New Experimental Opportunities in Spin-Physics for Meson Beams

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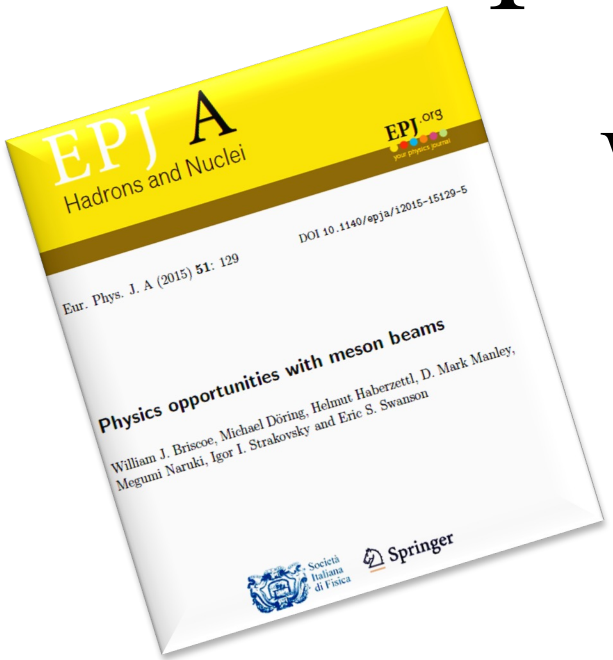
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Physics opportunities with meson beams

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The Need for New Meson Factories

- Electron facilities are producing meson photo- and electro-production data of excellent quality and quantity, much of which is related to spin physics.
- Meson-beam data for corresponding hadronic final states are of poor quality or non-existent.
- Inadequate input to interpret, analyze, and exploit full potential of EM data.
- Very few spin results using polarized targets and/or analysis of recoil particle spin.
- To exploit high-precision EM data, high-quality data from measurements with meson beams, with good angle and energy coverage, are needed to advance knowledge in baryon and meson spectroscopy and related hadron physics.
- We summarize unresolved issues in hadron physics and outline the opportunities and advances only possible with such facilities.

Meson Factories of the mid 20th Century

"*Meson factories are medium-energy accelerators (300-1000 MeV), capable of producing proton beams of much greater intensity than other types of existing machines.*" – The Ramsey Panel: Hans A. Bethe, chairman, Herman Feshbach, Harry Gove, W. W. Havens, Jr., Robert Christy, Gerald Phillips and Robert R. Wilson. Physics Today **17**, 68 (1964).

"*Accelerators that will produce 500—1000 MeV nucleons and mesons in beams thousands of times more intense than existing machines will be able to do experiments never before possible, increase precision of others and reveal processes now unknown*". Louis Rosen Physics Today **19**, 21 (1966)

→ LAMPF (USA), TRIUMF (Canada), SIN (Switzerland)

What Would a Modern Meson Facility Be?

- CM energy range up to 2.5 GeV offers physics opportunities with pion and kaon beams to study baryon and meson spectroscopy issues complementary to EM programs at facilities *e.g.*, JLab, MAMI, ELSA, SPring-8, and BEPC.
- Provides opportunities to contribute to full grasp of high-quality EM data.
- Not a competing effort, but an experimental program that
  - provides the hadronic complement of ongoing EM programs
  - provides common ground for better, more reliable, phenomenological and theoretical analyses. [1,2]

➢ Refs available online with supplemental materials and eventually in the proceedings of this conference.

Hadron Induced Reactions are Important

- White Paper [2] outlined some of the physics programs that could be advanced with new hadron-beam facilities.
- Studies of baryon spectroscopy, particularly search for "*missing resonances*" with hadronic beam data, would be combined with photo- and electroproduction data using coupled-channel analysis.
- A hadron beam facility would also advance hyperon spectroscopy and the study of strangeness in nuclear and hadronic physics where final state particles are self-analyzing.

Hyperon Spectrum is Important

- Well-aligned with goal found in the 2015 *Long Range Plan for Nuclear Science*: "*…a better understanding of the role of strange quarks became an important priority.*" [3]
- Knowledge low-lying spectra of mesons and hyperons very poor compared to that of the nucleon.
- Determination of pole positions and decays.
- Determination of hyperon spectra combined with measurements of spectra of charmonia and B particles at LHCb at CERN allows clearer understanding of soft QCD matter and approach to heavy quark symmetry. [4]

Recent studies that compare *LQCD* calculations of *thermodynamic*, statistical *Hadron Resonance Gas* models, and ratios between measured yields of different hadron species in heavy ion collisions provide indirect evidence for presence of "*missing*" resonances in these contexts.

Contribution order:

- ***Hyperons***
- Non-strange ***Baryons***
- ***Mesons***
- Light ***Nuclei***

Spectroscopy of Baryon and Hyperon Resonances Pion Beams are Needed

- Most knowledge of bound states of light quarks from PWAs of $\pi N \rightarrow \pi N$ scattering.
- Measurements of πN elastic scattering required to determine πN branching ratios.
- Without that - impossible to determine absolute branching ratios for other decay channels.
- Summary of resonance properties is provided in Review of Particle Physics.[5]
- Comparison of experimental results and models → "*missing resonances*".[6]

PDG22 has about **100** baryon resonances →

SU(6) x O(3) implies **434** baryon resonances if the **3 X 70-plets** and **4 X 56-plets** were completely occupied. **LQCD** predicts a similar number of baryon resonances.

Spectroscopy of Baryon and Hyperon Resonances Pion and Kaon Beams

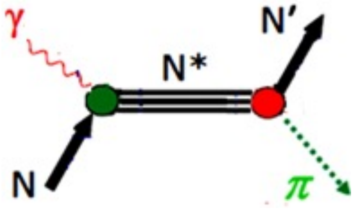
- Most existing Meson data on πN ηN, $K\Lambda$, $K\Sigma$ are 30 - 50 years old. [7]
- In many cases, systematic uncertainties were not reported or underestimated.
- Analyses agree on 4-star resonances visible in elastic πN scattering; poor pion-induced data led different analyses to claim different resonance content.
- No agreement on resonances that couple weakly to the πN channel. [8]
- First determinations of pole position for $\Lambda(1520)$ obtained only recently. [9]
- Intense kaon beams provide opportunities to locate missing resonances and establish properties of decay channels for higher excited states.

Spectroscopy of Baryon and Hyperon Resonances Pion and Kaon Beams

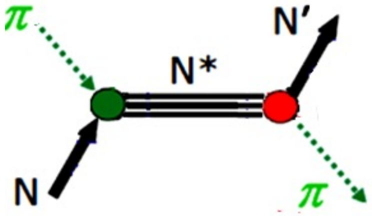
- Goals of EM facilities enhanced by hadron-beam data with quality of EM data.
- A vigorous program in hadronic physics requires facilities with pion/kaon beams.
- A facility in which a "complete program" of $\pi N \rightarrow \pi N$, $\pi^- p \rightarrow K^0\Lambda$, $\pi^- p \rightarrow K^0\Sigma^0$, $\pi^- p \rightarrow K^+\Sigma^-$, and $\pi^+ p \rightarrow K^+\Sigma^+$ can be measured would be very useful.
- *N.B.* hyperons *self analyzing* and thus we get this spin information for free.
- Full solid angle coverage required to study inelastic reactions such as $\pi^- p \rightarrow \eta n$, $\pi^+ p \rightarrow \pi^0\pi^+ p$, strangeness production and other reactions.
- Such a facility should be able to do baryon spectroscopy measurements up to W of about 2.5 GeV; this requires pion beams of about 2.85 GeV/c.
- The 2 GeV/c pion beam at J-PARC allows baryon spectroscopy measurements up to $W \approx 2150$ MeV; measurements are scheduled for the near future.

Studies with Pion Beams

- Measurements of final states involving a single pseudoscalar meson and a spin-1/2 baryon are important.
- Reactions involving πN channels include:



$$\begin{aligned} &\gamma p \to \pi^0 p, \quad && \pi^- p \to \pi^0 n, \\ &\gamma p \to \pi^+ n, && \pi^- p \to \pi^- p, \\ &\gamma n \to \pi^- p, && \pi^+ p \to \pi^+ p, \\ &\gamma n \to \pi^0 n. && \end{aligned}$$



- Data bases for these reactions larger than for other reactions.

More Studies with Pion Beams are Needed

- Figures 1, 2, and 3 summarize available data below center-of-mass energy $W = 2.5$ GeV for $\pi^+ p \to \pi^+ p$, $\pi^- p \to \pi^- p$, and $\pi^- p \to \pi^0 n$, respectively[10].
- πN elastic scattering data[11] allowed establishment of the 4-star resonances[12].
- $\pi N \to \pi N$ data are very old, have high systematic uncertainties and are incomplete.
- Few data A and R for $\pi^- p \to \pi^- p$ and $\pi^+ p \to \pi^+ p$ and for few energies and angles.
- No A and R data for $\pi^- p \to \pi^0 n$ and very few P data; these observables needed to construct unbiased partial-wave amplitudes.
- Dramatic improvement in statistics made possible in modern experimental physics (EPECUR) is demonstrated (for medium energies) in Fig. 4; similar improvement needed at lower energies.

