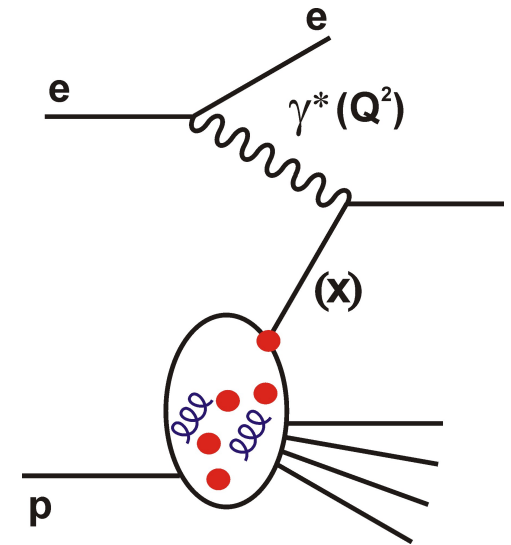


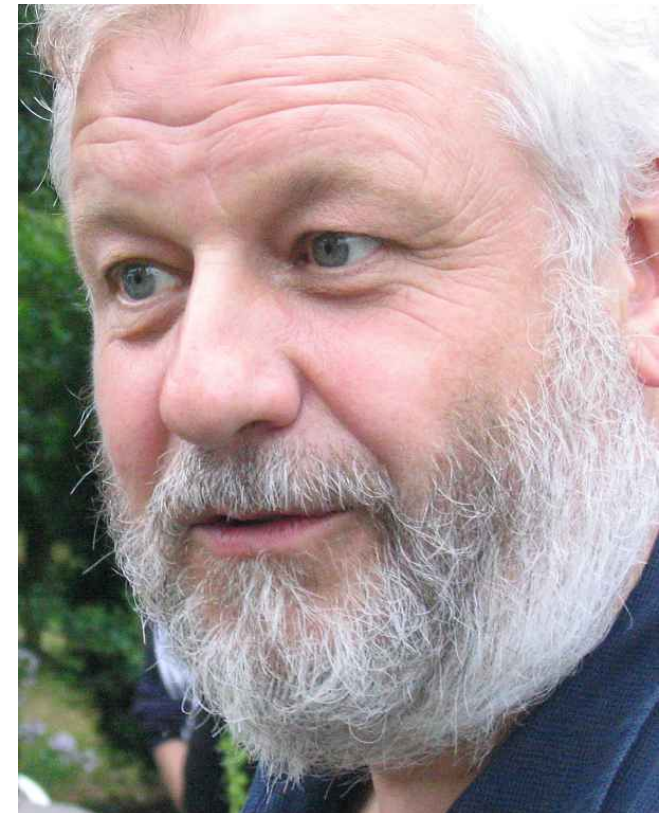
ep Physics at HERA with H1



Paul Newman
University of Birmingham

**Symposium in Honour
of Profs
Catherine de Clercq
Pierre Marage
Catherine Vander Velde**

**5 December 2014
Brussels**



Standing on the Shoulders of Giants

“It would be of great scientific interest if it were possible to have a supply of electrons ... of which the individual energy of motion is greater even than that of the alpha particle.”

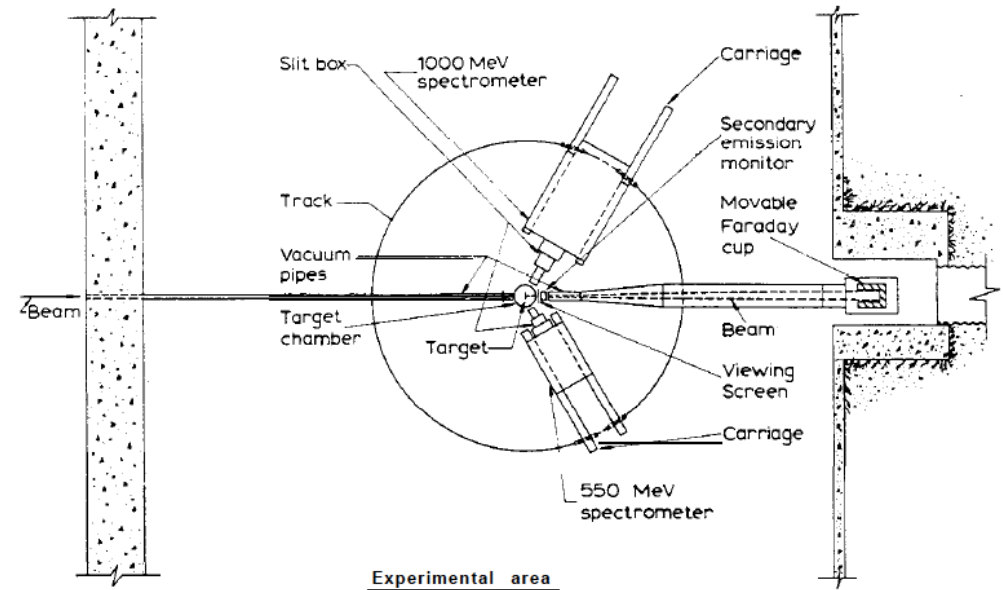
[Ernest Rutherford, Royal Society, London, (as PRS) 30 Nov 1927]



Standing on the Shoulders of Giants

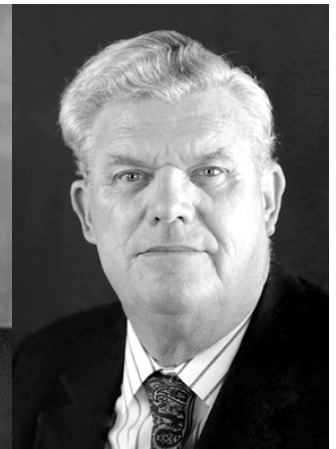
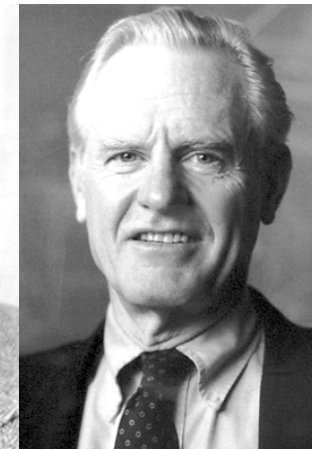
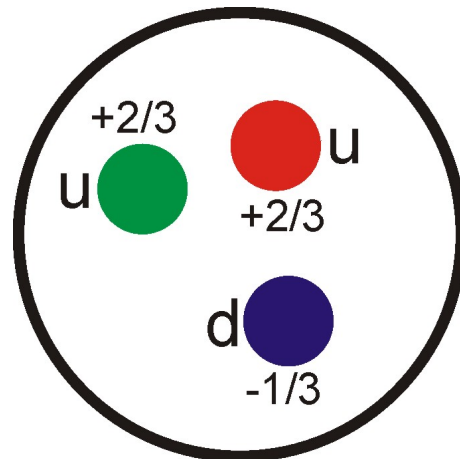
1950s: Hoffstadter

First observation
of finite proton size
using 2 MeV e beam



1969: SLAC

First direct observation of **quark substructure**
using a 20 GeV electron beam



HERA, DESY, Hamburg

(1992-2007)

... the only ever collider
of electron beams with
proton beams:

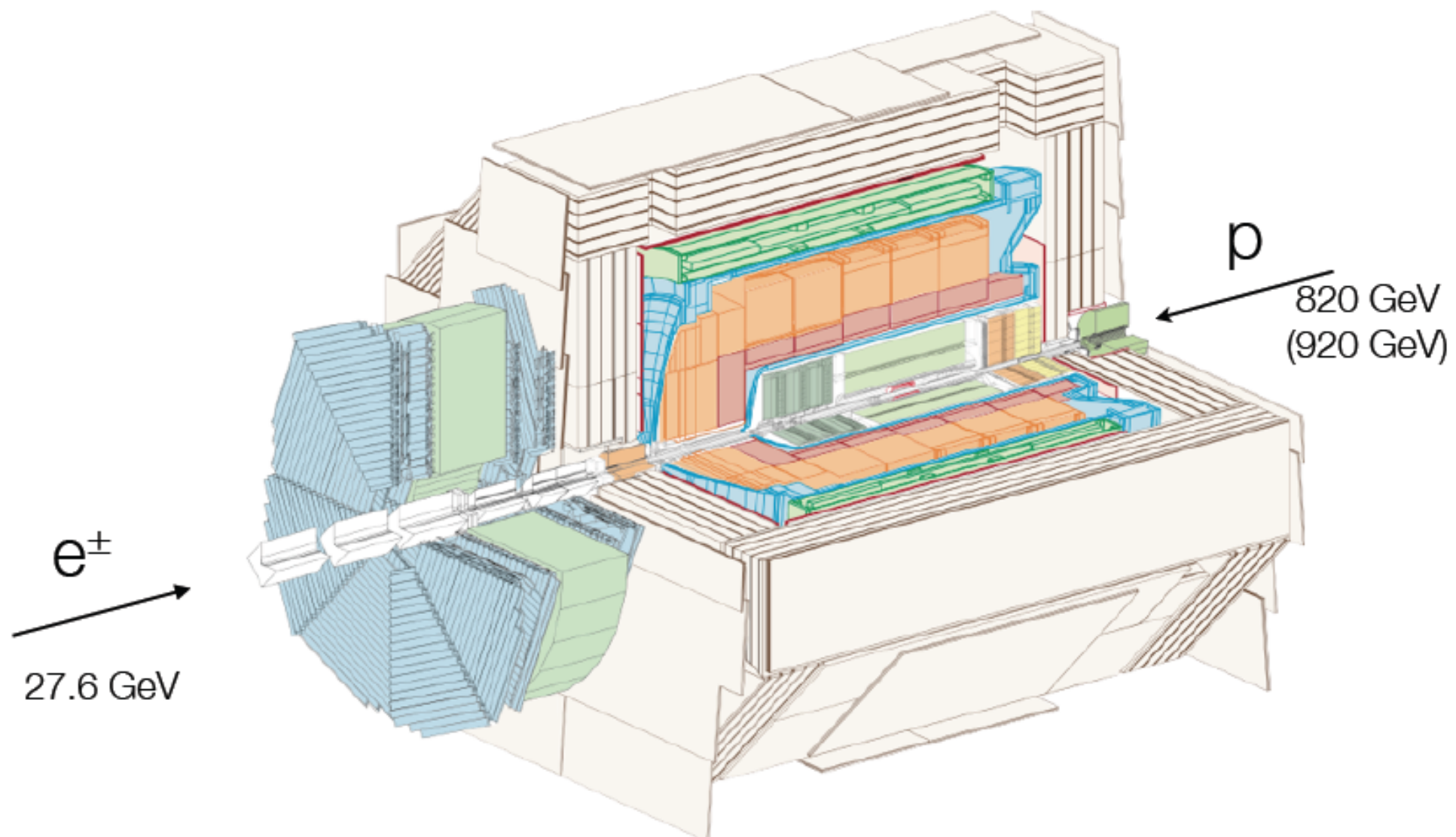
$$\sqrt{s_{ep}} \sim 300 \text{ GeV}$$



Equivalent to a 50 TeV beam on
a fixed target proton
~2500 times more than SLAC!

“World’s most powerful microscope”

The H1 Detector



The H1 Detector



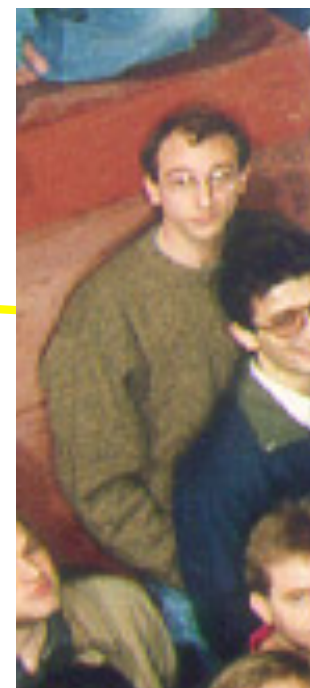
GeV
GeV)

27

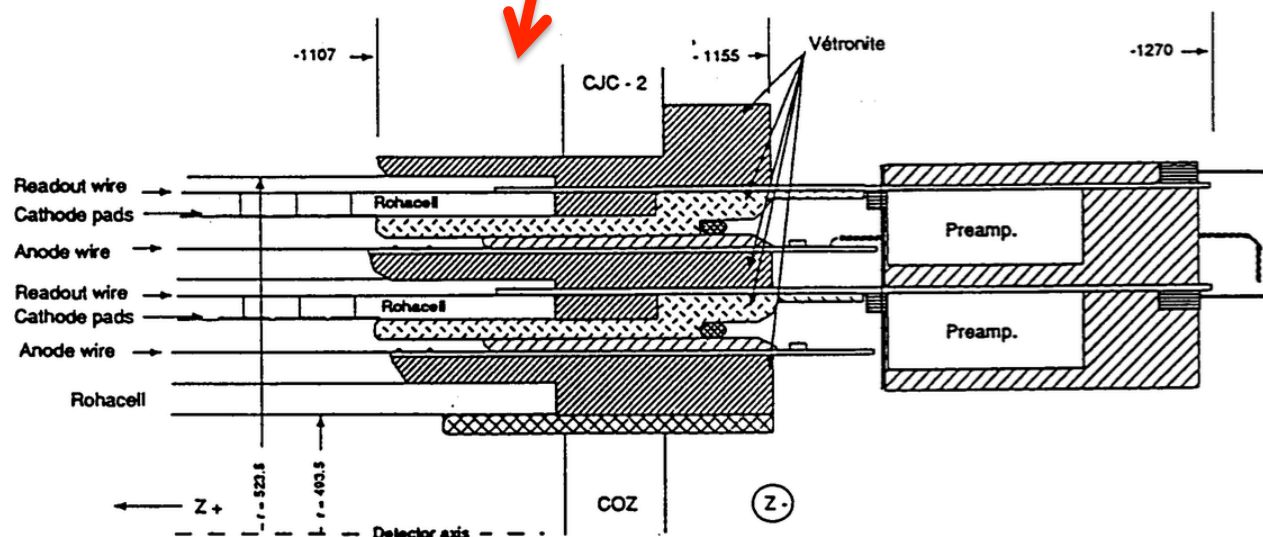
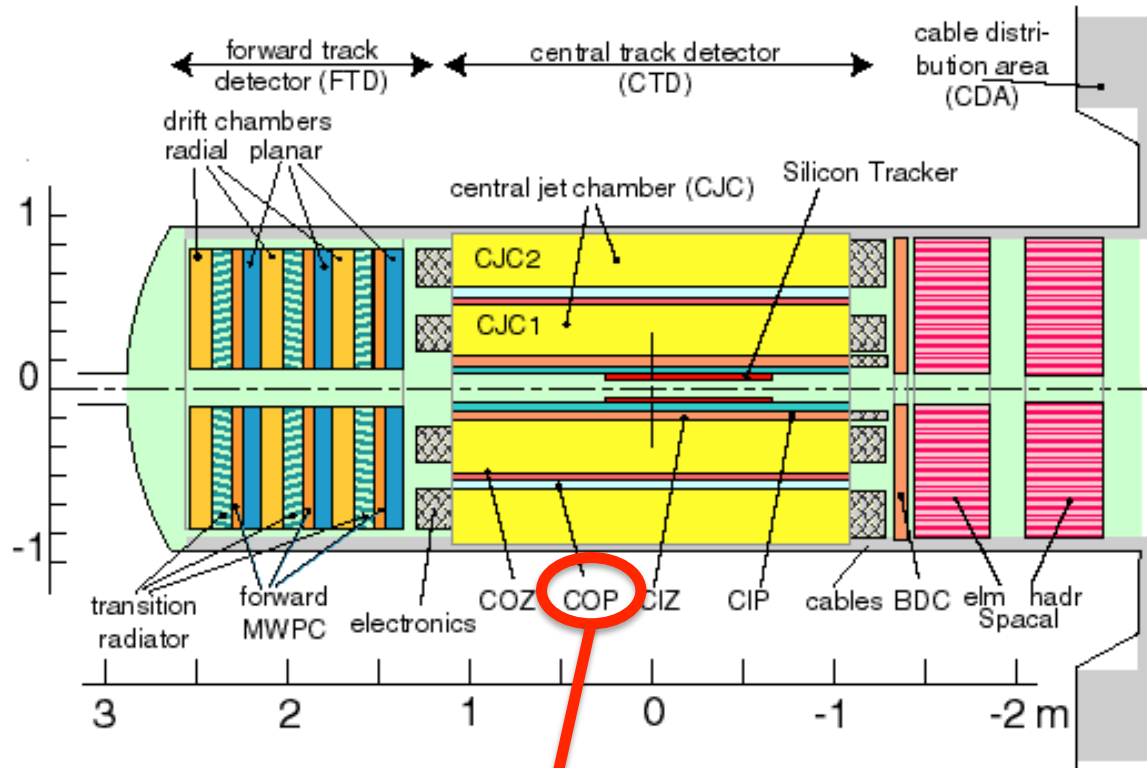
Early Collaboration Mugshot (1993)



Early Collaboration Mugshot (1993)



Belgian Contributions: Central Outer Proportional Chambers (COP)



COP production /
MWPC electronics

Tracking info +
'z-vertex' trigger
... fast timing signal
vital at 96ns bunch
crossing intervals

Worked so well, we
took it for granted.

