Properties of the $\Lambda(1405)$ Hyperon Measured at CLAS

Kei Moriya
with
Reinhard Schumacher

Carnegie Mellon University

September 15, 2009

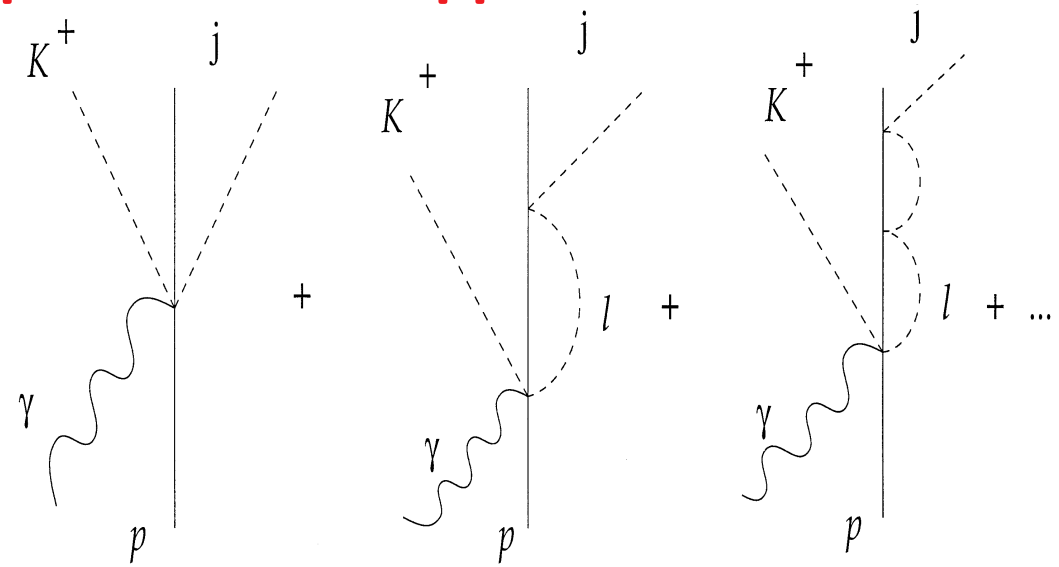
Outline

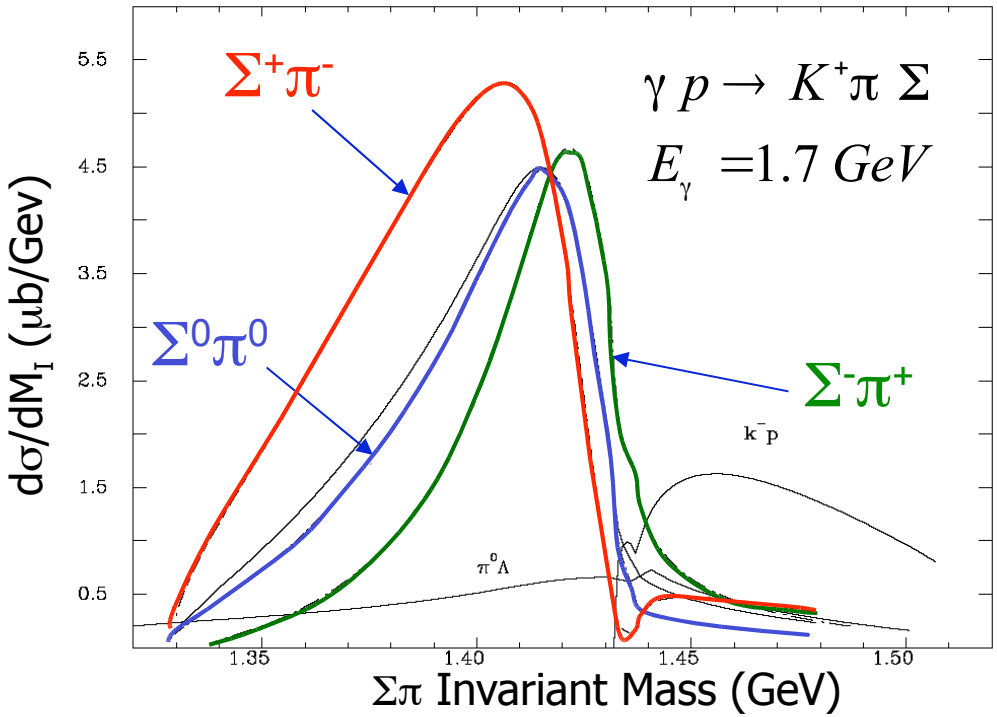
what is the $\Lambda(1405)$?

- **** resonance just below $N\overline{K}$ threshold
- $J^P = \frac{1}{2}^-$ (experimentally unconfirmed)
- can only be observed by reconstructing $(\Sigma\pi)^0$ spectrum
- past experiments have found the lineshape (= invariant $\Sigma\pi$ mass distribution) to be distorted from a simple Breit-Wigner form
- what is the nature of this distorted lineshape?
  - "normal" qqq-baryon resonance
  - $L = 1$ SU(3) singlet in constituent quark model
  - molecular $N\overline{K}$ bound state
  - uds singlet coupled to S-wave meson-baryon systems
  - $udsg$ hybrid, $qqqq\overline{q}$
  - dynamically generated resonance in unitary coupled channel approach

unitary coupled channel approach

dynamically generate $\Lambda(1405)$





J. C. Nacher et al., Phys. Lett. B455, 55 (1999)

difference in lineshape

$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

$$\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3}\left|T^{(0)}\right|^2 + O\left(T^{(2)}\right)$$

J. C. Nacher et al., Nucl. Phys. B455, 55

- difference in lineshapes is due to interference of isospin terms in calculation ($T^{(I)}$ represents amplitude of isospin I term)

goals of $\Lambda(1405)$ analysis

- measure the lineshape in the three $\Sigma\pi$ channels ($\Sigma^+\pi^-$, $\Sigma^0\pi^0$, $\Sigma^-\pi^+$)
- measure the differential cross section (angular dependence)
- determine the spin and parity

if distortion of lineshape is observed, this could be the first observation of a non-qqq baryonic structure

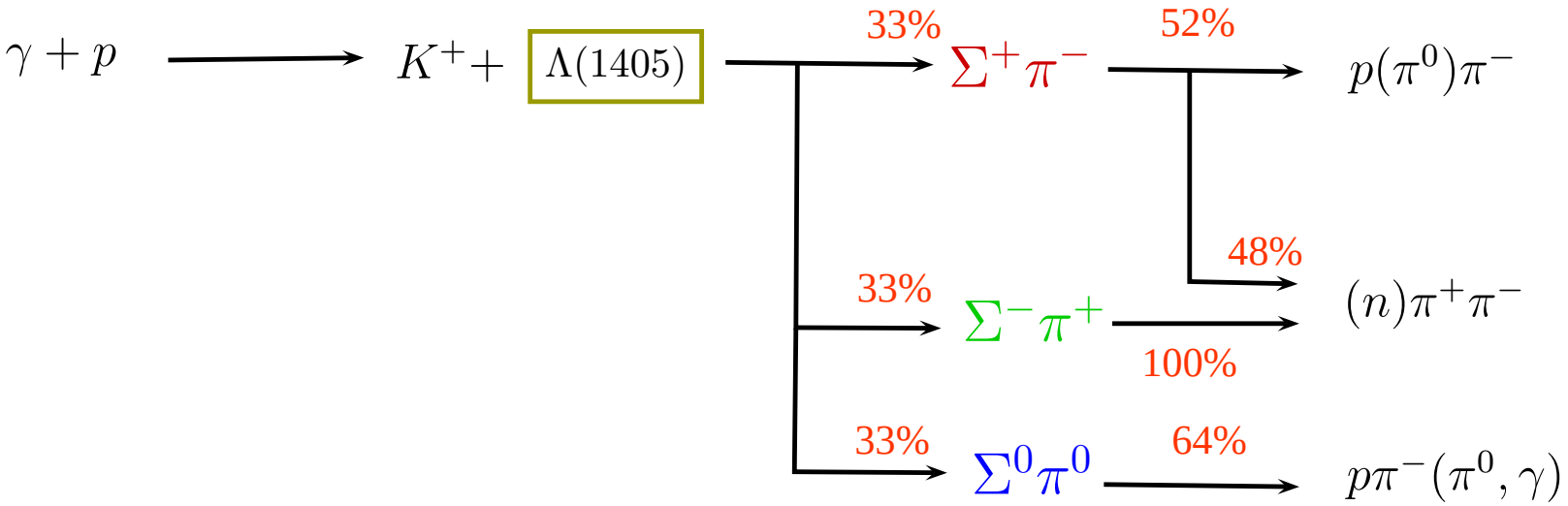
the g11a data set taken at CLAS

- ran from May to July 2004
- photoproduction experiment on a proton target
- photon energies from below $\Lambda(1405)$ threshold to 3.84 GeV
- large dataset with ~ 20 billion triggers
- current estimates of reconstructed $\Lambda(1405)$ events: ~ 272K

data is binned in:

- 10 bins of 100 MeV wide W bins
- ~ 20 bins of t in each W bin

reaction of interest

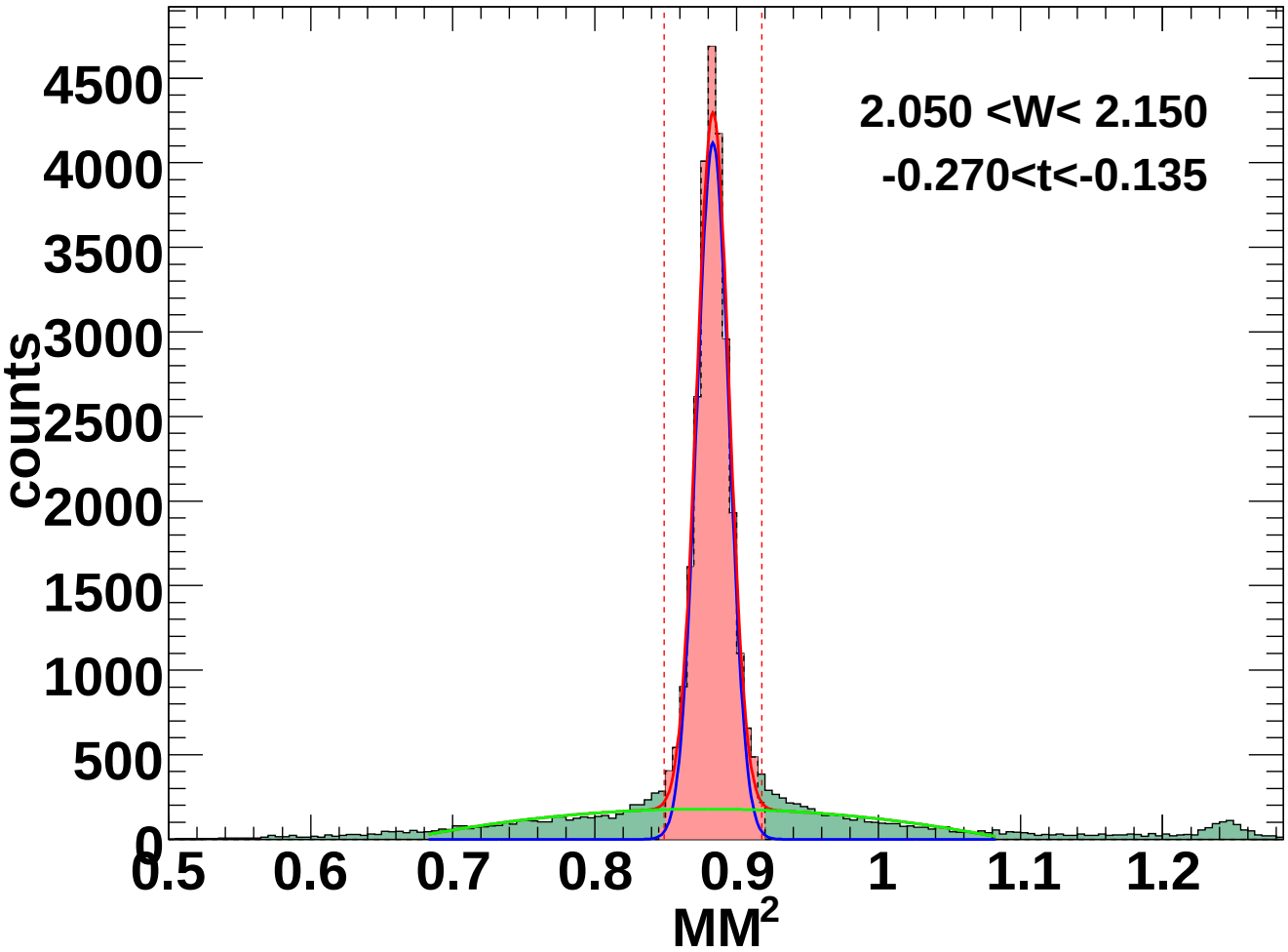


- 3 $\Sigma\pi$ decay channels (2 decay modes for $\Sigma^+\pi^-$)
- This will be the first experimental result to compare all 3 $\Sigma\pi$ decay modes

decay channel selection cut

example in 1 bin:

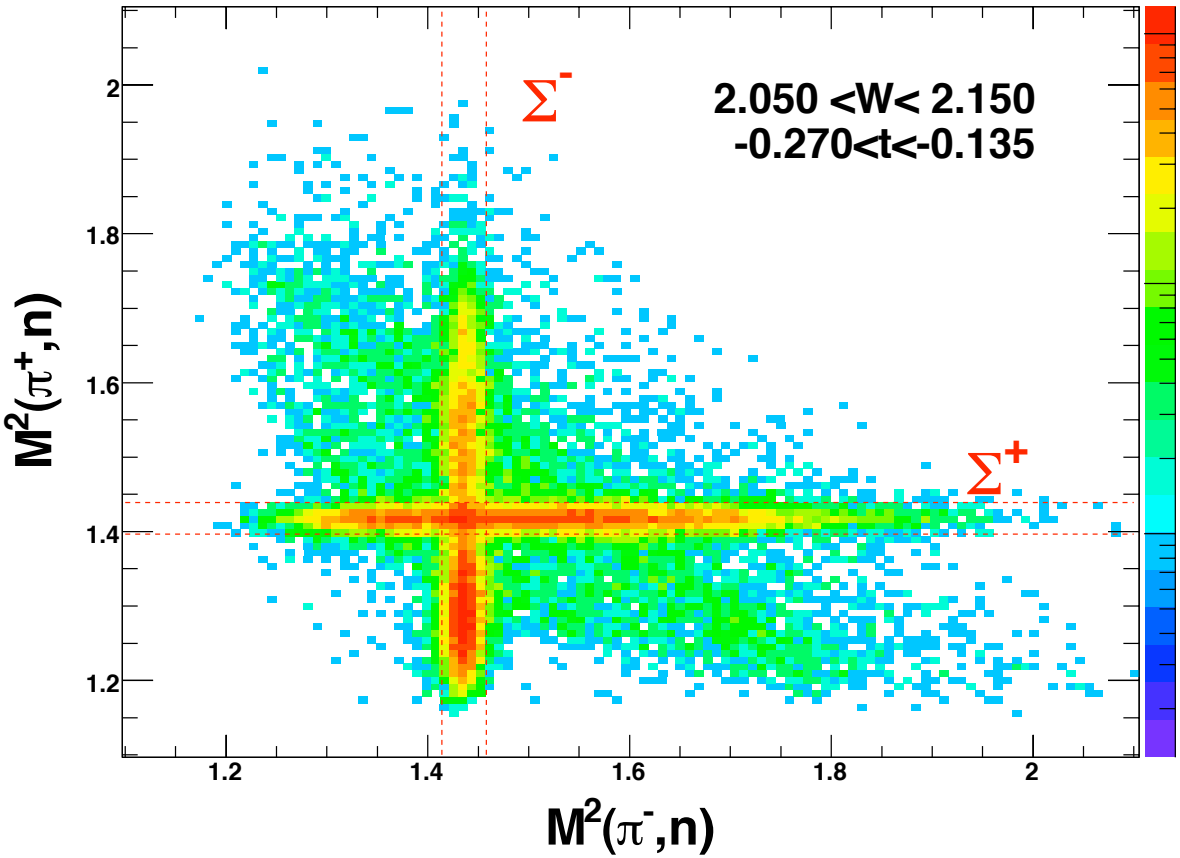
- $\gamma + \mathrm{p} \rightarrow K^+\pi^+\pi^-(n)$
- detect K^+, π^+, π^-, reconstruct missing neutron
- fit to Gaussian and select $\pm 3\sigma$ around neutron peak



intermediate ground state hyperon

example in 1 bin:

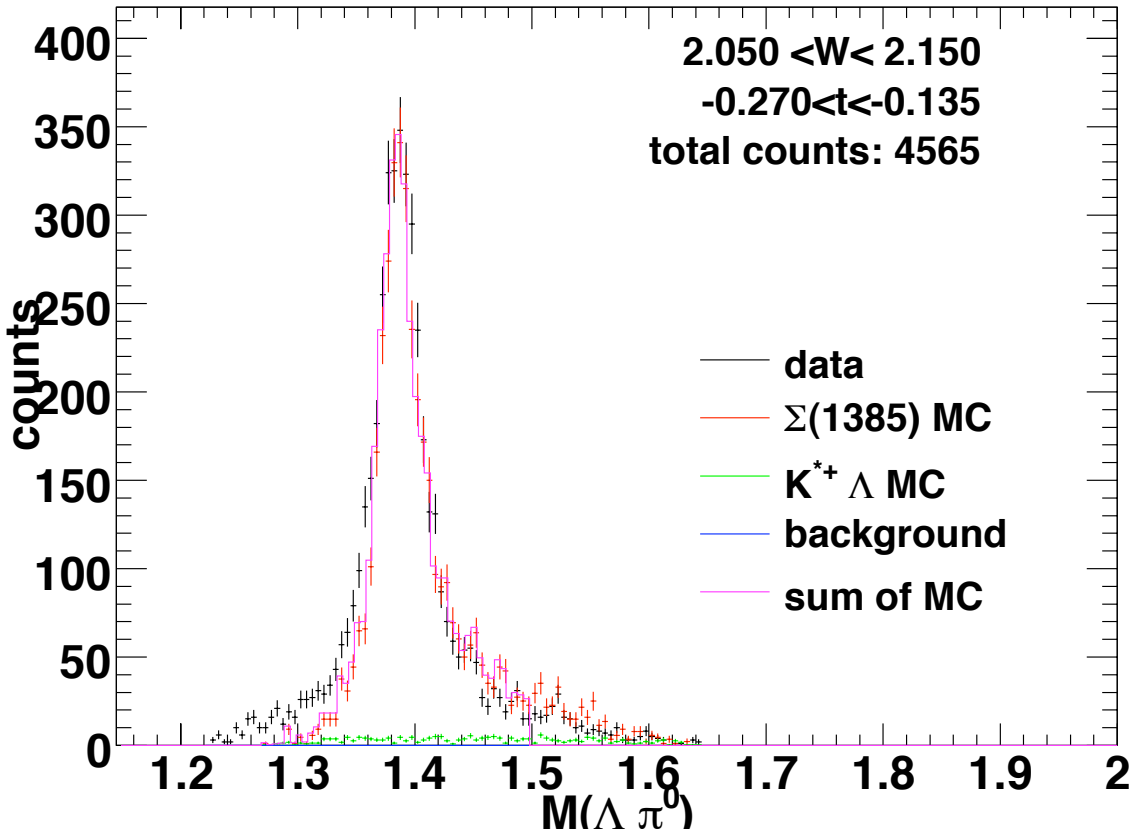
- neutron combined with $\pi^{\pm}$ reconstructs $\Sigma^{\pm}$
- project on each axis, select $\pm 2\sigma$, exclude other hyperon
- diagonal band (K^0 from $\pi^+\pi^-$) is also excluded



background (1) – $\Sigma(1385)$

- close in mass and width to $\Lambda(1405)$
- decays primarily to $\Lambda\pi^0$ (B.R. $\sim 88\%$)
- small B.R. to $\Sigma^{\pm}\pi^{\mp}$: $\sim 6\%$ each

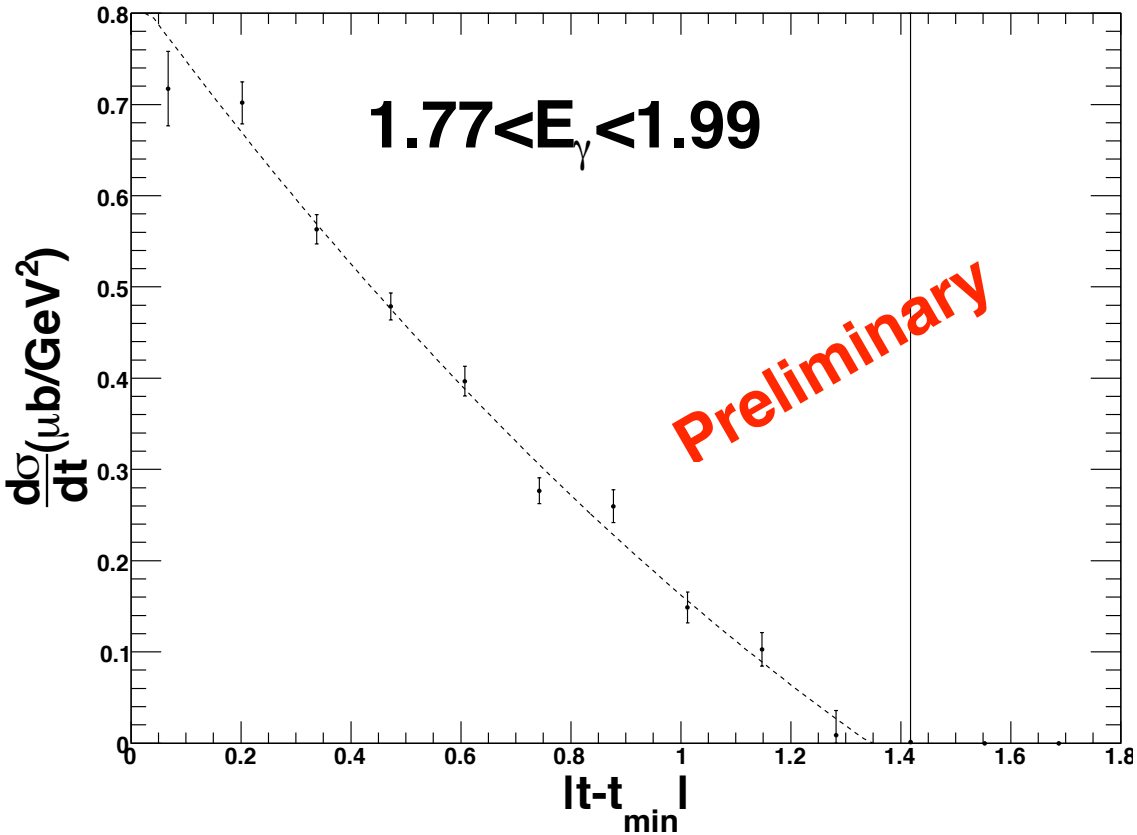
$\Rightarrow$ calculate $\Sigma(1385)$ cross section in each bin from $\Lambda\pi^0$ channel, then scale down by B.R. to extract yield in $\Sigma\pi$ channels



background (1) – $\Sigma(1385)$

- close in mass and width to $\Lambda(1405)$
- decays primarily to $\Lambda\pi^0$ (B.R. $\sim 88\%$)
- small B.R. to $\Sigma^{\pm}\pi^{\mp}$: $\sim 6\%$ each

$\Rightarrow$ calculate $\Sigma(1385)$ cross section in each bin from $\Lambda\pi^0$ channel, then scale down by B.R. to extract yield in $\Sigma\pi$ channels

