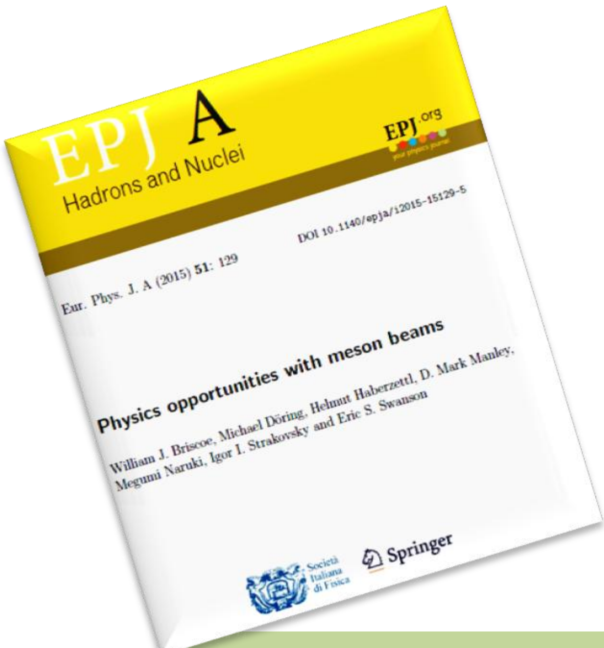
Hadron Physics at EIC Facility

*Igor Strakovsky**

The George Washington University


EPJ A

Hadrons and Nuclei

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Physics opportunities with meson beams

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Società Italiana di Fisica

Springer

- Hadron Spectroscopy.
- Opportunities with pion beams.
- Spectroscopy of hyperons.
- Meson spectroscopy.
- Physics opportunities.
- Summary.

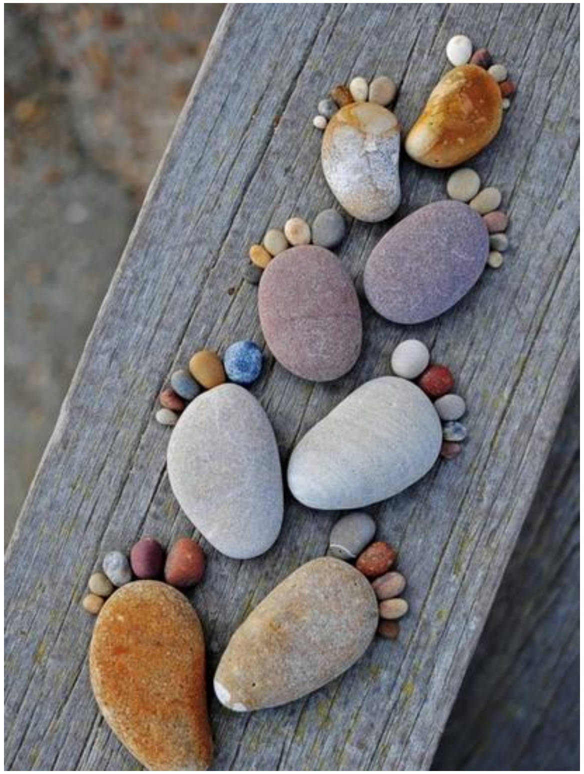
135 endorsers from 77 labs worldwide

*** Supported by DOE DE-SC0014133**

Hadron Spectroscopy

- To reap full benefit of high-precision **EM** studies & to advance our knowledge in **Baryon** & **Meson Spectroscopy**, new high-statistics data from **measurements** with **meson beams**, with good angle & energy coverage for wide range of reactions are critically needed.

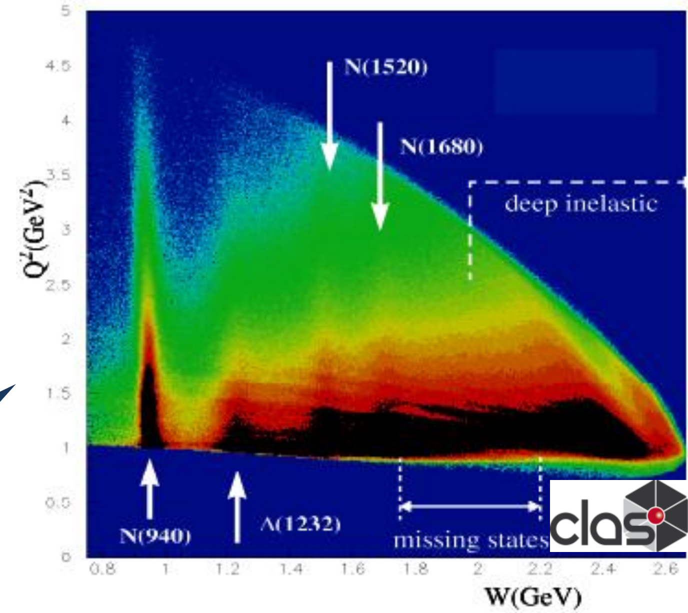
- To address this situation, **state-of-the-art Meson Facility** needs to be constructed.



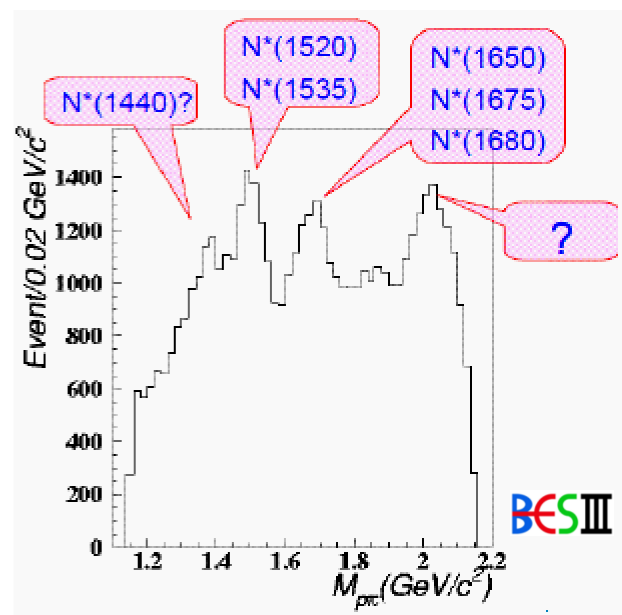
*There are Many Ways to Study N**

- **Prolific source** of **N*** & **Δ*** baryons is to measure many channels with different combinations of quantum numbers.

πN→πN, ππN, …
γN→πN, ππN, …
γ*N→πN, ππN, …
pp→ppπ^0, ppππ, …
J/ψ → p$\bar{p}$π^0, p$\bar{n}$π$^-$, …



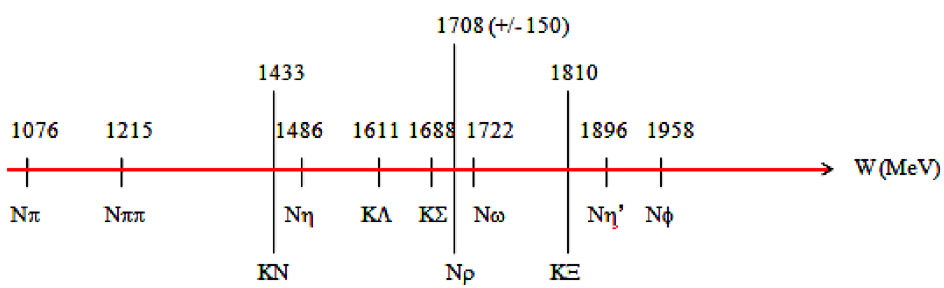
ep→epX



$J/\psi \rightarrow p\bar{n}\pi^-$

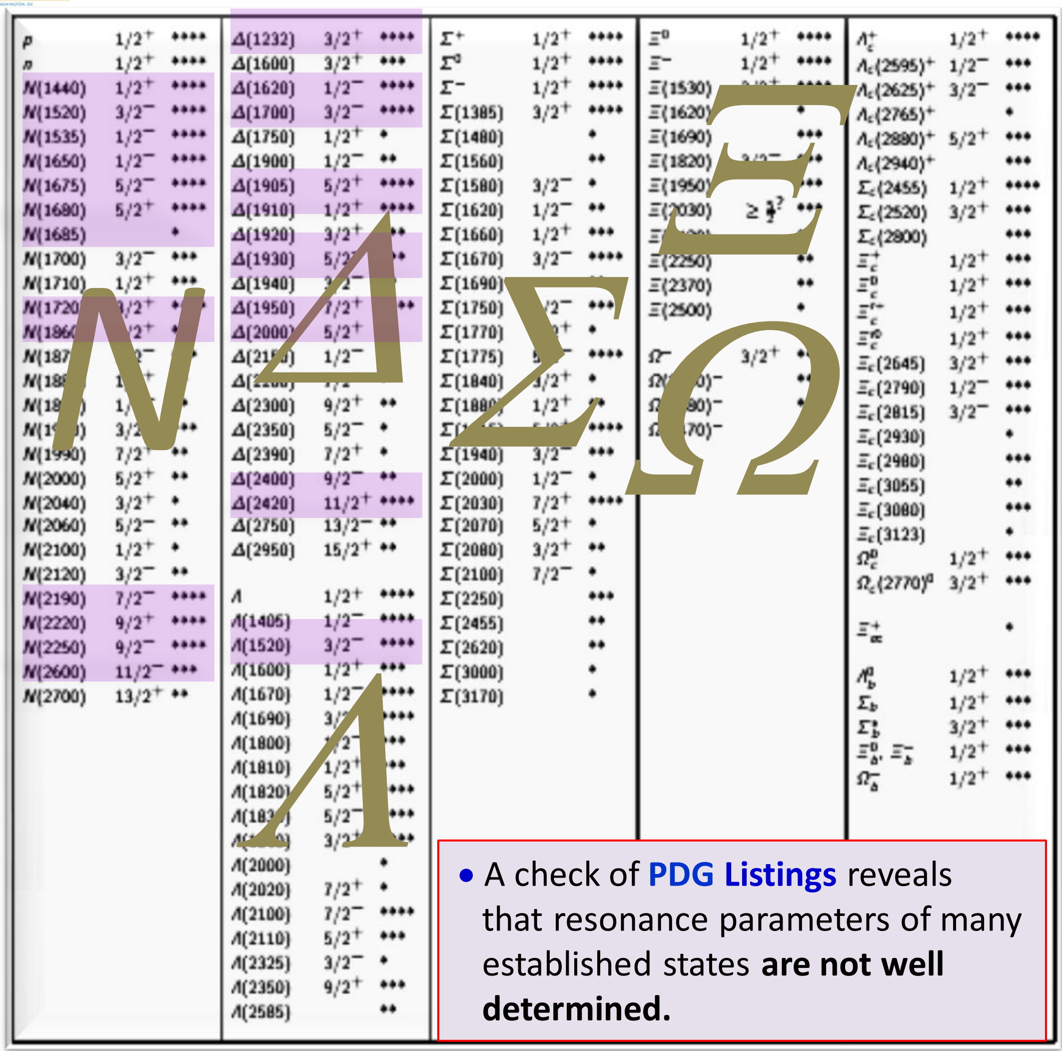
Most of **PDG Listings** info comes from **these sources**.

