Examining the evidence for exotic hadrons

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Renaissance of QCD and hadron spectroscopy

RHIC : QCD super-fluid, highly correlated, low viscosity liquid

Belle, CLEO, Babar: new heavy quark states, possibly meson-molecules or hybrids

CERN (Crystal Barrel) : scalar glueball

BNL (E852) : hybrid mesons

Spring8, Jlab, and others : pentaquark

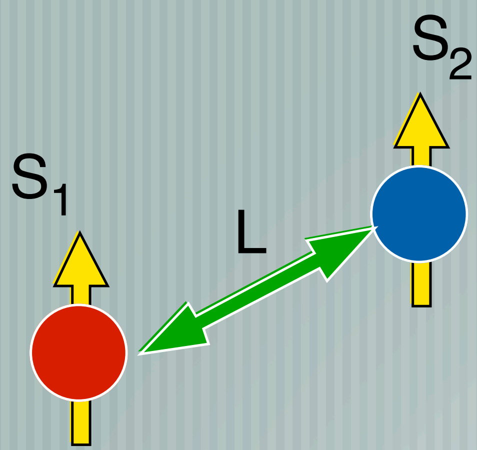
In this talk:

J^{PC} exotic : hybrid mesons

flavor exotic : pentaquarks

Mesons with $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$: Exotic Quantum Numbers

π_1



$S = S_1 + S_2$

$J = L + S$

$P = (-1)^{L+1}$

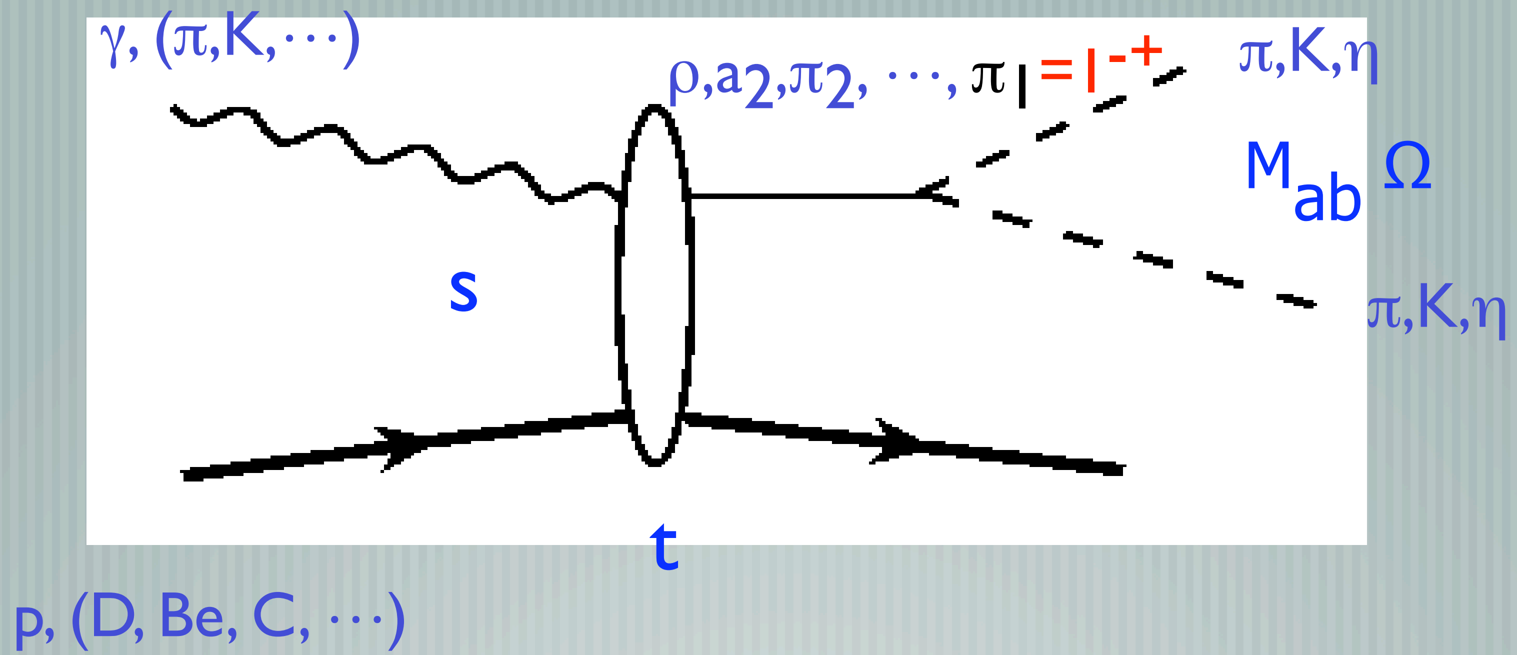
$C = (-1)^{L+S}$

Determine J^{PC} through Partial Wave Analysis

No need for muti-quarks (which have fall apart modes)
Can be formed from excitations of the confining (gluon) field
→ Probe of the confinement mechanism

Exciting (exotic) meson resonances

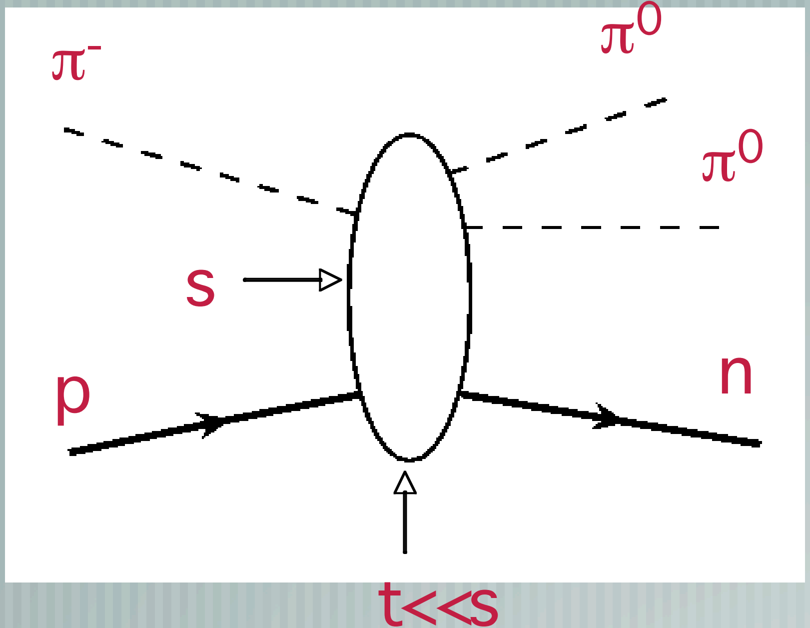
E852: $E_\pi = 18 GeV$

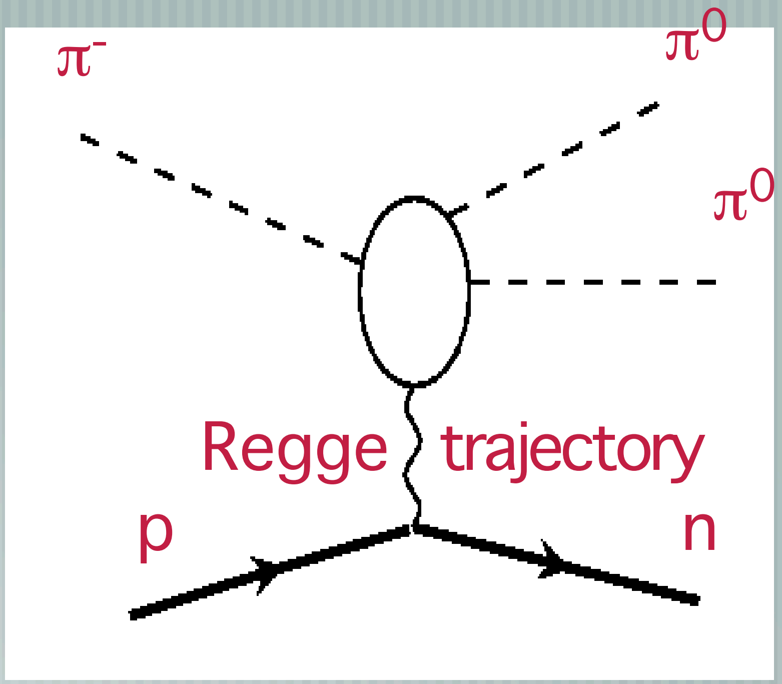


Peripheral production on the "meson cloud"

It is important to determine dependence on all kinematical variables, s,t,M_{ab} Ω

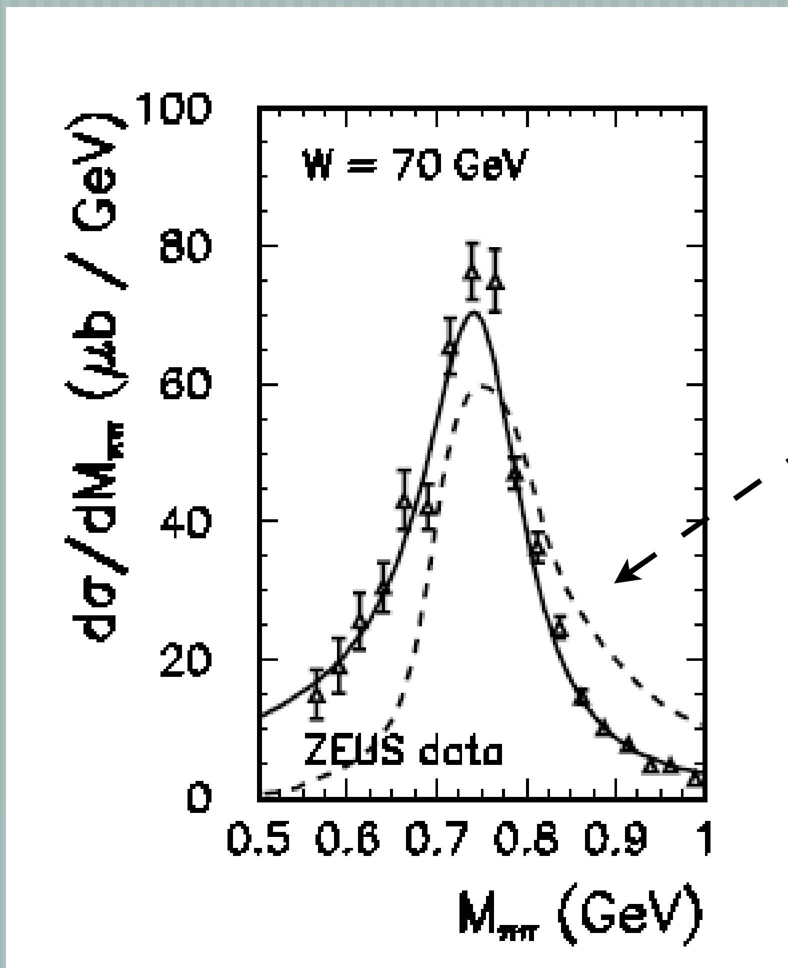
Extraction of amplitudes

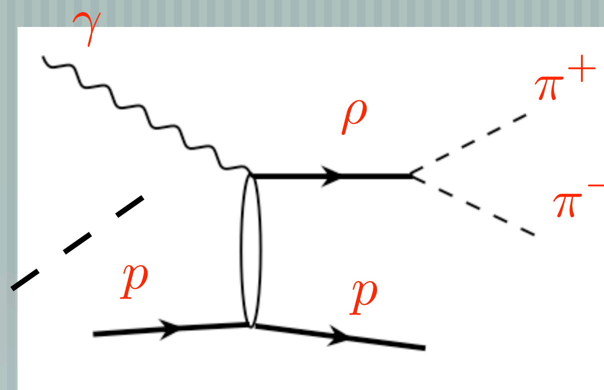




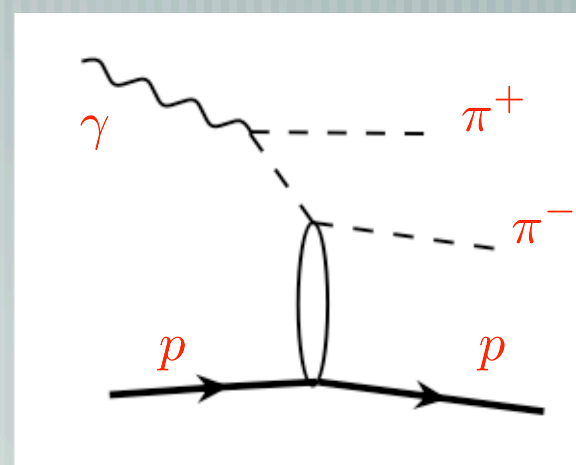
Regge and low-energy phenomenology via FMSR determine dependence on channel variables, s_{ij}

Backgrounds should be understood





Inelastic diffraction, (W > 2 GeV)



$$\sigma(\pi^+ p \to \pi^+ p) \neq \sigma(\pi^- p \to \pi^- p)$$

A.Szczurek, AS.

What’s new

- Unprecedented statistics
- Computational resources
- New theoretical developments :
  - low energy, (chiral) phenomenology
  - QCD, lattice
- High quality photon beams (exotic searches)

Theoretical expectations

Light quark 1^{-+}

Ref.	Method	N_f	M (GeV)
UKQCD 97	SW	0	1.87(20)
MILC 97	W	0	1.97(9)(30)
MILC 99	SW	0	2.11(10)
LaSch 99	W	2	1.9(2)

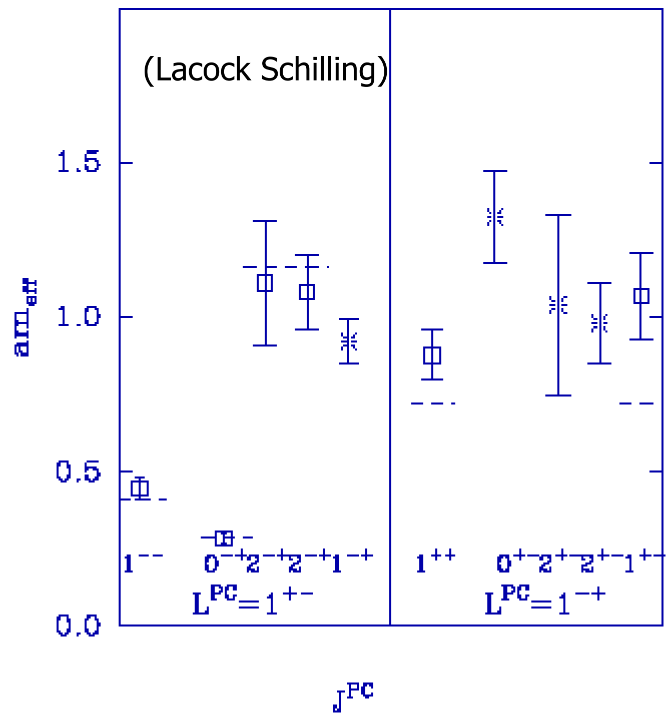
Calculation of lightest 1^{-+} Exotic suggests mass $\sim$ 2GeV

Charmonium 1^{-+}

Ref.	Method	ΔM (GeV)
MILC 97	W	1.34(8)(20)
MILC 99	SW	1.22(15)
CP-PACS 99	NR	1.323(13)
JKM 99	LBO	1.19

Excitations in excess of 1GeV

Lattice predictions



- $J^{PC} = 1^{-+}$ lowest state
- Higher masses difficult to resolve
- Chiral extrapolations 100-200 MeV

Thomas.AS

Decays

- Normal widths !

In large N_C same as for ordinary mesons $O(1/N_C)$ T. Cohen (98)

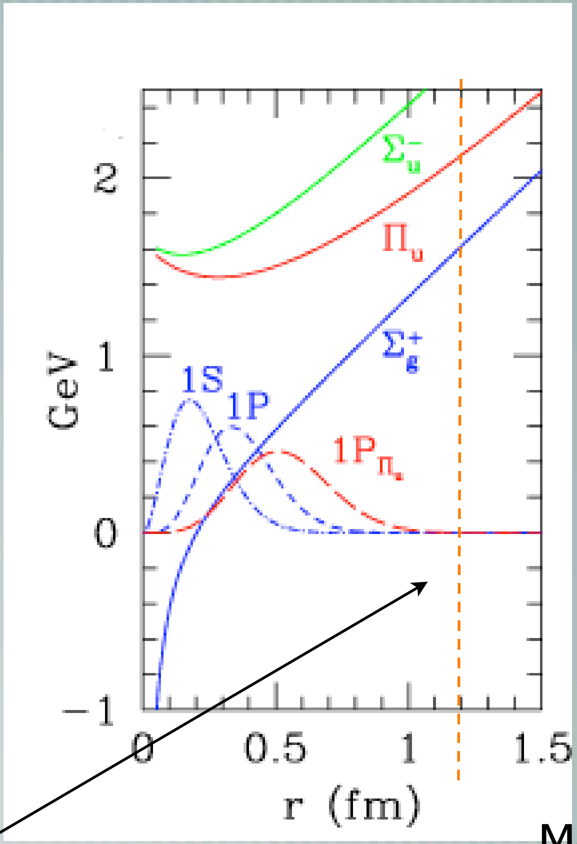
- Unusual decay modes !

Isgur, Kokosy, Paton (85)
Page, Swanson, AS (99)

1^{-+} (1.8 GeV)	$b_1 \pi$	$f_1 \pi$	$\rho \pi$	
PSS	S 73 D 1	S 9 D 0.04	P 13	Γ MeV
IKP	S 51 D 11	S 14 D 7	P 12	

Close, Dudek (04)

- Compact wave functions!



Juge, Kuti, Morningstar (99)

- Low lying states expected below string breaking !

Bali (00)

Exotic story

$\pi^- p \to \eta \pi^0 N$
$\to \eta \pi^- p$

($\eta\pi^0$) in P-wave has $J^{PC}=1^{-+}$!

$\pi^- p \to \eta\pi^- p$

$M = 1370 \pm 16^{+50}_{-30}$ MeV / c^2

$\Gamma = 385 \pm 40^{+65}_{-105}$ MeV / c^2

BNL (E852)
Confirmed by
Crystal Barrel similar mass, width

$\pi^- p \to \eta\pi^0 n$

New results: No consistent B-W resonance interpretation for the P-wave

P-wave consistent with meson-meson rescattering (Final State Interactions)

$\pi^- p \to \eta'\pi^- p$

$M = 1597 \pm 10^{+45}_{-10}$ MeV / c^2

$\Gamma = 340 \pm 40^{+50}_{-50}$ MeV / c^2

$\pi^- p \to \rho^0\pi^- p$

$M = 1593 \pm 8^{+29}_{-47}$ MeV / c^2

$\Gamma = 168 \pm 20^{+150}_{-12}$ MeV / c^2

Confirmed by VES
More E852 3π data to be analyzed

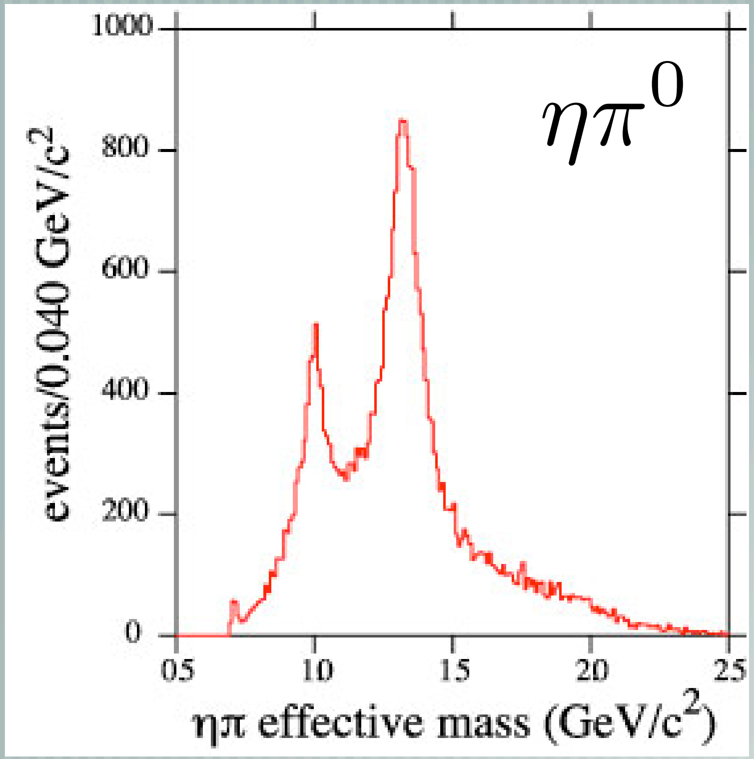
$\pi^- p \to b_1 \pi p$
$\pi^- p \to f_1 \pi p$

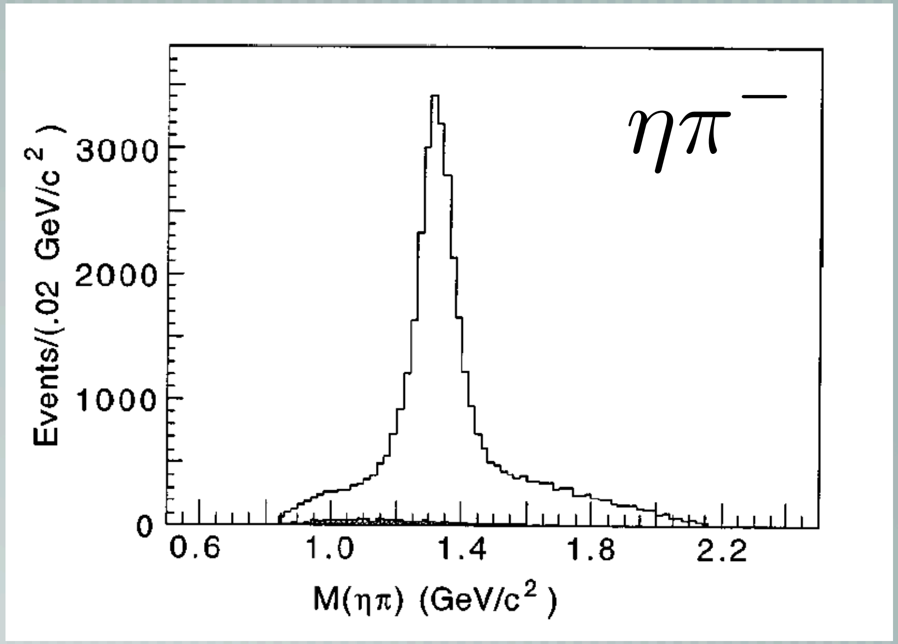
ηπ Production

$$\pi^-(18\ \text{GeV})p \rightarrow \begin{cases} \eta\pi^0 n \\ \eta\pi^- p \end{cases}$$

Neutral vs charged production:

- ✓ C is a good quantum number
- ✓ a_0 and a_2 are produced
- ✓ only one detector involved

