Baryon Spectroscopy Experiments at J-PARC and Elsewhere

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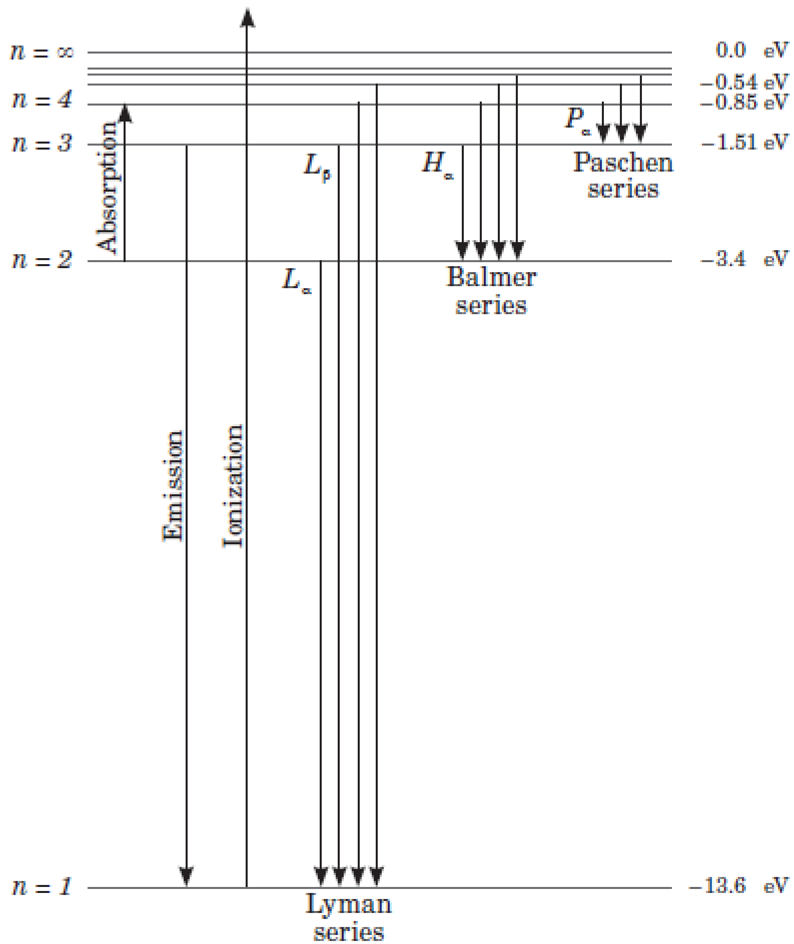
Some Background

- N* resonances are a prediction of the constituent quark model.
  - The most well-known is the Isgur-Karl model.
- Most N*'s identified in pion elastic scattering
  - Recently, photoproduction data has contributed.
  - ANL-Osaka and Bonn-Gatchina PWA see new N*'s.
- Lattice QCD now has predictions for N*'s.
  - Still waiting for calc's with realistic quark masses.

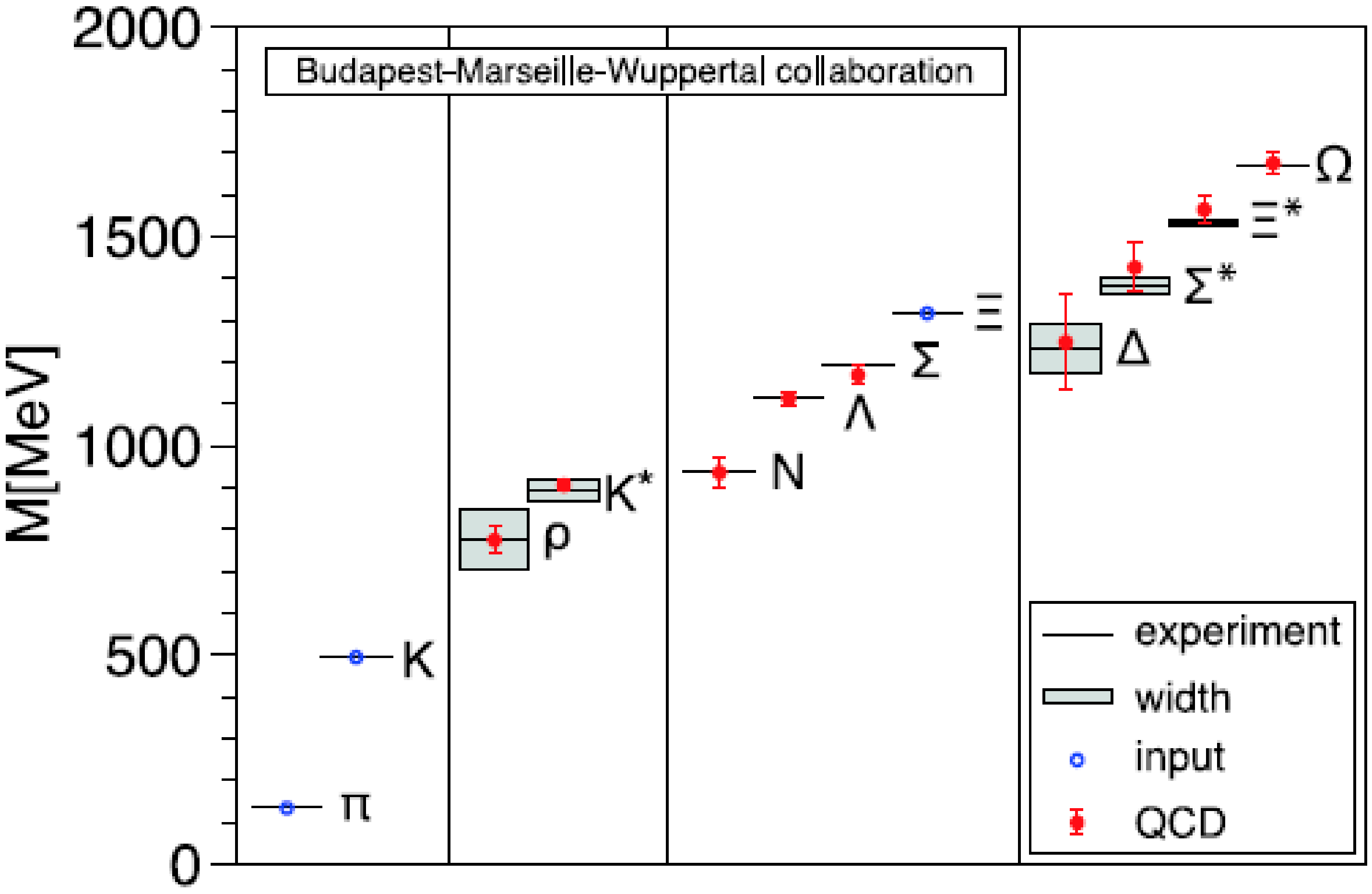
An Analogy



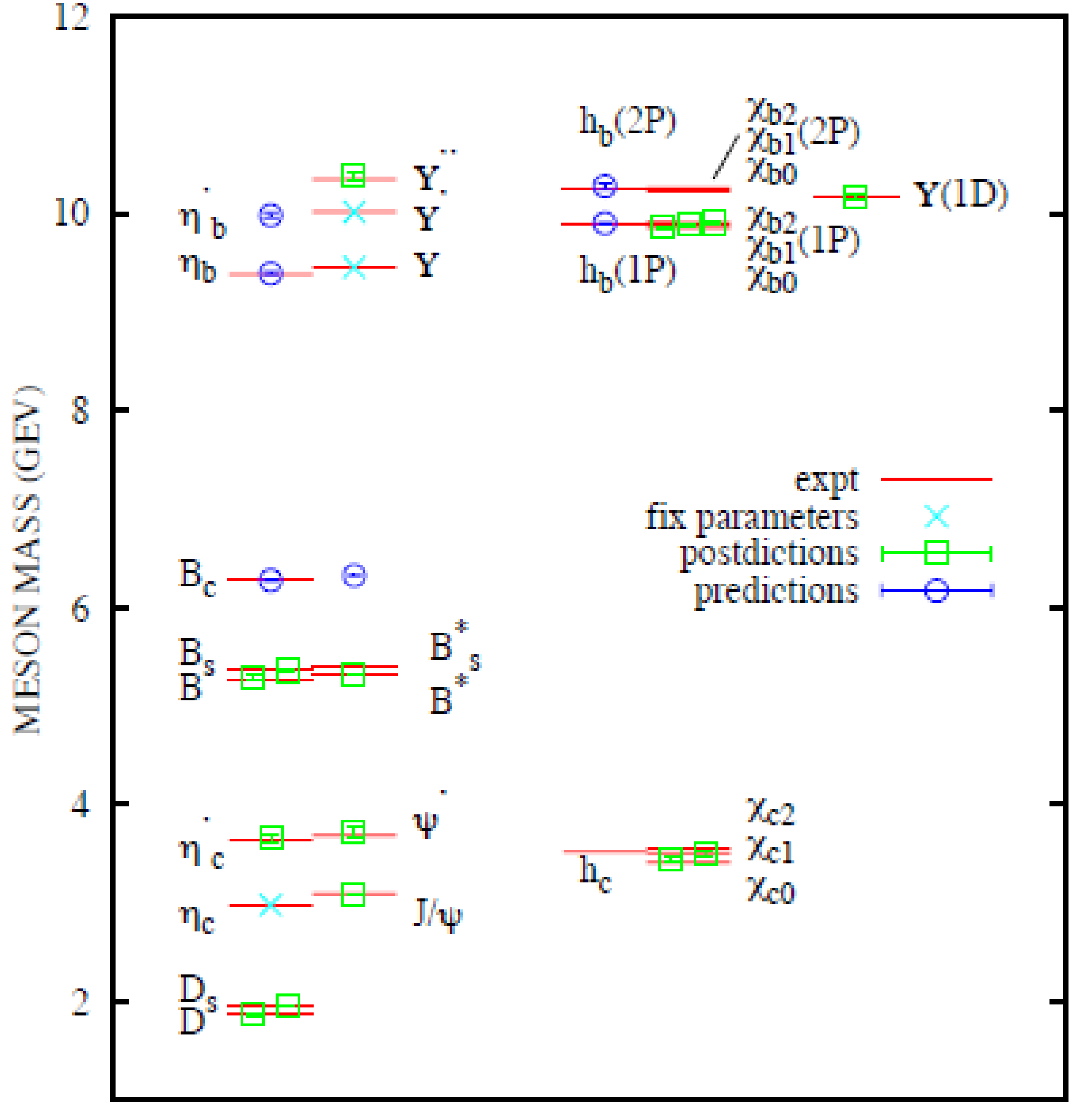
The spectrum of energy levels of the hydrogen atom provided insights into the structure of the atom from Bohr and later, with more precise data, to the theory of quantum mechanics.

Even today, the spectrum of hydrogen continues to give surprises (*e.g.* proton radius).

