# *Experimental searches for the pentaquark $\Theta^+$ baryon*

*(for the HERMES and CLAS collaborations).*

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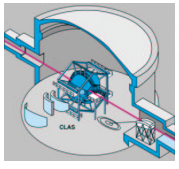
**College of William & Mary, Williamsburg, VA**

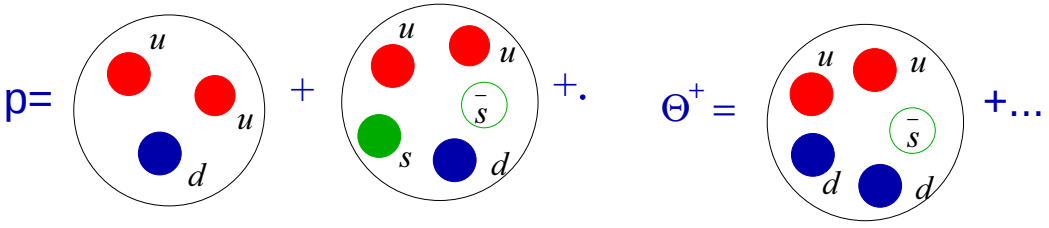


The College of WILLIAM & MARY

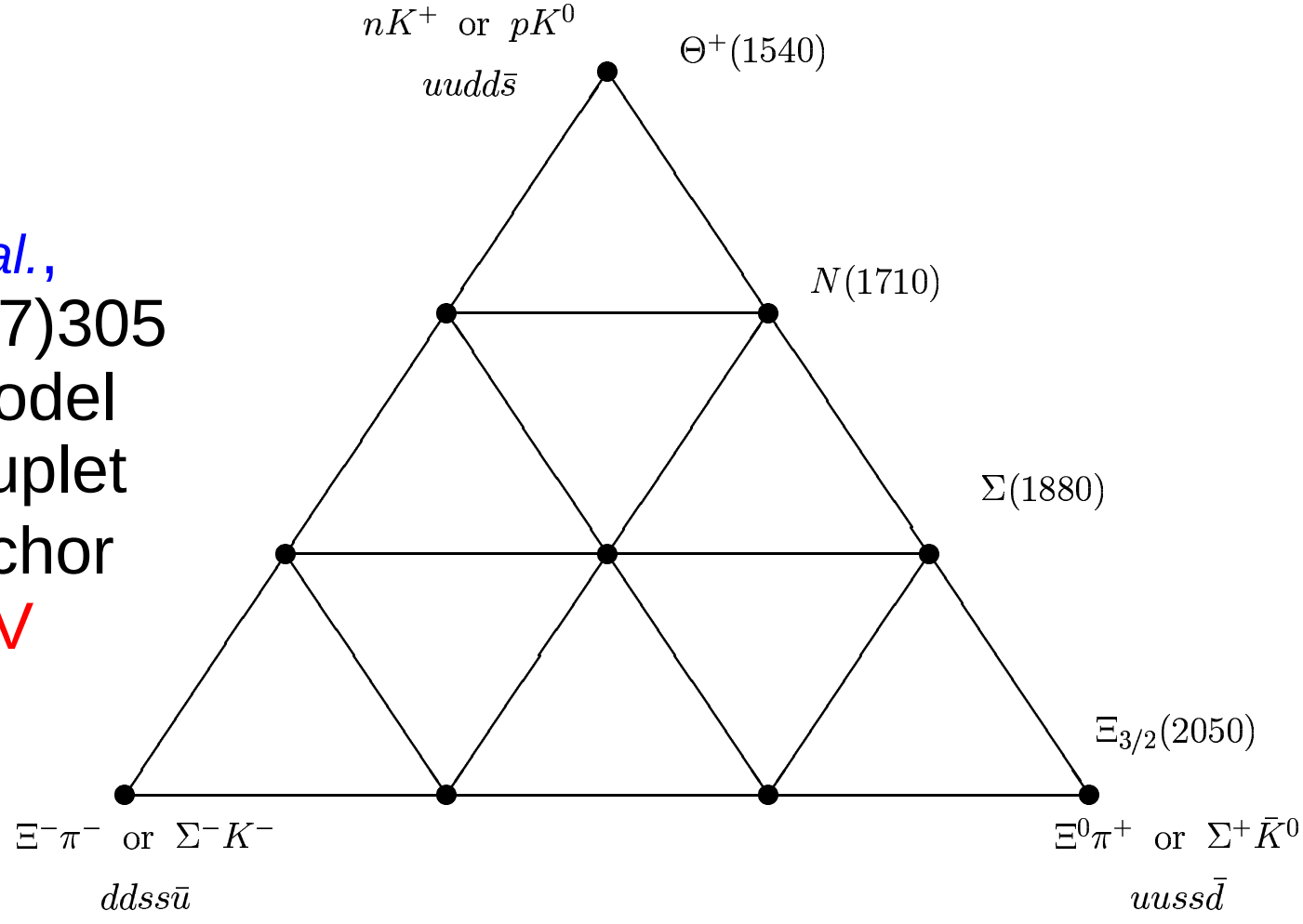
# Introduction

- 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 observations of a $qqqq\bar{q}$ pentaquark state have been made this year.

# Pentaquark Predictions



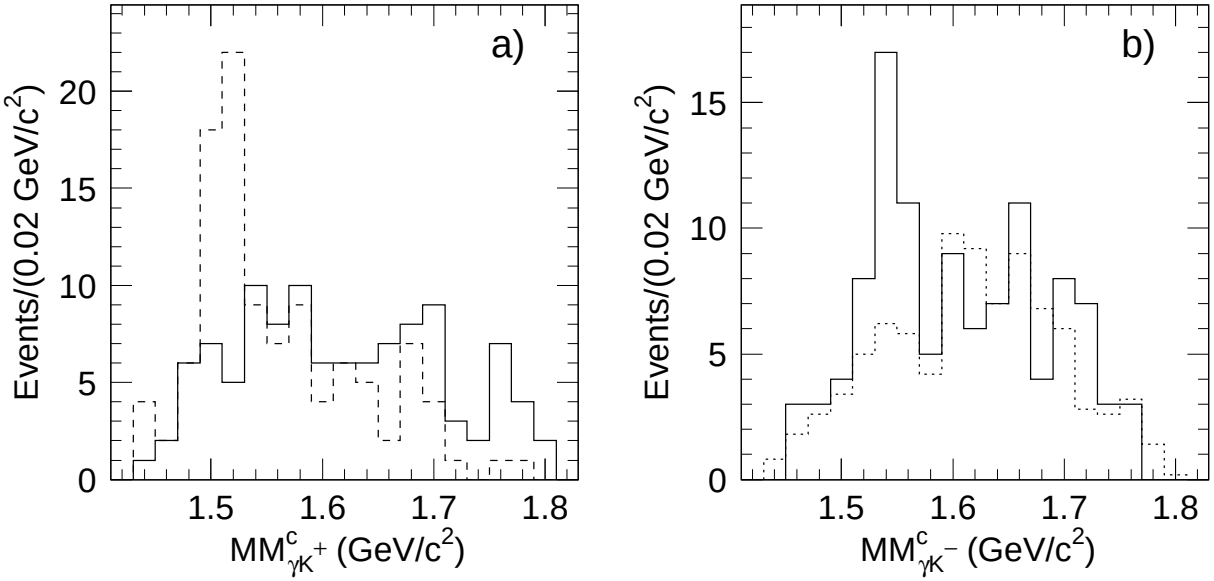

D. Diakonov *et al.*,
Z. Phys. **A359**(97)305
chiral soliton model
spin-$\frac{1}{2}$ anti-decuplet
$P_{11}(1710)$ as anchor
$M_{\Theta^+} = 1530$ MeV
$\Gamma \approx 15$ MeV
$S = +1,\ I = 0$



# LEPS at SPring-8

T. Nakano *et al.*,
hep-ex/0301020
PRL **91**(03)012002

$\gamma p \to K^+K^-p$
$\gamma n$ ($^{12}$C)$\to K^-(K^+n)$
$M_{\Theta^+} = 1540 \pm 10$ MeV
$\Gamma < 25$ MeV
$N_s/\sqrt{N_b} = 4.6$