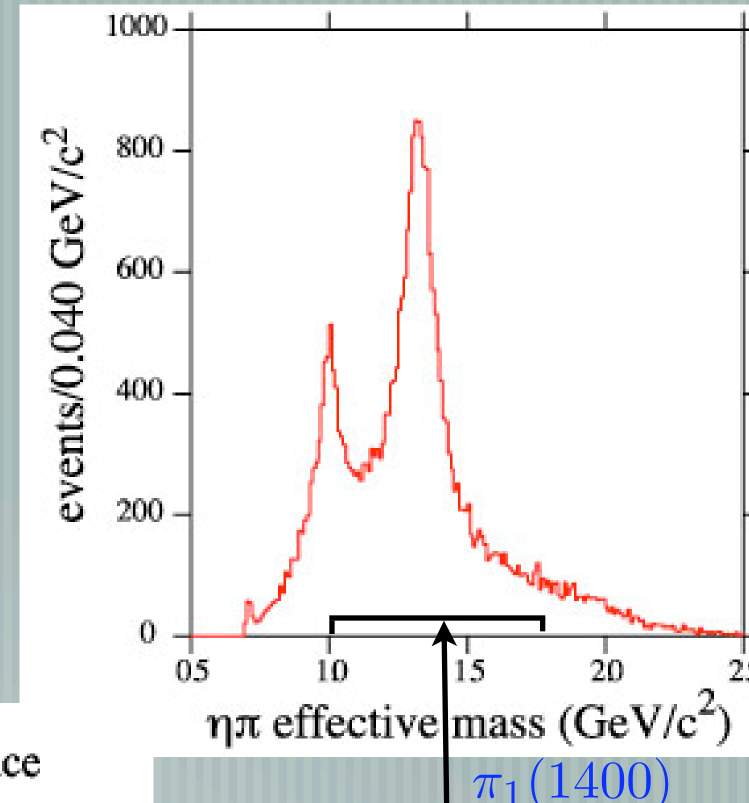


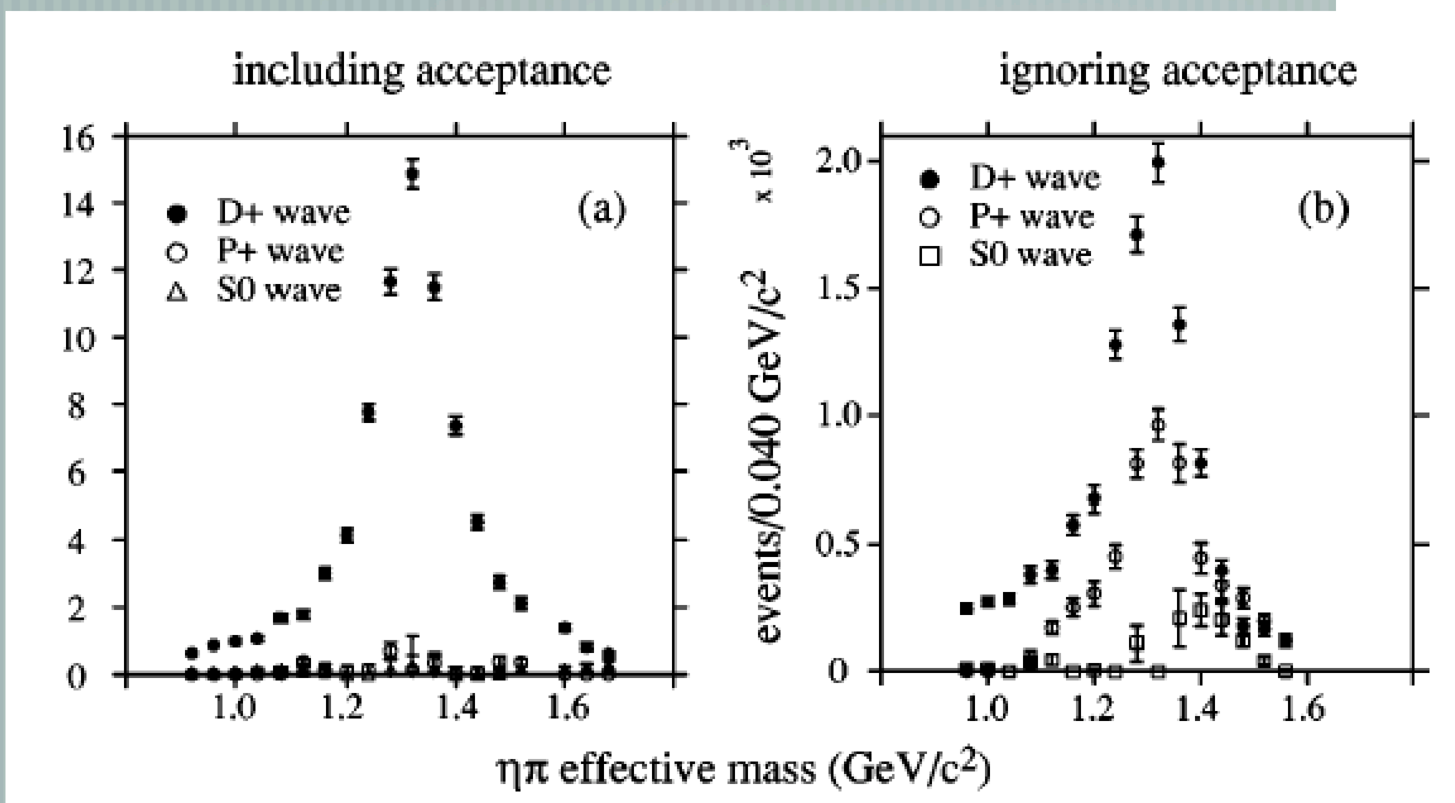


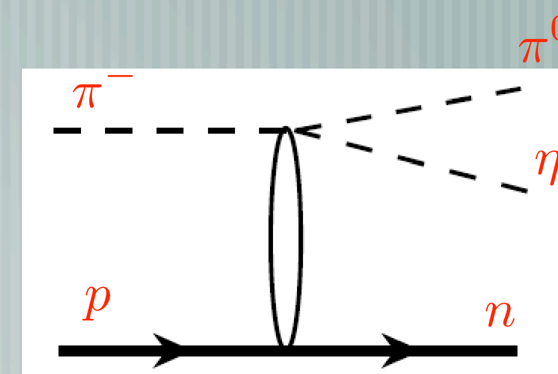
Have we seen exotic mesons
The $\pi_1(1400)$ story

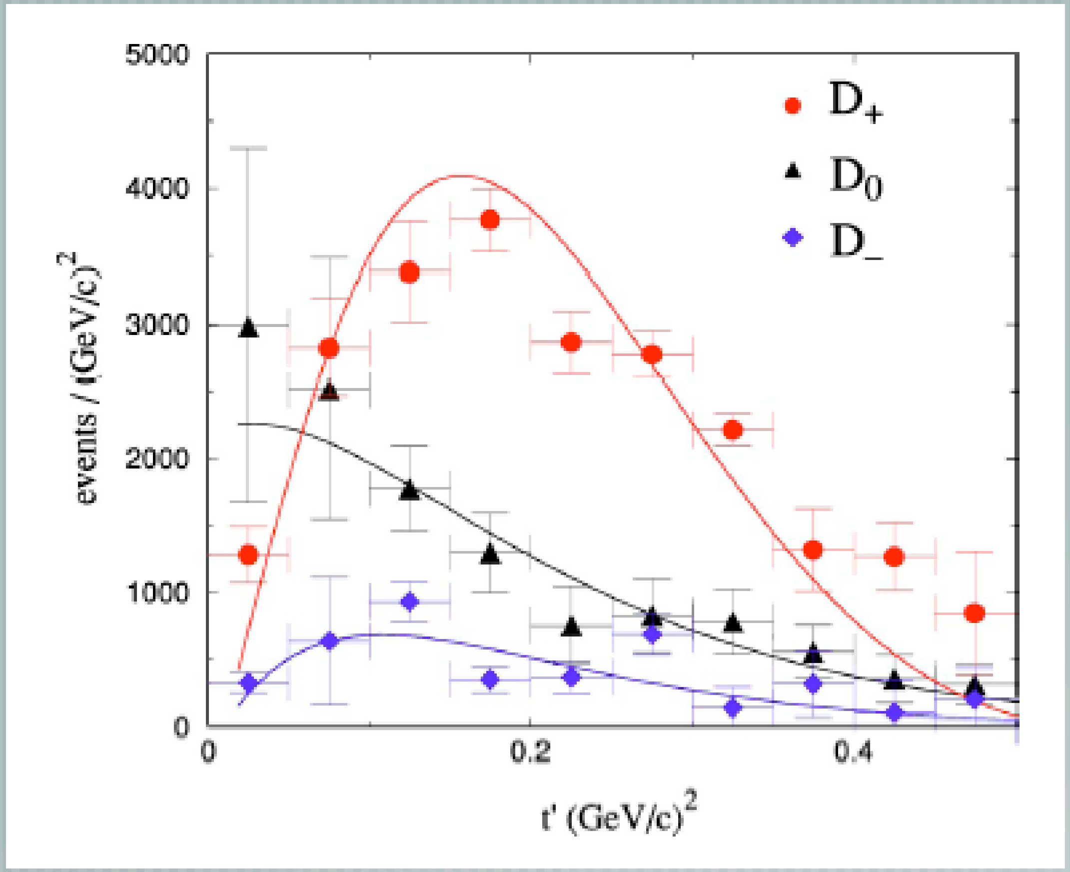
$$I(\Omega) = |SY_{00}(\Omega) + \sum_m P_m Y_{1m}(\Omega) + \cdots|^2$$

$$I(\Omega) \rightarrow I_{exp.}(\Omega) = I(\Omega) \text{ acceptance } (\Omega)$$

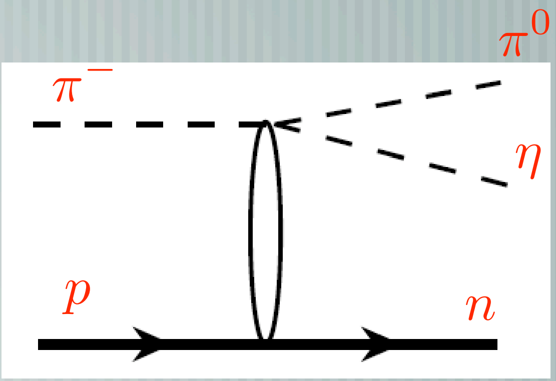






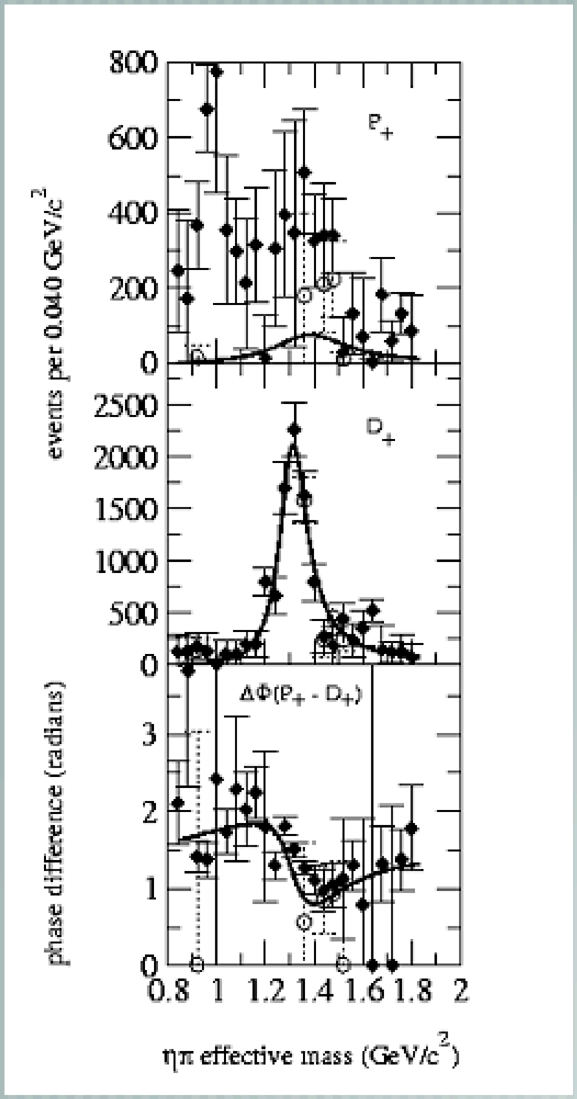


events / (GeV/c)^2
t' (GeV/c)^2
D+
D0
D_
0
1000
2000
3000
4000
5000
0
0.2
0.4



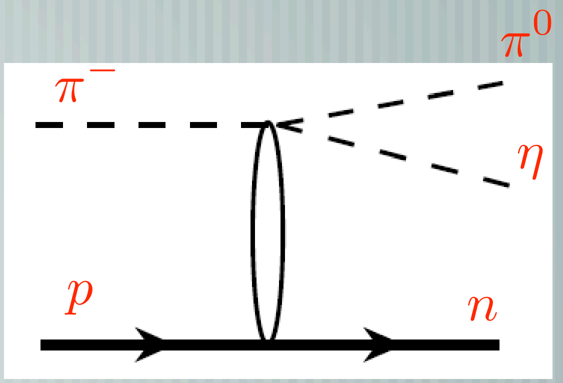
π^0
π^−
η
p
n

Assume BW resonance in all, M=-1,+1,0, P-waves

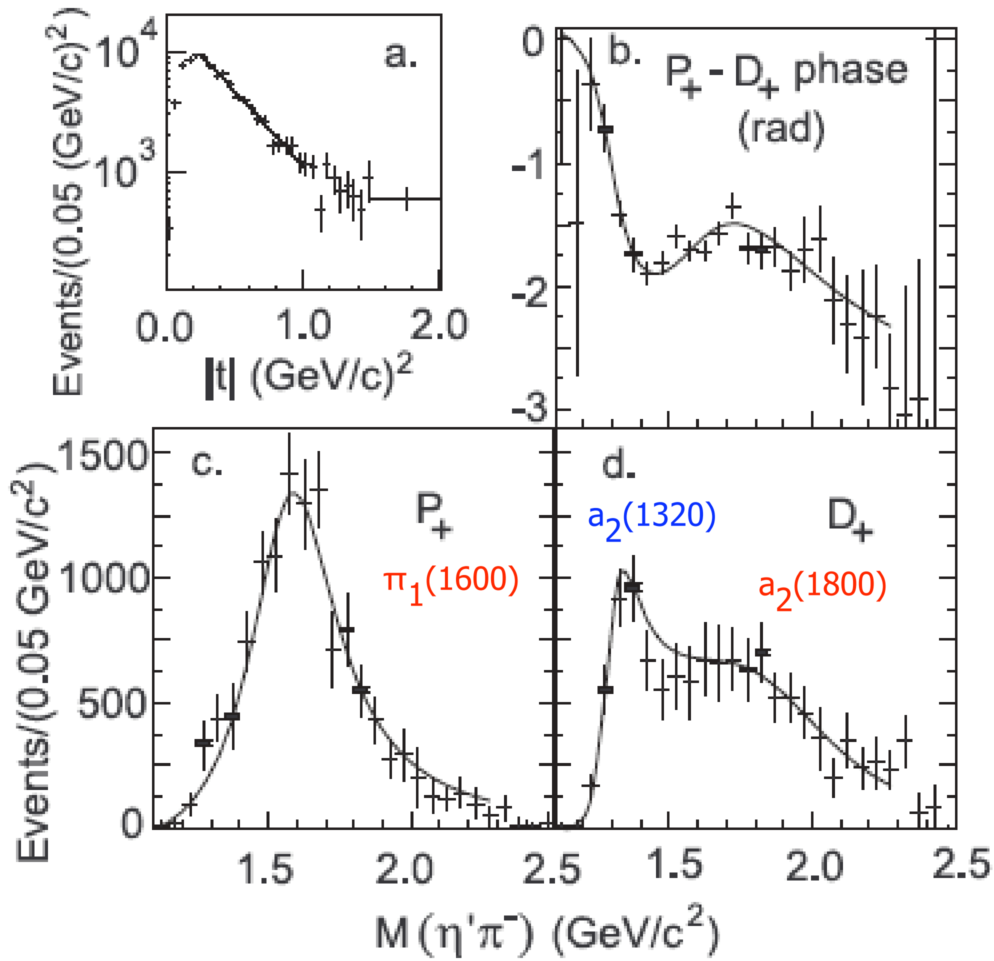


π_1(900 – 5GeV) emerges

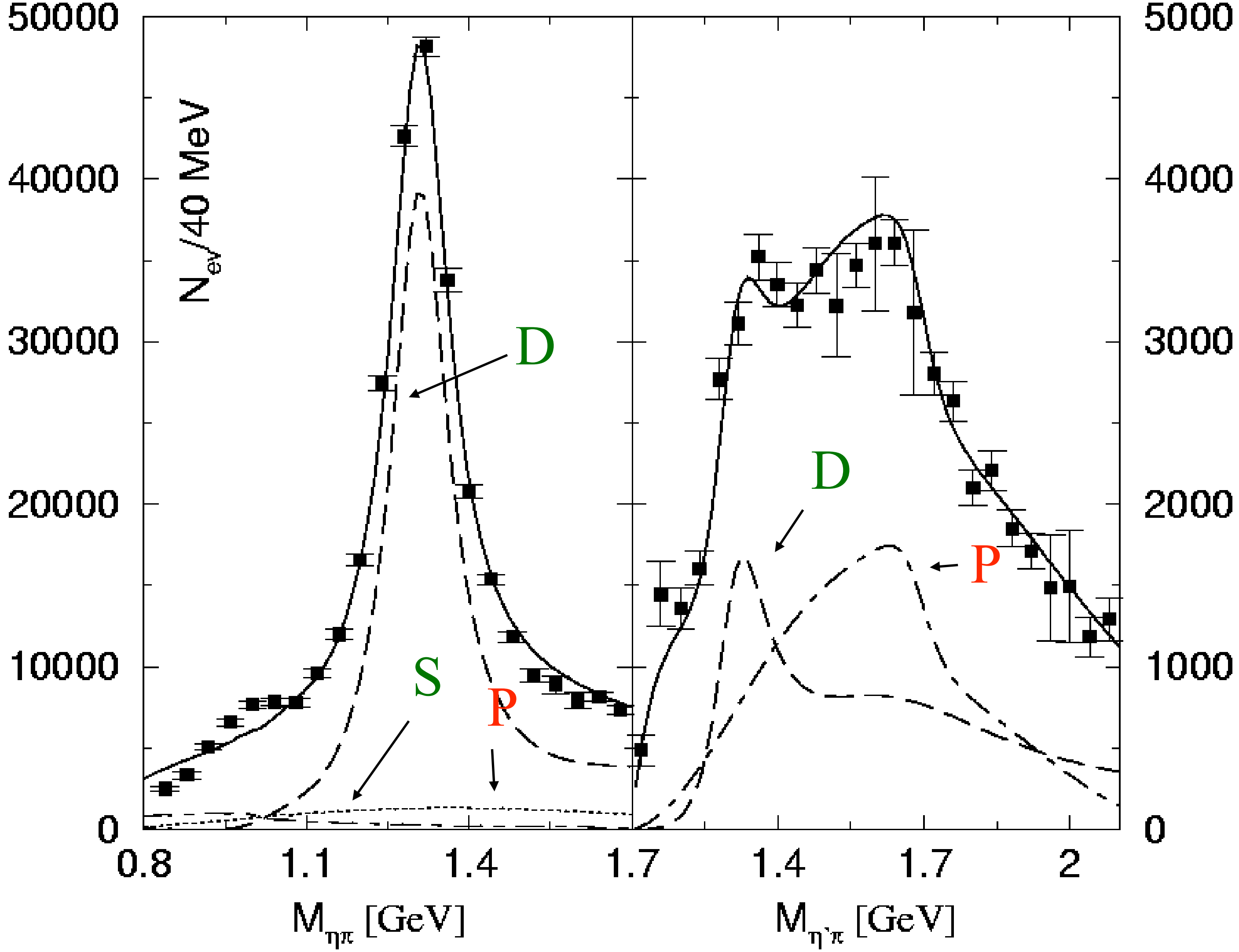
Intensity in the weak P-waves is strongly affected by the a_2(1320), strong wave due to acceptance corrections



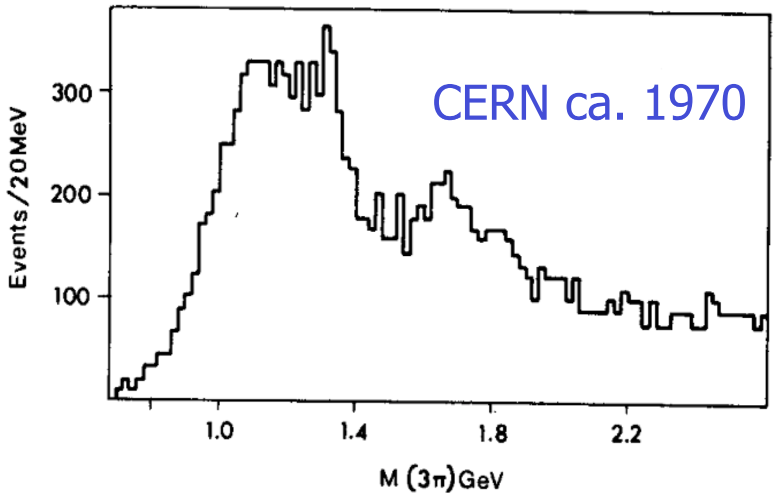
Clear P-wave in $\eta'\pi$

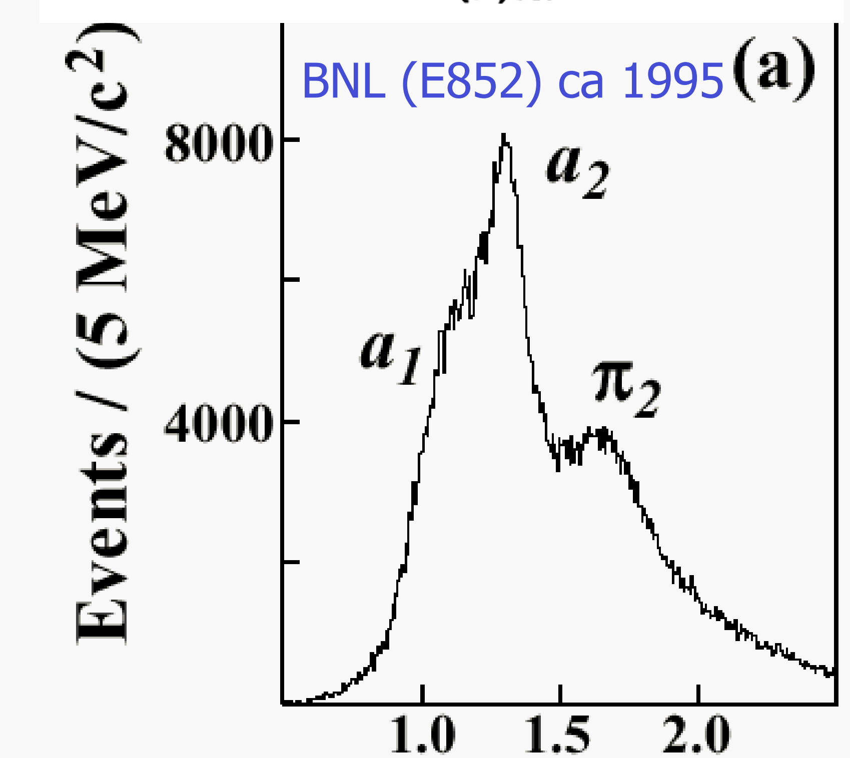


Results of coupled channel analysis of $\pi^- p \rightarrow \eta\pi^- p$
$\pi^- p \rightarrow \eta'\pi^- p$

