New Results on Vector Meson Production at HERA

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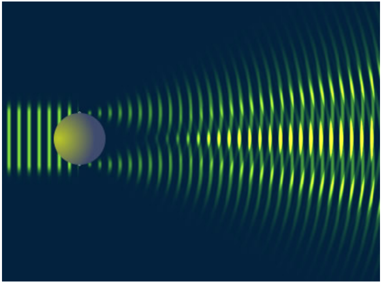
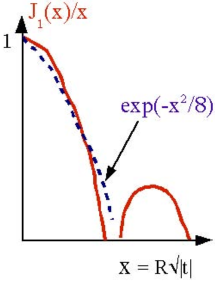
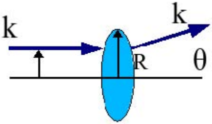
Outlook

1. Introduction: Vector Meson Production in Exclusive Diffraction in *ep* Scattering

2. New Results on Vector Mesons Production at HERA
   - ZEUS: cross section ratio $\psi(2S)/J/\psi(1S)$ in DIS
   - H1: Exclusive ρ^0 mesons with leading neutron in PHP





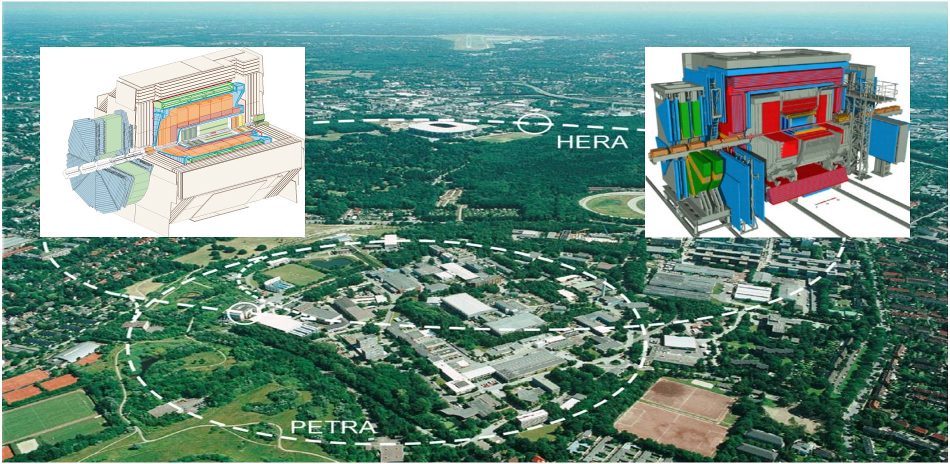


Light Scattering in Fraunhofer approximation (wavelength $\lambda \sim 1/k << R$)

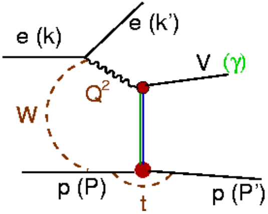
- $|t| = 4k^2 sin^2(\theta/2)$
- $d\sigma/dt \sim e^{-b|t|}$ (first diffractive peak approximated from Bessel function)
- $b = (R/2)^2 \rightarrow$ transverse size of the target

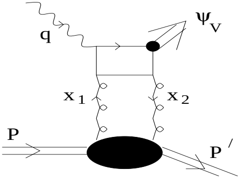
- in the presented studies: target $\equiv$ proton and photon energy $\gg 1$ GeV

World's first and only $e^{\pm}p$ collider, $\mathbf{E_e = 27.5\ GeV}$, $\mathbf{E_p = 920\ GeV}$ $(820, 575, 460\ \text{GeV})$



Total luminosity: $\int \mathcal{L} \sim \mathbf{500\ pb^{-1}}$ collected per experiment





Kinematics of the exclusive process

The proton stays intact !

Kinematics: $\mathbf{M_V^2}$, $\mathbf{Q^2}$, **W**, $|\mathbf{t}|$

M_V^2 - vector meson mass squared

Q^2 $(= -q^2 = -(k - k')^2)$ - the photon virtuality (emitted by the incoming electron):

- $Q^2 \approx 0$ GeV^2 PHP (*Photoproduction*)
- larger Q^2 for DIS (*Deep Inelastic Scattering*)

W - invariant mass of the γp system
Process sensitive to the **gluon density** in the proton

