considered

Uncertainty on σ_W prediction due to HQ treatment in PDFs reduced to 1 %

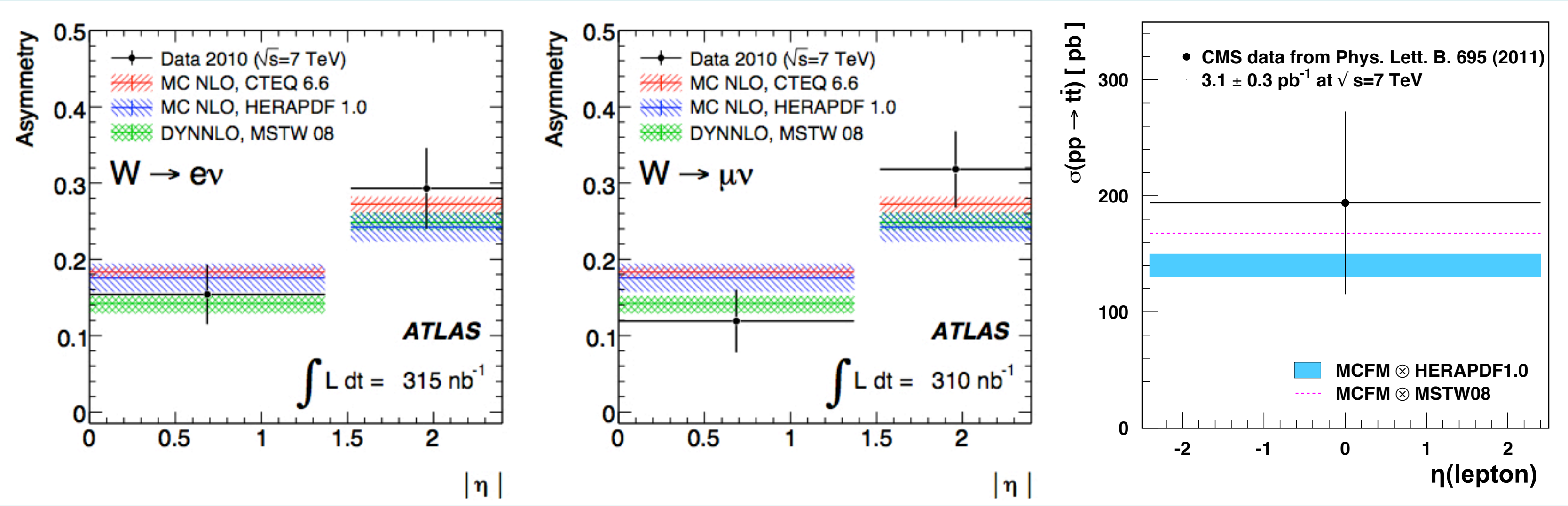
HERAPDF vs first LHC Data



HERAPDF vs first LHC Data



HERAPDF vs first LHC Data



So far the LHC data not very precise, but this will change very soon

⇒ best understanding of PDF is a must.

Summary

- Understanding of the LHC data demands precise PDFs

  HERA DIS data provide highest precision

- Heavy quarks: important, but quite some issue in QCD analyses

  HERA charm data provide severe constraints

  Example: PDF uncertainties on predictions for W and Z at the LHC

PDFs from HERA to the LHC is a success

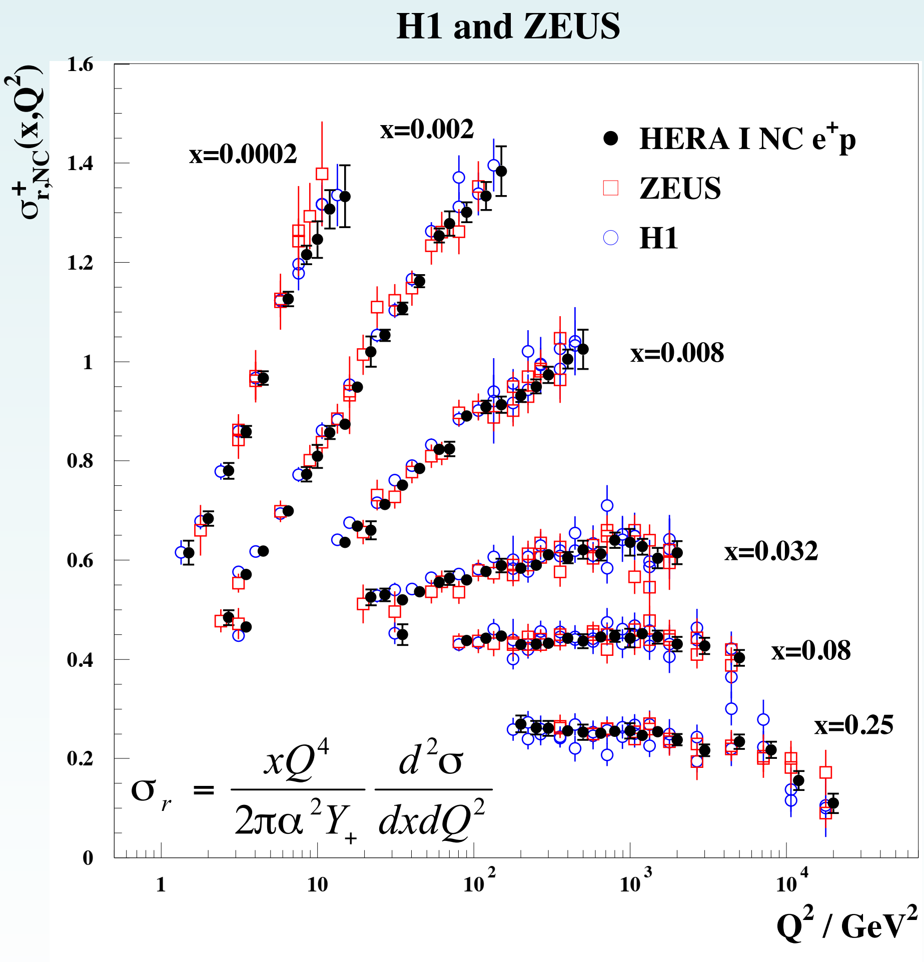
Common effort of experiments and theory needed

Back up

Ultimate precision DIS: combined HERA Data

Published in JHEP 01 (2010) 109 : complete HERA I data, $\mathcal{L}$~115 pb^{-1}

e.g. NC cross section vs Q^2: 6 bins in x



H1 and ZEUS data averaged:

- global fit of 1402 measurements
- 110 sources of systematic errors
- account for systematic correlations (cross-calibration of experiments)
- total uncertainty: *1-2%* for $Q^2 < 500$ GeV^2
- covered kinematics:

$$10^{-7} < x < 0.65,$$

$$0.05 < Q^2 < 30000 \text{ GeV}^2$$

Combination Procedure

Minimized value:

$$\chi^2(\vec{m},\vec{b}) = \sum_i \frac{\left(m^i - \sum_j \gamma^i_j m^i b_j - \mu^i\right)^2}{(\delta_{i,stat}\mu^i)^2 + (\delta_{i,unc} m^i)^2} + \sum_j b_j^2$$

μ^i measured value at point i

δ_i statistical, uncorrelated systematic error

γ^j_j – correlated systematic error

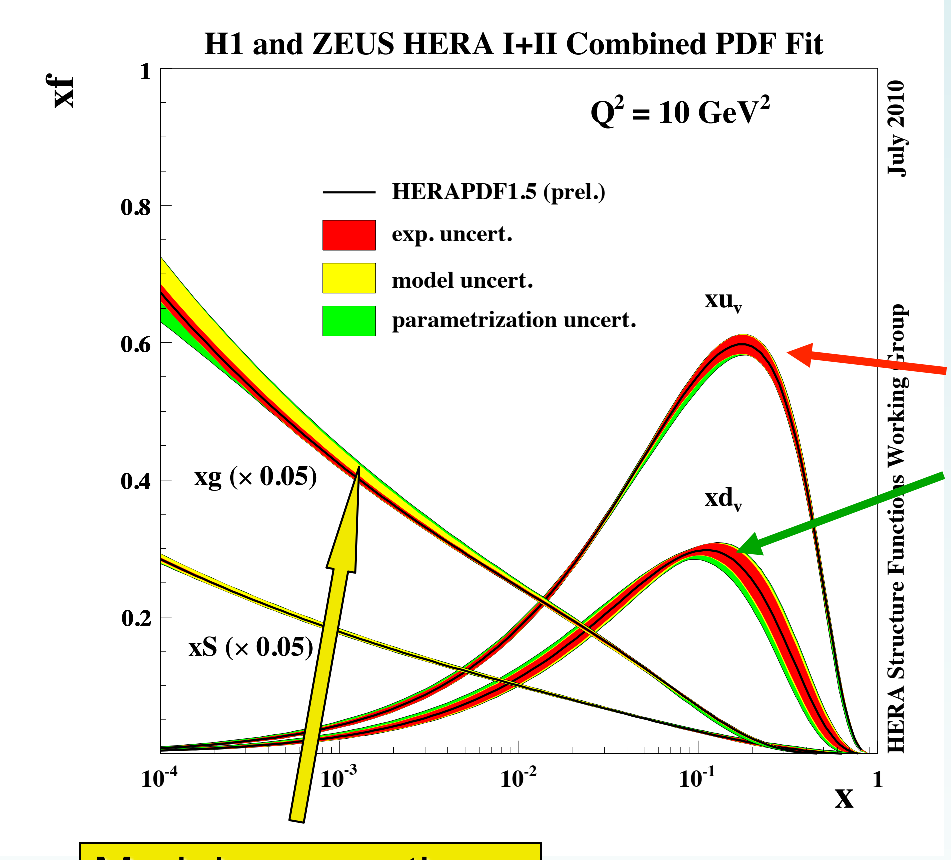
b_j – shift of correlated systematic error sources

m^i – true value (corresponds to min χ^2)

Measurements performed sometimes in slightly different range of (x,Q^2)

swimming to the common (x,Q^2) grid via NLO QCD in massive scheme

HERA Parton Density Functions



10 parameter fit, NLO DGLAP

Heavy quarks: massive

Variable Flavour Number Scheme

Scales: $\mu_r = \mu_f = Q^2$

Experimentally very precise

Parameterization at starting scale:

$$xg(x) = A_g x^{B_g} (1-x)^{C_g}$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}} (1-x)^{C_{u_v}} (1 + E_{u_v} x^2)$$

$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}$$

$$x\overline{U}(x) = A_{\overline{U}} x^{B_{\overline{U}}} (1-x)^{C_{\overline{U}}}$$

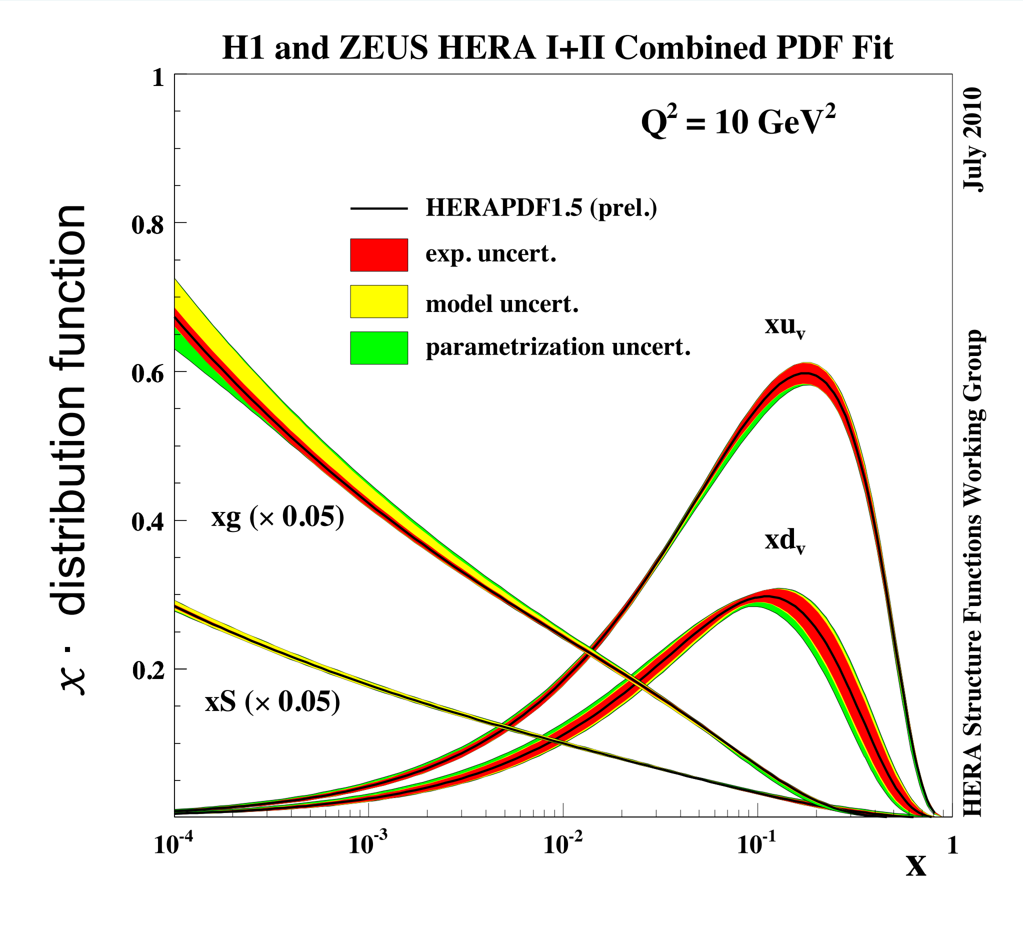
$$x\overline{D}(x) = A_{\overline{D}} x^{B_{\overline{D}}} (1-x)^{C_{\overline{D}}}$$

