The Θ^+ pentaquark search at HERMES

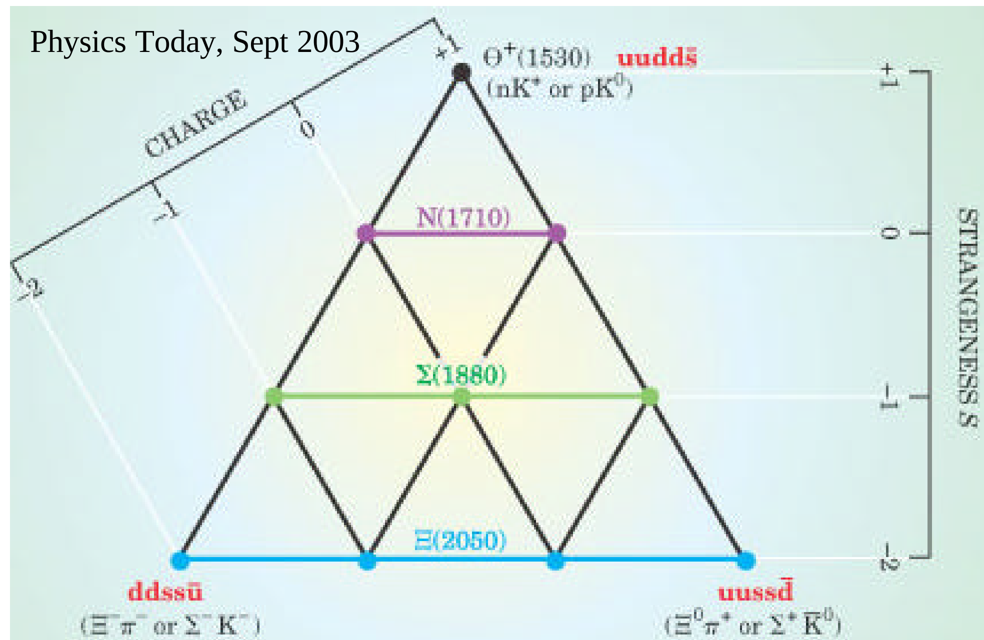
Paul E. Reimer
Argonne National Laboratory

- HERMES
- Pentaquark topology in HERMES
- pK_s mass spectrum
- Comparison with world data

11 Feburary 2004

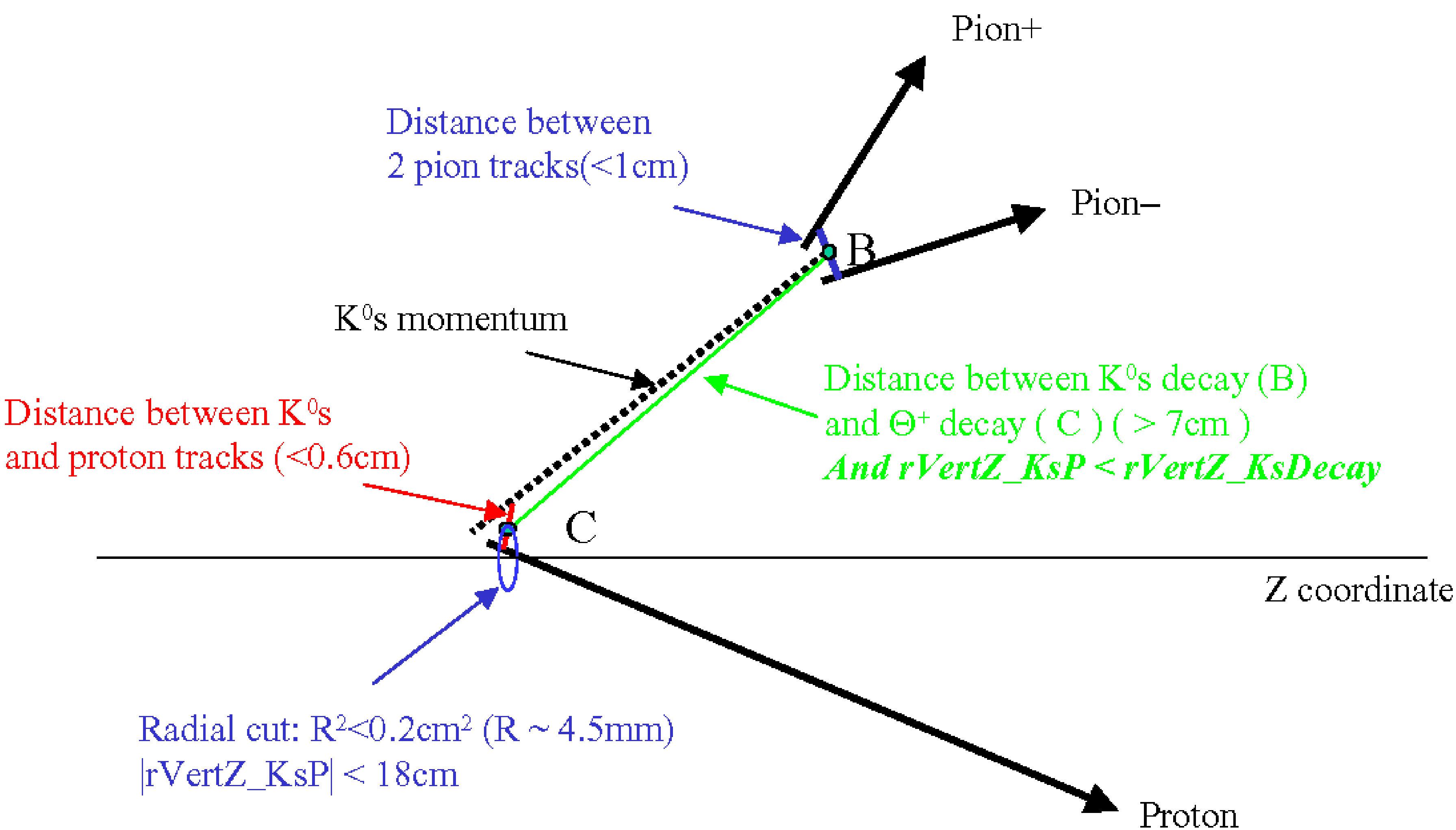
Brief Introduction

- Hadronic matter ⇔ color-neutral groups of quarks.
  - Only two groupings have been observed: Mesons $(q\bar{q})$ and Baryons (qqq)
  - All color-neutral states are allowed (expected?), *e.g.* dibaryons, hybirds, glueballs and pentaquarks
  - Experimental searches failed to observe any signal.
- Chiral Quark Solition Model predicted an anti-decuplet of pentaquarks.
  - Narrow (15-30 MeV)
  - Low mass (1530 MeV)
- Evidence reported by SPring-8, DIANA and CLAS
- HERMES is 6th group to report evidence for the Θ^+ pentaquark
  - quasi-real photo production at high energy on deuterium target in inclusive $ed \to pK_s X$



Corners are manifestly exotic—with an *unpaired* antiquark!

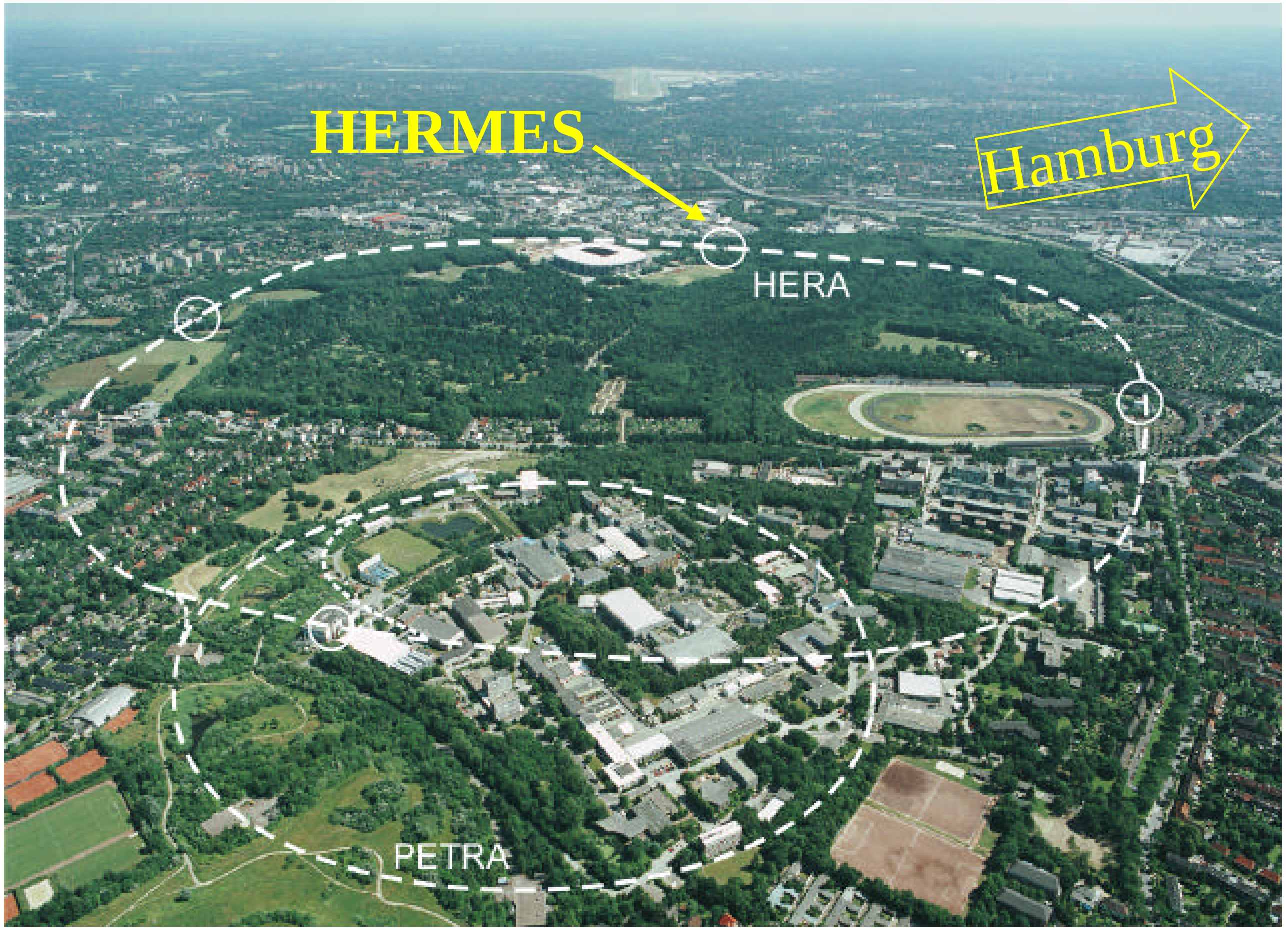
Event Topology: $eN \to pK_sX$, $K_s \to \pi^+\pi^-$