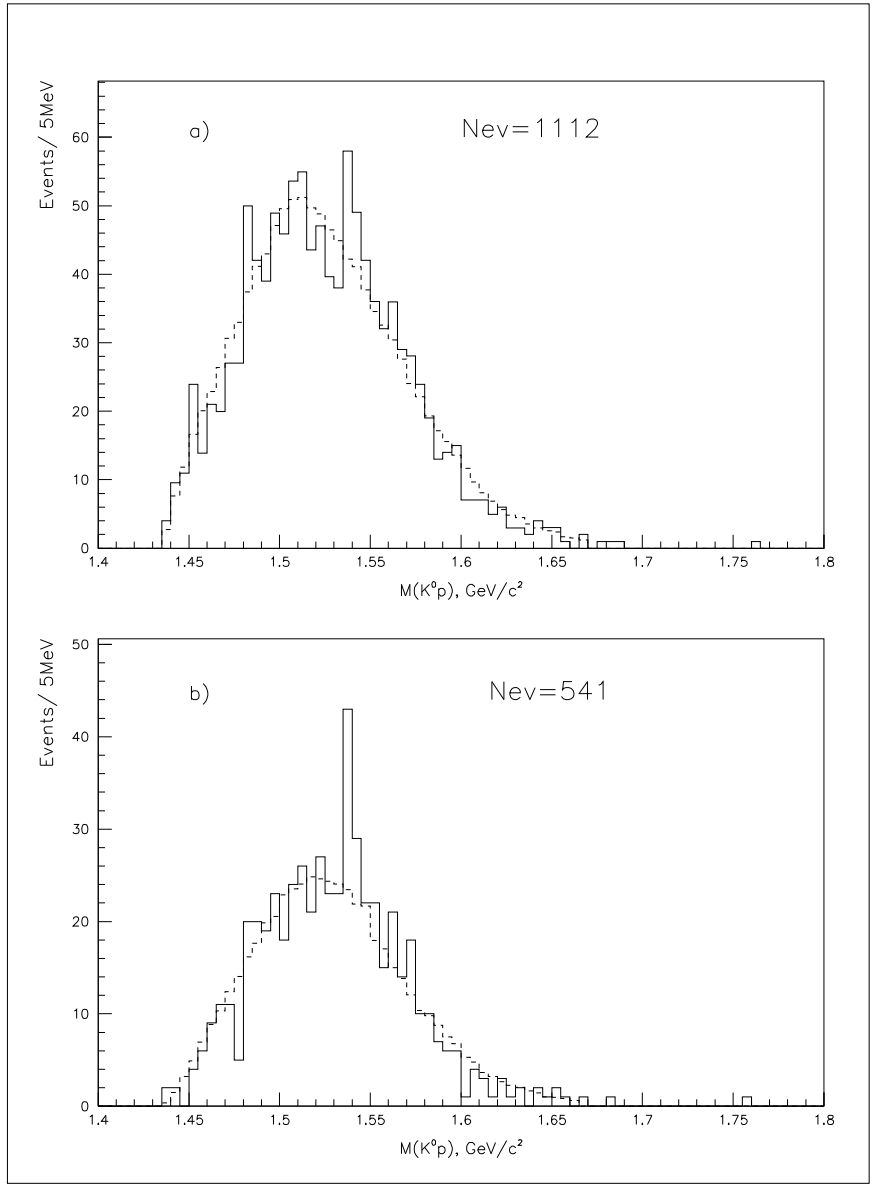



- $MM^c_{\gamma K^\pm} = MM_{\gamma K^\pm} - MM_{\gamma K^+K^-} + M_N$
- (a) CH target. Solid: $K^+K^-$ signal sample. Dashed: $p$ tag showing $\gamma p \to K^+\Lambda(1520) \to K^+K^-p$
- (b) Solid: CH target signal sample. Dashed: $LH_2$ target, same cuts.

# ITEP Bubble Chamber

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

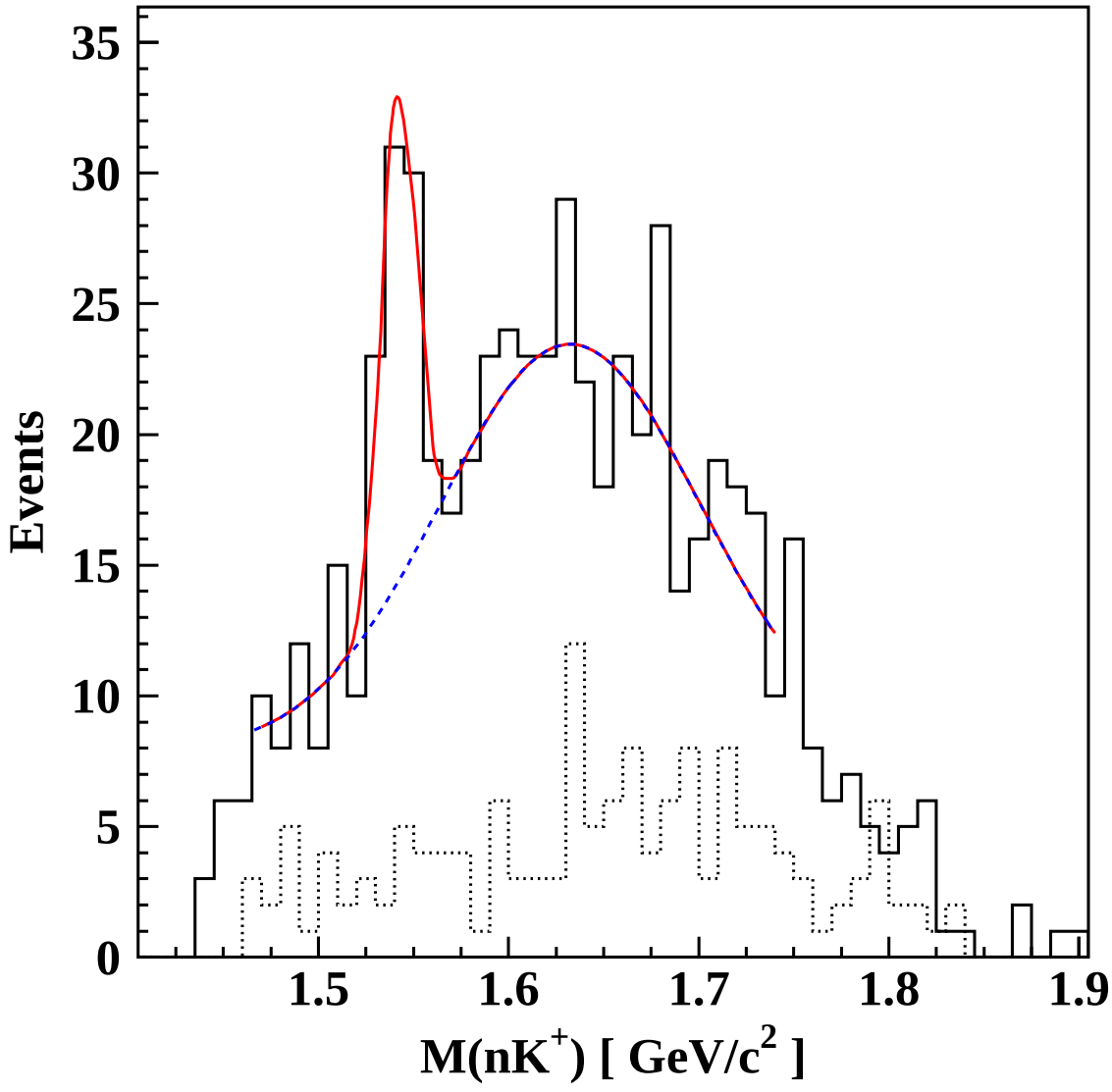
(a) all measured $K^0 p$ events
(b) $K^0 p$ events with $K^0$ and $p$ in the forward direction and on opposite sides of the beam



# CLAS d, Jefferson Lab

S. Stepanyan *et al.*,
hep-ex/0307018
$\gamma d \to pK^-(K^+n)$
$M_{\Theta^+} = 1542 \pm 5$ MeV
$\Gamma < 21$ MeV
$N_s/\sqrt{N_b} = 5.3$

