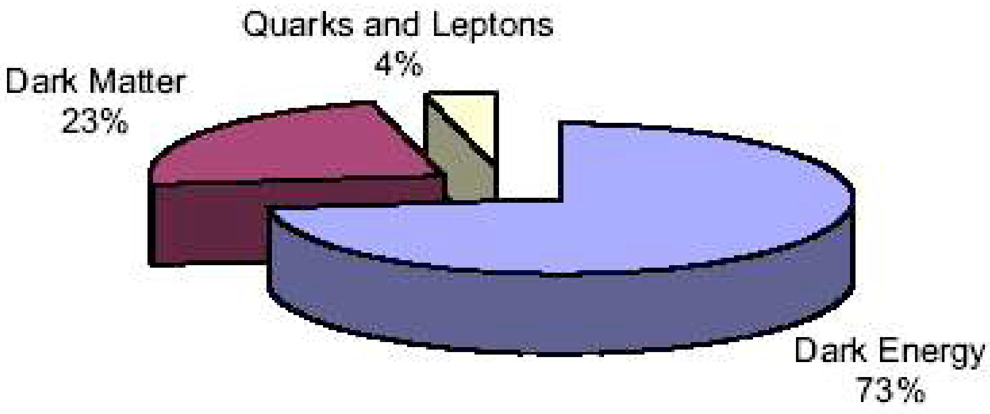
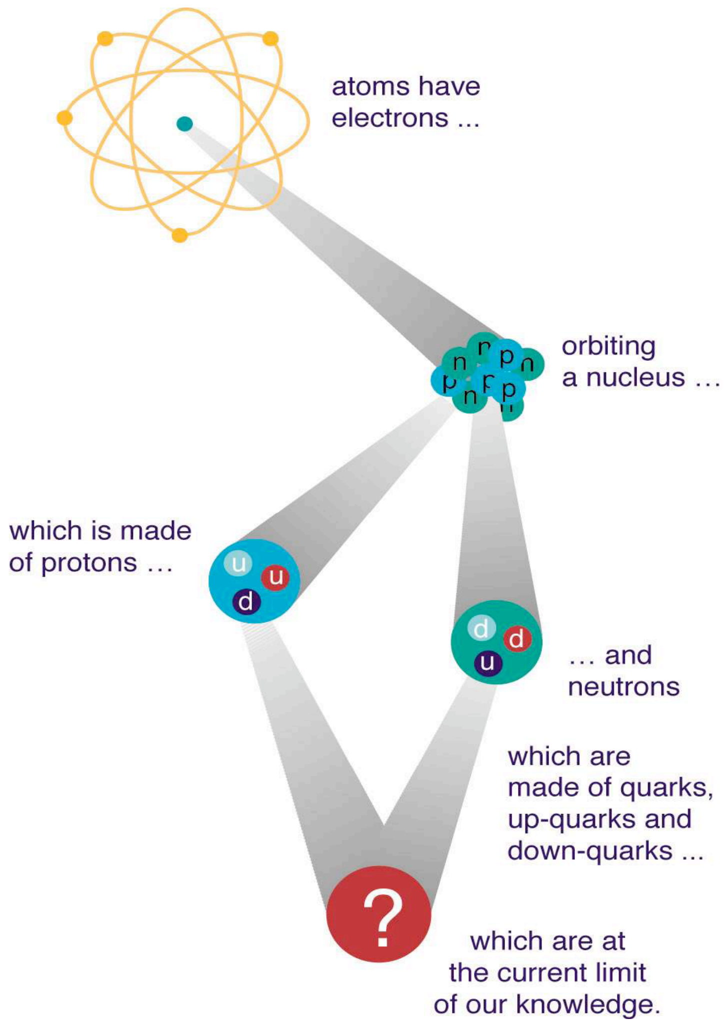
The lepton-proton energy frontier

Physics at HERA

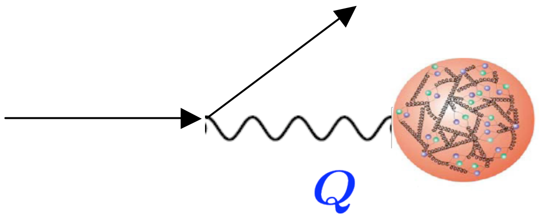
Cristinel DIACONU
CPP Marseille & DESY

Matter in the universe

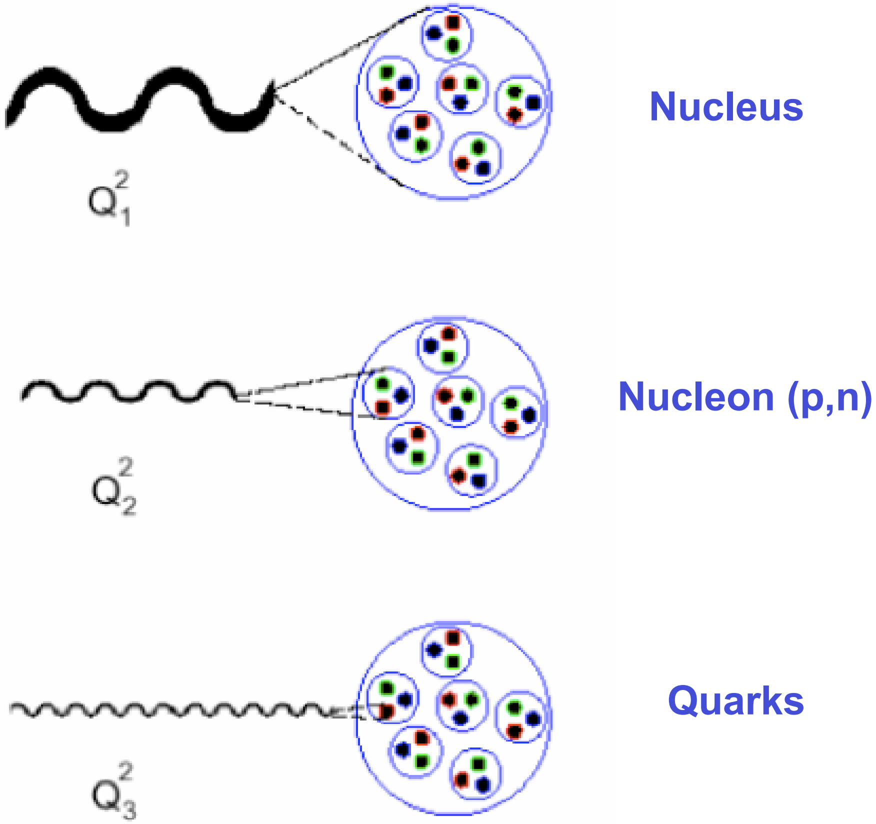




Probe the matter



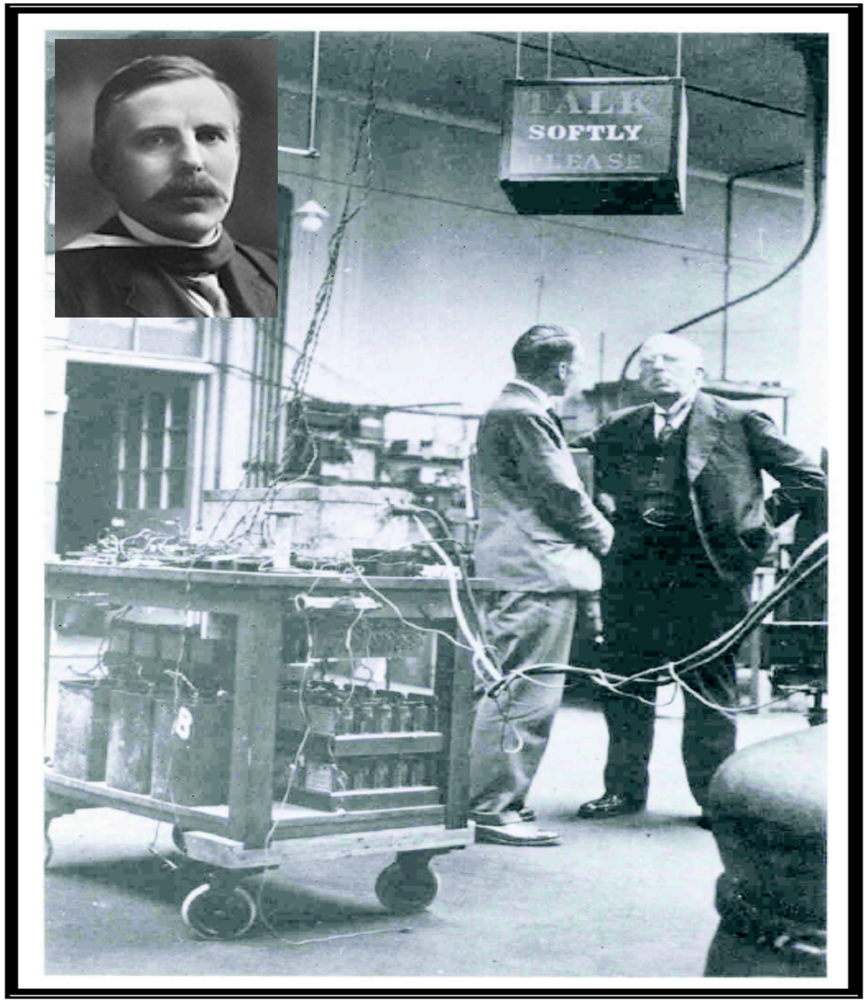
$$\delta\ [\mathrm{fm}] \simeq \frac{200\ \mathrm{MeV}}{Q}$$



$$Q_3^2 > Q_2^2 > Q_1^2$$

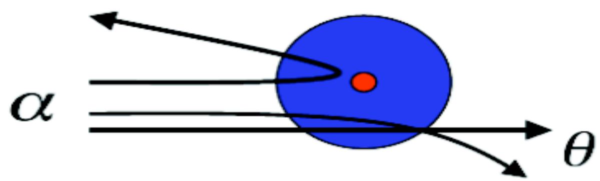
~100 years ago: Geiger, Marsden, Rutherford

”…as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."



GMR

Discovery of the atomic nucleus 1909



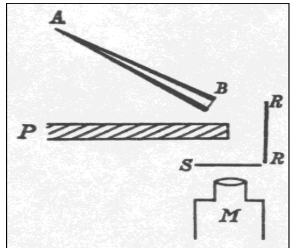
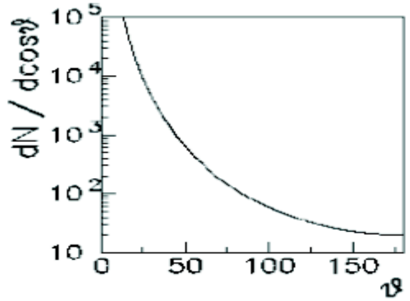


Fig. 1.

→ positively charged massive atomic nucleus

$$r_{nucleus} \approx r_{atom} / 10000 \approx 10^{-14}\,\mathrm{m}$$



$$\frac{dN}{d\Omega} \propto \frac{Z^2}{E^2} \frac{1}{4\sin^4\theta/2}$$

$$E_\alpha = 5.5\mathrm{MeV}$$

A “punctual” particle can probe a composed particle: the beginning of the “beam microscopy”

SLAC Linac

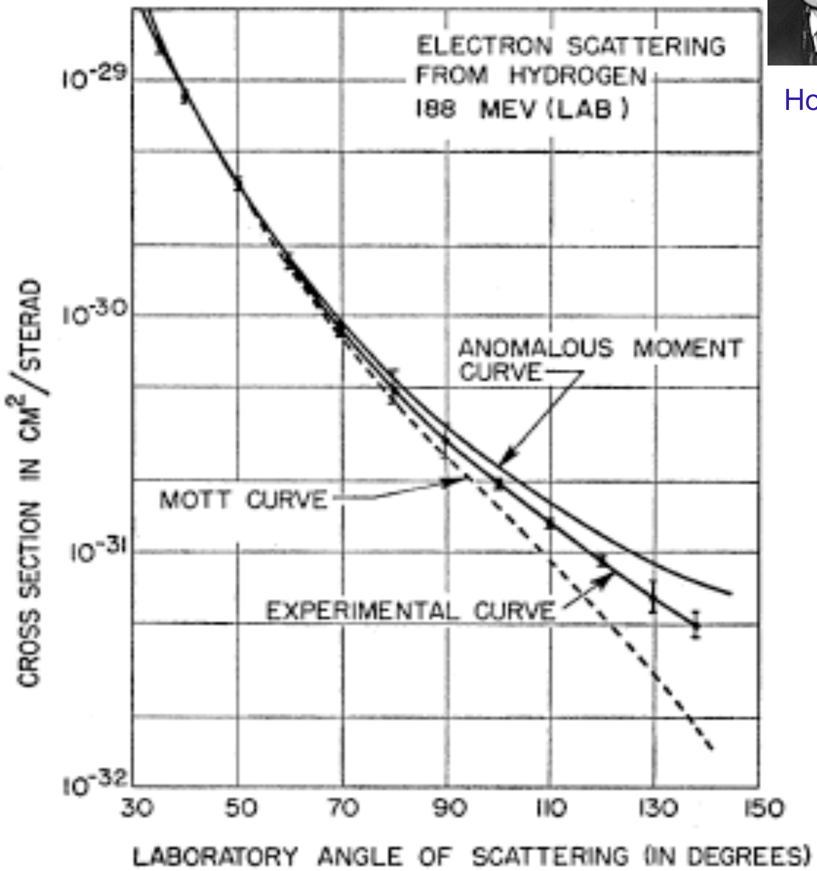

Hofstadter

Electron Scattering from the Proton*†‡

ROBERT HOFSTADTER AND ROBERT W. MCALLISTER
Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California

(Received January 24, 1955)

WITH apparatus previously described,[1,2] we have studied the elastic scattering of electrons of energies 100, 188, and 236 Mev from protons initially at rest. At 100 Mev and 188 Mev, the angular distributions of scattered electrons have been examined in the ranges 60°–138° and 35°–138°, respectively, in the laboratory frame. At 236 Mev, because of an inability of the analyzing magnet to bend electrons of energies larger than 192 Mev, we have studied the angular distribution between 90° and 138° in the laboratory frame. In all cases a gaseous hydrogen target was used.



proton were a spherical ball of charge, this rms radius would indicate a true radius of 9.5×10^{-14} cm, or in round numbers 1.0×10^{-13} cm. It is to be noted that if our interpretation is correct the Coulomb law of force has not been violated at distances as small as 7×10^{-14} cm.

$$P_{obs} = F(q)P_{point-particle}$$

Accountable by elastic scattering
over finite size **(~1fm)** charge distribution

To "resolve" the proton: need more energy!
Go to inelastic regime!
When Q2 >> M_p Deep Inelastic Scattering

SLAC experiments at high energy (1960)

High Energy electrons (20~GeV) new technology (klistrons)

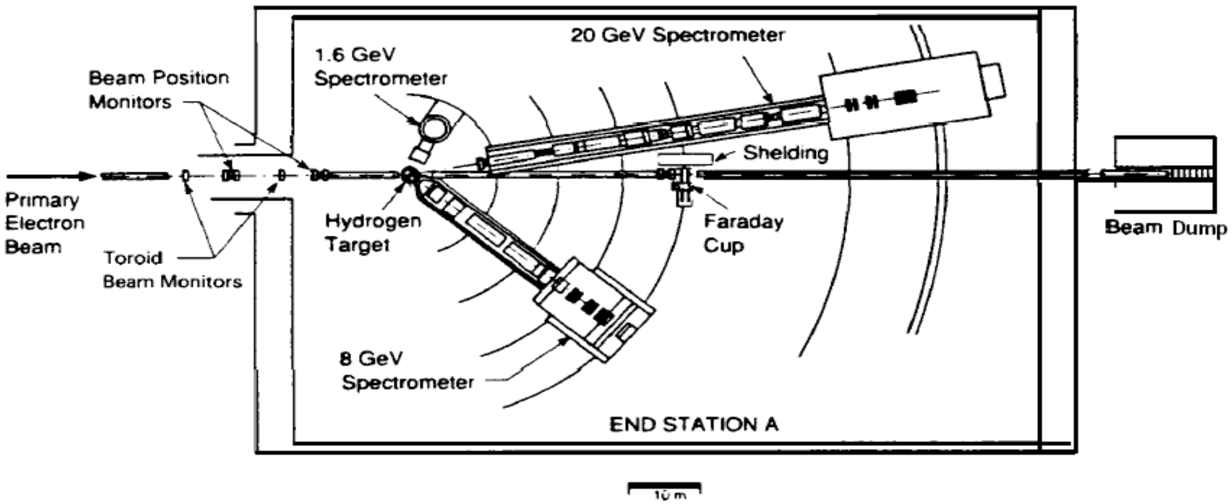
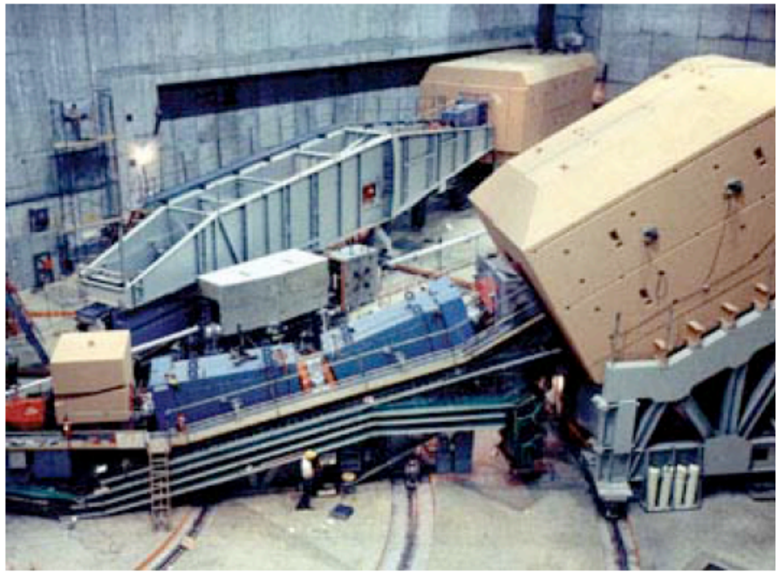
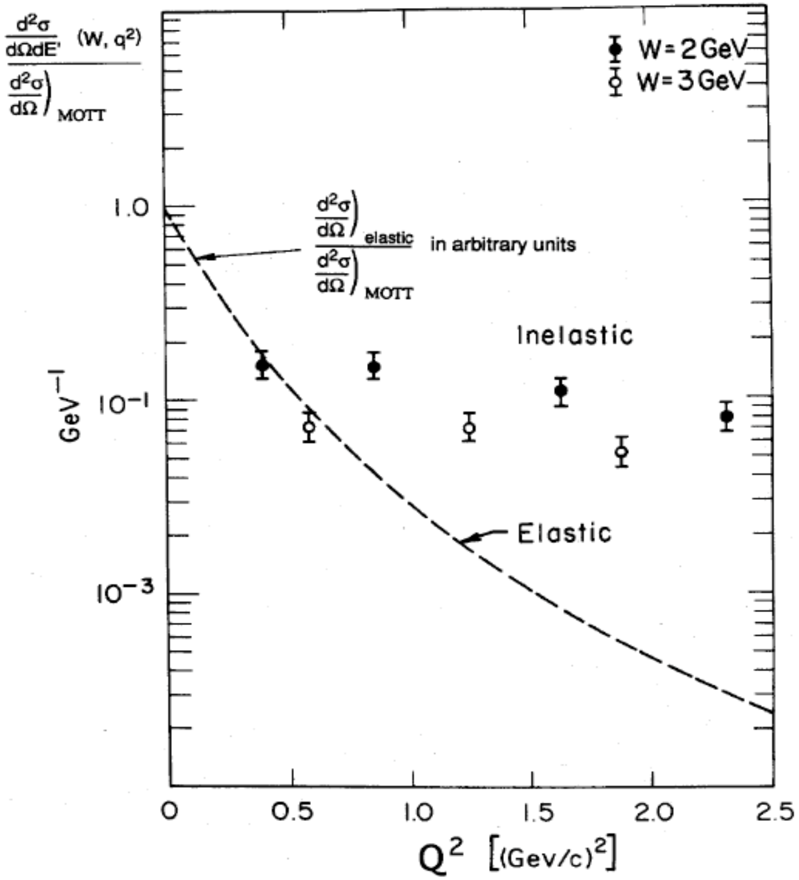


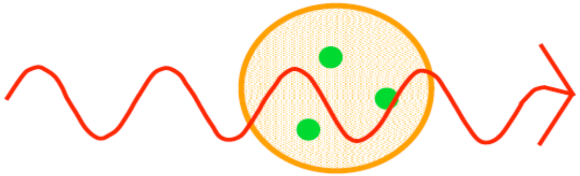
Fig. 14. Layout of spectrometers in End Station A. All three spectrometers can be rotated about the pivot. The 20 GeV spectrometer can be operated from about $1\frac{1}{2}^\circ$ to 25°, the 8 GeV from about 12° to over 90°. The 1.6 GeV spectrometer coverage is from $\sim 50^\circ - 150^\circ$.



40 years ago



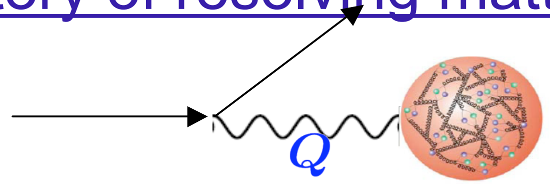
“Scaling” with Q: point-like partons



Richard E. Taylor Jerome I. Friedman Henry W. Kendall

The Nobel Prize in Physics 1990 "for their pioneering investigations concerning deep inelastic scattering of electrons on protons and bound neutrons, which have been of essential importance for the development of the quark model in particle physics"

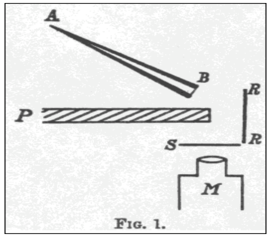
A short history of resolving matter structure



~100 years ago

Geiger, Marsden. (1909)
Rutherford(1911)

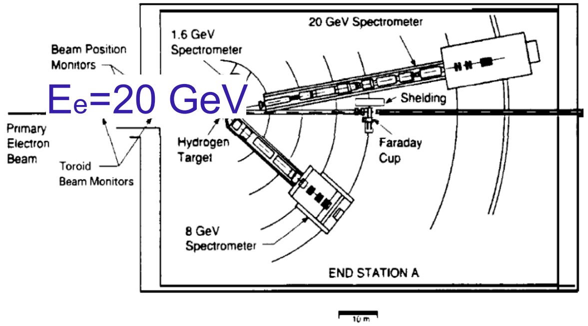
E_α=5.5 MeV



$$\delta\ [\mathrm{fm}] \simeq \frac{200\ \mathrm{MeV}}{Q}$$

40 years ago: partons

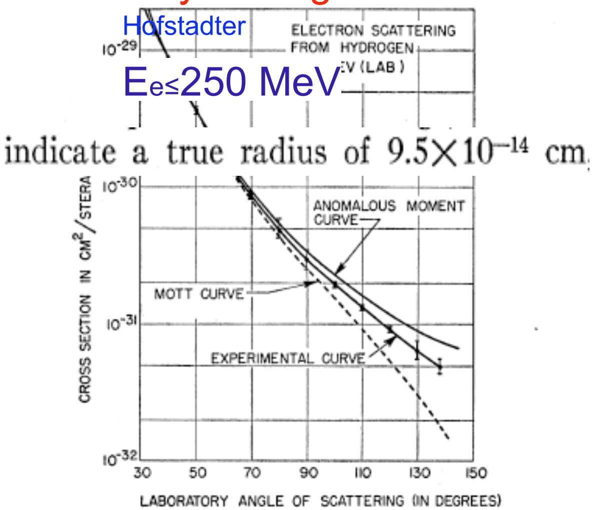
E_e=20 GeV

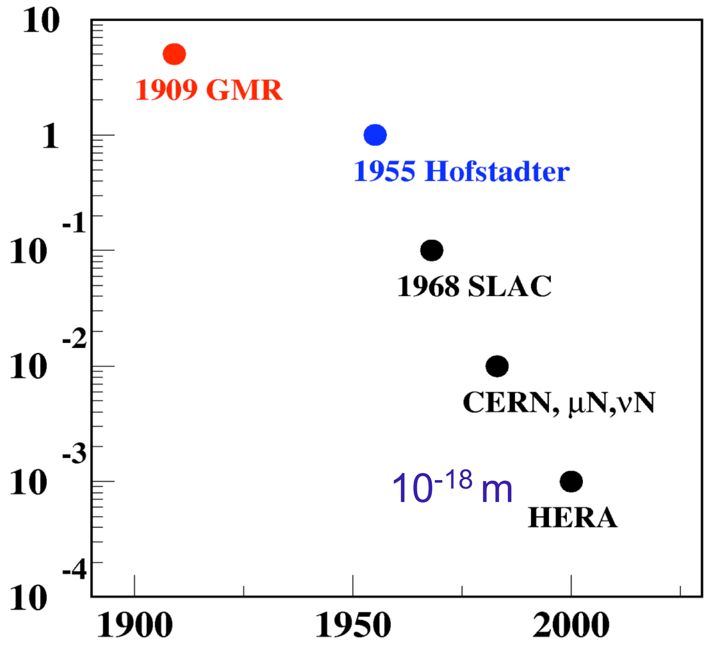


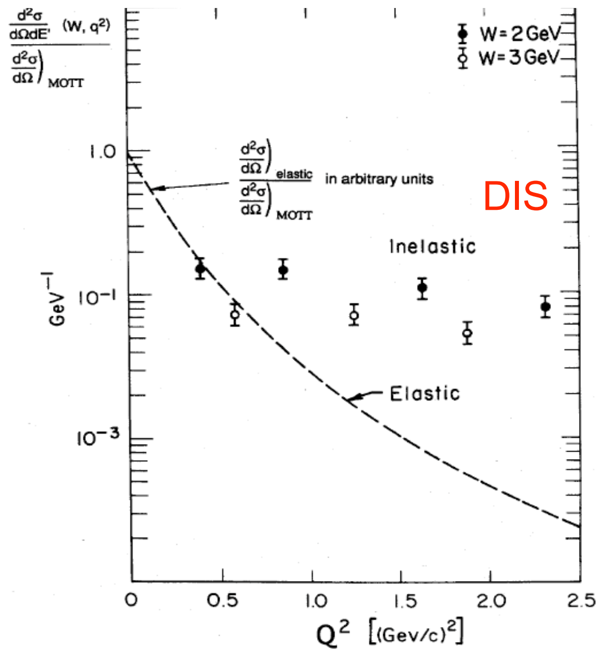
53 years ago

Hofstadter

$E_e \leq$250 MeV



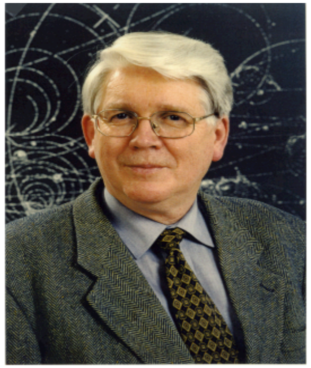




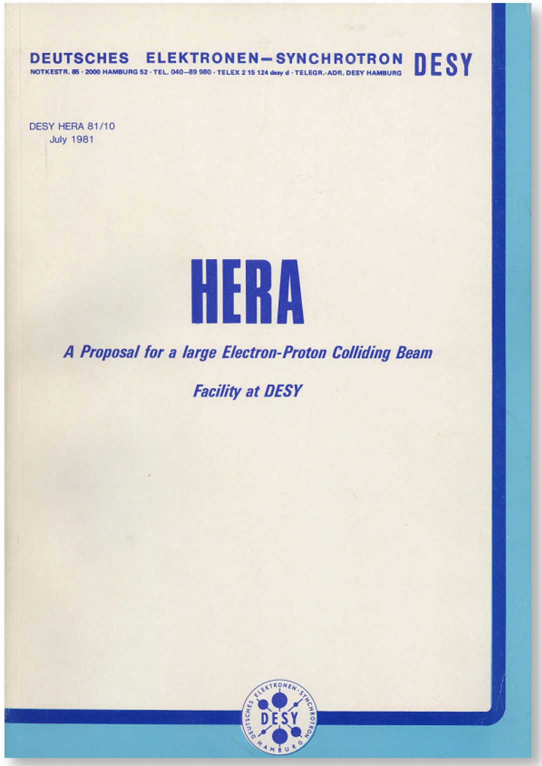
[polarised collisions since mid 70's]

HERA: The unique electron-proton collider

G. A. Voss

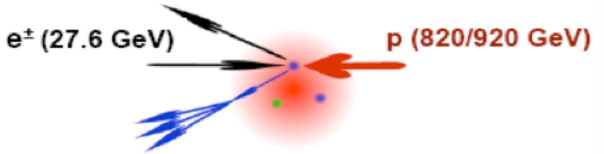


B. H. Wiik



Volker Soergel and the Minister of Science of Germany, Heinz Riesenhuber, at DESY (Hamburg) announcing on 6th of April 1984 that HERA will be built.

