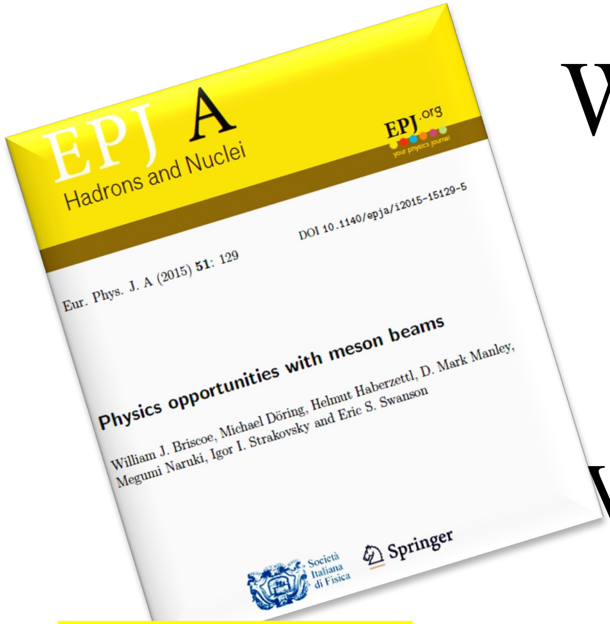
Experimental Opportunities in for Meson Beams at EIC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Physics opportunities with meson beams

William J. Briscoe, Michael Döring, Helmut Haberzettl, D. Mark Manley, Megumi Naruki, Igor I. Strakovsky and Eric S. Swanson

Società Italiana di Fisica
Springer

W.J. Briscoe and Igor Strakovsky

Department of Physics
The George Washington University
Virginia Science and Technology Campus
Ashburn, VA 20147

2015 White Paper
135 endorsers from 77 labs worldwide

The Need for New Meson Factories

- In recent years, electron facilities have measured meson photo- and electro-production data of excellent quality and quantity.
- Much of the outdated meson-beam data for corresponding hadronic final states are of poor quality or non-existent and provide inadequate input to interpret, analyze, and exploit the full potential of the EM data..
- To exploit the high-precision EM data, high-statistics data from measurements with meson beams with good angle and energy coverage are needed to advance the field in baryon and meson spectroscopy and related areas of hadron physics.
- Here we summarize unresolved issues in hadron physics and outlines the opportunities and advances only possible with such a facility.
- To connect this with the EIC we show the inroads we made in developing a conceptual justification for JLEIC with the hopes that we can develop a similar effort for the EIC at BNL.

A Little History: What was a Meson Factory in 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?

- It would have a CM energy range of at least 2.5 GeV to exploit the physics opportunities with pion and kaon beams complementary to EM programs at facilities: JLab, MAMI, ELSA, SPring-8, and BEPC.
- New higher energy and intensity meson facilities can contribute to the fuller understanding of recent high-quality EM data.
- This is not a competing effort, but an experimental program that
  - provides the hadronic complement of ongoing EM programs and
  - provides common ground for better, more reliable, phenomenological and theoretical analyses. [1,2]

➢ Refs available online with supplemental.

Hyperon Spectrum is Important

- This program well-aligned with a 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 of the low-lying spectra of mesons and hyperons is very poor in comparison with that of the nucleon.
- Better determination of pole positions and decays are needed.
- Determination of hyperon spectra combined with measurements of spectra of charmonia and B particles at LHCb at CERN allows for clearer understanding of soft QCD matter and the 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 current knowledge about the bound states of three light quarks comes from PWAs of πN → πN scattering performed at Meson Factories.
- More recant measurements of πN elastic scattering are required to determine absolute πN branching ratios.
- Without that information it is impossible to determine the 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

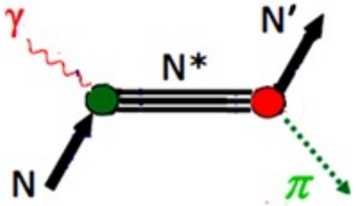
- Most existing Meson data on πN ηN, $K\Lambda$, $K\Sigma$ are 30 - 40 years old. [7]
- In many cases, systematic uncertainties were not reported or underestimated.
- While analyses agree on 4-star resonances visible in elastic πN scattering; poor pion-induced data led different analyses to claim inconsistent resonance content.
- No conclusive agreement on resonances that couple weakly to πN channel. [8]
- First determinations of pole position for $\Lambda(1520)$ obtained only recently. [9]
- Intense kaon beams would 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

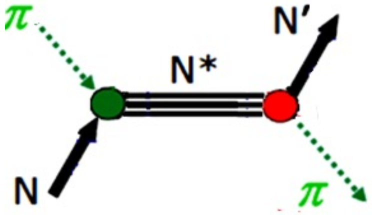
- Results of current EM facilities would be enhanced by high-quality hadron-beam data.
- A new program in hadronic physics requires both pion and kaon beams.
- A facility in which a "complete program" of $\pi N \rightarrow \pi N$, $\pi^- p \rightarrow K^0\Lambda$, $\pi^- p \rightarrow K^0\Sigma^0$, $\pi^- p \rightarrow K^+\Sigma^-$, and $\pi^+ p \rightarrow K^+\Sigma^+$ can be measured is essential;
- N.B. hyperons - self analyzing - get spin information for free.
- Full solid angle coverage to study inelastic reactions *e.g.*, $\pi^- p \rightarrow \eta n$, $\pi^+ p \rightarrow \pi^0\pi^+ p$.
- Should be able to perform baryon spectroscopy measurements to W ≥ 2.5 GeV; this requires pion beams ≥ 2.85 GeV/*c*.
- The 2 GeV/*c* pion beam at J-PARC only allows measurements to $W \approx 2.15$ GeV.

Status of Studies with Pion Beams

- Measurements of final states involving a single pseudoscalar meson and spin-1/2 baryons 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.

Why More Studies with Pion Beams are Needed

- Figures 1, 2, and 3 summarize current data $W < 2.5$ GeV for $\pi^+ p \to \pi^+ p$, $\pi^- p \to \pi^- p$, and $\pi^- p \to \pi^0 n$, respectively.
- πN elastic scattering data[11] allowed establishment of 4-star resonances[12].
- $\pi N \to \pi N$ data are old, have large systematic uncertainties and are incomplete.
- Few data A and R exist for $\pi^- p \to \pi^- p$ and $\pi^+ p \to \pi^+ p$ at few energies and angles.
- No A and R data for $\pi^- p \to \pi^0 n$ few P data.
- These observables needed to construct unbiased partial-wave amplitudes.
- Improvement in statistics recently shown with EPECUR (Fig. 4).

