Hadronic Cross Section Measurements for New Aspects of Hadron Spectroscopy

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J-PARC PAC

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Goals of this proposal

- Understanding the spectrum of excited states of the nucleon leads to a deeper understanding of non-perturbative QCD.
  - Similarly, the spectrum of excited states of the hydrogen atom led to advances in QM.
- Measurements of baryon excited states is difficult and requires a coordinated effort
  - Theoretical advances have made it clear that new data for $(\pi,2\pi)$ is badly needed.

Why now?

- For almost 40 years, there have been no new measurements on $(\pi,2\pi)$ in the nucleon resonance region.
  - For many years, elastic πN was good enough
- With precise new data on $\gamma N \rightarrow \pi N$, $\pi\pi N$ at Jefferson Lab, Bonn and elsewhere, along with theory advances, it becomes clear that hadronic-beam data is also needed to properly interpret the photoproduction data.

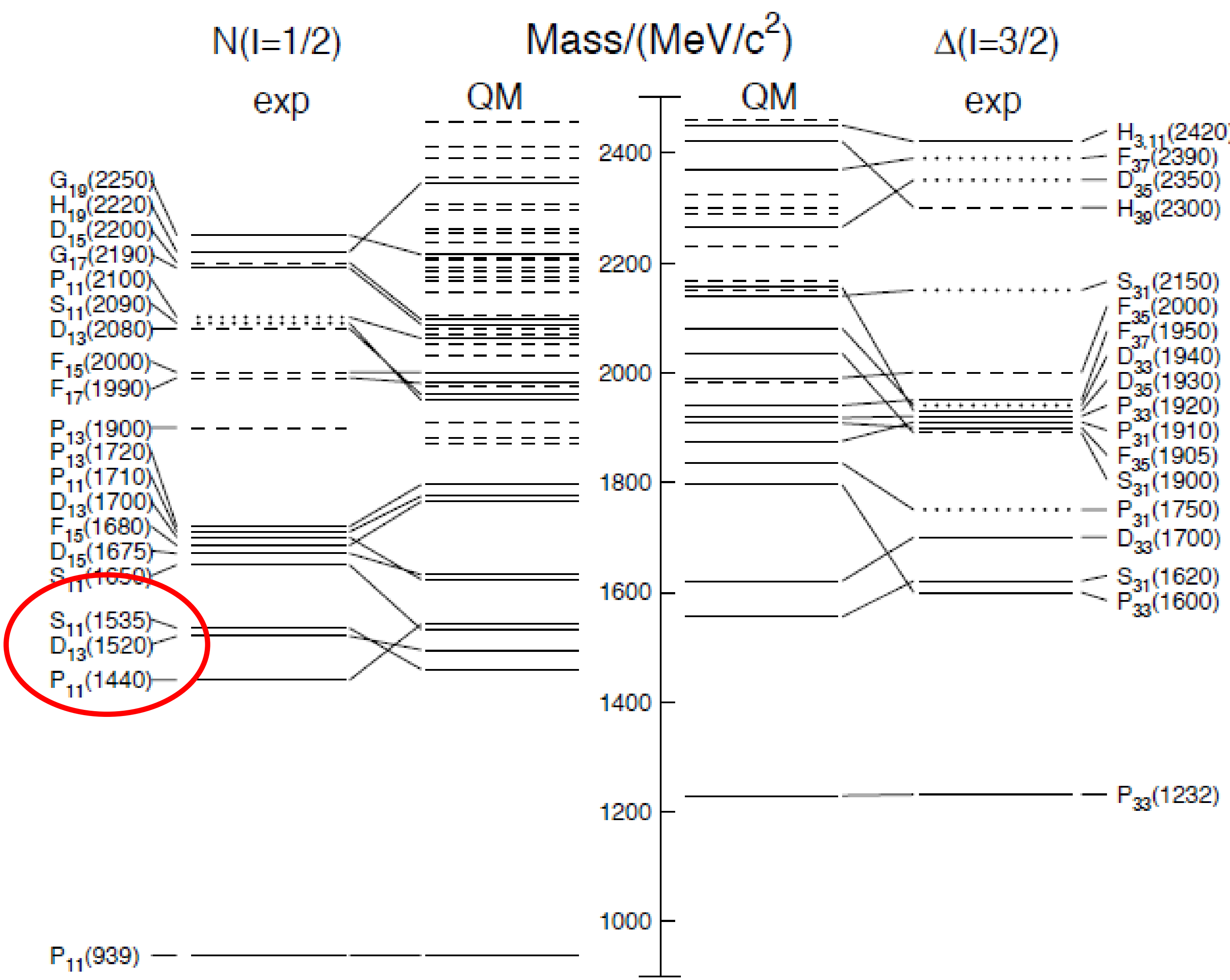
Joint Physics Interest

- Jefferson Lab and J-PARC share a common interest: to understand QCD.
  - The combination of high-quality hadronic data with double-polarization photoproduction data is more powerful than either one alone.
- Many participants of this proposal are from the USA and do research at Jefferson Lab.
  - Other international participants as well.
  - Over 40 participants from 15+ institutions.

New participants

- Since the proposal was submitted, there are additional international participants:
  - Alfred Svarc (Ruder Boskovic Institute, Hungary)
  - Sasa Ceci (RBI-Zagreb, Hungary)
  - Mirza Hadzimehmedovic and Hedim Osmanovic (University of Tulza, Bosnia/Herzegovina)
  - Tony Forest and Dustin McNulty (Idaho State University)

Masses: Exp vs. model (PDG)



In general, the quark model does a poor job describing N* masses. Also, many QM states are missing!

Image from PDG

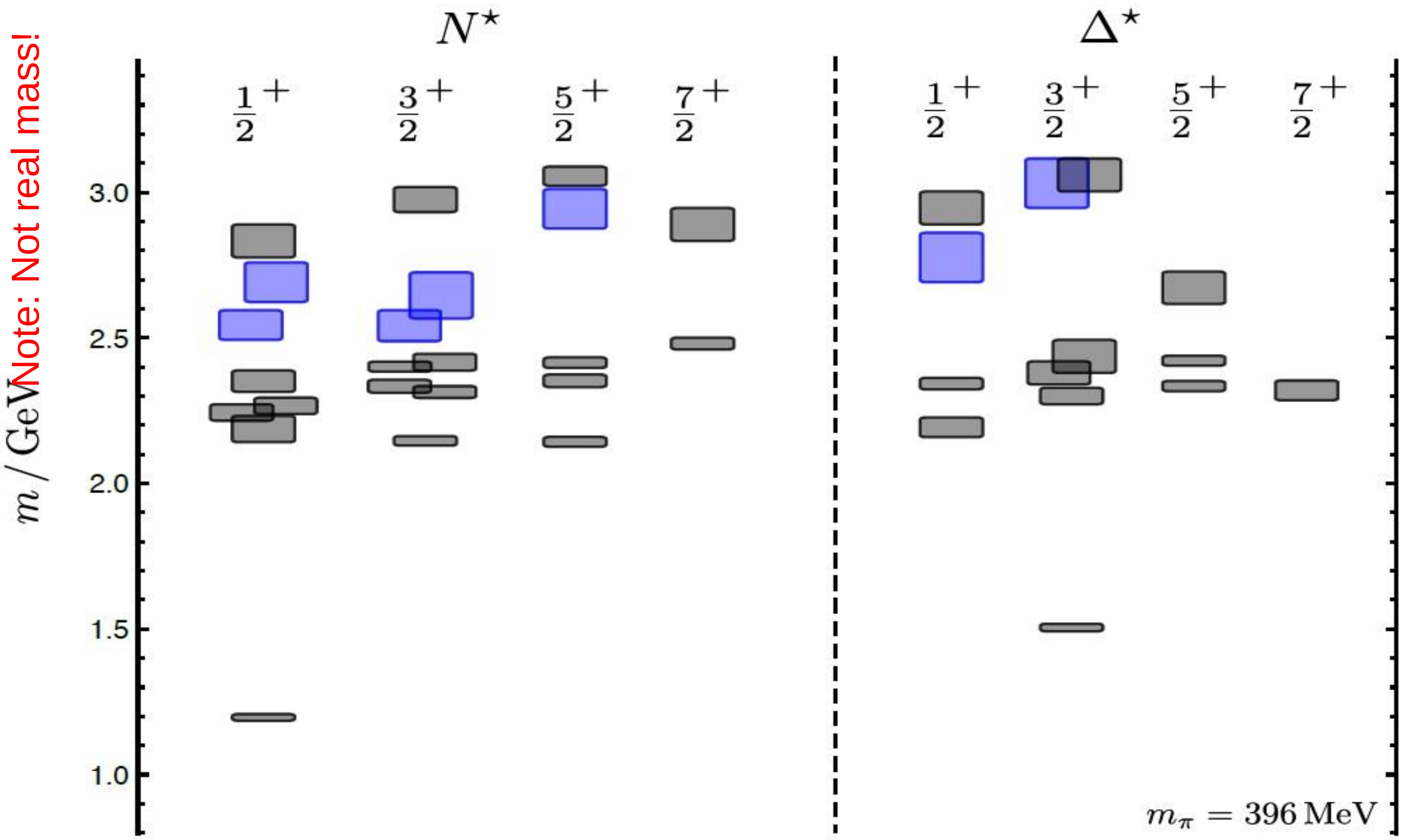
Capstick & Roberts (1993)

