Further Evidence for Formation of a Narrow Baryon Resonance with Positive Strangeness in K^+ Collisions with Xe Nuclei

DIANA collaboration of ITEP, Moscow & Frascati:

V.V. Barmin, A.E. Asratyan, V.S. Borisov,C. Curceanu, G.V. Davidenko, A.G. Dolgolenko, C. Guaraldo, M. A. Kubantsev, I.F. Larin, V.A. Matveev, V.A.Shebanov, N.N. Shishov, L.I. Sokolov, G.K. Tumanov

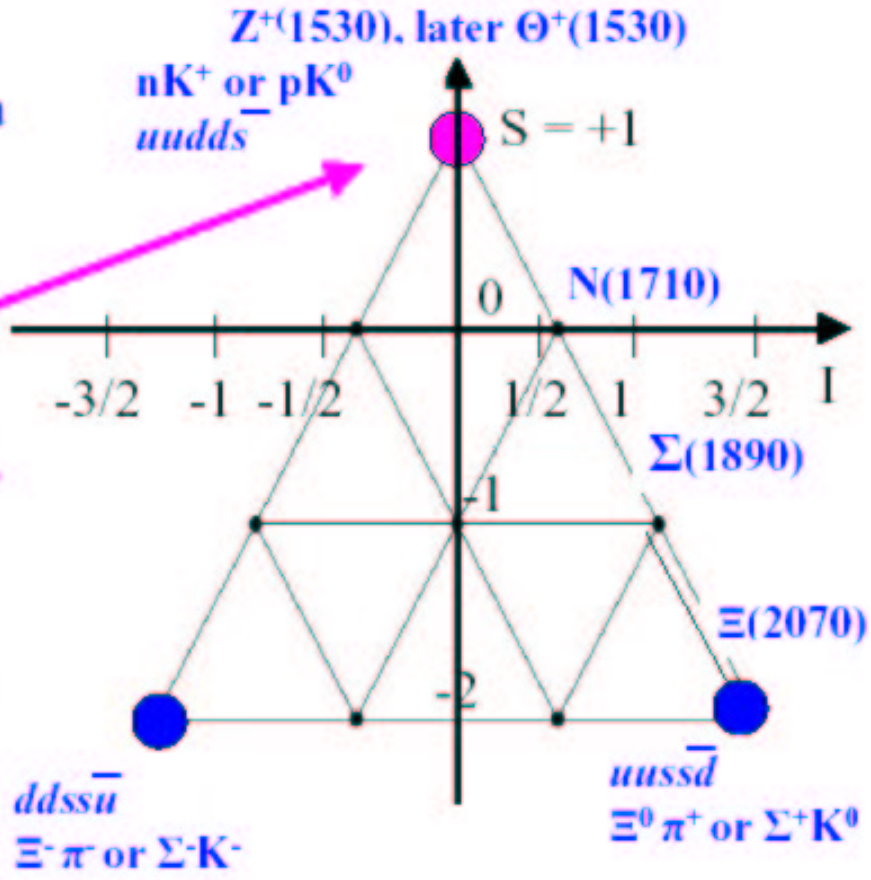
INTRODUCTION

In 1997 D. Diakonov, V. Petrov and M. Polyakov proposed, on basis of a chiral soliton model, a low-mass anti-decuplet of pentaquarks ($qqqq\bar{q}$).

Predicted lower state has mass of 1530 MeV/c^2 and narrow width <15 MeV/c^2.

Three baryons in the corners are exotic.

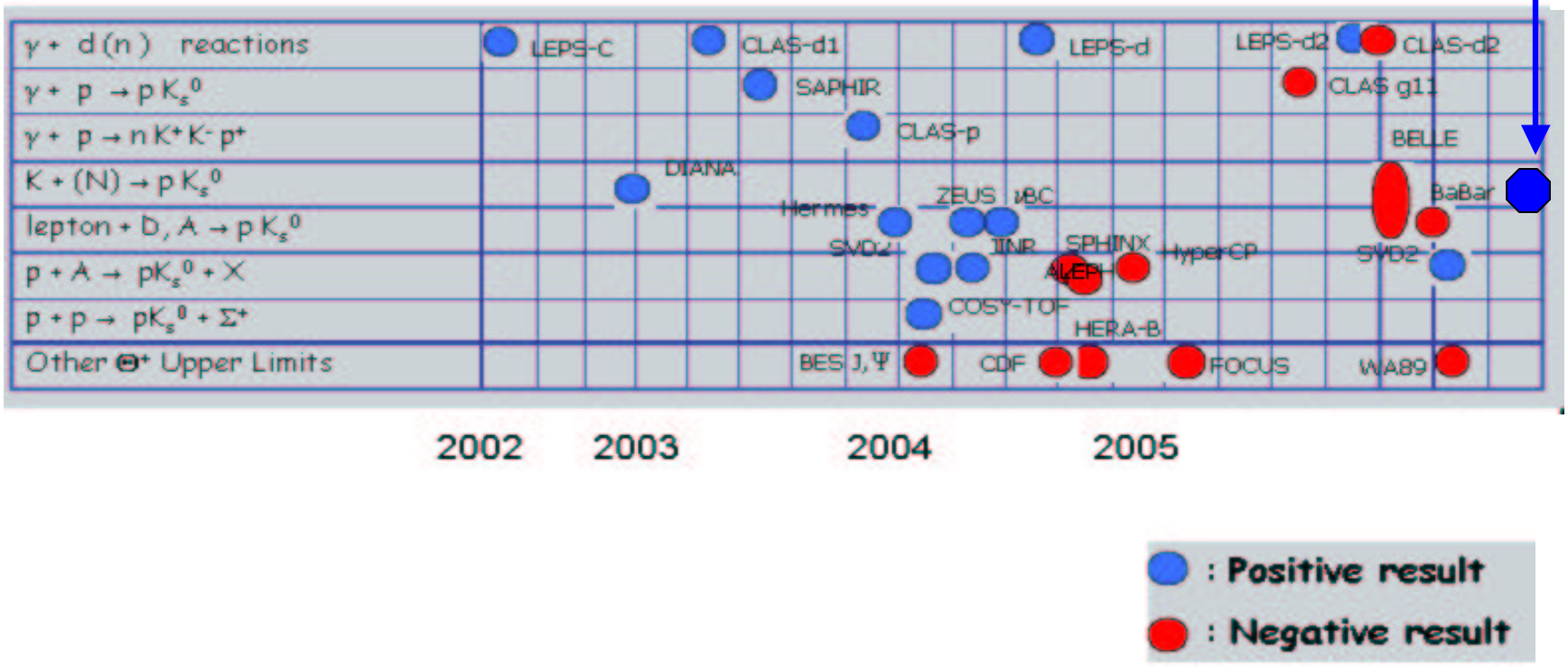
They have been bold enough to persuade experimentalists to look for these states, so in the beginning of 2003…



INTRODUCTION

Time dependent experimental status of Θ^+

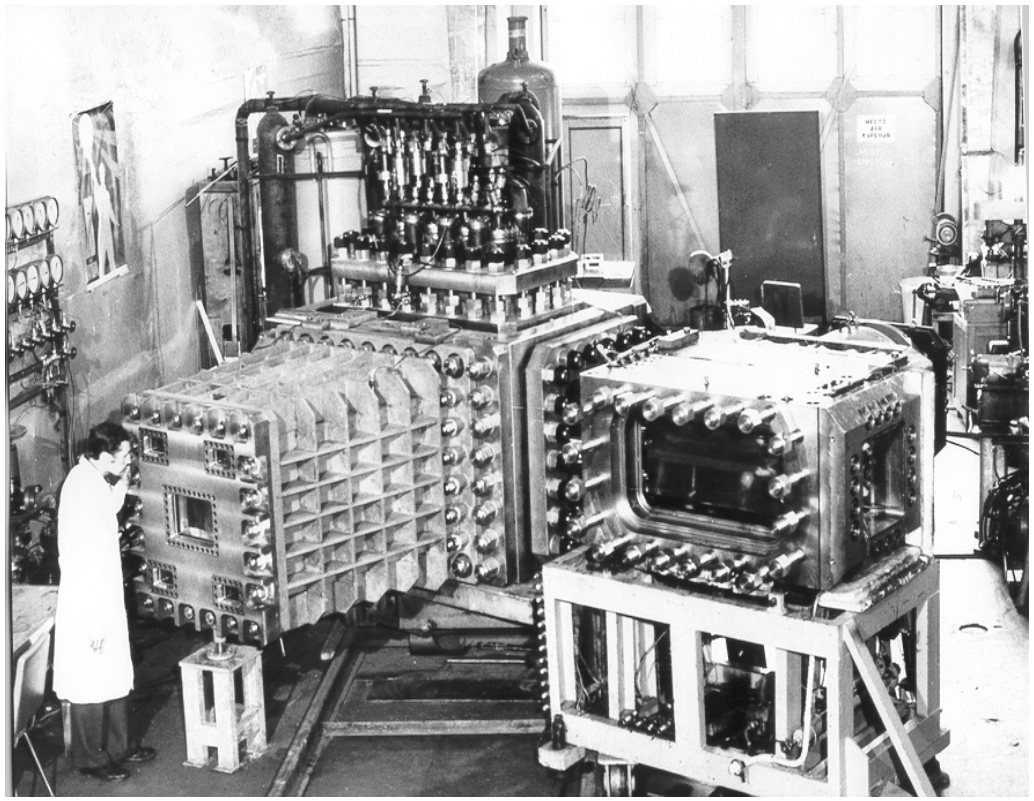
A new Diana result



INTRODUCTION

NEVER GIVE UP!

