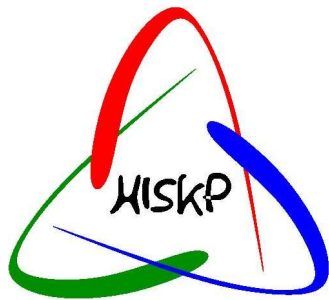


# Hadron Spectroscopy:

## Results and Ideas.



SFB/TR16



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International Workshop on  
NEW PARTIAL WAVE ANALYSIS TOOLS  
FOR NEXT GENERATION HADRON SPECTROSCOPY EXPERIMENTS

June 20-22, 2012 Camogli, Italy

# Hadron Spectroscopy: results and ideas

1. Why baryon spectroscopy
2. New results and PDG related issues
3. Baryon resonance spectrum: interpretation

Parity doublets and chiral symmetry

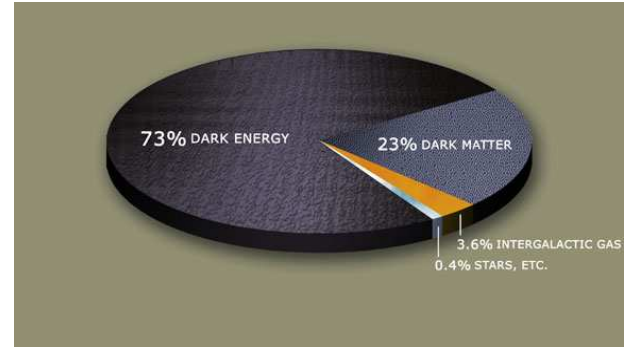
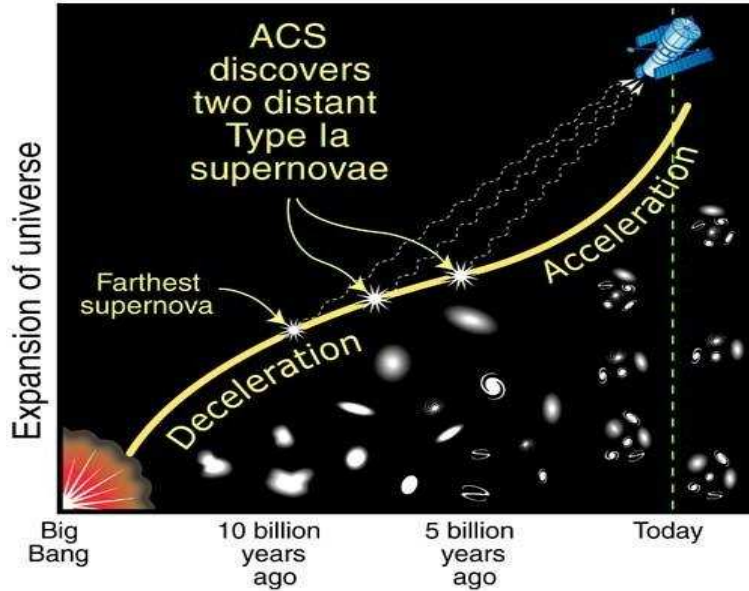
AdS/QCD

$SU(6) \otimes O(3)$

Dynamically generated resonances versus C.D.D. poles

4. New results from ELSA
5. Summary

# 1. Why Baryon Spectroscopy?

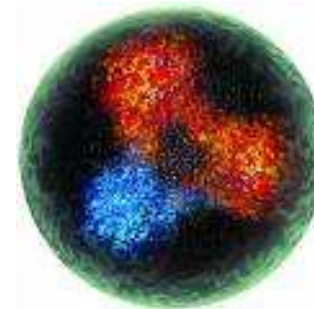


## ● Mass of the Universe:

Dark energy	73%	
Dark matter	23%	
Intergalactic gas	3.6%	} atoms
Stars	0.4%	

## ● Mass of atoms

Mass of quarks	1%
Mass of electrons	0.1%
Field energy	99%

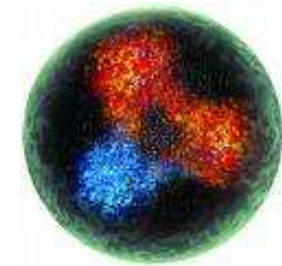


What are ↑ these objects?

- What are constituent quarks?

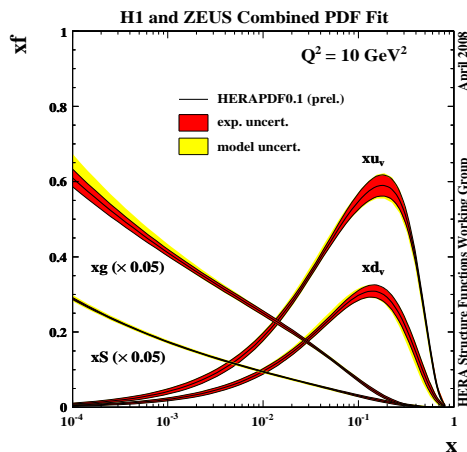
Mass is field energy!

$$M_N = \langle N | -\frac{9\alpha_s}{4\pi} (\mathbf{B}^2 - \mathbf{E}^2) + \sum_{\text{flavors}} m_i \bar{\psi}_i \psi_i | N \rangle .$$



- How to explore constituent quarks?

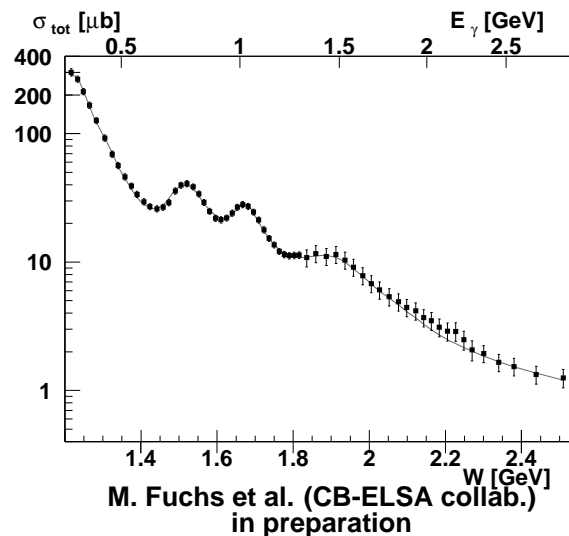
Nucleon tomography:



Goal: Distribution of linear and angular momenta of gluons and quarks in space

Collectivity is lost!

Nucleon spectroscopy:



M. Fuchs et al. (CB-ELSA collab.) in preparation

Wave length matches the size of constituents

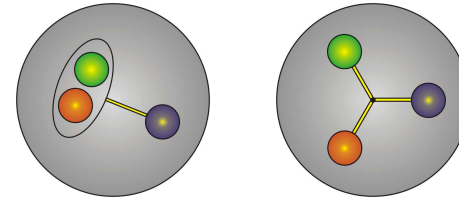
Explores collective response!

## Questions:

- Are constituent quarks the relevant degrees of freedom ?
- What are the effective forces between them ?

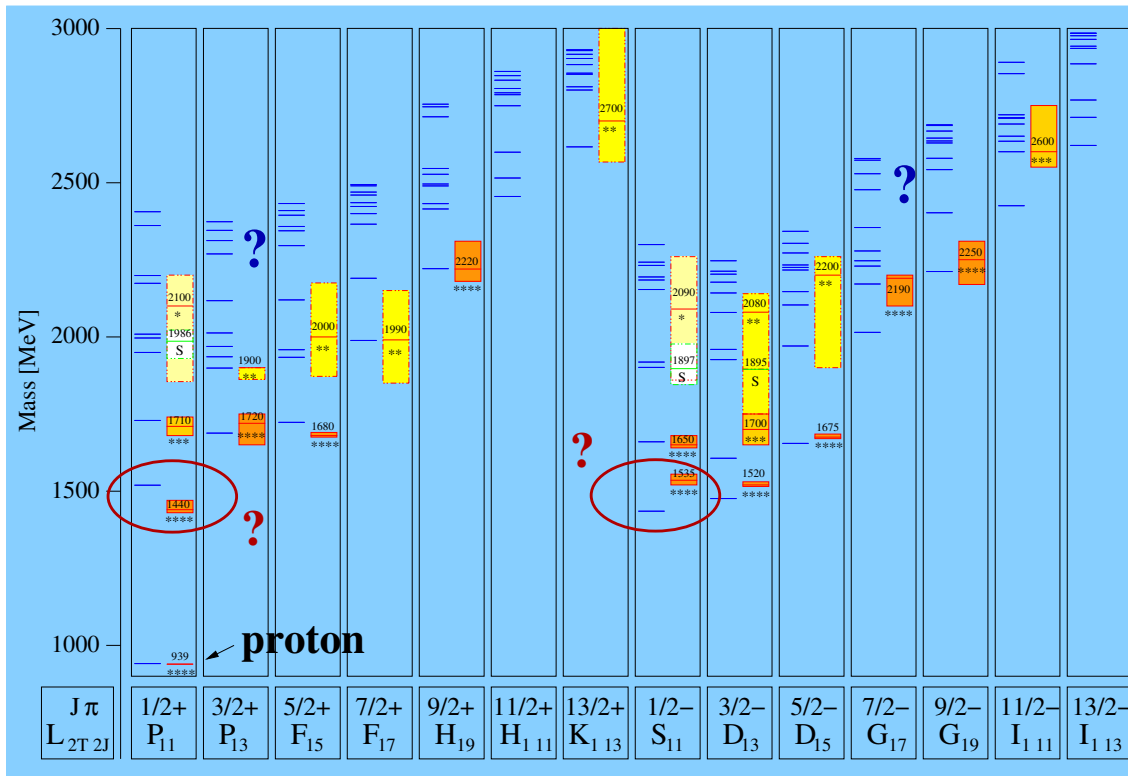
## Findings:

- Linear Regge trajectories
- Many more resonances expected in symmetric quark models than observed



Diquark substructure?  
QCD strings? AdS/QCD?

