Experimental evidence for the Θ^+ pentaquark

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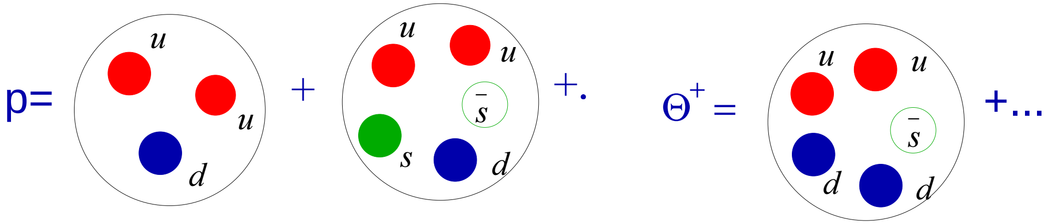
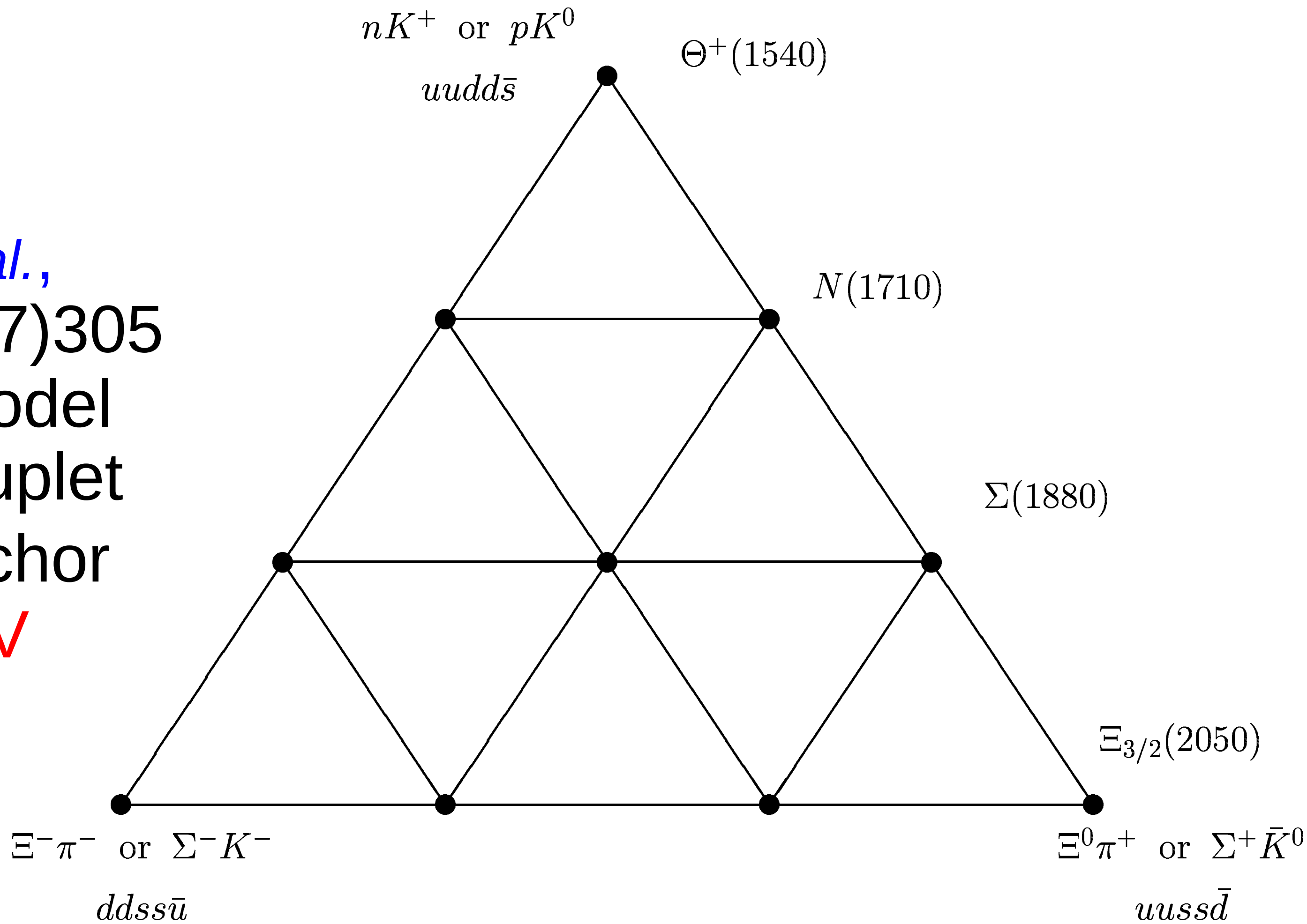
Introduction

- Hadrons come in qqq and $q\bar{q}$ configurations.
- QCD does not prohibit other quark combinations.
- Pentaquarks had been proposed (as early as 1976) but never seen (Lipkin, hep-ph/9804218).
- The first reported observations of a $qqqq\bar{q}$ pentaquark state have appeared in July 2003.
- At least 7 different experiments see a peak near 1540 MeV in either the pK_s^0 or nK^+ mass spectrum.
- At present there are no angular distributions or reliable cross sections for the observed peaks.

Pentaquark Predictions



D. Diakonov *et al.*,
Z. Phys. **A359**(97)305
chiral soliton model
spin-$\frac{1}{2}$ anti-decuplet
$P_{11}(1710)$ as anchor
$M_{\Theta^+} = 1530$ MeV
$\Gamma \approx 15$ MeV
$S = +1, I = 0$



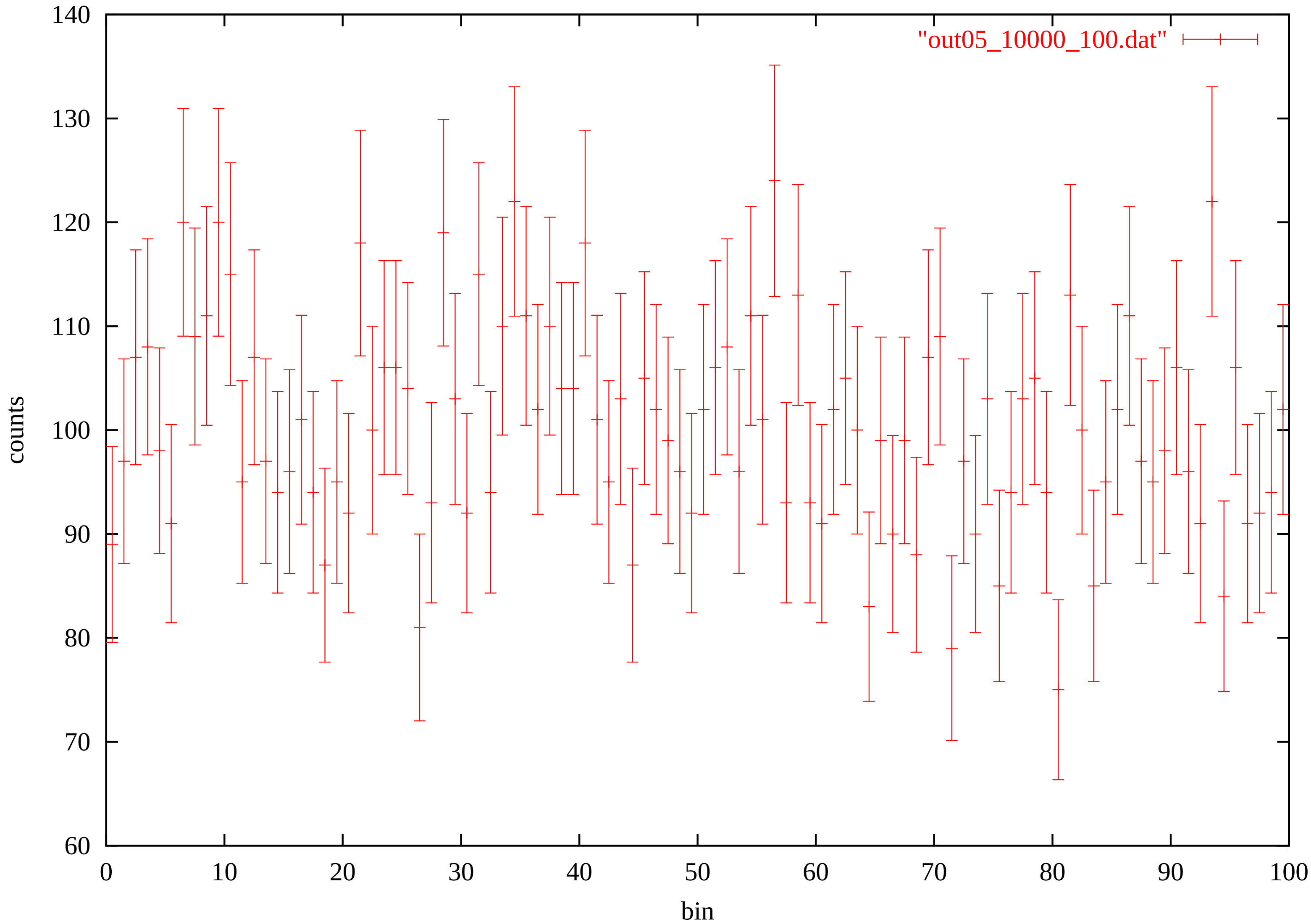
To see or not to see

- Why might we see a peak
  - statistical fluctuation
  - reflection of a higher-mass resonance
  - analysis cuts or detector acceptance
  - a peak exists
- Why might we not see a peak
  - too much background
  - poor resolution
  - insensitive reaction mechanism
  - a peak does not exist

Where's Waldo?

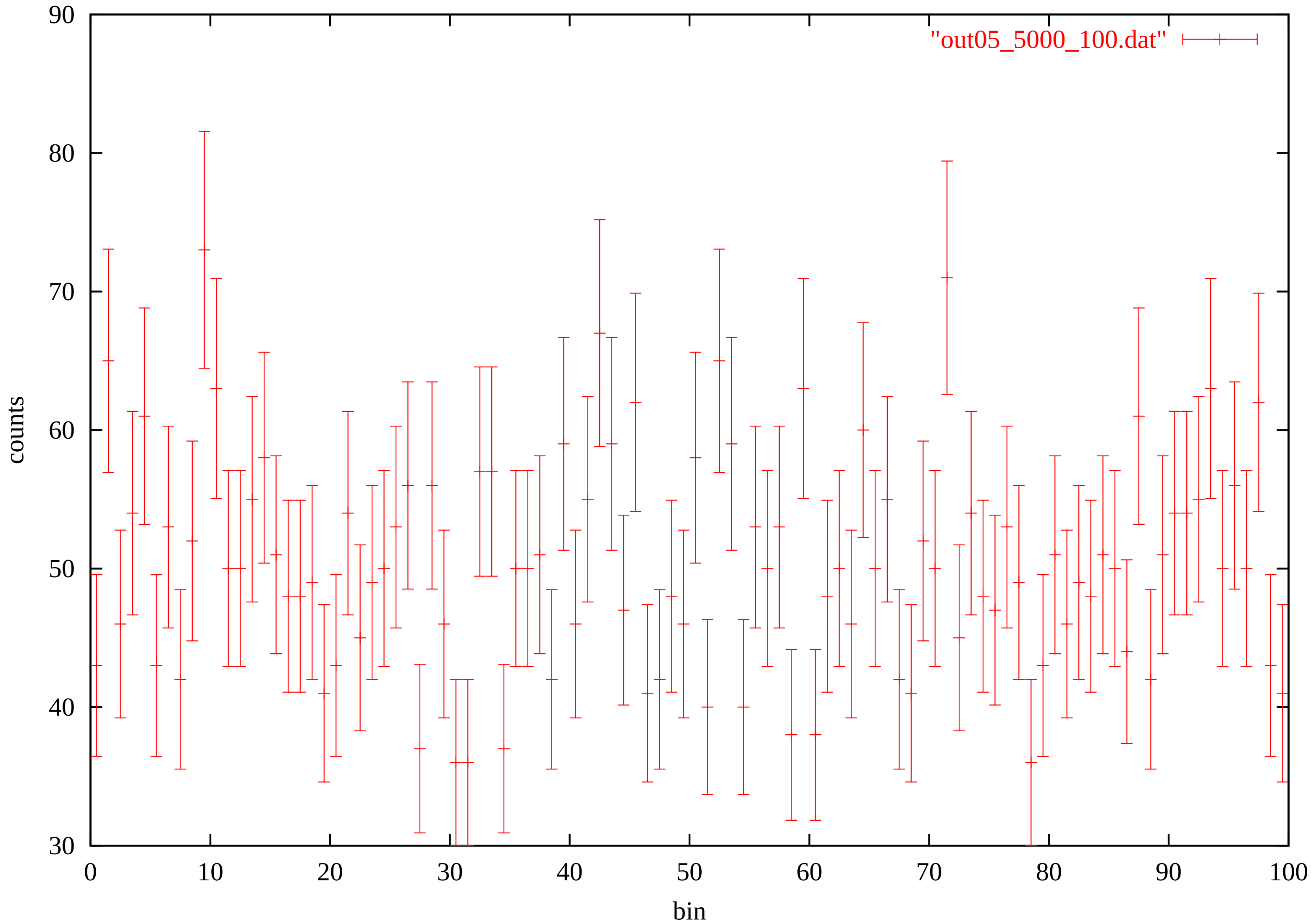
- Can you find Waldo in this picture?

Where's Waldo? (100)



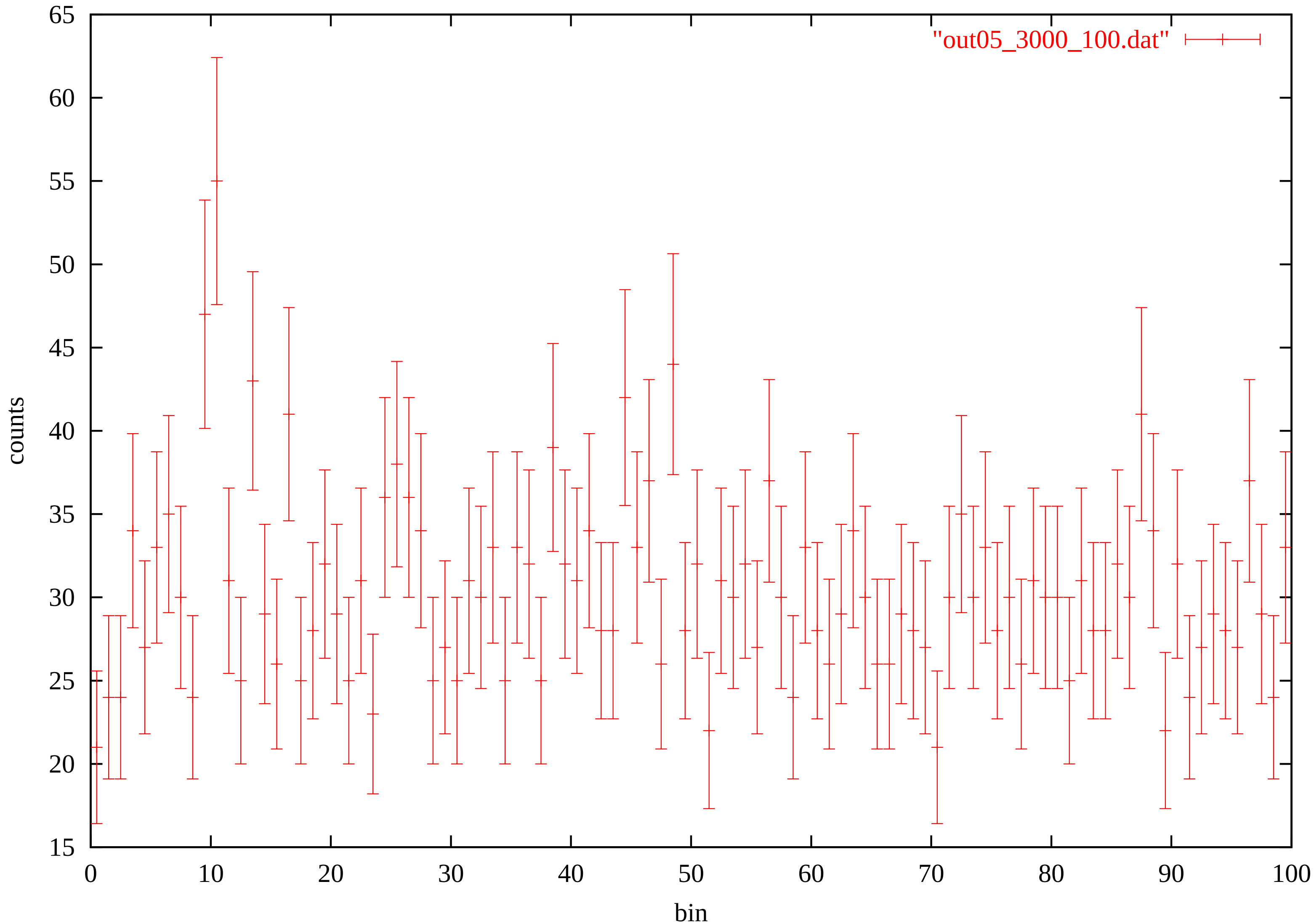
- Can you find the 40-count peak of width $\sigma = 0.5$?

