



## XI<sup>th</sup> Quark Confinement and the Hadron Spectrum

September 8-12, 2014  
Saint-Petersburg State University, Russia

# Hadron spectroscopy at CLAS and CLAS12

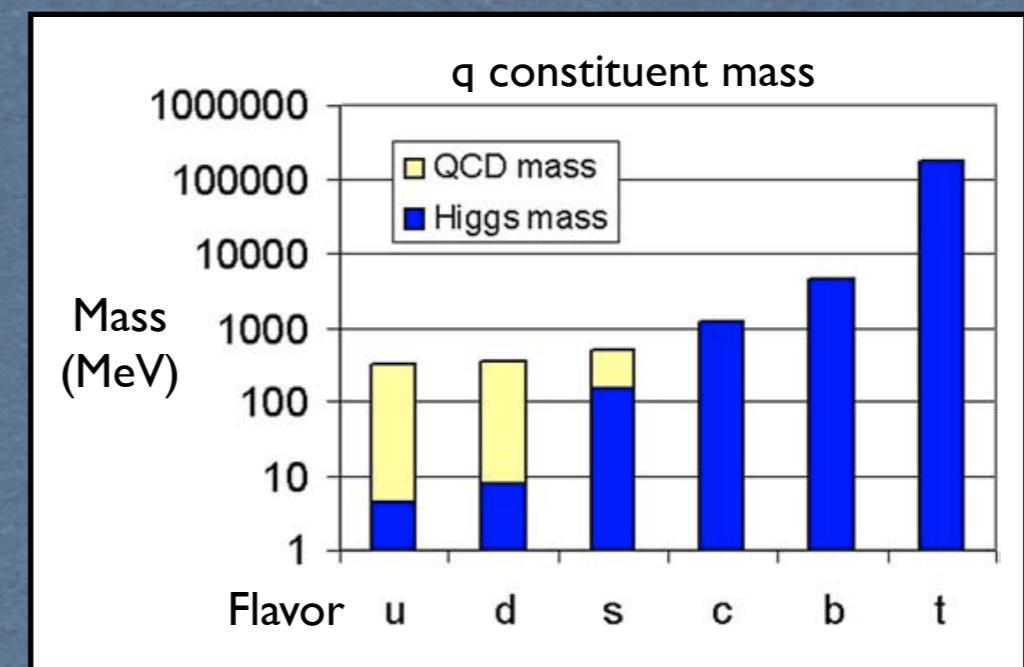
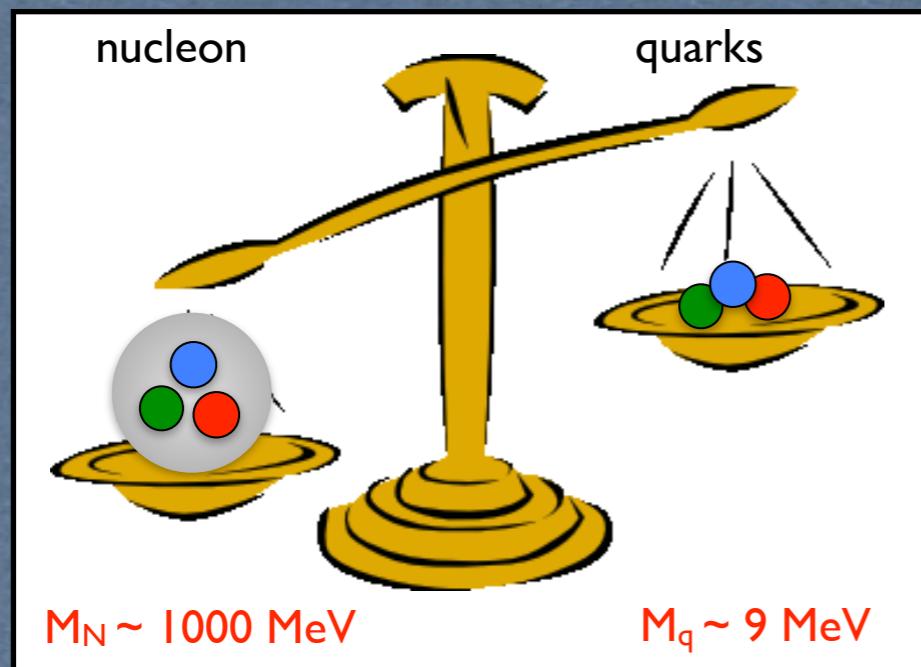


**M.Battaglieri**  
**INFN -GE**  
**Italy**



# Why hadron spectroscopy

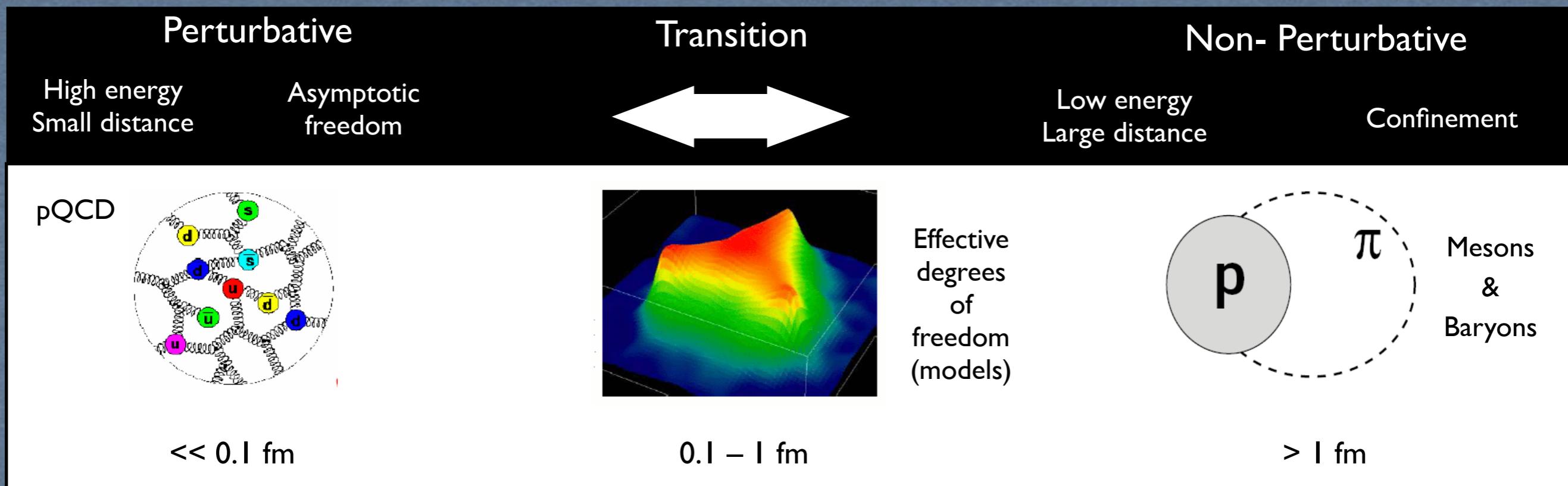
- \* The mass of the universe is mainly due to hadrons (nucleons forming nuclei)
- \* Quark masses only accounts for a small fraction of the nucleon mass: 99% is generated by dynamics of QCD confinement



- \* Light quark visible mass is dominated by QCD dressing effects

# Why hadron spectroscopy

- \* Quantitative understanding of quark and gluon confinement
- \* Revealing the nature of the mass of the hadrons
- \* See the QCD degrees of freedom at work
- \* Validate lattice-QCD predictions

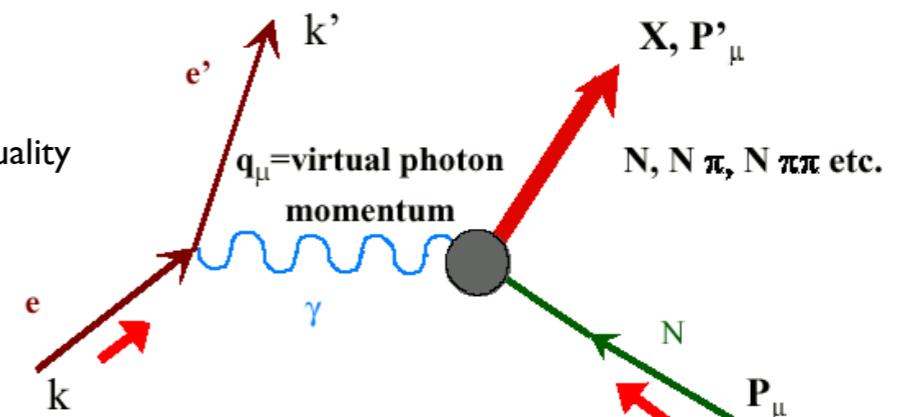


# The tool: electromagnetic interaction

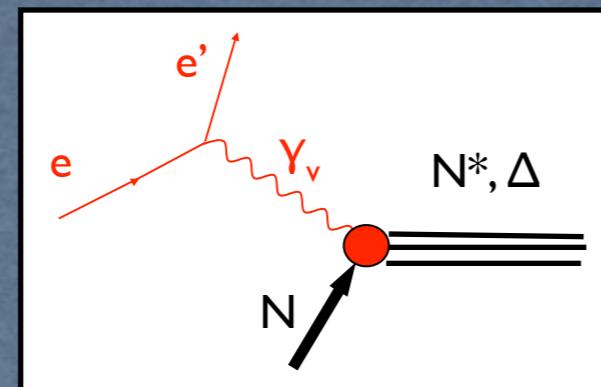
- weaker than strong interactions
- therefore calculable perturbatively
- based on the well-known QED

The scattering is normally analyzed in term of the One-Photon-Exchange approximation (OPE)

$-q^m q_m = Q^2$  = photon virtuality  
 $s$  = CM total energy  
 $t$  = momentum transfer



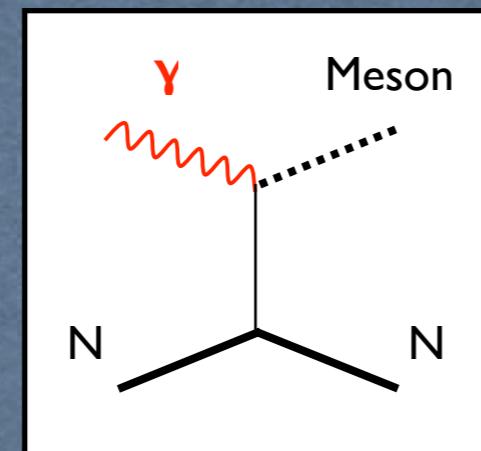
## Baryon spectroscopy



- Direct  $\gamma_v$  -  $qqq$  system coupling
- Establish the excitation spectrum
- Access to strong interaction dynamics ( $Q^2$  evolution of resonance form factors)

JLab today!

## Meson spectroscopy



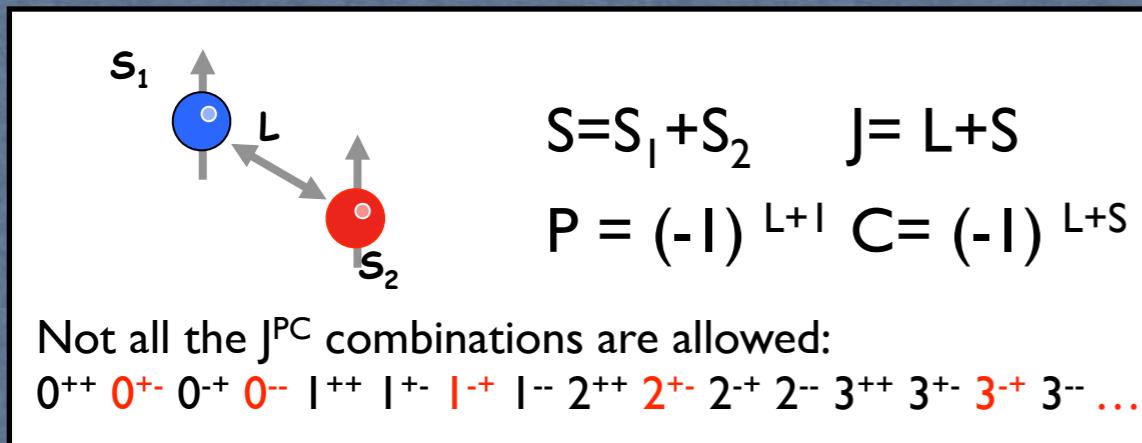
- $q\bar{q}$  system  $\rightarrow$  easier to study
- Access to gluonic degrees of freedom
- towards a quantitative understanding of quark and gluon confinement

JLab tomorrow!

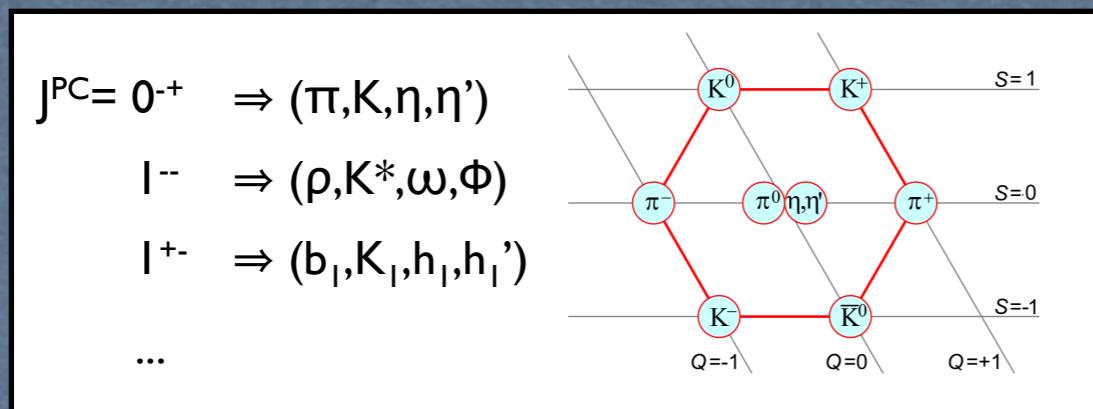
# The light quark meson spectrum

## Constituent Quark Model

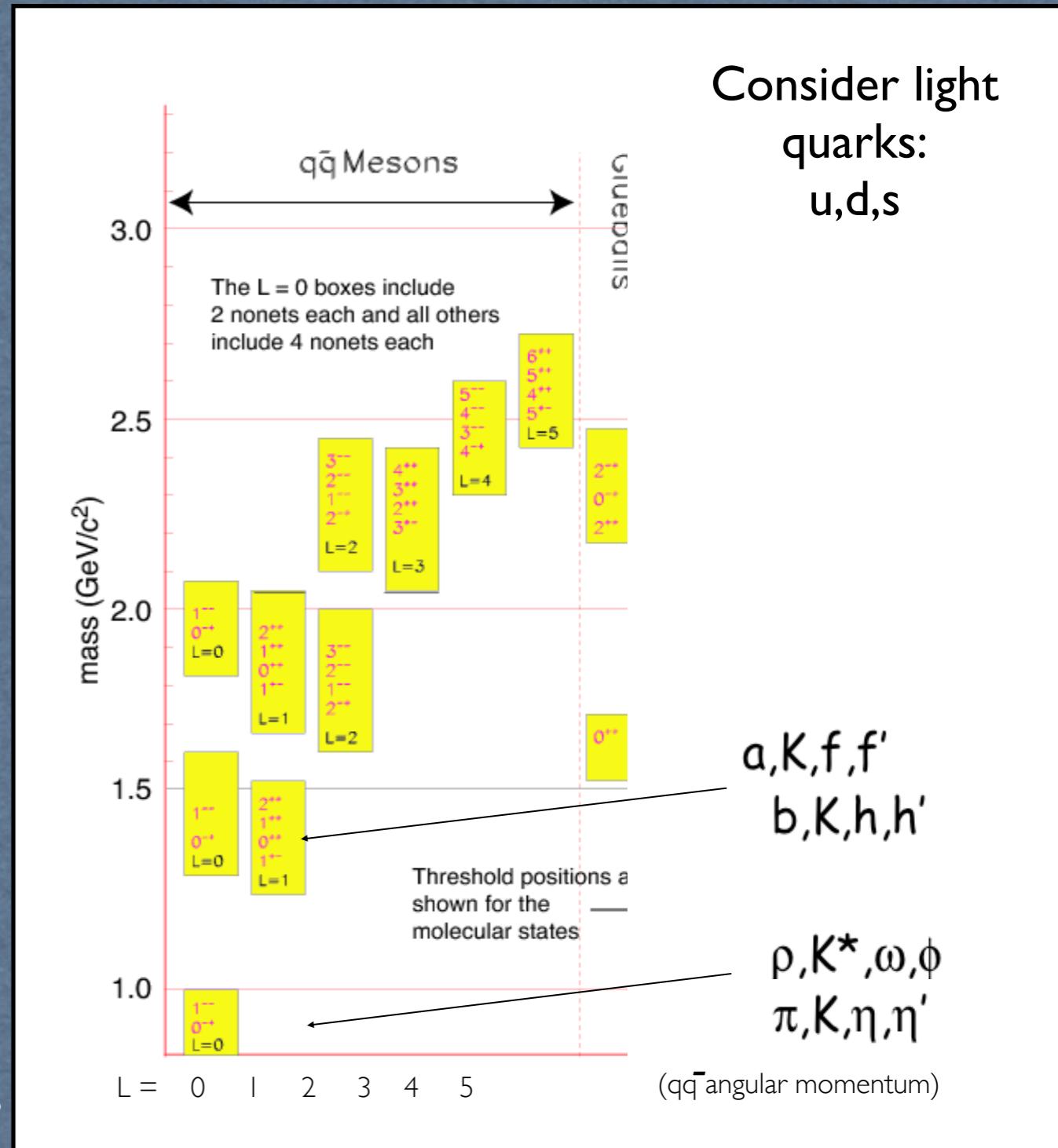
- Quark-antiquark pairs with total spin  $S=0,1$  and orbital angular momentum  $L$