H. Forkel and E. Klempt,  
Phys. Lett. B 679, 77 (2009).



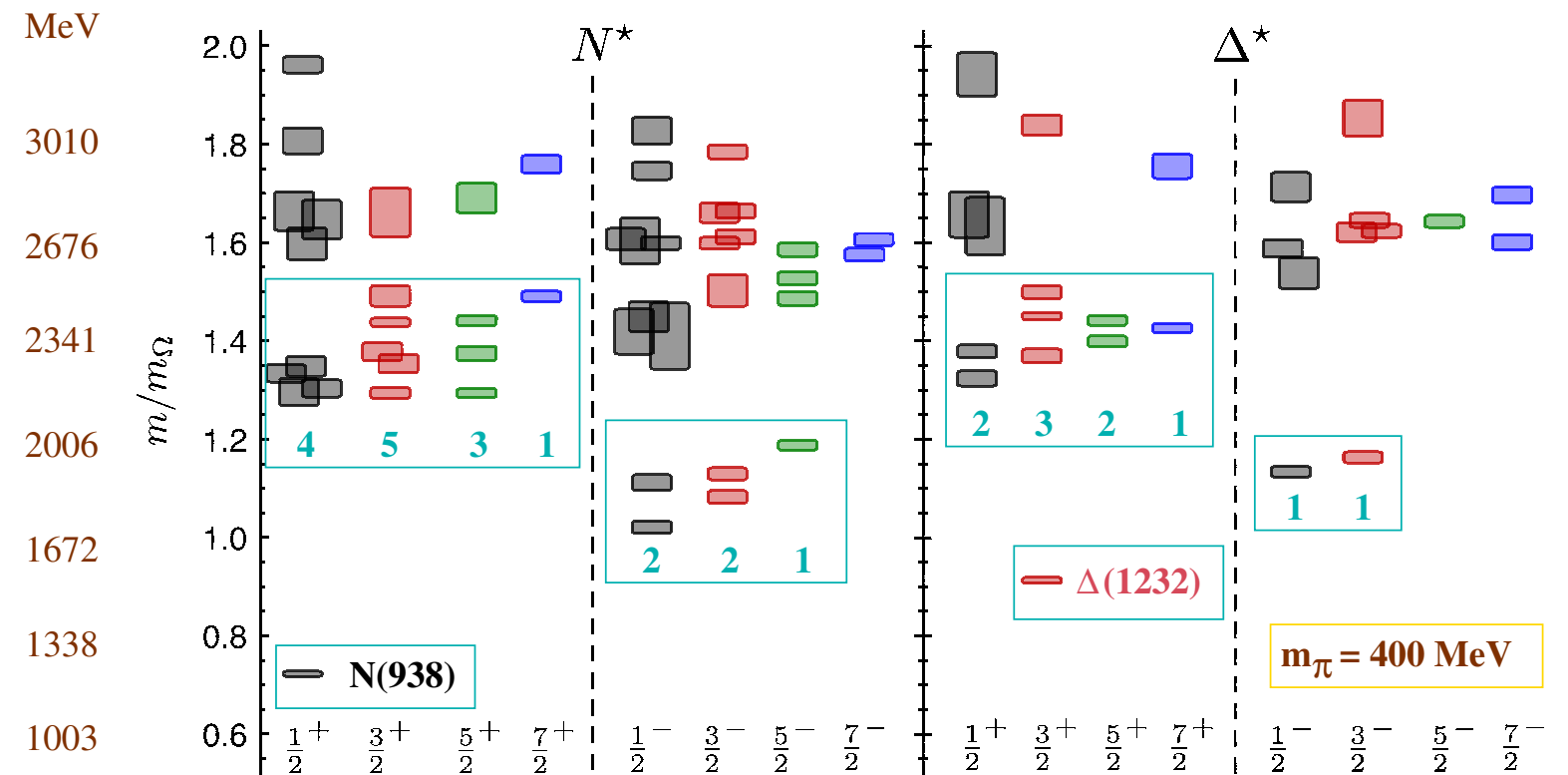
## Non-strange $N^*$ -resonances

U. Löring, B. Metsch, H. Petry, Eur. Phys. J. A 10, 395 (2001).

Constituent quarks  
confinement potential  
+ residual interaction

$\leftrightarrow$  wrong degrees of freedom ?

# Excited baryons from Lattice QCD



R.Edwards et al.,  
arXiv:1104.5152 [hep-ph]

$(m_\pi = 400 \text{ MeV})$

**Exhibits the features  $SU(6) \otimes O(3)$ -symmetry**

- Counting of levels consistent with non-rel. quark model
- Striking similarity with quark model
- No parity doubling

**The lattice seems not to solve the problems!**

# Hadron Spectroscopy: results and ideas

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AdS/QCD

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## 2. New results and PDG related issues

J. Beringer et al. (Particle Data Group), Phys. Rev. D86, 010001 (2012).

Resonance	Rating	$N_{PP}$	Resonance	Rating	$N_{PP}$	Resonance	Rating	$N_{PP}$
N(1440)1/2 <sup>+</sup>	****	13	N(1520)3/2 <sup>-</sup>	****	17	N(1535)1/2 <sup>-</sup>	****	15
N(1650)1/2 <sup>-</sup>	****	18	N(1675)5/2 <sup>-</sup>	****	14	N(1680)5/2 <sup>+</sup>	****	17
N(1685)	*		N(1700)3/2 <sup>-</sup>	***	15	N(1710)1/2 <sup>+</sup>	***	14
N(1720)3/2 <sup>+</sup>	****	17	N(1860)5/2 <sup>+</sup>	**	9	N(1875)3/2 <sup>-</sup>	***	16
N(1880)1/2 <sup>+</sup>	**	20	N(1895)1/2 <sup>-</sup>	**	17	N(1900)3/2 <sup>+</sup>	***	18
N(1990)7/2 <sup>+</sup>	**	9	N(2000)5/2 <sup>+</sup>	**	11	N(2040)3/2 <sup>+</sup>	*	
N(2060)5/2 <sup>-</sup>	**	13	N(2100)1/2 <sup>+</sup>	*		N(2150)3/2 <sup>-</sup>	**	11
N(2190)7/2 <sup>-</sup>	****	11	N(2220)7/2 <sup>-</sup>	****	7	N(2250)9/2 <sup>-</sup>	****	
N(2600)11/2 <sup>-</sup>	***		N(2700)13/2 <sup>+</sup>	**				
Δ(1232)	****	8	Δ(1600)3/2 <sup>+</sup>	***	12	Δ(1620)1/2 <sup>-</sup>	****	10
Δ(1700)3/2 <sup>-</sup>	****	11	Δ(1750)1/2 <sup>+</sup>	*		Δ(1900)1/2 <sup>-</sup>	**	13
Δ(1905)5/2 <sup>+</sup>	****	11	Δ(1910)1/2 <sup>+</sup>	****	13	Δ(1920)3/2 <sup>+</sup>	***	21
Δ(1930)5/2 <sup>-</sup>	***		Δ(1940)3/2 <sup>-</sup>	*	5	Δ(1950)7/2 <sup>+</sup>	****	13
Δ(2000)5/2 <sup>+</sup>	**		Δ(2150)1/2 <sup>-</sup>	*		Δ(2200)7/2 <sup>-</sup>	*	
Δ(2300)9/2 <sup>+</sup>	**		Δ(2350)3/2 <sup>-</sup>	*		Δ(2390)7/2 <sup>+</sup>	*	
Δ(2420)11/2 <sup>+</sup>	****		Δ(2400)9/2 <sup>-</sup>	****		Δ(2750)13/2 <sup>-</sup>	**	
Δ(2950)15/2 <sup>+</sup>	**							

E.g.: V. Kuznetsov *et al.*, Phys. Lett. B 647, 23 (2007); V. Kuznetsov *et al.*, Phys. Rev. C 83, 022201 (2011); I. Jaegle *et al.*, Eur. Phys. J. A 47, 89 (2011).

M. Ablikim *et al.* [BES Collaboration], Phys. Rev. D 80, 052004 (2009).

A. V. Anisovich, R. Beck, E. Klempt, V. A. Nikonov, A. V. Sarantsev and U. Thoma, Eur. Phys. J. A 48, 15 (2012);

$N_{PP}$  particle properties were determined; 400 in total. Be cautious, there are ambiguities !

Promoted to three-star resonance



# PDG related issues

## 1. Naming scheme:

- $\Delta^{++}(2420)$ : Need to know quantum numbers “by heart”
- $\Delta^{++}(2420)H_{3,11}$ : Refers to  $\pi^+ p$  scattering. Need to know that  $H$  corresponds to  $L = 5$ . Not straightforward to calculate  $N\omega$  partial wave (which is also  $L = 5$ ).
- $\Delta^{++}(2420)11/2^+$  is self explanatory and used in the new PDG edition.

2. Baryon part in PDG emphasizes properties of poles rather than of Breit-Wigner parameters

3. Branching ratios often not defined

**$a_1(1260)$  <sup>[k]</sup>**

$$I^G(J^{PC}) = 1^-(1^{++})$$

Mass  $m = 1230 \pm 40$  MeV <sup>[l]</sup>

Full width  $\Gamma = 250$  to  $600$  MeV

$a_1(1260)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$(\rho\pi)_{S\text{-wave}}$	seen	353
$(\rho\pi)_{D\text{-wave}}$	seen	353
$(\rho(1450)\pi)_{S\text{-wave}}$	seen	†
$(\rho(1450)\pi)_{D\text{-wave}}$	seen	†
$\sigma\pi$	seen	–
$f_0(980)\pi$	not seen	179
$f_0(1370)\pi$	seen	†
$f_2(1270)\pi$	seen	†
$K\bar{K}^*(892) + \text{c.c.}$	seen	†
$\pi\gamma$	seen	608

