The Missing Baryons Problem and the Need for Hadronic Data of the $(\pi,2\pi)$ Reaction

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JAEA Seminar

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Outline

- Review of quark model of baryons
- Lattice QCD predictions of baryons
- EBAC: extracting resonance properties
- Review of existing (π ,2π) data
- CLAS: 2π Photoproduction Data
- Experiment to measure (π ,2π) at J-PARC

Review: the Quark Model

The SU(6) model (SU(3)$_f$ x SU(2)$_{spin}$ gives for 3-quarks:

$$\mathbf{6} \otimes \mathbf{6} \otimes \mathbf{6} = \mathbf{56}_S \oplus \mathbf{70}_M \oplus \mathbf{70}_M \oplus \mathbf{20}_A$$

Where the multiplets are made up of octets and decuplets:

Ground State:

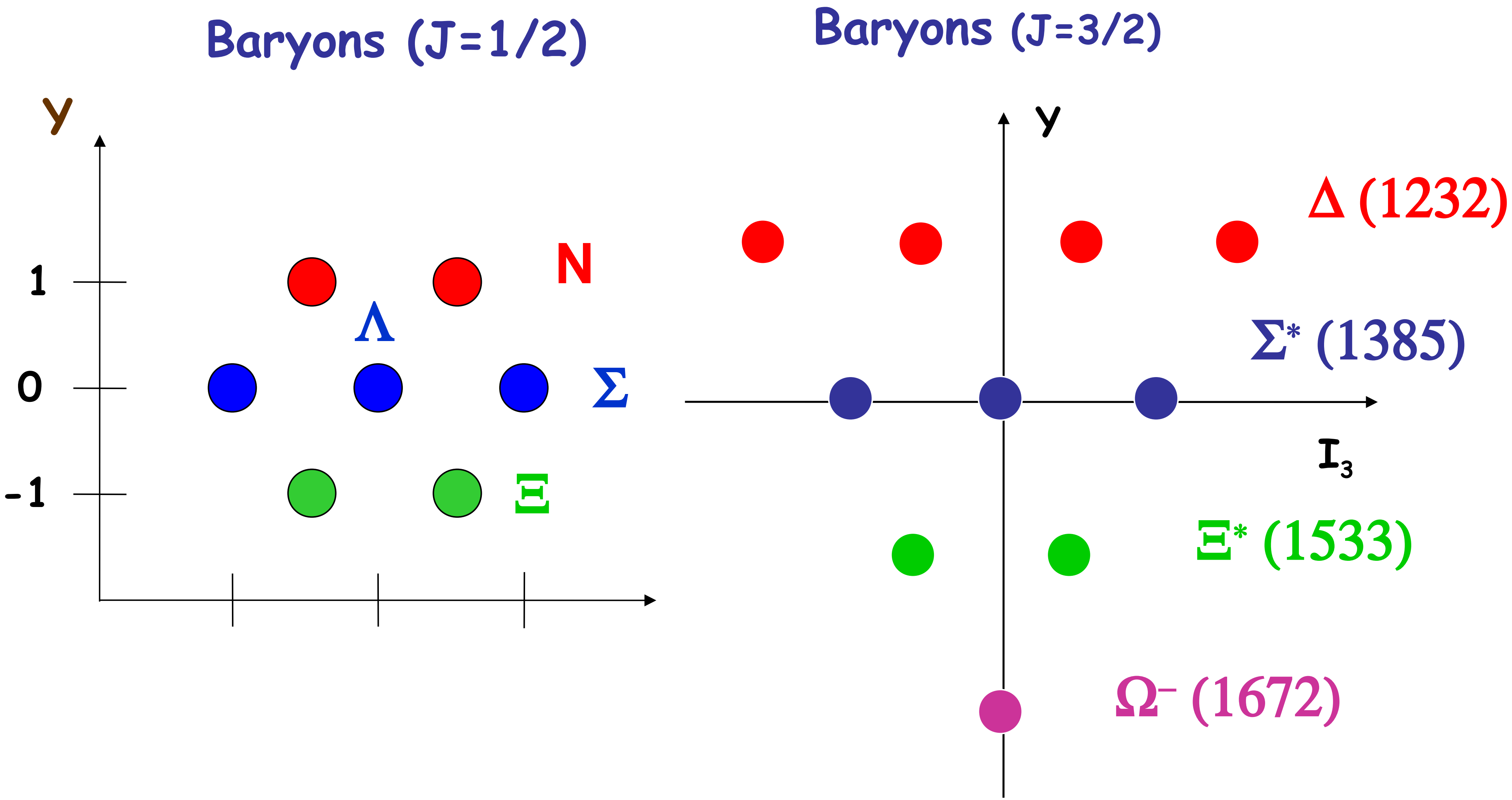
$$\mathbf{56} = {}^4\mathbf{10} \oplus {}^2\mathbf{8}$$

Excited States:

$$\mathbf{70} = {}^2\mathbf{10} \oplus {}^4\mathbf{8} \oplus {}^2\mathbf{8} \oplus {}^2\mathbf{1}$$

$$\mathbf{20} = {}^2\mathbf{8} \oplus {}^4\mathbf{1}\ ,$$

Ground State $56_S = {}^2 8 + {}^4 10$



Decuplet Assignments (PDG)

			S				
L=0	$3/2^+$	$(56,0^+_0)$	$3/2$	$\Delta(1232)$	$\Sigma(1385)$	$\Xi(1530)$	$\Omega(1672)$
	$3/2^+$	$(56,0^+_2)$	$3/2$	$\Delta(1600)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
L=1	$1/2^-$	$(70,1^-_1)$	$1/2$	$\Delta(1620)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
	$3/2^-$	$(70,1^-_1)$	$1/2$	$\Delta(1700)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
L=2	$5/2^+$	$(56,2^+_2)$	$3/2$	$\Delta(1905)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$
	$7/2^+$	$(56,2^+_2)$	$3/2$	$\Delta(1950)$	$\Sigma(2030)$	$\Xi(?)$	$\Omega(?)$
L=4	$11/2^+$	$(56,4^+_4)$	$3/2$	$\Delta(2420)$	$\Sigma(?)$	$\Xi(?)$	$\Omega(?)$

From π-scatt. database: all **** rated.

Lots of missing states! Lack of K-scatt. data or photoproduction data.

Octet Assignments (PDG)

	J^P	(D, L^P_N)	S	Octet members				Singlets
L=0	$1/2^+$	$(56,0^+_0)$	1/2	$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	
	$1/2^+$	$(56,0^+_2)$	1/2	$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$	$\Xi(?)$	
L=1	$1/2^-$	$(70,1^-_1)$	1/2	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(?)$	$\Lambda(1405)$
	$3/2^-$	$(70,1^-_1)$	1/2	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
	$1/2^-$	$(70,1^-_1)$	3/2	$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$	$\Xi(?)$	
	$3/2^-$	$(70,1^-_1)$	3/2	$N(1700)$	$\Lambda(?)$	$\Sigma(?)$	$\Xi(?)$	
	$5/2^-$	$(70,1^-_1)$	3/2	$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$	$\Xi(?)$	
L=0	$1/2^+$	$(70,0^+_2)$	1/2	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Xi(?)$	$\Lambda(?)$
L=2	$3/2^+$	$(56,2^+_2)$	1/2	$N(1720)$	$\Lambda(1890)$	$\Sigma(?)$	$\Xi(?)$	
	$5/2^+$	$(56,2^+_2)$	1/2	$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$	$\Xi(2030)$	

Mass hierarchy problem with L=1, S=3/2 !!

