Highlights in Light-Baryon Spectroscopy and Searches for Gluonic Excitations

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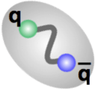
XIth Quark Confinement and the Hadron Spectrum

St. Petersburg, Russia

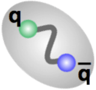
09/11/2014

Outline



Outline

1. Introduction
   - The Hadron Spectrum: Baryons and Mesons
2. Spectroscopy of Baryon Resonances
   - Complete Experiments
   - Polarization Observables in $\gamma p \to N\pi$
   - Decay Cascades of Excited Baryons
3. Meson Spectroscopy
   - Search for Gluonic Excitations
   - Hybrid Mesons in Photoproduction
4. Summary and Outlook



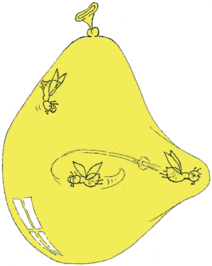
Strong-Coupling Quantum Chromodynamics (QCD)

$$\mathcal{L}_{\mathrm{QCD}} = \sum_q \bar{q}\,(i\gamma_\mu D^\mu \;-\; m_q)\,q$$

$$-\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

Strong processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD.



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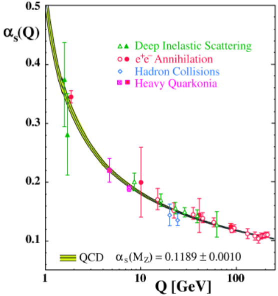
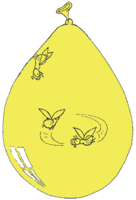
Confinement

"Strong QCD"



"pQCD"

→



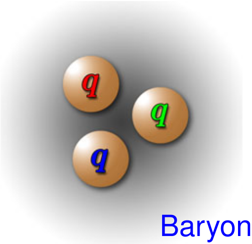
Asymptotic Freedom

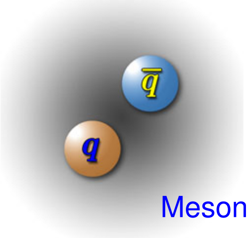
Hadrons: Baryons & Mesons

The strong coupling confines quarks and breaks chiral symmetry, and so defines the world of light hadrons.

Baryons are special because

- their structure is most obviously related to the color degree of freedom, e.g $|\Delta^{++}\rangle = |u^{\uparrow}u^{\uparrow}u^{\uparrow}\rangle$.
- they are the stuff of which our world is made.





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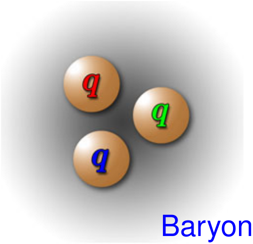
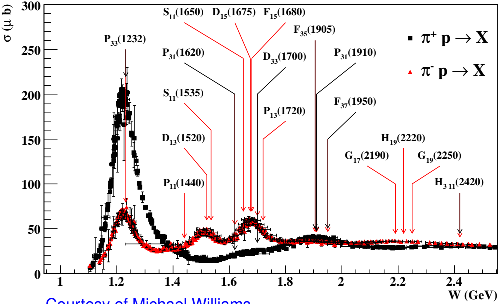


Baryons



Courtesy of Michael Williams

➜ PDG 2010, J. Phys. GG 37.

Great progress in recent years:
➜ γN & πN data

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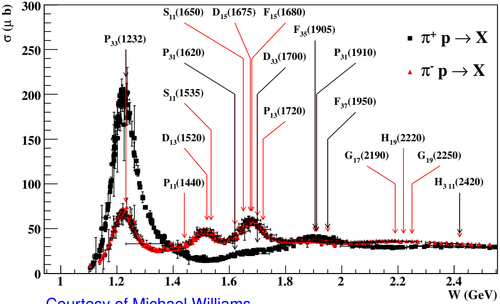
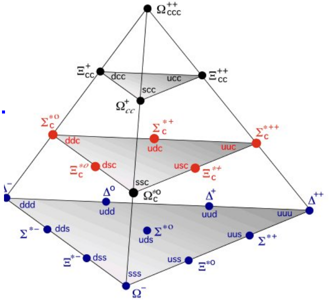


Courtesy of Michael Williams



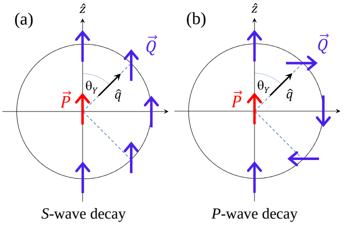
Many Y^* QN not measured:
(Quark model assignments)
➜ many Ξ^* and Ω^*, etc.

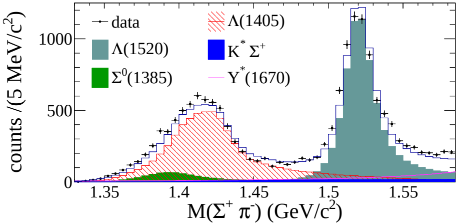
Spin and Parity Measurement of the $\Lambda(1405)$ Baryon

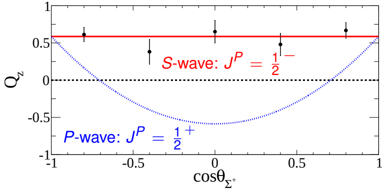
K. Moriya *et al.* [CLAS Collaboration], Phys. Rev. Lett. **112**, 082004 (2014)

Data for $\gamma p \to K^+ \Lambda(1405)$ support $\boxed{J^P = \frac{1}{2}^-}$

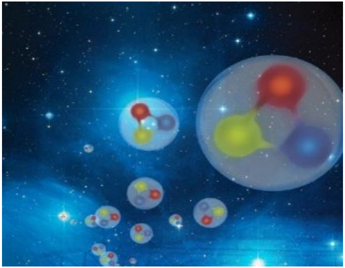
- Decay distribution of $\Lambda(1405) \to \Sigma^+ \pi^-$ consistent with $J = 1/2$.
- Polarization transfer, $\vec{Q}$, in $Y^* \to Y\pi$:
  - S-wave decay: $\vec{Q}$ independent of θ_Y







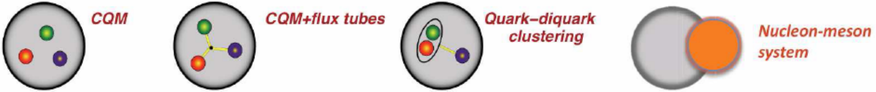
Non-Perturbative QCD



How does QCD give rise to excited hadrons?

