Deep Inelastic Scattering & Parton Densities at HERA

using data from

- Historical prelude
- Deep inelastic scattering
  Theory and Experiments
- HERA measurements:
  Cross sections and
  Structure functions
- Extraction of Parton Densities
- Open Issue(s) & Future PDF@HERA

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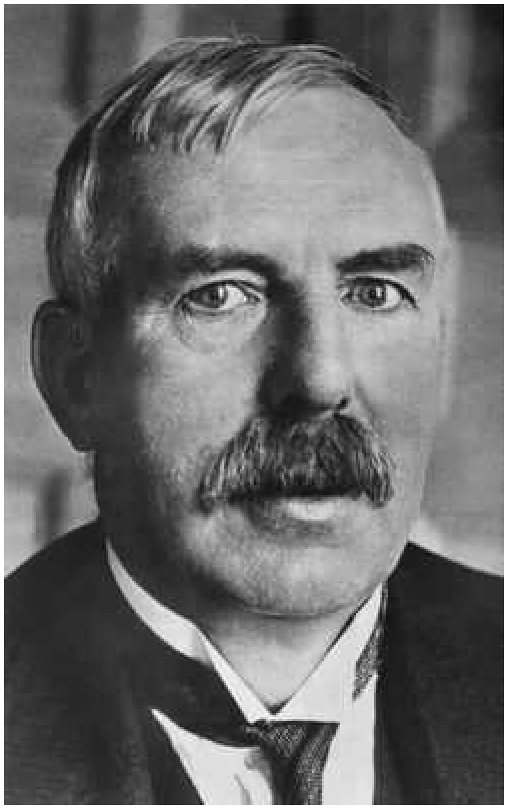
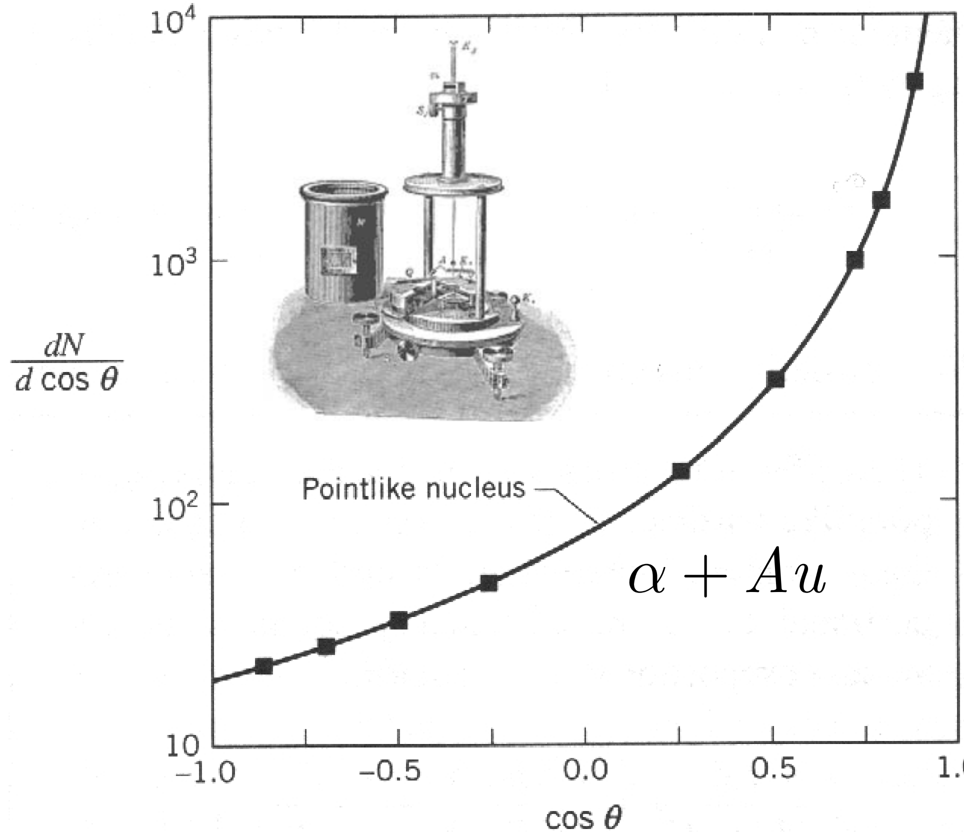
It all started with Ernest Rutherford …

The mother of all scattering experiments



E. Rutherford

Nobel Price 1908 (for chemistry!)



$$\frac{d\sigma}{d\Omega} = (zZ\alpha)^2 \left(\frac{\hbar c}{4E_{\mathrm{kin}}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

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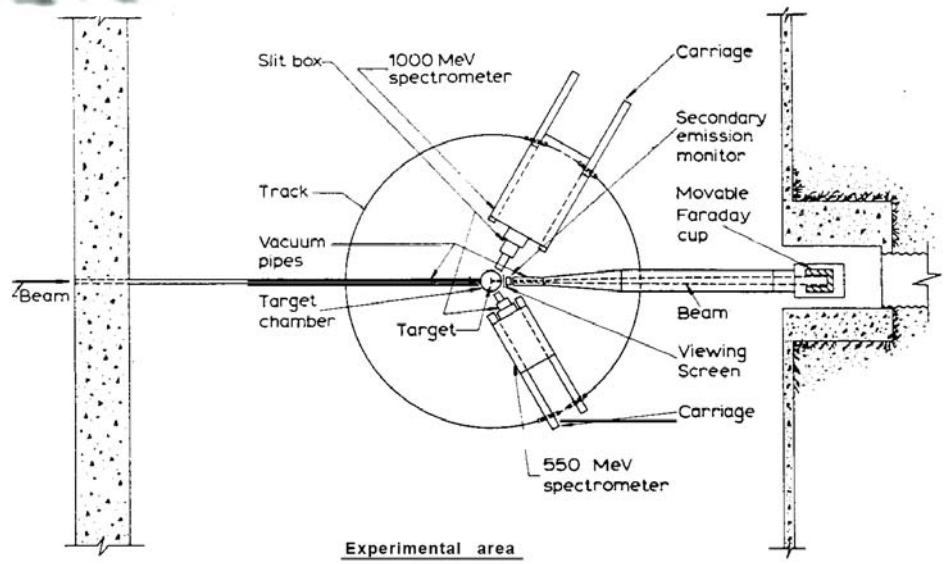
Pioneer of Electron Scattering: Robert Hofstadter

- electrons are elementary
- are sensitive only to charge
- can be easily produced and accelerated to high energy

$$\hbar c = 200 \ [\text{MeV fm}]$$

typical setup for an electron scattering experiment



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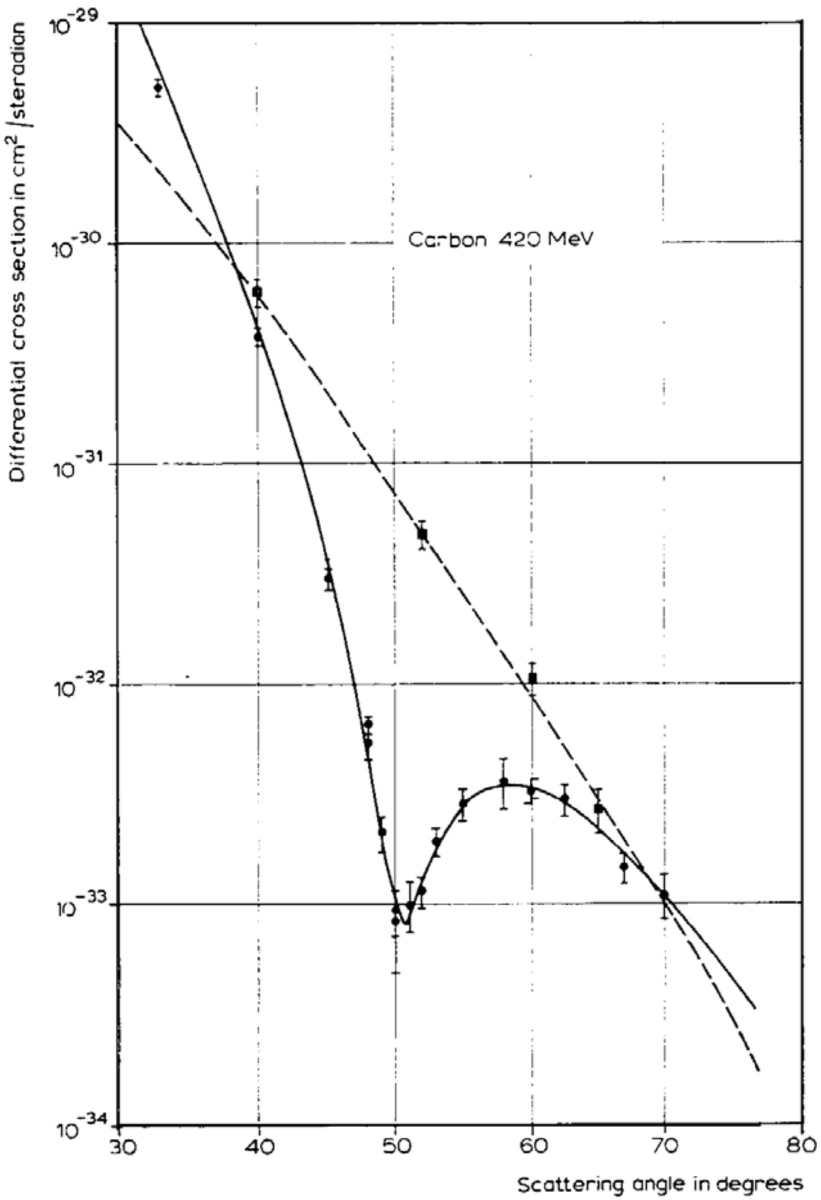
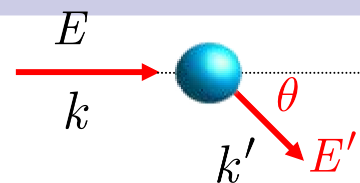
Figures from R. Hofstadter's Nobel Lecture, Dec. 11, 1961



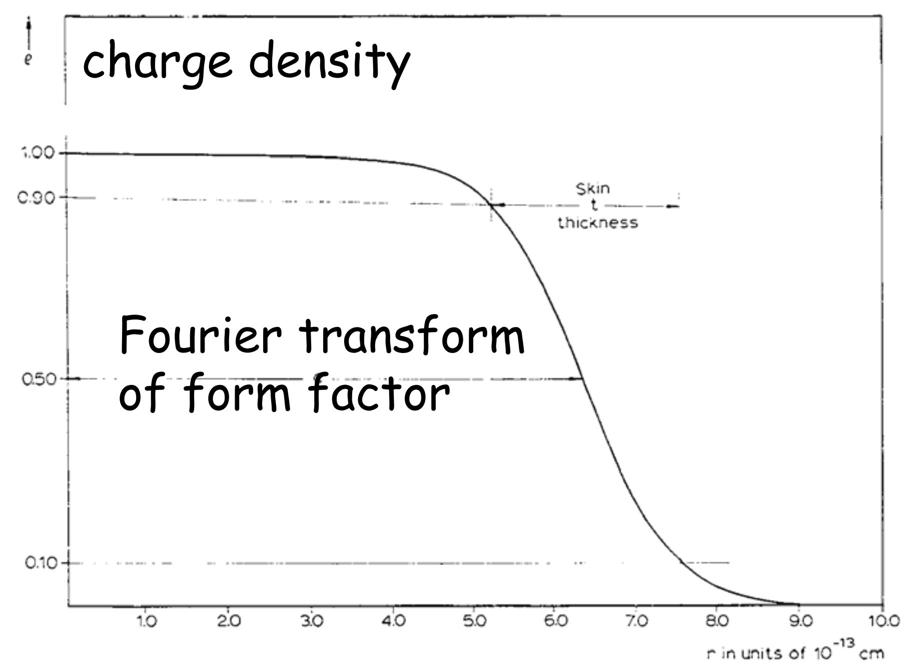
Elastic scattering:



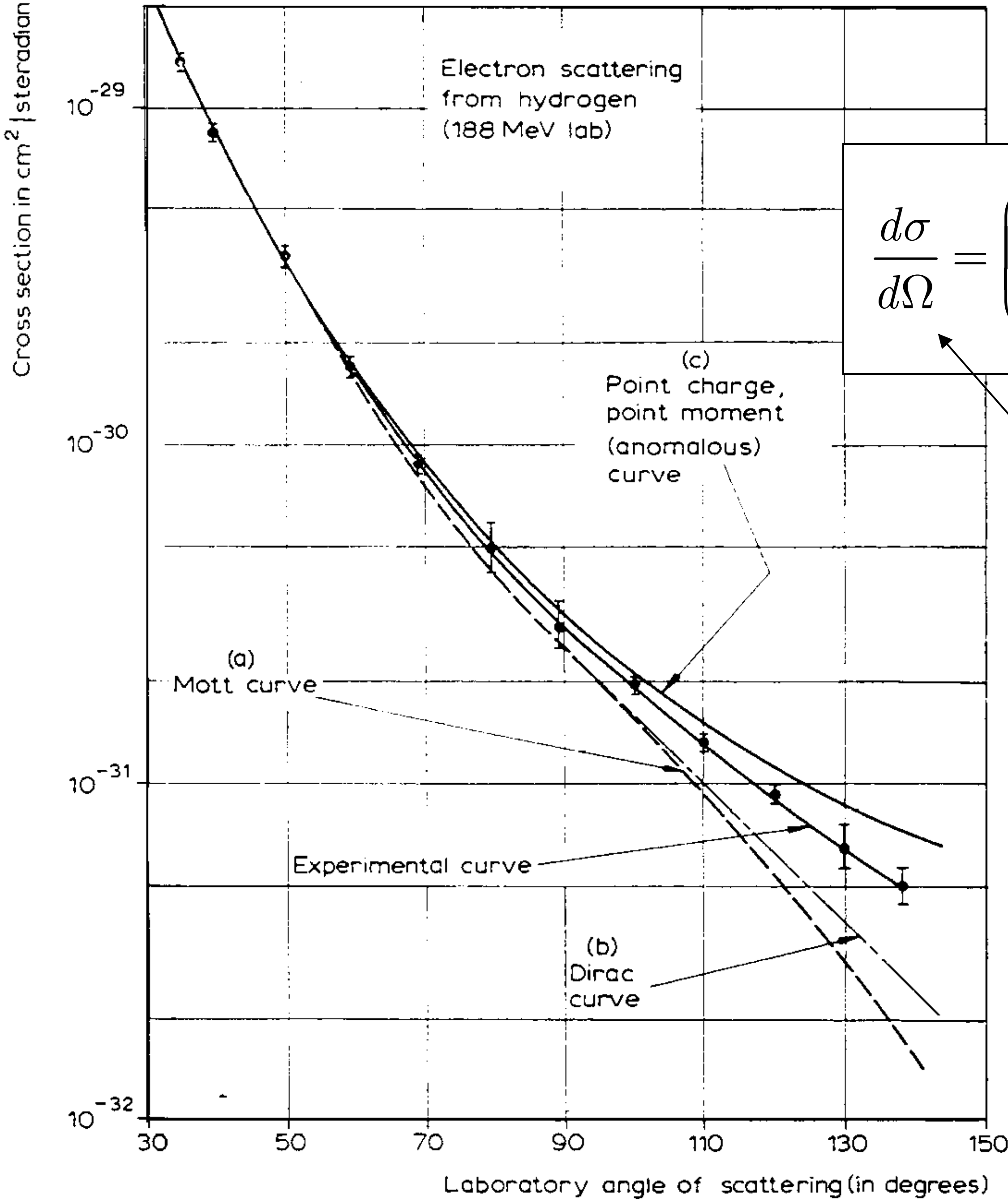
clear dip structure -> finite nuclear radius