Lattice Gauge: Ground States



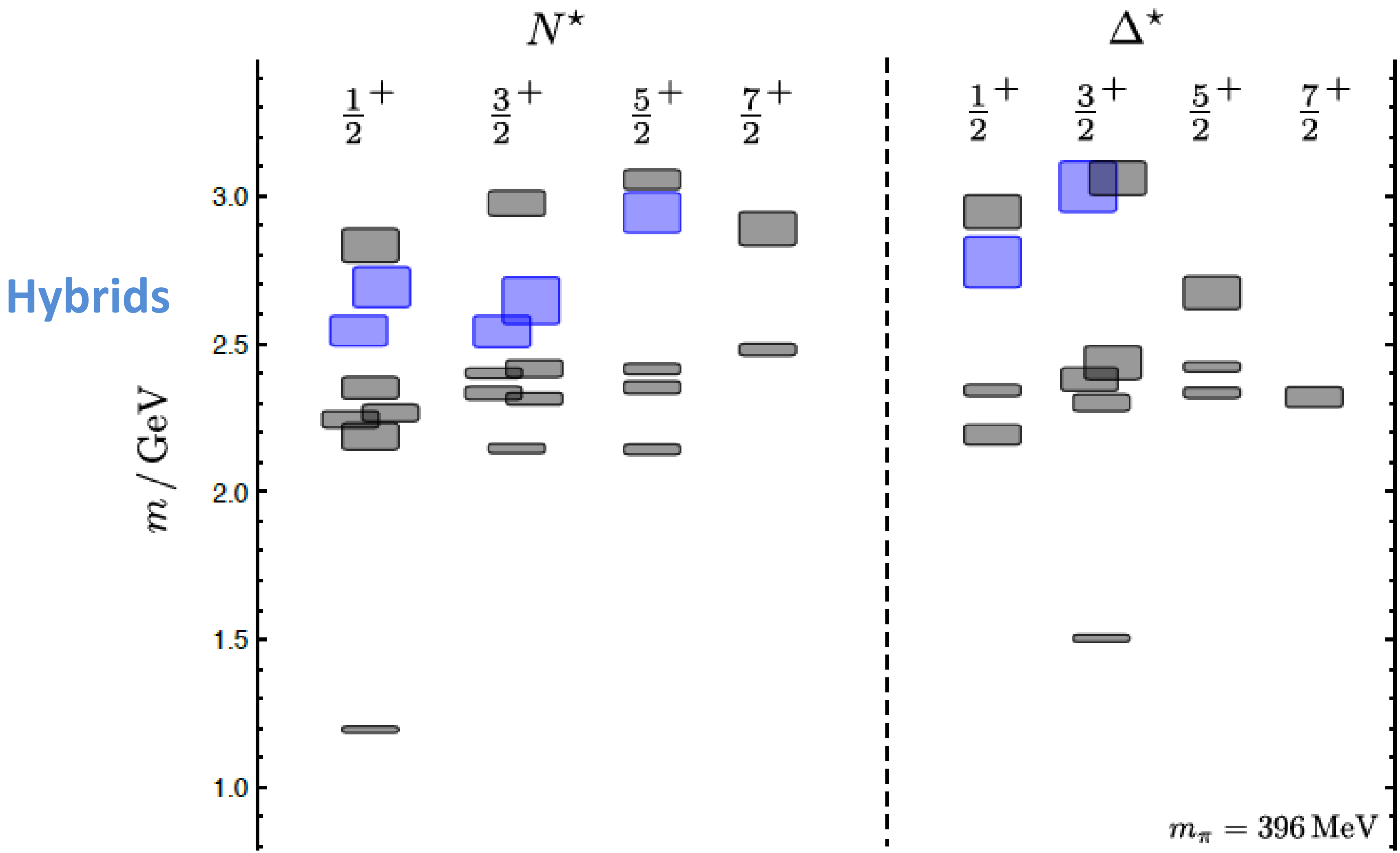
Lattice: heavy meson spectrum



But where are the XYZ states?

The N* Spectrum (lattice QCD)

J.J. Dudek and R.G. Edwards, PRD85 (2012) 054016

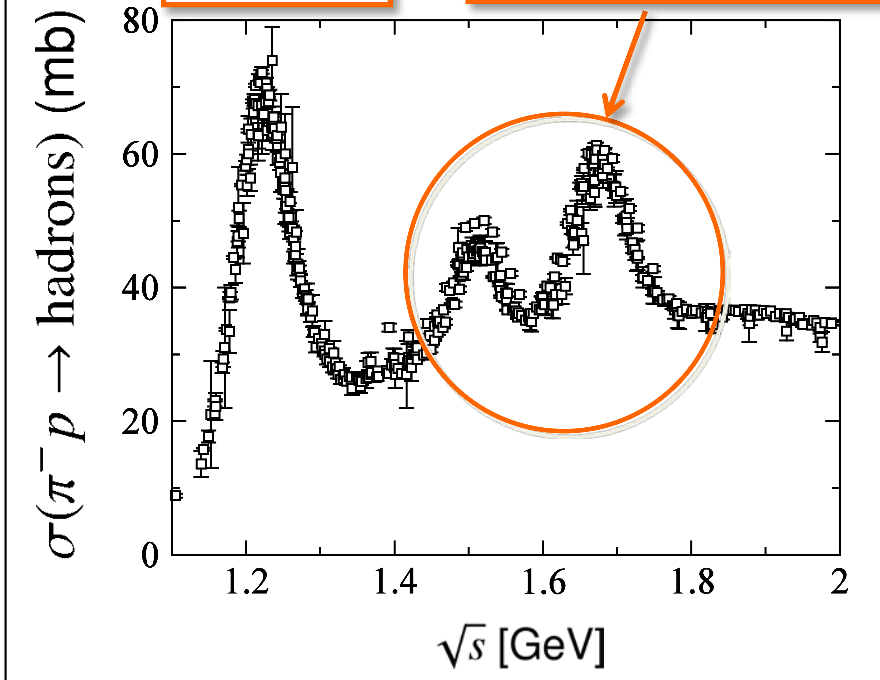


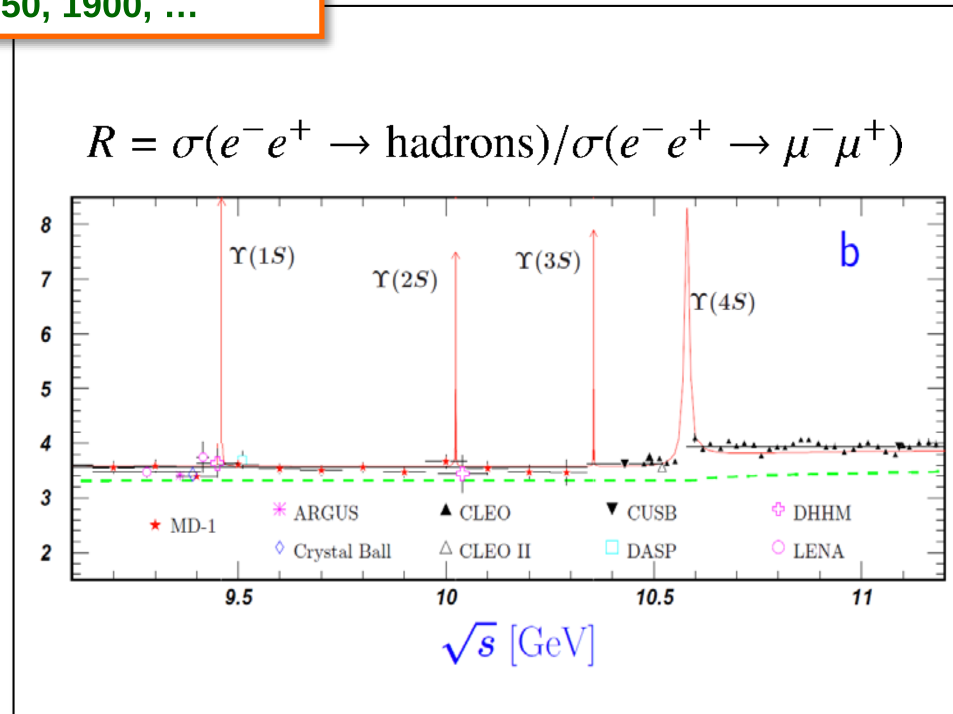
Physics of broad & overlapping resonances

Δ (1232)

N* : 1440, 1520, 1535, 1650, 1675, 1680, ...

Δ : 1600, 1620, 1700, 1750, 1900, …





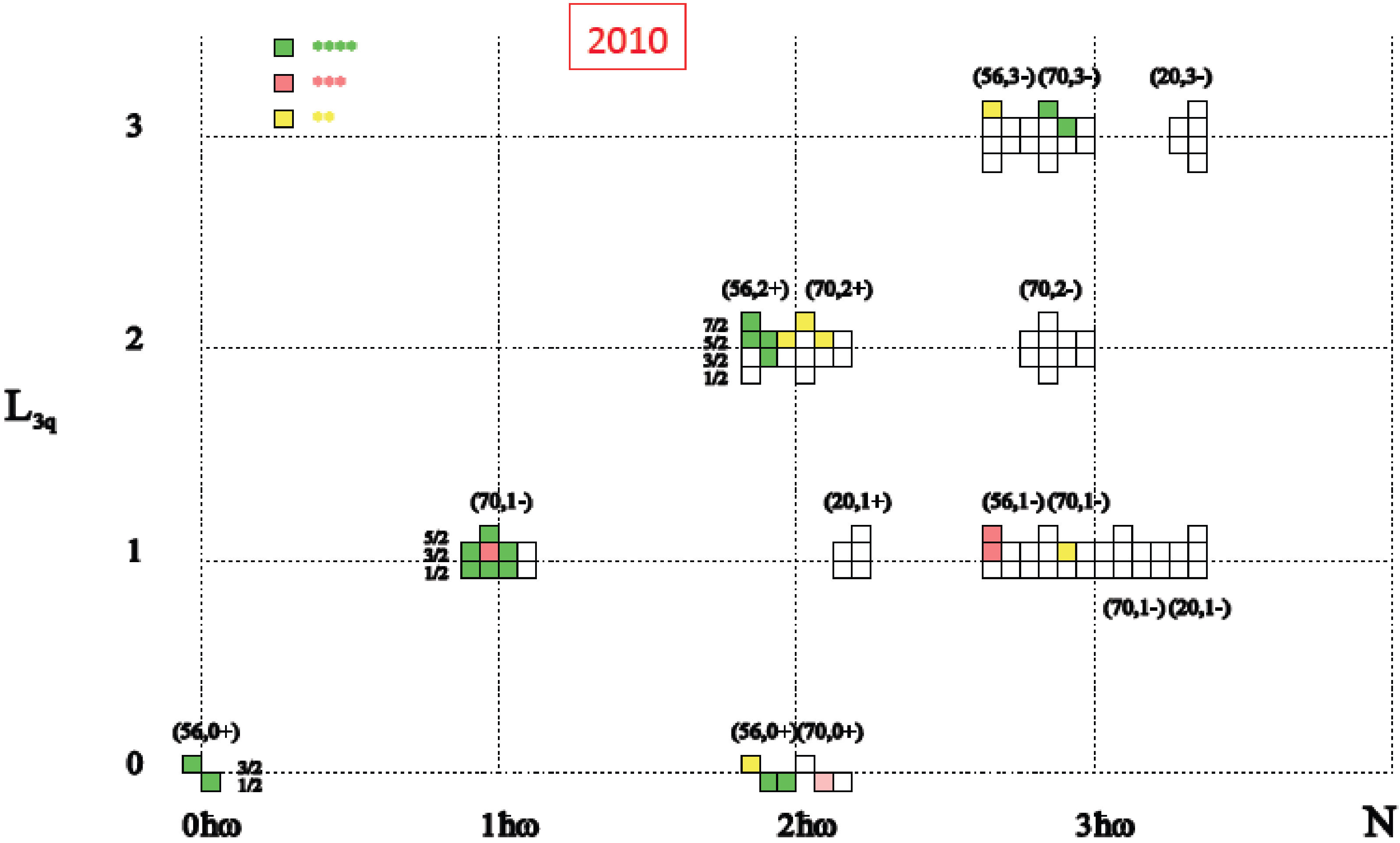
- ✓ **Width: a few hundred MeV.**
- ✓ **Resonances are highly overlapped in energy except Δ(1232).**

→Complex PWA is necessary

- ✓ **Width: ~10 keV to ~10 MeV**
- ✓ **Each resonance peak is clearly separated.**

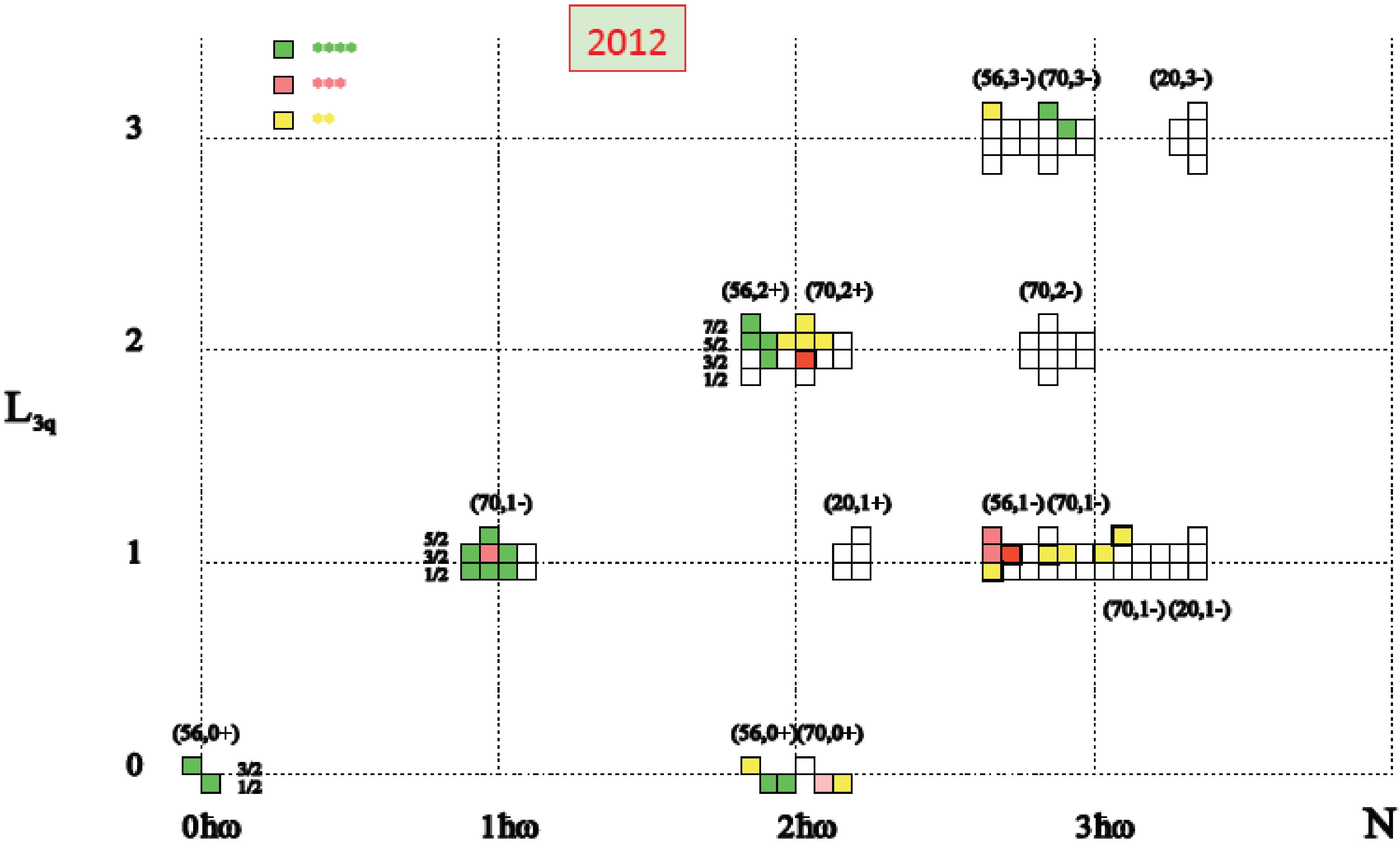
From: H. Kamano, JAEA seminar

Missing Baryon States (2010)



Empty/Yellow boxes are missing/uncertain baryon states.

