Hadron Spectroscopy at Jefferson Laboratory

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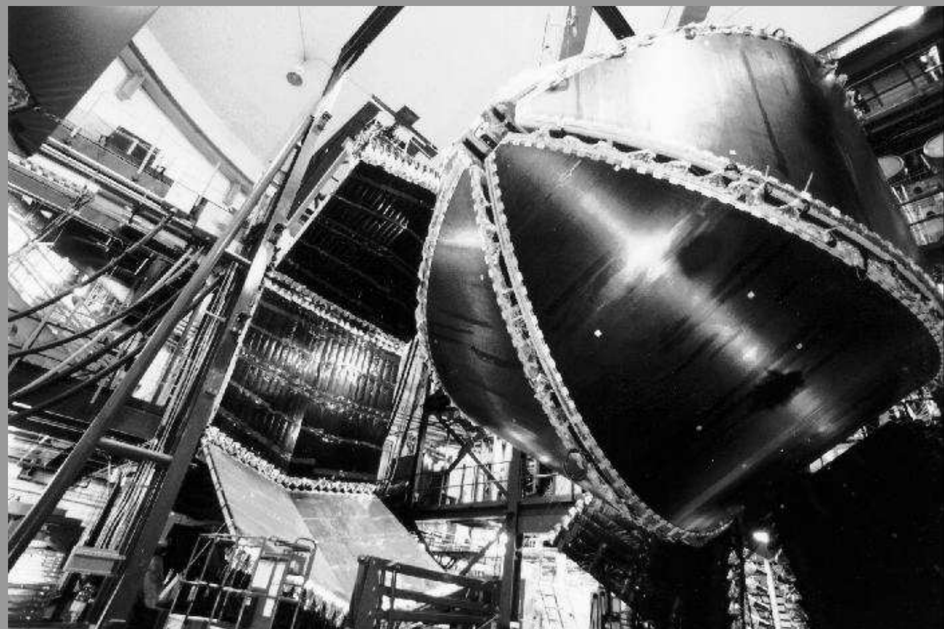


Hadron Spectroscopy at Jefferson Laboratory

N* electro-production

N* photo-production partial wave analysis

θ^+ photo-production on deuterium and hydrogen

Meson partial wave analysis

Ξ, Ξ^* photo-production

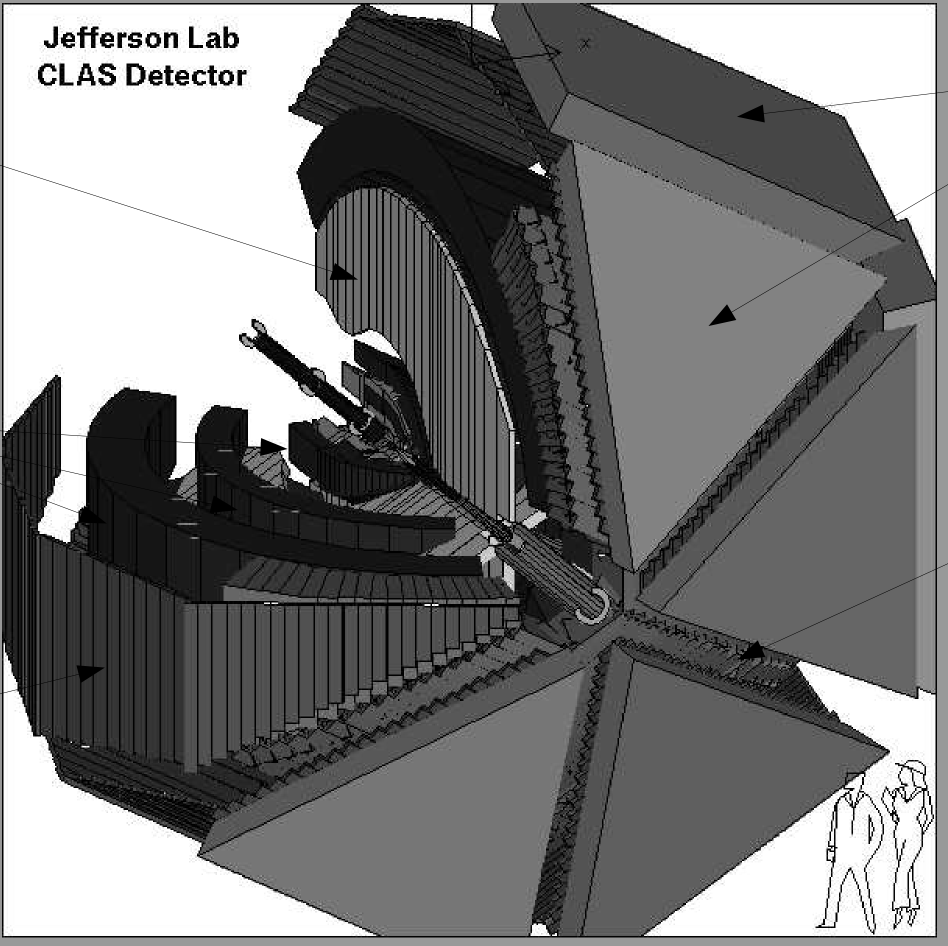
Future prospects at CLAS

Future prospects at JLab

Cebaf Large Acceptance Spectrometer (CLAS)

Superconducting Torus Magnet
6 Superconducting coils

Electromagnetic Calorimeter
Lead-Scintillator



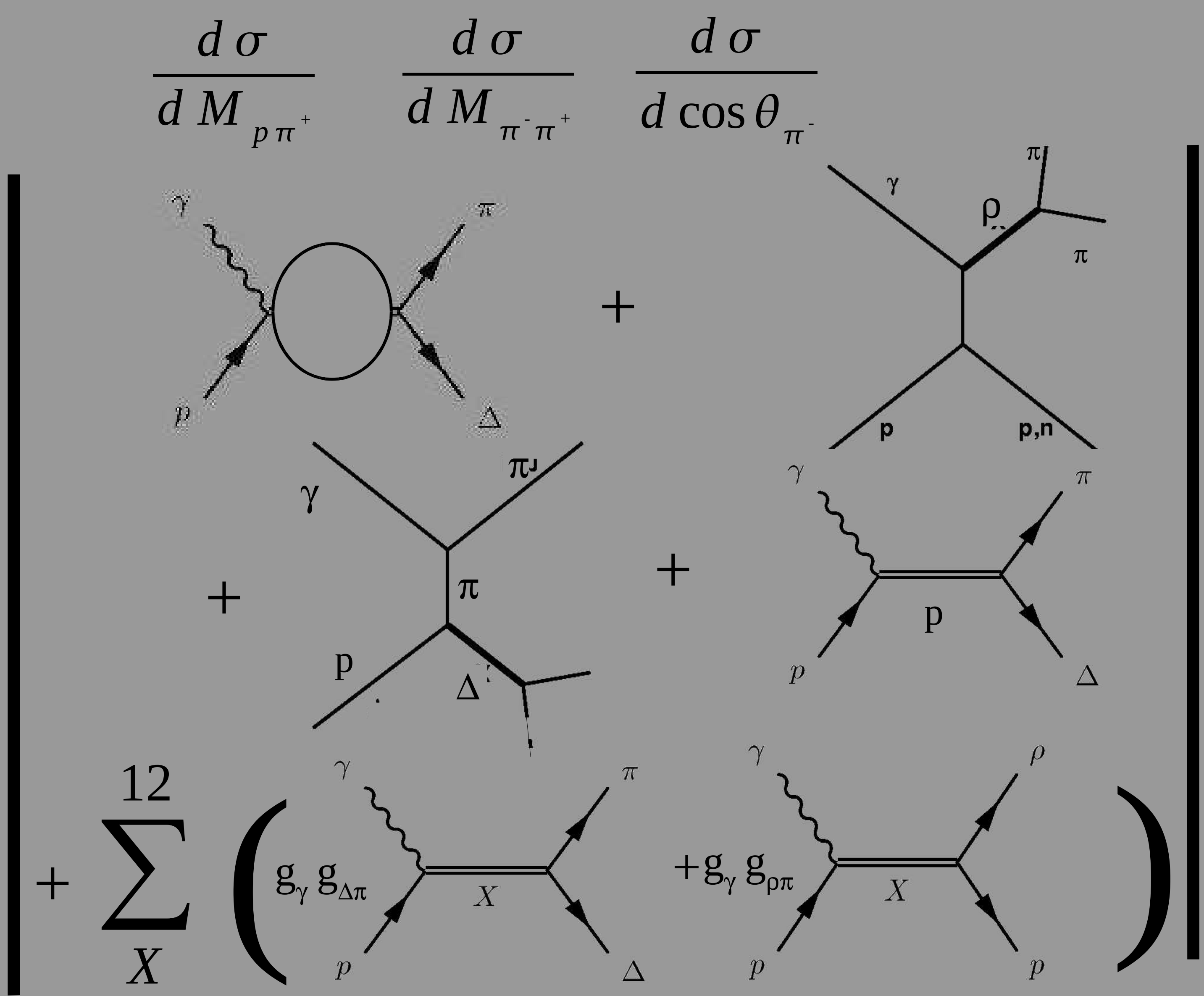
Drift Chambers
$Ar\text{-}CO_2$
6500 channels/sector

Gas Cherenkov Counter
e/π separation

Time-of-Flight Hodoscope
48 Scintillators/sector

$e\,p \rightarrow e'\pi^+\pi^- p$ Differential Cross Sections

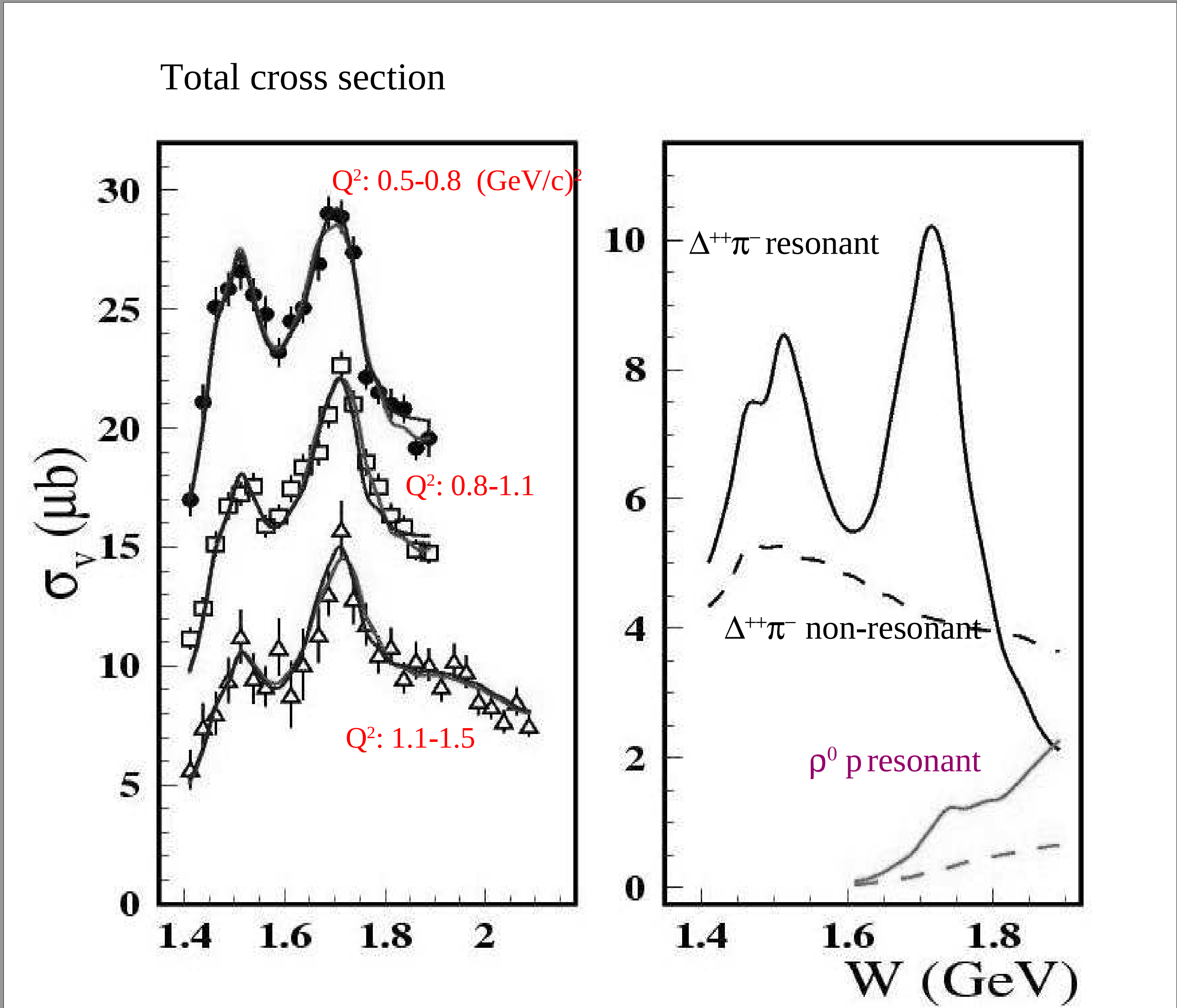
$$\frac{d\sigma}{dM_{p\pi^+}} \qquad \frac{d\sigma}{dM_{\pi^-\pi^+}} \qquad \frac{d\sigma}{d\cos\theta_{\pi^-}}$$



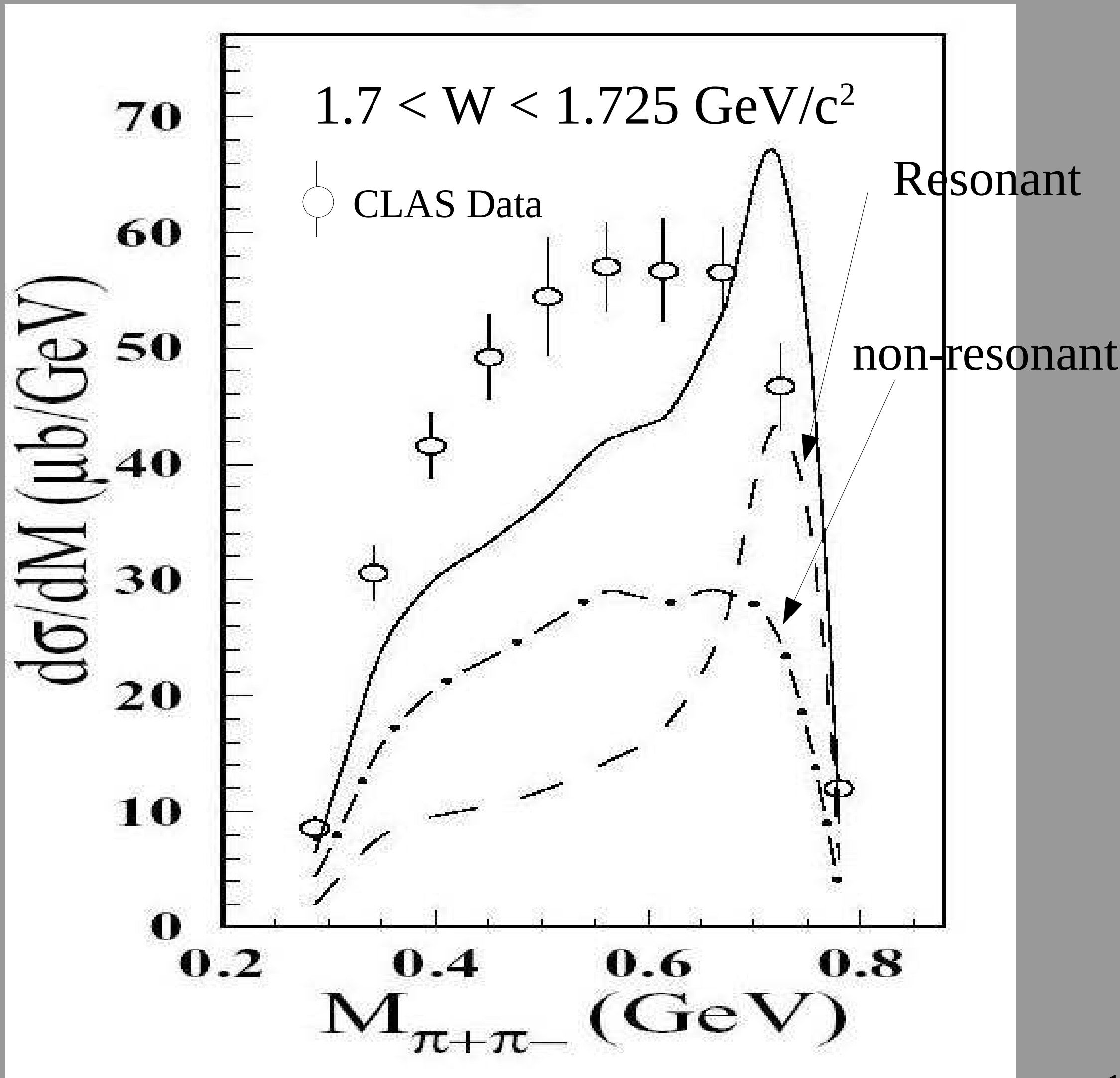
12 resonant states:

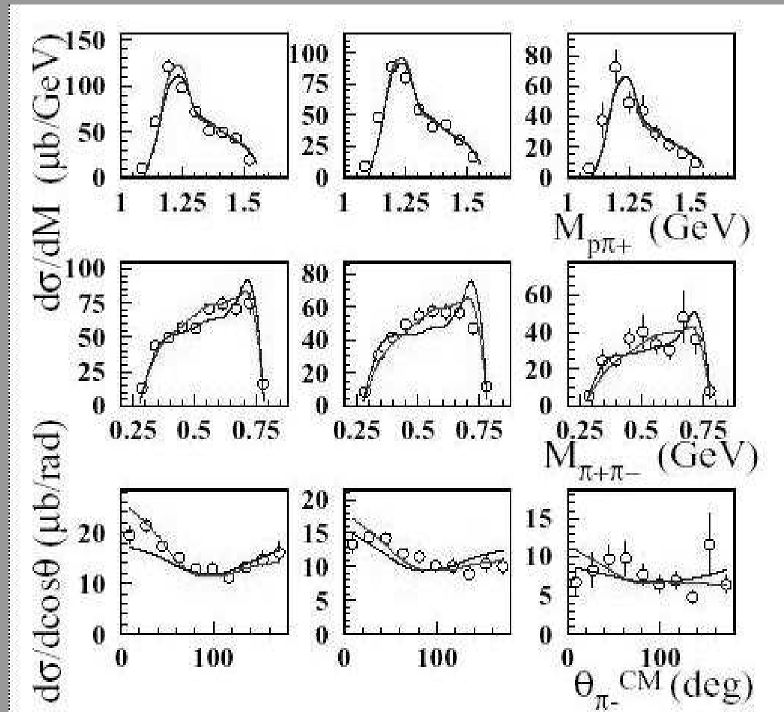
State	J^P
$P_{11}(1440)$	$\frac{1}{2}^+$
$D_{13}(1520)$	$\frac{3}{2}^-$
$S_{11}(1535)$	$\frac{1}{2}^-$
$S_{11}(1650)$	$\frac{1}{2}^-$
$D_{15}(1675)$	$\frac{5}{2}^-$
$F_{15}(1680)$	$\frac{5}{2}^+$
$P_{13}(1720)$	$\frac{3}{2}^+$
$D_{13}(1700)$	$\frac{3}{2}^-$
$S_{31}(1620)$	$\frac{1}{2}^-$
$D_{33}(1700)$	$\frac{3}{2}^-$
$F_{35}(1905)$	$\frac{5}{2}^+$
$F_{37}(1950)$	$\frac{7}{2}^+$

$\gamma^* p \rightarrow \pi^+ \pi^- p$



$\gamma^{*} p \rightarrow \pi^{+} \pi^{-} p$





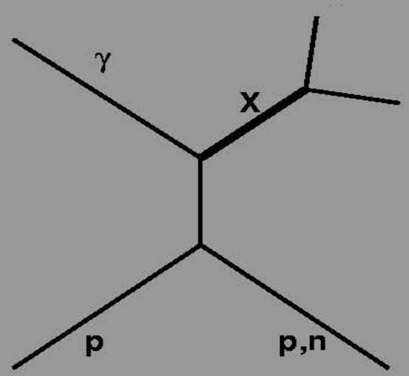
1) Change $P_{13}(1720)$ hadronic couplings

2) Introduce new P_{13} ~1700 MeV/c^2

Partial Wave Analysis Formalism (Mesons)

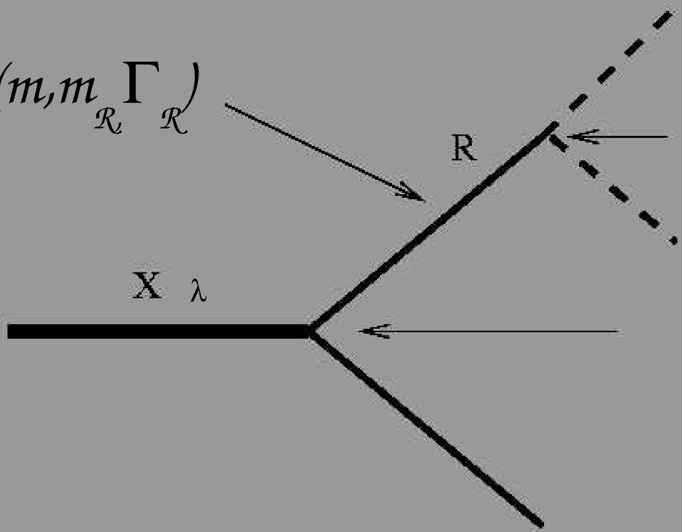
Angular Distributions:

$$I(\tau)=\sum_{\epsilon k}\sum_{X}\left|\;\right|^2$$



$$T_{fi} = \langle \vec{p}_1 \vec{p}_2 \ldots | T | \gamma\, p ; E \rangle$$
$$= \sum_{\alpha} \langle \vec{p}_1 \vec{p}_2 \ldots | \alpha \rangle \langle \alpha | T | \gamma\, p ; E \rangle$$
$$= \sum_{\alpha} \psi^{\alpha}(\tau_f) V^{\alpha}(E)$$

Breit-Wigner$(m, m_{\mathcal{R}}, \Gamma_{\mathcal{R}})$



Blatt-Weisskopf Barrier(p,L) $D^{J}_{M\lambda}(\phi\,\theta\,0)$

Blatt-Weisskopf Barrier(p,L) $D^{J}_{M\lambda}(\phi\,\theta\,0)$

Partial Wave Formalism

Distribution Function:

$$I(\tau)=\sum_{\epsilon k}\left|{}^{\epsilon}U_k(\tau)\right|^2 \quad \text{where} \quad {}^{\epsilon}U_k(\tau)=\sum_a {}^{\epsilon}V_{ak}\,{}^{\epsilon}A_a(\tau)$$

'a' denotes a partial wave: J^P |M| isobar L etc...