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Ruth} \left(\frac{E'}{E}\right) \cos^2 \frac{\theta}{2} \left|F(q)\right|^2$$

$q = k - k'$ form factor



Something is „wrong“ with the proton …

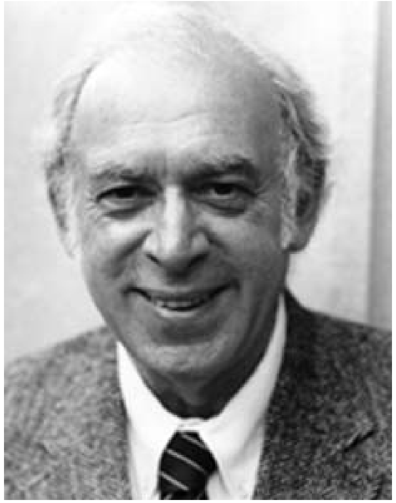


$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Ruth} \frac{E'}{E}\left(\cos^2\frac{\theta}{2} + \frac{q^2}{2M}\sin^2\frac{\theta}{2}\right)$$

Cross section for electron scattering on a spin 1/2 Dirac proton

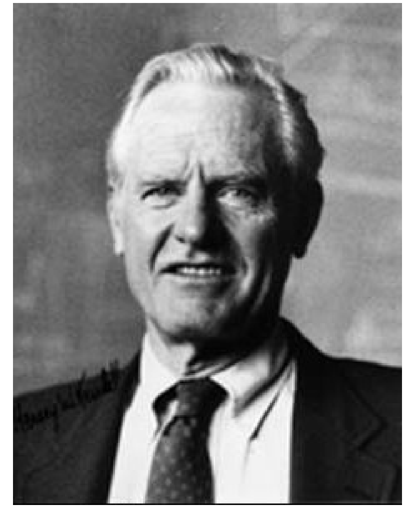
- the proton has an anomalous magnetic structure (NOT a Dirac particle)
- beam energy too small to resolve the proton structure

J. Friedman



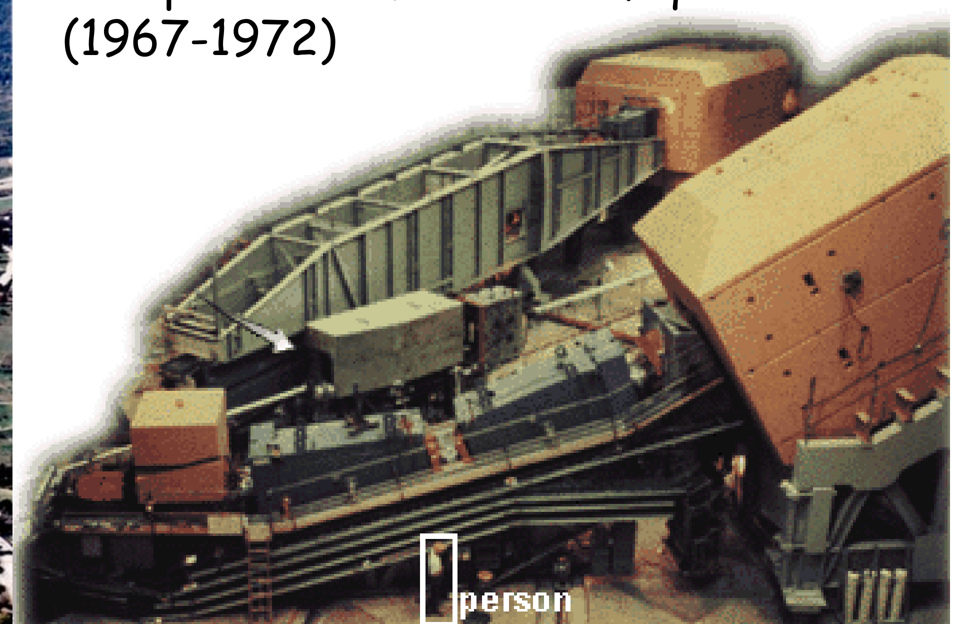
R. Taylor

H. Kendall



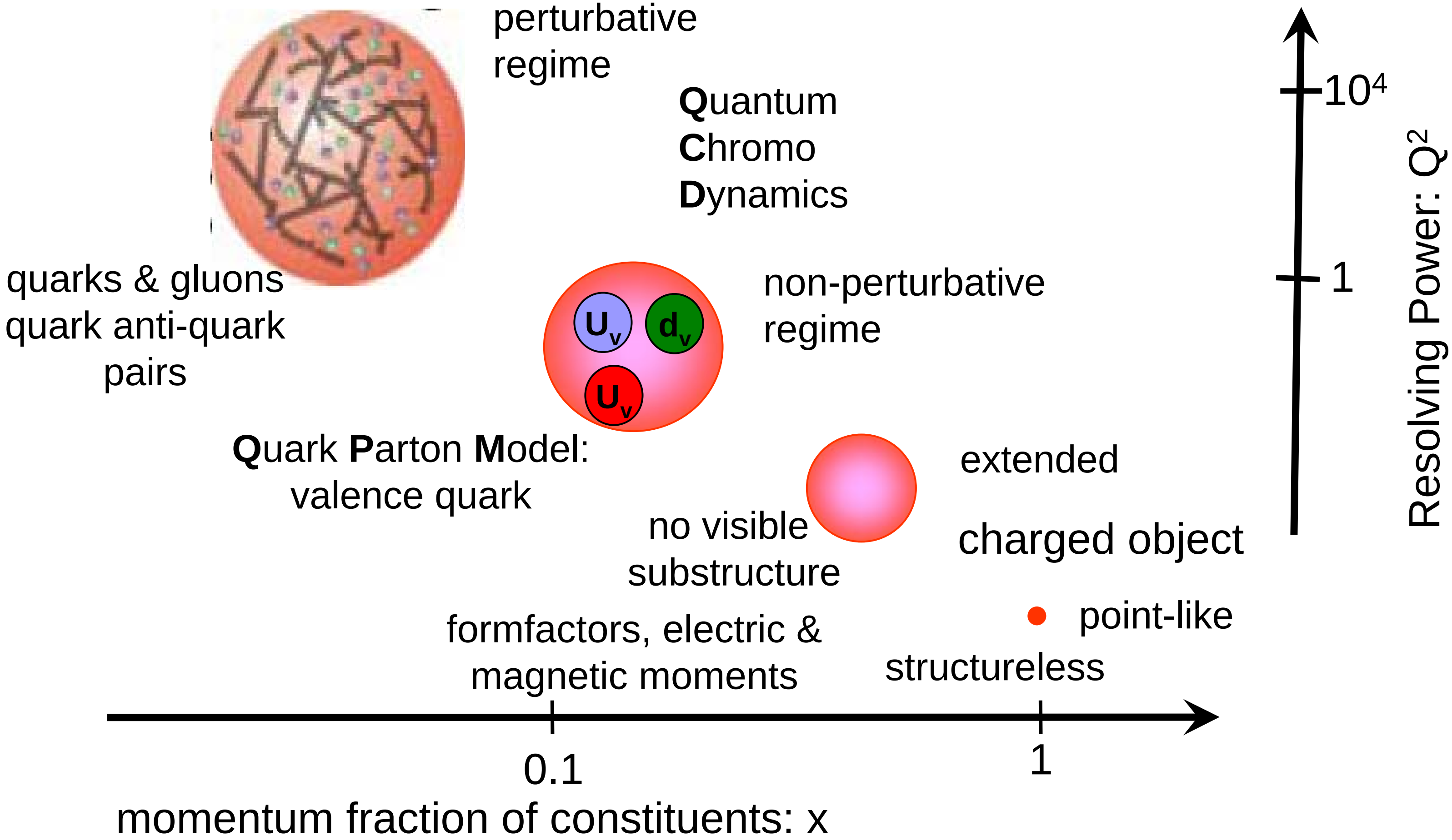
NP 1990

The proton is made out of quarks !
(1967-1972)



„Endstation A“ spectrometers

“Imaging” of the Proton



Low Q^2 : probing transition perturbative to non-perturbative QCD
Low x: probing quarks and gluons at high density
$\Delta E \Delta t \sim h \rightarrow$ high Q^2 “high resolution but time averaged picture”

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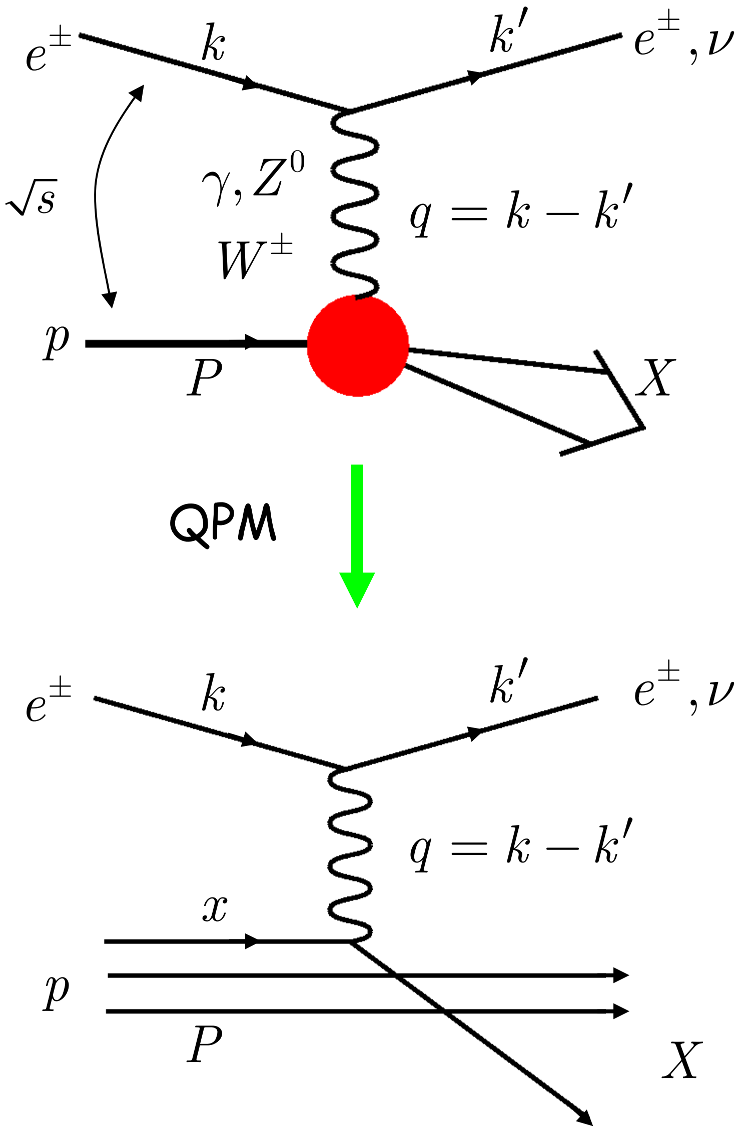
Deep Inelastic Scattering (DIS)



$$Q^2 = -(k - k')^2 = -q^2$$

(momentum transfer)^2

virtuality of $\gamma^*, Z^0, W^\pm$

→ („size" of the probe)$^{-1}$

$$x = \frac{Q^2}{2\, P \cdot q}$$

fraction of the proton momentum carried by the charged parton

$$y = \frac{P \cdot q}{P \cdot k}$$

fraction of the electron energy carried by the virtual photon („inelasticity")

$$s = (k + P)^2$$

center of mass energy of ep system

$$W^2 = M_X^2 = (q + P)^2$$

(mass)^2 of $\gamma^* p$ system

$$\boxed{Q^2 = sxy}$$

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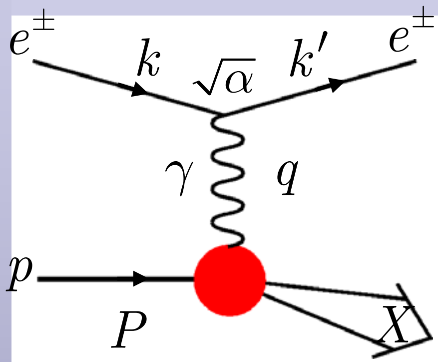
Cross Section and Structure Functions



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{\alpha^2}{2MQ^4}\frac{E'}{E} L_{\mu\nu} W^{\mu\nu}$$

$L_{\mu\nu}$ lepton tensor

$W_{\mu\nu}$ hadronic tensor

$$L_{\mu\nu} = 2\left[k_\mu k'_\nu + k'_\mu k_\nu + \frac{q^2}{2} g_{\mu\nu}\right]$$

← minimal electromagnetic coupling

(unpolarized particles)

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) 2F_1 + \left(P_\mu - \frac{P\cdot q}{q^2} q_\mu\right)\left(P_\nu - \frac{P\cdot q}{q^2} q_\nu\right)\frac{2}{P\cdot q} F_2$$

most general tensor satisfying charge conservation

NC cross section :

$$\frac{d^2\sigma(e^\pm p)}{dx\, dQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left[xy^2 F_1 + (1-y)F_2\right]$$

$$= \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 - y^2 F_L\right]$$

$$F_L \equiv F_2 - 2xF_1$$

longitudinal structure function

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

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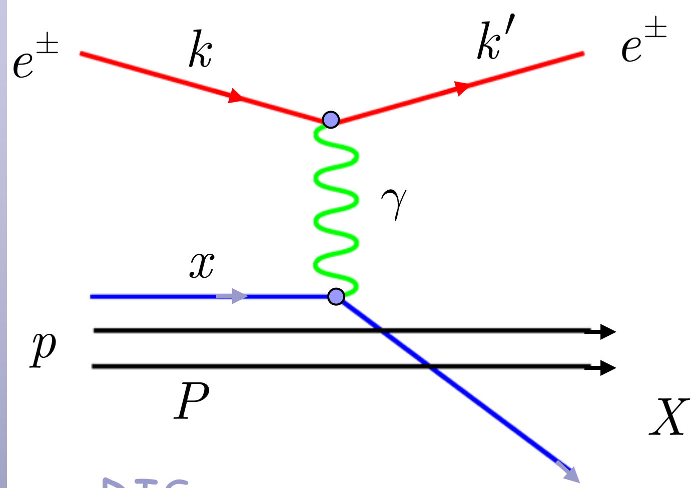
Structure Functions within the Quark-Parton-Model



