

HERA zero-degree detectors



Robert Ciesielski (Rockefeller University)

*Joint CFNS & RBRC Workshop on Physics and Detector Requirements at Zero-Degree of Colliders,
24-26 September 2019, CFNS, Stony Brook University, NY, USA*



HERA collider



- World's only ep collider, located at DESY Hamburg.
- Ended in June 2007, after 15 years of successful running.
- Two colliding experiments: H1 and ZEUS.

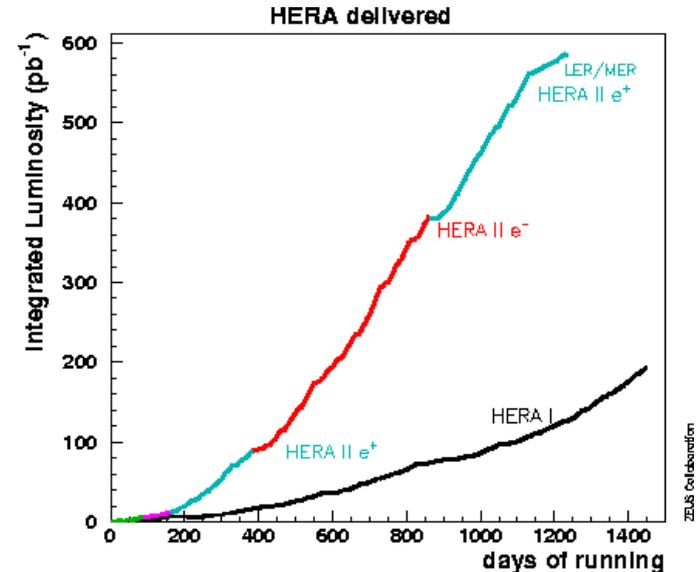


HERA I (1994-2000)

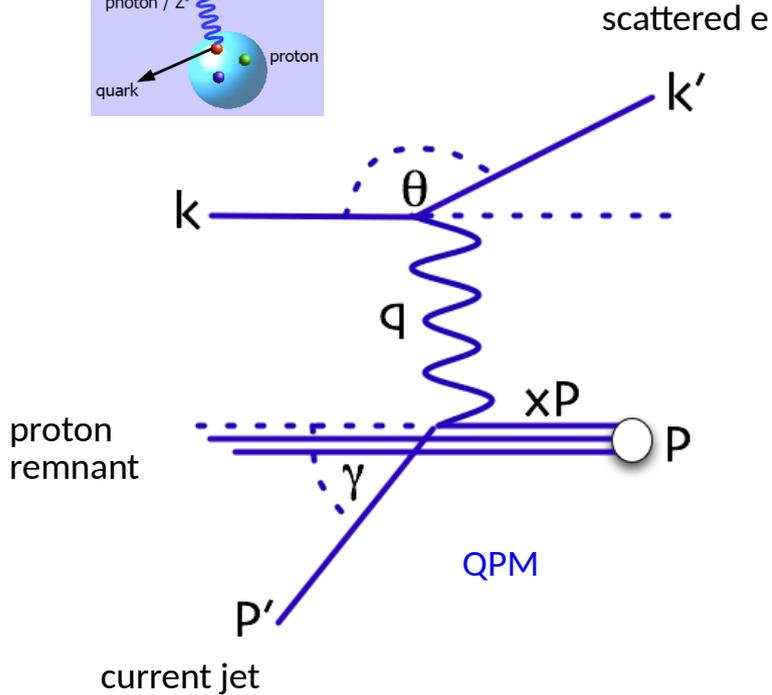
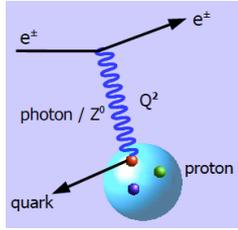
$L \sim 120 \text{ pb}^{-1}$ collected per experiment.
Mostly e^+p .

HERA II (2002-2007)

$L \sim 360 \text{ pb}^{-1}$ collected per experiment.
Similar amount of e^+p and e^-p .
Longitudinal polarisation of lepton beam ($P=0.3-0.4$).



Deep Inelastic Scattering (DIS)



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

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

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

$$Q^2 = s \cdot x \cdot y$$

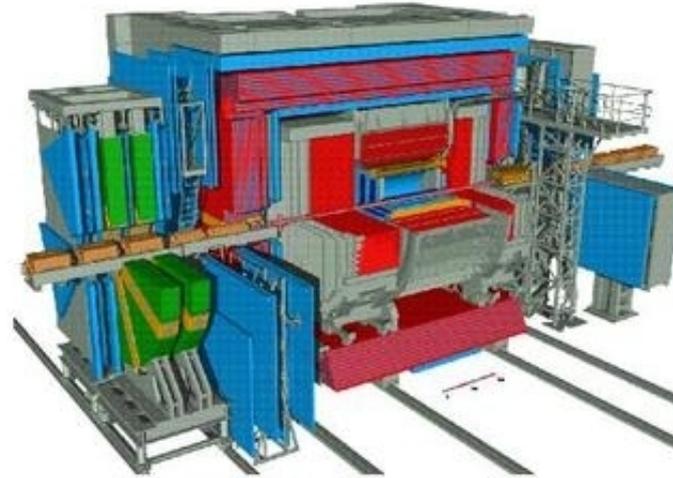
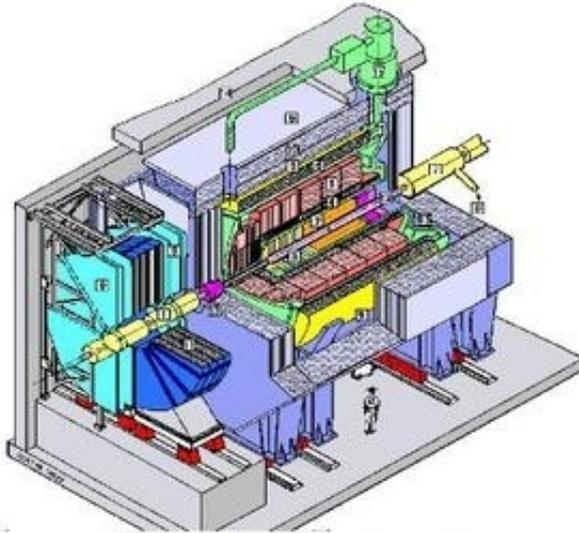
resolving power
(virtuality of the exchanged photon)

the Bjorken scaling variable
(momentum fraction of the struck quark)

the inelasticity

HERA kinematic range: 0 (photoproduction, PhP) $< Q^2 < 40000 \text{ GeV}^2$, $x > 10^{-6}$

Central detectors



Fine-grained LAr calorimeter:

$$4 < \theta < 154^\circ \quad \sigma_E/E = 12\%/\sqrt{E} \oplus 1\% \text{ (ele)}$$

$$\sigma_E/E = 55\%/\sqrt{E} \oplus 1\% \text{ (had)}$$

Backward lead-scintillator calorimeter:

$$154 < \theta_e < 174^\circ \quad \sigma_E/E = 7\%/\sqrt{E} \oplus 1\% \text{ (ele)}$$

Uranium-scintillator calorimeter:

$$\sigma_E/E = 18\%/\sqrt{E} \text{ (ele)} \quad 2.2 < \theta < 176.5^\circ$$

$$\sigma_E/E = 35\%/\sqrt{E} \text{ (had)}$$

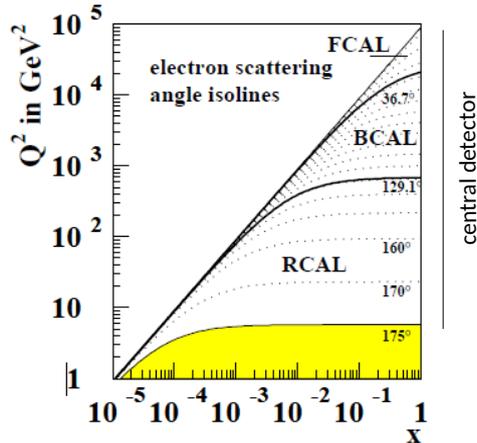
$$Q^2 > \sim 2 \text{ GeV}^2$$

+ central tracking detectors

Why small-angle detectors?