Where's Waldo? (50)



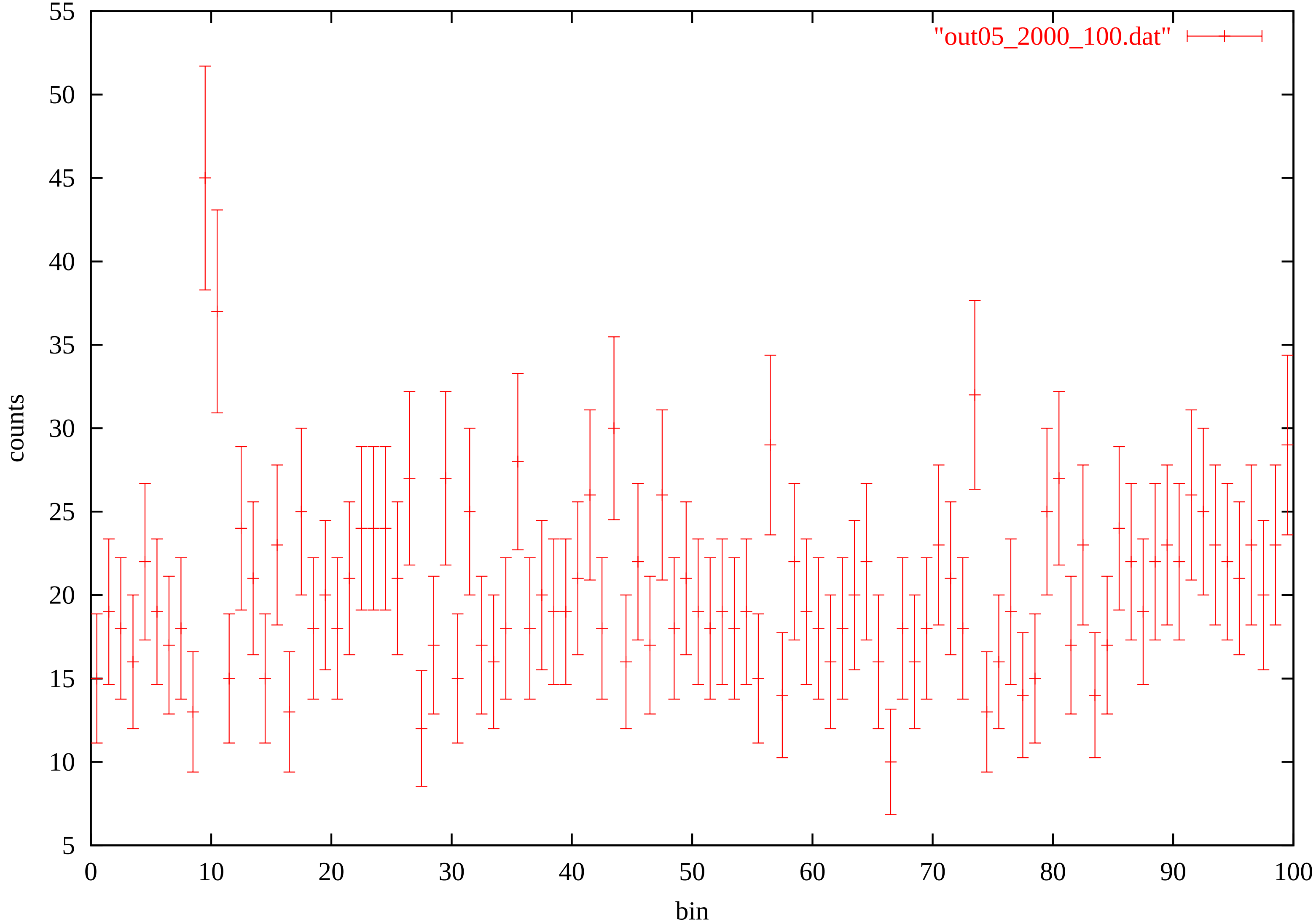
- Now can you find the 40-count peak of width $\sigma = 0.5$?

Where's Waldo? (30)



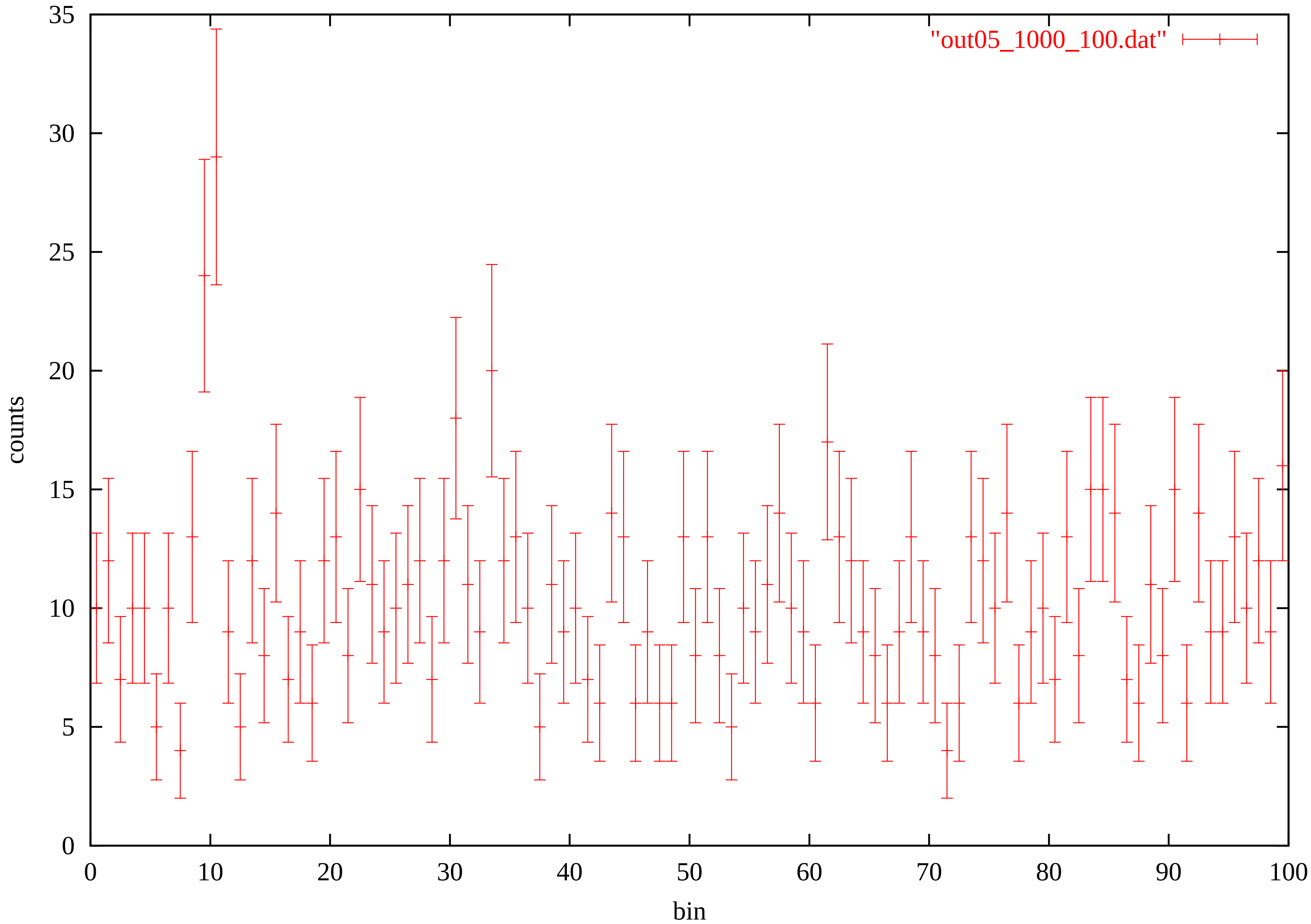
- And now can you find the 40-count peak of width $\sigma = 0.5$?

Where's Waldo? (20)



- And now?

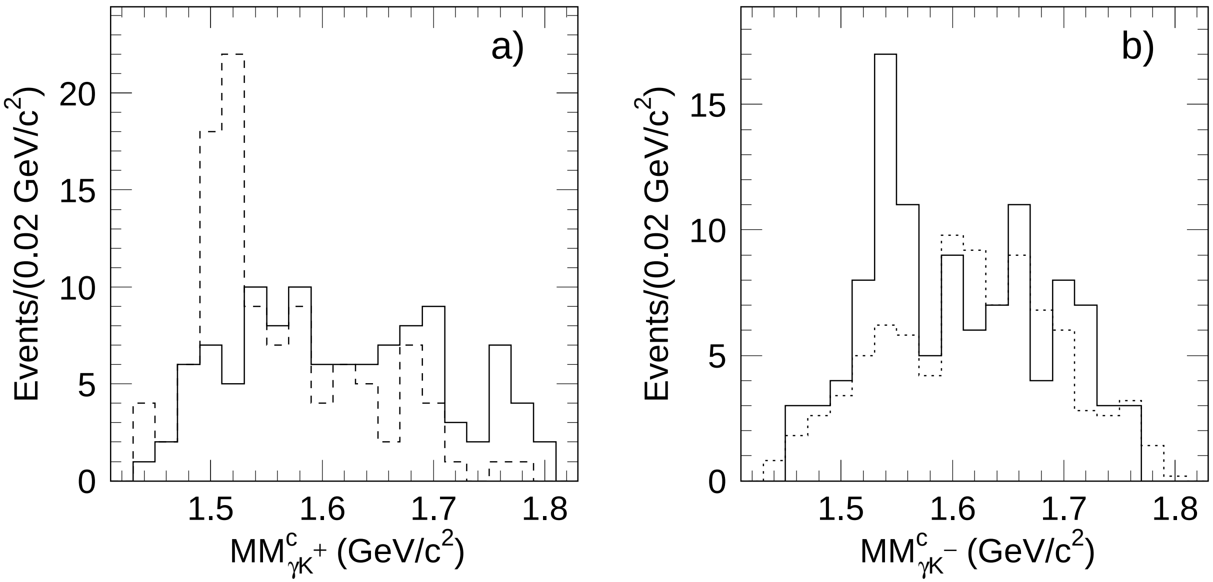
Where's Waldo? (10)



- All hope is lost unless the background can be reduced!

LEPS at SPring-8

T. Nakano *et al.*,
hep-ex/0301020
PRL **91**(03)012002
$\gamma p \to K^+ K^- p$
γn (^{12}C)$\to K^-(K^+ n)$
$M_{\Theta^+} = 1540 \pm 10$ MeV
$\Gamma < 25$ MeV
$N_s/\sqrt{N_b} = 4.6$

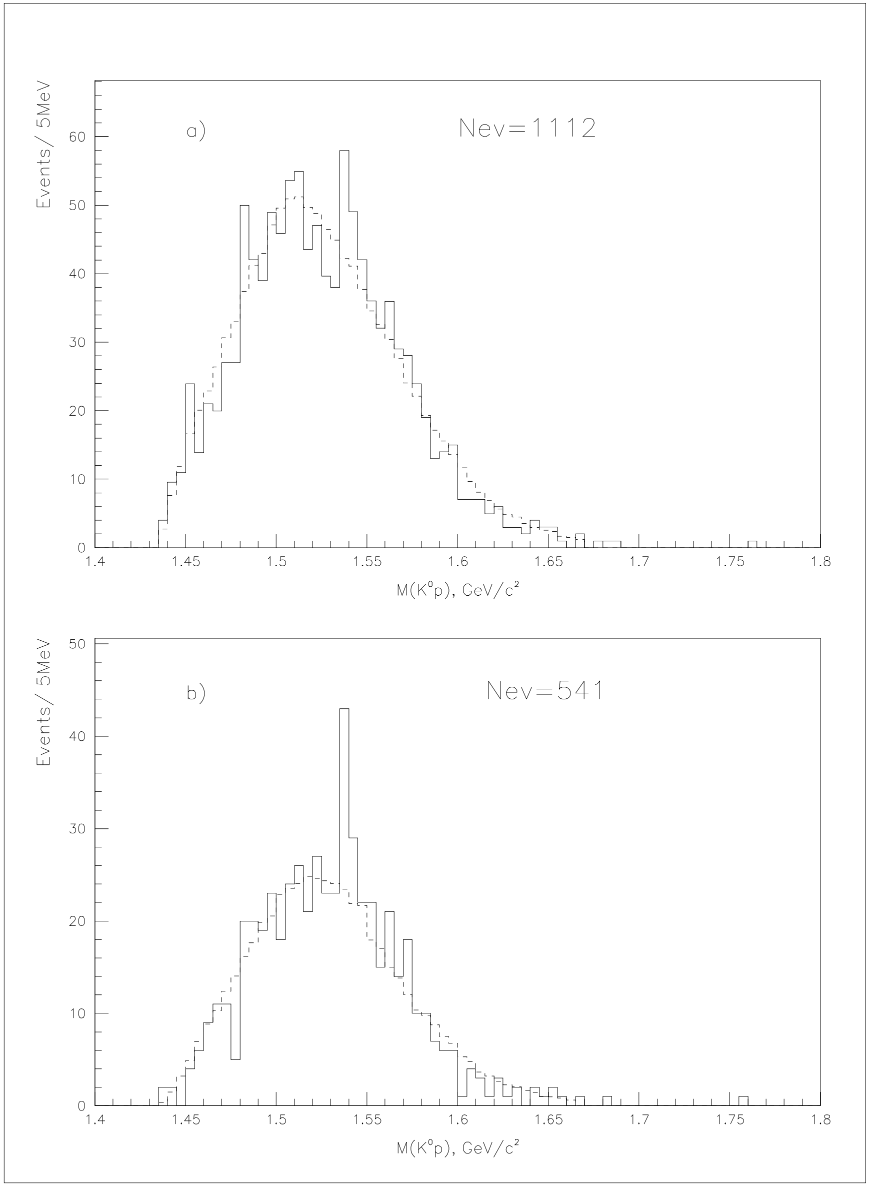


- $MM^c_{\gamma K^\pm} = MM_{\gamma K^\pm} - MM_{\gamma K^+ K^-} + M_N$
- (a) CH target. Solid: K^+K^- signal sample. Dashed: p tag showing $\gamma p \to K^+ \Lambda(1520) \to K^+ K^- p$
- (b) Solid: CH target signal sample. Dashed: LH_2 target, same cuts.