$\epsilon = + / -$ for even/odd naturalities, k represents non-interfering terms (rank), eg. external spins

Decay Amplitudes:

${}^{\epsilon}A_a(\tau)$: QM gives the angular form, calculated for each event
coupling constants absorbed into production amplitude

$$A_a \propto D^{J*}_{M\lambda}(\phi\,\theta\,0) \quad \textit{where} \quad \lambda=\lambda_1-\lambda_2$$

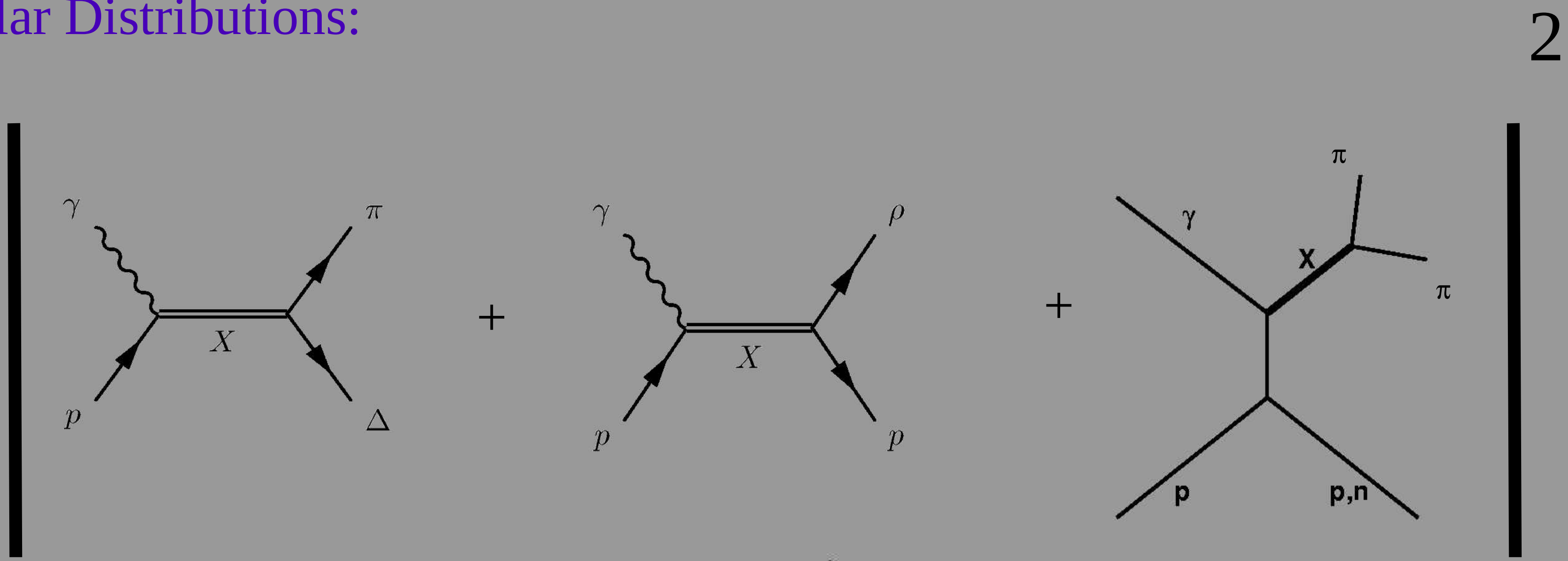
Production Amplitudes:

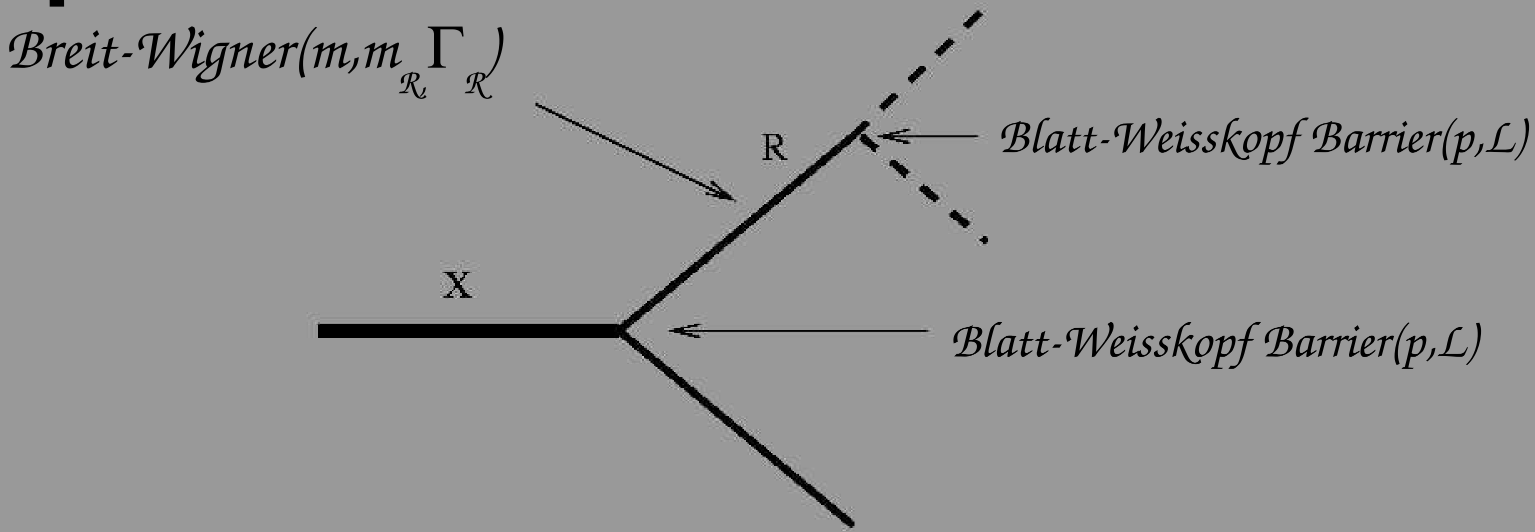
${}^{\epsilon}V_{ak}$: Fitted in mass and t bins

S.U. Chung, Spin Formalisms, CERN 71-8 (1971)

Partial Wave Formalism (s-channel)

Angular Distributions:





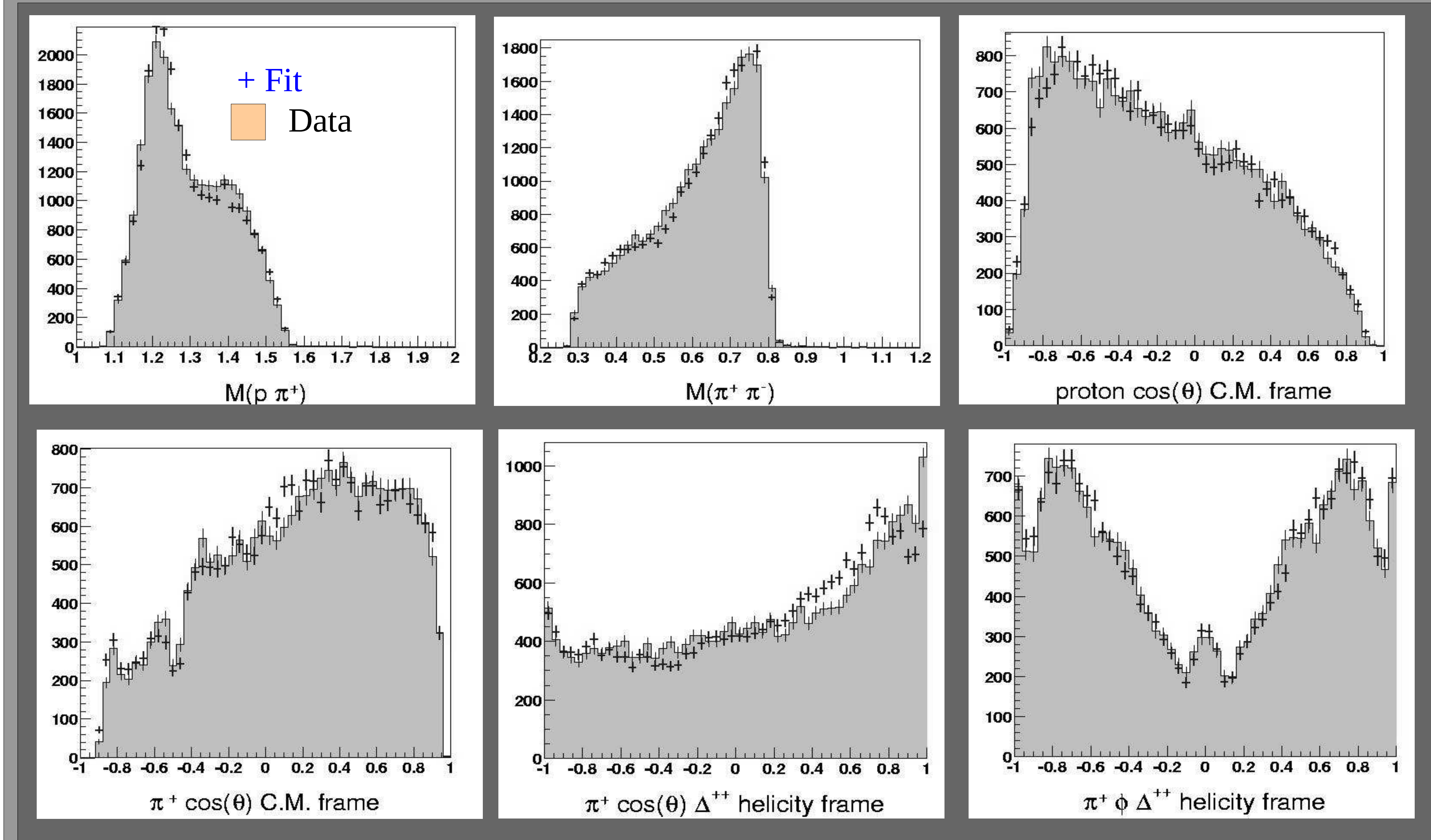
g_{1c} $\gamma\, p \rightarrow \pi^+ \pi^- p$

$$\frac{1}{8} \times 1.8\, \frac{events}{pb} = 230\, \frac{events}{nb}$$

J^P	M	Isobars
$1/2^+$	$1/2$	$\Delta\pi\ (\equiv \{\Delta^{++}\pi^-, \Delta^0\pi^+\})$
$1/2^-$	$1/2$	$\Delta\pi$, $(p\rho)_{(s=1/2)}$
$3/2^+$	$1/2, 3/2$	$(\Delta\pi)_{(\ell=1)}$, $(p\rho)_{(s=1/2)}$, $(p\rho)_{(s=3/2;\ell=1,3)}$, $N^\star(1440)\pi$
$3/2^-$	$1/2, 3/2$	$(\Delta\pi)_{(\ell=0,2)}$
$5/2^+$	$1/2, 3/2$	$(\Delta\pi)_{(\ell=1)}$, $p\sigma$
$5/2^-$	$1/2, 3/2$	$(\Delta\pi)_{(\ell=2)}$

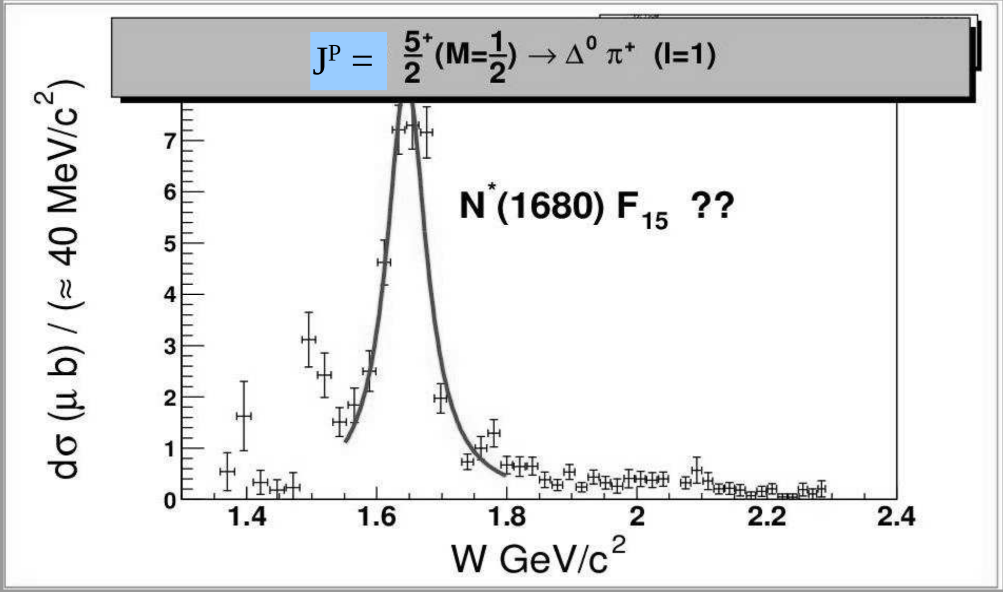
35 waves + ρ diffractive

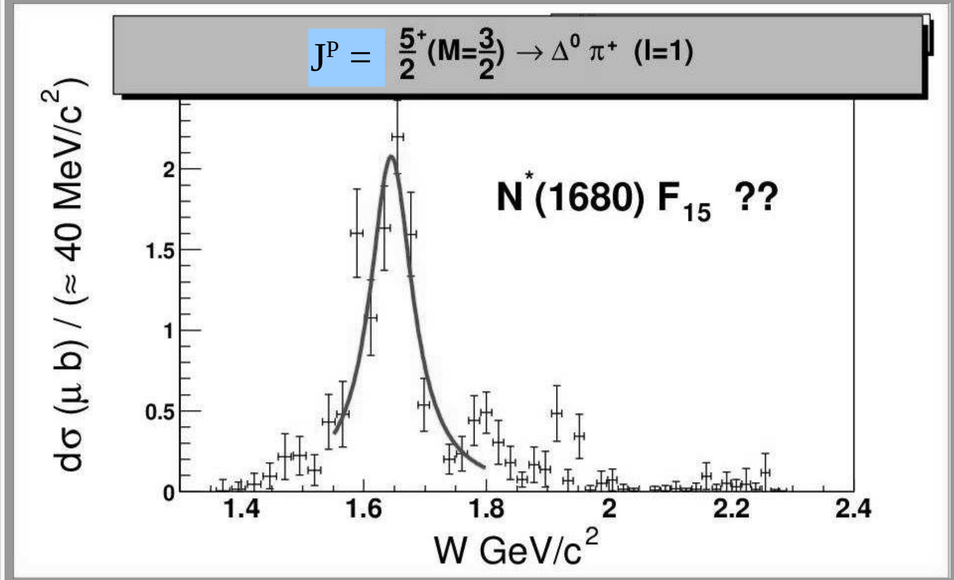
g_{1c} $\gamma p \rightarrow \pi^+ \pi^- p$ Data/Fit Comparison: $1.72 < W < 1.75$ (GeV/c²)

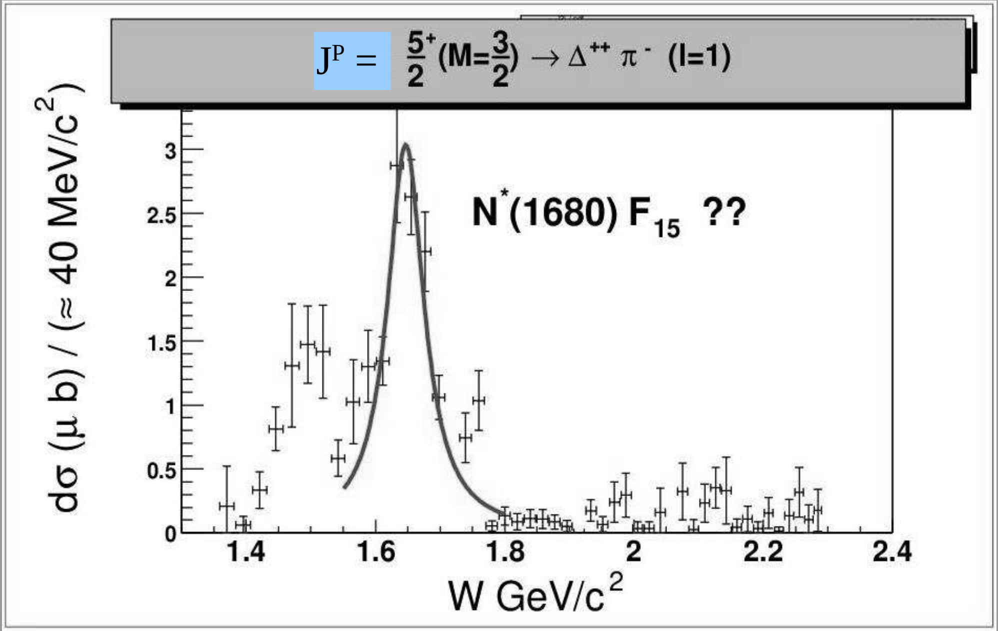


N*(1680) F_{15}

Preliminary







$$M = 1646\ MeV/c^2$$

$$\Gamma = 75\ MeV/c^2$$

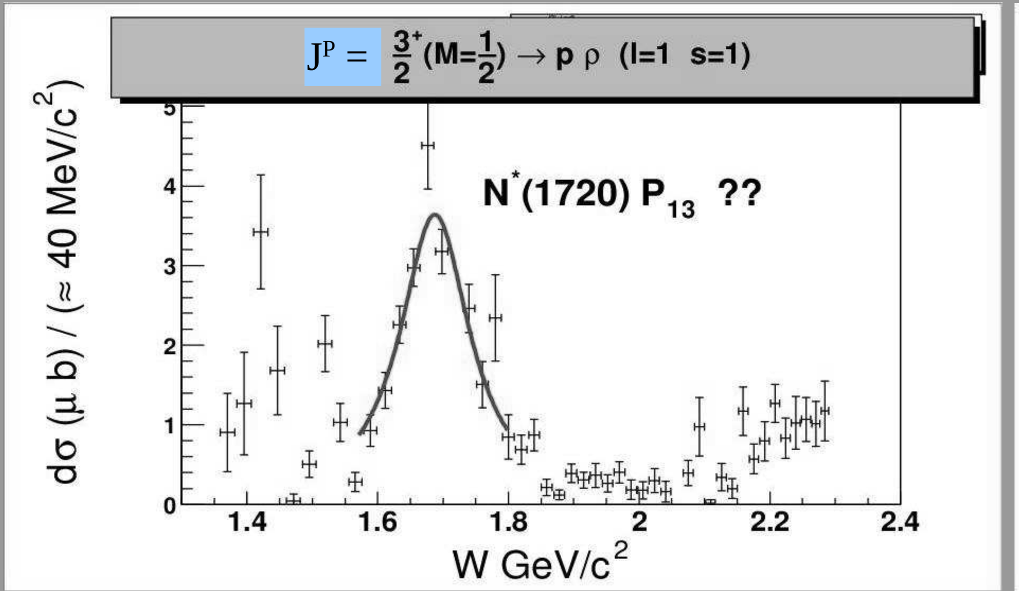
$$M_{PDG} = 1675 - 1690\ MeV/c^2$$

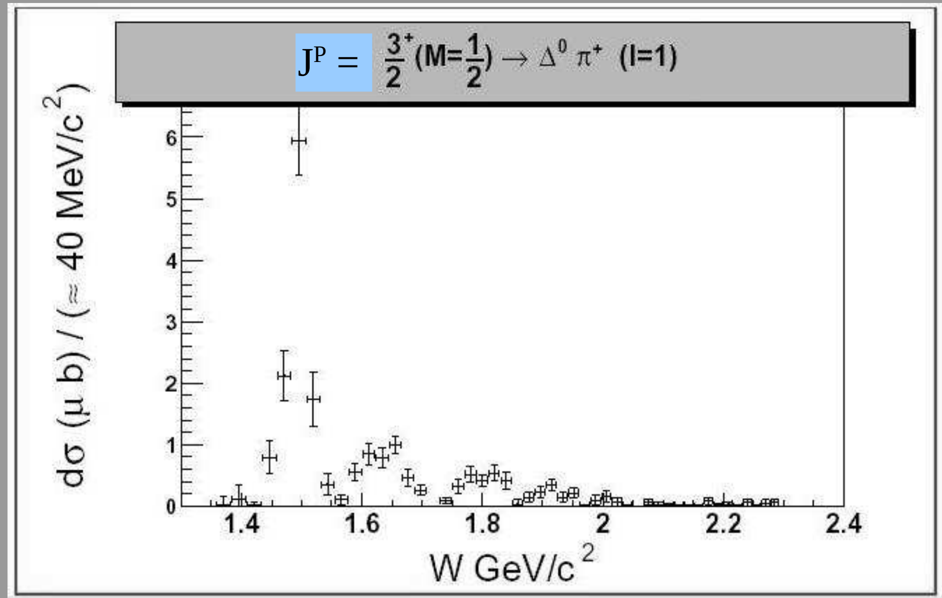
$$\Gamma_{PDG} = 120 - 140\ MeV/c^2$$

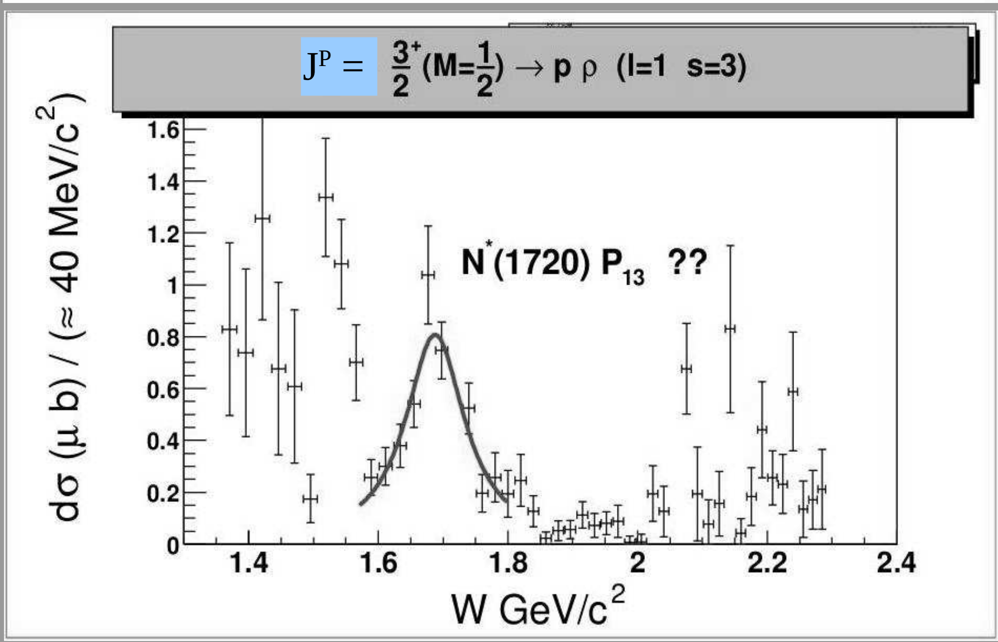
N*(1720) P_{13} Preliminary Δ(1600) P_{33}

