Deep Inelastic Scattering
DIS

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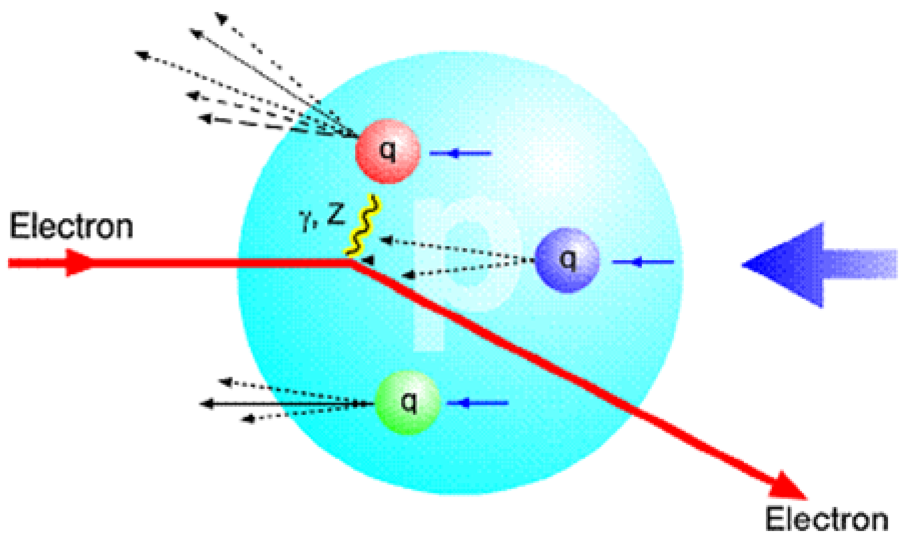


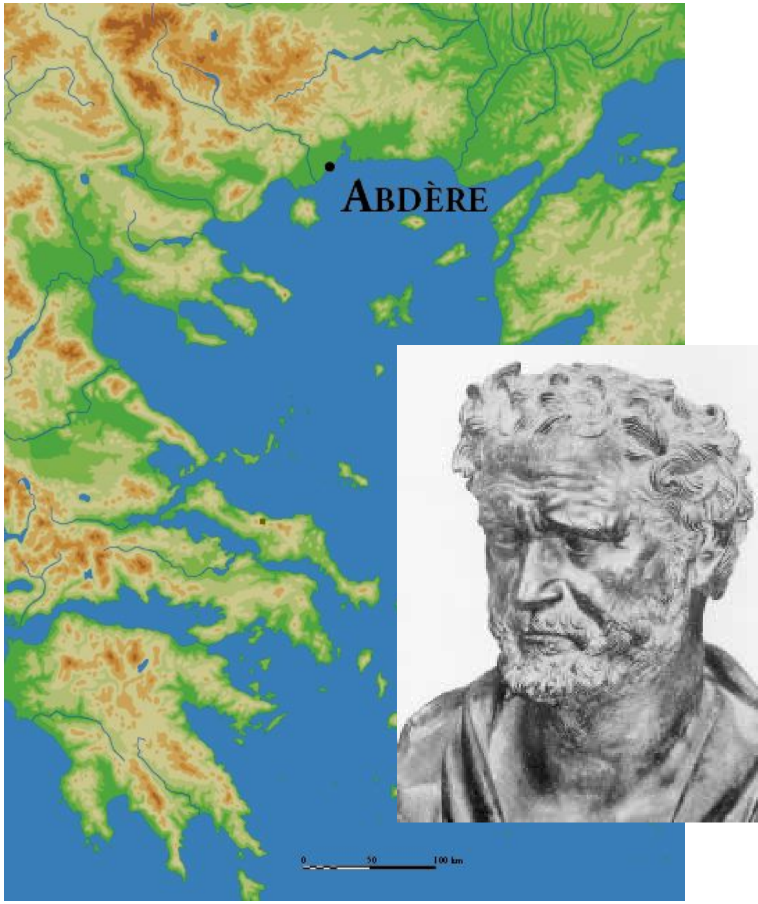
- Historical Prelude
- Introduction to DIS and proton structure
- Impact of recent results from HERA

Prelude: Antic “Gedankenexperiment”

Popular science book
by Leon Ledermann
“The God Particle”:

Slicing of
Feta cheese:

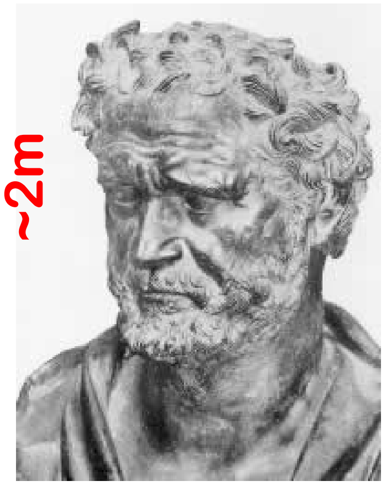
Could we continue the slicing for ever or do we end up with some smallest unit?



Demokrit (460 -371 v.Chr.):
“By convention hot, by convention cold, but in reality atoms and void, and also in reality we know nothing, since the truth is at bottom.”

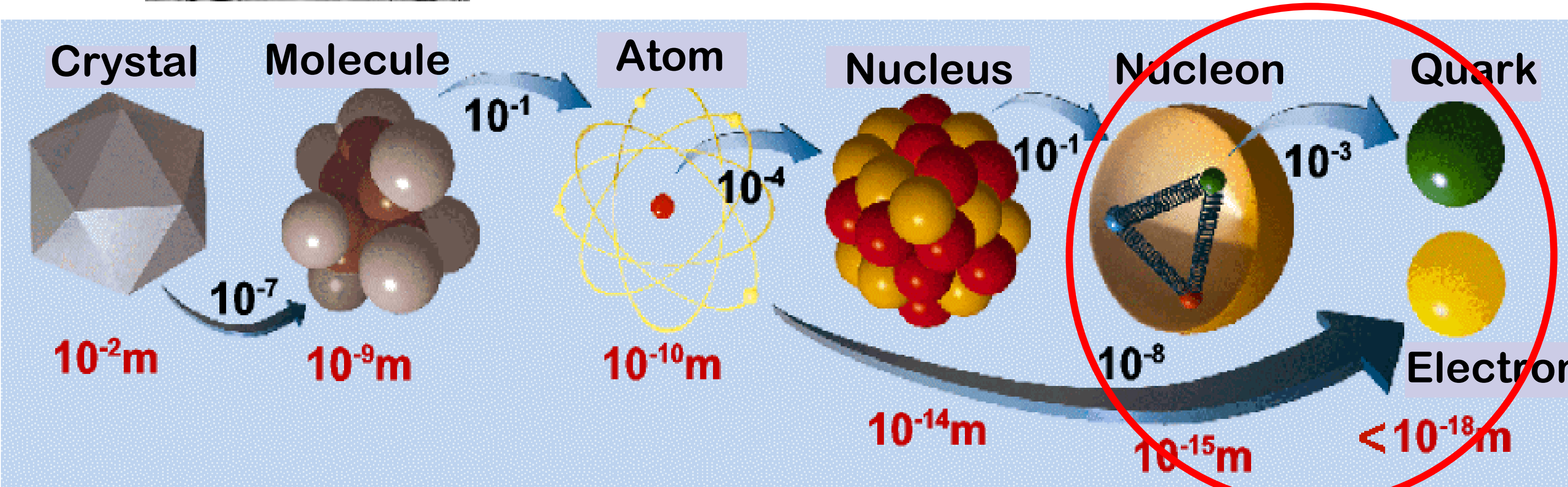
In search of the smallest particle

Human ~2m



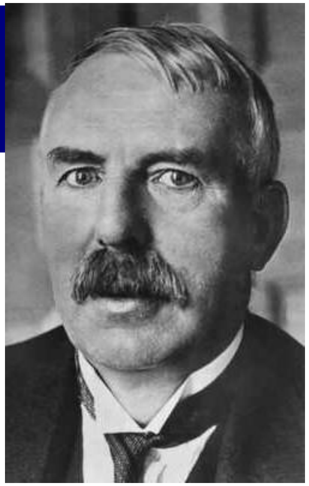
More than 2400 years after Demokrit we still ask the same question.

Employing the experimental methods of modern physics in search for answers.

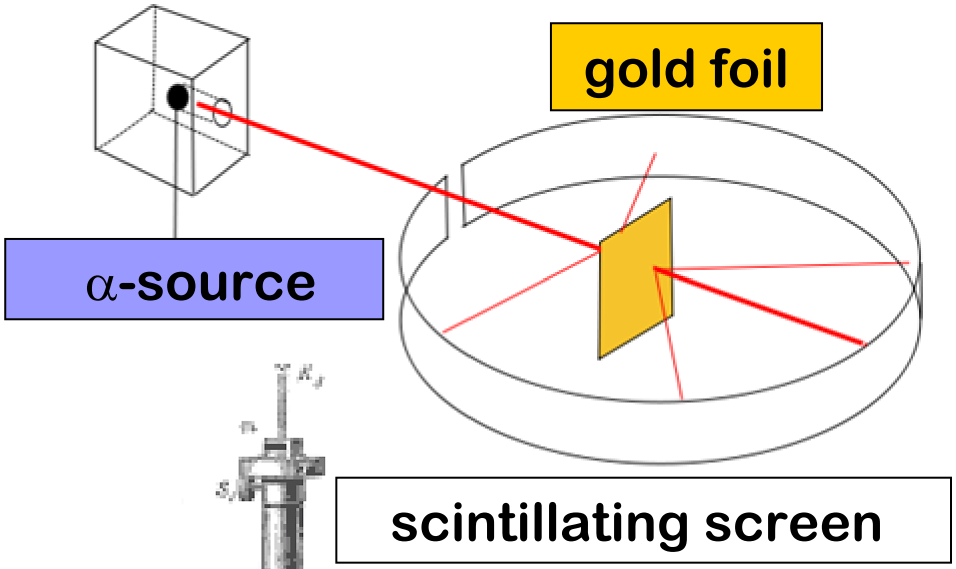


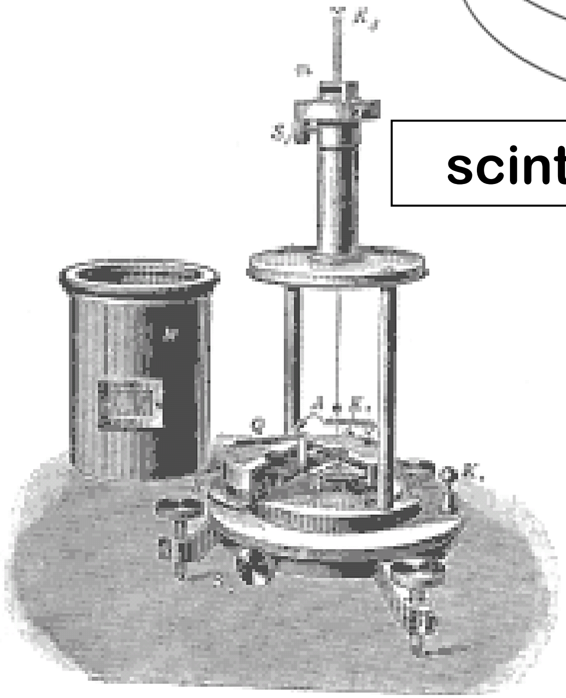
Focus of Deep inelastic scattering

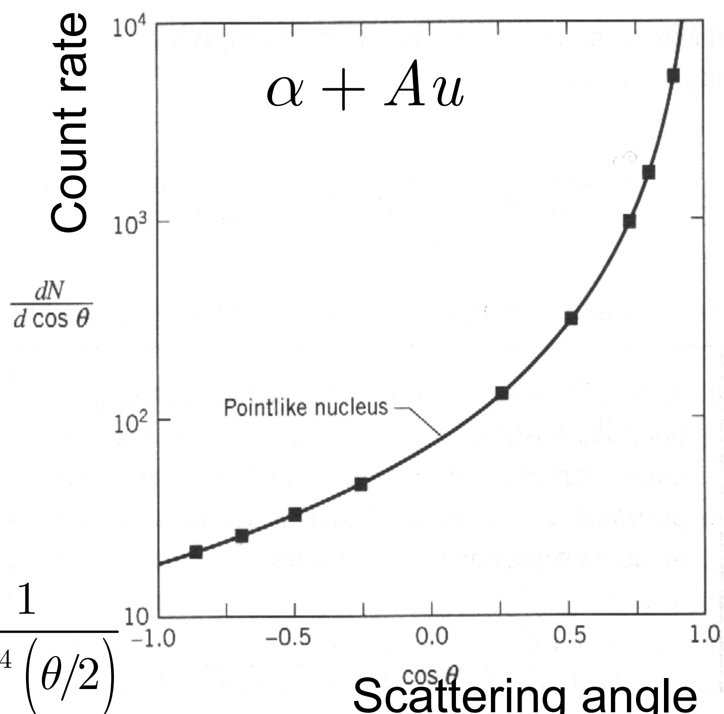
It all began with Ernest Rutherford .



The "mother" of all scattering experiments

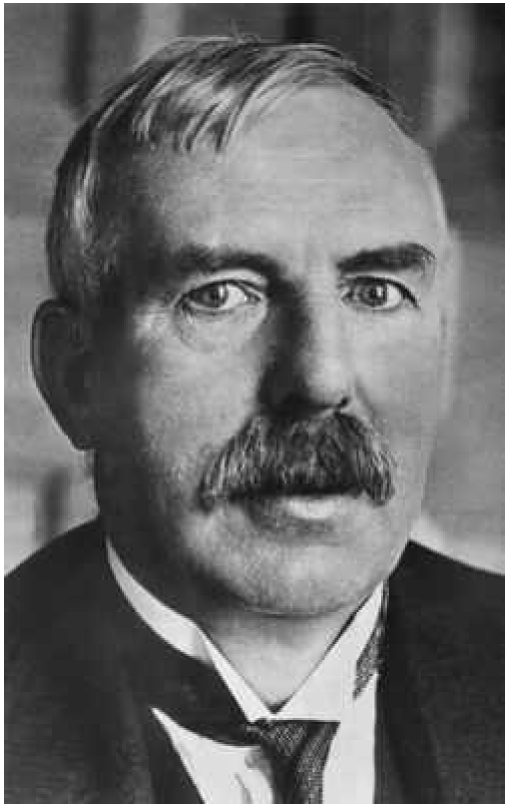






$$\frac{d\sigma}{d\Omega} = (zZ\alpha)^2 \left(\frac{\hbar c}{4E_{\text{kin}}}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

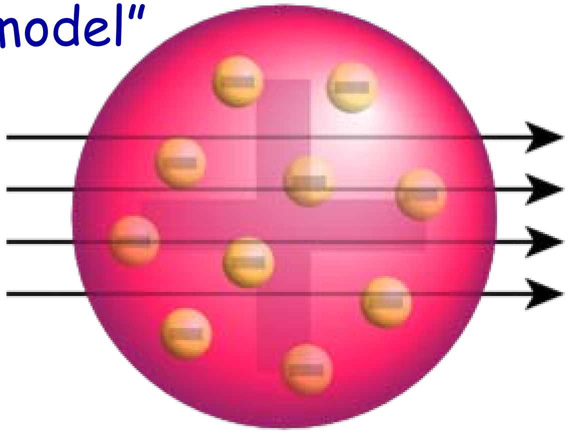
Ernest Rutherford Interpretatio



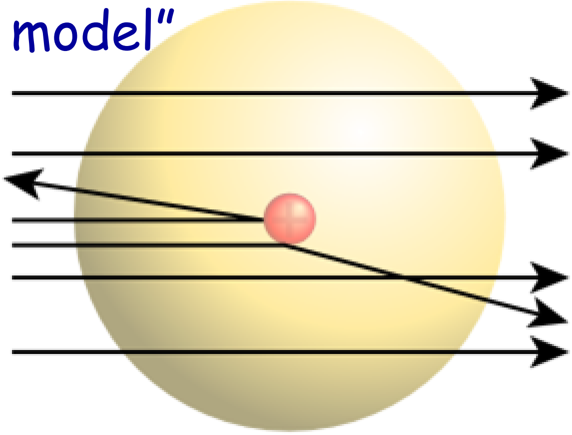
E. Rutherford

Nobel prize 1908 in Chemistry
(not for this ingenious idea!)

Thomson's old
"plum pudding model"

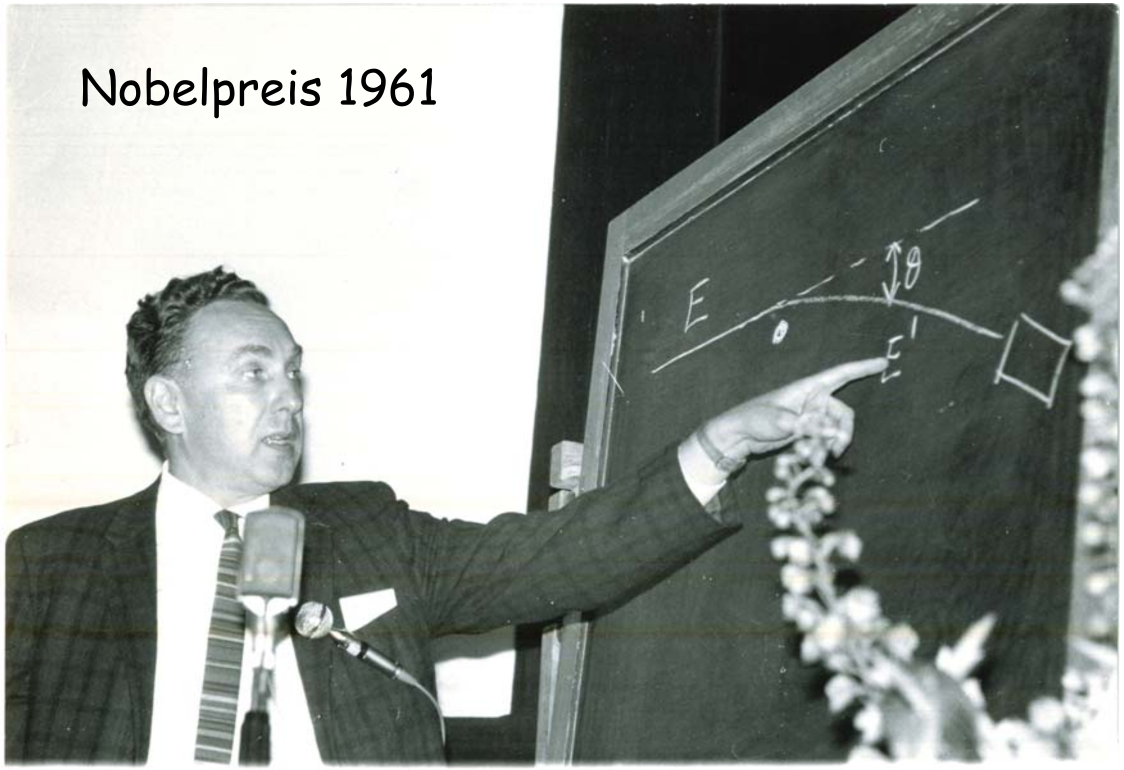


Rutherford's new
"planetary model"



Halo of electrons surrounding
a point like core, i.e. nucleus

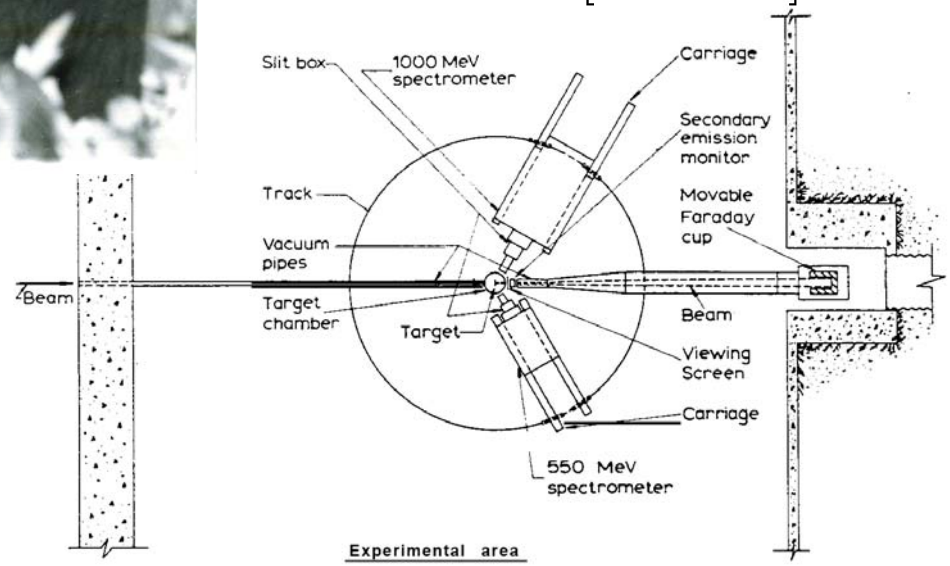
Pioneer of Electron Scattering: Robert Hofstadter



Electrons:
- Elementary particle
- Only sensitive to the charge distribution of the target
- Easy to produce, accelerate and detect

Rule of thumb: Resolution

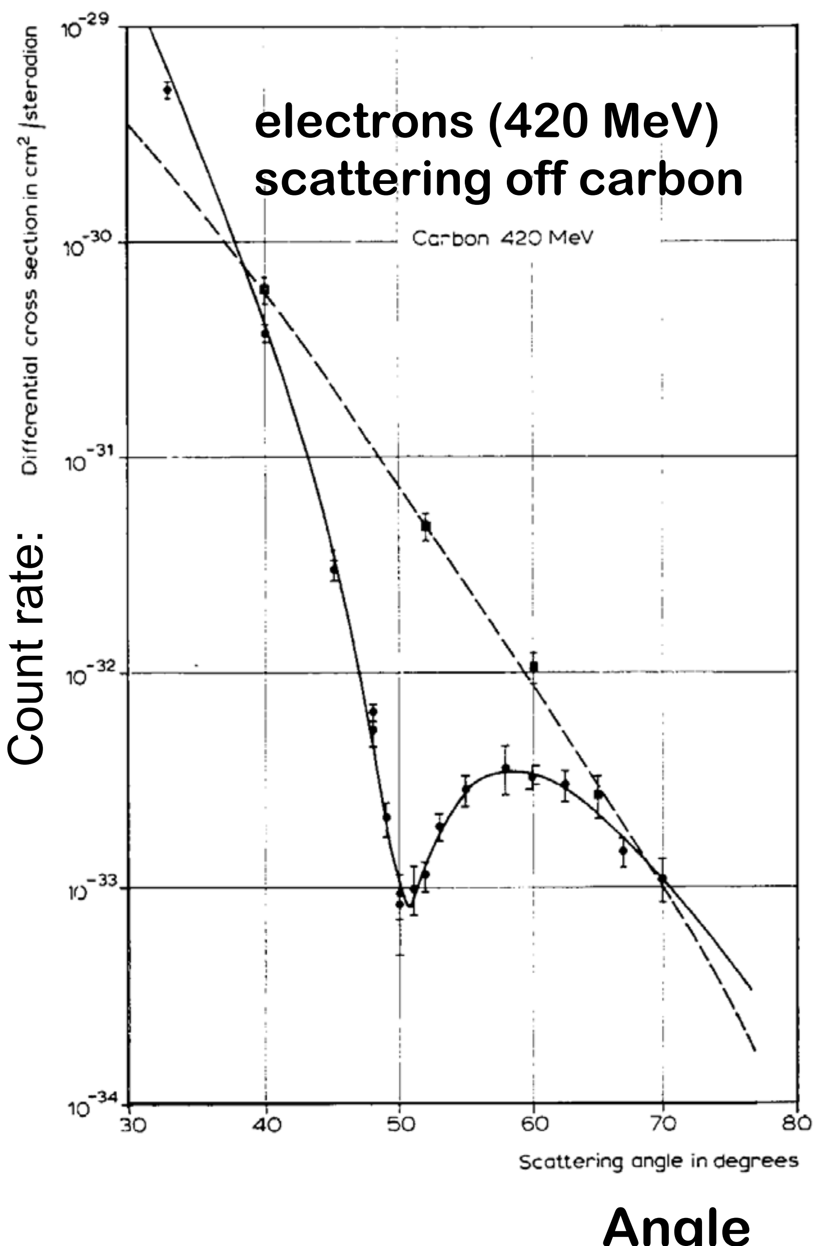
$$\hbar c = 200 \ [\mathrm{MeV\ fm}]$$



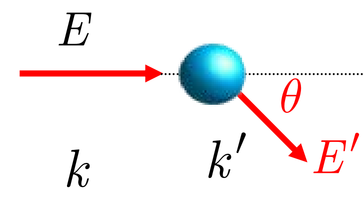
Typical design of an electron scattering experiment:

Beam of electron hits on a fixed target

Graphs from R. Hofstadter's Nobel-Lecture, Dez. 11, 1961



Elastic Scattering:

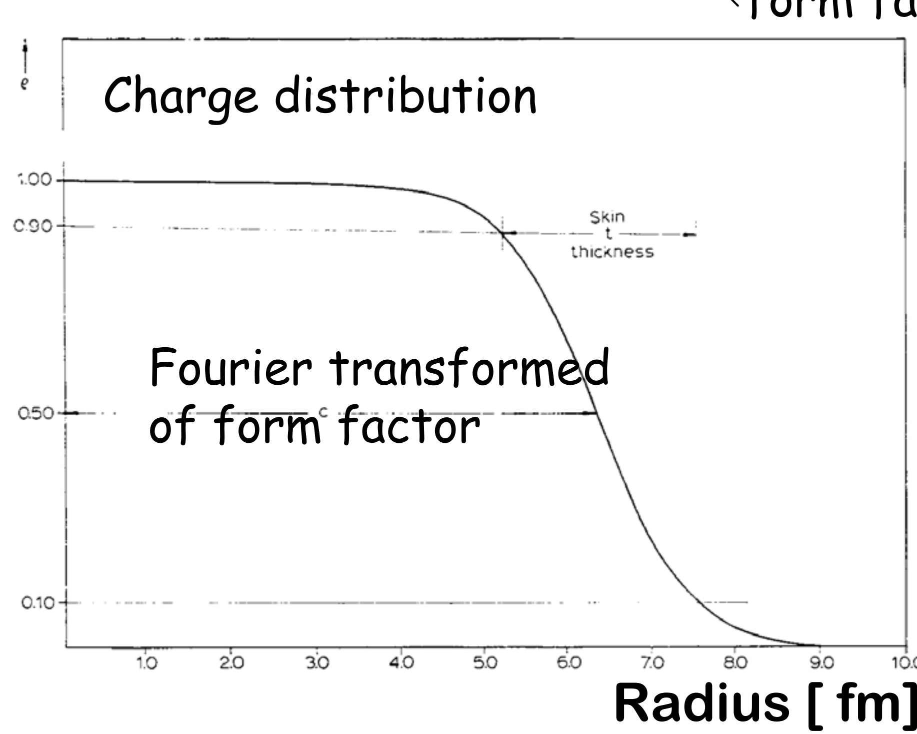


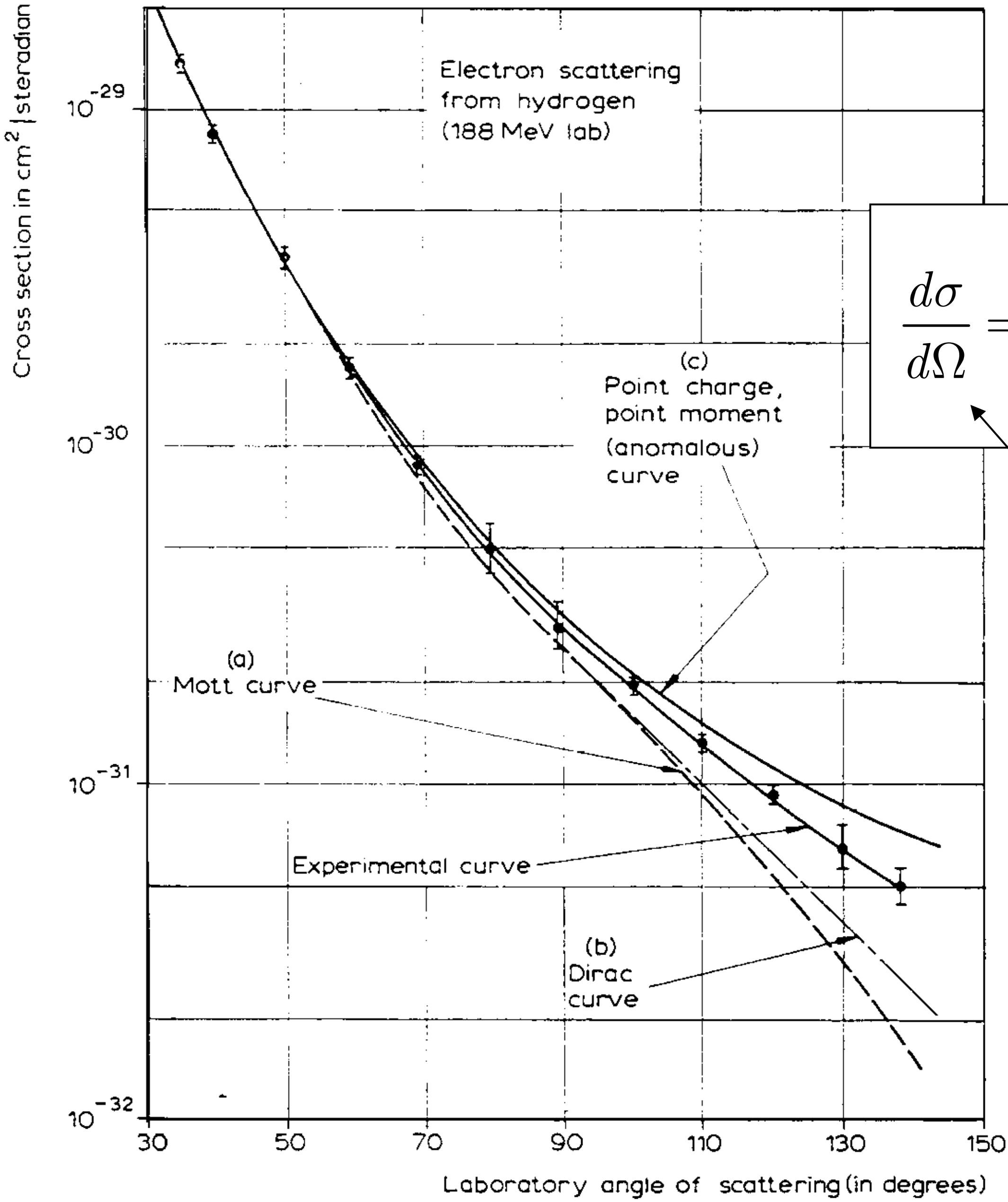
dip structure → finite nuclear radius

$$q = k - k'$$

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

form factor





Something is „wrong“ with the proton …

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

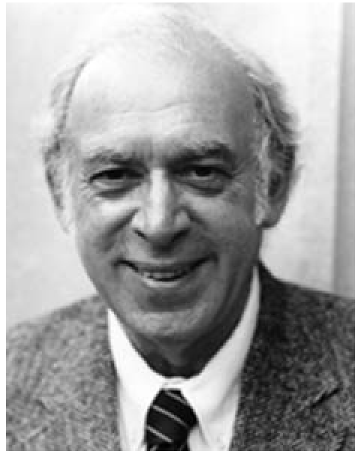
Cross section for electron scattering on a spin 1/2 Dirac proton

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

Pioneers of High Energy Physics

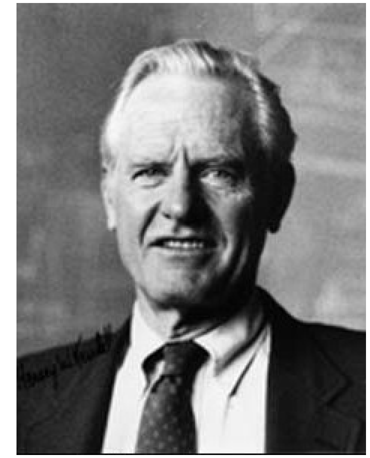
E_e (multi GeV)

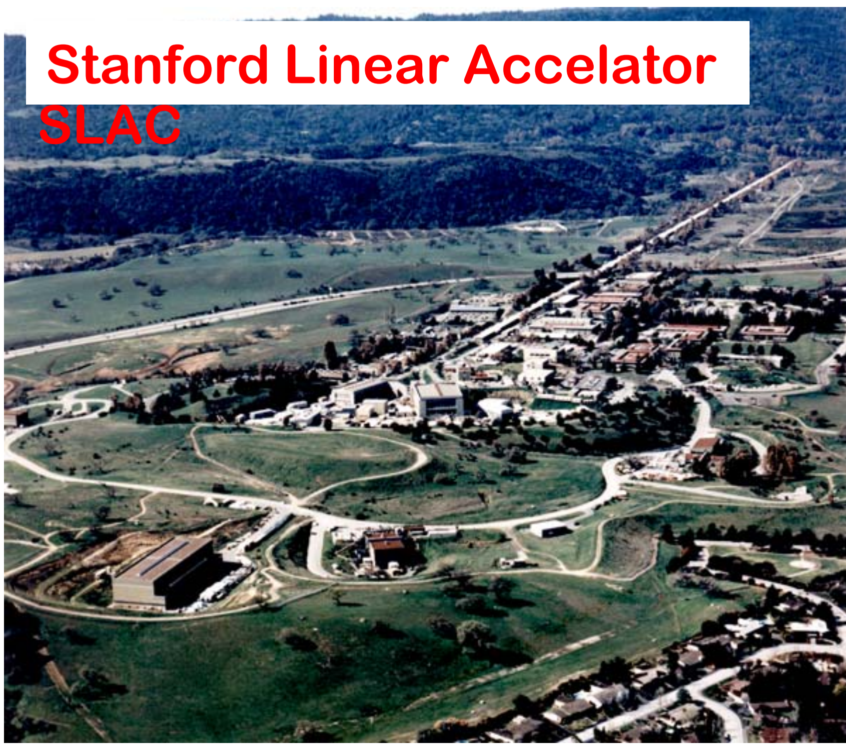
J. Friedman



R. Taylor

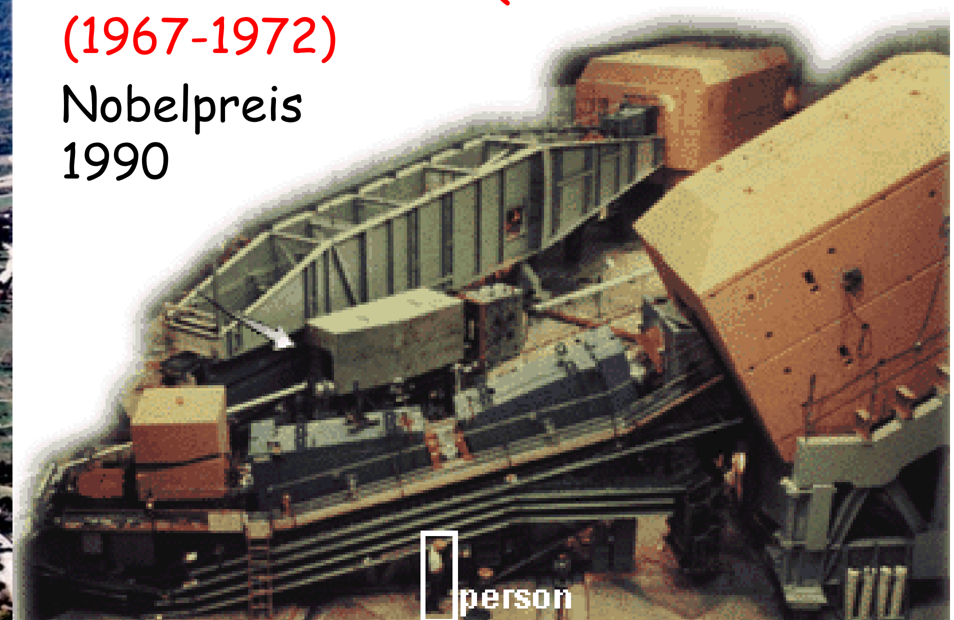
H. Kendall





Proton is made of Quarks !
(1967-1972)

Nobelpreis
1990

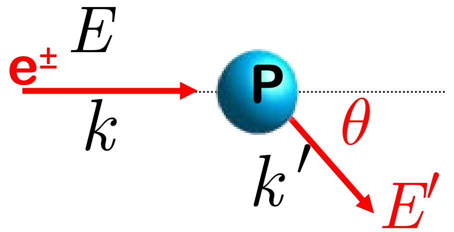


„Endstation A" spectrometers

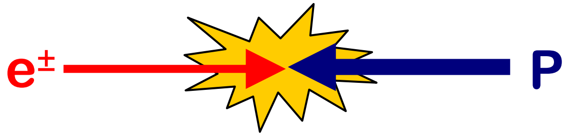
Resolving the Structure of the Protons

In order to resolve even smaller struktures
even higher energies are necessary

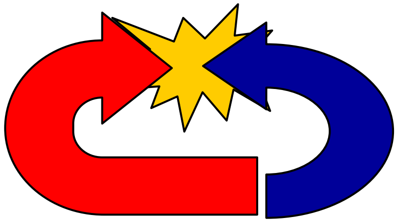
- So far: Electron beams on fixed targes (+μ,ν,... on p,d,Fe ...)



- Increasing the available centre-of-mass energy
  ➔ Colliding beams



- „Recycle" particle beams ➔ Storage Ring, Collider



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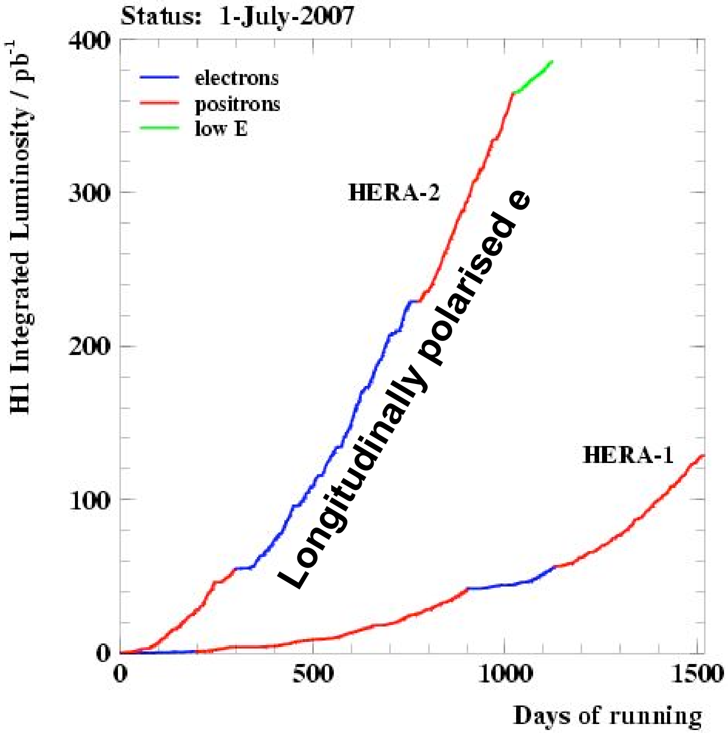
HERA *ep* Collider: 1992-2007



Two colliding beam experiments: H1 and ZEUS

~0.5 fb^{-1} collected per experiment

approximately same amount of collisions with

electrons and positrons of

Left- and right-handed polarisation

E_e = 27.5GeV, E_p = 920 GeV

dedicated low Ep runs

Ep = 460GeV,575 GeV

H1 & ZEUS Collaborations

Collaborations of 300-400 Physicists, at ~40 Institutes of ~15 Countries

Partons in the proton

Feynman's parton model: the nucleon is made up of point-like constituents (later identified with quarks and gluons) which behave incoherently.
The probability $f(x)$ for the parton f to carry the fraction x of the proton momentum is an intrinsic property of the nucleon and is process independent.

If I were thinking about an experiment where we collide protons with protons at, say, 14 (7)TeV: then this is great! Because:

-Protons are just a "beam of partons" (incoherent)
-The $f(x)$s, the "beam parameters", could be measured in some other process. (process independent)

Quarks and Gluons as partons

$u(x)$: up quark distribution
$\bar{u}(x)$: up anti-quark distribution
etc.