Studies with Meson Beams

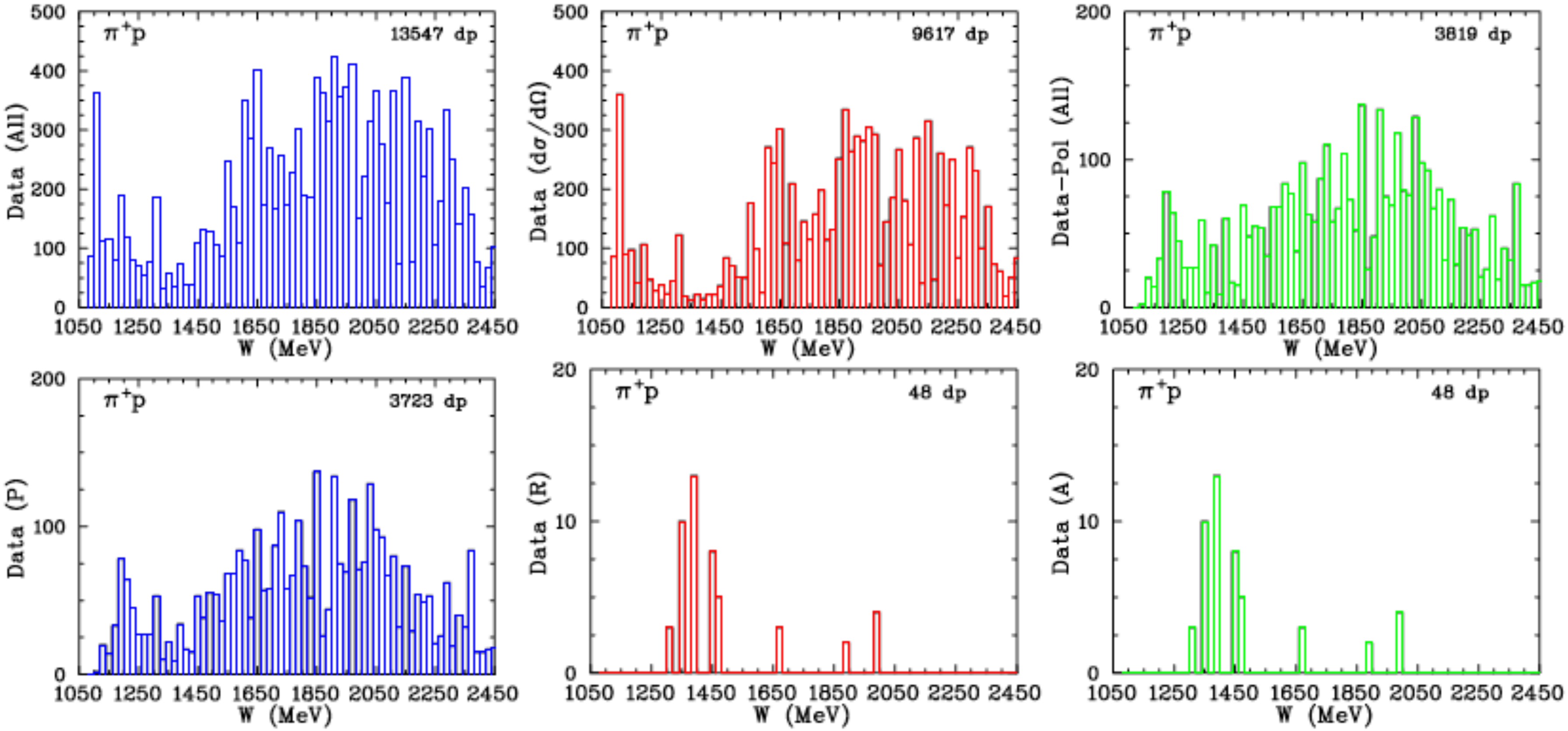


Fig 1 Data available for $\pi^+p \rightarrow \pi^+p$ as a function of *W*. [10] Row 1: (blue) total data for all observables, (red) differential cross-section ($d\sigma/d\Omega$) data, (green) polarization data available. Row 2: (blue) *P* observables data, (red) *R* spin data, (green) *A* spin observable data.

Studies with Meson Beams

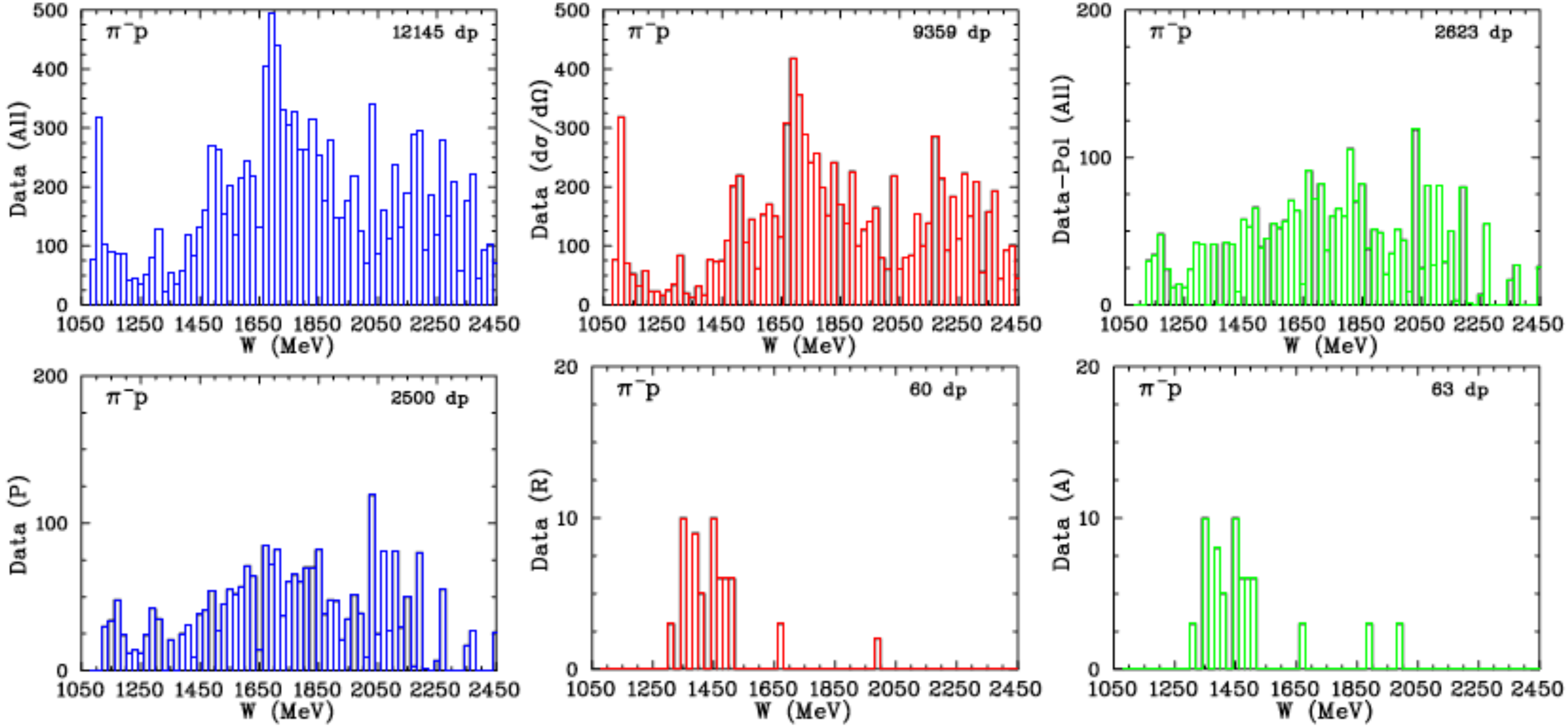


Fig 2 Data available for $\pi^-p \rightarrow \pi^-p$ as a function of W. [10] Row 1: (blue) total amount of data available for all observables, the second plot (red) differential cross-section ($d\sigma/d\Omega$) data, (green) polarization data. Row 2: (blue) P observables data, (red) R spin data available, (green) A spin data.