ITEP Bubble Chamber

A. Dolgolenko *et al.*,
hep-ex/0304040
K^+ Xe$\rightarrow K_s^0 p$Xe′
$M_{\Theta^+} = 1539 \pm 2$ MeV
$\Gamma < 9$ MeV
$N_s/\sqrt{N_b} = 4.4$

(a) all measured $K^0 p$ events
(b) $K^0 p$ events with K^0 and p in the forward direction and on opposite sides of the beam



CLAS d, Jefferson Lab

S. Stepanyan *et al.*,
hep-ex/0307018

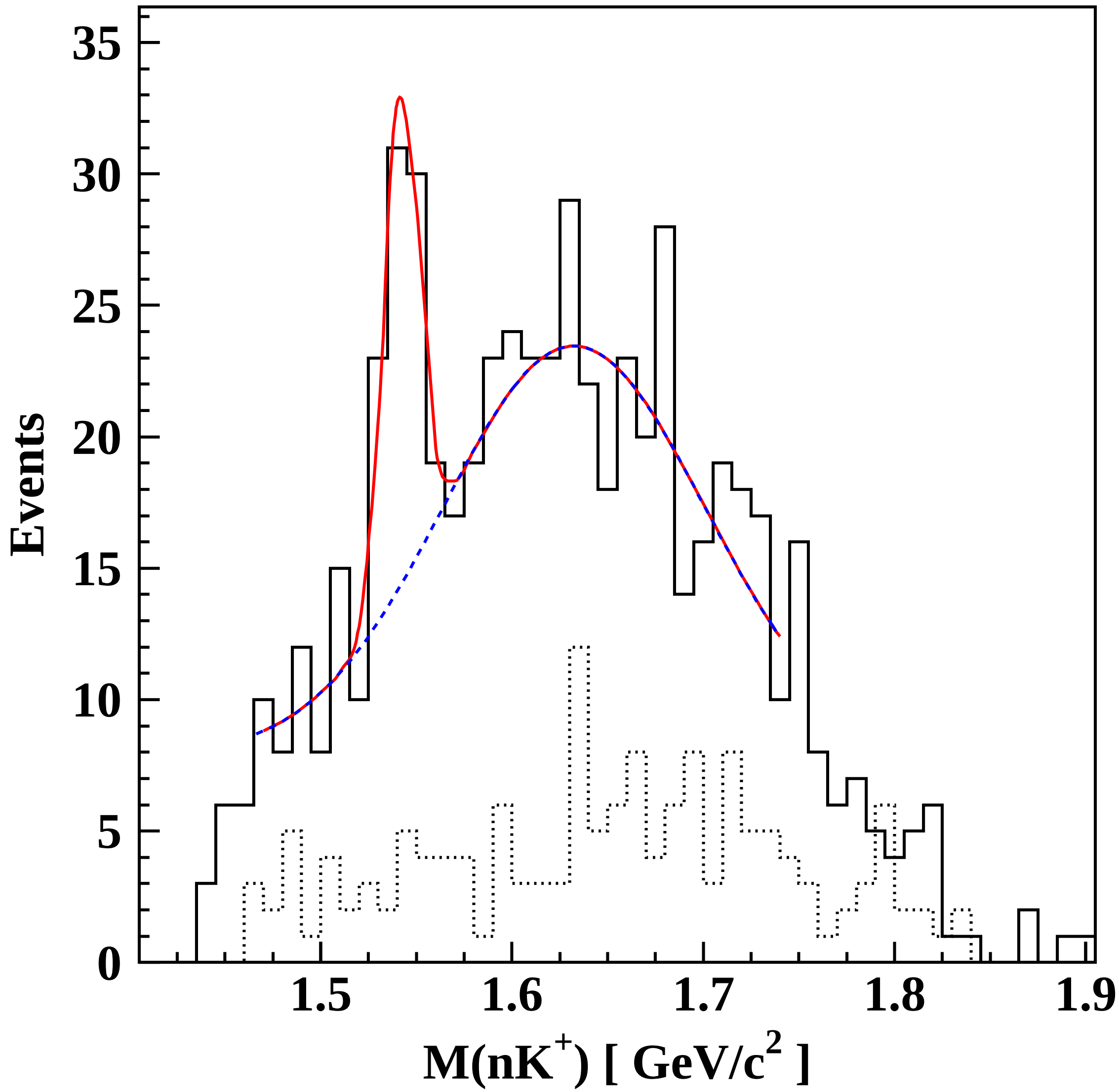
$\gamma d \to p K^- (K^+ n)$

$M_{\Theta^+} = 1542 \pm 5$ MeV

$\Gamma < 21$ MeV

$N_s / \sqrt{N_b} = 5.3$

signal (solid)
$\Lambda(1520)$ events (dotted)



SAPHIR, ELSA, Bonn

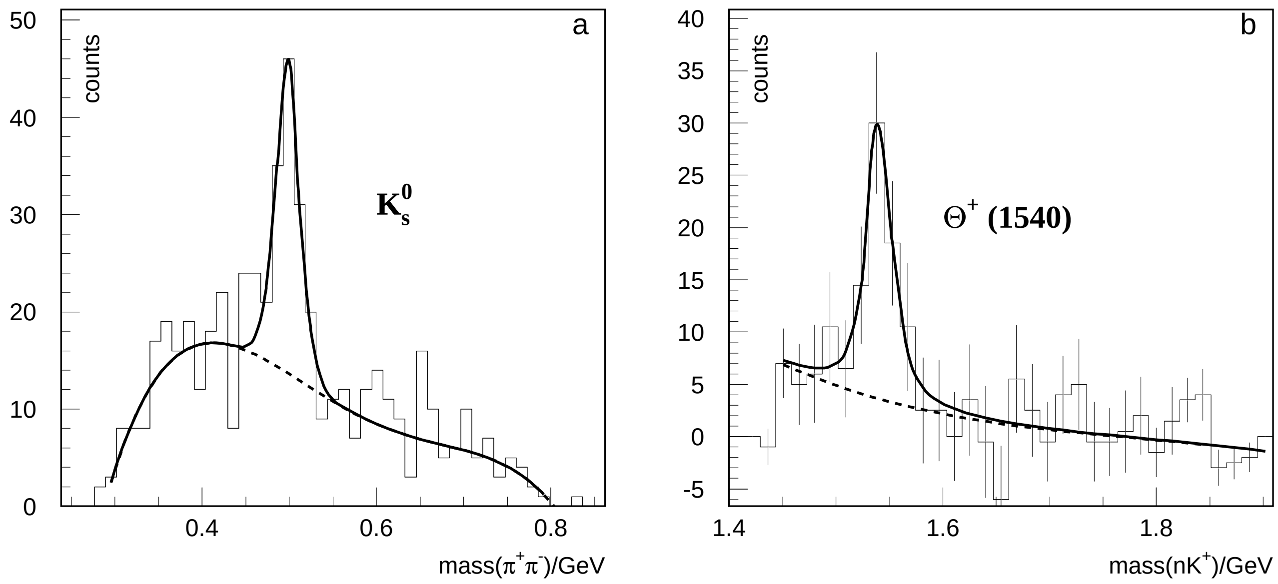
J. Barth *et al.*,
hep-ex/0307083

$\gamma p \to K_s^0 K^+ n$

$M_{\Theta^+} = 1540 \pm 6$ MeV

$\Gamma < 25$ MeV

$N_s/\sqrt{N_b} = 4.8$



- (a) $\pi^+\pi^-$ spectrum for nK^+ cut on Θ^+
- (b) nK^+ with $\pi^+\pi^-$ sideband background subtraction

CLAS, Jefferson Lab

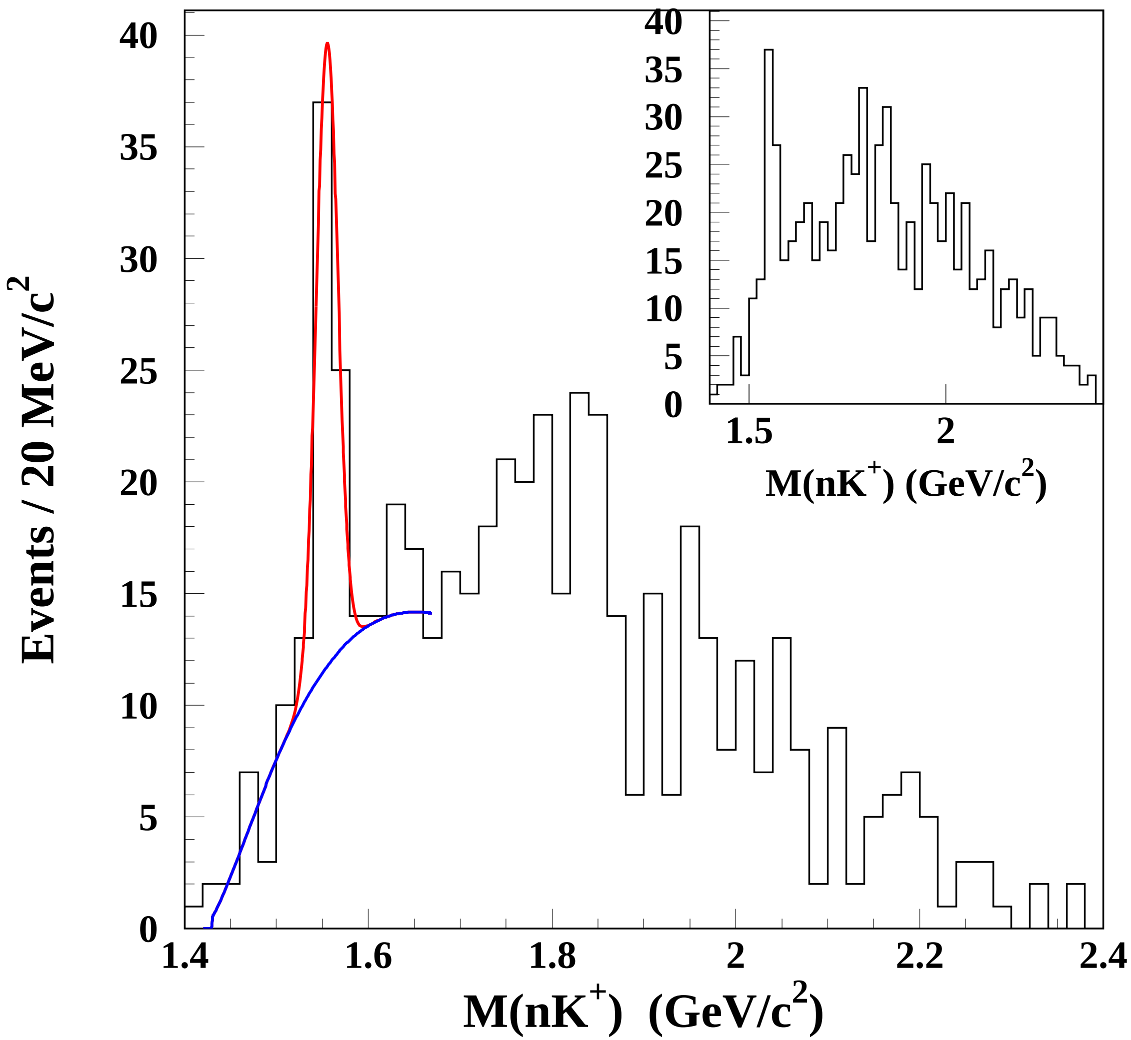
V. Kubarovsky *et al.*,
hep-ex/0311046

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

$M_{\Theta^+} = 1555 \pm 10$ MeV

$\Gamma < 26$ MeV

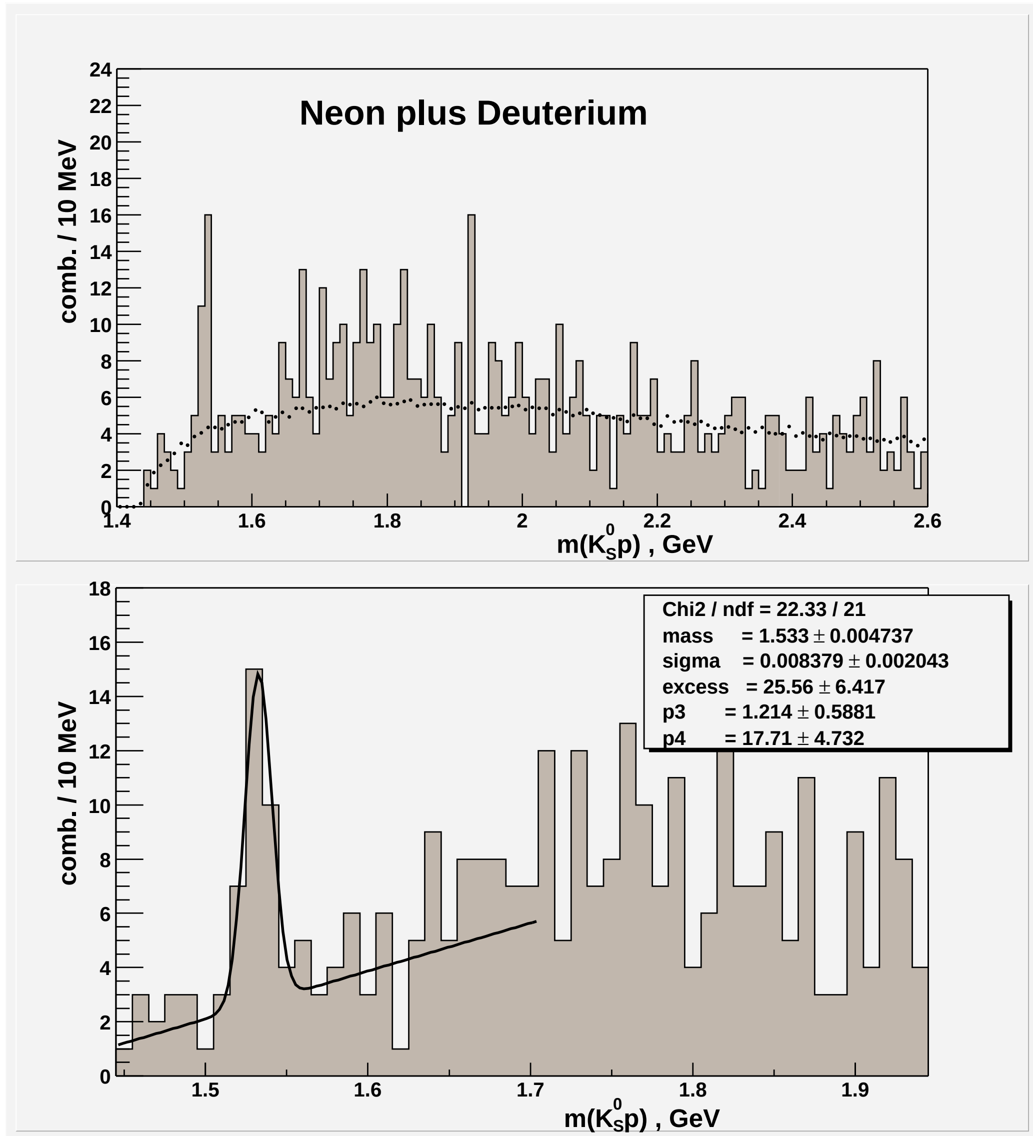
$N_s/\sqrt{N_b} = 7.8$



BEBC, CERN & $15'$ Bub. Ch., FNAL

A. Asratyan *et al.*,
hep-ex/0309042
$\nu(\bar{\nu})A \to K^0_s p X$
$M_{\Theta^+} = 1533 \pm 5$ MeV
$\Gamma < 20$ MeV
$N_s/\sqrt{N_b} = 6.7$

