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Study of exclusive electroproduction of ρ^0 mesons at low Q^2 using the ZEUS Beam Pipe Calorimeter at HERA

Teresa Barata Monteiro

(CERN EP/CMD)

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CONTACT : F. GIANOTTI
EP DIVISION
TEL. 8965

OUTLINE:

- **Introduction**
- **The Beam Pipe Calorimeter**
- ρ^0 **selection**
- **Efficiencies and backgrounds**
- **Results:**
  - **Mass spectrum**
  - $d\sigma/d|t|$ **distribution and shrinkage**
  - **Angular decay distributions and** $R = \frac{\sigma_L}{\sigma_T}$
  - ρ^0 **cross-section**
- **Conclusions**

INTRODUCTION

ep kinematics

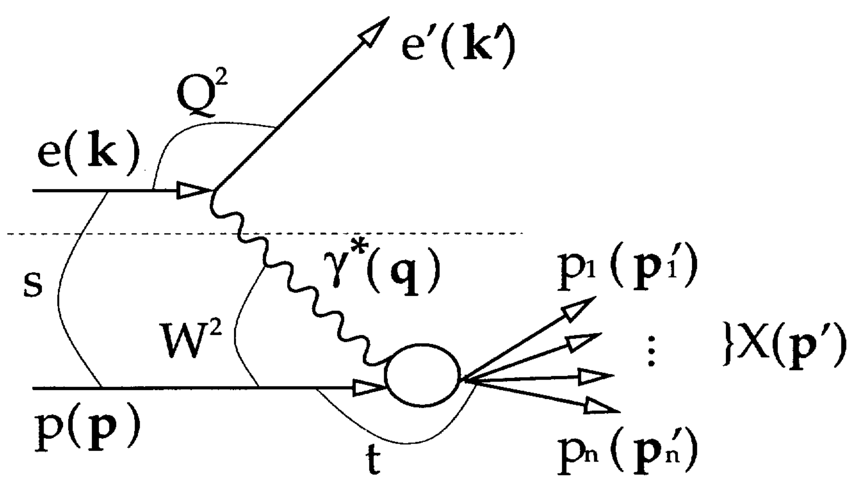
$s = (p+k)^2 \simeq 4E_eE_p$ — $\sqrt{s}$: ep **center-of-mass energy**

$Q^2 = -(k-k')^2 \simeq 2E_eE_{e'}(1+\cos\theta_{e'})$ — **Photon virtuality**

$y = \frac{p\cdot q}{p\cdot k} \simeq 1 - \frac{E_{e'}}{E_e}\frac{1-\cos\theta_{e'}}{2}$ — **Fractional energy transfer in proton rest frame**

$W^2 = (p+q)^2 \simeq sy - Q^2$ — $\gamma^* p$ **center-of-mass energy squared**

$x_{Bj} = \frac{Q^2}{2p\cdot q} \simeq \frac{Q^2}{sy}$ — **Fractional momentum of struck parton**



HERA:

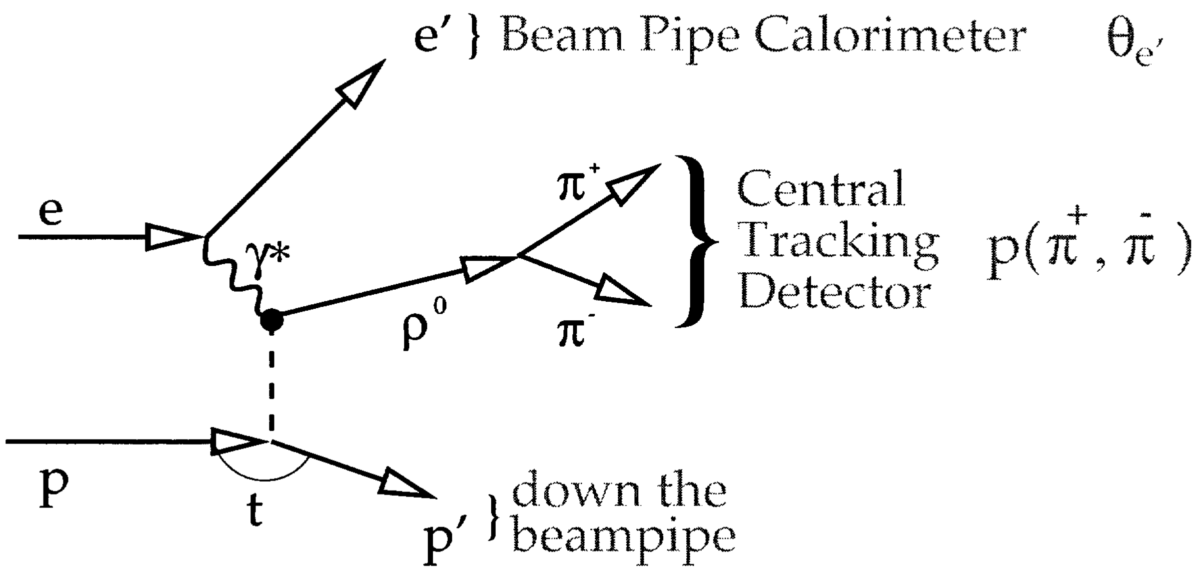
E_e=27.5 GeV

E_p=820 GeV

$ep \rightarrow e\rho^0 p$

$t = (p-p')^2 \simeq (p_\rho + p_{e'})^2_X + (p_\rho + p_{e'})^2_Y$

Momentum transfer at the proton vertex squared



$E_{e'}$ from energy and momentum conservation

(assuming no ISR):

$$E_{e'} = \frac{2E_e - (E-p_z)_{\pi^+} - (E-p_z)_{\pi^-}}{1-\cos\theta_{e'}}$$

Relating ep to $\gamma^* p$

$$\frac{d^2\sigma^{ep\to e\rho^0 p}}{dy\,dQ^2} =$$

$$\frac{\alpha}{2\pi}\frac{1}{Q^2}\frac{1+(1-y)^2}{y}\left[\sigma_T^{\gamma^* p\to\rho^0 p}(y,Q^2) + \frac{2(1-y)}{1+(1-y)^2}\sigma_L^{\gamma^* p\to\rho^0 p}(y,Q^2)\right]$$

$$\simeq \frac{\alpha}{2\pi}\frac{1}{Q^2}\frac{1+(1-y)^2}{y}\left[\sigma_T^{\gamma^* p\to\rho^0 p}(y,Q^2) + \sigma_L^{\gamma^* p\to\rho^0 p}(y,Q^2)\right]$$

Vector meson production at HERA:

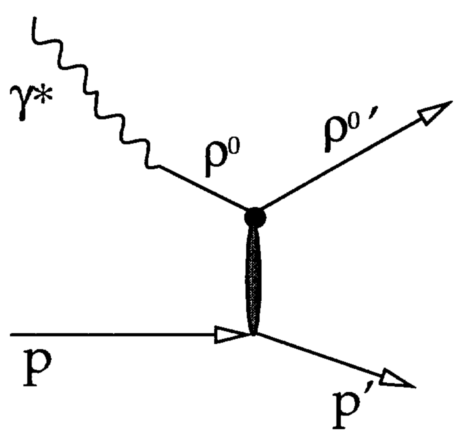
Soft phenomenological models

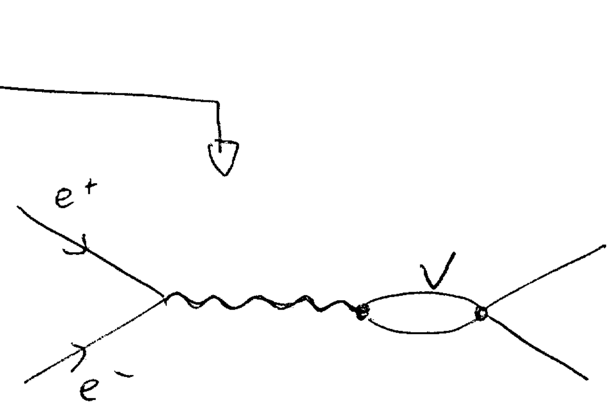
Vector meson dominance model (VDM):

The hadronic character of the photon

$$|\gamma^*\rangle = A|\gamma_B^*\rangle + \sqrt{\alpha}|h\rangle$$

$$\sqrt{\alpha}|h\rangle = \sum_{\rho,\omega,\phi}\frac{1}{f_V}\left(\frac{1}{1+\frac{Q^2}{M_V^2}}\right)|V\rangle$$





Q^2 **dependence of cross section**

$$\sigma_T^{\gamma^* p\to\rho^0 p}(W,Q^2) = \frac{4\pi\alpha}{f_\rho^2}\left(\frac{1}{1+\frac{Q^2}{M_\rho^2}}\right)^2 \sigma_T^{\rho^0 p\to\rho^0 p}(W)$$

$$\sigma_L^{\gamma^* p\to\rho^0 p}(W,Q^2) = \sigma_T^{\gamma^* p\to\rho^0 p}(W,Q^2)\cdot R(Q^2)$$

$$R(Q^2) = Q^2/M_\rho^2\,\xi_\rho$$

Regge theory and the Pomeron:

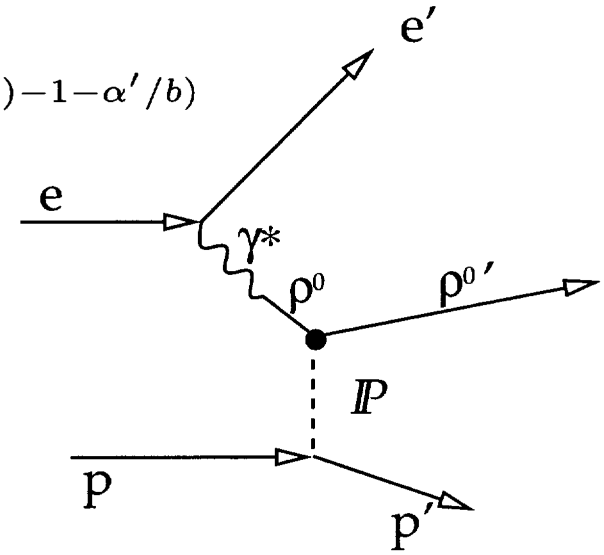
Pomeron exchange in t channel $(\alpha_P(0)\sim 1.08\,,\ \alpha'_P \sim 0.25)$

$$\frac{d\sigma^{\rho^0 p\to\rho^0 p}}{d|t|} = \left(\frac{W}{W_0}\right)^{4(\alpha(0)-1)} e^{-b(W)|t|}$$

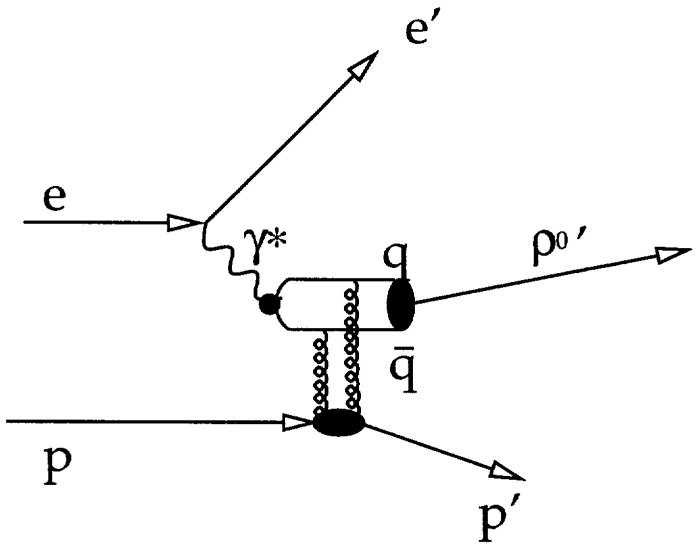
$b(W) = b_0 + 4\alpha' \ln(W/W_0) \rightarrow$ **Shrinkage**

$$\sigma^{\rho^0 p\to\rho^0 p} \propto \frac{W^{4(\alpha(0)-1)}}{b(W)} \sim W^{4(\alpha(0)-1-\alpha'/b)}$$