- $\Theta^+ \to pK_s$ decay channel—*not explicitly exotic channel*
- No neutron detection—cannot look in "traditional" nK^+ channel

DESY/HERA facility

- HERMES is located on the DESY-HERA lepton beam line.
- HERA e-p collider
  - 920 GeV protons
  - 26.7 GeV electrons, 9 to 45 mA beam.
- Internal polarized gas target (H, ^{2}H, etc.).
- Electron/Positron beam (polarized)



- Semi-inclusive DIS to determine the parton level spin structure of the proton

HERMES Collaboration

A. Airapetian, N. Akopov, Z. Akopov, M. Amarian, V.V. Ammosov, A. Andrus, E.C. Aschenauer, W. Augustyniak, R. Avakian, A. Avetissian, E. Avetissian, P. Bailey, D. Balin, V. Baturin, M. Beckmann, S. Belostotski, S. Bernreuther, N. Bianchi, H.P. Blok, H. Bottcher, A. Borissov, A. Borysenko, M. Bouwhuis, J. Brack, A. Brull, V. Bryzgalov, G.P. Capitani, T. Chen, X. Chen, H.C. Chiang, G. Ciullo, M. Contalbrigo, P.F. Dalpiaz, W. Deconinck, R. De Leo, L. De Nardo, E. De Sanctis, E. Devitsin, P. Di Nezza, M. Duren, M. Ehrenfried, A. Elalaoui-Moulay, G. Elbakian, F. Ellinghaus, U. Elschenbroich, J. Ely, R. Fabbri, A. Fantoni, A. Fechtchenko, L. Felawka, B. Fox, S. Frullani, G. Gapienko, V. Gapienko, F. Garibaldi, K. Garrow, E. Garutti, D. Gaskell, G. Gavrilov, V. Gharibyan, G. Graw, O. Grebeniouk, L.G. Greeniaus, I.M. Gregor, K. Hafidi, M. Hartig, D. Hasch, D. Heesbeen, M. Henoch, R. Hertenberger, W.H.A. Hesselink, A. Hillenbrand, M. Hoek, Y. Holler, B. Hommez, G. Iarygin, A. Ivanilov, A. Izotov, H.E. Jackson, A. Jgoun, R. Kaiser, E. Kinney, A. Kisselev, M. Kopytin, V. Korotkov, V. Kozlov, B. Krauss, V.G. Krivokhijine, L. Lagamba, L. Lapikas, A. Laziev, P. Lenisa, P. Liebing, L.A. Linden-Levy, K. Lipka, W. Lorenzon, H. Lu, J. Lu, S. Lu, X. Lu, B.Q. Ma, B. Maiheu, N.C.R. Makins, Y. Mao, B. Marianski, H. Marukyan, F. Masoli, V. Mexner, N. Meyners, O. Mikloukho, C.A. Miller, Y. Miyachi, V. Muccifora, A. Nagaitsev, E. Nappi, Y. Naryshkin, A. Nass, M. Negodaev, W.D. Nowak, K. Oganessyan, H. Ohsua, N. Pickert, S. Potashov, D.H. Potterveld, M. Raithel, D. Reggiani, P.E. Reimer, A. Reischl, A.R. Reolon, C. Riedl, K. Rith, G. Rosner, A. Rostomyan, L. Rubacek, J. Rubin, D. Ryckbosch, Y. Salomatin, I. Sanjiev, I. Savin, A. Schafer, C. Schill, G. Schnell, K.P. Schuler, J. Seele, R. Seidl, B. Seitz, R. Shanidze, C. Shearer, T.A. Shibata, V. Shutov, M.C. Simani, K. Sinram, M. Stancari, M. Statera, E. Steffens, J.J.M. Steijger, H. Stenzel, J. Stewart, F. Stinzing, U. Stosslein, P. Tait, H. Tanaka, S. Taroian, B. Tchuiko, A. Terkulov, A. Tkabladze, A. Trzcinski, M. Tytgat, A. Vandenbroucke, P. van der Nat, G. van der Steenhoven, M.C. Vetterli, V. Vikhrov, M.G. Vincter, C. Vogel, M. Vogt, J. Volmer, C. Weiskopf, J. Wendland, J. Wilbert, G. Ybeles Smit, Y. Ye, Z. Ye, S. Yen, W. Yu, B. Zihlmann, H. Zohrabian, P. Zupranski

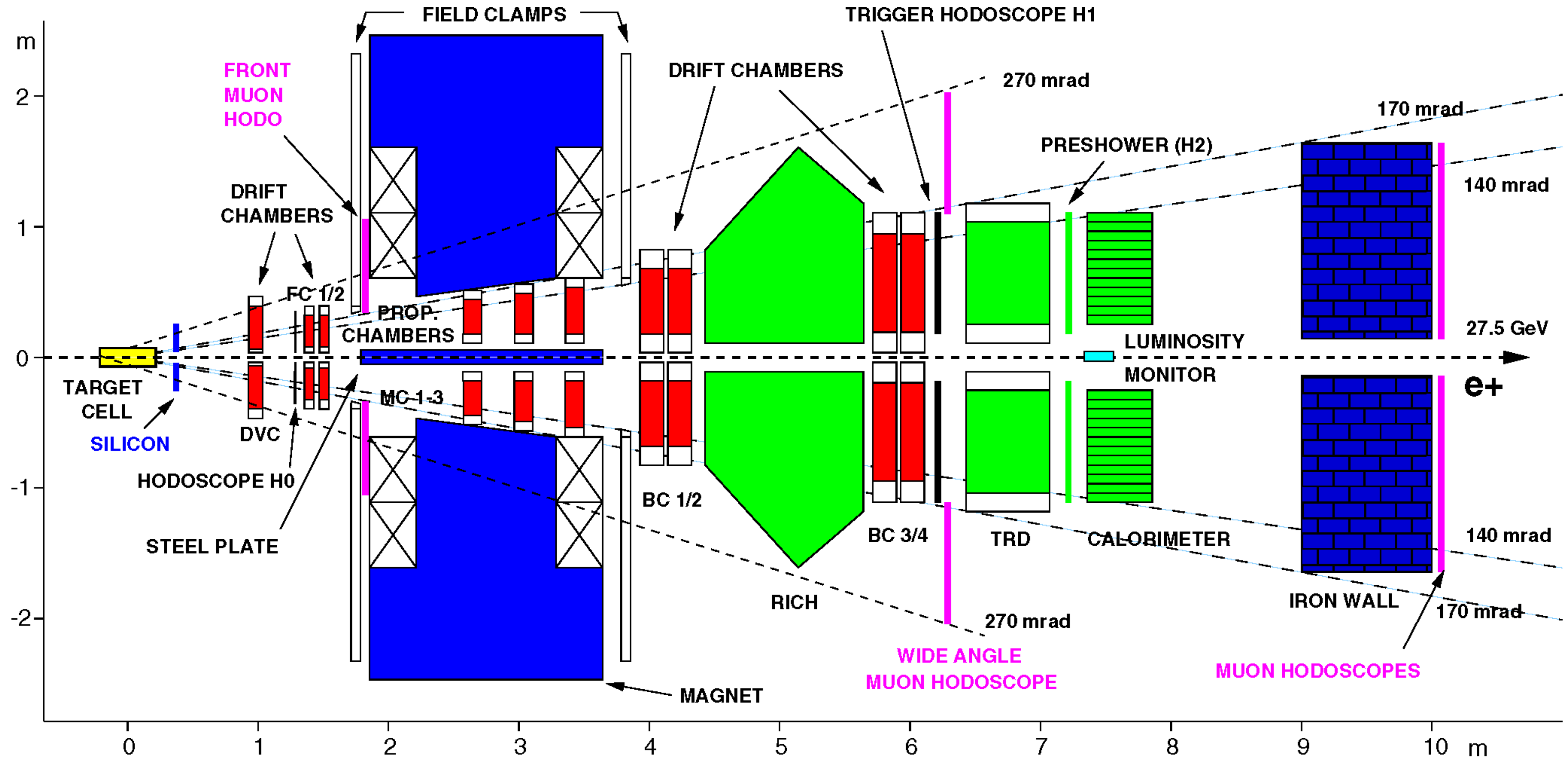
HERMES Collaboration

HERMES:

- HERa MEasurement of Spin
- Study the spin structure of the nucleon.
- 28 institutions

Alberta	Argonne	Bari
Beijing	Colorado	DESY-Hamburg
DESY-Zeuthen	Erlangen	Ferra
Gent	Glasgow	Geissen
Illinois	INFN-Frascati	INFN-Rome
JINR-Dubma	Barburg	MIT
Moscow	Munich	NIKHEF
Provinto	Regensburg	S. Petersburg
Tokyo	TRIUMF	Warsaw
	Yerevan	