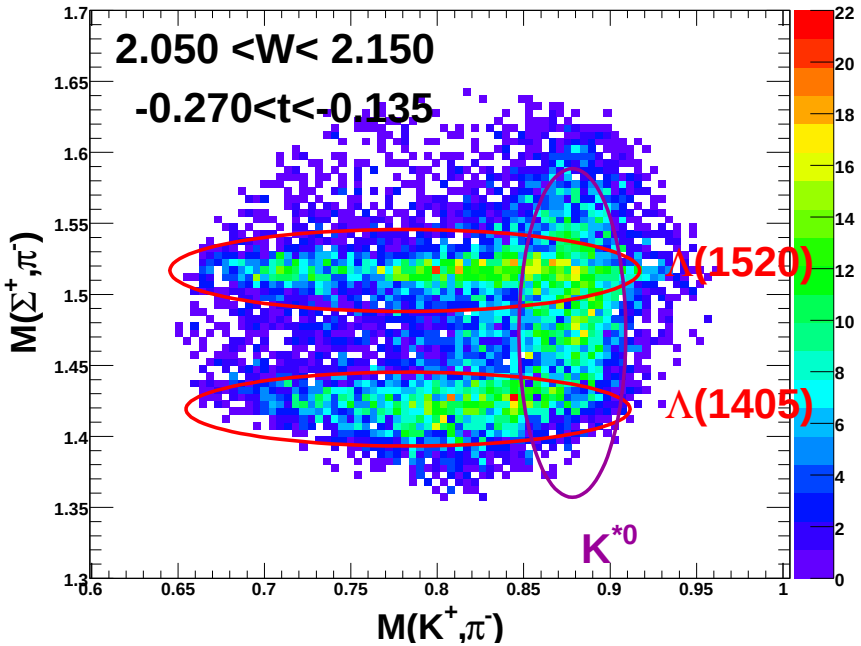


background (2) – $K^{*0}\Sigma^+$

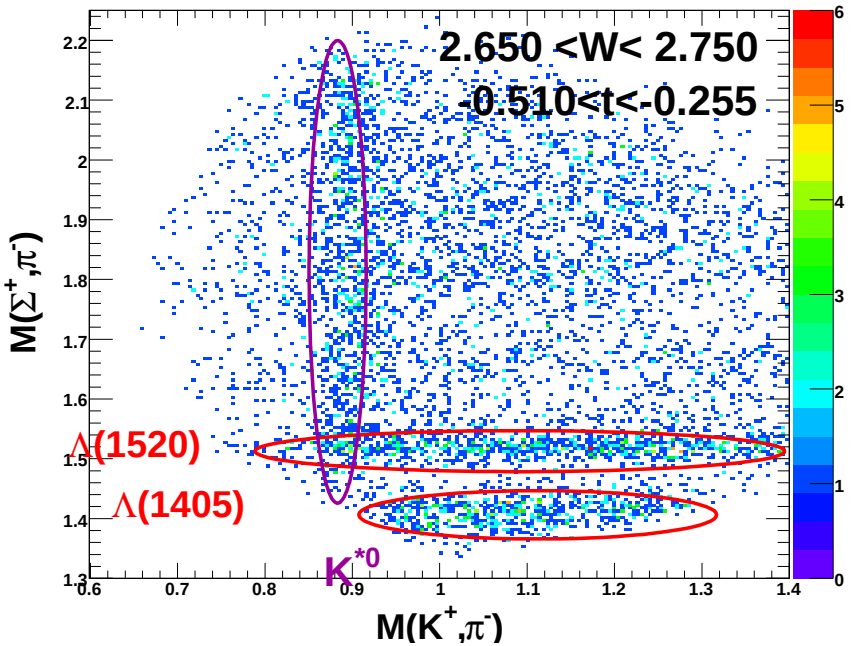
- $\Gamma \sim 50$ MeV
- strong overlap with $\Lambda(1405)$ in lower W bins, separated at higher energies

$\Rightarrow$ generated MC and subtract off incoherently
(checks need to be done for interference)

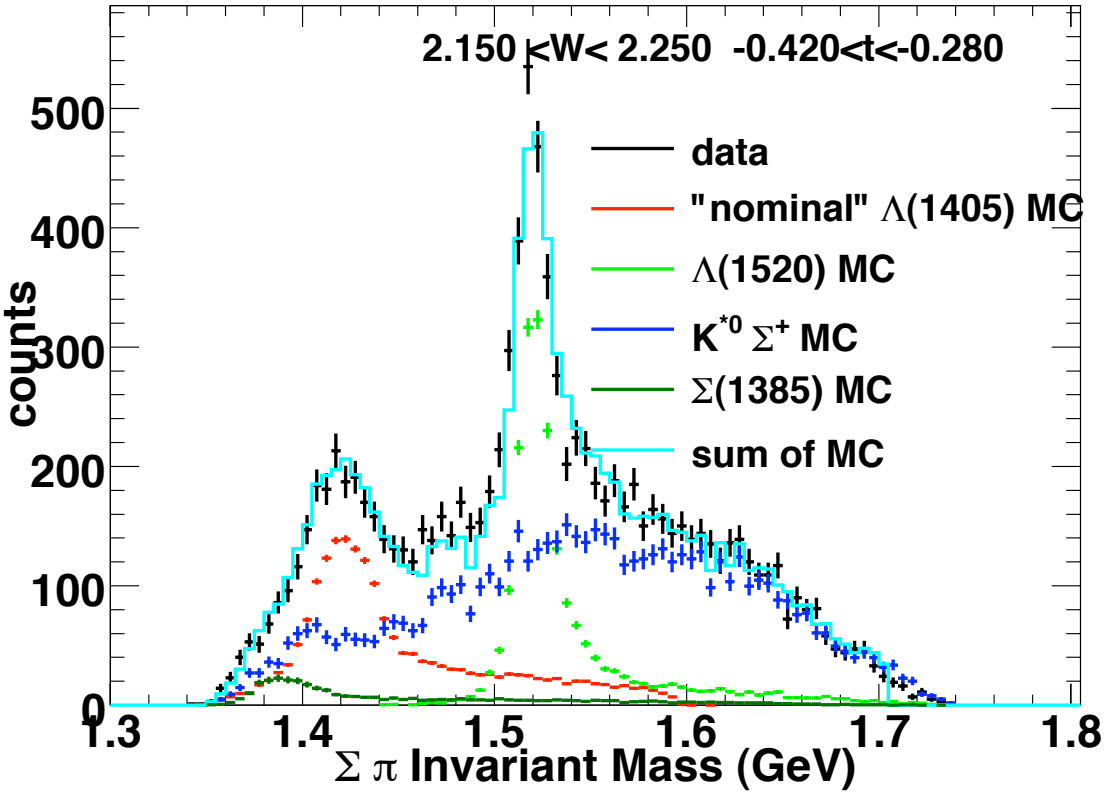
low energy bin



high energy bin



example of fit to lineshape



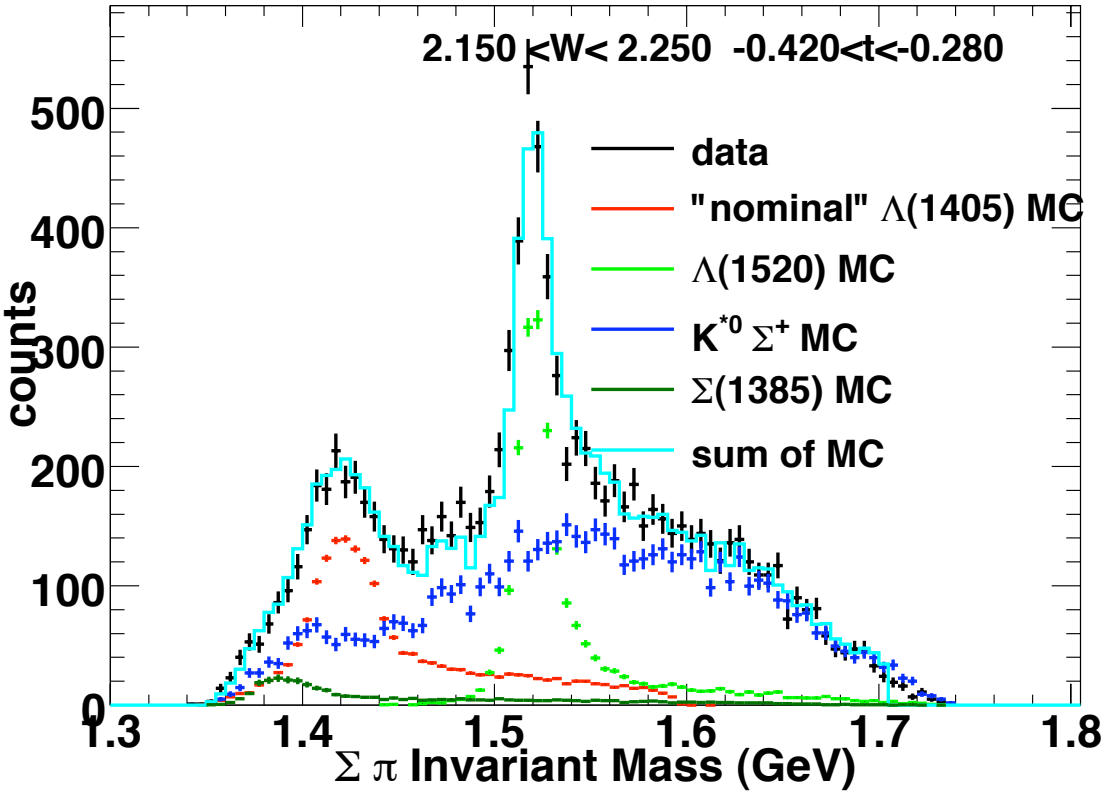
reaction:

$$\gamma + p \rightarrow K^+ + \boxed{\Lambda(1405)}$$
$$\rightarrow \boxed{\Sigma^+} + \pi^-$$
$$\rightarrow n + \pi^+$$

"nominal" $\Lambda(1405)$

- Monte Carlo generated with PDG values of mass, width
- all Monte Carlo was processed through detector simulation
- after fitting, this process was iterated

example of fit to lineshape



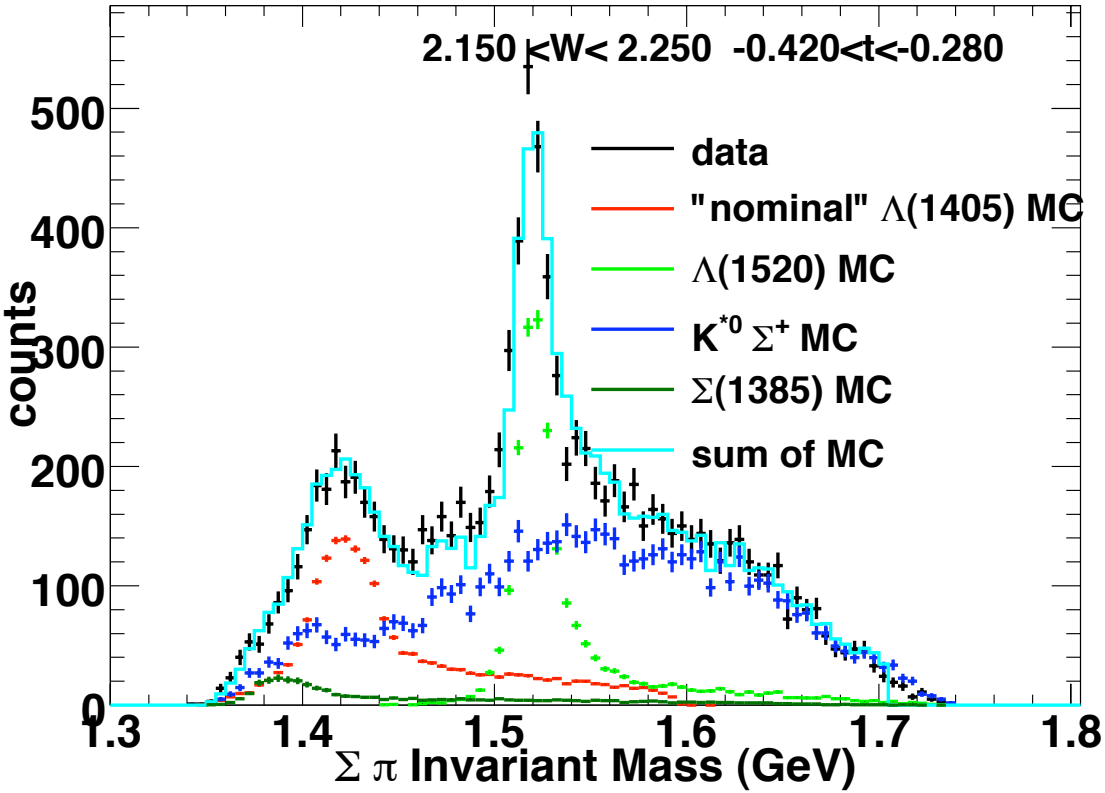
reaction:

$$\gamma + p \rightarrow K^+ + \boxed{\Lambda(1405)}$$
$$\rightarrow \boxed{\Sigma^+} + \pi^-$$
$$\rightarrow n + \pi^+$$