Missing Baryon States (2012)



Empty/Yellow boxes are missing/uncertain baryon states.

Evidence for new N* states and couplings

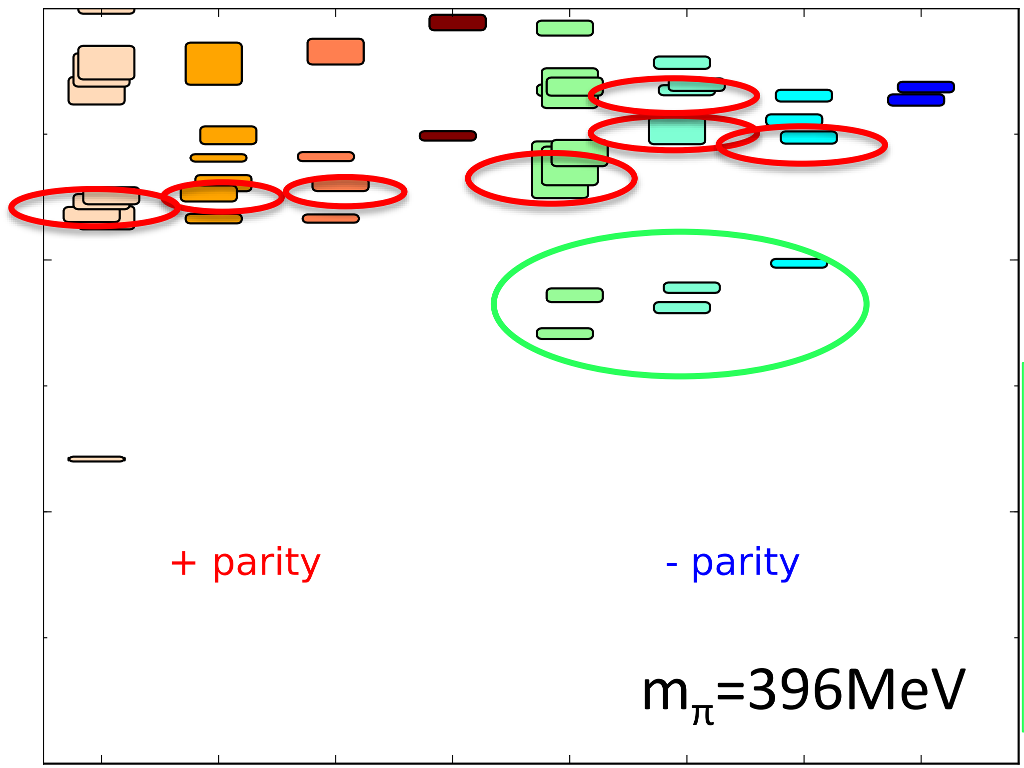
State N((mass)J^P	PDG 2010	PDG 2012	KΛ	KΣ	Nγ
N(1710)$1/2^+$	*** (not seen in GW analysis)	***	***	**	***
N(1880)$1/2^+$		**	**	*	**
N(1895)$1/2^-$		**	**	*	***
N(1900)$3/2^+$	**	***	***	**	***
N(1875)$3/2^-$		***	***	**	***
N(2150)$3/2^-$		**	**		**
N(2000)$5/2^+$	*	***	**	*	**
N(2060)$5/2^-$		***		**	***

Bonn-Gatchina Analysis – A.V. Anisovich et al., EPJ A48, 15 (2012)
(First coupled-channel analysis that includes nearly all new photoproduction data)

Do new states fit into LQCD projections?

R. Edwards et al., Phys.Rev. D84 (2011) 074508

N(1860)5/2$^+$
N(1900)3/2$^+$
N(1880)1/2$^+$



N(2060)5/2$^-$
N(2120)3/2$^-$
N(1875)3/2$^-$
N(1895)1/2$^-$

Known states:
N(1675)5/2$^-$
N(1700)3/2$^-$
N(1520)3/2$^-$
N(1650)1/2$^-$
N(1535)1/2$^-$

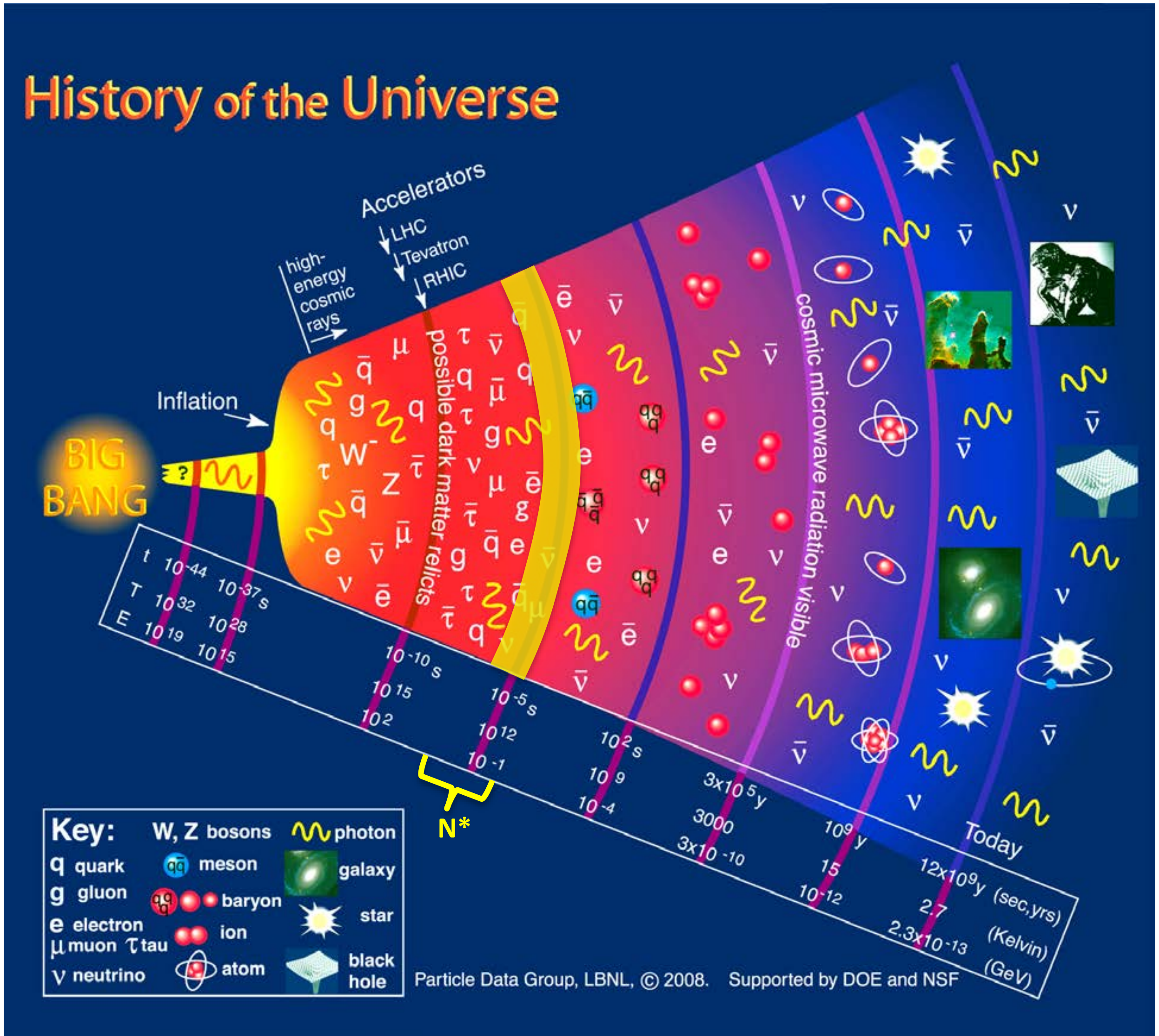
"Roper" state ~ 700 MeV too high

Lowest J$^-$ states ~ 300 MeV too high

Ignoring the mass scale, new candidate states fit with the J^P values predicted from LQCD.

Slide borrowed from V. Burkert.

Excited Baryons in the history of the Universe

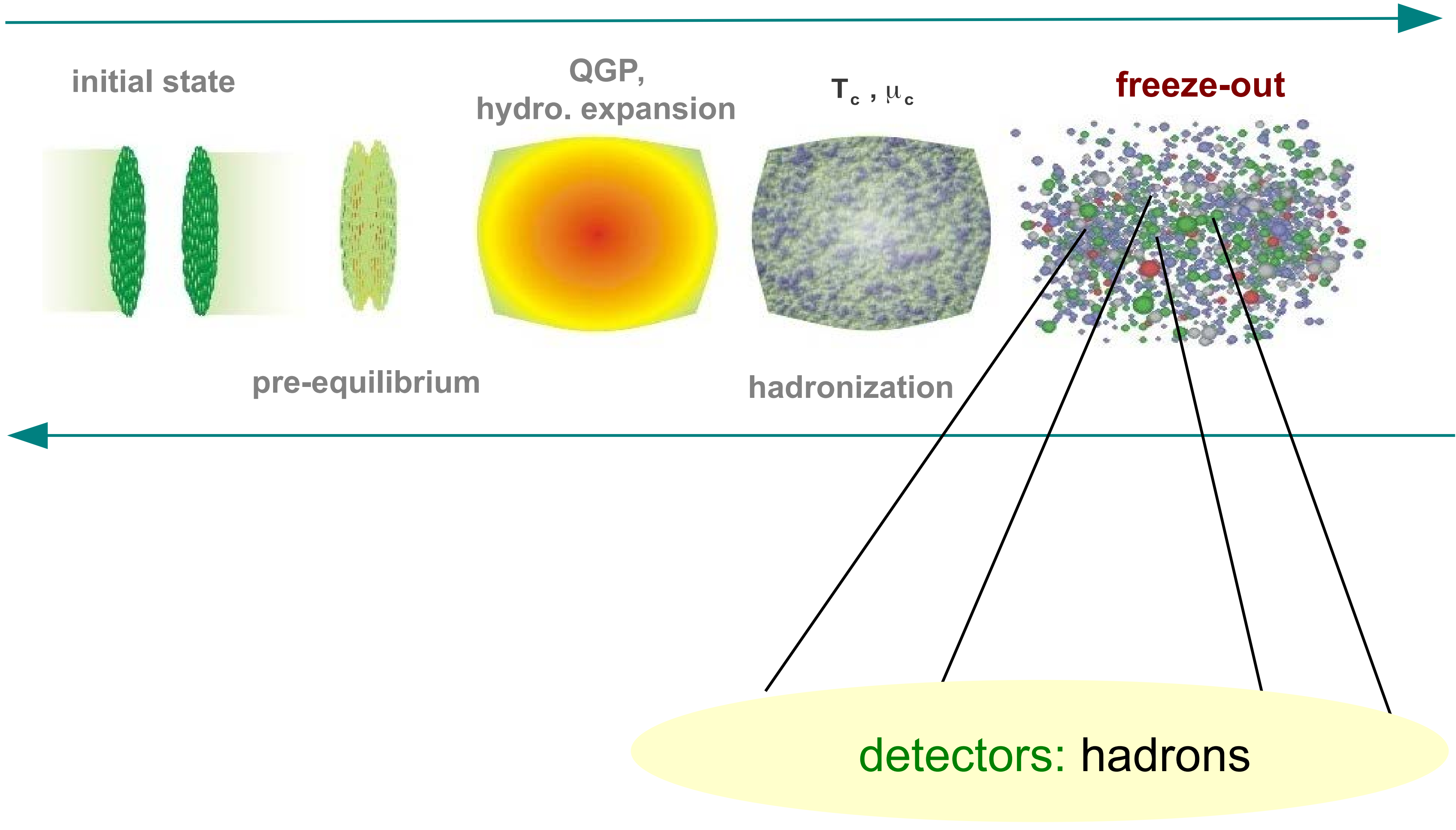


Excited baryons are at the transition between the quark-gluon liquid, described in **hot QCD**, and the confinement of quarks and gluons in nucleons, described in **strong QCD**. This period lasted ~ 10^{-6} seconds.