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



# SAPHIR, ELSA, Bonn

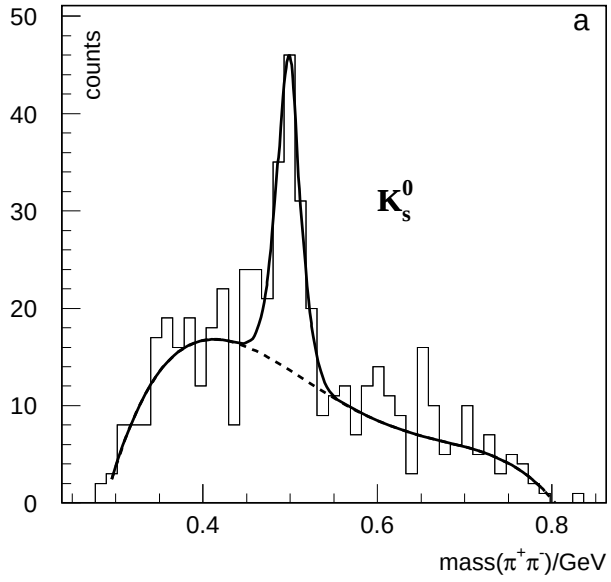
J. Barth *et al.*,
hep-ex/0307083

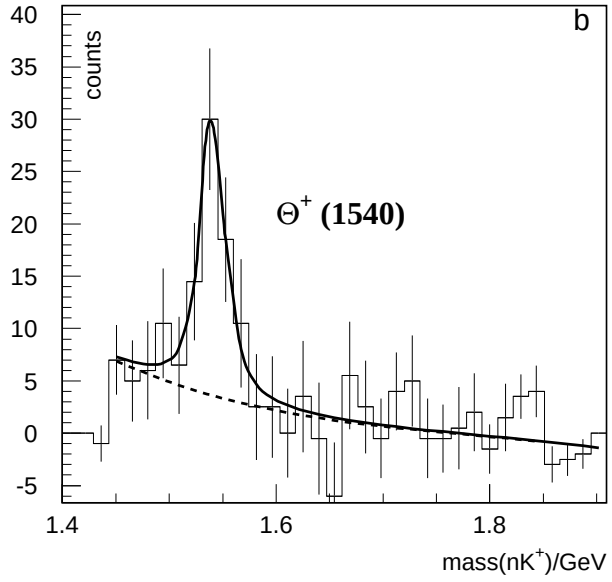
$\gamma p \to K^0_s K^+ n$

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

$\Gamma < 25$ MeV

$N_s/\sqrt{N_b} = 4.8$




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

# CLAS, Jefferson Lab

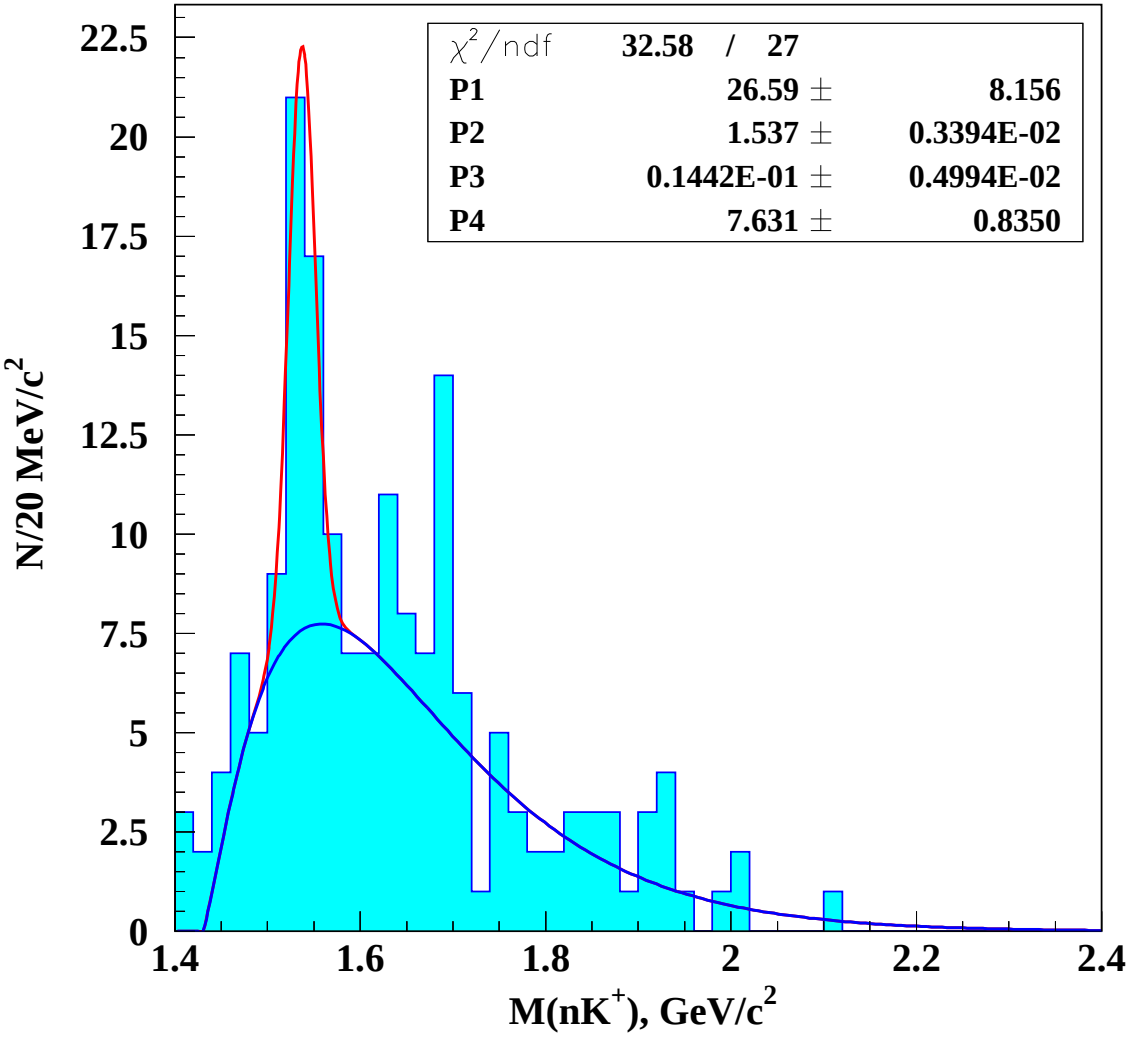
V. Kubarovsky *et al.*,
hep-ex/0307088

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

$M_{\Theta^+} = 1540 \pm 10$ MeV