Model state	$\lvert A_{N\pi} \rvert$ (MeV$^{\frac{1}{2}}$)	$N\pi$ state assignment	Rating	$\sqrt{\Gamma_{\rm tot}}(\mathrm{BR})_{N\pi}$ (MeV$^{\frac{1}{2}}$)
$[N\frac{1}{2}^-]_1(1460)$	14.7 ± 0.5	$N\frac{1}{2}^-(1535)$	****	8.0±2.8
$[N\frac{1}{2}^-]_2(1535)$	12.2 ± 0.8	$N\frac{1}{2}^-(1650)$	****	8.7±1.9
$[N\frac{3}{2}^-]_1(1495)$	8.6 ± 0.3	$N\frac{3}{2}^-(1520)$	****	8.3±0.9
$[N\frac{3}{2}^-]_2(1625)$	5.8 ± 0.6	$N\frac{3}{2}^-(1700)$	***	3.2±1.3
$[N\frac{5}{2}^-]_1(1630)$	5.3 ± 0.1	$N\frac{5}{2}^-(1675)$	****	7.7±0.7
$[N\frac{1}{2}^+]_2(1540)$	$20.3^{+0.8}_{-0.9}$	$N\frac{1}{2}^+(1440)$	****	19.9±3.0
$[N\frac{1}{2}^+]_3(1770)$	4.2 ± 0.1	$N\frac{1}{2}^+(1710)$	***	4.7±1.2
$[N\frac{1}{2}^+]_4(1880)$	$2.7^{+0.6}_{-0.9}$			
$[N\frac{1}{2}^+]_5(1975)$	$2.0^{+0.2}_{-0.3}$			
$[N\frac{3}{2}^+]_1(1795)$	14.1 ± 0.1	$N\frac{3}{2}^+(1720)$	****	5.5±1.6
$[N\frac{3}{2}^+]_2(1870)$	$6.1^{+0.6}_{-1.2}$			
$[N\frac{3}{2}^+]_3(1910)$	$1.0^{+0.1}_{-0.2}$			
$[N\frac{3}{2}^+]_4(1950)$	$4.1^{+0.4}_{-0.7}$			
$[N\frac{3}{2}^+]_5(2030)$	1.8 ± 0.2			

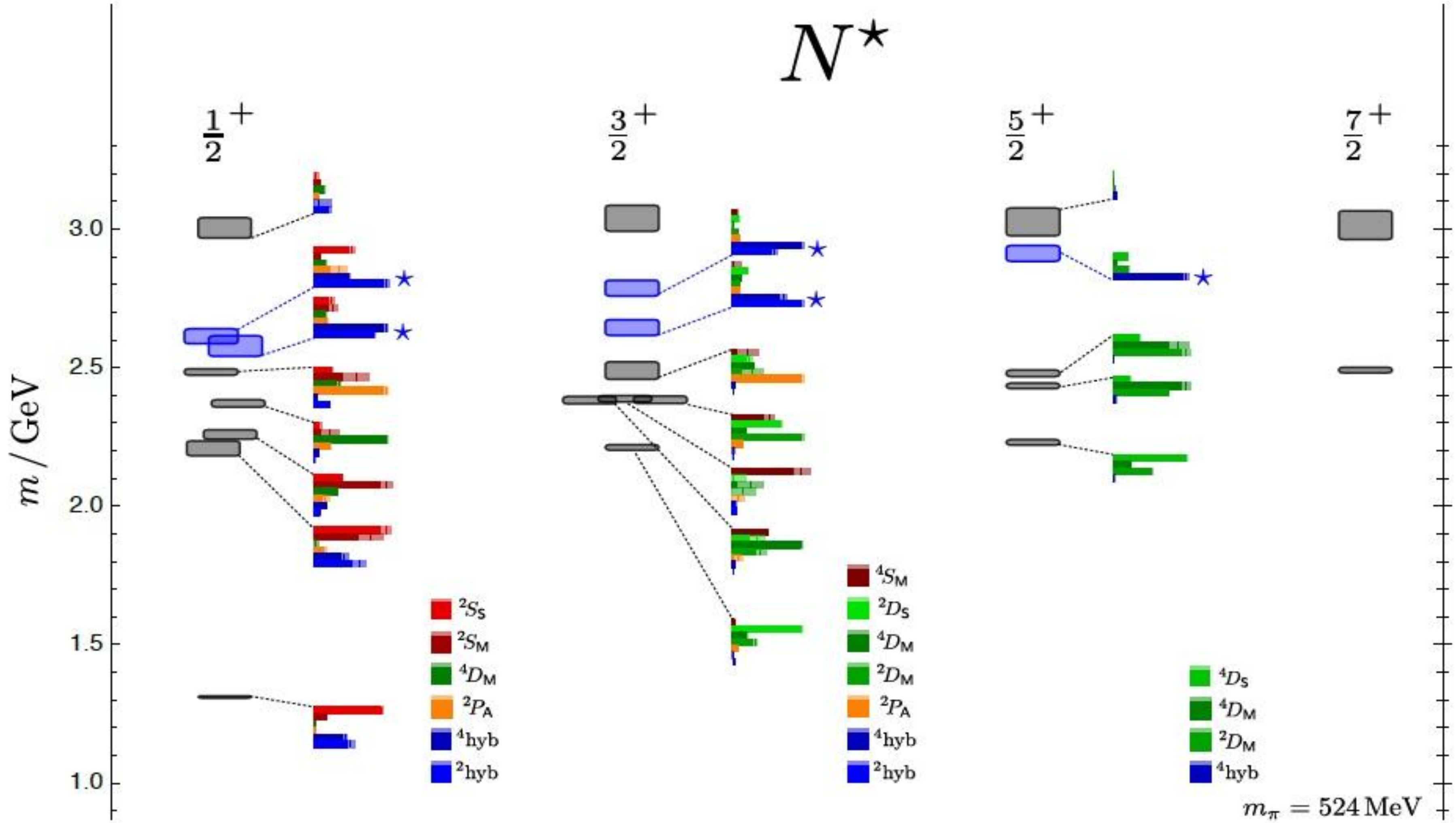
Even 20 years ago, this problem was known!