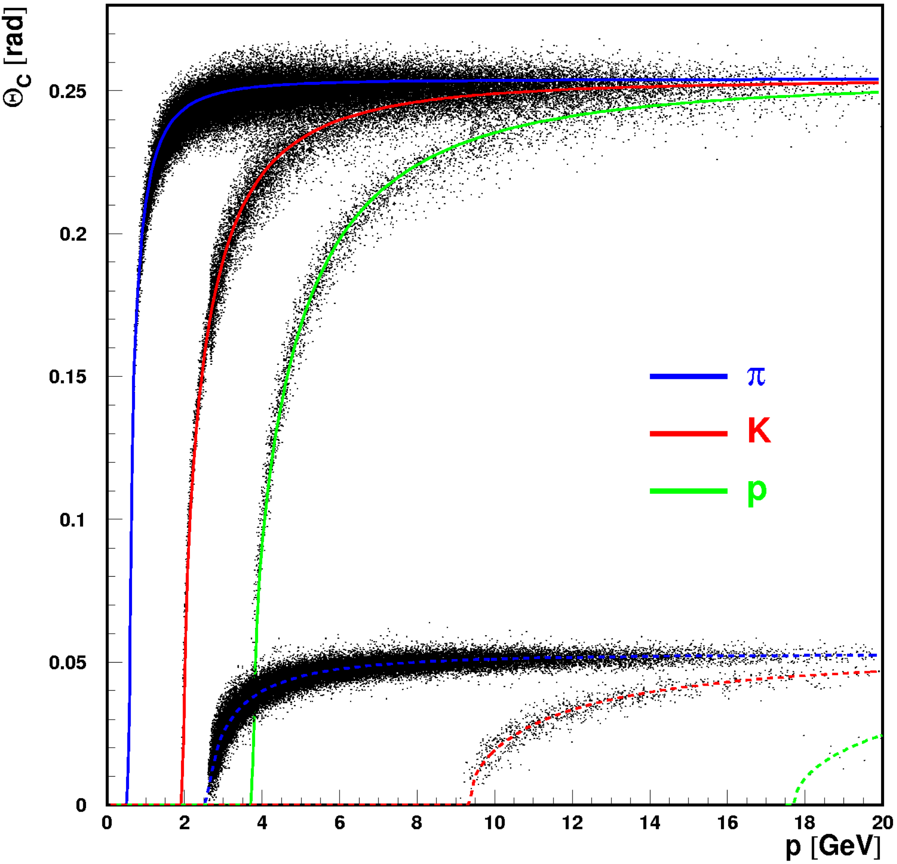
HERMES Spectrometer

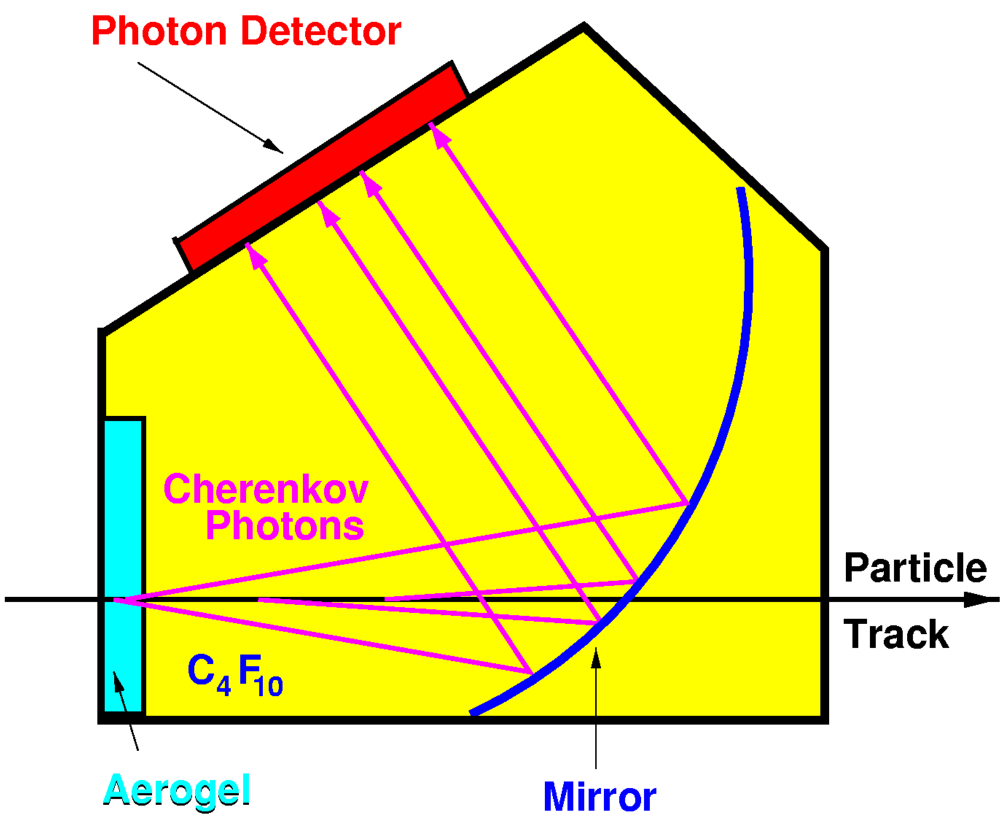


- Internal, longitudinally polarized gas target (averaged over polarization)
- ^{2}H target, $\rho_{Target} = 8{\cdot}10^{13}$ atoms/cm^2
- $\int L_0 dt = 250$ pb^{-1}
- $\pi^{\pm}$, $K^{\pm}$, proton id. with RICH

- Coincidence of scintillator hodoscopes, preshower counter and Pb-glass Calo.
- Coincidence between three scintillation hodoscopes, and two tracking planes.

Particle Identification: Rich





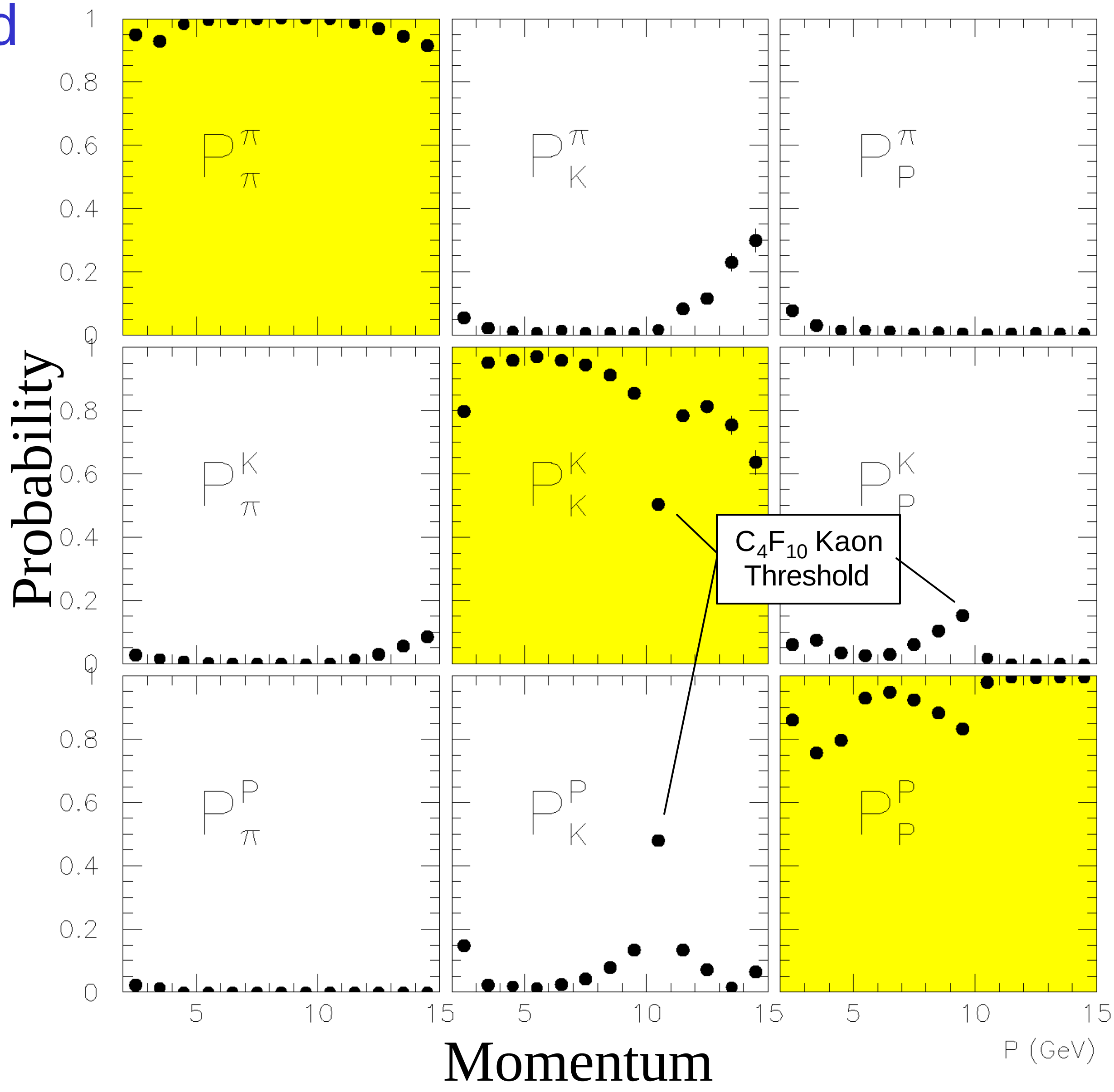
- Dual radiator rich (Aerogel and C_4F_{10})
- K, π, proton separation for 1 < p < 15 GeV/c

Particle Identification: Rich

- RICH identification and performance sensitive to event topology
- Monte Carlo based on Pythia6 used to determine efficiencies for "pentaquark" topology
- Negligible cross contamination for

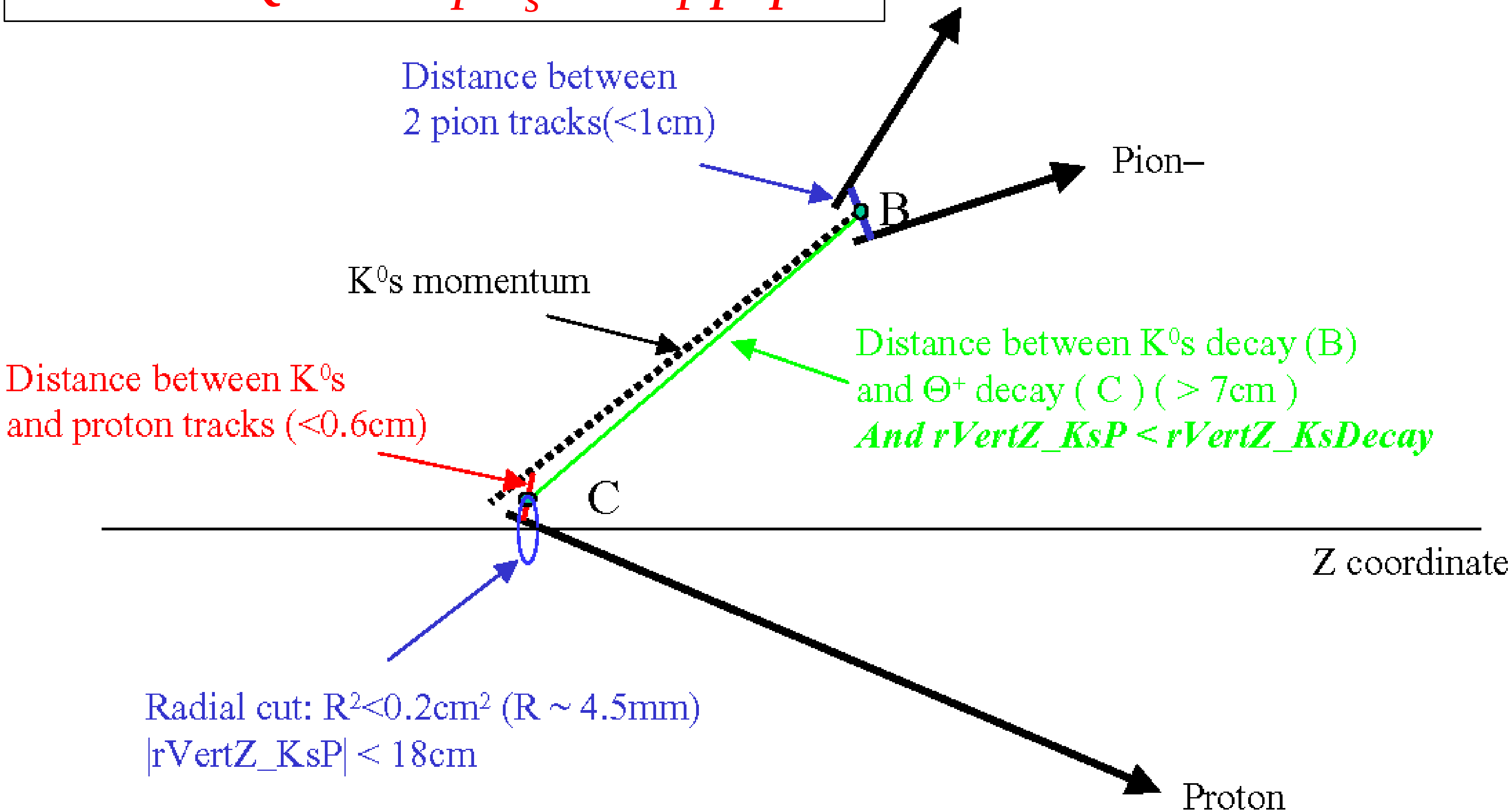
  $1 < p_\pi < 15$ GeV/c

  $4 < p_p < 9$ GeV/c



Event topology

$e^{+}\ {}^{2}H \rightarrow Q^{+}\ X \rightarrow pK_{s}\ X \rightarrow pp^{+}p^{-}\ X$

