PentaQuark-2003 Workshop

A Search for Neutral Baryon Resonances Below Pion Threshold at Jefferson Lab Hall A

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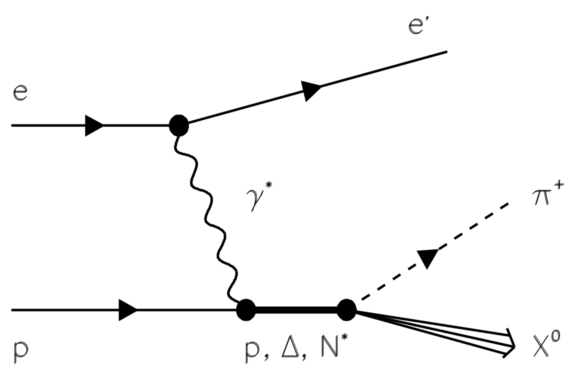
We conducted a 12 hour experiment at Jefferson Lab Hall-A for a high resolution missing mass search of:

$$p(e, e'\pi^+)X^0$$



- a search for narrow resonance X^0 in $0.97 < m_{X^0} < 1.06$ GeV.
- earlier "evidences" and "explanations".
- result of the Hall A search and possible improvements.

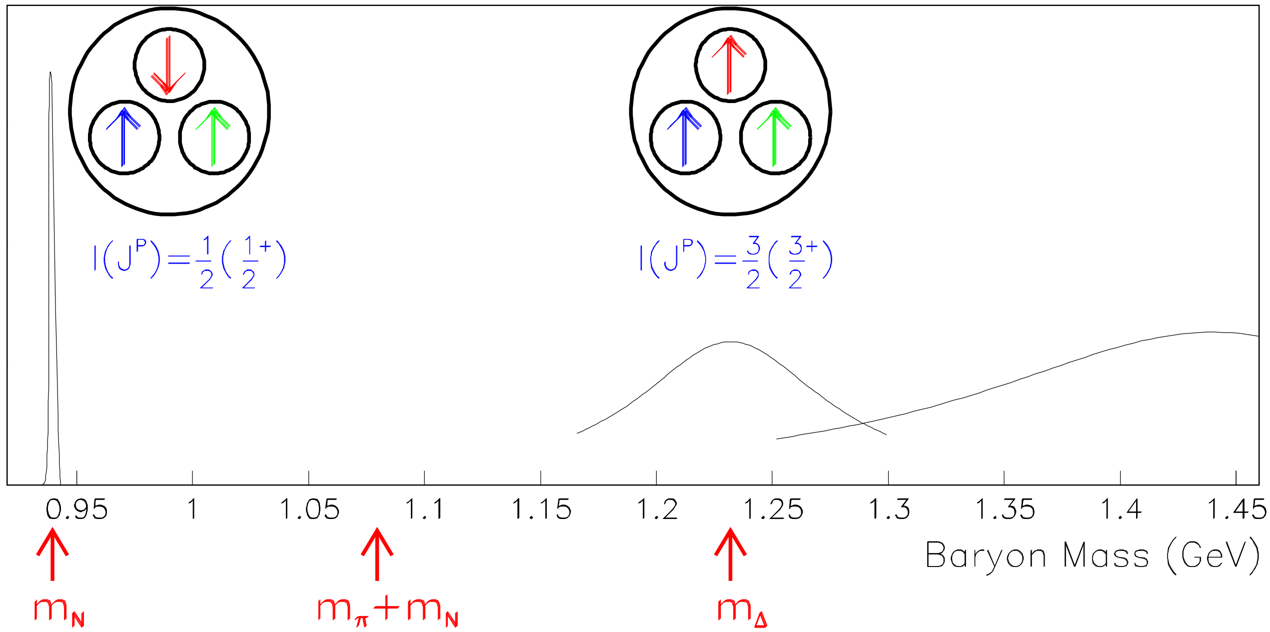
Results published in:

X. Jiang *et al.* Physical Review C 67, 028201 (2003).

The physics question:

Is there any neutral baryon resonance exist below pion threshold ?

Between the Nucleon and the Δ Resonance



- All nucleon resonances were found above pion threshold: Δ(1232), $N^\star$(1440,1520 and 1535 MeV), Δ(1600 and 1620 MeV) ...
- They are all net three quark color-singlet object.
- Quark spin-spin interaction explains the mass difference of $m_\Delta - m_N$.

But why there isn't any resonance below $m_N + m_\pi$?
It must be:

> Quark spin-flip creates the lowest possible excitation, other degrees of freedom need more energy to excite.

Quark models did not predict any resonance below $m_N + m_\pi$, nor did them explicitly rule out such a possibility.

If a nucleon resonance (X) exists below $m_N + m_\pi$:

Ya. Azimov, Phys. Lett. B32, 499 (1970).

- X must be a net three-quark color-singlet object of an ($X^0 X^+$) doublet and/or a quartet ($X^- X^0 X^+ X^{++}$).
- X must have a long lifetime and narrow width, only decays through photon channels ($X \to N\gamma$, $X \to N\gamma\gamma$).
- Could be discovered in pp, πp or ep reactions.

X must have small wave function overlap with regular baryons ($B = N, \Delta$ or $N^\star$).

The electroweak transition matrix elements:

$$\frac{g^2(A)_{XB}}{g^2(A)_{NB}} \approx \frac{g^2(V)_{XB}}{g^2(V)_{NB}} \equiv K_{EW} < 1.0,$$

where $g(A)$ and $g(V)$ are the axial and vector couplings.

The strong transition matrix elements:

$$\frac{g^2_{XB\pi}}{g^2_{NB\pi}} \equiv K_S < 1.0,$$

- One cannot establish an explicit argument that $K_{EW} \equiv K_S \equiv 0$ based on first principles.