- SU(3) flavor symmetry  
 $\rightarrow$  nonet ( $8 \oplus 1$ ) of degenerate states



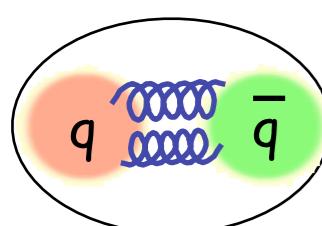
- Great success in describing the lower mass states
- A number of predicted states is not experimentally observed and assignments are uncertain



# The gluons and the meson spectrum

- Understanding gluonic excitations of mesons and the origin of confinement
- At high energy experimental evidence is found in jet production
- At lower energies the hadron spectrum carries information about the gluons that bind quarks
- Can we find hints of the glue in the meson spectrum?

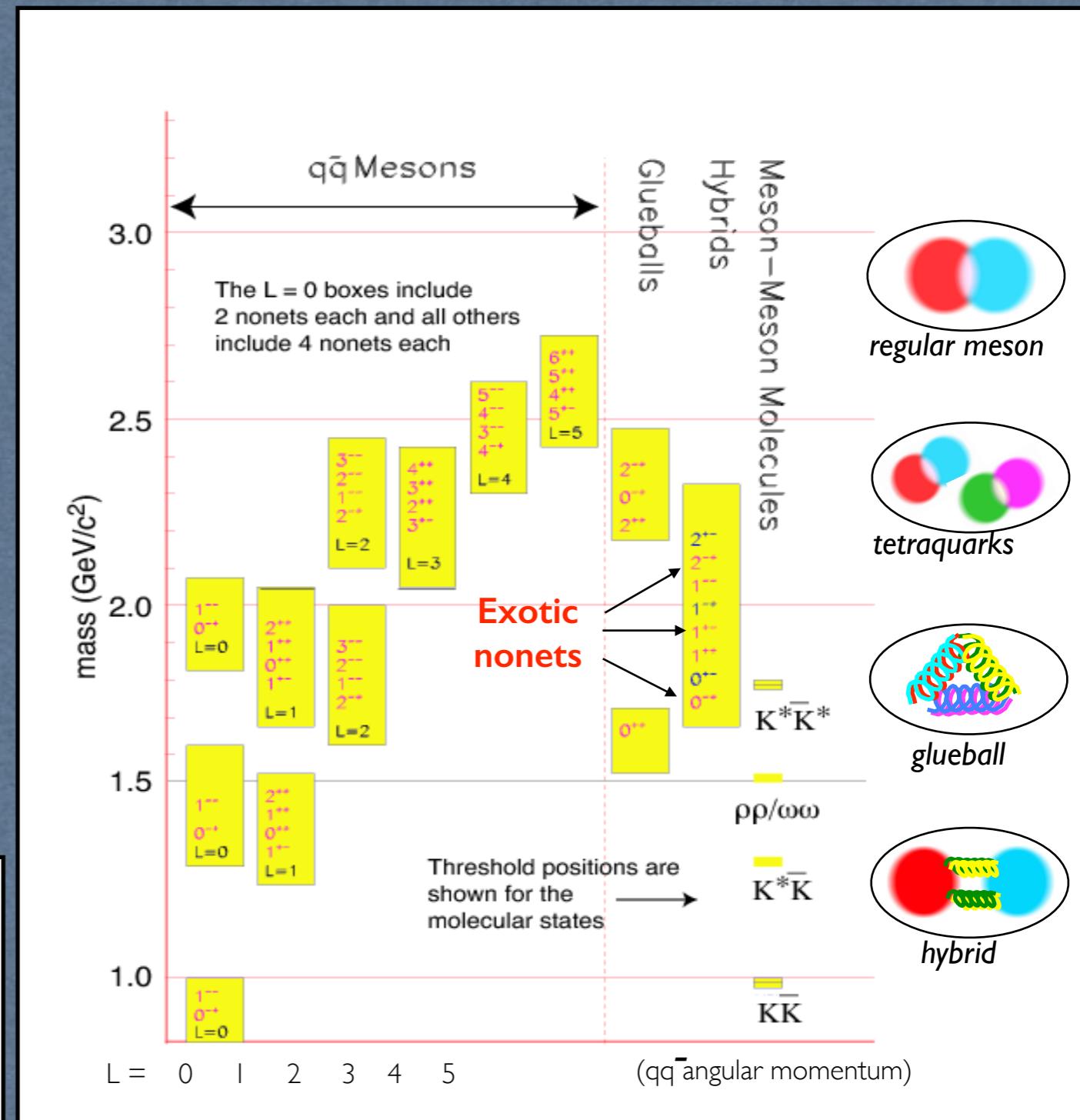
**Search for non-standard states with explicit gluonic degrees of freedom**



Not-allowed  $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \dots$

Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states

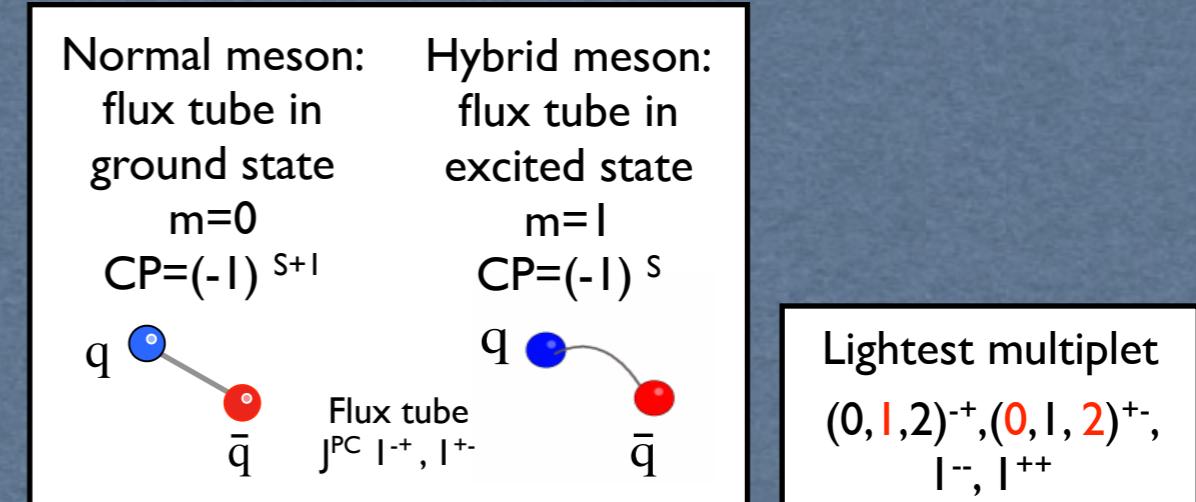
hybrid mesons



# Gluonic excitation models

## Flux tube model

- Gluonic field confined in a tube between q and anti-q
- Linear Regge trajectories
- Hybrid mesons as transverse oscillation of the tube
- Flux-tube breaking give rise to meson decay



## Bag model

- Quarks confined inside a cavity
- Full relativistic
- Gluonic excitation: gluonic field modes by boundary conditions

Lightest multiplet  
 $(0, 1, 2)^{-+}, 1^{--}$

## CQM + constituent gluon

- qq + massive transverse quasi-gluon ( $J_g Pg Cg$ )
- Gluon adds in relative S-wave to a qq pair is S-wave or P-wave

qq in S-wave +  
 $J_g Pg Cg = 1^{--}$  in S-wave

Lightest multiplet  
 $(0, 1, 2)^{++}, 1^{+-}$

qq in P-wave +  
 $J_g Pg Cg = 1^{--}$  in S-wave

Lightest multiplet  
 $0^{-}, (1^{-})^3, (2^{-})^2, 3^{-}, 0^{++}, 0^{-+}, 1^{-+}, 2^{-+}$

- Repulsive 3-body force selects  $J_g Pg Cg = 1^{+-}$  in relative P-wave added to a qq pair is S-wave or P-wave

qq in S-wave +  
 $J_g Pg Cg = 1^{+-}$  in P-wave

Lightest multiplet  
 $(0, 1, 2)^{-+}, 1^{--}$

qq in P-wave +  
 $J_g Pg Cg = 1^{+-}$  in P-wave

Lightest multiplet  
 $0^{+-}, (1^{+-})^3, (2^{+-})^2, 3^{+-}, (0, 1, 2)^{++}$

# Hybrids decay modes

- Decays can only be calculated within models:
  - ${}^3P_0$ :  $M \rightarrow qq$  with  $J^{PC}=0^{++}$
  - Flux-tube model:  $\pi b_1 : \pi f_1 : \pi \rho : \eta \pi : \eta' \pi$   
 $170 : 60 : 5-20 : 0-10 : 0-10$
- Some hints:
  - hybrids with vector  $qq$  quantum number
  - pairs of not identical mesons
  - pairs of  $L=0$  mesons suppressed
  - pairs of  $(L=0)(L=1)$  favored
- Lattice QCD
  - sparse results (so far)
  - width overestimates (compared to other models)

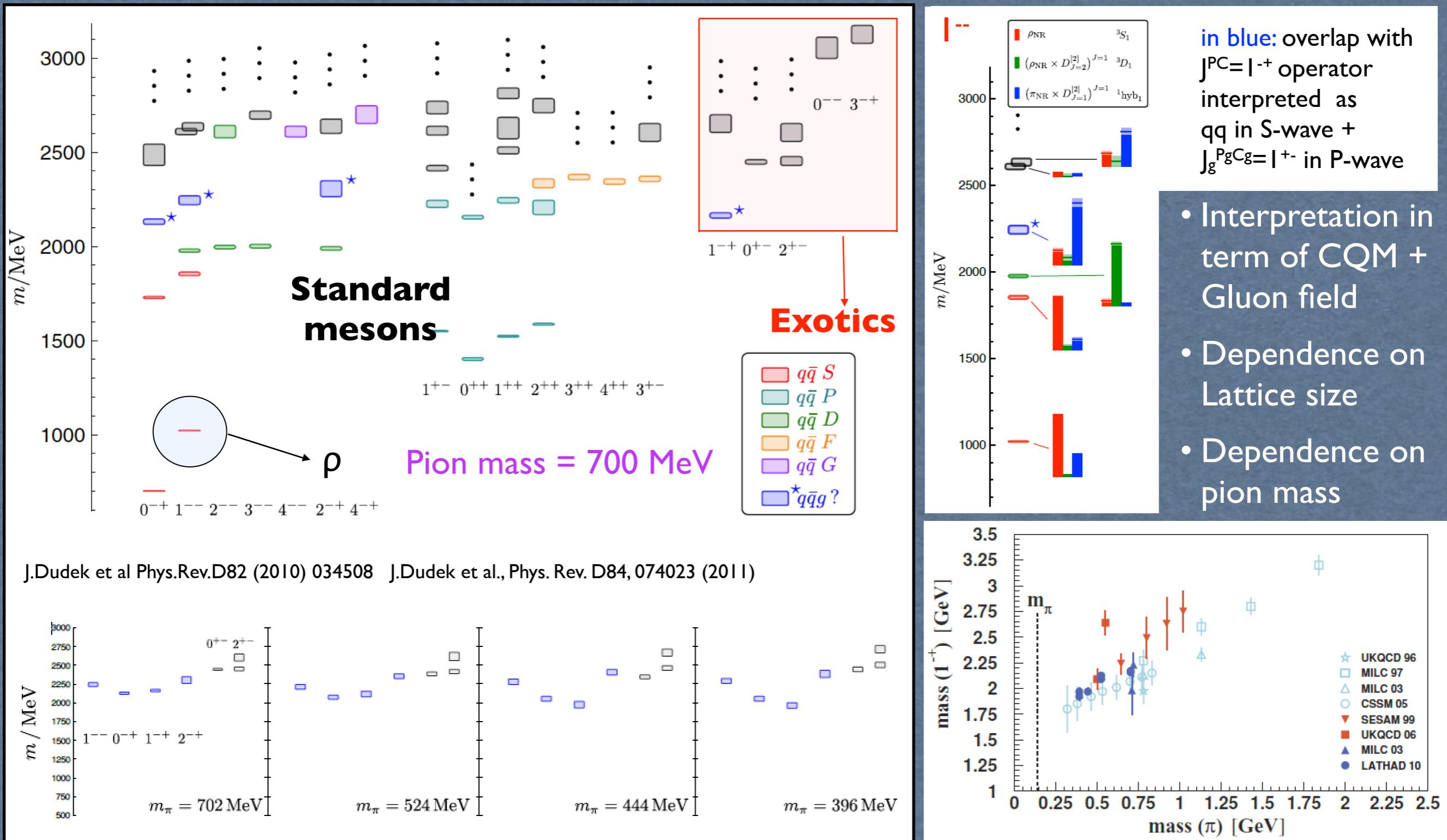
To define the experimental program we need to have reliable prediction of hybrids decay

Name	$J^{PC}$	Total width (MeV)		Large decays
		PSS	IKP	
$\pi_1$	$1^{-+}$	81–168	117	$b_1\pi, \rho\pi, f_1\pi, a_1\eta, \eta(1295)\pi, K_1^A K, K_1^B K$
$\eta_1$	$1^{-+}$	59–158	107	$a_1\pi, f_1\eta, \pi(1300)\pi, K_1^A K, K_1^B K$
$\eta'_1$	$1^{-+}$	95–216	172	$K_1^B K, K_1^A K, K^* K$
$b_0$	$0^{+-}$	247–429	665	$\pi(1300)\pi, h_1\pi$
$h_0$	$0^{+-}$	59–262	94	$b_1\pi, h_1\eta, K(1460)K$
$h'_0$	$0^{+-}$	259–490	426	$K(1460)K, K_1^A K, h_1\eta$
$b_2$	$2^{+-}$	5–11	248	$a_2\pi, a_1\pi, h_1\pi$
$h_2$	$2^{+-}$	4–12	166	$b_1\pi, \rho\pi$
$h'_2$	$2^{+-}$	5–18	79	$K_1^B K, K_1^A K, K_2^* K, h_1\eta$