Do we understand this transition?

Slide borrowed from V. Burkert.

Heavy-ion collisions: a sketch



freeze-out stage

' in HIC

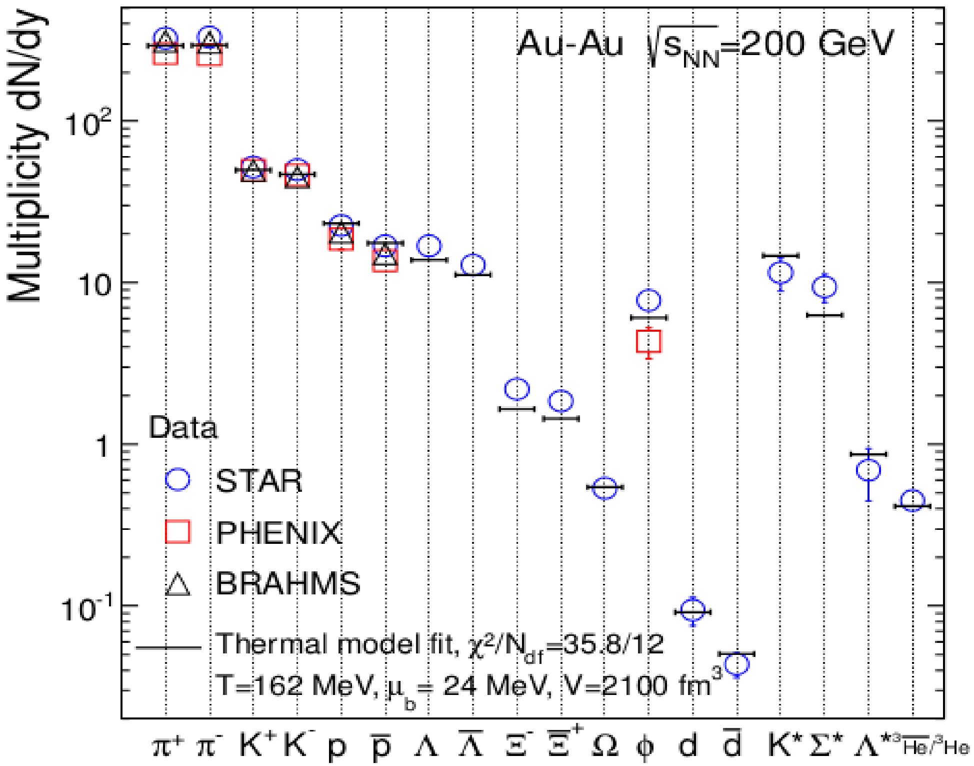
Slide borrowed from S. Mukherjee.

ons yields at the freeze-out

well described by: Hadron Resonance Gas (HRG)

thermal gas of uncorrelated hadrons with vacuum masses

thermal abundance of hadrons



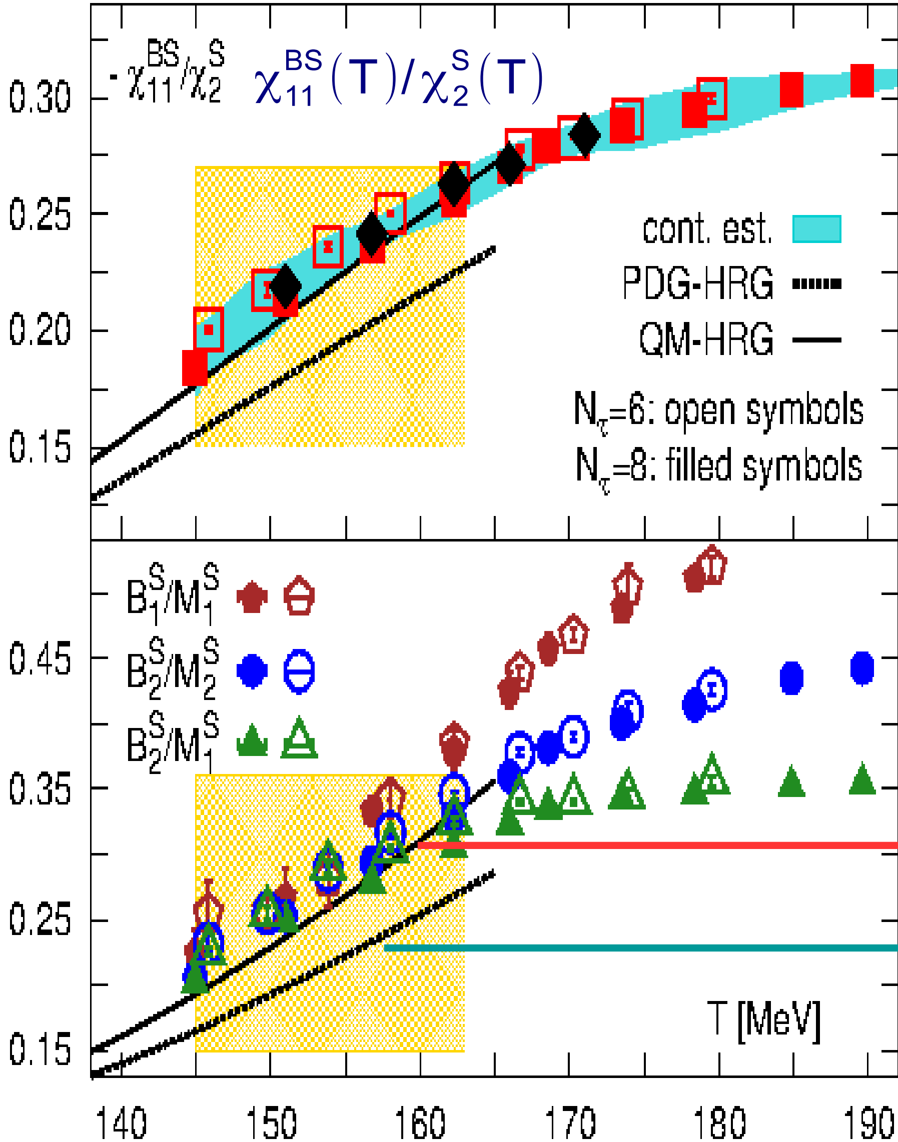
$$\left(T^f, \mu_B^f, \mu_Q^f, \mu_S^f\right)$$

Slide borrowed from S. Mukherjee.

Thermodynamic contributions of additional strange baryons

relative contributions of strange baryons to strange mesons

BNL-Bi: Phys. Rev. Lett. 113 (2014) 072001



$$M^S_1 = \chi^S_2 - \chi^{BS}_{22}$$

$$+\frac{1}{3}\left(4\,\chi^{BS}_{11} - \chi^{BS}_{13}\right)$$

+ undiscovered strange baryons

contributions of all expt. observed strange hadrons

Slide borrowed from S. Mukherjee.

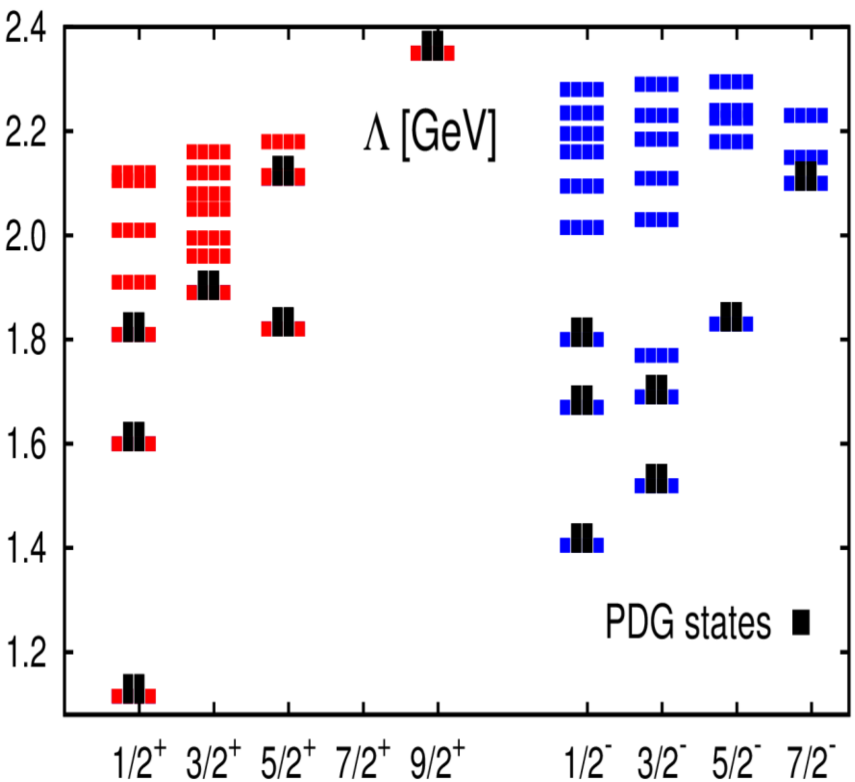
Probing hadron spectrum using thermodynamics

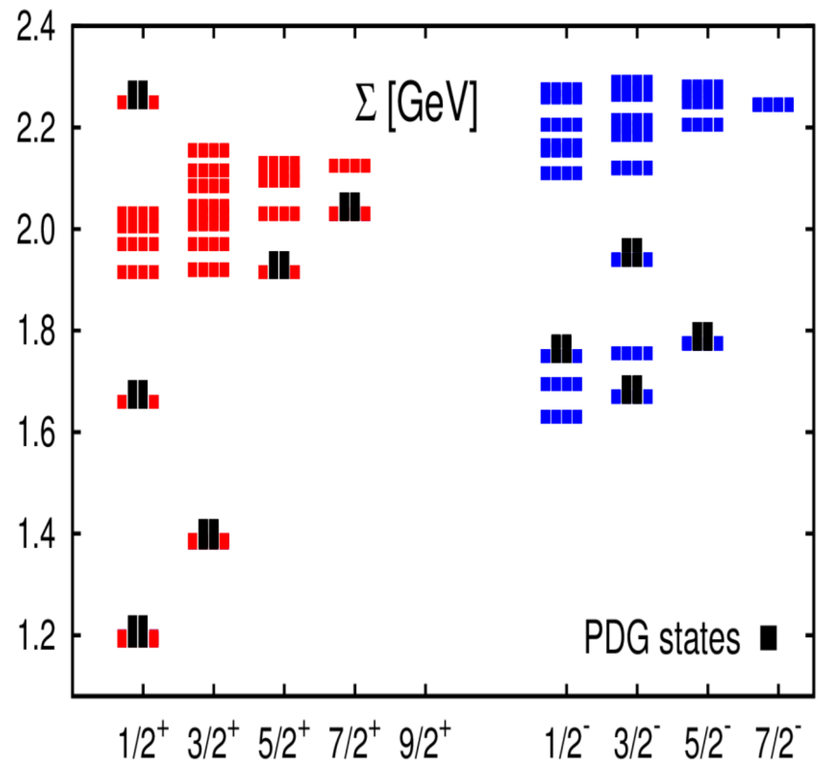
hadronic pressure: $P^S = \sum_{h \in \text{all hadrons}} P_h$

