Meson Production at HERA: From $\gamma I\!P$ via $\gamma\gamma$ towards $\gamma I\!D$ processes

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Outline of the Talk

- Introduction
- **Hadron-Hadron Interactions** and Odderon Contributions
- **Meson Production in** ep **Scattering** and Odderon Contributions
- **Detector** Description
- **Production of** η **and** η' **mesons**
- **Production of other mesons**
- Conclusions

Introduction

Hadron-hadron interactions

$\Longrightarrow$

no indication for contribution from $C = -1$ exchange ("Odderon") **at very high energies** (where meson exchange does not contribute)

however **no exclusion** of such a contribution possible

Partonic picture of diffractive scattering (model for the **Pomeron:** two gluon exchange)

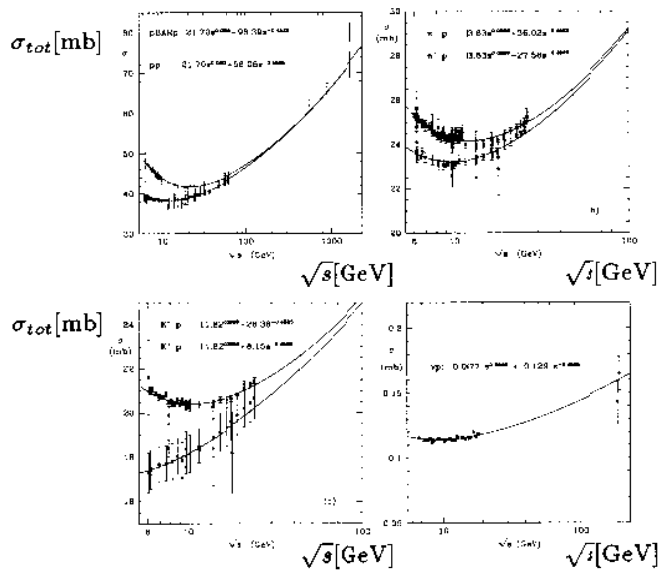
$\Longrightarrow$

expect contribution from exchange of three gluons (**model for the** Odderon)

HERA:

contribution to $C = +1$ **meson production** from Odderon induced process possible, in addition to **photon-photon** fusion

Hadron-Hadron Interactions



- Simple parametrization of **the total cross sections** for different reactions (Donnachie and Landshoff):

$$\sigma_{tot}(s) = As^{n_P} + Bs^{n_R}$$

  - **Pomeron** exchange $n_P = 0.0808$
  - **Reggeon** exchange (ρ, ω) $n_R = -0.4525$

Contribution from Amplitudes with Negative C Parity

Odderon: Contribution of **a pole** with $\alpha(t=0) \approx 1$ and amplitude odd under C parity
(similar to Pomeron, which is even under C parity)

Decomposition of **scattering amplitude** F_{pp} $(F_{\bar{p}p})$:

$$F_{pp}(F_{\bar{p}p}) = F_+ \pm F_-$$

with

$F_+(F_-)$ even (odd) under C parity

Existence of an **Odderon** contribution
(i.e. $F_- \neq 0$) for $\sqrt{s} \to \infty \Longrightarrow$

$$\boxed{\Delta\sigma_{tot} = \sigma^{tot}_{p\bar{p}} - \sigma^{tot}_{pp} \neq 0}$$

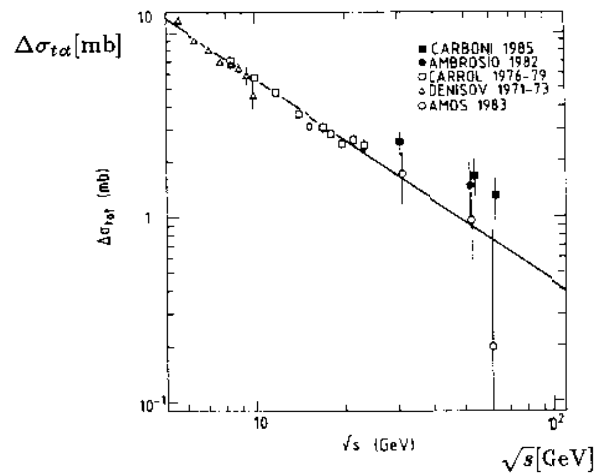
$$\boxed{\Delta\left(\frac{d\sigma}{dt}\right) = \frac{d\sigma_{p\bar{p}}}{dt} - \frac{d\sigma_{pp}}{dt} \neq 0}$$