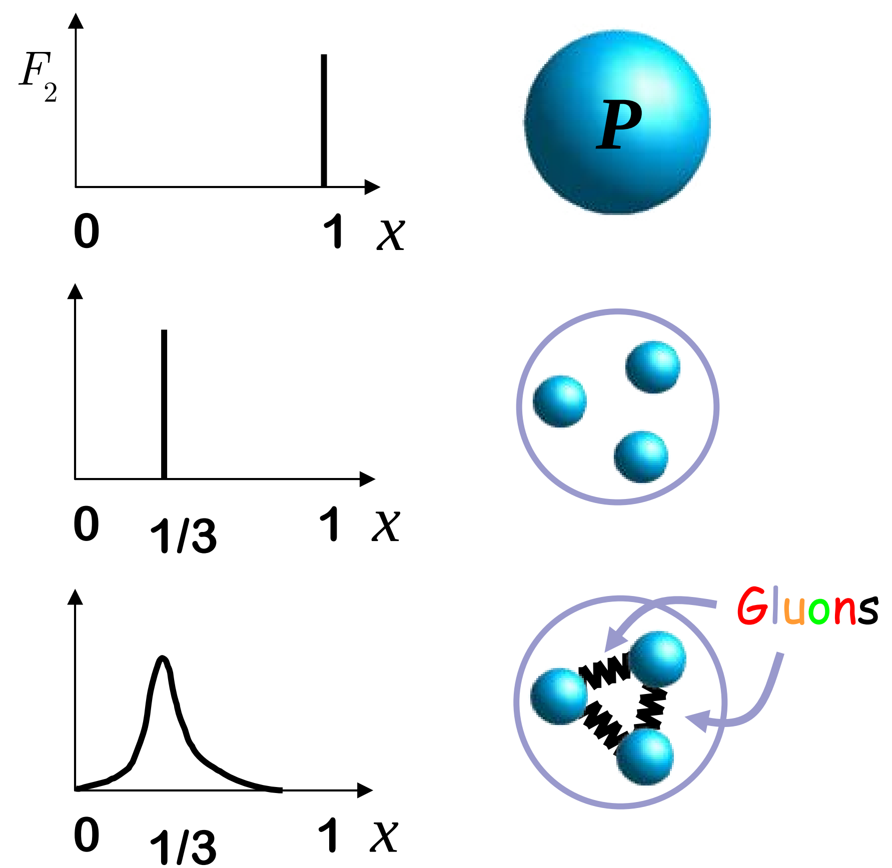
$$\frac{d^2\sigma(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 - y^2 F_L\right]$$

QPM: $F_2(x) = \sum_{i=u,d} e_i^2 x q_i(x)$

parton densities $xq_i(x)$ (pdf)

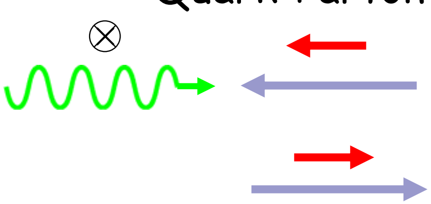
DIS =

- electron scatters off a charged constituent (parton) of the proton (= elastic scattering)
- identify the charged partons with QUARKS (= spin 1/2 fermions)



1/ 6 (Gluons carry half proton momentum)

→ Quark-Parton-Model (QPM)



$$\boxed{F_L = 0}$$

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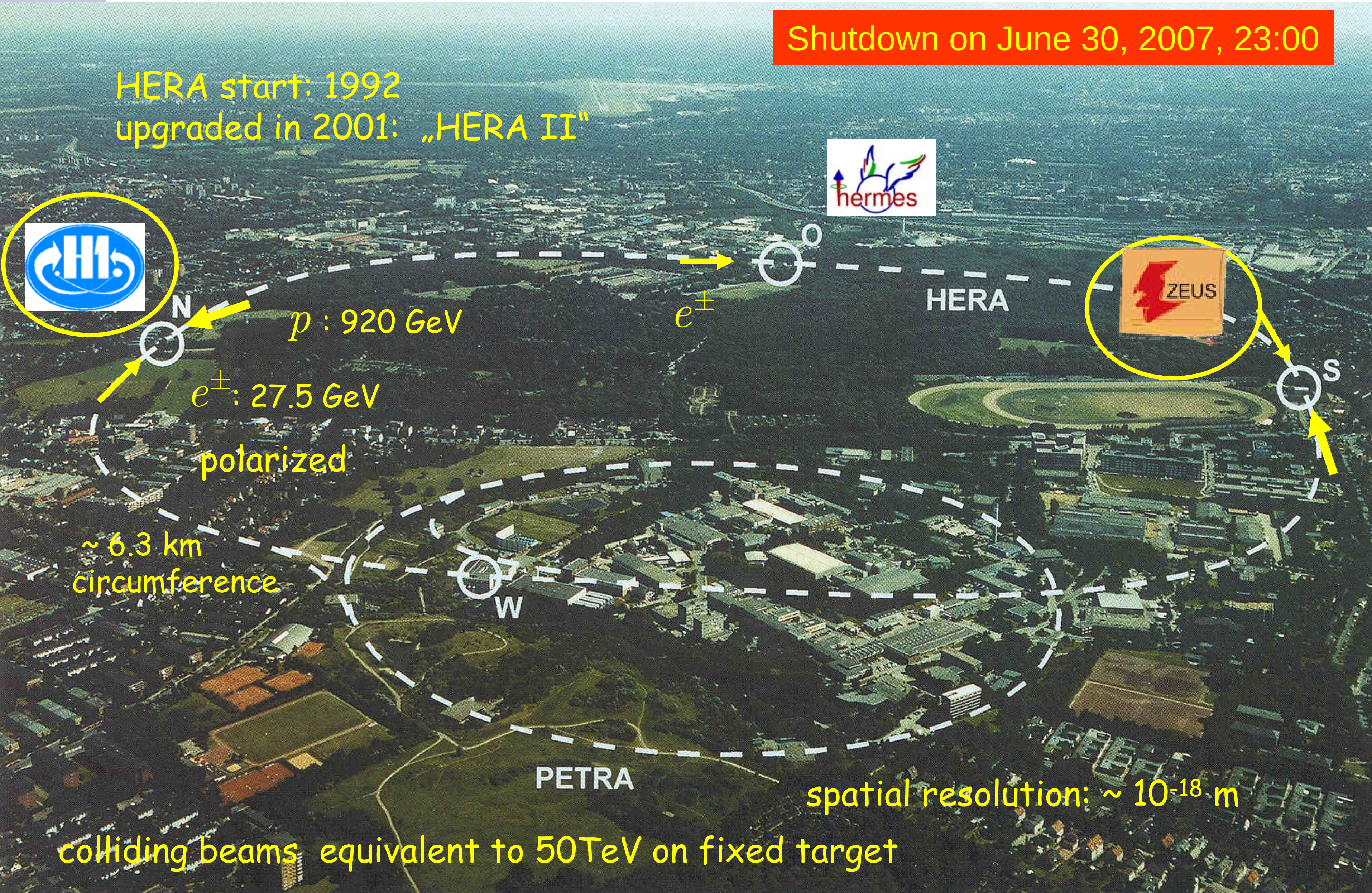
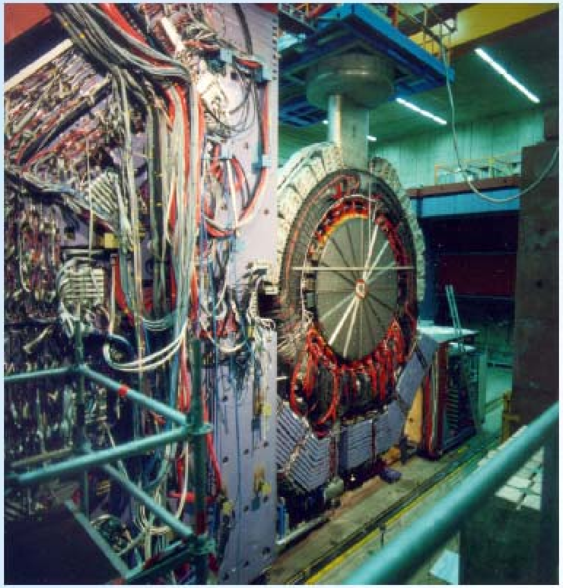
HERA – the world's largest electron microscope
(Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany)

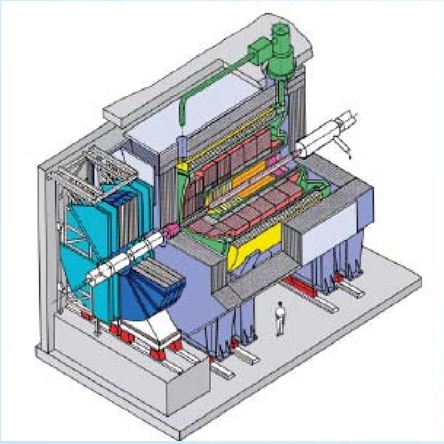


Collider Experiments at HERA

H1

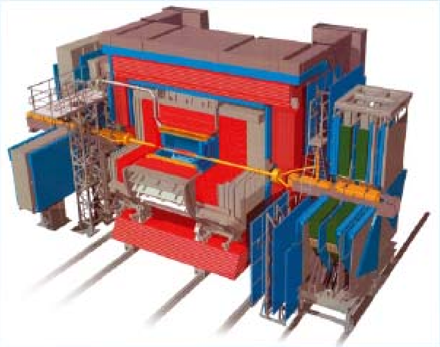
went for LAr





ZEUS

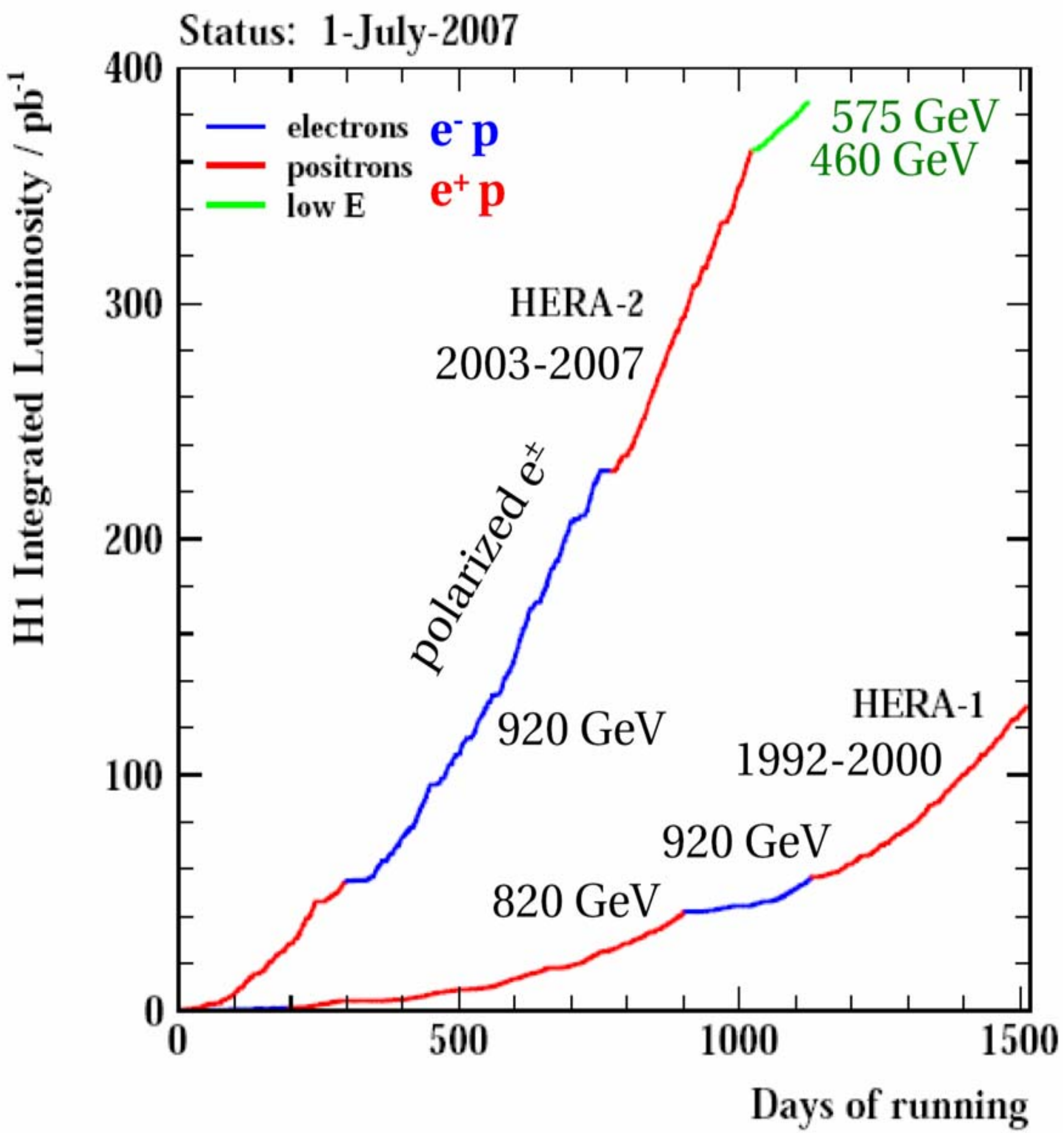
went for compen-sation



A final salute to our experiments

How we like to remember H1 and ZEUS

Hera Luminosity



HERA I: 1992-2000

HERA II upgrade:

- luminosity
- longitudinal polarization of the lepton beams (spin rotator pairs around the interaction regions)
- massive upgardes also for the detectors
- running efficiently from 2003 onwards
- Luminosity $L = 500\ pb^{-1}$ per exp.