Recent Lattice Calculations

Reference: J. Dudek et al.,, arXiv:1201.2349



Projection of N* to ^SL_J



Dynamical coupled-channels model of EBAC

For details see Matsuyama, Sato, Lee, Phys. Rep. 439,193 (2007)

- Partial wave (LSJ) amplitude of a ? b reaction:

$$T^{(LSJ)}_{a,b}(p_a, p_b; E) = V^{(LSJ)}_{a,b}(p_a, p_b) + \underbrace{\sum_c}_{\text{coupled-channels effect}} \int_0^\infty q^2 dq V^{(LSJ)}_{a,c}(p_a, q) G_c(q; E) T^{(LSJ)}_{c,b}(q, p_b; E)$$

- Reaction channels:

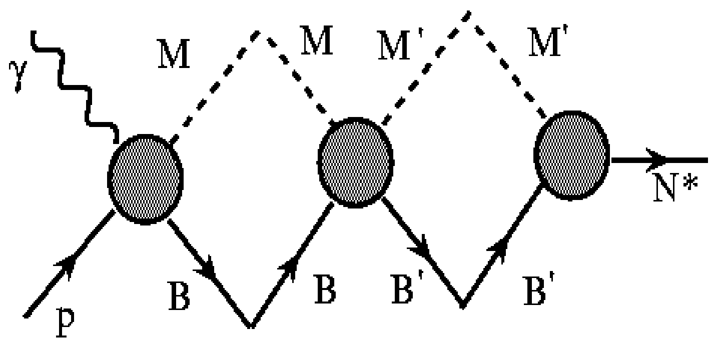
$$a, b, c = (\, \gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\boxed{\pi\Delta,\ \sigma N,\ \rho N,}}_{\pi\pi N}\ K\Lambda,\ K\Sigma\,, \cdots)$$

- Transition potentials:

$$V_{a,b} = \underbrace{v_{a,b}}_{\boxed{\text{Meson-exchange potentials (Derived from Lagrangians)}}} + \underbrace{\sum_{N^*} \frac{\Gamma^\dagger_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}}_{\boxed{\text{bare N* states}}}$$

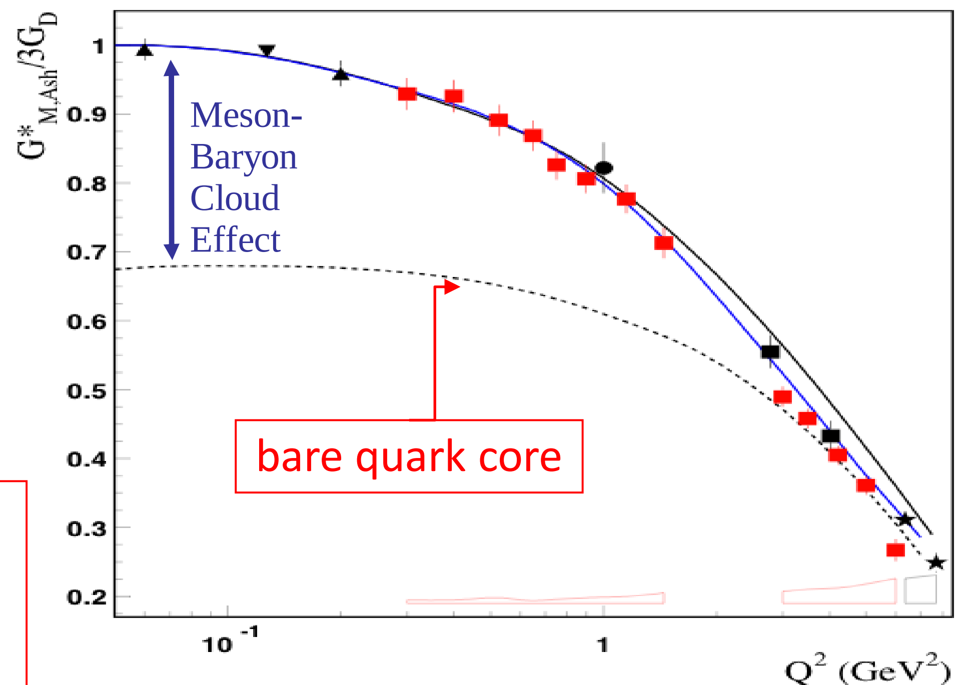
NΔ Transition Form Factor (GM) from EBAC

- One third of G*M at low Q^2 is due to contributions from meson–baryon (MB) dressing:



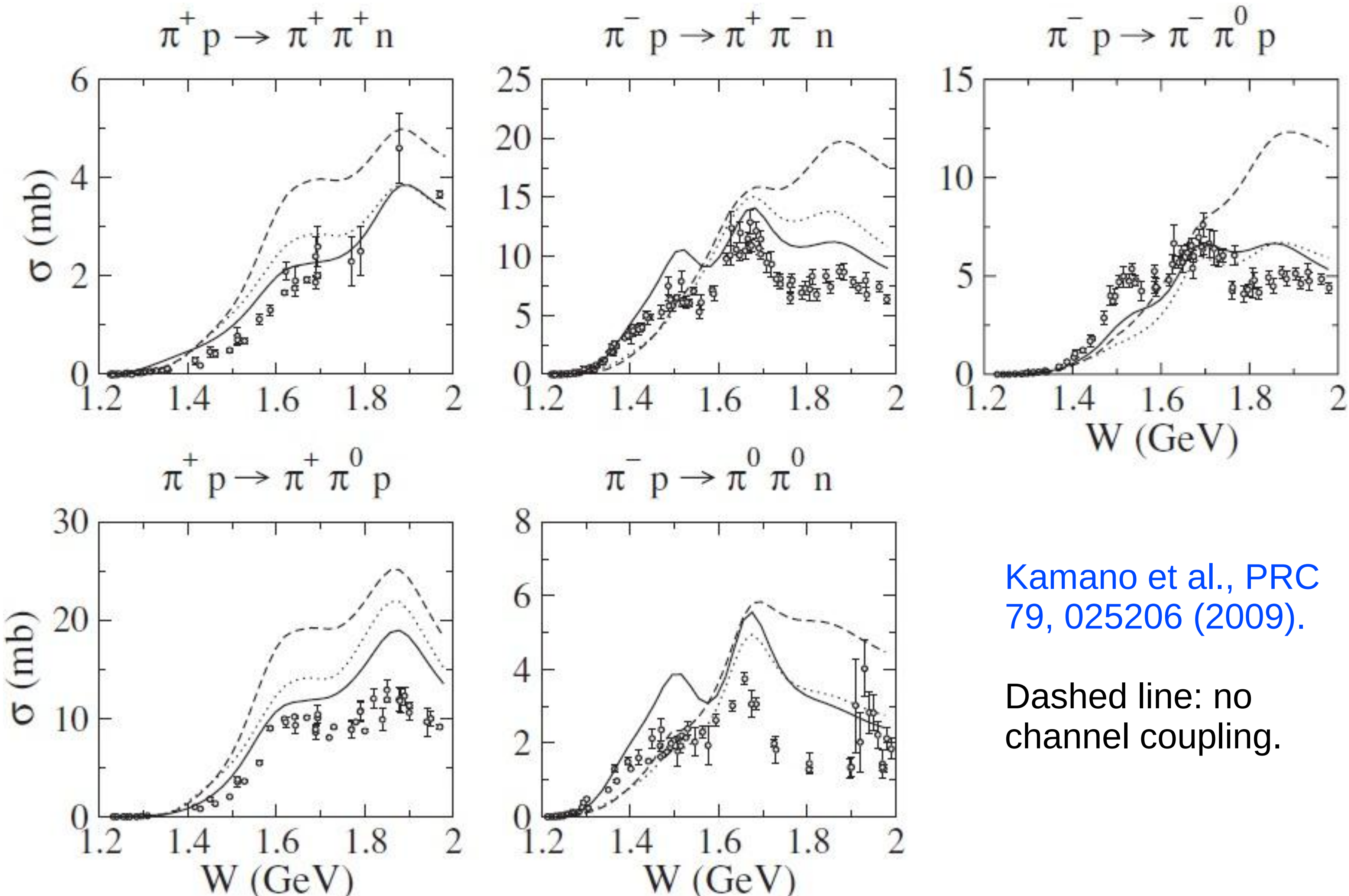
In the relativistic QM framework, the bare-core contribution is well described by the three-quark component of the wavefunction at high Q^2.