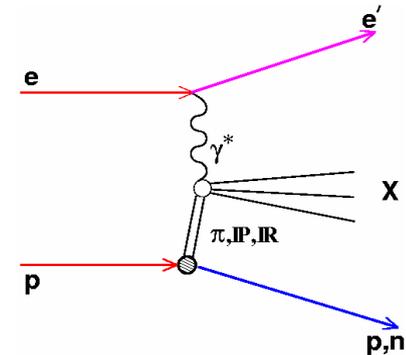
Backward (electron direction):

- Measure luminosity
- Tag PHP ($Q^2 \sim 0$)
- Investigate transition from PHP to DIS ($0 < Q^2 < 1 \text{ GeV}^2$)



Forward (proton direction):

- Improve energy measurement of hadronic system
- Improve diffractive studies
- Separate elastic from proton dissociative processes
- Tag forward leading particles (scattered protons/neutrons/photons)



Luminosity Monitor - HERA I

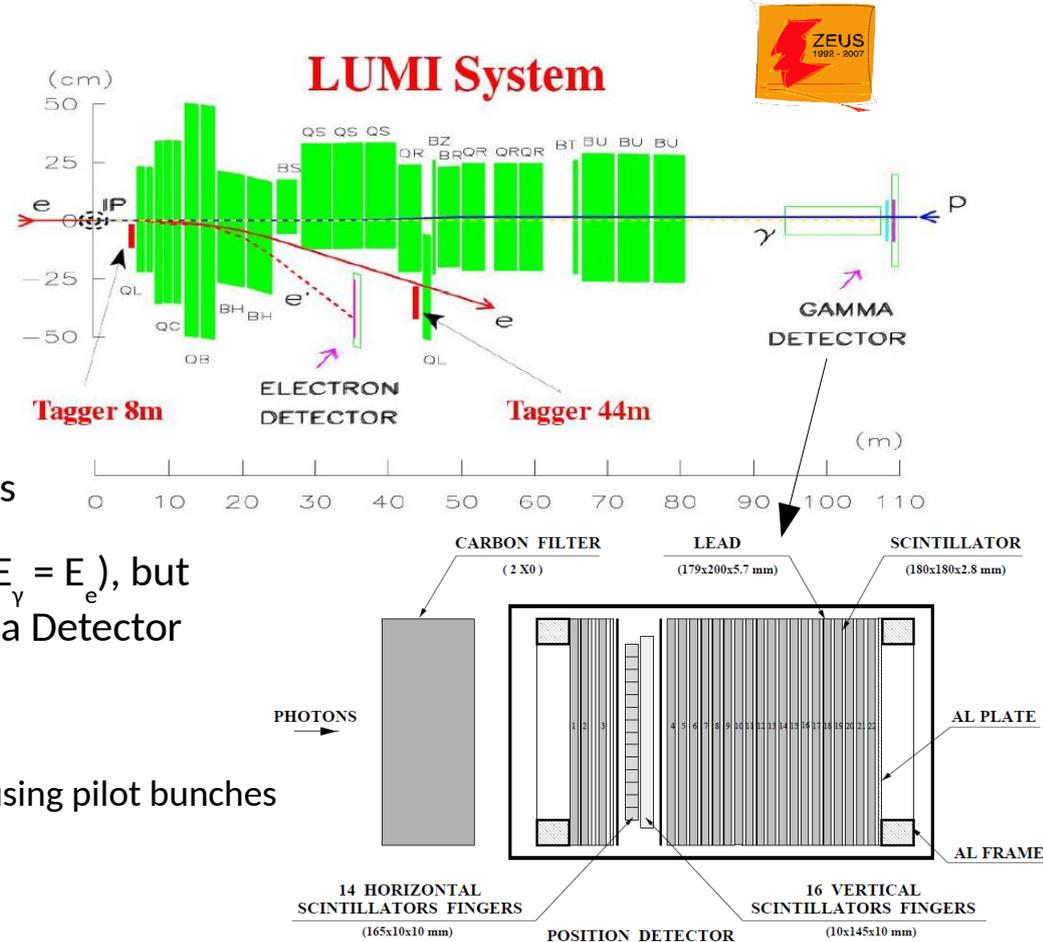
Similar system for H1

- Measure rate of bremsstrahlung process $ep \rightarrow ep\gamma$
- Photons in Gamma Detector (PCAL)
(lead/scintillator sampling calorimeter at $z=105\text{m}$)
- Electrons in Electron Detector
(lead/scintillator sampling calorimeter at $z=35\text{m}$)
- Tungsten/scintillator electron taggers at 8m and 44m for systematic checks and to tag photoproduction events
- Originally designed to measure $e\gamma$ coincidences ($E_{e'} + E_\gamma = E_e$), but good background conditions allowed to use only Gamma Detector

• Lumi:
$$L = 1 / \sigma_{BH}^{obs} [R_{tot} - (I_{tot} / I_0)R_0]$$

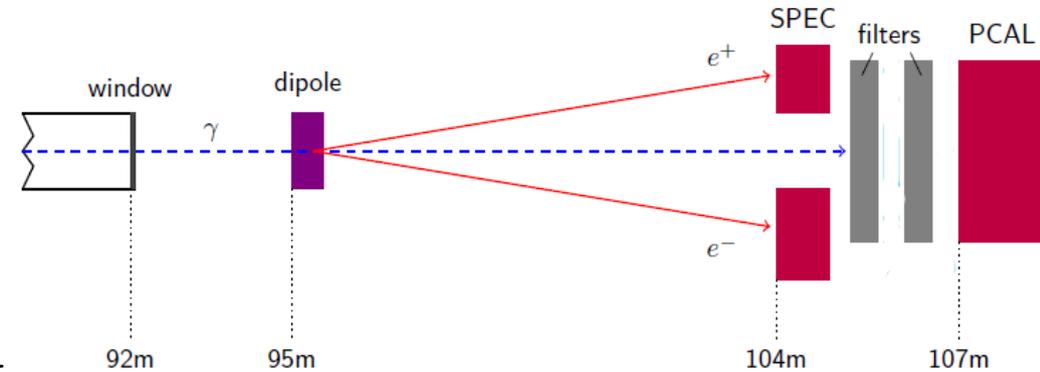
- R_0 - main background from beam gas scattering, subtracted using pilot bunches
(bunch structure at HERA-I: p 180, e 194, colliding 174)
- σ_{BH}^{obs} - Bether-Heitler cross section in fiducial region

- Total uncertainty of 1.05% (dominated by acceptance and E-scale uncertainty)



Luminosity Monitor – HERA II

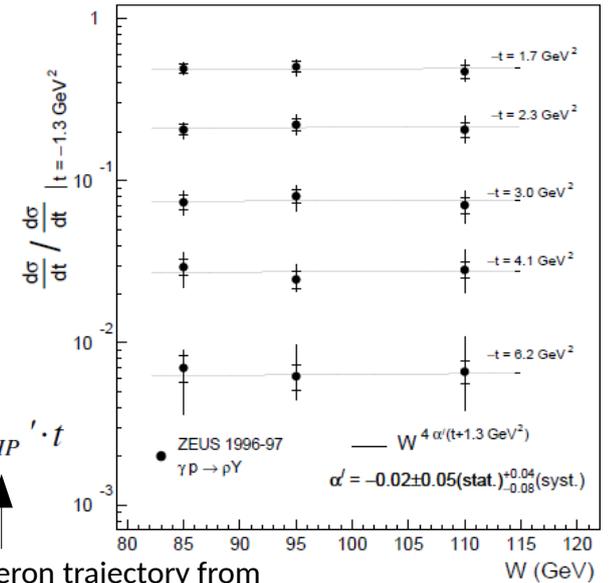
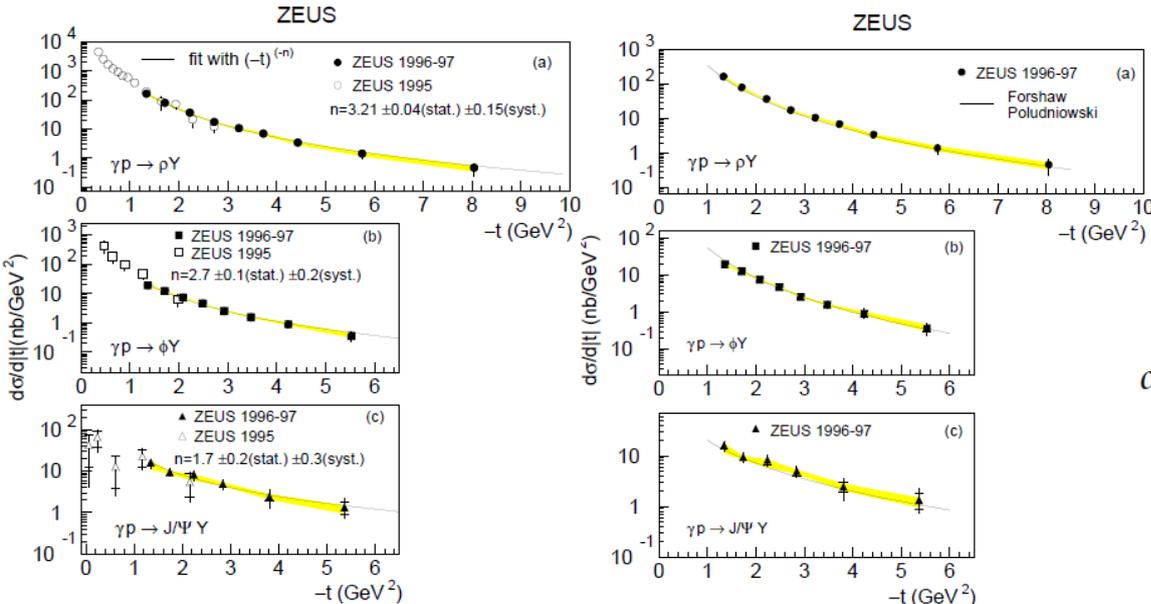
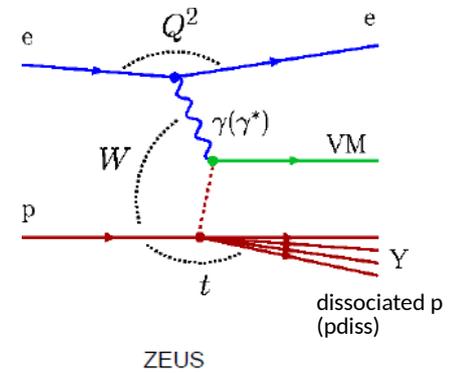
- Higher $e\gamma$ bremsstrahlung rate (x5) and significant increase in synchrotron radiation after the upgrade, reduced acceptance due to large beam divergence
- Photon detector upgraded with radiation hard calorimeter, with increased filter thickness ($2X_0 \rightarrow 4X_0$)
- Electron-positron pair spectrometer (SPEC) consisting of two tungsten/scintillator calorimeters added to measure photons from conversions (9% rate at beam-pipe exit window); *no synchrotron radiation, no radiation damage, no pileup*
- PCAL provides independent lumi measurement for systematic studies
- Total lumi uncertainty in HERA-II is 1.7%, (dominated by aperture and x position of the photon beam)