$|t|$ - 4-momentum transfer at the proton vertex
$t = (P - P')^2$

pQCD: M_V^2 and Q^2 - set the scale at which the W and $|t|$ are probed

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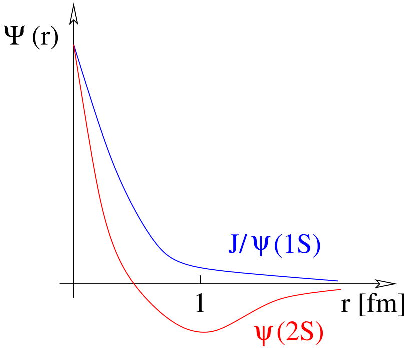
ZEUS: cross section ratio $\psi(2S)/J/\psi(1S)$ in DIS



$$\text{Ratio } R = \frac{\sigma_{\gamma p \to \psi(2S) p}}{\sigma_{\gamma p \to J/\psi(1S) p}}$$

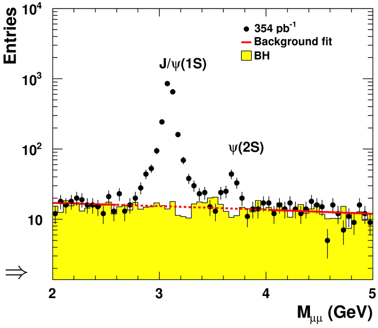
- sensitive to radial wave function of charmonium
- provides insight into the dynamics of the hard process

- $J/\psi(1S)$ and $\psi(2S)$ have distinctive wave functions
- $\psi(2S)$ has a node at ≈ 0.4 fm
- $\langle r^2_{\psi(2S)} \rangle \approx 2 \langle r^2_{J/\psi(1S)} \rangle$
- pQCD models predict $R \sim 0.17$ in PHP and rise of R with Q^2 in DIS

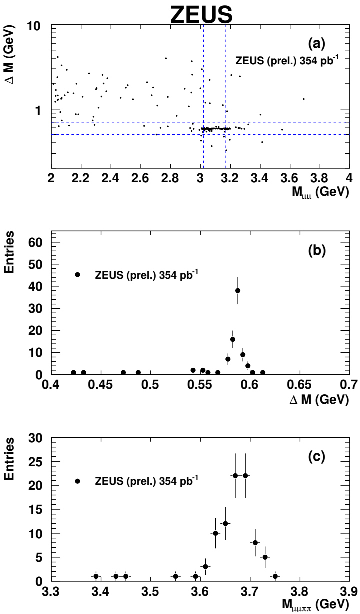
Investigated channels and data sample

- Analyzed channels
  - $\psi(2S) \to J/\psi + \pi^+\pi^-$; $J/\psi \to \mu^+\mu^-$
  - $\psi(2S) \to \mu^+\mu^-$
  - $J/\psi(1S) \to \mu^+\mu^-$
- HERA II DATA $\mathcal{L} = 354\ \mathrm{pb}^{-1}$ (2003 - 2007)
- MC Samples
  - Signal: DIFFVM for exclusive VM production (J/psi and ψ')
  - Background: GRAPE for non resonant muon pair production (Bethe-Heitler process)
- Event selection
  - scattered electron $E_{e'} > 10$ GeVin CAL
  - 2 (4 for $\psi(2S)$ 4-prongs decay) non-electron tracks from primary vertex, net charge $= 0$
  - two tracks identified as muons (CAL, F/B/R/MUO, BAC)
  - no other deposits not matched to tracks (above CAL noise)
- Kinematic range:
  - $30 \leq W \leq 210$ GeV
  - $5 \leq Q^2 \leq 70$ GeV^2
  - $|t| \leq 1$ GeV^2

$M(\mu^+\mu^-) \Rightarrow$



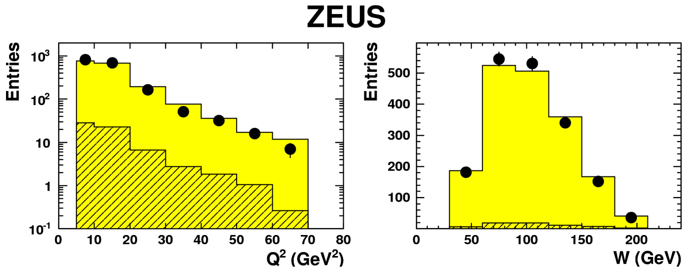
Selection specific for $\psi(2S) \to \mu^+\mu^-\pi^+\pi^-$ channel

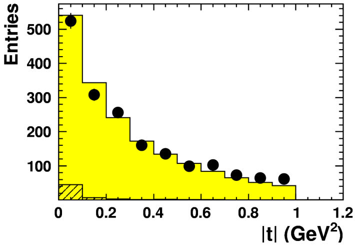


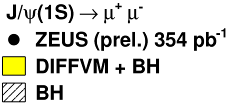
- ΔM vs. $M_{\mu^+\mu^-}$
  $\Delta M = M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$
  cascade decay of $\psi(2S)$