The area of Q2<7.0 GeV2 is far from pQCD domain



B.Julia-Diaz *et al.*, PRC 69, 035212 (2004)

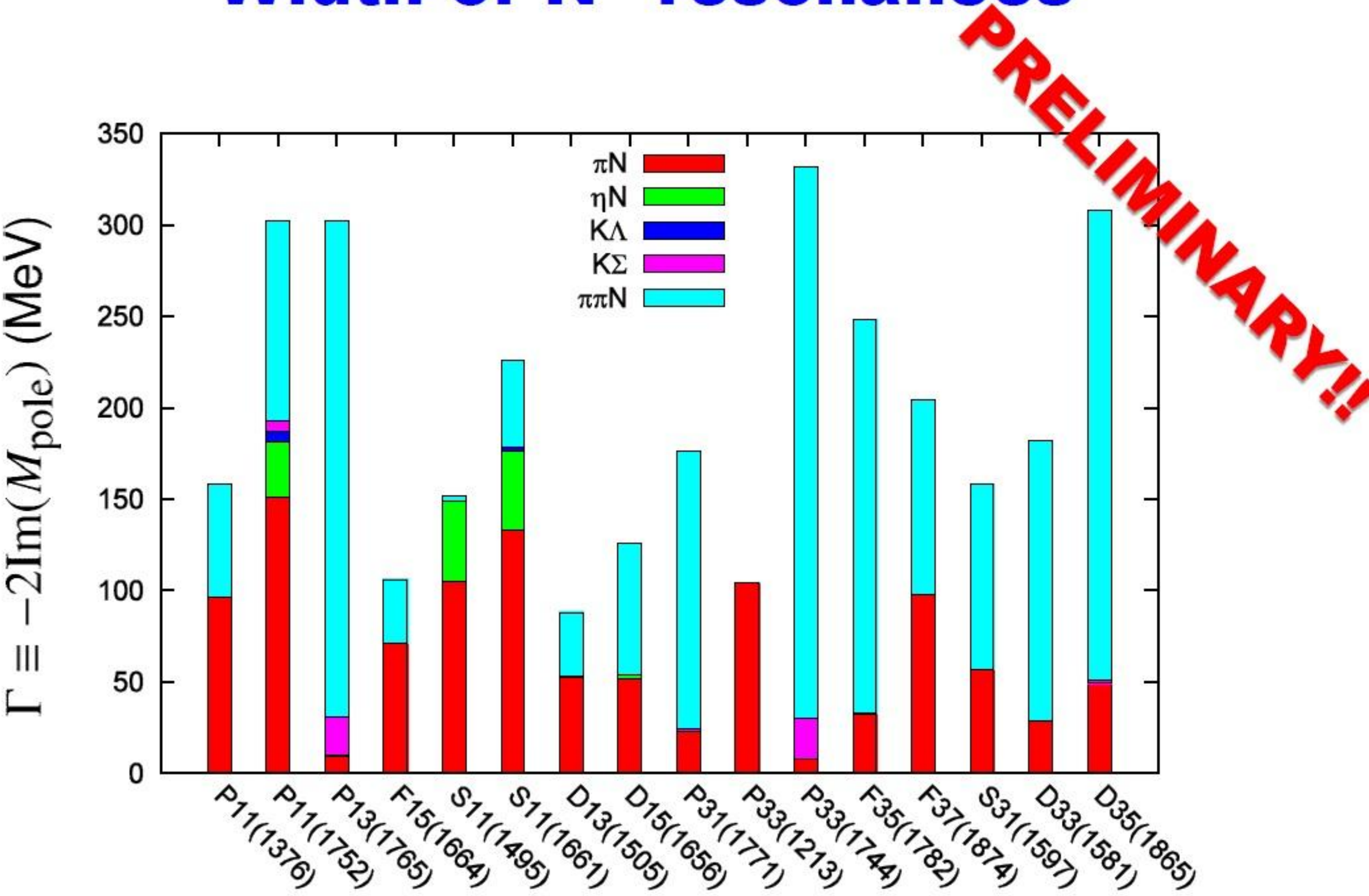
ππN Total Cross Sections



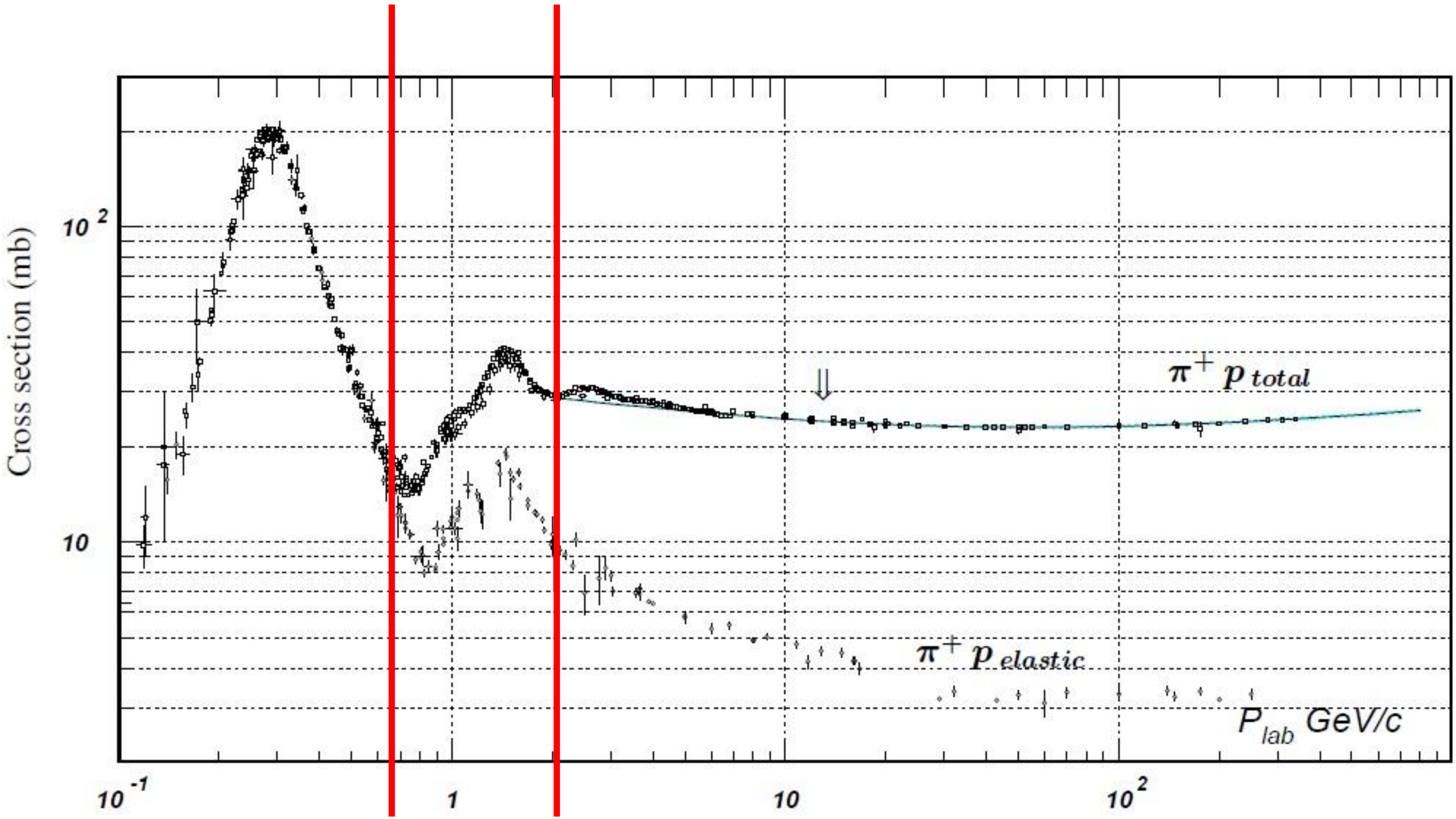
Kamano et al., PRC 79, 025206 (2009).

Dashed line: no channel coupling.

Width of N* resonances



π-N Total Cross Sections



The Primary Source of (π,2π)

Nuclear Physics B78 (1974) 233–250. North-Holland Publishing Company

EXPERIMENTAL RESULTS ON π^-p INTERACTIONS IN THE CM ENERGY RANGE 1.50 – 1.74 GeV

J. DOLBEAU, M. NEVEU, F.A. TRIANTIS * and C. COUTURES
Departement de Physique des Particules Elementaires, CEN, Saclay

Received 21 March 1974

Abstract: Channel cross sections, elastic differential cross sections and single pion production mass spectra and angular distributions are presented for π^-p interactions, based on 139 000 events observed at six energies in the center of mass region 1.50 – 1.74 GeV.