Studies with Meson Beams

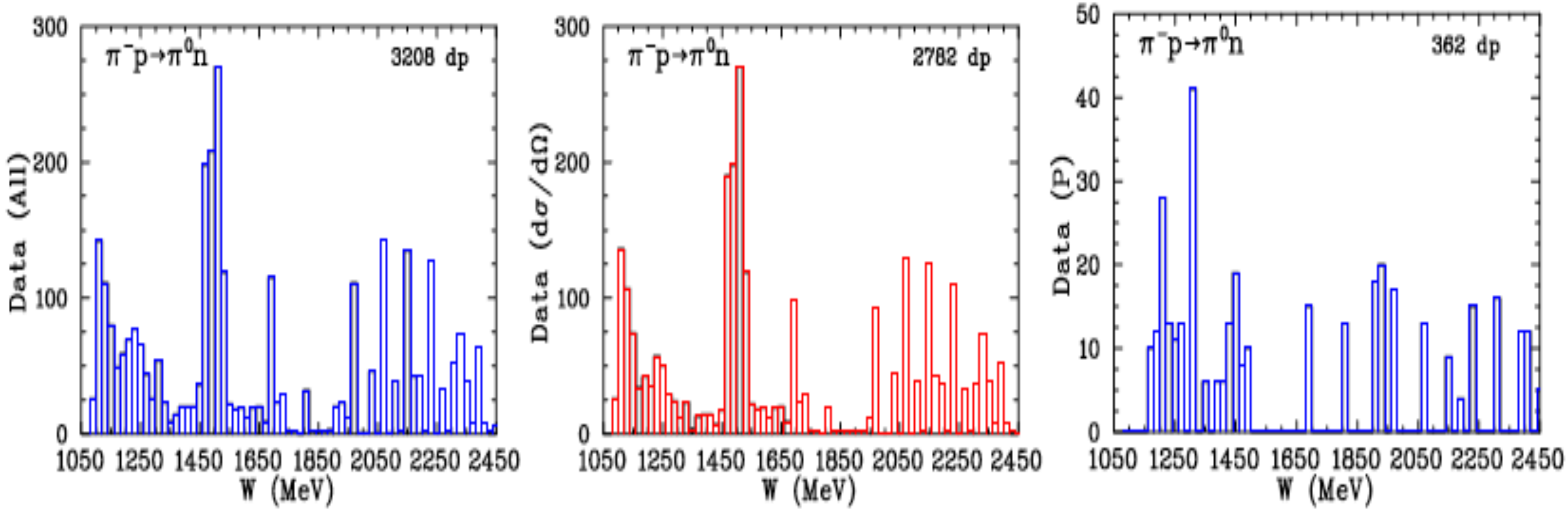


Fig 3 Data available for $\pi^- p \to \pi^0 n$ as a function of W [10]. (blue) shows total amount of data available for all observables, (red) shows differential cross-section (dσ/dΩ) data, (blue) shows the amount of polarization data.

Improved π-p Elastic Scattering Cross Section Measurements for EPECUR

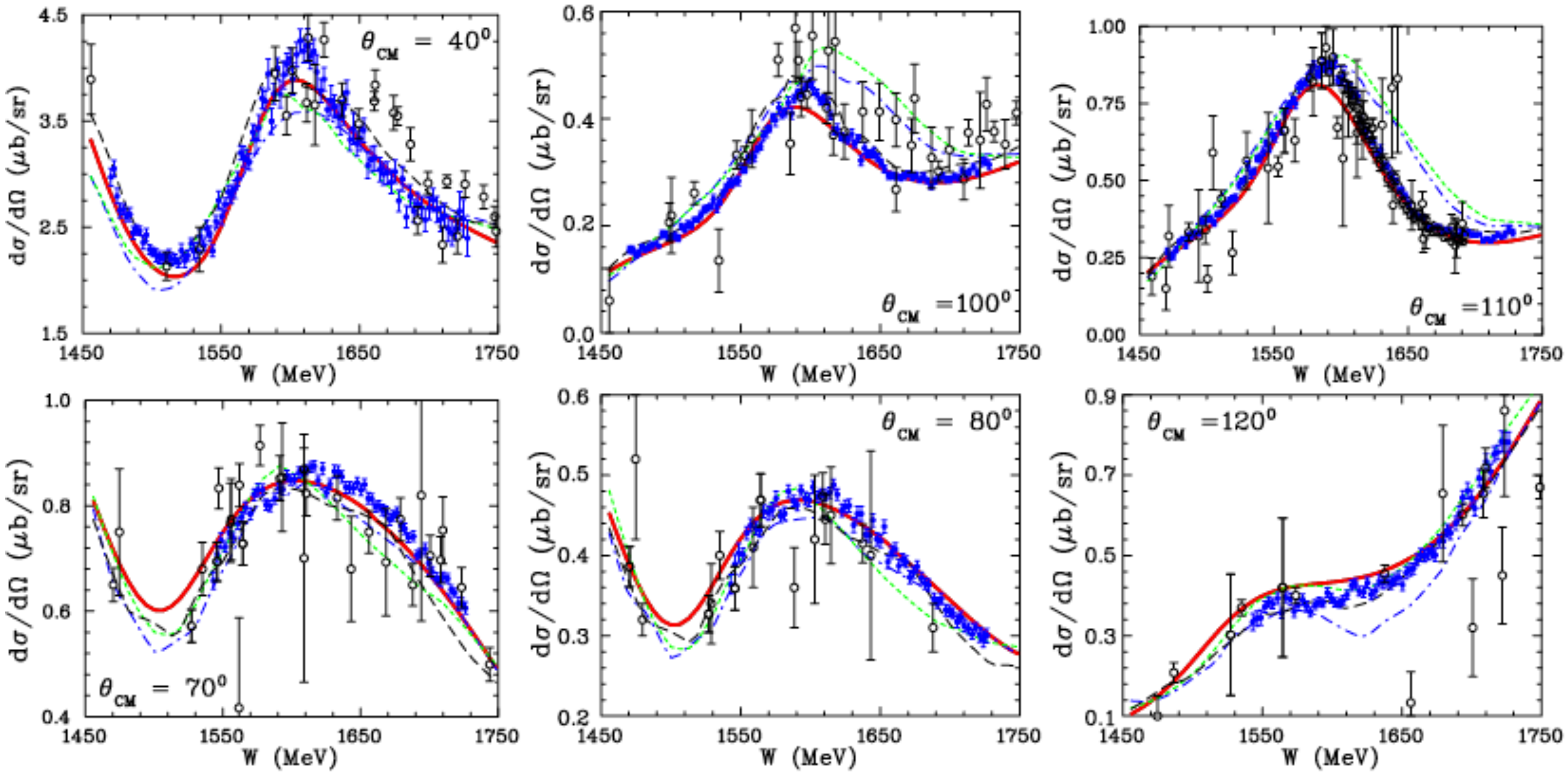


Fig 4 Differential cross section C.M. for π−p (top) and π+p (bottom) elastic scattering. EPECUR data (blue) [13] previous measurements [14] black. Data from earlier experiments within bins of $\Delta\theta_{CM} = \pm 1^0$. GWU fit, WI08 [11] red solid curve, older KH80 [15], KA84 [16], and CMB [17] fits blue dash-dotted, green short dashed, and black dashed curves, respectively.

Studies with Meson Beams

- Reactions including ηN and $K\Lambda$ channels notable – have pure isospin-1/2 contributions:

$$\gamma p \to \eta p, \qquad \pi^- p \to \eta n,$$
$$\gamma n \to \eta n,$$
$$\gamma p \to K^+\Lambda, \qquad \pi^- p \to K^0\Lambda,$$
$$\gamma n \to K^0\Lambda.$$

- Photoproduction reactions significant – opportunity to search for "missing resonances" in reactions that do not involve the πN channel.
- $\gamma p \to \eta p$ reaction key to EM goal of a "*complete measurement*" , a primary goal for our work at JLab.
- Combined γ- and π-induced reactions help separate EM and hadronic vertices.
- Coupled-channel analyses need precise data for $\pi^- p \to \eta n$.

Studies with Meson Beams

- Most $\pi^- p \to \eta n$ data published in 1970s unreliable above $W = 1620$ MeV.
- Measurements of $\pi^- p \to \eta n$ taken in 1990's by Crystal Ball Collaboration [18] – extended to peak of S_{11} at 1535 MeV.
- Figure 5 shows available data below $W = 2.5$ GeV for $\pi^- p \to \eta n$ - few polarization data exist for $\pi^- p \to \eta n$. Ref. [19] - imbalance of γ- *vs*. π-induced η data.
- Only by combining information from analyses of both πN elastic scattering and $\gamma N \to \pi N$ that it is possible to determine the $A_{1/2}$ and $A_{3/2}$ helicity couplings for N^*

