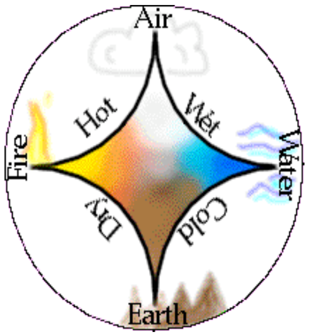
First Magurele School in High Energy Physics,
October 27, 2008

Structure Functions at HERA

Cristinel DIACONU
CPP Marseille & DESY

The (very) early days

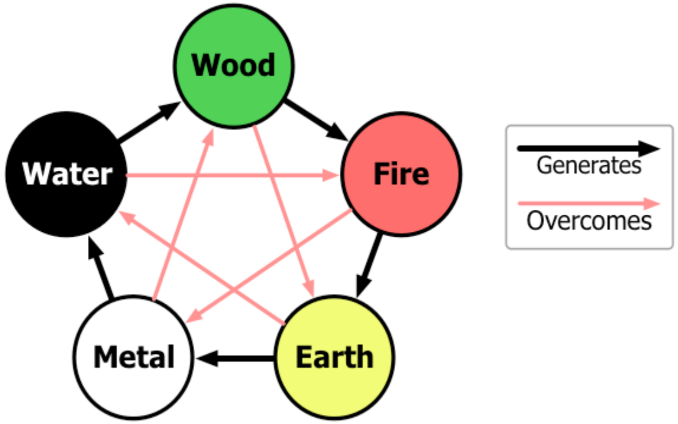
- Something must be fundamental, the 'bulding blocks'
- Models:
  - Aristotel, Heraclit et al., 4+1 elements “air,fire, water, earth”+quitessence



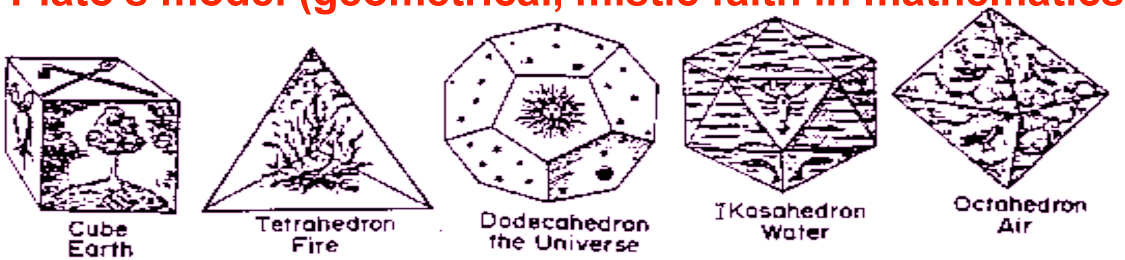
+

The 5th element

Asian version



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

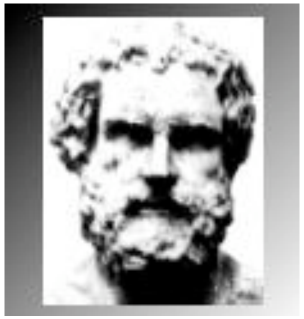


  - Leucip, Democrit: “Elementary particles” =atoms+space

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.

Geiger, Marsden, Rutherford
(20y)

GMR

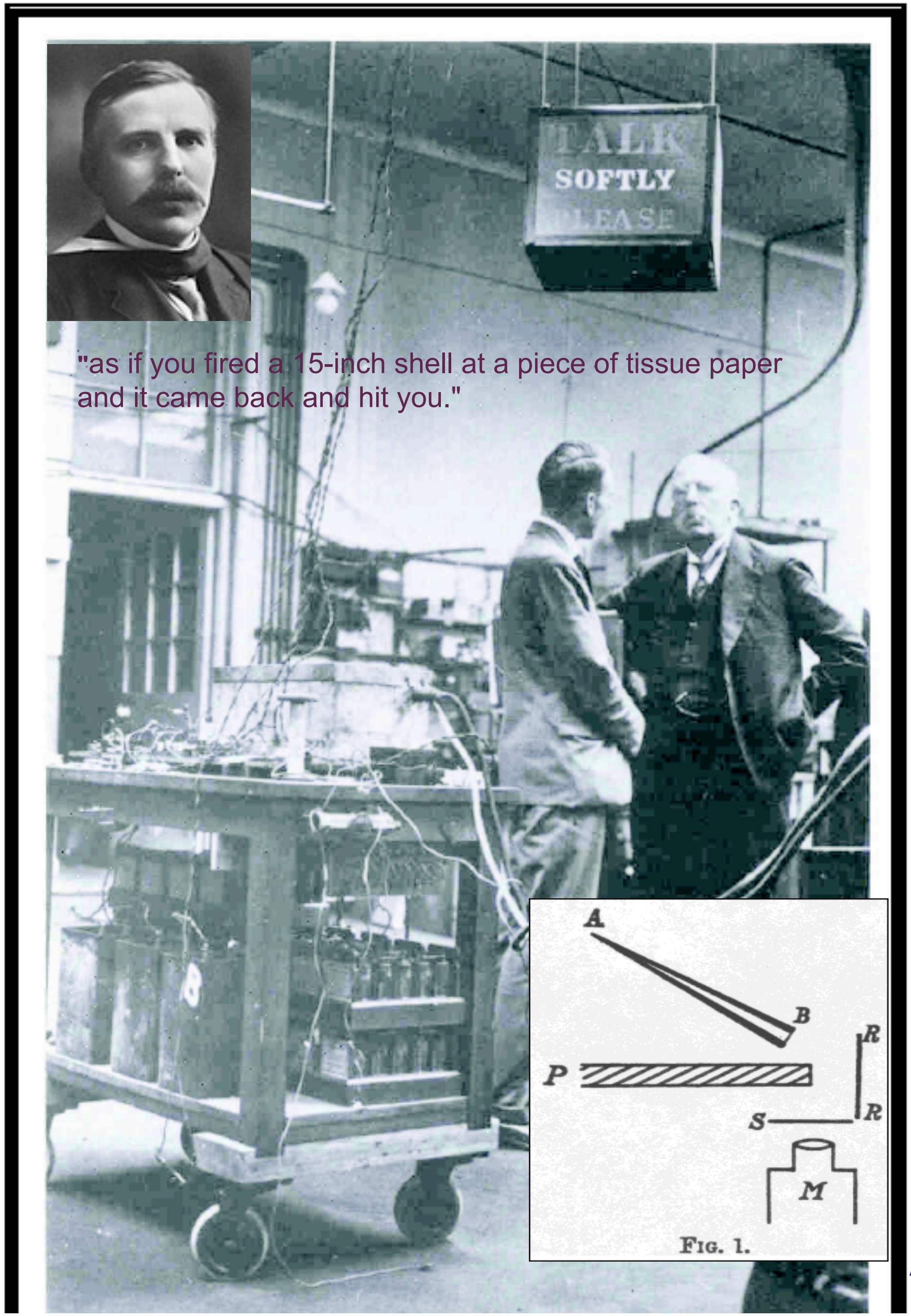
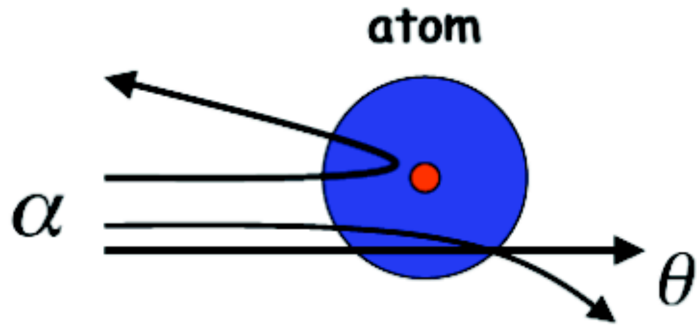


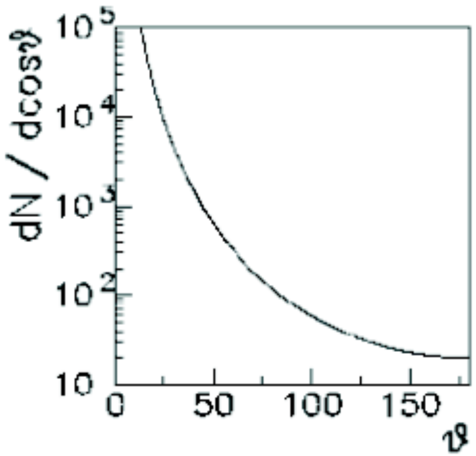
FIG. 1.

Discovery of the atomic nucleus 1909



↳ 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”

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)

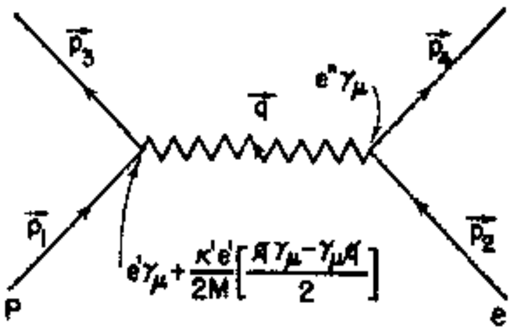
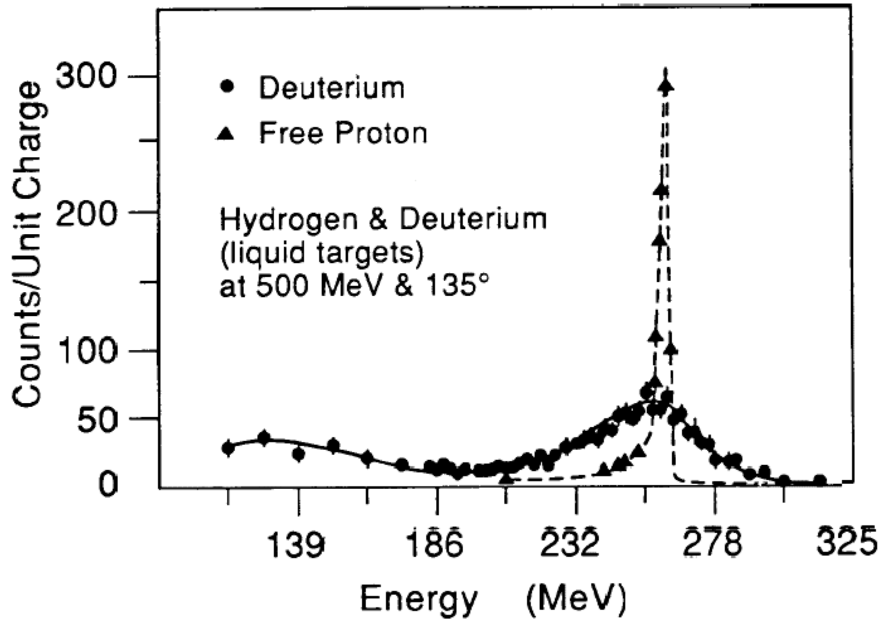


FIG. 1. Diagram for the elastic scattering of a physical proton and a physical electron. (The letter "q" with the bar through it in this figure is the same as the German letter, q, used in the text.)

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.

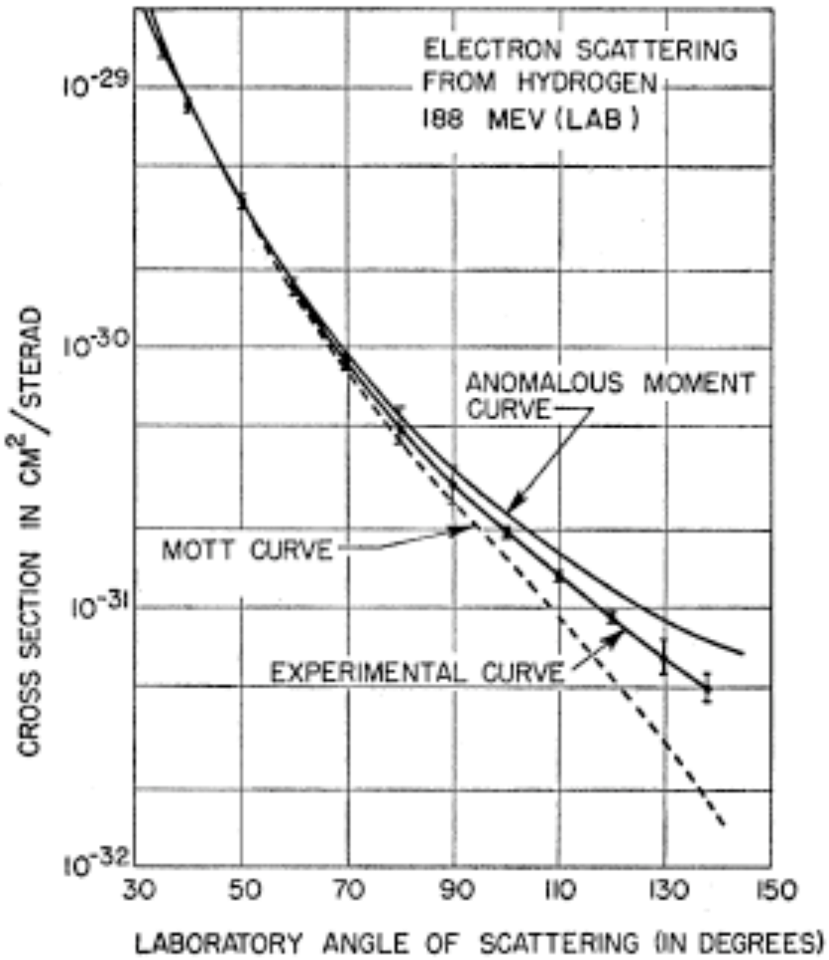
Hofstaeder



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.



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

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.

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)

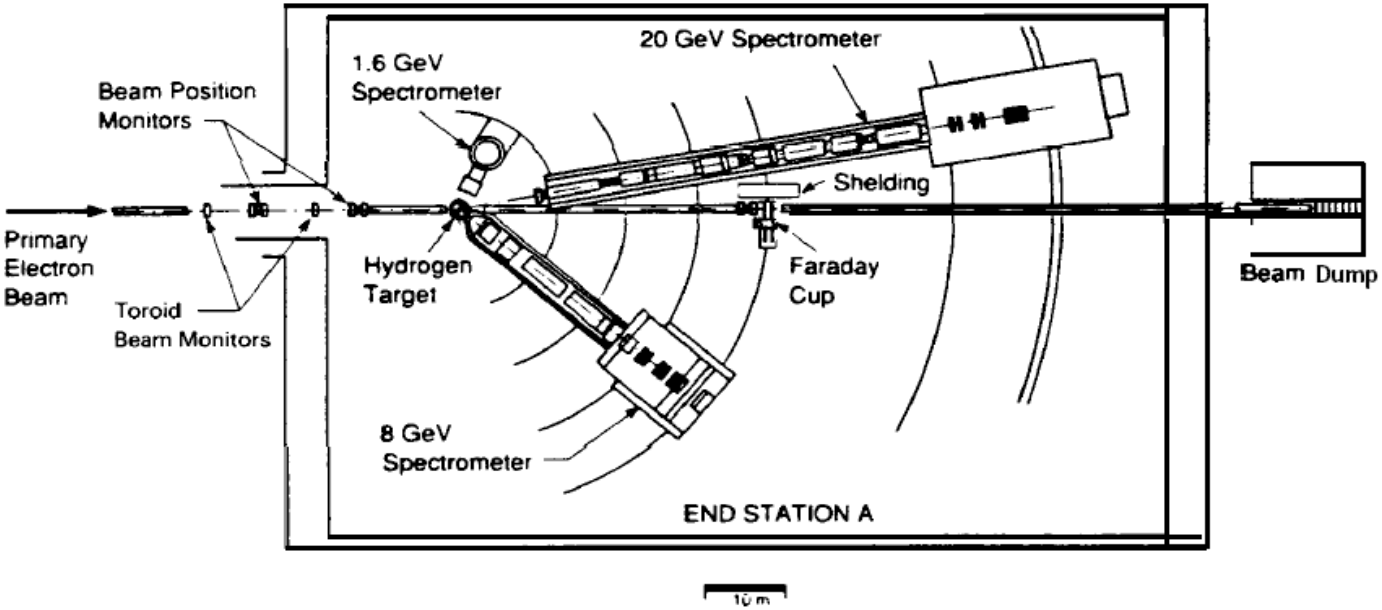
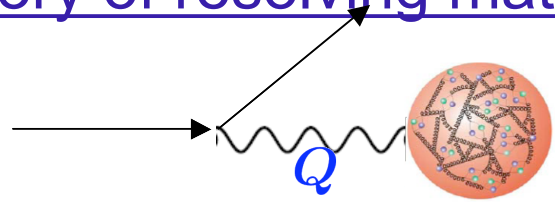


Fig. 14. Layout of spectrometers in End Station A. All three spectrometers can be rotated about the pivot. The 20 GcV spectrometer can be operated from about $1\frac{1}{2}^{\circ}$ to 25°, the 8 GeV from about 12° to over 90°. The 1.6 GcV spcctrometer coverage is from $\sim 50^{\circ} - 150^{\circ}$.

A short history of resolving matter structure

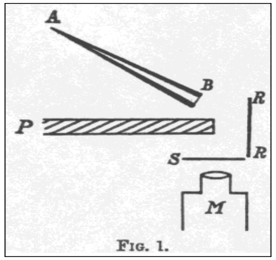


$$\delta \text{ [fm]} \simeq \frac{200 \text{ MeV}}{Q}$$

~100 years ago

Geiger, Marsden. (1909)
Rutherford(1911)

E_α=5.5 MeV

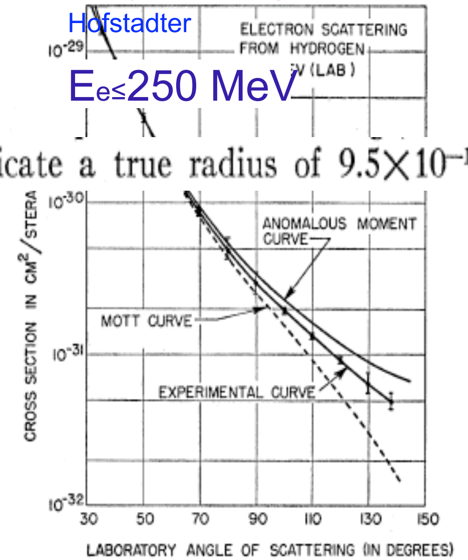


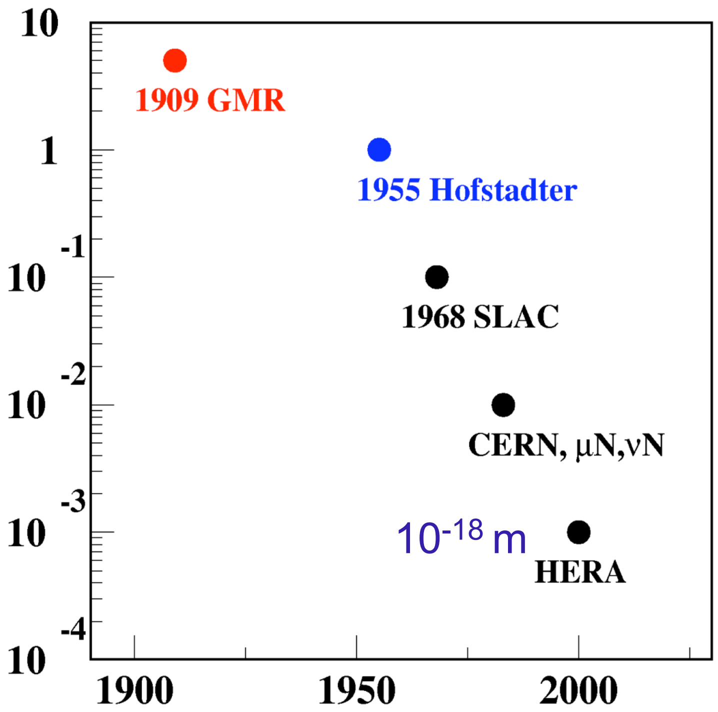
53 years ago

Hofstadter

$E_e \leq$250 MeV

indicate a true radius of 9.5×10^{-14} cm

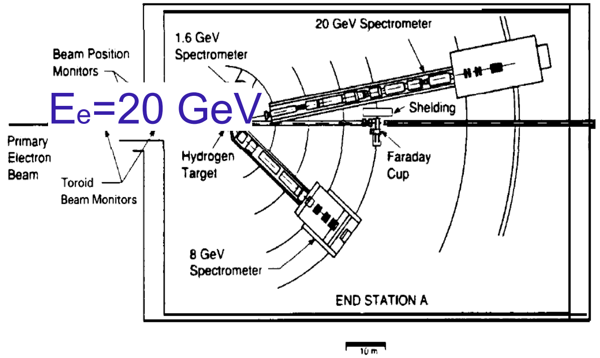


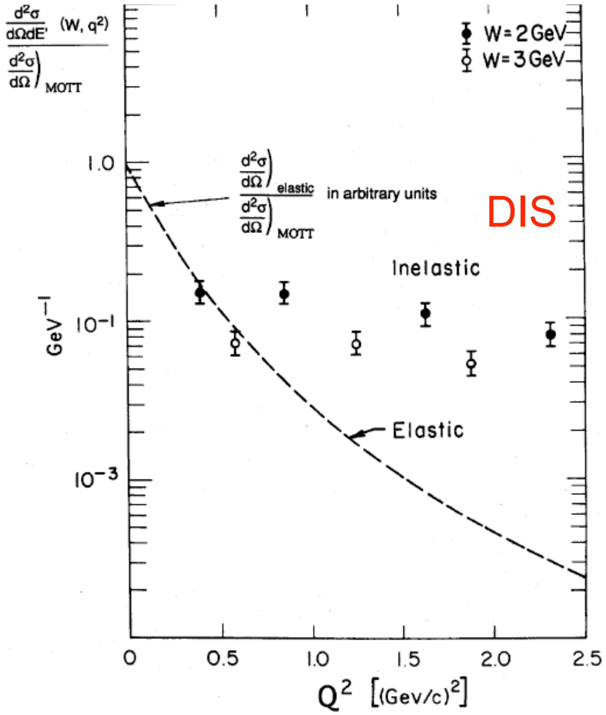


[polarised collisions since mid 70's]

40 years ago: partons

E_e=20 GeV



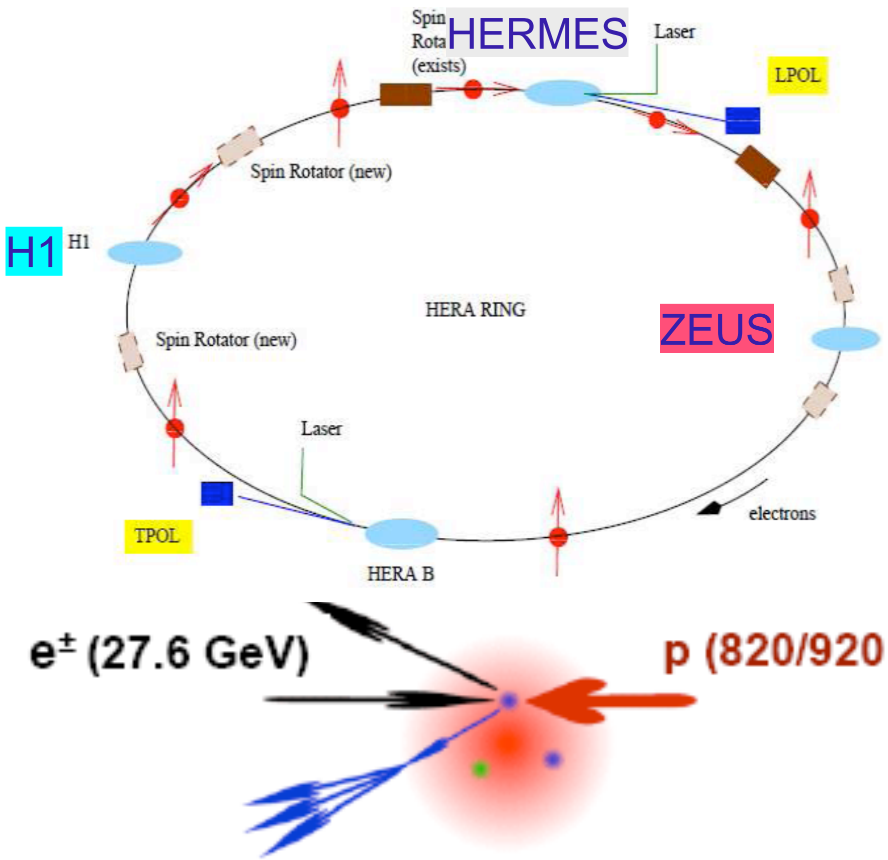


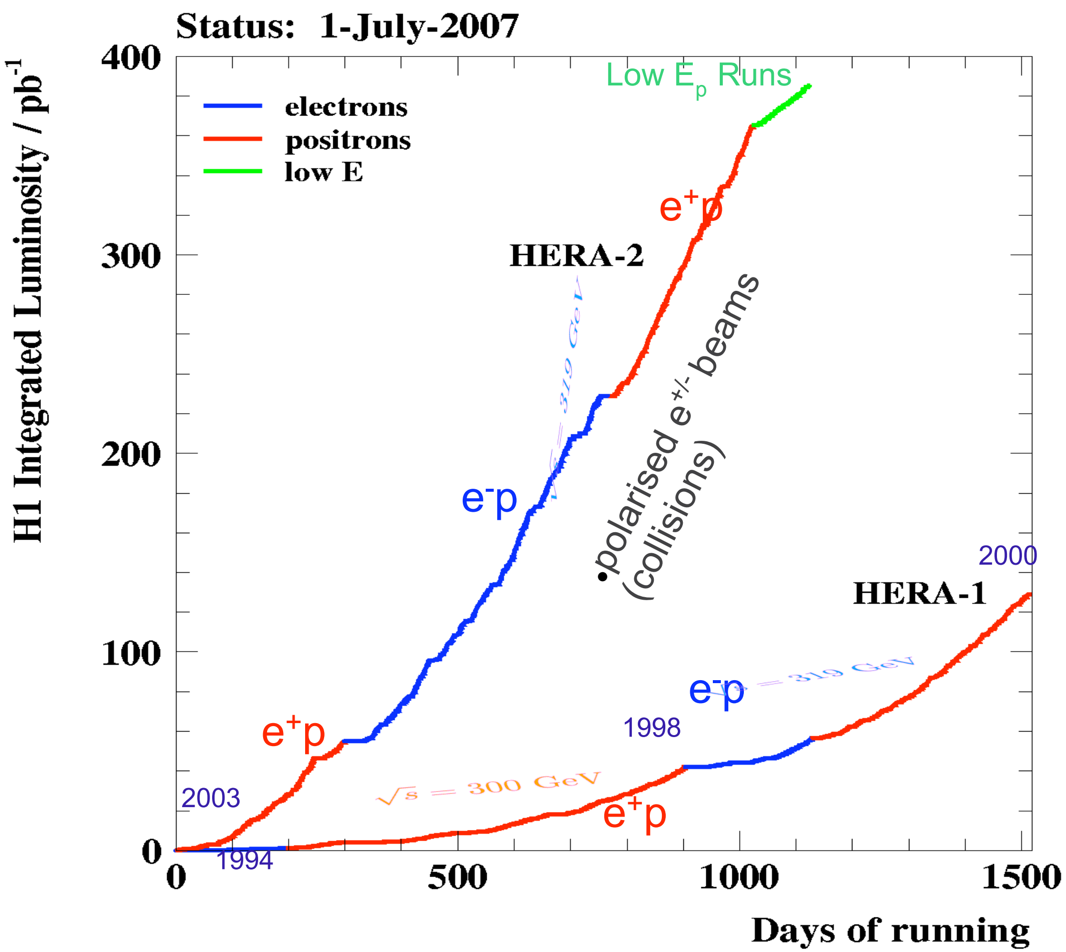
DIS

24 years ago

Volker Soergel and the Minister of Science of Germany, Heinz Riesenhuber,

HERA Collider: end in 2007



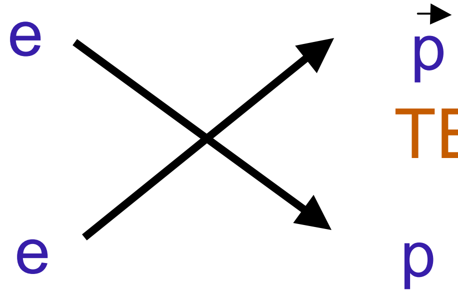


- HERA 1: 1992-2000 ~120 pb^{-1}/expt
- HERA 2: 2003-2007
  - Luminosity upgrade (x3)
  - Polarised electrons/positrons

