Light-Meson Spectroscopy

at Jefferson Lab

(GlueX and clas)

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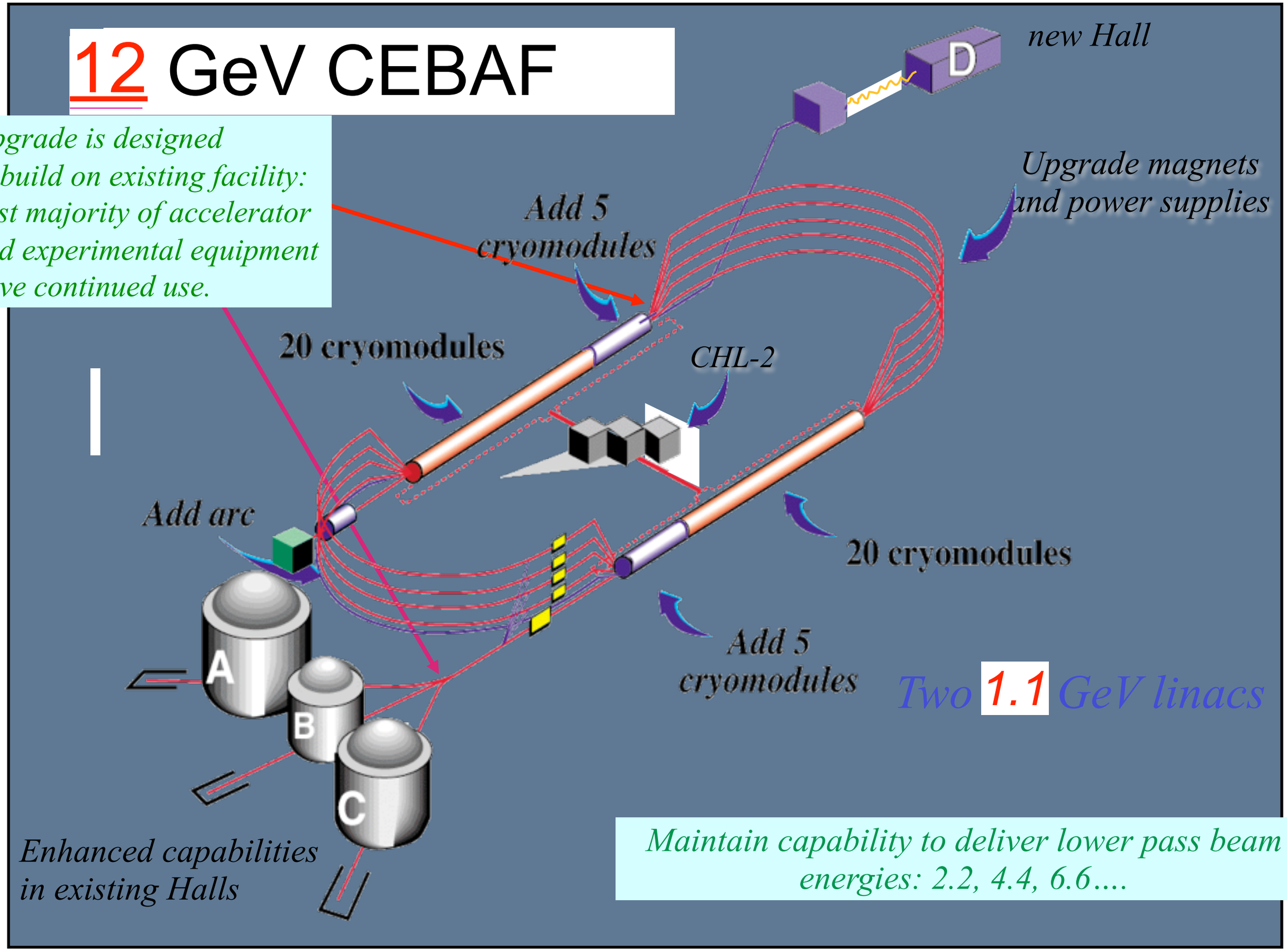
Norfolk State University
and
The Thomas Jefferson National Accelerator Facility

Outline

- **Jefferson Lab**
- **Meson Spectroscopy and QCD**
- **Status: Spectroscopy of (Exotic) Light-Mesons**
- **Photoproduction -Tools of Analysis - JPAC**
- **Past Jefferson Lab: CLAS6**
- **Future Jefferson Lab: GlueX and CLAS12**
- **Conclusions**

12 GeV CEBAF

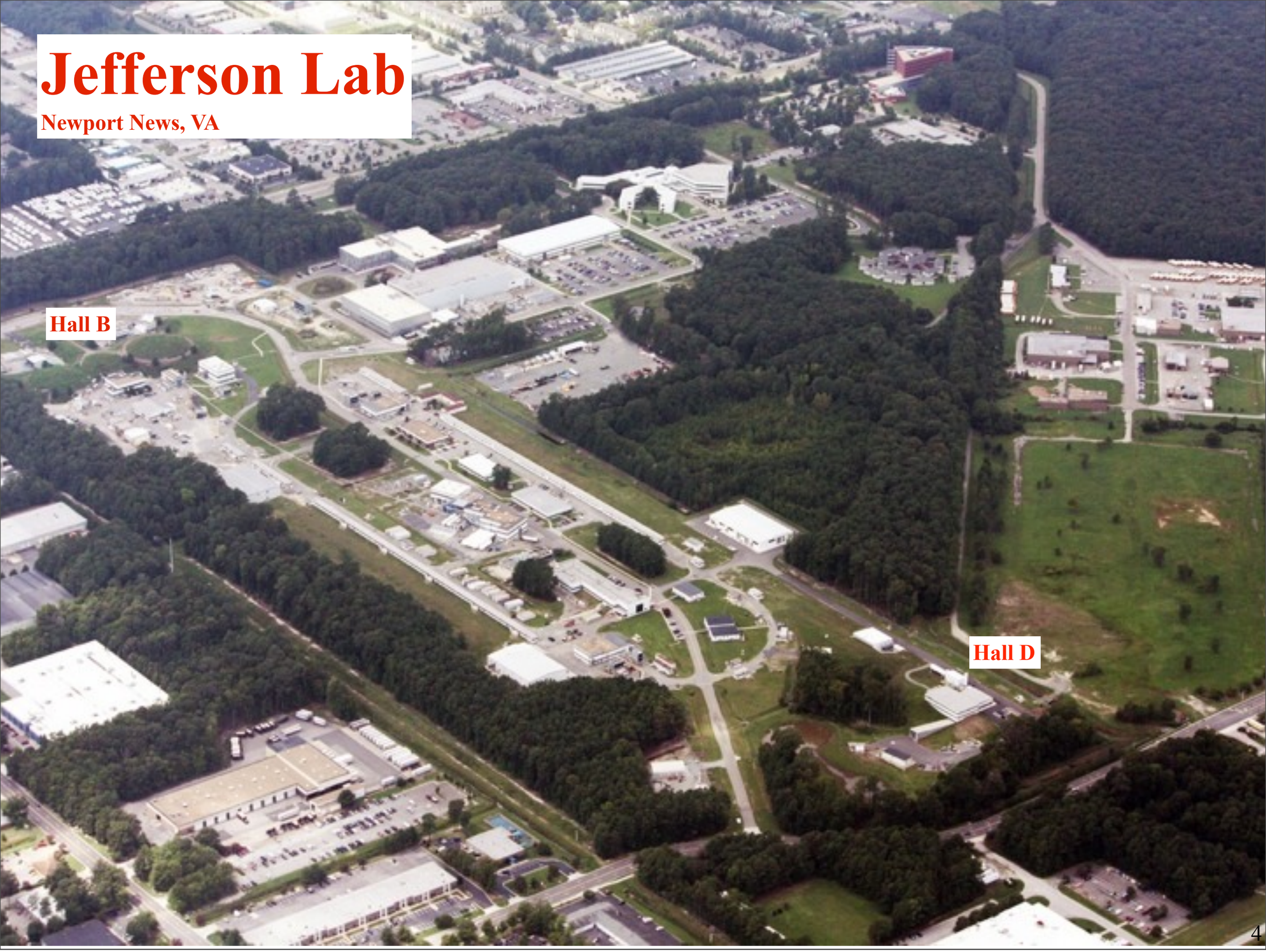
Upgrade is designed to build on existing facility: vast majority of accelerator and experimental equipment have continued use.



Maintain capability to deliver lower pass beam energies: 2.2, 4.4, 6.6….

Jefferson Lab

Newport News, VA

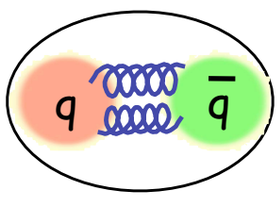


Topic	Hall A	Hall B	Hall C	Hall D	Other	Total
The Hadron spectra as probes of QCD (GluEx and heavy baryon and meson spectroscopy)		1		3		4
The transverse structure of the hadrons (Elastic and transition Form Factors)	5	3	2	1		11
The longitudinal structure of the hadrons (Unpolarized and polarized parton distribution functions)	2	3	6			11
The 3D structure of the hadrons (Generalized Parton Distributions and Transverse Momentum Distributions)	5	9	7			21
Hadrons and cold nuclear matter (Medium modification of the nucleons, quark hadronization, N-N correlations, hypernuclear spectroscopy, few-body experiments)	6	3	7		1	17
Low-energy tests of the Standard Model and Fundamental Symmetries	3	1		1	1	6
TOTAL	21	20	22	5	2	70

Gluons and the Meson Spectrum

- At high energies the gluon is externally observed in three-jets events
- At lower (intermediate energies) the hadron spectrum provides information about the gluons that bind quarks (CONFINEMENT)
- The properties of confinement are them related to the gluon binding of hadrons
- Can we find a simple manifestation of the glue in the hadron spectrum?

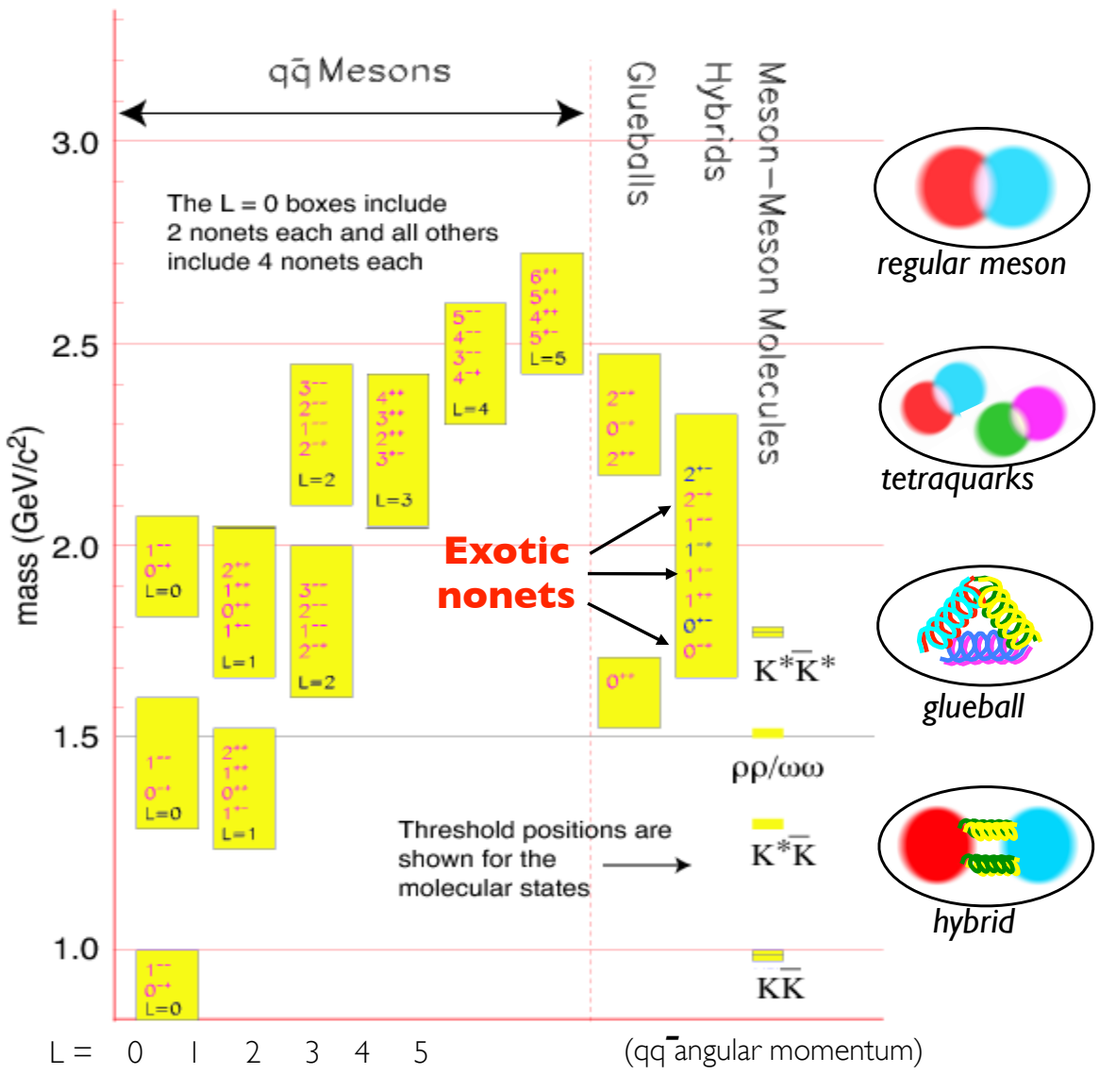
Search for non-standard states with explicit gluonic degrees of freedom



hybrid mesons

Not-allowed J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} ...