Upper: full spectrum
Lower: expanded scale
around the peak



HERMES, DESY

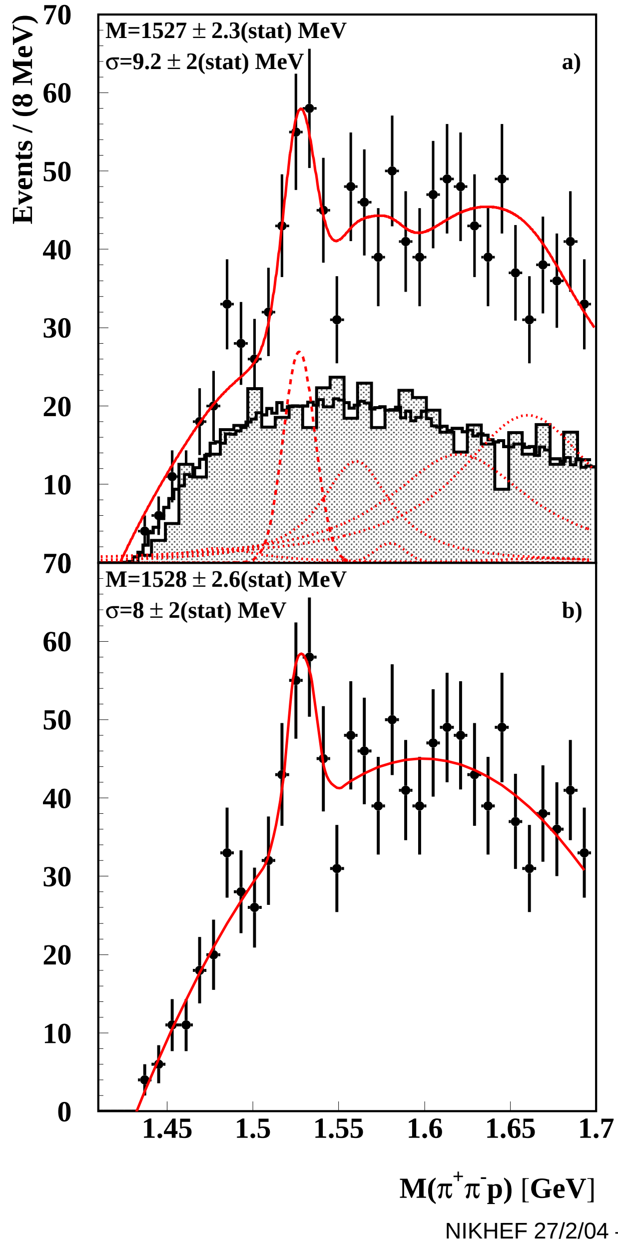
hepex/0312044

$\gamma d \to K^0_s p X$

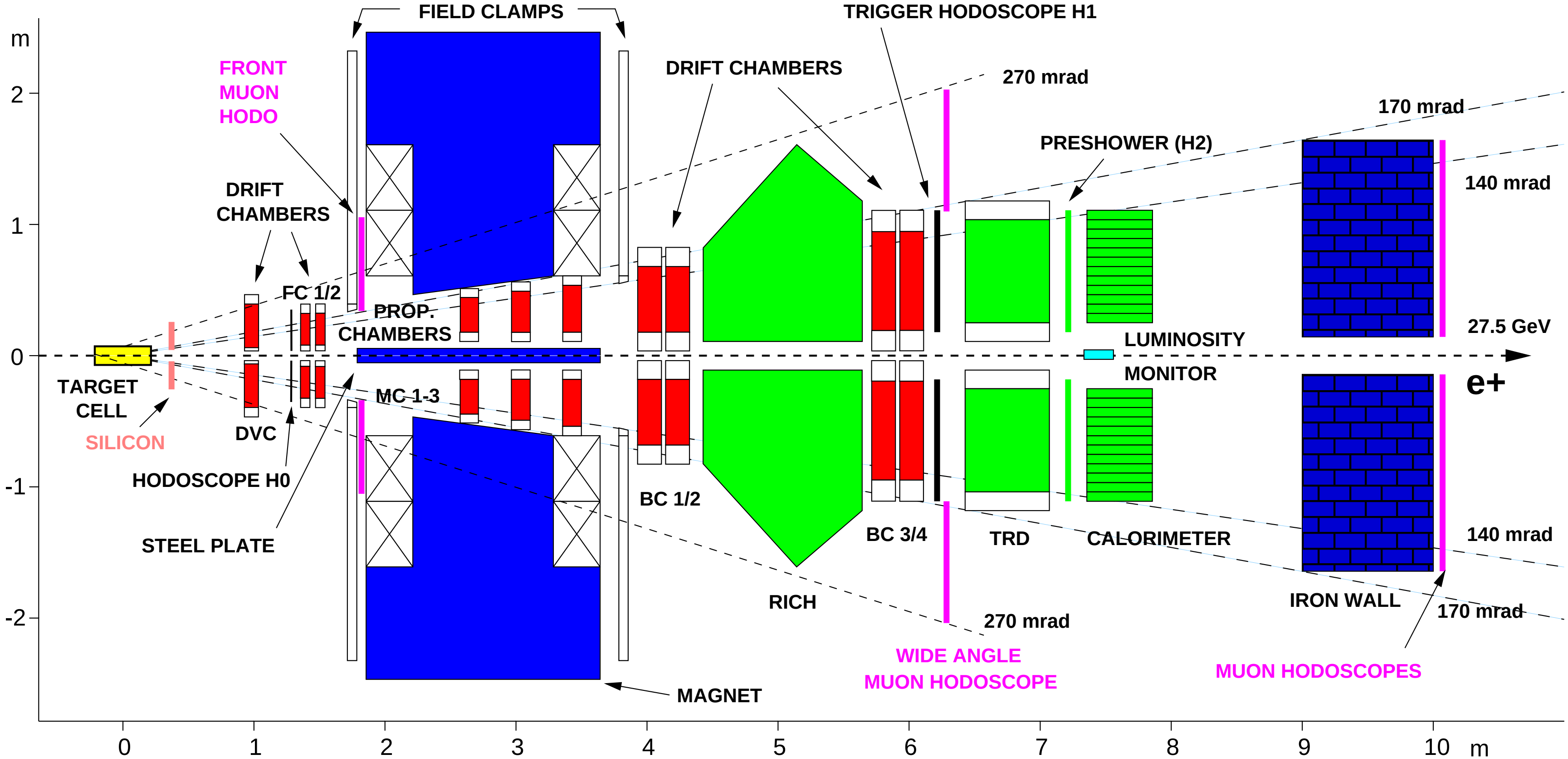
$M_{\Theta^+} = 1528 \pm 3$ MeV

$\Gamma < 17$ MeV

$N_s/\sqrt{N_b} = 4.7$

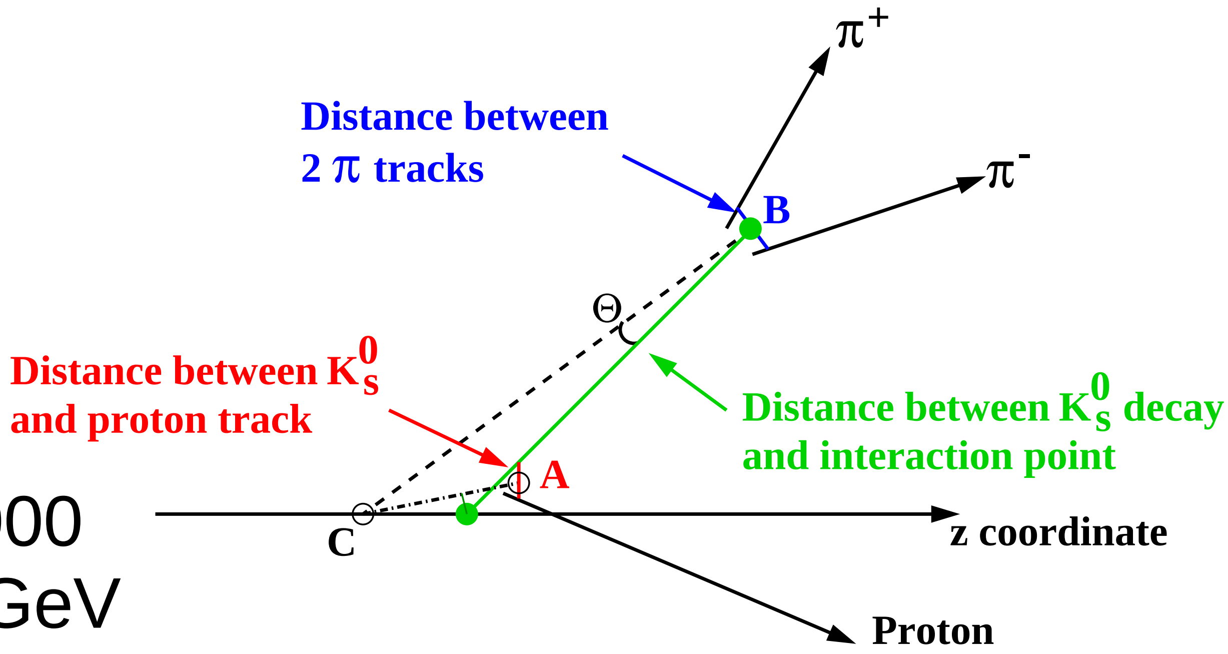


The HERMES experiment



HERMES Event Selection

$ed \to K_s^0 pX$
RICH PID
$E_{\rm beam} = 27.6$ GeV
d targets from 1998-2000
$4 < p_p < 9$, $1 < p_\pi < 15$ GeV
$\pi^+\pi^-$ track distance < 1 cm
pK_s^0 track distance < 0.6 cm
$\angle CBA < 2.6°$
K_s^0 decay length > 7 cm
$485 < M_{\pi^+\pi^-} < 509$ MeV
target vertex cut
fiducial volume cut
Eliminate $\Lambda^0(1116)$

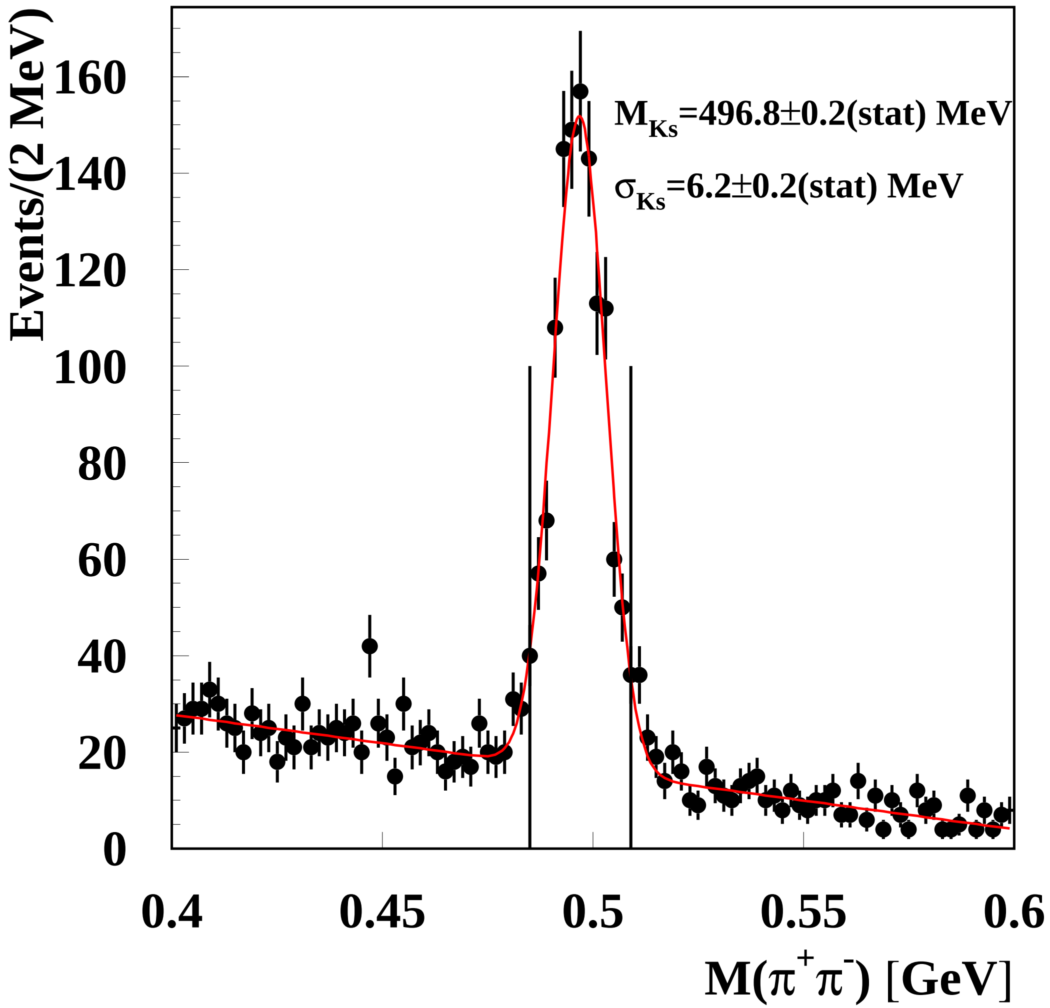


HERMES K_s *Identification*

- K_s^0 from $\pi^+\pi^-$
- M_K error < 1 MeV
- background is small
- width $\sigma = 7$ MeV
- 2σ cuts on K_s
- 1 MeV agreement