- **πN** elastic scattering is simplified due to constraints.
- **Resonance** spectra are correlated.
- Two-body final states need **few amplitudes**.



Baryon Sector at PDG14

GW Contribution



p	$1/2^+$	****
n	$1/2^+$	****
N(1440)	$1/2^+$	****
N(1520)	$3/2^-$	****
N(1535)	$1/2^-$	****
N(1650)	$1/2^-$	****
N(1675)	$5/2^-$	****
N(1680)	$5/2^+$	****
N(1685)		*
N(1700)	$3/2^-$	***
N(1710)	$1/2^+$	***
N(1720	[illegible]$/2^+$	[illegible]
N(186[illegible]	[illegible]2^+	[illegible]
N(187[illegible]	[illegible]2^-	[illegible]
N(188[illegible]	1[illegible]$^+$	[illegible]
N(18[illegible])	1/[illegible]	[illegible]
N(1[illegible])	3/[illegible]	[illegible]**
N(1990)	$7/2^+$	**
N(2000)	$5/2^+$	**
N(2040)	$3/2^+$	*
N(2060)	$5/2^-$	**
N(2100)	$1/2^+$	*
N(2120)	$3/2^-$	**
N(2190)	$7/2^-$	****
N(2220)	$9/2^+$	****
N(2250)	$9/2^-$	****
N(2600)	$11/2^-$	***
N(2700)	$13/2^+$	**

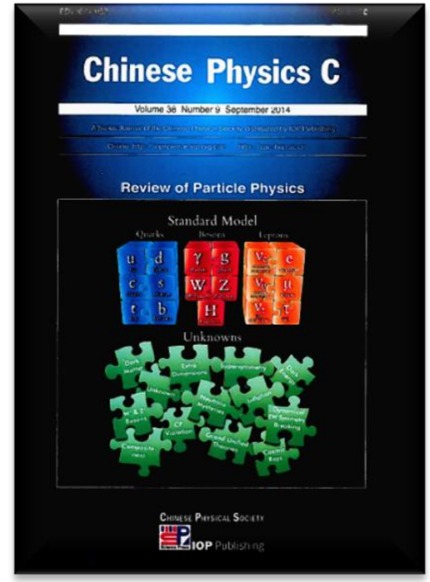
Δ(1232)	$3/2^+$	****
Δ(1600)	$3/2^+$	***
Δ(1620)	$1/2^-$	****
Δ(1700)	$3/2^-$	****
Δ(1750)	$1/2^+$	*
Δ(1900)	$1/2^-$	**
Δ(1905)	$5/2^+$	****
Δ(1910)	$1/2^+$	****
Δ(1920)	$3/2^+$	[illegible]
Δ(1930)	5/[illegible]	[illegible]
Δ(1940)	[illegible]	[illegible]
Δ(1950)	$7/2^+$	[illegible]
Δ(2000)	$5/2^+$	[illegible]
Δ(21[illegible])	$1/2^-$	[illegible]
Δ([illegible])	[illegible]	[illegible]
Δ(2300)	$9/2^+$	**
Δ(2350)	$5/2^-$	*
Δ(2390)	$7/2^+$	*
Δ(2400)	$9/2^-$	**
Δ(2420)	$11/2^+$	****
Δ(2750)	$13/2^-$	**
Δ(2950)	$15/2^+$	**
Λ	$1/2^+$	****
Λ(1405)	$1/2^-$	****
Λ(1520)	$3/2^-$	****
Λ(1600)	$1/2^+$	***
Λ(1670)	$1/2^-$	****
Λ(1690)	3/[illegible]	****
Λ(1800)	[illegible]$/2^-$	***
Λ(1810)	$1/2^+$	***
Λ(1820)	$5/2^+$	****
Λ(183[illegible])	$5/2^-$	****
Λ([illegible])	$3/2^+$	***
Λ(2000)		*
Λ(2020)	$7/2^+$	*
Λ(2100)	$7/2^-$	****
Λ(2110)	$5/2^+$	***
Λ(2325)	$3/2^-$	*
Λ(2350)	$9/2^+$	***
Λ(2585)		**

Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
Σ(1385)	$3/2^+$	****
Σ(1480)		*
Σ(1560)		**
Σ(1580)	$3/2^-$	*
Σ(1620)	$1/2^-$	**
Σ(1660)	$1/2^+$	***
Σ(1670)	$3/2^-$	****
Σ(1690)	[illegible]	[illegible]
Σ(1750)	[illegible]$/2^-$	***
Σ(1770)	[illegible]$^+$	*
Σ(1775)	5[illegible]	****
Σ(1840)	$3/2^+$	*
Σ(1880)	$1/2^+$	**
Σ([illegible])	[illegible]	****
Σ(1940)	$3/2^-$	***
Σ(2000)	$1/2^-$	*
Σ(2030)	$7/2^+$	****
Σ(2070)	$5/2^+$	*
Σ(2080)	$3/2^+$	**
Σ(2100)	$7/2^-$	*
Σ(2250)		***
Σ(2455)		**
Σ(2620)		**
Σ(3000)		*
Σ(3170)		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
Ξ(1530)	[illegible]	****
Ξ(1620)		*
Ξ(1690)		***
Ξ(1820)	[illegible]	***
Ξ(1950)		***
Ξ(2030)	$\geq \frac{5}{2}^?$	***
Ξ([illegible])	[illegible]	[illegible]
Ξ(2250)		**
Ξ(2370)		**
Ξ(2500)		*
Ω^-	$3/2^+$	[illegible]
Ω([illegible]$)^-$		[illegible]
Ω([illegible]$)^-$		[illegible]
Ω([illegible]$)^-$		[illegible]

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c^{\prime +}$	$1/2^+$	***
$\Xi_c^{\prime 0}$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
Ω_b^-	$1/2^+$	***

- A check of **PDG Listings** reveals that resonance parameters of many established states **are not well determined.**



- **PDG14** has **112 Baryon Resonances** (**58** of them are **4*** & **3***).
- For example for **SU(6) x O(3)**, it would be **434** resonances, if all revealed **three 70**– & **four 56**– multiplets were completed.

- There are **much more states** in **QCD** inspired models than **currently observed**.

Why We Need Meson Beams

- Great strides have been achieved over last **two decades** in increasing our knowledge of **Baryon** & **Meson Spectroscopy** with the help of **meson photo**- & **electro-**production data of unprecedented quality & quantity coming out of major **EM** facilities such as **JLab**, **MAMI**, **ELSA**, **SPring-8**, **ELPH**, **BEPC**, & others.

- **Meson-beam data** for different final states are mostly **outdated** & **largely of poor quality**, or even **non-existent**, & thus limit us in fully exploiting full potential of **new EM data**.

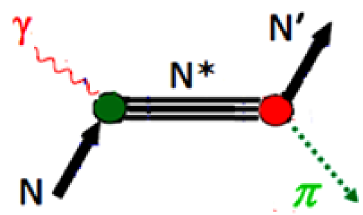
- We emphasize that what we advocate here is not competing project, but **experimental program** that provides **hadronic** complement of ongoing **EM program**, to furnish common ground for better & more reliable **phenomenological** & **theoretical** analyses based on **high-quality data**.

Status of Data for Specific Reactions

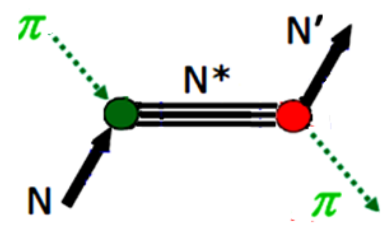
- Measurements of final states involving single **pseudoscalar meson** & **spin-1/2 baryon** are particularly interesting due to simple interpretation.

- The reactions involving **πN** channels include:

$\gamma p \rightarrow \pi^0 p$
$\gamma p \rightarrow \pi^+ n$
$\gamma n \rightarrow \pi^- p$
$\gamma n \rightarrow \pi^0 n$



$\pi^+ n \rightarrow \pi^0 p$
$\pi^+ n \rightarrow \pi^+ n$
$\pi^- p \rightarrow \pi^- p$
$\pi^- p \rightarrow \pi^0 n$
$\pi^+ p \rightarrow \pi^+ p$



- Only **$\pi^+ p \rightarrow \pi^+ p$** corresponds to **isospin 3/2** while rest of reactions is mixture of **isospins 1/2** & **3/2**.

Available data for **πN** elastic scattering are still **incomplete**.

- Measurements of **P**, **A**, & **R** observables (limited number of data available) are needed to construct truly unbiased **PW amplitudes**.

πN elastic scattering data have allowed establishment of **4*** resonances.