- $0.5 < \Delta M < 0.7$ GeV
  $3.02 < M_{\mu^+\mu^-} < 3.17$ GeV

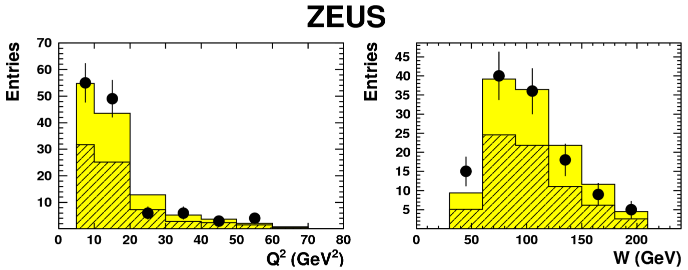
- $M(\mu^+\mu^-\pi^+\pi^-)$ after cleanup
  very clean signature
  ($\lesssim$ 3 background events)

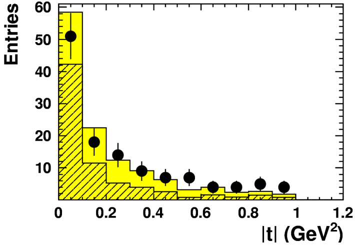


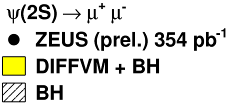




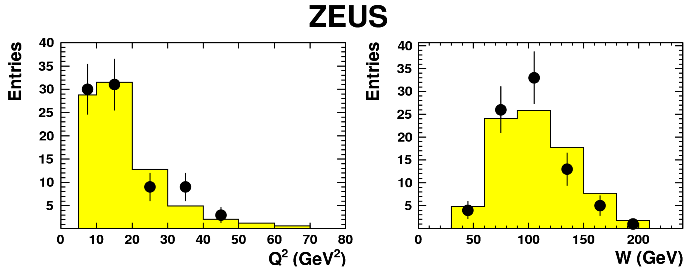
- MC reweighted in Q^2, $|t|$ and J/ψ decay angles to match the data
- good description $\to$ detector efficiency calculation

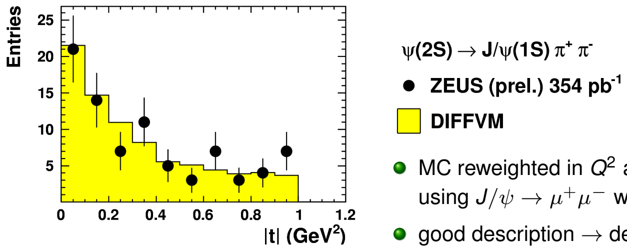






- MC reweighted in Q^2, $|t|$ and $\psi(2S)$ decay angles using $J/\psi \to \mu^+\mu^-$ weights
- good description $\to$ detector efficiency calculation





- MC reweighted in Q^2 and $|t|$ using $J/\psi \to \mu^+\mu^-$ weights
- good description $\to$ detector efficiency calculation

Cross section ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ for full kinematic range

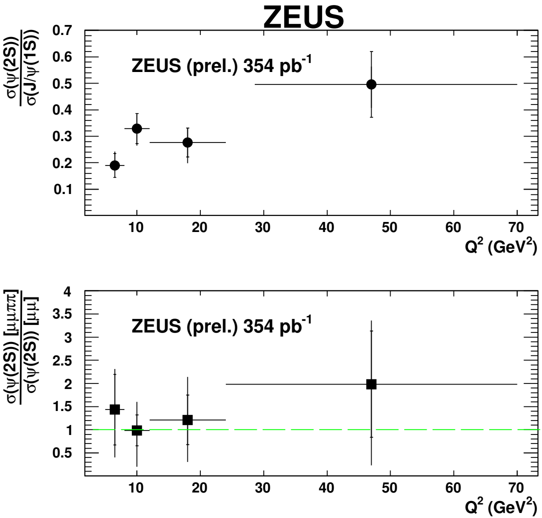
For $30 \leq W \leq 210$ GeV, $5 \leq Q^2 \leq 70$ GeV^2, $|t| \leq 1$ GeV^2

$\psi(2S)$ decay mode	$R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$
$\to J/\psi(\to \mu^+\mu^-)\pi^+\pi^-$	$0.29 \pm 0.04^{+0.02}_{-0.01}$
$\to \mu^+\mu^-$	$0.25 \pm 0.05^{+0.04}_{-0.02}$
combined	$0.28 \pm 0.03^{+0.02}_{-0.01}$