Studies with Meson Beams

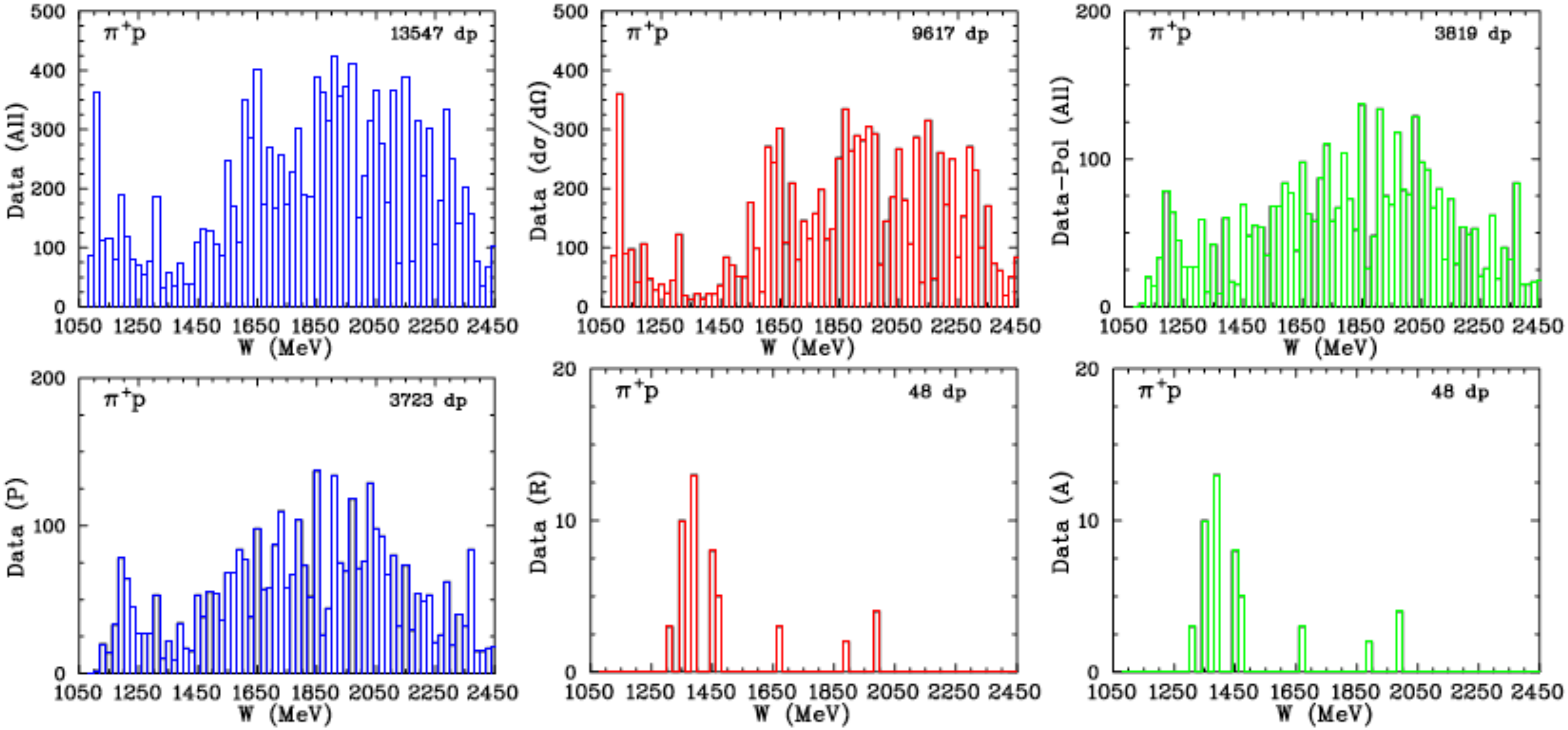


Fig 1 Data available for $\pi^+p \rightarrow \pi^+p$ W $\leq$ 2.45 GeV.[10] Row 1: (blue) total data for all observables, (red) $d\sigma/d\Omega$ data, (green) polarization data. Row 2: (blue) *P* spin data, (red) *R* spin data, (green) *A* spin data.

Studies with Meson Beams

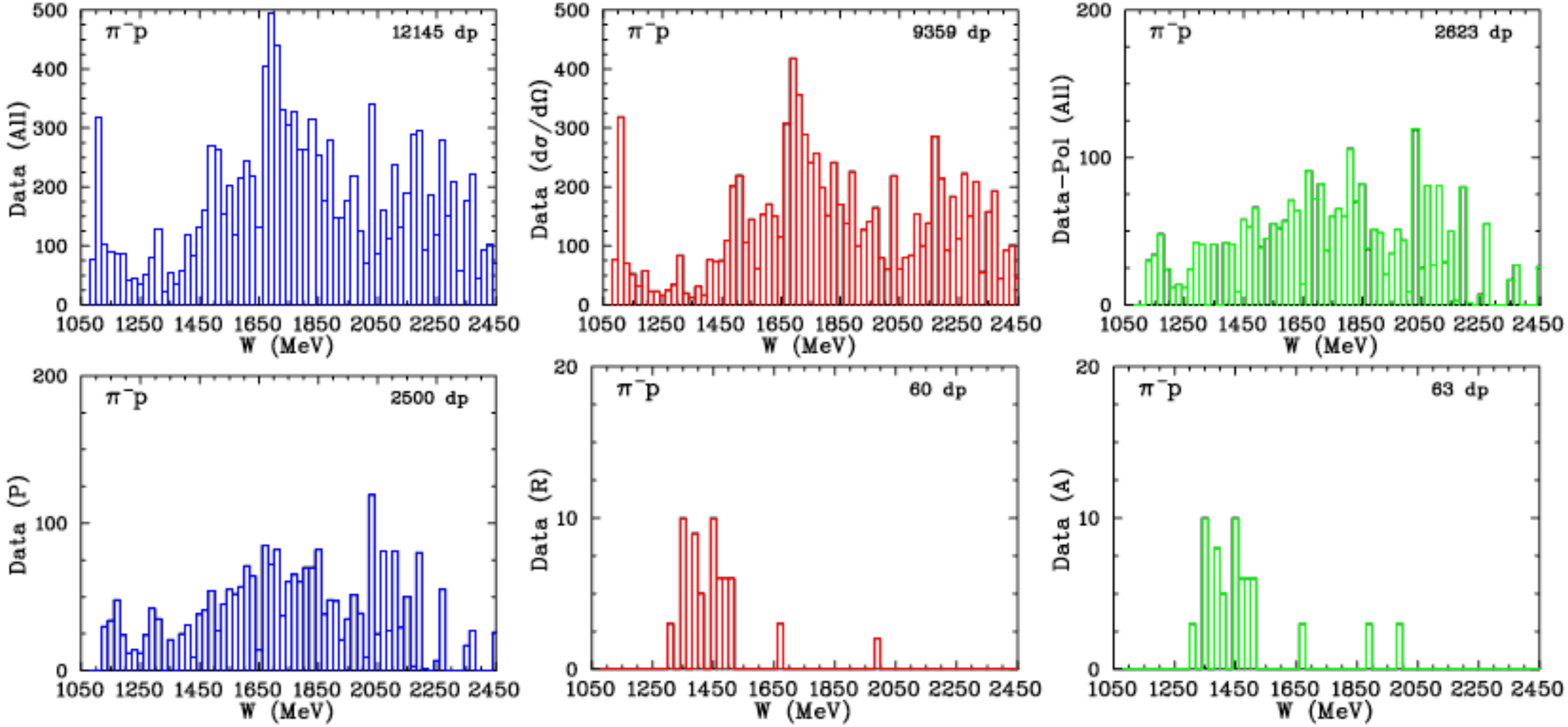


Fig 2 Data available for $\pi^- p \rightarrow \pi^- p$ for $W \leq 2.45$ GeV. [10] Row 1: (blue) data available for all observables, (red) dσ/dΩ data, (green) polarization data. Row 2: (blue) P spin data, (red) R spin data, (green) A spin data.