Here, there are more assignments, but are they correct?? (Maybe)

Phenomenology: L and S

Negative parity baryons:

$L; S$	$J^P = 1/2$	$J = 3/2$	$J = 5/2$
$L = 1; S = 1/2$	$N_{1/2^-}(1535)$	$N_{3/2^-}(1520)$	
$L = 1; S = 3/2$	$N_{1/2^-}(1650)$	$N_{3/2^-}(1700)$	$N_{5/2^-}(1675)$
$L = 1; S = 1/2$	$\Delta_{1/2^-}(1620)$	$\Delta_{3/2^-}(1700)$	

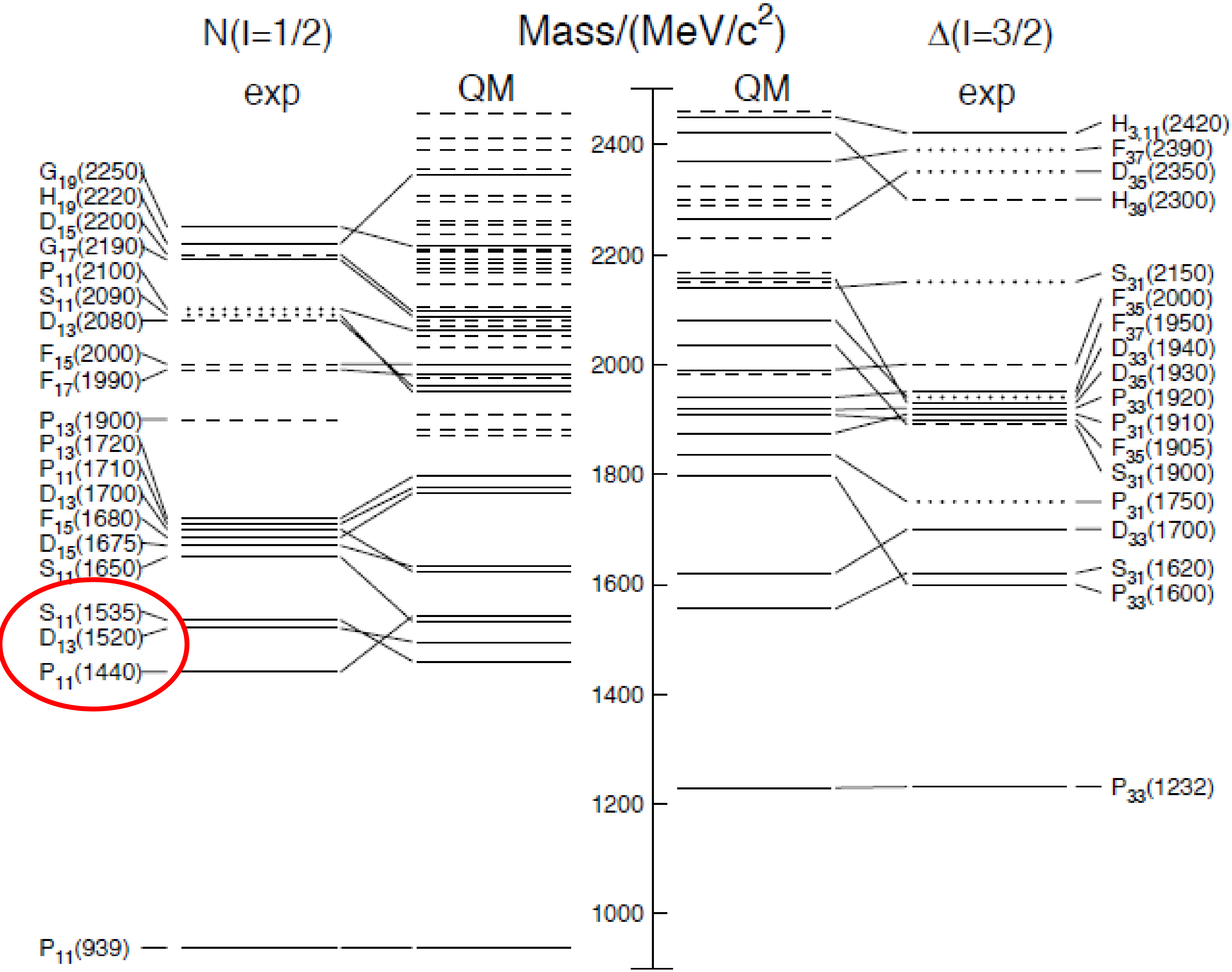
Positive parity baryons:

$L; S$	$J^P = 1/2^+$	$3/2^+$	$5/2^+$	$7/2^+$
$L = 2; S = 1/2$		$N_{3/2^+}(1720)$	$N_{5/2^+}(1680)$	
$L = 2; S = 3/2$	$N_{1/2^+}(1880)$	$N_{3/2^+}(1900)$	$N_{5/2^+}(2000)$	$N_{7/2^+}(1990)$
$L = 2; S = 3/2$	$\Delta_{1/2^+}(1910)$	$\Delta_{3/2^+}(1920)$	$\Delta_{5/2^+}(1905)$	$\Delta_{7/2^+}(1950)$

Masses seem to line up for a given value of L, S, not J!

SU(6) wavefunction: the fraction of “good” qq depends on S.

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)

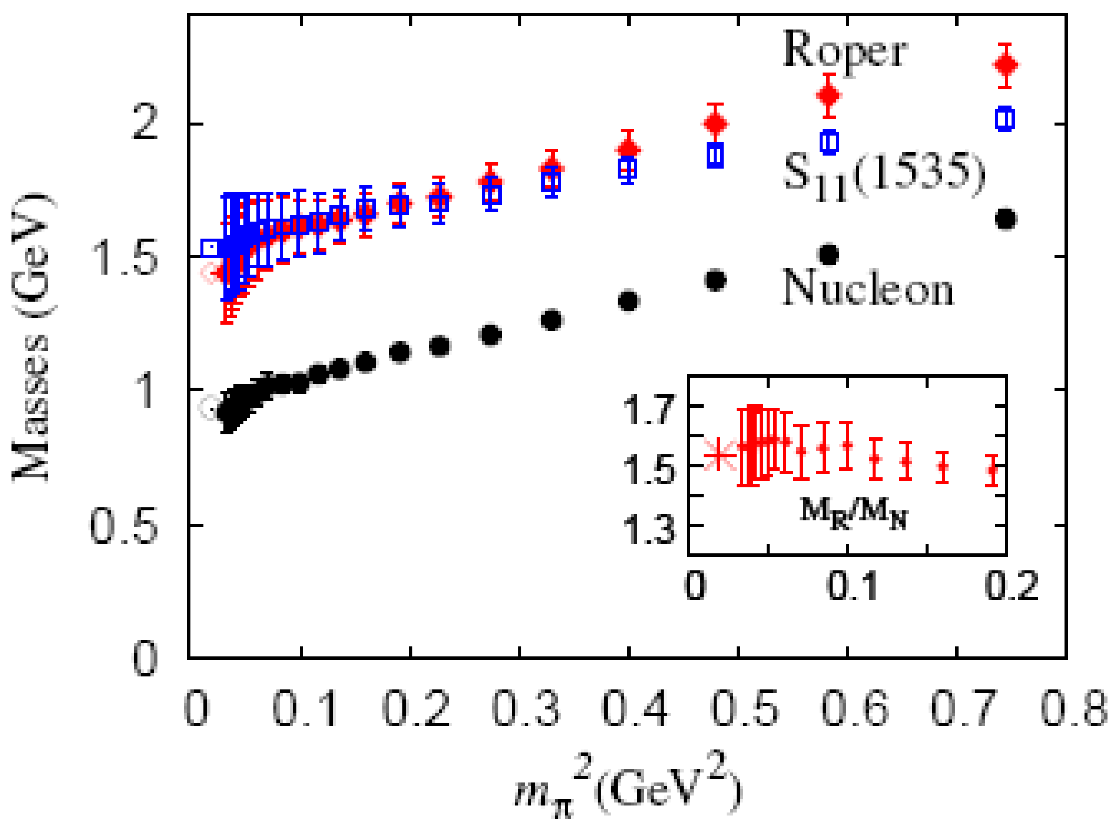
Model state	$\lvert A_{N\pi} \rvert$ ($\mathrm{MeV}^{\frac{1}{2}}$)	$N\pi$ state assignment	Rating	$\sqrt{\Gamma_{tot}}(\mathrm{BR})_{N\pi}$ ($\mathrm{MeV}^{\frac{1}{2}}$)
$[N\frac{1}{2}^-]_1(1460)$	14.7 ± 0.5	$N\frac{1}{2}^-(1535)$	****	8.0±2.8
$[N\frac{1}{2}^-]_2(1535)$	12.2 ± 0.8	$N\frac{1}{2}^-(1650)$	****	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!
(Note: just Nπ PWA.)

