Secondary Beam Possibilities

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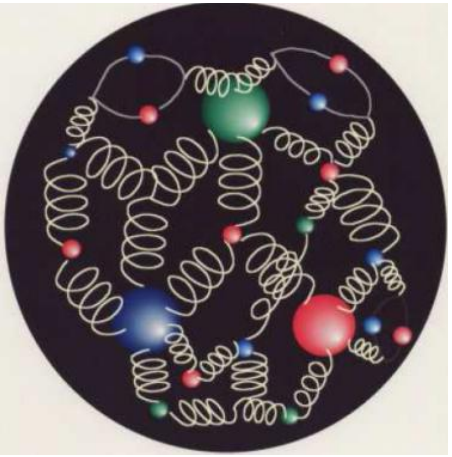
- Baryon Spectroscopy
  - Why and How we are doing that
- $\pi N \rightarrow$ Inelastic
  - $\pi^- p \rightarrow \eta n$, KY, ωn
  - $\pi N \rightarrow 2\pi N$
  - $\pi^- p \rightarrow e^+ e^- n$
  - Current Hadronic Projects
- What EIC may Do

Baryon Spectroscopy

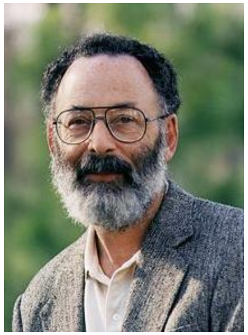


Why and How We are Doing that

Spectroscopy of Baryons

``It is clear that we still need much more information about the existence and parameters of many baryon states, especially in the N=2 mass region, before this question of non-minimal SU(6) x O(3) super-multiplet can be settled." **Dick Dalitz**, **1976.**

``The first problem is the notion of a resonance is not well defined. The ideal case is a narrow resonance far away from the thresholds, superimposed on slowly varying background. It can be described by a Breit-Wigner formula and is characterized by a pole in the analytic continuation of the partial wave amplitude into the low half of energy plane.'' **Gerhard Hoehler, 1987**.



``Why N*s are important – The *first* is that nucleons are the stuff of which our world is made. My *second* reason is that they are simplest system in which the quintessentially non-Abelian character of QCD is manifest. The *third* reason is that history has taught us that, while relatively simple, Baryons are sufficiently complex to reveal physics hidden from us in the mesons." **Nathan Isgur**, **2000**.

Baryon Spectroscopy from PDG

[J. Beringer *et al* [RPP] Phys Rev D **86**, 010001 (2012)]

A quick check of the **PDG listings** reveals that resonance parameters of many established states are not well determined

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]	****
$N(1860)$	[illegible]	**
$N(1875)$	[illegible]	[illegible]
$N(1880)$	[illegible]	[illegible]
$N(1895)$	[illegible]	[illegible]
$N(1900)$	[illegible]	[illegible]
[illegible]	$7/2^+$	[illegible]
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	[illegible]
$\Delta(1920)$	[illegible]	[illegible]
$\Delta(1930)$	[illegible]	[illegible]
$\Delta(1940)$	[illegible]	[illegible]
$\Delta(1950)$	$7/2^+$	[illegible]
[illegible]	$5/2^+$	[illegible]
[illegible]	[illegible]	[illegible]
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**

Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1800)$	[illegible]	[illegible]
$\Lambda(1810)$	[illegible]	[illegible]
$\Lambda(1820)$	[illegible]	[illegible]
$\Lambda(1830)$	$5/2^-$	[illegible]
[illegible]	$3/2^+$	[illegible]
[illegible]		
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

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

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	$3/2^+$	****
[illegible]	[illegible]	[illegible]
[illegible]		***
[illegible]	$3/2^-$	***
[illegible]		***
[illegible]	[illegible]	***
$\Xi(2120)$		[illegible]
[illegible]		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	[illegible]	****
[illegible]		[illegible]
[illegible]		[illegible]
[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	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
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^-	$1/2^+$	***

- **PDG12** has **112** (58 **4*** & **3*** of them) resonances.
- For example for **SU(6) x O(3)**, it would be **434** resonances, if all revealed three **70**– and four **56**– multiplets were filled in.

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

*There are Many Ways to Study N**

Prolific source of N* & Δ* baryons

Measure many channels with different combinations of quantum numbers.

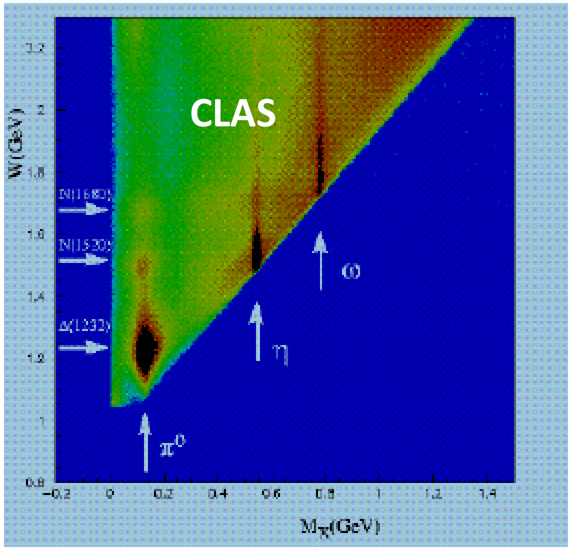
$\pi N \to \pi N, \pi\pi N, \ldots$

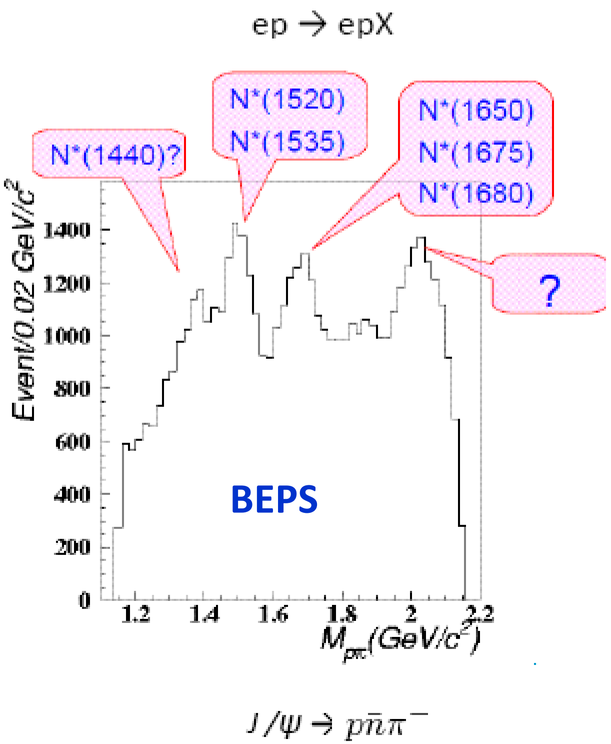
$\gamma N \to \pi N, \pi\pi N, \ldots$

$\gamma^* N \to \pi N, \pi\pi N, \ldots$

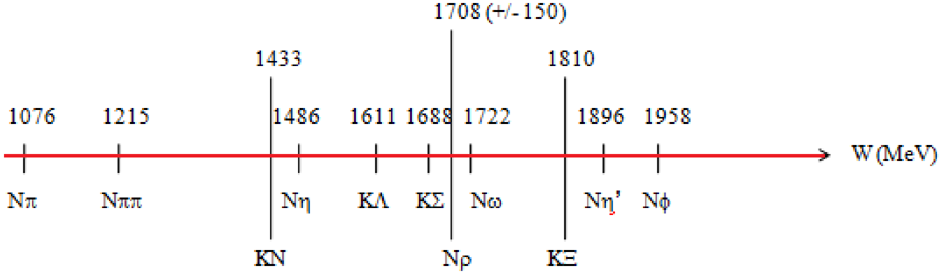
$pp \to pp\pi^0, pp\pi\pi, \ldots$

$J/\psi \to p\bar{p}\pi^0, p\bar{n}\pi^-, \ldots$





- Most of **PDG** info comes from these sources
- **πN** elastic scattering is highly constrained
- Resonance structure is correlated
- Two-body final state, fewer amplitudes



Where We Are Now…

- Certain experiments provide unique info about resonance decay properties.
  *For example, the helicity couplings **A1/2** and **A3/2** for **γp** and **γn** decays come only from **pion** photo- & electro-production measurements.*

- The helicity couplings in turn are normally extracted from the full energy-dependent multipole amplitudes.
  Until recently, the only available multipole amplitudes were for single pion photoproduction.

- A determination of **A1/2** and **A3/2** from meson photo- & electro-production requires knowledge of the corresponding hadronic couplings.
  Photo- & electro-production alone determines only the product of couplings to the γN and hadronic channels.

  Every phenomenology group [BnGa, EBAC, Gent, Giessen, Jaw, Juelich, MAID, & SAID] uses SAID πN results for constrain.

- Most modern **experimental efforts** focus on photo- or electro-production experiments – needed are high-precision complementary measurements with **hadron** beams (**pions** & **kaons**)
  PWAs are best way to determine **N*** properties
  – *Multichannel approaches can help resolve inconsistencies.*

PWA for non-strange Baryons & SAID Database

Originally: PWA arose as the technology to determine amplitude of the reaction via fitting scattering data which is a non-trivial mathematical problem
[*Solution of ill-posed problem*
– Hadamard, Tikhonov, *et al*]

Resonances appeared as a by-product
[Bound states objects with definite quantum numbers, mass, lifetime, *etc*]

That is the strategy of the GW/VPI πN PWA since 1987

CNS
Center for Nuclear Studies
Data Analysis Center

Below 4 GeV

Partial-Wave Analyses at GW
[See Instructions]

31,402	Pion-Nucleon	
	Pion-Pion-Nucleon	241,214 evts [W = 1320 to 1930 MeV]
5,267	Kaon-Nucleon	
	Nucleon-Nucleon	38,162
25,660	Pion Photoproduction	
	Pion Electroproduction	113,900
9,086	Kaon Photoproduction	
	Eta Photoproduction	6,235
1,030	Eta-Prime Photoproduction	
	Pion-Deuteron (elastic)	1,914
6,083	Pion-Deuteron to Proton+Proton	

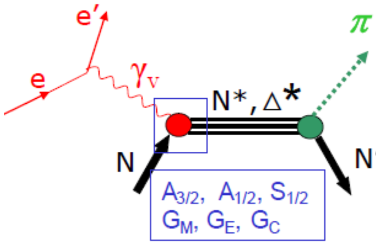
For $\pi \rightarrow 2\pi$, we use log-likelihood while for the rest – least-squares technologies

N* and Δ* States coupled to π N

[SAID: http://gwdac.phys.gwu.edu/]

- **GW SAID N* program consists of πN→πN ⟹ γN→πN ⟹ γ*N→πN**
  As was established by Dick Arndt on 1997

Assuming dominance of 2-hadronic channels [πN elastic & $\pi^- p \to \eta n$], we parameterize $\gamma^* N \to \pi N$ in terms of $\pi N \to \pi N$ amplitudes.