Studies with Meson Beams

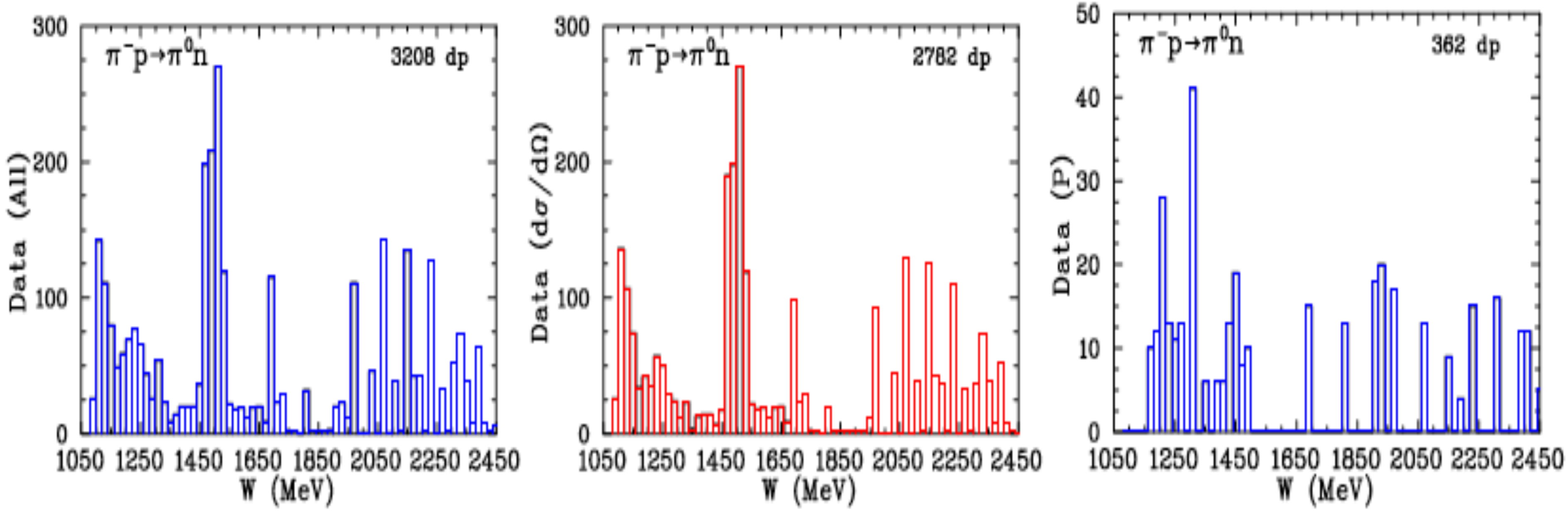


Fig 3 Data available for $\pi^-p \rightarrow \pi^0n$ $W \leq 2.45$ GeV[10]. (blue) total data available for all observables, (red) shows $d\sigma/d\Omega$) data, (blue) shows the amount of all polarization data.

Improved Cross Section Measurements from EPECUR

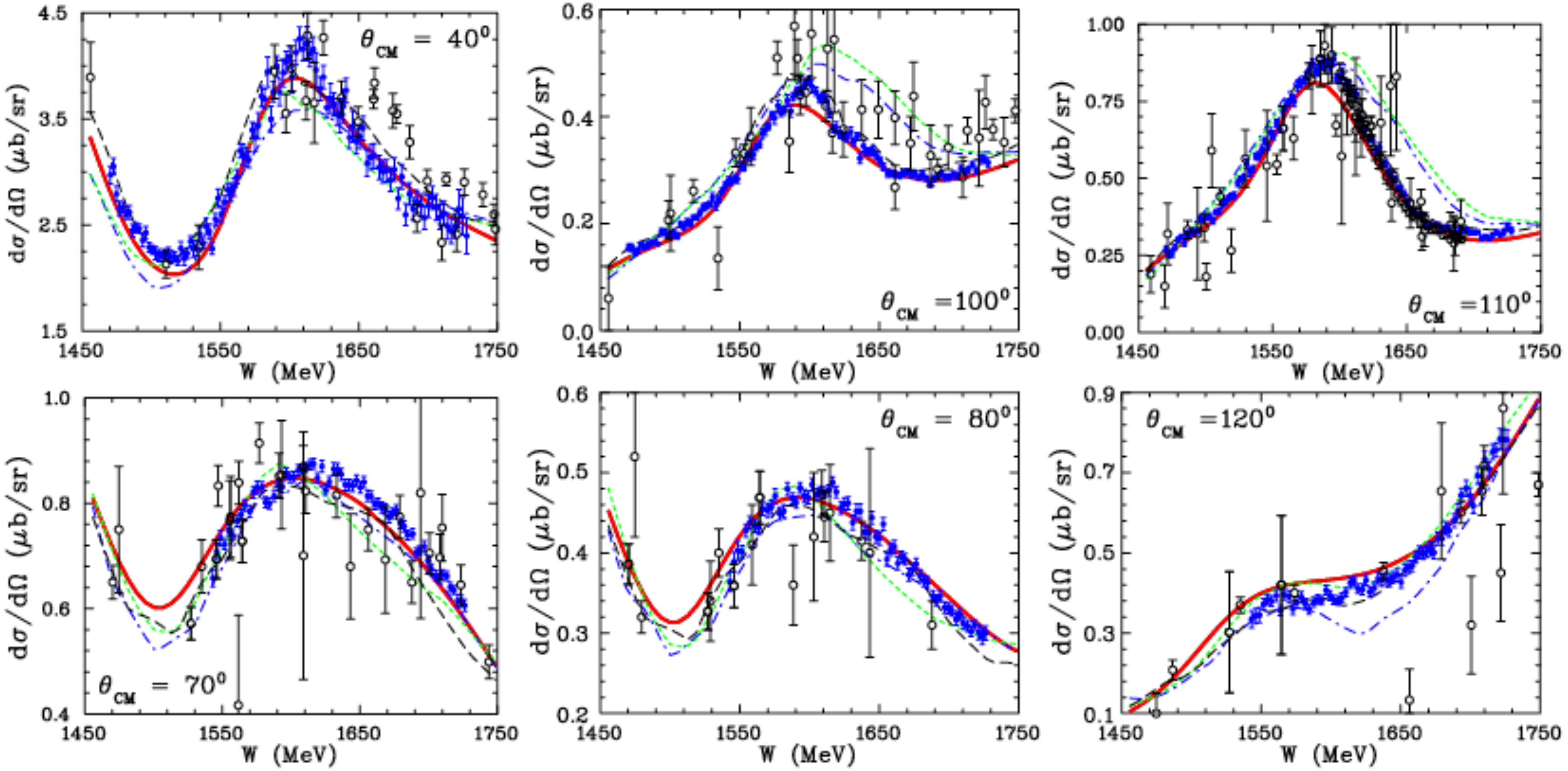


Fig 4 $d\sigma/d\Omega$ for π^-p (top) and π^+p (bottom) elastic scattering. EPECUR data (blue) [13] previous measurements [14] black. Data from earlier experiments within bins of $\Delta\theta_{CM} = \pm 1^0$. GWU SAID fit, WI08 [11] red solid curve, older KH80 [15], KA84 [16], and CMB [17] fits blue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

Newer Measurements from J-PARC

- Fig. 5 shows measurements of $I = 3/2$ $K^+\Sigma^0$ final state by J-PARC E19 Collaboration, compared older data; note improvement in uncertainties and angular range!
- Similar measurements would improve PWAs of $K\Sigma$ final state and help extract *S*-wave contributions needed in approaches based on unitary chiral perturbation theory.