$$\boxed{\Delta\rho = \rho_{p\bar{p}} - \rho_{pp} = \frac{\mathrm{Re}F_+ - \mathrm{Re}F_-}{\mathrm{Im}F_+ - \mathrm{Im}F_-} - \frac{\mathrm{Re}F_+ - \mathrm{Re}F_-}{\mathrm{Im}F_+ - \mathrm{Im}F_-} \neq 0}$$

without an Odderon contribution (i.e. $F_- = 0$)
all three differences **vanish** for $\sqrt{s} \to \infty$

Difference of Total Cross Sections

$$\boxed{\Delta\sigma_{tot} = \sigma^{tot}_{p\bar{p}} - \sigma^{tot}_{pp}}$$

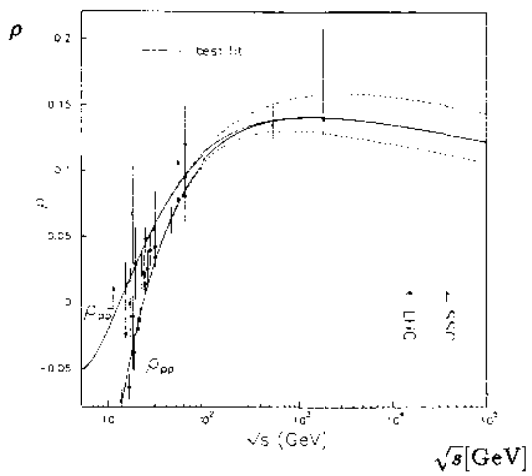


- Data only from ISR available (i.e. up to $\sqrt{s} = 63$ GeV)
- **Difference $\Delta\sigma_{tot}$ approaches 0** for large values of $\sqrt{s}$
- Regge Theory: $\Delta\sigma_{tot} \propto s^{-\alpha}$ (Meson contribution)
- Value of the exponent: $\alpha \approx 0.5$

$\Longrightarrow$ **no indication of an Odderon contribution**

Ratio of Real to Imaginary Part of the Scattering Amplitude

$$\rho(s) = \frac{\mathrm{Re}F(s,0)}{\mathrm{Im}F(s,0)}$$

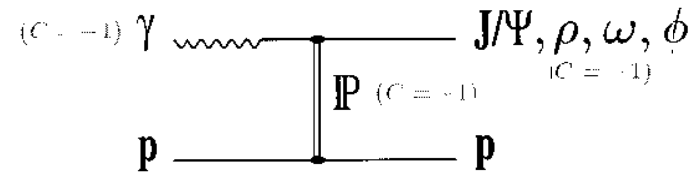


- Determination of the **interference** between **Coulomb** and **strong interaction** at $-t \approx 0.001$ GeV$^2/c^2$
- measurements of UA4/2 as well as E710 at FERMILA3 $\Longrightarrow \Delta\rho \approx 0$

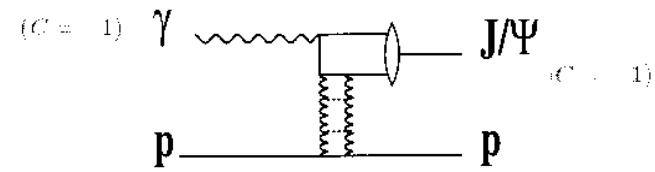
$\Longrightarrow$ **no indication of an Odderon contribution**

Production of $C = -1$ Mesons in Electron-Proton Scattering

- Known signal: Production of **vector mesons** ($C = -1$)
- Vectormeson Dominance Model (VDM) : **Photon fluctuates into a vector meson** (same quantum numbers) and may – in analogy to hadron-hadron scattering – **interact strongly with the proton**