Lattice QCD Calculations

Lattice: Roper Resonance

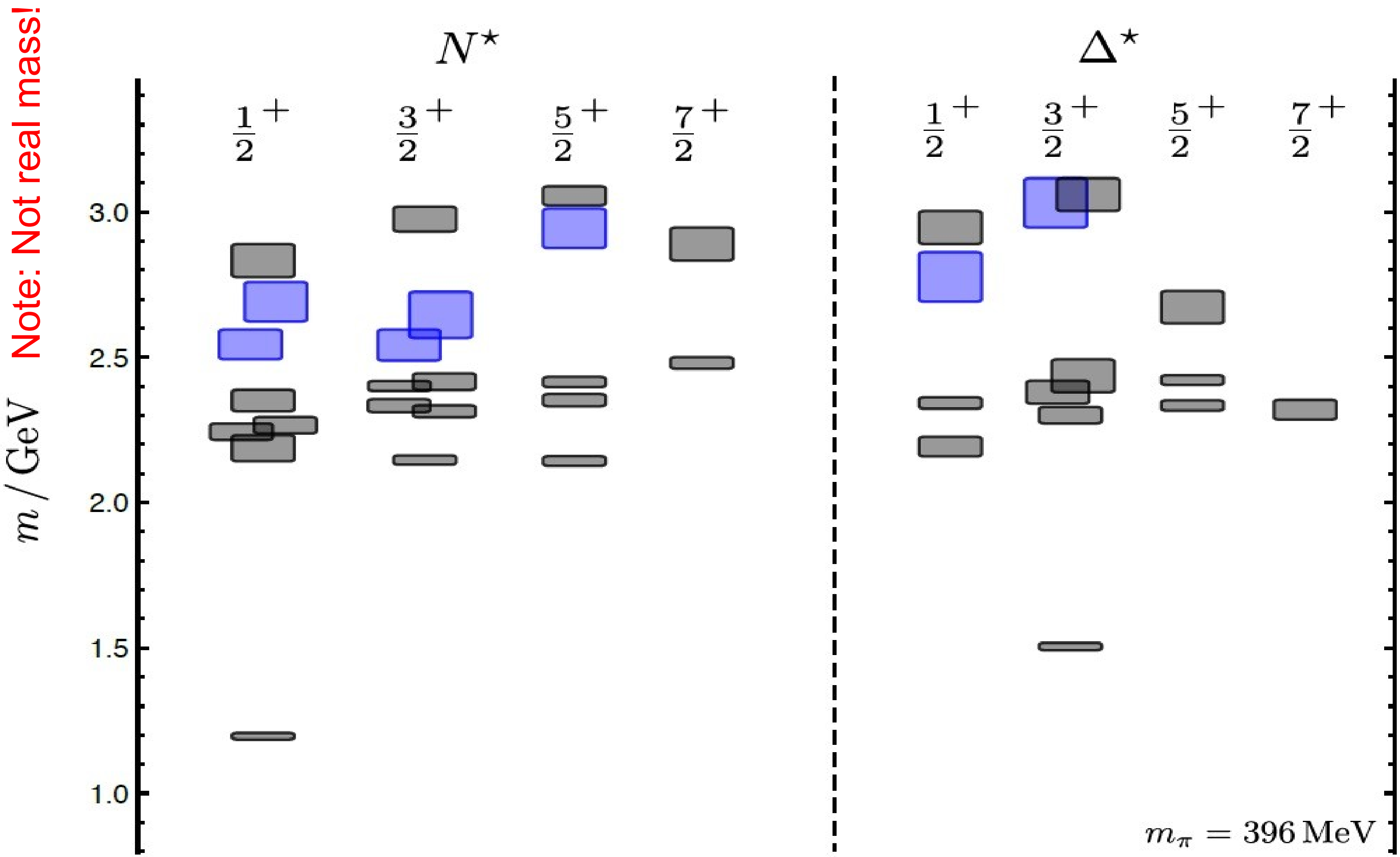
Dong et al., PLB605, 137 (2005)



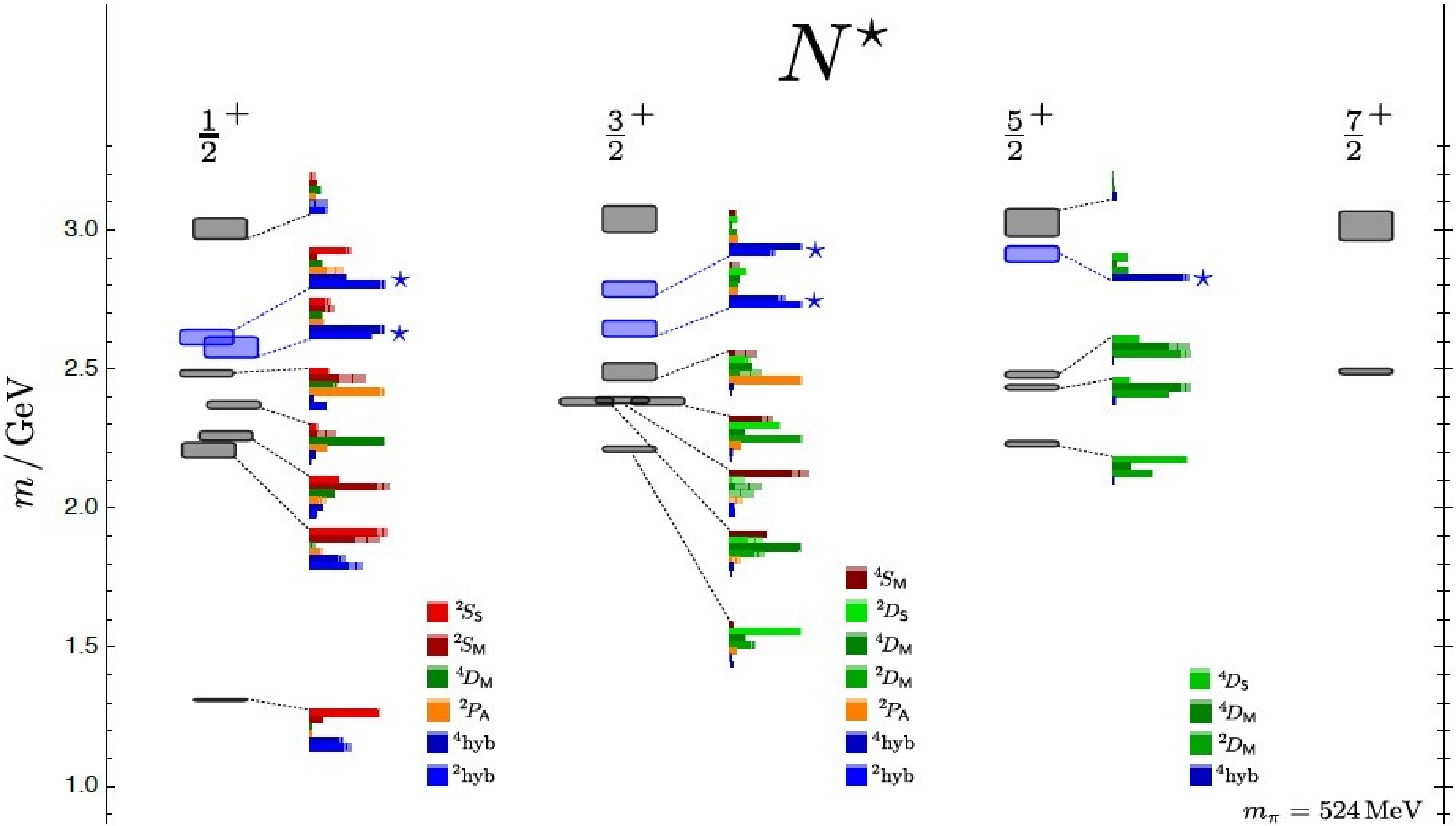
- **Bayesian statistics and constrained curve fitting**
- **N*(1440) crosses over at low pion mass (quenched)**
- **Not all theorists accept this chiral extrapolation.**