$\Sigma(1385)$

- strong overlap with $\Lambda(1405)$ due to close mass and width
- $\Lambda\pi^0$ decay mode was used to fix yield in $\Sigma\pi$ decay modes
- Monte Carlo generated with PDG values of mass, width

example of fit to lineshape



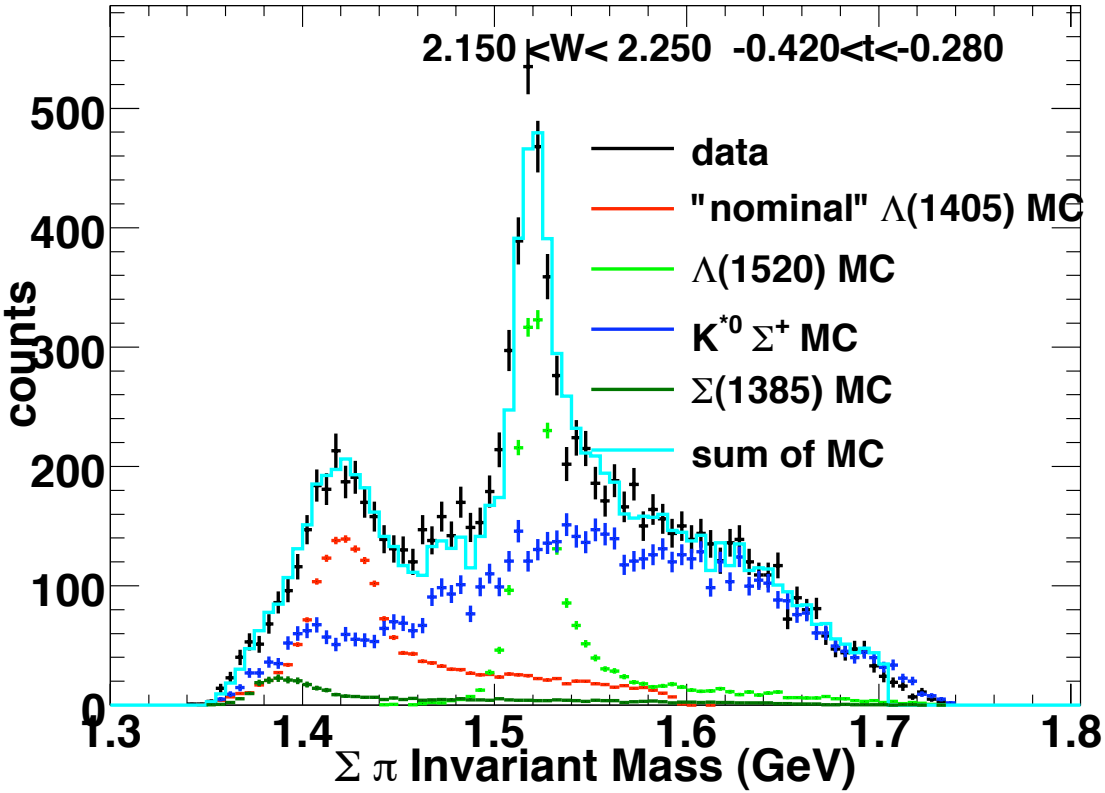
reaction:

$$\gamma + p \rightarrow K^+ + \boxed{\Lambda(1405)}$$
$$\rightarrow \boxed{\Sigma^+} + \pi^-$$
$$\rightarrow n + \pi^+$$

$\Lambda(1520)$

- Monte Carlo generated with PDG values of mass, width
- well-established Breit-Wigner lineshape

example of fit to lineshape



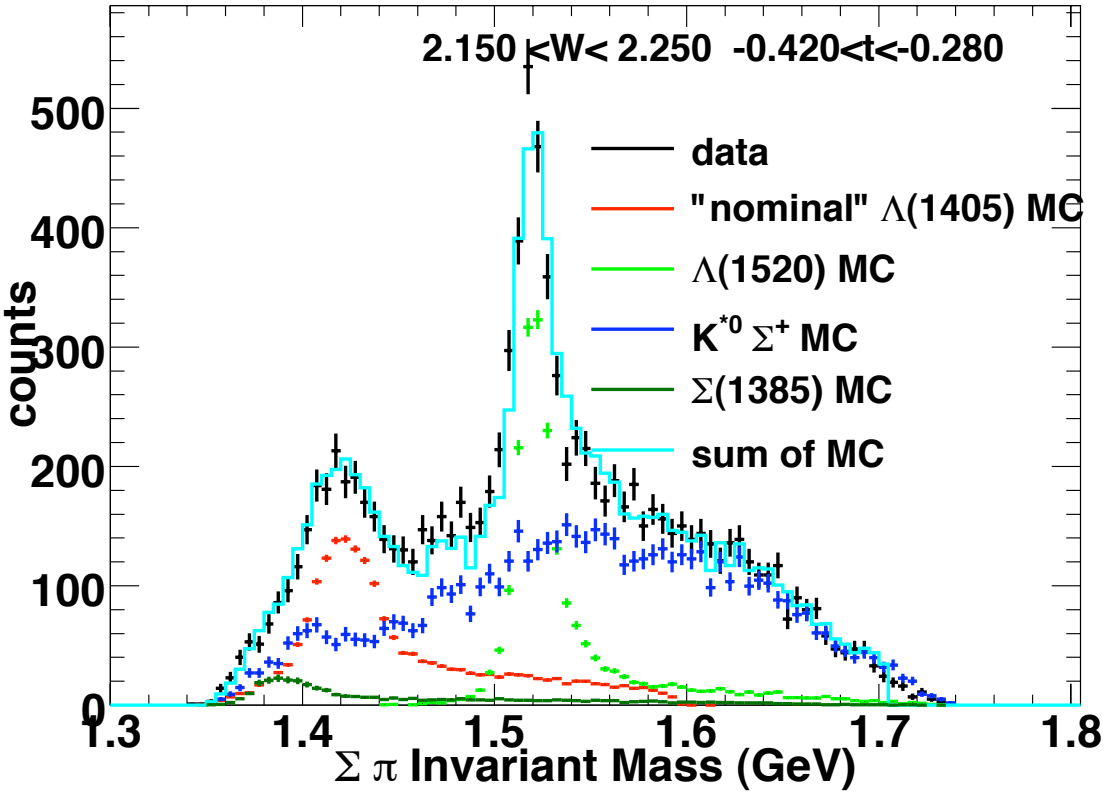
reaction:

$$\gamma + p \rightarrow K^+ + \boxed{\Lambda(1405)}$$
$$\rightarrow \boxed{\Sigma^+} + \pi^-$$
$$\rightarrow n + \pi^+$$

$\mathbf{K^{*0}}$

- strong kinematic overlap with $\Lambda(1405)$
- Monte Carlo generated with PDG values of mass, width

example of fit to lineshape



reaction:

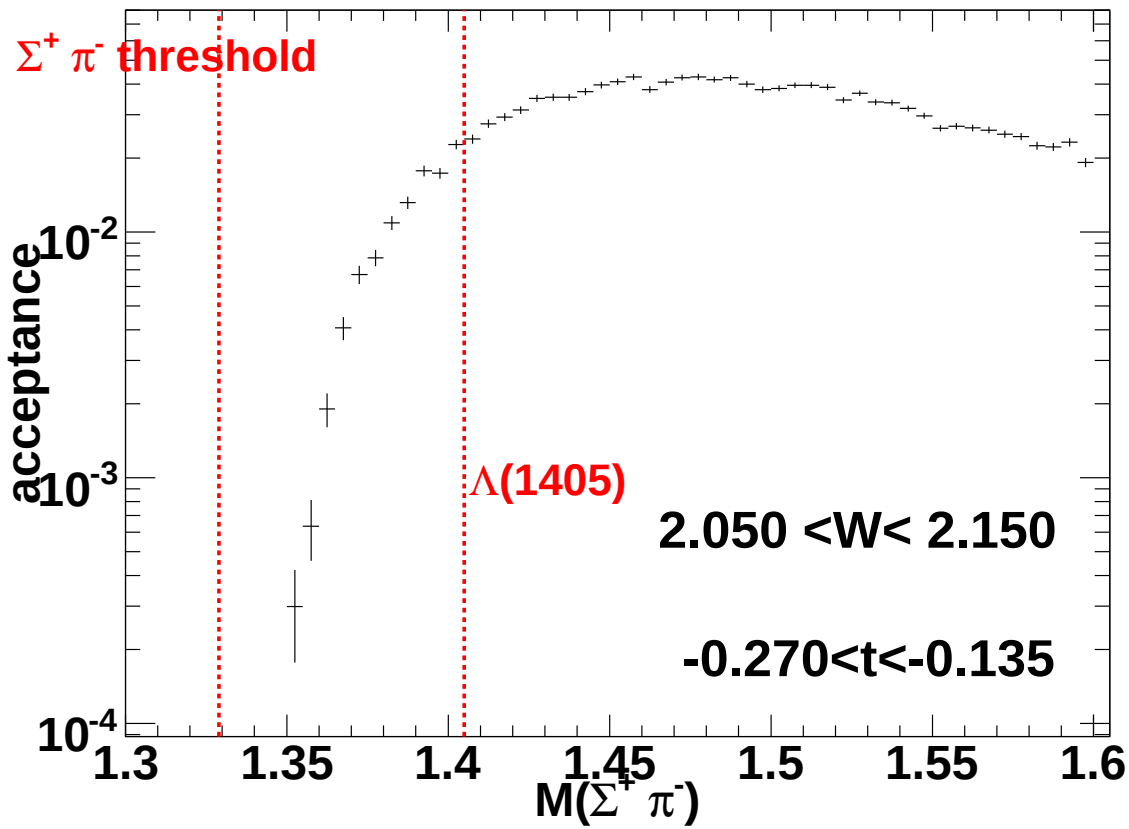
$$\gamma + p \rightarrow K^+ + \boxed{\Lambda(1405)}$$
$$\rightarrow \boxed{\Sigma^+} + \pi^-$$
$$\rightarrow n + \pi^+$$

$\Rightarrow$ after fitting with the above templates, we subtracted off contributions from the $\mathbf{\Sigma(1385)}$, $\mathbf{\Lambda(1520)}$, $\mathbf{K^{*0}}$, and assigned the remaining contribution to the $\mathbf{\Lambda(1405)}$

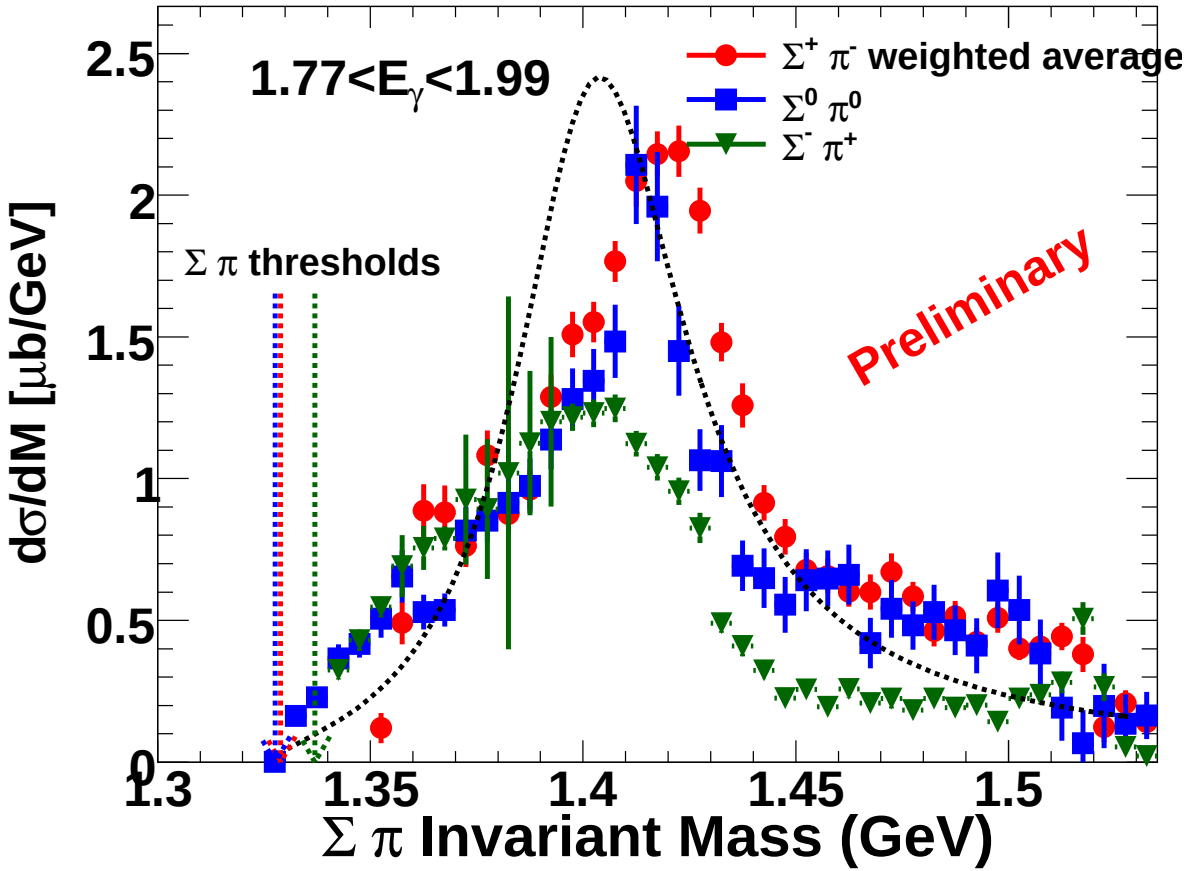
$\Rightarrow$ this process has been iterated

acceptance correction

- after subtracting background contributions, we are left with "residual" spectrum
- to correct for dependence of the lineshape on acceptance, we have calculated the acceptance as a function of lineshape
- our lineshape results are summed over the t bins in each energy bin