~200 pb^{-1} e^-p
~300 pb^{-1} e^+p

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 ->700 pb-1(delivered,$e^{\pm}$,$\pm P_e$)

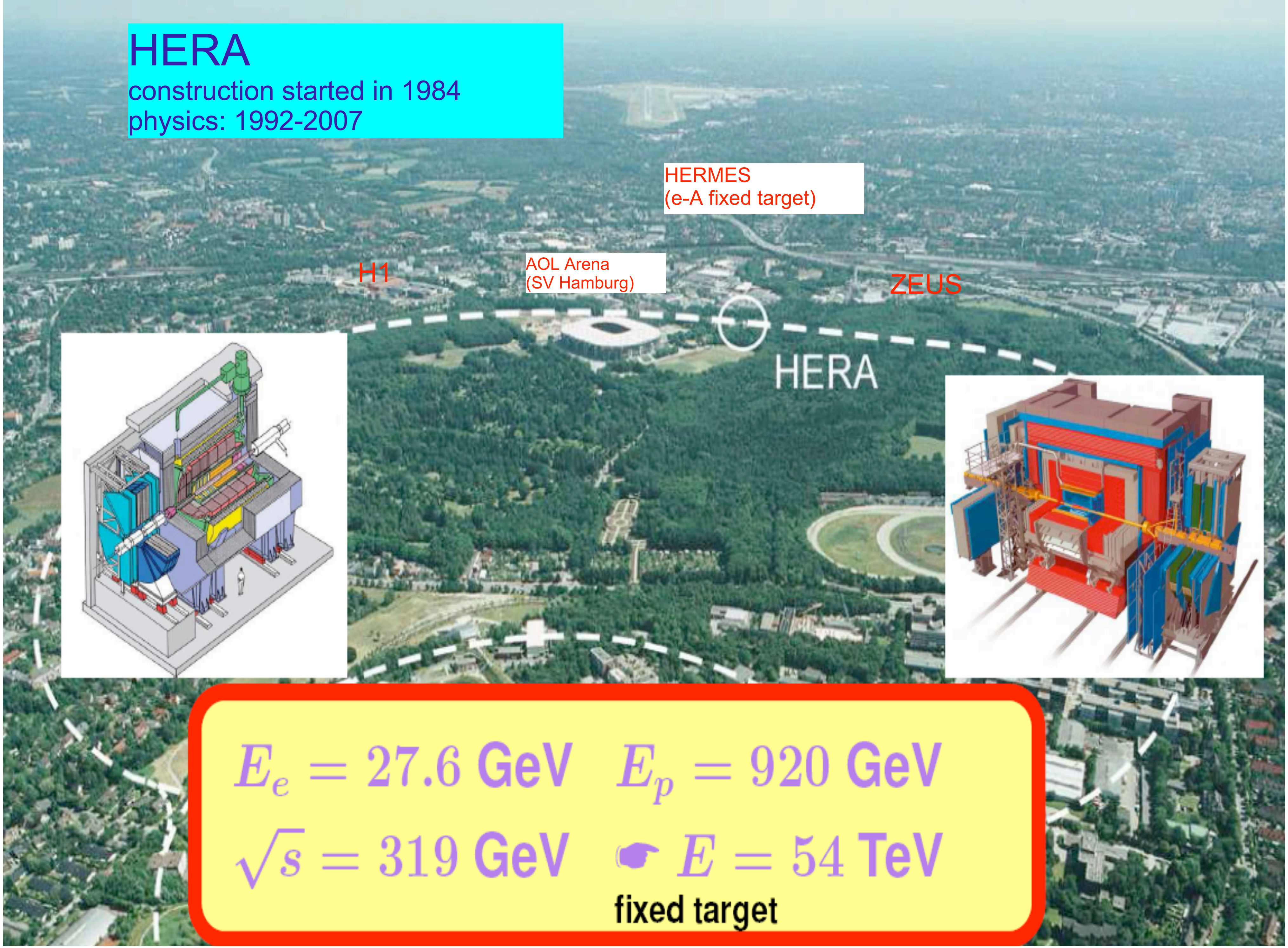
-> $p\bar{p}$ collider: CDF, D0

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

Run II E_{cm}=1.96 TeV
1fb^{-1} delivered
2009 -> 4-8 fb^{-1}

HERA

construction started in 1984
physics: 1992-2007

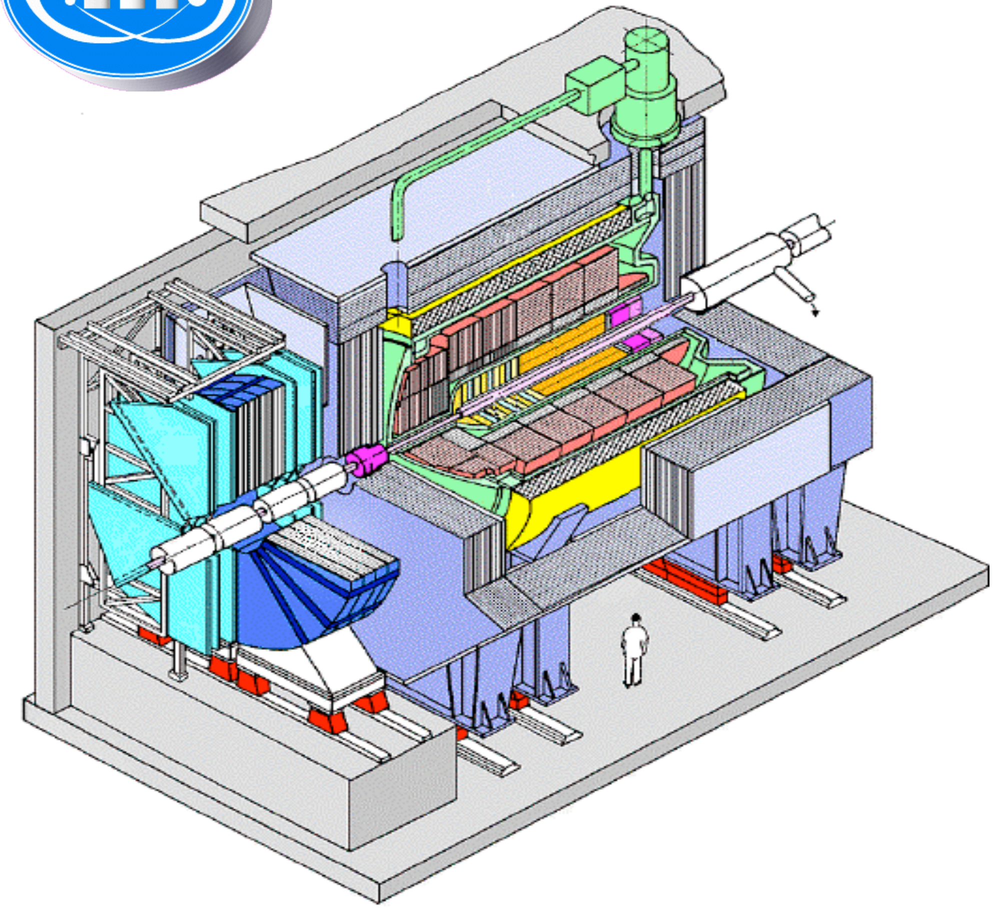


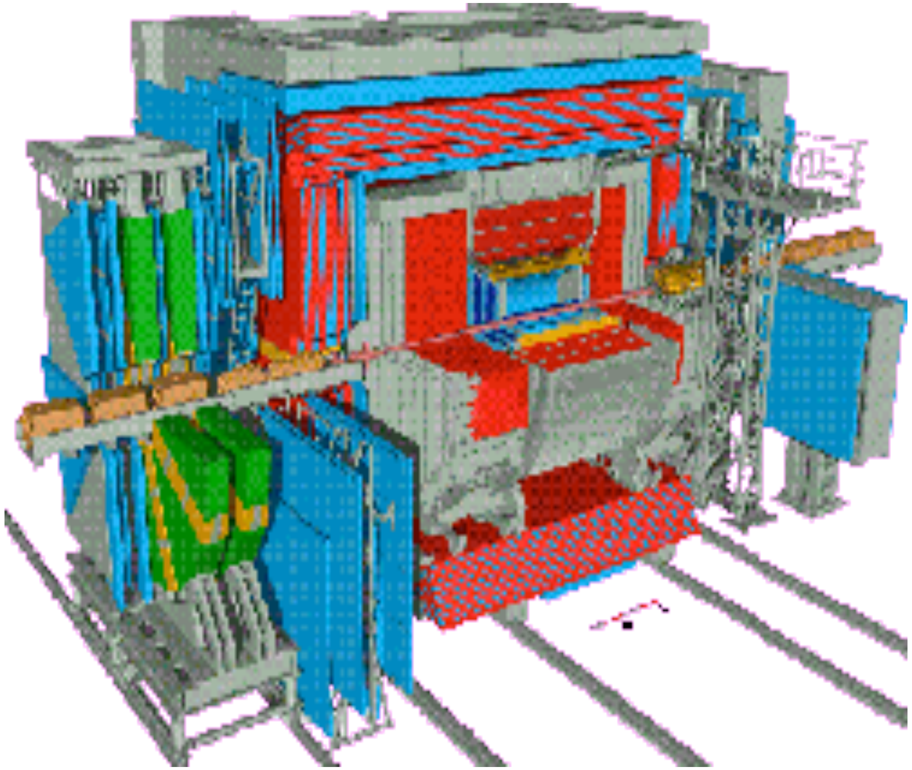
$E_e = 27.6$ GeV $E_p = 920$ GeV

$\sqrt{s} = 319$ GeV ☛ $E = 54$ TeV

fixed target

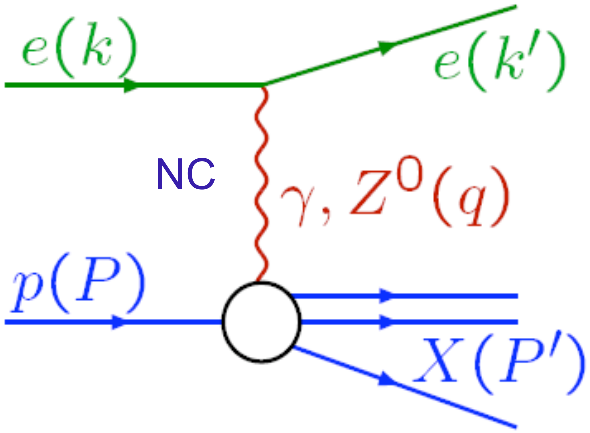
H1 and ZEUS detectors

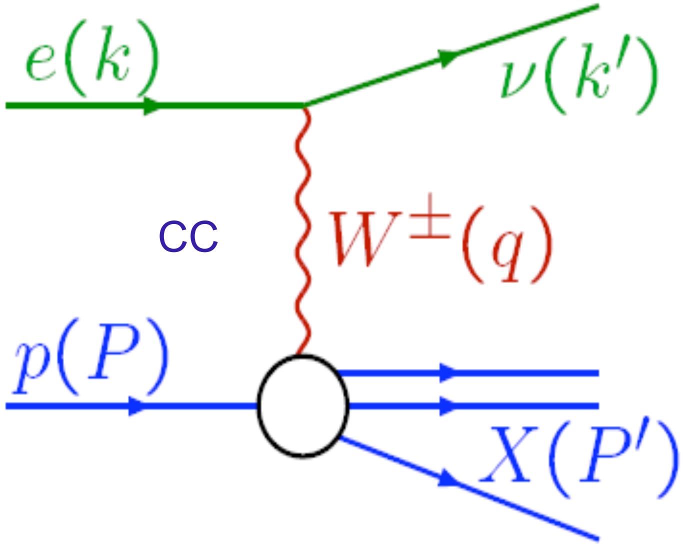




4π detectors, excellent tracking and calorimetry

Deep-Inelastic Scattering





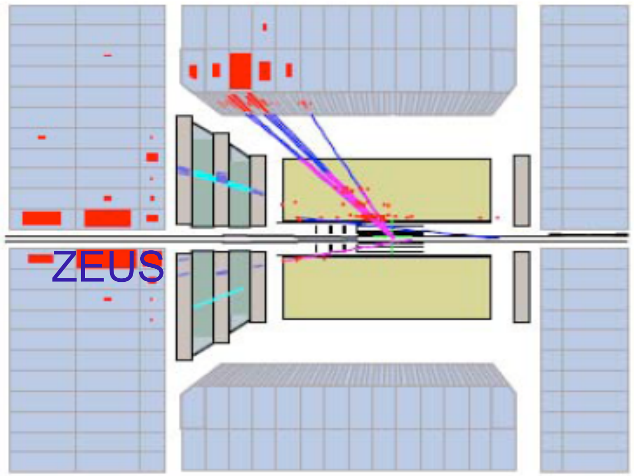
- $Q^2 = -q^2 = -(k - k')^2$
  virtuality/resolving power
- $x = \frac{Q^2}{2P\cdot q}$ Bjorken scaling variable, momentum fraction of the scattered parton
- $y = \frac{q\cdot P}{k\cdot P}$ inelasticity

Related by $Q^2 = xys$

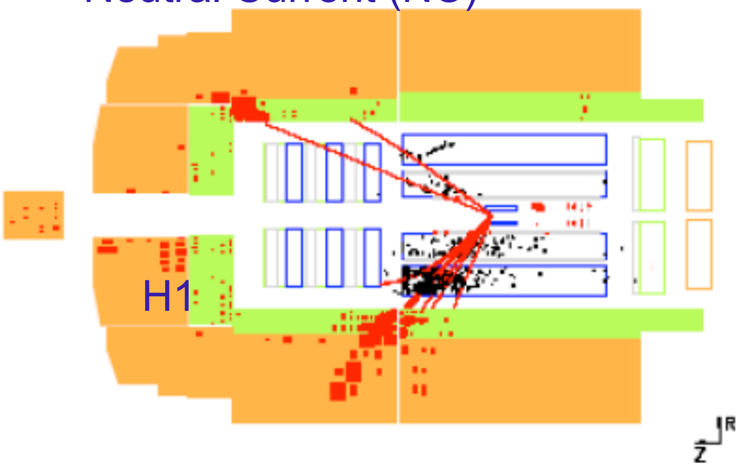
Partons = Quarks + Gluons (QCD improved quark parton model)

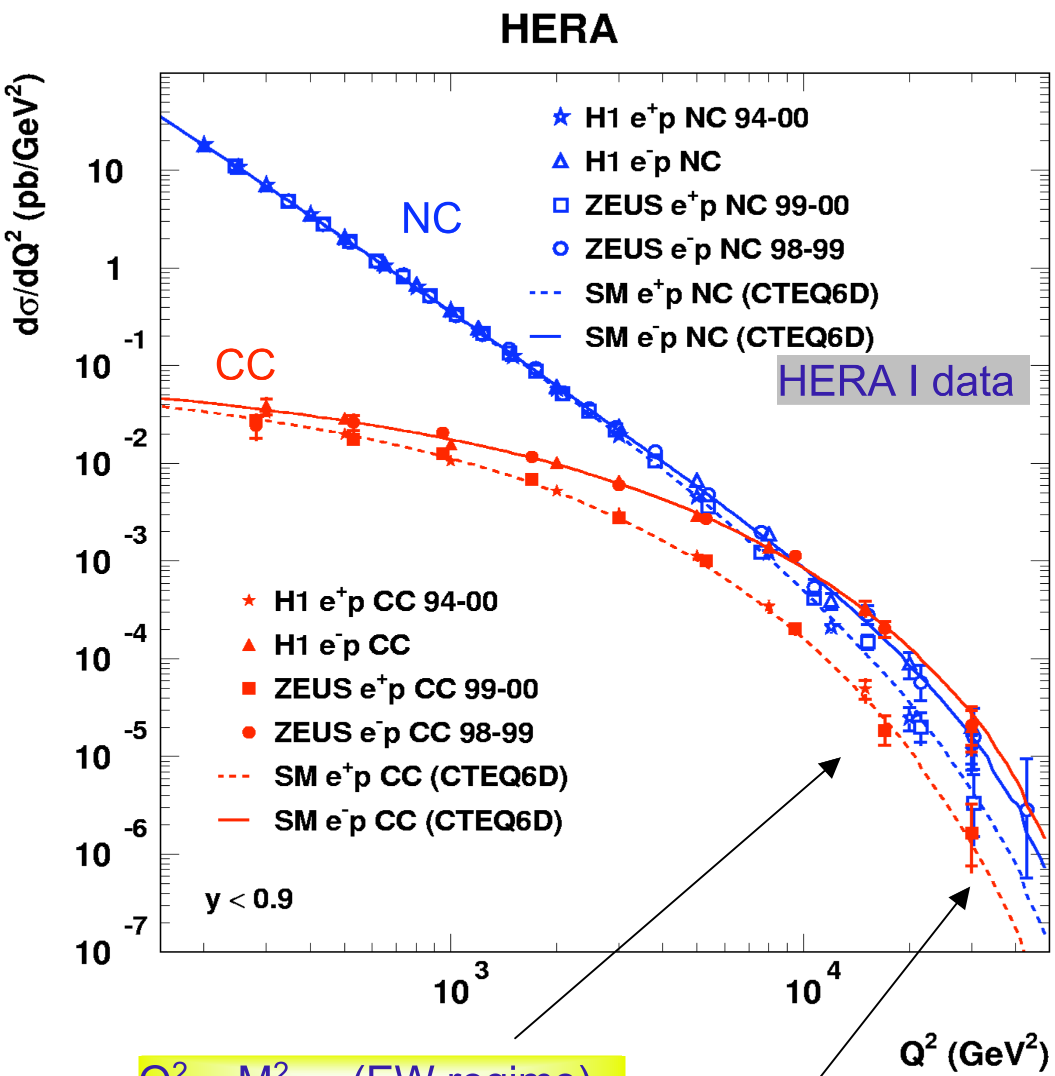
DIS at HERA

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

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

Leading Order picture of the proton

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

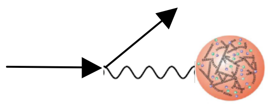
F_L

$$F_L \sim x\alpha_s g$$

gluons

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

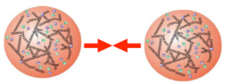
The PDF's mechanics:factorisation and evolution



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

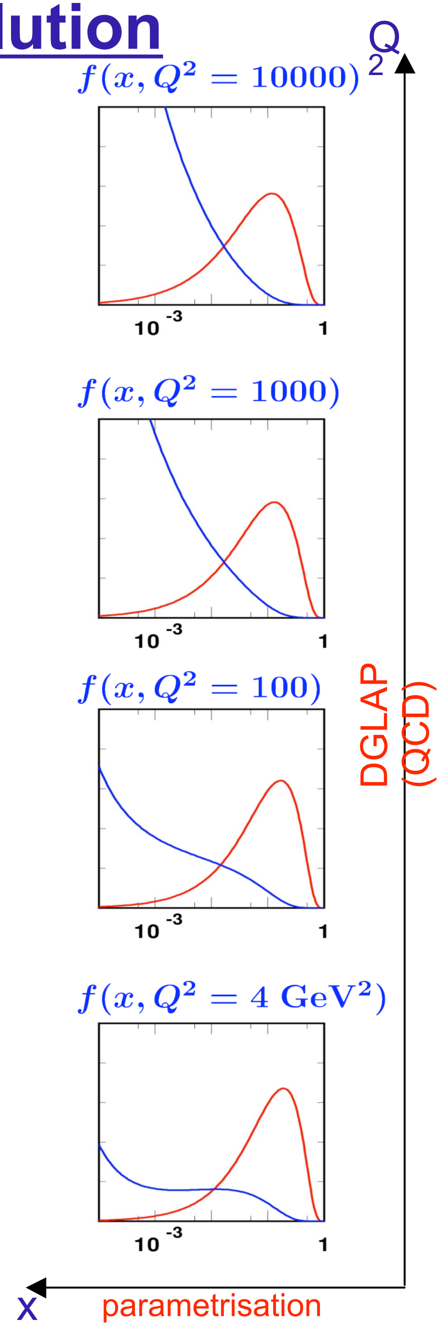
perturbative QCD — non-perturbative

factorisation



$$\sigma_{pp\to FS} \equiv \mathcal{C}_{\text{parton}-\text{parton}} \otimes f(x, Q^2) \otimes f(x, Q^2)$$

|| $E^2_{\text{CM parton-parton}}$



Input at scale Q^2_0 : parameterisation assumed (typically 20 parameters)
Evolution in Q^2 calculable in QCD (DGLAP):

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

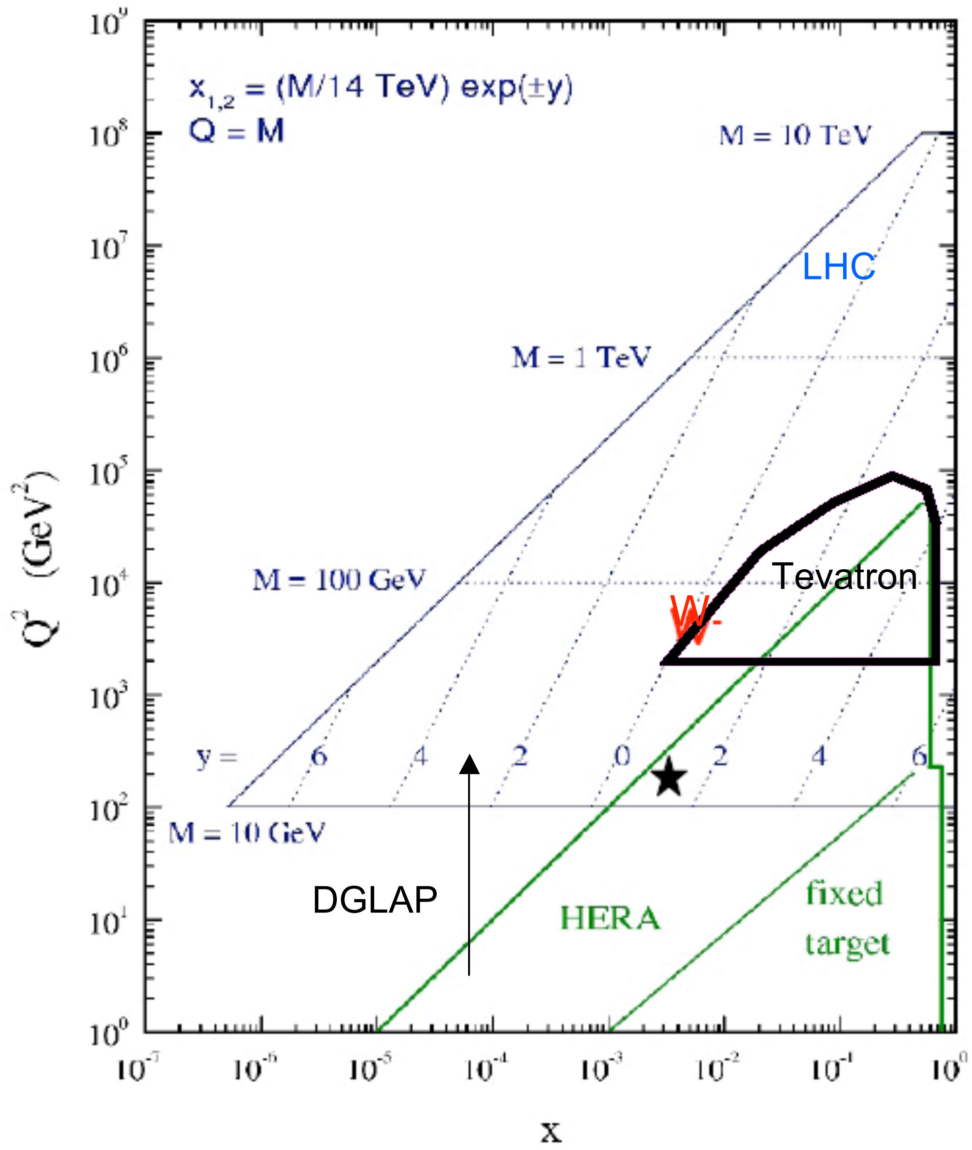
The PDF's play two (equivalent) roles:

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

DIS versus hadronic colliders

Example:
pp: W (at rest) corresponds to
$Q2=M_W^2 = 6400\ GeV^2$
x=0.005 for LHC
x=0.2 for Tevatron

For M=1 TeV (LHC) x>0.005



DIS data is the support for LHC predictions (beware the very low x!)
A number of improvements expected from Tevatron (in particular at high x)