Measurement using electron tagger at 44m

Diffractive photoproduction of vector mesons ($\rho, \phi, J/\Psi$) at high momentum transfer t

- Studies of exclusive processes show that Q^2 and MV provide the pQCD hard scale.
→ early pdiss result showing that t provides hard scale as well (BFKL regime).
- Scattered electron tagged in the 44m tagger ($E_{e'}=21-26$ GeV) → ensures very small Q^2 ($Q^2 < 0.01$ GeV²).
 t can be approximated by vector meson p_T^2 .



$$\alpha_{IP}(t) = \alpha_{IP}(0) + \alpha_{IP}' \cdot t$$

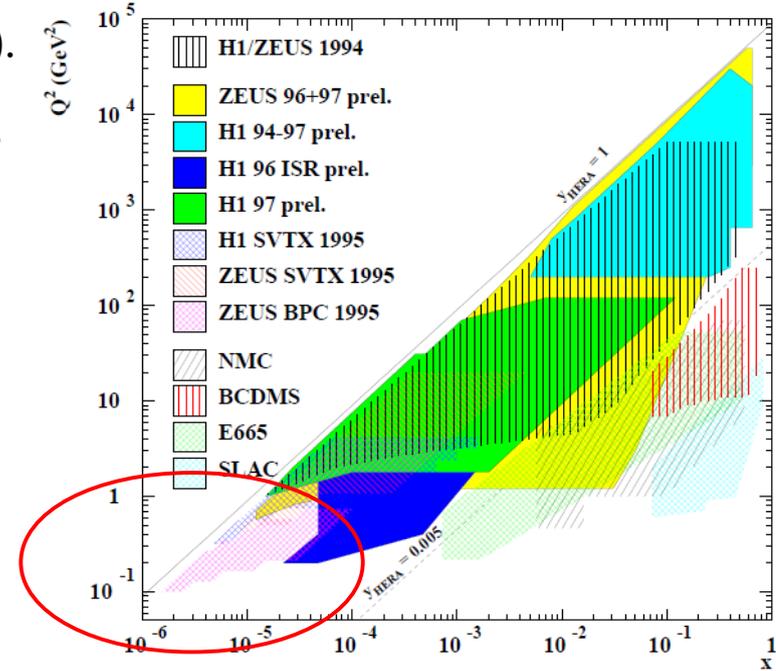
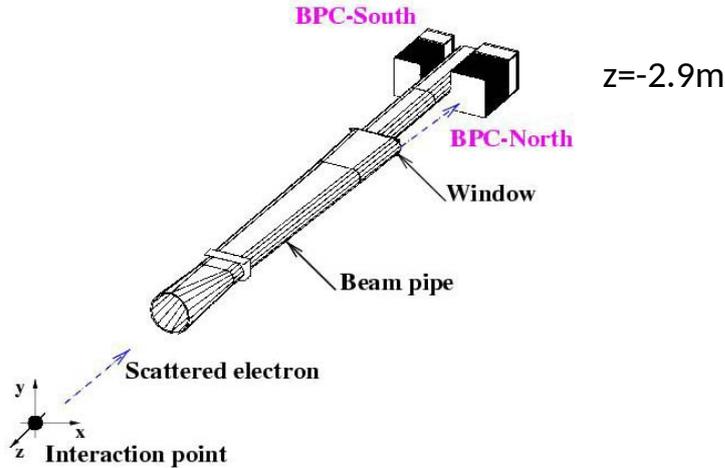
The slope of the Pomeron trajectory from the W dependence of the cross section in bins of t .

The result consistent with 0 (no shrinkage), in agreement with pQCD predictions.

Data at high t exhibit a power-law t dependence as predicted by pQCD
In good agreement with LO BFKL calculations of Forshaw and Poludniowski

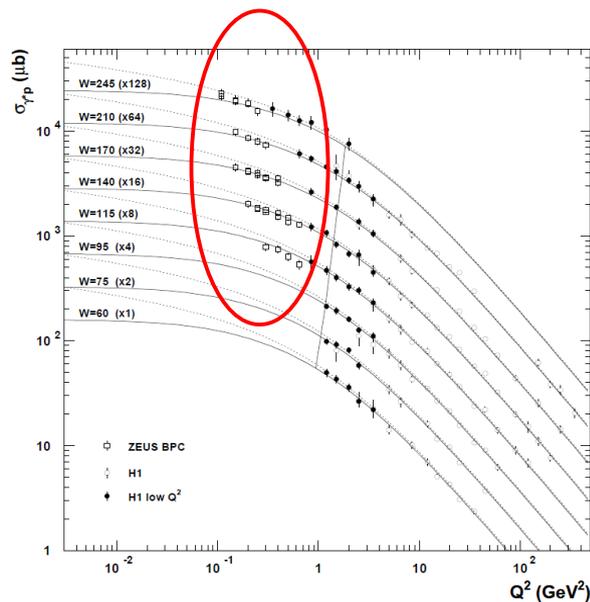
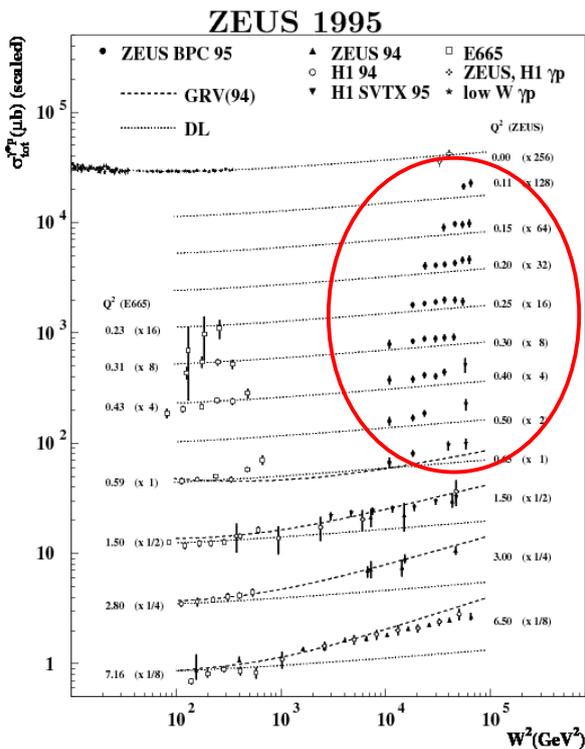
ZEUS Beam Pipe Calorimeter (BPC)

- Scattered electron detector at very low angles (1995, HERA I).
- Very low- x and Q^2 ($0.11 < Q^2 < 0.65 \text{ GeV}^2$).
- Two small electromagnetic tungsten/scintillator calorimeters located at $z = -2.9 \text{ m}$.