Complete (π,2π) Database

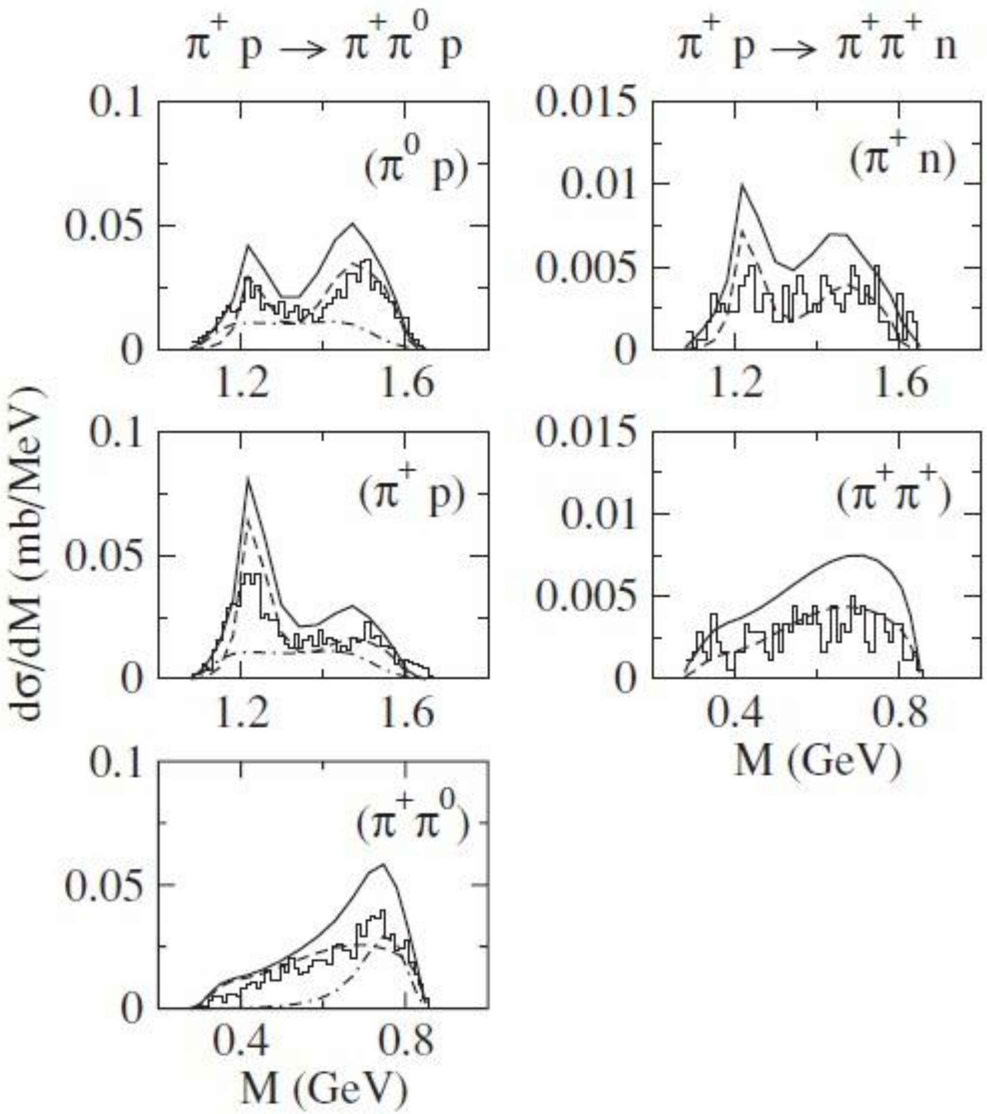
M. Manley, Phys. Rev. D 30, 904 (1984).

TABLE I. Summary of the number of events analyzed at each energy.

W (MeV)	$\pi^+\pi^-n$	$\pi^0\pi^-p$	$\pi^0\pi^+p$	$\pi^+\pi^+n$	Total
1340±20	1664	11	0	0	1675
1375±15	3893	145	15	2	4055
1400±10	3646	826	63	15	4550
1440±10	3790	1339	207	48	5384
1460±10	2074	971	152	36	3233
1480±10	7246	3776	537	128	11 687
1500±10	6224	4055	1160	250	11 689
1520±10	5650	4671	795	143	11 259
1540±10	6230	5320	1115	183	12 848
1565±15	2237	1598	2704	481	7020
1595±15	3065	1962	2864	483	8374
1620±10	0	0	4203	621	4824
1640±10	7437	4177	7939	1013	20 566
1660±10	7411	4273	4071	752	16 507
1680±10	8784	5340	4999	847	19 970
1700±10	8377	5394	5375	1007	20 153
1725±15	6265	4594	5679	524	17 062
1755±15	5442	4200	1316	18	10 976
1790±20	1966	1352	4715	228	8261
1830±20	3543	2223	2322	0	8088
1870±20	4342	3382	8190	557	16 471
1910±20	6036	4081	6445	0	16 562
Total	105 322	63 690	64 866	7336	241 214

Total number of events!

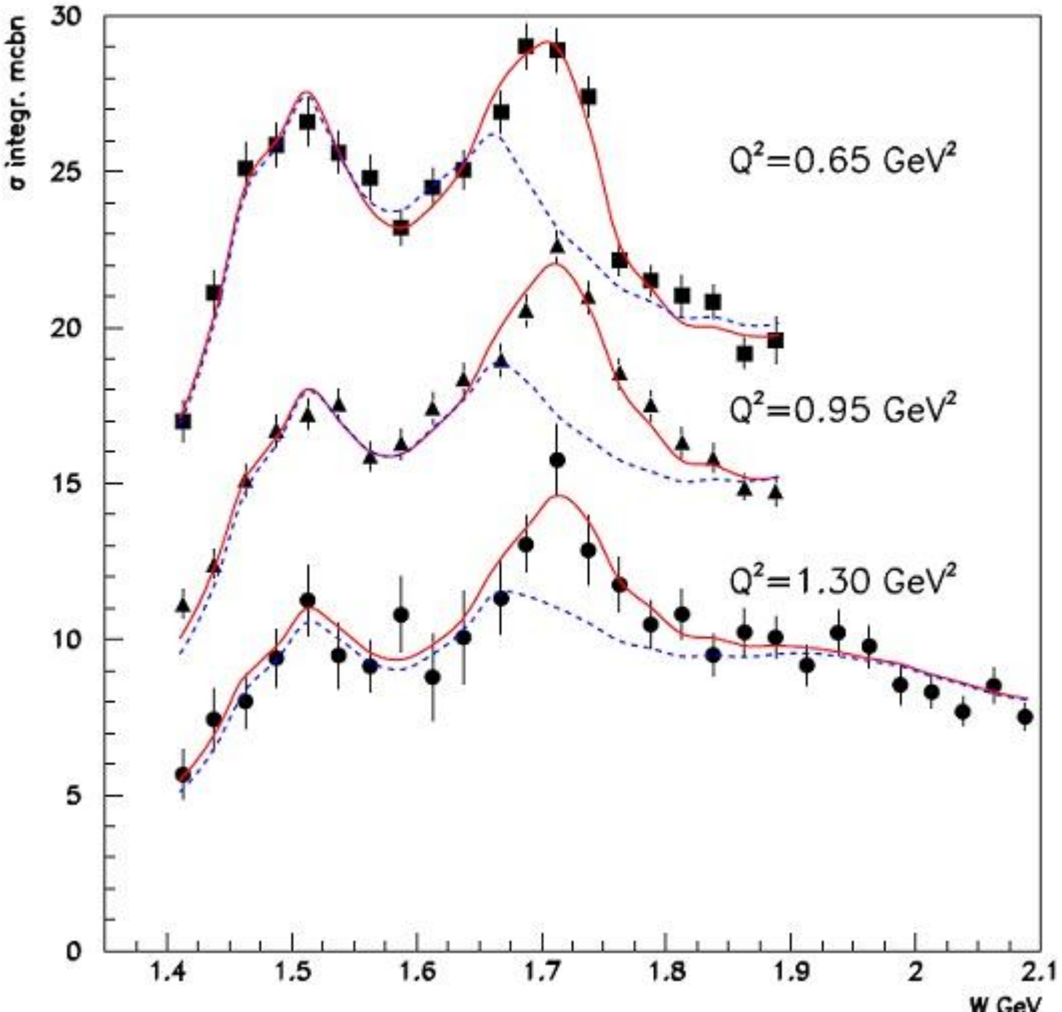
Mass Projections



Note: the normalization of these data is not known. The total cross sections were used to set the vertical scale.