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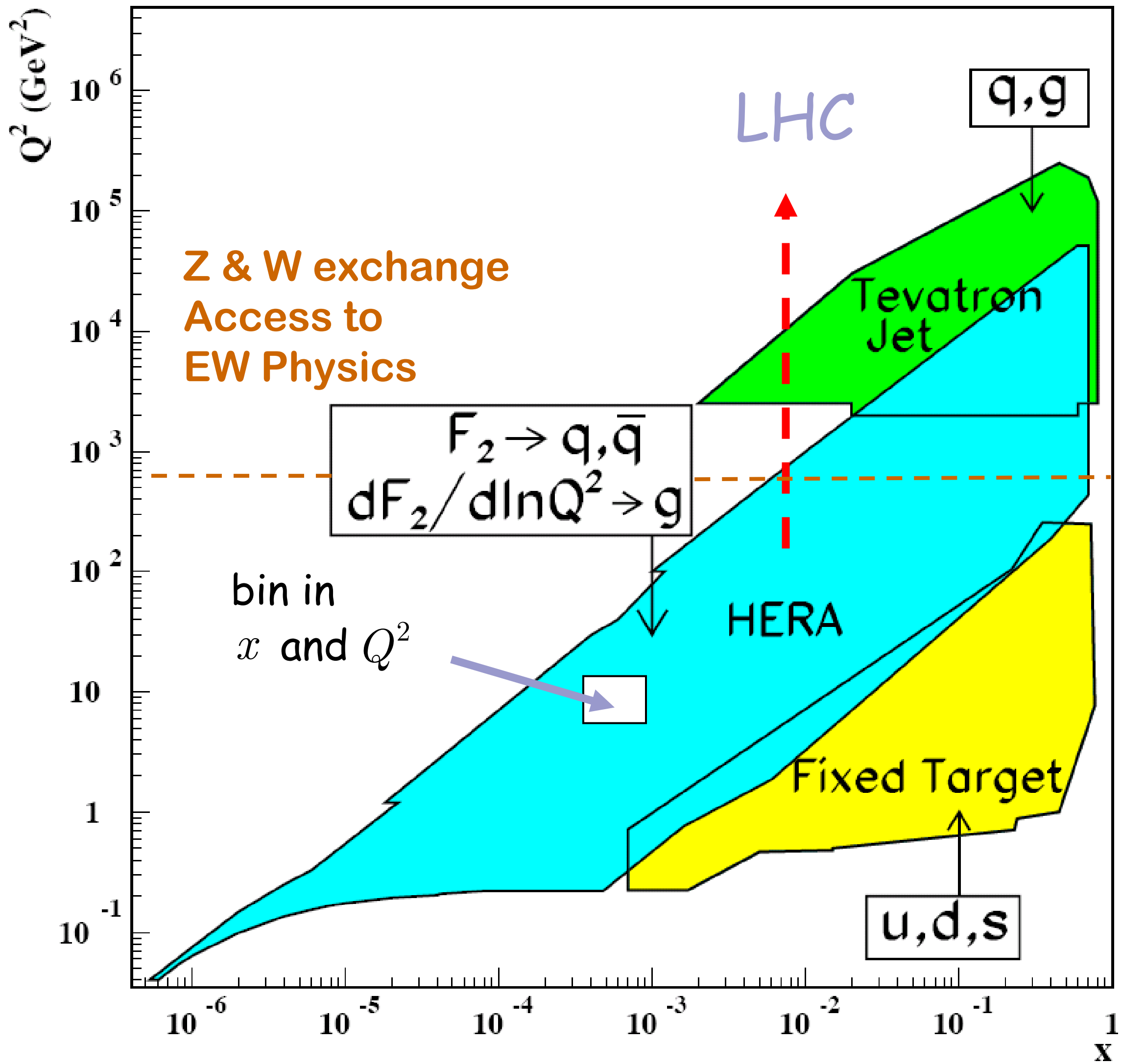
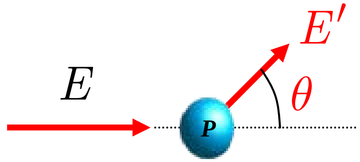
The Kinematic Reach of HERA



Determination of kinematics („e"-method) :



$$Q^2 = 4EE'\cos^2\left(\frac{\theta}{2}\right)$$

$$y = 1 - \frac{E'}{E}\sin^2\left(\frac{\theta}{2}\right)$$

$$x = \frac{Q^2}{sy}$$

Determination of cross sections :

$$\frac{d^2\sigma}{dx\,dQ^2} \sim \frac{N-B}{\mathcal{L}\,\varepsilon}$$

backgr.

efficiency

luminosity

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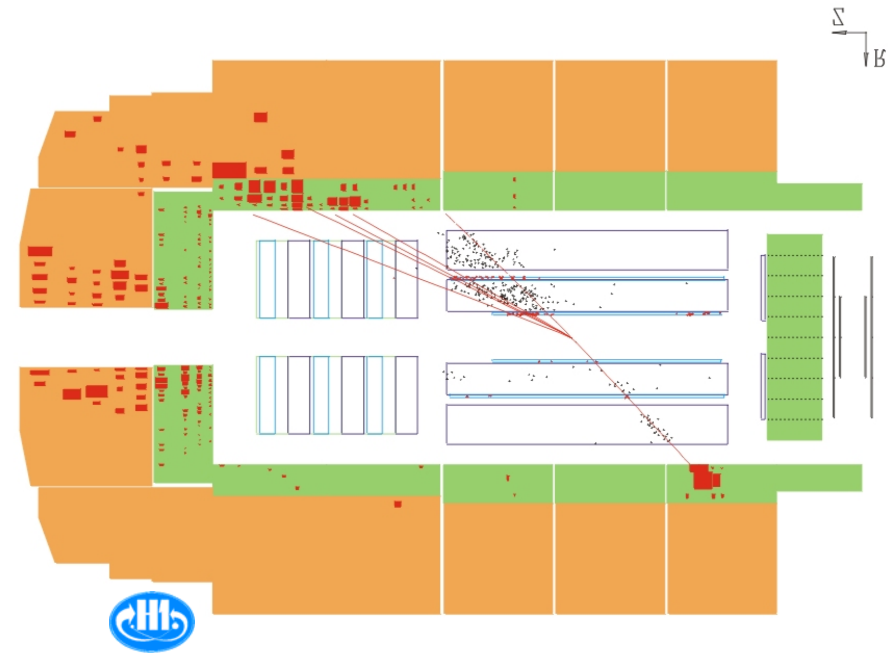
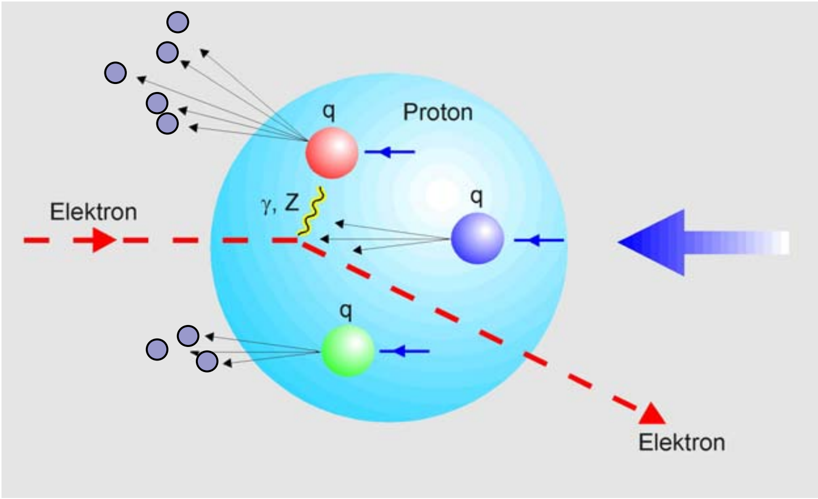
Electron Proton Scattering in Real Detectors ....

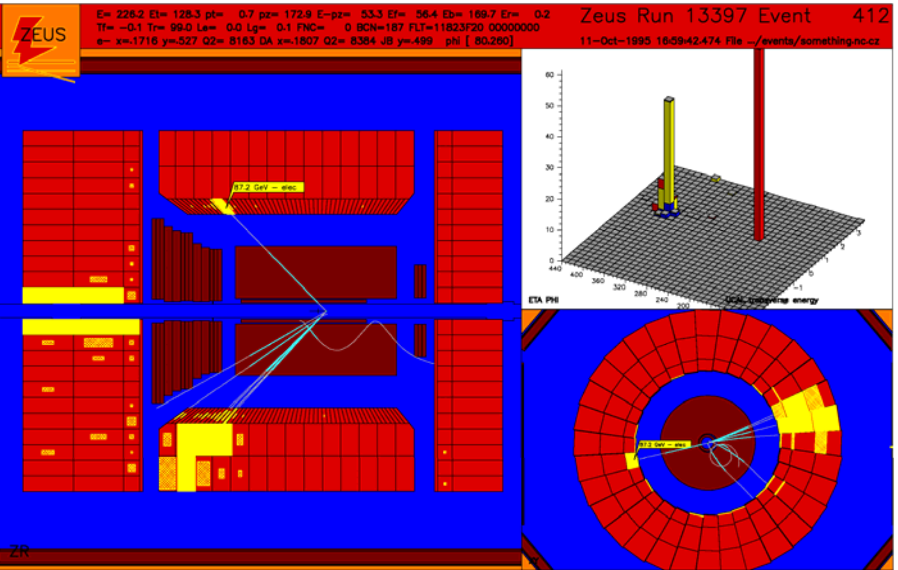




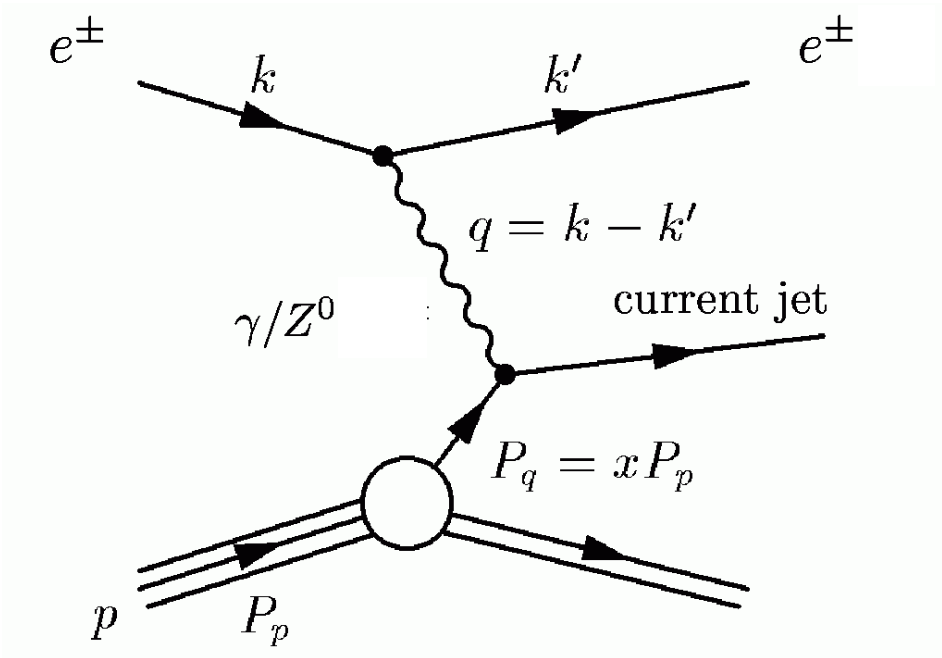
Netral current events in

H1 (medium Q^2)

ZEUS (large Q^2)



Deep Inelastic Scattering



Kinematic Variables

- **4-momentum transfer resolving power**
  $$Q^2 = -q^2 = -(k - k')^2$$
- **Bjørken scaling variable momentum fraction of struck parton**
  $$x = \frac{Q^2}{2p \cdot q}$$
- **Inelasticity:** $y = \frac{p \cdot q}{p \cdot k}$

Center of mass energy $\sqrt{s}$: $s = (k + p)^2$ **relation for fixed s:** $Q^2 = sxy$

- **Neutral current DIS cross section expressed by structure functions:**

$$\frac{d^2\sigma^{e^\pm p \to e^\pm X}}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \underbrace{\left(1 + (1-y)^2\right)}_{Y_\pm = 1 \pm (1-y)^2} \cdot \left(\boxed{F_2(x, Q^2)} - \frac{y^2}{Y_+} \boxed{F_L(x, Q^2)} \mp \frac{Y_-}{Y_+} \boxed{xF_3(x, Q^2)} \right)$$

valence & sea quarks

gluons

valence quarks

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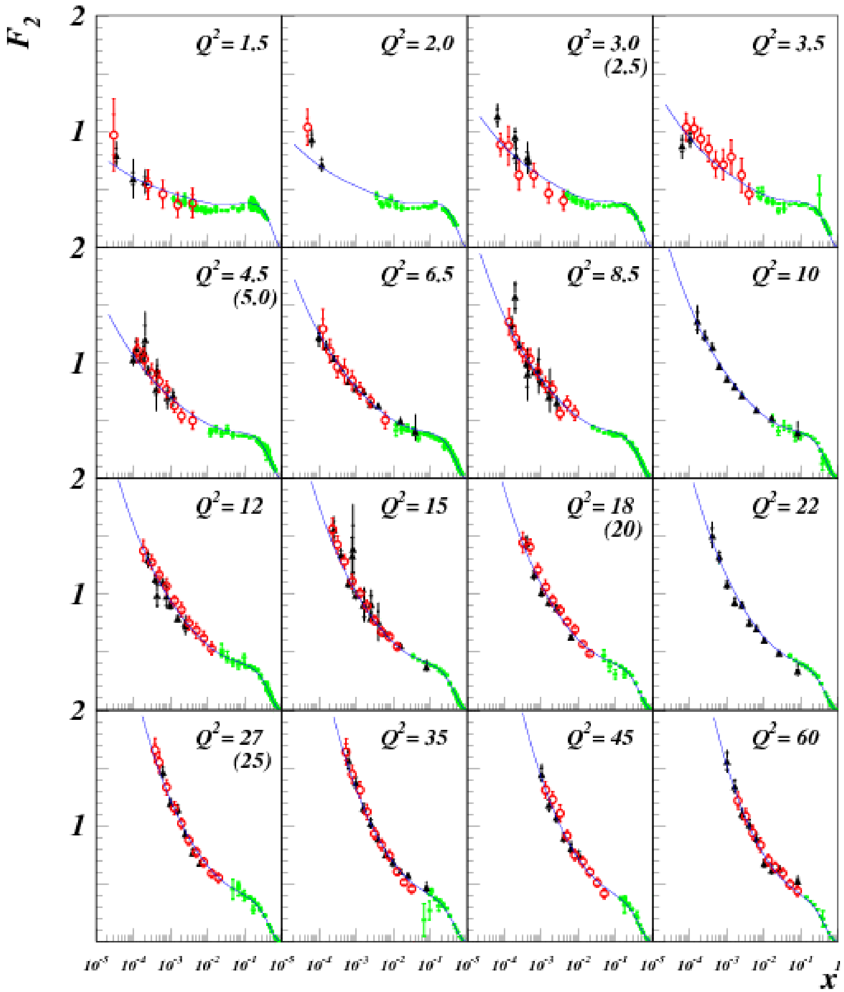
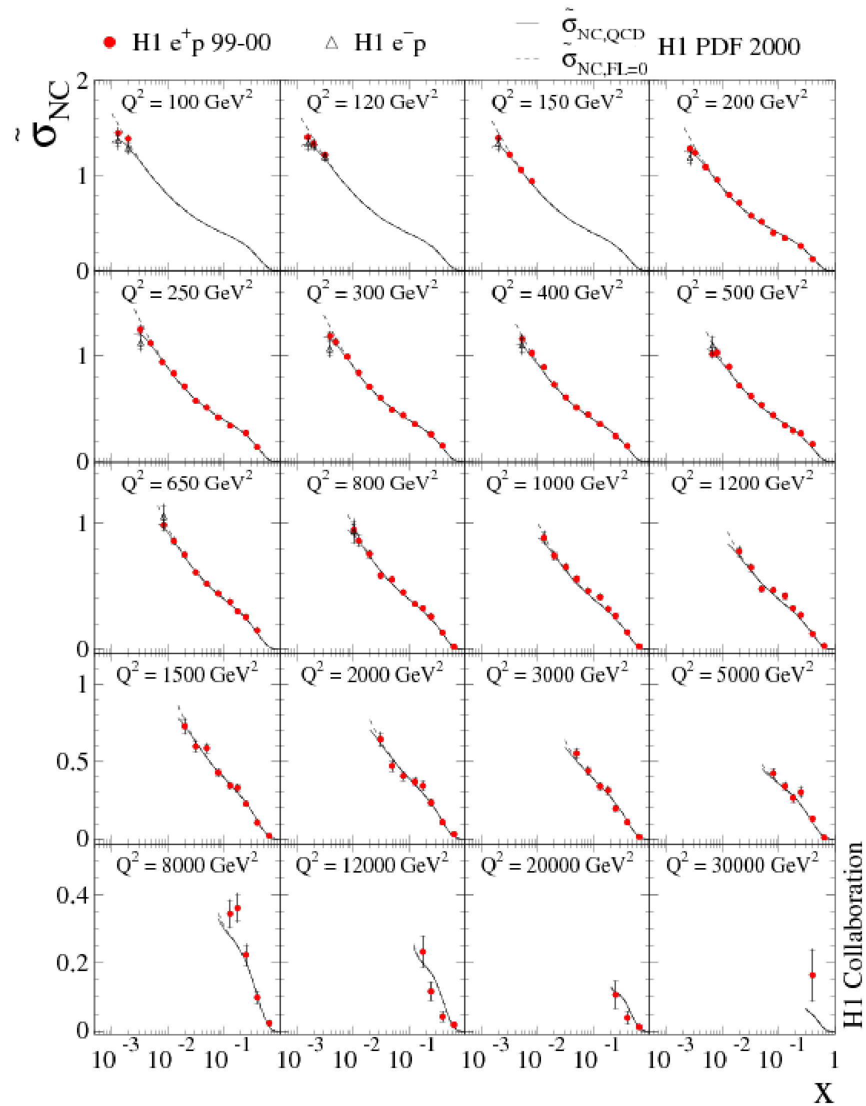
Reduced Cross Sections