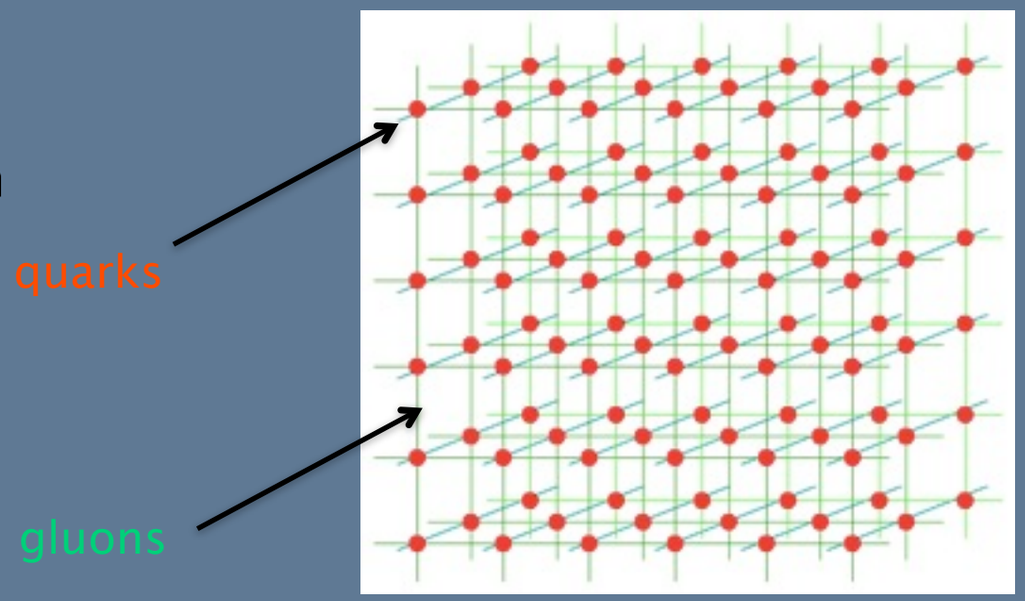
Unambiguous experimental signature for the presence of gluonic degrees of freedom in the spectrum of mesonic states

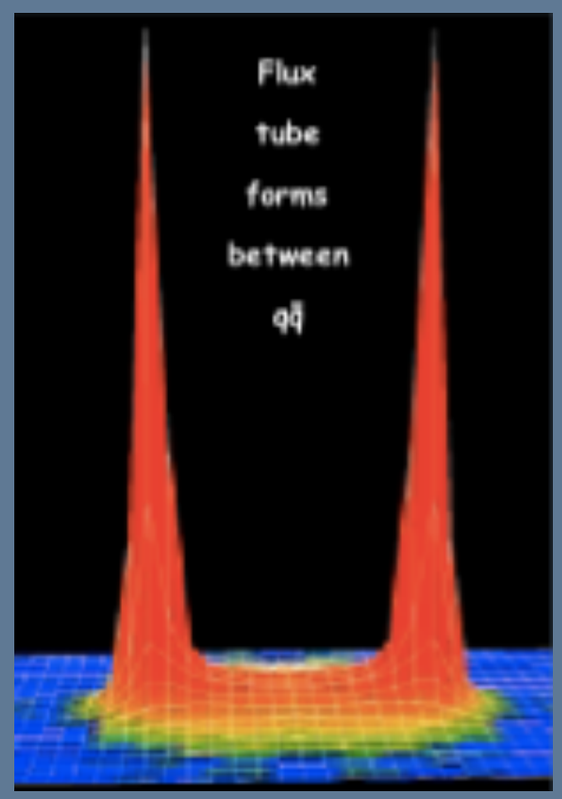


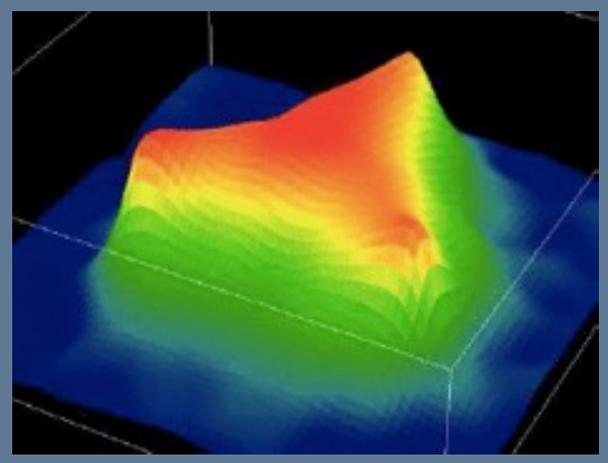
Lattice QCD - LQCD

Numerical solutions of (almost) QCD-Lagrangian (Path Integrals)

- hypercubic space-time lattice
- quarks reside on sites, gluons reside on links between sites



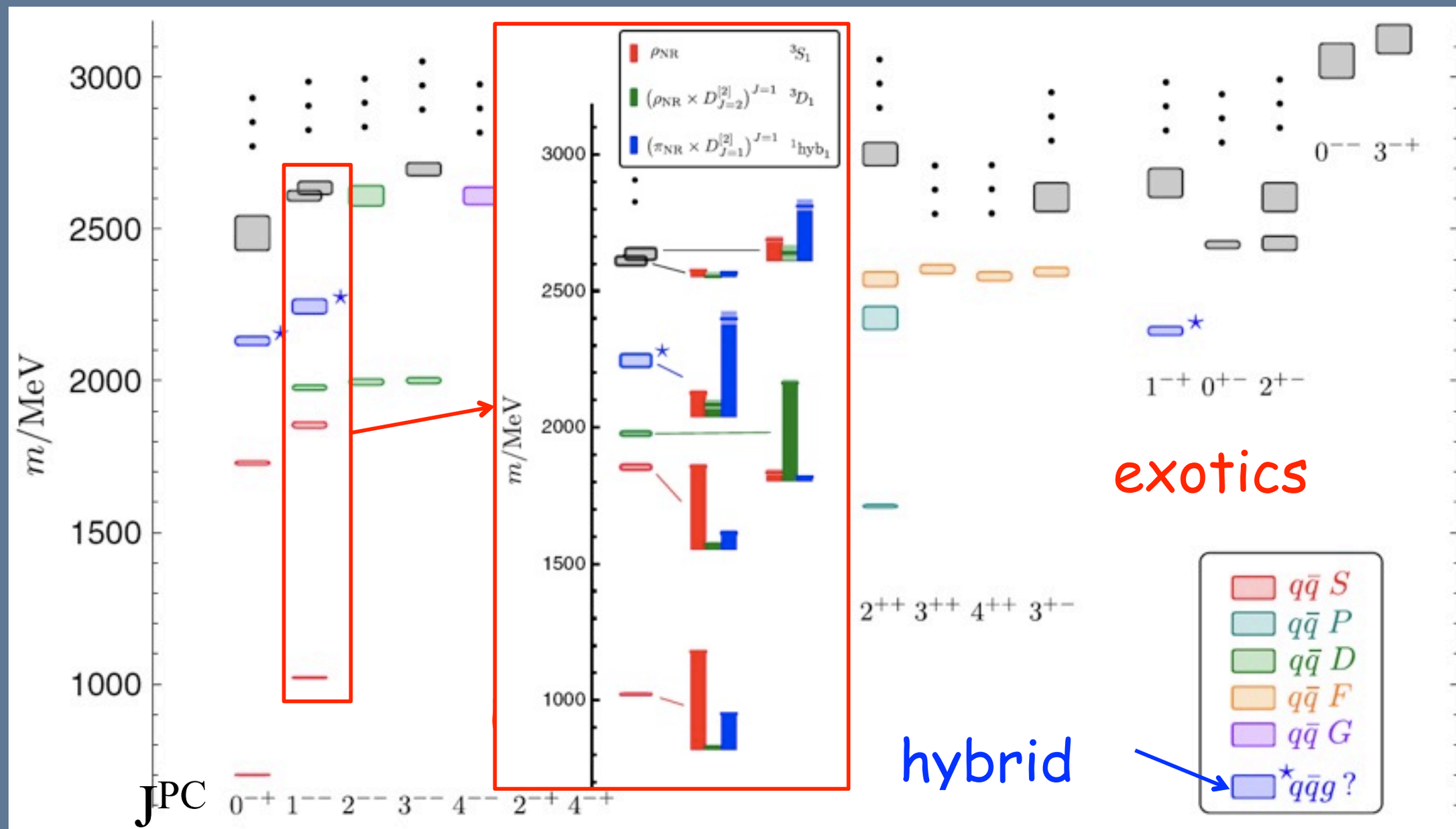




Effective Degrees of Freedom
at intermediate energies

Hadron Spectrum Collaboration
Dudek, Edwards et al
Jefferson Lab

LQCD is able to "predict" hybrids (exotics)

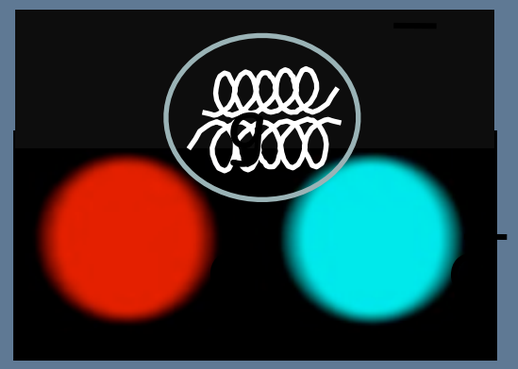


Isovector mesons, m_π~700

Dudek PRD 83 (2011)
Dudek PRD 84 (2011)

Two of today's most relevant topics in Meson Spectroscopy:

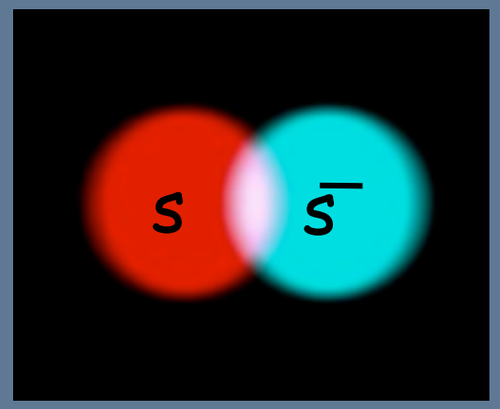
1) Search for Exotic Mesons



Search for non-standard - outside CQM (hybrid and exotic quantum numbers) states with explicit gluonic degrees of freedom

- Understanding the relevant degrees of freedom to describe hadrons
- Predicted by several phenological models (flux tube, bag model,...)
- Validate LQCD predictions on hybrids