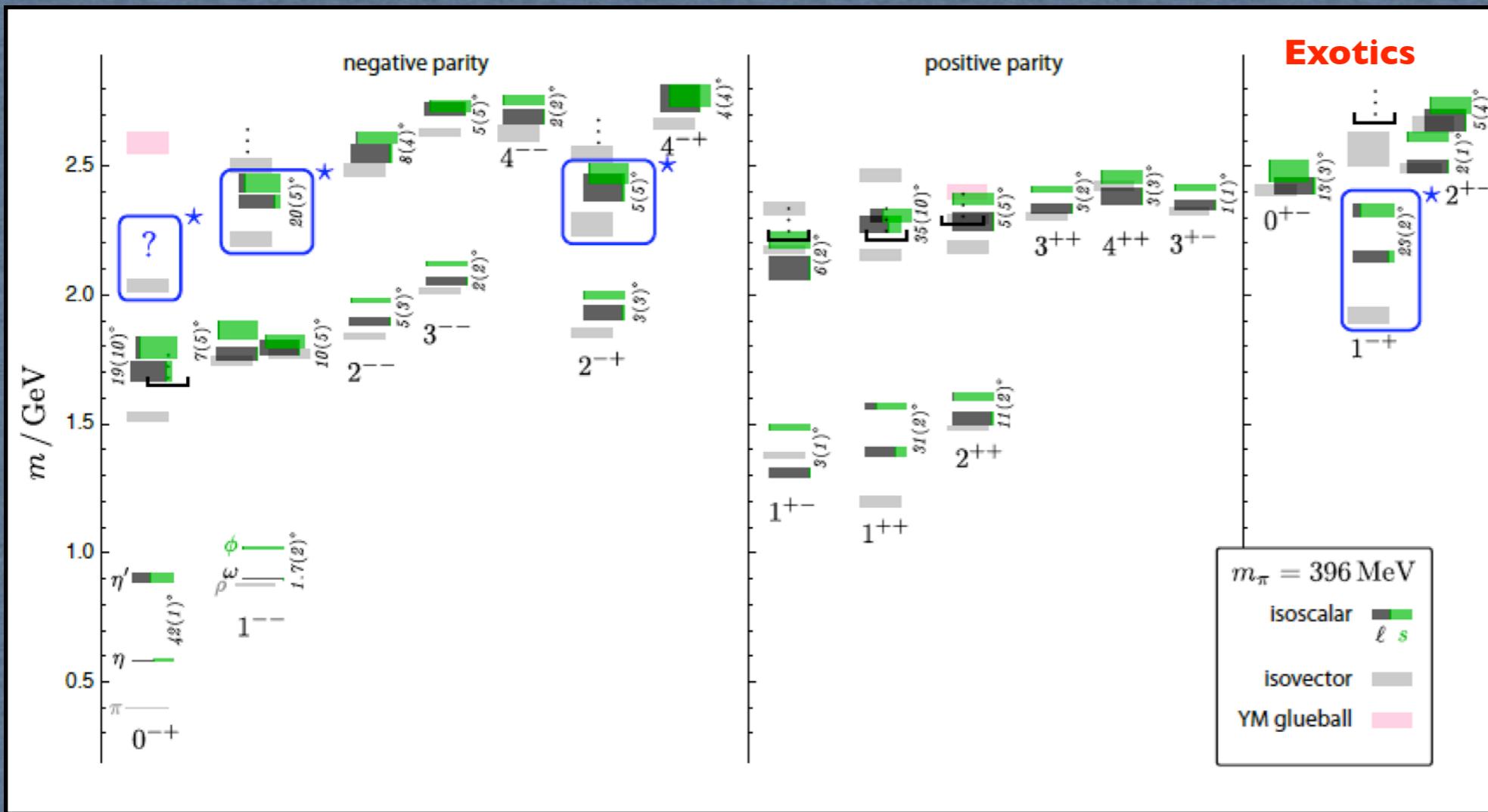
  

Particle	$J^{PC}$	Total width (MeV)		Large decays
		PSS	IKP	
$\rho_1$	$1^{--}$	70–121	112	$a_1\pi, \omega\pi, \rho\pi$
$\omega_1$	$1^{--}$	61–134	60	$\rho\pi, \omega\eta, \rho(1450)\pi$
$\phi_1$	$1^{--}$	95–155	120	$K_1^B K, K^* K, \phi\eta$
$a_1$	$1^{++}$	108–204	269	$\rho(1450)\pi, \rho\pi, K^* K$
$h_1$	$1^{++}$	43–130	436	$K^* K, a_1\pi$
$h'_1$	$1^{++}$	119–164	219	$K^*(1410)K, K^* K$
$\pi_0$	$0^{+-}$	102–224	132	$\rho\pi, f_0(1370)\pi$
$\eta_0$	$0^{+-}$	81–210	196	$a_0(1450)\pi, K^* K$
$\eta'_0$	$0^{+-}$	215–390	335	$K_0^* K, f_0(1370)\eta, K^* K$
$b_1$	$1^{+-}$	177–338	384	$\omega(1420)\pi, K^* K$
$h_1$	$1^{+-}$	305–529	632	$\rho(1450)\pi, \rho\pi, K^* K$
$h'_1$	$1^{+-}$	301–373	443	$K^*(1410)K, \phi\eta, K^* K$
$\pi_2$	$2^{-+}$	27–63	59	$\rho\pi, f_2\pi$
$\eta_2$	$2^{-+}$	27–58	69	$a_2\pi$
$\eta'_2$	$2^{-+}$	38–91	69	$K_2^* K, K^* K$

# Lattice QCD calculations



# **QCD Lattice calculations**



# Lattice-QCD predictions for the lowest hybrid states

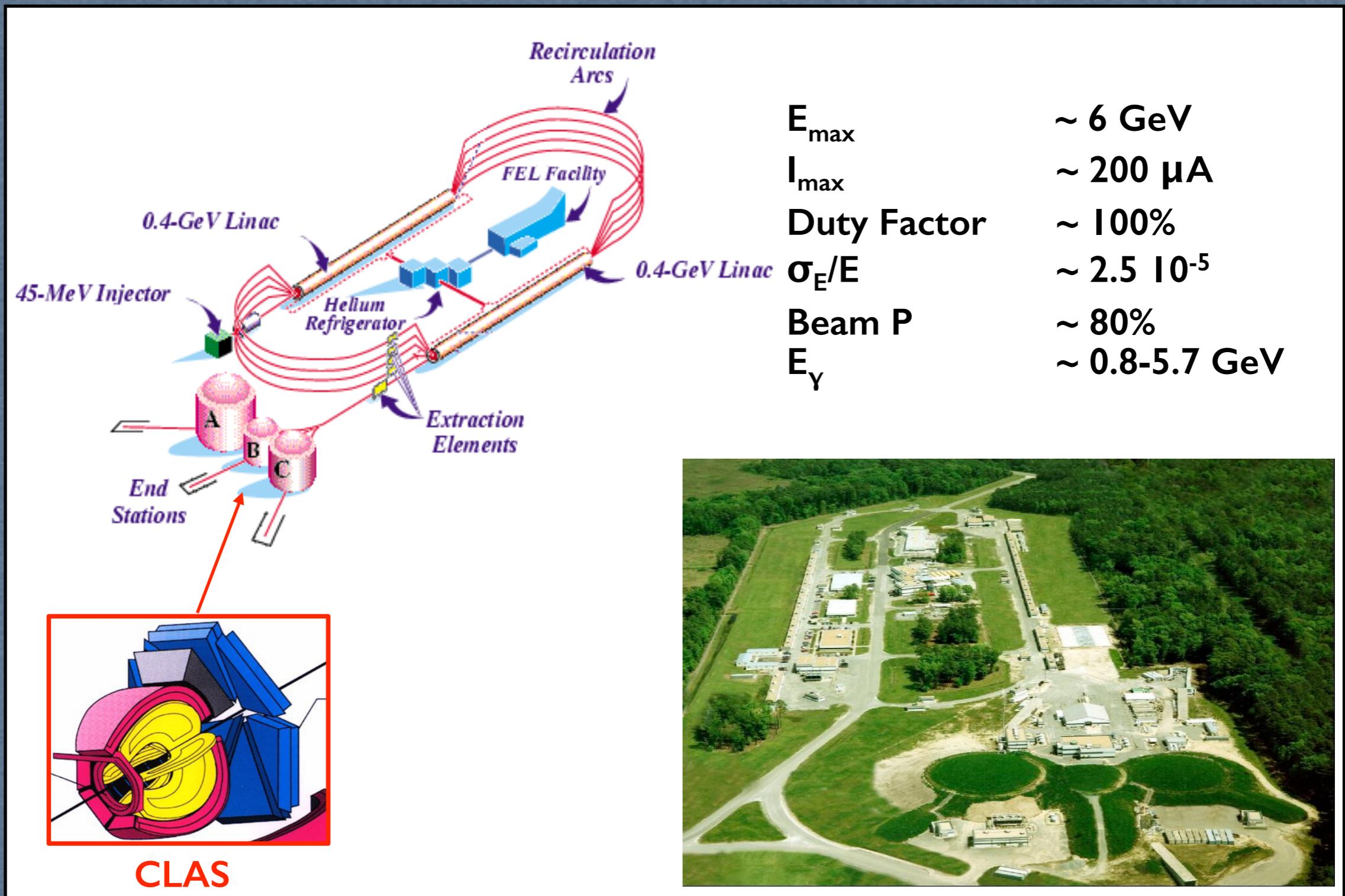
$0^{+-} \sim 2.0 \text{ GeV}$   
 $|^{-+} \sim |.6 \text{ GeV}$

# Hybrid mesons and glueballs mass range: 1.4 GeV - 3.0 GeV

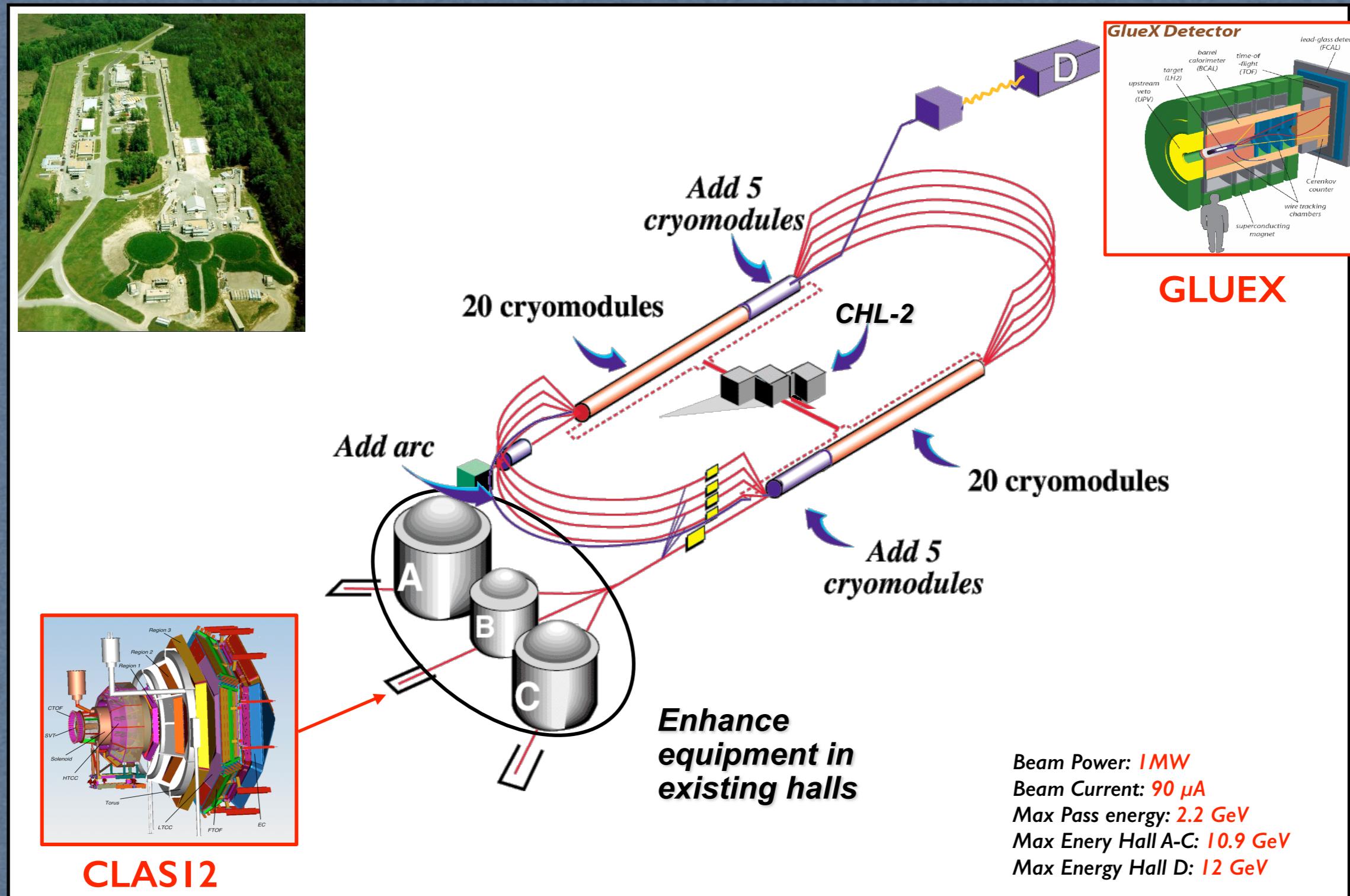
This mass range is accessible in photoproduction experiments with a beam energy in the range  $5 \text{ GeV} < E_\gamma < 12 \text{ GeV}$

# Perfectly matched to JLab12 energy!

# Jefferson Lab (yesterday)



# Jefferson Lab at 12 GeV



**CLAS12**

**Enhance  
equipment in  
existing halls**

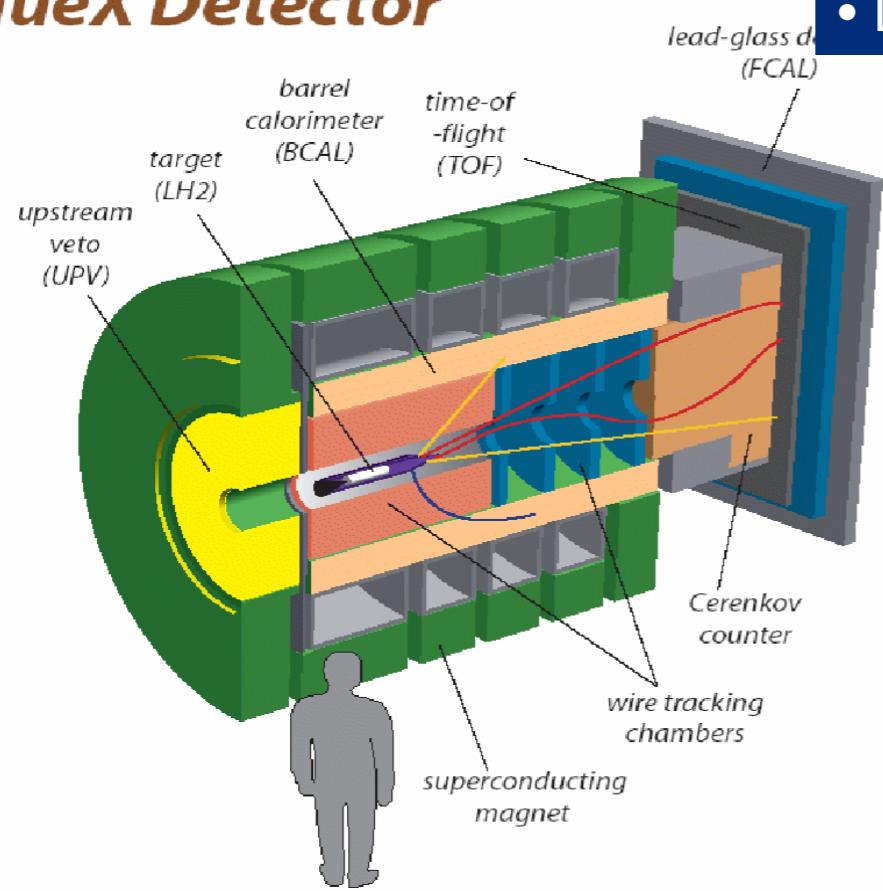
Beam Power: **1 MW**  
Beam Current: **90  $\mu\text{A}$**   
Max Pass energy: **2.2 GeV**  
Max Energy Hall A-C: **10.9 GeV**  
Max Energy Hall D: **12 GeV**

