Topics in Baryon Spectroscopy and Structure

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Overview

- Introduction, Multiplets, SU(6)xO(3)
- Analysis Tools, Equipment
- Electromagnetic Excitation of the Δ(1232)
- Structure of the Roper and other lower mass resonances.
- “Missing” Resonances
- Exotic Baryons (Pentaquarks)

I

II

III

Why N*'s are important

Nathan Isgur, N*2000 Conference

- Nucleons represent the real world, they must be at the center of any discussion on

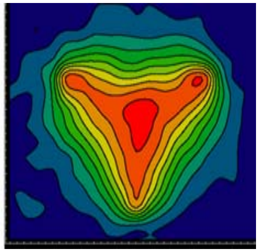
"why the world is the way it is"

- Nucleons represent the simplest system where

"the non-abelian character of QCD is manifest"

3-gluon vertex

Gluon flux simulation of a 3-quark system.



- Nucleons are complex enough to

"reveal physics hidden from us in mesons"

Gell-Mann & Zweig - Quark Model: 3 x 3 x 3 = 10 + 8 + 8 + 1

O. Greenberg - The Δ^{++} problem and "color"

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)

Phys. Rev. 85, 936 (1952)

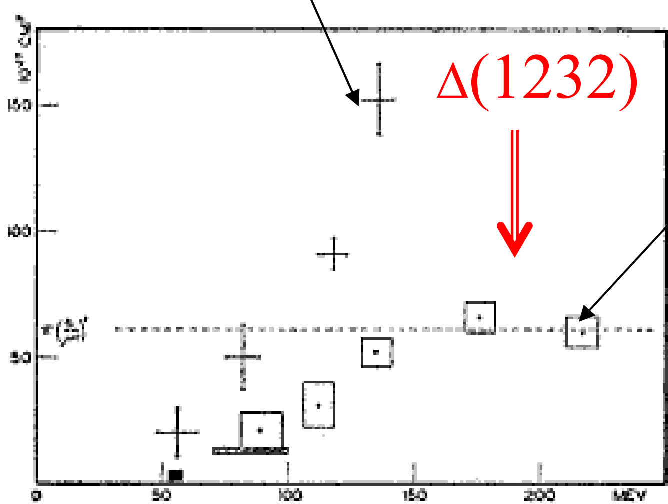
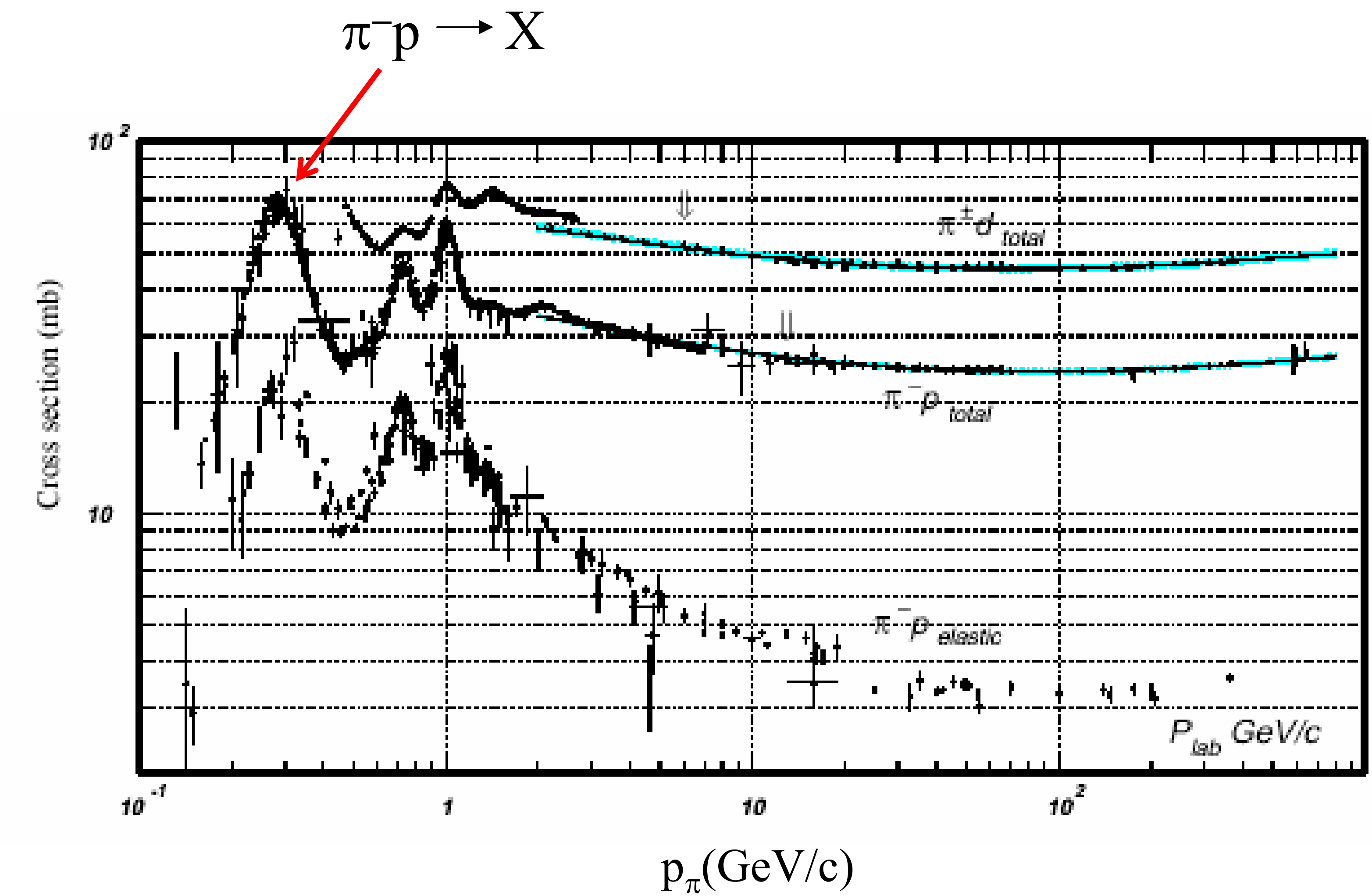


FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

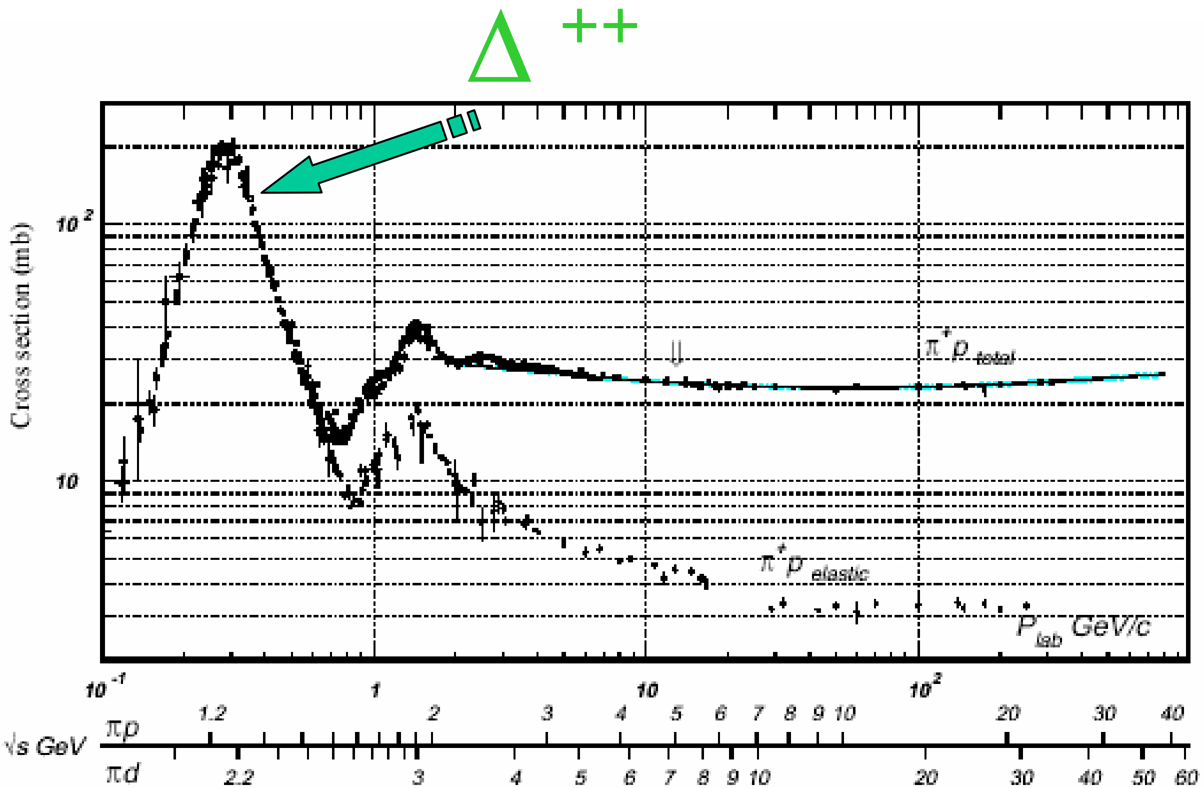
Besides the angular distribution, another important factor is the energy dependence. Here the theoretical expectation is that, if there is only one dominant intermediate state of spin 3/2 and isotopic spin 3/2, the total cross section of negative pions should at all points be less than $(8/3)\pi\lambda\!\!\!^{-2}$. Apparently, the experimental cross section above 150 Mev is larger than this limit, which indicates that other states contribute appreciably at these energies. Naturally, if a single state were dominant, one could expect that the cross sections would go through a maximum at an energy not far from the energy of the state involved. Unfortunately, we have not been able to push our measurements to sufficiently high energies to check on this point.

An energy excitation spectrum indicates that the proton has a substructure. This was two years later confirmed in elastic ep scattering by Hofstadter.

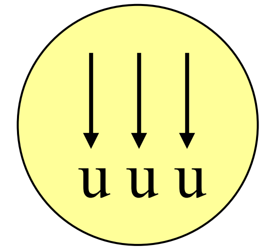
Total cross sections (PDG2004)



The $\Delta^{++}(1232)$ leads to "color"



Δ^{++}

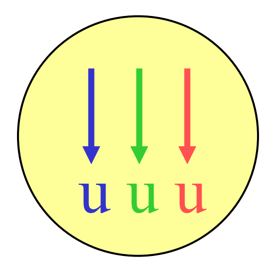


$$\Psi_s = \Psi_{flavor}\Psi_{spin}$$

O. Greenberg introduces a new quantum number to get asymmetric w.f.

$$\Psi_{as} = \Psi_{flavor}\Psi_{spin}\Psi_{color}$$

Δ^{++}

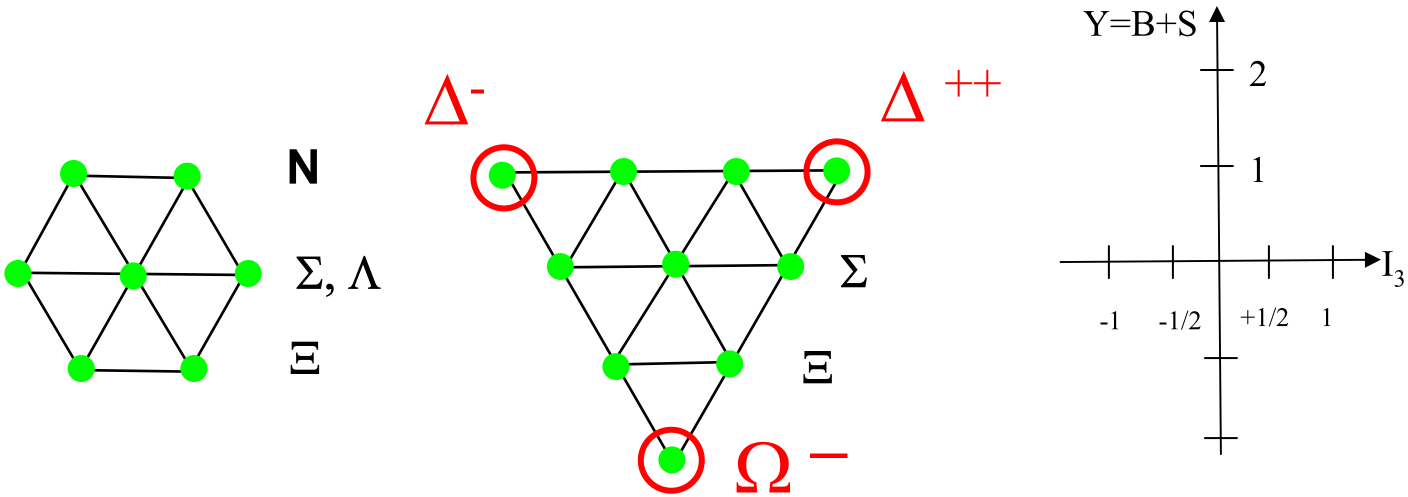


$\pi^+ p \longrightarrow \Delta^{++}$
is the largest πN cross section, but the Δ^{++} state is not allowed in CQM w/o color.

Baryon multiplets

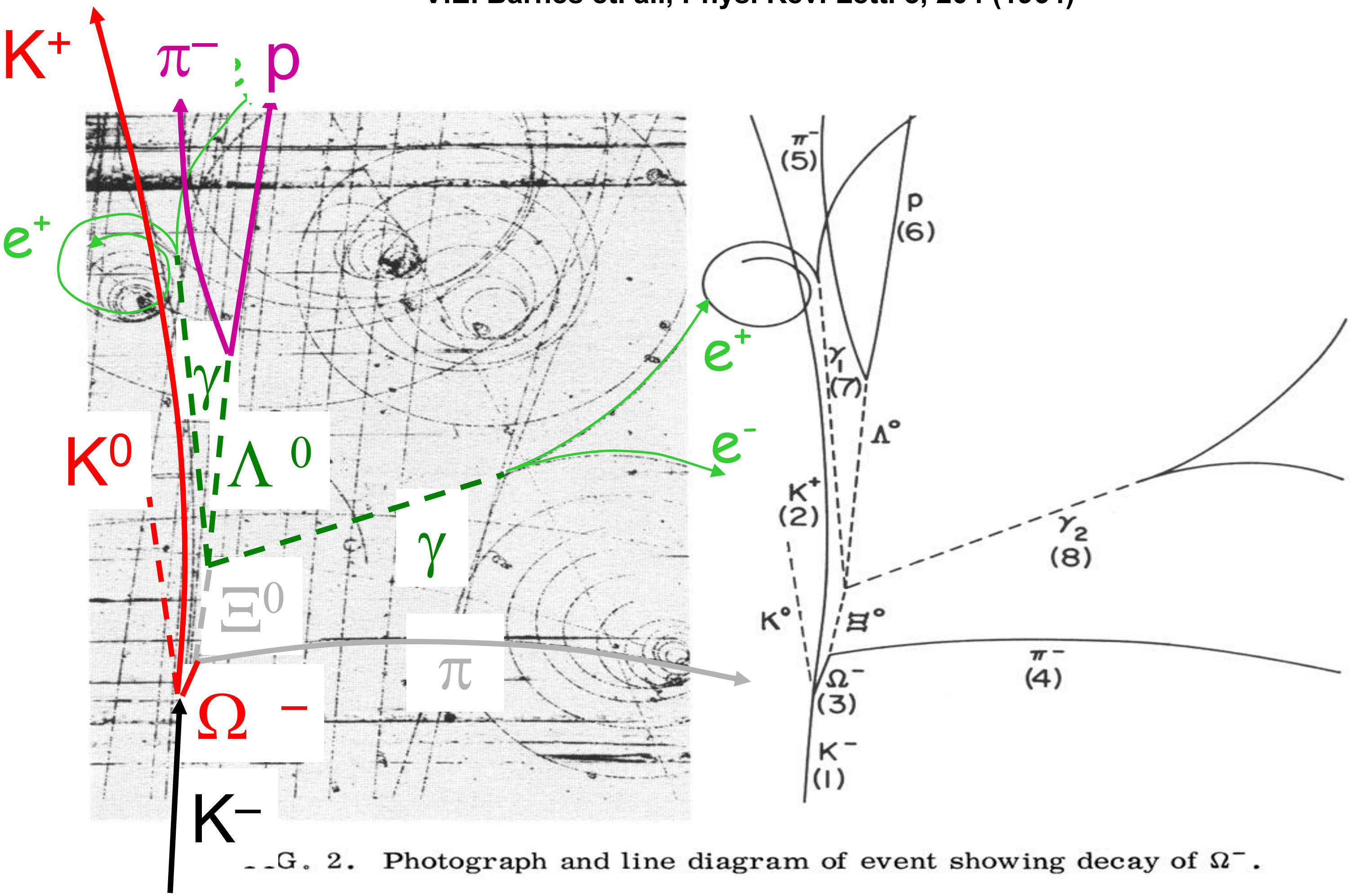
Baryons qqq

$$3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$$



Production and decay of $\Omega \rightarrow \Xi\,\pi$

V.E. Barnes et. al., Phys. Rev. Lett. 8, 204 (1964)



..G. 2. Photograph and line diagram of event showing decay of Ω^-.

Baryon Resonances and SU(6)xO(3)

|Baryon> : α |qqq> + β |qqq($q\bar{q}$)| + γ |qqqG> + ..

Lectures by F. Close

3 Flavors: {u,d,s} $\longrightarrow$ SU(3)

{qqq}: $\mathbf{3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1}$

Quark spin $s_q = ½$ $\longrightarrow$ SU(2)

{$\vec{q}\vec{q}\vec{q}$ }: $\mathbf{6 \otimes 6 \otimes 6 = 56 \oplus 70 \oplus 70 \oplus 20}$

SU(6) multiplets decompose into flavor multiplets:

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

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

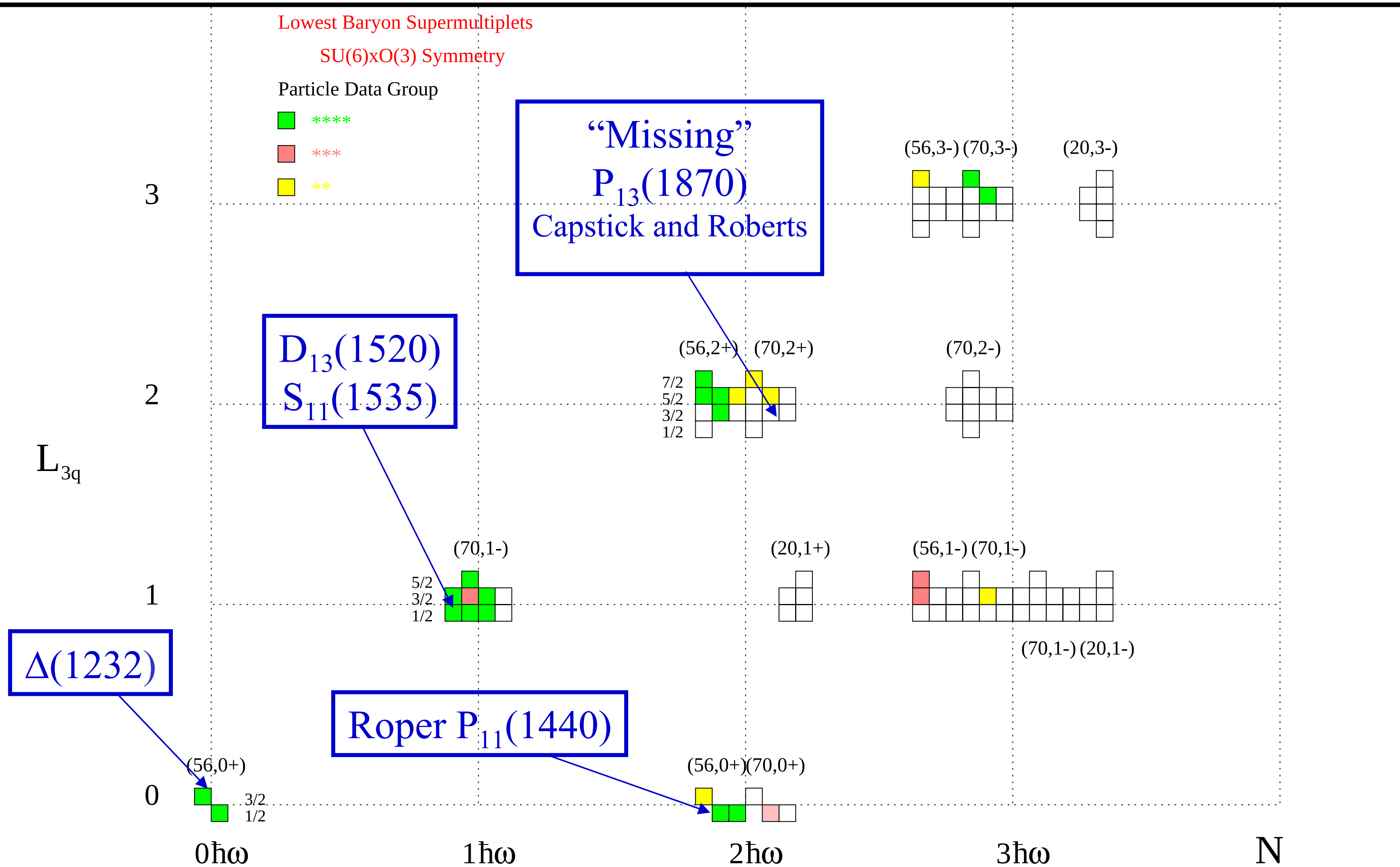
$\mathbf{20 = {}^2 8 \oplus {}^4 1}$

O(3)

Baryon spin: $\vec{J} = \vec{L} + \sum \vec{s}_i$

parity: $P = (-1)^L$

SU(6)xO(3) Classification of Baryons



Configuration Mixing in $[70,1^-]$

States with same I, J^p quantum numbers and different total quark spins $S_q = 1/2$ or $S_q = 3/2$, mix with mixing angle θ_M.

$$\begin{array}{cc} S_q = 1/2 & S_q = 3/2 \\ \downarrow & \downarrow \end{array}$$

The pure quark states $|N^2, 1/2^- >$ and $|N^4, 1/2^- >$ in [70,1-] project onto physical states $S_{11}(1535)$ and $S_{11}(1650)$.

$$|S_{11}(1535)> = \cos\theta_1 |N^2,1/2^-> - \sin\theta_1 |N^4, 1/2^->$$
$$|S_{11}(1650)> = \sin\theta_1 |N^2,1/2^-> + \cos\theta_1 |N^4, 1/2^->$$

$\Theta_1 = 31^o$ (measured in hadronic decays).

$\boxed{\text{Notation: } L^{p}_{2I,2J}}$

Similarly for $|N^2,3/2^- >$ and $|N^4,3/2^- >$

$$|D_{13}(1520)> = \cos\theta_2 |N^2,3/2^-> - \sin\theta_2 |N^4, 3/2^->$$
$$|D_{13}(1700)> = \sin\theta_2 |N^2,3/2^-> + \cos\theta_2 |N^4, 3/2^->$$

$\Theta_2 = 6^o$

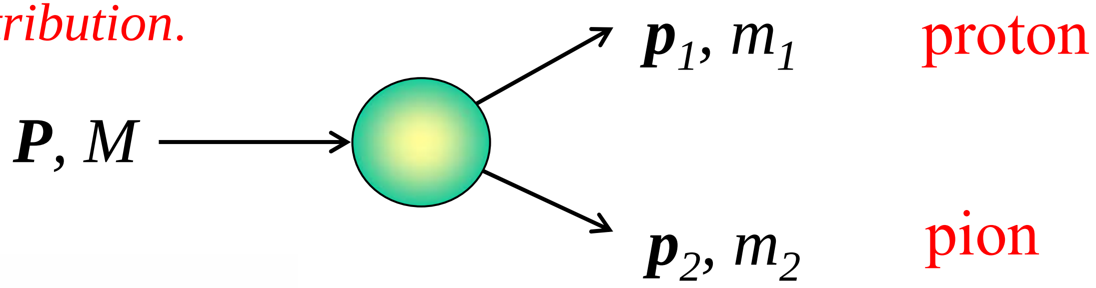
The $|N^4,5/2^- >$ quark state has no N^2 partner, and cannot mix.

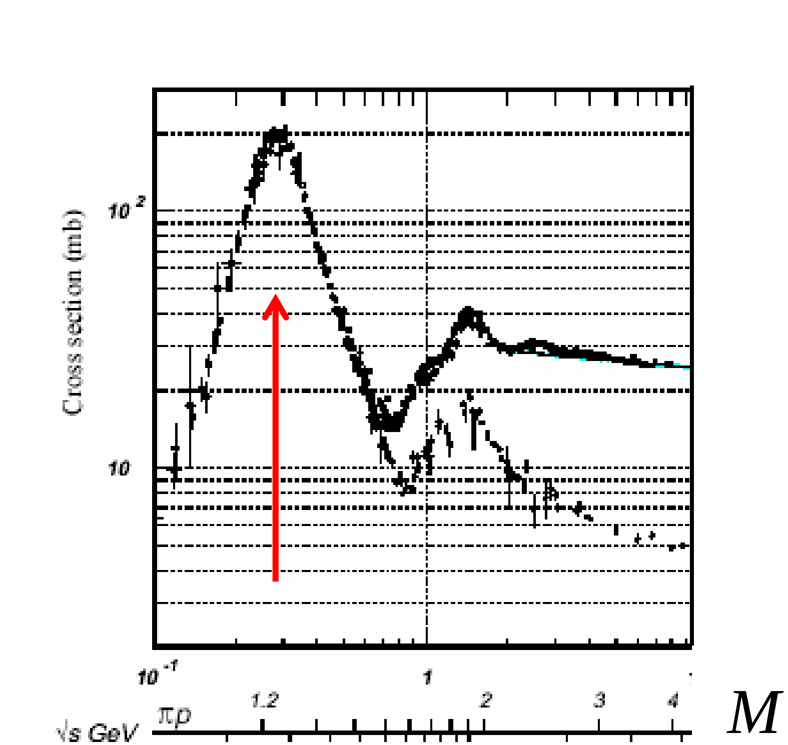
$$\Longrightarrow \quad |D_{15}(1675) > = |N^4,5/2^- >$$

Analysis Tools

Simple searches for resonances

For a 2-body decay one can search for resonance structures in the *invariant mass distribution.*





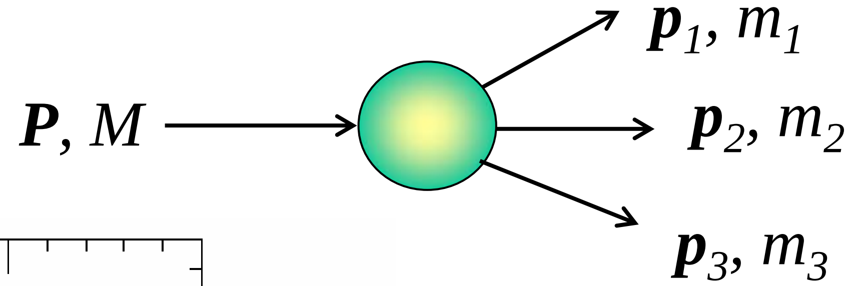
4-vectors

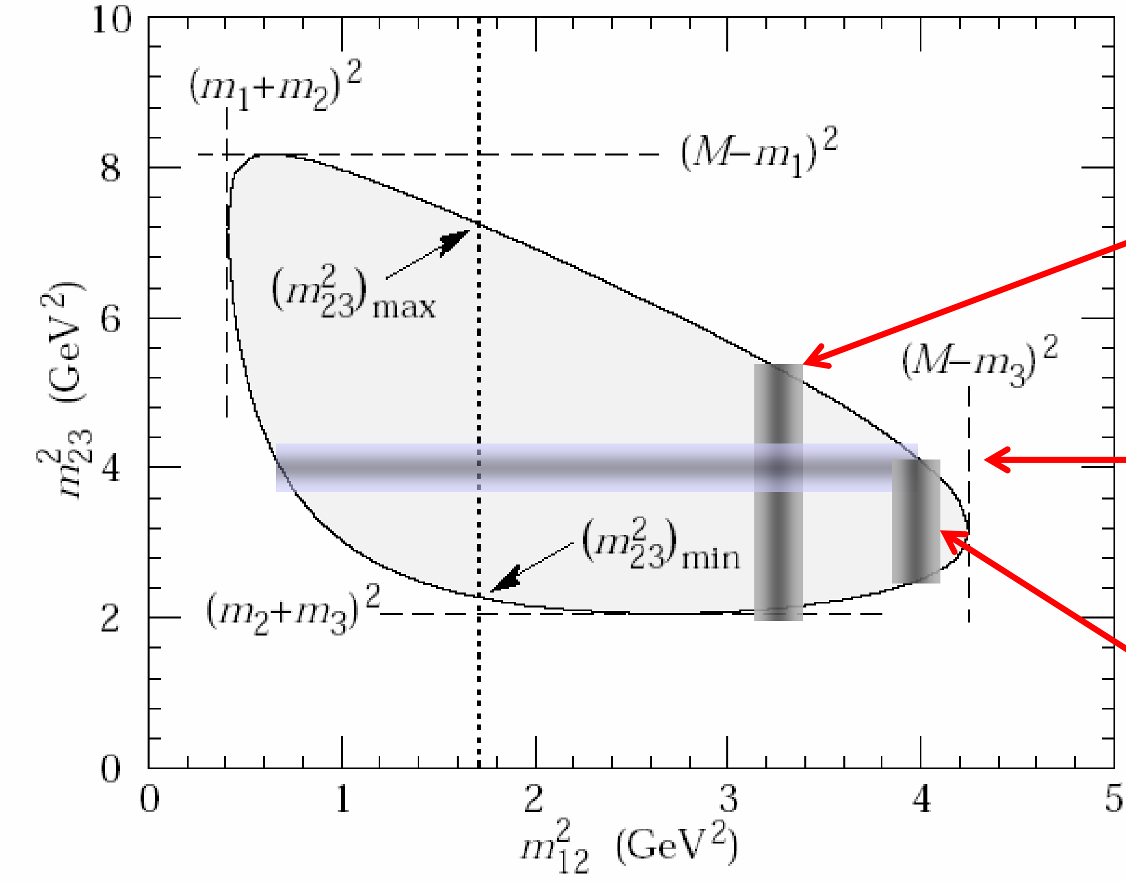
$$M^2 = (p_\mathrm{p} + p_\pi)^2$$

Rarely can resonances be observed just in mass distributions, e.g. if state is narrow, or if strongly excited.
It also gives no information on quantum numbers other than isospin.

Dalitz Plot for 3-body decay (e.g. $p\pi^+\overline{K^0}$)

3-body decay





Resonance at:

$m_{12} = 1.8$ GeV

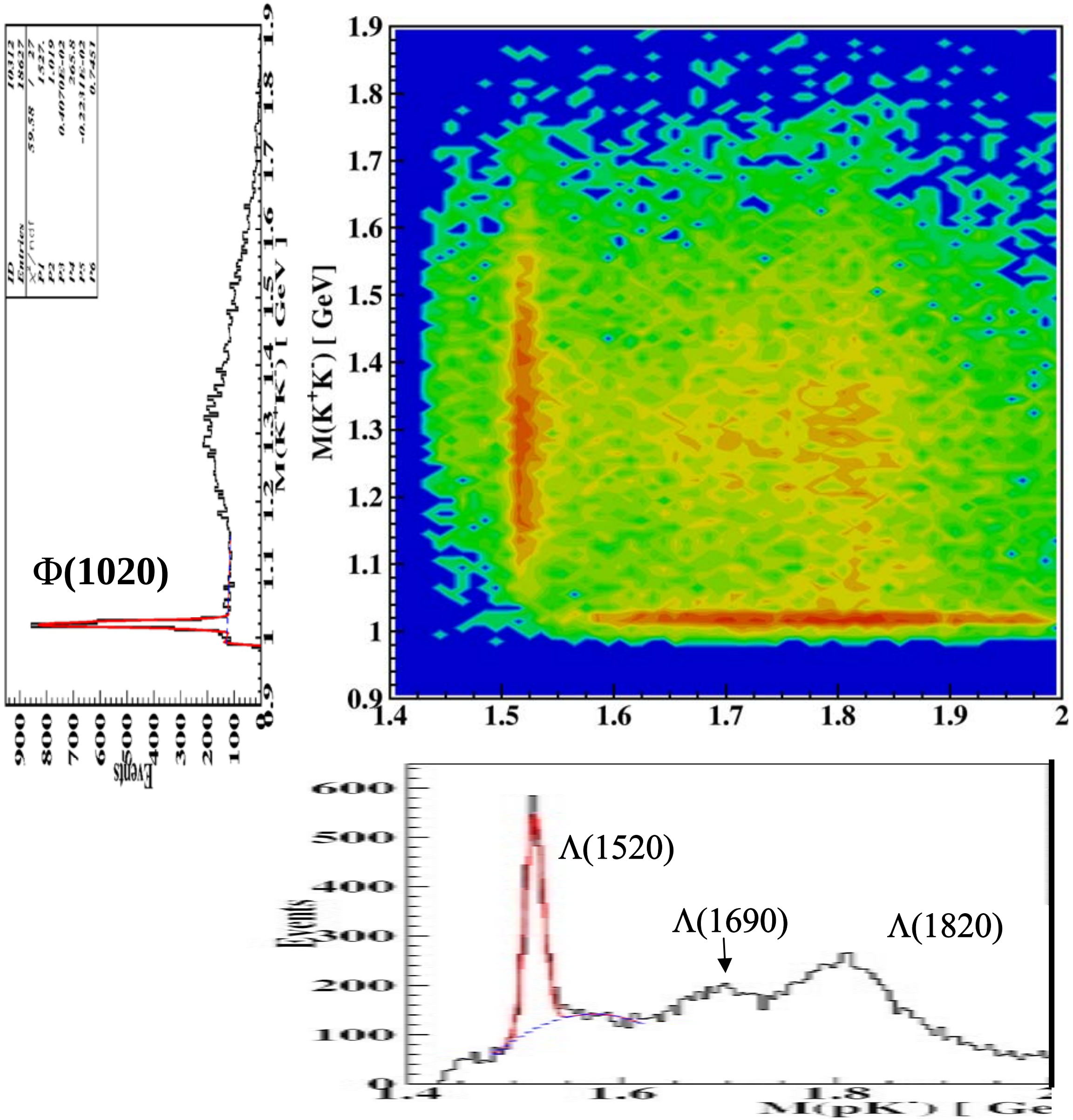
Resonance at:

$m_{23} = 2.0$ GeV

A narrow resonance at $m_{12} = 2.0$ GeV may appear like a broad enhancement in m_{23} (kinematical reflection).

Dalitz Plot: $\gamma p \longrightarrow pK^+K^-$

$E\gamma$ = 1.6-3.5 GeV



Argand Diagram

Elastic scattering amplitude of spinless particle with momentum k in cms:

$$f(k,\theta) = 1/k \sum_l (2l+1) a_l P_l(\cos\theta)$$

$$a_l = (\eta_l e^{2i\delta_l} - 1)/2i \,,$$

$0 \leqslant \eta_l \leqslant 1$, δ_l : phase shift of l^{th} partial wave

For purely elastic scattering: $\eta_l = 1$, (e.g. $\pi N \to \pi N$)

$$d\sigma/d\Omega = |f(k,\theta)|^2$$

Optical theorem:

$$\sigma_{tot} = 4\pi/k[\mathrm{Im}\, f(k,0)]$$

Cross section for l^{th} partial wave is bounded:

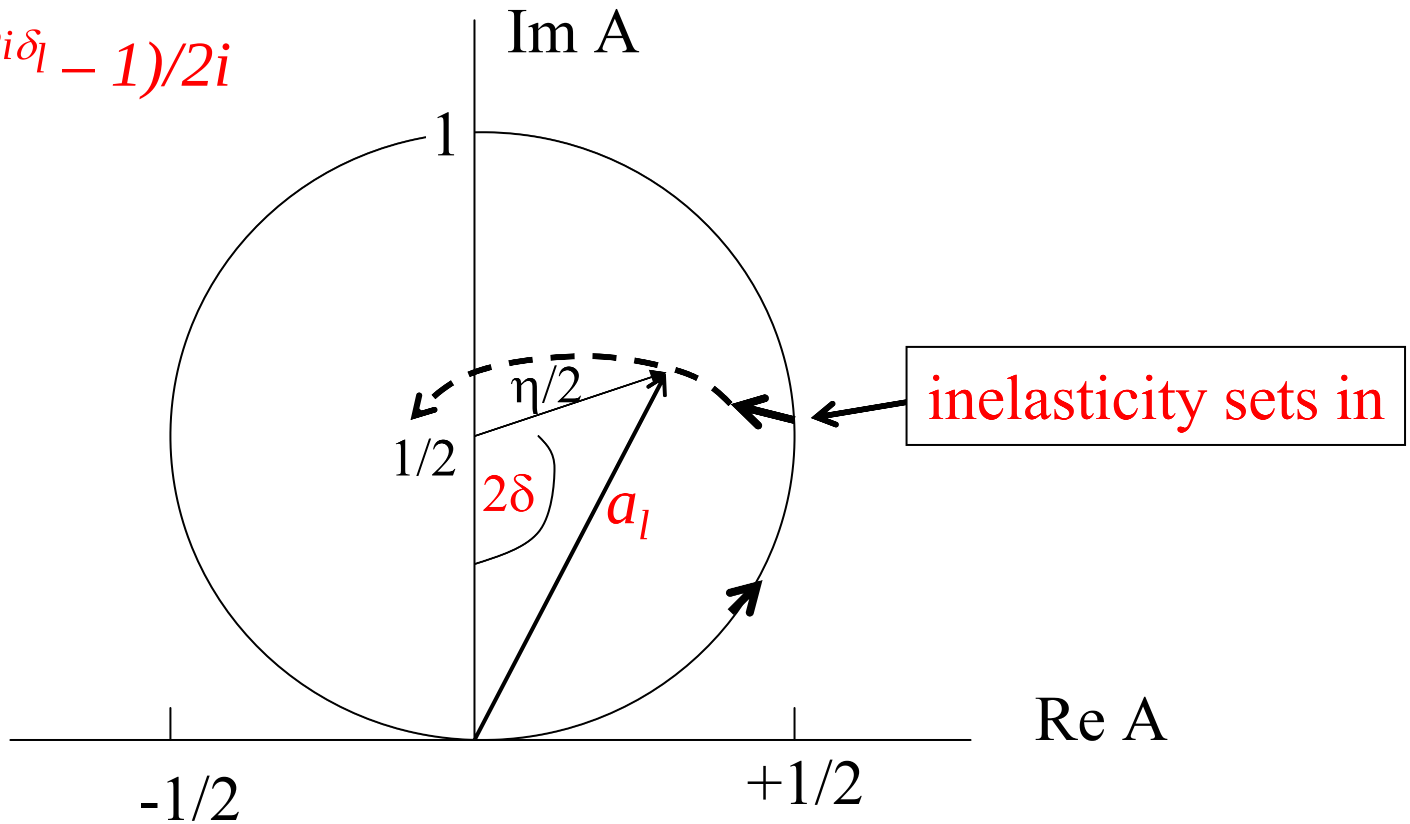
$$\sigma_l = 4\pi/k^2(2l+1)|a_l|^2 \leqslant 4\pi(2l+1)/k^2$$

Argand Diagram

a_l : partial wave amplitude evolving with energy.

The amplitude leaves the unitary circle where inelasticity sets in.

$$a_l = (\eta_l e^{2i\delta_l} - 1)/2i$$



Breit-Wigner Form

- B-W (non-relativistic) form for an elastic amplitude $\boldsymbol{a_l}$ with a resonance at cm energy E_R and elastic width Γ_{el} and total width Γ_{tot} is

$$\boxed{\boldsymbol{a_l} = \frac{\Gamma_{el}/2}{E_R - E - i\Gamma_{tot}/2}}$$

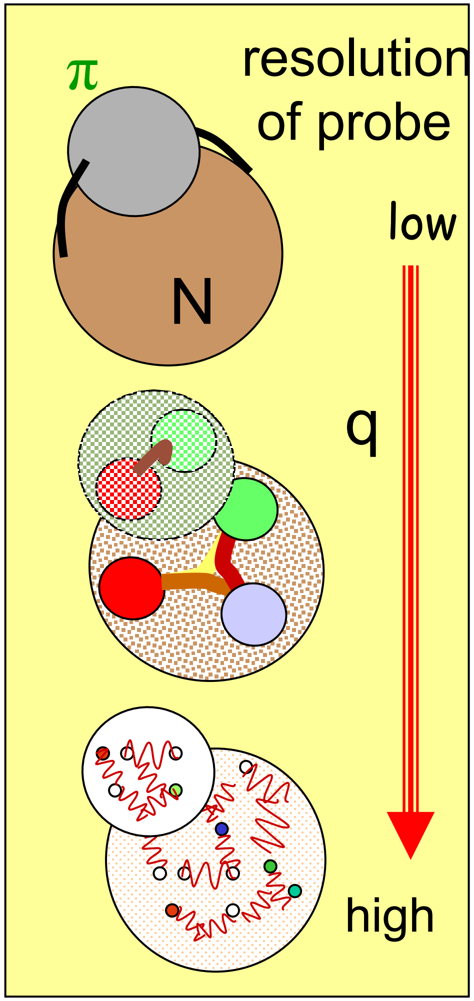
- Relativistic form:

$$\boldsymbol{a_l} = \frac{-m\Gamma_{el}}{s - m^2 - im\Gamma_{tot}}$$

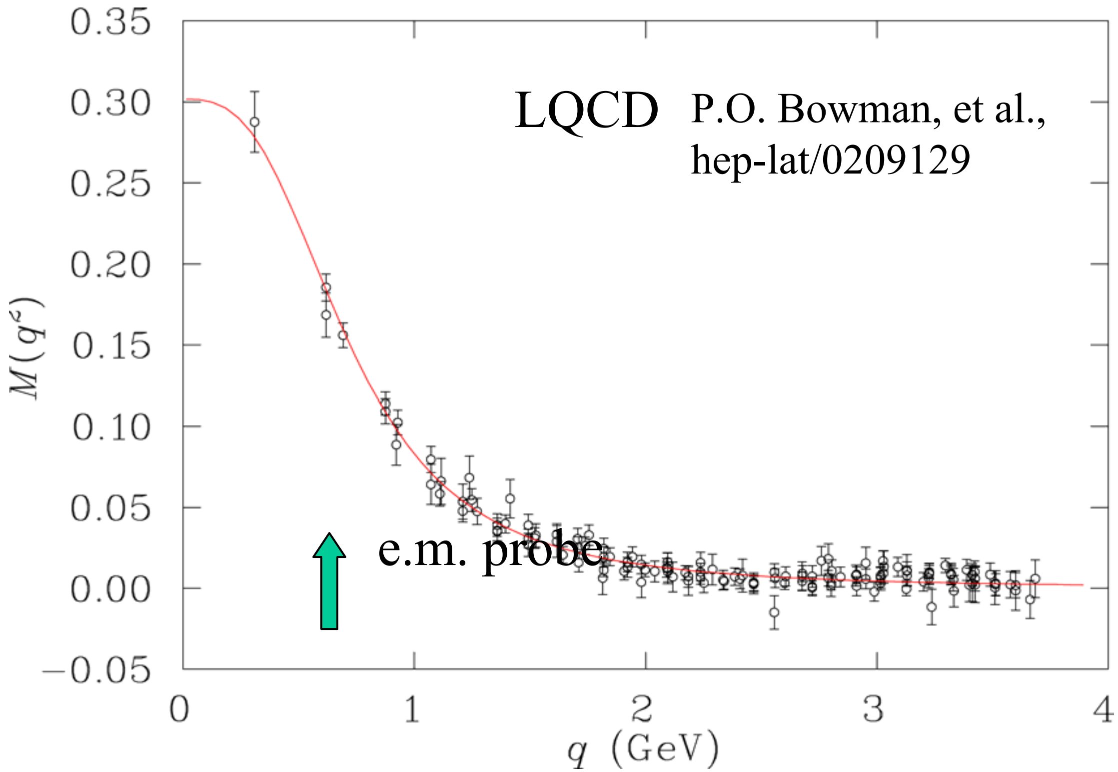
- Many other B-W forms exist, dependent of process dynamics.

Electromagnetic Excitation of Baryon Resonances

Why electroexcitation of N*s ?



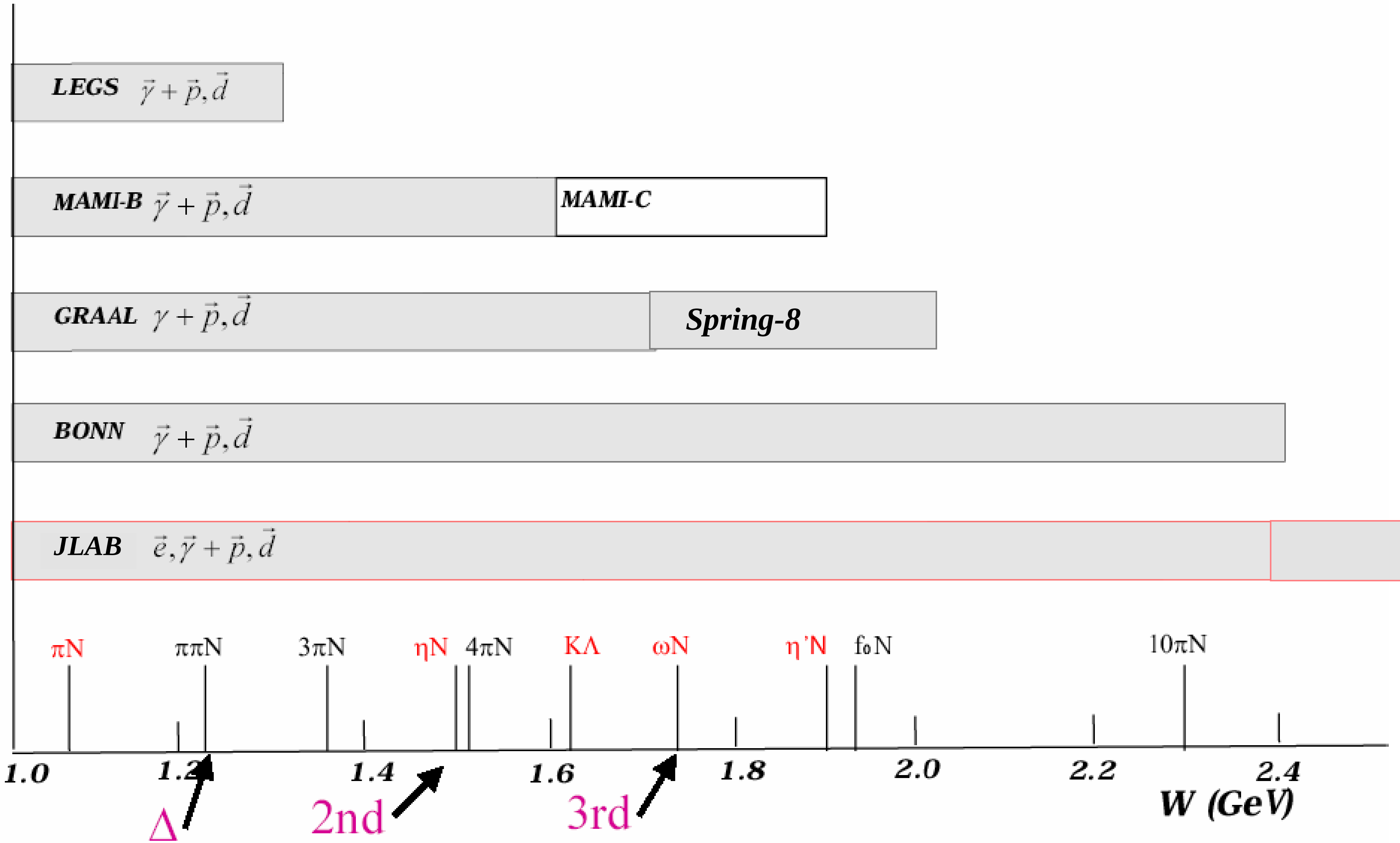
Addresses the question: What are the relevant degrees of freedom at different distance scales?



Spatial resolution ~1/q

=> Constituent quark model with fixed quark masses only justified at photon point and low q.

Reach of Current Accelerators



Large Acceptance Detectors for N* Physics.

CLAS: (photon and electron reactions)

- Final states with mostly charged particles.
- Operates with electron beams and with energy-tagged photon beams.
- Coverage for photons limited to lab angles $< 45^o$

Crystal Barrel-ELSA: (photon reactions)

- CsI crystals with excellent photon detection, e.g. $N\pi^o\pi^o$, $N\pi^o\eta$

SAPHIR-ELSA (photon reactions, detector dismantled)

- Charged particles in final state

GRAAL (photon reactions):

- BGO crystals, with excellent photon detection, limited charged particle, polarized laser-backscattered tagged photon

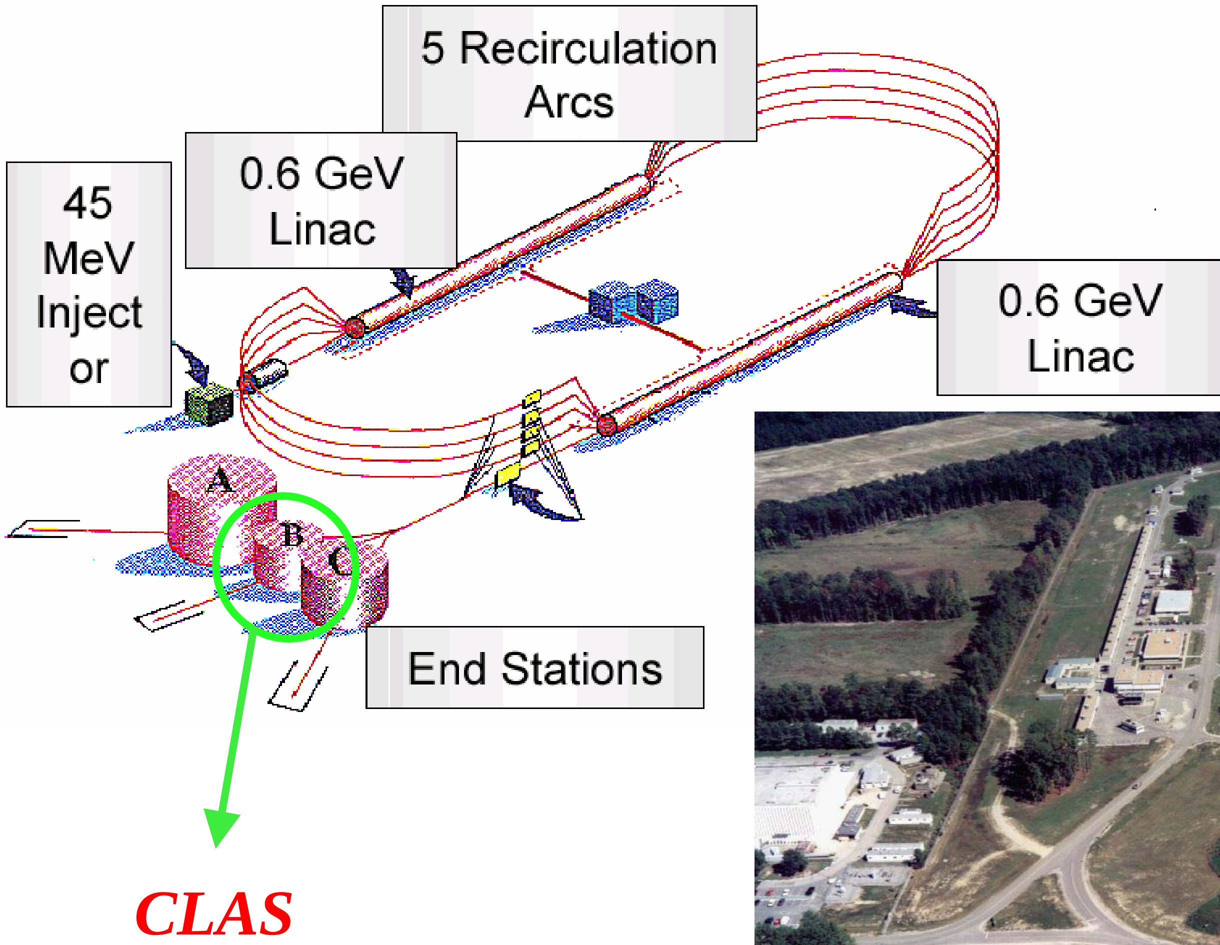
Crystal Ball – MAMI (photon reactions)

neutral final states with excellent resolution, limited W range

BES (Beijing) – N* in e^+e^- collisions.

Not included are setups for more specialized applications.