- **One** of the most convincing ways to study **Spectroscopy** of **N* & Δ*** is **πN PWA**

- Non-strange objects in the PDG Listings come mainly from:
  Karlsruhe-Helsinki, Carnegie-Mellon-Berkeley, GW/VPI, & BnGa now.
- The main source of EM couplings is the GW/VPI & BnGa analyses.

GW DAC [SAID] for $\pi N \rightarrow \pi N$ & $\pi^- p \rightarrow \eta n$

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

- Energy dependent SP06/WI08 and associated SES
- T = 0 – 2600 MeV [W = 1078 – 2460 MeV]
- 4-channel Chew-Mandelstam K-matrix parameterization [πN, πΔ, ρN, ηN]
- 3 mapping variables: $g^2/4\pi$, a[π^-p], Eth
- PWs = 30 πN {15 [I=1/2] + 15 [I=3/2]} + 4 ηN [l < 9]
- Prms = 99 [I=1/2] + 89 [I=3/2]

- **1st generation** ('57–'79)
  Used by CMB79 and KH84 analyses
  10k $\pi^\pm$p each & 1.5k CXS
  17% data is polarized
- **2nd generation** ('80–'06)
  → SAID fits
  13k $\pi^\pm$p each, 3k CXS & 0.3k $\pi^-p \rightarrow \eta n$
  25% data is polarized
  Meson Factories [LAMPF, TRIUMF, & PSI] are the main source of new measurements
  There is no discrimination against data
- **3rd generation** (07'+)
  New data may come from
  EPECURE, HADES, J-PARC, *etc*

Reaction	Data	χ^2
$\pi^+p \rightarrow \pi^+p$	13,354	27,136
$\pi^-p \rightarrow \pi^-p$	11,978	22,632
$\pi^-p \rightarrow \pi^0n$	3,115	6,068
$\pi^-p \rightarrow \eta n$	257	650
DR constraint	2,775	671
Total	31,479	57,157

[0 – 2600 MeV] → 10 data/MeV

[550 – 800 MeV] → 1 data/MeV

27 σ^{tot} & 37 P data above 800 MeV → 0.03 data/MeV

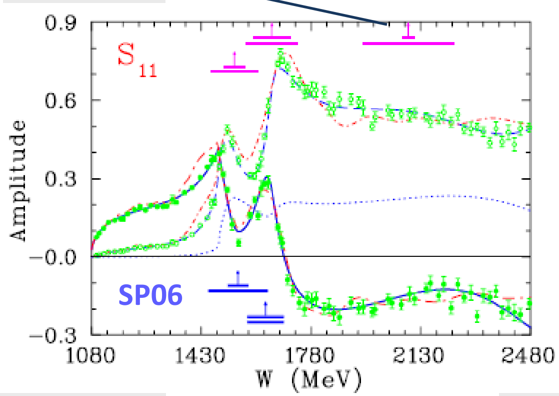
DRs have been derived from the *first principles*

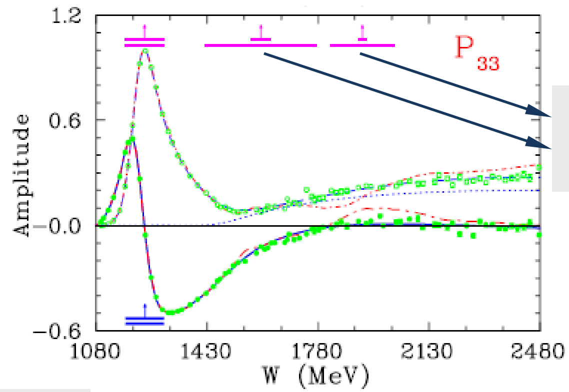
Partial Waves [$L_{(2I)(2J)}$]

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

Overall: the difference between KA'84 and GW'08 is rather small but…
resonances may be essentially different

N(2090)*

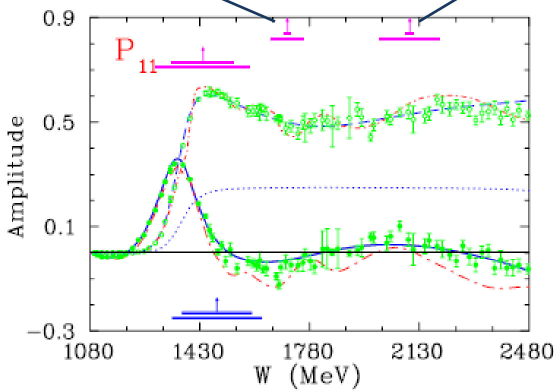


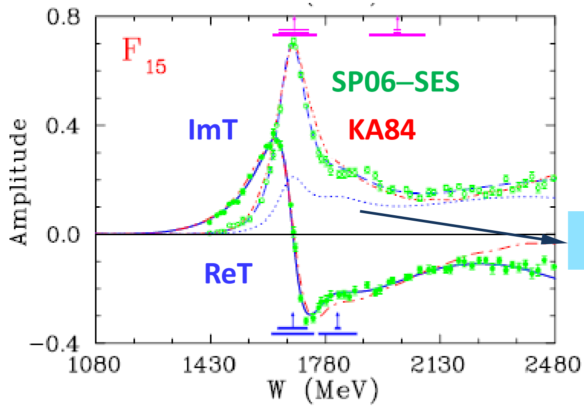


Δ(1920)***
Δ(1600)***

N(1710)***

N(2100)*





1964: 1.2k data below 700 MeV
2012: 32k data below 2600 MeV

$ImT - T^*T \geq 0$ [unitarity boundary]

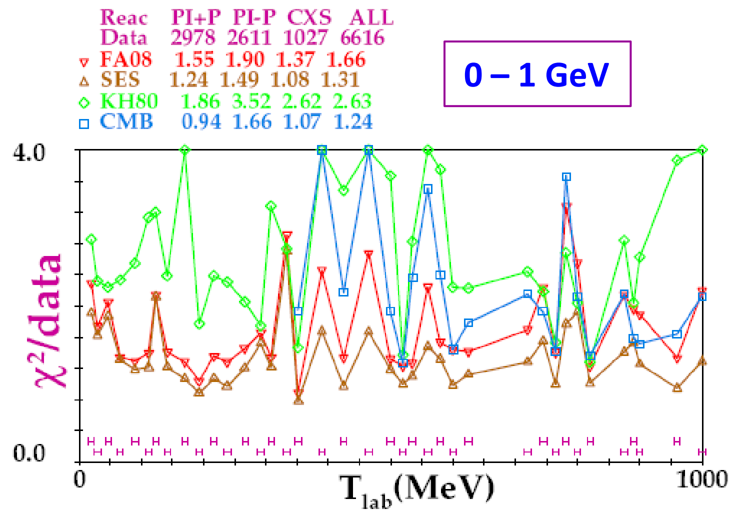
PDG12 [J. Beringer *et al* [RPP] J Phys D 86, 010001 (2012)]
KA84 [R. Koch, Z Phys C 29, 597 (1985)]

χ^2 *for different PWAs*

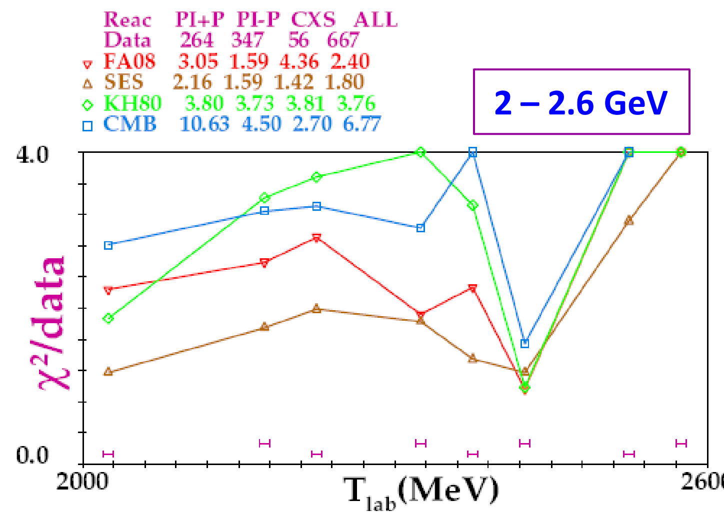
[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

Some of structures in **35**-year old solutions [**KH** and **CMB**] are still considered as resonances

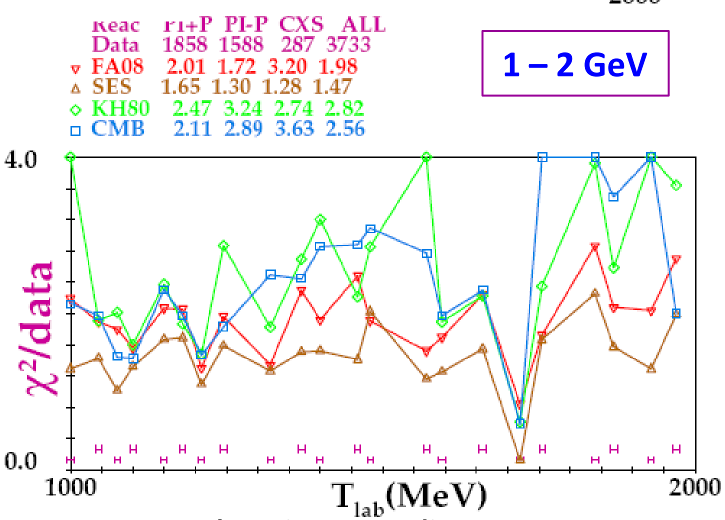
0 – 1 GeV



2 – 2.6 GeV



1 – 2 GeV



New Observables

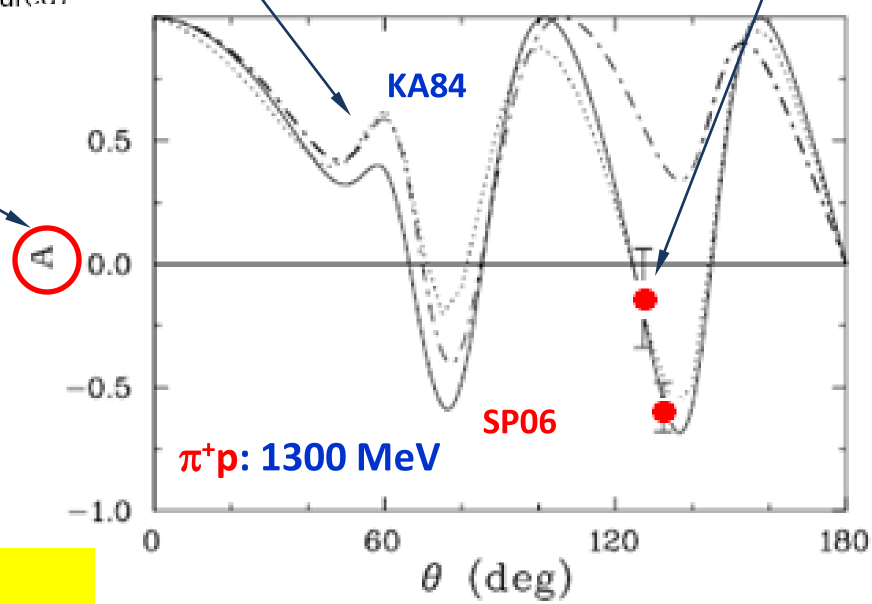
[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