expt. observed hadrons
+ unobserved ones

Quark Model

strange baryons

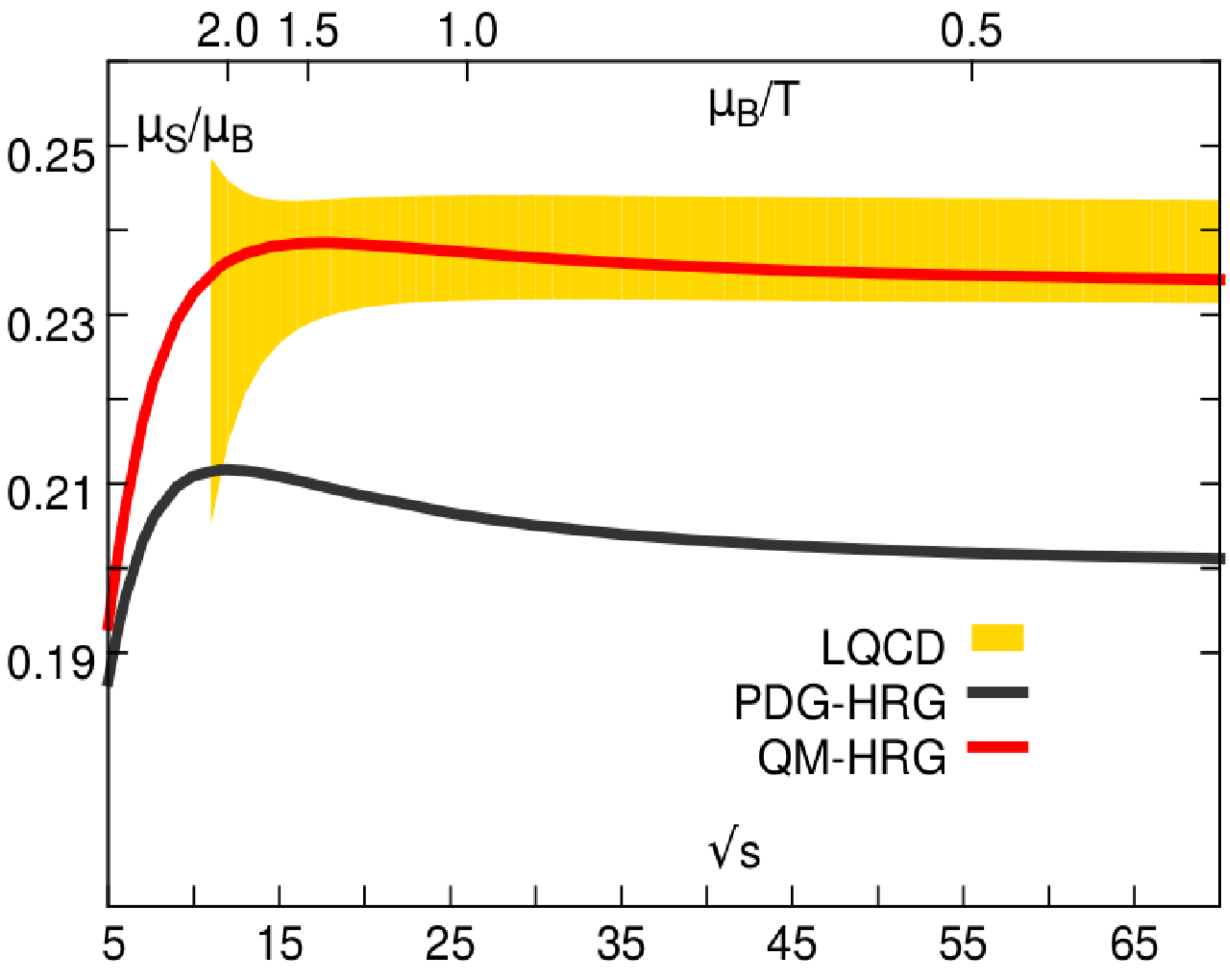




Capstick-Isgur: Phys. Rev. D34, 2809 (1986)

Slide borrowed from S. Mukherjee.

Additional strange hadrons & RHIC BES



signature for unobserved strange baryons persists for RHIC BES-II

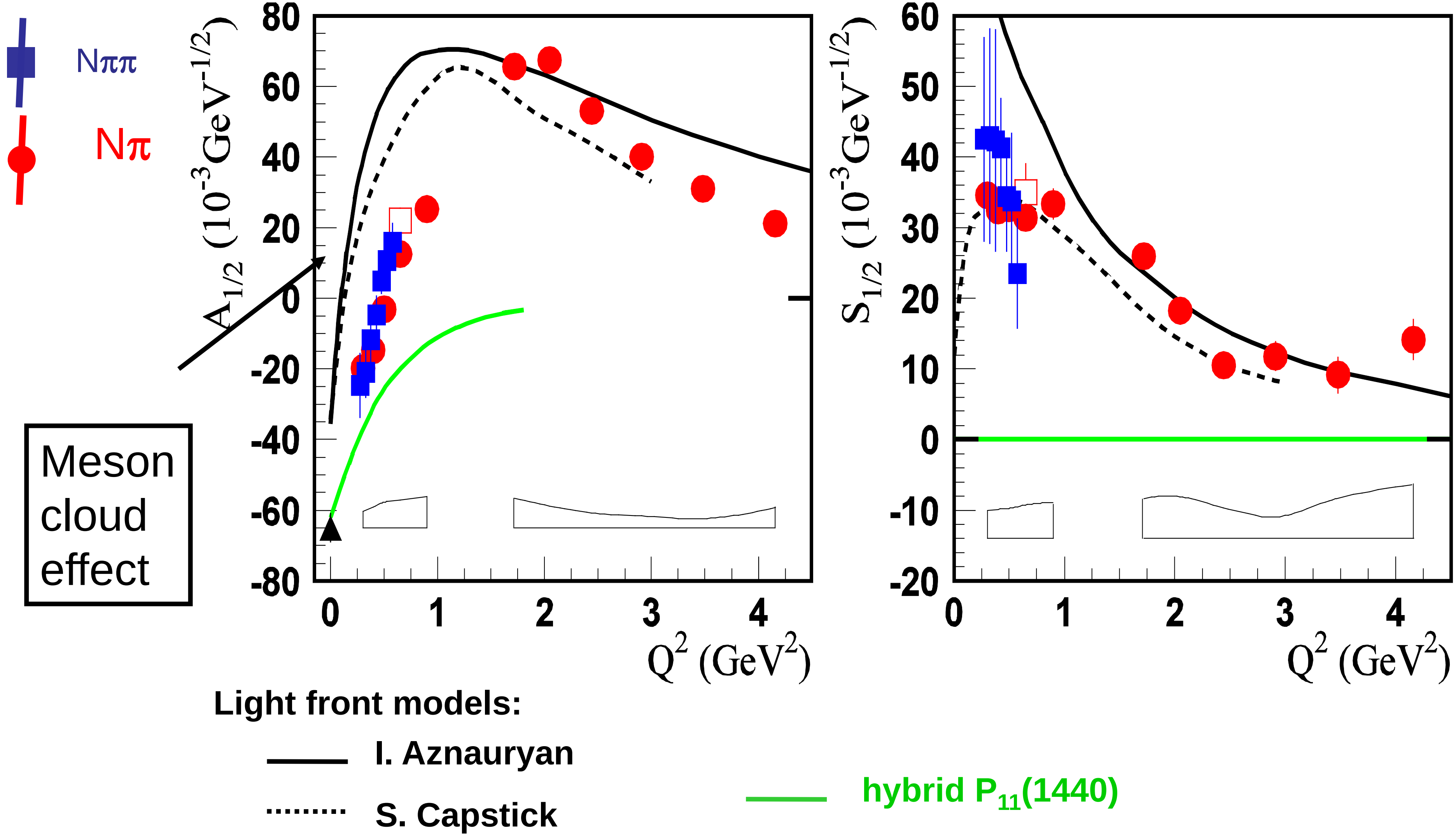
Summary of Introduction

- Both Lattice QCD and the quark model predict more resonances than have been detected.
  - Some of these are expected to couple strongly to two-pion decay, to be measured at E45.
- Theoretical tools to extract N*’s are improving
  - PWA from both ANL-Osaka and BoGa fine new N*
- Data from QCD freeze-out suggest more Y*’s
  - L(1405) decays asymmetric
  - Possible effect on n/p ratio in the early universe.

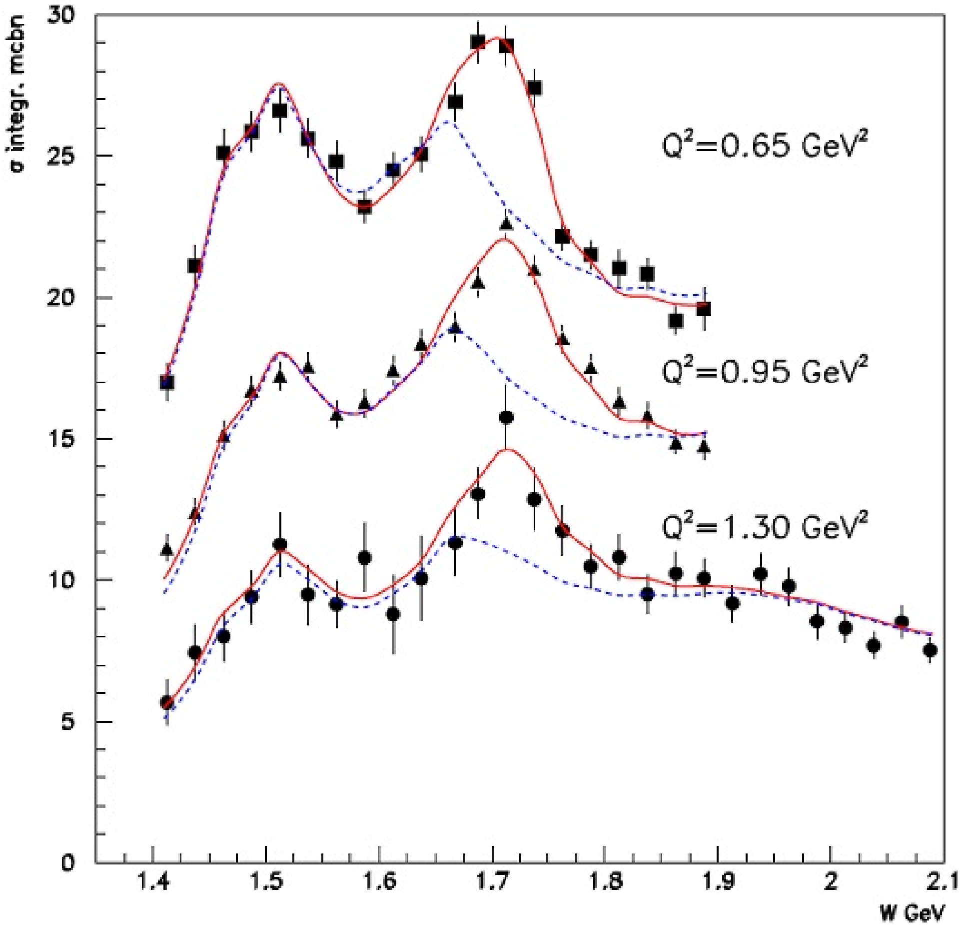
A Tale of Two Labs

- 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.
  - Of course, other labs also share this interest.
- It is becoming clear that both hadronic and photoproduction data are needed due to coupled-channels effects that naturally link them together.

$P_{11}(1440)$ couplings from CLAS



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



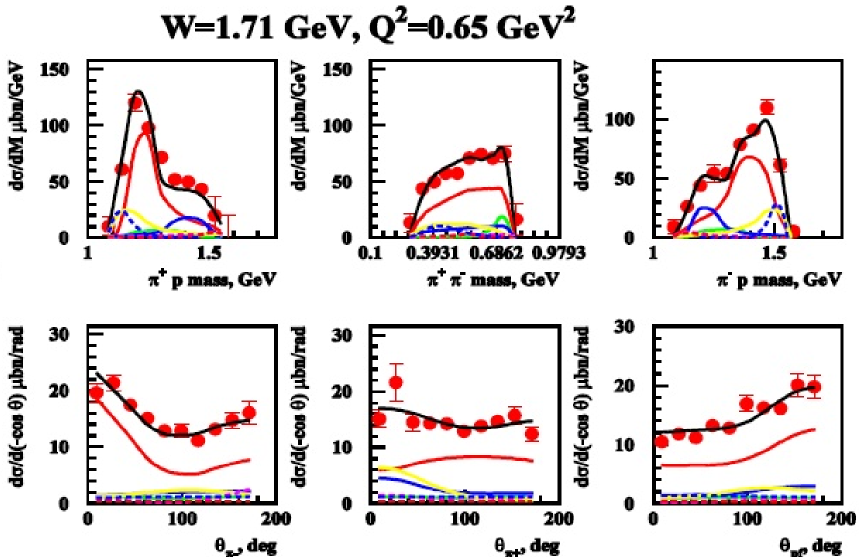
The BLUE dotted curve uses only the known resonances from the Particle Data Group.