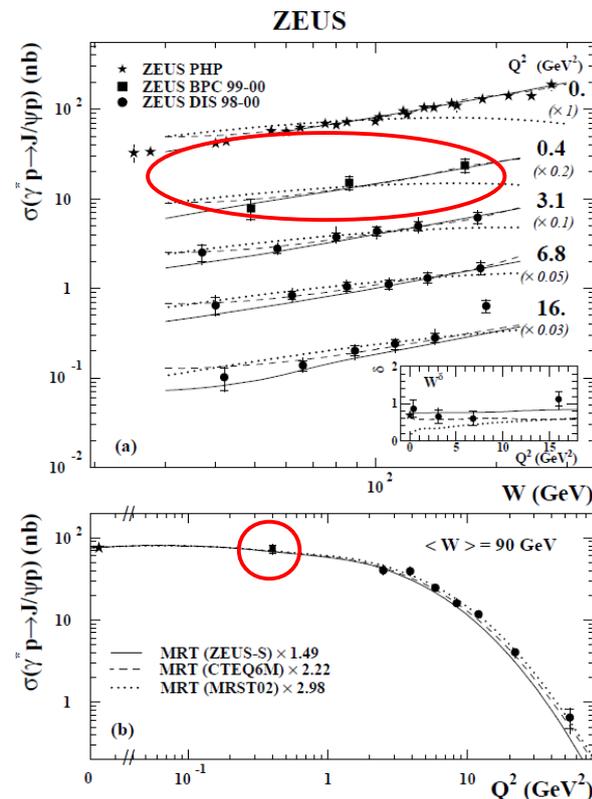


$$0.11 < Q^2 < 0.65 \text{ GeV}^2$$
$$2 \cdot 10^{-6} < x < 6 \cdot 10^{-5}$$

Measurements using BPC



GBW analysis
(dotted line - massless dipoles,
solid line - light-quark mass included)

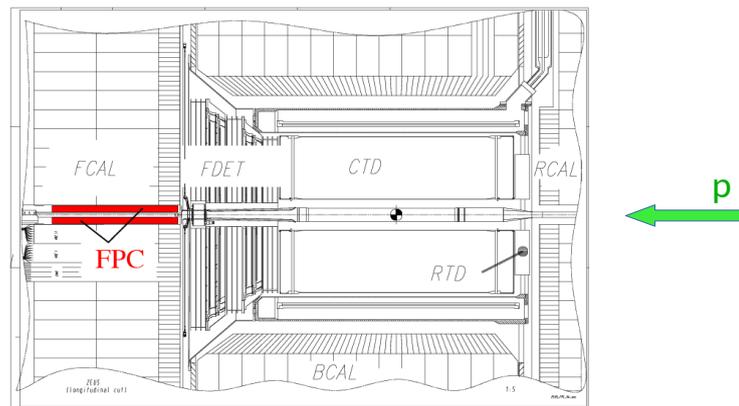
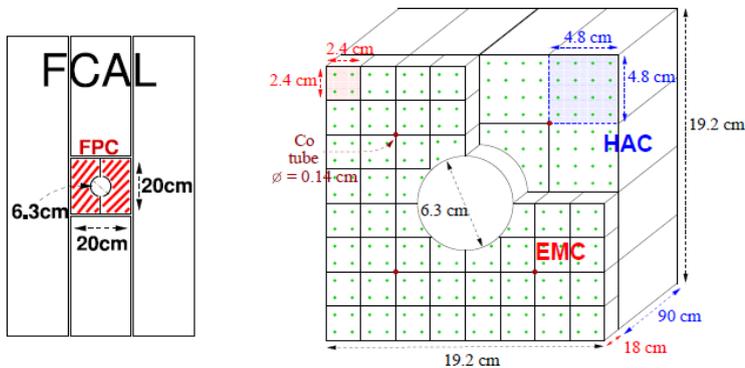


Inclusive $\gamma^* p \rightarrow X$ cross sections
in transition from DIS to photoproduction - valuable data to constrain theory

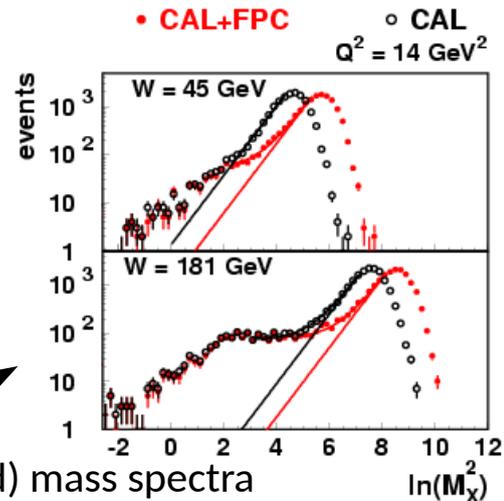
Exclusive $\gamma^* p \rightarrow J/\psi p$

ZEUS Forward Plug Calorimeter (FPC)

- Originally, 20 x 20 cm² ZEUS FCAL beam hole
- In 1997 (HERA II), a sampling lead/scintillator calorimeter added limiting the beam hole to 6.3 cm in diameter
- Extends the forward coverage from $\eta > 4$ to $\eta > 5$
- Position and energy measurement, EMC/HAD sections

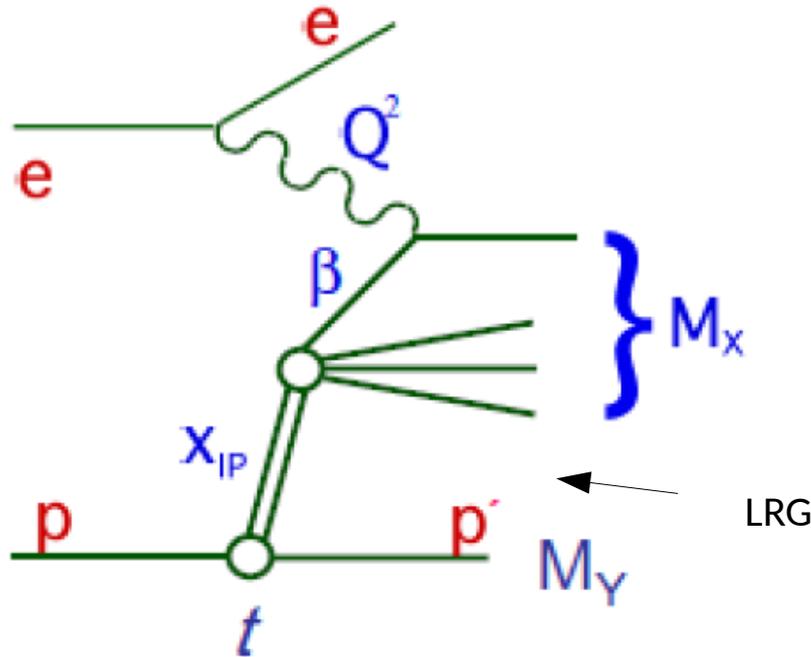


- Improvements in measurement of forward hadronic system, e.g.
- e.g better separation of diffractive (\sim flat) and non-diffractive (exponentially suppressed) mass spectra
- Used also as a tagger for proton dissociative events.
- HERA II: a machine magnet installed in the front of FCAL, hence no instrumentation due to dead material



Similar detector in H1, extending the H1 LAr coverage from $\eta > 3.5$ to $\eta > 5.5$

Very forward detectors for diffractive scattering



DIS variables:

$$Q^2 = -(k - k')^2 \quad y = \frac{p \cdot q}{p \cdot k}$$

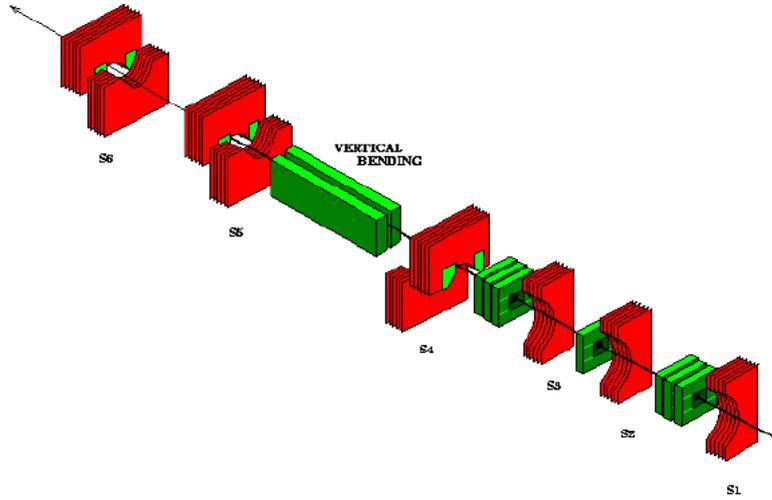
Diffractive variables:

$$x_{IP} = 1 - \frac{E'_p}{E_p} \quad t = (p - p')^2$$

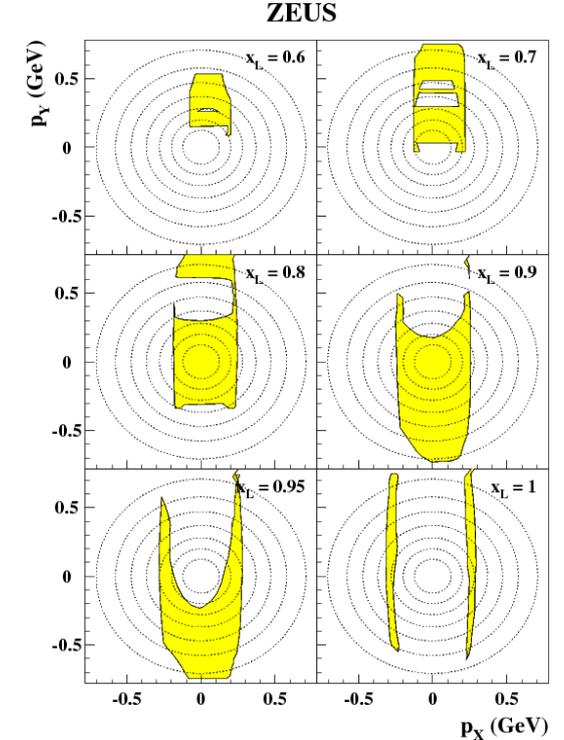
$$\beta = \frac{x_{Bj}}{x_{IP}} = \frac{Q^2}{s y x_{IP}}$$

Experimentally diffraction selected by tagging p' or by measuring Large Rapidity Gap (LRG) between p' and M_x