- This work, for the first time, established a direct experimental upper limit of K_S for the X^0 particle to 0.35×10^{-3} by measuring the cross section ratio of

$$\frac{\sigma_{p(e,e'\pi^+)X^0}}{\sigma_{p(e,e'\pi^+)n}}$$

Earlier Searches for X^{++}

The Particle Data Book documented two experiments:

TRIUMF-E544 A. J. Yavin and D. Frekers spokespersons.

S. Ram *et al.*, *Phys. Rev.* D **49**, 3120 (1994).

- sensitive to X^{++} only.
- $pp \rightarrow X^{++}n$ reaction, 460 MeV proton beam.
- directly detect X^{++} in magnetic spectrometer, through dE/dX measurement at the focal plane.
- no X^{++} event was observed.

$$\Rightarrow \qquad \frac{\sigma(pp \rightarrow nX^{++})}{\sigma(np \rightarrow pn)} \leq 7.5 \times 10^{-8}$$

Another search for charge $Z = \pm 2$ and $Z = \pm 5/3$ excited states was carried out at KEK using a 12-GeV proton beam in pp, $\pi^{+}p$ and $K^{+}p$ collisions. No candidate event was found in the mass range up to $M/Z = 1.2$ GeV/c^2, and an upper limit was established at the 10^{-9} level on the yield of an excited state relative to the pion yield.

T. T. Nakamura *et al.*, *Phys. Rev.* D **39**, 1261 (1989).

A Surprise in 1997

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Evidence for Narrow Baryon Resonances in Inelastic pp Scattering

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The reaction $pp \to p\pi^+N$ has been studied at three energies (T_p = 1520, 1805, and 2100 MeV) and six angles from 0° up to 17° (laboratory). Several narrow states have been observed in missing mass spectra at 1004, 1044, and 1094 MeV. Their widths are typically 1 order of magnitude smaller than the widths of N^* or Δ. Possible biases are discussed. These masses are in good agreement with those calculated within a simple phenomenological mass formula based on color magnetic interaction between two colored quark clusters. [S0031-9007(97)03686-7]

PACS numbers: 14.20.Gk, 12.40.Yx, 13.75.Cs, 14.20.Pt

The study of exotic hadrons (mesons and baryons) has been ongoing for several years, motivated by the possibility of relating these exotic states to multiquarks, hybrids, or glueballs. The experimental studies can be separated into two classes. The first class concerns studies of exotic mesons mainly, but also in a few cases of exotic baryons, with explicit exotic quantum numbers, or their exotic combinations. The second class of studies concerns low energy, narrow, exotic states with hidden exotic properties (strangeness or color, etc.) [1]. The main observable here is the small width of the observed structures. Even if such narrowness is not a firm signature [2], this is an essential characteristic from an experimental point of view. Some candidates with relatively large masses exist, and have been observed at Protvino, CERN, and Argonne, although the existence of some of them is still a subject of debate. The corresponding masses are above 1000 MeV for mesons and 1950 MeV for baryons. For experimental reasons (resolution and counting rates), nearly all results of low mass, narrow hadrons concern isovector dibaryons which are seen to be concentrated around certain values [3]. A number of authors have observed many candidates for such isovector narrow dibaryons. This mass spectrum agrees surprisingly well with a simple phenomenological mass formula [3] derived for two colored clusters in a diquark-quadriquark assumption inside an MIT (Massachusetts Institute of Technology) bag model. Different theoretical works have been performed on dibaryons. The first approaches within MIT spherical bags [4] have been improved using cloudy bags [5]. In these last calculations, dibaryons were found at masses close to 2.7 GeV. The same authors predict the existence of molecular states [2] in the lower mass region.

The experiment presented below is the study of the $pp \to p\pi^+N$ reaction. It was carried out using the proton beam at the Saturne Synchrotron and the SPES3 facility [6]. The incident proton energies were 1520, 1805, and 2100 MeV. The measurements were performed at six angles, for each energy, from 0° up to 17° [7]. The cryogenic H_2 target was 393 mg/cm^2 thick. Both particles, p and π^+, were detected in coincidence in the solid angle of 10^{-2} sr ($\Delta\theta = \Delta\phi = \pm 50$ mrd) of the magnetic spectrometer. The broad range of momenta studied by the detection, $600 < pc < 1400$ MeV at $B =$ 3.07 T, allowed the simultaneous study of a large range of missing masses ($939 < M_x < 1520$ MeV). The particle trajectories were localized using drift chambers. The trigger consists of four planes of scintillating hodoscopes. Time of flight measurements over a distance of 3 m, in conjunction with energy loss measurements, allow the identification of the detected particles. Events were lost when both trajectories intersected on each plane of the detector. A simulation code describing the detector has been written in order to correct for such inefficiencies. These corrections, normalizing the data by a factor of ~1.25, are smooth functions, except in a narrow range of $p\pi^+$ invariant masses corresponding to particles detected at the same position on the focal plane. Inside such an invariant mass range the data have been removed, since a peak on the correction function makes any eventual structure at the same mass doubtful.

The random coincidences and eventual wrong identification arising from $pp \to ppX$ events have been taken out using a second time of flight between both particles. The total coincidence window, common to all time of flight channels, was ±2 ns. Since certain events from a $pp \to ppX$ reaction can simulate real $pp \to p\pi^+X$ events, checks were carried out to ensure that their contribution is small. They are randomly distributed in the two-dimensional plot of invariant mass against missing mass. In a very small number of cases (0.6% of events), the data reduction code makes a wrong assignment between trigger and chamber informations. These events have been removed.