$b \sim 8 \rightarrow W^{0.2}$



Vector meson production at HERA: pQCD (high Q^2)



$$\left.\frac{d\sigma_L^{\gamma^* p \to V p}}{dt}\right|_{t=0} =$$

$$\frac{A}{Q^6}\alpha_S^2(Q^2)\left|\left(1+\frac{i\pi}{2}\frac{d}{d\ln x_{Bj}}\right)xg(x_{Bj},Q^2)\right|^2$$

Longitudinal contribution dominates cross section

(high Q^2)

$$\sigma^{\gamma^* p \to V p}(Q^2) \simeq \left(\frac{1}{Q^2}\right)^{2.5}$$

$$\sigma^{\gamma^* p \to V p}(W) \simeq W$$

t **and** W **dependences decoupled**

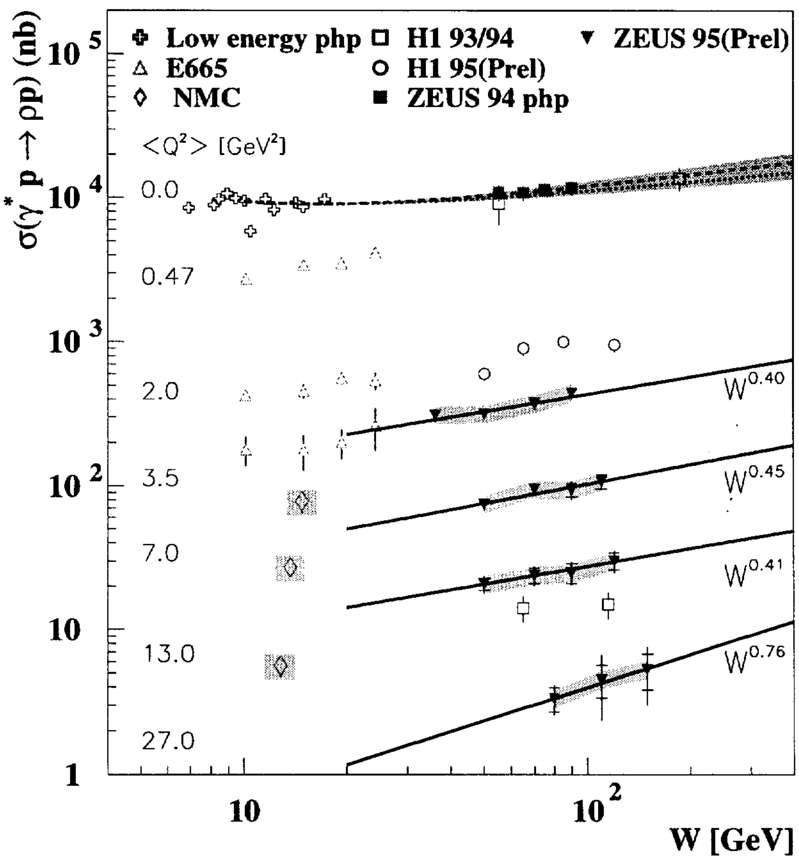
Existing results:

Photoproduction data ($Q^2 = 0$)

well described by soft models

High Q^2 data ($Q^2 > 4$ GeV^2)

agrees with pQCD predictions



What happens in between ?

Goal: Study transition between two regimes with accuracy that allows discrimination

THE BEAM PIPE CALORIMETER

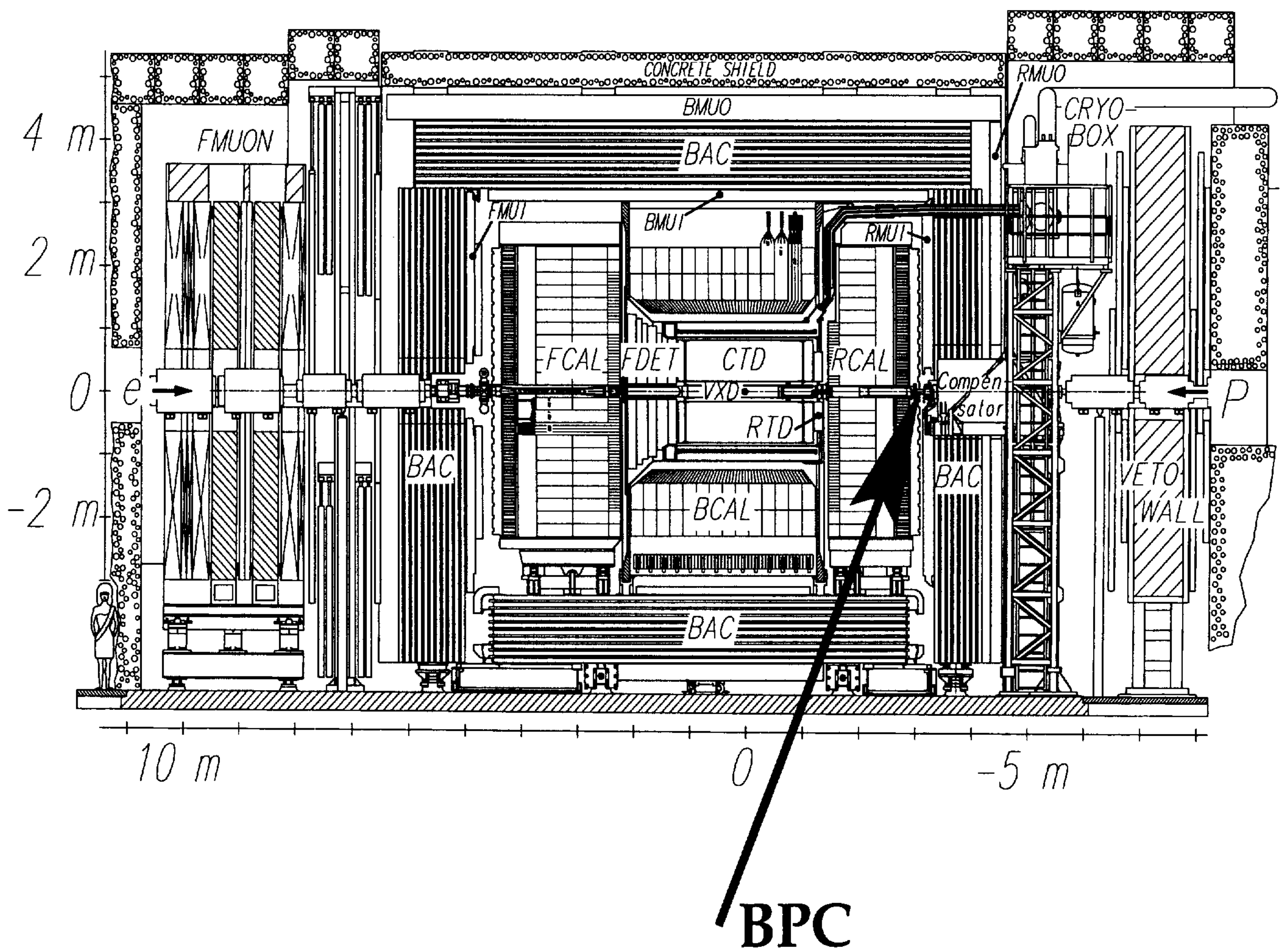
Detector installed in Winter 94/95

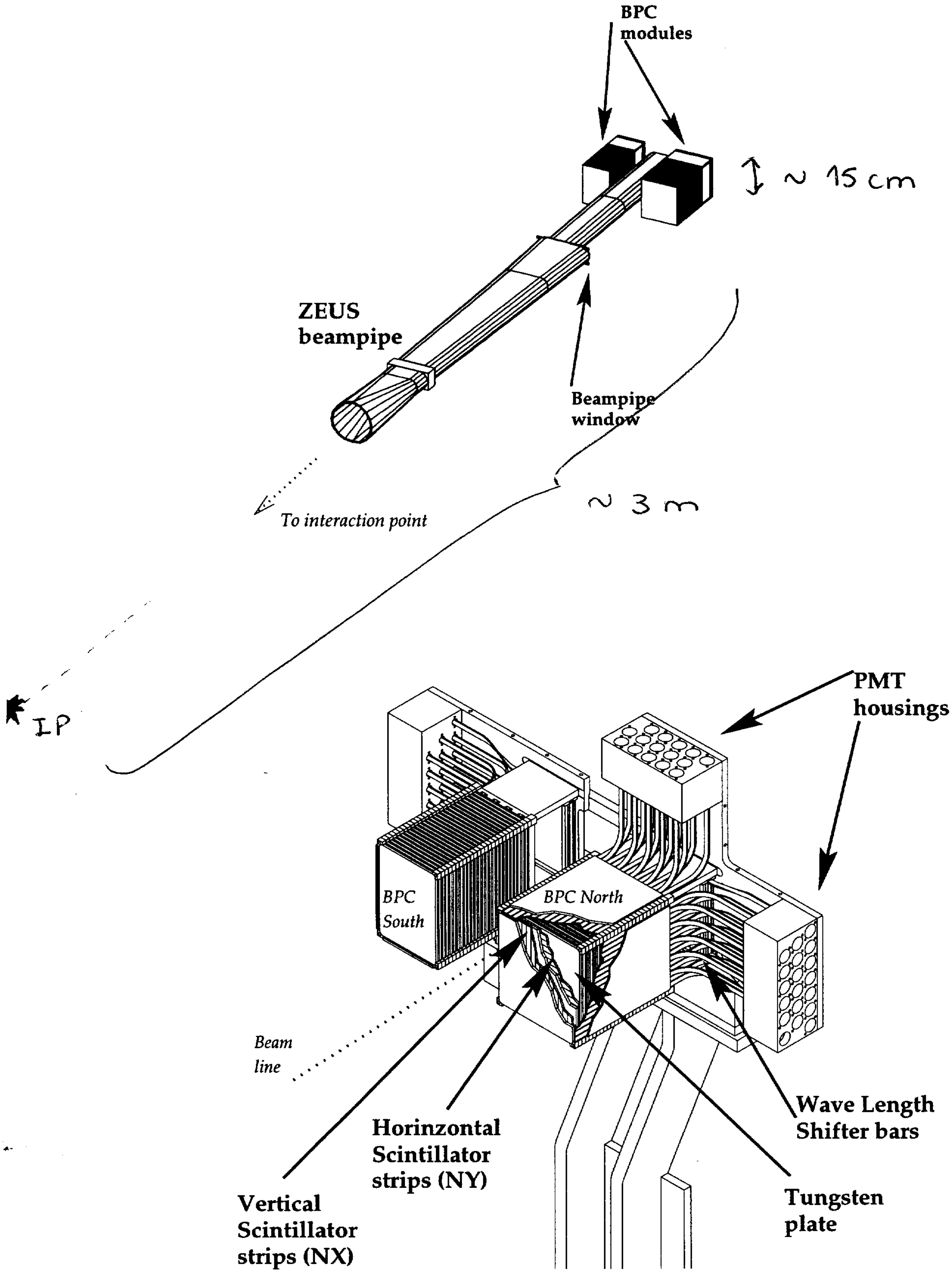
Detector specifications

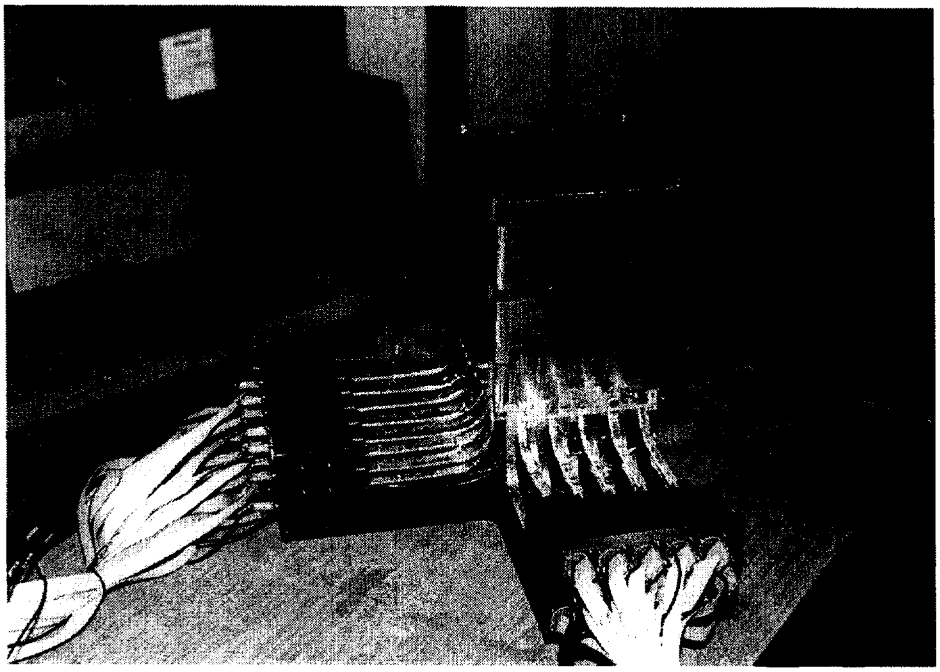
Energy resolution determined by requirements on structure function measurement $\rightarrow \frac{\sigma_{E'_e}}{E'_e} = \frac{17\%}{\sqrt{E_{e'}}}$