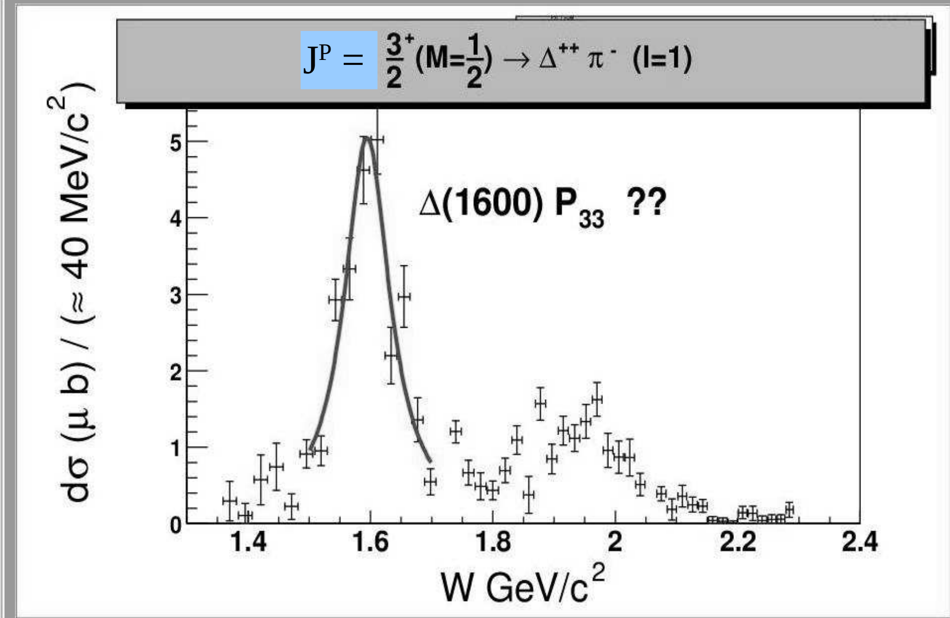
$M = 1595\ MeV/c^2$ *PDG* 1500 – 1700

$\Gamma = 90\ MeV/c^2$ $\Gamma \sim 350\ MeV/c^2$



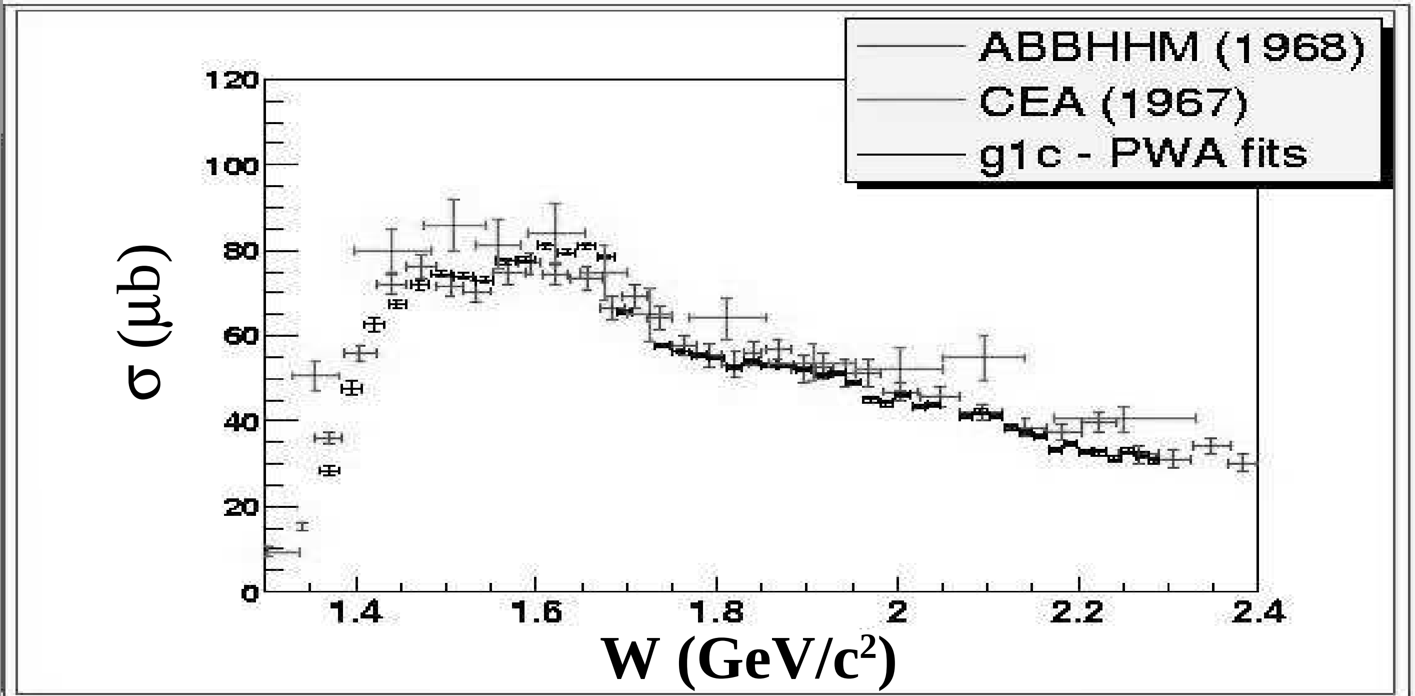


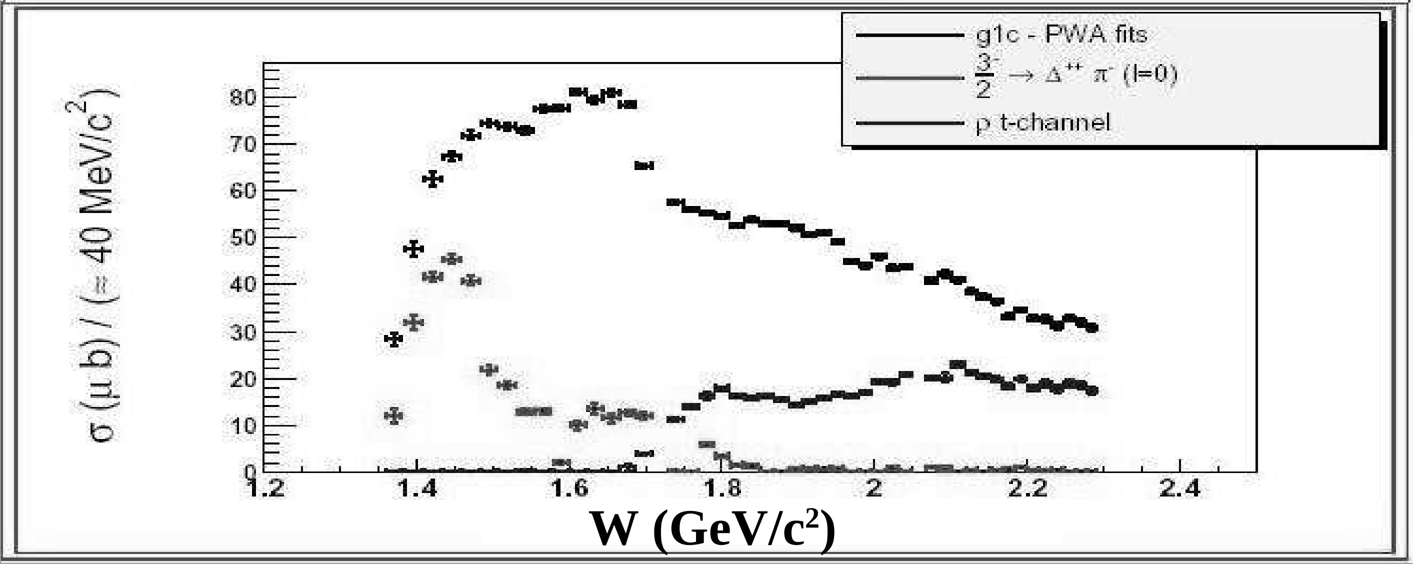




g_{1c} $\gamma\, p \rightarrow \pi^{+} \pi^{-} p$

Cross Section





SLAC (1969) $\gamma\, p \rightarrow \pi^- \pi^+ \pi^+ n$ 5.4 and 4.3 GeV 60 events/μb

Ballam et al., PRL **23**, 1322 (1969)

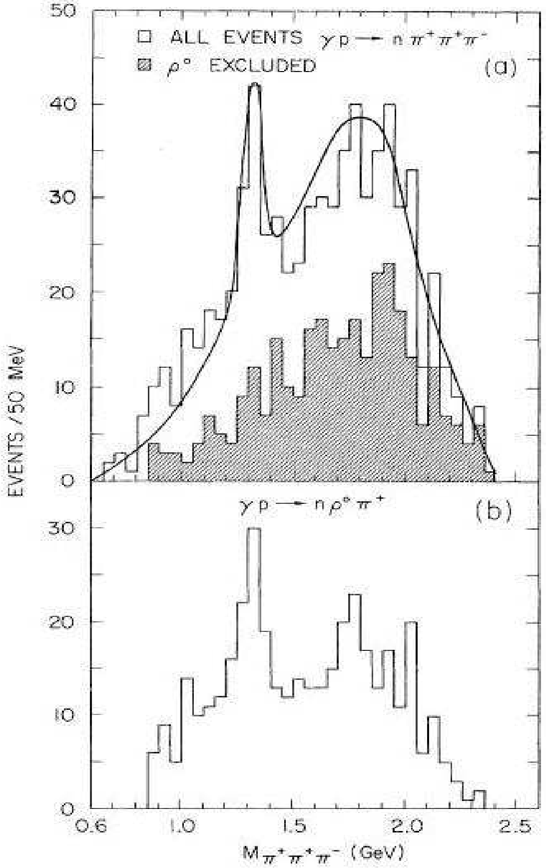


FIG. 1. (a) $M(\pi^+\pi^+\pi^-)$ distribution for $\gamma p \rightarrow n\pi^+\pi^+\pi^-$. The shaded area represents the $M(\pi^+\pi^+\pi^-)$ distribution for events with no $\pi^+\pi^-$ combination in the ρ^0 band (0.60–0.85 GeV). The curve is the best fit by an A_2 resonance plus invariant phase space (see text). (b) $M(\pi^+\pi^+\pi^-)$ distribution for events having at least one $\pi^+\pi^-$ combination in the ρ^0 band.

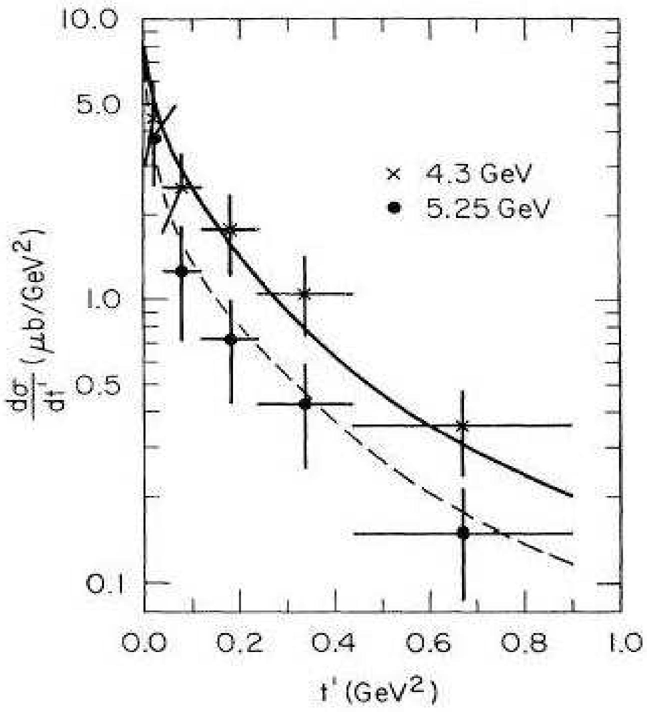
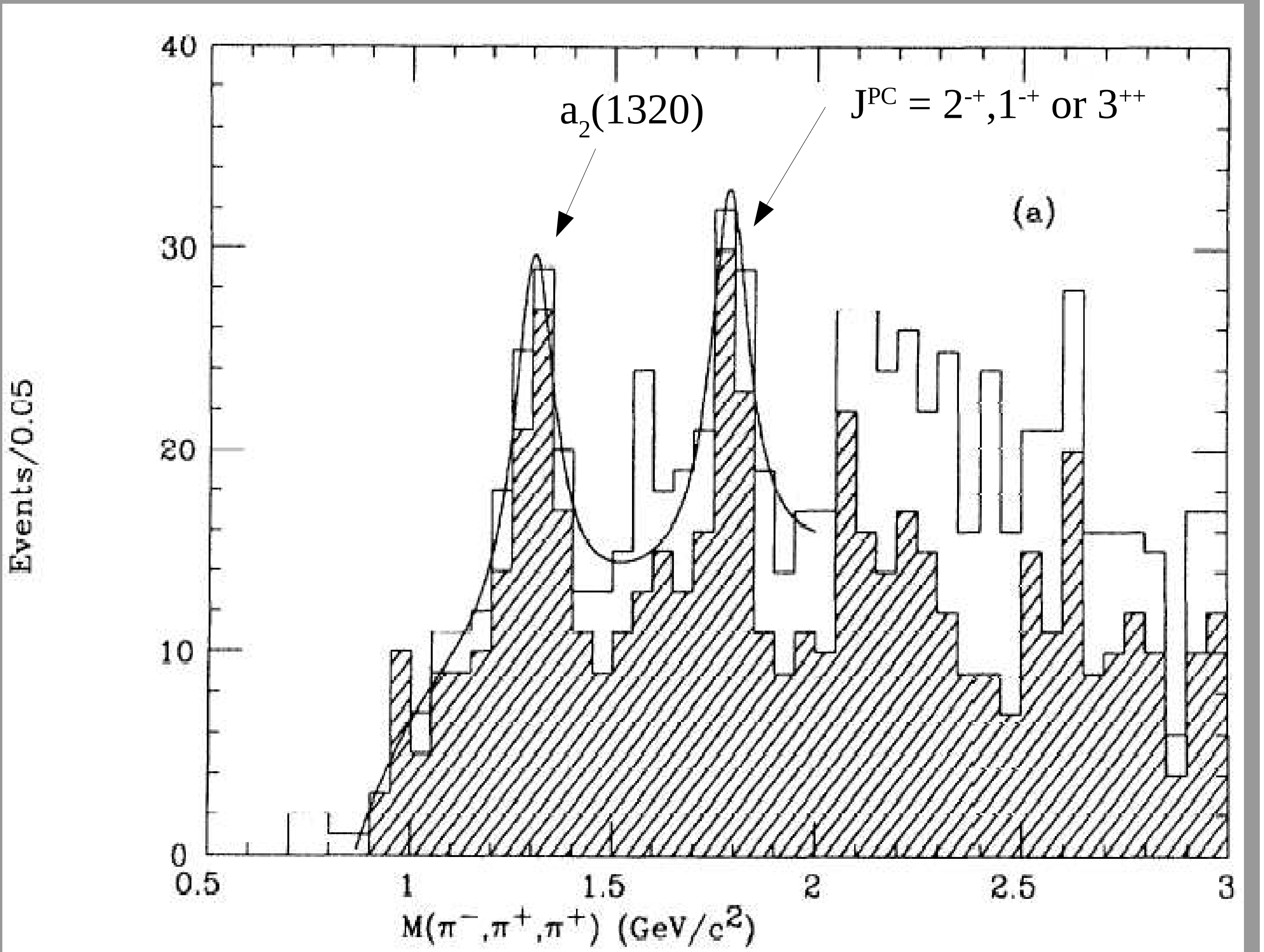


FIG. 2. $d\sigma/dt'$ for Reaction (2) with $M(3\pi) = 1.2$–1.4 GeV, normalized to $\sigma(A_2)$. The curves are the calculated A_2 cross sections using an OPE plus strong absorption model and correspond to an absorption radius of ≈1.0 F and a width of $\Gamma(A_2 \rightarrow \pi\gamma) = 0.55$ MeV.

SLAC Hybrid Bubble Chamber

$E_\gamma \approx 19\,GeV\ ,\Gamma = 1.7\,GeV$

Condo et al., PRD 43 #9, 2787 (1991)



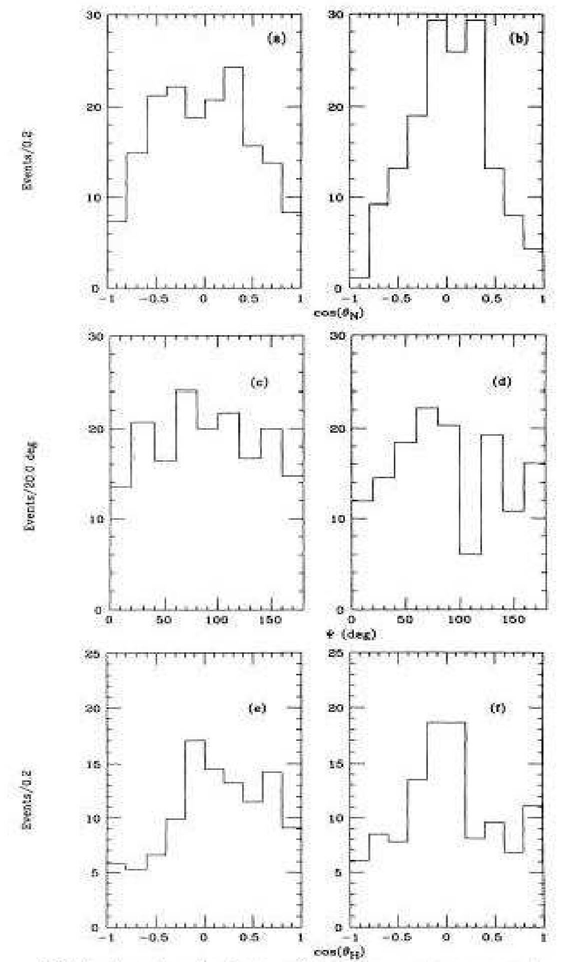


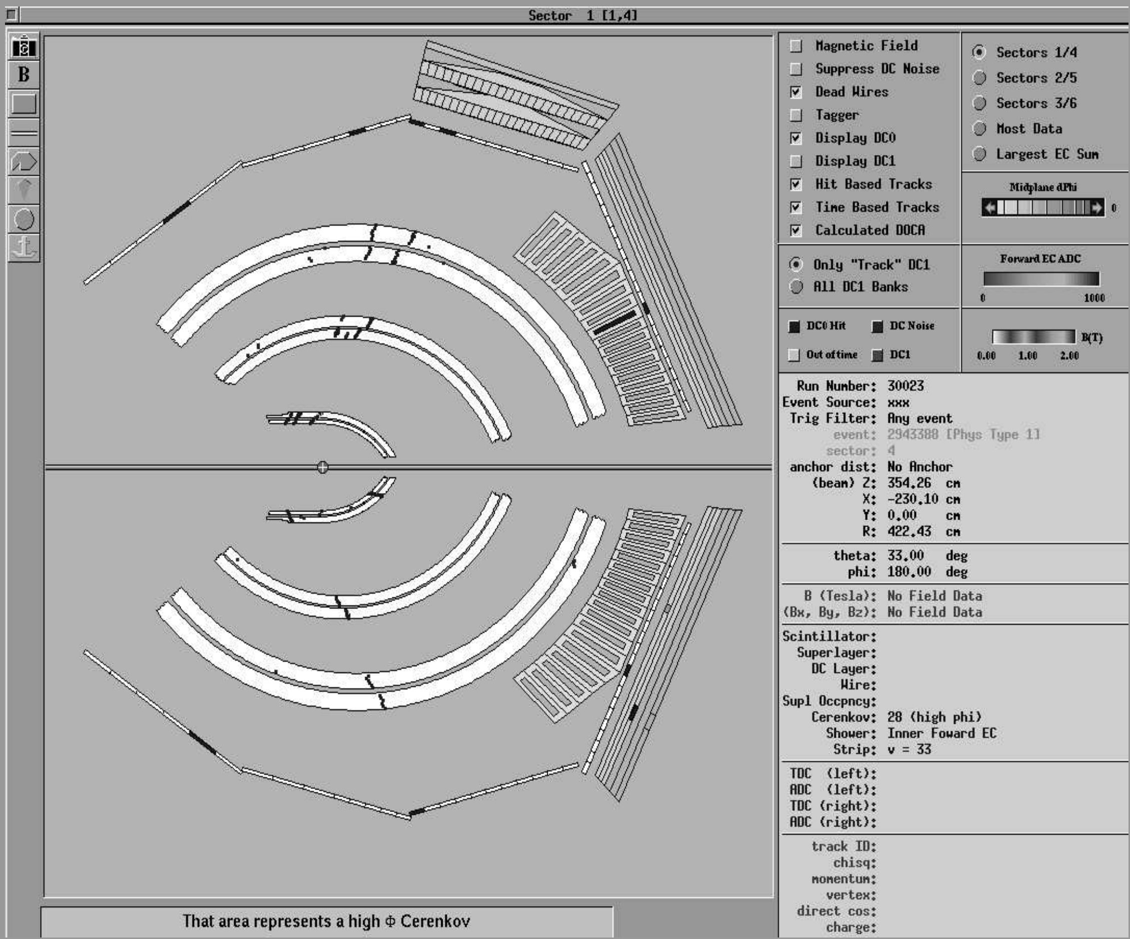
FIG. 3. Angular distributions for the resonant mass regions for the reactions $\gamma p \to \Delta^{2+} x^-(a,c,e)$ and $\gamma p \to n x^+(b,d,f)$. (a) and (b) are the distributions of the decay plane normal in the Gottfried-Jackson frame (θ_N). (c) and (d) are the distributions of the corresponding azimuth relative to the difference between the photon polarization direction and the normal to the production plane (Ψ). (e) and (f) are the ρ^0 helicity angular distributions (θ_H). All of the angular distributions have been corrected for experimental acceptances. The distributions for the negative meson include a small correction for $\rho^0 N^*$ removal as described in Ref. 6. The distributions for the positive meson, which include all events, are relatively unaffected by any $\rho^0 N^*$ contamination. None of these corrections has a material effect on the shape of any of the angular distributions presented in this paper.