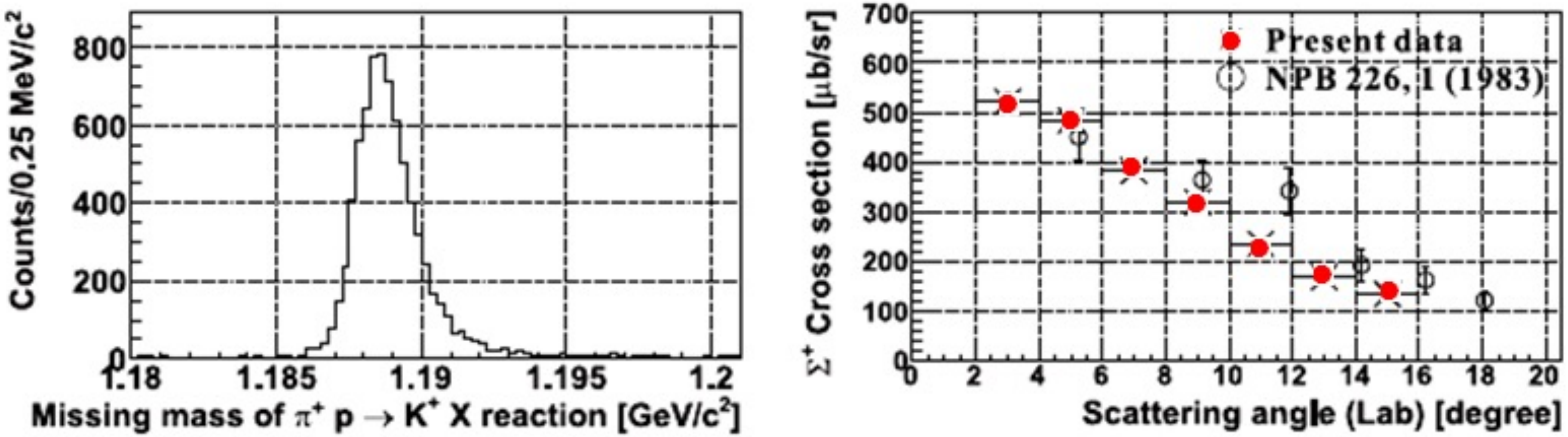
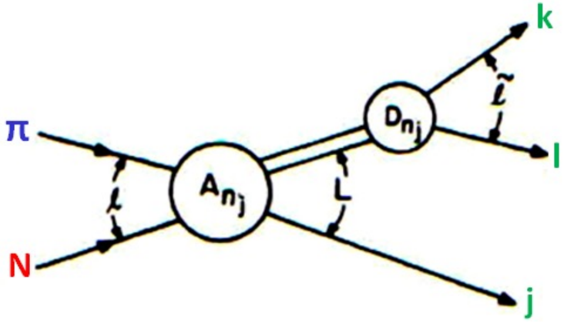


Fig. 5 $d\sigma/d\Omega$ of $\pi^+ p \to K^+\Sigma^+$ at $p_{\text{lab}} = 1.37$ GeV/c from J-PARC experiment [18], compared older data. [19]

Other Studies with Pion Beams

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

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

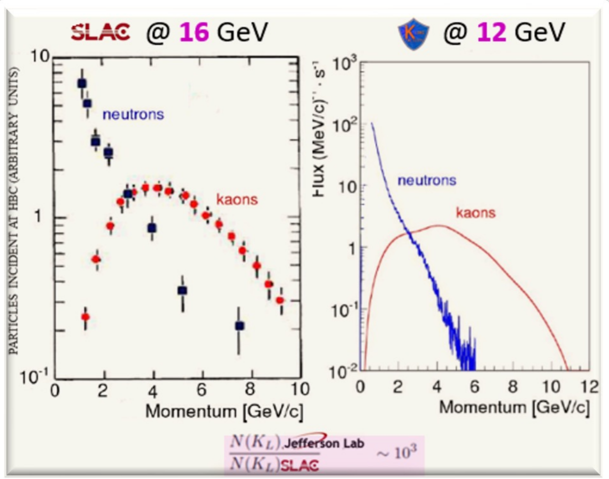


- Analysis/interpretation more complicated –> involve 3-body final states.
- $\pi N \rightarrow \pi\pi N$ reactions have lowest energy threshold of the inelastic hadronic channels and some of the largest cross sections.
- For most established N^* and Δ^* resonances, dominant inelastic decays that go to $\pi\pi N$ final states.
- Much of the $\pi N \rightarrow \pi\pi N$ data come from old bubble-chamber data analyzed in isobar-model PWA at W = 1320 to 1930 MeV [20].
- We 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. (Planned for E45 at J-PARC)

The K-Long Experiment at Jefferson Lab

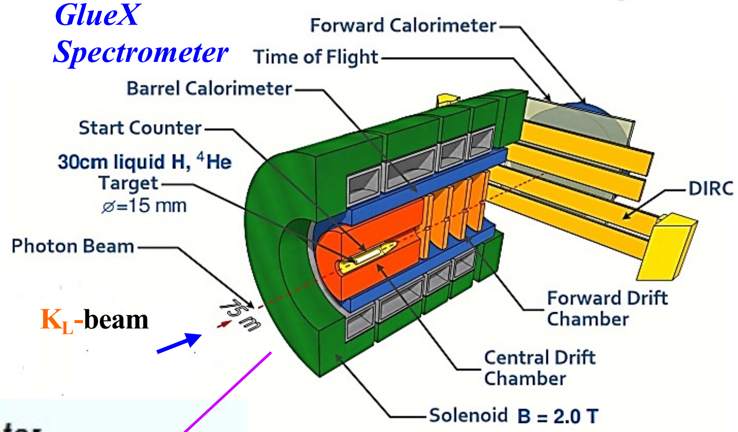
- The K-Long project is approved to install a secondary K_L beam line in Hall D at Jefferson Lab with a *flux three order of magnitude highe*r than SLAC.
- Scattering experiments on both *proton* and *neutron* targets.
- *First hadronic facility at Jefferson Lab.*
- We will measure *differential cross 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.