$\Gamma < 32$ MeV

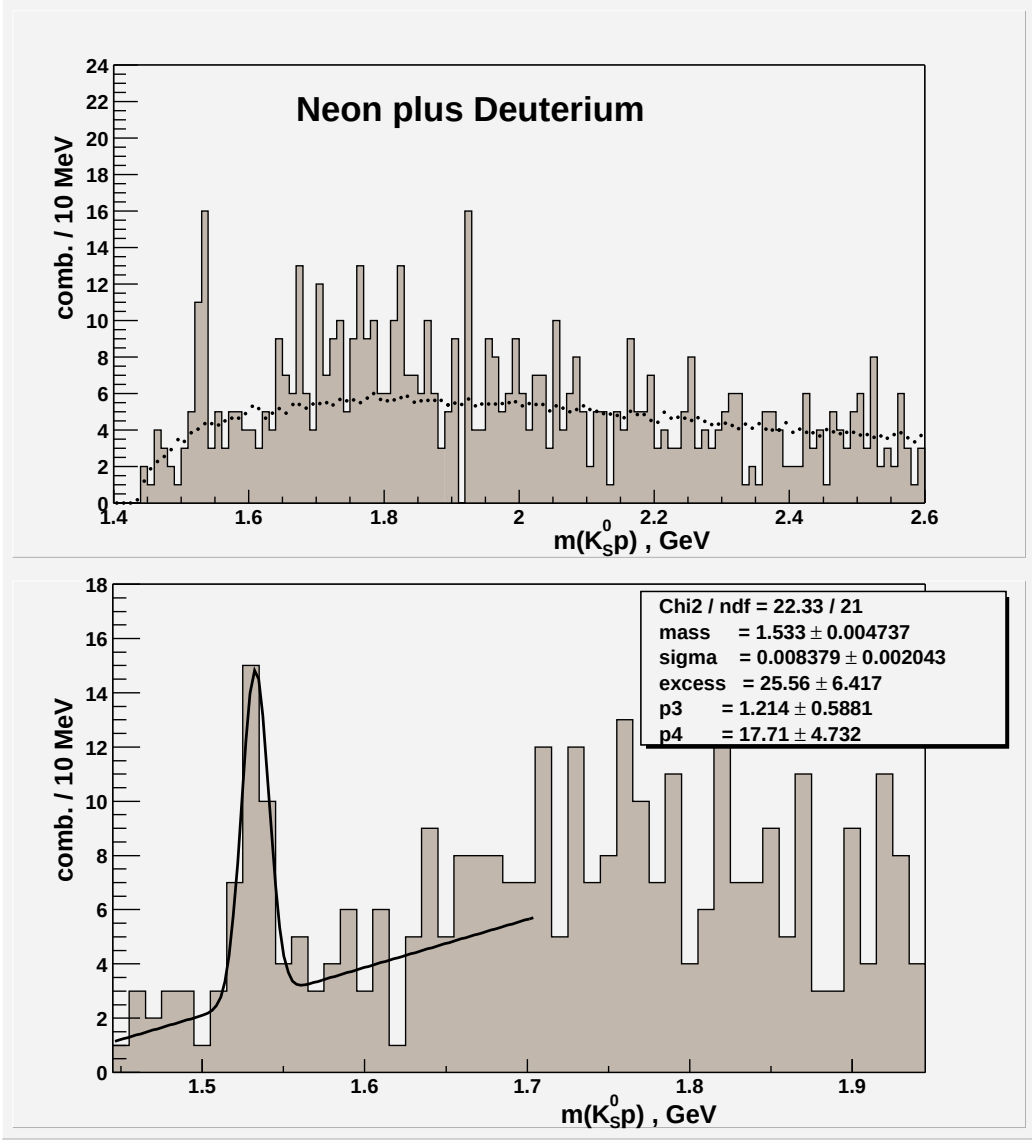
$N_s/\sqrt{N_b} = 4.8$



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

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

Upper: full spectrum
Lower: expanded scale around the peak



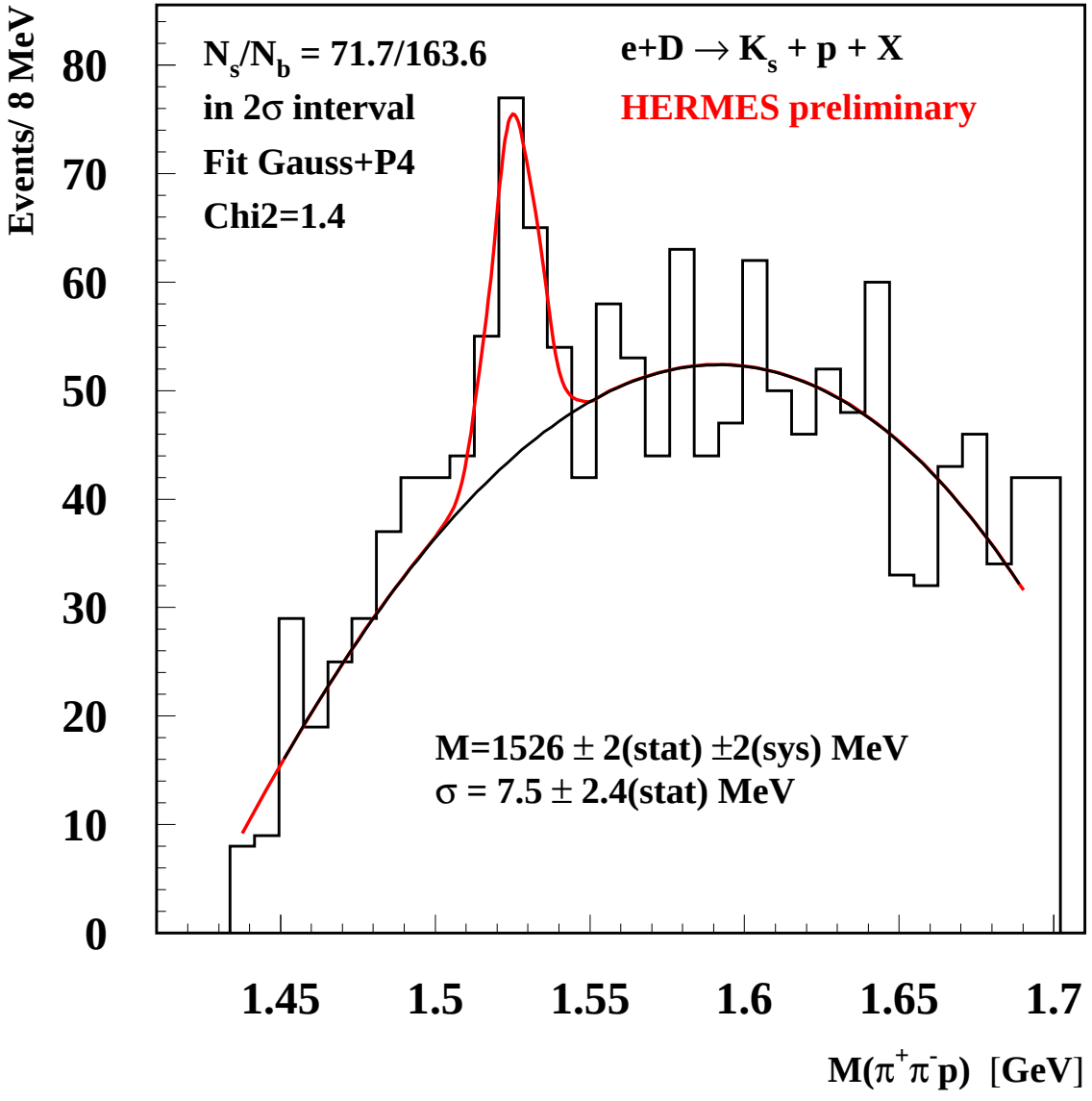
Just released

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

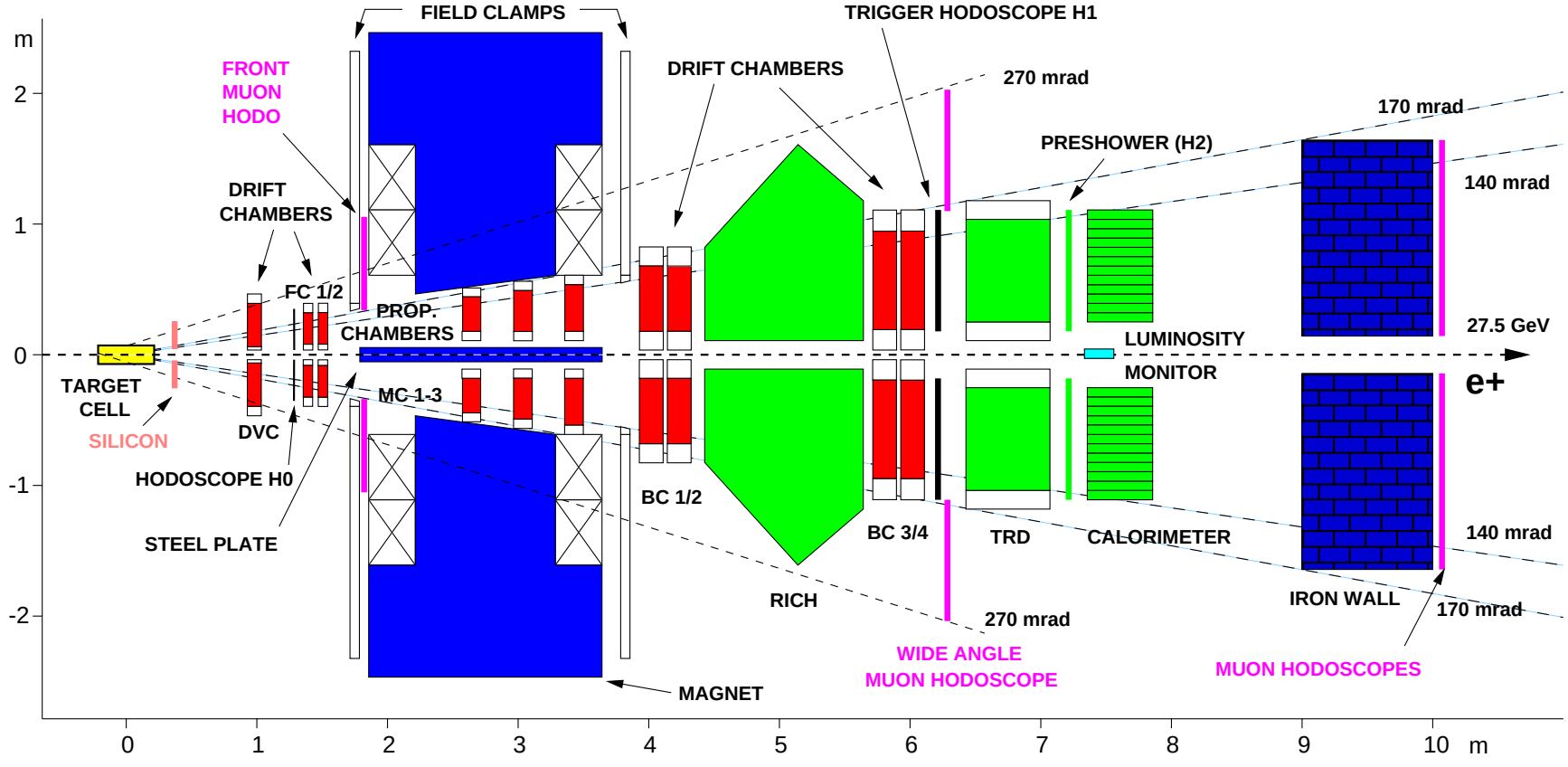
$M_{\Theta^+} = 1526 \pm 3$ MeV

$\Gamma < 18$ MeV

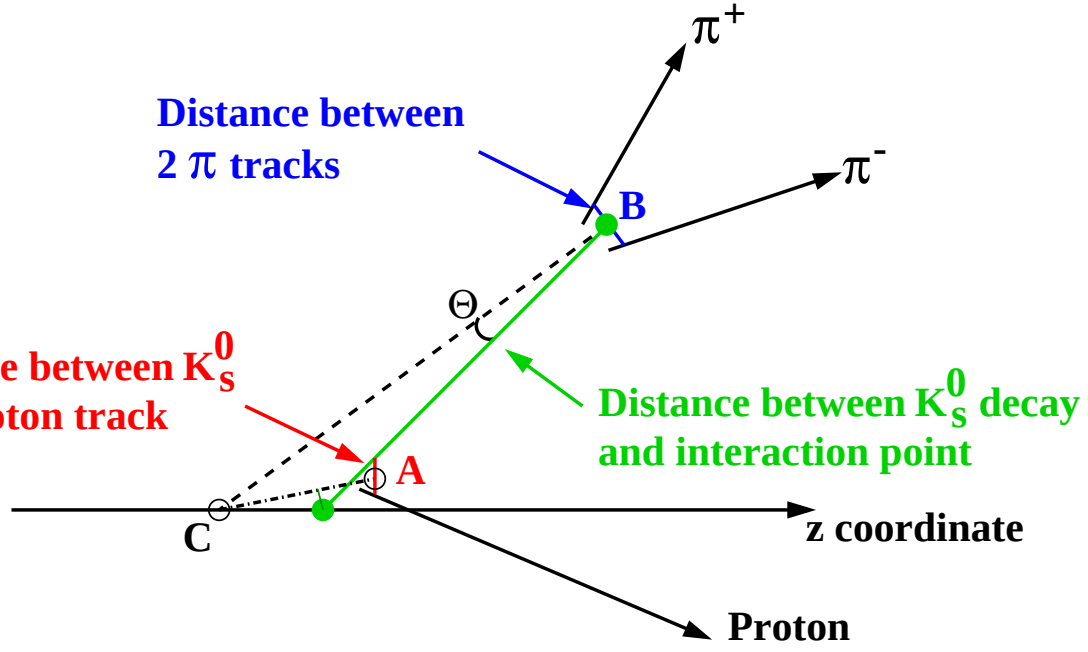
$N_s/\sqrt{N_b} = 5.6$