Studies with Meson Beams

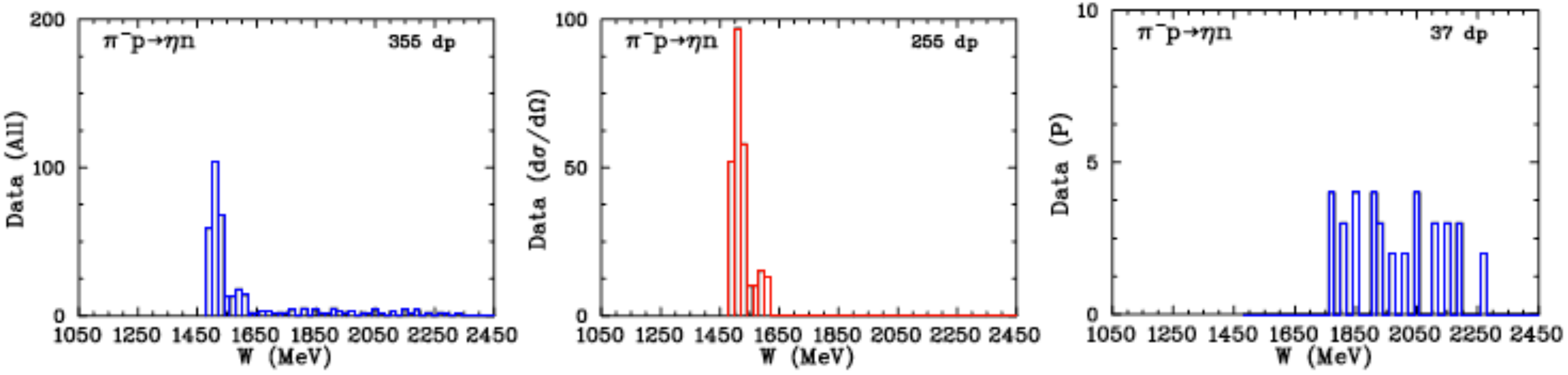


Fig 5 Data for π−p → ηn as a function of W [10]. (blue) total data available for all observables, (red) differential cross-section (dσ/dΩ) data, (blue) polarization data.

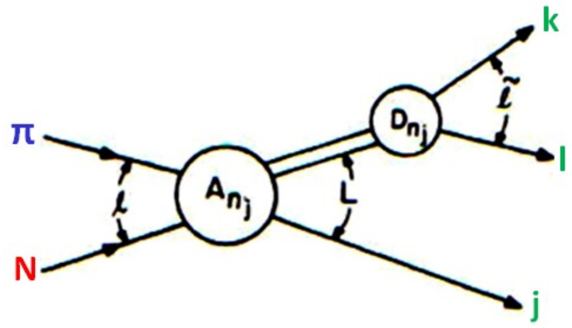
Studies with Meson Beams

- Study $\pi^- p \rightarrow K^0\Lambda$ urged by proposed resonances from $K\Lambda$ photo-production by Bonn-Gatchina [20, 21] and others [22].
- Large branching ratio into $K\Lambda$, pion-induced $K^0\Lambda$ production provides independent reaction to confirm these states.
- New states have weak branching fractions into πN channel.
- Less visible in elastic πN scattering.
- Expect signal of moderate strength for $\pi^- p \rightarrow K^0\Lambda$.

Other Studies with Meson Beams

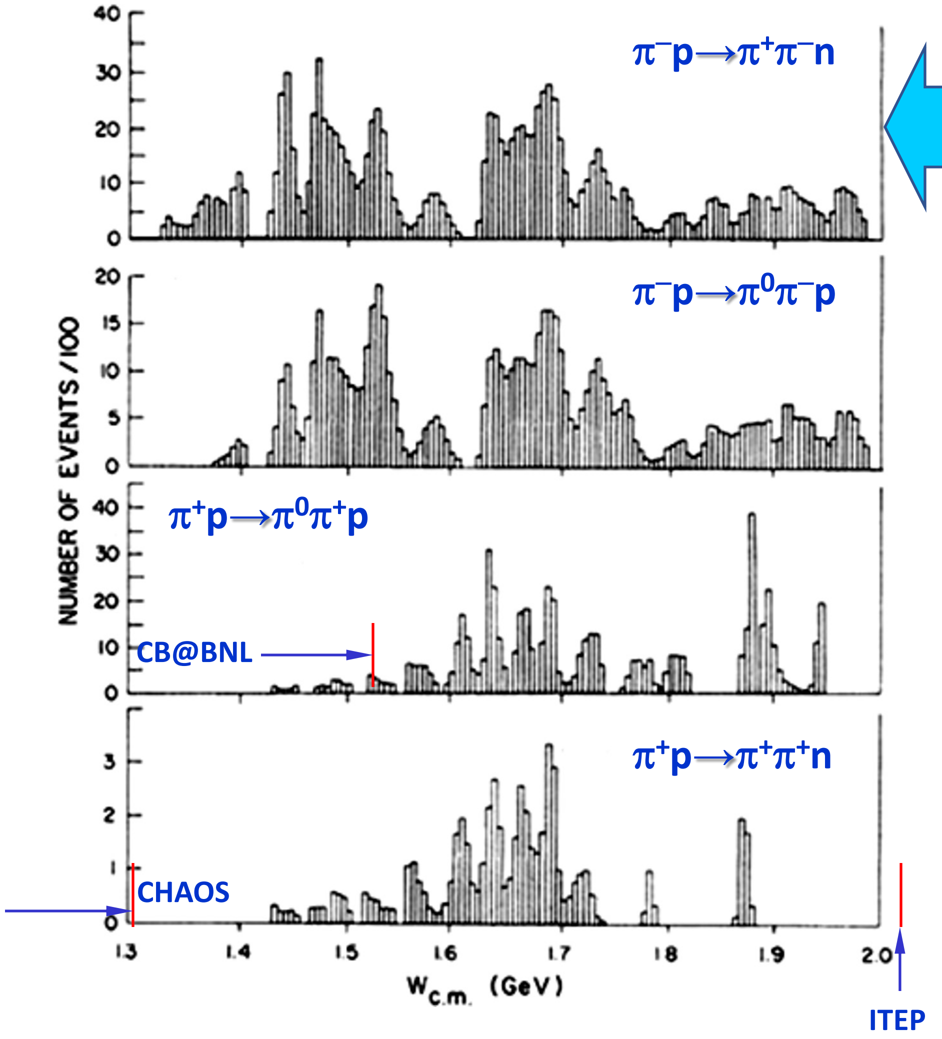
- Other measurable reactions include $\pi\pi N$ final states:

$$\begin{array}{ll} \gamma p \rightarrow \pi^0\pi^0 p, & \pi^- p \rightarrow \pi^0\pi^0 n, \\ \gamma p \rightarrow \pi^0\pi^+ n, & \pi^- p \rightarrow \pi^0\pi^- p, \\ \gamma p \rightarrow \pi^+\pi^- p, & \pi^- p \rightarrow \pi^+\pi^- n, \\ \gamma n \rightarrow \pi^0\pi^0 n, & \pi^+ p \rightarrow \pi^0\pi^+ p, \\ \gamma n \rightarrow \pi^0\pi^- p, & \pi^+ p \rightarrow \pi^+\pi^+ n, \\ \gamma n \rightarrow \pi^+\pi^- n. & \end{array}$$



- Analysis/interpretation more complicated – involve 3-body final states.
- $\pi N \rightarrow \pi\pi N$ - lowest energy threshold of inelastic channels & some of the largest cross sections.
- For most established N^* and Δ^* resonances, dominant inelastic decays go to $\pi\pi N$ final states.
- Much of $\pi N \rightarrow \pi\pi N$ information comes from bubble-chamber data analyzed in isobar-model PWA at W = 1320 to 1930 MeV [30].
- Need high-quality, high-statistics data for $\pi N \rightarrow \pi\pi N$ data that can be analyzed together with complementary data for $\gamma N \rightarrow \pi\pi N$ channels.
- To come from E45 J-PARC scheduled for 2025.

Preparation for J-PARC/E45 ➡ $\pi p \longrightarrow \pi\pi N$ *Measurements*



- **241,214 old Bubble Chamber** events for **$\pi p \to \pi\pi N$** analyzed in **Isobar-model PWA** at **W** = **1320** to **1930** MeV.

  Manley, Arndt *et al,* Phys Rev D **30**, 904 (1984)

- Post-Bubble Chamber measurements:
  - **349,611** events for **$\pi^- p \to \pi^0\pi^0 n$** from **CB@BNL** at **W** = **1213** to **1527** MeV.

    Prakhov *et al,* Phys Rev C **69**, 045202 (2004)
  - **20,000** events for **$\pi^{+-} p \to \pi^{+-}\pi^{-+} n$** from **CHAOS@TRIUMF** at **W** = **1257** to **1302** MeV.

    TRIUMF

    Kermani *et al,* Phys Rev C **58**, 3431 (1998)
  - **40,000** events for **$\pi^- \vec{p} \to \pi^-\pi^+ n$** from **ITEP** at **W** = **2060** MeV. (off chart)

    Alekseev *et al,* Phys At Nucl **61**, 174 (1998)

Other Studies with Meson Beams

- Related reactions involve the $K\Sigma$ channel:

$$\gamma p \to K^+\Sigma^0, \qquad \pi^- p \to K^0\Sigma^0,$$
$$\gamma p \to K^0\Sigma^+, \qquad \pi^- p \to K^+\Sigma^-,$$
$$\gamma n \to K^+\Sigma^-, \qquad \pi^+ p \to K^+\Sigma^+,$$
$$\gamma n \to K^0\Sigma^0.$$

- Except for $\pi^+ p \to K^+\Sigma^+$, these involve mixture of isospin 1/2 and 3/2.
- There are number of high-quality measurements involving $K\Sigma$ photoproduction, status of pion-induced reactions is rather dismal.
- Fewer data for $\pi^- p \to K\Sigma$, $\eta' N$, ωN, and φN than $\pi^- p \to \eta n$.