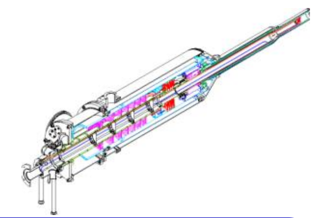
Some **Old** solutions may be not able to reproduce **New** measurements

πN scattering data:

dσ/dΩ (unpolarized)
P (polarized target or recoil nucleon)
R and A (polarized target and recoil measured)

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





Data:
ITEP: $\pi^+ p \rightarrow \pi^+ p$ @ 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 an important part of a hadron program

Summary of N^* and Δ^* Finding from GW πN PWA

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

- Standard PWA
  - Allows to determine the N^*s, Δ^*s, and their quantum numbers using
    - The complex energy plane &
    - Breit-Wigner technique
  - Tends (by construction) to miss narrow Resonances with $\Gamma < 30$ MeV
  - Reveals only wide Resonances, but not too wide ($\Gamma < 500$ MeV) & possessing not too small BR (BR > 4%)

GW SAID failed to confirm many of the 3-star and lower-rated states listed in PDG

PDG particle data group

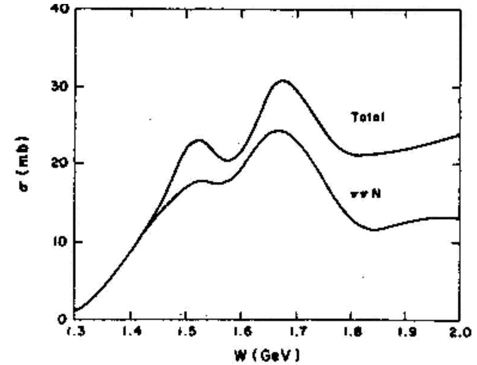
- PDG12 states — *The latest GWU analysis (Arndt06) finds no evidence for those resonances*

PDG12 ***	$\Delta(1600)P_{33}$, $N(1700)D_{13}$, $N(1710)P_{11}$, $\Delta(1920)P_{33}$
PDG12 **	$N(1900)P_{13}$, $\Delta(1900)S_{31}$, $N(1990)F_{17}$, $\Delta(2000)F_{35}$,
	$N(2080)D_{13}$, $N(2200)D_{15}$, $\Delta(2300)H_{39}$, $\Delta(2750)I_{313}$
PDG12 *	$\Delta(1750)P_{31}$, $\Delta(1940)D_{33}$, $N(2090)S_{11}$, $N(2100)P_{11}$,
	$\Delta(2150)S_{31}$, $\Delta(2200)G_{37}$, $\Delta(2350)D_{35}$, $\Delta(2390)F_{37}$

- Our study does suggest several 'new' N*s & Δ*s:

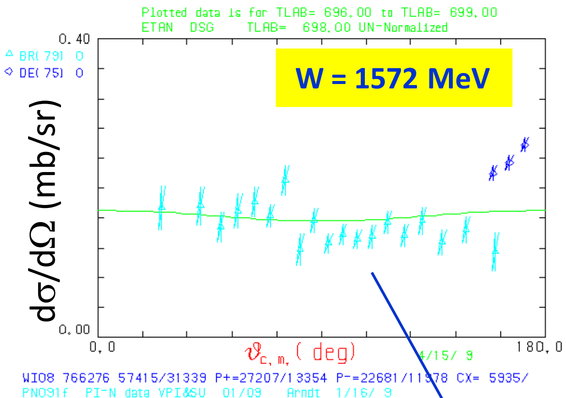
PDG12 ****	$\Delta(2420)H_{311}$
PDG12 ***	$\Delta(1930)D_{35}$, $N(1900)F_{15}$
PDG12 **	$\Delta(2400)G_{39}$
PDG12 new	$N(2245)H_{111}$

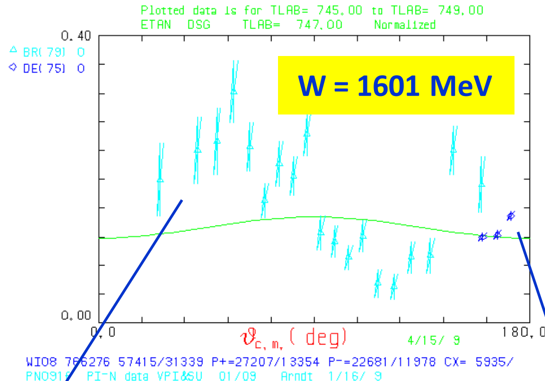
$\pi^- p \rightarrow$ *Inelastic*

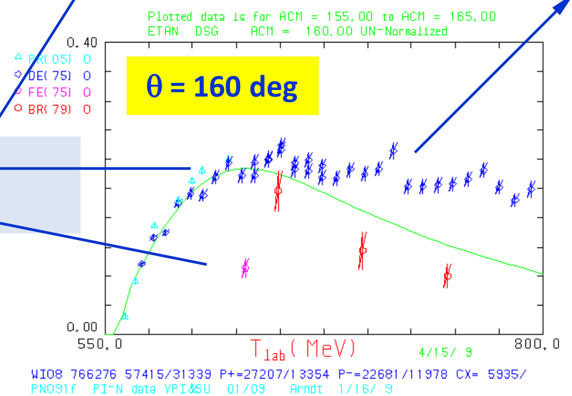


$\pi^- p \rightarrow \eta n$ Puzzle

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]







[Brown *et al*, Nucl Phys **B153**, 89 (1979)]
[Feltesse *et al*, Nucl Phys **B93**, 242 (1975)]

[Debenham *et al*, Phys Rev D **12**, 2545 (1975)]

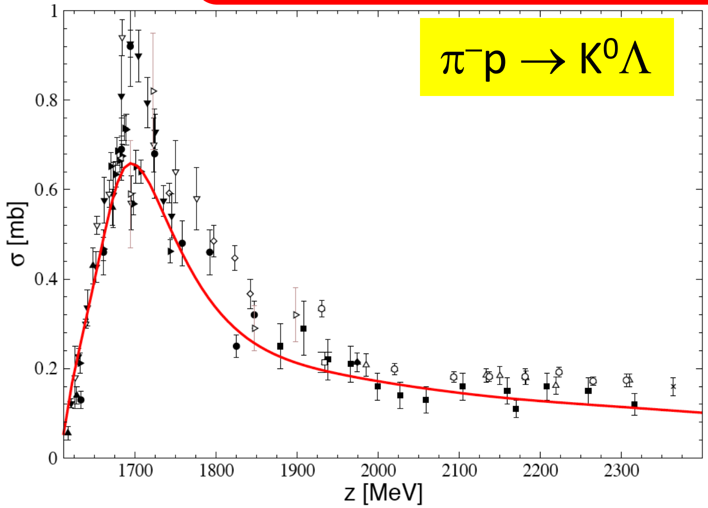
- **There are several independent evaluations:**
  - Arndt *et al* Phys Rev C **69**, 035213 (2004)
  - Clajus & Nefkens, πN News Lett **7**, 76 (1992)
  - Wighman *et al* Phys Rev D **38**, 3365 (1988)
  - Koch & Pietarinen, Nucl Phys **A336**, 331 (1980)
  - Cutkosky et al Phys Rev D **20**, 2804 (1979)

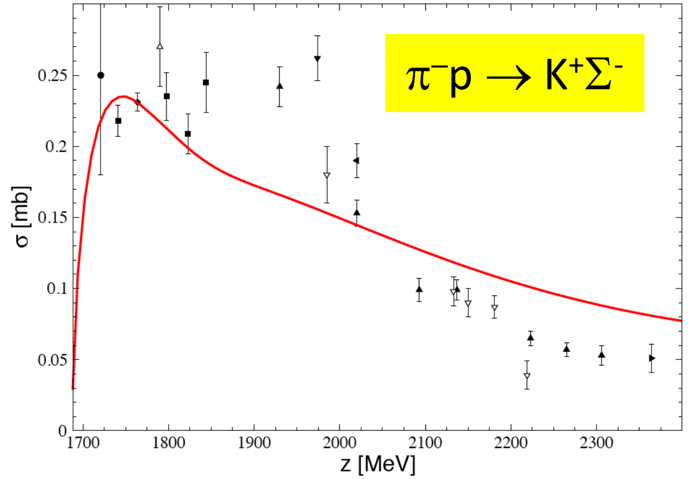
NIMROD (The 7GeV proton synchrotron) was the **7 GeV** proton synchrotron operating in the Rutherford Appleton Laboratory in UK between **1964** and **1978**

- Most of **NIMROD** data do not satisfy requirements
  [systematics (**10**% or more), momentum err (up to **50** MeV/c), and so on]
- For that reason, **SAID** is not able to use them in $\pi^- p \rightarrow \pi^- p$, $\pi^0 n$, & ηn PWA

$\pi N \rightarrow KY$ Puzzle

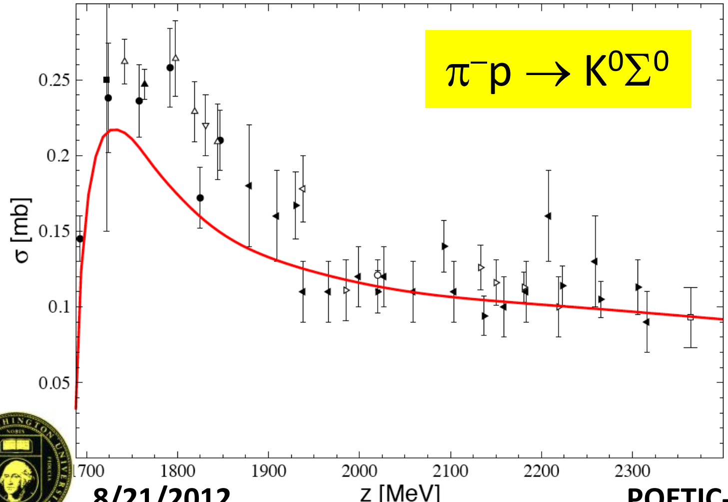
The evaluation for reactions with **KY**, **η'N**, **ωN**, **ϕN**, and so on final states are **not possible** now because of small databases