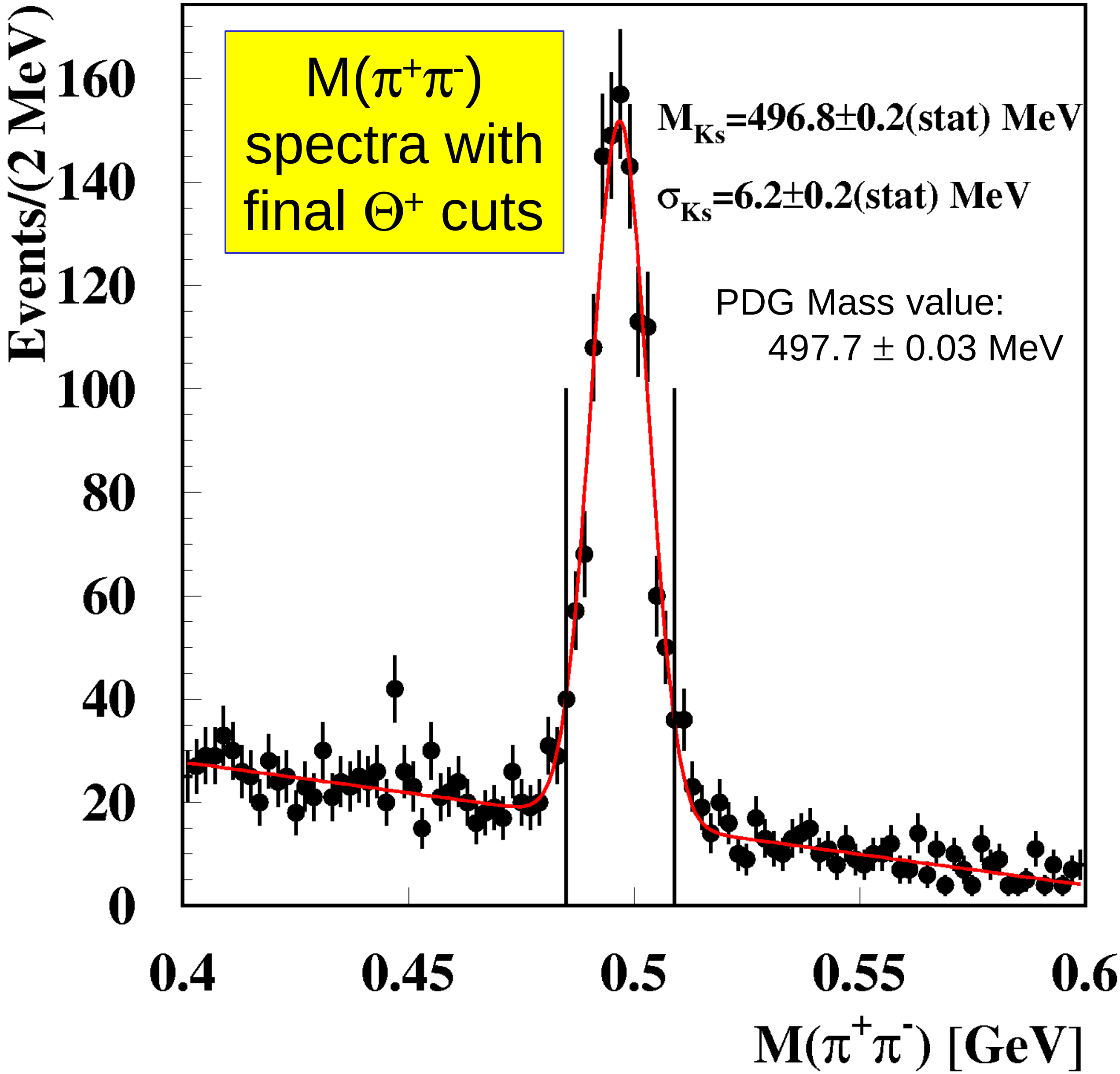


Events in which M(pπ⁻) = M[Λ(1116)] were removed.

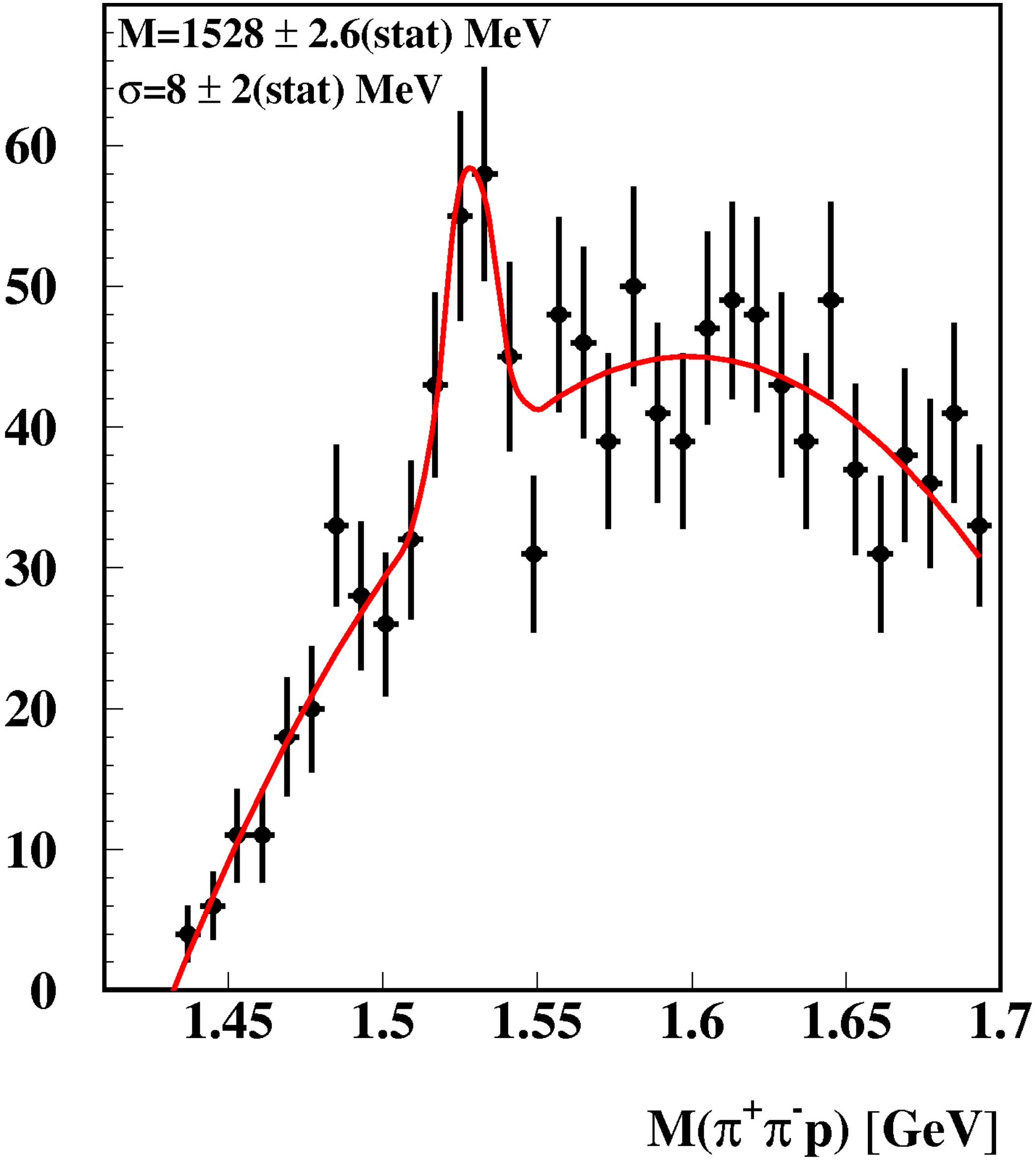
K_s reconstruction

- Cuts were tuned to maximize K_s yield and minimize K_s bkg.
- Select events within $\pm 2\sigma$ of K_s peak

- Cuts were ***not*** optimized based on $M(p\pi^+\pi^-)$ spectra.