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

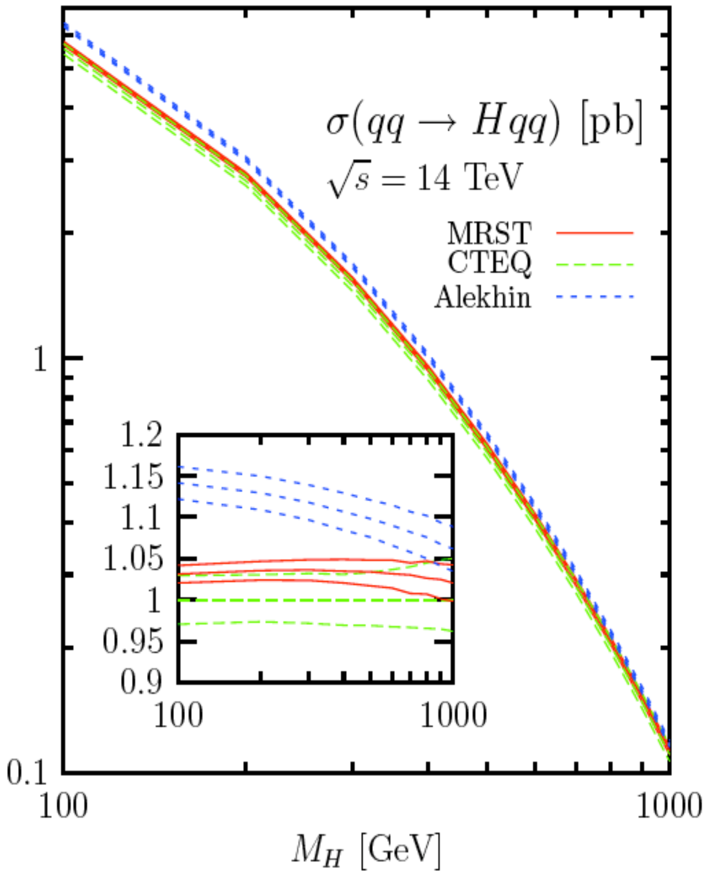
Difficult issues:

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

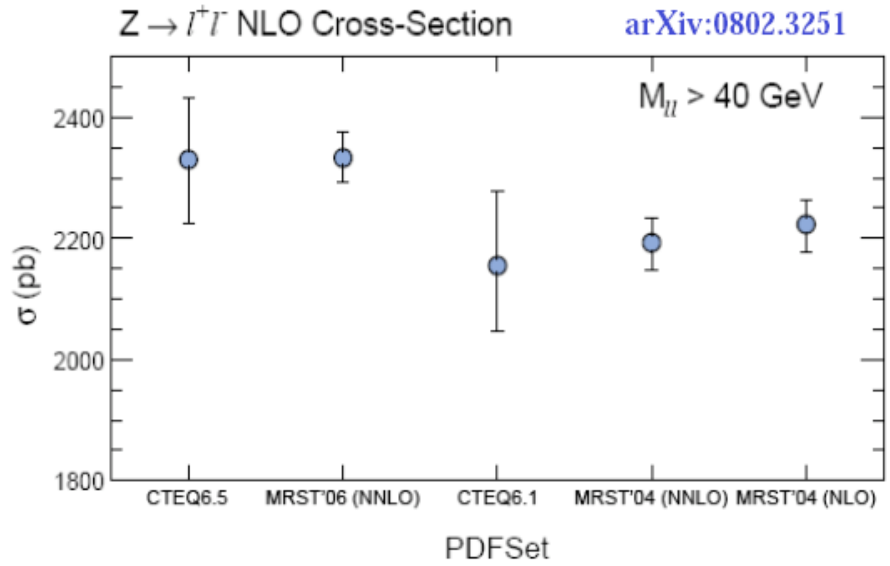
"unknown" systematics: "tensions" between data sets, tolerances

PDF errors determination

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

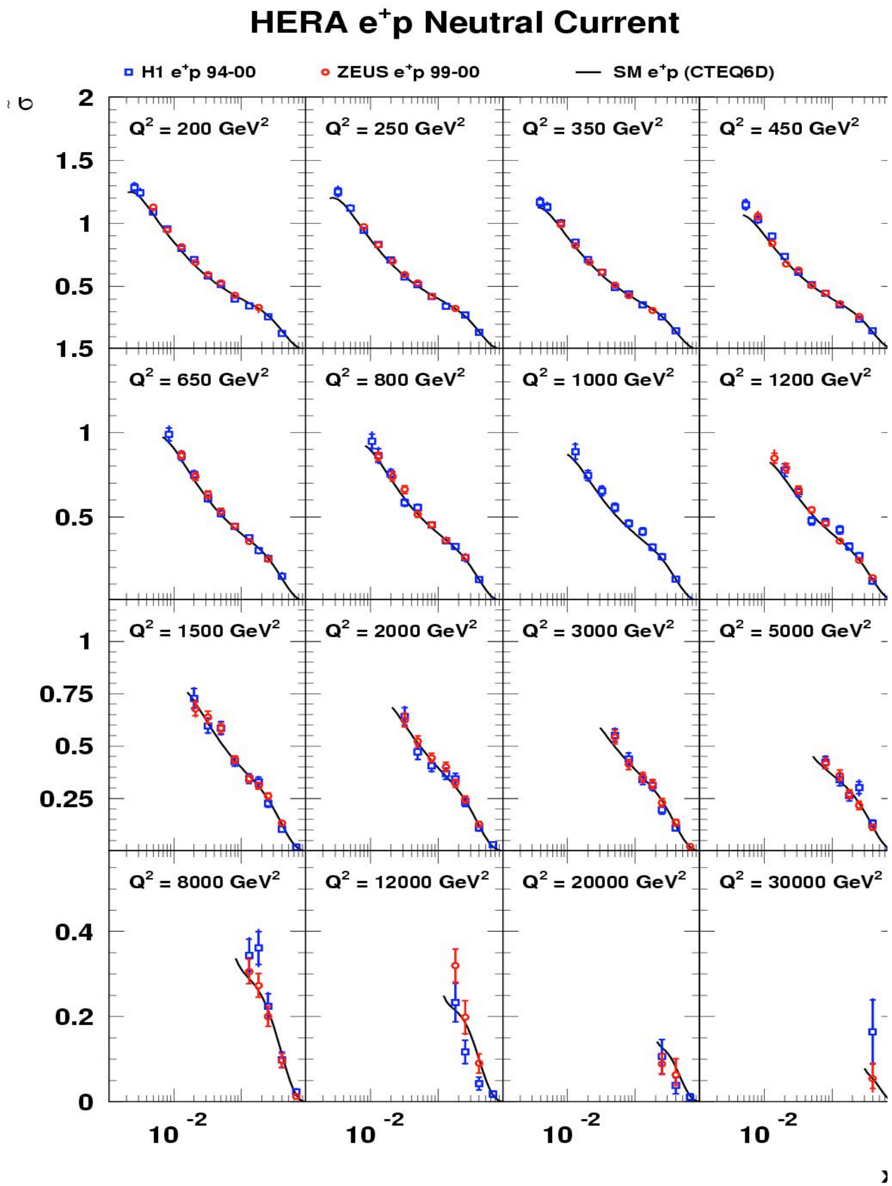
Various fits give incompatible results

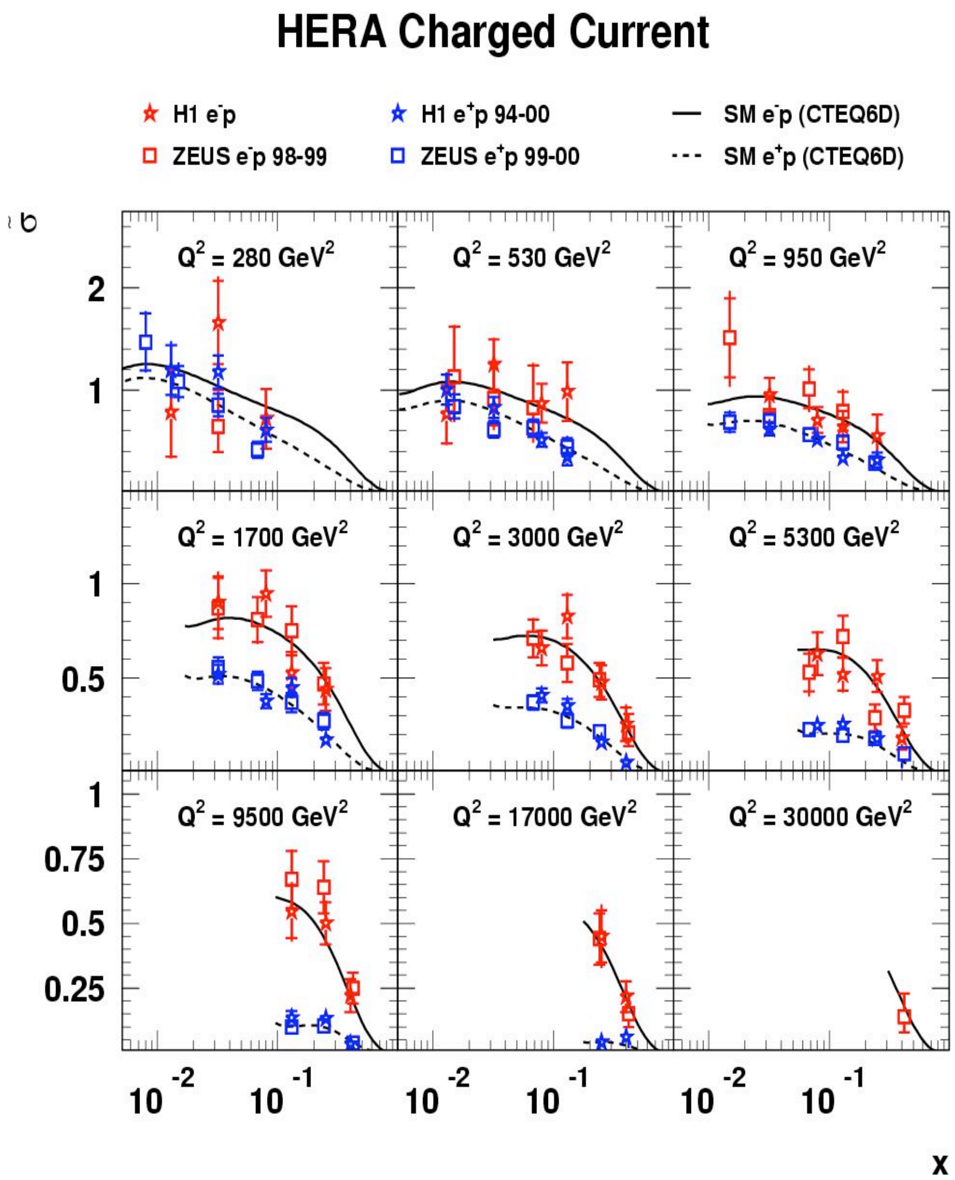
PDF error dominant for some standard signals

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 =>

DIS data from HERA

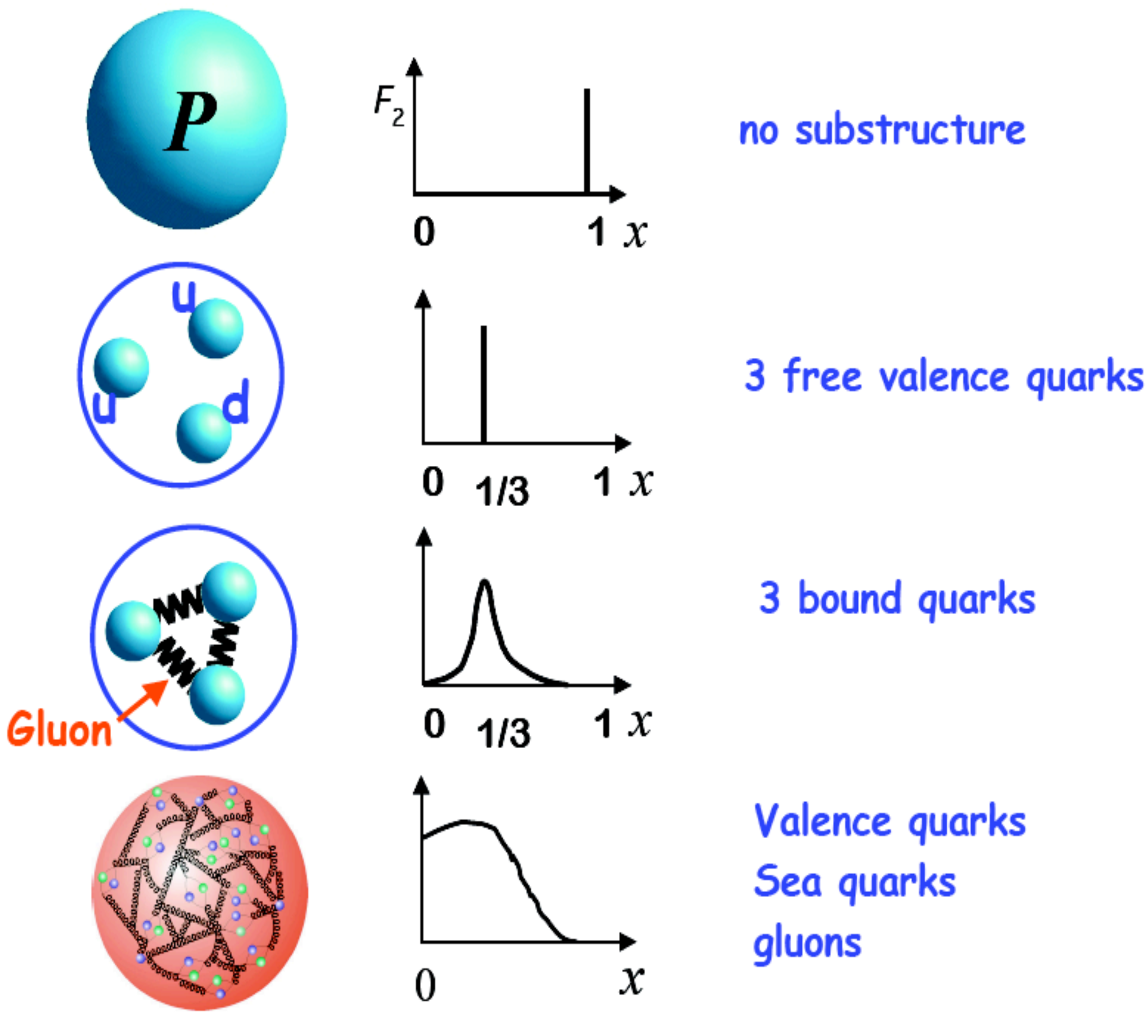




NC:precise and well in agreement with QCD

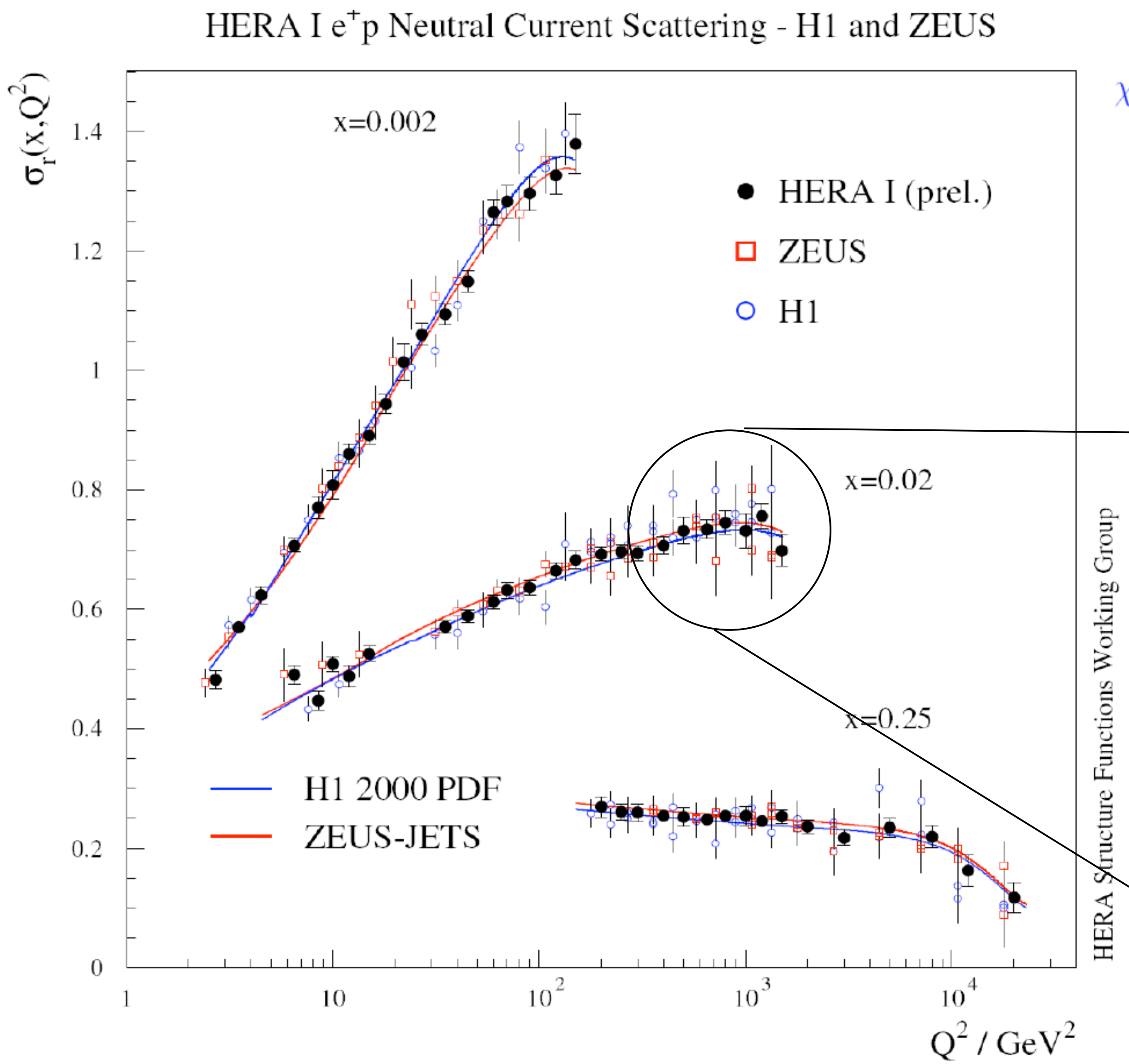
CC: provide flavour separation   H1/ZEUS data used in pdf fits separately

Phenomenology of F2



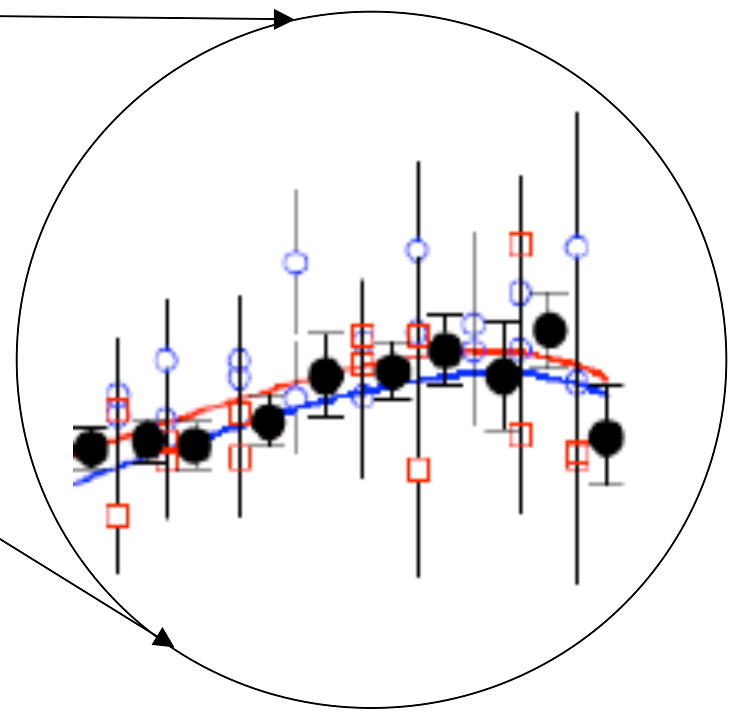
H1-ZEUS cross section combinations

Coherent treatment of experimental effects in the average procedure (Lagrange multipliers method)



$$\chi^2(\{F_2^{true}\},\{\alpha\}) = \sum_i \frac{\left[F_2^{i,true} - \left(F_2^i + \sum_j \frac{\partial F_2^i}{\partial \alpha_j}\alpha_j\right)\right]^2}{\sigma_{F_2}^2} + \sum_j \frac{\alpha_j^2}{\sigma_{\alpha_j}^2}.$$

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

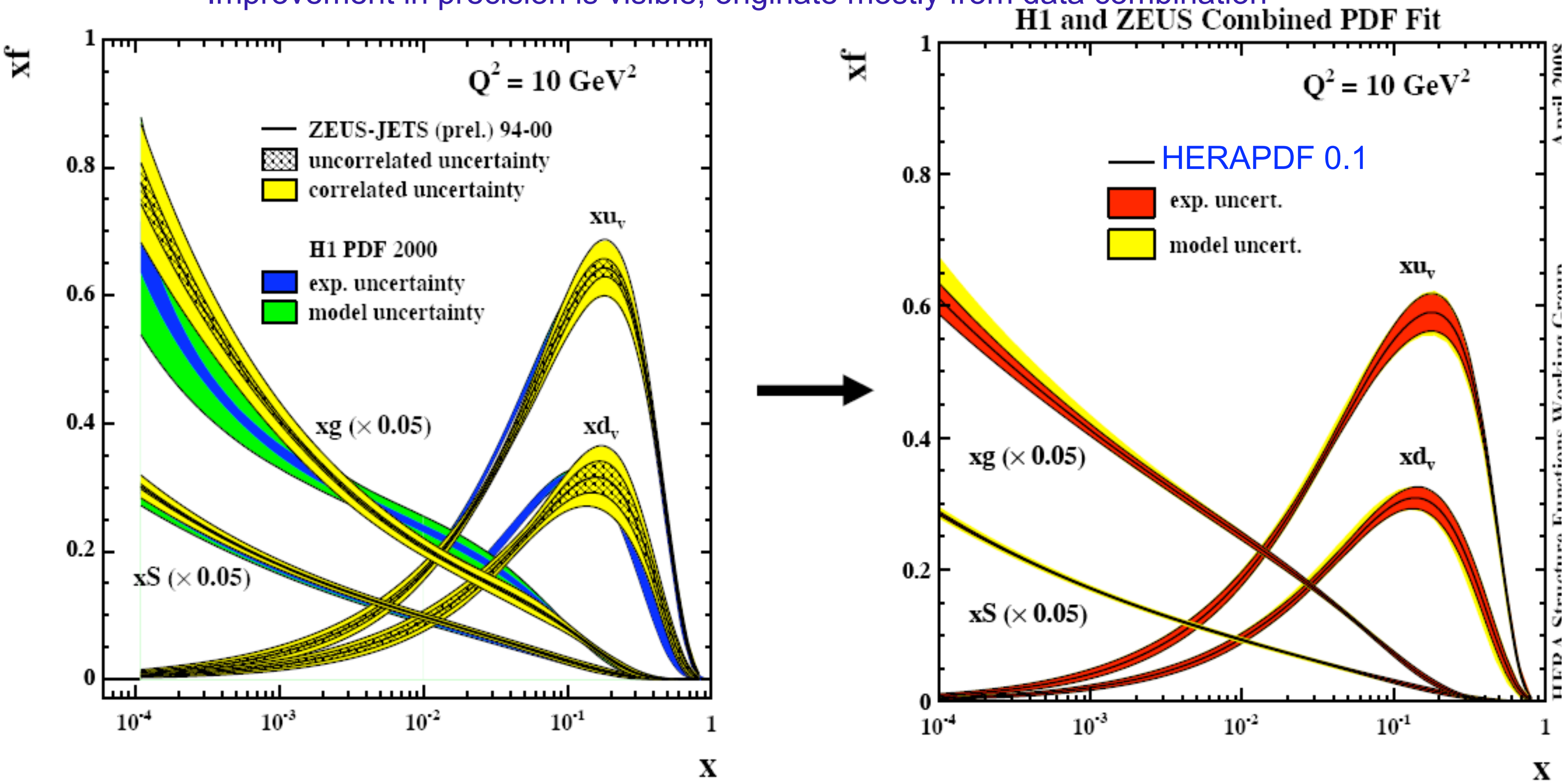


Improvements beyond the naively-expected sqrt(2): “cross calibration”

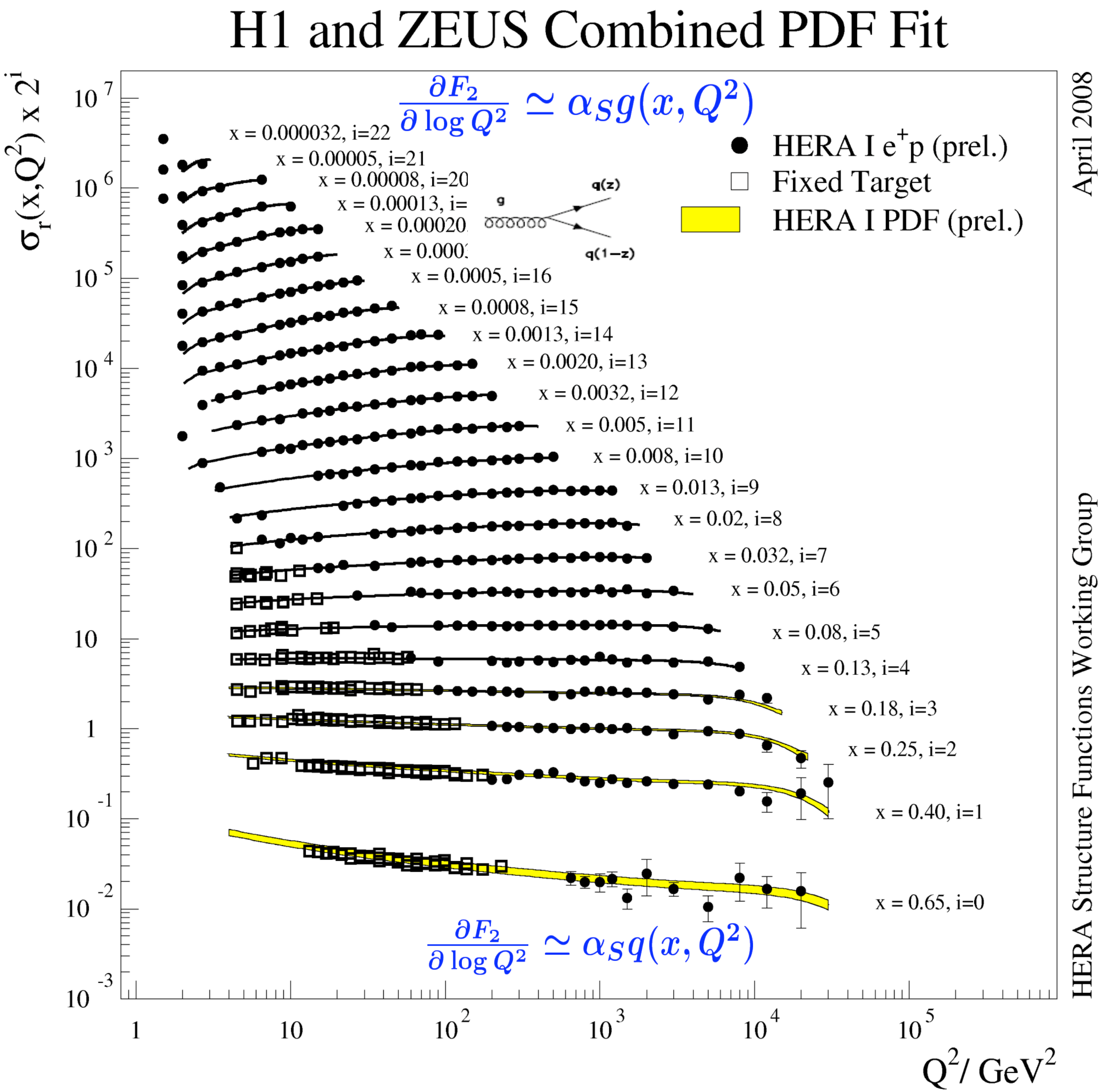
The common fit of the combined HERA I data