New Lattice Calculations

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



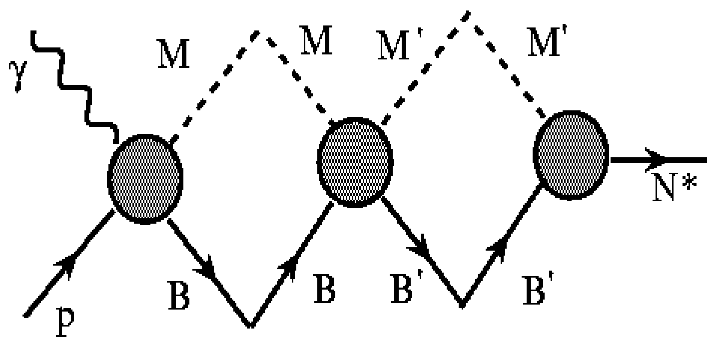
Projection of N* to $^{S}L_{J}$



EBAC: Excited Baryon Analysis Center

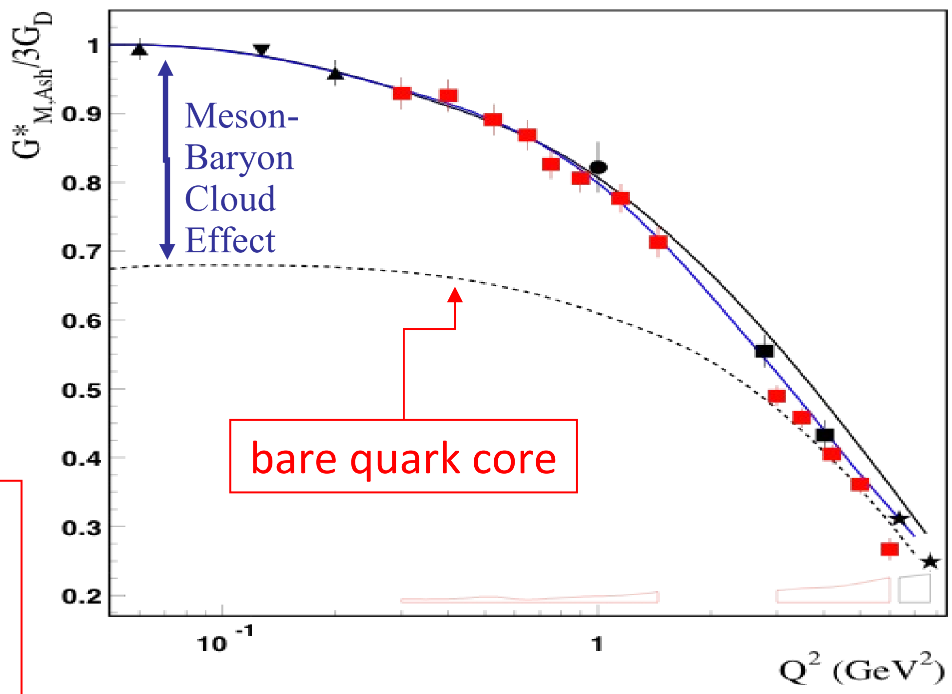
NΔ Transition Form Factor (GM) from EBAC analysis

- 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.

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



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

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:

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

coupled-channels effect

- Reaction channels:

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

$\pi\pi N$

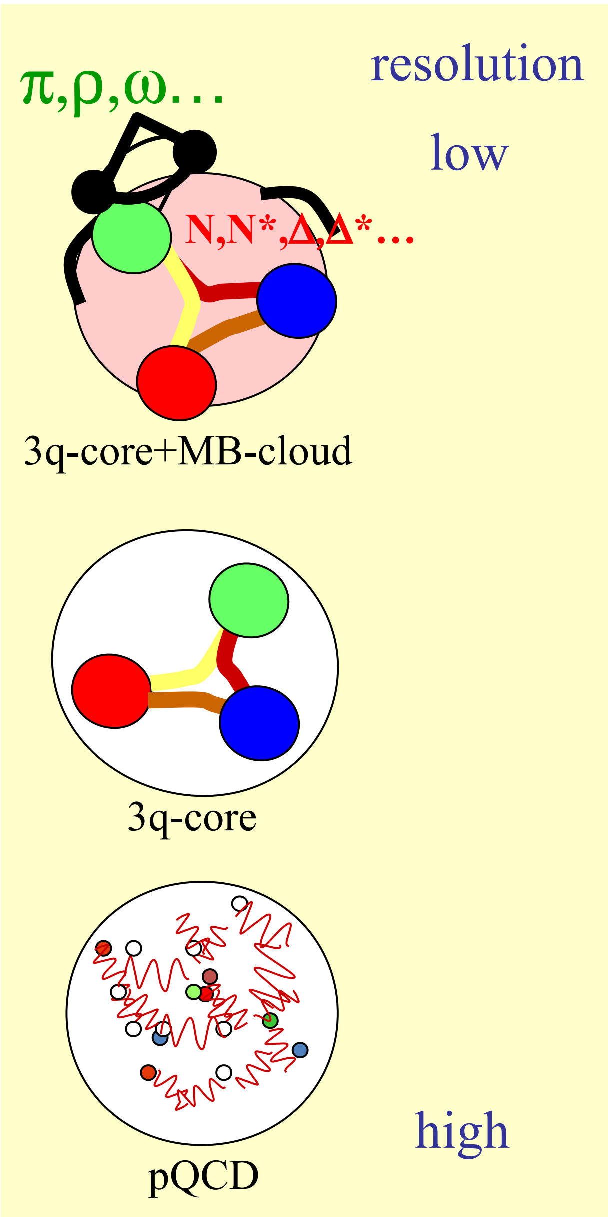
- Transition potentials:

$$V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,a} \Gamma_{N^*,b}}{E - M_{N^*}}$$