# Meson spectroscopy with photons at JLab- 12 GeV

- Determination of JPC of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification

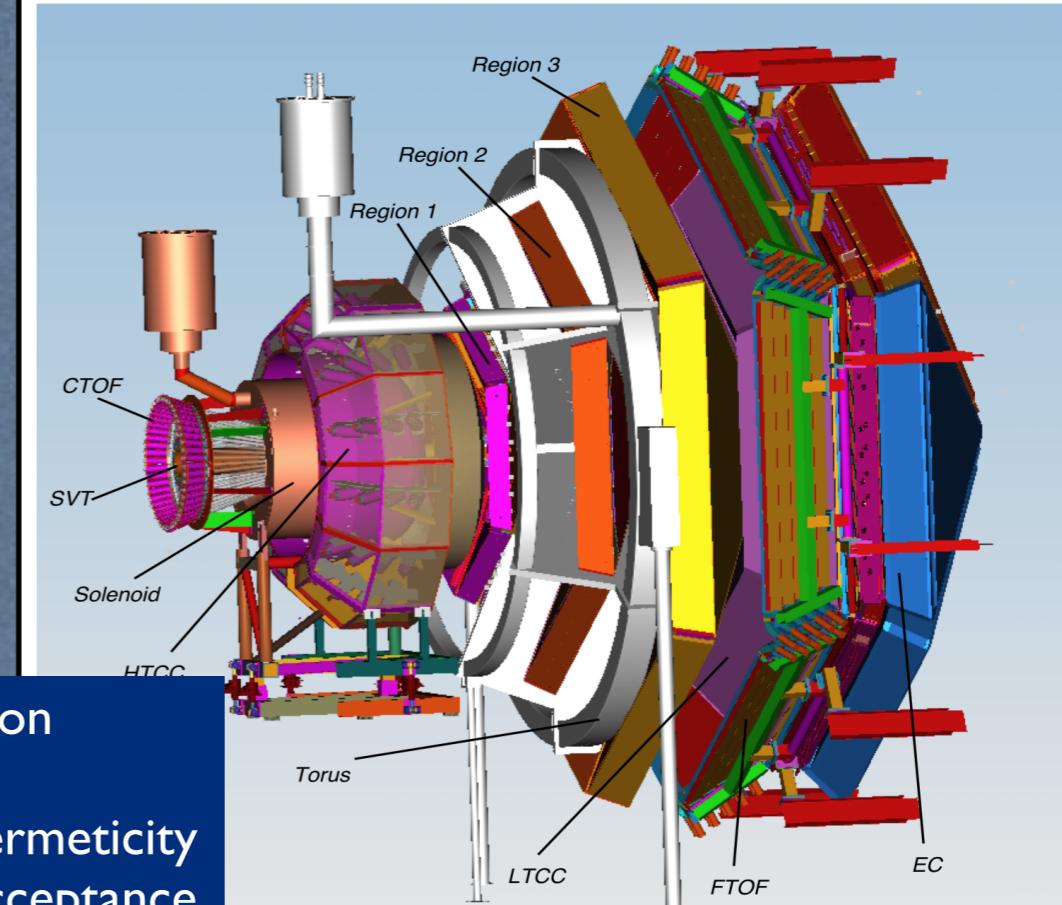
## Hall-D - GlueX Detector

### GlueX Detector



- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID

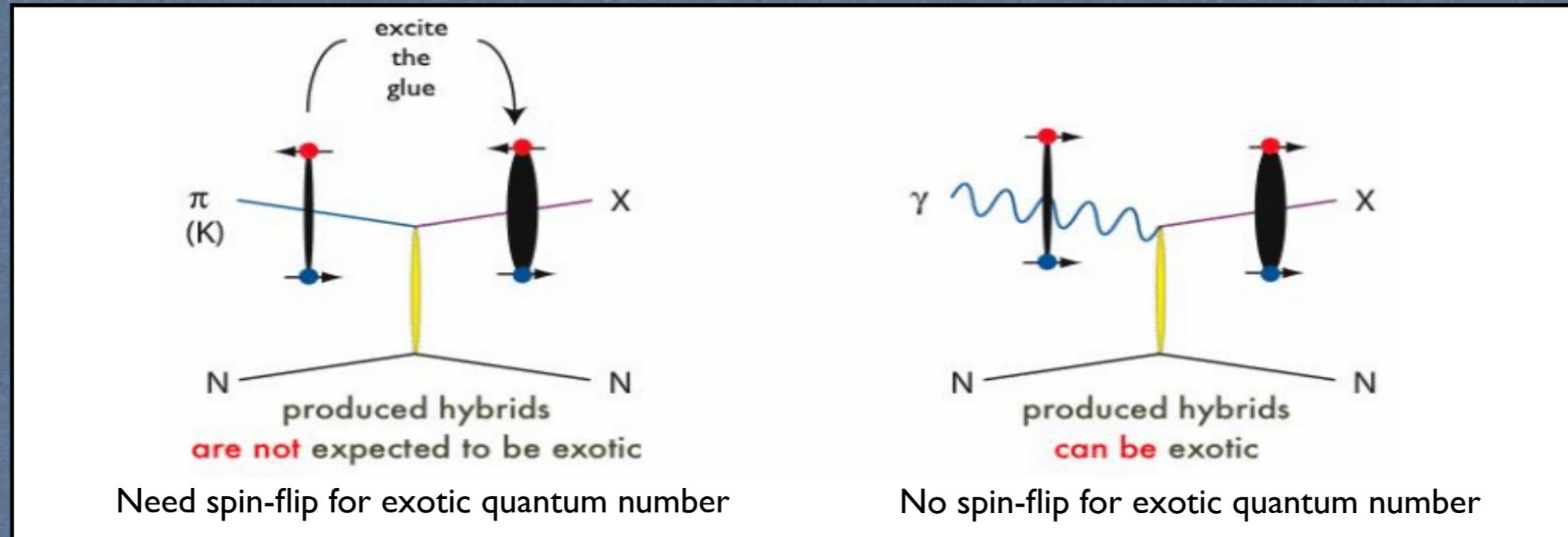
## Hall-B - CLAS12 Detector



- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance

# Why photoproduction

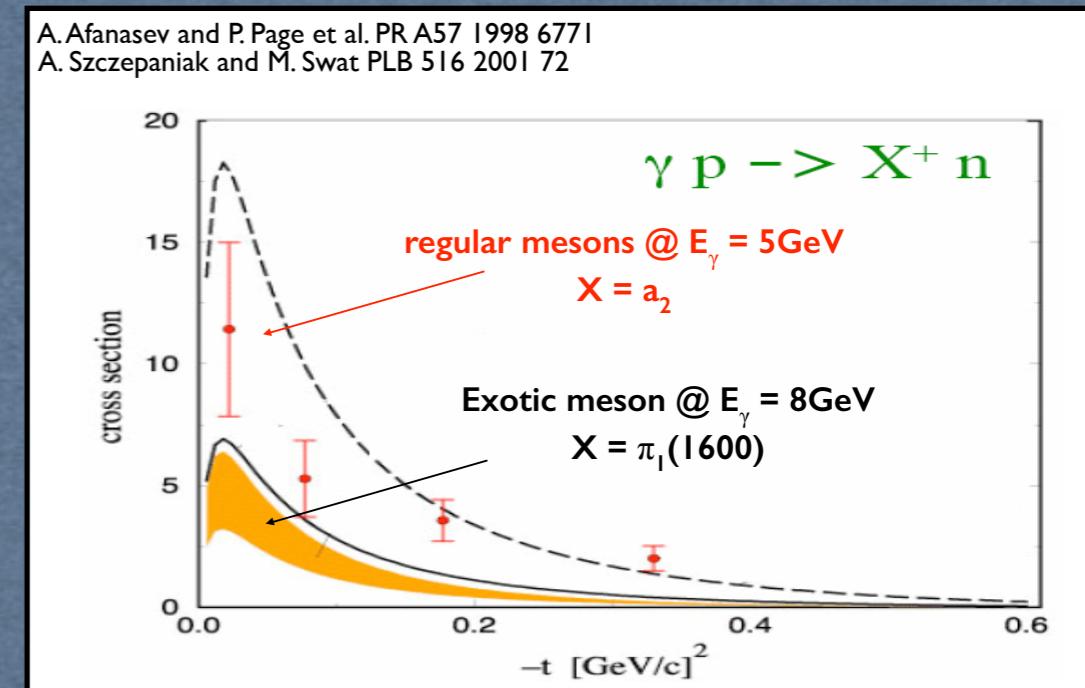
- ★ Photoproduction: exotic  $J^{PC}$  are more likely produced by  $S=1$  probe



- ★ Linear polarization acts like a filter to disentangle the production mechanisms and suppress bg

- ★ Production rate for exotics is expected comparable as for regular mesons

- ★ Few data (so far) but expected similar production rate as regular mesons



# Meson spectroscopy with photons at JLab-12GeV

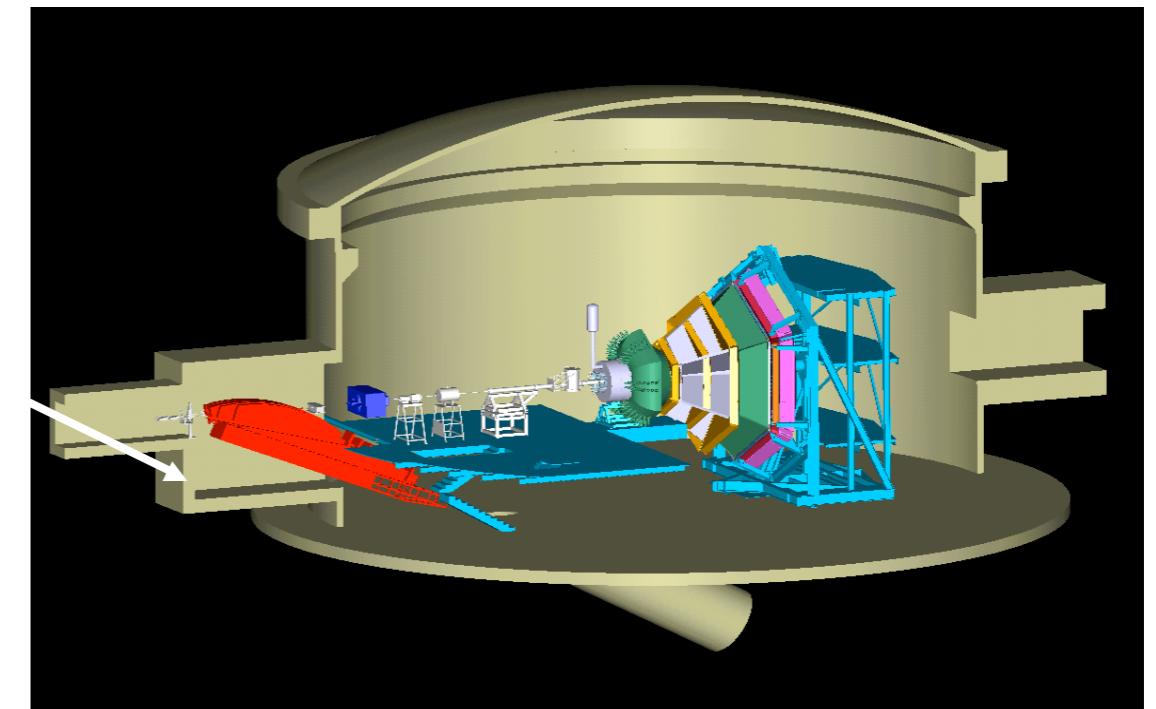
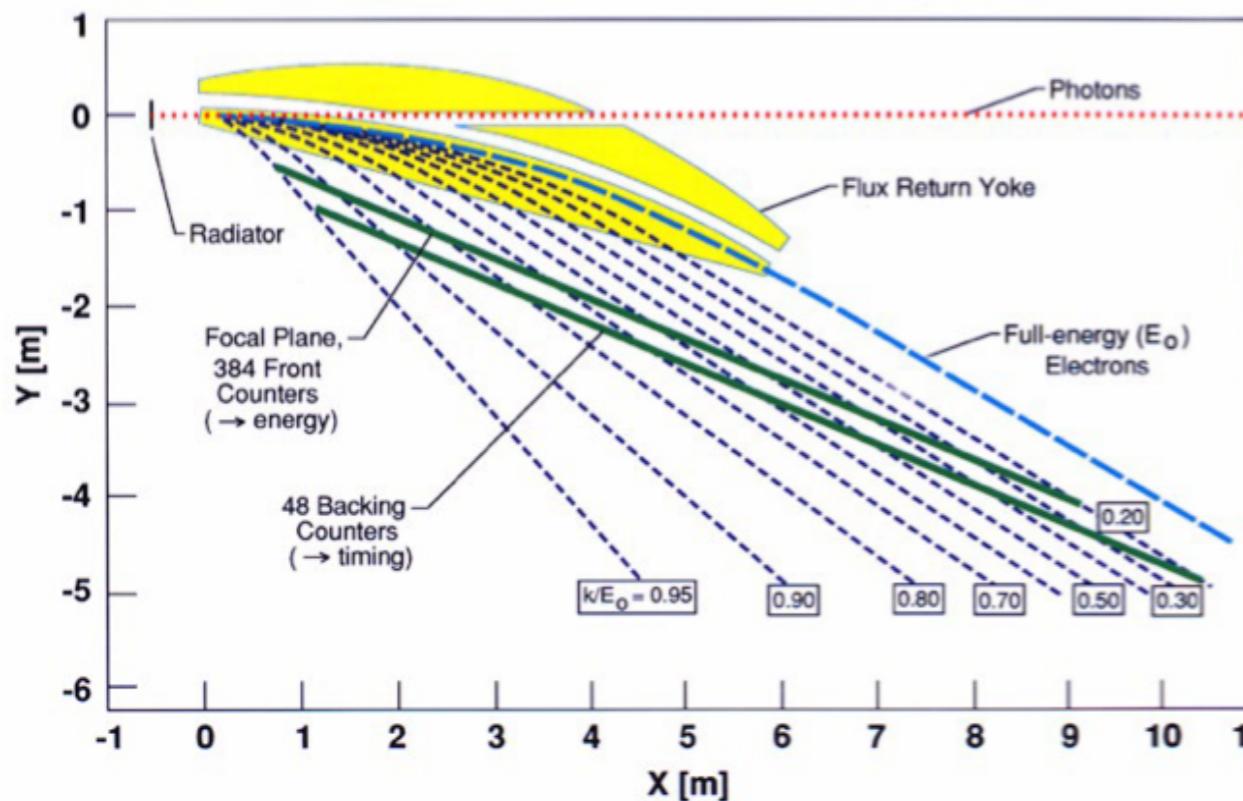
## Photon beam requirement

- ★ High luminosity
- ★ Tagger (initial photon energy) is required to add 'production' information to decay
- ★ Linear polarization is useful to simplify the PWA and essential to isolate the nature of the t-channel exchange