M(pπ⁺π⁻) Distribution

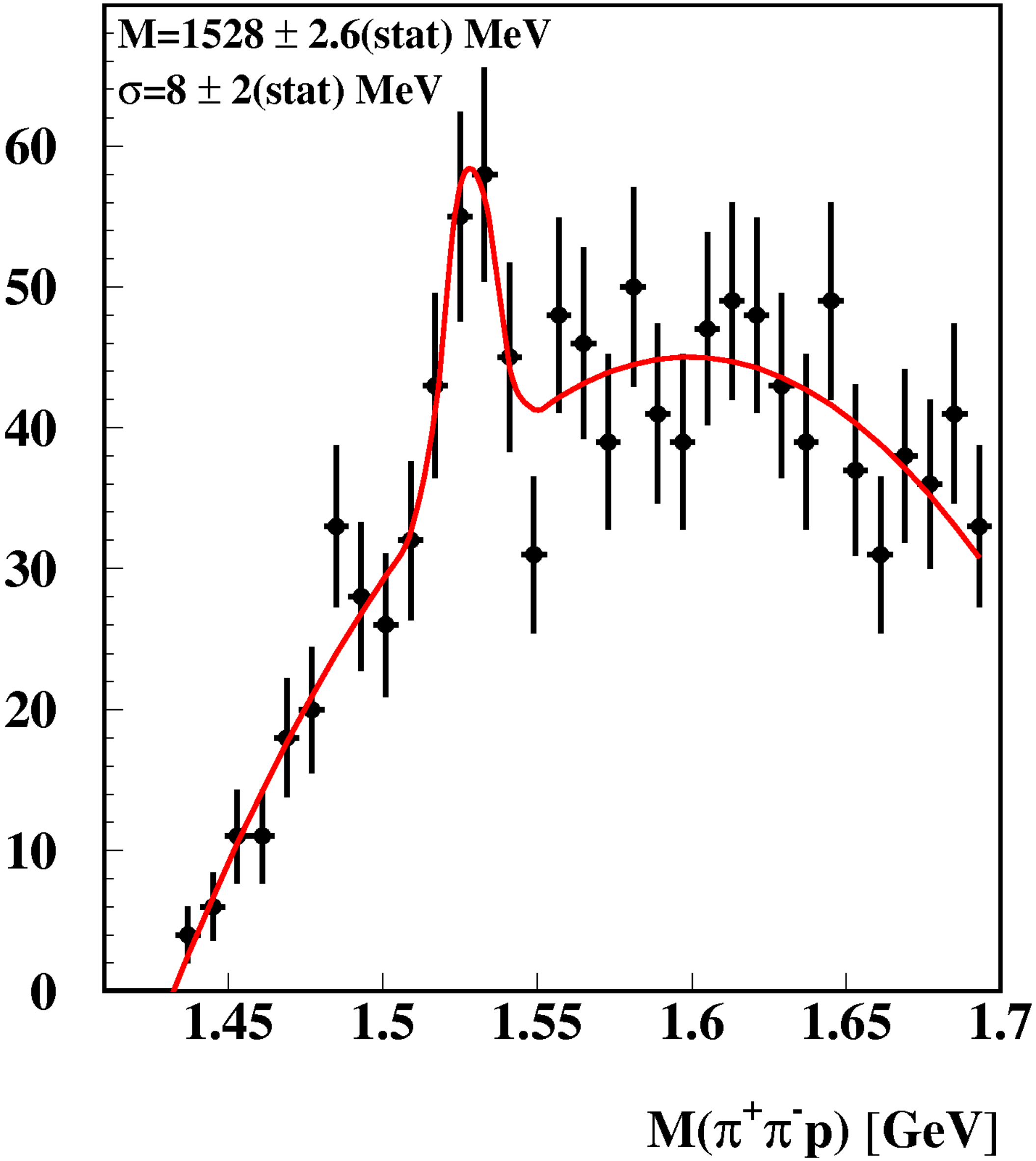


- Enhancement is observed:
  - Mass 1528 MeV
  - Width (σ) 7.5 MeV
- No known positively-charged, strange baryon in this region.
- Naïve significance of 4-6σ
- Alternative mass definition which assumes known K_s mass:

$$M'^{\,2}_{pK^0_s} \equiv \left(\sqrt{M_p^2 + p_p} + \sqrt{M_{K^0_s}^2 + p_{K^0_s}}\right)^2 - \left(p_p + p_{K^0_s}\right)^2$$

Better mass resolution by removing *some* of the experimental uncertainty from K_s reconstruction.

M(pπ⁺π⁻) fit and background

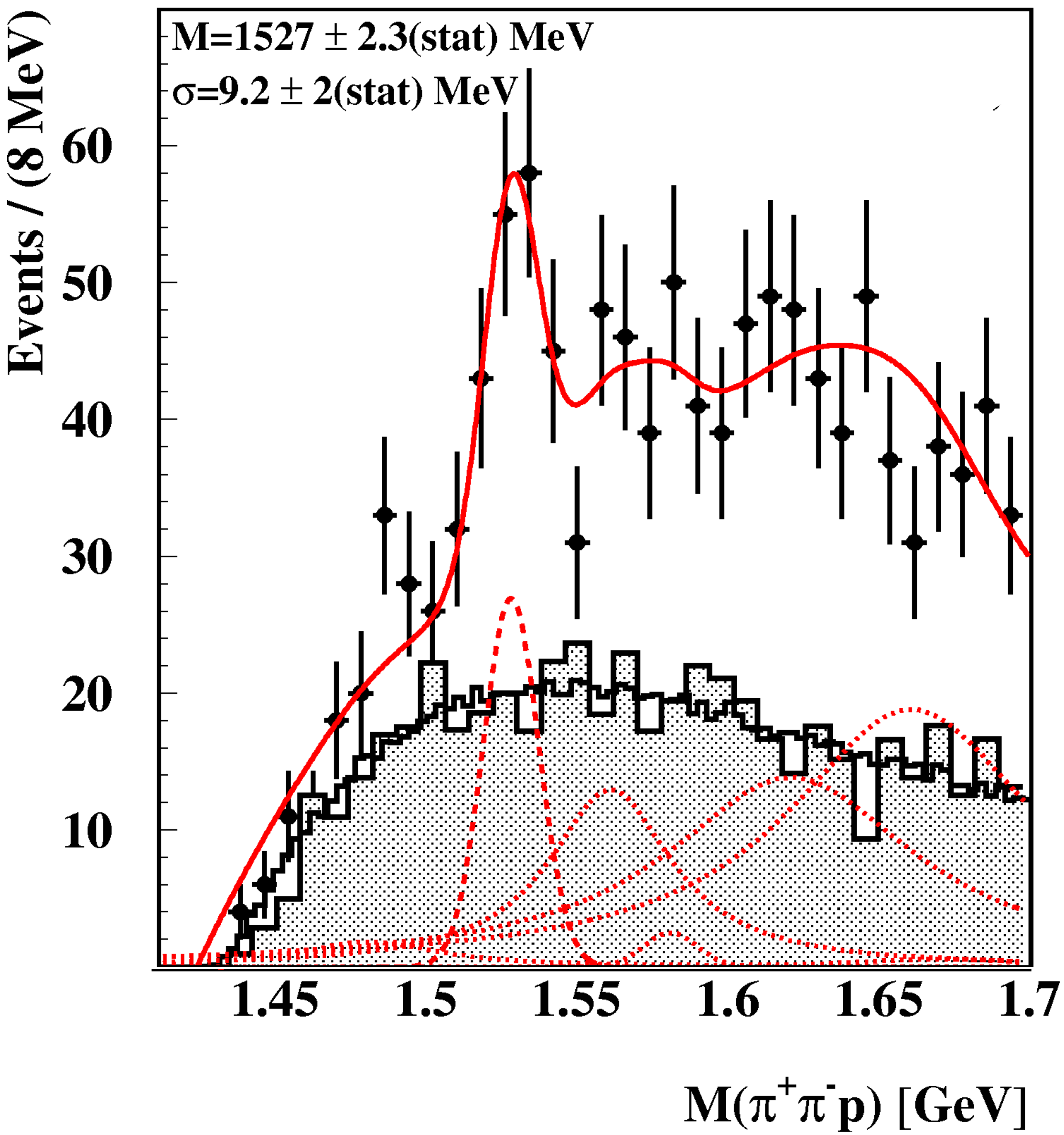


- All fits used **unbinned** maximum likelihood method—no bias from bin width or location.

Polynomial Background

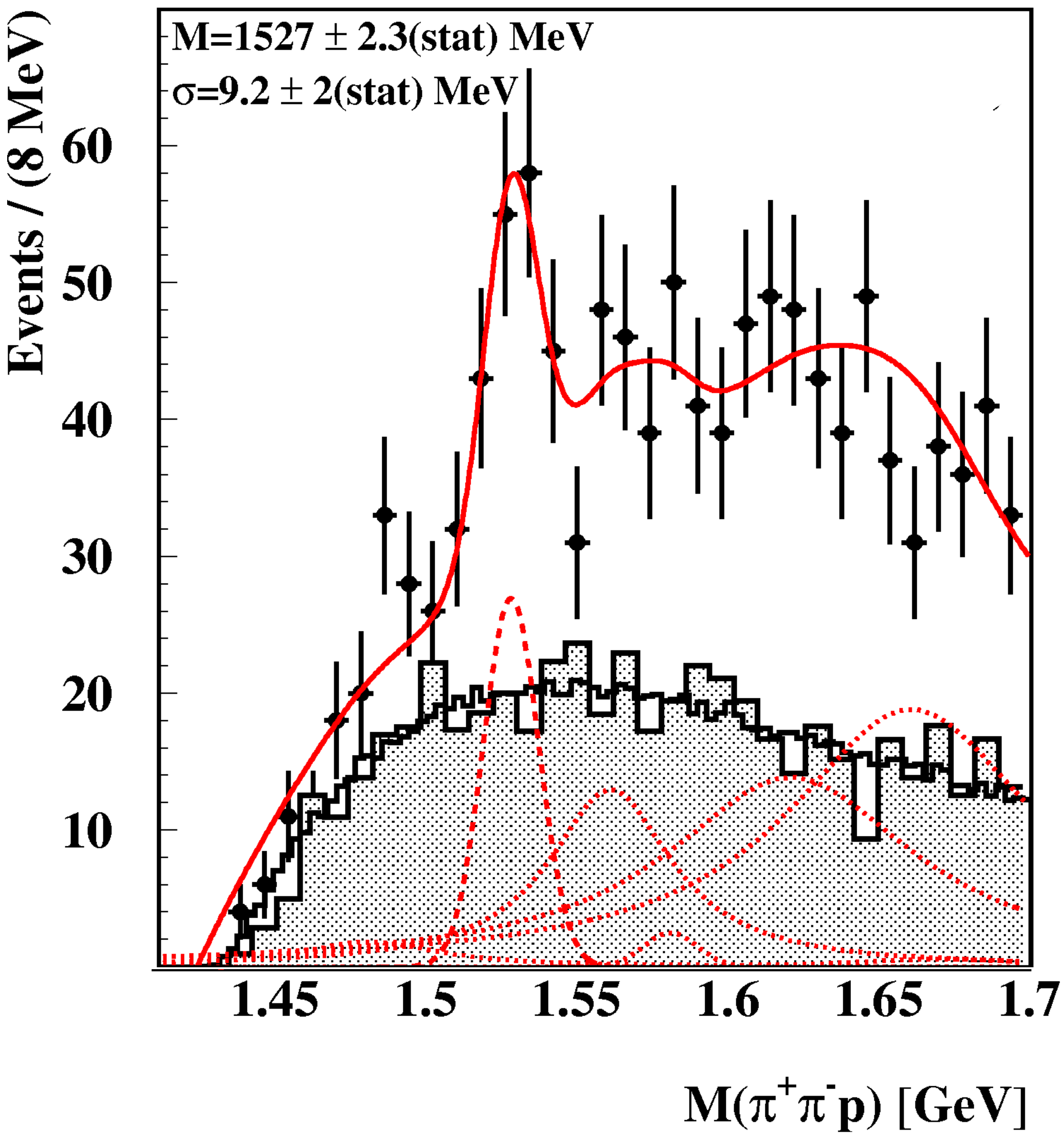
- Orthonormal Chebyshev polynomials
- Fit included up to 3rd order Chebyshev polynomials
- Referred to as "fit b"

Background: PYTHIA6, Mixed Events



- Hatched—PYTHIA6 Monte Carlo (luminosity normalized)
- Solid—Mixed event bkg. (normalized to PYTHIA6)
  - reproduces PYTHIA6 shape.
- PYTHIA6 *does not include* excited Σ^* hyperons in this region. PDG lists many such resonances!