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

	M, GeV	Γ_{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



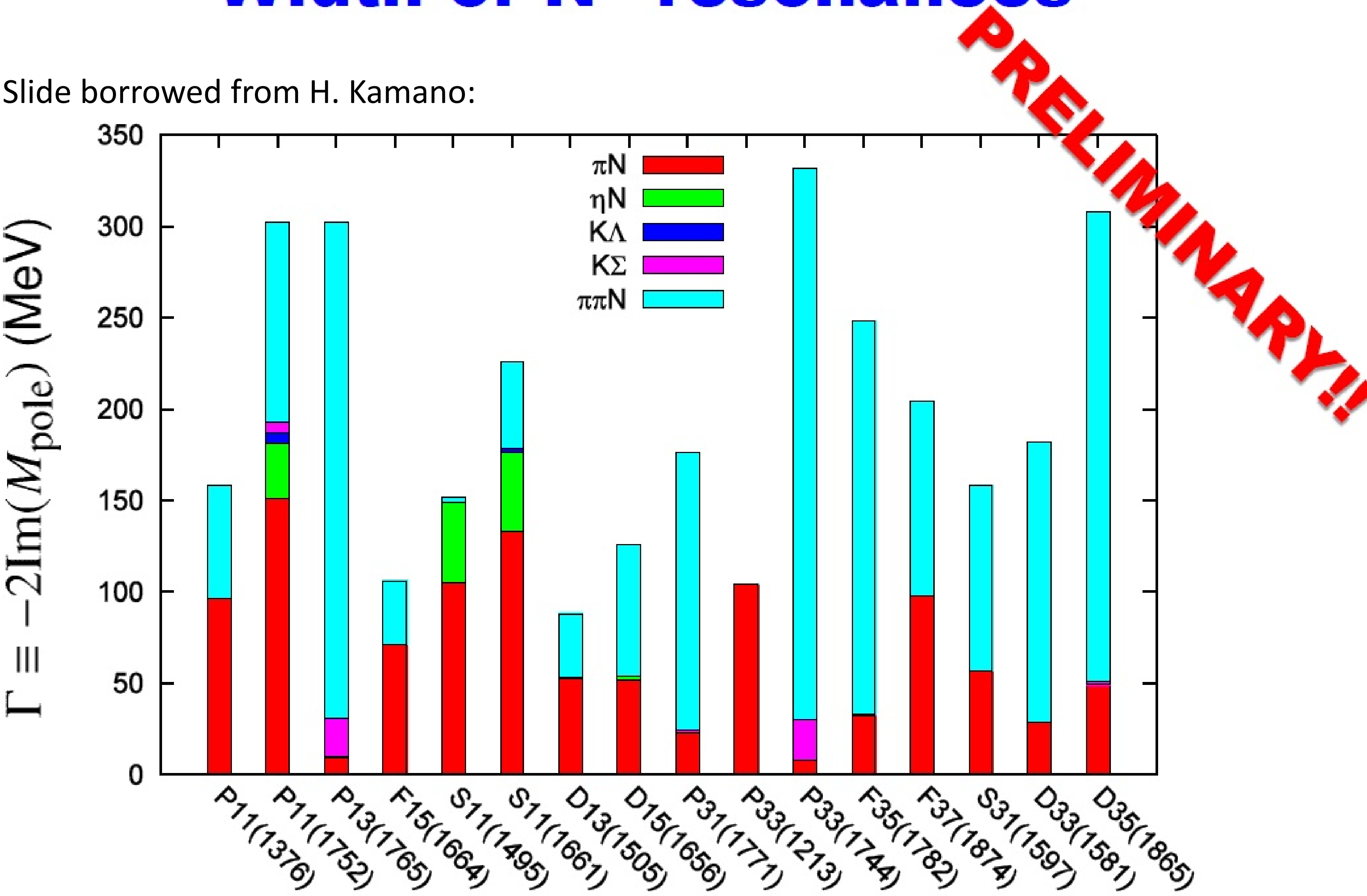
hadronic parameters of $3/2^+(1725)$ candidate state as well as of others N*'s were varied within PDG uncertainties - $2.78<\chi^2/\text{d.p.}<2.9$

	M, GeV	Γ_{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.

Width of N* resonances

Slide borrowed from H. Kamano:

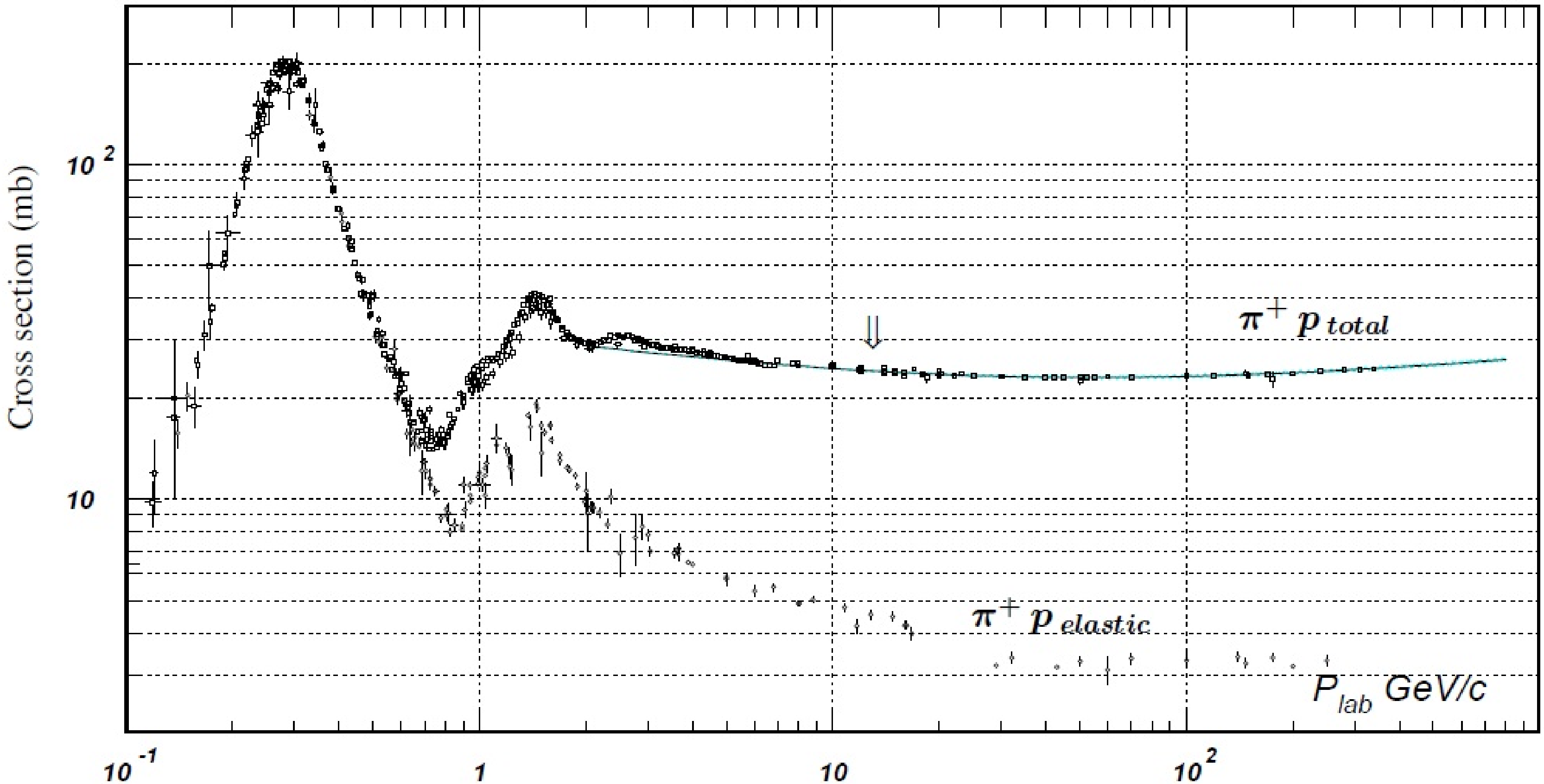


What data do we need?

- 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.

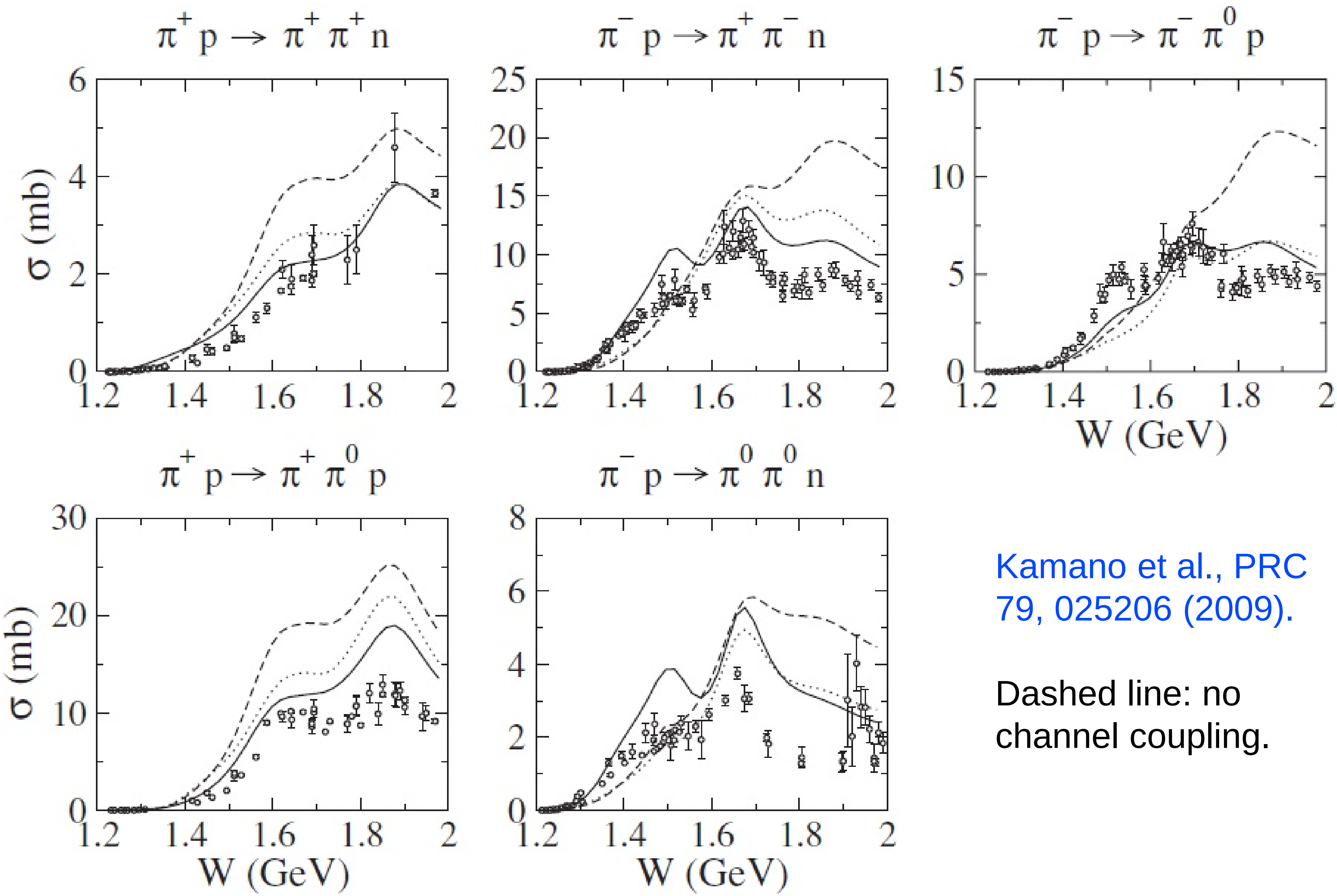
π-N Total Cross Sections

Copied from the PDG's Review of Particle Properties:



Most of the difference between total and elastic is due to multiple-pions

ππN Total Cross Sections



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

Dashed line: no channel coupling.