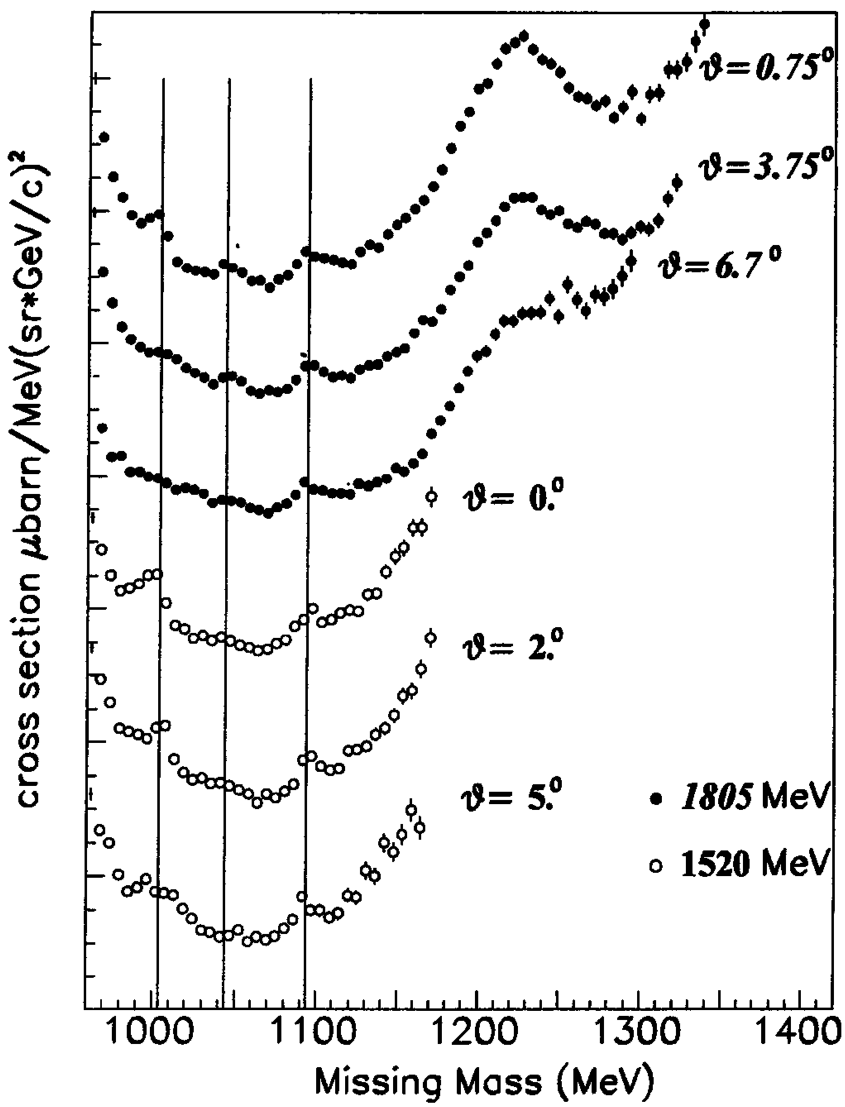
The necessary conditions required for narrow and small structures study were fullfilled in this experiment. These are (i) a good mass resolution; the σ on missing mass increases from 2.5 up to 9.4 MeV for spectrometer angles 5

B. Tatischeff *et al.*

Narrow structures were claimed in missing mass spectra at 1004,1044 and 1094 MeV.

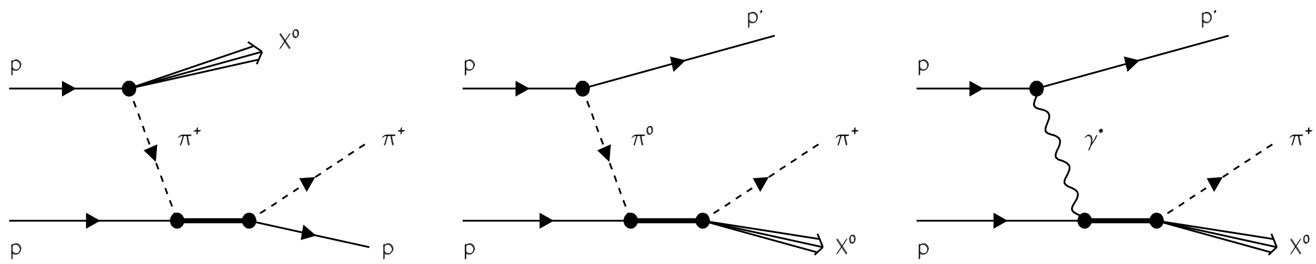
Experiment at the Saturne Synchrotron, France.

- sensitive to X^0 only.
- $pp \to p\pi^+ X^0$ reaction, T_p =1520, 1805, 2100 MeV.
- detect scattered proton and π^+ in magnetic spectrometer.
- reconstruct missing mass.