World Neutral and Charged PionPR Data

W < 2.5 GeV

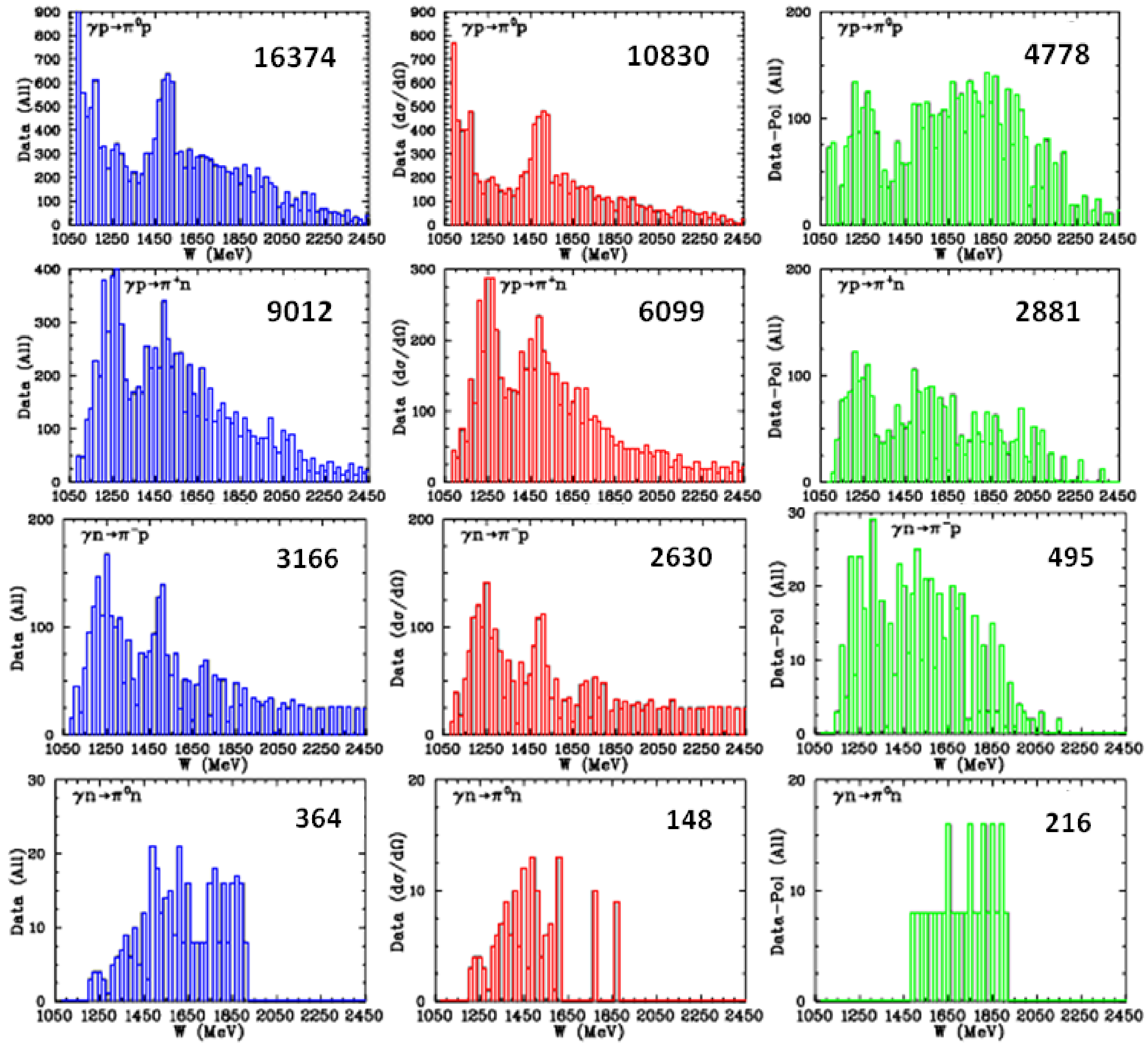
Full | **UnPol** | **Pol**

$\gamma p \to \pi^0 p$

$\gamma p \to \pi^+ n$

$\gamma n \to \pi^- p$

$\gamma n \to \pi^0 n$



Existing $\gamma n \to \pi^- p$ data contain mainly $d\sigma/d\Omega$, 15% of which are from polarized measurements.

World Pion-Nucleon Elastic (& CXC) Data

2623

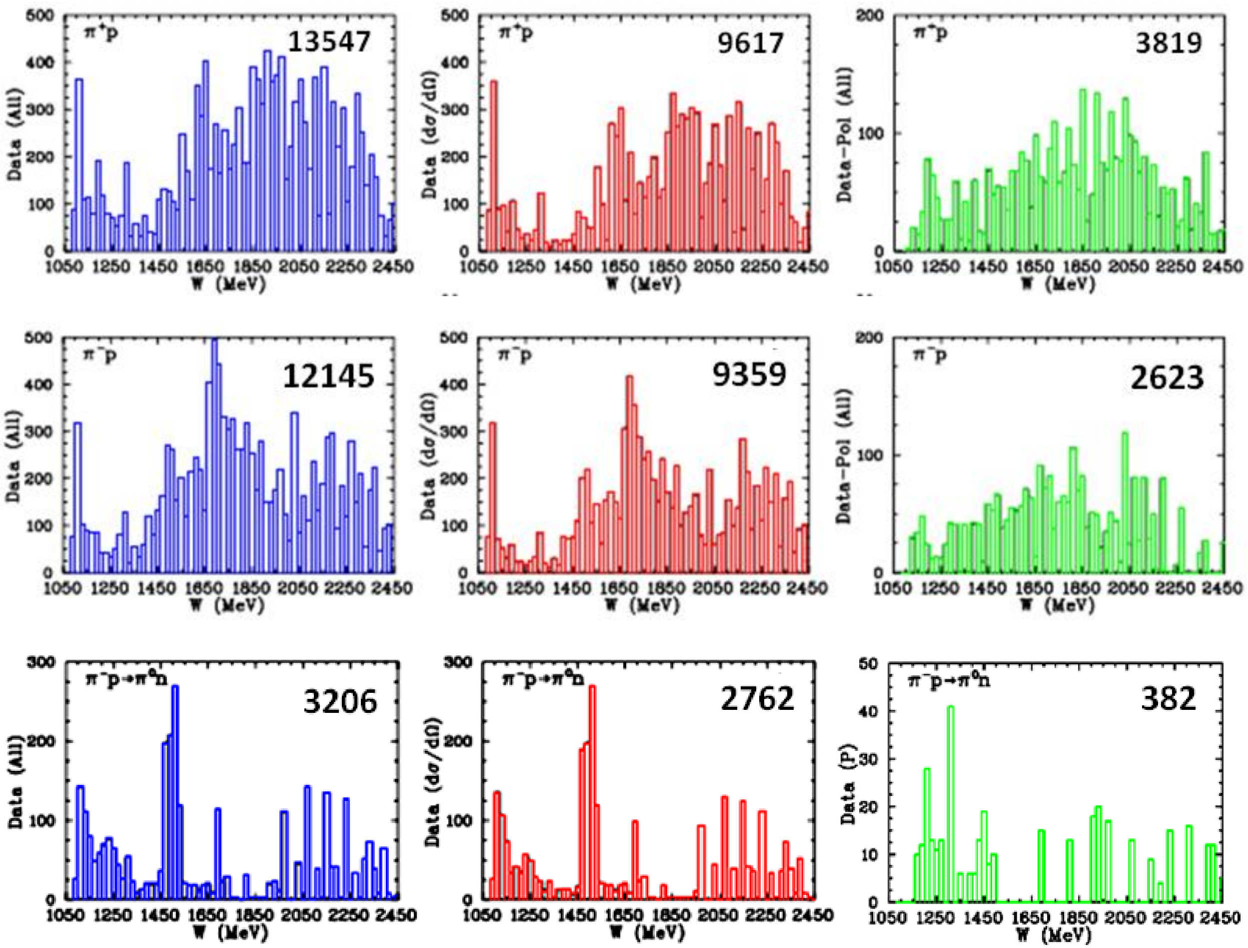
W < 2.5 GeV

Full | **UnPol** | **Pol**

$\pi^+p \rightarrow \pi^+p$

$\pi^-p \rightarrow \pi^-p$

$\pi^-p \rightarrow \pi^0n$



CXS database is small fraction of elastic measurements.

New Observables

PHYSICAL REVIEW C 74, 045205 (2006)

Extended partial-wave analysis of πN scattering data

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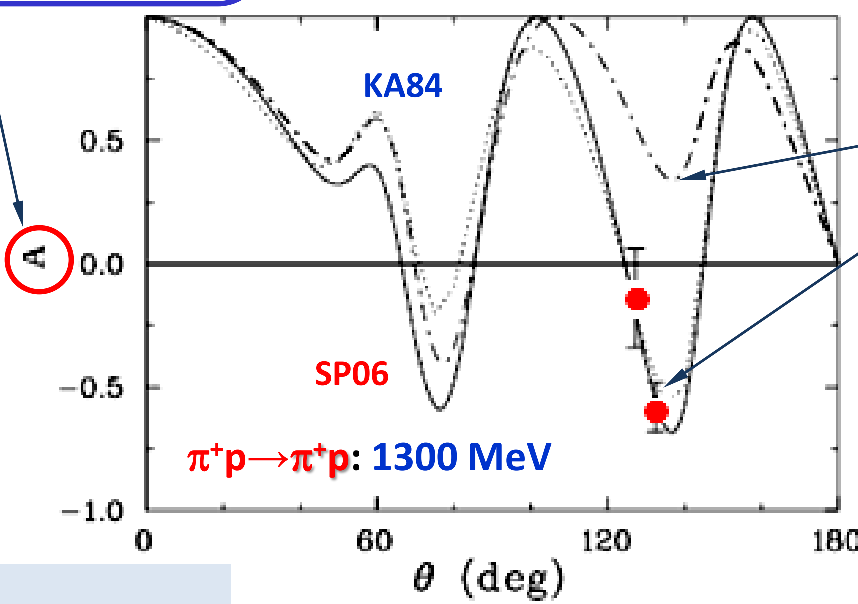
Center for Nuclear Studies, Department of Physics, The George Washington University, Washington, DC 20052, USA

(Received 7 June 2006; published 23 October 2006)

- πN scattering data:

$d\sigma/d\Omega$	(unpolarized)
P	(polarized target or recoil nucleon)
R and A	(polarized target and recoil measured)

Not Independent: $P^2 + R^2 + A^2 = 1$



- **Older PWA** solutions may be not able to reproduce **New** measurements.

Data:
ITEP: π⁺p→π⁺p @ 1300 MeV
I. Alekseev *et al,* Phys Lett B 351, 585 (1995)
PWA:
KA84: Karlsruhe-Helsinki fit, 1984
KB84: KH Barrelet corrected solution, 1997
SP06: GW fit, 2006

- **Polarized measurements** would also be important part of **hadron program**.