ZEUS Preliminary

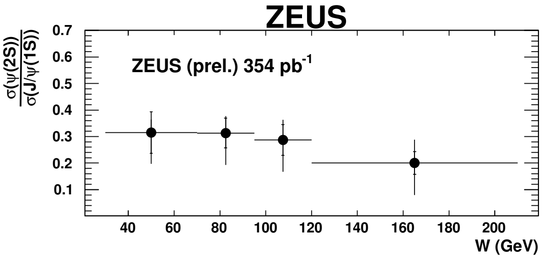
- both channels provide consistent results
- $R_{\psi(2S)\to J/\psi\pi^+\pi^-} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to J/\psi\pi^+\pi^-}} \cdot \frac{1}{BR_{\psi(2S)\to J/\psi\pi^+\pi^-}}$
- $R_{\psi(2S)\to\mu^+\mu^-} = \frac{\sigma_{\psi(2S)}}{\sigma_{J/\psi(1S)}} = \frac{N_{\psi(2S)}}{N_{J/\psi(1S)}} \cdot \frac{Acc_{J/\psi(1S)\to\mu^+\mu^-}}{Acc_{\psi(2S)\to\mu^+\mu^-}} \cdot \frac{BR_{J/\psi(1S)\to\mu^+\mu^-}}{BR_{\psi(2S)\to\mu^+\mu^-}}$
- $Acc_i = \frac{N_i^{reco}}{N_i^{true}}$

Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. Q^2

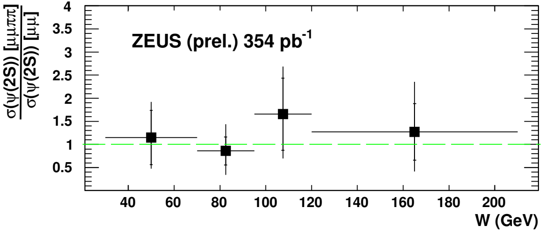


- *R* raises with Q^2
- $\frac{\sigma(\psi(2S) \to \mu^+\mu^-\pi^+\pi^-)}{\sigma(\psi(2S) \to \mu^+\mu^-)}$

Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. W

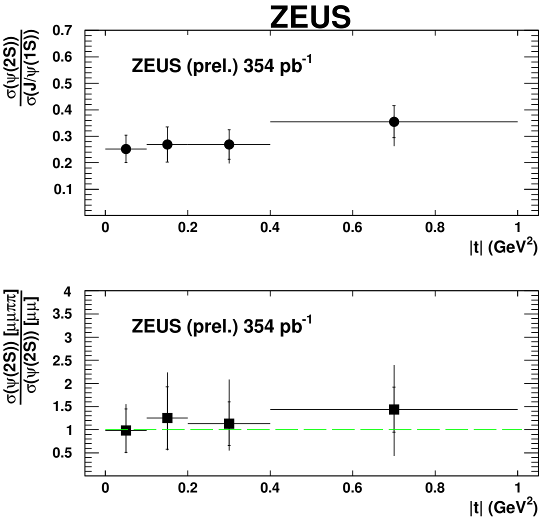


- *R independent of W*



- $\frac{\sigma(\psi(2S)\to\mu^+\mu^-\pi^+\pi^-)}{\sigma(\psi(2S)\to\mu^+\mu^-)}$

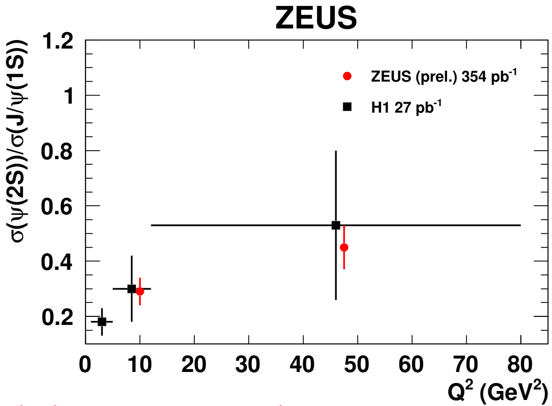
Ratio $R = \frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ vs. $|t|$



- R independent of $|t|$
- $\frac{\sigma(\psi(2S)\rightarrow\mu^+\mu^-\pi^+\pi^-)}{\sigma(\psi(2S)\rightarrow\mu^+\mu^-)}$