B. Tatischeff *et al.*

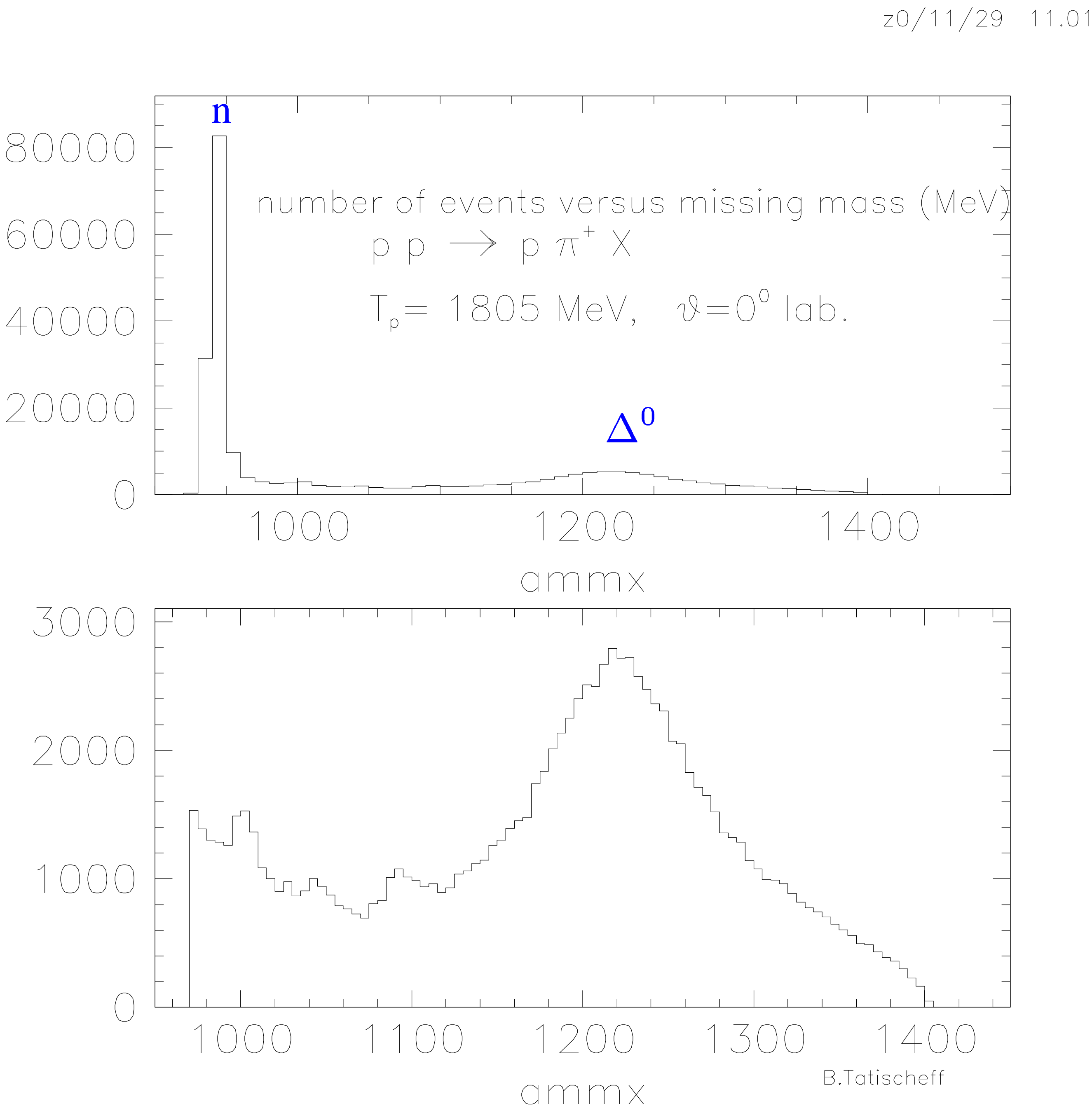
The reaction $pp \to p\pi^+ X^0$:



- structures exist for two different proton beam energies and three different proton scattering angles.
- the most significant structure is 17 standard deviations away from the statistical fluctuation.
- width of the structures is consistent with the experimental resolution.
- not detector flaws or PID mis-identifications.
- not collimator or target effects.

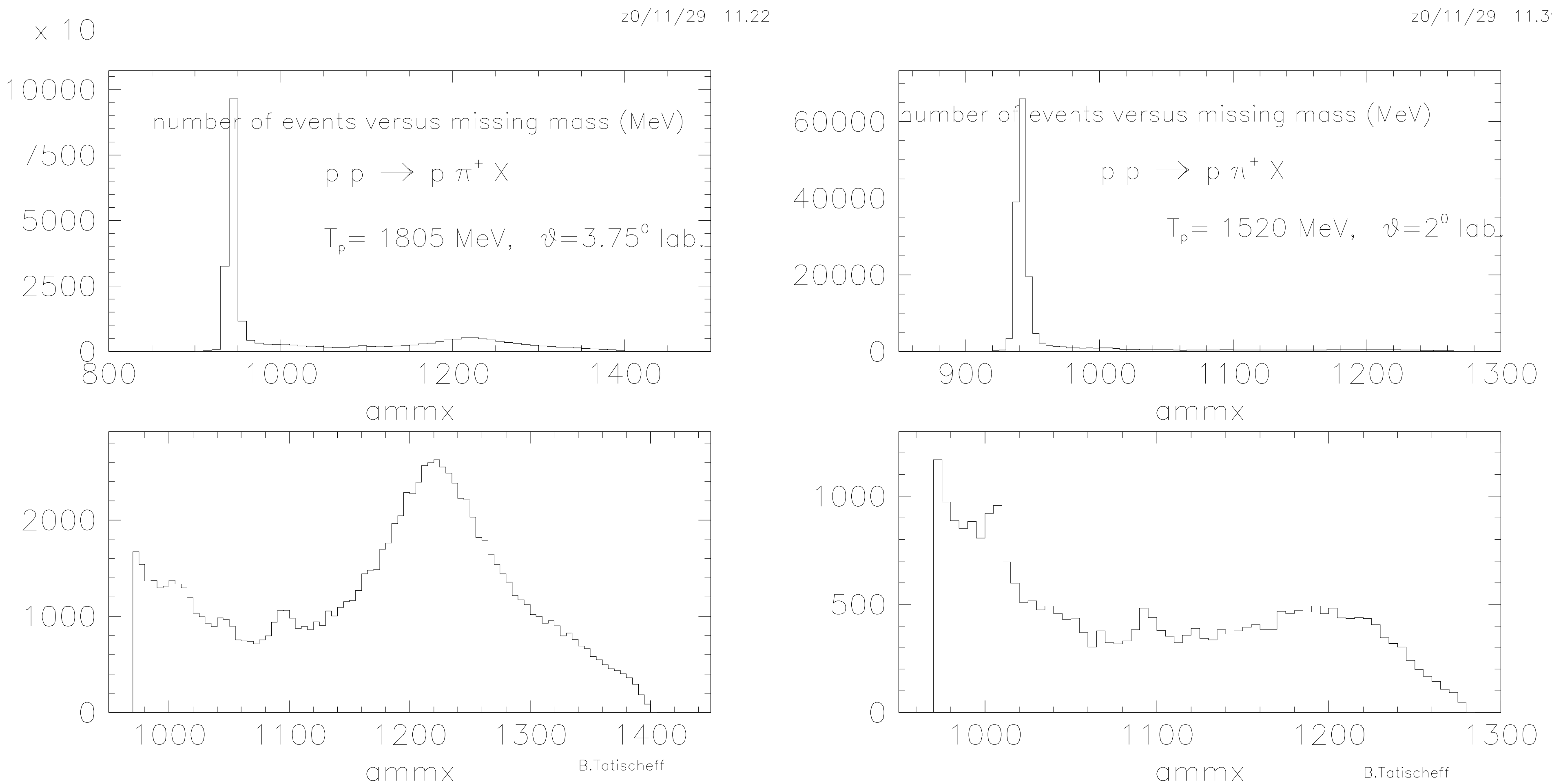
B. Tatischeff *et al.* $pp \to p\pi^+ X^0$