Position resolution $\rightarrow < 1$ **mm**

Overview of the ZEUS Detector
(longitudinal cut)




BPC
modules
~ 15 cm
ZEUS
beampipe
Beampipe
window
To interaction point
~ 3 m
IP
PMT
housings
BPC
South
BPC North
Beam
line
Wave Length
Shifter bars
Horinzontal
Scintillator
strips (NY)
Tungsten
plate
Vertical
Scintillator
strips (NX)



- **EM tungsten-scintillator sampling calorimeter,** $\sim 24X_0$
- **7.9 mm scintillator fingers, alternating in X and Y**
- **Readout: WLS + mini PMTs (Hamamatsu R5600)**
- **Energy resolution:** $\frac{17\%}{\sqrt{E_{e'}}}$
- **Uniformity and absolute energy scale:** $\pm 0.5\%$
- **Position resolution:** < 1 **mm**
- **Absolute position in ZEUS:** ± 0.5 **mm**
- **Time resolution:** < 1 **ns**
- **Online vertex determination**

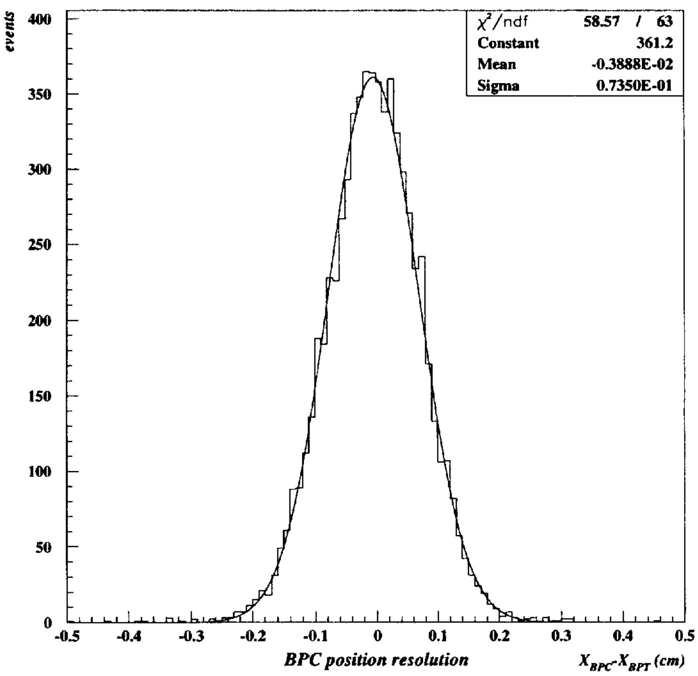
Position reconstruction

$$X = \frac{\sum_X w(i)X(i)}{\sum_X w_i}$$

$$w(i) = \max(0, [w_0 + \ln(\frac{E_X(i)}{E_{XTot}})])$$

w_0 **cutoff optimized with EGS4 MC simulation for position resolution and bias**

BPC position resolution (*in-situ*)



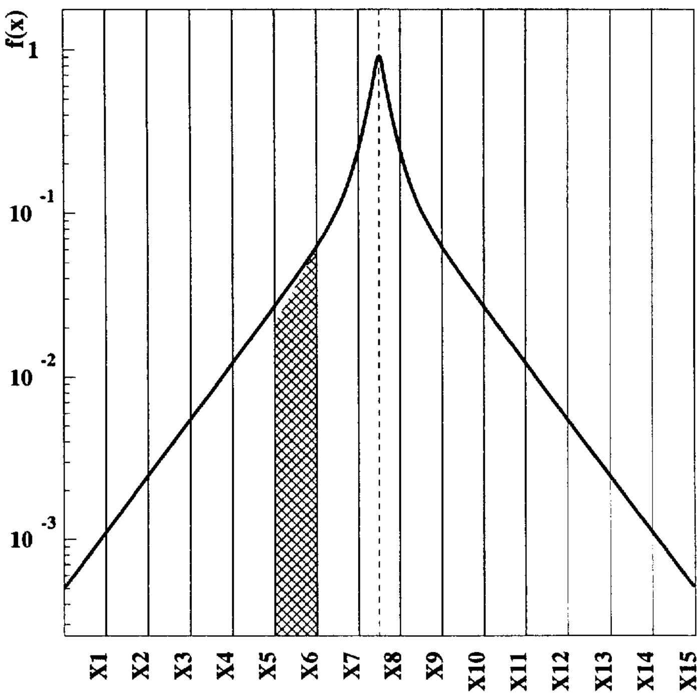
X_{BPC}-$X_{Tracker}$

BPC resolution < 1 mm

Shower width:

$$\sigma_X^2 = \frac{\sum_X w(i)(X(i)-X)^2}{\sum_X w_i}$$

Energy reconstruction



$$E_X(i) = \int_{strip} \left(\frac{dE}{dx} dx\right)$$

$$E_{TotX} = \sum_{Ncluster} E_X(i) \cdot [C_X(i) \cdot ATTcor_X(Y) \cdot LEAKcor(X)]$$

CORRECTION FACTORS

$$E_{TotY} = \sum_{Ncluster} E_Y(i) \cdot [C_Y(i) \cdot ATTcor_Y(X) \cdot LEAKcor(X)]$$

$$E_{Tot} = S \cdot (E_{TotX} + E_{TotY})$$

Ncluster=4

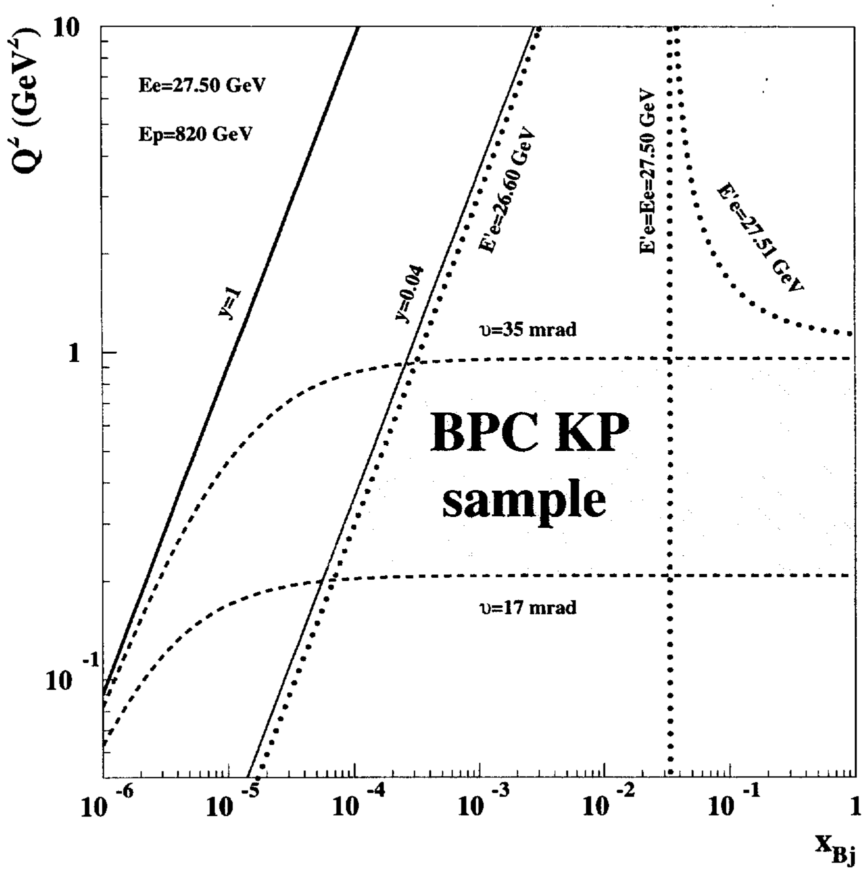
Energy calibration

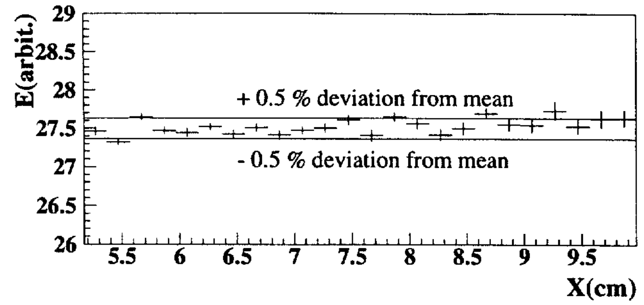
Relative calibration (uniformity): **Using Kinematic Peak (KP) events, correct for:**

- **Transverse shower leakage** $LEAKcor$
- **Attenuation along scintillator fingers** $ATTcor$
- **Strip-to-strip calibration** $C_X(i)$

Absolute calibration: **Energy scale** S **from:**

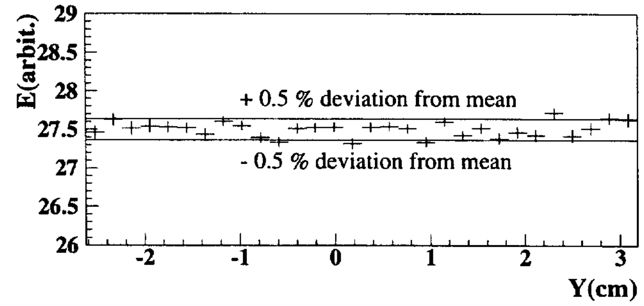
- **Comparison of KP events with Monte Carlo simulation**
- **Overconstrained elastic** ρ^0 **events**