Recent ***ITEP*** *for* $\pi^{-+} p \rightarrow \pi^{-+} p$

EPECUR

- New precise cross section measurements:
  $\Delta\sigma$ = **0.5%** stat, **Δp** = **1 MeV**, ***$\Delta\vartheta$*** **=** **±1°**

PHYSICAL REVIEW C 91, 025205 (2015)

High-precision measurements of πp elastic differential cross sections in the second resonance region

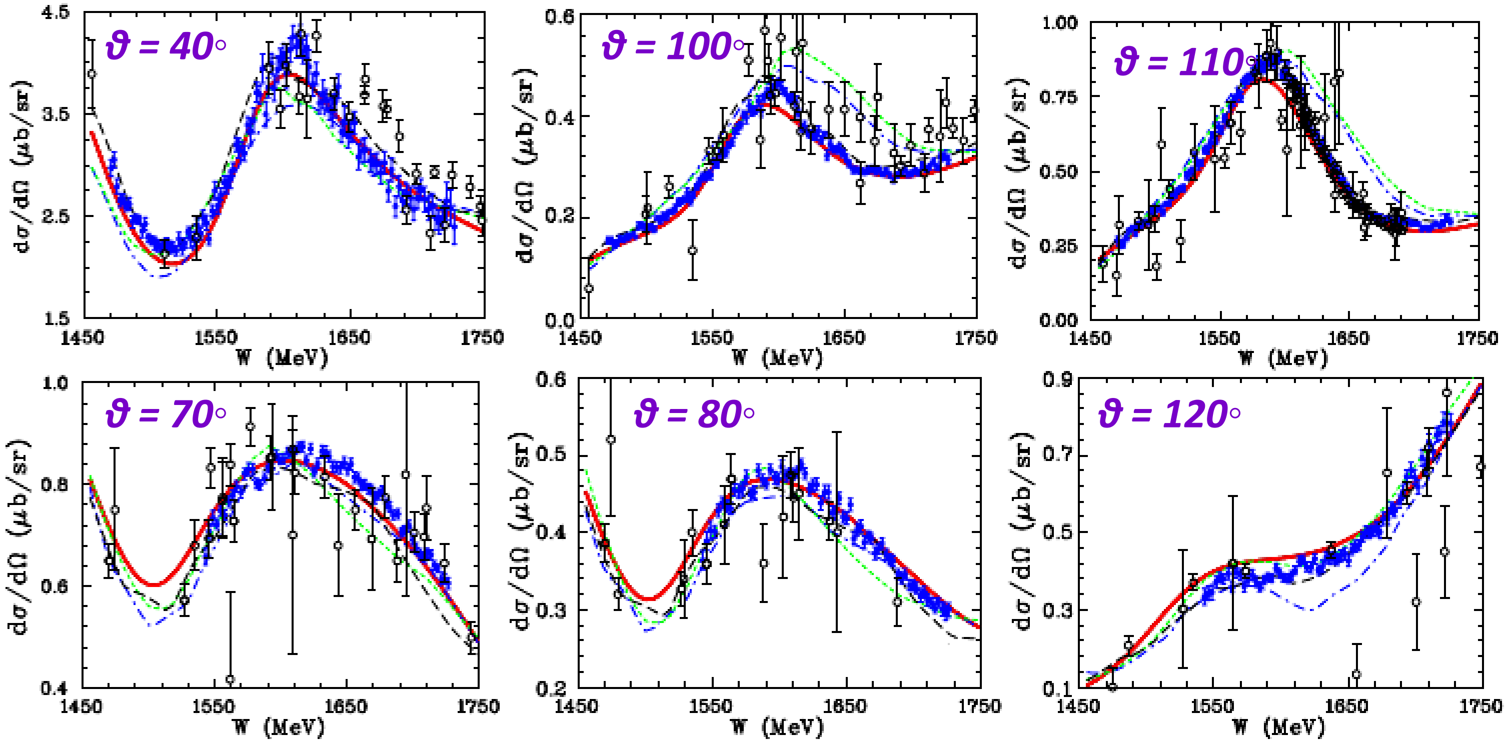
I. G. Alekseev,[1] V. A. Andreev,[3] I. G. Bordyuzhin,[1,5] W. J. Briscoe,[2] Ye. A. Filimonov,[3] V. V. Golubev,[3] A. B. Gridnev,[3] D. V. Kalinkin,[1] L. I. Koroleva,[1] N. G. Kozlenko,[3] V. S. Kozlov,[3] A. G. Krivshich,[3] B. V. Morozov,[1] V. M. Nesterov,[1] D. V. Novinsky,[3] V. V. Ryltsov,[1] M. Sadler,[4] B. M. Shurygin,[1] I. I. Strakovsky,[2] A. D. Sulimov,[1] V. V. Sumachev,[3] D. N. Svirida,[1] V. I. Tarakanov,[3] V. Yu. Trautman,[3] and R. L. Workman[2]
(EPECUR Collaboration and GW INS Data Analysis Center)

$\pi^-p \rightarrow \pi^-p$

4277 dσ/dΩ:
800 – 1243 MeV/c
40 – 122 deg

$\pi^+p \rightarrow \pi^+p$

2638 dσ/dΩ:
918 – 1240 MeV/c
40 – 122 deg



- **CMB** analysis is here more **successful** when compared to versions of **KH** analyses.

Predictions: WI08, KH80, KA84, CMB

Status of Data for Specific Reactions

- Reactions that involve ηN & $K\Lambda$ channels are **notable** because they have pure **isospin-1/2** contributions:

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

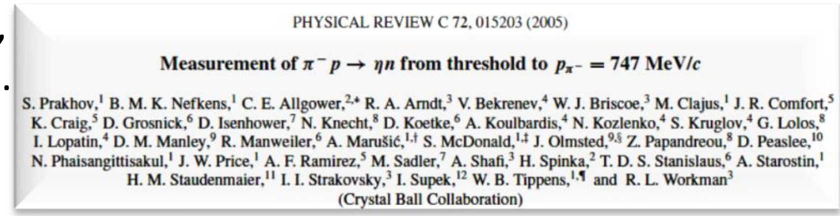
- Analyses of **photoproduction** combined with **pion-induced** reactions permit separating **EM** & **hadronic vertices**.

- It is only by **combining information** from analyses of both πN elastic scattering & $\gamma N \to \pi N$ that make it possible to determine $A_{1/2}$ & $A_{3/2}$ **helicity** couplings for N^* & Δ^* **resonances**.

Revival of $\pi^- p \to \eta n$

- $\gamma p \to \eta p$ is one of **key reactions** in which experimentalists hope to do ``*complete measurement*'' & determine **PW** amplitudes **directly**.
- Any **coupled-channel analysis** of those measurements will need precise data for **$\pi^- p \to \eta n$**.

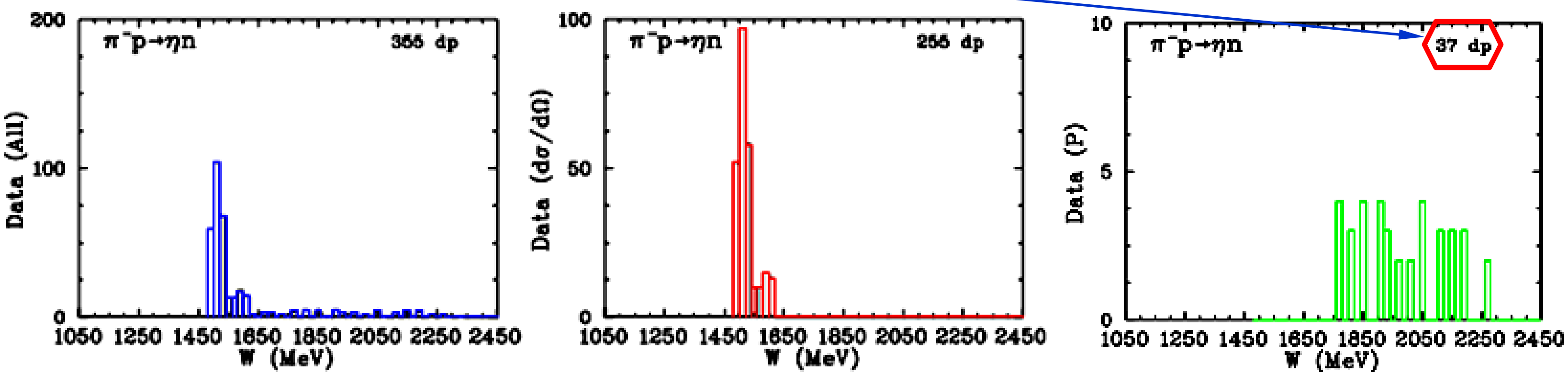
- Most of available data for **$\pi^- p \to \eta n$** come from measurements published in **1970**s, which have been **evaluated** by **several groups** as being **unreliable** above **W** = **1620** MeV.
- Precise new data were measured by **Crystal Ball** Collab, but these extend only up to peak of first **S_{11}**-resonance.


PHYSICAL REVIEW C 72, 015203 (2005)

Measurement of $\pi^- p \to \eta n$ from threshold to $p_{\pi^-} = 747$ MeV/c

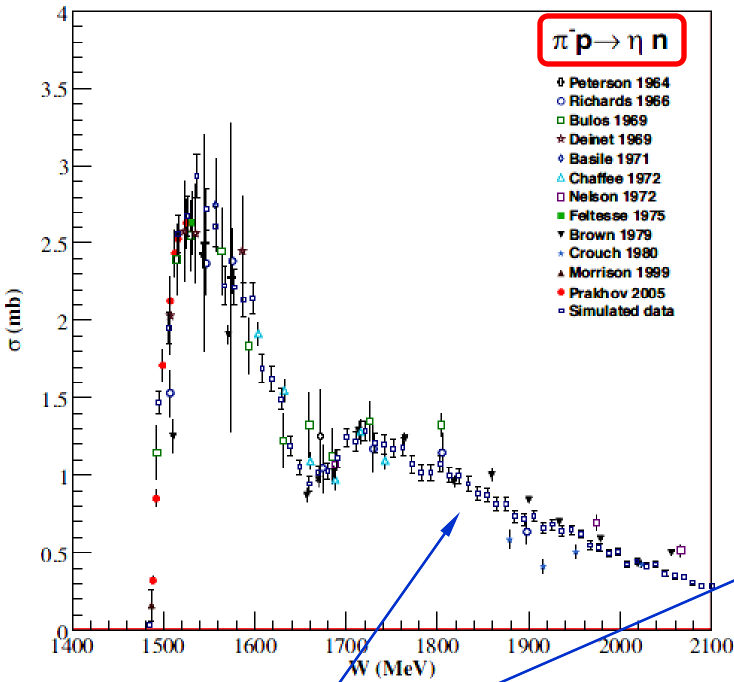
S. Prakhov,[1] B. M. K. Nefkens,[1] C. E. Allgower,[2,*] R. A. Arndt,[3] V. Bekrenev,[4] W. J. Briscoe,[3] M. Clajus,[1] J. R. Comfort,[5] K. Craig,[5] D. Grosnick,[6] D. Isenhower,[7] N. Knecht,[8] D. Koetke,[6] A. Koulbardis,[4] N. Kozlenko,[4] S. Kruglov,[4] G. Lolos,[8] I. Lopatin,[4] D. M. Manley,[9] R. Manweiler,[6] A. Marušić,[1,†] S. McDonald,[1,‡] J. Olmsted,[9,§] Z. Papandreou,[8] D. Peaslee,[10] N. Phaisangittisakul,[1] J. W. Price,[1] A. F. Ramirez,[5] M. Sadler,[7] A. Shafi,[3] H. Spinka,[2] T. D. S. Stanislaus,[6] A. Starostin,[1] H. M. Staudenmaier,[11] I. I. Strakovsky,[3] I. Supek,[12] W. B. Tippens,[1,¶] and R. L. Workman[3]
(Crystal Ball Collaboration)