Missing mass spectra, $T_p = 1805$ MeV, $\theta_p = 0.75^\circ$:



$$\frac{\sigma(pp \to p\pi^+ X^0)}{\sigma(pp \to p\pi^+ n)} \approx 1 - 5 \times 10^{-4}$$

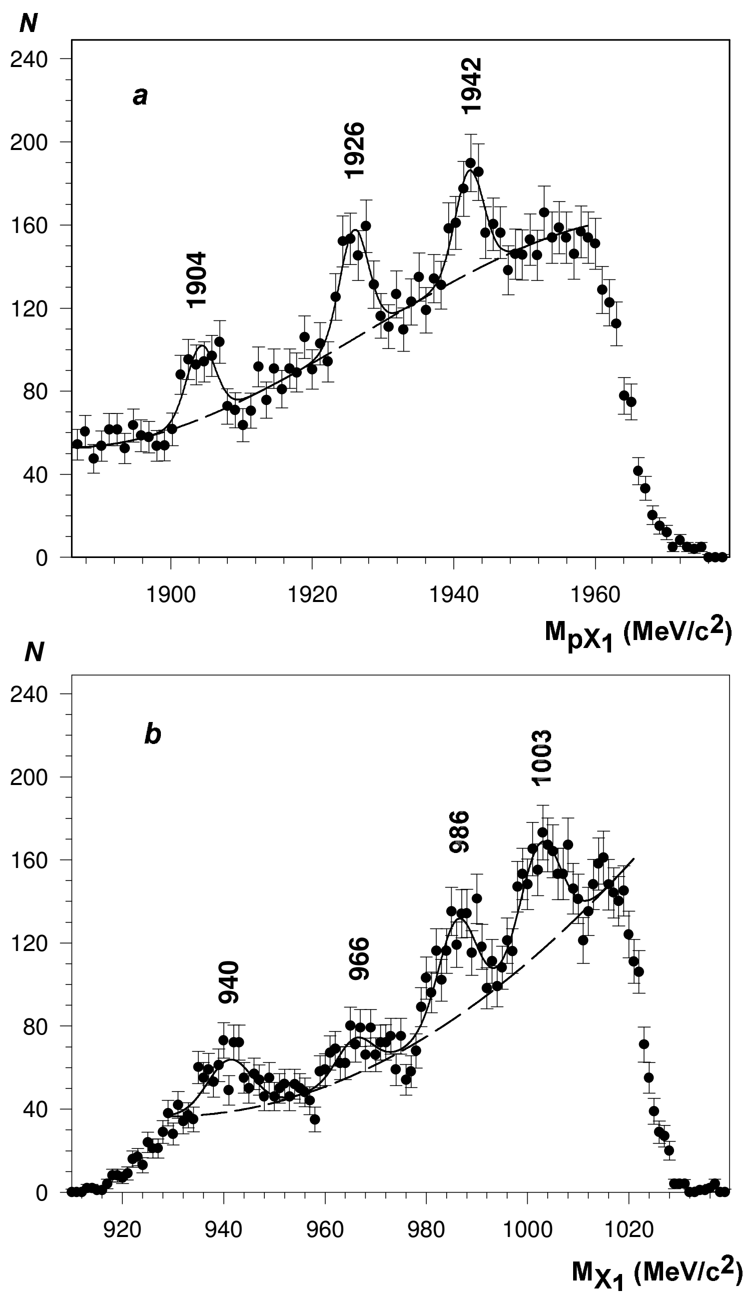
B. Tatischeff *et al.* Missing Mass Spectra of $pp \rightarrow p\pi^+X^0$



Another Possible Evidence

L. V. Fil'kov, V. L.Kashevarov, E. S. Konobeevskiy *et al.*, hep-ex/0006029, and earlier work at *Phys. Rev.* C **61**, 044004 (2000).

- $pd \to ppX_1$ reaction with 305 MeV proton beam,
- claimed "dibaryon-type" peaks in pX_1 mass.
- claimed single baryon peaks in X_1 mass, interpreted as supporting evidence for the narrow baryon resonances.



More Evidences were Cited as Private Communications

Additional evidence might exist (Year 2000):

- possible evidence of X^0 at 1007 MeV 2-4 sigma above statistics in $p(e, e'\pi^+)X^0$ reaction at Mainz.

  M. Kohl, G. Schrieder, C. Rangacharyulu and A. Richter, private communications.
- possible evidence of X^+ in Compton scattering at Mainz.