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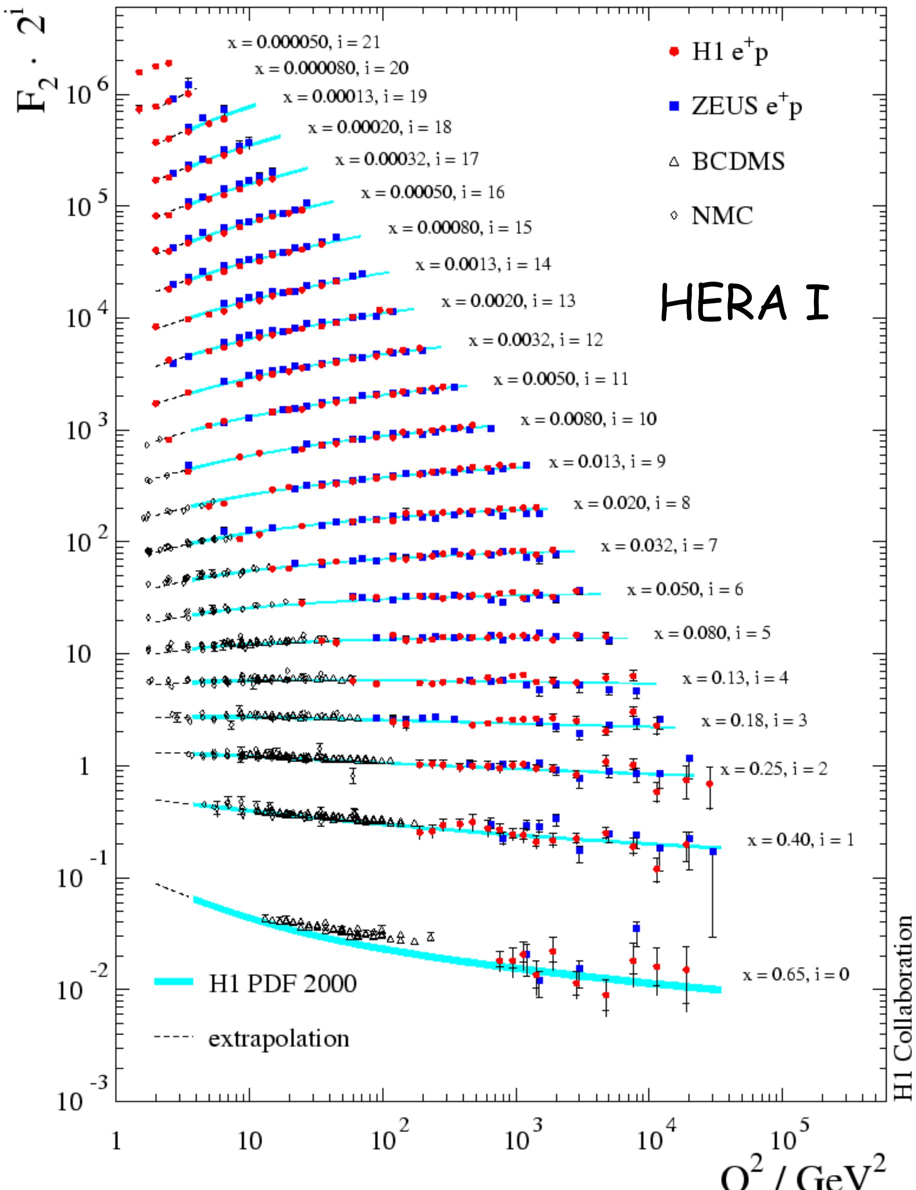
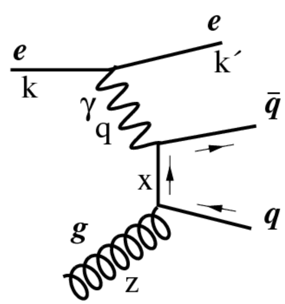
Structure Function F_2



- H1 & ZEUS extended fixed target kinematic regime in x and Q^2 by 2 Orders

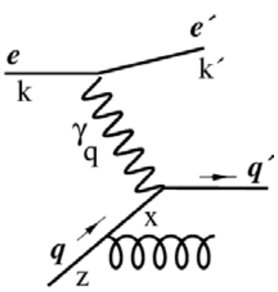
- Described by DGLAP

- Scaling violations →QCD (QPM: $F2 = \Sigma_i q_i(x)$)



rise at low x

drop at high x



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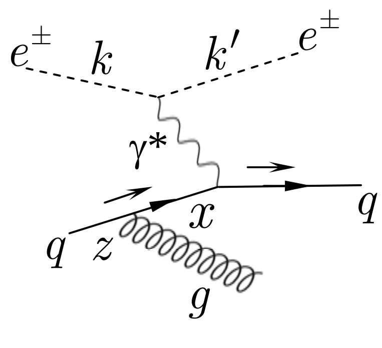
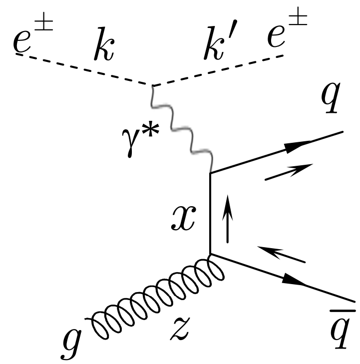
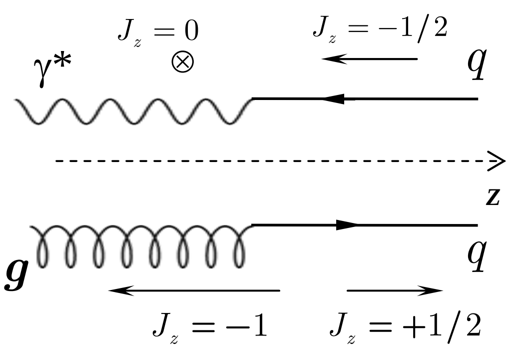
The Longitudinal Structure Function F_L

LO QCD :

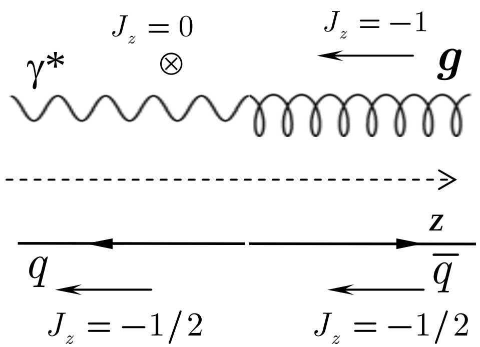


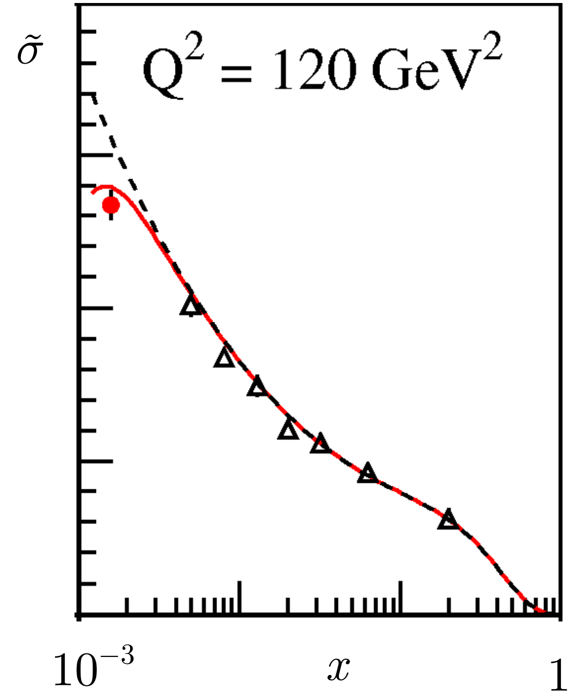




initial state

final state





$$F_L = \frac{Y_+}{y^2}\left(F_2^{\mathrm{QCD}} - \tilde{\sigma}\right)$$

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

in principle need 2 measurements at different $\sqrt{s}$

extrapolated in Q^2 using DGLAP

F_L important at high $y\,(=\text{low } x)$

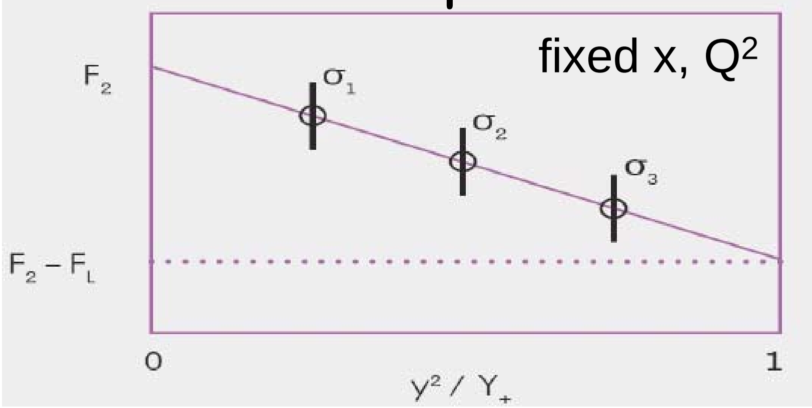
„Subtraction method"

Direct Measurement of F_L

- **Neutral current DIS cross section expressed by structure functions:**

$$\frac{d^2\sigma^{e^\pm p\to e^\pm X}}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\underbrace{\left(1+(1-y)^2\right)}_{Y_\pm = 1\pm(1-y)^2}\cdot\underbrace{\left(F_2(x,Q^2) - \frac{y^2}{Y_+}F_L(x,Q^2)\right)}_{\tilde{\sigma}:\ \text{Reduced cross section}}$$

Rosenbluth plot



$$F_2(x,Q^2) = \sigma_r(x,Q^2,y=0)$$

$$F_L(x,Q^2) = -\frac{\partial\sigma_r(x,Q^2,y)}{\partial\left(y^2/Y_+\right)}$$

Measure σ_r at fixed x, Q2 but varying y

$$y = Q^2/sx \qquad \sqrt{s} = ep \text{ center-of-mass energy}$$

Varying y →varying s → dedicated low E_p runs at end of HERA

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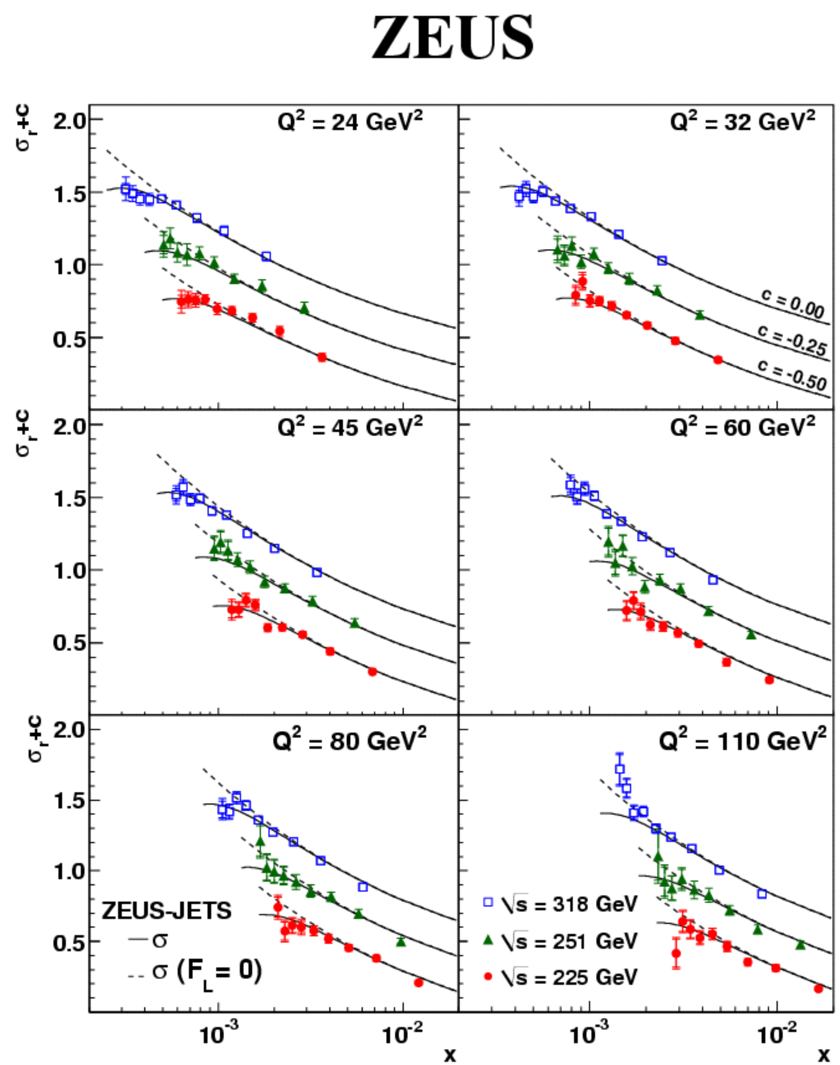
Coss Sections at low x, high y