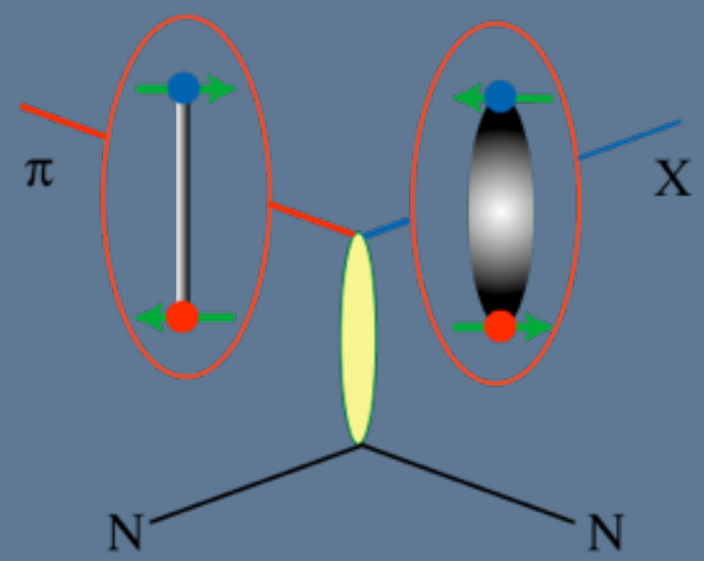
2) Study of Strangeonia

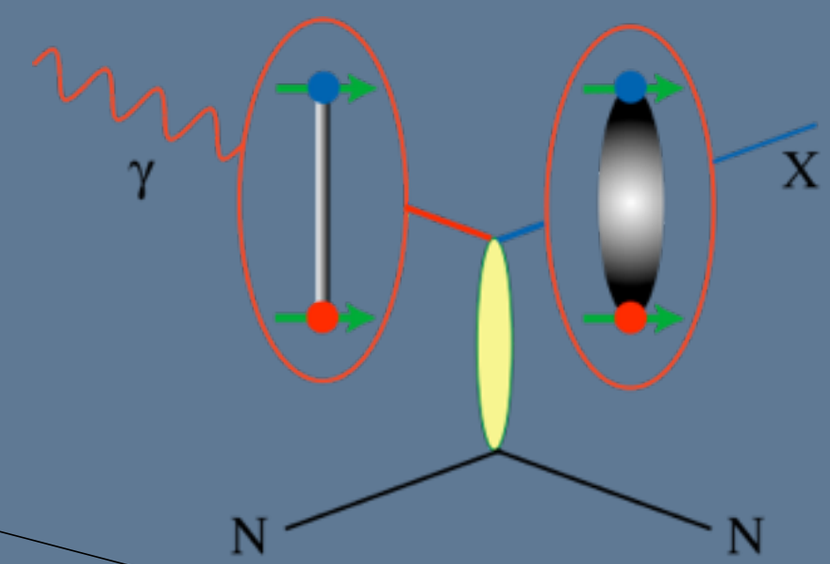


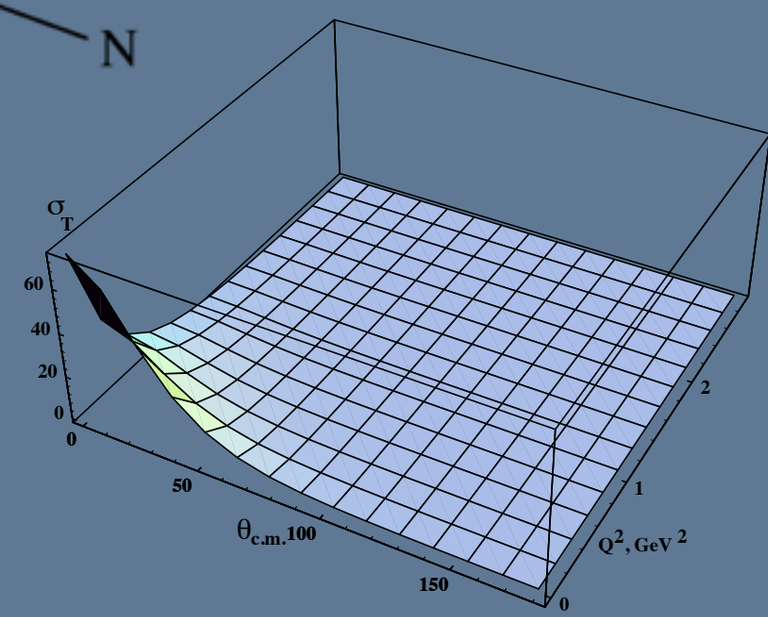
- Intermediate states between light and heavy mesons (a bridge to PQCD?).
- Of about 22 resonances expected below a mass of 2.5 GeV, only 7 are "relatively" well established.
- Strangeonia hybrids have been predicted just above a mass of 2 GeV.

Why photoproduction?

We see the photons in the Vector Dominance Model (VMD) - quark-antiquark pairs







Afanasev, Page

Prediction of larger cross-sections a low-Q^2 (Q^2=0)

Status of Hybrid (Exotic) Search

$\pi_1(1400)$

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

See also the mini-review under non-$q\bar{q}$ candidates in PDG 06, Journal of Physics, G **33** 1 (2006).

$\pi_1(1400)$ MASS

VALUE (MeV)	EVTS	DOCUMENT ID	TECN	CHG	COMMENT
1354 ±25	**OUR AVERAGE**	Error includes scale factor of 1.8. See the ideogram below.			

BNL-E852
CERN-COMPASS

$\pi_1(1600)$

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$2014 \pm 20 \pm 16$	$230 \pm 32 \pm 73$	145k	LU	05	B852	18 $\pi^- p \to \omega \pi^- \pi^0 p$
$2001 \pm 30 \pm 92$	$333 \pm 52 \pm 49$	69k	KUHN	04	B852	18 $\pi^- p \to \eta \pi^+ \pi^- \pi^- p$

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Unlikely Hybrid
Dynamical origin?

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Challenge in 3π to separate exotic π_1 from π_2
Cleaner $\eta'\pi$ signal

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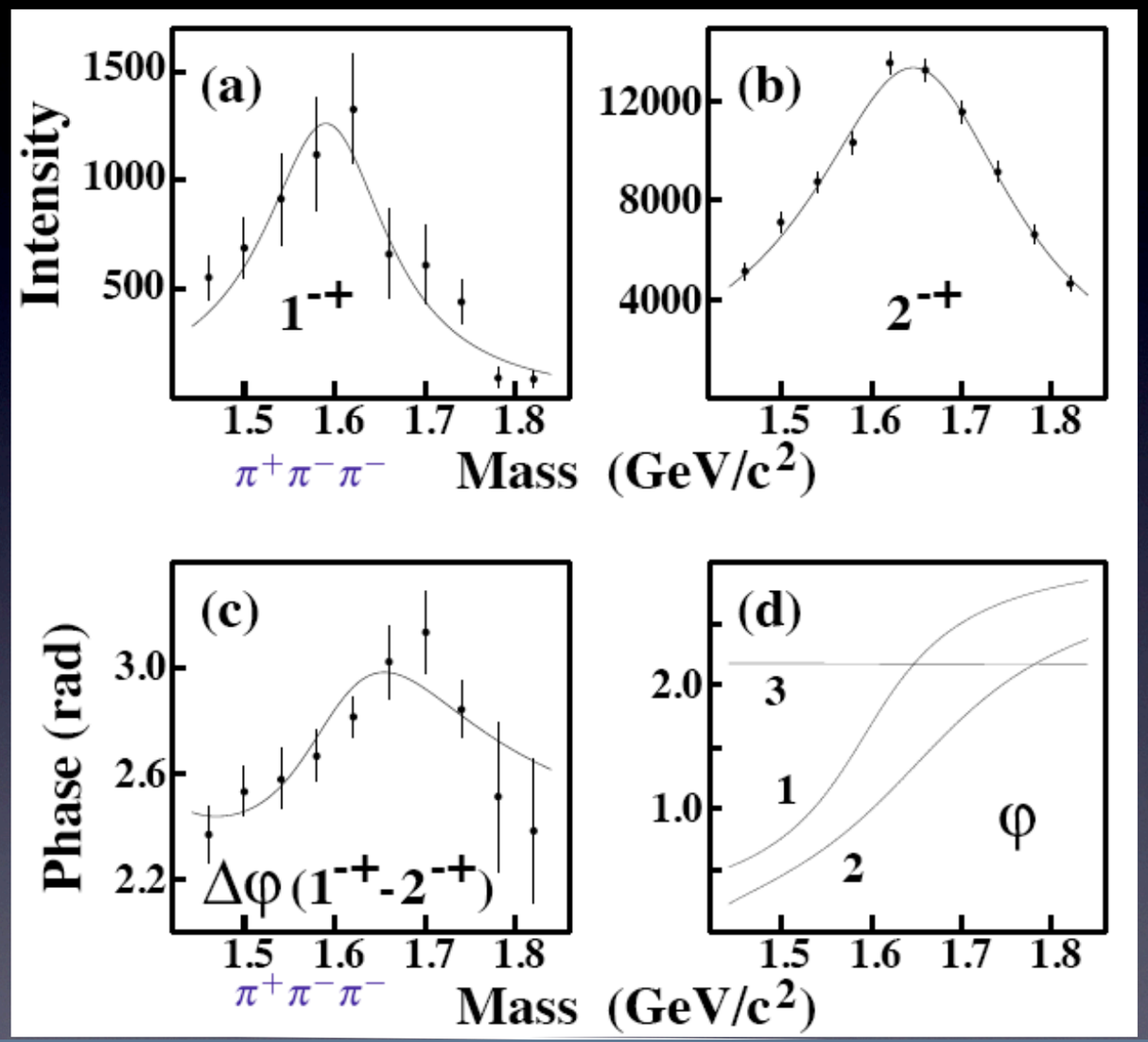
Listed among "further states" Needs confirmation

E852 250000 events/1997 $\pi^- p \rightarrow \pi^- \pi^- \pi^+ p$



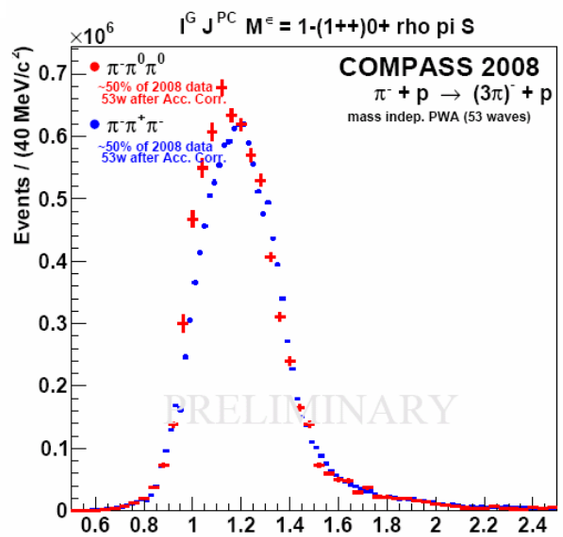
PRL 81, 5760 (1998)
PRD 65, 072001 (2002)