ZEUS to H1 comparison

- cross check: ZEUS data analyzed in Q^2 bins used by H1: [EPJ **C10** (1999) 373.] $(5-12)$ GeV^2 and $(12-80)$ GeV^2
- $40 < W < 180$ GeV and $1 < Q^2 < 80$ GeV^2



- both measurements are in agreement
- improved accuracy due to the increased statistic of HERA II data

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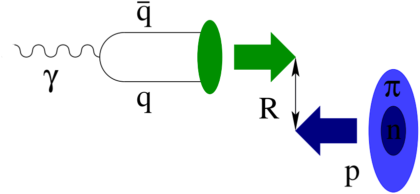
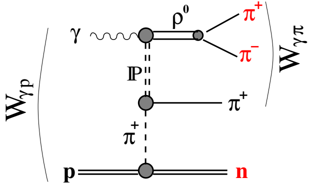


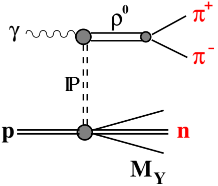
- **First observation** of exclusive **VM photoproduction on** (virtual) **pion** $\gamma\pi^+ \to VM + \pi^+$
  - unique opportunity at HERA (γ, π^+ beams existed before, but not the target)
  - extends the landscape of Vector Meson production at HERA
- **experimental challenge**
  - trigger: tagged PHP too large W to register the VM; untagged PHP very large rate, requires prescaling
  - limited acceptance for (very) forward π and neutron ($\eta_{LAB} > 6$)
- **advantages of H1 during HERA-II run**
  - improved Forward Neutron Calorimeter (FNC) (identifies and measures n and γ/π^0)
  - efficient Fast Track Trigger (FTT) allows to collect untagged soft PHP events

Physics process and analysis phase space

- $\gamma^* + p \to \rho^0 \pi^+ n, \quad \rho^0 \to \pi^+\pi^-$

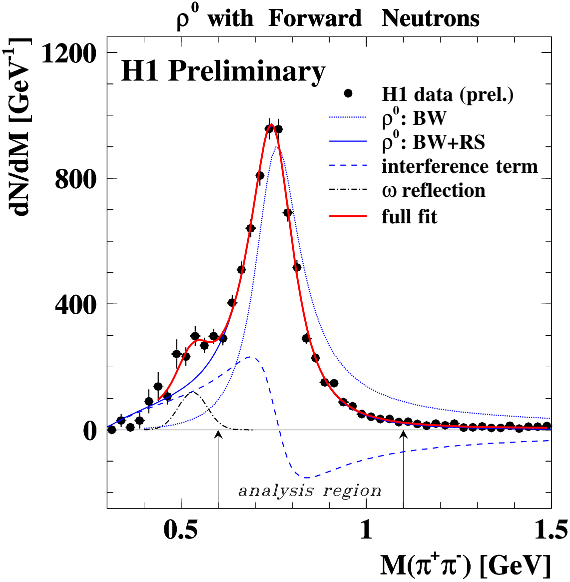


- **Key observables**
  - $x_L = E_n/E_p$ (or $x_\pi = 1 - x_L$, distribution: $\sim f_{\pi/p}(x_L)$)
  - W dependence: $\sim W^\delta$, nature of exchanged object
  - t-slope, $dN/d|t| \sim exp(-b|t|)$, $b \sim R^2$, size of the interaction region
- **Kinematics**
  - Photoproduction: $Q^2 < 2\ \text{GeV}^2$, $\langle Q^2 \rangle = 0.05\ \text{GeV}^2$
  - Low p_t: $|t| < 1\ \text{GeV}^2$, $\langle |t| \rangle = 0.20\ \text{GeV}^2$, $t = (P_\gamma - P_{\rho^0})^2$ (at top vertex)
  - small mass: $0.3 < m_{\pi\pi} < 1.5$ GeV
  - track acceptance in Central Tracker: $20 < W_{\gamma p} < 100$ GeV, $\langle W_{\gamma p} \rangle = 48$ GeV
    $W_{\gamma p} = \sqrt{2(E - p_z)_\rho E_p}$, $W_{\gamma\pi} = W_{\gamma p}\sqrt{1 - x_L}$
  - Forward neutron: $E_n > 120$ GeV, $\theta_n < 0.75$ mrad