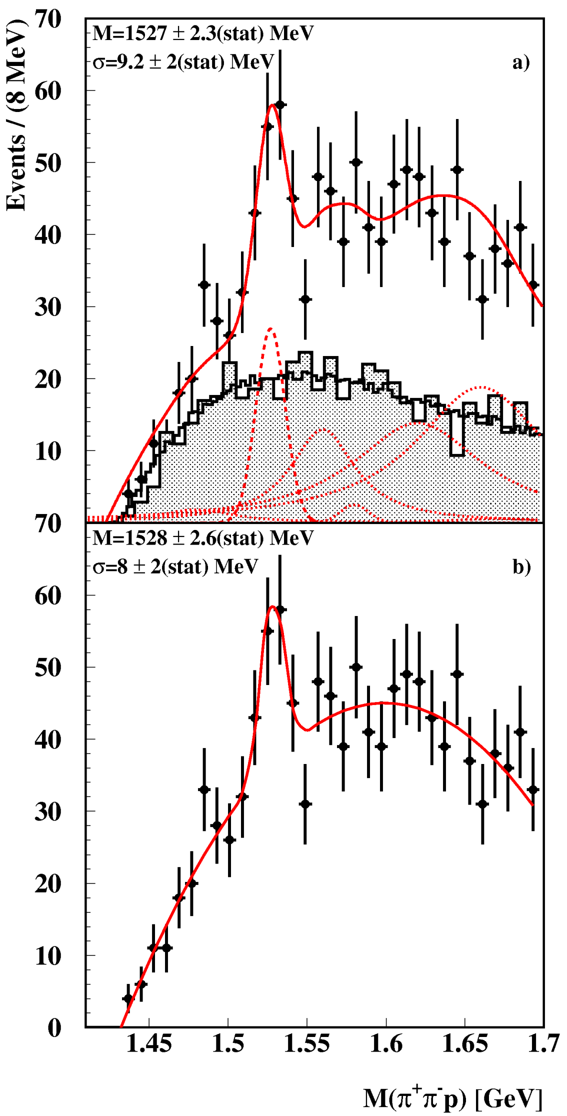
Background: PYTHIA6, Mixed Events



Mass (MeV)	Γ (MeV)	PDG Status
1480	55	*
1560	47	**
1580	13	**
1620	100	***
1660	100	***
1670	60	****

- Mass and width fixed at PDG values.
- Strength of resonance treated as a free parameter.

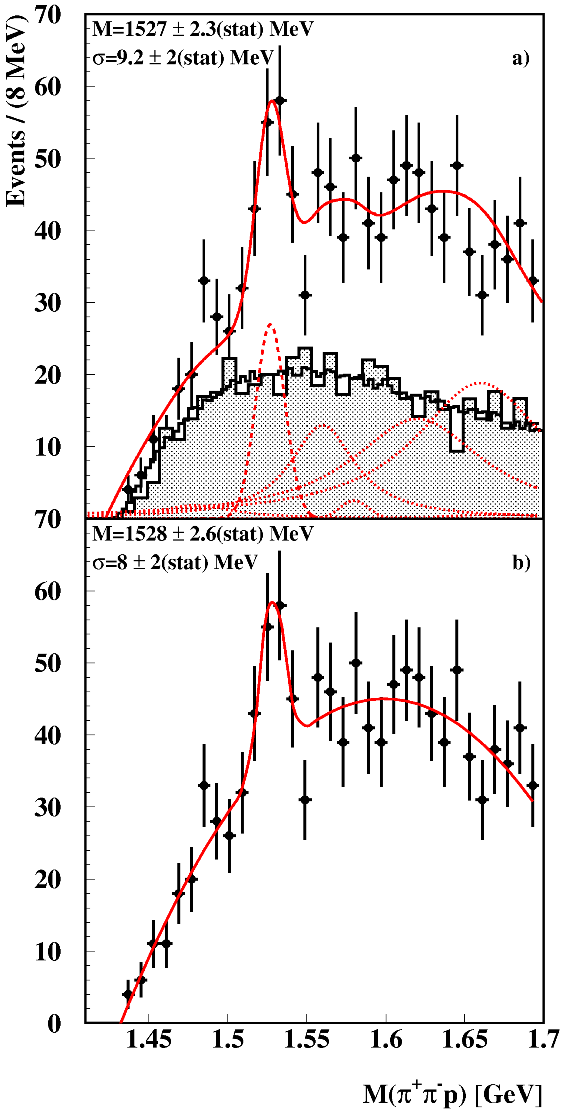
Fit Results



Fit	Θ^+ Mass (MeV)	FWHM (MeV)	Significance Naïve	Significance Actual
a	1527.0±2.3±2.1	22±5±2	6.1σ	4.3σ
a′	1527.0±2.5±2.1	24±5±2	6.3σ	4.2σ
b	1528.0±2.6±2.1	19±5±2	4.7σ	3.7σ
b′	1527.8±3.0±2.1	20±5±2	4.2σ	3.4σ

- Mass:
  - 1528 ± 2.6 ± 2.1 MeV
  - Less than world average
- Width:
  - 19±5±2 MeV
  - *Possibly* larger than experimental resolution
- Significance:
  - 3.4-4.3σ Actual significance
  - Naïve vs. Actual

Fit Results and Significance



- Naïve significance:
  - $N_{signal} / (N_{bkg})^{1/2}$
  - Events are counted within a 2σ window of the centroid of the peak.
- Improved significance:
  - $N_{signal} / (N_{bkg} + \delta N_{bkg})^{1/2}$
  - Frequently used by statistics books, but requires knowledge of the background shape and uncertainty.
- Actual significance:
  - $N_{signal} / \delta N_{signal}$
  - N_{signal} and δN_{signal} determined from the overall fit.
  - δN_{signal} is fully correlated uncertainty
  - measures peak's difference from 0 in terms of its own uncertainty.

3.4-4.4 s Actual Significance

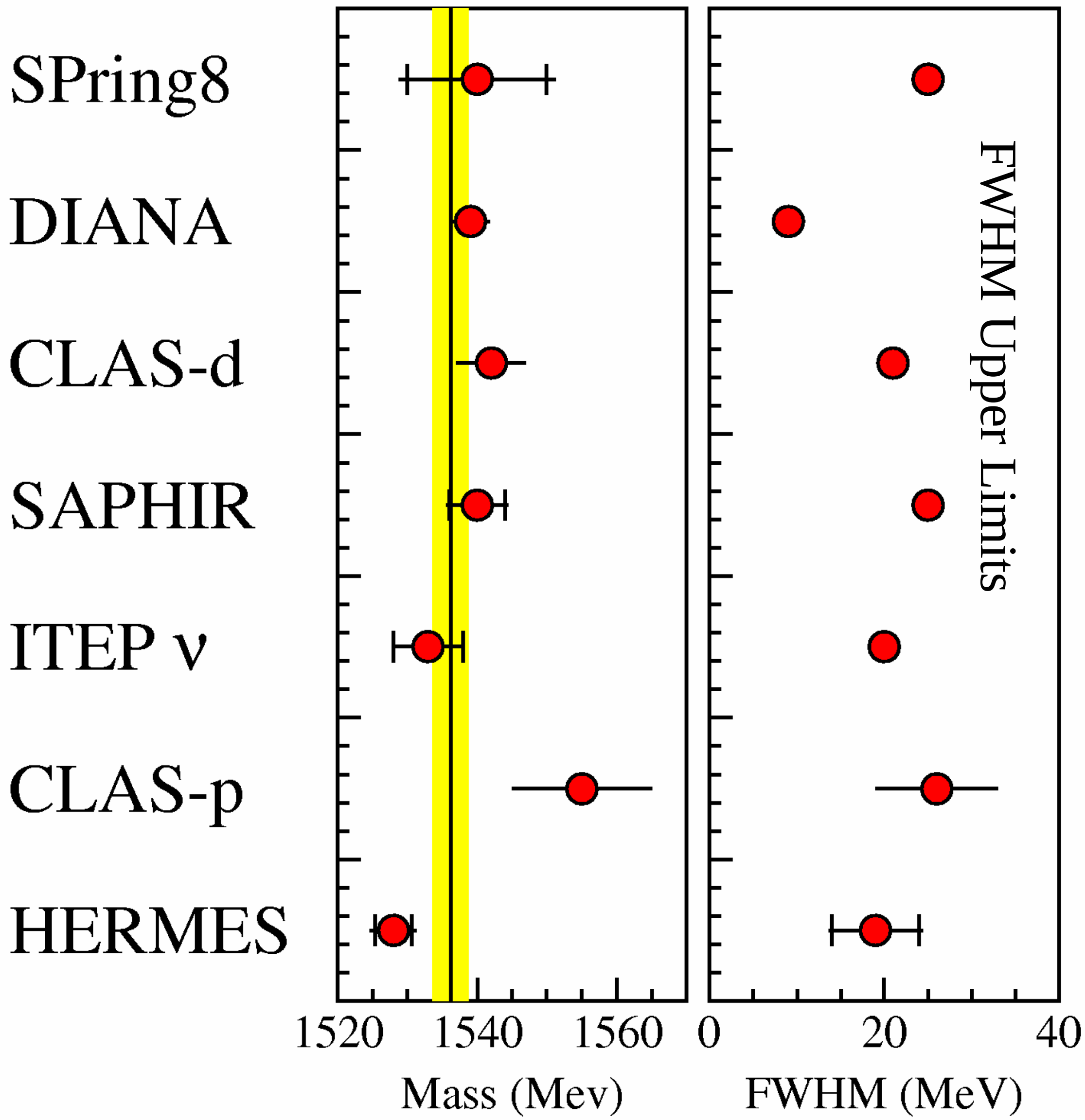
Mass: Comparison with other Expts

M(Θ⁺)

- HERMES
  1528 ± 2.6 ± 2.1 MeV
- World Average
  1536.2 ± 2.6 MeV

Width(Θ⁺)

- World data:
  FWHM < 20 MeV
- HERMES:
  FWHM = 19 ± 5 ± 2 MeV
  – *Possibly* larger than instrumental resolution from MC of apparatus.