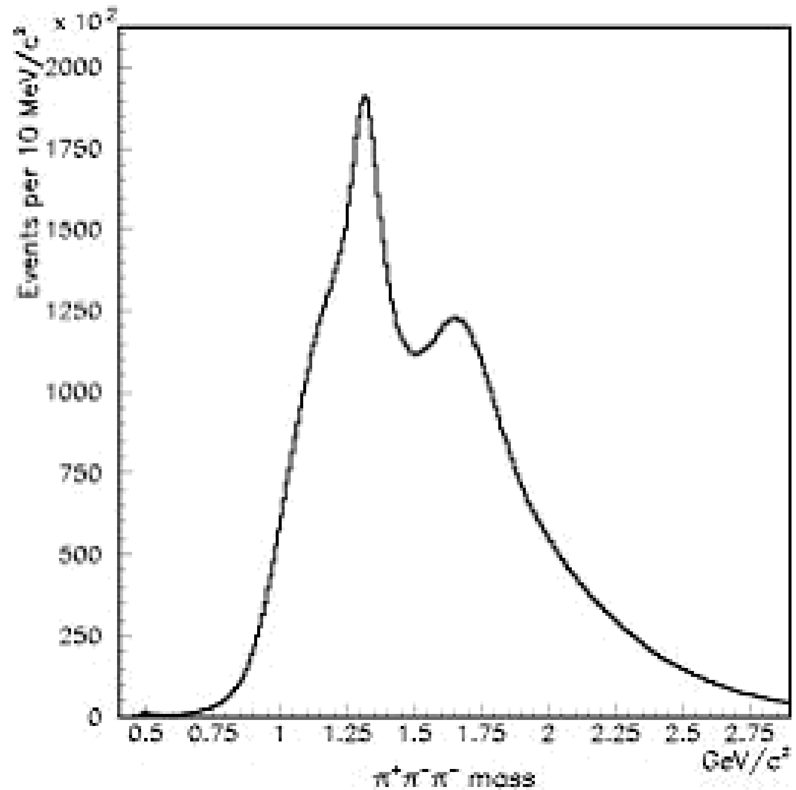


$\pi^- p \rightarrow \pi^-\pi^+\pi^- p$



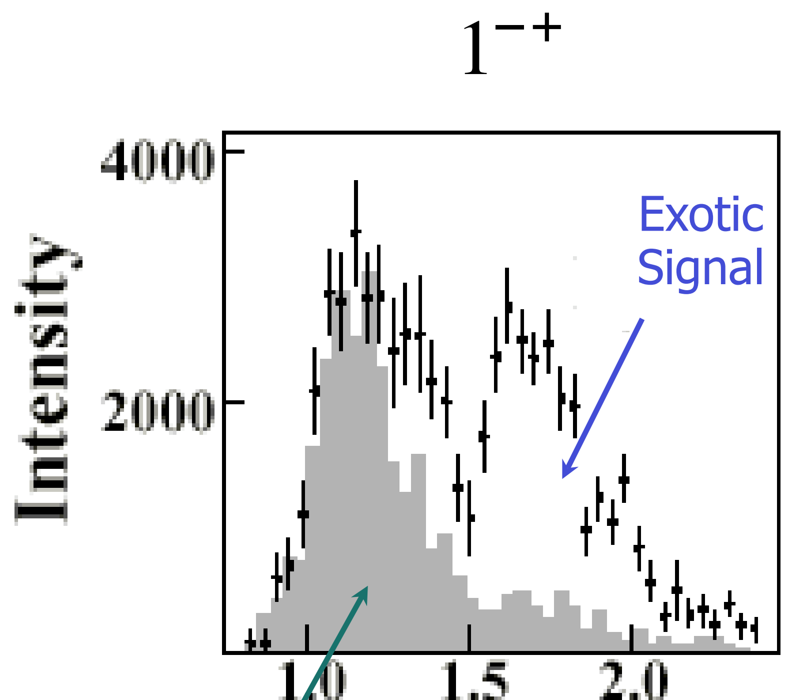


E852 2003
Full sample



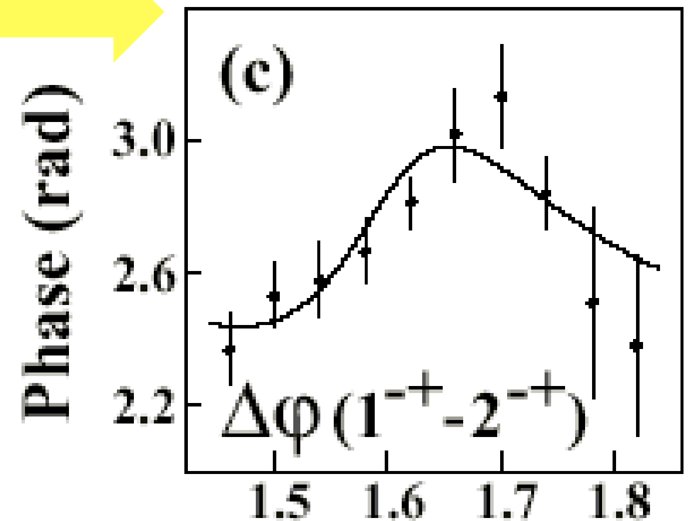
Have we seen exotic mesons

The $\pi_1(1600)$ story in $\pi^+\pi^-\pi^-$

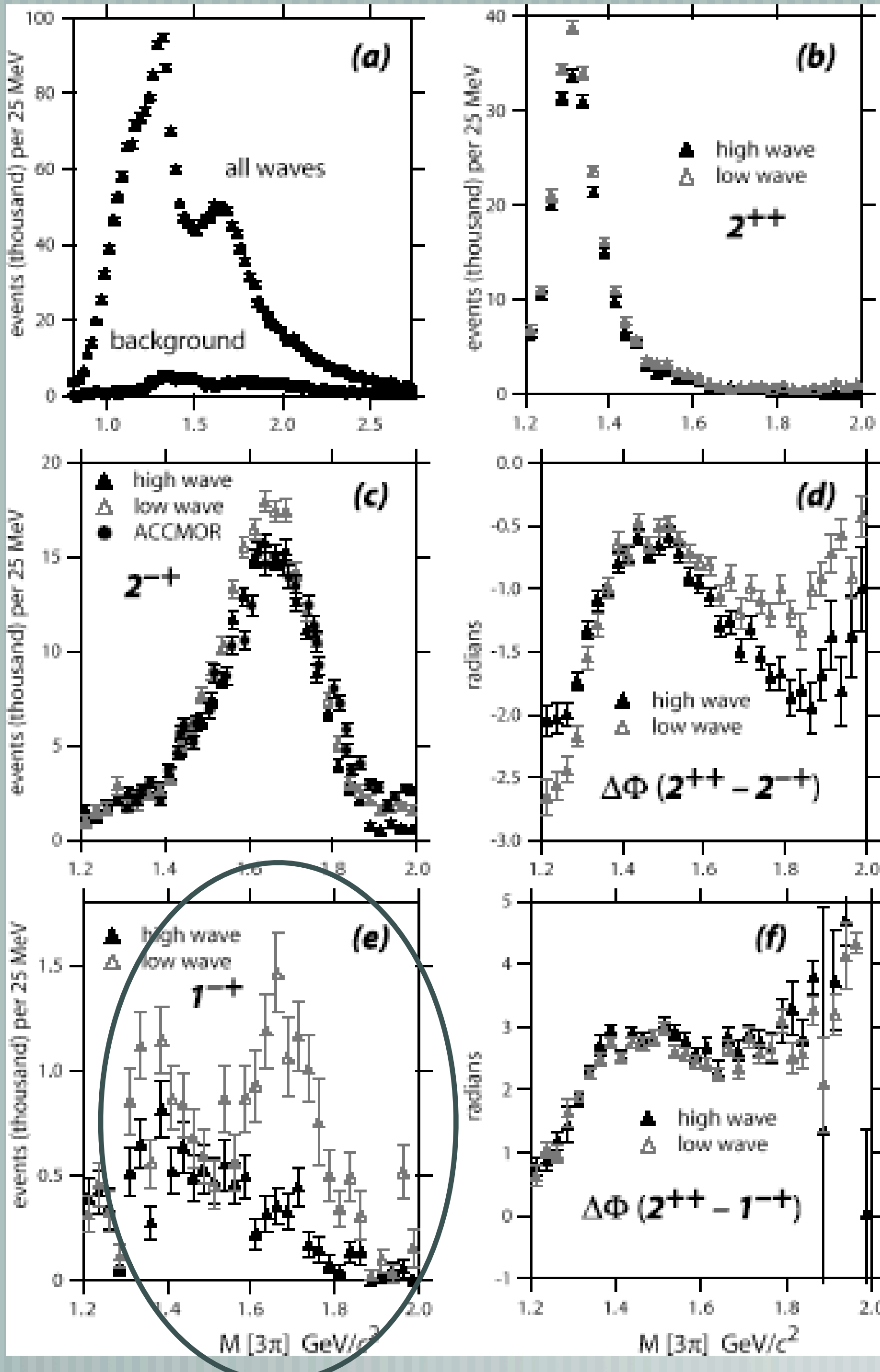


Leakage
From
Non-exotic Wave
due to imperfectly
understood acceptance

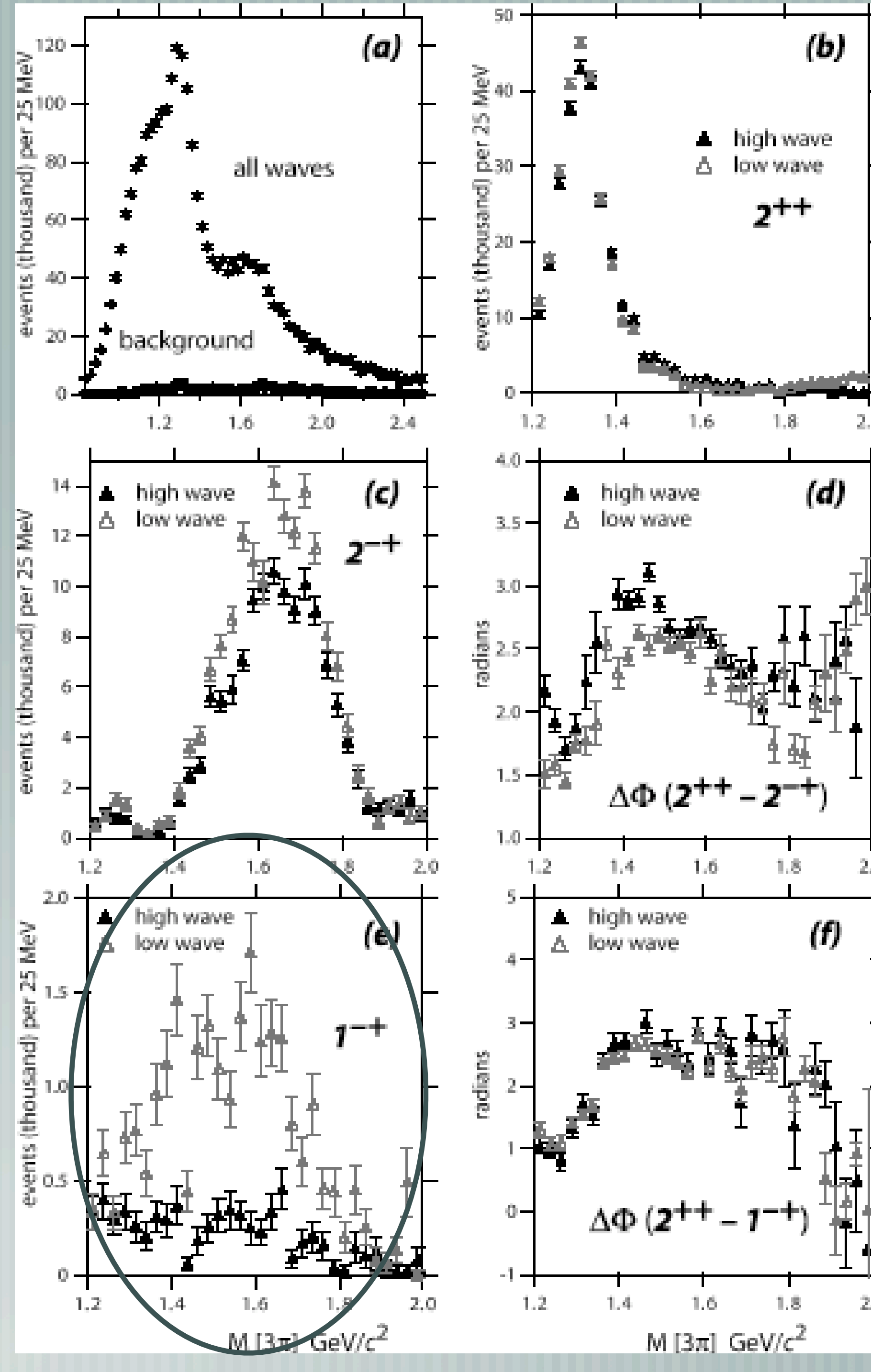
Correlation of
Phase
&
Intensity



Based on 250K events Currently analyzing 10M events!



$\pi^+\pi^-\pi^-$



$\pi^0\pi^0\pi^-$

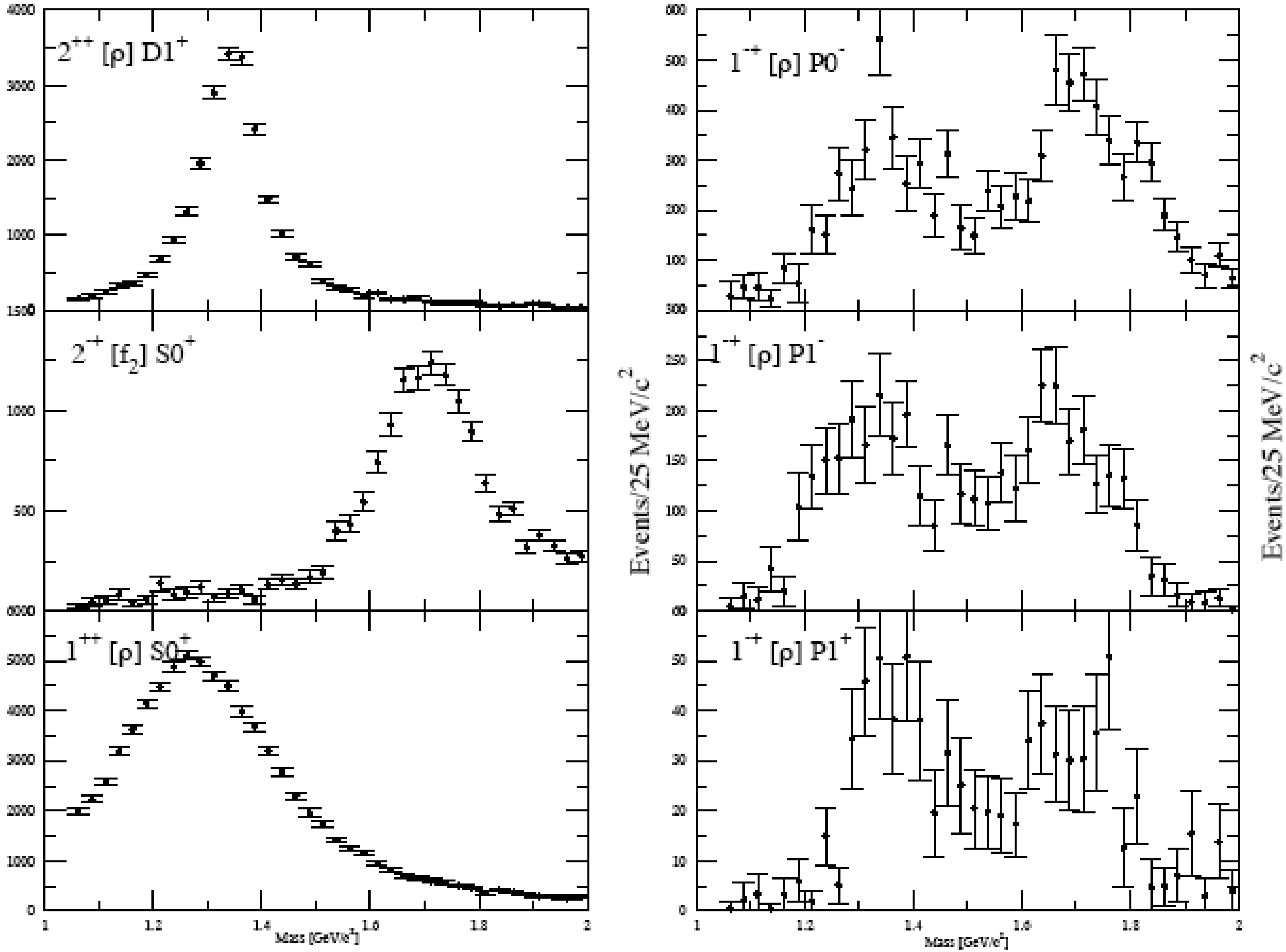


Figure 5. PWA on artificial data sample without acceptance correction and with insufficient number of waves. Notice how leakage shows up in all exotic waves.

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Further results from charge-exchange photoproduction

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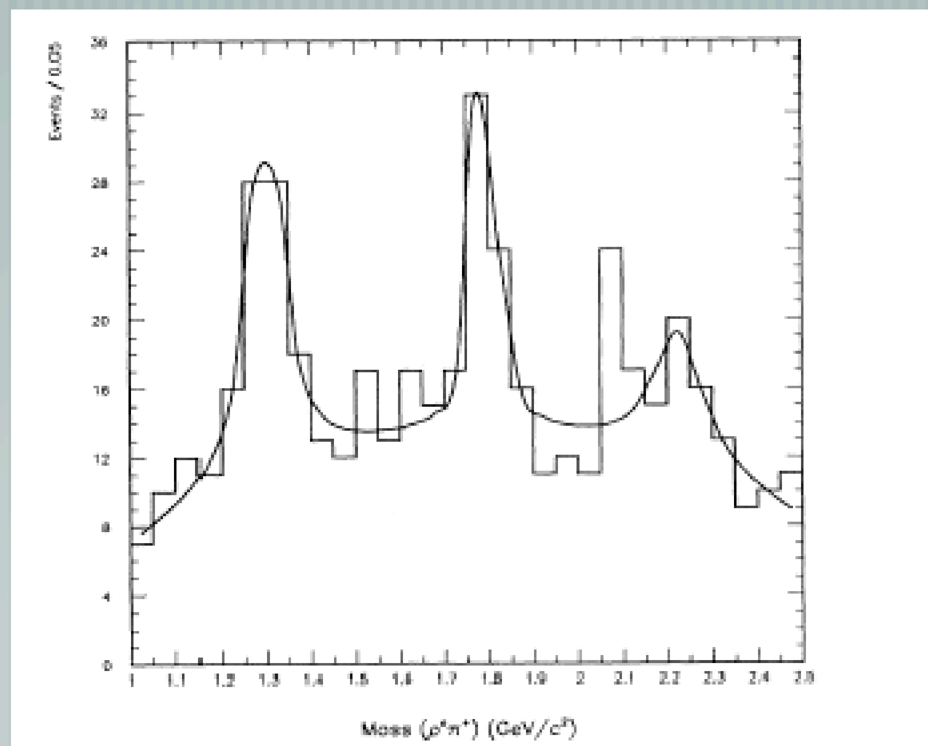


Role of Photons

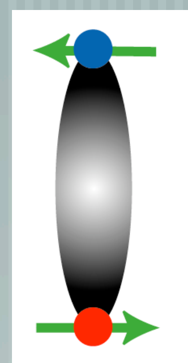
Quarks $\oplus$ **Excited Flux Tube** → **Hybrid Meson**

$S = 0$

$L = 0$

$J^{PC} = 0^{-+}$

like π, K



$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

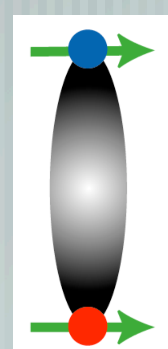
$$J^{PC} = \begin{cases} 1^{--} \\ 1^{++} \end{cases}$$

$S = 1$

$L = 0$

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

like γ, ρ



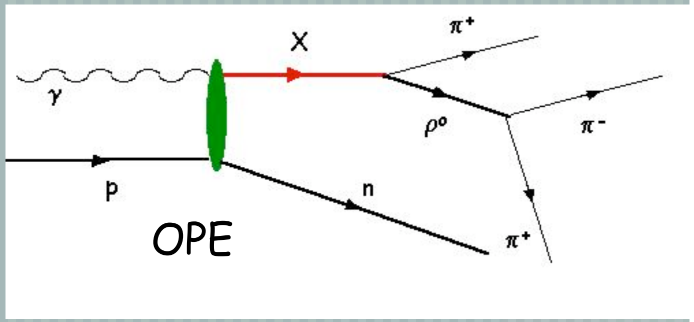
$$J^{PC} = \begin{cases} 1^{+-} \\ 1^{-+} \end{cases}$$

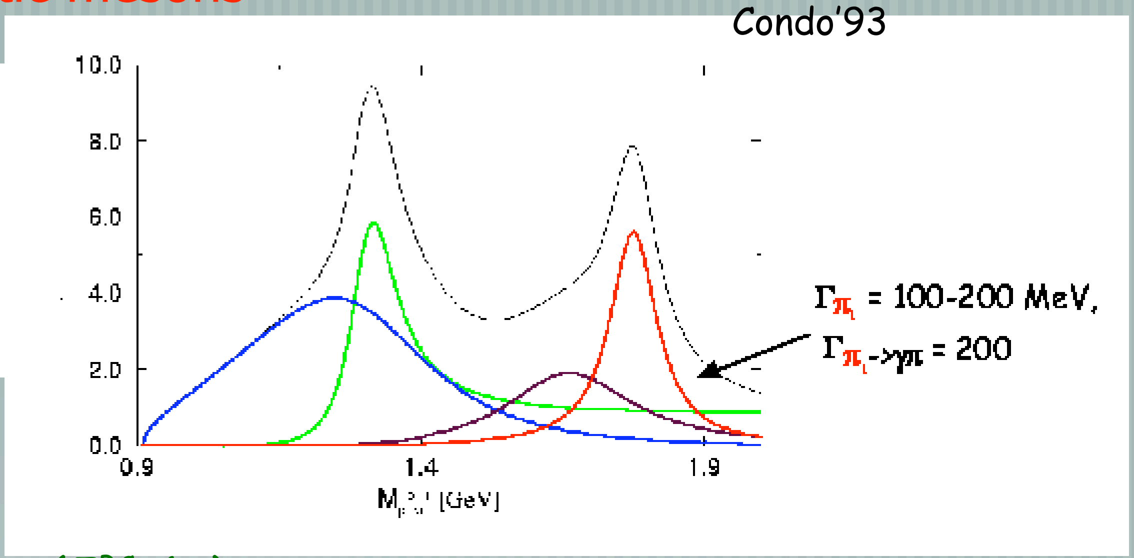
Exotic

$$J^{PC} = \begin{cases} 0^{-+} \quad 1^{-+} \quad 2^{-+} \\ 0^{+-} \quad 1^{+-} \quad 2^{+-} \end{cases}$$