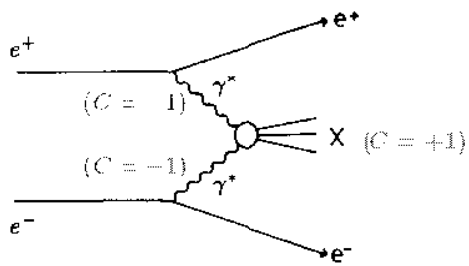
- Pomeron exchange



- Two-gluon exchange (with the presence of a hard scale – quark mass m_c, photon virtuality Q^2, momentum transfer squared t – a **perturbative** treatment is possible)

Production of Mesons in Two-Photon Processes

Electron-Positron Storage Rings as **photon sources**:



For small resonances ($\Gamma_R \ll M_R$) within the **Weizsäcker-Williams approximation** ($Q^2 \to 0$ and $Q^2 \ll W^2$):

$$\sigma(e^+e^- \to e^+e^- R) \approx 16\alpha^2 (\ln \frac{E}{m_e})^2 f(\frac{M_R}{2E})(2J+1)\frac{\Gamma_{\gamma\gamma}}{M_R^3}$$

with the Low function

$$f(x) = (2+x^2)^2 \ln(\frac{1}{x}) - (1-x^2)(3+x^2)$$

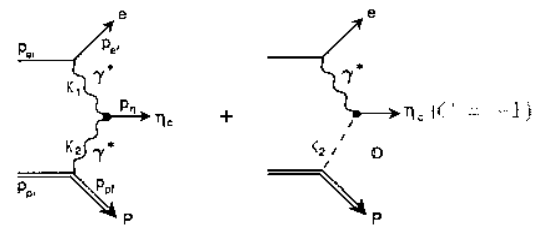
$$\Longrightarrow \quad \sigma(e^+e^- \to e^+e^- R) \propto \Gamma_{\gamma\gamma}$$

Allows the **measurement of the partial width** $\Gamma_{\gamma\gamma}$ of the meson for the **decay** into **two photons**!

Production of $C = +1$ Mesons in Electron-Proton Scattering

$C = +1$ mesons are produced via

- Two-photon process
- Odderon-photon fusion (**Schäfer, Mankiewicz and Nachtmann** - Workshop on HERA Physics, 1991)



$SU(3)$ quark **flavour** eigenstates $|\eta_1\rangle$ and $|\eta_8\rangle \Longrightarrow$

$$|\eta\rangle = \sin\vartheta|\eta_1\rangle + \cos\vartheta|\eta_8\rangle$$
$$|\eta'\rangle = \cos\vartheta|\eta_1\rangle - \sin\vartheta|\eta_8\rangle$$

Mixing angle $\vartheta \approx 10 - 20°$

Coupling of Odderon $\propto$ baryon number of quarks

- $\eta' \Longrightarrow$ **decoupling** of the Odderon
- $\eta \Longrightarrow$ **maximal contribution** due to Odderon

$\Longrightarrow$ Measure cross section ratio $\sigma(ep \to e\eta p)/\sigma(ep \to e\eta' p)$

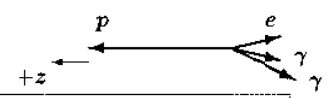
Exclusive η (η') Production

Process:

$$ep \rightarrow e \; \eta(\eta') \; p$$
$$\hookrightarrow \gamma\gamma$$

Selection criteria:

- **scattered positron** in positron tagger
  $\Longrightarrow 0.3 < y < 0.7$ and $Q^2 < 0.01 \mathrm{GeV}^2/c^2$
- at least **two clusters** (photon candidates) in the **SPACAL**
- **rest of detector empty**
  $\Longrightarrow$ no tracks from charged particles in the central and forward tracking detectors
  $\Longrightarrow$ no reconstructed vertex
- Cut for **exclusive** production:



$$(E - p_z c)_{e\gamma\gamma} = (E - p_z c)_e + (E - p_z c)_{\gamma_1\gamma_2} \stackrel{!}{=} 2E_e^{beam}$$