Model assumptions:

$Q_0^2 = 1.9\ GeV^2$, $\alpha_s(M_Z) = 0.1176$

$m_c = 1.4\ GeV$; $m_b = 4.75\ GeV$; $f_s(Q_0^2) = 0.31$

Modern Understanding of the Proton



HERA PDF:

use consistent data set: H1+ZEUS

proper treatment of error correlations

Global PDF Fit Groups:

(ABKM,CTEQ,GJR,MSTW,NNPDF)

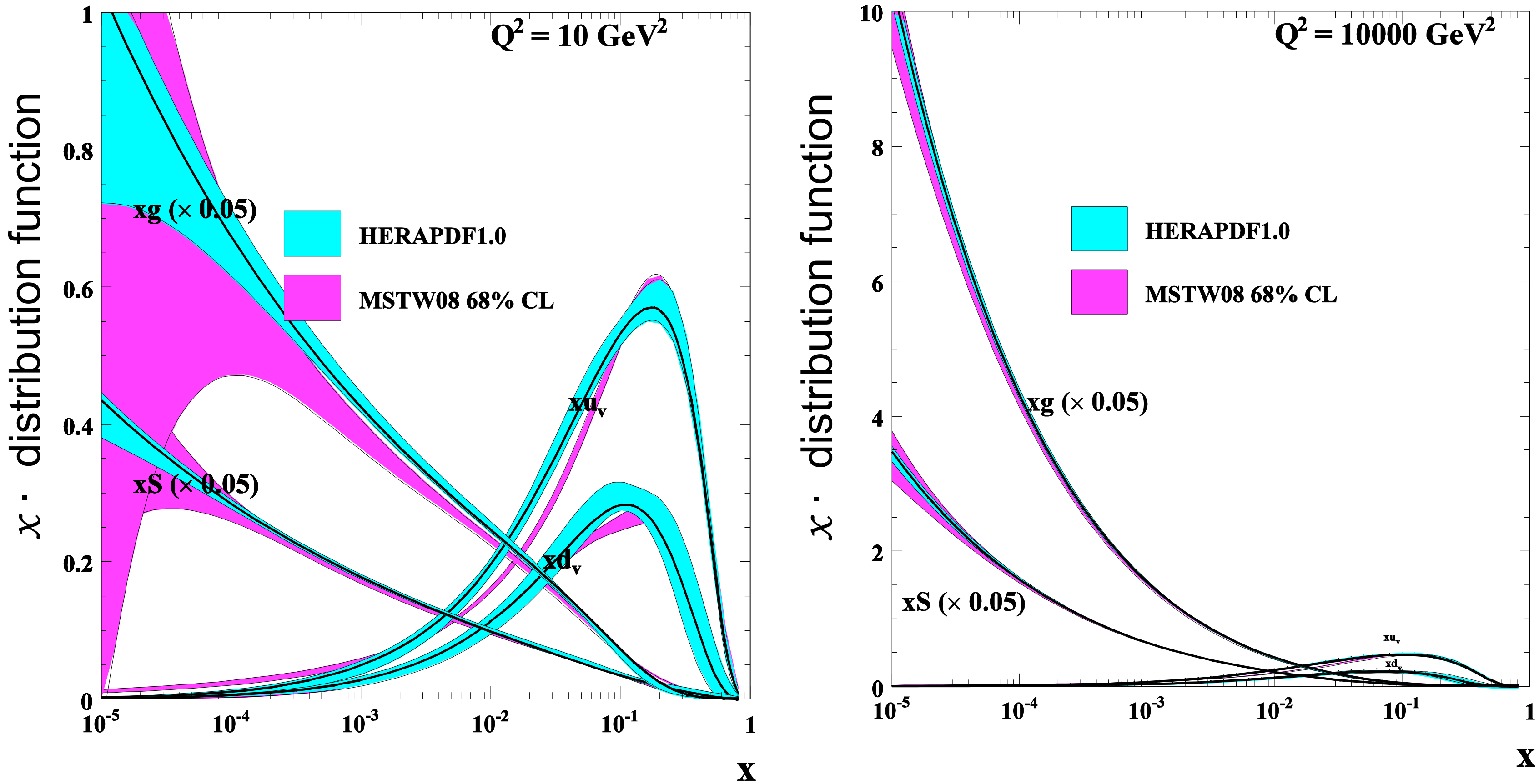
use more data sets from different experiments

error correlations sometimes unclear

not all include combined HERA data

all treat heavy quarks differently

HERA PDFs vs global QCD analysis



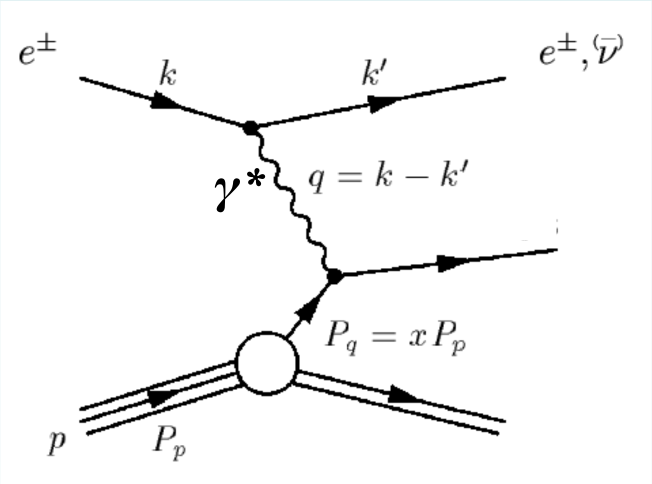
HERAPDF compared to one of the global PDF Fit results:

- much better precision in gluon and sea
- differences in valence

ep Scattering in Quark-Parton Picture

Think of scattering of longitudinal and transverse polarized photons:

y (or $Y_{\pm}=1\pm(1-y)^2$) related to photon polarization



cross section:

$$\sigma \sim \sigma_T + 2(1-y)/Y_+ \, \sigma_L$$

transverse polarized γ helicity ±1

longitudinally polarized γ helicity 0

Kinematics:

$x=-q^2/2p\cdot q$ *Bjorken scaling variable*

$Q^2=-q^2$ *photon virtuality*

$y=p\cdot q/p\cdot k$ *transferred γ energy fraction*

ep Scattering in Quark-Parton Picture

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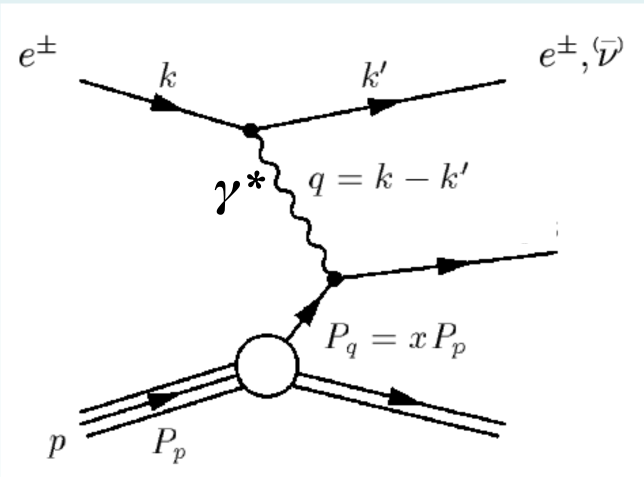


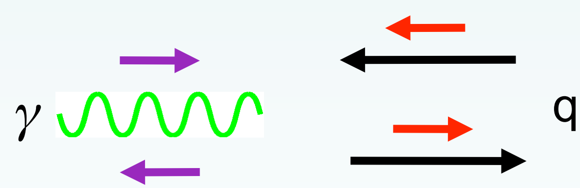
cross section:

$$\sigma \sim \sigma_T + 2(1-y)/Y_+ \, \sigma_L$$

transverse polarized γ helicity ±1

longitudinally polarized γ helicity 0

Parton Model: scattering off a quark (s=½):



helicity conservation ⇨ $\sigma_L=0$

Kinematics:

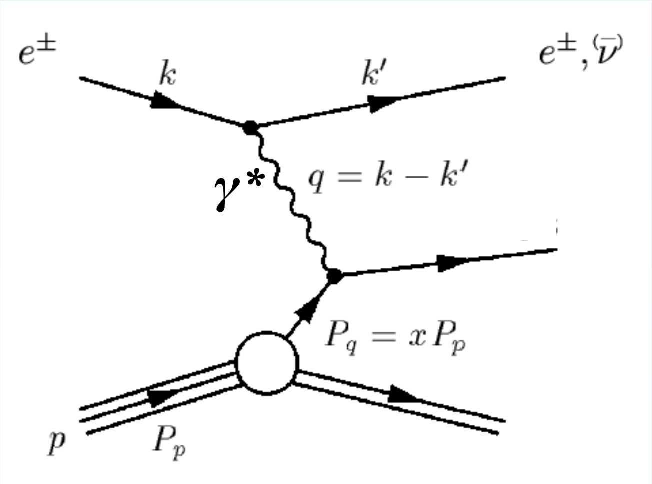
$x=-q^2/2p\cdot q$ *Bjorken scaling variable*

$Q^2=-q^2$ *photon virtuality*

$y=p\cdot q/p\cdot k$ *transferred γ energy fraction*

Proton Structure Functions

Cross Section of ep scattering expressed via proton structure functions



$$\frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2 - y^2 F_L \pm xF_3\right]$$

measured

Kinematics:

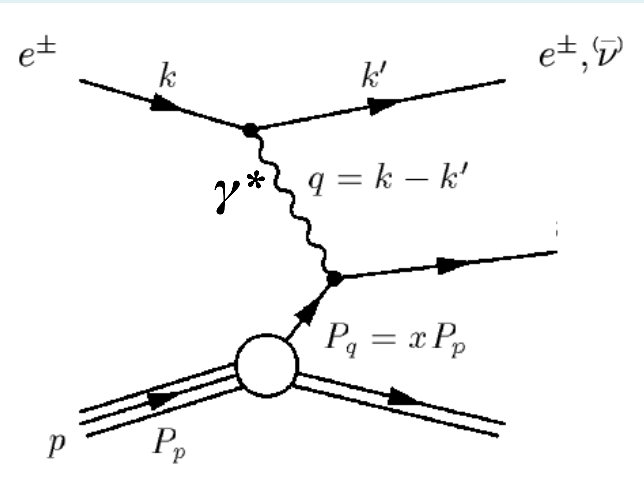
x=-$q^2/2p{\cdot}q$ *Bjorken scaling variable*

Q^2 =-q^2 *photon virtuality*

y=$p{\cdot}q\ /\ p{\cdot}k$ *transferred γ energy fraction*

Proton Structure Functions

Cross Section of ep scattering expressed via proton structure functions



$$\frac{d^2\sigma}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[(1+(1-y)^2)F_2 - y^2 F_L \pm xF_3\right]$$

measured

Quark-Parton-Model:

$F_L \sim \sigma_L \; = 0$

$$F_2 = \sum_q x e_q^2 (q(x) + \bar{q}(x))$$

Kinematics:

$x = -q^2 / 2p \cdot q$ *Bjorken scaling variable*

$Q^2 = -q^2$ *photon virtuality*

$y = p \cdot q \,/\, p \cdot k$ *transferred γ energy fraction*

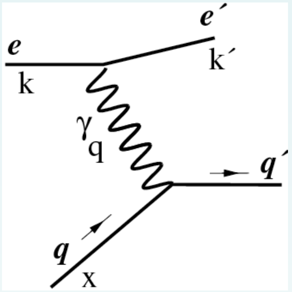
Parton Distribution Functions (PDFs):
probability to find a q in a proton carrying x fraction of its momentum

Another way to access the gluon directly: F_L

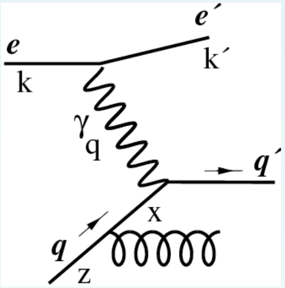
Remind of photon- scattering: $F_2 \sim (\sigma_T + \sigma_L), F_L \sim \sigma_L$

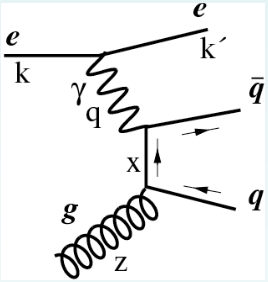
Angular momentum conservation: spin ½ quark absorbs spin-1 photon