So only parallel quark spins lead to exotic J^{PC}

Photo production enhances exotic mesons





1^{-+} exotic : S=1, L=1

γ --> $\rho(J^{PC}=1^{--})$ --> $\pi_1(J^{PC}=1^{-+})$

VMD

"pluck" the string ($S=1, L_{QQ}=0 \to L_g=1$)

	J^{PC}	$\rho\pi$ decay mode	Mass (MeV)	Γ (Mev)	$\Gamma_{3\pi}/\Gamma$	σ_γ (μb)
a_1	1^{++}	S D	1260	400	99% 1%	~0.03
a_1	2^{++}	D	1320	110	70%	~0.50
π_2	2^{-+}	P F	1670	260	30% 1%	~0.02
π_1	1^{-+}	P	1600	160	50%	~0.02

the pentaquark story

Work done in part in collaboration with Alex Dzierba and Curtis Meyer

5q: positive results

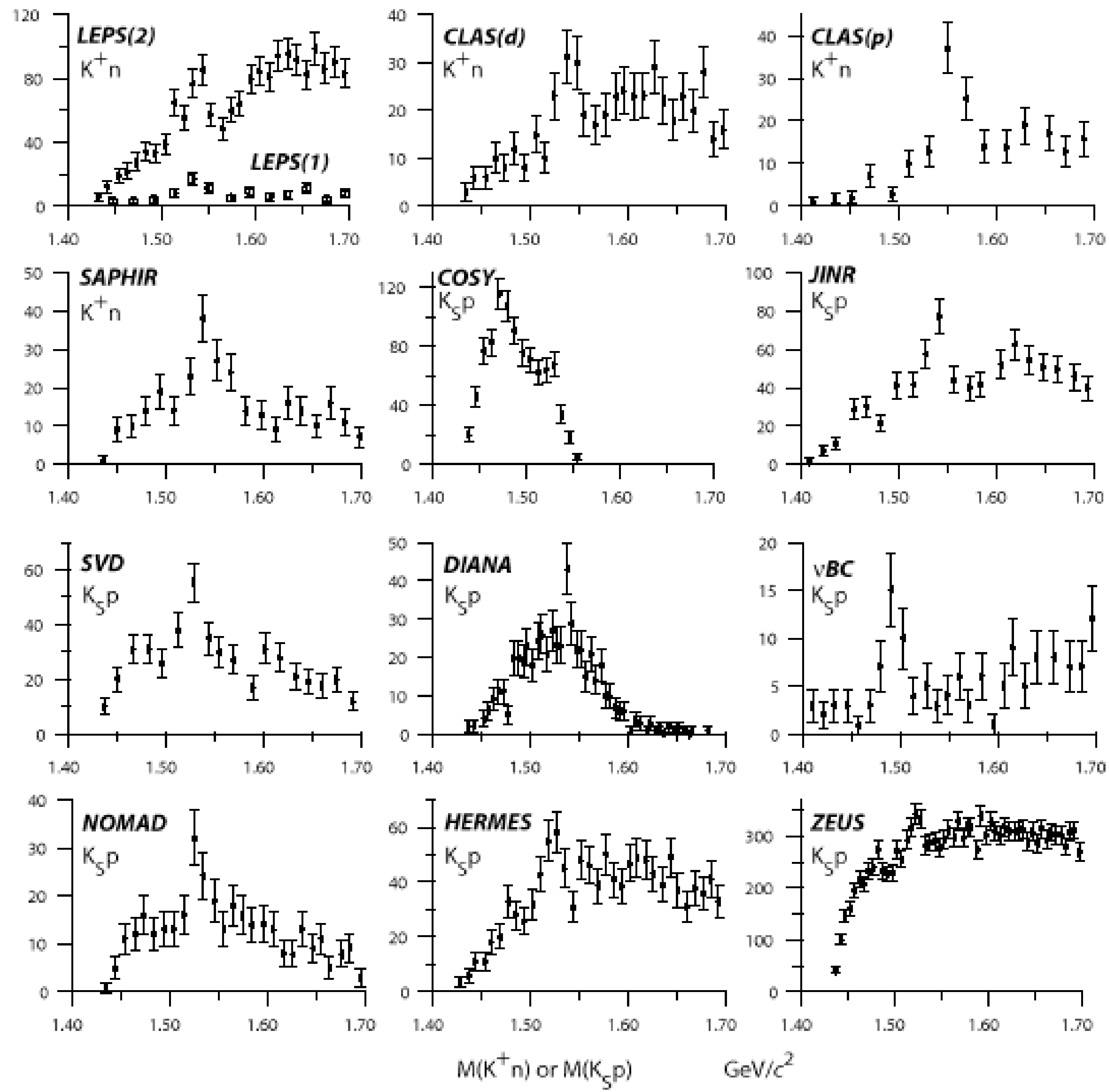


Table 1. Positive signals for pentaquark states. Please see the text regarding the final state neutron in the LEPS, CLAS and SAPHIR experiments.

Experiment	Reaction	State	Mode	Reference
LEPS(1)	$\gamma C_{12} \rightarrow K^+K^-X$	θ^+	K^+n	[4]
LEPS(2)	$\gamma d \rightarrow K^+K^-X$	θ^+	K^+n	[5]
CLAS(d)	$\gamma d \rightarrow K^+K^-(n)p$	θ^+	K^+n	[6]
CLAS(p)	$\gamma p \rightarrow K^+K^-\pi^+(n)$	θ^+	K^+n	[7]
SAPHIR	$\gamma p \rightarrow K^0_S K^+(n)$	θ^+	K^+n	[8]
COSY	$pp \rightarrow \Sigma^+ K^0_S p$	θ^+	$K^0_S p$	[9]
JINR	$p(C_3H_8) \rightarrow K^0_S pX$	θ^+	$K^0_S p$	[10]
SVD	$pA \rightarrow K^0_S pX$	θ^+	$K^0_S p$	[11]
DIANA	$K^+Xe \rightarrow K^0_S p(Xe)'$	θ^+	$K^0_S p$	[12]
νBC	$\nu A \rightarrow K^0_S pX$	θ^+	$K^0_S p$	[13]
NOMAD	$\nu A \rightarrow K^0_S pX$	θ^+	$K^0_S p$	[14]
HERMES	quasi-real photoproduction	θ^+	$K^0_S p$	[15]
ZEUS	$ep \rightarrow K^0_S pX$	θ^+	$K^0_S p$	[16]
NA49	$pp \rightarrow \Xi\pi X$	Ξ_5	$\Xi\pi$	[17]
H1	$ep \rightarrow (D^*p)X$	θ_c	D^*p	[18]

Dzierba, Meyer, AS

5q: negative results

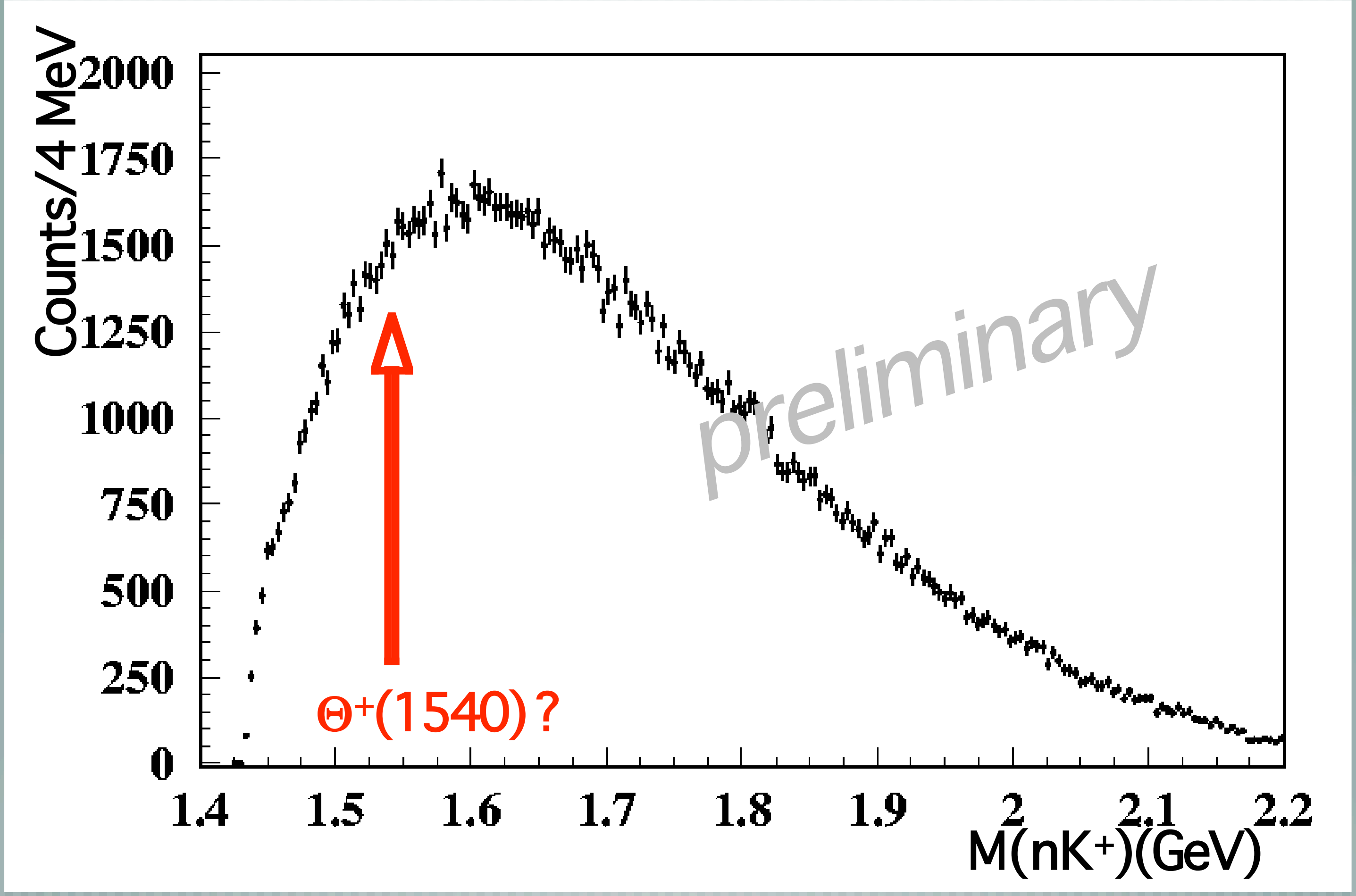
Table 2. Recent negative searches for pentaquark states. For each pentaquark state (P) we indicated with a $-$ that the state was not included in the search while $\Downarrow$ indicates that the state was searched for and not observed and $\Uparrow$ indicates that the state was searched for and observed.

Experiment	Search Reaction	θ^+	Ξ_5	θ_c	Reference
ALEPH	Hadronic Z decays	$\Downarrow$	$\Downarrow$	$\Downarrow$	[19]
BaBar	$e^+e^- \to \Upsilon(4S)$	$\Downarrow$	$\Downarrow$	$-$	[20]
BELLE	$KN \to PX$	$\Downarrow$	$-$	$\Downarrow$	[21]
BES	$e^+e^- \to J/\psi(\psi(2S) \to \theta\bar{\theta}$	$\Downarrow$	$-$	$\Downarrow$	[22]
CDF	$p\bar{p} \to PX$	$\Downarrow$	$\Downarrow$	$\Downarrow$	[23]
COMPASS	$\mu^+(^6LiD) \to PX$	$\Downarrow$	$\Downarrow$	$-$	[24]
DELPHI	Hadronic Z decays	$\Downarrow$	$-$	$-$	[25]
E690	$pp \to PX$	$\Downarrow$	$\Downarrow$	$-$	[26]
FOCUS	$\gamma p \to PX$	$\Downarrow$	$\Downarrow$	$\Downarrow$	[27]
HERA-B	$pA \to PX$	$\Downarrow$	$\Downarrow$	$-$	[28]
HyperCP	$(\pi^+, K^+, p)Cu \to PX$	$\Downarrow$	$-$	$-$	[29]
LASS	$K^+p \to K^+n\pi^+$	$\Downarrow$	$-$	$-$	[30]
L3	$\gamma\gamma \to \theta\bar{\theta}$	$\Downarrow$	$-$	$-$	[25, 31]
PHENIX	$AuAu \to PX$	$\Downarrow$	$-$	$-$	[32]
SELEX	$(\pi, p, \Sigma)p \to PX$	$\Downarrow$	$-$	$-$	[33]
SPHINX	$pC(N) \to \theta^+C(N)$	$\Downarrow$	$-$	$-$	[34]
WA89	$\Sigma^-N \to PX$	$-$	$\Downarrow$	$-$	[36]
ZEUS	$ep \to PX$	$\Uparrow$	$\Downarrow$	$\Downarrow$	[16, 37, 38]

Table 3. A tabulation of statistics for the observations of the θ^+. See text for descriptions of the statistical significance as quoted in the three columns of ratios. The column labeled Published is the significance quoted in the publication.

Experiment	Signal s	Background b	Significance Published	$\frac{s}{\sqrt{b}}$	$\frac{s}{\sqrt{s+b}}$	$\frac{s}{\sqrt{s+2b}}$
LEPS(1) [4]	19	17	4.6	4.6	3.2	2.6
LEPS(2) [5]	56	162		4.4	3.8	2.9
CLAS(d) [6]	43	54	5.2	5.9	4.4	3.5
CLAS(p) [7]	41	35	7.8	6.9	4.7	3.9
SAPHIR [8]	55	56	4.8	7.3	5.2	4.3
COSY [9]	57	95	$4-6$	5.9	4.7	3.7
JINR [10]	88	192	5.5	6.4	5.3	4.1
SVD [11]	35	93	5.6	3.6	3.1	2.4
DIANA [12]	29	44	4.4	4.4	3.4	2.7
νBC [13]	18	9	6.7	6.0	3.5	3.0
NOMAD [14]	33	59	4.3	4.3	3.4	2.7
HERMES [15]	51	150	$4.3-6.2$	4.2	3.6	2.7
ZEUS [16]	230	1080	4.6	7.0	6.4	4.7

nK^+ Mass Spectrum



- the nK^+ mass spectrum is smooth
- no structure is observed at a mass of ~1540 MeV

Comparison with SAPHIR results

Observed Yields

SAPHIR

$N(\Theta^+)/N(\Lambda^*) \sim 63/630 \sim 10\%$

CLAS

$N(\Theta^+)/N(\Lambda^*) < 110/53000 < 0.2\%$ (95%CL)

Cross Sections

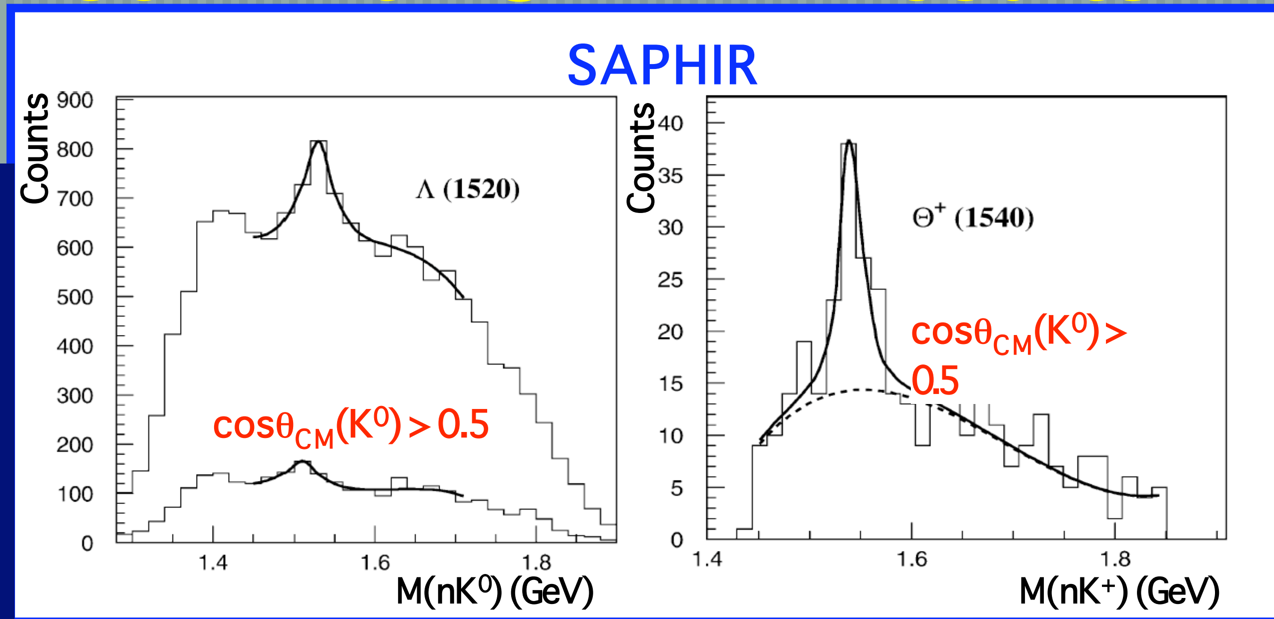
SAPHIR

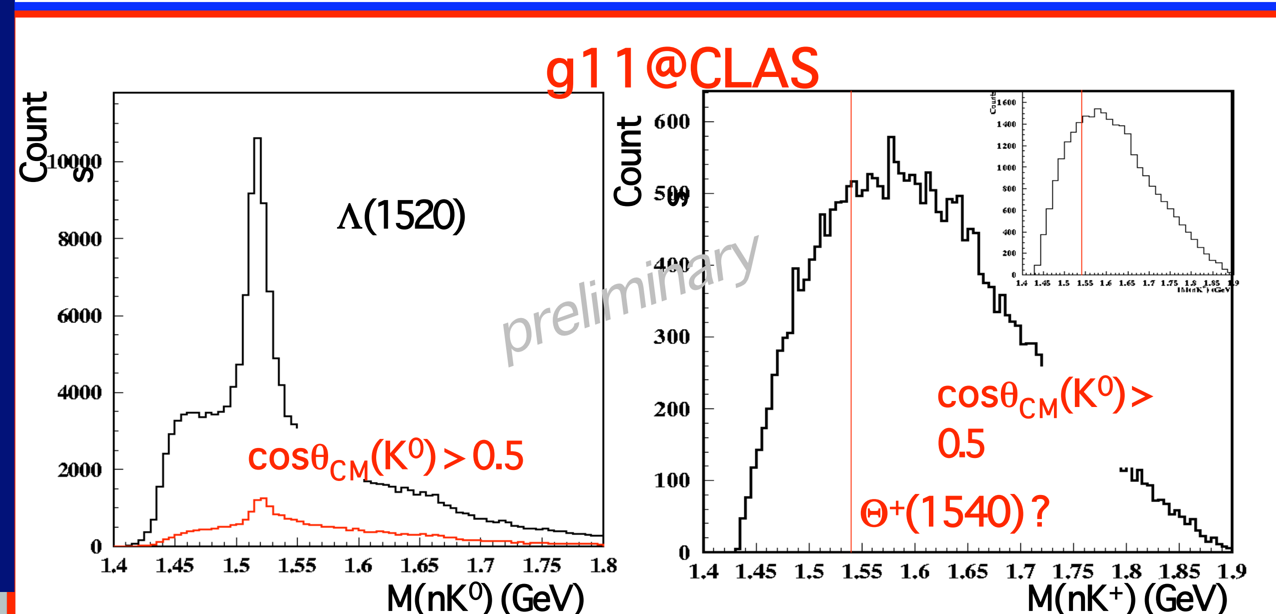
$\sigma_{\gamma p \to \Theta^+ K^0} \sim 300$ nb

reanalysis 50 nb

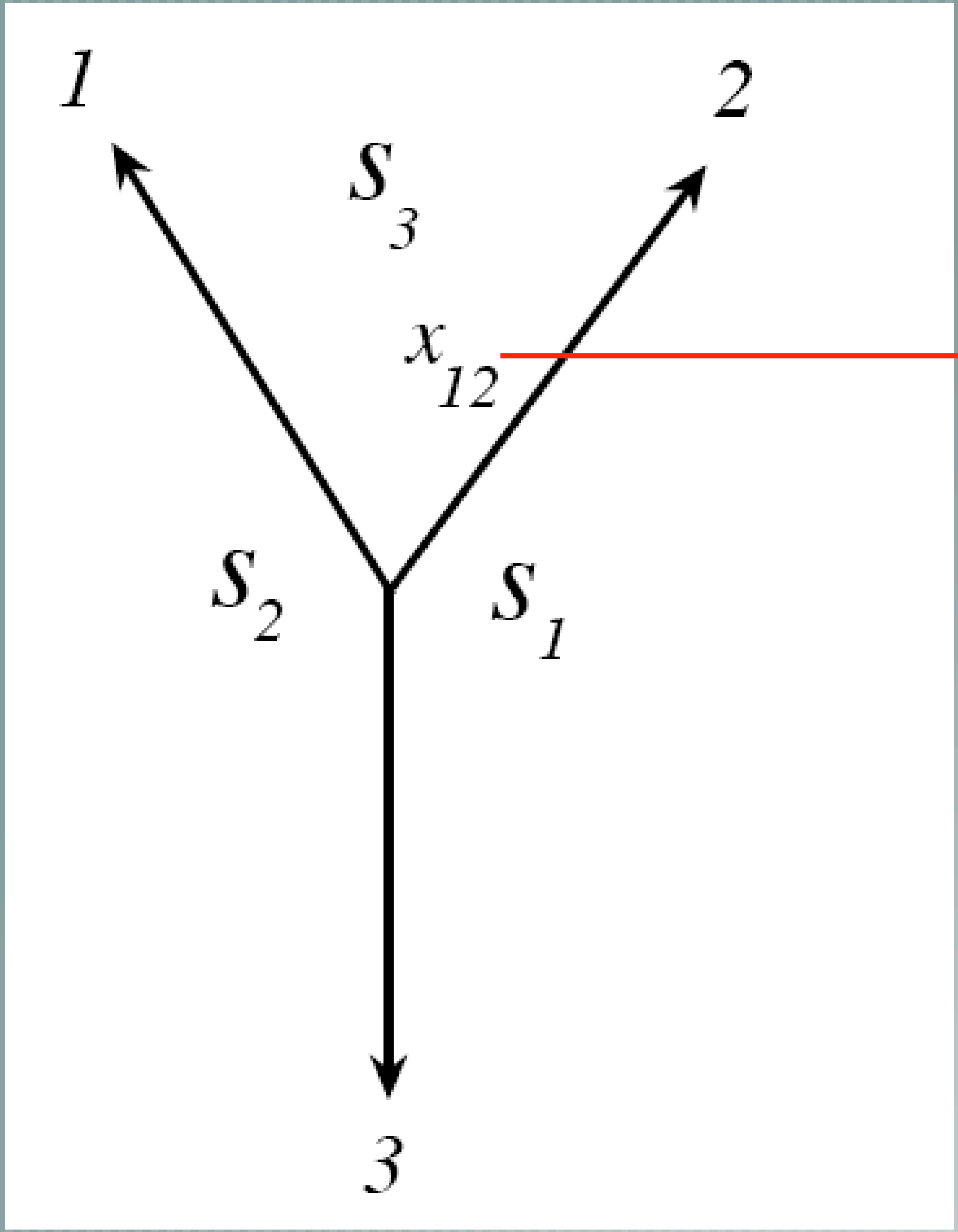
CLAS

$\sigma_{\gamma p \to \Theta^+ K^0} < 1\text{-}4$ nb





Kinematic reflections



3 body kinematics

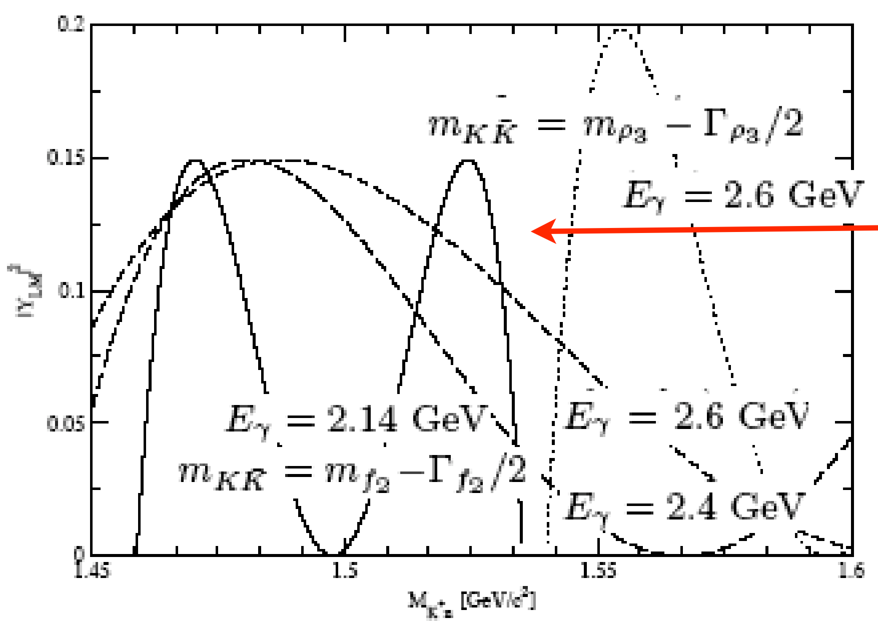
$$s_1 + s_2 + s_3 = s - m_1^2 - m_2^2 - m_3^2$$