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

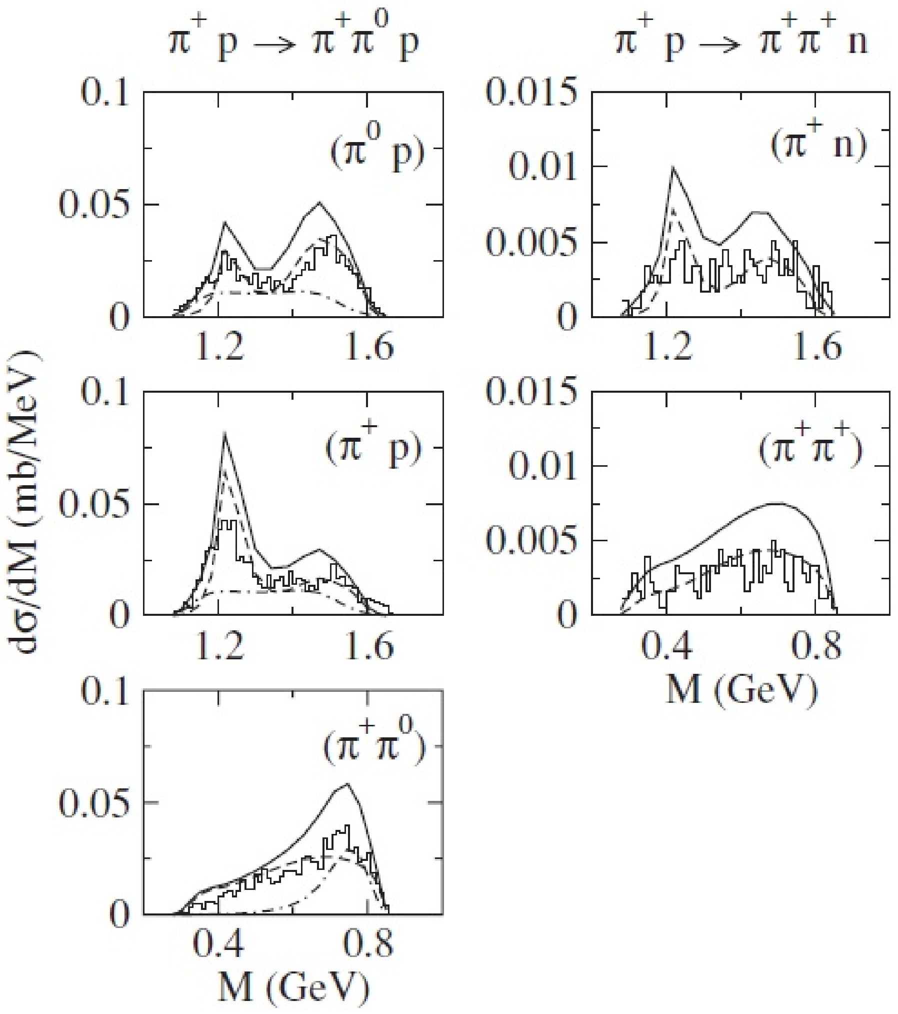
M. Manley, Phys. Rev. D 30, 904 (1984).

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



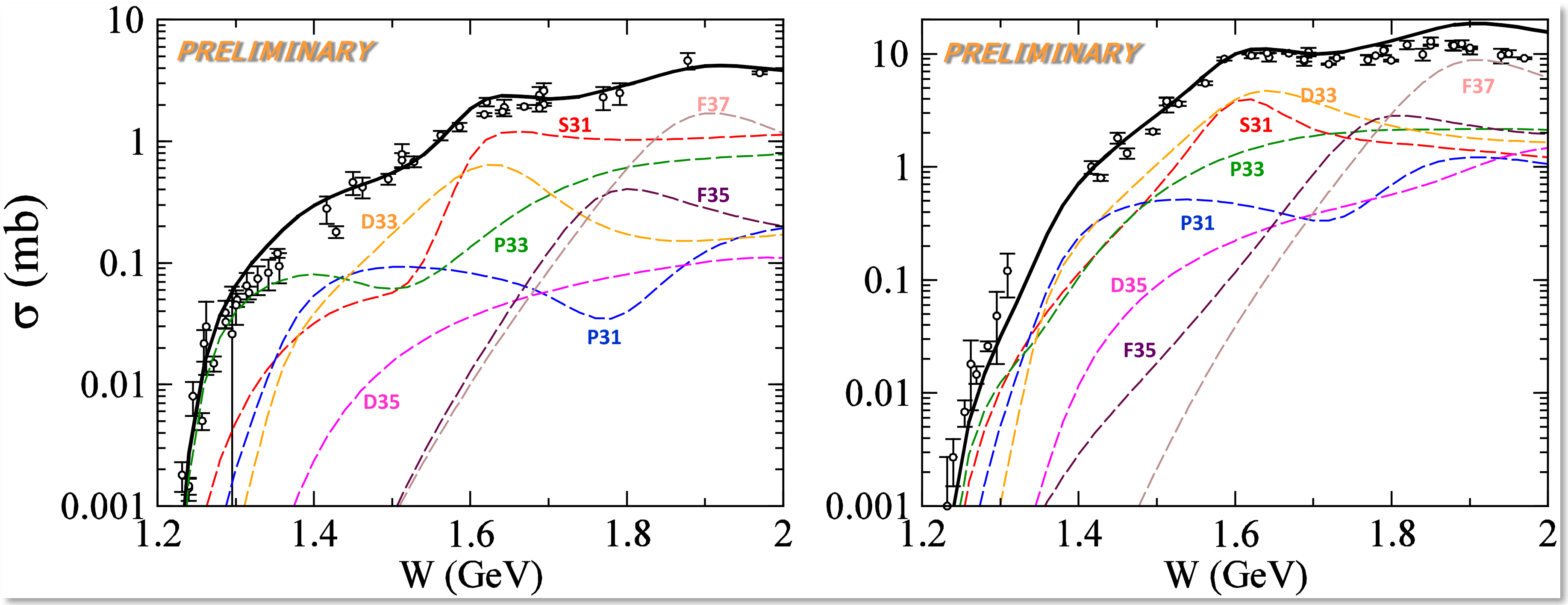
Note: the normalization of these data is not known. The total cross sections were used to set the vertical scale.

The solid curves are the full calculation using only πN elastic data. The other curves are for partial contributions from ρ and Δ isobars.

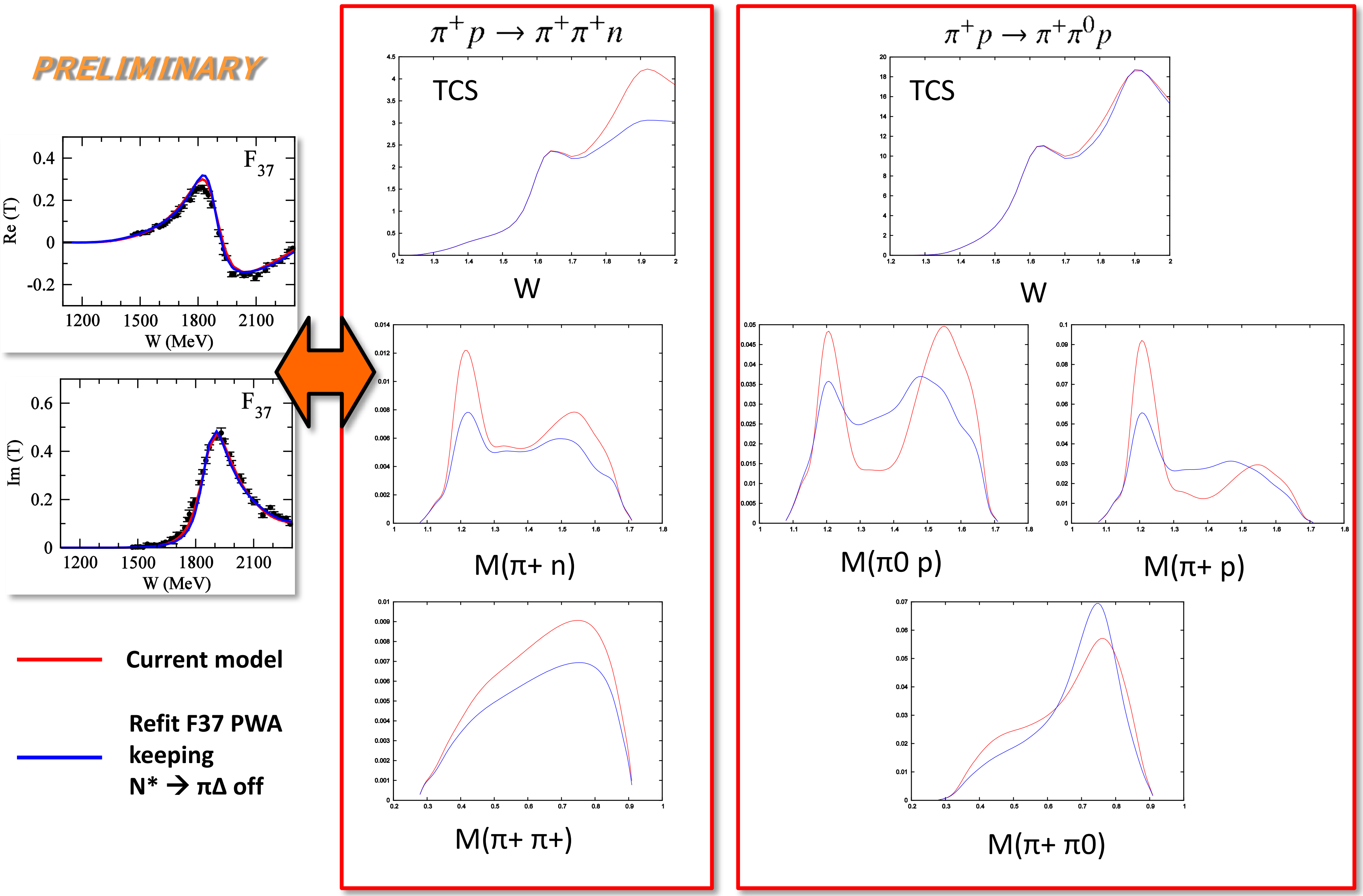
N* contributions to (π,2π)

Calculations by H. Kamano:

$\pi^+ p \to \pi^+ \pi^+ n$ $\qquad\qquad$ $\pi^+ p \to \pi^+ \pi^0 p$

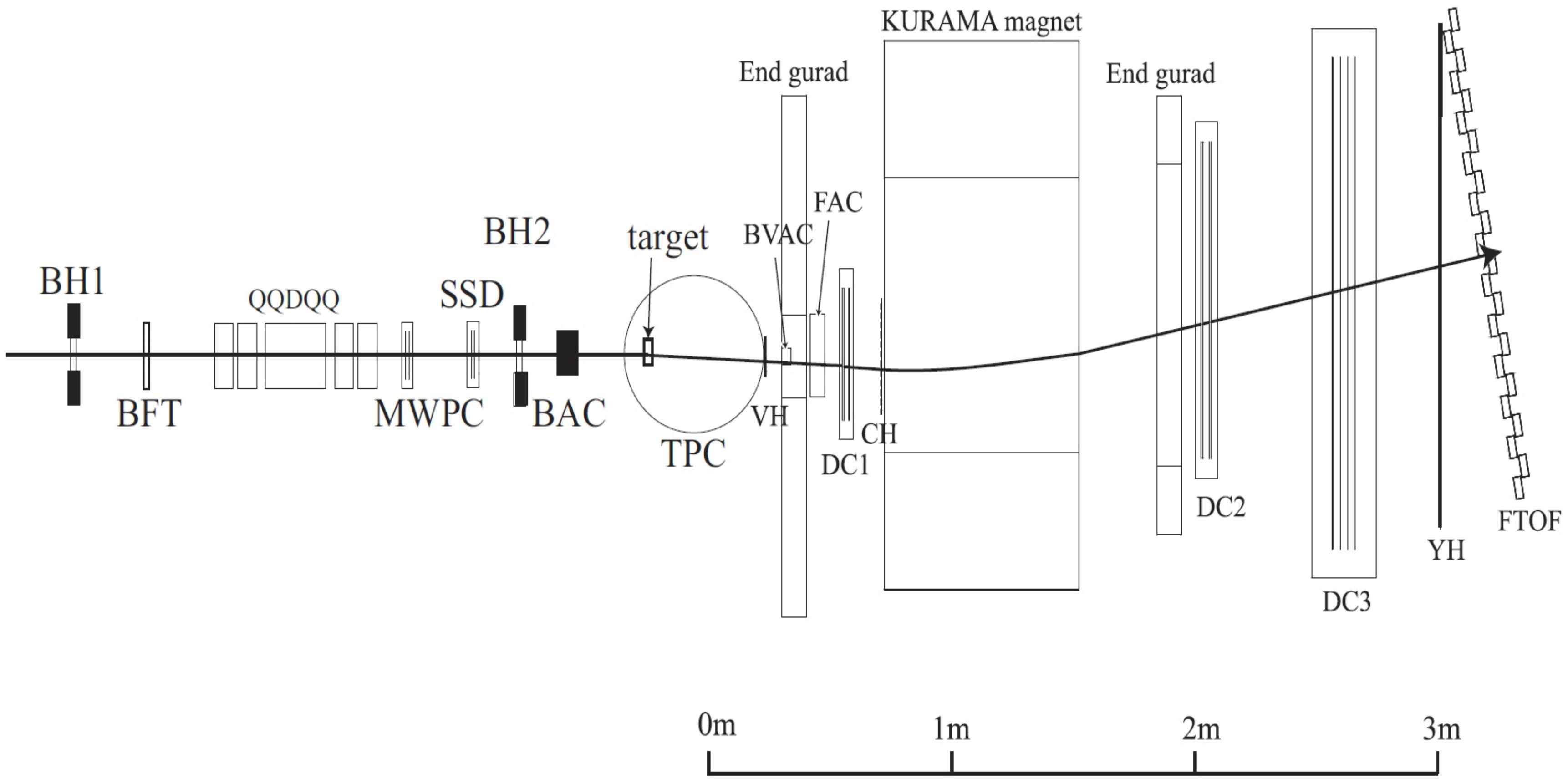


This is one of only several possible PWA fits.