Uniformity of response

$\pm 0.5\%$

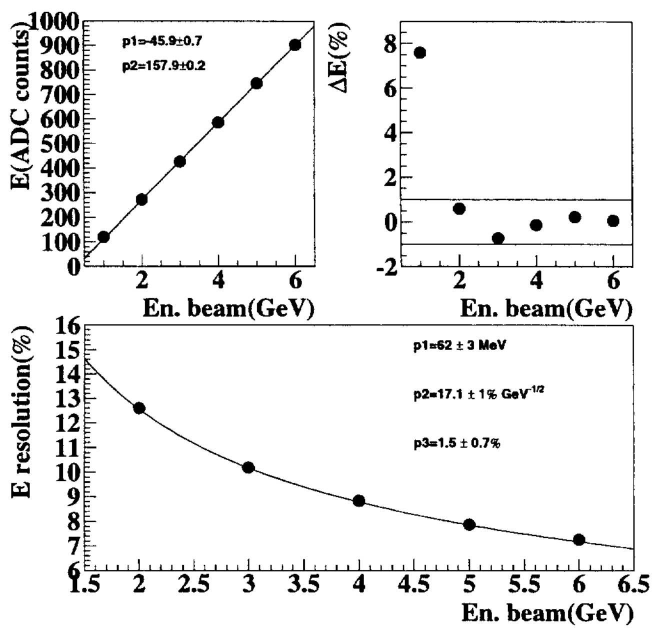


Absolute energy scale

$\sim \pm 0.5\%$

Energy resolution in testbeam

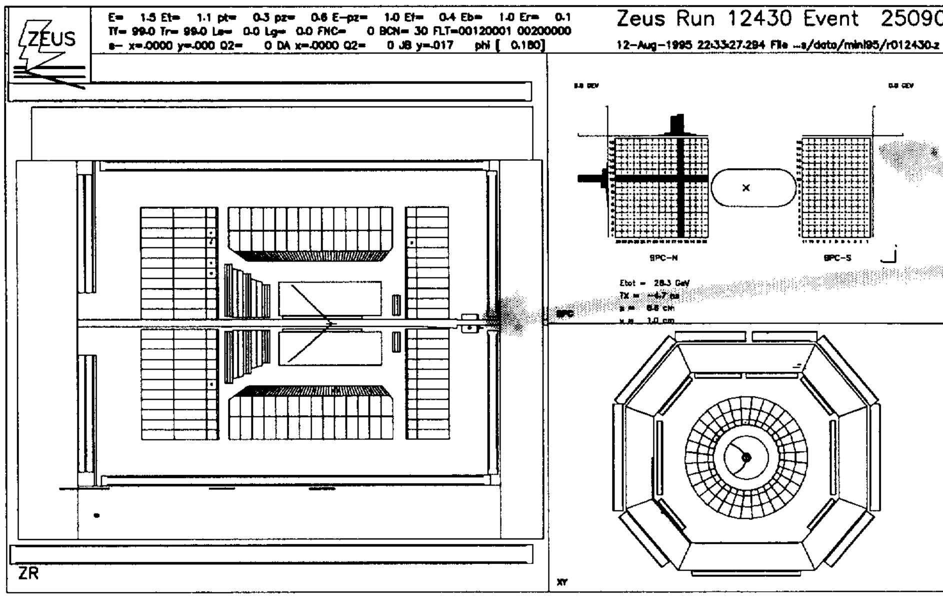
E_e: **1-6 GeV**



Sampling term

$\sim \frac{17\%}{\sqrt{E}}$

ρ^0 SELECTION Selection cuts



Tracking requirements

2 opposite charge tracks

$|Z_{vtx}| < 50$ **cm**

$|\eta| < 1.75, p_T > 150$ **MeV**

Kinematic requirements

$0.6 < M_{\pi\pi} < 1.2$ **GeV**

$0.25 < Q^2 < 0.85$ **GeV^2**

$20 < W < 90$ **GeV**

BPC requirements

t_{BPC} **compatible w/** ep

X_{BPC}, Y_{BPC} **in fiducial area**

$E_{BPC} > 20$ **GeV**

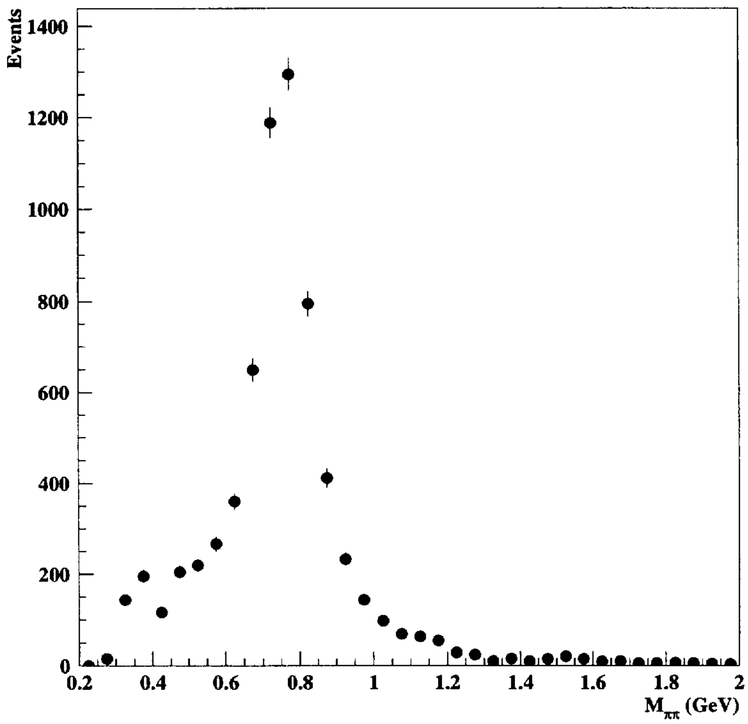
$\sigma_{BPC} < 0.7$ **cm**

Elasticity requirements

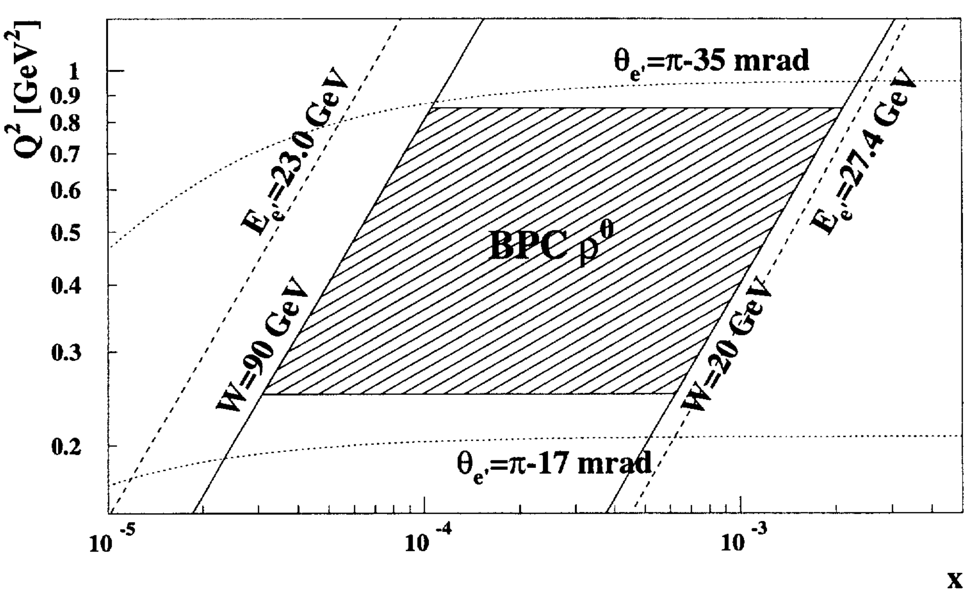
CAL-track matching

($\mathcal{L} = 3.82$ **pb^{-1})**

Final sample

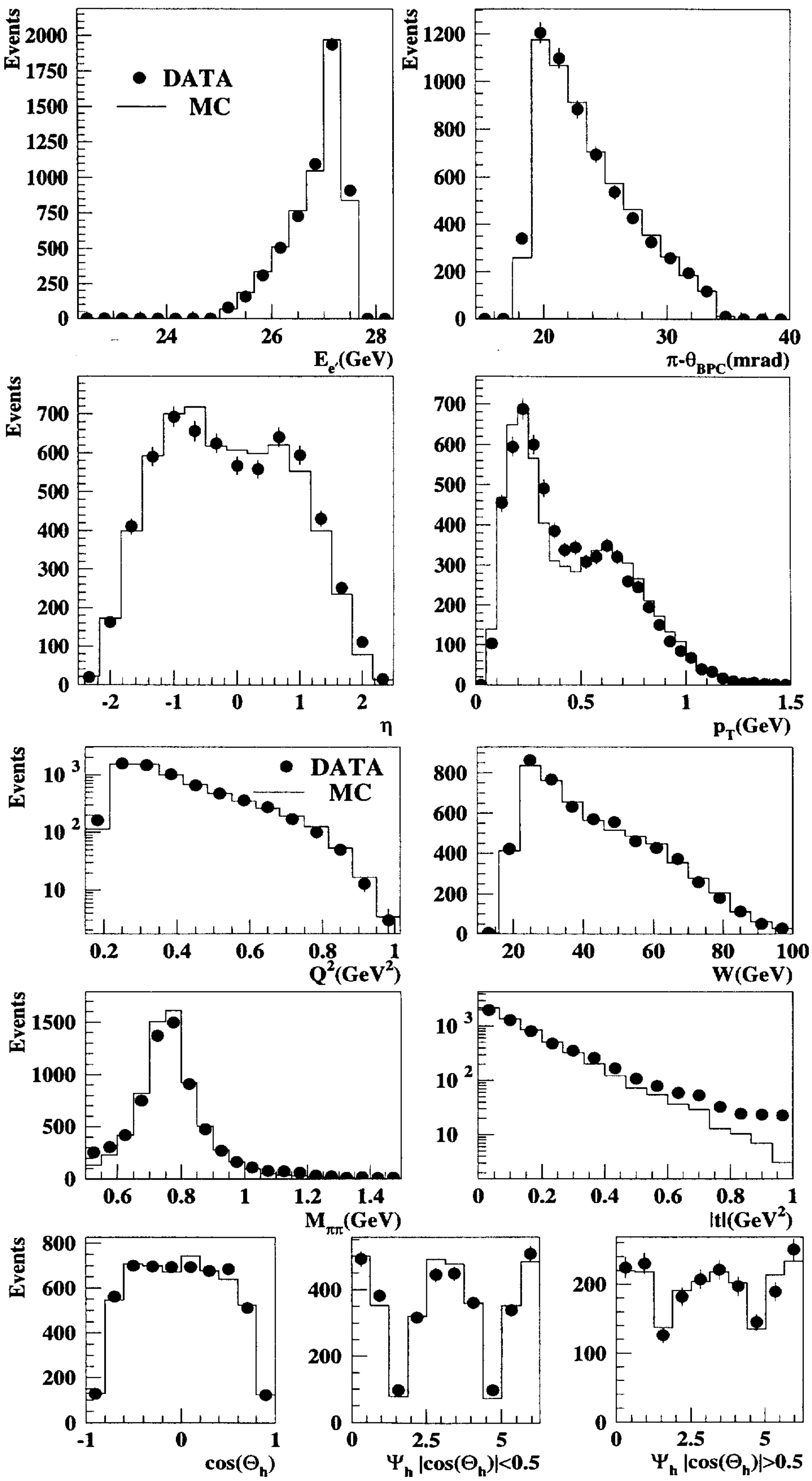


Mass distribution



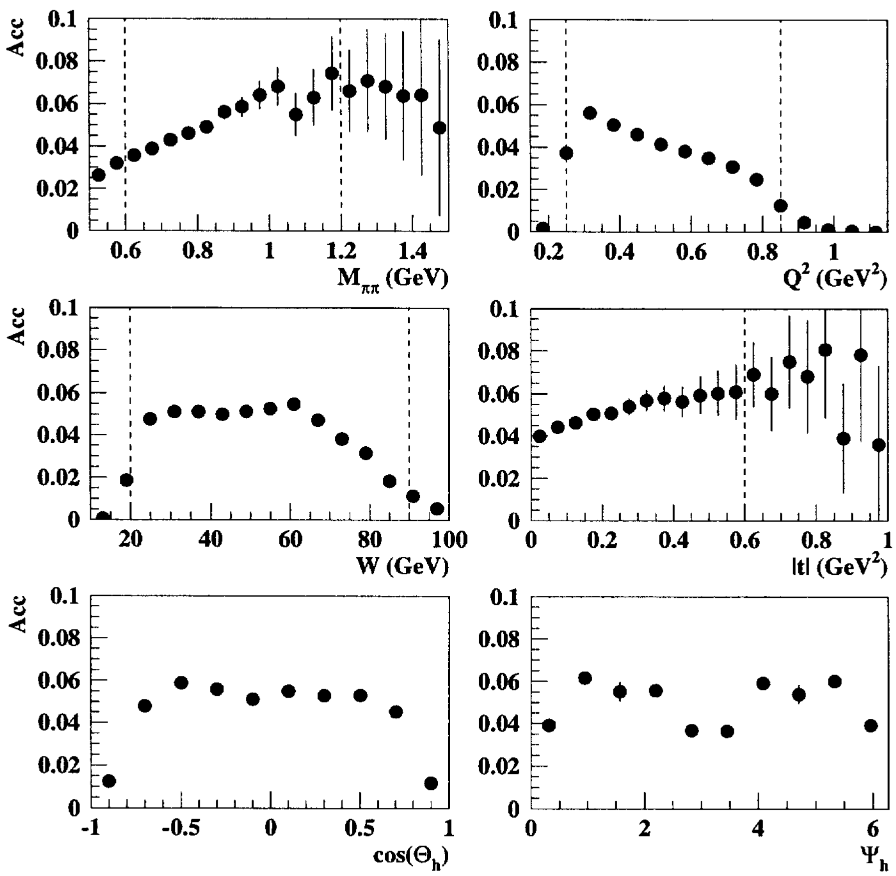
Kinematic coverage

EFF and BKGDS Comparison of data and (elastic) MC



Generalised acceptance (from elastic ρ^0 MC)