- σ_r measured at 3 different $\sqrt{s}$
- comparison to ZEUS-JETS PDF prediction witl $F_L = F_L$(QCD) and F_L=0
- F_L causes suppression at low x
- Small effect but big enough to extract FL and F2



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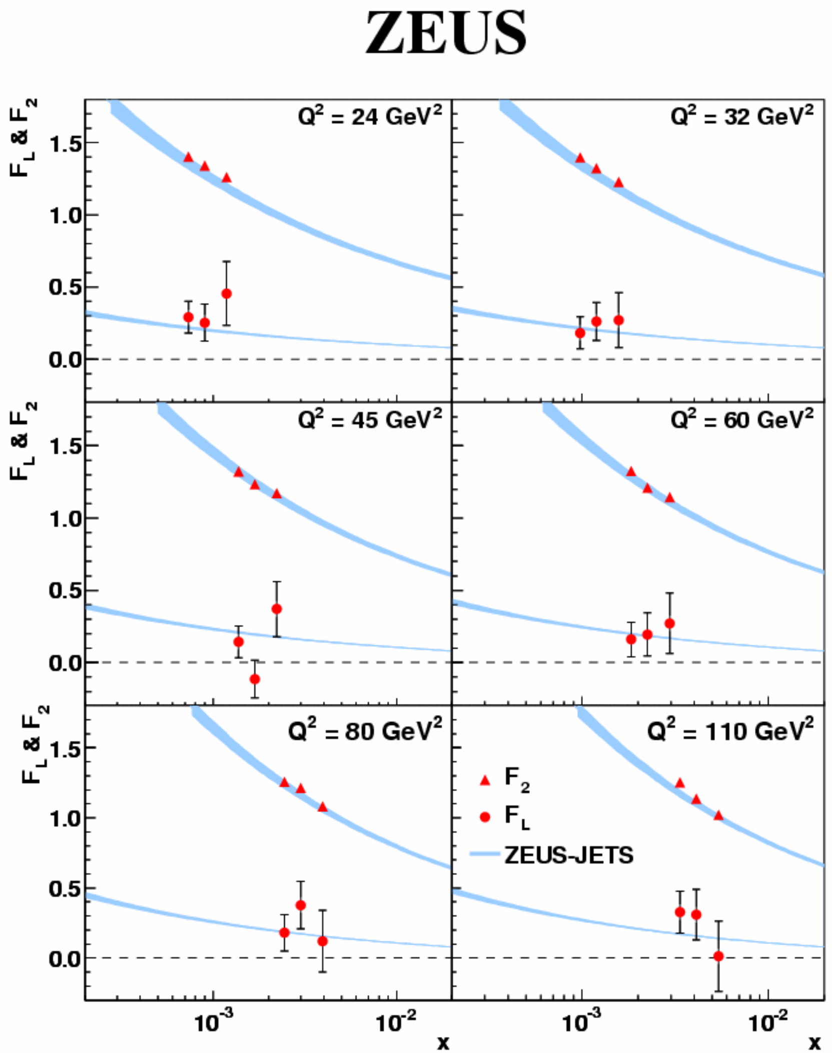
Extracted Structure Functions

- Simultaneous extraction of $F_L(x,Q^2)$ and $F_2(x,Q^2)$
- Error bars: experimental errors (stat & syst)
- Data support non-zero F_L
- Consistent with expectation from QCD



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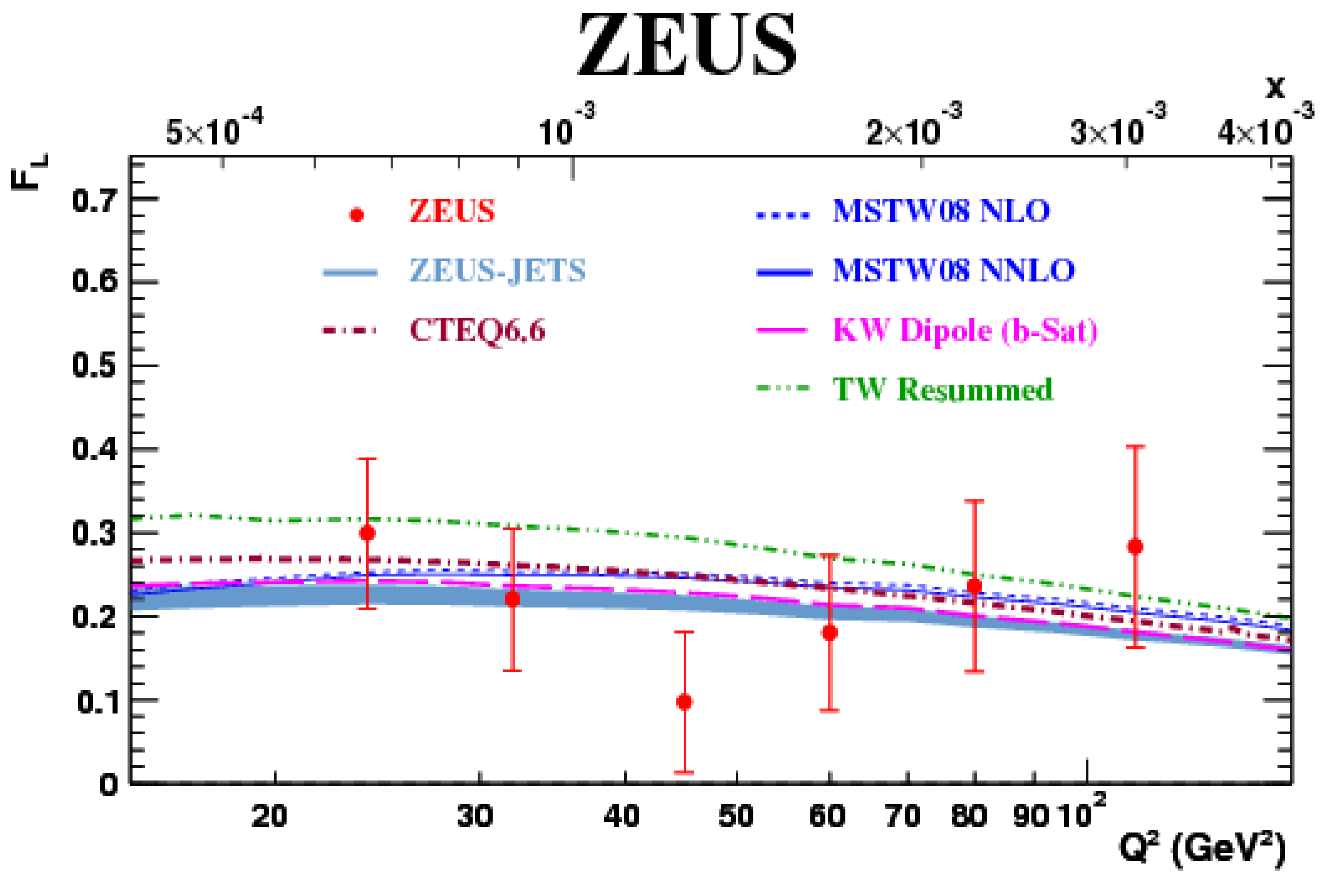
Longitudinal Structure Function

- $F_L(Q^2)$ i.e. averaged x
- FL cleary non-zero



- **Compared to various predictions, consistent with data**
- **Import Cross check of QCD**

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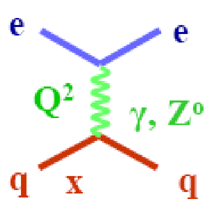
Input to HERA PDF Fits

Inclusive DIS data: Neutral Current and Charged Current

- NC

$$\frac{d^2\sigma^{e^\pm p\to e^\pm X}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\underbrace{\left(1+(1-y)^2\right)}_{Y_\pm=1\pm(1-y)^2}\cdot\left(\tilde{F}_2\left(x,Q^2\right)-\frac{y^2}{Y_+}\tilde{F}_L\left(x,Q^2\right)\mp\frac{Y_-}{Y_+}x\tilde{F}_3\left(x,Q^2\right)\right)$$

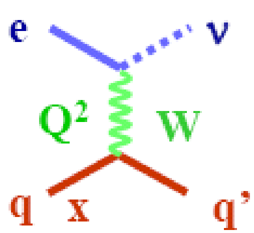


$$\tilde{F}_2 = \sum_i A_i(Q^2)\left[xq_i + x\bar{q}_i\right] \Rightarrow F_2^{em} = \frac{4}{9}x\left(u+\bar{u}+c+\bar{c}\right)+\frac{1}{9}x\left(d+\bar{d}+s+\bar{s}\right)$$

$$x\tilde{F}_3 = \sum_i B_i(Q^2)\left[xq_i - x\bar{q}_i\right] \Rightarrow xF_3 = B_U x\left(u-\bar{u}+c-\bar{c}\right)+B_D x\left(d-\bar{d}+s-\bar{s}\right)$$

Electroweak Coefficient Functions $A_i(Q^2)$, $B_i(Q^2)$ (QED: $A_i=e_i^2$)

- CC



$$\sigma_{CC}(e^+p) \propto x\left[(1-y^2)\left(d+s\right)+\left(\bar{u}+\bar{c}\right)\right]\times(1+P_e)$$

$$\sigma_{CC}(e^-p) \propto x\left[\left(u+c\right)+(1-y^2)\left(\bar{d}+\bar{s}\right)\right]\times(1-P_e)$$

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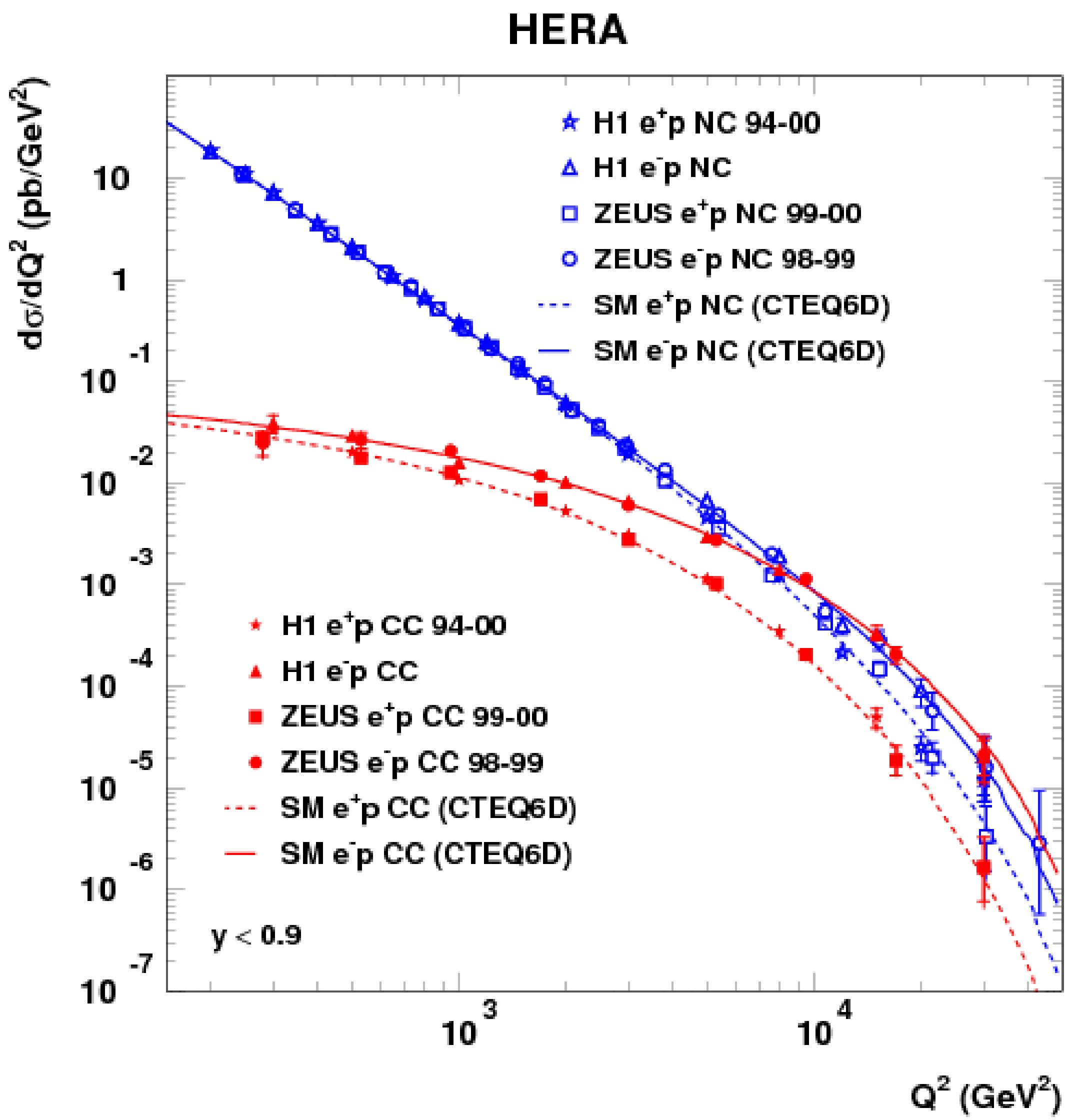
Electroweak Unification at High Q^2 (NC & CC)