1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. What role do gluonic excitations play in the spectroscopy of light mesons, and can they help explain quark confinement?

Baryons: What are the fundamental degrees of freedom inside a nucleon? Constituent quarks? How do degrees change with varying quark masses?



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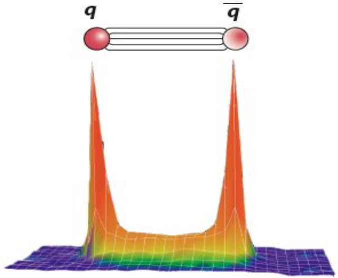

How does QCD give rise to excited hadrons?

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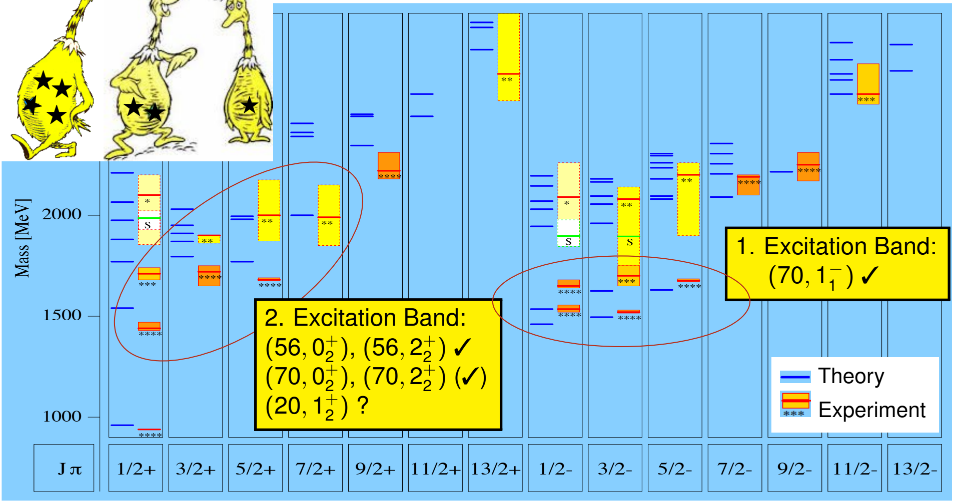
Mesons: What are the properties of the predicted states beyond simple quark-antiquark systems (hybrid mesons, glueballs, ...)?

➜ Gluonic Excitations provide a measurement of the excited QCD potential.

Hybrid baryons are possible but do not carry “exotic” quantum numbers.

Spectrum of N^* Resonances (PDG < 2012)

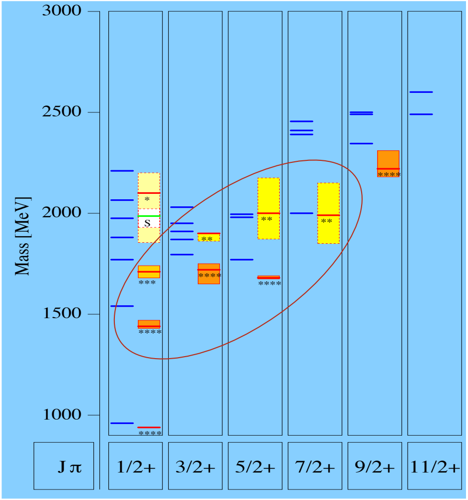
—— S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809



1. Excitation Band: $(70, 1_1^-)$ ✓

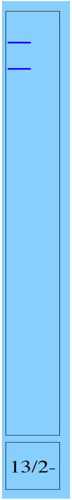
2. Excitation Band:
$(56, 0_2^+)$, $(56, 2_2^+)$ ✓
$(70, 0_2^+)$, $(70, 2_2^+)$ (✓)
$(20, 1_2^+)$?

Spectrum of N^* Resonances



V.C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	* * **	* * **
$N(1520)$	$3/2^-$ (D_{13})	* * **	* * **
$N(1535)$	$1/2^-$ (S_{11})	* * **	* * **
$N(1650)$	$1/2^-$ (S_{11})	* * **	* * **
$N(1675)$	$5/2^-$ (D_{15})	* * **	* * **
$N(1680)$	$5/2^+$ (F_{15})	* * **	* * **
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	* * *	* * *
$N(1710)$	$1/2^+$ (P_{11})	* * *	* * *
$N(1720)$	$3/2^+$ (P_{13})	* * **	* * **
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		* * *
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	* * *
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~N(2080)~~	D_{13}	**	
~~N(2090)~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	* * **	* * **
~~N(2200)~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	* * **	* * **