HERA Experimental Complex

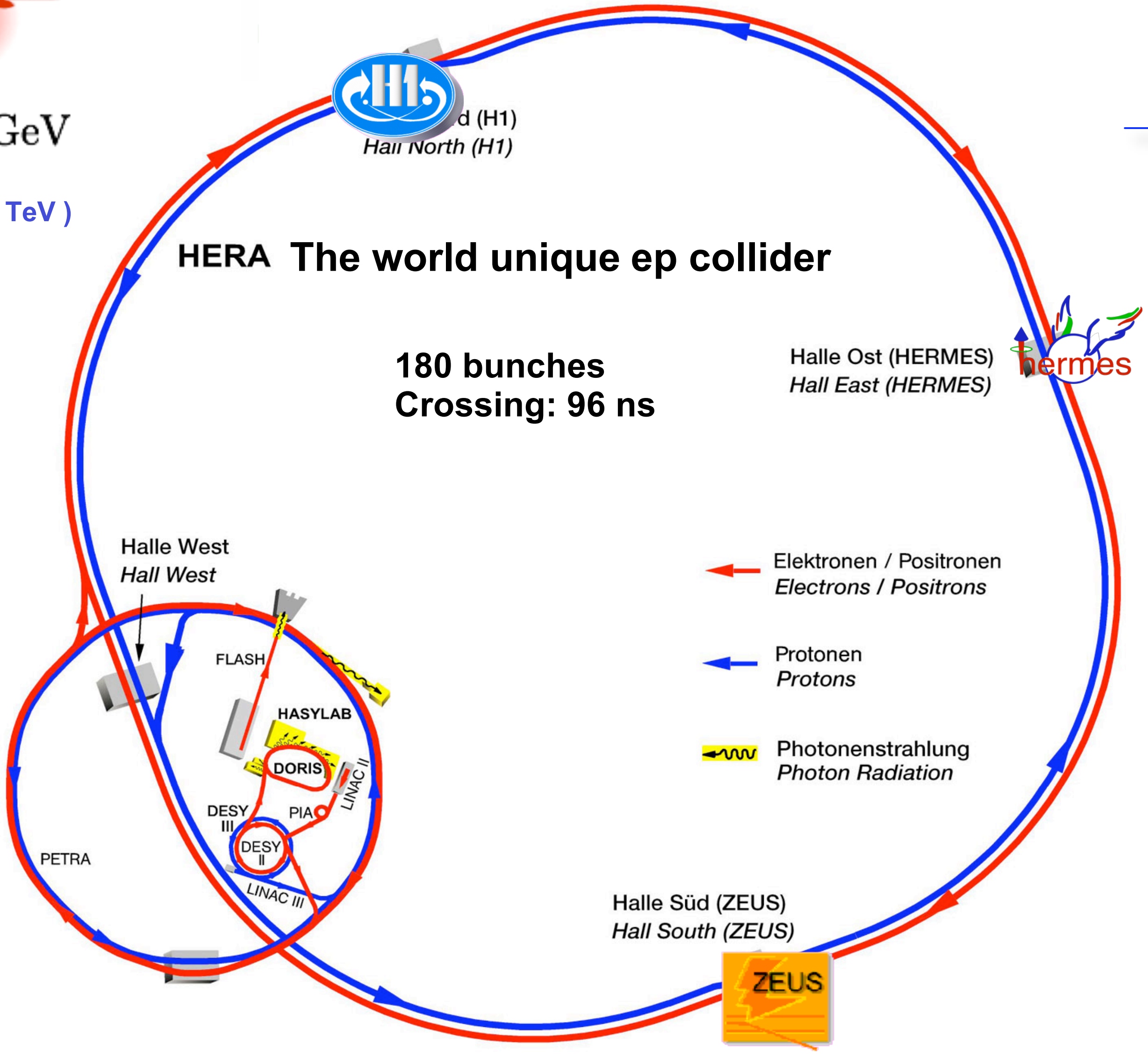


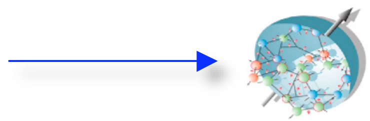
$$E_{cm} = 320 \text{ GeV}$$

(equivalent $E_{beam\text{-}FT}$=50 TeV)

HERA The world unique ep collider

180 bunches
Crossing: 96 ns





$$E_{cm} = 7 \text{ GeV}$$

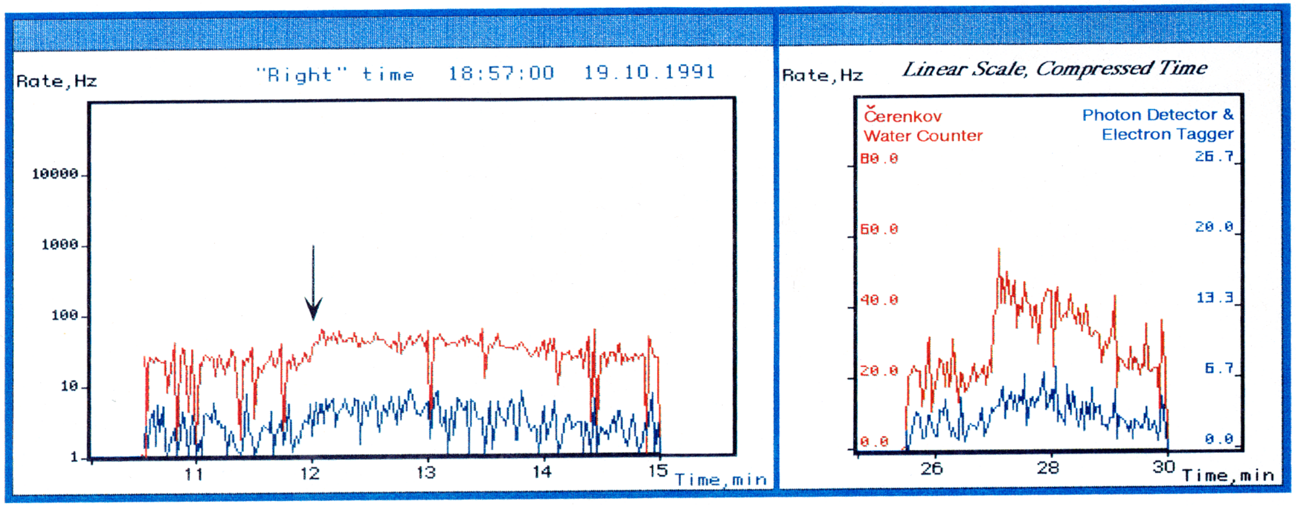

hermes
HERA
ZEUS
PETRA

First Luminosity 1991

FIRST HERA e-p COLLISIONS

AS OBSERVED BY THE H1 LUMINOSITY-DETECTOR MONITORING SYSTEM

SATURDAY 19 OCTOBER 1991, 18:54



Electron Energy	12 GeV
Proton Energy	480 GeV
Expected Luminosity	$0.95 \times 10^{26} \pm 30\%\ cm^{-2}s^{-1}$
Measured Luminosity	$1.03 \times 10^{26} \pm 13\%\ cm^{-2}s^{-1}$

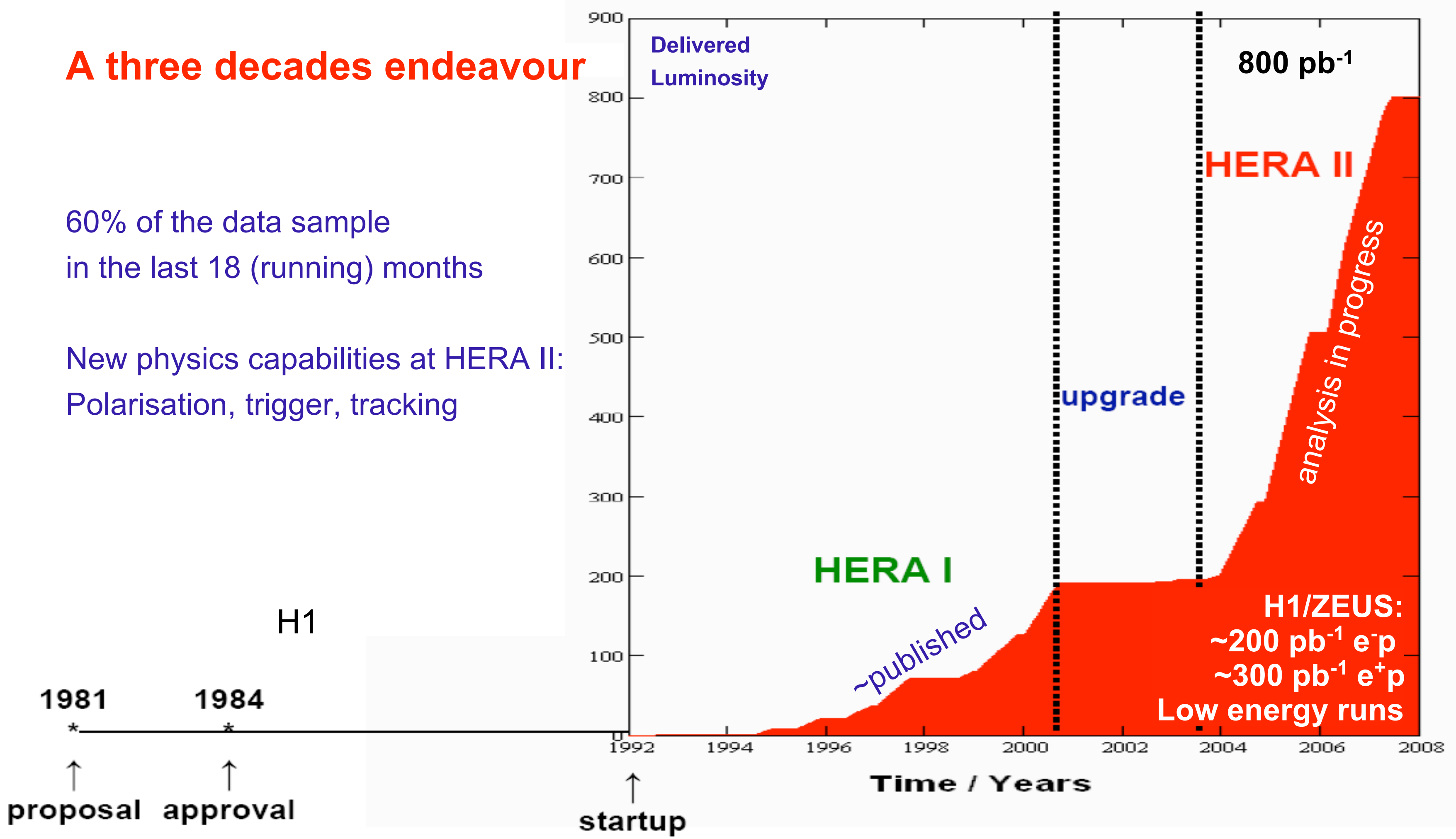
HERA
construction started in 1984
physics: 1992-2007

HERA Program

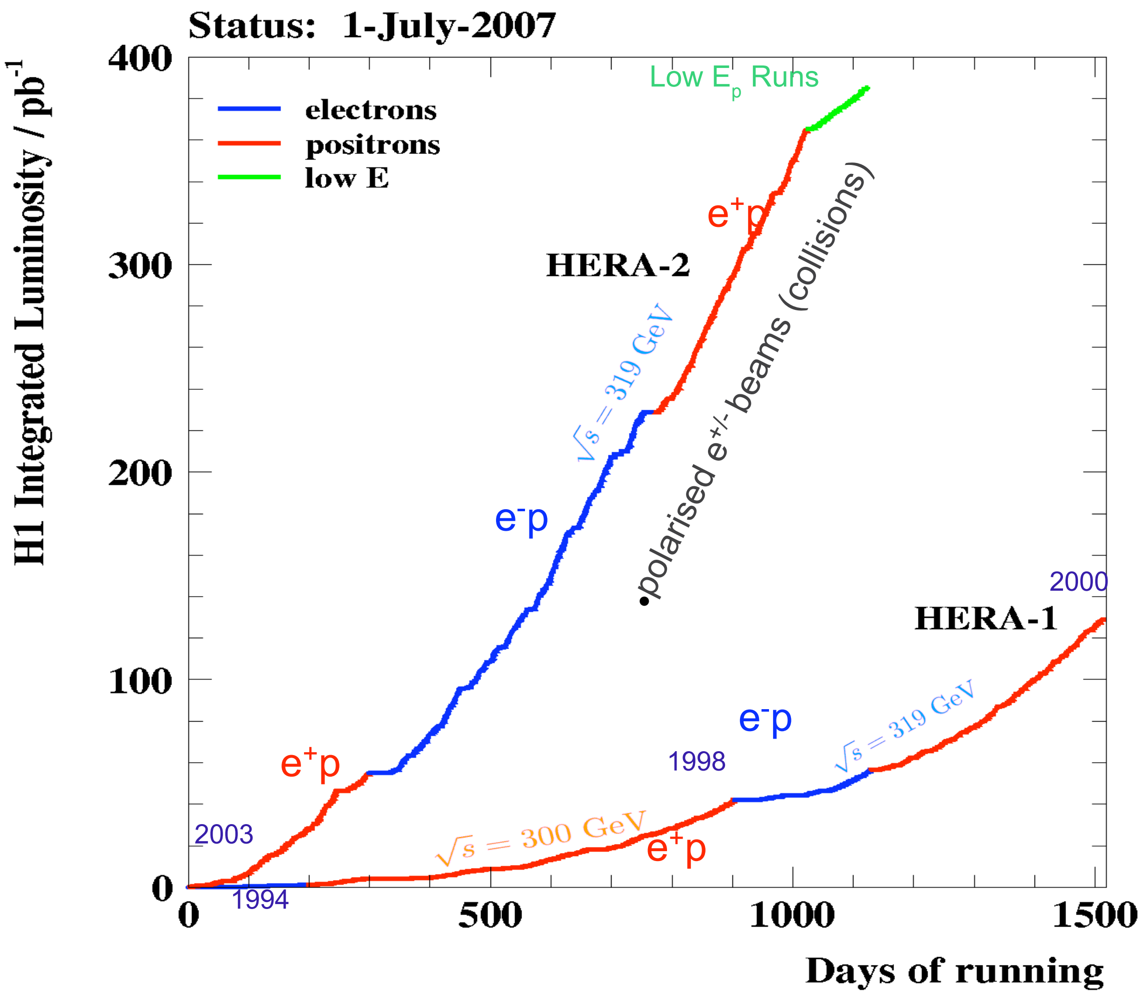
A three decades endeavour

60% of the data sample
in the last 18 (running) months

New physics capabilities at HERA II:
Polarisation, trigger, tracking

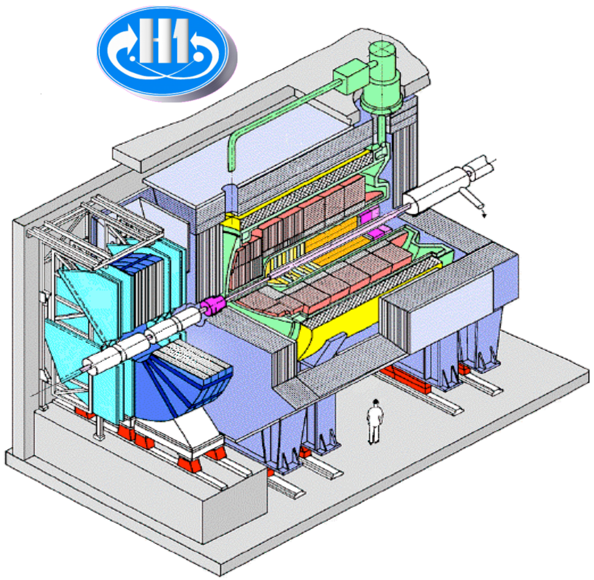


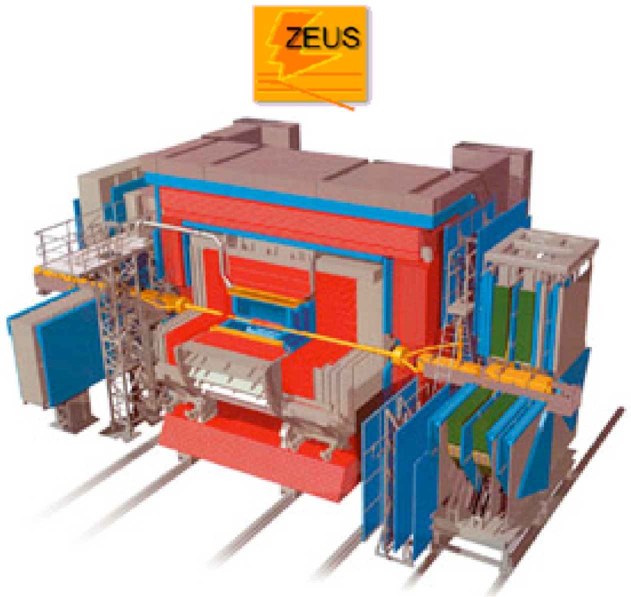
HERA Luminosity



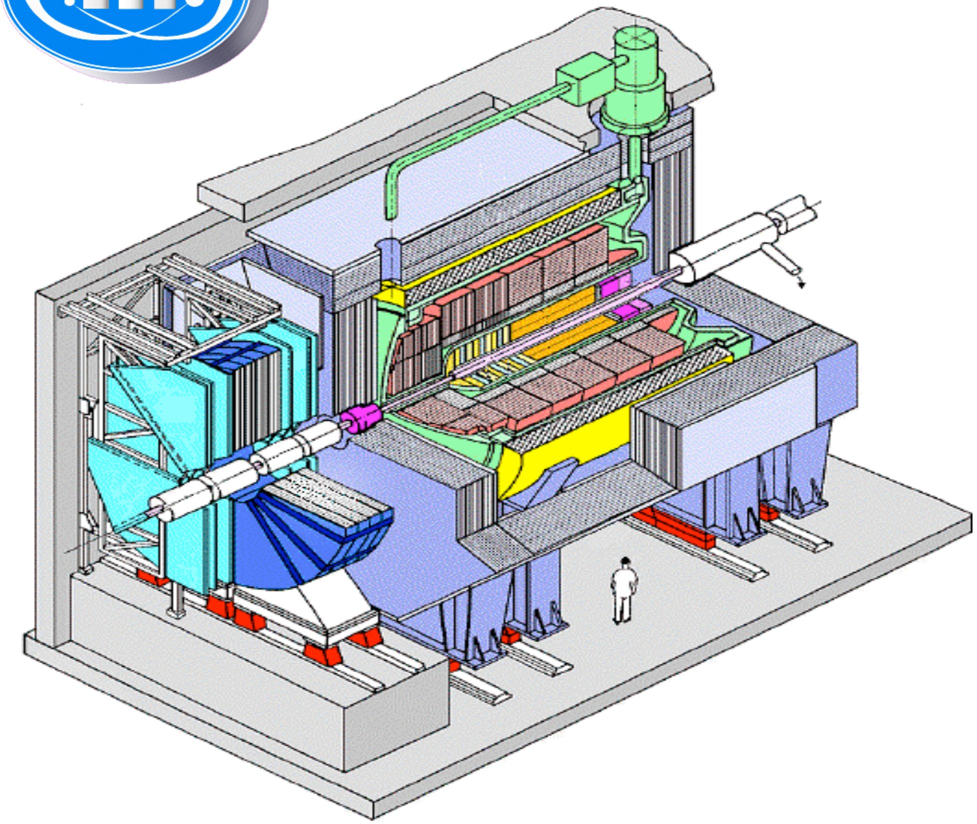
The Detectors

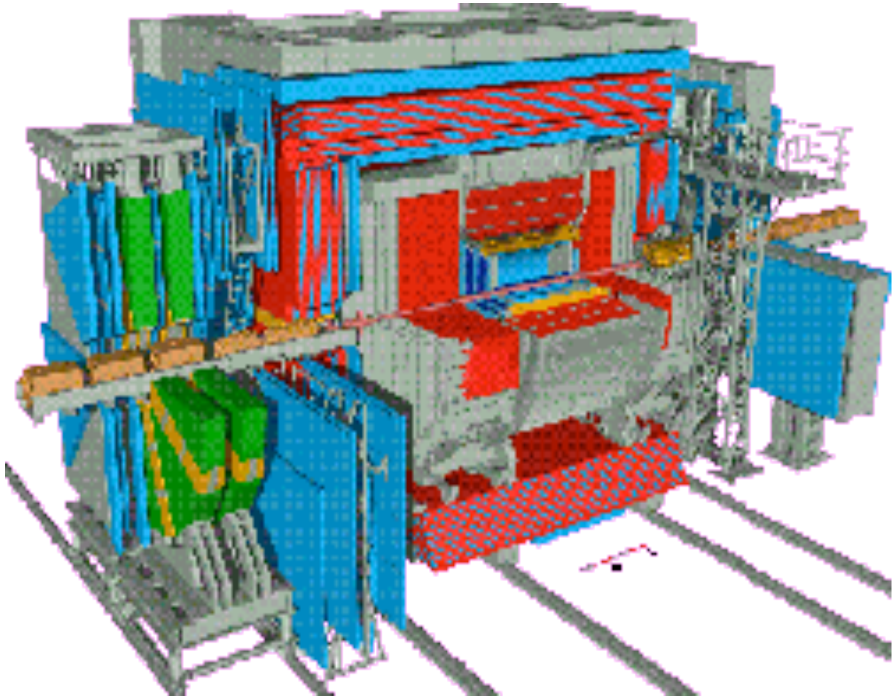
Complex detectors, large international collaborations (~800 physicists)





H1 and ZEUS detectors



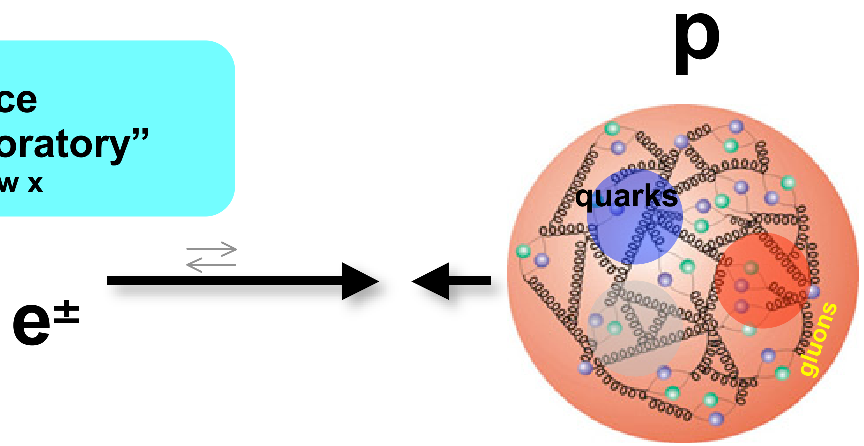


4π detectors, excellent tracking and calorimetry

The Physics at HERA

The proton structure
with unprecedented precision
Parton distribution functions for the future

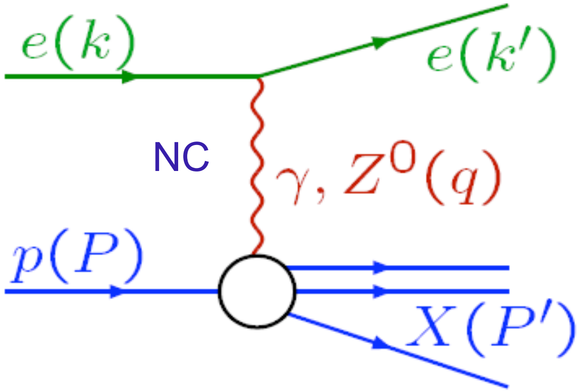
The strong force
in a clean "laboratory"
Jets, Diffraction, Low x

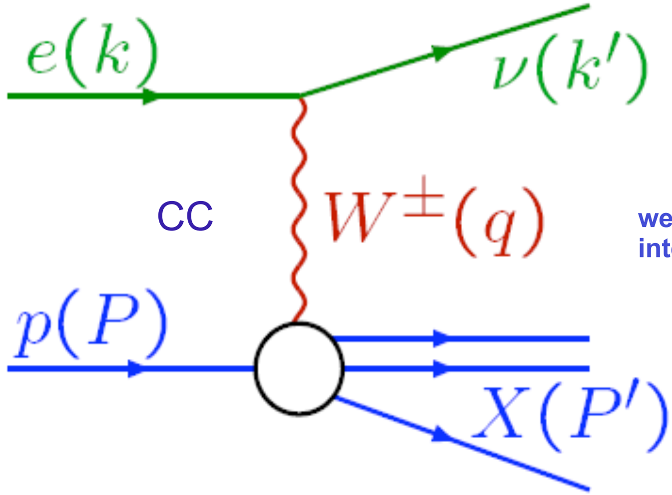


The proton spin surgery
Longitudinal and transverse spin measurements

The new physics
at the energy frontier

Deep-Inelastic Scattering





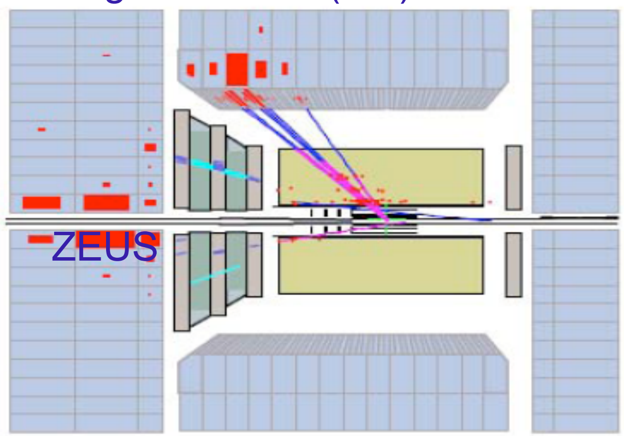
weak interactions

- $Q^2 = -q^2 = -(k-k')^2$ virtuality/resolving power
- $x = \frac{Q^2}{2P\cdot q}$ Bjorken scaling variable, momentum fraction of the scattered parton
- $y = \frac{q\cdot P}{k\cdot P}$ inelasticity

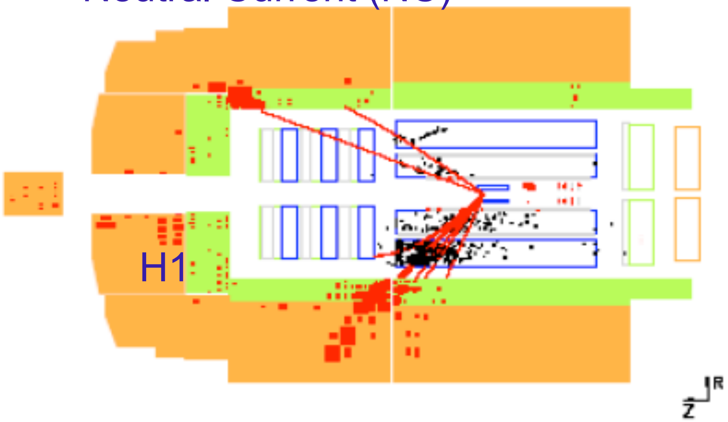
Related by $Q^2 = xys$

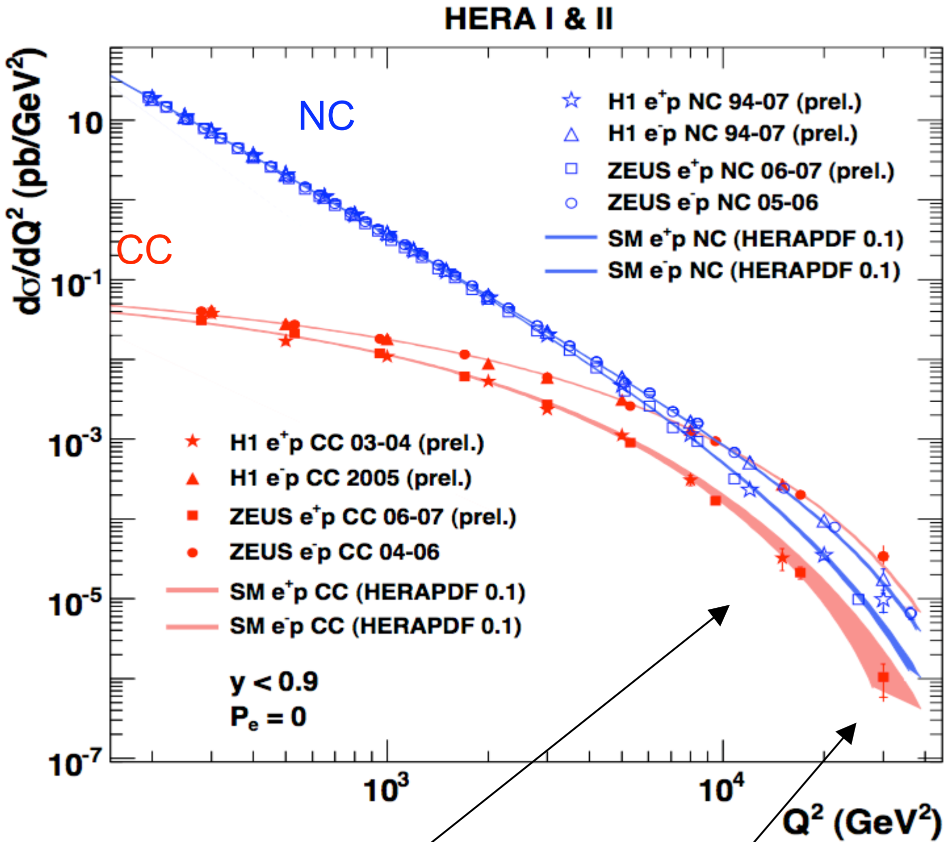
DIS at HERA

Charged Current (CC)



Neutral Current (NC)

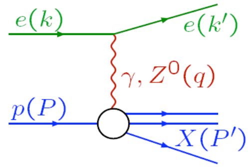




$Q^2 \sim M^2_{W,Z}$ (EW regime)

$r_{quark} < 10^{-18}$m
"p"/1000

DIS: Cross sections, structure functions, partons



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

Leading Order picture of the proton

Parton Distribution Functions

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

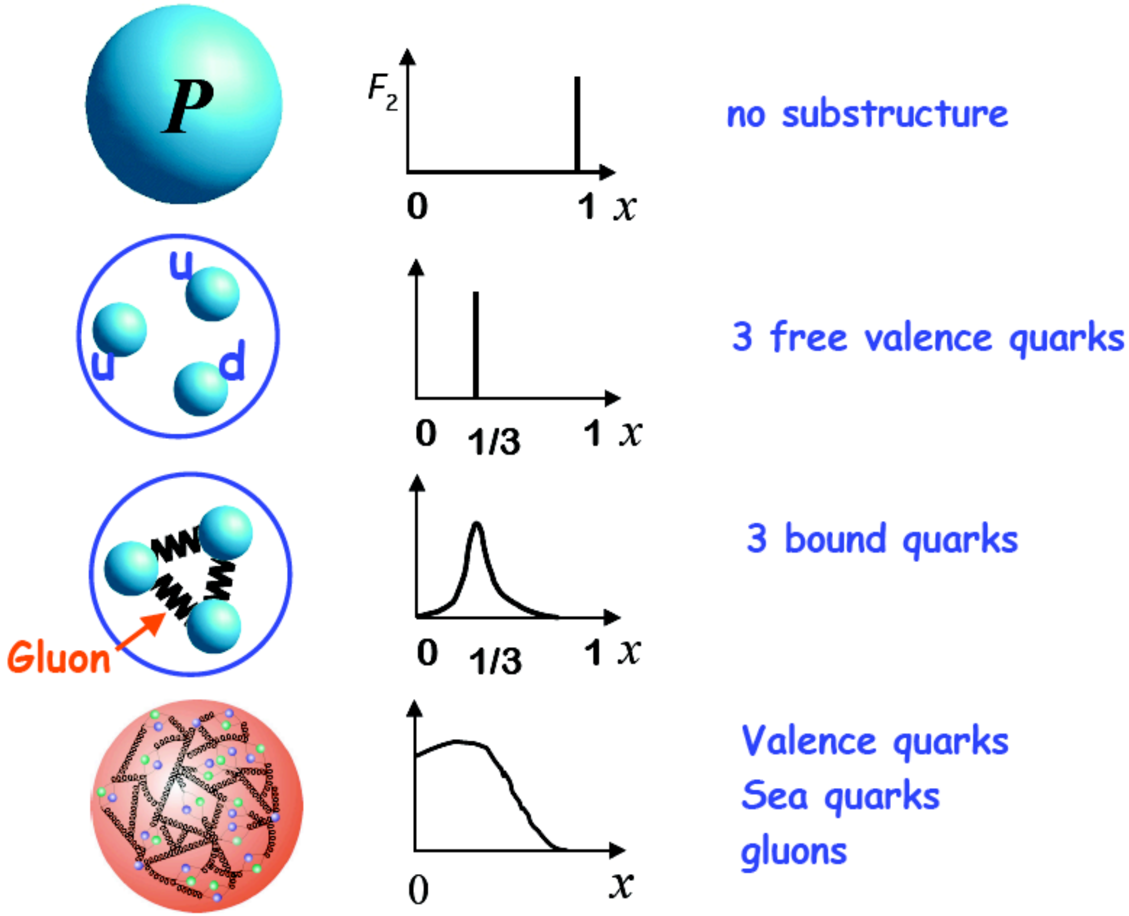
gluons from scaling violations

F_3 $$\left[xF_3^{\gamma Z}, xF_3^Z\right] = 2x\sum_q \left[e_q a_q, v_q a_q\right](q-\bar{q})$$ (valence) quarks