Other Studies with Meson Beams

- Neutral hyperons Λ^* and Σ^* were systematically studied in formation processes:

$$K^-p \to K^-p, \qquad K^-p \to \pi^+\Sigma^-,$$
$$K^-p \to K^0n, \qquad K^-p \to \pi^0\Sigma^0,$$
$$K^-p \to \pi^0\Lambda, \qquad K^-p \to \pi^-\Sigma^+.$$

- Analyses of $K^-p \to \pi^0\Lambda$ yield fits agree for differential cross section and polarization, but differ for spin rotation parameter β. [36,37]
- Data for β are limited to measurements at only seven energies. [38]
- β more sensitive to contributions from high PWs than $d\sigma/d\boldsymbol{\Omega}$ or polarization.
- Need new measurements with polarized target.

Other Studies with Meson Beams

- In addition, Σ^{*-} can be produced in K^-n reactions with a deuteron target:

$$K^-n \to \pi^-\Lambda, \qquad K^-n \to \pi^0\Sigma^-, \quad K^-n \to \pi^-\Sigma^0.$$

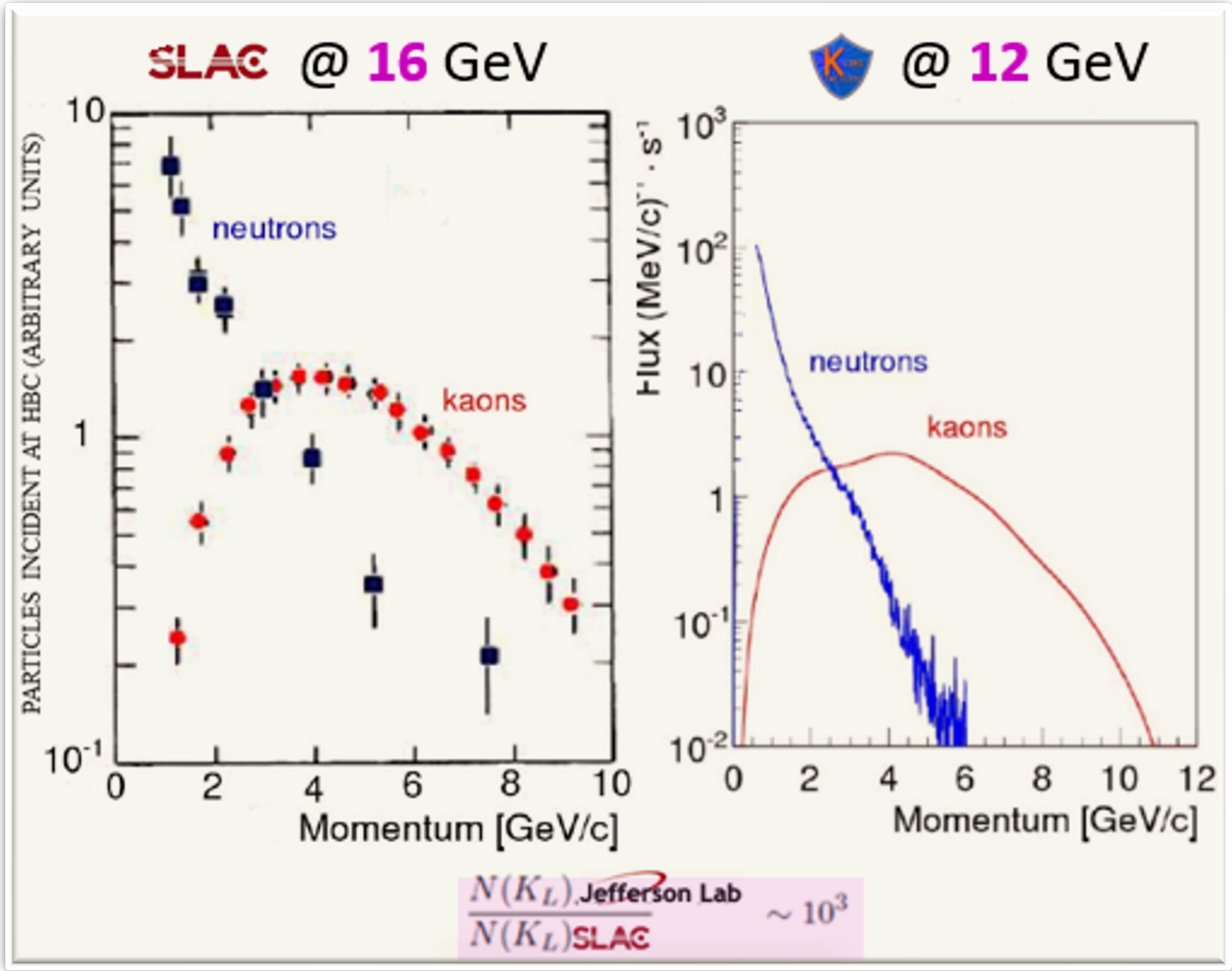
- PWA powerful for disentangling overlapping states, especially above 1.6 GeV/c^2 for Λ^* (Σ^*) resonances.
- *N.B.* $\Lambda(1405)1/2^-$ and $\Sigma(1385)3/2^+$ lie below the KN threshold; properties of these states obtained only through production processes such as

$$K^-p \to \pi^-\Sigma^{*+} \to \pi^-\pi^+\Lambda^*.$$

- t-channel process provides "*virtual*" K^0 beam – allows production of Σ^{*+}.
- $\Lambda(1405)1/2^-$ and $\Sigma(1385)3/2^+$ identified in decay of $\Sigma\pi$ and $\Lambda\pi/\Sigma\pi$.

The K-Long Experiment at Jefferson Lab

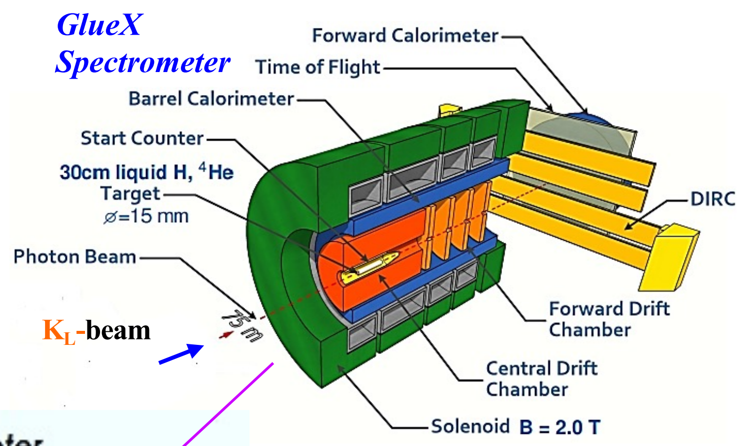
- The K-Long project approved to build a secondary K_L beam line in Hall D at Jefferson Lab with a *flux three order of magnitude higher* than SLAC.
- Scattering experiments on both *proton* and *neutron* targets.
- *First hadronic facility at Jefferson Lab.*
- We will measure *differential cross sections* and *(self) polarization* of *hyperons* with ***GlueX*** detector to enable precise *PWA* to determine ***all resonances*** up to W=2500 MeV.
- We will perform *strange meson spectroscopy* to locate *pole* positions in I = *1/2 and 3/2* channels.