Data from **1996** (27.5 GeV e^+, 820 GeV p): $\int \mathcal{L} dt \approx 5$ pb^{-1}

Expected cross sections based on RESPRO model (for e^+e^-, authors: E.R. Boudinov and M.V. Shevlyagin), modified for ep: FORM FACTOR $\gamma^*\gamma^*\eta$ VERTEX, PROTON MASS

RESPRO	$\sigma^{tot}(ee)$	$\sigma^{tot}(ep)$	$\sigma^{vis}_{\gamma p}\left(\frac{0.2<y<0.8}{Q^2<0.01\ \mathrm{GeV}^2/c^2}\right)$
η	2.7 nb	1.0 nb	190 pb
η'	4.0 nb	1.4 nb	420 pb

Properties of the η and η' Meson

η: $J^{PC} = 0^{-+}$

Mass:

$$M = (547.45 \pm 0.19)\ \mathrm{MeV}/c^2$$

Total Width:

$$\Gamma = (1.18 \pm 0.11)\ \mathrm{keV}/c^2$$

Neutral Decay modes:

decay mode	B.R.
$\eta \rightarrow 2\gamma$	39.25 %
$\eta \rightarrow 3\pi^0$	32.1 %

η': $J^{PC} = 0^{--}$

Mass:

$$M = (957.77 \pm 0.14)\ \mathrm{MeV}/c^2$$

Total Width:

$$\Gamma = (201 \pm 16)\ \mathrm{keV}/c^2$$

Neutral Decay modes:

decay mode	B.R.
$\eta' \rightarrow \pi^0\pi^0\eta$	20.8 %
$\eta' \rightarrow 2\gamma$	2.12 %

Detector Description

Since 1995: SPACAL (SPAghetti CALorimeter) in the backward region of H1

- **lead/scintillating-fibre** calorimeter (with photomultiplier readout)
- very good **energy resolution**: $\sigma/E = 7\ \%/\sqrt{E/\mathrm{GeV}} \oplus 1\ \%$
- fine **granularity**: cell size $4 \times 4\ \mathrm{cm}^2$
- good **position resolution**: $4.4\ \mathrm{mm}/\sqrt{E/\mathrm{GeV}} + 1\ \mathrm{mm}$
- **angular acceptance**: $153^\circ < \vartheta < 177.5^\circ$
- good **time resolution**: < 1 ns

$\Longrightarrow$ Improved measurement of the scattered positron for the **inclusive cross section** ("F_2")

$\Longrightarrow$ Improved measurement of the **hadronic final state** in the backward direction

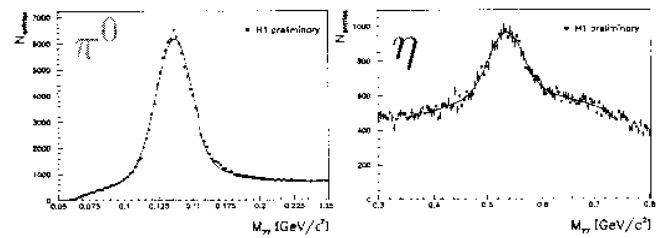
$\Longrightarrow$ In addition: reconstruction of mesons via their two photon decay mode is possible

$$M_{\gamma\gamma} = \sqrt{(\mathbf{p}_{\gamma_1} + \mathbf{p}_{\gamma_2})^2}$$

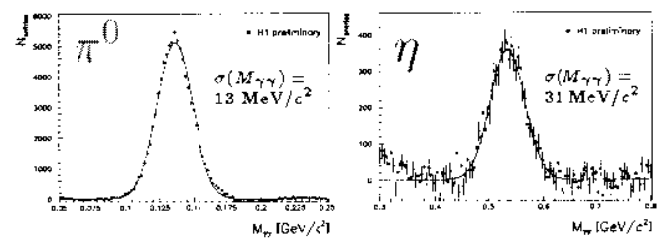
where $\mathbf{p}_{\gamma_i}$ $(i = 1, 2)$ is the 4-momentum of photon candidate i (electromagnetic cluster in the calorimeter)

The SPACAL Performance

Before background subtraction:



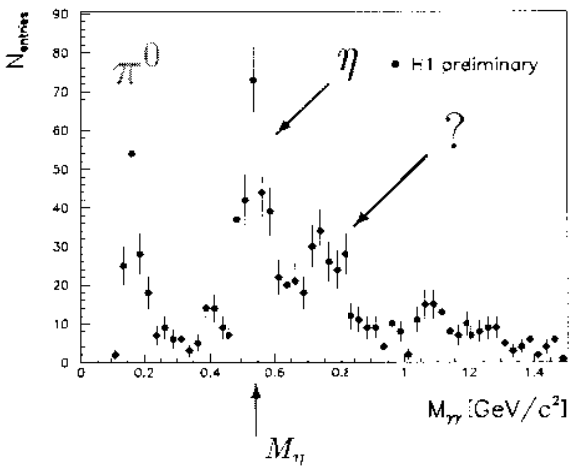
After background subtraction:



SPACAL	π^0	η
E_{γ_i}	> 1 GeV	> 1.5 GeV
$\mu(M_{\gamma\gamma})$	135 MeV/c^2	535 MeV/c^2
$\sigma(M_{\gamma\gamma})$	13 MeV/c^2	31 MeV/c^2

(NB: the π^0 is used for a calibration of the SPACAL at photon energies from 0.3 to 1.5 GeV)

Production of η Mesons: $\gamma\gamma$ Final State (1)

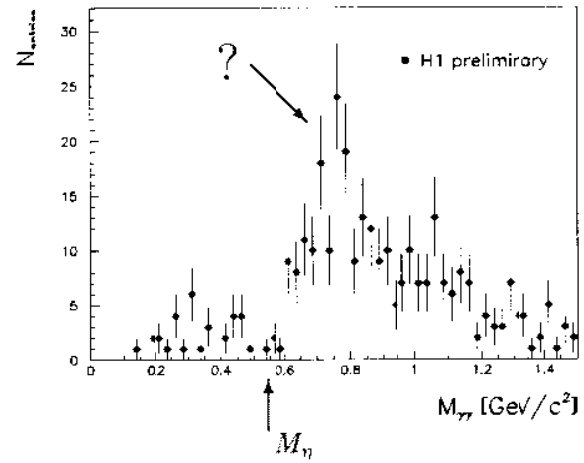


- **vertex**, reconstructed from charged tracks
- **exactly two clusters** (photon candidates) in SPACAL
- $E_{\gamma_i} > 0.7$ GeV $(i = 1,2)$
- $8 < E_{\gamma_1} + E_{\gamma_2} < 20$ GeV
- $(E - p_z c)_{e\gamma\gamma} > 50$ GeV

$\Longrightarrow$ **Signal of π^0 and η mesons**

$\Longrightarrow$ However: events have at least one charged particle in the central detector $\Longrightarrow$ **not completely exclusive**

Production of η Mesons: $\gamma\gamma$ Final State (2)



- **no reconstructed vertex** (no charged tracks in central detector)
- **exactly two clusters** (photon candidates) in SPACAL
- $E_{\gamma_i} > 0.7$ GeV $(i = 1,2)$
- $8 < E_{\gamma_1} + E_{\gamma_2} < 20$ GeV
- $(E - p_z c)_{e\gamma\gamma} > 50$ GeV

$\Longrightarrow$ **No indication for an exclusive η or η' signal** for $\int \mathcal{L} dt \approx 5\text{pb}^{-1}$

$\Longrightarrow$ But: resonance like signal in $M_{\pi\gamma}$ at $\approx 800\,\text{MeV}/c^2$ (?)