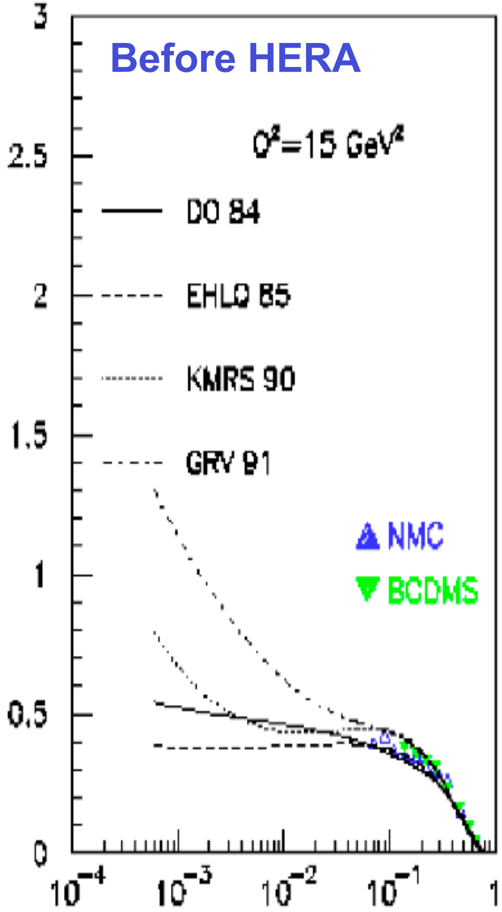
F_L $$F_L \sim x\alpha_s g$$ gluons

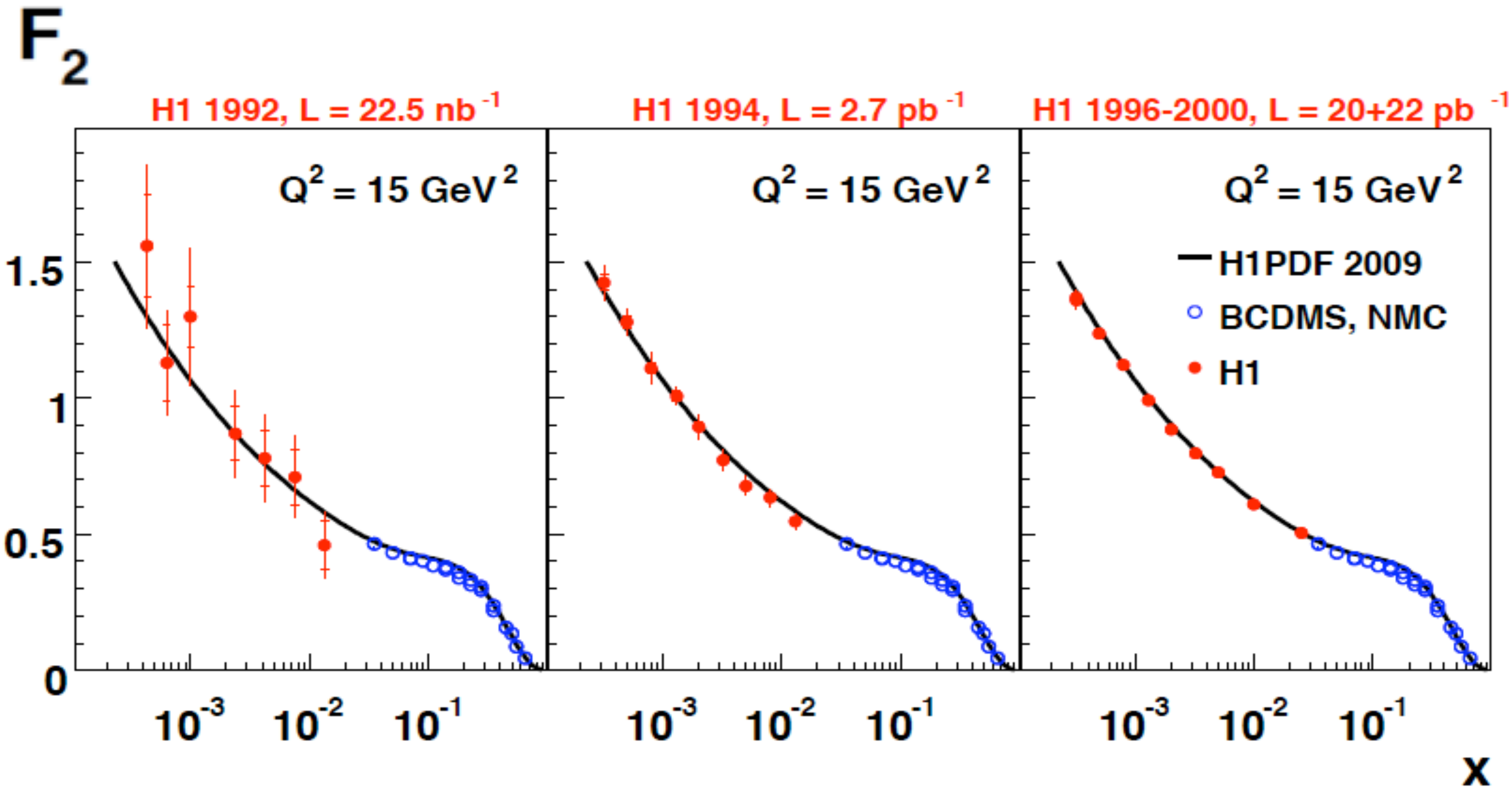
CC: similar decomposition, but different quarks combinations accessed
flavour sensitive (separate in e+p/e-p)

Proton make-up

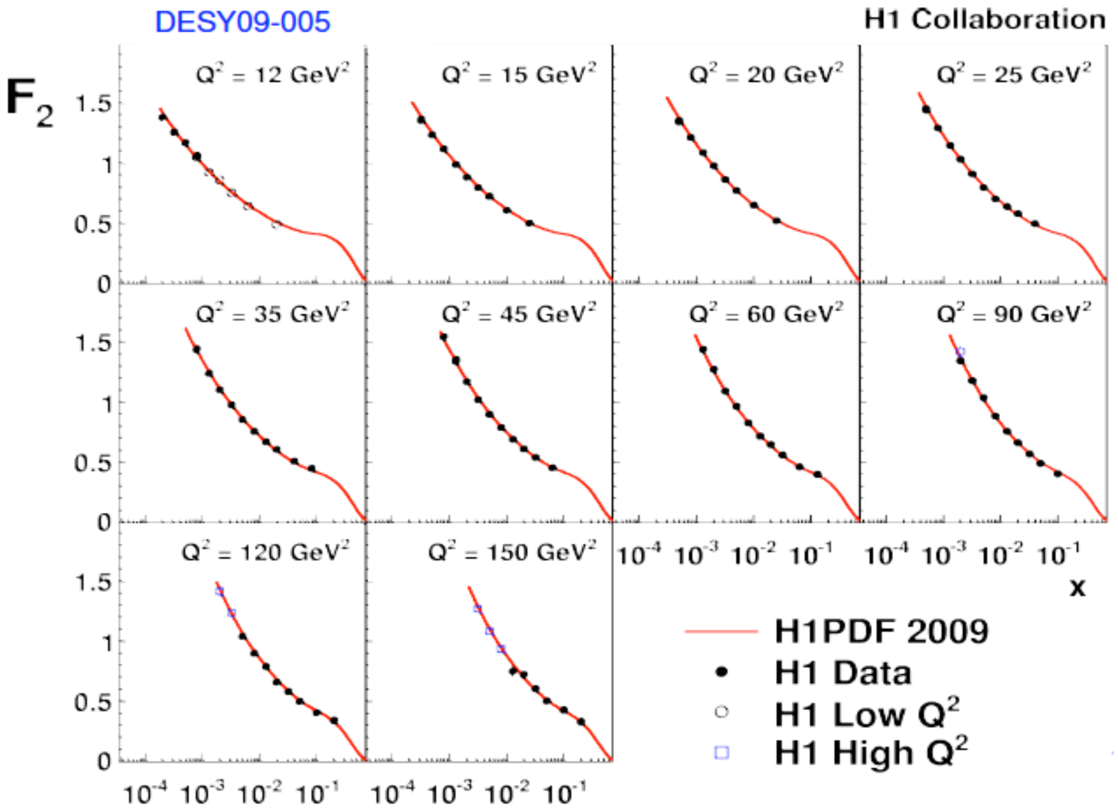


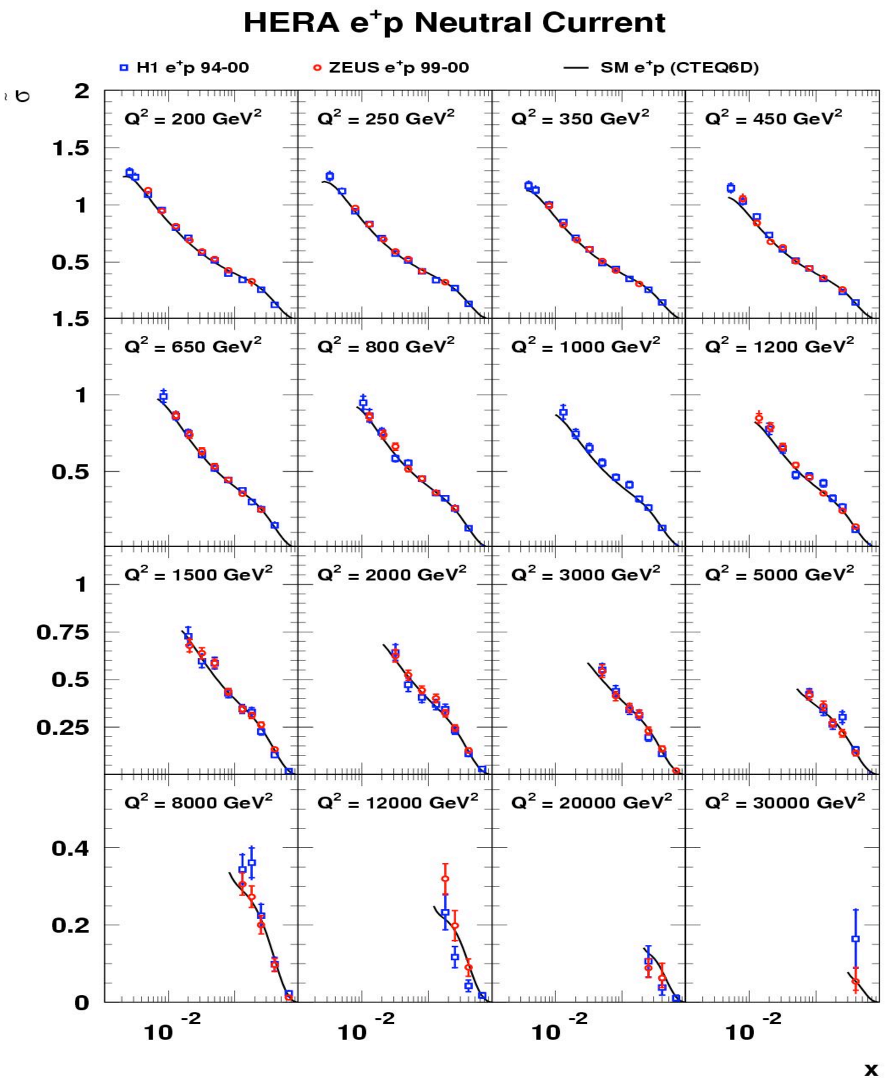
HERA Data at low x





DIS data from HERA



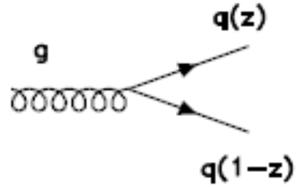


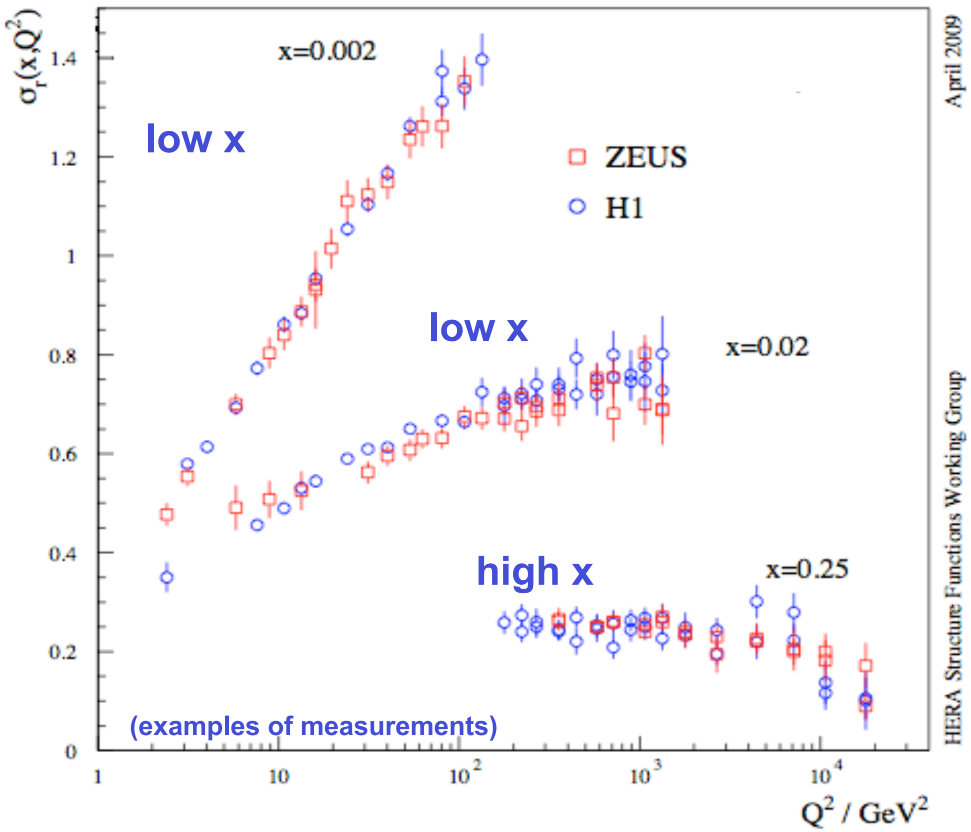
NC:cover a large domain in Q2, precise, in well in agreement with QCD

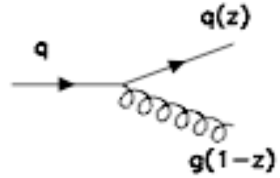
Evolution with Q^2: Scaling Violations

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

$$\frac{\partial F_2}{\partial \log Q^2} \simeq \alpha_S g(x, Q^2)$$







$$\frac{\partial F_2}{\partial \log Q^2} \simeq \alpha_S q(x, Q^2)$$

A clean way to constrain the gluon and to extract the strong coupling

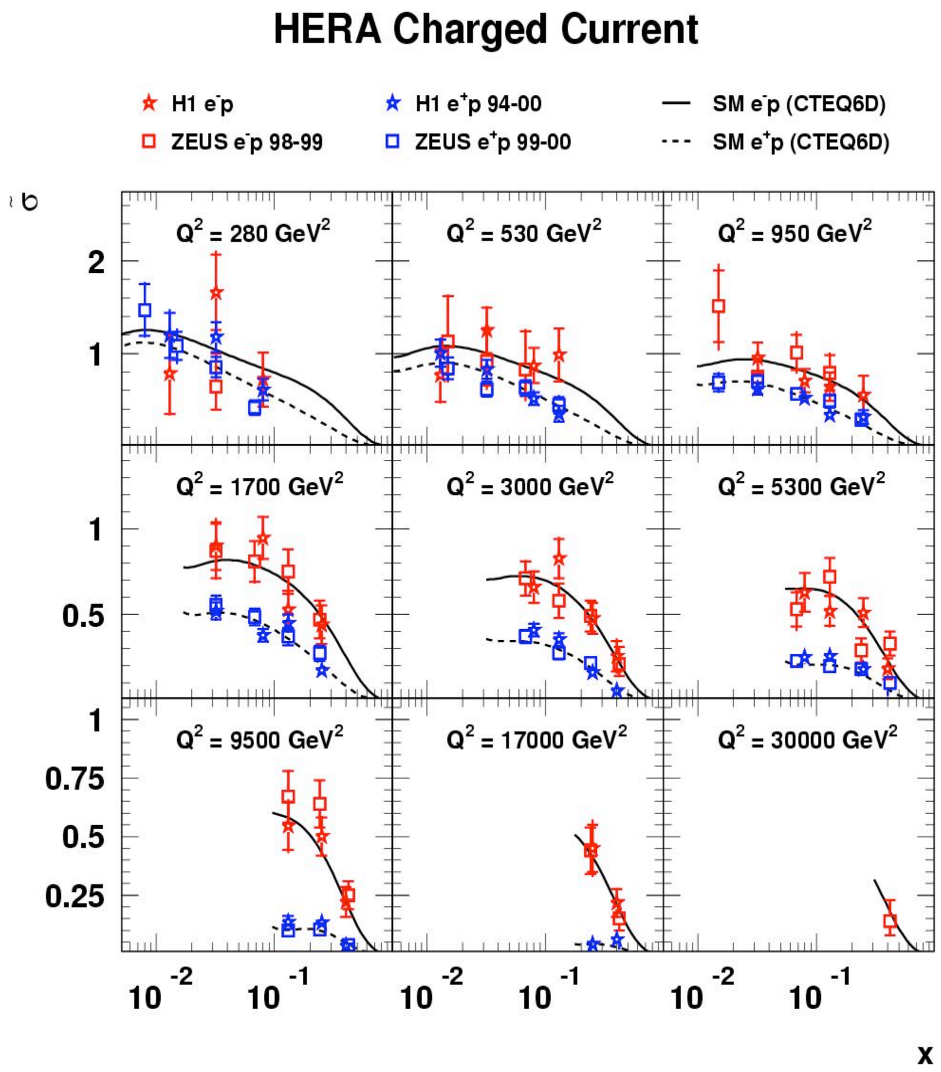
Charged Current

$$\tilde{\sigma}^{+}_{CC} \sim \overline{u} + \overline{c} + (1-y)^2 (d + s)$$

$$\tilde{\sigma}^{-}_{CC} \sim u + c + (1-y)^2 (\overline{d} + \overline{s})$$

- $e^{+} p$ most sensitive to $d(x, Q^2)$
- $e^{-} p$ most sensitive to $u(x, Q^2)$

Disentangle quark favours

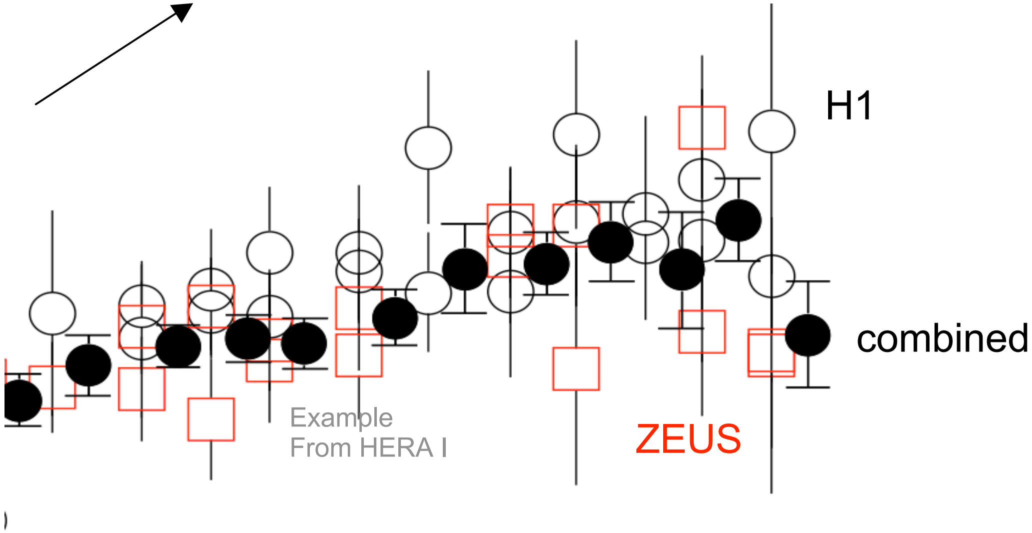


Sharpen the output: H1 and ZEUS data combination

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

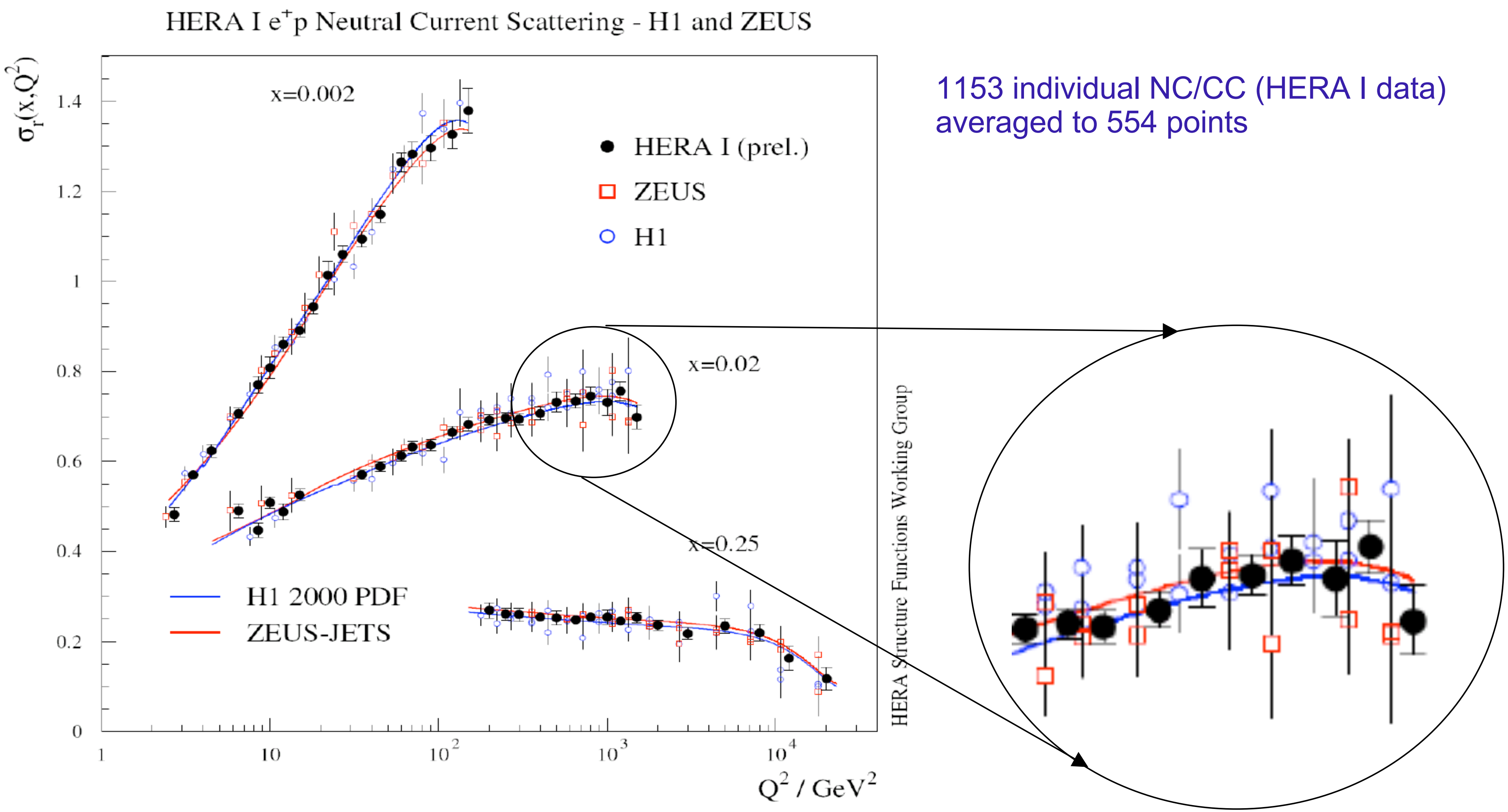
"Double" the statistics

Extra-constrain the coherent systematics



Improve the precision by "cross-calibration" of the systematic effects

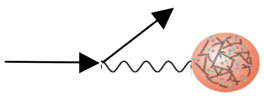
H1-ZEUS cross section combinations



1153 individual NC/CC (HERA I data) averaged to 554 points

High Precision => PDF's

The PDF determination: factorisation and evolution



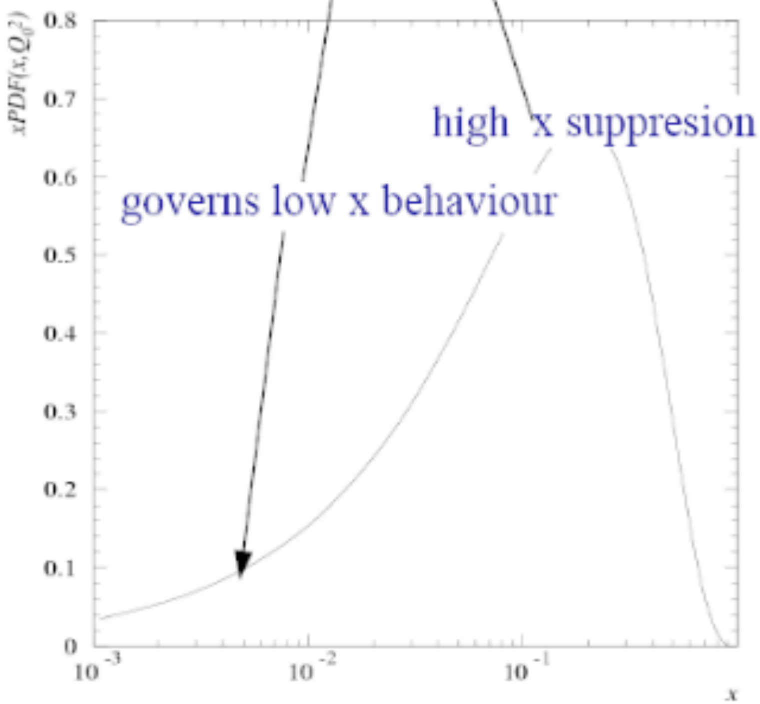
$$\sigma_{DIS} \equiv \mathcal{C}_{\mathrm{lepton-parton}} \otimes f(x, Q^2)$$

perturbative QCD — non-perturbative

factorisation

PDF Parametrisation at scale Q^2_0 : typically 20 parameters

$$xPDF(x, Q_0^2) = Ax^b(1-x)^c(1 + dx + e\sqrt{x} + fx^2 + gx^3)$$

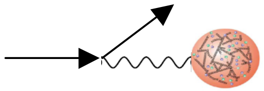


parameters A,b,c,d,e,f optimised in fit for each PDF

some parameters constrained by sum rules e.g. momentum sum = 1

$$\int u_v dx = 2 \qquad \int d_v dx = 1$$

The PDF determination: factorisation and evolution



$$\sigma_{DIS} \equiv \mathcal{C}_{lepton-parton} \otimes f(x, Q^2)$$

perturbative QCD

non-perturbative

factorisation

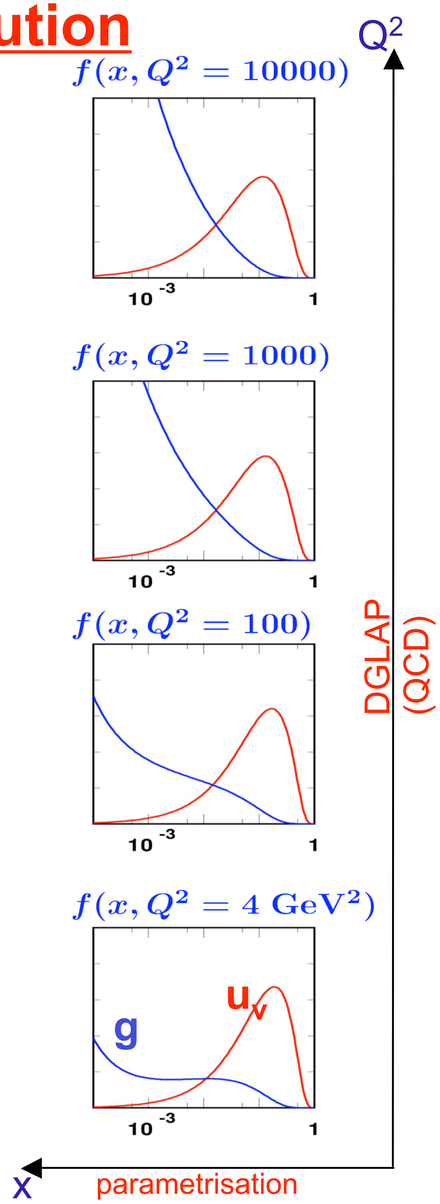
PDF: parametrisation at scale Q^2_0

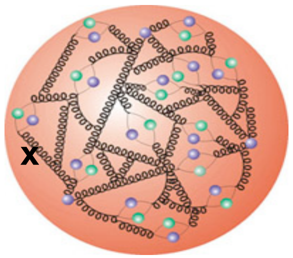
Evolution in Q^2 calculable in QCD (DGLAP):

$$\frac{\partial}{\partial Q^2} f_i(x, Q^2) = \sum P^{i,j} \otimes f_j(x, Q^2)$$

The PDF's play two (equivalent) roles:

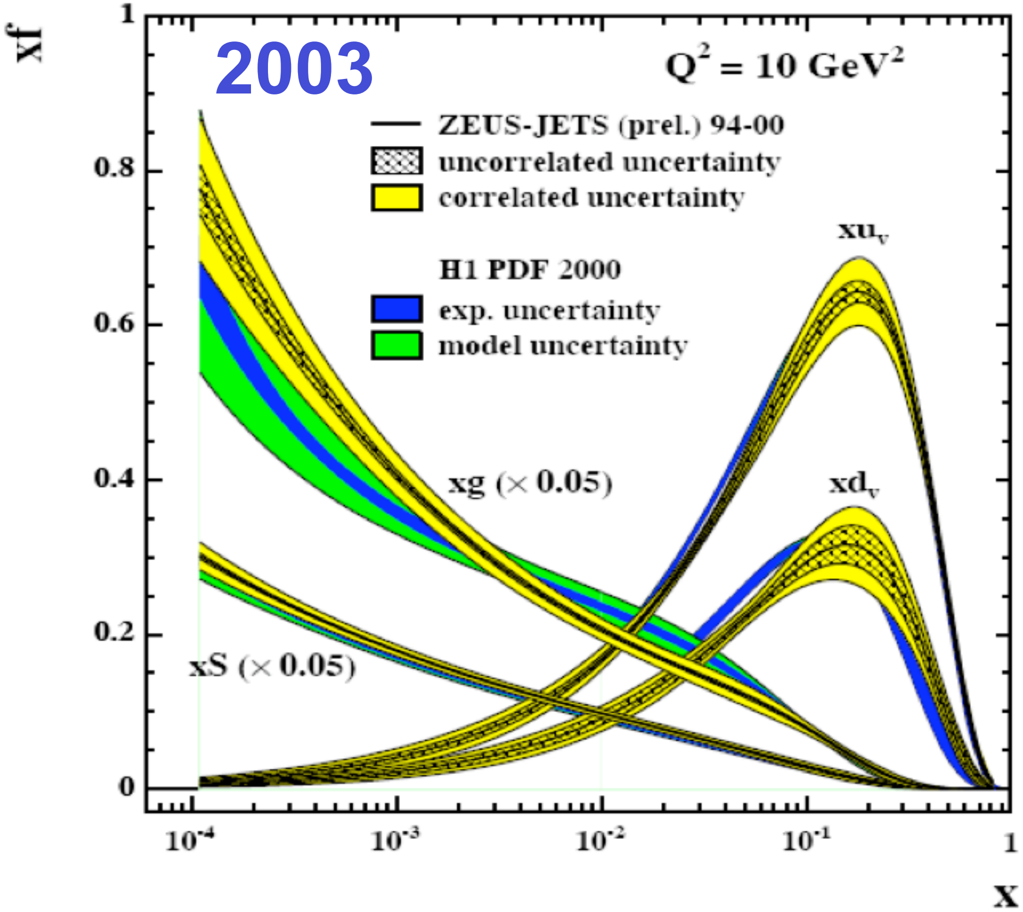
- nucleon chemistry: understand how the baryonic matter is made
- predictions via factorisation ansatz (for instance for LHC)