The solid curves are the full calculation using only πN elastic data. The other curves do not include some coupled-channels effects.

CLAS: $e\ p \rightarrow e'\ p\ \pi^+\ \pi^-$



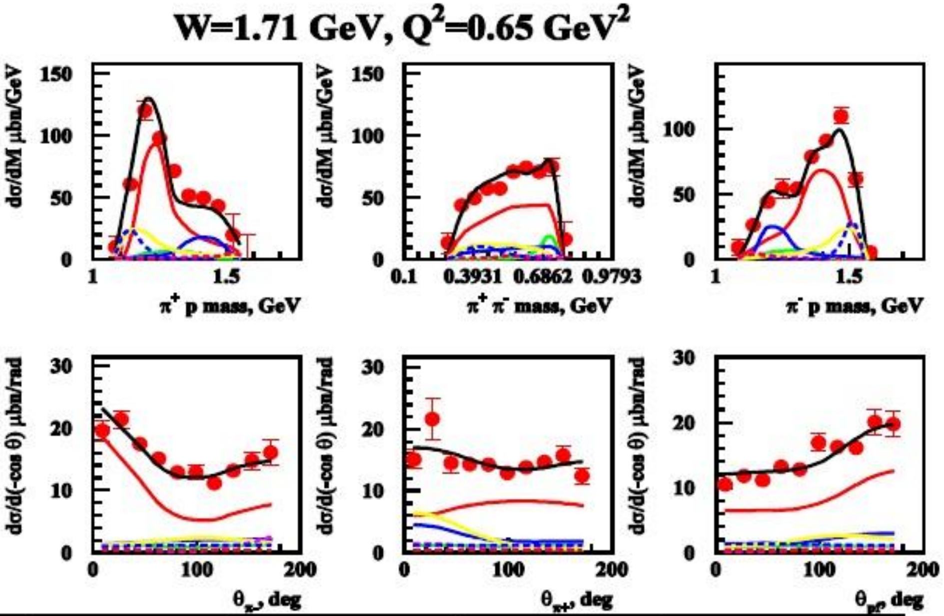
The BLUE dotted curve uses only the known resonances from the Particle Data Group.

The RED solid curve includes an extra resonance not seen from the PWA of πN data alone.

CLAS: Partial Wave Analysis

$P_{13}(1720)$ state with hadronic decays fit to the CLAS data - $2.94<\chi^2/\mathrm{d.p.}<3.15$

	M, GeV	$\Gamma_{tot,}$ MeV	BF($\pi\Delta$) %	BF(ρp) %
$P_{13}(1720)$ CLAS	1.728± 0.005	133±19	66±26	16±11
$P_{13}(1720)$ PDG	1.70 - 1.75	150-300	comp. with 0.	70-85



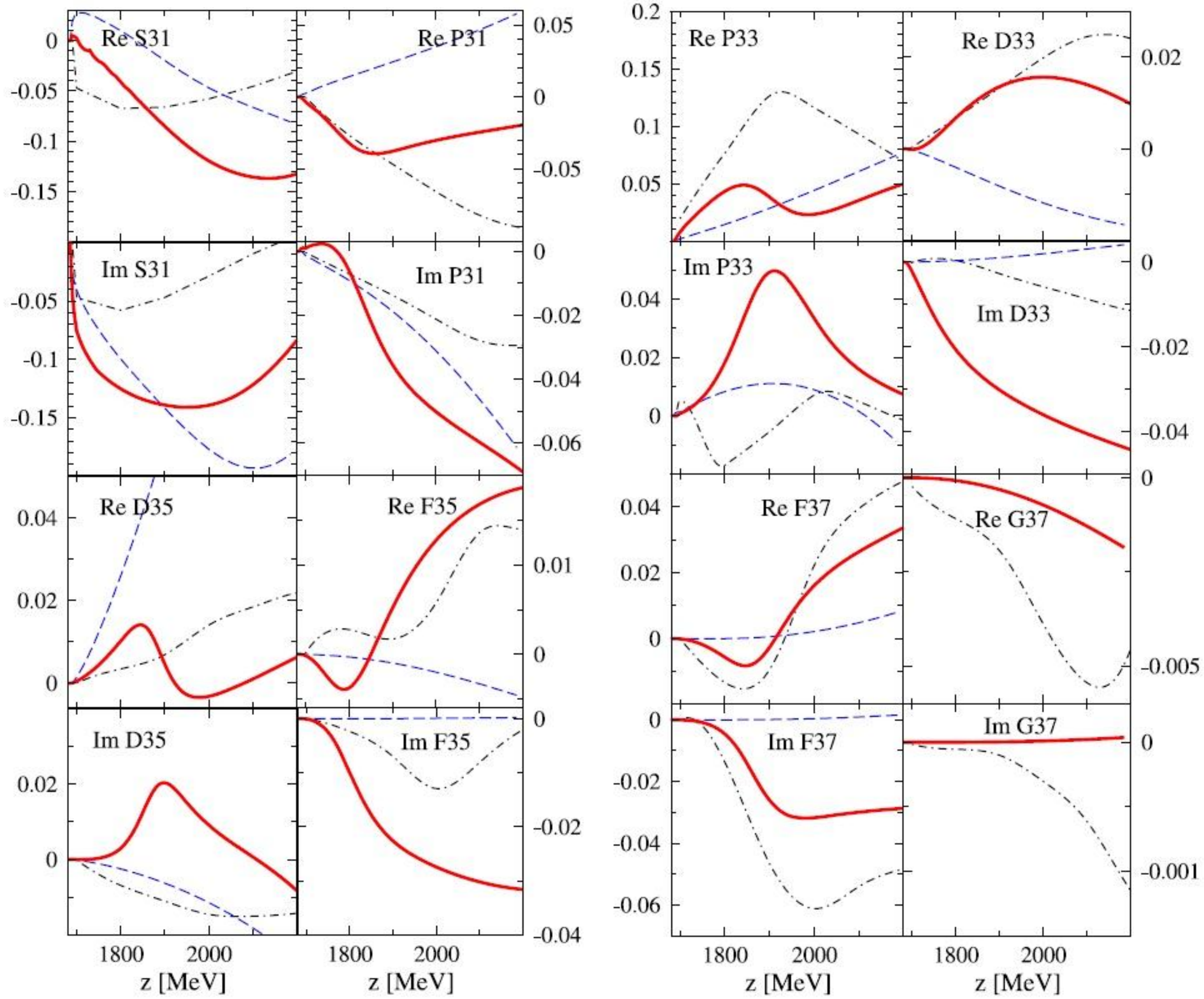
hadronic parameters of $3/2^+(1725)$ candidate state as well as of others N*'s were varied within PDG uncertainties - $2.78<\chi^2/\mathrm{d.p.}<2.9$

	M, GeV	$\Gamma_{tot,}$ MeV	BF($\pi\Delta$) %	BF(ρp) %
3/2+(1725)	1.725± 0.004	80±6.0	48±10	7.7±2.2
$P_{13}(1720)$	1.747± 0.004	161±31	comp. with 0.	60-100

Additional final state: KY data

- Data for $K\Lambda$ and $K\Sigma$ come for free
  - Cross sections are smaller, but the final state is two-body, so less data are needed.
  - These final states have two charged particles and hence will be part of the trigger.
- Data on $\pi^+ p \rightarrow K^+\Sigma^+$ are especially useful
  - Only isospin 3/2 contributes: Δ resonances.
  - Is the $\Delta(1600)$ the I=3/2 partner of the Roper?