MWPC experts contact list

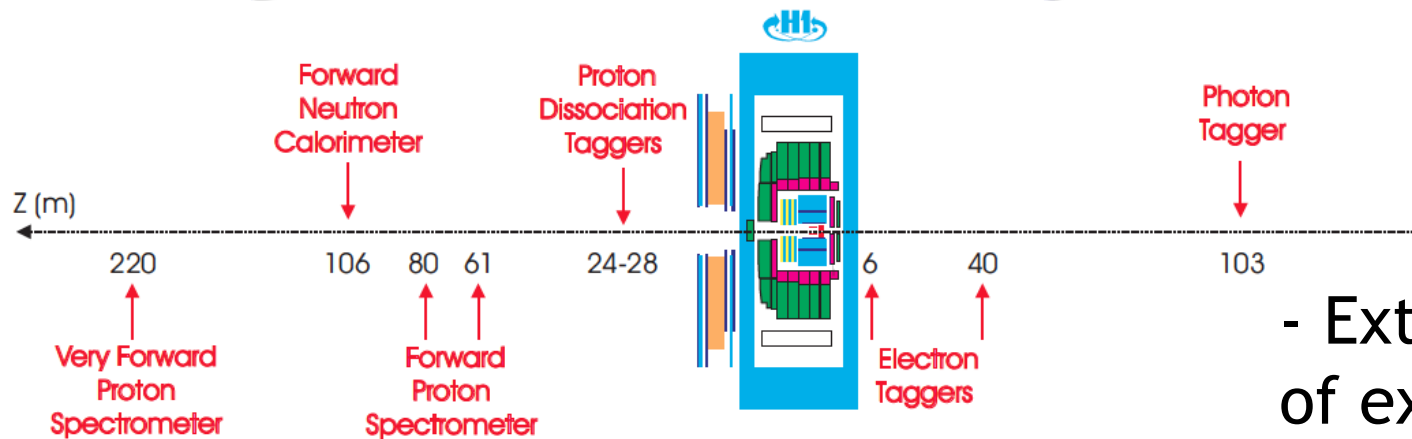
The person presently on call can be found [on this list](#).

Use the Cityphone-number **435 42 62** to contact him or her.

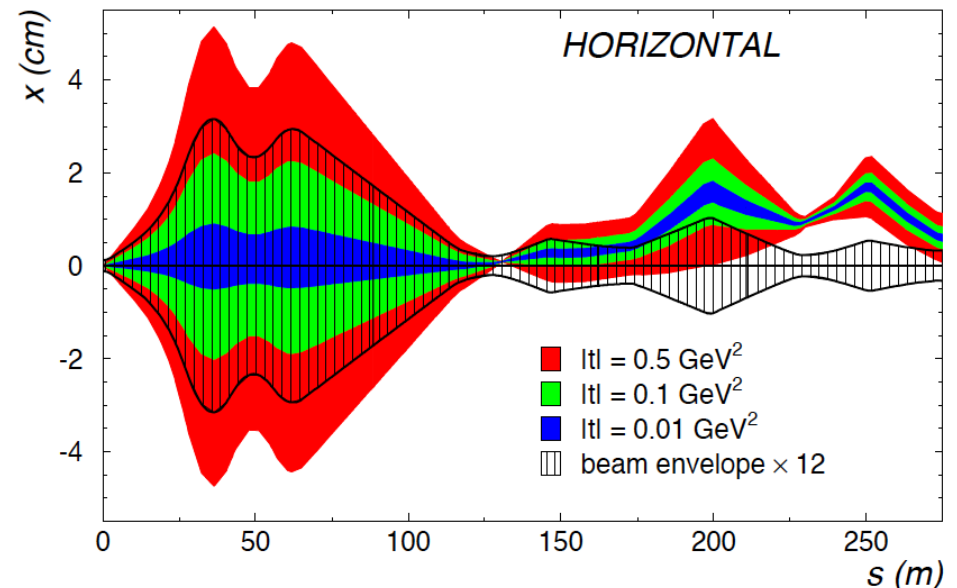
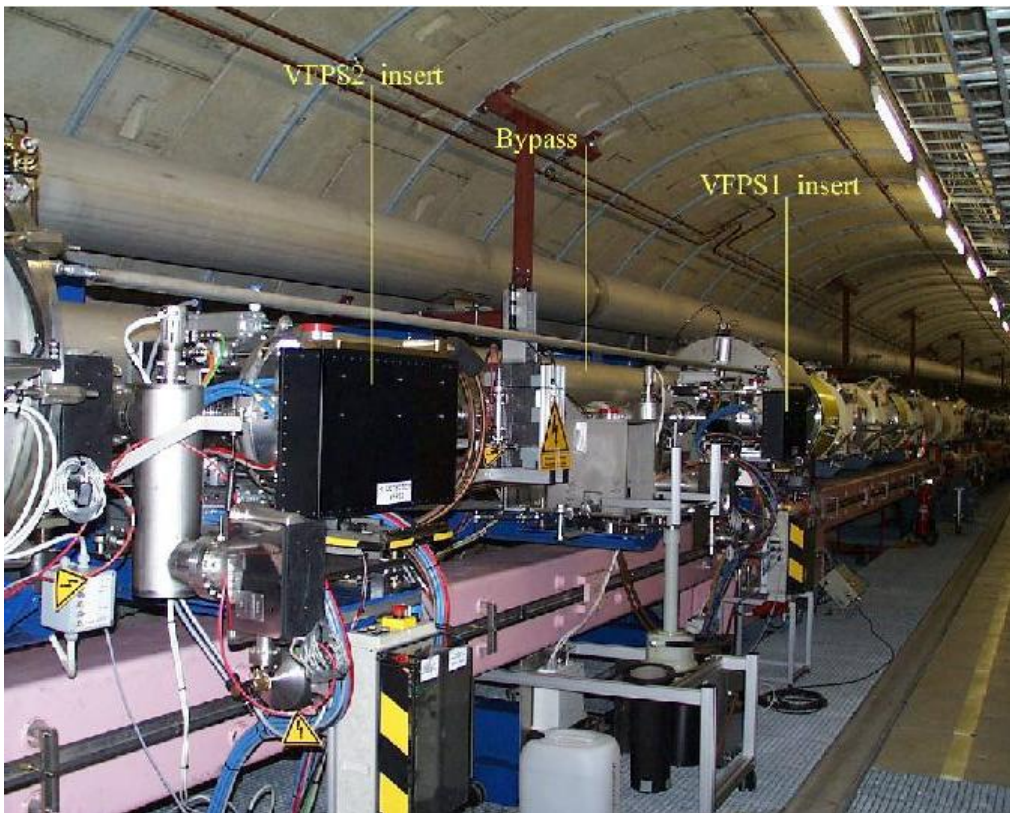
Component	Name	DESY	Home
CIP	Stefan Hengstmann	27 13	399 01 815
	Jürgen Kroseberg	30 84	432 51 613
	Felix Sefkow	25 69	04121 78 415
COP	Robert Roosen	20 84 or 42 25	00322 629 32 17
	Laurent Favart	20 84 or 42 25	00322 629 32 07
	Samvel Ghazaryan	29 42	-
FPC	Zhiqing Zhang	29 41	00331 64 46 84 81
	Samvel Ghazaryan	29 42	-
Readout	Robert Roosen	20 84 or 42 25	00322 629 32 17

To send mail to any of them, just click on the name.

Belgian Contribution to Upgrades: Very Forward Proton Spectrometer (VFPS)



- Extended capability of experiment!
- Testing ground for FP420, TOTEM



Belgian Contribution to Upgrades: Very Forward Proton Spectrometer (VFPS)

H1-5/00-582
PRC-01/00

H1-5/00-582
PRC-01/00

Proposal for Installation of a Very Forward Proton Spectrometer in H1 after 2000

L. Favart, D. Johnson, P. Marage, R. Roosen,

Inter-University Institute for High Energies ULB-VUB, Brussels, Belgium

E.A. De Wolf, P. Van Mechelen, T. Anthonis

Universitaire Instelling Antwerpen, Wilrijk, Belgium

L. Jönsson, H. Jung,

Physics Department, University of Lund, Lund, Sweden

V. Blobel, F. Büsser, V. Jemanov, A. Meyer, B. Naroska, F. Niebergall, J. Schütt, H. Spitzer,
R. vanStaa

University Hamburg II Institut f. Experimentalphysik, Hamburg, Germany

P.R. Newman,

School of Physics and Space Research, University of Birmingham, Birmingham, UK

Addendum VFPS proposal : Acceptances

H1-15/00-xxx

Addendum VFPS : Background rates

Last revised October 24, 2001

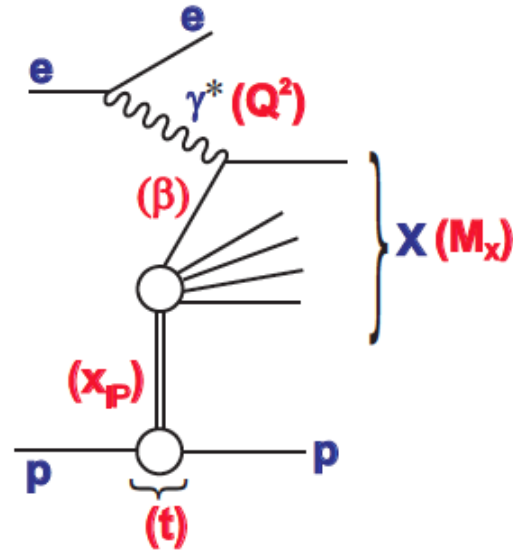
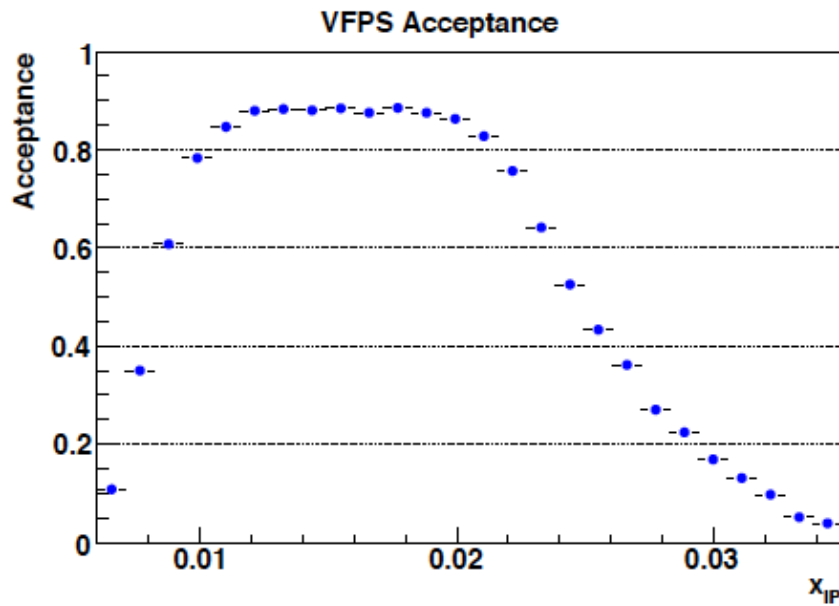
Abstract

A new, very forward proton spectrometer (VFPS) with large acceptance is proposed to be installed in the proton beam of the H1 experiment after the luminosity upgrade in the year 2000. The spectrometer, located at 220 m downstream of the interaction point is based on the Roman Pot technique and consists of two stations situated in the cold section of the proton beam line. The proposal presents the physics motivations, a description the proton spectrometer, a technical solution for the installation in the cold beam section, a cost estimate and time planning.

Study on Acceptances and Resolutions of the H1 VFPS Detector

Addendum to proposal DESY PRC 01/00

VFPS Physics

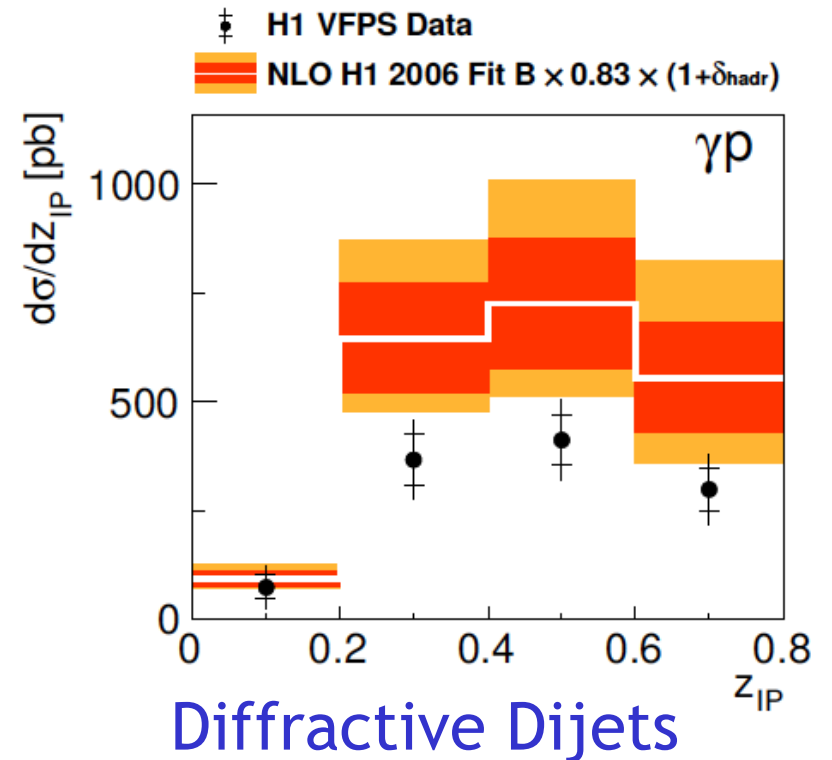
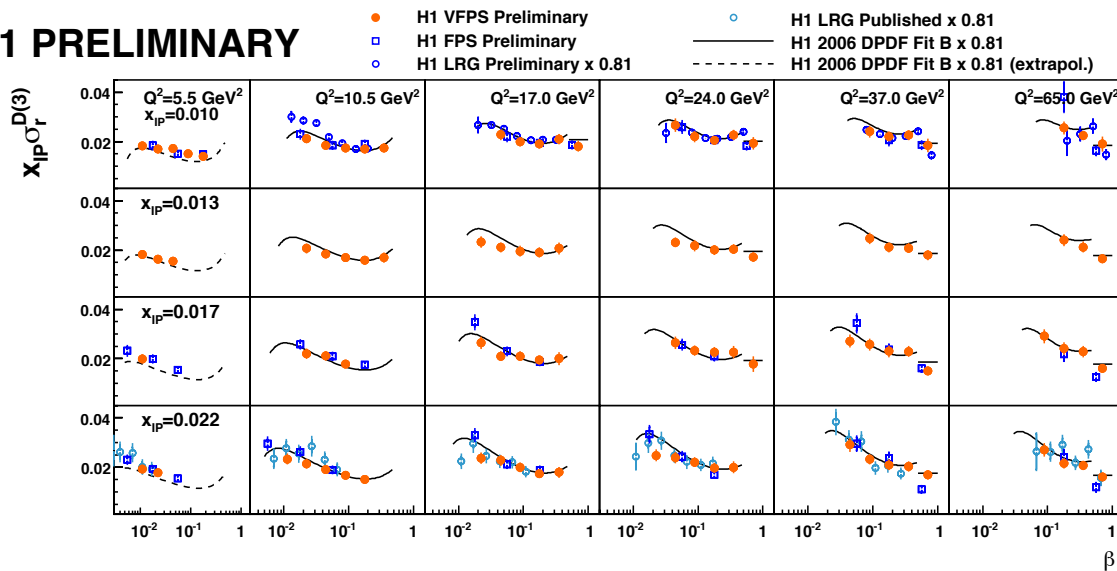