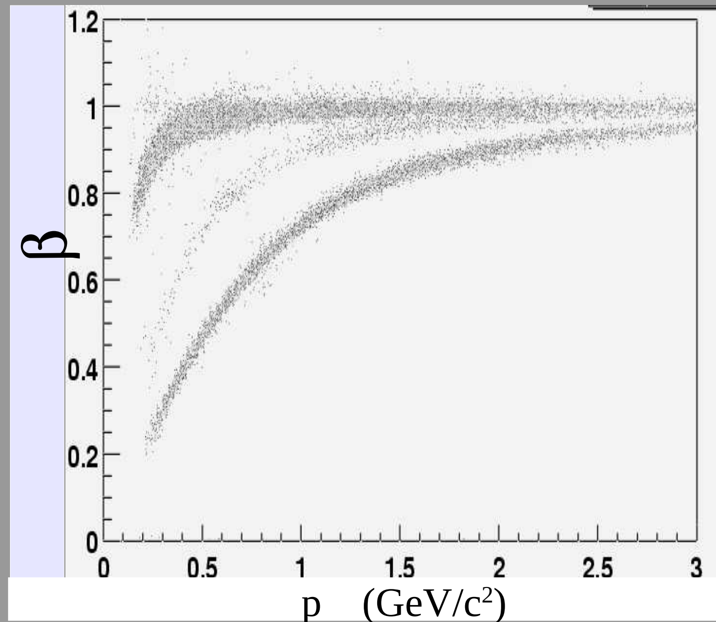
g6c Run: 5.7 GeV Electron
August 17-September 11,2001

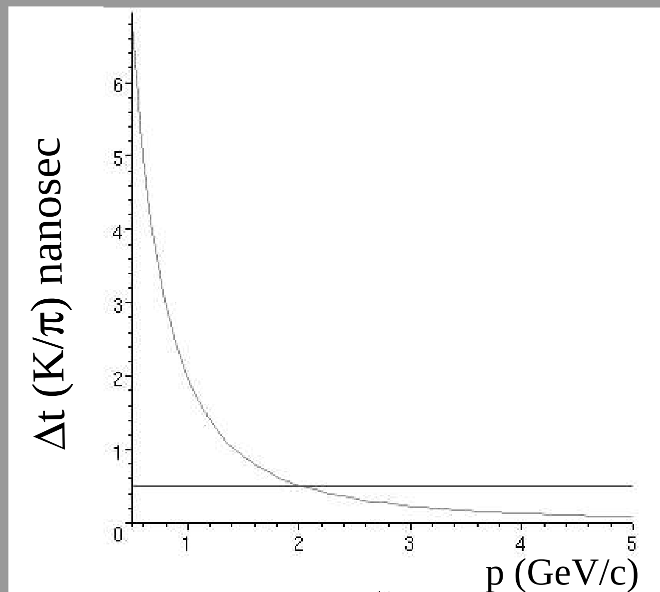
$4.8 < E\gamma < 5.4$ GeV

γ Flux: ~5 x 10^6/sec

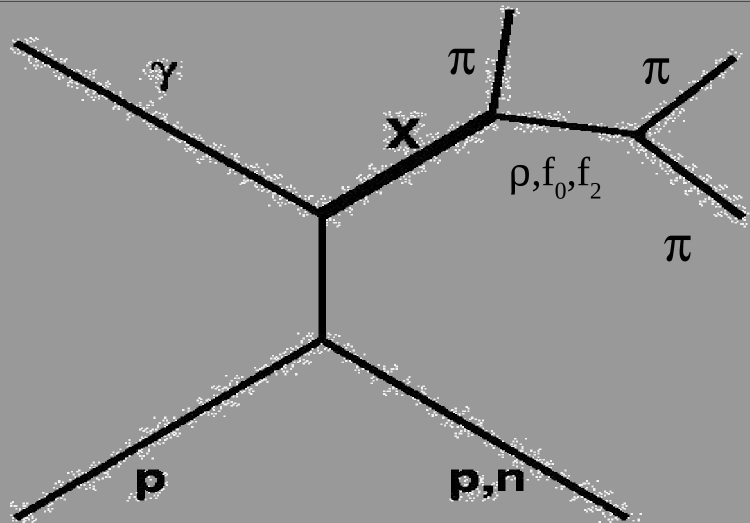
sensitivity: ~2.7 events/pb

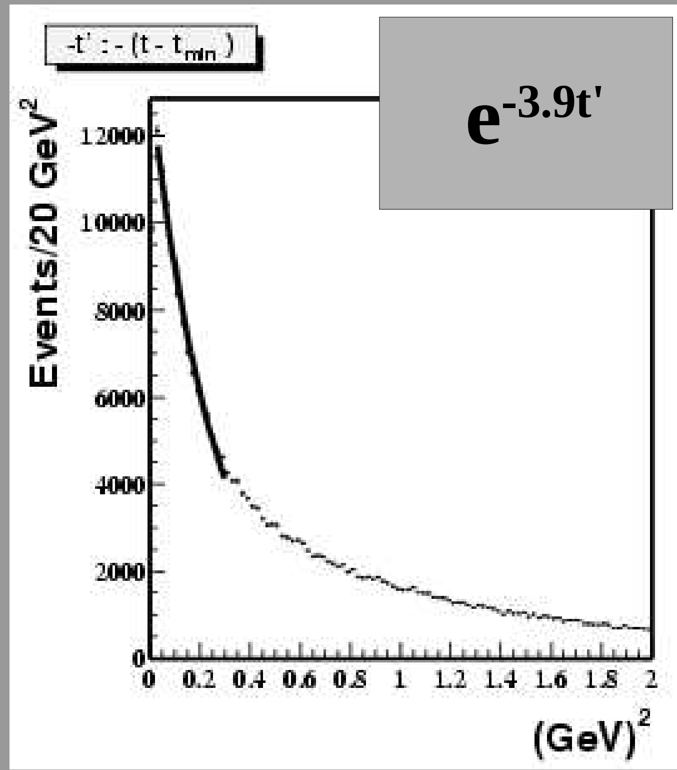


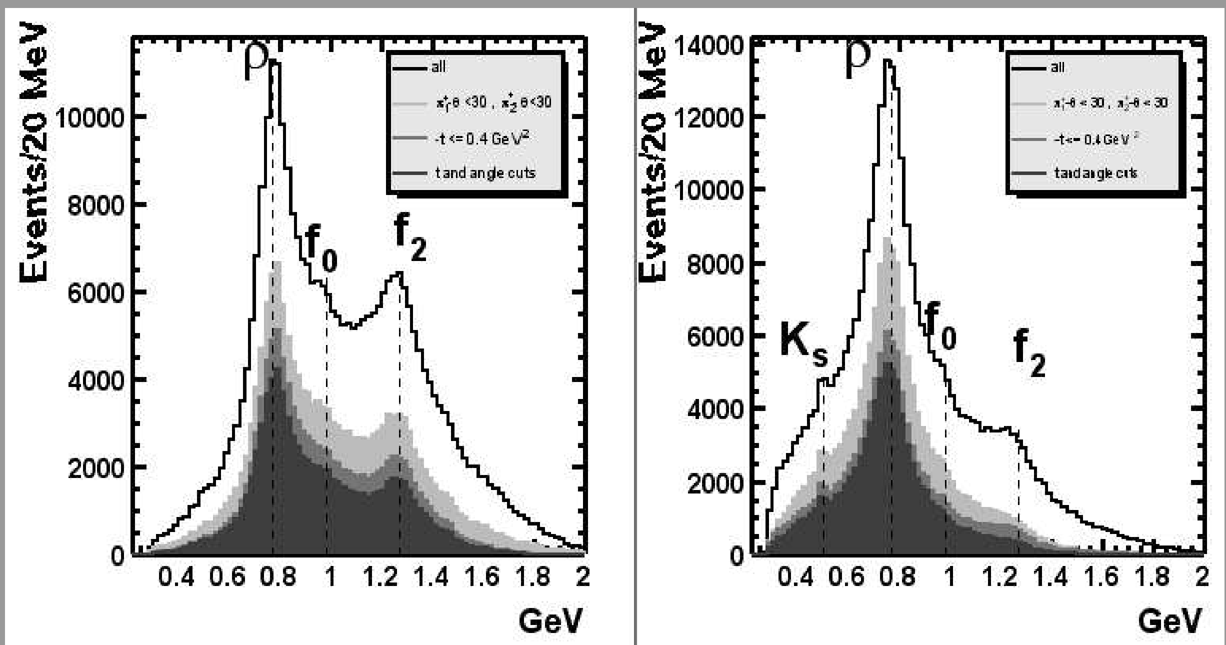




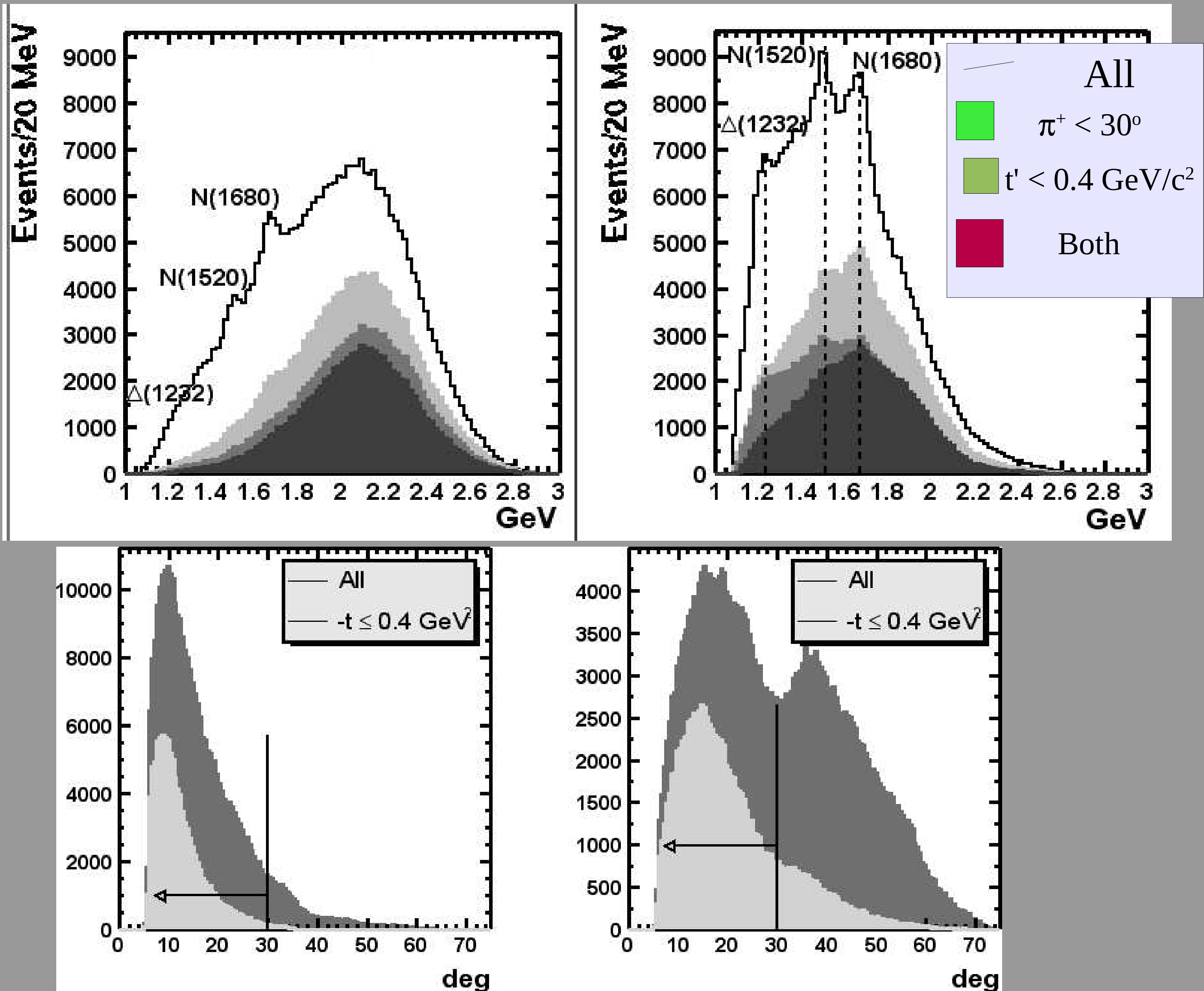
g_{6c} $\gamma\, p \rightarrow \pi^- \pi^+ \pi^+ n$ $4.8 < E_\gamma < 5.4$ Gev



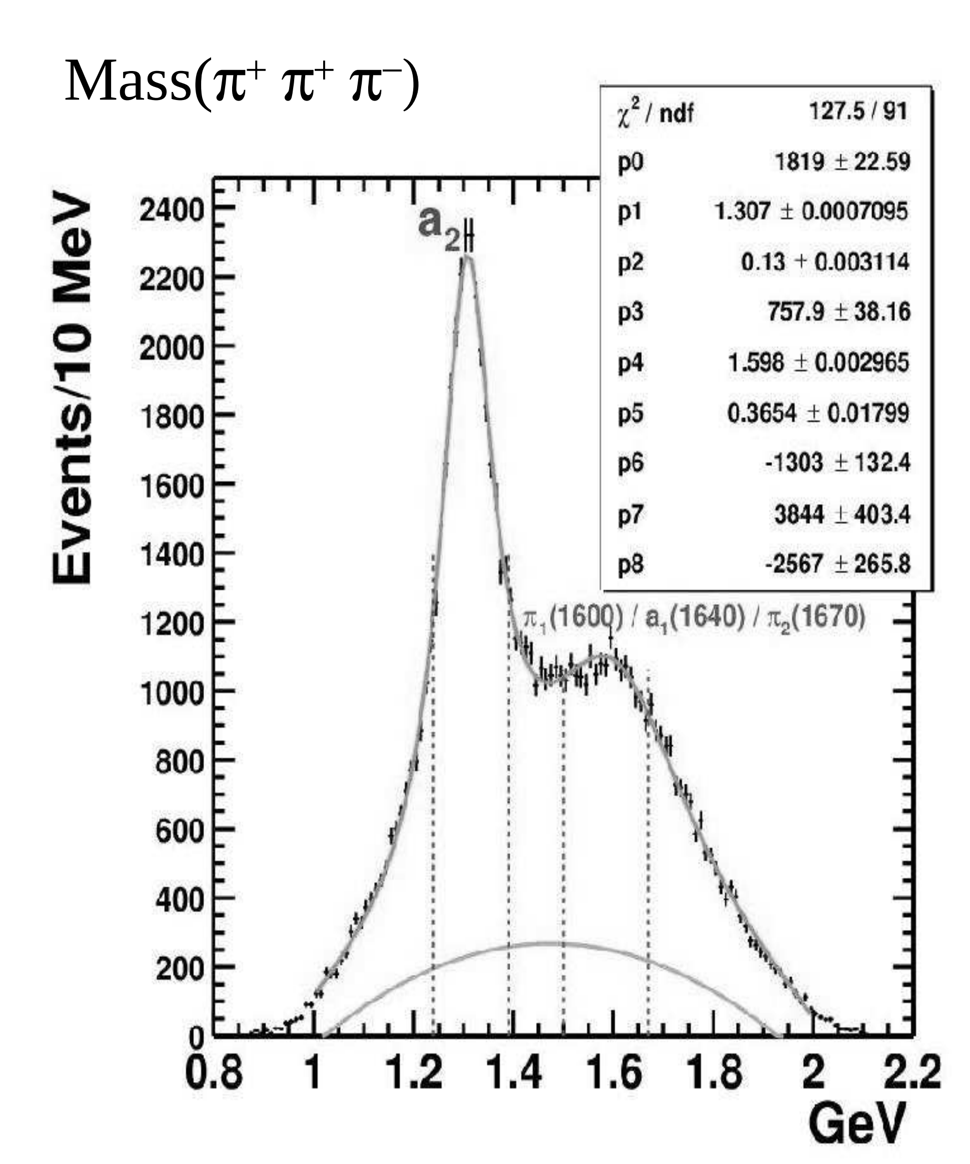




g_{6c} $\gamma p \to \pi^- \pi^+ \pi^+ n$ $4.8 < E_\gamma < 5.4$ Gev



g_{6c} $\gamma\, p \rightarrow \pi^- \pi^+ \pi^+ n$ $4.8 < E_\gamma < 5.4$ Gev

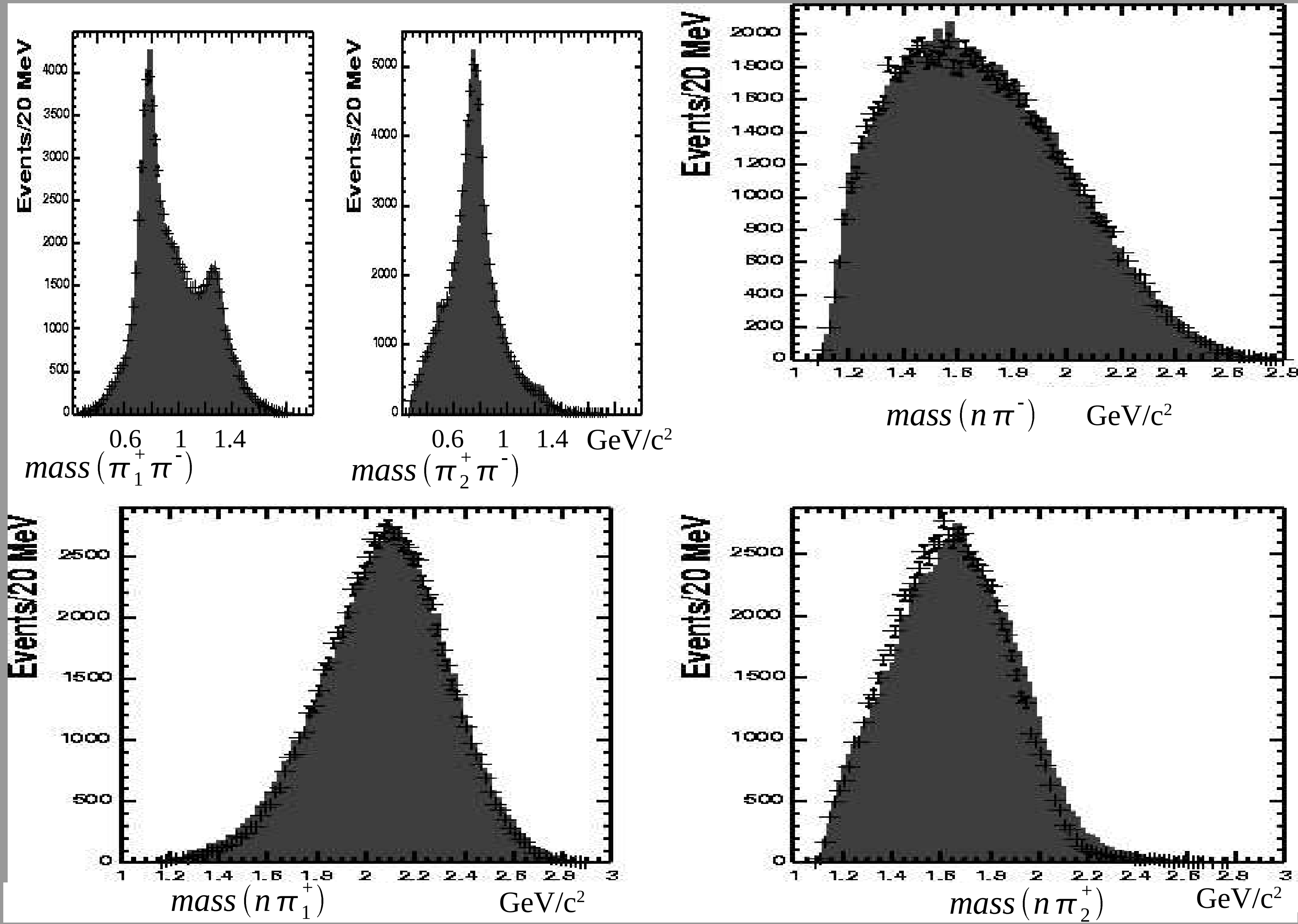


Partial Waves:

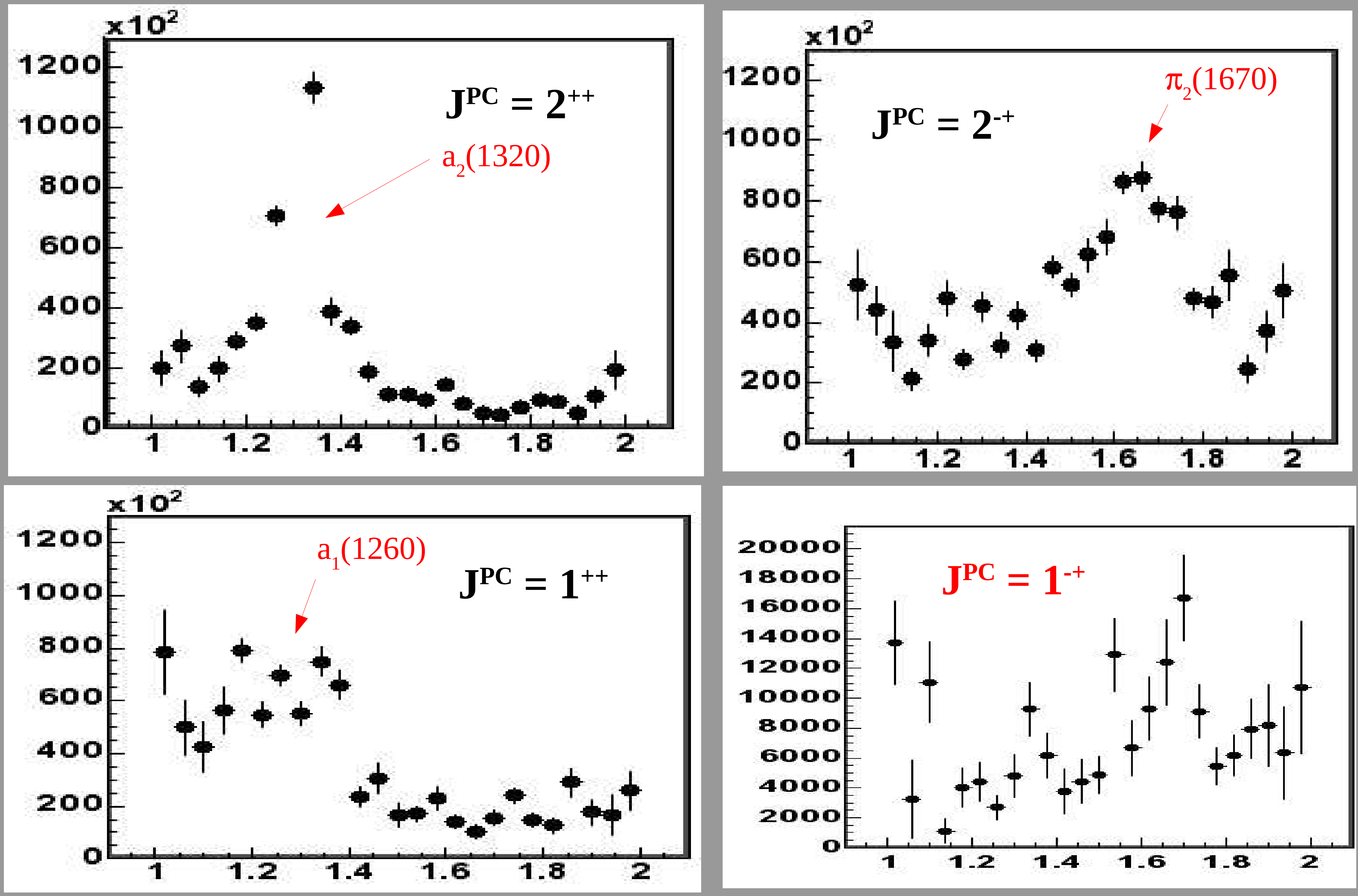
J^{PC}	m^ϵ	L	Isobar	# Waves
0^{-+}	0^+	0	σ	1
0^{-+}	0^+	0	$f_0(980)$	1
0^{-+}	0^+	1	$\rho(770)$	1
1^{++}	$0^+, 1^\pm$	0,2	$\rho(770)$	6
1^{++}	$0^+, 1^\pm$	1	σ	3
1^{-+}	$0^-, 1^\pm$	1	$\rho(770)$	3
2^{++}	$0^-, 1^\pm, 2^\pm$	2	$\rho(770)$	5
2^{-+}	$0^+, 1^\pm$	1,3	$\rho(770)$	6
2^{-+}	$0^+, 1^\pm$	2	σ	3
2^{-+}	$0^+, 1^\pm$	0,2	$f_2(1270)$	6
Background				

Total of 36 waves (complex amplitudes) $\Rightarrow$ 72 parameters

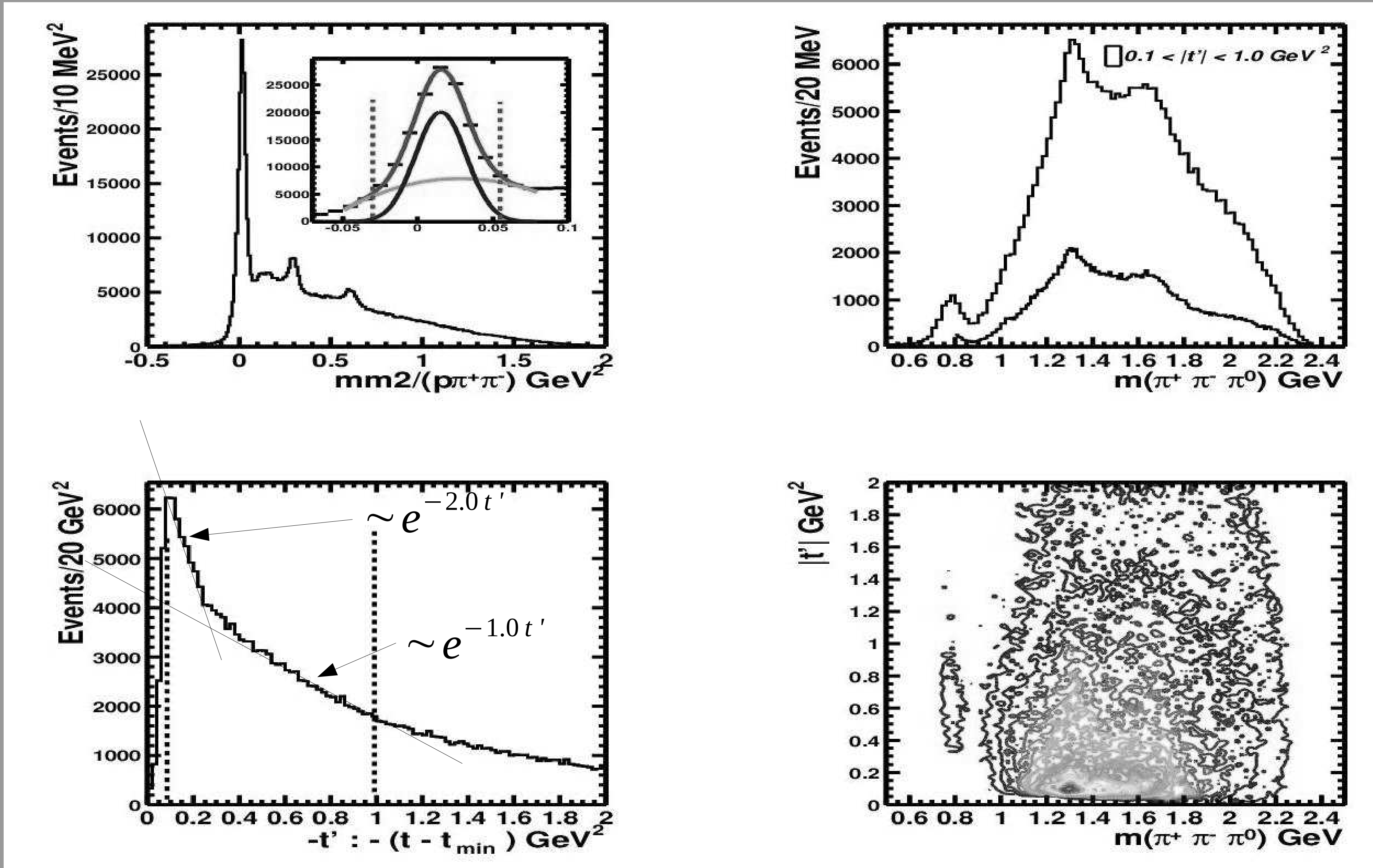
Partial Wave Fit Quality



Partial Wave Analysis $\gamma\, p \rightarrow \pi^- \pi^+ \pi^+ n$ Preliminary



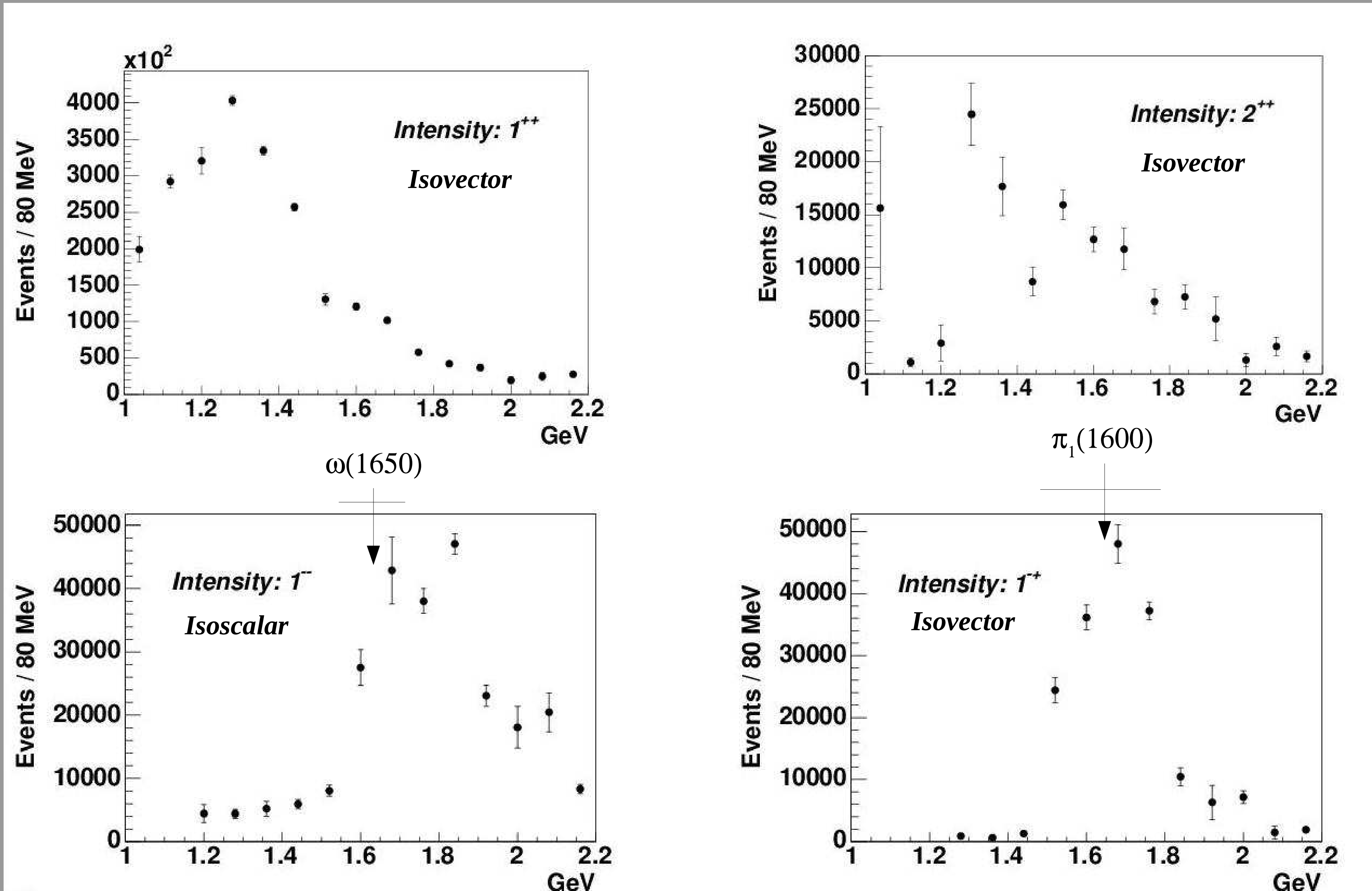
g_{6c} $\gamma p \to \pi^- \pi^+ \pi^0 p$ $4.8 < E_\gamma < 5.4$ GeV



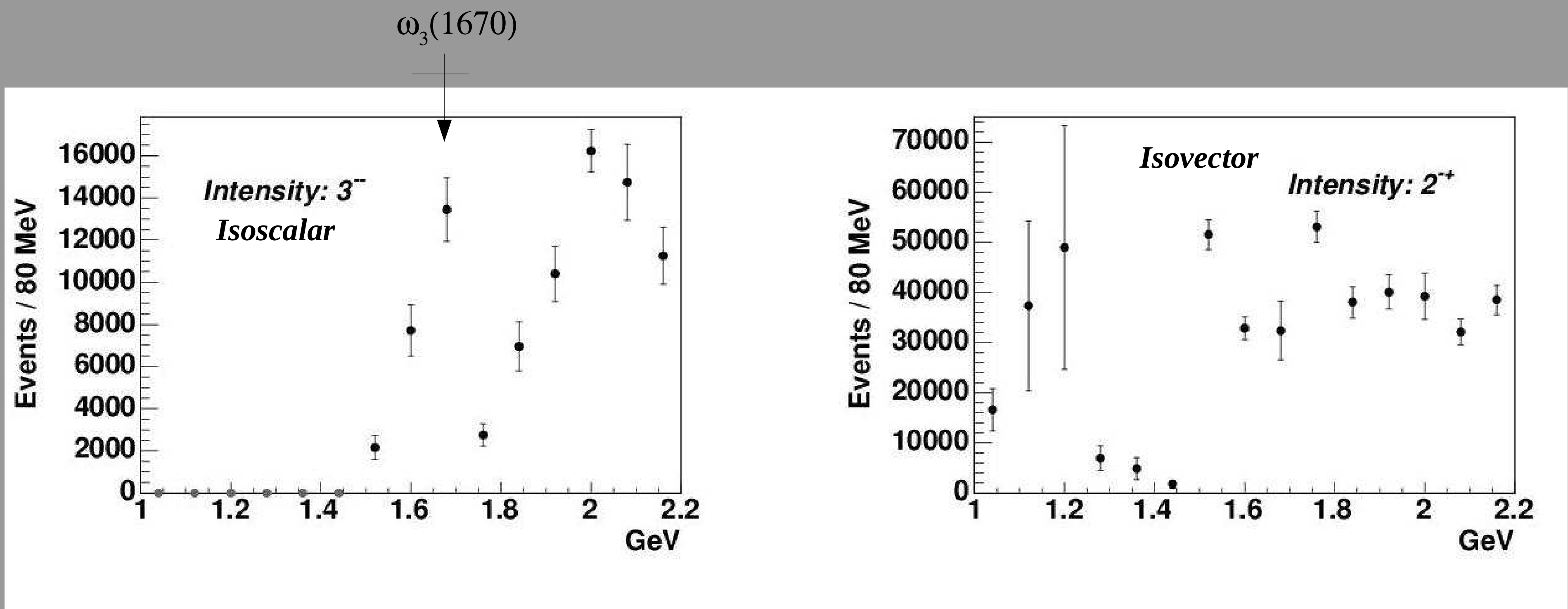
g_{6c} $\gamma\, p \rightarrow \pi^- \pi^+ \pi^0\, p$ $4.8 < E_\gamma < 5.4$ GeV

J^PC	M^ϵ	L	Isobars
1^{++}	$0^+, 1^\pm$	$0, 2$	$[\rho(770)]\pi$
1^{--}	$0^-, 1^\pm$	1	$[\rho(770)]\pi$
1^{-+}	$0^-, 1^+$	1	$[\rho(770)]\pi$
2^{++}	$0^-, 1^+$	2	$[\rho(770)]\pi$
2^{-+}	$0^+, 1^\pm$	0	$[f_2(1270)]\pi$
	0^+	2	$[f_2(1270)]\pi$
	$0^+, 1^\pm$	$1, 3$	$[\rho(770)]\pi$
2^{+-}	0^-	2	$[\rho(770)]\pi$
3^{--}	$0^-, 1^+$	3	$[\rho(770)]\pi$
3^{++}	$0^-, 1^\pm$	1	$[f_2(1270)]\pi$
4^{++}	$0^-, 1^-$	3	$[f_2(1270)]\pi$
Background			21 waves

g_{6c} $\gamma\, p \rightarrow \pi^- \pi^+ \pi^0\, p$ $4.8 < E_\gamma < 5.4$ GeV Preliminary

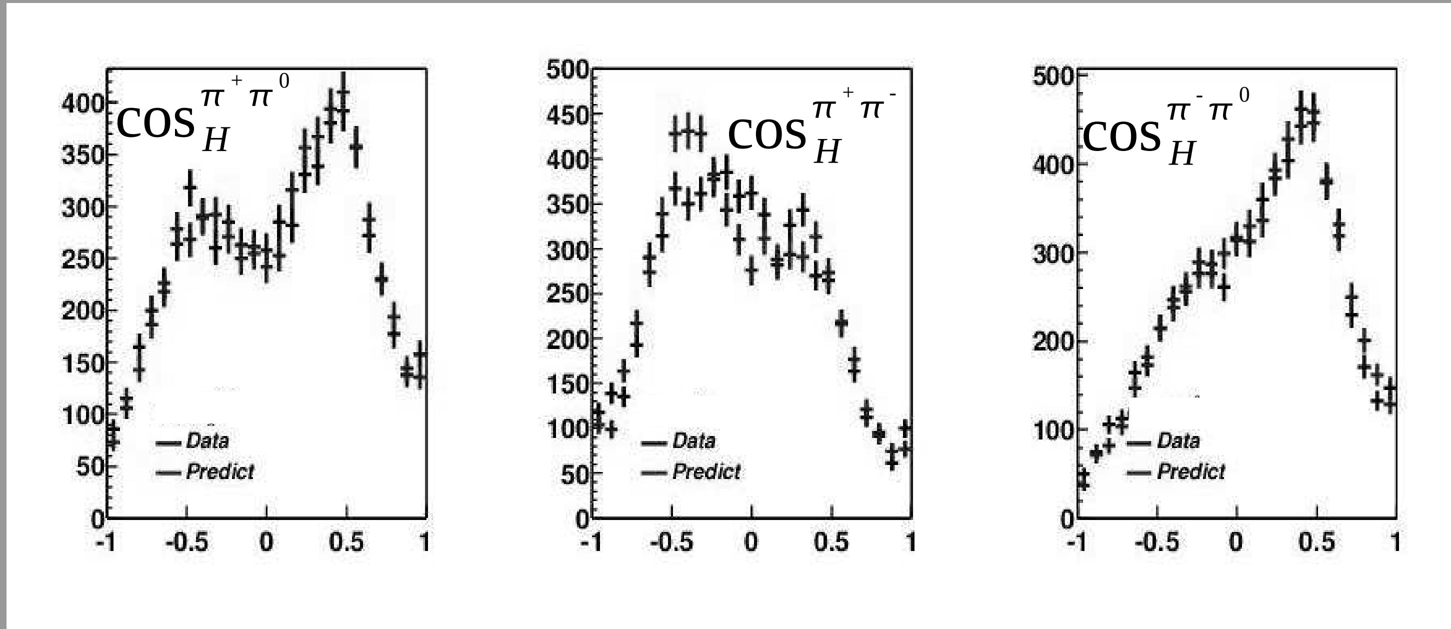


g_{6c} $\gamma\, p \rightarrow \pi^- \pi^+ \pi^0\, p$ $4.8 < E_\gamma < 5.4$ GeV Preliminary