First 2002 Observation of Θ^+ in K^+Xe Interactions



The DIANA chamber under preparation

A separated beam of K^+ mesons with momentum of 750 MeV/c from the ITEP 10 GeV proton accelerator irradiates the DIANA chamber

filled with liquid Xenon:

Density: 2.2 g/cm ^{3},

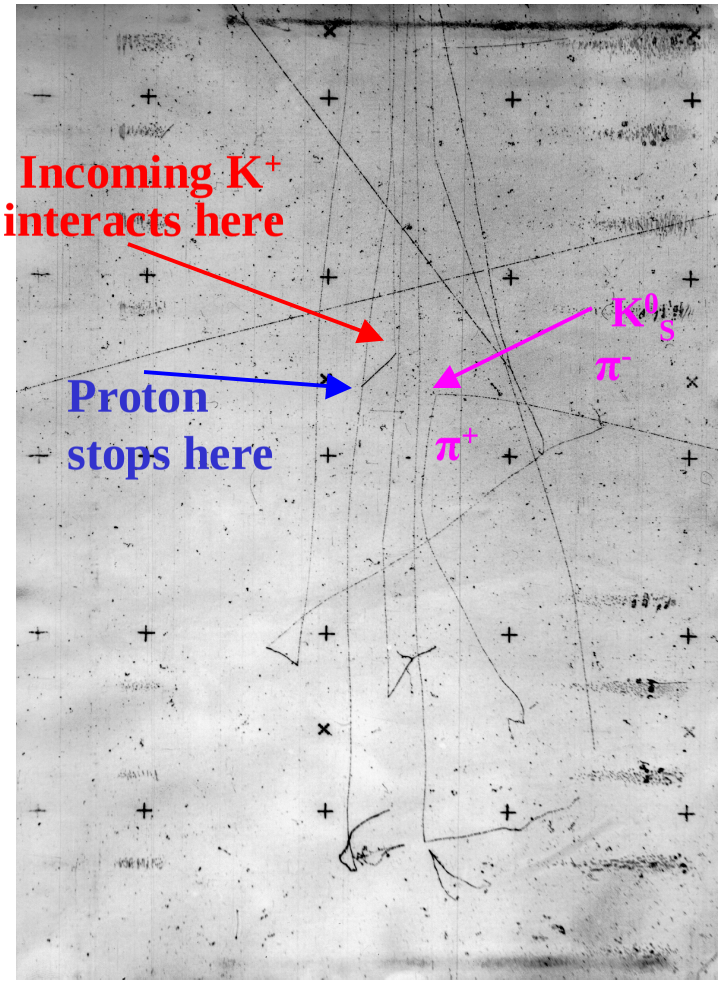
Rad. length: 3.7 cm.

Volume: 700 liters

Viewed with 4 cameras

No magnetic field

First 2002 Observation of Θ^+ in K^+Xe Interactions



Charged particle momentum measurement and identification are by range and ionization .

Range of an incident kaon before interaction determines energy of the reaction ($\Delta p/p_{beam}$ = 4%):

$K^+ + N \rightarrow P + K^0$ (+1 strangeness!)

K^0_S are fitted to the vertex.

On recorded 10^6 kaon tracks found ~35000 events with visible decays:

$K^0_S \rightarrow \pi^+\pi^-$ and $K^0_S \rightarrow \pi^0\pi^0$

Only events with one proton and $K^0_S \rightarrow \pi^+\pi^-$ were selected.

First 2002 Observation of Θ^+ in K^+Xe Interactions

To preserve accuracy of the measurements we dropped events with:
protons with p_p<180 MeV/c,
K^0 with p_K<170 MeV/c and decay distance < 2.5 mm

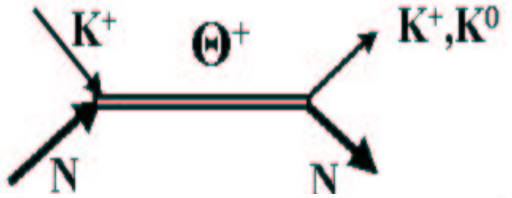
Momentum resolution is estimated: ~ 2% for the K^0 and proton,

Resolution in angle between K^0 and proton is ~ 2^0 in the lab system

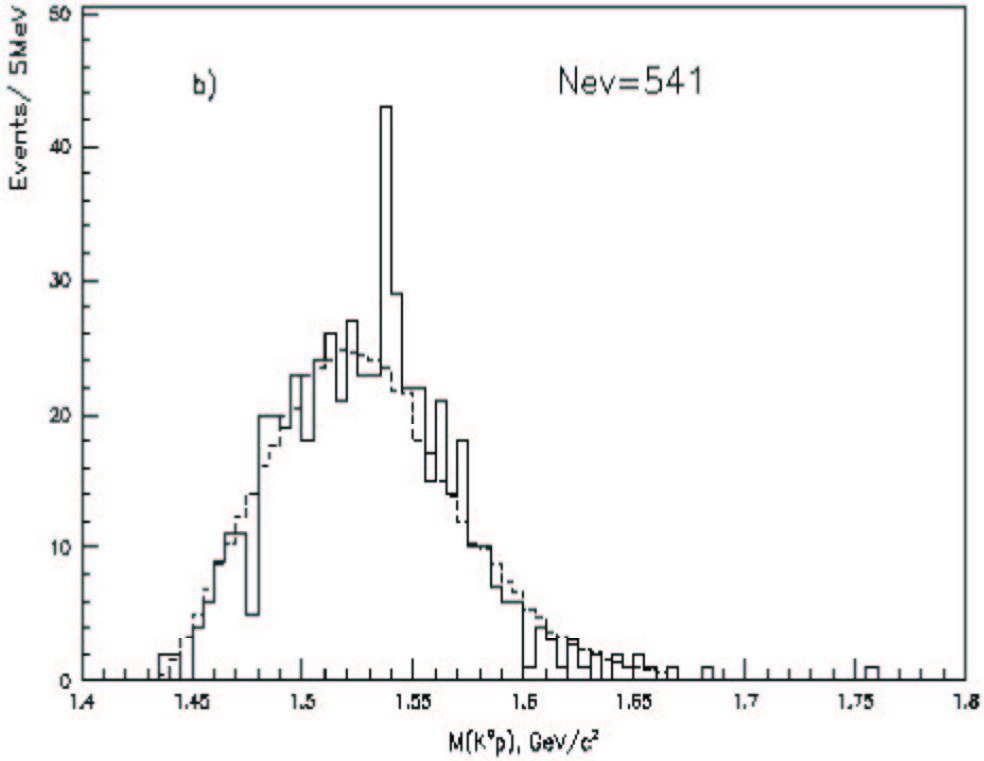
Estimation of K^0 p effective mass reconstruction accuracy was made with Monte-Carlo (~3 MeV/c^2) and verified with decays $\Lambda^0 \rightarrow p + \pi^-$ with observed M(p π^-) width of σ = 3.3± 1.0 MeV/c^2 in the same momentum range

First 2002 Observation of Θ^+ in K^+Xe Interactions

V.V. Barmin et al, Phys. Atom. Nucl. 66, 1715 (2003)