Momentum has to add up to 1 ("momentum sum rule")

$$\boxed{\int x[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)+s(x)+\bar{s}(x)+\ldots.]dx = 1}$$

Quantum numbers of the nucleon has to be right

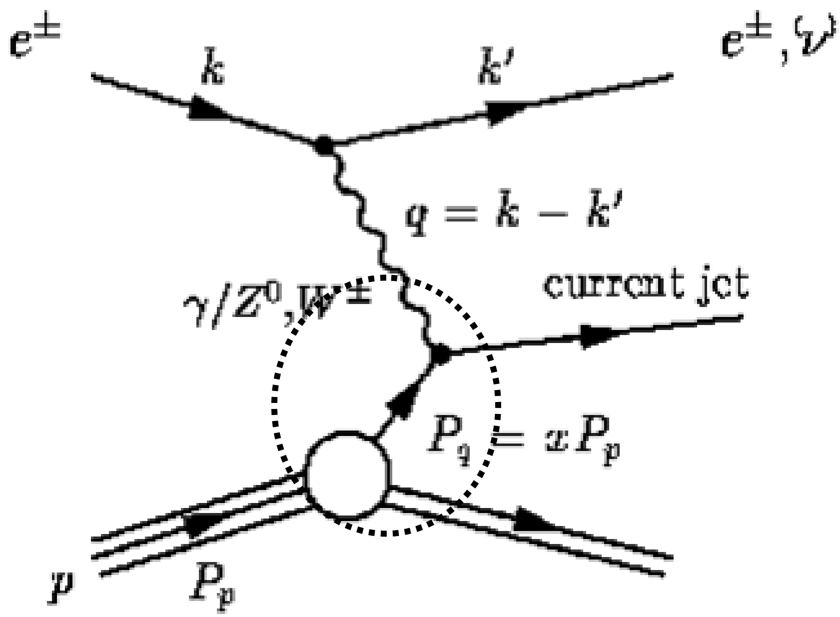
So for a proton:

$$\int[u(x)-\bar{u}(x)]dx=2 \qquad \int[d(x)-\bar{d}(x)]dx=1$$

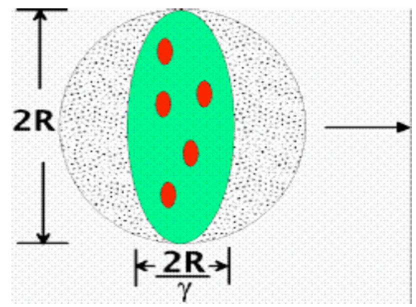
$$\int[s(x)-\bar{s}(x)+\ldots\ldots]dx=0$$

DIS kinematics

ep collision



proton in "∞" momentum frame



No transverse momentum

$0 \leq x \leq 1$

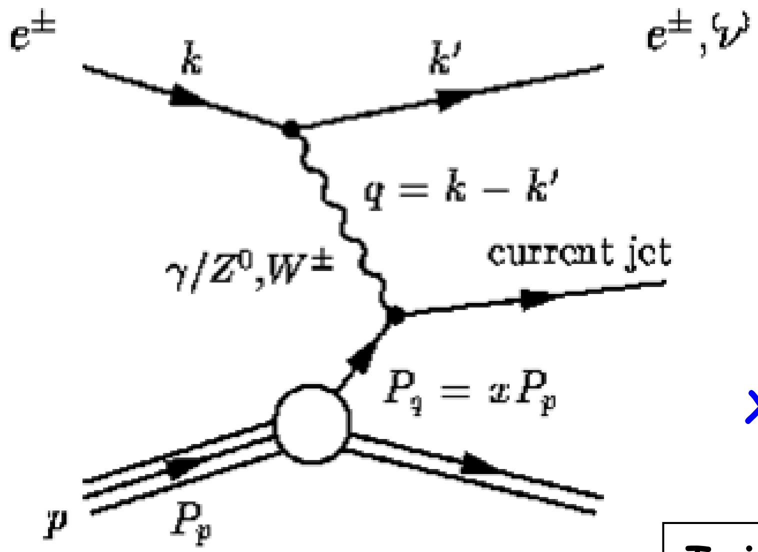
x = fractional longitudinal momentum carried by the struck parton

$\sqrt{s}$ = ep cms energy

$Q^2 = -q^2$ = 4-momentum transfer squared (or virtuality of the "photon")

DIS kinematics

ep collision



Final electron energy

Initial electron energy

$$Q^2 = -q^2 = -(k-k')^2 = 2E_e E'_e(1+\cos\theta_e)$$

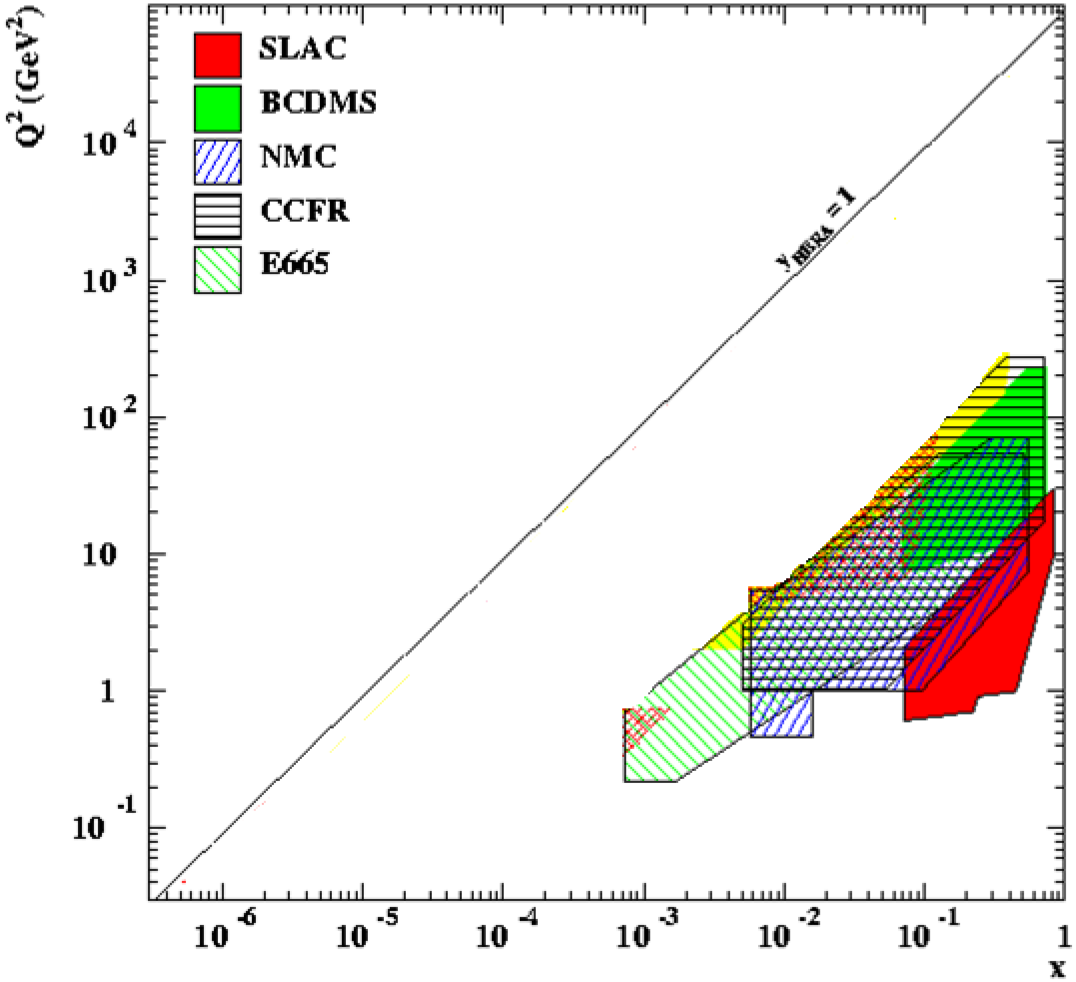
$$x = Q^2/2P\cdot q = \frac{E_e}{E_p}\,\frac{E'_e\,(1+\cos\theta_e)}{2E_e - E'_e(1-\cos\theta_e)}$$

Initial proton energy

Electron scattering angle

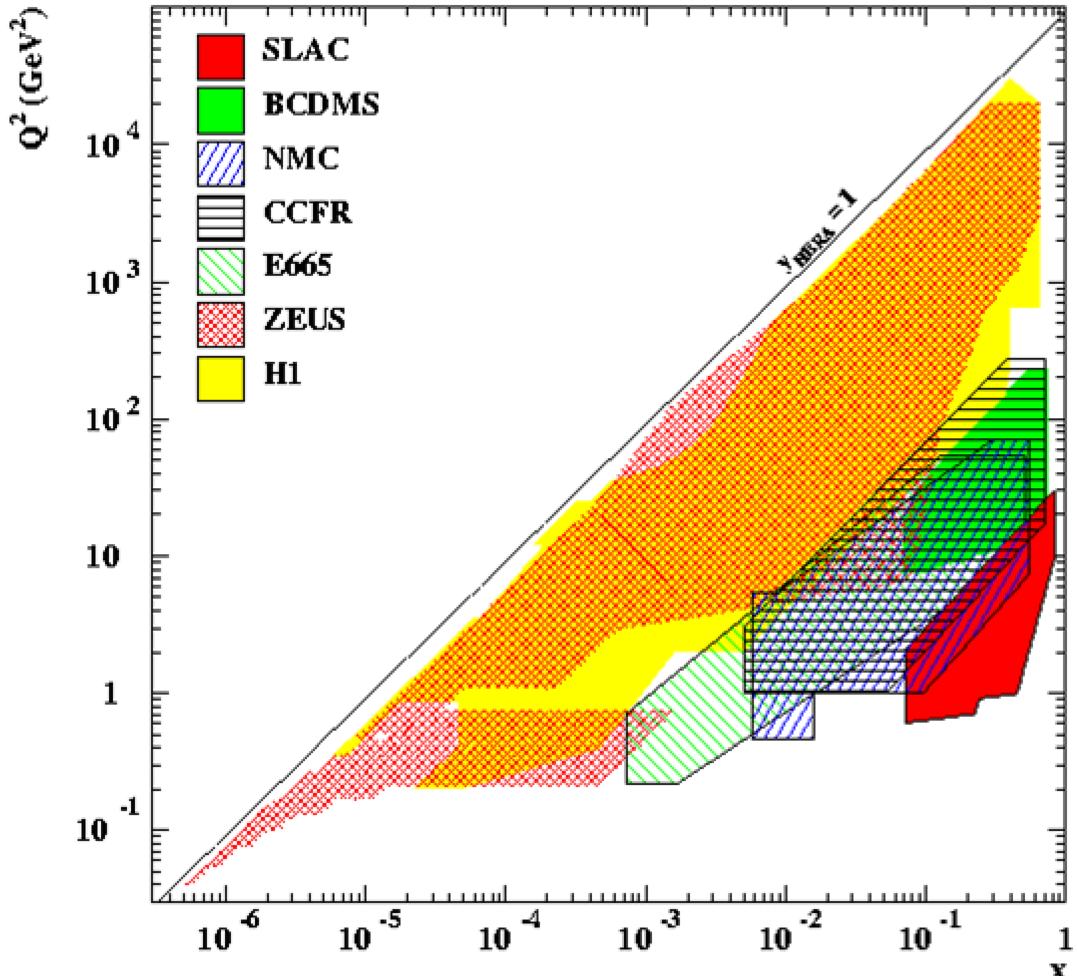
Everything we need can be reconstructed from the measurement of E'_e and θ_e (in principle).

Deep Inelastic Scattering experiments



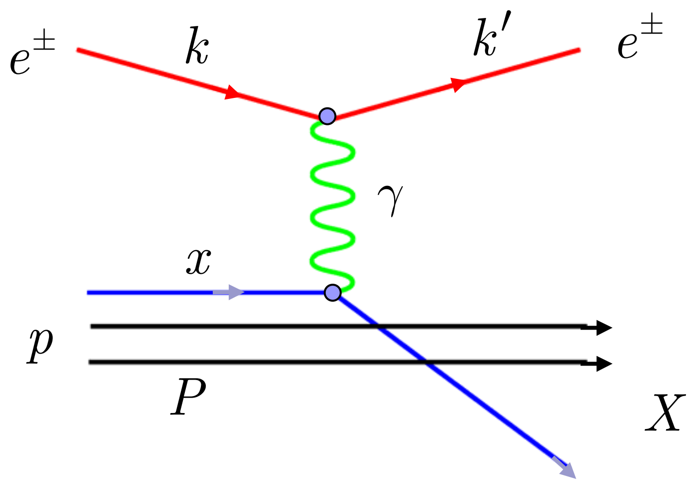
Fixed target DIS at SLAC, FNAL and CERN completed ~ 10-25 years ago

Deep Inelastic Scattering experiments



HERA collider: H1 and ZEUS experiments
1992 – 2007 (data analysis ongoing)

Structure Functions within the Quark-Parton-Model

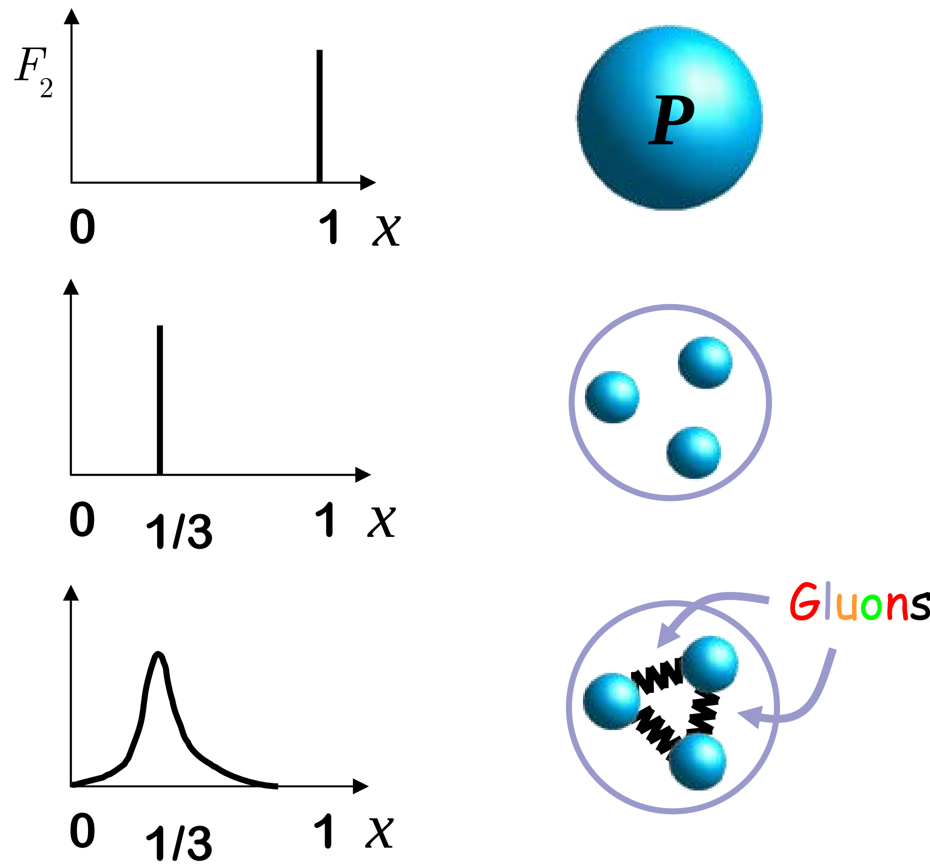


$$\frac{d^2\sigma(e^\pm p)}{dx\,dQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+ F_2 - y^2 F_L\right]$$

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

parton densities

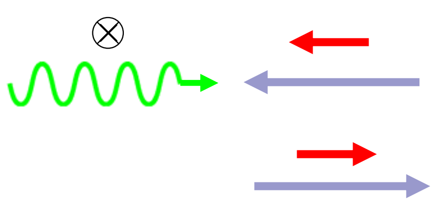
$xq_i(x)$ (pdf)



DIS =

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

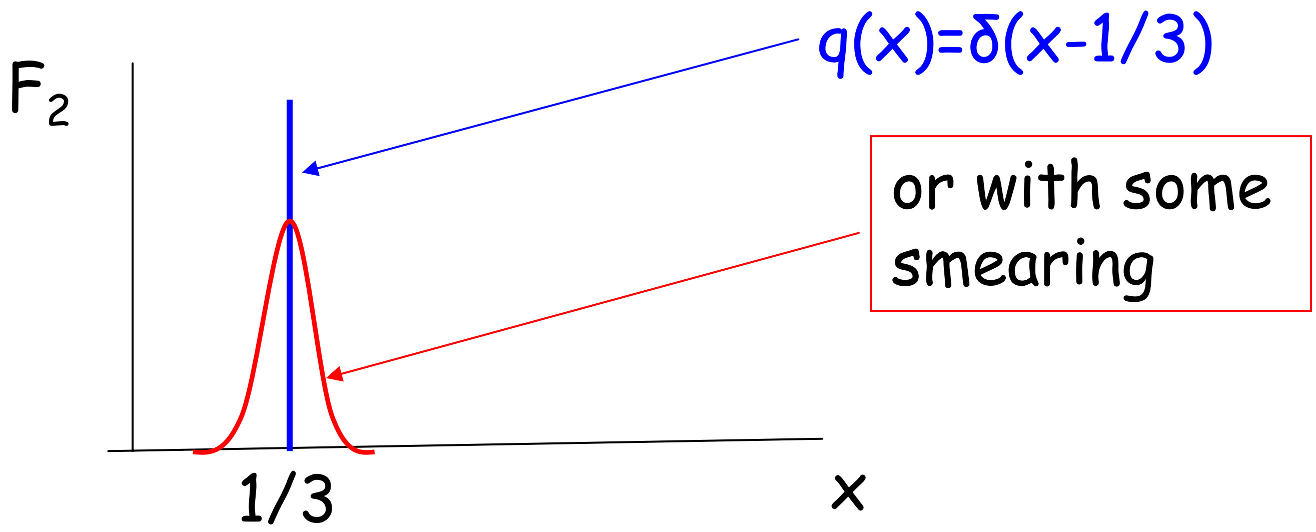
→ Quark-Parton-Model (QPM)



$$\boxed{F_L = 0}$$

IF, proton was made of 3 quarks each with 1/3 of proton's momentum:

$$F_2 = x\sum e_q^2 q(x)$$

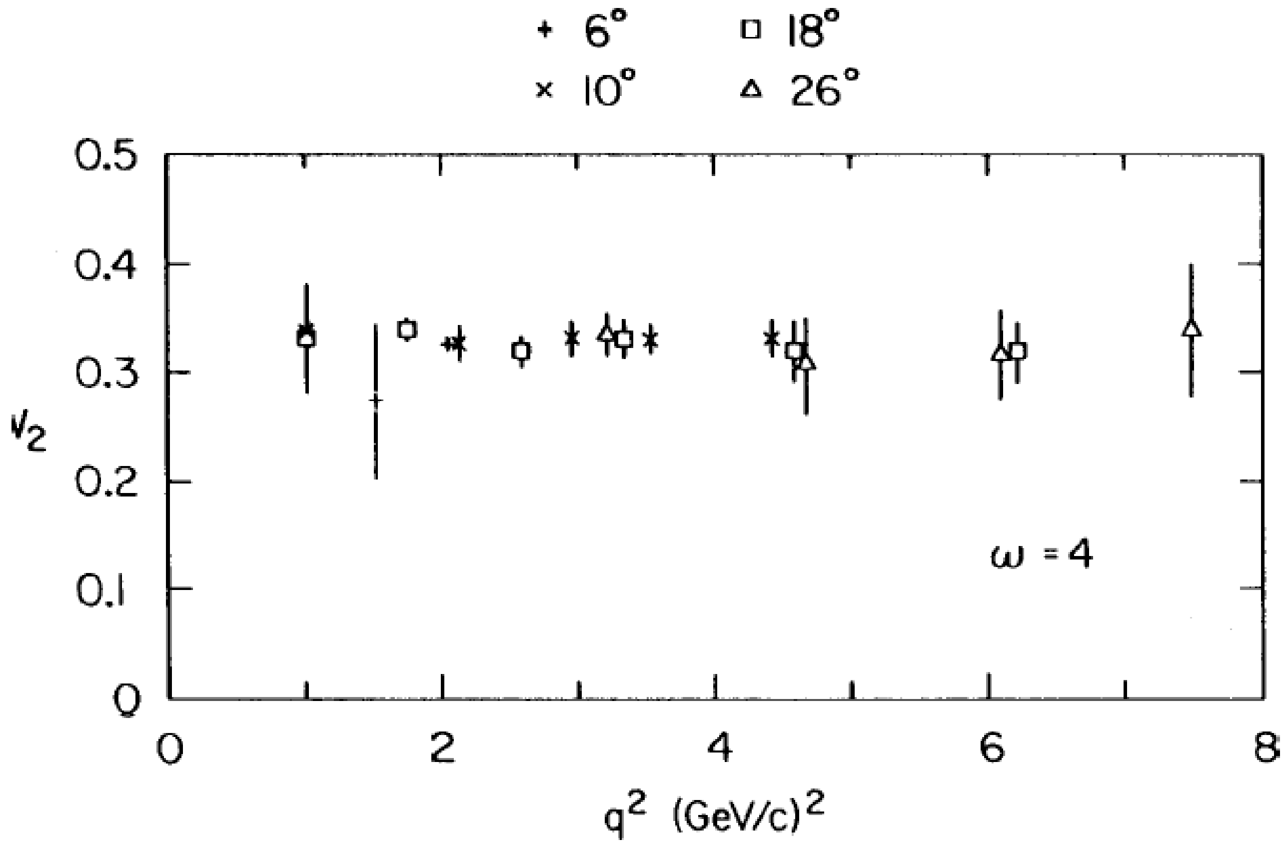


The partons are point-like and incoherent then Q^2 shouldn't matter.

→ Bjorken scaling: F_2 has no Q^2 dependence.

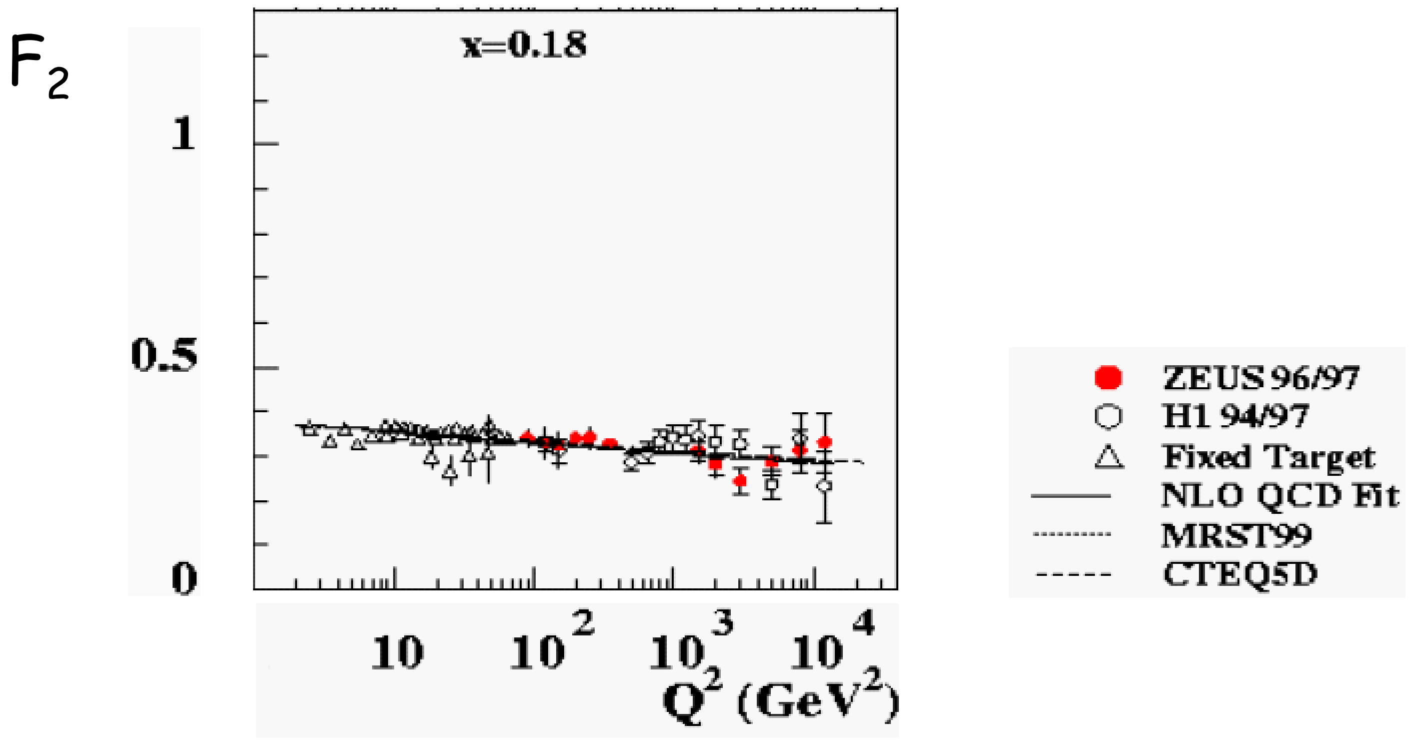
Let's look at some data→

Results from SLAC-MIT experiment



Seems to be....

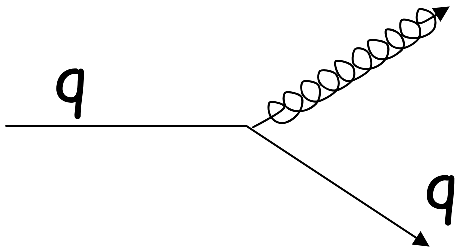
Proton Structure Function F_2



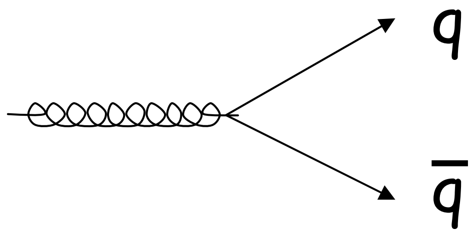
Seems to be.... NOT

So what does this mean..?

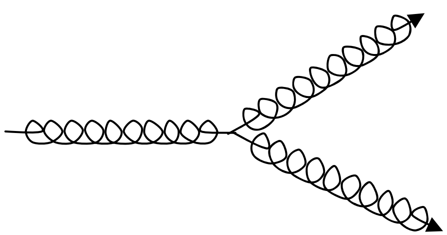
QCD, of course:



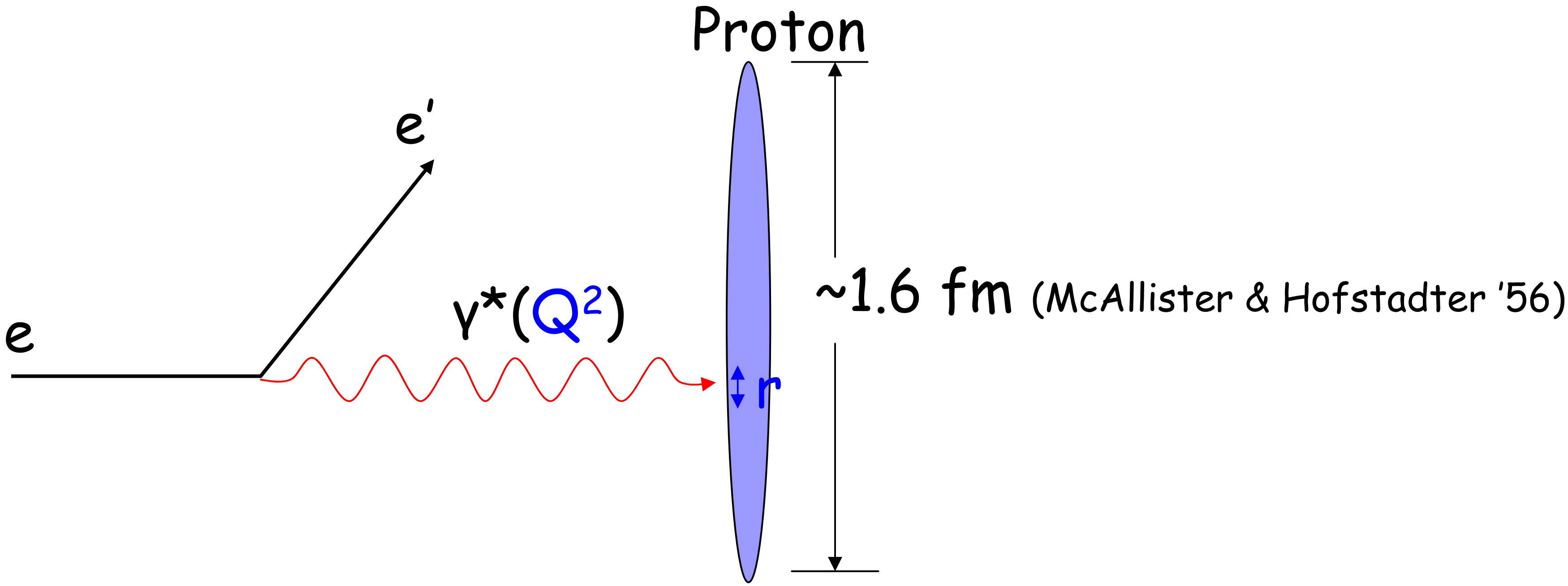
quarks radiate gluons



gluons can produce $q\bar{q}$ pairs



gluons can radiate gluons!



Virtuality (4-momentum transfer) Q gives the distance scale r at which the proton is probed.

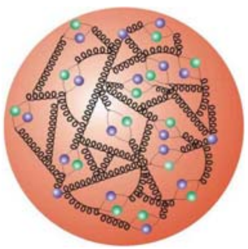
$r \approx \hbar c/Q = 0.2\,\mathrm{fm}/Q[\mathrm{GeV}]$

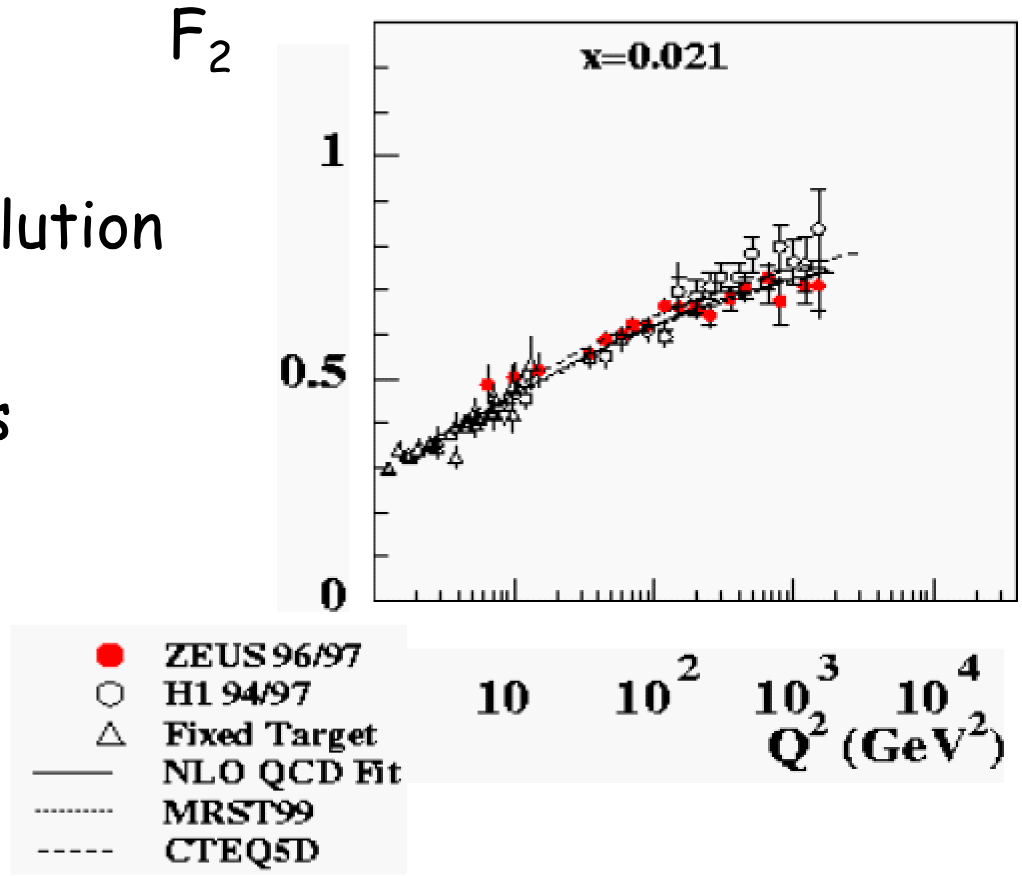
CERN, FNAL fixed target DIS:	$r_{min} \approx$ 1/100 proton dia.
HERA ep collider DIS:	$r_{min} \approx$ 1/1000 proton dia.

HERA: E_e=27.5 GeV, E_P=920 GeV

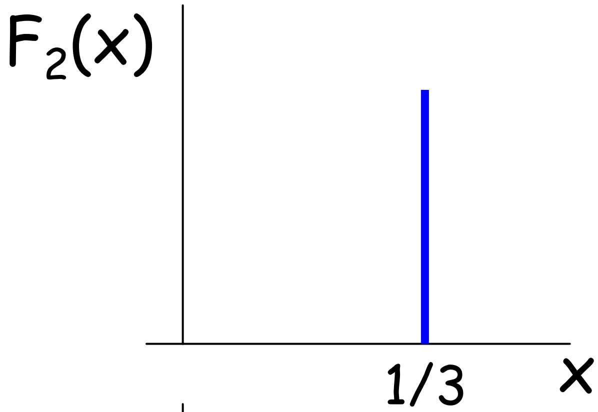
The higher the resolution (i.e. higher the Q^2)

the more branchings to lower x we "see".

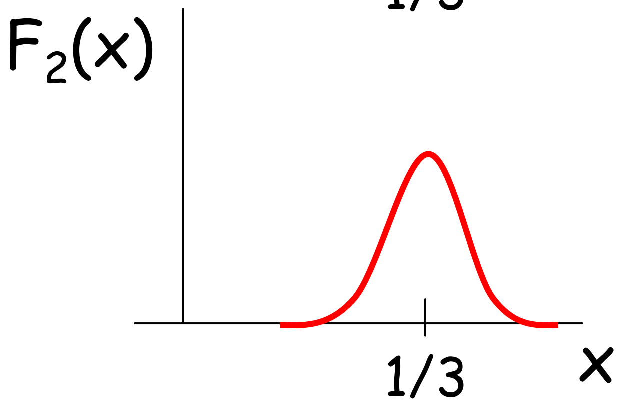




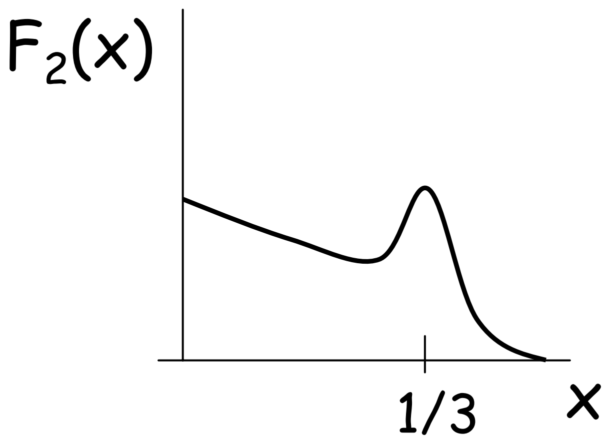
So what do we expect F_2 as a function of x at a fixed Q^2 to look like?



Three quarks with 1/3 of total proton momentum each.

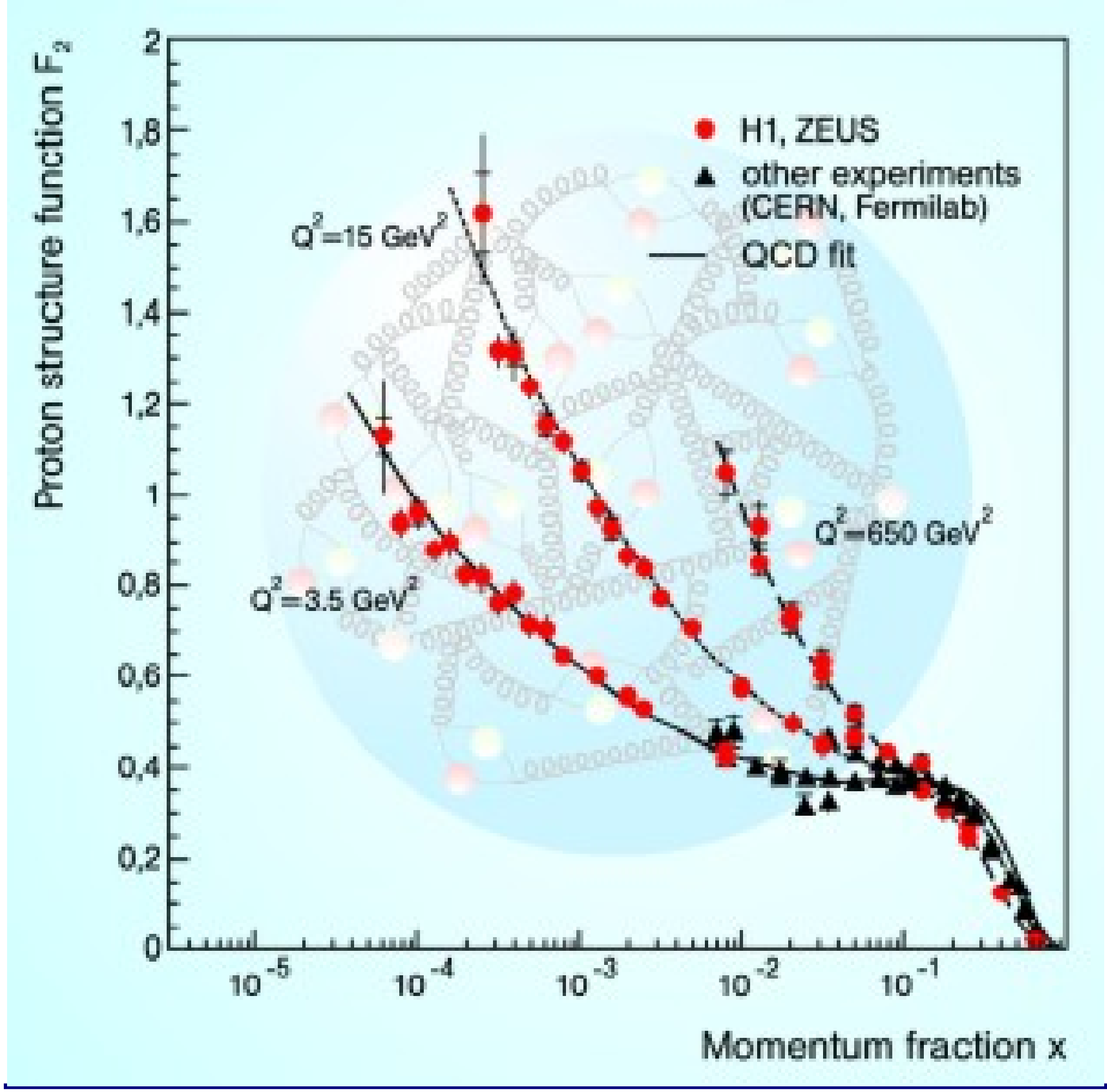


Three quarks with some momentum smearing.



The three quarks radiate partons at low x.

Proton Structure Function F_2

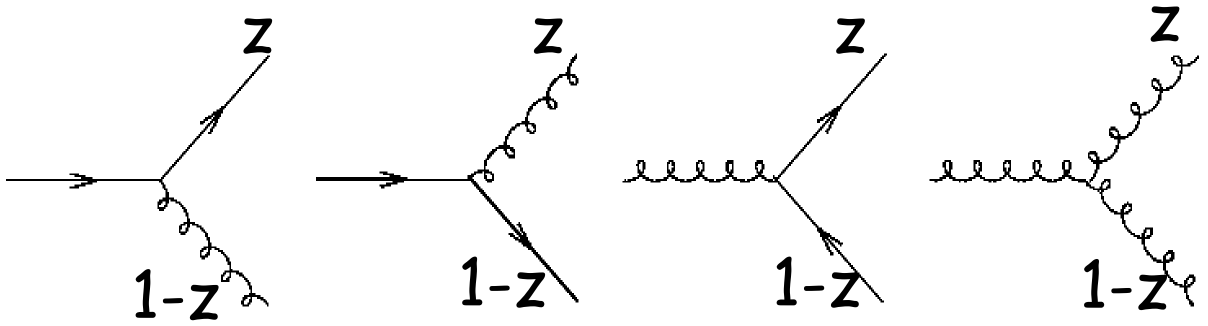


How this change with Q^2 happens quantitatively described by the:

Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (= DGLAP) equations

DGLAP equations are easy to "understand" intuitively

First we have the four "splitting functions"



$P_{ab}(z)$: the probability that parton a will radiate a parton b with the fraction z of the original momentum carried by a.

Now DGLAP equations (schematically)

convolution

$$\frac{dq_f(x,Q^2)}{d\ln Q^2} = \alpha_s\,[q_f \otimes P_{qq} + g \otimes P_{gq}]$$

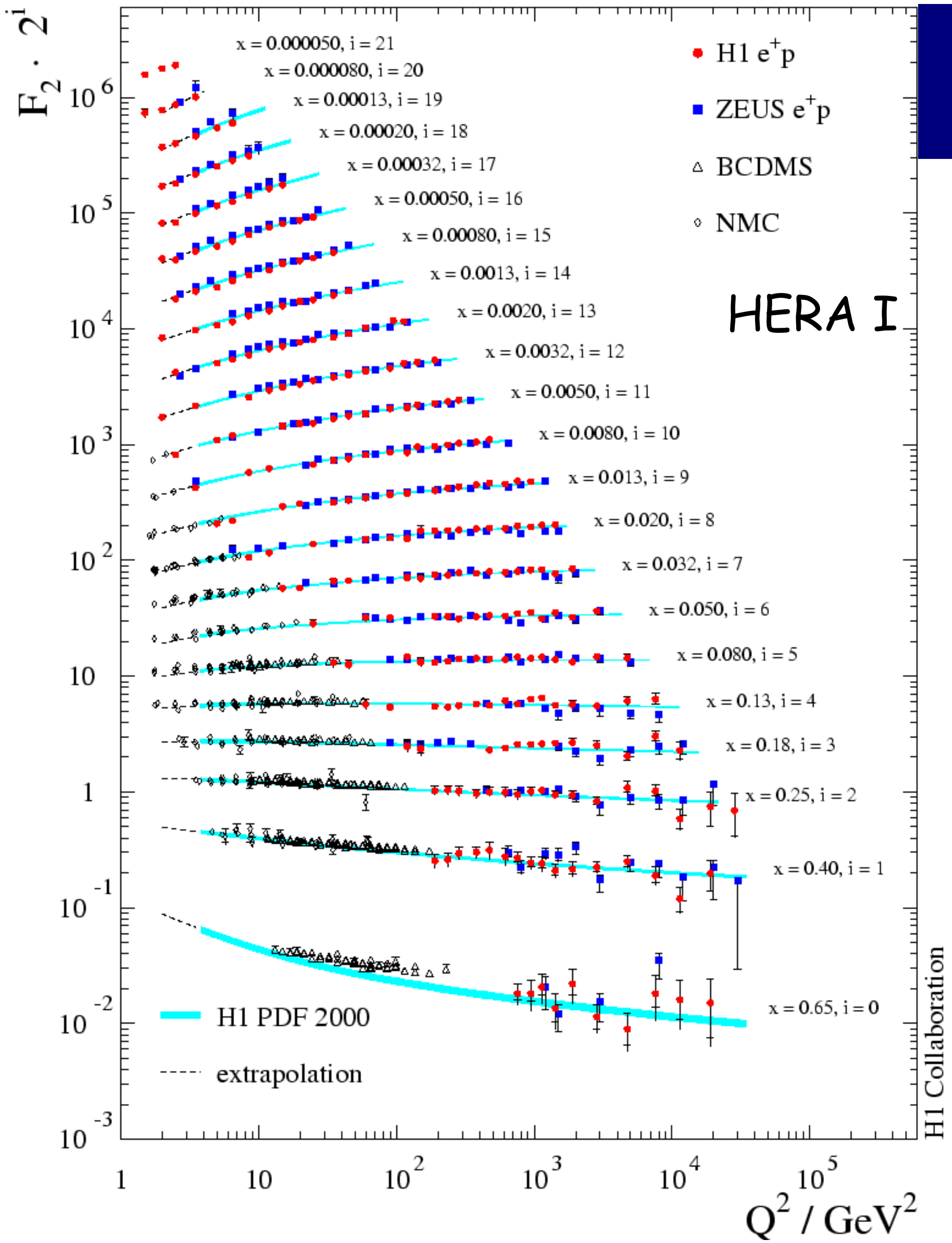
strong coupling constant

Change of quark distribution q with Q^2
is given by the probability that q and g radiate q.