**$N(1900) 3/2^+$**

$$I(J^P) = \frac{1}{2}(3^+)$$

Breit-Wigner mass  $\approx 1900$  MeV

Breit-Wigner full width  $\sim 250$  MeV

Re(pole position) =  $1900 \pm 30$  MeV

$-2\text{Im}(\text{pole position}) = 200^{+100}_{-60}$  MeV

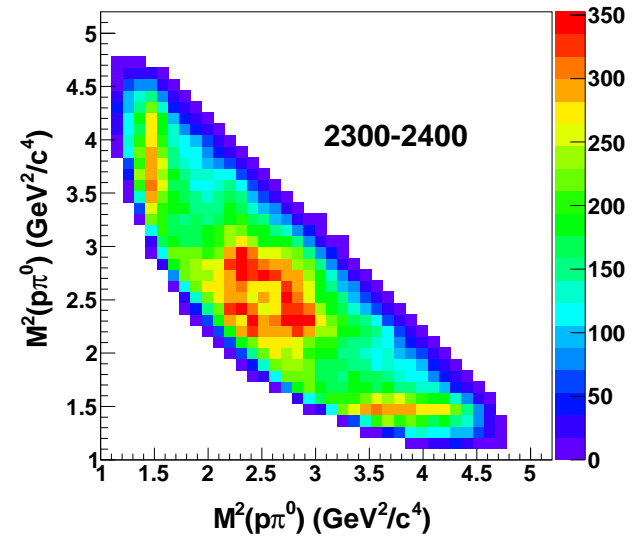
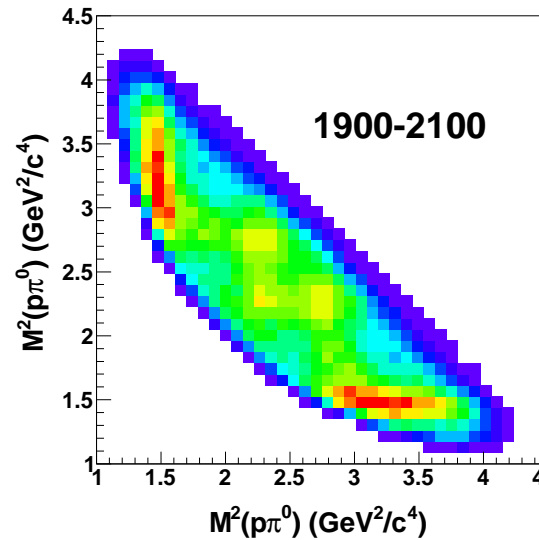
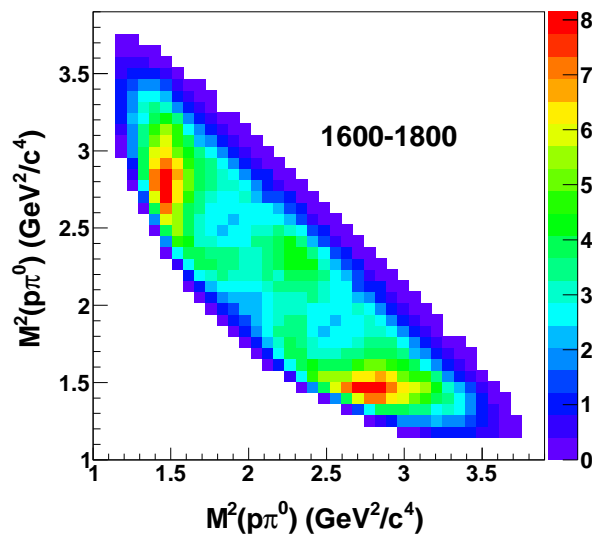
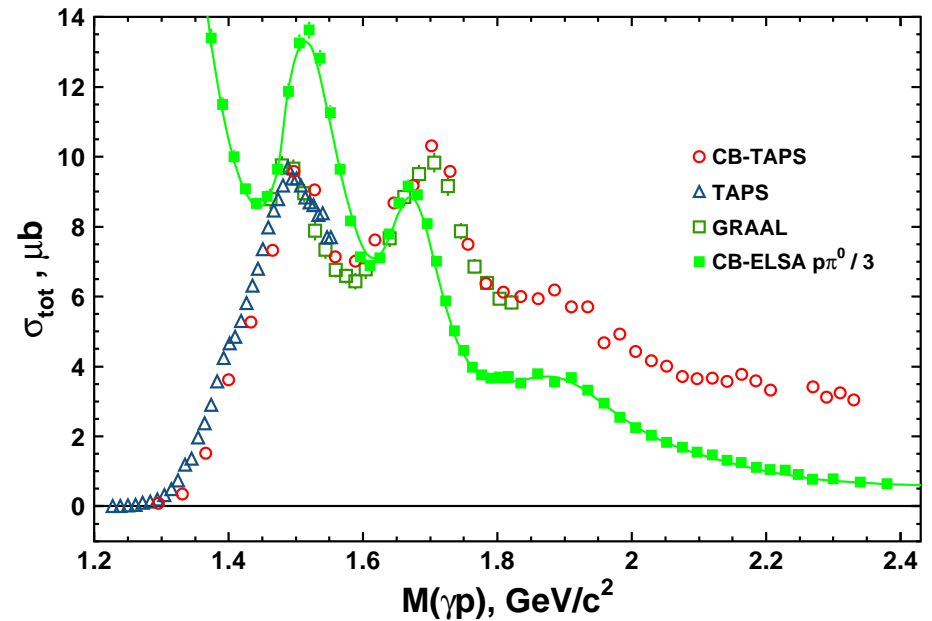
$N(1900)$ DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	$\rho$ (MeV/c)
$N\pi$	$\sim 10$ %	710
$N\eta$	$\sim 12$ %	579
$N\omega$	( $39 \pm 9$ ) %	401
$\Lambda K$	0–10 %	477
$\Sigma K$	( $5.0 \pm 2.0$ ) %	410

$$\gamma p \rightarrow p\pi^0 \text{ and } \gamma p \rightarrow p2\pi^0$$

- Cascades via

$$\Delta(1232), N(1520)3/2^-, N(1680)5/2^+$$

- Peak position change, pole positions remain



## Three definitions of branching ratios:

1.  $BR_a = \Gamma_a / \Gamma_{BW}$ ,  $m_{BW} \Gamma_a = g_a^2 \rho_a(m_{BW}^2)$ ,

where the energy dependent partial is defined by

$$\sqrt{s} \Gamma_a(s) = g_a^2 \rho_a(s), g_a \text{ coupling constant, } \rho_a \text{ phase space.}$$

$$\sum BR_a = 1 \text{ satisfied.}$$

2.  $BR'_a = \int_{\text{threshold}}^{\infty} \frac{ds}{\pi} \frac{g_a^2 \rho(s)}{(m_{BW}^2 - s)^2 + (\sum_a g_a^2 \rho_a(s))^2}$ .

This definition allows for subthreshold decays. It corresponds to intuition but  $\sum BR'_a = 1$  needs to be imposed.

3.  $BR_{\text{pole}}(\text{channel } b) = \frac{|Res(\pi N \rightarrow b)|^2}{|Res(\pi N \rightarrow N\pi)| \cdot (\Gamma_{\text{pole}}/2)}$ .

The latter definition uses only pole related quantities.

# Hadron Spectroscopy: results and ideas

1. Why baryon spectroscopy
2. New results and PDG related issues
3. **Baryon resonance spectrum: interpretation**

**Parity doublets and chiral symmetry**

**AdS/QCD**

**$SU(6) \otimes O(3)$**

**Dynamically generated resonances versus C.D.D. poles**

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### 3. Baryon resonance spectrum: interpretation

#### 3.1 Parity doublets and chiral symmetry

In the limit of massless quarks:

1. Pseudoscalar mesons become massless Goldstone bosons
2. Parity partners acquire the same mass
3. Spontaneous symmetry breaking leads to hadronic masses

Vector mesons

$\approx 700$  MeV

Nucleon mass  $M_N$

$\approx 1000$  MeV

Its parity partner  $N(1535)1/2^-$  acquires a mass

$\approx 1500$  MeV

$N(1650)1/2^-$	$N(1700)3/2^-$	$N(1675)5/2^-$	$\Delta(2200)7/2^-$
$N(1710)1/2^+$	$N(1720)3/2^+$	$N(1680)5/2^+$	$\Delta(1905)7/2^+$ a.o.
$N(1895)1/2^-$	$N(1880)3/2^-$	$N(2060)5/2^-$	$N(2180)7/2^-$
$N(1870)1/2^+$	$N(1890)3/2^+$	$N(2090)5/2^+$	$N(2105)7/2^+$

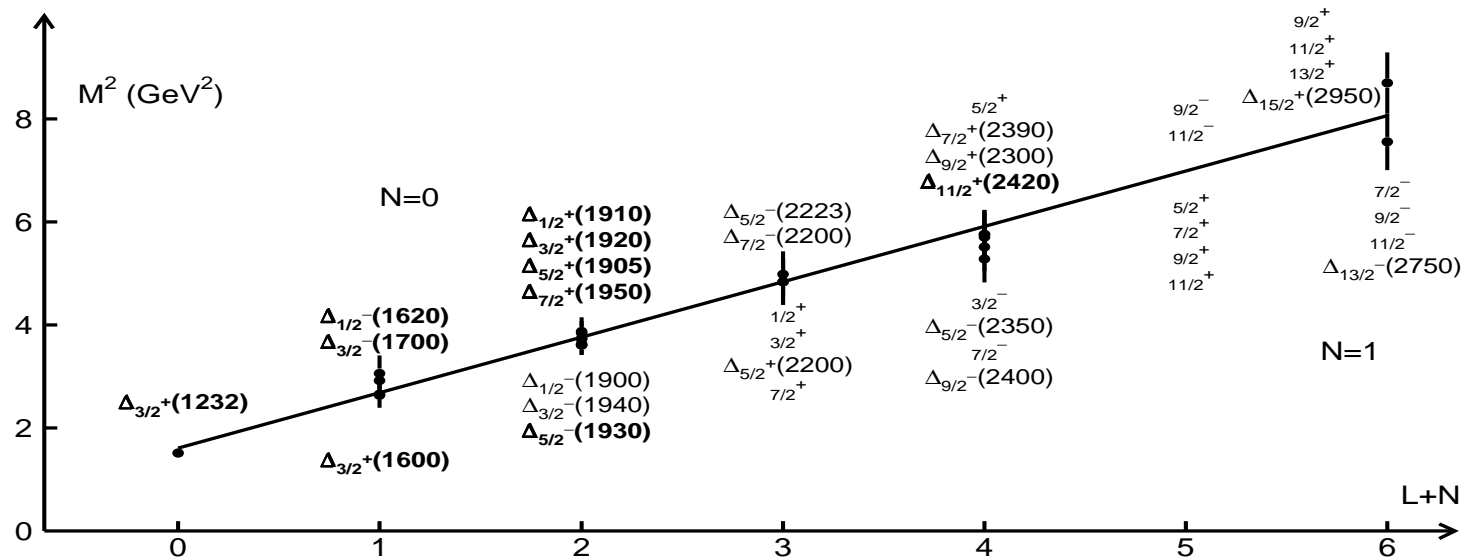
Nucleon resonances organized as parity doublets (solution BnGa2011-02).