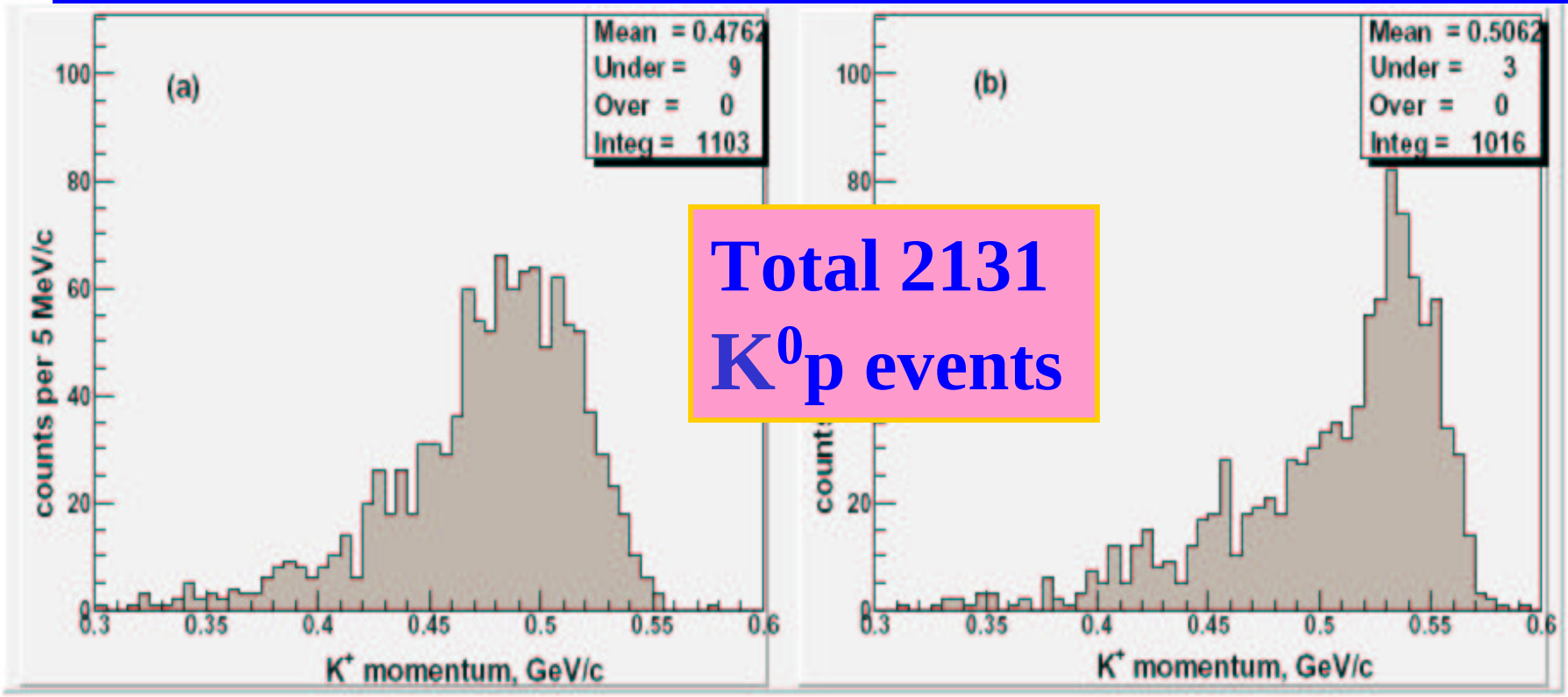
Under topological cuts:
θ_K <100°, θ_P <100°, cos Φ_{pK} < 0
the peak of total 73 events has estimated background of 44 events, resulting in statistical significance of $S/\sqrt{B} = 4.4\ \sigma$
Fit of the peak yields:
$M = 1539 \pm 2$ MeV/c^2
$\Gamma < 9$ MeV/c^2 (compatible with instrumental resolution)



Further Observation of Θ^+ in K^+Xe Interactions

New statistics with improved analysis

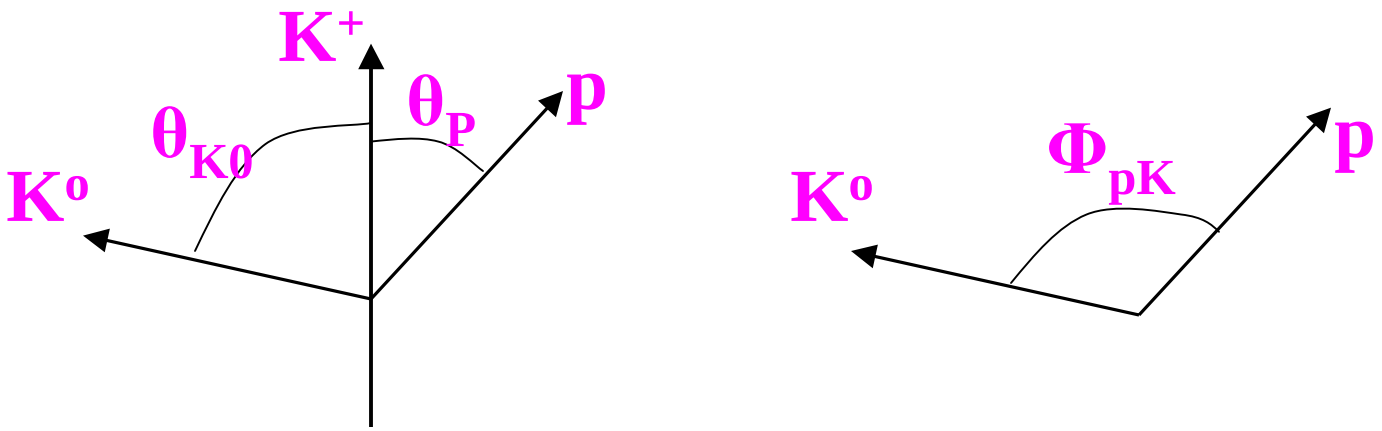
Further Observation of Θ^+ in K^+Xe Interactions: Old and New Statistics



Total 2131 K^0p events

Incident K^+ momentum for measured events of the reaction $K^+Xe \rightarrow K^0 pX'$. The old and new data are shown in (a) and (b)

Further Observation of Θ^+ in K^+Xe Interactions: event selections



We demonstrate rejection power of the selections:
$\theta_K < 100^o$, $\theta_P < 100^o$ and $\cos(\Phi_{pK}) < 0$
to re-scatterings using a simple Monte-Carlo of the reaction $K^+Xe \rightarrow K^opXe'$ in nuclear environment (no resonances included).

$K^+Xe \rightarrow K^o pXe'$ Interactions: Monte-Carlo Simulation

We follow *A. Sibtsev et al, Eur.Phys.J. A23,491 (2005)* defining energy of a bound neutron as

$E_n = m_N - 2\varepsilon - p_n^2/(2m_N)$

m_N - a mass of free neutron,

ε= 7 MeV - the mean binding energy,

p_n- Fermi momentum

We use:

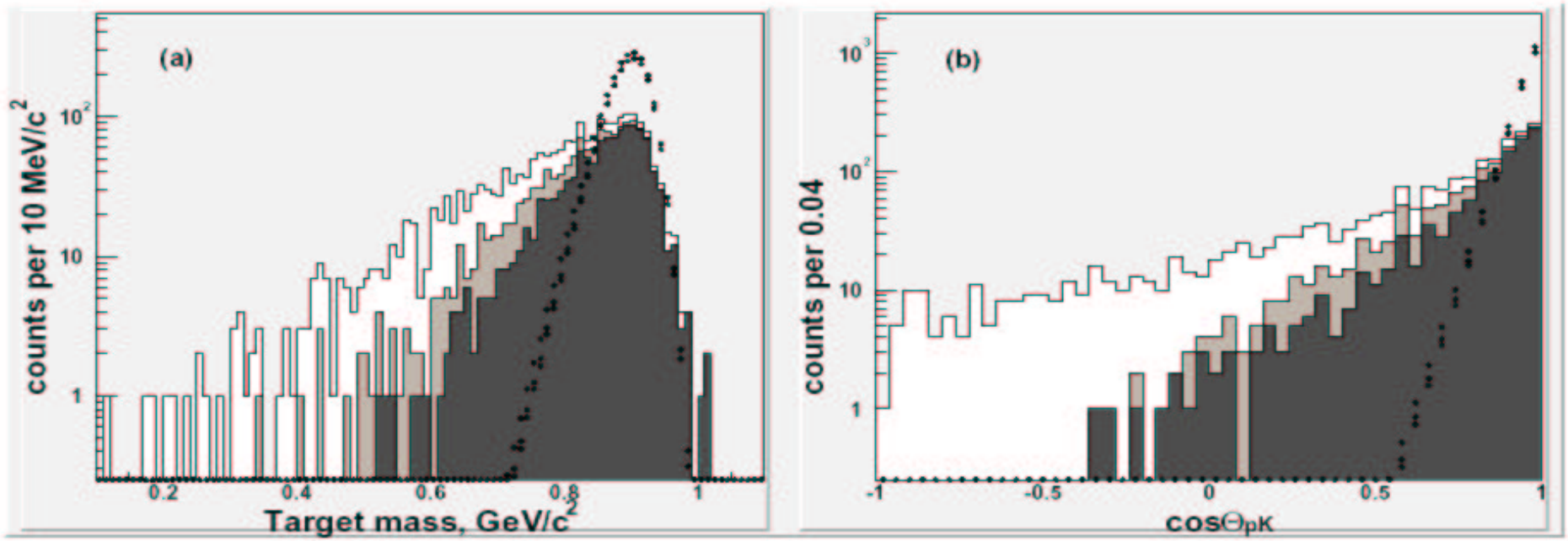
the Fermi-momentum distribution for the Xenon nucleus with maximum near 170 MeV/c;