  R. Beck, private communications, cited in T. Walcher, hep-ph/0111279.

  In the differential cross section for Compton scattering at forward angle, a peak was observed at $E_\gamma = 115$ MeV, corresponds to $M = 1047$ MeV.

Possible Explanation (I): Colored Quark Clusters

A hand-waving model assuming colored quark clusters. (B. Tatischeff *et al.*)

- two clusters with spin $s_1(s_2)$ and isospin $i_1(i_2)$, such as $(q\bar{q})^2$-q^3 and q^2-q.
- color magnetic interactions, the mass formula for two colored quark clusters:

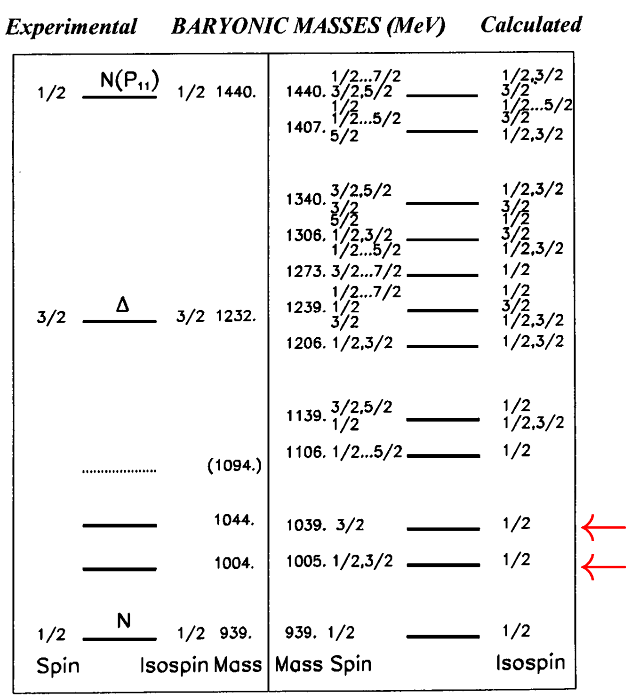
$$M = M_0 + M_1 \left[i_1(i_1+1) + i_2(i_2+1) + (1/3)s_1(s_1+1) + (1/3)s_2(s_2+1) \right]$$

- fixed nucleon mass assuming:
  $i_1 = s_1 = 0,\ i_2 = s_2 = 1/2.$
- fixed Roper (1440 MeV) mass assuming:
  $i_1 = 1,\ s_1 = 0,\ i_2 = 3/2,\ s_2 = 1/2.$

⇒ fixed $M_0 = 838.2$ MeV, $M_1 = 100.3$ MeV.

⇒ predicted Δ at 1206 and 1239 MeV.

⇒ predicted low mass states at 1005 and 1039 MeV.



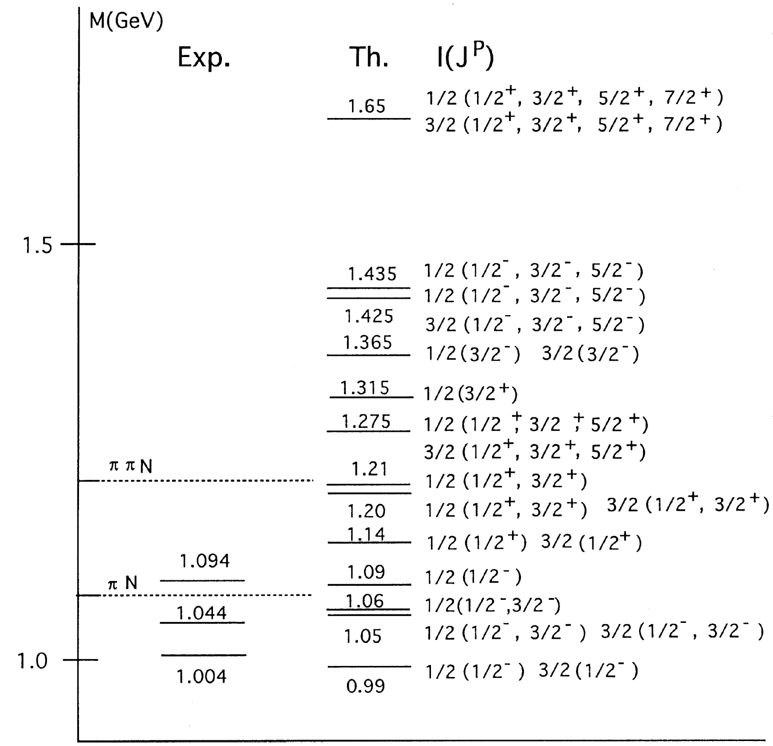
Possible Explanation (II): Colorless Quark Clusters

Use the mass formula of the diquark cluster model which does not assume colored quark clusters and does not involve any new free parameter.

(N. Konno, *Nuovo Cimento* A **111**, 1393 (1998))

- a quark system $q^k\bar{q}^h$ in the jj-coupling dominated scheme.
- all parameters were fixed earlier.

  (K. Konno, *Phys. Rev.* D **35**, 239 (1987).)



$\Rightarrow$ predicted low mass states at 0.99, 1.05 and 1.06 GeV.