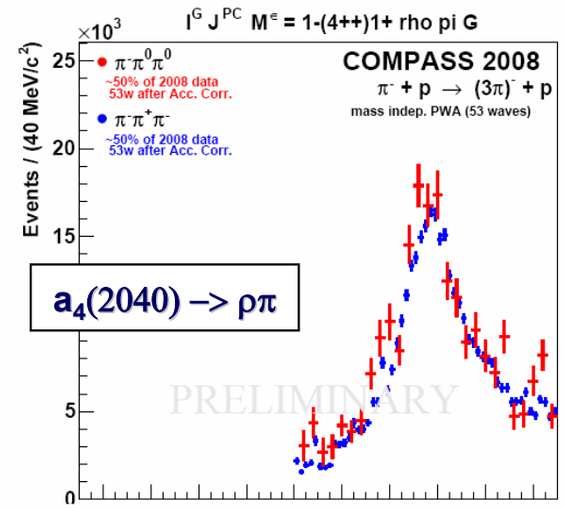
$$M = 1593 \pm 8^{+29}_{-47}\ MeV$$

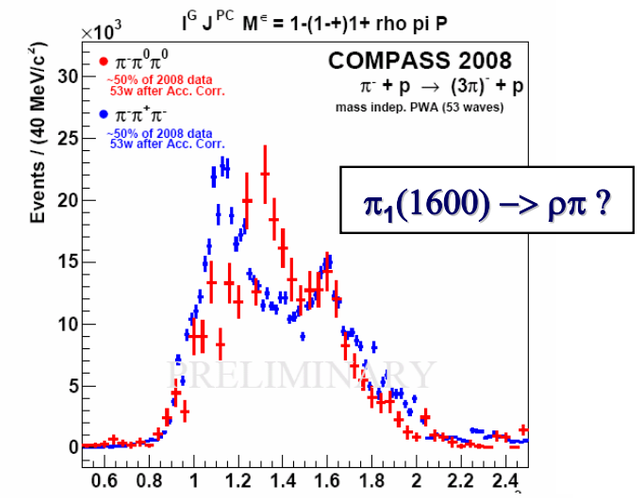
$$\Gamma = 168 \pm 20^{+150}_{-12}\ MeV$$

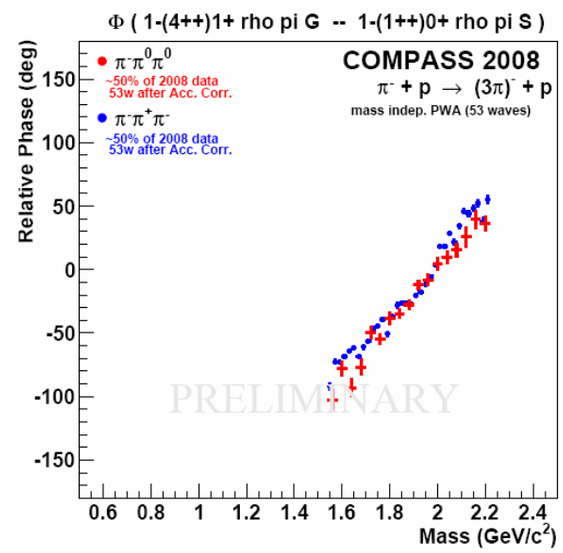
Comparison: Neutral vs. charged mode

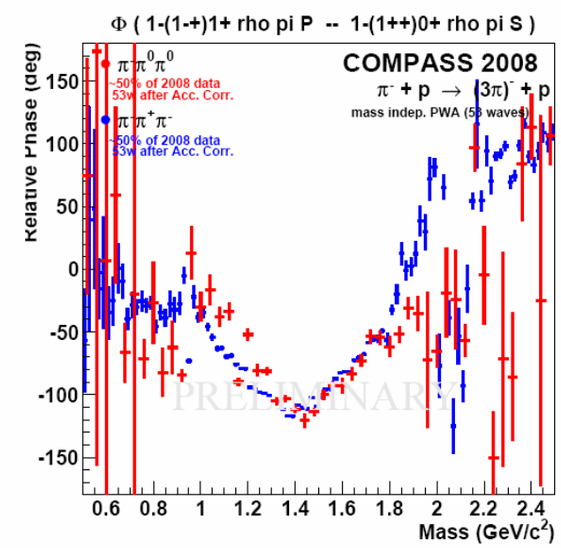
Intensities and relative phase – very small & exotic wave











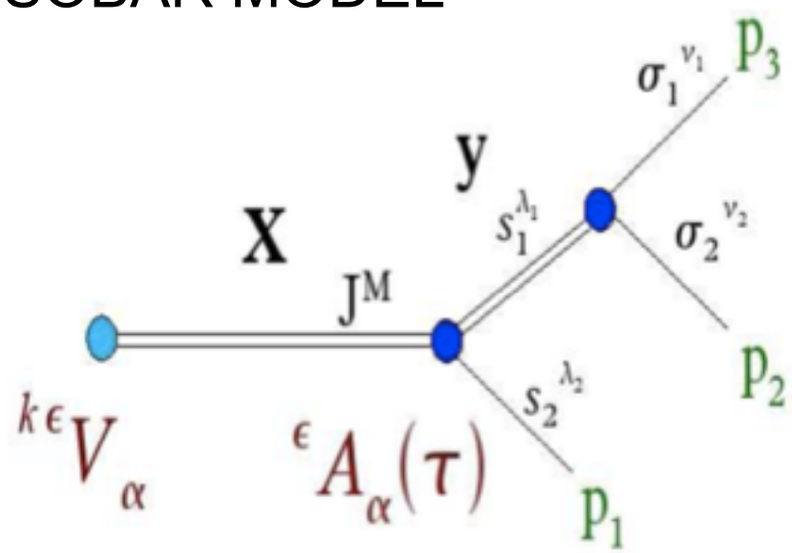
$\pi_1(1600) \rightarrow \rho\pi$?

Before any strong conclusion:
- More systematic studies
- Mass-dependent fit

Partial Wave Analysis at CLAS (in a slide)

1) Helicity formalism
2) Isobar Model

ISOBAR MODEL



$$ {}^{\epsilon}A_\alpha(\tau) = A_X^{\lambda_1\lambda_2;M} * A_y^{\nu_1\nu_2;\lambda_1} $$

Fitted parameters
(production amplitudes)

M, t

$$ I(\tau) = \sum_{k\epsilon\epsilon'} \epsilon\epsilon' \rho_{\epsilon\epsilon'}(\tau) \sum_{\alpha\alpha'} {}^{k\epsilon'}V^*_{\alpha'} \; {}^{\epsilon'}A^*_{\alpha'}(\tau) \; {}^{k\epsilon}V_\alpha \; {}^{\epsilon}A^*_\alpha(\tau) $$

Minimize "Extended" Likelihood

$$ \mathcal{L} \propto \frac{\bar{n}}{n!} e^{-\bar{n}} \prod_i^n \frac{I(\tau_i)}{\int I(\tau)\eta(\tau)d\tau} $$

or

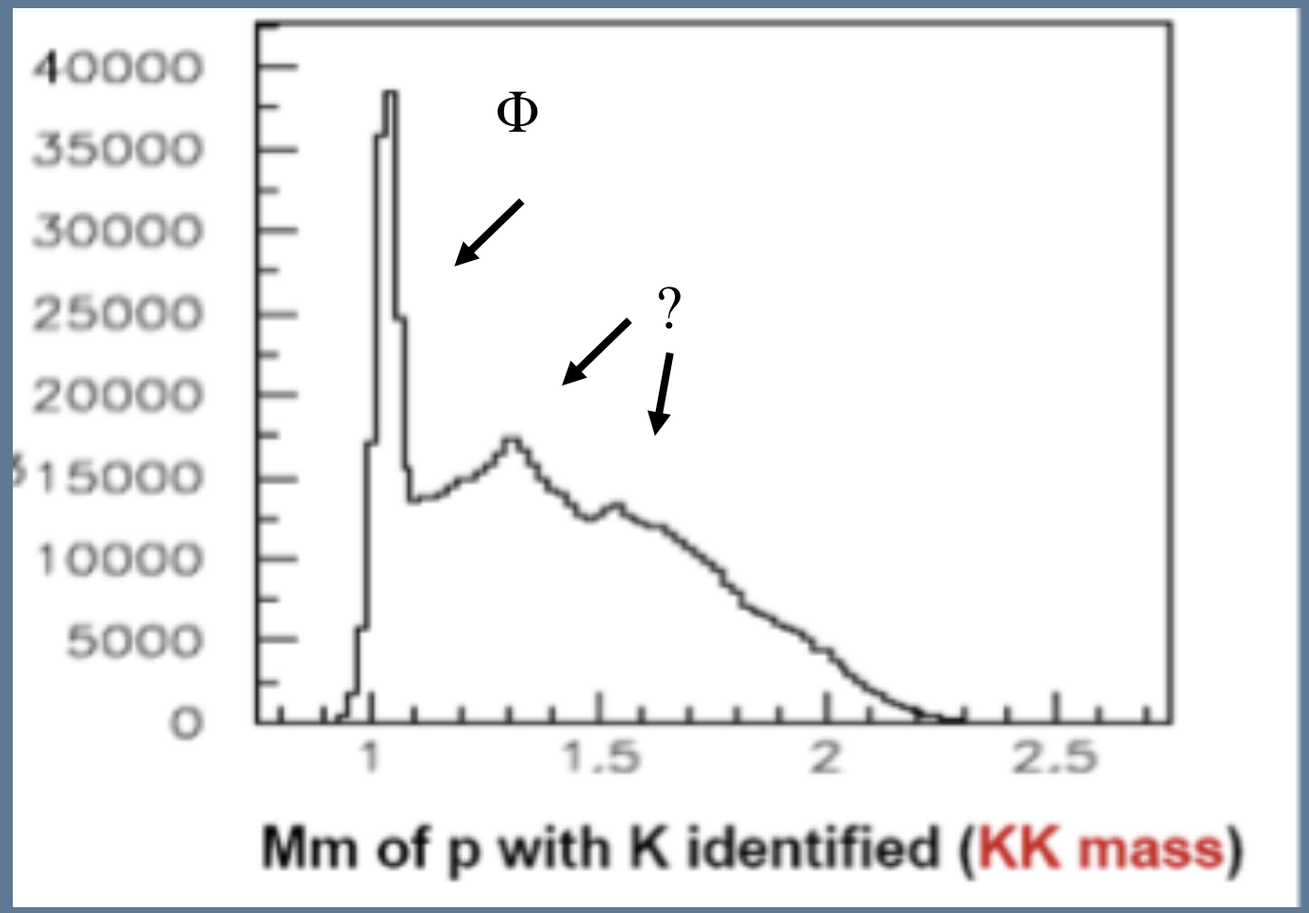
$$ \ln \mathcal{L} = \sum_i^{N_o} \ln\{ \sum_{k,\epsilon,\alpha,\alpha'} {}^{\epsilon}V_{k\alpha} \, {}^{\epsilon}V^*_{k\alpha'} \, {}^{\epsilon}A_\alpha(\tau) \, {}^{\epsilon}A^*_{\alpha'}(\tau)\} - \sum_{k,\epsilon,\alpha,\alpha'} {}^{\epsilon}V_{k\alpha} \, {}^{\epsilon}V^*_{k\alpha'} \, {}^{\epsilon}\Phi^{\eta}_{\alpha\alpha'} $$

where

$$ {}^{\epsilon}\Phi^{\eta}_{\alpha\alpha'} = \int {}^{\epsilon}A_\alpha(\tau) \, {}^{\epsilon}A^*_{\alpha'}(\tau)\eta(\tau)pq \, d\tau. $$

Normalization integral

What resonances are hidden under the mass distribution?



Preliminary data from CLAS6-g12

✓ Resonances are:

★ overlapping
★ interfering
★ wide
★ small cross-sections
★ non-resonant backgrounds
★ ...

Meson SpectroscopyStrategies at JLab

- Use 8.4−9 GeV linearly polarized photons (12 GeV electron beam)
  - Identify (naturality) production mechanisms
  - Open phase space to separate meson/baryon production products
  - Sensitivity to masses up to ~ 2.8 GeV/c^2
- Use hermetic detector with large acceptance
  - Decay modes expected to have multiple particles
  - Hermetic coverage for charged and neutral particles
  - Medium resolution: momentum (~ 1-4%), energy (2-20%)
  - High data acquisition rate to enable amplitude analysis
- Perform amplitude analysis
  - Identify wide and rare (small cross sections) resonances
  - Use all available S-Matrix physics constraints on fittings
  - Identify the J^{PC} of resonances -phase motions -interference patterns
  - Check consistency of results in different decay modes

Experiment ⟷ Theory

Joint Physics Analysis Center (JPAC)

Jefferson Lab, Indiana U., GWU, Peking U.