With a 12 GeV electron beam only few choices

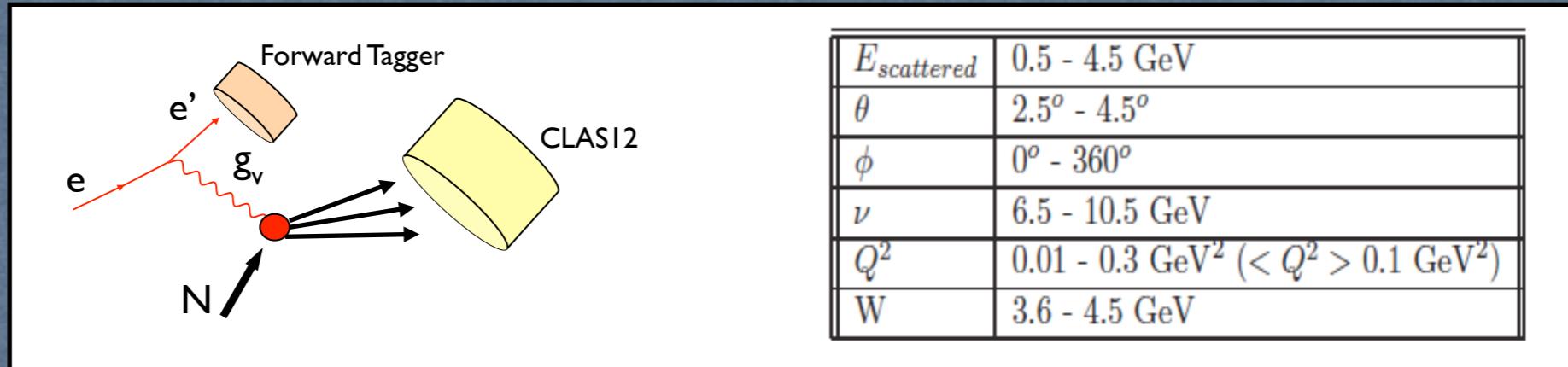
- Bremsstrahlung (Hall-D)
- Low  $Q^2$  electroproduction (Hall-B)

The Hall-B real photon tagger



The Hall-B existing dipole magnet can not deflect the 11 GeV primary beam on the beam-dump

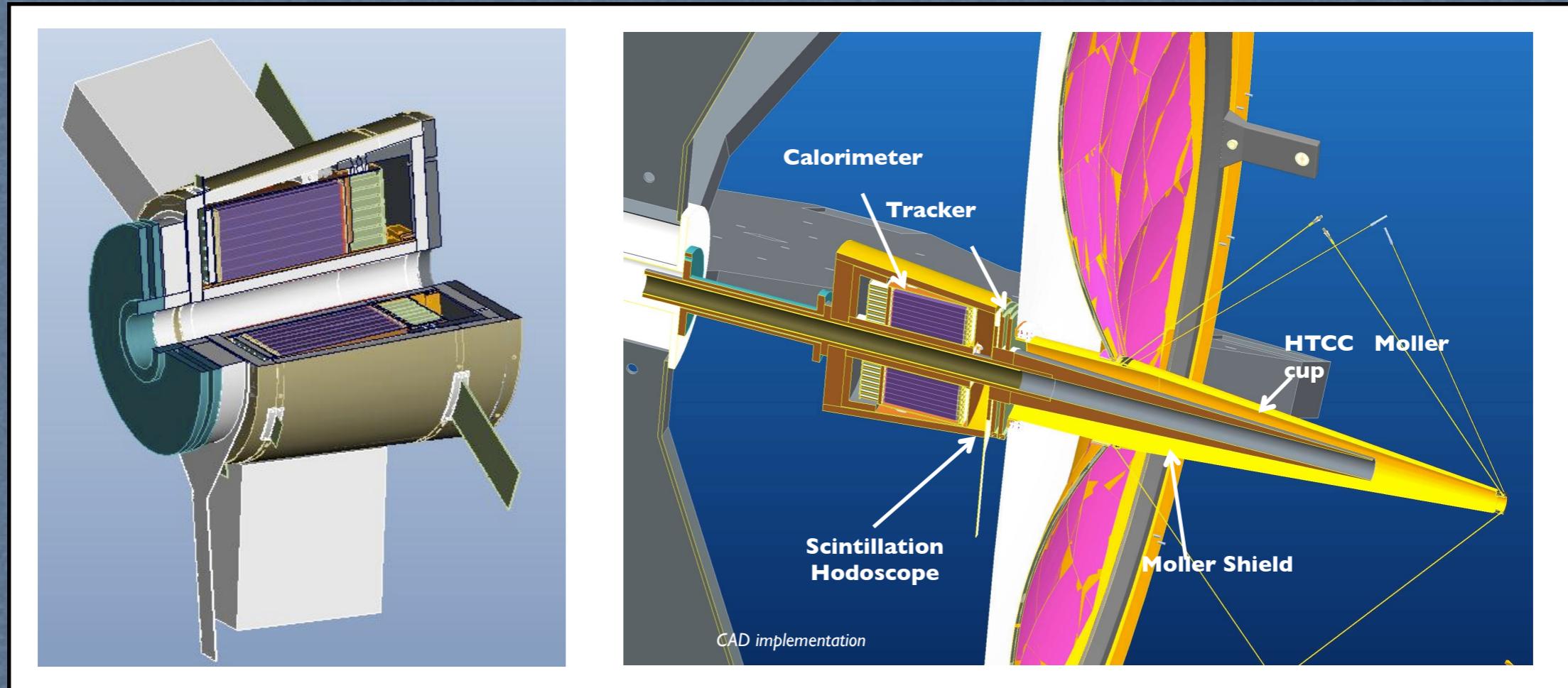
# Quasi-real photoproduction with CLAS12 (Low $Q^2$ electron scattering)



- ★ Electron scattering at “0” degrees ( $2.5^\circ$  -  $4.5^\circ$ )  
low  $Q^2$  virtual photon  $\Leftrightarrow$  real photon
- ★ Photon tagged by detecting the scattered electron at low angles  
High energy photons  $6.5 < E_g < 10.5 \text{ GeV}$
- ★ Quasi-real photons are linearly polarized  
Polarization  $\sim 70\% - 10\%$  (measured event-by-event)
- ★ High Luminosity (unique opportunity to run thin gas target!)  
Equivalent photon flux  $N_\gamma \sim 5 \cdot 10^8$  on 5cm  $H_2$  ( $L=10^{35} \text{ cm}^{-2}\text{s}^{-1}$ )
- ★ Multiparticle hadronic states detected in CLAS12  
High resolution and excellent PID (kaon identification)

Complementary to Hall-D (GLUEX)

# The Forward Tagger for CLAS12

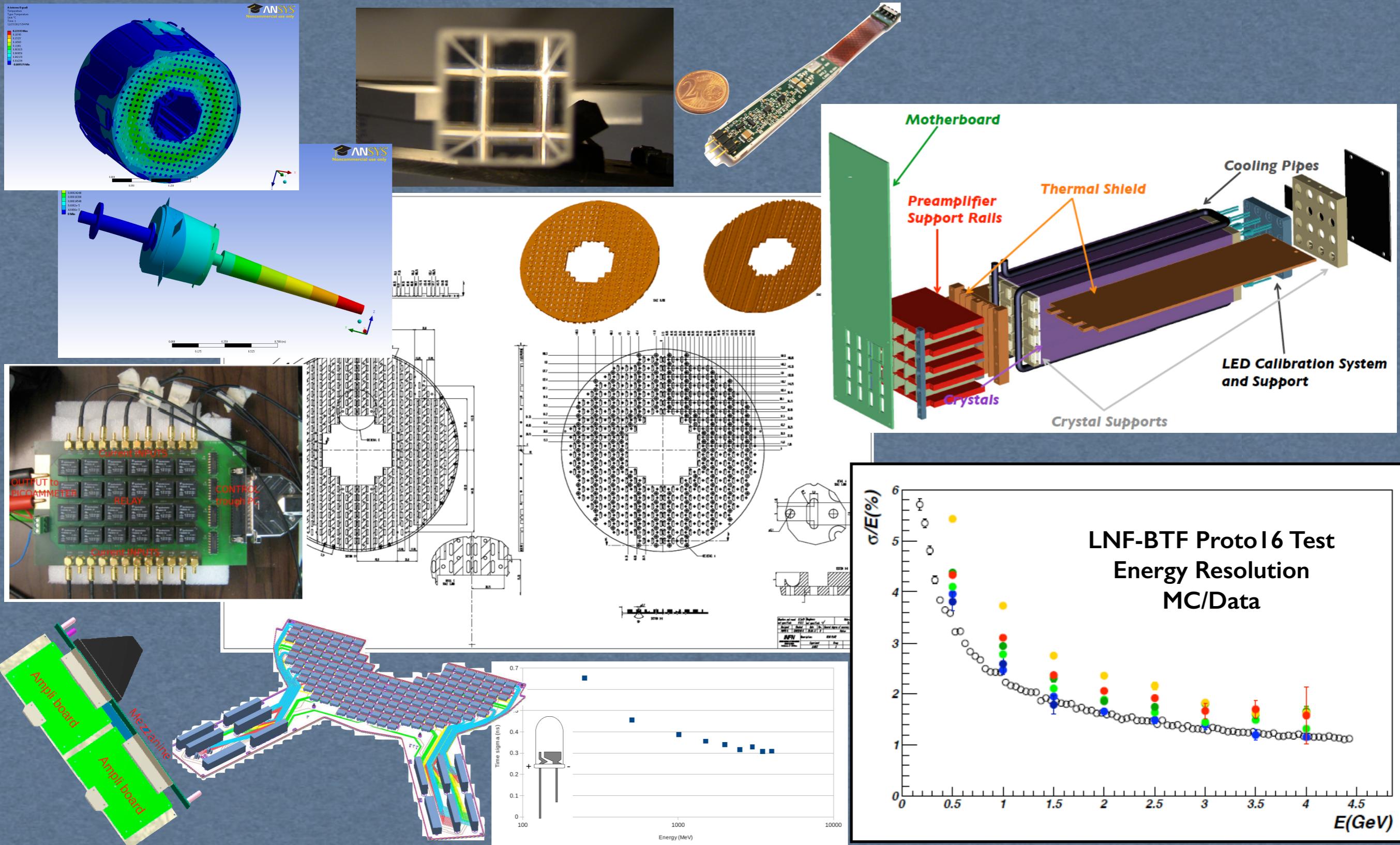


**FT-Cal:** PbWO<sub>4</sub> calorimeter  
electron energy/momentun  
Photon energy ( $\nu = E - E'$ )  
Polarization  $\epsilon^{-1} \approx 1 + \nu^2/2EE'$

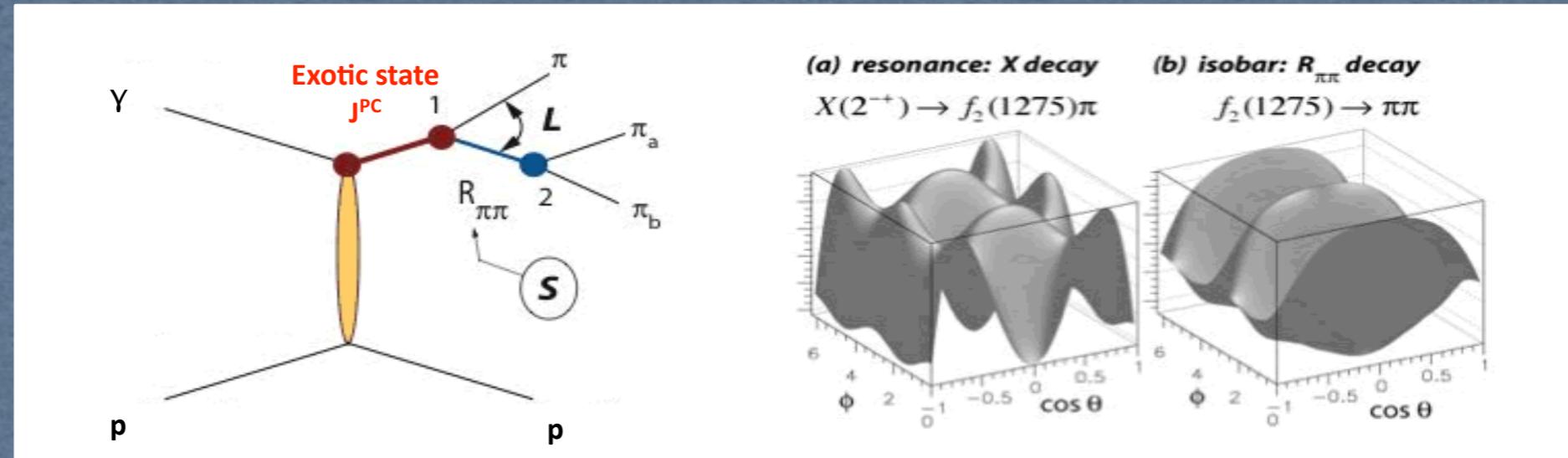
**FT-Hodo:** Scintillator tiles  
veto for photons  
**Edinburgh+JMU+NSU**

**FT-Trck:** MicroMegas detectors  
electron angles and polarization plane  
**Saclay + Ohio**

# FT design, prototyping and construction



# From the data to the spectrum: Partial Wave Analysis



- Parametrize the cross section in term of partial waves
- Fit to data to extract amplitudes
- A model is needed to parametrize amplitudes: Isobar Model, Dispersion Relations, ...

**Is this adequate for current and future experiments?**

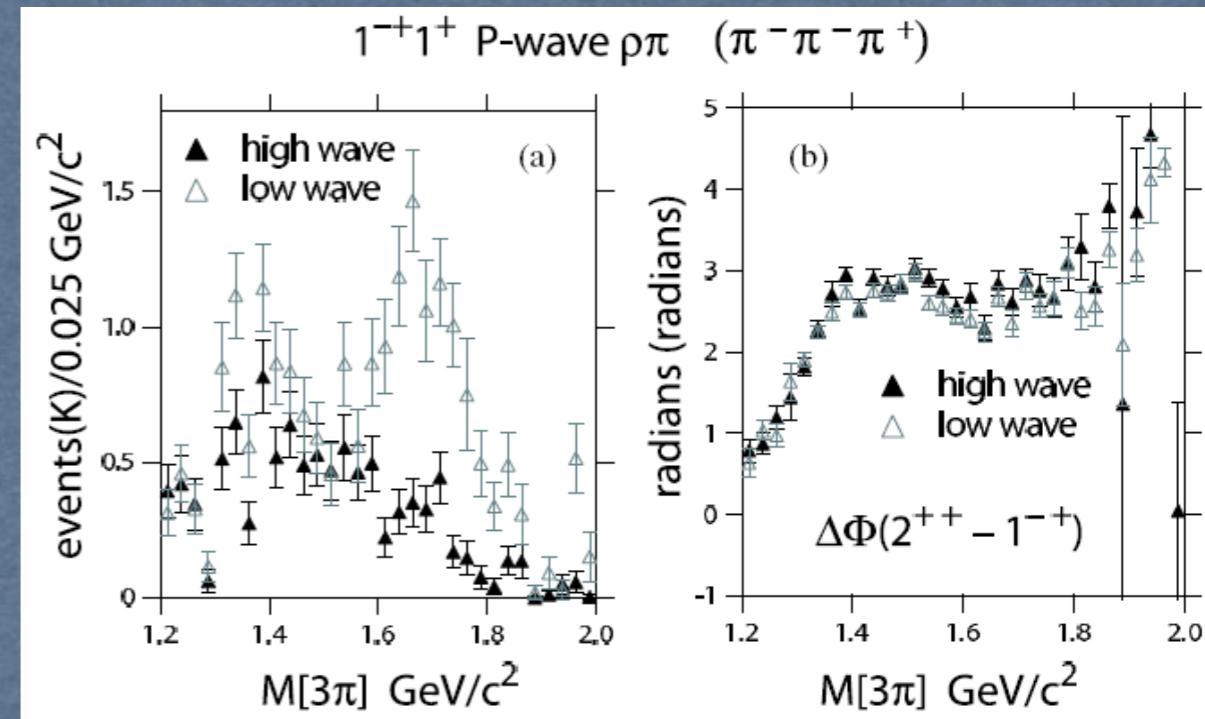
- Exotics, if exist, are tiny: how to deal with the background?
- How to go beyond the Isobar Model?
- Do the amplitudes incorporate all the necessary constraints?
- Are experimental data precise and abundant enough to constraint PWA?