Same for gluons:

$$\frac{dg(x,Q^2)}{d\ln Q^2} = \alpha_s\,[\sum q_f \otimes P_{qg} + g \otimes P_{gg}]$$

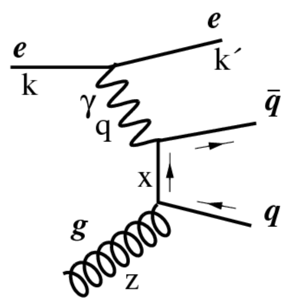
Structure Function F_2



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

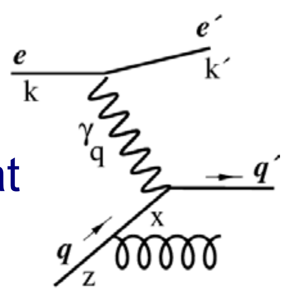
- H1 & ZEUS extended fixed target kinematic regime in x and Q^2 by 2 Orders
- Described by DGLAP

Scaling violations



rise at low x

drop at high x



DGLAP fit (or QCD fit) extracts the parton distributions from measurements.

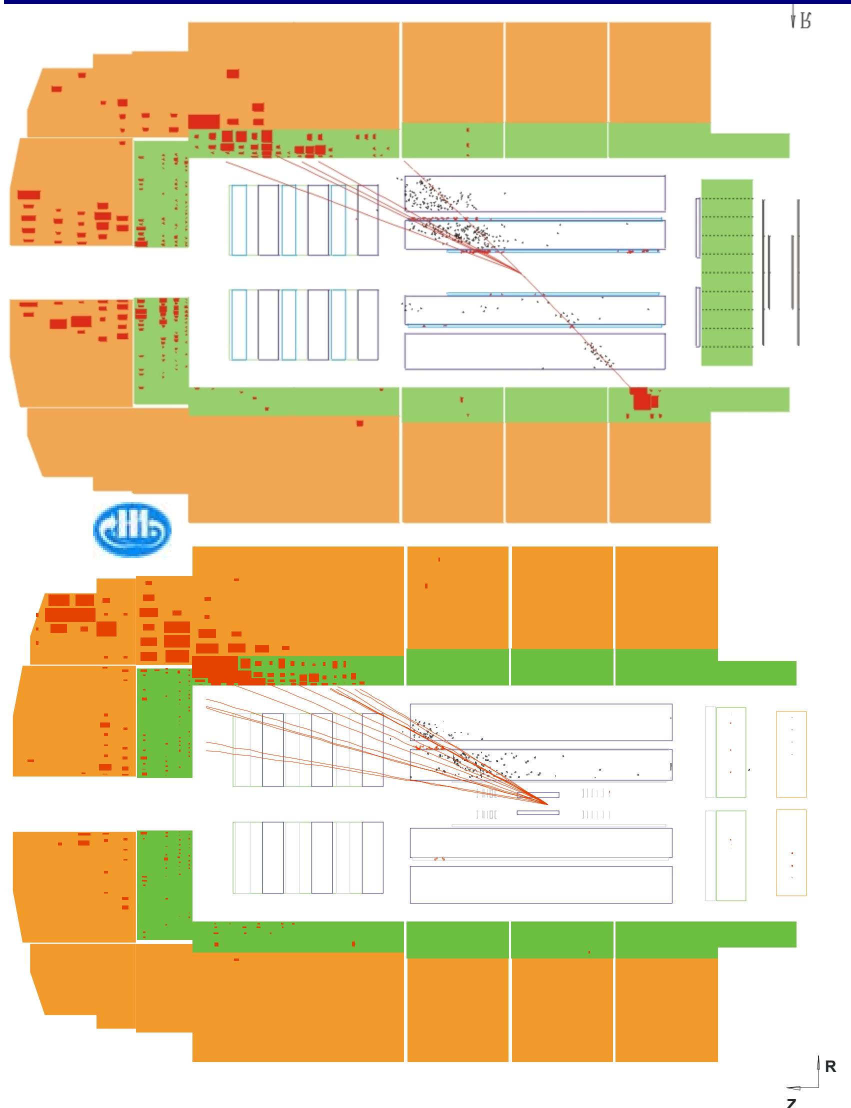
Step 1: parameterise the parton momentum density $f(x)$ at some Q^2, e.g.: $f(x)=Ax^B(1-x)^C(1+Dx+Ex^2)$

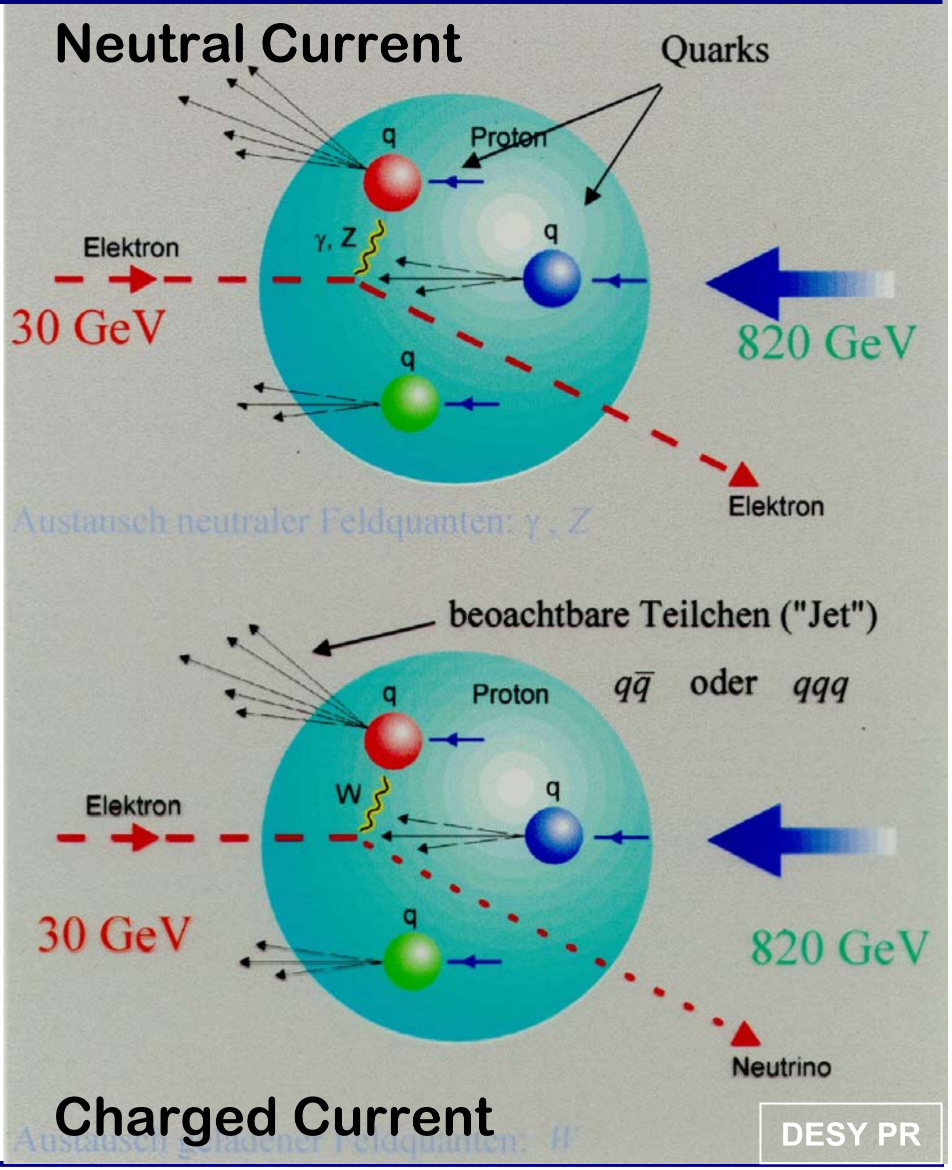
$u_v(x)$ u-valence
$d_v(x)$ d-valence
"The original three quarks"
$g(x)$ gluon
$S(x)$ sum of all "sea" (i.e. non valence) quarks
(or $\bar{U}=\bar{u}+\bar{c}(+\bar{t})$ & $\bar{D}=\bar{d}+\bar{s}+\bar{b}$)

Step 2: find the parameters by fitting to DIS (and other) data using DGLAP equations to evolve $f(x)$ in Q^2.

Caveat! Not as easy: fit 4 PDFs (or 5), input one $F_2=\Sigma e_q^2(q+\bar{q})$ (+ $\partial F_2/\partial \ln Q^2 \sim \alpha_s g(x)$) different measurements needed, e.g. fix target data (→global PDF fits) … or → see next slide

HERA high Q^2 Data





times 2 for e+p and e-p

Neutral Current Cross Section

$$\frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^{\mp} \mp Y_- x\tilde{F}_3^{\pm} - y^2\tilde{F}_L^{\pm}\right]$$

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

$$\kappa = \frac{1}{4\sin^2\theta_w\cos^2\theta_w}\frac{Q^2}{Q^2+M_Z^2}$$

Generalized structure functions:

$$\tilde{F}_2^{\pm} = F_2^{\gamma} + \kappa(-v_e \pm P_e a_e)F_2^{\gamma Z} + \kappa^2(v_e^2 + a_e^2 \pm 2P_e v_e a_e)F_2^Z$$

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

$$\left[F_2^{\gamma}, F_2^{\gamma Z}, F_2^Z\right] = \sum_q \left[e_q^2, 2e_q v_q, v_q^2 + a_q^2\right] x(q+\bar{q})$$

$$\left[xF_3^{\gamma Z}, xF_3^Z\right] = \sum_q \left[e_q a_q, v_q a_q\right] 2x(q-\bar{q})$$

Charged Current Cross Section

$$\frac{d^2\sigma^{CC}(e^{\pm}p)}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \tilde{\sigma}_{CC}^{e^{\pm}p}$$

CC reduced cross section

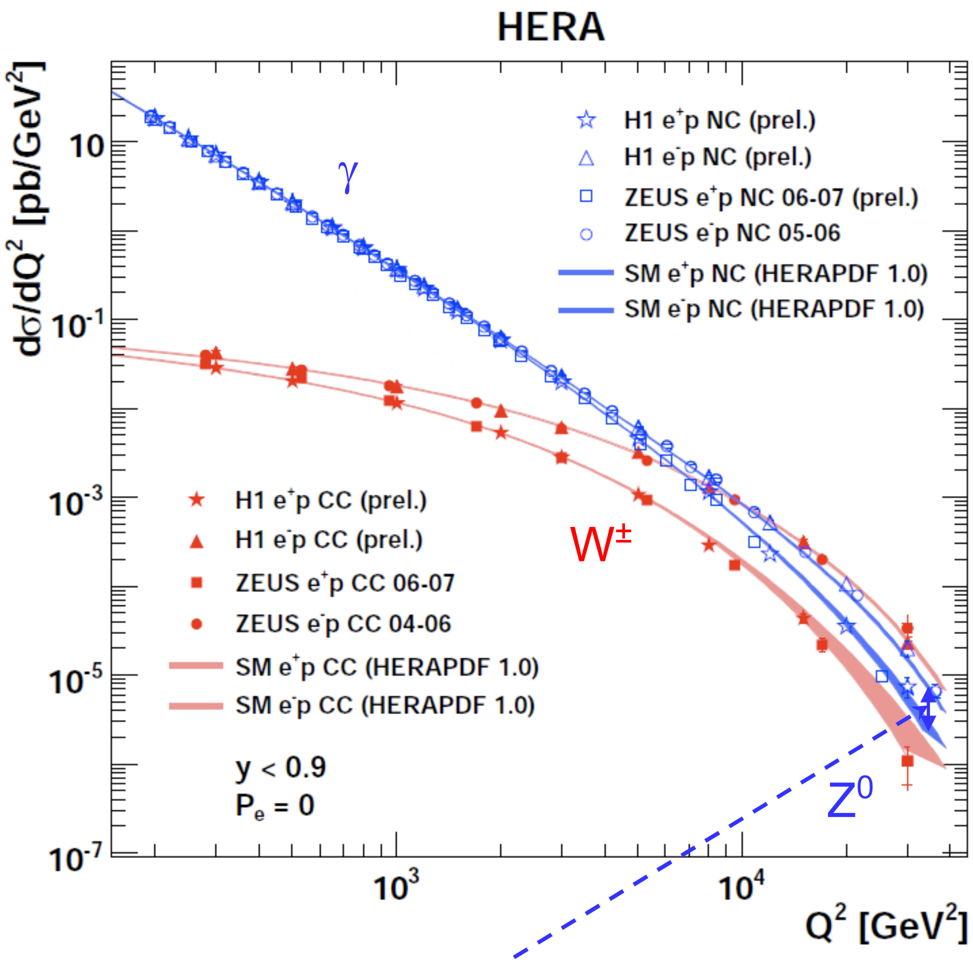
e^+/e^- sensitive to different quark densities:

$$\tilde{\sigma}_{CC}^{e^+p} = x\left[\bar{u}+\bar{c}\right] + (1-y)^2 x\left[d+s\right]$$

$$\tilde{\sigma}_{CC}^{e^-p} = x\left[u+c\right] + (1-y)^2 x\left[\bar{d}+\bar{s}\right]$$

CC gives sensitivity to different combinations of quarks as NC.

Electroweak Unification



difference in e^+ and e^- for NC in high Q^2 region comes from contribution of Z exchange

NC: $\frac{d\sigma}{dQ^2} \sim \frac{1}{Q^4}$

CC: $\frac{d\sigma}{dQ^2} \sim \frac{1}{(Q^2 + M_W^2)^2}$

EW component of SM:
NC and CC cross sections are similar at $Q^2 \approx M_Z^2, M_W^2$

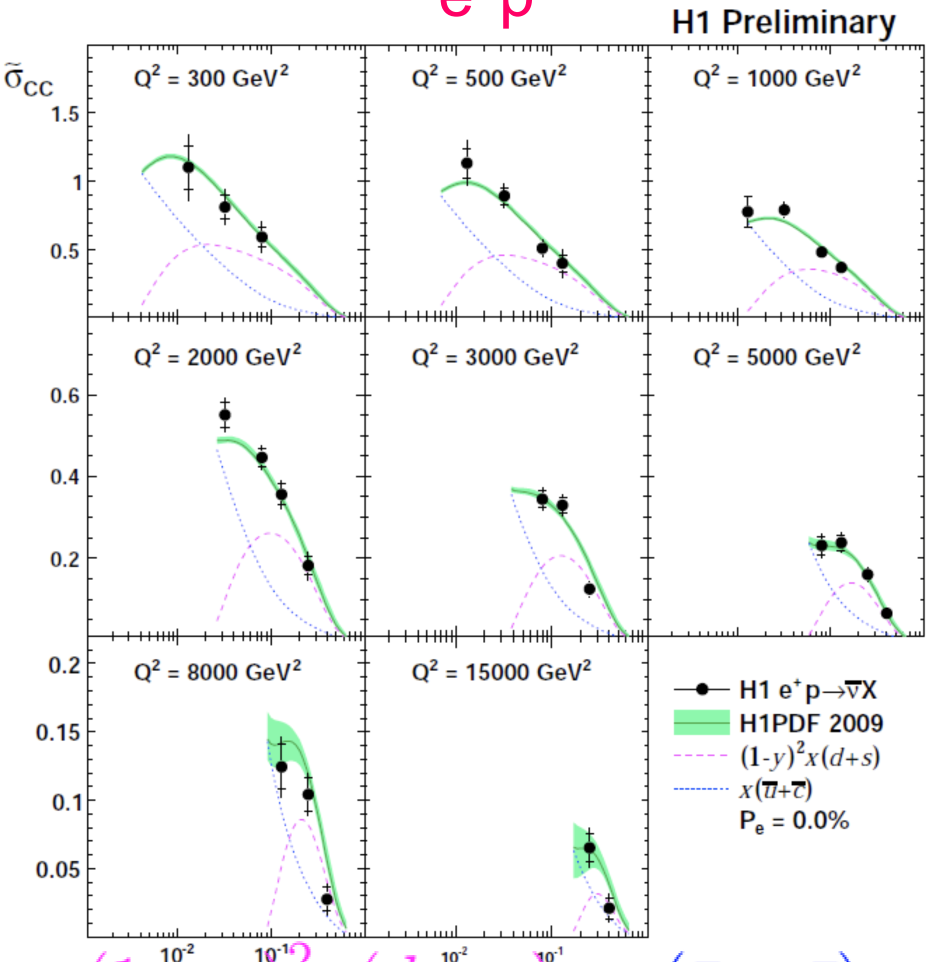
Data compared with SM

Good agreement over full range

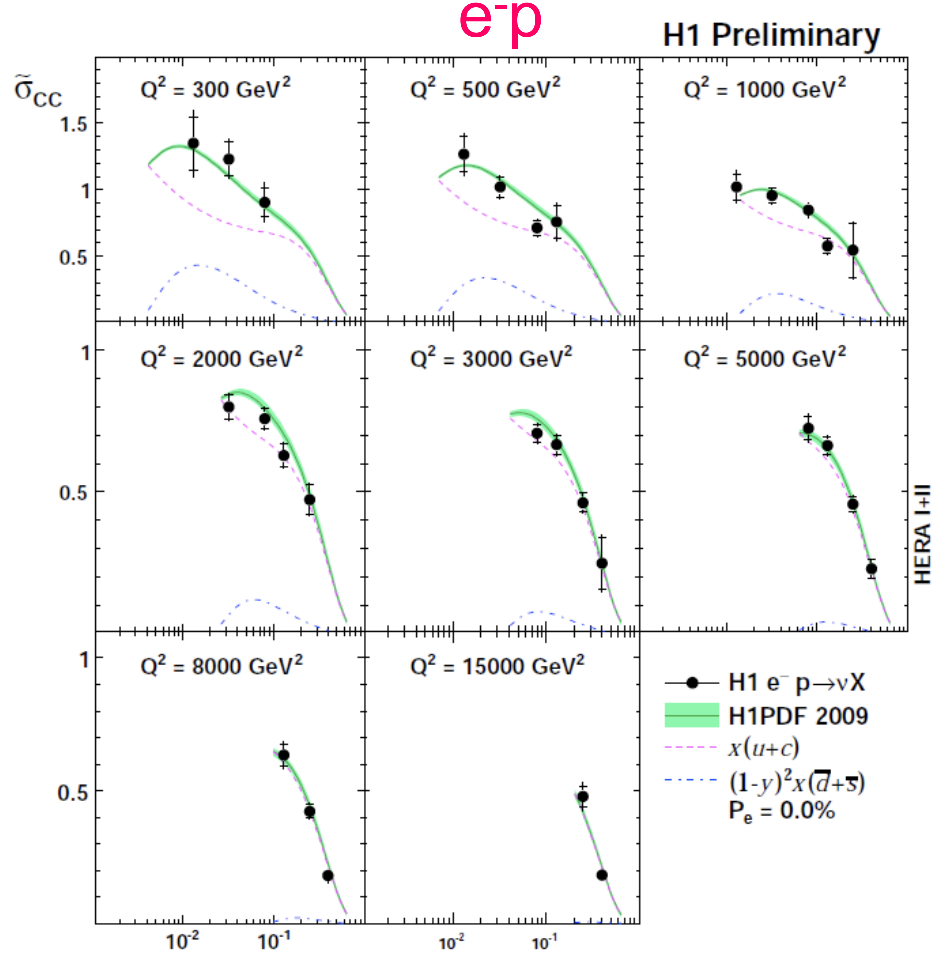
Charged Current Cross Sections

Results from entire HERA-II data set

e^+p

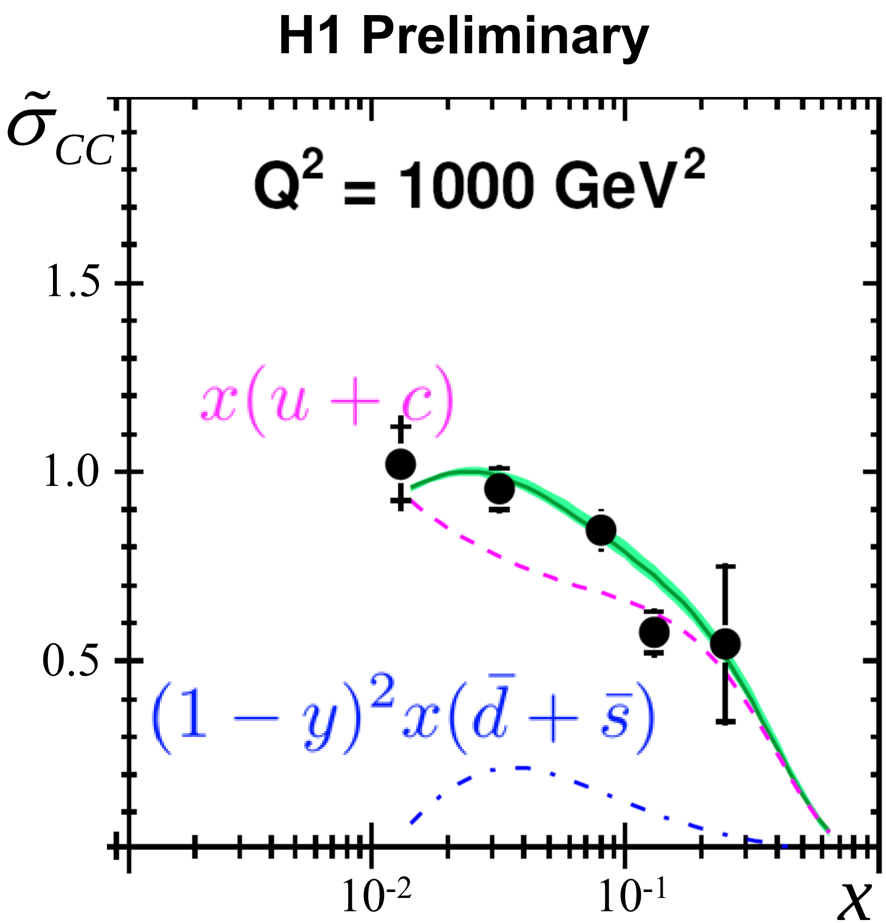


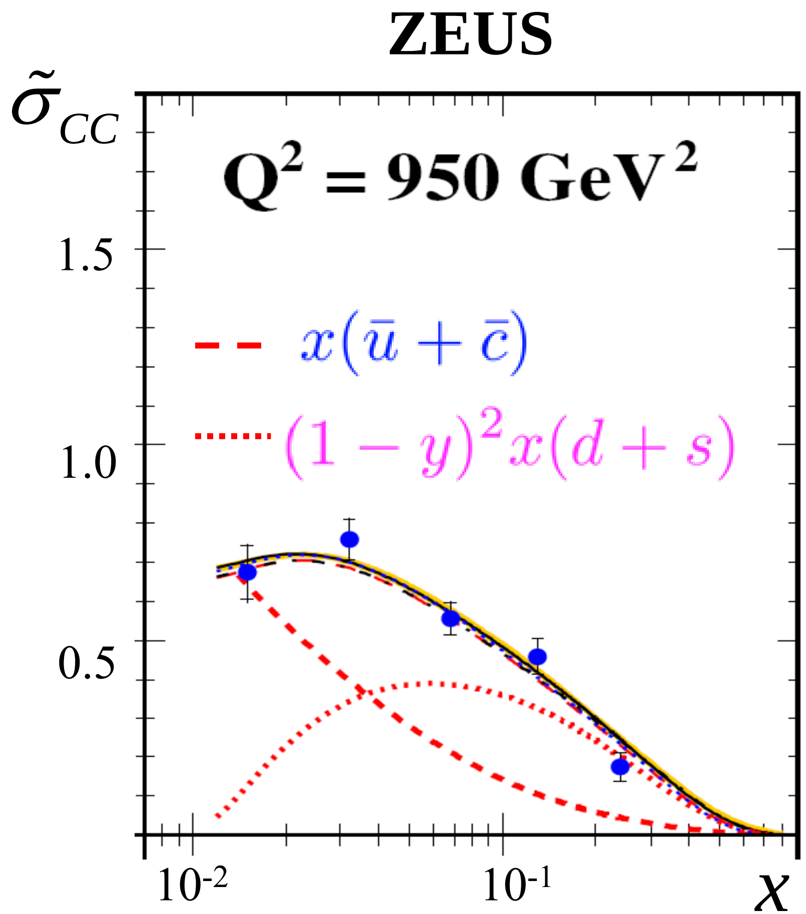
e^-p



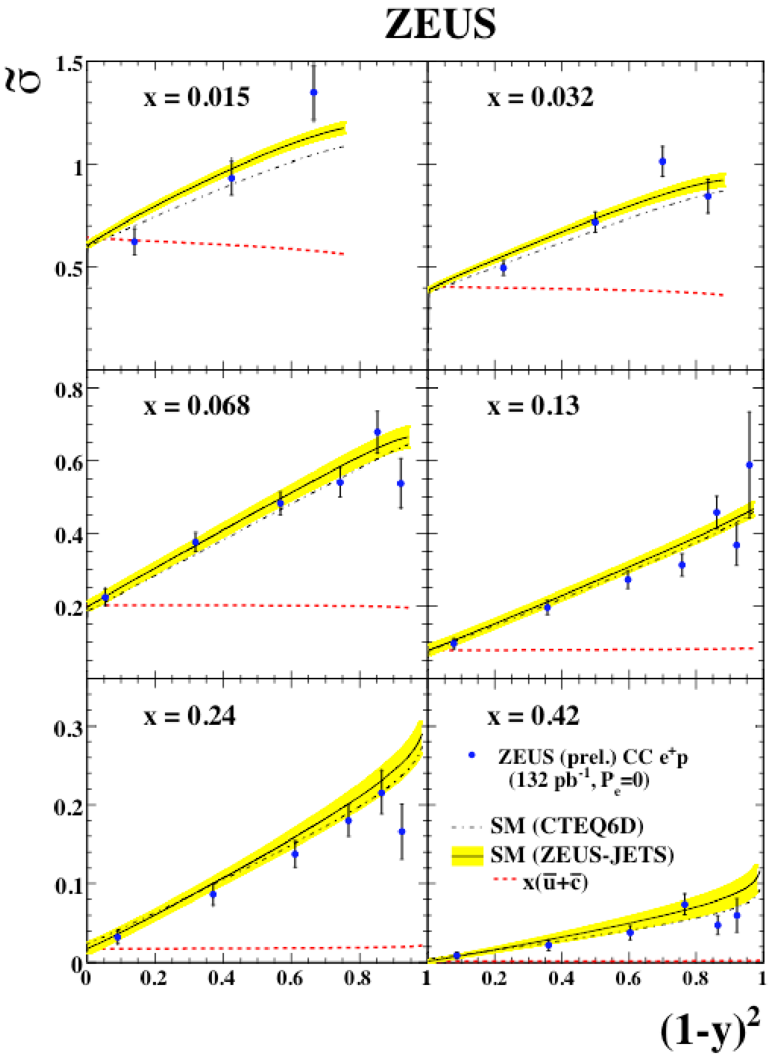
$(1-y)^2 x(d+s)$ $\quad x(\bar{u}+\bar{c})$ $\quad (1-y)^2 x(\bar{d}+\bar{s})$ $\quad x(u+c)$

Quark Antiquark Decomposition





Quark Antiquark Decomposition



Unpolarized reduced CC e⁺p cross section in bins of x as a function of $(1-y)^2$
→ Helicity structure of CC

At leading order in QCD:

intercept   slope

$$\tilde{\sigma}_{CC}^{e^+p} = x\,[\bar{u} + \bar{c}] + (1-y)^2 x\,[d + s]$$

Data are well described by SM calculations
- ZEUS-JETS fit
- global fits CTEQ6

Neutral Current: xF_3

NC cross section:

$$\tilde{\sigma}^{\pm} = \frac{d^2\sigma^{NC}(e^{\pm}p)}{dxdQ^2}\frac{xQ^4}{2\pi\alpha^2}\frac{1}{Y_+} = \tilde{F}_2 \mp \frac{Y_-}{Y_+}x\tilde{F}_3 - \frac{y^2}{Y_+}\tilde{F}_L$$

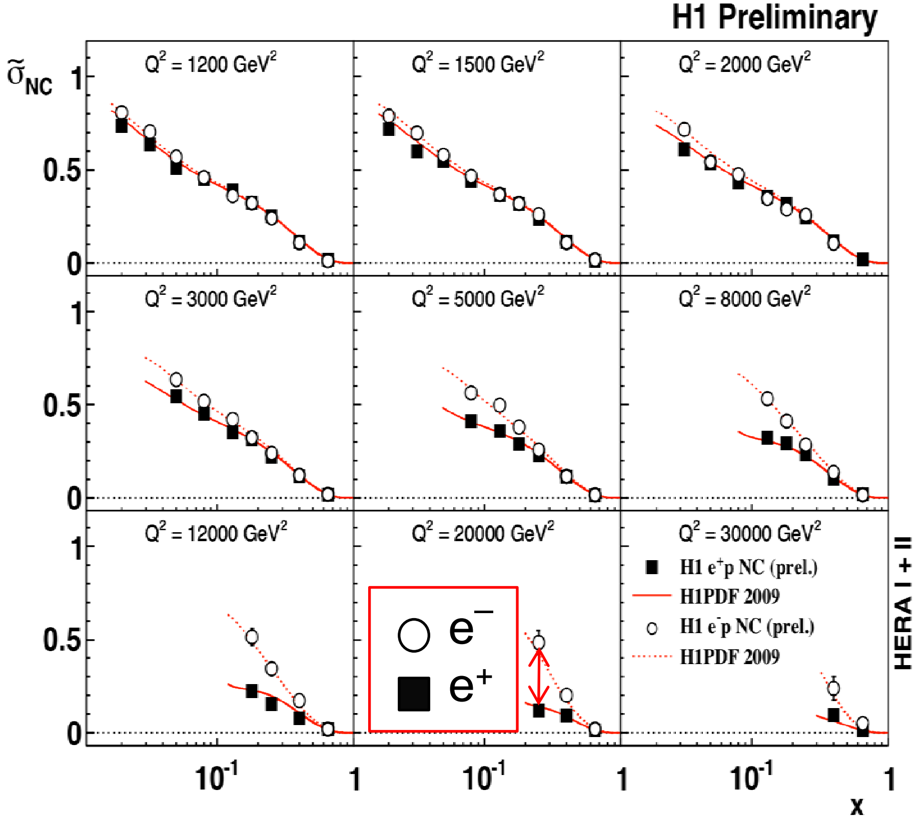
$$\rightarrow \quad x\tilde{F}_3 = \frac{Y_+}{2Y_-}\left[\tilde{\sigma}^- - \tilde{\sigma}^+\right]$$

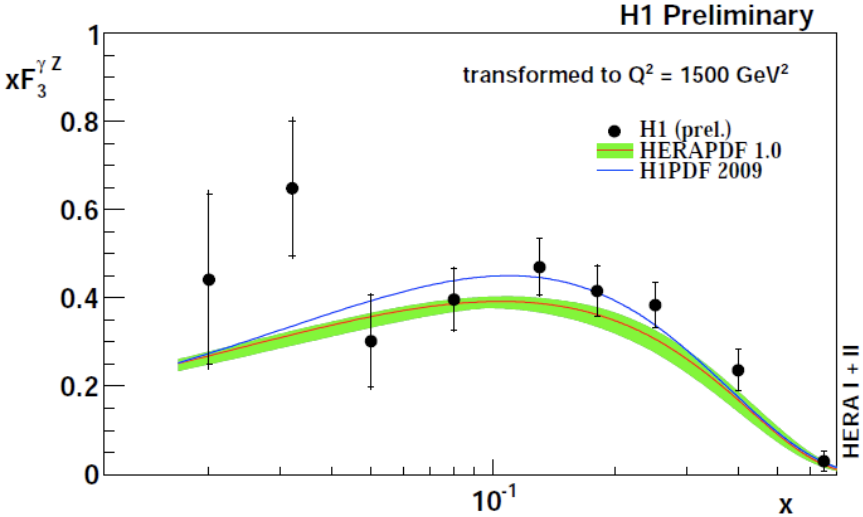
dominant contribution to xF_3:

$$xF_3^{\gamma Z} \simeq x\tilde{F}_3 \frac{(Q^2+M_Z^2)}{\alpha^2\kappa Q^2}$$

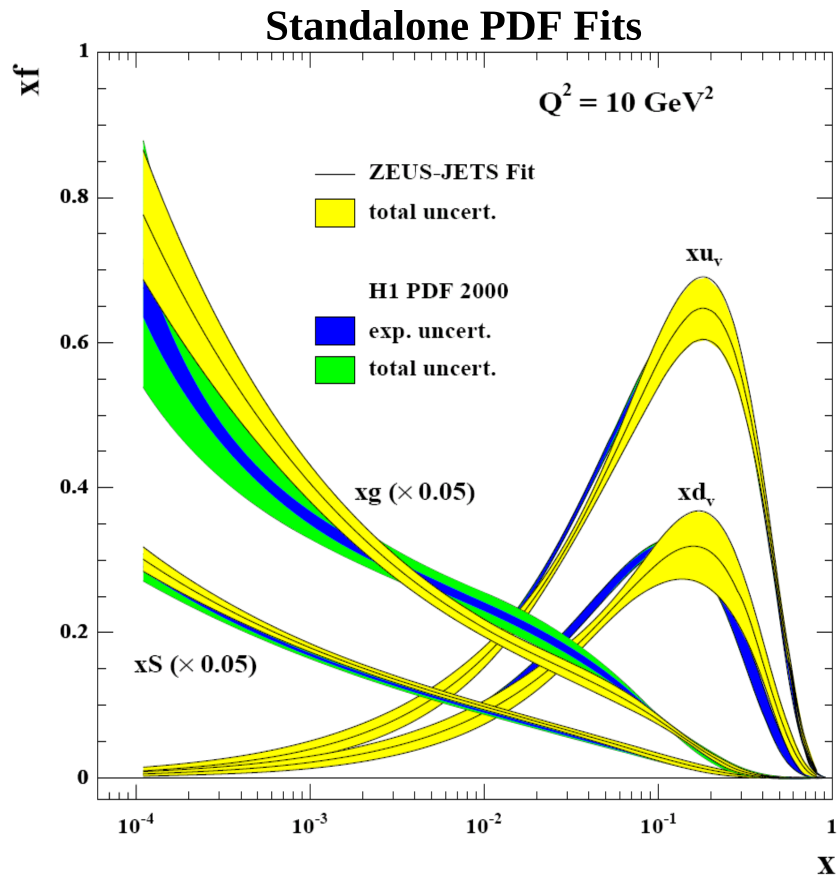
$$xF_3^{\gamma Z} \propto x(q-\bar{q})$$