- 12 GeV upgrade at JLab: *CLAS, GlueX, etc.*
  - Aim: → Complete understanding of the *hadron spectrum*
    → discover *new resonances* e.g, gluonic excitations (states where glue builds their J^{PC})
  - Tools: *Amplitude analyses of data*
    To find new resonances not bump-hunting, but search for poles
    ⇒ must build in S-Matrix constraints
    + state-of-the-art knowledge
    of reaction dynamics

Hadron spectrum, exotics

ChPT + Analyticity + Unitarity
Dispersion Relations
Regge Theory, Models

Experimental Data
CLAS, GlueX, JEF, COMPASS, BESS, LHCb, PANDA,…

FFs, resonance parameters: M_R, Γ_R, couplings

Emilie Passemar

Software

Home / Browse / Science & Engineering / Physics / ROOTPWA

ROOTPWA Beta

Brought to you by: bgrube, legordian, sneubert

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Git Repository

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Description

We have moved to github!
Please visit us at https://github.com/ROOTPWA-Maintainers/ROOTPWA.

#######################

ROOTPWA is a toolkit for partial-wave analysis of multi-particle final states produced in high-energy particle reactions. It is used to determine hadron spectra from experimental data.

NOTE: The code is only accessible through the git repository in the "Code" section of this website. Please refer to the README file on how to get and install ROOTPWA and on how to contribute to the project.

Home / Browse / AmpTools

AmpTools

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Description

A utility library for performing amplitude analysis on particle physics data.

ComPWA: A common amplitude analysis framework for PANDA

M Michel[1], F Feldbauer[1,2], K Götzen[1,3], P Jasinski[1,2], A Karavdina[2], K Peters[1,3], M Fritsch[1,2]

[1] Helmholtz-Institut Mainz, Germany
[2] Johannes Gutenberg-Universität Mainz, Germany
[3] GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

E-mail: michel@kph.uni-mainz.de

Abstract. A large part of the physics program of the PANDA experiment at FAIR deals with the search for new conventional and exotic hadronic states like e.g. hybrids and glueballs. For many analyses PANDA will need an amplitude analysis, e.g. a partial wave analysis (PWA), to identify possible candidates and for the classification of known states. Therefore, a new, agile and efficient amplitude analysis framework ComPWA is under development. It is modularized to provide easy extension with models and formalisms as well as fitting of multiple datasets, even from different experiments. Experience from existing PWA programs was used to fix the requirements of the framework and to prevent it from restrictions. It will provide the standard estimation and optimization routines like Minuit2 and the Geneva library and be open to insert additional ones. The challenges involve parallelization, fitting with a high number of free parameters, managing complex meta-fits and quality assurance/comparability of fits. To test and develop the software, it will be used with data from running experiments like BaBar or BESIII. These proceedings show the status of the framework implementation as well as first test results.

Jefferson Lab > PYPWA

Jefferson Lab
EXPLORING THE NATURE OF MATTER

LINKS
- PYPWA Home
- General Description
- Installation
- Tutorials
- Documentation - Sphinx
- Software Download
- Wiki
- References
- Contact Us

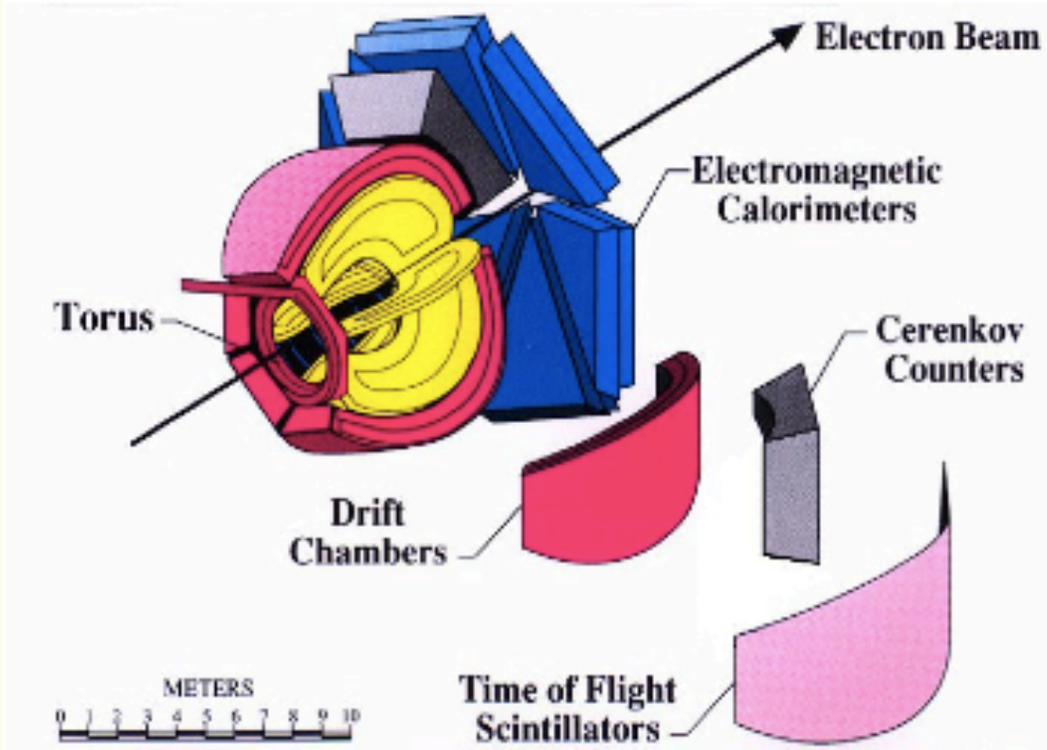
A Partial-Wave/Amplitude Analysis Software Framework

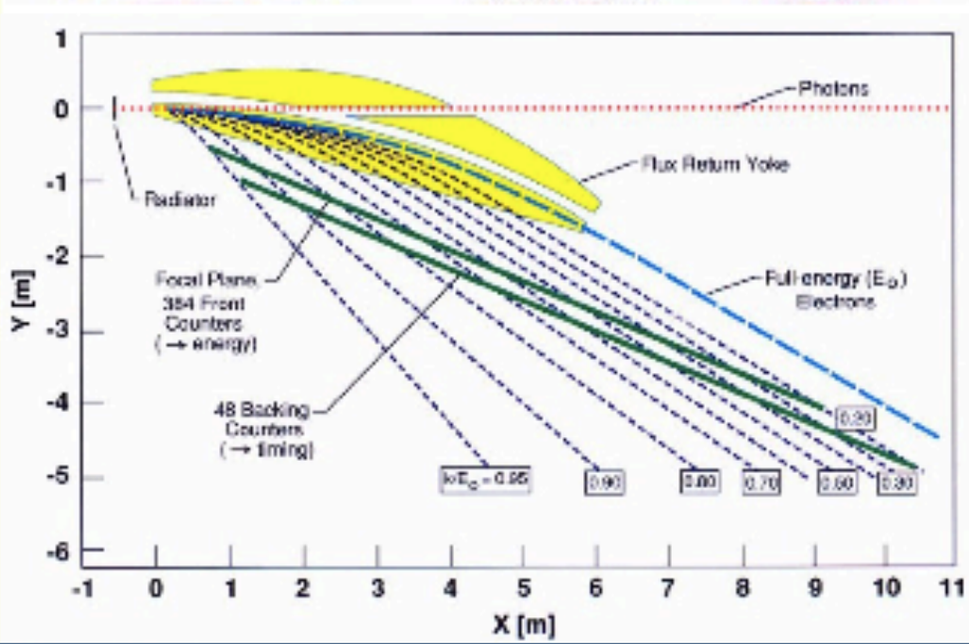
PyPWA
Thomas Jefferson National Accelerator Facility
Newport News, VA

Home

PyPWA software framework can be used to perform parametric model fitting to data. In particular, Partial Wave and Amplitude Analysis (PWA) of multiparticle final states. PyPWA is designed for photoproduction experiments using linear polarized beams. The software makes use of the resources at the JLab Scientific Computer Center (Linux farm). PyPWA extract model parameters from data by performing extended likehood fits. Although general amplitudes can be used, the framework includes a specific realization of the Isobar model, with extensions to include Deck-type and baryon vertices corrections. Tutorials (Step-by-step instructions) leading to a full PWA of data and the use of simulation and general fitting procedures are included. Most of the code is in Python, but hybrid code (in Cyhon or Fortran) has been used when appropiate. Scripting for use in parallel coprocessors (Xeon-Phi or GPUs) are expected in the near future. The goal of this software framework is to create a user friedly enviroment for PWA of linear polarized photoproduction experiments.

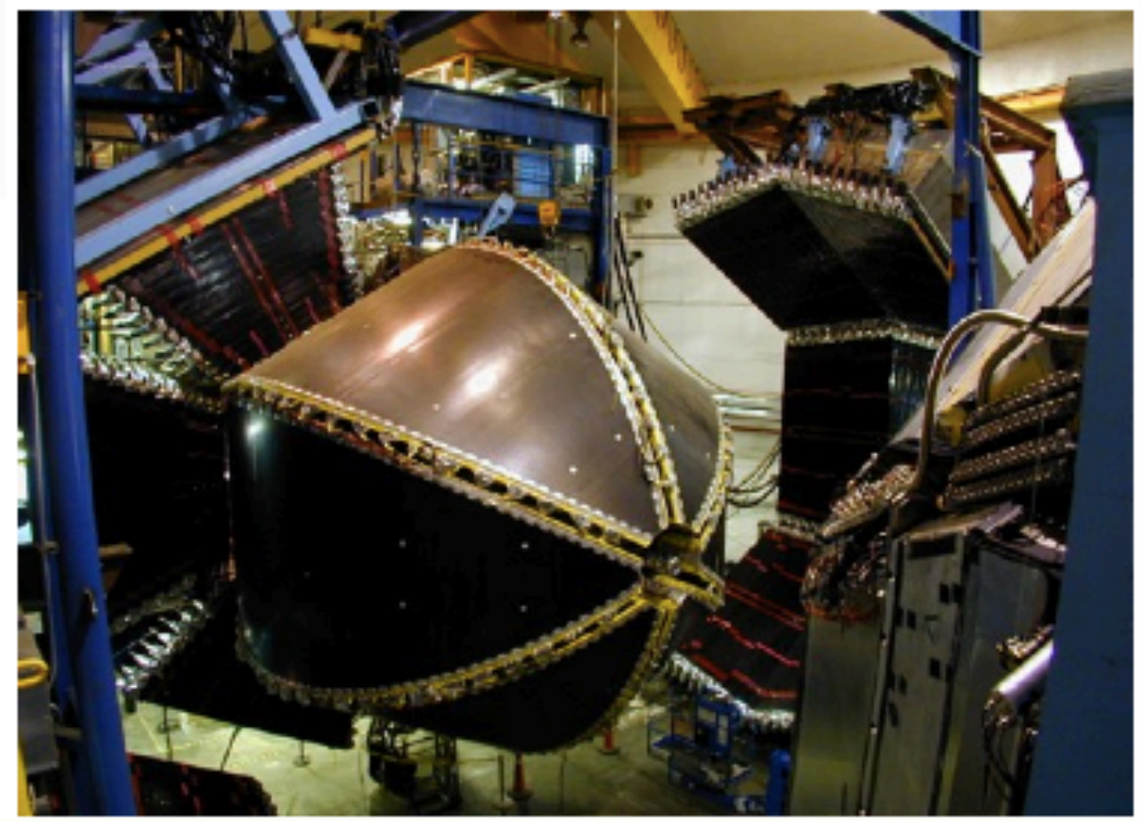
The CEBAF Large Acceptance Spectrometer CLAS6