Partons parametrized at Q_0^2 = 4 GeV^2 (Data Q^2>3.5 GeV^2)
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



The combined data compared to the fit



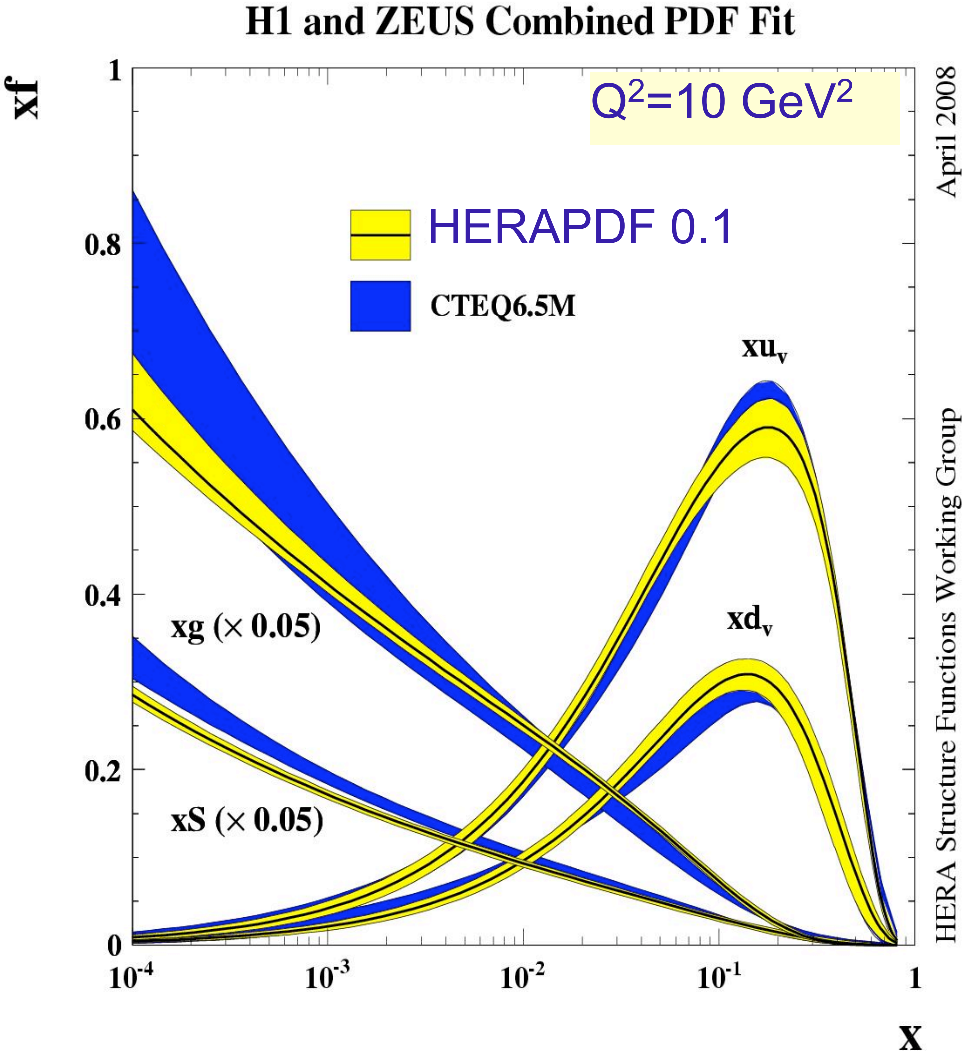
$$\tilde{\sigma}^{\pm}_{NC} = \frac{d^2\sigma^{e^\pm p}_{NC}}{dx dQ^2} \frac{xQ^4}{2\pi\alpha^2 Y_+}$$

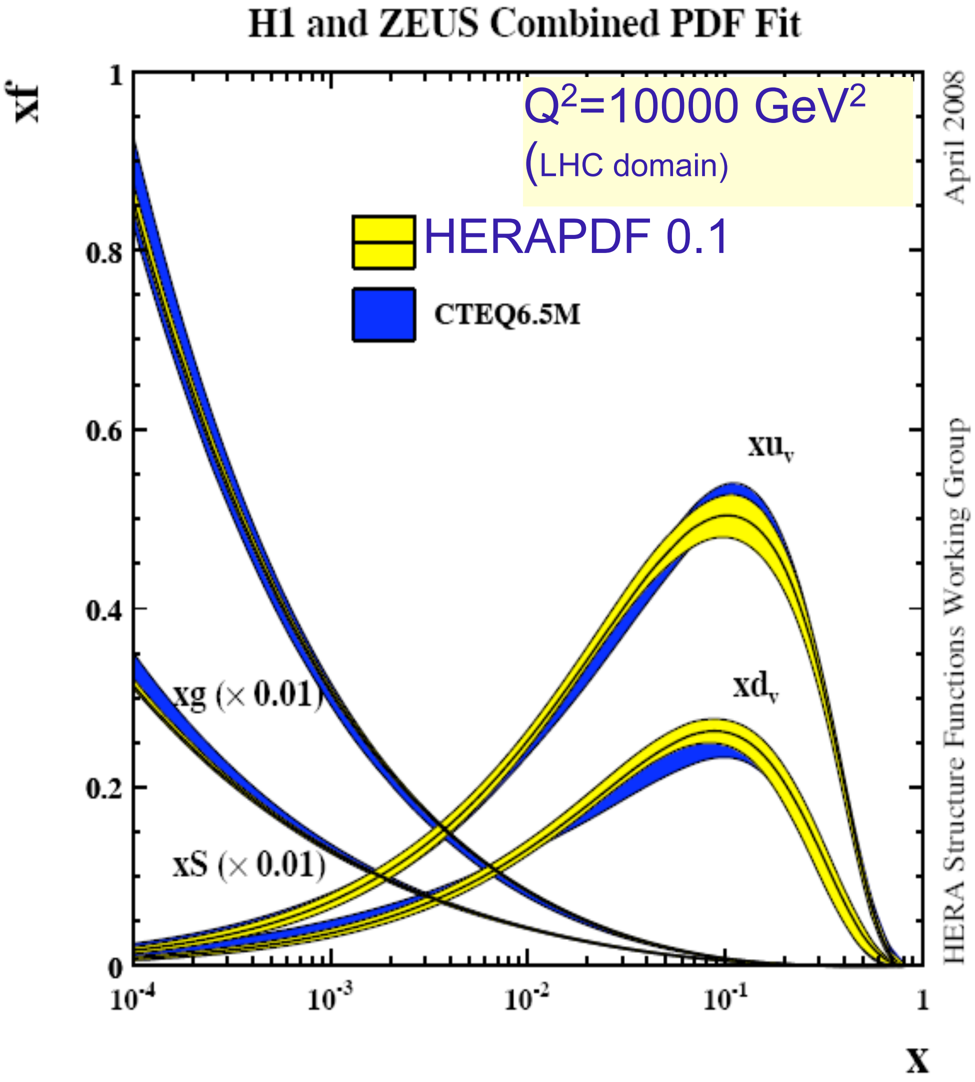
Precise data in the scaling violations regions (gluon)

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

Dramatic increase in precision

Side by side with global fits

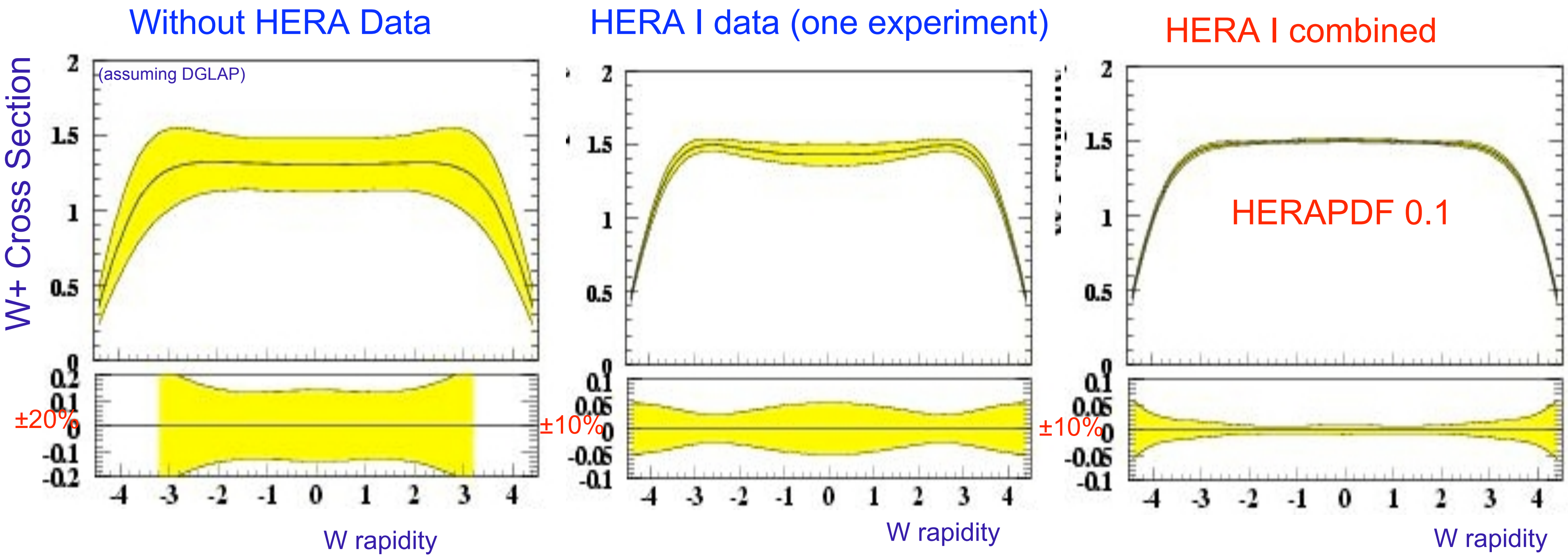




Improvement most notably at low x
The data precision is driving the improvement
Treatement of errors and parametrisation issues

Predictions for W/Z boson production at LHC

A.Cooper-Sarkar and E.Perez



Only the fit uncertainty shown here, no model variations
The step in experimental precision is significant ~2%

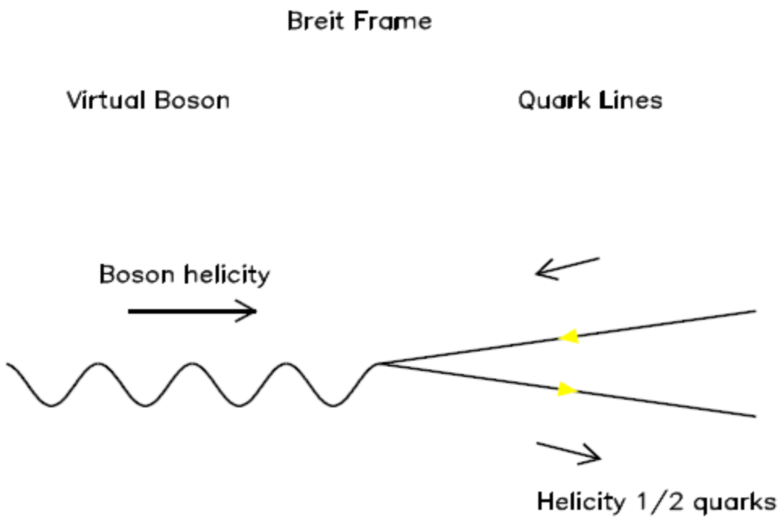
More data to be included (low Q2, bulk, HERA II data high x/Q^2) => ultimate precision

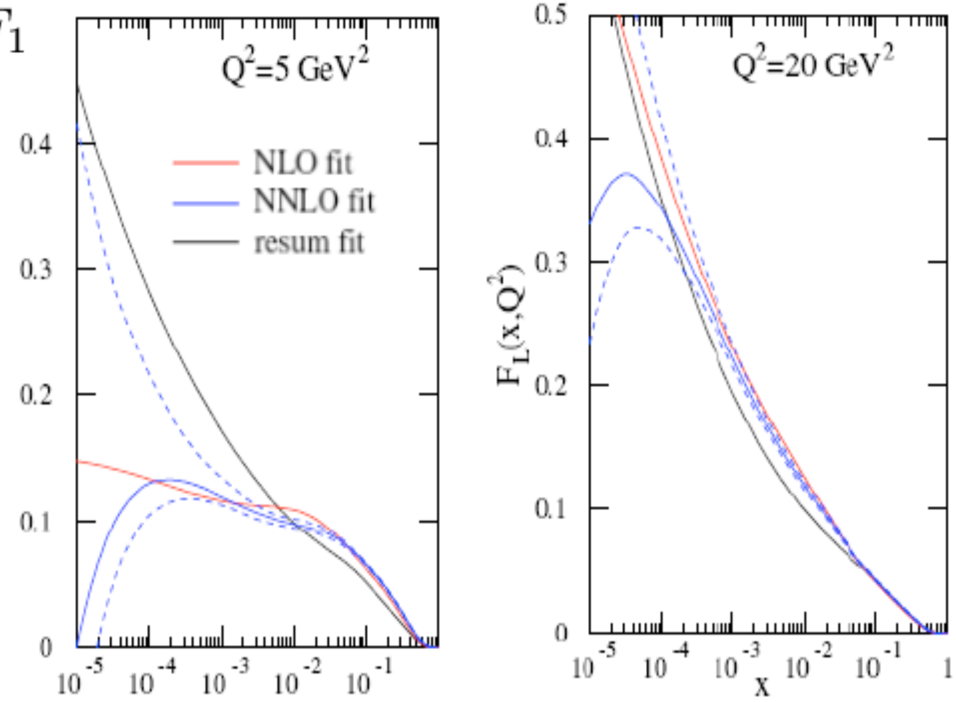
Longitudinal Structure Function F_L

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

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

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





R.Thorne, DIS08

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

Altarelli, Martinelli, 1978

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

Direct F_L measurement

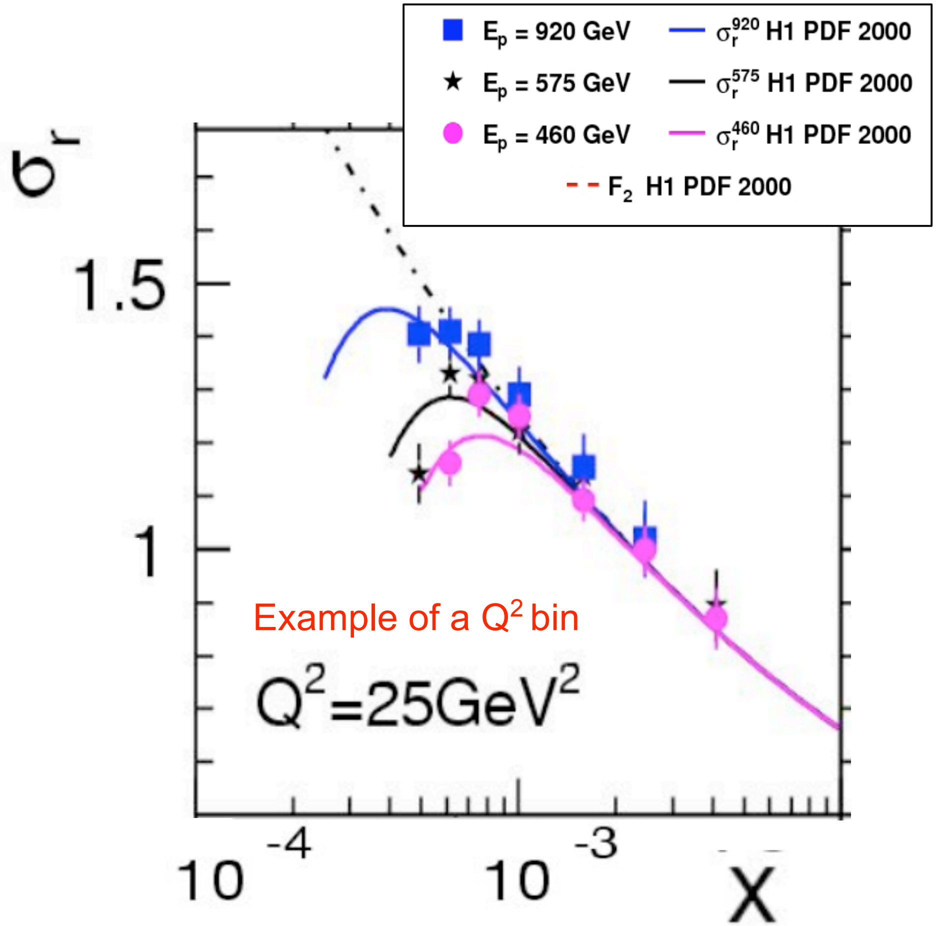
Method:

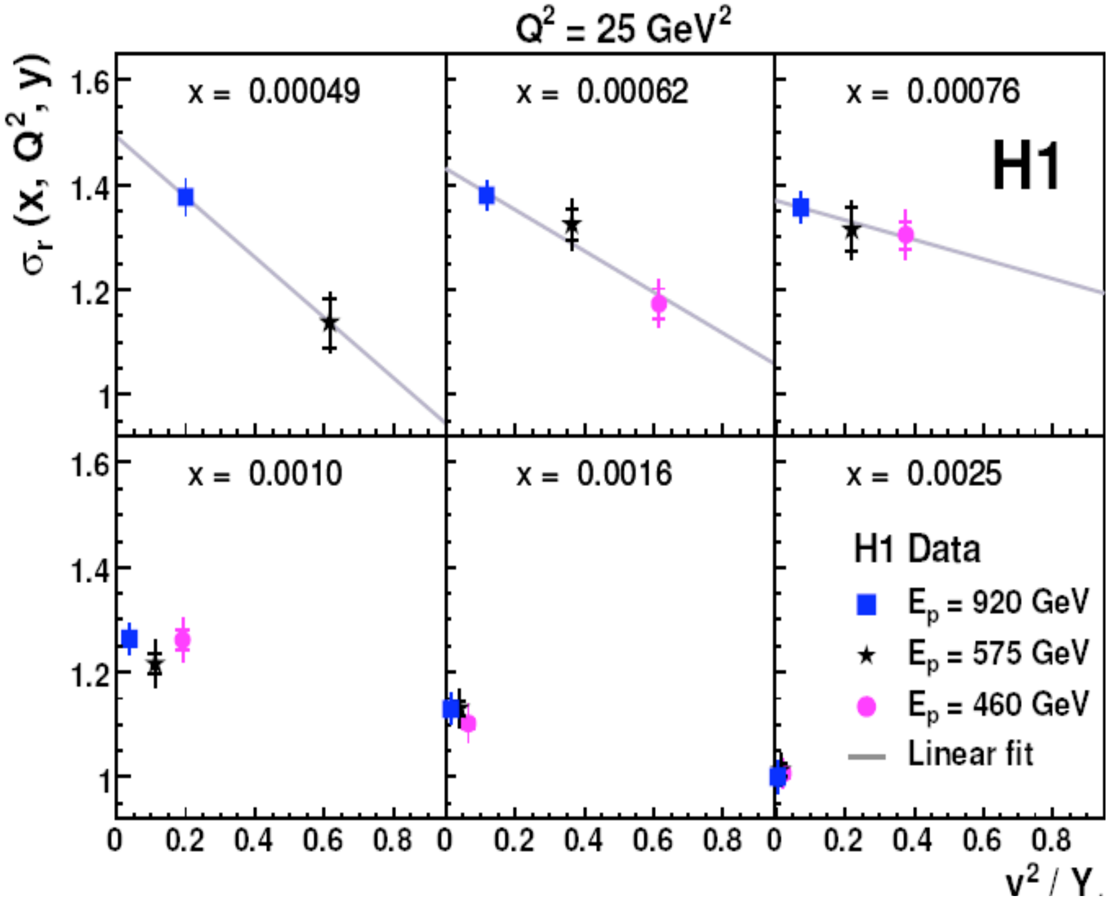
keep x,Q^2 constant, vary y: ys=y's'=Q^2/x

Vary s : Special Runs E_p=460,575 GeV

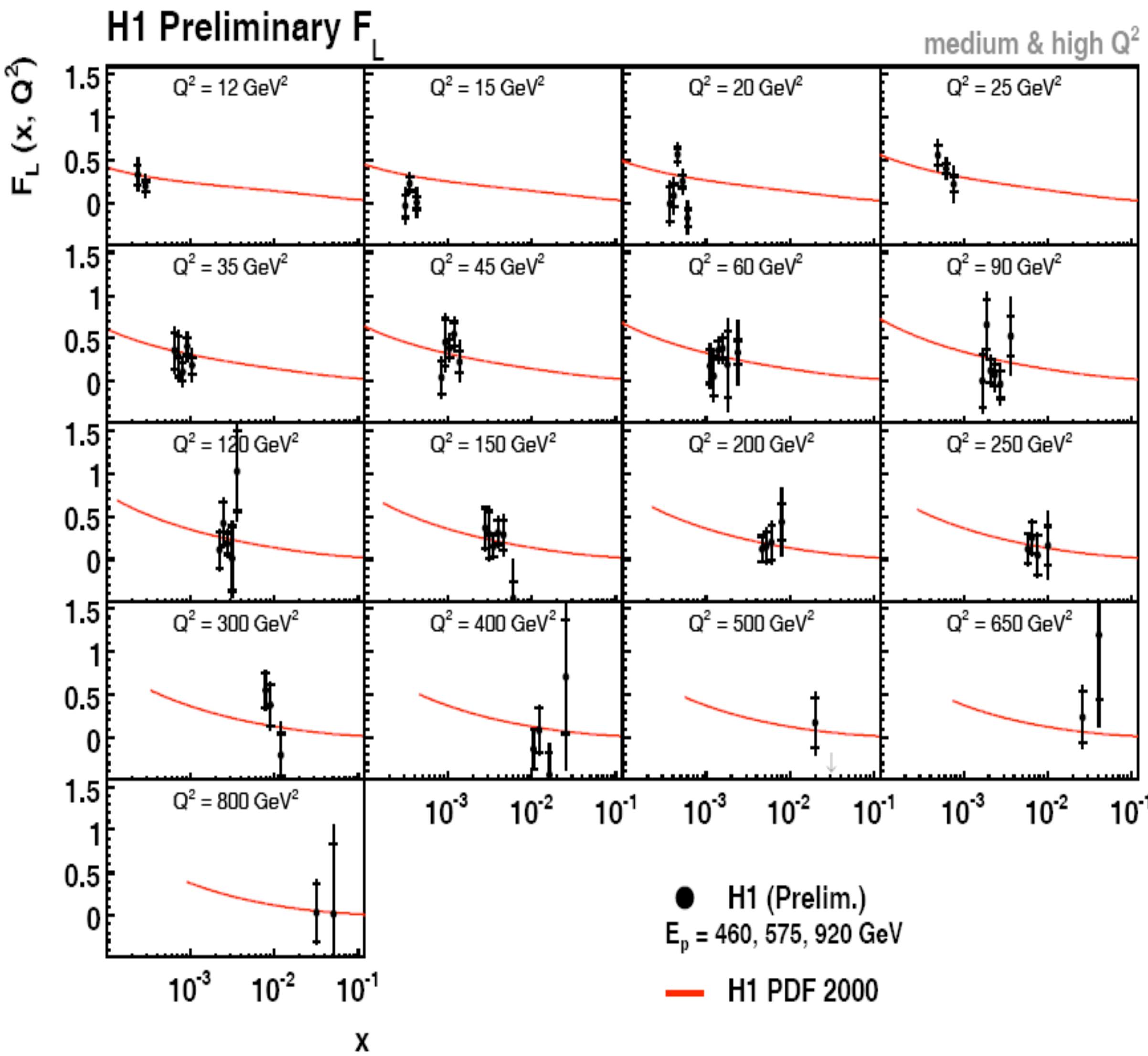
$$\sigma \sim F_2(x,Q^2) + f(y)\, F_L(x,Q^2)$$

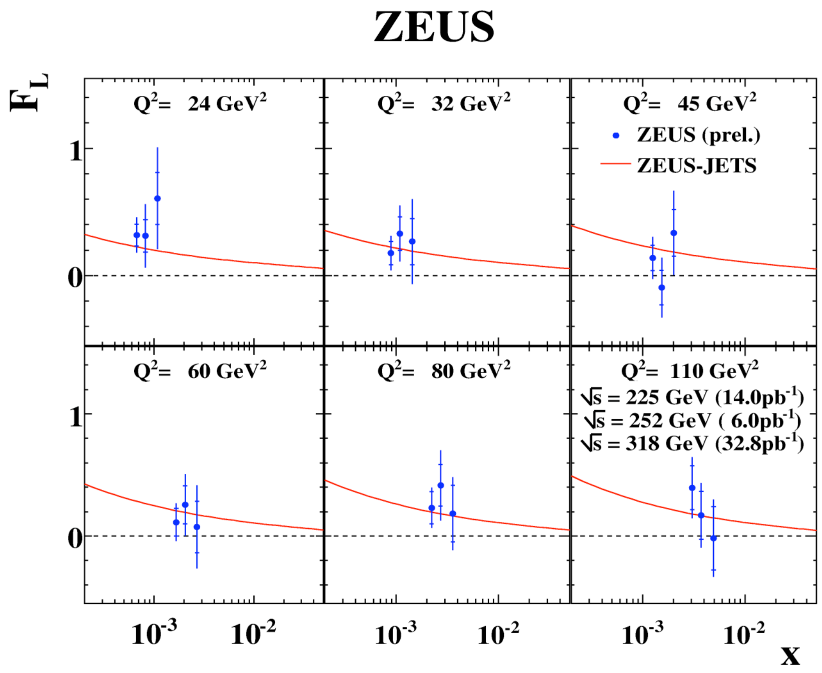
$$F_L \sim C(y) * (\sigma(E_p^1) - \sigma(E_p^2))$$