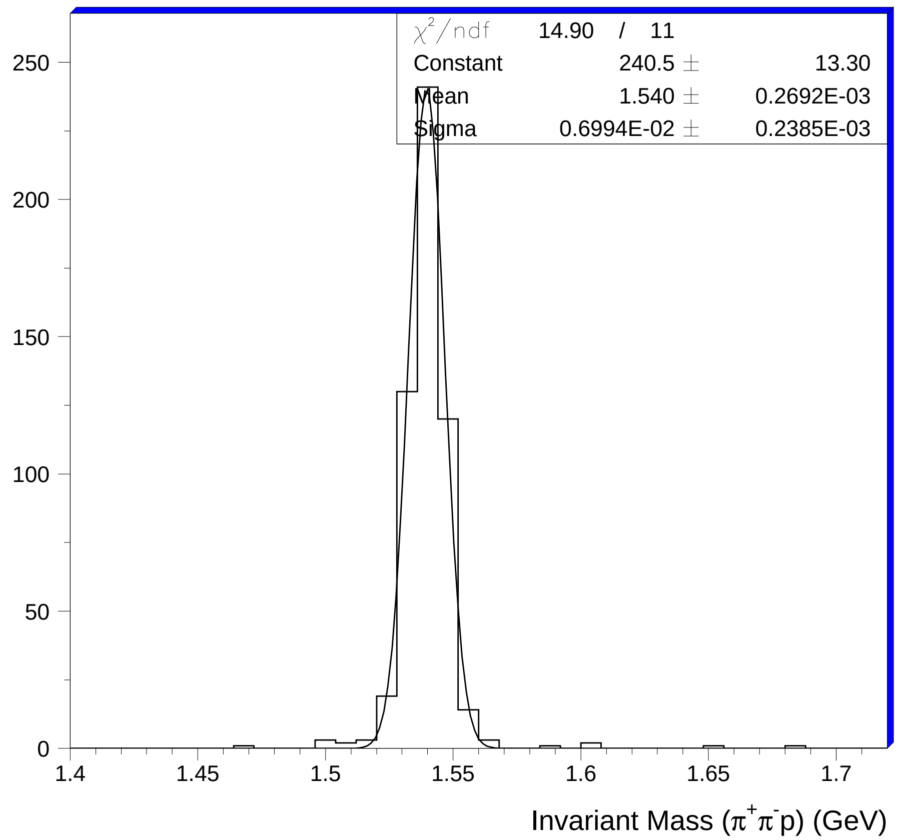
with PDG mass for:

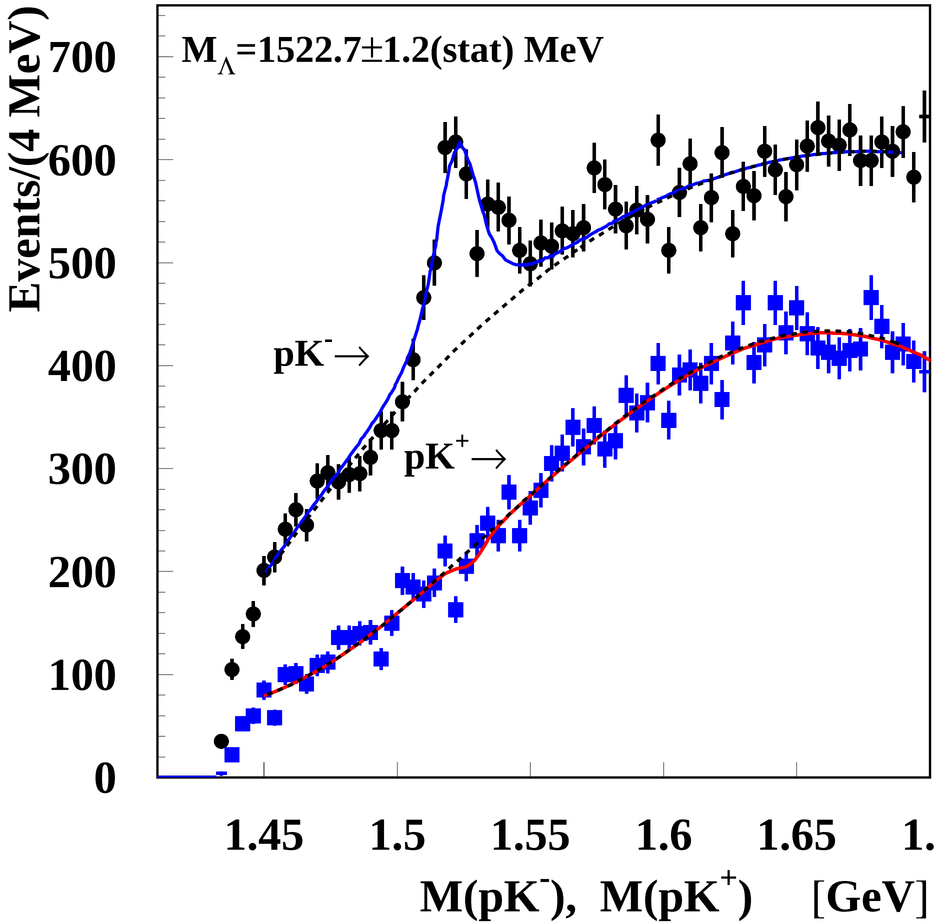
$$\rho(770)[\pi^+\pi^-]$$
$$\phi(1020)[K^+K^-]$$
$$\bar{\Lambda}(1116)[\bar{p}\pi^+]$$
$$\Lambda^*(1520)[K^-p]$$



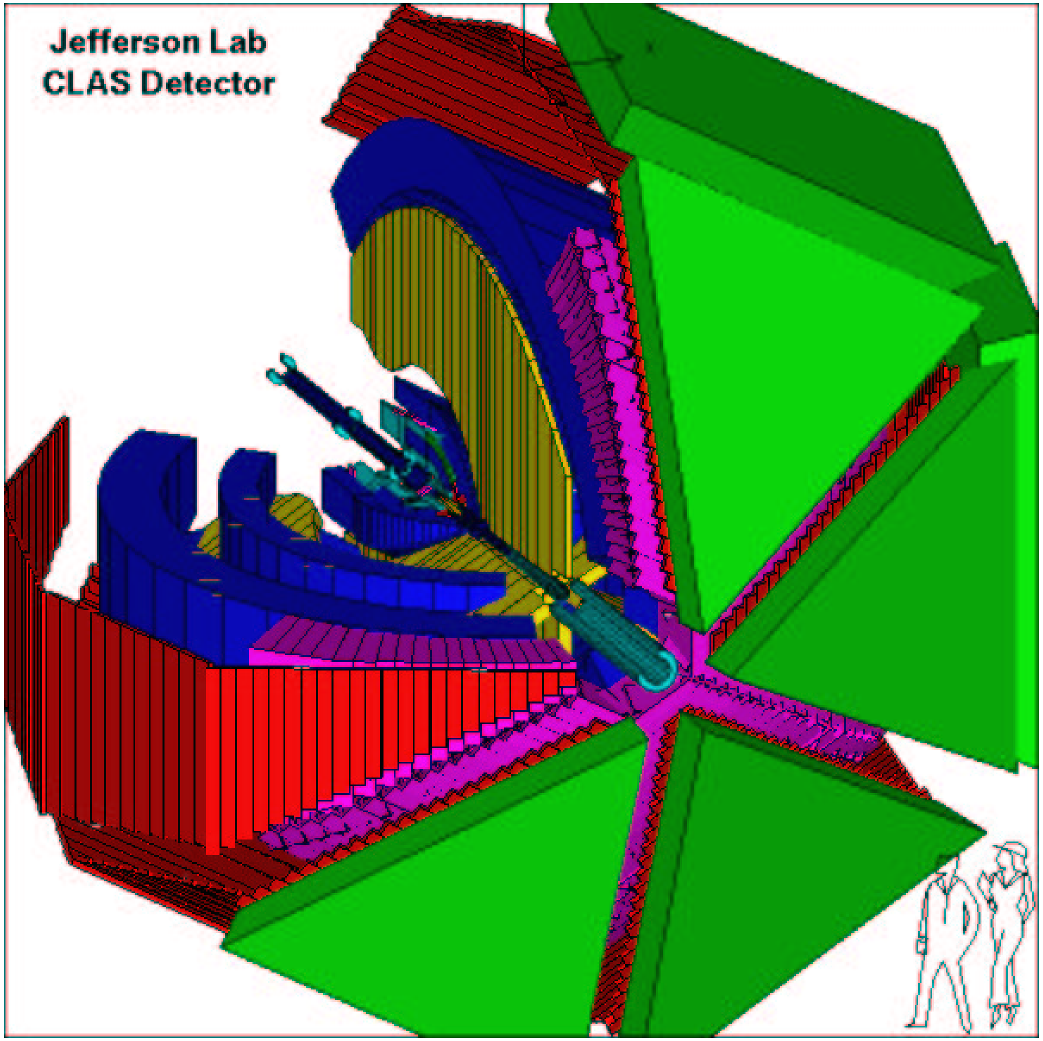
HERMES MC and pK data

- Left: MC simulation with $\Gamma = 2$ MeV, $M = 1540$ MeV. MC result: $M = 1540 \pm 0.3$ MeV and $\sigma = 7 \pm 0.2$ MeV.
- Right: $K^- p$ and $K^+ p$ spectra



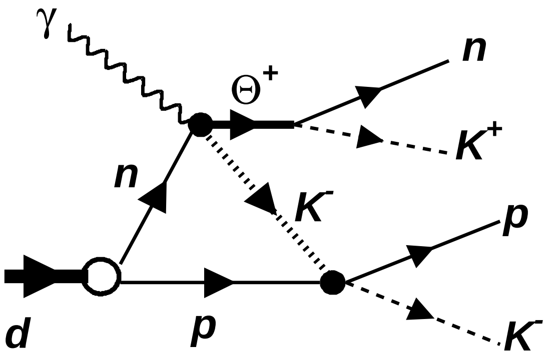


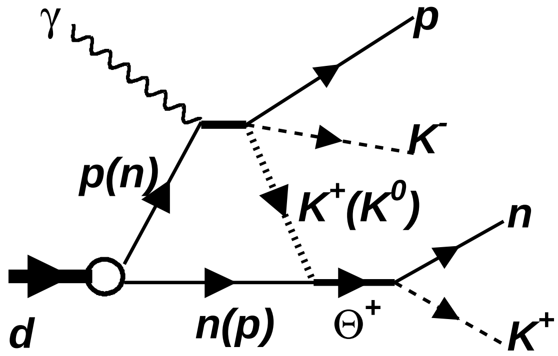
The CLAS spectrometer



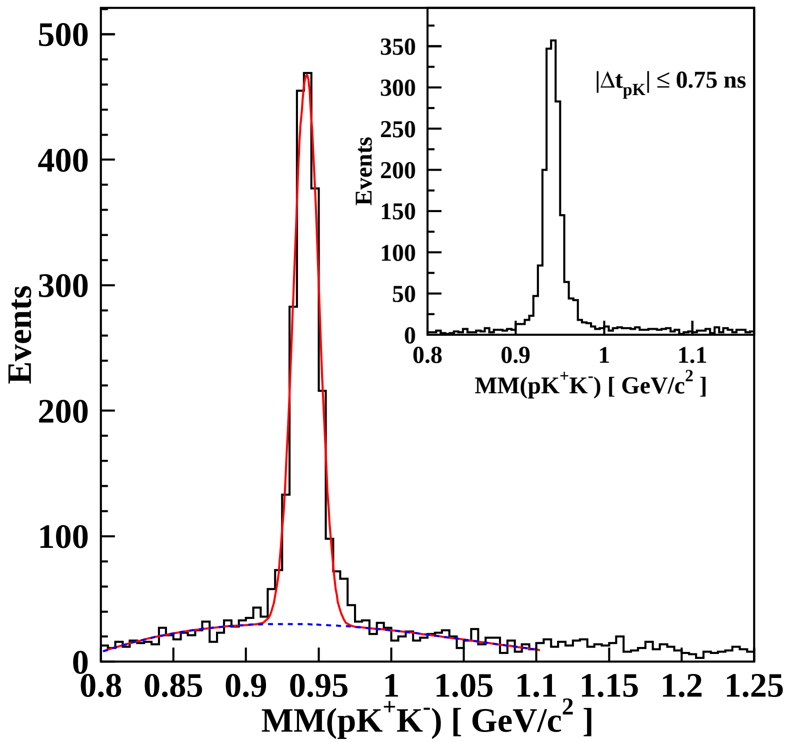
$E_e = $ 2.474, 3.115 GeV
10^{-4} r.l. radiator
photon tagger
$4 \times 10^6 \gamma$/s
$2.3 \times 10^{12} \gamma >$ 1.51 GeV
3–5% energy resolution

CLAS Deuteron

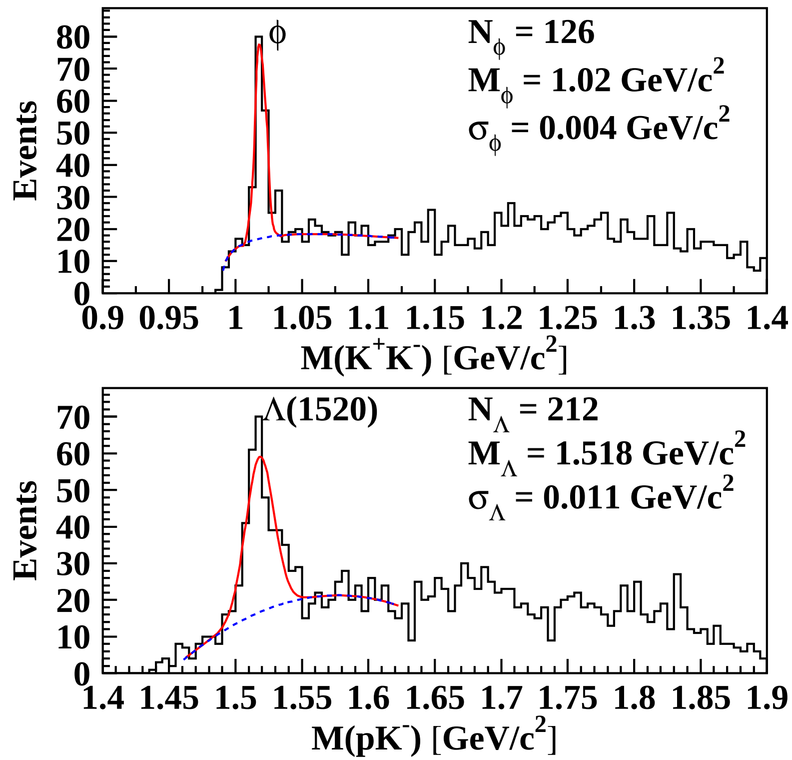




a)