- Unprecedented acceptance

- Analysis of full HERA-II data nearing completion

Inclusive Diffractive DIS

H1 PRELIMINARY

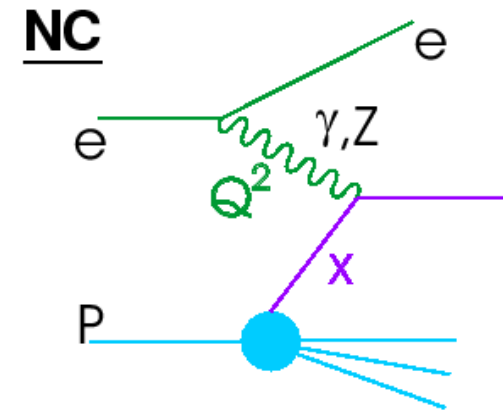


Diffractive Dijets

HERA and Proton Structure

Q^2 : exchanged boson resolving power

x : fractional momentum
of struck quark



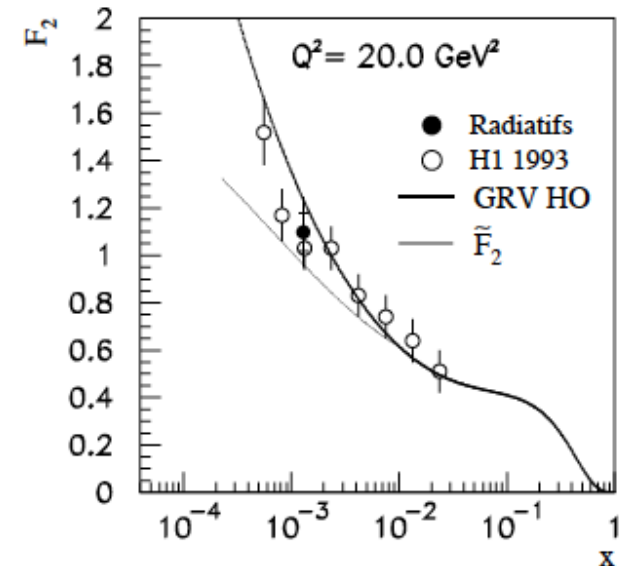
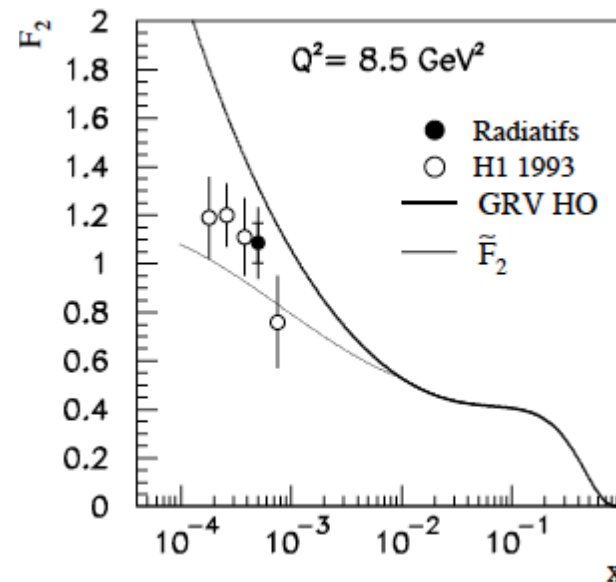
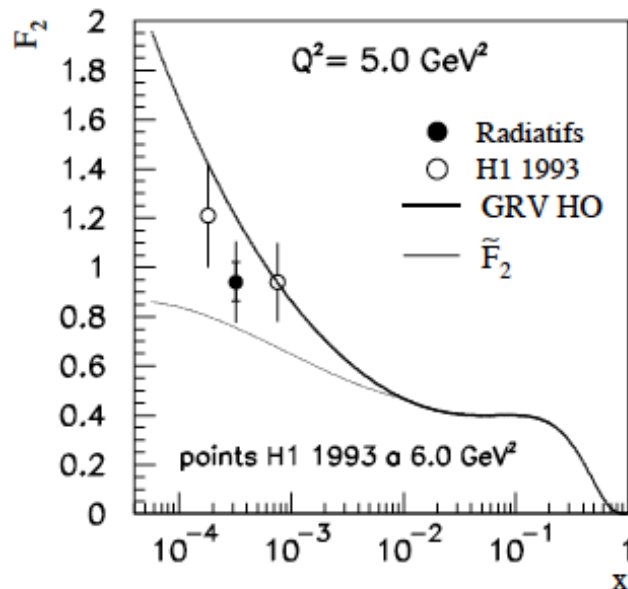
Mesure de la fonction de structure F_2 du proton
à HERA, utilisant les interactions profondément
inélastiques radiatives (ordre α^3).

... an early IIHE contribution ...

Dissertation présentée en vue
de l'obtention du titre de
Docteur en Sciences

Laurent FAVART

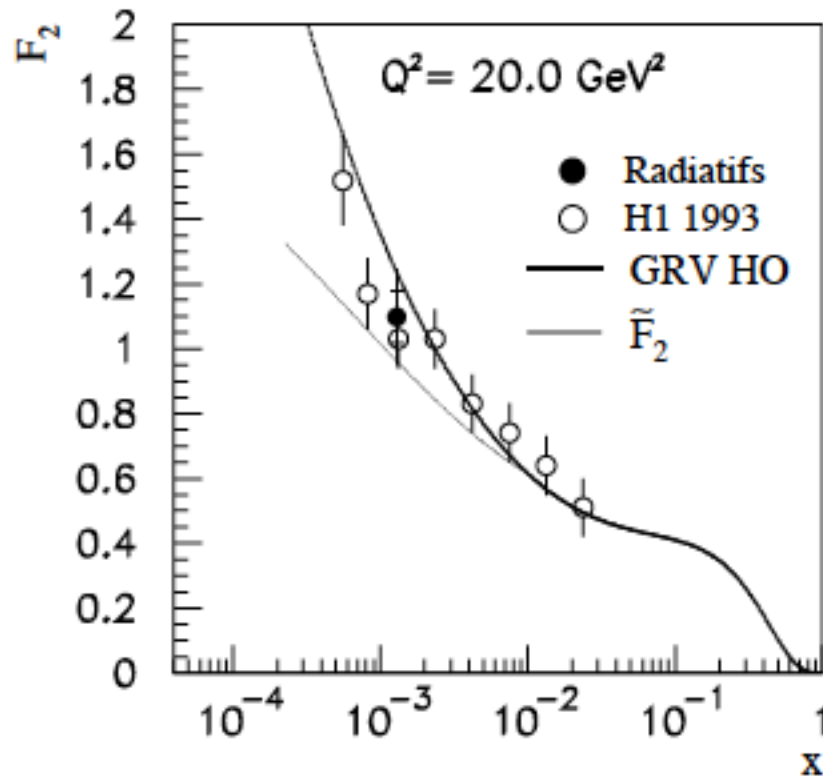
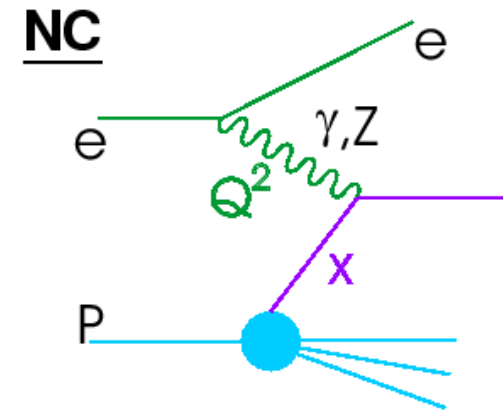
Novembre 1995



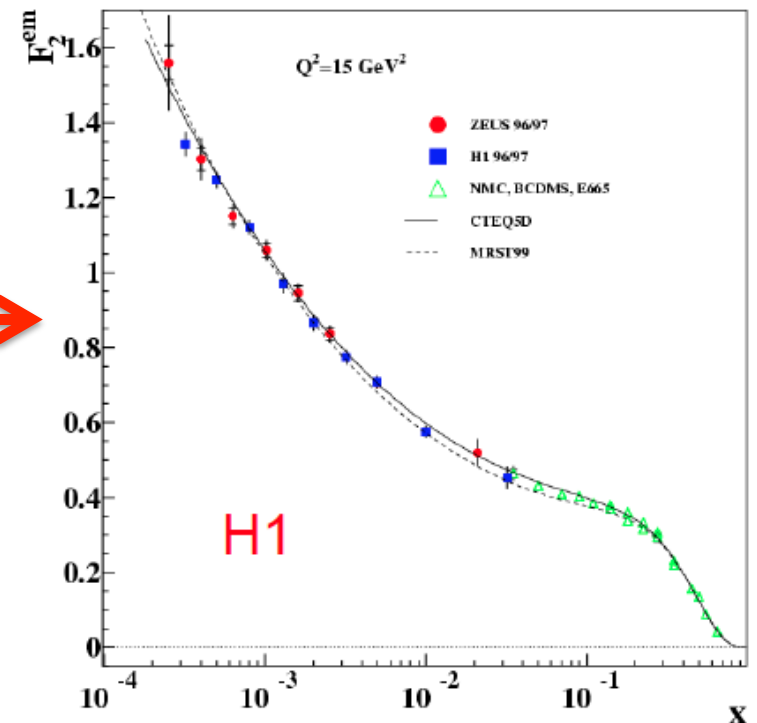
HERA and Proton Structure

Q^2 : exchanged boson resolving power

x : fractional momentum of struck quark



1993 data

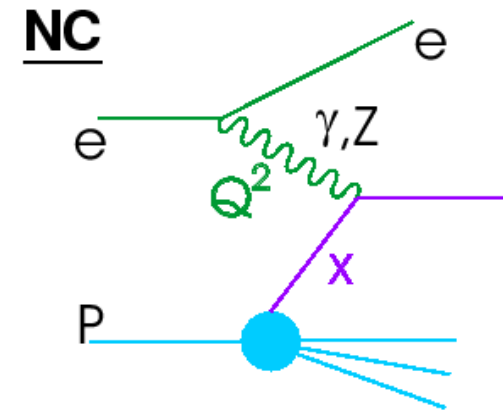


1997 data

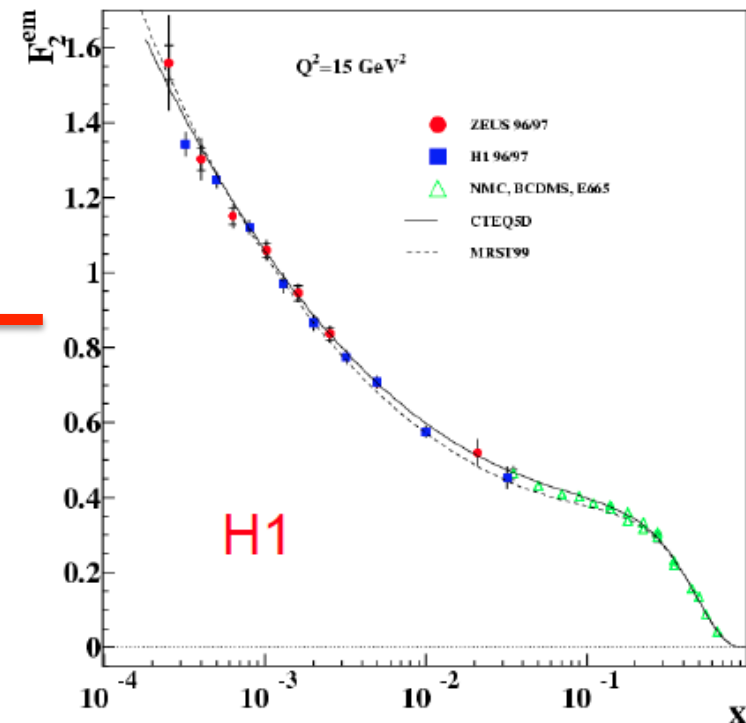
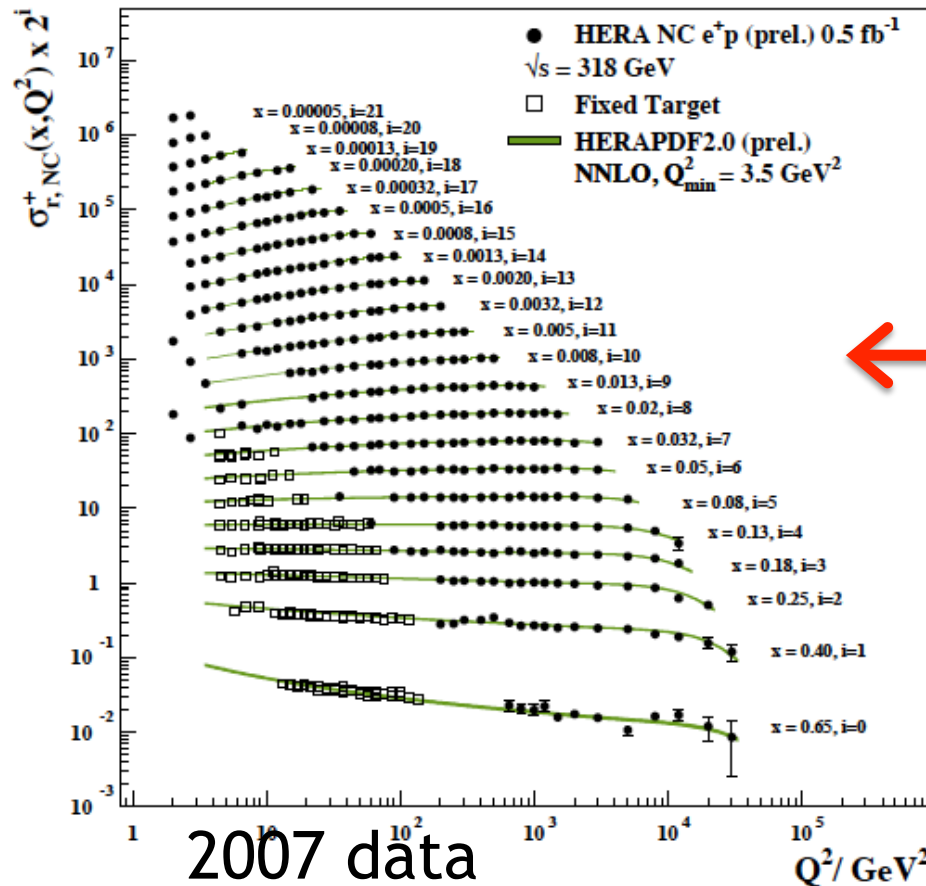
HERA and Proton Structure