Restoration of chiral symmetry?

L. Y. Glozman, Phys. Rept. 444, 1 (2007)

Meson and baryon resonances on the leading Regge trajectory have no parity partner!

## 3.2 AdS/QCD



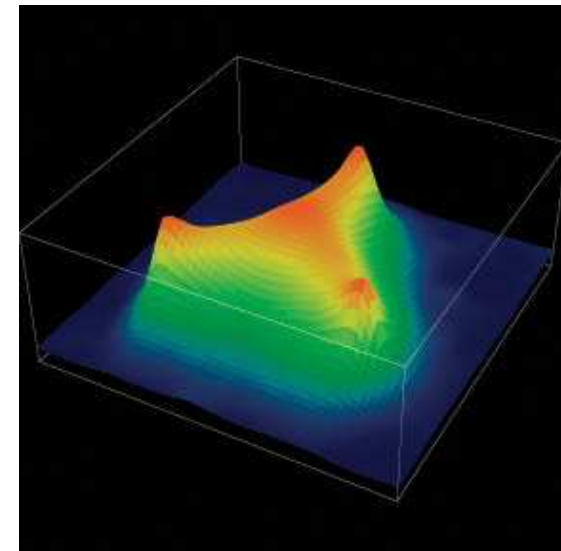
Regge trajectory of  $\Delta$  resonances:  $M^2 \propto L + N$ : non-relativistic concept !

- Mass is stored in strings which expand  $\propto L + N$
- $(l_1, l_2), (n_1, n_2) \implies (L, N)$
- Constituent quark mass is ill-defined
- AdS/QCD:

H. Forkel and E. Klempt,  
Phys. Lett. B 679, 77 (2009).

$$M^2 = a \cdot (L + N + 3/2) - b \alpha_D$$

- Two-parameter fit reproduces mass spectrum  $2 \times$  better than quark models, Skyrme models (or LQCD) !



### 3.3 $SU(6) \otimes O(3)$

$J^P =$		$\frac{1}{2}^+$	$\frac{3}{2}^+$	$\frac{5}{2}^+$	$\frac{7}{2}^+$
$(56, 2_2^+)$	$S = 3/2; L = 2; N=0$	$\Delta_{1/2^+} (1910)$	$\Delta_{3/2^+} (1920)$	$\Delta_{5/2^+} (1905)$	$\Delta_{7/2^+} (1950)$
	$S = 1/2; L = 2; N=0$		$N_{3/2^+} (1720)$	$N_{5/2^+} (1620)$	
$(70, 2_2^+)$	$S = 1/2; L = 2; N=0$		$\Delta_{3/2^+}$	$\Delta_{5/2^+}$	
	$S = 3/2; L = 2; N=0$	$N_{1/2^+} (1880)$	$N_{3/2^+} (1900)$	$N_{5/2^+} (2000)$	$N_{7/2^+} (1990)$
	$S = 1/2; L = 2; N=0$		$N_{3/2^+}$	$N_{5/2^+}$	
2 <sup>nd</sup> $(20, 1_2^+)$	$S = 1/2; L = 1; N=0$	$N_{1/2^+}$	$N_{3/2^+}$		
$(56, 0_2^+)$	$S = 3/2; L = 0; N=1$		$\Delta_{3/2^+} (1600)$		
	$S = 1/2; L = 0; N=1$	$N_{1/2^+} (1440)$			
$(70, 0_2^+)$	$S = 1/2; L = 0; N=1$	$\Delta_{1/2^+} (1750)$	does not exist		
	$S = 3/2; L = 0; N=1$		$N_{3/2^+}$		
	$S = 1/2; L = 0; N=1$	$N_{1/2^+} (1710)$	$4^{\text{th}}$ shell		
1 <sup>st</sup>	$(70, 1_1^-)$ $S = 1/2; L = 1; N=0$	$\Delta_{1/2^-} (1620)$	$\Delta_{3/2^-} (1700)$		
	$S = 3/2; L = 1; N=0$	$N_{1/2^-} (1650)$	$N_{3/2^-} (1700)$	$N_{5/2^-} (1675)$	
	$S = 1/2; L = 1; N=0$	$N_{1/2^-} (1535)$	$N_{3/2^-} (1520)$		
0 <sup>th</sup>	$(56, 0_0^+)$ $S = 3/2; L = 0; N=0$		$\Delta_{3/2^+} (1232)$		
	$S = 1/2; L = 0; N=0$	$N_{1/2^+} (939)$			

Some multiplets are fully, others completely empty.

Why ?

- There is a spin-doublet  $N_{1/2-}$  (1880),  $N_{3/2-}$  (1890).

There is no close-by  $N_{5/2-}$

There is no close-by spin triplet.

There is  $\Delta_{1/2-}$  (1900),  $\Delta_{3/2-}$  (1940),  $\Delta_{5/2-}$  (1930)

$$\text{SU}(6): \quad 56 = {}^4 10 + {}^2 8$$

A symmetric spin-flavor wave function with  $L = 1$  excludes  $N = 0$ .

**These resonances are radial excitations belonging to the third shell**

- There are for negative-parity resonances

$N_{3/2-}$  (2130),  $N_{5/2-}$  (2075),  $N_{7/2-}$  (2185),  $N_{9/2-}$  (2250).

These may form a spin quartet

There is no evidence for a  $(N_{3/2-}, N_{5/2-})$  doublet

There is a  $\Delta_{7/2-}$  (2200); likely,  $\Delta_{5/2-}$  is missing (GWU: 2223 MeV).

$$\text{SU}(6): \quad 70 = {}^2 10 + {}^4 8 + {}^2 8 + {}^2 1$$

**These resonances can be assigned to the third shell  $L = 3$**



$3^{\text{rd}}$	$J^P =$	$\frac{1}{2}^-$	$\frac{3}{2}^-$	$\frac{5}{2}^-$	$\frac{7}{2}^-$	$\frac{9}{2}^-$
$(56, 1_3^-)$	$S = 3/2; L = 1; N=1$ $S = 1/2; L = 1; N=1$	$\Delta_{1/2^-} (1900)$ $N_{1/2^-} (1880)$	$\Delta_{3/2^-} (1940)$ $N_{3/2^-} (1870)$	$\Delta_{5/2^-} (1930)$		
$(70, 3_3^-)$	$S = 1/2; L = 3; N=0$ $S = 3/2; L = 3; N=0$ $S = 1/2; L = 3; N=0$		$N_{3/2^-} (2170)$	$\Delta_{5/2^-} (2223)$ $N_{5/2^-} (2070)$	$\Delta_{7/2^-} (2200)$ $N_{7/2^-} (2190)$	$N_{9/2^-} (2250)$
		$(56, 3_3^-), (20, 3_3^-), (70, 2_3^-), (70, 1_3^-), (70, 1_3^-), (20, 1_3^-):$ Many states predicted, no candidates known				

There are two multiplets completely filled, six multiplets completely empty. Why?

- Minimal and maximal moments of inertia ?
- Consequence of string dynamics ?

### 3.4 dynamically generated resonances versus C.D.D. poles

$\sigma; \Lambda(1405); \dots$

$\rho; \Delta(1232); \dots$

- Meson-meson interactions:

Meson resonances can be interpreted as

$q\bar{q}$	$q\bar{q}q\bar{q}$	$q\bar{q}g$	$gg$	$m_1m_2$
mesons	tetraquarks	hybrids	glueballs	molecules

- Meson-baryon interactions:

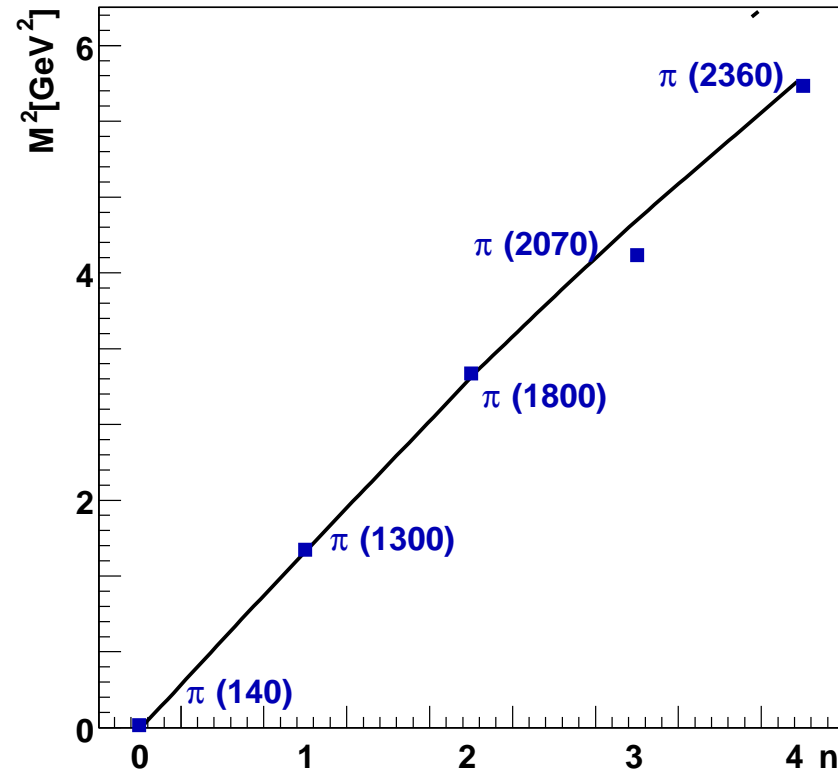
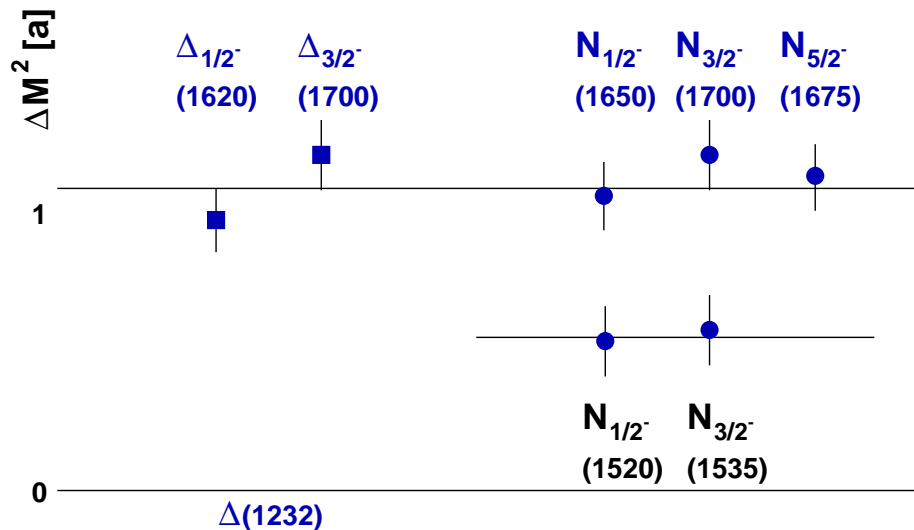
Baryon resonances can be interpreted as

$qqq$	$qqqq\bar{q}$	$qqqg$	$b_1m_2$
baryons	pentaquarks	hybrids	molecules

- Are all these Fock components realized and mix?  
Even the quark model predicts too many baryon states!