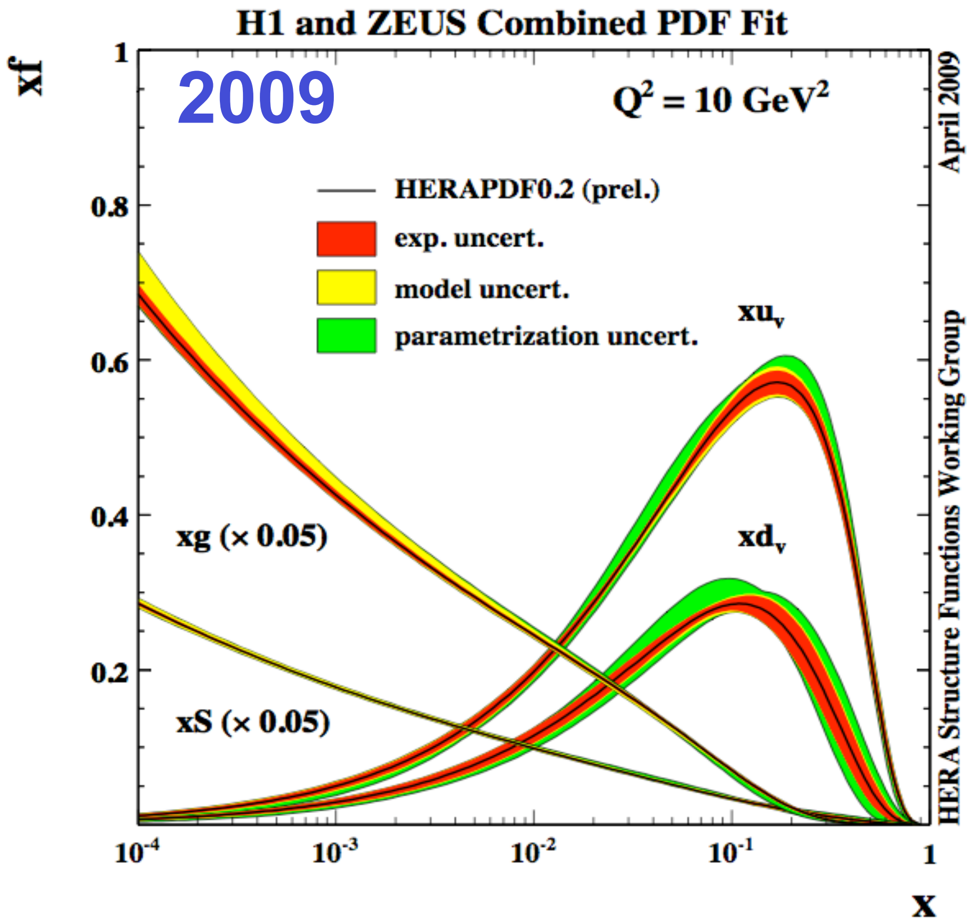




The common fit of the combined HERA I data

Experimental+Model uncertainties taken into account
Errors of the fit estimated using $\Delta\chi^2$=1

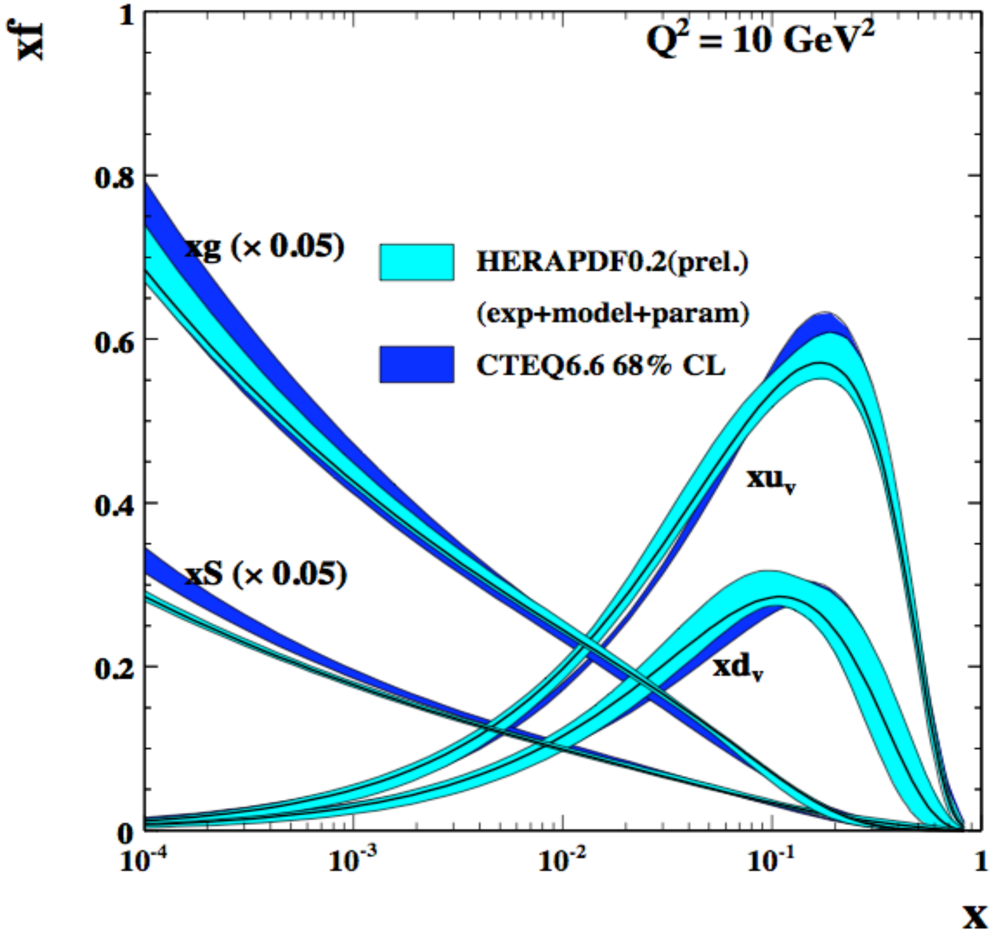


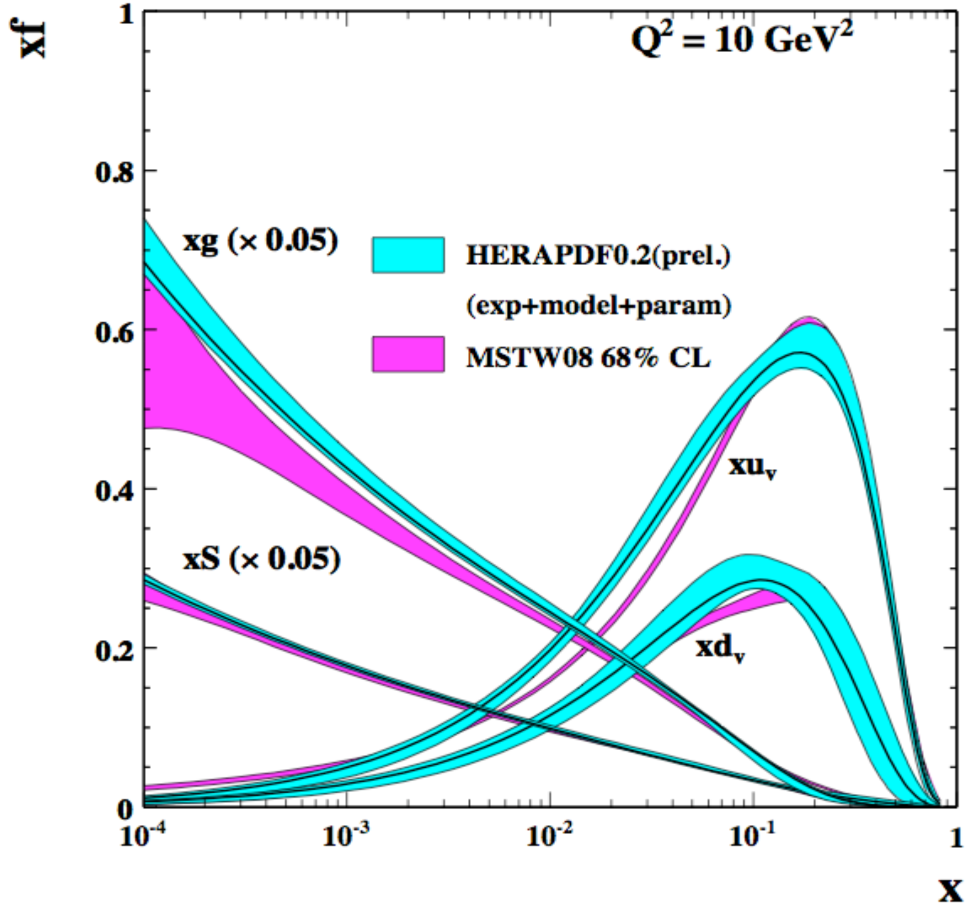


Improvement in precision is visible, originate mostly from data combination

HERAPDF compared to global fits

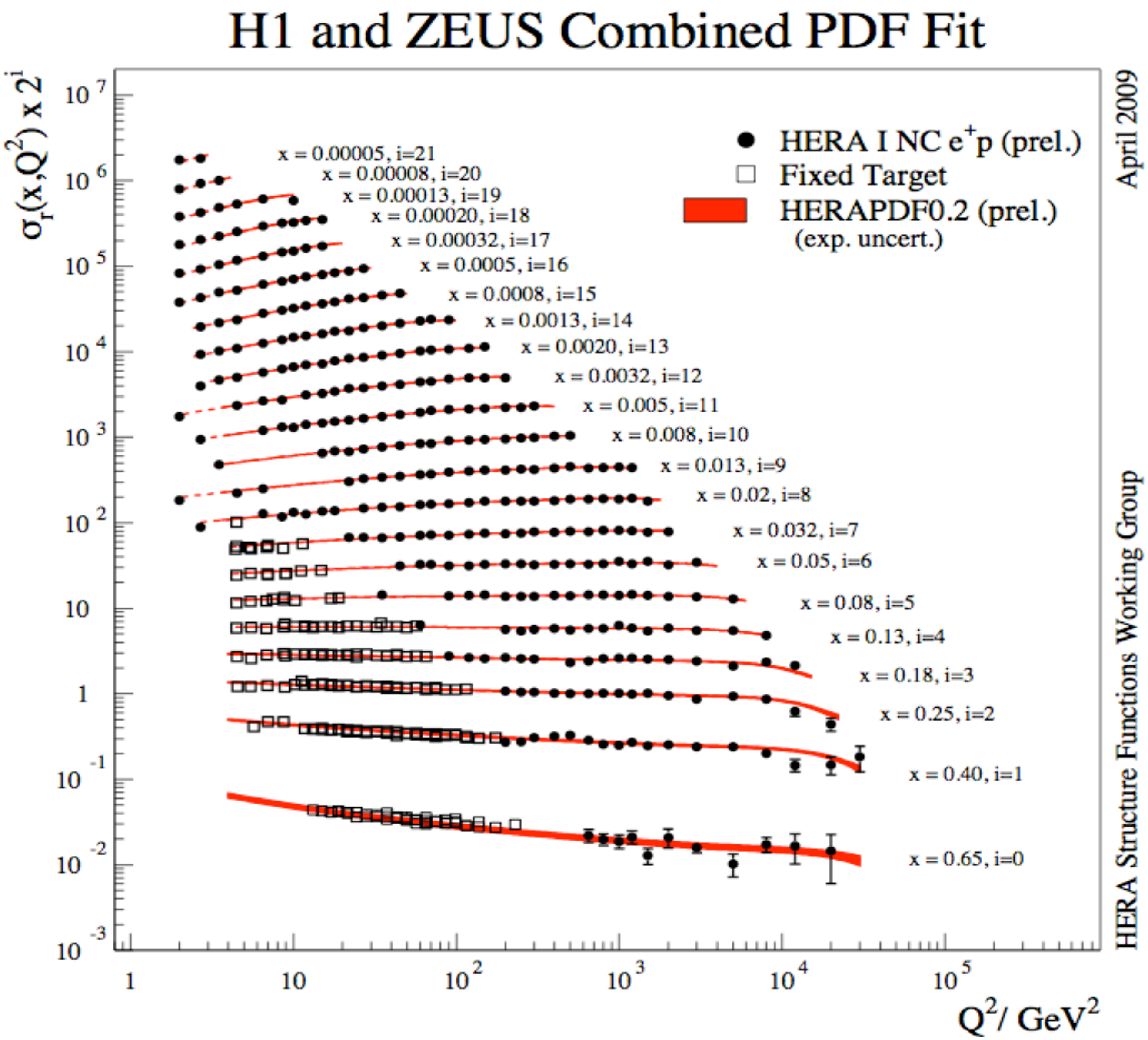
Global Fits: include more/diverse data from pp, fixed target





Interesting comparisons and studies of PDFs for LHC
HERA PDF: A fit of a coherent DIS data set

The combined data compared to the fit



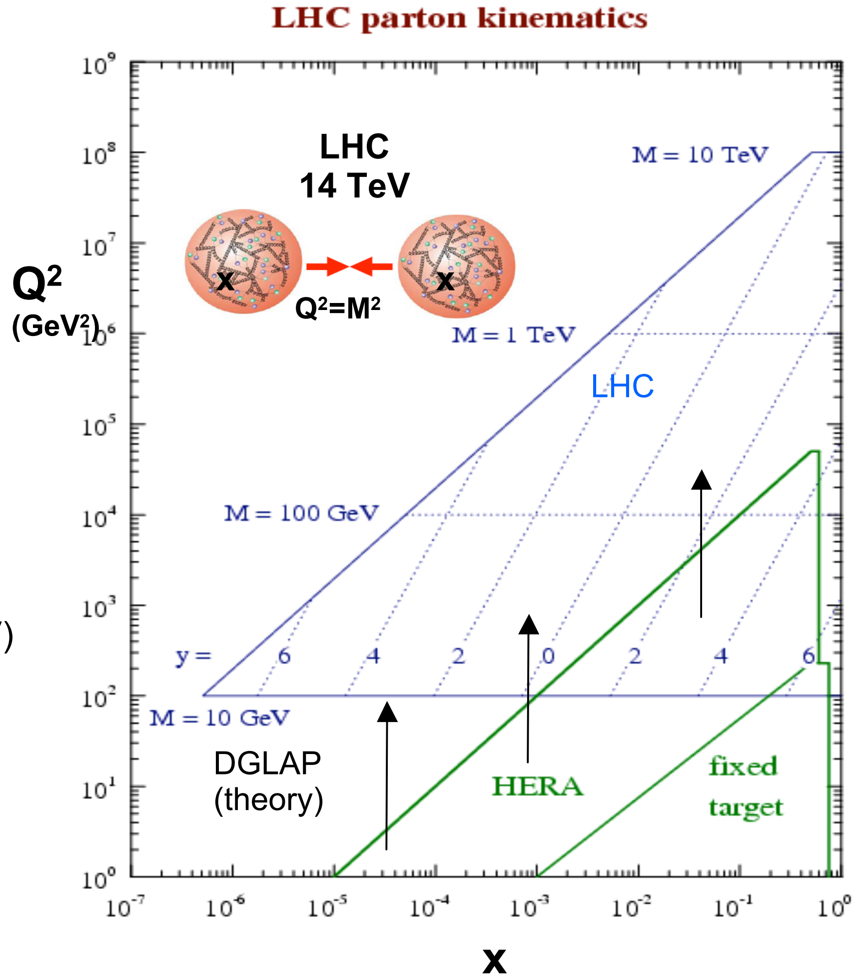
$$\tilde{\sigma}^{\pm}_{NC} = \frac{d^2\sigma^{e^{\pm}p}_{NC}}{dx\,dQ^2}\,\frac{xQ^4}{2\pi\alpha^2 Y_+}$$

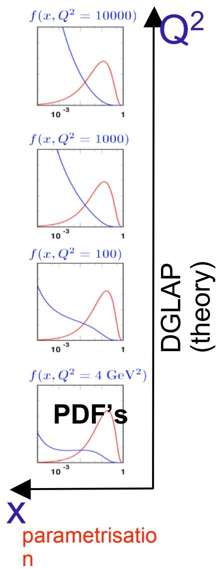
Precise data in the scaling violations regions (gluon)

Coherent data sets combined: vast coverage of the proton “map”

Dramatic increase in precision

HERA and LHC





Example

pp: W (at rest) corresponds to

$Q^2=M_W^2=6400\ GeV^2$

x=0.2 for Tevatron (1.96 TeV)

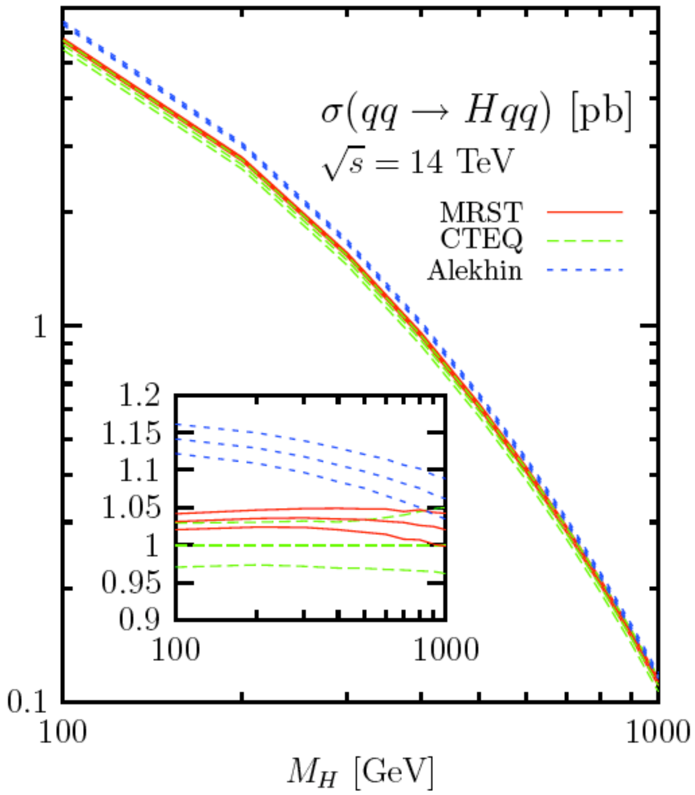
x=0.005 for LHC (14 TeV)

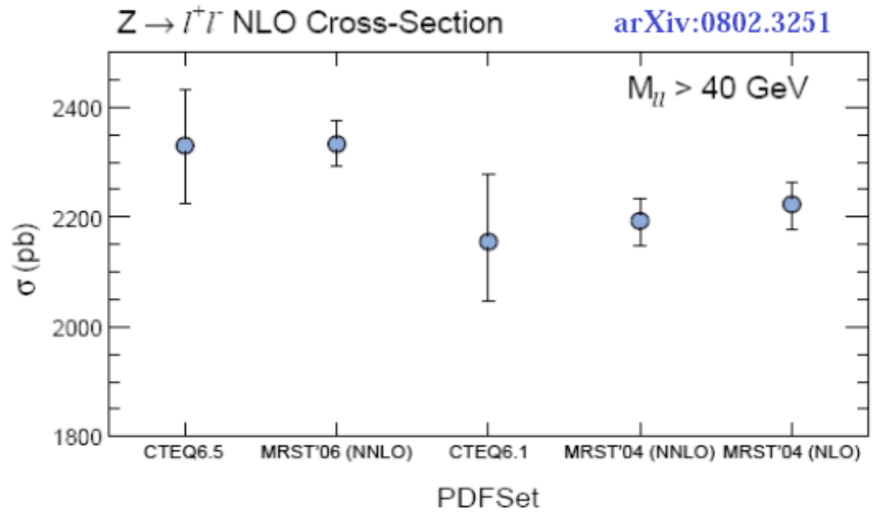
DIS data is the support for LHC predictions (beware the very low x!)

Precision in PDF's is mandatory for some areas of LHC physics

Predictions for LHC, some examples

N.Adam et al.
arXiv:0802.3251





Total Theoretical Uncertainty (%)

Uncertainty	Cross-Section $\Delta\sigma$	Acceptance ΔA
Missing $O(\alpha)$ EWK	0.38 ± 0.26	0.96 ± 0.21
Total QCD Uncertainty	1.51 ± 0.75	2.55 ± 0.79
PDF Uncertainty	3.79	1.32
Total Uncertainty	4.1 ± 0.3	3.0 ± 0.7

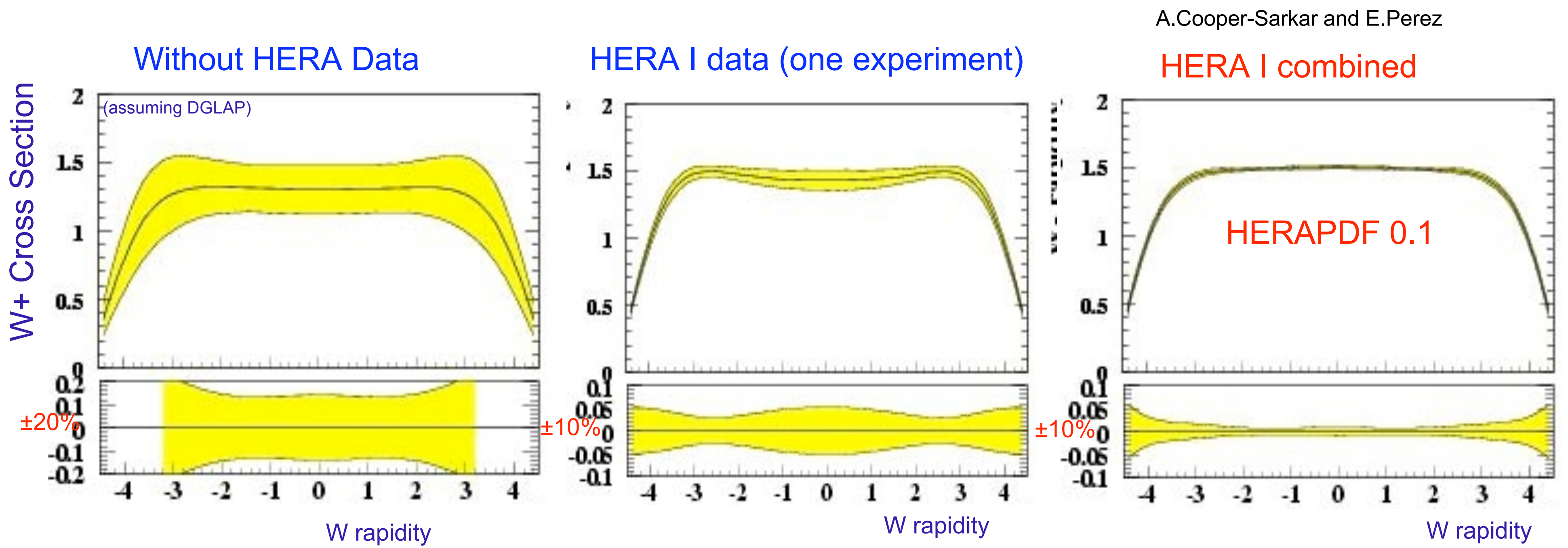
Various fits give incompatible results

PDF error dominant for some standard signals

The variations in the P_T spectra due to PDF's can be limiting factor for non-resonant searches

More precise data for PDF's is the best medicine

Example: W boson production at LHC



Only the fit uncertainty shown here, no model variations

The step in experimental precision is significant ~2%

More data to be included:

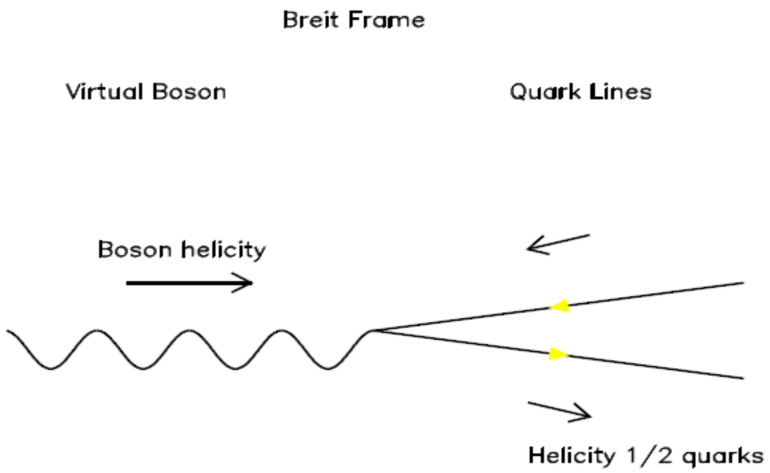
HERA II data high x/Q^2 => ultimate precision to be obtained

Longitudinal Structure Function F_L

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

$$R = \sigma_L/\sigma_T = (F_2 - 2xF_1)/2xF_1 = F_L/2xF_1$$

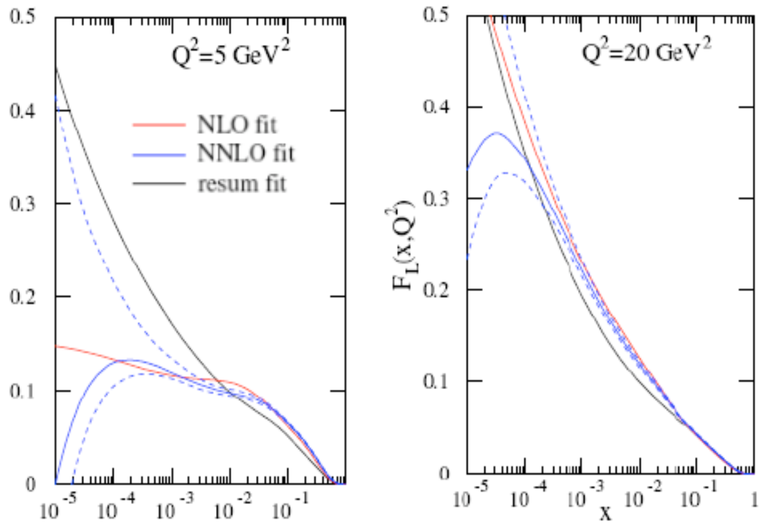
=0 for spin ½ partons in QPM
(Callan-Gross)



$$F_L(x,Q^2) \sim \alpha_s x g(x,Q^2)$$

Altarelli, Martinelli, 1978

Fundamental form factor of the proton
Proportional to the gluon, important for PDF's
Discriminate between theoretical approaches



R.Thorne, DIS08

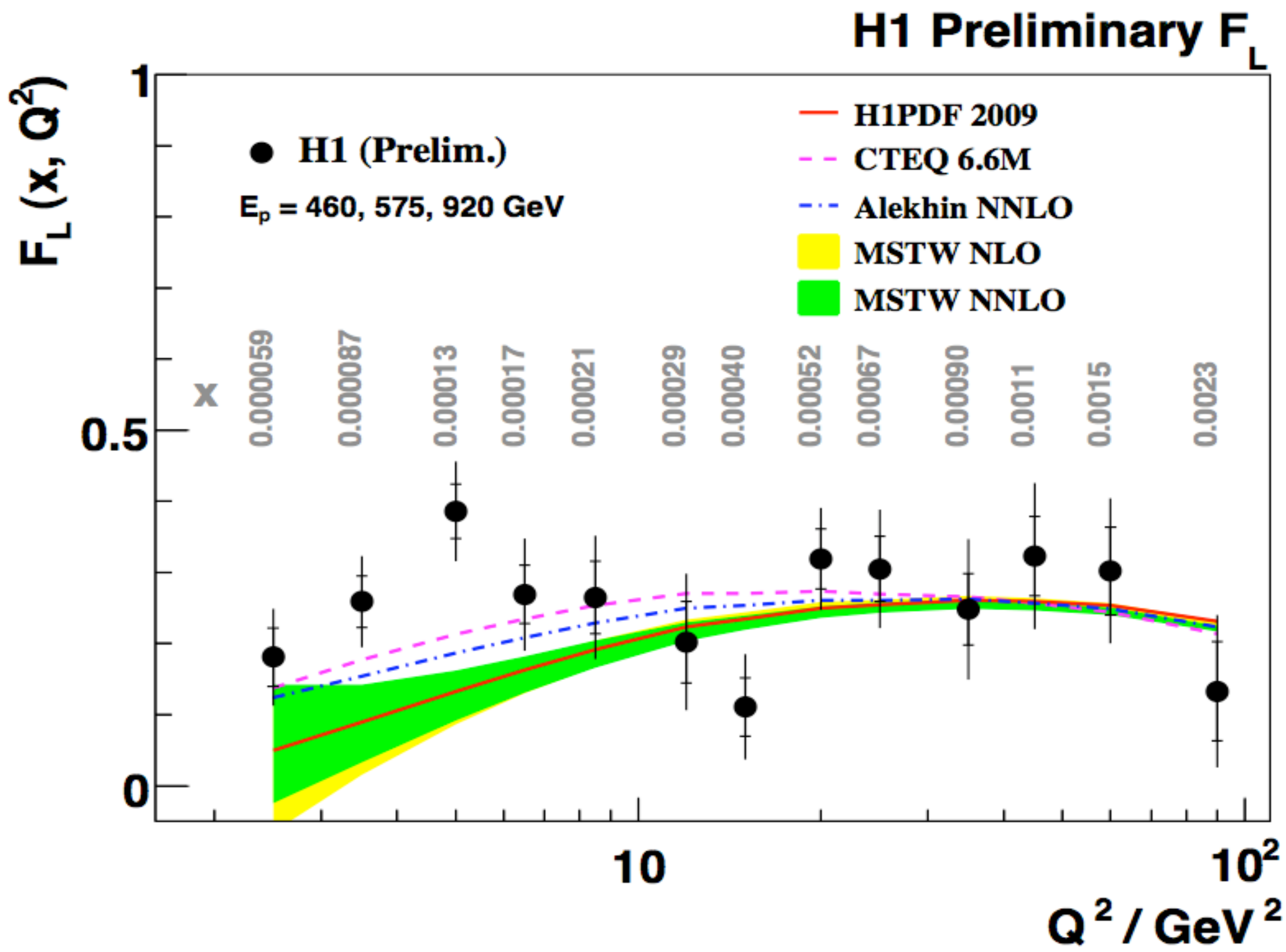
Experimental Method:

keep x,Q^2 constant, vary y: $ys=y's'=Q^2/x$

Vary s : Special Runs E_p=460,575 GeV

$$F_L \sim C(y) * (\sigma(E_p^1) - \sigma(E_p^2))$$

F_L averaged in each Q^2 bin



Work ongoing to extend to lower Q^2/x: test QCD, constrain gluon

Let the electroweak force be with you : xF_3

$$\tilde{\sigma}^{\pm}_{NC} = \tilde{F}_2 - \frac{y^2}{Y_+}\tilde{F}_L \mp \frac{Y_-}{Y_+}x\tilde{F}_3$$

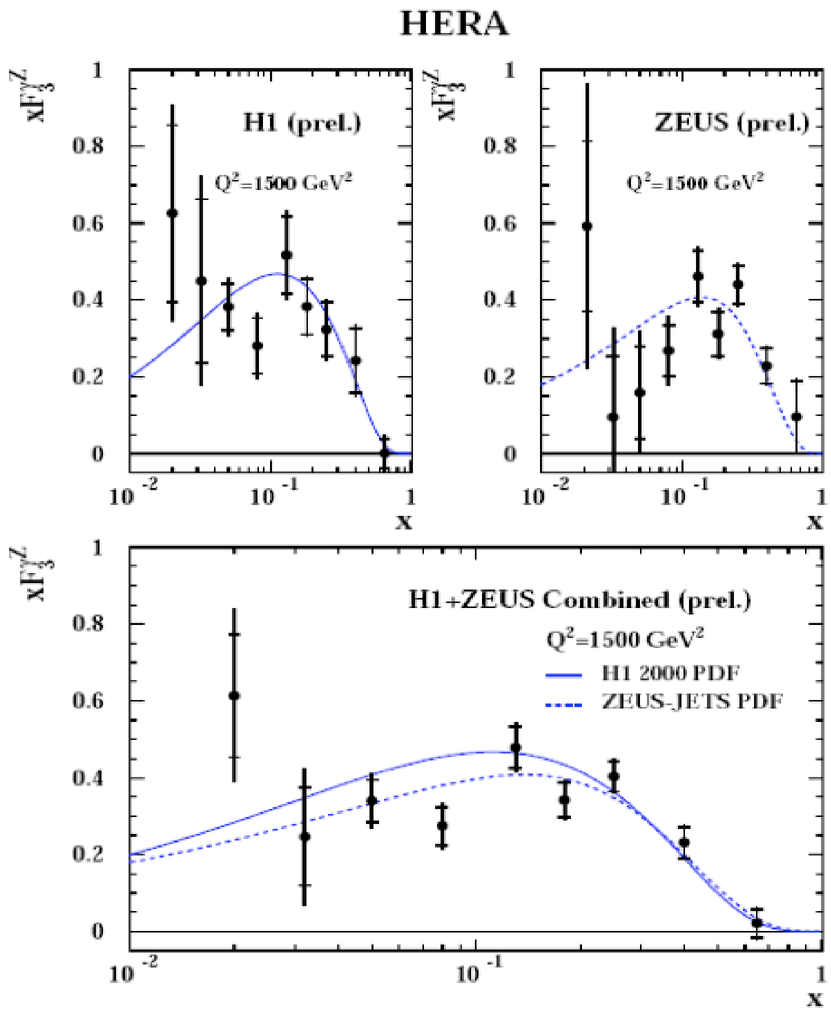
From (net) unpolarized $e^{\pm}p$ NC cross sections the structure function $x\tilde{F}_3$ is determined

$$x\tilde{F}_3 = -\frac{Y_+}{2Y_-}\left(\tilde{\sigma}^{+}_{NC} - \tilde{\sigma}^{-}_{NC}\right)$$