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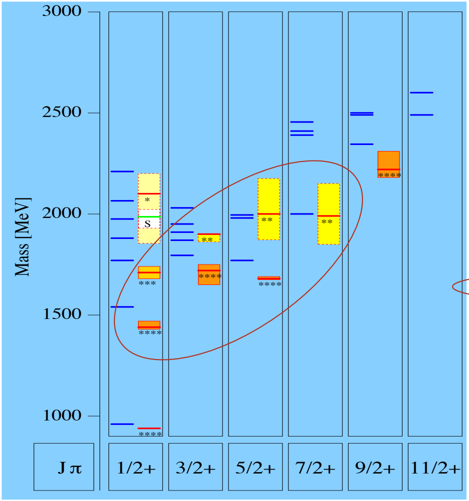

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$N(1685)$			∗
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$N(1710)$	$1/2^+$ (P_{11})	∗∗∗	∗∗∗
$N(1720)$	$3/2^+$ (P_{13})	∗∗∗∗	∗∗∗∗
$N(1860)$	$5/2^+$		∗∗
$N(1875)$	$3/2^-$		∗∗∗
$N(1880)$	$1/2^+$		∗∗
$N(1895)$	$1/2^-$		∗∗
$N(1900)$	$3/2^+$ (P_{13})	∗∗	∗∗∗
$N(1990)$	$7/2^+$ (F_{17})	∗∗	∗∗
$N(2000)$	$5/2^+$ (F_{15})	∗∗	∗∗
~~$N(2080)$~~	D_{13}	∗∗	
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$N(2100)$	$1/2^+$ (P_{11})	∗	∗
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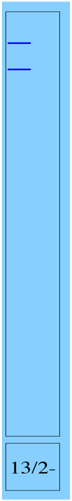
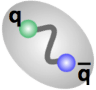
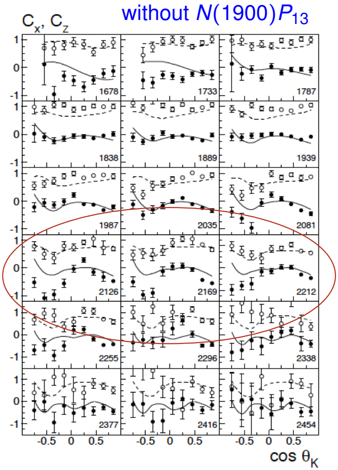
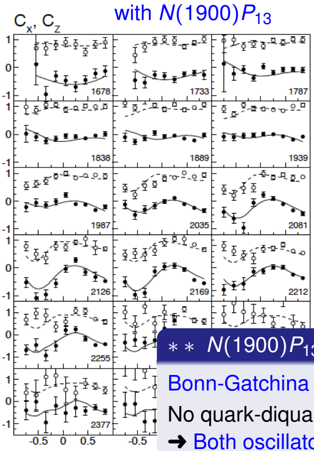


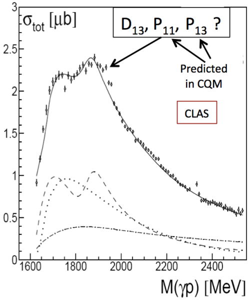
Outline



Polarization Transfer in $\vec{\gamma} p \to K^+ \vec{\Lambda}$: $C_x,\ C_z$







$* *\ N(1900)P_{13},\ N(2000)F_{15},\ N(1990)F_{17}$

Bonn-Gatchina PWA requires $N(1900)P_{13}$

No quark-diquark oscillations!

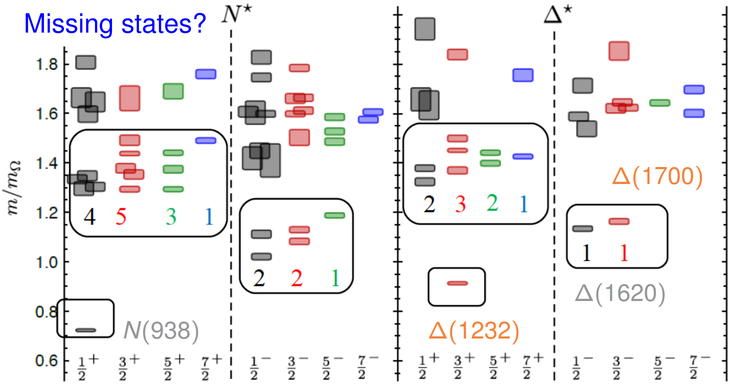
➜ Both oscillators need to be excited.

R. Bradford *et al.* [CLAS Collab.], PRC **75**, 035205 (2007) [➜ R. Schumacher, Parallel II:B5]

Fits: BoGa-Model, V. A. Nikonov *et al.*, Phys. Lett. B **662**, 245 (2008)

Baryon Spectroscopy from Lattice QCD

R. Edwards *et al.*, Phys. Rev. D **84**, 074508 (2011)

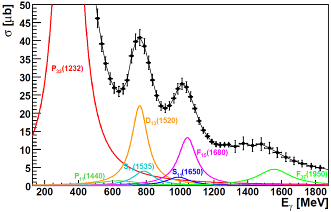


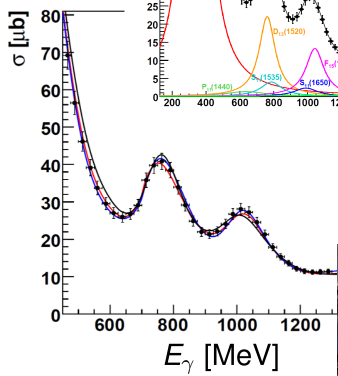
$m_\pi = 396$ MeV

Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

➜ Counting of levels consistent with non-rel. quark model, no parity doubling

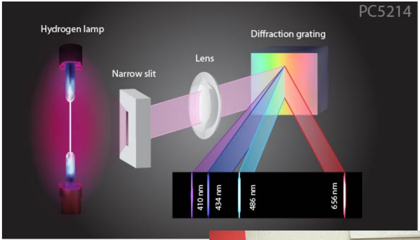
Why are Polarization Observables Important?