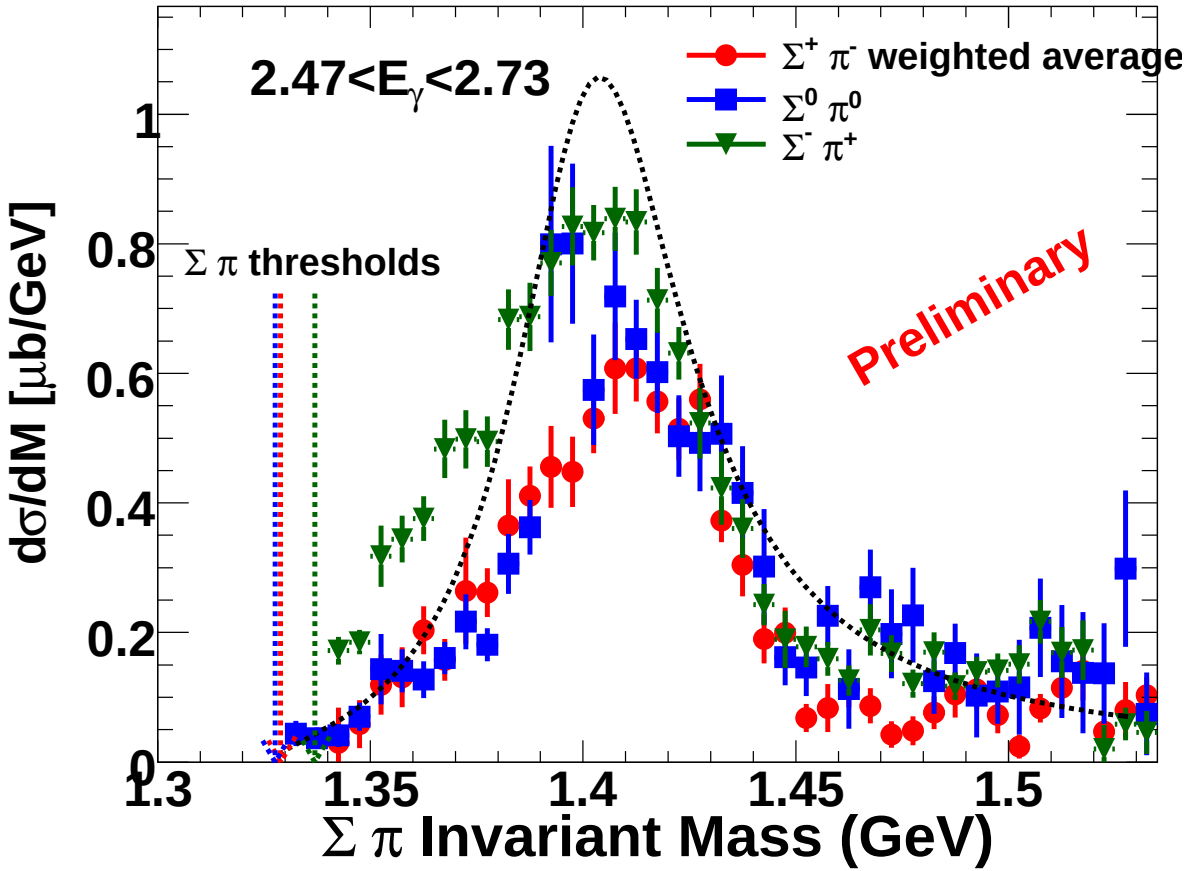
results of lineshape after acceptance correction



different lineshapes for each $\Sigma\pi$ decay mode

- lineshapes do appear different for each $\Sigma\pi$ decay mode
- $\Sigma^+\pi^-$ decay mode has peak at highest mass, narrow than $\Sigma^-\pi^+$

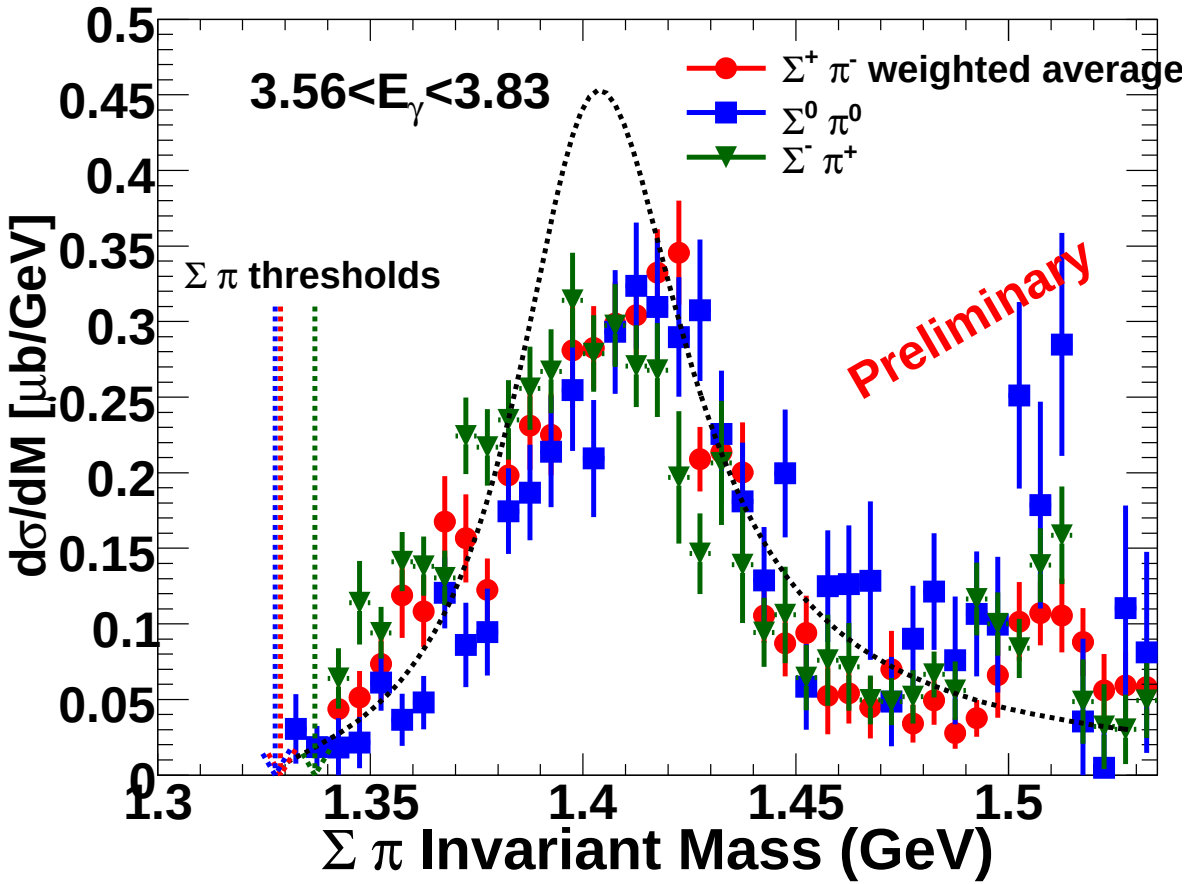
results of lineshape after acceptance correction



different lineshapes for each $\Sigma\pi$ decay mode

- lineshapes do appear different for each $\Sigma\pi$ decay mode
- $\Sigma^+\pi^-$ decay mode has peak at highest mass, narrow than $\Sigma^-\pi^+$

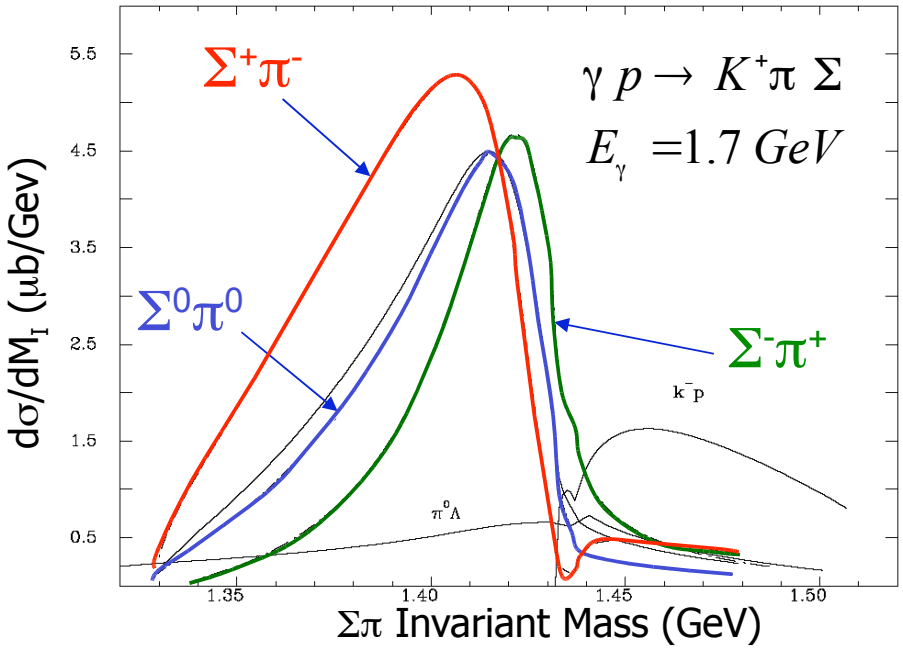
results of lineshape after acceptance correction



different lineshapes for each $\Sigma\pi$ decay mode

- lineshapes do appear different for each $\Sigma\pi$ decay mode
- $\Sigma^+\pi^-$ decay mode has peak at highest mass, narrow than $\Sigma^-\pi^+$

theory prediction from chiral unitary approach



J. C. Nacher et al., Nucl. Phys. B455, 55

$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

$$\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3}\left|T^{(0)}\right|^2 + O\left(T^{(2)}\right)$$