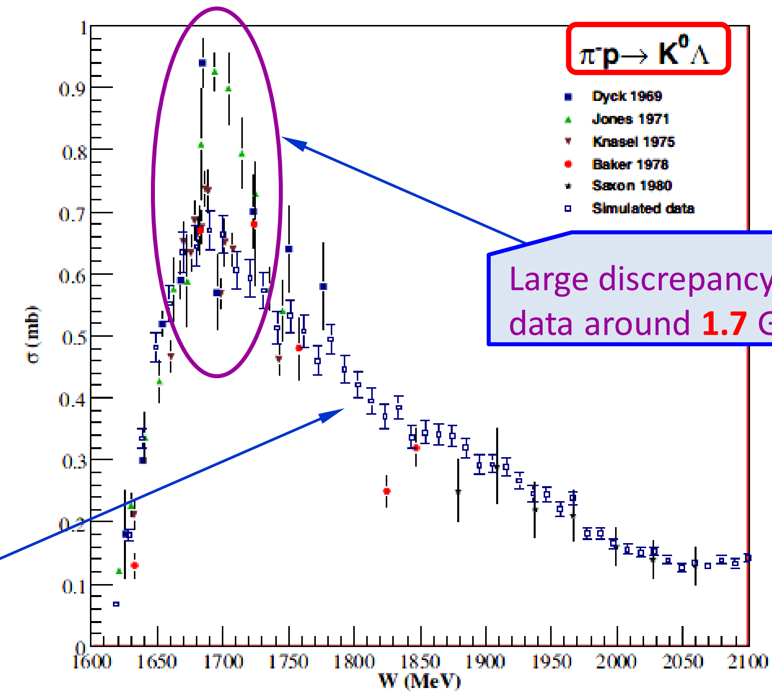
Very few polarized data for this reaction exist.
dσ/dΩ and **P** are taken at different energies .



- Available data for **$\pi^- p$** reactions with **KY**, **η'N**, **ωN**, & **ϕN** final states are generally equally **bad** or even **worse**.

Possible Improvement of $\pi^- p \to \eta n$ & $\pi^- p \to K^0 \Lambda$ Data





Large discrepancy in exp data around **1.7** GeV.

- **Projection data** with **5%** uncertainties and with an energy scan at **10** MeV intervals, which is comparable to **modern photoproduction** measurements.

- More precise data for reaction $\pi^- p \to K^0 \Lambda$ (together with $K^- p \to \pi^0 \Lambda$ & $\pi^0 \Sigma^0$) would enable study of **SU(3)** symmetry & its breaking.

Status of Data with Strangeness Production

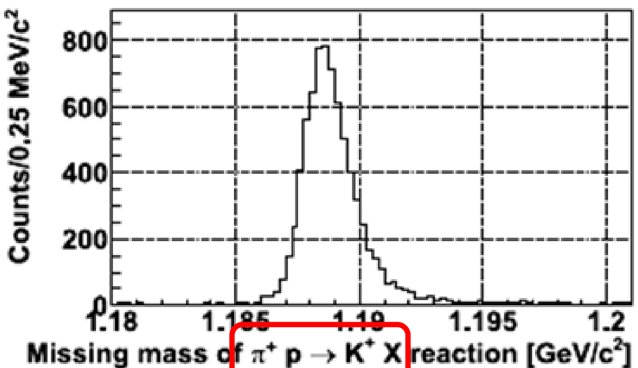
$\gamma p \to K^+\Sigma^0$
$\gamma p \to K^0\Sigma^+$
$\gamma n \to K^+\Sigma^-$
$\gamma n \to K^0\Sigma^0$

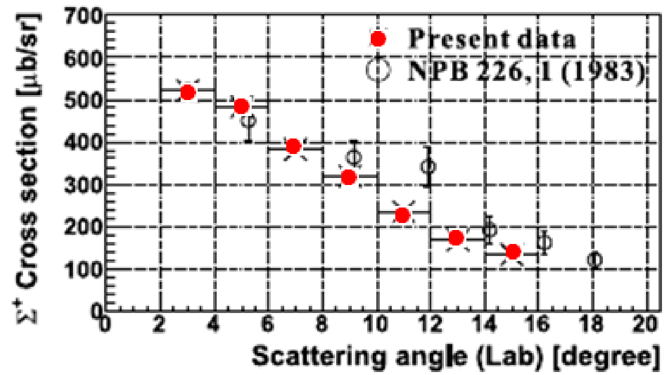
- Group of related reactions involve **KΣ** channel:

$\pi^+ n \to K^+\Sigma^0$
$\pi^+ n \to K^0\Sigma^+$
$\pi^- p \to K^+\Sigma^-$
$\pi^- p \to K^0\Sigma^0$
$\pi^- n \to K^0\Sigma^-$
$\pi^+ p \to K^+\Sigma^+$

- Except for $\pi^+ p \to K^+\Sigma^+$, these reactions involve mixture of **isospins 1/2** & **3/2**.
- Although there have been number of recent high-quality measurements involving **KΣ** photoproduction, status of complementary reactions measured with **pion beams** is rather **dark**.

[K. Shirotori *et al,* Phys Rev Lett **109**, 132002 (2012)]





J-PARC

- Measurements like these, over more comprehensive energy range, will greatly improve **PWA**s of **KΣ** final state and, in return, help to extract **S**-wave contribution needed, e.g., in approaches based on **unitarized chiral perturbation theory**.

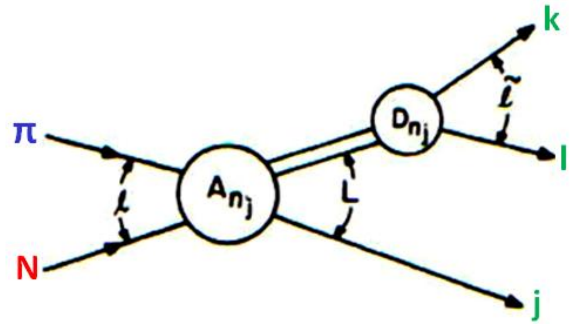
The Durham HepData Project

There are generally fewer data for $\pi^- p$ reactions with **KΣ**, **η'N**, **ωN**, & **φN** final states than for $\pi^- p \to \eta n$.

Status of Data for Multi-pion Reactions

- Important reactions that can be studied are those with **$\pi\pi N$** final states:

$\gamma p \to \pi^0\pi^0 p$	$\pi^+ n \to \pi^0\pi^0 p$
$\gamma p \to \pi^0\pi^+ n$	$\pi^+ n \to \pi^0\pi^+ n$
$\gamma p \to \pi^+\pi^- p$	$\pi^+ n \to \pi^+\pi^- p$
$\gamma n \to \pi^0\pi^- p$	$\pi^- p \to \pi^0\pi^- p$
$\gamma n \to \pi^0\pi^0 n$	$\pi^- p \to \pi^0\pi^0 n$
$\gamma n \to \pi^+\pi^- n$	$\pi^- p \to \pi^+\pi^- n$



- **$\pi N \to \pi\pi N$** reactions have the **lowest energy threshold** of all **inelastic hadronic** reactions & some of **largest cross sections**.

- Analysis & interpretation of data from these reactions are **more complex** because of **3-body** final states.

Dominant inelastic decays for most established **N*** & **Δ*** resonances are to **$\pi\pi N$** final states.

- Our knowledge of **πΔ**, **ρN**, & other quasi-two-body **$\pi\pi N$** channels comes mainly from **Isobar-model** analyses of **$\pi N \to \pi\pi N$** data.

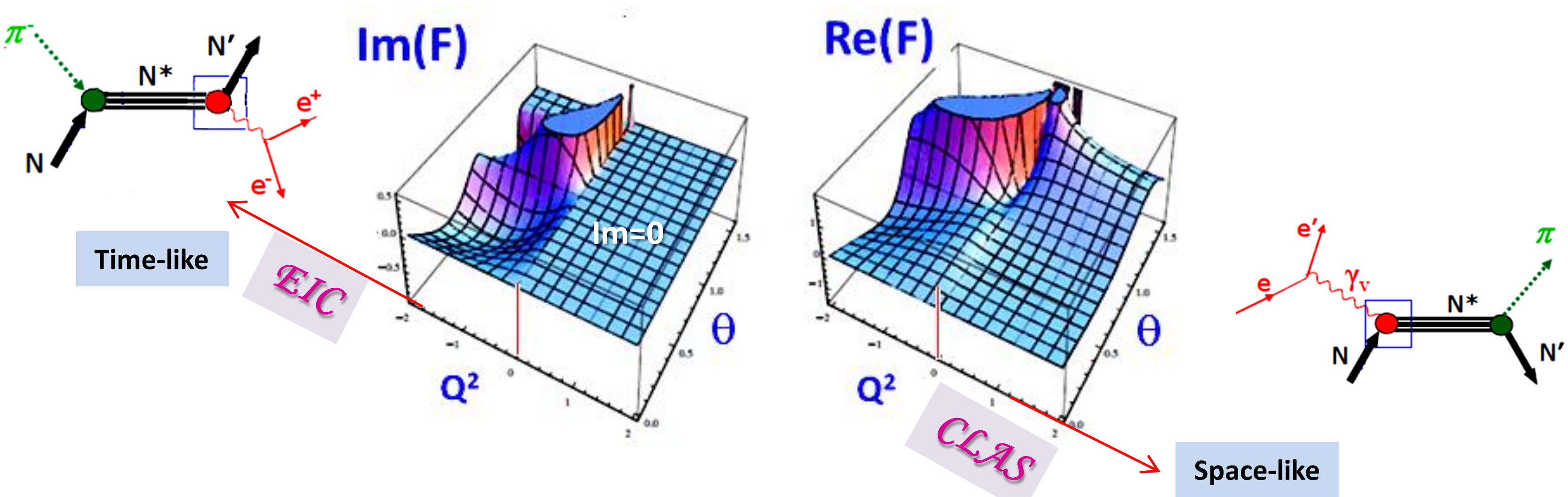
- Larger **experimental database** (including **pol** measurements) is **needed** to determine precisely the **PW** amplitudes because so many amplitudes are **required** to describe **3-body** final states.