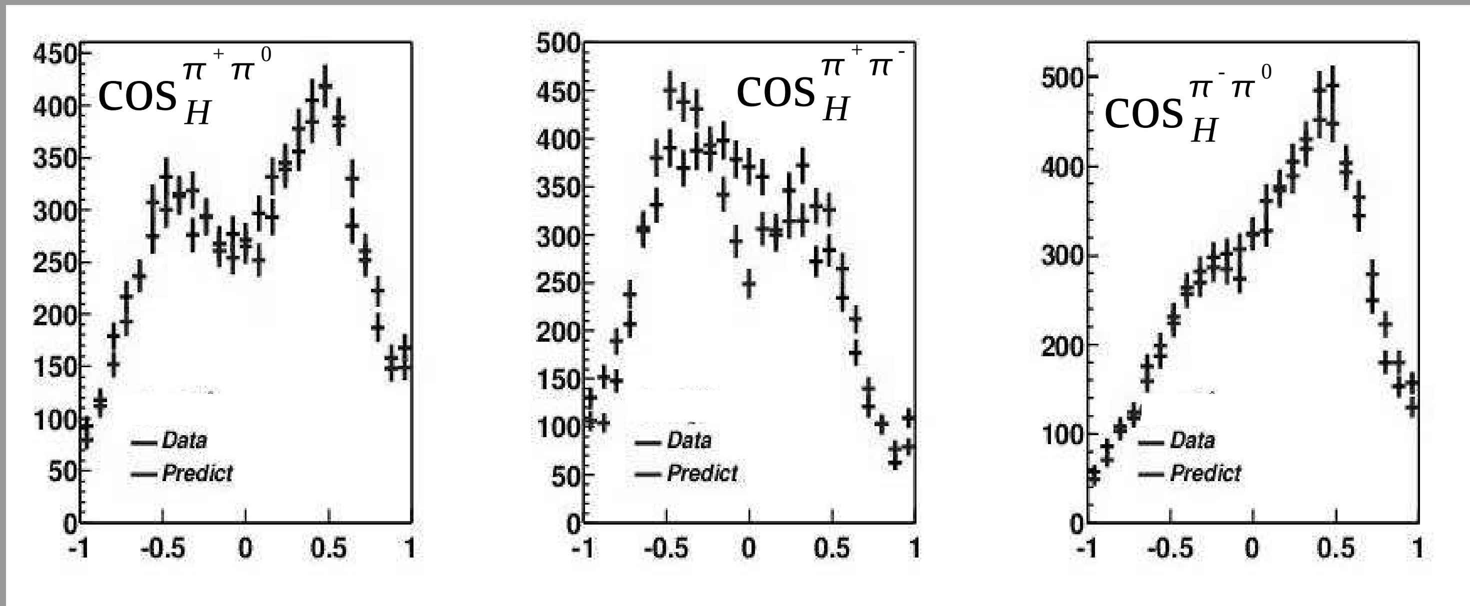


g_{6c} $\gamma\, p \rightarrow \pi^- \pi^+ \pi^0\, p$ 4.8 < E_γ < 5.4 GeV

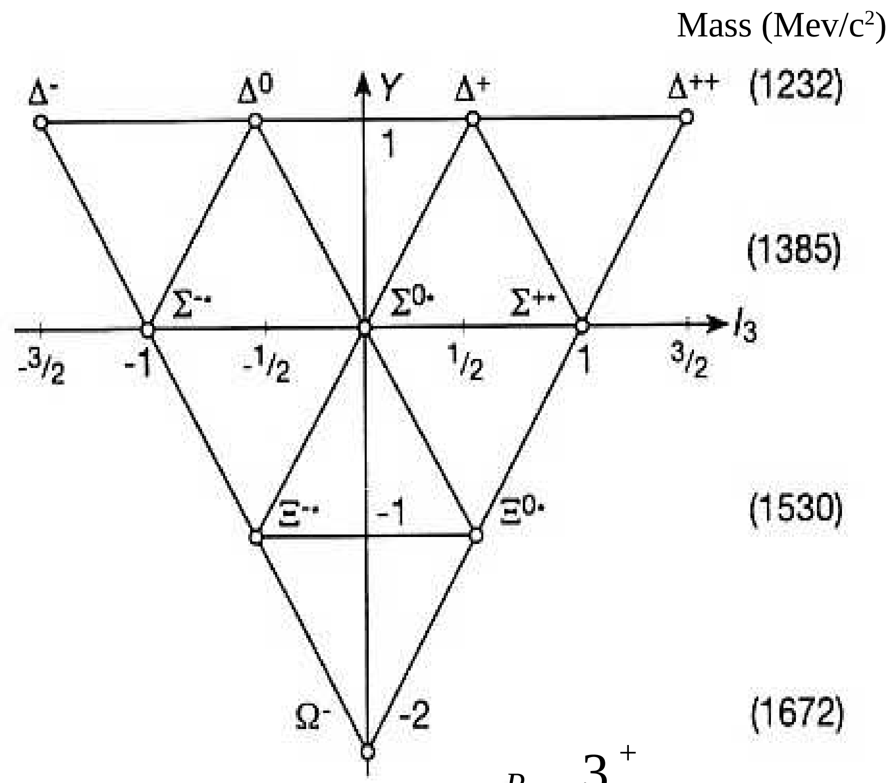
Including $J^{PC}=1^{-+}$



Excluding $J^{PC}=1^{-+}$

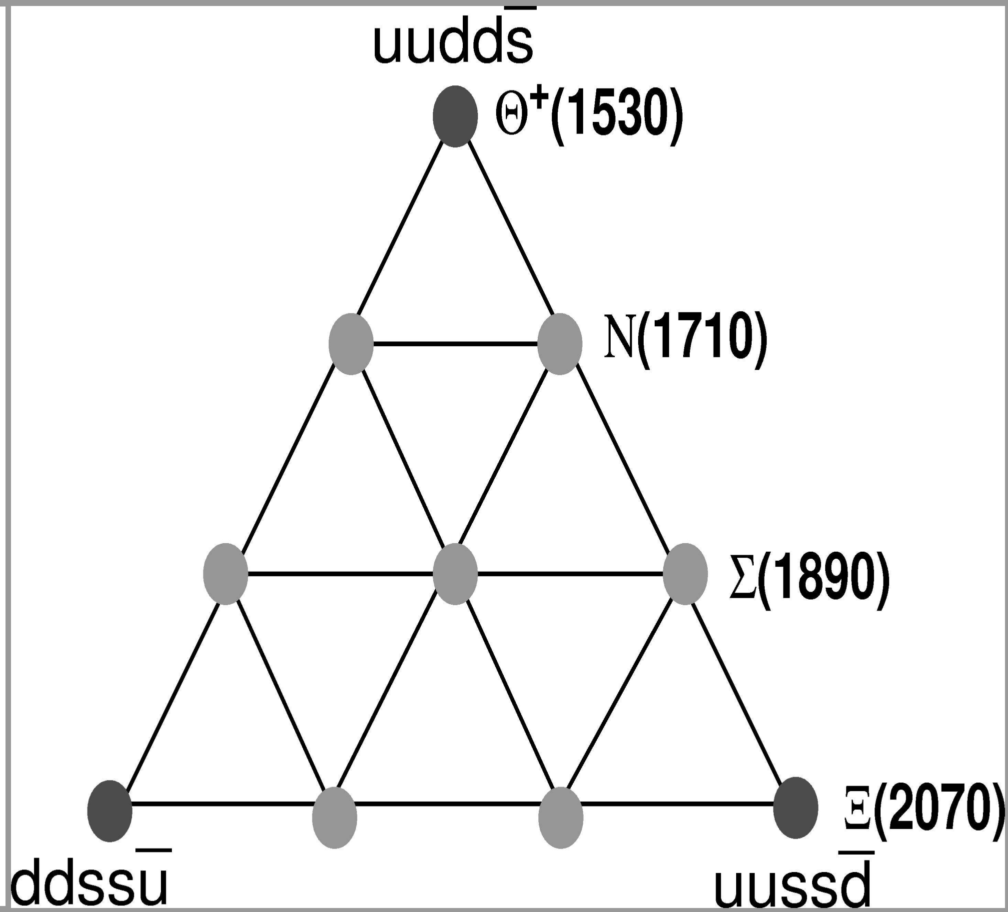


Baryon decuplet

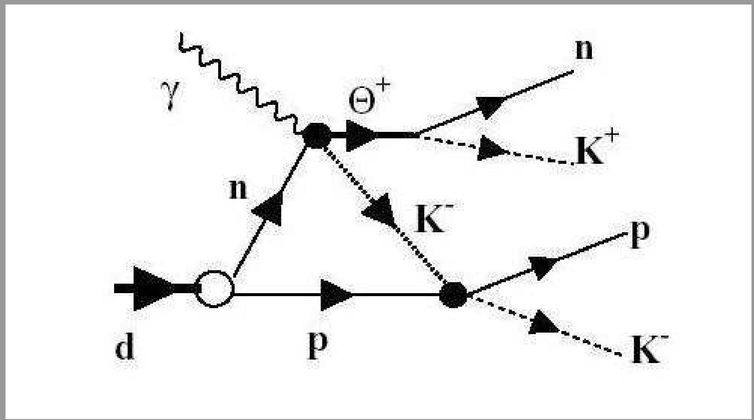


Baryons: **10**

$$J^P = \frac{3}{2}^+$$



g_{6c} $\gamma\, d \rightarrow K^- K^+ n\, p$



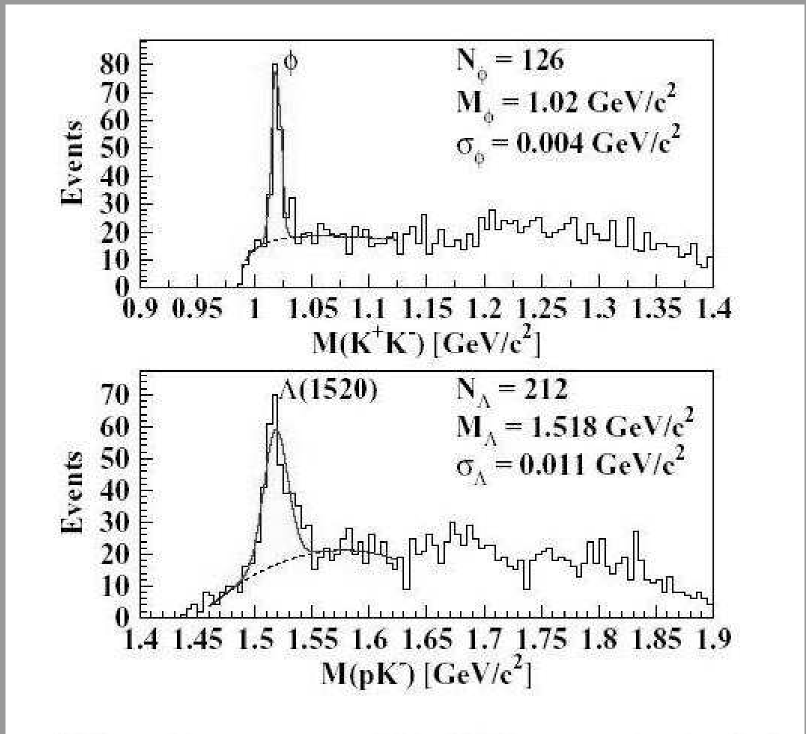
2 Data Runs:

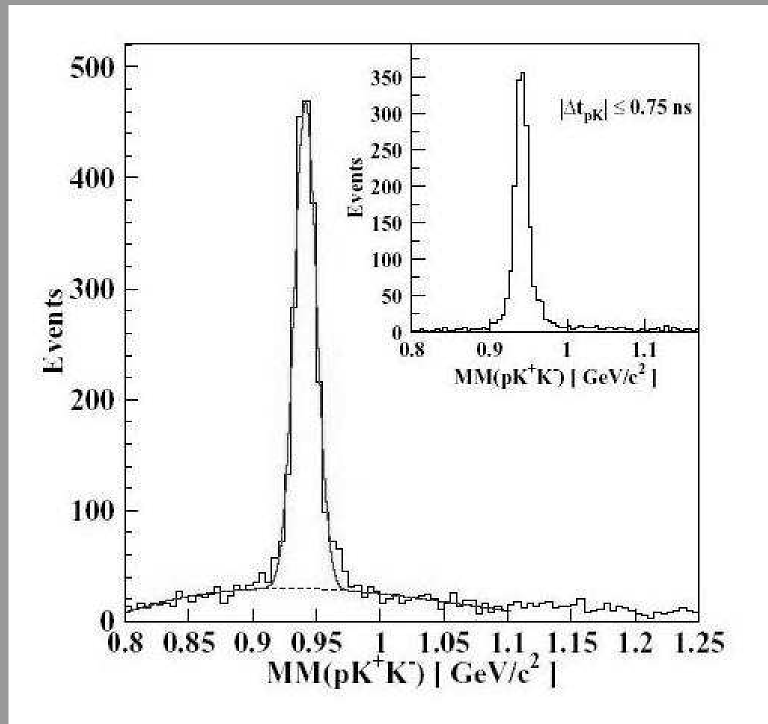
$1.51 < E_\gamma < 2.35$ GeV

0.7 events/pbarn

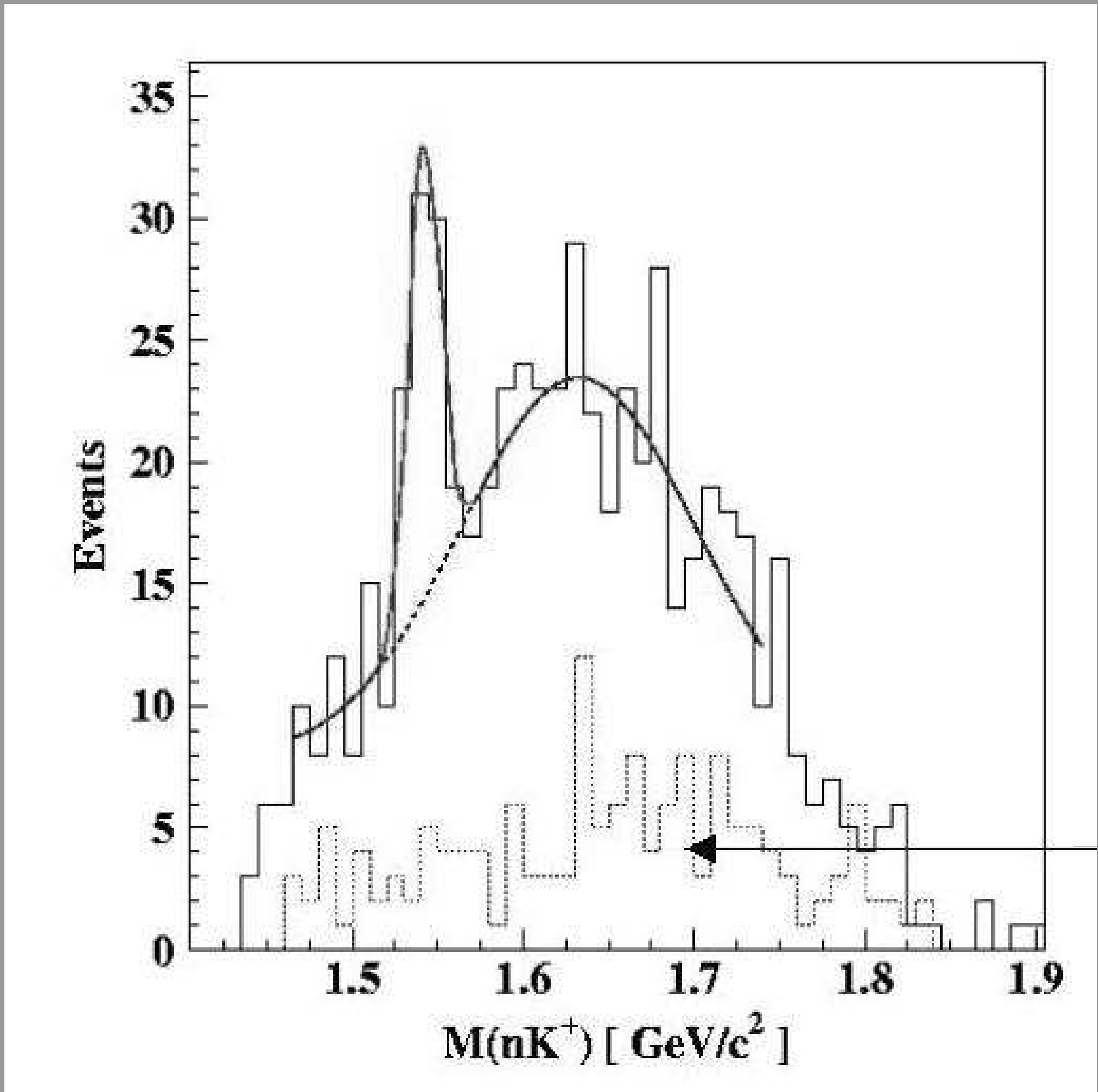
$1.51 < E_\gamma < 2.96$ GeV

0.3events/pbarn





g_{6c} $\gamma d \rightarrow K^{-} K^{+} n p$



~42 events

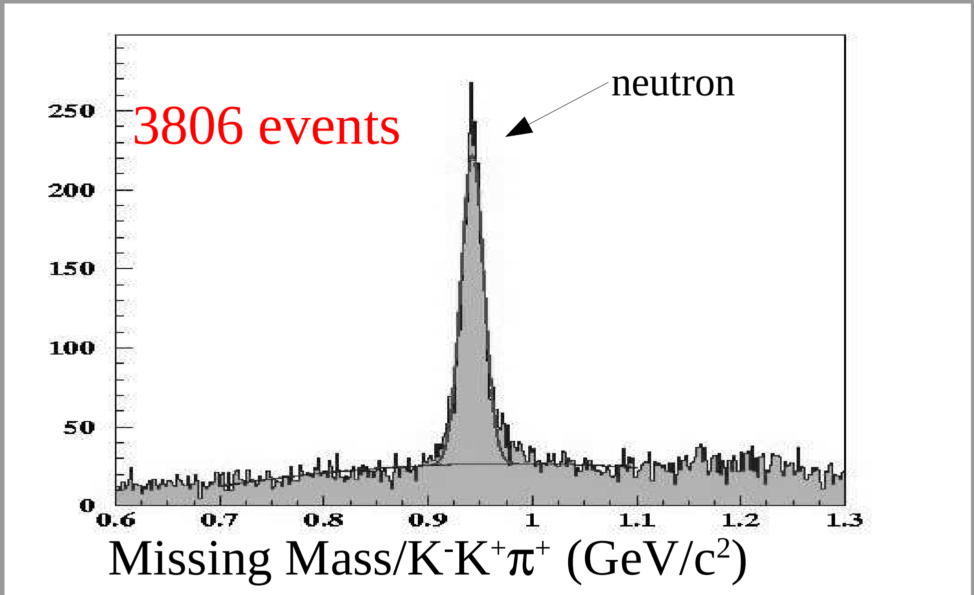
$M = 1542\, MeV/c^2 \pm 5$

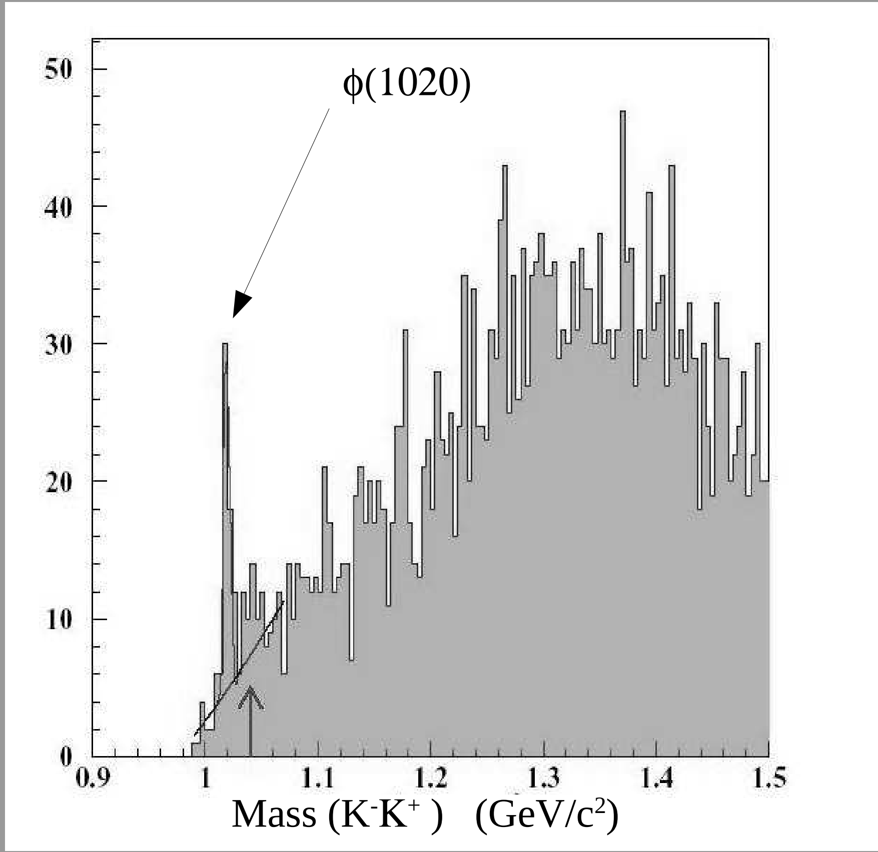
$\Gamma \sim 21\, MeV/c^2$

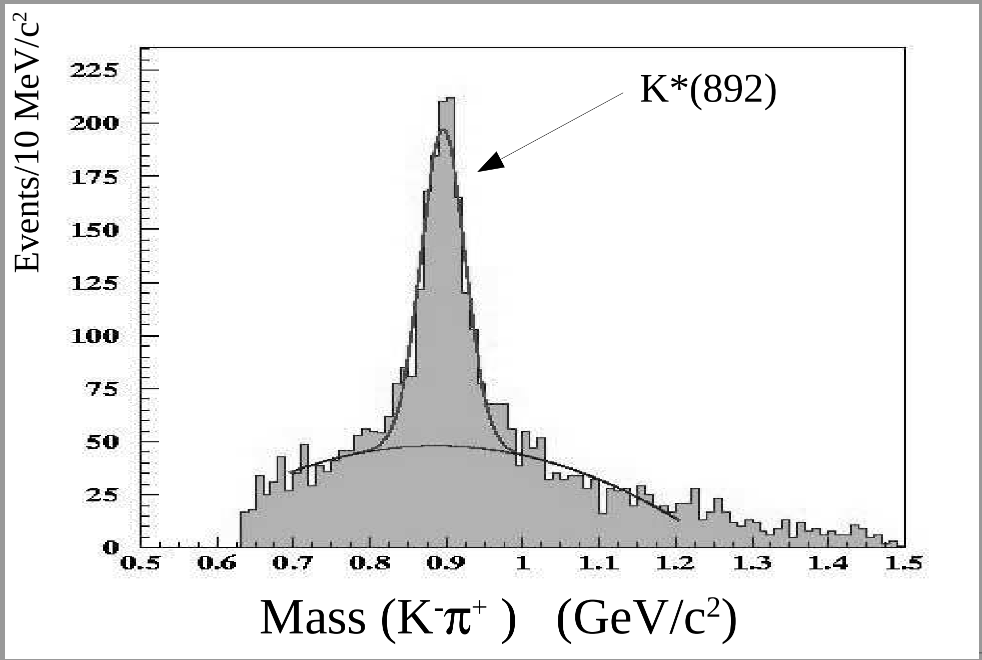
~5.3 σ

Λ(1520) events

$g_{6a\text{-}b}$ $\gamma\, p \rightarrow K^- K^+ \pi^+ n$ 3.0 < E_γ < 5.25 GeV



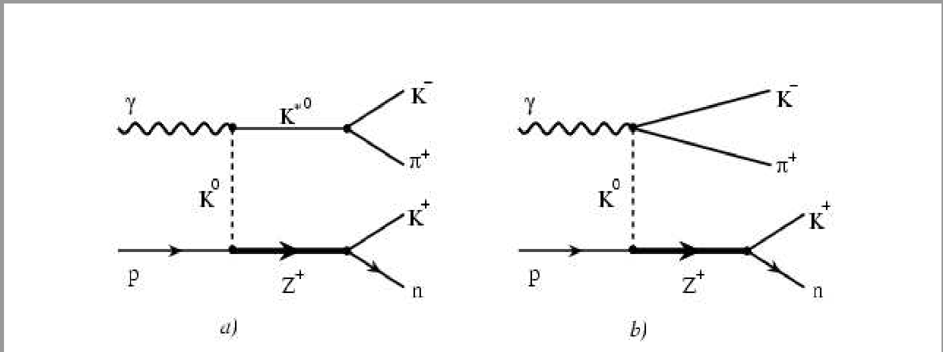


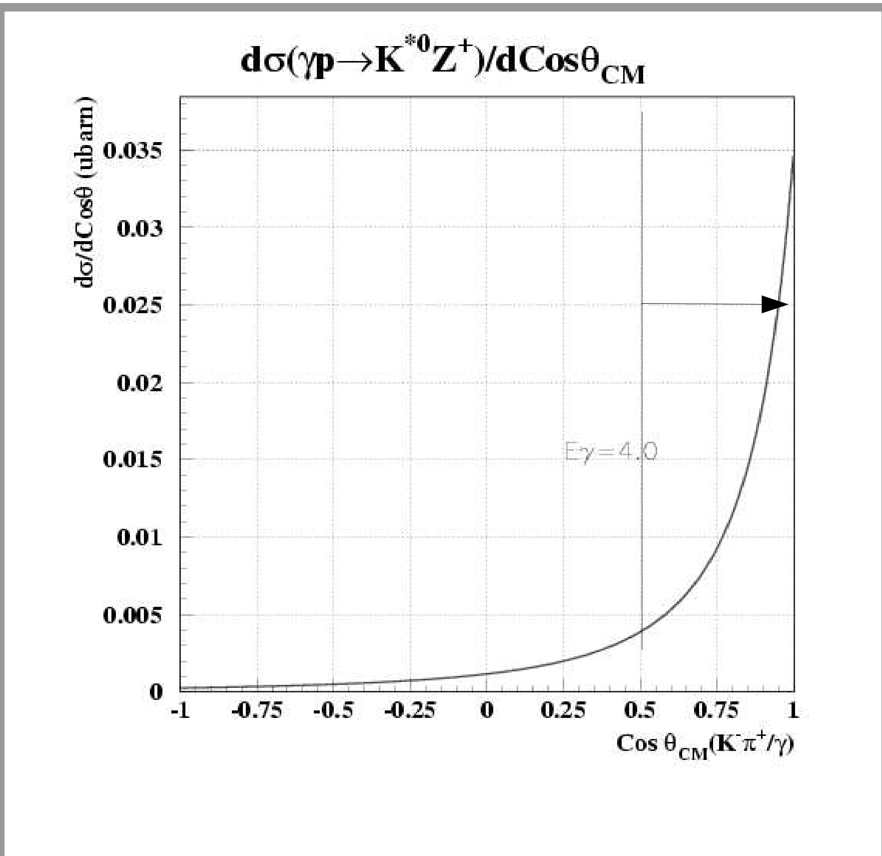


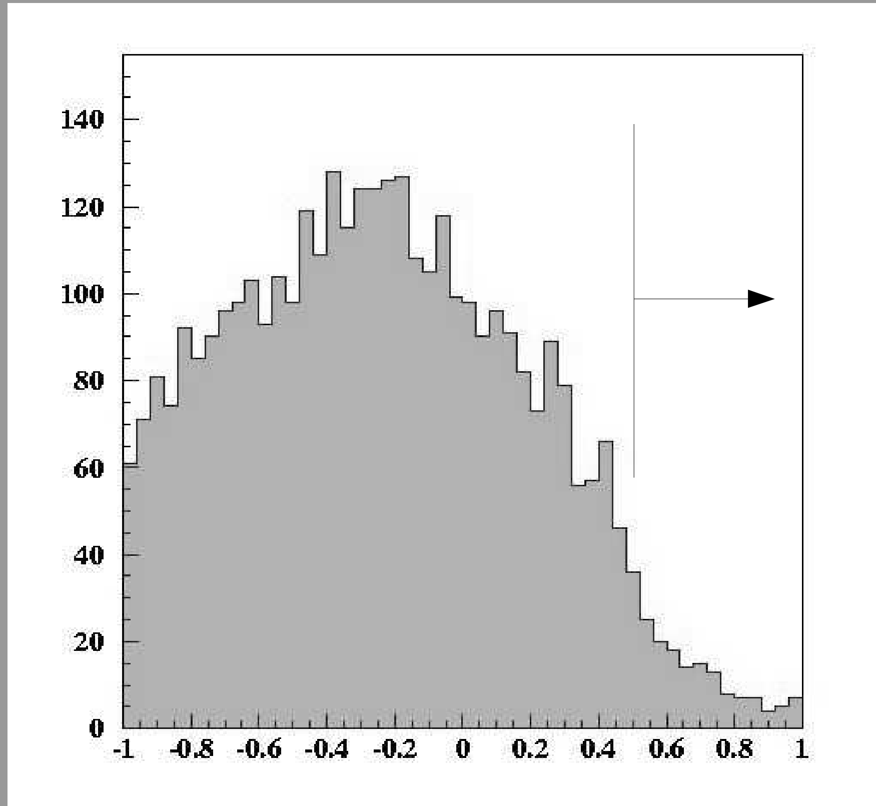
2 Data Runs

2 events/pbarn

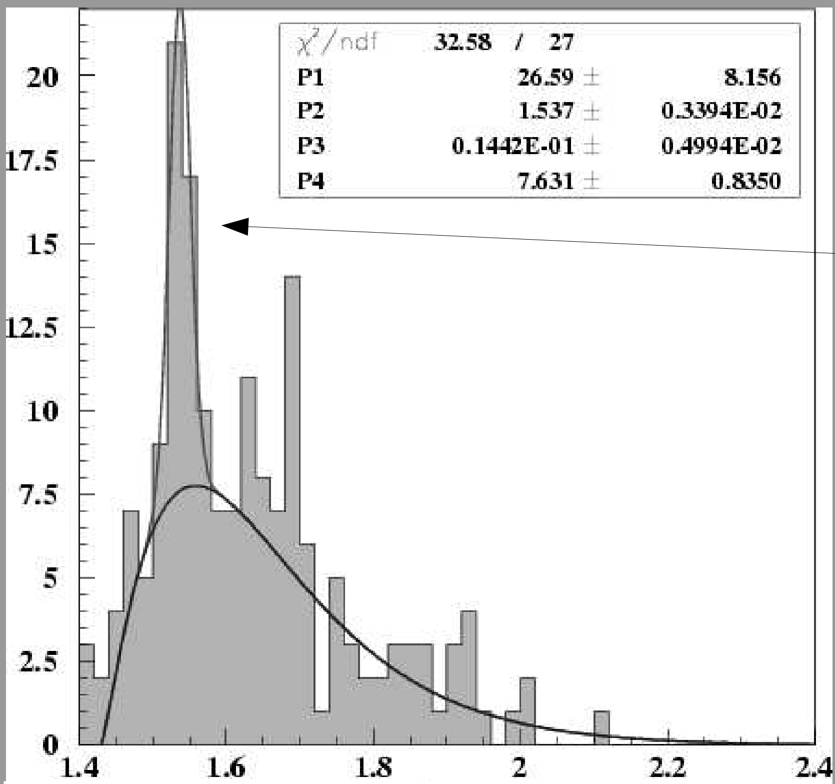
$g_{6a\text{-}b}$ $\gamma p \rightarrow K^- K^+ \pi^+ n$ 3.0 < E_γ < 5.25 GeV







g$_{6a\text{-}b}$ $\gamma\, p \rightarrow K^- K^+ \pi^+ n$ 3.0 < E$_\gamma$ < 5.25 GeV



Mass (nK$^+$) (GeV/c^2)

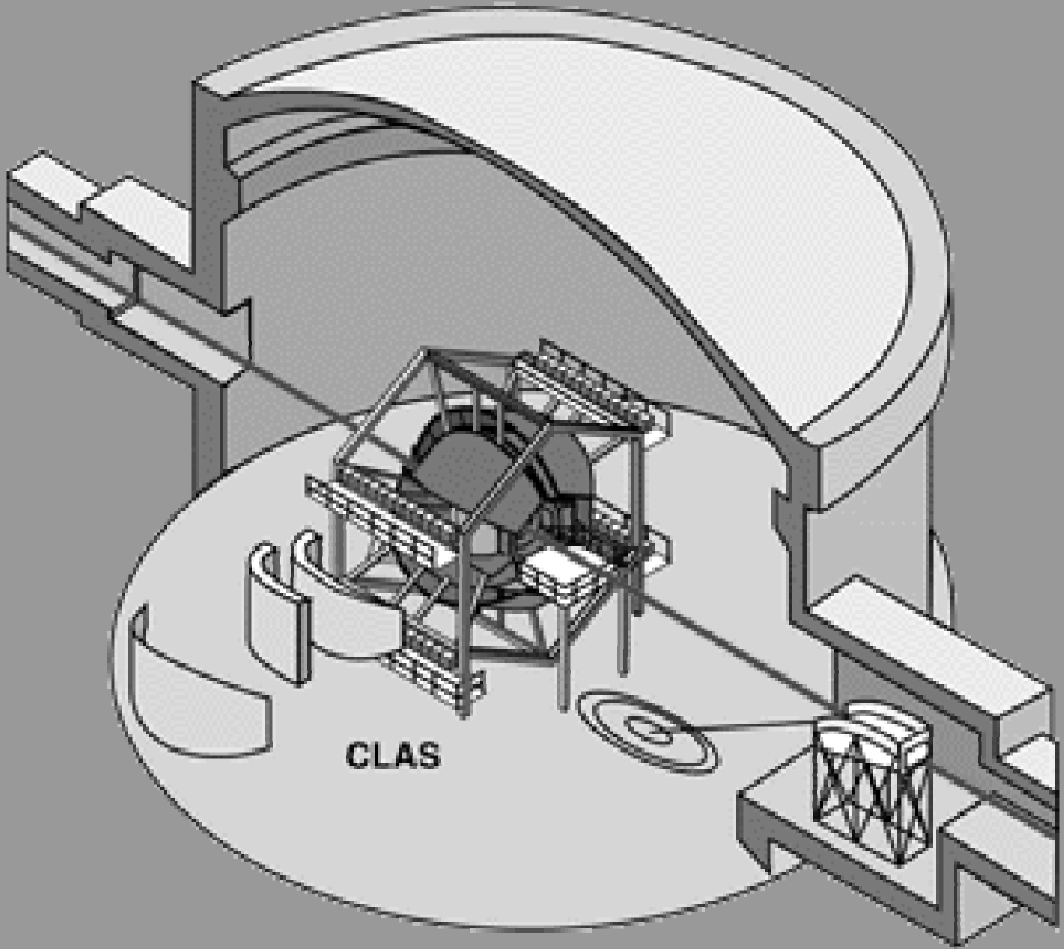
~26.6 events

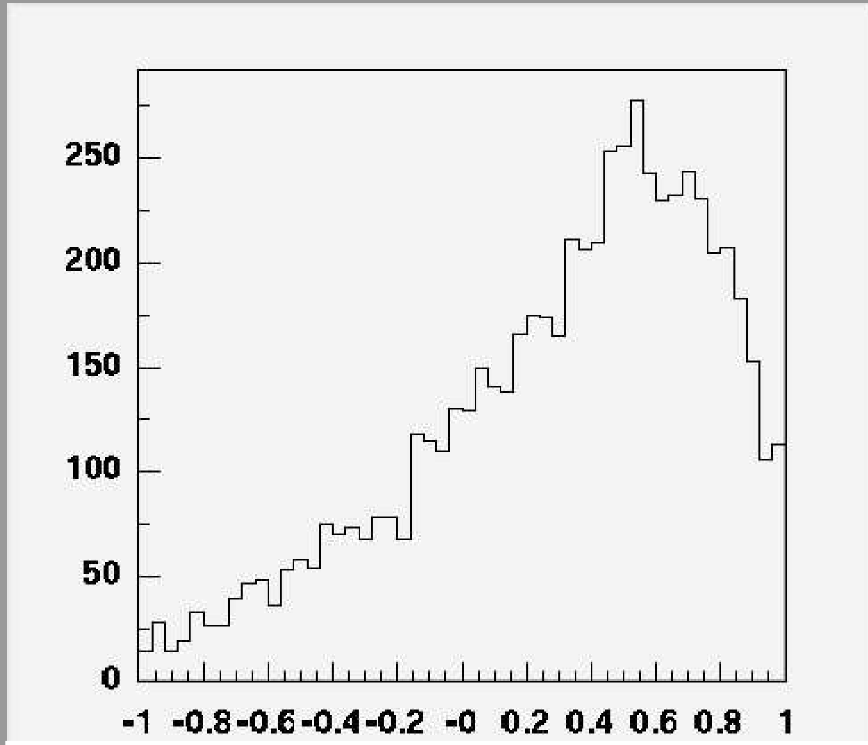
background: 30.4 events

$\Gamma \sim 33\, MeV/c^2$

~4.8 σ

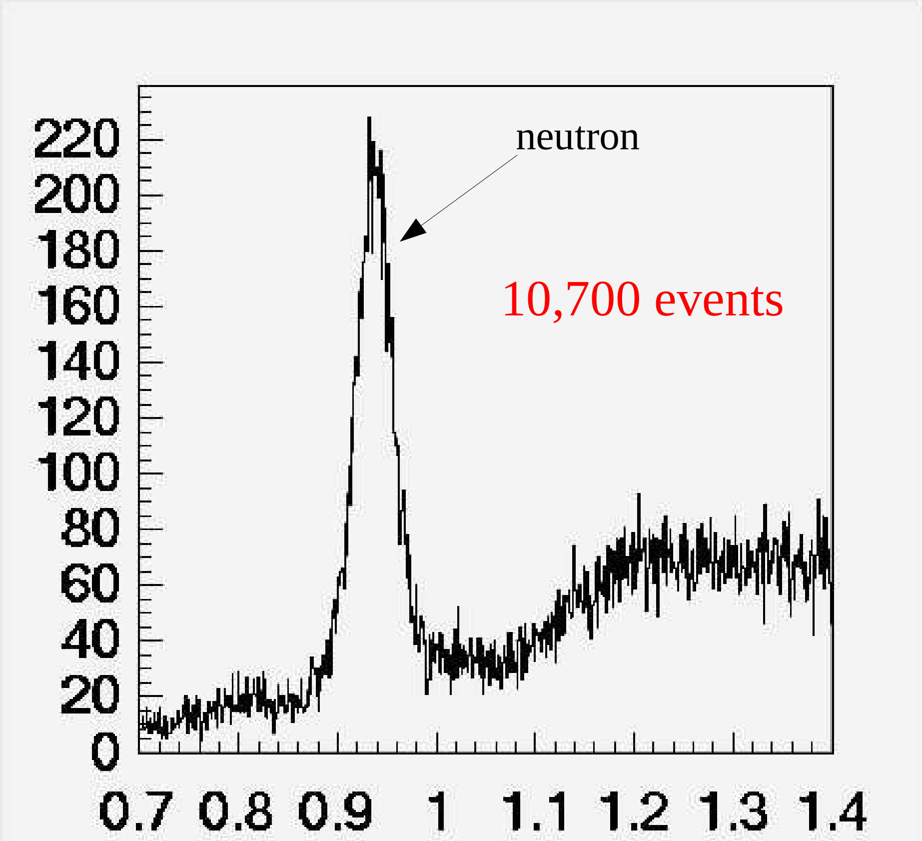
g_{6c} $\gamma p \rightarrow K^- K^+ \pi^+ n$ $4.8 < E_\gamma < 5.4$ GeV



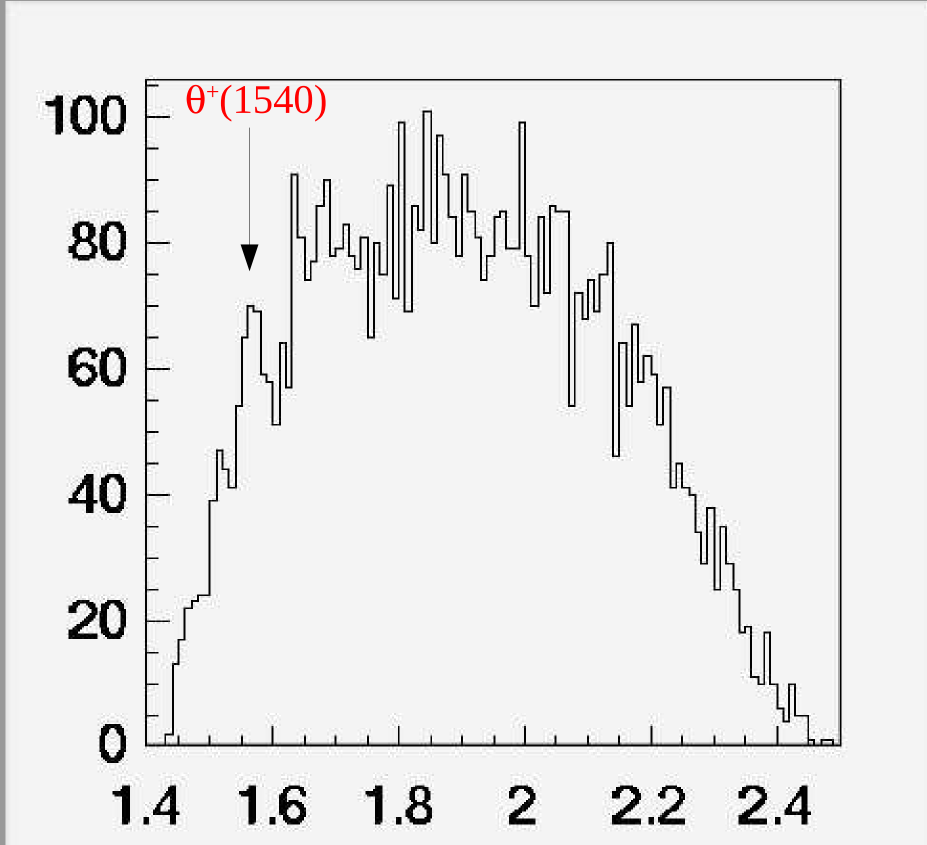


cos θ* (K- π+)

g_{6c} $\gamma\, p \rightarrow K^- K^+ \pi^+ n$ 4.8 < E_γ < 5.4 GeV

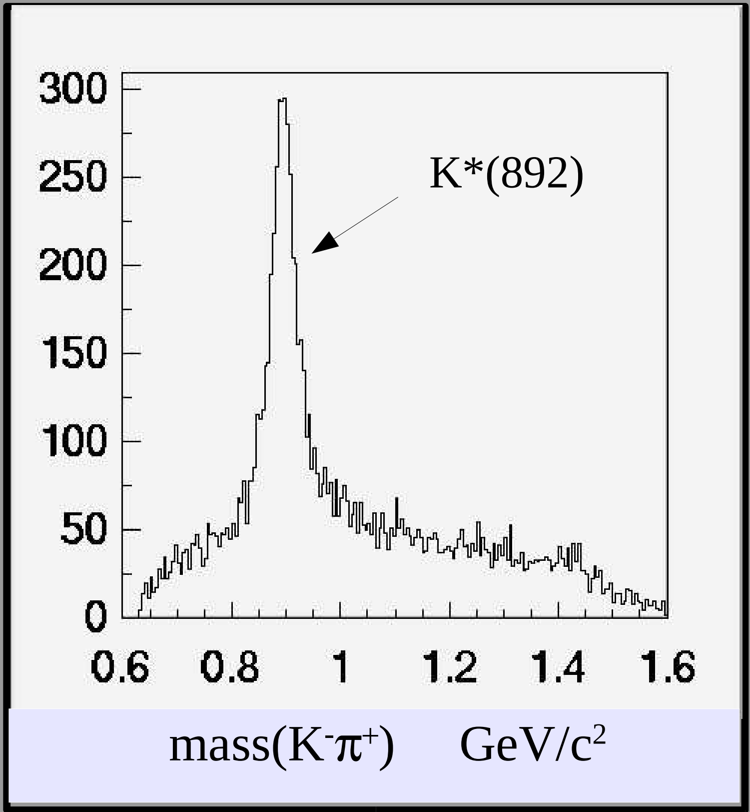


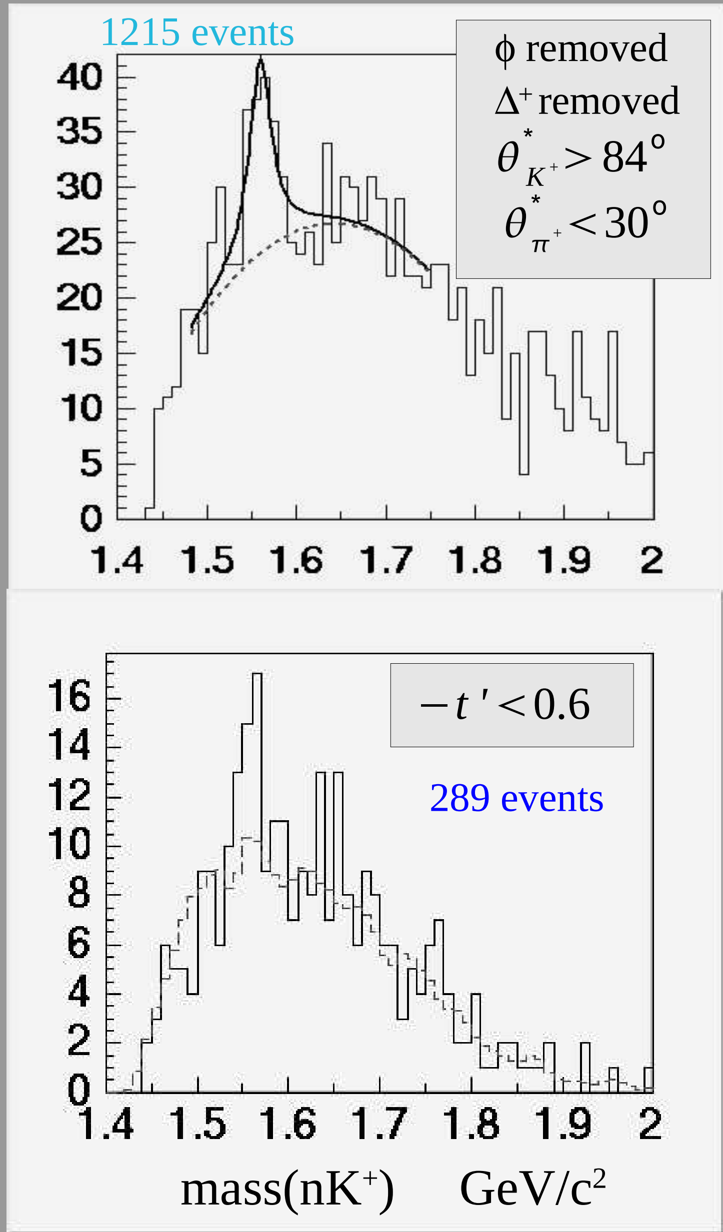
Missing Mass/$K^-K^+\pi^+$ (GeV/c^2)