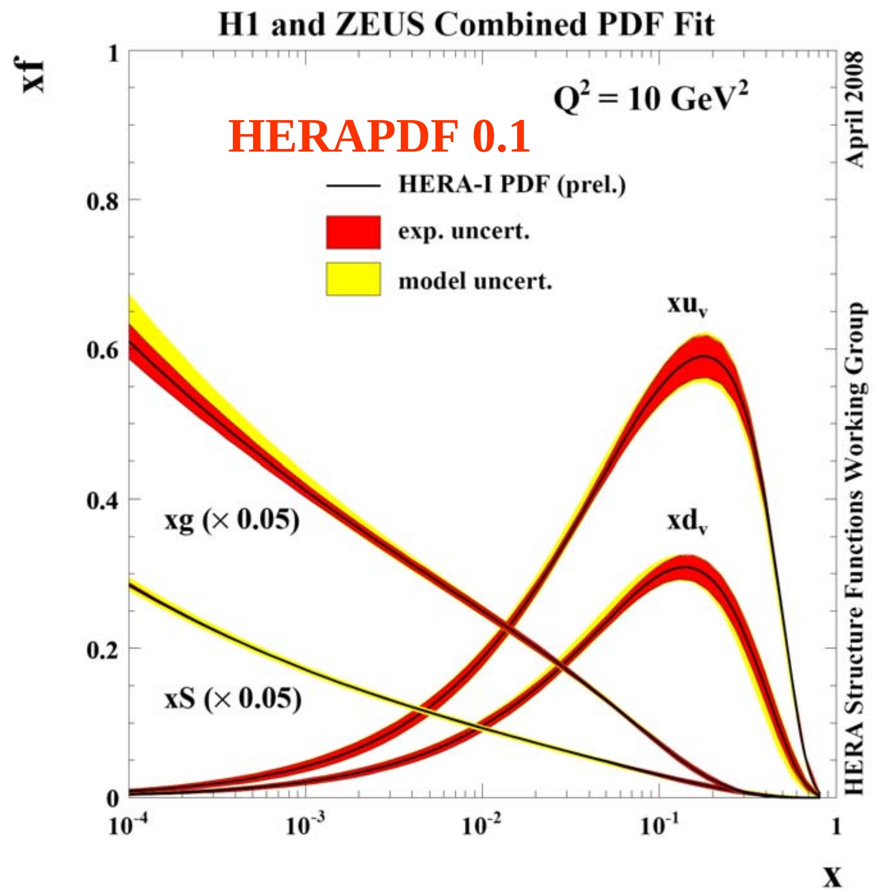
Sensitivity to valence quarks





PDF Fits on HERA I Data

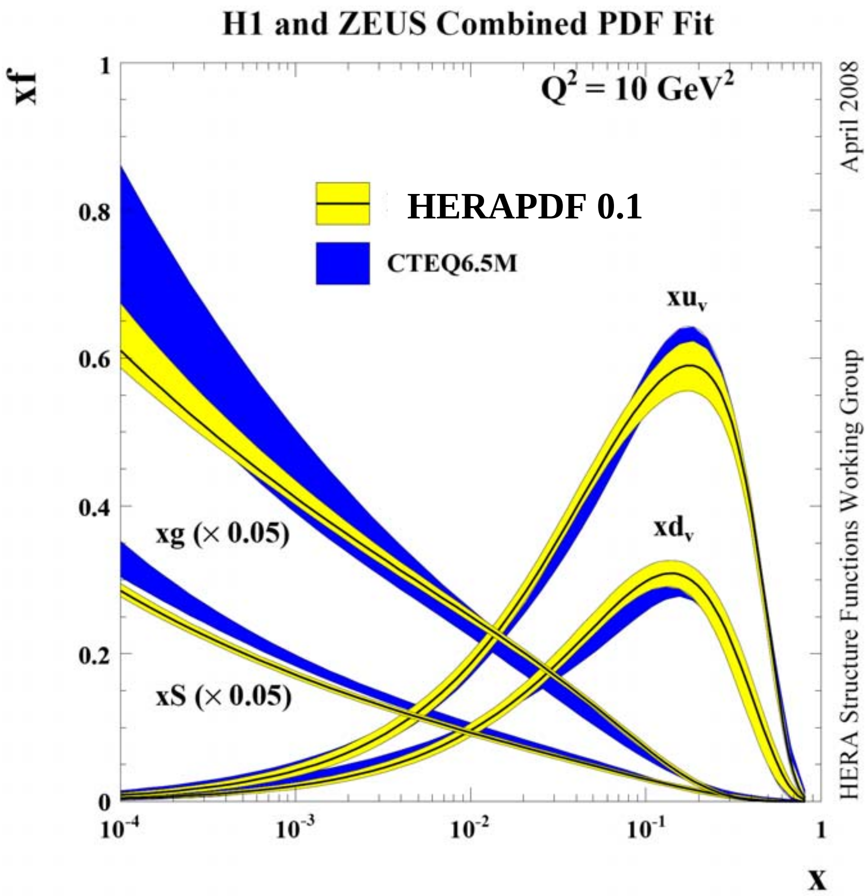


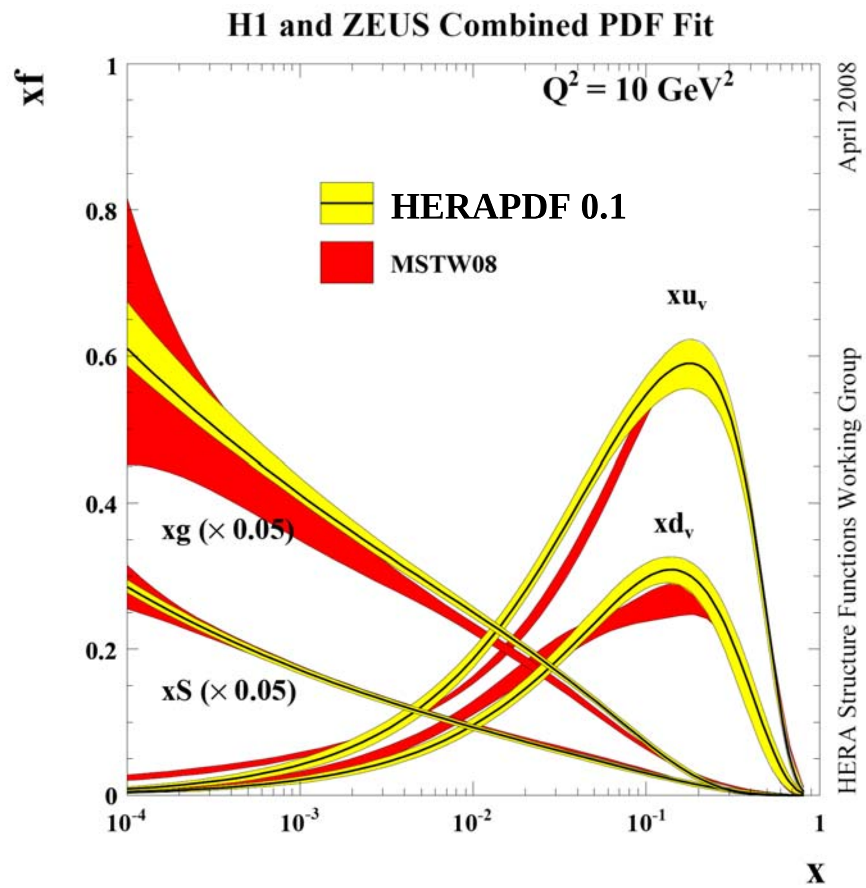


Impressive reduction of uncertainties of combined analysis

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

Comparison to Global Fits

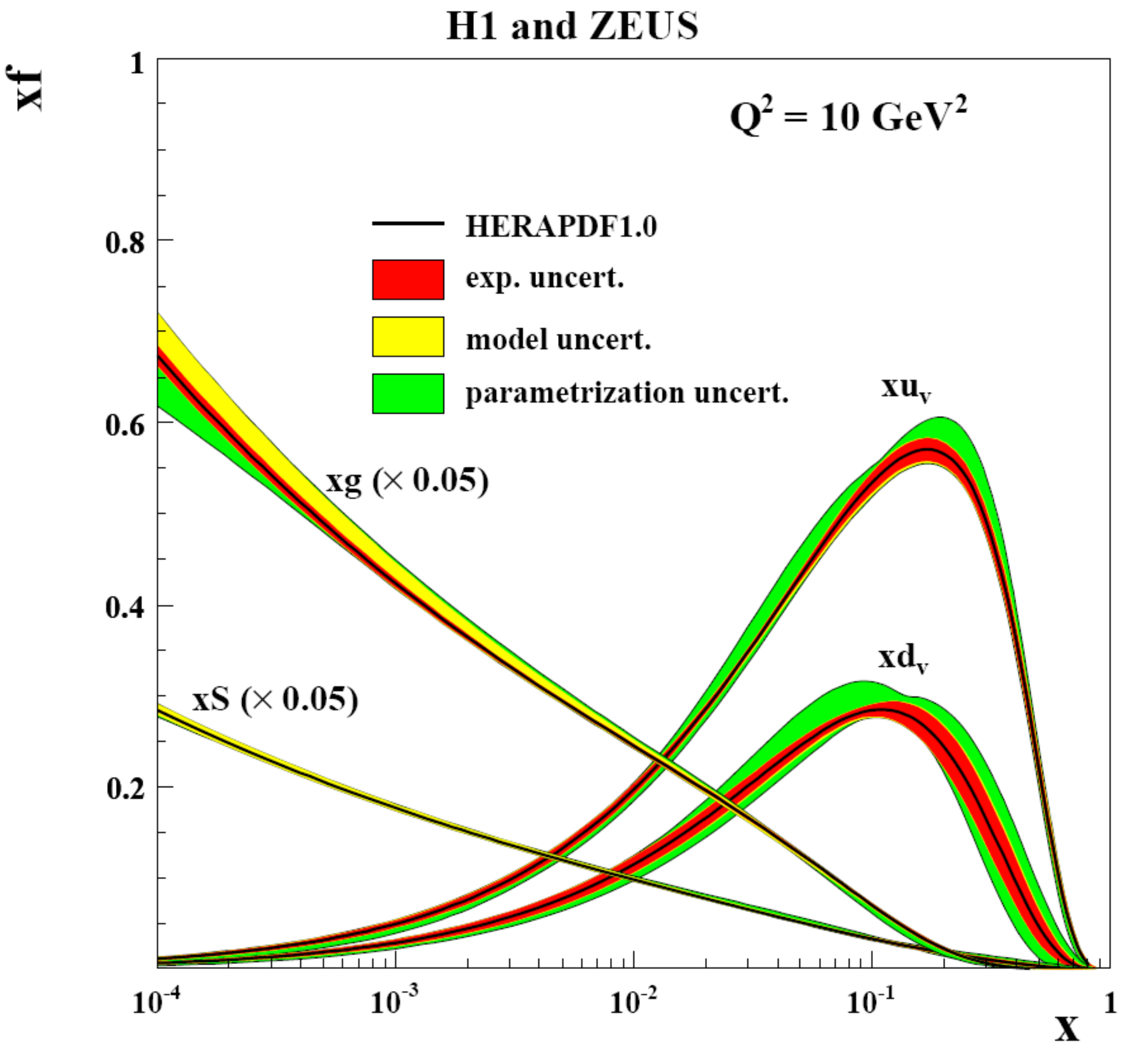




Deep Inelastic Scattering

Second Lecture

2^{nd} Lecture: Outline



Yesterday:

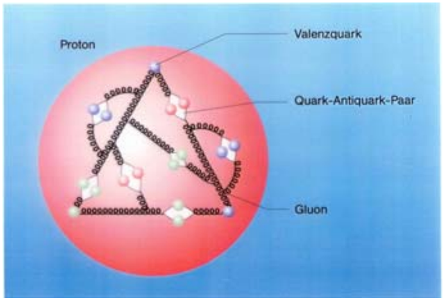
- Developed a "picture" of the proton (PDFs and DGLAP evolution)

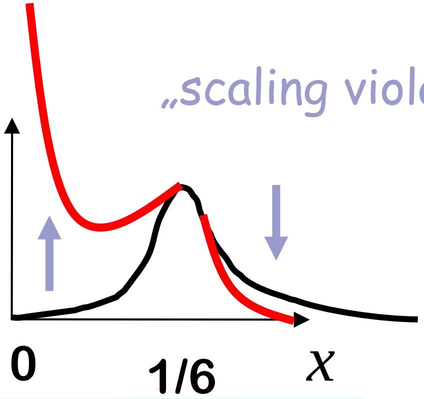
Today:

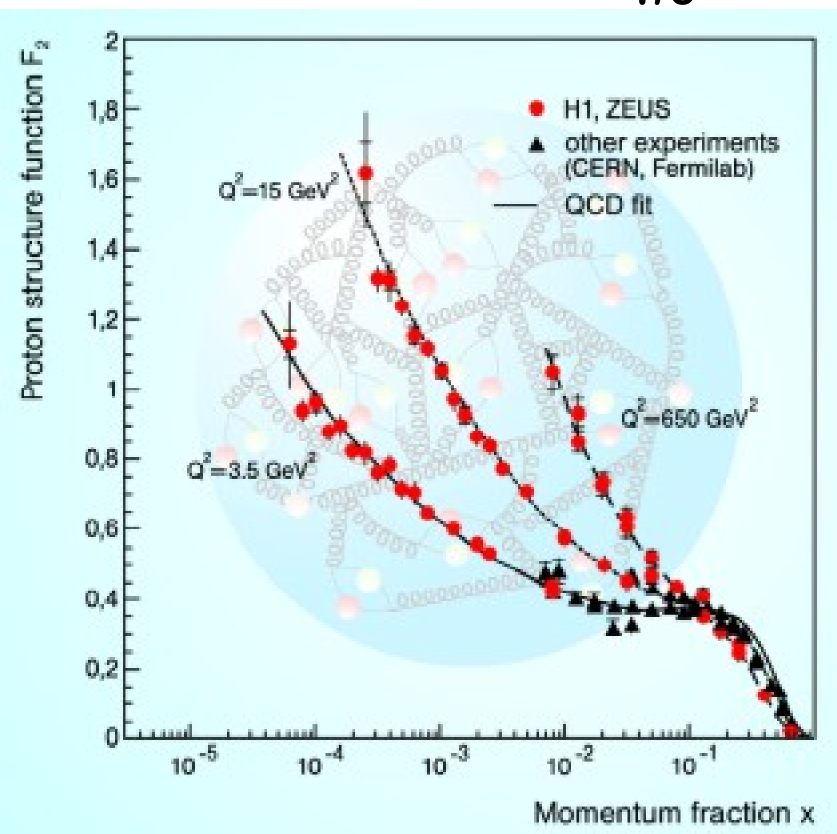
- Explore validity of this picture
- Ultimate precision of the HERA measurements
- Additional constraints on PDFs from HERA:
  Jets, FL, Heavy Quarks
- Relation to
  Tevatron and LHC

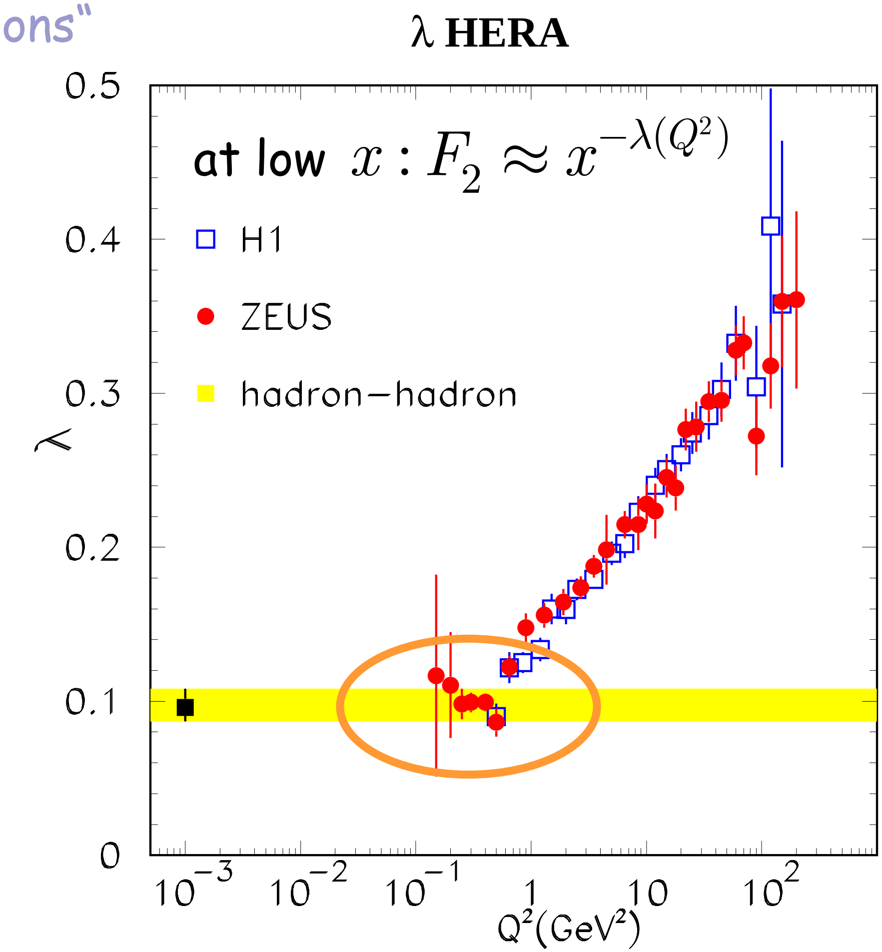
- Polarized CC & NC
  (if time allows,
  beautiful physics!)

HERA's Surprise: The Strong Rise of F_2 towards low x



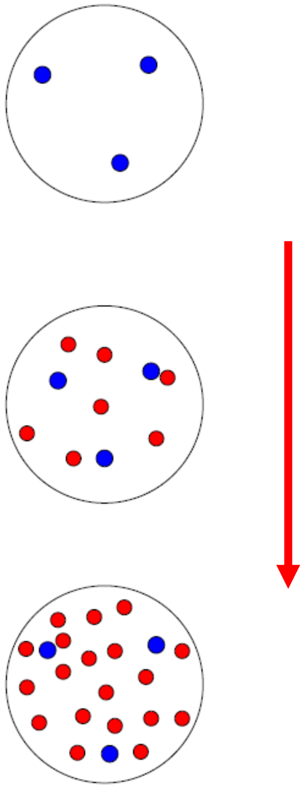






Transition from the perturbative to the non-perturbative regime

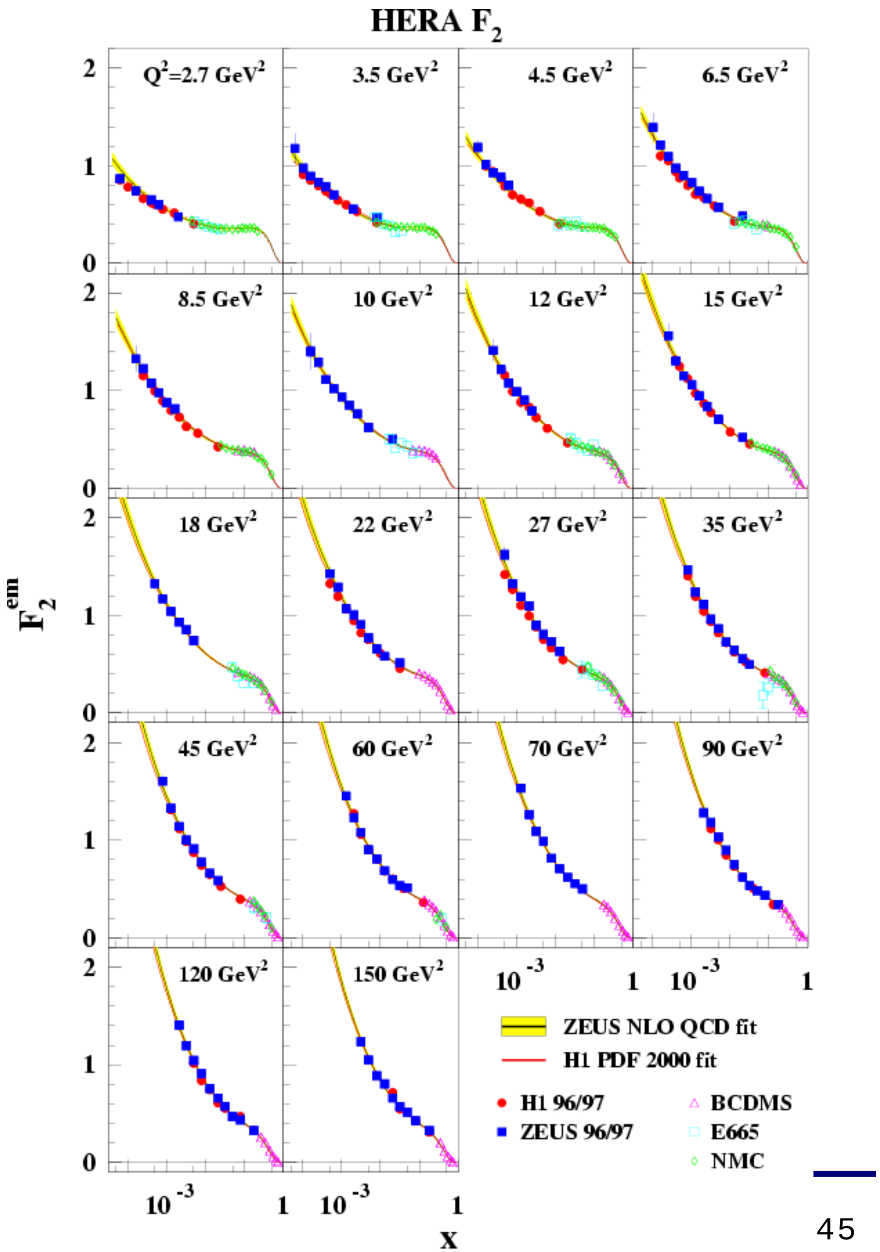
Low x, Large Parton Densities and Saturation



at fixed resolution scale (Q^2) go to very large hadronic center of mass energy

low x $\quad x = \dfrac{Q^2}{Q^2 + W^2}$

ultimately expect partons to overlap („saturation")



Rise of PDFs should flatten with decreasing x $\quad \left(\dfrac{1}{x}\right)^{\lambda} \rightarrow \ln\dfrac{1}{x}$

No saturation observed at HERA

Combination of H1 and ZEUS Measurements

- Ultimate precision is obtained by combining the H1 and ZEUS measurements

- The combination procedure is performed before QCD analysis:
  - The combination of data is performed using the χ^2 minimisation procedure

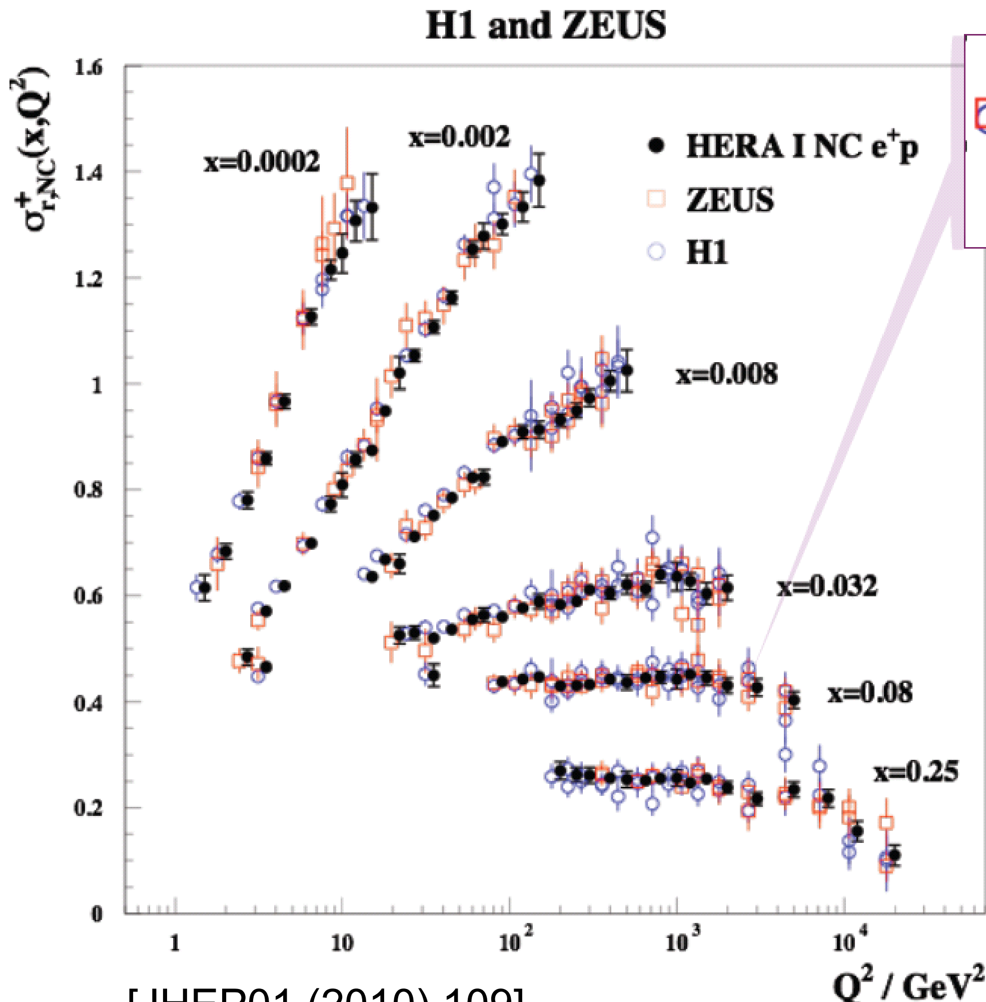
    χ^2 definition → backup slides

    - 1402 of HERA I H1 and ZEUS measurements were combined into 741 unique cross section points with 113 correlated systematic sources.

    - Improvement on 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.

Results of Combining H1 and ZEUS

$F_2 \sim$



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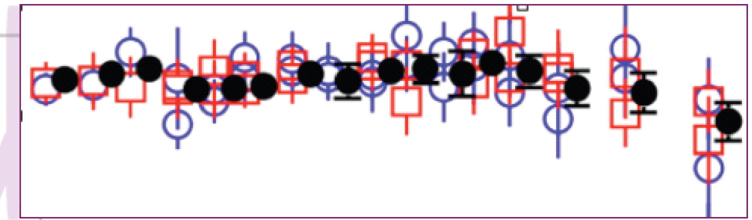
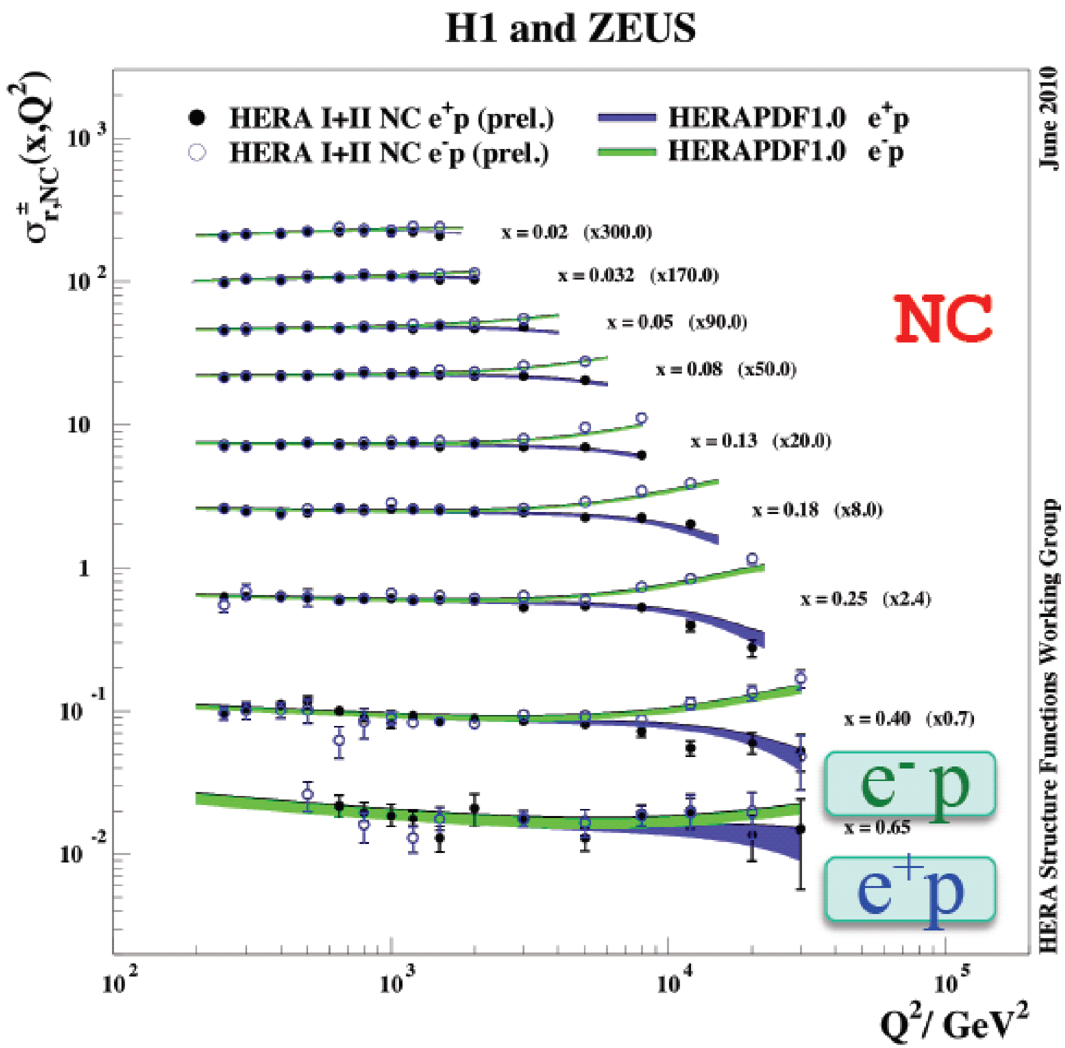


The combination procedure yields a consistent data set:

- χ^2/dof=637/656
- 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!

HERA I +II Combined NC



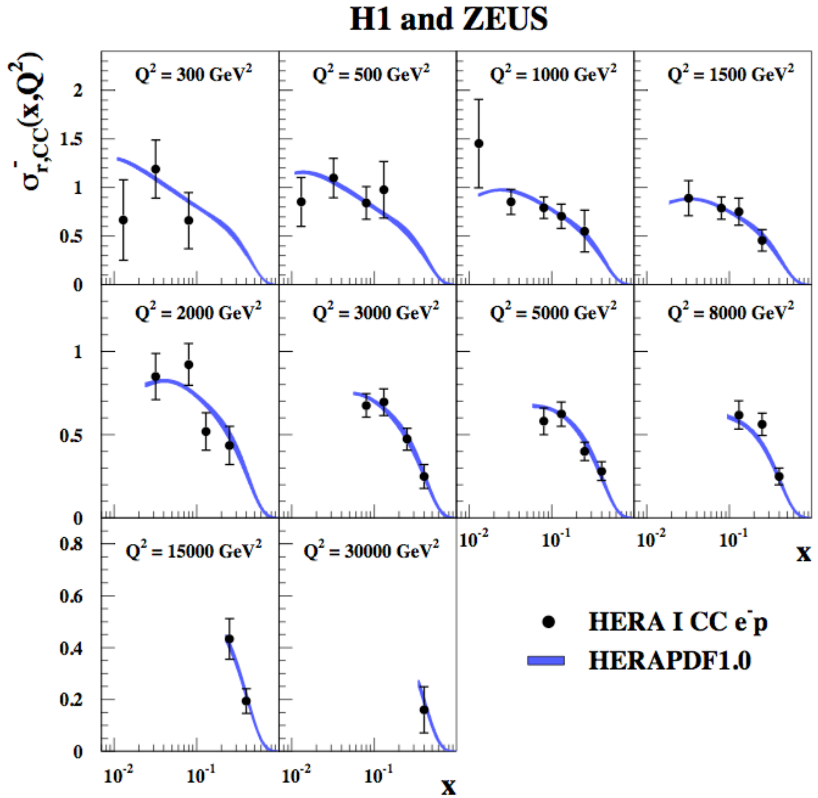
$$\tilde{\sigma}^{\pm}_{NC} \equiv \frac{d^2\sigma^{e^\pm p}_{NC}}{dx\,dQ^2}\,\frac{xQ^4}{2\pi\alpha^2}\,\frac{1}{Y_+}$$

$$\equiv \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+}x\tilde{F}_3$$

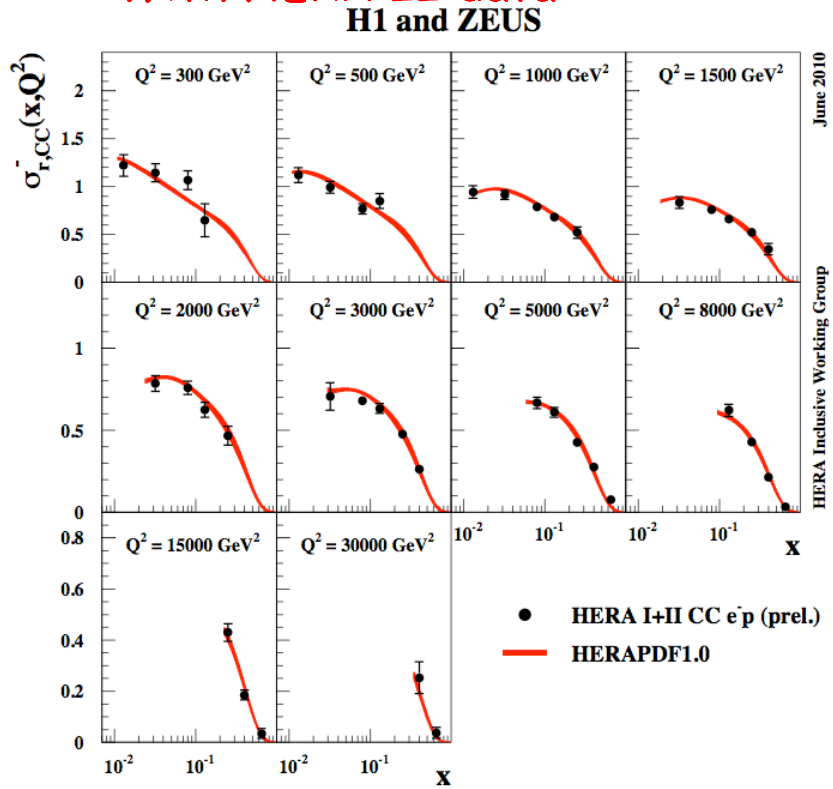
HERA I+II Combined CC

$$\tilde{\sigma}_{CC}^{-} \sim (xu + xc) + (1-y)^2 (x\bar{d} + x\bar{s})$$

Without HERA II data



With HERA II data



QCD Analysis Framework

- **Data Sets**
  - HERA I combined data [JHEP01 (2010) 109]
  - add HERA-II data (NC+CC high Q2, low Ep, F2cc,…)

- QCD Fit settings:
  - NLO (and NNLO) DGLAP evolution equations
  - TR VFNS (as for MSTW08)
    - Other schemes were investigated as well: **TR** (optimal), ACOT (full and χ), FFNS
  - PDF parametrised at the starting scale Q_0^2:

$$G, u_{val}, d_{val}, \bar{U} = \bar{u}(+\bar{c}), \bar{D} = \bar{d} + \bar{s}(+\bar{b})$$

$$xf(x,Q_0^2) = Ax^B(1-x)^C(1+Dx+Ex^2)$$

  - Apply quark number and momentum sum rules
  - The optimum number of parameters chosen by saturation of the χ^2
    - central fit with 10 free parameters
    - χ^2/dof=574/582

Scheme	TRVFNS
Evolution	QCDNUM17.02
Order	NLO
Q_0^2	1.9 GeV^2
$f_s = s/D$	0.31
Renorm. scale	Q^2
Factor. scale	Q^2
Q^2_{min}	3.5 GeV^2
$\alpha_S(M_Z)$	0.1176
M_c	1.4 GeV
M_b	4.75 GeV

Sources of PDF uncertainties at HERA

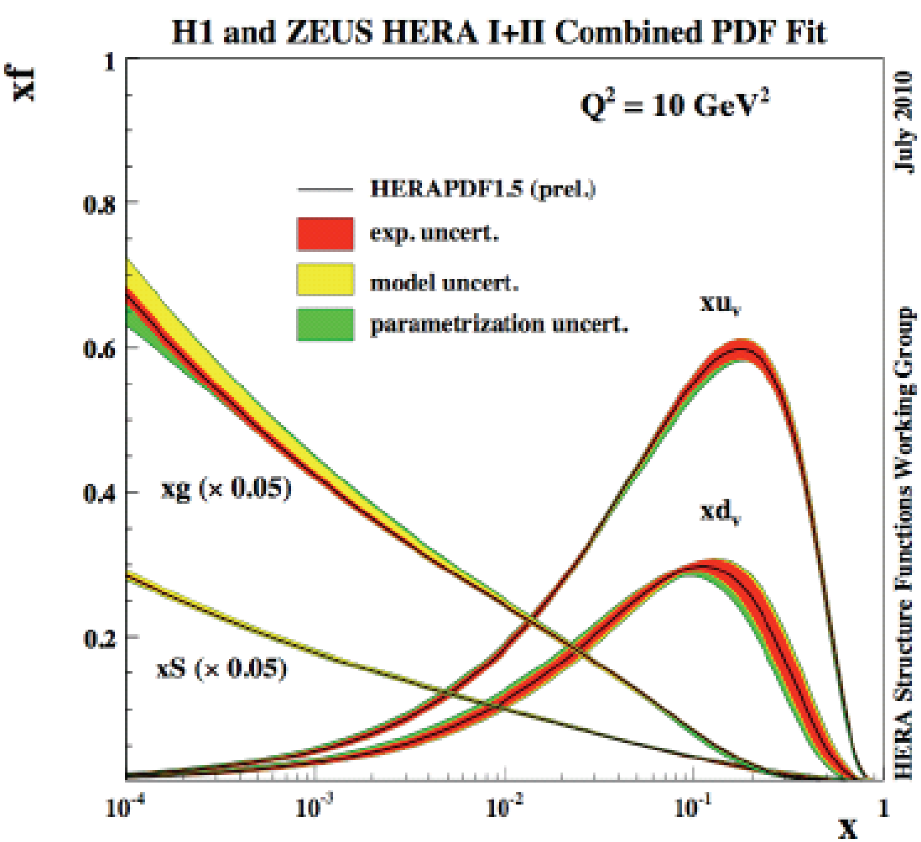
- **Experimental Uncertainties:**
  - Consistent data sets → use $\Delta\chi^2 = 1$
- **Model Uncertainties:**
  - following variations have been considered

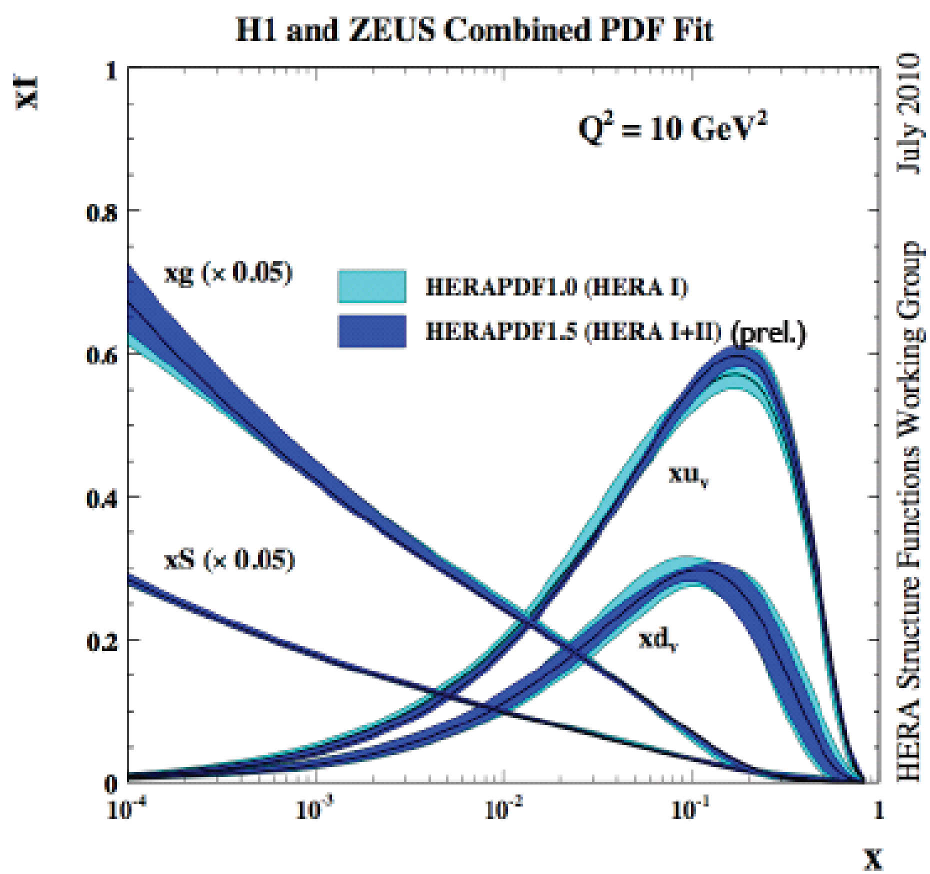
Variation	Standard Value	Lower Limit	Upper Limit
f_s	0.31	0.23	0.38
m_c [GeV]	1.4	1.35	1.65
m_b [GeV]	4.75	4.3	5.0
Q^2_{min} [GeV^2]	3.5	2.5	5.0

- **Parametrisation Uncertainties:**
  - An envelope formed from PDF fits using other variants of parametrisation form at the starting scale:
    - Scanning of 11 parameter space
    - Q_0^2 variation and negative gluon parametrisation
    - Relaxing assumptions used for central fit

HERAPDF1.5 vs. HERAPDF1.0

- xg, xu_v, xd_v, xSea ($xSea=x\overline{U}+x\overline{D}$) at the starting scale $Q_0^2=1.9$ GeV^2



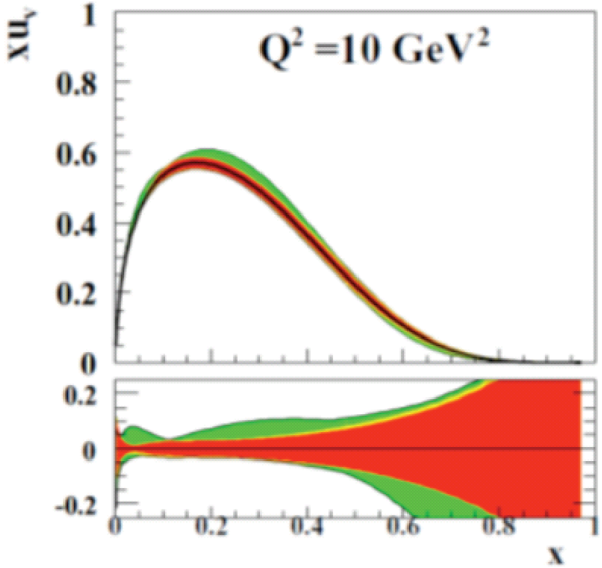


- Inclusion of the HERA II data reduces the uncertainties on PDFs in the high x region especially visible on the valence distributions!
  - See HERAPDF1.5(prel) vs HERAPDF1.0

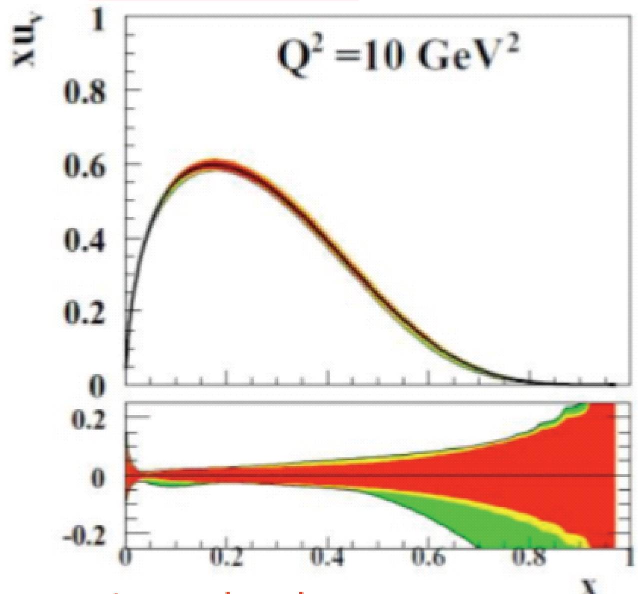
Fits to New Combined HERA data: HERAPDF1.5

- Propagate new data through QCD fit analysis to produce a new set of HERAPDFs: HERAPDF1.5
  - For preliminary studies use same settings as for HERAPDF1.0
  - Parametrisation uncertainty will be further investigated for final release.

HERAPDF1.0



HERAPDF1.5



$\Rightarrow$Experimental uncertainty reduced

$\Rightarrow$Parametrisation uncertainty reduced

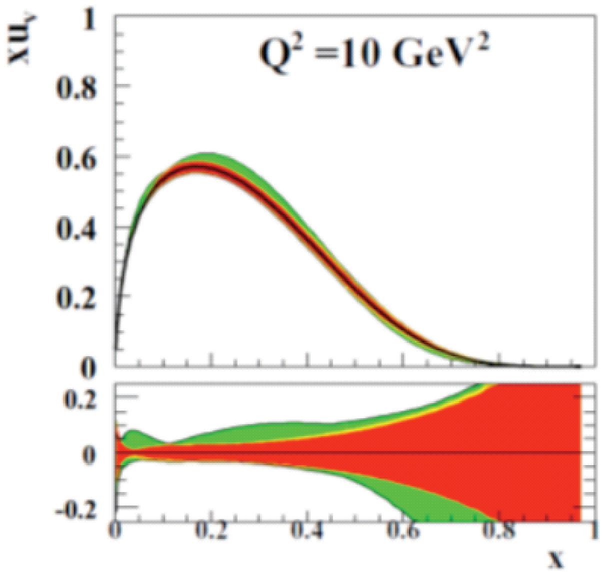
Fits to New Combined HERA data: HERAPDF1.5

- Propagate new data through QCD fit analysis to produce a new set of HERAPDFs:
  HERAPDF1.5

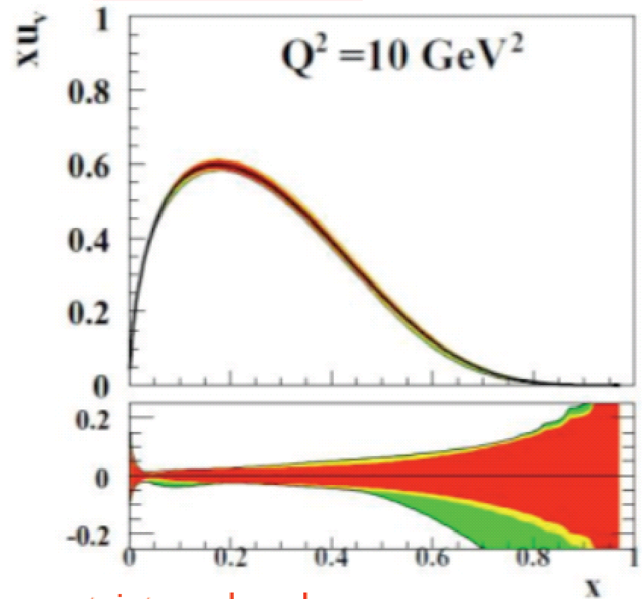
  NC & CC inclusive

  - same settings as for HERAPDF1.0
  - Parametrisation uncertainty will be further investigated for final release.