Q^2 : exchanged boson resolving power

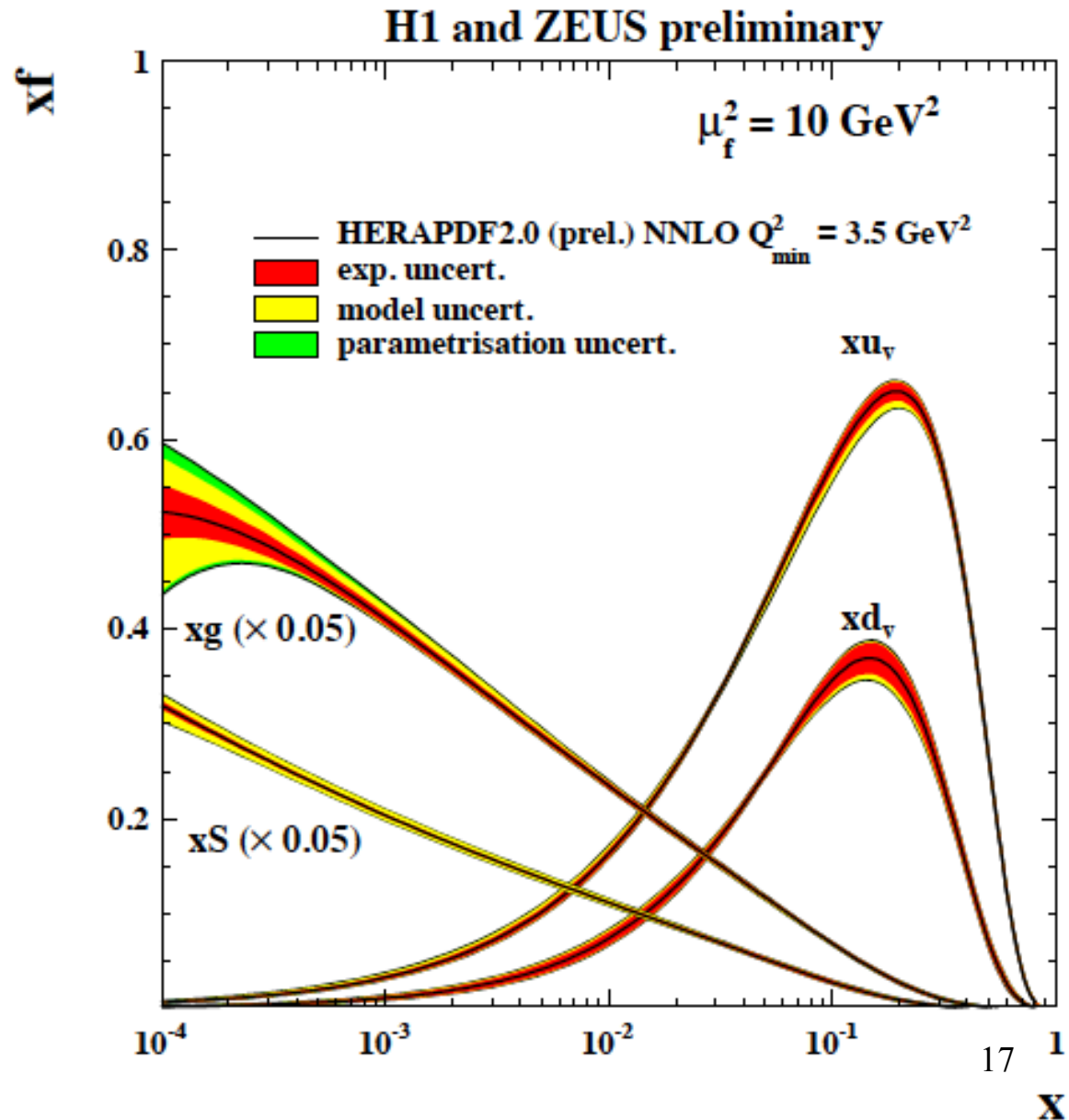
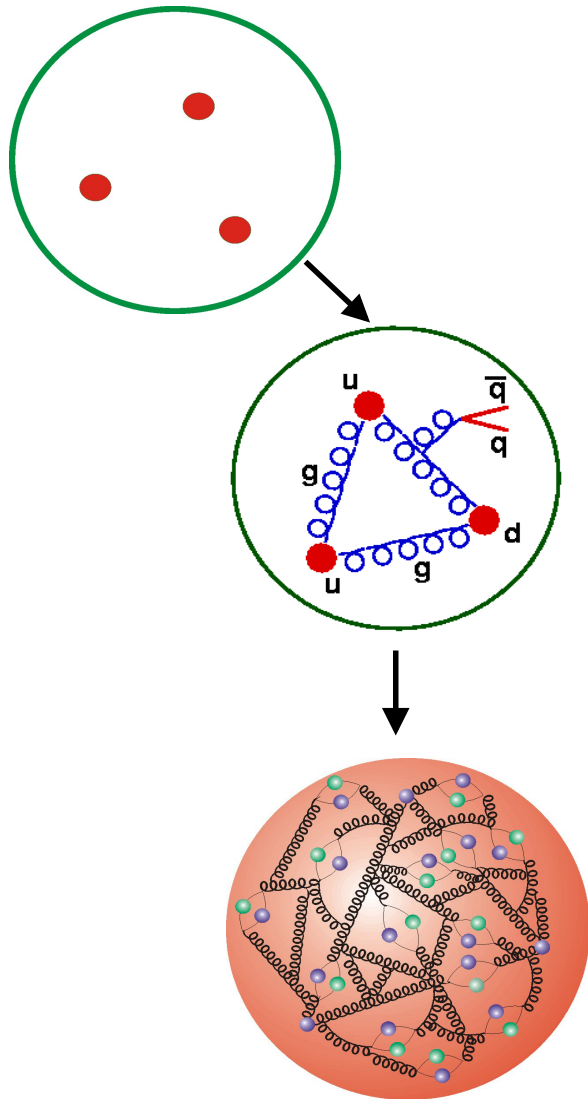
x : fractional momentum of struck quark



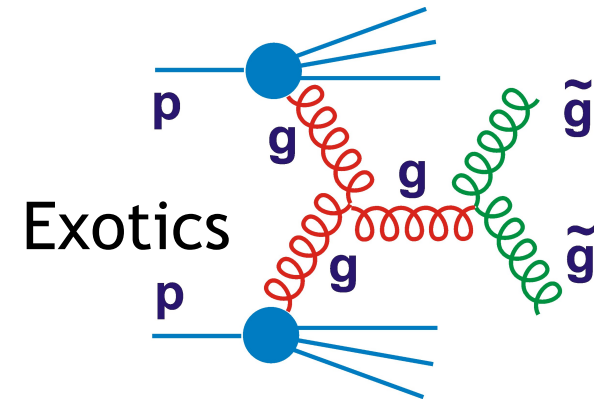
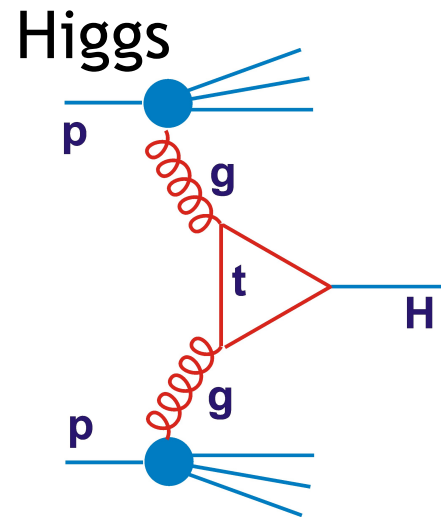
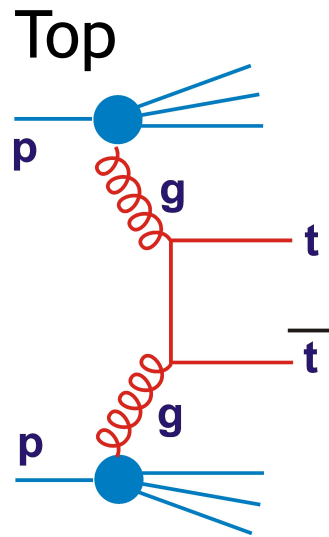
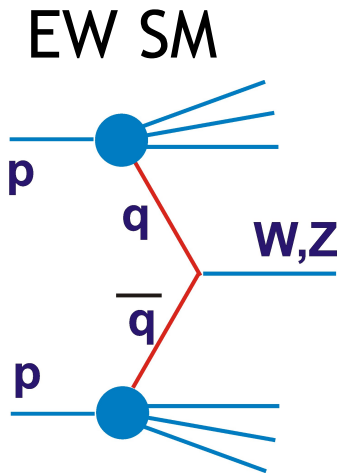
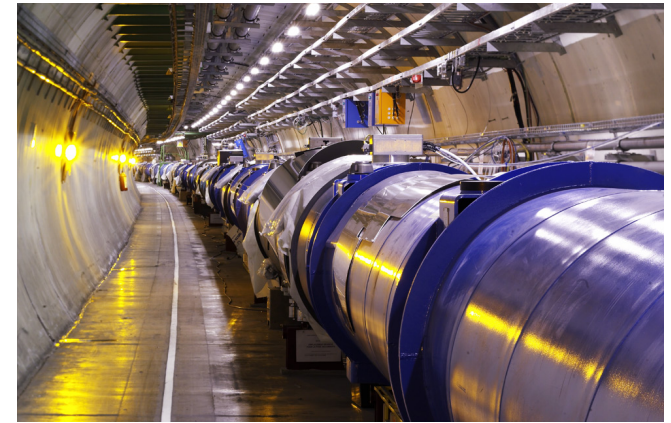
H1 and ZEUS preliminary



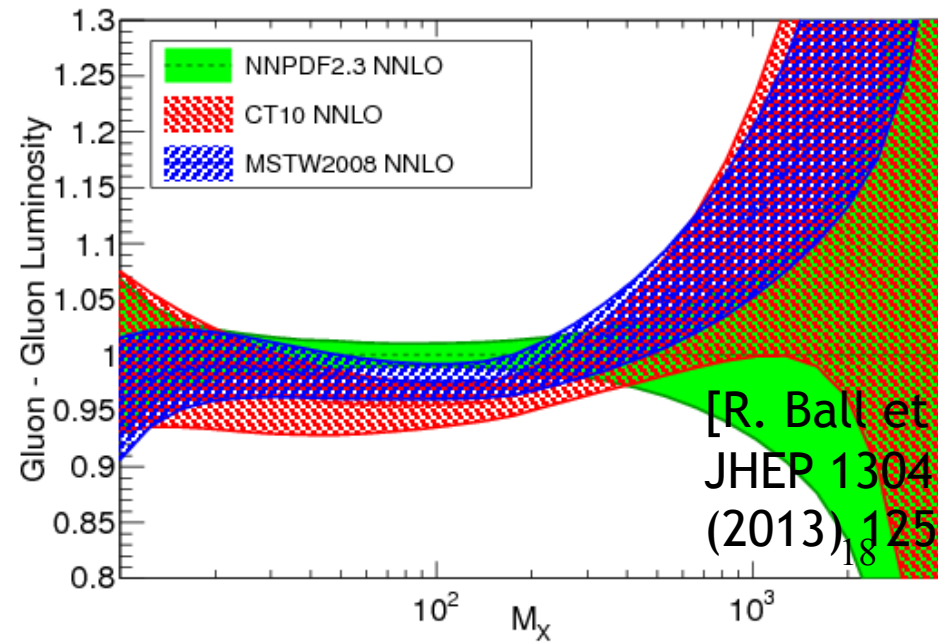
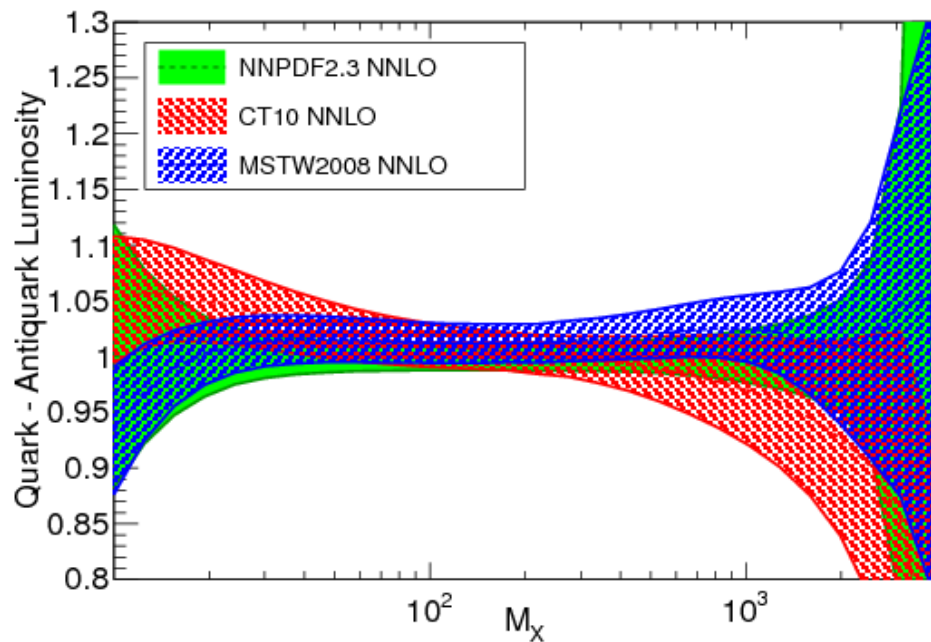
Final Picture of the Proton through the view of the HERA MicroAttoscope



HERA's PDFs at LHC

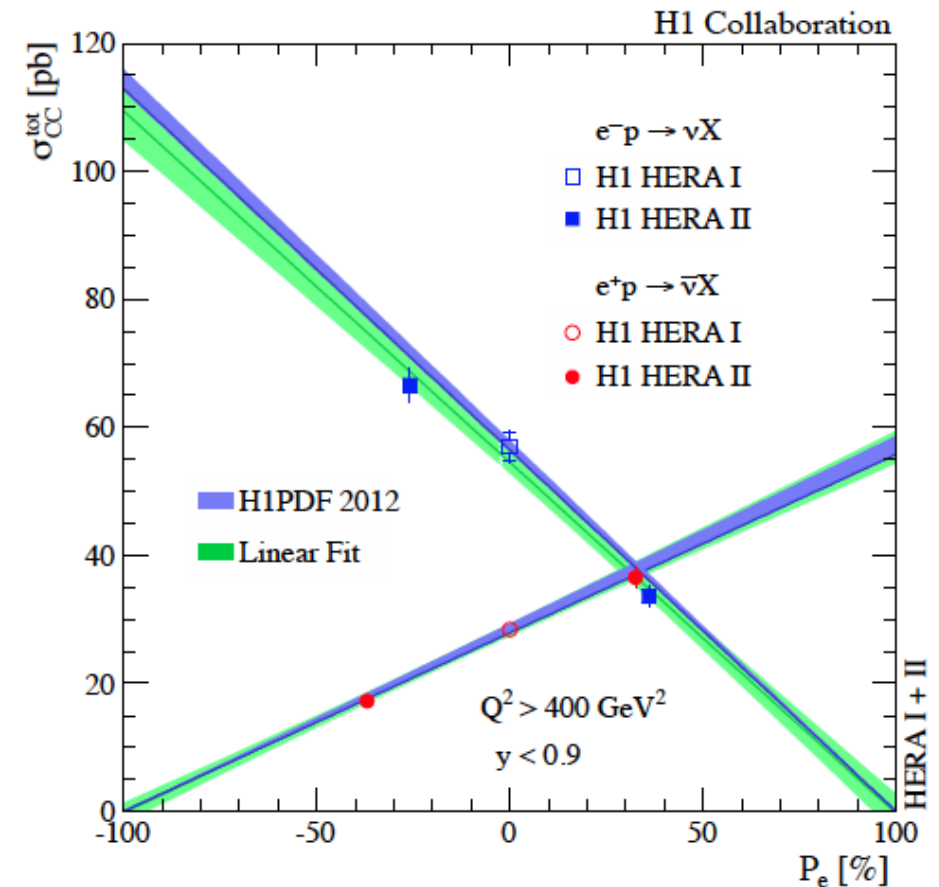
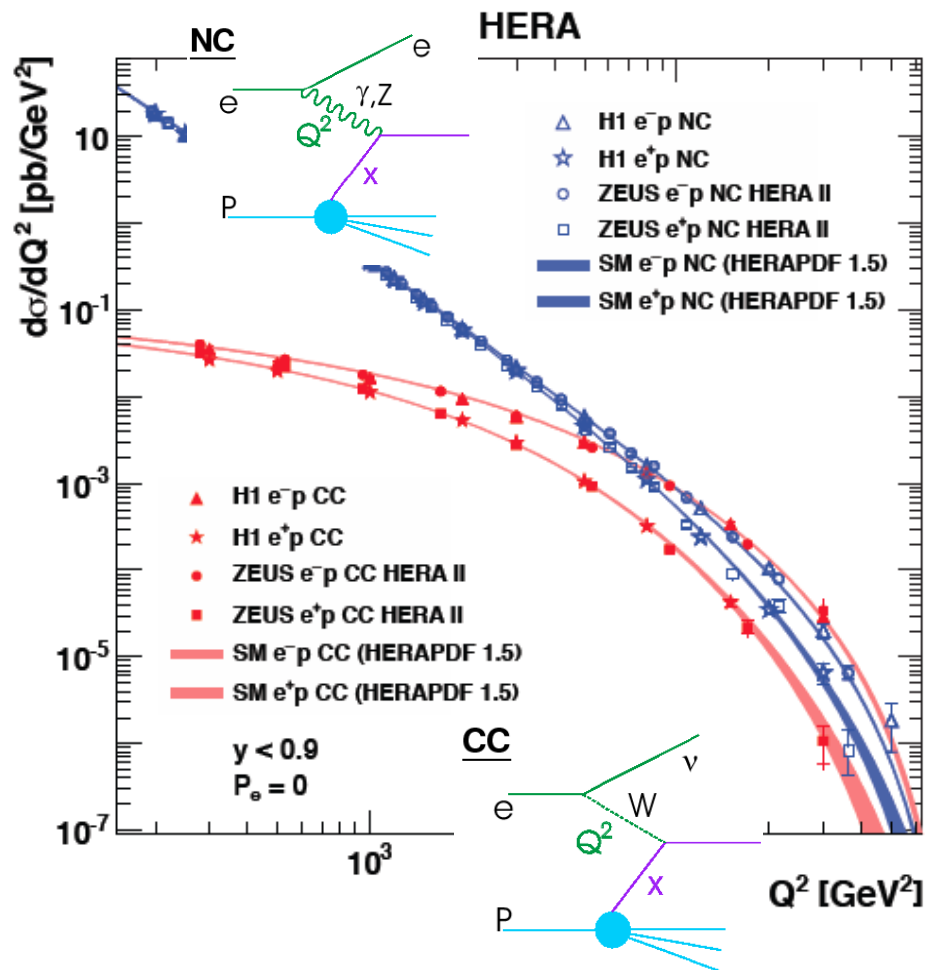


LHC 8 TeV - Ratio to NNPDF2.3 NNLO - $\alpha_s = 0.118$

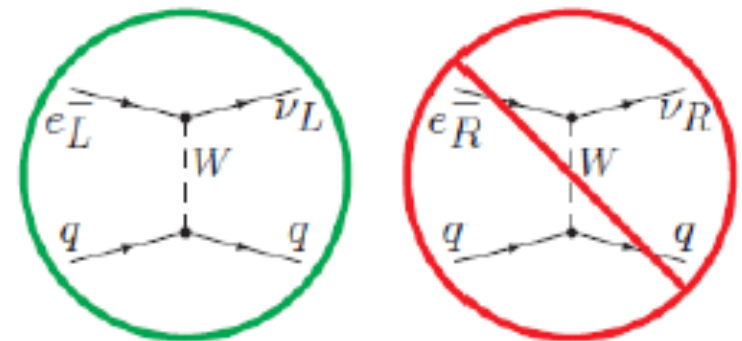


[R. Ball et al.,
JHEP 1304
(2013), 125]