PRELIMINARY
F37
Re (T)
W (MeV)
Im (T)
$\pi^+ p \to \pi^+\pi^+ n$
$\pi^+ p \to \pi^+\pi^0 p$
TCS
W
M(π+ n)
M(π+ π+)
M(π0 p)
M(π+ p)
M(π+ π0)
Current model
Refit F37 PWA
keeping
N* → πΔ off

J-PARC Experiment

K1.8 beamline with TPC



Experimental Setup for E42/E45
Hyp-TPC Spectrometer

Measure $(\pi,2\pi)$ in large acceptance TPC

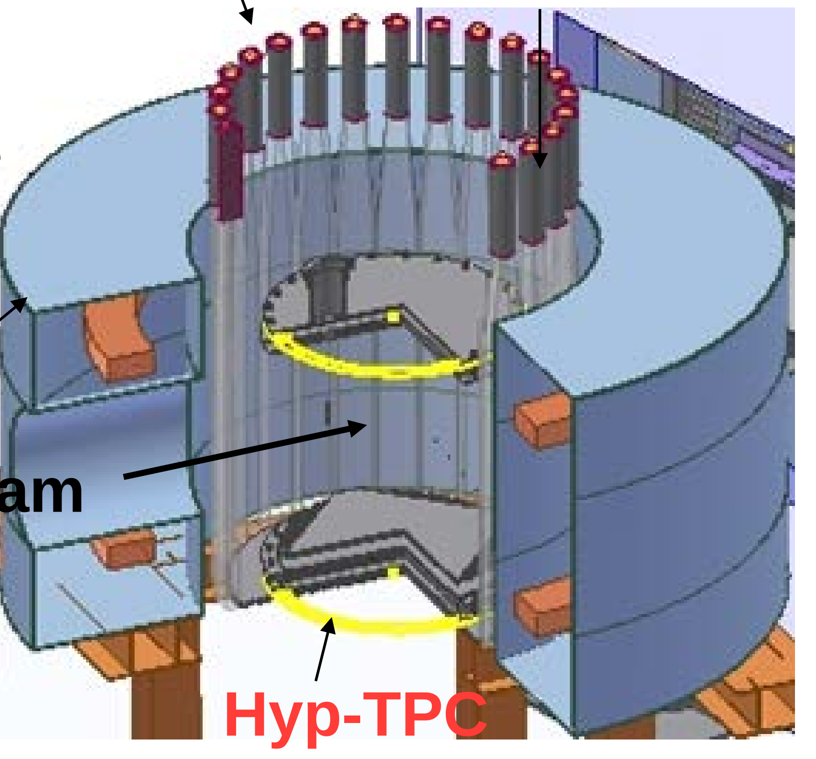
$\pi^- p \rightarrow \pi^+ \pi^- n,\ \pi^0 \pi^- p$

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

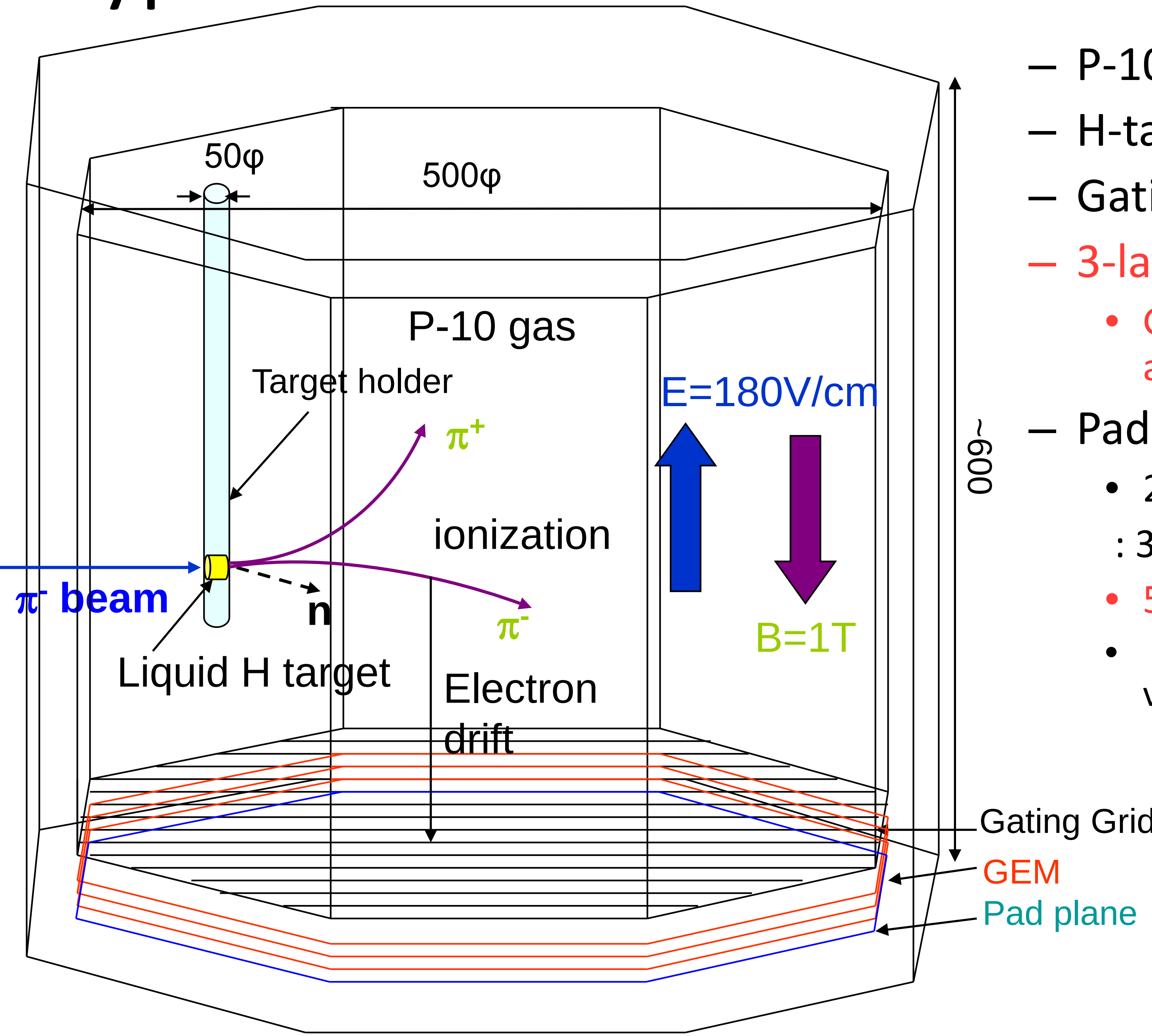
π^{+-} *beam ~ 1M/spill (p=0.6-2.0 GeV/c)*

Liquid-proton target

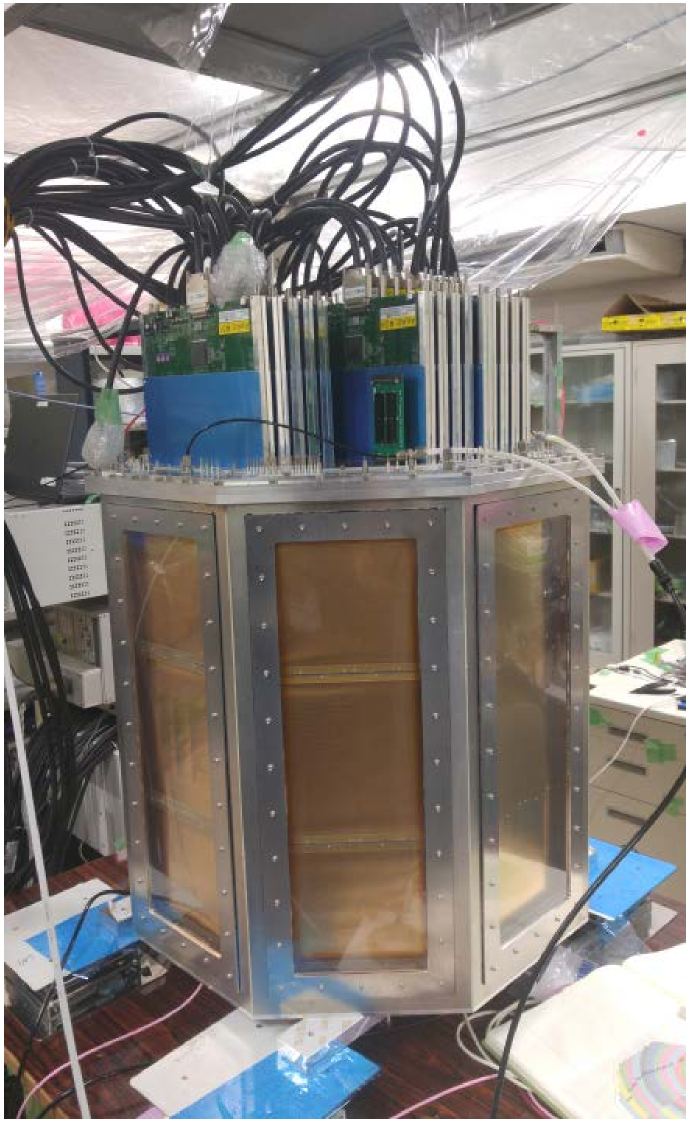
Trigger: Two charged particles in hodoscope

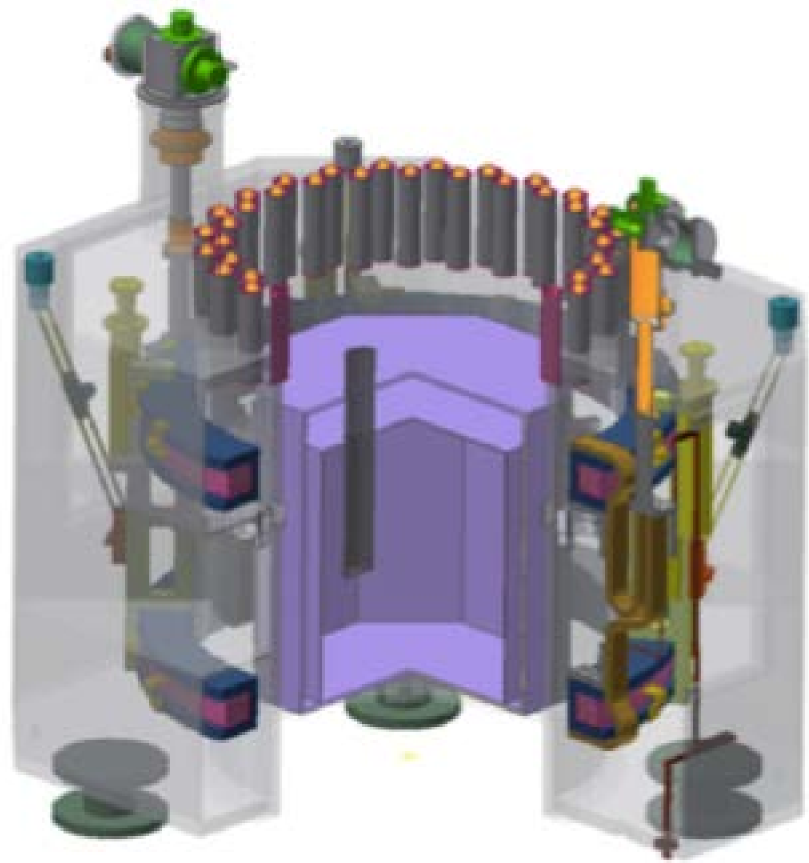


Hyp-TPC from E42 can be modified



- P-10 gas
- H-target in TPC
- Gating grid wires
- 3-layer GEM
  - Good performance at high beam rates
- Pad size
  - 2.5 x 9~13 mm
  - : 30 layers
  - 5045 pads in total
  - π/K/p PID with dE/dx vs p





Expected statistics

Total $(\pi,2\pi)$ cross section : ~2 mb
Pion beam rate : ~10^6 (per 6 second spill)
5cm thick Liquid Hydrogen target
TPC acceptance of 50%
Result: 200 events / spill

Energy coverage: W=1.50 – 2.15 GeV
26 energy bins(ΔW=0.025)
20 angle bins
10K events / bin
Result: 24M events in 45 shifts (2 months)

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.
- My opinion: without quality $(\pi, 2\pi)$ data, it is difficult to see how the N* spectrum can be extracted with PWA techniques.