ZEUS Leading Proton Spectrometer (LPS)



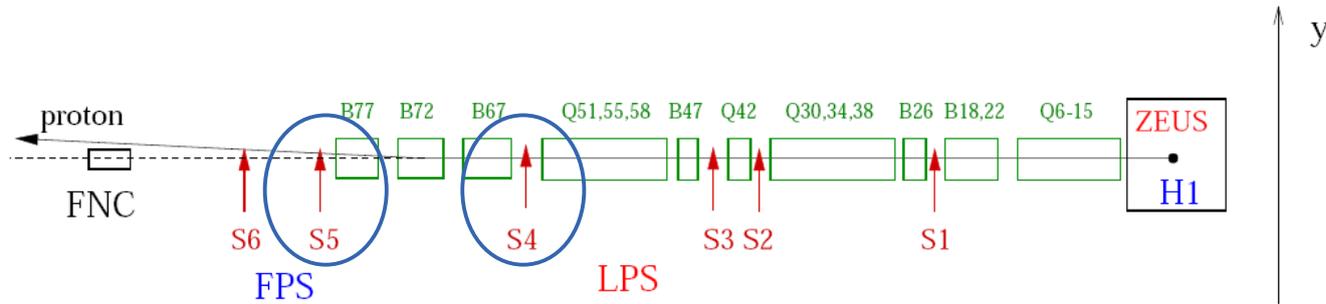
- Set of 6 detectors at various positions from IP, up to 100m
- S1-S3 – horizontal stations
- S4-S5 – vertical stations
- Each station: 6 planes of silicon detectors to measure proton track
- In operation during HERA-I period



Geometrical acceptance
in bins of $x_L = E_p'/E_p$

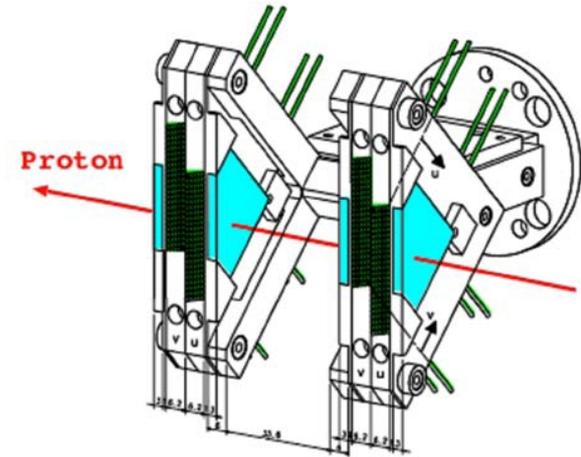
- Acceptance: $0.2 < p_T < 0.5$ GeV for proton elastic peak ($x_L = 1$)
- Overall acceptance for elastic photoproduction of ρ^0 about 6%.

H1 Forward Proton Spectrometer (FPS)

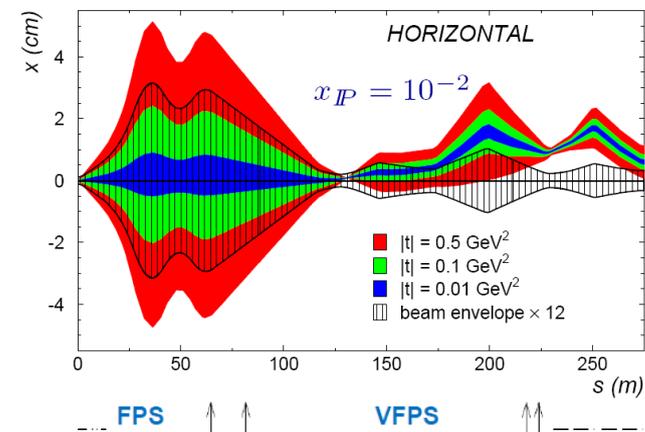
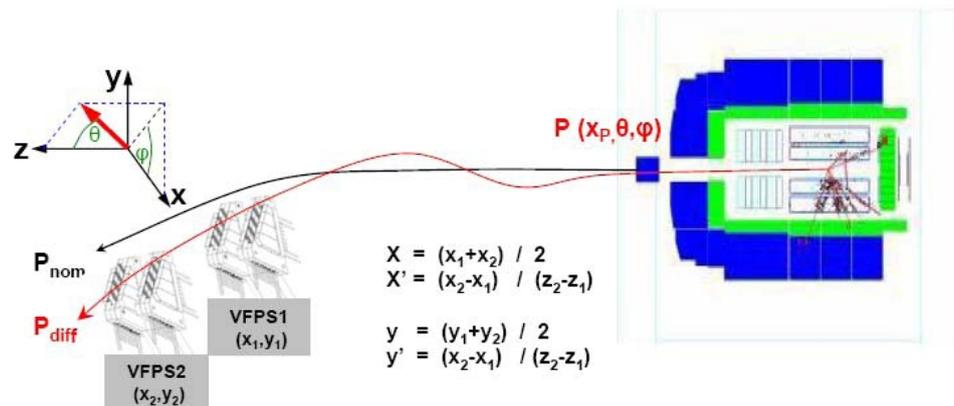


- 2 horizontal and 2 vertical stations at 61 and 80 m
- Each station: two measurements of the angle of the proton
- 5 layers of scintilating fibers
- In operation in HERA-I and HERA-II periods

Similar p_T range as for ZEUS LPS



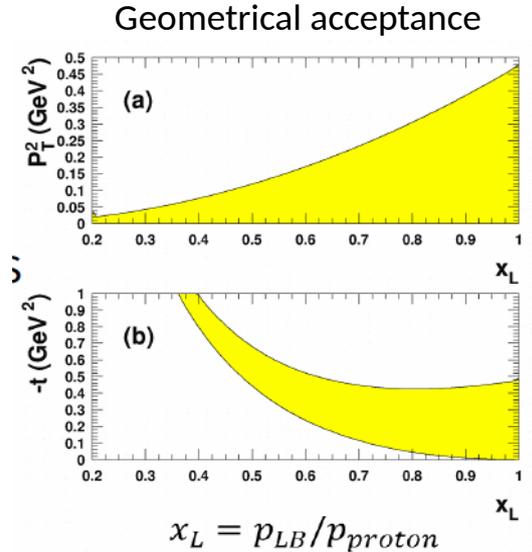
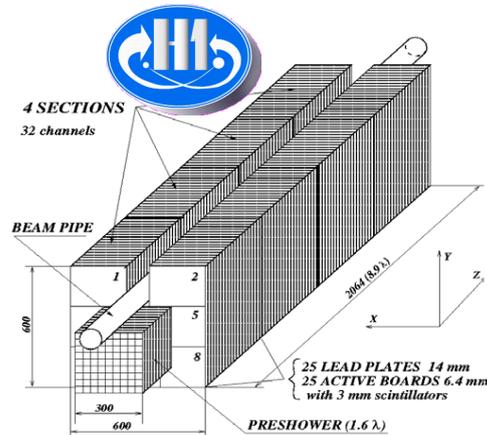
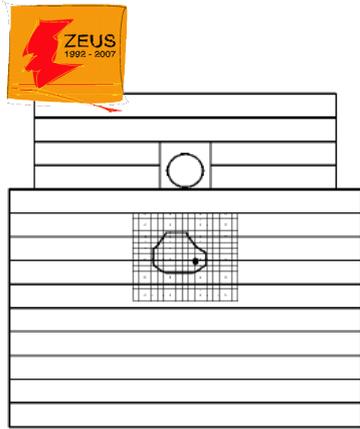
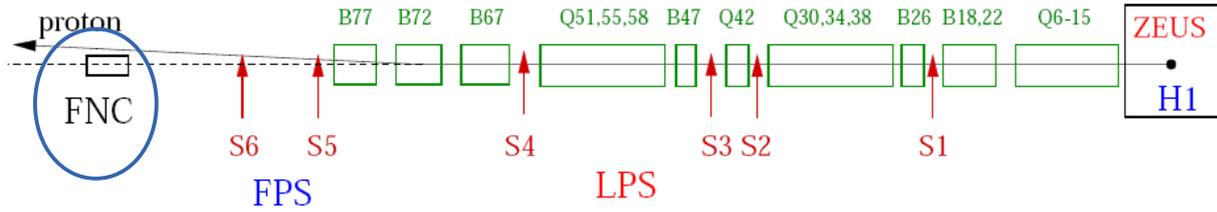
H1 Very Forward Proton Spectrometer (VFPS)



- 2 stations at 218 and 222 m
- Each station with 2 scintillating fiber detectors
- Each fiber detectors measures the position of the proton
- In operation in HERA-II period (2005-2007)

- Large acceptance in x_{IP} , full coverage in $|t| < 0.25 \text{ GeV}^2$ (down to $t=0$)
- Complementary to FPS (smaller x_{IP} , limited t)

Forward Neutron Calorimeters (FNC)