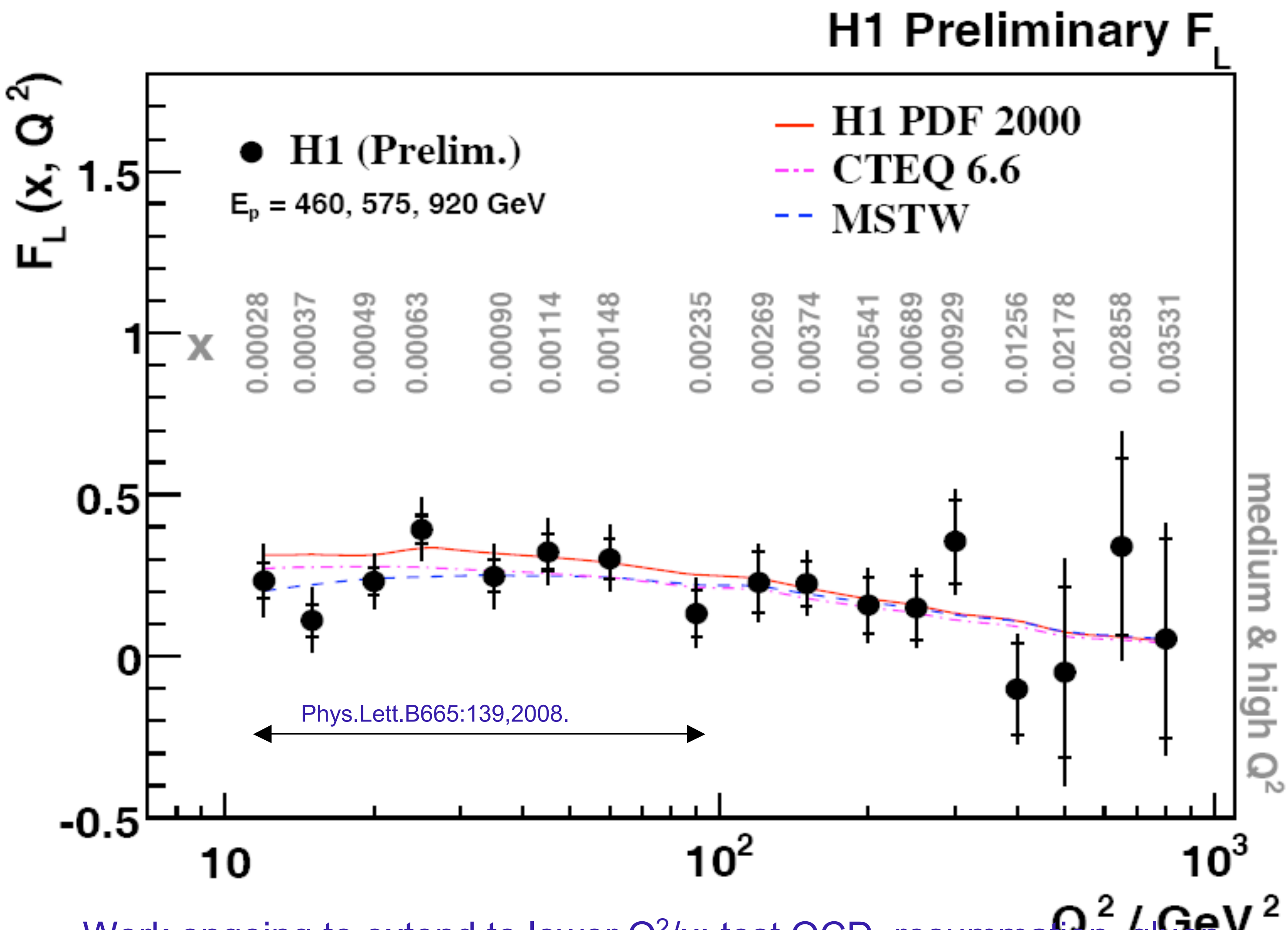
Direct F_L measurement





Measurements compatible with QCD predictions

F_L averaged in each Q^2 bin

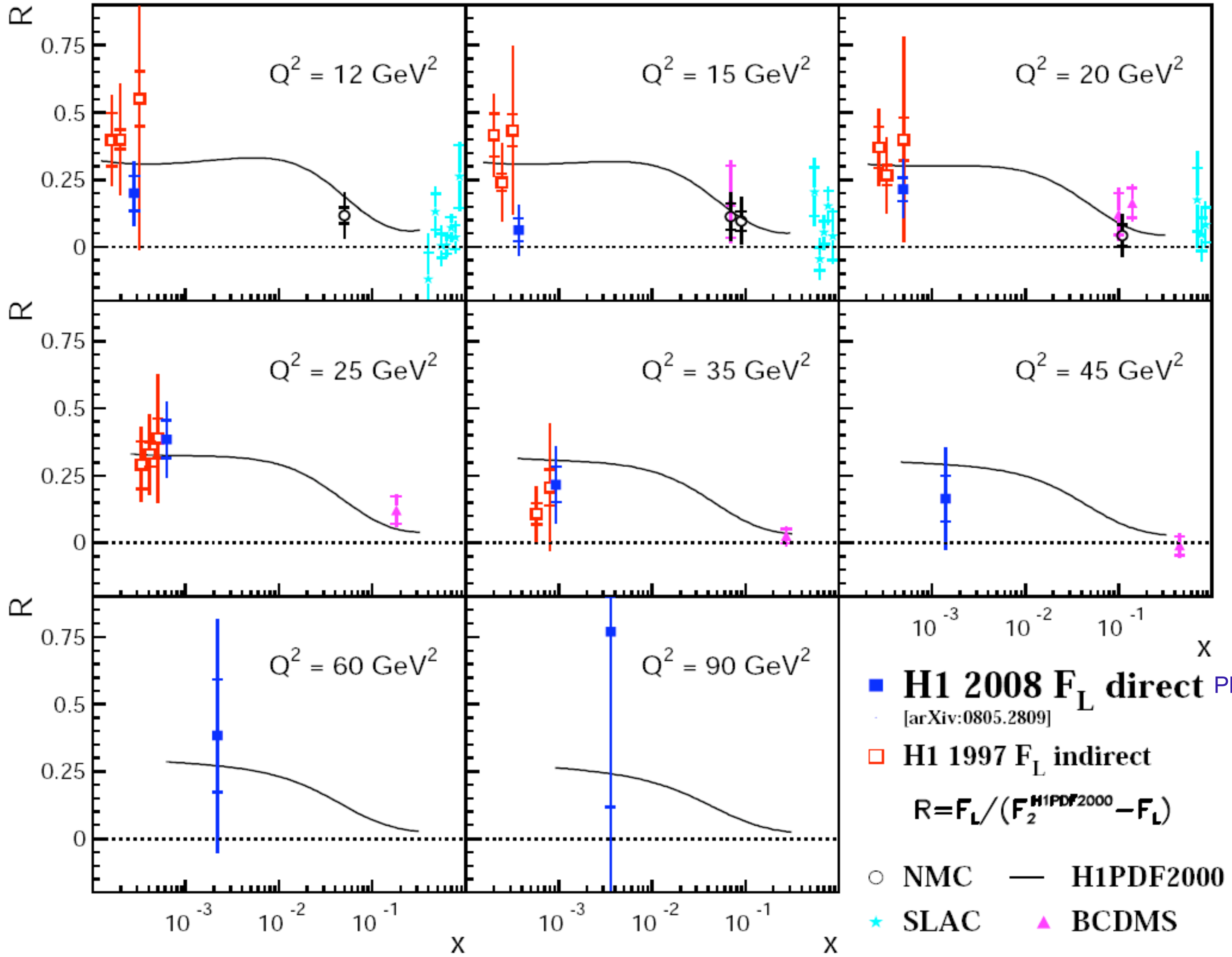


Work ongoing to extend to lower Q^2/x: test QCD, resummation, gluon

Comparison with target data and indirect determinations

The gluon "turn-on" at low x clearly visible

Q^2 range
of the first
publication
"medium Q^2"

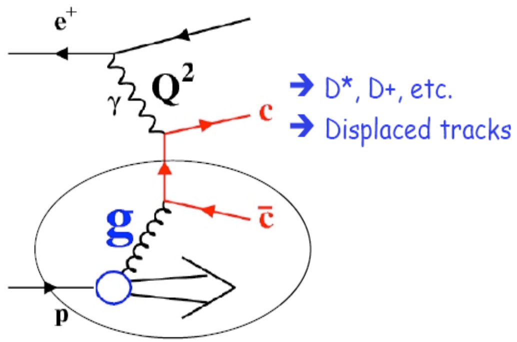


Phys.Lett.B665:139,2008

Proton's charm

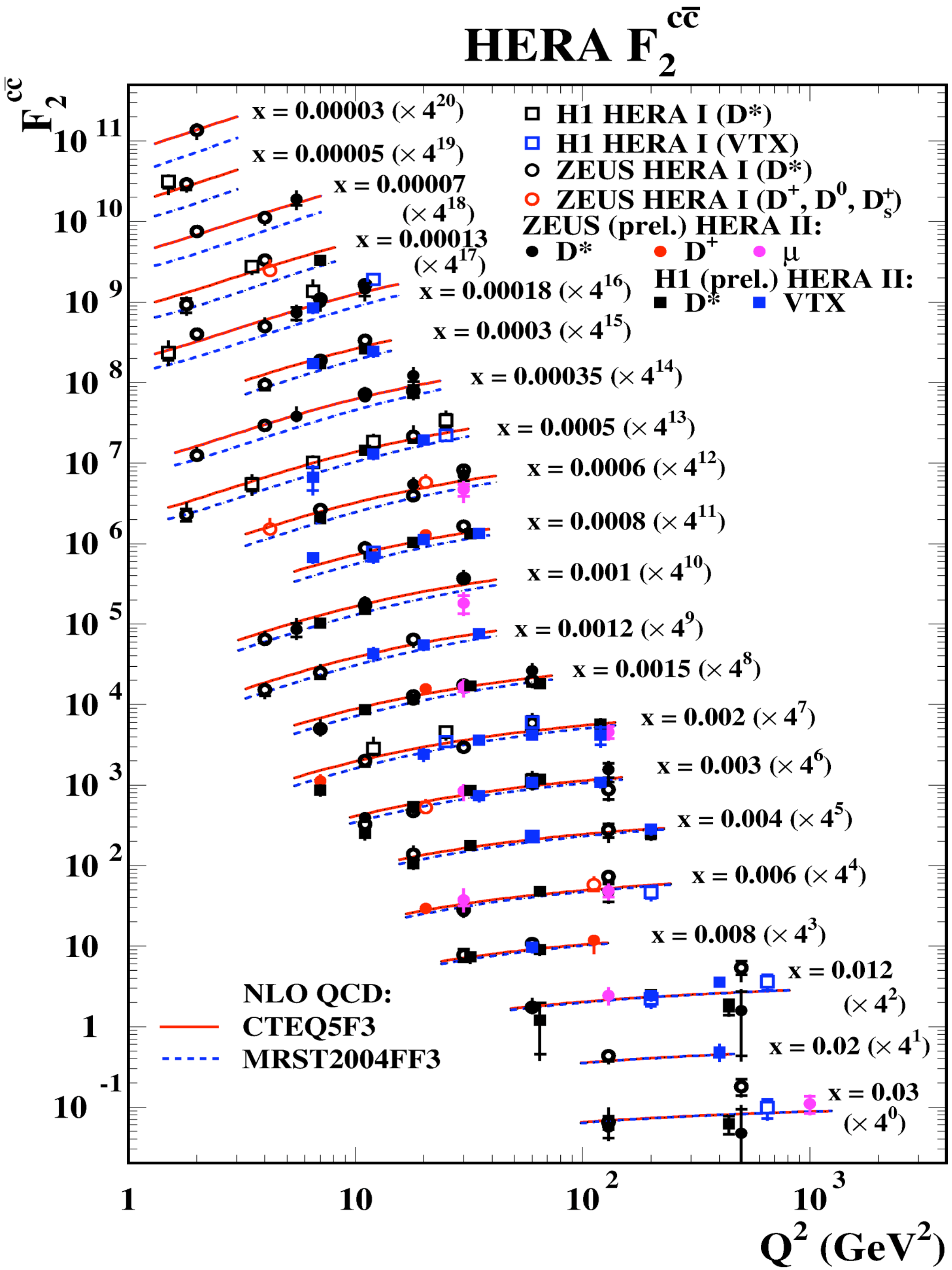
$$\sigma_r^{cc/bb} = F_2^{cc/bb} - y^2/Y_+ F_L^{cc/bb}$$

Tags: D*, lifetime
But more QCD into the game
Fortunately, large quark mass helps



Produced via boson-gluon fusion
sensitivity to the gluon

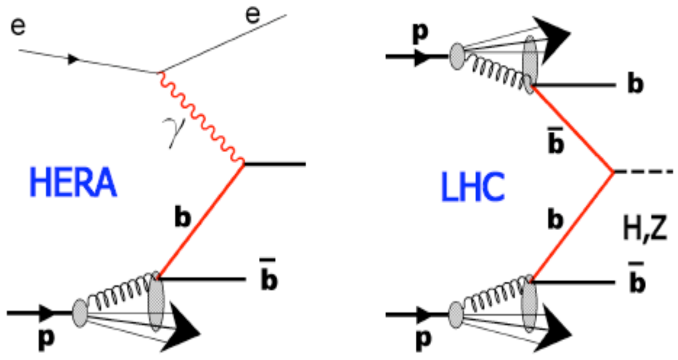
Precision to 5% (or less) possible
Theory has to follow
(mass schemes, NLO etc,)
especially visible for Q2≤m_c^2)

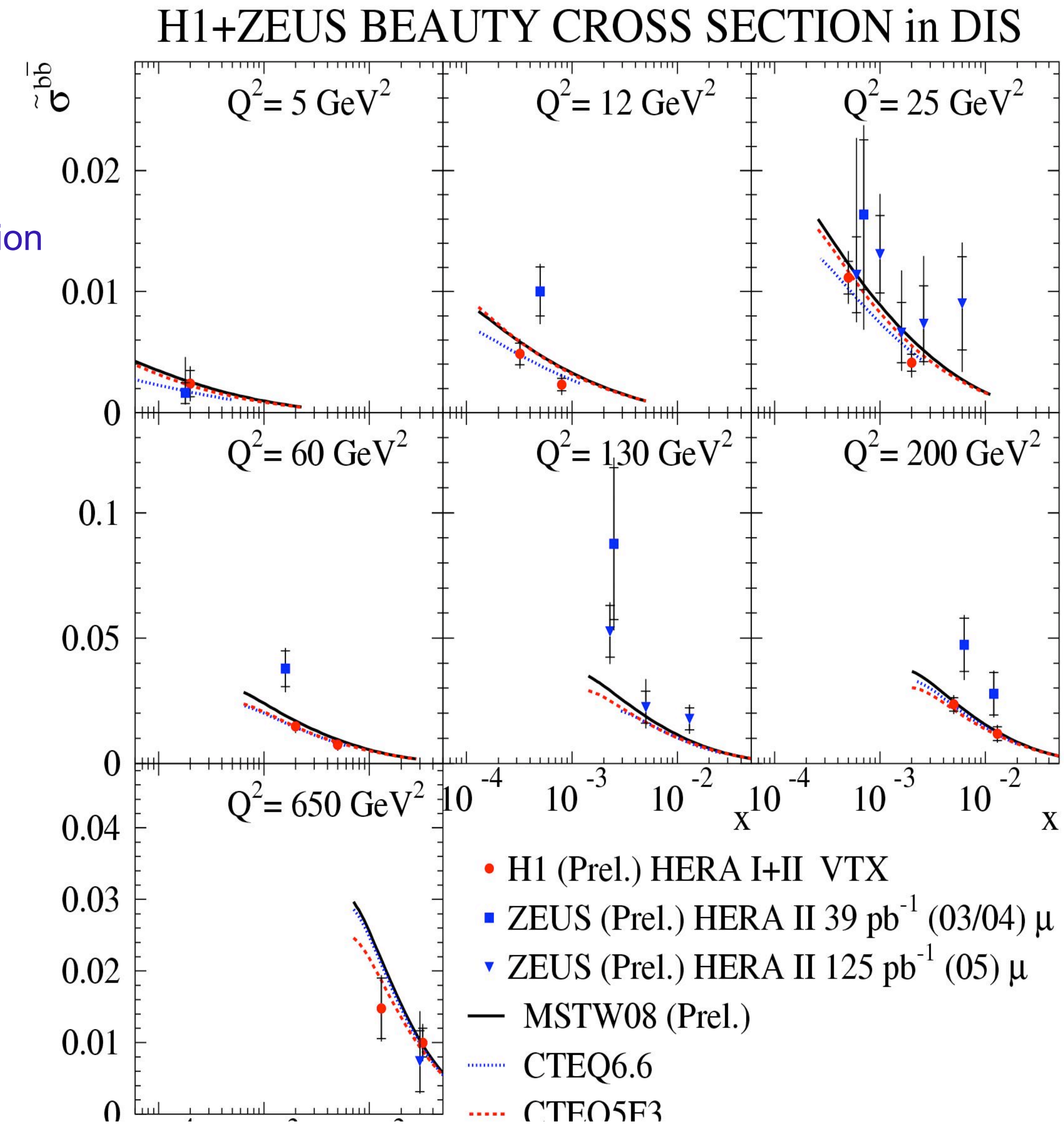


Proton's beauty

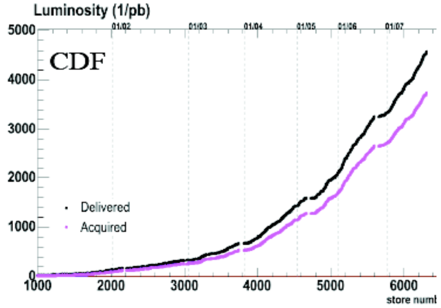
HERA II data with lifetime methods
More data available for ultimate precision

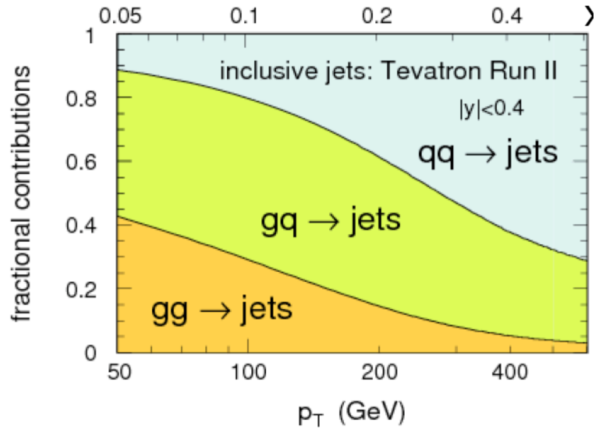
Flavour control in PDF is crucial
for some aspects of the LHC physics





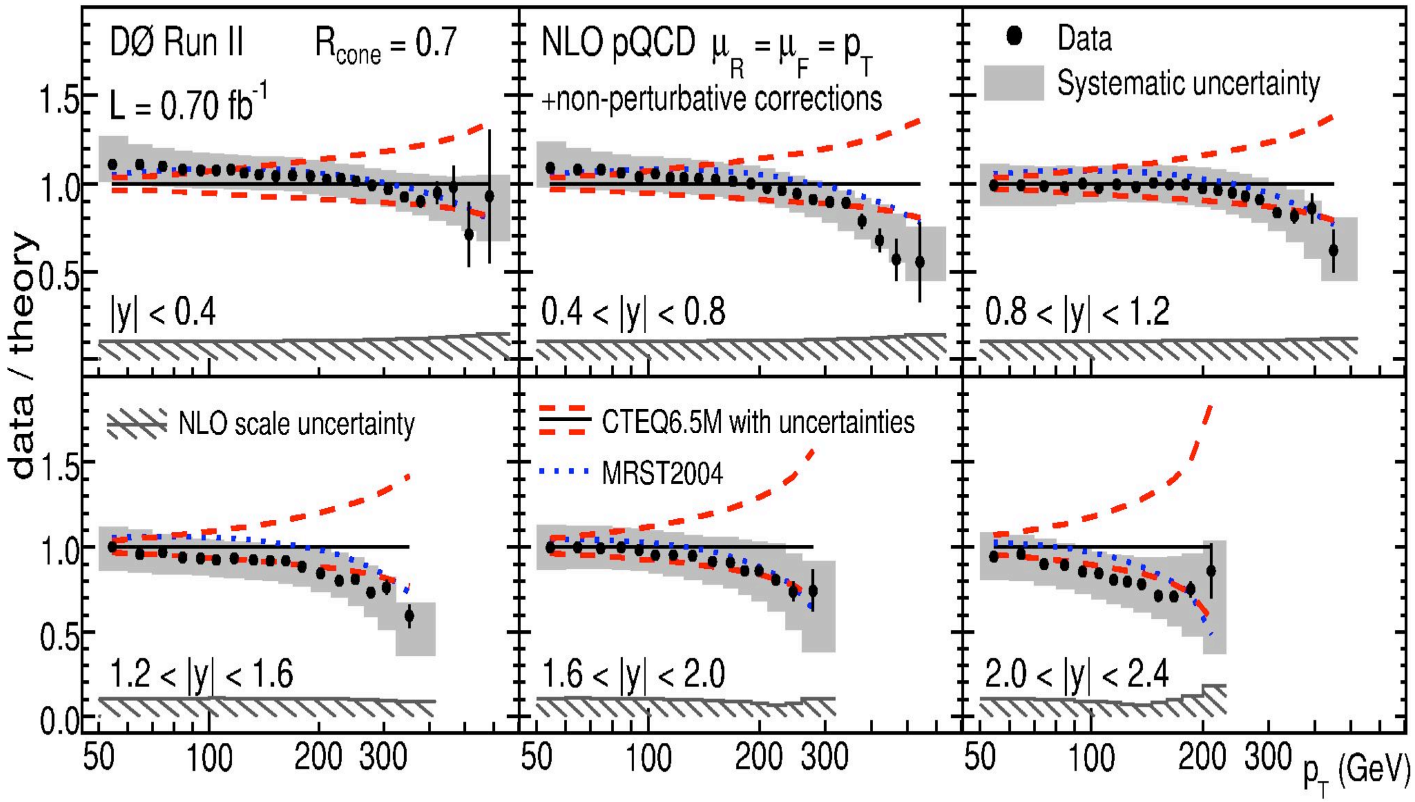
Jets production at Tevatron





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

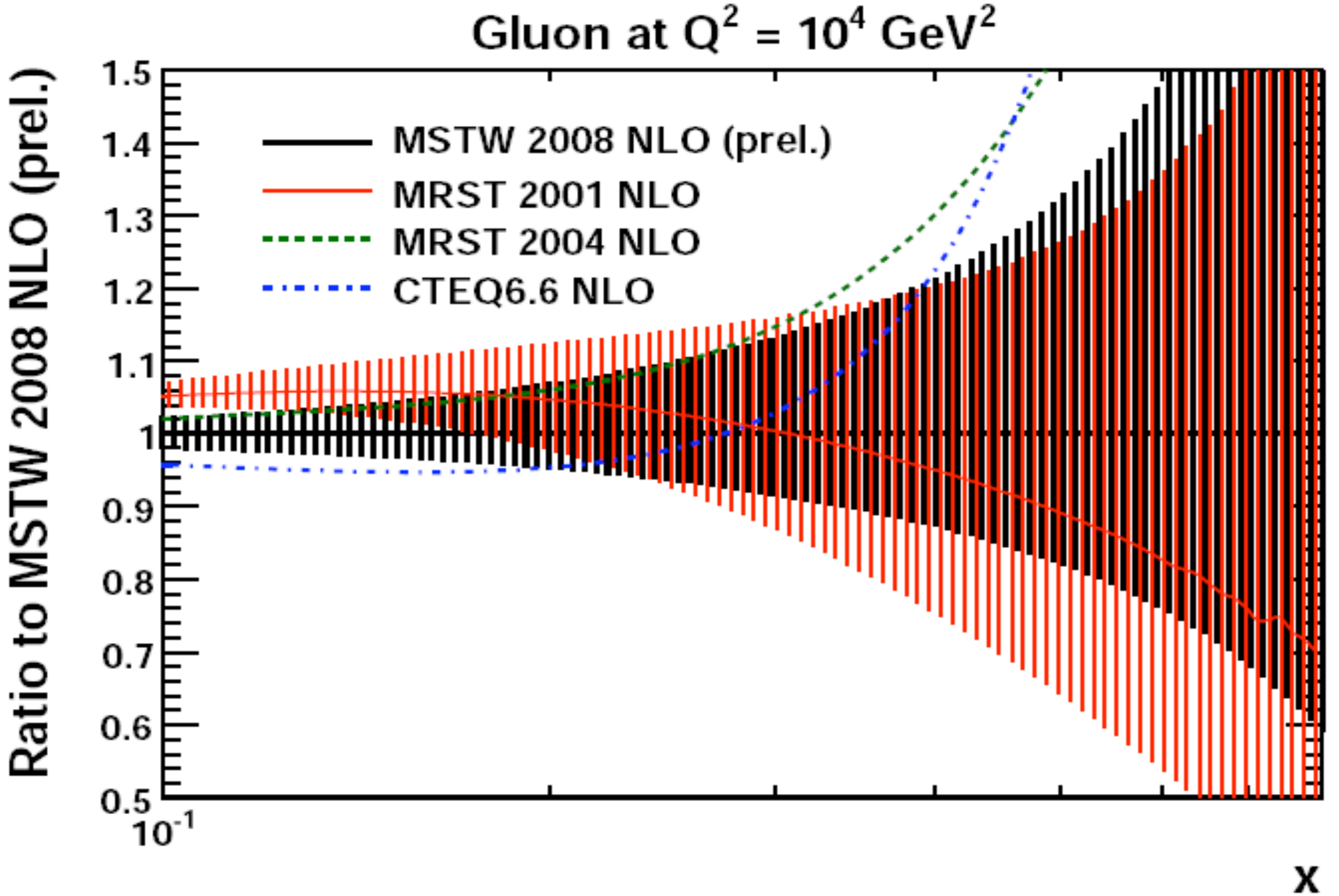


Similar study by CDF
Consistent data
to be included in the fit

Impact of the high E_T jet data on gluon at high x

MSTW 2008 analysis

G. Watt, DIS 2008



New data prefer smaller gluon at high x

W asymmetry at Tevatron

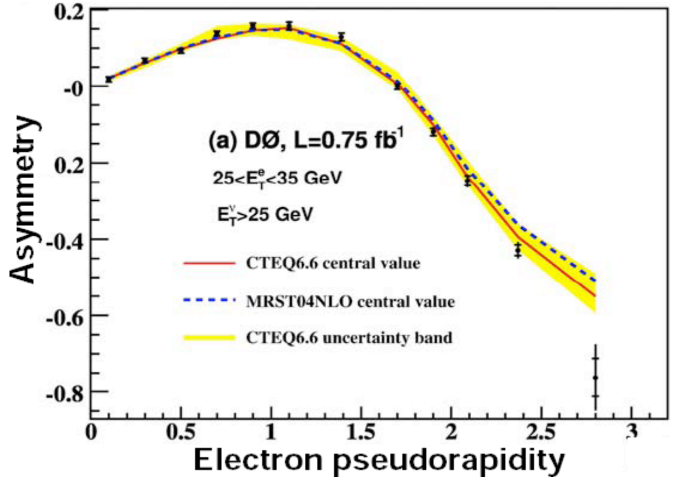
$Q^2 \approx M_W^2, \ x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y_W}$