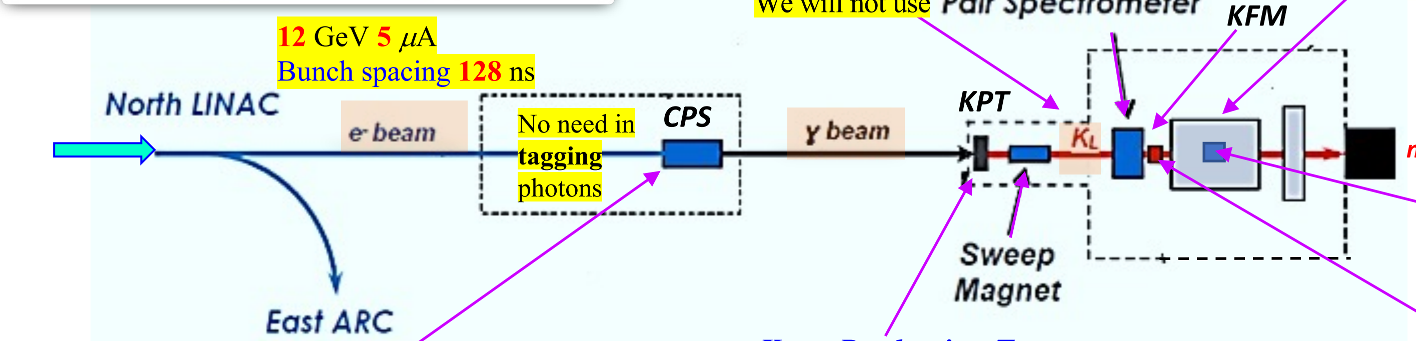
Hall D Beam Line for



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

GlueX Spectrometer



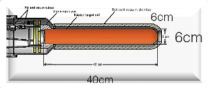


We will not use Pair Spectrometer

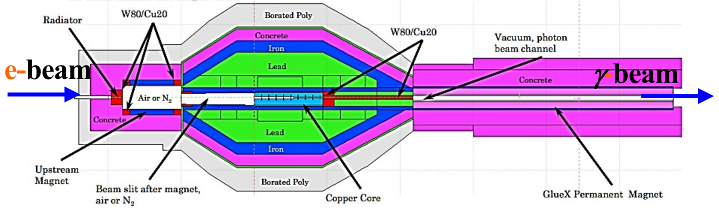
12 GeV 5 μA
Bunch spacing 128 ns

No need in **tagging** photons

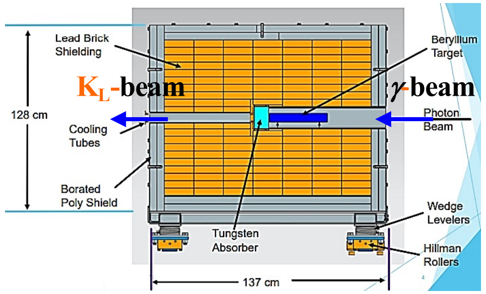
LH$_2$/LD$_2$-target



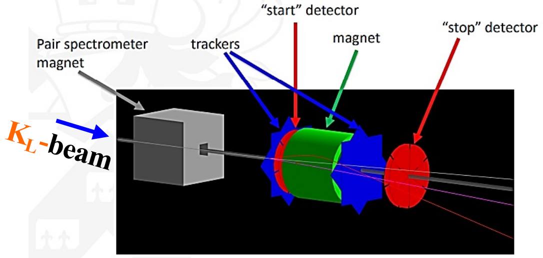
Compact Photon Source



Kaon Production Target

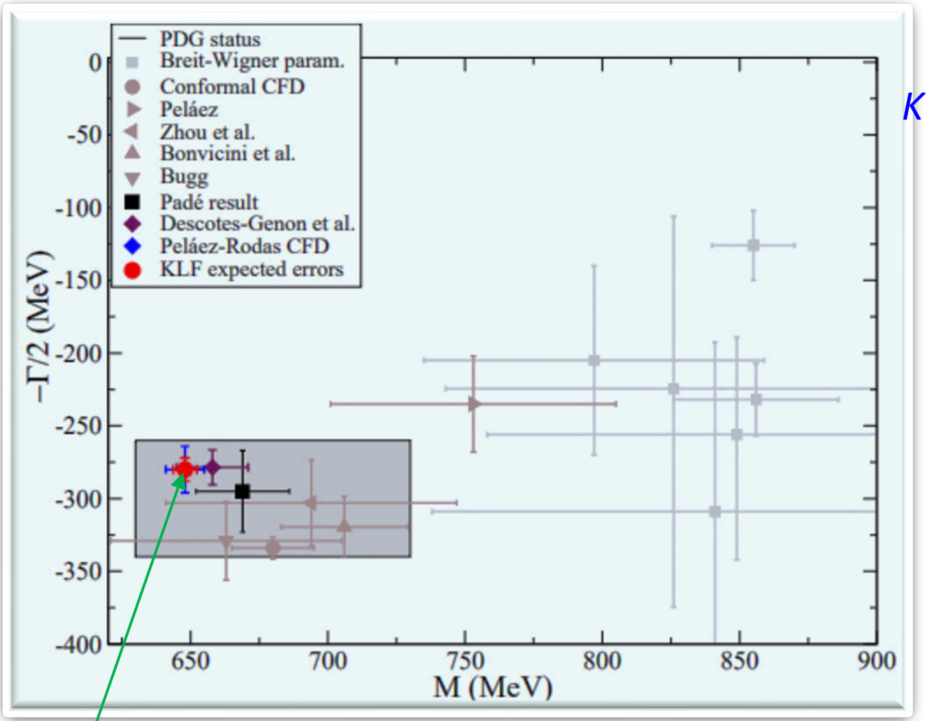


Kaon Flux Monitor



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

Summary of Meson Spectroscopy



K(700)*

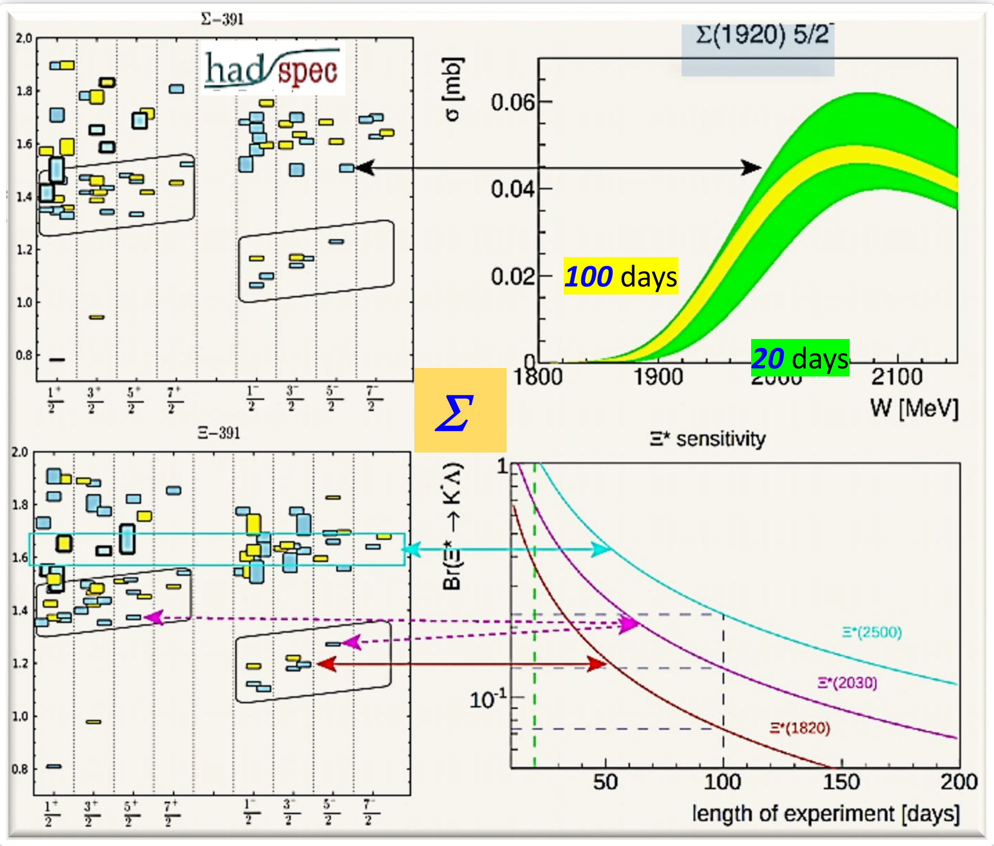
100 days

- *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)

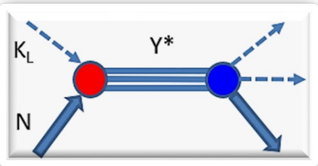
- K_L will have significant *impact* on our knowledge of Kp *scattering amplitudes*.
- Improve conflicting determinations of *heavy K* parameters*.
- Help to settle tension between phenomenological determination of *scattering lengths* from data vs *ChPT* & *LQCD*.
- For *K*(700)*, it will reduce:
  - *uncertainties* in *mass* by factor of *two* and
  - *uncertainties* in *width* by factor of *five*.
- Help to clarify debated of its *existence*, and therefore, long standing problem of existence of the *scalar* meson *nonet*.