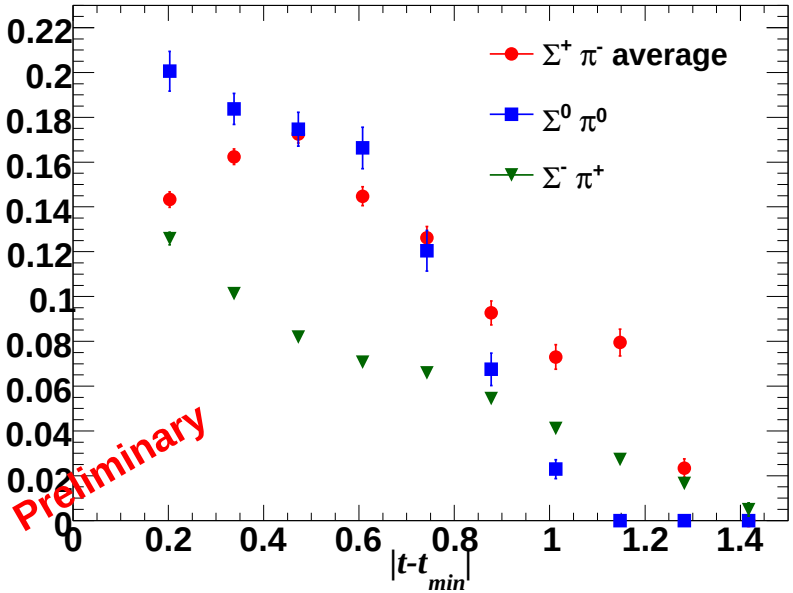
- $\Sigma^-\pi^+$ decay mode peaks at highest mass, most narrow
- difference in lineshapes is due to interference of isospin terms in calculation ($T^{(I)}$ represents amplitude of isospin I term)

differential cross sections

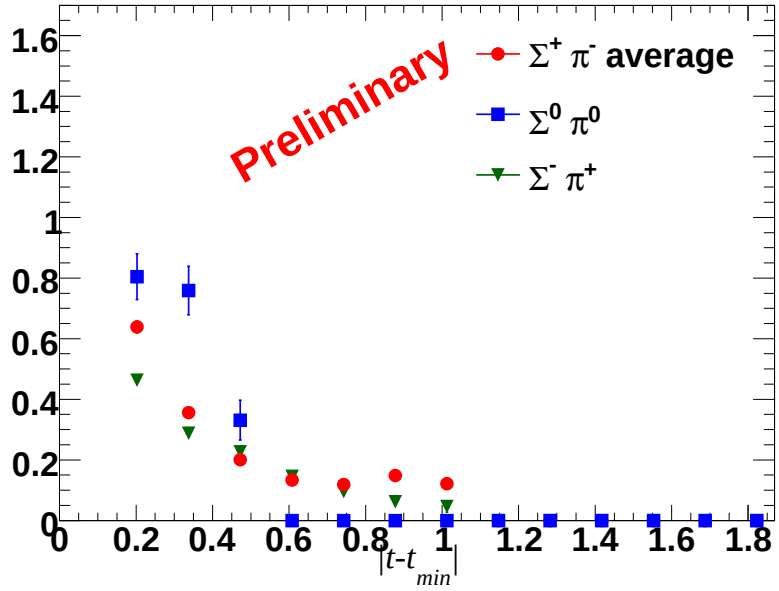
- summing over the lineshape gives differential cross section ($M(\Sigma\pi) < 1.500$ GeV)
- $\Lambda(1520)$ serves as a check of systematics
- at lower energies where lineshapes differ, differences in $\frac{\mathrm{d}\sigma}{\mathrm{d}t}$ are observed

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}[\mu b/\mathrm{GeV}^2] \text{ for } 2.050 < W < 2.150 \text{ (GeV)}$$

$\Lambda(1405)$



$\Lambda(1520)$

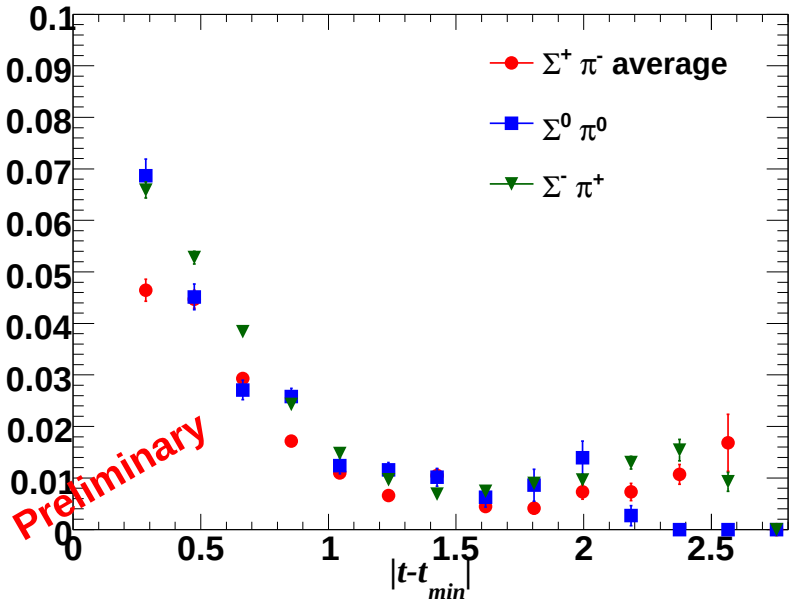


differential cross sections

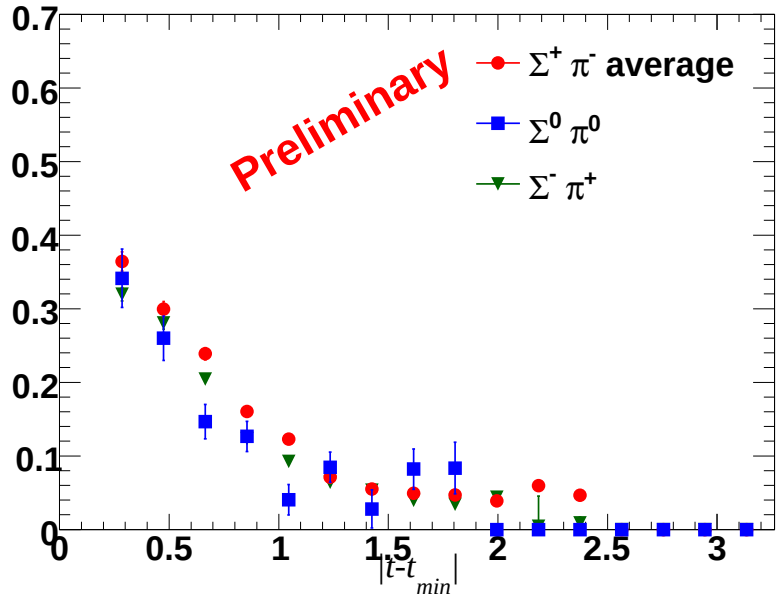
- summing over the lineshape gives differential cross section ($M(\Sigma\pi) < 1.500$ GeV)
- $\Lambda(1520)$ serves as a check of systematics
- at lower energies where lineshapes differ, differences in $\frac{\mathrm{d}\sigma}{\mathrm{d}t}$ are observed

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}[\mu b/\mathrm{GeV}^2] \text{ for } 2.350 < W < 2.450 \text{ (GeV)}$$

$\Lambda(1405)$



$\Lambda(1520)$

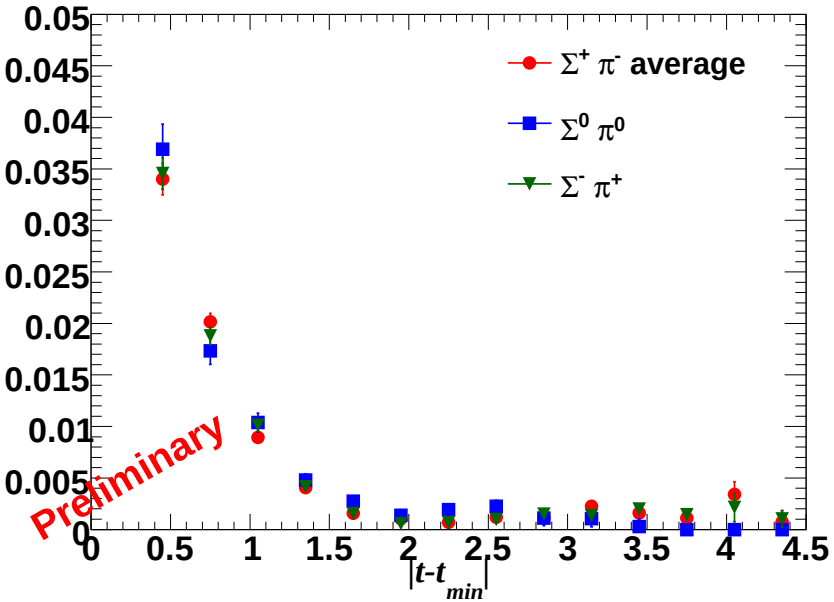


differential cross sections

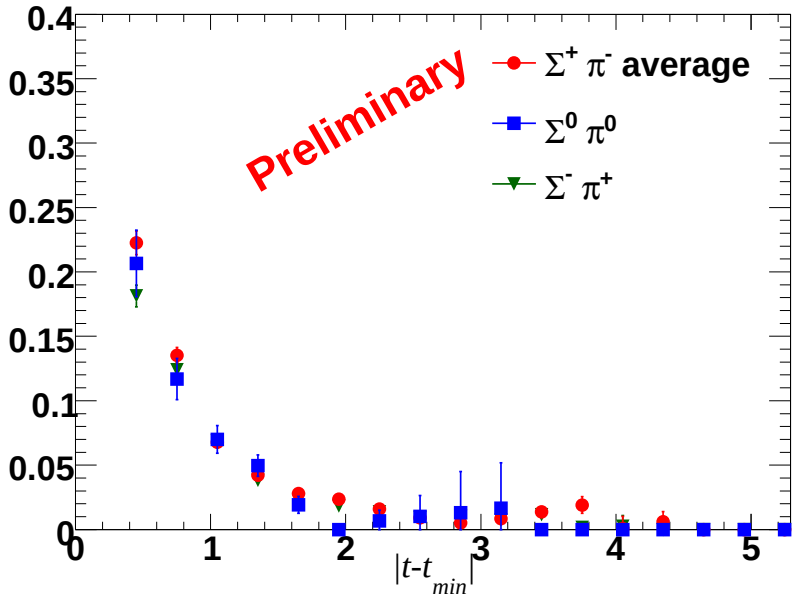
- summing over the lineshape gives differential cross section ($M(\Sigma\pi) < 1.500$ GeV)
- $\Lambda(1520)$ serves as a check of systematics
- at lower energies where lineshapes differ, differences in $\frac{\mathrm{d}\sigma}{\mathrm{d}t}$ are observed

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}[\mu b/\mathrm{GeV}^2] \text{ for } 2.750 < W < 2.840 \text{ (GeV)}$$

$\Lambda(1405)$



$\Lambda(1520)$

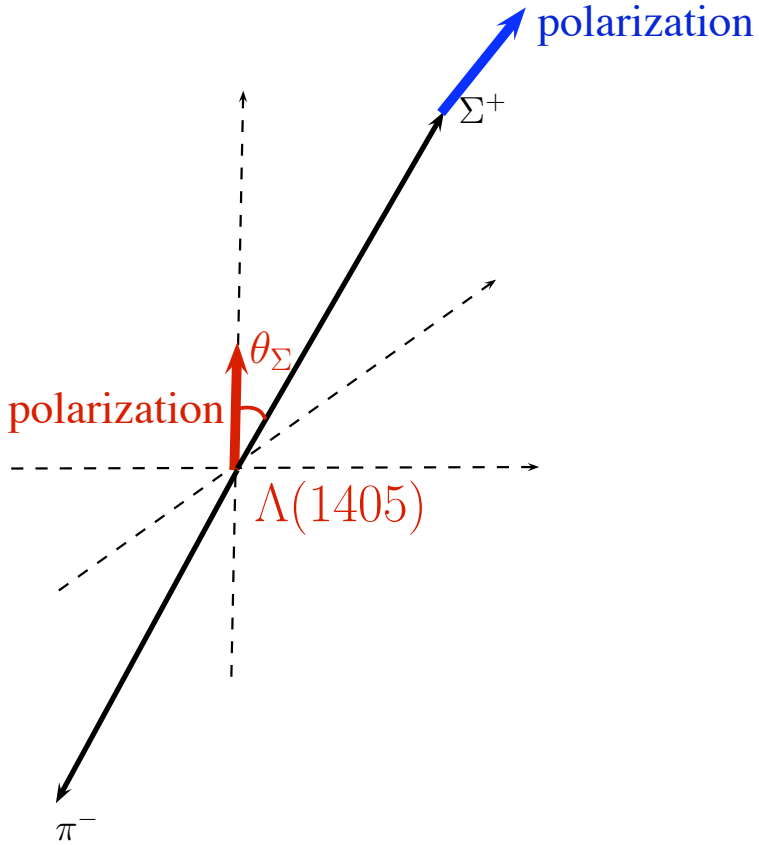


$\mathbf{J^P}$ of $\mathbf{\Lambda(1405)}$

no previous **direct experimental evidence** for the spin and parity (PDG assumes $1/2^-$) "Note on the $\Lambda(1405)$ " 2000 PDG, R.H. Dalitz

How do we measure these quantities?