## Two examples:

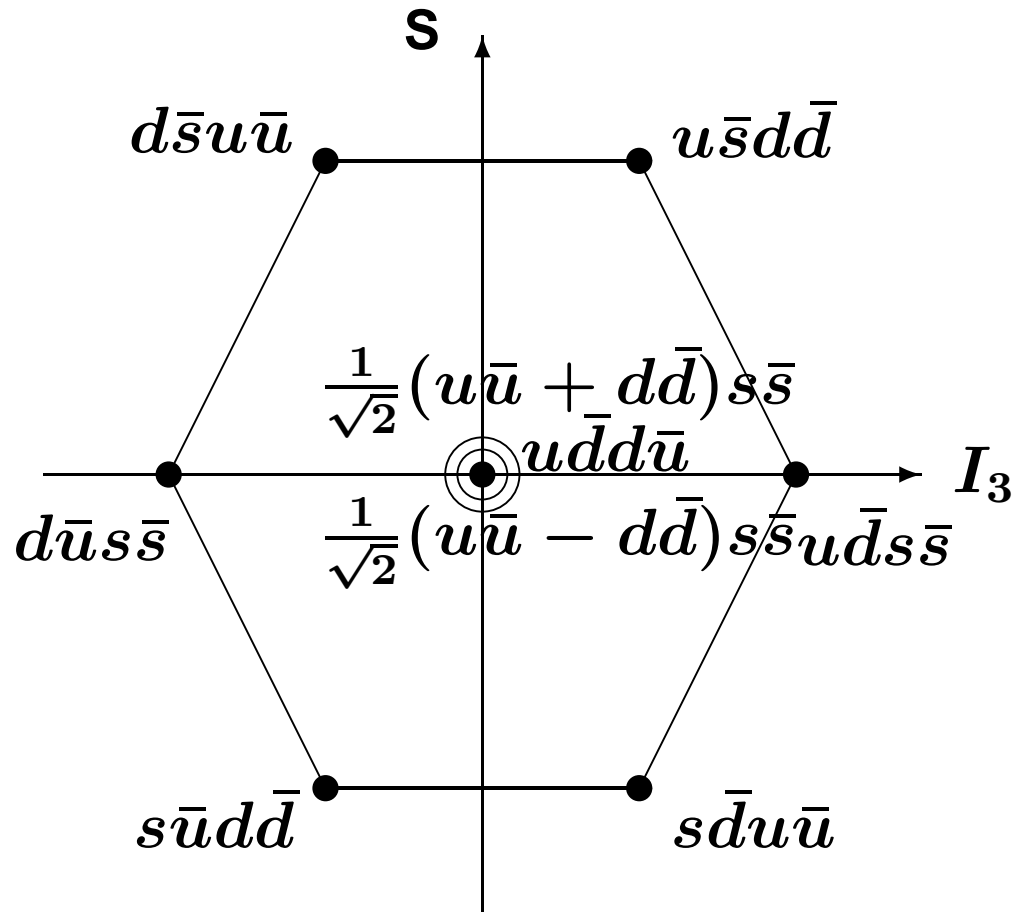
- The quark model predicts five negative-parity  $N$  resonances
- $N(1535)1/2^-$  can be generated dynamically from  $N\eta - \Sigma K$  interactions



- $q\bar{q}$  meson resonances fall onto Regge trajectories
- $q\bar{q}g$  hybrids are predicted

## A third example: scalar mesons

Jaffe: Four quarks in S-wave, pairs of quarks in color  $\bar{3}$  (antiquarks in 3), energetically favored over  $q\bar{q}$  with orbital excitation.



$$\underline{f_0, a_0 = n\bar{n}s\bar{s}, 980 \text{ MeV}}$$

$$\underline{\kappa = n\bar{s}n\bar{n}, 670 \text{ MeV}}$$

$$\underline{\sigma = n\bar{n}n\bar{n}, 460 \text{ MeV}}$$

9  $q\bar{q}$ , 9  $q\bar{q}q\bar{q}$  states  $\Rightarrow$  SU(4)

## Including $c$ quarks:

There are 36 tetraquark states with quark pairs in color  $\bar{3}$ , 16 of them have a  $q\bar{q}$  component, 20 are flavor exotics. There is a subset of 10 tetraquark states with open charm having a symmetry where the two quarks can form a  $\bar{3}$  and two antiquarks a  $3$ ,

**6 of them have a  $q\bar{q}$  component. 4 of them are flavor exotics.**

$$\begin{array}{l} c\bar{d}u\bar{u} \ ; \ c\bar{d}s\bar{s} \ ; \ c\bar{d}d\bar{s} \ ; \ c\bar{d}s\bar{u} \ ; \ c\bar{d}u\bar{s} \\ c\bar{u}d\bar{d} \ ; \ c\bar{u}s\bar{s} \ ; \ c\bar{u}u\bar{s} \ ; \ c\bar{u}s\bar{d} \ ; \ c\bar{u}d\bar{s} \end{array}$$

$$D_0^*(2400) = c\bar{n}(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}; \quad D_{s_0}^*(2317)$$

**Flavor exotics have never been observed. So even if the dominant configuration has a four-quark nature, the  $q\bar{q}$  component is essential to form a bound or resonant state!**

## Conclusion:

The Fock expansion is realized in the form

$$|\psi(Q)\rangle = \alpha_1|qqq(Q)\rangle + \alpha_2|qqqq\bar{q}(Q)\rangle + \alpha_3|qqqg(Q)\rangle + \alpha_4|b_1m_2(Q)\rangle$$

**and there are no additional states beyond the quark model**  
(perhaps exotics, perhaps chemistry of heavy-light systems)

**This does not exclude that mesons like  $a_0(980)$  have a large or even dominant  $K\bar{K}$  configuration but the raison d'être is their  $q\bar{q}$  component.**

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Parity doublets and chiral symmetry