HERAPDF1.0



HERAPDF1.5



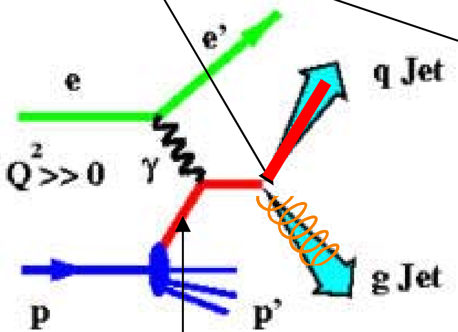
⇒Experimental uncertainty reduced

⇒Parametrisation uncertainty reduced

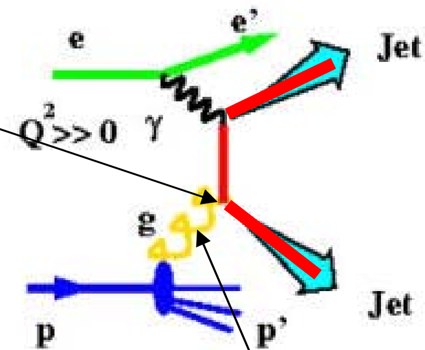
Jet production in DIS (HERA)

Sensitive to α_s

$\sigma_{jet} \sim \alpha_s \cdot f(x)$



QCD-COMPTON



Boson Gluon Fusion (BGF)

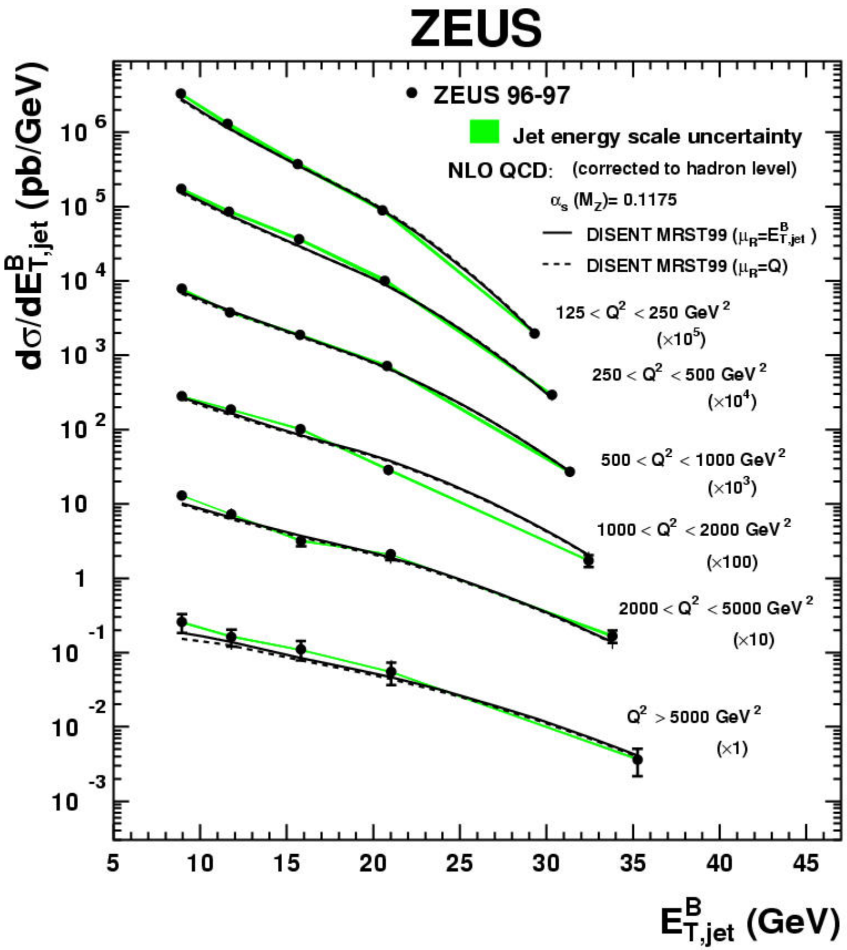
Sensitive to quarks
$\sim 10^{-2} < x < \sim 10^{-1}$

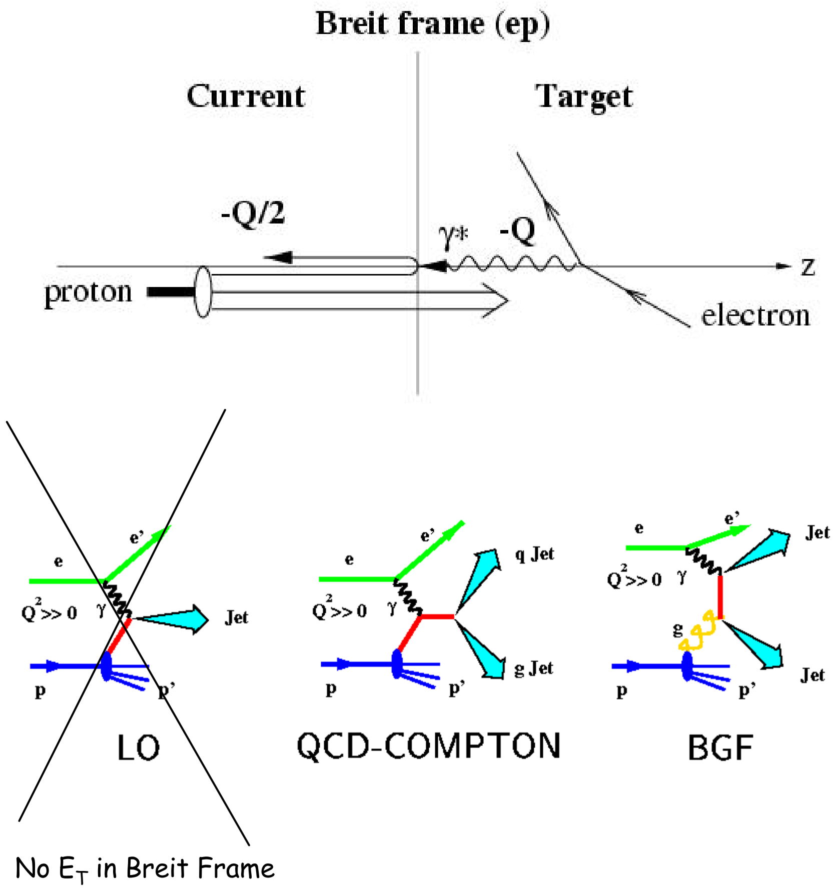
Same range as NC and CC

Sensitive to gluon
$\sim 10^{-3} < x < \sim 10^{-2}$

complementary
to gluon from F_2

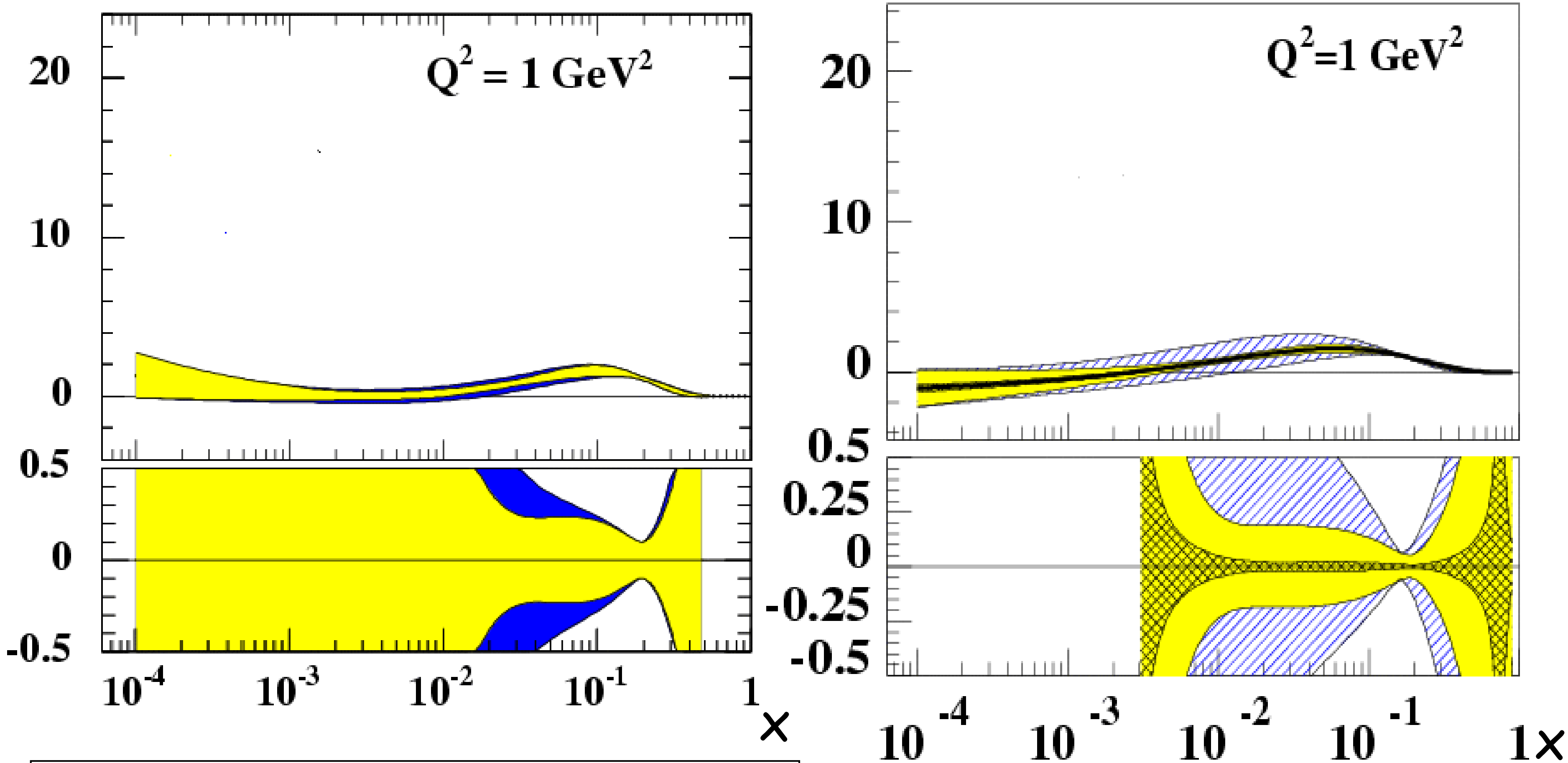
Jet measurements in Breit frame





Jet production cross-section used in QCD fit →

Gluon distributions

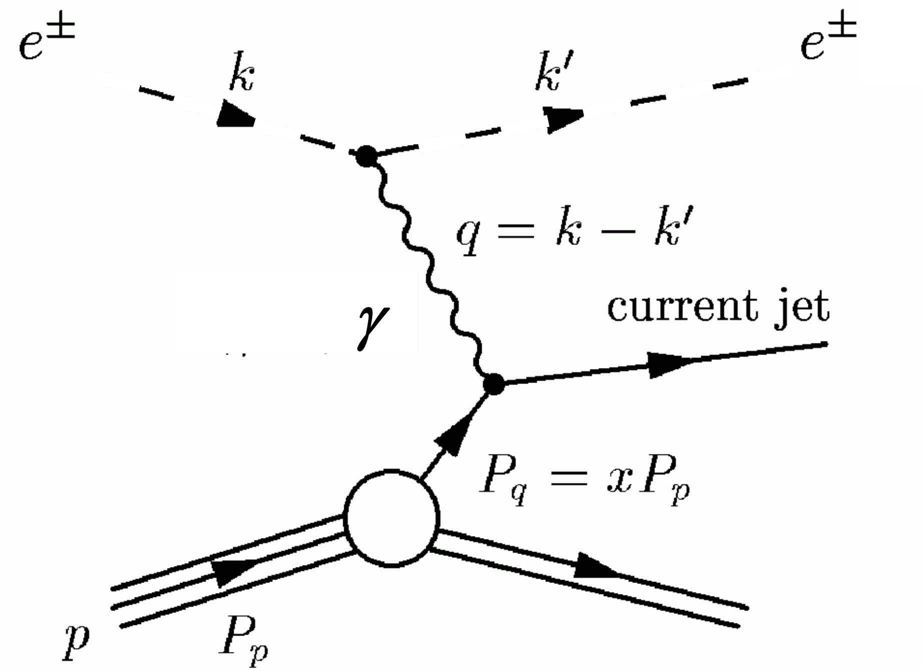


Using only HERA (ZEUS) data including NC,CC and jets

Using HERA (ZEUS) F_2 data and FNAL, CERN fixed tgt

Photon Proton Scattering

- **DIS ep scattering may be interpreted as scattering of an virtual photon off an proton**
- **The virtual photon may be transversely or longitudinally polarized**



γp Cross Sections:

$$\sigma_T^{\gamma p} = \frac{4\pi\alpha}{Q^2} 2xF_1 = \frac{4\pi\alpha}{Q^2}(F_2 - F_L)$$

$$\sigma_L^{\gamma p} = \frac{4\pi\alpha}{Q^2}(F_2 - 2xF_1) = \frac{4\pi\alpha}{Q^2} F_L$$

$$\frac{\sigma_L^{\gamma p}}{\sigma_T^{\gamma p}} = R = \frac{F_L}{F_2 - F_L}$$

Quark Parton Model (QPM)

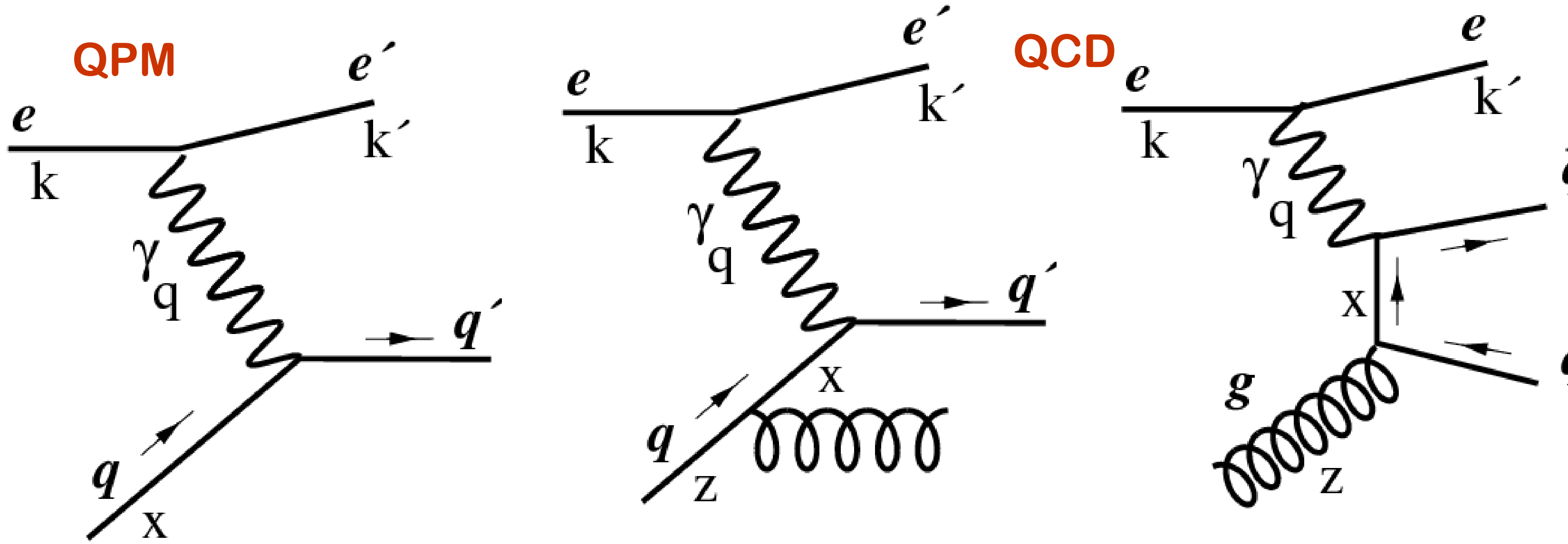
$$F_1(x) = \frac{1}{2x}\sum_q e_q^2 xq(x)$$

$$F_2(x) = \sum_q e_q^2 xq(x)$$

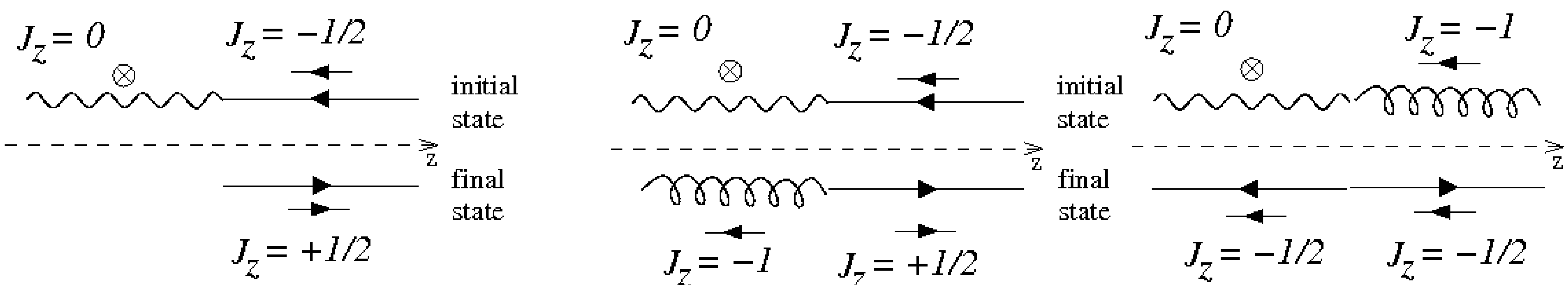
$$F_L(x) = F_2 - 2xF_1 = 0$$

Callan Gross relation

Longitudinal Structure Function F_L



Scattering of longitudinally polarized photons on quarks in helicity frame



J_z conservation not possible

$$F_L \propto \sigma_L = 0$$

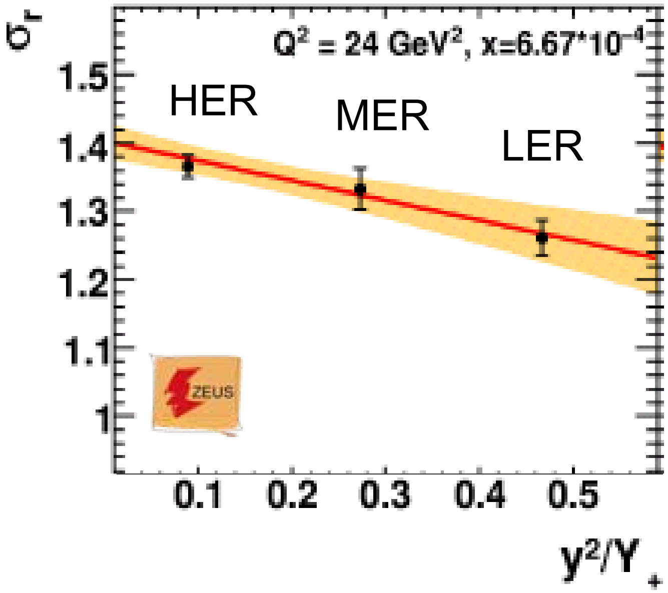
$$F_L = \frac{\alpha_s}{4\pi} x^2 \int_x^1 \frac{dz}{z^3} \left[\frac{16}{3} \sum_q z e_q^2 (q + \bar{q}) + 8 \sum_q e_q^2 \left(1 - \frac{x}{z}\right) \cdot z g \right]$$

access to gluon density

Measurement of FL

Measure cross sections
at same x and Q^2 but different $y = Q^2/x \cdot s$ → vary s

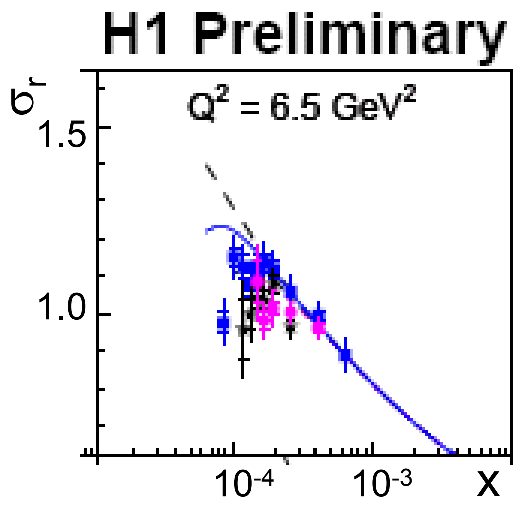
$$\sigma_r = F_2\left(x,Q^2\right) - \frac{y^2}{Y_+} F_L\left(x,Q^2\right)$$

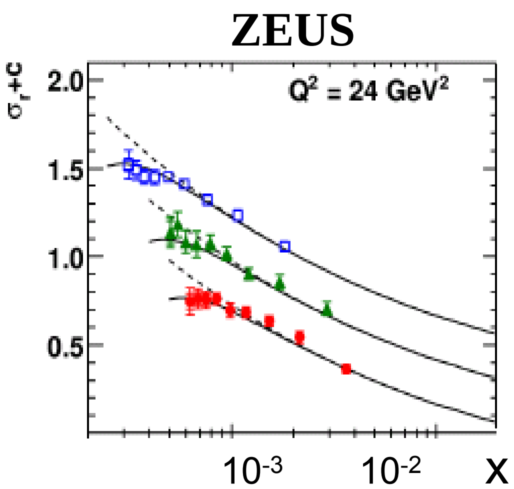


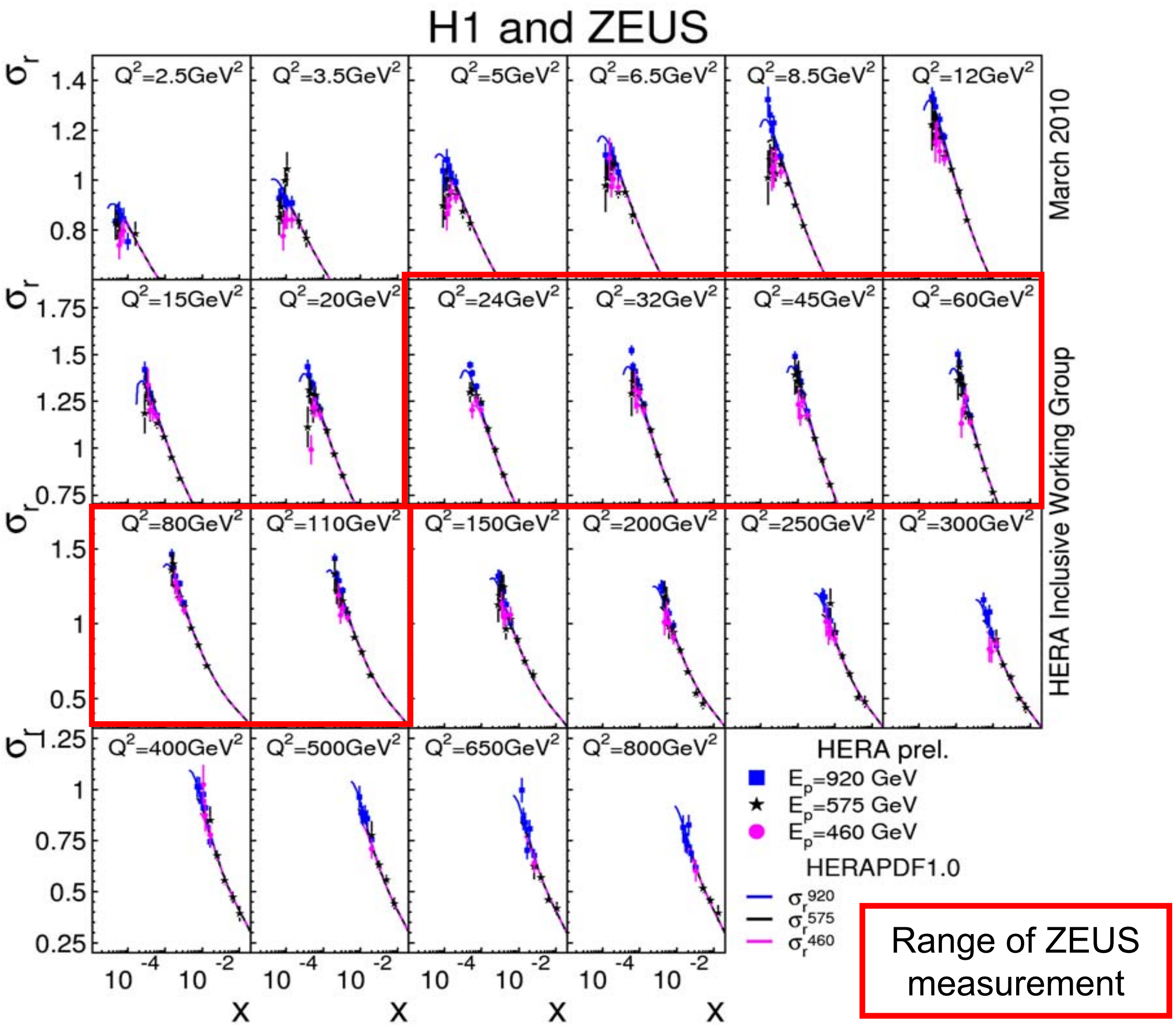
- Change proton beam energy to change cms energy
  - E_p = 920 GeV, High Energy Run (HER)
  - E_p = 575 GeV, Medium Energy Run (MER):
  - E_p = 460 GeV, Low Energy Run
- Large lever arm in y^2/Y_+
- Measure at high y in LER

- Extended measurement to high y region
  $y = 1 - E'_e/E_e(1-\cos\theta)$ →high y means low E'_e

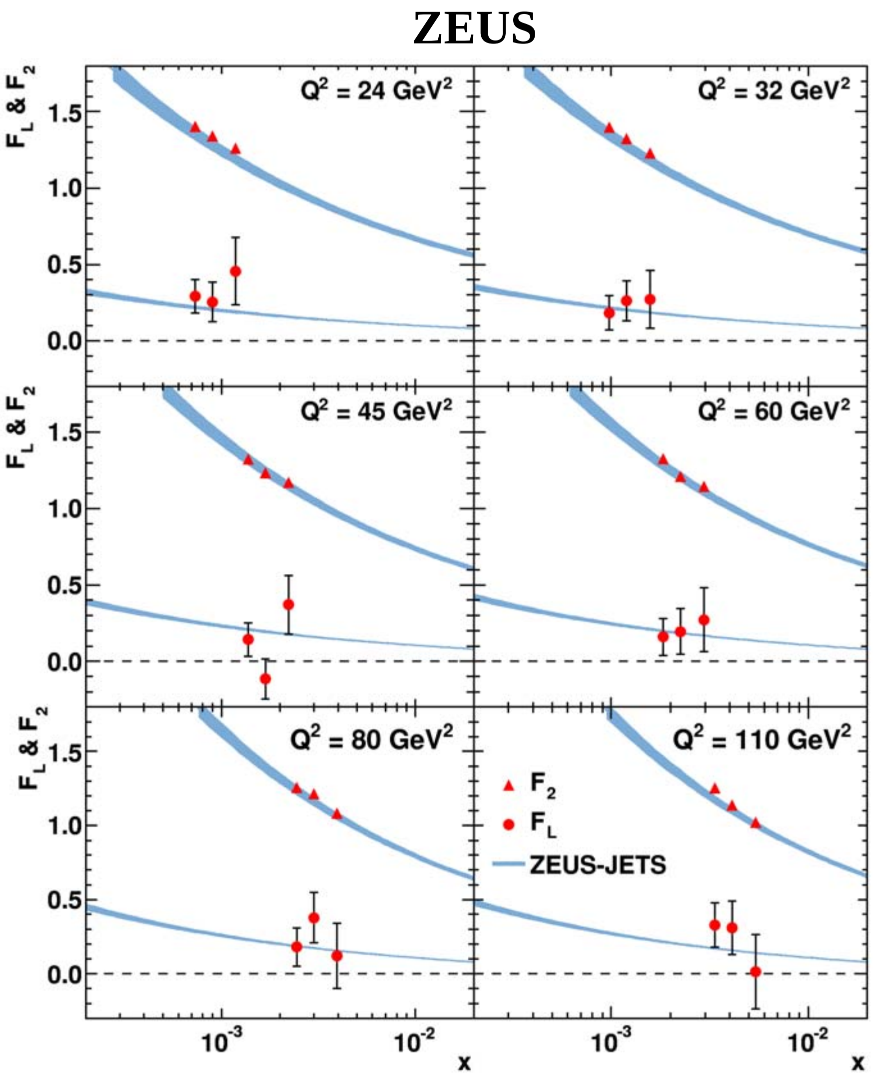
Combined low E_p Cross Sections





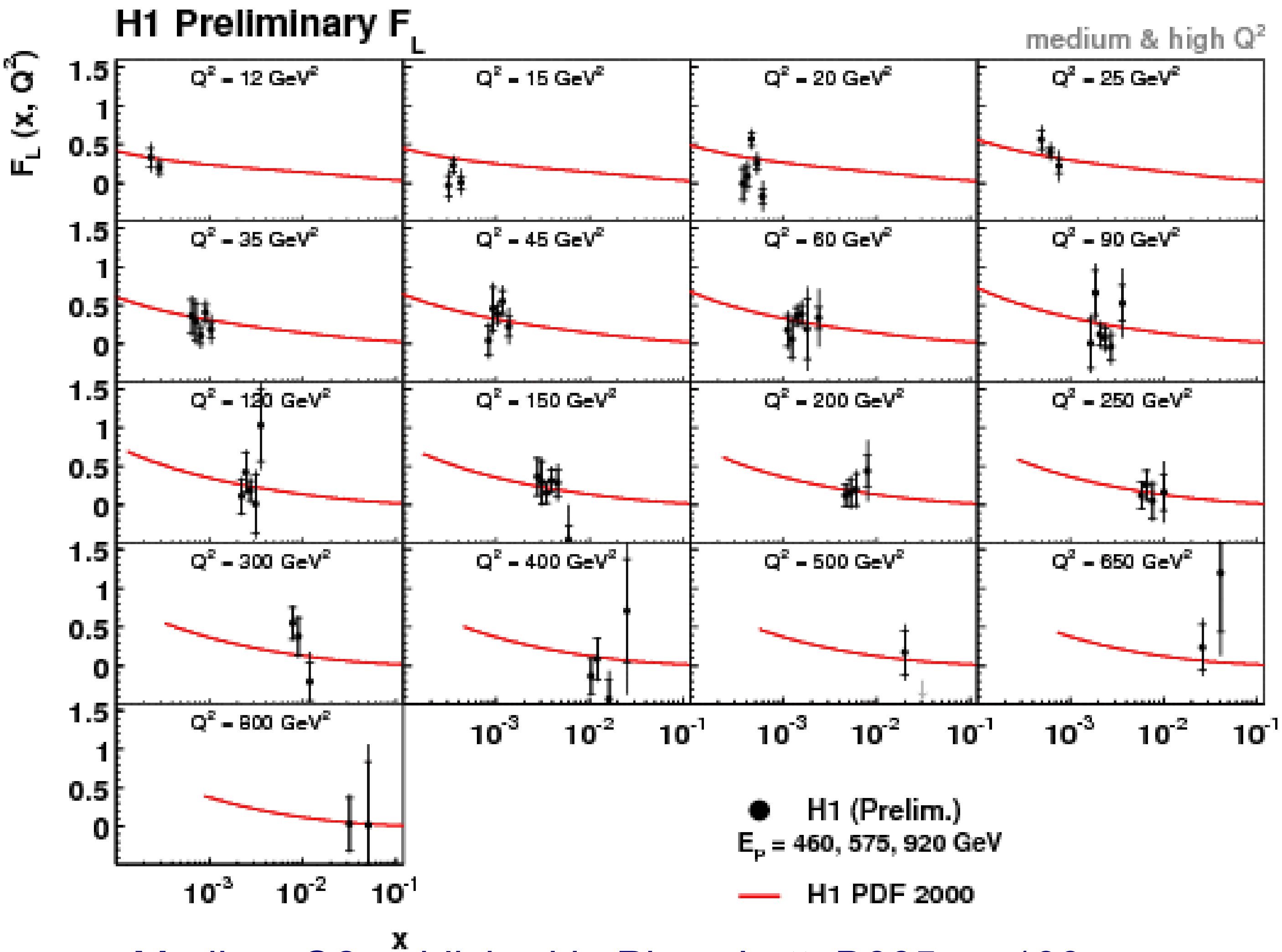


Extracted F_L and F_2



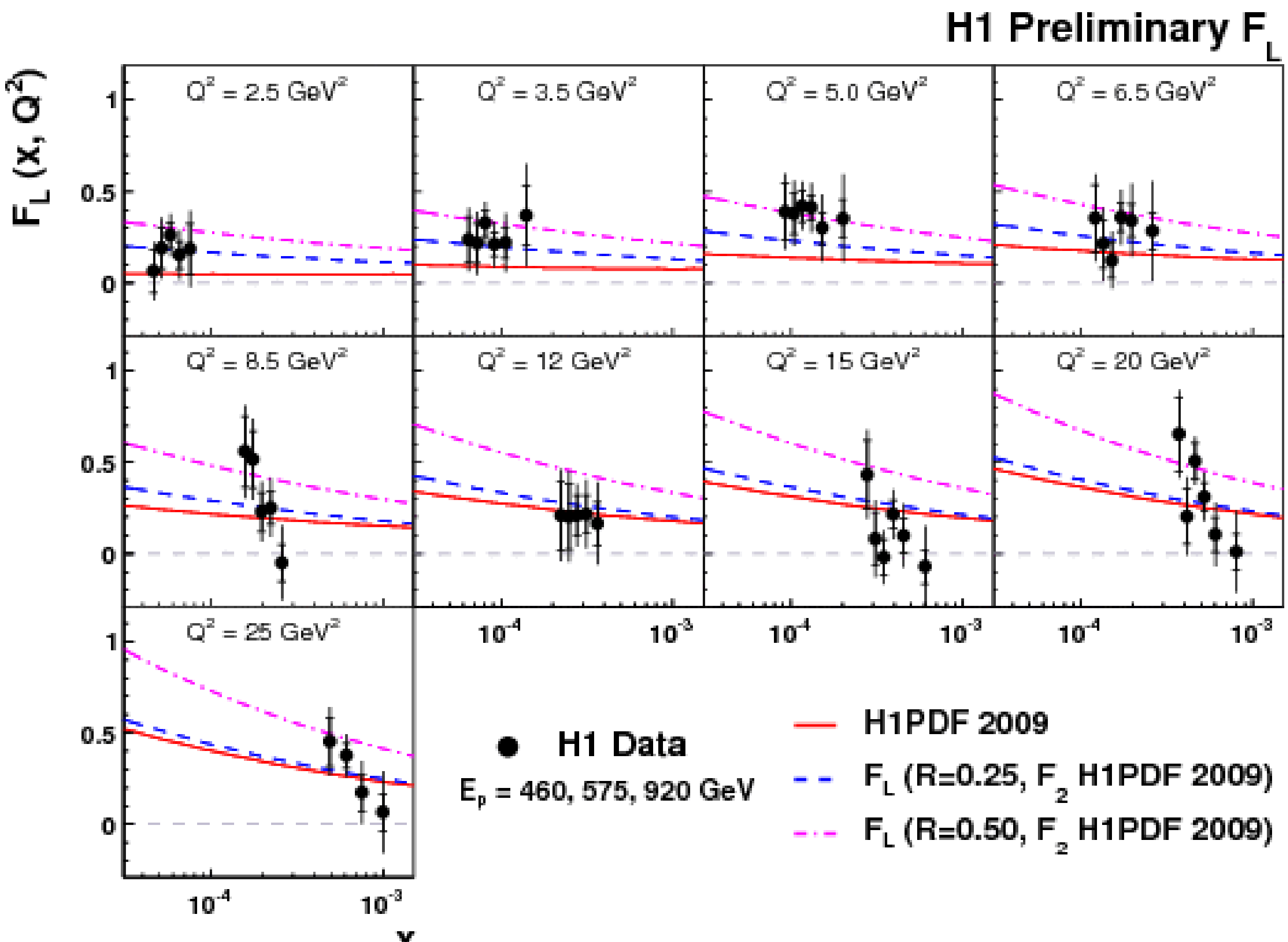
- First F_2 measurement without assumptions on F_L
- Data support a non-zero F_L
- Predictions for F_2 and F_L are consistent with data

Extracted F_L – medium & high Q^2



Medium Q2 published in Phys. Lett. B665, p. 139

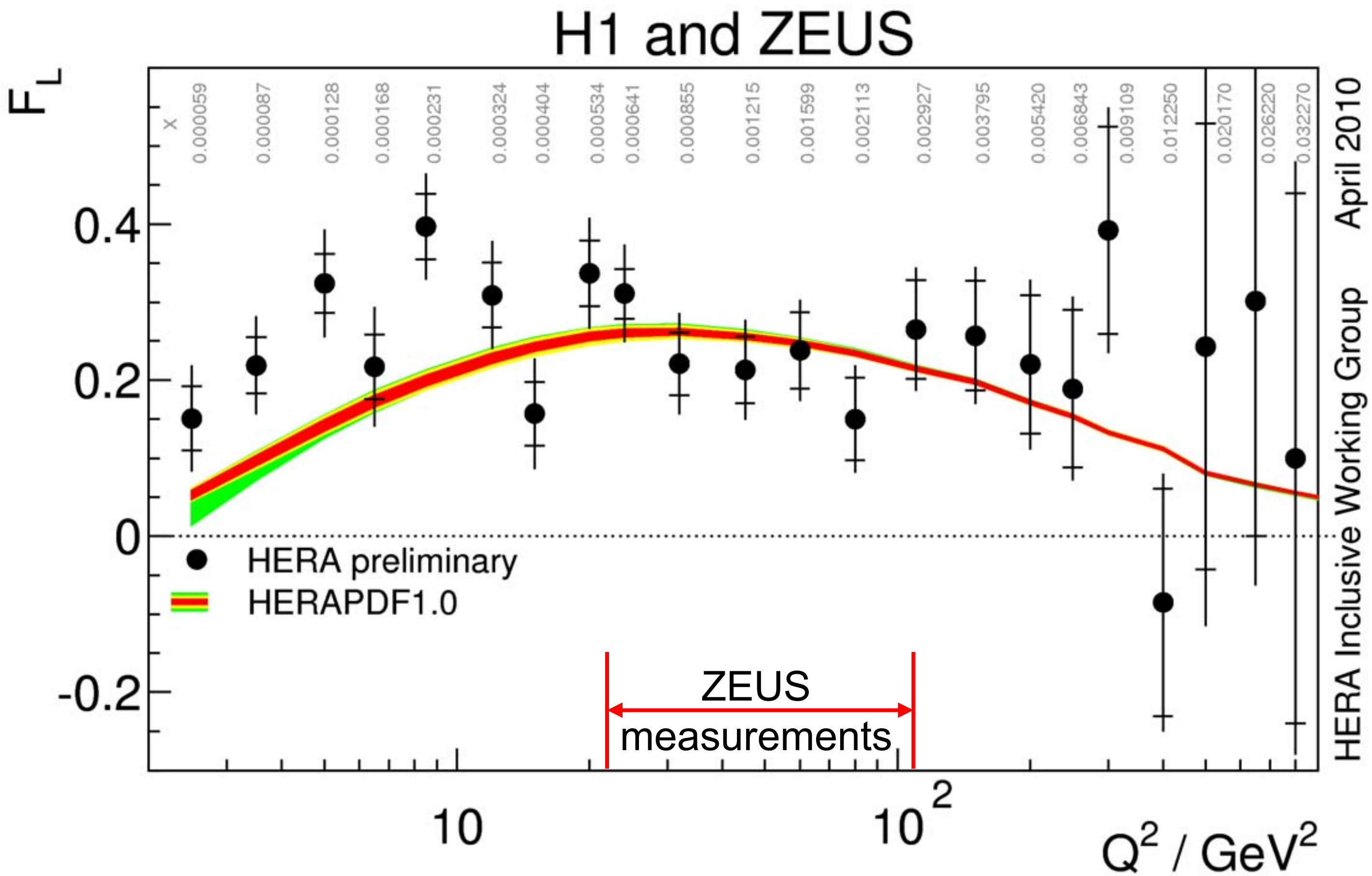
Extracted F_L – Low Q^2



F_L measured down to Q^2 = 2.5 GeV^2 !