cos of the helicity angle of 1 in the (12) rest frame

$$s_2 = s_2(s_1, s, x_{12})$$

$$\gamma n \to K^+ K^- n$$

3-particle Dalitz plot



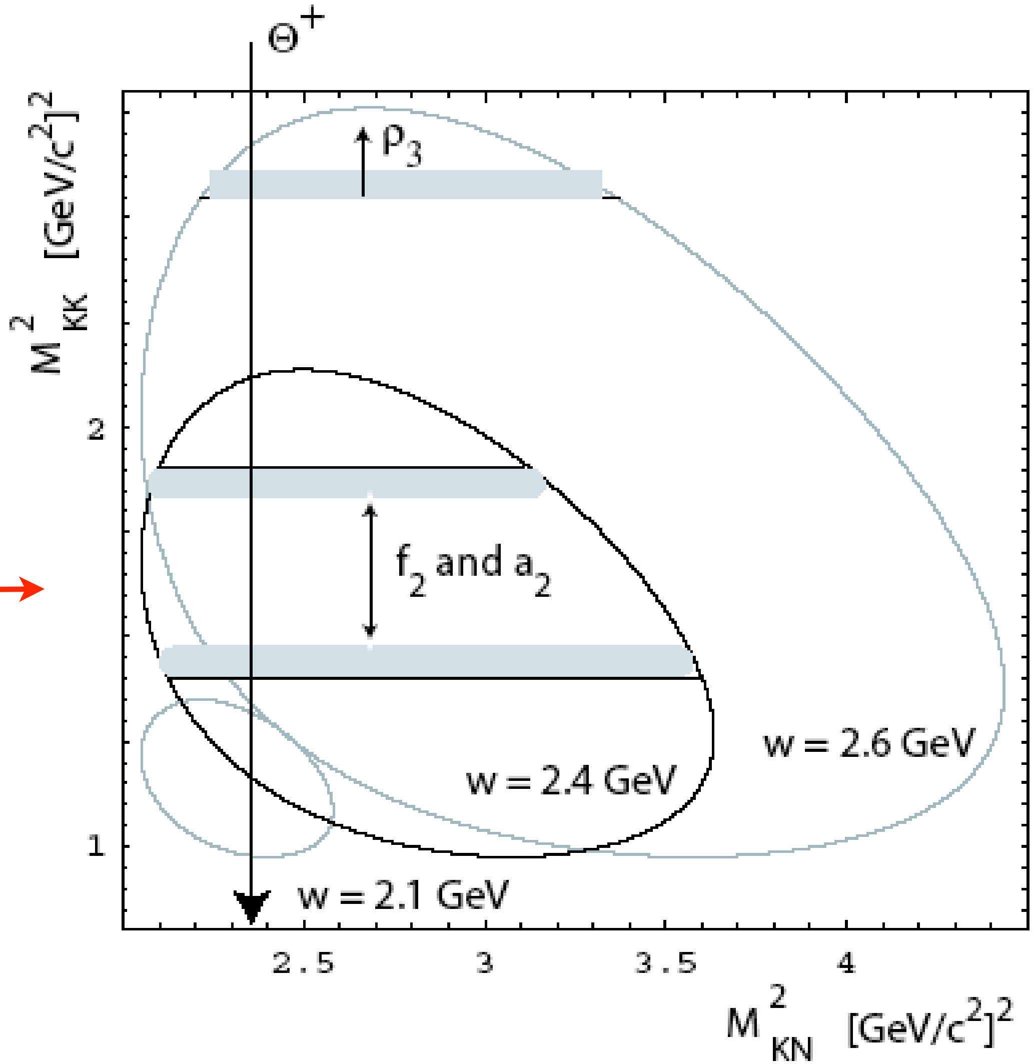


FIG. 1: Boundaries of the m^2_{KK} versus m^2_{KN} Dalitz plot for three different values of w, the energy available to the $K\bar{K}N$ system, 2.1, 2.4 and 2.6 GeV. For the data of ref. [2], the observed distribution in w rises from 2.1 GeV, peaks at 2.4 and falls to zero near 2.6 GeV. Horizontal lines denote the region spanned by the f_2 and a_2 mesons defined by their half-widths and the region of the ρ_3 starting with its central mass less its half-width. The vertical line denotes the square of the Θ mass.

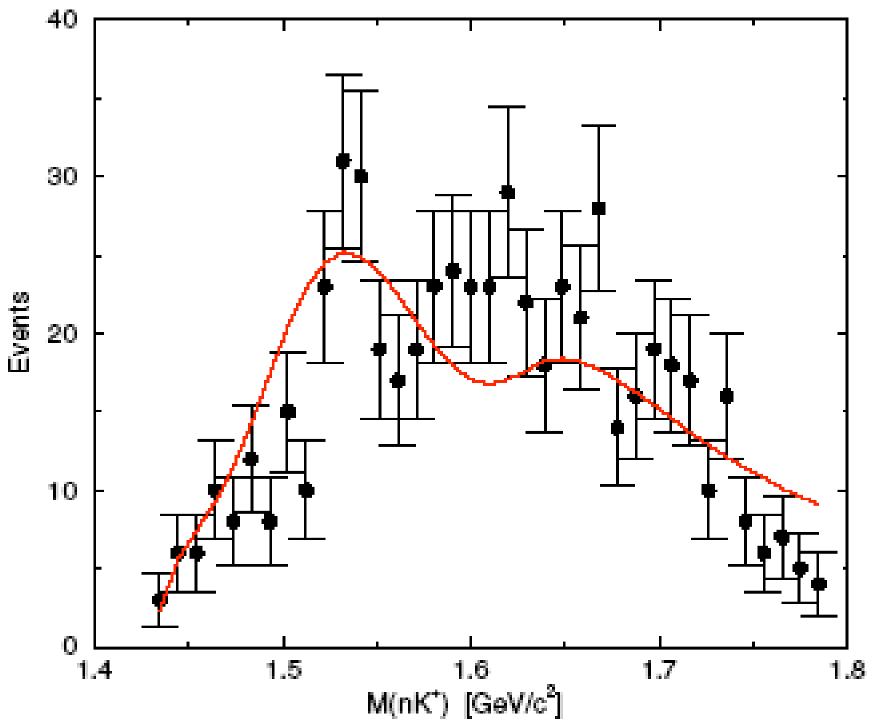
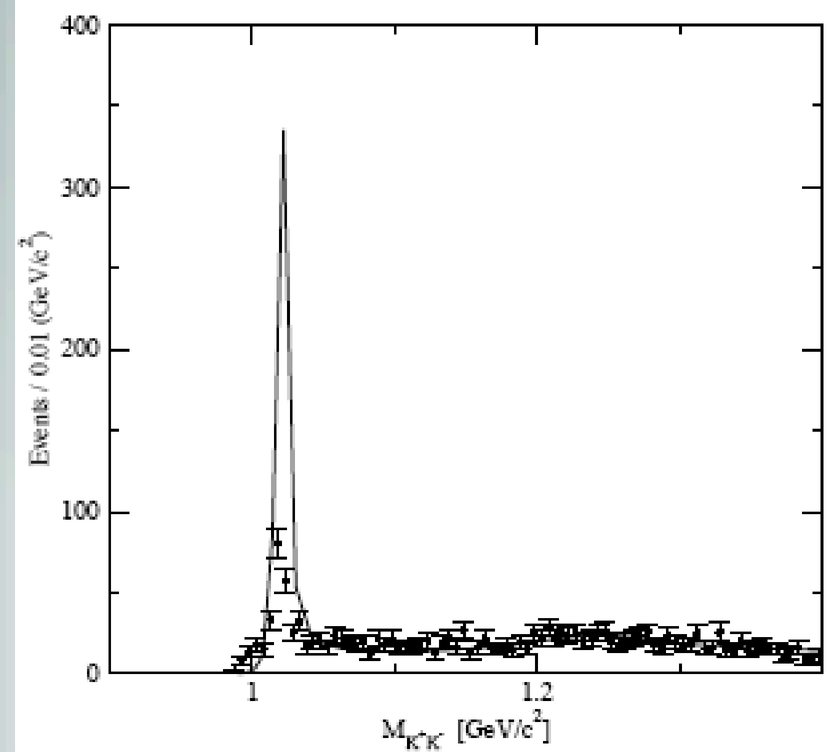


FIG. 3: The calculated (solid line) m_{KN} distribution, as described in the text, compared with the data from [2]

Reaction	Beam energy GeV	Cross Section μb	Ref
$\gamma p \to f_2 p$	2.3-2.6	1.3 ± 0.37	[6]
$\gamma p \to f_2 p$	2.6-3.25	0.39 ± 0.13	[6]
$\gamma p \to f_2 p$	3.25-4.0	0.19 ± 0.06	[6]
$\gamma p \to f_2 p$	4.0-6.3	0.1 ± 0.1	[6]
$\gamma p \to a_2^+ n$	4.2 ± 0.5	1.14 ± 0.43	[7]
$\gamma p \to a_2^+ n$	5.25 ± 0.55	0.85 ± 0.43	[7]
$\gamma p \to a_2^+ n$	7.5 ± 0.7	0.43 ± 0.43	[7]
$\gamma p \to K^+ K^- p$	2.8	1.0 ± 0.1	[8]
$\gamma p \to K^+ K^- p$	4.7	0.7 ± 0.1	[8]

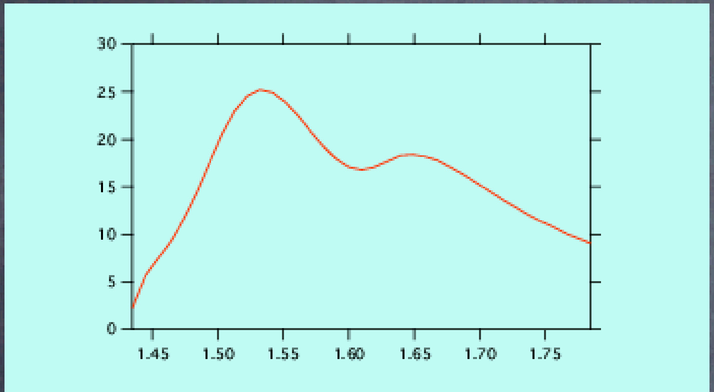
TABLE I: Photoproduction cross sections for the $f_2(1275)$ and $a_2(1320)$ resonances and the K^+K^- final state.

Physical background has structure >> reduces the statistical significance of the signal

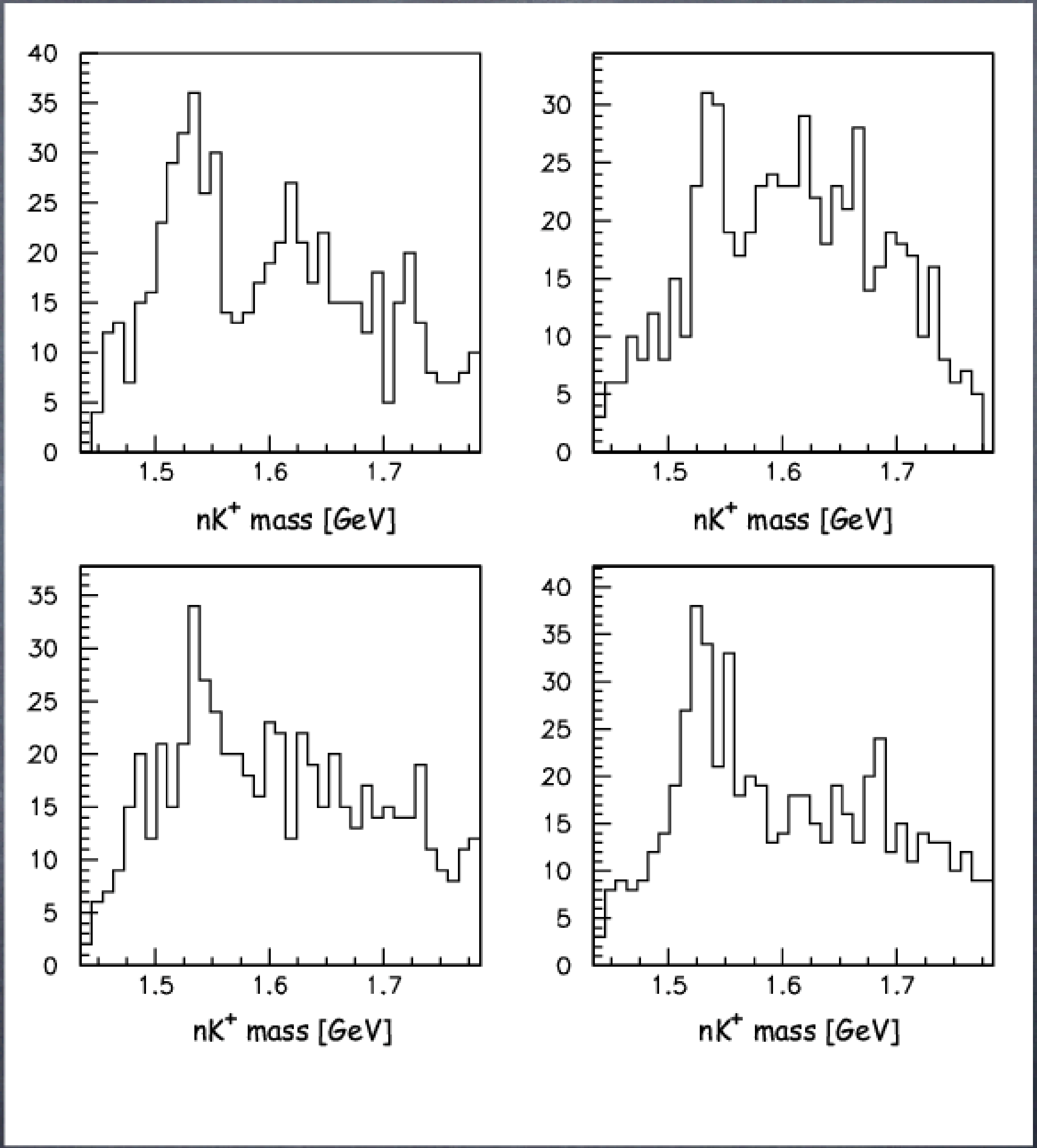


Fake Peaks

Enhancement is broad
- but starting with:



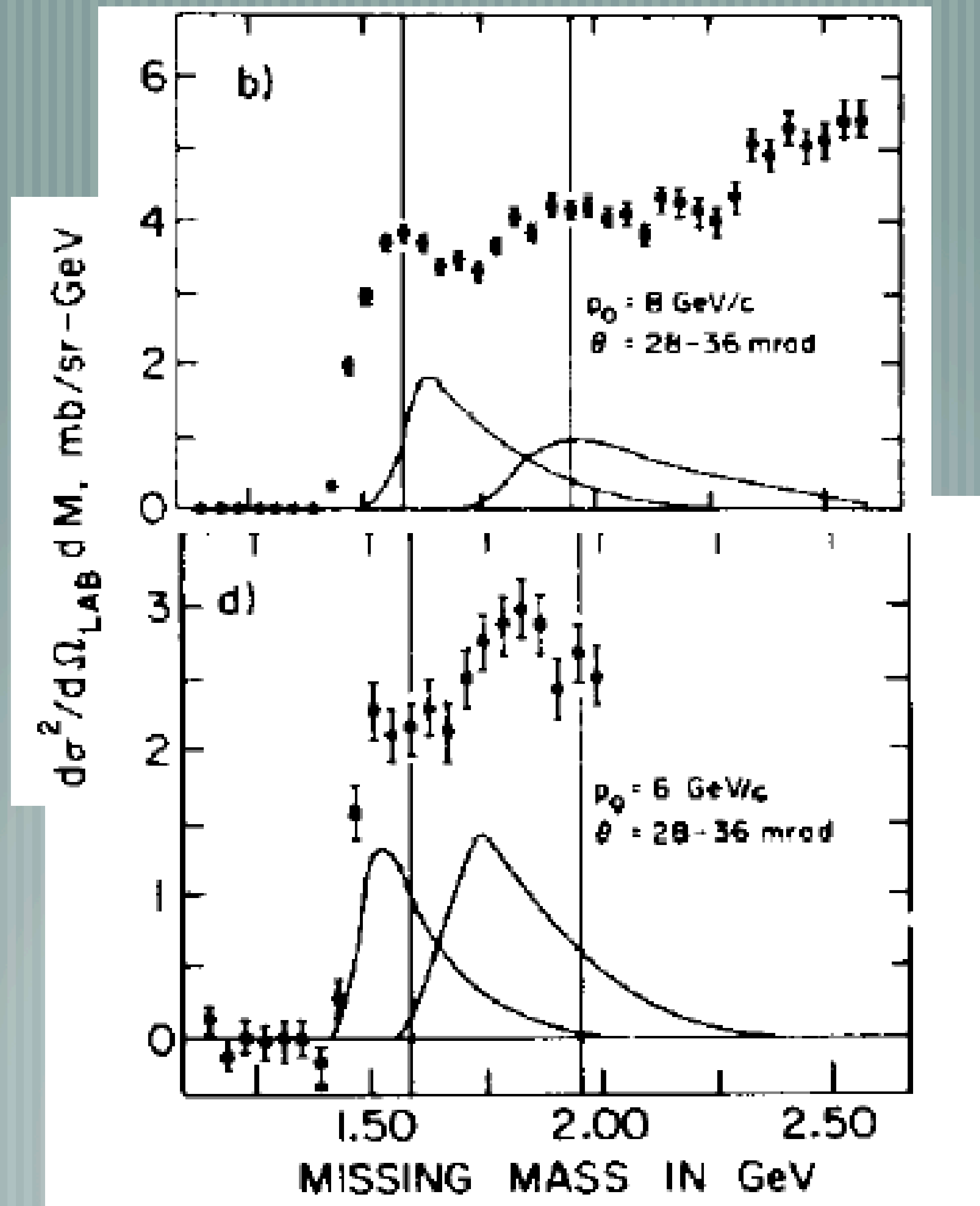
as a parent distribution generate 40 random histograms with 600 events each - 3 of these along with CLAS results appear here



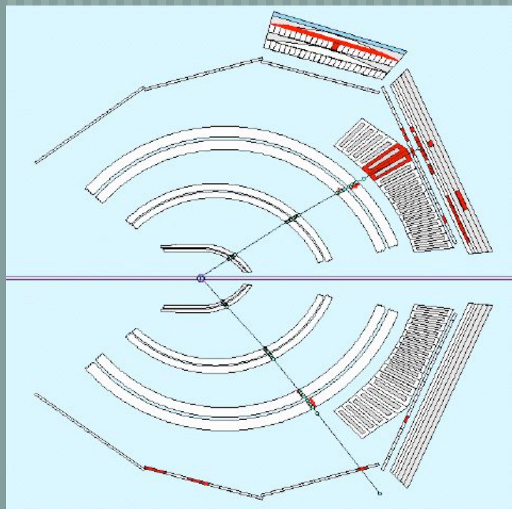
SEARCH FOR THE Z* IN $\pi^- + p \rightarrow K^- + Z^*$ AT 6 AND 8 GeV/c ‡

E. W. ANDERSON, E. J. BLESER‡‡, H. R. BLIEDEN, G. B. COLLINS, D. GARELICK
J. MENES and F. TURKOT
Brookhaven National Laboratory, Upton, New York, USA

$$\pi^- + p \rightarrow B^{*-} + p$$
$$\quad\quad \hookrightarrow K^0 + K^-$$
$$\rightarrow B^{*0} + n$$
$$\quad\quad \hookrightarrow K^+ + K^- .$$