Form-Factor Measurements

- **Inverse Pion Electroproducion** is the only process which allows determination of **EM nucleon** & **pion form-factors** in intervals:

$0 < k^2 < 4\,M^2$ $\qquad$ $0 < k^2 < 4\,m_\pi^2$

which are kinematically **unattainable** from e^+e^- initial states.

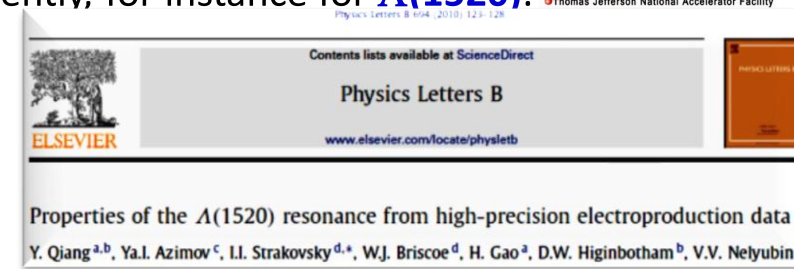


- $\pi^- p \rightarrow e^+e^- n$ measurements will significantly complement current studies of the evolution of **baryon** properties with increasing momentum transfer in **electroproduction** by investigating the case of ***time-like virtual photon***.

Spectroscopy of Hyperons

- Our current experimental knowledge of Λ^* & Σ^* resonances is far **worse** than our knowledge of **N*** & Δ^* resonances, but they are **equally fundamental**.

- **Pole** position for hyperons began to be studies only recently, for instance for **Λ(1520)**. Jefferson Lab Thomas Jefferson National Accelerator Facility


Physics Letters B 694 (2010) 123–128

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Properties of the Λ(1520) resonance from high-precision electroproduction data

Y. Qiang[a,b], Ya.I. Azimov[c], I.I. Strakovsky[d,*], W.J. Briscoe[d], H. Gao[a], D.W. Higinbotham[b], V.V. Nelyubin[e]

- Clearly, complete understanding of **three-quark bound** states requires to learn baryon resonances in ``**strange sector**''.

- One of secondary beam problems is that **Kaon yield** is less than **pion one** by factor of about **500**.
- This is main reason why there are limited exp data for **Kaon** induced measurements & there are negligible **polarized** measurements.

- Line shape of **Λ(1405)1/2$^-$** can be studied in **K^-p** & **K^-d** (**K^-n**) reactions. Comparison between **pion**- & **Kaon**-induced reactions together with **photoprod** is important.
- Measured $\pi\Sigma/\pi\pi\Sigma$ **BR** for **Σ(1670)** produced in reaction **$K^-p\to\pi^-\Sigma(1670)^+$** depends strongly on momentum transfer, and it has been suggested that there exist two **Σ(1670)'s** with the same mass and quantum numbers, one with large $\pi\pi\Sigma$ **BR** and other with large $\pi\Sigma$ **BR**.

Status of Data for Kaon Induced Reactions

- **Hyperons Λ^*** & Σ^* have been systematically studied in following formation processes:

$$K^-p \to K^-p$$
$$K^-p \to \overline{K}^0 n$$
$$K^-p \to \pi^0\Lambda$$

$$K^-p \to \pi^+\Sigma^-$$
$$K^-p \to \pi^0\Sigma^0$$
$$K^-p \to \pi^-\Sigma^+$$

$$K^-n \to \pi^-\Lambda$$
$$K^-n \to \pi^0\Sigma^-$$
$$K^-n \to \pi^-\Sigma^0$$

- Most of our knowledge about **multi-strange baryons** was obtained from **old data** measured with **Bubble Chambers**.

- The lack of appropriate **beams** & **detectors** in **past** greatly **limits** our **knowledge**.

- **Cascade hyperon resonances** could be studied with high-momentum **Kaon beams** & modern **multi particle spectrometers**.

PDG particle data group: Currently only **cascade** ground states of **spin-1/2** & **spin-3/2** are well identified.

- For **excited** states, possible production reactions with **Kaon** beams are:

$$K^-p \to K^+\Xi^{*-}$$
$$K^-p \to K^{*+}\Xi^{*-}$$
$$K^-p \to K^{*0}\Xi^{*0}$$

$$K^-p \to K^+\pi^+\pi^-\Xi^{*-}$$
$$K^-p \to K^+\pi^-\Xi^{*0}$$

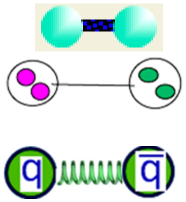
Meson Spectroscopy

- Although it was **light Hadron Spectroscopy** that led the way to discovery of **color degrees** of freedom & **QCD**, much of field remains poorly understood, both **theoretically** & **experimentally**.

- **Availability** of **pion** & **Kaon** beams provide important opportunity to improve situation.

- Experimentally, **Meson Spectroscopy** can be investigated by using **PWA**s to determine quantum numbers from angular distributions of final-state particle distributions.

- The **chief areas** of interest in **Meson Spectroscopy** are



scalar mesons,
multiquark states,
glueballs, &
hybrids.

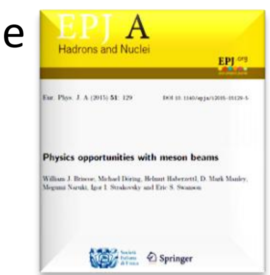
- Experimental effort with **meson beams** will complement **GlueX** experiment at **JLab**, which seeks to explore properties of **hybrids** with photon beam.

Physics Opportunities

- The current plans of runs at modern **Hadron Facilities** [**J-PARC**, **HADES**, **COMPASS**, & **PANDA**] will greatly improve database; however, there are **no plans** for **polarized** measurements.

- New **Meson Facility** would need large-acceptance **detector** & availability of **polarized** target.

- In particular, such dedicated facility should be able to provide features listed in recent **White Paper**:



Treasure box

Electron Ion Collider

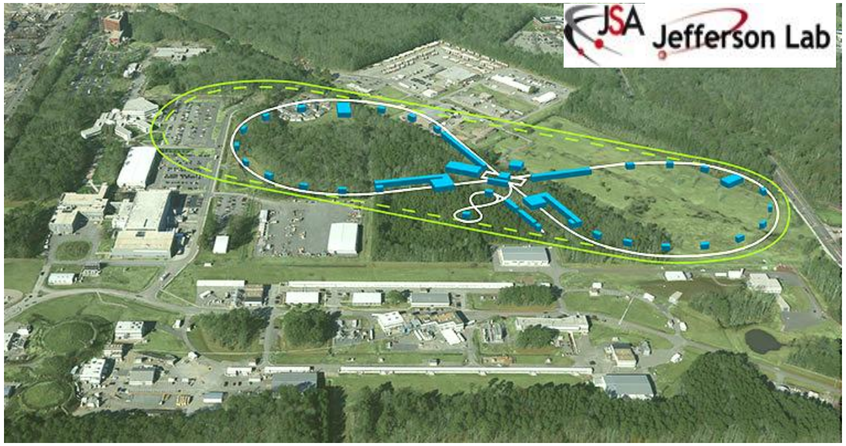
NSAC LRP 2015:

1. *``Continue existing projects: **CEBAF**, FRIB, RHIC."*
2. *``...a U.S.-led ton-scale neutrinoless double beta decay experiment."*
3. ***``...a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."***
4. *``...small-scale and mid-scale projects and initiatives that enable forefront research at universities and labs."*

*``A major **experimental initiative** continues to be the search for the so-called `**missing baryons**'...*
*The **experimental data** are, therefore, suggestive of a more intricate manifestation of **QCD** in baryons..."*