Summary of Hyperon Spectroscopy with K_{Long} Beam



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

- K_L sensitivity with *100 days* of running will allow observation of *hyperons* with good precision.
- *Why should it be done with K_L beam* ?
  Only realistic way to observe ***s***-channel resonances having all ***momenta*** of K_L together "*tagged*" *kaons.*
- *Why should it be done at Jefferson Lab*?
  Because there are no other existing facilities where this can be done.
- *Why should we care about dozens of missing states* ?
  Because is is a goal of the LRP!



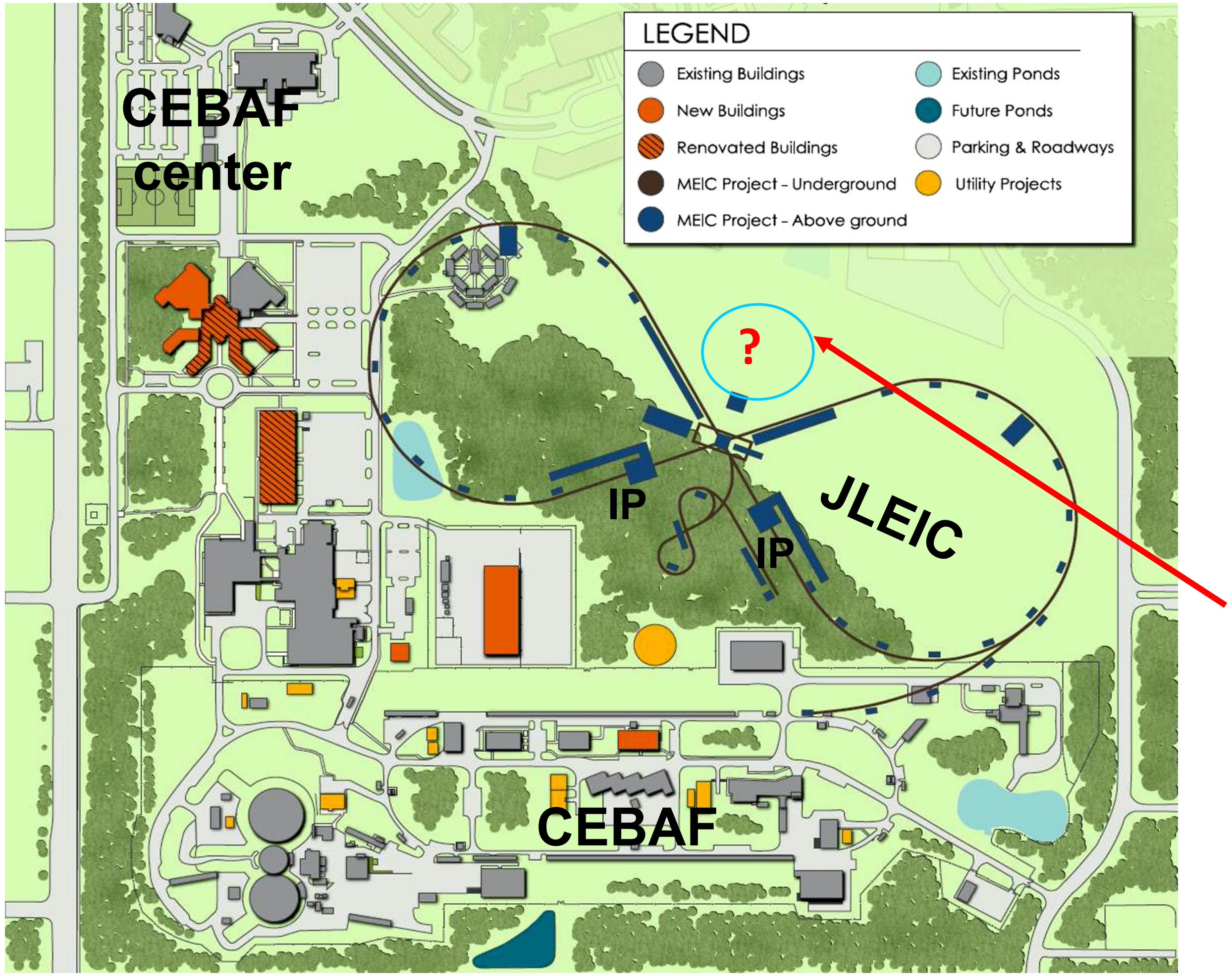
…The new capabilities of the 12-GeV era facilitate a detailed study of baryons containing two and three strange quarks. Knowledge of the spectrum of these states will further enhance our understanding of the manifestation of QCD in the three-quark arena.

2015 *LRP* for Nuclear Science.

Meson Beam at EIC?
Let’s Look at Example of Previous Work Done

- We spent much time developing a preliminary conceptual design of a Meson Facility at JLEIC.
- This was published in a White paper[1] just before the decision was made to build EIC at BNL.
- Design we had produced only works at JLEIC, but may give us an insight as to what may be possible at BNL EIC in conjunction with the second detector.
- We present this as a “learning by example” moment with the hopes of interesting new blood in this project.

JLab Campus Layout



JLEIC:

- W = **15** – **65** GeV.
- *Protons*: **20** – **100** GeV.
- *Luminosity*:
  10^{33} to 10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$ per IP.
- **2.2** km.

Ion Booster:

- *Protons*: **8** GeV.
- Booster design based on super-ferric magnet technology.
- 313.5 m.

It would have gone here!

Meson Hadron Facility :

- *Pions*:
  $<$ **3** GeV.
  10^{7} s^{-1}.
  $\Delta p/p < 2\%$.
- *Kaons*:
  $<$ **2** GeV.
  10^{5} s^{-1}.

Conceptional Development of Meson Facility for JLEIC

- Based 8 GeV booster design: 313.5 m, 260 ns spill, 2 s ramp up/down cycle, synchrotron magnets.
- Design intensity 1×10^{12} protons (160 nC/spill) ~ 0.6 kW,
  - two orders of magnitude below BNL/AGS meson beamlines,
  - three orders of magnitude less than J-PARC.
  - The time-averaged current ~ 80 nA.
- Assumed 8 GeV booster parameters were frozen as in Ref. [21]
- What is needed to modify design to produce useful π and K beams.
- JLEIC booster would inject into main ring only a fraction each day; it would be available for π/K physics remainder of the time.

Conceptional Development of Meson Facility for JLEIC

- JLEIC booster had short duty factor – unsuitable for proposed physics due to detector instantaneous rate limit.
- Need beam particles delivered at lower rate over a longer period.
- Booster modified for slow extraction would be cost-effective but would require major redesign.
- A solution to that did not involve design change: add stretcher ring.
- Simplest stretcher design providing ~ 100% duty factor was to extract booster beam into and fill one turn of ring over 260 ns spill.
  - Required ring of radius of 12.3 m with 39 1m long fixed dipoles of 4.3 T.

Conceptional Development of Meson Facility for JLEIC

- A more compatibe and less costly option was
  - double the stretcher diameter,
  - fill half circumference each spill,
  - halve the field to 2.16 T and
  - use resistive magnets of simular design to booster magnets.
- This plan allowed ~ CW beam extraction with good duty factor using resonant slow extraction while booster magnets were ramping.
- Time-average beam ~ 5×10^{11} p/s extracted from stretcher into transfer line to production target for secondary particles (π/K) into dedicated hadron hall.
- We look to see what π/K fluxes might be achieved.