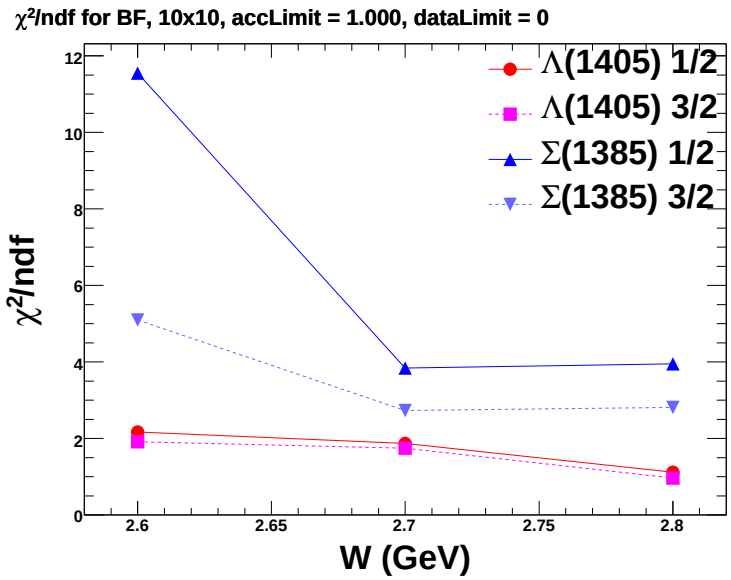
- **spin** – measure distribution into $\Sigma\pi$
  - flat distribution is best evidence possible for $J = 1/2$
- **parity** – measure polarization of Σ from $\Lambda(1405)$
  - Polarization direction as a function of Σ decay angle will be determined by J^P of $\Lambda(1405)$



determination of spin

fits to $J = \frac{1}{2}, \frac{3}{2}$ distributions done to $\Lambda(1405) \rightarrow \Sigma^+\pi^-$ / $\Sigma(1385) \rightarrow \Lambda\pi^0$

- 3 bins of W centered at $2.6, 2.7, 2.8$ GeV with forward K^+angles
- selected region has kinematic separation from K^{*0} background



distribution of $J = 1/2$:

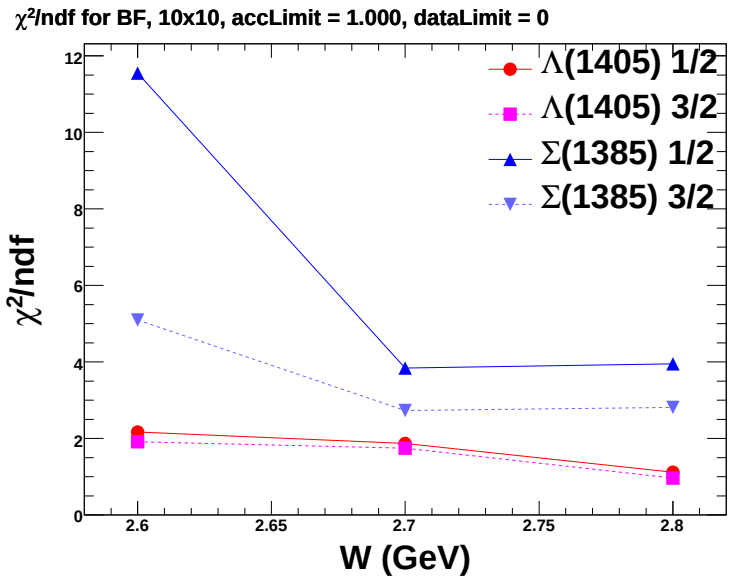
$$I(\theta, \phi) = \frac{C}{4\pi}$$

(no parameters for shape of distribution)

determination of spin

fits to $J = \frac{1}{2}, \frac{3}{2}$ distributions done to
$\Lambda(1405) \rightarrow \Sigma^+\pi^-$ / $\Sigma(1385) \rightarrow \Lambda\pi^0$

- 3 bins of W centered at $2.6, 2.7, 2.8$ GeV with forward K^+angles
- selected region has kinematic separation from K^{*0} background



distribution of $J = 3/2$ (z-axis in production plane):

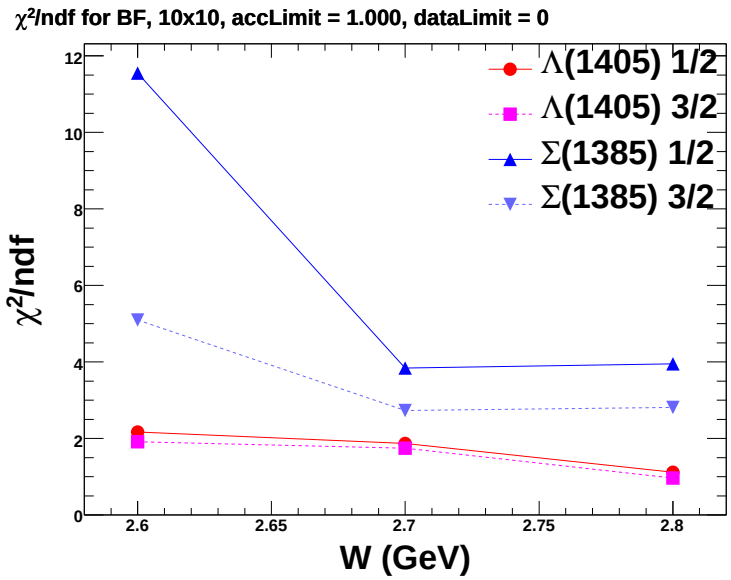
$$I(\theta,\phi) = \frac{C}{4\pi}\left[1 - \sqrt{5}t_2^0\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) + \Re t_2^1\sqrt{\frac{15}{2}}\sin 2\theta\cos\phi - \Re t_2^2\sqrt{\frac{15}{2}}\sin^2\theta\cos 2\phi\right]$$

(3 parameters for shape of distribution)
(t_L^M are "multipole parameters" N. Byers CERN report 67-20)

determination of spin

fits to $J = \frac{1}{2}, \frac{3}{2}$ distributions done to
$\Lambda(1405) \rightarrow \Sigma^+\pi^-$ / $\Sigma(1385) \rightarrow \Lambda\pi^0$

- 3 bins of W centered at $2.6, 2.7, 2.8$ GeV with forward K^+angles
- selected region has kinematic separation from K^{*0} background



distribution of $J = 3/2$ (z-axis out of production plane):

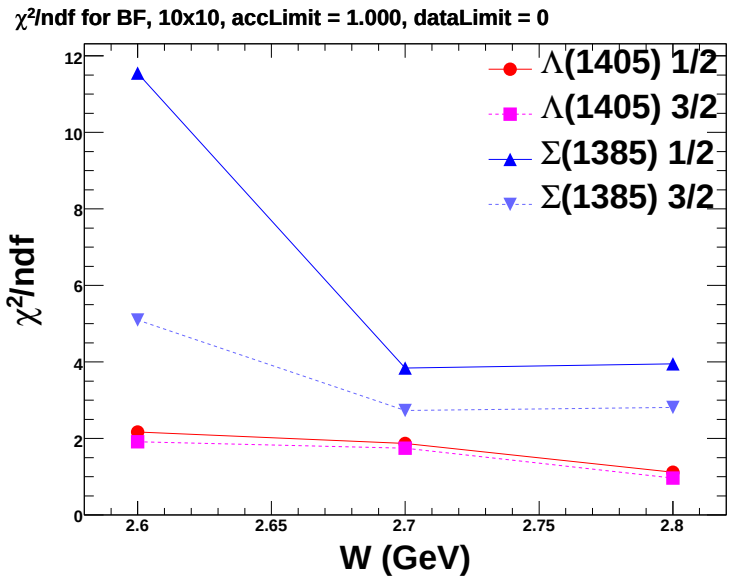
$$I(\theta,\phi) = \frac{C}{4\pi}\left[1 - \sqrt{5}t_2^0\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) - \Re t_2^2\sqrt{\frac{15}{2}}\sin^2\theta\cos 2\phi - \Im t_2^2\sqrt{\frac{15}{2}}\sin^2\theta\sin 2\phi\right]$$

(3 parameters for shape of distribution)
(t_L^M are "multipole parameters" N. Byers CERN report 67-20)

determination of spin

fits to $J = \frac{1}{2}, \frac{3}{2}$ distributions done to $\Lambda(1405) \rightarrow \Sigma^+\pi^-$ / $\Sigma(1385) \rightarrow \Lambda\pi^0$

- 3 bins of W centered at $2.6, 2.7, 2.8$ GeV with forward K^+angles
- selected region has kinematic separation from K^{*0} background

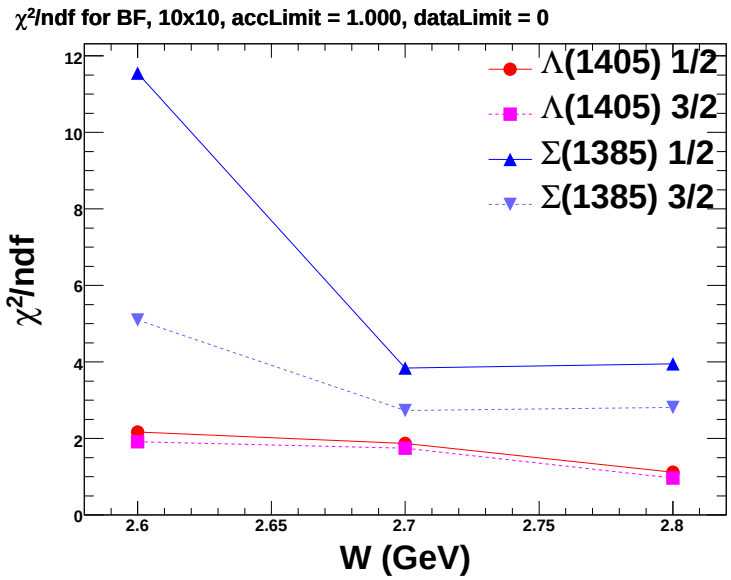


with $J = 3/2$ fit, χ^2/ndf is reduced for $\Sigma(1385)$, but almost no reduction for $\Lambda(1405)$

determination of spin

fits to $J = \frac{1}{2}, \frac{3}{2}$ distributions done to $\Lambda(1405) \rightarrow \Sigma^+\pi^-$ / $\Sigma(1385) \rightarrow \Lambda\pi^0$

- 3 bins of W centered at $2.6, 2.7, 2.8$ GeV with forward K^+angles
- selected region has kinematic separation from K^{*0} background

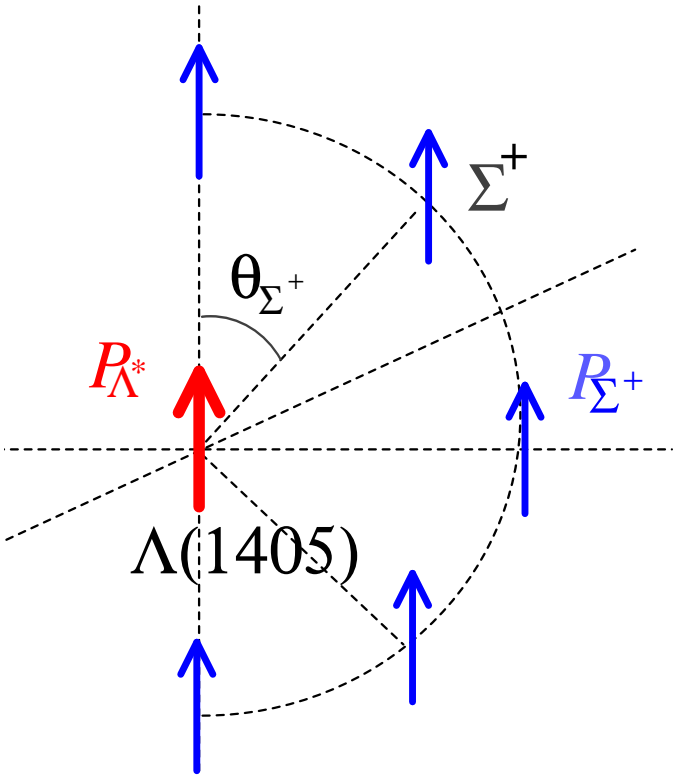


with $J = 3/2$ fit, χ^2/ndf is reduced for $\Sigma(1385)$, but almost no reduction for $\Lambda(1405)$