# The HERMES experiment



# HERMES Event Selection




$ed \rightarrow K^0_s pX$

RICH PID

$E_{\mathrm{beam}} = 27.6$ GeV

d targets from 1998-2000

$4 < p_p < 9$, $1 < p_\pi < 15$ GeV

$\pi^+\pi^-$ track distance $< 1$ cm

$pK^0_s$ track distance $< 0.6$ cm

$\angle CBA < 2.6°$

$K^0_s$ decay length $> 7$ cm

$485 < M_{\pi^+\pi^-} < 509$ MeV

target vertex cut

fiducial volume cut

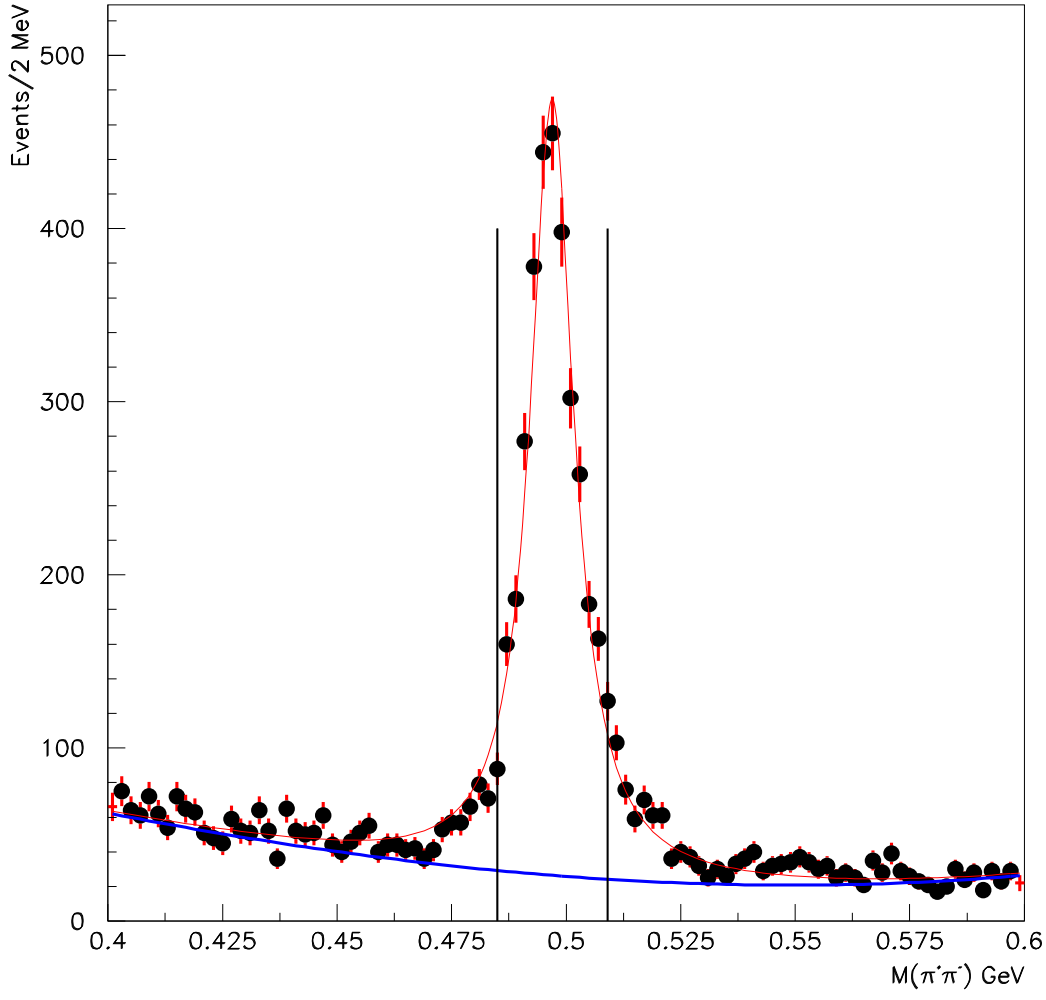
Eliminate $\Lambda^0(1116)$

# HERMES $K_s$ Identification

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

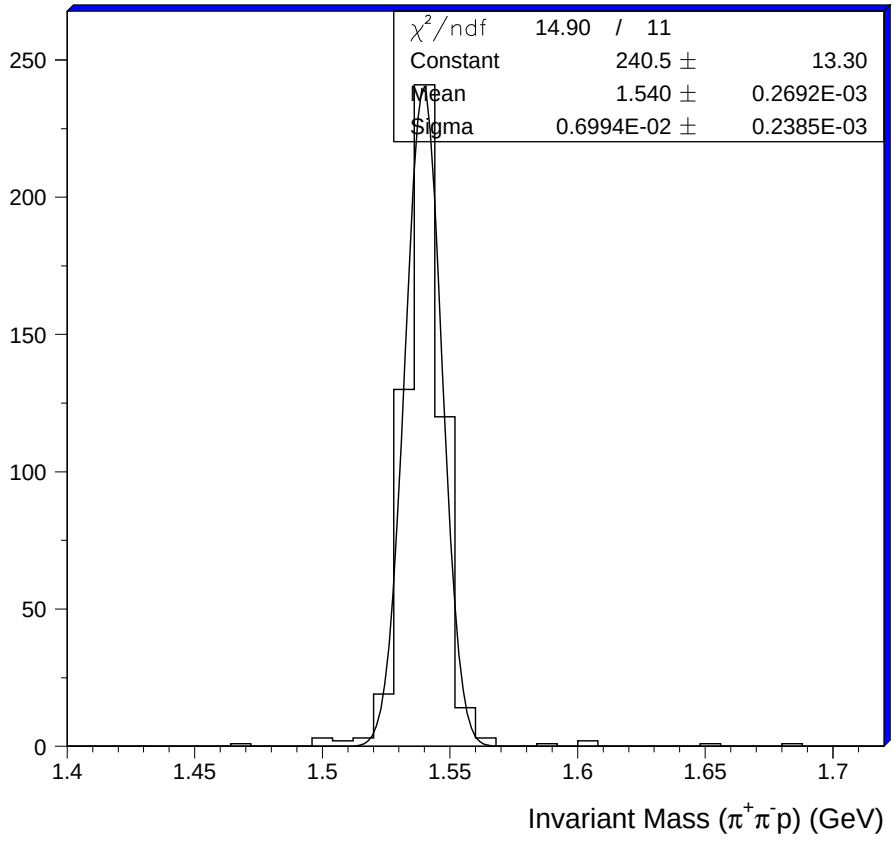
with PDG mass for:

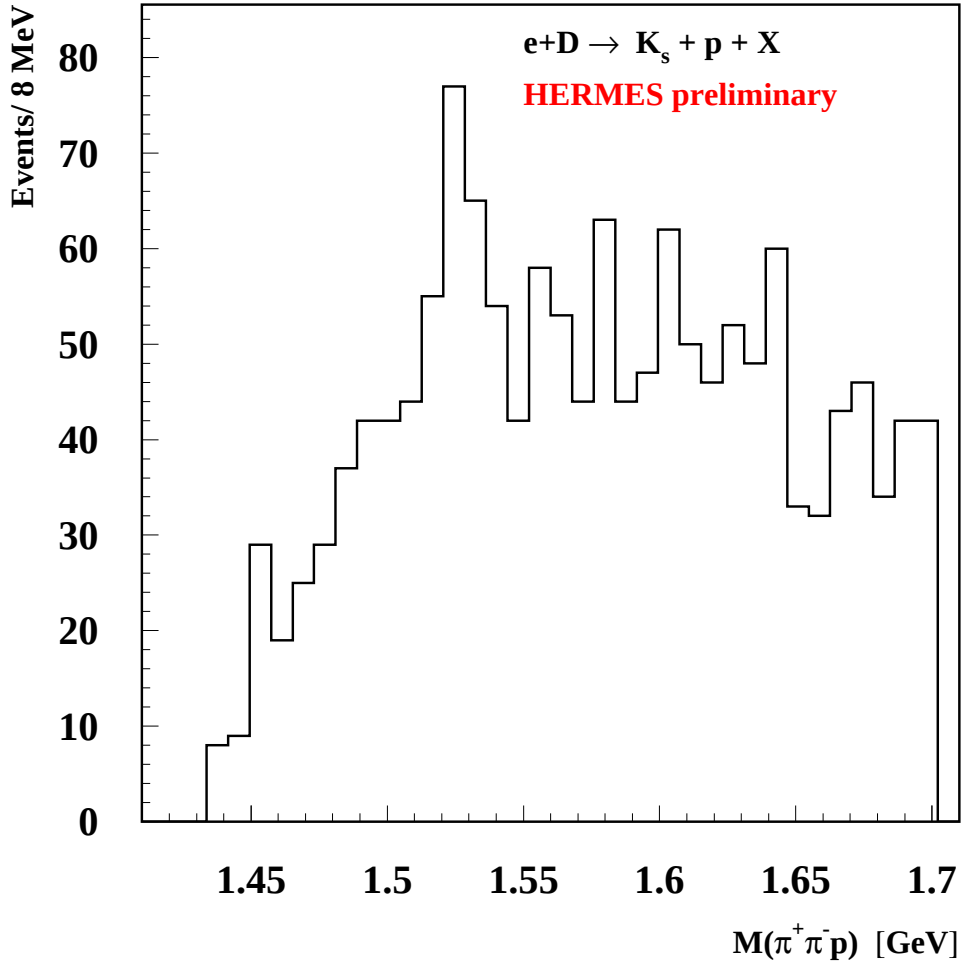
$\rho(770)[\pi^+\pi^-]$
$\phi(1020)[K^+K^-]$
$\bar{\Lambda}(1116)[\bar{p}\pi^+]$
$\Lambda^*(1520)[K^-p]$



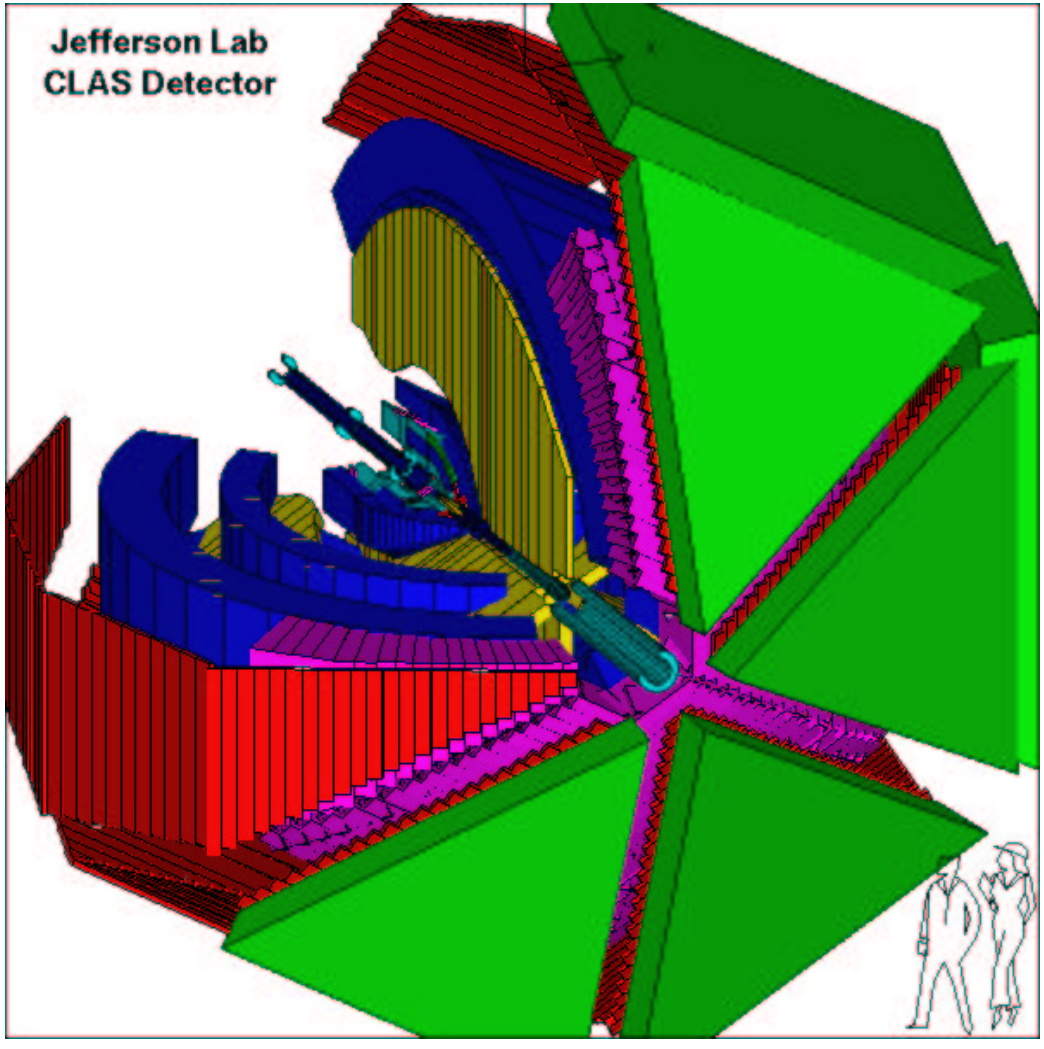
# HERMES MC and result

- 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: final $K^0_s p$ spectrum