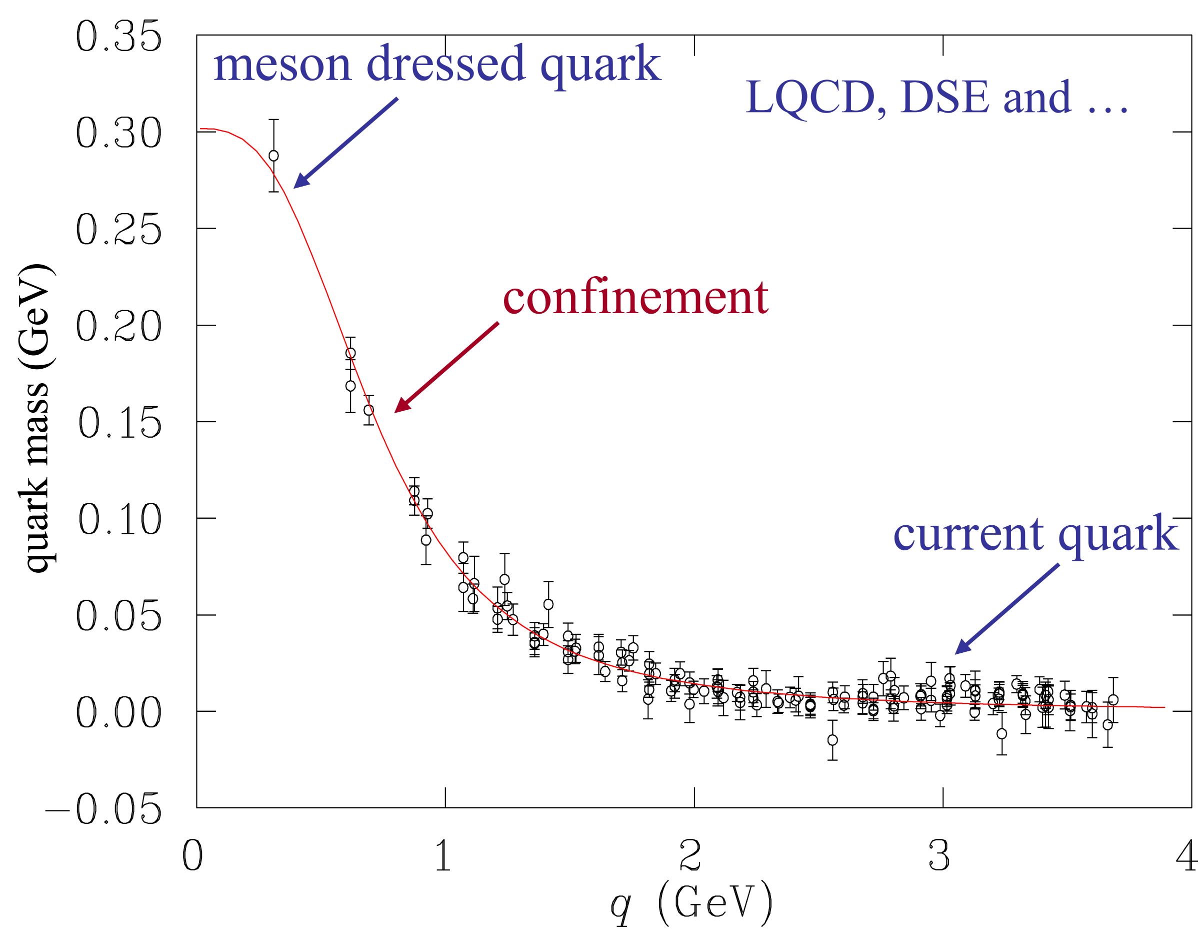
Meson-exchange potentials (Derived from Lagrangians)

bare N* states

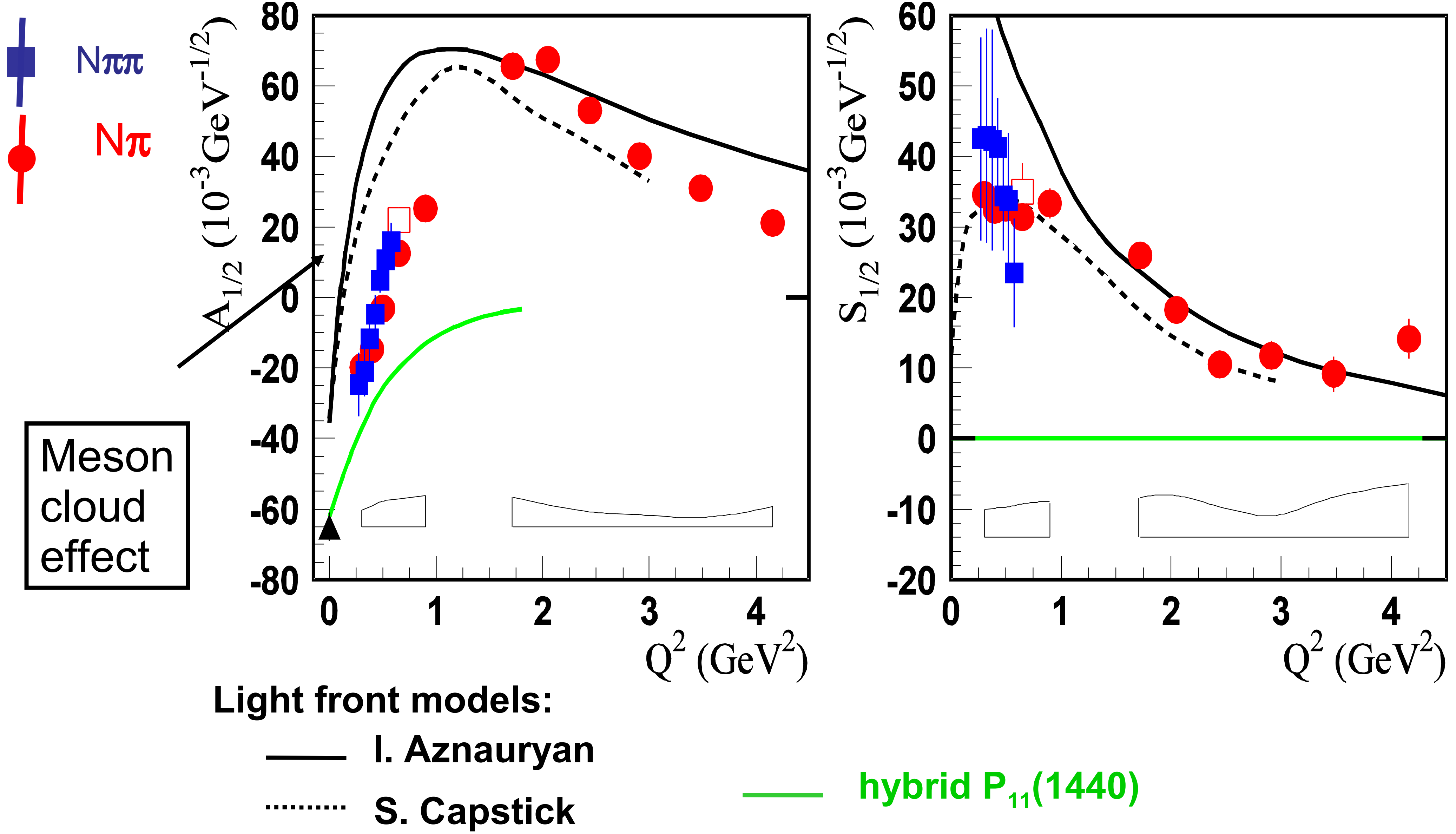
Hadron Structure with Electromagnetic Probes