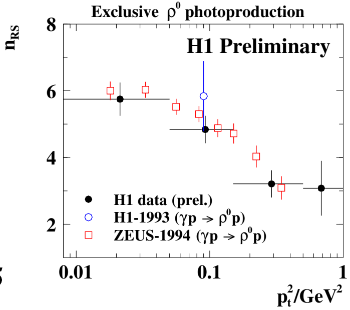


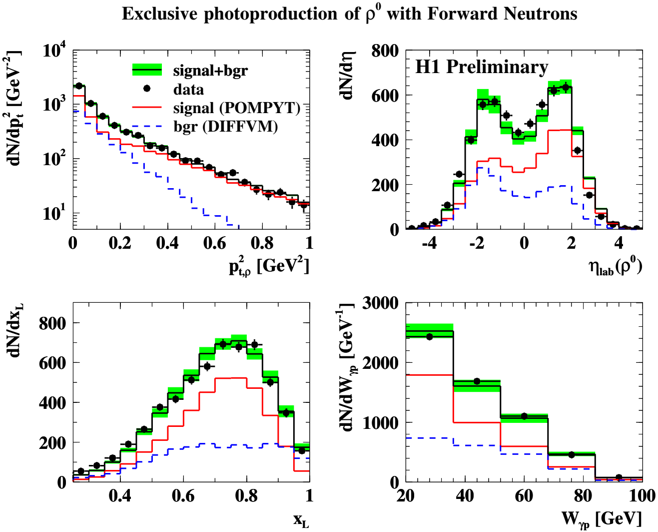
- No hard scale present: Regge framework is most adequate
- Diffractive BG has irreducible component: $M_Y = N^* \to n\pi^+$

ρ^0 meson shape



- $\frac{dN}{dM_{\pi\pi}} \propto BW_\rho(M_{\pi\pi})\left(\frac{M_\rho}{M_{\pi\pi}}\right)^{n_{RS}}$
- $M = 764 \pm 3$ MeV
- $\Gamma = 154 \pm 5$ MeV
- skewing (Ross and Stodolsky) $n_{RS} = 4.17 \pm 0.27$

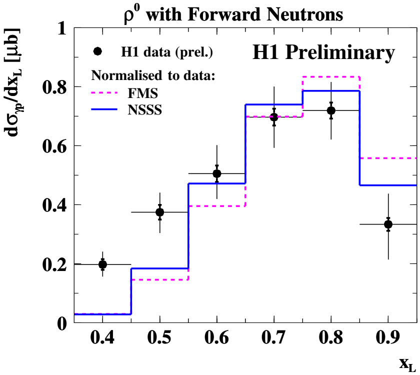




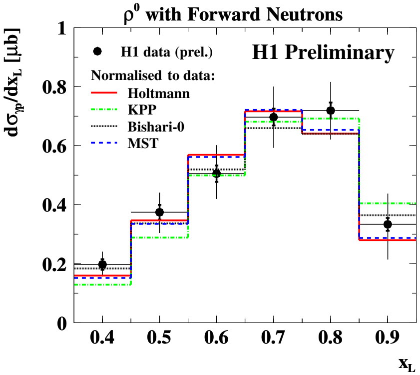
Data points are shown with stat. errors only; green band represents estimated uncertainty on the p.diss BG fraction

Pion fluxes verified by H1 data

Classes of π-fluxes restricted by comparing the x_L distribution



Example of fluxes excluded by the data (too soft pions "in the proton")



Fluxes compatible with H1 data ($\chi^2 = 2.1$ to 5.5 for 6 points)

Total Cross Sections: H1 Preliminary

- $\sigma_{\gamma p} = \frac{\sigma_{ep}}{\int f_{\gamma/e}(y,Q^2)dydQ^2} = \frac{N_{\rm DATA} - N_{\rm BG}}{\mathcal{L}(A\cdot\epsilon)\mathcal{F}} \cdot C_p$
  - $N_{\rm BG}$ - proton dissociation background from MC
  - $\mathcal{L}$ - integrated luminosity
  - $A \cdot \epsilon$ - acceptance and efficiency corrections
  - $\mathcal{F}$ - photon flux integrated over $20 < W < 100$ GeV, $Q^2 < 2$ GeV^2
  - C_p - correction due to the extrapolation to the full ρ^0 mass range

For $0.35 < x_L < 0.95$, $20 < W < 100$ GeV, $\theta_n < 0.75$ mrad

$$\sigma(\gamma p \to \rho^0 n(\pi^+)) = (280 \pm 6_{\rm stat} \pm 46_{\rm syst})\ \text{nb}$$

- $\sigma_{\gamma\pi}(\langle W_{\gamma\pi}\rangle) = \frac{\sigma_{\gamma p}}{\int f_{\pi^+/p}(x_L,t)dx_L dt}$