# The CLAS spectrometer




$E_e = 2.474, 3.115$ GeV

$10^{-4}$ r.l. radiator

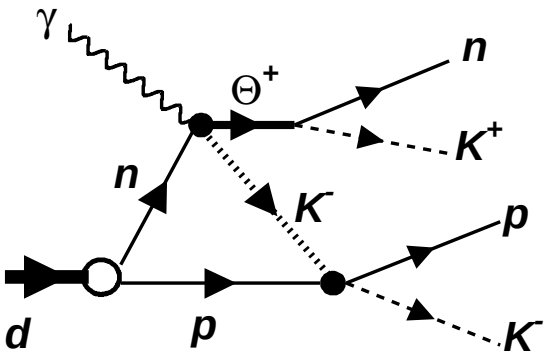
photon tagger

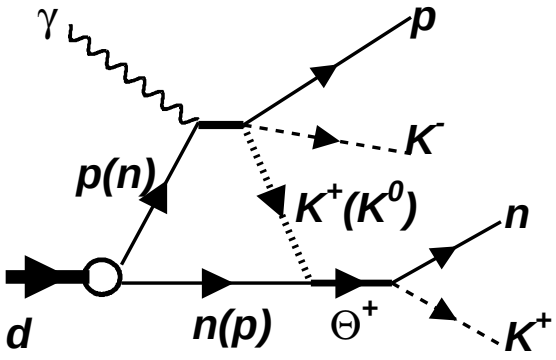
$4 \times 10^6 \gamma$/s

$2.3 \times 10^{12} \gamma > 1.51$ GeV

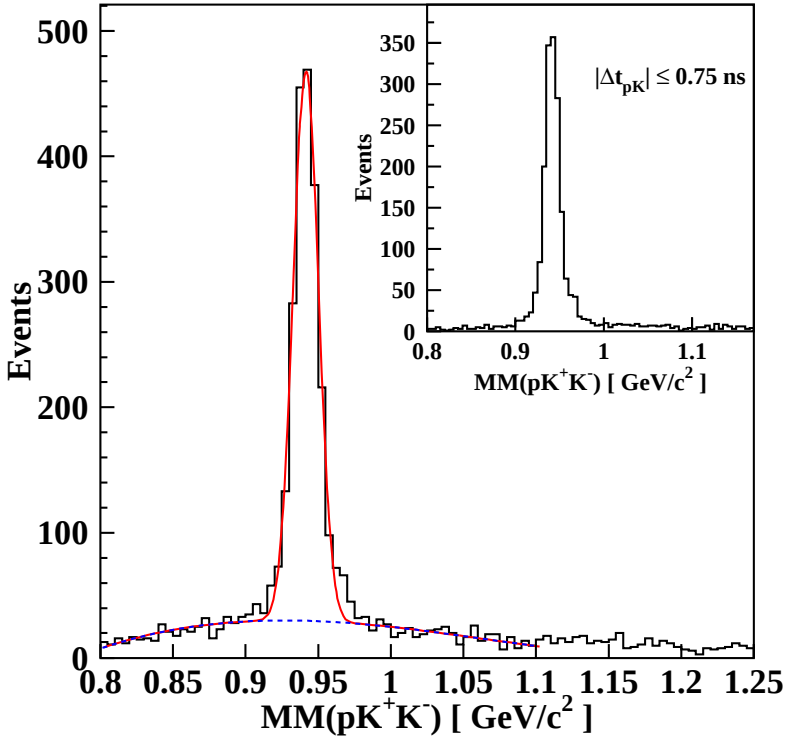
3–5% energy resolution

# CLAS Deuteron

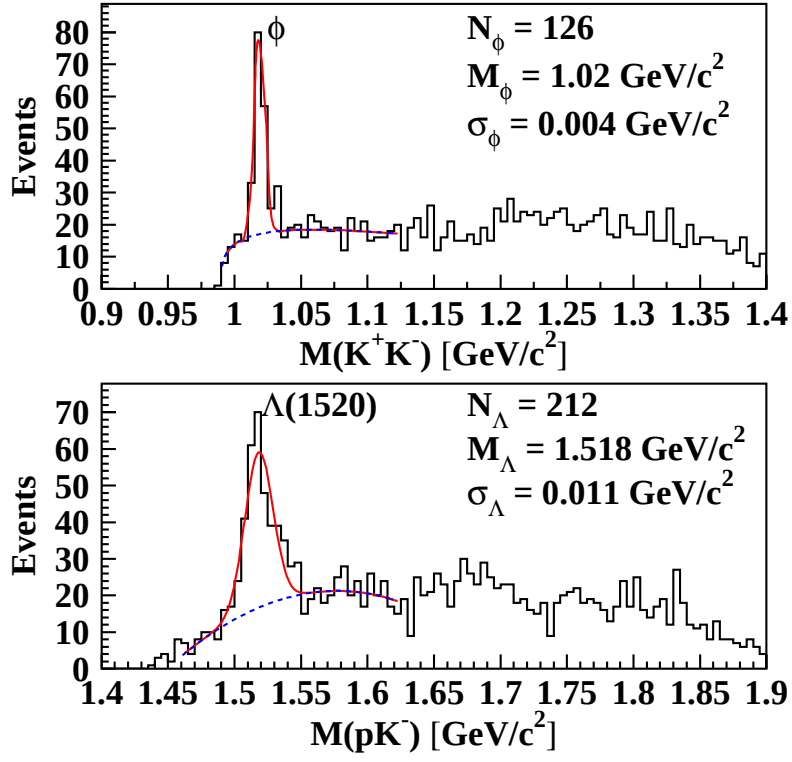


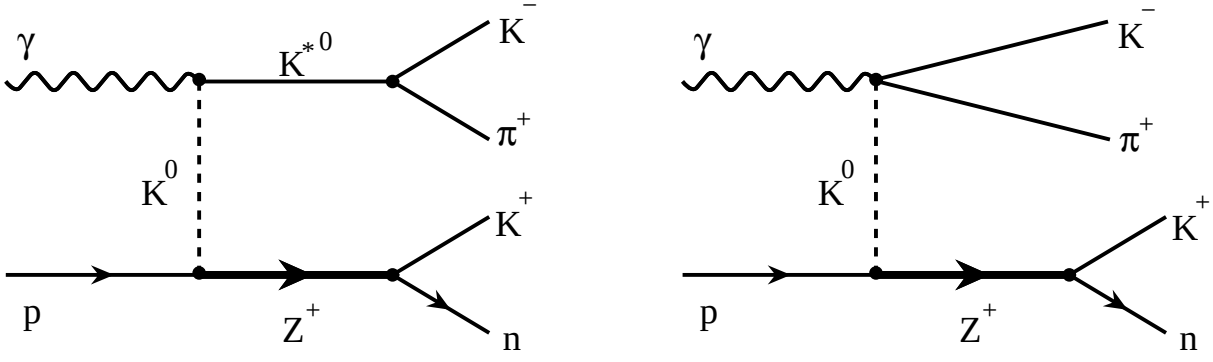

a)



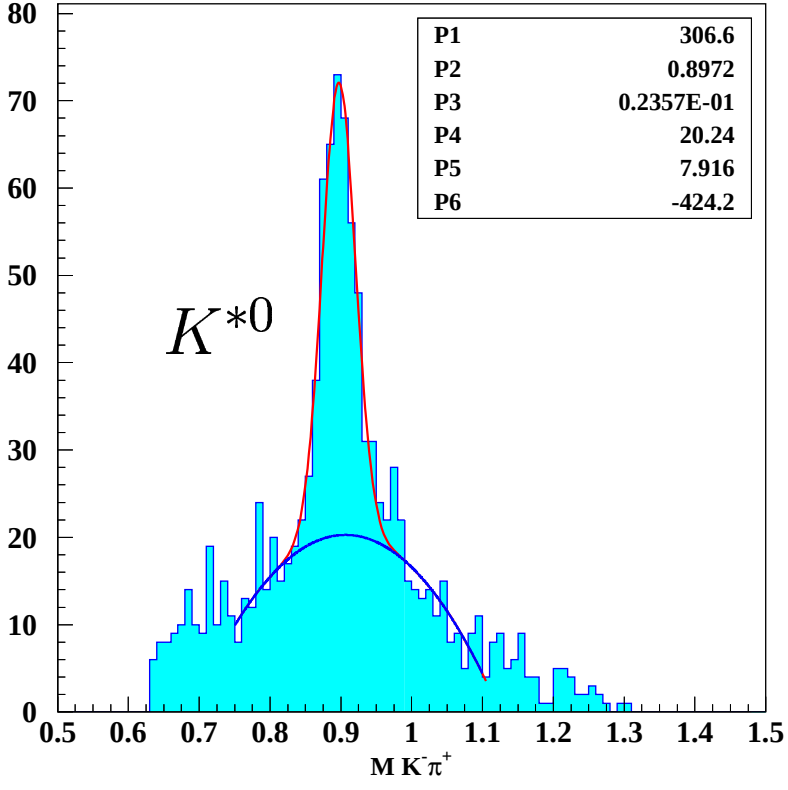

b)