Properties of the ω Meson

Mass:

$$\boxed{m = (781.94 \pm 0.12)\ \mathrm{MeV}/c^2}$$

Total Width:

$$\boxed{\Gamma = (8.43 \pm 0.10)\ \mathrm{MeV}/c^2}$$

Decay modes:

decay mode	B.R.
$\omega \to \pi^+\pi^-\pi^0$	88.8 %
$\omega \to \gamma\pi^0$	8.5 %
$\omega \to \pi^+\pi^-$	2.21 %

$$\omega \to \gamma\ \pi^0$$
$$\hookrightarrow \gamma\gamma$$

If one of the photons is "lost" (e.g. outside of the geometrical acceptance)

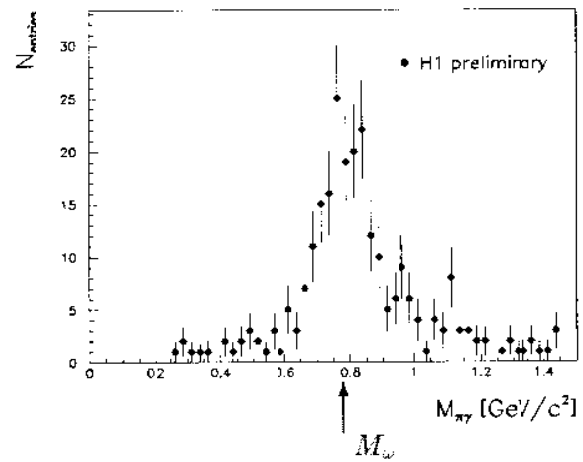
$\Longrightarrow$

$\boxed{\omega \to \text{"}\gamma\gamma\text{"}}$ signature

If this is true

$\Longrightarrow$ reconstruction of ω mesons in the $\gamma\pi^0$ decay should be possible

Production of ω Mesons: $\gamma\pi^0$ Final State



- **no reconstructed vertex** (no charged tracks in central detector)
- **exactly three clusters** (photon candidates) in SPACAL
- $E_{\gamma_i} > 0.8$ GeV ($i = 1, \ldots, 3$)
- $(E - p_z c)_{e\gamma\pi^0} > 49$ GeV
- **mass constrained fit** to π^0 mass

$\Longrightarrow$ **Clear signal of $\omega \to \gamma\pi^0$** (three photon final state)

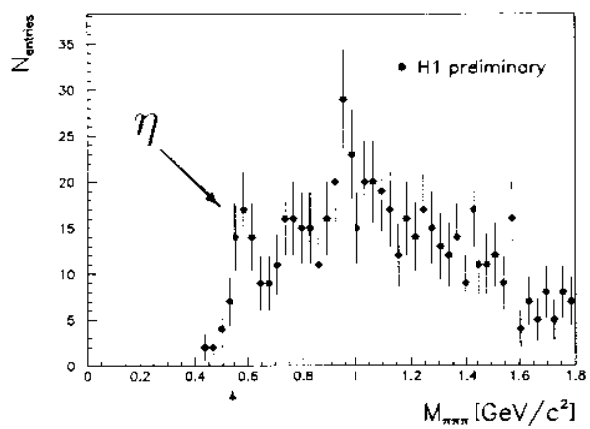
$\Longrightarrow$ **Compatible with elastic production of ω mesons**

Measure cross section at high W $165 < W < 250$ GeV

(cf. ZEUS: ω production for $70 < W < 90$ GeV)

Production of η Mesons: $\pi^0\pi^0\pi^0$ Final State

SPACAL $\Longrightarrow$ precise measurement of π^0 and η mesons
$\Longrightarrow$ look for **resonances decaying** into π^0's and η's



M_η

- **vertex**, reconstructed from charged tracks
- **exactly six clusters** (photon candidates) in SPACAL
- $E_{\gamma_i} > 0.2$ GeV $(i = 1, \ldots, 6)$
- **no cut** on $(E - p_z c)_{e\pi^0\pi^0\pi^0}$
- **mass constrained fit** to π^0 mass

$\Longrightarrow$ **signal** of the η meson (inclusive) in the $3\pi^0$ final state
$\Longrightarrow$ no background from ω $\Longrightarrow$ use for Odderon search