For $\langle W_{\gamma\pi}\rangle = 22$ GeV

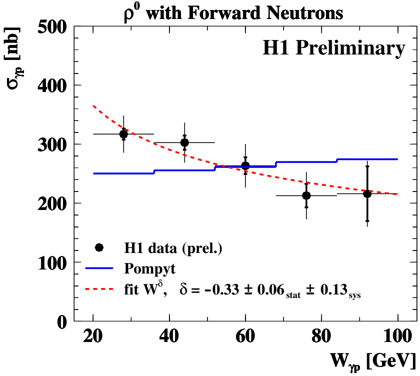
$$\sigma_{el}(\gamma\pi^+ \to \rho^0\pi^+) = (2.03 \pm 0.34_{\rm exp} \pm 0.51_{\rm model})\ \mu\text{b}$$

taking interpolated value of $\sigma(\gamma p \to \rho^0 p) = 9.5\ \mu$b at corresponding energy

$r_{\rm el} = \sigma^{el}_{\gamma\pi}/\sigma^{el}_{\gamma p} = 0.21 \pm 0.06$ (cf. $r_{\rm tot} = \sigma^{tot}_{\gamma\pi}/\sigma^{tot}_{\gamma p} = 0.32 \pm 0.03$ [ZEUS, Nucl. Phys. **B637** (2002) 3.])

inner error bars: statistical uncertainty

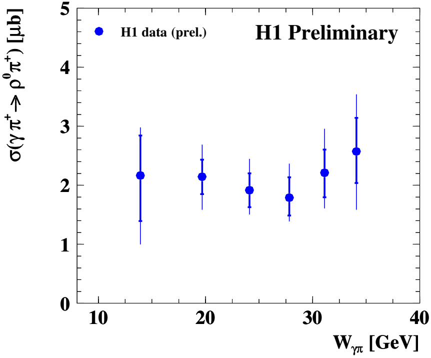
outer error bars: $\sqrt{\text{stat}^2 + \text{syst}^2}$



Regge motivated power law fit W^{δ} yields $\delta < 0$ in qualitative agreement with DPP and in contrast to MC, $\delta_{MC} = 0.08 \pm 0.02$ as expected from purely $\mathbb{P}$ exchange

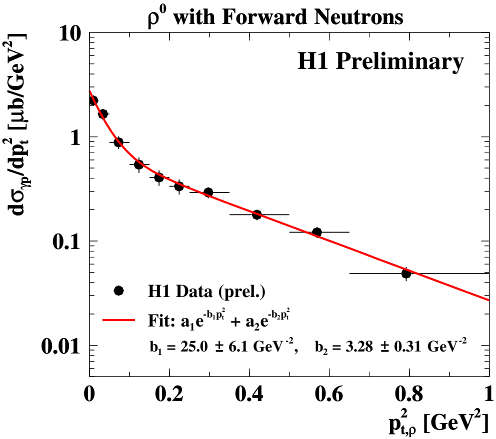
inner error bars: total experimental uncertainty

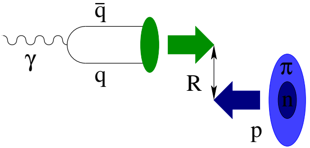
outer error bars: $\sqrt{\text{exp}^2 + \text{model}^2}$

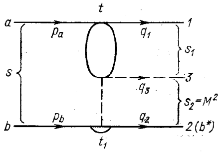


Holtmann flux is used for the central values, conservative model uncertainty $\sim$ 25%

Differential cross section in $p_{t,\rho}^2$

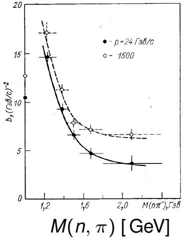






DPP: 2 → 3

ISR: b vs. $M_{n,\pi}$



- In geometric picture: $\langle r^2 \rangle = 2b_1 \cdot (\hbar c)^2 \simeq 2$ fm^2 $\Rightarrow (1.6 R_p)^2 \Rightarrow$ ultra-peripheral process
- DPP model: low mass $\pi^+ n$ state $\rightarrow$ large slope, high mass $\rightarrow$ small (less steep) slope

Summary and Conclusions

- Ratio of $\frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ using HERA II data was measured in the kinematic range: $30 \leq W \leq 210$ GeV, $5 \leq Q^2 \leq 70$ GeV^2, $|t| \leq 1$ GeV^2
- The ratio increases with Q^2 and is constant as a function of W and $|t|$
- ZEUS measurement will be extended to $2 < W < 5$ GeV^2 using HERA I data
- **Theoretical calculations of the ratio $\frac{\sigma(\psi(2S))}{\sigma(J/\psi(1S))}$ are welcome :).**

- Cross section for the exclusive PHP of ρ^0 mesons associated with leading neutron has been measured for the first time at HERA
- Differential cross sections for the reaction $\gamma p \to \rho^0 n \pi^+$ are compatible with model of Double Peripheral Process (DPP)
- The elastic photon-pion cross section, $\sigma(\gamma\pi^+ \to \rho^0\pi^+)$ was extracted in the One Pion Exchange (OPE) approximation

Thank You For Your Attention

BACKUP PLOTS FOLLOWS...