Mass of Colorless Quark Clusters $q^k\bar{q}^h$

$$\begin{aligned} M &= (k+h)m + M\left(1p\frac{1}{2}\right)n\left(1p\frac{1}{2}\right) + M\left(1p\frac{3}{2}\right)n\left(1p\frac{3}{2}\right) \\ &+ M\left(1d\frac{3}{2}\right)n\left(1d\frac{3}{2}\right) + M\left(2s\frac{1}{2}\right)n\left(2s\frac{1}{2}\right) + M\left(2p\frac{1}{2}\right)n\left(2p\frac{1}{2}\right) \\ &+ \Delta_0\left(n_{\phi_0}+n_{\bar{\phi}_0}\right) + \Delta_1\left(n_{\phi_1}+n_{\bar{\phi}_1}\right) + \sum \Delta_{TS}, \end{aligned} \tag{1}$$

in which

$$\Delta_0 = a - \frac{3}{4}b, \qquad \Delta_1 = a + \frac{1}{4}b, \tag{2}$$

$$M\left(1p\frac{1}{2}\right) = \omega - \frac{\omega^2}{2m}, \quad M\left(1d\frac{3}{2}\right) = 2\omega - \frac{3\omega^2}{4m}. \tag{3}$$

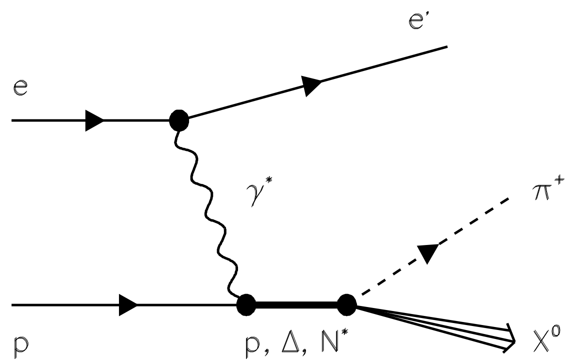
All free parameters were fixed using data of baryon masses and the πd phase-shift,

$$m = \omega = 300\, MeV, \;\; a = 187\, MeV, \;\; b = 195\, MeV,$$

$$\Delta_{00} = \Delta_{11} = 0, \;\; \Delta_{10} = -60\, MeV, \;\; \Delta_{01} = 10\, MeV.$$

This Experiment: the $p(e, e'\pi^+)X^0$ Reaction

If X^0 exist, it could be a decay product of an off-shell p, Δ or $N^\star$.



We took advantages of two high resolution magnetic spectrometers in Hall A.

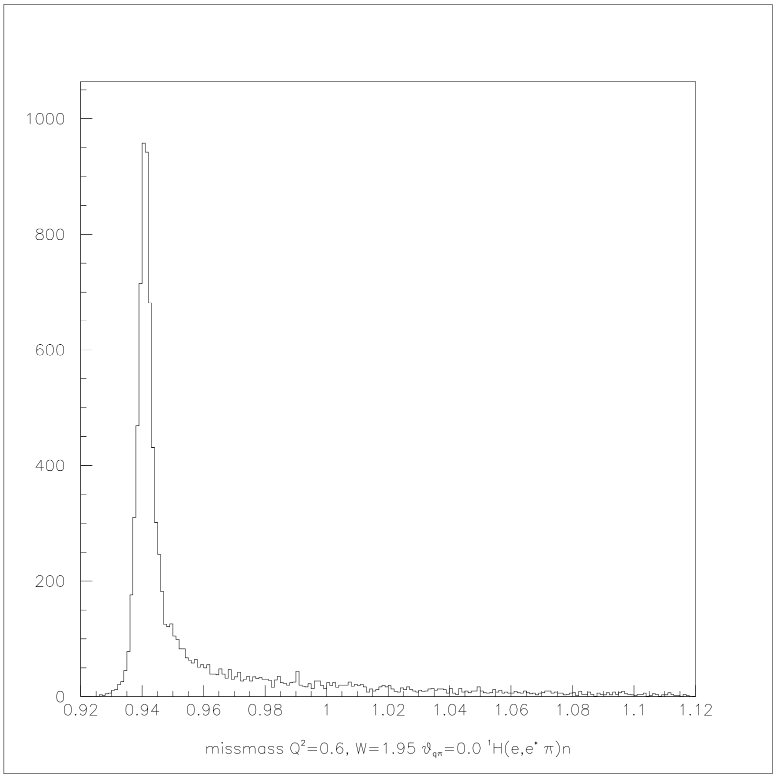
- a high resolution missing mass measurement ($\Gamma_{M_{miss}} = 2.0$ MeV, Γ: FWHM).
- good PID for π^-/e and π^+/p separation.
- coincident timing resolution $\Gamma_{tof} \approx 2.0$ ns.
- high statistics.

Existing Hall B and Hall C data:

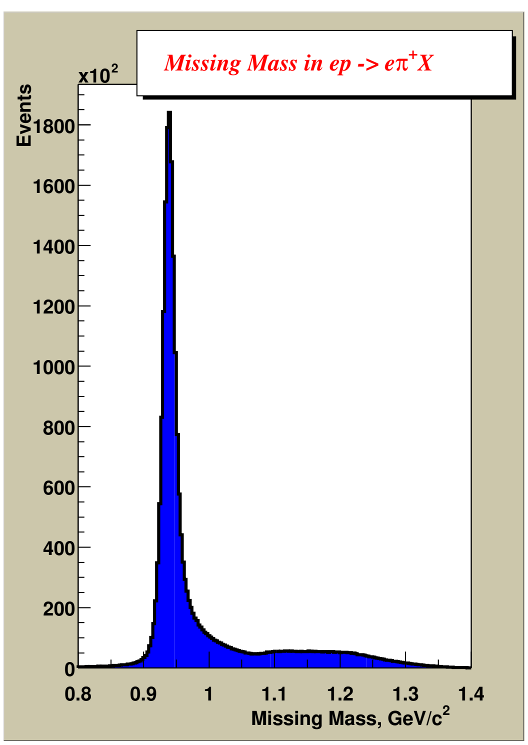
- Data from Hall-C E93021.
- Data from Hall-B e1c.

Existing JLab Data: No Resonances

From D. Mack Hall C E93021:



From L. Elouadrhiri Hall-B e1c:



This Experiment: Kinematics

E_0=1.722 GeV, on a 15 cm LH_2 target, I=33 μ A.