γZ interference dominates $x\tilde{F}_3$, sensitive to the valence quarks and only weakly Q^2 dependent

$$xF_3^{\gamma Z} = \frac{x}{3}(2u_v + d_v + \Delta)$$

$$\Delta = 2(u_{sea} - \bar{u} + c - \bar{c}) + (d_{sea} - \bar{d} + s - \bar{s})$$



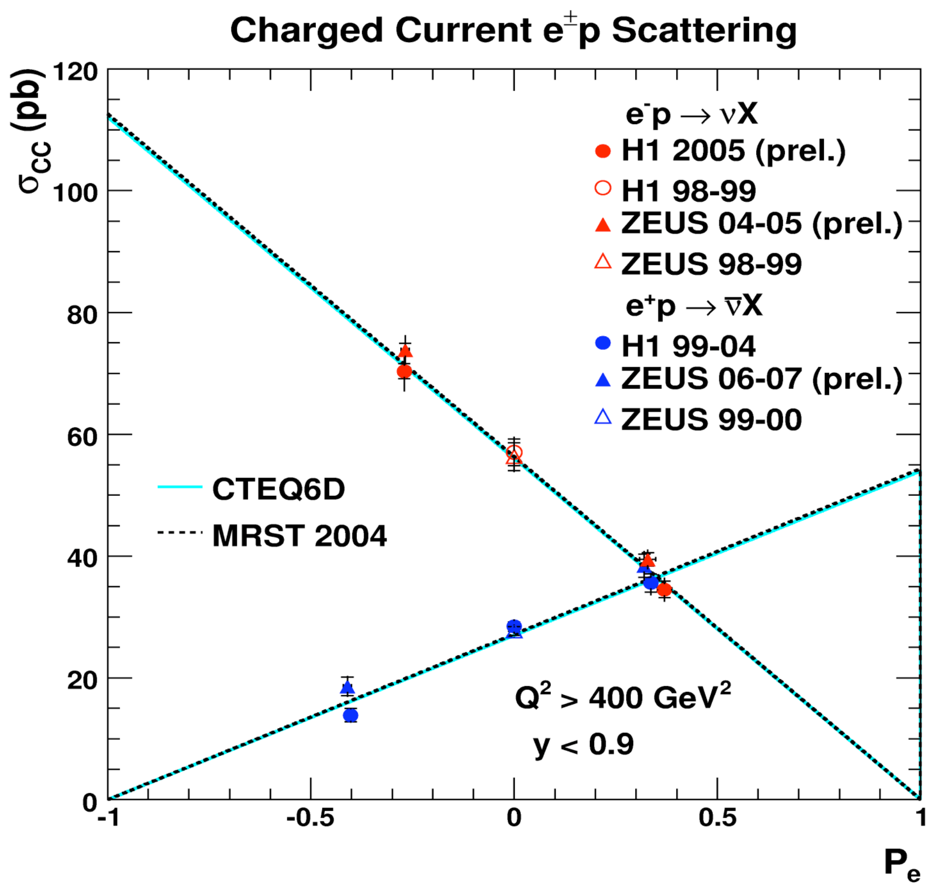
HERA II results with polarized beams

HERA can run with $e^{\pm}$
and both e-beam polarisations (P=0.25-0.4)

$$\sigma^{e^{\pm}p}(P) = (1 \pm P)\,\sigma^{e^{\pm}p}_{P=0}$$

CC: linear dependence established in DIS at HERA

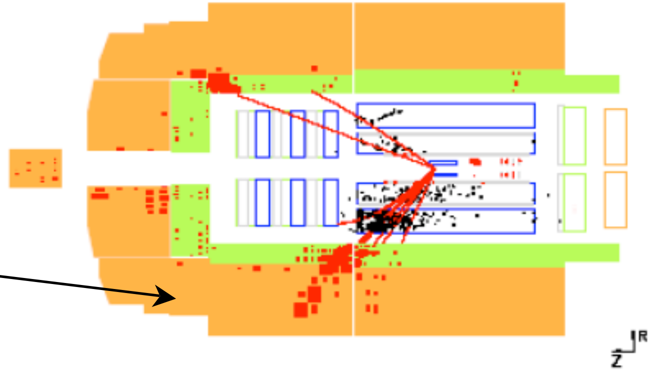
Compatible with V-A structure (no RH currents)



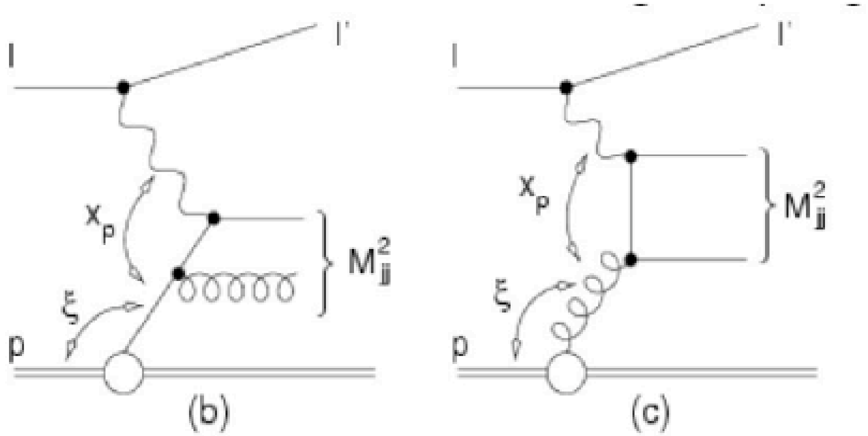
CHARM (1979):
$\nu_{\mu} N \rightarrow \mu X$

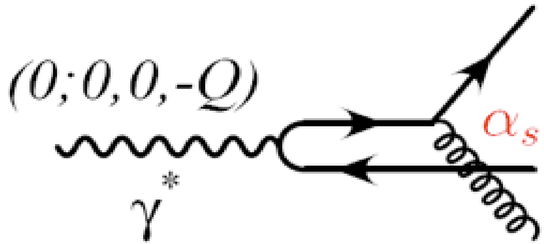
It may be concluded that positive muons produced by interactions of high-energy antineutrinos with nuclei have a longitudinal polarization oriented along their momentum direction. Within the experimental errors the helicity is found to be +1, consistent with a purely V, A form of the interaction. An upper limit

Proton as a laboratory for the strong force



Investigate the
Hadronic Final State

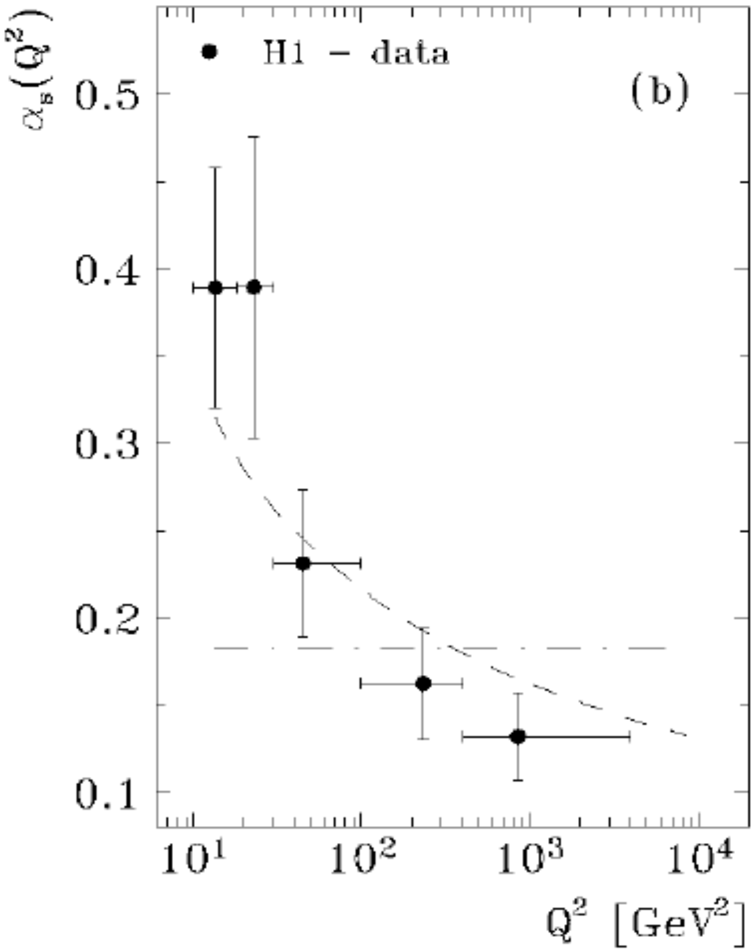




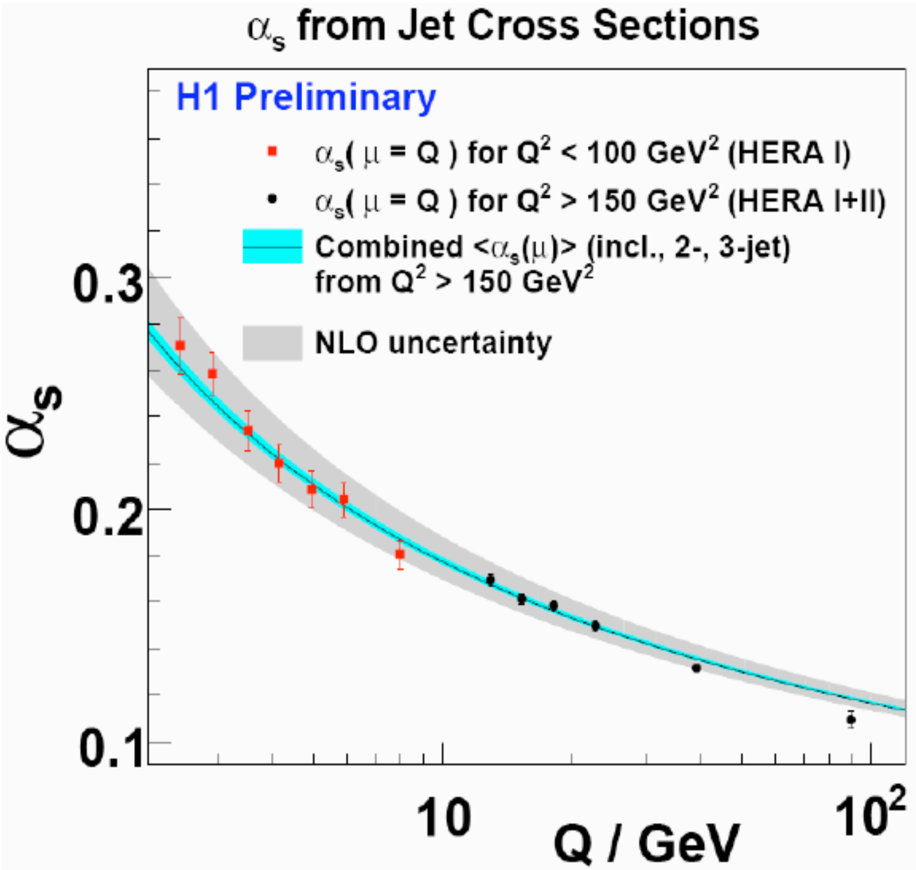
Jet production probe:
- -the strong coupling
- -gluon density in the proton

Running of the strong coupling

1994

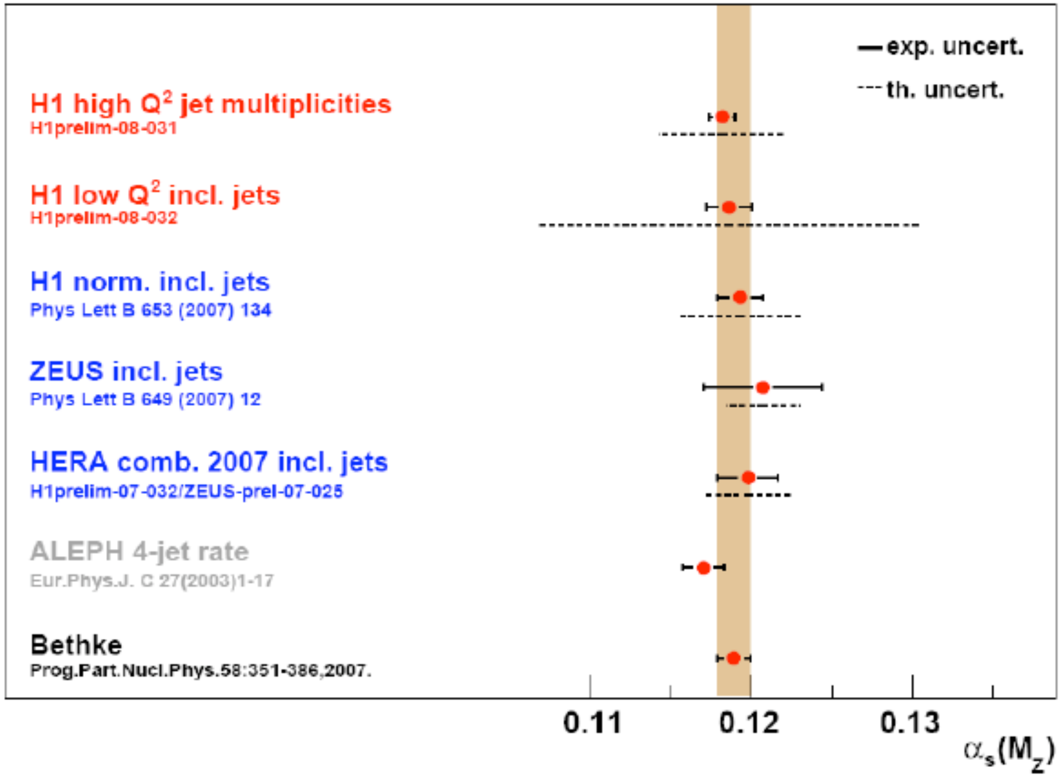


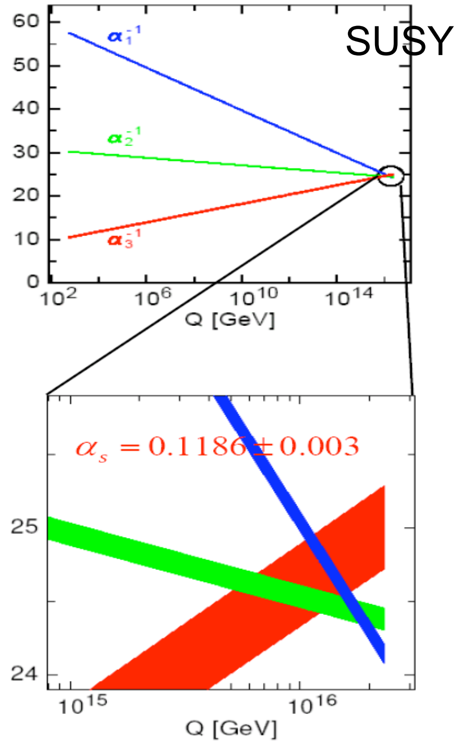
$$\alpha_s(Q_2) = \frac{\alpha_s(\mu^2)}{1 + \beta(\alpha_s(\mu^2)) \log(Q^2/\mu^2)}$$



Uncertainty largely dominated by the theory !

Strong force measurement





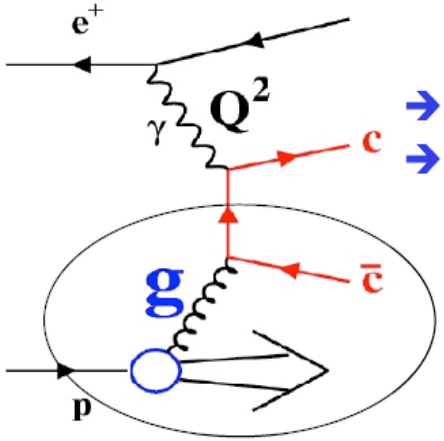
hep-ph/0407067 B.Allanach ... P.Zerwas

Present precision:
0.6% (exp) +3-4% theory

Fundamental Measurement: a bridge to the future
More data to come (combinations)

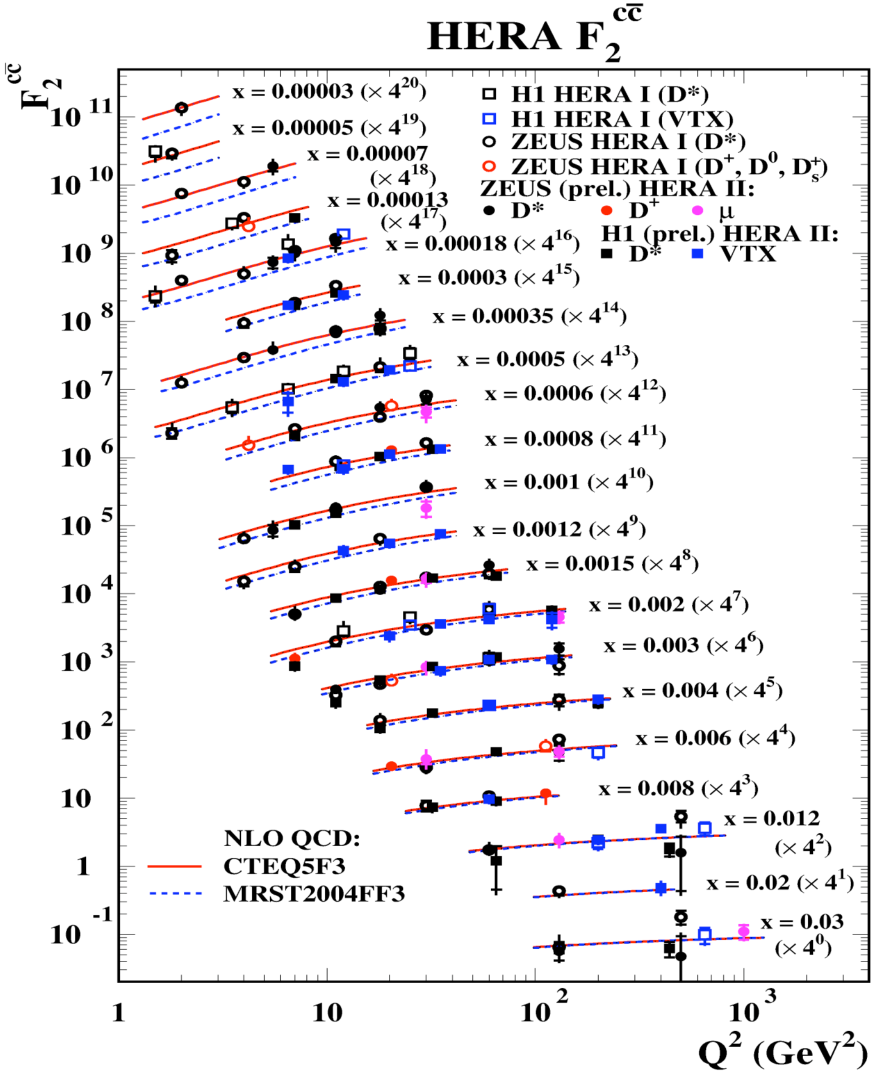
Proton's charm

The proton "contains" charm (1.6 GeV) and beauty (4.4 GeV) quarks



➔ D*, D+, etc.

➔ Displaced tracks



$$\sigma_r^{cc/bb} = F_2^{cc/bb} - y^2/Y_+ F_L^{cc/bb}$$

About 20% of the proton is charm

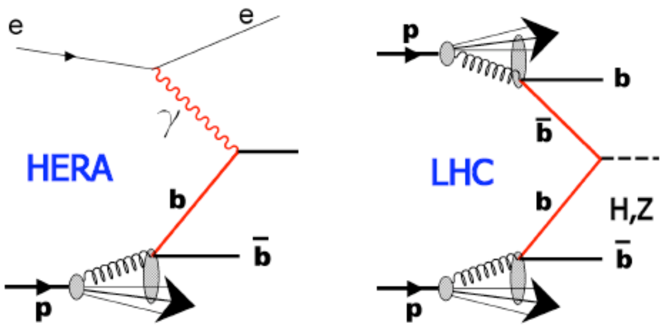
QCD tests

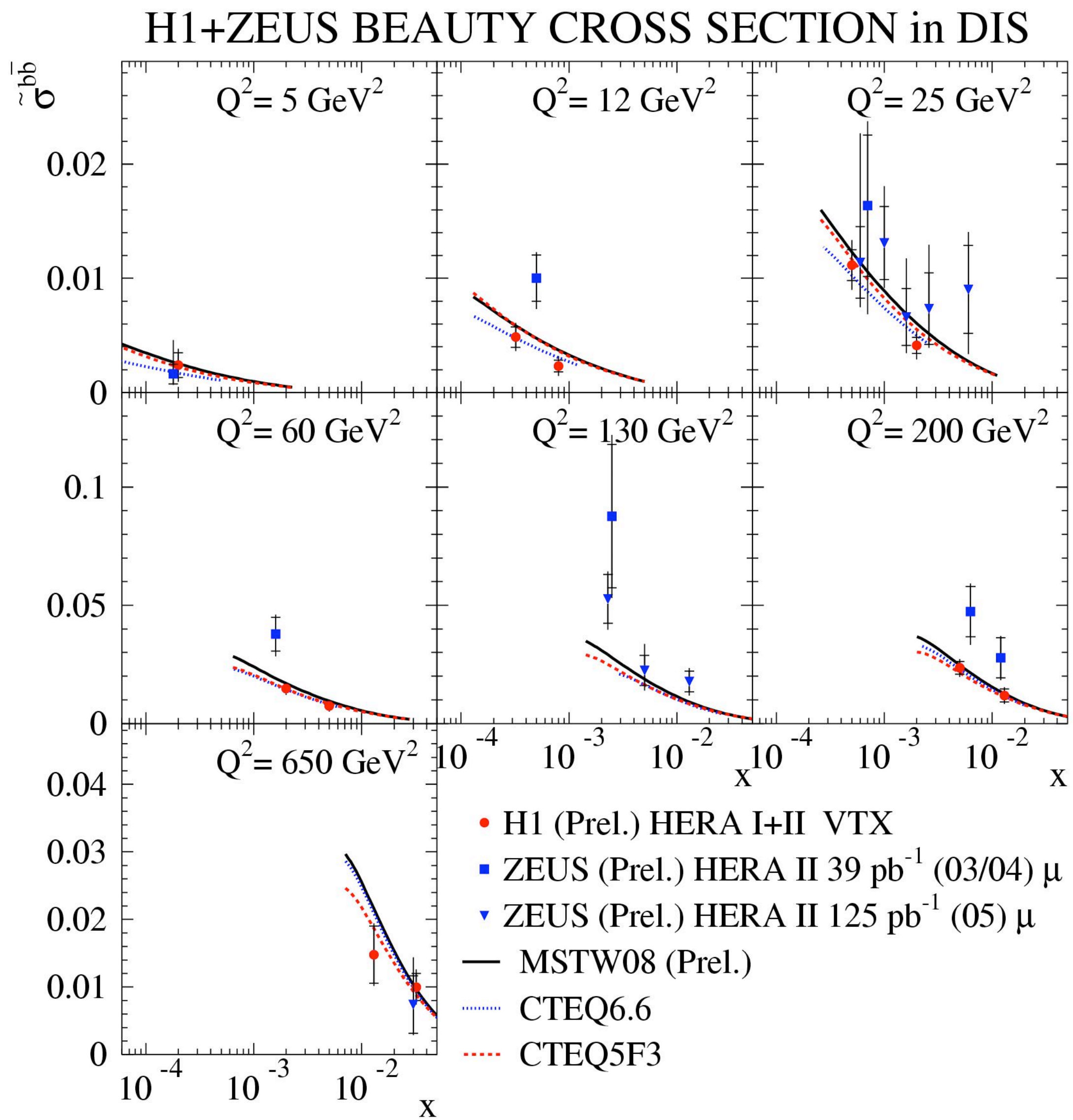
Further constraints on PDF's
gluon

Proton's beauty

About 1% of the proton is beauty

Flavour control in PDF is crucial
for some aspects of the LHC physics

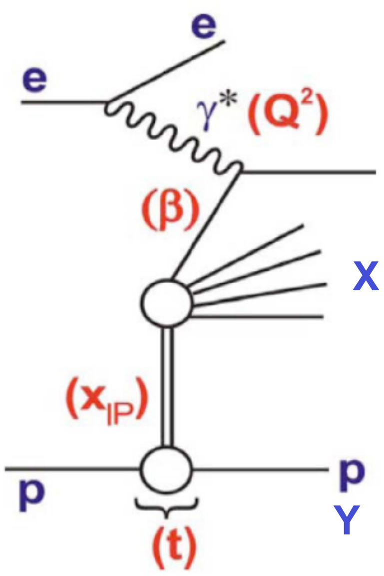




More data is available
for the final heavy flavour analyses

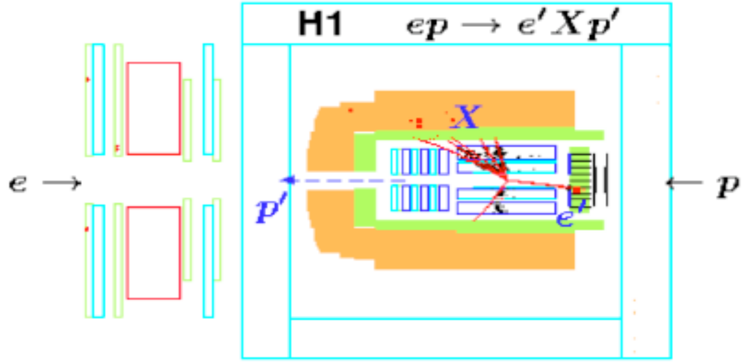
Hard Diffraction at HERA

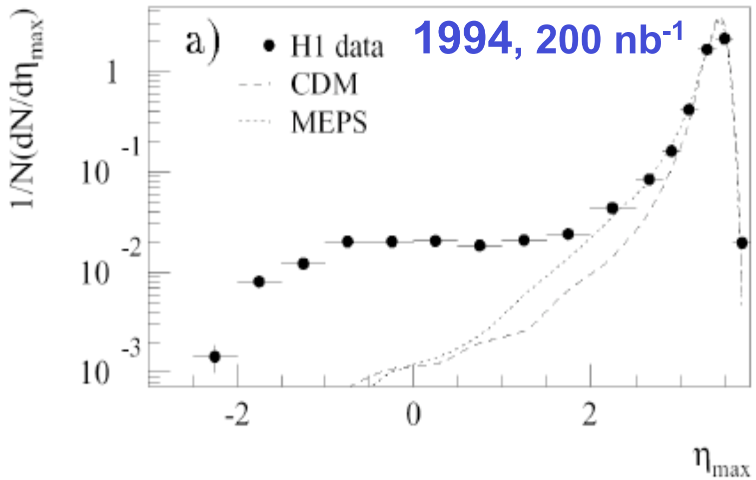
10% of DIS events are diffractive:
produced via an colourless exchange



empty rapidity region (gap)

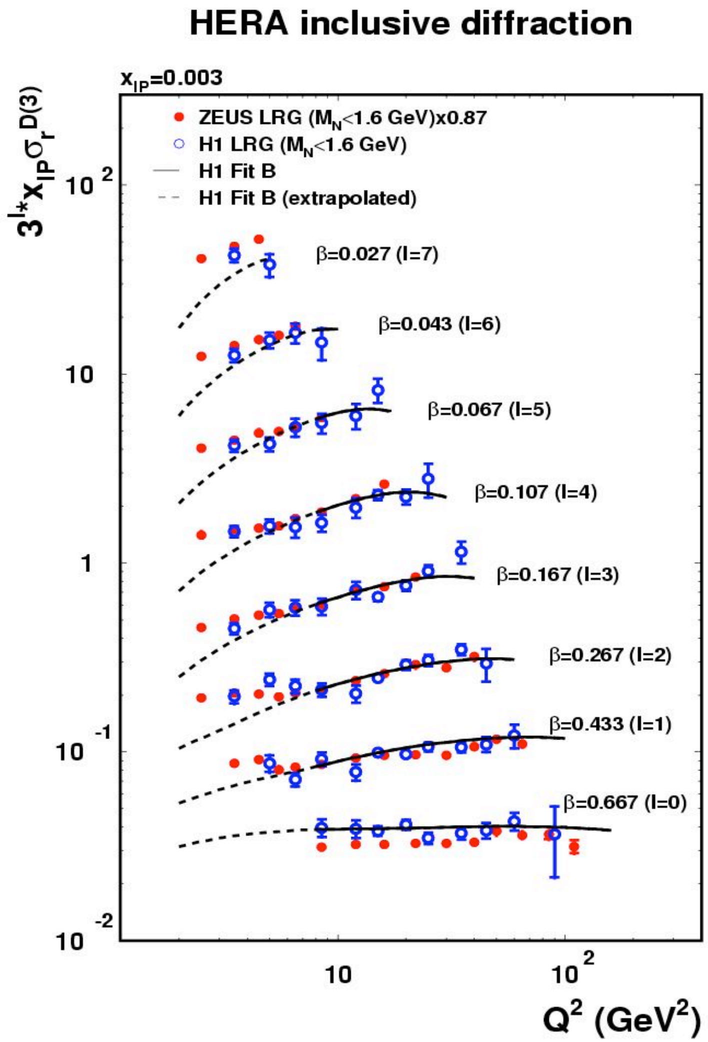
or intact proton detected
down the beampipe
(roman pots)



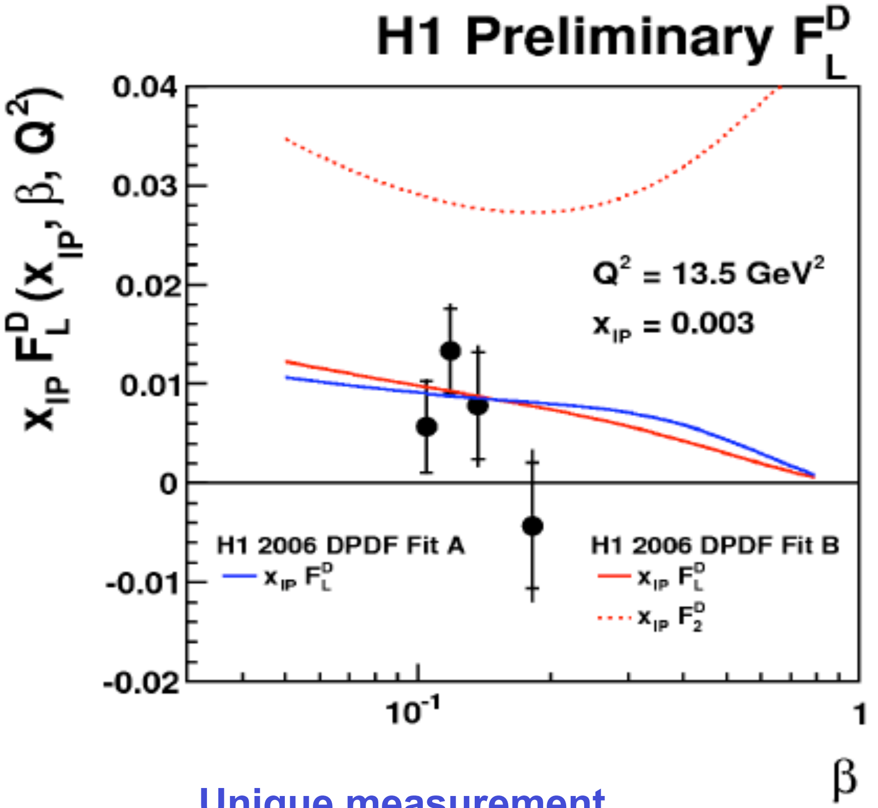


assume factorisation:
determine the structure of the diffractive exchange

“Diffractive” proton structure



$$\sigma_r^D \propto F_2^D - \frac{y^2}{1+(1-y)^2} F_L^D$$



Unique measurement,
in agreement with the theory

H1 and ZEUS corrected to the same phase space
Ready for combination,more data to come: constraint diffractive phenomena at LHC