Pion and Kaon Intensity Estimates for Meson Facility for JLEIC

- Given 80 nA CW, 8 GeV/c protons, we estimated the fluxes of pions and kaons as a function of secondary particle momentum and channel production angle.
- Used parametrizations of Sanford & Wang (SW) to estimate number of πs [22] and Ks [23] generated at production target /GeV/c /steradian /interacting proton.
- Used this as input to procedure of Yamamoto [24] that includes effects of
  - secondary particle production efficiency
  - nuclear absorption cross sections of protons on different production targets,
  - solid angle and momentum acceptance, and
  - decay factors for typical secondary-particle channels.
- Yields $\pi^{\pm}$ and $K^{\pm}$ fluxes at end of secondary beamline as function of production angle for given production target and secondary-particle beamline.
- *N.B.* Yamamoto described design of KEK K2 line with similar conditions
  - 1×10^{12} protons at 12 GeV.

Pion and Kaon Intensity Estimates for Meson Facility for JLEIC

- The π/K yields Y are determined from the
  - SW rates $d^2N/(d\Omega dp) = (1/\sigma_a)\, d^2\sigma/(d\Omega dp)$,
  - the proton flux F_i on the production target,
  - the production efficiency η for secondary particles per incident proton,
  - the nuclear absorption cross section σ_a associated with the protons on the production target,
  - the secondary channel characteristics: solid angle $d\Omega$, momentum bite $\Delta p/p$, momentum p, and decay factor d using:

$$Y = F_i\, \eta/\sigma_a\, d^2\sigma/d\Omega dp\ \Delta\Omega\ (\Delta p/p)\ pd$$

Pion and Kaon Intensity Estimates for Meson Facility for JLEIC

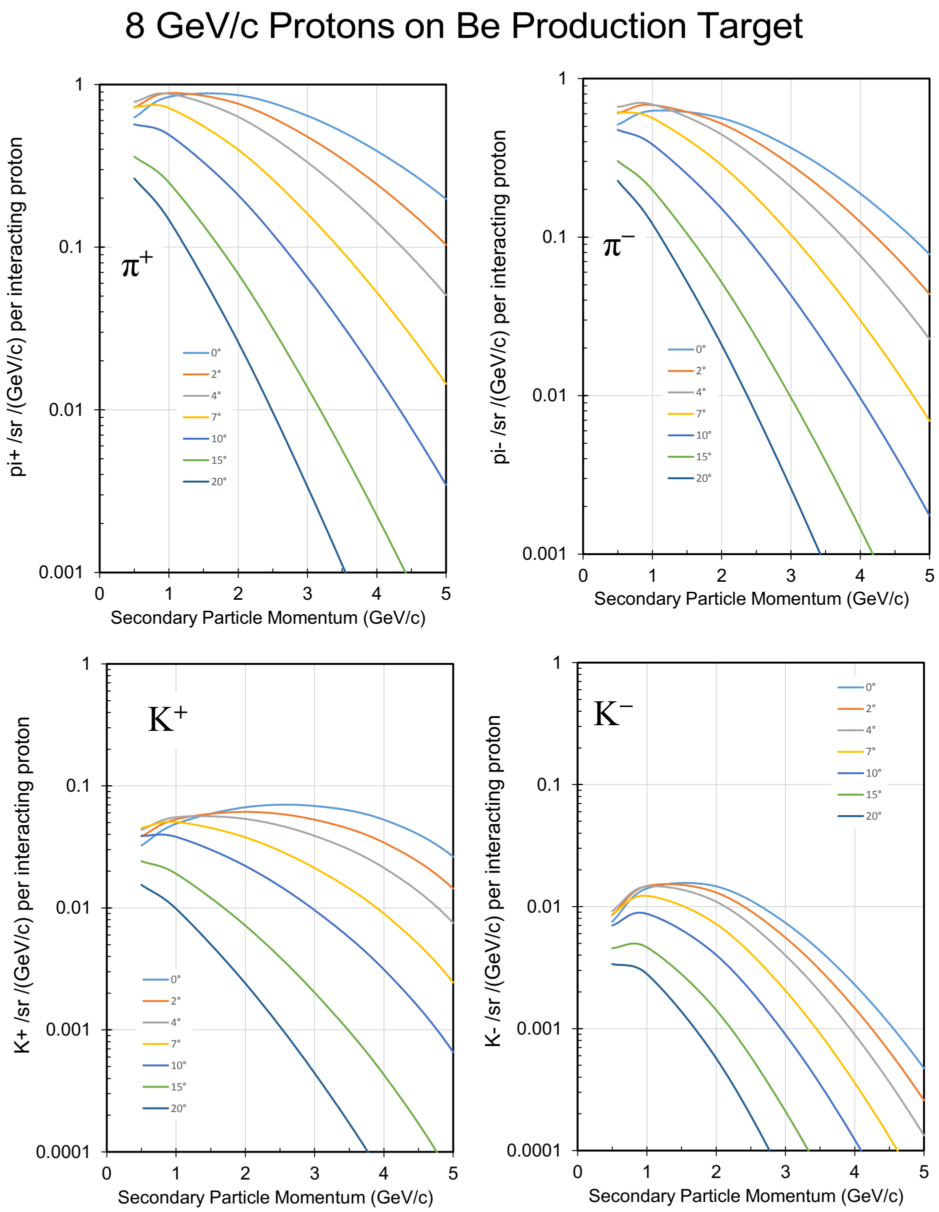
- Used a proton flux $F_i = 5 \times 10^{11}$ protons/s CW at 8 GeV, a 6 cm platinum target $\sigma_a = 1798$ mb, $\eta = 0.365$.
- Scaled σ_a and η from SW rates for Be target ($\sigma_a = 227$ mb and $\eta = 0.14$).
- Channel 30 m long with 3.125 msr and $\Delta p/p=2\%$.
- Decay factor d is probability that a secondary particle of mass M, mean life τ , and momentum p survives a distance x = 30 m:

$$d(x) = \exp(-M x/(p c\tau))$$

- Using Yamamoto, we determine production efficiency from absorption lengths in Ref. 25 for protons, pions, and kaons.