H1: ρ^0 with leading neutron: Analysis Summary

- **Data Sample**: 2006-7 e^+ runs, $\sqrt{s} = 319$ GeV, $\int L = 1.16$ pb^{-1},
  $\sim$ 6600 events in final sample
- **Tracking**: two opposite charge tracks fitted to event vertex $|z_{vtx}| < 30$ cm,
  $p_t^{tr} > 0.2$ GeV, $20^\circ < \theta^{tr} < 160^\circ$
  effective mass range $M_{\pi\pi} \in (0.6, 1.1)$ GeV,
  extrapolated for $\sigma(\rho^0)$ to $(0.28, 1.5)$ GeV
- **FNC**: high energy neutron $E_n > 120$ GeV, within good acceptance $\theta_n < 0.75$ mrad
  BG fraction from x_L shape fit: $F_{bg} = 0.36 \pm 0.06$ (subtracted from the data)
- **Exclusivity**: no deposits above detector noise level
  except two pions from ρ^0 decay and the leading neutron
- **Monte Carlo modeling**
  - Signal (Double Peripheral Process DPP): POMPYT $\times$ PYTHIA6
    (π-flux $\times$ elastic $\gamma\pi \to \rho^0\pi$)
  - Background: DIFFVM (elastic, p-diss, γ-diss, double diss)

$$\frac{d^2\sigma_{\gamma p}(W^2, x_L, t)}{dx_L dt} = f_{\pi/p}(x_L, t)\sigma_{\gamma\pi}((1-x_L)W^2)$$

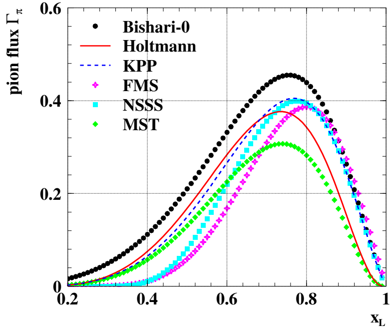
$$\frac{d\sigma_{\gamma p}}{dx_L} = \int_{t_0(x_L)}^{t_{min}(x_L)} f_{\pi/p}(x_L, t)dt \cdot \sigma_{\gamma\pi}(W_{\gamma\pi})$$

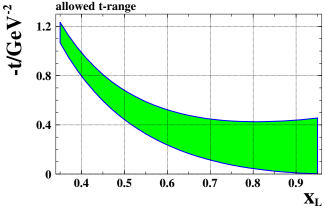
where $t = -\frac{p_{t,n}^2}{x_L} - \frac{(1-x_L)(m_n^2 - m_P^2 x_L)}{x_L}$

$\sigma_{\gamma\pi}(W_{\gamma\pi}) = \frac{1}{\Gamma_\pi(x_L)}\frac{d\sigma_{\gamma p}}{dx_L}$ and $\overline{\sigma_{\gamma\pi}}(\langle W_{\gamma\pi}\rangle) = \frac{\sigma_{\gamma p}}{\int \Gamma_\pi}$

where $\Gamma_\pi = \int_{t_0(x_L)}^{t_{min}(x_L)} f_{\pi/p}(x_L, t)dt$

Very many pion fluxes has been proposed...





← allowed t-range due to the FNC acceptance

Typical examples of pion fluxes:

$f_{\pi^+/p}(x_L, t) = \frac{1}{2\pi}\frac{g_{p\pi N}^2}{4\pi}(1-x_L)\frac{-t}{(m_\pi^2 - t)^2} exp[R_{\pi N}^2 \frac{m_\pi^2 - t}{1-x_L}]$ – H. Holtmann at al., *Nucl. Phys.* **A596** (1996) 631.

$f_{\pi^+/p}(x_L, t) = \frac{1}{2\pi}\frac{g_{p\pi N}^2}{4\pi}(1-x_L)^{1-2\alpha'_\pi t}\frac{-t}{(m_\pi^2 - t)^2} exp[R_\pi^2(m_\pi^2 - t)]$ – B. Kopeliovich at al., *Z. Phys.* **C73** (1996) 125.