$\sigma_{NC} >> \sigma_{CC}$

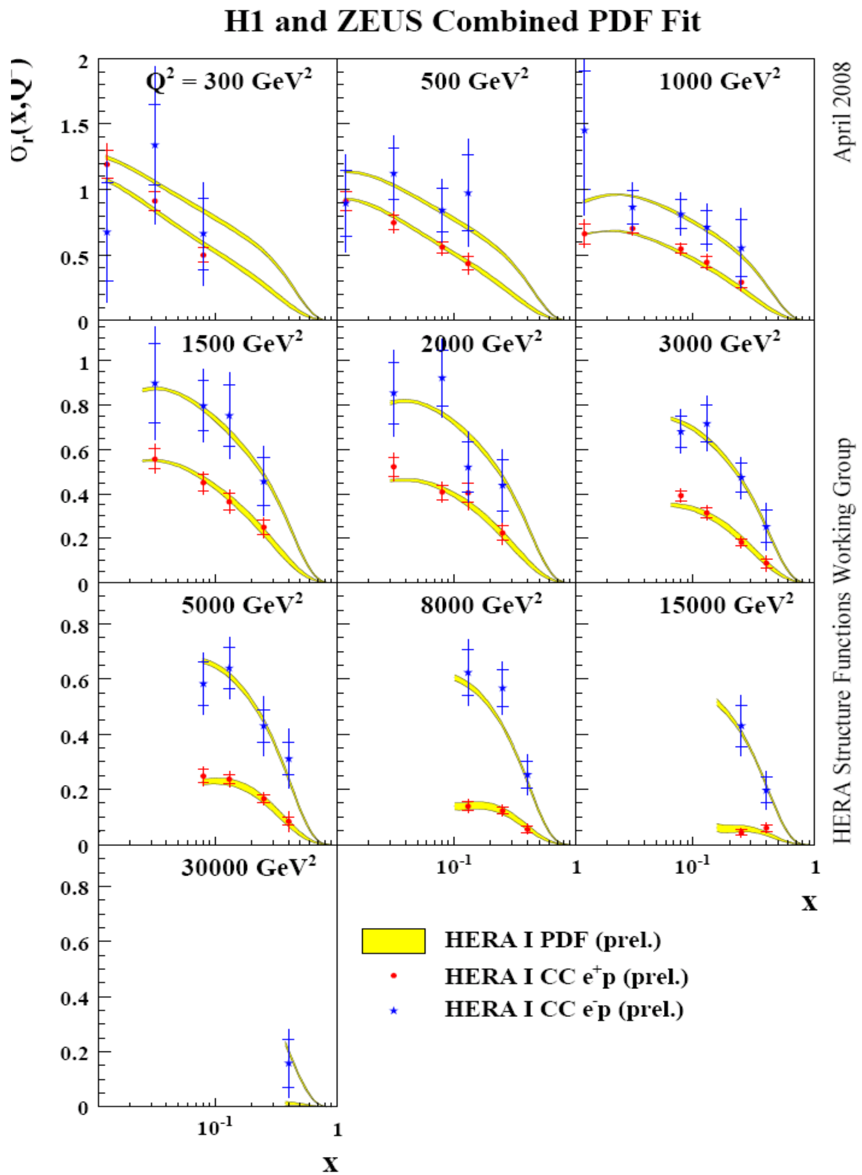
for $Q^2 << M_Z^2$

(photon exchange dominates)

$Q^2 \geq M_Z^2$: $\sigma_{CC} \sim \sigma_{NC}$

manifest
electroweak unification

Charged Current Cross Section



CC Cross section provide flavor sensible constrains at high x

$$\sigma_{CC}(e^+p) \propto x\left[(1-y^2)D + \bar{U}\right]$$

$$\sigma_{CC}(e^-p) \propto x\left[U + (1-y^2)\bar{D}\right]$$

Improved precision of σ_{CC} By combining H1 and ZEUS

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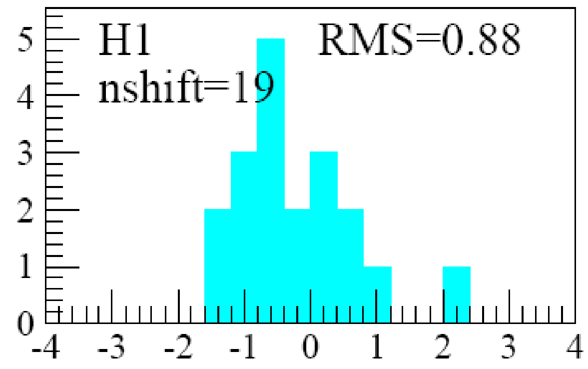
PDF Fit: χ^2-Definition

$$\chi^2 = \sum_k^{n_{exp}} \sum_i^{N_k} \frac{\left(\sigma_{k,i}^{exp} - \sigma_{k,i}^{th} \cdot (1 - n_k \delta_k^{norm} - \sum_j^{n_s(k)} s_{k,j}\, \delta_{k,i,j}^{syst})\right)^2}{\delta_{k,i}^{sta\,2} + \delta_{k,i}^{unc\,2}}$$

$$+ \sum_k^{n_{exp}} n_k^2 + \sum_k^{n_{exp}} \sum_j^{n_{s(k)}} s_{j,k}^2$$

- We explicitly allow the data points to be shifted by the fit



$\sigma_{k,i}^{exp}$:	measurement i of dataset k	$\delta_{k,i}^{unc}$:	uncorrelated systematic error
$\sigma_{k,i}^{th}$:	prediction for data point i of dataset k	$\delta_{k,i,j}^{sys}$:	correlated systematic error of source j
n_{exp}:	number of datasets	δ_k^{norm}:	uncertainty of dataset normalization
N_k:	number of data points in dataset k	n_k:	shift of normalization
$\delta_{k,i}^{sta}$:	statistical error	$s_{k,j}$:	shift of systematic of source j

"Pascaud and Zomer" method, extended χ^2 (preprint LAL-95-05):

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Details on HERAPDF 0.1

Chosen form of the PDF parametrization at Q_0^2

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2+Fx^3\ldots)$$

	A	B	C	D	E
gluon	sum rule				
u_v	sum rule				
d_v	sum rule	$=B(u_v)$			
U_{bar}	Lim $x \to 0$ $\overline{u}/\overline{d} \to 1$				
D_{bar}		$=B(\overline{U})$			

The number of parameters for each parton has been optimized

Optimization means starting with only BLUE parameters and adding D, E,F parameters until there is no further $\chi2$ advantage

PDFs fiited: gluon, u_v, d_v, $U_{bar}=u_{bar}+c_{bar}$, $D_{bar}=d_{bar}+s_{bar}+b_{bar}$

Sea flavour break-up at Q_0: s = fs*D, c=fc*U , $AU_{bar}=(1-fs)/(1-fc)AD_{bar}$ — Lim $x \to 0$ $u_{bar}/d_{bar} \to 1$

fs = 0.33D (s=0.5d), fc = 0.15U consistent with dynamical generation

mc=1.4 GeV mass of charm quark mb=4.75 GeV mass of beauty quark

Zero-mass variable flavour number heavy quark scheme (for now)

$Q_0^2 = 4\ \mathrm{GeV}^2$ input scale $Q^2_{min} = 3.5\ \mathrm{GeV}^2$ minimum Q^2 of input data

$\alpha_s(Mz) = 0.1176$ PDG2006 value

Renormalization and factorization scales = Q^2

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Comparison of Separate H1 and ZEUS PDF Fits

$$xf(x) = Ax^B(1-x)^C(1+Dx+Ex^2+Fx^3...)$$

Alternative form of PDF parametrization: H1 style

	A	B	C	D	E	F
gluon	sum rule					
U	$\lim_{x\to 0} \bar{u}/\bar{d} \to 1$			sum rule		
D		$=B(U)$		sum rule		
U_{bar}	$=A(U)$	$=B(U)$				
D_{bar}	$=A(D)$	$=B(U)$				

PDFs: gluon, $U=u+c$, $U_{bar}=u_{bar}+c_{bar}$, $D=d+s+b$, $D_{bar}=d_{bar}+s_{bar}+b_{bar}$

Sea flavour break-up at Q_0: $s = fs{*}D$, $c=fc{*}U$ $AU=(1-fs)/(1-fc)AD$

Alternative form of PDF parametrization: ZEUS style

	A	B	C	D	E!
gluon	From Sum Rule				0.
u_v	From Sum Rule				
d_v	From Sum Rule	$= B_{uv}$			0.
$u_{bar} - d_{bar}$	from Z_S_11 fit	from Z_S_11 fit	from Z_S_11 fit	0.	0.
Sea				0.	0.

PDFs: gluon, u_v, d_v, Sea= $u_{sea}+u_{bar}+d_{sea}+d_{bar}+s+s_{bar}+c+c_{bar}$

Sea flavour break-up at Q_0: $s_{bar} = (d_{bar}+u_{bar})/4$, charm dynamically generated,

$d_{bar}-u_{bar}$ fixed to fit E866 data

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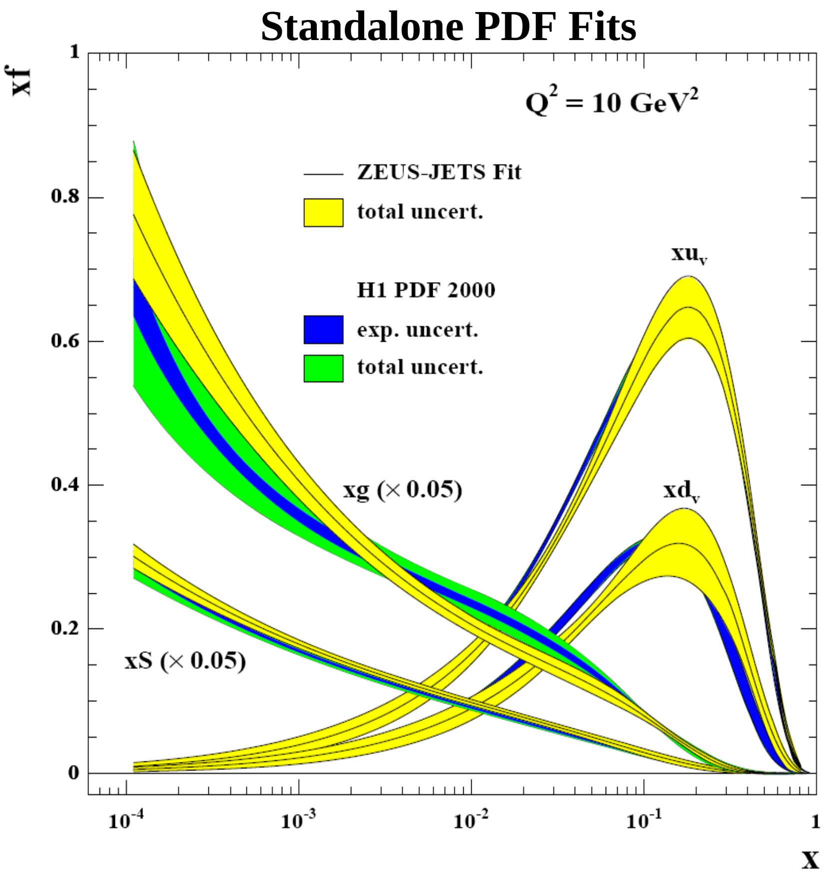
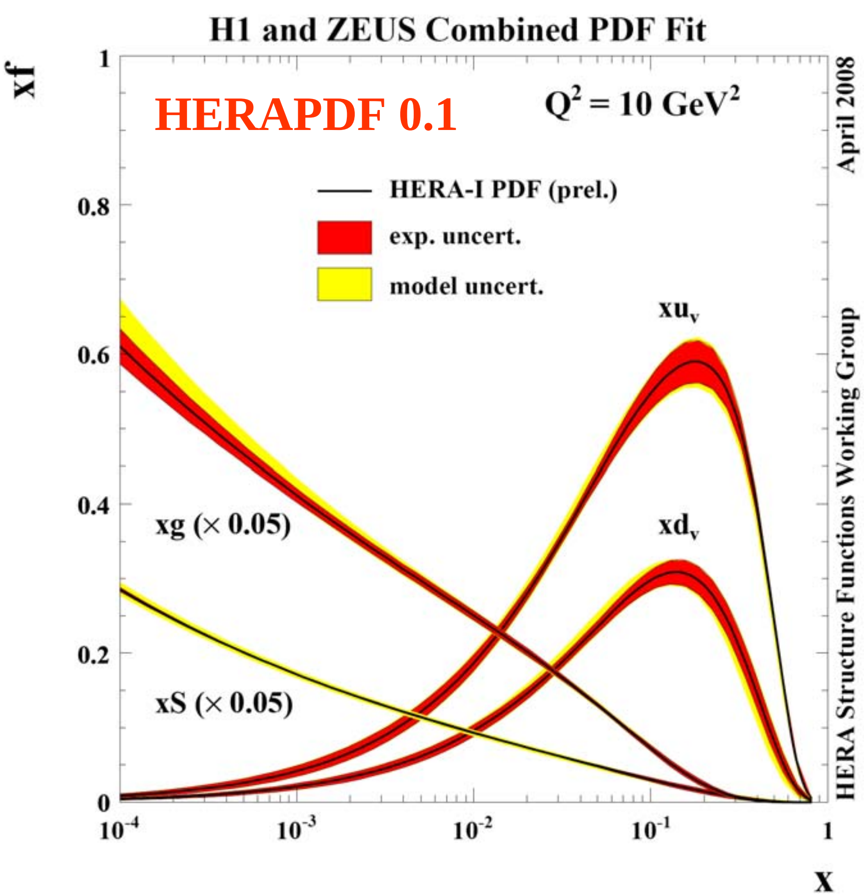
PDF Fits on HERA I Data





Impressive reduction of uncertainties of combined PDFs

Model uncertainty: variation of charm and bottom mass, starting scale Q_0^2, Q^2_{min} of included data, strange and charm fraction at starting scale