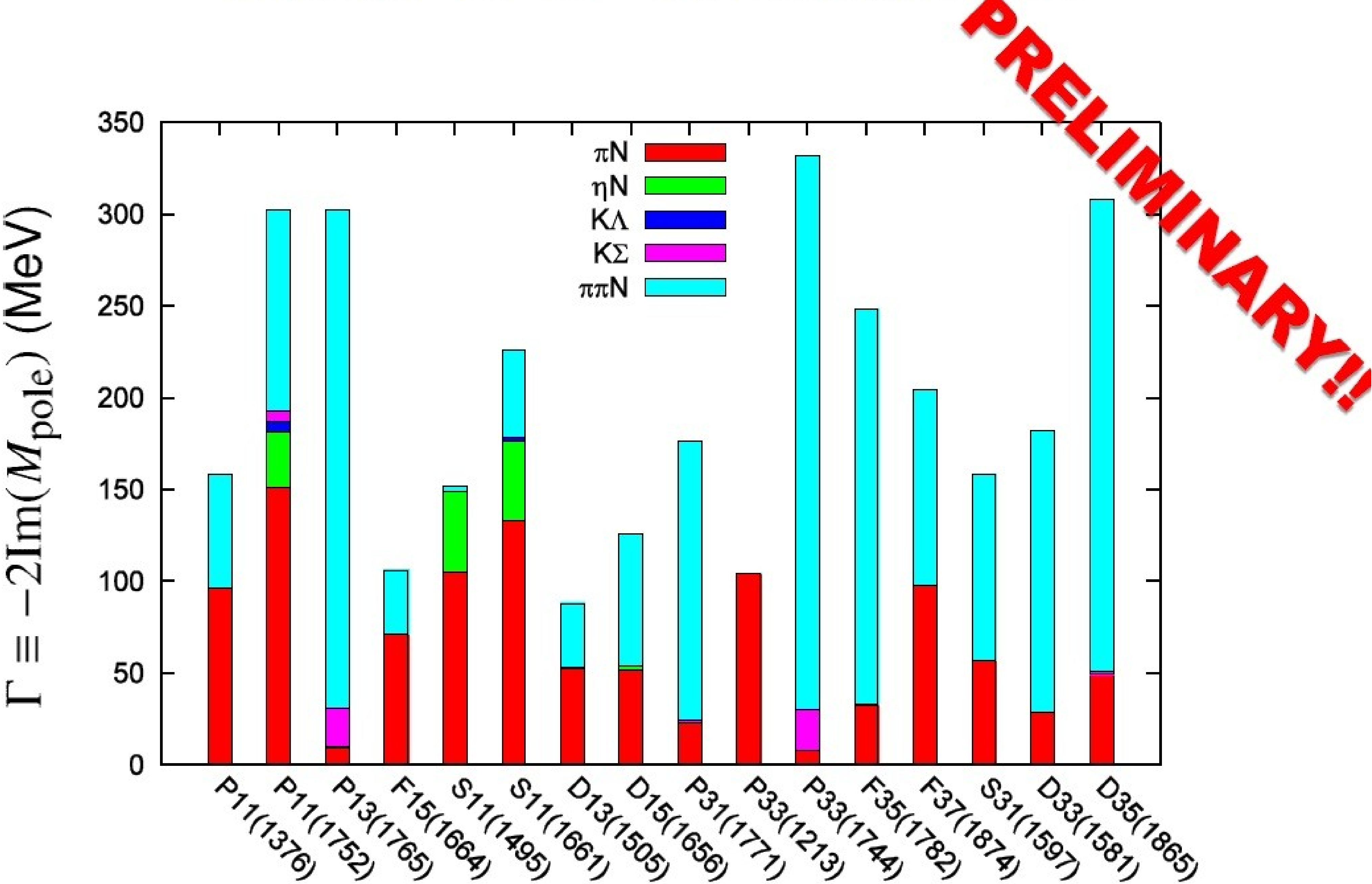
Quark mass extrapolated to the chiral limit, where q is the momentum variable of the tree-level quark propagator (curve=DSE, data=LQCD).



P_{11}(1440) couplings from CLAS



Width of N* resonances



World data for H(π,2π) Reaction

The Primary Source of $(\pi,2\pi)$

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

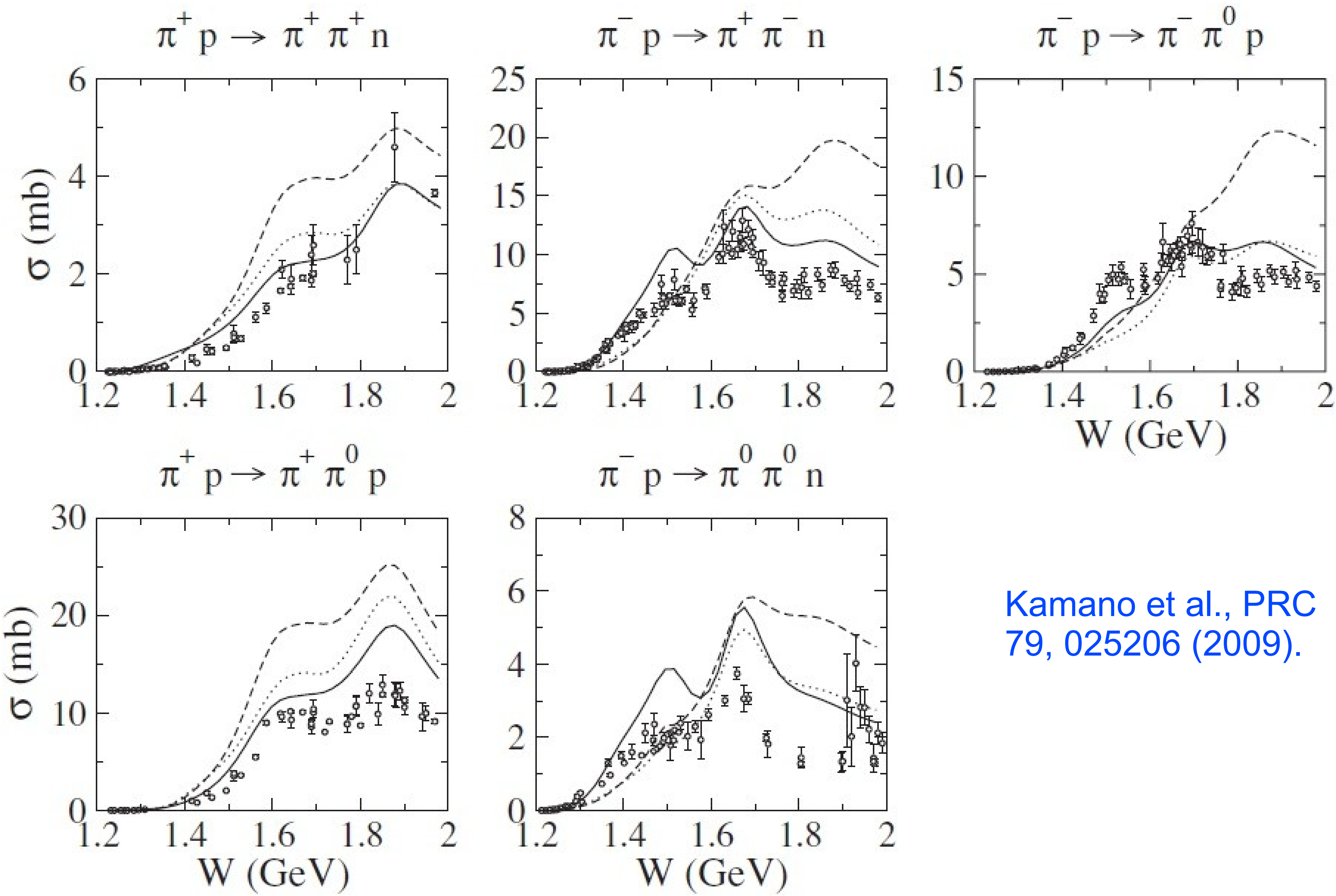
M. Manley, Phys. Rev. D 30, 904 (1984).