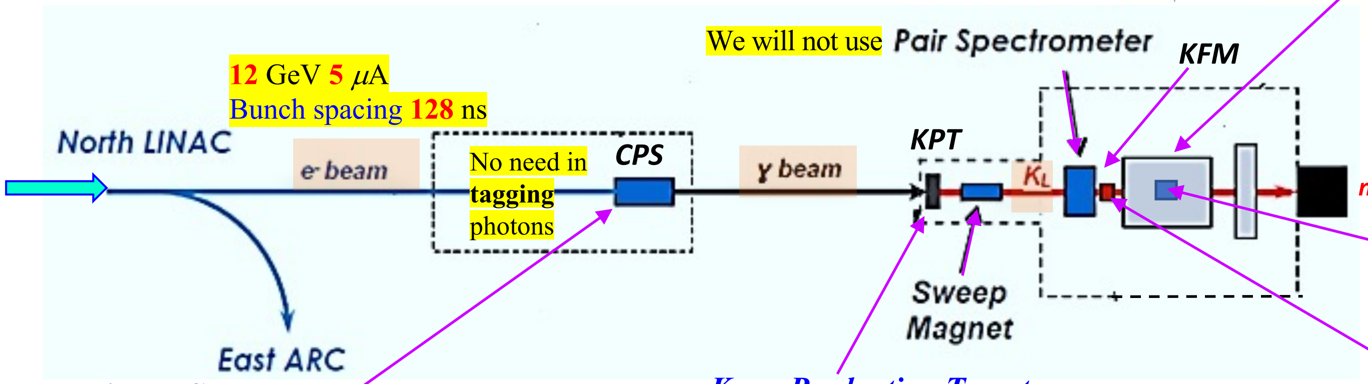


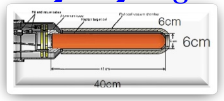
$$\frac{N(K_L)\ \text{Jefferson Lab}}{N(K_L)\ \text{SLAC}} = 10^3$$

Hall D Beam Line for

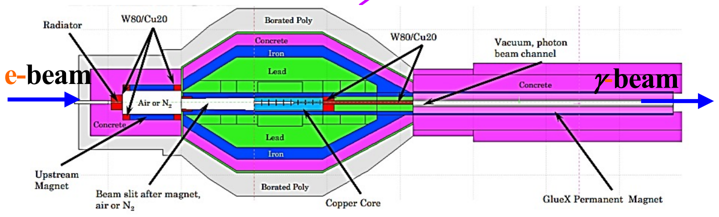
D. Day *et al*. Nucl Instrum Meth A **957**, 163429 (**2020**)



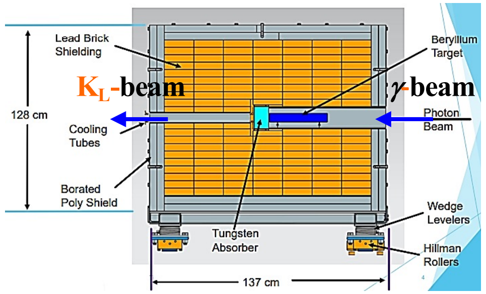




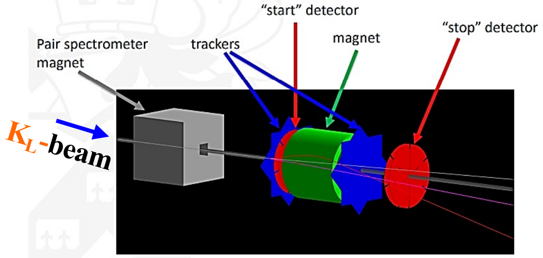
Compact Photon Source



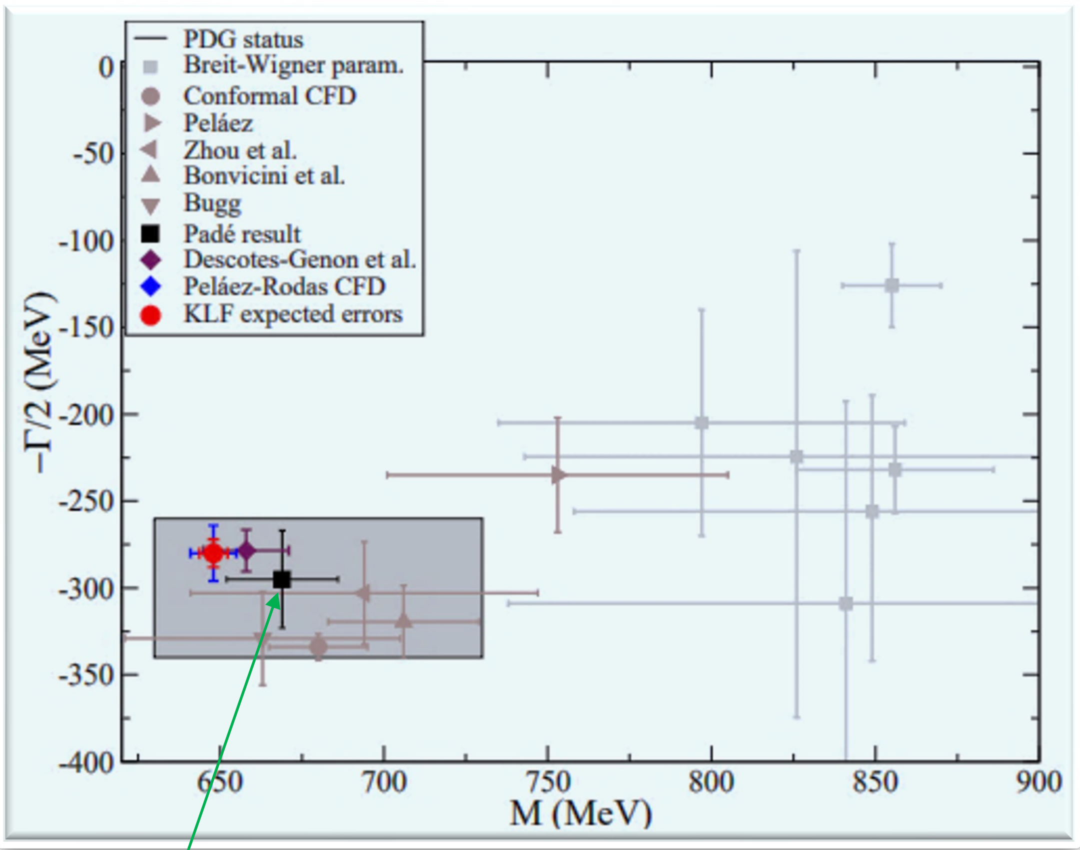
Kaon Production Target



Kaon Flux Monitor



Summary of Meson Spectroscopy



100 days

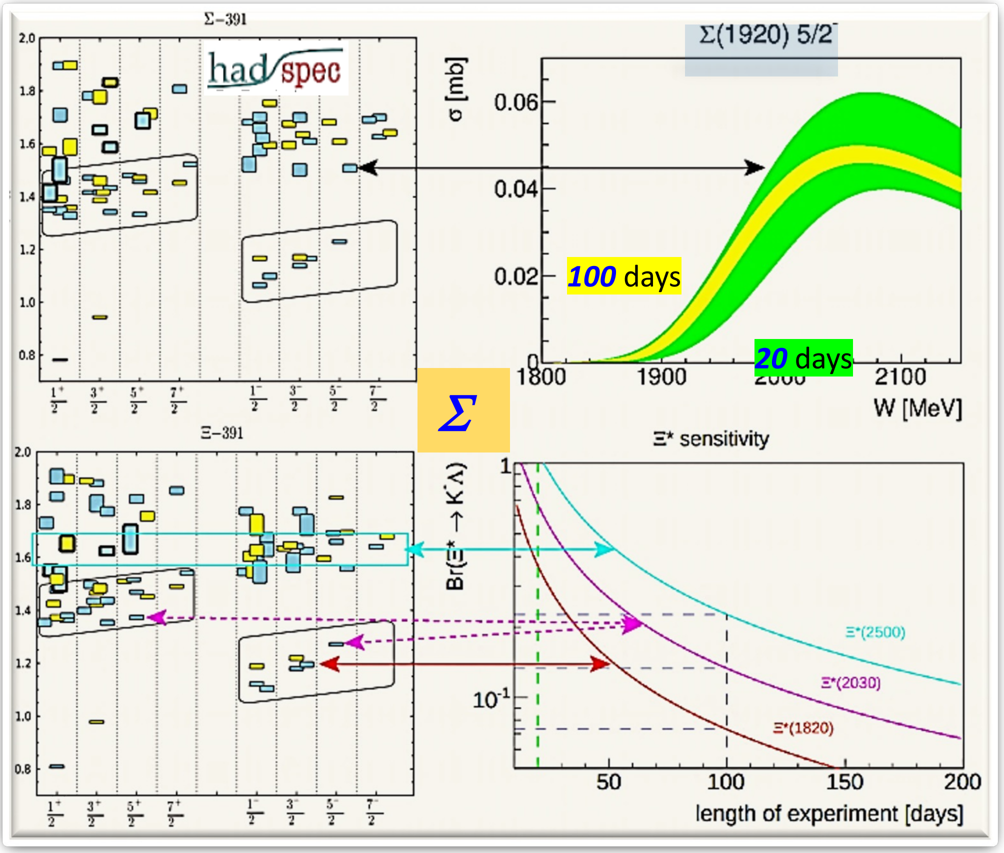
- *Roy-Steiner* dispersion approach
  $M - i\Gamma/2 = (648 \pm 4) - i(280 \pm 8)$ MeV

J.R. Pelaez *et al* Phys Rev D **93**, 074025 (2016)

K(700)*

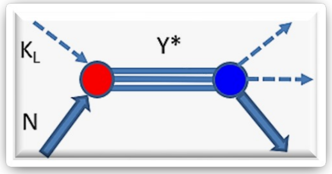
- K_L – significant *impact* on knowledge of Kp *scattering amplitudes*.
- Improve determination of *heavy K* parameters*.
- Help to settle tension between phenomenological determination of *scattering lengths* from data vs calculations based on *ChPT & LQCD*.
- For *K*(700)*, it will reduce:
  - *uncertainties* in *mass* by factor of *two* and
  - *uncertainties* in *width* by factor of *five*. .
- Settle long-debated *existence* of *scalar* meson *nonet*.