Θ^+ Mass: Other resonances

	$K_s \to \pi^+\pi^-$	$\Lambda(1116) \to p\pi^-$	$\Lambda(1520) \to pK^-$	$\Xi^-(1321) \to p\pi^-\pi^-$
Obs. Mass (MeV)	496.8±0.2	1115.70±0.01	1522.7±1.9	1321.5±0.3
PDG Mass (MeV)	497.67	1115.68	1519.5±1.0	1321.31±0.13
Width—data (σ MeV)	6.2±0.2	2.6± 0.1	4.4±3.7	3.1±0.3
Width—MC (σ MeV)	5.4	2.1	3.5	2.5
Decay p_{CM} (MeV)	206	101	244	139 ($\Lambda\pi^-$)

- Masses of known particles are well reproduced
- Estimate systematic uncertainty of ±1.9 MeV

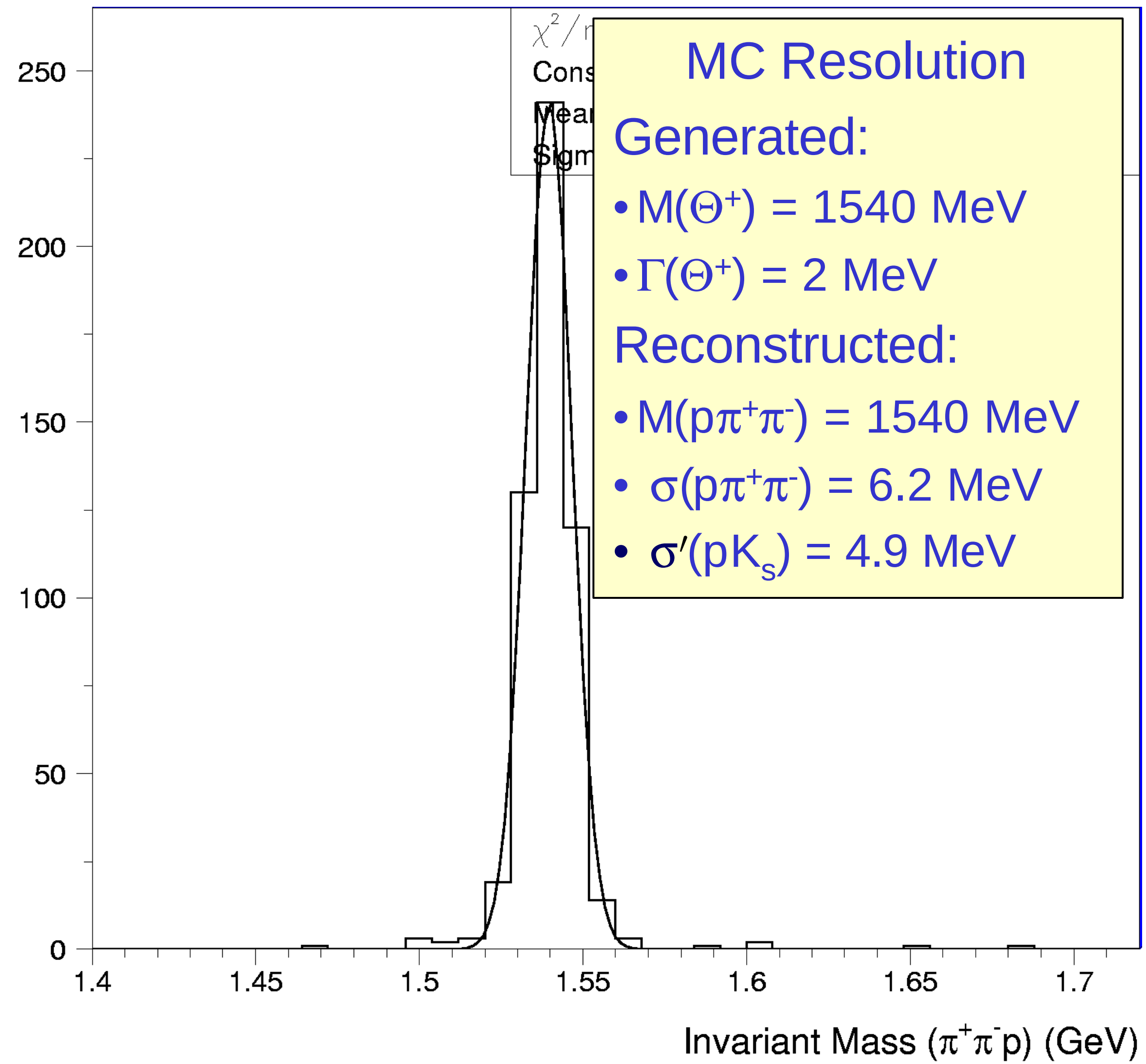
- Widths are reasonably estimated (well slightly underestimated) by the Monte Carlo

Θ^+ "toy" Monte Carlo

- No model of pentaquark photoproduction
- HERMES "toy" model:
  - p_z falling distribution similar to observed Λ distribution in HERMES
  - p_T Gaussian, σ = 0.4 GeV, typical of parton p_T and similar to Λ distribution in HERMES
  - Accept($\Theta^+ \rightarrow pK_s$) $\approx$ 0.05%
  - $\sigma(\Theta^+) \approx$ 100-200 nb $\pm$ 25%
- Refit data with Breit-Wigner convoluted with Gaussian (width fixed at simulated resolution)

G(Q$^+$) = 17 $\pm$ 9 $\pm$ 3 MeV

(Ave. of a′ and b′ fits)



MC Resolution

Generated:
- $M(\Theta^+)$ = 1540 MeV
- $\Gamma(\Theta^+)$ = 2 MeV

Reconstructed:
- $M(p\pi^+\pi^-)$ = 1540 MeV
- $\sigma(p\pi^+\pi^-)$ = 6.2 MeV
- $\sigma'(pK_s)$ = 4.9 MeV

Caveat: No other resonance with equivalent topology to cross check Monte Carlo

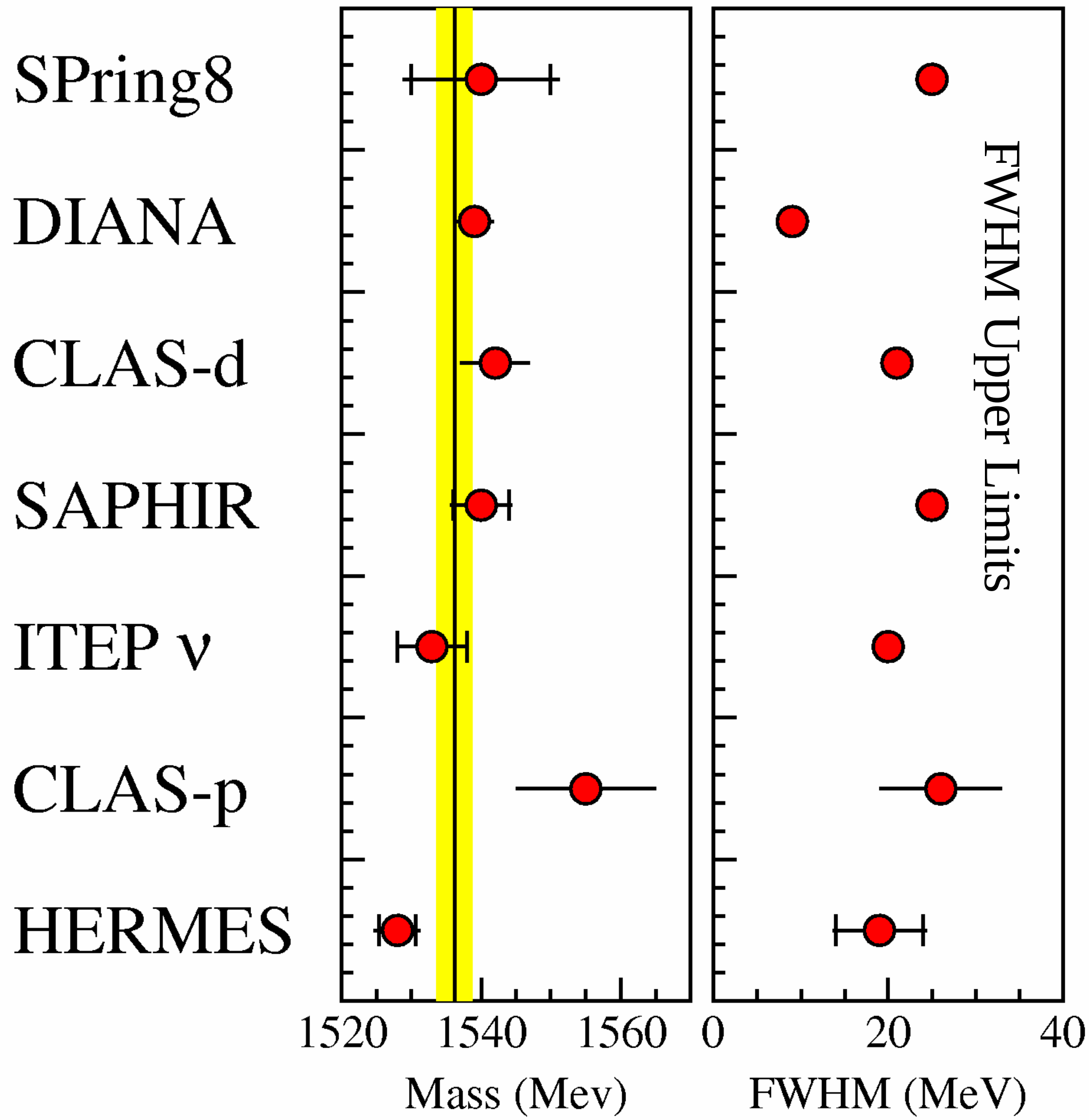
Mass: Comparison with other Expts

M(Θ⁺)

- HERMES
  1528 ± 2.6 ± 2.1 MeV
- World Average
  1536.2 ± 2.6 MeV

Width(Θ⁺)

- World data:
  FWHM < 20 MeV
- HERMES:
  – Fit to data:
  FWHM = 19 ± 5 ± 2 MeV
  – ***Possibly*** larger than instrumental resolution from MC of apparatus.