QPM



QCD





quark helicity ± ½ , F_L=0

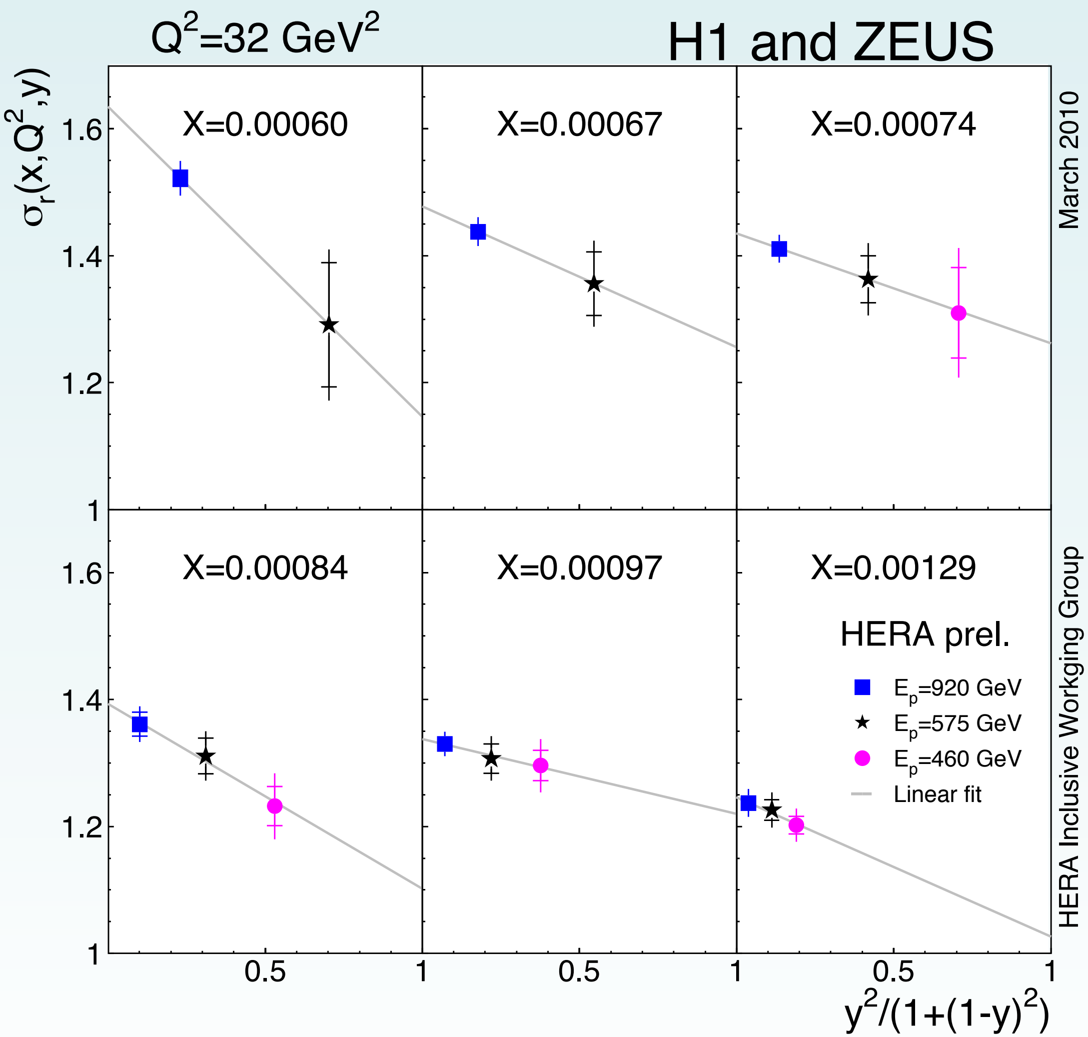
off-shell quarks may absorb longitudinal photons

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

quarks radiating a gluon

gluons splitting into quarks

Extraction of F_L



measurements @ same Q^2,x

$E_p=920$ GeV

$E_p=575$ GeV

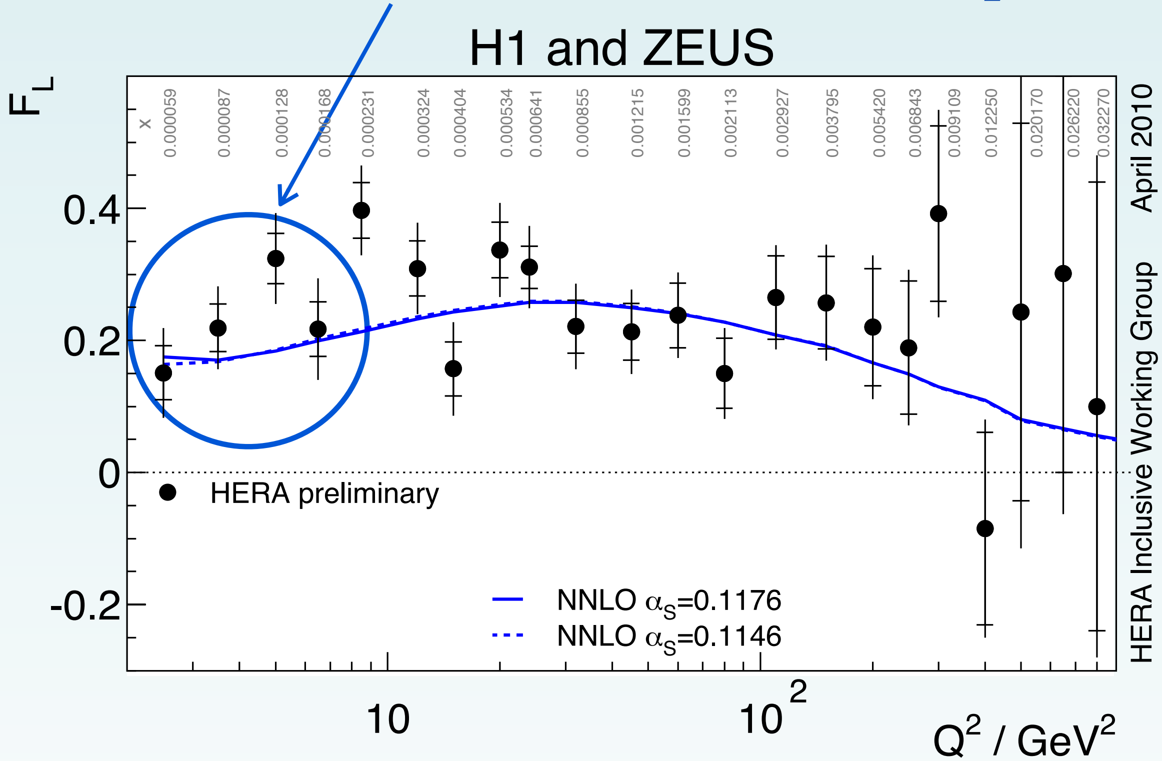
$E_p=460$ GeV

Intercept: F_2

Slope: F_L

HERA PDF Fits at NNLO

QCD using NNLO PDF predicts different F_L shape



First HERA PDF Fits at NNLO:

lhapdf grids available https://www.desy.de/h1zeus/combined_results/

NNLO has impact on F_L at low Q^2

HQ Contribution to the Proton Structure

Can be determined experimentally: e.g. “charm structure function”:

$$F_2^{cc} \propto \frac{Q^2 \times \alpha_s}{m_c^2} \int \frac{dx}{x} \times e_c^2 \, g(x_g, Q^2) \times C(\ldots)$$