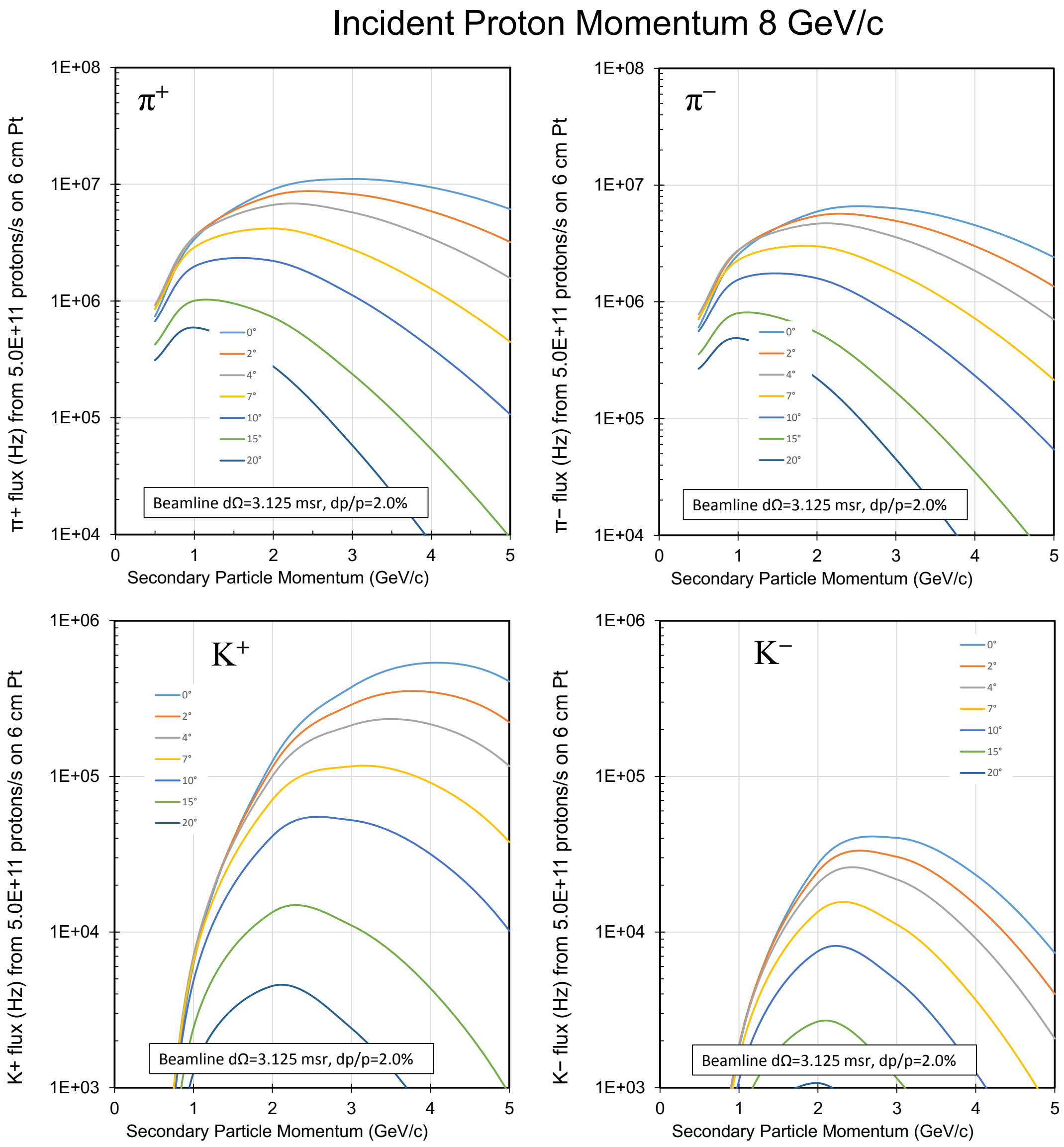
8 GeV/c Protons on Be Production Target

Pion and Kaon production rates on beryllium per steradian per GeV/c per interacting proton for 5×10^{11} protons/s CW at 8 GeV. The legend denotes different assumptions for the production angle



Incident Proton Momentum 8 GeV/c

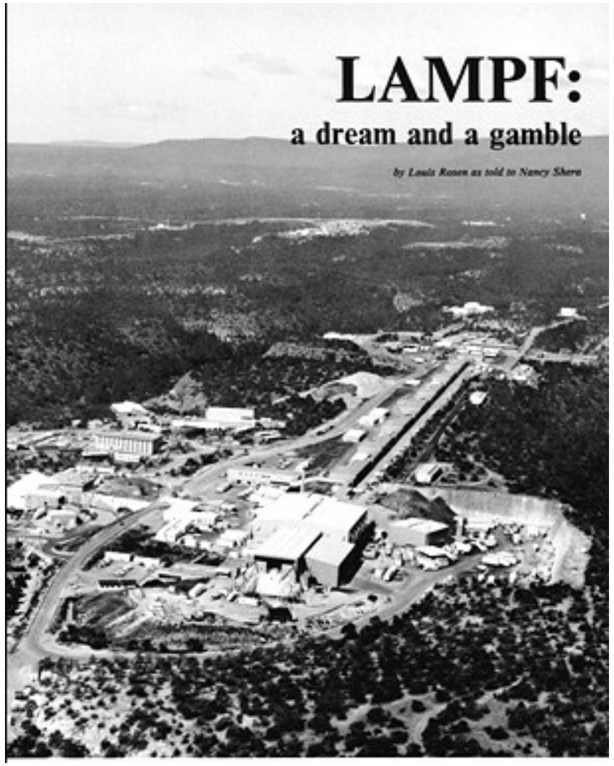
Pion and Kaon rates that could be expected at the end of a 30 m-long channel with a solid angle of 3.125 msr and a momentum bite of 2% Δp/p. The production target is assumed to be 6 cm Platinum. Decay along the length of the channel, as well as secondary particle production efficiency and nuclear absorption cross sections of the protons on the Platinum target are also factored into this prediction. The legend denotes different assumptions for the production angle.

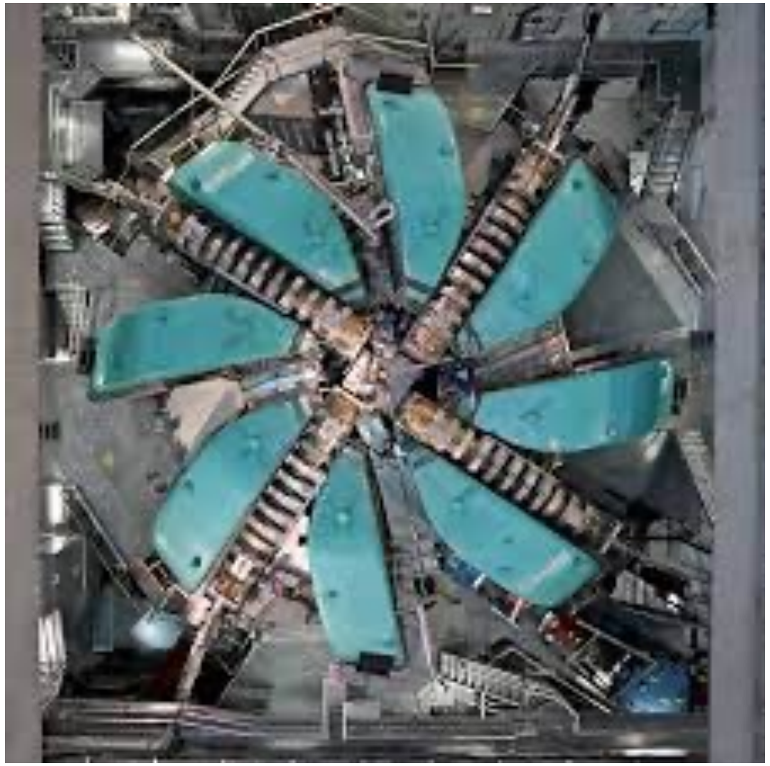


Summary – What is Needed Today

- Goals of EM facilities enhanced by hadron-beam data of quality similar to EM data.
- Vigorous program in hadronic physics requires modern facility with π and K beams.
- A Meson Factory where πN and KN elastic and inelastic scattering (including hyperon production) is measured with high precision and full solid angle is very useful.
- Such a facility ideally should allow measurements $W \geq 2.5$ GeV, which would require pion beams with momenta ≥ 2.85 GeV/c.
- The 2 GeV/c pion beam at J-PARC only allow measurements to $W \approx 2150$ MeV.
- We encourage work on a conceptual design of a “Meson Factory” for the BNL EIC that ideally could be compatible with the future second detector.

Thanks for Listening





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