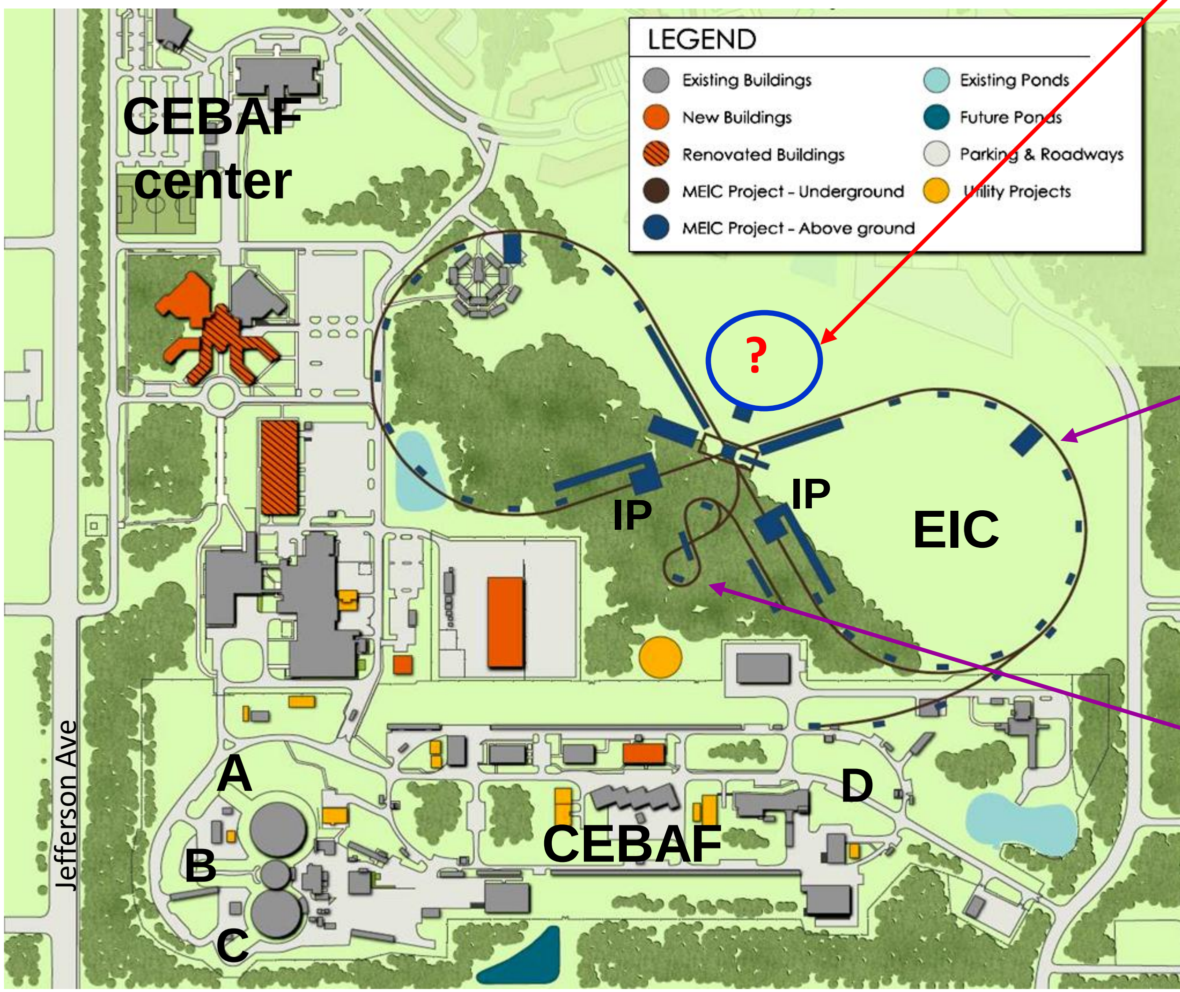
*``For many years, there were both theoretical and experimental reasons to believe that the **strange sea quarks** might play a significant role in the nucleon's structure; a better understanding of the role of **strange quarks** became an important priority."*

Why EIC and Why at Jefferson Lab ?



- ***EIC Facility*** design meets experimental needs:
  - Broad CM energy range.
  - High luminosity.
  - Wide range of ion species.
- ***Green Field*** new **Ion Complex** provide opportunity for modern design for highest performance.
- Large established **user community** at **JLab**.
- ***Meson Facility*** would allow keep **JLab Ion Booster** longer busy (to use much more than ``**several minutes**” a day), which would be much more effective use of ***EIC Facility***, **without significant increase of the cost of JLab Ion Booster**.

JLab Campus Layout



Meson Facility [good to have]:

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

EIC Facility:

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

Ion Booster:

- *Protons*: **8** GeV.
- Booster design based on super-ferric magnet technology.
- *Circumference*: **273** m.

JLab for Hyperon Spectroscopy

- We have outlined some of **physics programs** that could be advanced with **EIC** especially appended by **Meson Facility**.

- Those include studies of **baryon** spectroscopy, particularly search for ``**missing resonances**" with hadronic beam data that would be analyzed together with **photo**- & **electro-**production data using modern **coupled-channel** analysis methods.

- **Meson Facility** would also advance **hyperon spectroscopy** and study of **strangeness** in nuclear & hadronic physics.

- Searches for **exotic states** (highly anticipated, but never observed unambiguously), such as **multiquarks**, **glueballs**, & **hybrids** would be greatly enhanced by availability of **Meson Facility**.

- Simply discovering of missing **low-lying meson states** would also assist in constructing new models for apparent **properties** of **QCD**, thereby improving our understanding of this strongly coupled **non-linear quantum field theory.**

Thank You





Yakov Azimov
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Mark Manley
Vasily Morozov
Megumi Naruki
Eric Swanson





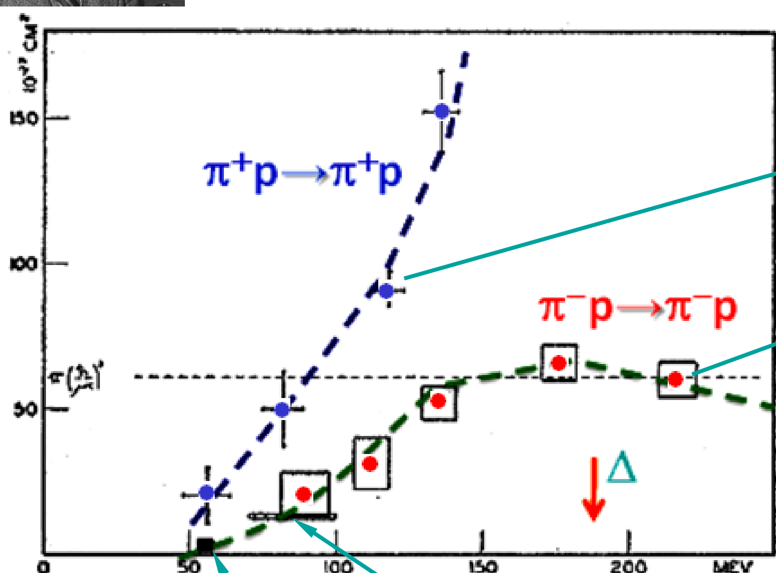
The First Baryon Resonance Discovery

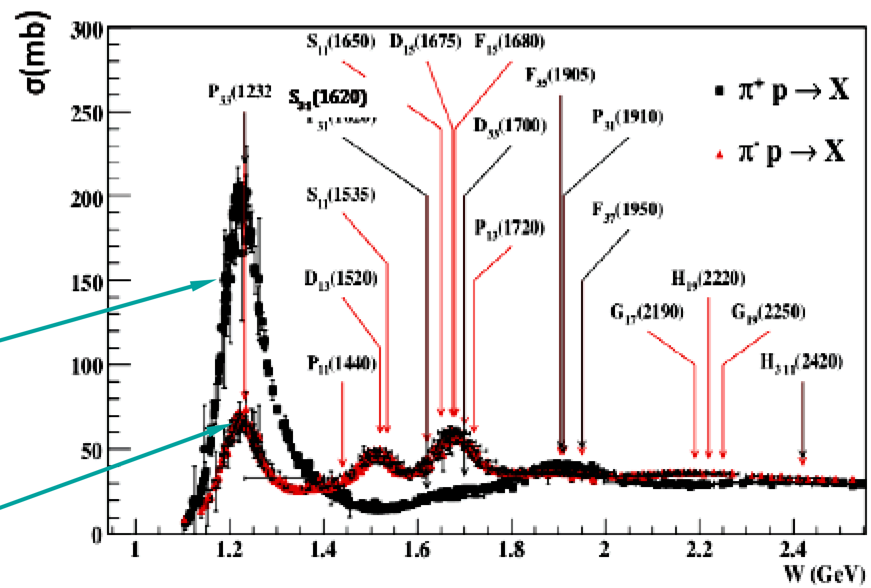
936 LETTERS TO THE EDITOR

Total Cross Sections of Positive Pions in Hydrogen*

H. L. ANDERSON, E. FERMI, E. A. LONG,† AND D. E. NAGLE
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 21, 1952)

Δ(1232)3/2⁺





- Then, since **1952** many states were **discovered** in **$\pi N \to \pi N$**.

PWA for Baryons

Originally **PWA** arose as technology to determine amplitude of reaction via **fitting** scattering data.
That is **non-trivial mathematical problem** – looking for solution of **ill-posed** problem following to **Hadamard** and **Tikhonov**.


Resonances appeared as **by-product**
[bound states objects with definite quantum numbers, mass, lifetime, & so on].

Most of our current knowledge about bound states of **three light quarks** has come mainly from **$\pi N \to \pi N$** **PWAs**:

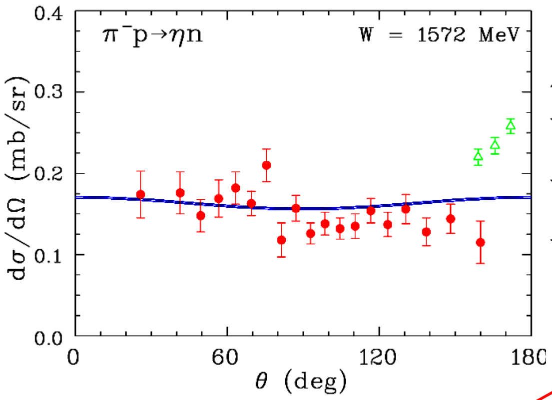
Karlsruhe-**Helsinki**,

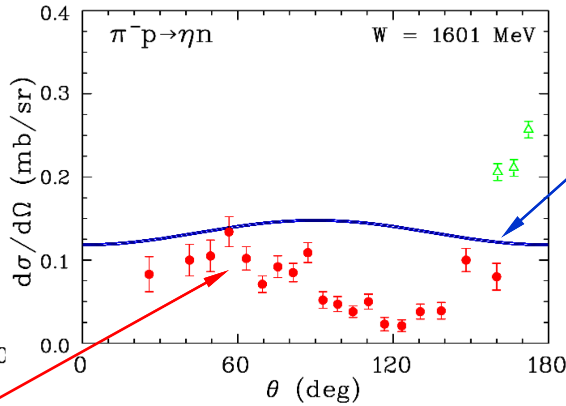
Carnegie-**Mellon**-**Berkeley**,

& **GW**.


Main source of **EM** couplings is **GW** & **BnGa** analyses.