- use and combine different charm tagging methods

measure cross sections of charm and beauty production in DIS:

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

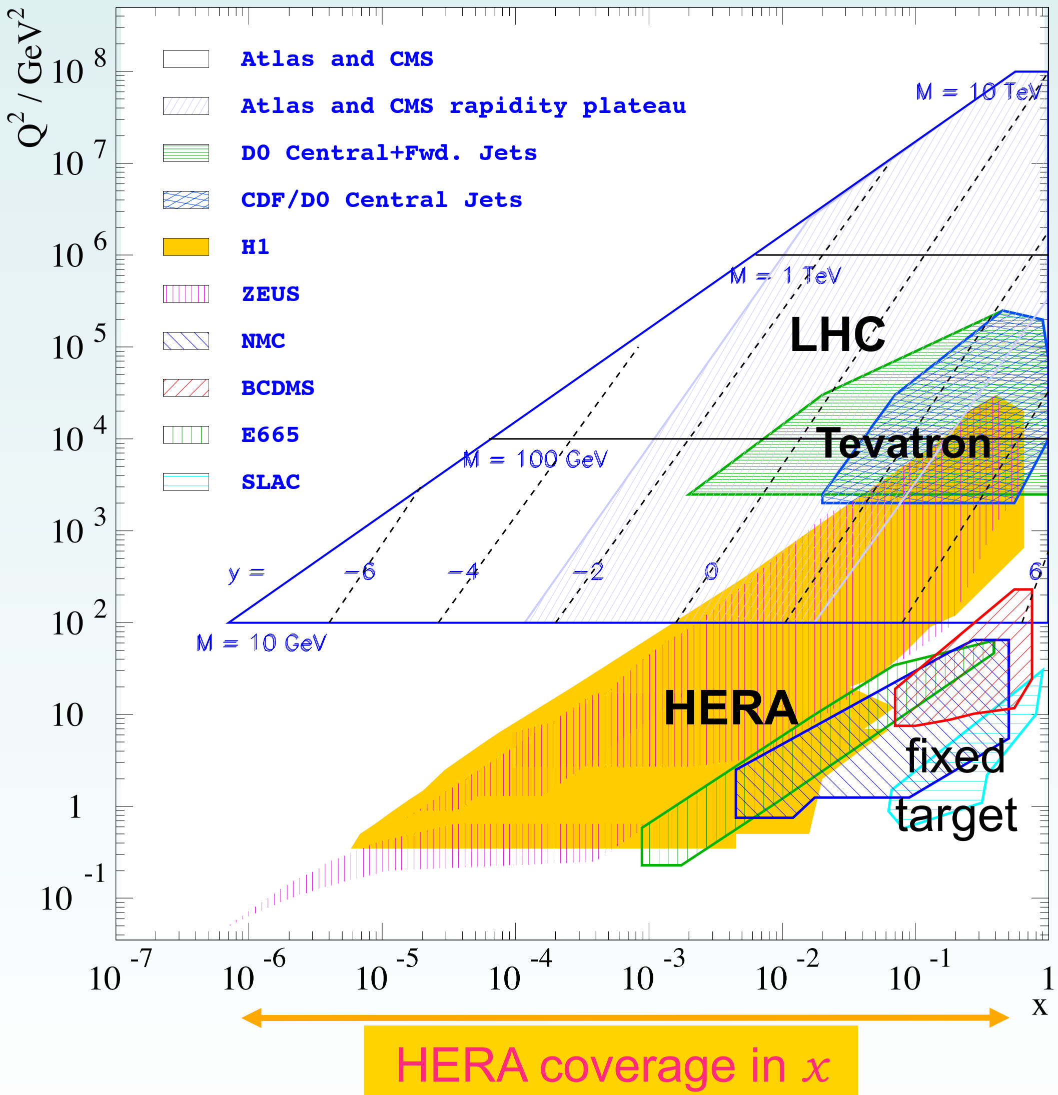
- Direct test of different schemes of HQ treatment in PDF fits

- Can be included in the full QCD analysis of DIS cross sections

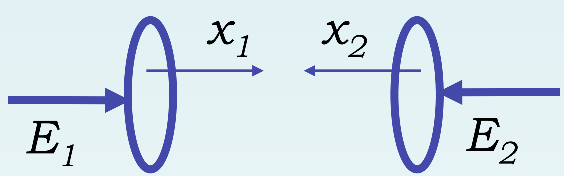
additional constrain on the gluon density in the proton

reduce parameterization uncertainty

PDFs From HERA to Tevatron and the LHC



Kinematics in pp collisions



Center-of-mass energy:

$$s = 4 \cdot E_1 \cdot E_2$$

2-parton interaction:

$$\hat{s} = x_1 \cdot x_2 \cdot s \geq M$$

Energy scale M = Q

$$x_{1,2} = \frac{M}{\sqrt{s}} \cdot exp(\pm y)$$

rapidity

Proton collisions at the LHC

LHC: p-p collisions at $\sqrt{s}$ = 7, 10, 14 TeV

Goal @ LHC: Higgs and new physics

Main challenge: Background suppression

Main Background: QCD

Hard processes > 80% gluon-gluon fusion

Cross section ~ $|g(x)|^2$

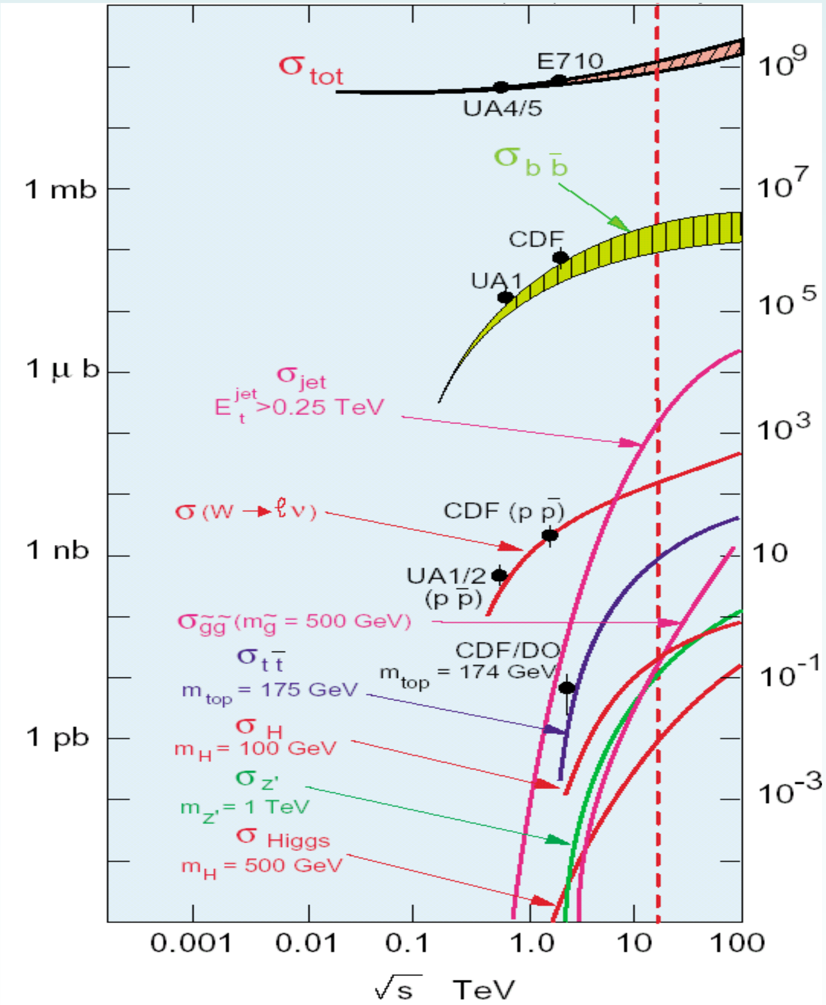
Precision of the gluon density essential!

Luminosity: e.g. $u\bar{d} \rightarrow W^+ \rightarrow l^+ \nu_l$

Precision of light quark densities essential!

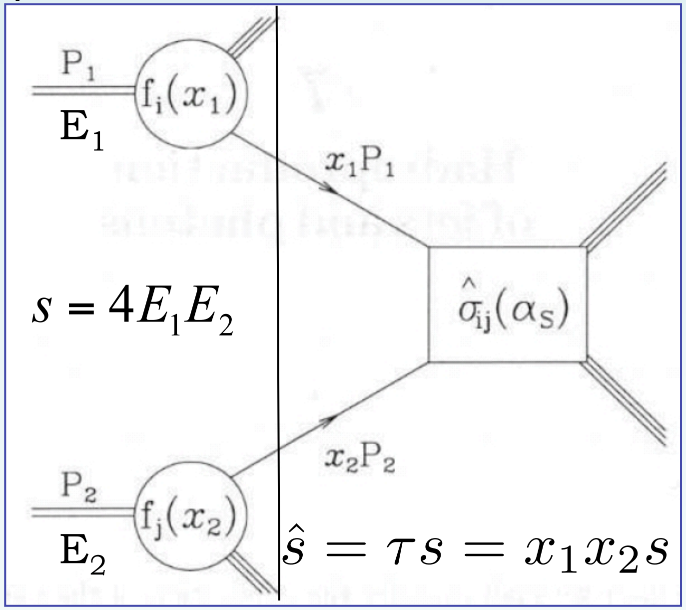
Key issue: understanding of the proton

Rate and cross sections of *pp* collisions



Proton-Proton Collisions at High Energies

proton structure *hard interaction*



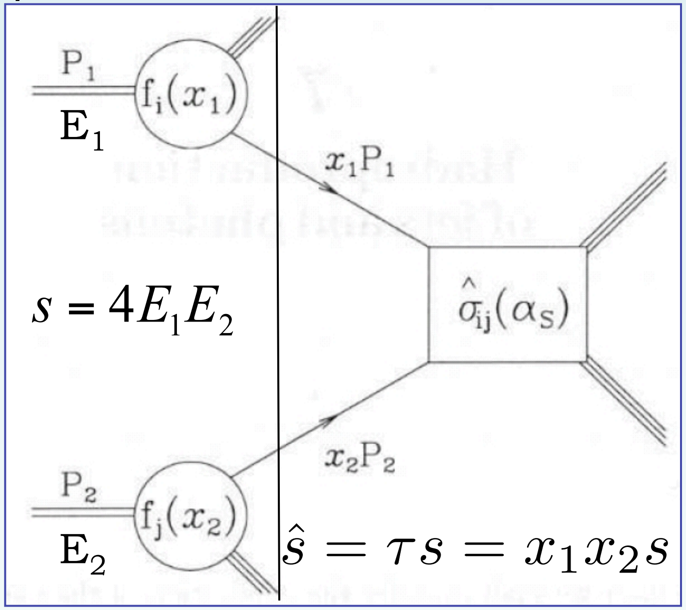
Structure: $f_i(x,Q^2) = q_i\,(x,Q^2),\ g(x,Q^2)$,

f_i - beam parameters, **process independent**

Hard 2-parton interaction calculable in pQCD

Proton-Proton Collisions at High Energies

proton structure *hard interaction*



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f_i - beam parameters, **process independent**

Hard 2-parton interaction calculable in pQCD

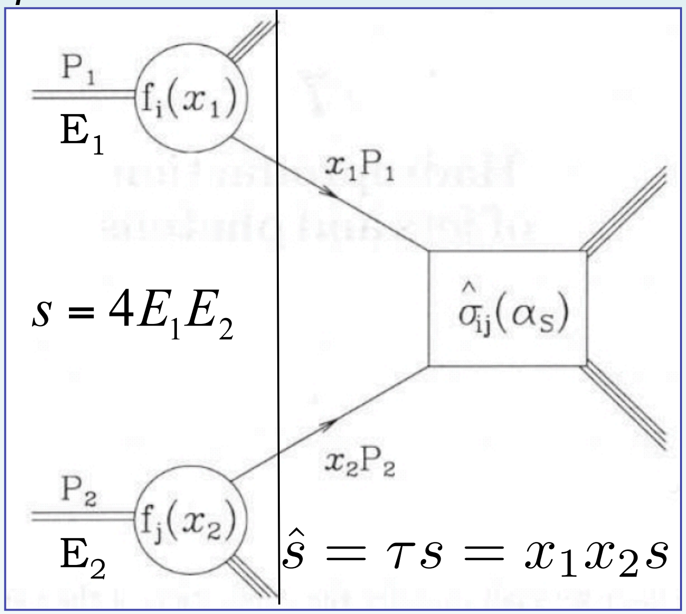
Factorization: PDF⊗ hard sub-process ME

$$\sigma(s) = \sum_{i,j} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{dL_{ij}(\mu_F^2)}{d\tau} \cdot \hat{s} \cdot \boxed{\hat{\sigma}_{ij}}$$

$$\tau \cdot \frac{dL_{ij}}{d\tau} \propto \int_0^1 dx_1 dx_2 (x_1 f_i(x_1,\mu_F^2) \cdot x_2 f_j(x_2,\mu_F^2)) + (1 \leftrightarrow 2)\delta(\tau - x_1 x_2)$$