HERA as collider at Fermi Scale

before LHC (pp, 14 TeV)

LEP

e $\quad\quad$ $\bar{p}$

e $\quad\quad$ p

TEVATRON

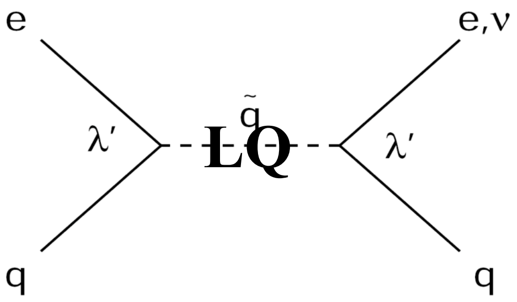
209 GeV

HERA

1.96 TeV

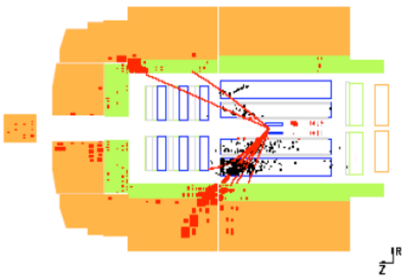
320 GeV

LeptoQuarks Searches

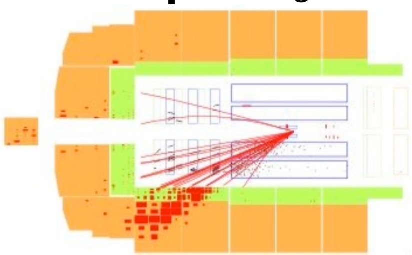


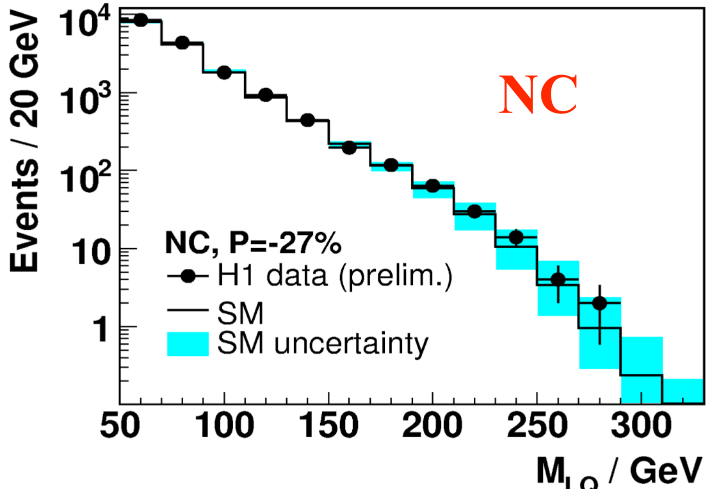
Lepton-jet resonance

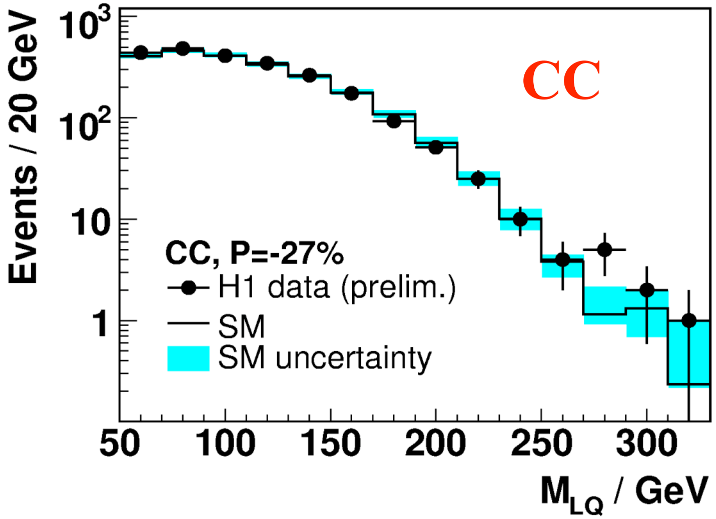
e+jet



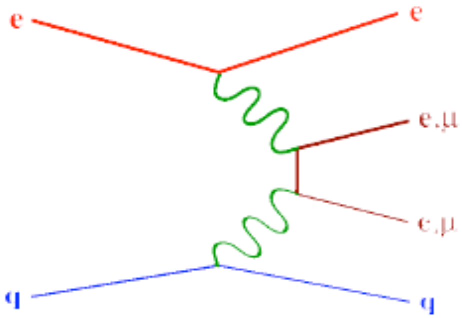
P_T^{miss}+jet

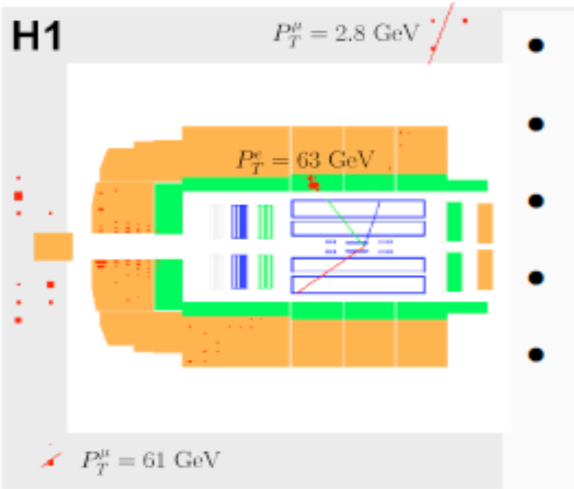






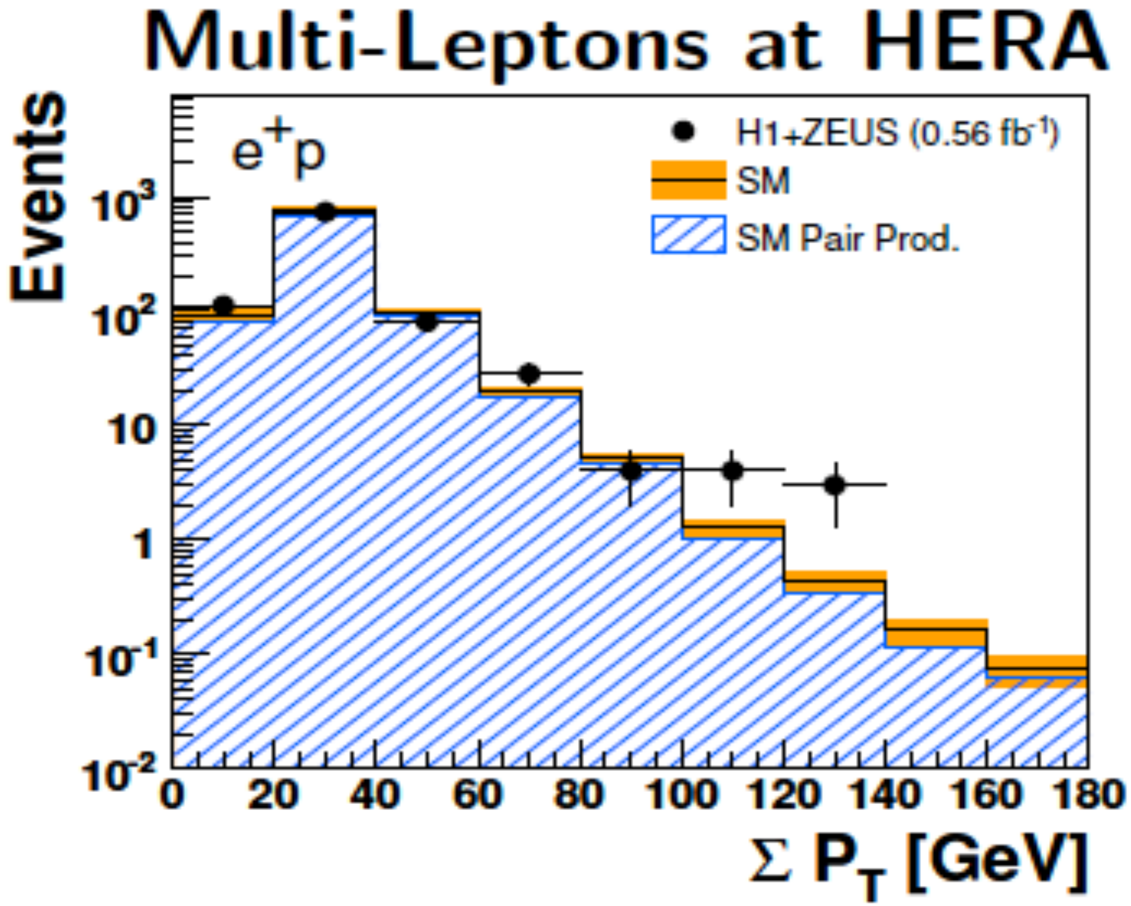
Multi-Leptons from ep collisions



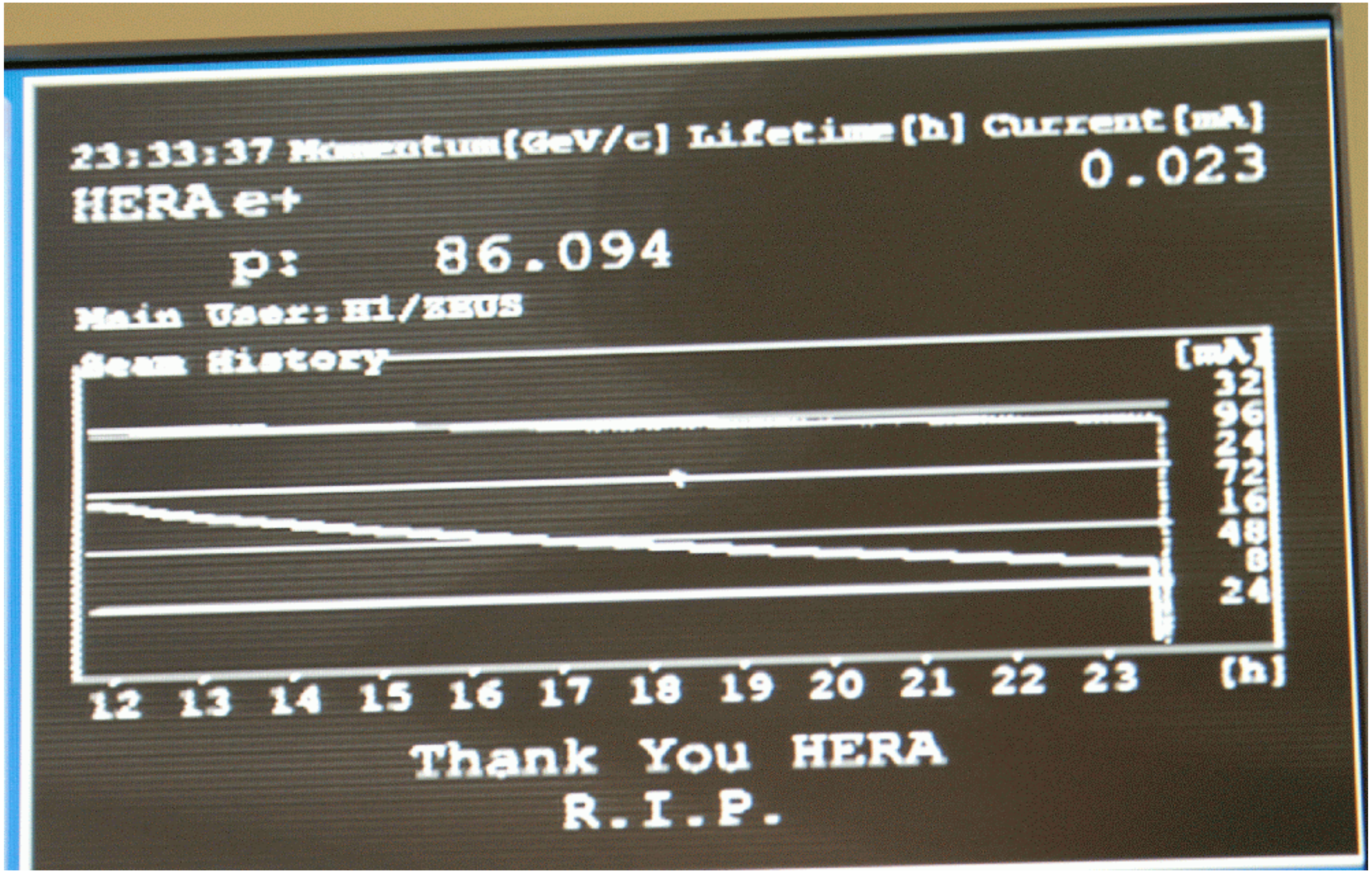


H1+ZEUS at $\Sigma P_T > 100$ GeV

	DATA	SM prediction	
e^+p	7	1.94 ± 0.17	2.6σ
e^-p	0	1.19 ± 0.12	



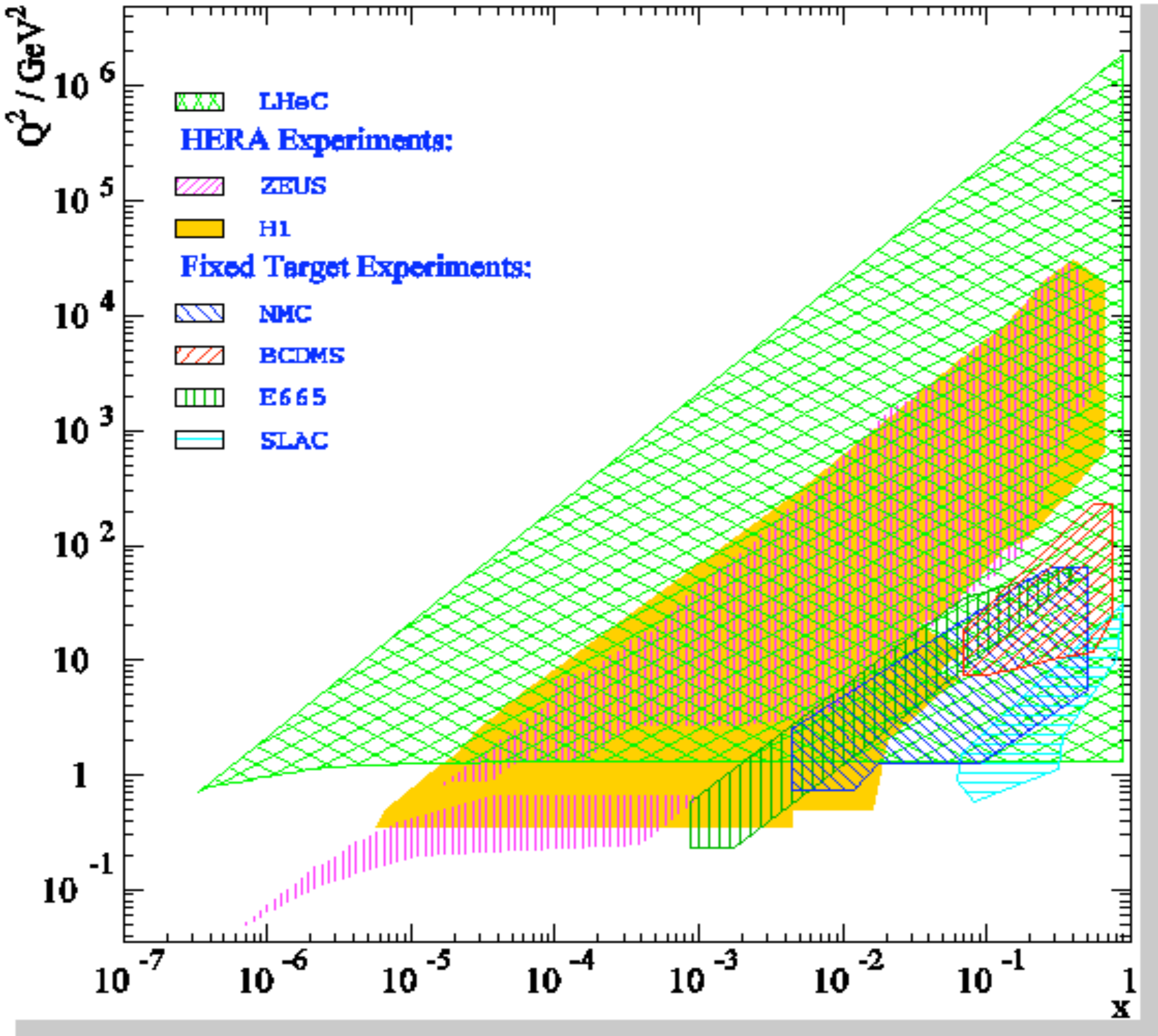
HERA end of run: June 30, 2007, 23h30



It will take a few more years to obtain the final precision

Next machine: LheC e(70 GeV) x p(7 TeV)

ECFA Project



Conclusions

- **HERA was an unique collider at the energy frontier and a three decade endeavour with fundamental contributions**
  - **Proton structure measurements over an large phase space and with 1% precision**
  - **Decisive tests of the QCD in all regimes**
  - **Investigation of the energy frontier**
- **Data harvest is still under intense analysis**
  - **Will hand over the best possible physics outcome to LHC and beyond**

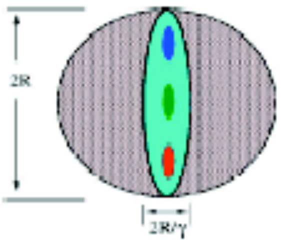
"…the search for ever-smaller and ever-more-fundamental particles will go on as Man retain the curiosity he has always demonstrated."
Hofstader, 1961

Backup

Gluon counting

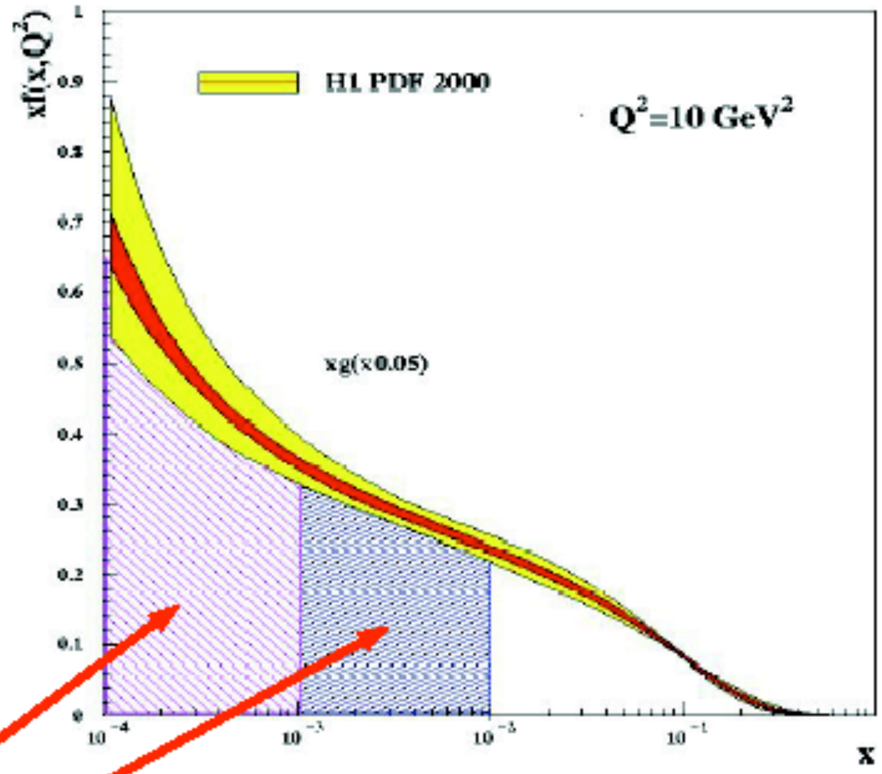
- number of gluons in long. phase space dx/x : $xg(x,\mu^2)dx/x$
- occupation area:
  nr of gluons x (trans size)²

$$g(x,\mu^2)\frac{1}{\mu^2}$$



- saturation starts when:

$$\frac{\alpha_s(\mu^2)}{\mu^2}xg(x,\mu^2)\frac{dx}{x} \geq \pi R^2$$



- gluon density is very large:~ 90 or 45 Gluons !!!!!
- with R ~ 1 GeV⁻¹ we obtain:

$$\frac{0.2}{10GeV^{-1}}100 \sim \pi$$

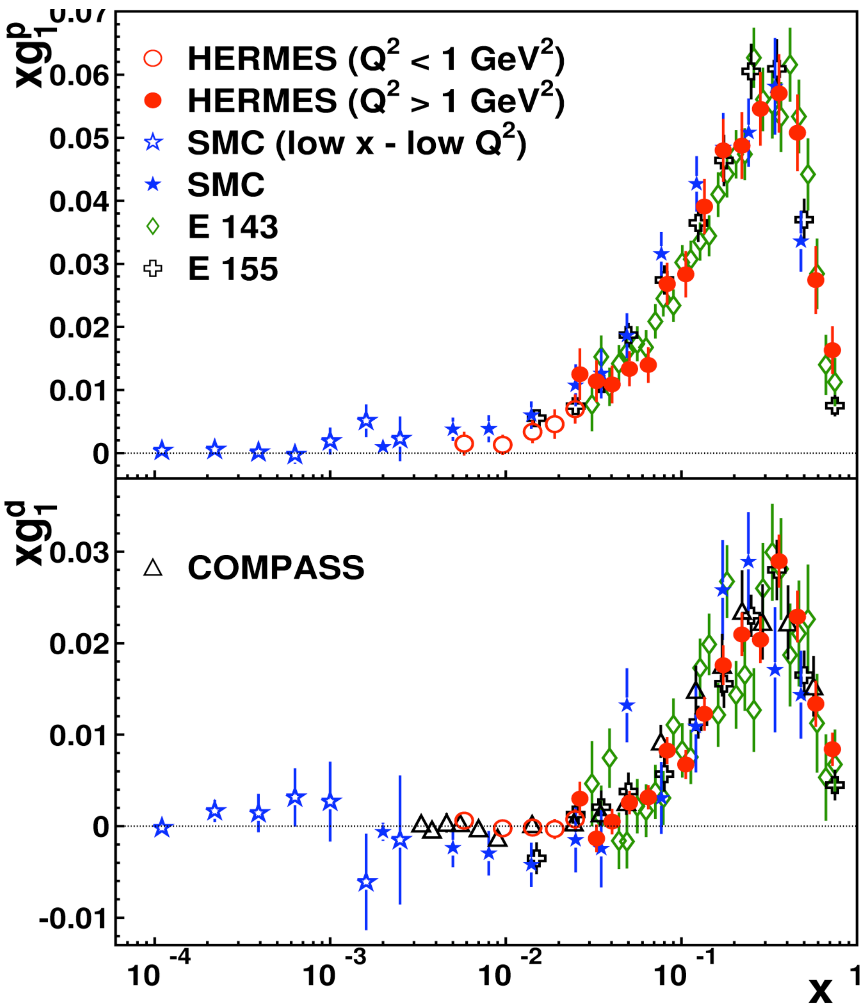
!!!!!

The spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_z^q + L_z^G$$

Polarised lepton beam, polarised (H,D,...) targets

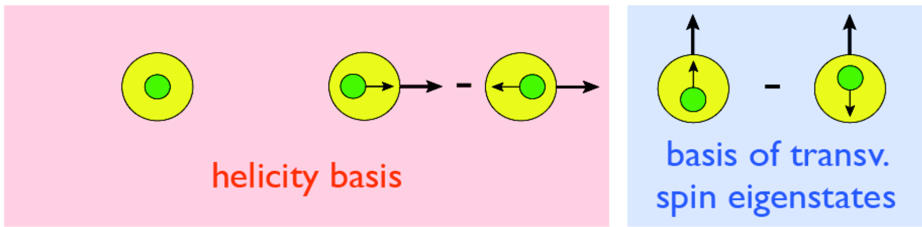
$$\sigma_{LL} \equiv \frac{1}{2}(\sigma^{\overleftarrow{\Leftarrow}} - \sigma^{\overrightarrow{\Rightarrow}})/2 \simeq g_1^{p,n}(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q^{p,n}(x,Q^2) + \Delta\bar{q}^{p,n}(x,Q^2)\right]$$



$$\Delta\Sigma \simeq 0.33$$

Use final states and angular distributions to further pin down the spin

momentum distribution	helicity distribution	transversity distribution
$q(x)$	$\Delta q(x)$	$\delta q(x) = h_1^q(x)$



all three DFs needed for complete description of the nucleon!

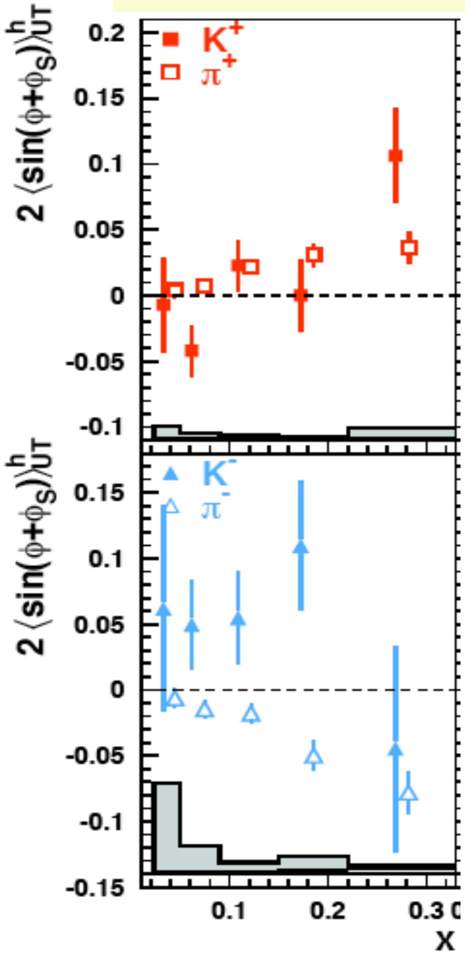
Level arm in Q^2 not large:
gluon contribution not constrained
=> semi-inclusive data

HERMES PRELIMINARY

Asymmetries

Collins

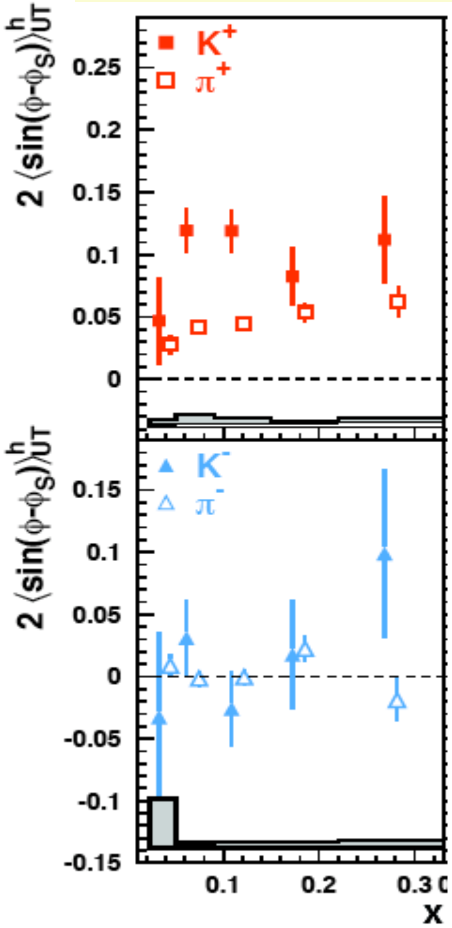
$$A_C \propto \delta q \otimes H_1^{\perp}$$



information from another process on Collins FF (BELLE) allows extraction of δq (eg Anselmino et al Phys.Rev.D75:054032,2007)

Sievers

$$A_S \propto f_{1T}^{\perp} \otimes D_1^q$$



describes correlation between intrinsic transverse quark momentum (p_T) and transverse nucleon spin

Implies non-zero angular momentum

Direct F_L measurement

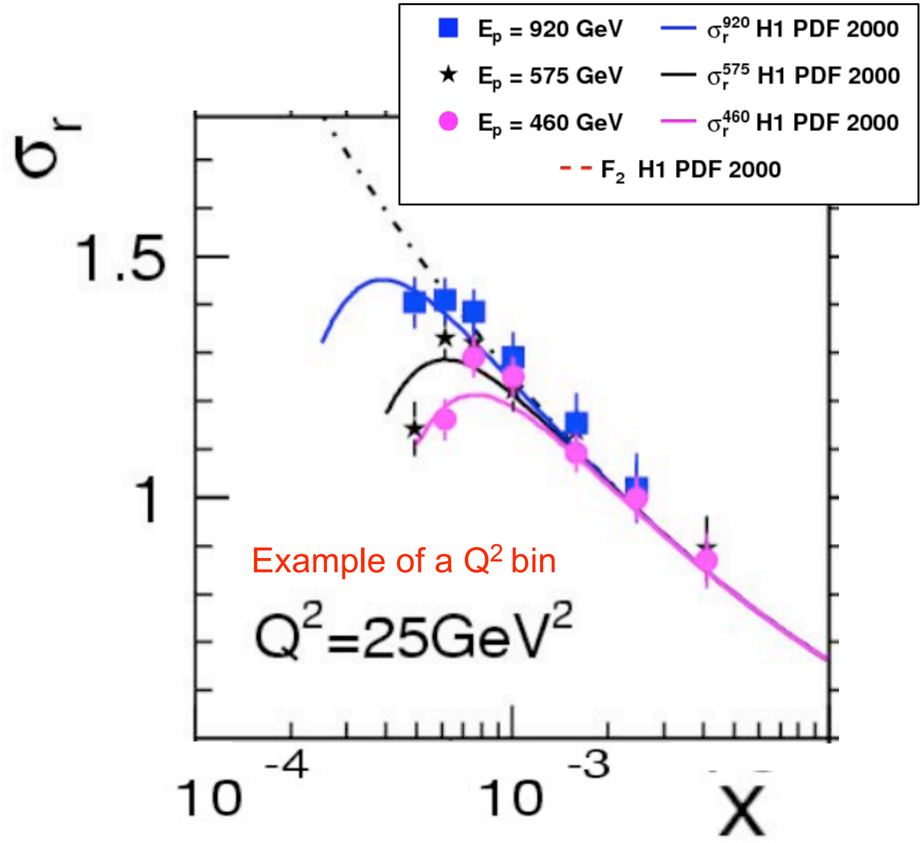
Method:

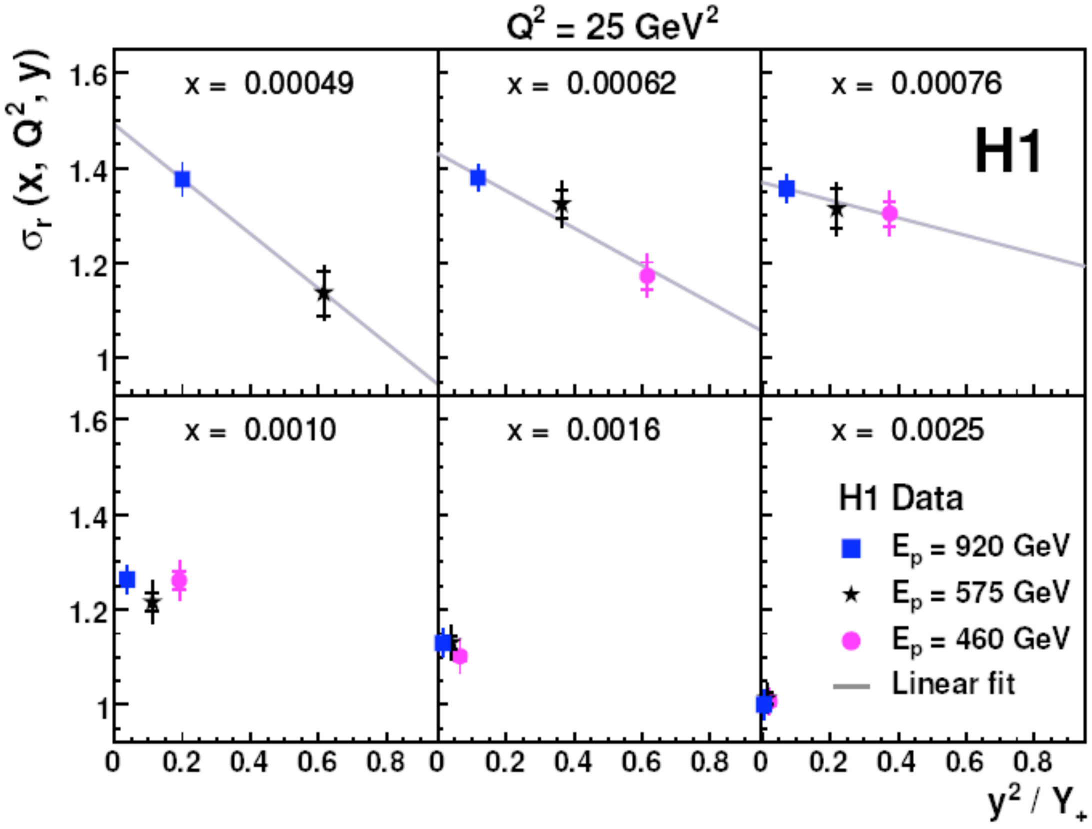
keep x, Q^2 constant, vary y: $ys = y's' = Q^2/x$