JLab Site: The 6 GeV CW Electron Accelerator



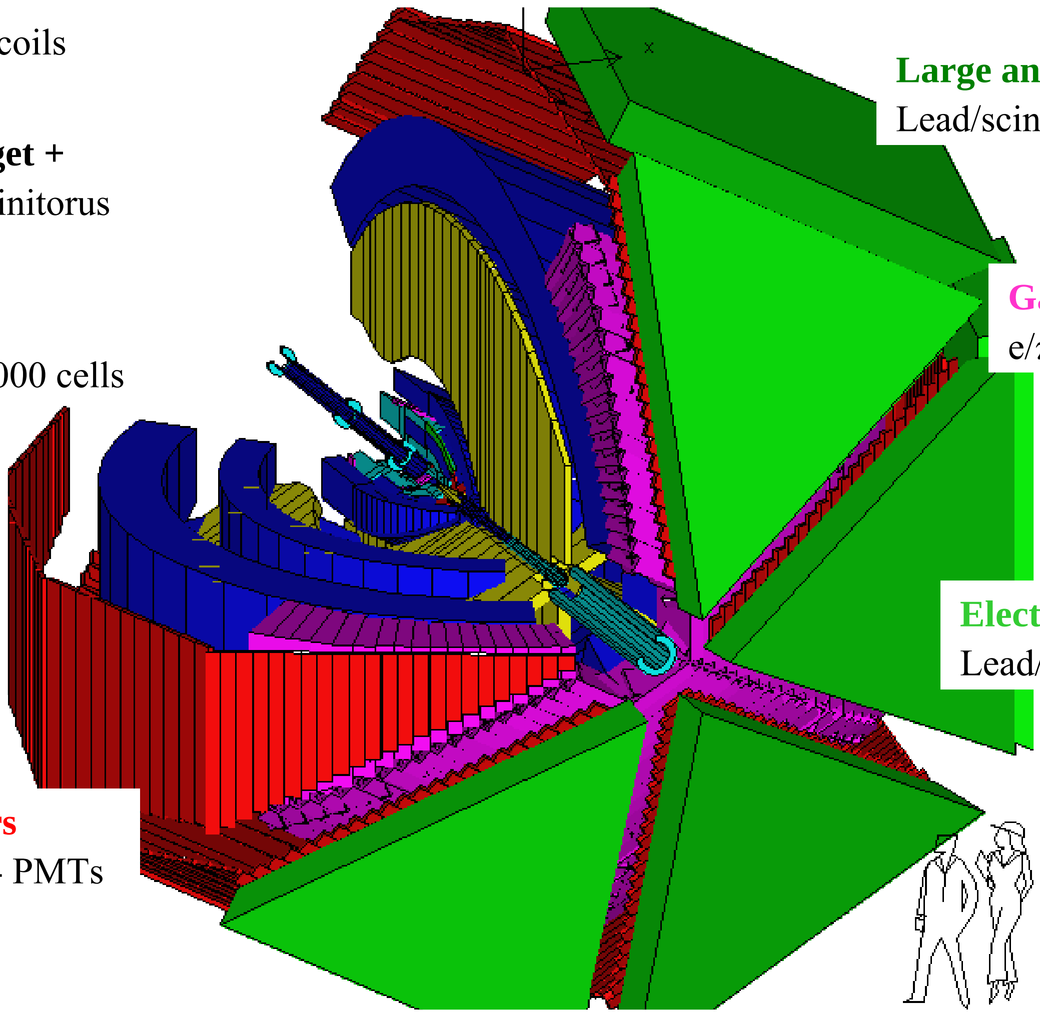
E_{max}	~ 6 GeV
I_{max}	~ 200 μA
Duty Factor	~ 100%
σ_E/E	~ 2.5 10^{-5}
Beam P	~ 80%
E_{γ}(tagged)	~ 0.8- 5.5 GeV

CEBAF Large Acceptance Spectrometer

Torus magnet
6 superconducting coils

Liquid D_2 (H_2)target +
γ start counter; e minitorus

Drift chambers
argon/CO_2 gas, 35,000 cells



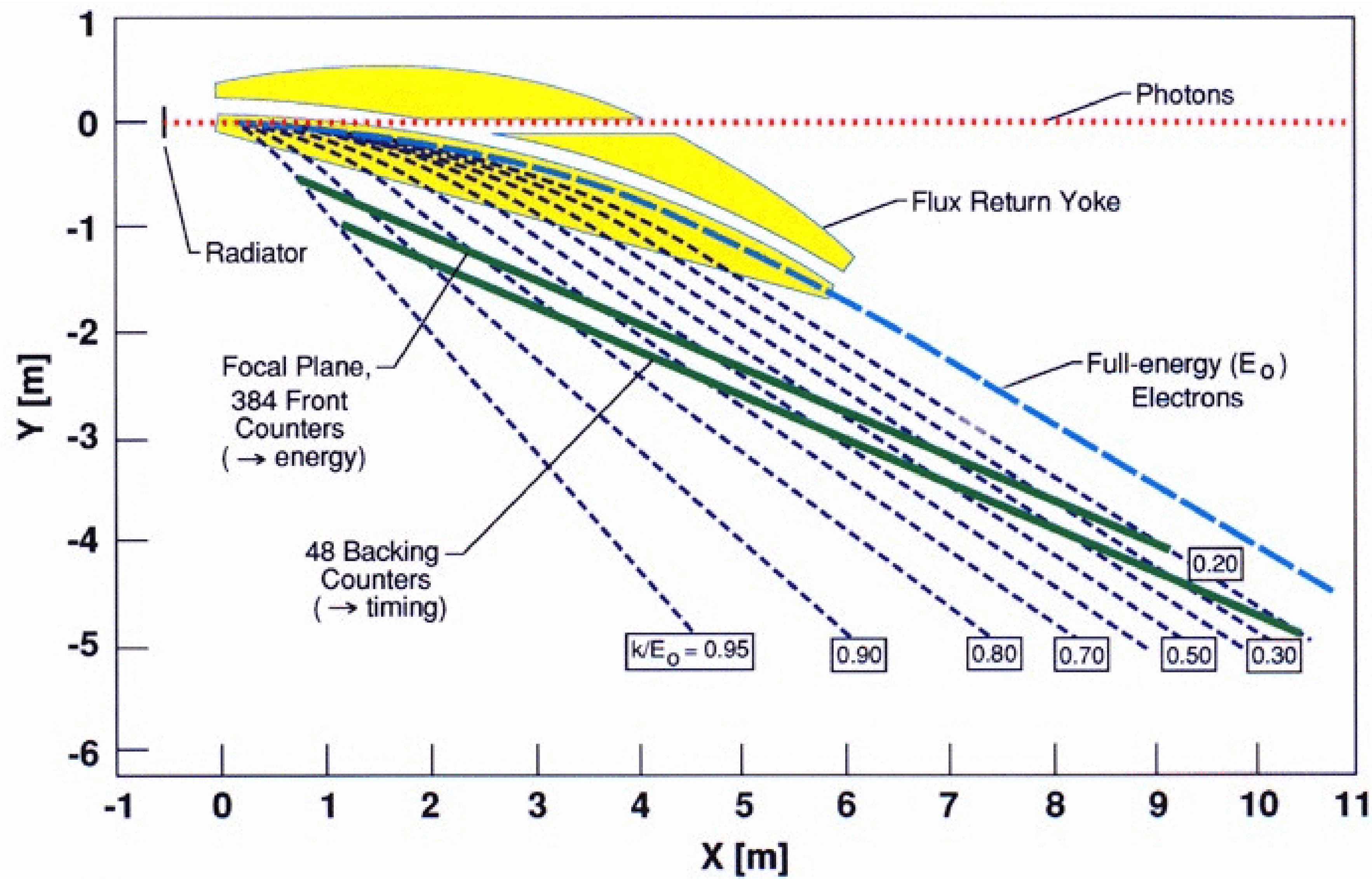
Large angle calorimeters
Lead/scintillator, 512 PMTs

Gas Cherenkov counters
e/π separation, 216 PMTs

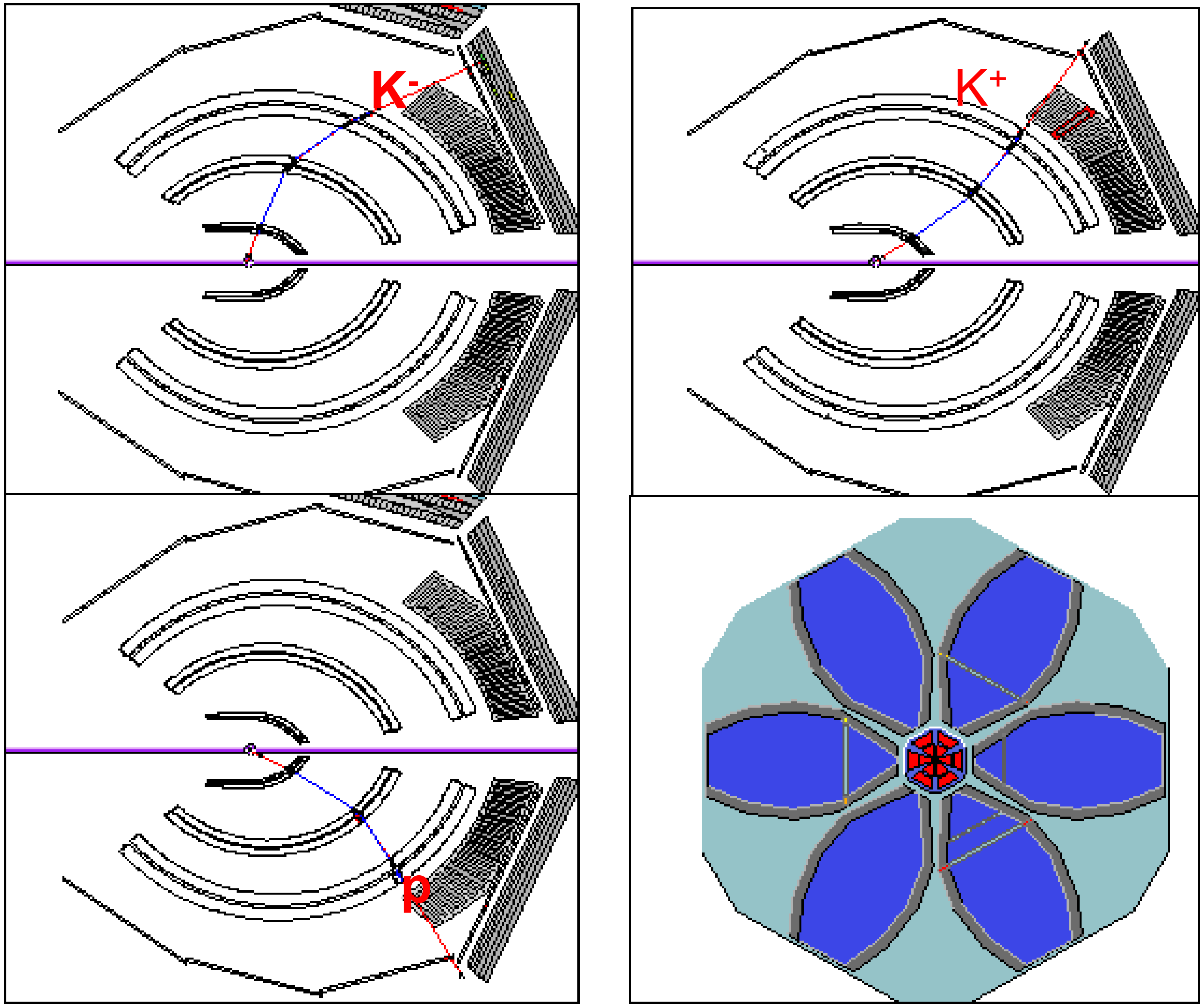
Electromagnetic calorimeters
Lead/scintillator, 1296 PMTs

Time-of-flight counters
plastic scintillators, 684 PMTs

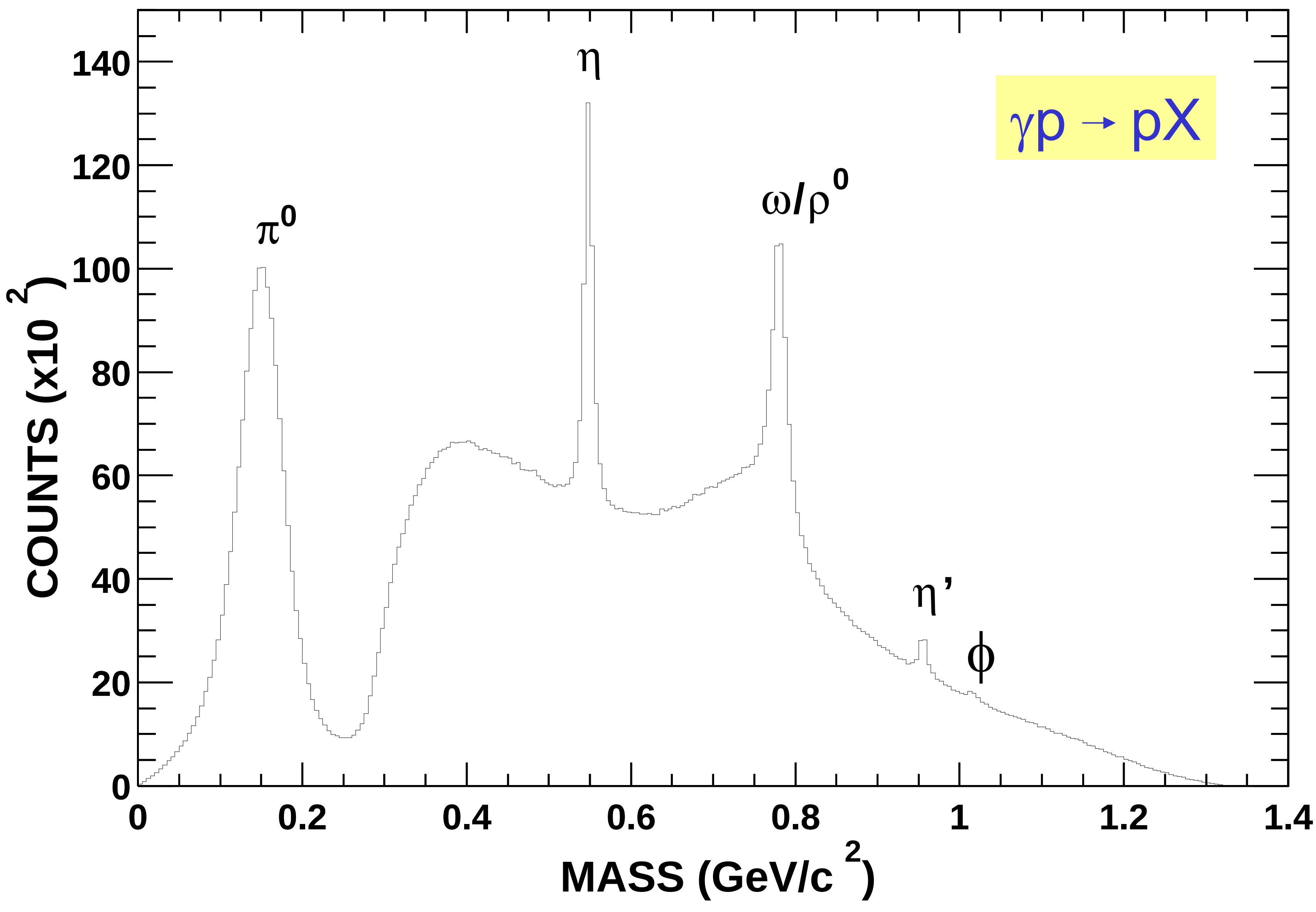
The CLAS Photon Tagger



Single Event $\gamma d \rightarrow p\, K^{+} K^{-} X$



Missing Mass Distribution

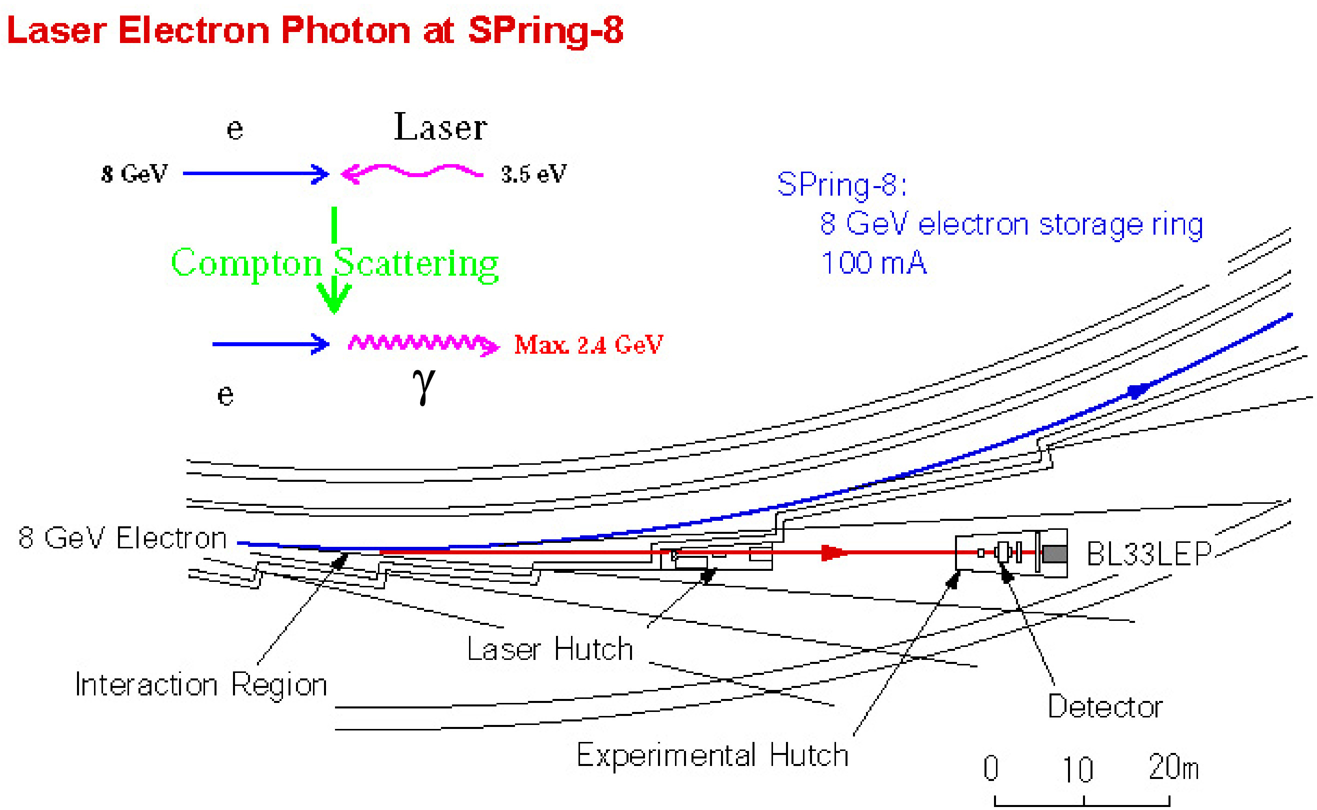


Super Photon ring-8 GeV SPring-8

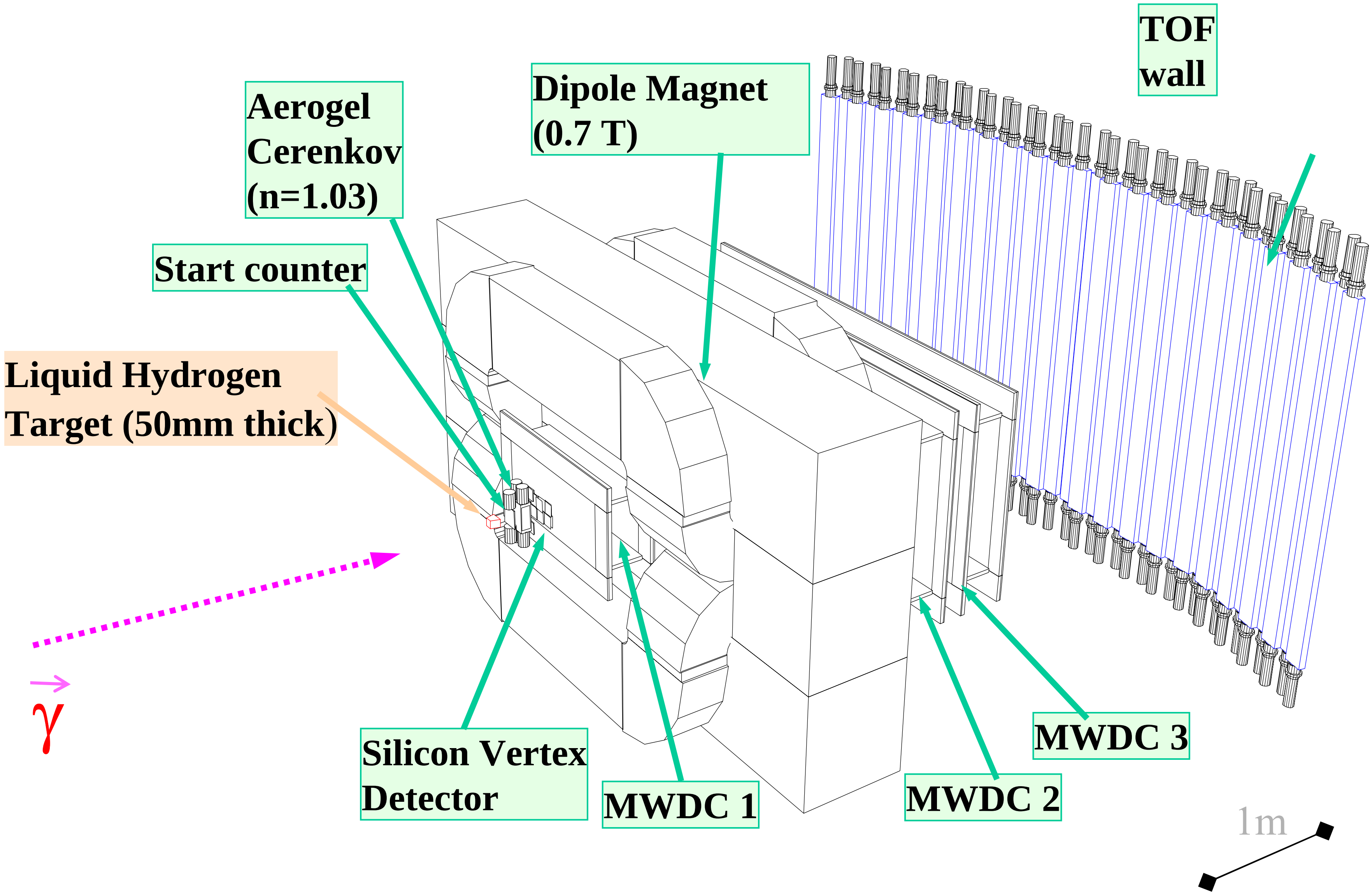
- Third-generation synchrotron radiation facility
- Circumference: 1436 m
- 8 GeV
- 100 mA
- 62 beamlines

Laser Electron Photon facility at SPring-8

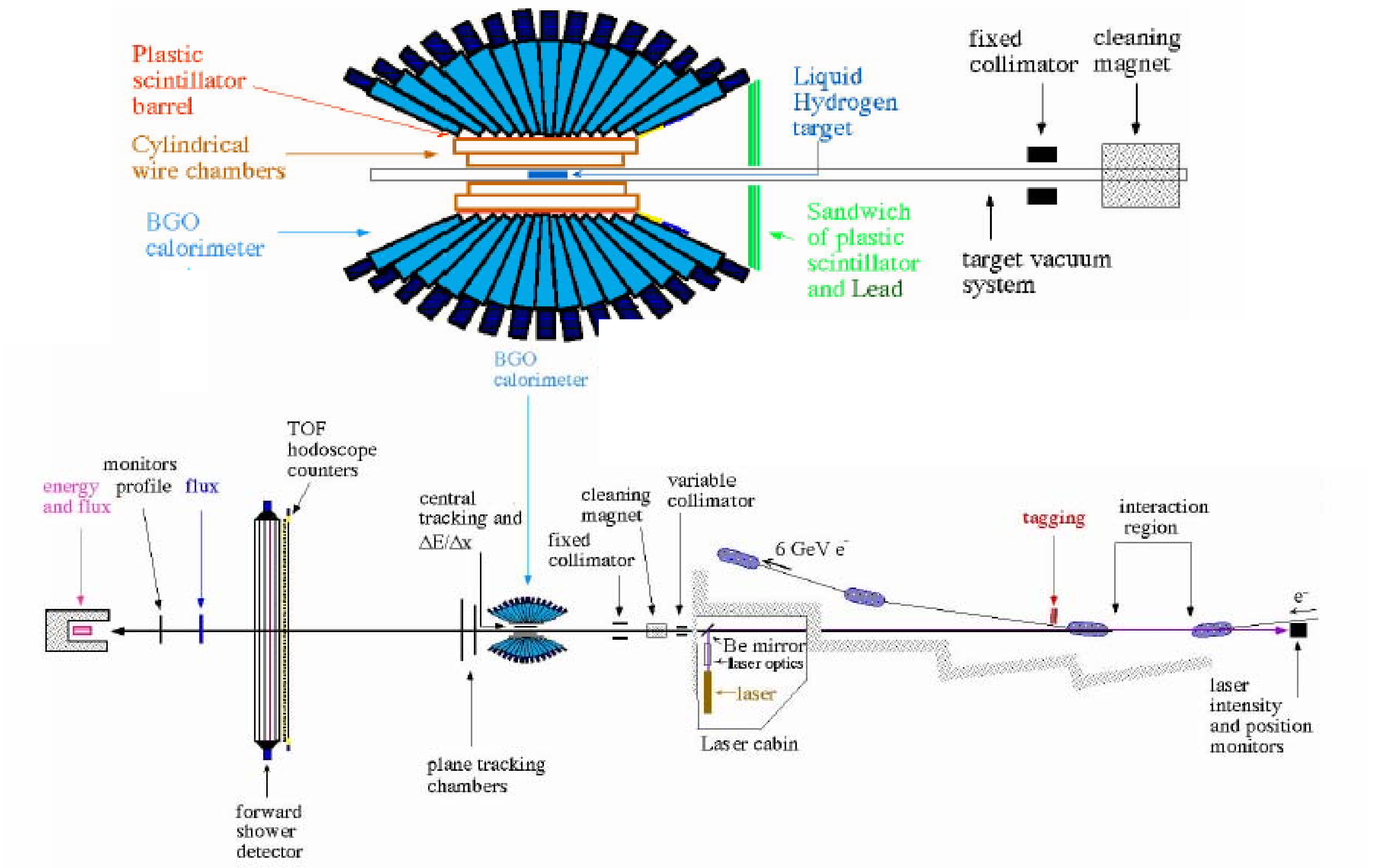
in operation since 2000



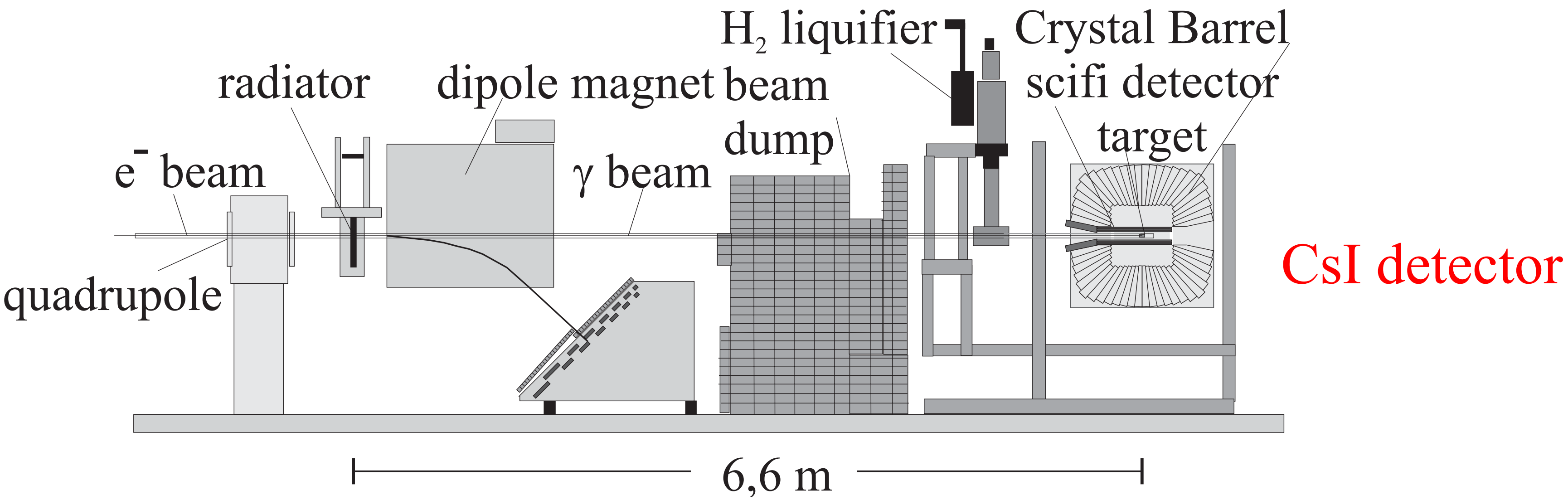
LEPS detector



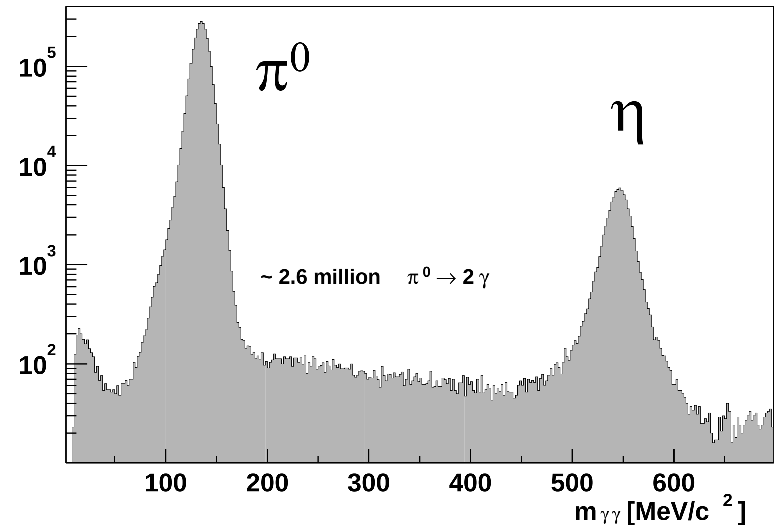
The GRAAL Experiment



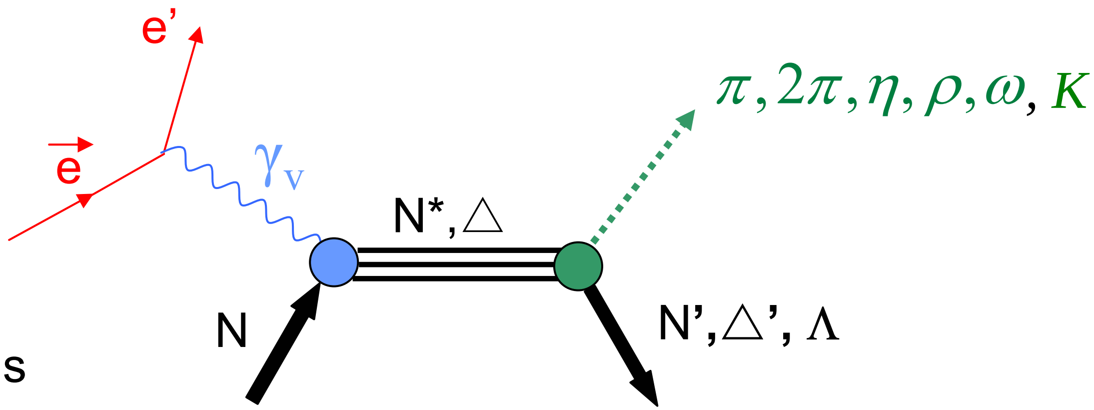
The Crystal Barrel @ ELSA



$\gamma\gamma$ invariant mass



Electromagnetic Excitation of N*'s

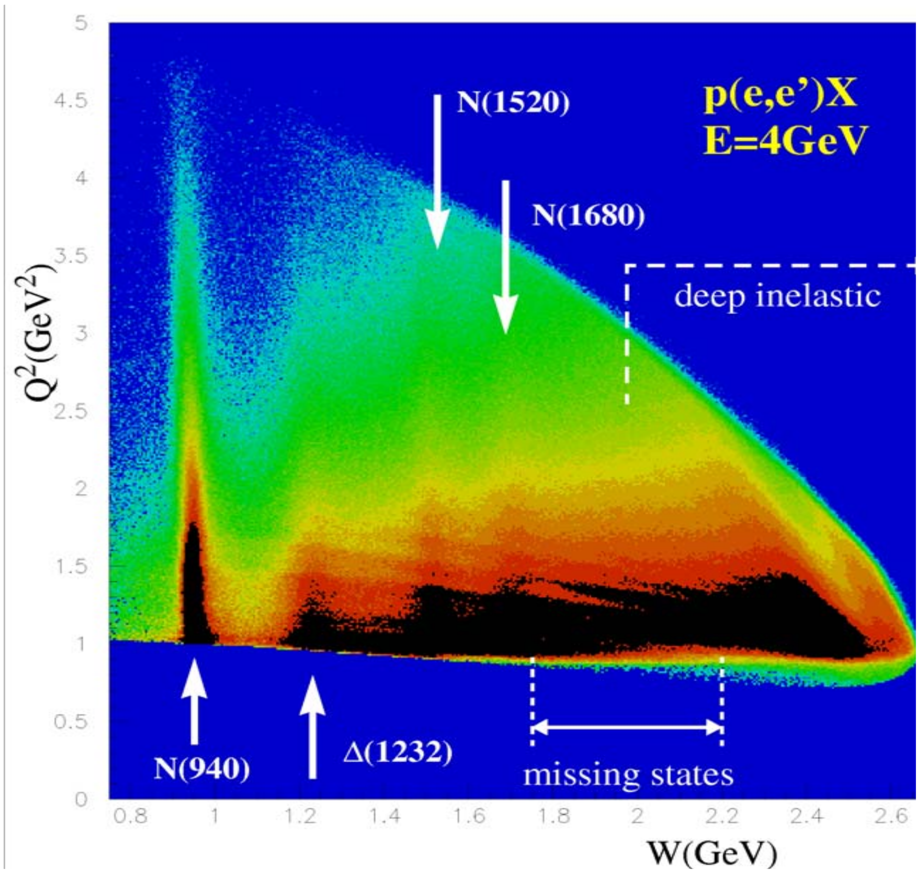


Primary Goals

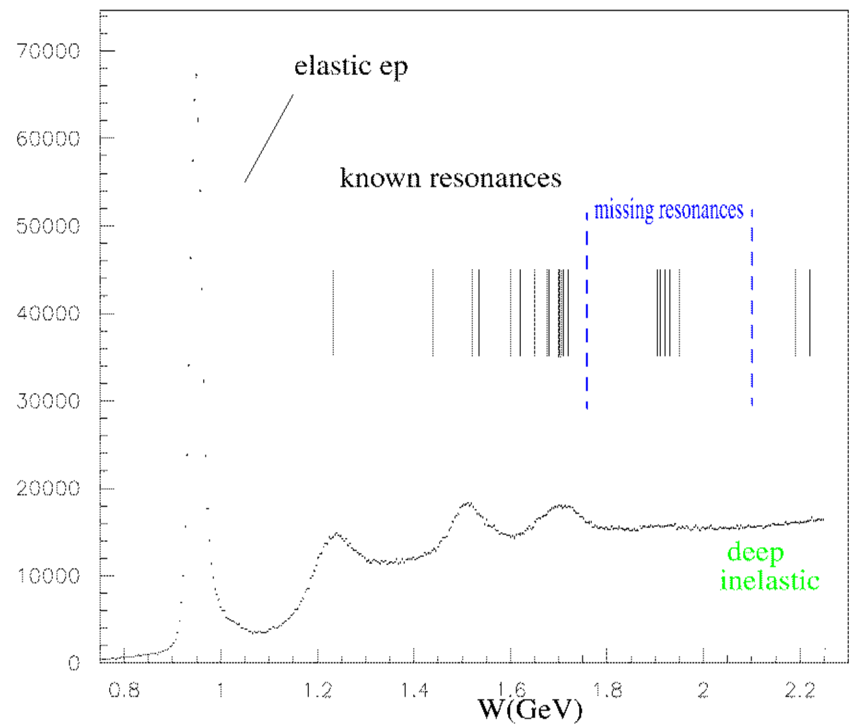
- Extract photocoupling amplitudes for known △,N* resonances
  - Partial wave and isospin decomposition of hadronic decay
  - Assume EM and strong interaction vertices factorize
  - Helicity amplitudes $A_{3/2}$ $A_{1/2}$ $S_{1/2}$ and their Q^2 dependence
  - Study quark wave function and symmetries
  - Quark models: relativity, gluons vs. mesons.
- Identify missing resonances expected from SU(6)xO(3)
  - More selective hadronic decays: $2\pi, \eta, \rho, \omega, K\Lambda$

Inclusive Electron Scattering

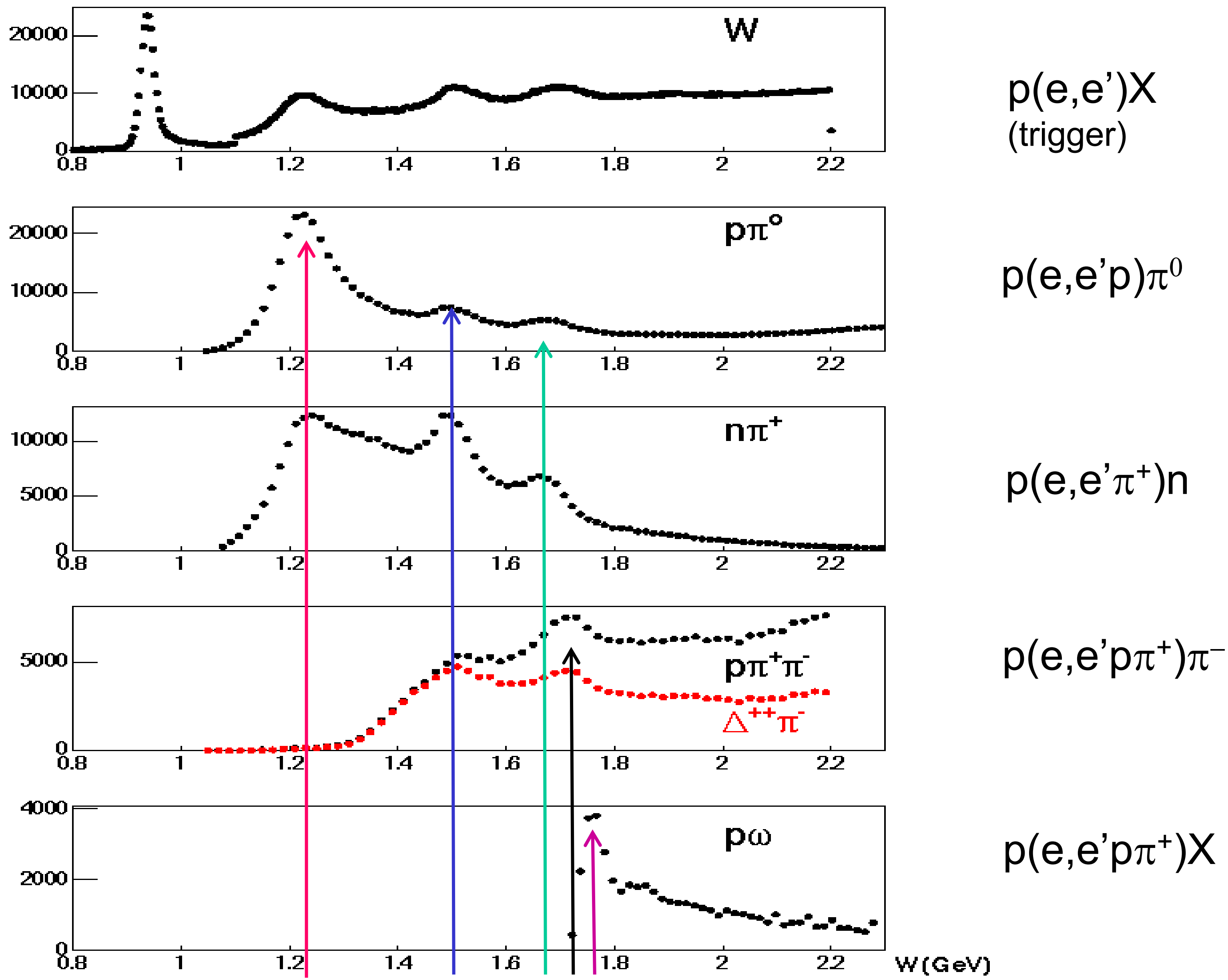
p(e,e')X



Inclusive scattering ep → eX

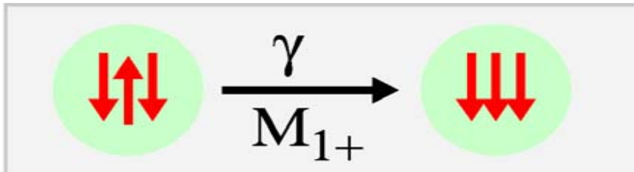


W-Dependence of Selected Channels at 4 GeV

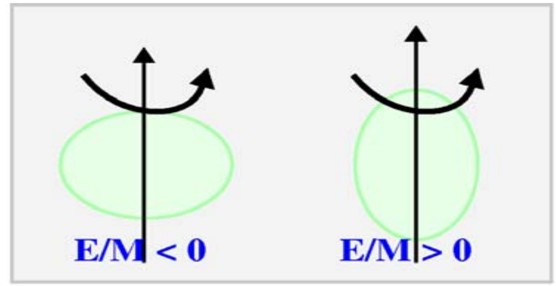


NΔ(1232) Transition

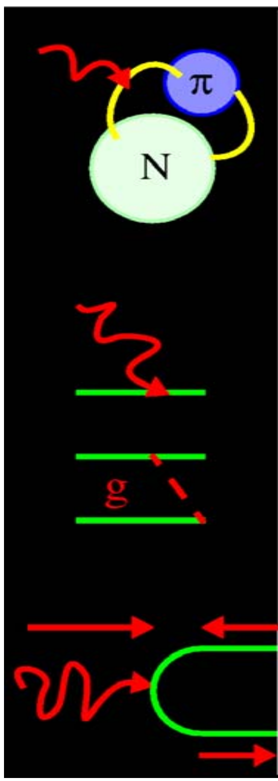
N-Δ(1232) Quadrupole Transition



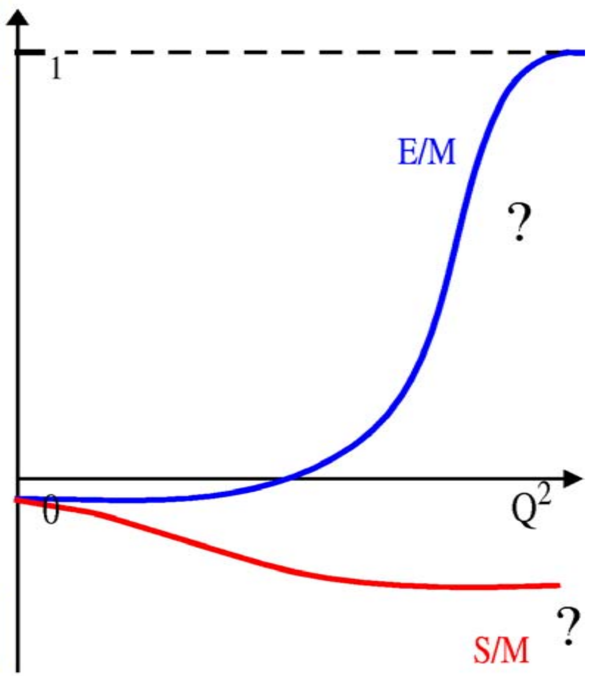
SU(6): $E_{1+}=S_{1+}=0$



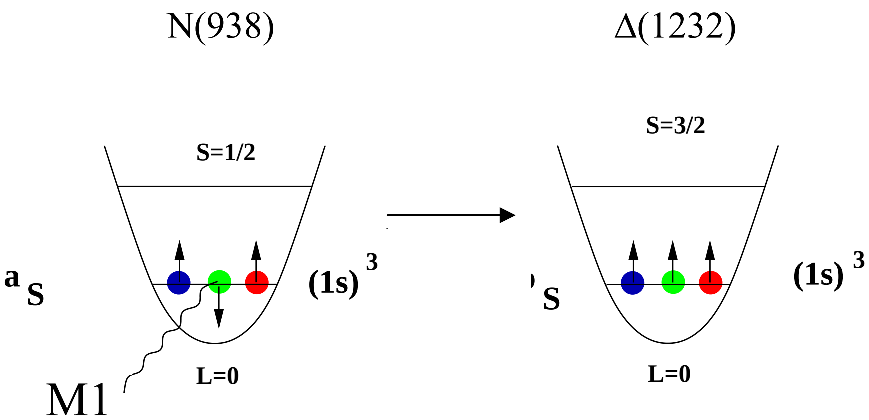
(A. Buchmann, E. Henley, 2000)

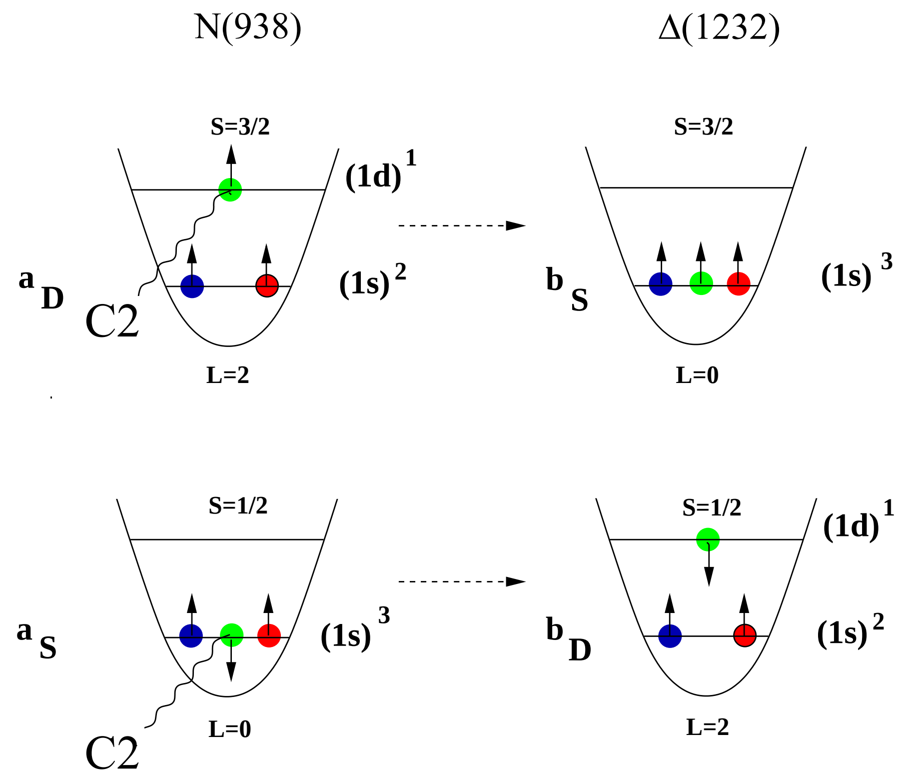


	E/M	S/M
pion cloud	~0.03	~0.1
one-gluon exch.	~ 0.01	
pQCD	+1	const.



NΔ - Quadrupole transition in SQT





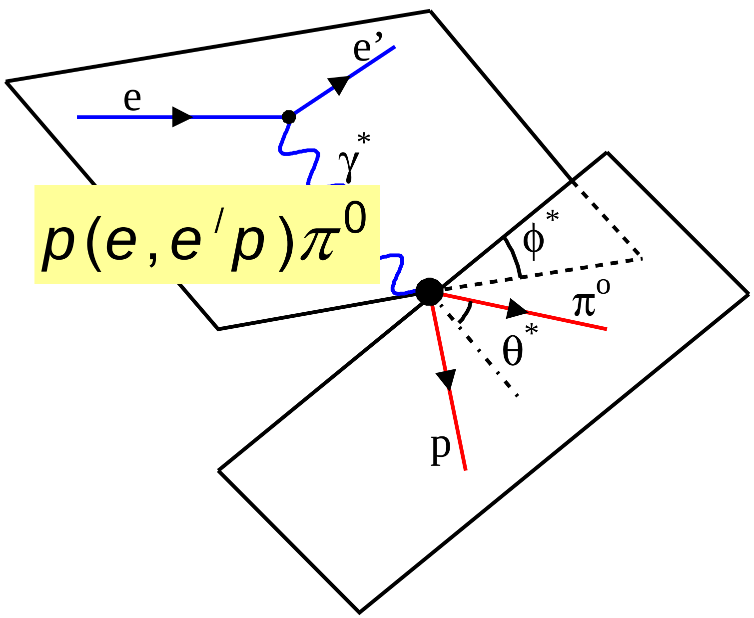
Magnetic single quark
Transition.

Coulomb single quark
transition.

Pion Electroproduction Structure Functions

$$\frac{d^2\sigma}{d\Omega_\pi^*} = \frac{p_\pi^*}{k_\gamma^*}\left(\sigma_T + \varepsilon_L\sigma_L + \varepsilon\,\sigma_{TT}\sin^2\theta_\pi^*\cos 2\phi_\pi^* + \sqrt{2\varepsilon_L(\varepsilon+1)}\,\sigma_{LT}\sin\theta_\pi^*\cos\phi_\pi^*\right)$$

M_{1+}^2 $\quad$ $\mathrm{Re}(E_{1+}^* M_{1+})$ $\quad$ $\mathrm{Re}(S_{1+}^* M_{1+})$



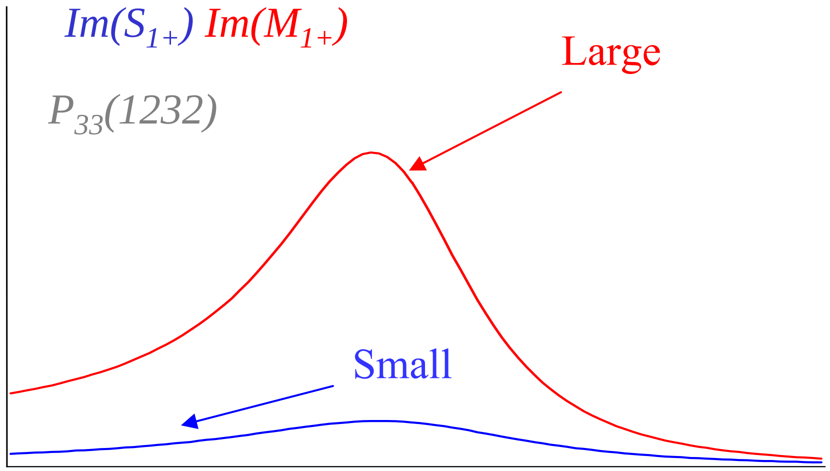
- Longitudinal sensitivity w/o Rosenbluth separation.
- Measurement requires out-of-plane detection of hadronic decay.
- Structure functions extracted from fits to ϕ^* distributions for each (Q^2 ,W, cosθ^*) point.
- LT and TT interference sensitive to weak quadrupole and longitudinal multipoles.

The Power of Interference I

- Unpolarized structure function

$$\sigma_{LT} \sim Re(L^*T) = Re(L)Re(T) + Im(L)Im(T)$$

  – Amplify small resonance multipole by an interfering larger resonance multipole



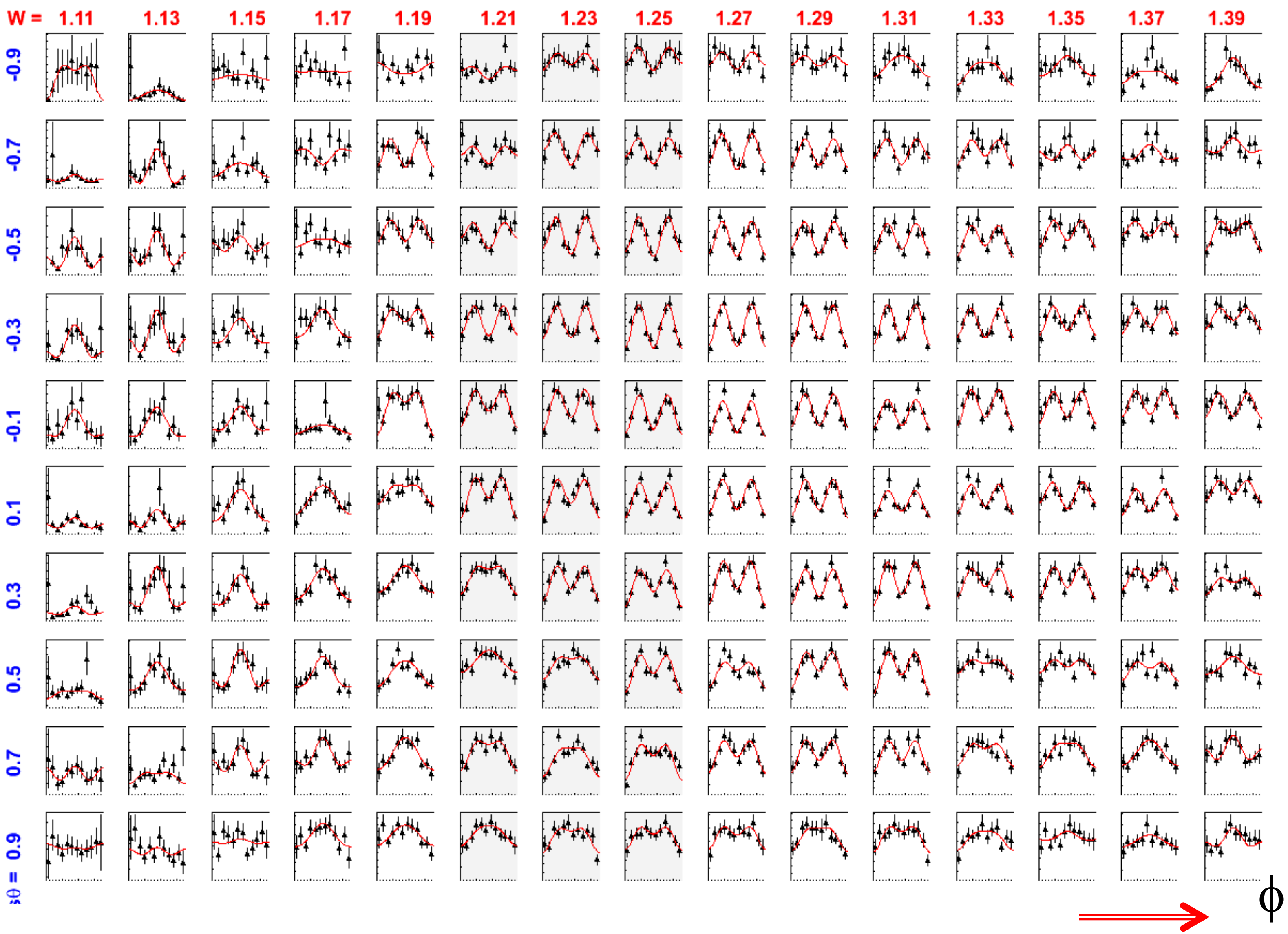
Truncated Multipole Expansion in Δ(1232) Region

- s, p waves only, J_{max}= 3/2 , M_{1+} dominance, i.e. retain only terms containing M_{1+}

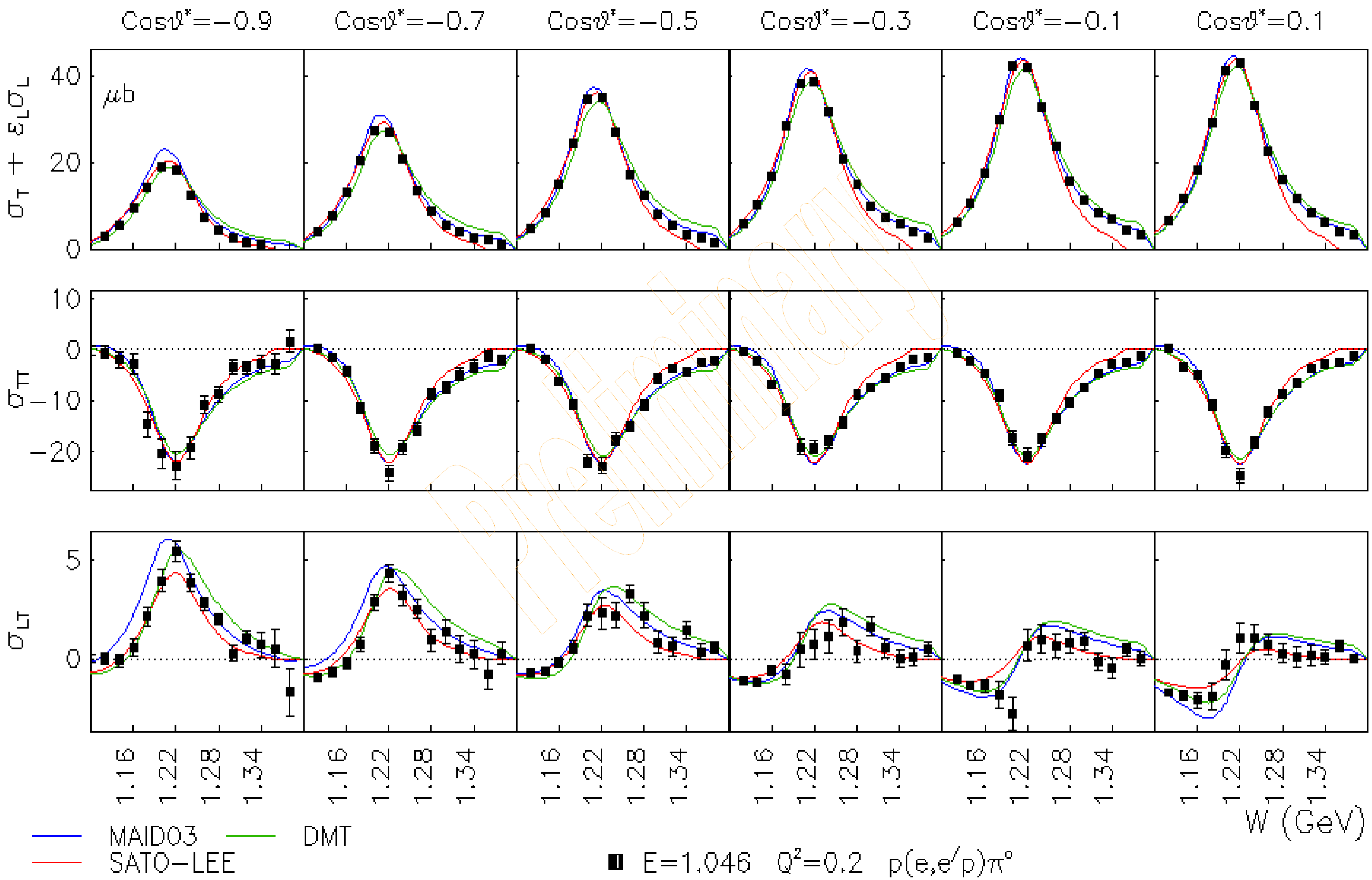
$$
\begin{aligned}
\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} \approx \frac{|\vec{p}_\pi W|}{KM} \Big\{ & \tfrac{5}{2}|M_{1+}|^2 - 3\,\mathrm{Re}(M_{1+}E_{1+}^*) + \mathrm{Re}(M_{1+}M_{1-}^*) \\
& + 2\cos\theta\,\mathrm{Re}(E_{0+}M_{1+}^*) \\
& + \cos^2\theta\,\left[-\tfrac{3}{2}|M_{1+}|^2 + 9\,\mathrm{Re}(M_{1+}E_{1+}^*) - 3\,\mathrm{Re}(M_{1-}M_{1+}^*)\right] \\
& + \epsilon\,\sin^2\theta\,\cos 2\phi\,\left[-\tfrac{3}{2}|M_{1+}|^2 - 3\,\mathrm{Re}(M_{1+}E_{1+}^*)\right] \\
& - \sqrt{2\epsilon_\mathrm{L}(\epsilon+1)}\,\sin\theta\,\cos\phi\,\left[\mathrm{Re}(S_{0+}M_{1+}^*) + 6\cos\theta\,\mathrm{Re}(S_{1+}M_{1+}^*)\right]\Big\},
\end{aligned}
$$

- 6 unknown terms remain, which can be determined uniquely by measuring the azimuthal and polar angle dependence of the cross section.