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

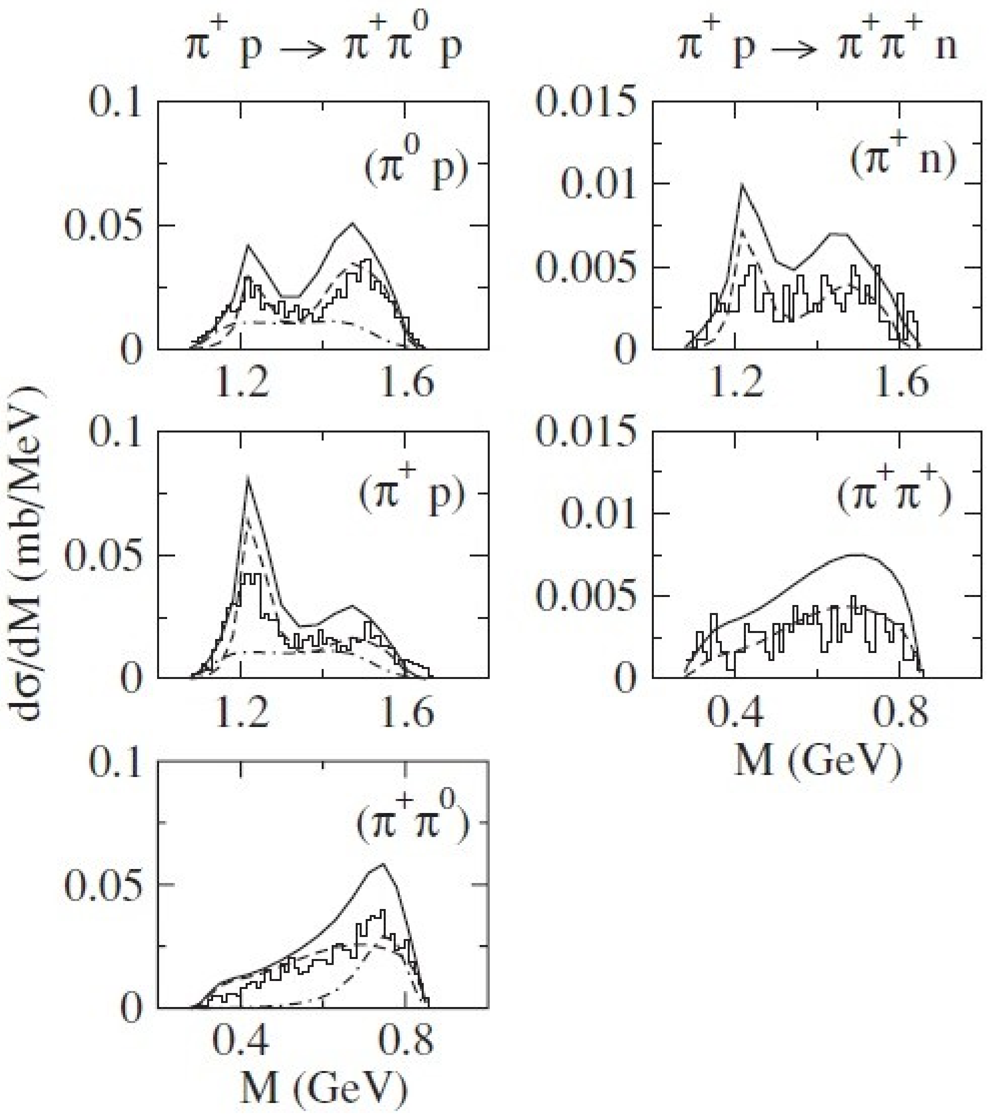
Total number of events!

Total Cross Sections



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

Mass Projections

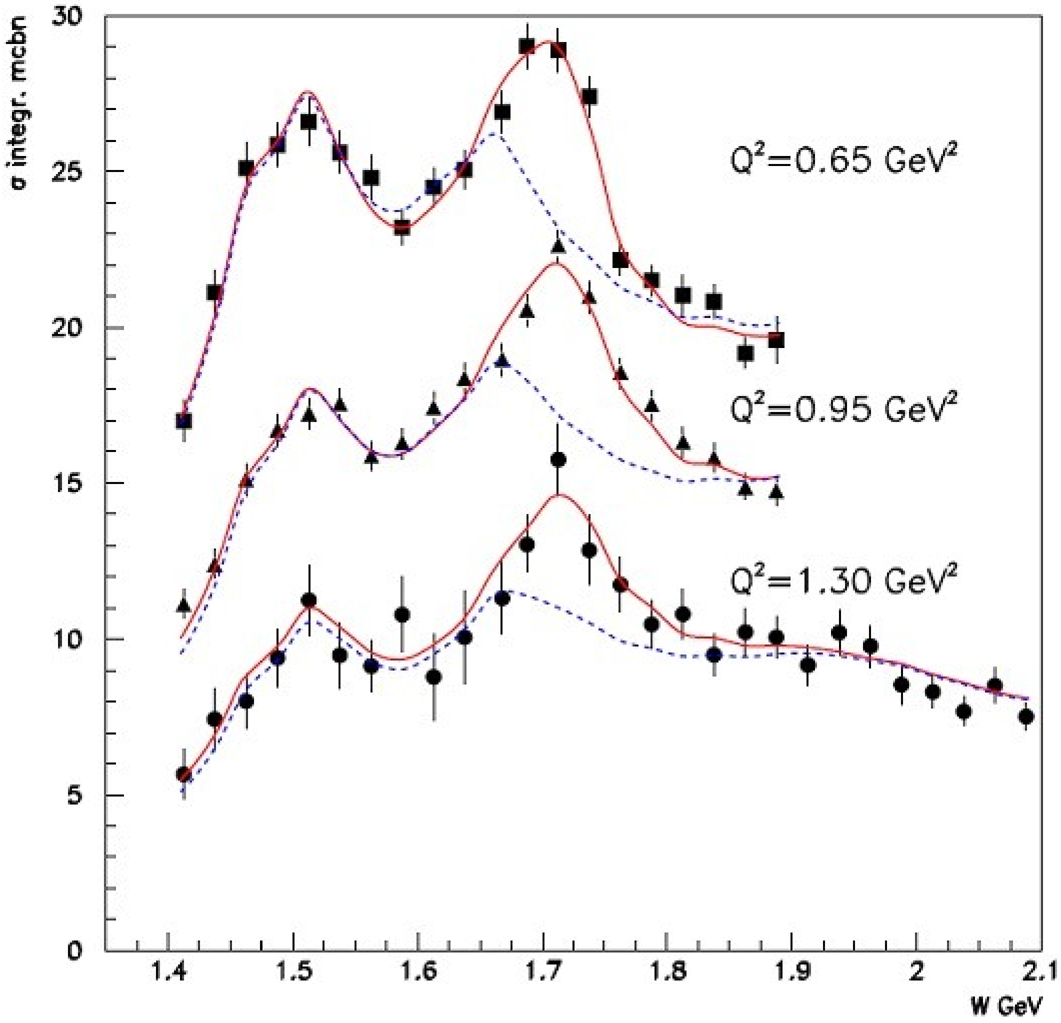


Note: the normalization of these data is uncertain. The total cross sections were used to set the vertical scale.

The solid curves are the full calculation. The other curves do not include some coupled-channels effects.

CLAS: 2π Photoproduction Data

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



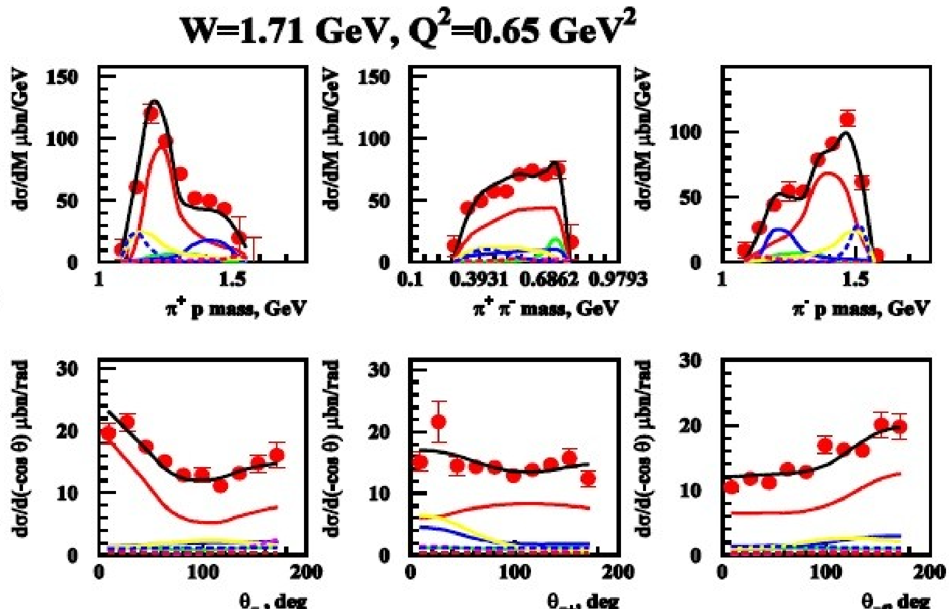
The BLUE dotted curve uses only the known resonances from the Particle Data Group.