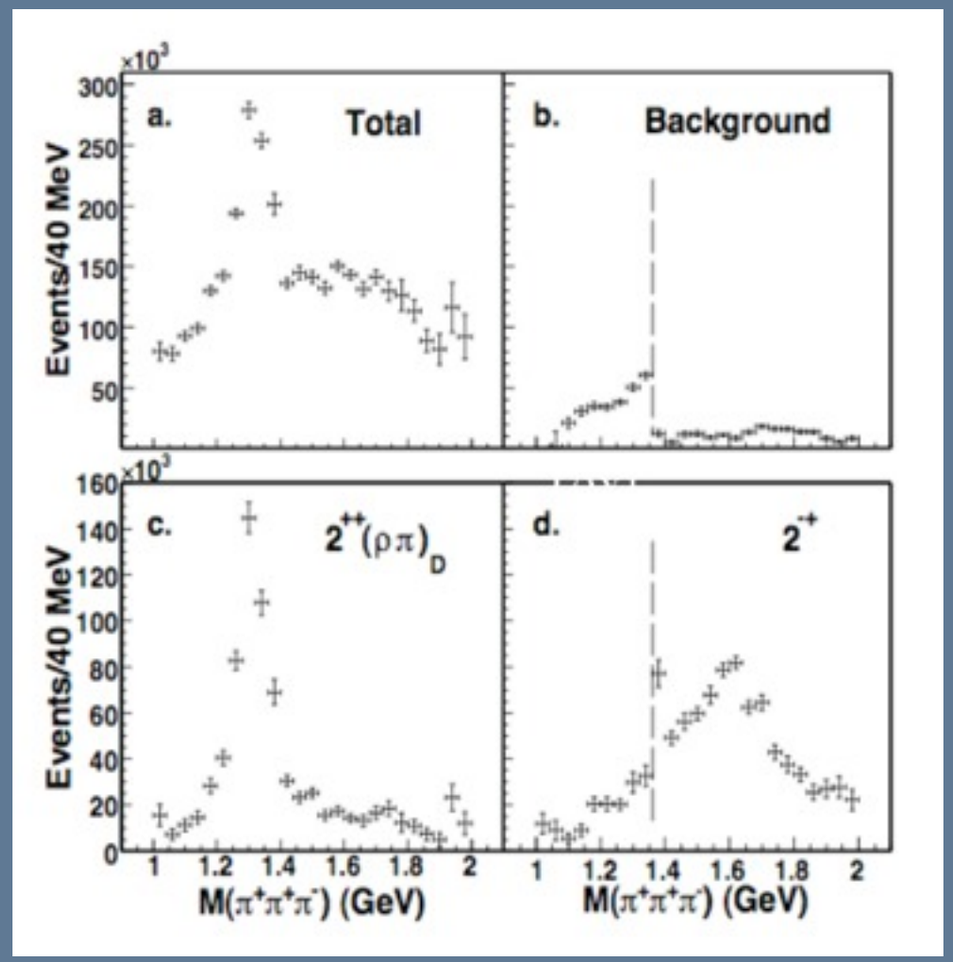
Performance

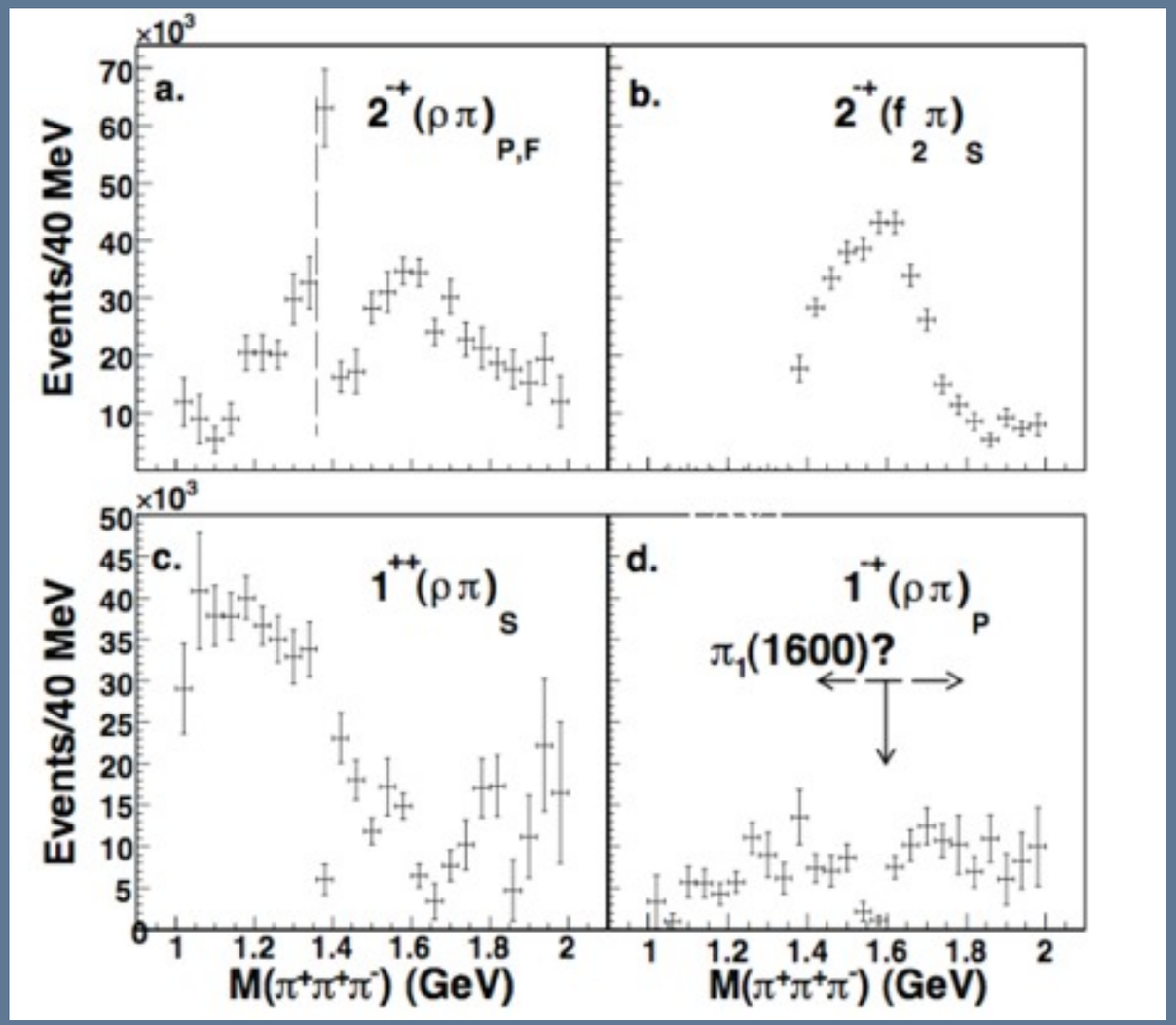
- ★ $L = 10^{34}\ cm^{-2}\ s^{-1}$
- ★ $\int B\,dl = 2.5$ T m
- ★ $\Delta p/p \sim 0.5\text{-}1$ %
- ★ 4π acceptance
- ★ Best suited for multiparticle final states
- ★ Bremsstrahlung Photon Tagger ($\Delta E_\gamma/E_\gamma \sim 10^{-3}$)



Unpolarised 4.8-5.2 GeV photon beam

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





- Clear evidence of non-exotic 2^{++} state $a_2(1320)$
- No-evidence of exotic 1^{-+} state $\pi_1(1600)$ at the expected yield

$\sigma_{\pi 1} < 13.5$ n*b*

(<2% of a_2)

Nozar, et al
Phys.Rev.Lett.
102:102002,2009.
e-Print: arXiv:
0805.4438 [hep-ex]

CLAS6 - g12 run

Search for new forms of hadronic matter in photoproduction

- Data taking completed in 2008
- Photon Energy up to 5.5 GeV
- More than 26 billion triggers (2-prong + 3-prong)
- Total Luminosity: 68 pb^{-1}
- Data processing completed and physics analysis in progress

Several exclusive channels are being analyzed

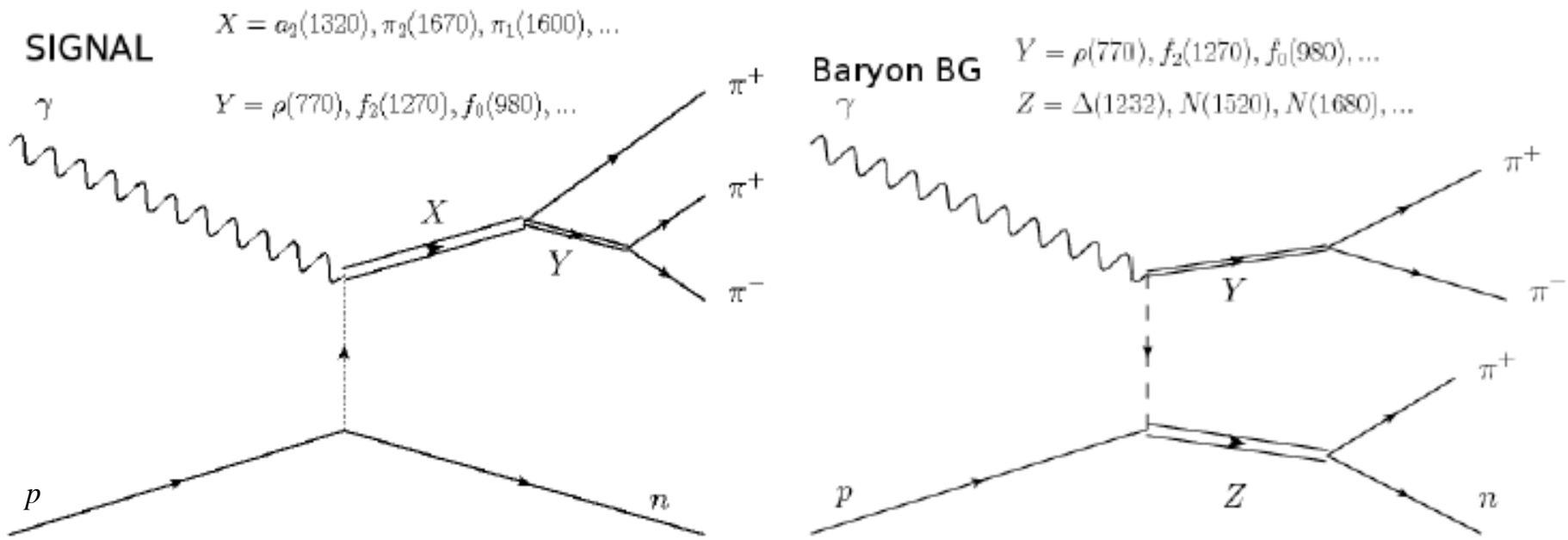
$\gamma p \rightarrow \pi^+\pi^+\pi^-(n)$
$\gamma p \rightarrow (\pi^0)\pi^+\pi^- p$
$\gamma p \rightarrow K^+K^+ (\Xi^{*-})(1530)$
$\gamma p \rightarrow pK^+K^- (\eta\Phi)$
$\gamma p \rightarrow (p\pi^{+\Delta}) \pi^-(\eta)$
$\gamma p \rightarrow \pi^+K^+K^-(n)$
$\gamma p \rightarrow e^+e^- p$
...

Meson Spectroscopy
- Search for exotic mesons
- Study of Strangeonia
- ...