Θ^+ Mass: Other resonances

	$K_s \to \pi^+\pi^-$	$\Lambda(1116) \to p\pi^-$	$\Lambda(1520) \to pK^-$	$\Xi^-(1321) \to p\pi^-\pi^-$
Obs. Mass (MeV)	496.8±0.2	1115.70±0.01	1522.7±1.9	1321.5±0.3
PDG Mass (MeV)	497.67	1115.68	1519.5±1.0	1321.31±0.13
Width—data (σ MeV)	6.2±0.2	2.6± 0.1	4.4±3.7	3.1±0.3
Width—MC (σ MeV)	5.4	2.1	3.5	2.5
Decay p_{CM} (MeV)	206	101	244	139 ($\Lambda\pi^-$)

- Masses of known particles are well reproduced
- Estimate systematic uncertainty of ±1.9 MeV

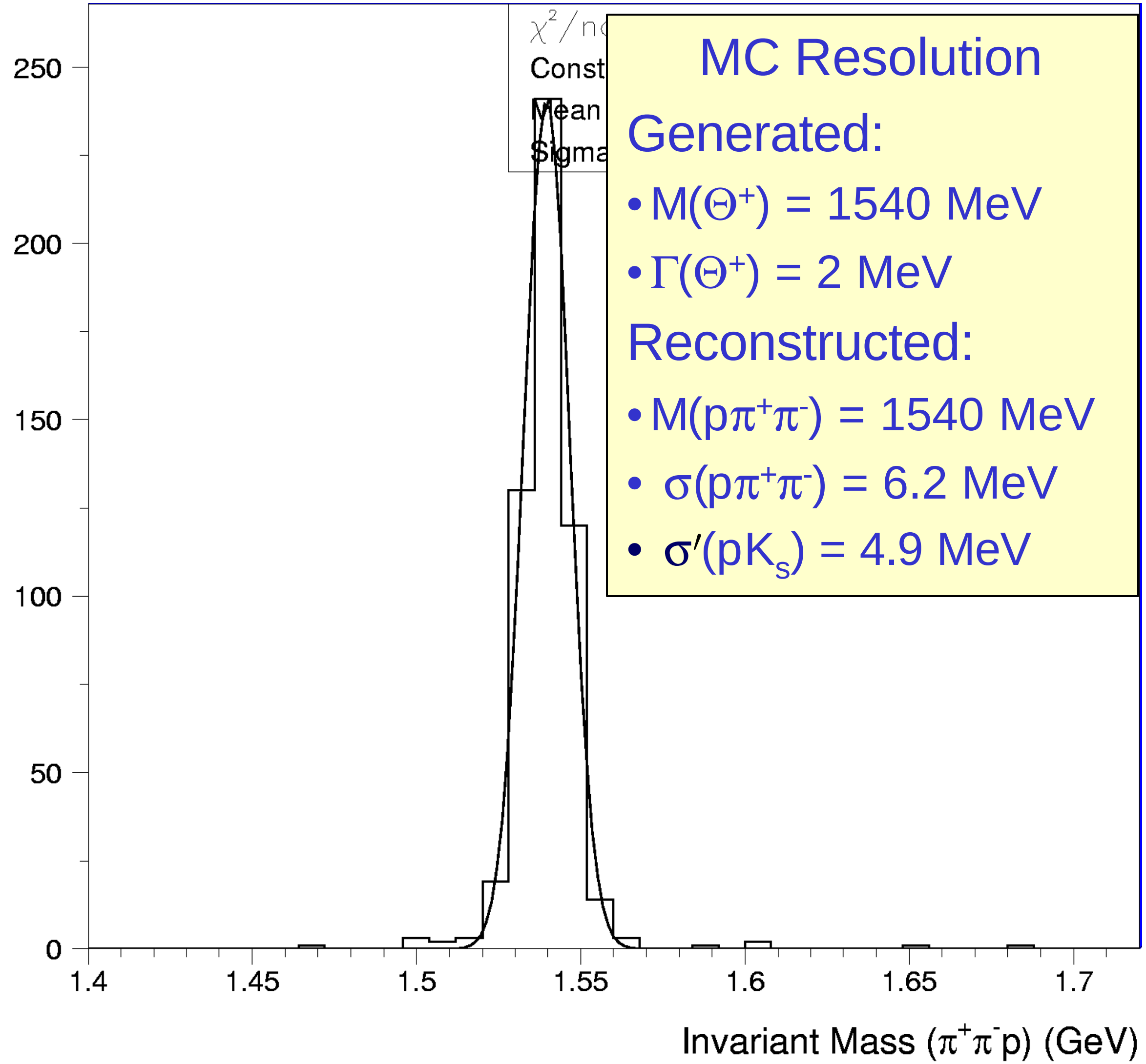
- Widths are reasonably estimated (well slightly underestimated) by the Monte Carlo

Θ^+ "toy" Monte Carlo

- No model of pentaquark photoproduction
- HERMES "toy" model:
  - p_z falling distribution similar to observed Λ distribution in HERMES
  - p_T Gaussian, σ = 0.4 GeV, typical of parton p_T and similar to Λ distribution in HERMES
  - Accept($\Theta^+ \rightarrow pK_s$) $\approx$ 0.05%
  - $\sigma(\Theta^+) \approx$ 100-200 nb $\pm$ 25%
- Refit data with Breit-Wigner convoluted with Gaussian (width fixed at simulated resolution)

G(Q$^+$) = 17 $\pm$ 9 $\pm$ 3 MeV

(Ave. of a′ and b′ fits)



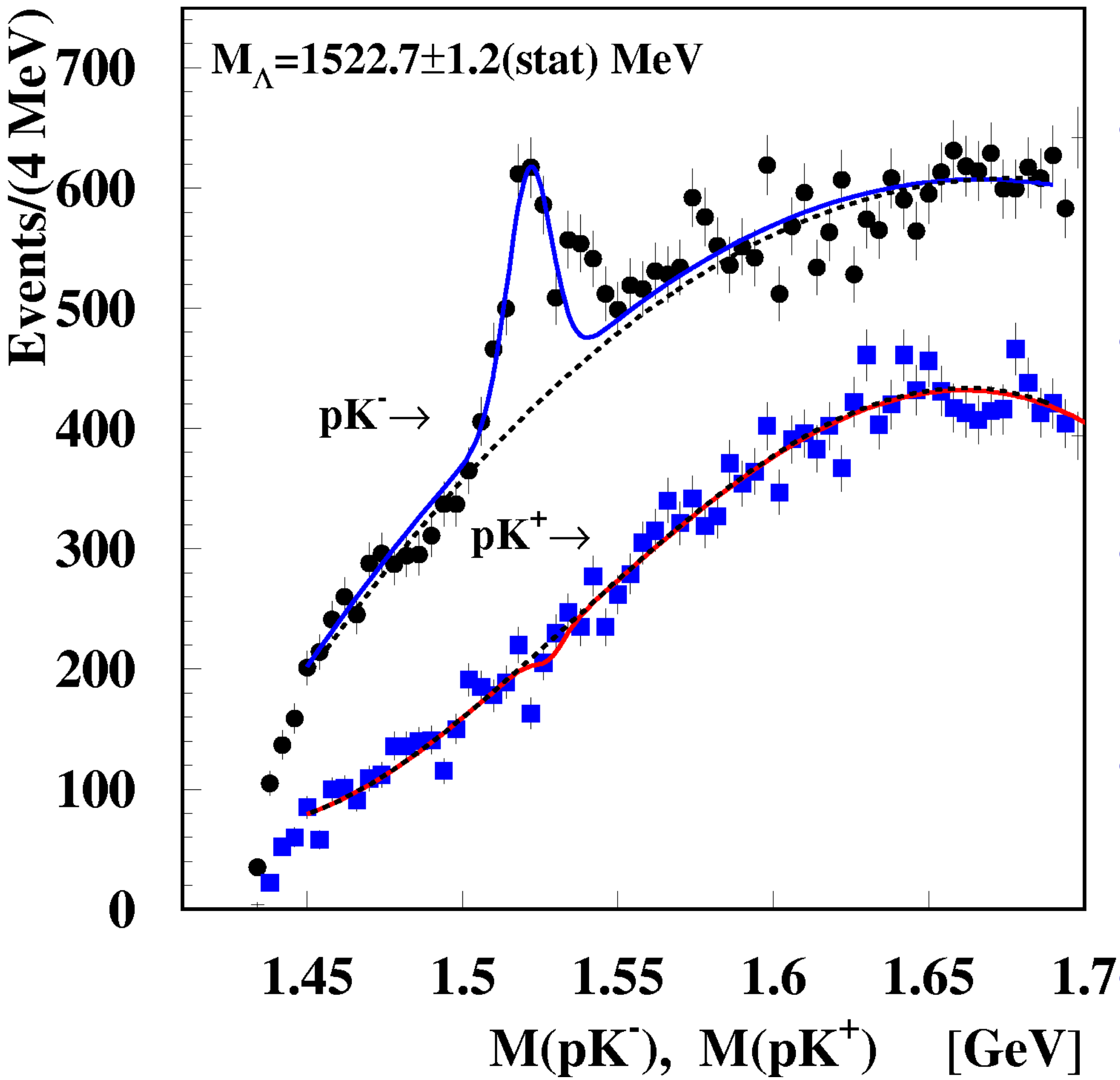
MC Resolution

Generated:
- $M(\Theta^+)$ = 1540 MeV
- $\Gamma(\Theta^+)$ = 2 MeV

Reconstructed:
- $M(p\pi^+\pi^-)$ = 1540 MeV
- $\sigma(p\pi^+\pi^-)$ = 6.2 MeV
- $\sigma'(pK_s)$ = 4.9 MeV

Caveat: No other resonance with equivalent topology to cross check Monte Carlo

Θ^+ isospin: the Θ^{++}



Study of *pK*$^\pm$ Channels

- Clear peak observed for Λ(1520) in pK$^-$ spectrum
- No peak observed in pK$^+$ spectrum (Θ^{++} channel)
- Upper limit of 0 counts at 91% confidence for Θ^{++}
- MC acceptance for both Λ(1520) and Θ^{++} is approximately 1.5%
- σ[Λ(1520)] ≈ 62 nb (large systematic uncertainties)

Conclusions

- HERMES detects an enhancement in the pK_s invariant mass spectrum:

  M_{pKs} = 1528 ± 2.6(stat) ± 2.1(syst) MeV/c^2

- Fitted width ***possibly*** greater than experimental resolution:

  Γ = 17 ± 9 (stat) ± 3 (syst) MeV/c^2

- This peak is associated with the exotic Θ^+ pentaquark resonance—caveat: HERMES has no strangeness tag.
- No evidence for Θ^{++} is observed.

- Future: HERMES now has a dedicated pentaquark trigger and will collect more data (until 200?).
- See A. Airapetian *et al.* (HERMES collaboration) to be published in Phys. Lett. B, hep-ex/0312044.