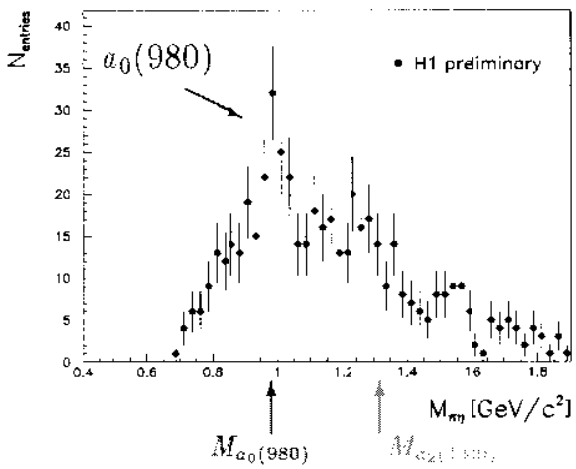
Other Resonances in Two-Photon Processes

- search for Odderon induced process with η and η' mesons
  $\Longrightarrow$ **background** from $\omega \to \gamma\pi^0$ to $M_{\gamma\gamma}$ spectra
- use **other decay modes** of the η and η' mesons
  (e.g. $\eta \to \pi^0\pi^0\pi^0$ or $\eta' \to \eta\pi^0\pi^0$)
- use **other** $C = +1$ **resonances** to be produced
  via $\gamma\gamma$ and $\gamma\mathcal{O}$ interactions

- e.g. the scalar meson $a_0(980)$
  and the tensor meson $a_2(1320)$

	$a_0(980)$	$a_2(1320)$
J^{PC}	0^{++}	2^{++}
M [MeV/c^2]	983.5 ± 0.9	1318.1 ± 0.7
Γ [MeV/c^2]	50 - 100	107 ± 5
B.R. to $\eta\pi^0$	dominant	14.5 %

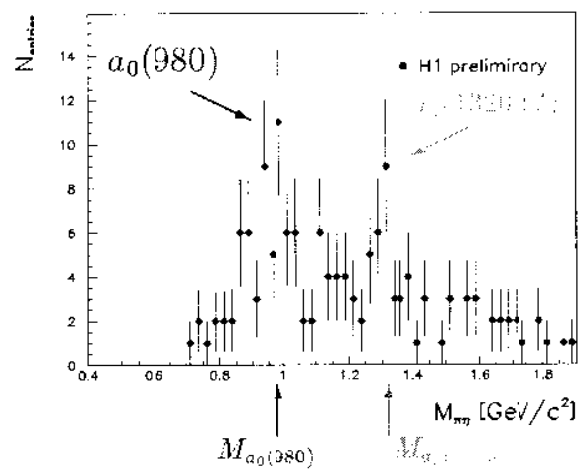
Production of Other Mesons: $\eta\pi^0$ Final State (1)



- **vertex**, reconstructed from charged tracks
- $E_{\gamma_i} > 1$ GeV $(i = 1, \ldots, 4)$
- $(E - p_z c)_{e\eta\pi^0} > 49$ GeV
- **mass constrained fit** to π^0 (resp. η) mass

$\Longrightarrow$ signal of the $a_0(980)$ meson (inclusive)

Production of Other Mesons: $\eta\pi^0$ Final State (2)



- **vertex**, reconstructed from charged tracks
- $E_{\gamma_i} > 1.4$ GeV $(i = 1, \ldots, 4)$
- $(E - p_z c)_{e\eta\pi^0} > 47$ GeV
- **mass constrained fit** to π^0 (resp. η) mass

$\Longrightarrow$ **indication** of the $a_2(1320)$ meson (inclusive)

Conclusions

- **SPACAL is well suited to measure** resonances decaying into multi photon final states
- **First search** : for contributions from **Odderon** induced meson production at **HERA**
- **No signal for exclusive production** of η (η') mesons (via $\gamma\gamma$ or $\gamma\mathcal{O}$) $\Longrightarrow$ Determine upper limit on cross section
- **Nice signal of** $\omega \to \gamma\pi^0$ $\Longrightarrow$ Measure cross section at high W: ($165 < W < 250$ GeV)
- **Outlook** for Odderon search : more $\int \mathcal{L} dt$, other mesons ($a_0, a_2, \ldots$), other channels ($\eta \to \pi^0\pi^0\pi^0$, $\eta' \to \eta\pi^0\pi^0$)