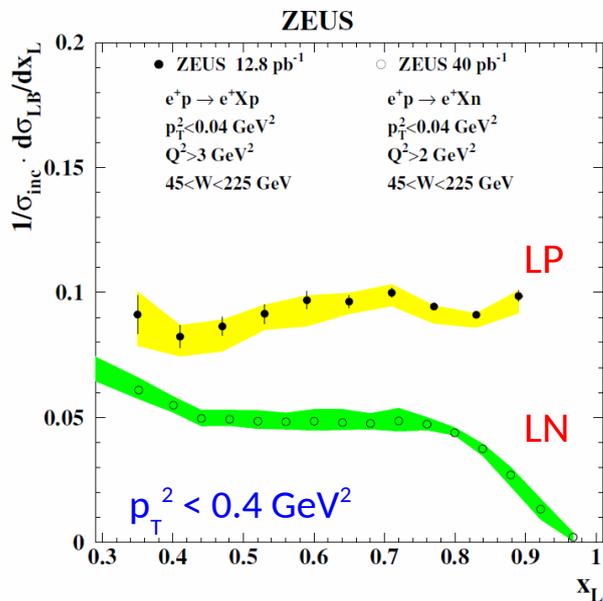


- Iron/scintillator hadronic calorimeter (with scintillator tracker) at 110 m
- Acceptance limited by beam aperture ($\theta < 0.8$ mrad, $\sim 30\%$ of azimuthal coverage)

Measurements with leading barions in LPS/FPC/FNC

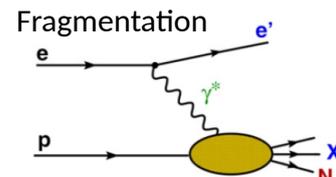
Leading Proton (LP) and Leading Neutron (LN) production in DIS

LP vs LN and production mechanism

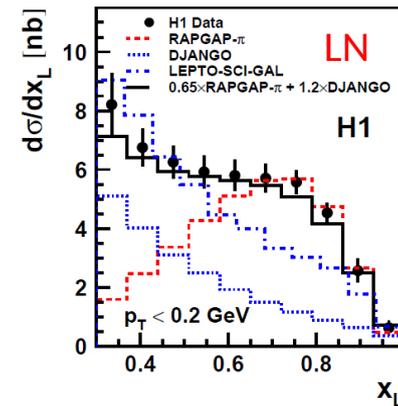
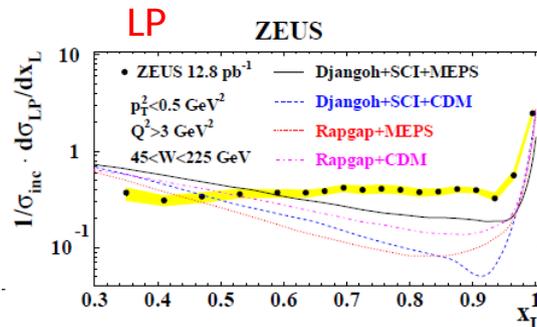
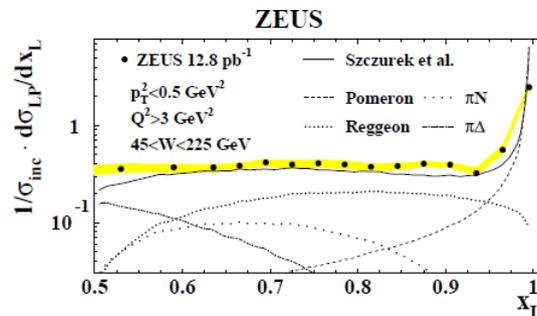
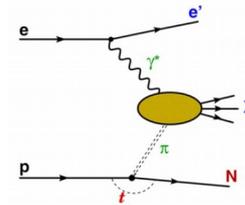


The same p_T range.

For pure isovector exchange (eg. π) one expects LP=1/2*LN
Additional isoscalar (eg. IP) exchanges contribute to LP



One Pion Exchange (OPE)

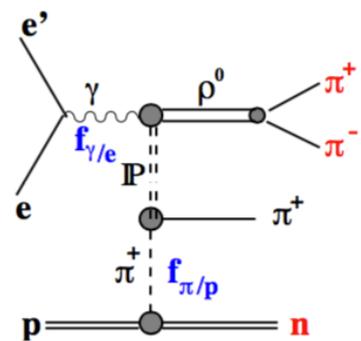
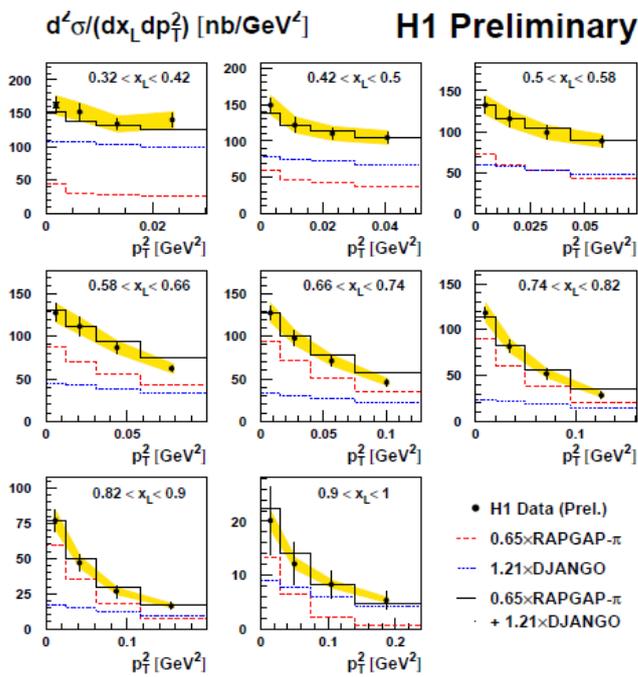


LN: Fragmentation at low x_L (DIANGO),
OPE (RAPGAP-π) dominates high x_L

LP: Fragmentation models do not describe flat x_L dependence,
Data agree with isoscalar and isovector exchanges.

LN in DIS

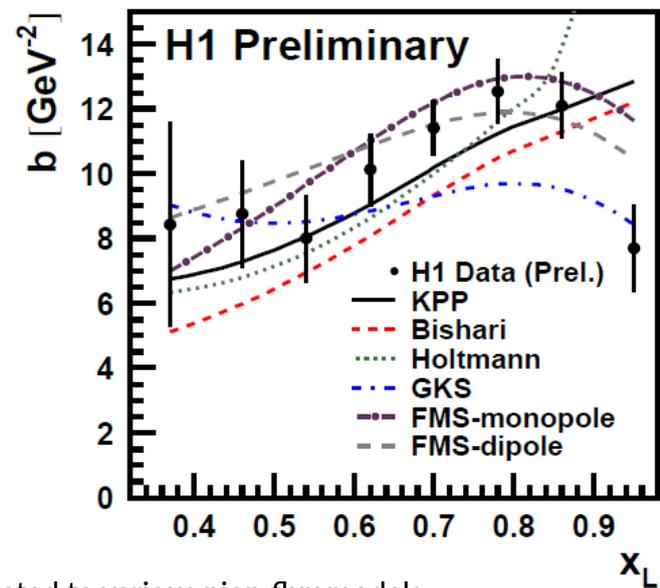
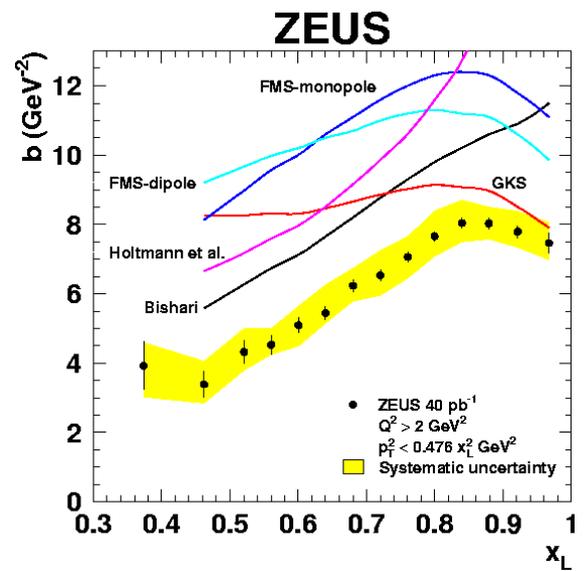
p_T^2 dependence in bins of x_L



$$d\sigma_{\gamma^* p \rightarrow n\pi} = f_{\pi/p}(x_L, t) \times d\sigma_{\gamma^* \pi \rightarrow X}$$