Data are consistent with R~0.25 (F_L =0.2 · F_2)

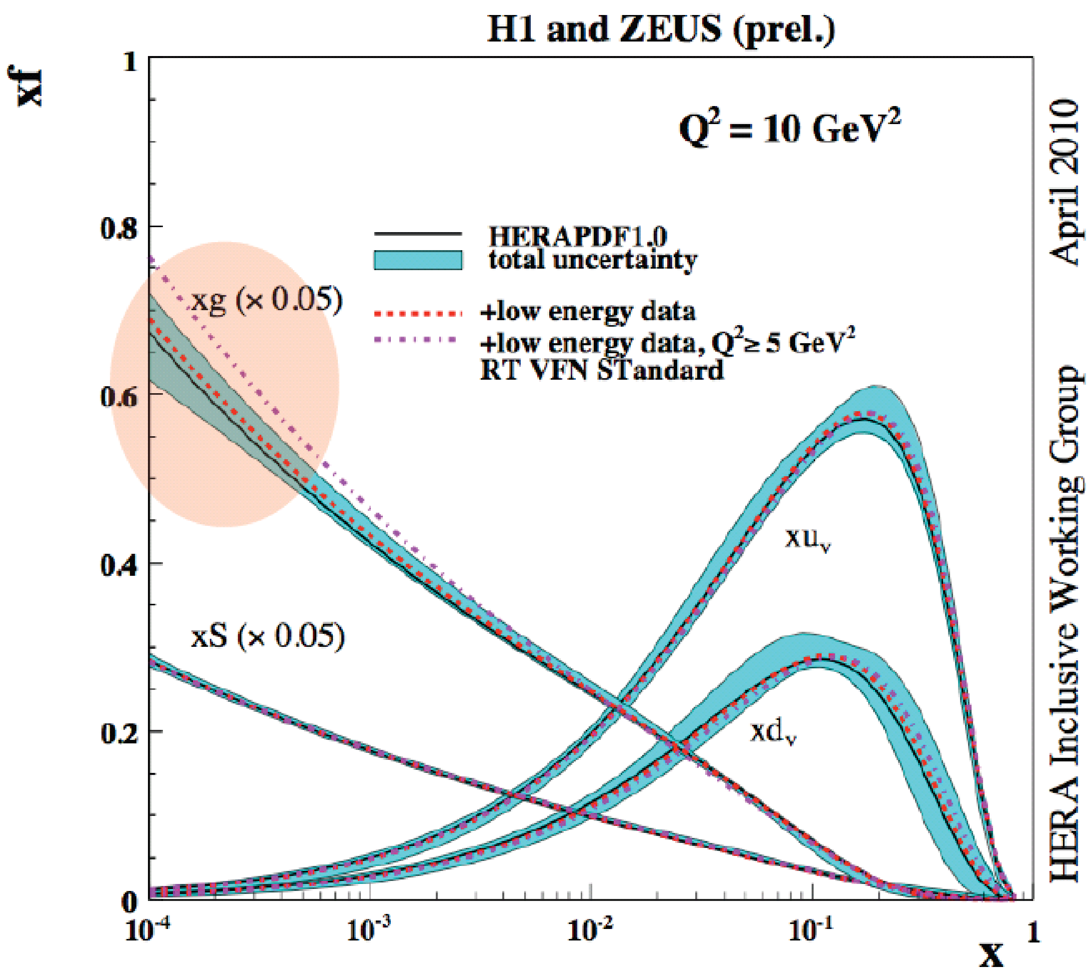
H1 + ZEUS Combined F_L



Good agreement between data and predictions for Q^2>10 GeV^2.

F_L at low Q^2 above prediction using HERAPDF1.0

HERAPDF including low E_p data



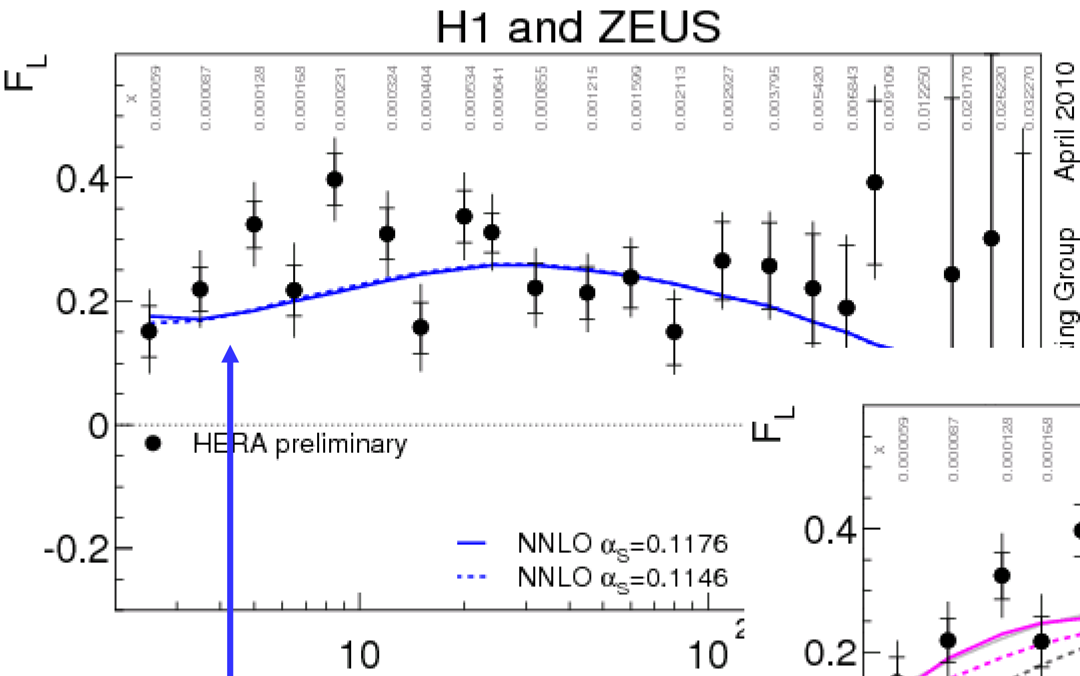
- PDFs from the new fit agree very well with HERAPDF1.0

Data sets	HERAPDF1.0	+ Low Energy data
Total χ^2/dof	574/582	818/806

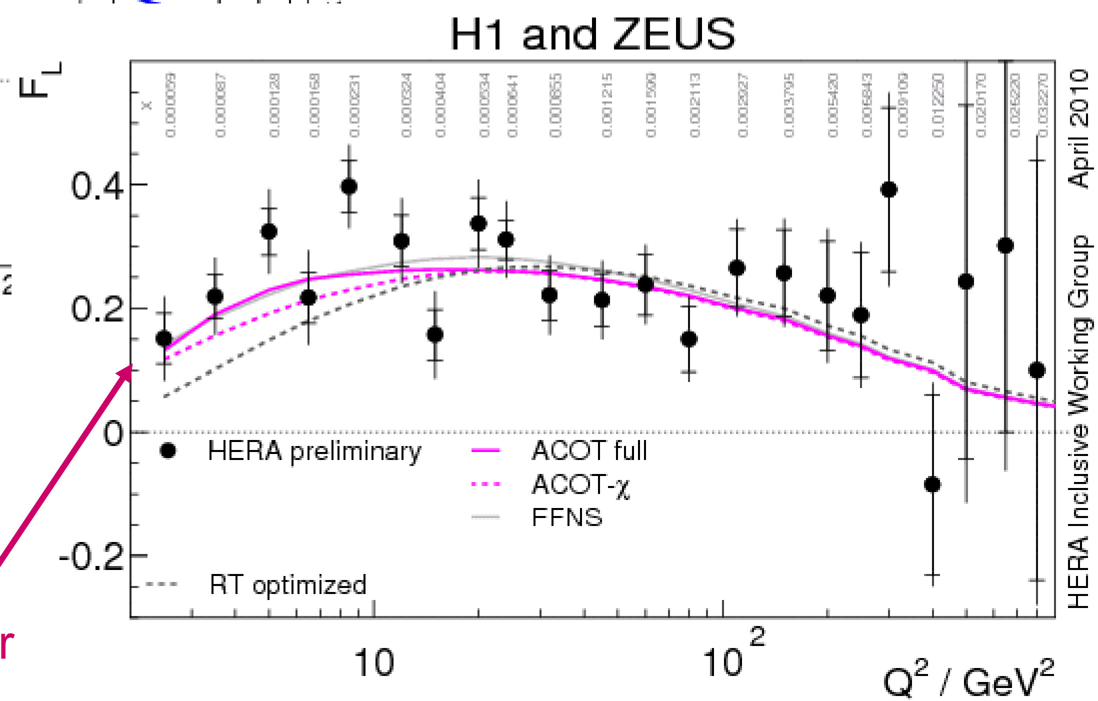
However, The $Q^2 \geq 5\ GeV^2$ cut brings large improvement in χ^2 [818/806 → 698/771] and it yields different shapes for gluon and sea PDFs.

- for HERAPDF1.0, Q^2 cut variation is included in the model uncertainty, but it had smaller effect.

Variants of Predictions for F_L



Higher Order calculation

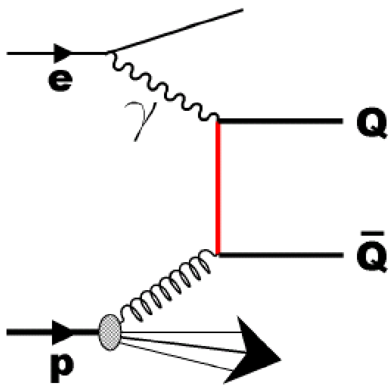


Variation of heavy flavour treatment

Heavy Quarkproduction in DIS

Fixed Flavour–Number Scheme (FFNS)

c (b)only from hard scattering,
3 (4) active flavours in p



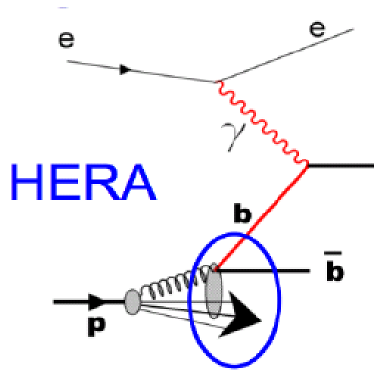
leading order: boson-gluon fusion

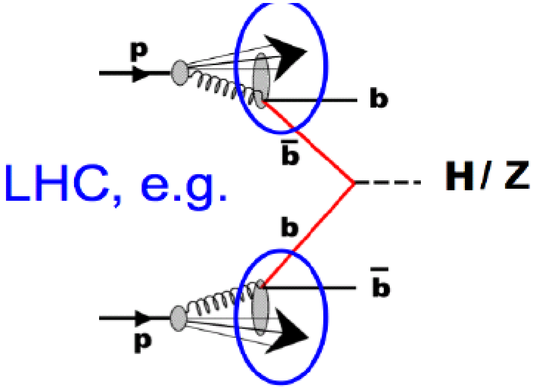
Direct access to $g(x)$

FFNS spoiled when Q^2, $p_T \gg m_Q$
e.g. large $\log(Q^2/m_Q^2)$

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

c, b active flavours in p





resums $\log(Q^2/m^2)$

c,b: massless partons:
ZM-VFNS fails at $Q^2 \leq \mathcal{O}(m_Q^2)$

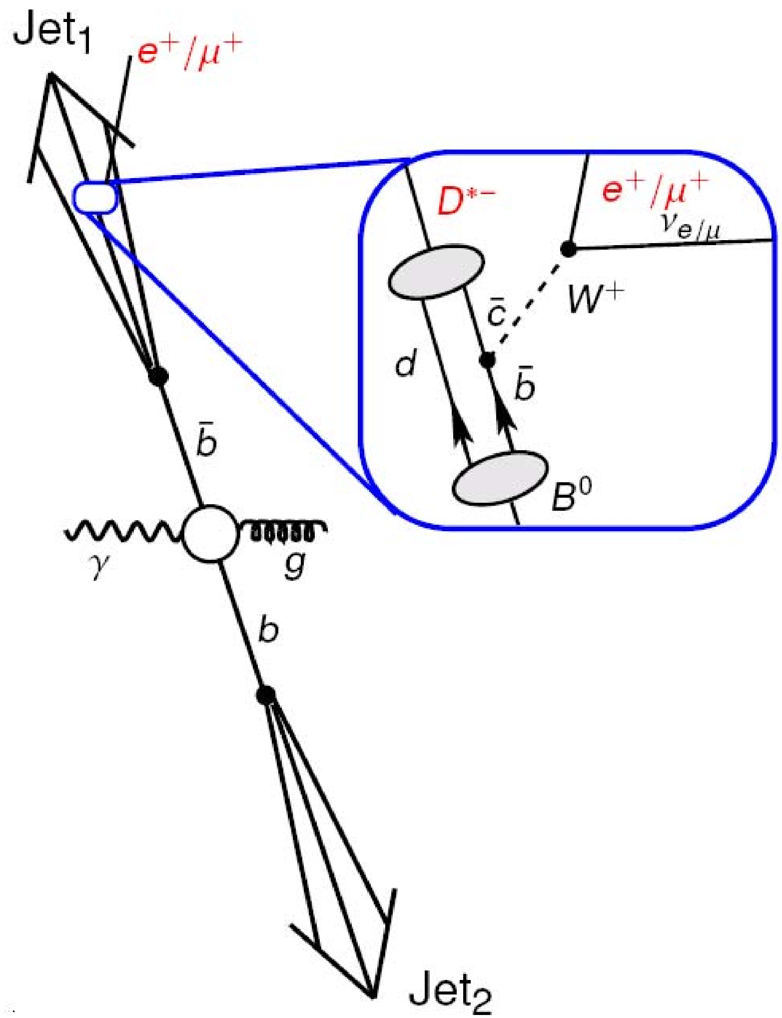
needed at high-energy colliders

c, b PDFs can be directly tested in DIS

Heavy Flavour Tagging

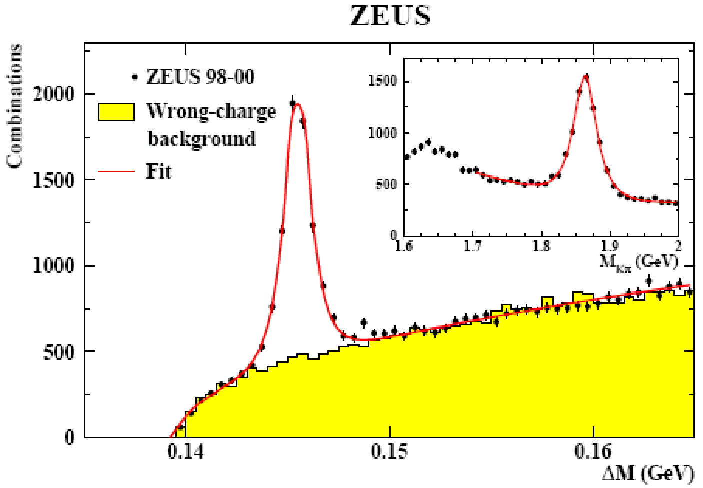
Different experimental techniques used (combined) for heavy flavour tagging:

- Decay spectra
  p_T^{rel} of lepton to jet axis
- Lifetime information
  Measure impact parameter with respect to primary vertex (beamspot)
- Meson identification
  $D^{*\pm}$ tagging ("Golden Decay")

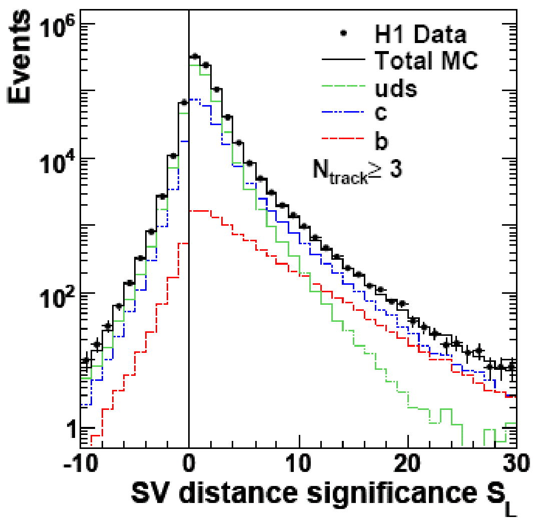


H1 + ZEUS Charm Measurements

- ZEUS, D^{*+}, HERA I, L=82+37 pb^{-1} (hep-ex/9908012, hep-ex/0308068)
- H1, D^{*+}, HERA I, L=47 pb^{-1} (hep-ex/0608042)
- H1, D^{*+}, HERA II prel., L=340 pb^{-1} (high-Q^2 part: arXiv:0911.3989)
- ZEUS, D^+, D^0, 2005 data, L=134 pb^{-1} (arXiv:0704.3562 [hep-ex])
- ZEUS, μ, 2005 data, L=121 pb^{-1} (arXiv:0904.3487 [hep-ex])
- H1, lifetime tag, HERA I, L=57 pb^{-1} (hep-ex/0411046, hep-ex/0507081)
- H1 lifetime tag, HERA II prel, L=189 pb^{-1} (now in arXiv:0907.2643)



D^{*+} signal (ZEUS HERA-I 98-00)



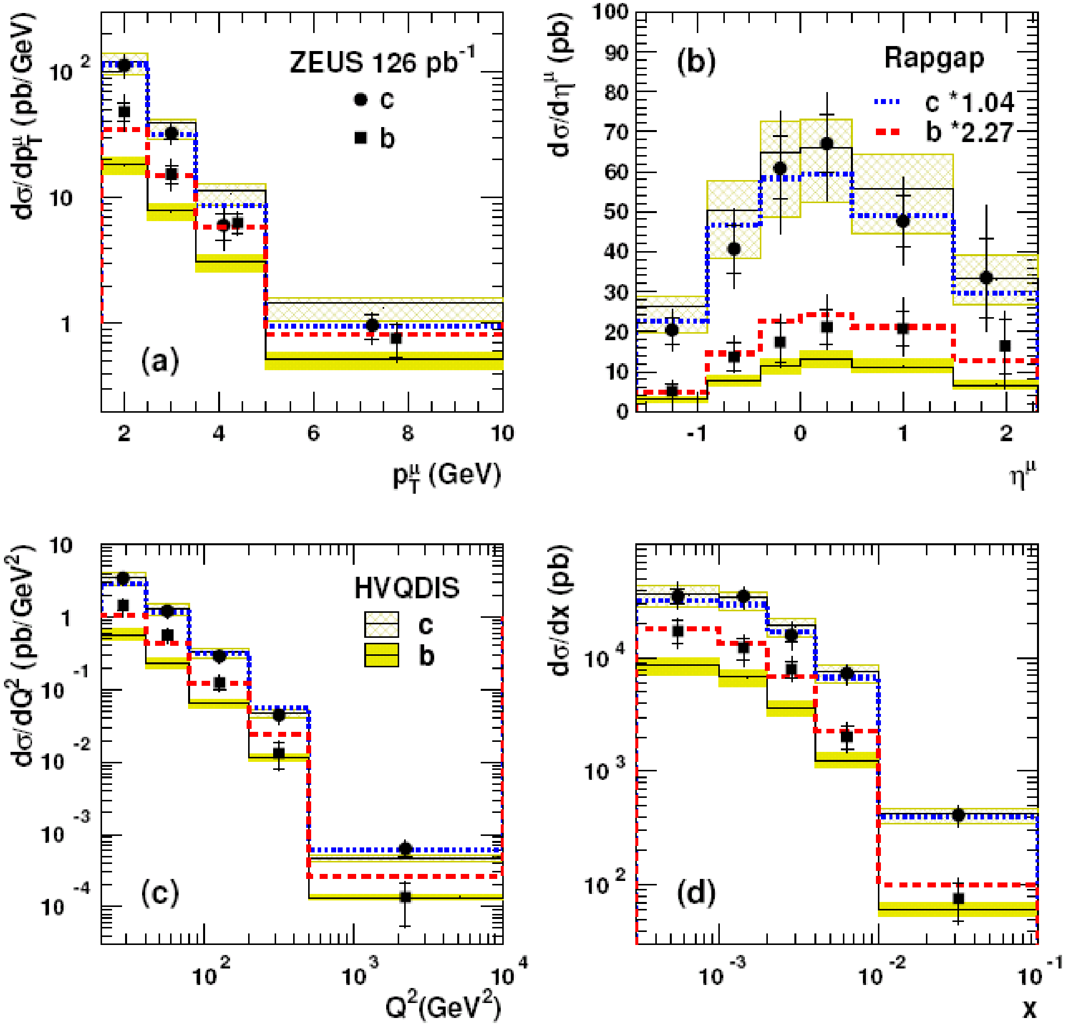
Secondary vertex significance (H1 lifetime tag)

Measurement: Visible Cross Section

Example:

Semileptonic decays into μ

Simultaneous extraction of charm and beauty cross sections



Charm Structure Function: $F_2^{c\bar{c}}$

$F_2^{c\bar{c}}$ is the part of the F_2 structure function with a $c\bar{c}$ in the final state:

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

$$Y_+ = 1 + (1-y)^2$$

(note: definition may differ from that used by theorists, see Forte et al. arXiv:1001.2312)

D mesons (or μ) production measured in "visible" phase space

typically $|\eta(D^*)| < 1.5$, $p_T(D^*) > 1.5$ GeV

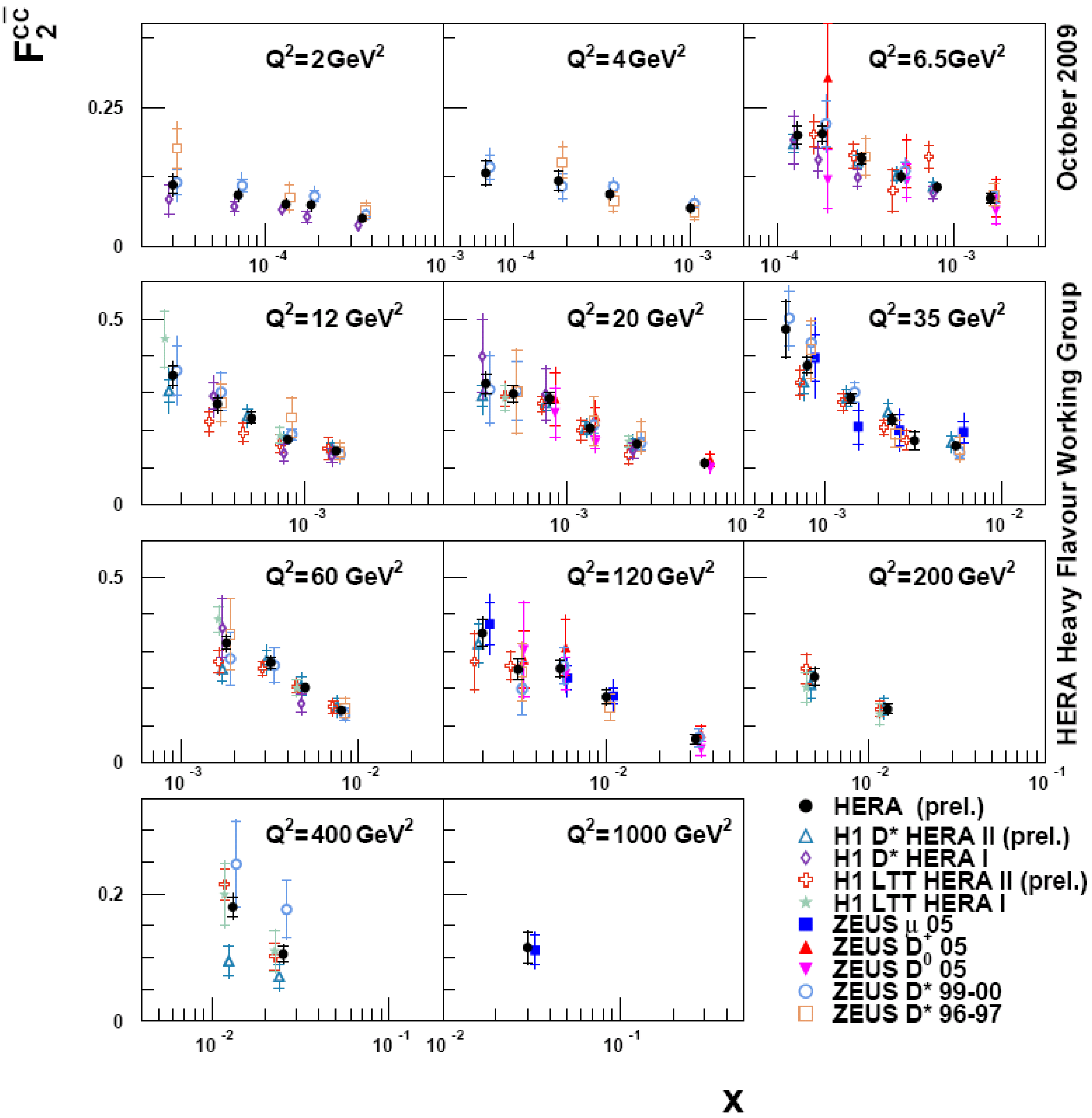
$F_2^{c\bar{c}}$ extracted using theory-based correction:

$$F_2^{c\bar{c}}(x,Q^2) = \sigma_{\text{vis,bin}} \frac{F_2^{c\bar{c},\text{theo.}}(x,Q^2)}{\sigma_{\text{vis,bin}}^{\text{theo.}}}$$

Similarly for inclusive lifetime tagging:
experiments mostly sensitive to events with several central high-p_T tracks

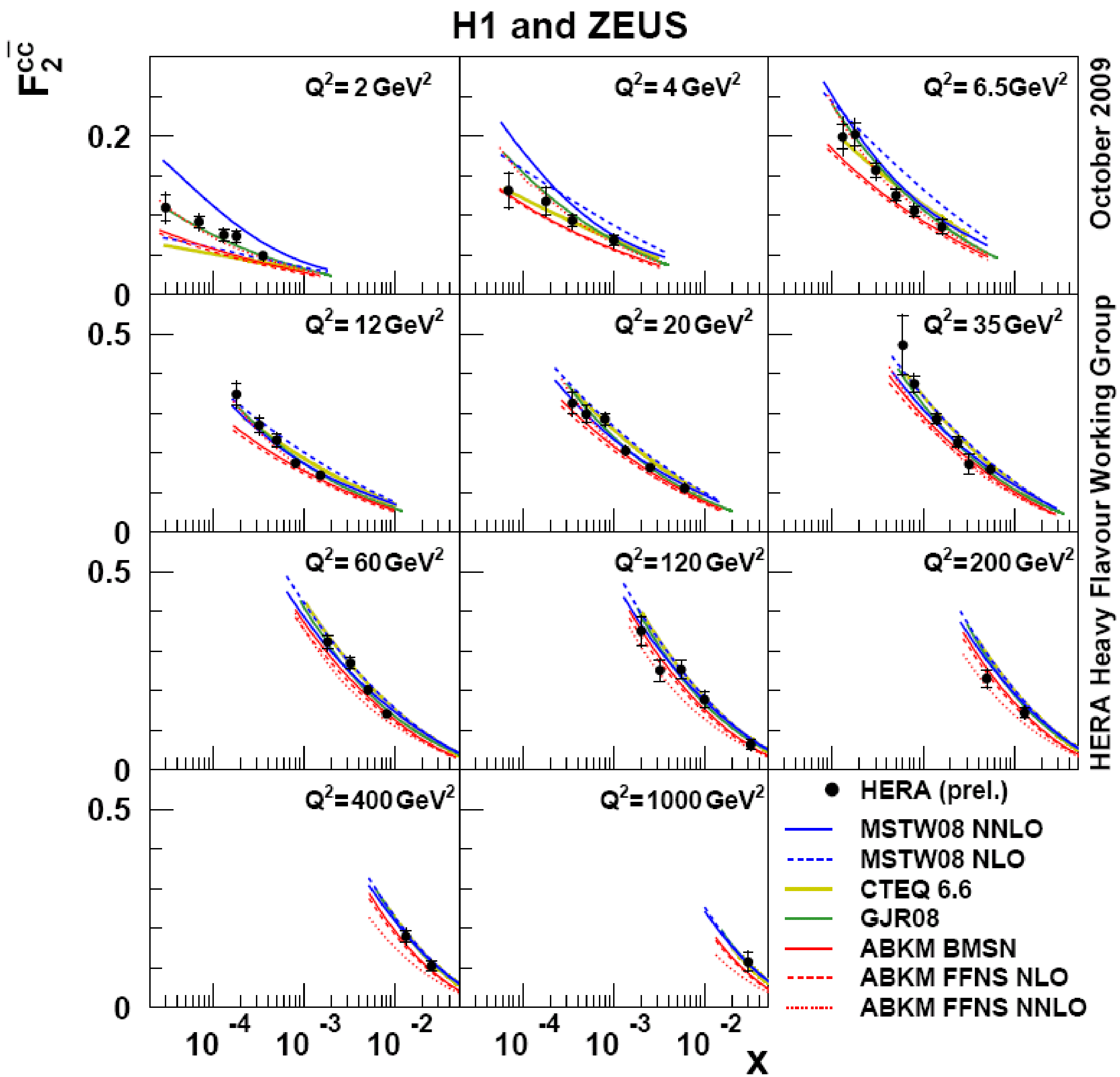
Combined $F_2^{c\bar{c}}$ to individual measurements

- method similar to inclusive combination arxiv:0911.0884
- 156 measurements + 54 correl. syst. $\Rightarrow$ 46 combined points
- data are compatible $\chi^2/\text{ndof} = 88/110$
- precision $7-10\%$ for $6.5 \leq Q^2 \leq 60$ GeV^2
- $Q^2 \leq 4$ GeV^2 D^* HERA-I data
- $Q^2 \leq 20$ GeV^2 sizeable correlated theoretical uncertainty



Combined $F_2^{c\bar{c}}$ vs. various Theories

- data can distinguish between different theoretical predictions
- FFNS:
  GJR08
  ABKM FFNS
- GM-VFNS:
  MSTW08
  CTEQ6.6
  ABKM BMSN

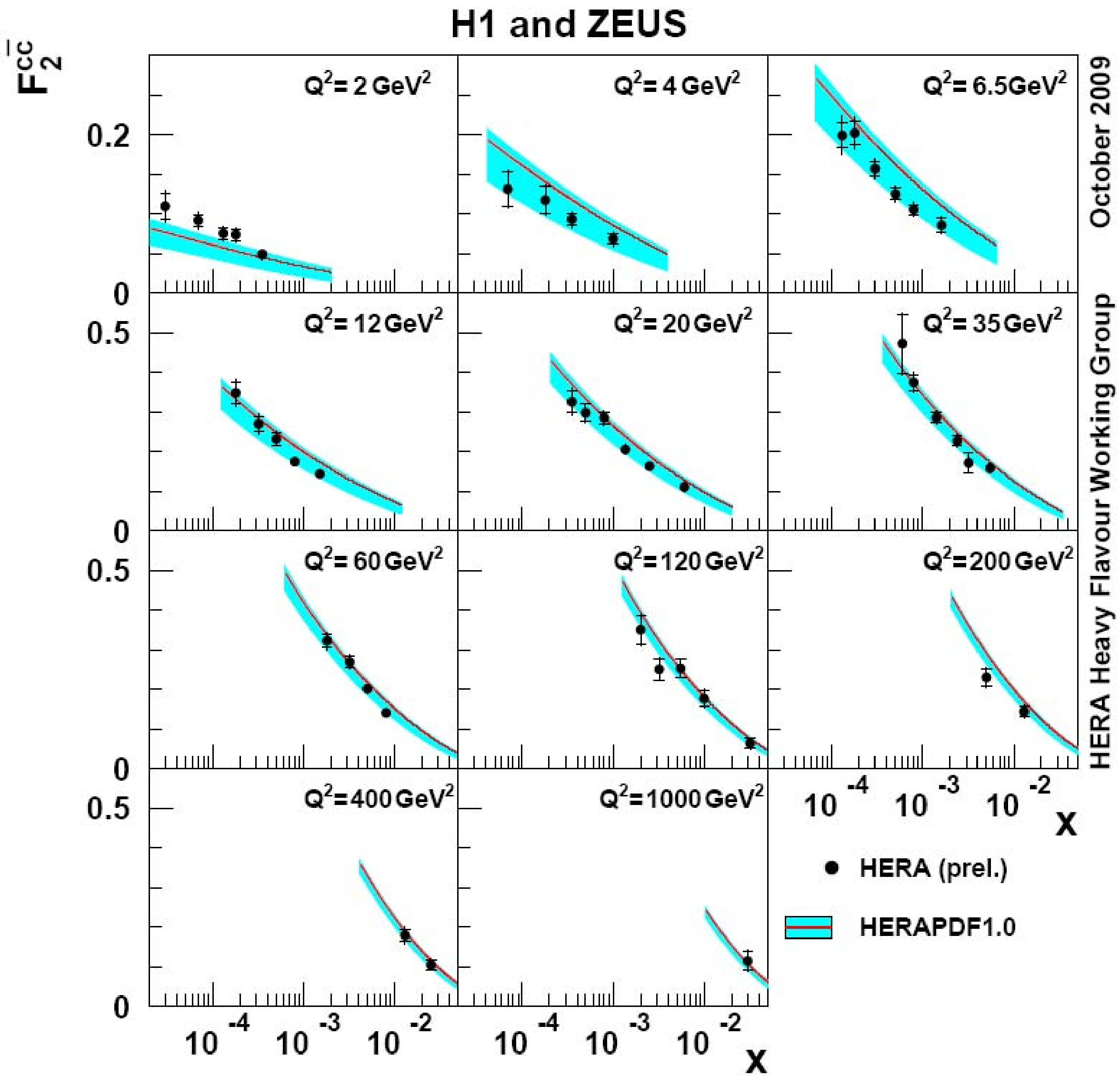


H1-ZEUS combined $F_2^{c\bar{c}}$ vs. HERAPDF1.0

- HERAPDF 1.0 fit to inclusive HERA I data
- RT GM-VFNS (as MSTW08)
- Central curve: $m_c = 1.4$ GeV

  band:
  $m_c = 1.3$GeV (upper)
  $m_c = 1.65$GeV (lower)

  [pole mass (PDG): 1.47 – 1.83 GeV]



Adding combined $F_2^{c\bar{c}}$ to HERAPDF1.0 Fit

- Fit HERA I + $F_2^{c\bar{c}}$

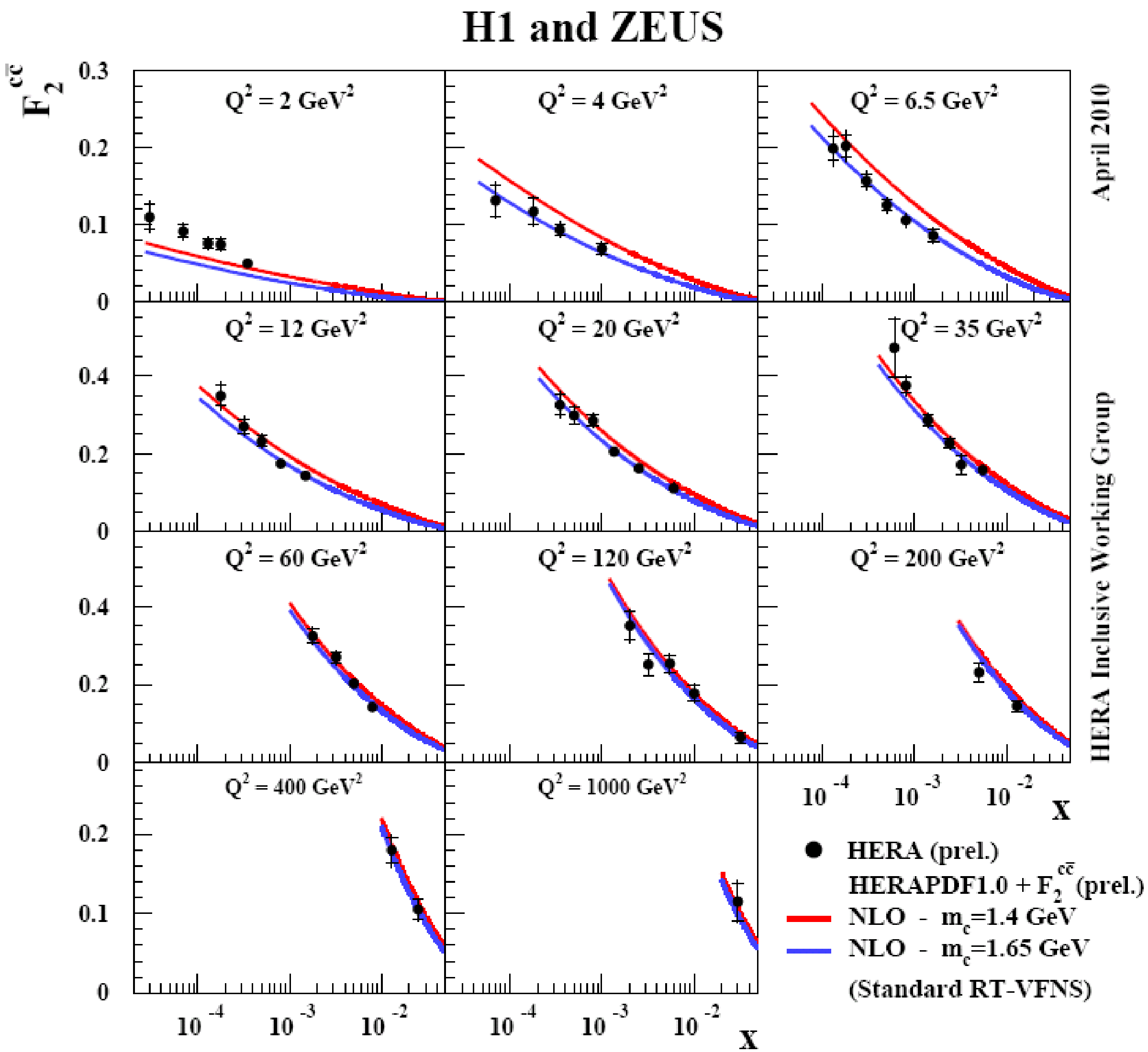
  $Q^2 > 3.5\ \mathrm{GeV}^2$ ($Q^2 = 2\ \mathrm{GeV}^2$ bin excluded)

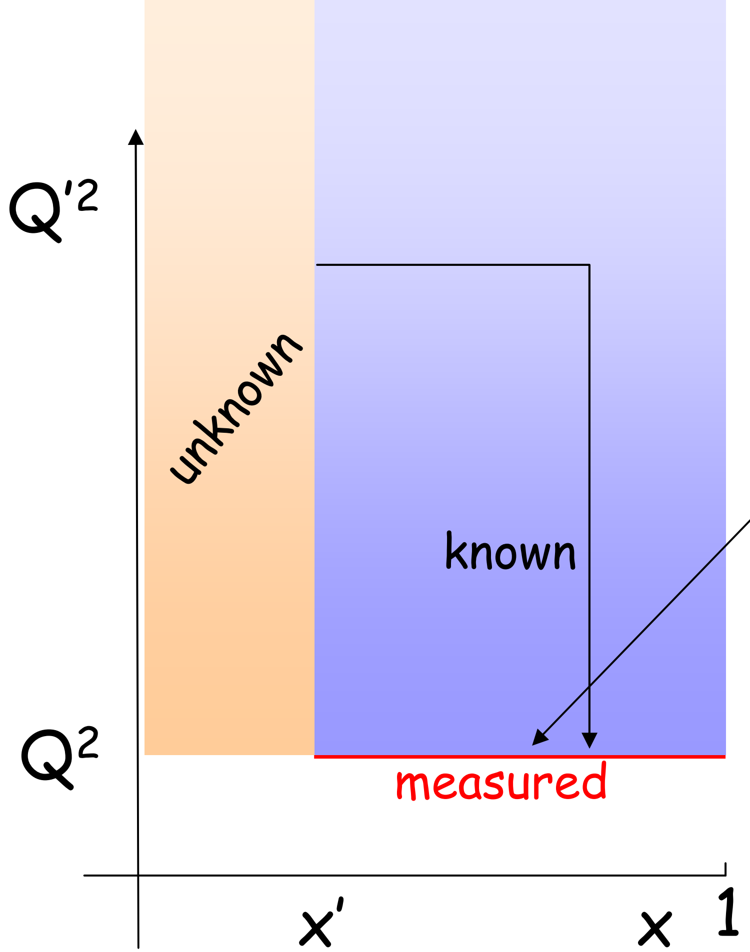
  41 charm points

- RT GM-VFNS

- $m_c = 1.4$ GeV
  $\chi^2_{\text{charm}} = 134.5/41$

  $m_c = 1.65$ GeV
  $\chi^2_{\text{charm}} = 43.5/41$





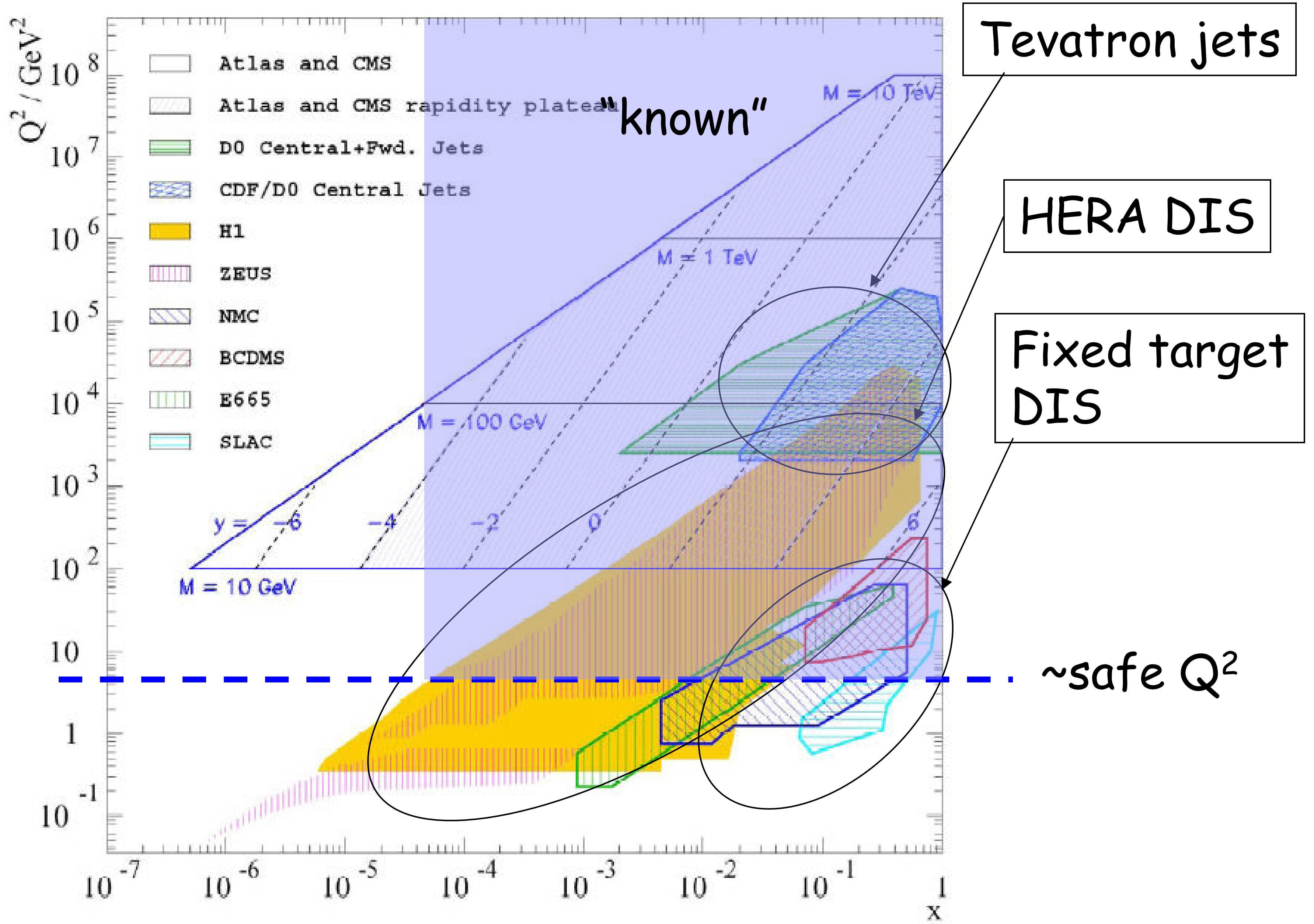
A parton at x at Q^2 is a source of partons at $x' < x$ at $Q'^2 > Q^2$.