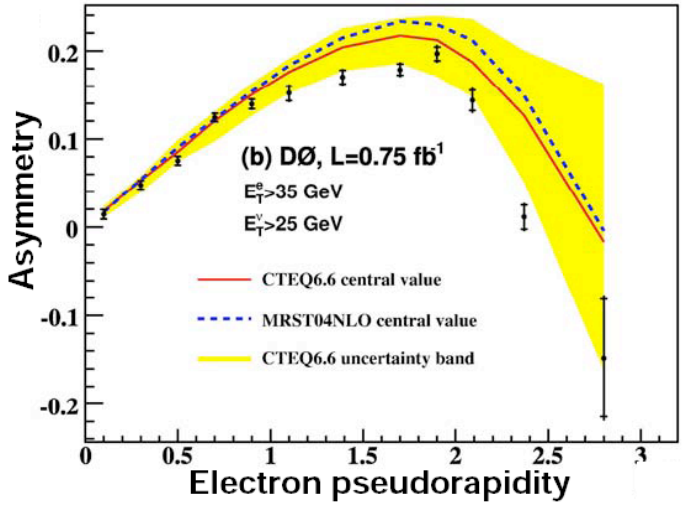
$$A_W(y) = \frac{d\sigma(W^+)/dy - d\sigma(W^-)/dy}{d\sigma(W^+)/dy + d\sigma(W^-)/dy} \approx \frac{u(x_1)d(x_2) - d(x_1)u(x_2)}{u(x_1)d(x_2) + d(x_1)u(x_2)},$$

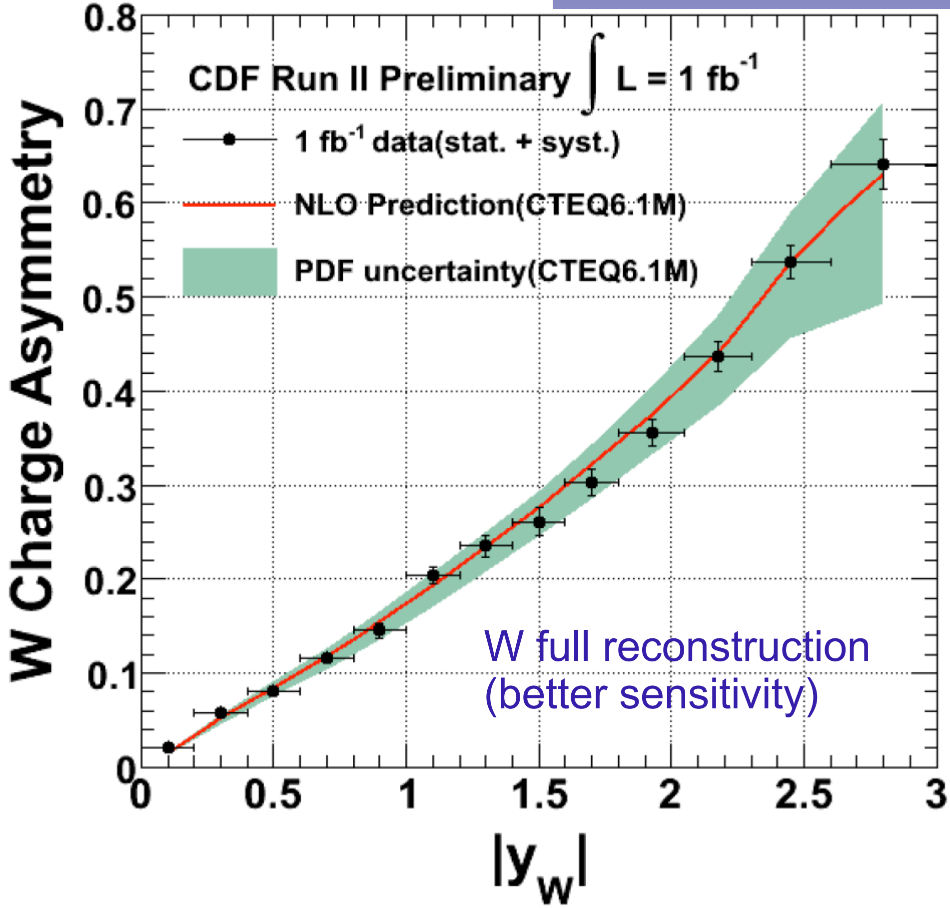
$$x_{1,2} = x_0 \exp(\pm y), \qquad x_0 = \frac{M_W}{\sqrt{s}}$$

New electron data, in ET bins

$0.002 < x < 0.8$ (1)







Promising precision for u/d ratio at high x

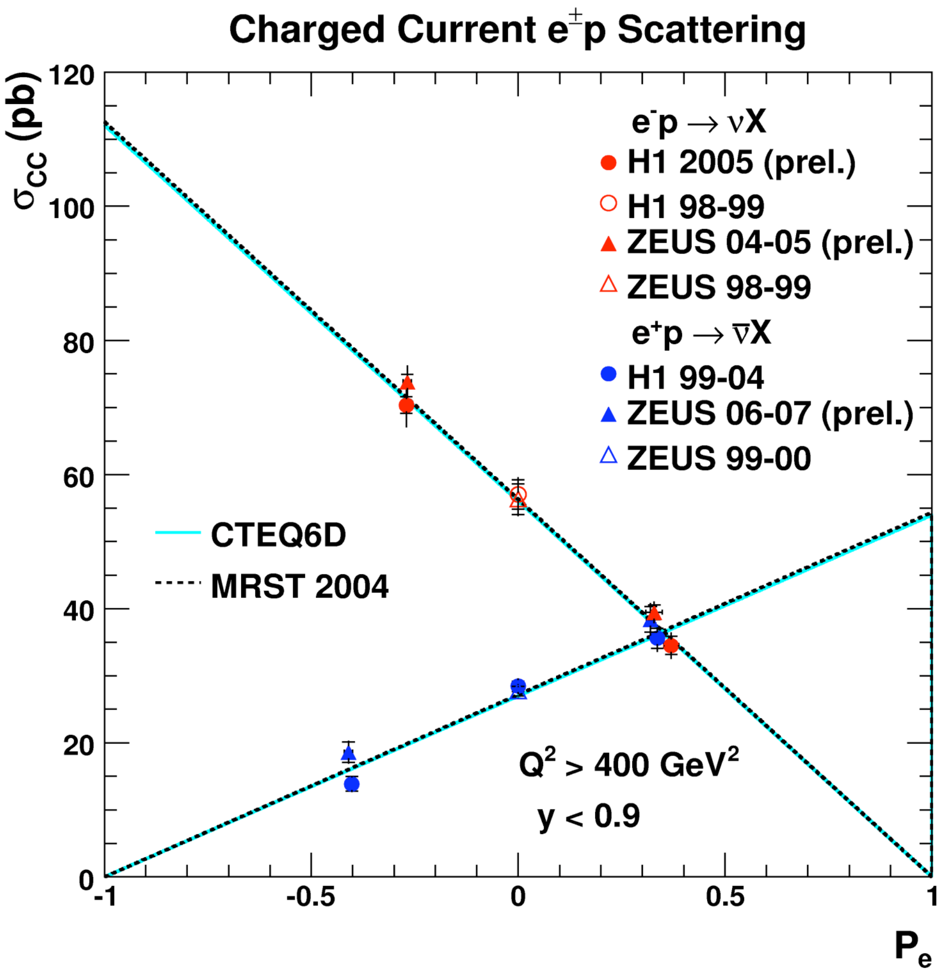
HERA II results with polarized beams

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

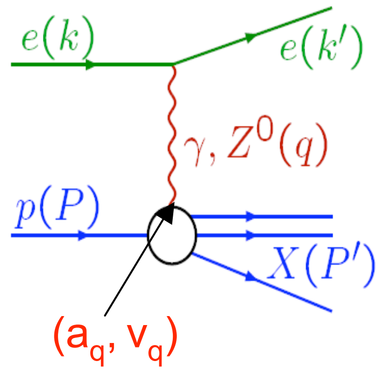
Compatible with V-A structure
(no RH currents)



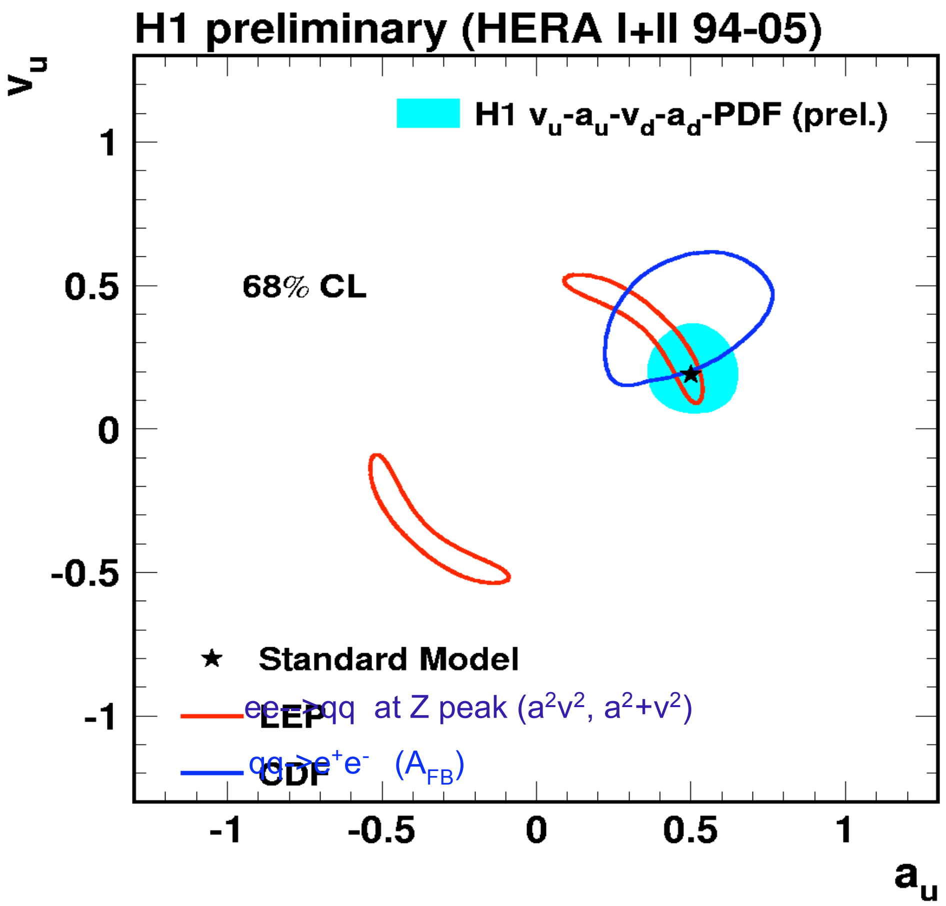
CHARM (1979):
$\nu_{\mu} N \rightarrow \mu X$

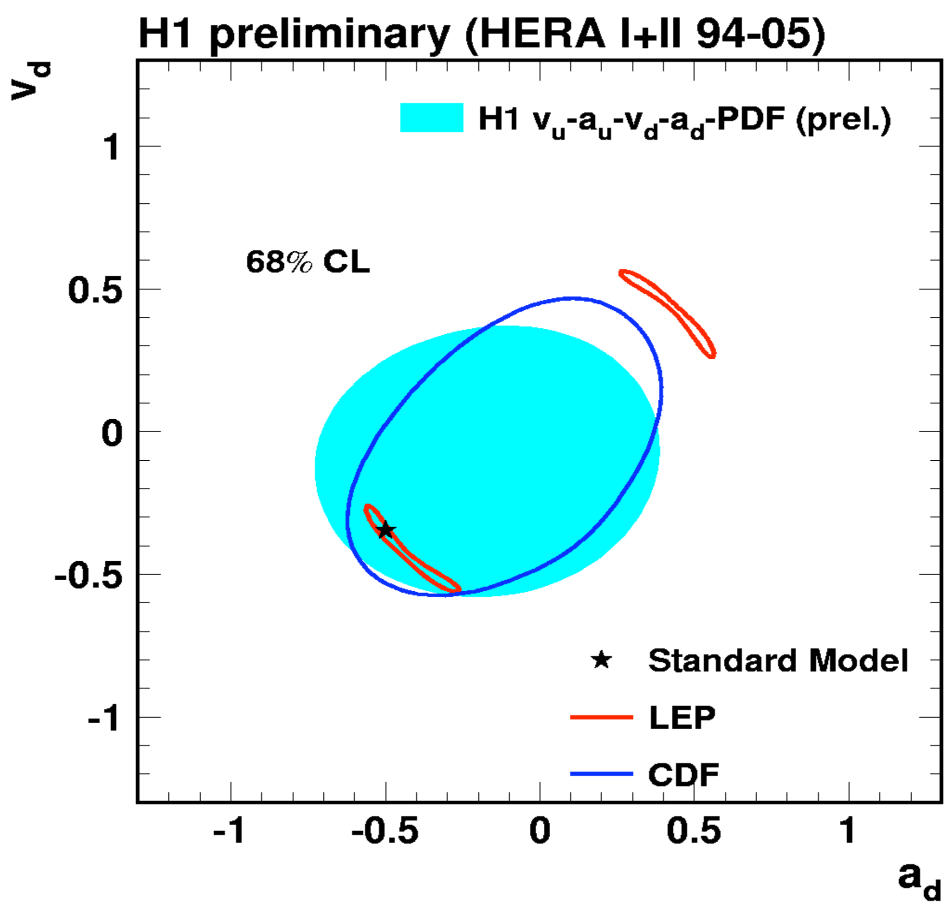
It may be concluded that positive muons produced by interactions of high-energy antineutrinos with nuclei have a longitudinal polarization oriented along their momentum direction. Within the experimental

Light quark couplings to Z

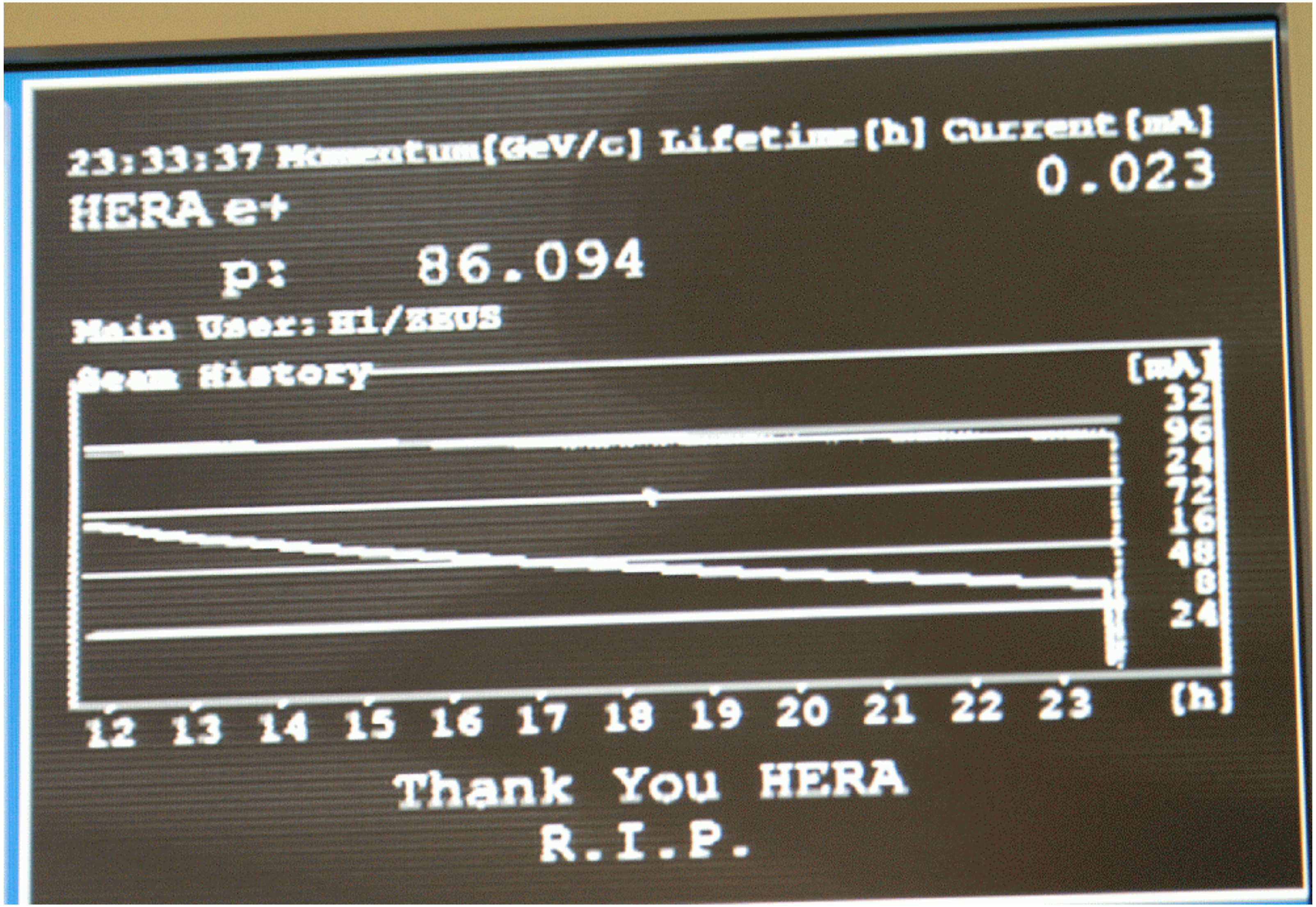


NC/CC data=> full QCD/EW Fit: PDF's+light quarks couplings
Now taking advantage of polarisation @HERA II : new fit





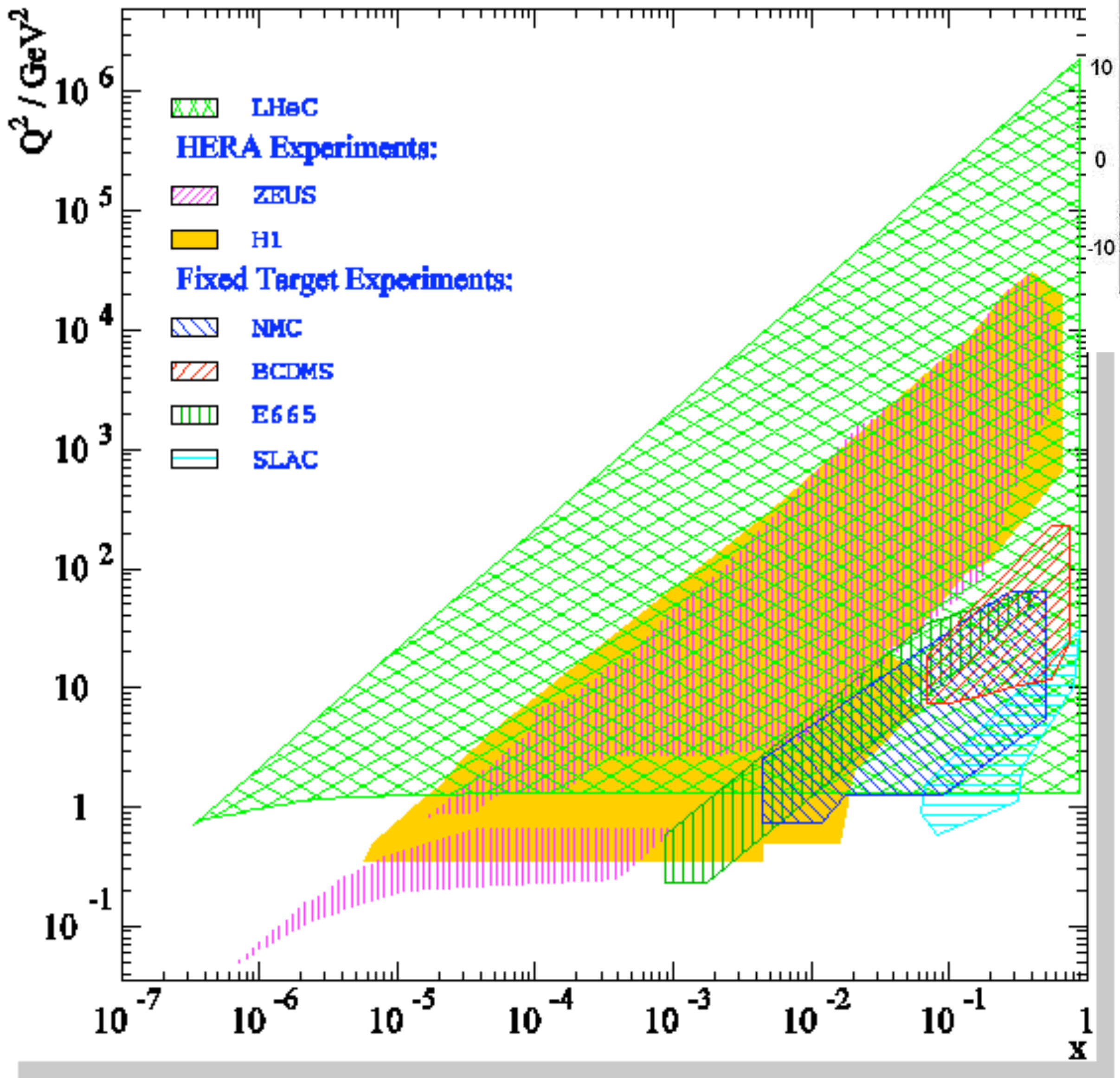
HERA end of run: June 30, 2007, 23h30

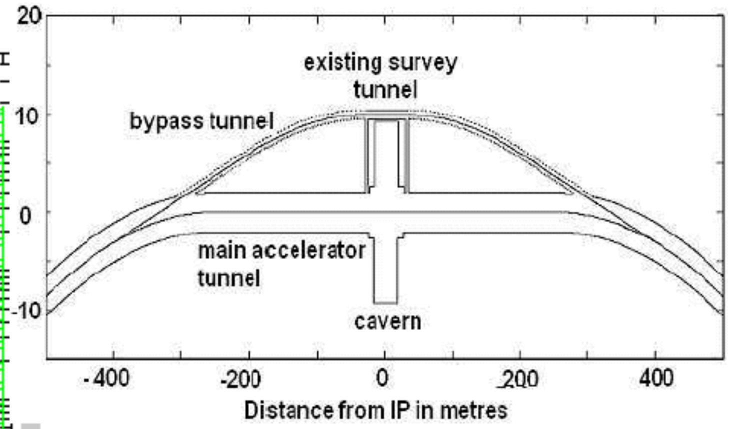


It will take a few more years to fully analyse the data...

LheC e(70 GeV) x p(7 TeV)

ECFA Project





Instead of conclusions...

...

if all the efforts that we expend on the discussions on which form of field theory one should use were devoted to arguing for a higher-energy accelerator so that we can do more experiments over the next generation and really learn more about the basic structure of matter.

Murray Gell-Mann, Rochester Conference, 1966

Dogmas are absolutely essential for the progress of Science but they become tragic if they succeed in stopping experimentation designed to prove them wrong.