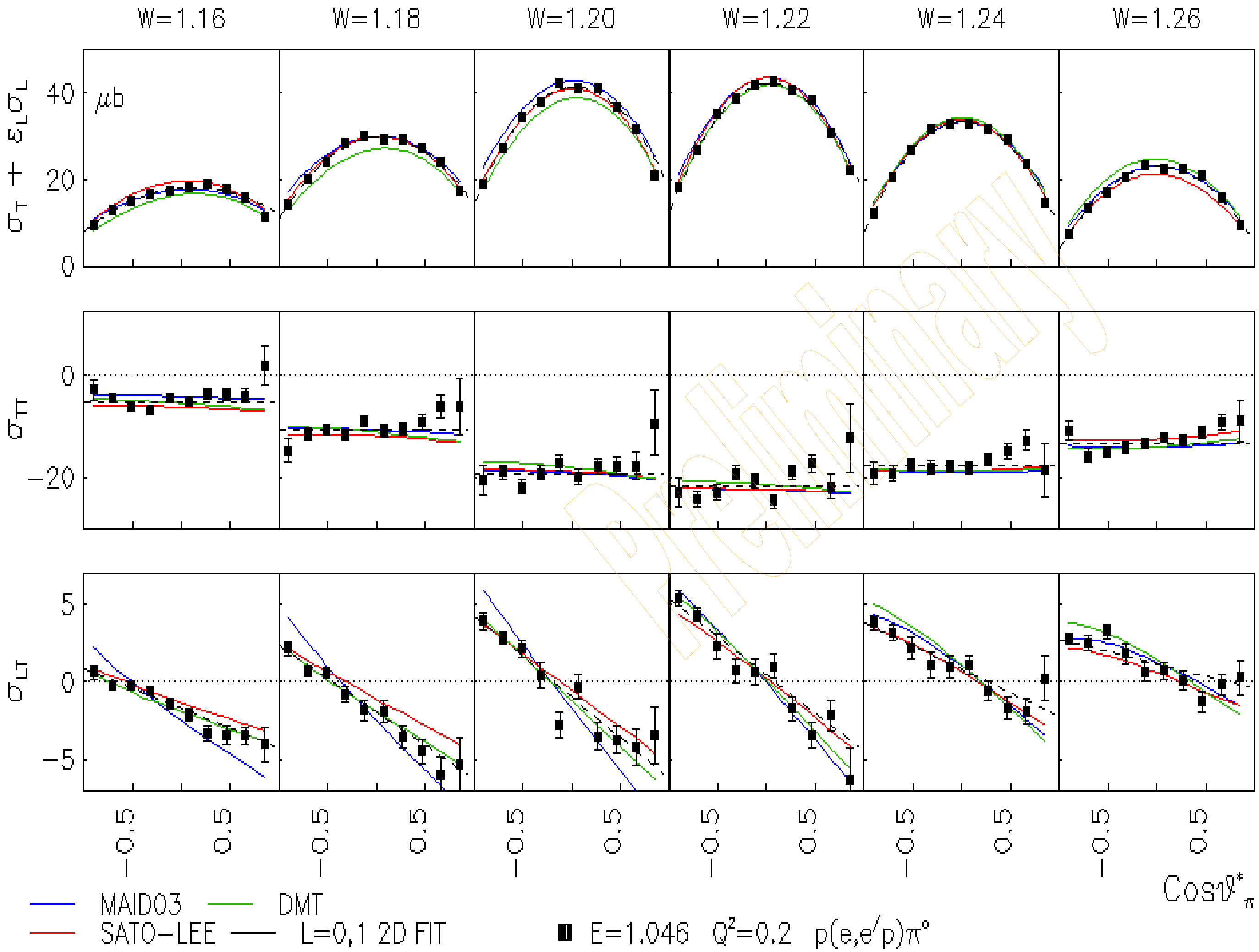
N* program – NΔ(1232) transition



Structure Functions - Invariant Mass W



Structure Functions - cos θ*

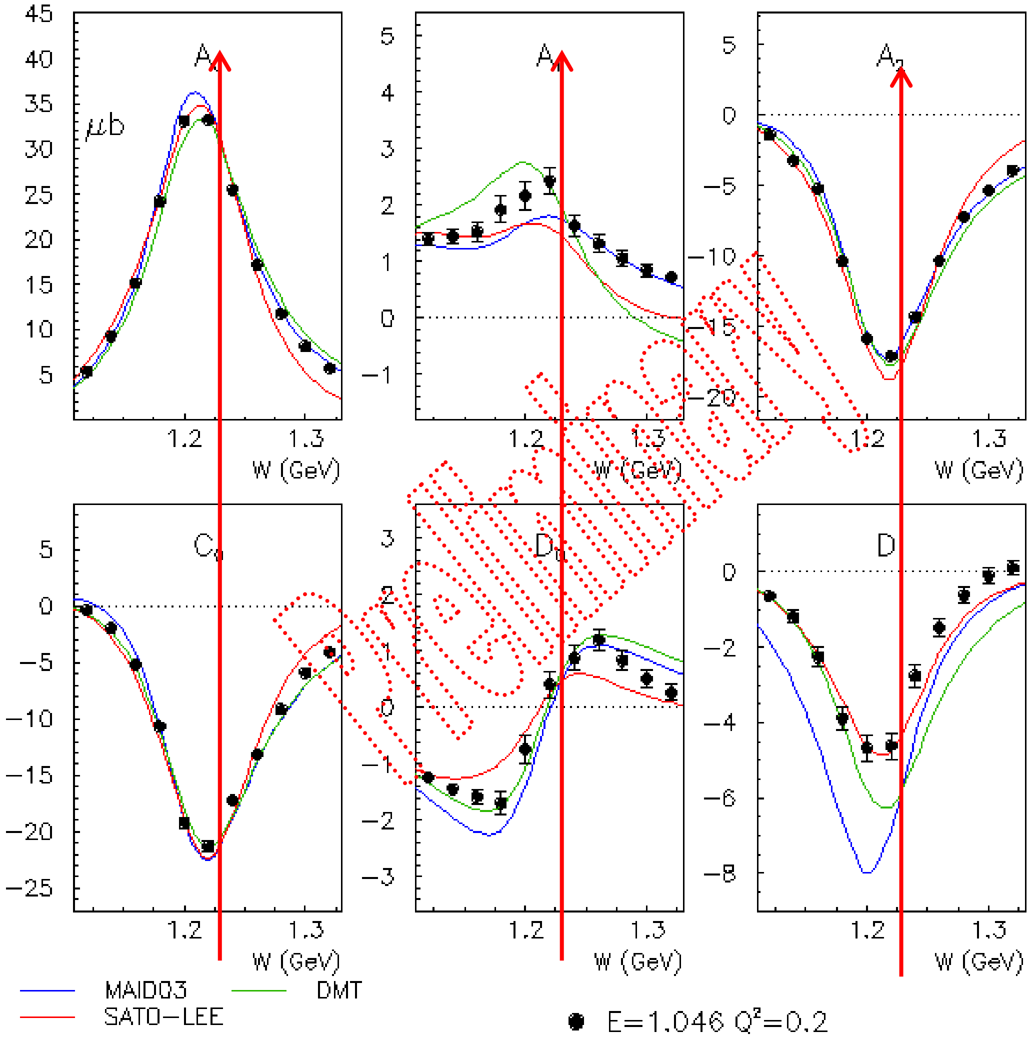


$|M_{1+}|^2(1-3/5\cos^2\theta)$

$-|M_{1+}|^2-2\mathrm{Re}(M_{1+}E_{1+}^*)$

$A+6\cos\theta\mathrm{Re}(M_{1+}S_{1+}^*)$

Legendre Expansion of Structure Functions



$$\sigma_T + \varepsilon_L \sigma_L = A_0 + A_1 P_1 + A_2 P_2$$
$$\sigma_{TT} = C_0$$
$$\sigma_{LT} = D_0 + D_1 P_1$$

(M_{1+} dominance)

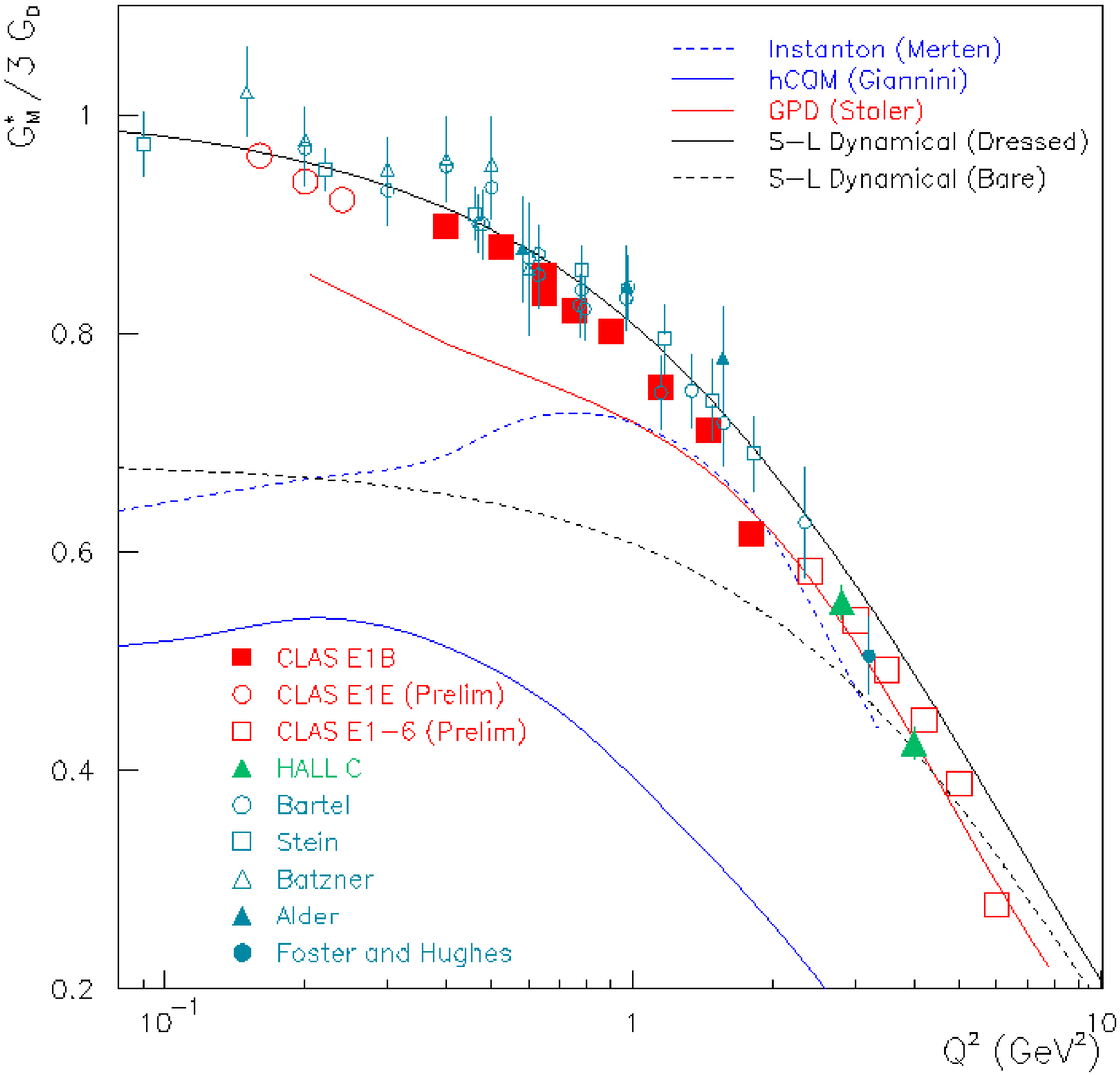
Resonant Multipoles

$$|M_{1+}|^2 = A_o / 2$$
$$\mathrm{Re}(E_{1+}M_{1+}^*) = \left(A_2 - 2C_0/3\right)/8$$
$$\mathrm{Re}(S_{1+}M_{1+}^*) = D_1/6$$

Non-Resonant Multipoles

$$\mathrm{Re}(E_{0+}M_{1+}^*) = A_1/2$$
$$\mathrm{Re}(S_{0+}M_{1+}^*) = D_0$$
$$\mathrm{Re}(M_{1-}M_{1+}^*) = -\left(A_2 + 2\left(A_0 + C_0\right)\right)/8$$

Electroproduction of △(1232)



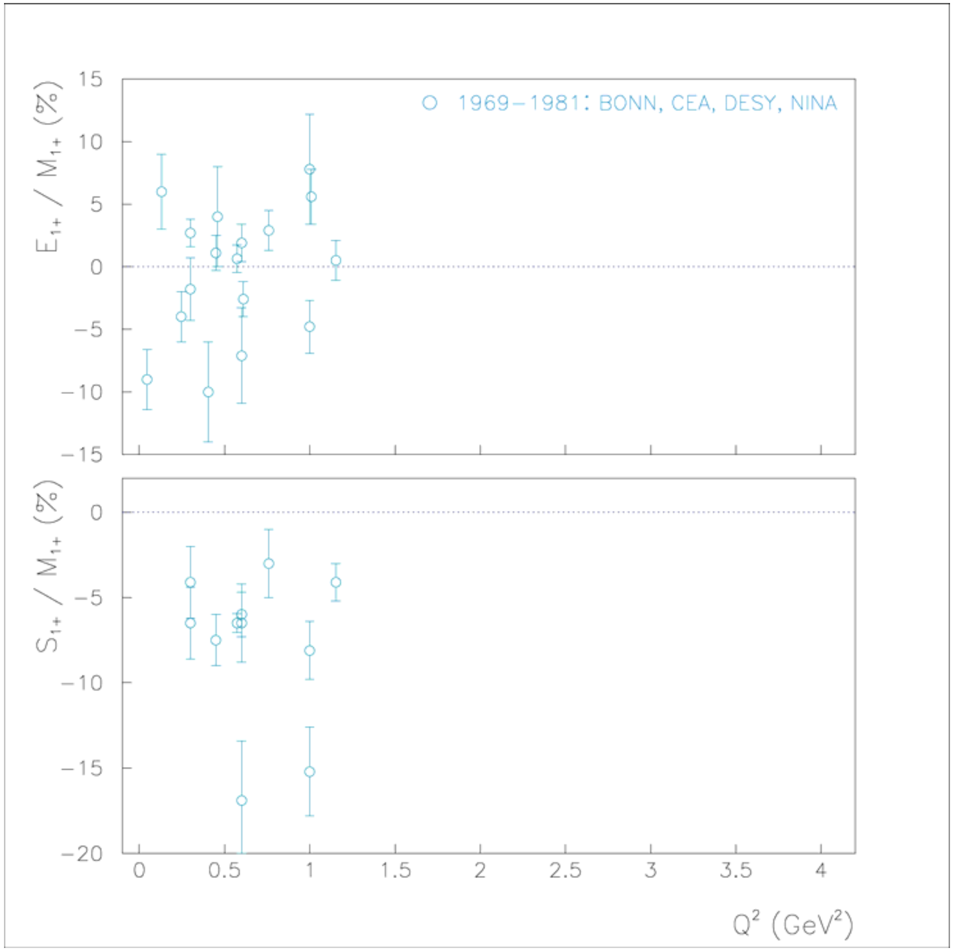
$Im(M_{1+}) \Rightarrow G^*_M$

Recent quark models still fall short at low Q^2

Missing $q\bar{q}$ strength?

Sea quarks?

Multipole Ratios R_{EM}, R_{SM} before 1999

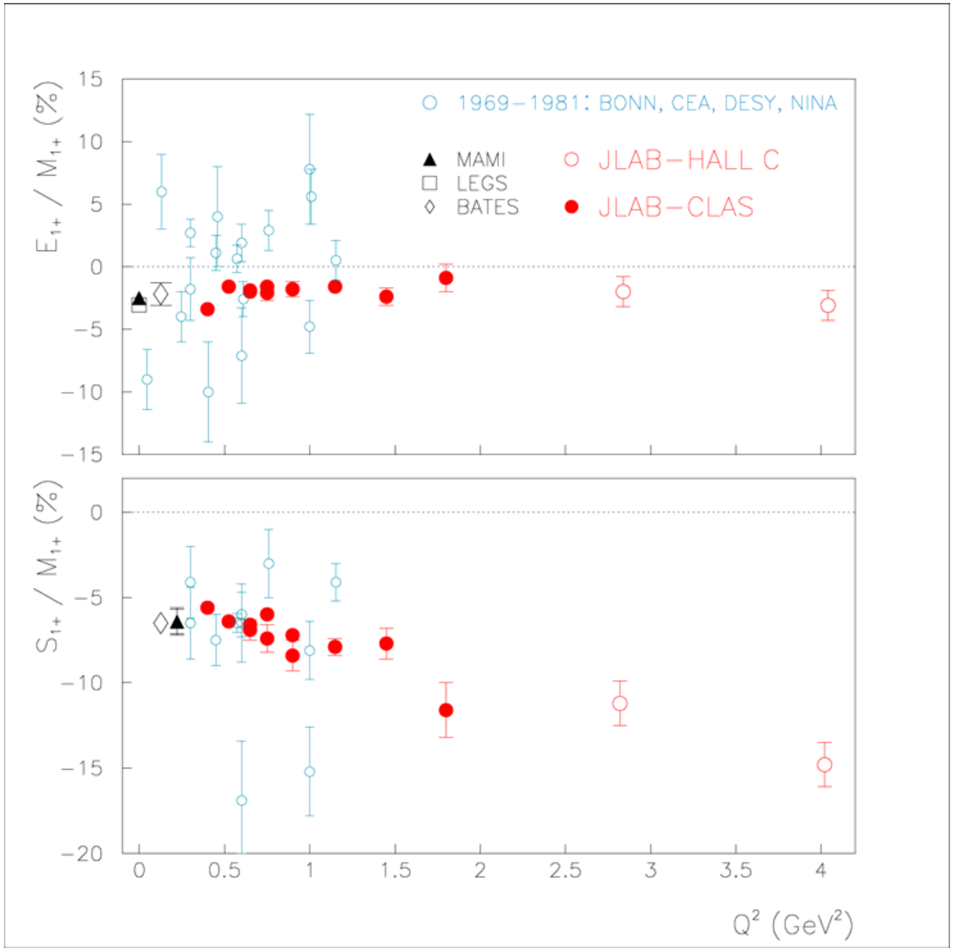


Sign?

Q^2 dependence?

- Data could not determine sign or Q^2 dependence

Multipole Ratios R_{EM}, R_{SM} in 2002



Sign?

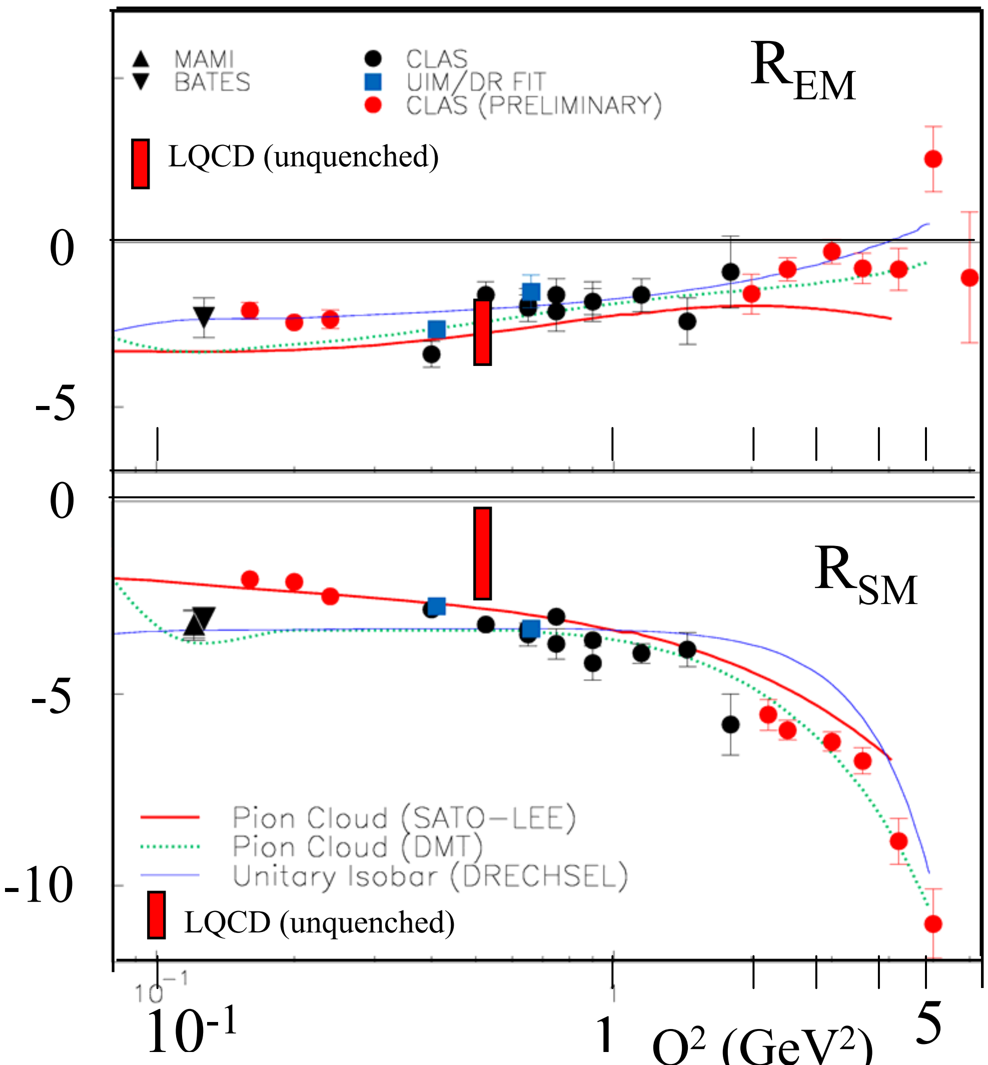
< 0 !

Q^2 dependence

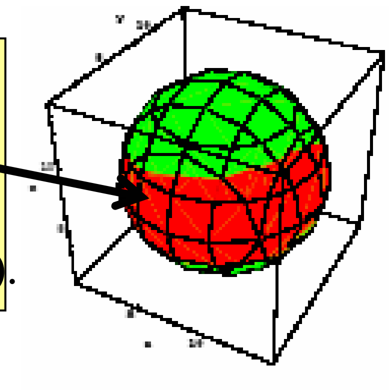
Slope < 0 !

- No trend towards zero crossing and pQCD behavior is observed for Q^2 up to 4 GeV^2.

R_{EM}, R_{SM} in 2004

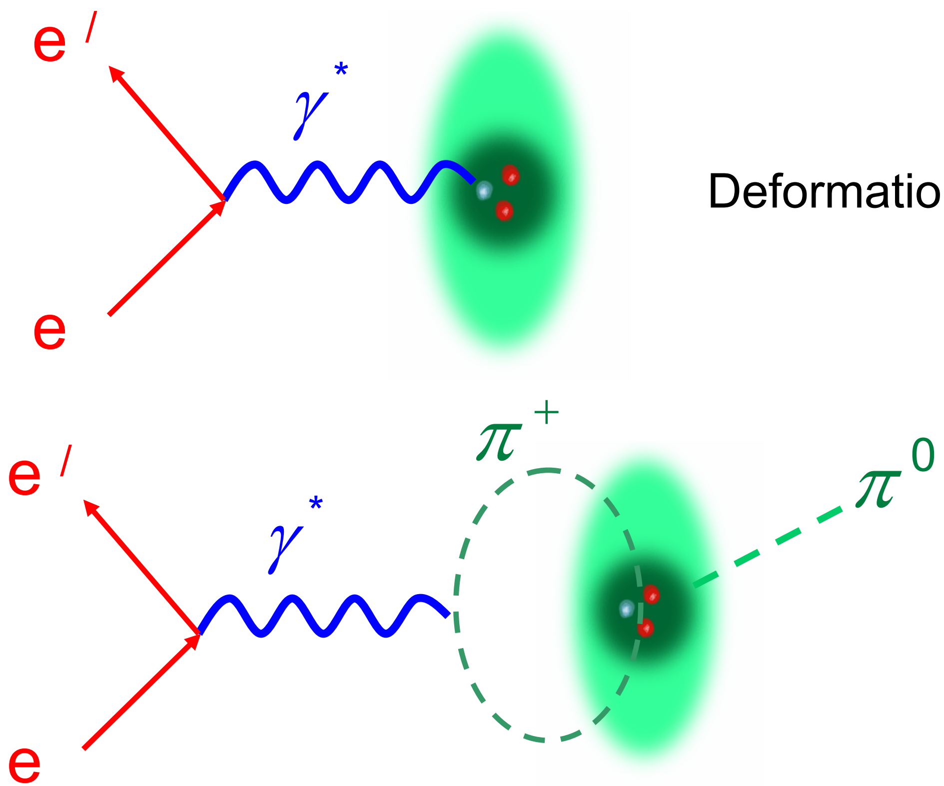


Deviation from spherical symmetry of the Δ(1232) in LQCD (unquenched).



Dynamical models attribute the deformation to contributions of the pion cloud at low Q^2.

What does empirical E_{1+}/M_{1+} ratio measure?



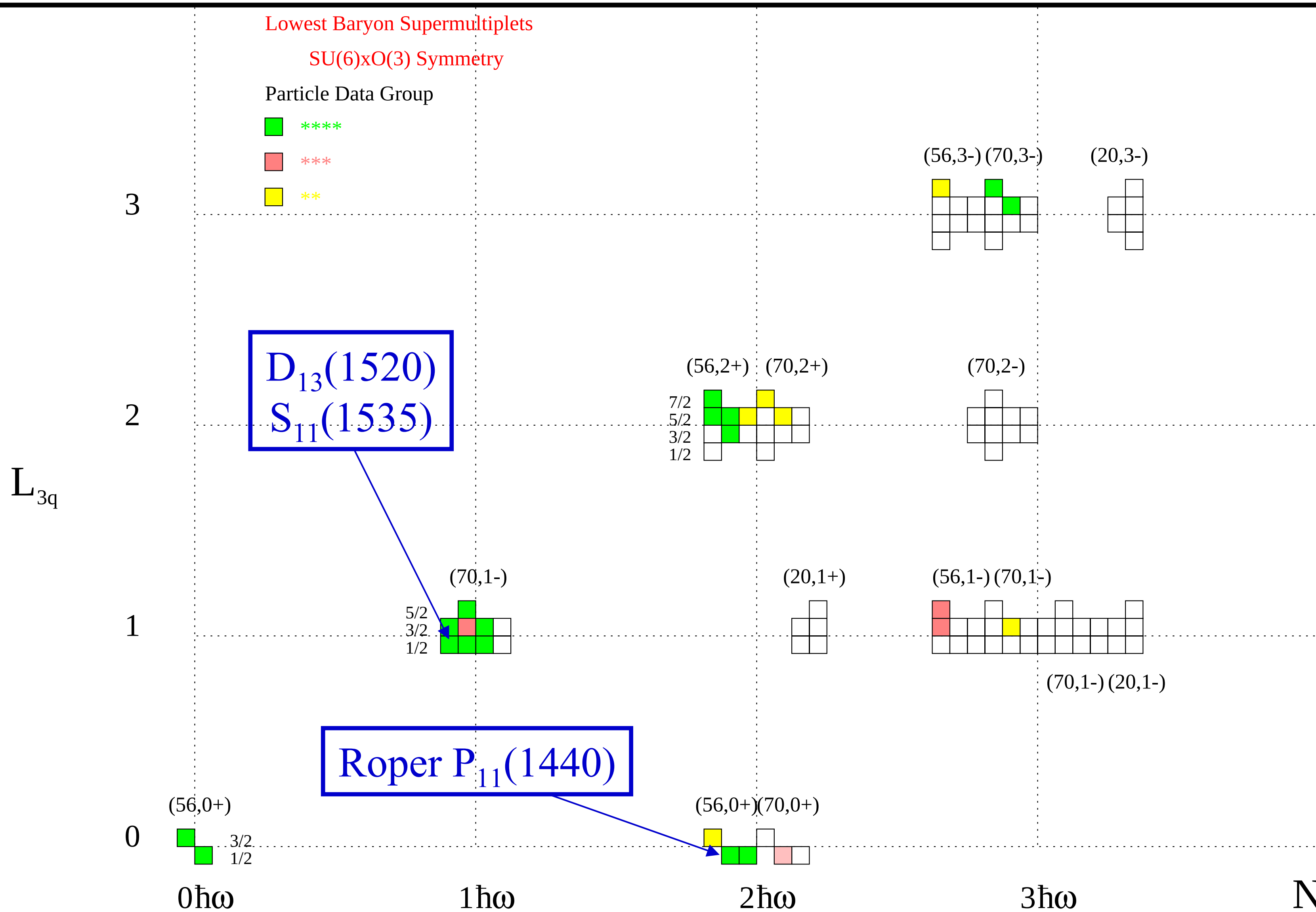
Deformation of N,△ quark core?

Shape of pion cloud?

Answer will depend on wavelength of probe.
With increasing resolution, we are mapping out the shape of the Δ vs. the distance scale.

The nature of the Roper $P_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$

SU(6)xO(3) Classification of Baryons



What are the issues?

$P_{11}(1440)$:

Poorly understood in nrCQMs
Alternative models:

- Light front kinematics (relativity)
- Hybrid baryon with gluonic excitation $|q^3G\rangle$
- Quark core with large meson cloud $|q^3m\rangle$
- Nucleon-sigma molecule $|N m\rangle$
- Dynamically generated resonance

$S_{11}(1535)$:

Hard form factor
Not a quark resonance, but $\bar{K}\Sigma$ dynamical system?

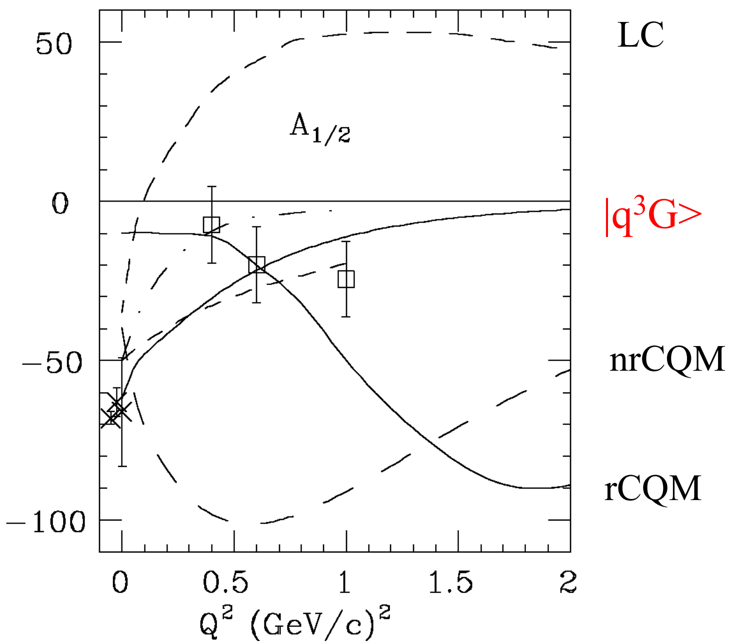
$D_{13}(1520)$:

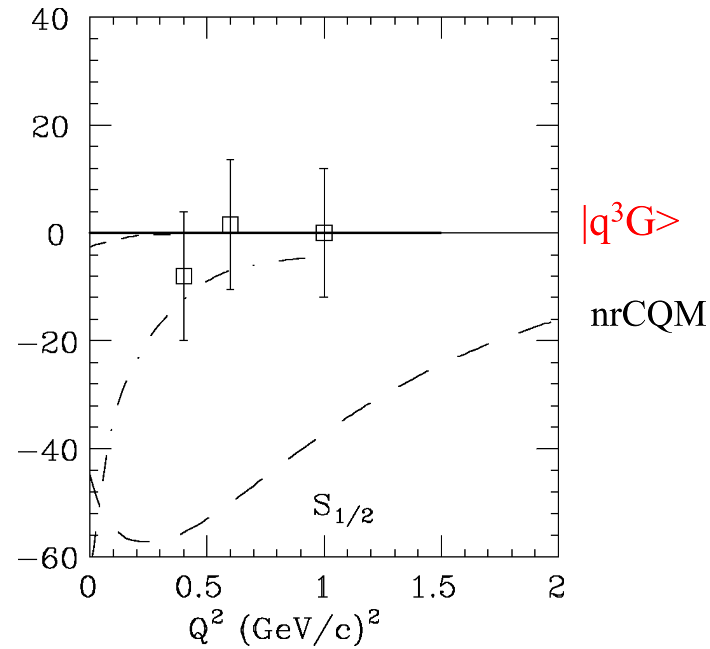
Change of helicity structure with increasing Q^2 from $\lambda=3/2$ dominance to $\lambda=1/2$ dominance, predicted in nrCQMs, pQCD.

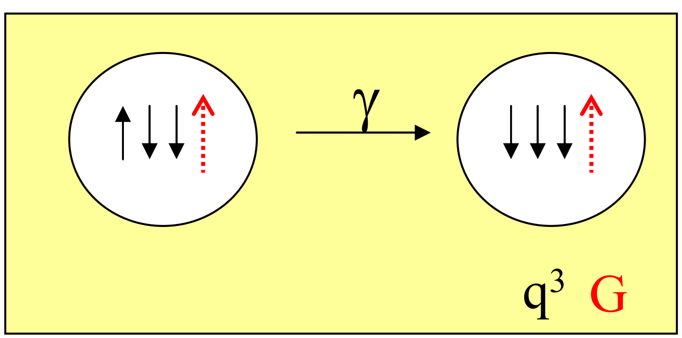
CQM: $$\frac{A_{1/2}^{D13}}{A_{3/2}^{D13}} = \frac{-1}{\sqrt{3}}\left(\frac{\vec{Q}^2}{\alpha^2} - 1\right)$$

Photocoupling Amplitudes of the $P_{11}(1440)$

(status of **2003**, data are from the 1970's & 80's, $p\pi^0$ cross sections only)





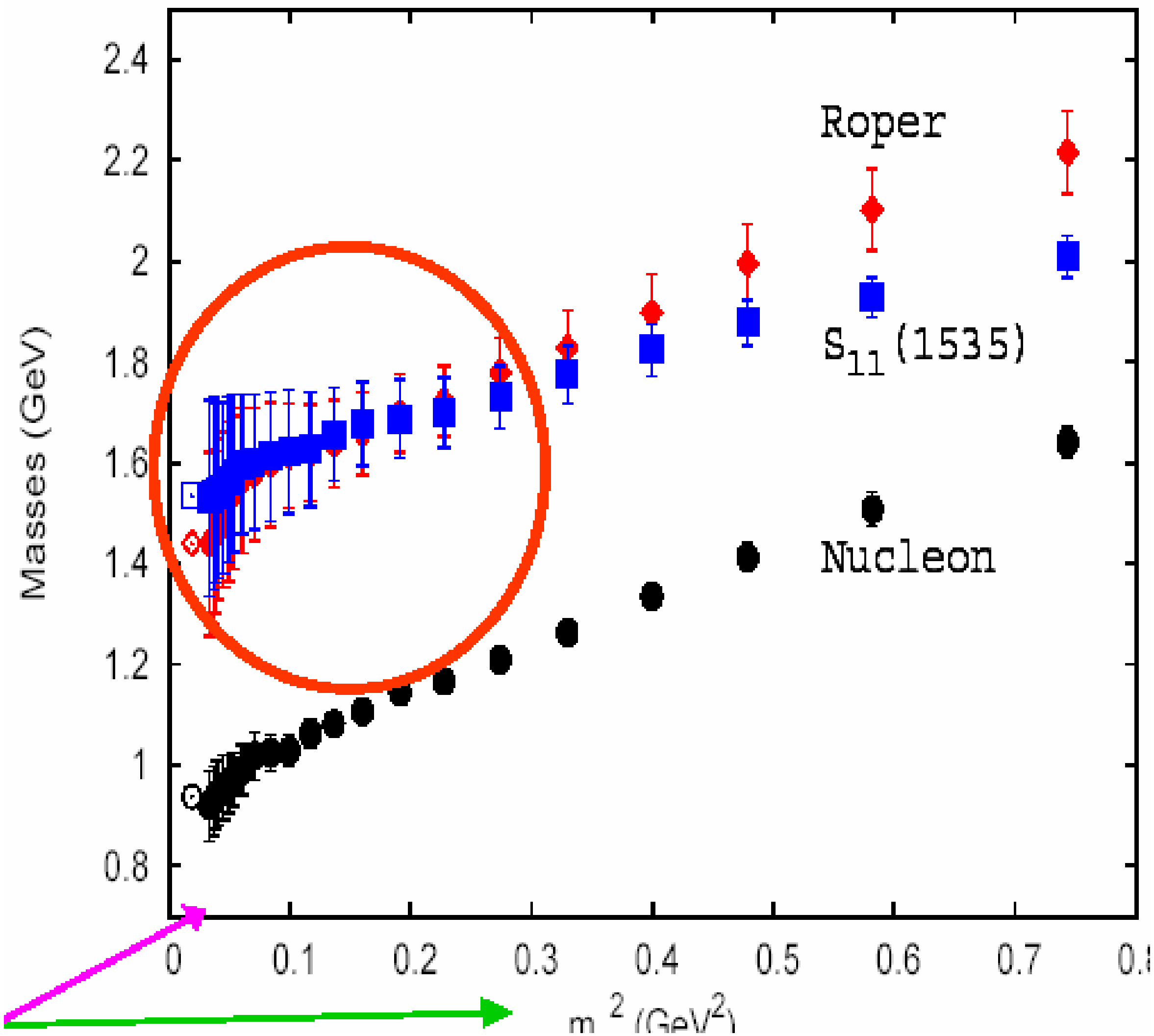


The failure of CQMs to describe the photocoupling amplitudes led to the development of the hybrid model $|q^3G>$. In non-rel. approximation $A_{1/2}(Q^2)$, $S_{1/2}(Q^2)$ behave like the $\Delta(1232)$ amplitudes.

Lattice calculations of $P_{11}(1440)$, $S_{11}(1535)$

=> Christine Davies

F. Lee, N*2004



Masses of both states well reproduced in quenched LQCD with 3 valence quarks.

Resonance analyses above the Delta.

- Above the $\Delta(1232)$ many multipoles can contribute.

- Resonance parameters are extracted in somewhat model-dependent fashion with approaches such as Unitary Isobar Models and Dispersion Relations, tuned to previous data.

- Parameterizations incorporate theoretical constraints such as known Born terms, unitarized amplitudes, and different isospin channels.

A detailed discussion of analyses approaches is given in:
V.Burkert, and T.S.-H. Lee, nucl-exp/0407020 (2004)

Global Analysis of Nucleon Resonances

- Based on **Unitary Isobar Model**.
- Includes all resonances seen in photoproduction PWA
- Breit-Wigner resonant amplitudes:

$$\boxed{A_{l\pm}(W) = a_{l\pm}\left(\frac{q_r}{q}\frac{k_r}{k}\frac{\Gamma_\pi\Gamma_\gamma}{\eta_\pi\,\Gamma}\right)^{1/2} \times \frac{M\Gamma}{M^2 - W^2 - iM\Gamma_{total}}}$$

- Fixed background from nucleon pole diagrams, *t*-channel pion, ρ- and ω-meson exchange.
- Regge behavior for $W^2 > 2.5$ GeV^2 with a smooth transition from UIM to Regge background:

$$\boxed{B_{tot} = B_{born}\frac{1}{1+(W-W_0)^2} + B_{regge}\frac{(W-W_0)^2}{1+(W-W_0)^2}}$$

- Phase modifications to resonant P_{33} amplitudes to satisfy Watson's theorem below 2-pion threshold.

Dispersion Relations

- Causality, analyticity constrain real and imaginary amplitudes:

$$\mathrm{Re}\, B_i^{(\pm,0)}(s,t,Q^2) = Born + \frac{P}{\pi}\int_{thr}^{\infty} \mathrm{Im}\, B_i^{(\pm,0)}(s',t,Q^2)\left(\frac{1}{s'-s} \pm \frac{1}{s'-u}\right) ds'$$

- Born term is nucleon pole in *s*- and *u*-channels and meson-exchange in *t*-channel.
- Dispersion integrals summed over 3 energy regions:

$$\int_{thr}^{\infty} ds' = \int_{thr}^{2.2GeV^2} ds' + \int_{2.2GeV^2}^{3GeV^2} ds' + \int_{3GeV^2}^{\infty} ds'$$

- Integrals over resonance region saturated by known resonances (Breit-Wigner). $P_{33}(1232)$ amplitudes found by solving integral equations.
- Integrals over high energy region are calculated through π,ρ,ω,b_1,a_1 Regge poles. However, these contributions were found negligible in Regions 1 and 2.
- For η channel, contributions of Roper $P_{11}(1440)$ and $S_{11}(1535)$ to unphysical region $s<(m_\eta+m_N)^2$ of dispersion integral included.

Isospin Amplitudes

- Nucleon resonances are eigenstates of isospin, with I = 1/2 , 3/2.
- Final states in electromagnetic meson production are not eigenstates of isospin.
- The photon transfers Δ I = 0, 1 resulting in 3 isospin amplitudes for π production:

T^s: Isoscalar, $I_{mN} = 1/2$

T_1^v: Isovector, $I_{mN} = 1/2$

T_3^v: Isovector, $I_{mN} = 3/2$

For π production from proton target:

$$\langle \pi^+ \mathrm{n} | T | \gamma_\mathrm{v} \mathrm{p} \rangle = \sqrt{\frac{1}{3}}\, T_3^\mathrm{v} - \sqrt{\frac{2}{3}}\, (T_1^\mathrm{v} - T^\mathrm{s}) \,,$$

$$\langle \pi^0 \mathrm{p} | T | \gamma_\mathrm{v} \mathrm{p} \rangle = \sqrt{\frac{2}{3}}\, T_3^\mathrm{v} + \sqrt{\frac{1}{3}}\, (T_1^\mathrm{v} - T^\mathrm{s}) \,,$$

Examples: P_{33} (1232), I = 3/2 => $\boldsymbol{T_3^v}$ contributes => $(\pi^+ n/\pi^0 p)^2 = 1/2$

P_{11} (1440), I = 1/2 => $\boldsymbol{T^s}$, $\boldsymbol{T_1^v}$ contribute => $(\pi^+ n/\pi^0 p)^2 = 2$

=> Need both channels to separate Δ and N* states

The Roper $P_{11}(1440)$ as a gluonic partner of the nucleon ?

Because gluonic baryons do not have "exotic" quantum numbers they must be distinguished from ordinary baryons in different ways.

" ... electromagnetic transition form factors are a powerful tool in distinguishing regular $|q^3>$ states from $|q^3G>$ states."

" … more complete data are needed to study the apparently strong Q^2 dependence of $A_{1/2}$ at small Q^2, and to establish more accurate values for the longitudinal coupling."

VB in: Czechoslovac Journal of Physics, Vol. 46, No. 7/8 (1996)

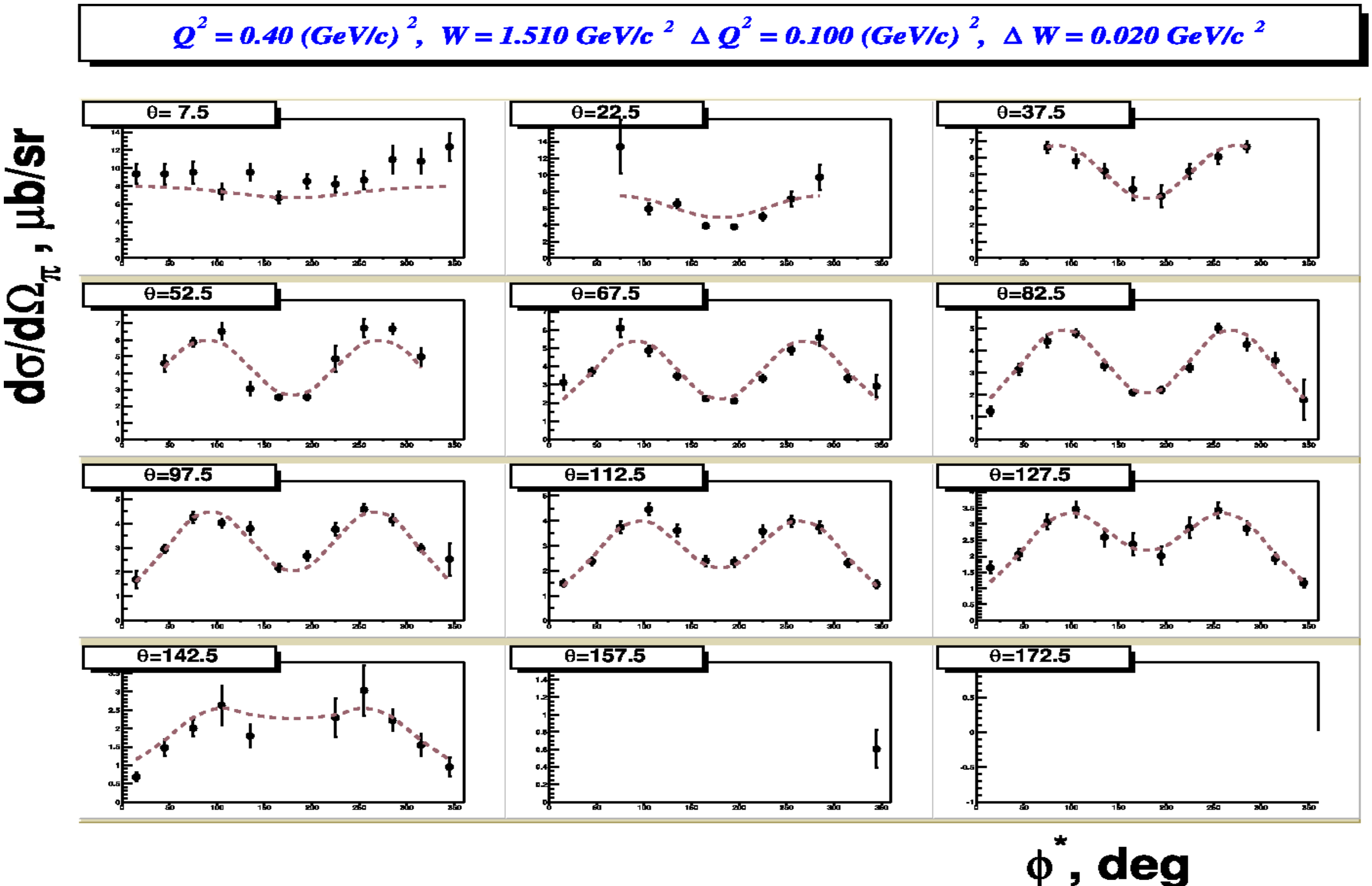
Fit Summary

data points:15,447 , E_e = 1.515, 1.645 GeV

Observable	Q^2	Data points	$\chi^2/data$ UIM	$\chi^2/data$ DR
$\frac{d\sigma}{d\Omega}(\pi^0)$	0.40	3530	1.22	1.21
	0.65	3818	1.22	1.39
$\frac{d\sigma}{d\Omega}(\pi^+)$	0.40	2308	1.69	1.97
	0.65	1716	1.48	1.75
$A_{LT'}(\pi^0)$	0.40	956	1.14	1.25
	0.65	805	1.07	1.30
$A_{LT'}(\pi^+)$	0.40	918	1.18	1.63
	0.65	812	1.18	1.15
$\frac{d\sigma}{d\Omega}(\eta)$	0.375	172	1.32	1.33
	0.750	412	1.42	1.45

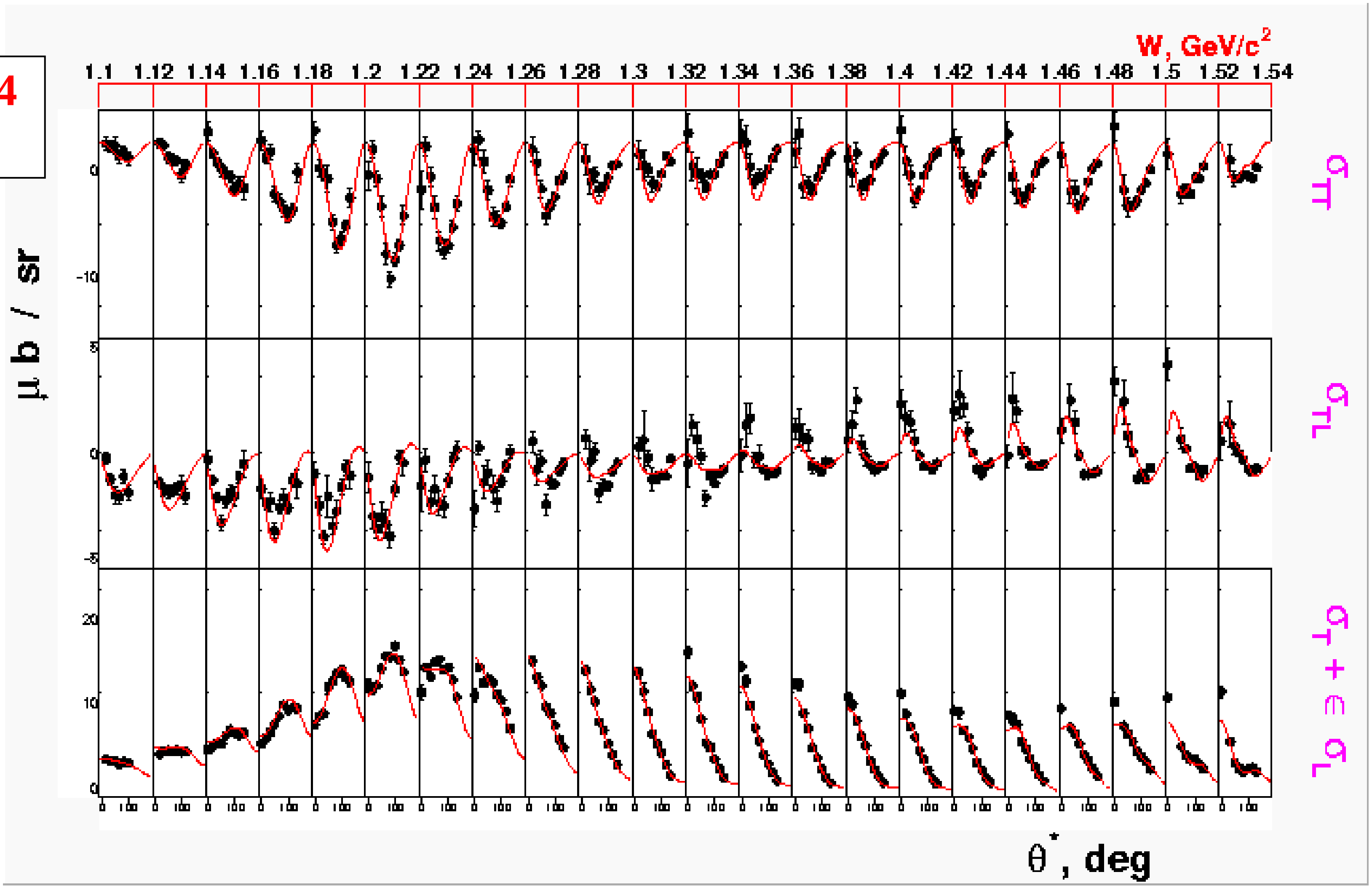
Fits for $ep \to en\pi^+$

$$\frac{d^2\sigma}{d\Omega_\pi^*} = \frac{p_\pi^*}{k_\gamma^*}\left(\sigma_T + \varepsilon_L \sigma_L + \varepsilon\,\sigma_{TT}\,\sin^2\theta_\pi^*\cos 2\phi_\pi^* + \sqrt{2\varepsilon_L(\varepsilon+1)}\,\sigma_{LT}\,\sin\theta_\pi^*\cos\phi_\pi^*\right)$$