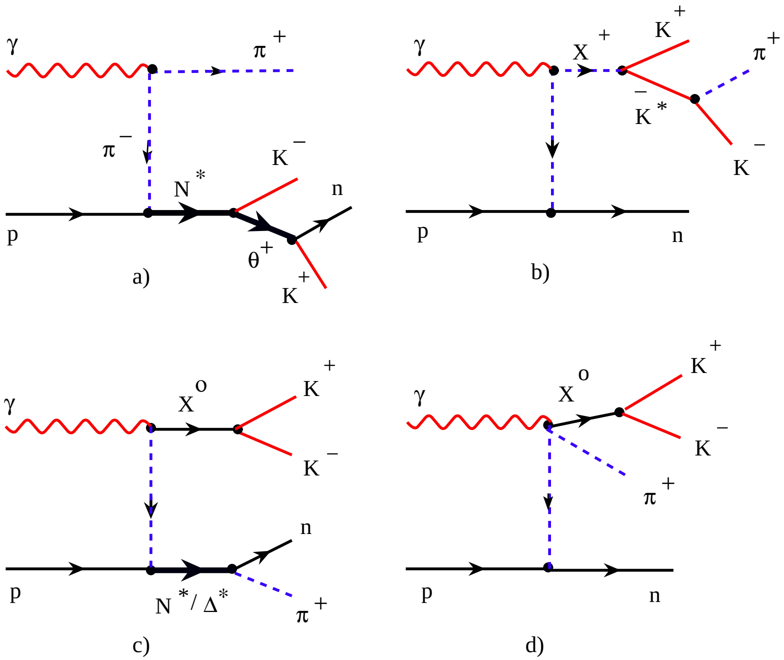


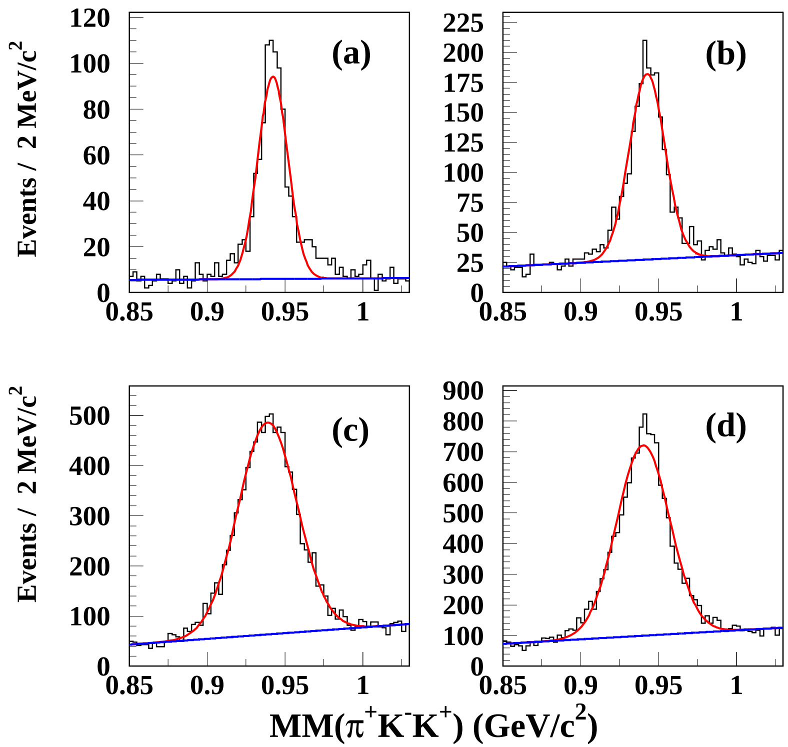
b)



CLAS Proton

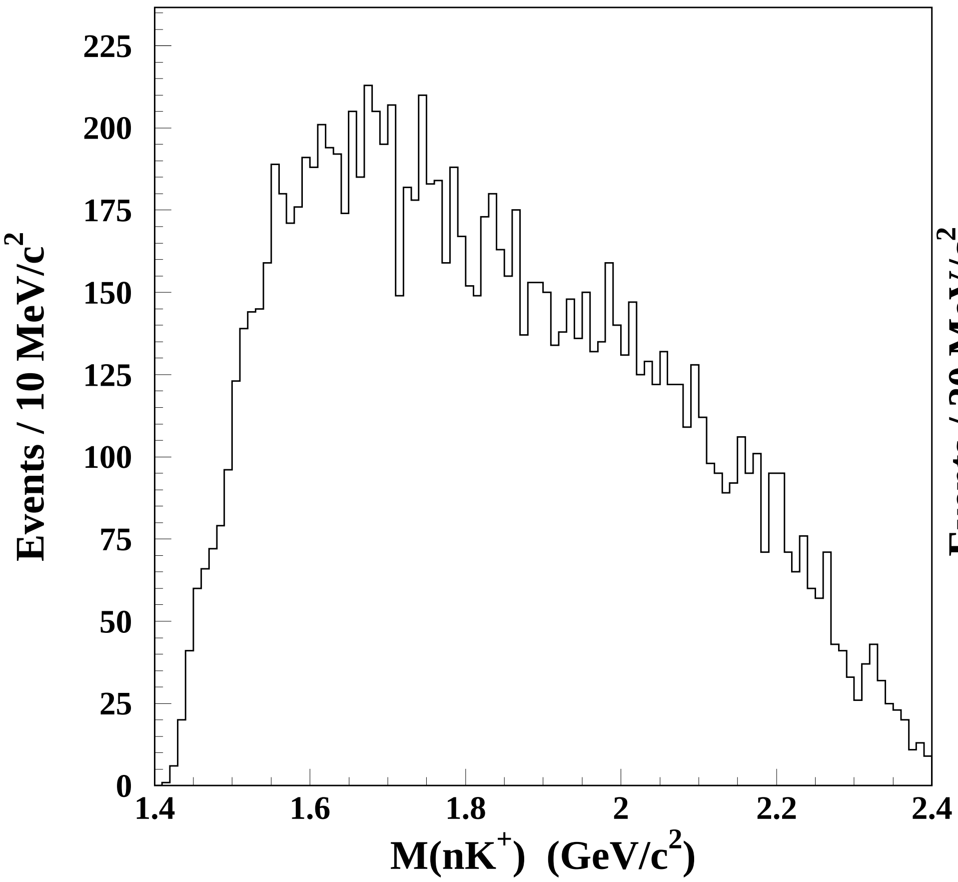
left: Possible signal and background right: missing mass

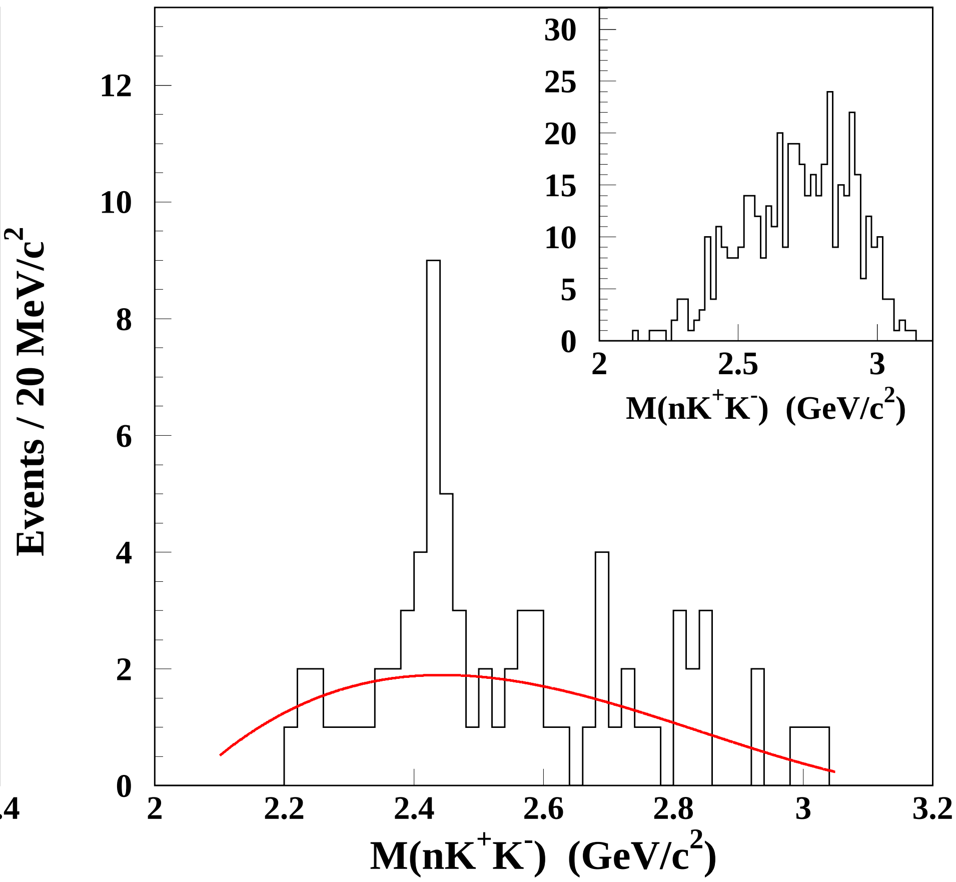




CLAS Proton

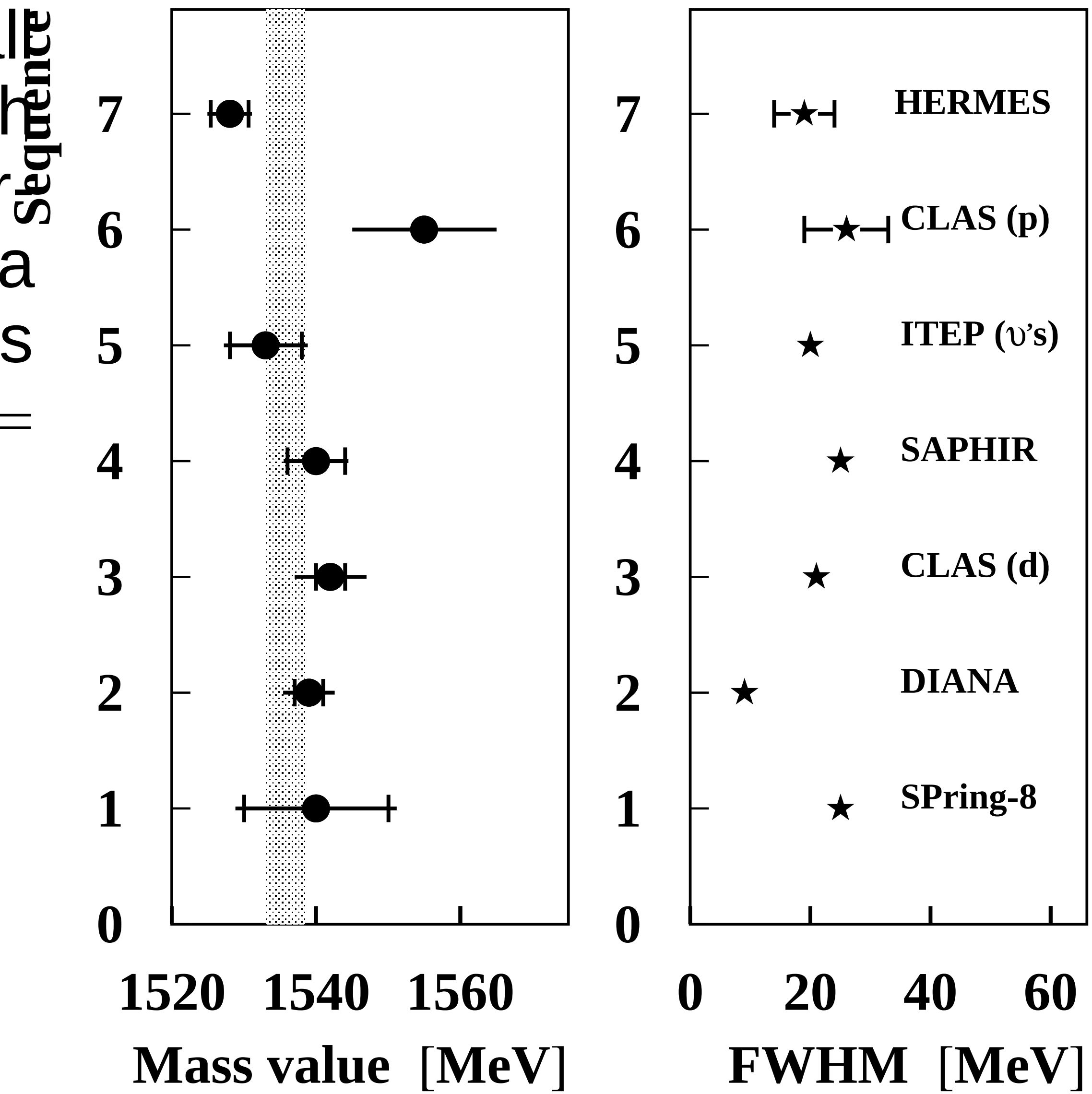
- left: $M(nK^+)$ without cuts
- right: $M(nK^+K^-)$ in Θ^+ peak and above (inset)





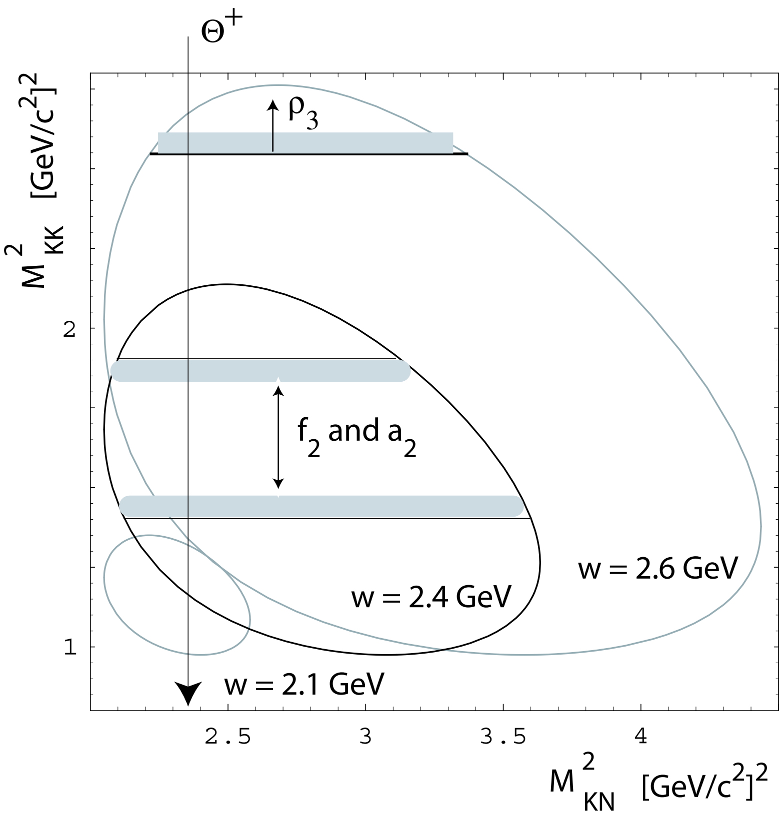
Comparison of Experiments

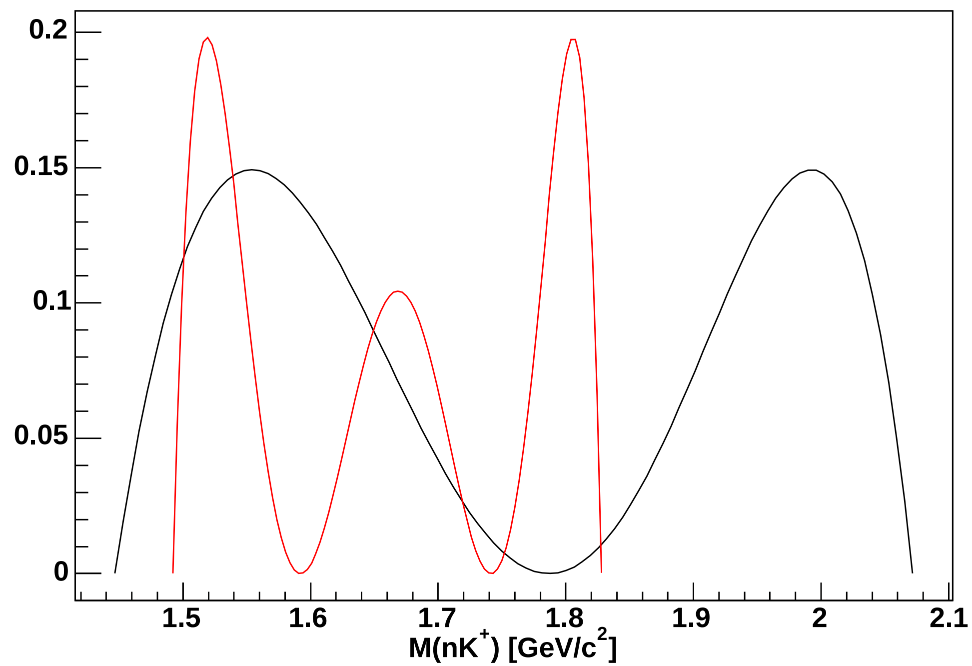
Seven experiments all show a peak with width less than each experiment's resolution at a consistent value of mass World average is $M = 1536 \pm 3$ MeV



Reflections?