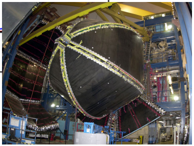




$\gamma p \to p\pi^0$

Atomic Spectrum of Hydrogen





ELSA
MAMI
GRAAL
SPring-8
...

CLAS@JLab

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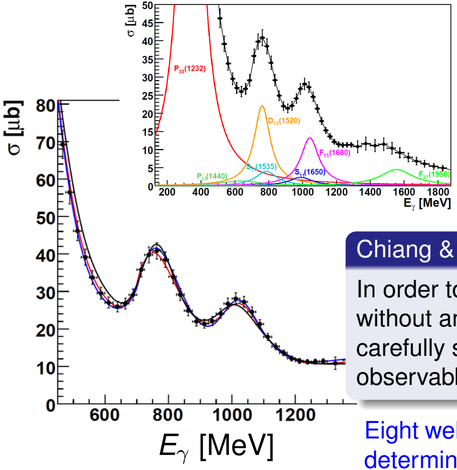


$\gamma p \to p\pi^0$

For single-meson production:

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F) - \Lambda_y (-T + \delta_l P \cos 2\phi) - \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E)\}$$

Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

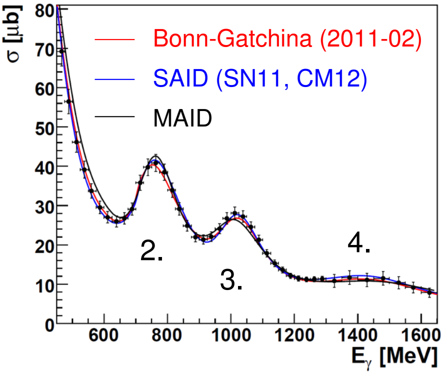
In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: four double-spin observables along with four single-spin observables.

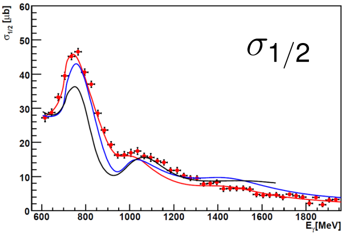
Eight well-chosen measurements are needed to fully determine production amplitudes F_1, F_2, F_3, and F_4.

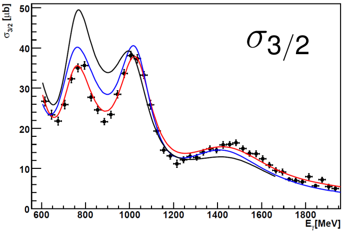
Example: Ambiguities in $\gamma p \to p \pi^0$

Helicity Difference:

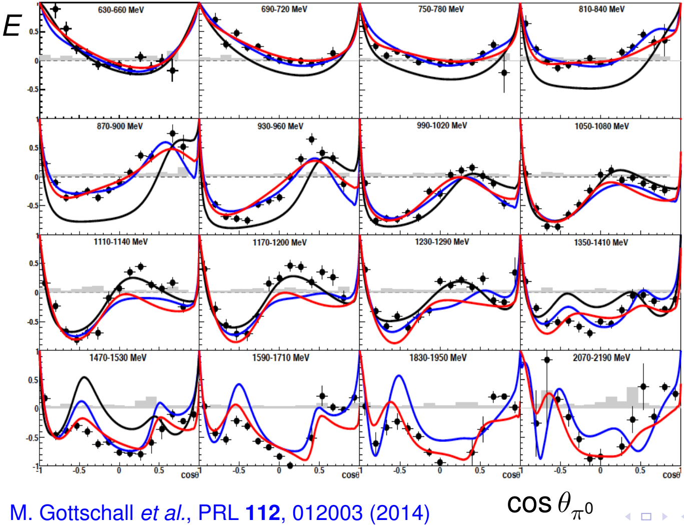
$$E = -\frac{1}{2\,\Lambda_z\,\delta_\odot}\,\frac{N^{\rightarrow\Rightarrow} - N^{\rightarrow\Leftarrow}}{N^{\rightarrow\Rightarrow} + N^{\rightarrow\Leftarrow}}$$







Helicity Asymmetry E in $\vec{\gamma}\,\vec{p} \to p\,\pi^0$ @ ELSA



$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

$E_\gamma \in [0.6, 2.2]$ GeV

- • CBELSA/TAPS
- — Maid
- — Said (CM12)
- — BoGa (2011_2)

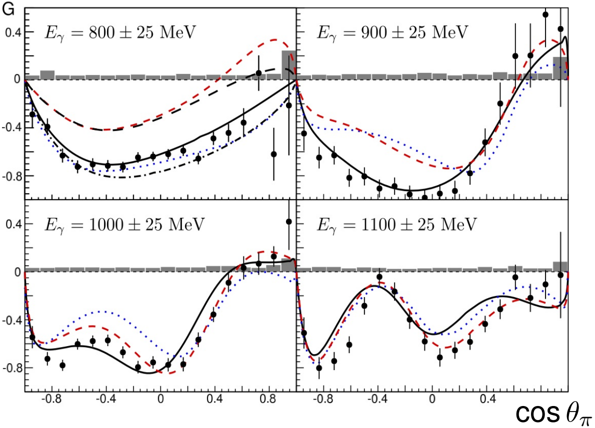
Angular distributions sensitive to interference between resonances.