$\Rightarrow$ best possible evidence for $J = 1/2$

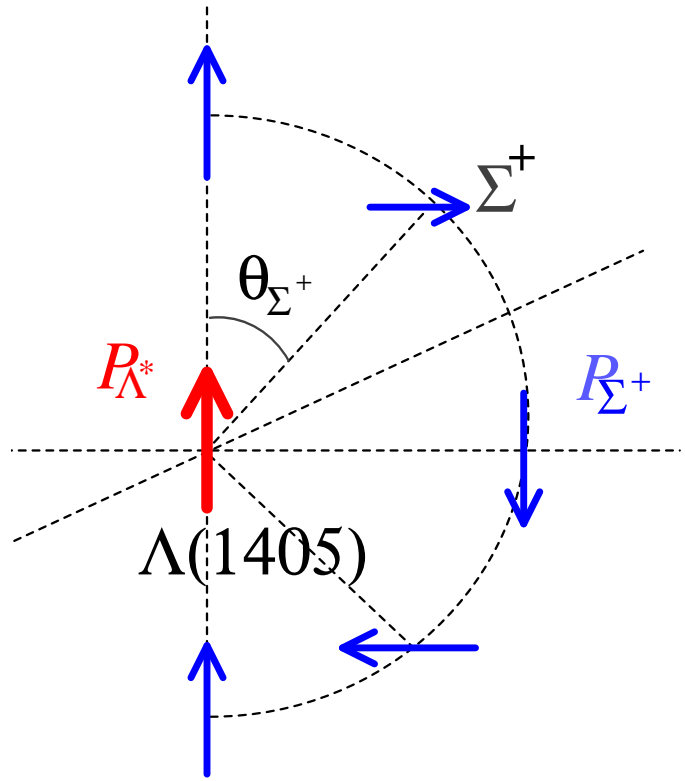
s-wave, p-wave scenario

$$\underline{L = 0 \text{ (s-wave)}}$$
$$\vec{P}_{\Sigma^+} = \vec{P}_{\Lambda^*}$$



$\Lambda(1405) \rightarrow \Sigma\pi$ is s-wave
$\Leftrightarrow J^P = 1/2^-$

$$\underline{L = 1 \text{ (p-wave)}}$$
$$\vec{P}_{\Sigma^+} = |\vec{P}_{\Lambda^*}|\hat{n}(2\theta_{\Sigma^+})$$

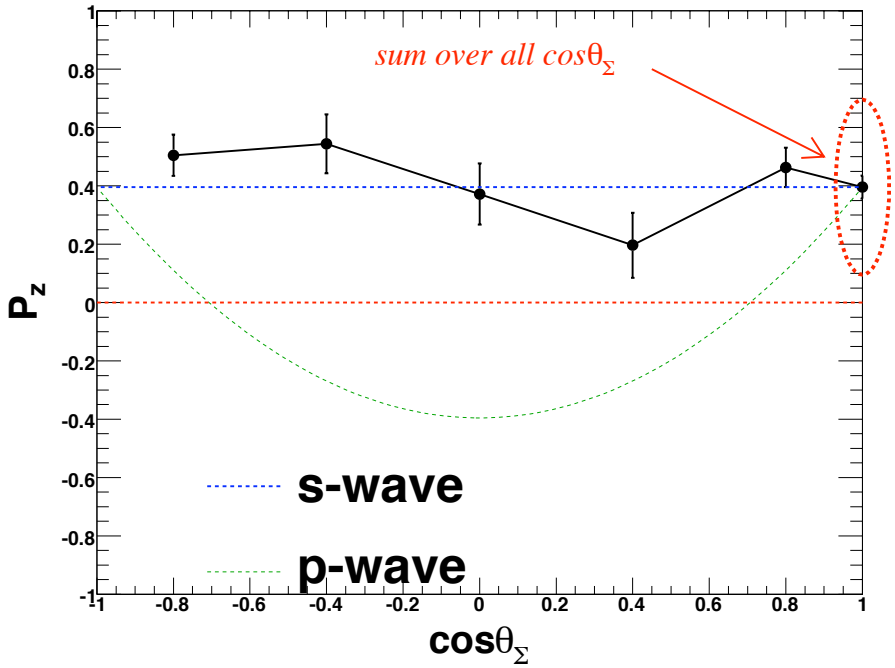


$\Lambda(1405) \rightarrow \Sigma\pi$ is p-wave
$\Leftrightarrow J^P = 1/2^+$

determination of parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

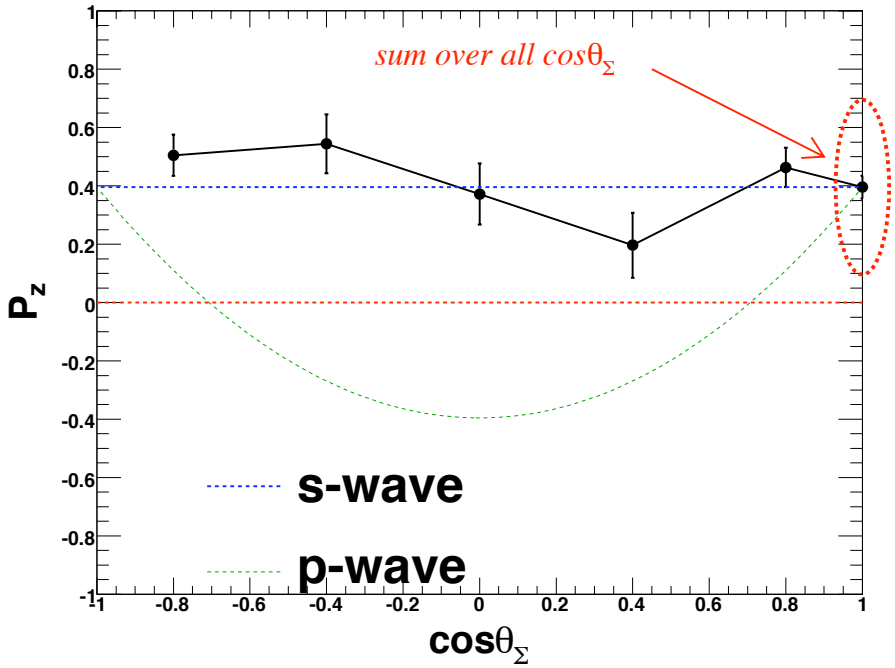
- $W = 2.6$ GeV
- forward K^+angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+\pi^-$,
  $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$



determination of parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward K^+angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+\pi^-$,
  $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$

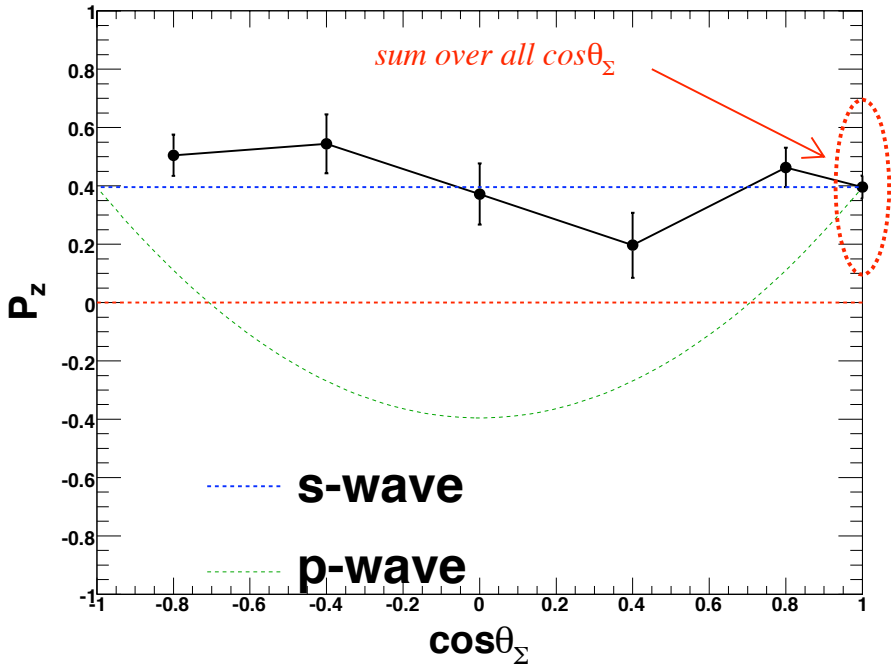


polarization does not change with Σ^+ angle (θ_{Σ^+})

determination of parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward K^+angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+\pi^-$,
  $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$



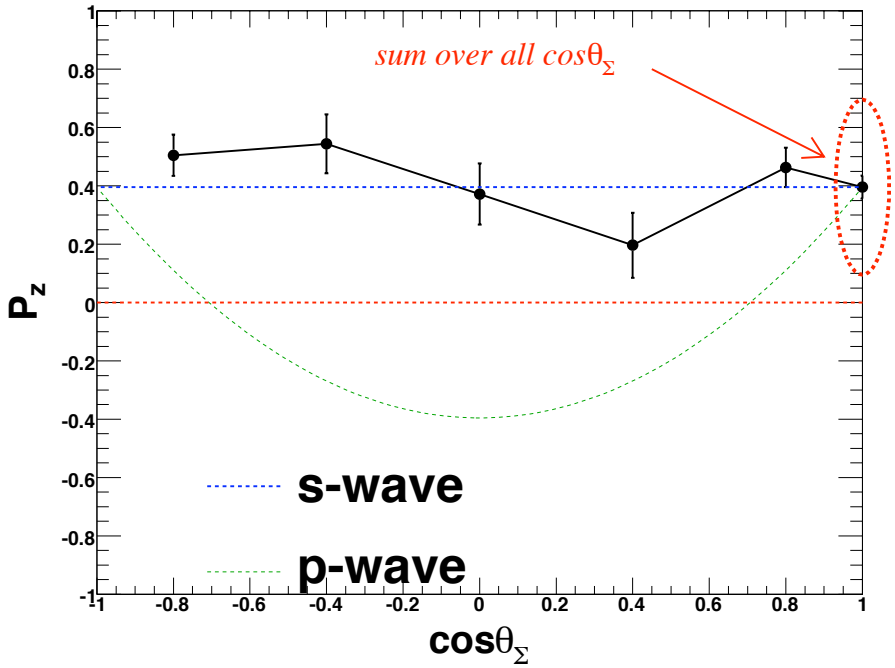
polarization does not change with Σ^+ angle (θ_{Σ^+})

$\Rightarrow J^P = 1/2^-$ is confirmed

determination of parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward K^+angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+\pi^-$,
  $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$



polarization does not change with Σ^+ angle (θ_{Σ^+})

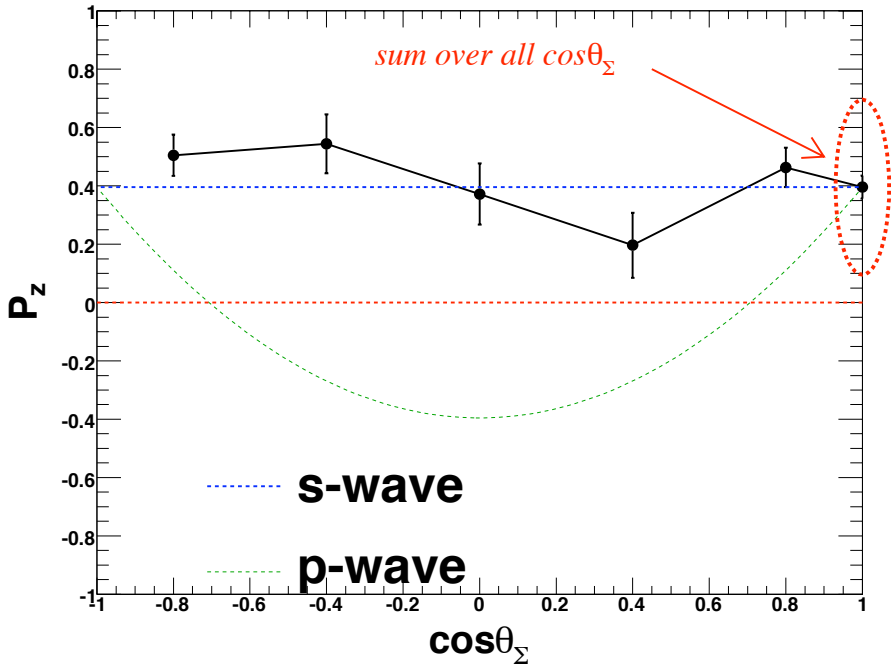
$\Rightarrow J^P = 1/2^-$ is confirmed

furthermore, this measured Σ^+ polarization **is** the $\Lambda(1405)$ polarization

determination of parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward K^+angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+\pi^-$,
  $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$



polarization does not change with Σ^+ angle (θ_{Σ^+})

$\Rightarrow J^P = 1/2^-$ is confirmed

furthermore, this measured Σ^+ polarization **is** the $\Lambda(1405)$ polarization

$\Rightarrow \Lambda(1405)$ is produced with $\sim +40\%$ polarization

conclusion

- high statistics measurement of $\Lambda(1405)$ photoproduction has been done with CLAS at Jlab
- **difference in lineshape** has been observed
- **difference in differential cross section** has been observed
- **spin and parity are experimentally established for the first time**
- **polarization of $\Lambda(1405)$ is found to be $\sim +40\%$ at $W \sim 2.6$ GeV, forward K^+ angles**

$\Rightarrow$ **best evidence to date of possible deviation from a simple qqq-structure.**