HERAoism & the Electroweak Standard Model



- Electroweak Unification in space-like region
- Chirality / parity violation of the weak interaction



HERAoism & Searches for New Physics

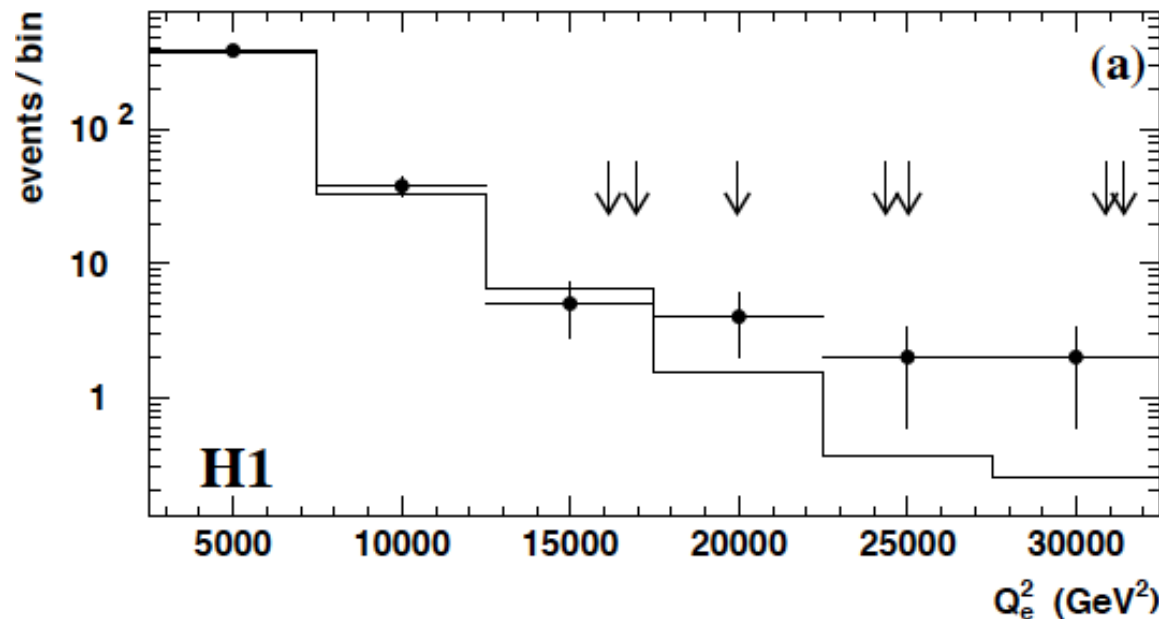
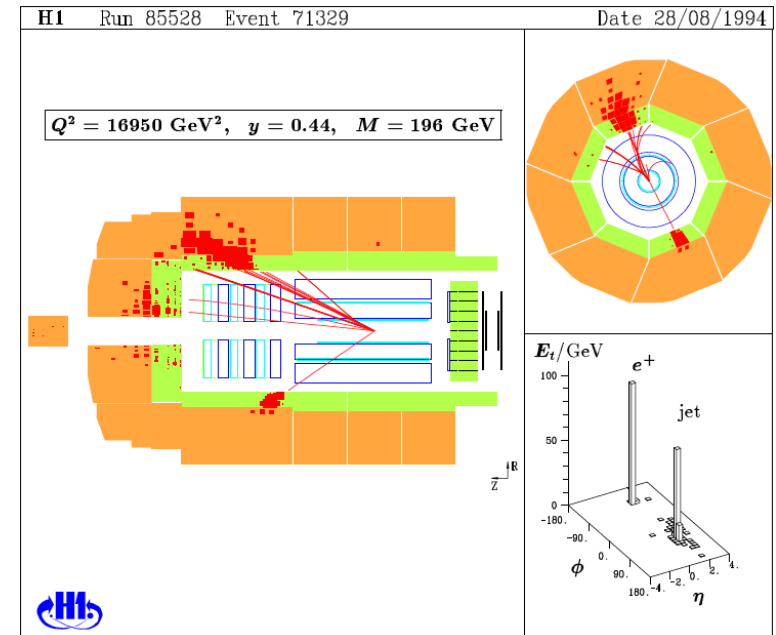
There were moments of excitement:

DESY 97-24
February 13th 1997

ISSN 0418-9833

Observation of Events at Very High Q^2 in ep
Collisions at HERA

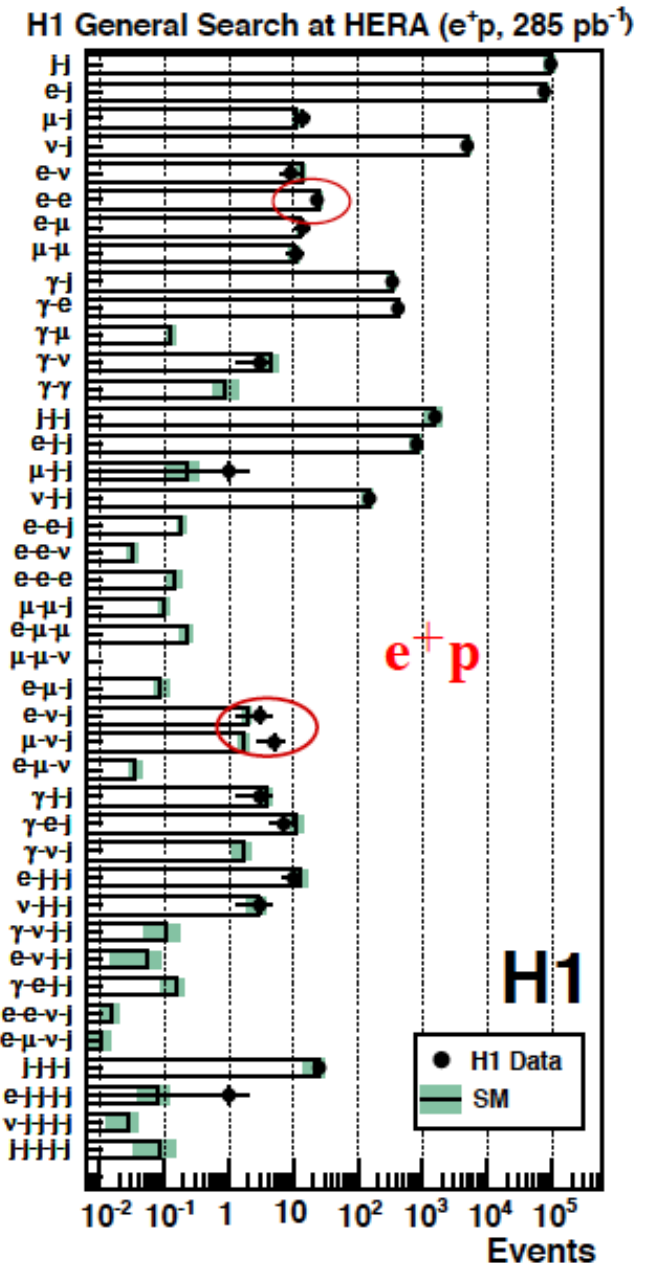
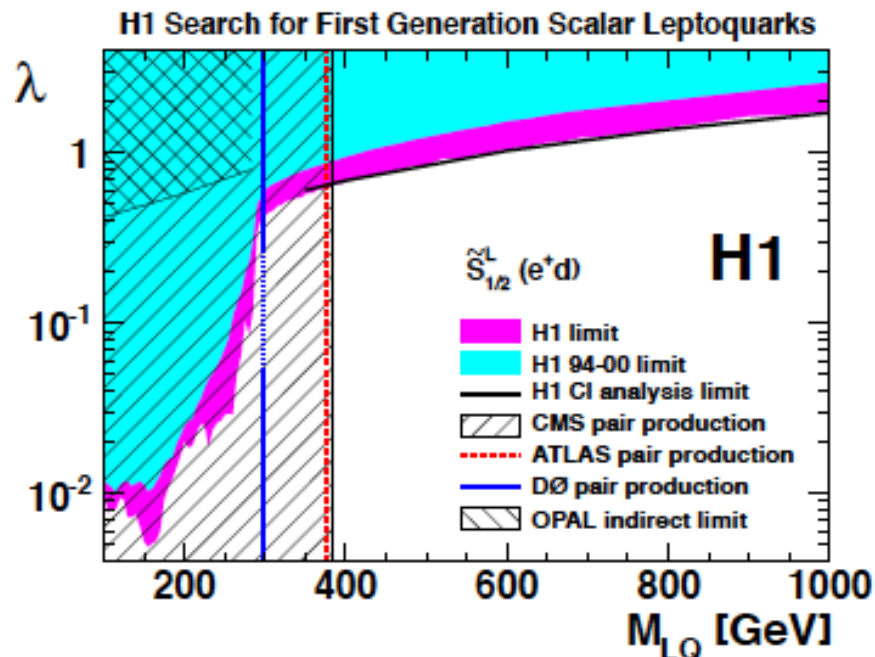
H1 Collaboration



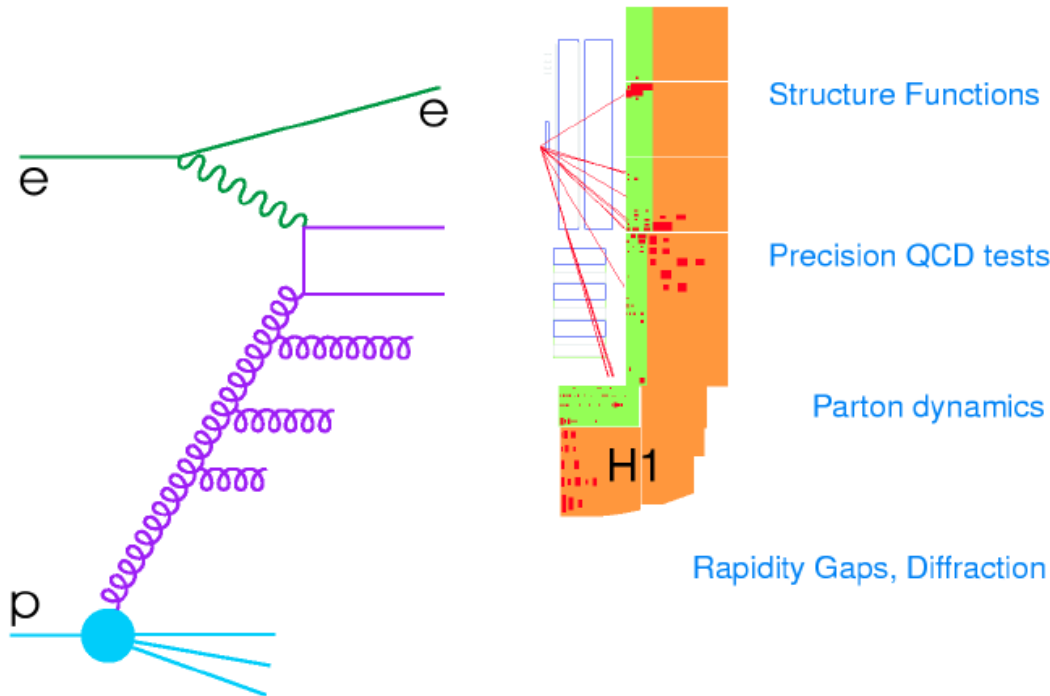
Signal sadly
became less
significant
with further
data.

HERAoism & Searches for New Physics

- Finally, fantastic agreement with SM across wide range of final states.
- No deviations bigger than $\sim 2.5\sigma$.
- Compositeness $R_q < 0.65 \times 10^{-18} \text{ m}$

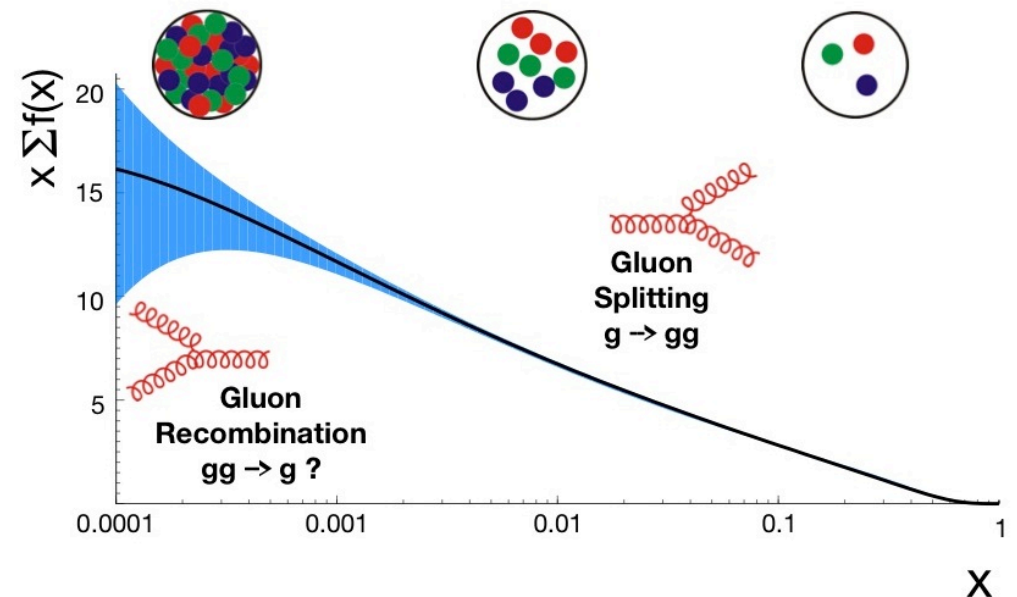
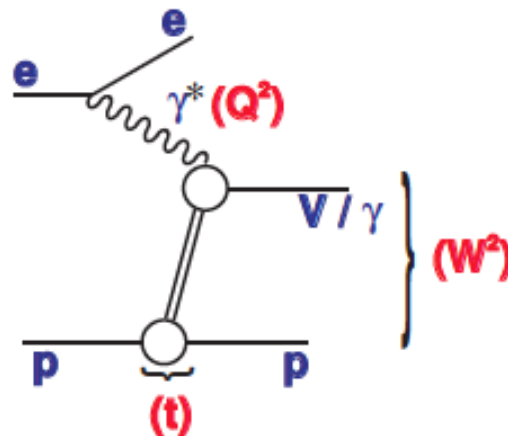


HERAoism & The Strong Interaction

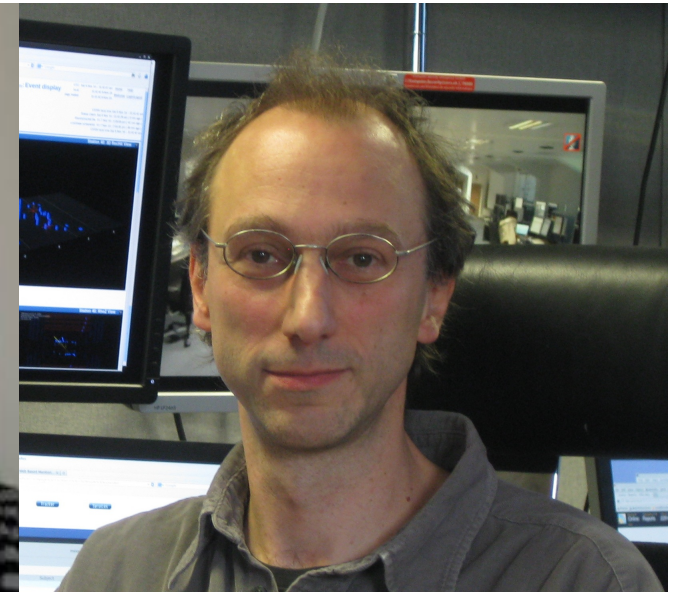


Unique laboratory for precision testing of QCD and searching for novel dynamics at low $x \rightarrow$ Confinement and hadronic mass generation ...

Seminal Belgian work on diffractive & exclusive processes...