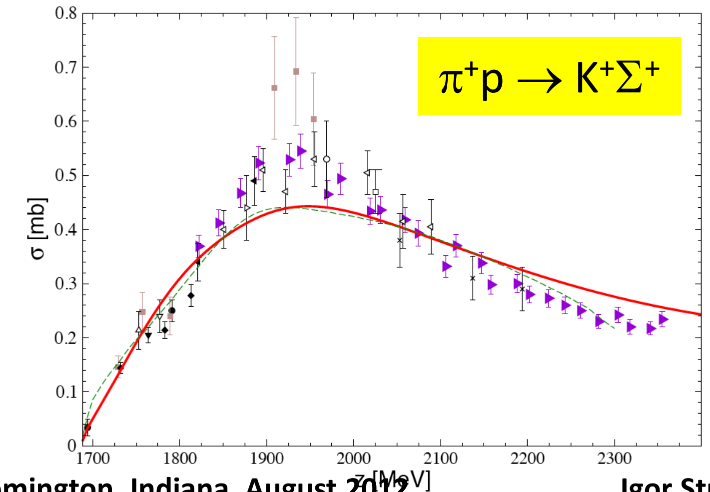




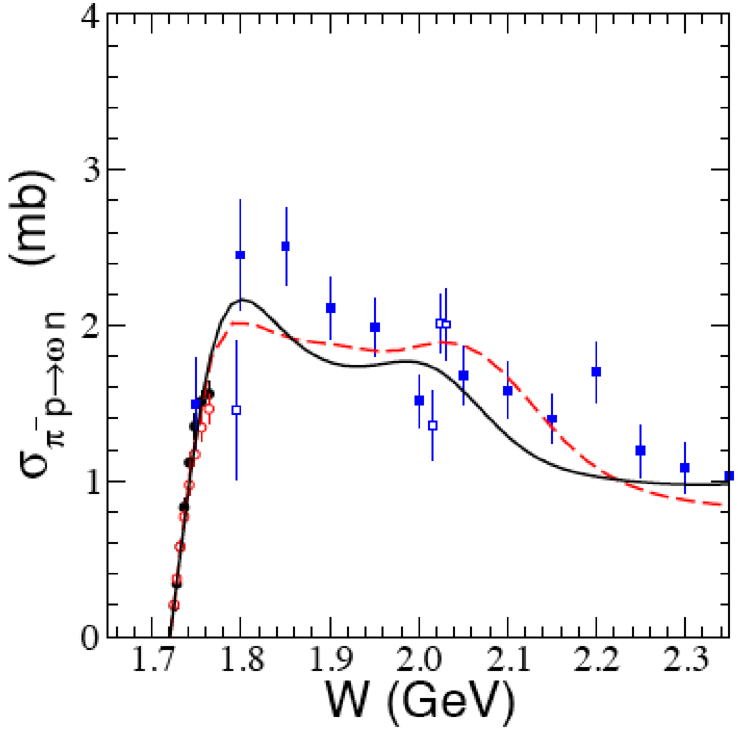
Curves: Jülich DCC model 2012

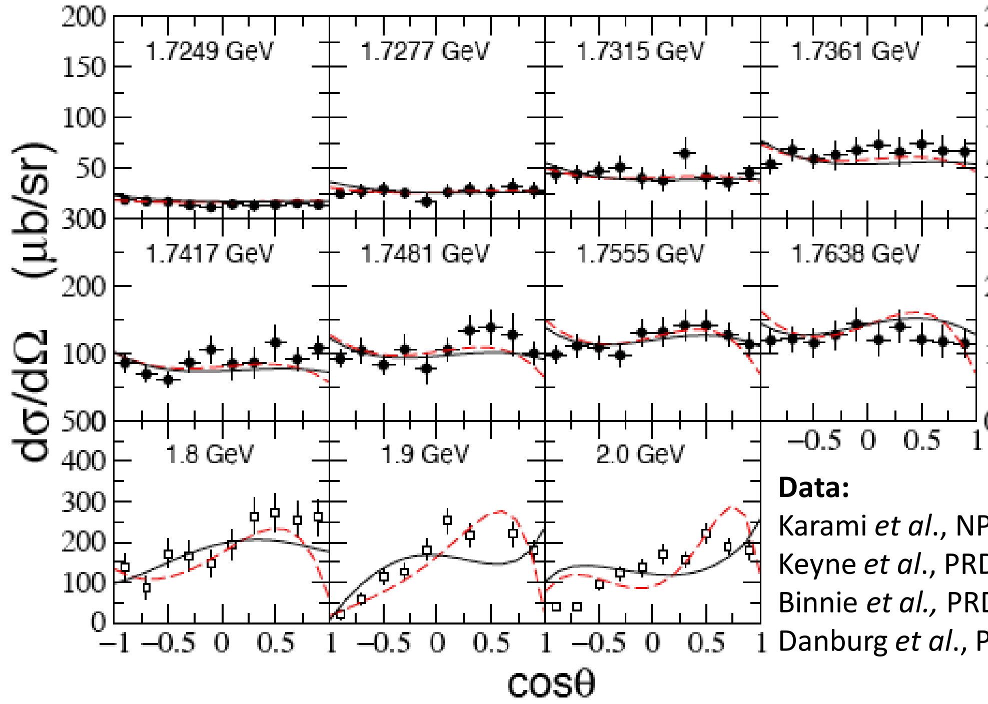
Courtesy of Kanzo Nakayama, GW EIC Workshop, April 2012





$\pi^- p \rightarrow \omega n$ Puzzle





Data:
Karami *et al.*, NPB**154**'79
Keyne *et al.*, PRD**14**'76
Binnie *et al.*, PRD**8**'73
Danburg *et al.*, PRD**2**'70

Controversy? :

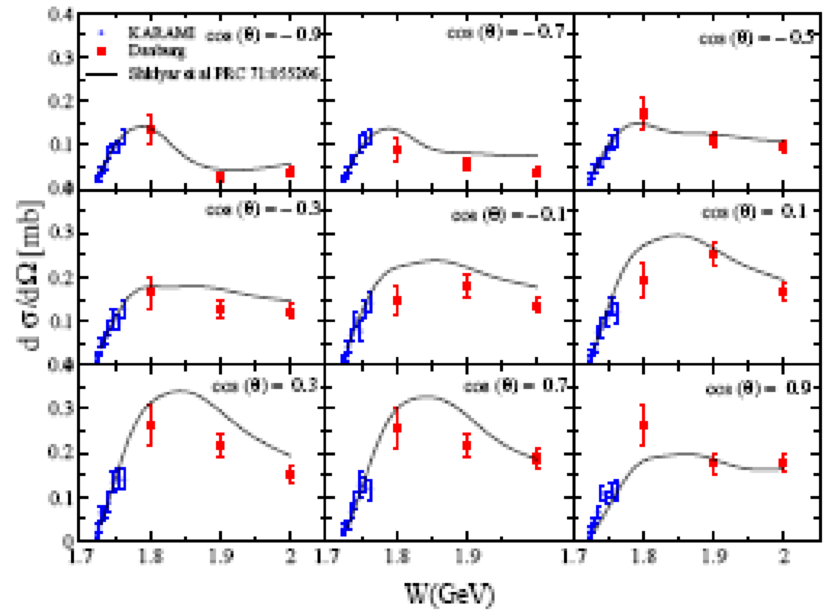
Sibirtsev & Cassing, EPJA**7**'00
Titov *et al.*, arXiv:nucl-th/0102032
Hanhart *et al.*, arXiv:hep-ph/0107245
Penner & Mosel, arXiv:nucl-th/0111024

Courtesy of Kanzo Nakayama, GW EIC Workshop, April 2012

needs to be re-measured (HADES at GSI)

$\pi^- p \to \omega n$ *Puzzle*

Shklyar et al,
PRC 71:055206,2005



- $\gamma p \to \omega p$: strong t-channel background $\to$ other reaction mechanisms are shadowed: hard to see any resonance contributions
- $\pi N \to \omega N$: almost NO data in the region region 1.76...2.0 GeV - standard PWA not possible
- contributions from many groups: Lutz, Wolf, Friman, Titov, Sibirtsev, Zhao, Shklyar, Mosel, Penner - no general conclusion on N^* contributions

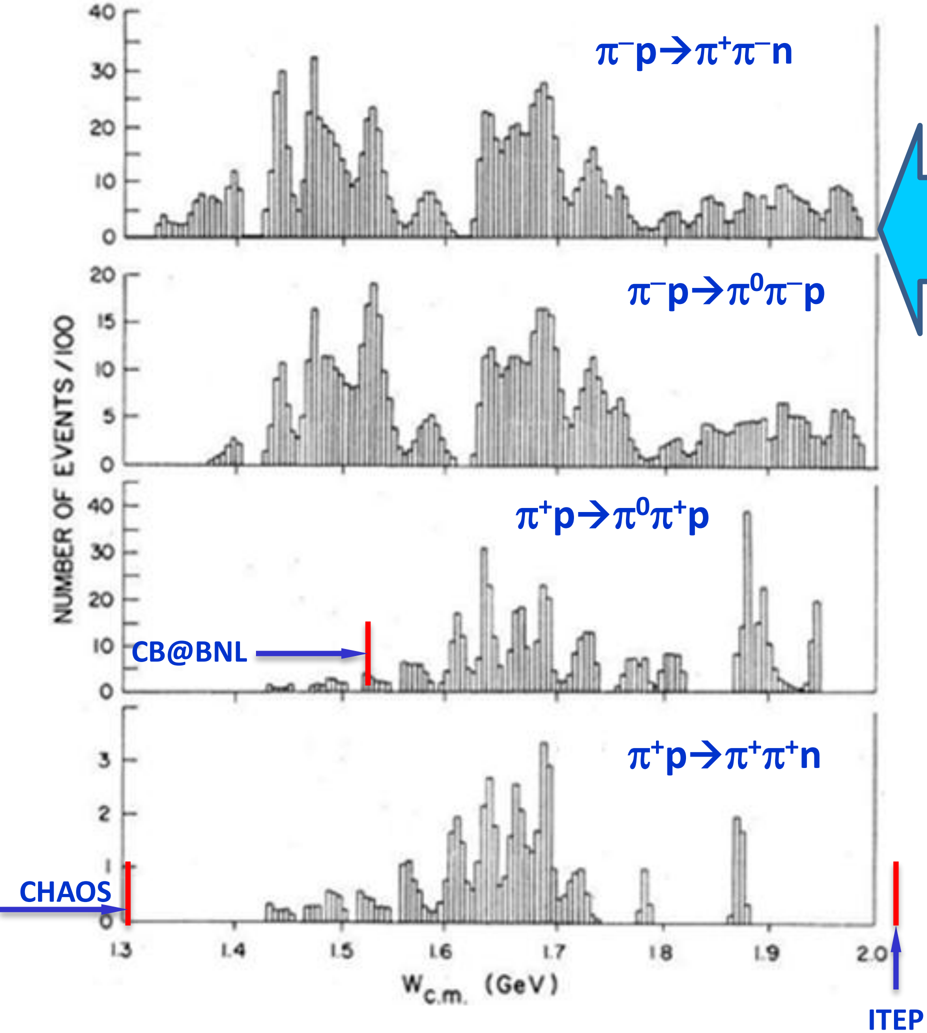
Courtesy of Vitaly Shklyar, HADES Workshop, May 2012

$\pi \rightarrow 2\pi$

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

Our knowledge of **πΔ**, **ρN**, and other quasi-two-body **ππN** channels comes mainly from **Isobar-model** analyses of the **πN→ππN** data.