Electron-arm:

$P_e = -1.040$ GeV/c, $\phi_e = 19.0°$.

Hadron-arm:

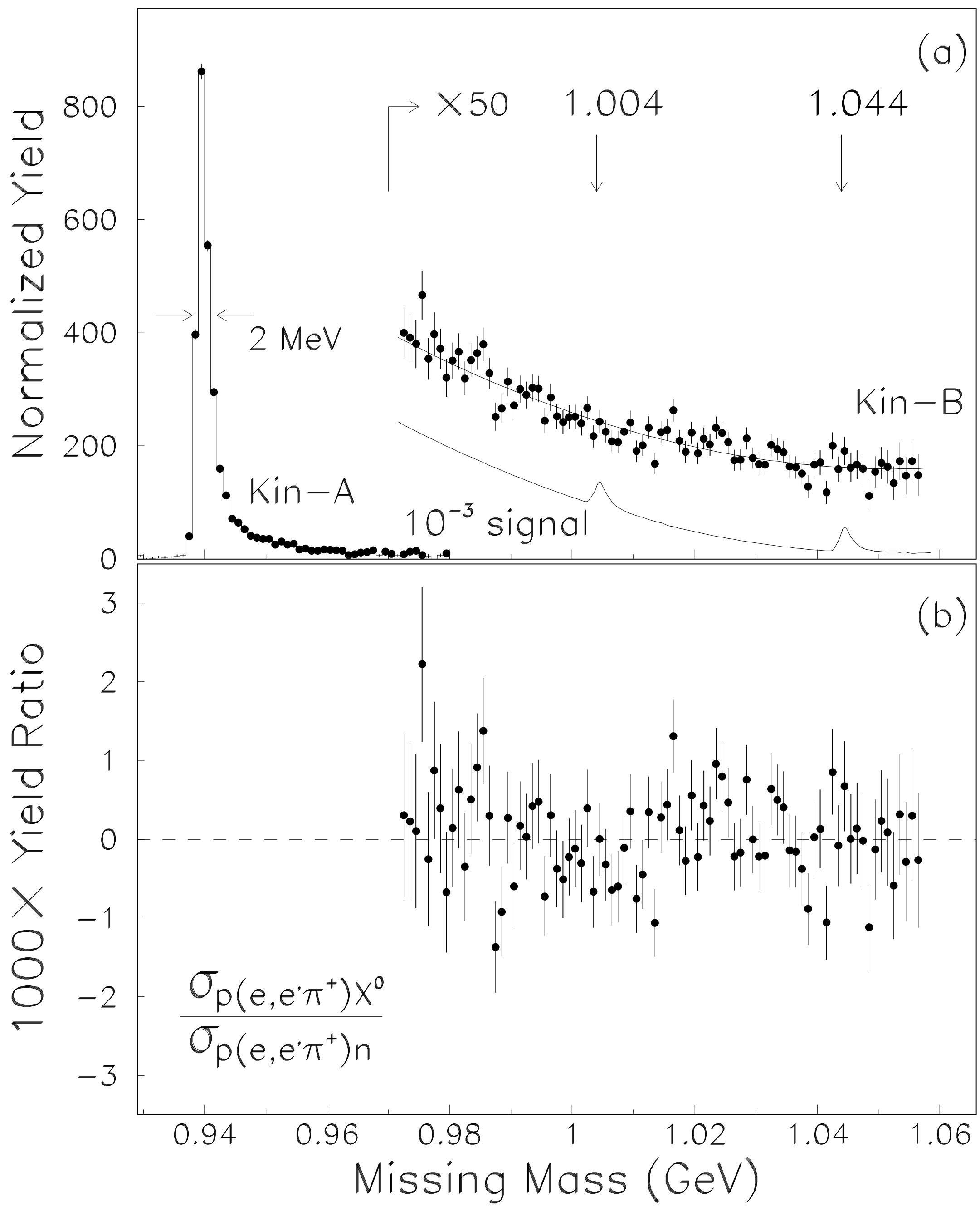
$P_h = +0.621$ GeV/c, $\phi_h = 41.6°$.

for 1.5 hour on $p(e, e'\pi^+)n$ reaction.

and then set $P_h = +0.527$ GeV/c, cover missing mass region of 0.970 to 1.060 GeV.

We chose $Q^2 = 0.2$ (GeV/c)^2, and invariant mass of the $\pi^+ X^0$ system to be $W \approx 1440$ MeV.

The Result of the Hall A X^0 Search



$$K_S \equiv \frac{\sigma_{p(e,e'\pi^+)X^0}}{\sigma_{p(e,e'\pi^+)n}} \leq 0.35 \times 10^{-3}$$

Summary

Evidences were claimed on the existence of narrow baryon resonances at 1004, 1044 MeV.

We conducted a high resolution missing mass search in the $p(e, e'\pi^+)X^0$ channel, and set an upper limit on the existence of such resonances:

$$\frac{\sigma_{p(e,e'\pi^+)X^0}}{\sigma_{p(e,e'\pi^+)n}} \leq 0.35 \times 10^{-3}.$$

Improvements for future searches:

- missing mass resolution: 2.0 MeV $\Rightarrow$ 0.5 MeV.
- time-of-flight resolution: 2.0 ns $\Rightarrow$ 0.5 ns.
- beam time: 12 hours $\Rightarrow$ 360 hours (15 days).
- suppress radiative tail by tagging recoil neutrons. Reject co-plane neutrons.

A carefully planned experiment can achieve sensitivity of

$$\frac{\sigma_{p(e,e'\pi^+)X^0}}{\sigma_{p(e,e'\pi^+)n}} = 10^{-6} \sim 10^{-5}.$$