experimental flux of K^+ mesons;

experimental momentum and angular resolutions.

Re-scattering in the nucleus is not accounted for.

$K^+Xe \rightarrow K^0pXe'$ Interactions: Re-scattering Rejection: Simulation vs Data



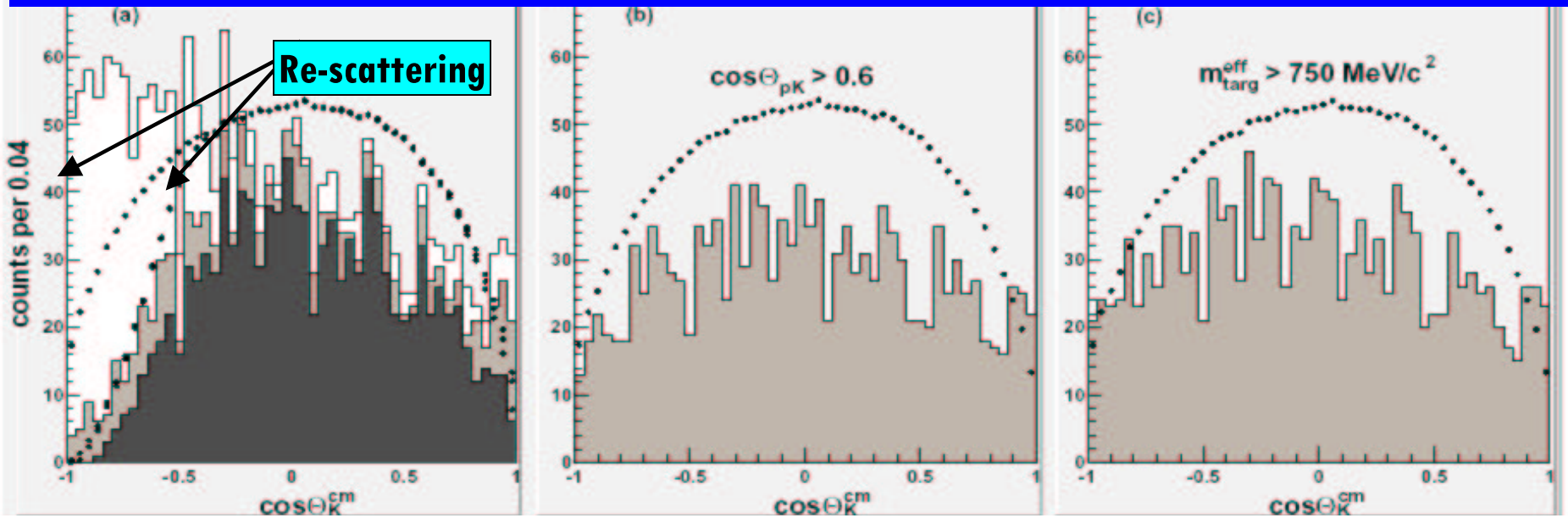
Observed (histograms) and simulated (dots) distributions in effective target mass (a) and cosine of angle between the K^0 p and K^+ directions in the lab system (b):

no cuts - open and upper dots

θ_K <100° and θ_P <100° - light-shaded and middle dots

and cos Φ_{pK} < 0 - dark-shaded one and lower dots (full cuts)

$K^+Xe \rightarrow K^0pXe'$ Interactions: Re-scattering Rejection: Simulation vs Data



Observed (histograms) and simulated (dots) cosine of angle between the K^0 and K^+ directions in the K^0p rest frame:

(a) no cuts - open one and upper dots

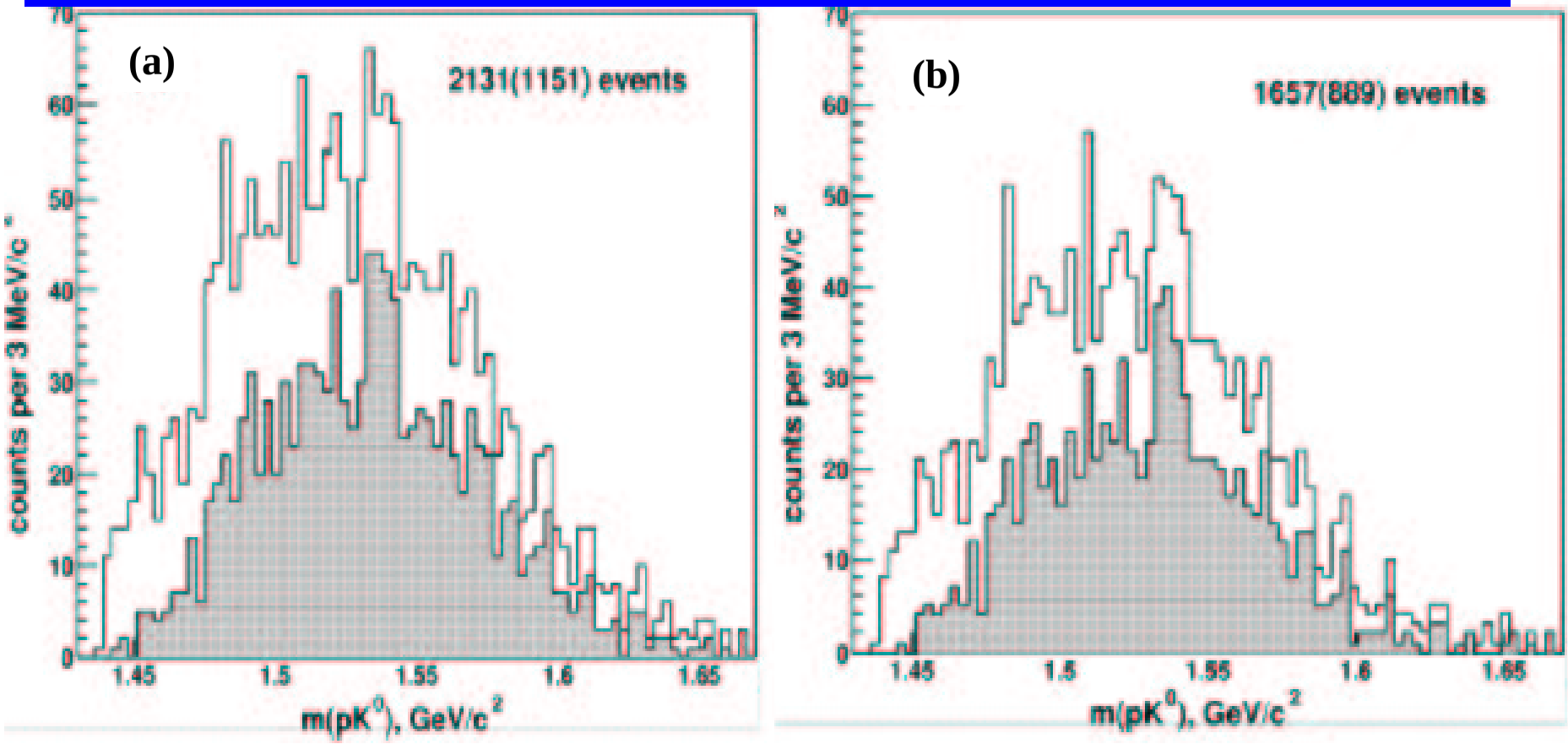
θ_K <100° and θ_p <100° - light-shaded one and middle dots

and $\cos(\Phi_{pK}) < 0$: dark-shaded and lower dots (full cuts)