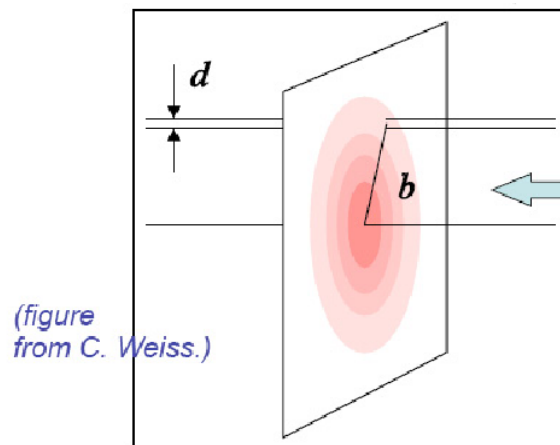
Guided by Pierre, IIHE / Belgian scientists
were at the forefront of understanding
diffraction in QCD for the first time



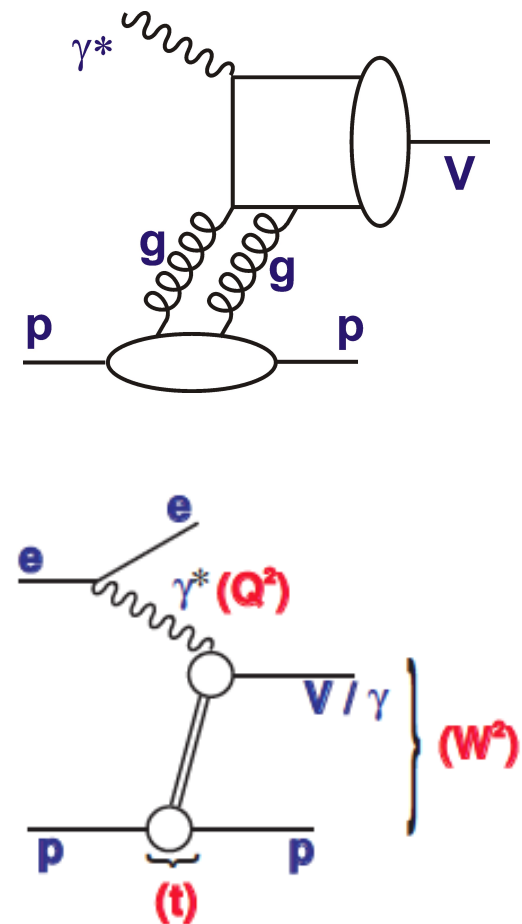
Exclusive/Diffractive Channels & Low x Gluons

- 1) [Low-Nussinov] interpretation as 2 gluon exchange enhances sensitivity to low x gluon
- 2) Additional variable t gives access to impact parameter (b) dependent amplitudes

→ Large t (small b) probes densest packed part of proton?



Central black region growing with decrease of x .



Exclusive ρ^0 and ϕ Production at H1

DESY 96-023
February 1996

DESY 99-010
February 1999

DESY 00-070
May 2000

DESY 02-027
March 2002

DESY 09-093
June 2009

ISSN 0418-9833

Measurement

A measurement
of diffractive

Diffractive Electroproduction of ρ and ϕ Mesons at HERA

H1 Collaboration

Elastic and

Abstract

Diffractive electroproduction of ρ and ϕ mesons is measured at HERA with the H1 detector in the elastic and proton dissociative channels. The data correspond to an integrated luminosity of 51 pb^{-1} . About 10500 ρ and 2000 ϕ events are analysed in the kinematic range of squared photon virtuality $2.5 \leq Q^2 \leq 60 \text{ GeV}^2$, photon-proton centre of mass energy $35 \leq W \leq 180 \text{ GeV}$ and squared four-momentum transfer to the proton $|t| \leq 3 \text{ GeV}^2$. The total, longitudinal and transverse cross sections are measured as a function of Q^2 , W and $|t|$. The measurements show a transition to a dominantly “hard” behaviour, typical of high gluon densities and small $q\bar{q}$ dipoles, for Q^2 larger than 10 to 20 GeV^2 . They support flavour independence of the diffractive exchange, expressed in terms of the scaling variable $(Q^2 + M_V^2)/4$, and proton vertex factorisation. The spin density matrix elements are measured as a function of kinematic variables. The ratio of the longitudinal to transverse cross sections, the ratio of the helicity amplitudes and their relative phases are extracted. Several of these measurements have not been performed before and bring new information on the dynamics of diffraction in a QCD framework. The measurements are discussed in the context of models using generalised parton distributions or universal dipole cross sections.

The total cross
 $Q^2 > 8 \text{ GeV}^2$.
The measured
The dependence
and the momentum
on the polar angle
determined. The
interplay of h

The elastic
a photon
energy in
the ρ reso
matrix ele
level of 8
of the cross
They suggest
dependence
sections.

The elastic
photon virtuality
130 GeV.
the four-momentum
and scaled
within error
analysis is
sections for
significant

The helicity
is studied in
the proton
collected with
 $40 < W <$
A significant
is observed.
These t dependence
exchange of

Exclusive ρ^0 and ϕ Production at H1

... more of a treatise!...

DESY 09-093
June 2009

ISSN 0418-9833

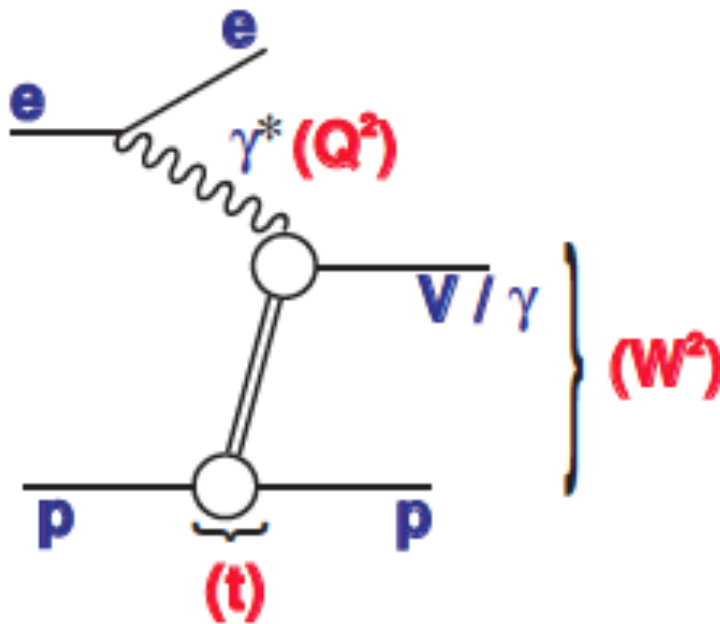
preprint had 113 pages ...
“probably not a letter”

Diffractive Electroproduction of ρ and ϕ Mesons at HERA

H1 Collaboration

Abstract

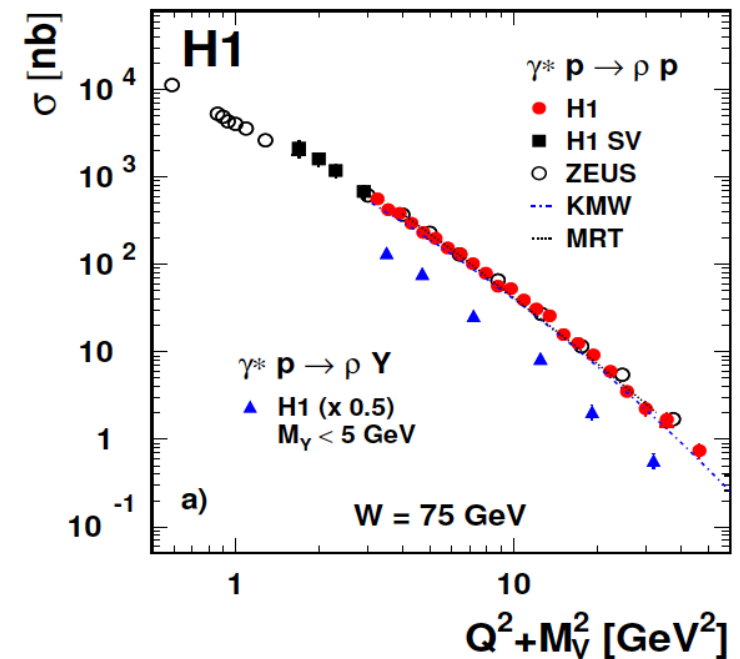
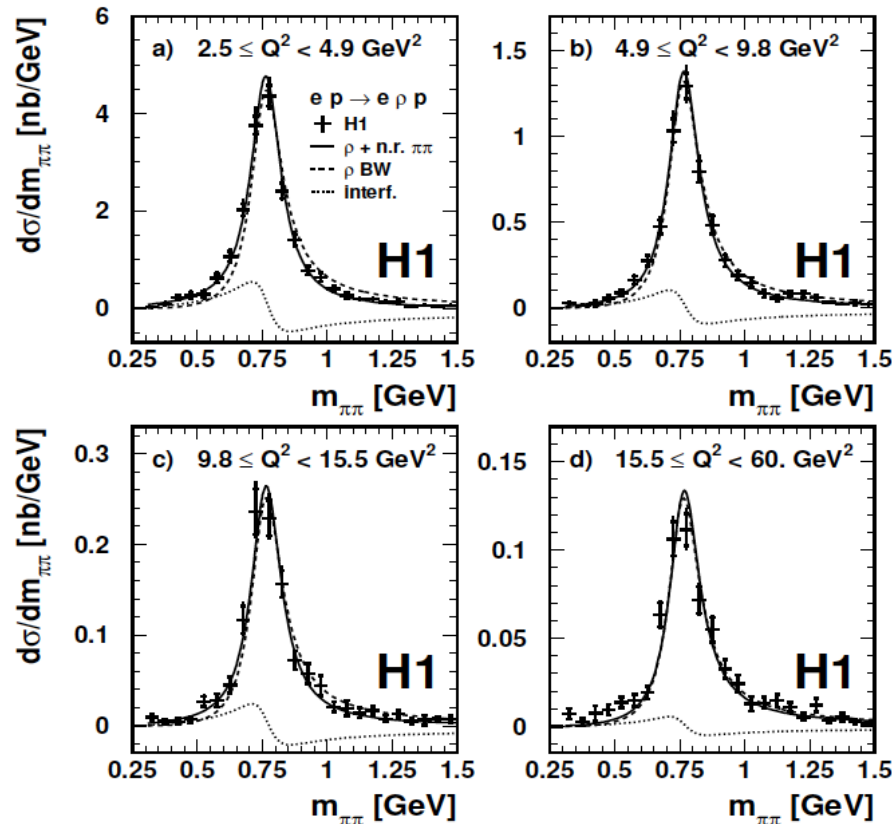
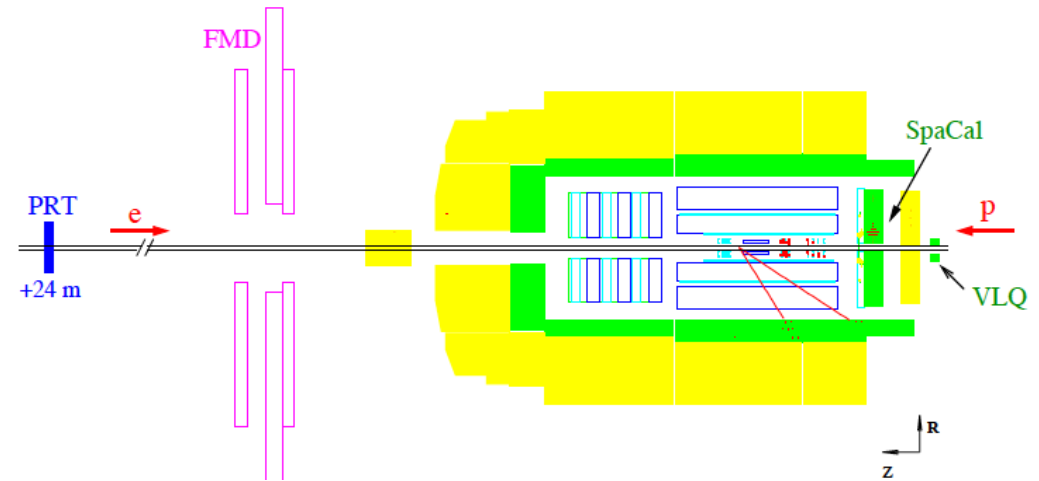
Diffractive electroproduction of ρ and ϕ mesons is measured at HERA with the H1 detector in the elastic and proton dissociative channels. The data correspond to an integrated luminosity of 51 pb^{-1} . About 10500 ρ and 2000 ϕ events are analysed in the kinematic range of squared photon virtuality $2.5 \leq Q^2 \leq 60 \text{ GeV}^2$, photon-proton centre of mass energy $35 \leq W \leq 180 \text{ GeV}$ and squared four-momentum transfer to the proton $|t| \leq 3 \text{ GeV}^2$. The total, longitudinal and transverse cross sections are measured as a function of Q^2 , W and $|t|$. The measurements show a transition to a dominantly “hard” behaviour, typical of high gluon densities and small $q\bar{q}$ dipoles, for Q^2 larger than 10 to 20 GeV^2 . They support flavour independence of the diffractive exchange, expressed in terms of the scaling variable $(Q^2 + M_V^2)/4$, and proton vertex factorisation. The spin density matrix elements are measured as a function of kinematic variables. The ratio of the longitudinal to transverse cross sections, the ratio of the helicity amplitudes and their relative phases are extracted. Several of these measurements have not been performed before and bring new information on the dynamics of diffraction in a QCD framework. The measurements are discussed in the context of models using generalised parton distributions or universal dipole cross sections.



Elastic ρ^0 , ϕ : Selection and Signals

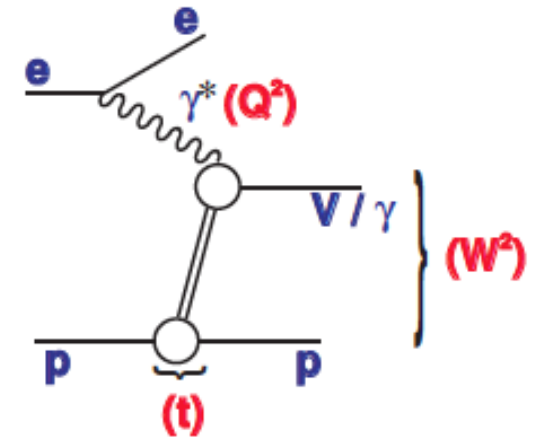
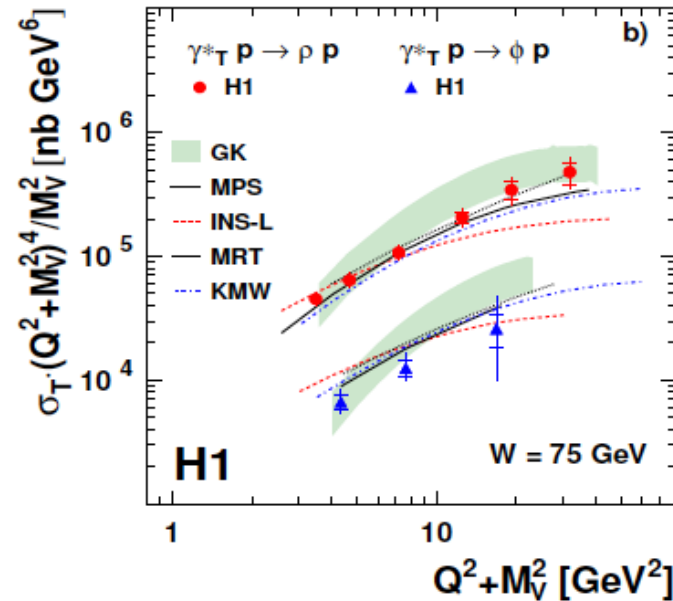
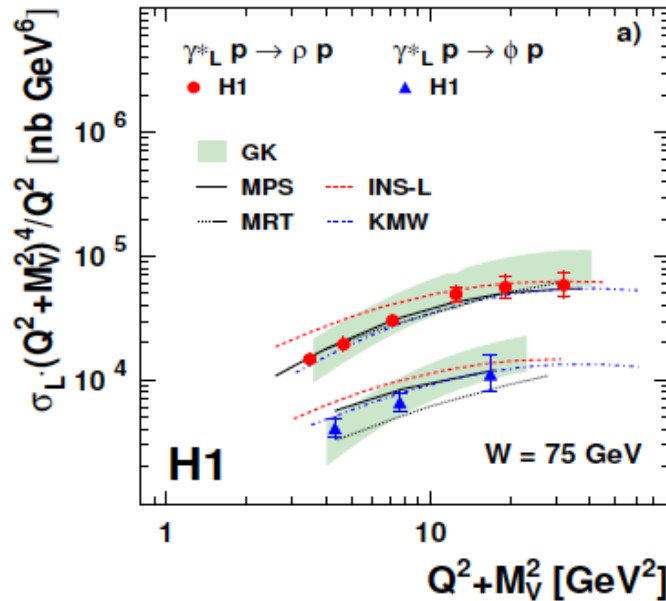
$$\rho^0 \rightarrow \pi^+\pi^- \quad \phi \rightarrow K^+K^-$$

- 1 scattered electron
- 2 oppositely charged tracks
- Detector otherwise empty

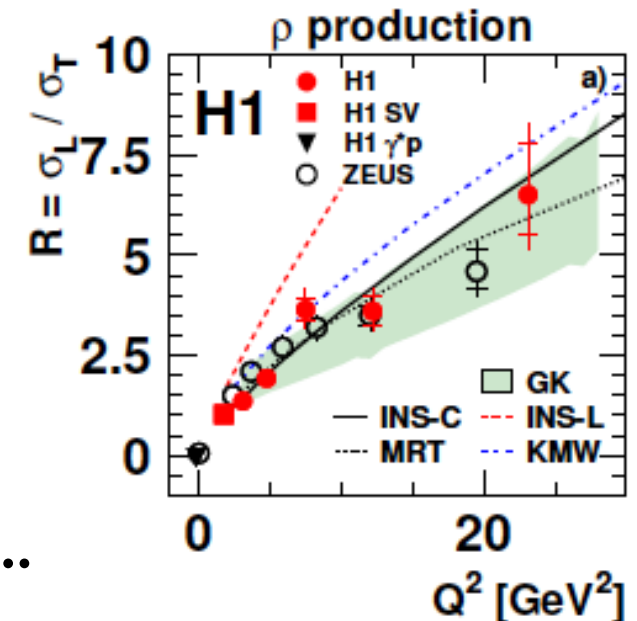


- Fundamentally higher twist
 → Cross section falls fast with Q^2

Elastic ρ^0 , ϕ : Scale Dependence



- Fully understanding the Q^2 dependence was hard!... delicate interplay between longitudinally and transversely polarised photon cross sections
- QCD theory had to work hard to catch up ...