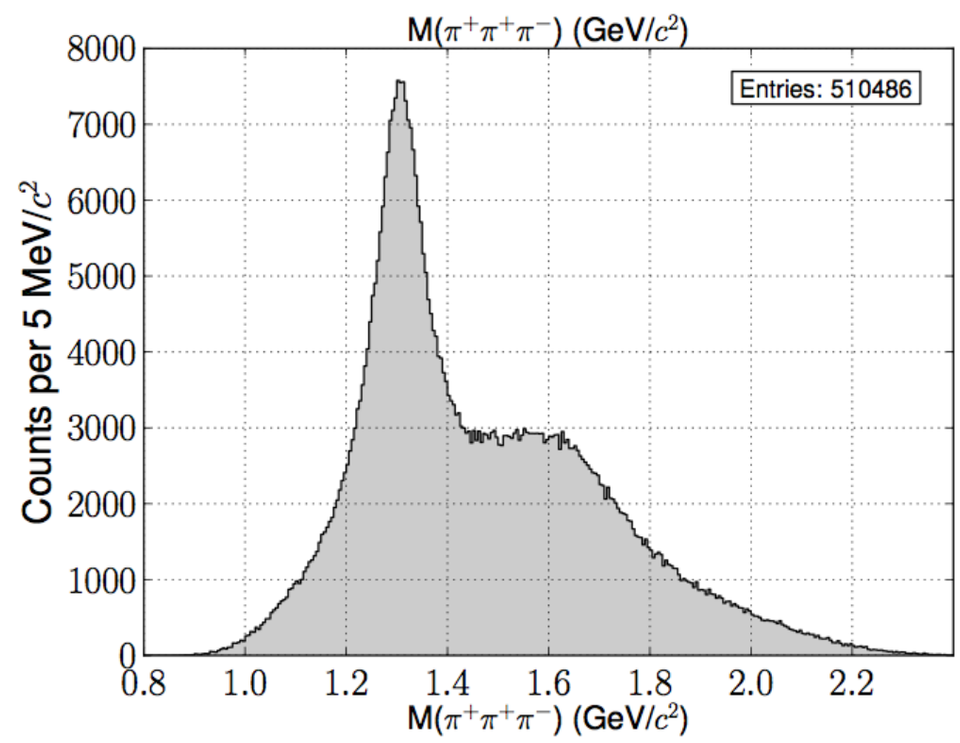
Baryon Spectroscopy
- Cascades

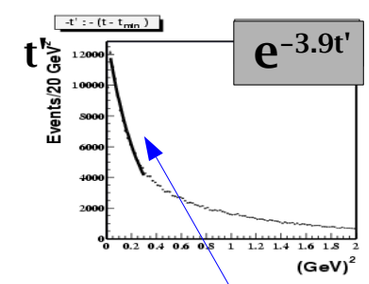
Search for π_1 (1600)

C. Bookwalter thesis - FSU



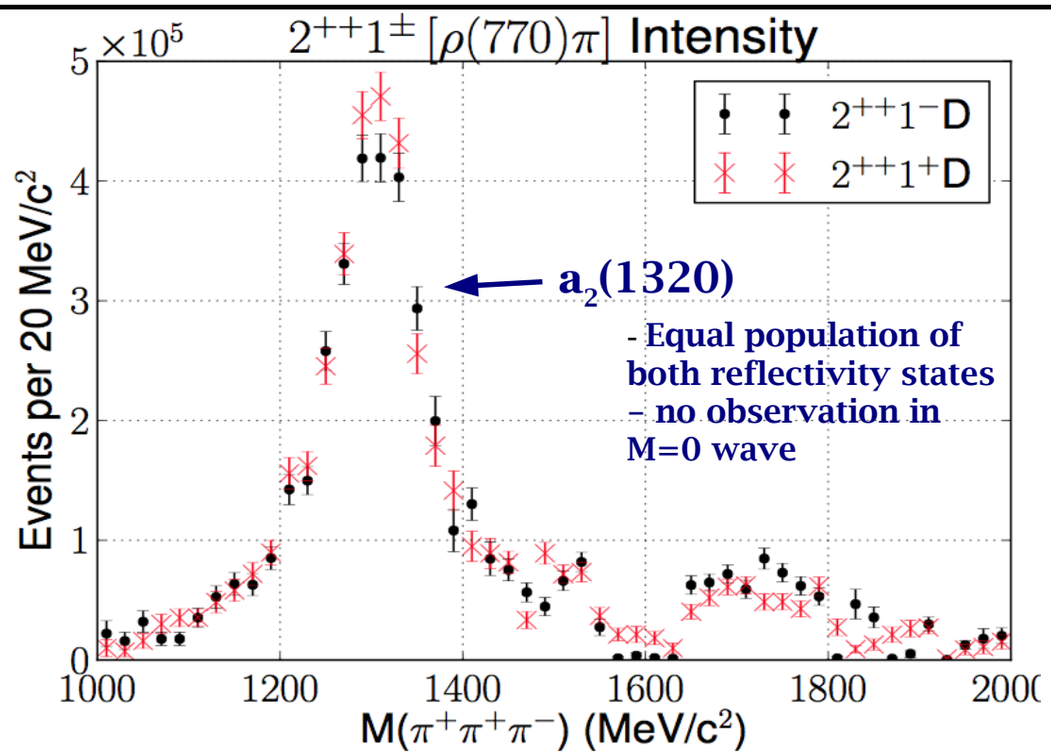
CLAS6-g12

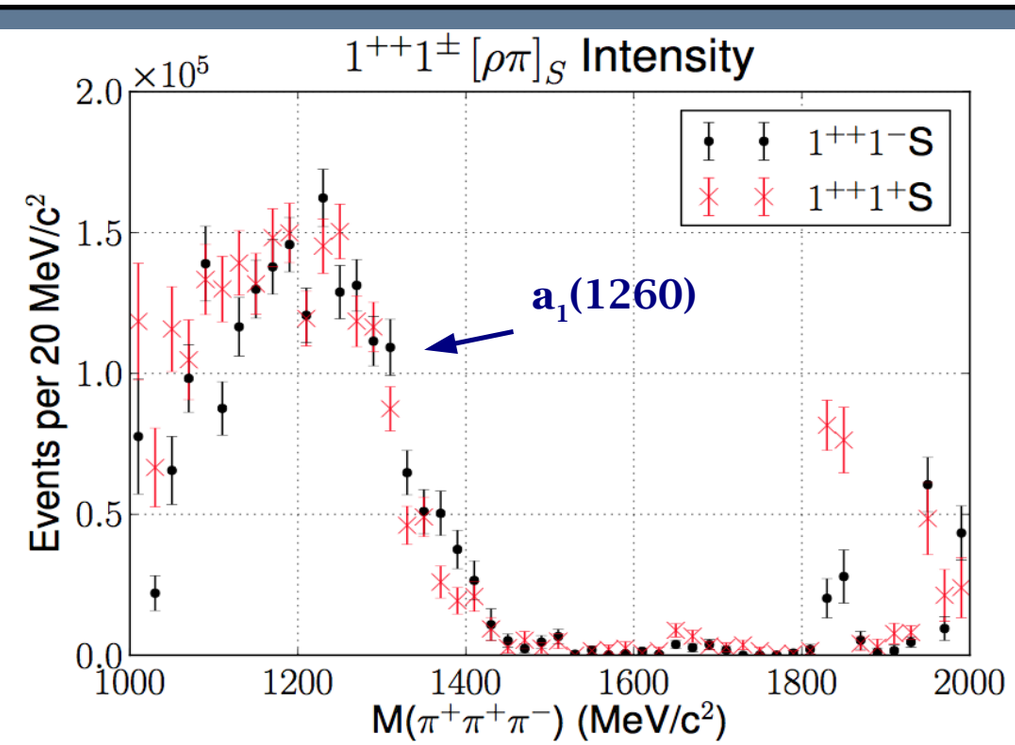


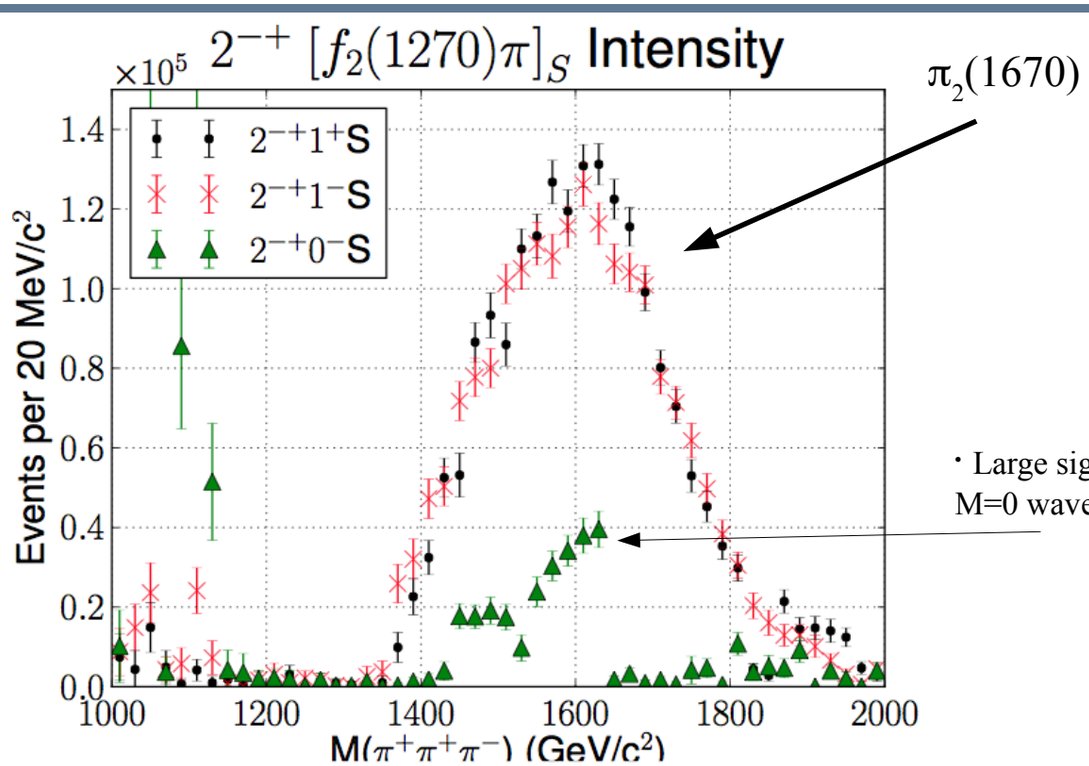


Sharp **t** dependence consistent with π-exchange production

Baryon background cuts: $|t'| < 0.1$ & $\theta_{lab}(\pi^+) < 25^o$







- Large signal in M=0 wave

Major waves

J^{PC}	M^{ϵ}	L	Y	# waves
1^{++}	$1^{\pm}$	S	$\rho(770)$	2
1^{++}	$1^{\pm}, 0^{+}$	D	$\rho(770)$	3
1^{-+}	$0^{-}, 1^{\pm}$	P	$\rho(770)$	3
2^{++}	$1^{\pm}$	D	$\rho(770)$	2
2^{-+}	$0^{-}, 1^{\pm}$	S, P, D	$f_2(1270)$, $\rho(770)$	9

+ isotropic background wave

unpolarized beam

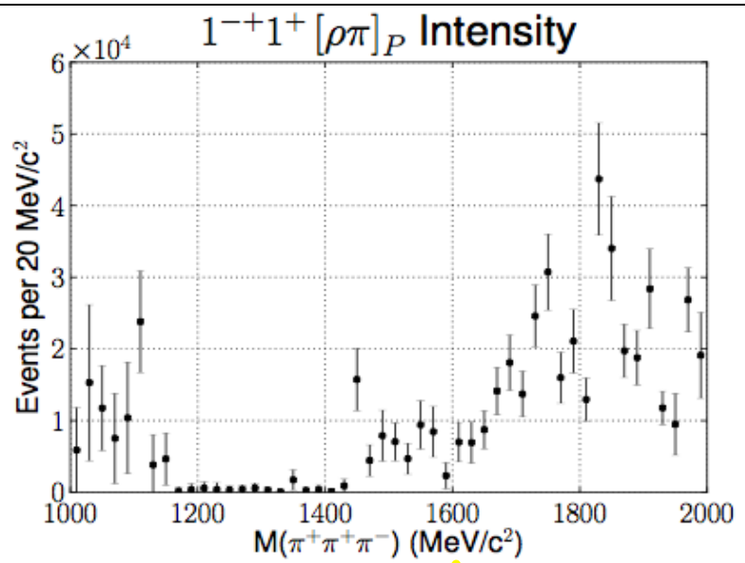
- Photon beam is a coherent mixture of both parity eigenstates
- Final states of different reflectivity do not interfere