(b) alternative cut: $\cos(\Theta_{pK}) > 0.6$

(c) alternative cut: m^{eff}_{targ} >750 MeV/c^2

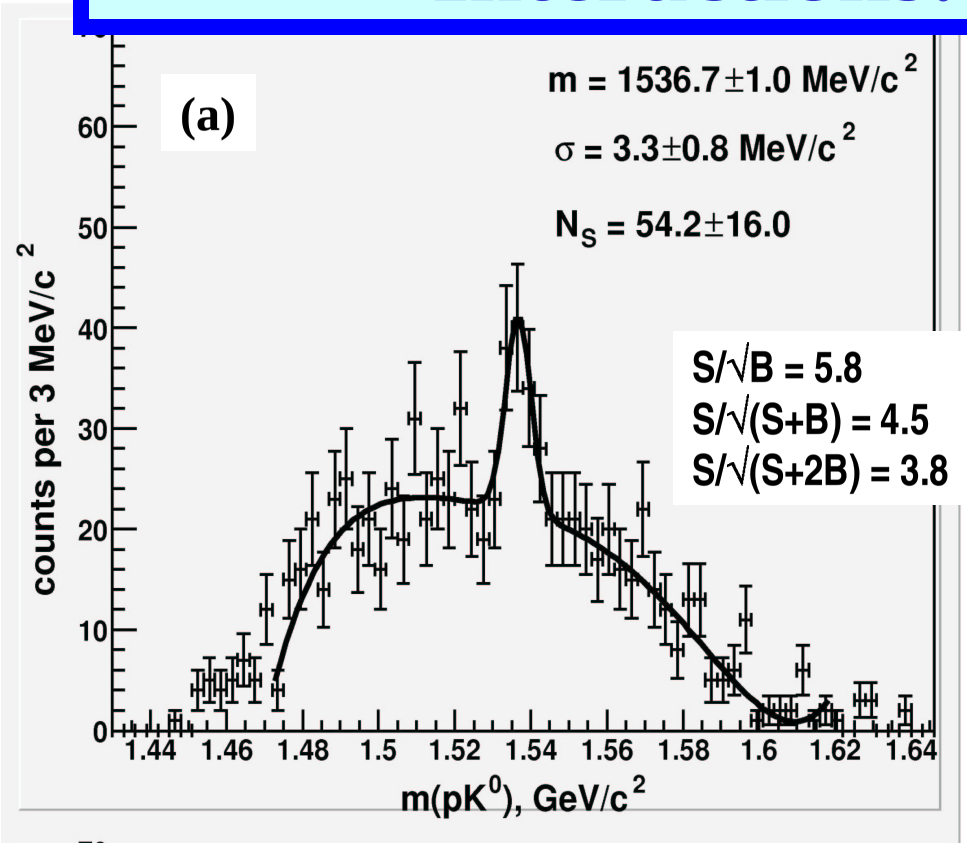
Further Observation of Θ^+ in K^+Xe Interactions: "Old Cuts"

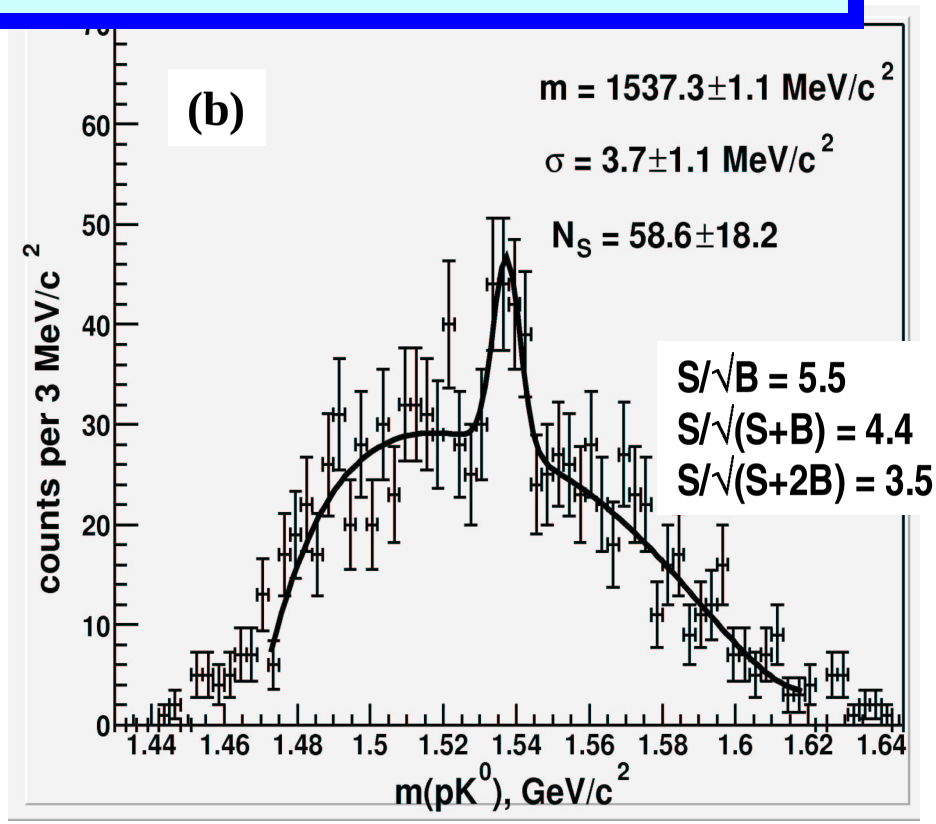


Effective mass of the pK^0 for full range of p_{beam} (a) and p_{beam} < 530 MeV/c (b): background is getting lower by factor ~1.5

Shaded histograms are for standard cuts: θ_K <100° , θ_p <100° and Φ > 90°

Further Observation of Θ^+ in K^+Xe Interactions: "Old Cuts"

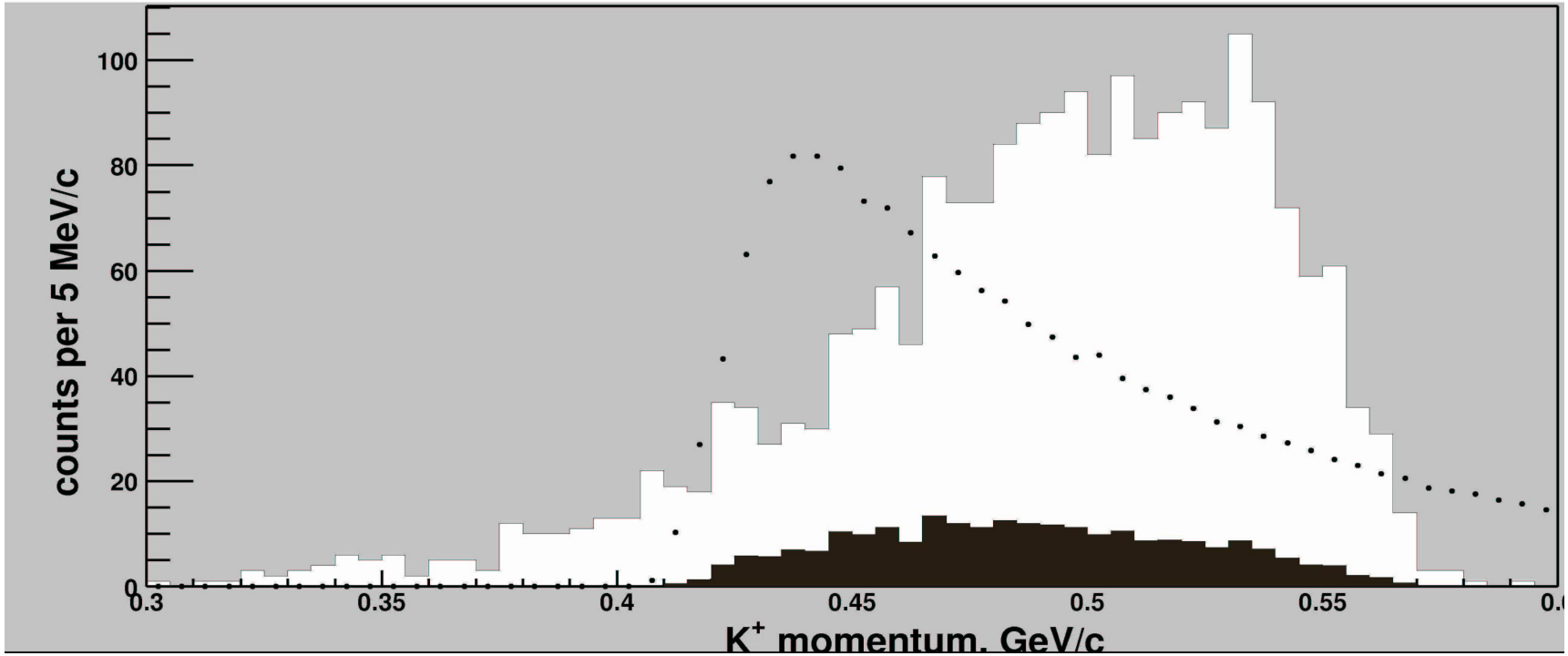




Fit of distributions of pK^0 mass to Gaussian with fifth-order polynomial for θ_K <100°, θ_p <100° and Φ > 90°:

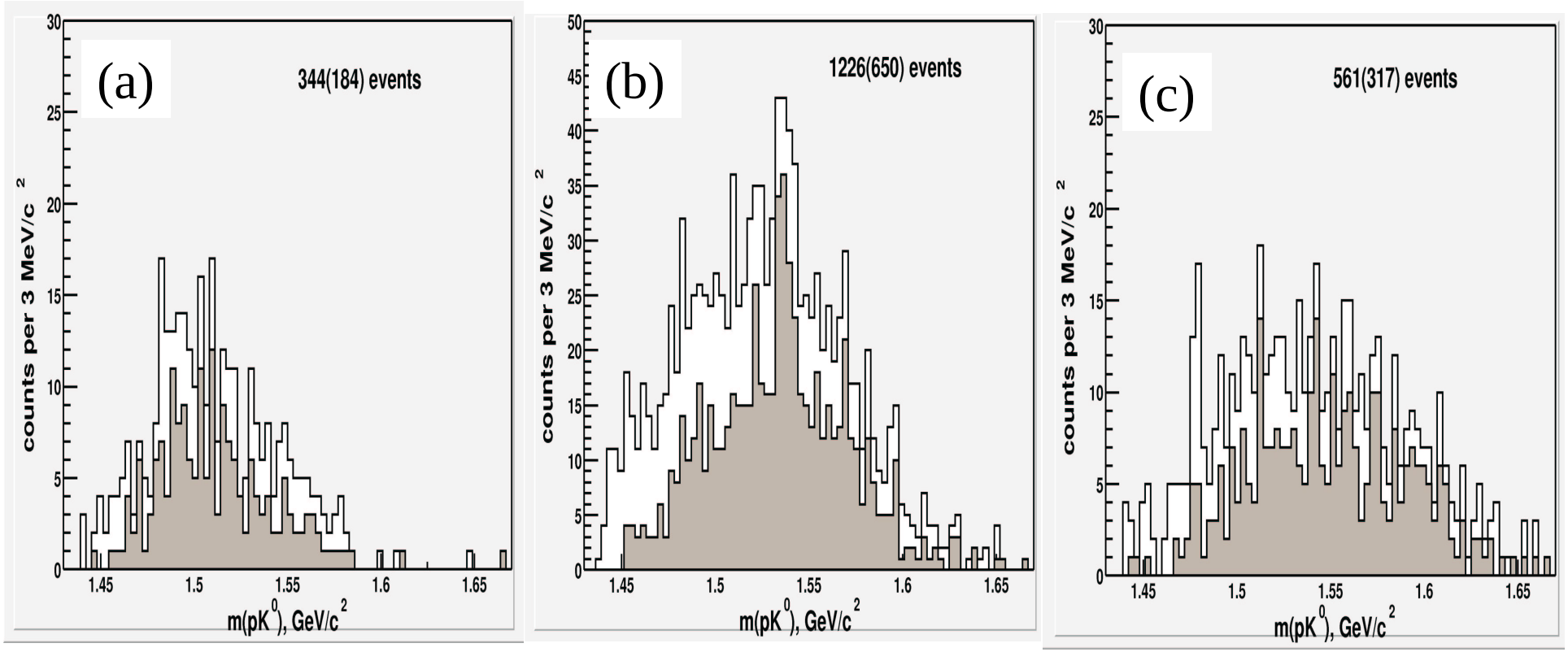
(a) p_{beam} < 530 MeV/c and (b) for full range of p_{beam}

Further Observation of Θ^+ in K^+Xe Interactions: Monte-Carlo



Open histogram: incident K^+ momentum for all measured events
Dotted histogram: the simulated ratio between resonant and non-resonant contributions for resonance with mass of 1537 MeV/c^2
Shaded histogram: predicted lineshape of the pK^0 resonance normalized to the number of events in $1532 < m(pK^0) < 1544$ MeV/c^2 before cuts

Θ^+ in K^+Xe Interactions: "Old Cuts" in the Primary Momentum Windows

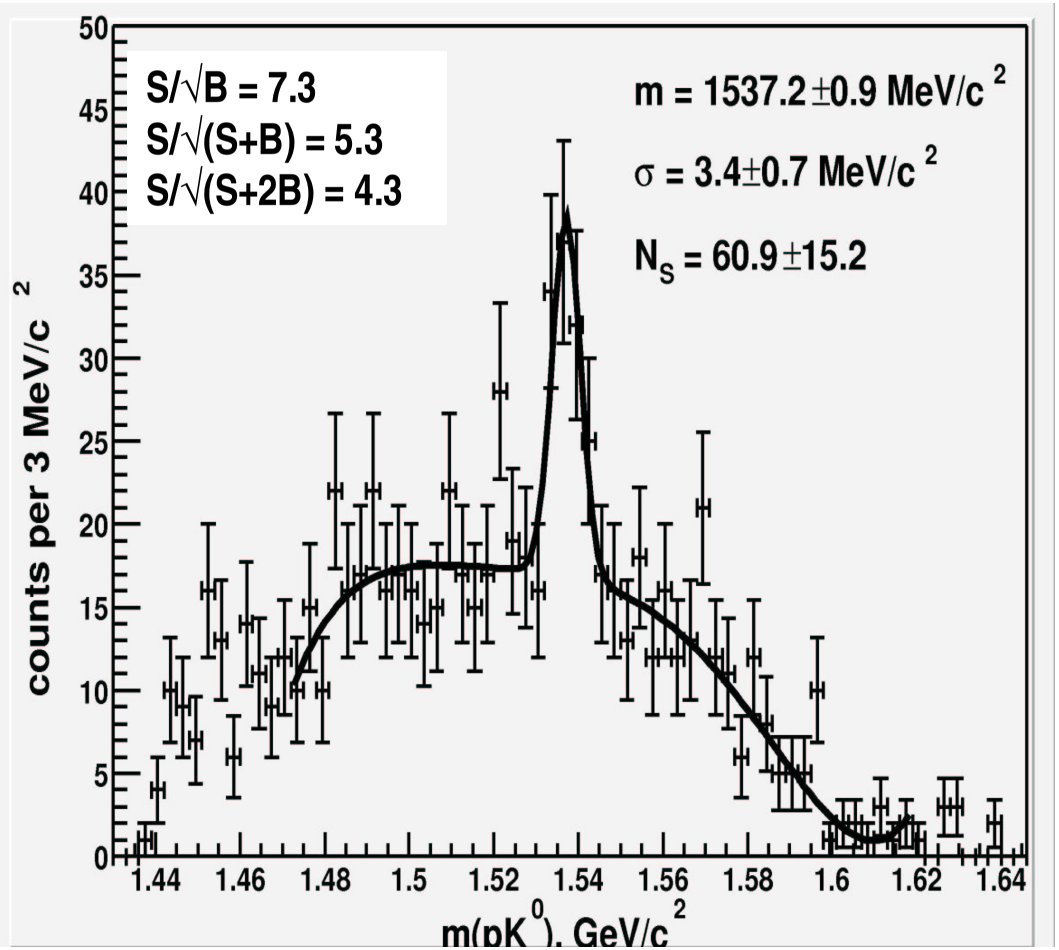


K^0p effective mass distributions for K^+ momentum intervals:

(a) $p_{beam} < 445$ MeV/c; (b) $445 < p_{beam} < 525$ MeV/c; (c) $p_{beam} > 525$ MeV/c