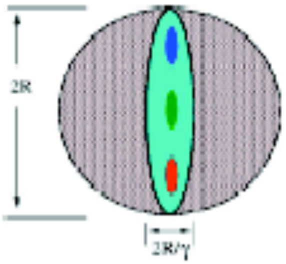
Abdus Salam, Rochester Conference, 1976

Backup

Gluon counting

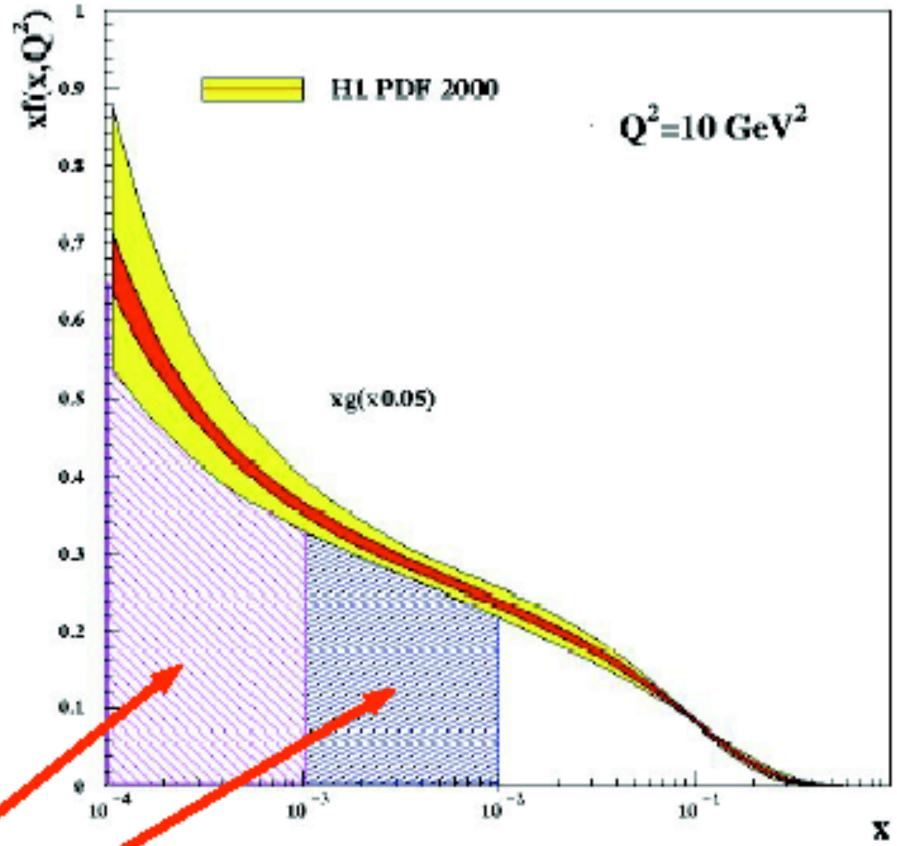
- number of gluons in long. phase space dx/x : $xg(x,\mu^2)dx/x$
- occupation area:
  nr of gluons x (trans size)^2

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



- 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:

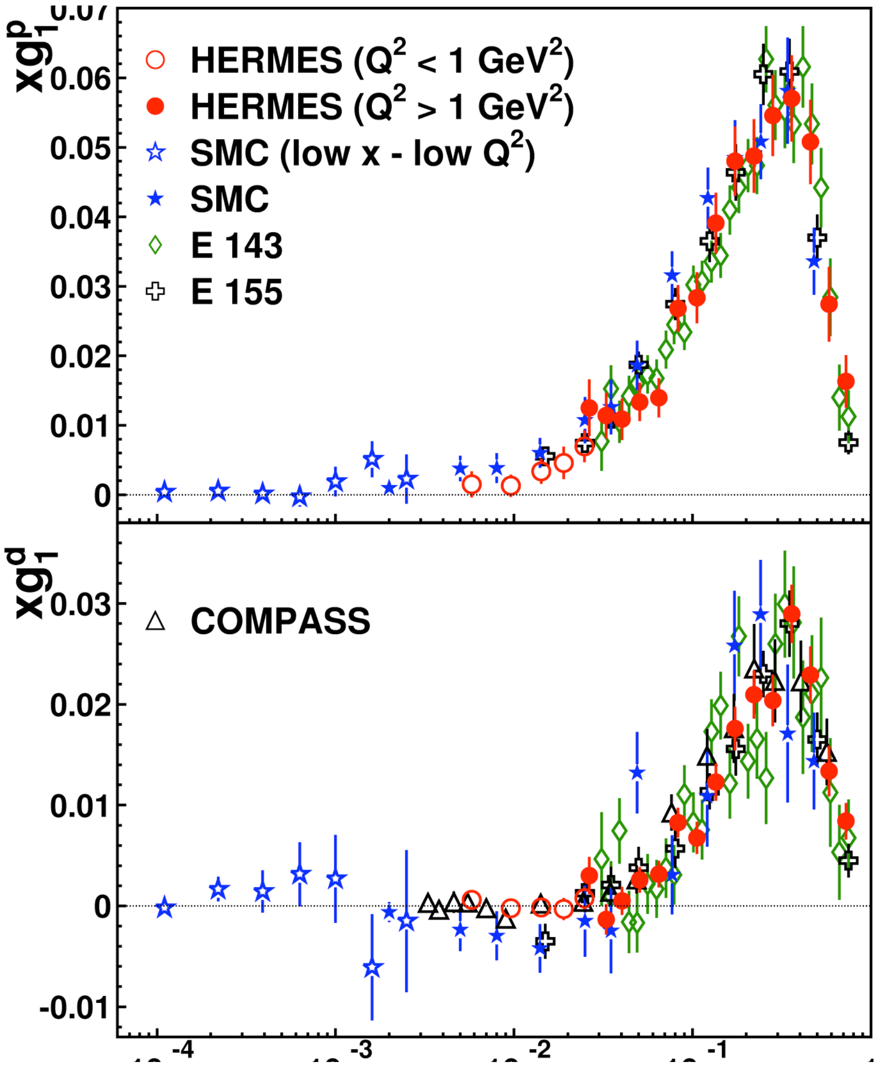
$$\frac{0.2}{10GeV^{-1}}100 \sim \pi \qquad !!!!!$$

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

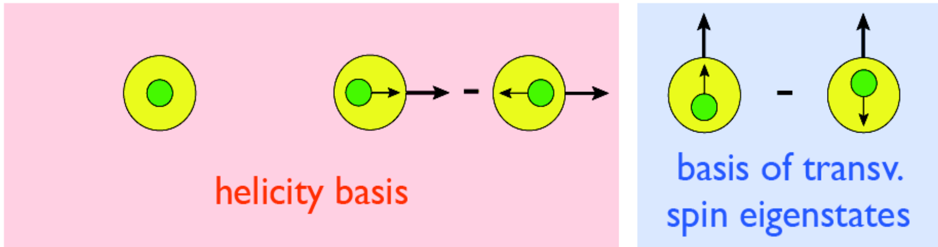
$$\sigma_{LL} \equiv \frac{1}{2}(\sigma^{\rightleftarrows} - \sigma^{\rightrightarrows})/2 \simeq g_1^{p,n}(x,Q^2) = \frac{1}{2}\sum_q e_q^2 \left[\Delta q^{p,n}(x,Q^2) + \Delta\bar{q}^{p,n}(x,Q^2)\right]$$



$$\Delta\Sigma \simeq 0.33$$

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!

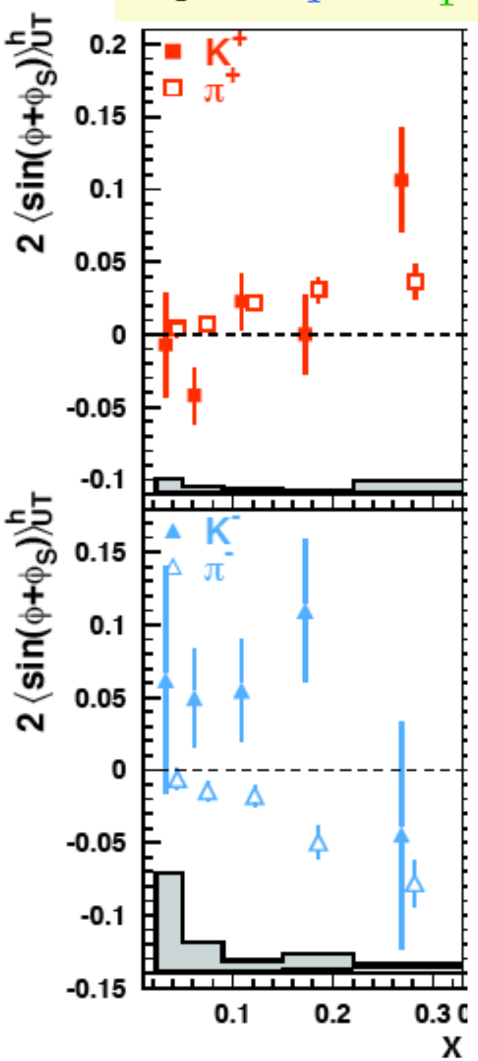
Level arm in Q^2 not large:
gluon contribution not constrained
=> semi-inclusive data

HERMES PRELIMINARY

Asymmetries

Collins

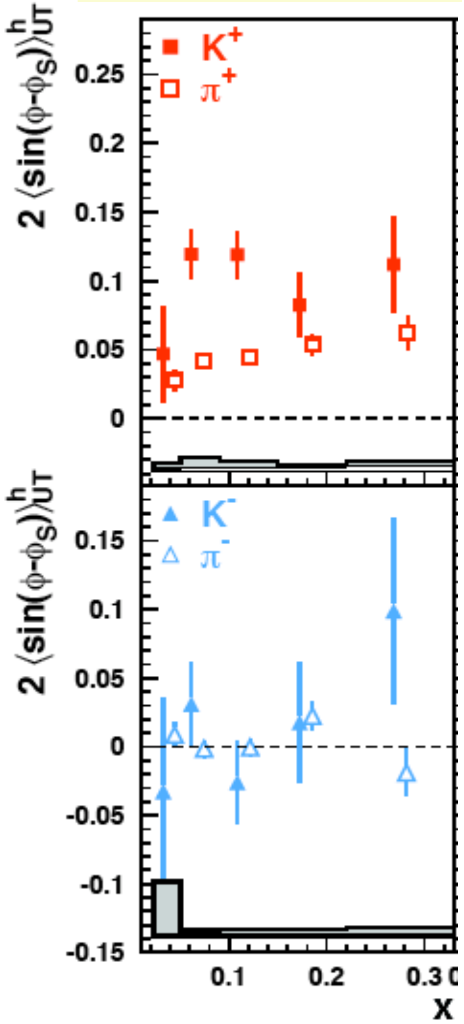
$A_C \propto \delta q \otimes H_1^{\perp}$



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

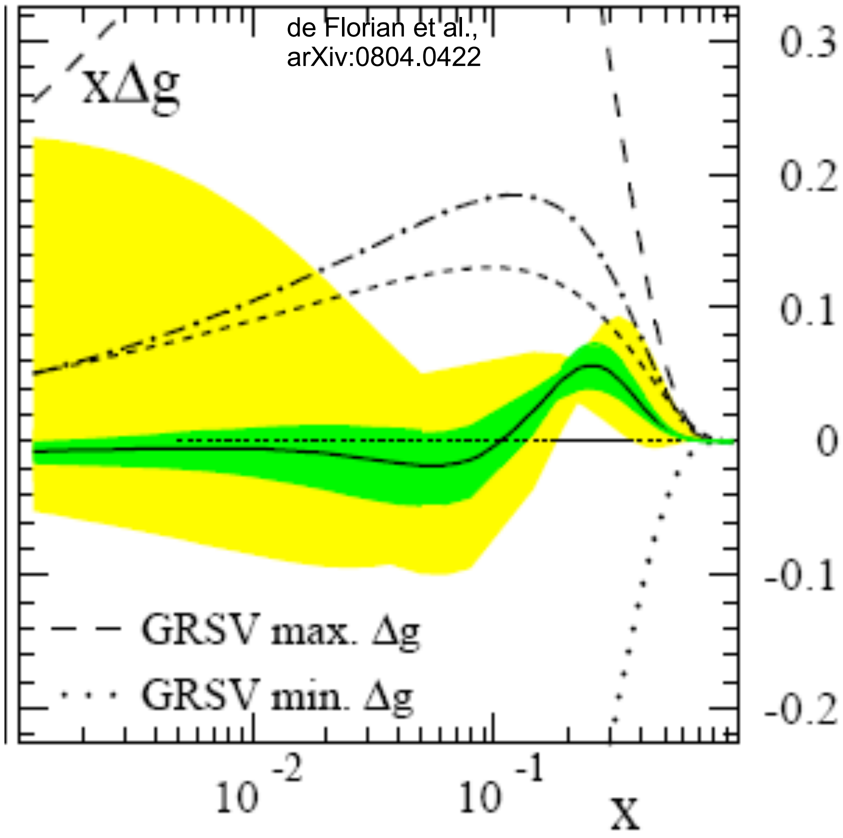
Implies non-zero angular momentum

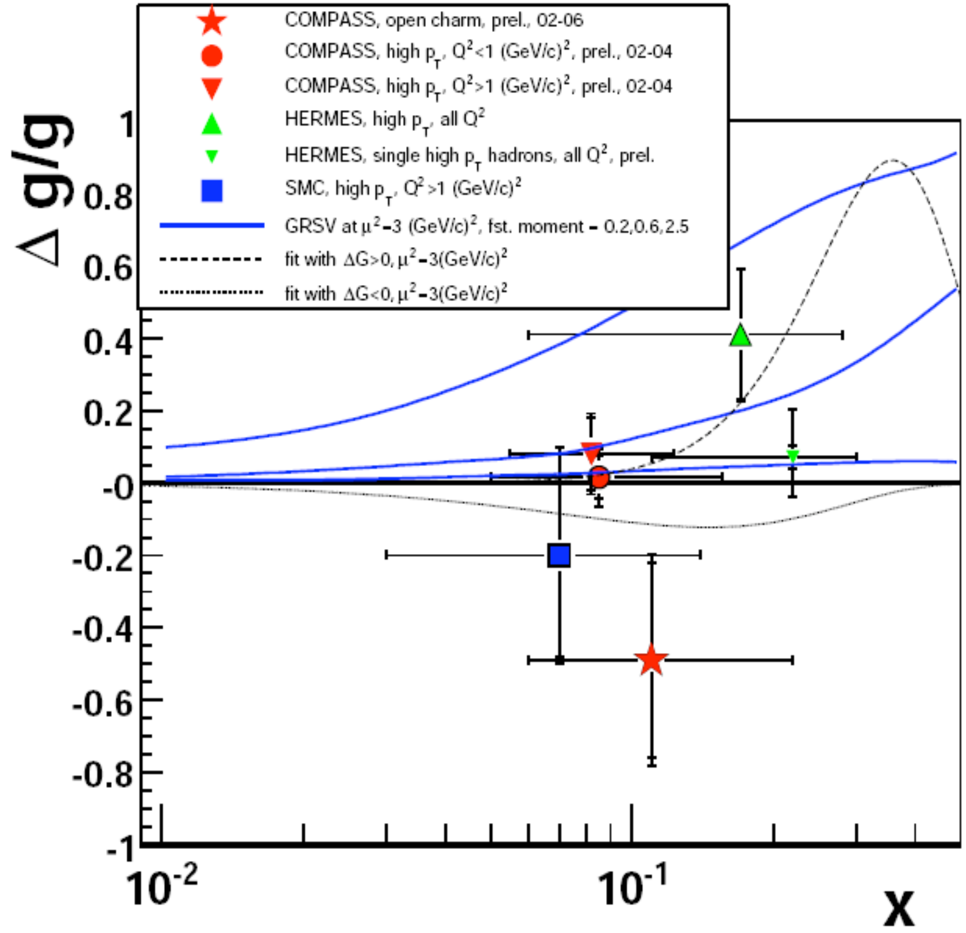
Gluon contribution to the spin

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



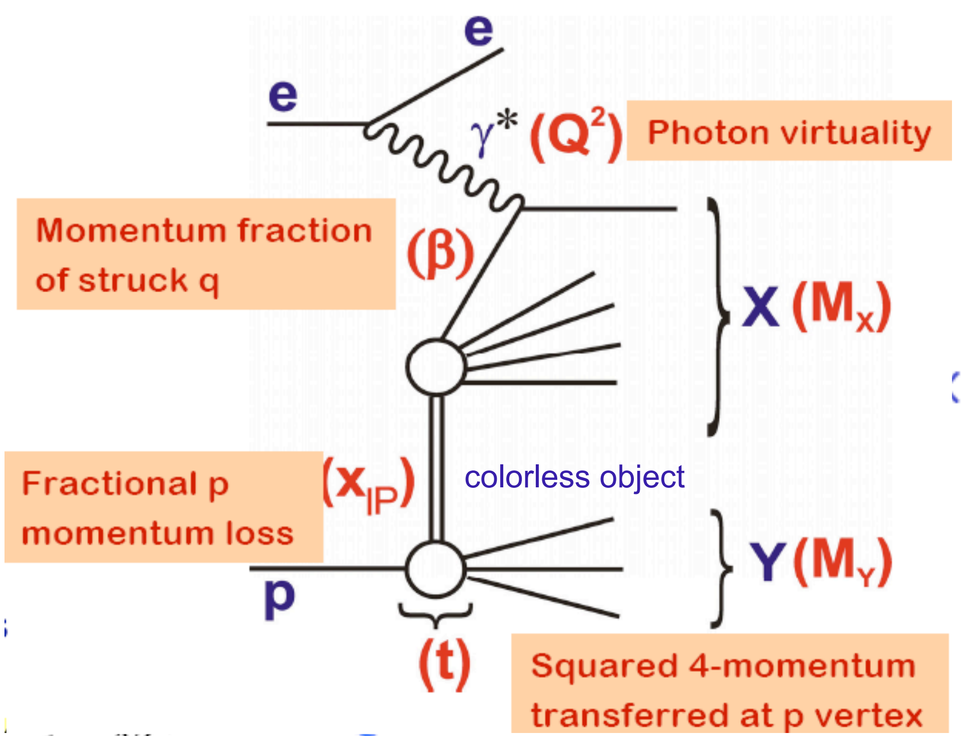


Extreme options now excluded

Extend x range in pp at RHIC

Hard Diffraction at HERA

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



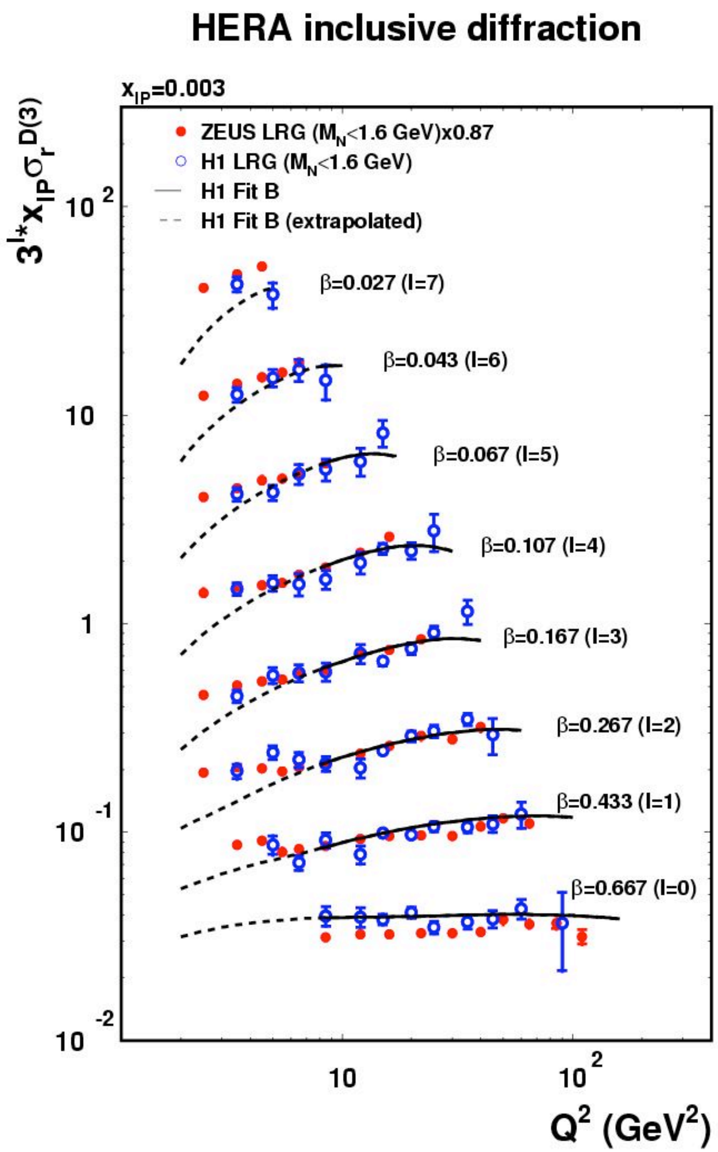
empty rapidity region (gap)

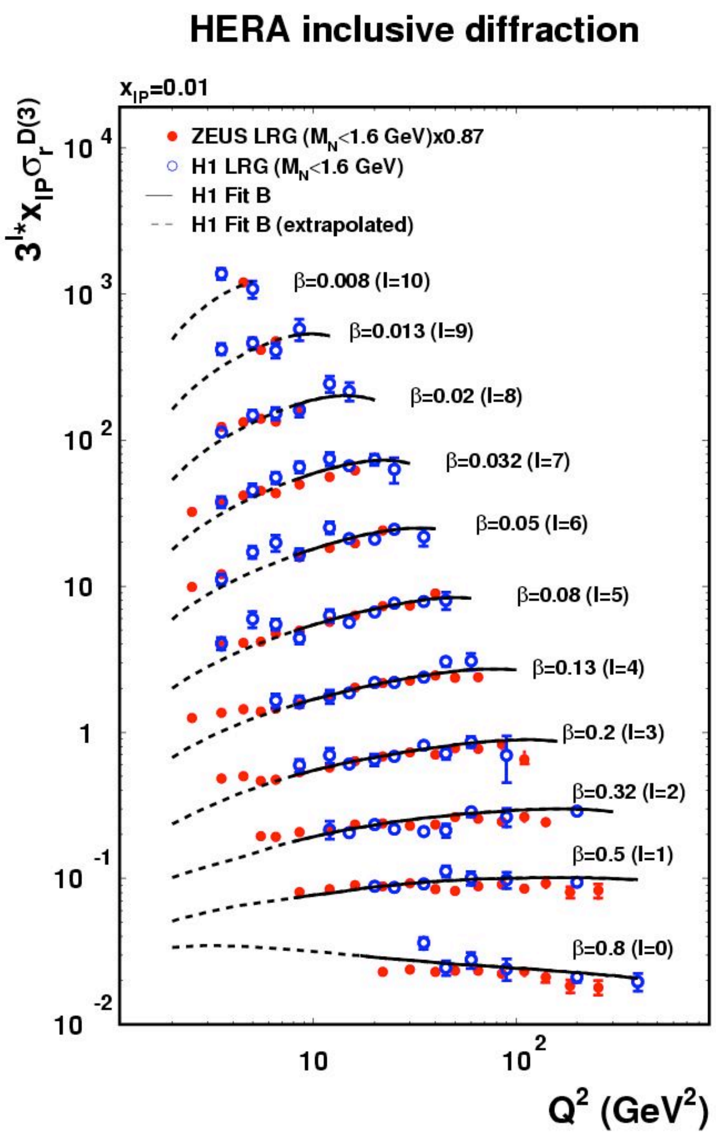
or intact proton detected down the beampipe (roman pots)

$$\frac{d\sigma^{NC}_{diff}}{dx_{IP}dtd\beta dQ^2} \propto \frac{1}{Q^4} F_2^{D(4)}(x_{IP}, t, \beta, Q^2)$$

assuming factorisation: structure of the diffractive echnage

H1 and ZEUS M_N<1.6 GeV



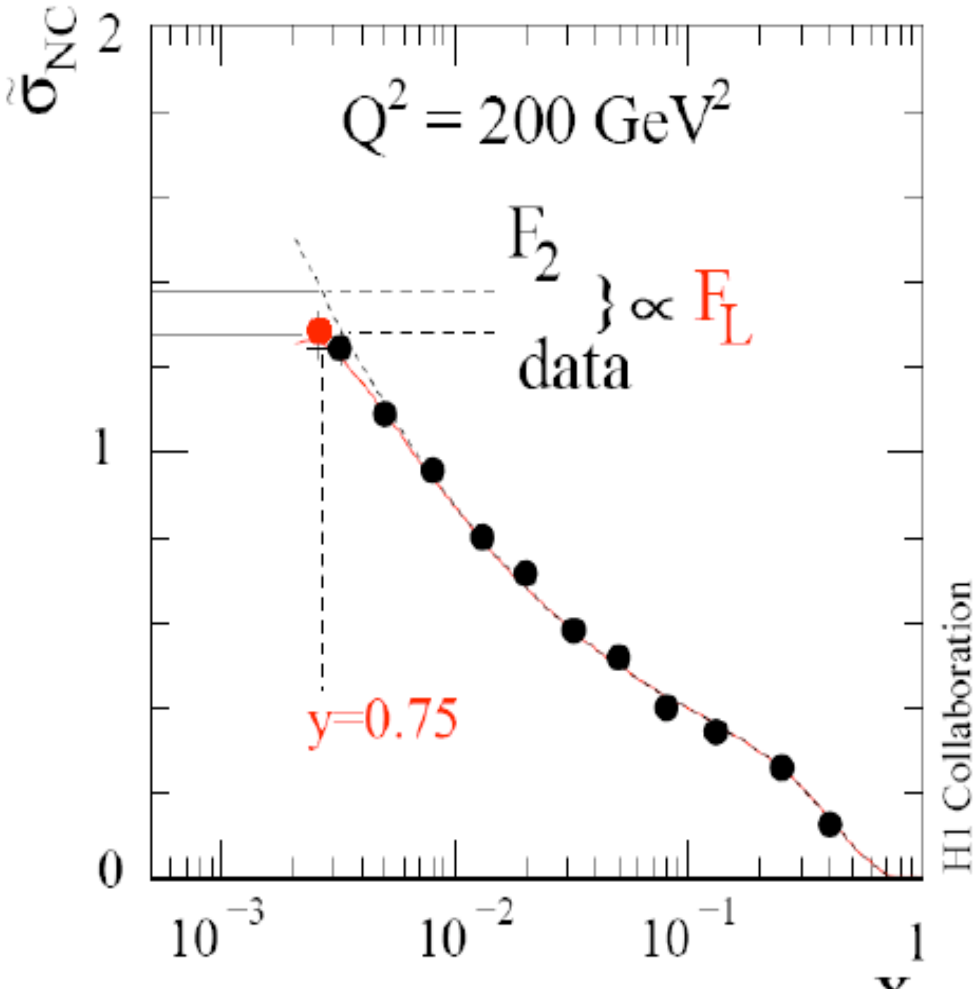


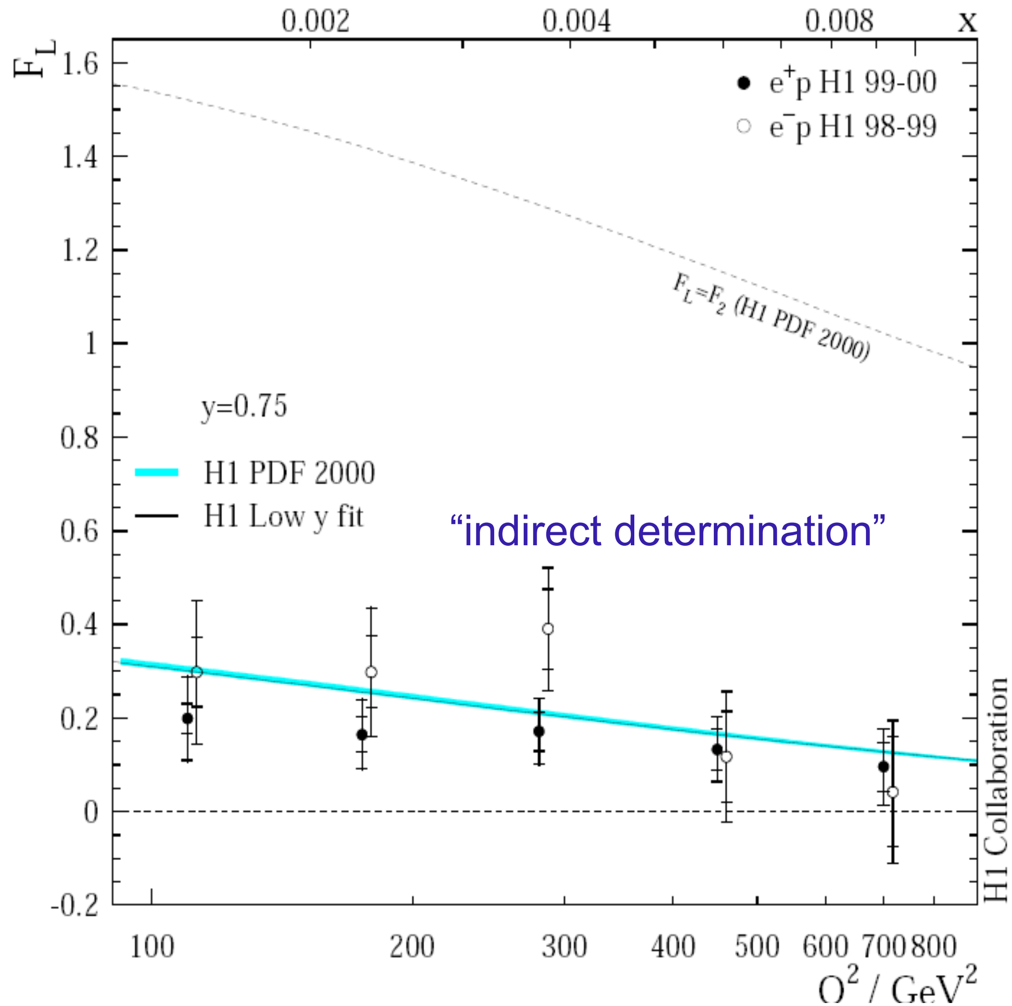
H1 and ZEUS corrected to the same phase space