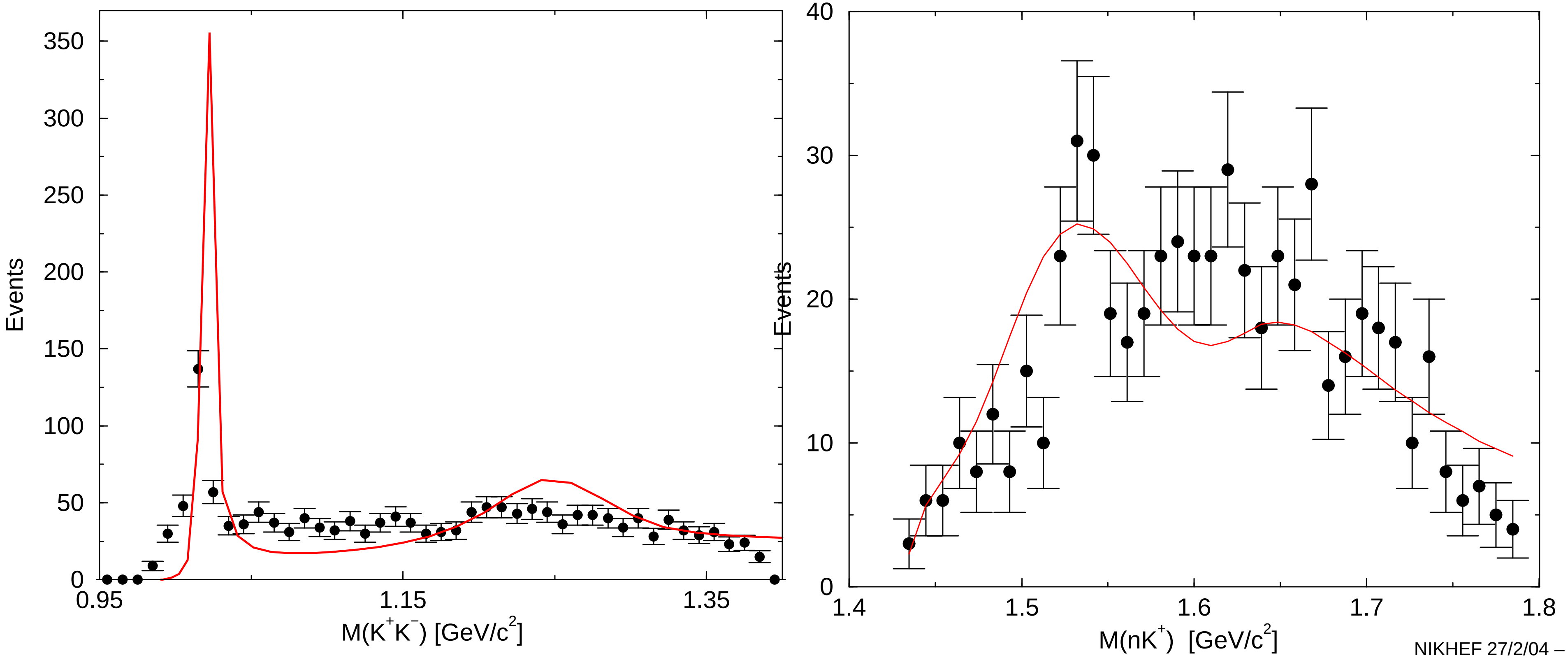
- A.R. Dzierba, *et al.*; KKN exclusive final states
- Dalitz plot; $M(nK^+)$ for a_2 with $|Y_2^{\pm1}|^2$ and ρ_3 with $|Y_3^{\pm1}|^2$



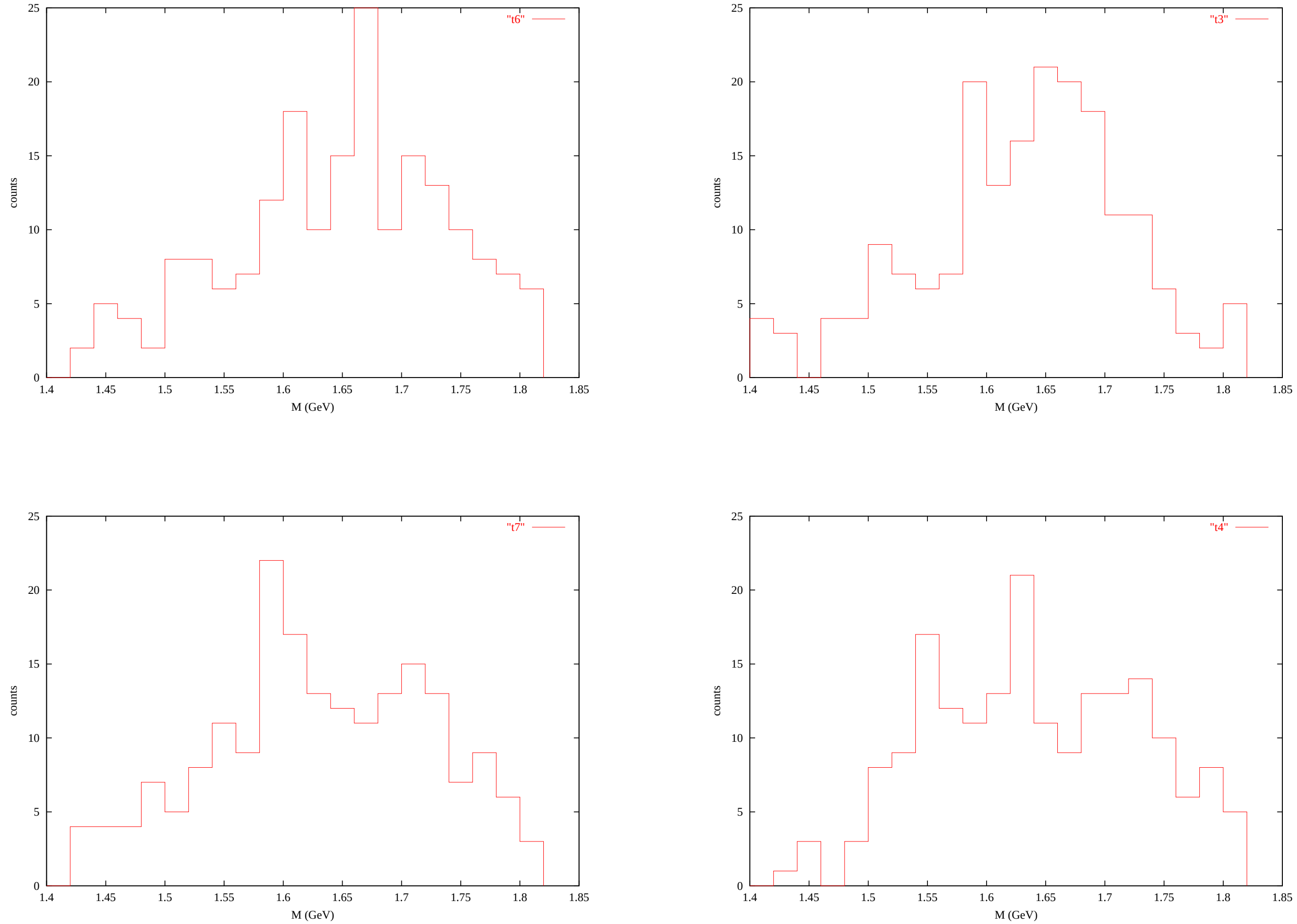


Reflections?

- A.R. Dzierba, *et al.*; $M(nK^+)$ and $M(K^+K^-)$ spectra
- Some hint of a peak, but it's too broad and $M(K^+K^-)$ doesn't match
- Data are from CLAS (deuteron)

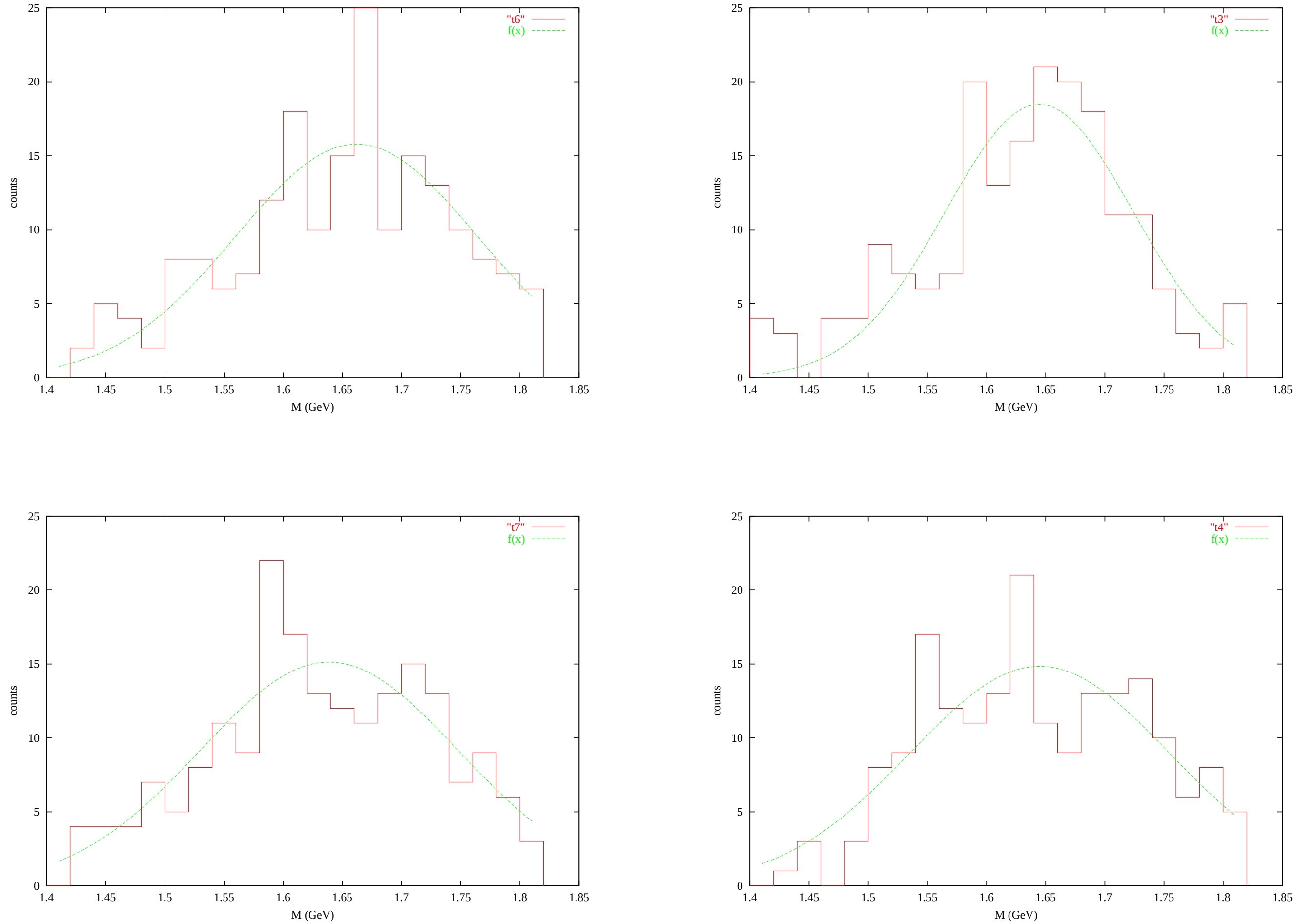


Spot the Resonance



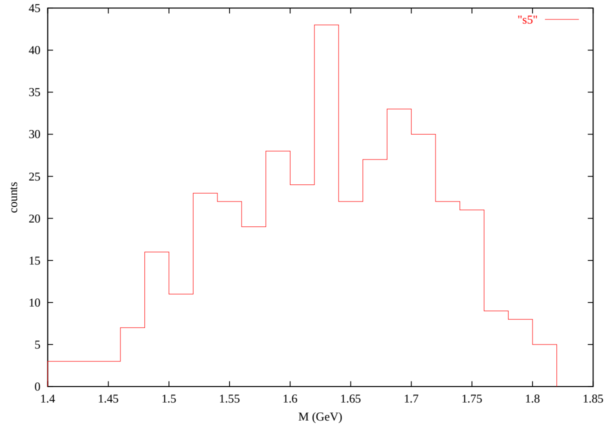
- Are there resonance peaks in these spectra?