... not every bump is a resonance and not every resonance is a bump!

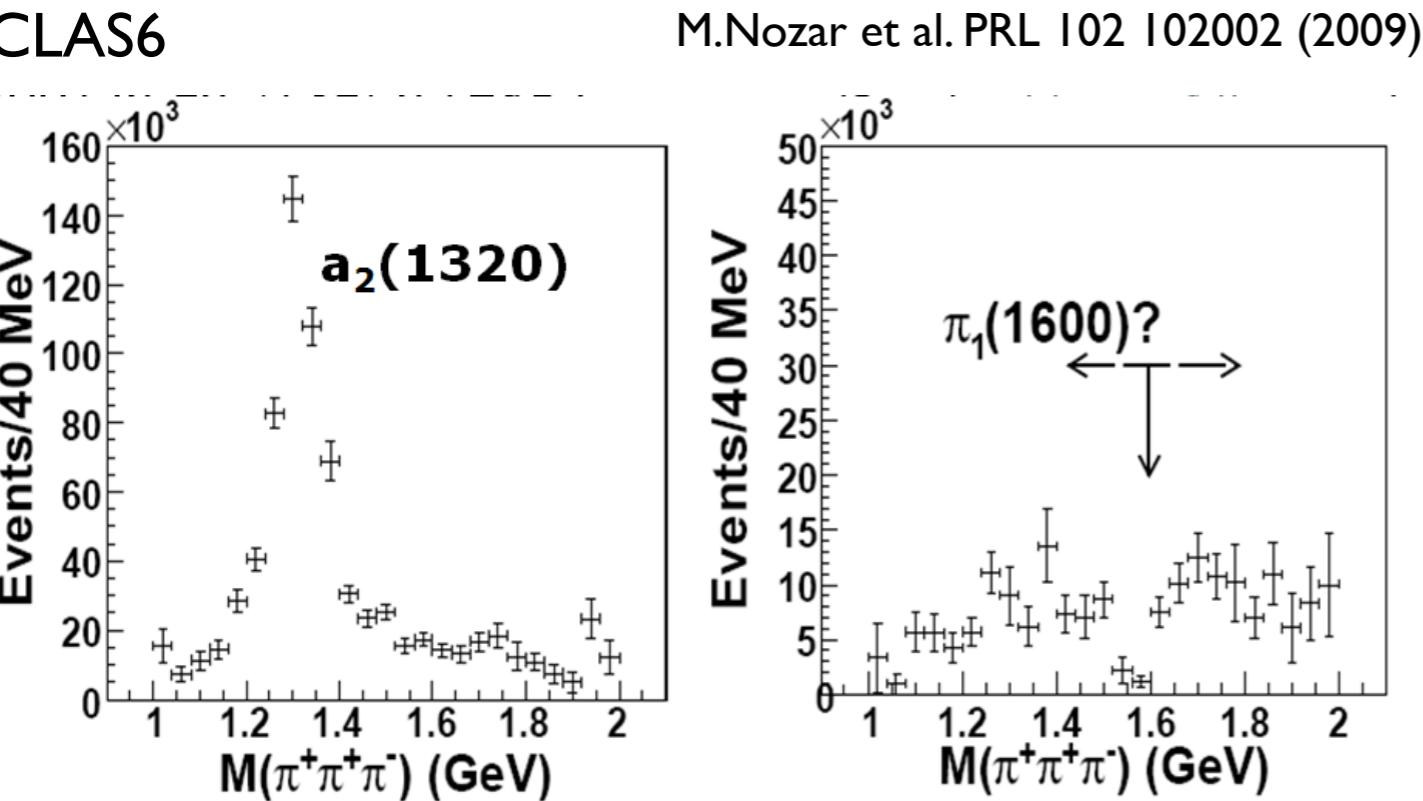
# Partial Wave Analysis (PWA)

**Reference reaction**  
 $\gamma p \rightarrow (n) \pi^+ \pi^+ \pi^-$

- \* Possible evidence of exotic meson  $\pi_1(1600)$  in  $\pi^- p \rightarrow p \pi^- \pi^- \pi^+$  (E852-Brookhaven)
- \* Not confirmed in a re-analysis of a higher statistic sample
- \* Now confirmed by COMPASS
- \* Simple final state with low bg



CLAS6

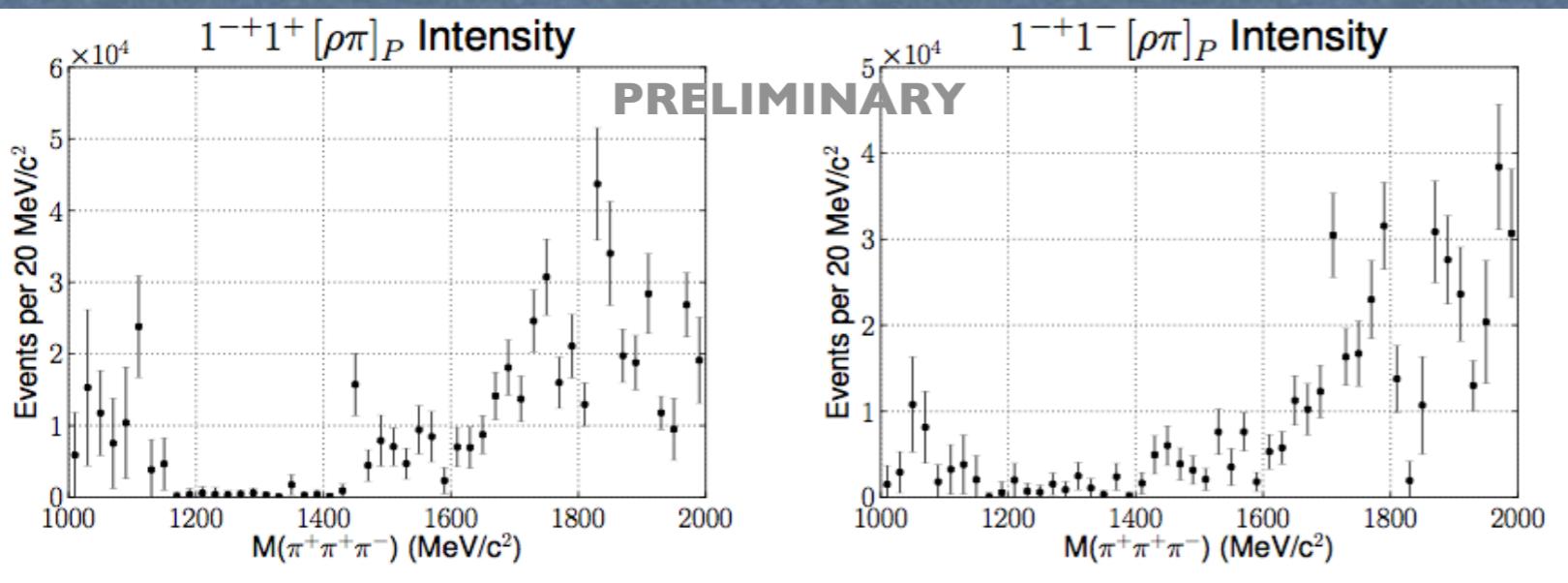
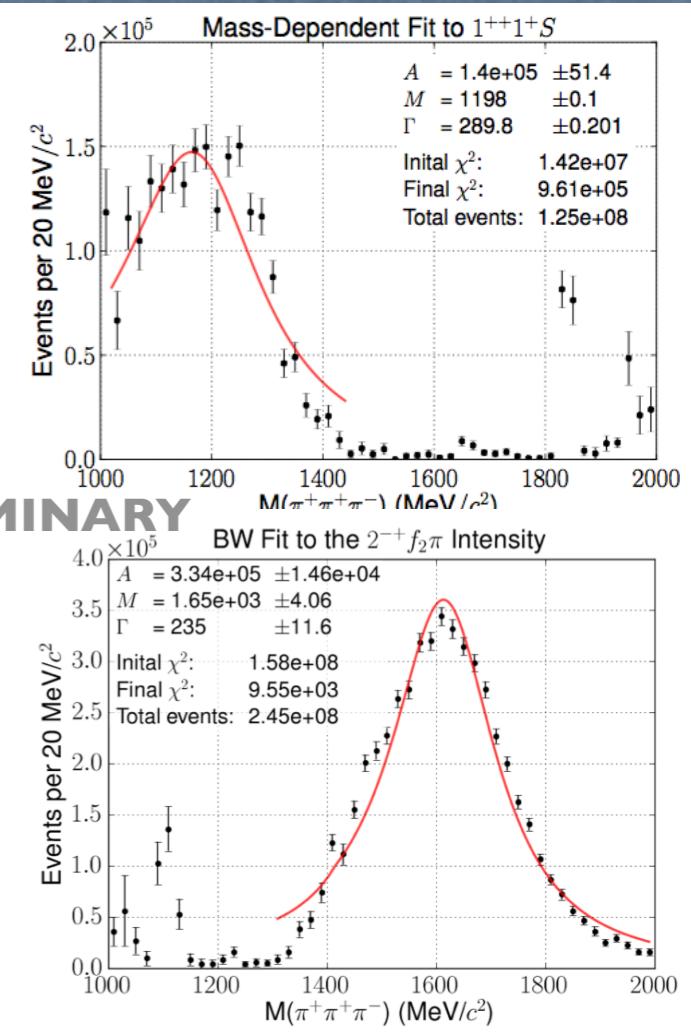
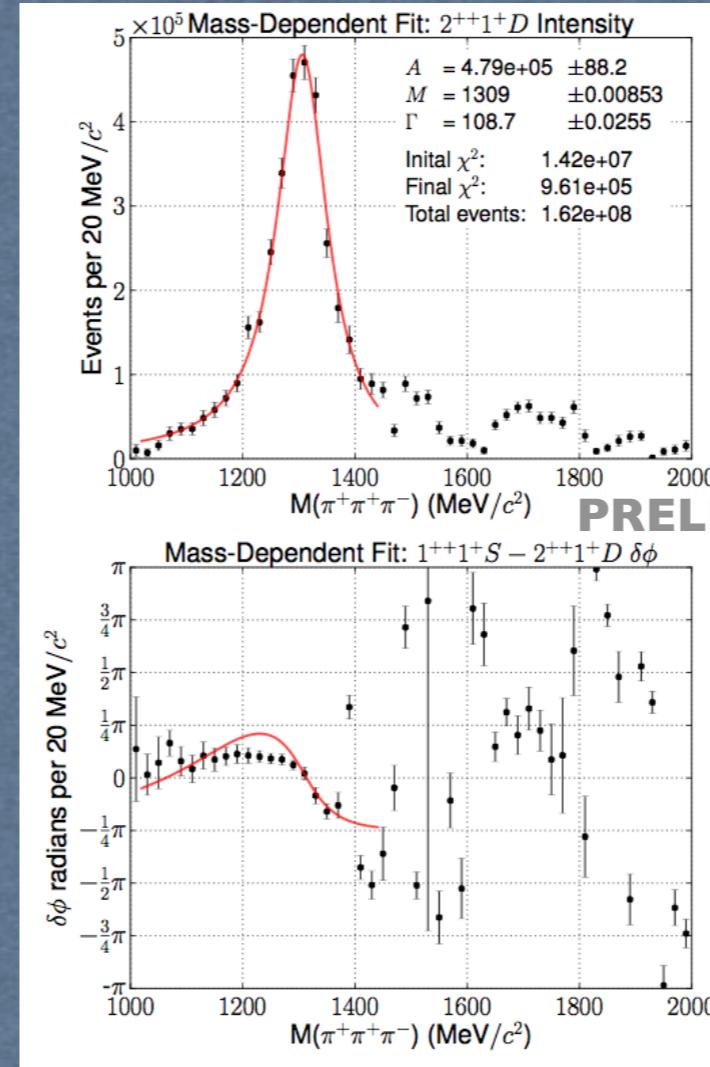
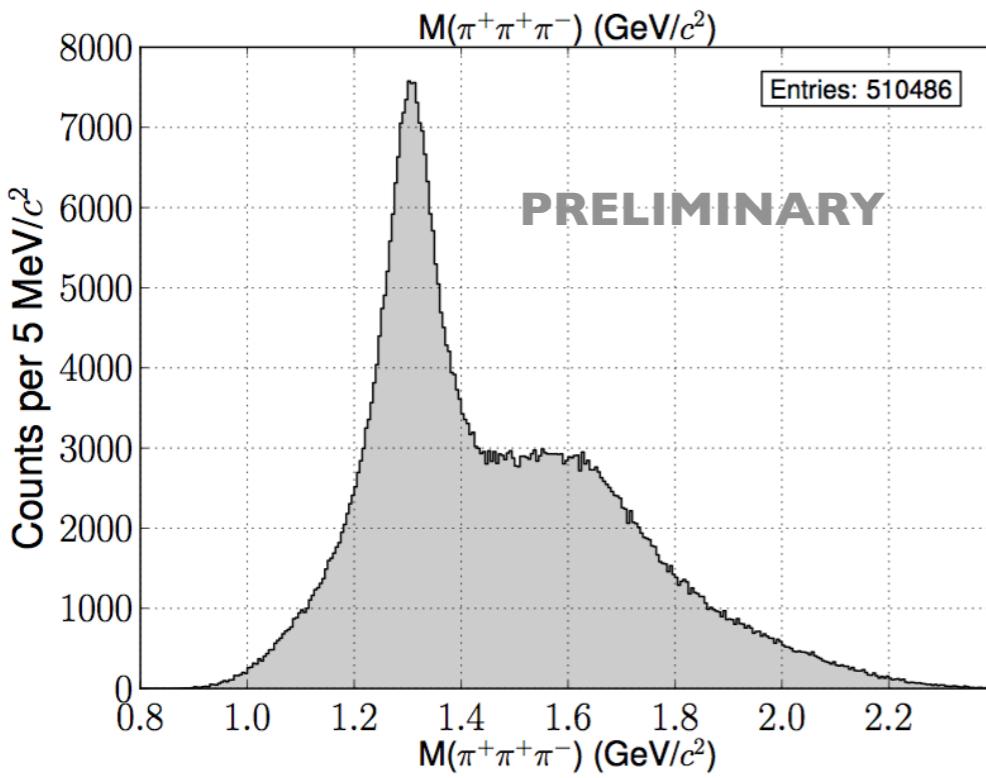


Clear evidence of non-exotic  
2++ state  $a_2(1320)$

No-evidence of exotic 1-+ state  $\pi_1(1600)$   
Relevance of baryon resonance background

Pioneering PWA in CLAS

# The $3\pi$ system with CLAS gl2 data set



Evidence of dominant resonances  
and no-evidence of exotic state  
confirmed

PWA in CLAS is feasible!  
Needs to have higher energy,  
higher statistics and test  
other final states  
→ CLAS12

# PWA with CLAS12

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

- The process is described as sum of 8 isobar channels:

$a_2 \rightarrow \rho \pi$  (D-wave)

$a_1 \rightarrow \rho \pi$  (S-wave)

$a_1 \rightarrow \rho \pi$  (D-wave)

$\pi_2 \rightarrow \rho \pi$  (P-wave)

$\pi_2 \rightarrow \rho \pi$  (F-wave)