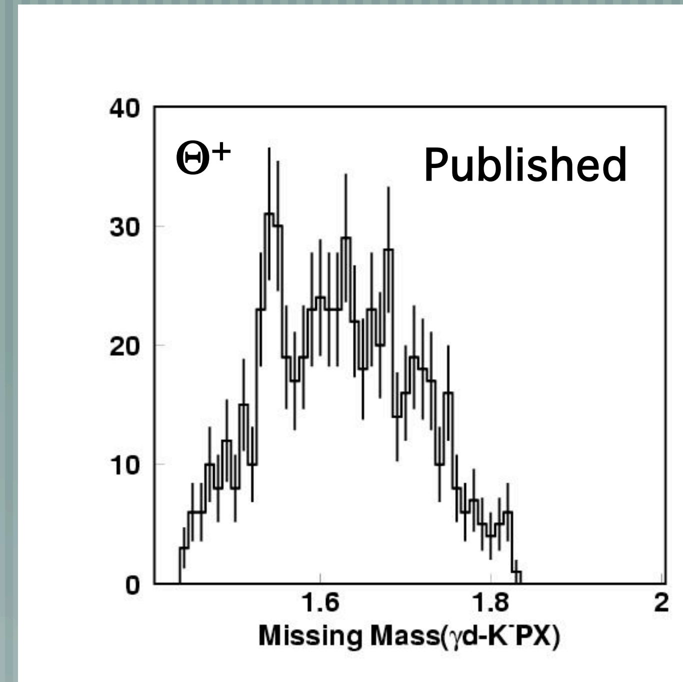
Curtis Meyer : Argonne talk

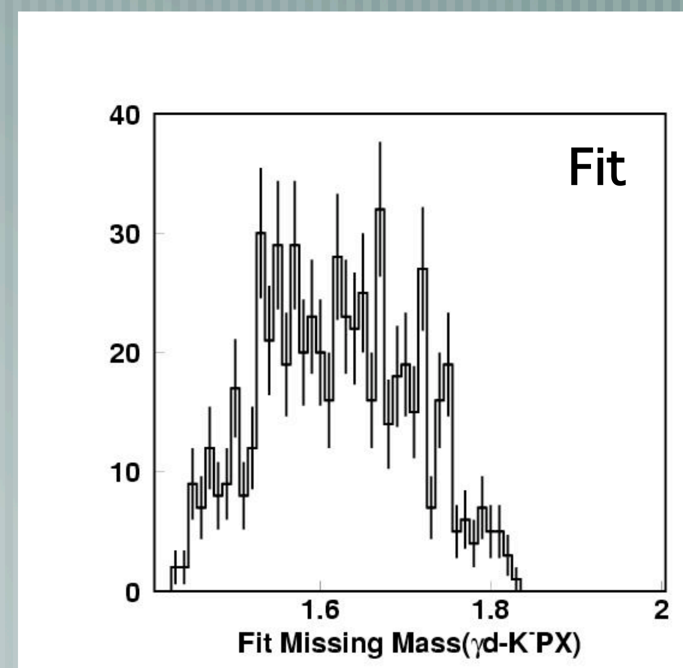


CLAS

$\gamma\, d \to K^+ K^- p\, (n)_{miss}$

Reaction is unknown





NOT AN OFFICIAL CLAS RESULT

Independent analysis of the data:

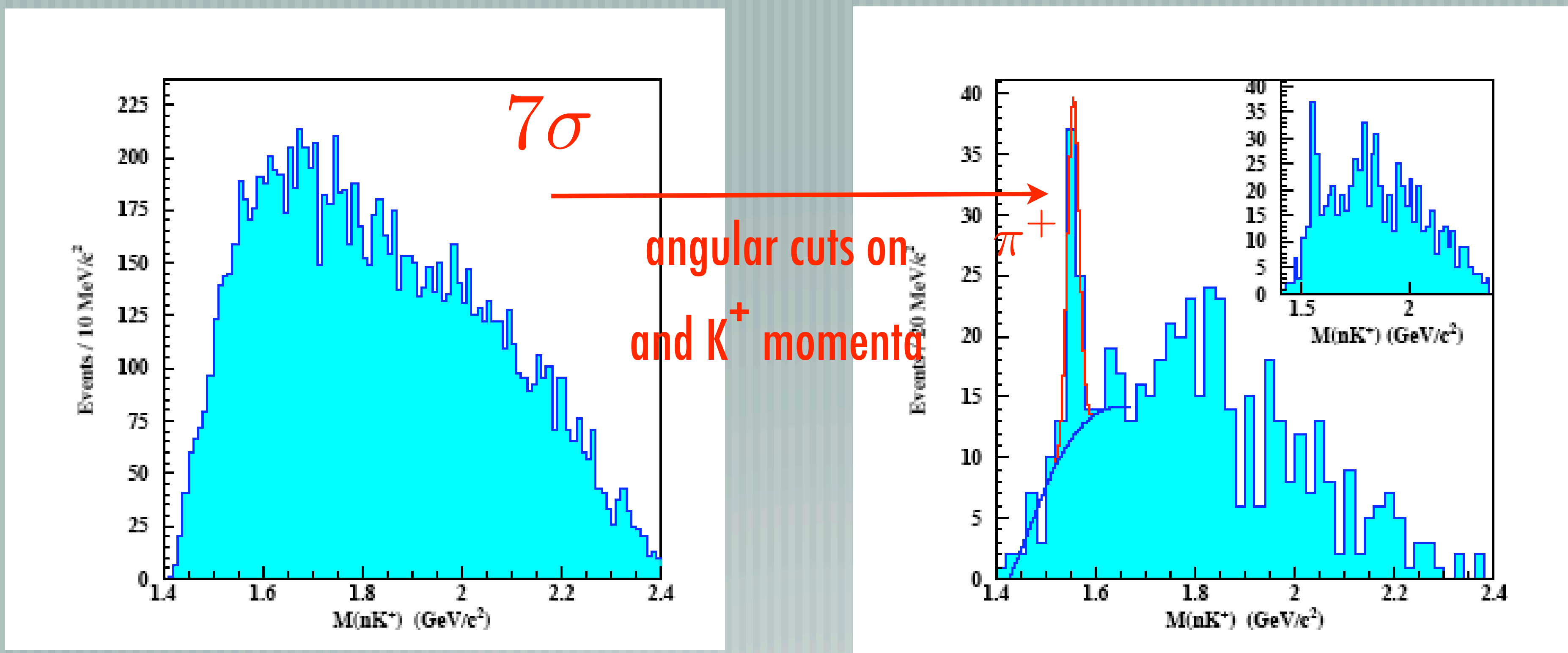
energy loss corrections from target
1C-Kinematic fit to final state

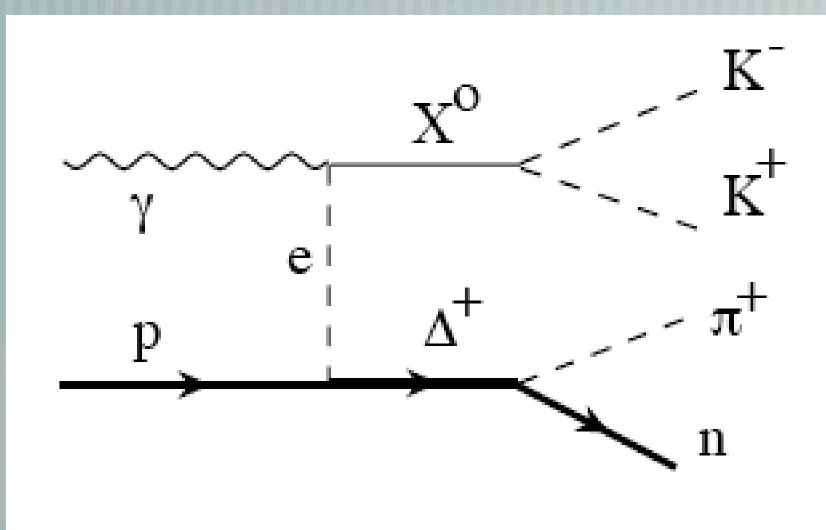
Flat confidence level
Known resonances get sharper and have the right mass: $\Lambda(1520)$ $\phi(1020)$

Evidence for higher mass Λ, Σ*'s and either the $a_2(1320)$ or $f_2(1270)$ is sharper.

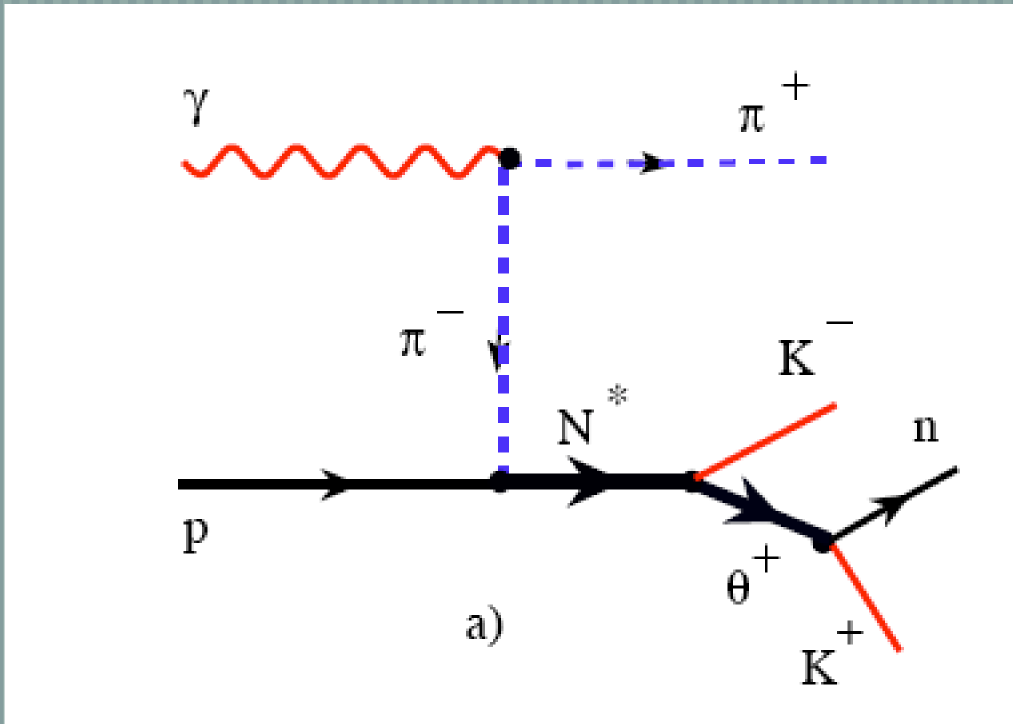
Disturbing Effect on the Θ^+ !

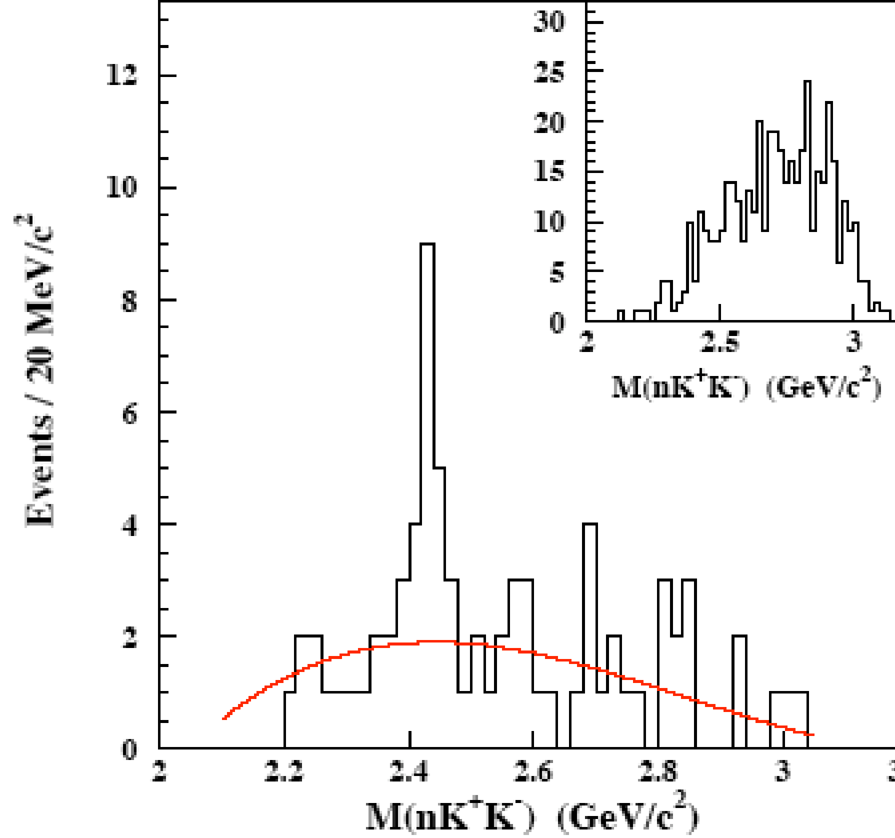
CLAS (proton) $\gamma p \to \pi^+ K^- K^+ n$

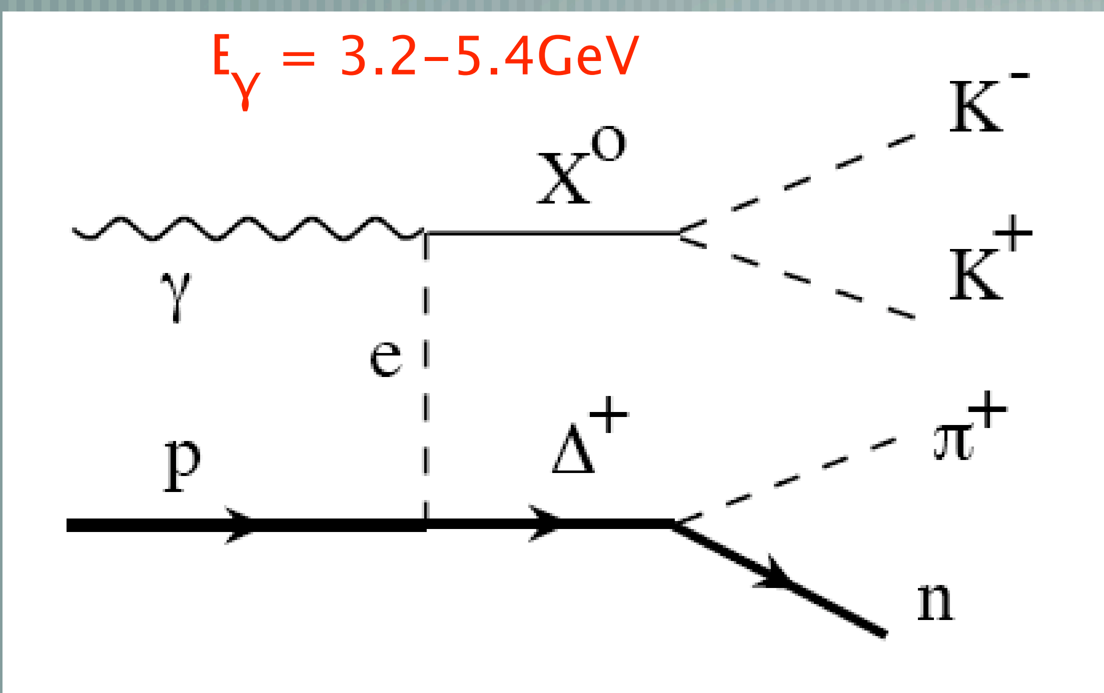




Can generate resonance-like structure in K^+K^-n spectrum and π^+ momentum cut enhances kinematic reflections from decays of K^+K^- resonances





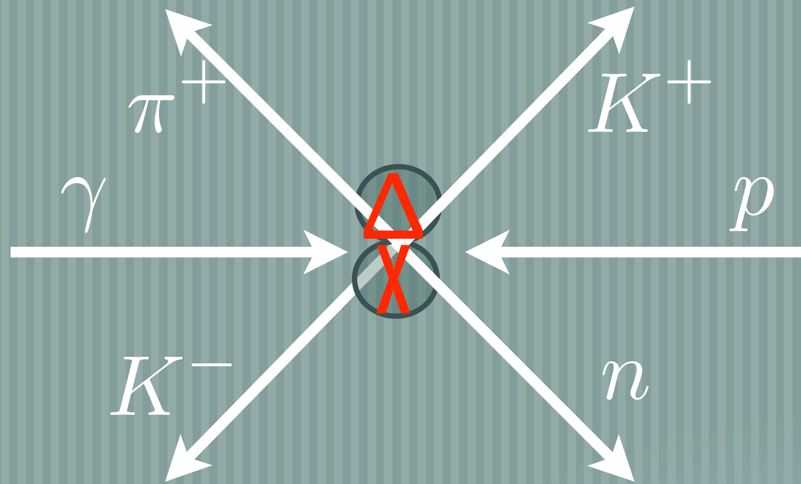


Threshold energies

$X = f_2$ W=2.51GeV

$X = a_2$ W=2.55GeV

$X = \rho_3$ W=3.31GeV



"N*" mass

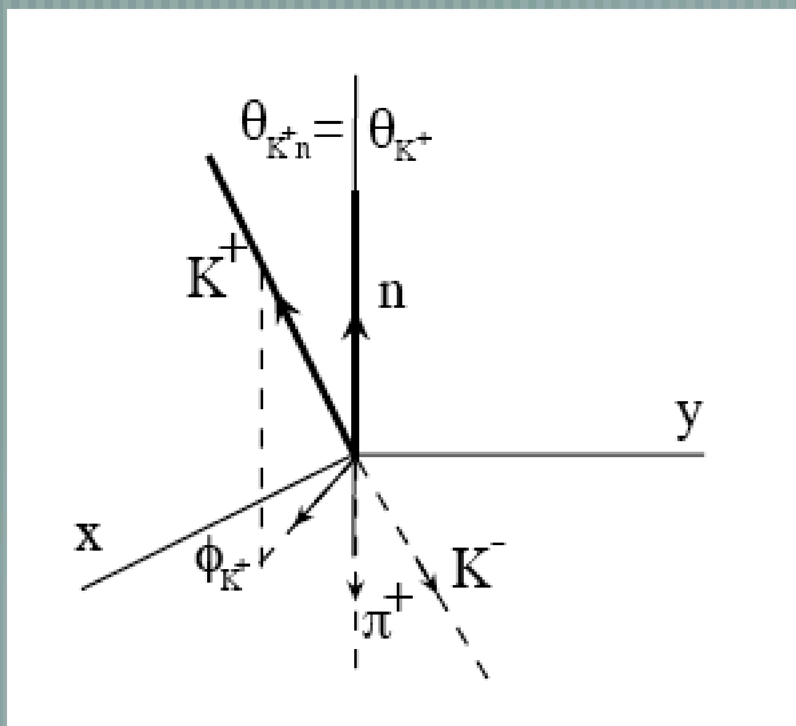
$$M_{N^*} = 2.23 GeV$$

$$M_{N^*} = 2.27 GeV$$

$$M_{N^*} = 2.64 GeV$$

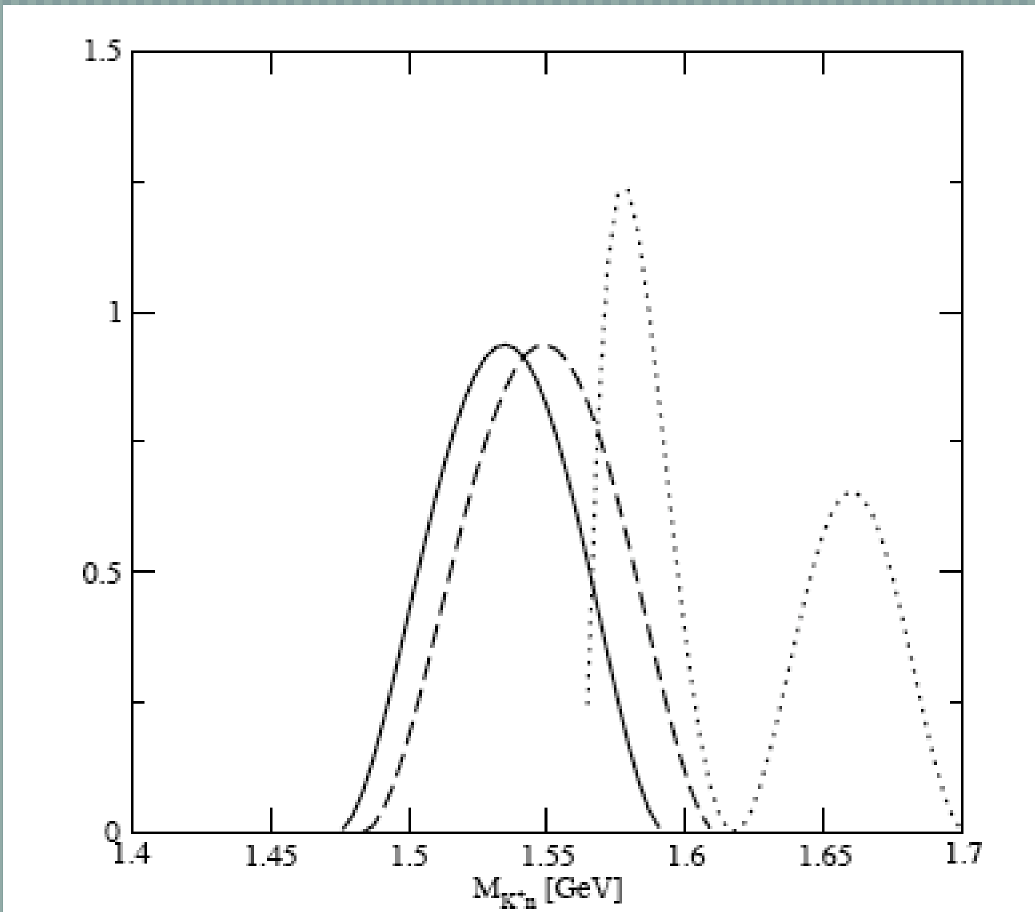
$$M_{nK^+K^-} = M_{N^*}$$

is sharp !



$$\cos\theta^*_\pi > 0.8$$

correlates n with $K^+ K^-$ helicity ->possible kinematic reflection from $K^+ K^-$ resonance



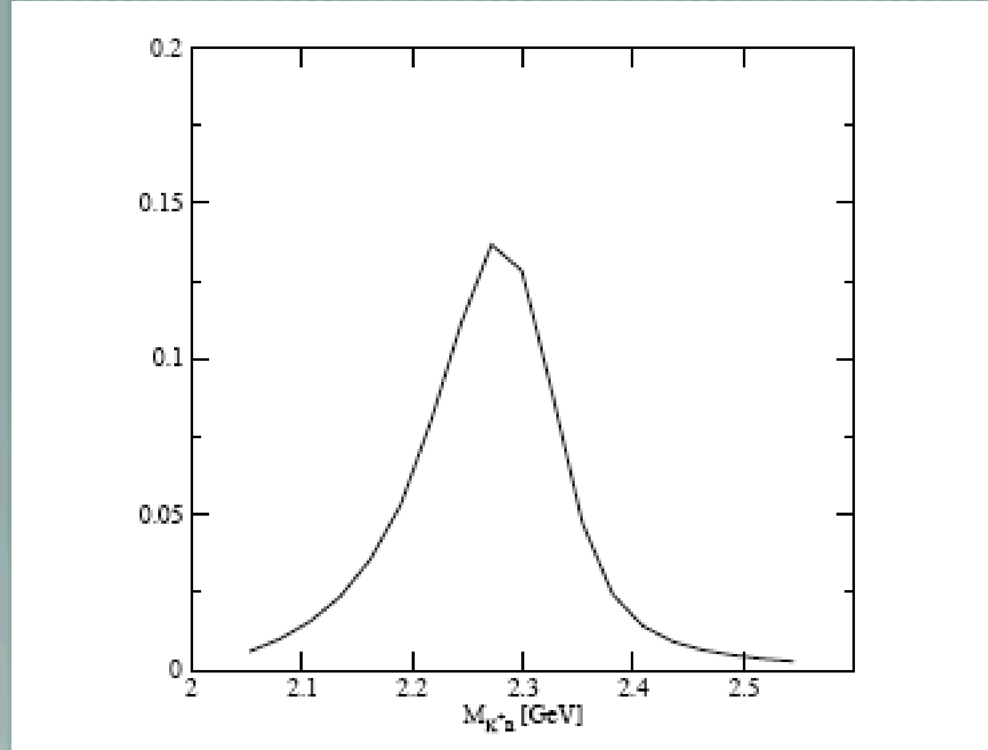


FIG. 3: The nK^+ mass distribution as described by $\int d\phi_{K+}|Y_{J_X,\lambda_X}(\theta_{K+n},\phi_{K+})|^2$, for $\Delta = \Delta(1232)$ and $J_X = \lambda_X = 2$, $X = f_2$, (solid line), $J_X = \lambda_X = 2$, $X = a_2$, (dashed line), and $J_X = 3$, $\lambda_X = 1$, $X = \rho_3$ (dotted line). The $M_{nK^+K^-}$ invariant masses for the three cases are $2.22, 2.27$ and 2.64 GeV, respectively.