$\pi N \to \pi\pi N$ Measurements

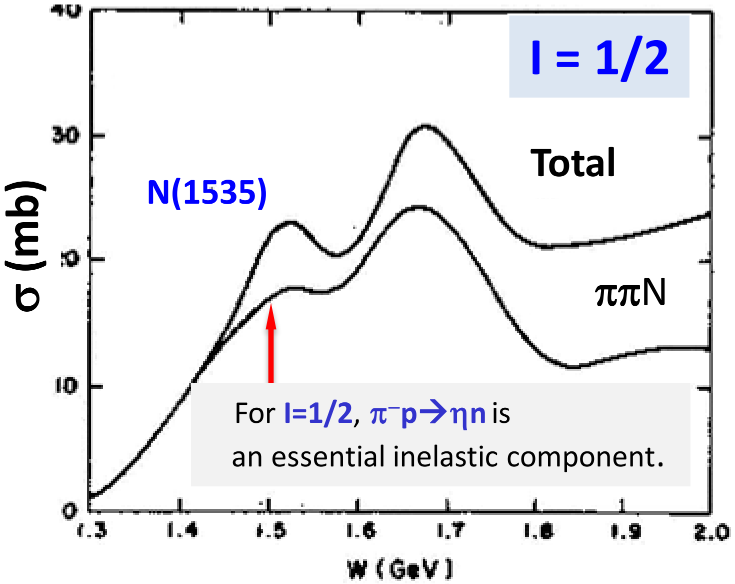


- **241,214** **Bubble Chamber** events for **$\pi N \to \pi\pi N$** have been analyzed in **Isobar-model** **PWA** at W = **1320** to **1930** MeV.
  [D.M. Manley, **R. Arndt**, Y. Goradia, V. Teplitz, Phys Rev D **30**, 904 (1984)]

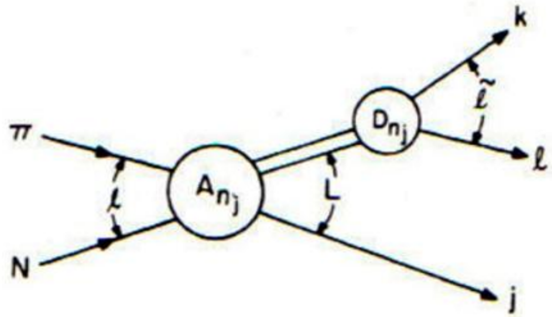
- Recent **post-Bubble Chamber** measurements:
  - **349,611** events for **$\pi^- p \to \pi^0\pi^0 n$** from **CB@BNL** at W = **1213** to **1527** MeV.
    [S. Prakhov *et al* Phys Rev C **69**, 045202 (2004)]
  - **20,000** events for **$\pi^{+-} p \to \pi^{+-}\pi^{-+} n$** from **CHAOS@TRIUMF** at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

$\pi N \rightarrow \pi \pi N$ in Isobar Model

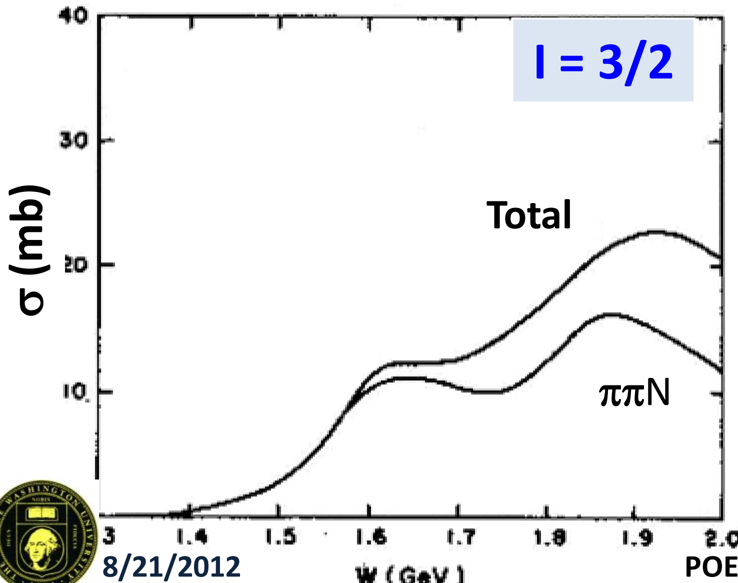
[D.M. Manley, R. Arndt, Y. Goradia, V. Teplitz, Phys Rev D **30**, 904 (1984)]



- $\pi N \rightarrow \pi\pi N$ is the dominant inelastic reaction in πN scattering above **1300** MeV, $\sigma_{inel} \sim \sigma(\pi\pi N)$
- Drawbacks – analysis of 3-body final states is complicated (many partial waves are involved).



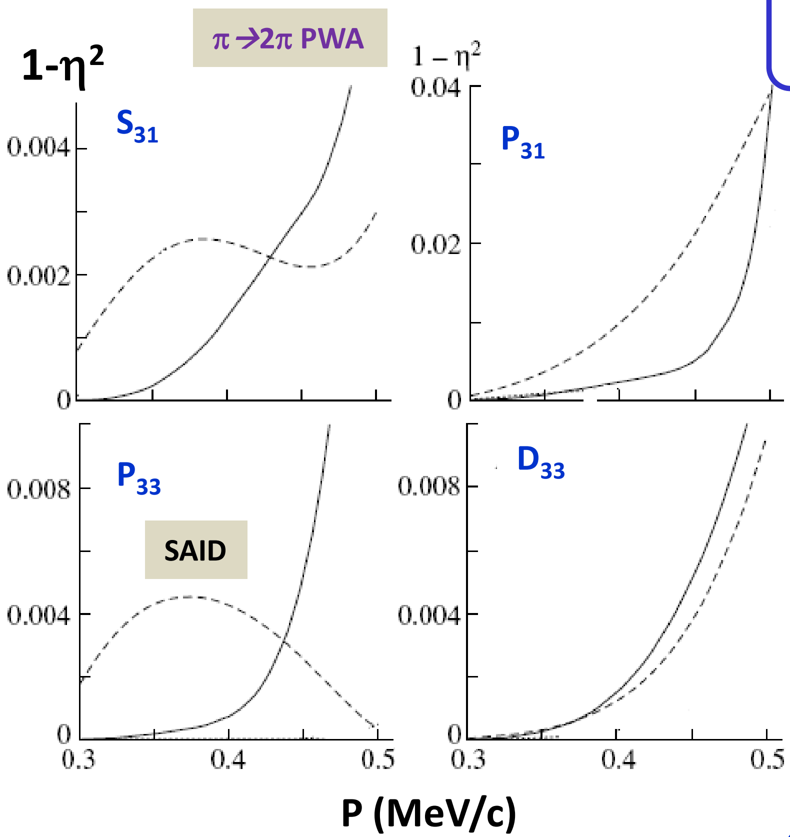
The **total amplitude** for a given charge channel can be written as a coherent sum over all **isobars** and **partial waves**.



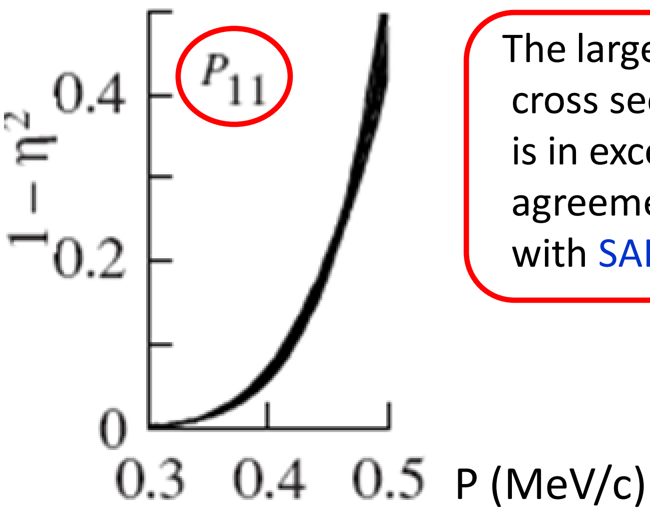
- Many of the **3**- and **4**-star resonances have large decay branching ratios to **ππN** channels.
- There remains a strong need for detailed new measurements in all charge channels**!**

$\pi N \to \pi \pi N$ in Isobar Model at low Energies

[V. Kozhevnikov & S. Sherman, Phys Atom Nucl **71**, 1860 (2008)]



Unfortunately, it is hard to merge **πN→πN** and **πN→ππN** databases to make a joint **PWA** now.

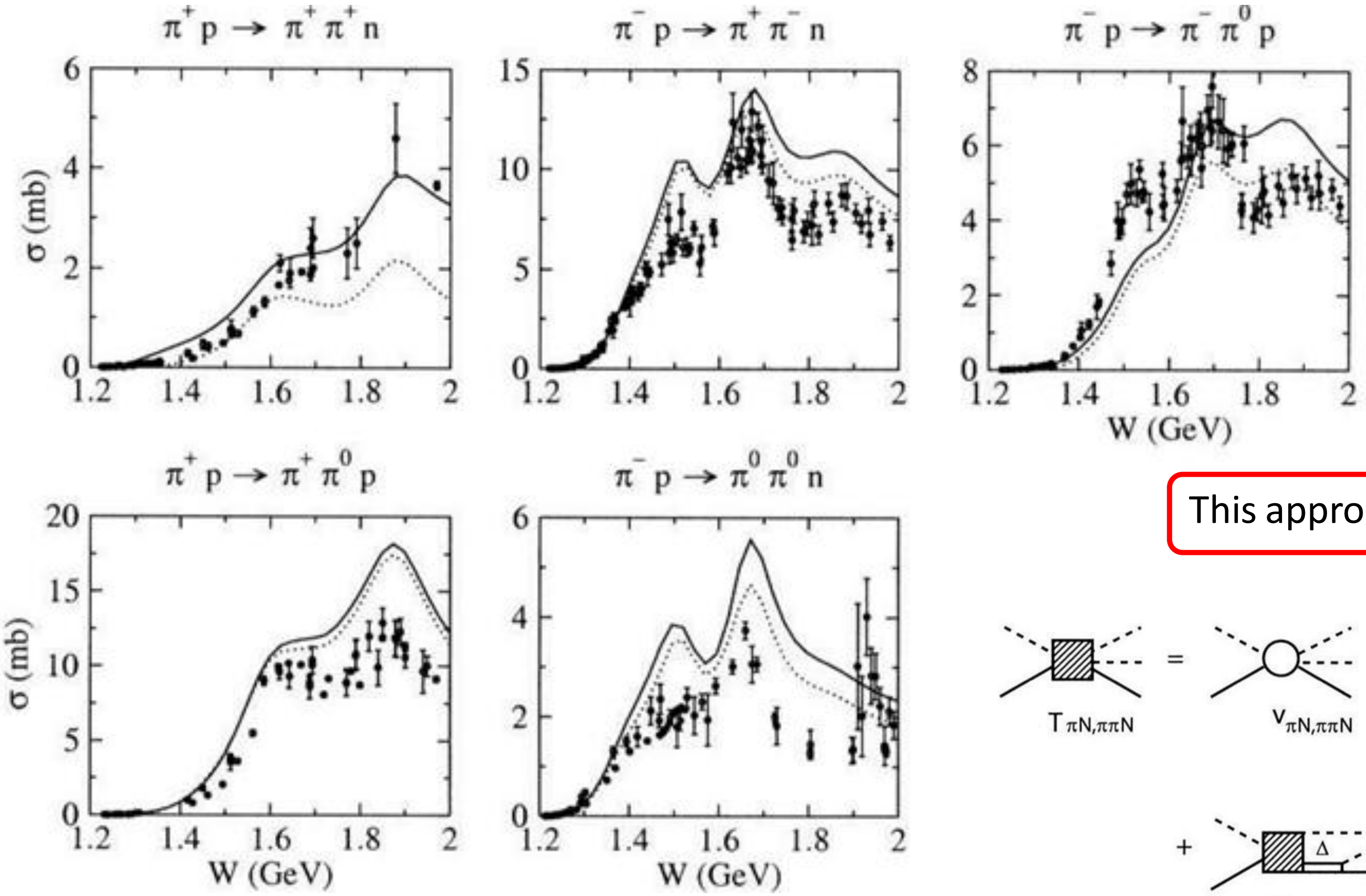


The largest **inelastic** cross section in **P_{11}** is in excellent agreement with SAID-SP06.