Fits to Structure Functions $ep \longrightarrow en\pi^+$

Q^2=0.4 GeV^2

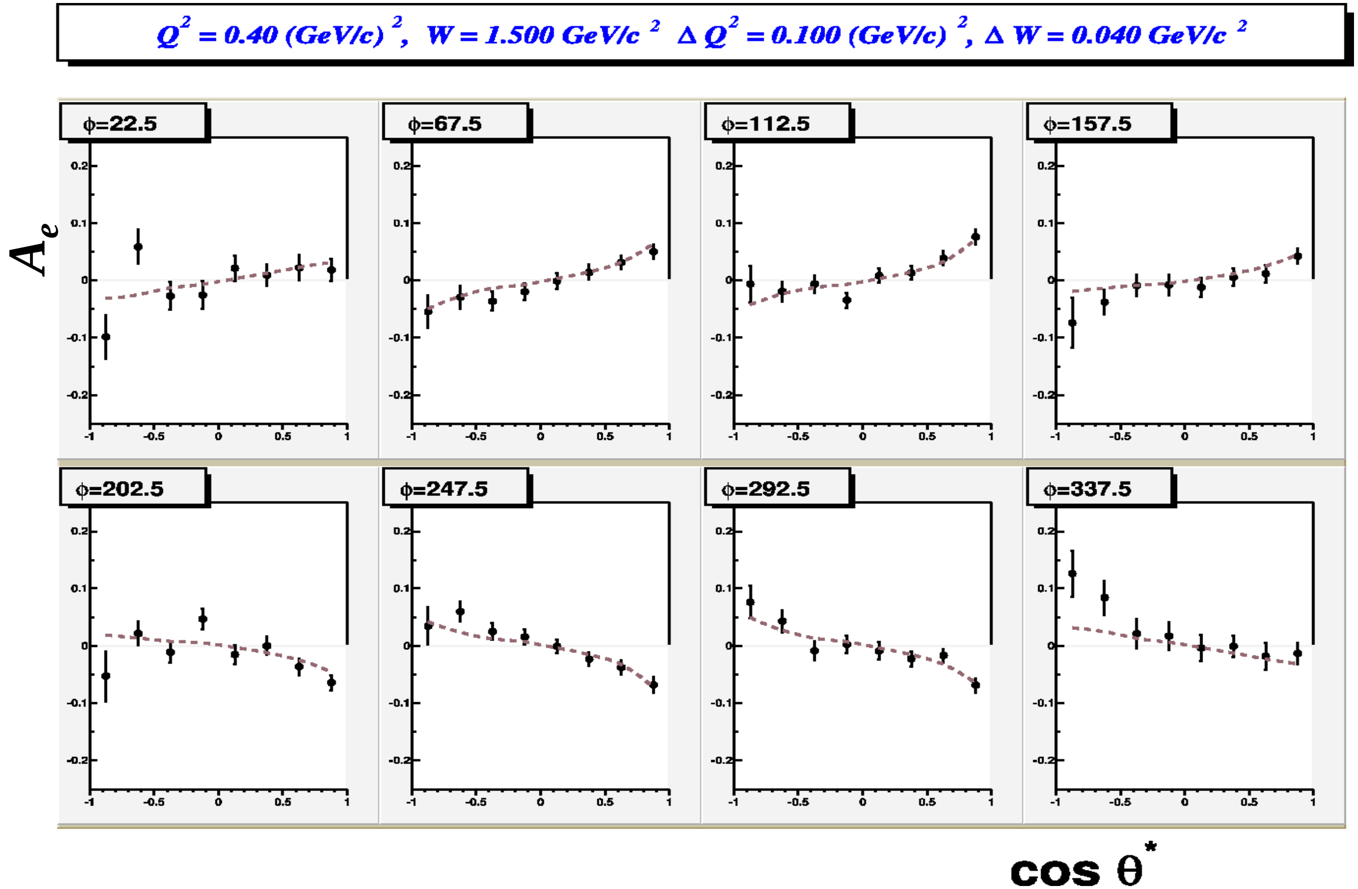


UIM Fits for $\vec{e}p \rightarrow en\pi^+$

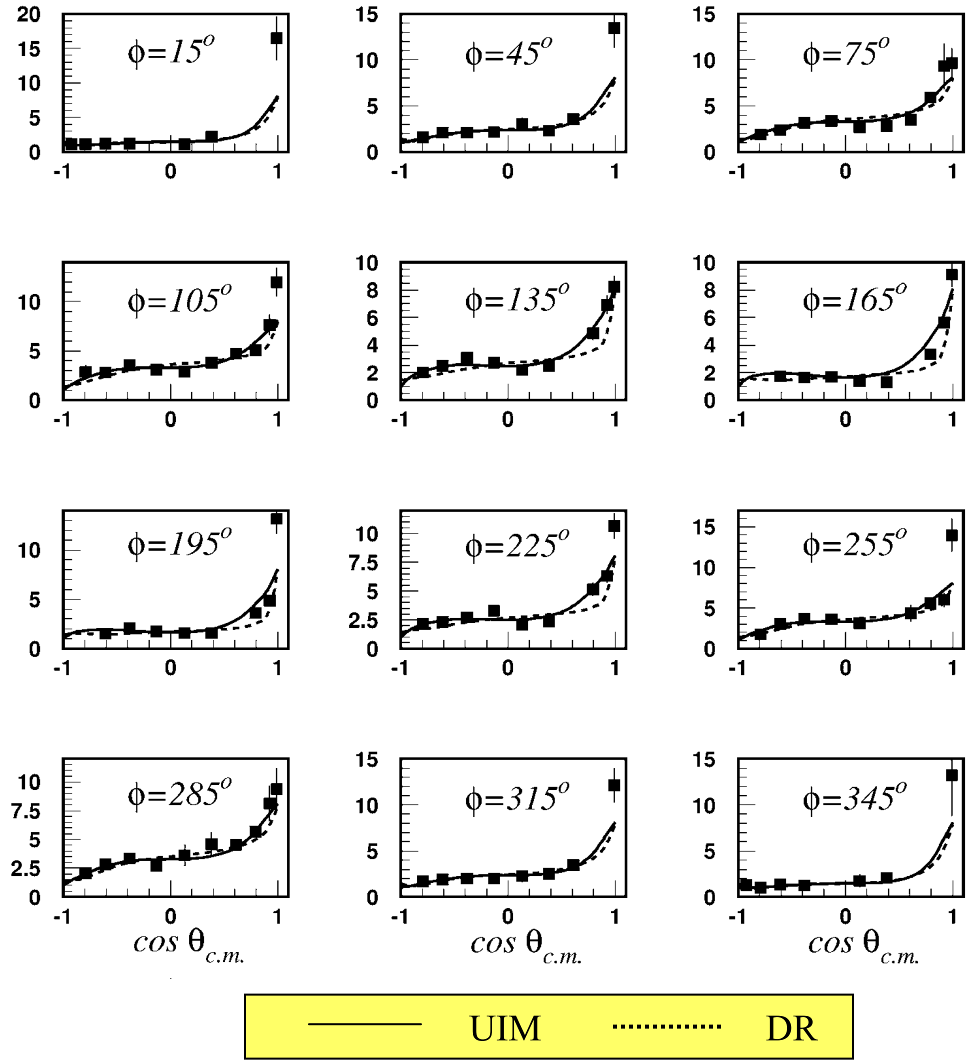
$$A_e = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$

Polarized beam $\Rightarrow$ $\pm h\sqrt{2\varepsilon_L(1-\varepsilon)}\,\sigma'_{LT}\,\sin\theta^*_\pi\,\sin\phi^*_\pi$

beam helicity



UIM vs DR Fits for $ep \rightarrow en\pi^+$



Q^2=0.4 GeV^2

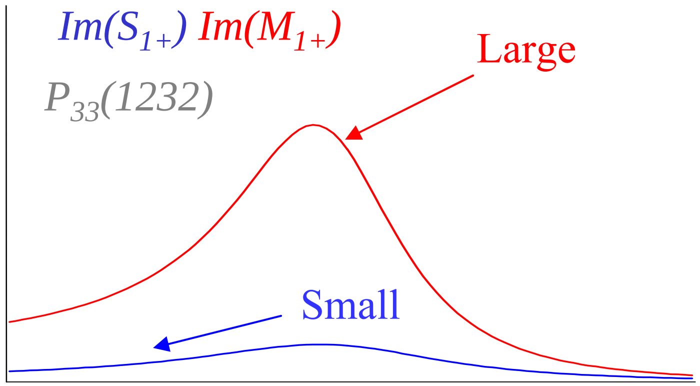
W = 1.53 GeV

Power of Interference II

- Unpolarized structure function

$$\sigma_{LT} \sim Re(L^*T) = Re(L)Re(T) + Im(L)Im(T)$$

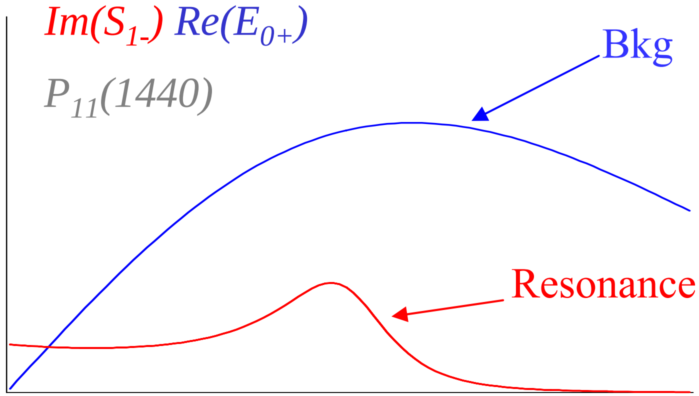
  – Amplify small resonance multipole by an interfering larger resonance multipole



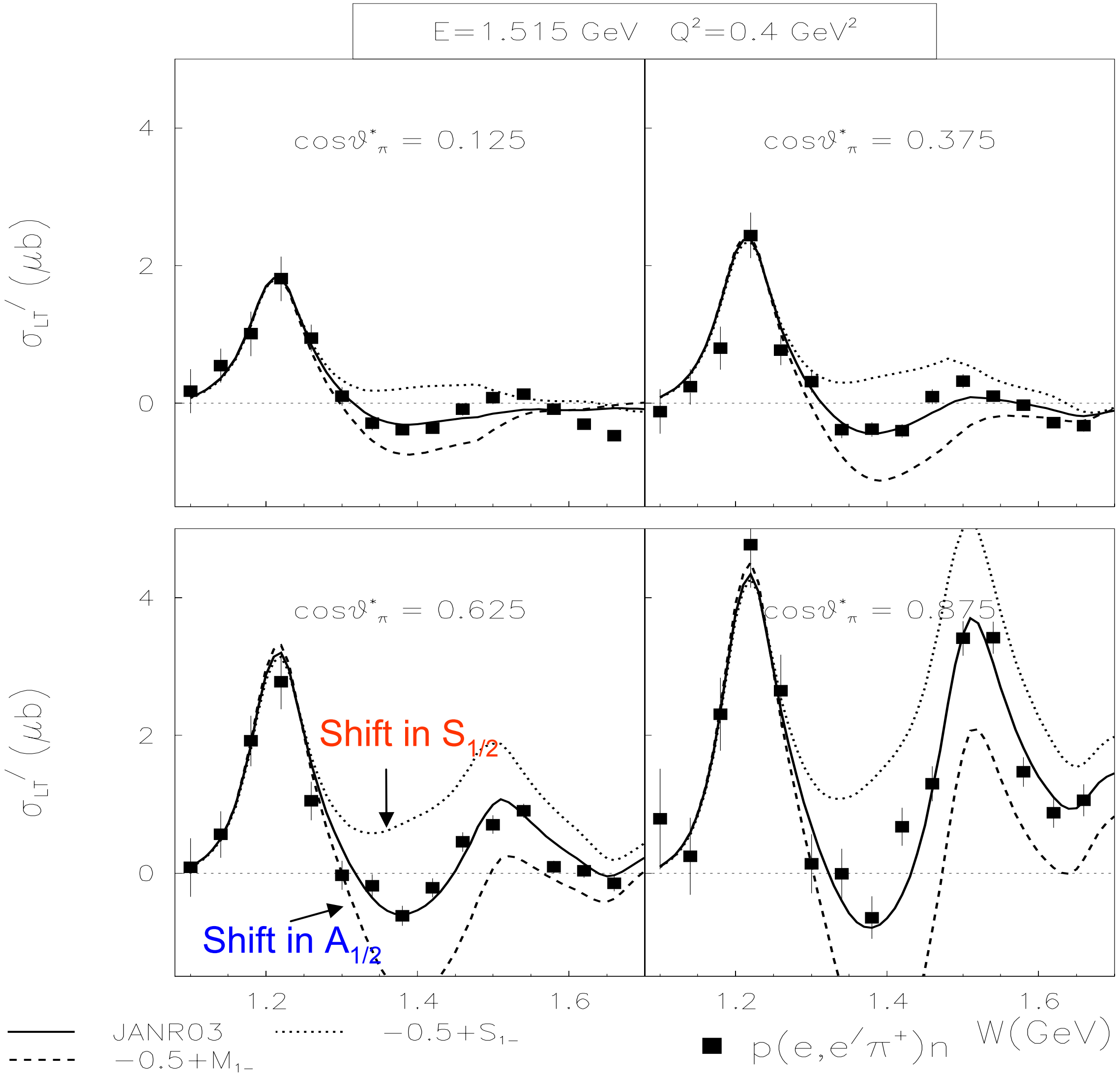
- Polarized structure function

$$\sigma_{LT'} \sim Im(L^*T) = Re(L)Im(T) + Im(L)Re(T)$$

  – Amplify resonance multipole by a large background amplitude



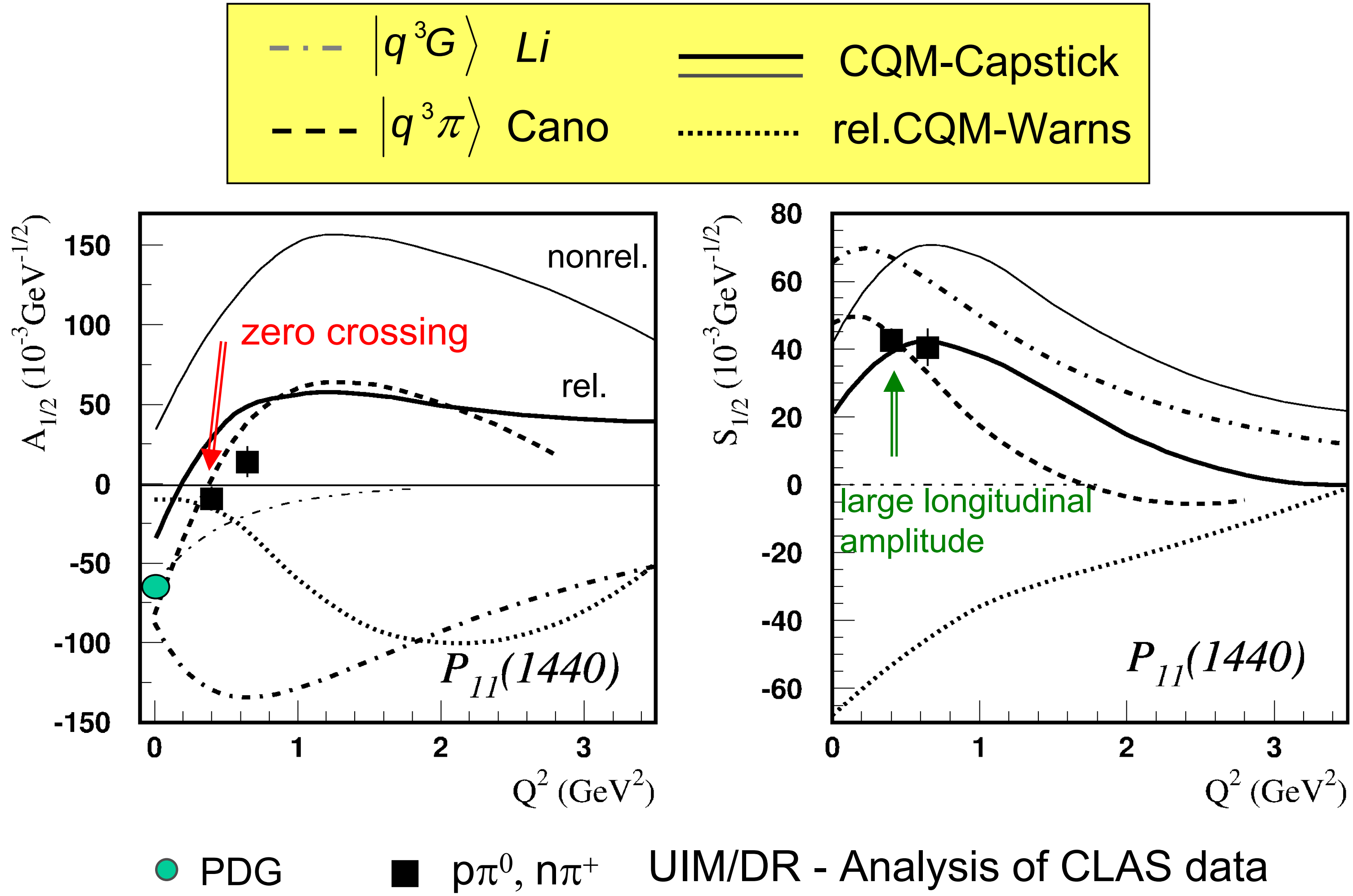
Sensitivity to $P_{11}(1440)$



$\vec{e}p \longrightarrow e\pi^+n$

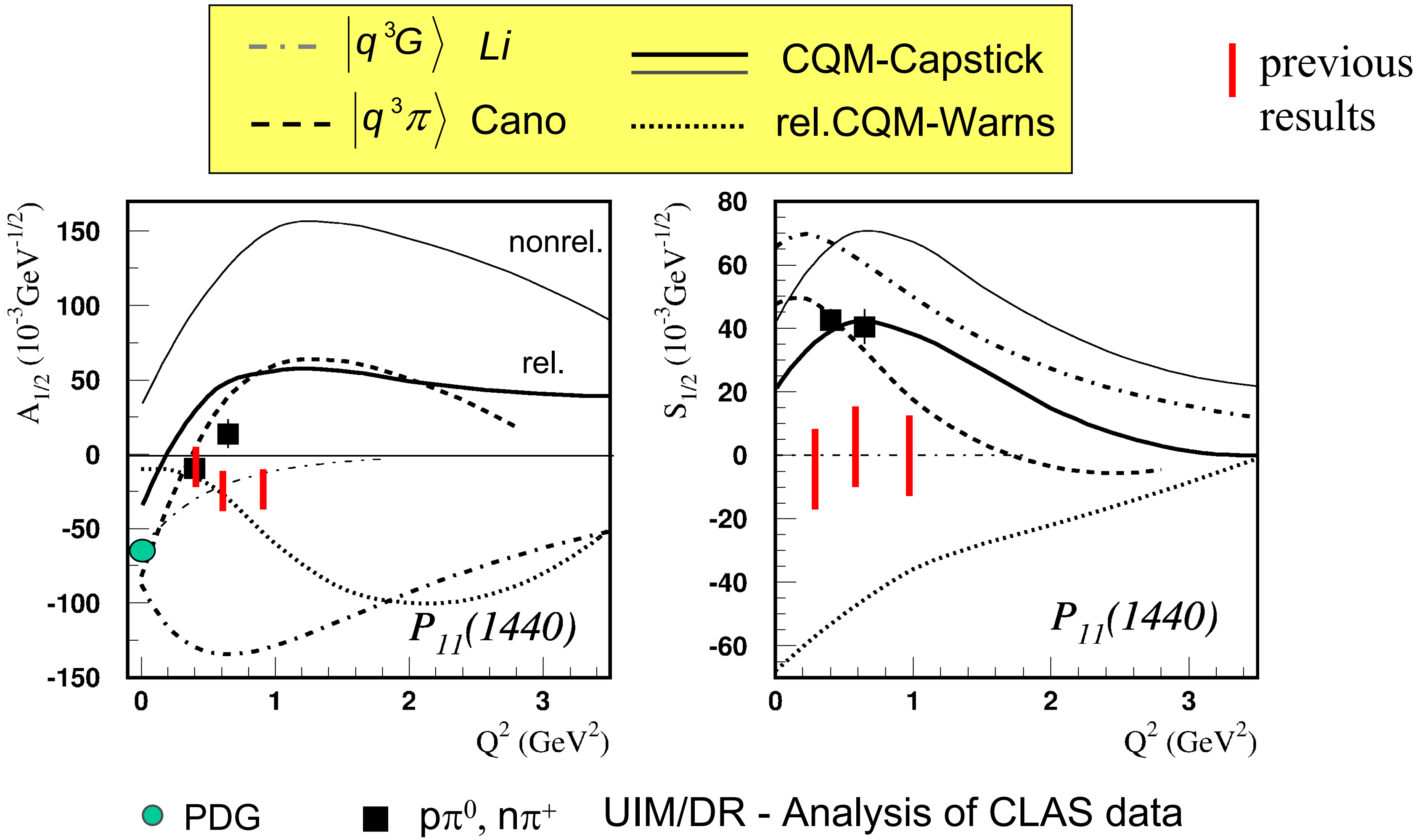
Polarized structure functions are sensitive to imaginary part of $P_{11}(1440)$ through interference with real Born background.

Roper $P_{11}(1440)$ - Electrocoupling amplitudes



Meson contribution or relativity are needed to describe data.

Roper $P_{11}(1440)$ - Electrocoupling amplitudes



UIM/DR - Analysis of CLAS data

Meson contribution or relativity are needed to describe data.

Comments on the Roper results

- LQCD shows a 3-quark component. Does it exclude a meson-nucleon resonance?

- Roper resonance transition formfactors not described in non-relativistic CQM. If relativity (LC) is included the description is improved.

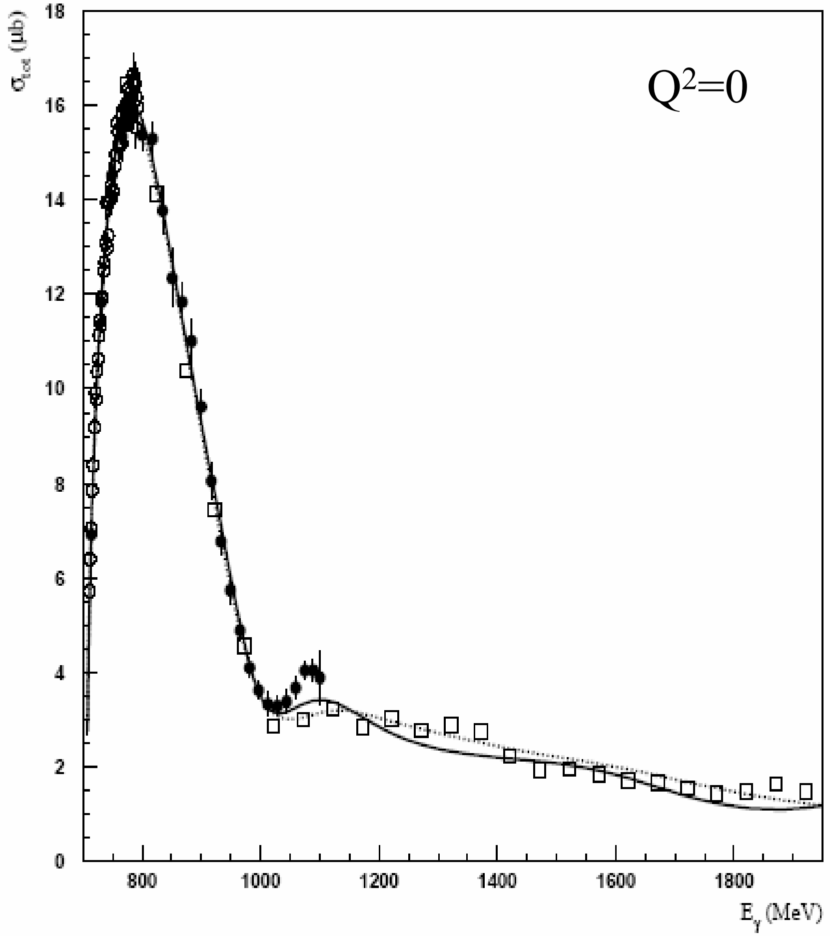
- Best description in model with large meson cloud.

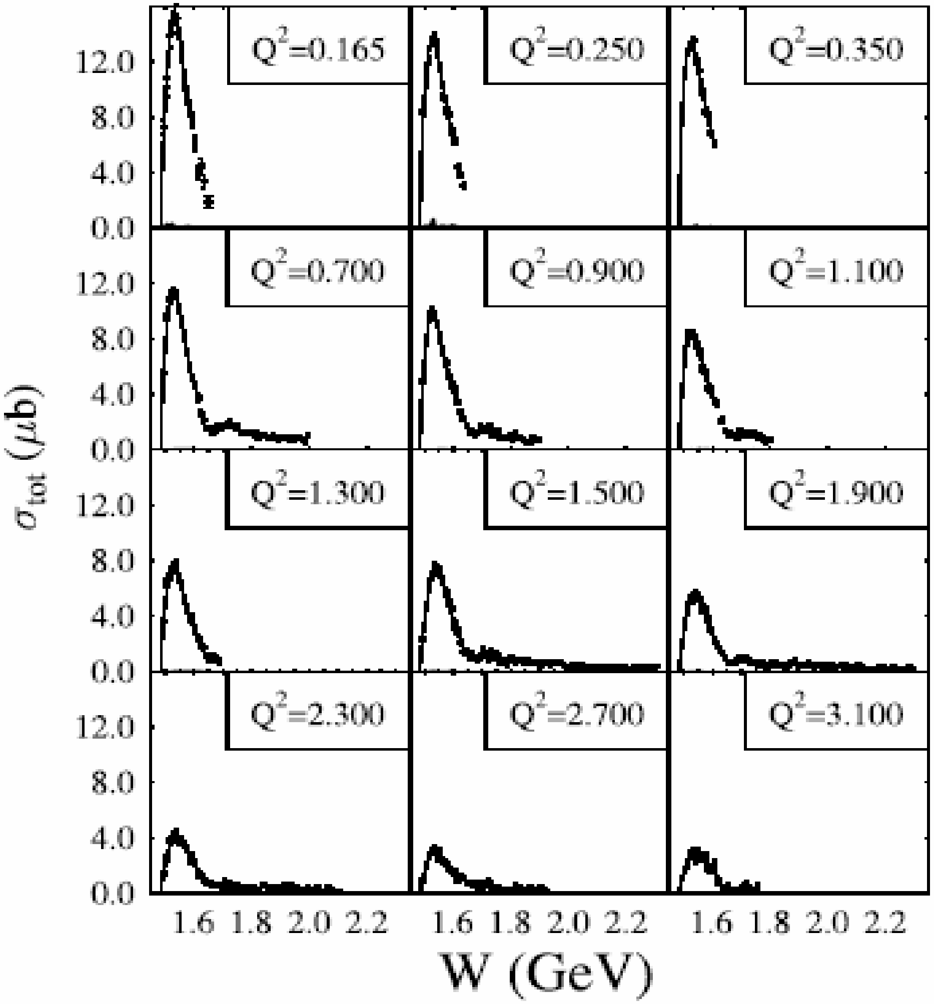
- Gluonic excitation, i.e. a hybrid baryon, seems ruled out due to strong longitudinal coupling.

- Other models need to predict transition form factors as a sensitive test of internal structure.

The $S_{11}(1535)$ – an isolated resonance

$S_{11} \longrightarrow p\eta$ (~55%)





The $S_{11}(1535)$ – an isolated resonance

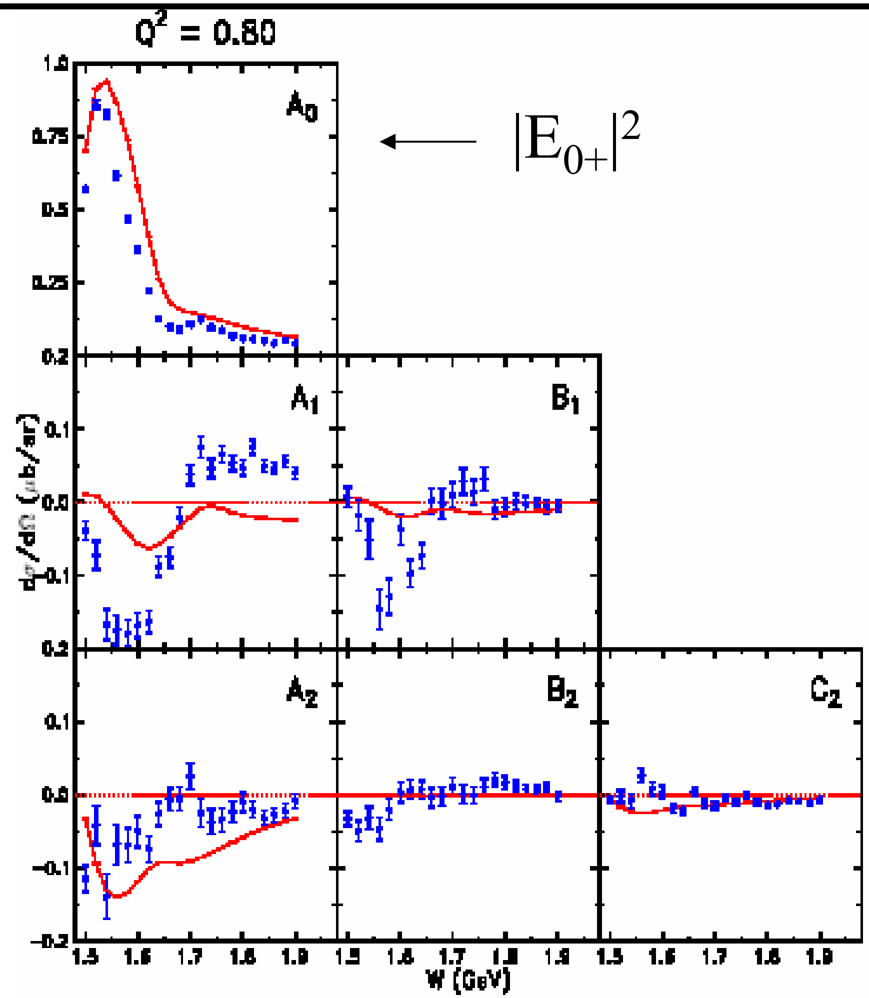
Use same approximation as for the $\Delta(1232)$.

$$\frac{d\sigma_T}{d\Omega^*_\eta} + \epsilon\frac{d\sigma_L}{d\Omega^*_\eta} = \sum_{\ell=0}^{\infty} A_\ell P_\ell(\cos\theta^*_\eta)$$

$$\sqrt{2\epsilon(\epsilon+1)}\frac{d\sigma_{LT}}{d\Omega^*_\eta} = \sum_{\ell=1}^{\infty} B_\ell P'_\ell(\cos\theta^*_\eta)$$

$$\epsilon\frac{d\sigma_{TT}}{d\Omega^*_\eta} = \sum_{\ell=2}^{\infty} C_\ell P''_\ell(\cos\theta^*_\eta)$$

For $l_{max}=2$

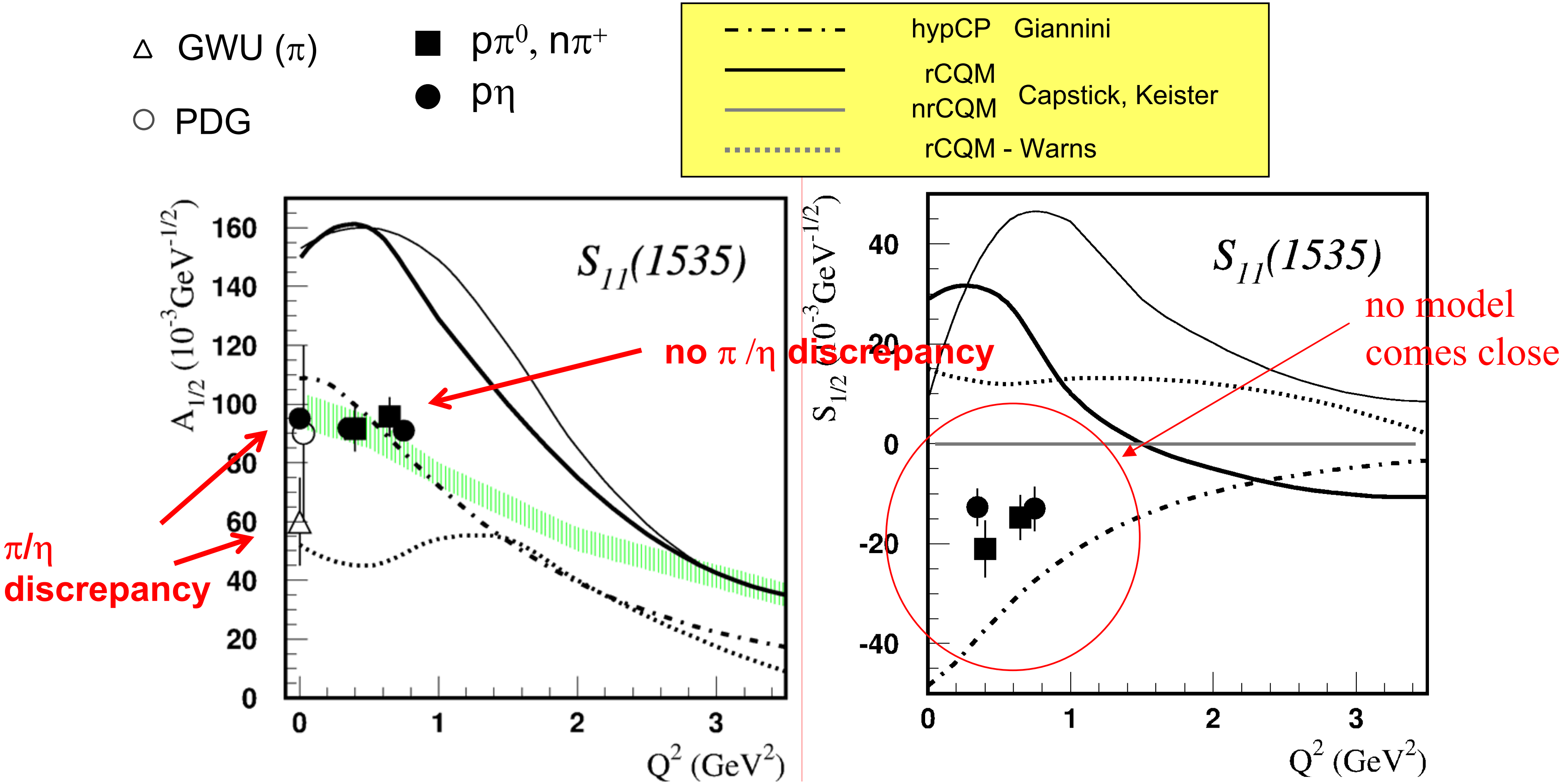


$|E_{0+}|^2$

There is no interference between the resonant multipoles E_{0+} and S_{0+} in this approximation. Assume S_{0+} is small, use resonance approximation to extract $|E_{0+}|$ => $A_{1/2}$.

$S_{11}(1535)$ - Electrocoupling amplitudes

UIM/DR - Analysis of CLAS data



Power of Interference III

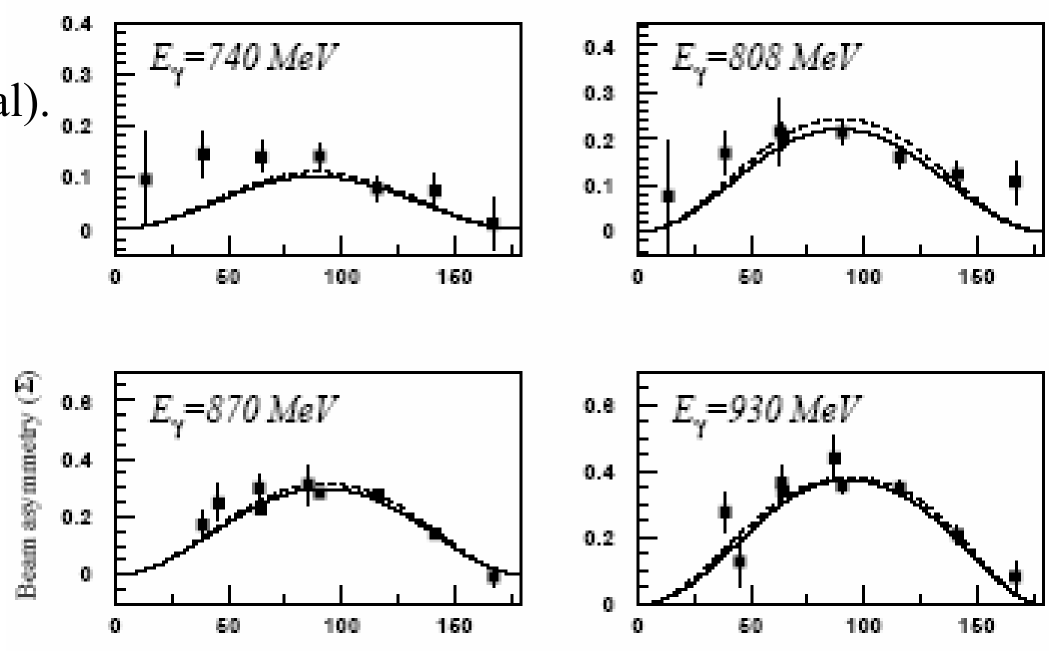
$\vec{\gamma}\, p \longrightarrow p\eta$

- Measuring the small $D_{13} \longrightarrow p\eta$ and $F_{15} \longrightarrow p\eta$ branching ratios with linearly polarized photons, Σ_γ (real) or σ_{TT} (virtual).

- The D_{13} is known to have a very small coupling to $p\eta$. But how small is it?

The beam asymmetry can be expressed in terms of multipoles:

$$\boxed{\Sigma_\gamma \approx \frac{3\sin^2\theta Re[E^*_{0+}(E_{2-}+M_{2-})]}{|E_{0+}|^2}}$$

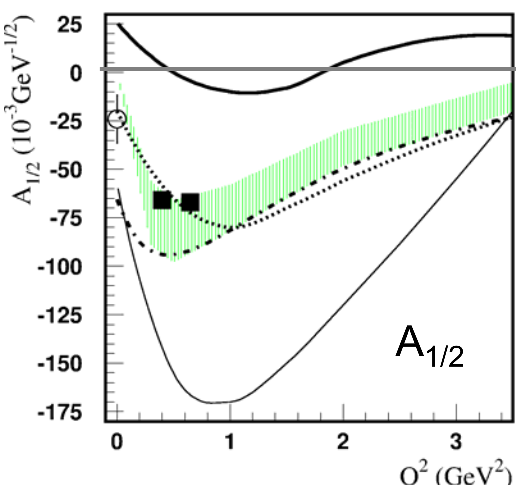


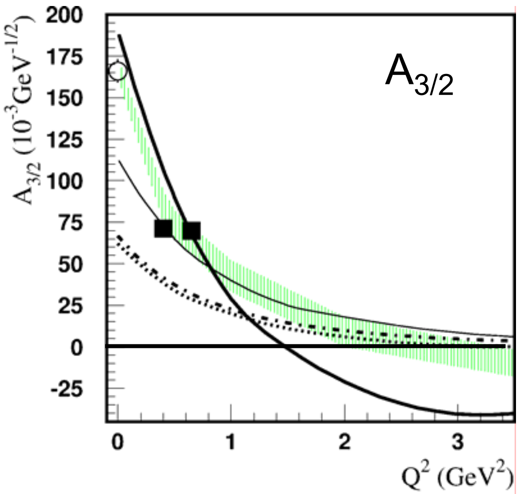
The E_{0+} multipole is known from the S_{11} resonance analysis described earlier, and the η - multipoles $E_{2-}+M_{2-}$ of the D_{13} can be determined. The angular distributions show a $\sin^2\theta$ dependence.

The F_{15} b.r. can be determined by fitting the distortion from the $\sin^2\theta$ distribution at the F_{15} mass.

Resonance	Mass(MeV)	$\Gamma(MeV)$	$\beta_{\eta N}(\%)$	$\beta_{\pi N}(\%)$
$D_{13}(1520)$	1520	120	0.05 ± 0.02	50 - 60
$F_{15}(1680)$	1675	130	0.15 ± 0.03	60 - 70

$D_{13}(1520)$ – Electrocoupling amplitudes

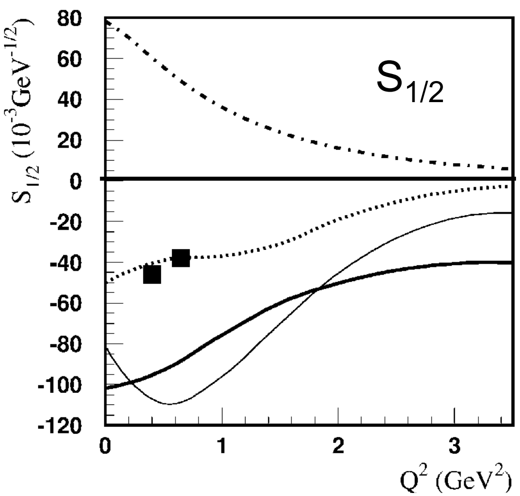




CQM prediction:

$$\frac{A_{1/2}^{D13}}{A_{3/2}^{D13}} = -\frac{1}{\sqrt{3}}\left(\frac{\vec{Q}^2}{\alpha^2} - 1\right)$$

$A_{1/2}$ dominance at high Q^2.



- · - · - ·	hypCP	Giannini
———	rCQM	Capstick, Keister
———	nrCQM	Capstick, Keister
············	rCQM - Warns	

○ PDG average

UIM/DR - Analysis of CLAS data

■ $p\pi^0$, $n\pi^+$

$A_{1/2}/A_{3/2} \sim Q^2$

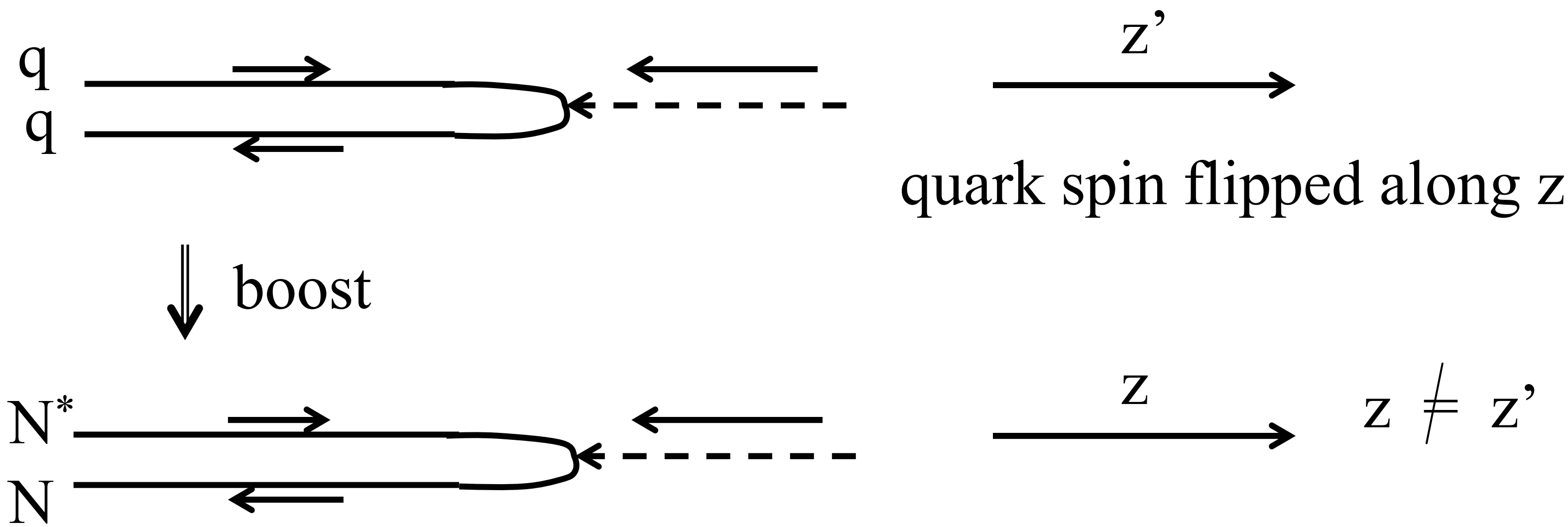
at large Q^2, consistent with pQCD prediction.

Single Quark Transition Model

(F. Close, Quarks and Partons)

Basic process: $\gamma q \rightarrow q$

In a frame where the process is collinear:



$\gamma q \longrightarrow q$ not collinear along z => σ_z **and** L_z can be flipped

Single Quark Transition Model

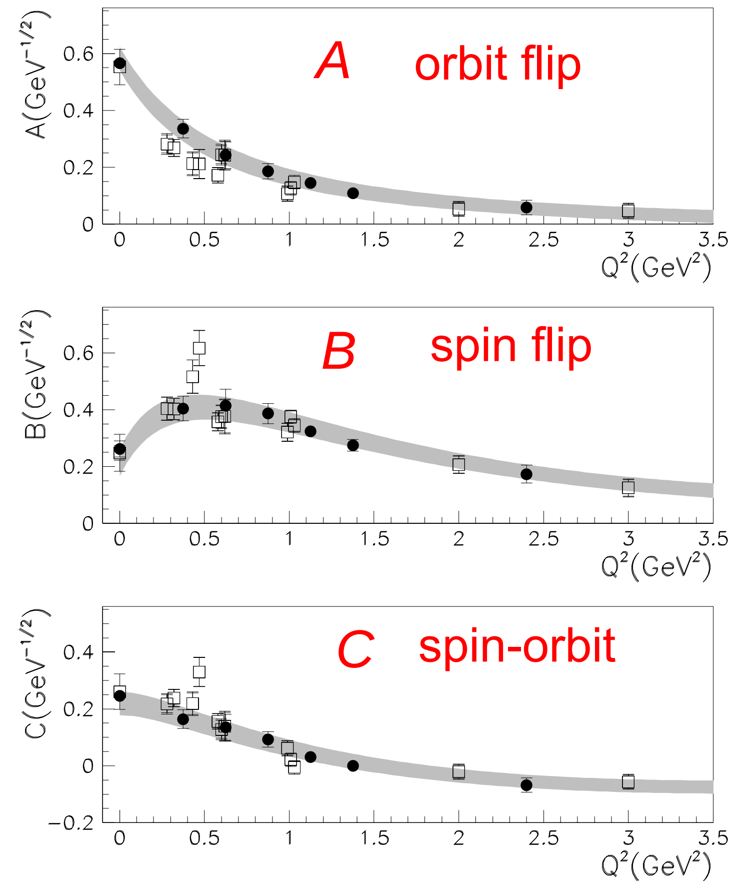
EM transitions between all members of two SU(6)xO(3) multiplets expressed as 4 reduced matrix elements *A,B,C,D.*

$$J^{+} = A L^{+} + B\,\sigma^{+} L_z + C\,\sigma_z L^{+} + D\,\sigma^{-} L^{+} L^{+}$$

$\Delta L_z = 1$ $\quad$ $\Delta S_z = 1$ $\quad$ $\Delta L_z = 1,\ \Delta S_z = 1$ $\quad$ $\Delta L_z = 2,\ \Delta S_z = 1$

Example: $\left[56, 0^{+}\right] \rightarrow \left[70, 1^{-}\right]$ $\quad$ (*D*=0)

Fit A,B,C to $D_{13}(1535)$ and $S_{11}(1520)$



$A_{3/2}$, $A_{1/2}$ ⟵ SU(6) Clebsch-Gordon ⟶ *A,B,C,D*

Predicts 16 amplitudes of same supermultiplet

Single Quark Transition Model

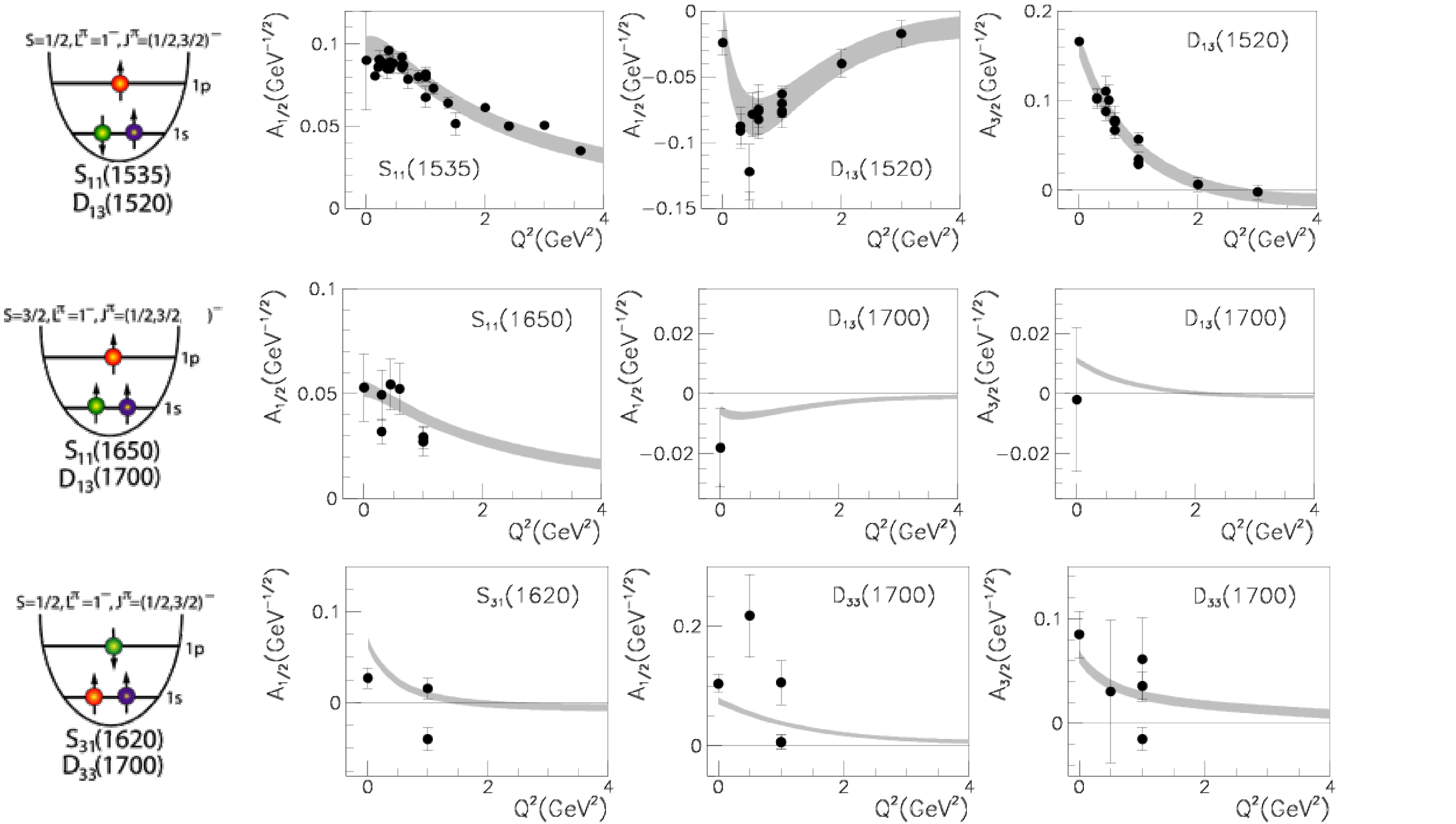
Photocoupling amplitudes $\Longleftrightarrow$ SQTM amplitudes

(C-G coefficients and mixing angles)

State	Proton target	Neutron target
$S_{11}(1535)$	$A^{+}_{1/2} = \frac{1}{6}(A+B-C)\cos\theta$	$A^{\circ}_{1/2} = -\frac{1}{6}(A+\frac{1}{6}B-\frac{1}{3}C)$
$D_{13}(1520)$	$A^{+}_{1/2} = \frac{1}{6\sqrt{2}}(A-2B-C)$	$A^{\circ}_{1/2} = -\frac{1}{18\sqrt{2}}(3A-2B-C)$
	$A^{+}_{3/2} = \frac{1}{2\sqrt{6}}(A+C)$	$A^{\circ}_{3/2} = \frac{1}{6\sqrt{6}}(3A-C)$
$S_{11}(1650)$	$A^{+}_{1/2} = \frac{1}{6}(A+B-C)\sin\theta$	$A^{\circ}_{1/2} = \frac{1}{18}(B-C)$
$D_{13}(1700)$	$A^{+}_{1/2} = 0$	$A^{\circ}_{1/2} = \frac{1}{18\sqrt{5}}(B-4C)$
	$A^{+}_{3/2} = 0$	$A^{\circ}_{3/2} = \frac{1}{6\sqrt{15}}(3B-2C)$
$D_{15}(1675)$	$A^{+}_{1/2} = 0$	$A^{\circ}_{1/2} = -\frac{1}{6\sqrt{5}}(B+C)$
	$A^{+}_{3/2} = 0$	$A^{\circ}_{3/2} = -\frac{1}{6}\sqrt{\frac{2}{5}}(B+C)$
$D_{33}(1700)$	$A^{+}_{1/2} = \frac{1}{6\sqrt{2}}(A-2B-C)$	same
	$A^{+}_{3/2} = \frac{1}{2\sqrt{6}}(A+C)$	same
$S_{31}(1620)$	$A^{+}_{1/2} = \frac{1}{18}(3A-B+C)$	same

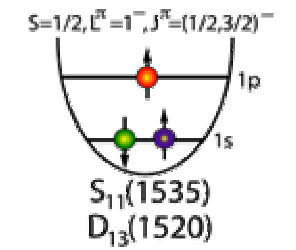
Single Quark Transition Model Predictions for $[56,0^+]\rightarrow[70,1^-]$ Transitions

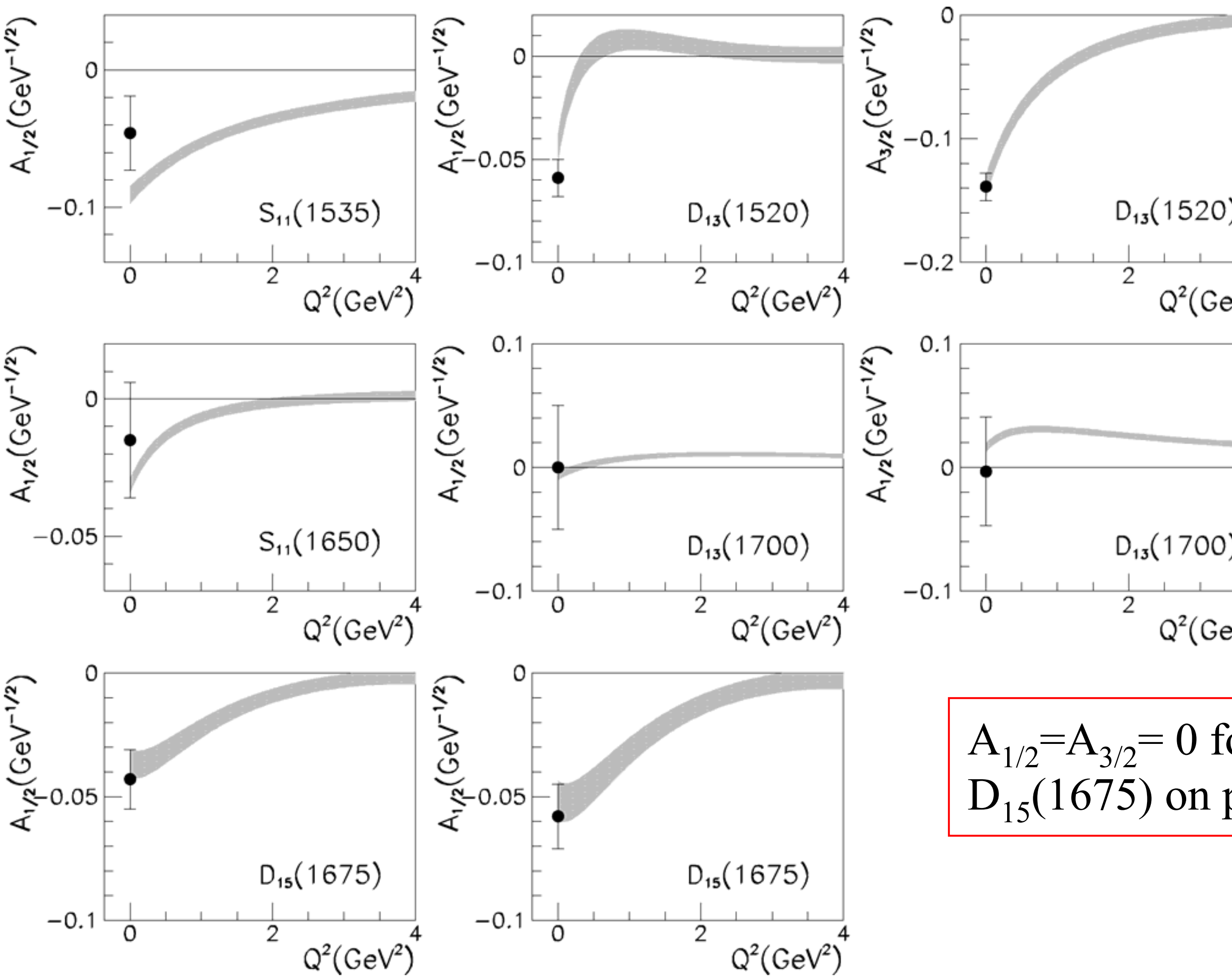
Proton

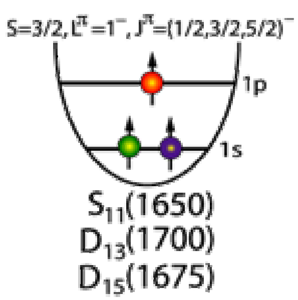


Single Quark Transition Model Predictions for $[56,0^+] \rightarrow [70,1^-]$ Transitions

Neutron







$A_{1/2}=A_{3/2}= 0$ for $D_{15}(1675)$ on protons

Searching for
New Baryon States

"Missing" Baryon States

Quark models with underlying SU(6)xO(3) symmetry predict many states, not observed in either hadronic experiments or in meson photo- and electro-production.