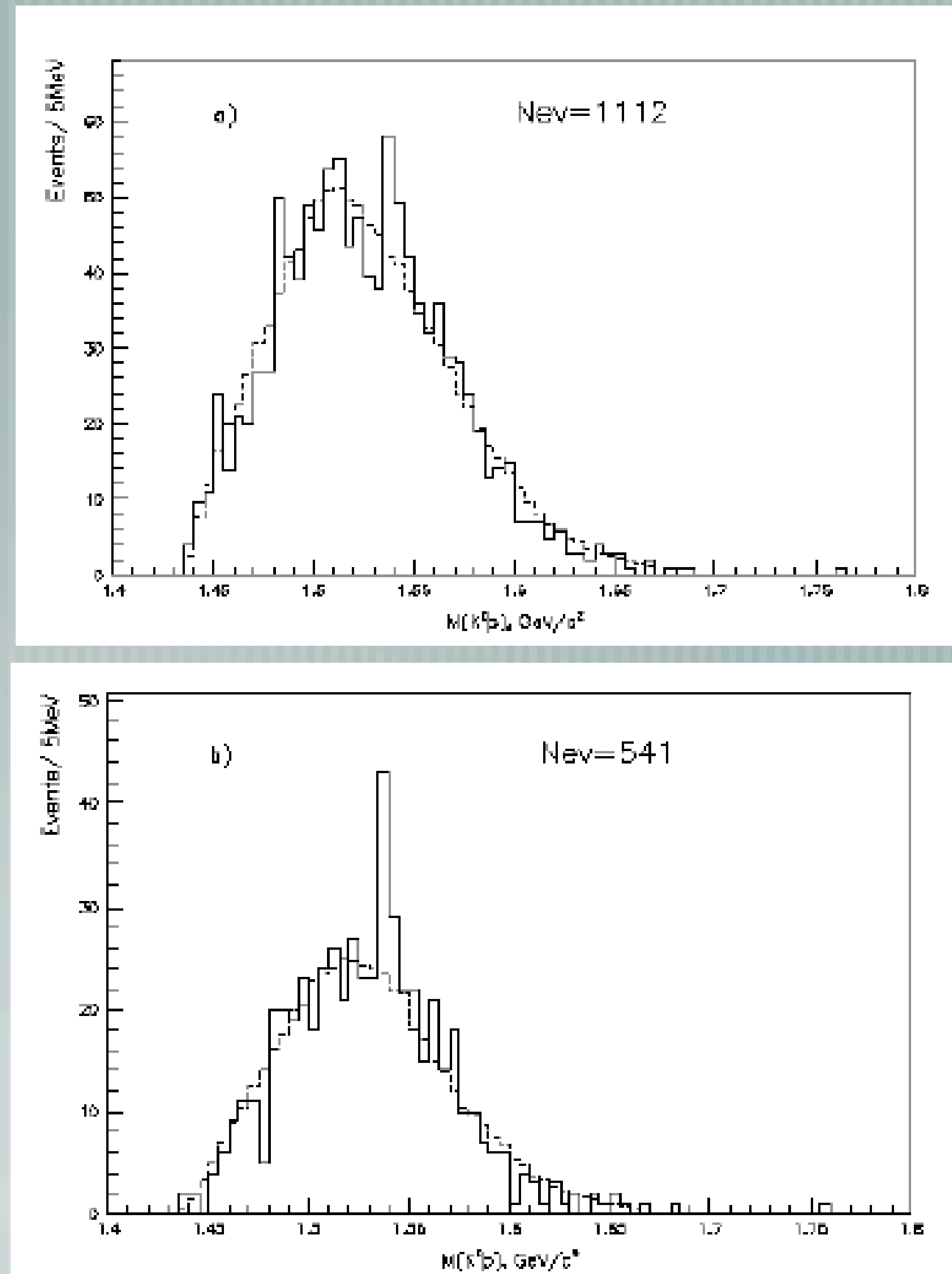
DIANA (ITEP, Xe bubble chamber, 850MeV K-beam)

$$K^+ Xe \rightarrow K_s^0 p Xe'$$

no magnetic field

particle identified by their range in Xe

angular cut, p and Ks in the forward direction



M.Zavertyaev, (hep-ph/0311250)

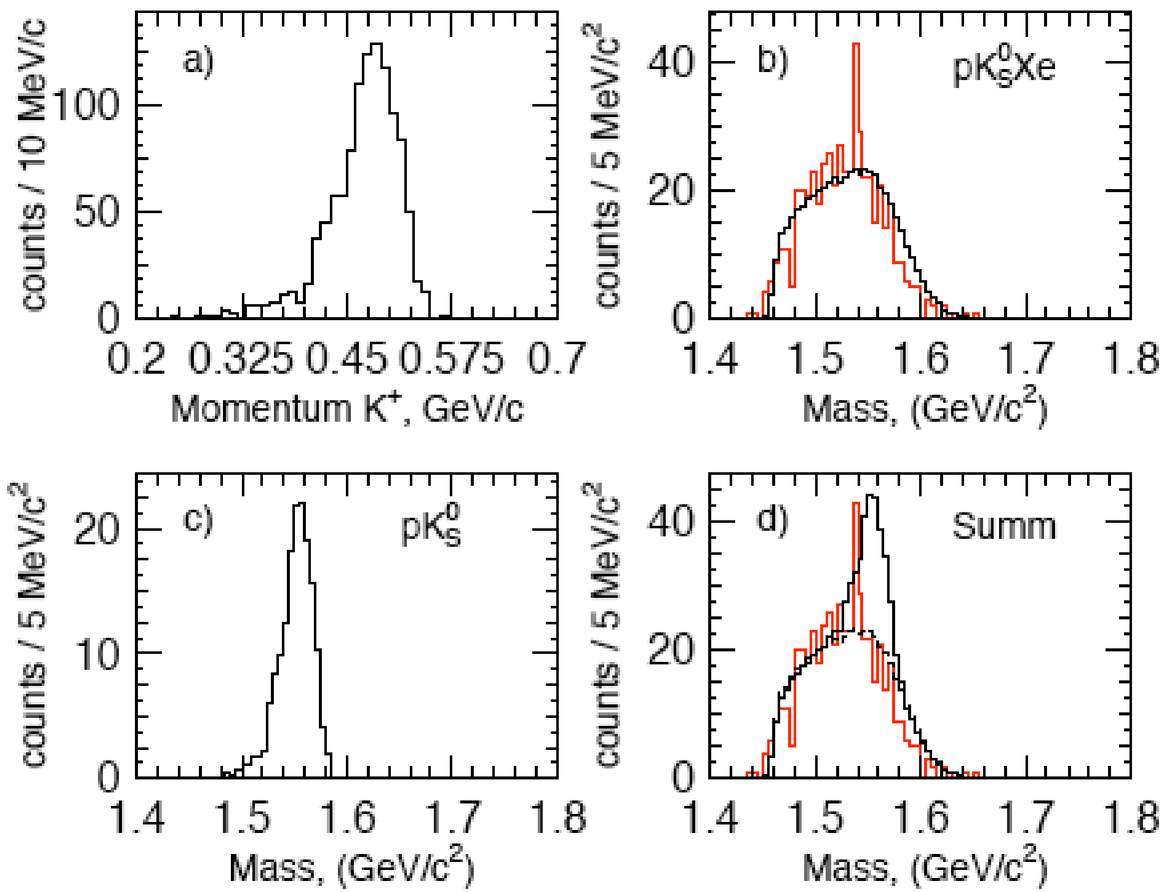


Figure 2: The experimental beam momentum [5] and MC mass spectra distribution corresponding to: b) reaction $K^+Xe \rightarrow K^0_s pXe'$; c) reaction $K^+n \rightarrow K^0_s p$; d) the summ of both b) and c); The histogram in red corresponds to the experimental mass distribution from [5].

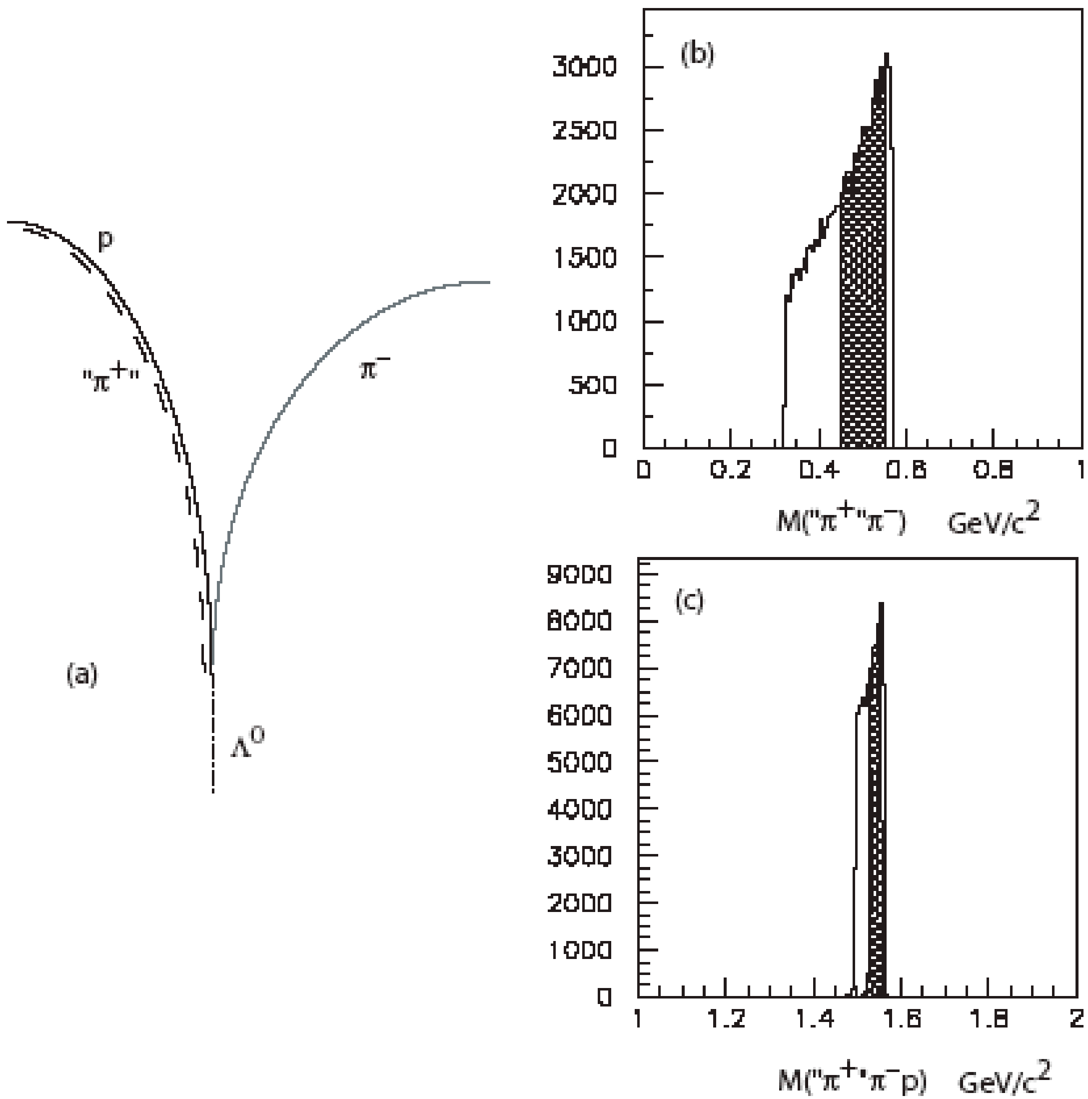
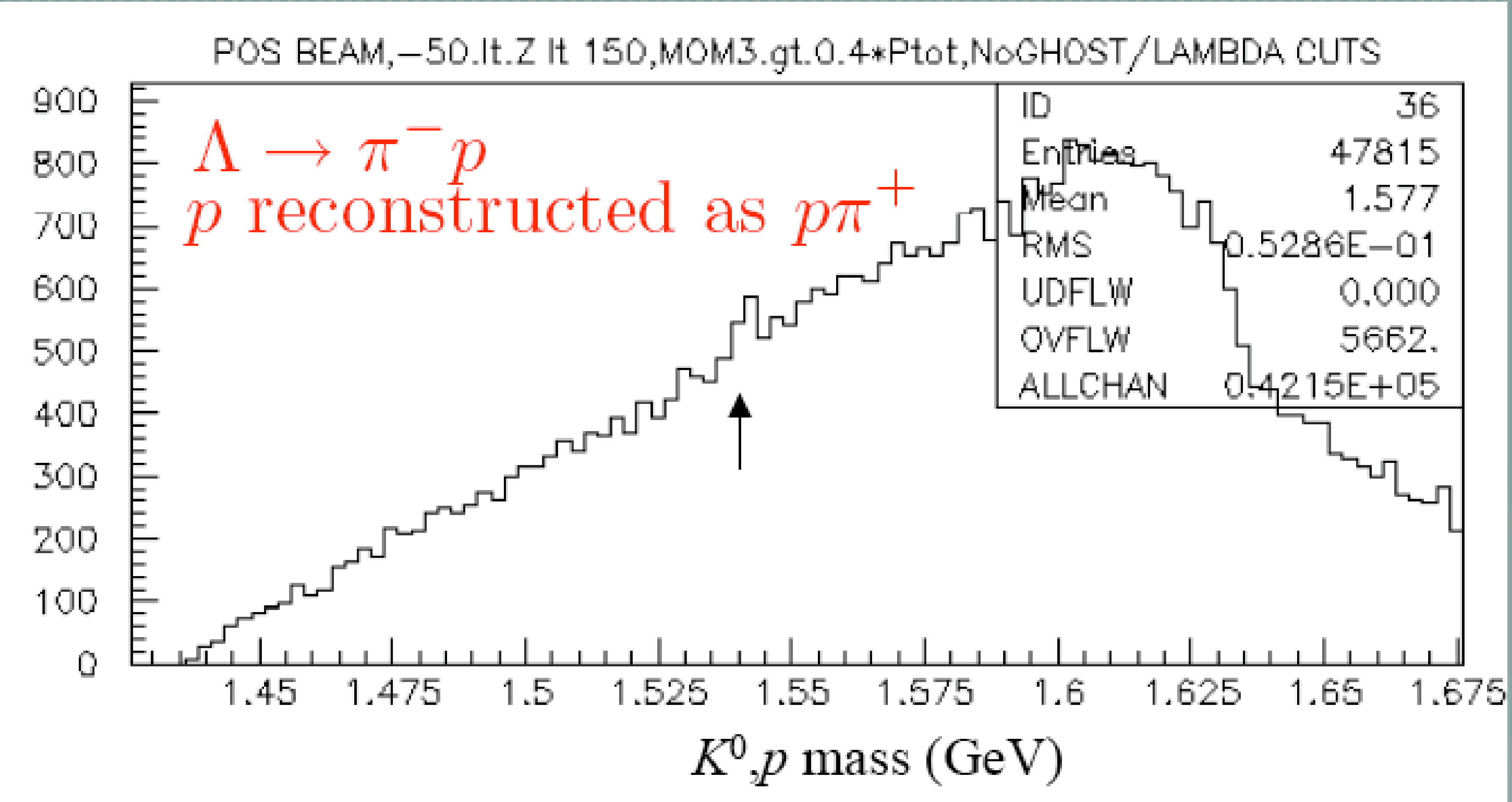
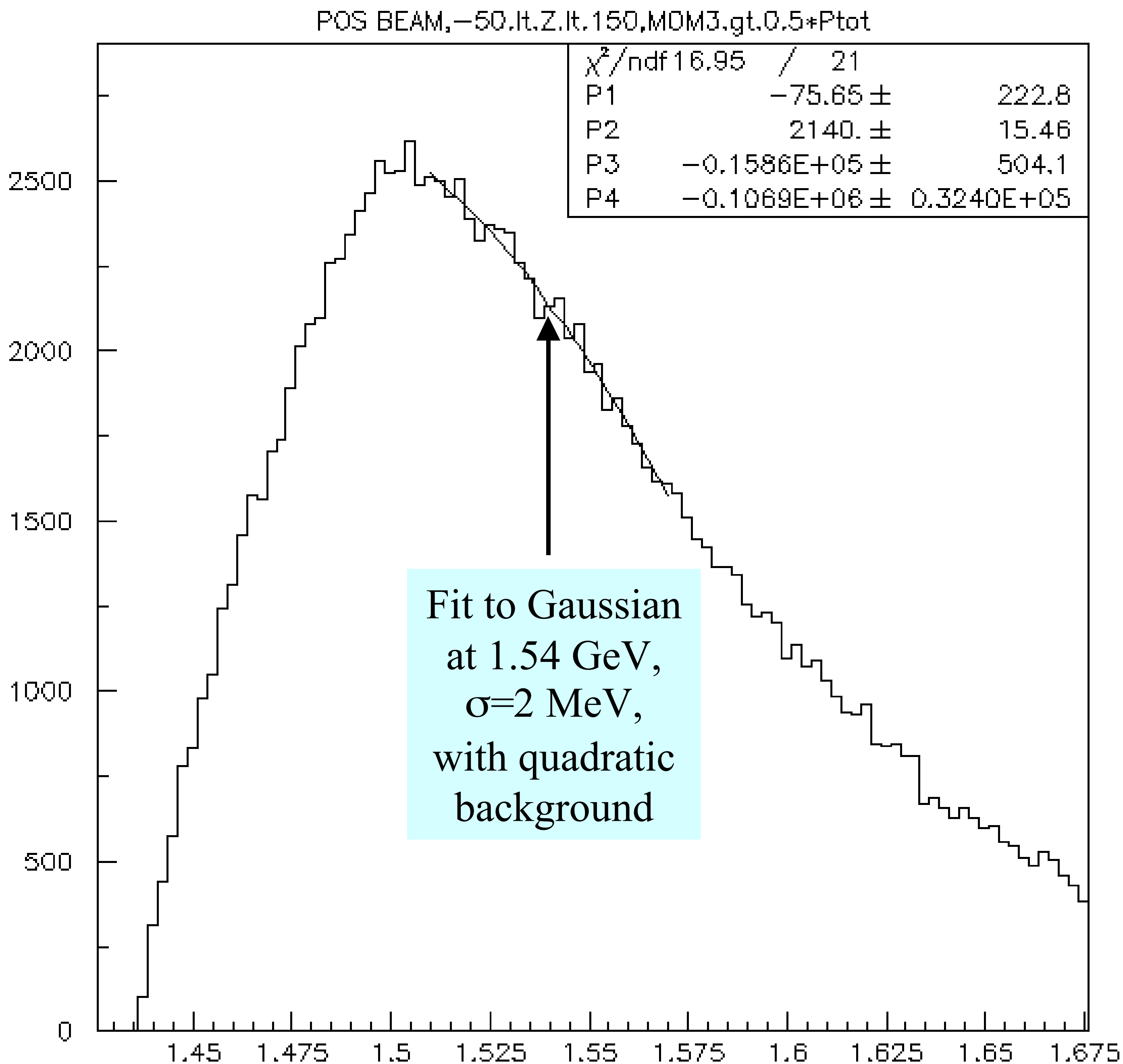


Figure 5. Figure (a) is a schematic of the decay $\Lambda^0(1115) \rightarrow \pi^- p$. The effect of spurious *ghost* tracks from the reconstruction software is considered. In this case a π^+ track is generated. When combined with the π^- from the Λ^0 the effective mass clusters about 0.5 GeV/c^2 as in Figure (b) and when the ghost track is combined with the Λ^0 decay products the effective mass clusters around 1.5 GeV/c^2 as seen in Figure (c). In the shaded distributions the "π^+"π^- mass is required to be near the K^0_S. The mean of the shaded portion of the distribution in Figure (c) is 1.54 GeV/c^2, the mass of the θ^+. In this study the Λ^0 momentum in the LAB frame was uniform from 2 to 100 GeV/c.



Hyper CP @ FNAL

E871/HyperCP, M.Longo @ QNP04



K^0-p mass, either sign

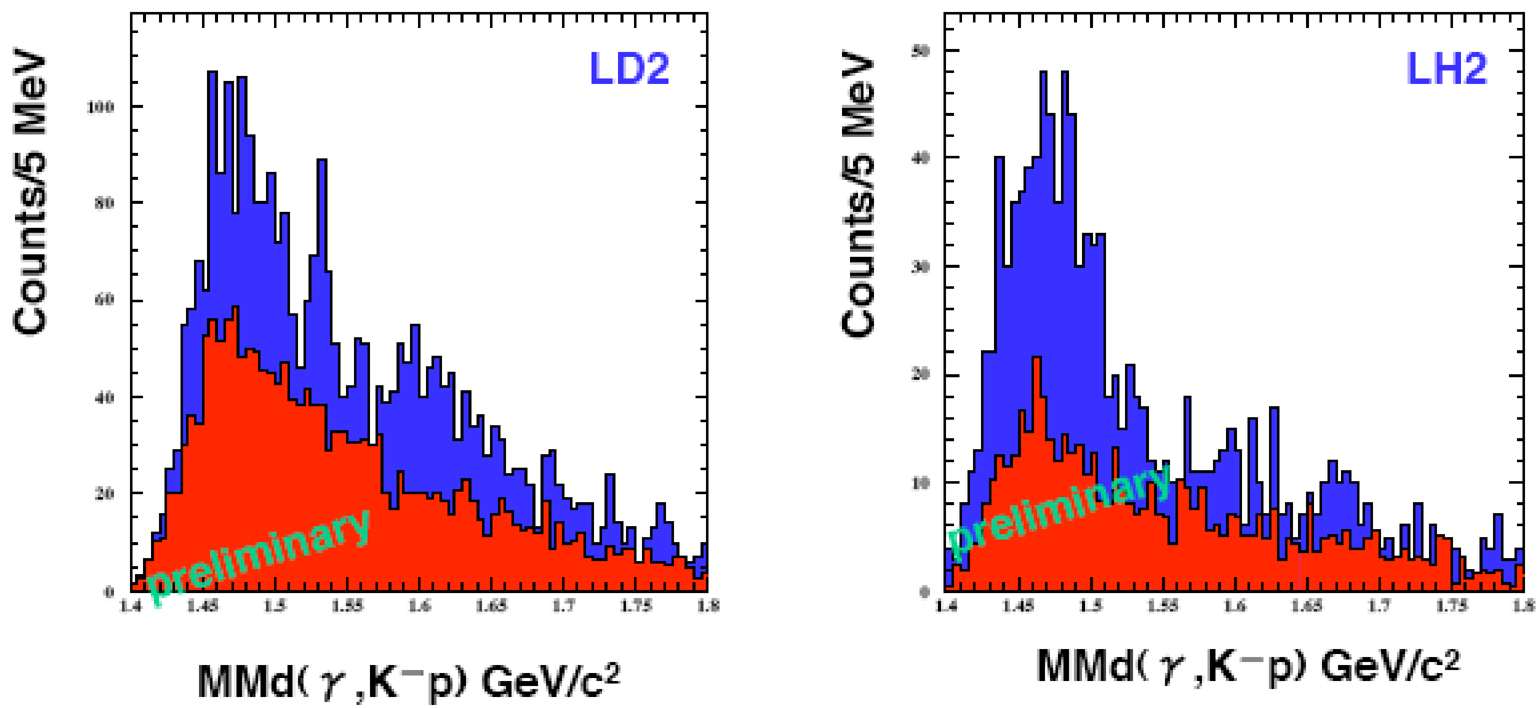
90% CL limit ~370 events out of 150000 K^0-p candidates.
P1 is the amplitude of the gaussian.
Bins are 2 MeV

HyperCP Preliminary

Pentaquark sightings come from low statistics, low resolution, low-energy experiments with kinematically constrained final states after complicated cuts are imposed.