The distribution of $p_T^2 (=t)$ is defined solely by the pion flux

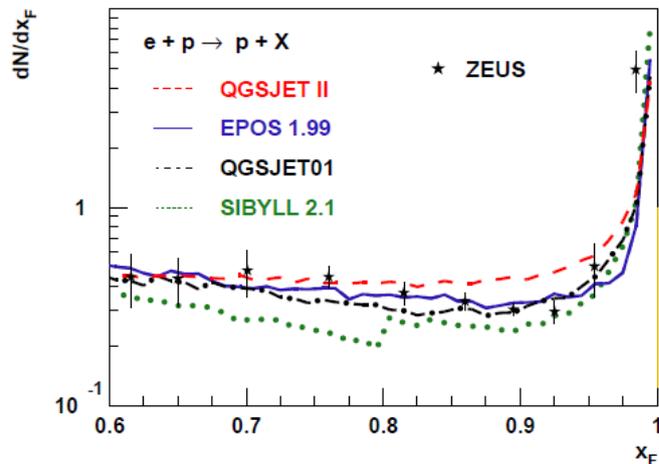
Sensitivity to the pion flux



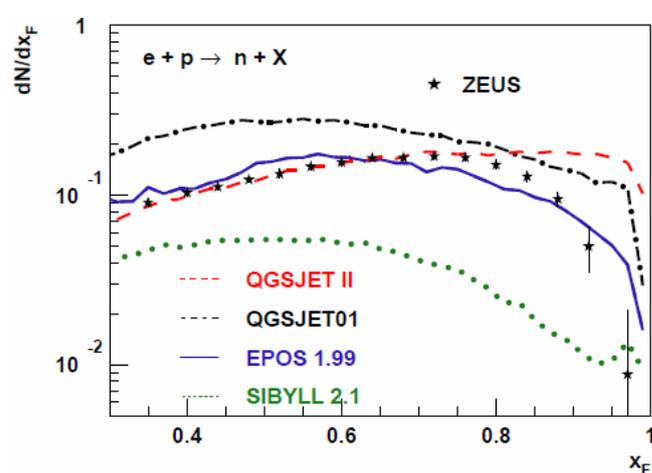
Slope of exponential p_T^2 dependence compared to various pion-flux models

Comparison to cosmic-ray physics models (DIS)

LP

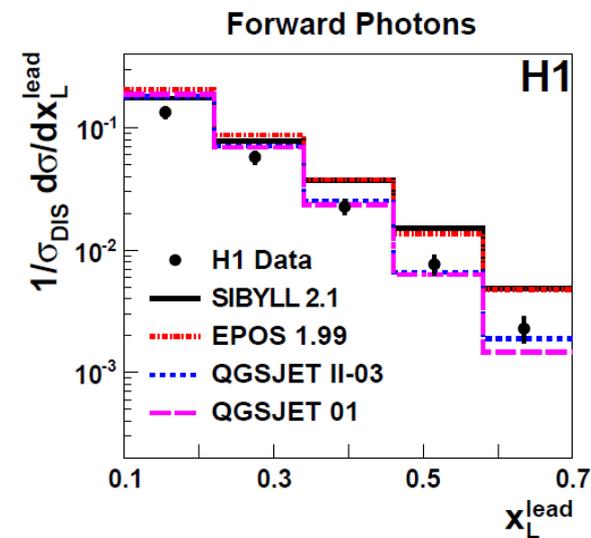


LN



Leading Photon

(EMC deposits in FNC)

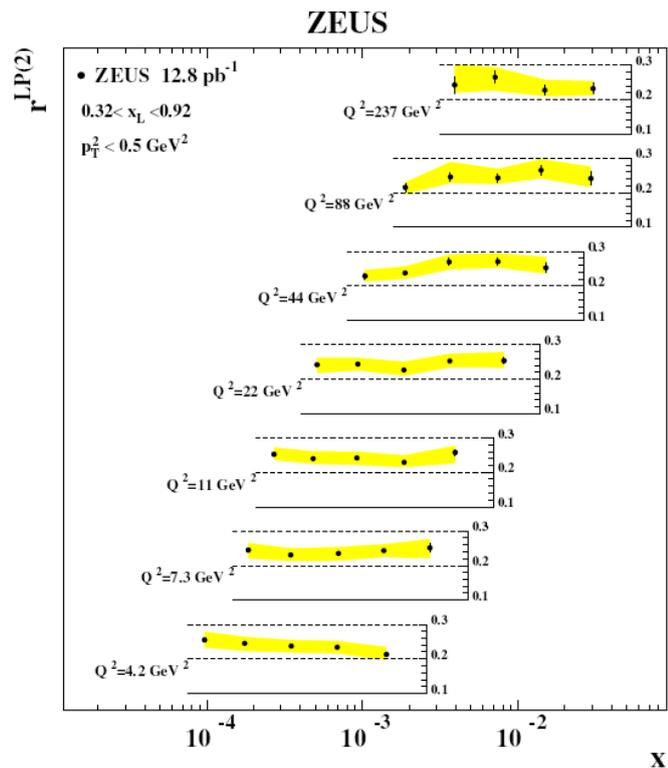


While models describe relatively well the LP data,
They differ significantly for the LN data, and leading photon data.

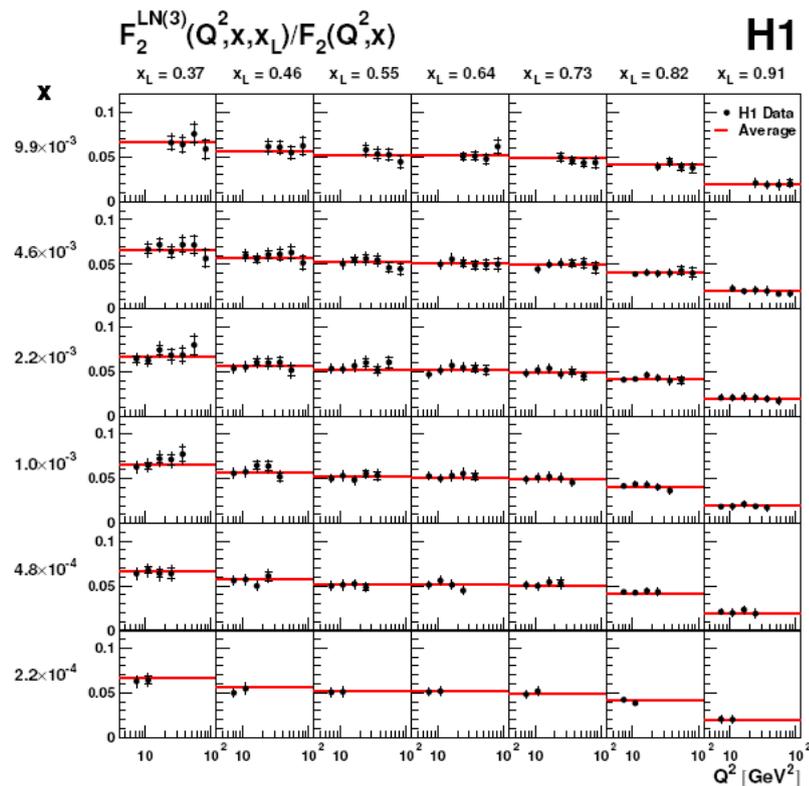
Data have potential to constrain cosmic-ray modeling.

Ratio of LP and LN to inclusive cross sections in DIS

LP to inclusive cross section vs x

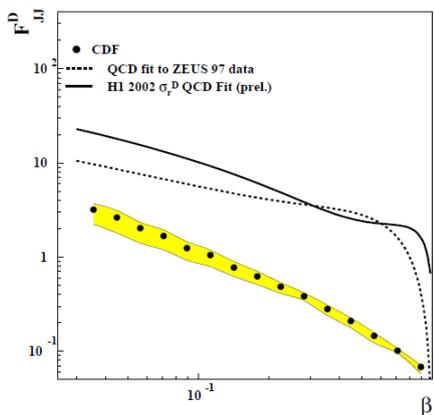


LN to inclusive cross section vs Q^2



Ratios fairly independent of Q^2 and x – factorization, confirms hypothesis of limiting fragmentation

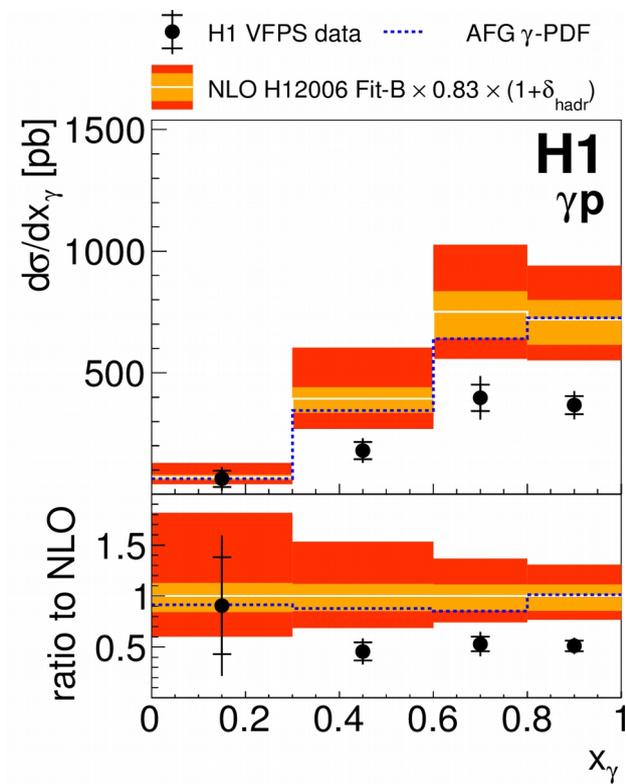
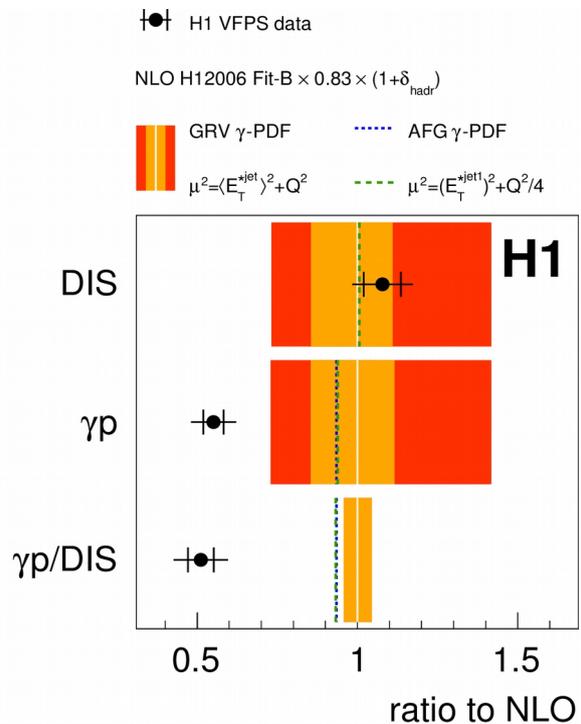
Diffraction dijets in PhP and DIS with VFPS