Shaded areas are for cuts $\theta_K < 100^o$, $\theta_P < 100^o$ and $\Phi > 90^o$

Θ^+ in K^+Xe Interactions: "Old Cuts Relaxed" in the Primary Momentum Windows



Fit of K^0p effective mass distributions for

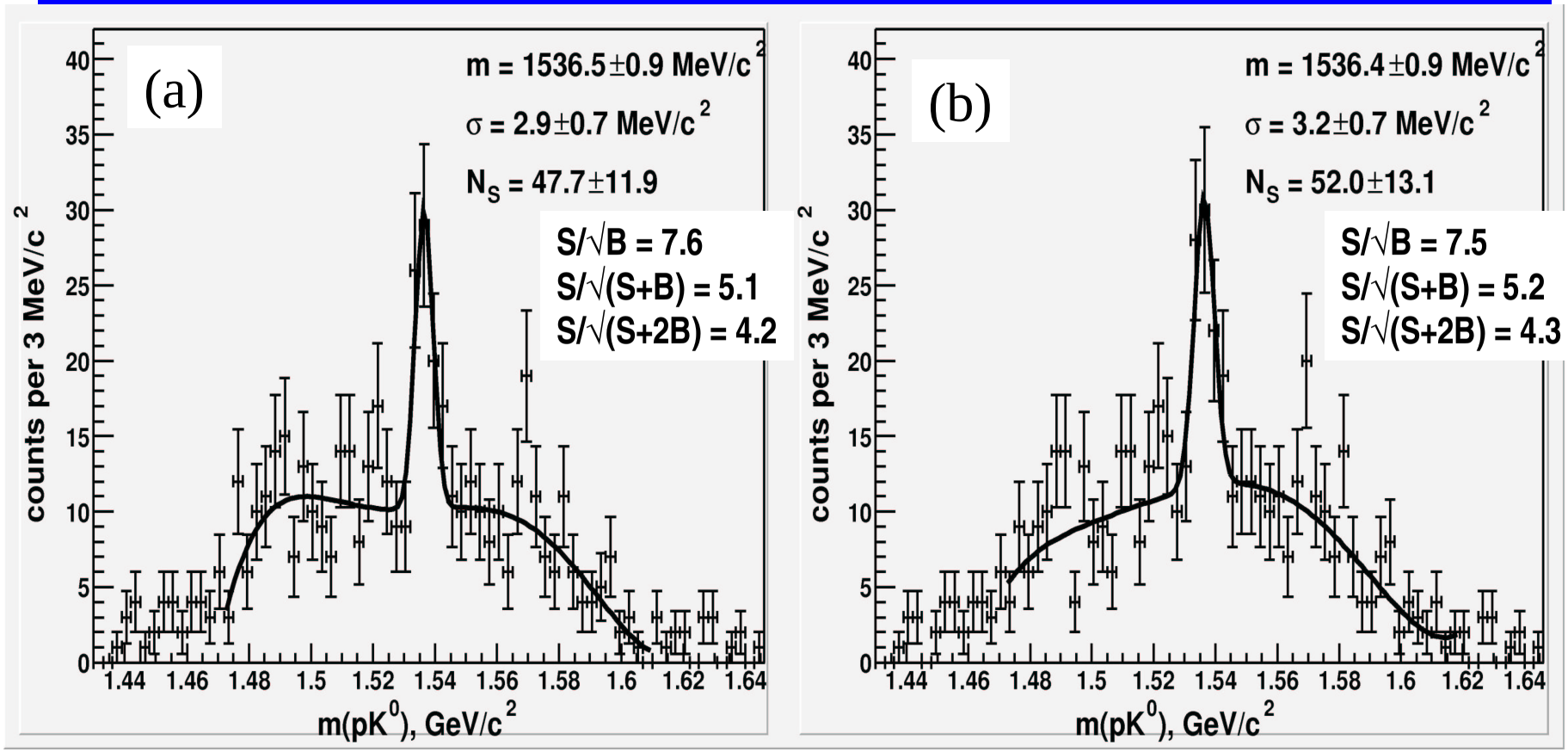
$445 < p_{beam} < 525$ MeV/c

and

$\theta_K < 100^o$, $\theta_P < 100^o$

(no Φ cut)

Θ^+ in K^+Xe Interactions:"New Cuts" in the Primary Momentum Windows



Fits of Kop effective mass for 445 < pbeam < 525 MeV/c and $|\cos\theta^{cm}_K| < 0.6$ for

(a) - $\cos\theta_{pK} > 0.6$

(b) - $m^{eff}_{targ} > 0.750$ MeV/c²

Intrinsic width of the Θ^+ baryon

The width of the observed pK^0 peak

$$\Gamma < 9 \text{ MeV}/c^2 \text{ (90\% C.L.)}$$

is consistent with instrumental resolution.

According *R.N. Cahn and G.H. Trilling, Phys.Rev. D69, 011501 (2004)* intrinsic width of a pK^0 resonance formed in the charge-exchange reaction $K^+n \rightarrow K^0p$ is:

$$\Gamma = \frac{N^{\text{peak}}}{N^{\text{bkgd}}} \times \frac{\sigma^{\text{CE}}}{107\text{mb}} \times \frac{\Delta m}{B_i B_f},$$

N^{peak} - number of events in the resonance peak

N^{bkgd} – number of events of charge-exchange background under the peak,

σ^{CE} = 4.1 ± 0.3 mb is the cross section for $K^+n \rightarrow K^0p$,

B_i and B_f are branchings for the initial and final states ($B_i = B_f = 1/2$ for I = 0, 1)

Δm is the $m(pK^0_S)$ interval under the peak.

From DIANA publication it was estimated: $\Gamma = 0.9 \pm 0.3$ MeV /c^2.

Observation of Θ^+ in in K^+Xe Interactions: Intrinsic width of the Resonance

Under our selections we found:

signal in the peak (1532-1544 MeV/c^2):

$$N_{peak} = 60 \pm 15 \text{ events}$$

an "original" (before re-interactions) background under the peak:

$$N_{bkgd} = 310 \pm 47 \text{ events}$$

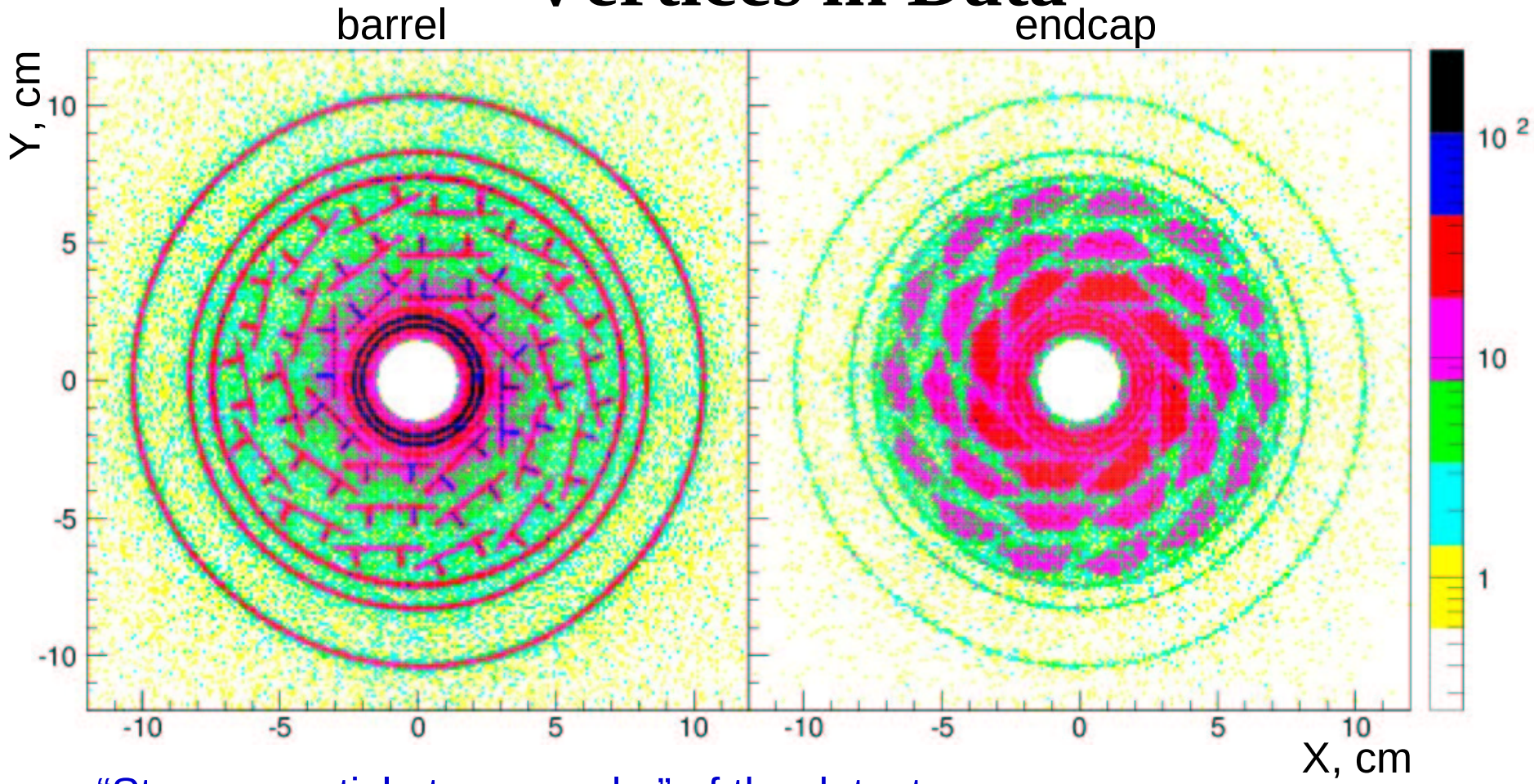
Applying formula above we obtain:

$$\Gamma = 0.36 \pm 0.11 \text{ MeV}/c^2 \text{ (no simulation systematic included).}$$

It was assumed that the bulk of produced Θ^+ neither decay nor re-interact inside the nucleus.

We estimate the non-resonant pK^0 background before re-scattering from the simulated m(pK^0) distribution, applying experimental selections to the original number of all events with $K^0_S \rightarrow \pi^+\pi^-$ of 4060 ± 400 from scan, 60 ± 7% survive upon rejecting K^0_S mesons with L < 2.5 mm, protons and K^0_S mesons that have re-interacted in liquid Xenon, and un-measurable events. 2440 ± 370 events were used for normalization

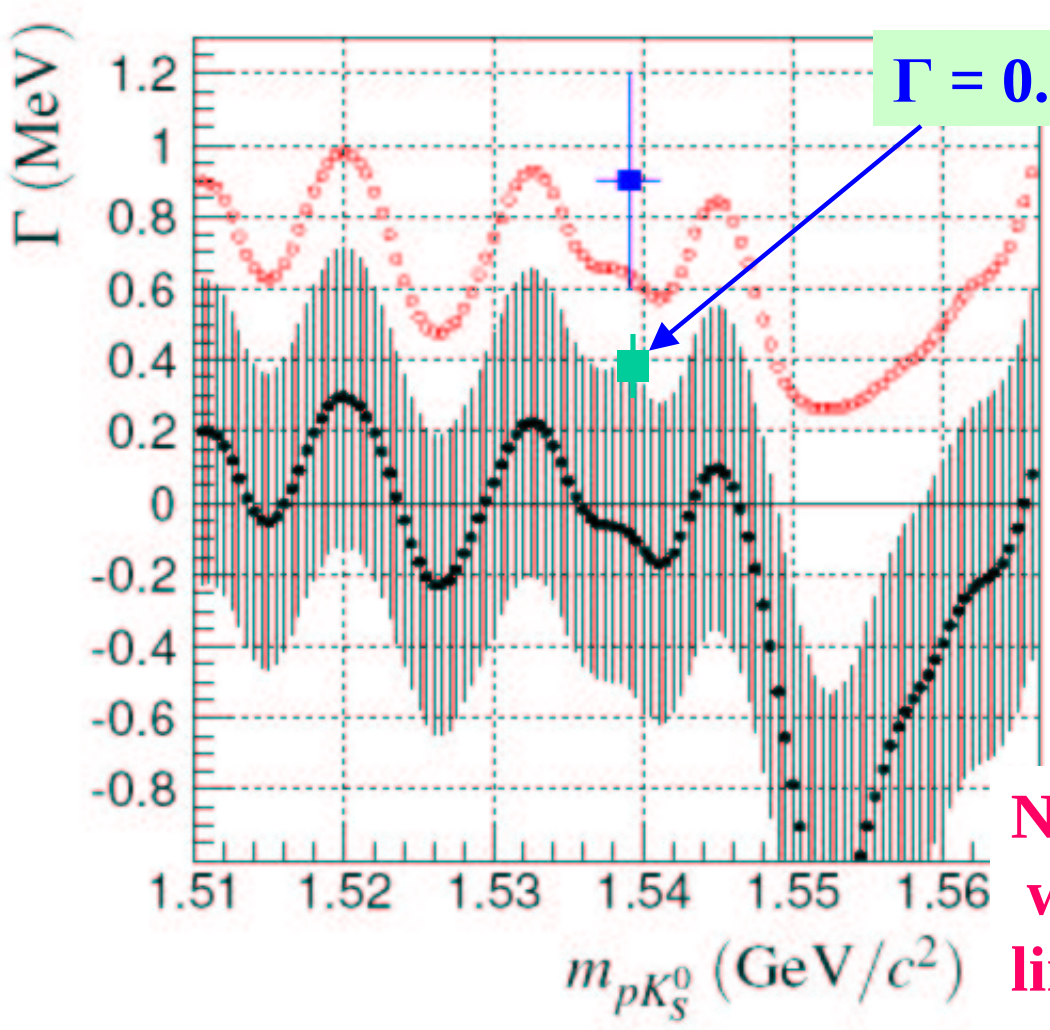
BELLE: XY Distribution of Secondary pK^- Vertices in Data



"Strange particle tomography" of the detector.

⇒ Selected pK vertices originate from nuclear interactions.

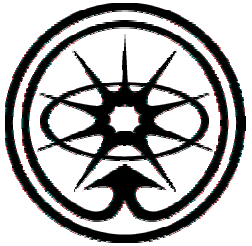
Intrinsic width of the Θ^+ : comparison with the Belle Result



$\Gamma = 0.36 \pm 0.11$ MeV/c^2

No contradiction with the upper limit set by BELLE.

Observation of Θ^+ in in K^+Xe Interactions: Conclusions



A narrow pK^0 resonance has been observed in the charge-exchange reaction $K^+n \to K^0p$ on a neutron bound in the Xenon nucleus. The resonance mass is Estimated:

$$m = 1537 \pm 2\ MeV/c^2$$

The visible width of the peak

$$\sigma = 3.4 \pm 0.7\ MeV/c^2$$

is consistent with being due to instrumental resolution and an upper limit on intrinsic width:

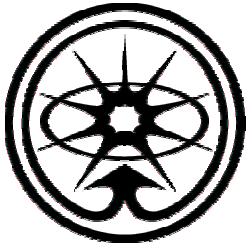
$$\Gamma < 9\ MeV/c^2$$

The signal is observed in a restricted interval of incident K^+ momentum, consistent with smearing of a narrow pK^0 resonance by Fermi motion of the target neutron.

More precise estimate of the width is obtained from the ratio between the numbers of resonant and non-resonant charge-exchange events:

$$\Gamma = 0.36 \pm 0.11\ MeV/c^2$$

Observation of Θ^+ in in K^+Xe Interactions: Conclusions



With an excess of ~ 60 events over a fitted background of ~ 68 events, statistical significance of the signal is

$$S/\sqrt{B} = 7.3\ ,\ S/\sqrt{(S+B)} = 5.3,\ S/\sqrt{(S+2B)} = 4.3$$

We interpret this observation as strong evidence for formation of a pentaquark baryon with positive strangeness in the charge -exchange reaction $K^+n \rightarrow K^0p$ on a bound neutron.
The results reported confirm and reinforce our earlier observation based on part of the present statistics of DIANA experiment.
The measurements and data analysis are still in progress.

Observation of Θ^+ in in K^+Xe Interactions

Comparison of the signal significance under various cuts applied:

	p.16(a)	p.16(b)	p.19	p.20(a)	p.20(b)
Signal (S)	54	58	60	47	52
Background (B)	88	112	68	38	48
Efficiency (Simulation)	0.75	0.80	0.90	0.6	0.7
S/sqrt(B)	5.8	5.5	7.3	7.6	7.5
S/sqrt(B+S)	4.5	4.4	5.3	5.1	5.2
S/Sqrt(2B+S)	3.8	3.5	4.3	4.2	4.3