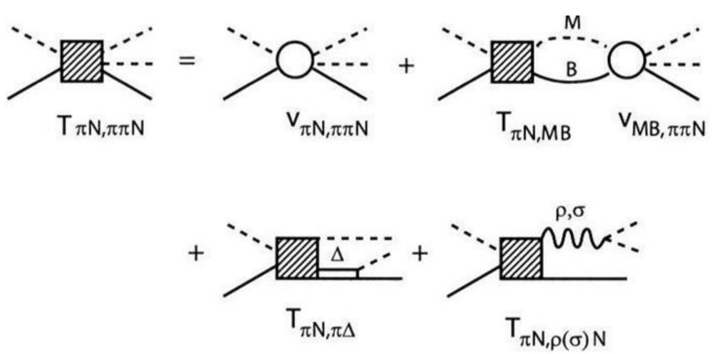
A complete analysis of **γN→ππN** ideally would require fitting all data obtained with both **pion** and **photon** beams.

EBAC Dynamical Coupled-Channels Study of $\pi N \rightarrow \pi\pi N$ Reactions

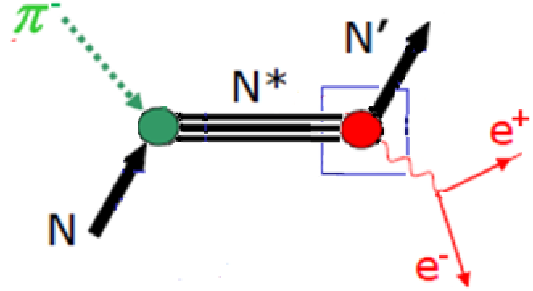
[H. Kamano, et al, Phys Rev C 79, 025206 (**2009**)]



This approach may work

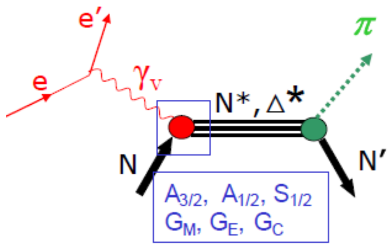


Inverse Pion Electroproduction



SAID for Pion Electro Production

- Energy dependent SM08 and associated SES & SQS
- W = 1080 – 2000 MeV Q^2 = 0 – 6 GeV^2
- PWs = 60 [multipoles]   [J < 6]
- Prms = 171
- Constraint: πN + Pion Photo Prod PWAs [no theoretical input]



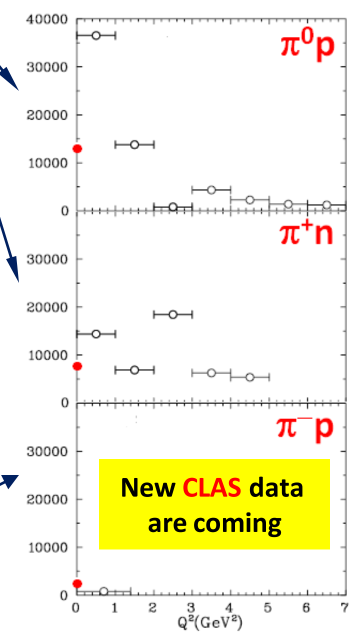
- 0.85 World Electro Prod from JLab CLAS

- PWA Problems:
  - Additional [S] Multipoles
  - Q^2 dependence

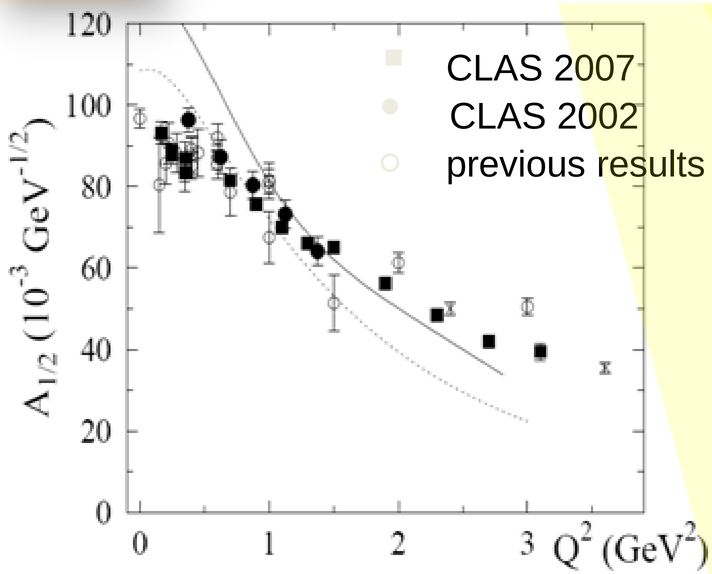
- Database Problems:
  - Most of data are unPolarized measurements
  - There are no $\pi^0 n$ data and very few $\pi^- p$ [no Pol measurements] That does not allow to determine n-couplings at $Q^2 > 0$

Reaction	Data	χ^2
$\gamma^* p \to \pi^0 p$	55,766	81,284
$\gamma^* p \to \pi^+ n$	51,312	80,004
Redundant	14,772	17,375
Total	121,850	178,663
$\gamma N \to \pi N$	25,358	53,458
All Photo*	147,208	232,121
$\pi N \to \pi N$	31,479	57,157
All πN	178,687	289,278
$\gamma^* n \to \pi^- p$	801	
$\gamma^* n \to \pi^0 n$	No Data	

Q^2-Data

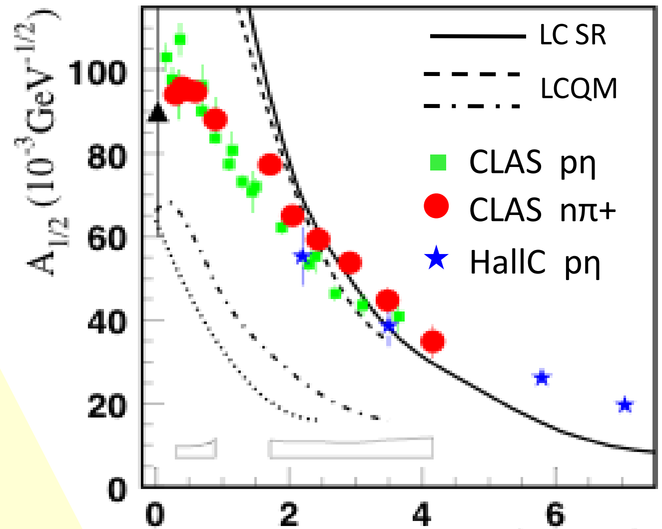


Helicity Amplitudes : $S_{11}(1535)$

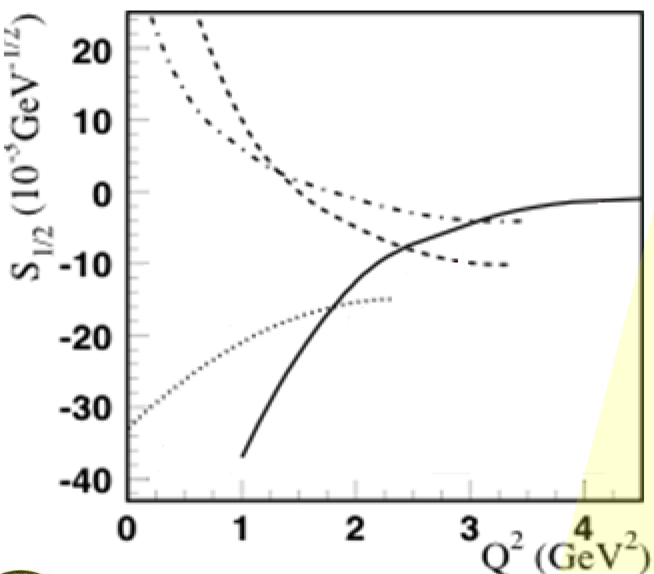


Analysis of pη assumes $S_{1/2}=0$

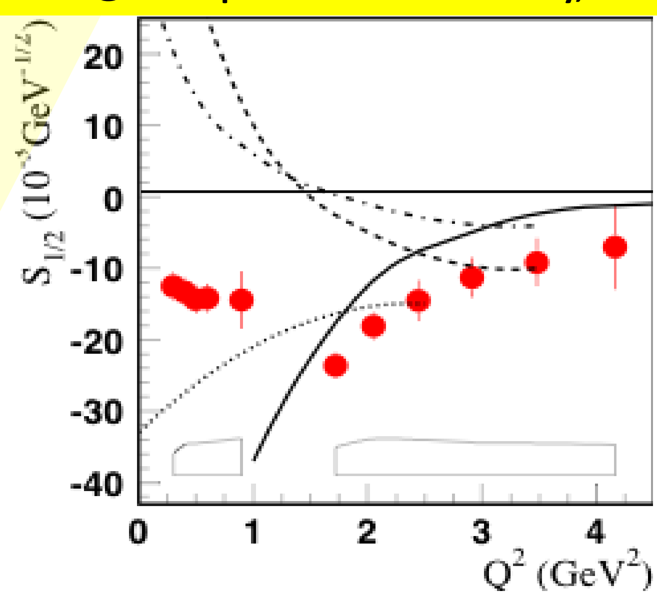
Branching ratios $\beta_{N\pi} = \beta_{N\eta} = 0.45$



Courtesy of Kijun Park, QCD2010 @ Montpillier France June -July, 2010



- $A_{1/2}(Q^2)$ from Nπ and pη are consistent
- First extraction of $S_{1/2}(Q^2)$ amplitude.