AdS/QCD

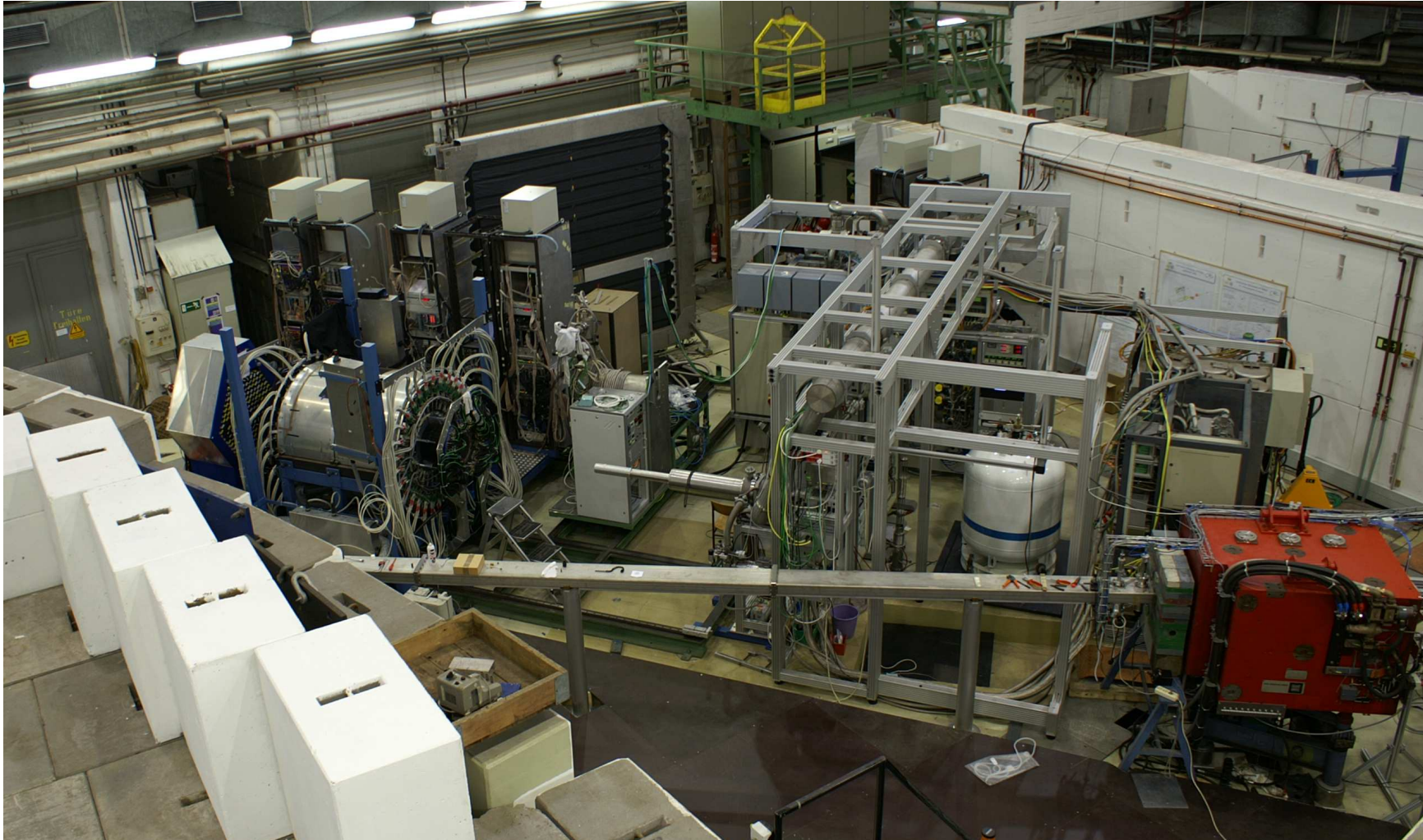
$$SU(6) \otimes O(3)$$

Dynamically generated resonances versus C.D.D. poles

4. **New results from ELSA**
5. Summary

### 3. New Results from ELSA

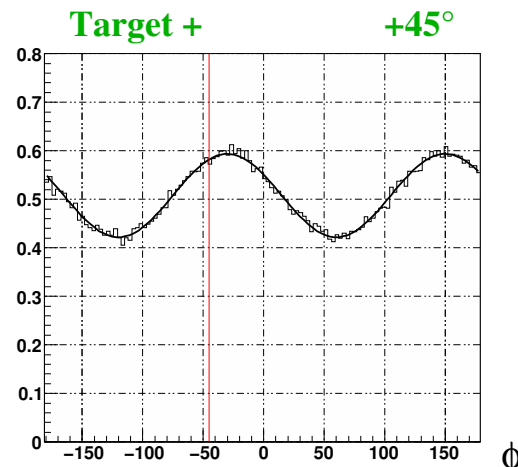
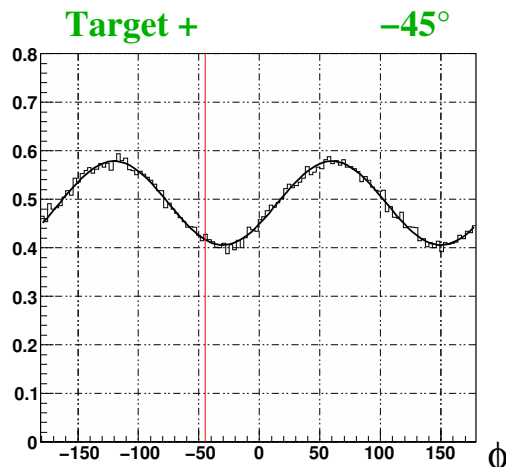
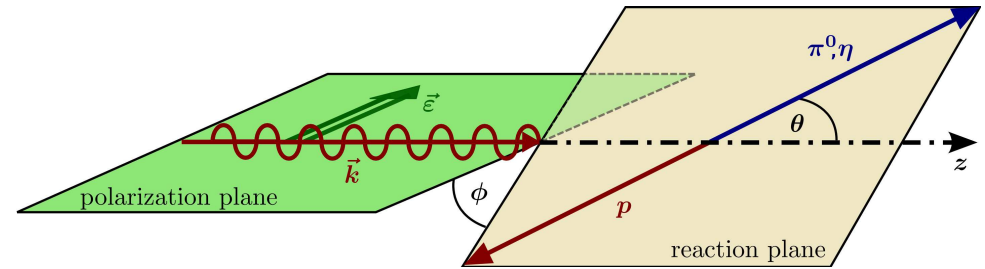
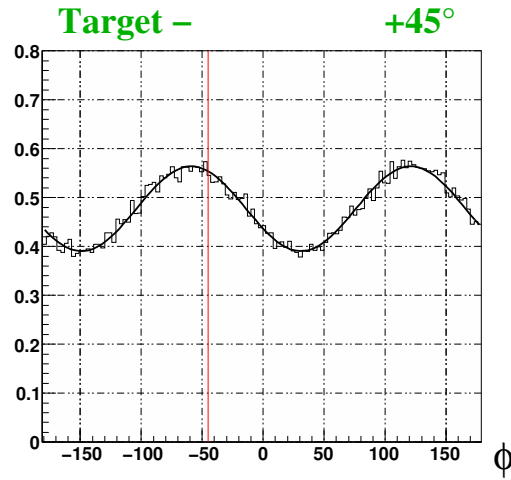
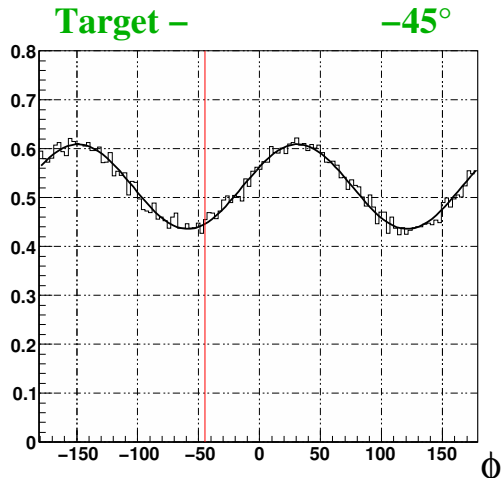
**ELSA**



**A step forward towards a complete experiment**

Linearly polarized photons, longitudinally polarized target

$$\frac{d\sigma}{d\Omega}(\Phi) = \frac{d\sigma}{d\Omega_0} \cdot \left( 1 - P_{\gamma}^{\text{lin}} \Sigma \cos(2\phi) + P_{\gamma}^{\text{lin}} P_z \underline{G} \sin(2\phi) \right)$$



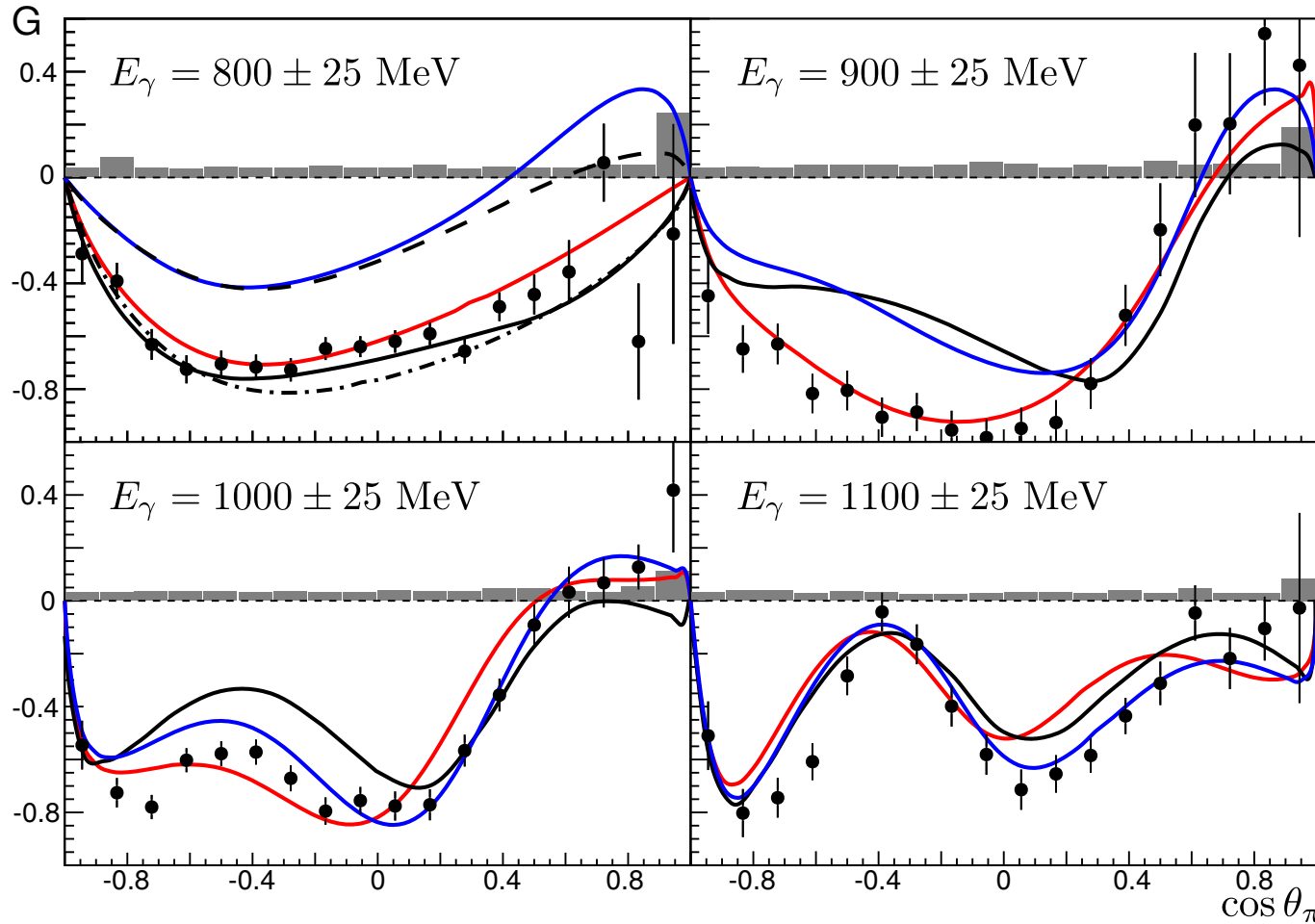
$\vec{\gamma}\vec{p} \rightarrow p\pi^0$   
 ( $E_{\gamma}=750-1200$  MeV)

⇒ Clear effect  
 from G observed



Linearly polarized photons, longitudinally polarized target: G

$$\frac{d\sigma}{d\Omega}(\Phi) = \frac{d\sigma}{d\Omega_0} \cdot (1 - P_\gamma^{\text{lin}} \Sigma \cos(2\phi) + P_\gamma^{\text{lin}} P_z G \sin(2\phi))$$