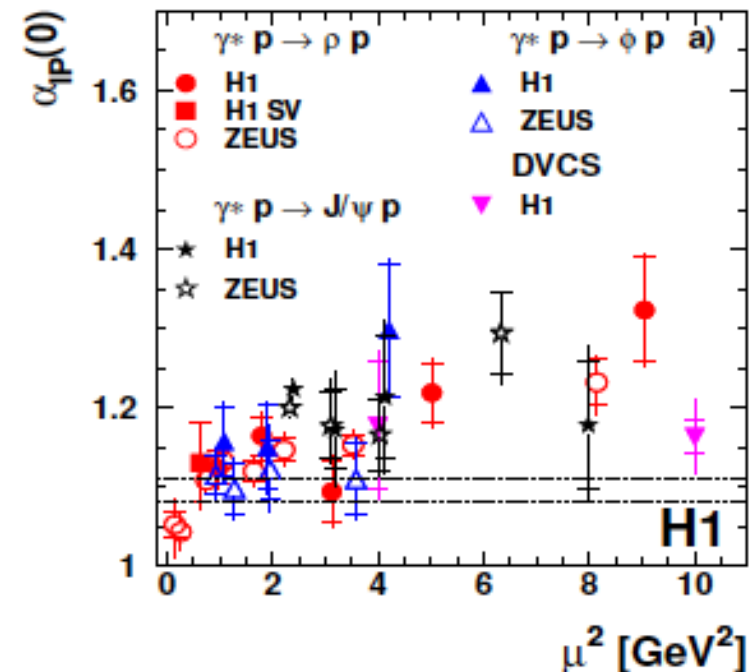
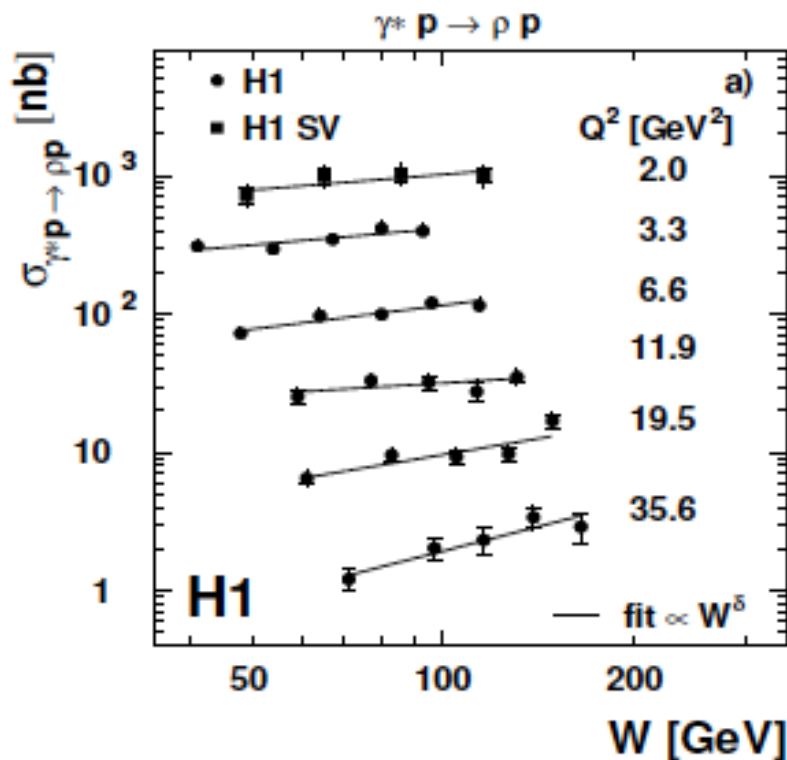
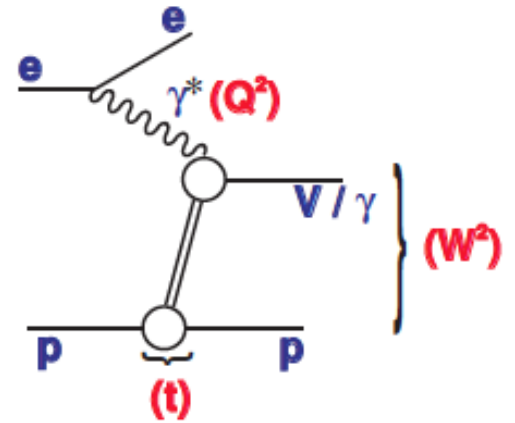


Elastic ρ^0 , ϕ : Energy Dependence

- Energy (W) dependence steepens with increasing hardness of scale (Q^2)

- The classic transition from soft to hard regime

- Interpretation in terms of both pomeron / Regge language and (hard) proton gluon density

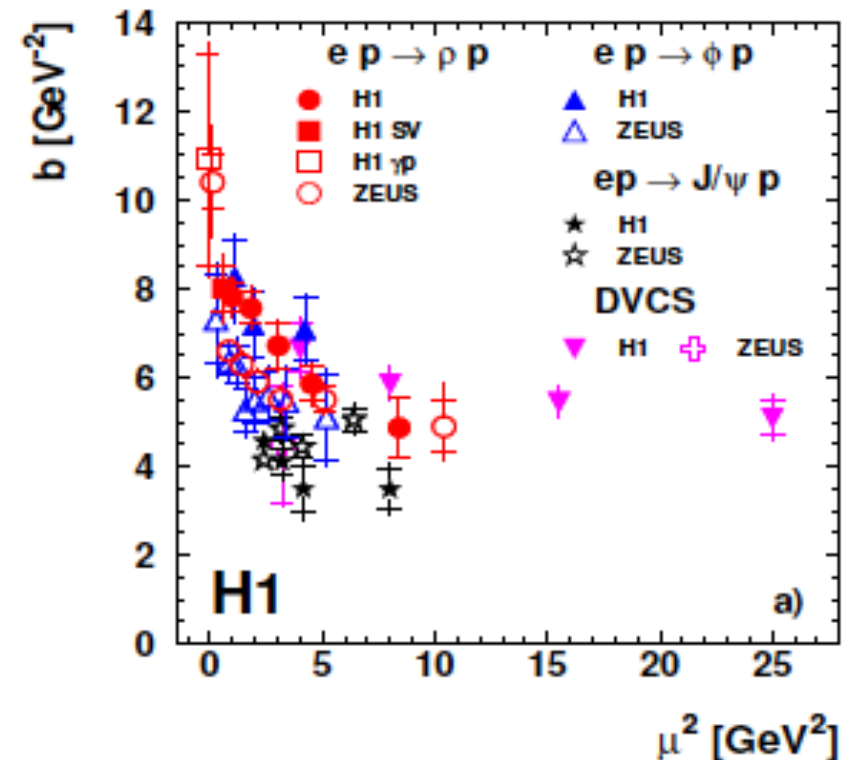
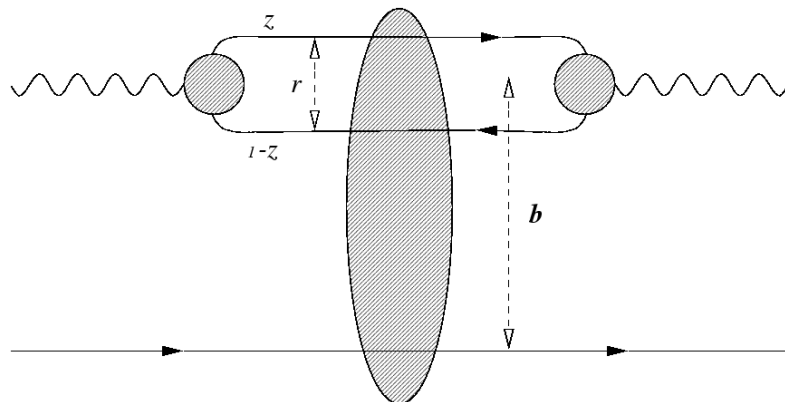
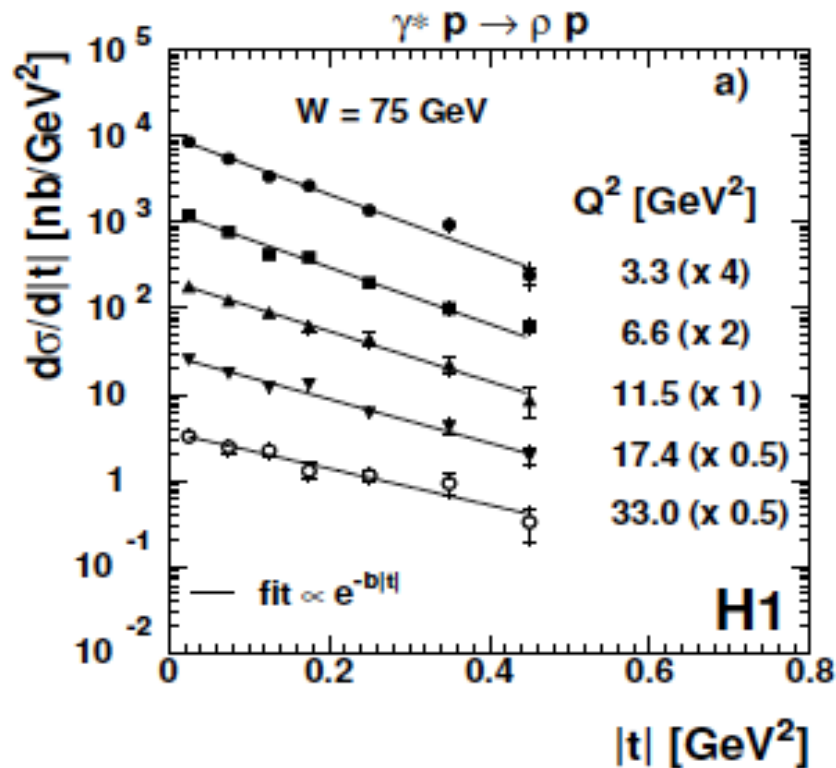


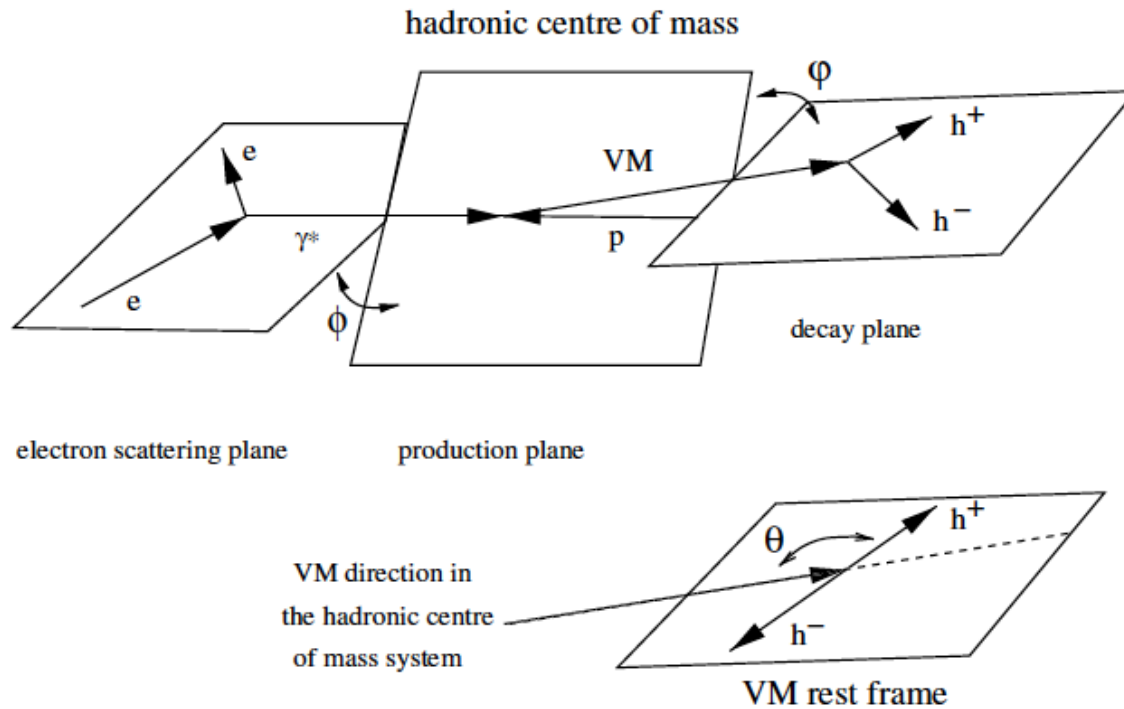
Elastic ρ^0, ϕ : Dependence on t

t dependence reveals details of
 $\gamma \rightarrow q\bar{q}$ dipole

... and measures proton size as
 $r \rightarrow 0$ (i.e. $Q^2 \rightarrow \infty$)

Approximate scaling for all VMs +
DVCS when plotted v $Q^2 + M_2$



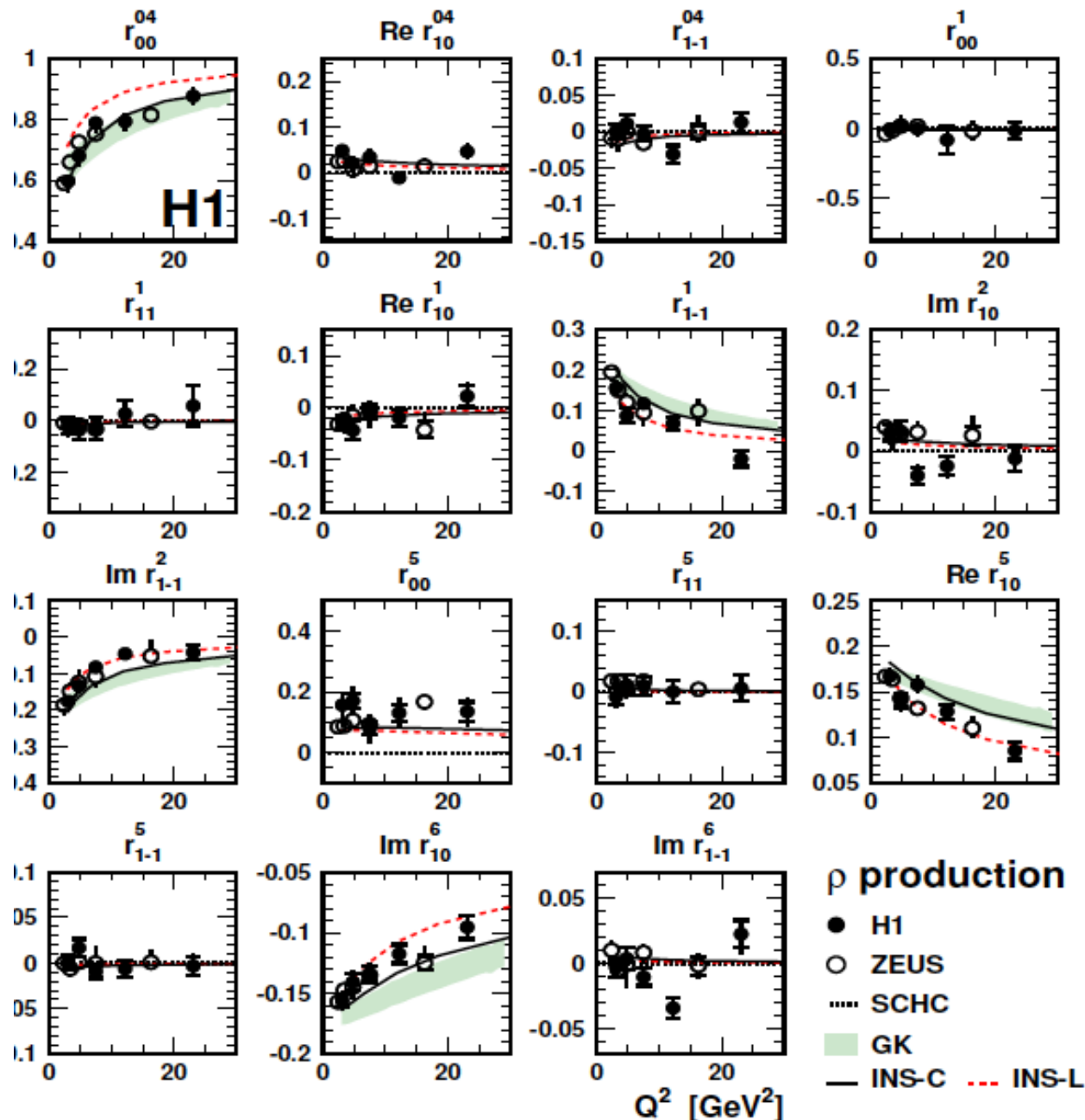


Elastic ρ^0 , ϕ : Spin Density Matrix Elements

... required a certain
'attention to detail' ...