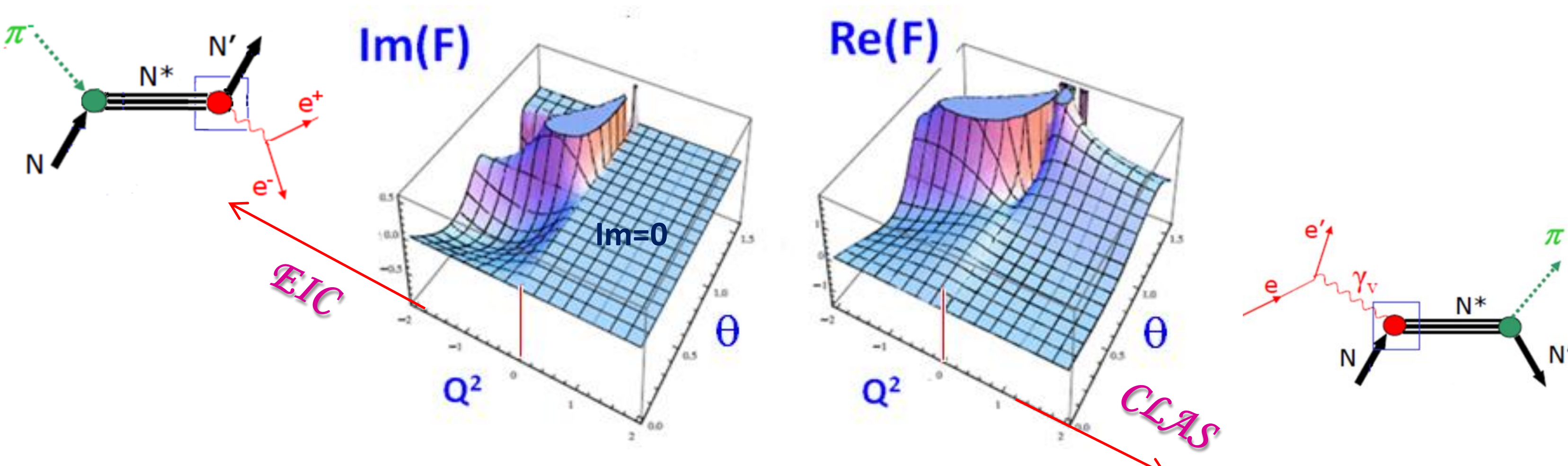
Inverse Pion Electroproduction (IPE)

- **IPE** is the only process which allows the determination of **EM nucleon & pion formfactors** in the intervals:

$0 < k^2 < 4\,M^2 = 3.53\ \mathrm{GeV}^2$

$0 < k^2 < 4\,m_\pi = 0.08\ \mathrm{GeV}^2$

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



IPE $\pi^-p \rightarrow e^+e^-n$ measurements will significantly complement the current **electroproduction $\gamma^*N \rightarrow \pi N$** study for the evolution of baryon properties with increasing momentum transfer by investigation of the case for the ***time-like virtual photon***.

Experimental Difficulties of IPE

Difficulties in the experimental study of IPE arise from the need of a high rejection of competitive processes:

- The Xsection of π^-p elastic is $d\sigma/d\Omega \sim 10^{-27}$ cm^2/sr and is concentrated in the forward direction.
  Therefore e^- and e^+ of IPE are conveniently detected at ~90^0 with respect of π^-–beam, where the elastically scattered hadrons are strongly reduced.

- Xsection for π^+ production, i.e., $\pi^-p \rightarrow n\pi^-\pi^+$ is about **1000** times greater than that of **IPE**.
  The corresponding pions at 90^0 are very soft and can be suppressed strongly by threshold Cherenkov counters.

- The reactions with a **gamma** ray converted into a **Dalitz pair**, contribute a rather unpleasant background.

- The most important processes are $\pi^-p \rightarrow n\pi^0$ & $\pi^-p \rightarrow n\gamma$, which contribute ~ **60%** and **40%** of the counting rate due to capture in hydrogen of π^- at rest against **0.7%** from **IPE**.

Current Hadronic Projects

There are several **Hadronic projects** in Progress

EPECURE @ ITEP [2009-2011], **HADES** @ GSI [2013-2014], & **J-PARC** [2015+ ?]

$\pi^- p \rightarrow \pi^- p$, $K\Lambda$
$\pi^+ p \rightarrow \pi^+ p$

$\pi^- p \rightarrow \pi^- p, \pi^0 n, 2\pi N$, KY, γn, $e^+ e^- n$
$\pi^+ p \rightarrow \pi^+ p$, $2\pi N$

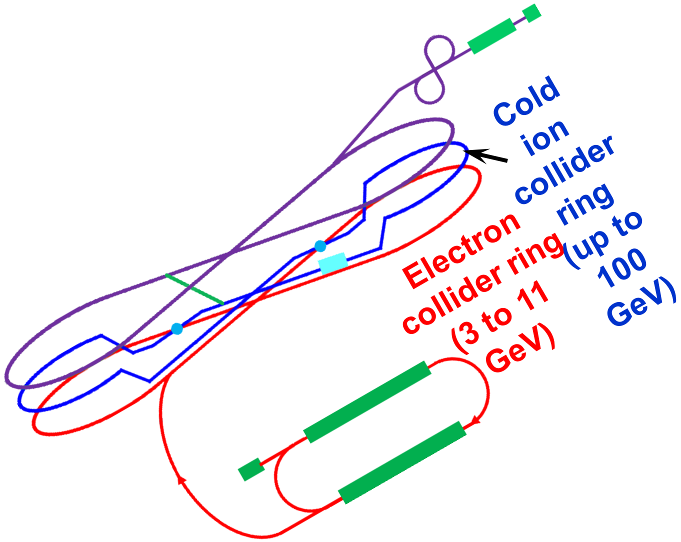
$\pi^\pm p \rightarrow \pi^\pm p$, $2\pi N$, KY

Igor Alekseev *Piotr Salabura* *Ken Hicks*

That is Not Enough

In particular, no pol target measurements

What EIC may Do



As an Illustration

Perspectives of Extension for EIC

PHYSICS WITH SECONDARY HADRON BEAMS IN THE 21ST CENTURY

http://gwdac.phys.gwu.edu/~igor/Ashburn2012/Home.html

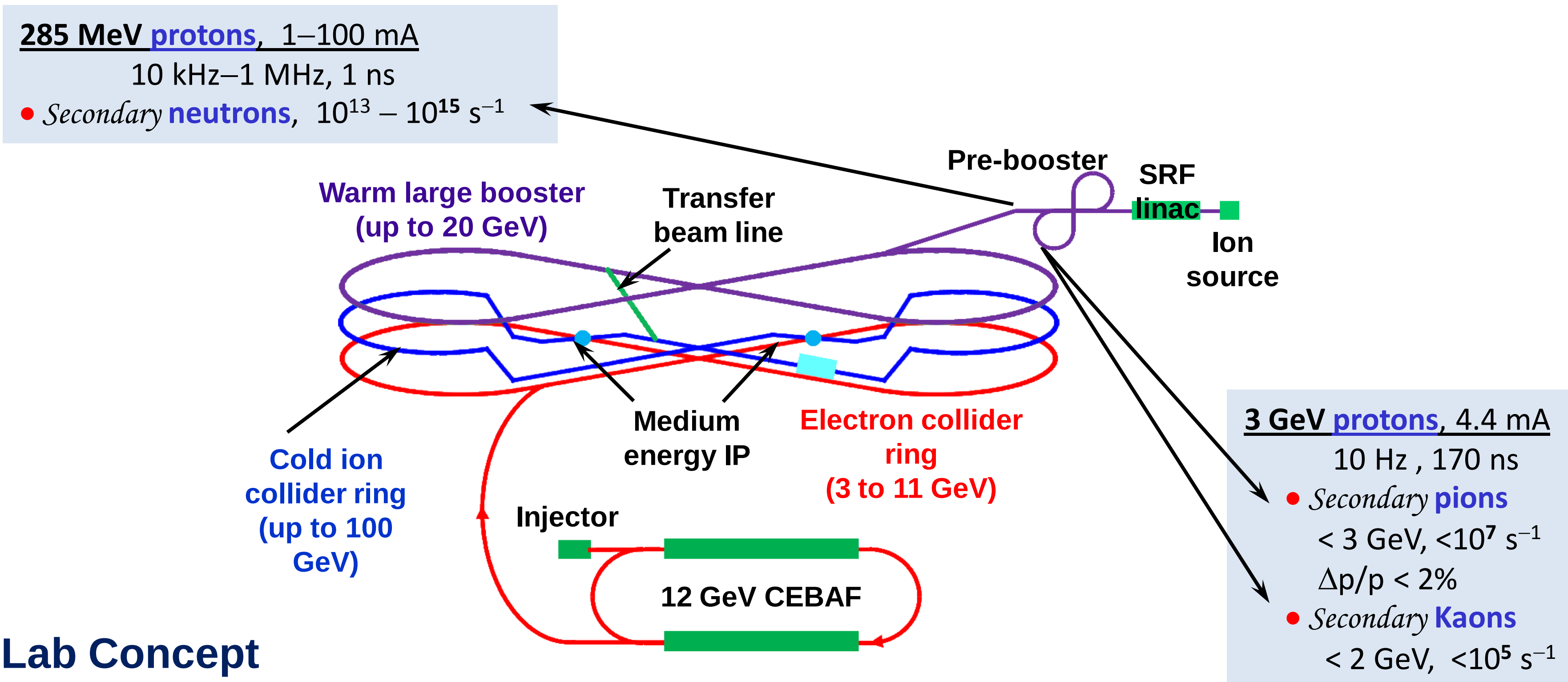
April 7th, 2012 - Ashburn, VA

- This is a far-reaching program that will benefit both the coming **JLab EIC complex** and the **resonance-physics** [baryon and meson] program, which is one of the top priorities at the **Jefferson Lab**.

- The second piece is a **neutron** facility that is critical for the US Energy Program, *i.e., for upcoming Generation IV Nuclear* ***Reactors*** *and Acceleration Driven System (**ADS**).*

- So we can longer keep the **JLab pre-Booster** and **Linac** busy [to use more than ``*several minutes*" a day], which would be a much more effective use of the EIC facility, **without significant increase of the cost of the JLab pre-Booster and Linac.**

I'm afraid my talk will NEVER be a replacement for not attending the Workshop …, which has been very good and full of very good talks and results !



JLab Concept

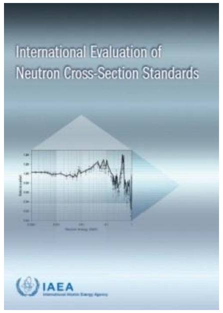
- Initial configuration (MEIC):
  - 3-11 GeV on 20-100 GeV ep/eA collider
  - fully-polarized, longitudinal and transverse
  - luminosity: up to few x 10^{34} e-nucleons cm^{-2} s^{-1}
- Upgradable to higher energies (250 GeV protons)

Courtesy of Rolf Ent, JLab Users Group Meeting, June 2012

Why Intense Neutron Beam at EIC?

- The information about the **neutron-nucleus** interaction is important in many applications:
  - **Medical** physics,
  - **Astrophysics** [(n, γ), (n, α), and others],
  - **Transmutation** of nuclear waste [(n, f), (n, γ), and others],
  - **Energy generation**, and
  - The conceptual design of an innovative **nuclear reactor** being carried out in the course of the **Generation IV** initiative and
  - **Acceleration Driven System** (**ADS**) [(n, f), and neutron-actinoid elastic and inelastic scattering].