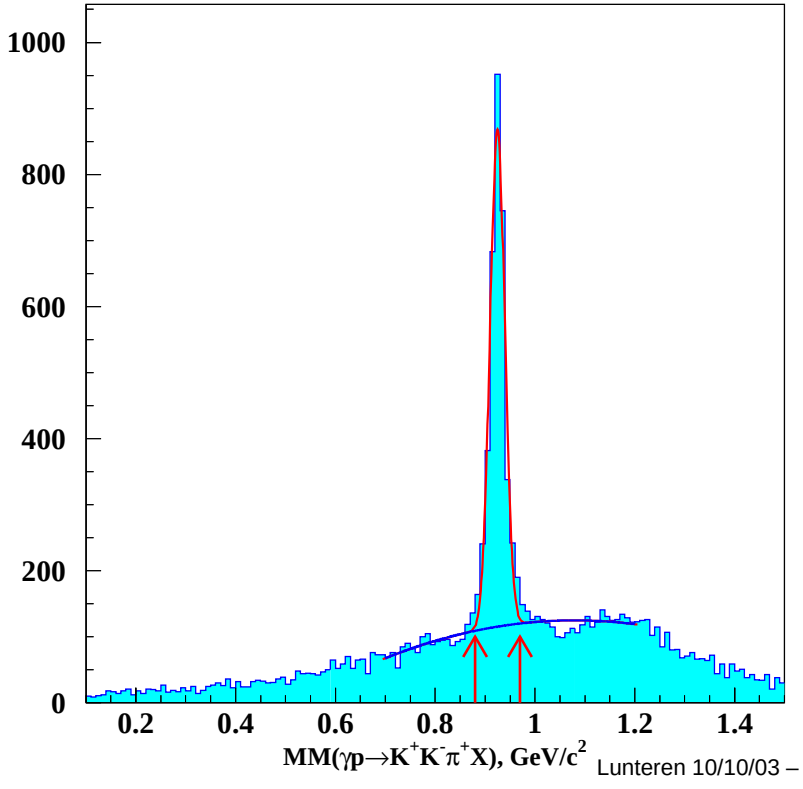


# CLAS Proton



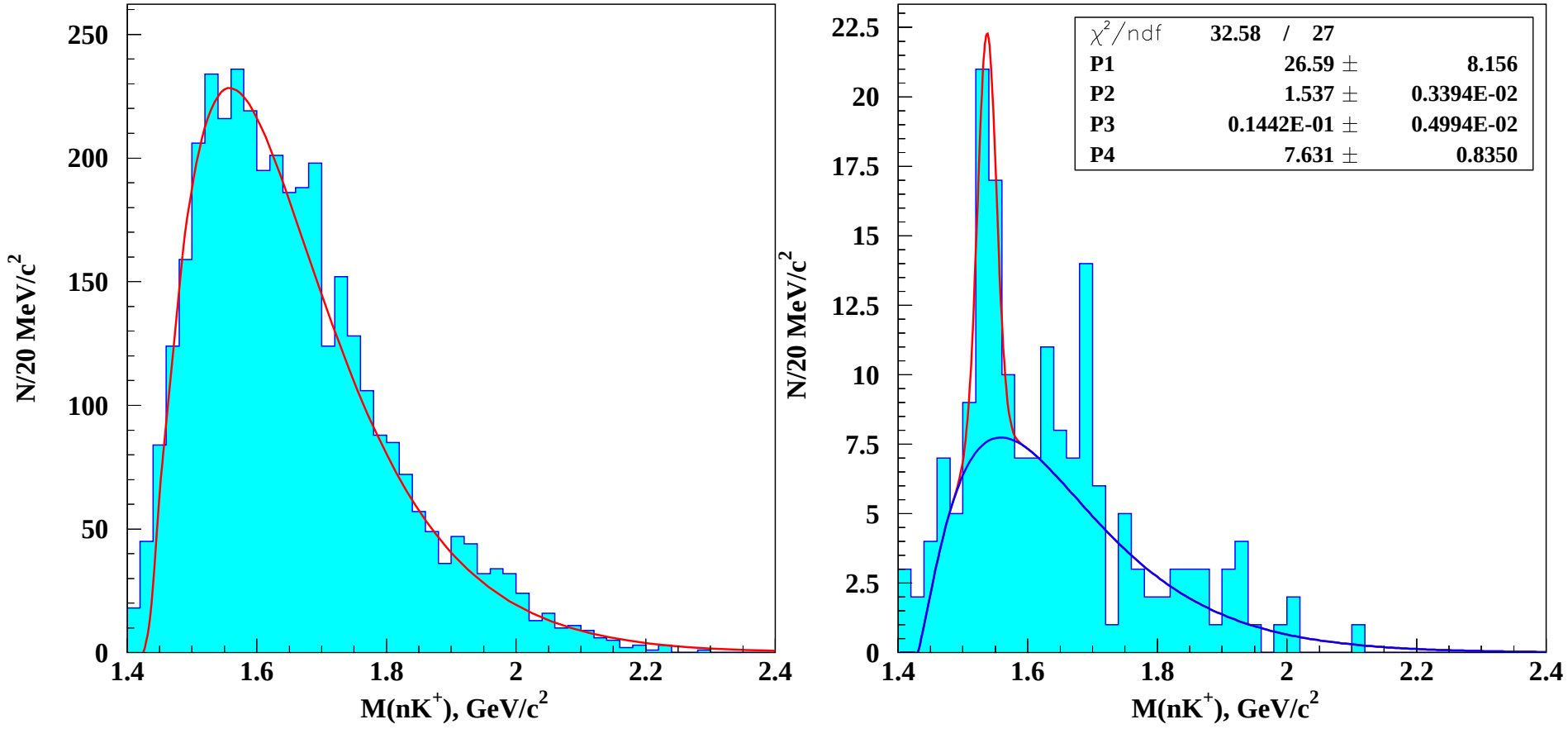

*a)* left: MM $\pi^+K^-$ cut on $n$ *b)* right: MM $\gamma p \to \pi^+K^-K^+X$



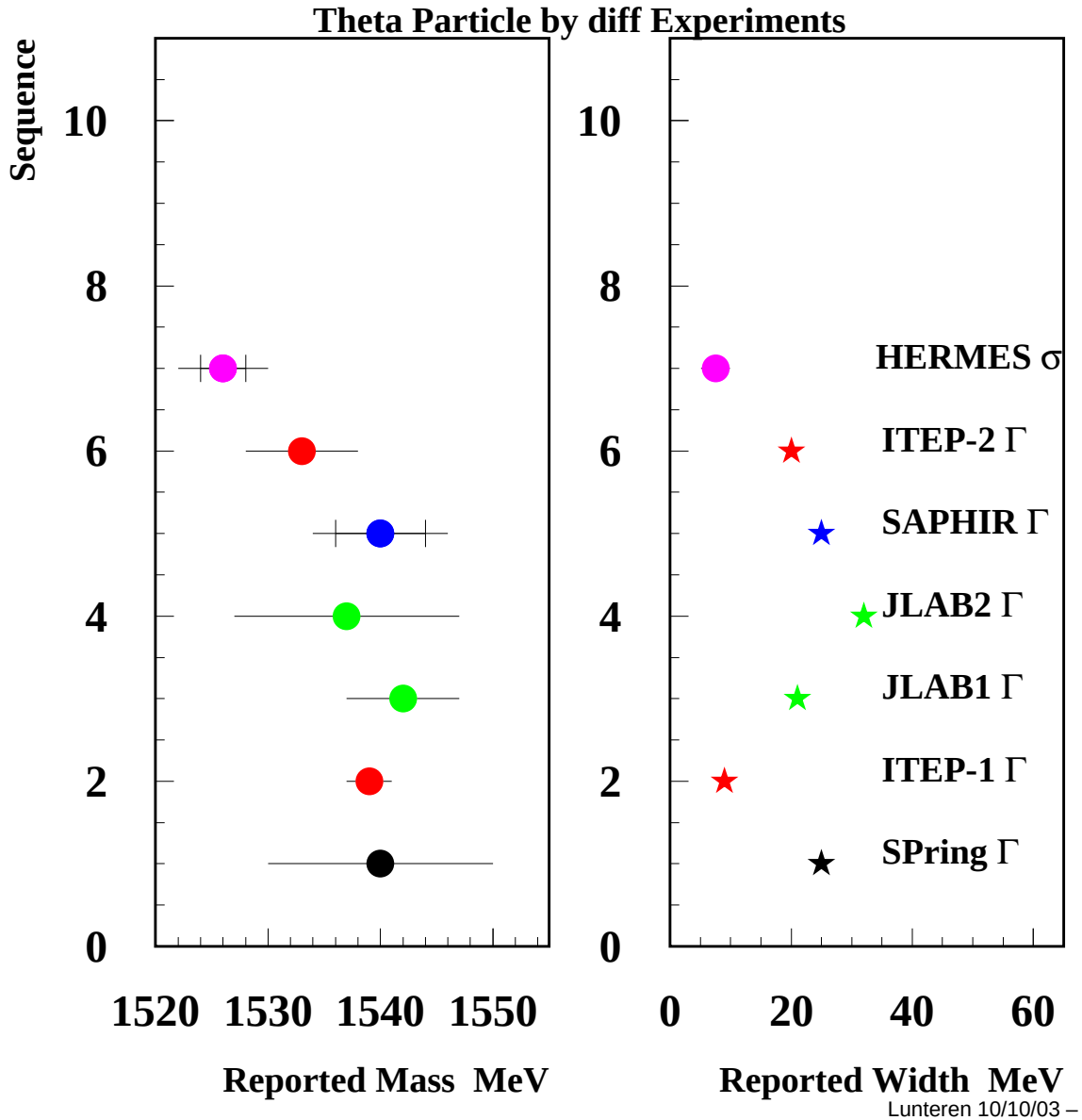



# CLAS Proton

- left: all $\gamma p \to \pi^+ K^- K^+ n$ events
- right: cut on $\cos\theta_{\rm cm}$, the angle between the $(K^-\pi^+)$ system and the $\gamma$



# Comparison of Experiments



# Conclusions

- $uudd\bar{s}$ state seen with mass 1525–1540 MeV.
- Little is known about the quantum numbers.
- Probably $I = 0$: no state in $pK^+$ mass spectrum.
- JLab CLAS E03-113 (Hicks, Stepanyan) approved for 30 days with $20\times$ current statistics.
- Much more data expected from HERMES.
- Theoretical models are rampant. $1700 < M_{\Xi^{--}} < 2100$ MeV.
- The search is on for more pentaquarks.
- CERN NA49 hep-ex/0310014 (8 Oct): first evidence for $ddss\bar{u}$; $N_s/\sqrt{N_b} = 4.0$; $\Xi^{--}$ at $1862 \pm 2$ MeV; $\Gamma < 18$ MeV.