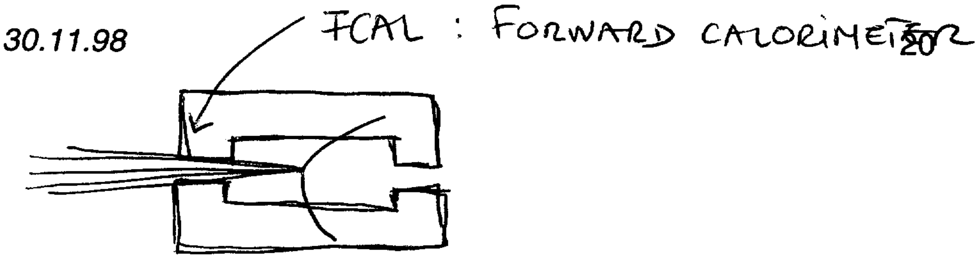
$$Acc(i) = \frac{\textbf{Events reconstructed in bin } i_{rec}}{\textbf{Events generated in bin } i_{gen}}$$



Also:

No bias in reconstructed variables

Analysis binning chosen from statistics and resolution considerations



Backgrounds

Main source: low masses proton dissociation

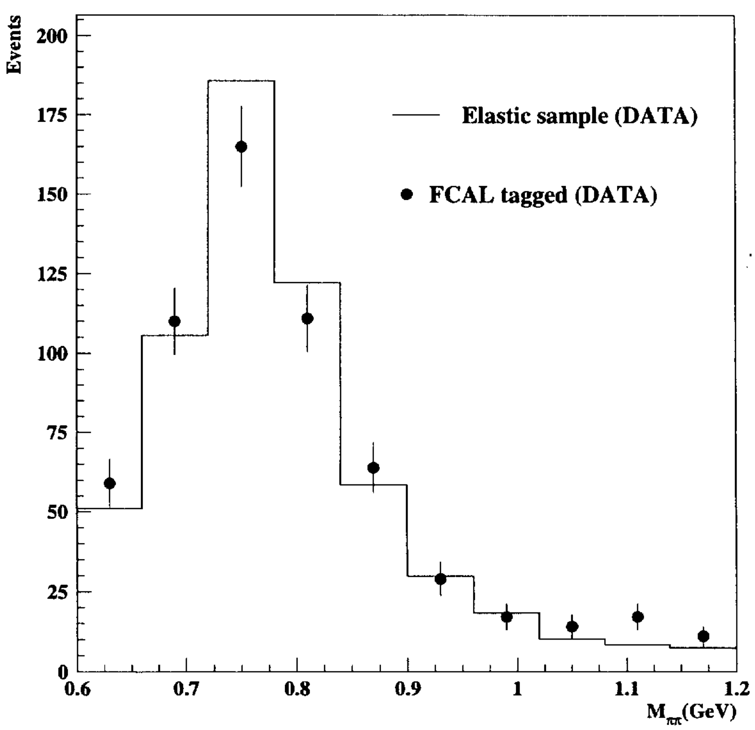
Estimate background using proton dissociative events with FCAL TAG

Analysis selection relaxing CAL-track matching (FCAL)

$+ > 1$ **GeV FCAL beam pipe**

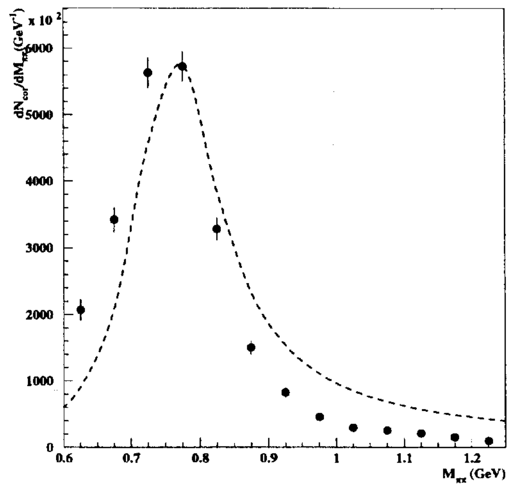
$\longrightarrow$ Extrapolate using inelastic ρ^0 MC to 'unseen' region

(remnant escapes through beampipe)



Flat contamination in Q^2, W **and** $\cos\theta_h$**:**

$23\% \pm 2.5\% \pm 7\%$; **parametrized versus** t

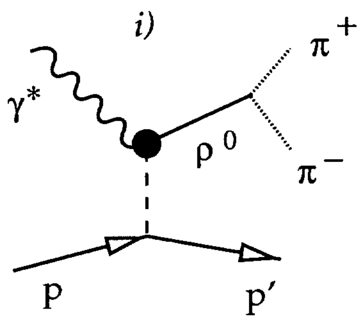


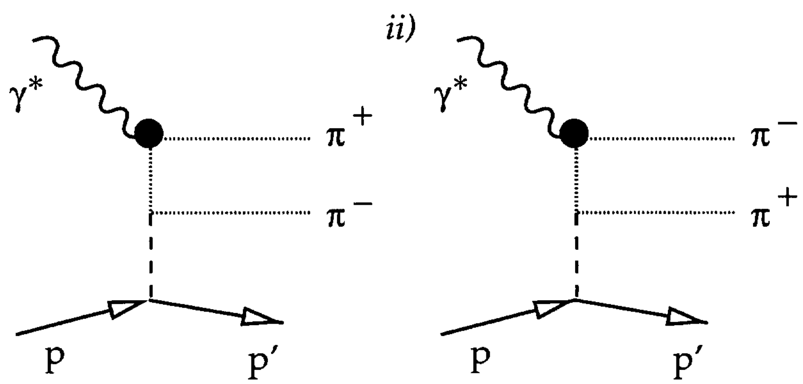
RESULTS

Mass spectrum

PDG: $M_\rho = 770.0 \pm 0.8$ **MeV,** $\Gamma_\rho = 150.7 \pm 1.1$ **MeV**

Söding model: interference w/ non-resonant $\pi\pi$ production

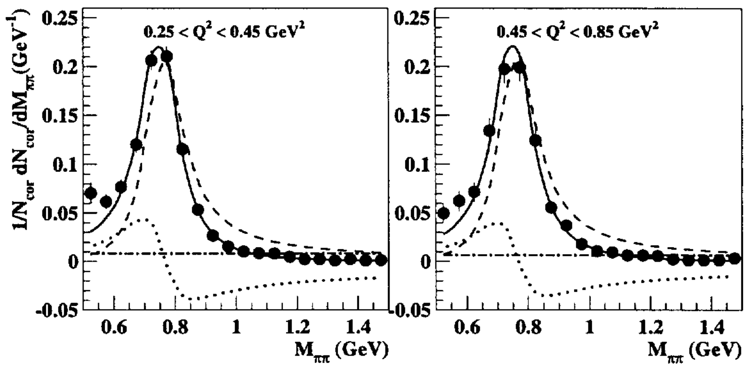




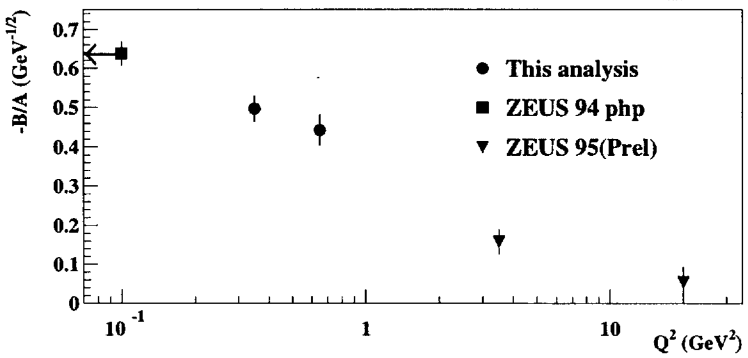
$$dN_{corr}/dM_{\pi\pi} = \left| A \left(\frac{\sqrt{M_{\pi\pi} M_\rho \Gamma_\rho}}{M_{\pi\pi}^2 - M_\rho^2 + i M_\rho \Gamma_\rho} + \frac{B}{A} \right) \right|^2$$

Söding fit

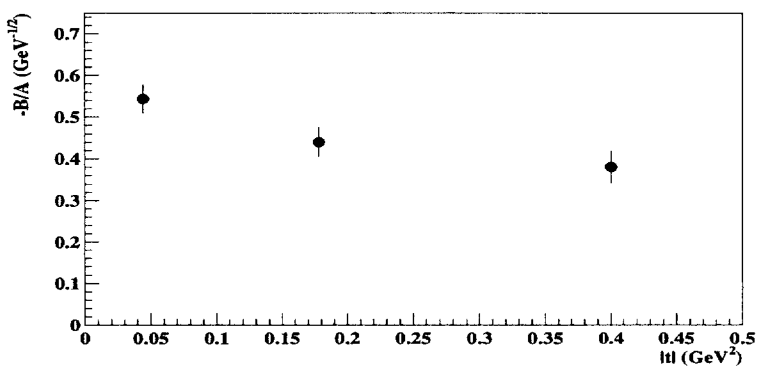
(2 Q^2 bins)