Partial wave solutions: KY data



We need better quality data to resolve the PWA ambiguities.

Connection to Hypernuclei

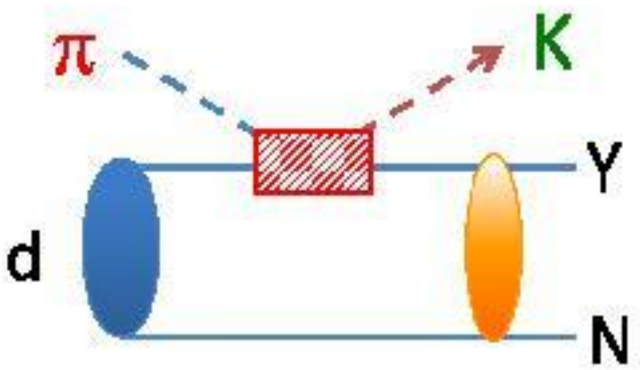


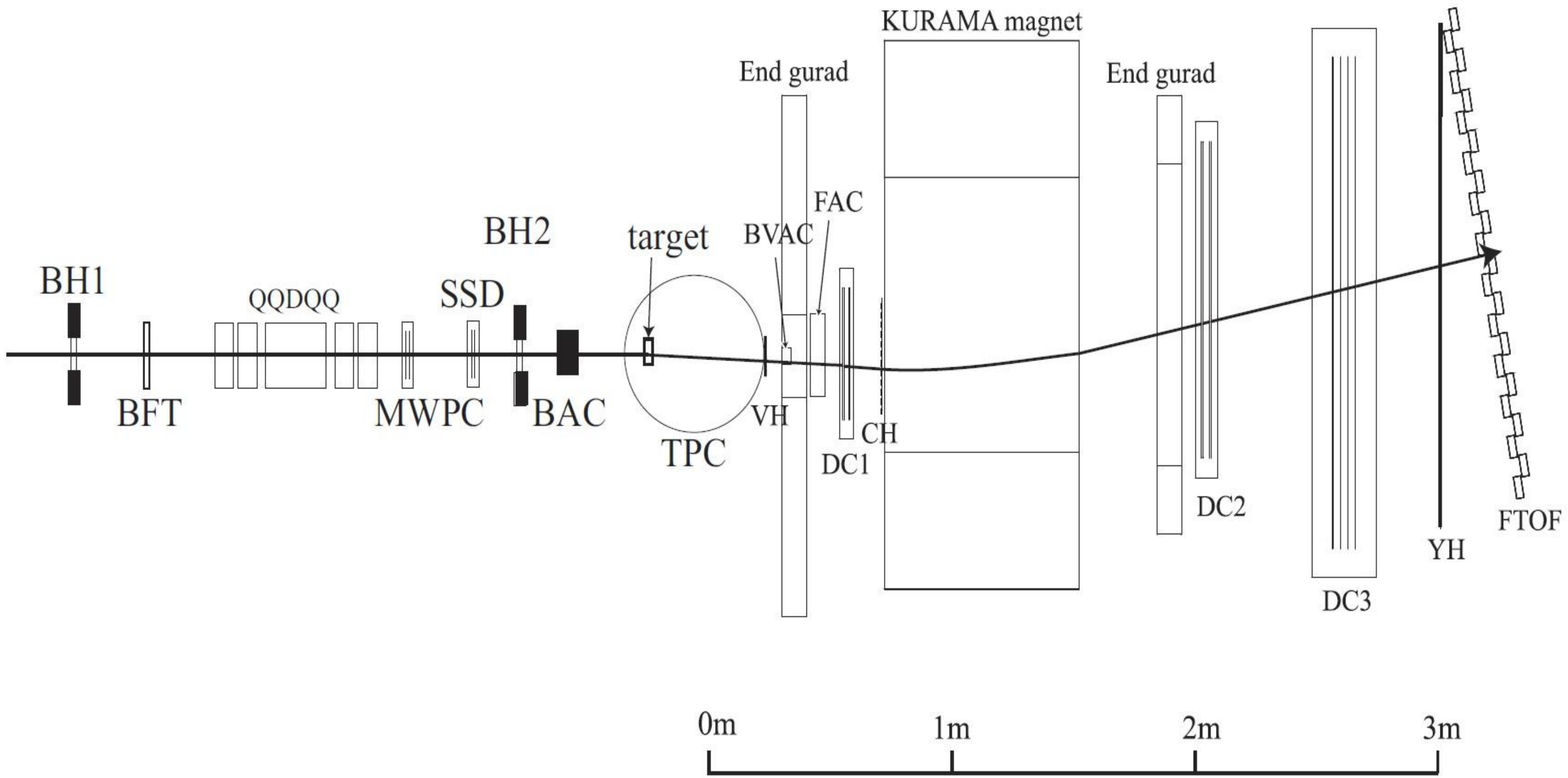
Diagram showing the YN interaction studied through FSI of the (π,K) reaction on the deuteron.

To calculate this, one first needs better data for the basic (π,K) reaction on the nucleon.

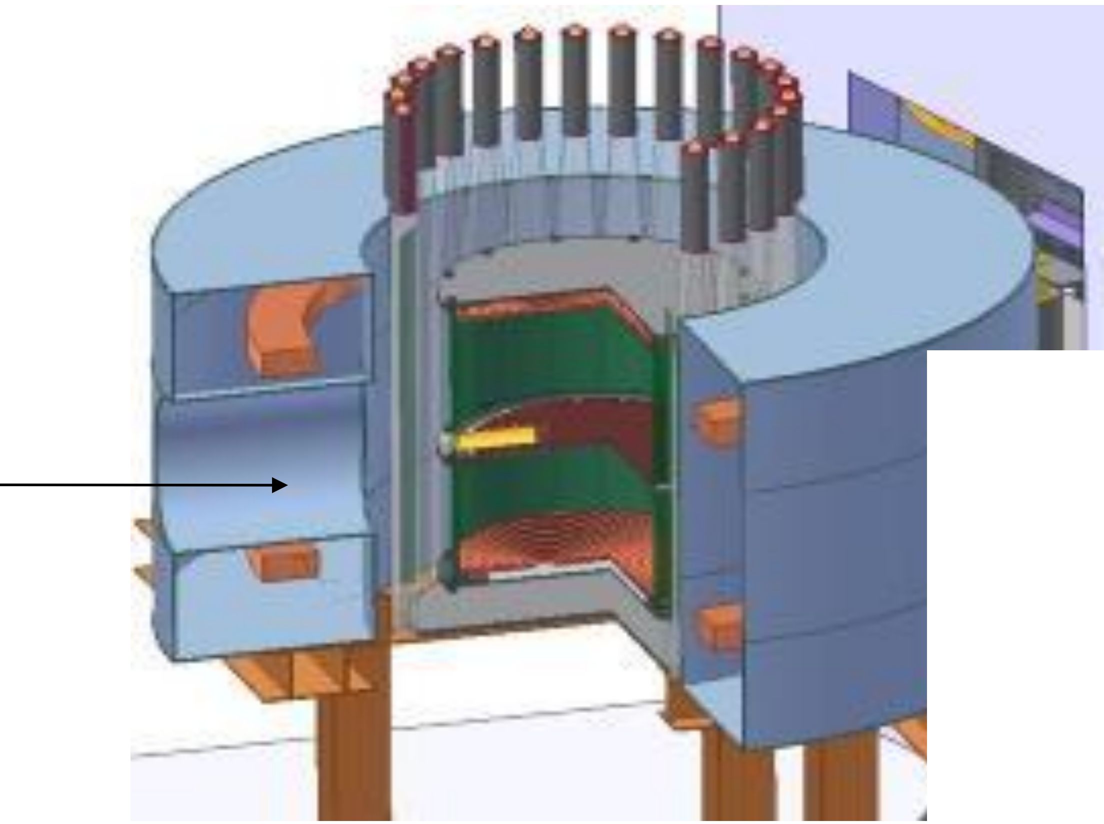
Studies of hypernuclei have provided potentials for the YN force in nuclei, and now Lattice calculations have made predictions for free YN scattering. The data from this proposal will provide the (π,K) data over a broad range of kinematics needed to constrain the first part of the calculation.