Vary s : Special Runs E_p=460,575 GeV

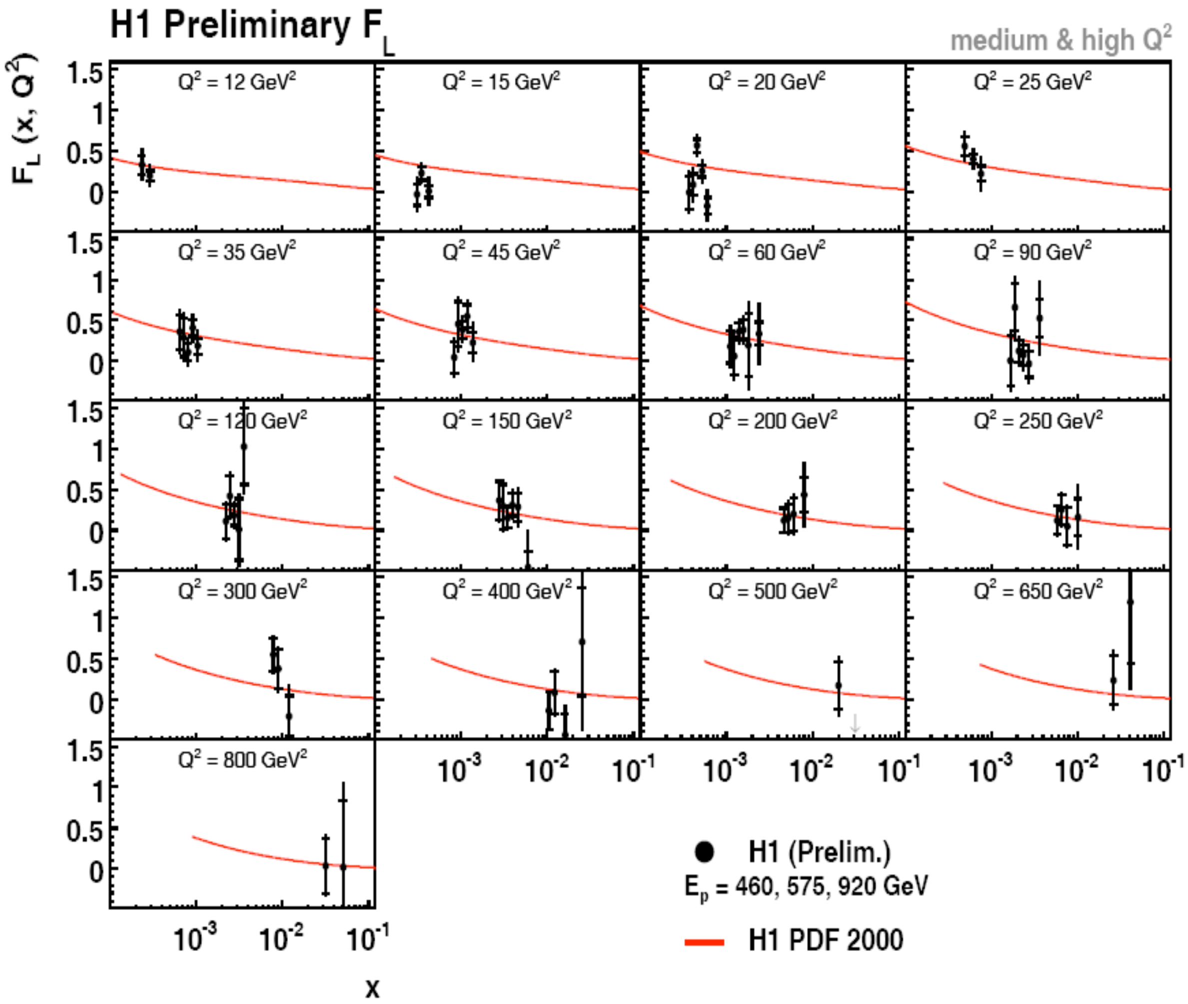
$$\sigma \sim F_2(x,Q^2) + f(y)\ F_L(x,Q^2)$$

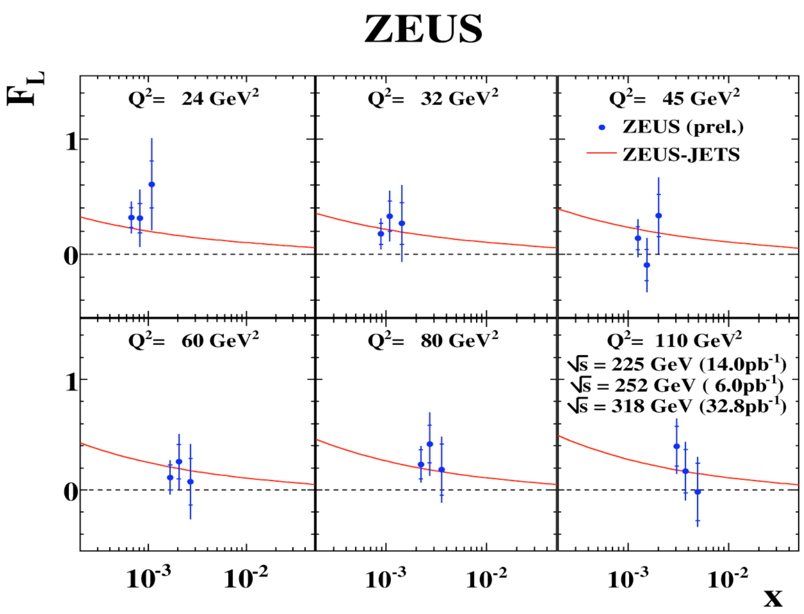
$$F_L \sim C(y) * (\sigma(E_p^1) - \sigma(E_p^2))$$





Direct F_L measurement





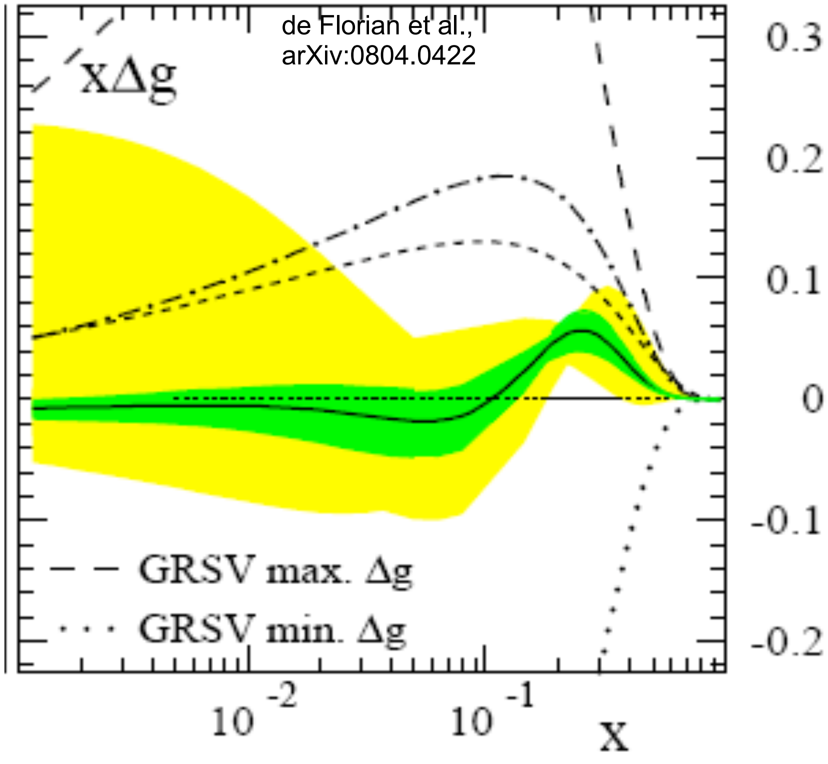
Measurements compatible with QCD predictions

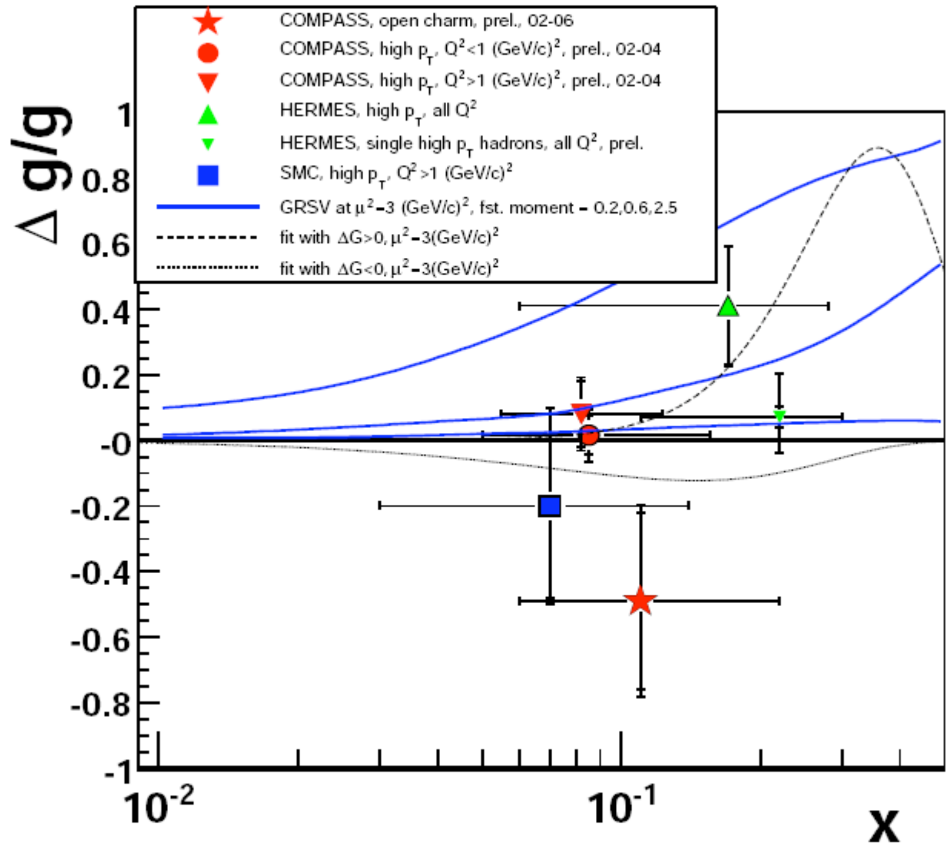
Gluon contribution to the spin

Understanding the gluon is crucial for the proton structure

Extracted via semi-inclusive processes: meson production in polarised DIS and pp (RHIC)

Global pol-analysis: extract polarised PDF's





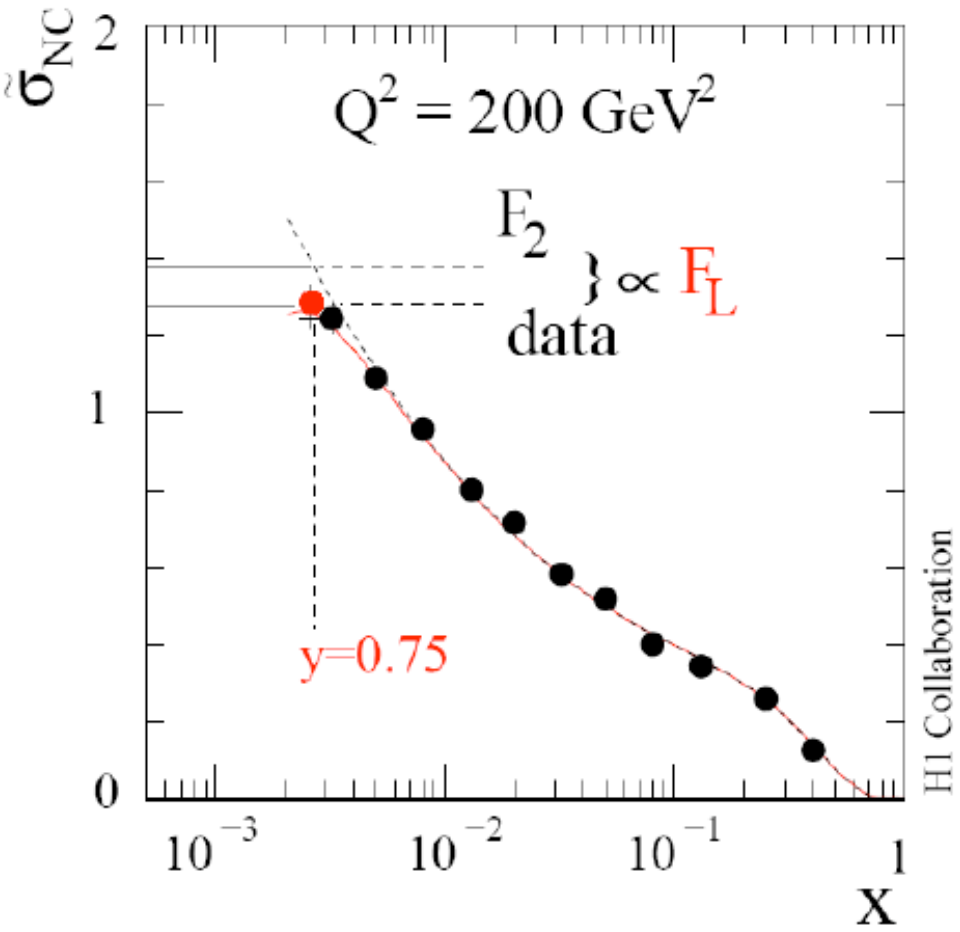
Extreme options now excluded
Extend x-range in pp at RHIC

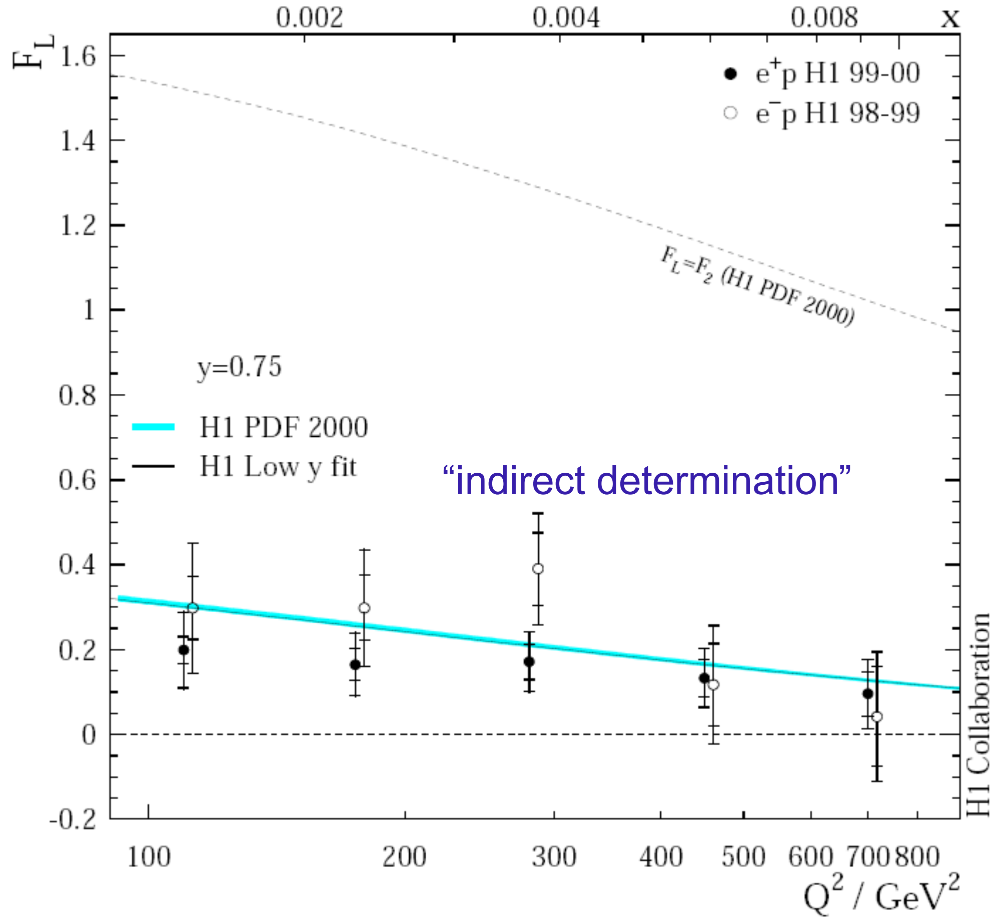
59

Indirect Determination

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

see bending at high y
assume F2 -> extract FL

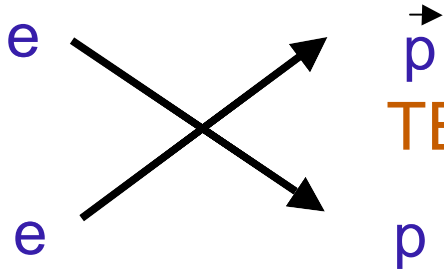




"indirect determination"

Colliders at Fermi Scale

LEP



TEVATRON

HERA

-> e+e- collider(2000)
E_{cm}=90-209 GeV
Lumi=900 pb-1/exp.(phys)
ALEPH,DELPHI
L3,OPAL

SLC: polarized e^+e^-
at Z peak

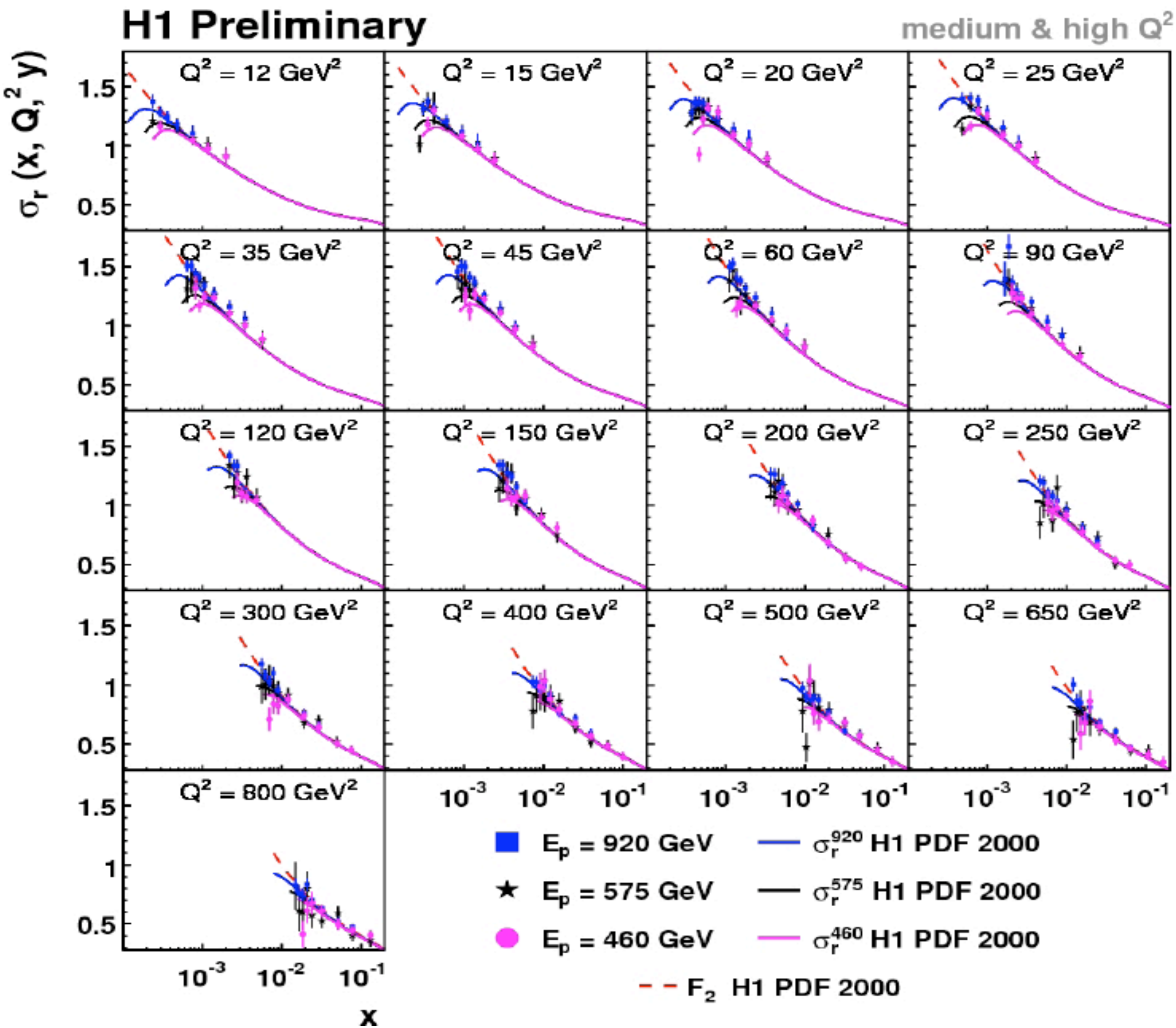
-> $e^{\pm}p$ collider
E_{cm}=320 GeV
H1, ZEUS
HERA I 120 pb-1/expt(phys.)
HERA II 2007 ->800 pb-1(delivered,$e^{\pm}$,$\pm P_e$)

-> $p\bar{p}$ collider: CDF, D0

Run I E_{cm}=1.8 TeV
130 pb^{-1}/exp.(phys.)

Run II E_{cm}=1.96 TeV

2011 -> 8-10 fb^{-1}



H1 Preliminary
medium & high Q²
σr (x, Q², y)
Q² = 12 GeV²
Q² = 15 GeV²
Q² = 20 GeV²
Q² = 25 GeV²
Q² = 35 GeV²
Q² = 45 GeV²
Q² = 60 GeV²
Q² = 90 GeV²
Q² = 120 GeV²
Q² = 150 GeV²
Q² = 200 GeV²
Q² = 250 GeV²
Q² = 300 GeV²
Q² = 400 GeV²
Q² = 500 GeV²
Q² = 650 GeV²
Q² = 800 GeV²
x
Ep = 920 GeV
Ep = 575 GeV
Ep = 460 GeV
σr920 H1 PDF 2000
σr575 H1 PDF 2000
σr460 H1 PDF 2000
F2 H1 PDF 2000

MSTW 2008 (input data)

Data set	$N_{\text{pts.}}$
H1 MB 99 e^+p NC	8
H1 MB 97 e^+p NC	64
H1 low Q^2 96–97 e^+p NC	80
H1 high Q^2 98–99 e^-p NC	126
H1 high Q^2 99–00 e^+p NC	147
ZEUS SVX 95 e^+p NC	30
ZEUS 96–97 e^+p NC	144
ZEUS 98–99 e^-p NC	92
ZEUS 99–00 e^+p NC	90
H1 99–00 e^+p CC	28
ZEUS 99–00 e^+p CC	30
H1/ZEUS $e^{\pm}p$ F_2^{charm}	83
H1 99–00 e^+p incl. jets	24
ZEUS 96–97 e^+p incl. jets	30
ZEUS 98–00 $e^{\pm}p$ incl. jets	30
DØ II $p\bar{p}$ incl. jets	110
CDF II $p\bar{p}$ incl. jets	76
CDF II $W \to l\nu$ asym.	22
DØ II $W \to l\nu$ asym.	10
DØ II Z rap.	28
CDF II Z rap.	29

Data set	$N_{\text{pts.}}$
BCDMS μp F_2	163
BCDMS μd F_2	151
NMC μp F_2	123
NMC μd F_2	123
NMC $\mu n/\mu p$	148
E665 μp F_2	53
E665 μd F_2	53
SLAC ep F_2	37
SLAC ed F_2	38
NMC/BCDMS/SLAC F_L	31
E866/NuSea pp DY	184
E866/NuSea pd/pp DY	15
NuTeV νN F_2	53
CHORUS νN F_2	42
NuTeV νN xF_3	45
CHORUS νN xF_3	33
CCFR $\nu N \to \mu\mu X$	86
NuTeV $\nu N \to \mu\mu X$	84
All data sets	**2743**

- Red = New w.r.t. MRST 2006 fit.

H1, ZEUS: $F_2^{e^{\pm}p}(x,Q^2)$
BCDMS: $F_2^{\mu p}(x,Q^2)$, $F_2^{\mu d}(x,Q^2)$
NMC: $F_2^{\mu p}(x,Q^2)$, $F_2^{\mu d}(x,Q^2)$, $\frac{F_2^{\mu n}(x,Q^2)}{F_2^{\mu p}(x,Q^2)}$
SLAC: $F_2^{\mu p}(x,Q^2)$, $F_2^{\mu d}(x,Q^2)$
E665: $F_2^{\mu p}(x,Q^2)$, $F_2^{\mu d}(x,Q^2)$
CCFR: $F_2^{\nu(\bar{\nu})p}(x,Q^2)$, $F_3^{\nu(\bar{\nu})p}(x,Q^2)$

$\Rightarrow$ q, $\bar{q}$ at all x; g at moderate and small x

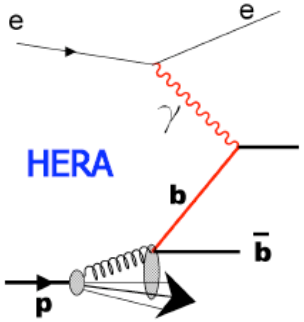
E605, E702, E866: $pN \to \mu\bar{\mu} + X$ $\Rightarrow$ $\bar{q}$, (g)
E605: Drell-Yan p, n asymmetry $\Rightarrow$ $\bar{u}$, $\bar{d}$
CDF: W rapidity asymmetry $\Rightarrow$ u/d ratio at high-x
CDF, D0: Inclusive jet data $\Rightarrow$ g at high-x
CCFR, NuTeV: Dimuon data $\Rightarrow$ s, $\bar{s}$ sea

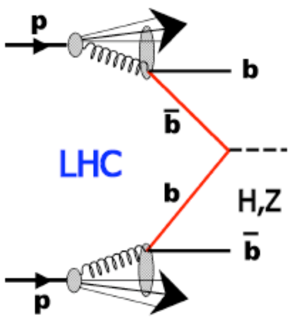
No prompt photon data are included in the fits nowadays

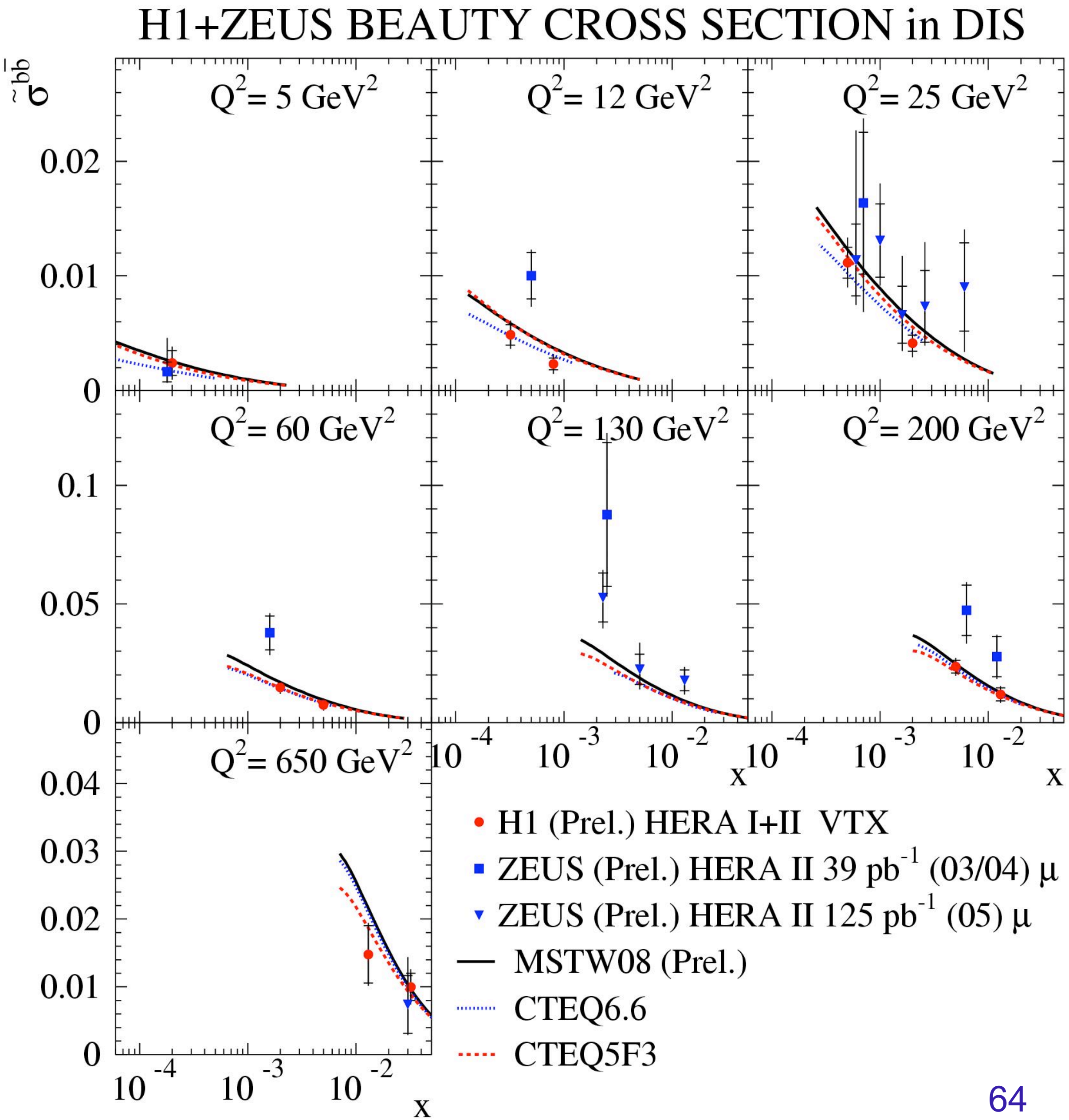
Proton's beauty

HERA II data with lifetime methods
More data available for ultimate precision

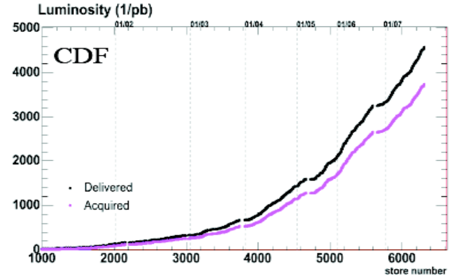
Flavour control in PDF is crucial
for some aspects of the LHC physics