— MAID — BnGa — SAID

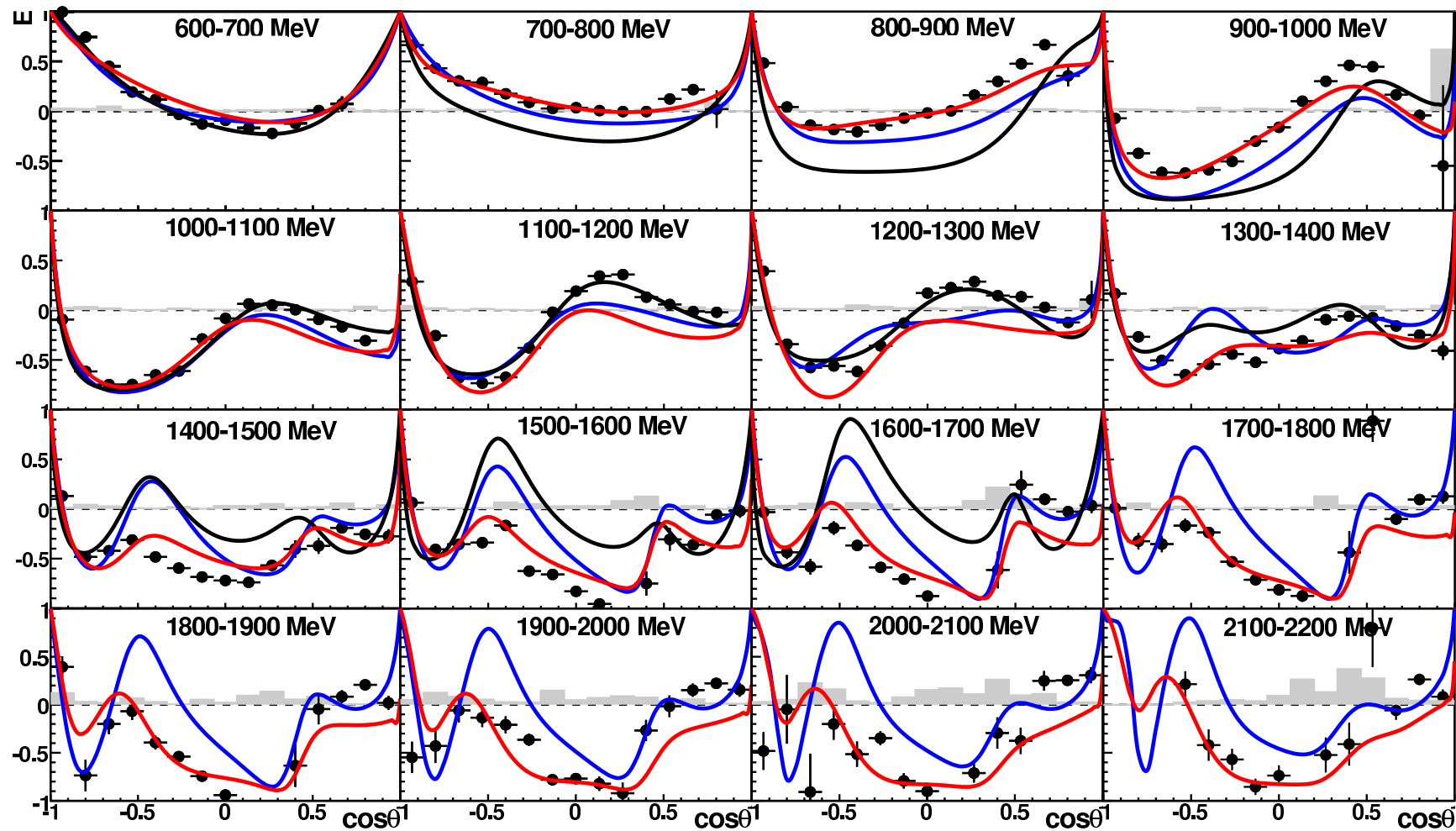
already in the second resonance region:  
significant differences !

related to the  $E_{0+}$ ,  $E_{2-}$ -multipoles

$\leftrightarrow 1/2^-, 3/2^-$ -partial waves

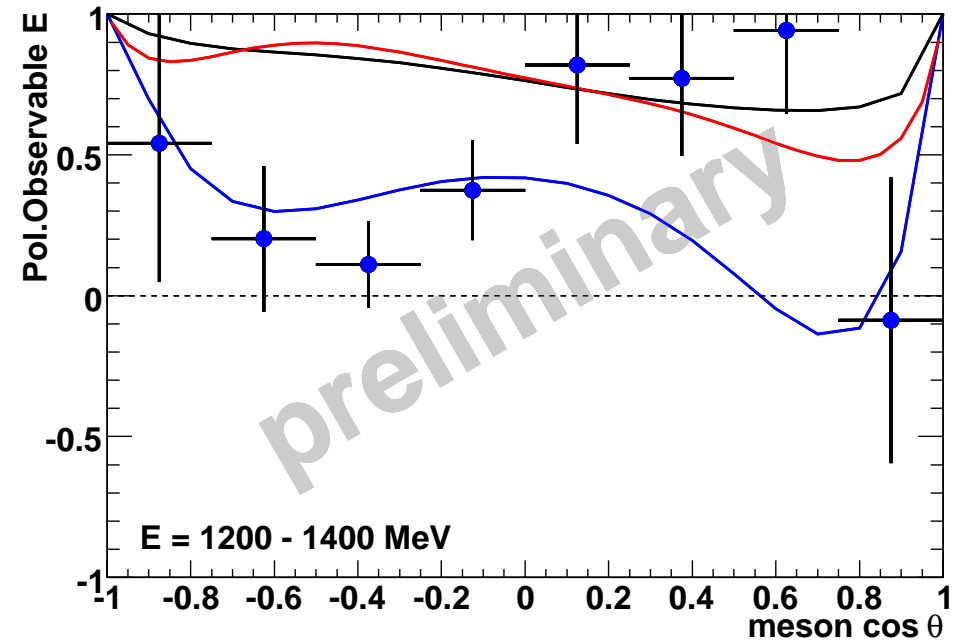
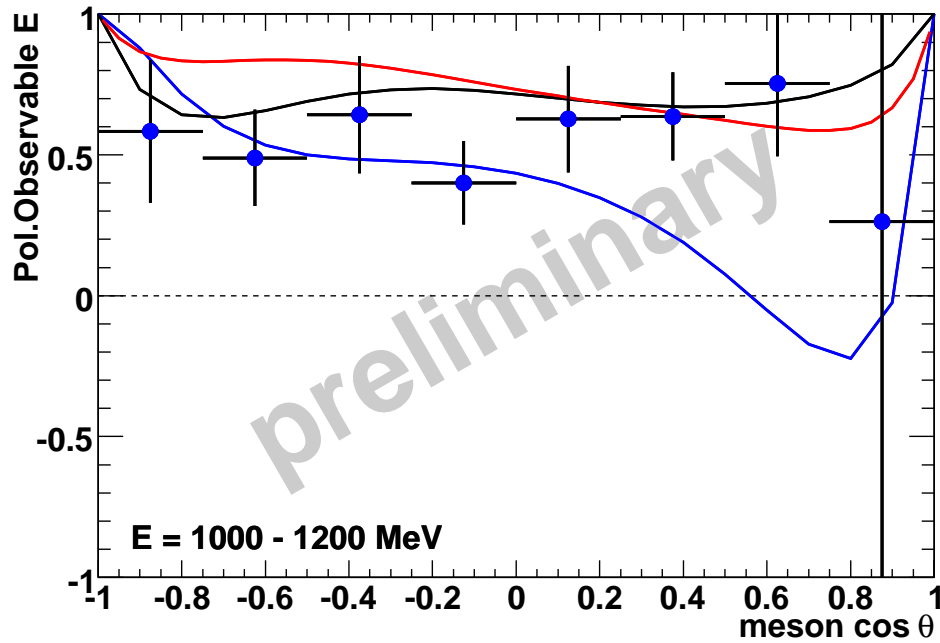
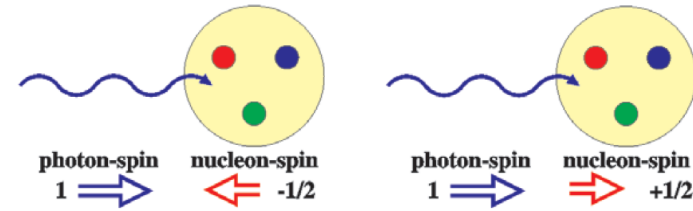
# CBELSA/TAPS: Double pol. exp. $\vec{\gamma}\vec{p} \rightarrow p\pi^0$ (M.Gottschall)