High resolution, high statisitcs, experiments with both low- and high-particle multiplicity do not report the pentaquarks.

$K^{-}p$ missing mass in $\Lambda(1520)$ and sideband region.



$1.50 < M(K^{-}p) < 1.54$

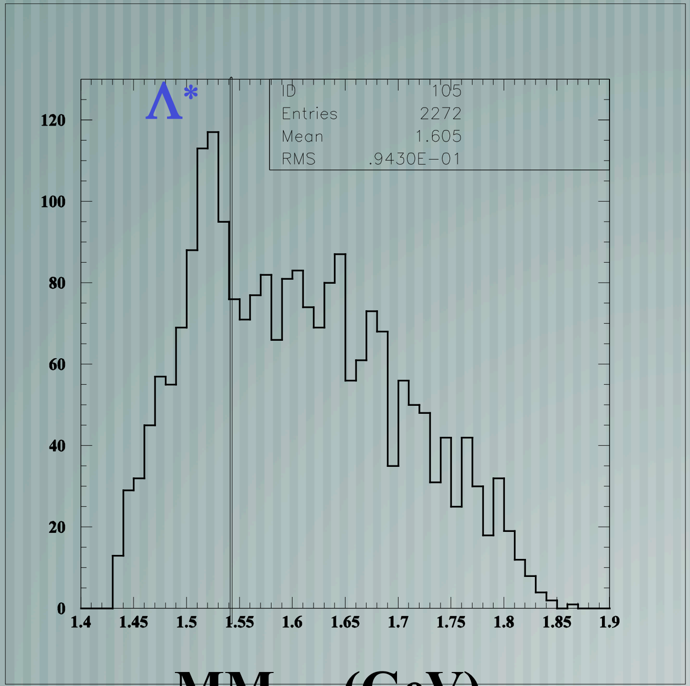
$0.4(1.46 < M(K^{-}p) < 1.50) + 0.4(1.54 < M(K^{-}p) < 1.58)$

Nakano QNP2004

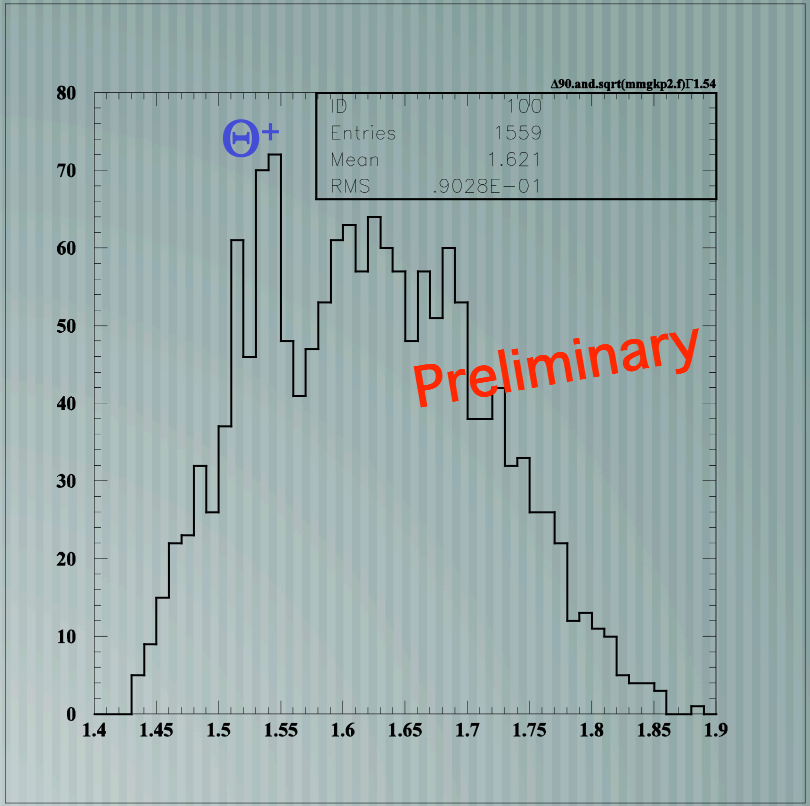
Kinematical reflection (II)

Remove Λ(1520) contribution

$MM_{\gamma K+} > 1.54$

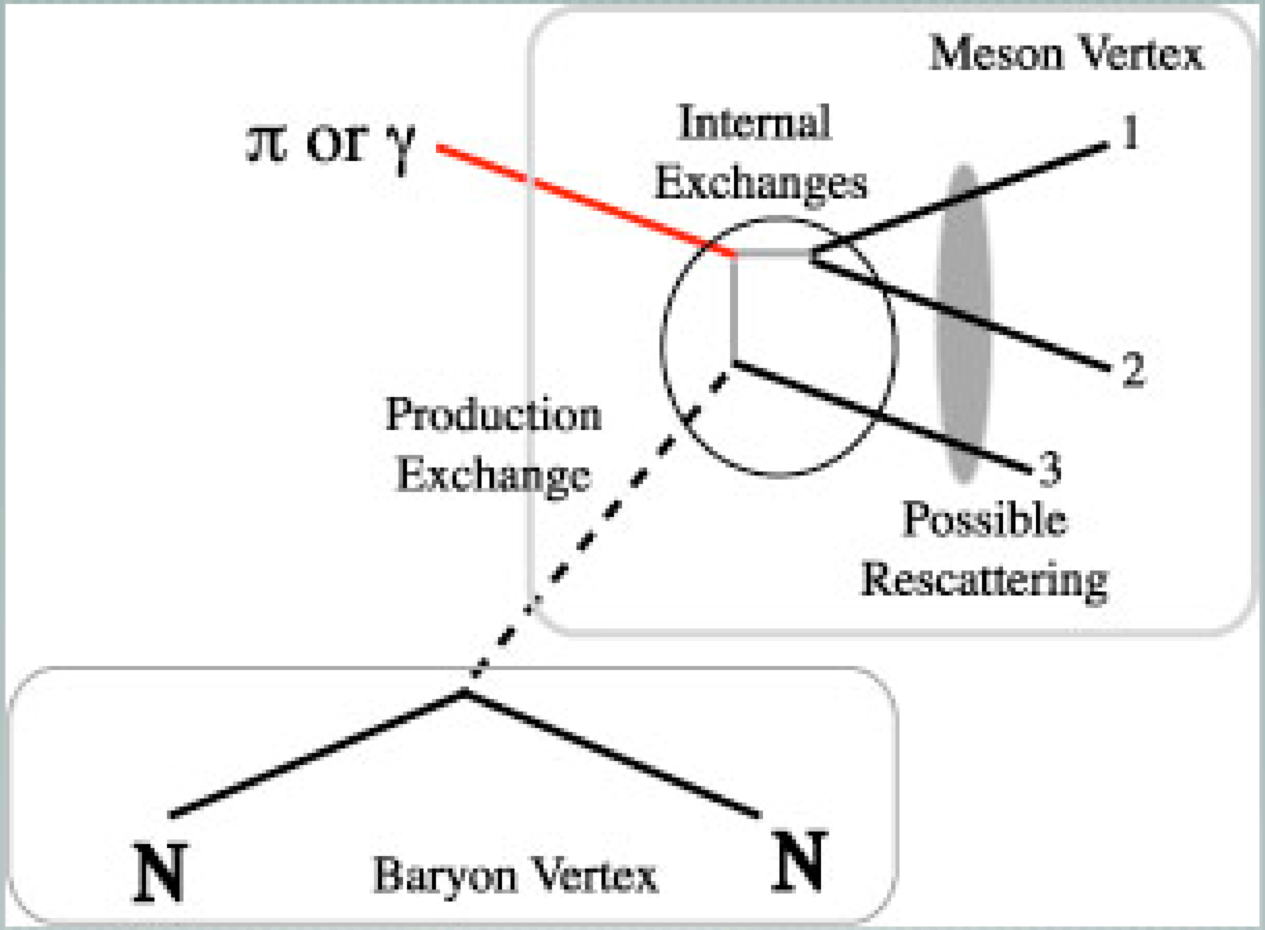


$MM_{\gamma K+}$ (GeV)

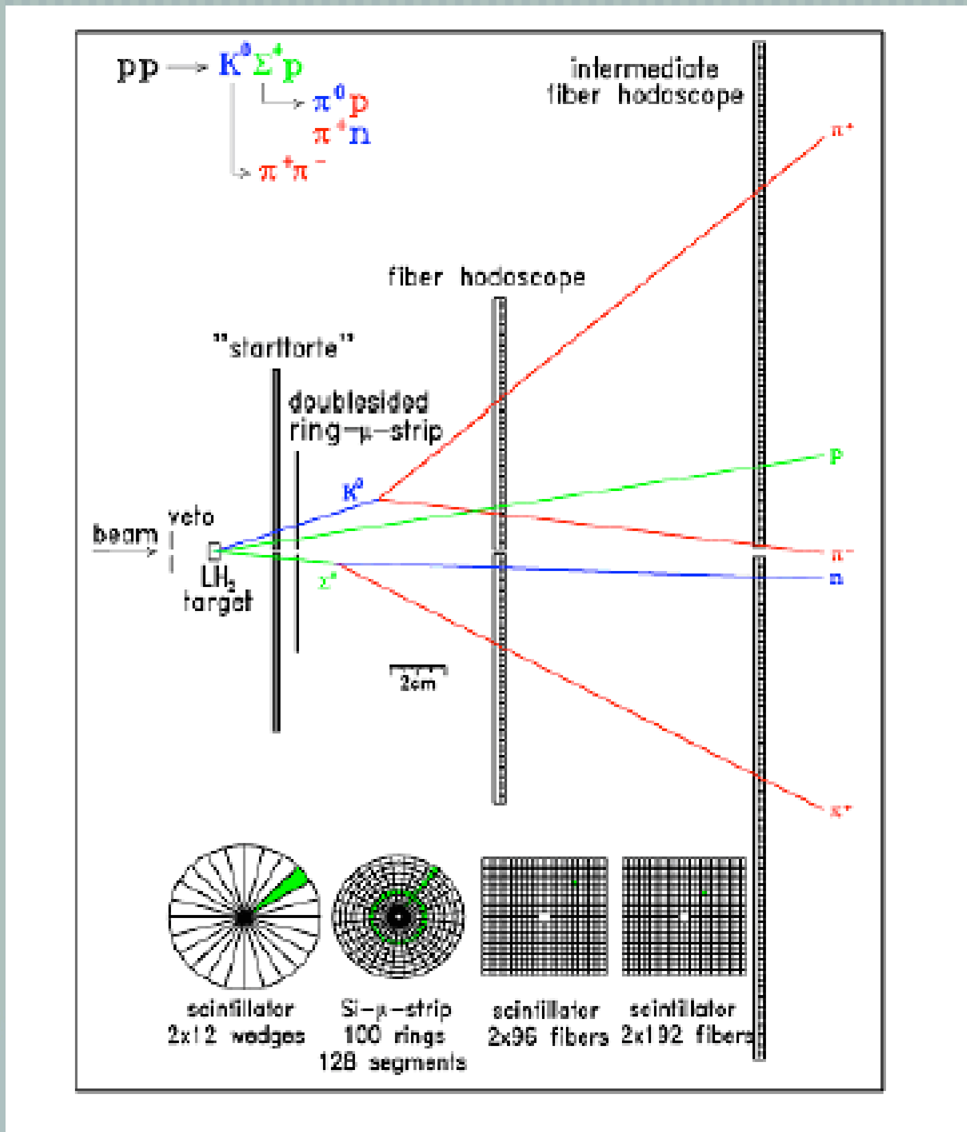


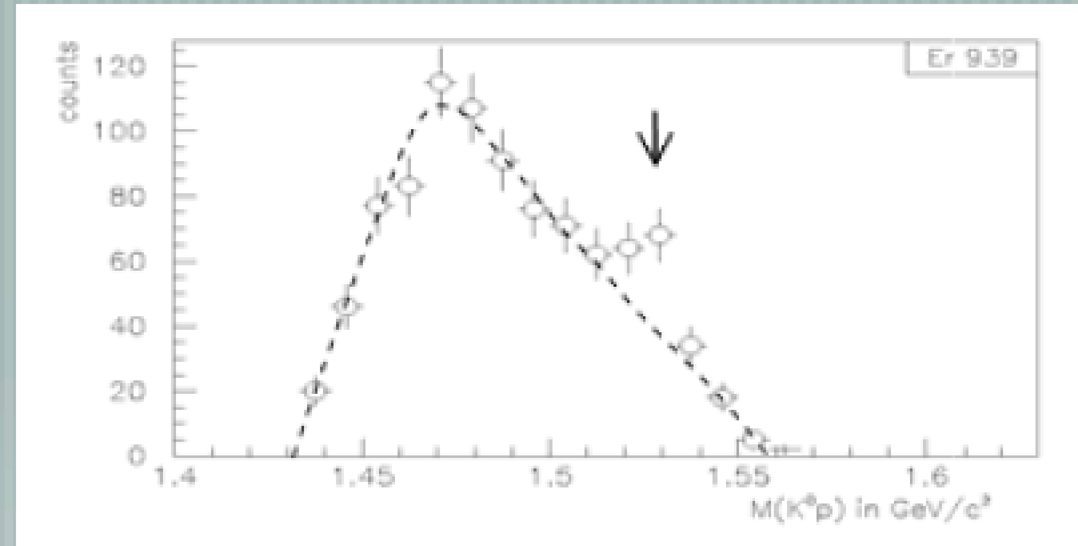
$MM_{\gamma K-}$ (GeV)

Three Pion Challenges

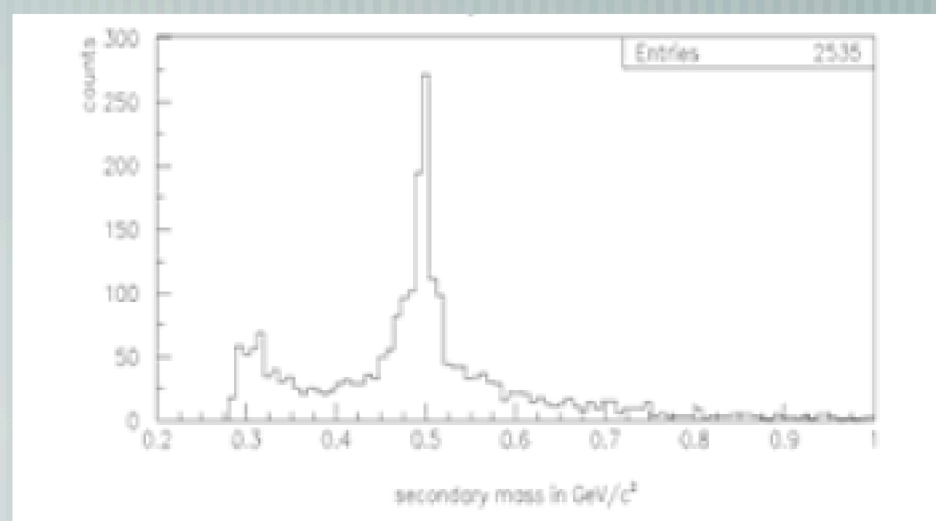


COSY-TOF $pp \to \Sigma^+ K^0_S p$





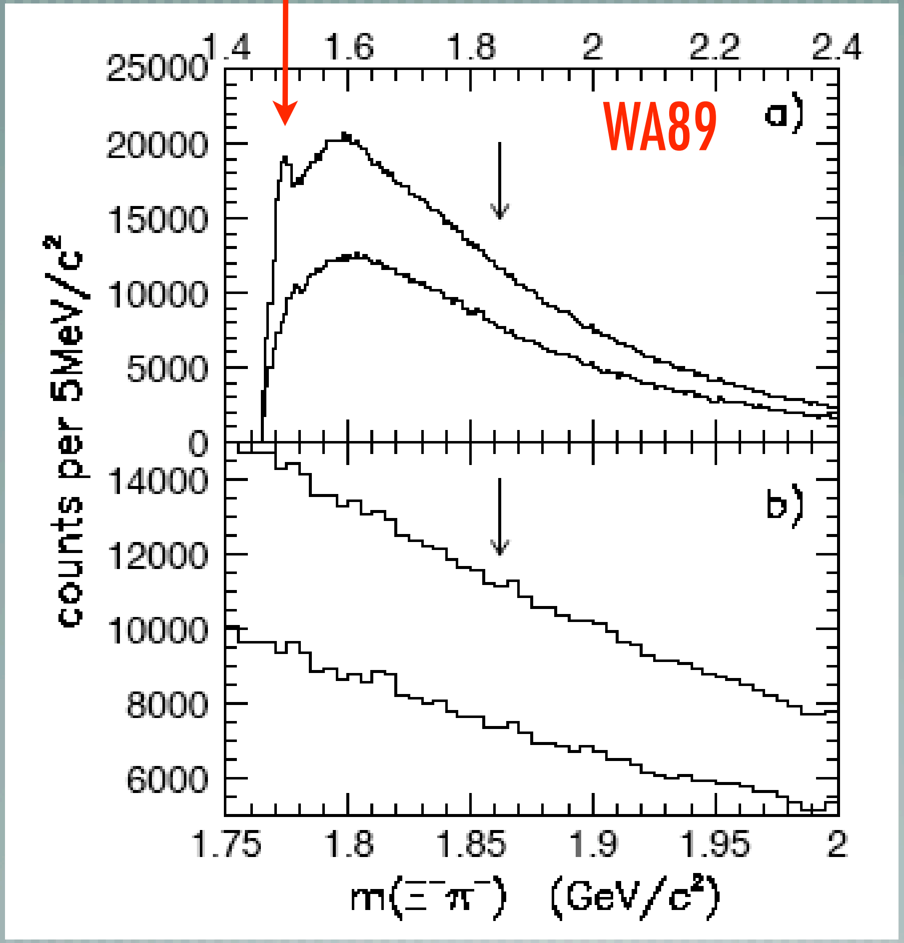
no magnetic filed, PID, pure geometry TOF no used in this analysis !



ghost tracks from

$\Xi^- \to \Lambda\pi^- \to p\pi^-\pi^-$ with one π^-

reconstructed as 2 tracks



The Charm Pentaquark and Kinematic Reflection.

M.Zavertyaev

hep-ex/0501028

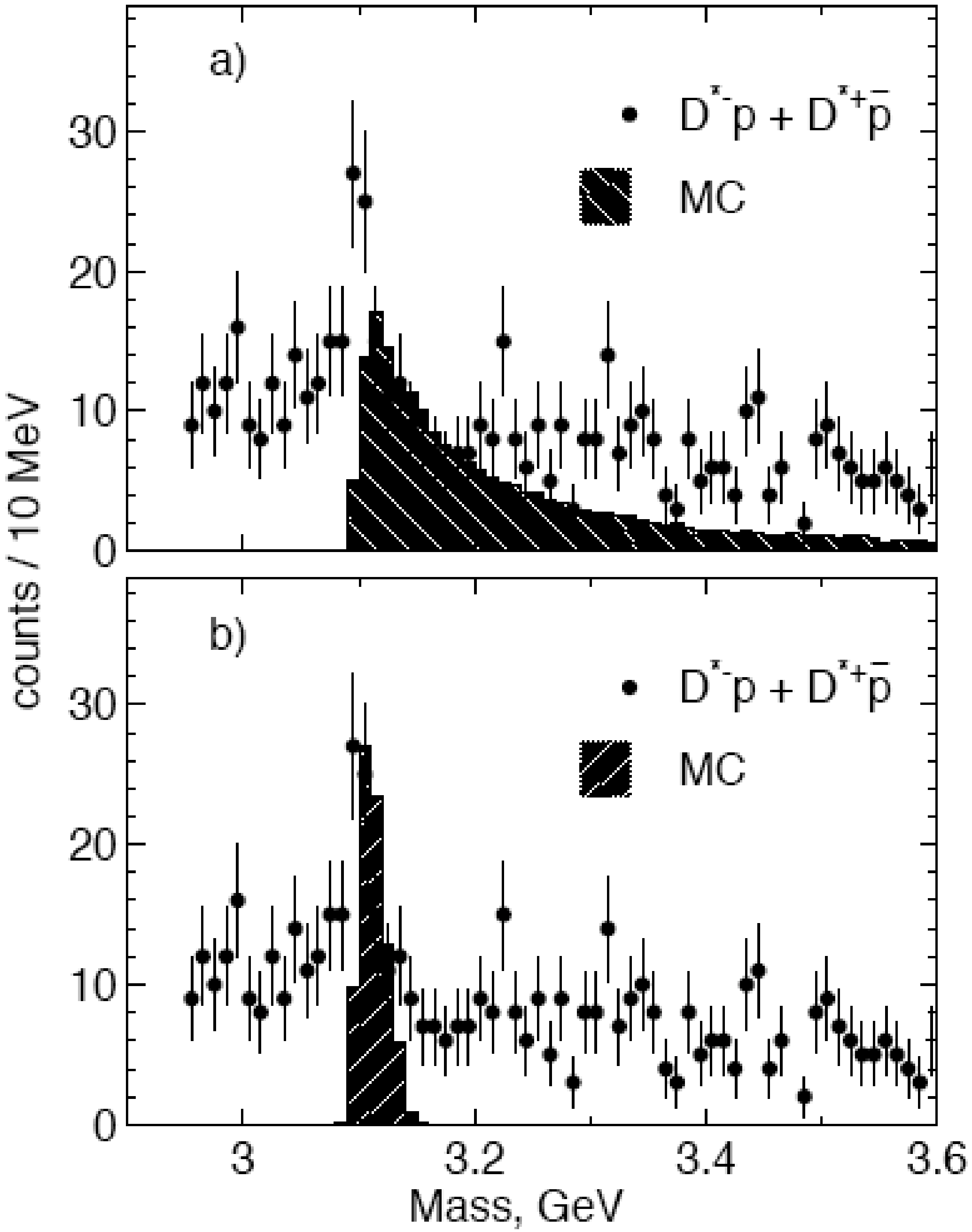


Figure 1: The invariant mass spectra of the $D^{*-}p + D^{*+}\bar{p}$ (taken from [1]) and Monte-Carlo simulation: a) no cut on the "proton" momentum; b) with the cut on the "proton" momentum >20 GeV/c.

$$D^{*+} \to D^0\pi^+$$
$$\to K^-\pi^+\pi^+$$

$$K^- \to K^- ``\bar{p}"$$