M. Gottschall *et al.*, PRL **112**, 012003 (2014)

Asymmetry G in $\vec{\gamma}\,\vec{p} \to p\,\pi^0$ @ ELSA

➜ J. Hartmann, Parallel III: B10 "Light Quarks" (more results from ELSA)

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi + \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F) - \Lambda_y (-T + \delta_l P \cos 2\phi) - \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E)\}$$

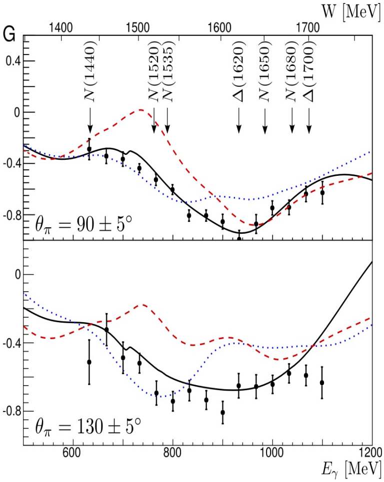


Surprisingly, π production also not well understood at lower energies:

— BoGa
- - SAID
···· MAID

A. Thiel *et al.*, PRL **109**, 102001 (2012)

Asymmetry G in $\vec{\gamma}\vec{p} \to p\pi^0$ @ ELSA



$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi$$
$$+ \Lambda_x (-\delta_l H \sin 2\phi + \delta_\odot F)$$
$$- \Lambda_y (-T + \delta_l P \cos 2\phi)$$
$$- \Lambda_z (-\delta_l G \sin 2\phi + \delta_\odot E)\}$$

$\theta_\pi = 90 \pm 5°$

$\theta_\pi = 130 \pm 5°$

Surprisingly, π production also not well understood at lower energies.

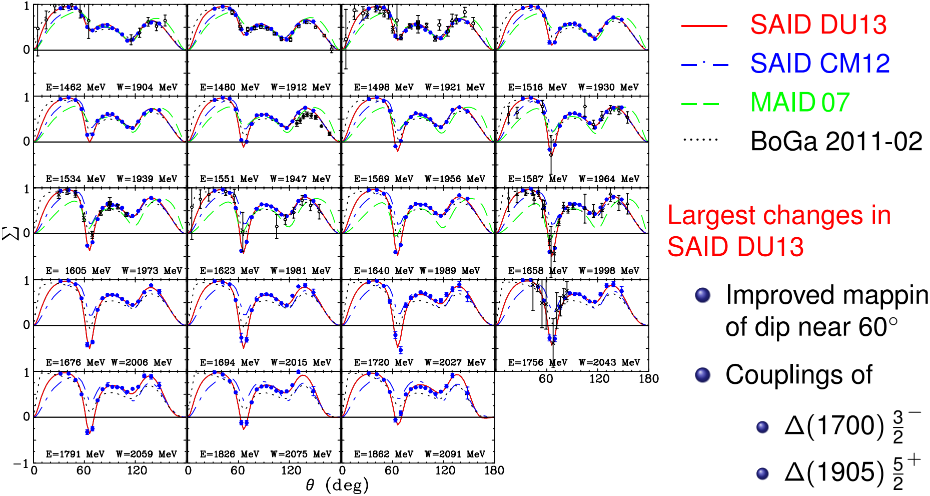
Below 1 GeV, discrepancies can be traced to the E_{0+} and E_{2-} multipoles, which are related to certain resonances:

E_{0+}: $N(1535)\,\frac{1}{2}^-$, $N(1650)\,\frac{1}{2}^-$, $\Delta(1620)\,\frac{1}{2}^-$

E_{2-}: $N(1520)\,\frac{3}{2}^-$, $\Delta(1700)\,\frac{3}{2}^-$

A. Thiel *et al.*, PRL **109**, 102001 (2012)

Beam Asymmetry Σ in $\vec{\gamma} p \to p \pi^0$ @ CLAS (g8b)



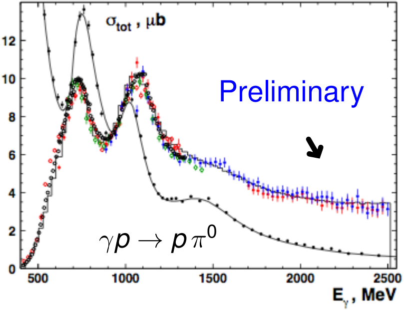
Largest changes in SAID DU13

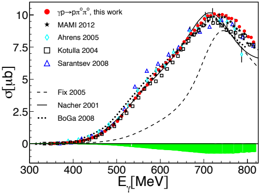
- Improved mapping of dip near 60°
- Couplings of
  - $\Delta(1700)\,\frac{3}{2}^-$
  - $\Delta(1905)\,\frac{5}{2}^+$

M. Dugger *et al.* [CLAS Collaboration], PRC **88**, 065203 (2013)

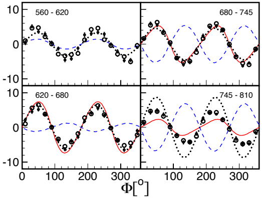
Observation of Decay Cascades in $\gamma p \to p\pi^0\pi^0$

F. Zehr *et al.*, Eur. Phys. J. A **48**, 98 (2012) @MAMI





Cross Sections

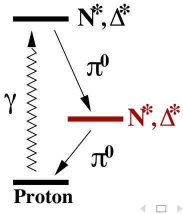


Beam Asymmetry, $I^{\odot}$

Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

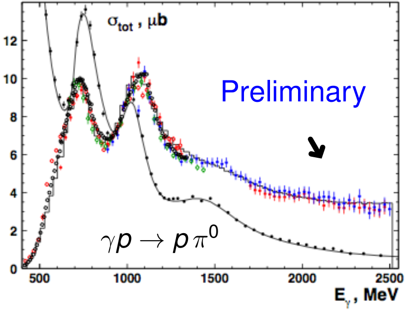
—— Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. *et al.* @ELSA



➜ Search for states in decay cascades!