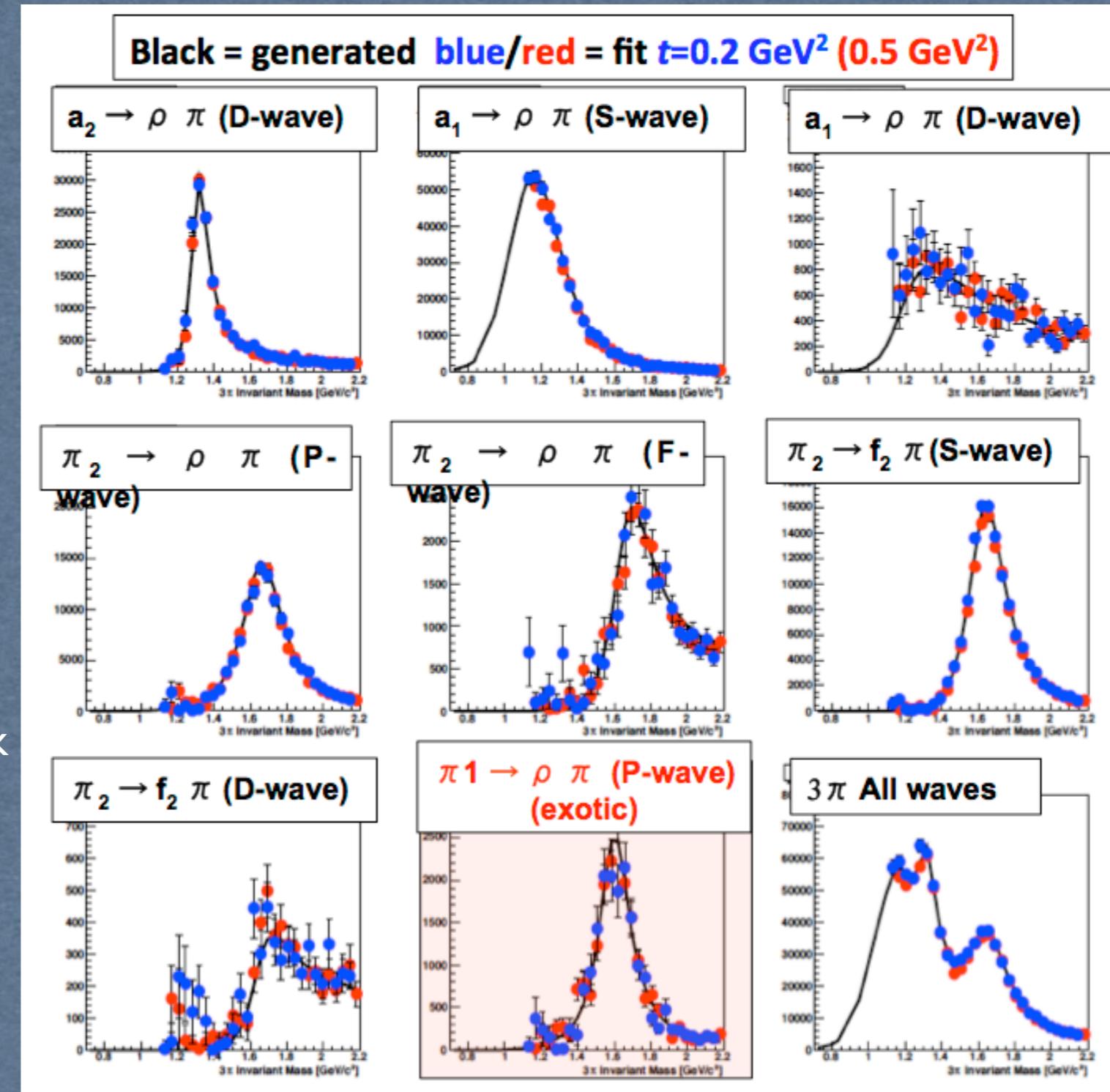
$\pi_2 \rightarrow f_2 \pi$  (S-wave)

$\pi_2 \rightarrow f_2 \pi$  (D-wave)

$\pi_1 \rightarrow \rho \pi$  (P-wave) (exotic)

- Amplitudes calculated by A.Szczepaniak and P.Guo
- CLAS12 acceptance projected and fitted
- PWA is stable against CLAS12 acceptance/ resolution distortion

**PWA in CLAS12 is feasible!**



# Other examples of PWA with CLAS

MB, R.DeVita A. Szczepaniak et al Phys.Rev.Lett. 102:102001,2009  
 MB, R.DeVita A. Szczepaniak et al Phys.Rev. D80:072005,2009

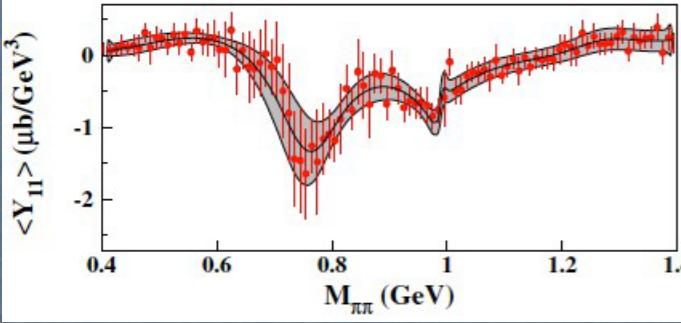
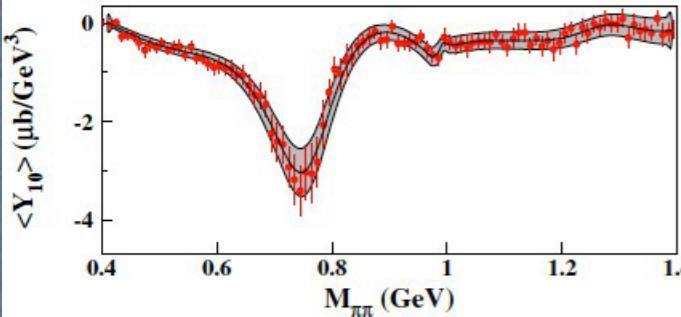
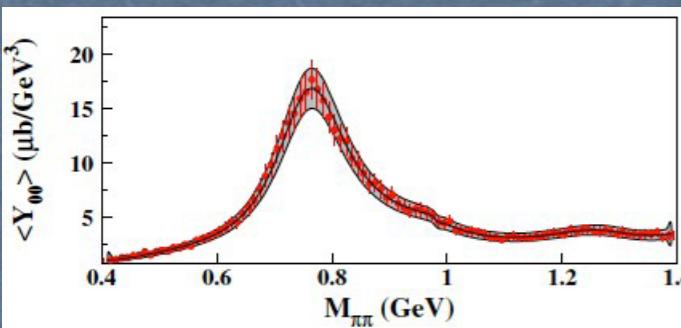
$\gamma p \rightarrow p \pi^+ \pi^-$

$M(\pi^+ \pi^-)$  spectrum below 1.5 GeV:

P-wave:  $\rho$  meson

D-wave:  $f_2(1270)$

S-wave:  $\sigma$ ,  $f_0(980)$  and  $f_0(1320)$



$$\langle Y_{\lambda\mu} \rangle(E_\gamma, t, M) = \frac{1}{\sqrt{4\pi}} \int d\Omega_\pi \frac{d\sigma}{dt dm d\Omega_\pi} Y_{\lambda\mu}(\Omega_\pi)$$

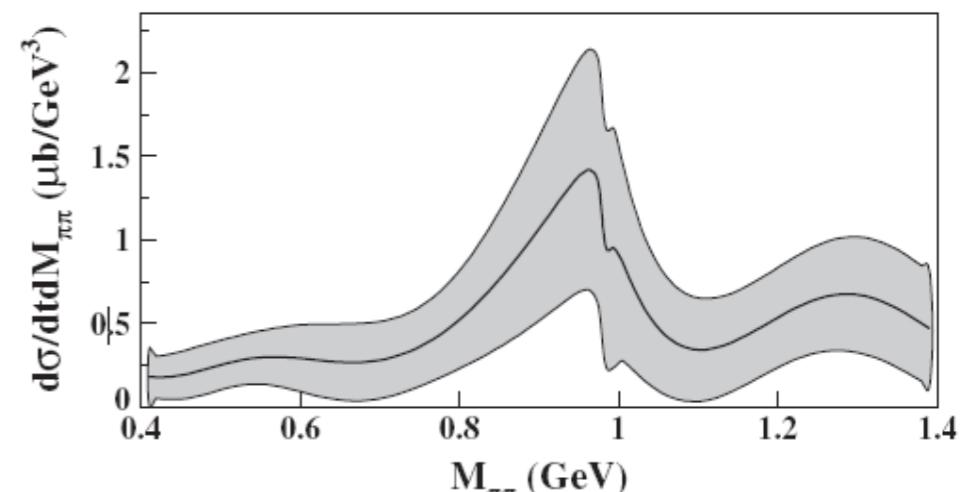
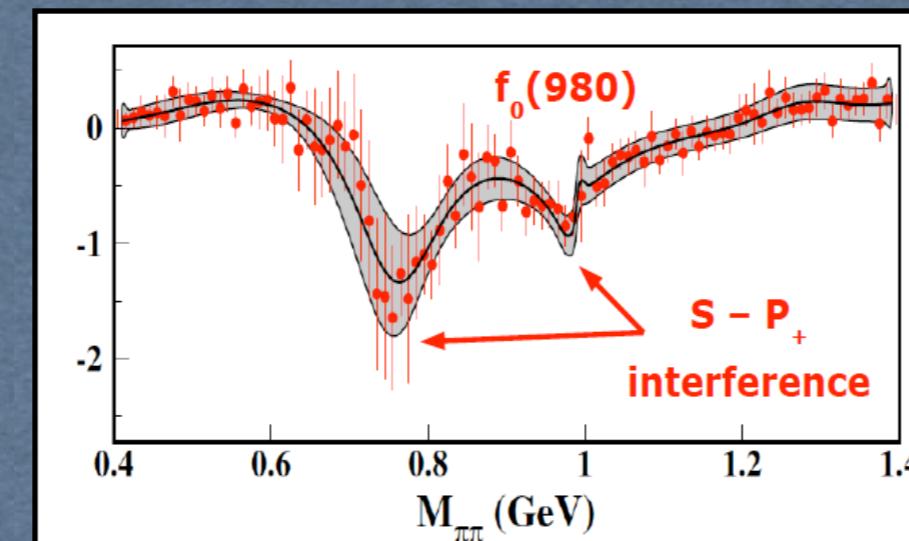
**Amplitude parametrization (Dispersion relation)**

Related to  $\pi\pi$  scattering matrix: phase-shift, inelasticity, S-P-D-F amplitude in  $0.4 \text{ GeV} < M_{\pi\pi} < 1.4 \text{ GeV}$

$$a_{lm,I}(s) = \frac{1}{2} [I + S_{lm,I}(s)] \tilde{a}_{lm,I}(s) - \frac{1}{\pi} D_{lm,I}^{-1}(s) PV \int_{s_{th}} ds' \frac{N_{lm,I}(s') \rho(s') \tilde{a}_{lm,I}(s')}{s' - s}$$

$$\tilde{a}_{lm,I} = [\mathcal{A} + \mathcal{B}s + \mathcal{C}s^2 + \dots][k]$$

Expanded in a Taylor series: coefficient fit to the experimental moment



First observation of the  $f_0(980)$  in a photoproduction experiment

# Other examples of PWA with CLAS

$\gamma p \rightarrow p \omega \rightarrow p \pi\pi\pi$

Decay decouples production from genuine meson-meson interaction

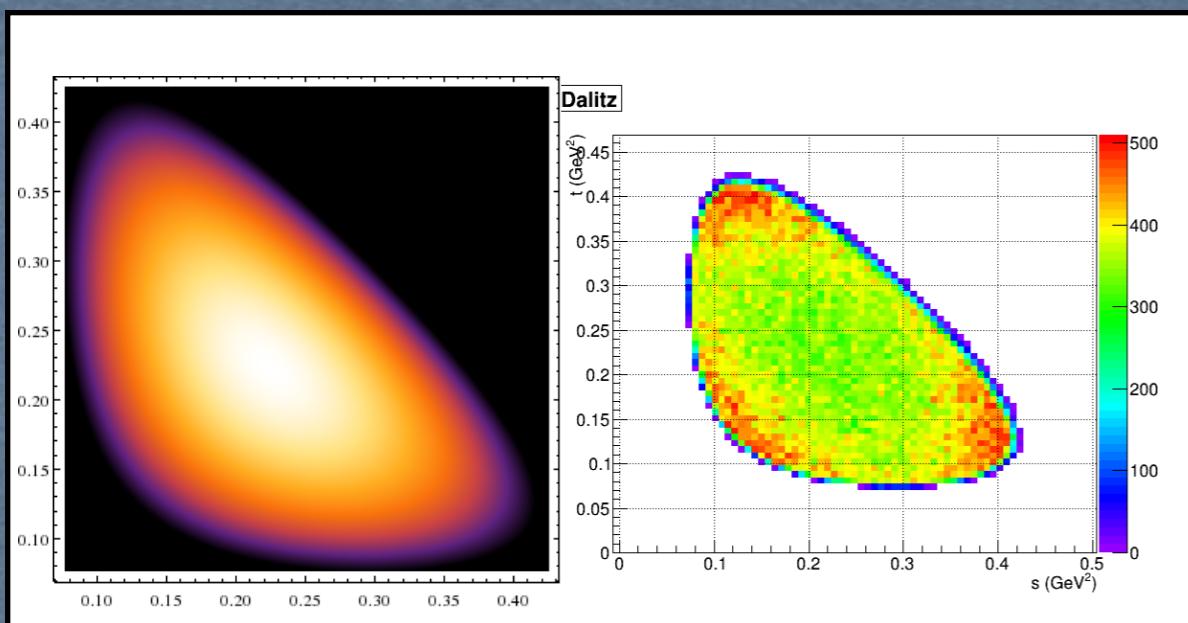
- $M(\pi^+\pi^-) < 0.45$  GeV
- 3-body effects

$$A_\lambda = \varepsilon_{\mu\nu\alpha\beta} p_+^\nu p_-^\alpha p_0^\beta \varepsilon_\lambda^\mu A(s, t, u)$$

$$I = \sum_{\lambda, \lambda'} A_\lambda^* \rho_{\lambda'}^\lambda A_{\lambda'} = K^2 W_\rho(\theta, \phi) |A|^2$$

$$K^2 = s t u - m^2(M^2 - m^2)^2 = |\vec{p}_a \times \vec{p}_b|^2$$

$W_\rho(\theta, \phi)$  : Spin density matrix



## B<sub>4</sub> amplitude

A.Szczepaniak & M.Pennington extension of Veneziano amplitude (arXiv:1403.5782)

- Correct analytic structure (poles)
- Proper asymptotic behaviour (Regge)

$$A_{n,m}(s, t) = \frac{\Gamma(n - \alpha_s)\Gamma(n - \alpha_t)}{\Gamma(n + m - \alpha_s - \alpha_t)} \quad 1 \leq m \leq n$$

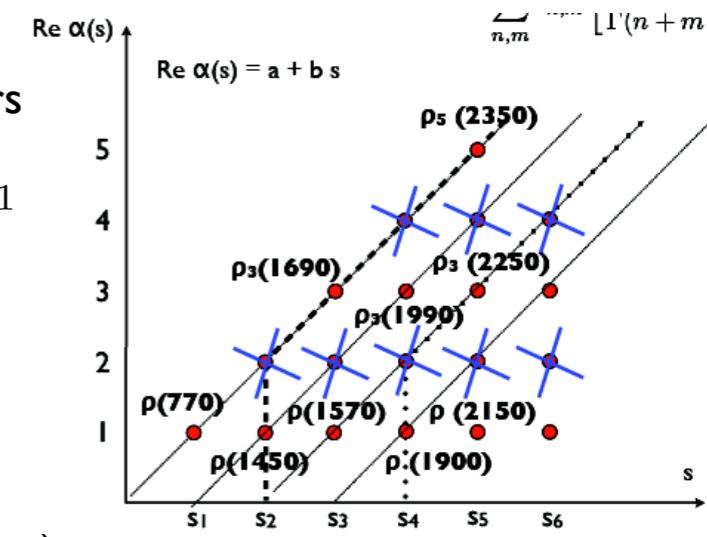
$$A_n(s, t) = \frac{2n - \alpha_s - \alpha_t}{(n - \alpha_s)(n - \alpha_t)} \sum_{i=1}^n a_{n,i} (-\alpha_s - \alpha_t)^{i-1} \cdot$$

$$\cdot \frac{\Gamma(N + 1 - \alpha_s)\Gamma(N + 1 - \alpha_t)}{\Gamma(N + 1 - n)\Gamma(N + n + 1 - \alpha_s - \alpha_t)}$$