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

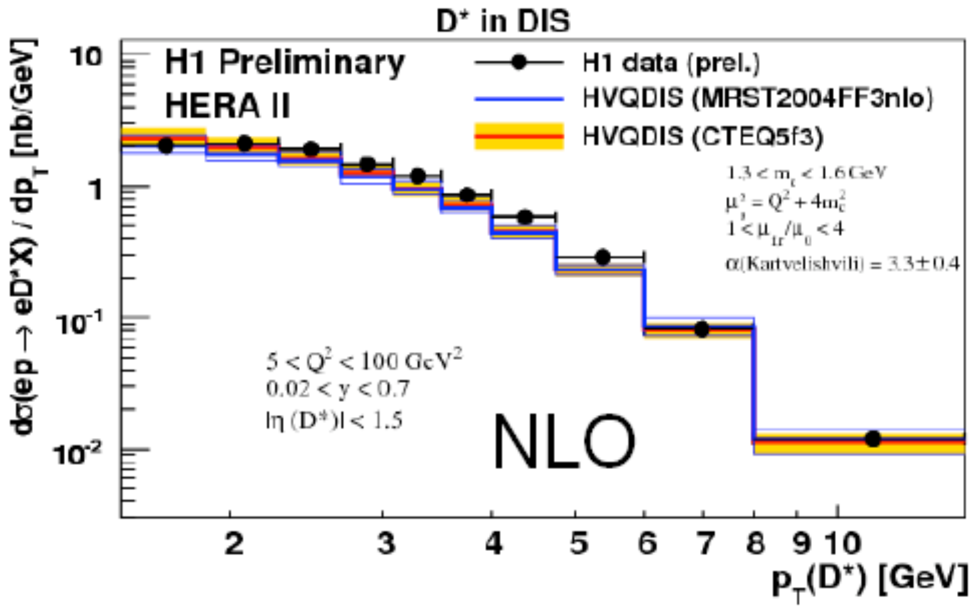


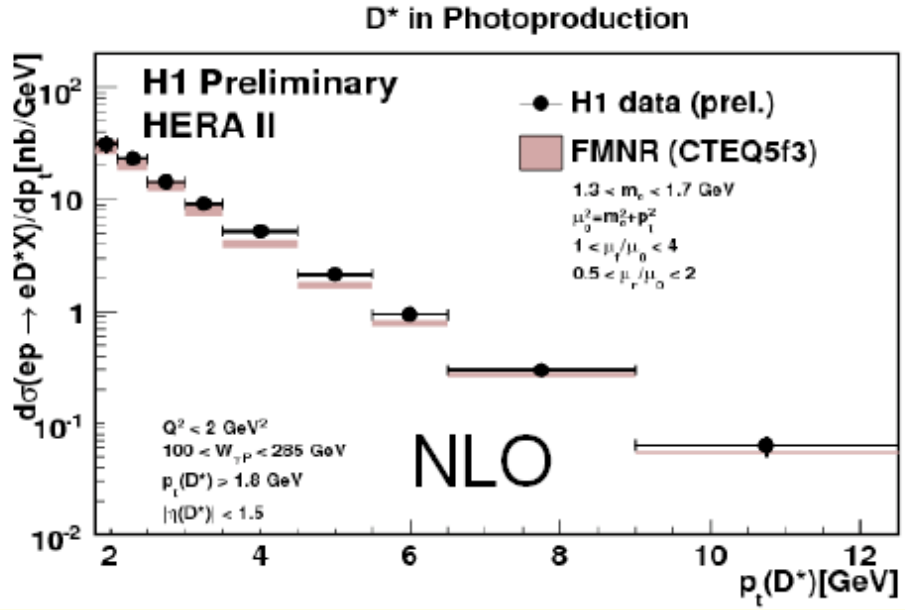


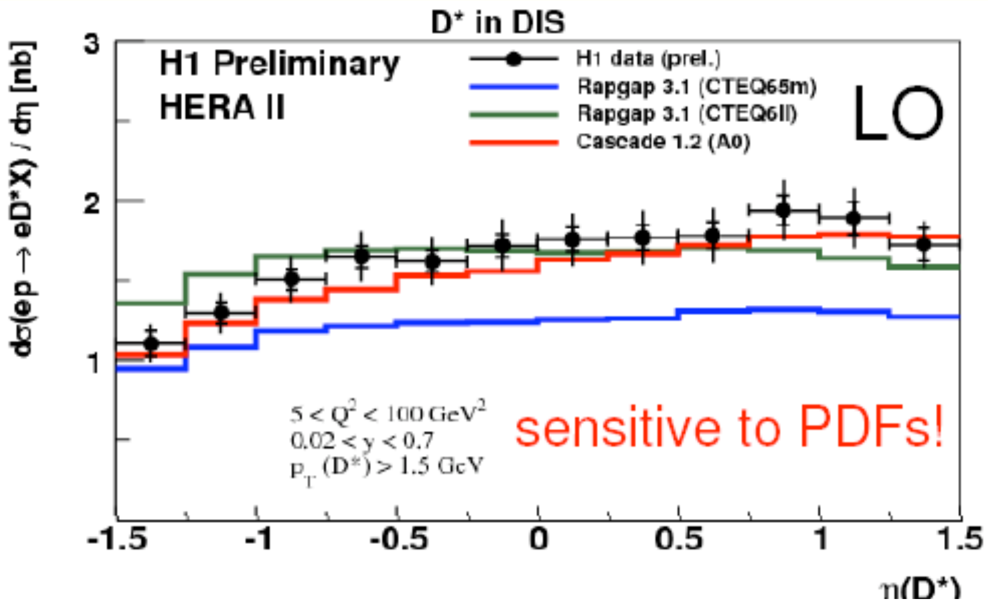
More charm with HERA II data

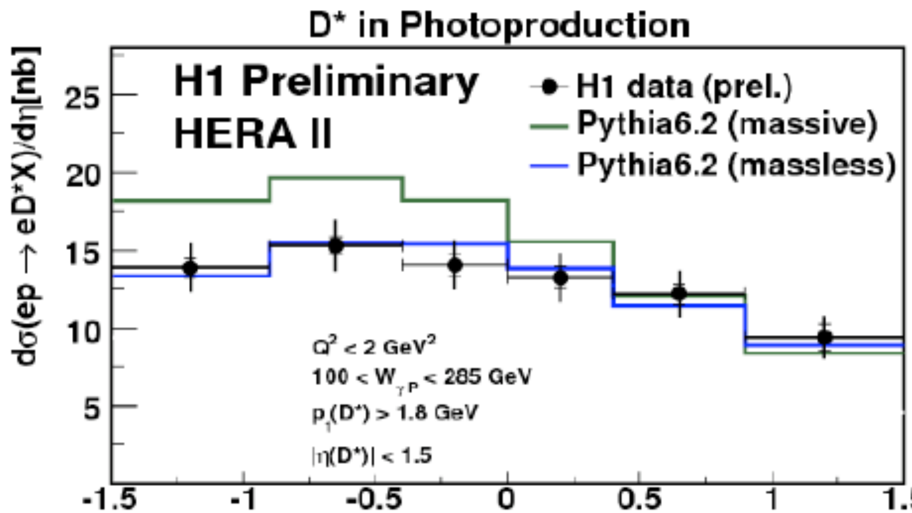
DIS

Photoproduction



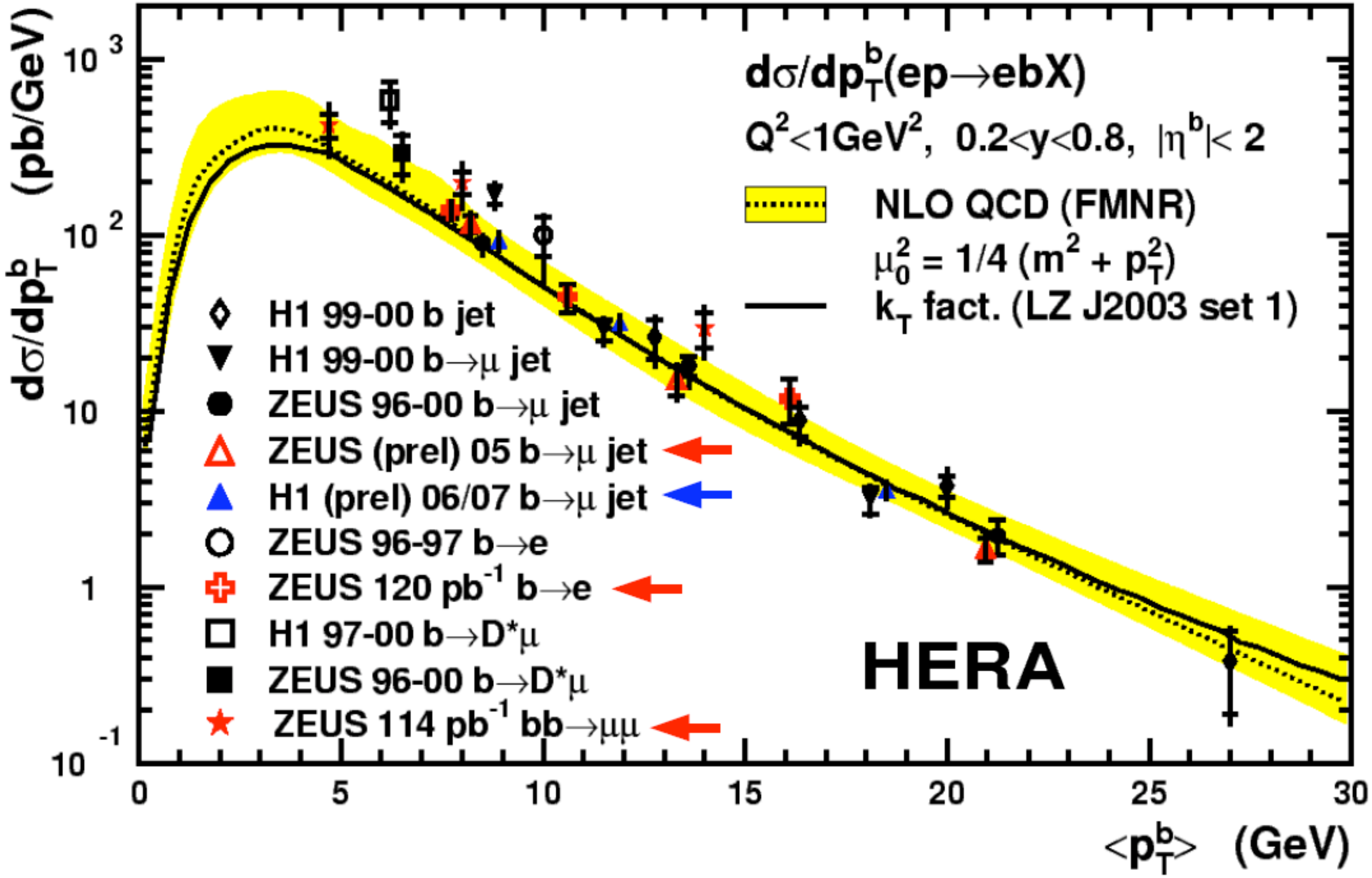


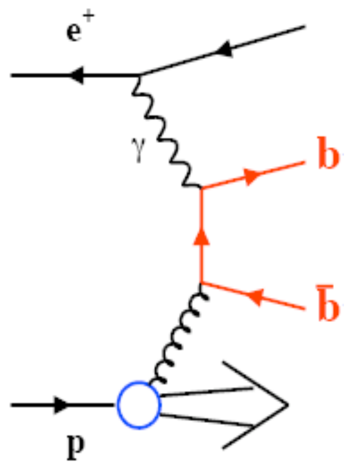


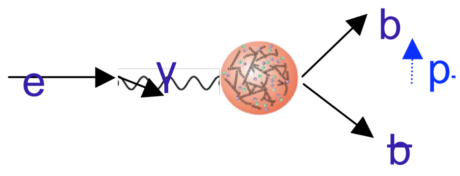


best description by massless Pythia η(D*)

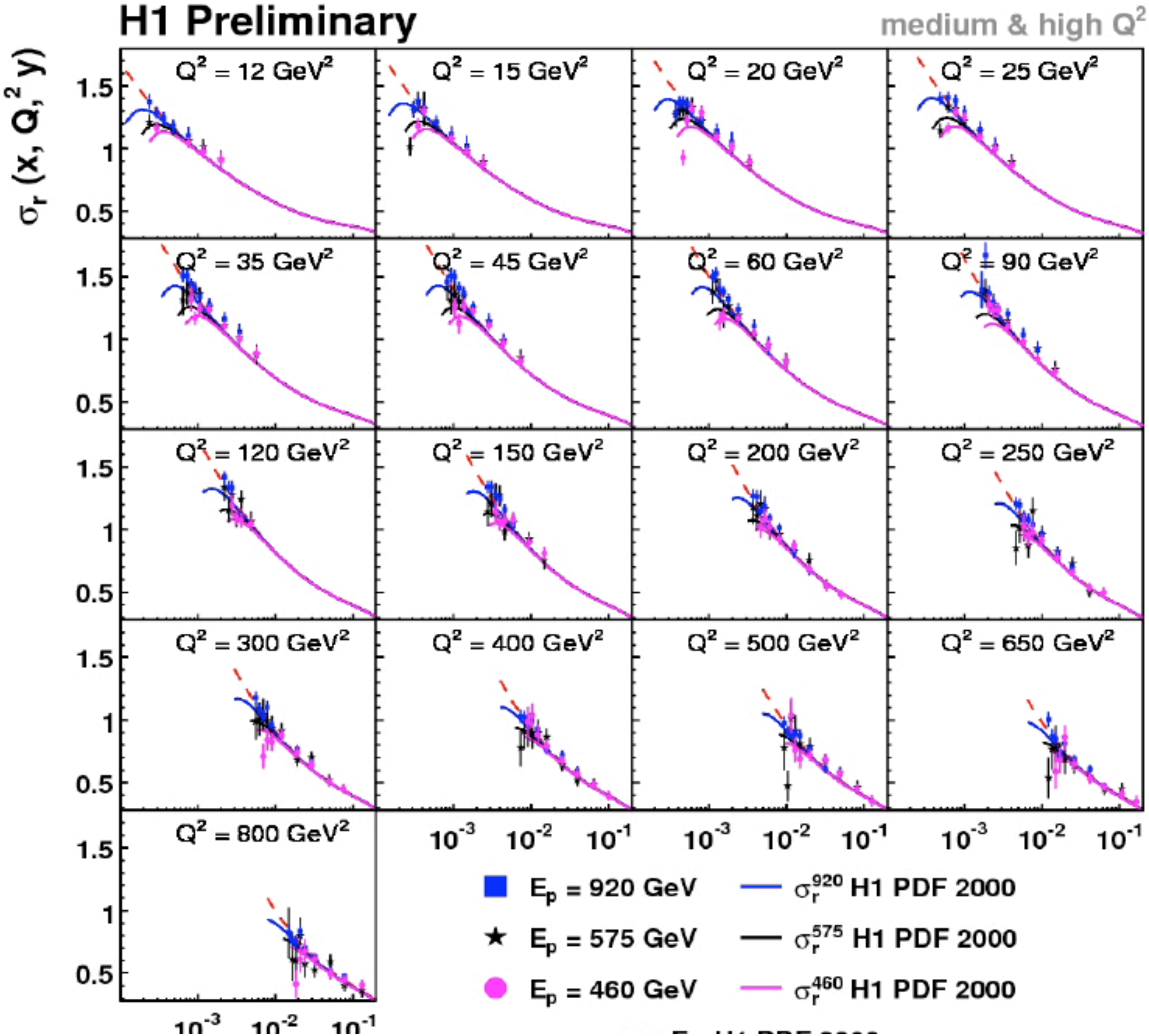
Photo-Produced Beauty



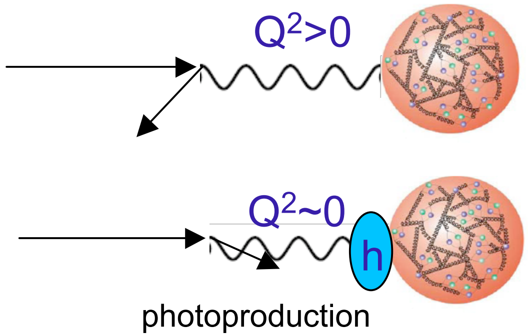


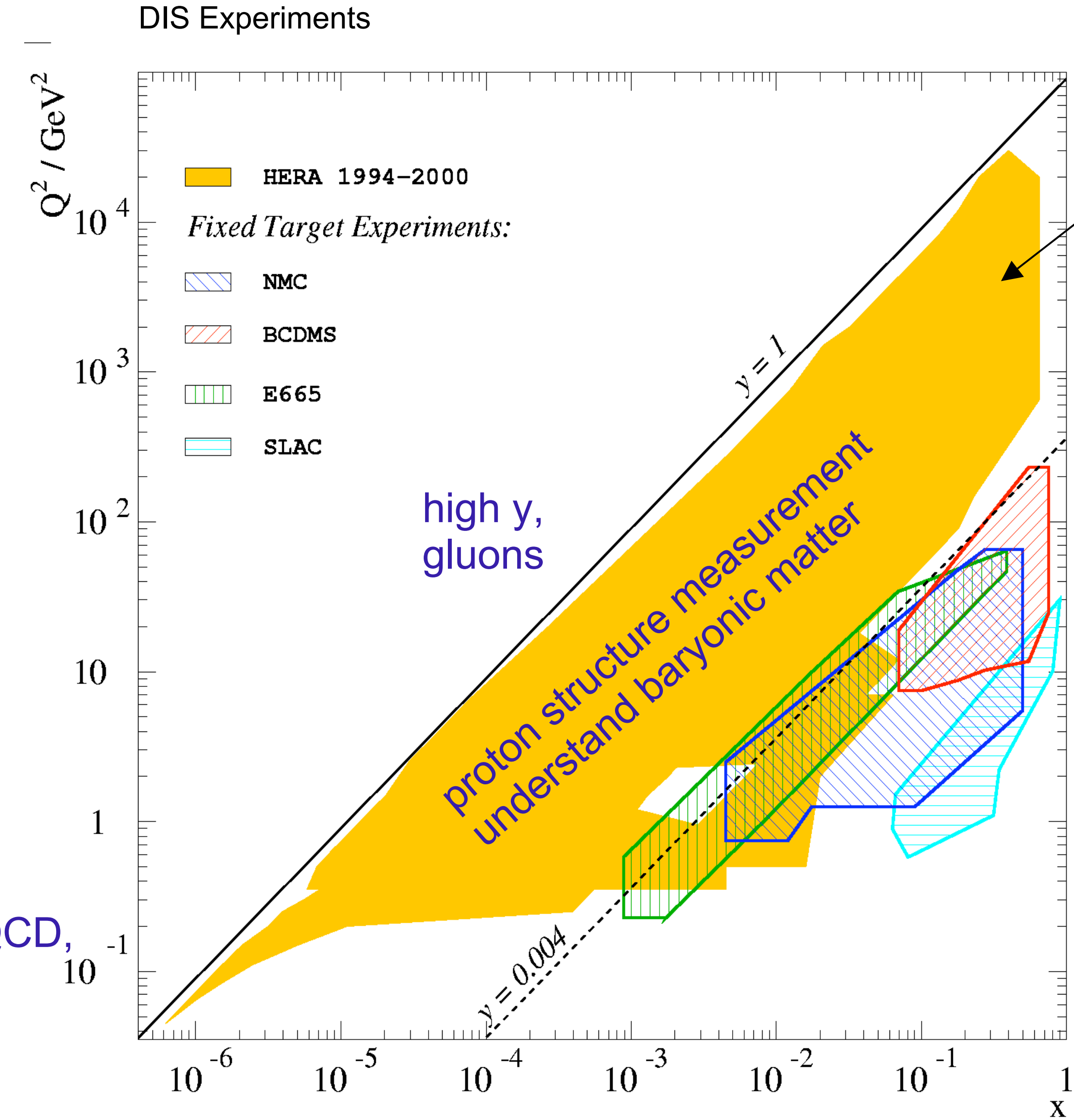


Recent precise measurements in agreement with theory


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
Ep = 920 GeV
Ep = 575 GeV
Ep = 460 GeV
σr920 H1 PDF 2000
σr575 H1 PDF 2000
σr460 H1 PDF 2000

The proton map in the kinematic plane





Highest
collision energy
EW+searches

Non-perturbative QCD,
transition

Use the final state processes (exclusive)

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**

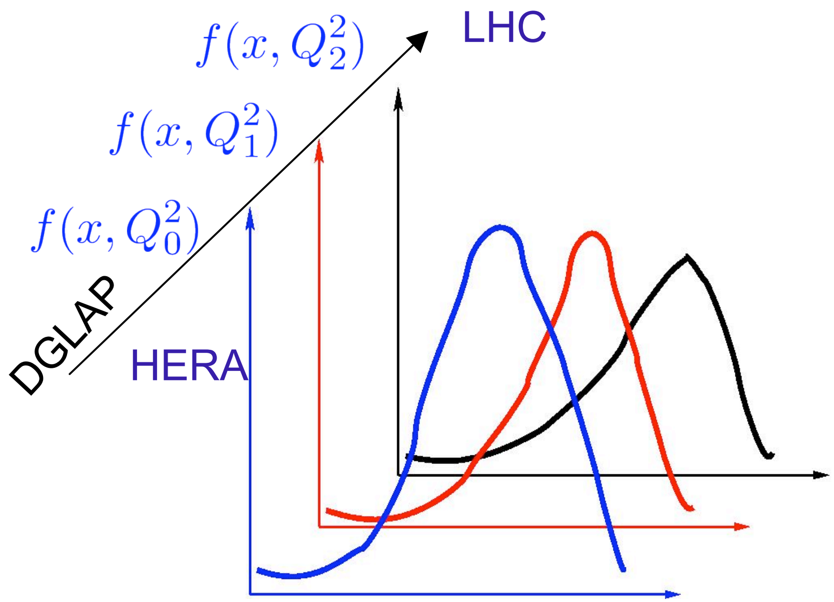
- Red = New w.r.t. MRST 2006 fit.

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

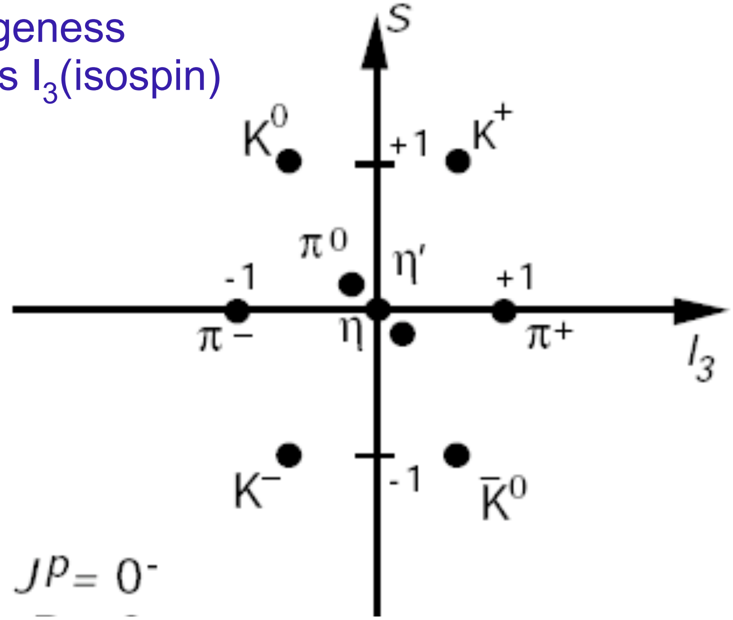


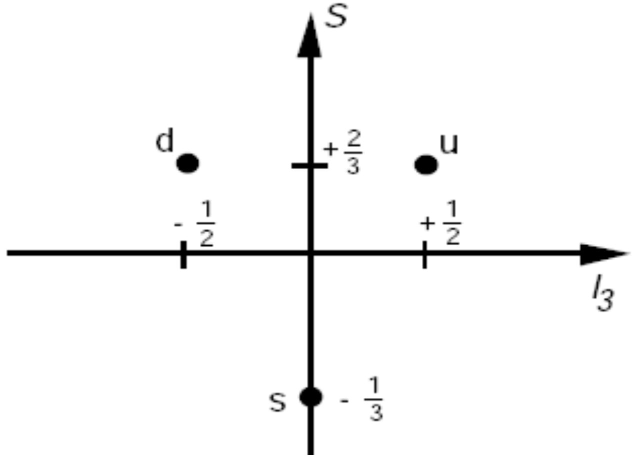
low x remain delicate theoretically
large ln x corrections/validity DGLAP
experimental data is crucial in this regime

Hadrons from quarks

e(1896) p(1908) n(1932)
30-60's plenty of new “particles”: hadrons
lots of “chemistry” and “zoology”: Mendeleev (economical) method: do a table!

strangeness
versus I_3(isospin)





	I	I_z	S	Q
u	$\frac{1}{2}$	$+\frac{1}{2}$	0	$+\frac{2}{3}$
d	$\frac{1}{2}$	$-\frac{1}{2}$	0	$-\frac{1}{3}$
s	0	0	-1	$-\frac{1}{3}$

fractional charge!

fractional
charges

Mesons:
$q\bar{q}$