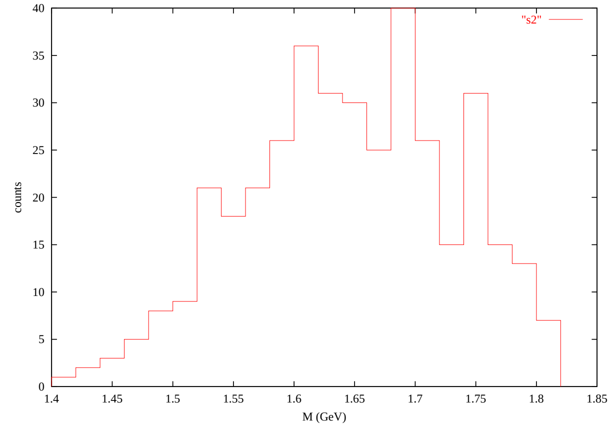
Spot the Resonance

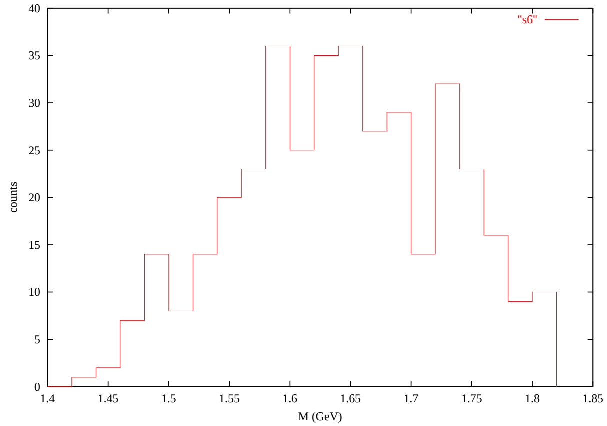


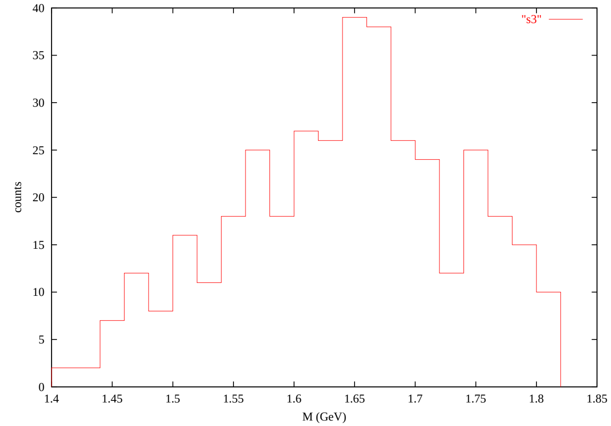
- With gaussian fits

Spot the Resonance



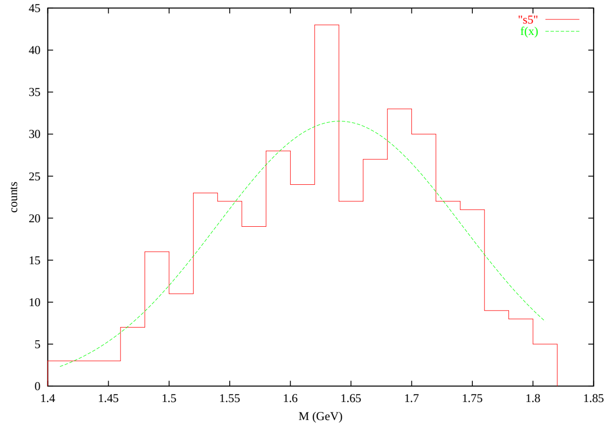


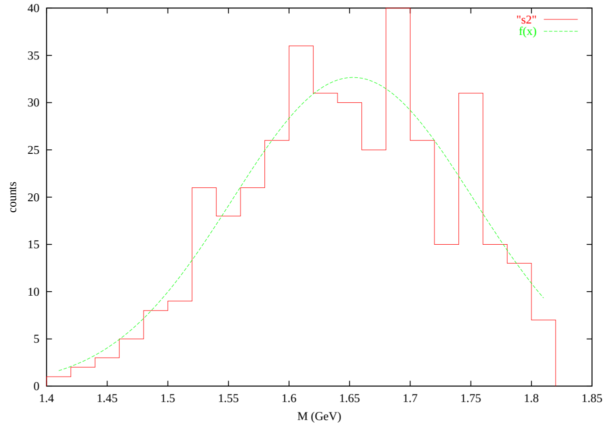


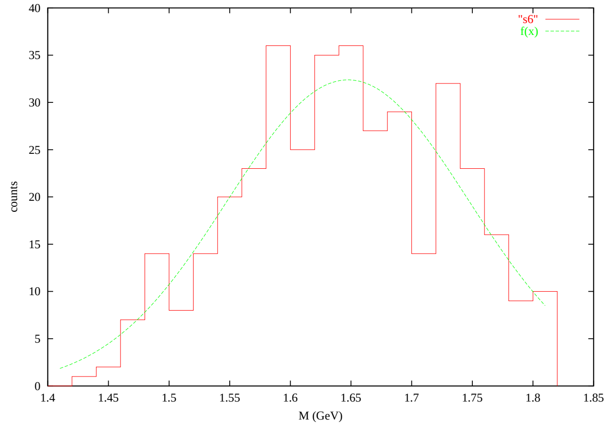


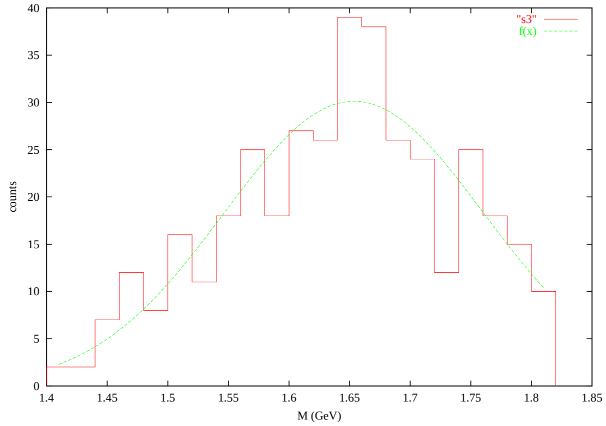
- Now, with better statistics

Spot the Resonance



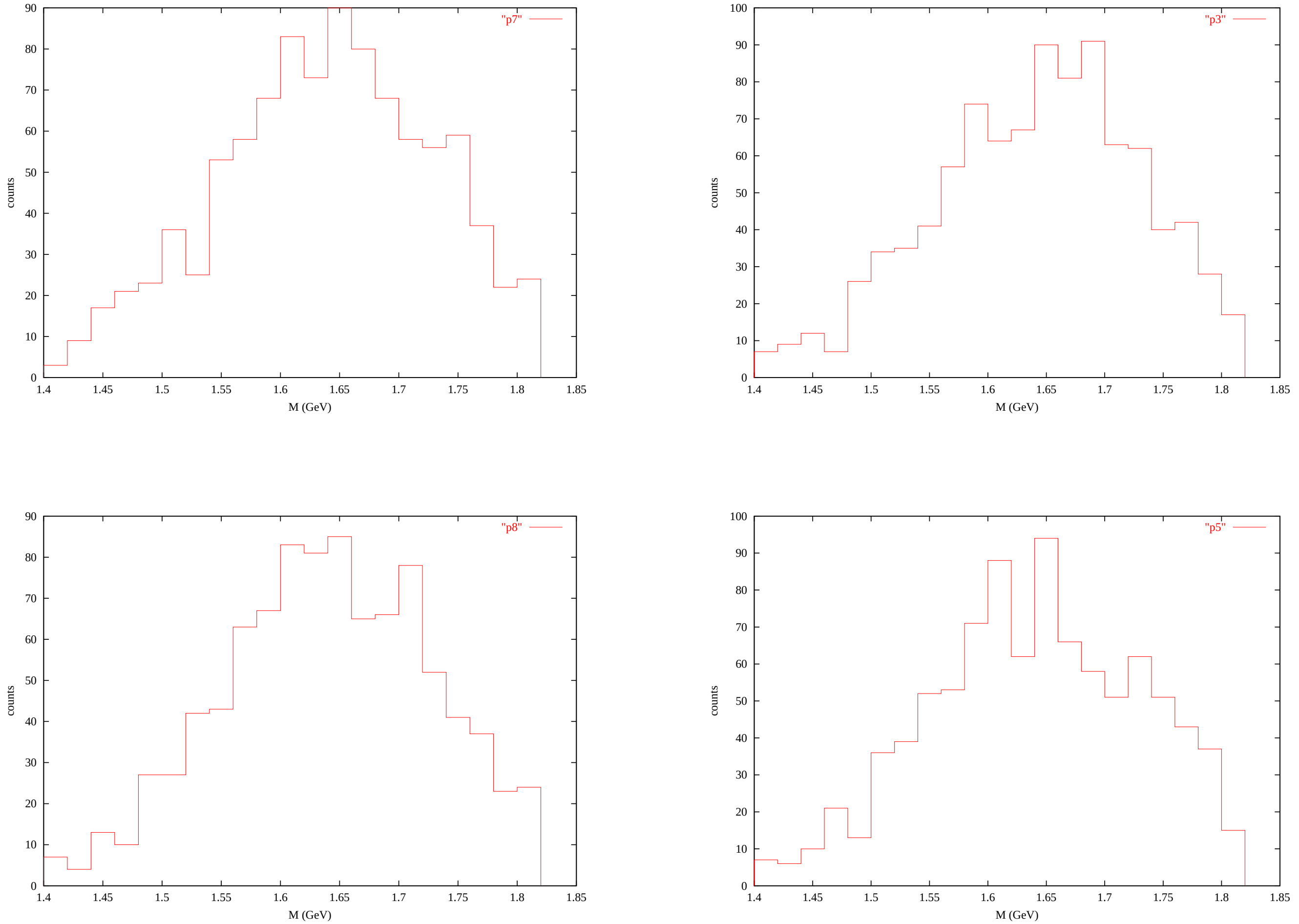






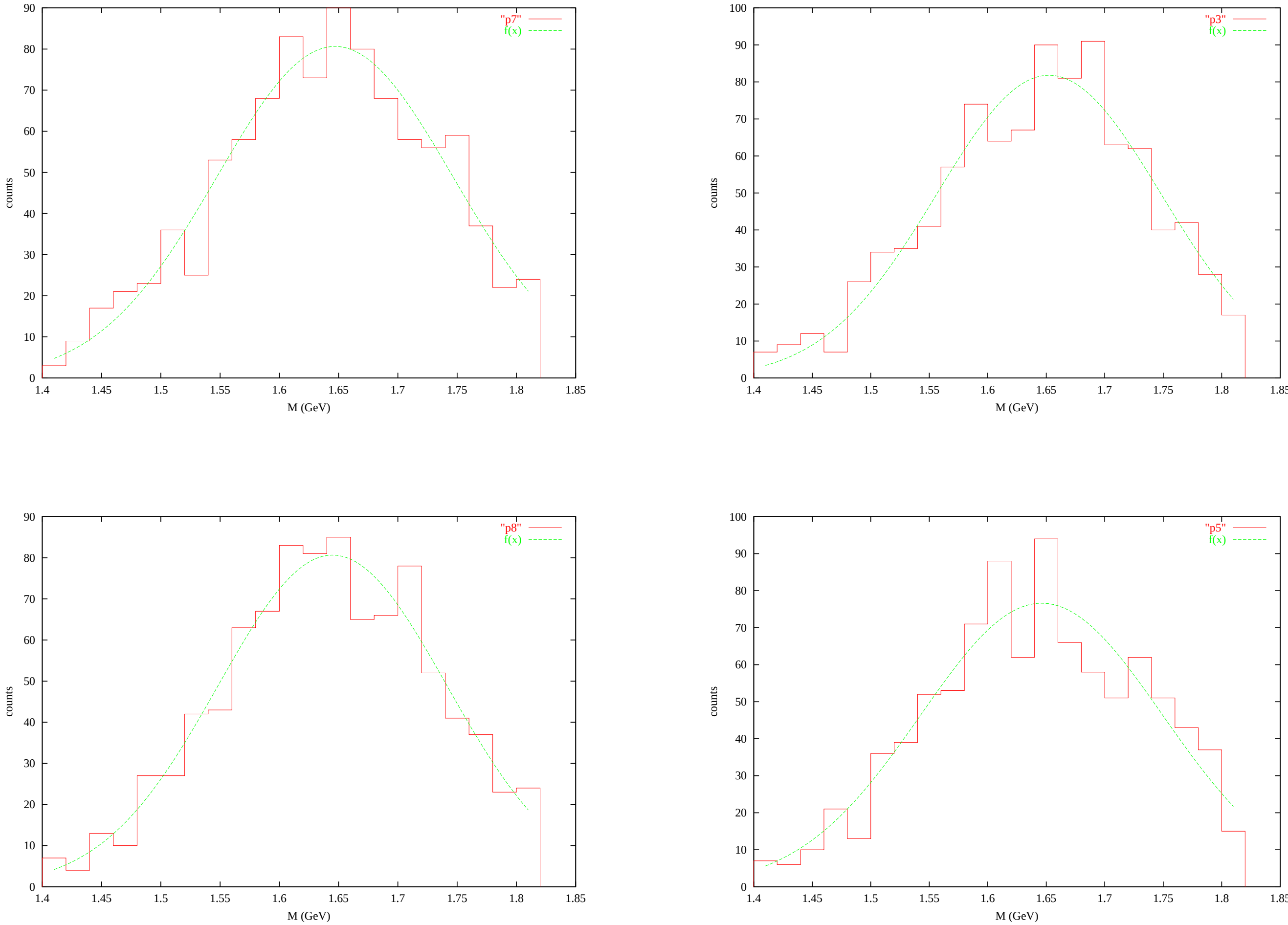
- With gaussian fits

Spot the Resonance



- Better statistics still

Spot the Resonance



- Gaussian distributions: $\mu = 1.65$, $\sigma = 0.2$; 200, 400, 1000 events.

Summary Table

Expt	Reaction	$\Delta\Omega$ (%)	$E_{\rm beam}$ (GeV)
SPring-8	γ^{12}C $\rightarrow K^+K^-(n)$	3	1.5–2.35
DIANA	$K^+Xe \rightarrow K^0p$(Xe′)	100	0.850
SAPHIR	$\gamma p \rightarrow K^+K^0_s(n)$	60	0.87–2.6
CLAS	$\gamma d \rightarrow K^+K^-p(n)$	50	1.51–3.10
BEBC/15′	$\nu[\bar{\nu}]$Ne[D]$\rightarrow K^0_s p\mu(X)$	100	57
HERMES	$\gamma^* d \rightarrow pK^0_s(X)$	1	27.6
CLAS	$\gamma p \rightarrow \pi^+K^-K^+(n)$	50	3–5.47

Summary Table

Expt	Detectors	Cuts applied
SPring-8	SSD,DC,TOF,B,Ch	$M_{\gamma KK} \neq M_n$; $M_{KK} \neq M_\phi$; $p_h > 0.35$; $\vec{p}_h$ in SSD acc.; no signal in SSD w/i 45mm
DIANA	BubbleC,B=0	$L_{K^0} > 2.5$mm; $P_{K^+} < 0.53$; $P_{K^0_s} > 0.17$; $\theta_{p,K^0} < 100°$; $\cos\phi_{pK^0} < 0$
SAPHIR	B,DC,TOF	$M_{\pi\pi} = M_{K^0}$; $\cos\theta_{K^0_s} > 0.5$
CLAS	DC,B,Ch,TOF,Cal	$\Delta t < 0.75$ns; $p_{K^+} < 1.0$; $p_n > 0.08$; $M_{pK^-} \neq M_{\Lambda(1520)}$; $M_{KK} \neq M_\phi$
BEBC/15′	BubbleC,B	$p_\mu > 4$; $0.3 < p_p < 0.9$
HERMES	DC,B,TOF,Cal,RICH	$V_{\pi\pi} < 10$mm; $V_{pK^0_s} < 4$mm; $L_{K^0_s} > 70$mm; $4 < p_p < 9$; $1 < p_\pi < 15$; $M_{\pi\pi} = M_{K^0_s}$
CLAS	DC,B,Ch,TOF,Cal	$-t < 0.28$ GeV^2; $\cos\theta^*_K < 0.6$; $\cos\theta^*_{\pi^+} > 0.8$; $M_{\pi KK} = M_n$

Summary Table

Expt	N_s	N_b	M_{Θ^+}	Γ	Ex	MC
SPring-8	19	17	$1540 \pm 10 \pm 50$	< 25	Y	N
DIANA	29	44	$1539 \pm 2 \pm \text{few}$	< 9	Y	N
SAPHIR	55	56	$1540 \pm 4 \pm 2$	< 25	Y	N
CLAS	43	54	$1542 \pm 2 \pm 5$	< 21	Y	Y
BEBC/15′	27	8	1533 ± 5	< 20	N	N
HERMES	60	130	$1528 \pm 2 \pm 2$	< 20	N	Y
CLAS	38	24	$1555 \pm 1 \pm 10$	< 26	Y	N

Conclusions

- $uudd\bar{s}$ state seen with mass 1536 ± 3 MeV.
- Little is known about the quantum numbers.
- Probably $I = 0$: no state in pK^+ mass spectrum.
- Much more data is expected: JLab CLAS E03-113 approved for 30 days with $20\times$ current statistics; HERMES improved trigger; etc.
- Θ^+ is difficult to find in pp reactions where combinatorial backgrounds are high. Maybe Θ^+ is fragile.
- CERN NA49 hep-ex/0310014 (8 Oct): first evidence for $ddss\bar{u}$; $N_s/\sqrt{N_b} = 4.0$; Ξ^{--} at 1862 ± 2 MeV; $\Gamma < 18$ MeV. Unverified by other experiments.