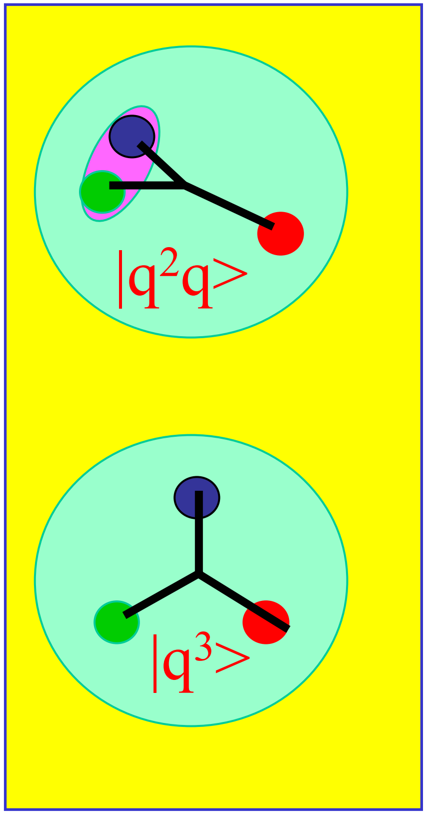
Possible solutions:

1. States don't exist, e.g. di-quark model predicts fewer states, with different underlying symmetry group
2. States exist but have not been found.

Possible reason: they decouple from π N-channel.

Model expectations: Hadronic couplings to $N\pi\,\pi$ ($\Delta\,\pi$, $N\rho$) much larger, while photocouplings are more comparable to those for observed states.

Other channels sensitive to "missing" states are: $K\Lambda$, $K\Sigma$, $p\omega$



Baryons - PDG values

$L_{2I,2J}(Mass)$	Multiplet	Status	$L_{2I,2J}$(Mass)	Multiplet	Status
$P_{11}(938)$	$(56,0^+)$	****	$P_{33}(1232)$	$(56,0^+)$	****
$S_{11}(1535)$	$(70,1^-)$	****	$S_{31}(1620)$	$(70,1^-)$	****
$S_{11}(1650)$	$(70,1^-)$	****			
$D_{13}(1520)$	$(70,1^-)$	****	$D_{33}(1700)$	$(70,1^-)$	****
$D_{13}(1700)$	$(70,1^-)$	***			
$D_{15}(1675)$	$(70,1^-)$	****			
$P_{11}(1440)$	$(56,0^+)$	****	$P_{31}(1875)$	$(56,2^+)$	****
$P_{11}(1710)$	$(70,0^+)$	***	$P_{31}(1835)$	$(70,0^+)$	
$P_{11}(1880)$	$(70,2^+)$				
$P_{11}(1975)$	$(20,1^+)$				
$P_{13}(1720)$	$(56,2^+)$	****	$P_{33}(1600)$	$(56,0^+)$	***
$P_{13}(1870)$	$(70,0^+)$	*	$P_{33}(1980)$	$(56,2^+)$	***
$P_{13}(1910)$	$(70,2^+)$		$P_{33}(1985)$	$(70,2^+)$	
$P_{13}(1950)$	$(70,2^+)$				
$P_{13}(2030)$	$(20,1^+)$				
$F_{15}(1680)$	$(56,2^+)$	****	$F_{35}(1905)$	$(56,0^+)$	****
$F_{15}(2000)$	$(70,2^+)$	**	$F_{35}(2000)$	$(70,2^+)$	**
$F_{15}(1995)$	$(70,2^+)$				
$F_{17}(1990)$	$(70,2^+)$	**	$F_{37}(1950)$	$(56,2^+)$	****

Diquark model predictions - Lichtenberg *(Phys Rev, 1969)*

$L_{2I,2J}(Mass)$	Multiplet	Status	$L_{2I,2J}$(Mass)	Multiplet	Status
P_{11}(938)	$(56,0^+)$	****	P_{33}(1232)	$(56,0^+)$	****
S_{11}(1535)	$(70,1^-)$	****	S_{31}(1620)	$(70,1^-)$	****
S_{11}(1650)	$(70,1^-)$	****			
D_{13}(1520)	$(70,1^-)$	****	D_{33}(1700)	$(70,1^-)$	****
D_{13}(1700)	$(70,1^-)$	***			
D_{15}(1675)	$(70,1^-)$	****			
P_{11}(1440)	$(56,0^+)$	****	P_{31}(1875)	$(56,2^+)$	****
P_{11}(1710)	$(70,0^+)$	***	P_{31}(1835)	$(70,0^+)$	
P_{11}(1880)	$(70,2^+)$				
P_{11}(1975)	$(20,1^+)$				
P_{13}(1720)	$(56,2^+)$	****	P_{33}(1600)	$(56,0^+)$	***
P_{13}(1870)	$(70,0^+)$	*	P_{33}(1920)	$(56,2^+)$	***
P_{13}(1910)	$(70,2^+)$		P_{33}(1985)	$(70,2^+)$	
P_{13}(1950)	$(70,2^+)$				
P_{13}(2030)	$(20,1^+)$				
F_{15}(1680)	$(56,2^+)$	****	F_{35}(1905)	$(56,0^+)$	****
F_{15}(2000)	$(70,2^+)$	**	F_{35}(2000)	$(70,2^+)$	**
F_{15}(1995)	$(70,2^+)$				
F_{17}(1990)	$(70,2^+)$	**	F_{37}(1950)	$(56,2^+)$	****

Evidence for new baryon states?

- Is the $P_{33}(1600)$ is really there?

- One more $3/2^{+}(1720)$ state ?

- A new N*(2000) ?

- New resonances in $p\omega$, $K\Lambda$?

Search for Baryon States in $\gamma p \longrightarrow p\pi^+\pi^-$

Two methods:

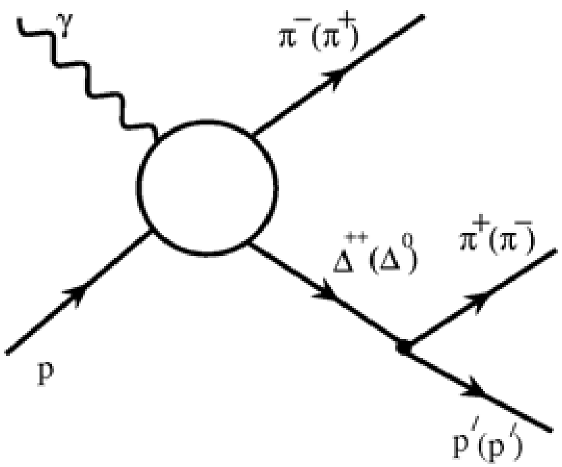
- Isobar models (similar approach as in single pion analysis):
  - energy-dependences of amplitudes are parameterized.
  - fits to one-dimensional projections.

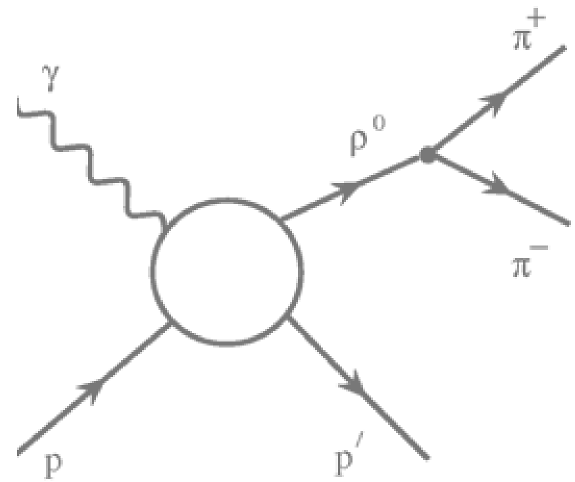
- Event-by event analysis:
  - fit partial-wave content independently for every energy bin.
  - makes maximum use of all correlations in the multi-dimensional phase space.
  - ambiguities can give multiple solutions.

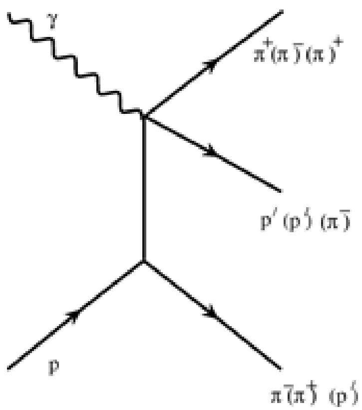
  - A variation of this method uses energy-dependent partial waves in isobar formulation.

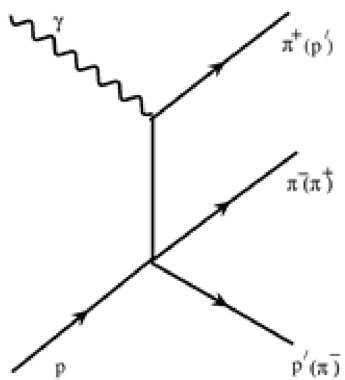
Search for Baryon States in $\gamma p \rightarrow p\pi^+\pi^-$

JLab-MSU Dynamical Isobar Model



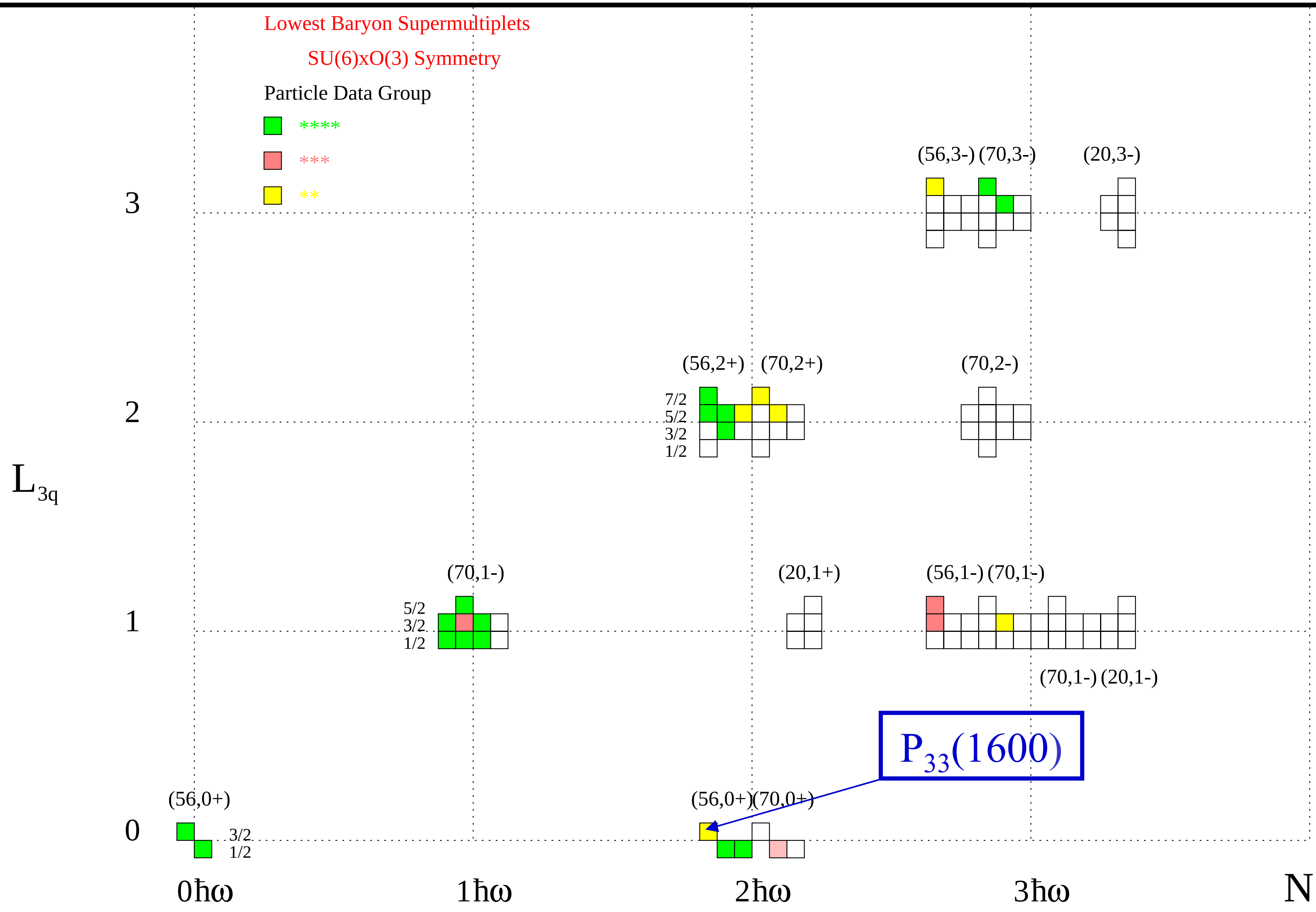






Residual production mechanism

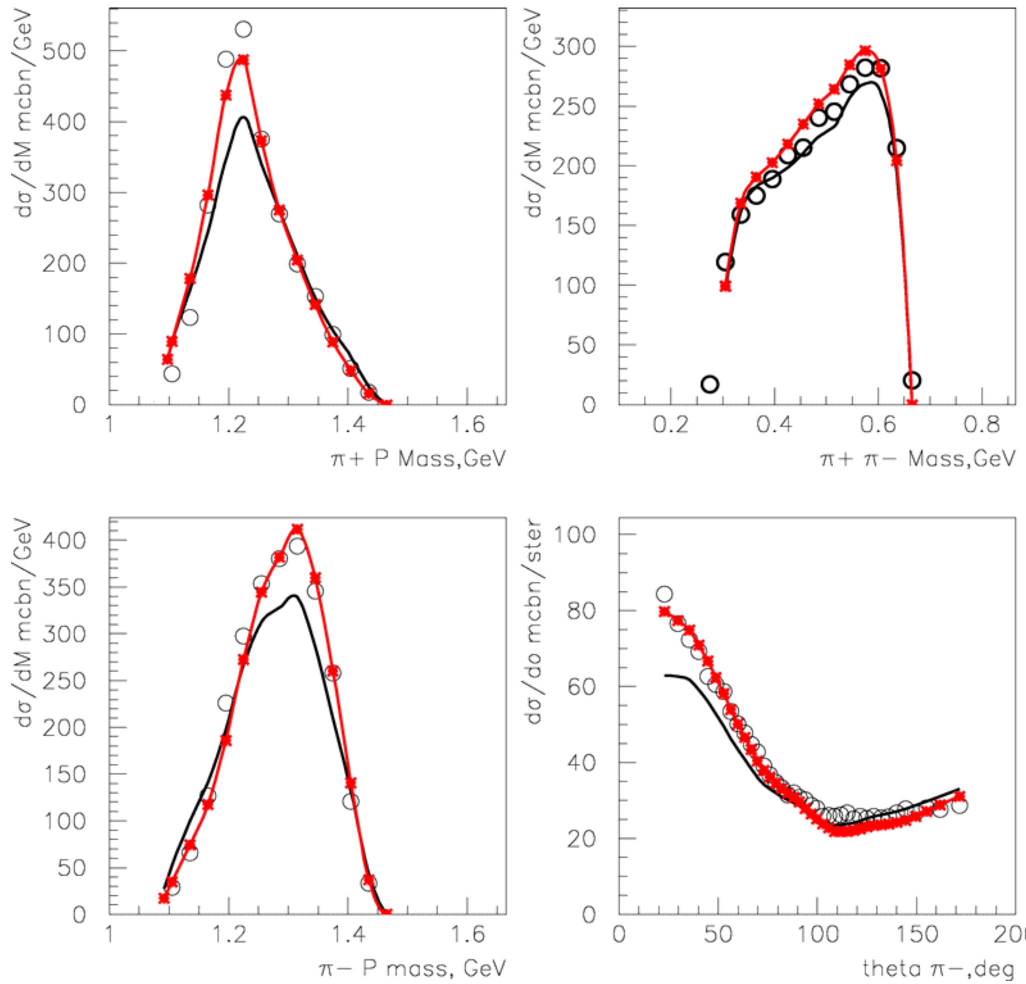
SU(6)xO(3) Classification of Baryons



Evidence for $P_{33}(1600)$ *** state

$\gamma\, p \longrightarrow p\pi^{+}\pi^{-}$

Sample data W=1.59 GeV



Fit to high statistics photoproduction data requires inclusion of $P_{33}(1600)$ state.

no $P_{33}(1600)$

with $P_{33}(1600)$

$P_{33}(1600)$ state parameters

	this analysis	world
Mass, MeV	**1686 ± 10**	**1550 - 1700 PDG** **1687 ± 44 Dytman** **1706 ± 10 Manley**
Total decay width, MeV	**338 ± 100**	**250 - 450 PDG** **493 ± 75 Dytman** **430 ± 75 Manley**
BF ($\pi\Delta$), %	**65 ± 6**	**40 -70 PDG** **59 ± 10 Dytman** **67 ± 5 Manley**
$\mathbf{A_{1/2}}$	**-30 ± 10**	**- 29 ± 20 PDG**
$\mathbf{A_{3/2}}$	**-17 ± 10**	**-19 ± 20 PDG**

$A_{1/2}$, $A_{3/2}$ [$GeV^{-1/2} * 100$]

A new 3/2+(1720) baryon state?

- JLab-MSU Dynamical Model Analysis

Contributions from conventional states only

Fit with new 3/2+(1720) state

M.Ripani et. al.
Phys. Rev. Lett.91, 022002 (2003)

Difference between curves due to signal from possible 3/2+(1720) state

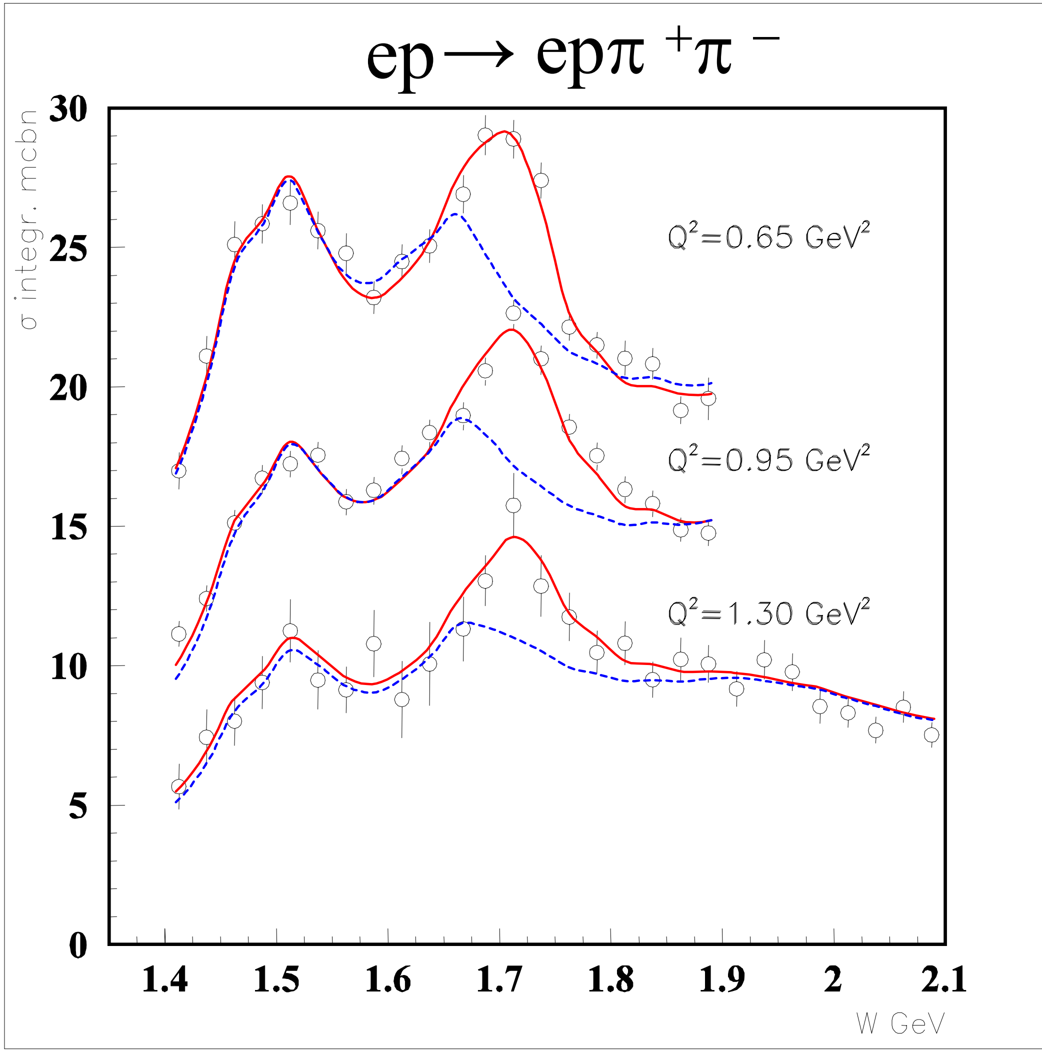
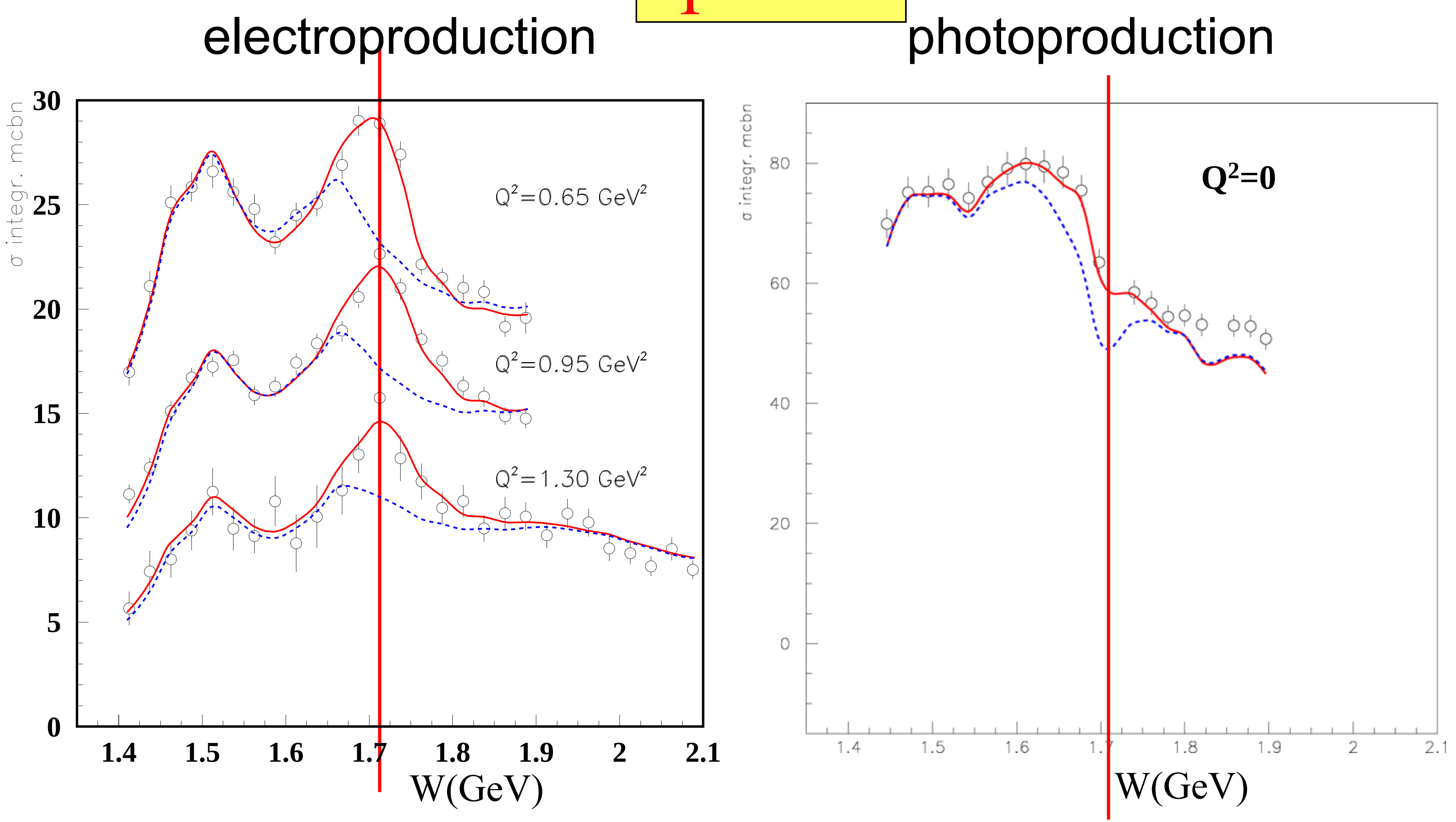


Photo- and electroproduction comparsion

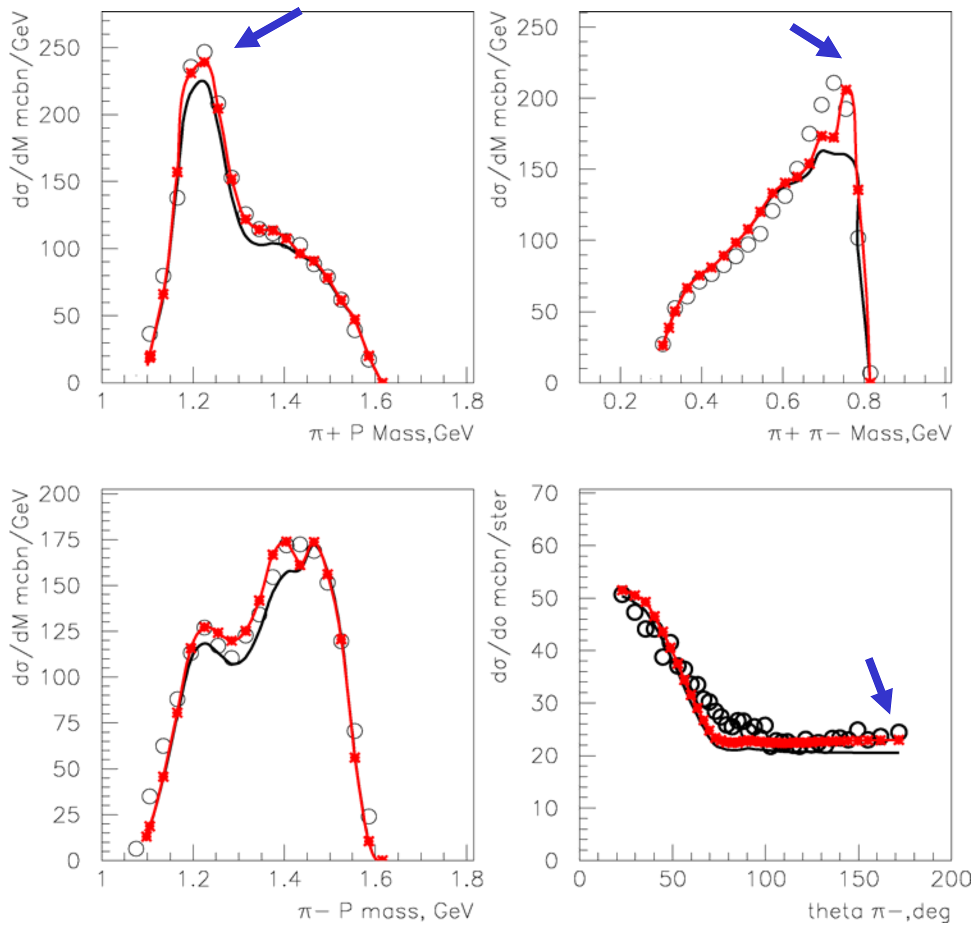
$p\pi^+\pi^-$



Photoexcitation of $P_{13}(1720)$ in $p\pi^+\pi^-$

W=1.74 GeV

$P_{13}(1720)$ state shows stronger presence in γp data.



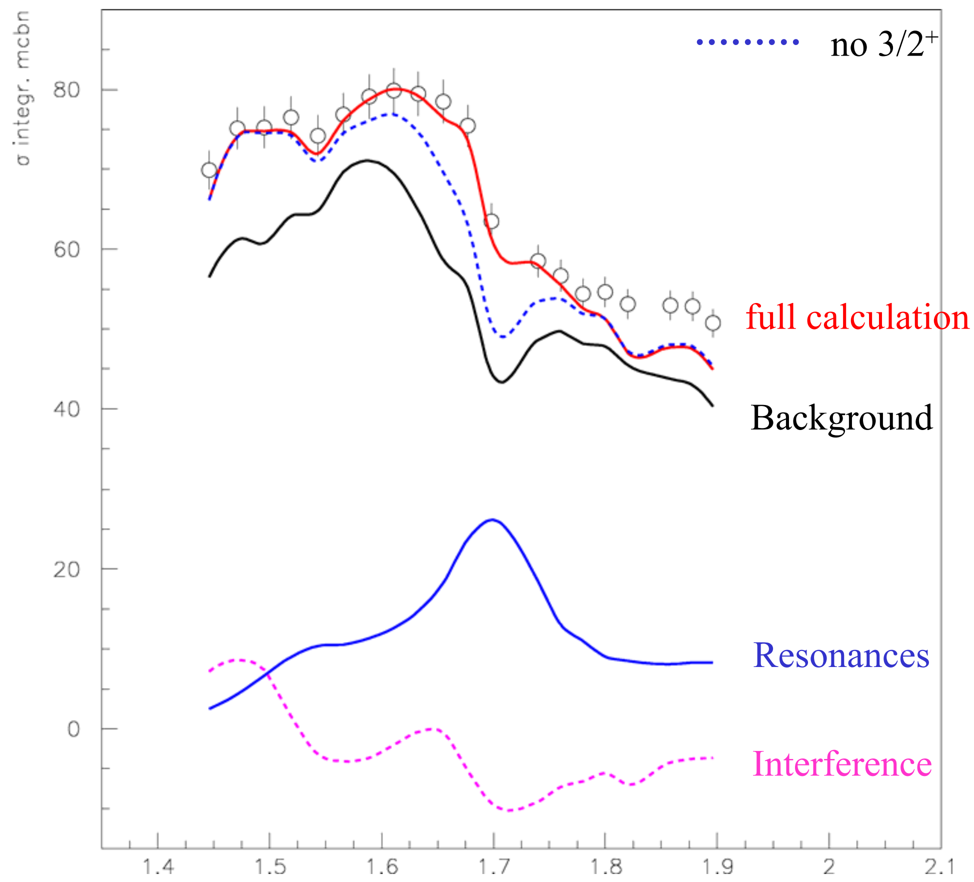
PDG photocouplings

Enhanced photocouplings fitted to the CLAS data

Total $\gamma p \longrightarrow p\pi^+\pi^-$ cross-section off protons.

- Hadronic couplings and mass derived from the fit of virtual photon data, and $3/2^+(1720)$ photocouplings fitted to the real photon data.

- Signal from $3/2^+(1720)$ state present, but masked by large background and destructive N*/background interference.

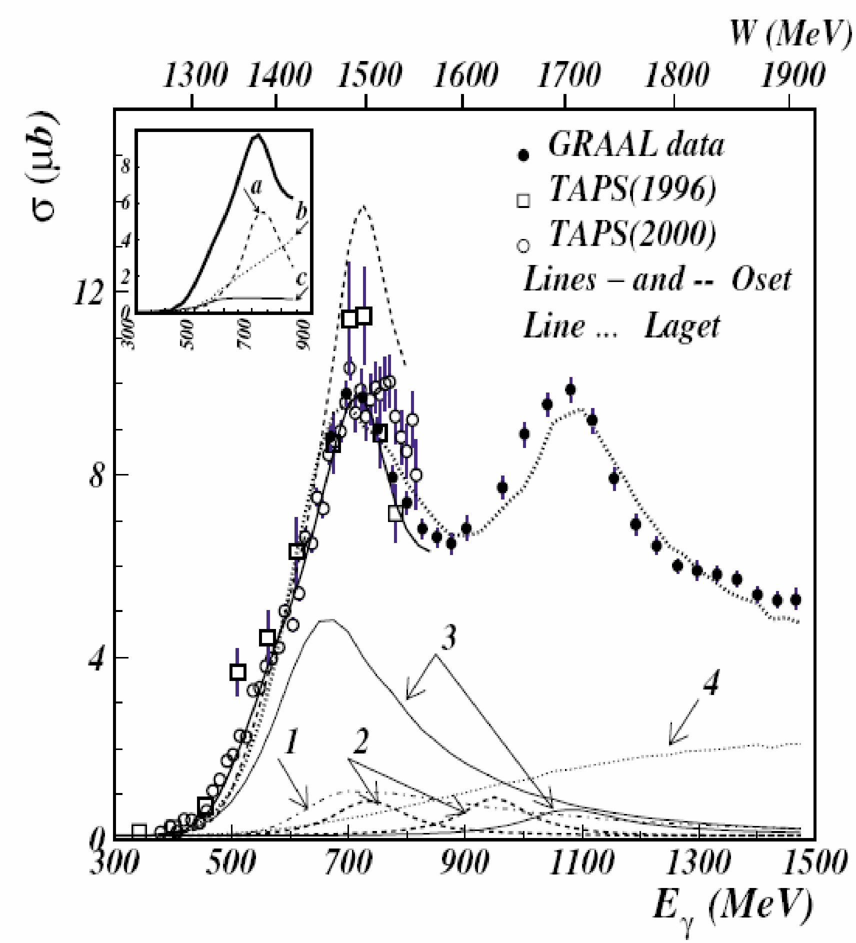


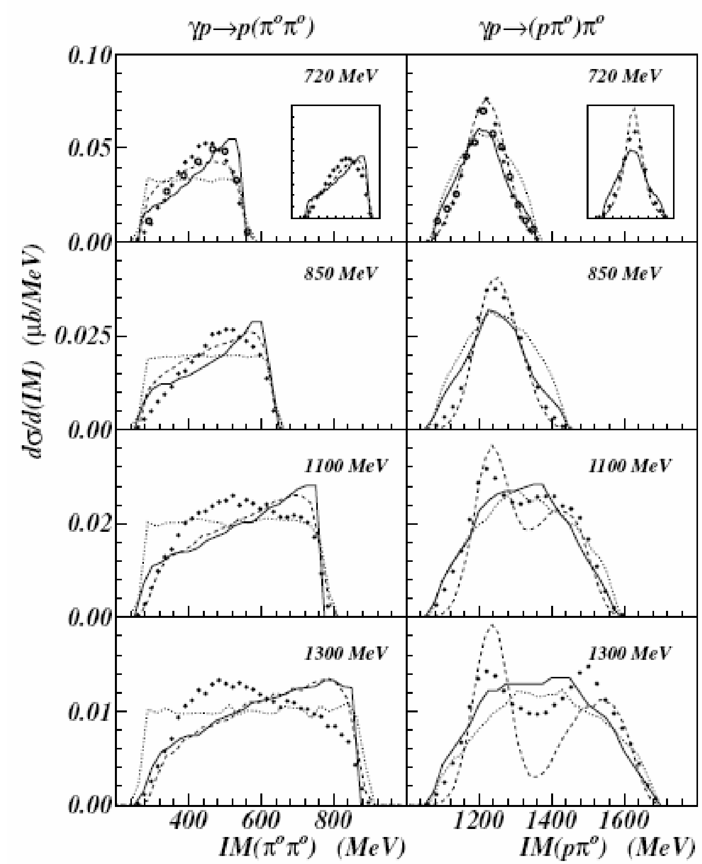
Parameters derived from combined analysis

Mass and decays

	Mass, MeV	Total width, MeV	BF($\pi\Delta$), %	BF(ρP), %
“New $3/2^+$ State”	1722	92	50	11
PDG P13(1720)	1650-1750	100-200	not observed	70 – 85

Resonances in $\gamma p \longrightarrow \pi^0 \pi^0 p$





The first mass peak is due to the $P_{11}(1440)$ and $D_{13}(1520)$, while the second peak was concluded to be due to the $P_{11}(1710)$. A large photocoupling for that state is needed to fit the data. This is not supported by single pion analysis which finds a small photocoupling for the $P_{11}(1710)$. Also, the diff. cross sections are not well reproduced by the fit (compared with analysis of $p\pi^+\pi^-$).

Partial Wave Analysis - another way of analyzing complex final states.

Partial Wave Formalism for $\gamma p \longrightarrow p\pi^+\pi^-$

- Transition matrix:

$$T_{fi} = \langle p\pi^+\pi^-;\tau_f|T|\gamma p;E\rangle$$

$$= \sum_{\alpha}\langle p\pi^+\pi^-;\tau_f|\alpha\rangle\langle\alpha|T_{\alpha i}|\gamma p;E\rangle$$

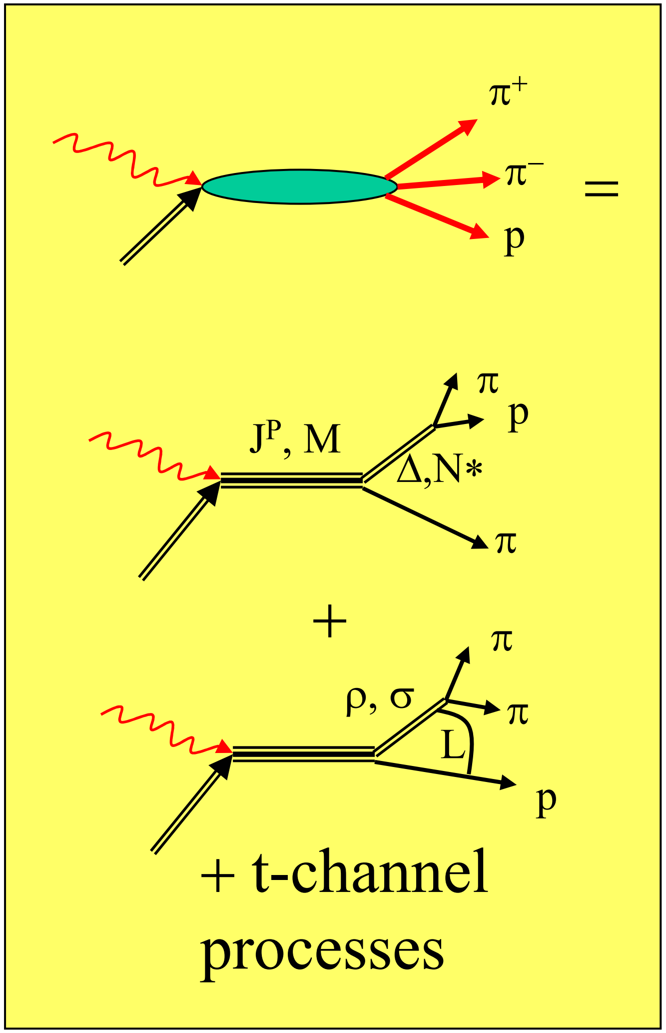
$$= \sum_{\alpha}\psi^{\alpha}(\tau_f)V^{\alpha}(E)$$

$$|\alpha\rangle = |J^P M,\text{isobar},l,s,\lambda_f\rangle$$

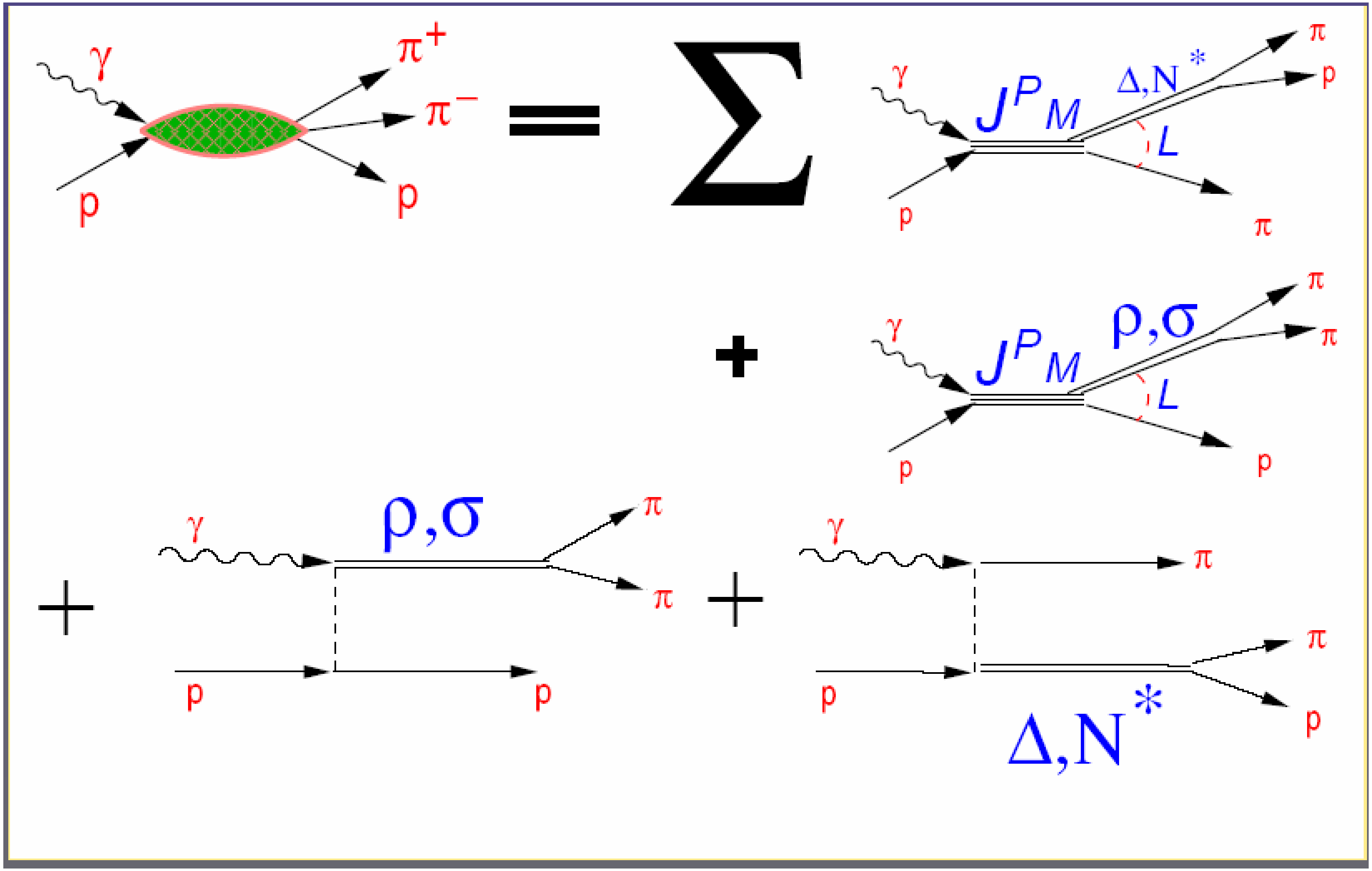
- Decay amplitude $\psi^{\alpha}(\tau_f)$ calculated using isobar model:

  E.g. $J^P = 3/2^+$, $M = +1/2 \longrightarrow \Delta^{++}\pi^-(l=1)$, $\lambda_f = +½$

- Production amplitude $V^{\alpha}(E)$ is fitted in unbinned maximum likelihood procedure. Assume $V^{\alpha}(E)$ is independent of E in small energy range. *No assumptions are made on intermediate resonances, only on quantum numbers.*



Sum over intermediate states



Partial Wave Decomposition of T_{fi}

For a *small* range of incident energies near $E\ldots$

$$\begin{aligned} T_{fi} &= \langle p\pi^+\pi^-;\tau_f|T|\gamma p;E\rangle \\ &= \sum_\alpha \langle p\pi^+\pi^-;\tau_f|\alpha\rangle\langle\alpha|T_{\alpha i}|\gamma p;E\rangle \\ &= \sum_\alpha \psi^\alpha(\tau_f)V^\alpha(E) \end{aligned}$$

- $|\alpha\rangle$ = $|J^P M,$ **isobar**$, \ell, s, \lambda_f\rangle$
- *Calculate* decay amplitude $\psi^\alpha(\tau_f)$ using isobar model

  E.g. $\frac{3}{2}^+(M=+\frac{1}{2}) \rightarrow \Delta^{++}\pi^-(\ell=1), \lambda_f=+\frac{1}{2}$
- *Fit* production amplitude $V^\alpha(E)$ using unbinned extended maximum likelihood

  Note: Assume $V^\alpha(E)$ doesn't vary within this energy range

  ("Energy independent")

J^P	M	Isobars	# of waves	Motivation
$\frac{1}{2}^+$	$\frac{1}{2}$	$\Delta\pi$	2	$P_{11}(1440)$, $P_{11}(1710)$
$\frac{1}{2}^-$	$\frac{1}{2}$	$\Delta\pi$	2	$S_{11}(1535)$, $S_{11}(1650)$
	$\frac{1}{2}$	$(p\rho)_{(s=1/2;\ell=0)}$	1	$S_{31}(1620)$
$\frac{3}{2}^+$	$\frac{1}{2}, \frac{3}{2}$	$(\Delta\pi)_{(\ell=1)}$	4	$P_{13}(1720)$, $P_{33}(1600)$
	$\frac{1}{2}, \frac{3}{2}$	$(p\rho)_{(s=1/2;\ell=1)}$	2	
$\frac{3}{2}^-$	$\frac{1}{2}, \frac{3}{2}$	$(\Delta\pi)_{(\ell=0,2)}$	8	$D_{13}(1520)$, $D_{13}(1700)$
	$\frac{1}{2}, \frac{3}{2}$	$(p\rho)_{(s=3/2;\ell=0,2)}$	4	$D_{33}(1700)$
$\frac{5}{2}^+$	$\frac{1}{2}, \frac{3}{2}$	$(\Delta\pi)_{(\ell=1)}$	4	$F_{15}(1680)$
	$\frac{1}{2}, \frac{3}{2}$	$p\sigma$	2	
$\frac{5}{2}^-$	$\frac{1}{2}, \frac{3}{2}$	$(\Delta\pi)_{(\ell=2)}$	4	$F_{15}(1675)$
t-channel ρ	$\frac{1}{2}, \frac{3}{2}$	$\lambda_\rho = +1, -1$	4	
		Total # of waves	37	

Focus on $W < 1.9$ GeV/c^2

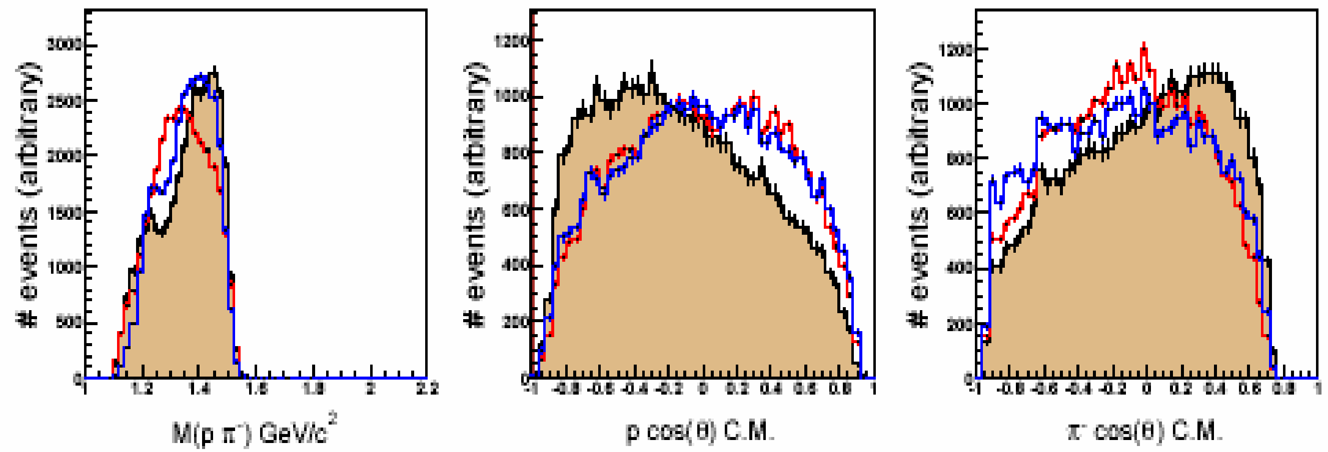
Waves used in the following analysis

J^P	M	Isobars	Motivation
$1/2^+$	1/2	$\Delta\pi$ $(=\{\Delta^{++}\pi^-, \Delta^o\pi^+\})$	$P_{11}(1440)$, $P_{11}(1710)$
$1/2^-$	1/2	$\Delta\pi$, $(p\rho)_{(s=1/2}$	$S_{11}(1535)$, $S_{11}(1650)$, $S_{31}(1620)$
$3/2^+$	1/2, 3/2	$(\Delta\pi)_{(l=1)}$,$(p\rho)_{(s=1/2)}$,$(p\rho)_{(s=3/2;l=1,3)}$ $N^*(1440)\pi$	$P_{13}(1720)$, $P_{33}(1600)$
$3/2^-$	1/2, 3/2	$(\Delta\pi)$ $_{(l=0,2)}$	$D_{13}(1520)$, $D_{13}(1700)$ $D_{33}(1700)$
$5/2^+$	1/2, 3/2	$(\Delta\pi)_{(l=1)}$, $p\sigma$	$F_{15}(1860)$
$5/2^-$	1/2, 3/2	$(\Delta\pi)_{(l=2)}$	$D_{15}(1675)$

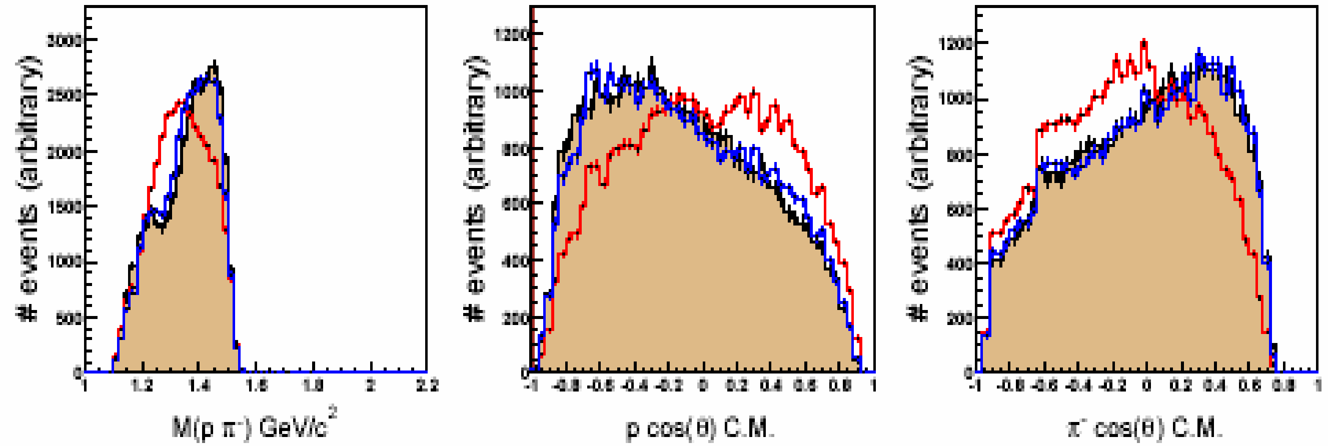
- Total of 35 waves (complex amplitudes)
- Diffractive production (“t-channel”) also included