Circularly polarized photons, longitudinally polarized target: E



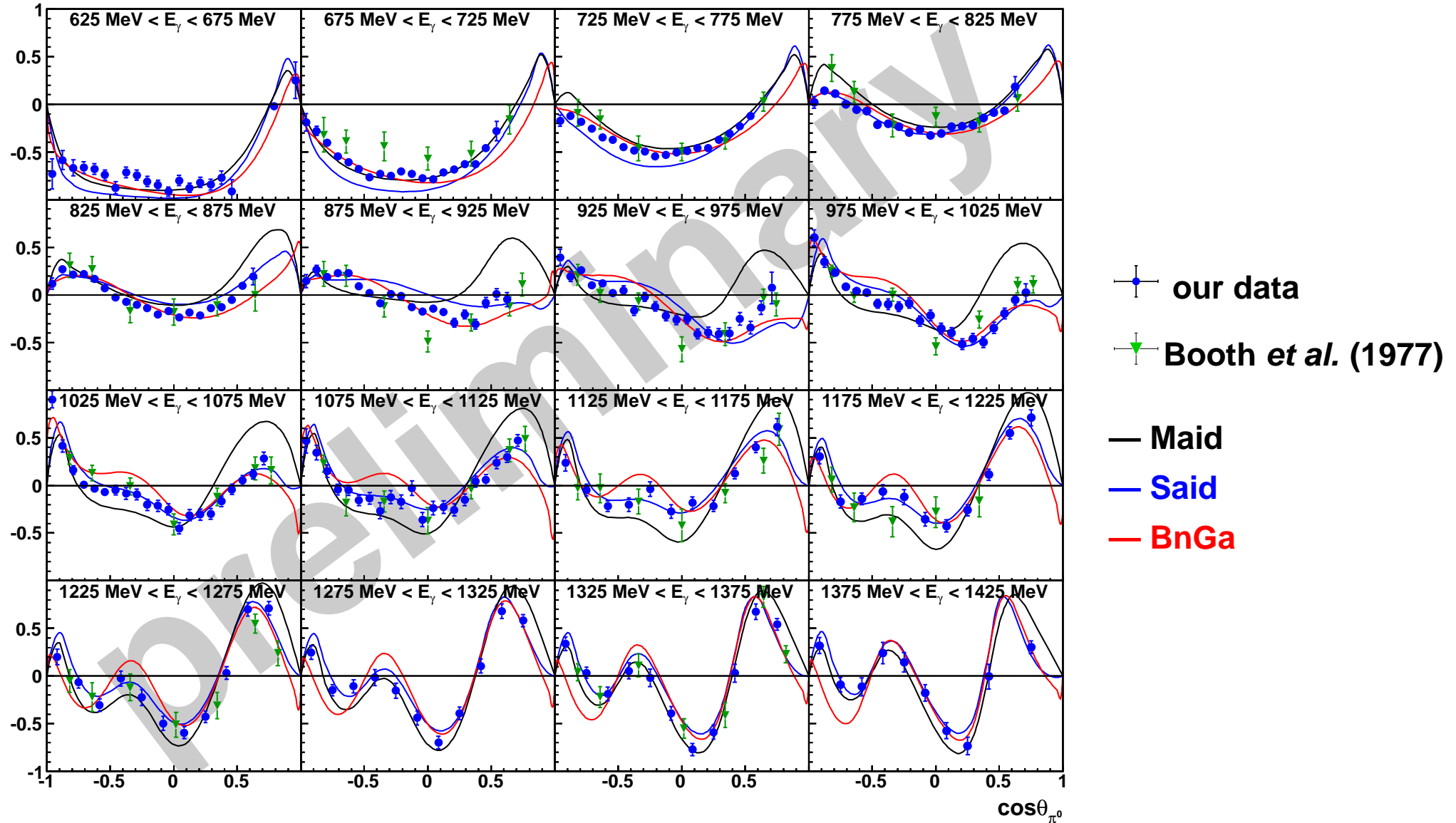
– MAID – BnGa – SAID

Circularly polarized photons, longitudinally polarized target: E

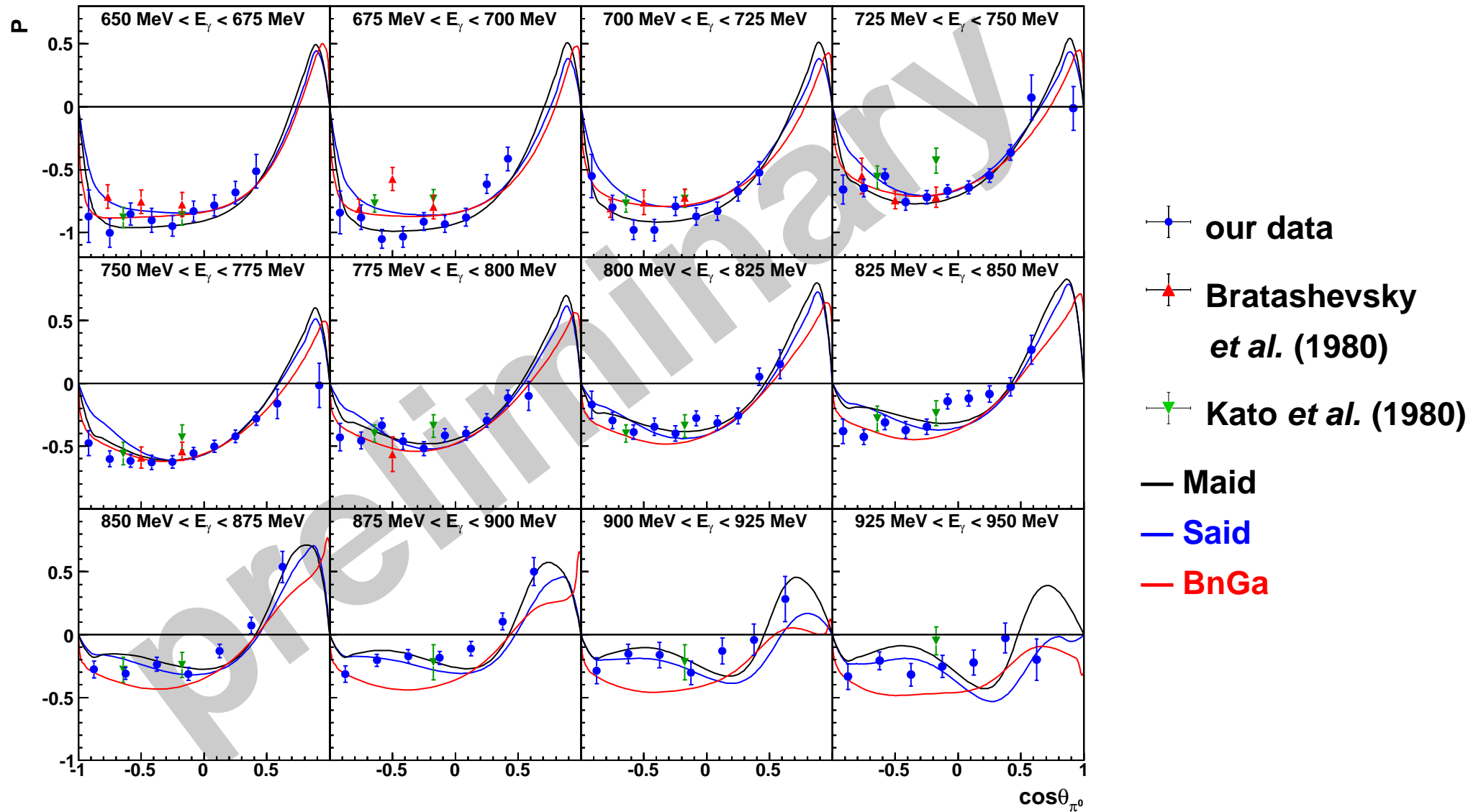


– MAID – BnGa – SAID

Linear photon polarization, transversally polarized target: T

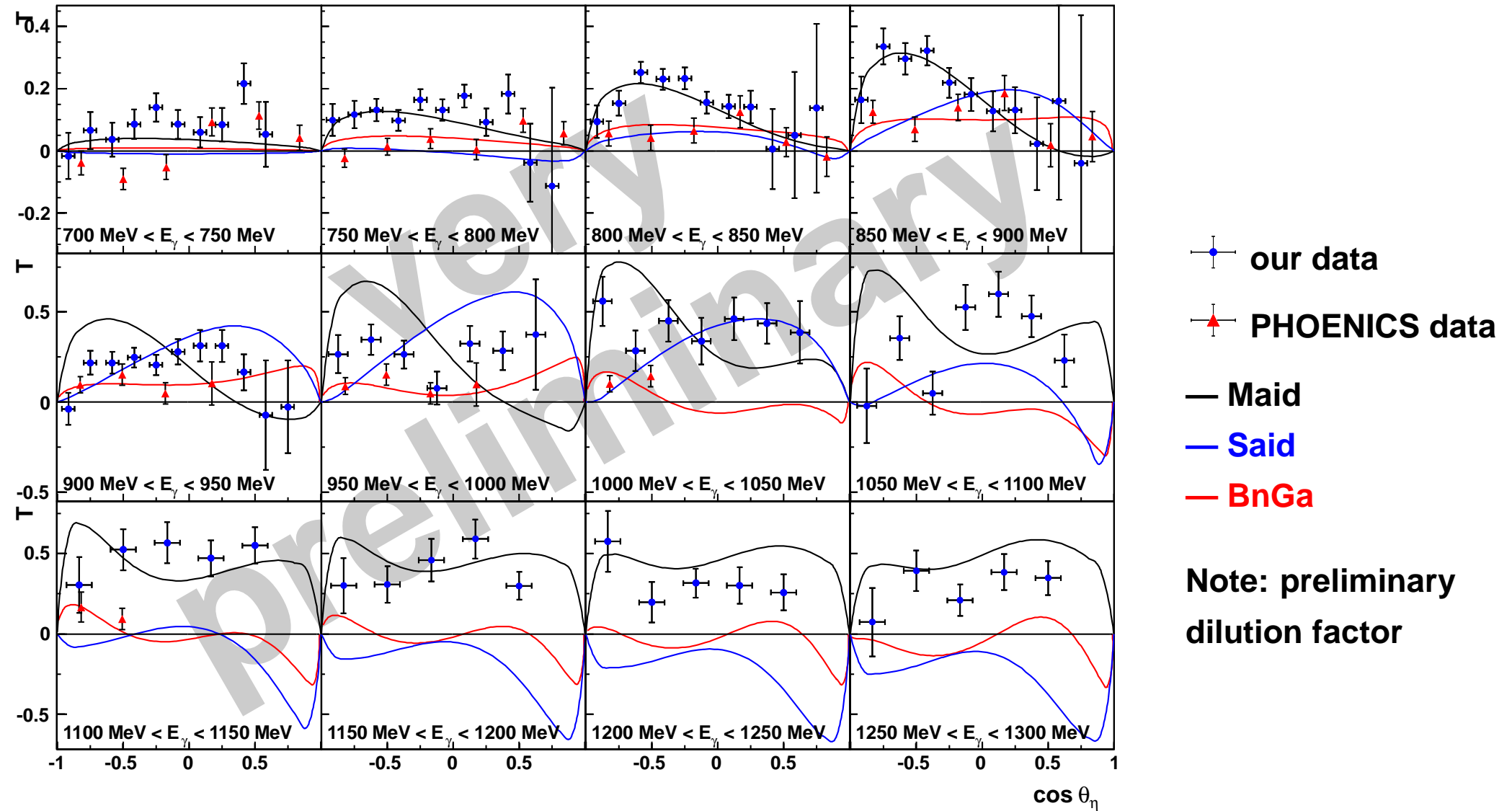


## ⇒ Measurement of the recoil polarization: P



# CBELSA/TAPS: Double pol. exp. $\vec{\gamma}\vec{p} \rightarrow p\eta$ (J. Hartmann, Bonn)

Linear photon polarization, transversally polarized target: T



# Hadron Spectroscopy: results and ideas

1. Why baryon spectroscopy
2. New results and PDG related issues
3. Baryon resonance spectrum: interpretation

Parity doublets and chiral symmetry

AdS/QCD

$$SU(6) \otimes O(3)$$

Dynamically generated resonances versus C.D.D. poles

4. New results from ELSA
- 5. Summary**

## 5. Summary

- **Photoproduction experiments begin to make a significant impact on the spectrum of baryon resonances**
- **New data are being analyzed at Bonn, Jlab, Mainz**
- **Excellent prospects for the future**
- **The problem of missing resonances persists**
- **The dynamical reason why resonances are missing is unresolved:**
  - Chiral symmetry restoration ?**
  - Are complete multiplets missing ?**
  - Constituent quarks or strings ?**