Summary of Hyperon Spectroscopy with K_L Beam



R. G. Edwards *et al*, Phys Rev D **87**, 054506 (2013)

- K_L sensitivity with *100 days* of running will allow the discovery of many *hyperons* with good precision.
- *Why should it be done with K_L beam* ?
  Only realizable way to observe ***s***-channel resonances having all ***momenta*** of K_L at once ("*tagged*" *kaons*) .

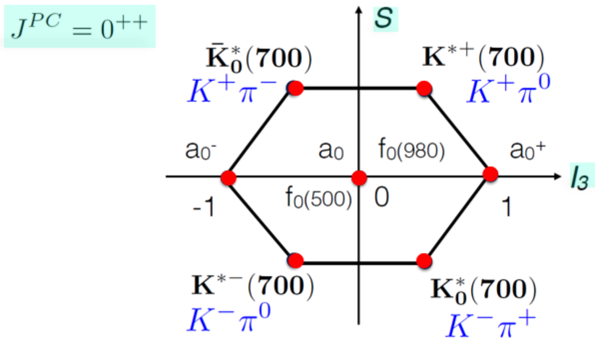


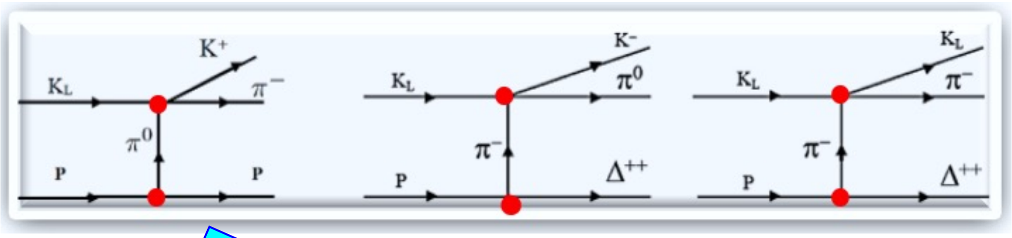
- *Why should it be done at Jefferson Lab*?
  No other existing facilities where this can be done.
- *Why should we care about dozens of missing states* ?
  Goal of the LRP!

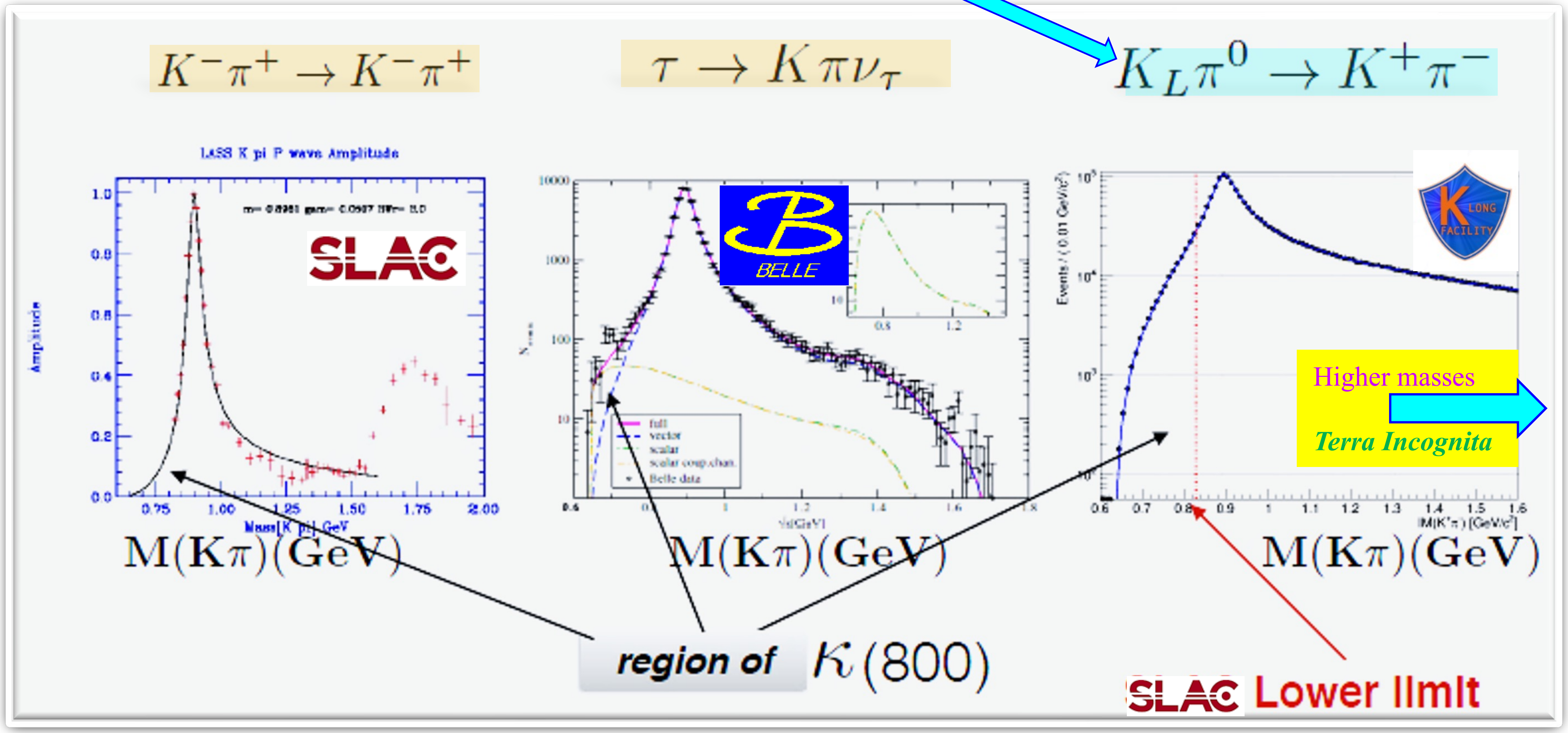
…The new capabilities of the 12-GeV era facilitate a detailed study of baryons containing two and three strange quarks. Knowledge of the spectrum of these states will further enhance our understanding of the manifestation of QCD in the three-quark arena.

2015 *LRP* for Nuclear Science.

Proposed Measurements for $K\pi$ Scattering



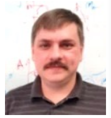




E12-19-001

Strange Hadron Spectroscopy with Secondary K_L Beam in Hall D

arXiv:2008.08215v2 [nucl-ex] 14 Sep 2020



Experimental Support:

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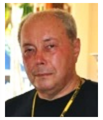

Extensive Theoretical Support

e-Print: 2008.08215 [nucl-ex]

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E12-12-19-001

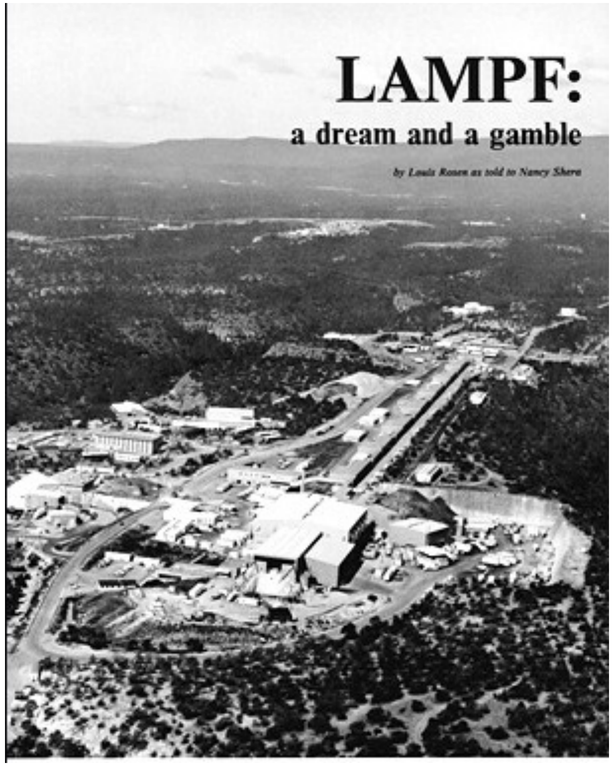
This Happens because of Strong Support & Dedicated Efforts of Collaboration