J-PARC Experiment

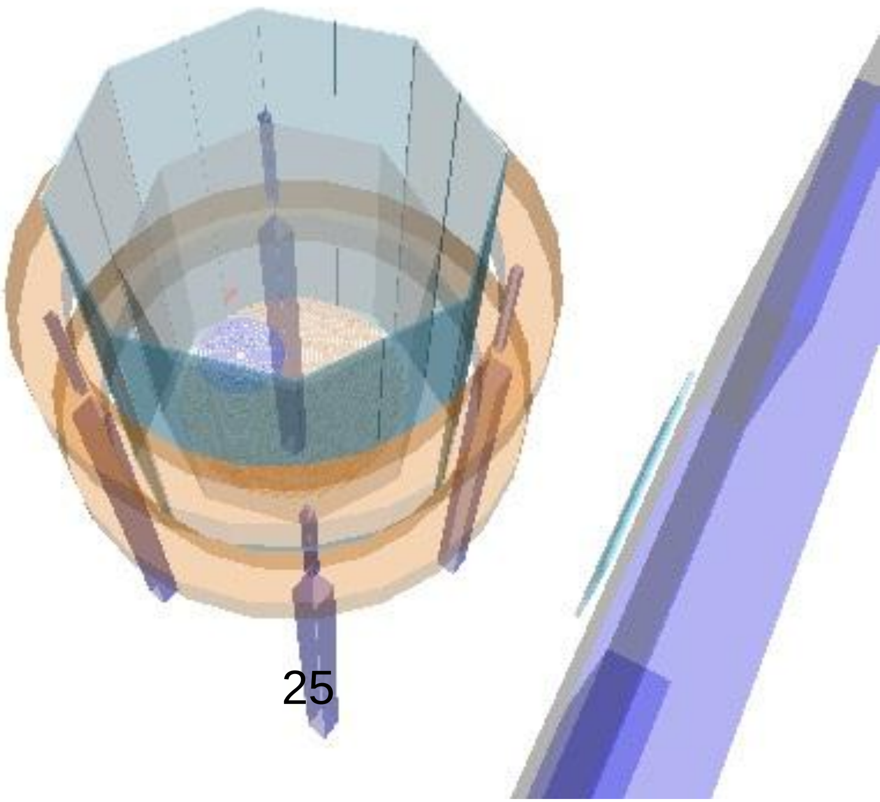
K1.8 beamline with TPC



Same TPC as for H-dibaryon



Top view of TPC as visualized by GEANT



Pion beam enters between the magnet coils.

Count Rate Estimates

Assume a total cross section for $(\pi,2\pi)$ of 2 mb.

Pion beam rate is about 10^6 (per 6 second spill).

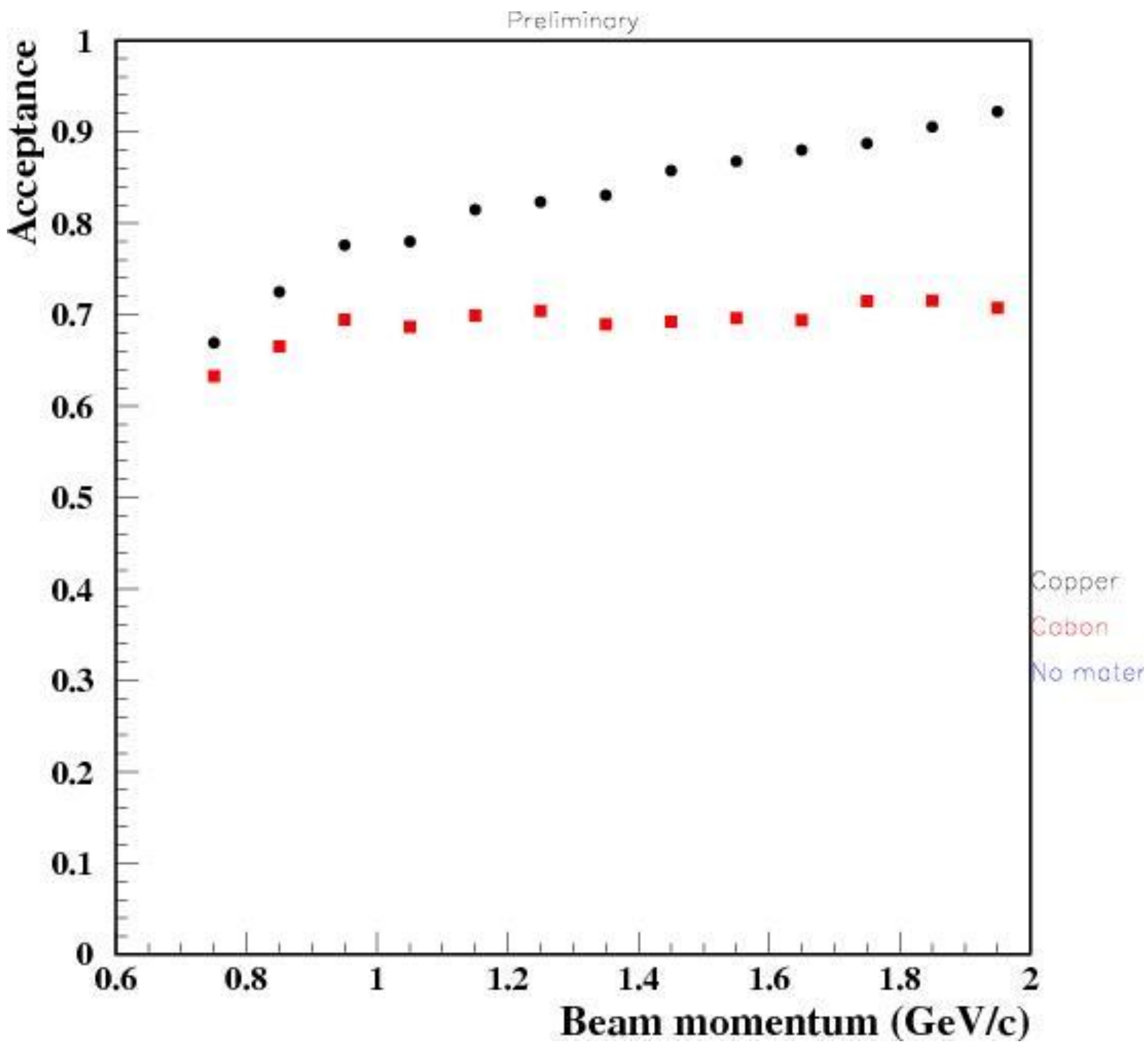
Liquid Hydrogen target of length 5 cm.

TPC acceptance of 50% (70% for each particle)

100% computer livetime (using event buffering)

Result: 200 events per spill cycle.

GEANT simulations: TPC



Black: one particle trigger

Red: two-particle trigger

Beam Time Estimate

Need wide energy coverage: W=1.50 – 2.15 GeV

Take small energy steps: ΔW=0.025 (26 beams)

Need both π^+ and π^- beams

Angular distributions: take 20 angle bins

10,000 counts per bin (multi-dimensional analysis)

Result: request 14+25+6 = 45 shifts total

Other Considerations

Trigger: 2 charged particles.

Elastic scattering increases rates by 2.

→ Data acquisition may be near the limit

→ Most of elastic events go to forward angle

Detailed simulations are dependent on the exact details of the TPC construction

Acceptance factors estimated from the same TPC design as H-particle search proposal

Experimental Summary

With just 15 days of beamtime on the K1.8 line with the TPC could increase the database for (π,2π) by several orders of magnitude.

These data are necessary if we want to know the true poles of the N* spectrum.

General Summary

The N* spectrum is a long-standing problem.

Today, we know that dynamical coupled-channels calculations are needed.

→ Coupled channels requires hadronic data.

→ Many N* states couple to 2π decay.

Without quality (π,2π) data, it is difficult to see how the N* spectrum can be extracted.

The experiment can only be done at J-PARC.

Tokyo Sky Tree: world’s highest building

Sometimes you want to reach for the sky…

but first you need a strong foundation.