In fact, any parton at $x > x'$ at Q^2 is a source.

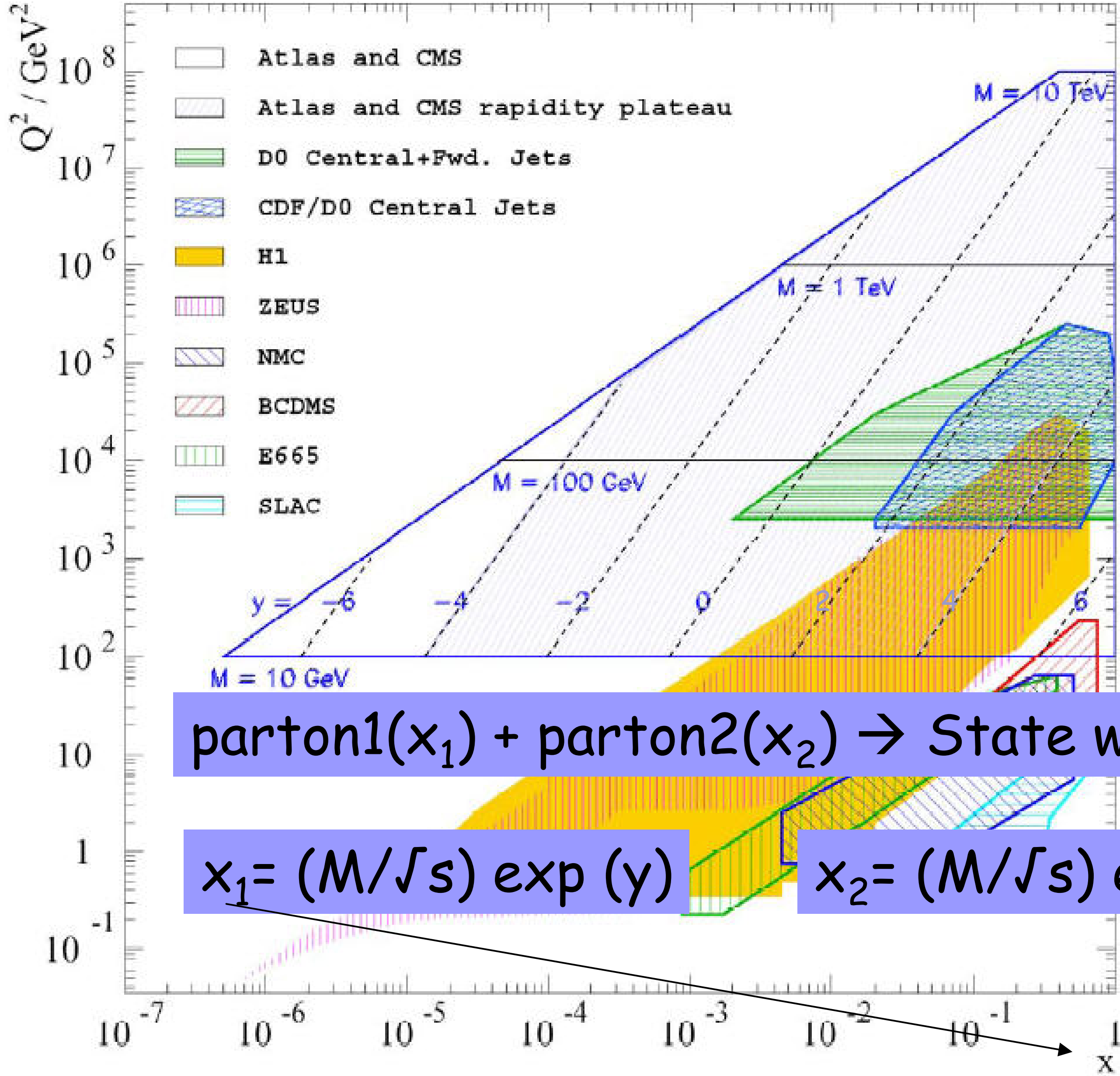
To know the parton density at x', Q'^2 it's necessary (and sufficient) to know the parton density in the range: $x' \leq x \leq 1$ at some lower Q^2.

If you know the partons in range $x' \leq x \leq 1$ at some Q^2, then you know the partons in the range $x' \leq x \leq 1$ for all $Q'^2 > Q^2$.

What does this mean for the LHC? →


Tevatron jets
HERA DIS
Fixed target DIS
"known"
~safe Q^2
Atlas and CMS
Atlas and CMS rapidity plateau
D0 Central+Fwd. Jets
CDF/D0 Central Jets
H1
ZEUS
NMC
BCDMS
E665
SLAC
M = 10 TeV
M = 1 TeV
M = 100 GeV
M = 10 GeV
y = -6 -4 -2 0 2 4 6
Q^2 / GeV^2
x

LHC (or hadron-hadron) parton kinematics



rapidity:

$$y = \frac{1}{2}\ln\left(\frac{E+P_Z}{E-P_Z}\right)$$

pseudo-rapidity:

$$\eta = -\ln \tan(\theta/2)$$

angle wrt beam

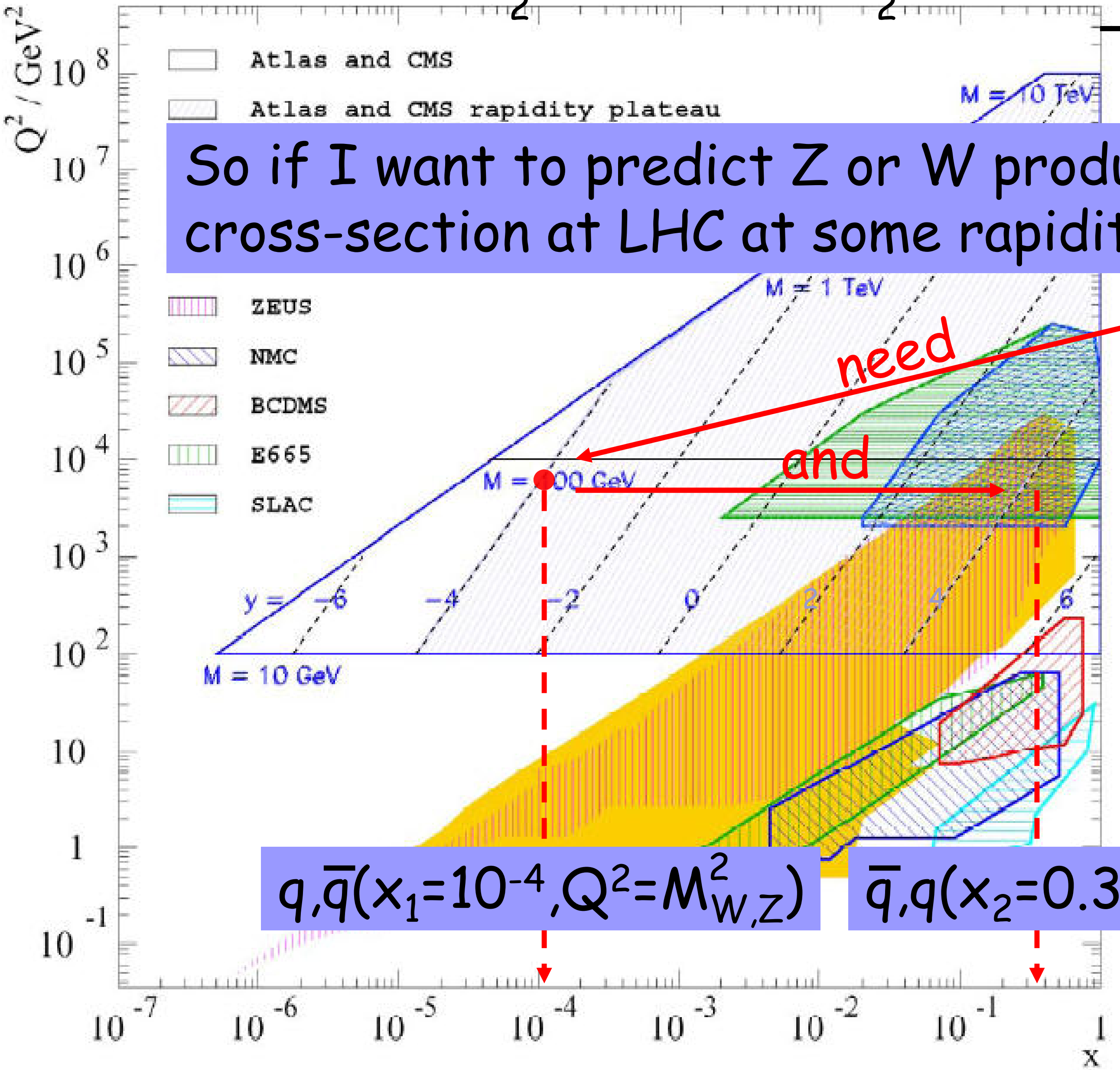
parton1(x_1) + parton2(x_2) → State with mass M

$x_1 = (M/\sqrt{s})\exp(y)$

$x_2 = (M/\sqrt{s})\exp(-y)$

$\sigma_{(pp \to W,Z+X)} \sim q,\underline{q}(x_1, M^2_{W,Z}) \times \underline{q},q(x_2, M^2_{W,Z}) \times \sigma_{(qq \to W,Z)}$

So if I want to predict Z or W production cross-section at LHC at some rapidity y, say, -4:

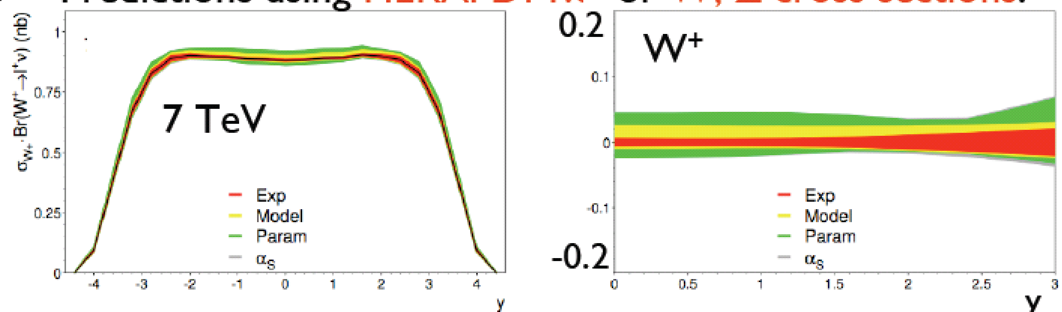


$q,\overline{q}(x_1=10^{-4}, Q^2=M^2_{W,Z})$ $\overline{q},q(x_2=0.3, Q^2=M^2_{W,Z})$

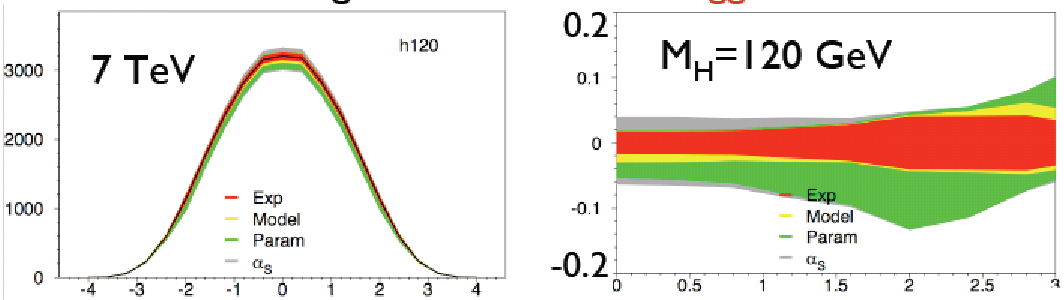
Predictions for LHC using partons from DIS

Examples:

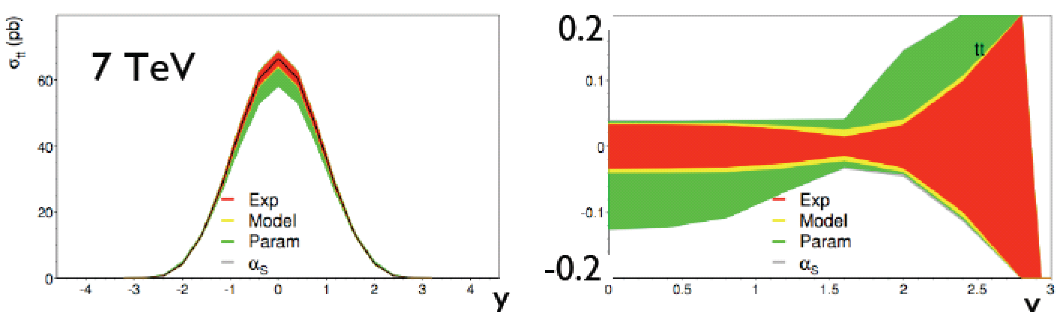
- Predictions using HERAPDF1.0 for W, Z cross sections.



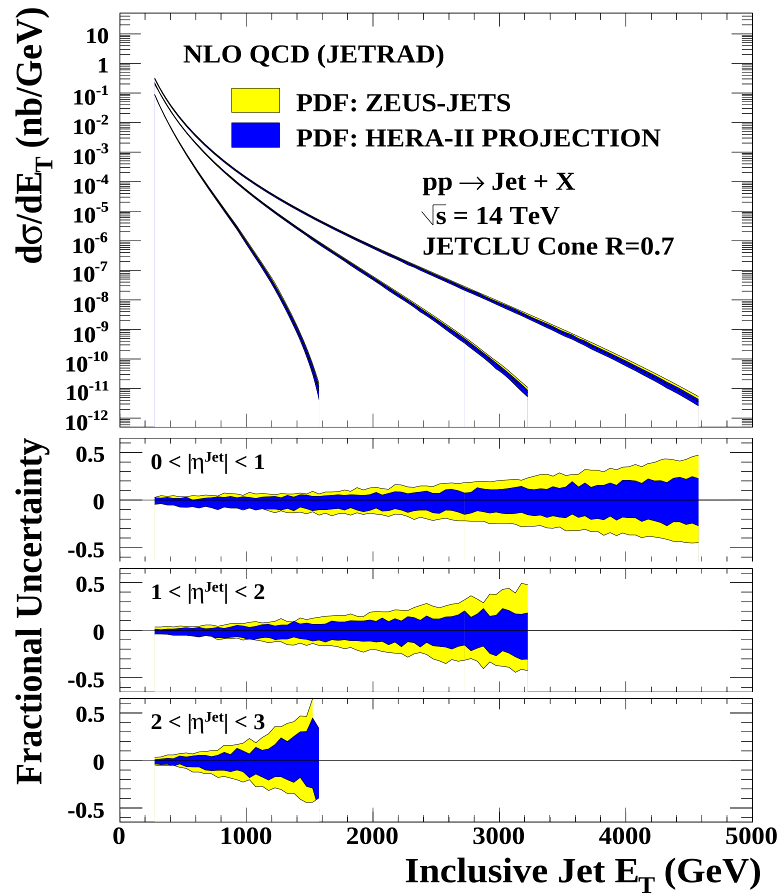
- Predictions using HERAPDF1.0 for Higgs cross sections.



- Predictions using HERAPDF1.0 for top cross sections.

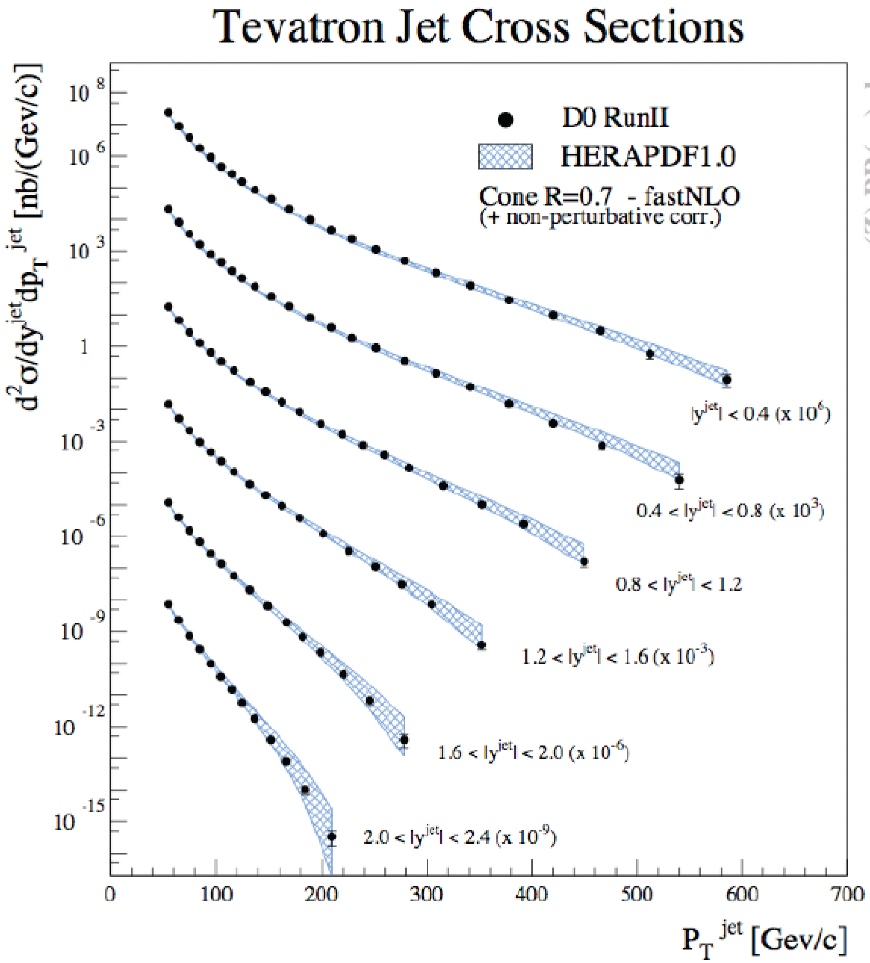


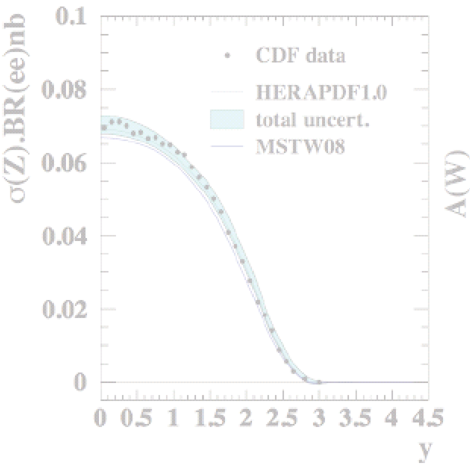
Jet production at LHC

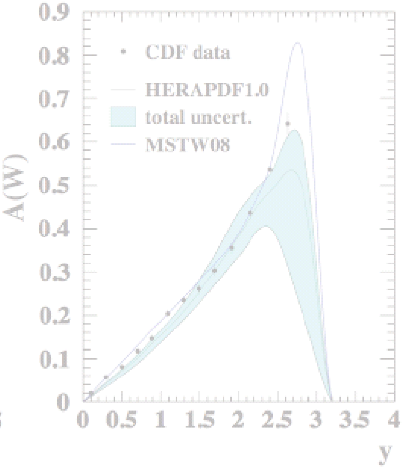


Exciting times ahead,
LHC experiments started to
do these measurements

HERAPDF1.0 vs. Tevatron Data



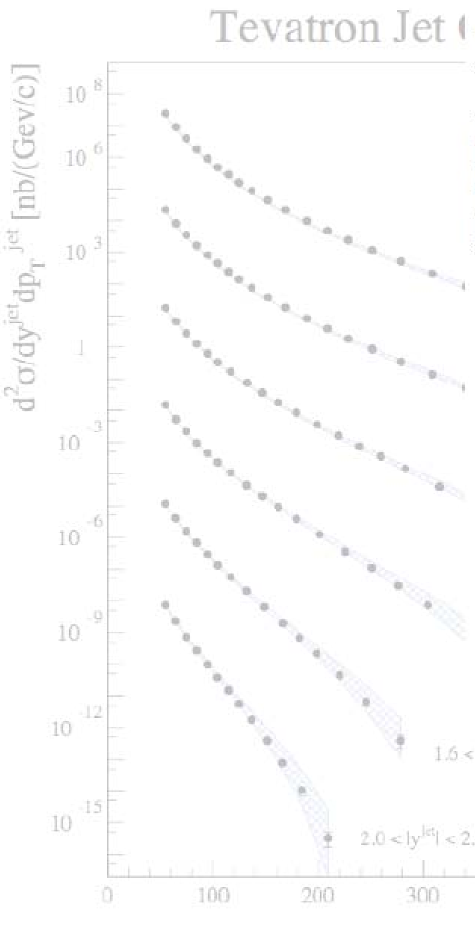


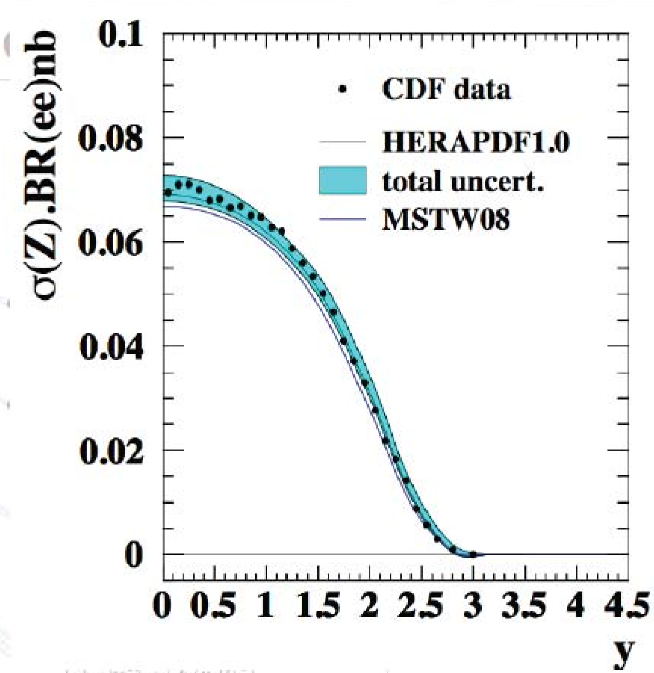


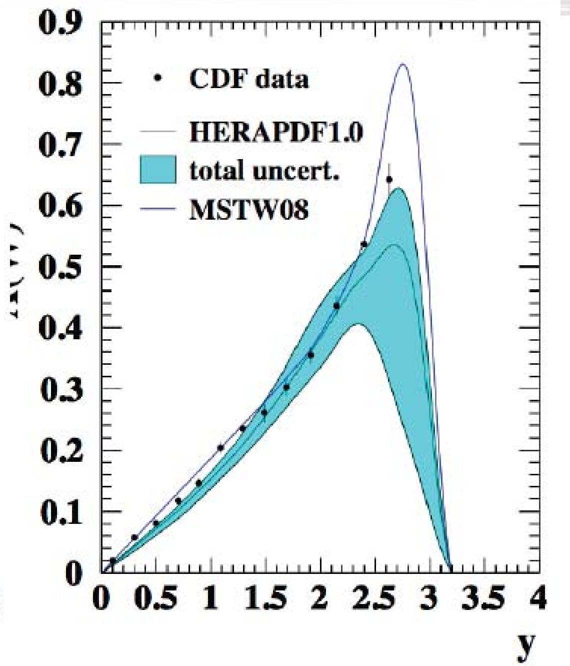
- Predictions for high-E_T jet cross-sections with full uncertainties compared to the D0 data
- DIS data from HERA predicts Tevatron jets production from ppbar process.
- Z and W at Tevatron are well predicted by HERAPDF1.0

- Hence, there is a universal description of partonic processes and all can be described with: HERA input, SM couplings and pQCD evolution!

HERAPDF1.0 vs. Tevatron Data







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- DIS data from HERA predicts Tevatron jets production from ppbar process.
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- Hence, there is a universal description of partonic processes and all can be described with: HERA input, SM couplings and pQCD evolution!

If time allows:

Deep Inelastic Scattering with Polarized Leptons:

Demonstration of
the chiral structure of
electroweak interactions

Charged Current Cross Section

$$\frac{d^2\sigma^{CC}(e^{\pm}p)}{dxdQ^2} = (1 \pm P_e)\frac{G_F^2}{4\pi x}\left(\frac{M_W^2}{M_W^2+Q^2}\right)^2 \tilde{\sigma}_{CC}^{e^{\pm}p}$$

CC reduced cross section

e^+/e^- sensitive to different quark densities:

$$\tilde{\sigma}_{CC}^{e^+p} = x\left[\bar{u}+\bar{c}\right] + (1-y)^2 x\left[d+s\right]$$

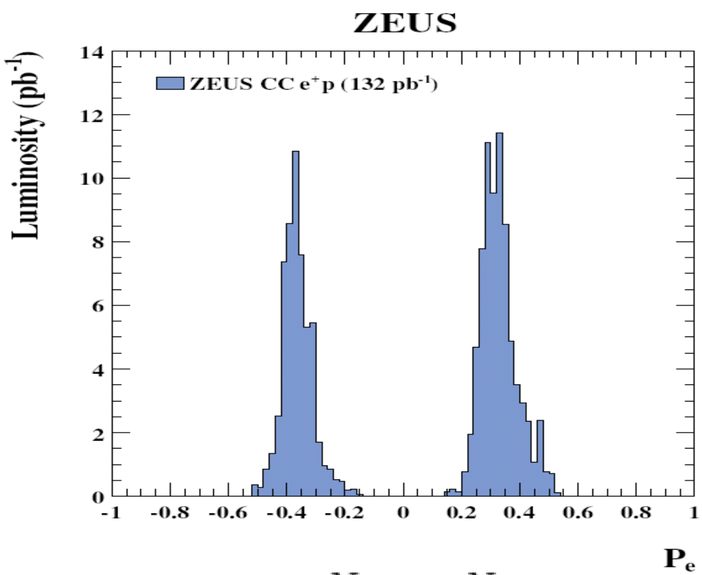
$$\tilde{\sigma}_{CC}^{e^-p} = x\left[u+c\right] + (1-y)^2 x\left[\bar{d}+\bar{s}\right]$$

CC gives sensitivity to different combinations of quarks as NC.

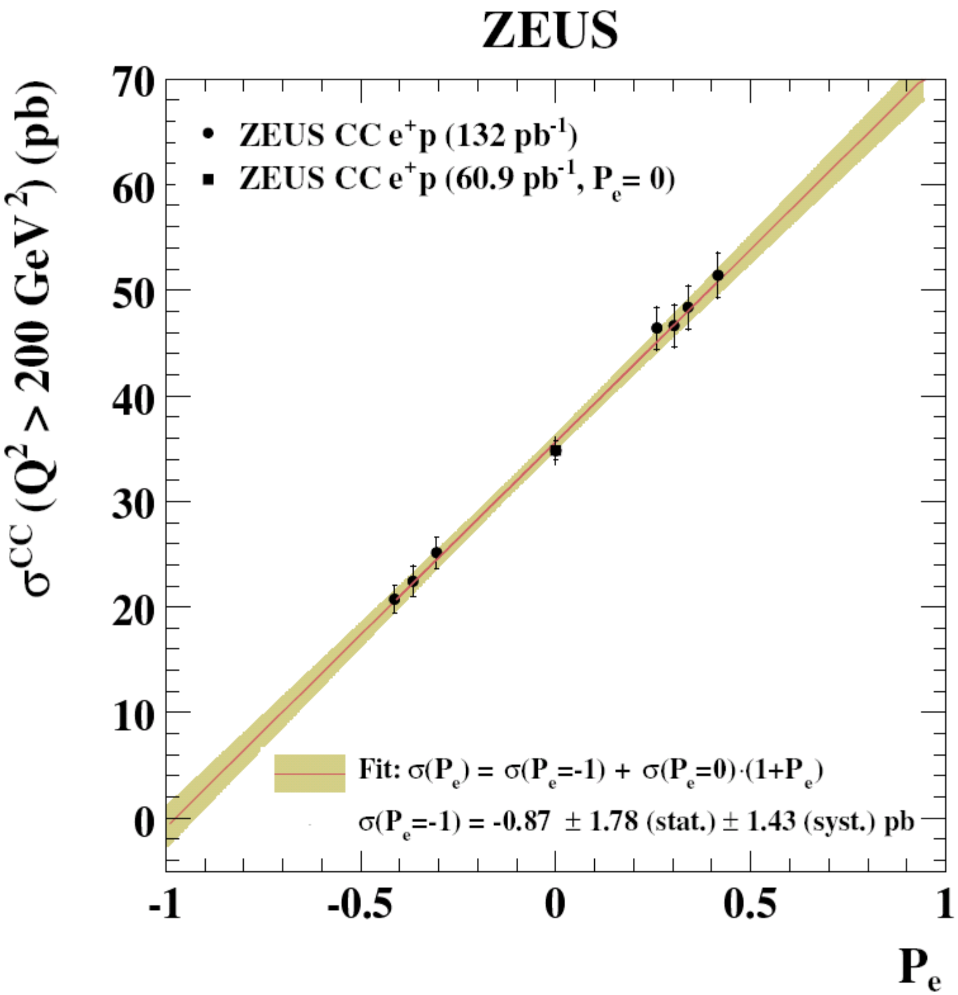
Polarized Charged Current cross section

Linear dependence of σ^{CC} on P_e

$$\sigma^{CC}(e^{\pm}p) = (1 \pm P_e)\sigma^{CC}_{P_e=0}(e^{\pm}p)$$



$$P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}}$$



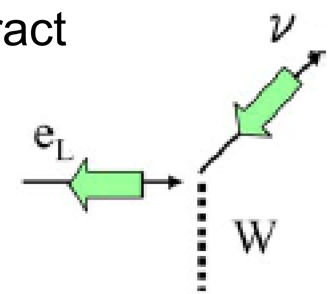
Total Charged Current Cross Section

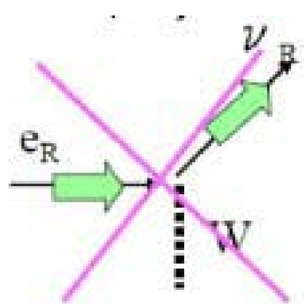
Linear dependence of σ^{CC} on P_e

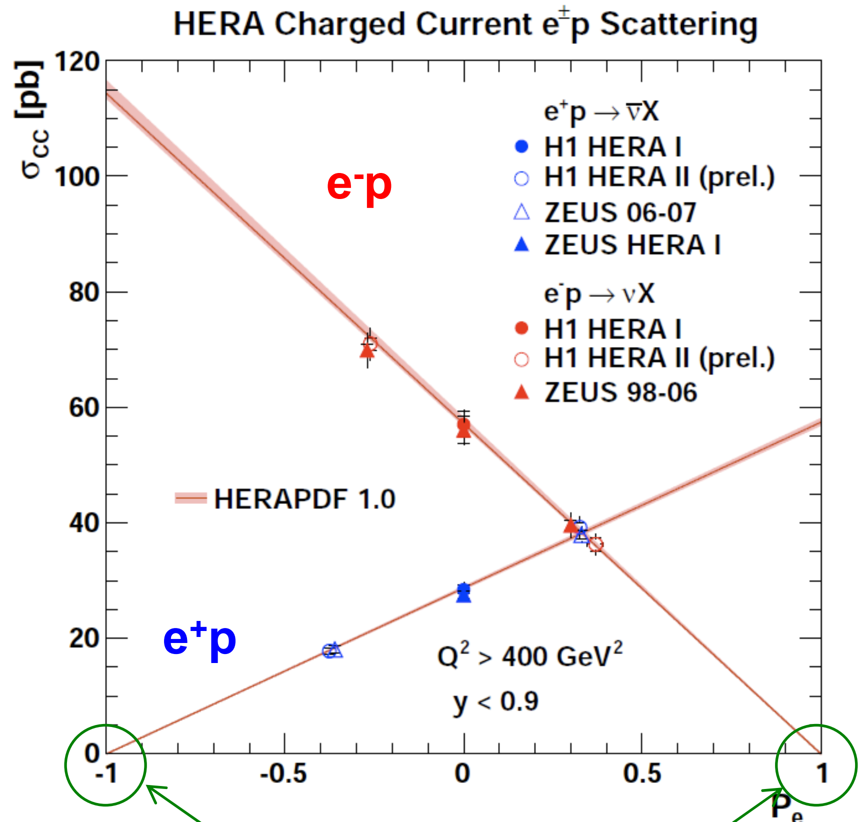
$$\sigma^{CC}(e^{\pm}p) = (1 \pm P_e)\sigma^{CC}_{P_e=0}(e^{\pm}p)$$

$$P_e = \frac{N_{RH} - N_{LH}}{N_{RH} + N_{LH}}$$

SM: weak CC interactions:
only left handed particles
(right handed anti-particles)
interact



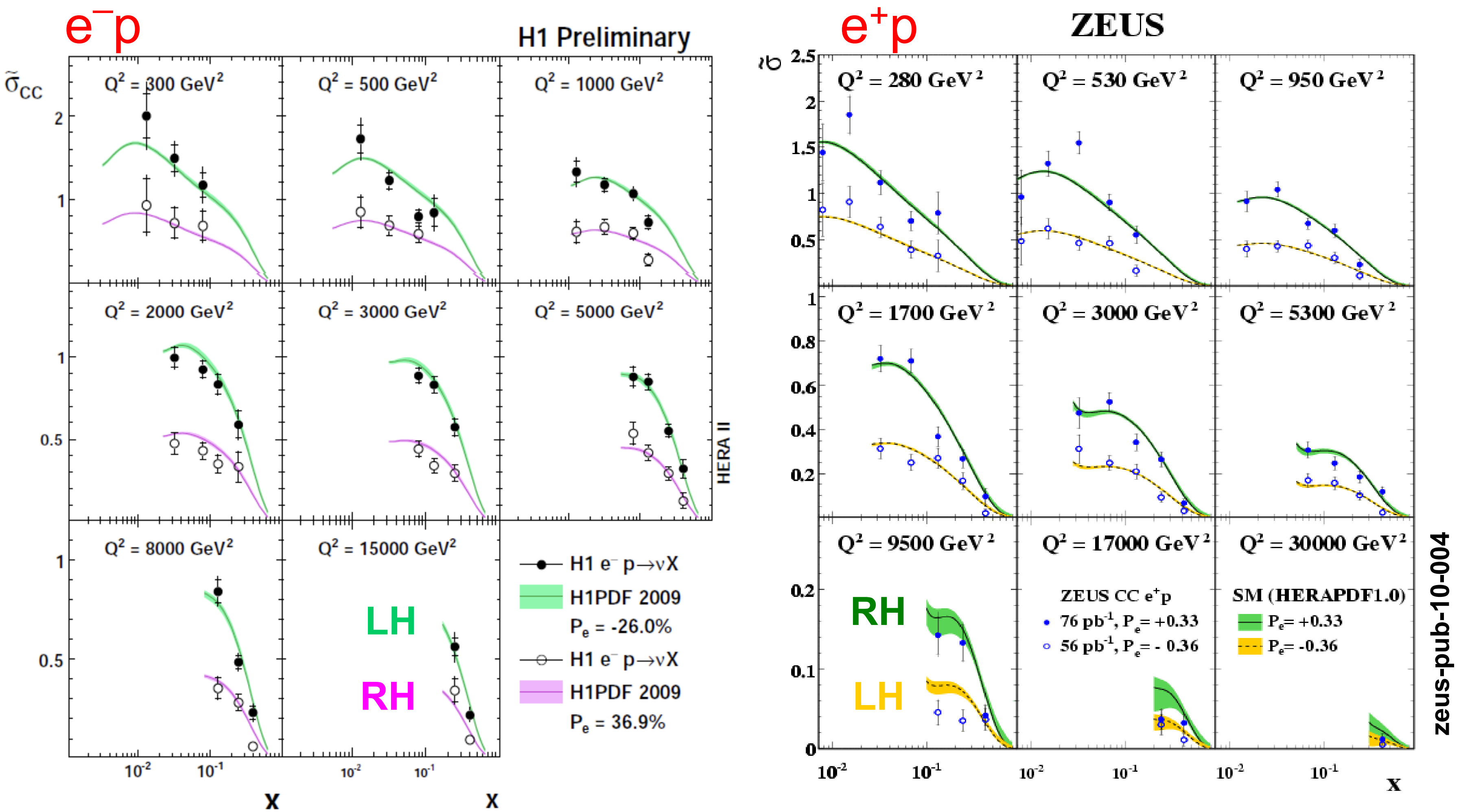




SM: No right-handed weak currents

ZEUS and H1 in agreement with SM

Polarised CC Cross Sections



Predictions of SM give good description of data

Neutral Current Cross Section

$$\frac{d^2\sigma^{NC}(e^\pm p)}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}\left[Y_+\tilde{F}_2^\mp \mp Y_- x\tilde{F}_3^\pm - y^2\tilde{F}_L^\pm\right]$$

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

$$\kappa = \frac{1}{4\sin^2\theta_w\cos^2\theta_w}\frac{Q^2}{Q^2+M_Z^2}$$

Generalized structure functions:

$$\tilde{F}_2^\pm = F_2^\gamma + \kappa(-v_e \pm P_e a_e)F_2^{\gamma Z} + \kappa^2(v_e^2 + a_e^2 \pm 2P_e v_e a_e)F_2^Z$$

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

$$\left[F_2^\gamma, F_2^{\gamma Z}, F_2^Z\right] = \sum_q \left[e_q^2, 2e_q v_q, v_q^2 + a_q^2\right] x(q+\bar{q})$$

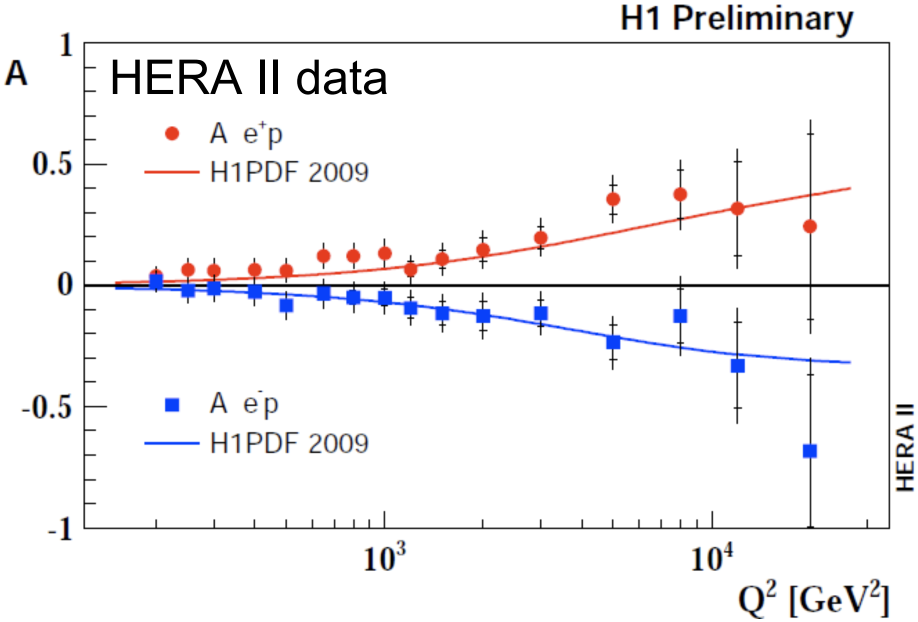
$$\left[xF_3^{\gamma Z}, xF_3^Z\right] = \sum_q \left[e_q a_q, v_q a_q\right] 2x(q-\bar{q})$$

Polarized NC measurements

The charge dependent polarization asymmetries in neutral currents
→ direct measure of EW effects

Polarization asymmetries (A) sensitive to ratio of γZ interference term to F_2
A is proportional to $a_e v_q$ combination

$$A\pm = \frac{2}{P_R - P_L}\frac{\sigma^\pm(P_R) - \sigma^\pm(P_L)}{\sigma^\pm(P_R) + \sigma^\pm(P_L)} \simeq \mp\kappa a_e \frac{F_2^{\gamma Z}}{F_2}$$



neglecting Z term, the generalized structure function F_2 is expressed:

$$\tilde{F}_2^\pm \approx F_2^\gamma + \kappa(-v_e \pm P_e a_e)F_2^{\gamma Z}$$

At LO: $F_2^{\gamma Z} = x\sum_q 2e_q v_q(q+\bar{q})$

Data well described by SM

Combined EW and QCD Fits

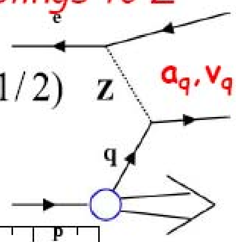
Extend NLO QCD fits of NC/CC HERA data to fit also *the light u and d couplings to Z*

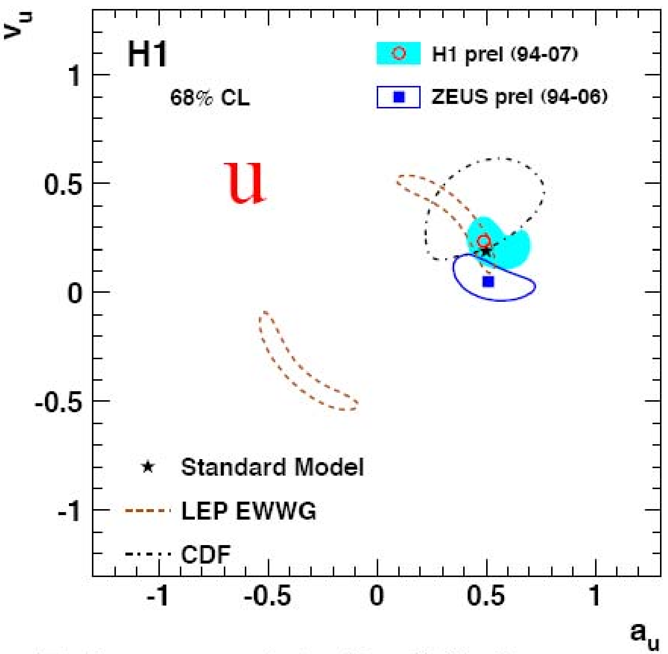
H1: a'la HERAPDF1.0 NLO QCD fit

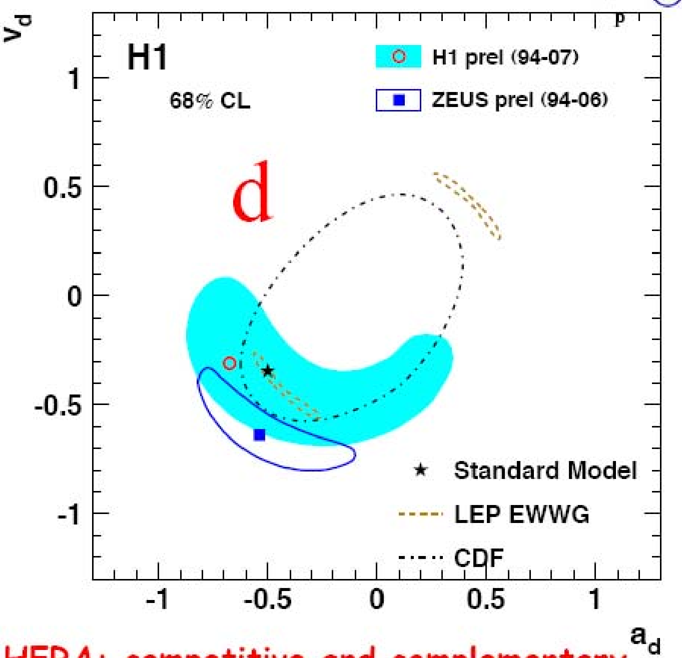
ZEUS: a'la ZEUS-JETS NLO QCD fit

$$a_q = I_q^3 \rightarrow (a_u = +1/2; a_d = -1/2)$$

$$v_q = I_q^3 - 2e_q \sin^2\theta_W$$







TeVatron: qq'→e^+e^- (Drell-Yan), A_{FB}

LEP EWWG: ee→qq at Z (a^2v^2,a^2+v^2)

→ HERA: competitive and complementary
→ much improved precision due to polarized HERA II
→ will be further improved with combined H1&ZEUS

Summary

What have we learnt from DIS in the last 30 -35years?