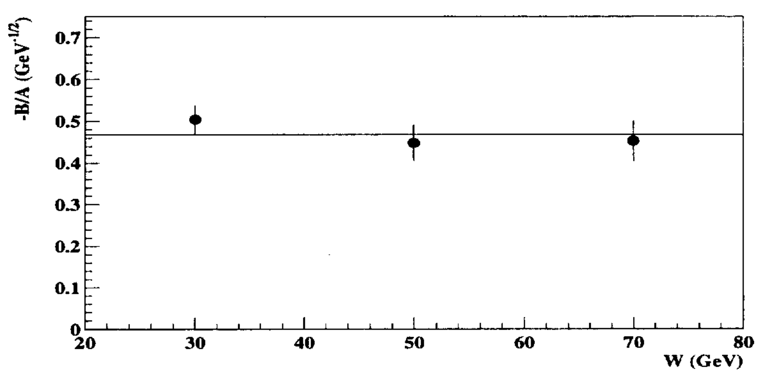
B/A versus Q^2



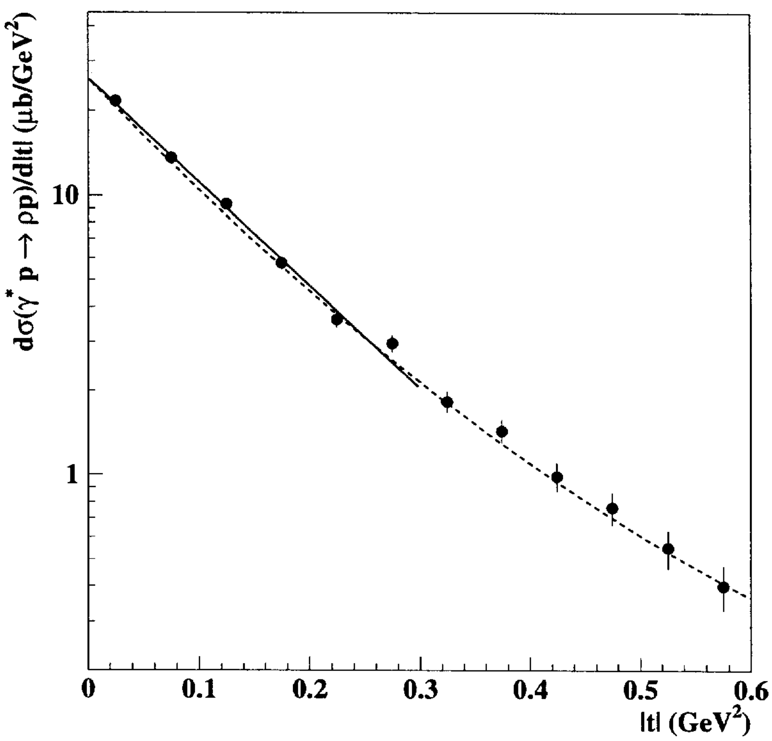
B/A versus $|t|$



B/A versus W



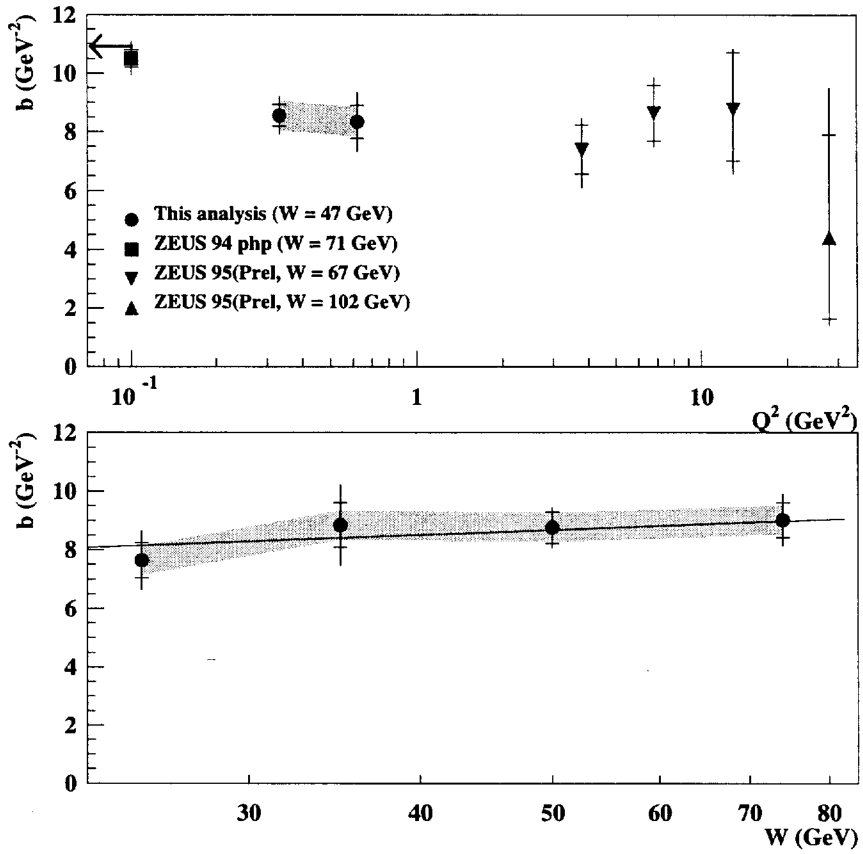
$d\sigma/d|t|$ distribution (for $\pi^+\pi^-$ events)



Described by

$e^{-b|t|}$ **for** $|t| < 0.3$ **GeV**^{2} **or**

$e^{-b|t|+ct^2}$ **for** $|t| \leq 0.6$ **GeV**^{2}



b slopes

Shrinkage

$$\frac{d\sigma^{\gamma^* p \to \rho^0 p}}{d|t|} = \left(\frac{W^2}{W_0^2}\right)^{2(\alpha(0)-1)} e^{-b(W)}|t|$$

$$b(W) = b_0 + 2\alpha' \ln(W^2/W_0^2)$$

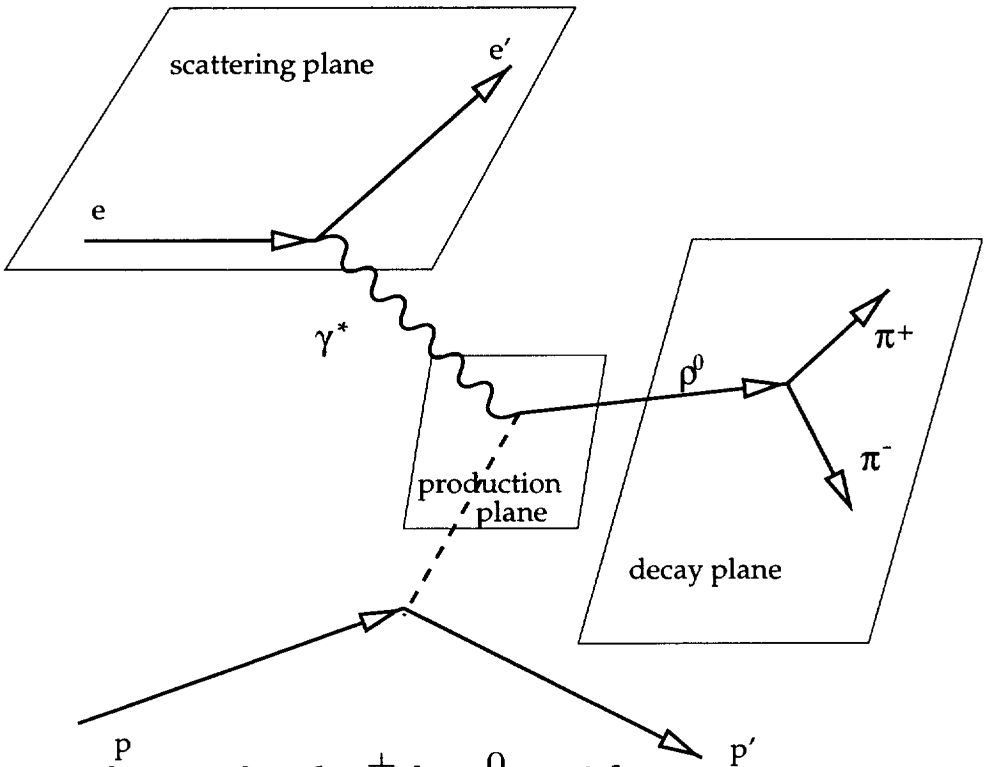
Bi-dimensional fit to $\frac{d\sigma^{\gamma^* p \to \rho^0 p}}{d|t|}$**:**

$$\alpha(0) = 1.055 \pm 0.016 \pm 0.019$$

$$\alpha' = 0.194 \pm 0.088 \pm 0.09 \text{ (GeV}^{-2}\text{)}$$

Consistent with DL fits to hadron-hadron

Angular decay distributions:



θ_h: **polar angle of π^+ in ρ^0 rest frame**

ϕ_h: **angle between the ρ^0 production and the decay planes**

Φ_h: **angle between production plane and scattering plan**

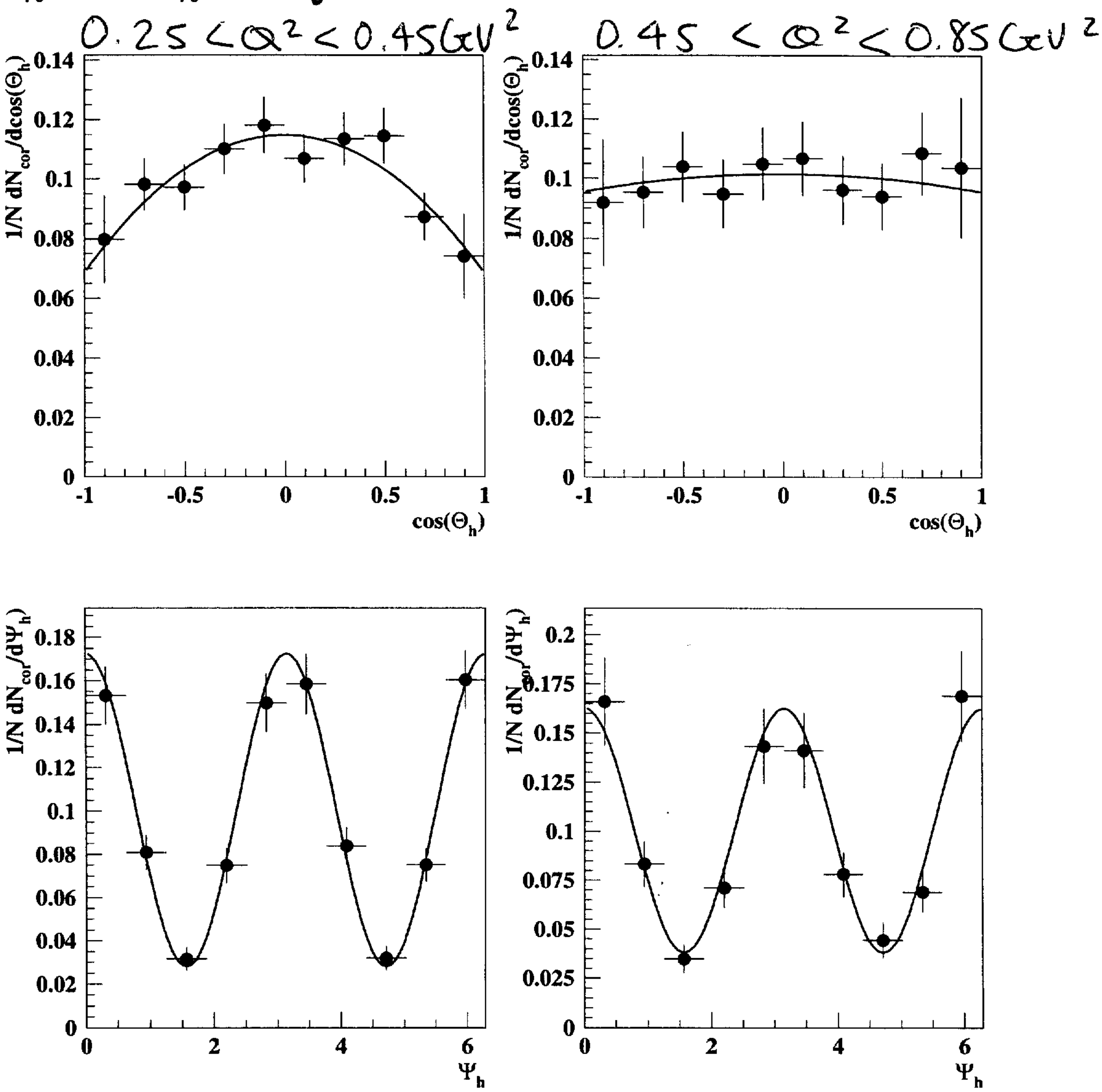
$\Psi_h = \phi_h - \Phi_h$

If helicity is conserved in s-channel (SCHC)