- **Neutron-proton** scattering is used as the **primary standard** in measurements involving neutron-induced nuclear reactions. Its cross section is used in determining the flux of incoming neutrons.
- In **2007**, the International Atomic Energy Agency (**IAEA**) within the **International Evaluation of Neutron Cross Section Standards** highly rated the GW DAC [**SAID**] group work:

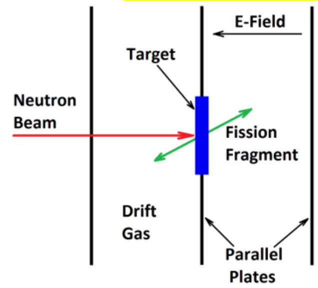


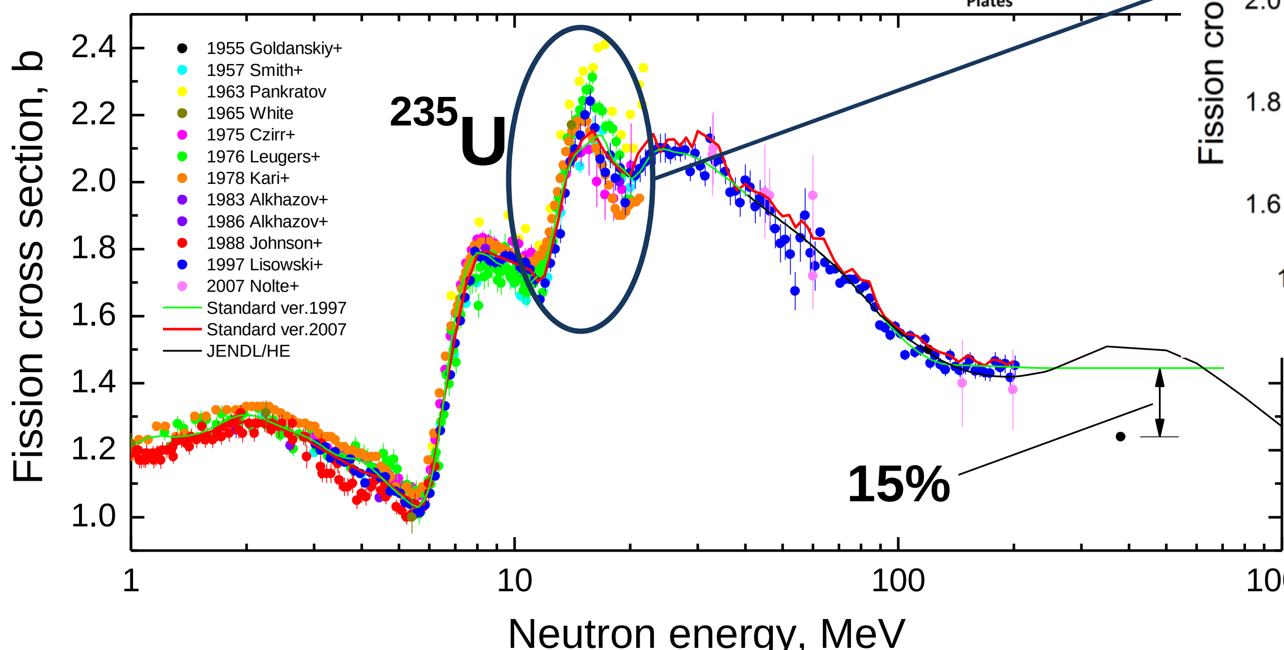
The Arndt evaluation was accepted by the NEANDC/INDC as a primary standard for cross section measurements in the 20–350 MeV range.

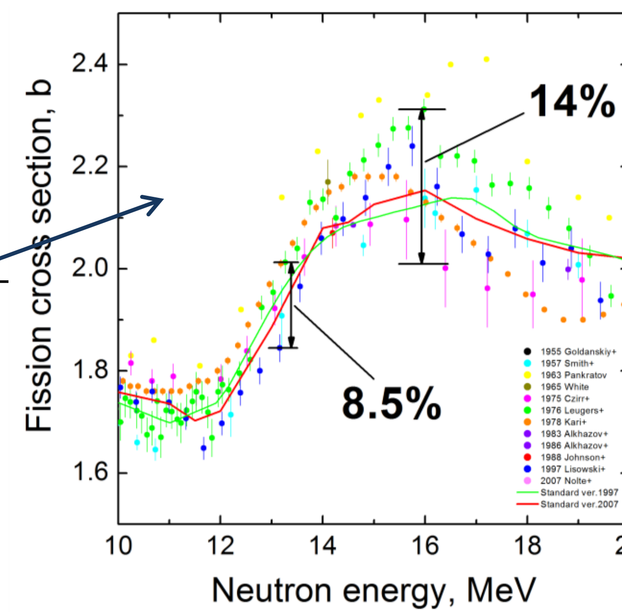
Existing ^{235}U(n,f) XS data for fast Neutrons

Courtesy of Alexander Laptev, GW EIC Workshop, April 2012

- **The most popular detector is a parallel-plate fission ionization chamber (FIC)**







- **Increasing quality of neutron-induced nuclear reaction measurements requires a high quality standard for np Xsections, reproducing total np Xsections with an accuracy of 1% or better (E < 20 MeV)**

Conclusions

- Hadronic beams of **EIC** may help to solve a wide circle of problems.

- **99%** contributions of resonance self energy (total width) is due to haronic decay channels. *That means that the pole position is defined by hadronic channels; the analysis of photo- & electro-production needs hadronic channels as input.*

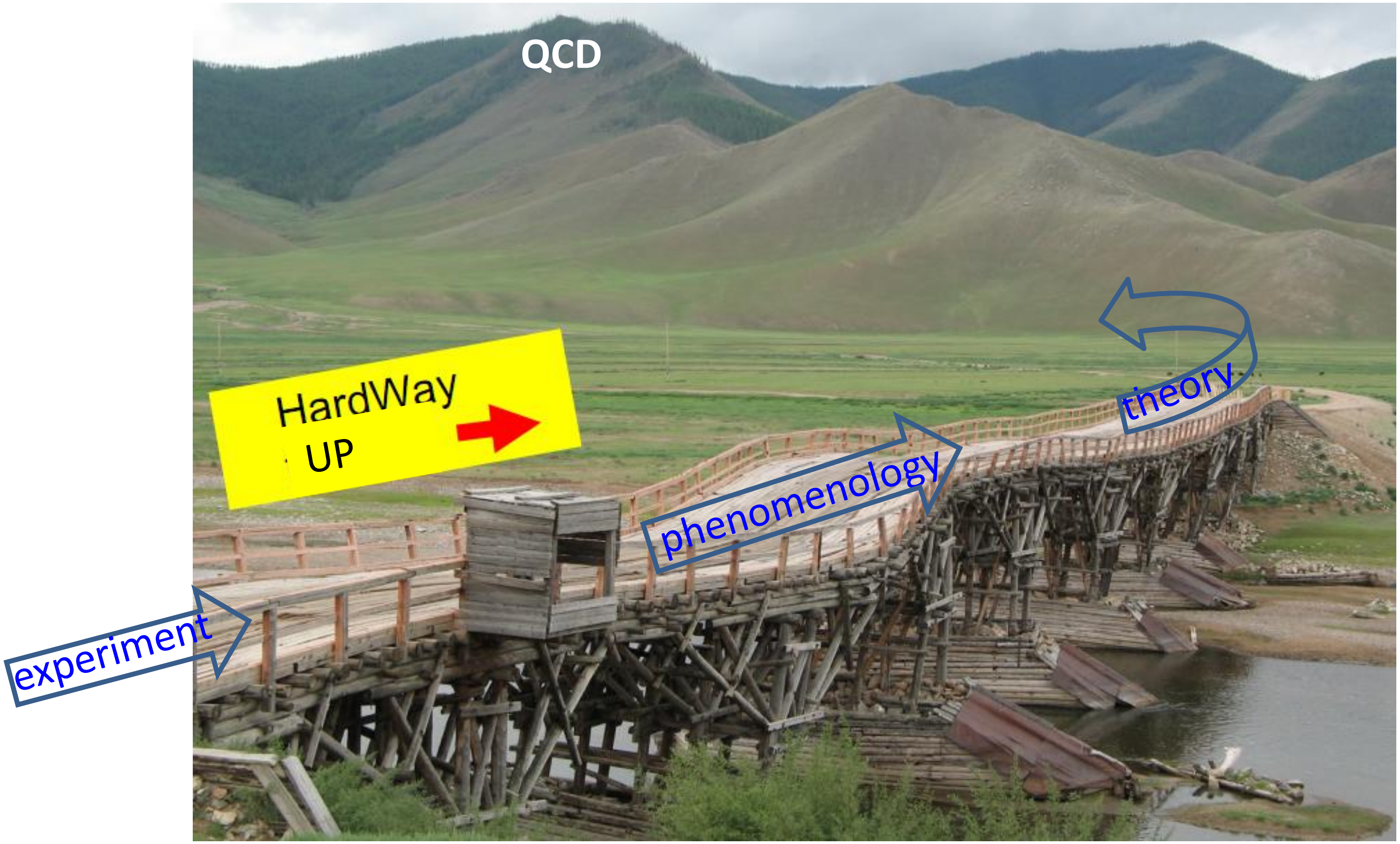
- Most of discovered **4*** resonances have pion decay **BR $\geq$ 30 %** (there is nothing smaller than **4%**, presumably because of insufficient sensitivity). *One may hope that by increasing **experimental resolution** we could get access to **N*** with smaller pion decay branching ratio.*

- One may hope that for inelastic reactions, e.g., **$\pi N \rightarrow \eta N$** one could see states with small pion branching rations. *The reason is that production cross section is proportional to the product of **Br(πN)***Br(ηN)**. The small **Br(πN)** could be compensated by the large **Br(ηN)**. This is also true for other inelastic channels...*

- **Ambiguous** and **imprecise** partial-wave amplitudes and resonance parameters will result unless hadronic data with similar precision to modern **EM** data are measured.

- A vast array of hadron phenomenology, critical for further insight into **non-perturbative QCD**, can be probed.

Phenomenology for Baryon Resonances



Thank you everybody who attended and contributed
the *Physics with Secondary Hadron Beams in the 21st Century* Workshop at GW

A. Afanasev (GW), Ya. Azimov (PNPI), W.J. Briscoe (GW), Y. Derbenev (JLab), M.S. Dewey (NIST), M. Doering (FZ Juelich), B. Erdelyi (ANL), A. Eskandarian (GW), H. Haberzettl (GW), R.P. Johnson (Muons Inc.), F.J. Klein (CUA), A.B. Laptev (LANL), D.M. Manley (Kent U.), K. Nakayama (UGa), B.E. Norum (UVa), P.N. Ostroumov (ANL), E. Pasyuk (JLab), M. Pennington (JLab), W. Roberts (FSU), V. Shklyar (Giessen U.), G. Smith (JLab), A. Szczepaniak (IU), F. Tovesson (LANL), D. Watts (Edinburgh U.), R.L. Workman (GW), and Y. Zhang (JLab)