- **Verified the basic idea of QPM**
- **Established QCD as the theory of the strong interaction**
- **Measurement of essential parameters: Parton Distribution Functions, αs(MZ) and the running of α_s**
- **Discovery of neutral currents**
- **Vivid demonstration of the unification of weak interaction and electromagnetism at high Q2**
- **Verification of the chiral structure of electroweak interactions (polarized cross sections)**

Final Remarks

- There are many other DIS physics topics I did not cover here.
  - Electoweak physics (?)
  - Jet physics (algorithms, substructure, running of α_s, …)
  - Polarized DIS (polarized targets)
  - Diffraction, Exclusive Vector Meson production
  - low Q^2 physics, transition to non-perturbative QCD
  - Beyond the SM searches
  - Future machines (LHeC)
  - …

New fixed target experiments
High x, nuclear corrections,…

- Some health warnings:
  - Most of what I talked about is a leading-order picture.
    In practice, most things are done at least to next-to-leading order.
    At NLO, the interpretation of the results are not as straight-forward.
  - Many people worry about whether we are not missing something fundamentally with the picture of DGLAP equations.
    - Much of the data are at very low x: DGLAP is a $\ln Q^2$ approximation. Why aren't $\ln(1/x)$ terms important…or are they? → BFKL equations.
    - The density of the partons, especially that of the gluons is getting very high. When and where should we worry about "shadowing", "gluon recombination" etc.
    - The idea of incoherence of partons may be breaking down in some kinematic regions: phenomenon of "hard diffraction" is difficult to understand in terms of partons without correlations to each other.

Backup

χ^2 Definition

$$\chi^2_{\exp}(M^{i,\text{true}}, \Delta\alpha_j) = \sum_i \frac{\left[M^{i,\text{true}} - \left(M^i + \sum_j \frac{\partial M^i}{\partial \alpha_j} \Delta\alpha_j \right) \right]^2}{\sigma_i^2} + \sum_j \frac{\Delta\alpha_j^2}{\sigma_{\alpha_j}^2}$$

M^i measured central values

σ_i statistical and uncorrelated systematic uncertainties

σ_{α_j} correlated uncertainty

$\frac{\partial M^i}{\partial \alpha_j}$ Sensitivity of the data to the systematic source *j*

$M^{i,\text{true}}$ Fitted H1-ZEUS combined cross section

$\frac{\partial M^i}{\partial \alpha_j}\Delta\alpha_j$ Fitted shift of the *i* data due to the systematic source *j*

If $\Delta\alpha_j = 0$ it coincides with a standard average

Caution: Most errors are provided as relative errors, a smaller value of cross section has smaller absolute error bias toward smaller averages
Can be avoided by modified χ^2 definition: insert $M^{i,true}/M^i$

Modified χ^2 definition

Caution: Most errors are provided as relative errors, a smaller value of cross section has smaller absolute error, bias toward smaller averages
Can be avoided by modified χ^2 definition:

$$\chi^2_{\rm exp}\left(M^{i,\rm true},\Delta\alpha_j\right)=\sum_i\frac{\left[M^{i,\rm true}-\left(M^i+\sum_j\frac{\partial M^i}{\partial\alpha_j}\frac{M^{i,\rm true}}{M^i}\Delta\alpha_j\right)\right]^2}{\left(\sigma_i\frac{M^{i,\rm true}}{M^i}\right)^2}+\sum_j\frac{\Delta\alpha_j^2}{\sigma^2_{\alpha_j}}$$

Normalization uncertainty is clearly a relative (multiplicative).

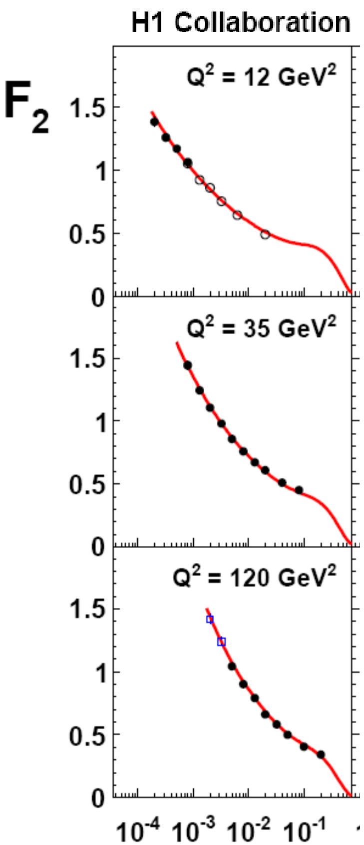
Are other systematic errors as additive or multiplicative errors?
Choice of best treatment is debatable. Does it matter?
Impact is mostly negligible, except at very large Q2 and x where statistical errors and fluctuation are largest.

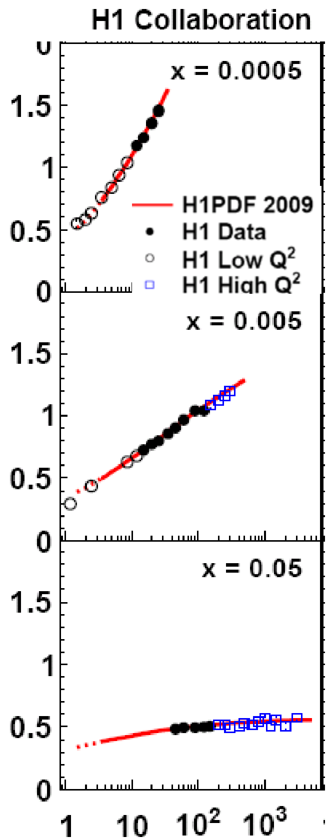
How to deal with this freedom in systematic error treatment?
→ Additional correlated uncertainty of averaged data points

F_2 at medium Q^2

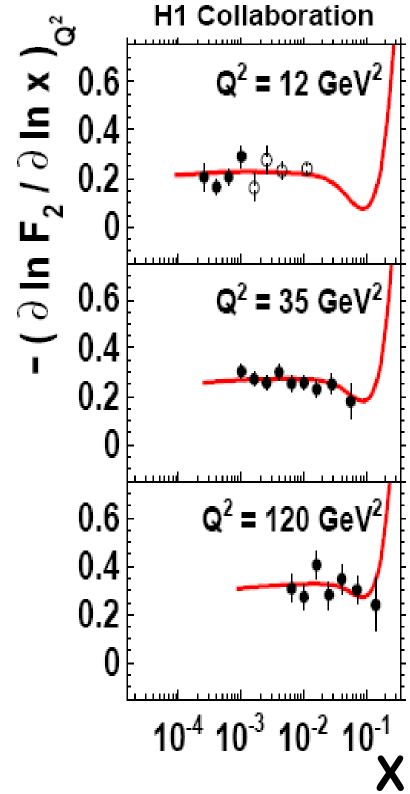
New measurement (L = 22pb^{-1}, 2000) combined with published results (96/97)

$s_r \sim F_2$ ($12 < Q^2 < 150\,\mathrm{GeV}^2$, $y<0.6$) impressive accuracy 1.3 - 2%

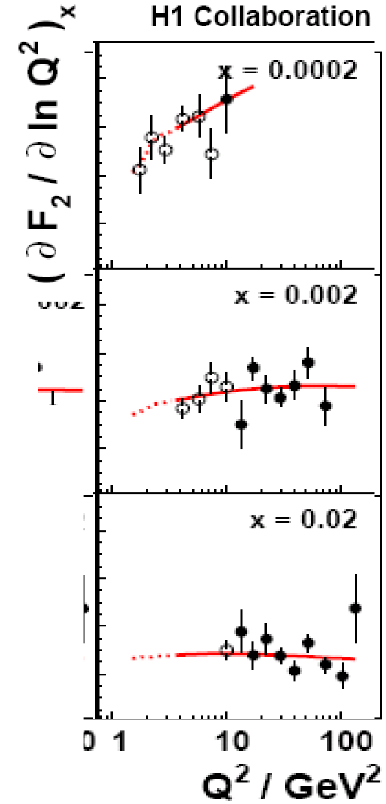




Steep rise described by QCD

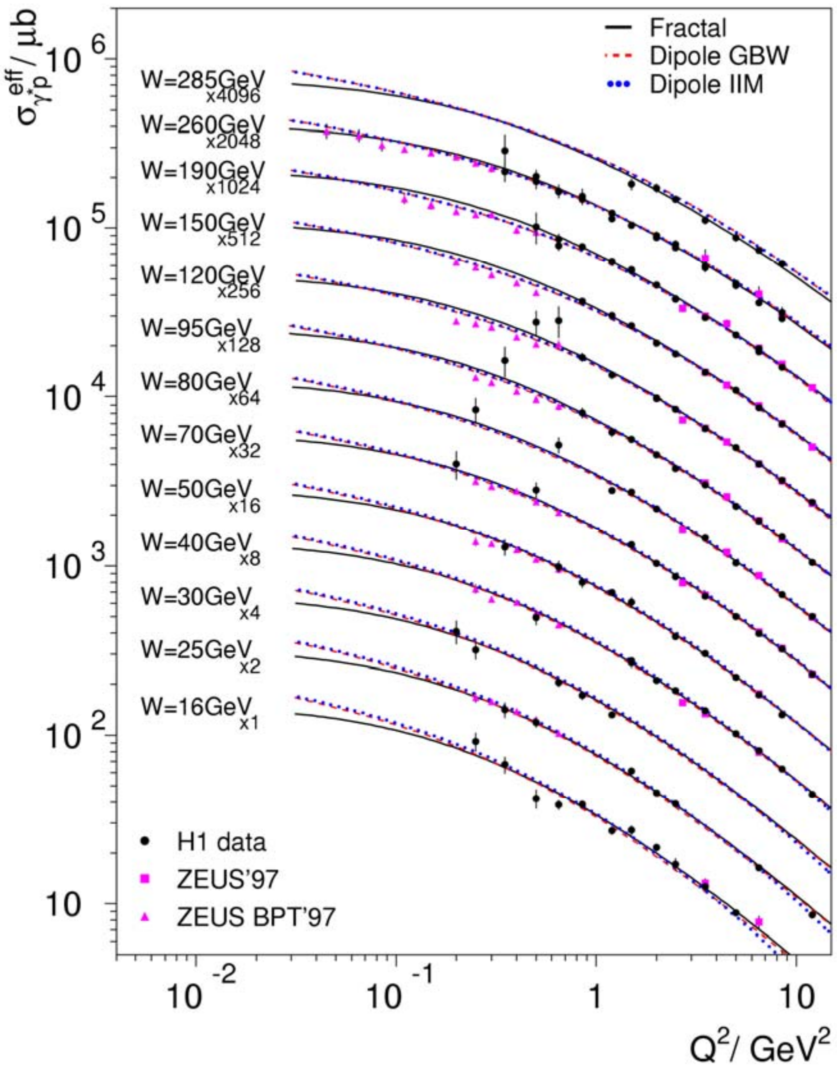


Rise compatible with $F_2 \propto x^{-\lambda}$



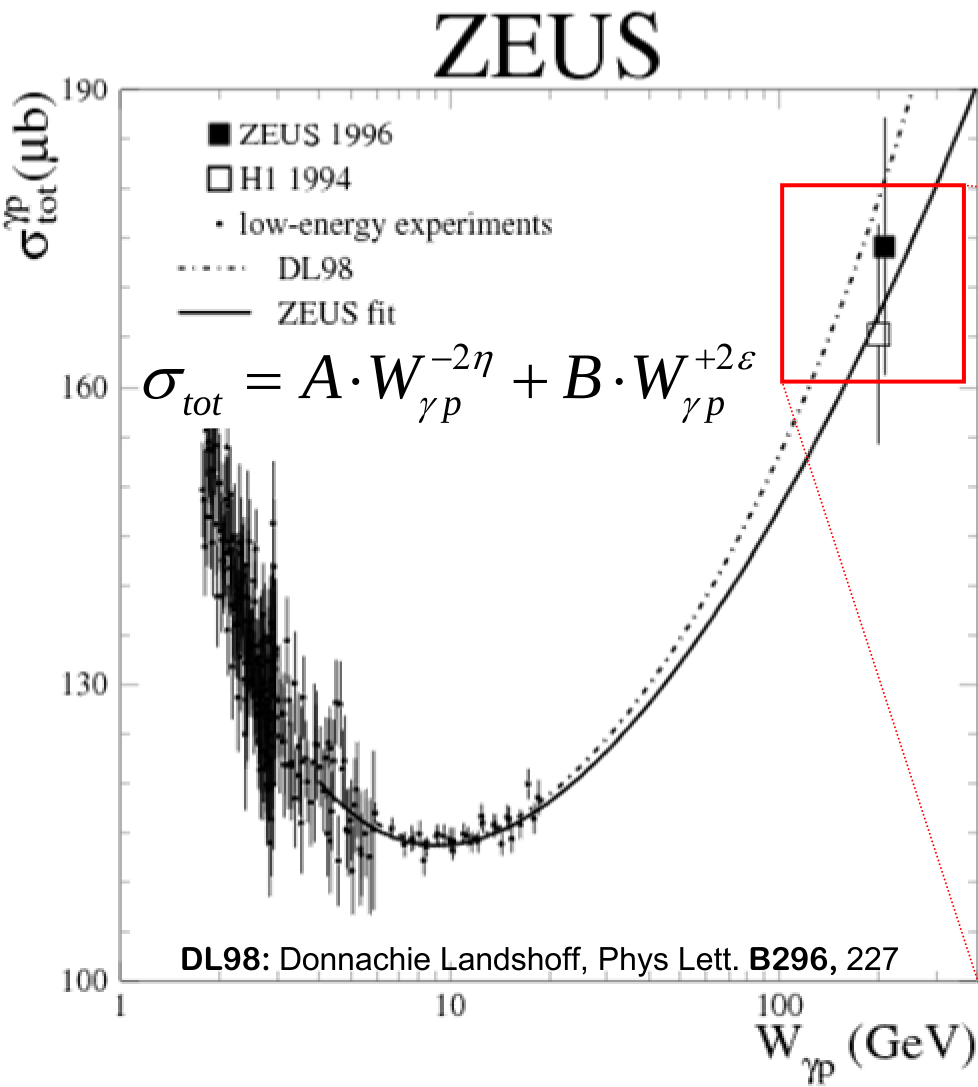
Effect of Gluon dynamics well described by fit

NC Measurement at low Q^2



- Measurement presented as effective γ^*p cross section
- precision of combined measurements better than 2%
- Smooth transition from perturbative to non-perturbative regime at $Q^2 \sim 1 GeV^2$

Total Photon-Proton Cross Section

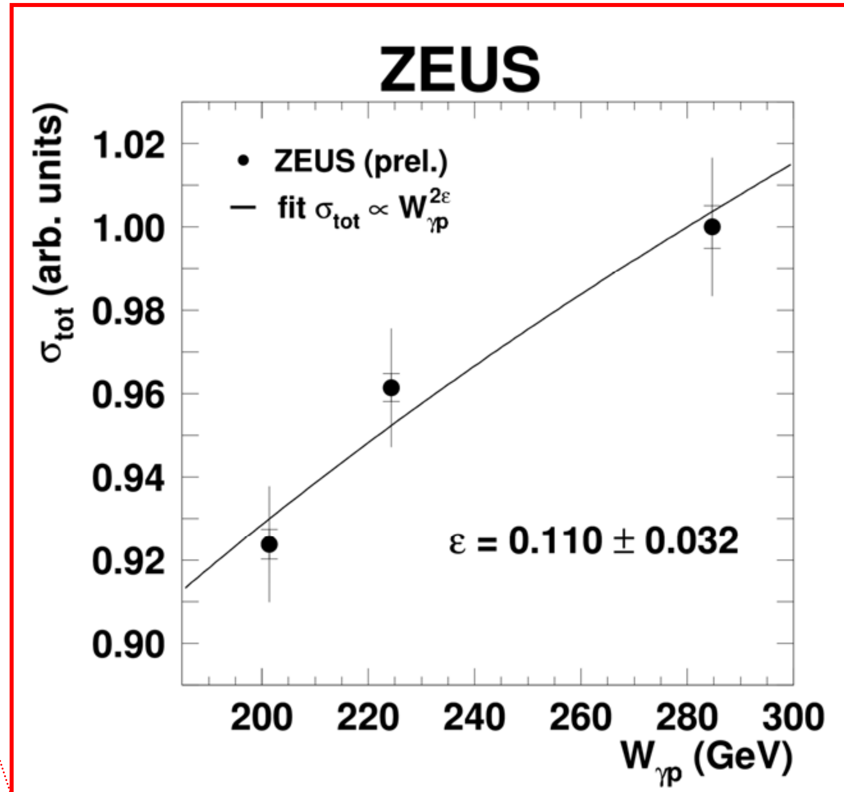


$$\sigma_{tot} = A \cdot W_{\gamma p}^{-2\eta} + B \cdot W_{\gamma p}^{+2\varepsilon}$$

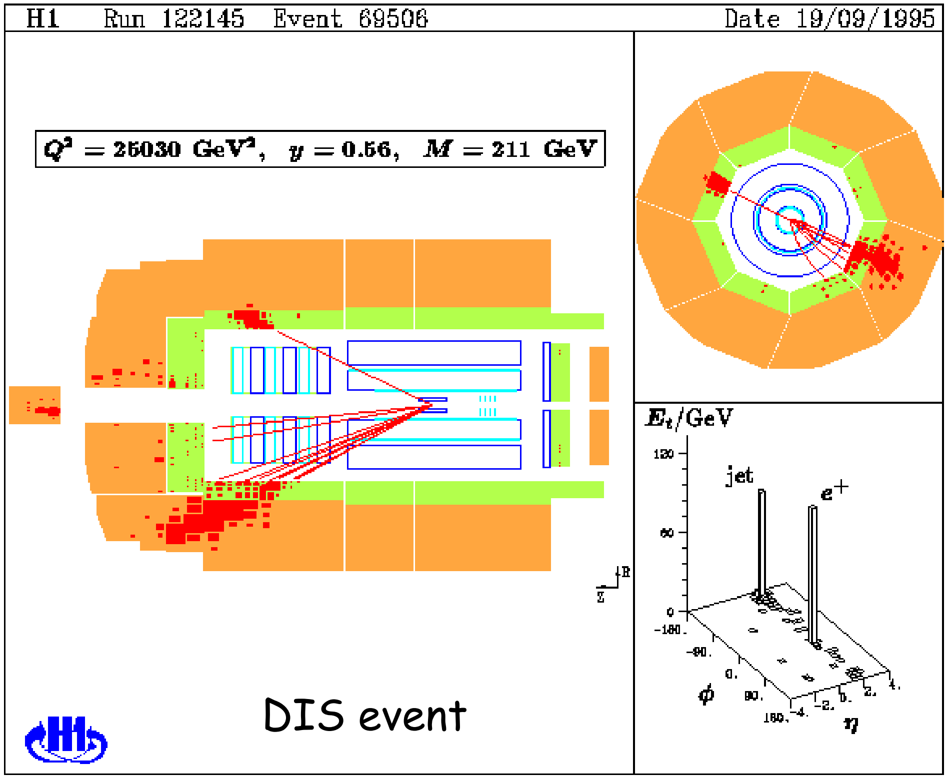
DL98: Donnachie Landshoff, Phys Lett. **B296,** 227

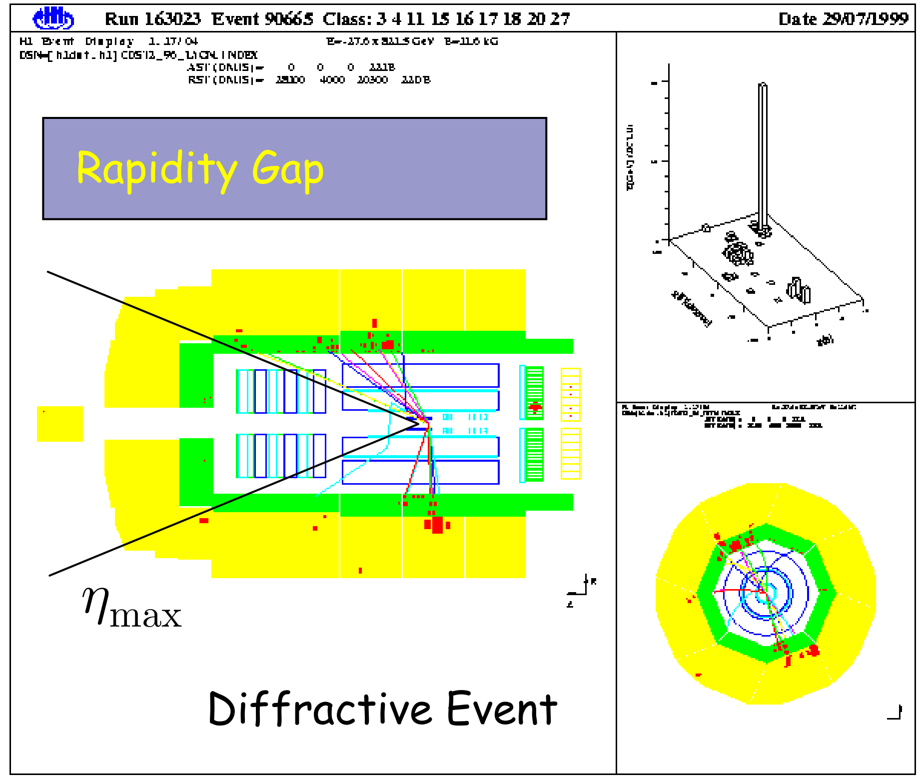
Measurements at 3 proton energies

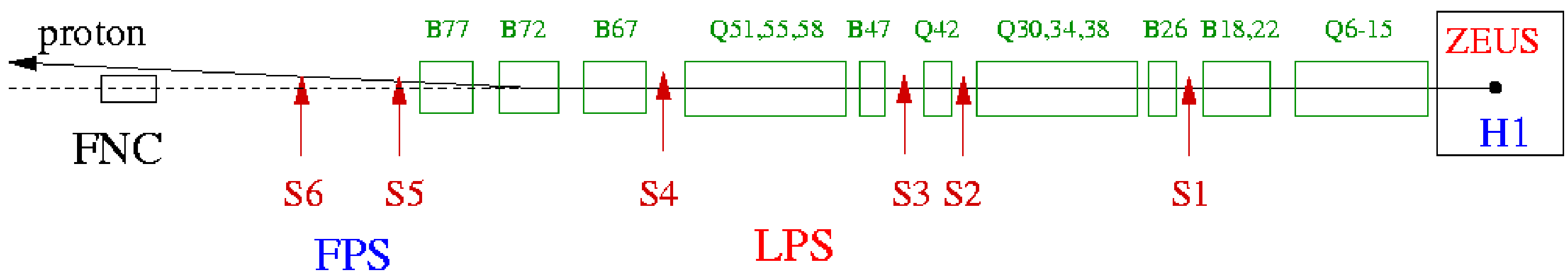
Slope with $W_{\gamma p}$ locally extracted



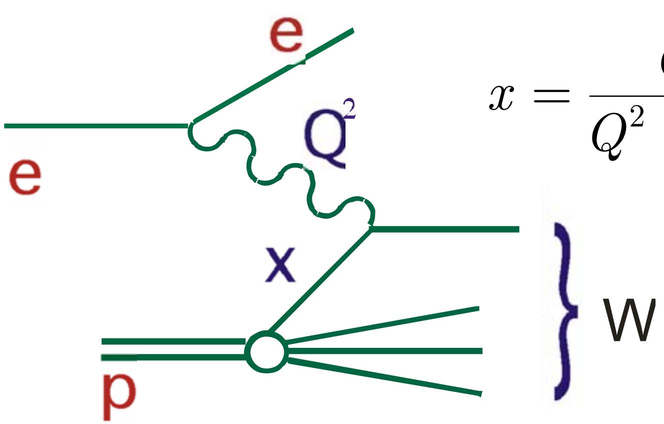
Diffraction: A New Class of Events at HERA



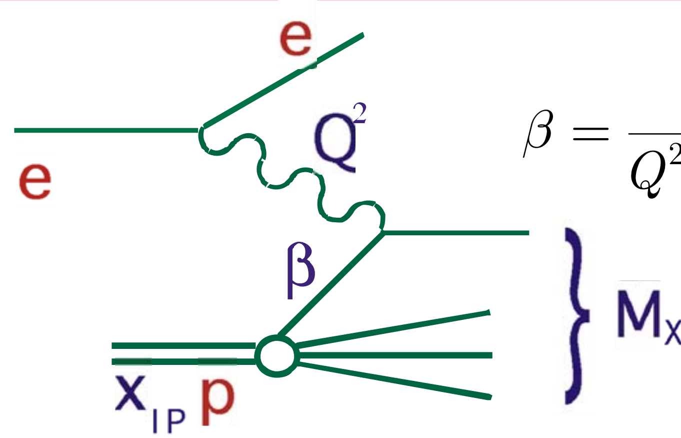




Diffraction: Further „constituents“ in the proton?



$$x = \frac{Q^2}{Q^2 + W^2}$$

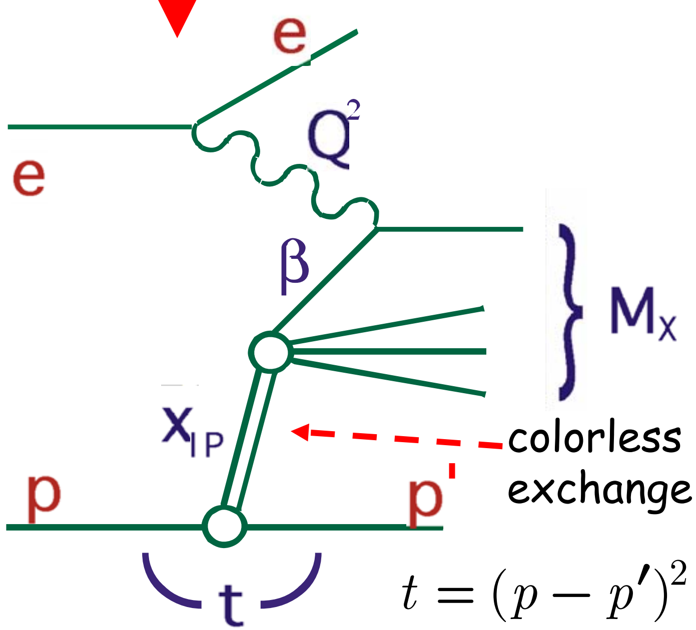


$$\beta = \frac{Q^2}{Q^2 + M_X^2}$$

$$x_{\mathbf{P}} = \frac{Q^2 + M_X^2}{Q^2 + W^2}$$

$$\boxed{x \text{ (DIS)} \Leftrightarrow \beta \text{ (Diff. DIS)}}$$

momentum fraction of color singlet exchange relative to the proton



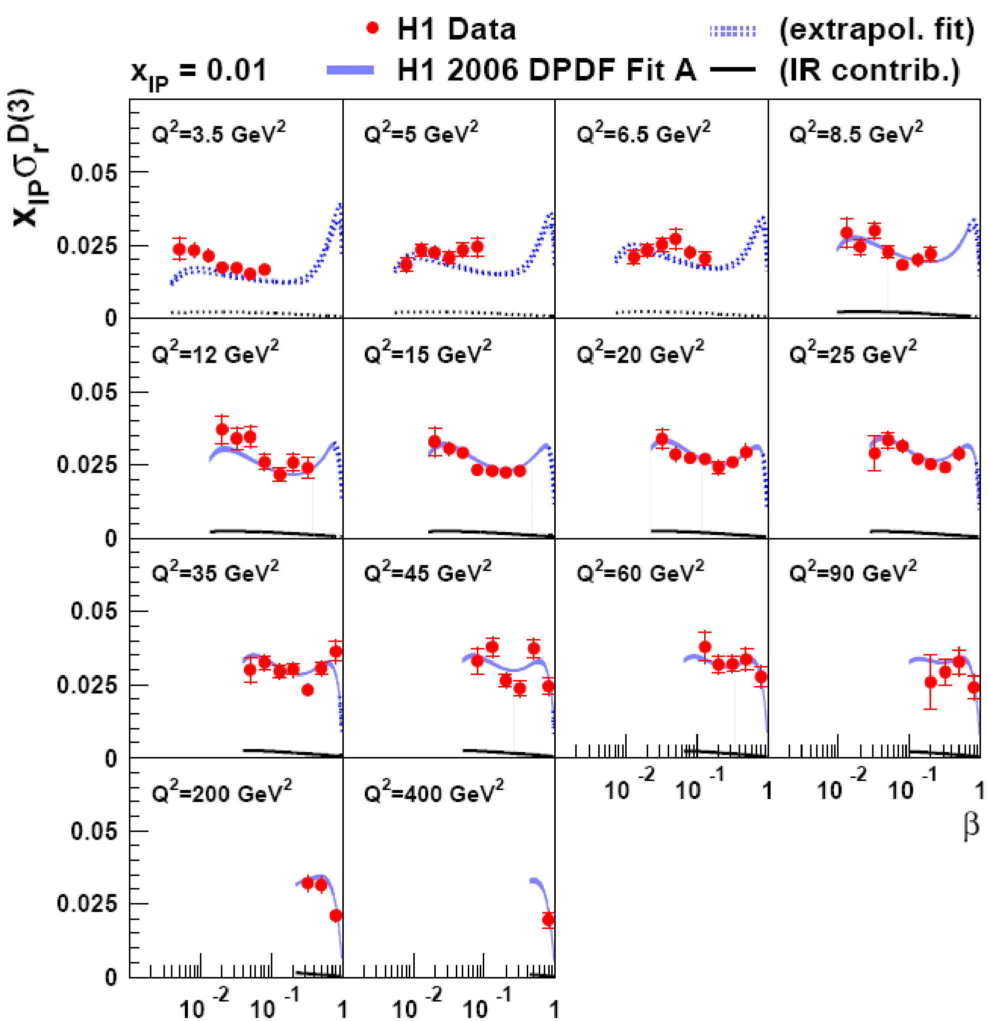
leaves a „rapiditiy gap“ between M_X and p'

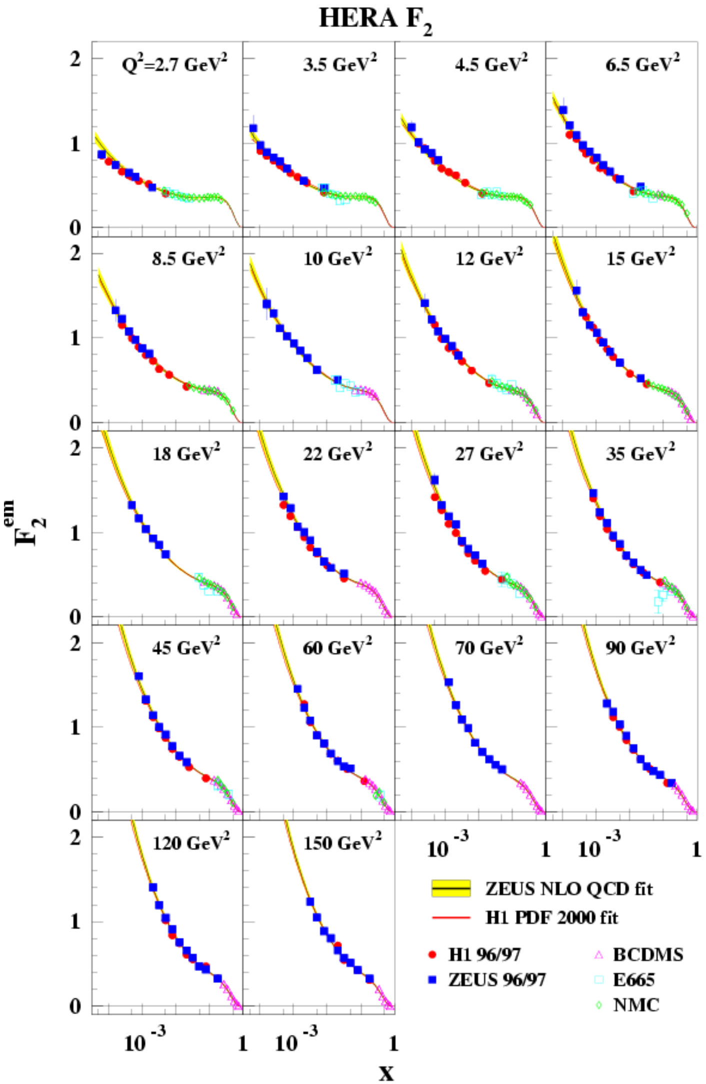
emitted particle: „Pomeron“

$t = (p - p')^2$ (momentum transfer)^2 at proton vertex

Diffractive vs Inclusive DIS: x-dependence

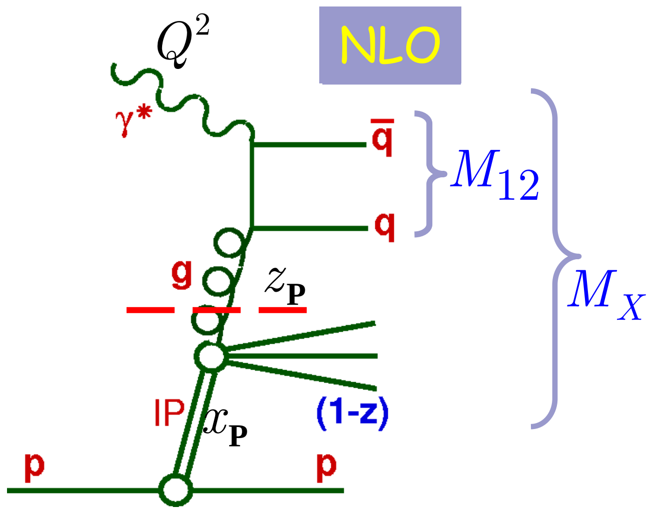
β (Diff. DIS) $\Leftrightarrow$ x (DIS)





weak dependence on β , similar to the photon (few partons ?)

Partonic Structure of Diffraction

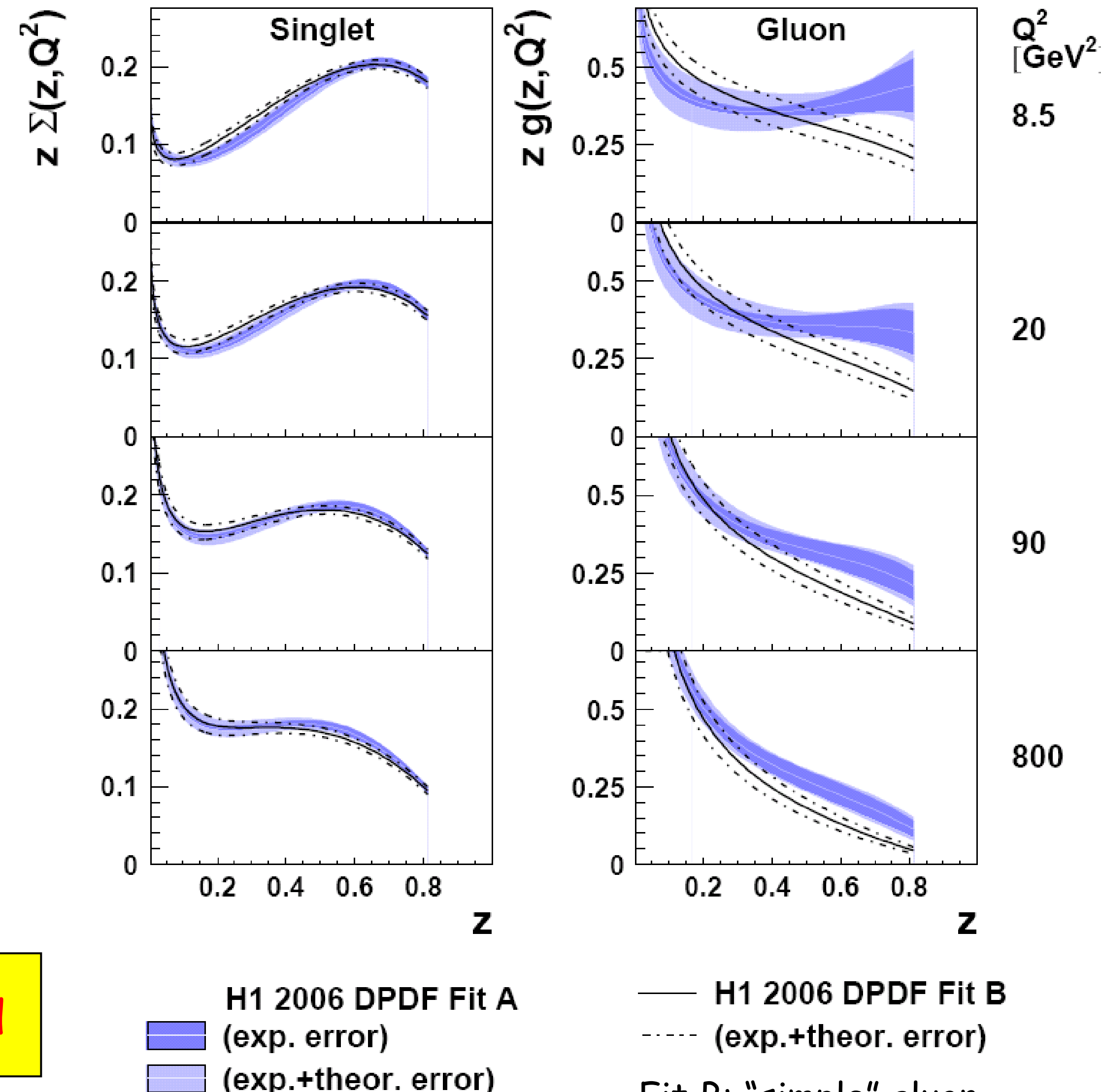


$$z_{\mathbf{P}} = \frac{Q^2 + M_{12}^2}{Q^2 + M_X^2}$$

Gluon momentum fraction:

$$(\mathbf{70} \pm \mathbf{5})\%$$

Diffraction is gluon-dominated



Fit B: “simple” gluon