Observation of Decay Cascades in $\gamma p \to p\pi^0\pi^0$



Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

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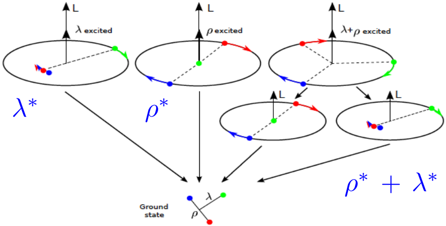
Nucleon states with $S = \frac{3}{2}$ require spatial wave functions of mixed symmetry. For $L = 2$ the wave functions do have equal admixtures of $\mathcal{M}_\mathcal{S}$ and

$$\mathcal{M}_\mathcal{A} = [\phi_{0p}(\vec{\rho}) \times \phi_{0p}(\vec{\lambda})]^{(L=2)},$$

a component in which both the ρ and the λ oscillator are excited simultaneously.



Observation of Decay Cascades in $\gamma p \to p \pi^0 \pi^0$

Decays observed in PWA into, e.g.

$$\left.\begin{array}{l} N(1880)\,1/2^+ \\ N(1900)\,3/2^+ \\ N(2000)\,5/2^+ \\ N(1990)\,7/2^+ \end{array}\right\} \begin{array}{l} N(1520)\pi \\ N(1535)\pi \\ N(1680)\pi \\ N\sigma\ (I=1) \end{array}$$

➜ Quartet of $(\mathbf{70}, 2_2^+)$ with $S = \frac{3}{2}$.

Observation of new decay modes in the decay of N^* resonances; weak at most in Δ^* decays.

—— Bonn-Gatchina PWA

V. Sokhoyan, E. Gutz, V. C. *et al.* @ELSA

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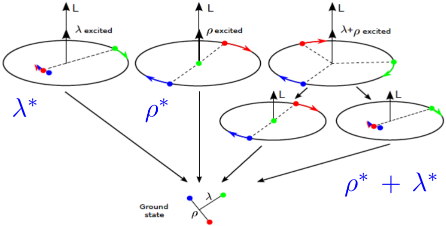
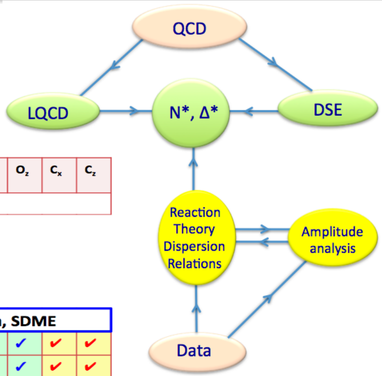


- ➜ M. Battaglieri, Parallel II: B5 “Light Quarks”
- ➜ V. Crede, Parallel III: B10 “Light Quarks” (more results from CLAS@JLab)



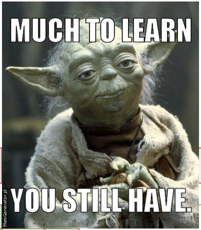
Observables	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
✔ published	✓ acquired or under analysis															
$p\pi^0$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓	(✓)	✓	✓	✓	✓			**Proton targets**					
$p\eta$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\eta'$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓	(✓)	✓	✓	✓	✓	**Tensor polarization, SDME**							
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
$p\pi^-$	✔	✓		(✓)	✓	✓	✓									
$p\rho^-$	✓	✓		(✓)	✓	✓	✓				**Neutron targets**					
$K^-\Sigma^+$	✓	✓		(✓)	✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

Table representing CLAS@JLab measurements.

Need more observables on:

$$\gamma p \to p\pi\pi,\ p\pi\eta$$

$$\gamma p \to p\pi\omega,\ \ldots$$

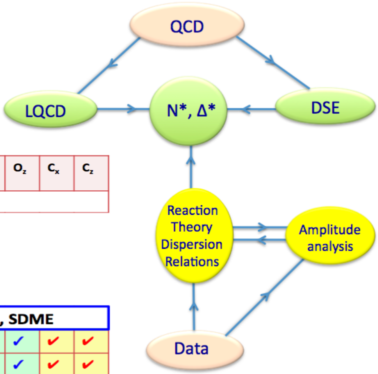


Observables	σ	Σ	T	P	E	F						L_z	O_x	O_z	C_x	C_z
✔ published	✓ acquired or under analysis															
$p\pi^0$	✔	✔	✓	(✓)	✓	✓										
$n\pi^+$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$p\eta$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\eta'$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓	(✓)	✓	✓	✓	✓	Tensor polarization, SDME							
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
$p\pi^-$	✔	✓		(✓)	✓	✓	✓									
$p\rho^-$	✓	✓		(✓)	✓	✓	✓									
$K^-\Sigma^+$	✓	✓		(✓)	✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

Proton targets

Neutron targets

Table representing CLAS@JLab measurements.

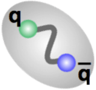


Need more observables on:

$$\gamma p \to p\pi\pi,\ p\pi\eta$$

$$\gamma p \to p\pi\omega,\ \ldots$$

Outline



Quark-Model Classification: Ordinary Mesons

Quantum Numbers $[q\bar{q}]$ ($J^{PC} \equiv {}^{2S+1}L_J$)

- Parity: $P = (-1)^{L+1}$
- Charge Conjugation: $C = (-1)^{L+S}$ (defined for neutral mesons)
- G parity: $G = C\,(-1)^I$

$L = 0,\ S = 0:$

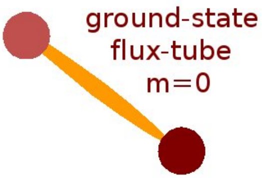
e.g. $\pi,\ \eta$ ($J^{PC} = 0^{-+}$)