$W^{unpol}(\cos\theta_h, \Psi_h) = \frac{3}{4\pi}[\frac{1}{2}(1 - r^{04}_{00}) + \frac{1}{2}(3r^{04}_{00} -$
$1)\cos^2\theta_h \varepsilon r^1_{1-1}\sin^2\theta_h\cos 2\Psi_h -$
$2\sqrt{\varepsilon(1+\varepsilon)}Re(r^5_{10})\sin 2\theta_h\cos\Psi_h]$

r^{nm}_{ij}: ρ^0 **spin density matrix elements**

$\cos\theta_h$ **and** Ψ_h **in 2** Q^2 **bins:**



Results of bi-dimensional fits superimposed in plots

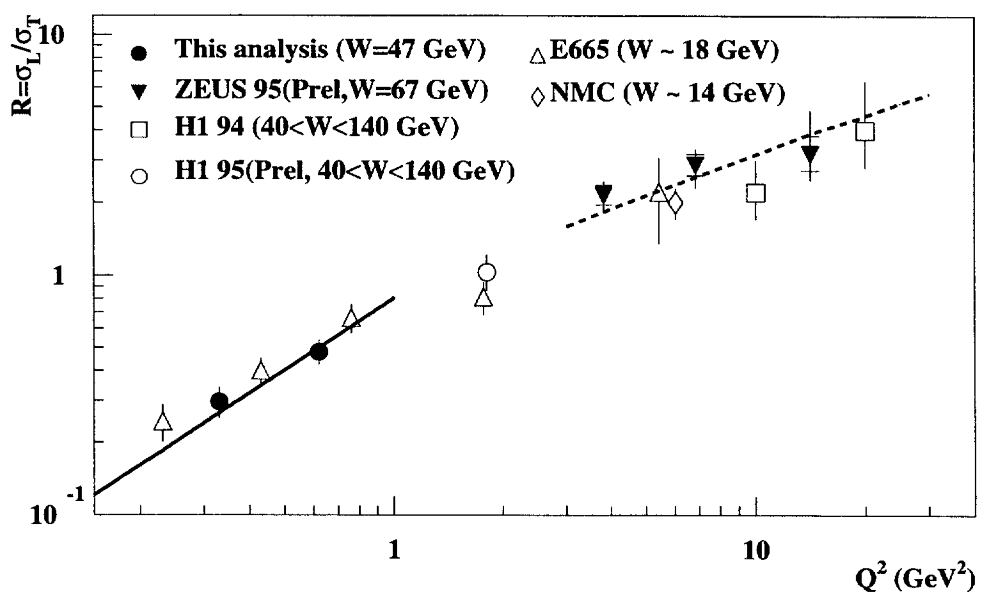
If SCHC and natural parity in t-channel ($P = (-1)^J$)

$r^1_{1-1} = \frac{1}{2}(1 - r^{04}_{00}) \rightarrow$ verified

$R = \sigma_L / \sigma_T$

If SCHC

$$R = \frac{r_{00}^{04}}{\varepsilon(1 - r_{00}^{04})}$$



Fit (BPC points) to $R = \xi_\rho \frac{Q^2}{M_\rho}$ **:**

$\xi_\rho = 0.48 \pm 0.03 \pm 0.03$

$\gamma^* p \to \rho^0 p$ **cross section**

Extraction method:

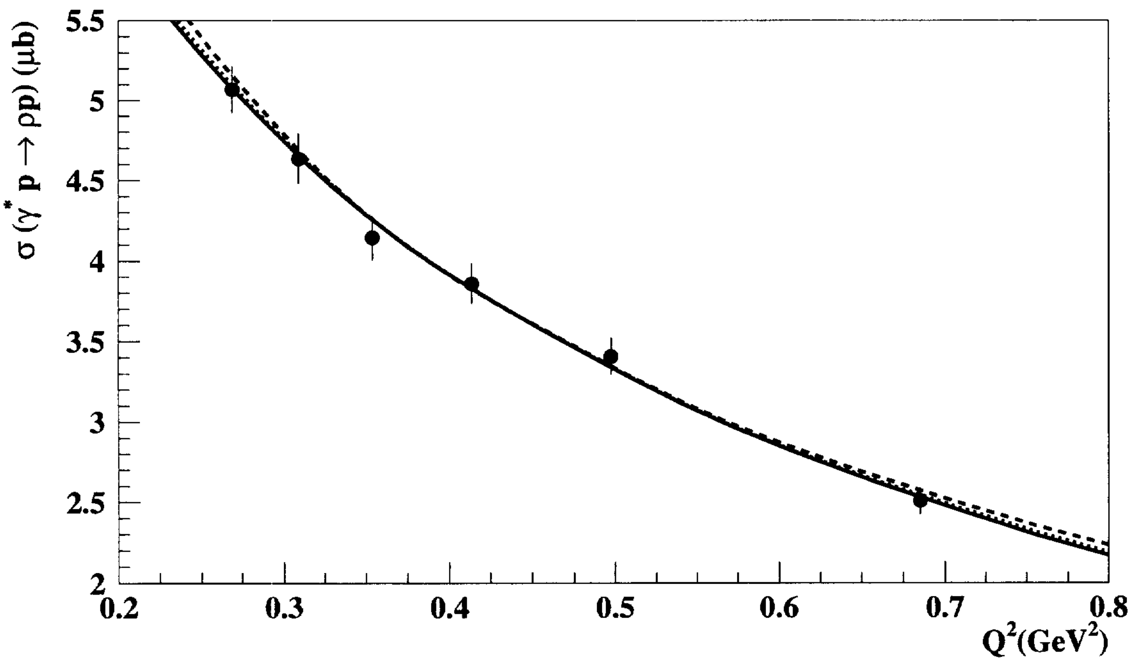
$\sigma^{\gamma^* p \to \rho^0 p}$ **from** $\sigma^{ep \to e\rho^0 p}$,

$\sigma^{ep \to e\rho^0 p}_{Q2bin,Wbin} = \frac{\mathcal{N}_\rho}{\mathcal{L}}$

$\mathcal{N}_\rho = \int_{M_{min}}^{M_{max}} \frac{dN_{cor}}{dM_{\pi\pi}} dM_{\pi\pi}$,

$M_{min} = 2 \cdot M_\pi$, $M_{max} = M_\rho + 5 \cdot \Gamma_\rho$

$W_0 = 51$ **GeV**



$$\sigma^{\gamma^* p \to \rho^0 p}(Q^2) = \sigma(0) \left(\frac{1+\xi_\rho \frac{Q^2}{M_\rho^2}}{1+\frac{Q^2}{M_\rho^2}} \right)^2$$ **(dashed line):**

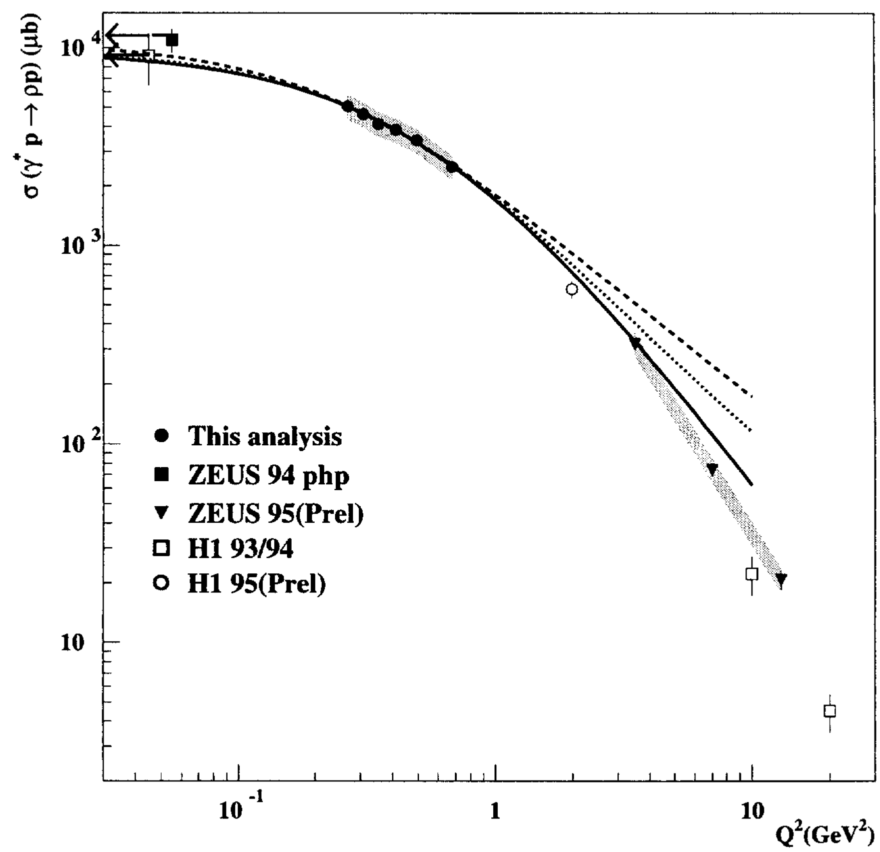
$\sigma(0)$**=9.97 $\pm$ 0.48 $\pm$ 0.92 μb, ξ_ρ = 0.16 $\pm$ 0.07 $\pm$ 0.19**

$$\sigma^{\gamma^* p \to \rho^0 p}(Q^2) = \sigma(0) \left(\frac{1+R(Q^2)}{1+\frac{Q^2}{M_{eff}^2}} \right)^2$$ **(dotted line):**

$\sigma(0)$**=10.97 $\pm$ 1.33 $\pm$ 1.77 μb, M_{eff}=0.66 $\pm$ 0.05 $\pm$ 0.10 GeV**

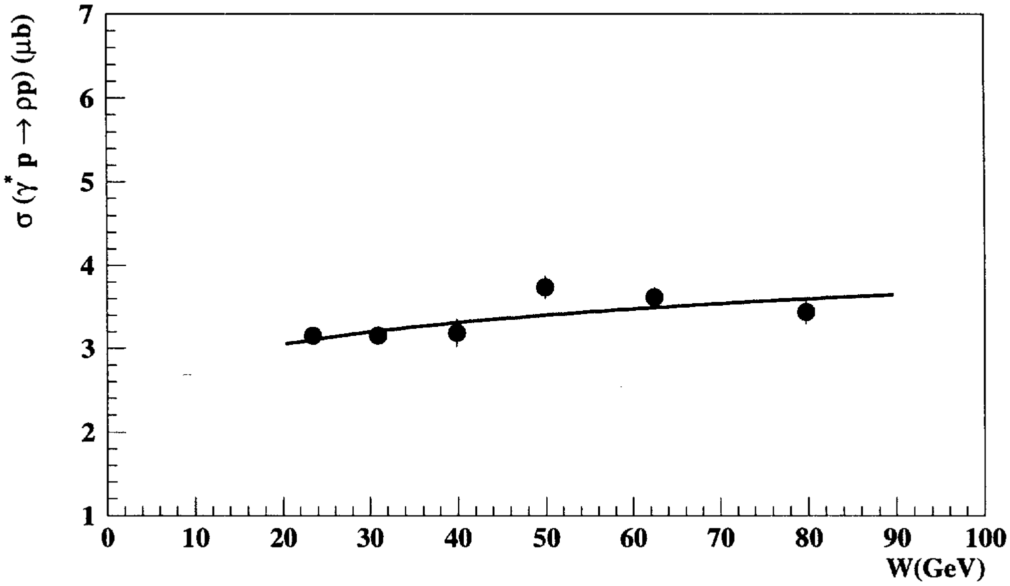
$$\sigma^{\gamma^* p \to \rho^0 p}(Q^2) = \sigma(0) \left(\frac{1}{1+\frac{Q^2}{M_\rho^2}} \right)^n$$ **(solid line):**