$$\begin{aligned}
 W(\theta, \varphi, \phi) = & \frac{3}{4\pi} \left\{ \frac{1}{2}(1 - r_{00}^{04}) + \frac{1}{2}(3 r_{00}^{04} - 1) \cos^2 \theta \right. \\
 & - \sqrt{2} \operatorname{Re} r_{10}^{04} \sin 2\theta \cos \varphi - r_{1-1}^{04} \sin^2 \theta \cos 2\varphi \\
 & - \varepsilon \cos 2\phi \left(r_{11}^1 \sin^2 \theta + r_{00}^1 \cos^2 \theta - \sqrt{2} \operatorname{Re} r_{10}^1 \sin 2\theta \cos \varphi \right. \\
 & \quad \left. - r_{1-1}^1 \sin^2 \theta \cos 2\varphi \right) \\
 & - \varepsilon \sin 2\phi \left(\sqrt{2} \operatorname{Im} r_{10}^2 \sin 2\theta \sin \varphi + \operatorname{Im} r_{1-1}^2 \sin^2 \theta \sin 2\varphi \right) \\
 & + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi \left(r_{11}^5 \sin^2 \theta + r_{00}^5 \cos^2 \theta \right. \\
 & \quad \left. - \sqrt{2} \operatorname{Re} r_{10}^5 \sin 2\theta \cos \varphi - r_{1-1}^5 \sin^2 \theta \cos 2\varphi \right) \\
 & + \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi \left(\sqrt{2} \operatorname{Im} r_{10}^6 \sin 2\theta \sin \varphi \right. \\
 & \quad \left. + \operatorname{Im} r_{1-1}^6 \sin^2 \theta \sin 2\varphi \right) \left. \right\}.
 \end{aligned}$$

Elastic ρ^0 , ϕ : Spin Density Matrix Elements



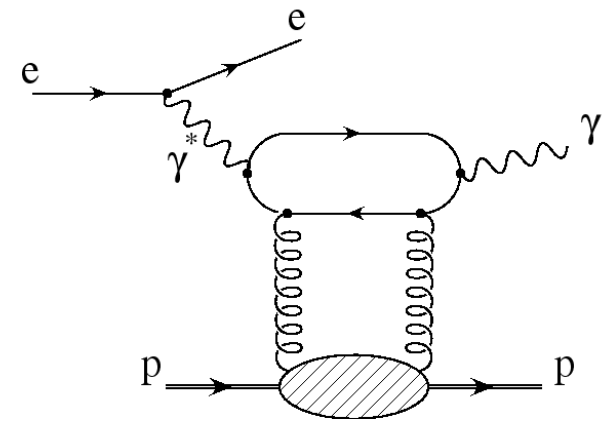
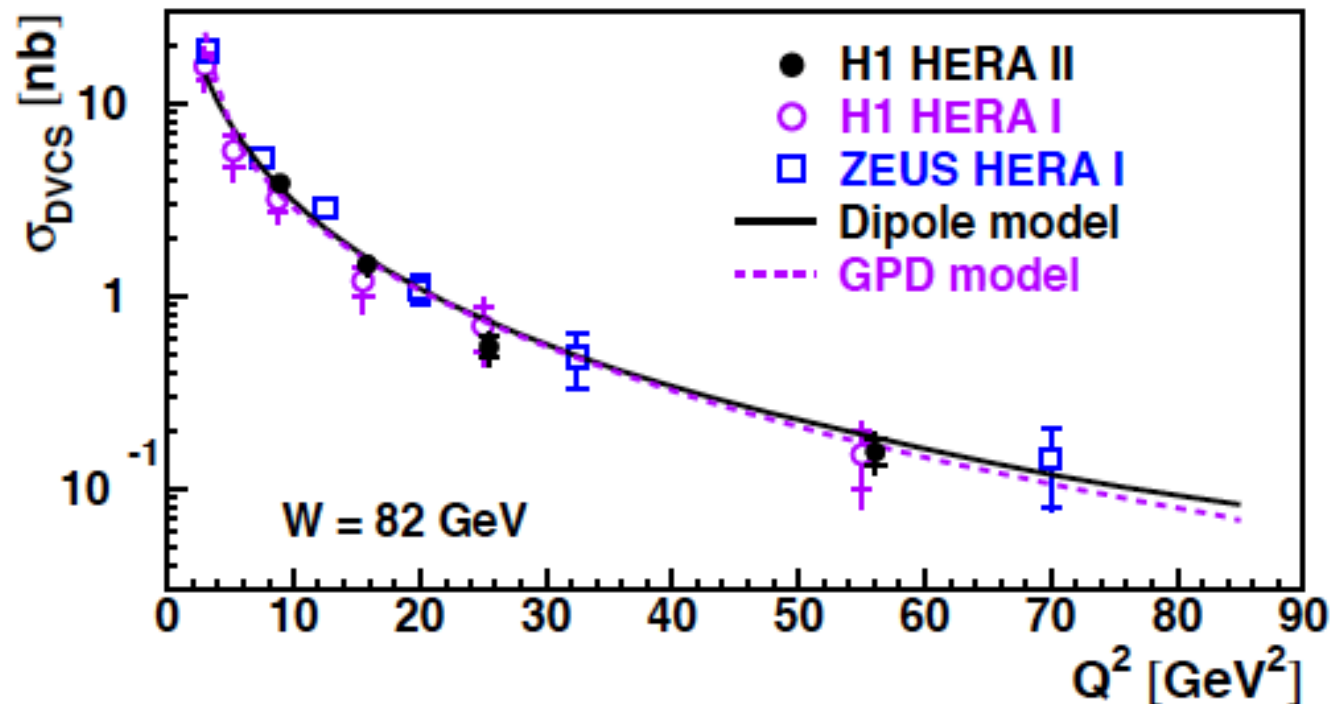
... measured
differentially
in several
variables

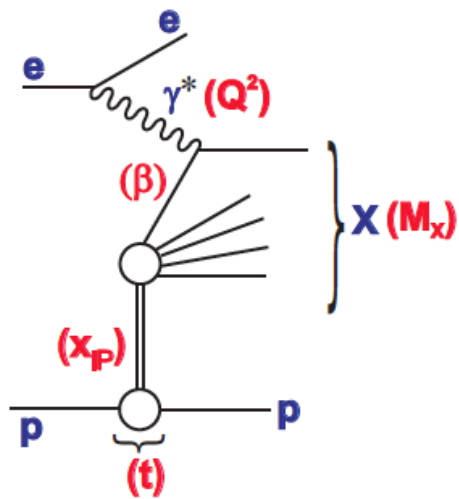
s-channel helicity
non-conservation
quantified

QCD models
successfully
tested.

Deeply Virtual Compton Scattering ($ep \rightarrow e\gamma p$)

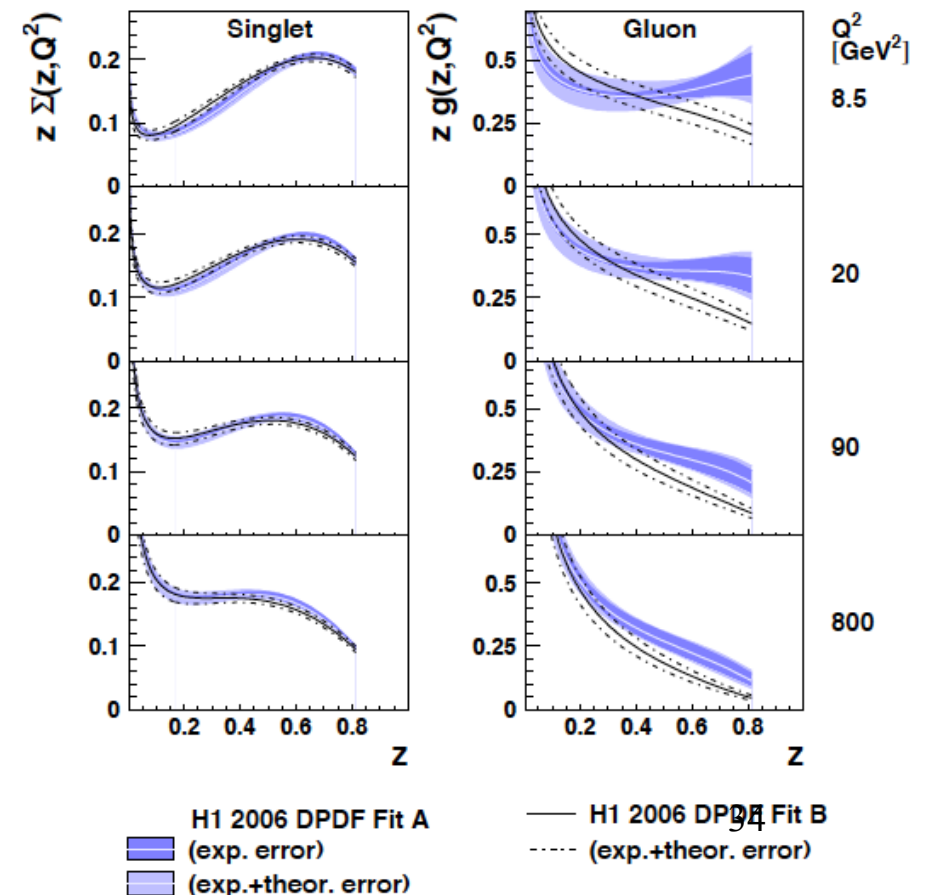
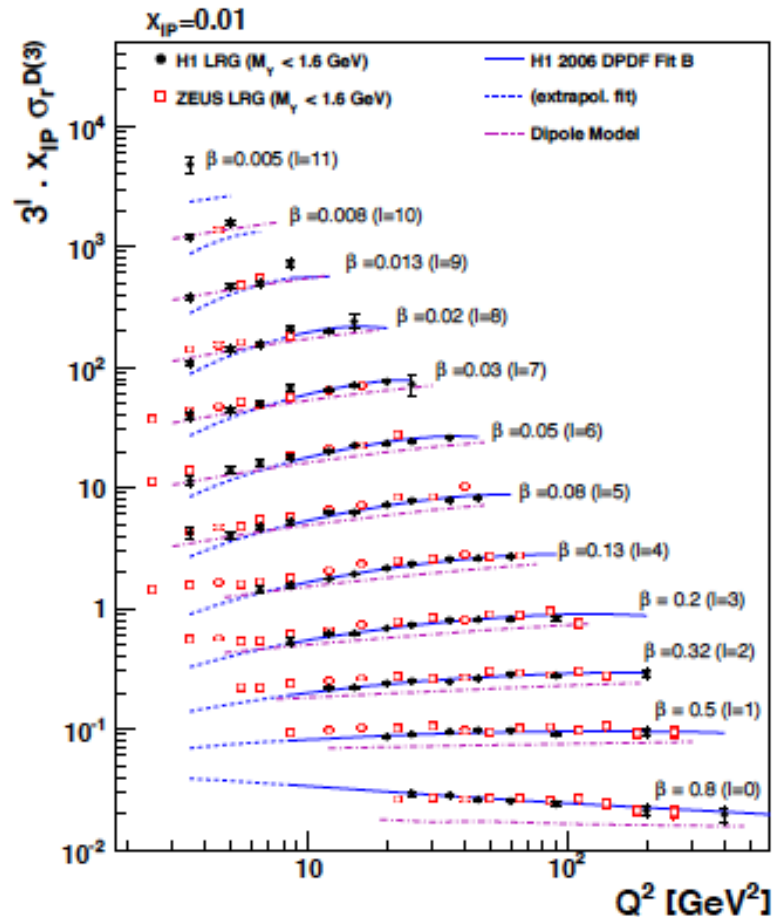
- Lower cross sections than VMs due to g coupling
- Directly sensitive to proton transverse structure $\rightarrow$ GPDs
- Major Belgian role in first HERA studies and interpretation





Inclusive Diffraction / Pomeron Structure

- 3 (4)-fold differential cross sections
- DGLAP QCD analysis
→ pomeron parton structure
- Detailed tests in diffractive final states



The Story Continues

DESY 14-200
November 2014

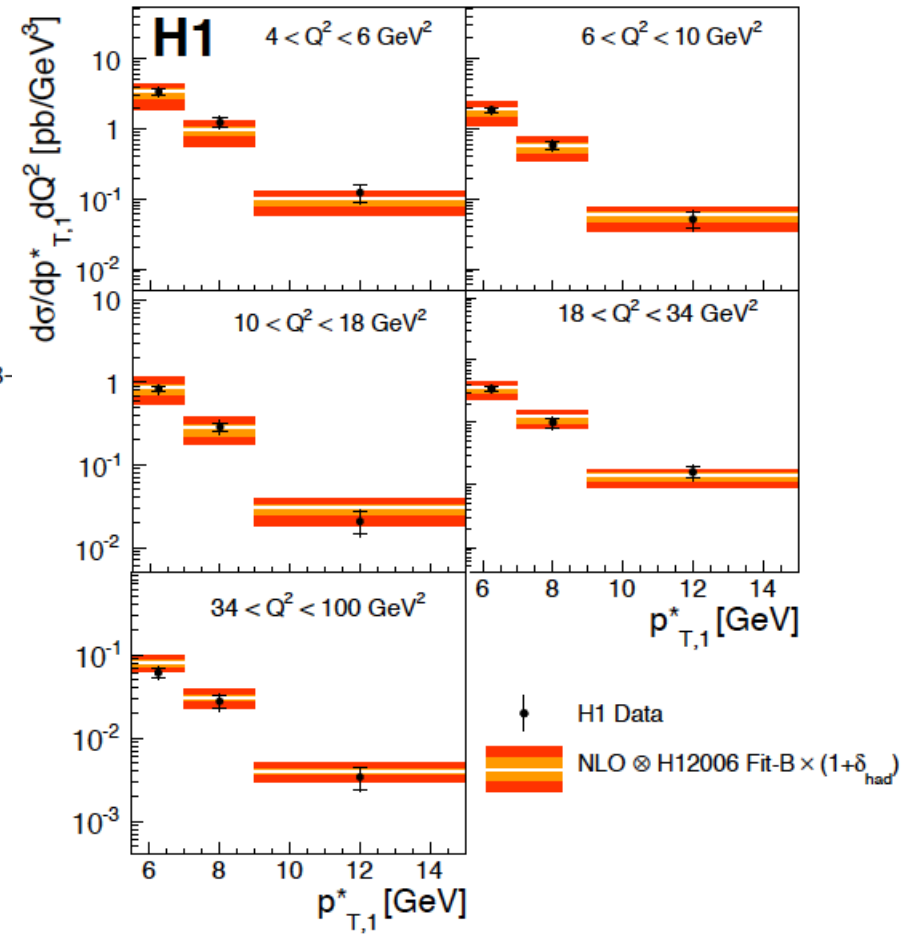
ISSN 0418-

Measurement of Dijet Production in Diffractive Deep-Inelastic ep Scattering at HERA

H1 Collaboration

Abstract

A measurement is presented of single- and double-differential dijet cross sections in diffractive deep-inelastic ep scattering at HERA using data collected by the H1 experiment corresponding to an integrated luminosity of 290 pb^{-1} . The investigated phase space is spanned by the photon virtuality in the range of $4 < Q^2 < 100 \text{ GeV}^2$ and by the fractional proton longitudinal momentum loss $x_P < 0.03$. The resulting cross sections are compared with next-to-leading order QCD predictions based on diffractive parton distribution functions and the value of the strong coupling constant is extracted.



... with more in the pipeline ...

Watch this space ...

Final Remarks

- HERA ... a `different' sort of collider
- Scientifically prolific and influential
- Sense of community & collaboration: good `growing up' environment
- Major Belgian contributions!

- `Herr Prof' Marage ...
... led by example
... constantly enthusiastic
... natural curiosity /desire
to measure and understand
... was never happy until job
was done completely
... motivated and inspired
the next generation