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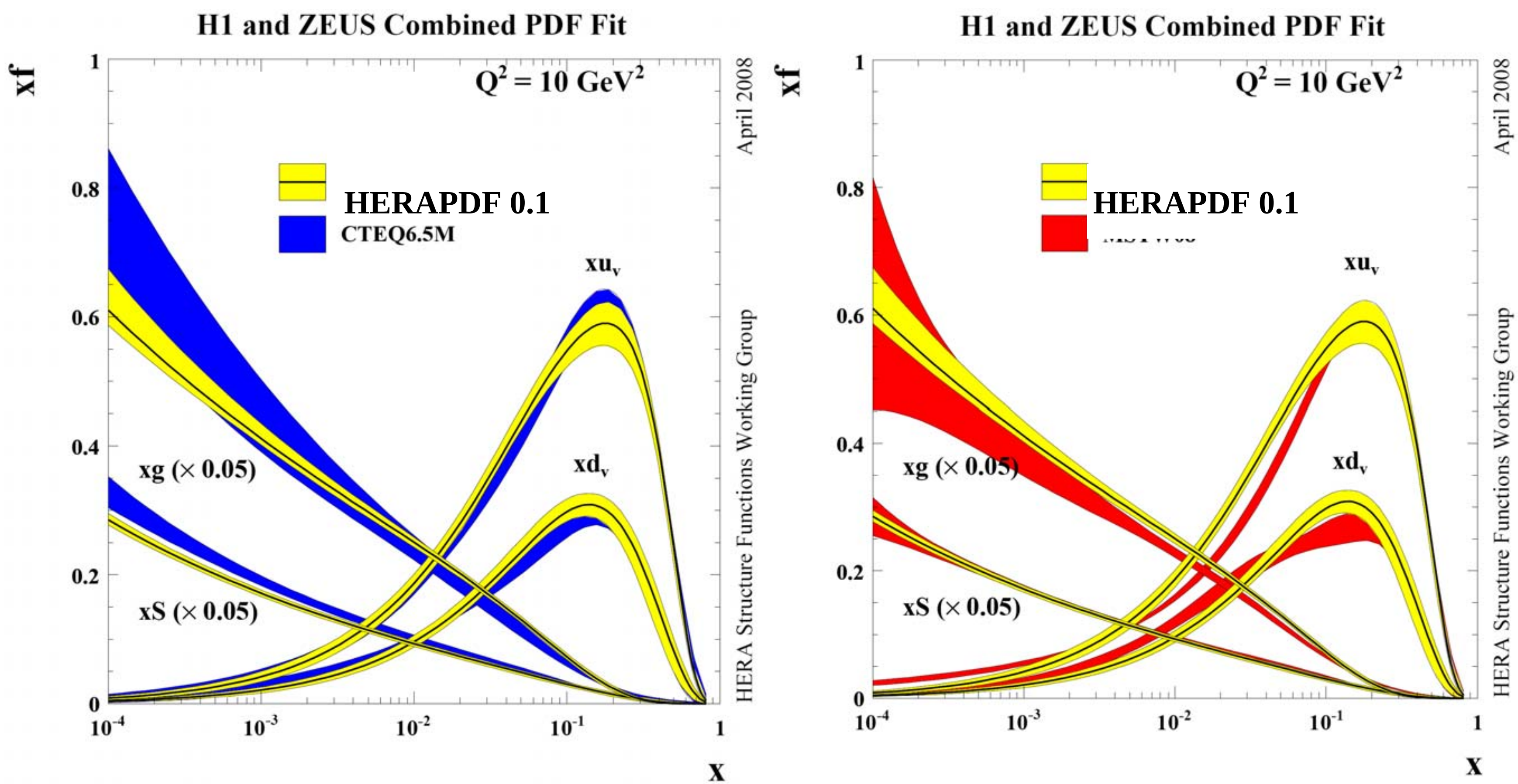
Comparison to Global Fits



not a completely fair comparison:
HERA combined data were not available to global fitters

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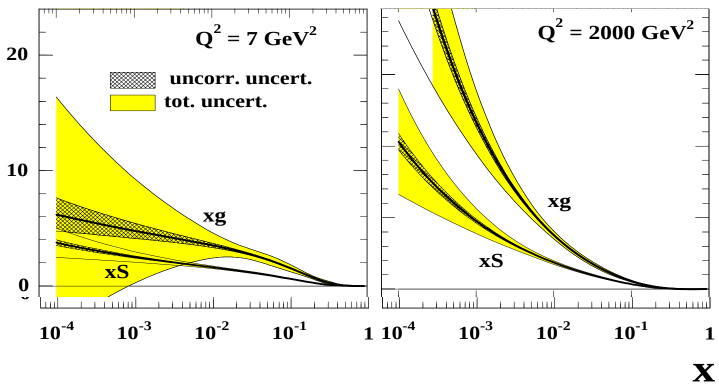
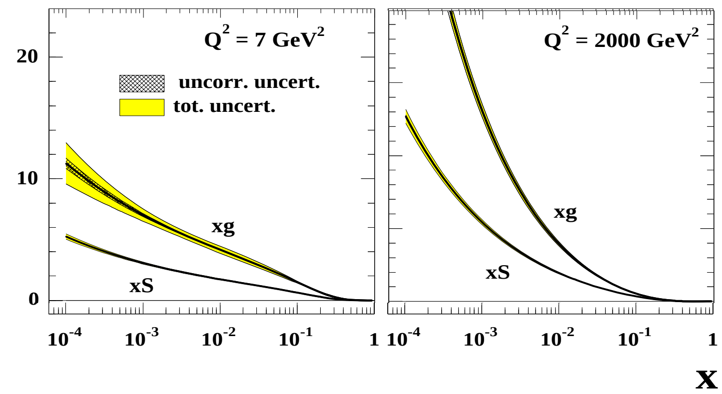
Impact of HERA data

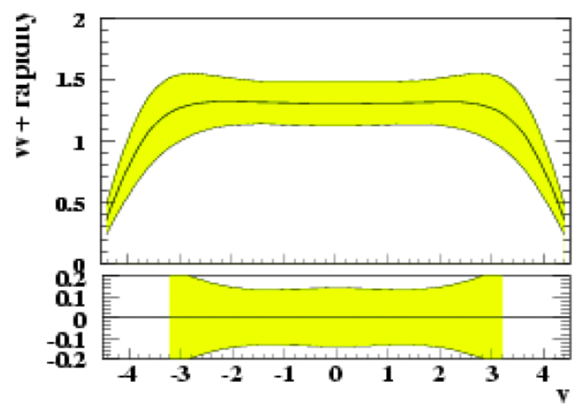
Pre-HERA uncert. in gluon/sea PDFs

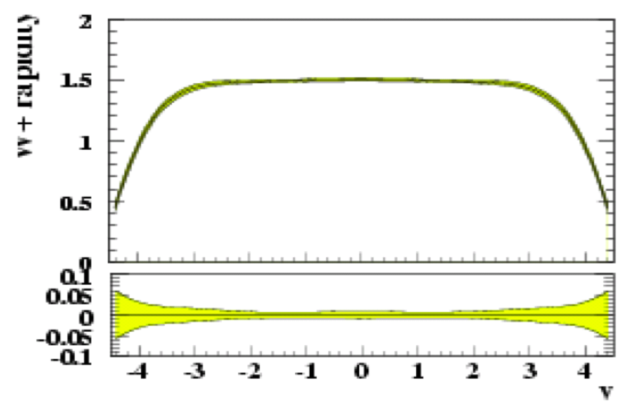


HERA PDFs combining H1 and ZEUS



Example: W^+ production at the LHC (Study by A. Cooper-Sakar)





Note: Error bands are experimental uncertainties only
model uncertainty will become increasingly important

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Open Issue
Light flavor decomposition of the $q\bar{q}$ sea

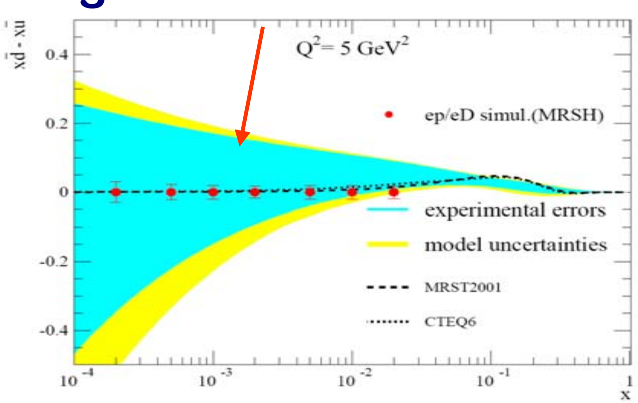
PDF fits conventionally assume

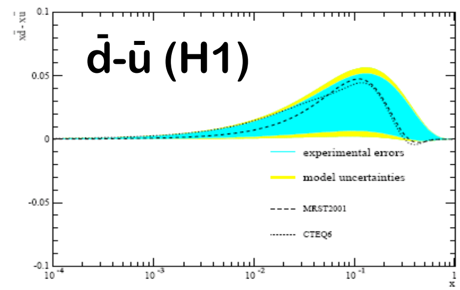
$$x\bar{d} - x\bar{u} \xrightarrow{x \to 0} 0$$

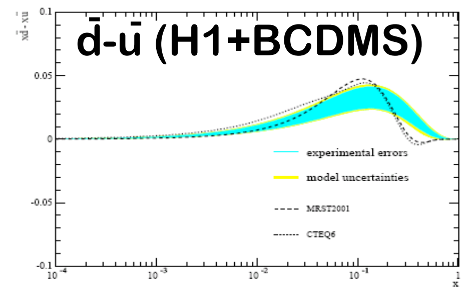
NMC found $\bar{d} \neq \bar{u}$ at medium x

Here is what happens when the xd – xu constraint at low x is relaxed

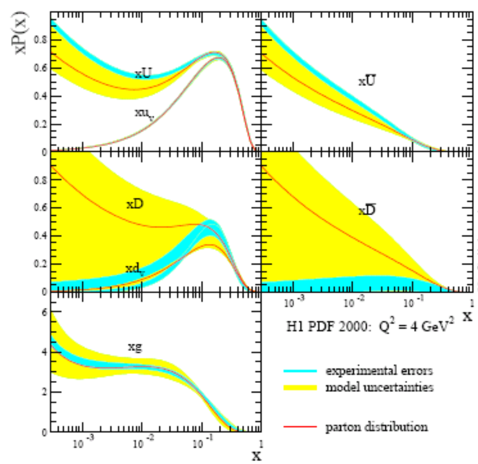
A deuteron run at HERA Could have disentangled the light flavor sea







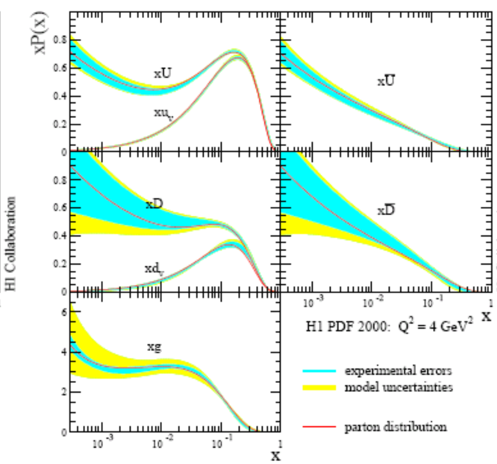
H1 only (HERA I)



Poorly constrained

Attempt to fit U and D Only one input: F_2 ep

H1 +BCDMS



Fit stabilized by fixed target data (sum rules help)

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Future HERA PDF Fits

- So far only part of the inclusive HERA I were used → HERAPDF0.1

➔Incorporate all NC and CC from HERA I&II

➔Include jet cross sections
→constrain high x gluon

➔Include charm and beauty
→ flavor decomposition of the sea

➔Charged & Neutral current cross sections with polarized $e^{\pm}$ beams
→ constrain valence quark region

Conclusion

- Deep Inelastic Scattering revealed the Structure of Nucleon

- Parton Densities of Proton obtained from inclusive cross section measurements

-

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Backup slides

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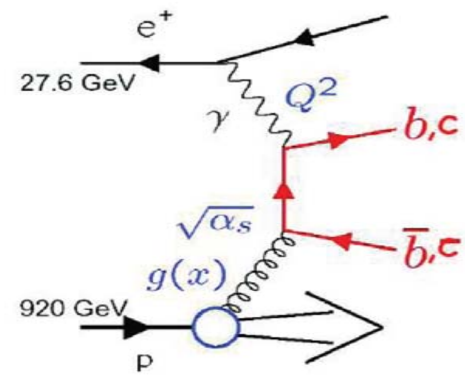
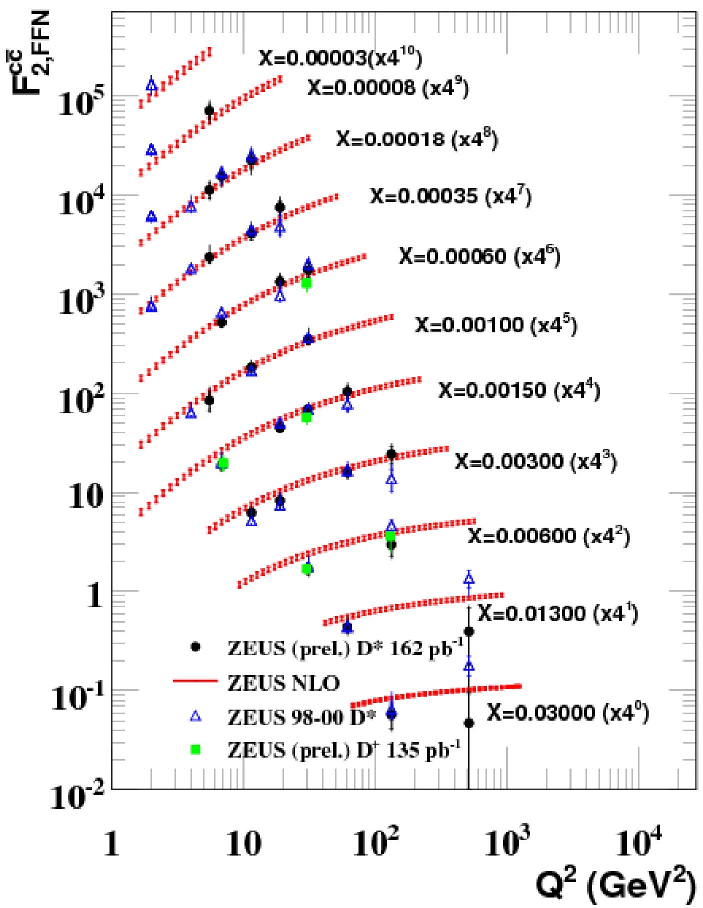
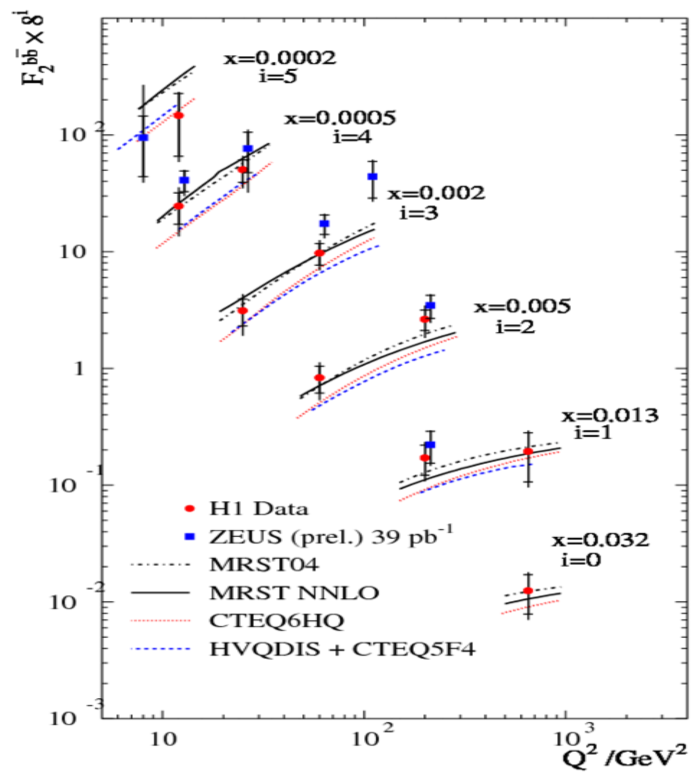
Charm & Beauty Structure

Charm and Beauty production in DIS is driven by gluons in the proton

Charm tag: reconstruct D mesons
Beauty tag: displaced vertex, soft μ







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