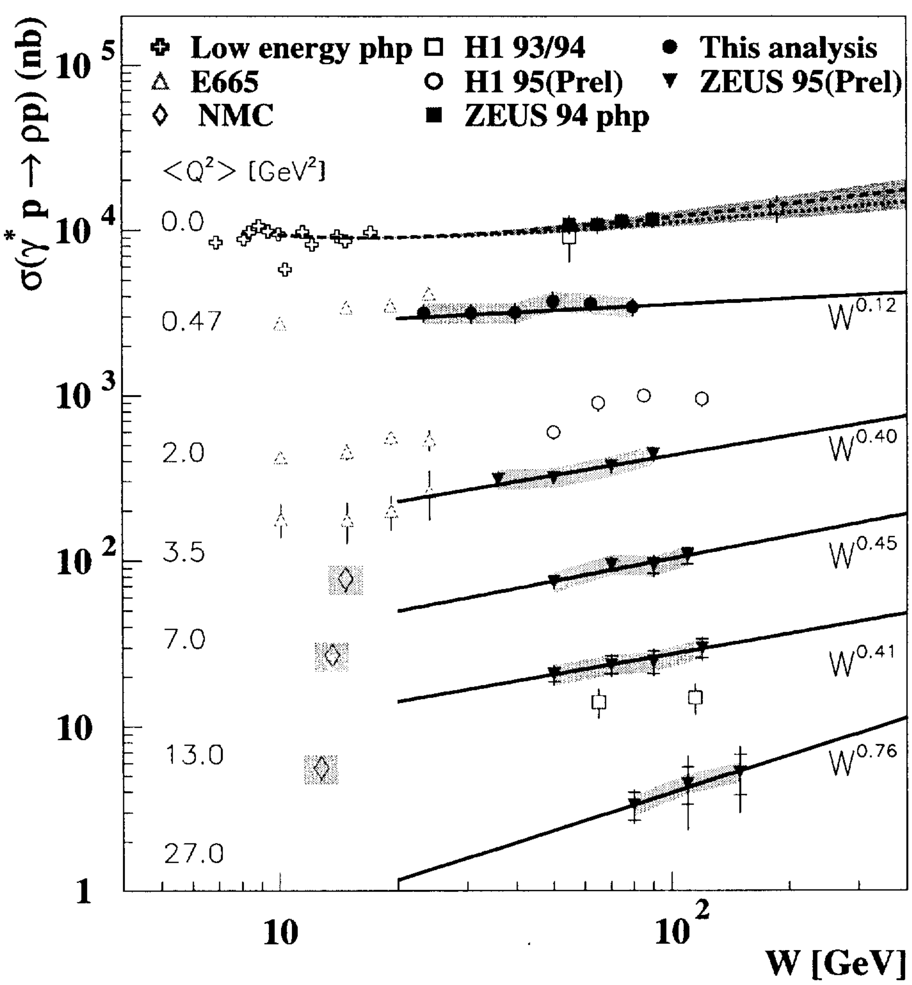
$\sigma(0)$**=9.70 $\pm$ 0.51 $\pm$ 1.00 μb, n=1.75 $\pm$ 0.10 $\pm$ 0.29**



$$\sigma^{\gamma^* p \rightarrow \rho^0 p}(W) \propto W^{\delta}\text{: } \delta = \mathbf{0.12 \pm 0.03 \pm 0.08}$$

$$Q_0^2 = 0.47\ \mathbf{GeV}^2$$





Systematic studies impact on cross sections

Error source	Typical uncertainty (%)	Comment
Tracking requirements	1-8	
BPC requirements	3-5	10% at low Q^2
Matching	2-9	
Elastic MC paramet.	1-4	
Extraction of ρ^0 signal	0-4	Söding model
Extraction of ρ^0 signal	10	Other ρ^0 models
Proton dissociative ρ^0	7	Normalization
Elastic ω and ϕ	1.6	Normalization
Photon diff. dissociation	3	Normalization
Beam gas interactions	1.5	Normalization
Trigger efficiency	5.5	Normalization
Photon flux	1	Normalization
Radiative corrections	2	Normalization
Luminosity	1.1	Normalization
Total uncertainty	9%-14% $\oplus$ 14% (norm)	

CONCLUSIONS

- $\gamma^* p \to \rho^0 p$ **studied for first time at HERA for** $0.25 < Q^2 < 0.85$ **GeV**^{2}, $20 < W < 90$ **GeV,** $|t| < 0.6$ **GeV**^{2} **using a new ZEUS** Beam Pipe Calorimeter

- ρ^0 **mass shape well described by Söding model. Relative production of non-resonant** $\pi^+\pi^-$ **decreases with** Q^2

- $d\sigma^{\gamma^* p \to \pi^+\pi^- p}/d|t|$ **well described by single exponential for** $|t| < 0.3$ **GeV**^{2}**. Indications of slight decrease of diffractive slope with** Q^2**.**

- **Evidence of W dependence of the** $|t|$ **slope (shrinkage). The Pomeron trajectory consistent with Donnachie and Landshoff Regge-type fits to hadron-hadron.**

- **Values of the spin density matrix elements were determined under assumption of SCHC. Results consistent with this assumption, and natural parity exchange in** t**-channel.**

- $R = \sigma_L^{\gamma^* p \to \rho^0 p} / \sigma_T^{\gamma^* p \to \rho^0 p}$ **at low Q^2 grows linearly with Q^2.**

- **Q^2 dependence of cross section described by** $\sigma(Q^2) \propto 1/(1 + Q^2/M_\rho^2)^n$,
n=1.75$\pm$0.10(stat)$\pm$0.29(sys)

- **W dependence of cross section described by** $\sigma \propto W^\delta_{\gamma^* p \to \rho^0 p}$, **$\delta$=0.12$\pm$0.03(stat)$\pm$0.08(syst)**

- **ρ^0 production for 0.25$< Q^2 <$ 0.85 GeV^2, $20 < W < 90$ GeV shows features of soft diffractive processes, with some indications of transitional character (B/A vs Q^2, b vs Q^2). The soft behaviours observed here agree with Photoproduction results but cannot be extended far beyond Q^2 of this analysis.**

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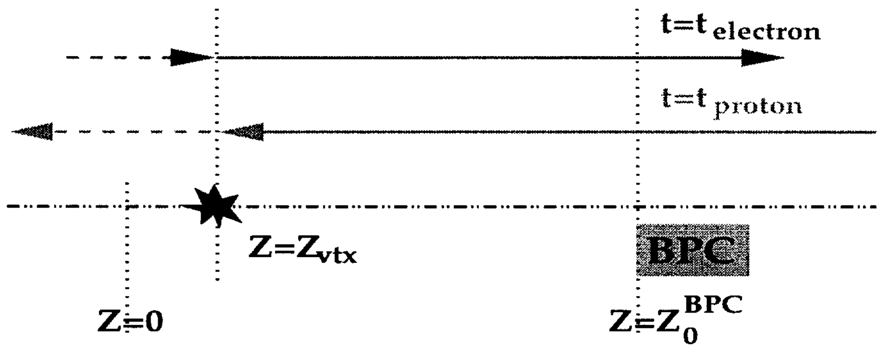
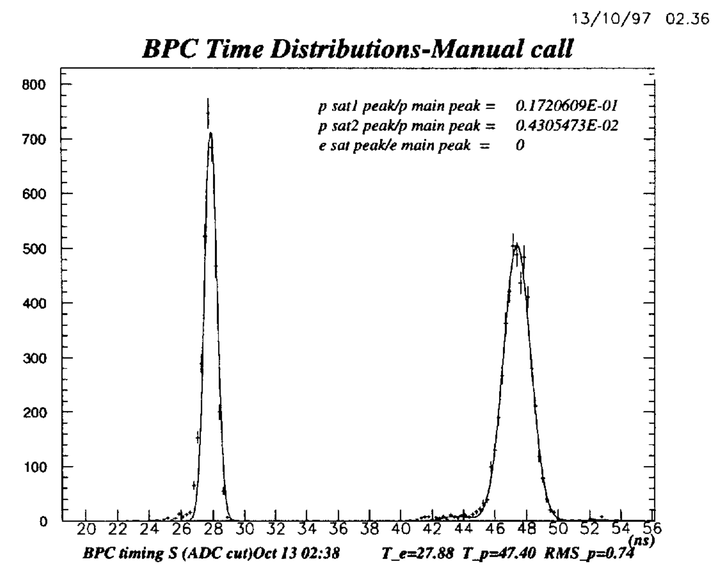
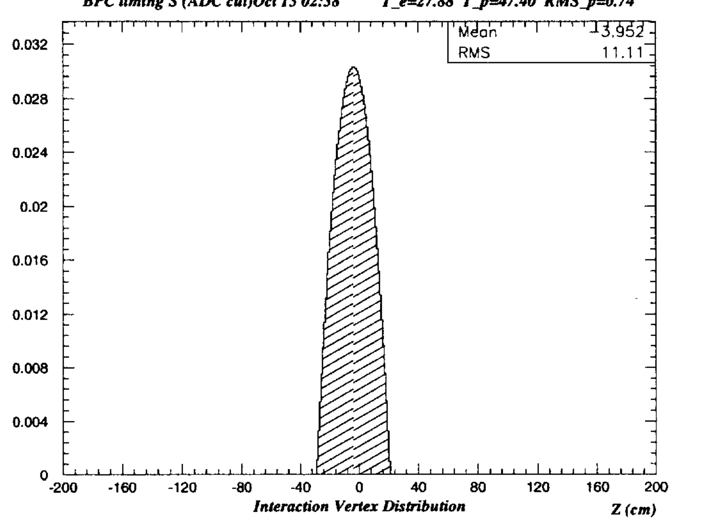
Online vertex determination using the BPC

$$Z_{vtx} = \frac{(t_{proton} - t_{electron}) \times c}{2} + Z_0^{BPC}$$

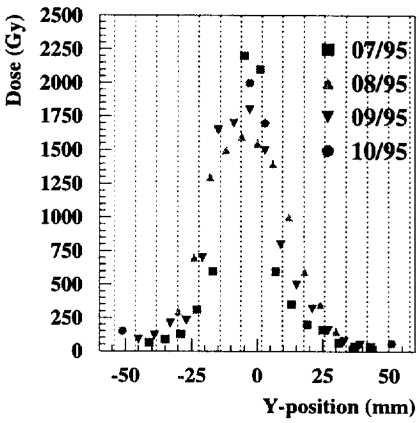


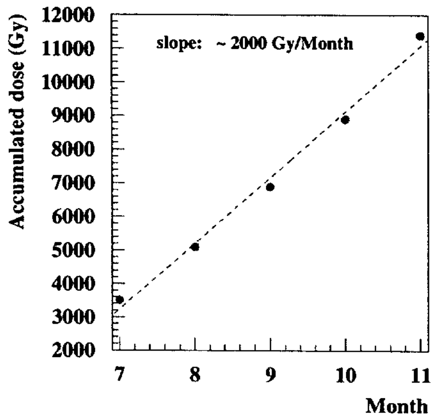




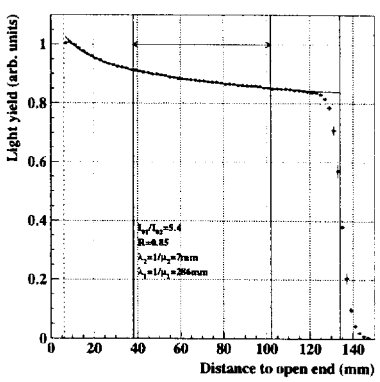
Radiation dose

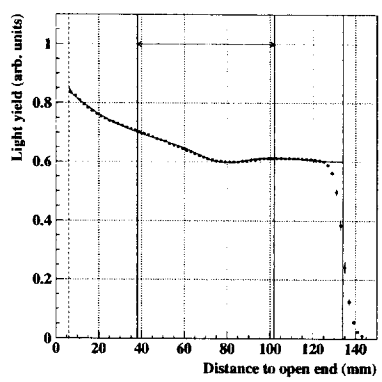
BPC received 12 kGy over 5 monthes (1 Gy = 100 rad)





Scintillator finger response: before and after iradiation





Able to compensate with offline calibration