Partial wave fits to $p\pi^+\pi^-$ data for W = 1.69 – 1.71 GeV

4 waves

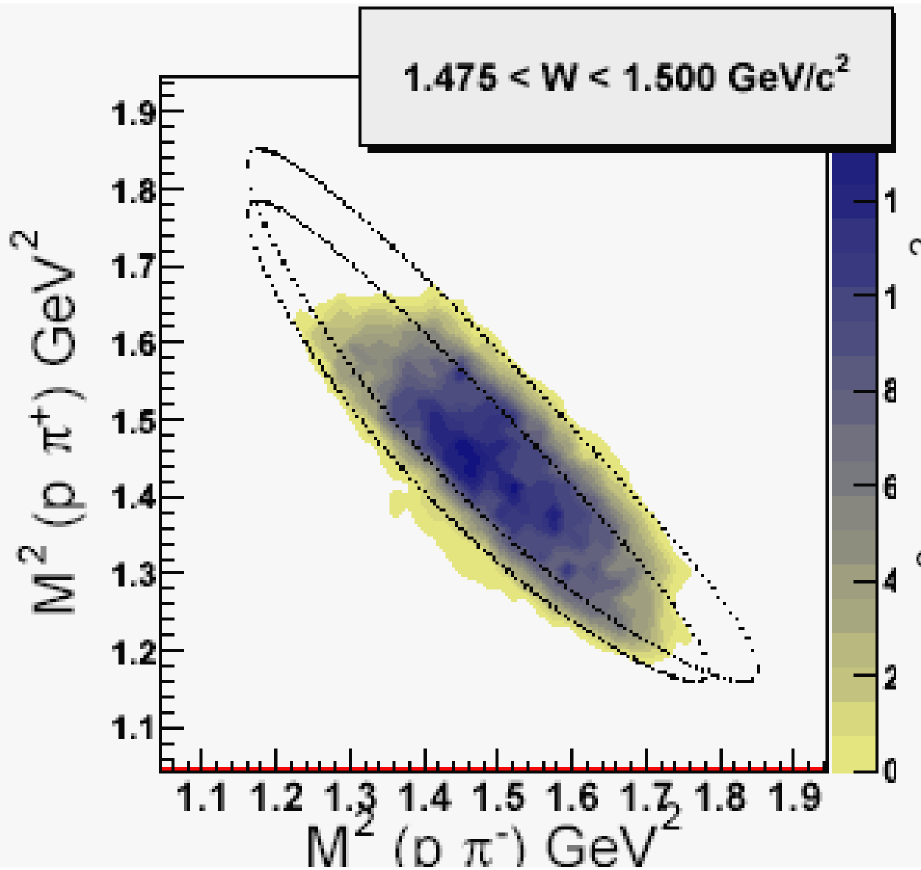


37 waves

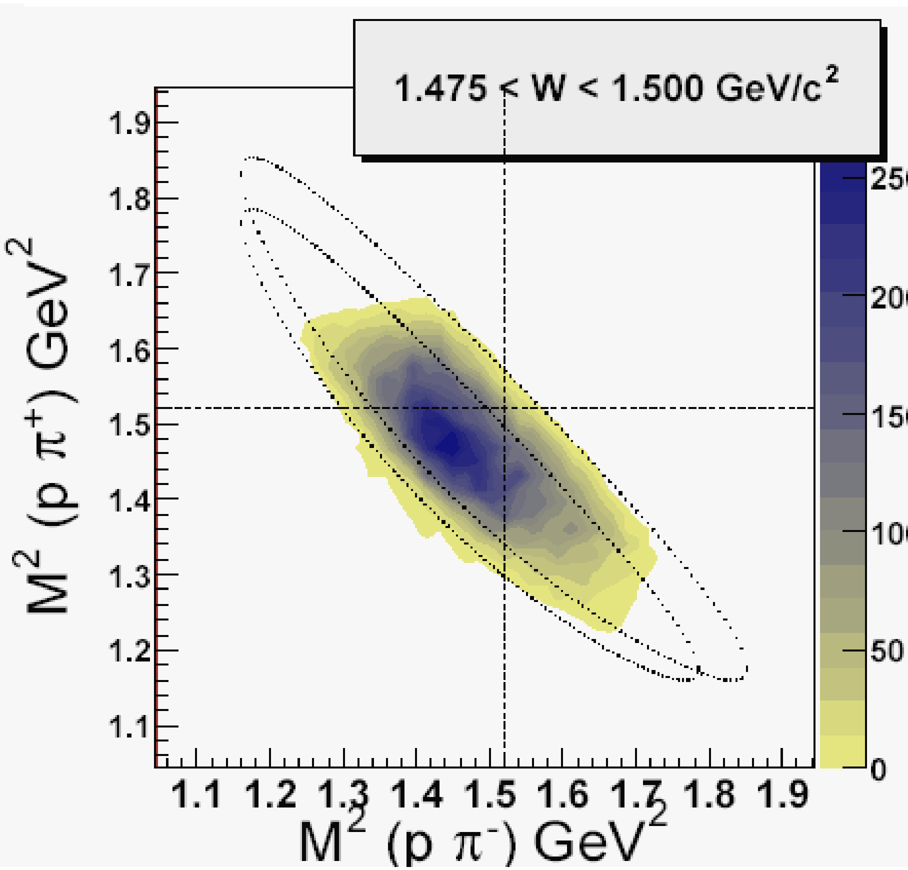


Dalitz Plot for $p\pi^+\pi^-$

Data

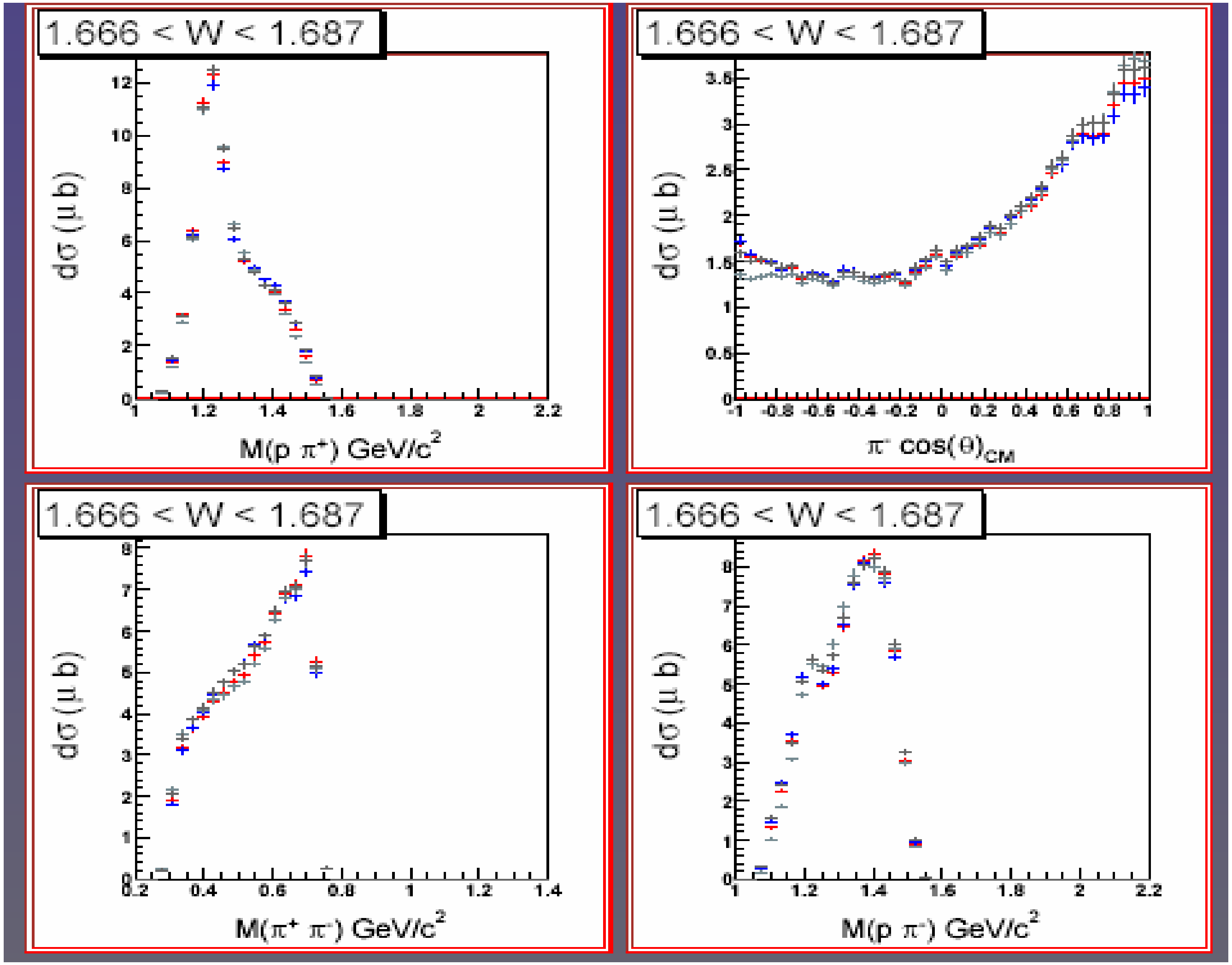


Monte Carlo



Comparison with Isobar Model Fit

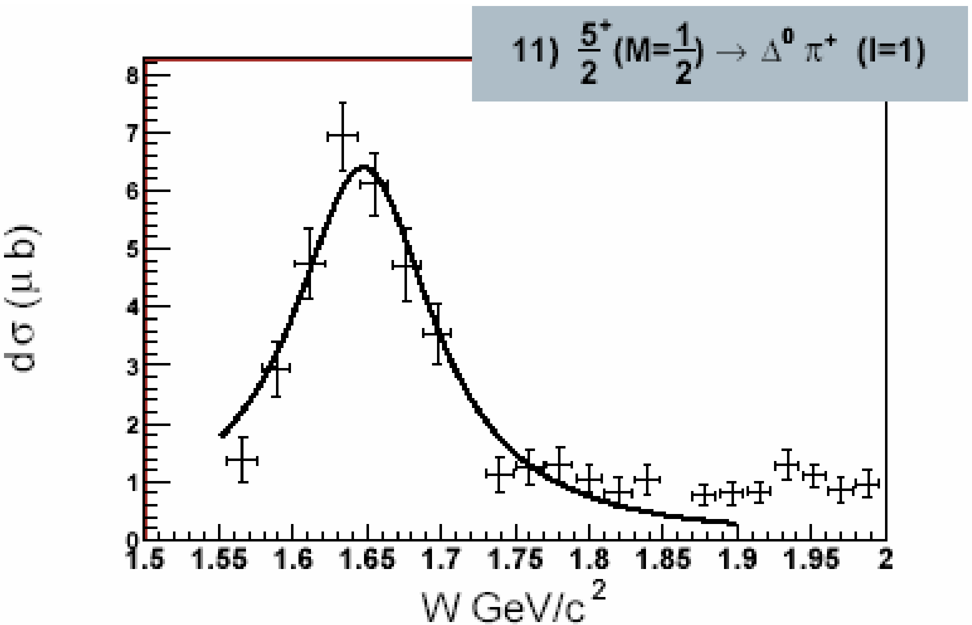
… shows good agreement between the two methods

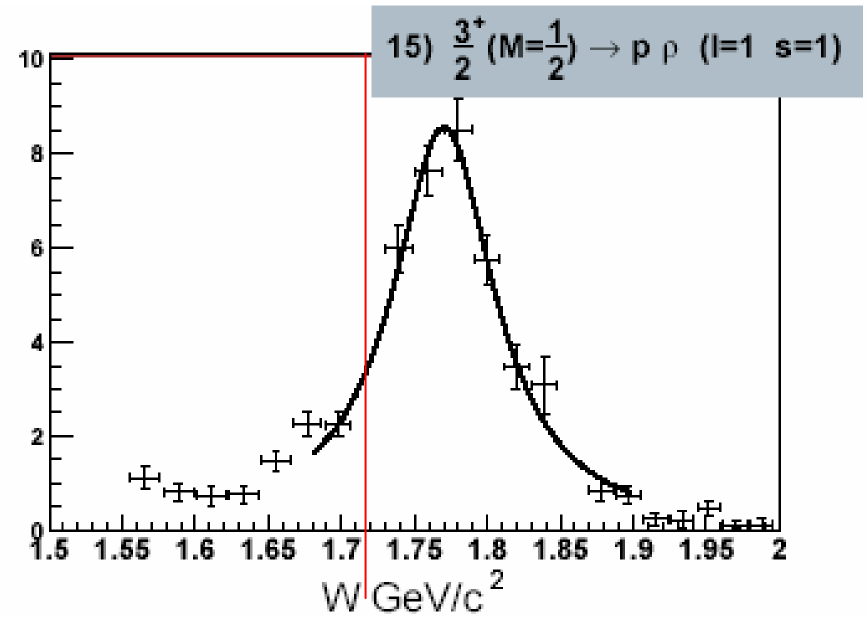


Can we discover new baryons with this technique?

$F_{15}(1680)$

$P_{13}(1720)$?





M ~ 1650 MeV, Γ ~ 115 MeV

M ~ 1770 MeV, Γ ~ 85 MeV

Mass shifts due to interference effects?

Other searches for new baryon states.

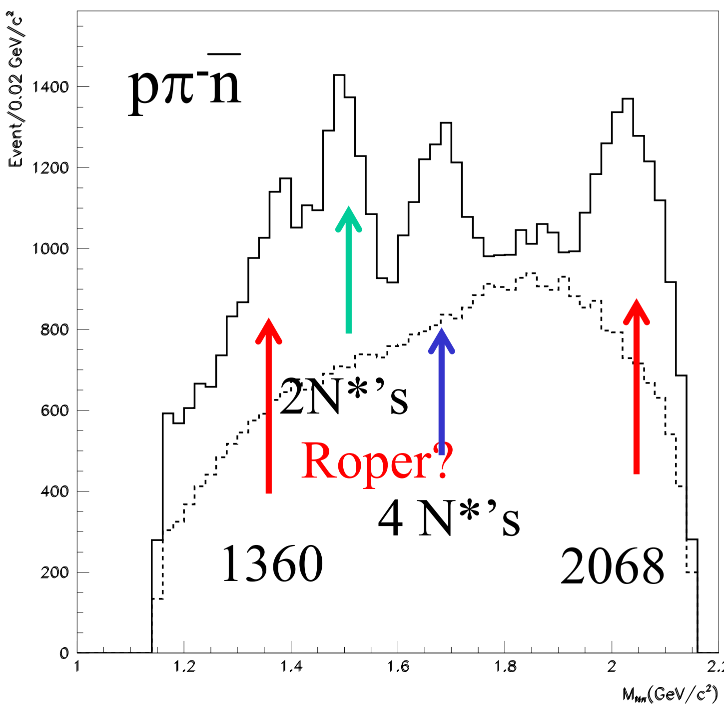
New N* resonance in J/ψ decays ?

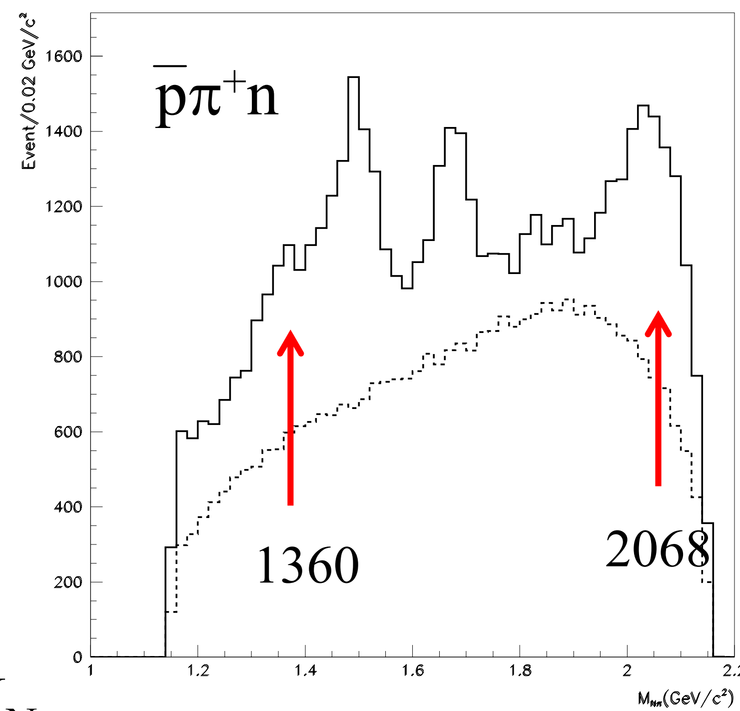
New data from BEPC (e^+e^- collider in Beijing) suggest a new N* state at ~2068 MeV observed in:

$e^+e^- \longrightarrow J/\psi \longrightarrow N\bar{N}\pi$

Why is there no Δ(1232) peak?

- Isospin conservation in decay => $I_{\pi N} = \frac{1}{2}$.



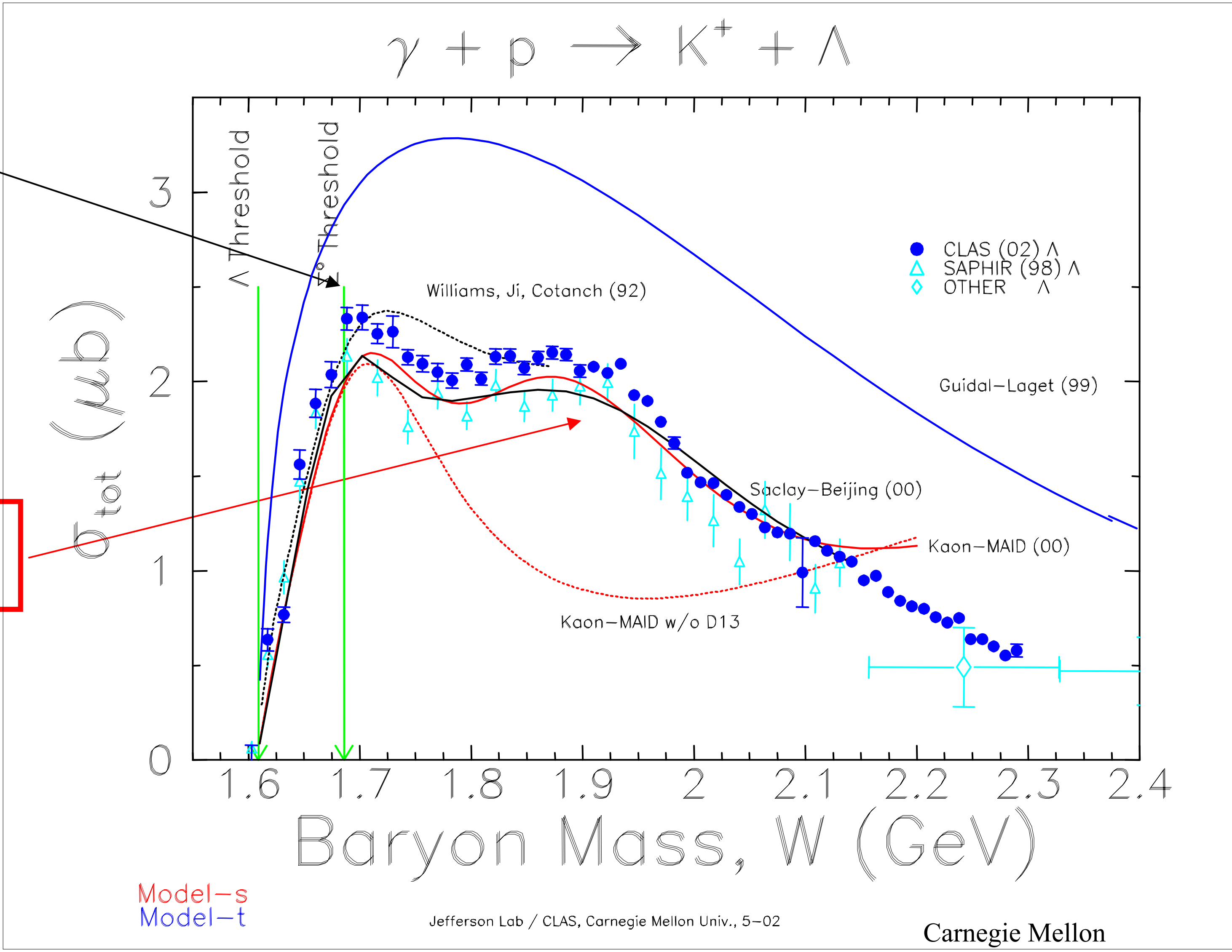


$M_{N\pi}$

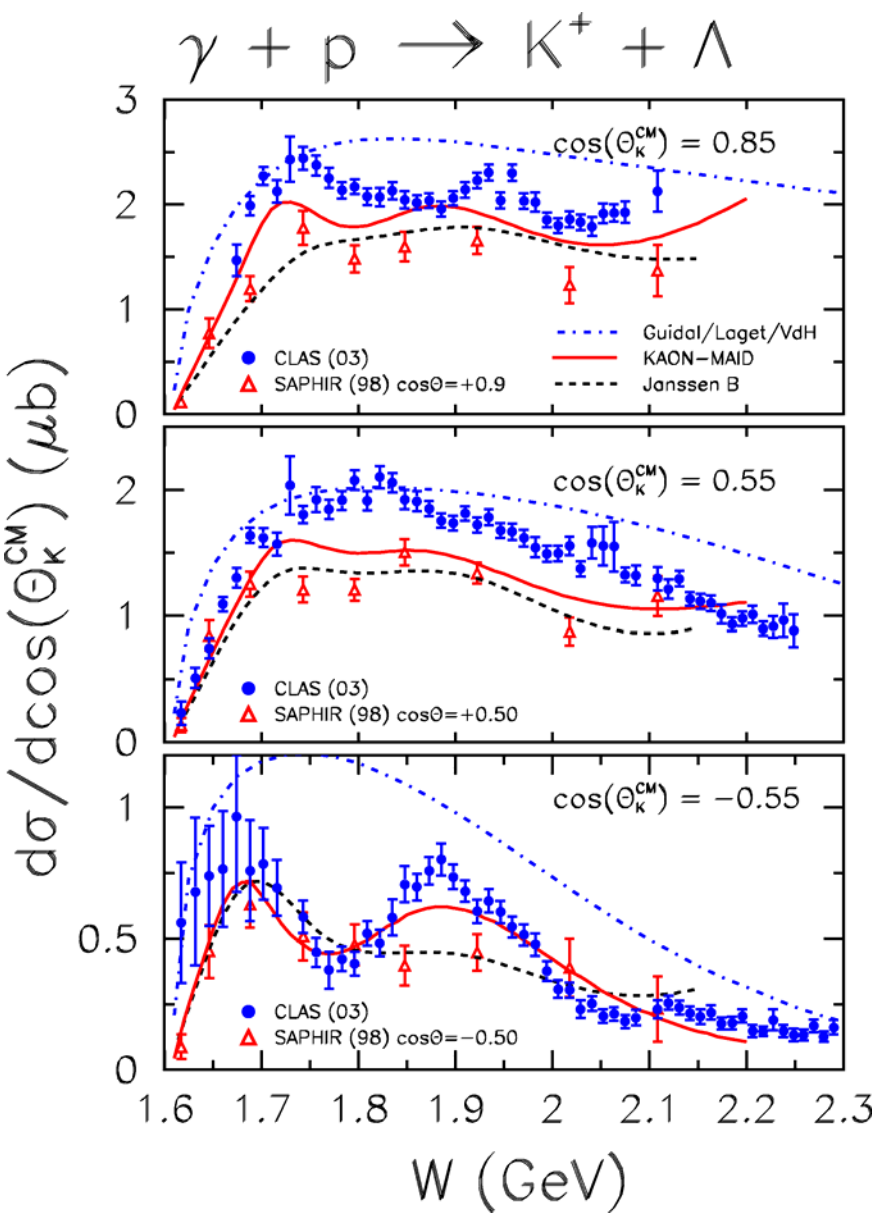
Strangeness Photoproduction

Dominant resonances
$S_{11}(1650)$
$P_{11}(1710)$
$P_{13}(1720)$

$D_{13}(1895)$?



Strangeness Photoproduction

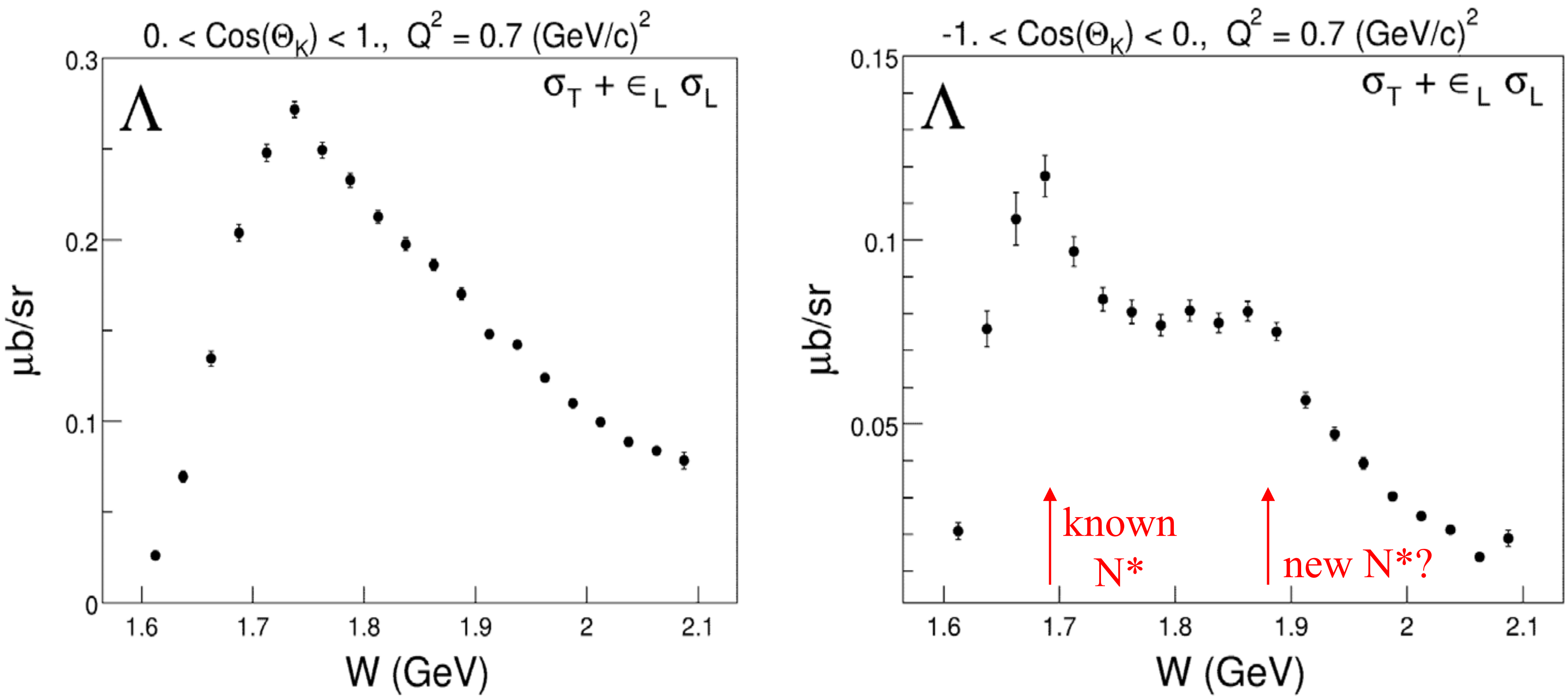


- Sample of data covering the full kinematic range in energy and angles for $K^+\Lambda$ and $K^+\Sigma$, including recoil polarization
- Data indicate significant resonance contributions, interfering with each other and with non-resonant amplitudes.
- Extraction of resonance parameters requires a large effort in partial wave analysis and reaction theory.

Strangeness in electroproduction

CLAS $\gamma^* p \longrightarrow K^+\Lambda$

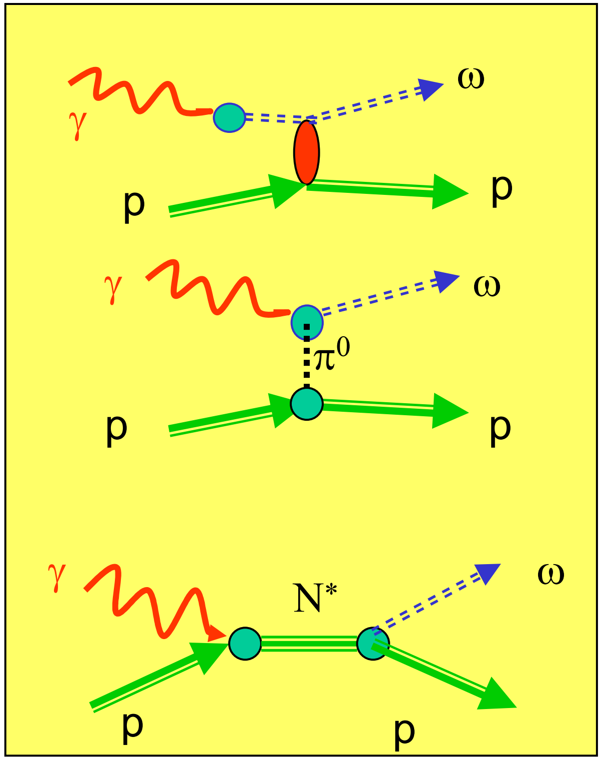
forward hemisphere backward hemishere

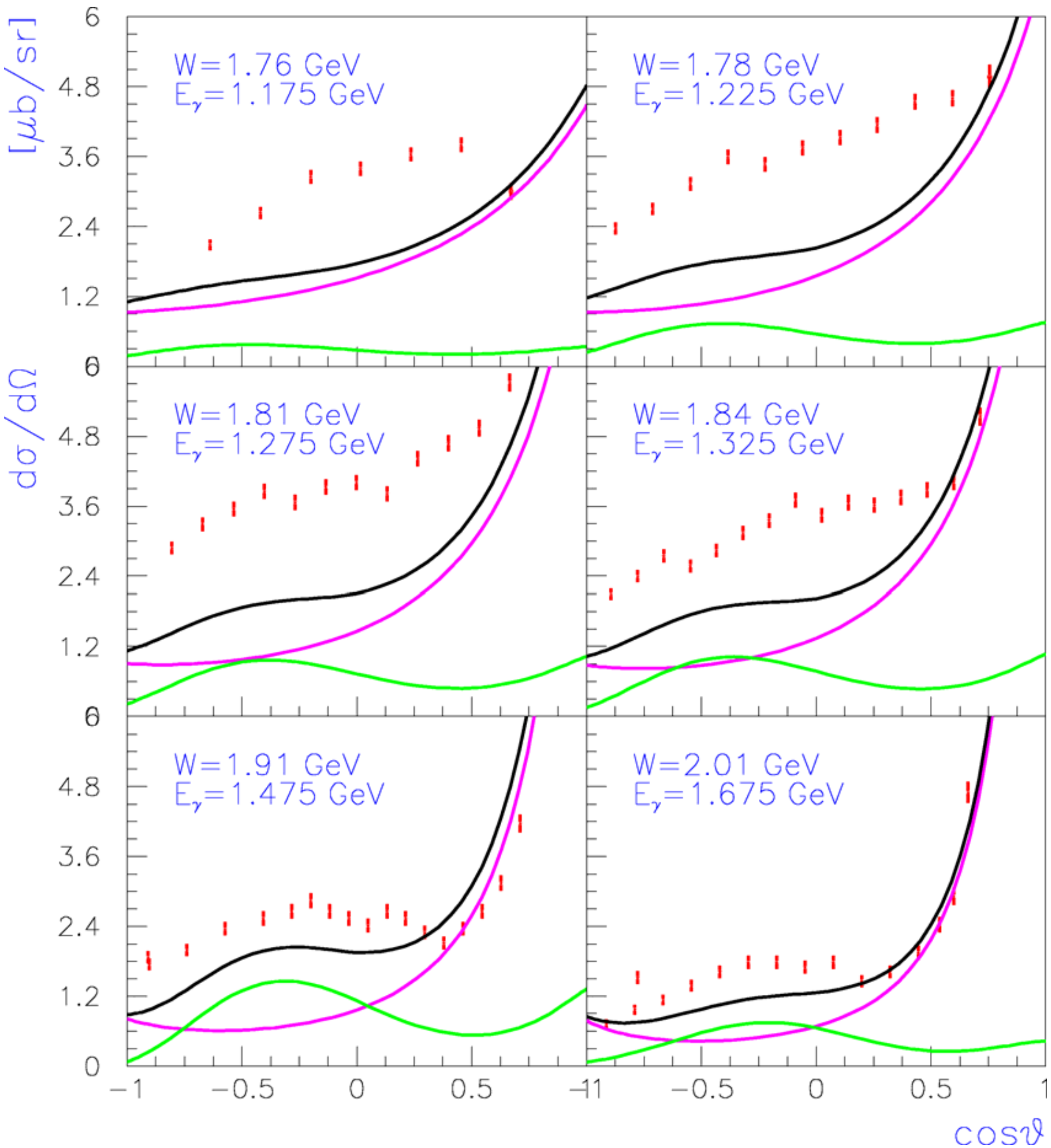


Resonances in $\gamma p \longrightarrow p\omega$?

Model: Y. Oh

- OPE + Pomeron
- N* Capstick model
- Sum

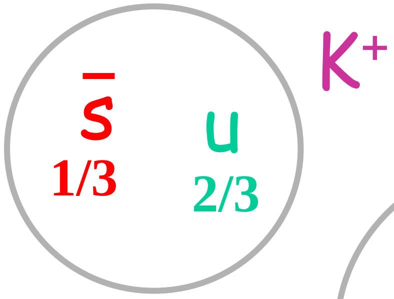




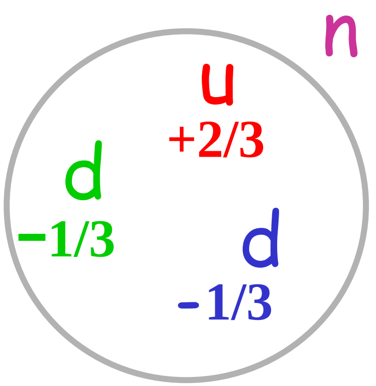
Pentaquark baryons - are we discovering a new form of matter?

From Meson & Baryons to Pentaquarks

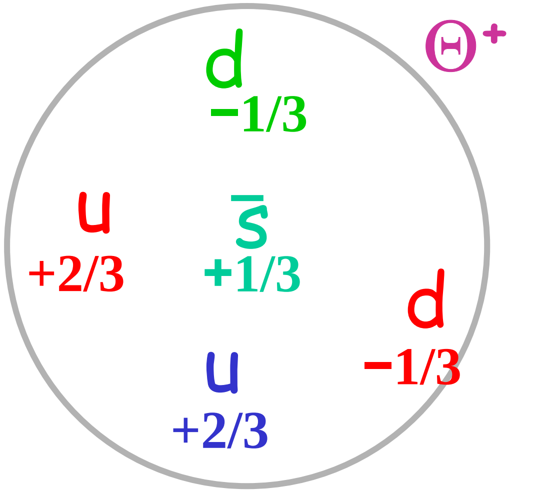
Mesons: quark-antiquark pair



Baryons: three quarks (valence)



Pentaquarks: 4 quarks + 1 antiquark



QCD requires that hadrons must be colorless

Types of Pentaquarks

- “Non-exotic” pentaquarks
  - The antiquark has the same flavor as one of the other quarks
  - Difficult to distinguish from 3-quark baryons

Example: $uuds\bar{s}$, same quantum numbers as uud

Strangeness = 0 + 0 + 0 - 1 + 1 = 0

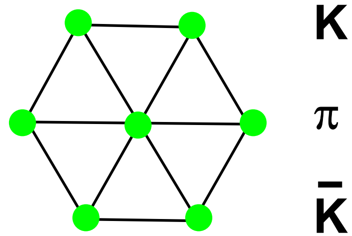
- “Exotic” pentaquarks
  - The antiquark has a flavor different from the other 4 quarks
  - They have quantum numbers different from any 3-quark baryon
  - Unique identification using experimental conservation laws

Example: $uudd\bar{s}$

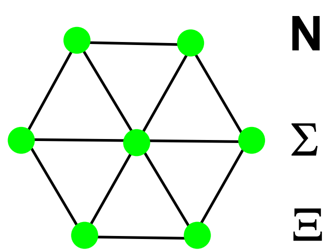
Strangeness = 0 + 0 + 0 + 0 + 1 = +1

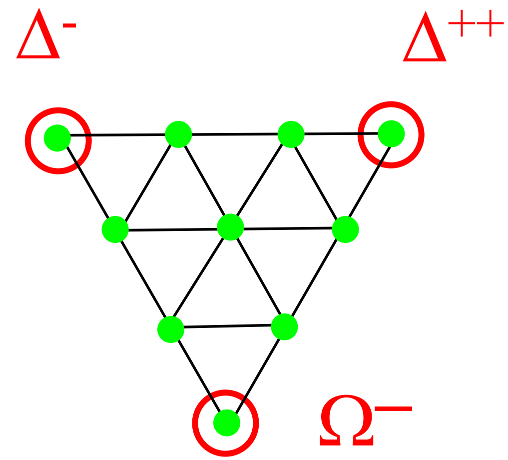
Hadron Multiplets

Mesons $q\bar{q}$

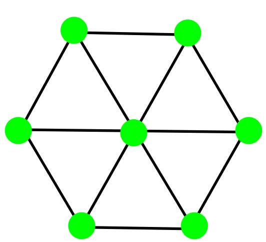


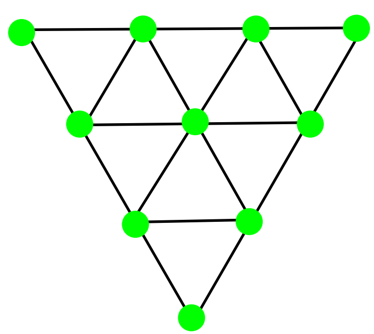
Baryons qqq

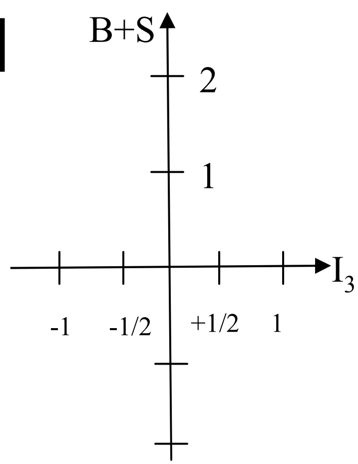


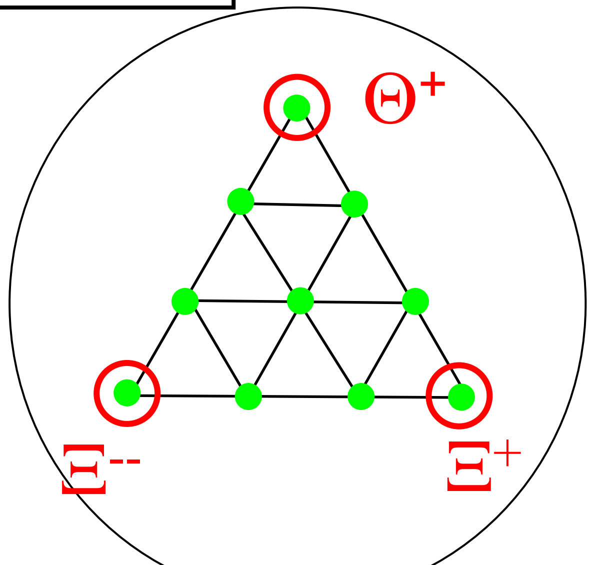


Baryons built from $qqqq\bar{q}$



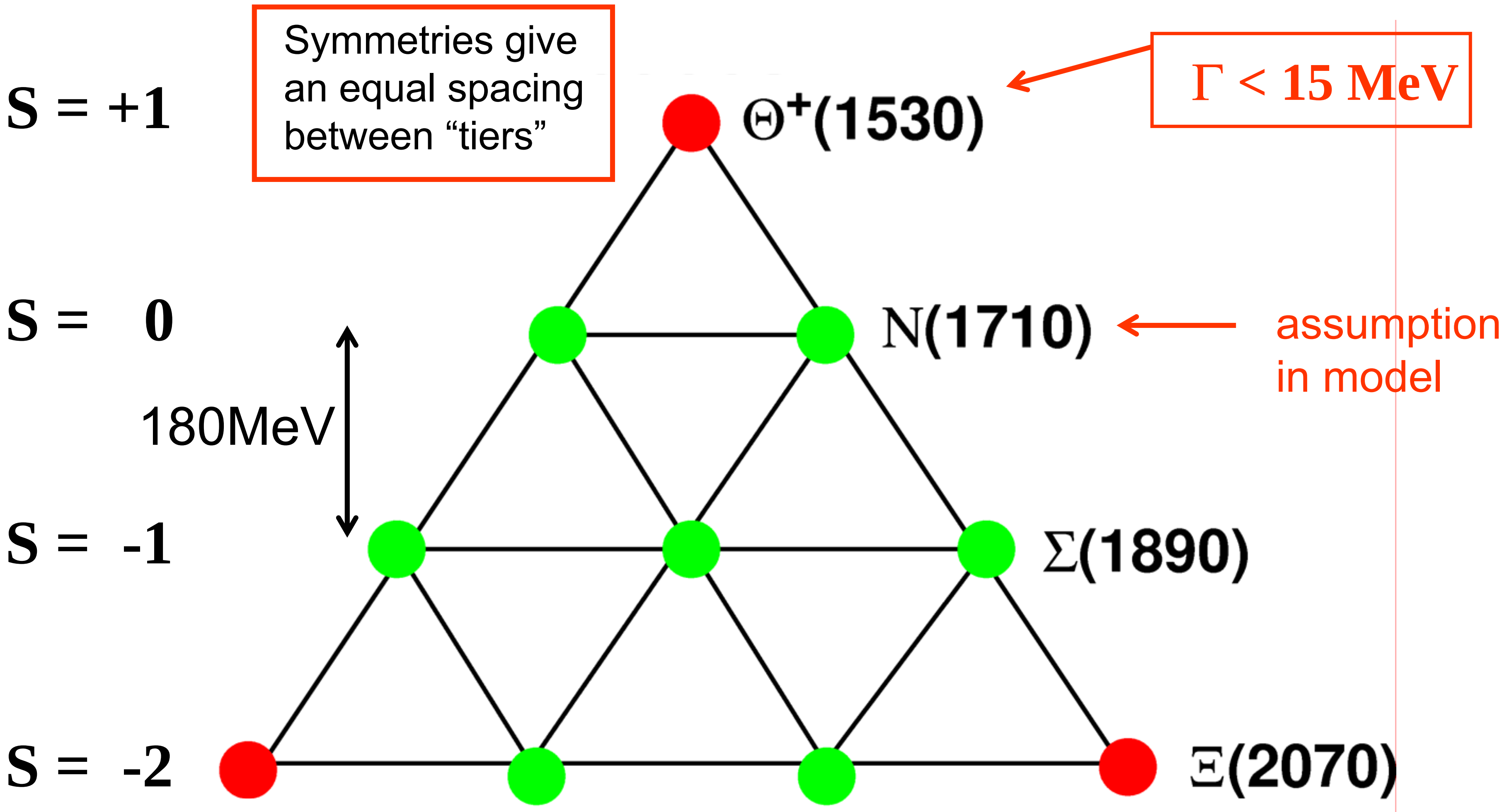






The Anti-decuplet in the Chiral Soliton Model

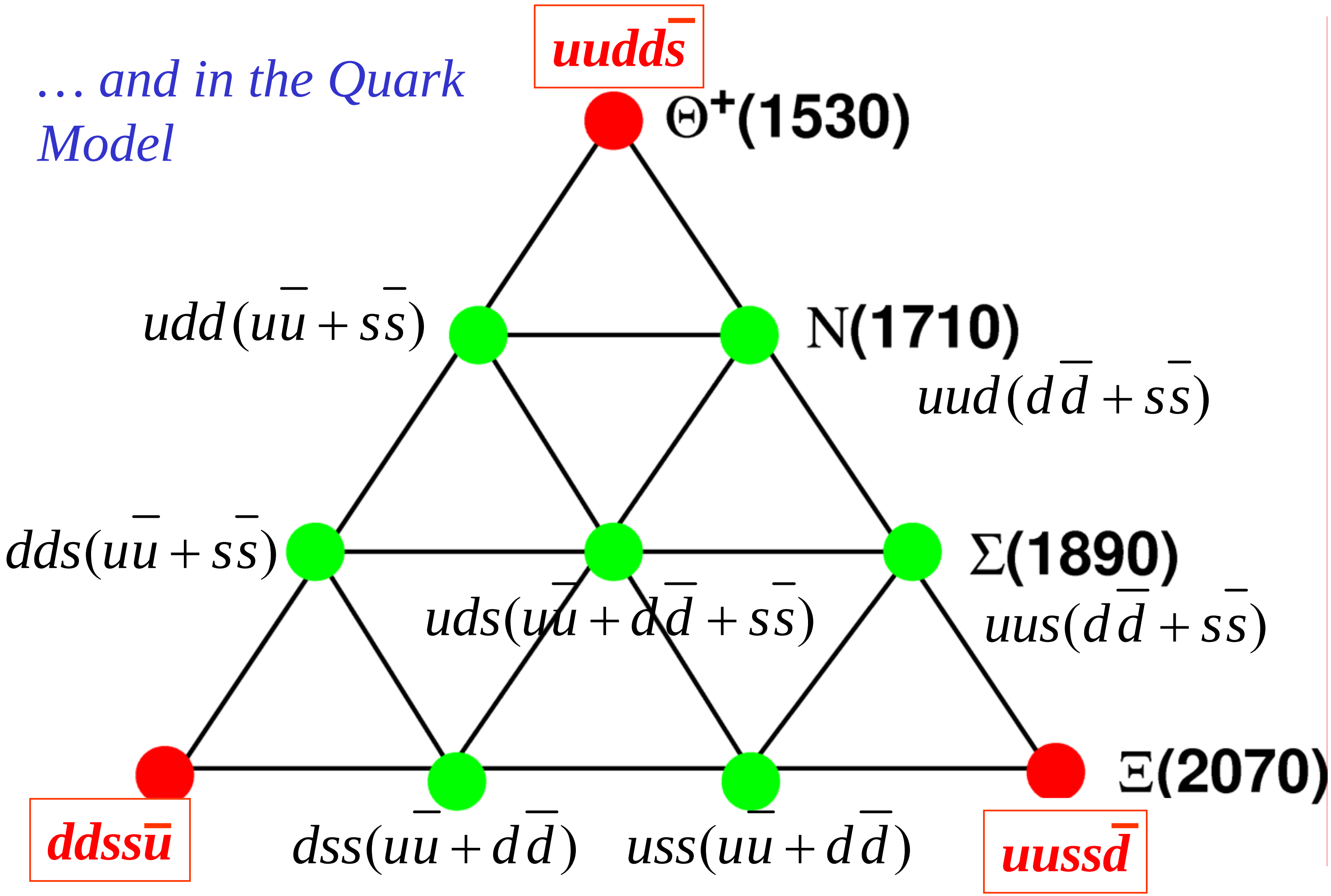
D. Diakonov, V. Petrov, M. Polyakov, Z.Phys.A359, 305 (1997)



The Anti-decuplet in the Chiral Soliton Model

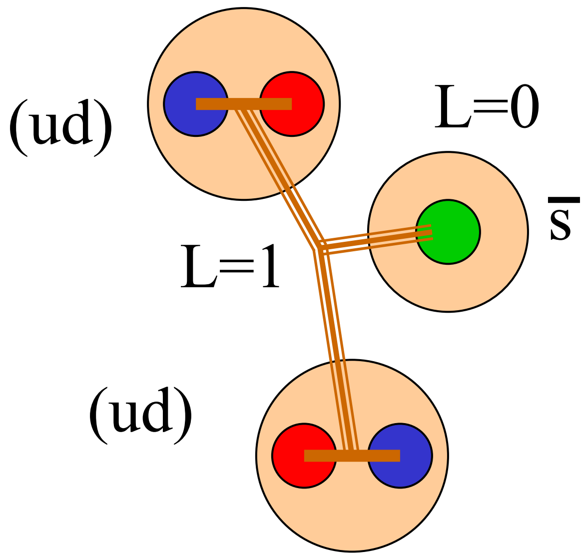
D. Diakonov, V. Petrov, M. Polyakov, Z.Phys.A359, 305 (1997)

… and in the Quark Model



Some quark descriptions of the Θ^+ Pentaquark

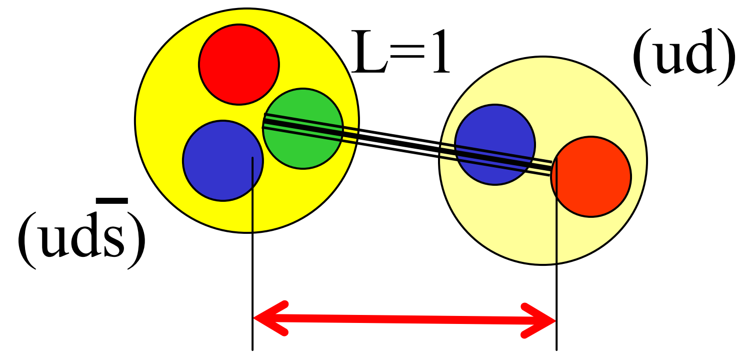
$(qq)\bar{q}$ description (Jaffe, Wilczek)



L=1, one unit of orbital angular momentum needed to obtain $\boxed{J^P = ½^+}$ as in the χSM

$(qq\bar{q})(qq)$ description (Karliner, Lipkin)

two color non-singlets

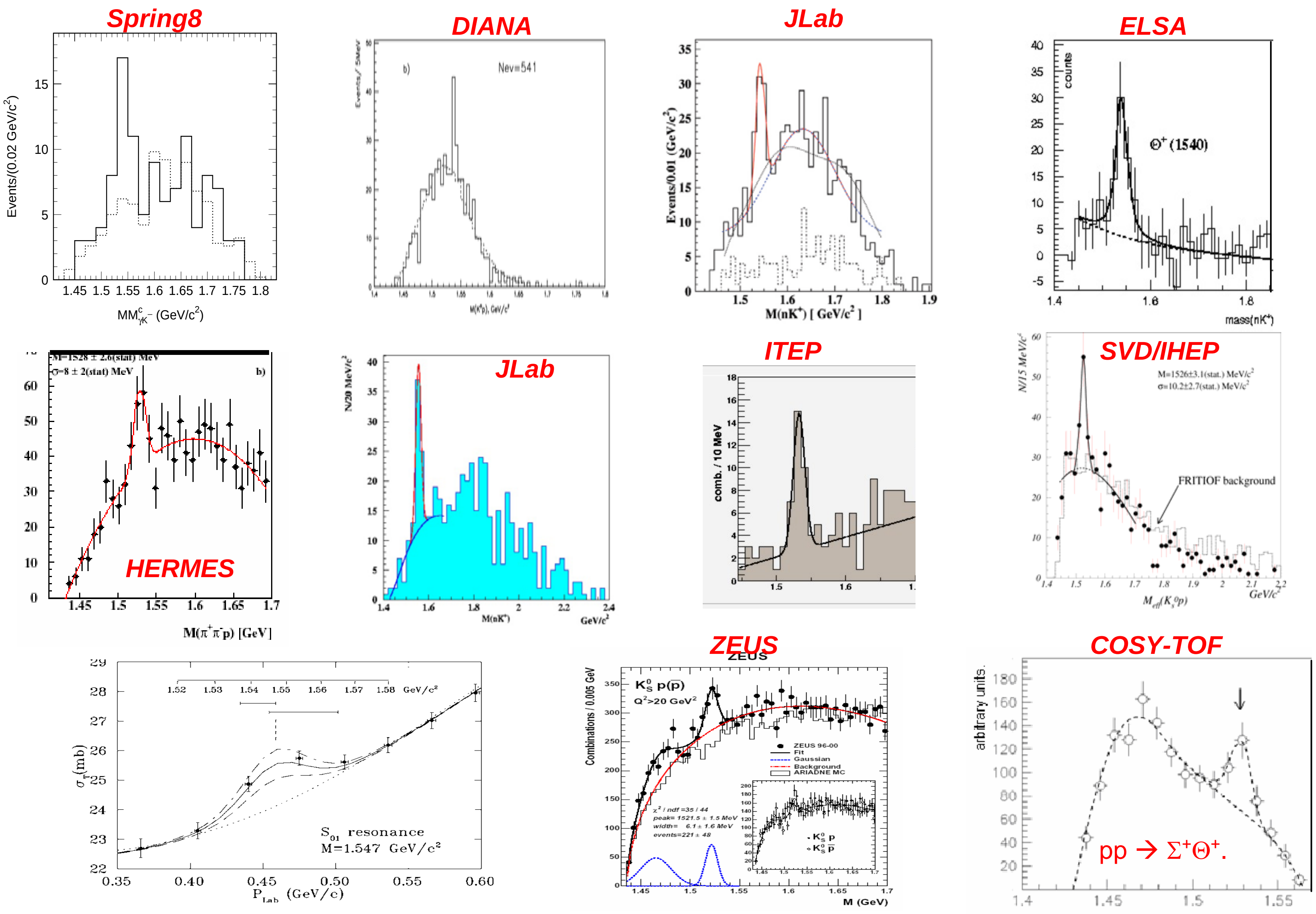


distance > color magnetic force

$\boxed{J^P = ½^+}$

LQCD:	$J^P = ½^-$	2 groups
	$½^+$	1 group
	no signal	1 group

Evidence for Θ^+ Pentaquark



→ G. Rosner

Θ^+(1540) as seen with e.m. probes

T. Nakano et al., PRL91, 012002 (2003)

The LEPS experiment at SPring8

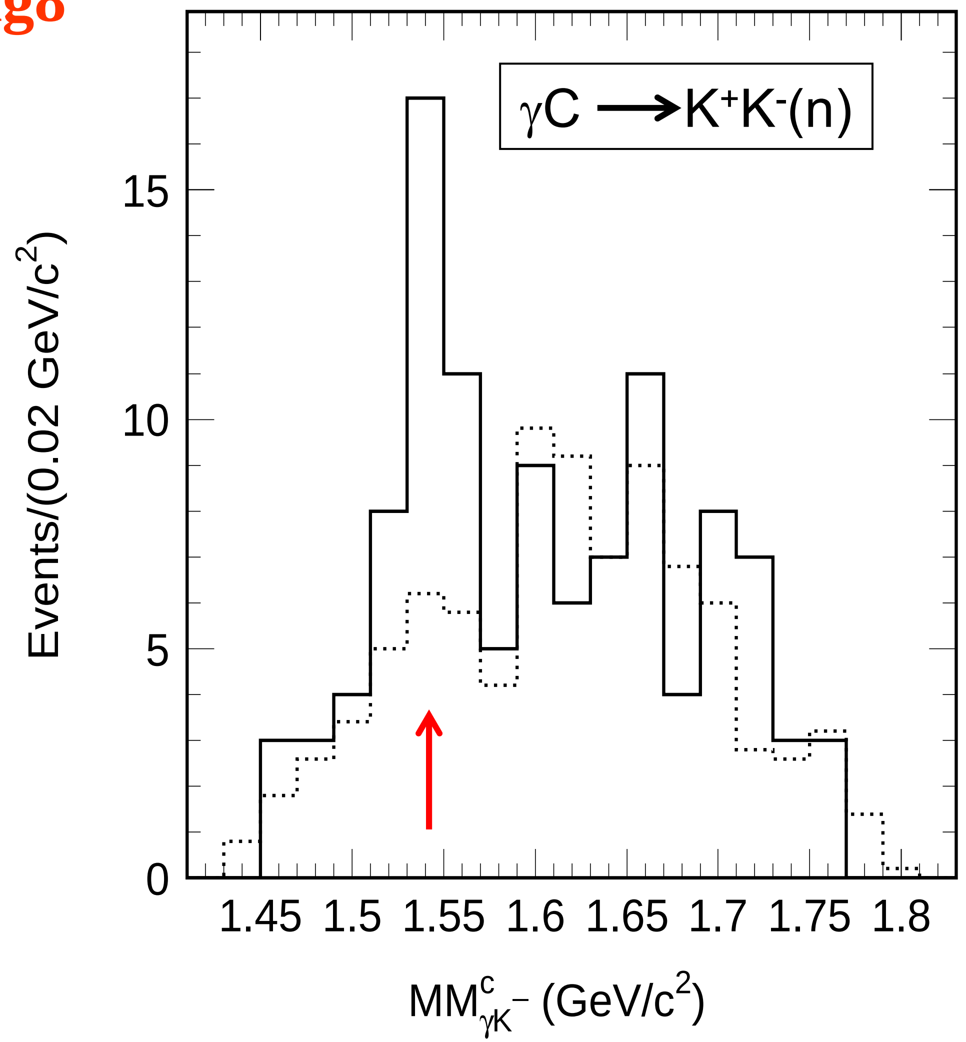
$\gamma\,^{12}C \longrightarrow K^-K^+X$

- K^+K^- observed at forward angles. Interaction on neutron ensured by veto for protons.

-After corrections for Fermi motion a peak of ~20 events is observed in K^- miss. mass.

Comment: First claim of Θ^+, but low statistics result.