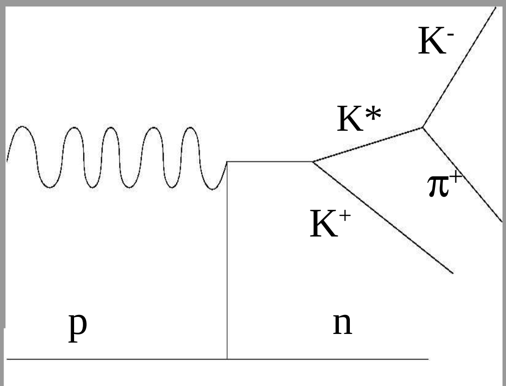


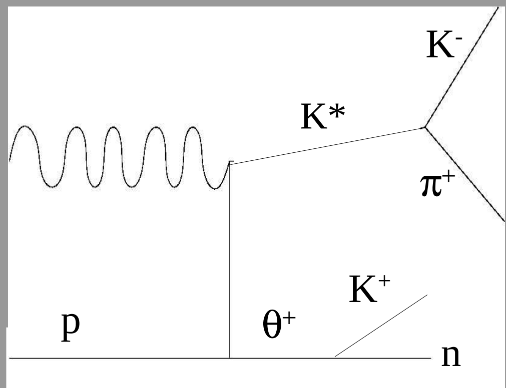
Mass (nK^+) (GeV/c^2)

g_{6c} $\gamma\, p \rightarrow K^- K^+ \pi^+ n$ $4.8 < E_\gamma < 5.4$ GeV

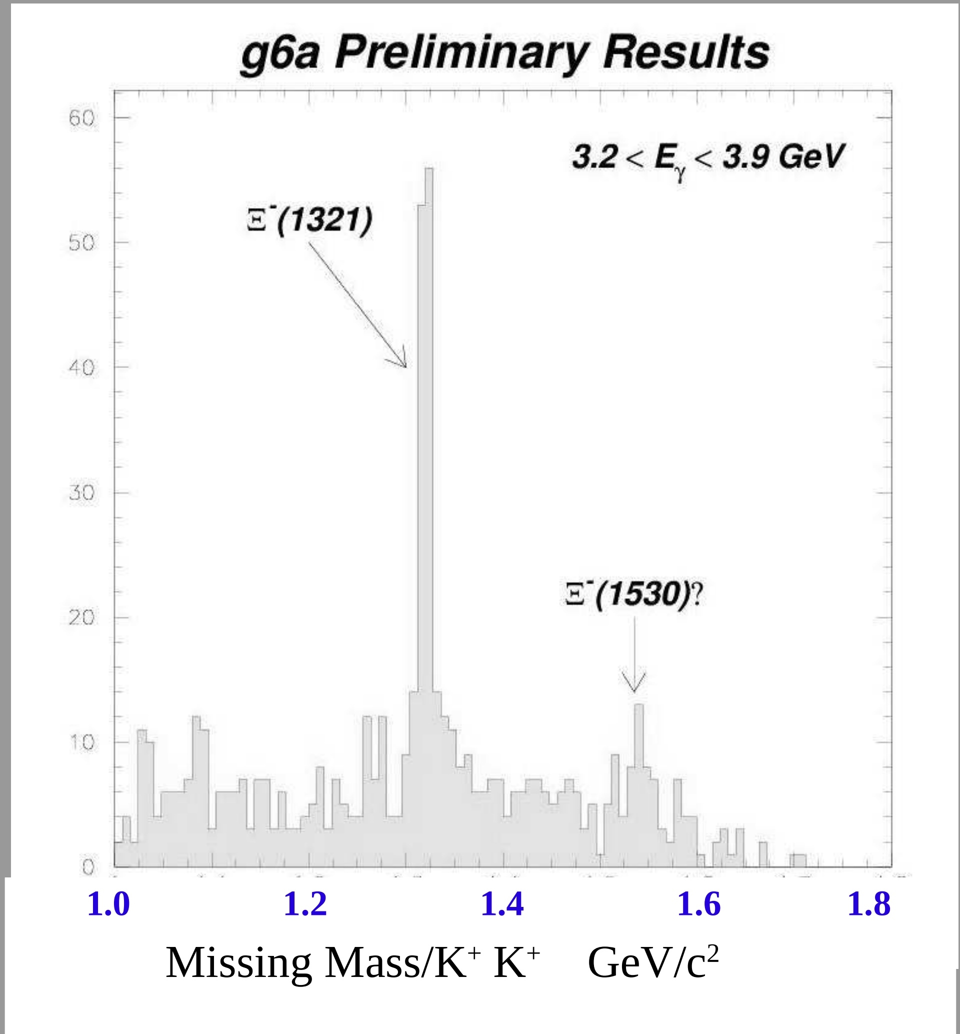


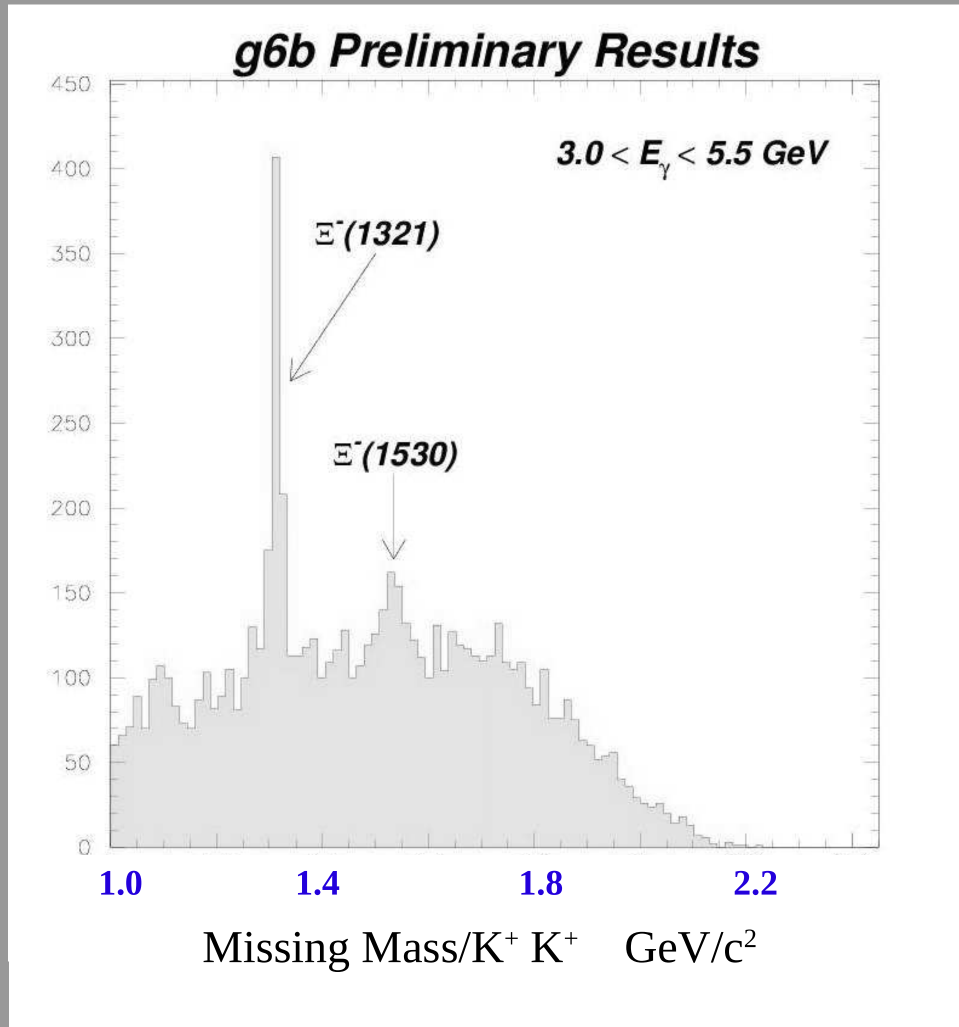






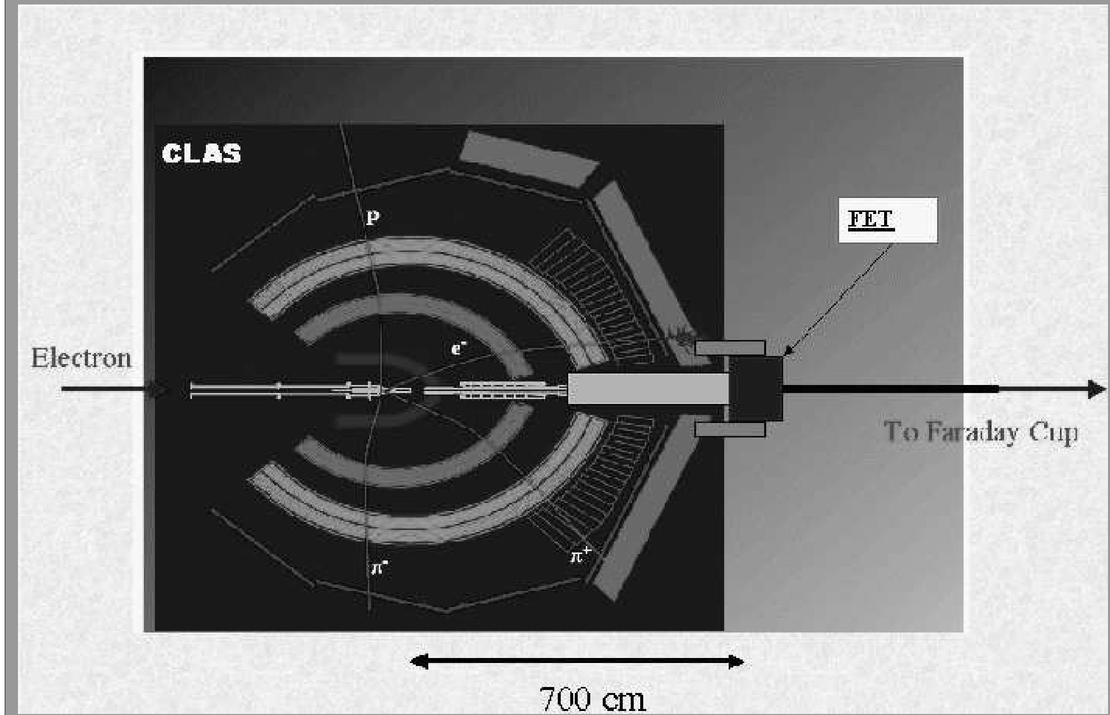
$g_{6a\text{-}b}$ $\gamma\, p \rightarrow K^+ K^+ X$



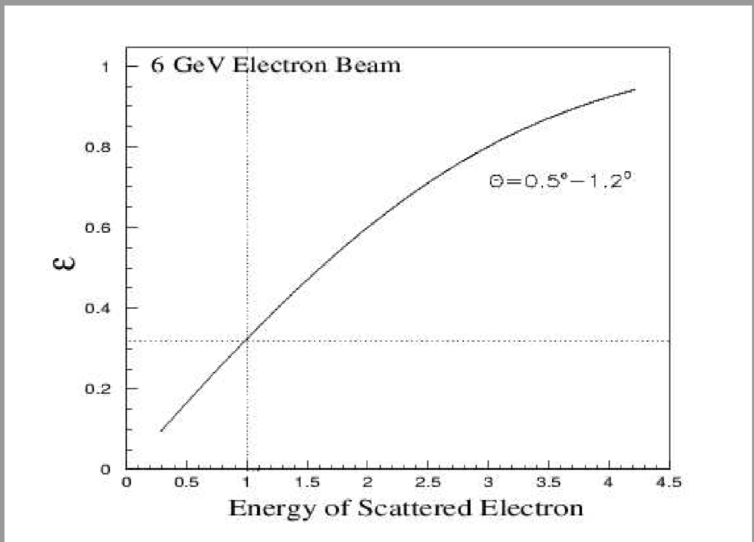


J. Price, J. Ducote, B.M.K. Nefkens (UCLA)

Meson Spectroscopy with Near Real Linear Polarized Photons at CLAS

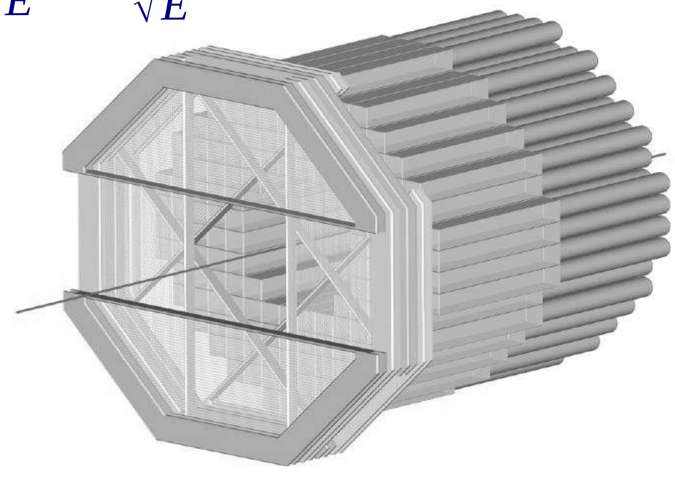


γ* Polarization

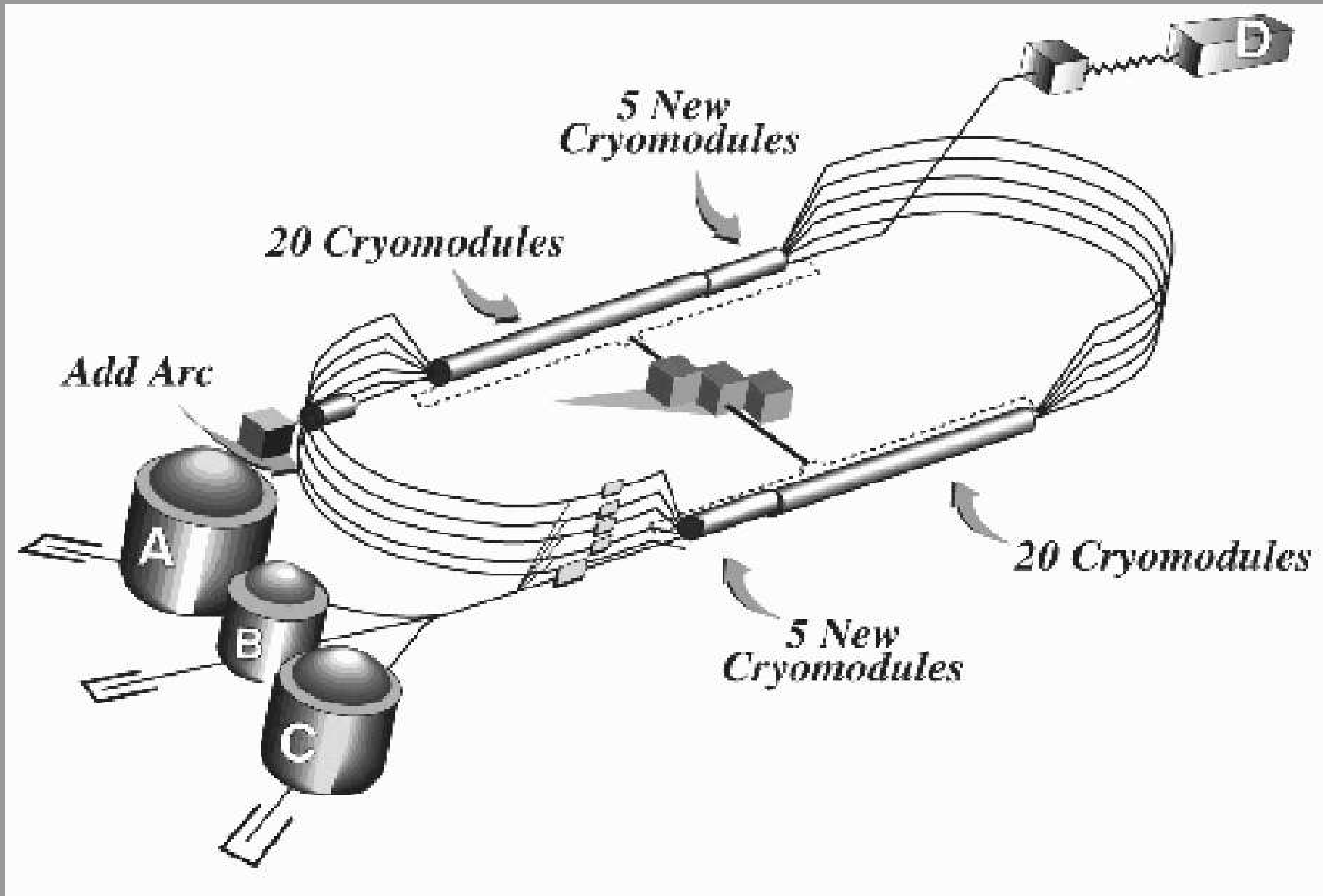


$PbWO_4$ or PbF_2 Calorimeter:

$$\frac{\Delta E}{E} \propto \frac{2.5\%}{\sqrt{E}}$$

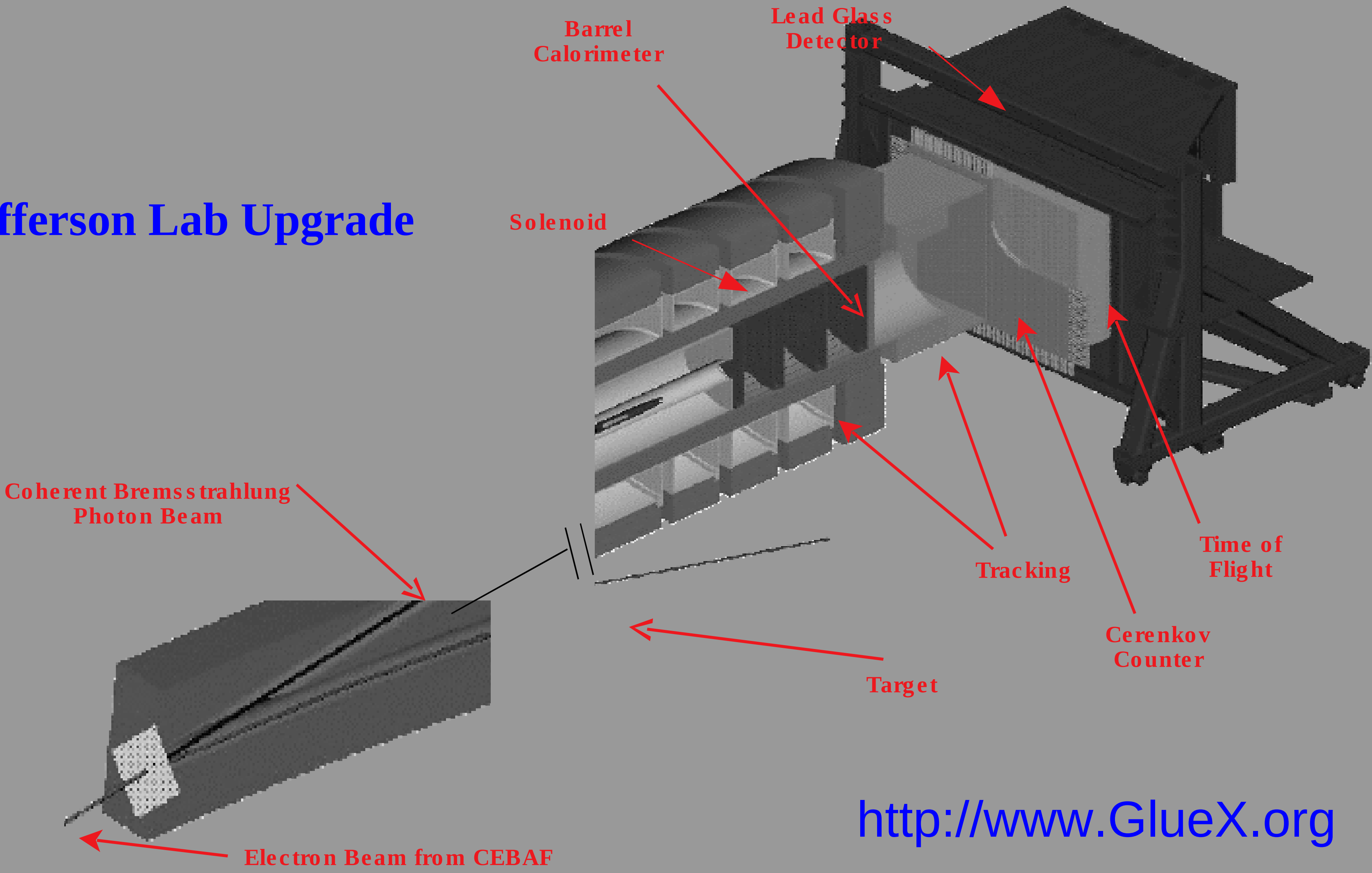


CEBAF 12 GeV Upgrade



Hall D

Jefferson Lab Upgrade



http://www.GlueX.org

and furthermore,

Ken Hicks:

Evidence for the θ⁺ Pentaquark at LEPS and CLAS — Exotics II

Paul Eugenio:

Proton-Antiproton Photo-production at CLAS — Reactions I