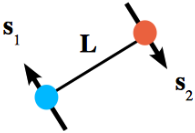
$L = 0,\ S = 1:$

e.g. $\rho,\ \omega,\ \phi$ ($J^{PC} = 1^{--}$)

$L = 1,\ S = 0:$

e.g. $h_1,\ b_1$ ($J^{PC} = 1^{+-}$)





Quark-Model Classification: Ordinary & Exotic Mesons

Quantum Numbers $[q\bar{q}]$ ($J^{PC} \equiv {}^{2S+1}L_J$)

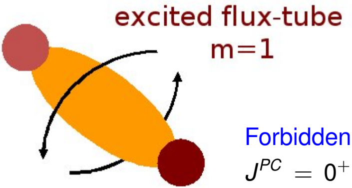
- Parity: $P = (-1)^{L+1}$
- Charge Conjugation: $C = (-1)^{L+S}$ (defined for neutral mesons)
- G parity: $G = C\,(-1)^I$

$L = 0,\ S = 0$:

e.g. $\pi,\ \eta$ ($J^{PC} = 0^{-+}$)

$L = 0,\ S = 1$:

e.g. $\rho,\ \omega,\ \phi$ ($J^{PC} = 1^{--}$)

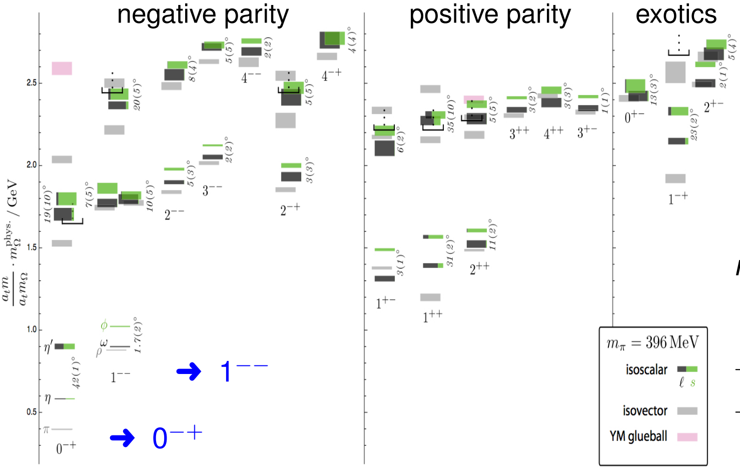


12 GeV CEBAF upgrade has high priority (DOE Office of Science, Long Range Plan) "[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement."

Forbidden States (Exotics):

$J^{PC} = 0^{+-},\ 0^{--},\ 1^{-+},\ 2^{+-}\ \cdots$

Meson Spectroscopy on the Lattice



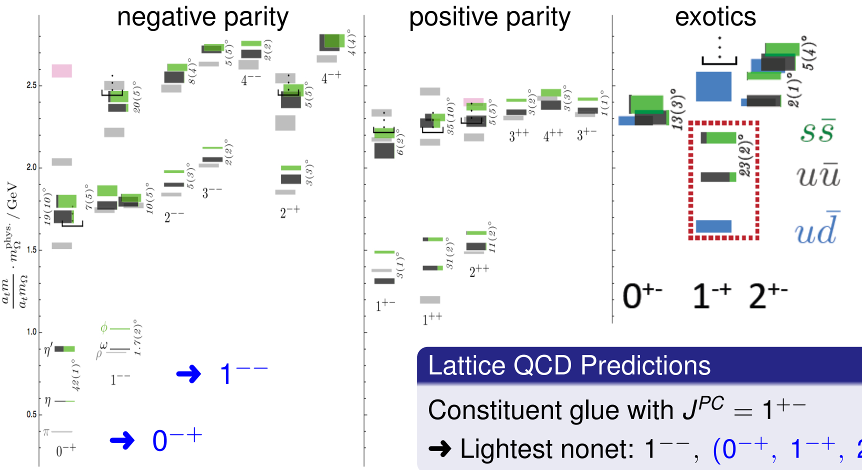
$m_\pi = 396$ MeV

→ isoscalar

→ isovector

J. J. Dudek *et al.*, Phys. Rev. D **83**, 111502 (2011)

Meson Spectroscopy on the Lattice



Lattice QCD Predictions

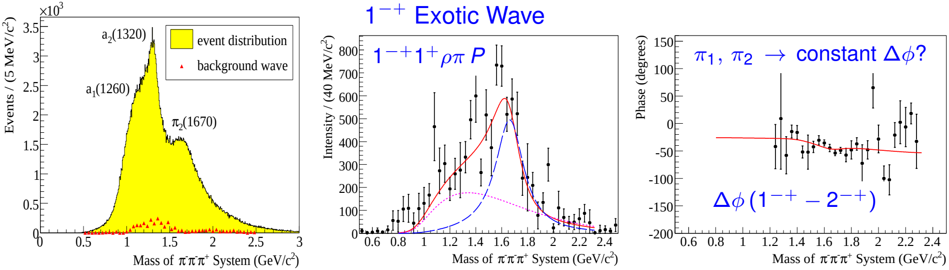
Constituent glue with $J^{PC} = 1^{+-}$

→ Lightest nonet: 1^{--}, $(0^{-+}, 1^{-+}, 2^{-+})$

J. J. Dudek *et al.*, PRD **83**, 111502 (2011)

COMPASS Experiment (1): $\pi^- \, Pb \to \pi^- \pi^- \pi^+ \, (Pb)$

M. Alekseev *et al.*, PRL **104**, 241803 (2010)



Based on $\sim 420,000$ events using a 180 GeV π beam:

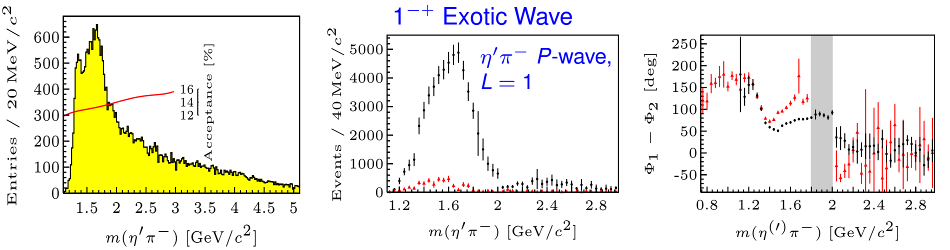
$\pi_1(1600)$:	$M = 1660$ MeV	$\pi_2(1670)$:	$M = 1658$ MeV
	$\Gamma = 269$ MeV		$\Gamma = 271$ MeV

➜ Exotic 1^{-+} wave dominantly produced in natural-parity ($M^\epsilon = 1^+$) exchange.

COMPASS Experiment (2): $\pi^- p \to \eta^{(\prime)} \pi^- (p)$

➜ F. Haas, Parallel II: B7 "Light Quarks"

C. Adolph *et al.*, arXiv:1408.4286 [hep-ex]



Collaboration refrains from proposing resonance parameters for exotic *P* wave.

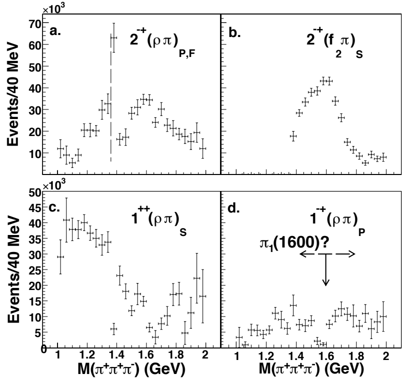
- Odd partial waves with $L = 1, 3, 5$ (non-$q\bar{q}$ QN) suppressed in $\eta\pi^-$ with respect to $\eta'\pi^-$. Even partial waves similar (intensity & phase behavior).
- Dominant $\mathbf{8} \otimes \mathbf{8}$ $(\eta\pi)$ & $\mathbf{1} \otimes \mathbf{8}$ $(\eta'\pi)$ nature of $SU(3)$ flavor configurations
  ➜ $gq\bar{q}$ and $q\bar{q}q\bar{q}$ configurations predicted to have $\mathbf{1} \otimes \mathbf{8}$ character.

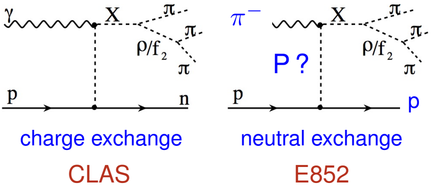
Meson Spectroscopy in Photoproduction: CLAS

Results on light mesons from CLAS at Jefferson Lab

Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system:

(M. Nozar *et al.*, Phys. Rev. Lett. **102**, 102002 (2009))

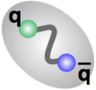




CLAS does not observe a resonant structure in the 1^{-+} $(\rho\pi)_P$ partial wave in charge exchange (confirmed with higher statistics, PhD 2012).

➜ Consistent with $\pi_1(1600)$ photoproduction via Pomeron exchange.

Outline



Summary and Outlook

Our understanding of baryon resonances has made great leaps forward. There is good evidence that most of the known states (listed in the PDG) will also be confirmed in photoproduction and that new states will be revealed:

- Goal of performing (almost) complete experiments has been (almost) achieved; significant contributions from (double-)polarization experiments.
- Still too early to nail down degrees of freedom in excited baryons?
  Well, is any of the different approaches THE correct one?
  Or, do they just represent different legitimate views?

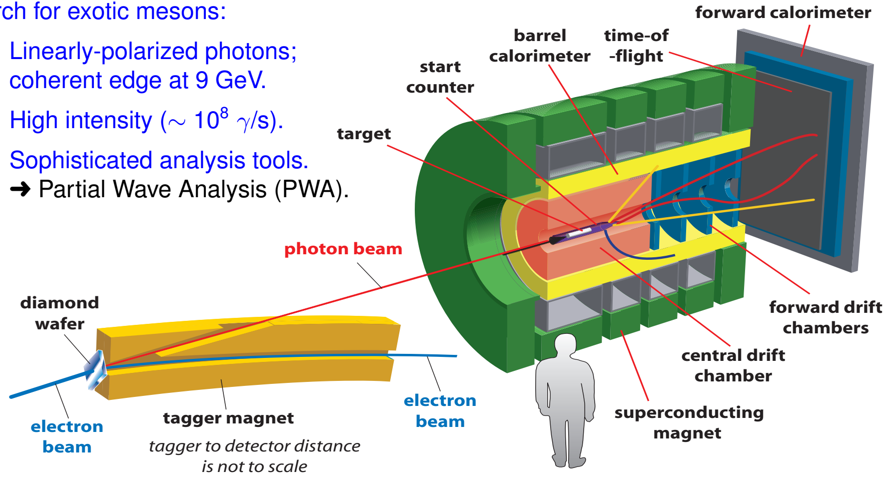
I think we are moving toward a new exciting era in meson spectroscopy (COMPASS@CERN, BES III, PANDA, etc.):

- GlueX in Hall-D at JLab will start to commission in about three weeks ...

Advances in both theory and experiment will allow us to finally understand QCD and confinement.

Search for exotic mesons:

- Linearly-polarized photons; coherent edge at 9 GeV.
- High intensity ($\sim 10^8$ γ/s).
- Sophisticated analysis tools.
  ➜ Partial Wave Analysis (PWA).



➜ M. Shepherd, Plenary 2