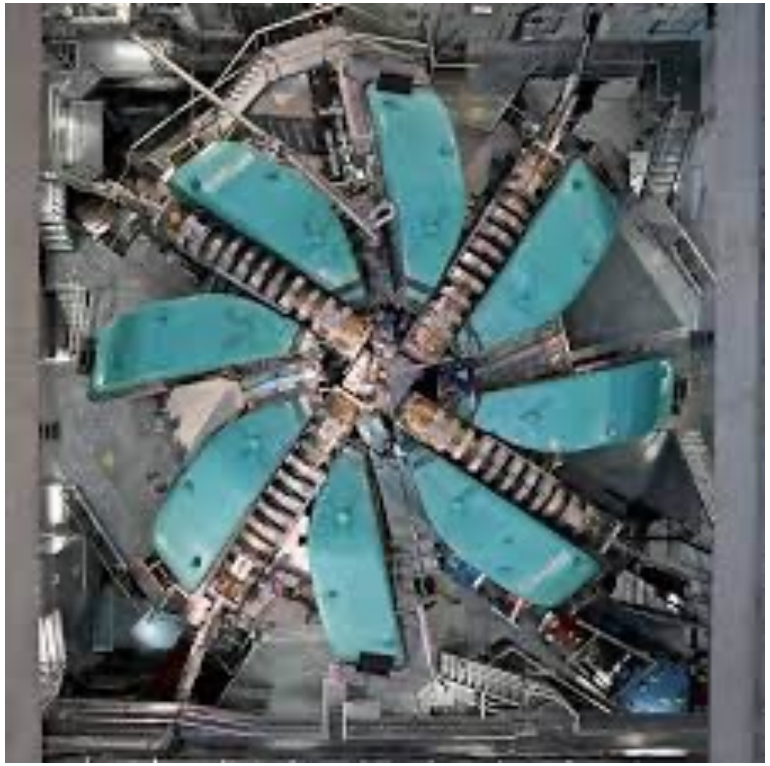
126 experimentalists &
42 theorists
from 74 labs
across 20 countries
worldwide

Summary – What is Needed Today

- Goals of EM facilities greatly enhanced by having hadron-beam data comparable to that of EM data.
- Vigorous program in hadronic physics requires modern meson facilities with pion and kaon beams.
- "Meson Factory" in which πN elastic scattering and the reactions *e.g.* $\pi^- p \to K^0\Lambda$, $\pi^- p \to K^0\Sigma^0$, $\pi^- p \to K^+\Sigma^-$, and $\pi^+ p \to K^+\Sigma^+$ can be measured with high precision.
- Full solid angle coverage to study inelastic reactions: $\pi^- p \to \eta n$, $\pi^+ p \to \pi^0\pi^+ p$, among others.
- Baryon spectroscopy measurements up to W of ~2.5 GeV would require π beams with of ~2.85 GeV/c.
- The 2 GeV/c pion beam at J-PARC allows baryon spectroscopy measurements to $W \approx 2150$ MeV.
- Kaon beams such as produced by the K_L experiment would allow performance of a full range of experiments as described.

Thanks for Listening





Supplemental Material

- Available online
- Stuff for longer talk
- Stuff for the proceedings
- References

Studies with Meson Beams

- Striking example of why improved data for pion-induced kaon production are necessary is given by the $N(1710)1/2^{+}$.
- Properties/existence debated – intimately intertwined with the reaction $\pi^{-}p \rightarrow K^{0}\Lambda$; similar arguments apply to the $N(1900)3/2^{+}$. [23]
- The latter resonance was also found in kaon photoproduction [22], which makes its study in the reaction $\pi^{-}p \rightarrow K^{0}\Lambda$ especially promising.
- Precise data for $\pi^{-}p \rightarrow K^{0}\Lambda$ (combined with $K^{-}p \rightarrow K^{0}\Xi^{0}$) enable study of SU(3) flavor symmetry and its breaking.
- SU(3) flavor symmetry relations could be confirmed to surprising accuracy by comparing the reactions $\pi^{-}p \rightarrow \eta n$ and $K^{-}p \rightarrow \eta\Lambda$. [24]
- Simultaneous study of $\pi^{-}p \rightarrow K^{0}\Lambda$ and $K^{-}p \rightarrow K^{0}\Xi^{0}$ would allow for another test of SU(3) flavor symmetry.

Studies with Meson Beams

- Drop in $\gamma N \rightarrow K^0\Sigma^+$ σ, with change in $d\sigma/d\Omega$ at ELSA[27] should be visible in $\pi N \rightarrow K\Sigma$[28]; better measurements of πN needed to shed light on this.
- $\pi^- p \rightarrow K^+\Sigma^-$ where no meson t-channel exchanges possible sensitive to u-channel exchanges; models[29] cannot describe σ near $W = 2$ GeV - new resonances.
- Self-analyzing property of hyperons allows measuring P with improved accuracy in future J-PARC experiments.
- Measurements of $d\sigma/d\Omega$ & P will be possible at J-PARC; we encourage this activity.
- $\pi N \rightarrow K^0\Lambda$, $K^0\Sigma^0$, $K^+\Sigma^-$, and $K^+\Sigma^+$ yields complementary/exclusive information compared to γN.
- Larger angular range, smaller systematic uncertainties, finer energy bins needed to confirm recently discovered resonances, to discover new resonances inaccessible in photoproduction, and to test theoretical multichannel concepts.

Studies with Meson Beams

- Few data for $\pi^- p \rightarrow \omega n$ lead to ambiguous PWA solutions in PWAs[31] and are worthless in constraining PWAs of ω photoproduction.
- ωN threshold region attractive to searching for new resonances – reaction threshold is located at the higher-energy edge of the third resonance region – the RPP[5] shows 7 N^* states with mass 1650 – 1720 MeV.
- This energy range may contain unknown N^* resonances that couple more strongly to ωN than to other meson-baryon channels.
- Signs for resonances with low star rating have recently been found in $\eta' N$ production. [32, 33]
- In φ photoproduction, broad, pronounced structure for $E_\gamma = 1.8 – 2.3$ GeV was found [34] that could come from a resonant state; it should be visible in pion-induced φ production, for which little data exist. [35]
- More precise data from pion beams would help clarify all three situations.

Studies with Meson Beams

- Spin and parity of $\Lambda(1405)$ measured in $\gamma p \to K^+\Lambda(1405)$ - confirmed to be $1/2^-$ as expected[39]; nature of $\Lambda(1405)^{1/2-}$ still an issue.
- Lineshape of $\Lambda(1405)$ depends on reaction channel [40 - 42]; comparing p- and K-induced reactions with photoproduction important.
- Lineshape of $\Lambda(1405)$ differs in $\pi^+\Sigma^-$ and $\pi^-\Sigma^+$ decays – result of isospin interference between different $\pi\Sigma$ channels.
- The $\pi^\pm\Sigma^\mp$ spectra measured in $\pi^-p \to K^0\Lambda(1405)$ [43] and $K^-p \to \pi^+\pi^-\Lambda(1405)$ [44] and neutral $\pi^0\Sigma^0$ measured in $K^-p \to \pi^0\pi^0\Sigma^0$ [45].
- Observed peak position near 1405 MeV in charged $\pi\Sigma$ spectra; peak in the neutral channel is near 1420 MeV. All three $\pi\Sigma$ channels studied recently in a single experiment using the $\gamma p \to K^+\Sigma\pi$ reaction [46].
- Efforts in the lineshape study ongoing at JLab and J-PARC.

Studies with Meson Beams

- Cascades can be studied with high-momentum kaon beams and multiparticle spectrometers.
- Our knowledge of multi-strange baryons obtained from data measured with bubble chambers, lack of appropriate beams and detectors limited our knowledge.
- Only cascade ground states of spin-1/2 and spin-3/2 are well identified.
- Production of excited states possible kaon beams:

$$K^- p \rightarrow K^+ \Xi^{*-},\ K^- p \rightarrow K^{*+} \Xi^{*-},\ K^- p \rightarrow K^{*0} \Xi^{*0}.$$

- Model-independent guidance for analyzing processes and theory found in Refs. [47, 48]
- Other production processes with single or multi pions *e.g.:*

$$K^- p \rightarrow K^+ \pi^+ \pi^- \Xi^{*-},\ K^- p \rightarrow K^+ \pi^- \Xi^{*0}.$$

- Analysis of decay vertex efficient for suppressing background processes; masses, widths, and decay modes to be studied at J-PARC.
- These measurements will be complementary to planned measurements at CLAS12 to study Ξ^* states via several reactions such as $\gamma p \rightarrow K^+ K^+ (\Xi^{*-})$ and $\gamma p \rightarrow K^+ K^+ \pi^- (\Xi^{*0})$. [49]

Studies with Meson Beams

- High-momentum kaon beams are crucial for producing Ω baryons in the inclusive reaction $K^- p \longrightarrow \Omega^{*-} X$ by measuring decay particles.
- The Ω^- production mechanism should be quite specific since it is the first baryon with constituents of which none could come from the target proton.
- These measurements will be complementary to planned measurements at CLAS12 to measure Ω photo- production on the proton target. [49]
- Specific plans are to make the first precise measurement of the Ω^- differential cross section in $\gamma p \longrightarrow \Omega^- K^+ K^+ K^0$ and to search for Ω^* resonances.

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