LEPS/Spring8



CEBAF Large Acceptance Spectrometer

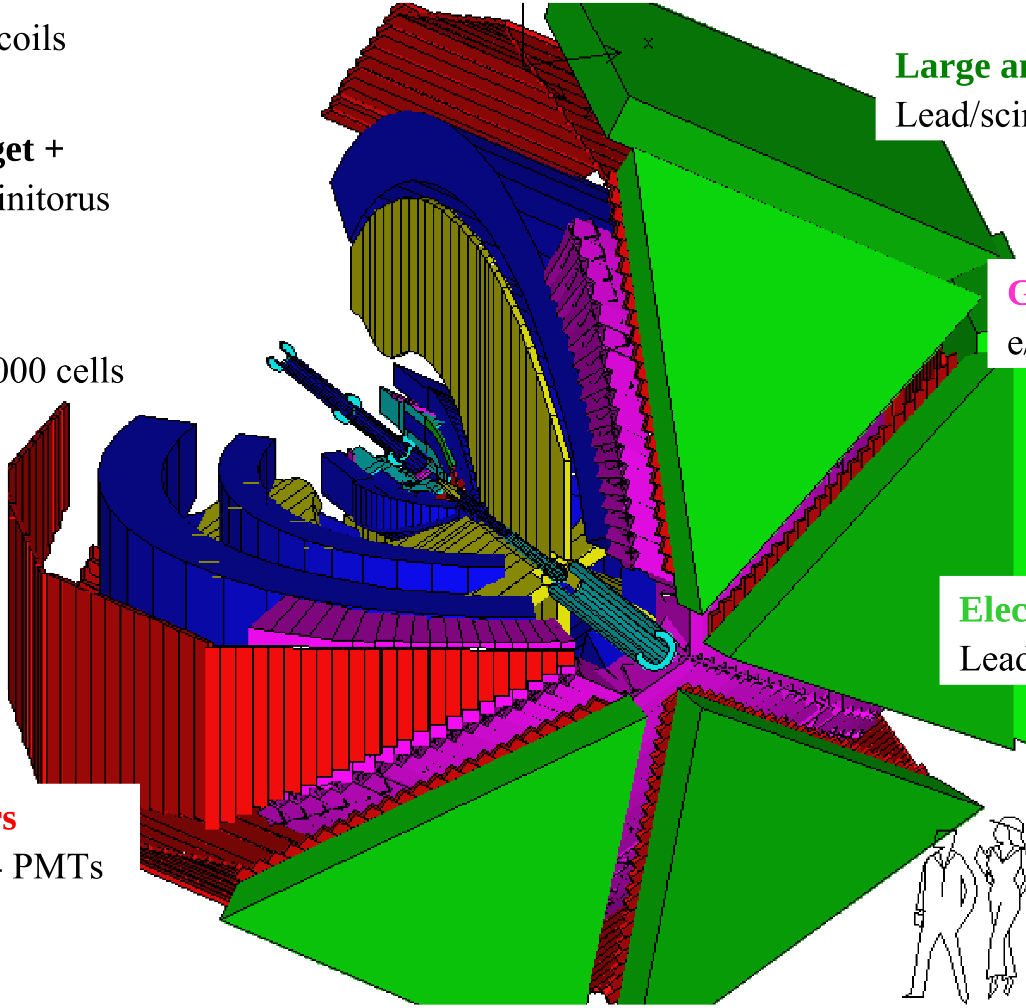
Torus magnet
6 superconducting coils

Liquid D_2 (H_2)target +
γ start counter; e minitorus

Drift chambers
argon/CO_2 gas, 35,000 cells

Large angle calorimeters
Lead/scintillator, 512 PMTs

Gas Cherenkov counters
e/π separation, 216 PMTs



Electromagnetic calorimeters
Lead/scintillator, 1296 PMTs

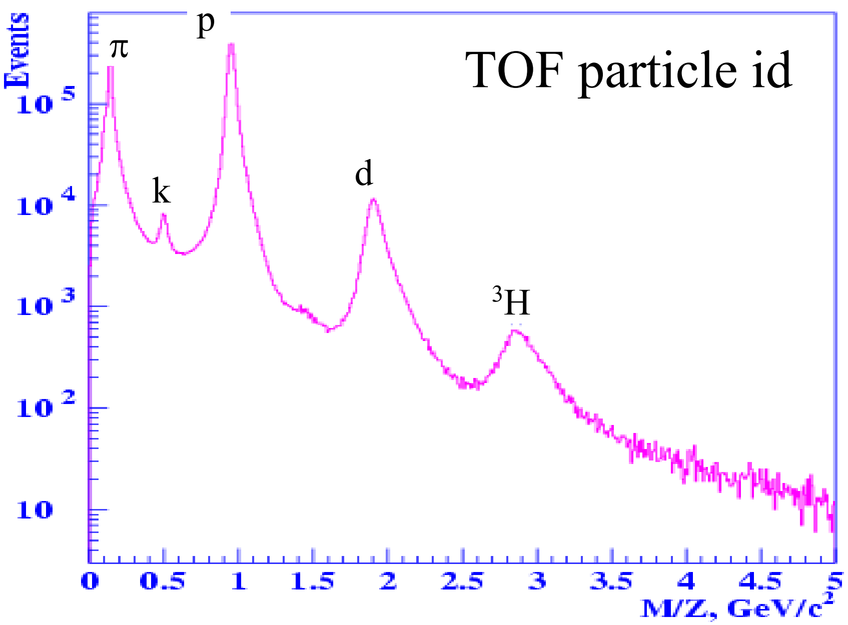
Time-of-flight counters
plastic scintillators, 684 PMTs

CLAS - Exclusive production from deuterium

Photon beam on deuterium

E_γ = 1 - 3 GeV

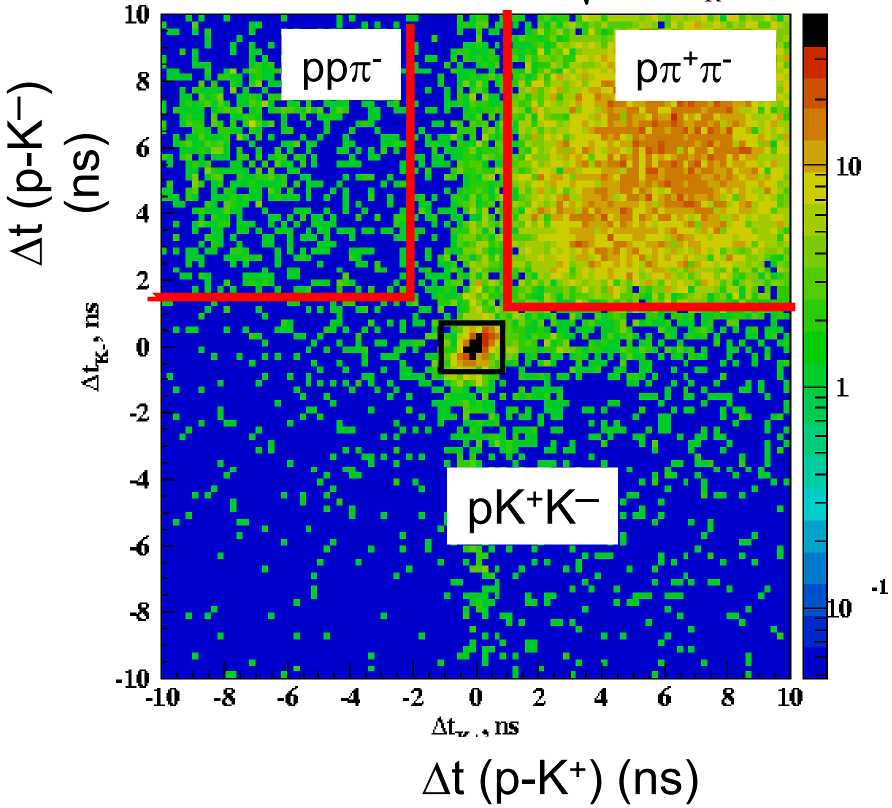
$\gamma D \longrightarrow K^- p K^+ n$



- $K^- p K^+$ event reconstruction

Kaon time relative to proton time

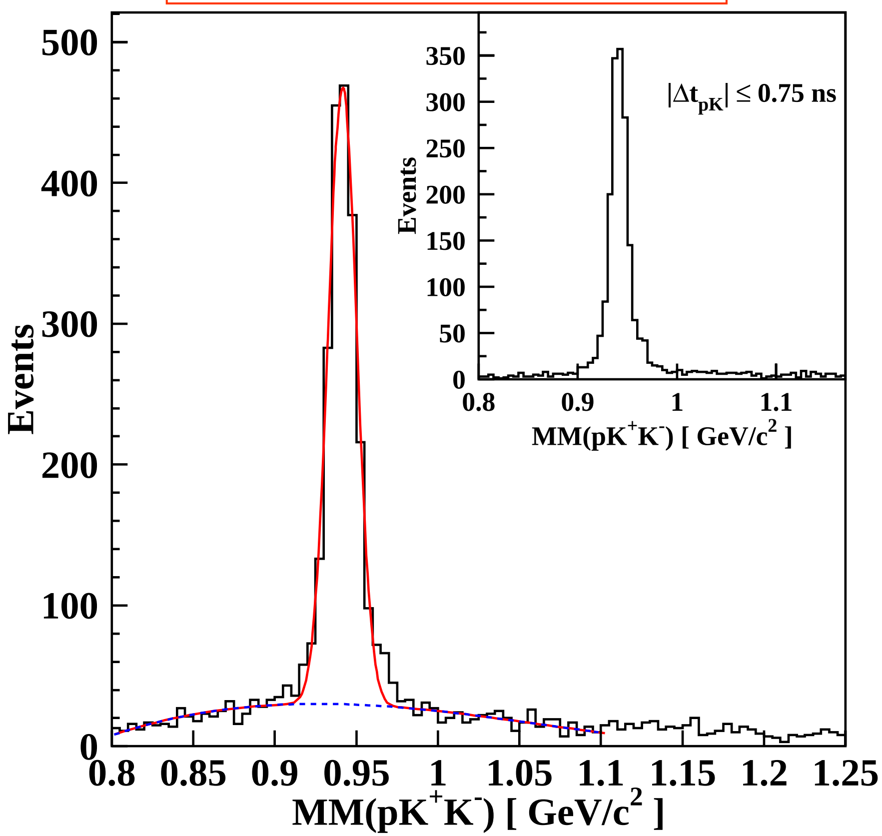
$$\Delta t_K = t - \frac{R}{\beta_c \cdot c};\ \beta_c = \frac{p}{\sqrt{p^2 + m_K^2}}$$



Process identification and event selection

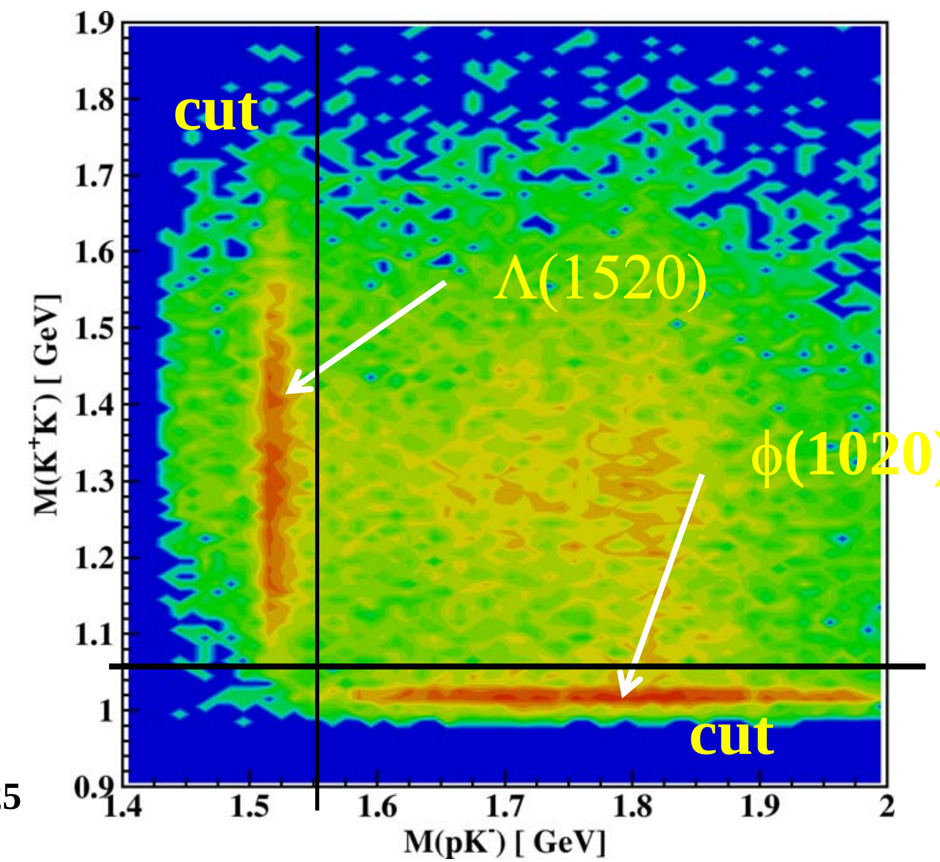
Missing mass technique

$\gamma D \longrightarrow K^{-}pK^{+}n$



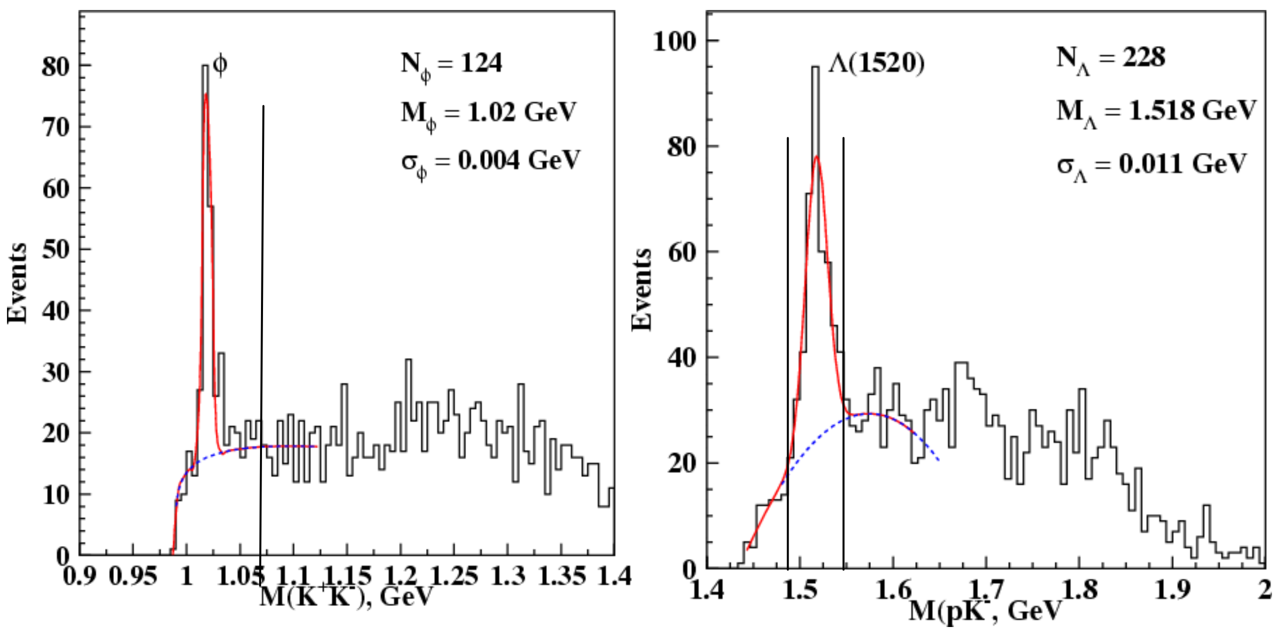
↑ Neutrons mass

3-body Dalitz plot

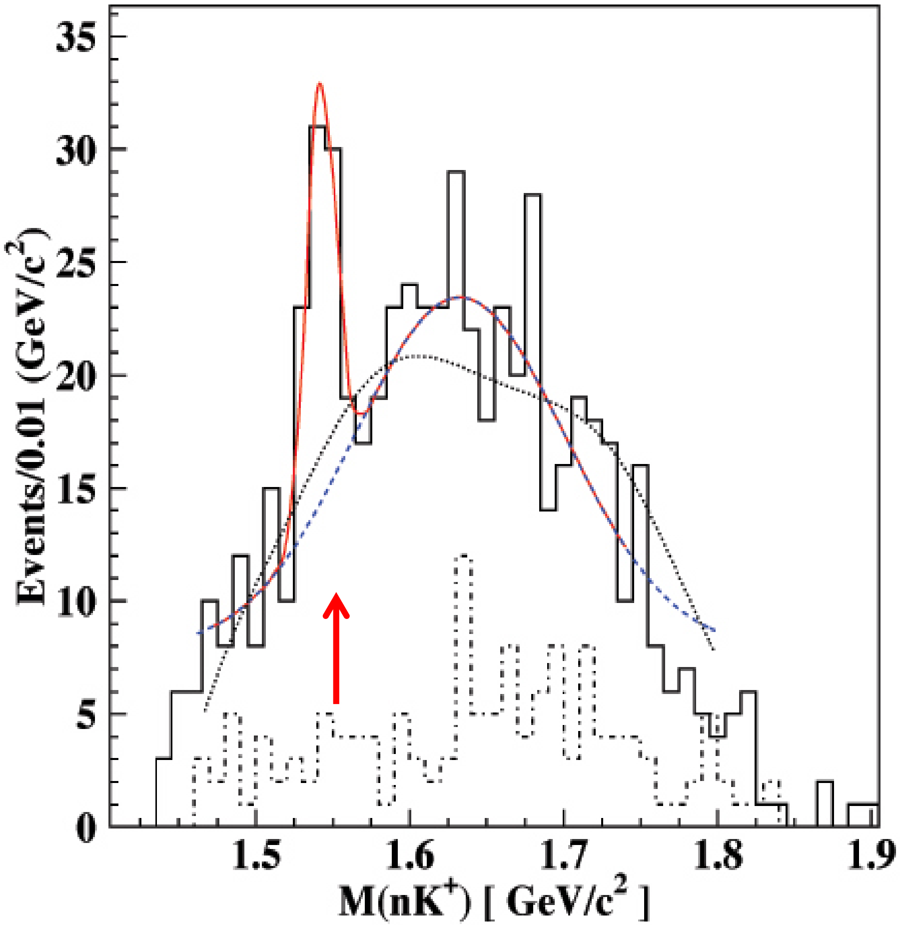


CLAS - The $\Theta^+(1540)$ on Deuterium.

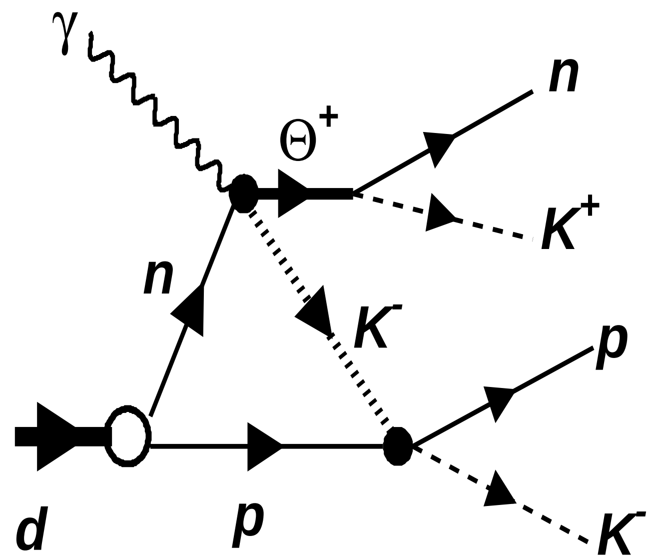
Removal Cuts:	$M(K^+K^-)$	< 1.070 GeV	- removes $\phi(1020)$
	$1.485 < M(pK^-)$	< 1.551 GeV	- removes $\Lambda(1520)$
	p_n	< 80 MeV/c	- removes spectator neutrons
	p_{K^+}	> 1 GeV/c	- reduces background at $M(nK^+) > 1.7$ GeV



$\Theta^+(1540)$ in CLAS



S. Stepanyan et al., PRL91, 252001 (2003)



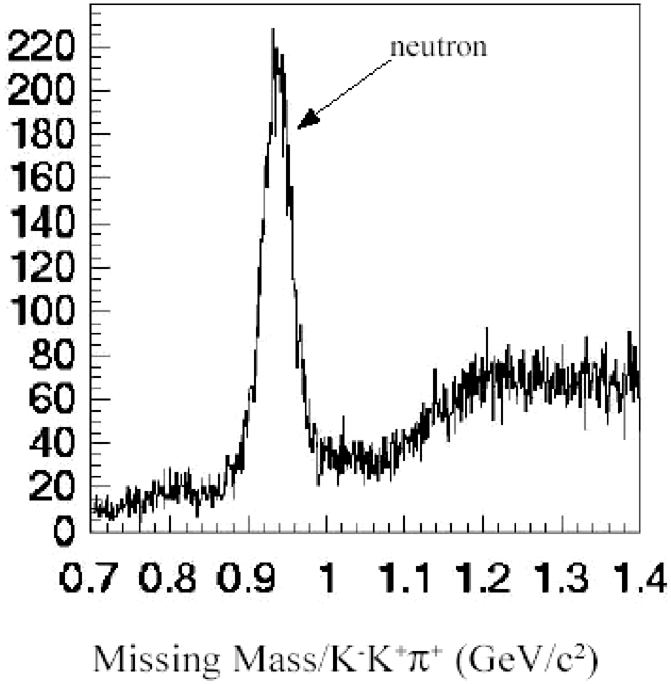
a)

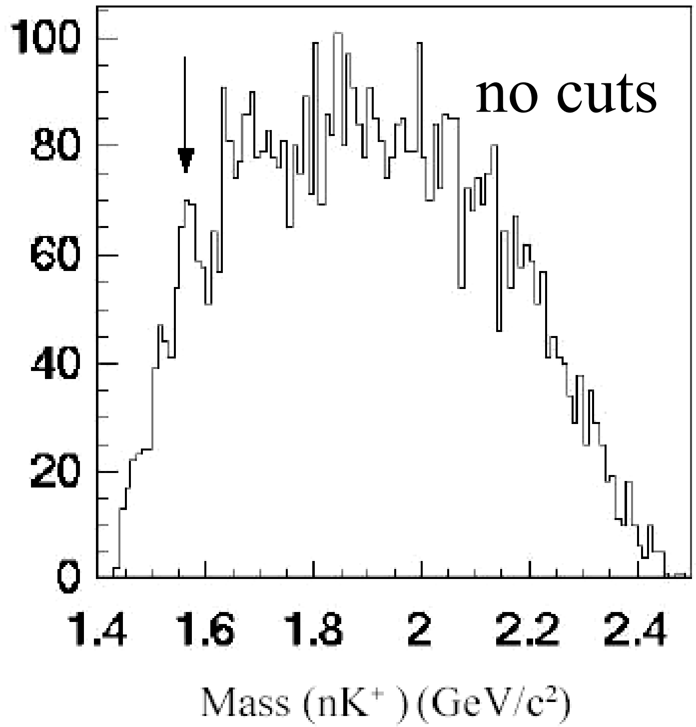
Requires rescattering from proton to allow detection of proton in CLAS.

CLAS – Exclusive Production on Hydrogen

$4.8 < E_\gamma < 5.4$ GeV

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

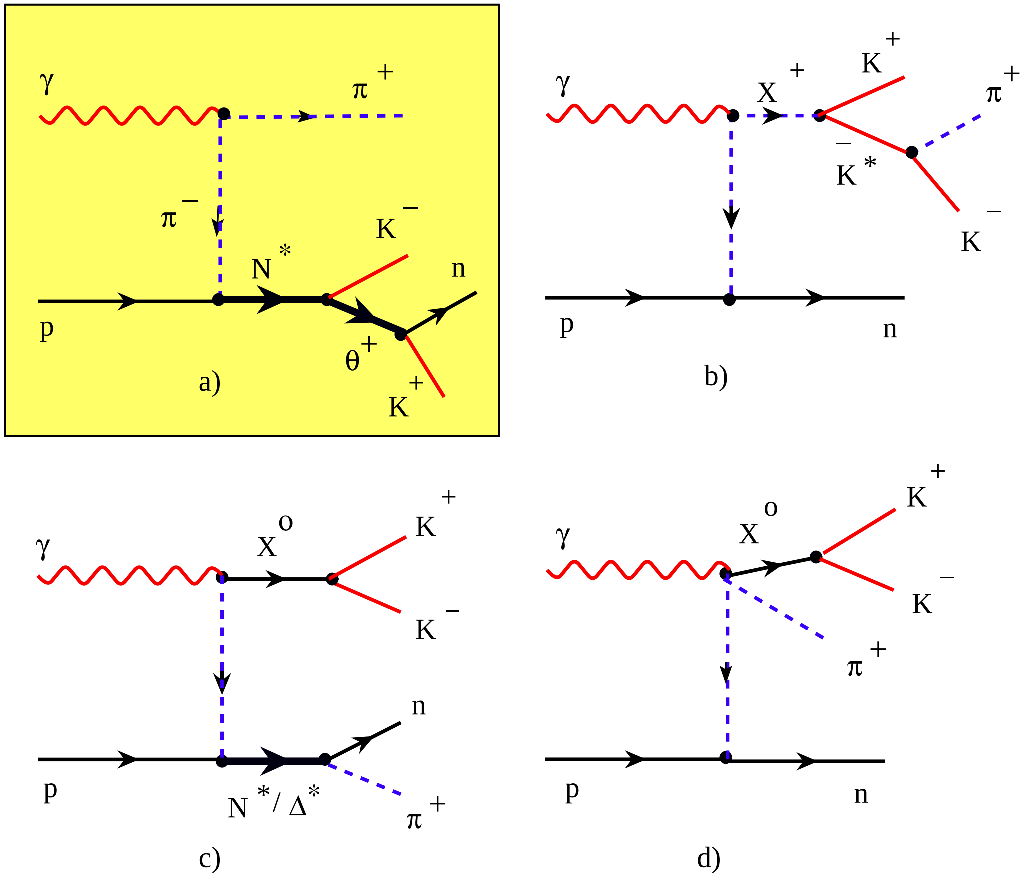




- Further cuts are motivated by assumptions on production mechanism.

Exclusive Production on Hydrogen

Possible production mechanism



- Select t-channel process by tagging forward π^+ and reducing K^+ from t channel processes

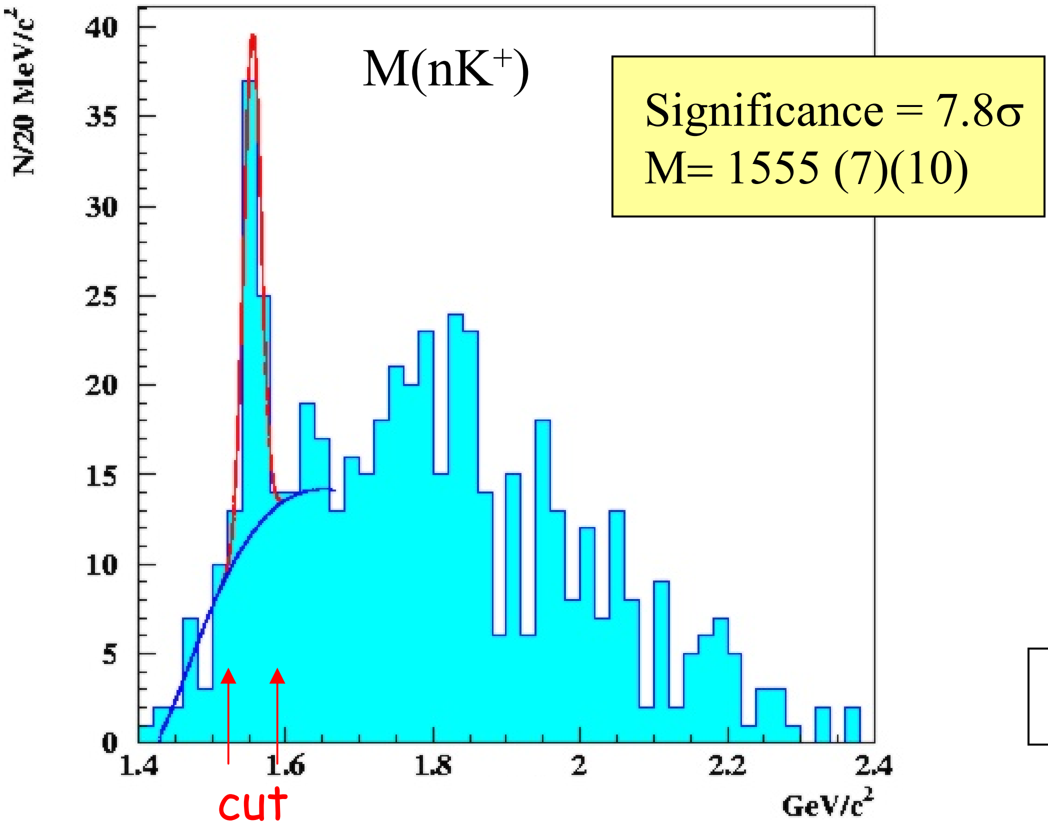
- $\cos\theta^*_{\pi^+} > 0.8$
- $\cos\theta^*_{K^+} < 0.6$

(in c.m. frame)

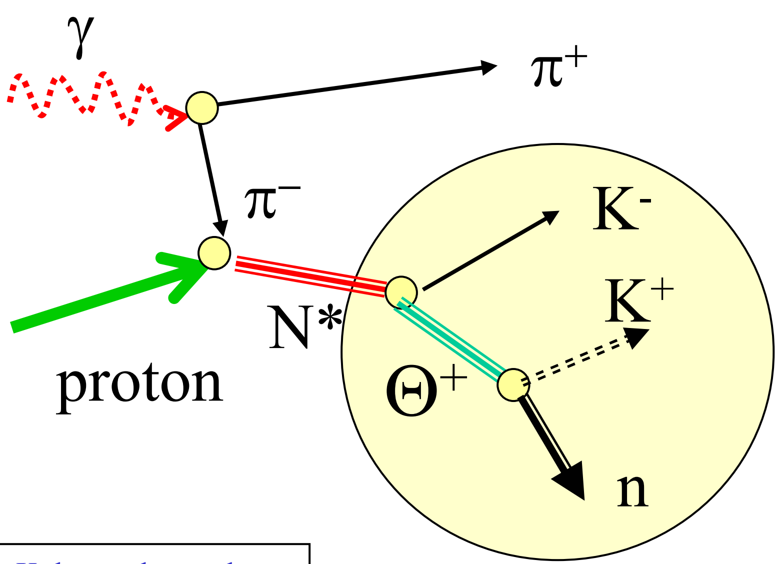
CLAS - $\Theta^+(1540)$ on protons

$E\gamma = 3 - 5.4$ GeV

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



- Θ^+ production through N^* resonance decays?



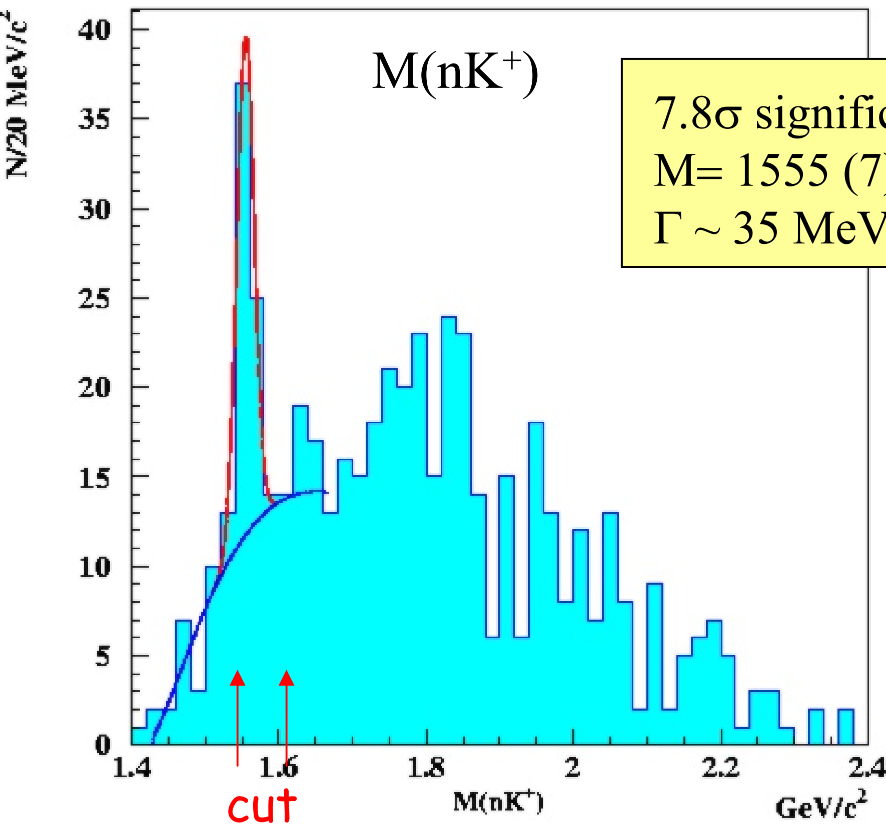
V. Kubarovsky et al.,
PRL 92, 032001 (2004)

CLAS - Θ^+ production mechanism?

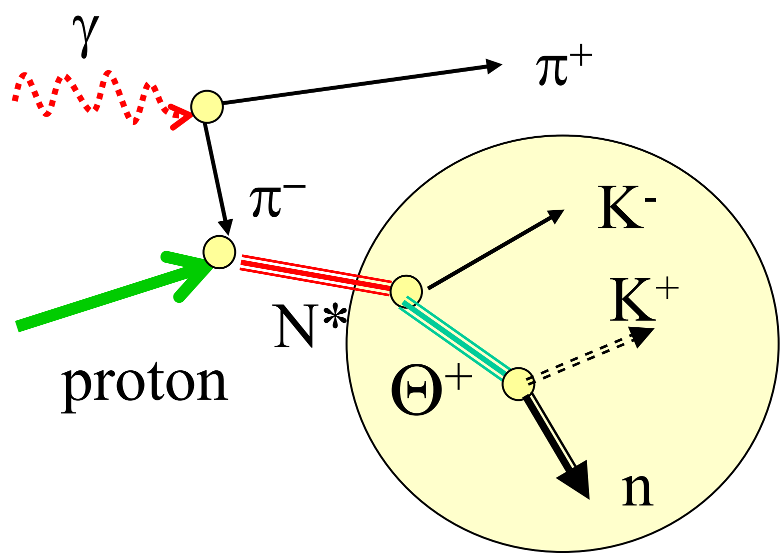
$E\gamma$ = 3 - 5.4 GeV

$\gamma p \Longrightarrow \pi^+ K^+ K^- n$

7.8σ significance
M= 1555 (7)(10)
Γ ~ 35 MeV

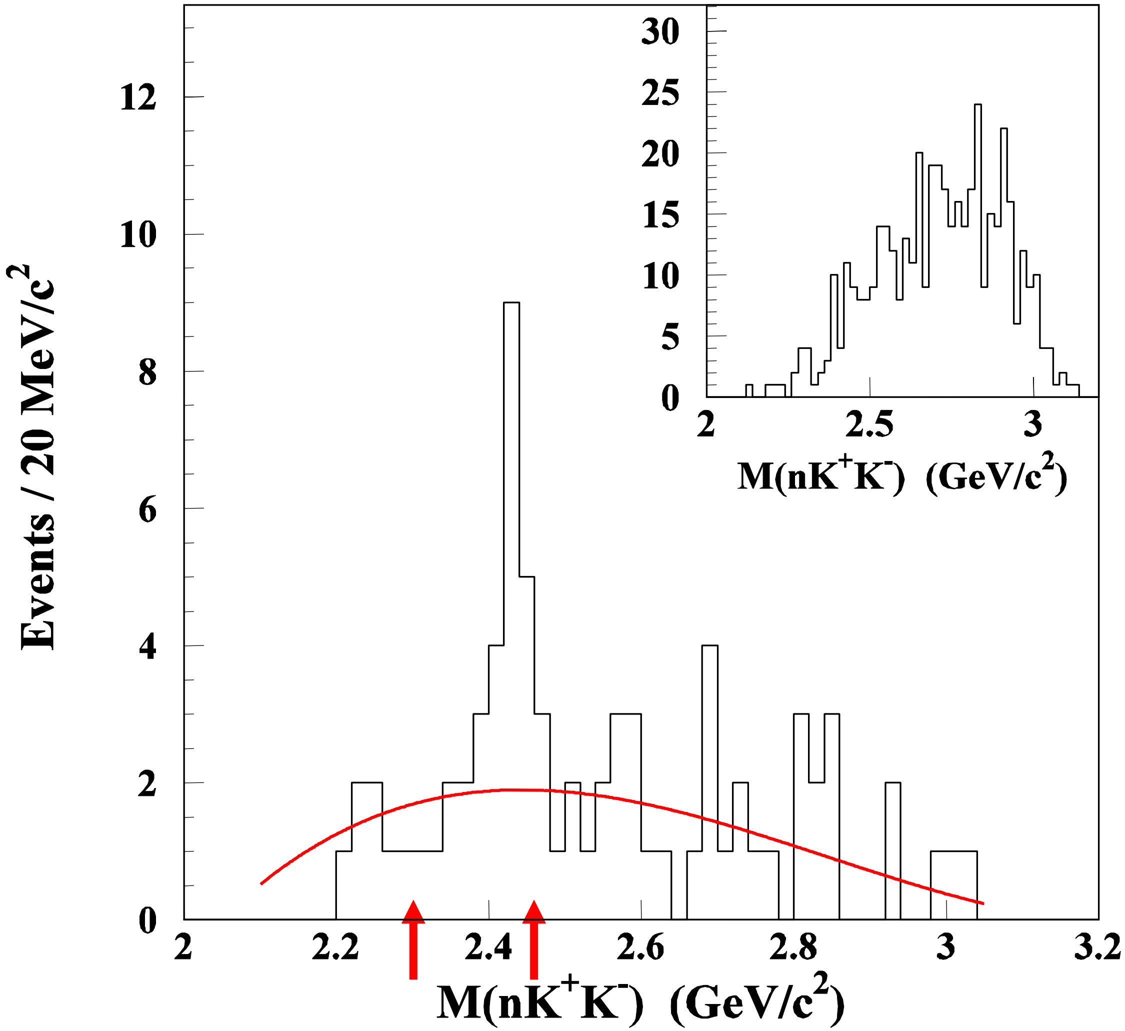


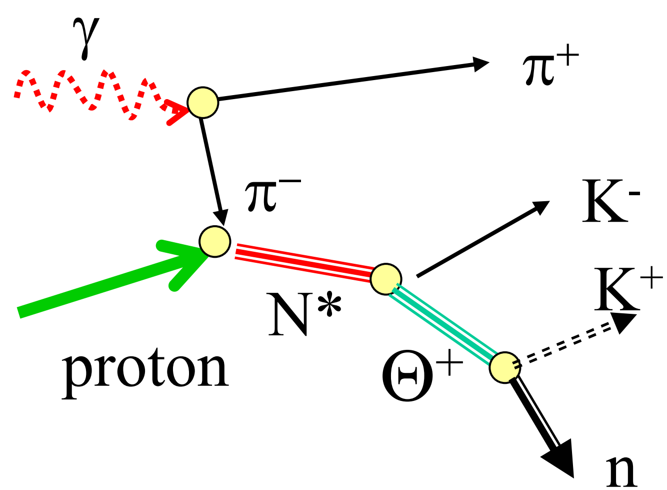
- Θ^+ production through N^* resonance decays?



- Cut on Θ^+ mass, and plot $M(nK^+K^-)$

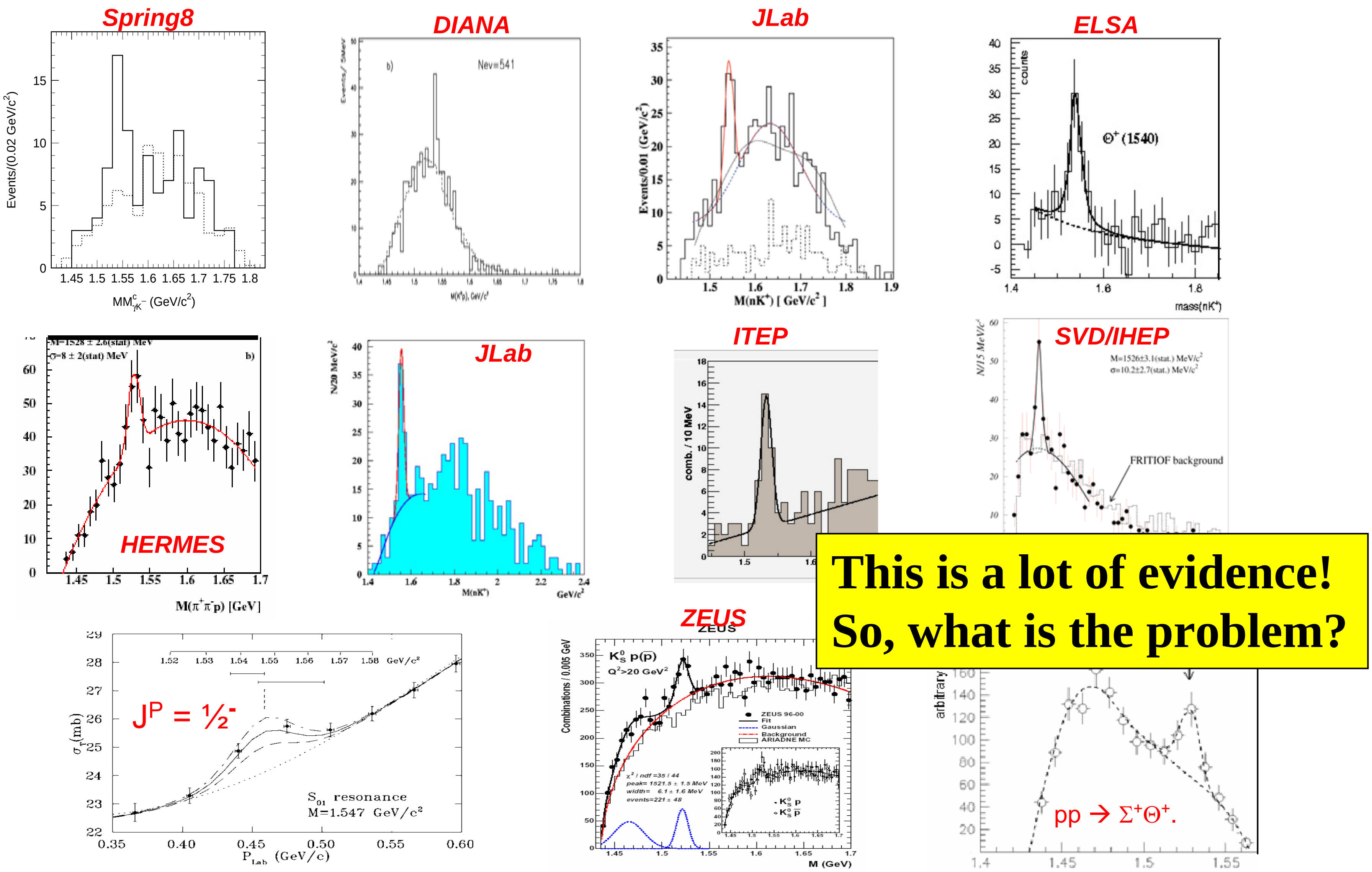
CLAS - Θ^+(1540) and N* ?





- What do π^-p scattering data say?
- π^-p cross section data in PDG have a gap in the mass range 2.3–2.43 GeV.

Evidence for Θ+ Pentaquark



So, what is the problem?

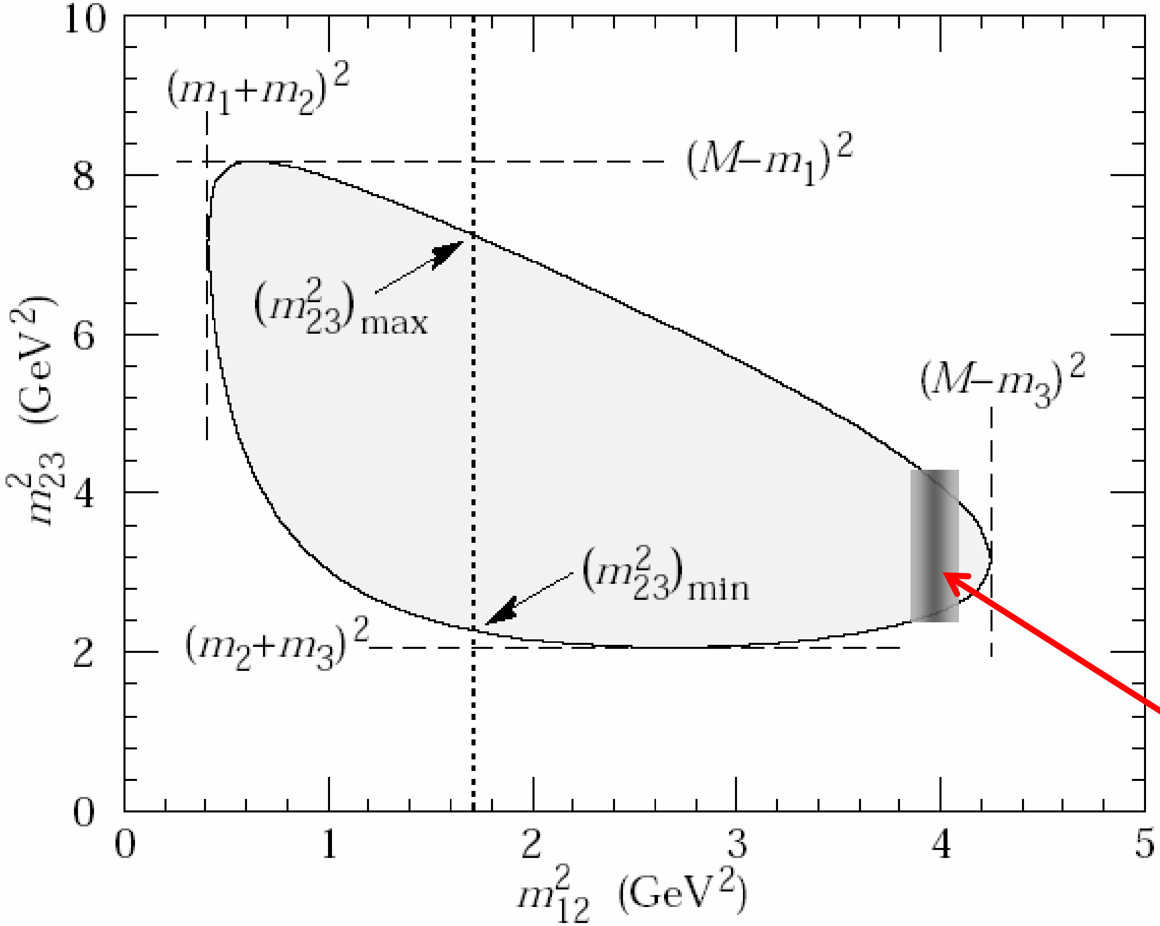
- If Pentaquark baryons exist it is the most important finding in hadronic physics since the J/Ψ discovery. It is absolutely necessary to obtain fully convincing experimental data.

- Many experiments see positive Θ^+ signal with specific kinematical cuts, taken together they represent an impressive significance. However, few experiment have fully convincing results:
    - significance is often optimistically estimated ~ 4–6σ
    - background estimates are not always justified
    - masses are not fully consistent (1525–1555) MeV
    - are kinematical reflections excluded?

- Many high energy experiments present null results. This adds a level of uncertainty until we understand the sensitivities in various experiments.

- The very narrow width of ~1 MeV is not understood, although models have been developed that allow Θ^+ widths of < 1 MeV.

Reminder - Kinematical Reflection

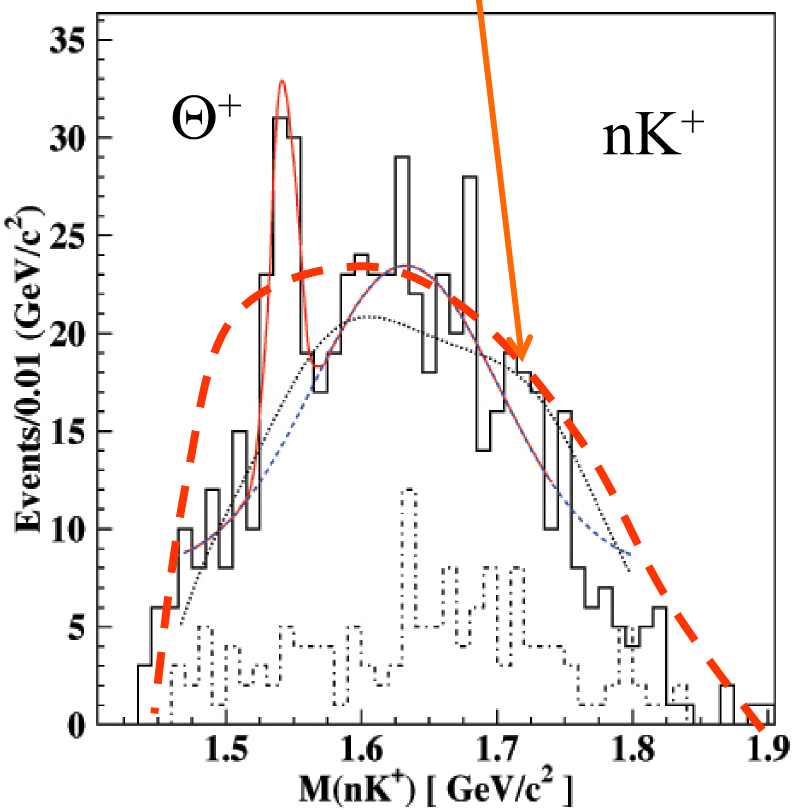


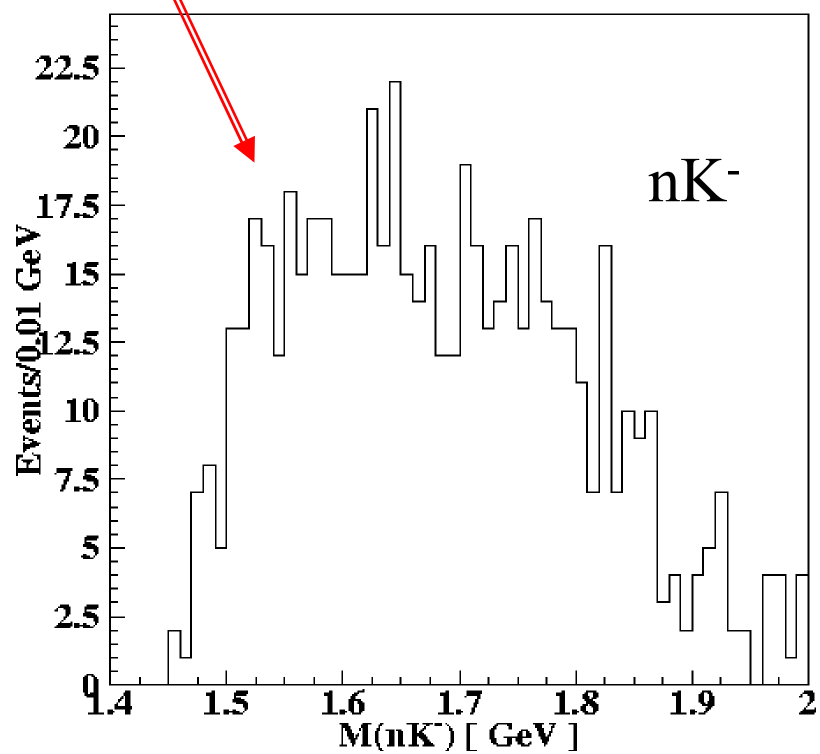
A narrow resonance in m_{12} near kinematical limit may appear like a broad enhancement in m_{23} (kinematical reflection).

The $\Theta^+(1540)$ as a kinematical reflection ?

Is this a more realistic background?

If kinematical reflections from $M \rightarrow K^+K^-$ can generate the Θ^+ peak, they should show up in nK^- as well, assume isospin symmetry.

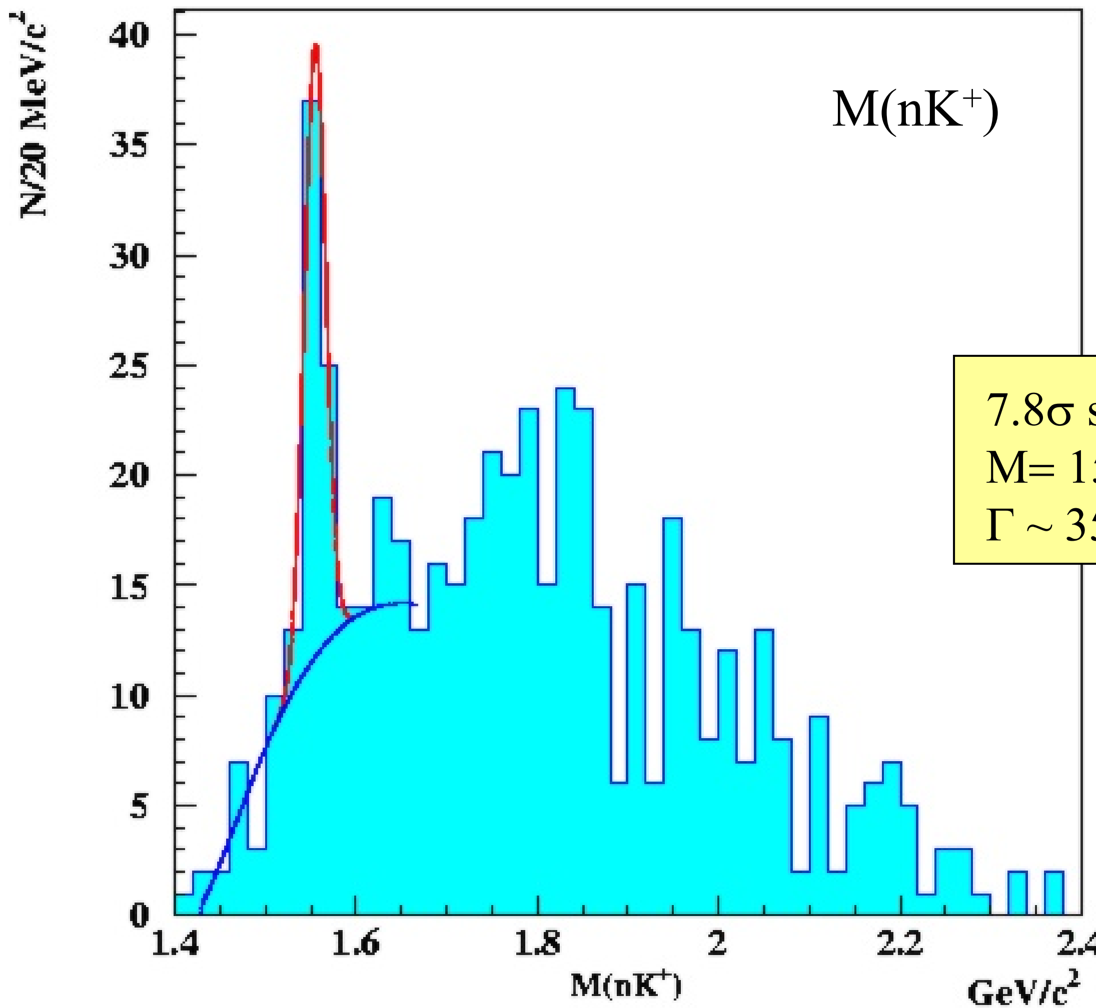




Kinematic reflections do not seem to generate narrow nK^- peak

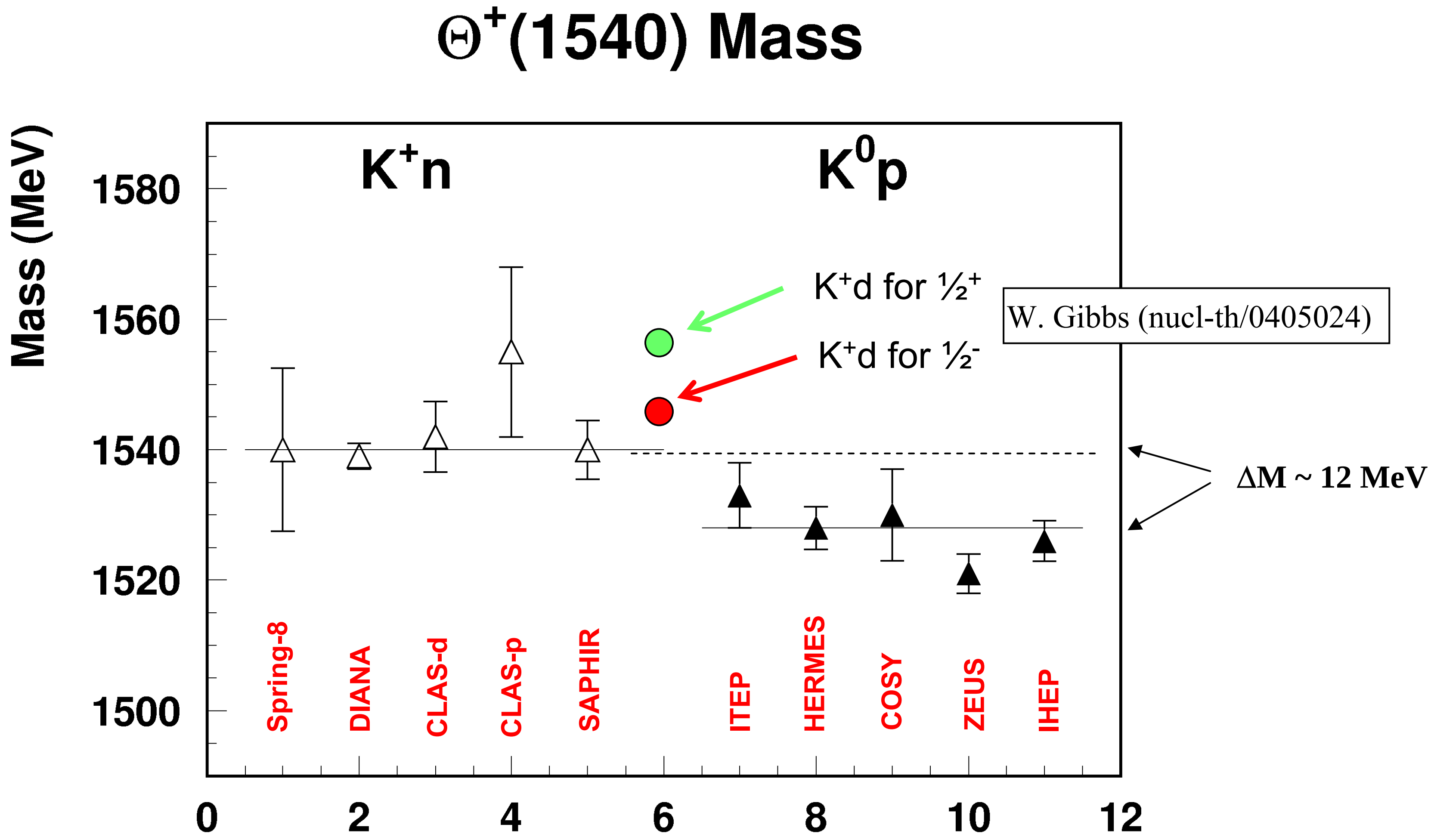
Nobody can ***seriously*** suggest that this is a kinematical reflection!