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 - $2.94<\chi^2/d.p.<3.15$

	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



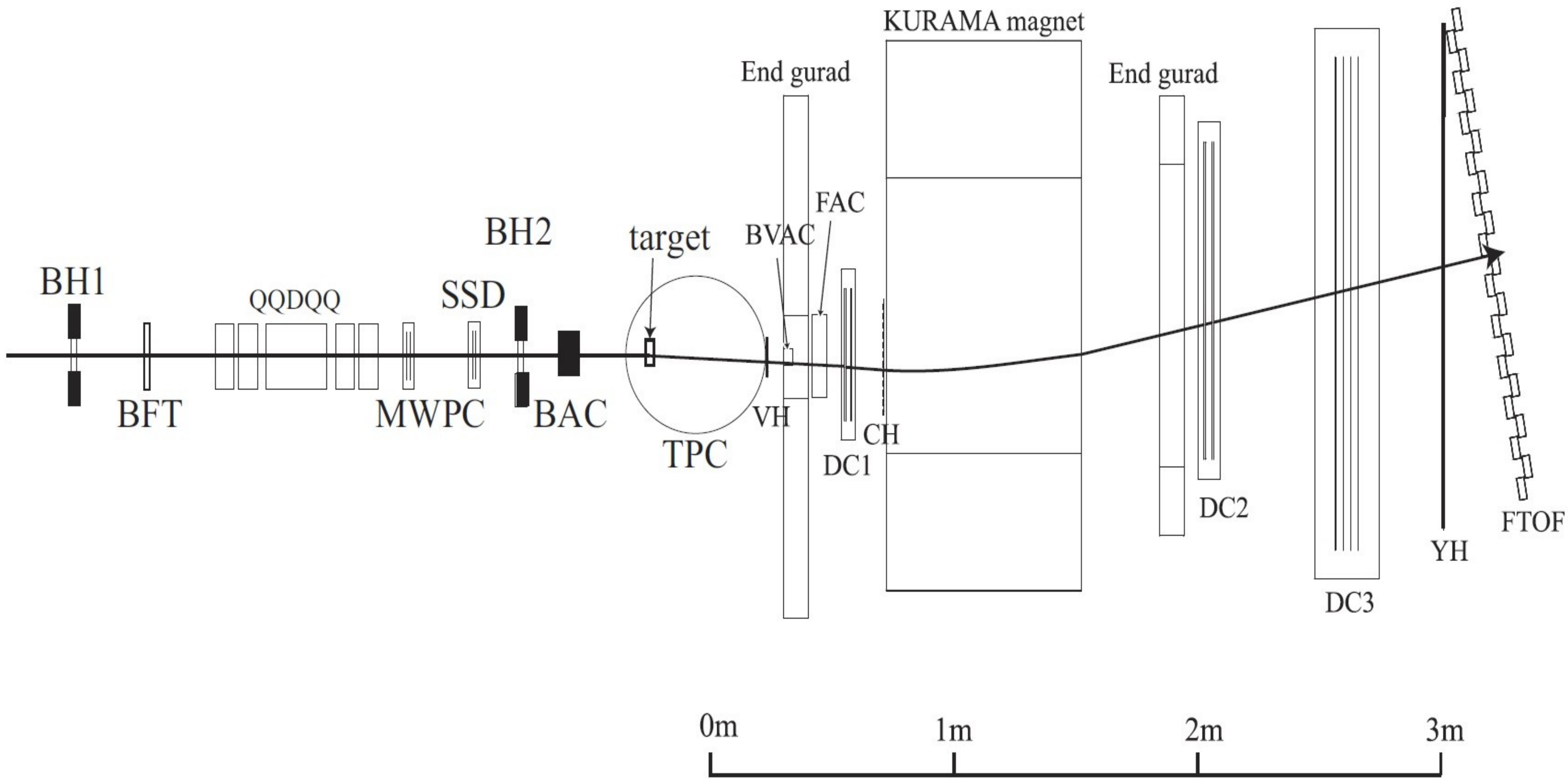
hadronic parameters of $3/2^+(1725)$ candidate state as well as of others N*'s were varied within PDG uncertainties - $2.78<\chi^2/d.p.<2.9$

	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

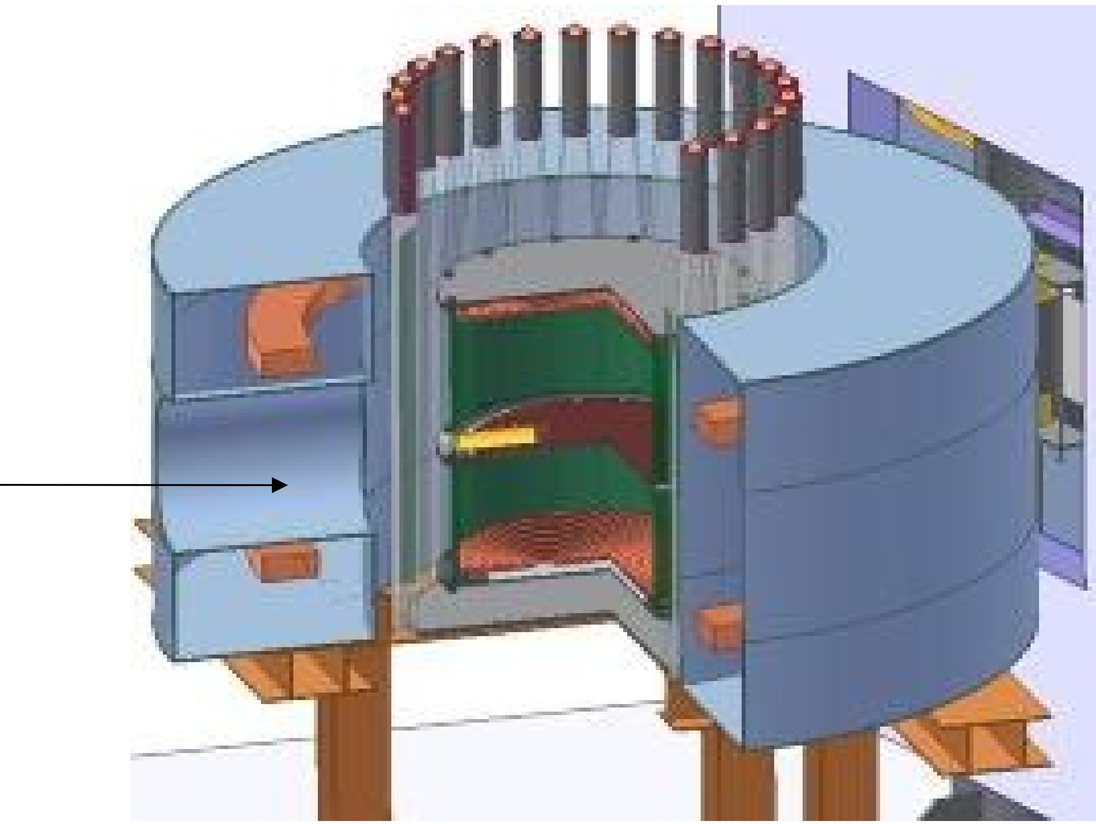
A new P_{13} resonance, much lower in mass than the quark model prediction, is necessary to fit the data.

J-PARC Experiment

K1.8 beamline with TPC



Same TPC as for H-dibaryon



Pion beam enters between the magnet coils.

Enlarged view of the TPC with the target off-center. Note: LH2 target would come in from the top.

Count Rate Estimates

Assume a total cross section for $(\pi,2\pi)$ of 10 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: 1000 events per spill.

Beam Time Estimate

Need wide energy coverage: W=1.35 – 2.15 GeV

Take small energy steps: ΔW=0.025 (30 beams)

Need both π^+ and π^- beams

Angular distributions: take 20 angle bins

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

Result: Need a total of 20 shifts (plus overhead)

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 spect.

Detailed simulations are needed to understand the trigger rates!

Acceptance factors are just estimated!

Experimental Summary

With just 20 shifts of beamtime on the K1.8 line with the TPC could increase the database for $(\pi,2\pi)$ by several orders of magnitude.

These data are necessary if we want to solve the problem 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 $(\pi,2\pi)$ data, it is difficult to see how the N* spectrum can be extracted.

The experiment can only be done at J-PARC.