The residue of  $A_n(s, t)$  for  $a_s = n$  is a polynomial of order  $(n-1)$  in  $t$ .  
 → The coefficients  $a_{n,i}$  must be constrained to cancel even  $t$  powers

$$\text{Res}A_n = \sum_{i=1}^n a_{n,i} (-n - \alpha_t)^{i-1}$$

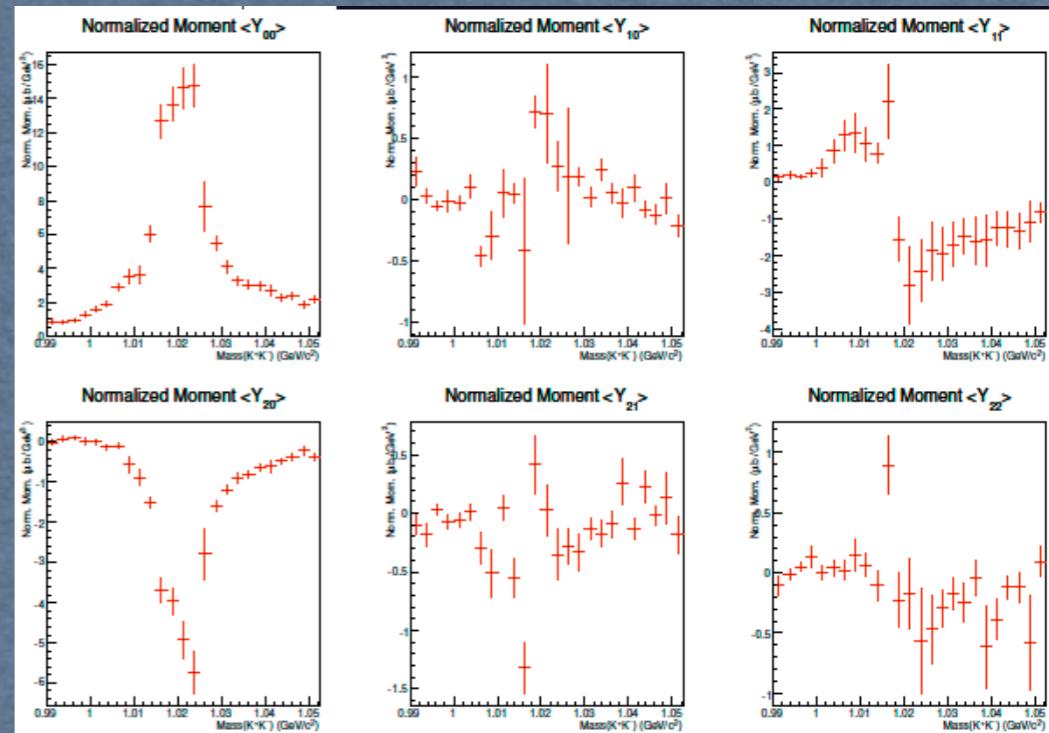
- $n=1$  ok
- $n=2$   $a_{2,2} = 0$
- $n=3$   $a_{3,1} = 2*a_{3,2} * (3+a_0)$
- $n=4$   $a_{4,4} = 0$  and  $a_{4,2} = 2*a_{4,1} * (4+a_0)$
- ...



# Work in progress

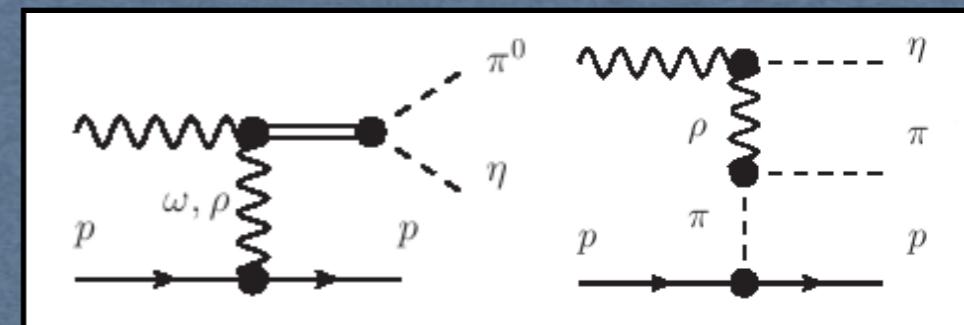
$\gamma p \rightarrow p k k$

- S.Lombardo (IU)
- Full analysis from g11 CLAS6 data set
- S-P interference in 2k system



$\gamma p \rightarrow p \pi \eta$

- A.Celentano (Genova) PhD Thesis
- Amplitudes provided by V.Mathieu (ECT\*) and A.Szczepaniak (IU&JLab)
- Preliminary analysis on CLAS6 data to fix parameters
- Full projection on CLAS12 and PWA



$\gamma p \rightarrow p \pi \eta'$ ,  $\gamma p \rightarrow p \pi \omega$ ,  $\gamma p \rightarrow p \pi \varphi$ ,  $\gamma p \rightarrow p \eta \varphi$ ,  $\gamma p \rightarrow p k k \pi$ ,  $\gamma p \rightarrow p k k \pi \pi$ ,  $\gamma p \rightarrow p k k \omega$

- Theoretical support:

A.Szczepaniak, V.Mathieu, E.Santopinto (INFN-GE), A.Vassallo (GE), J.Ferretti (UMAS)

- Experimental Analysis:

S.Fegan (INFN-GE), A. Filippi (INFN-TO), S.Hughes (Edinburgh), K.Hicks (OhioU),  
S.Lombardo (Cornell), A.Rizzo (RomaTV), L.Zana (Edinburgh)

# How to develop a strong analysis framework?

# ★ Implementing reliable amplitudes

- Check amplitudes with existing data

# ★Developing common tools and procedures:

- Common PWA framework across different experiments (eg AmpTools)
  - Wider data access and distribution
  - Computing: fitting procedures, GPUs, etc.

# ★Learning & teaching

- Promote exchanges between experimentalists and theorists
  - “HS data analysis for dummies” and “HS theory revealed”
  - Workshops and schools to share expertise and establish common rules

# Prepare the framework for future experiments

**Establish shared  
procedures and tests to  
claim a discovery of  
new physics**

## Promote a two-ways communication EXP- THE



# ECT\* European Centre for Theoretical Studies in Nuclear Physics and Related Areas

PEOPLE @ ECT       REACHING ECT\*       INFORMATION FOR VISITORS

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- HOME
- ECT\*
- MEETINGS
- DOCTORAL TRAINING PROGRAM
- TALENT
- LOGIN
- JOBS
- AuroraScience
- ASSOCIATES
- LINKS

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- BOARD AREA  
(PWD Restricted)

## 2011 Conferences, Workshops

Amplitude Analysis in Hadron Spectroscopy

Registration      [Poster](#)      [Program](#)      [Talks](#)

**Organizers:**

A. Szczepaniak (*Indiana University*)  
C. Hanhart (*Institut fuer Kernphysik Forschungszentrum Juelich*)  
M. Pennington (*Jefferson Laboratory*)  
E. Santopinto (*INFN, Genova*)  
U. Wiedner (*Ruhr University*)

**Secretary in charge:** Ines Campo



**HASPECT week - Genova - November 27 - 30**

Participants Marco Battaglieri, Andrea Celentano, Raffaella De Vita, Stuart Fegan, Jean-Marc Laget, Adam Szczepaniak, Andrea Vassallo

Remote connection Dave Ireland

Agenda DRAFT

**Tuesday, November 27**

- Vincent and Andrea meeting for eta-pi channel
- Sal and Marco meeting for moments analysis

**Wednesday, November 28**

- Morning
  - 10:00 Beginning of the meeting
  - 10:10 - 12:30: the MesonEx physics program
    - Golden channels
    - Systematic measurements
    - Systematic amplitude calculations
    - Tasks assignment and resources: PhD projects, collaborations ...
- Afternoon: Individual meetings
  - 14:00 - 15:00 Focused discussions: Adam, Elena Marco on haspect day
  - 15:00 - 16:00 Focused discussions: Andrea V. Elena and Adam
  - 16:00 - 17:00 Focused discussions: Jean-Marc , Elena, Andrea V. and V.

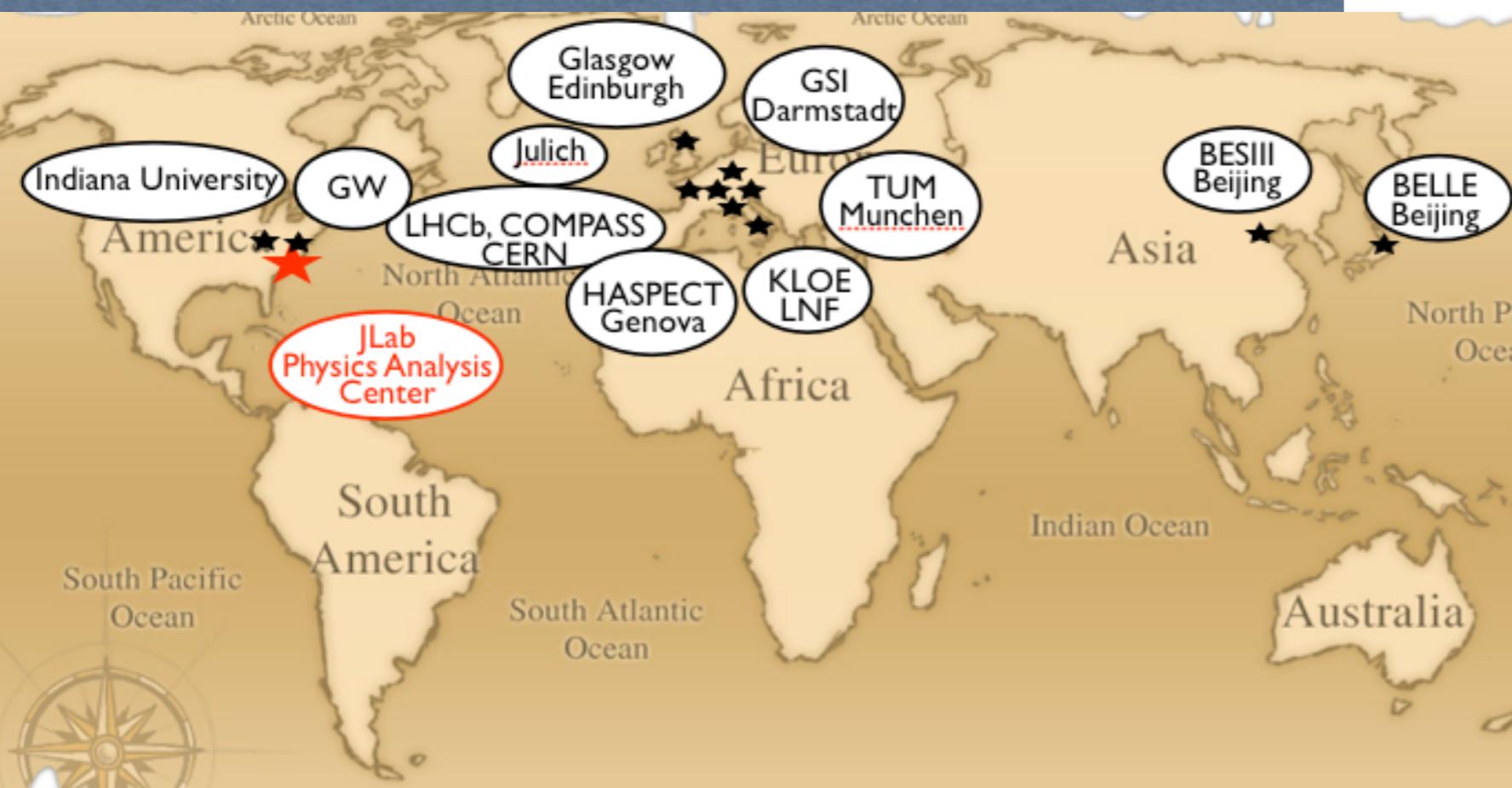
**Thursday, November 29**

- Morning

# HASPECT: Act locally but think globally!

## Global strategy:

- \* Creation of twin and parallel centers for both analysis and theory development
- \* Collaboration and exchanges: personnel, short visits, ...
- \* Coordination via JLab Physics Analysis Center
- \* Creation of a “Hadron spectrum” working group



**Hadron Spectroscopy Portal**

HOME EXPERIMENTS ANALYSIS THEORY MESONS LINKS

**Jefferson Lab** Thomas Jefferson National Accelerator Facility **FAIR@GSI** **CERN** Institute of High Energy Physics Chinese Academy of Sciences

This page contains details of how to parametrize two pions isobar.

**Two Pions**

- Descriptions
- Parametrization
- Applications
- References
- Comments
- Resources

### TWO PIONS PARAMETRIZATION

#### Description

The  $\pi\pi$  amplitude depends on two variables, the invariant mass squared  $s$  and the scattering angle in the center of mass  $\theta$ . Final states are not eigenstates of the isospin. For neutral systems we have

$$\begin{aligned}\pi^0\pi^0 &= -\frac{1}{\sqrt{3}}F^{(0)}(s, \theta) + \frac{2}{\sqrt{3}}F^{(2)}(s, \theta), \\ \pi^+\pi^- &= +\frac{1}{\sqrt{3}}F^{(0)}(s, \theta) + \frac{1}{\sqrt{2}}F^{(1)}(s, \theta) + \frac{1}{\sqrt{6}}F^{(2)}(s, \theta)\end{aligned}$$

Charged systems can be decomposed similarly. The isospin functions  $F^{(I)}(s, \theta)$  do not depend on the isospin projection. The angular dependence is factorized via a partial wave expansion:

$$F^{(I)}(s, \theta) = (2\ell+1)\sum_{\ell} (2\ell+1)P_{\ell}(\cos \theta)F_{\ell}^{(I)}(s).$$

Factor 2 comes from Bose symmetry between the two  $\pi^0$  and the sum runs on even (odd)  $\ell$  for even (odd) isospin  $I$ . For  $\pi^+\pi^-$  there is a factor of 2 but the sum is also restricted to angular momentum of given parity by conjugaison charge. In term of phase shift  $\delta$ , scattering length  $a$ , and breakup momentum  $\rho(s) = \frac{1}{2}\sqrt{s-4m_{\pi}^2}$ , we have for each wave:

$$F_{\ell}^{(I)}(s) = \frac{2\sqrt{s}}{\pi\rho(s)} \left[ \frac{\eta_{\ell}^{(I)} e^{2i\delta_{\ell}^{(I)}} - 1}{2i} \right] \equiv \frac{2\sqrt{s}}{\pi\rho(s)} \hat{F}_{\ell}^{(I)}(s).$$

$\hat{F}_{\ell}^{(I)}(s)$  is defined to start at 0 at threshold.

V.Mathieu

- \* Common funding plans:
  - European-FP7 (EU calls and local): HadronS-HPH, Synergy grants
  - DOE-Topical -collaboration proposals
  - Helmholtz Virtual-Institutes

# Conclusions

- Recent LQCD results renew interest in Hadron Spectroscopy
- First PWA results obtained with CLAS detector in photoproduction
- Comprehensive meson spectroscopy program at JLab (GlueX & CLAS12)
- Exotics and strangeness-rich mesons search with CLAS12 detector exploiting excellent resolution and particle ID
- Bremsstrahlung and Low  $Q^2$  electron scattering to produce a high intensity, linear polarized, real (Hall-D) and quasi-real (Hall-B) photon beam
- New analysis framework: global effort to provide a robust analysis framework (PWA, amplitudes, FSI, ...)

**Dedicated detectors and high intensity photon beams at JLab-12 are under construction, ready to run in a near future!**