$\gamma p \Rightarrow \pi^+ K^+ K^- n$



7.8σ significance
M= 1555 (7)(10)
Γ ~ 35 MeV

Is there a problem with the mass?



Mass shift could be due to different background shapes, final state interactions, and different interference effects in the two channels.

Are the null experiments sensitive to $\Theta^+(1540)$?

Several high energy experiments have analyzed their data in the search for the Θ^+. In the following, I examine two of them, **BaBaR** and **Belle**, both detectors to study e^+e^- interactions at high energy to study B mesons.

They use very different techniques, and neither has seen a signal.

=> **BaBaR** studies particles produced in e^+e^- annihilations and subsequent quark fragmentation processes.

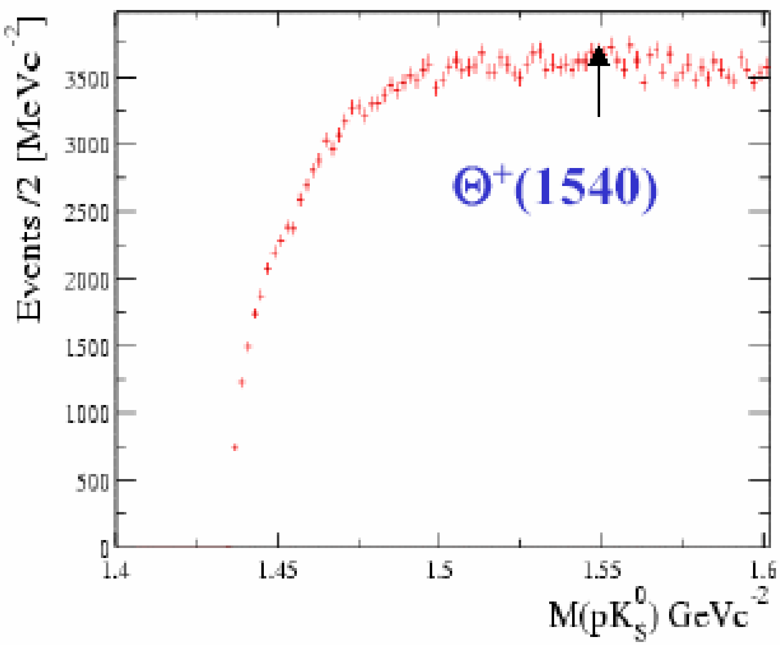
=> **Belle** uses K^+ and K^- produced in the fragmentation. They study K^+-nucleus scattering in their silicon (?) tracking Detectors. This is similar to the DIANA experiment that measured K^+Xe in a bubble chamber where they saw a Θ^+ signal

Do these results contradict experiments that have seen a signal?

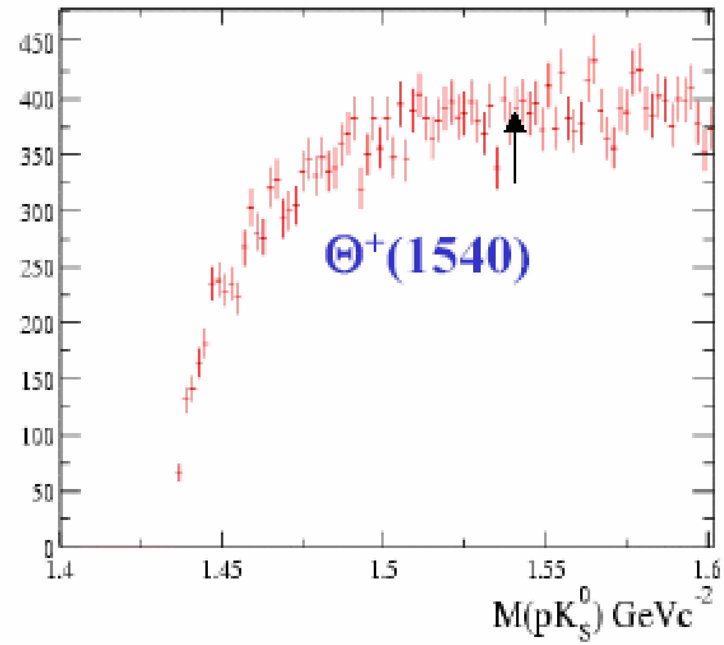
$\Theta^+(p\,K_s)(1540)$ Invariant Mass

No signal observed in any p* region (SFL > 0.0 cm)

$0.0 < p^* < 0.5$ GeV/c



$3.5 < p^* < 4.0$ GeV/c

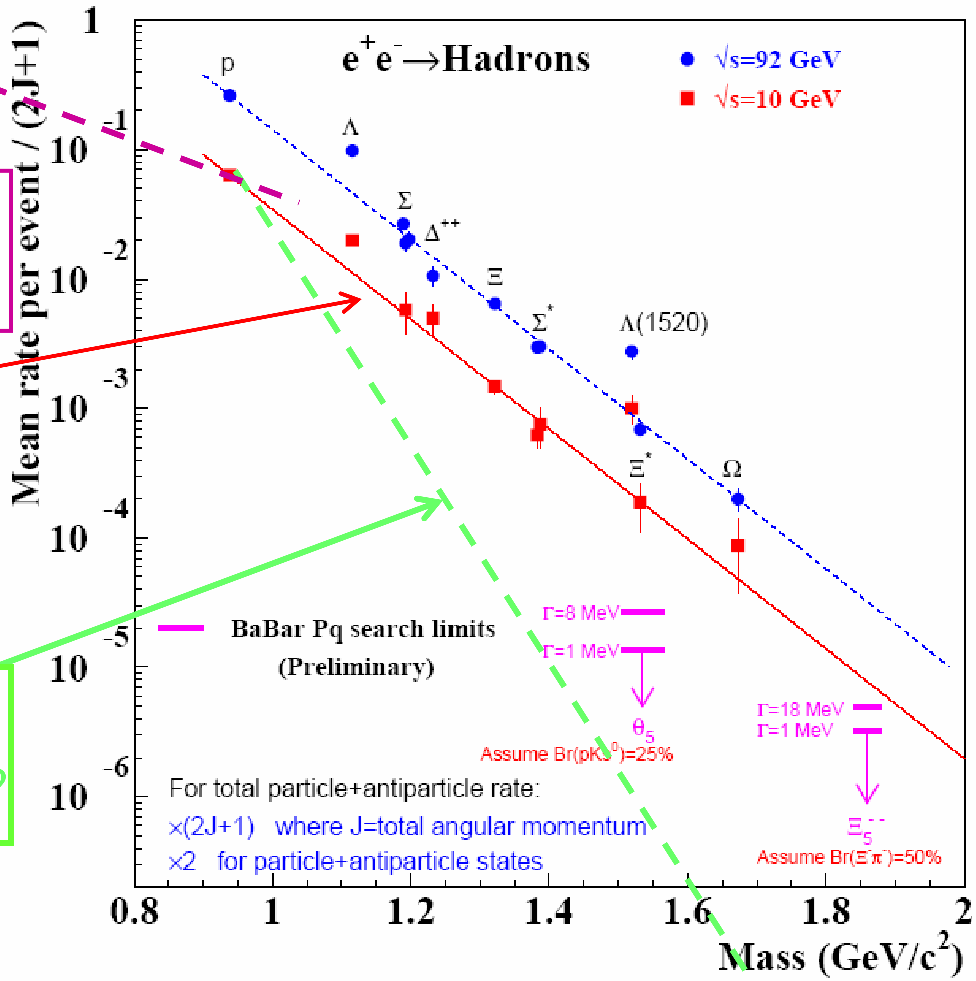


Hadron production in e^+e^-

Slope for p.s. mesons

Slope for baryons

Slope for Pentaquark??



Slope:

Pseudoscalar mesons:

~ 10^{-2}/GeV/c^2 (need to generate one $q\bar{q}$ pair)

Baryons:

~ 10^{-4} /GeV/c^2 (need to generate two pairs)

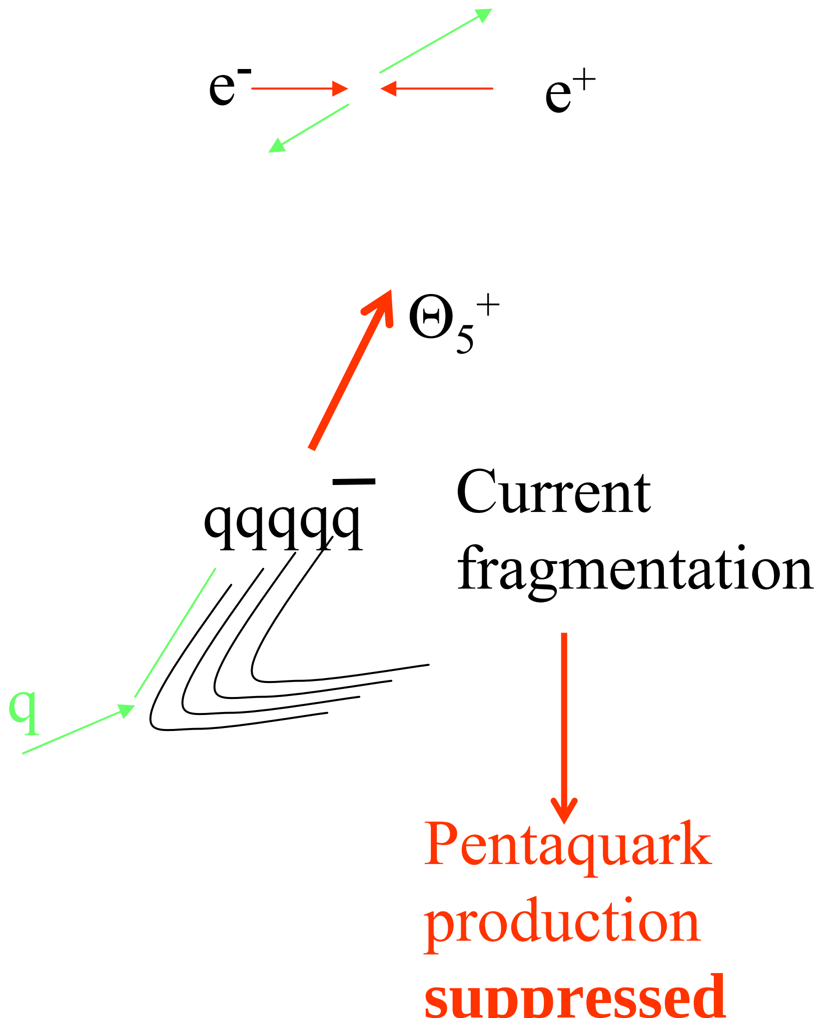
Pentaquarks:

~ 10^{-8} /GeV/c^2 (?) (need to generate 4 pairs)

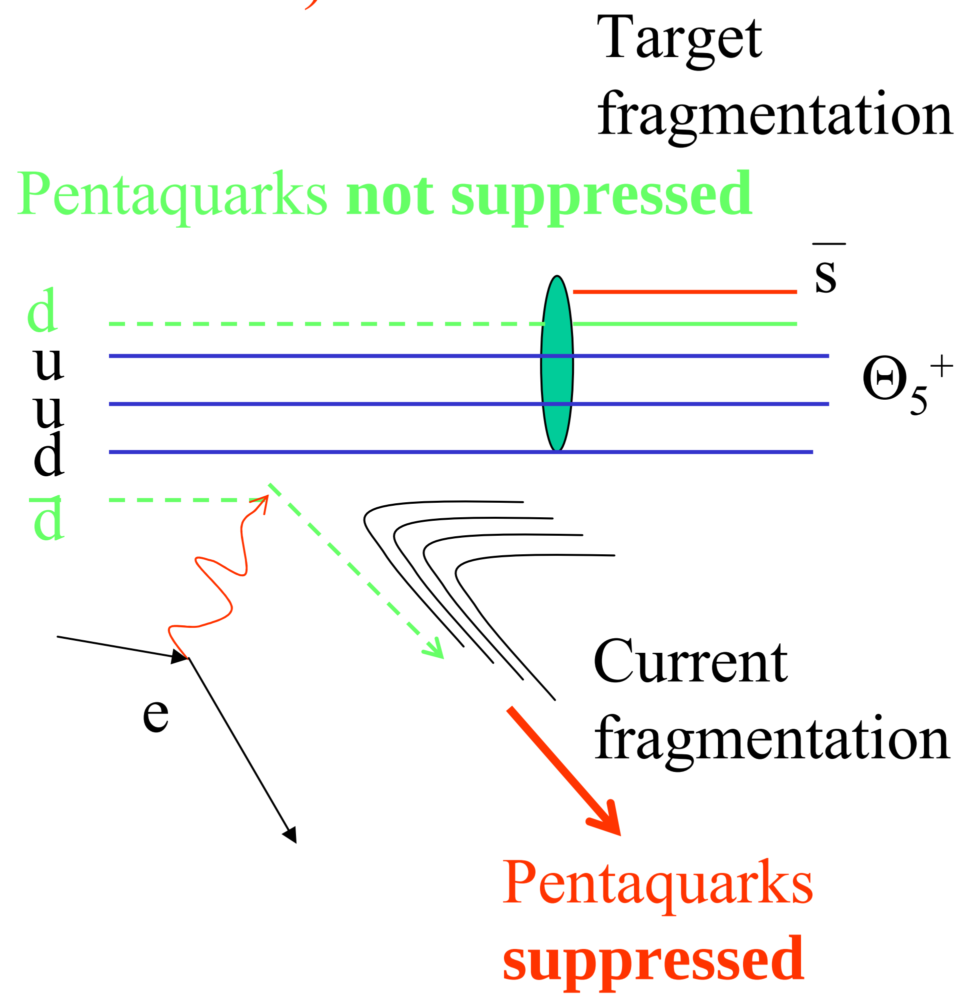
$\Longrightarrow$ Pentaquark production in direct e^+e^- collisions likely requires orders of magnitudes higher rates than available.

Pentaquarks in Quark Fragmentation?

Pentaquarks in e^+e^- (BaBaR)?



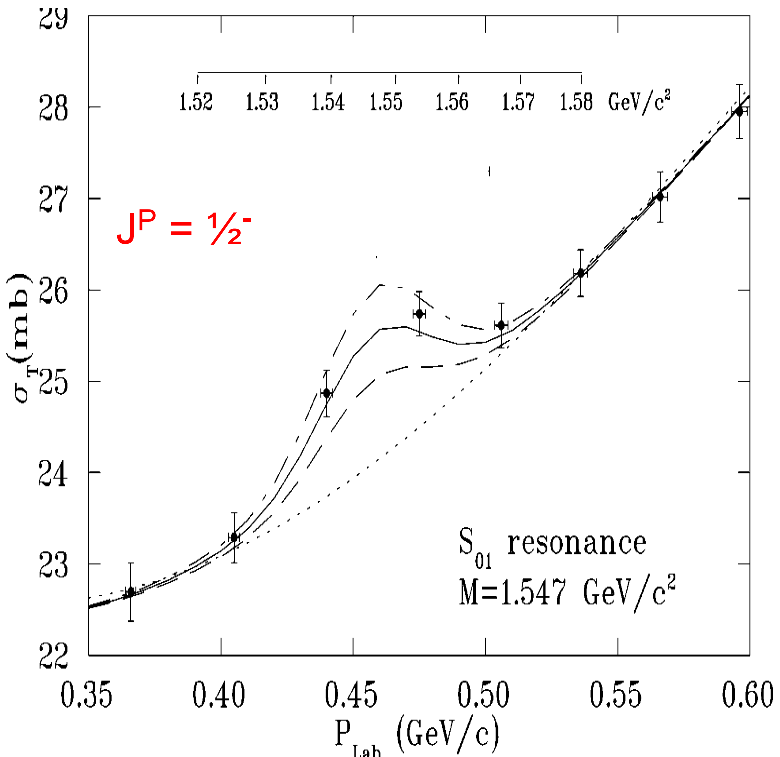
Pentaquarks in ep ? (ZEUS, H1, HERMES)

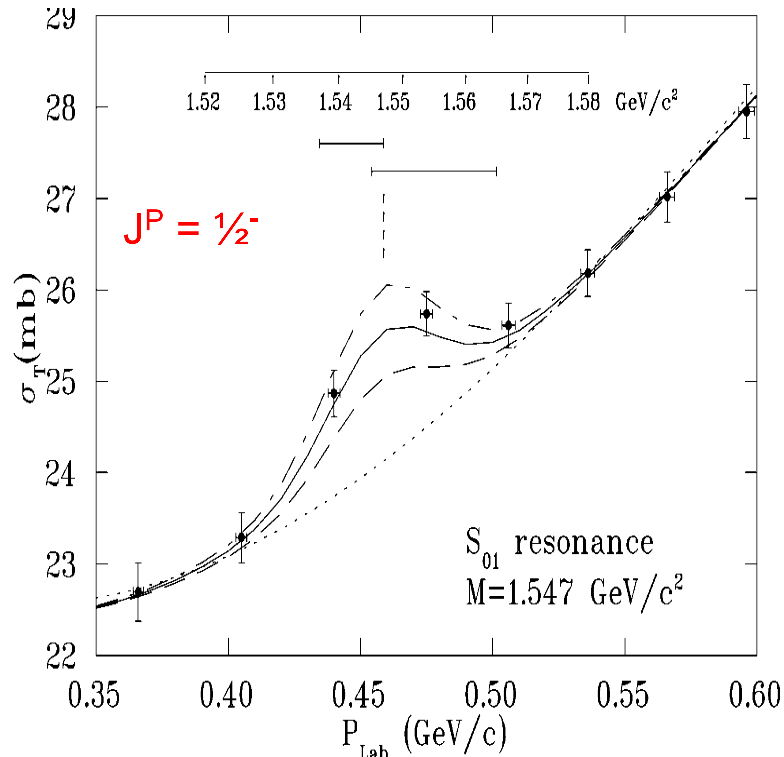


What do we know about the width of Θ^+?

$K^+d \rightarrow X$

W. Gibbs, nucl-th/0405024 (2004)

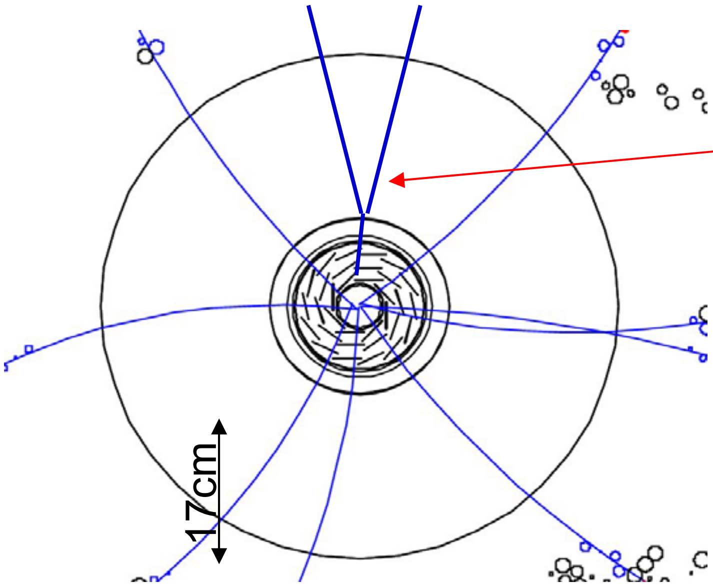




Γ_Θ = 0.9 +/-0.3 MeV ($K^+d \rightarrow X$)

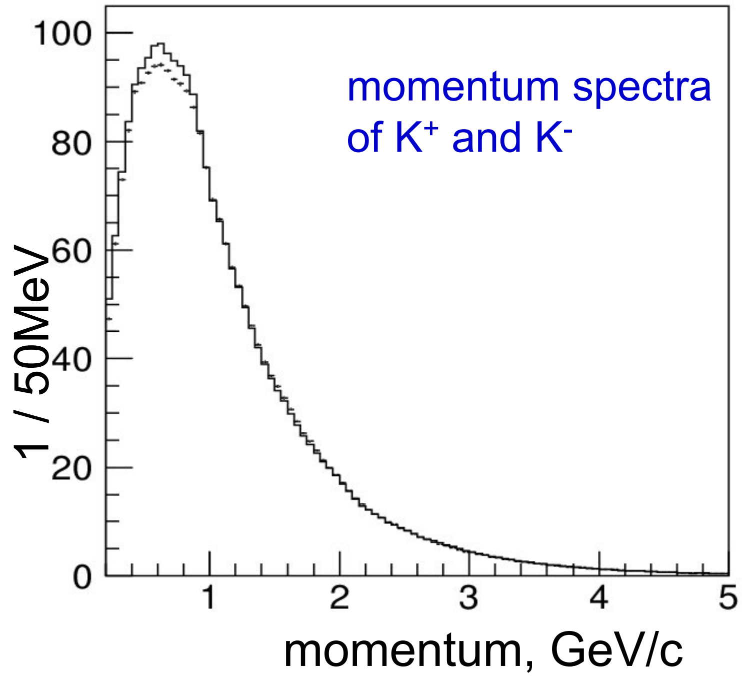
Same width is obtained from analysis of DIANA results on K^+Xe scattering. (*R. Cahn and G. Trilling, PRD69, 11401(2004)*)

Belle: The basic idea

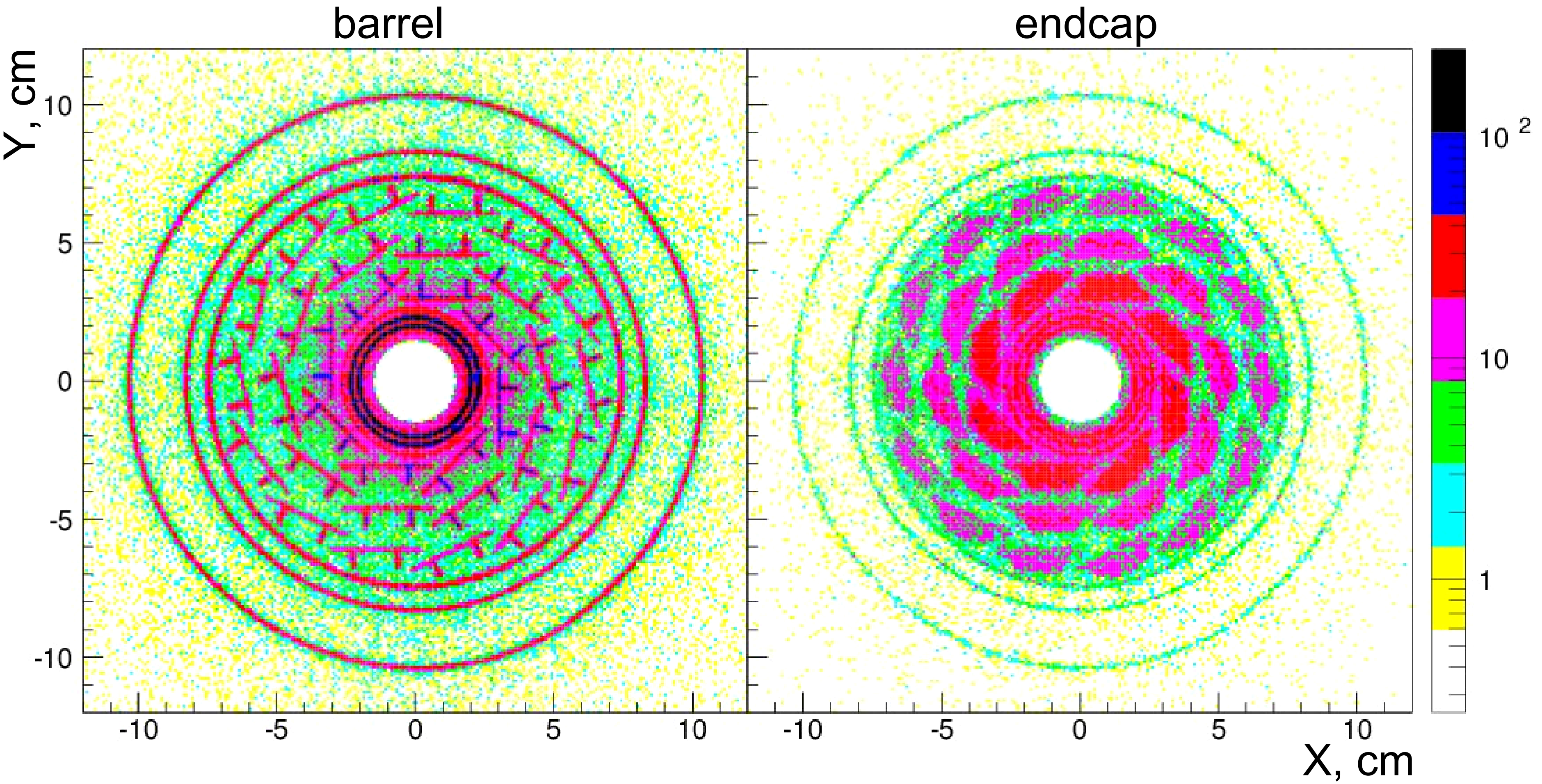


- Small fraction of kaons interacts in the detector material. Select secondary pK pairs to search for the pentaquarks.

- Momentum spectrum of the projectile is soft.
  $\Rightarrow$ low energy regime.

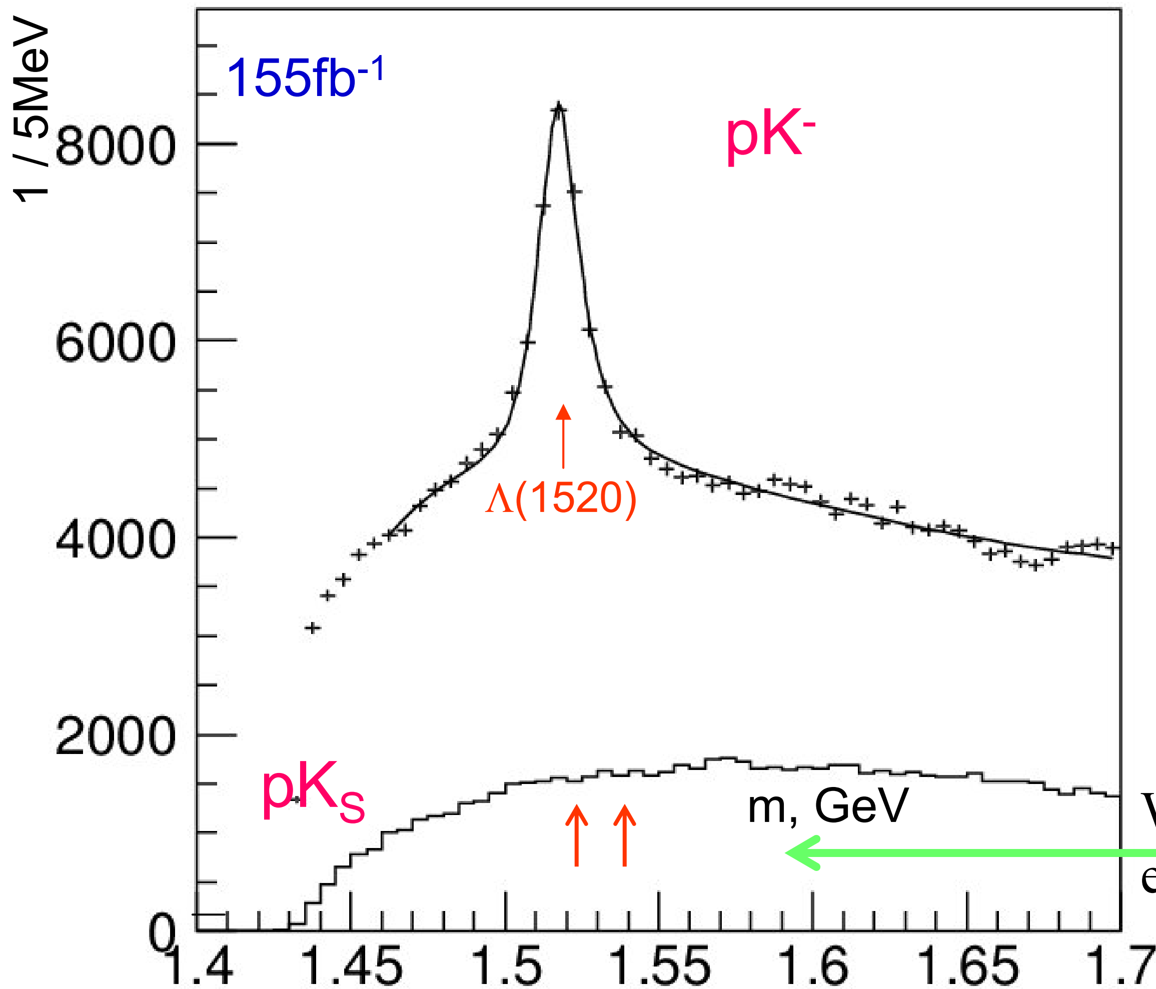


Belle: Distribution of Secondary pK^- Vertices in Data



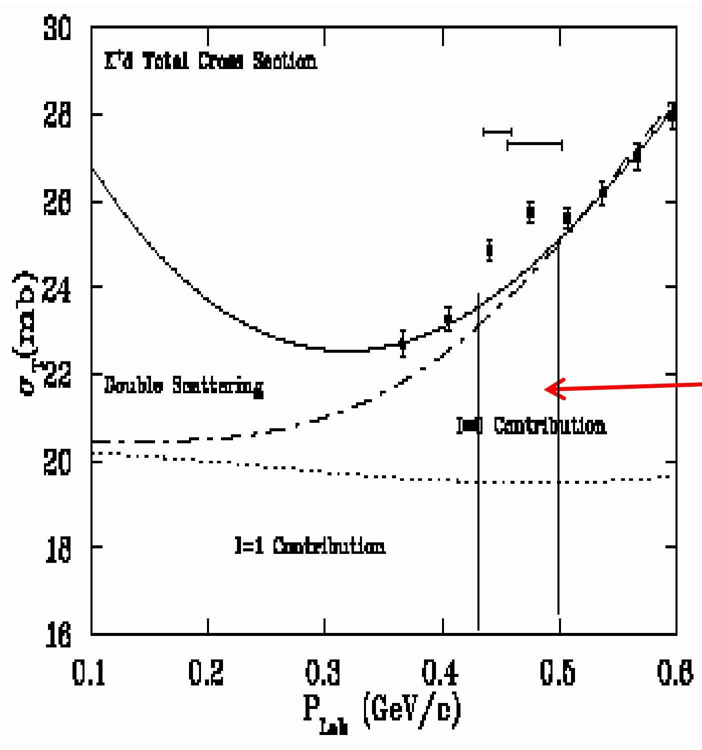
“Strange particle tomography” of the detector.

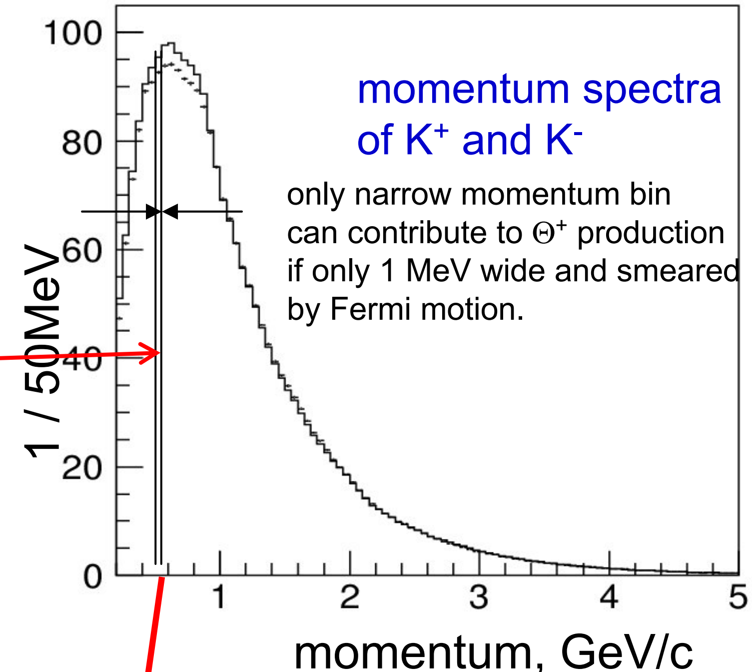
Belle: Mass Spectra of Secondary pK



What should we have expected here?

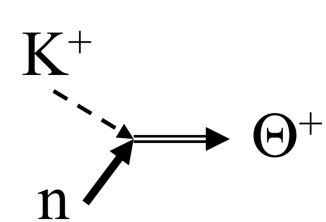
σ_{tot}: K^+d



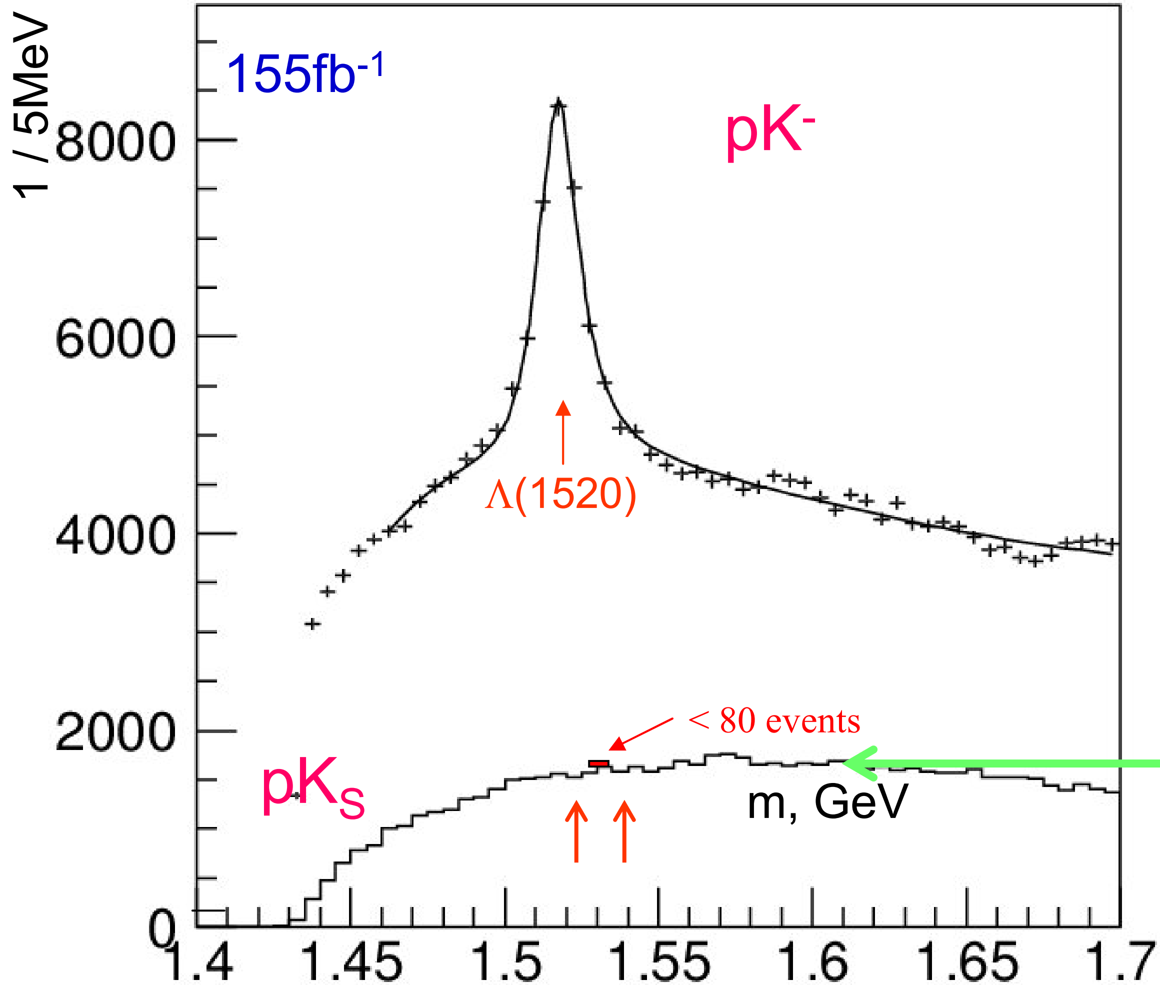


Θ^+ width: 0.9+/-0.3 MeV

Momentum range possibly contributing to Θ^+ production.



Belle: Mass Spectra of Secondary pK



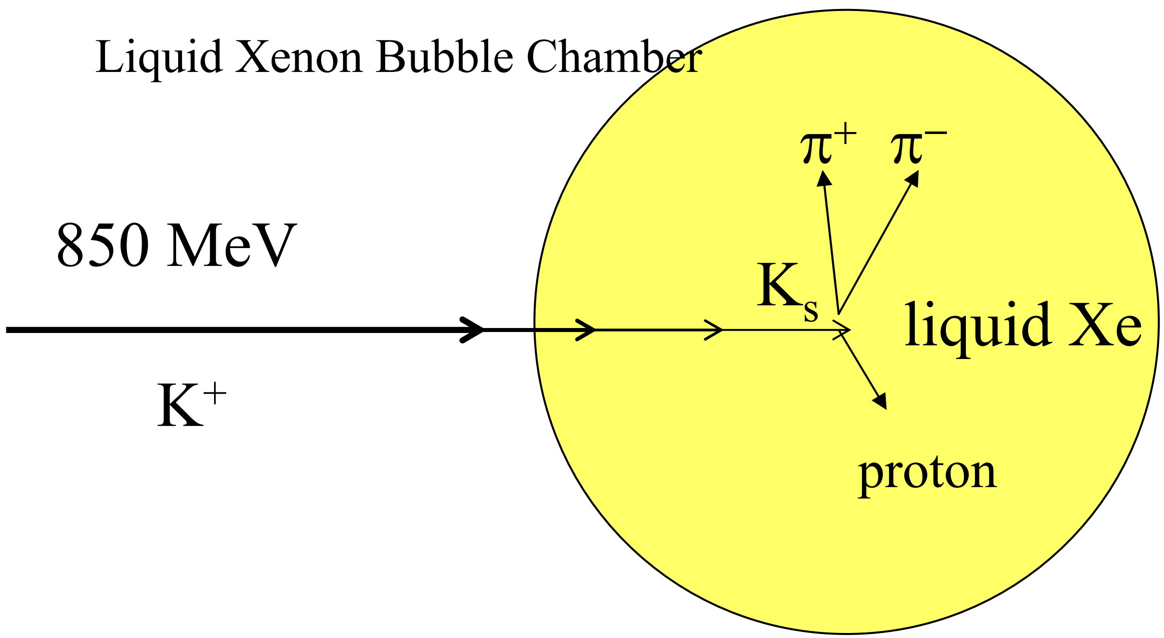
For I=0:

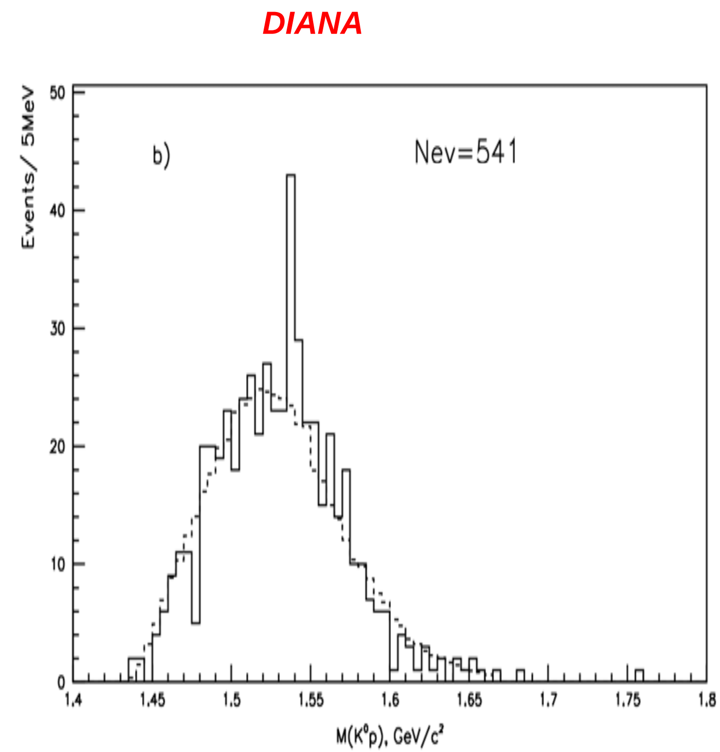
nK^+: pK^0_s: pK^0_L

2 : 1 : 1

This is approx. what we should have expected here! Assume that background events have same isospin structure as Θ^+ events.

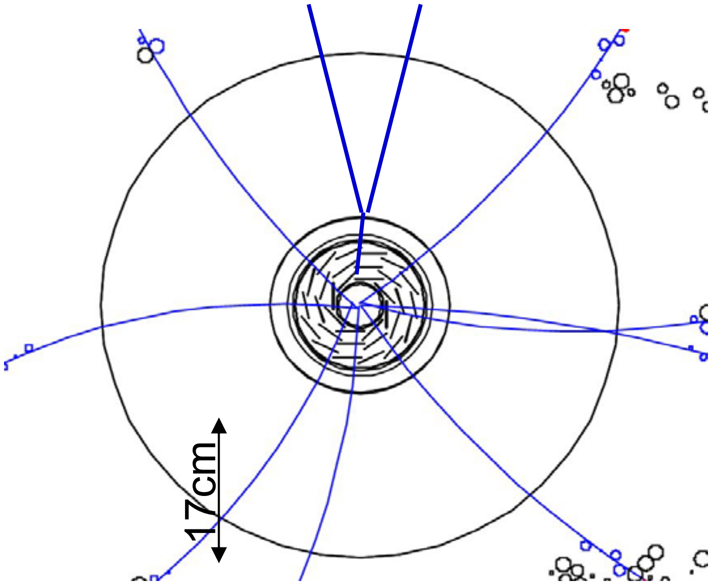
Principle of the DIANA Experiment

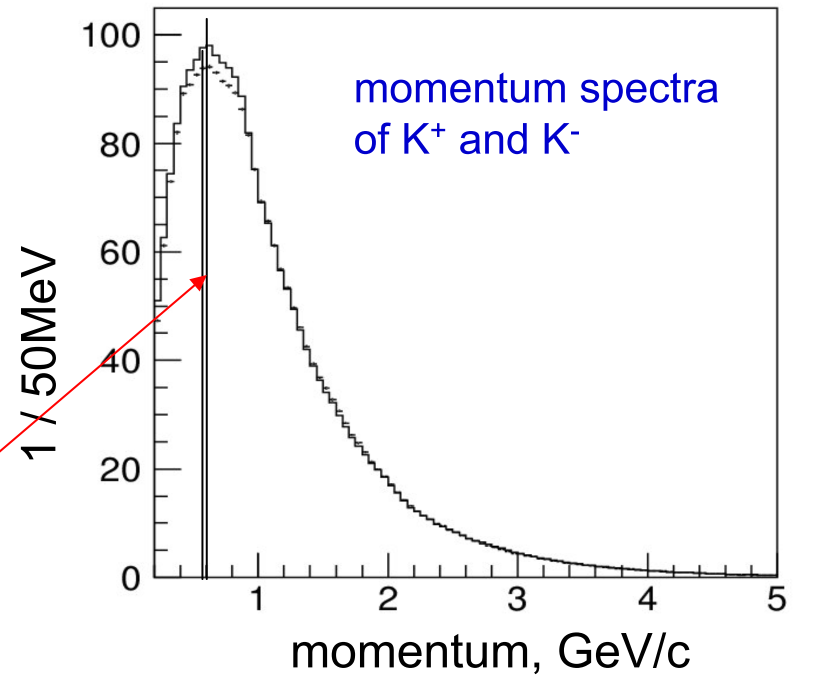




- The K^+ beam gets slowed down in the Xe bubble chamber and comes to a stop if no interaction occurs.
- Every K^+ has the chance to generate a Θ^+ within a few MeV energy bin, unless it interacts before it is sufficiently slowed down.
- This is a much more efficient way of using K^+ compared to using a broad band beam on a thin target.

Belle: Compare with DIANA





Kaon momentum range
that may contribute to Θ^+
excitation in nuclei ~ 50MeV/c.

Note that this restriction is absent
in the DIANA experiment where the K+
looses momentum continuously throughout
the interaction region, i.e. every K^+ has
the chance to contribute to the Θ^+ signal.

K^+Si/C (thin) K^+Xe(thick)

Belle versus DIANA
Mom. spectrum 850MeV/c

Summary of Θ^+

- Existing "Null" Experiments need to prove their sensitivity to the Θ^+ before they can claim anything. Proving a negative is, of course, difficult. The best is to reproduce the experiments that have seen the signal and repeat them with higher statistics, better systematics, etc.. This is what is happening at JLab.

- High energy experiments studying **current fragmentation** processes may not have sensitivity to see any signal.

- Sensitivity should be much higher in **target fragmentation** region (HERMES, ZEUS, H1).

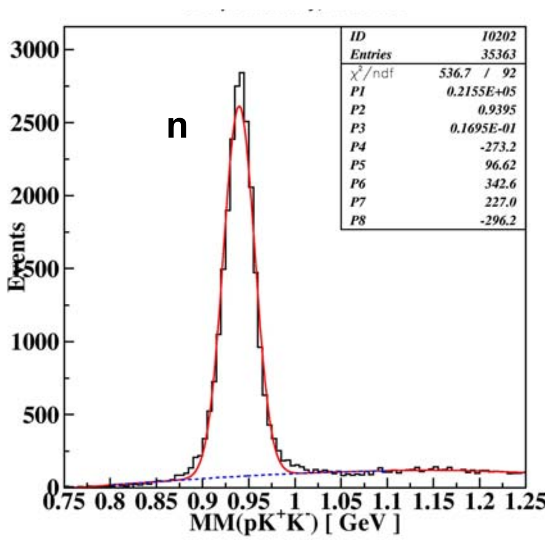
- Experiments using **broad band momentum spectrum** in secondary interaction (K+-nucleus) must compare with DIANA and K^+D scattering results and prove sensitivity

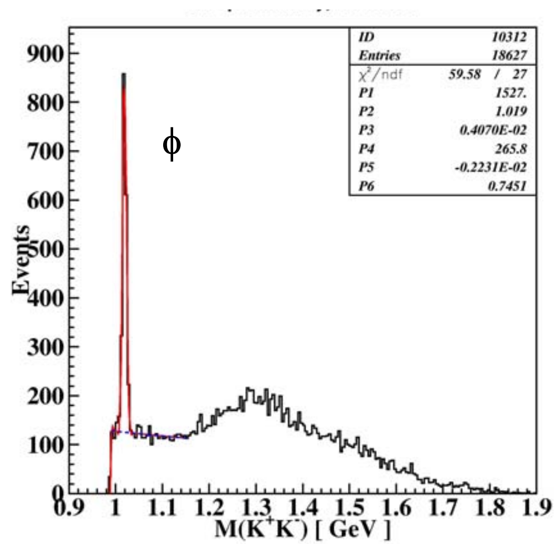
What's next with CLAS?

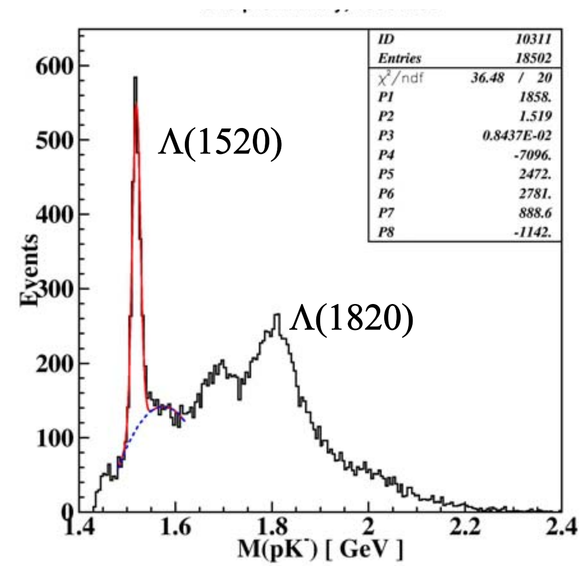
- CLAS at JLab finished data taking with two runs
  - Statistics > 10 times with deuterium target
  - high statistics run on hydrogen target
  - Other high statistics runs at higher energy are in preparation

CLAS - G10 "online" plots

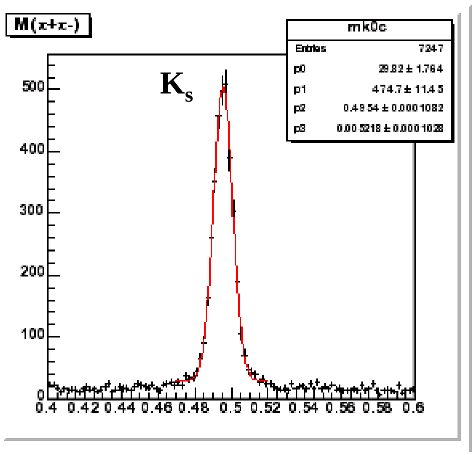
Fully exclusive processes: $\gamma d \longrightarrow K^- p K^+ n$







$\gamma d \longrightarrow K^- p K_s(\pi^+\pi^-) p_{sp}$



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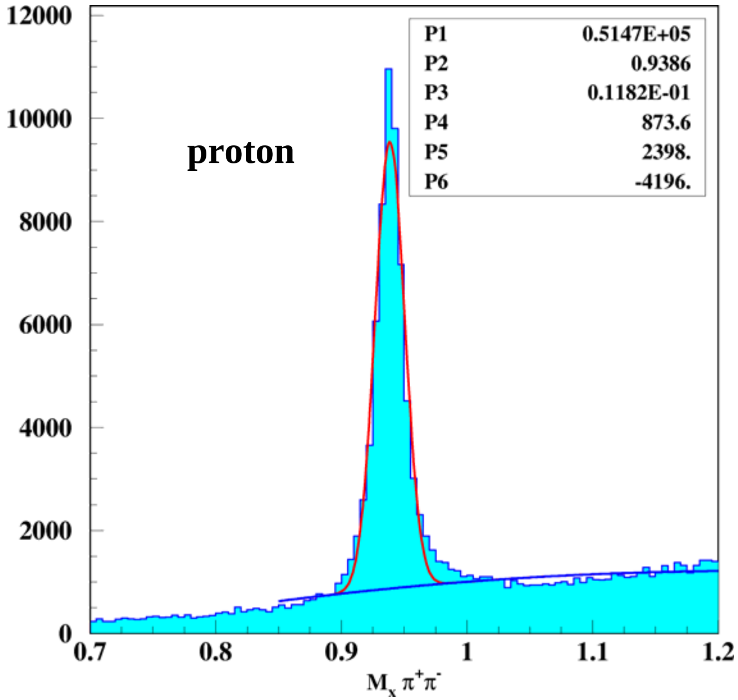
Bryan McKinnon

CLAS - G11 "online" plots

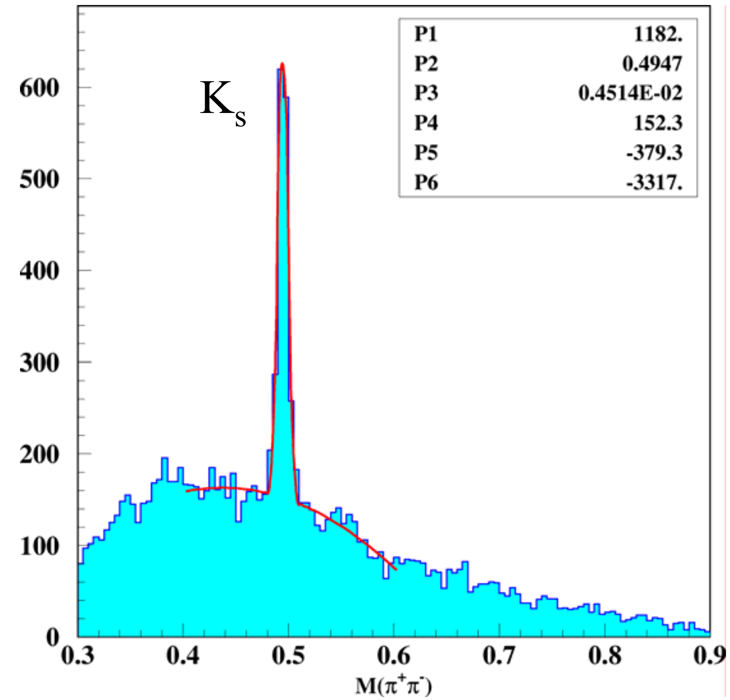
$\gamma p \rightarrow K_s K^+(n); K_s K_s p; K^+K^-p; K^+K^-\pi^+(n)$

$\gamma p \longrightarrow \pi^+\pi^-(p)$

(calibration reaction)



$\gamma p \longrightarrow \pi^+\pi^-K^+(n)$



The End of my Lectures