Proton-Proton Collisions at High Energies

proton structure *hard interaction*



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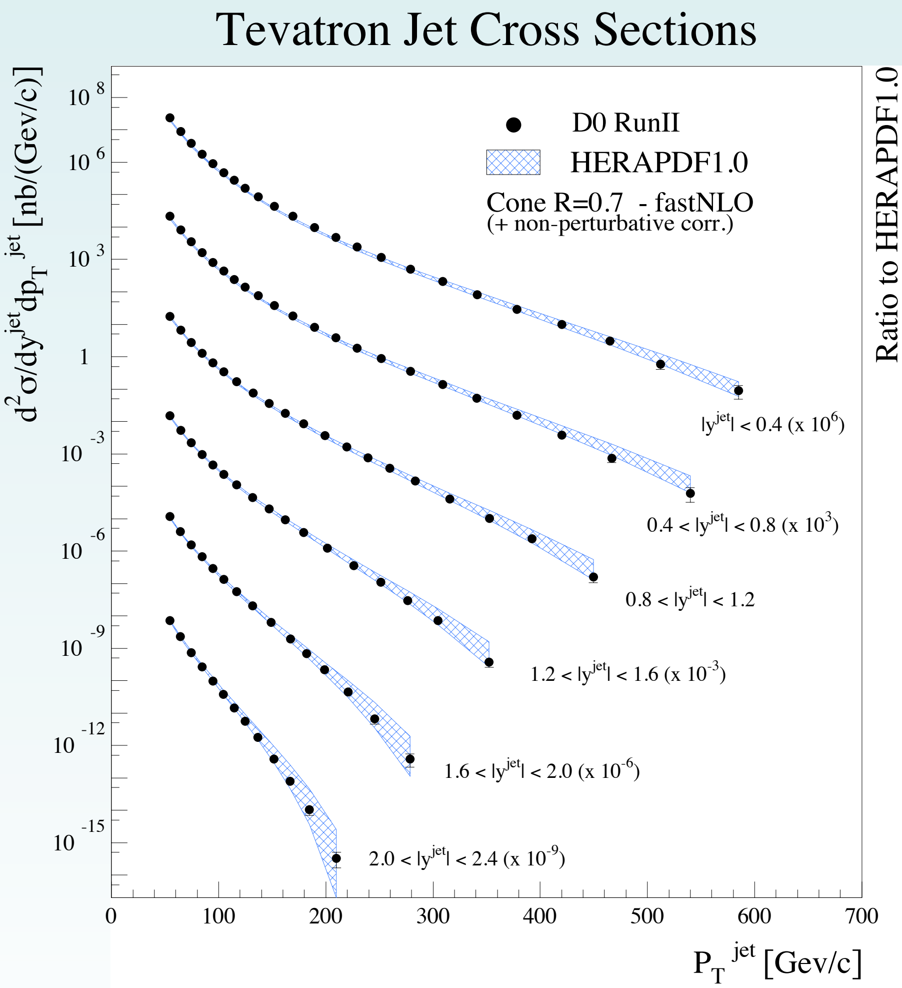
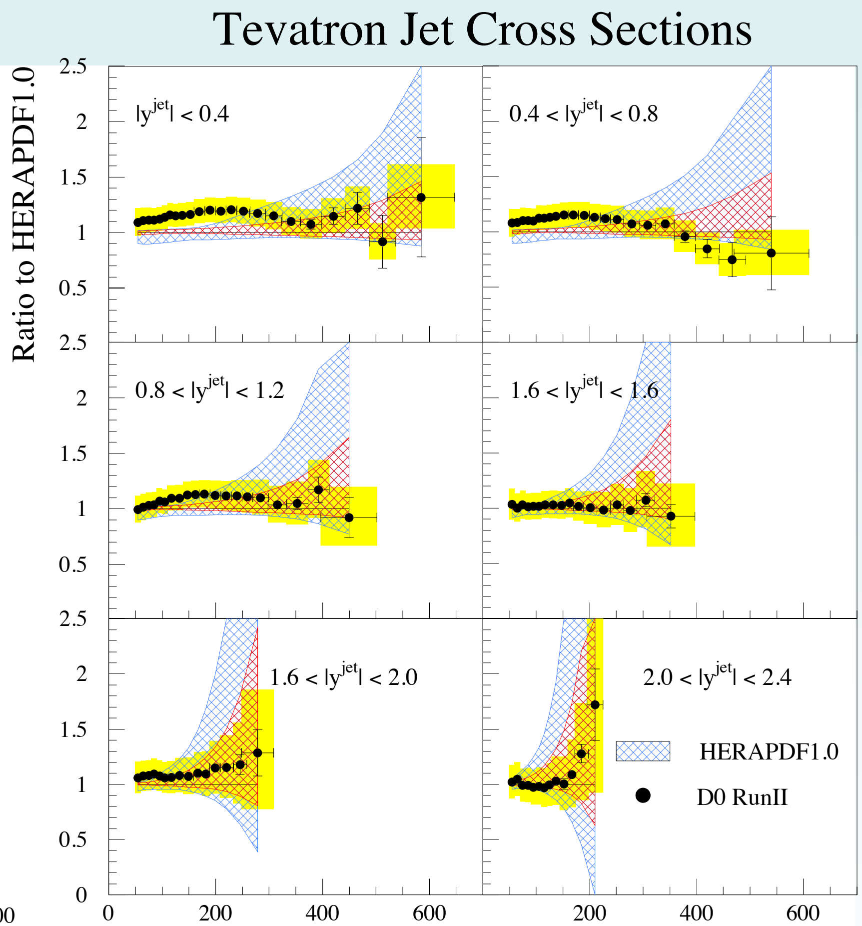
Precision of PDFs essential!

HERAPDF vs Jets at TEVATRON





only PDF uncertainties shown

Predictions based on HERAPDF in agreement with TEVATRON data