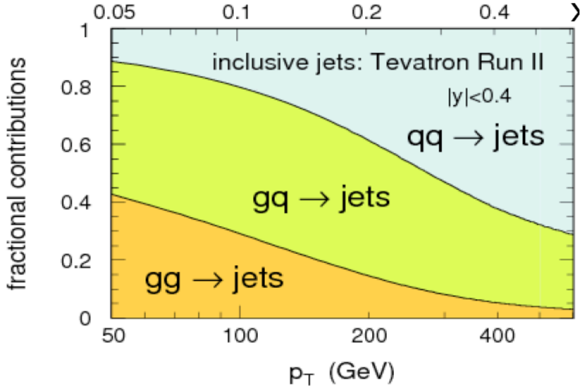




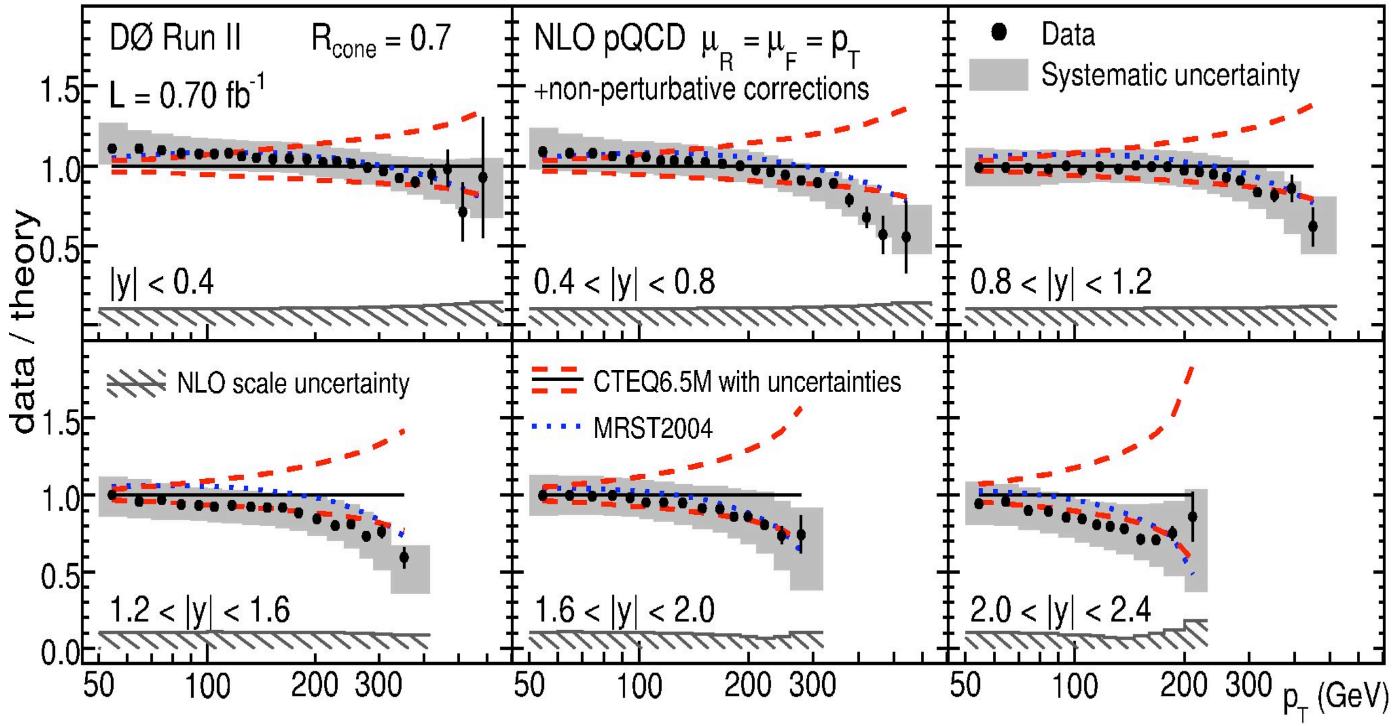
Jets production at Tevatron



xT = 2pT / sqrt(s)



Impressive achievement in energy scale control (1%)
Sensitive to gluon at high x
Precision with present global fits
(partially) Included in MSTW, more to come



Similar study by CDF
Consistent data
to be included in the fit

W asymmetry at Tevatron

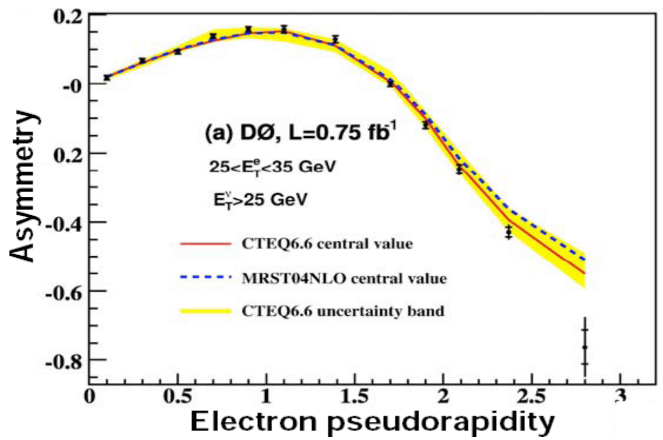
$Q^2 \approx M_W^2,\quad x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y_W}$

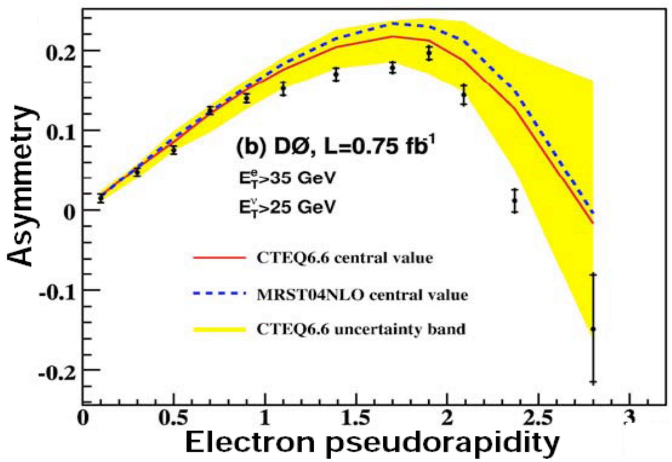
$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)}$$

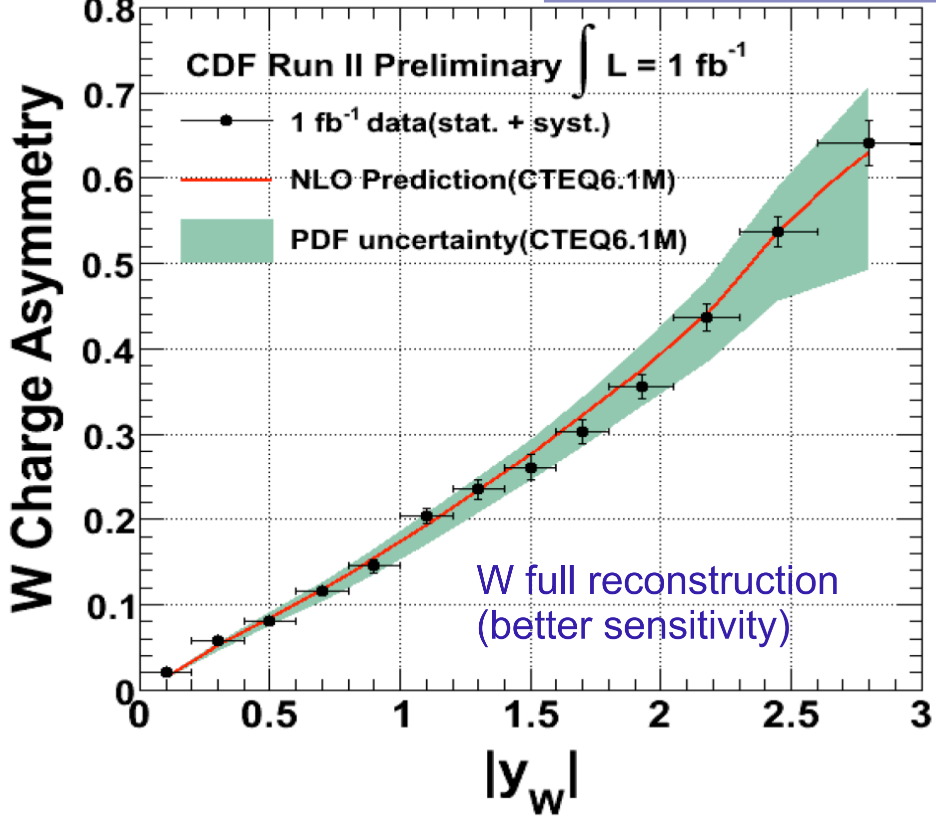
$$x_{1,2} = x_0 \exp(\pm y), \qquad x_0 = \frac{M_W}{\sqrt{s}}$$

New electron data, in ET bins

0.002 < x < 0.8 (1)







W full reconstruction
(better sensitivity)

Promising precision for u/d ratio at high x
Similar results for Z asymmetry

The data for PDF's

Process	Experiments	Constraints
DIS Collisions	H1,ZEUS	q,g
DIS Fixed Target	BCDMS, NMC,E665,SLAC	q,g
pp collision :jets, W/Z asym.	CDF,D0	g, u/d at high x
DIS neutrino-N	NuTev,Chorus,CCFR	q,g (s)
pp/pN Drell Yan	E605,E702, E866/NuSea	q,g

Global fits: determination of PDF's using the available data sets [Ex: MSTW08 2743 measurements]

MSTW, CTEQ, AKP, NNPDF (DIS data), HERAPDF (HERA averaged data, see later)

PDF4LHC: Common effort to converge on technical and physics issues

Difficult issues:

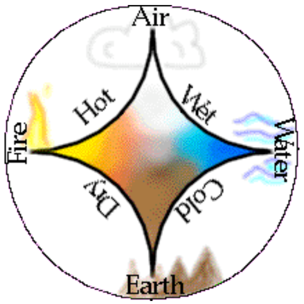
"model" uncertainties: parametrisation, flavour/sea-valence decompositions...

"unknown" systematics: "tensions" between data sets, tolerances

PDF errors determination

The (very) early days

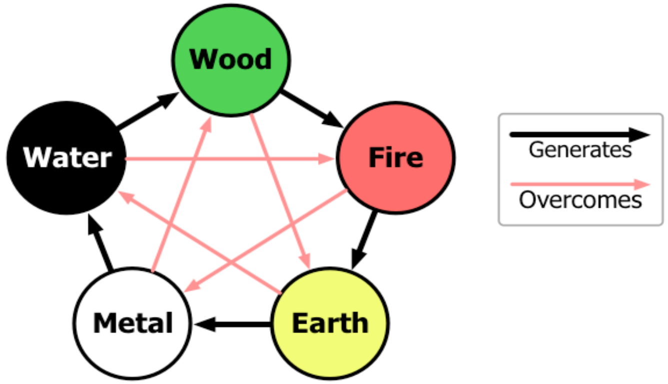
- Something must be fundamental, the 'bulding blocks'
- Models:
  - Aristotel, Heraclit et al., 4+1 elements “air,fire, water, earth”+quitessence



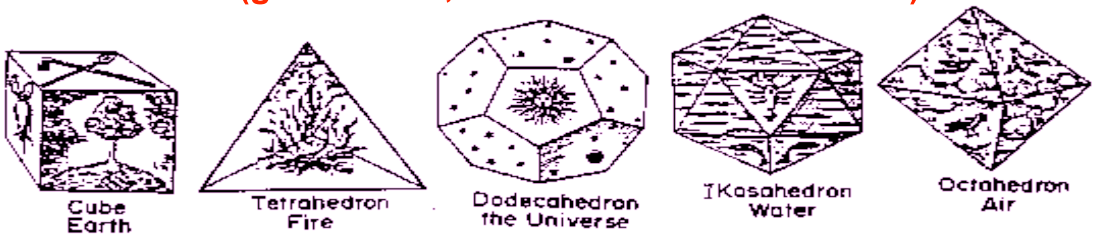
+

The 5th element

Asian version



  - **Plato's model (geometrical, mistic faith in mathematics)**

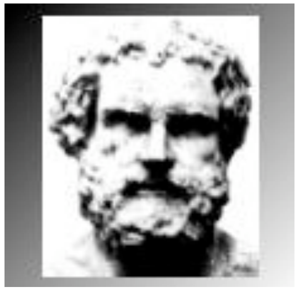


  - Leucipus, Democritos: “Elementary particles” =atoms+space

    By convention there is color, by convention sweetness,

    by convention bitterness, but in reality there are atoms and space.

    Democritus (400 BC)



Elements, elements....

- Lavoisier, Davy: show at least one of the 4/5 elements are composed, there are chemical elements
- composed of “atoms”
- Mendeleev: tabulate the ~50 elements discovered by ~1850
  - chemical properties repeat
  - able to predict new elements
    - ==>>substructure!

Property	Ekasilicon	Germanium
atomic mass	72	72.59
density (g/cm^3)	5.5	5.35
melting point (°C)	high	947
color	gray	gray
oxide type	refractory dioxide	refractory dioxi
oxide density (g/cm^3)	4.7	4.7
oxide activity	feebly basic	feebly basic
chloride boils	under 100°C	86°C ($GeCl_4$)

On the Relationship of the Properties of the Elements to their Atomic Weights

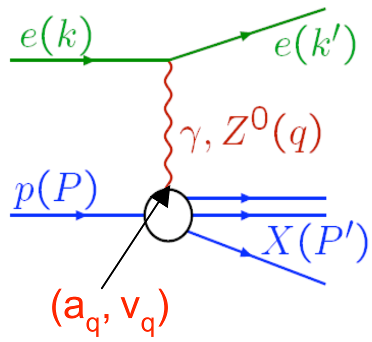
D. Mendelejeff, *Zeitscrift für Chemie* **12**, 405-406 (1869):

Ueber die Beziehungen der Eigenschaften zu den Atomgewichten der Elemente. Von D. Mendelejeff. — Ordnet man Elemente nach zunehmenden Atomgewichten in verticale Reihen so, dass die Horizontalreihen analoge Elemente enthalten, wieder nach zunehmendem Atomgewicht geordnet, so erhält man folgende Zusammenstellung, aus der sich einige allgemeinere Folgerungen ableiten lassen.

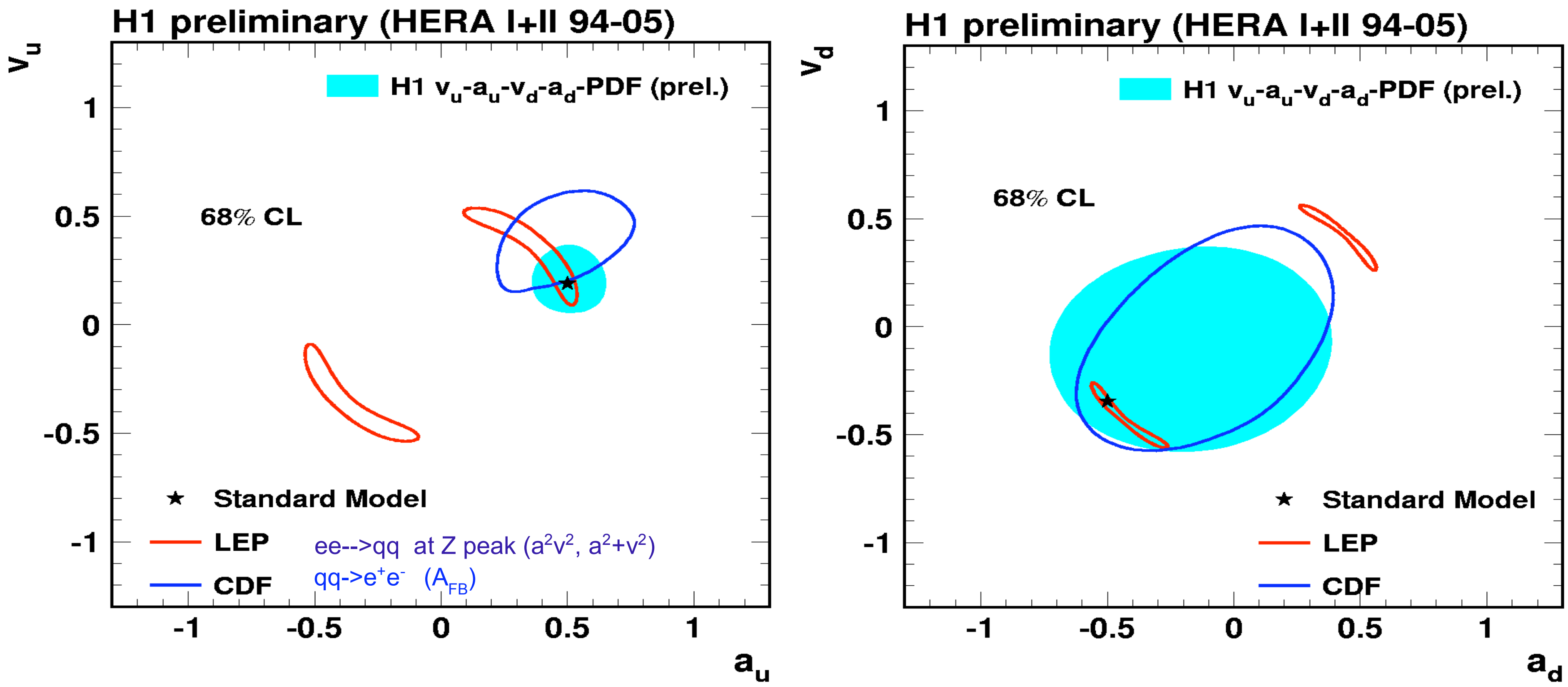
			Ti = 50	Zr = 90	? = 180
			V = 51	Nb = 94	Ta = 182
			Cr = 52	Mo = 96	W = 186
			Mn = 55	Rh = 104,4	Pt = 197,4
			Fe = 56	Ru = 104,4	Ir = 198
			Ni = Co = 59	Pd = 106,6	Os = 199
H = 1			Cu = 63,4	Ag = 108	Hg = 200
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112	
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?
	C = 12	Si = 28	? = 70	Sn = 118	
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?
	O = 16	S = 32	Se = 79,4	Te = 128?	
	F = 19	Cl = 35,5	Br = 80	J = 127	
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207
		? = 45	Ce = 92		
		?Er = 56	La = 94		
		?Yt = 60	Di = 95		
		?In = 75,6	Th = 118?		

1. Die nach der Grösse des Atomgewichts geordneten Elemente zeigen eine stufenweise Abänderung in den Eigenschaften.
2. Chemisch-analoge Elemente haben entweder übereinstimmende Atomgewichte (Pt, Ir, Os), oder letztere nehmen gleichviel zu (K, Rb, Cs).
3. Das Anordnen nach den Atomgewichten entspricht der *Werthigkeit* der Elemente und bis zu einem gewissen Grade der Verschiedenheit im chemischen Verhalten, z. B. Li, Be, B, C, N, O, F.
4. Die in der Natur verbreitetsten Elemente haben *kleine* Atomgewichte

Light quark couplings to Z



NC/CC data=> full QCD/EW Fit: PDF's+light quarks couplings
Taking advantage of polarisation @HERA II



Proton resists bombardement: elastic scattering

PHYSICAL REVIEW VOLUME 79, NUMBER 4 AUGUST 15, 1950

High Energy Elastic Scattering of Electrons on Protons

M. N. Rosenbluth
Stanford University, Stanford, California

(Received March 28, 1950)

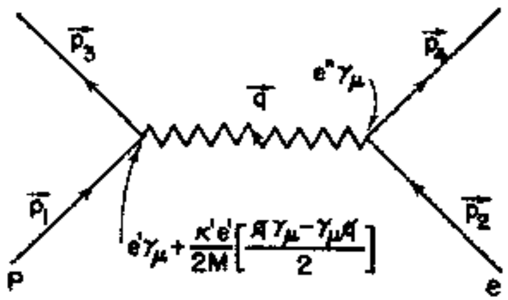
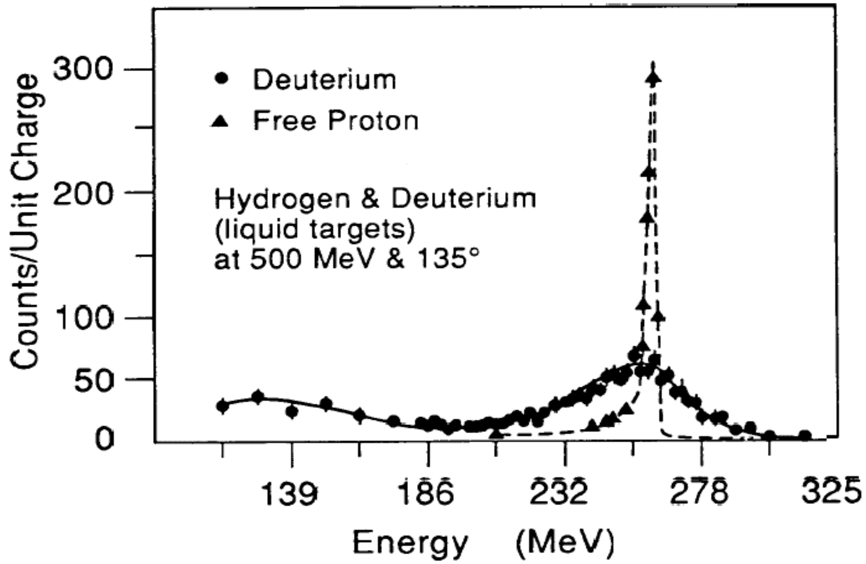


FIG. 1. Diagram for the elastic scattering of a physical proton and a physical electron. (The letter "q" with the bar through it in this figure is the same as the German letter, q, used in the text.)

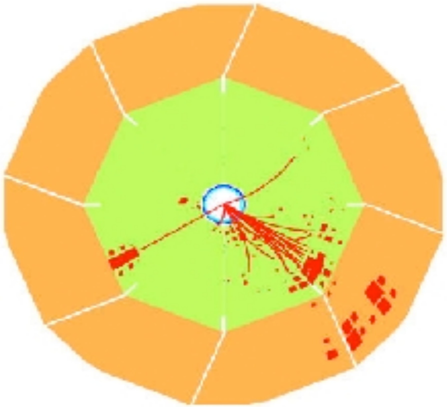
I. INTRODUCTION

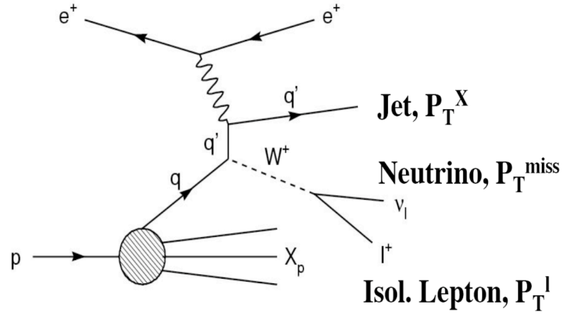
THE Stanford linear electron accelerator program is expected to make available large currents of relativistic electrons with various energies ranging from 6 to 1000 Mev. Among the experiments of considerable interest which may then be performed is the elastic scattering of electrons on protons. This may be done on a hydrogen gas or liquid target. Despite the smallness of the cross section at high energies, the expected large intensity of the beam should render the experiments possible.

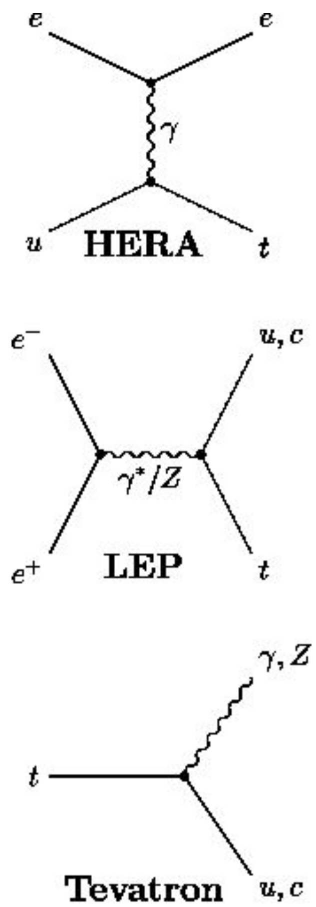
Hofstadter

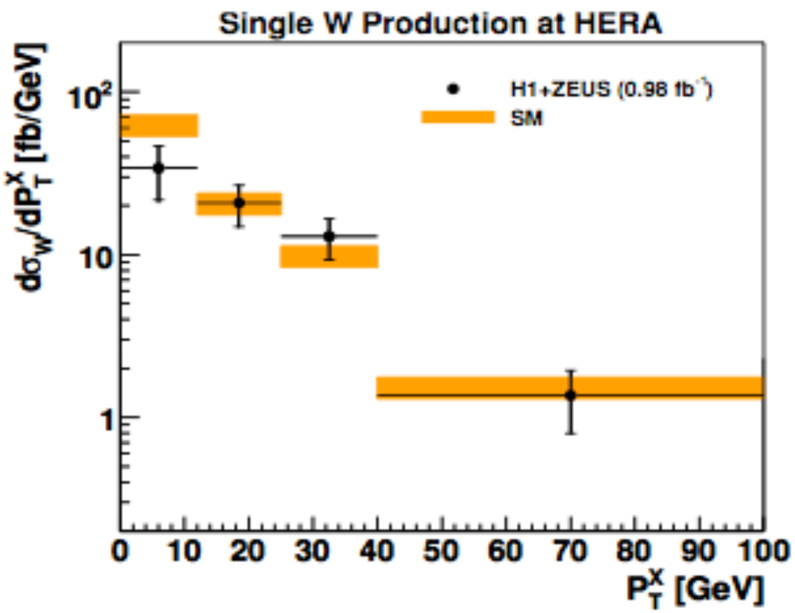


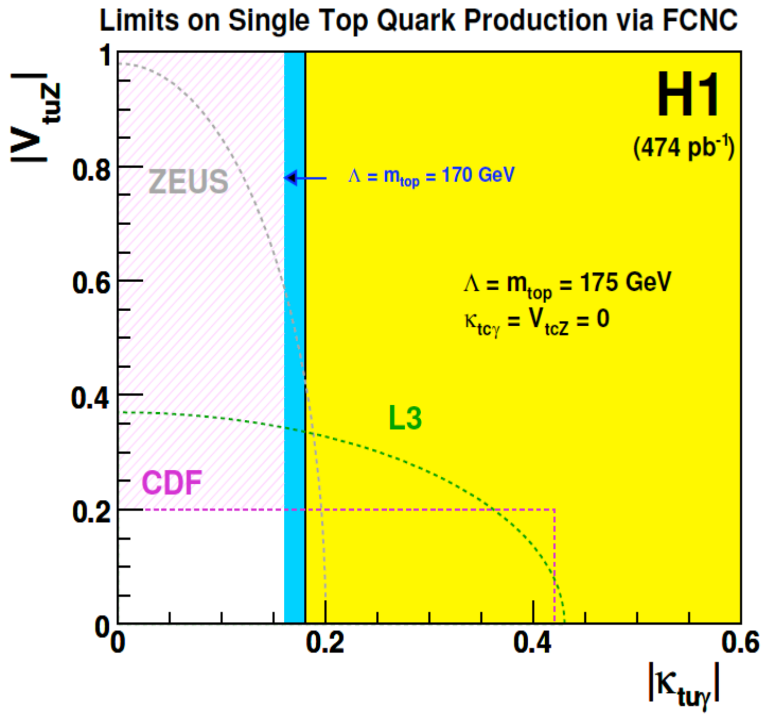
W production



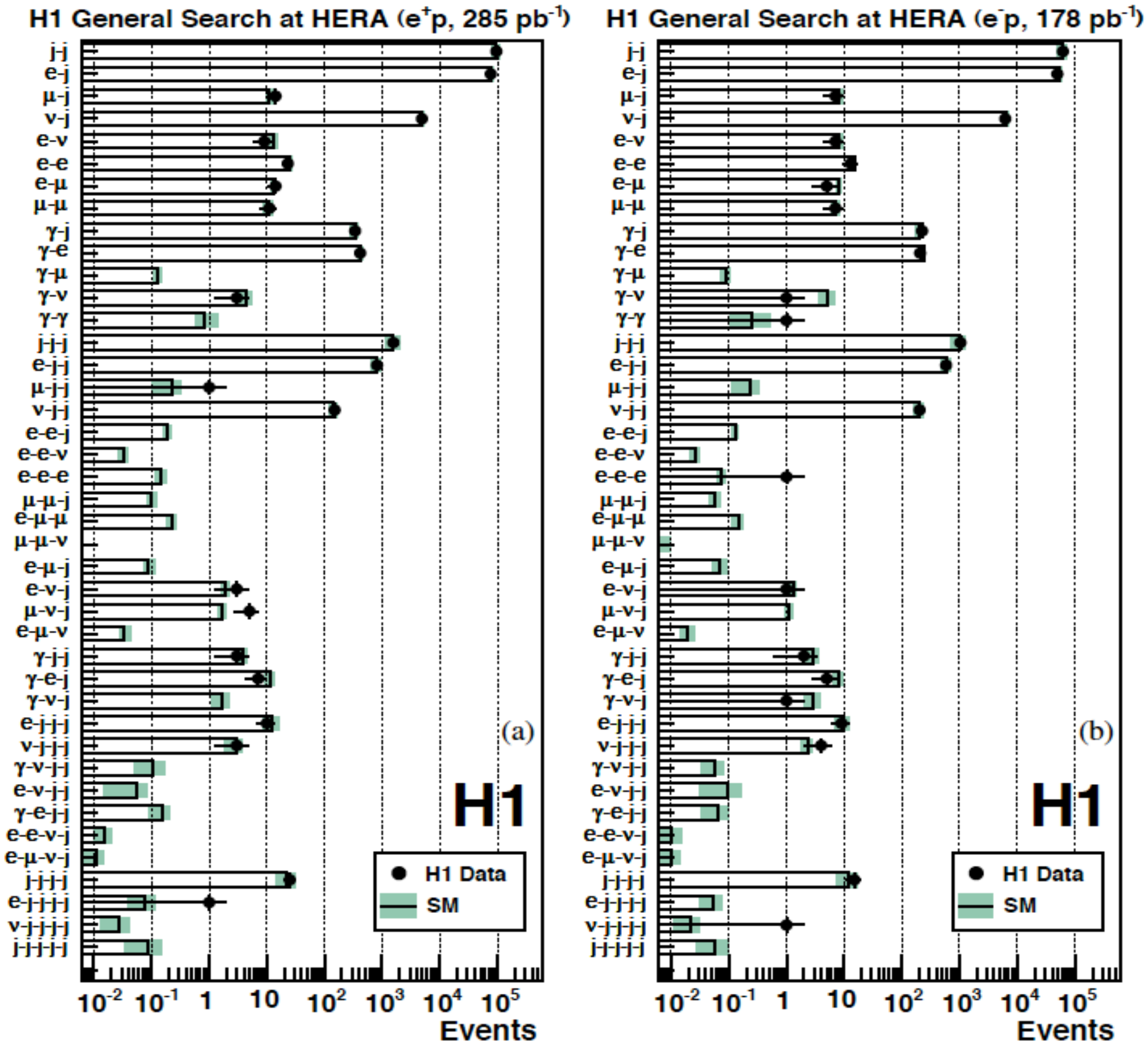


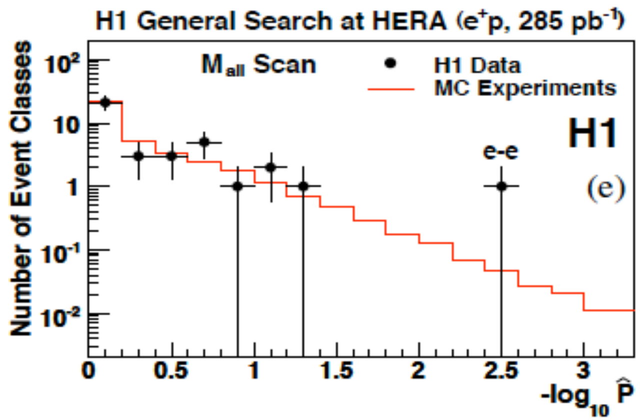






Generic Search for New Physics





Extraordinary description in all channels
But: no signal beyond the SM