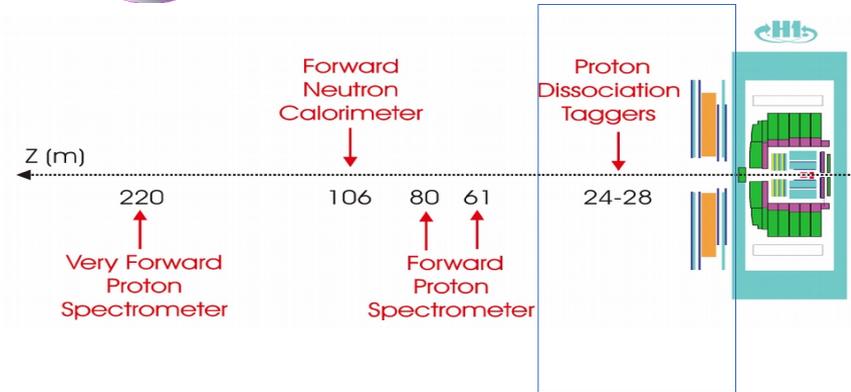
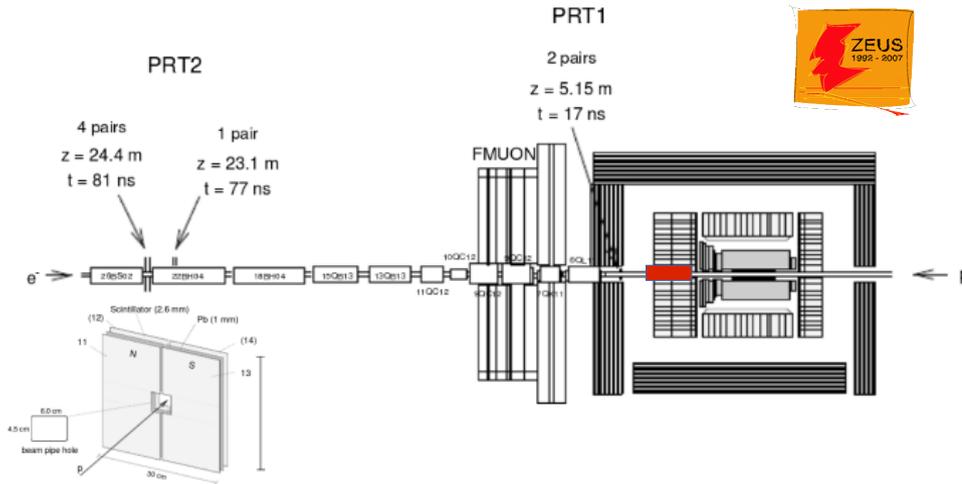
NLO predictions based on HERA DPDFs fail to describe diffractive jet production in hadron colliders (data/NLO suppression ~ 0.2).

Is suppression observed at HERA in Photoproduction?

Photoproduction suppressed by ~ 0.5 .
 Not related to proton dissociation (p-tag).
 No clear dependence on any variable.



Proton Dissociation Taggers



HERA-I data:

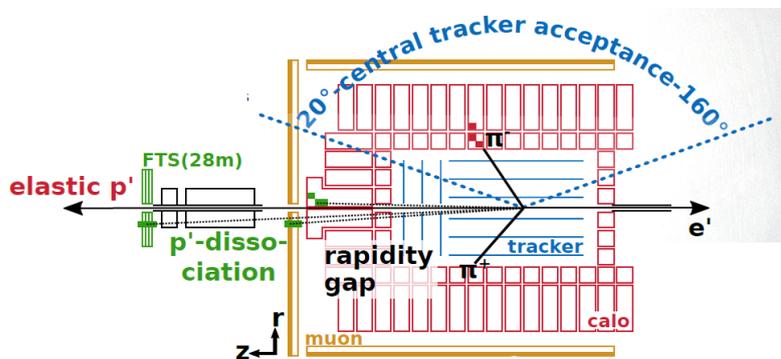
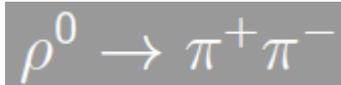
- FPC calorimeter: $4 < \eta < 5$
- Proton Remnant Taggers, PRT1/PRT2: $4 < \eta < 7$ (scintillators at 5 and 24 m)

HERA-I/II data:

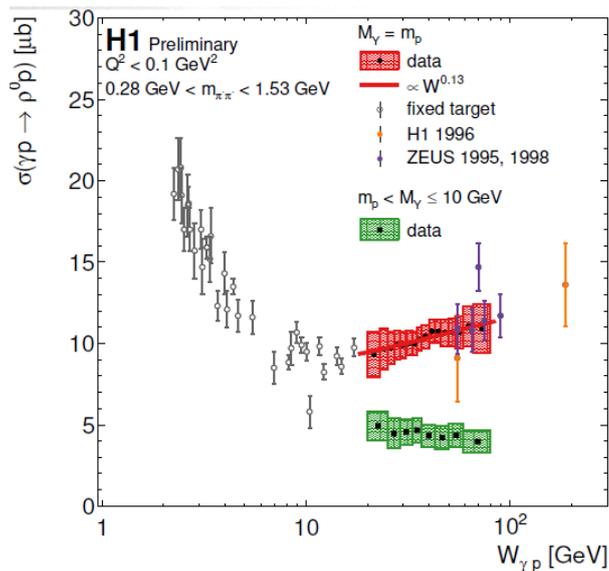
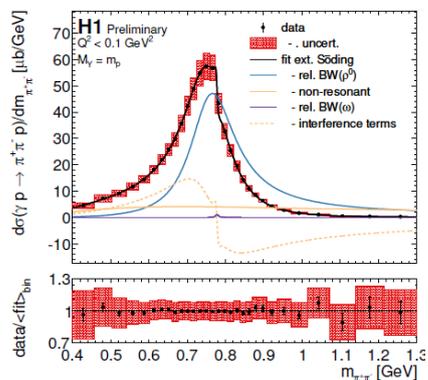
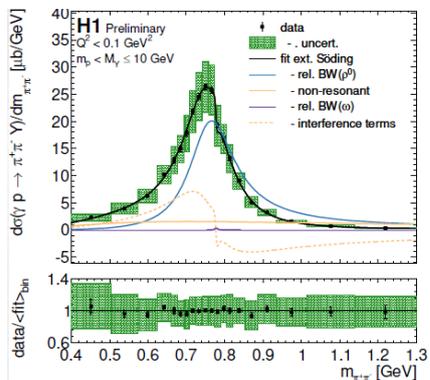
- Forward Muon Detector, FMD: $1.9 < \eta < 3.7$
- FPC calorimeter: $3.5 < \eta < 5.5$
- Forward Tagger System, FTS: $6 < \eta < 7.5$ (system of scintillators at 24-28m)

Aim: tag or remove events with diffractive masses $M_Y \geq \sim 10 \text{ GeV}$

Example: recent H1 measurement of ρ^0 with pdiss taggers



• elastic vs proton-dissociation: tag using forward detectors



- measure ρ^0 $W_{\gamma p}$ dependence in range $20 < W_{\gamma p} < 80$ GeV
- fills "gap" between fixed target and HERA measurements
- elastic cross-section rises $w / \sim W_{\gamma p}^{0.13}$
- p-dissociative consistent with constant in fiducial PS
- high statistical precision
- but very large systematic uncertainties
- $W_{\gamma p}$ shape uncertainty dominated by trigger



Summary

- A brief overview of zero-angle (and small-angle) detectors at HERA was given
- The detectors were installed:
 - in the electron direction: to measure luminosity, tag photoproduction (PHP, $Q^2 \sim 0$) events, and to investigate transition from PHP to DIS ($0 < Q^2 < 1 \text{ GeV}^2$)
 - in the proton direction: to improve energy measurement of hadronic system, separate diffractive processes with the intact proton and the dissociated proton system, and to tag forward leading particles (p/n)
- allowing an unquestionable HERA success in investigating low-x structure of the proton
- Thank you for your attention!