Where we are in $\pi^- p \to \eta n$

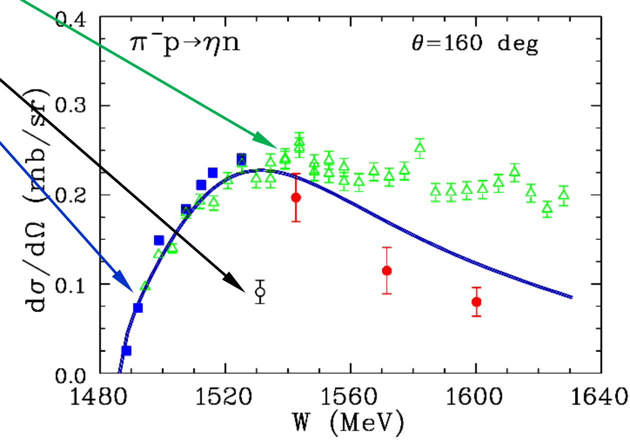




- **There were several independent evaluations:**
  - Arndt *et al*, Phys Rev C **69**, 035213 (2004)
  - Clajus & Nefkens, πN News Lett **7**, 76 (1992)
  - Wighman *et al*, Phys Rev D **38**, 3365 (1988)
  - Koch & Pietarinen, Nucl Phys **A336**, 331 (1980)
  - Cutkosky *et al*, Phys Rev D **20**, 2804 (1979)

There are 27 σ^{tot} & 37 P reliable data above T = 800 MeV → 0.03 data/MeV

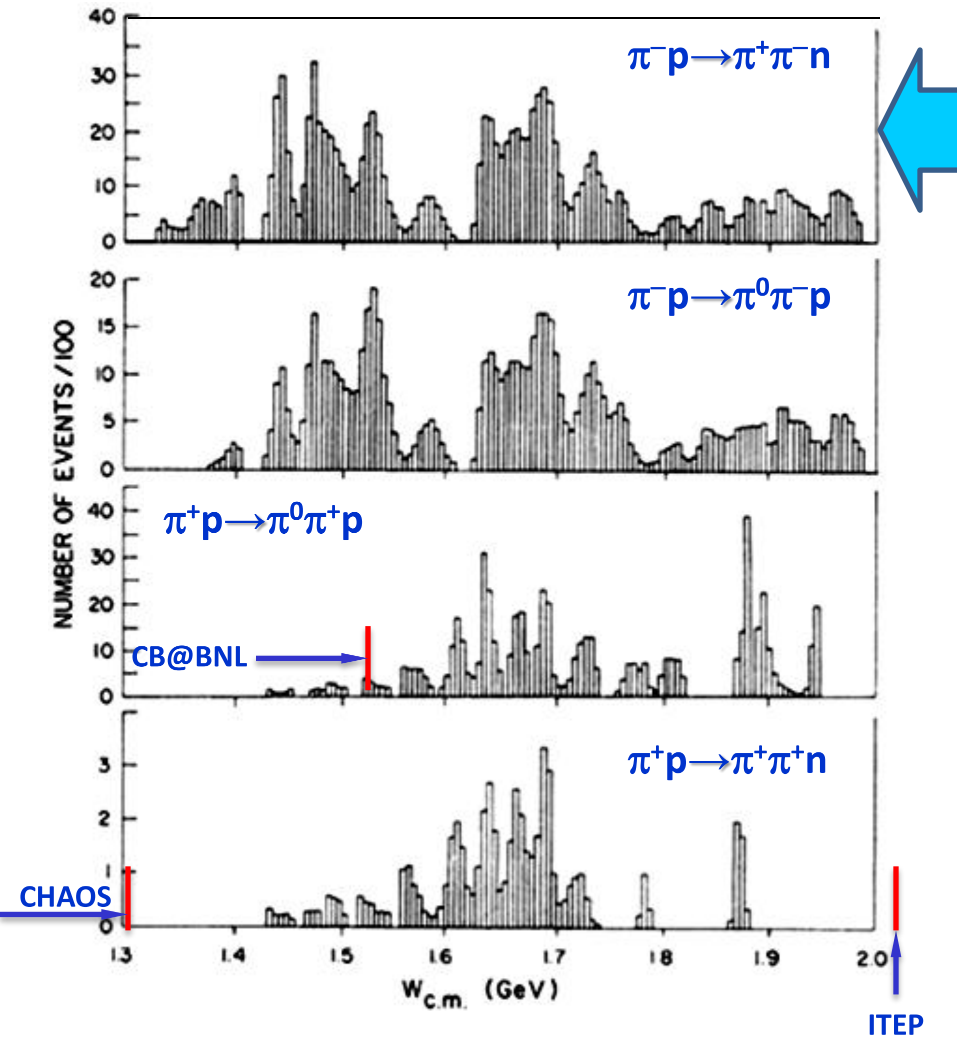
RHEL: Brown *et al*, Nucl Phys **B153**, 89 (1979)
RHEL: Debenham *et al*, Phys Rev D **12**, 2545 (1975)
Saclay: Feltesse *et al*, Nucl Phys **B93**, 242 (1975)
BNL: Prakhov *et al*, Phys Rev C **72**, 015203 (2005)



- Most of previous data do not satisfy requirements [systematics (10% or more), momentum err (up to 50 MeV/c), and so on].

- **Evaluation** for reactions with **KY**, **η'N**, **ωN**, **φN**, & so on final states are **not possible now** because of small/limited databases.

$\pi p \rightarrow \pi\pi N$ *Measurements*

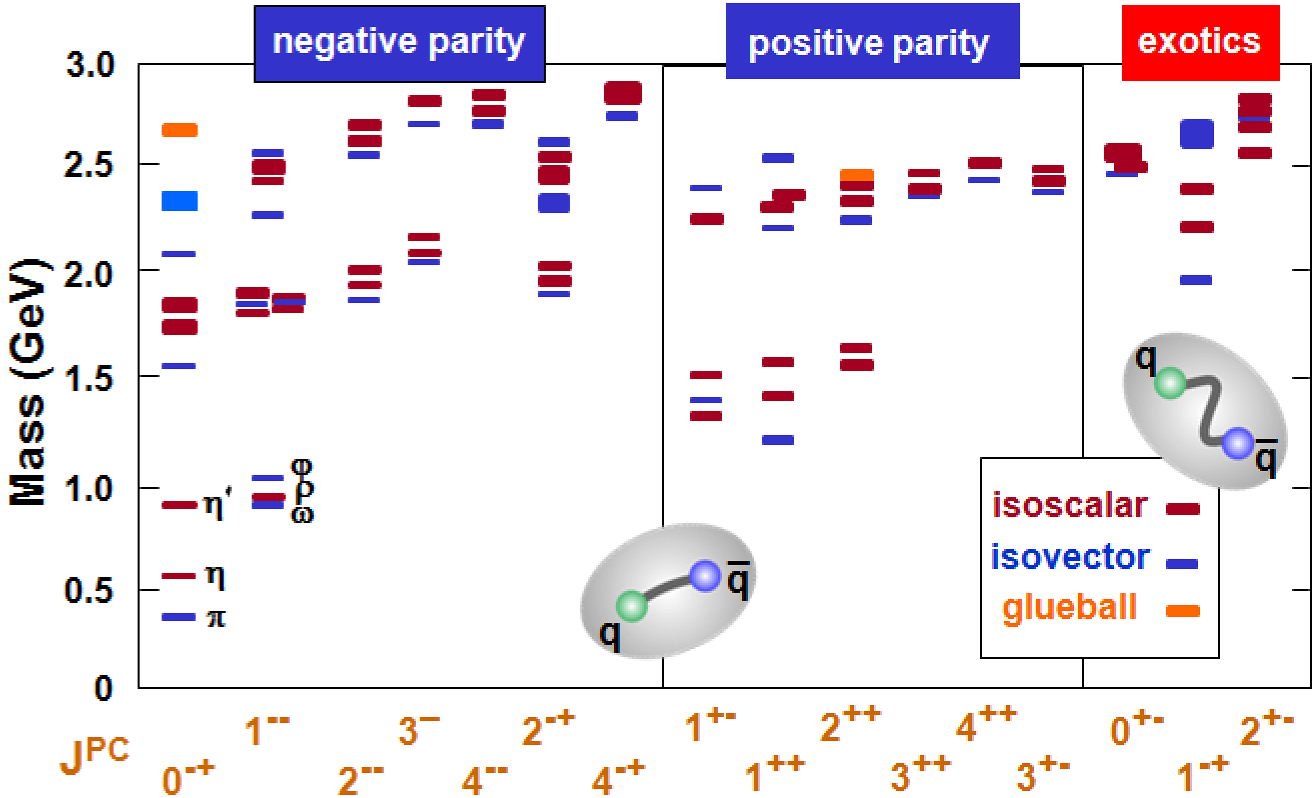


- **241,214** **Bubble Chamber** events for $\pi p \rightarrow \pi\pi N$ have been analyzed in **Isobar-model** **PWA** at **W** = **1320** to **1930** MeV.
  [M. Manley, R. Arndt *et al,* Phys Rev D **30**, 904 (1984)]

- Post-Bubble Chamber measurements:
  - **349,611** events for $\pi^- p \rightarrow \pi^0\pi^0 n$ from **CB@BNL** at **W** = **1213** to **1527** MeV.
    [S.Prakhov *et al,* Phys Rev C **69**, 045202 (2004)]
  - **20,000** events for $\pi^{+-} p \rightarrow \pi^{+-}\pi^{-+} n$ from **CHAOS@TRIUMF** at **W** = **1257** to **1302** MeV.
    TRIUMF [M. Kermani *et al,* Phys Rev C **58**, 3431 (1998)]
  - **40,000** events for $\pi^- \vec{p} \rightarrow \pi^-\pi^+ n$ from **ITEP** at **W** = **2060** MeV.
    [I. Alekseev *et al,* Phys At Nucl **61**, 174 (1998)]

Lattice Computation of the Light Meson Spectrum

- **Lattice QCD** simulations for **excited baryons** are considerably more complicated than for **excited mesons** due to signal-to-noise & combinatorial problems of contractions of three quarks instead of two.



[J.J. Dudek *et al,* Phys Rev D **88**, 094505 (2013)]

Status of Search for Glueballs

- The quantum numbers for exotics: multiquark, glueball, or hybrid are 0^{--}, $(odd)^{-+}$, & $(even)^{+-}$.

- Lattice **glueball** spectrum below **3** GeV.

[Y. Chen *et al,* Phys Rev D **73**, 014516 (2006)]

J^{PC}	Mass (MeV)
0^{++}	1710 (50)(80)
2^{++}	2390 (30)(120)
0^{-+}	2560 (35)(120)
1^{+-}	2989 (30)(140)

- Unfortunately, there are no **glueballs** have been **definitively identified**.

- Promising earlier candidate called **ξ(2200)** has not withstood careful analysis.

- At present, the best candidate is **f_0(1500)** [or possibly **f_0(1710)**], which appears as supernumerary state in enigmatic scalar meson sector.

[C. Amsler and F.E. Close, Phys Rev D **53**, 295 (1996)]