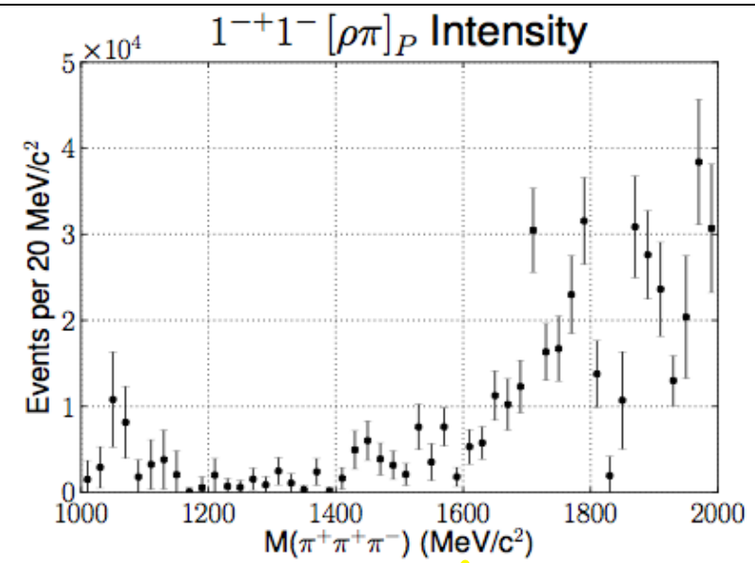
π exchange dominance

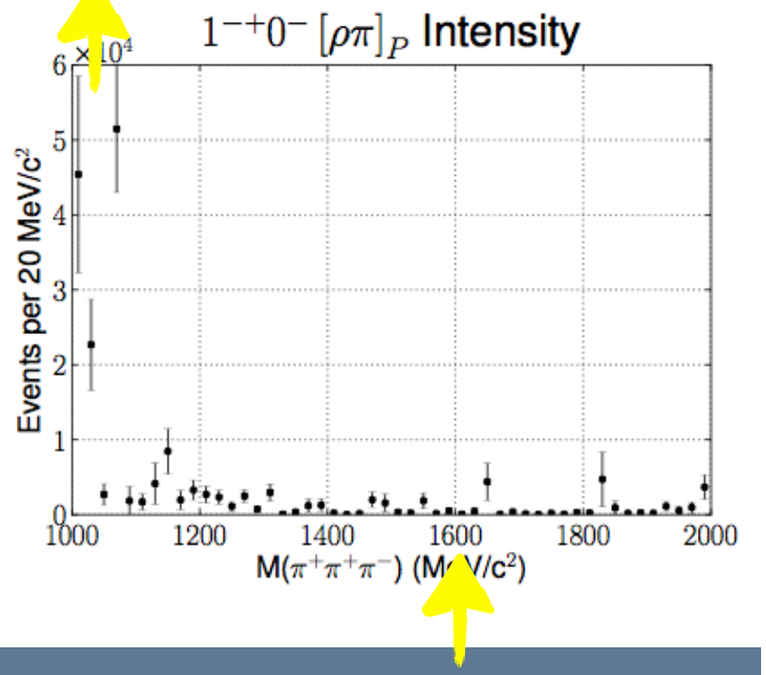
- Equal production of $M^{\epsilon} = 1^{+}$ and 1^{-} (ambiguity)
- No $M^{\epsilon} = 0^{\epsilon}$
  - No J=0 meson production (spin zero filter)

5

C. Bookwalter thesis - FSU



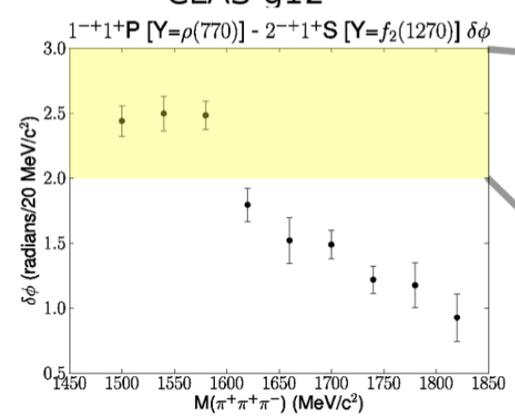




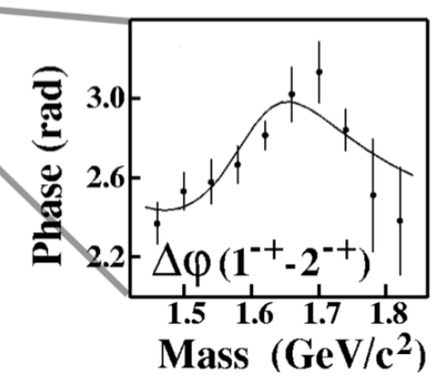
preliminary

- No clear resonance signal
- High mass results fluctuate
- Accounts for at most 2% of total intensity

CLAS g12



BNL-E852



- No evidence for exotic 1^{-+} phase motion
- Phase motion consistent with resonating 2^{-+}

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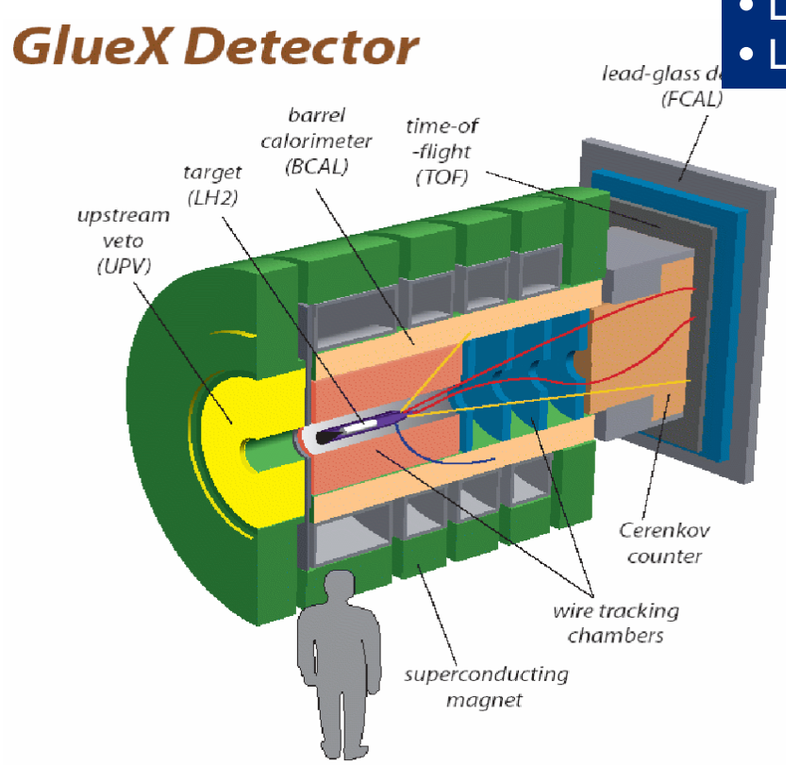
Meson spectroscopy with photons at JLab-12 GeV

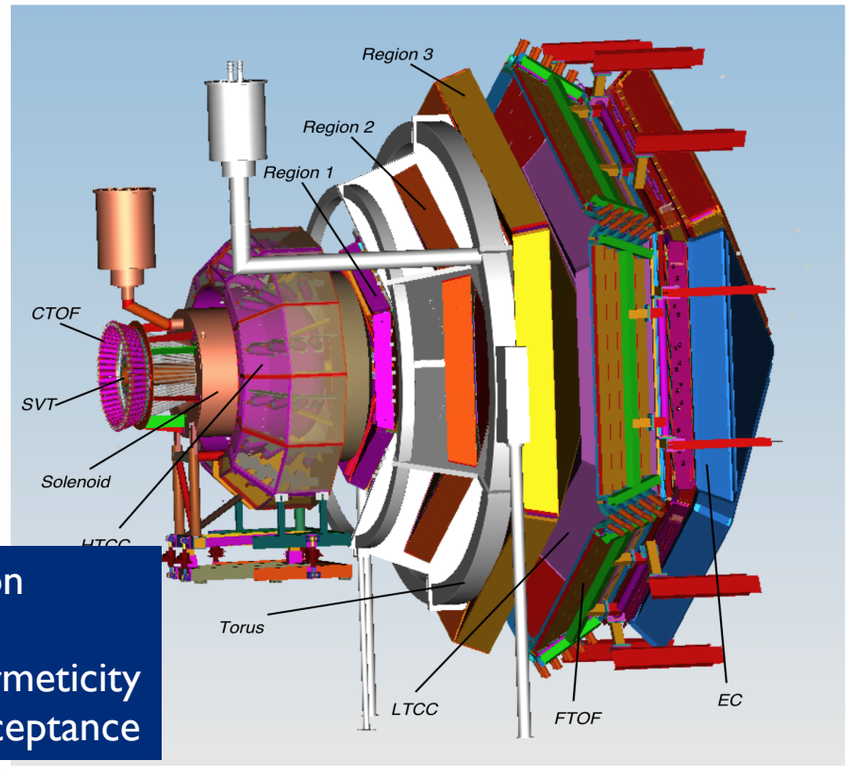
- Determination of JPC of meson states requires PWA
- Decay and production of exclusive reactions
- Good acceptance, energy resolution, particle identification

Hall-D - GlueX Detector

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



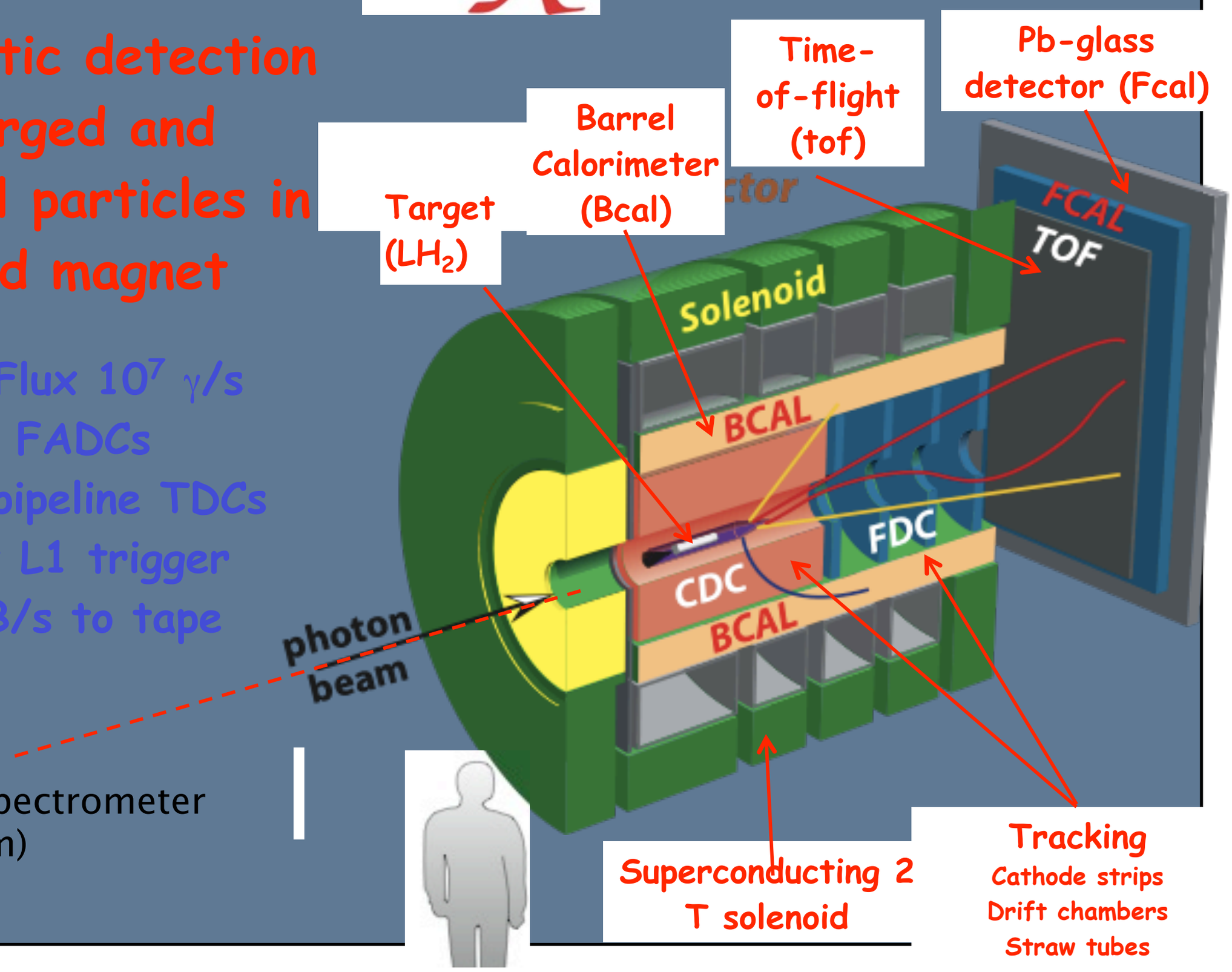
Hall-B - CLAS12 Detector



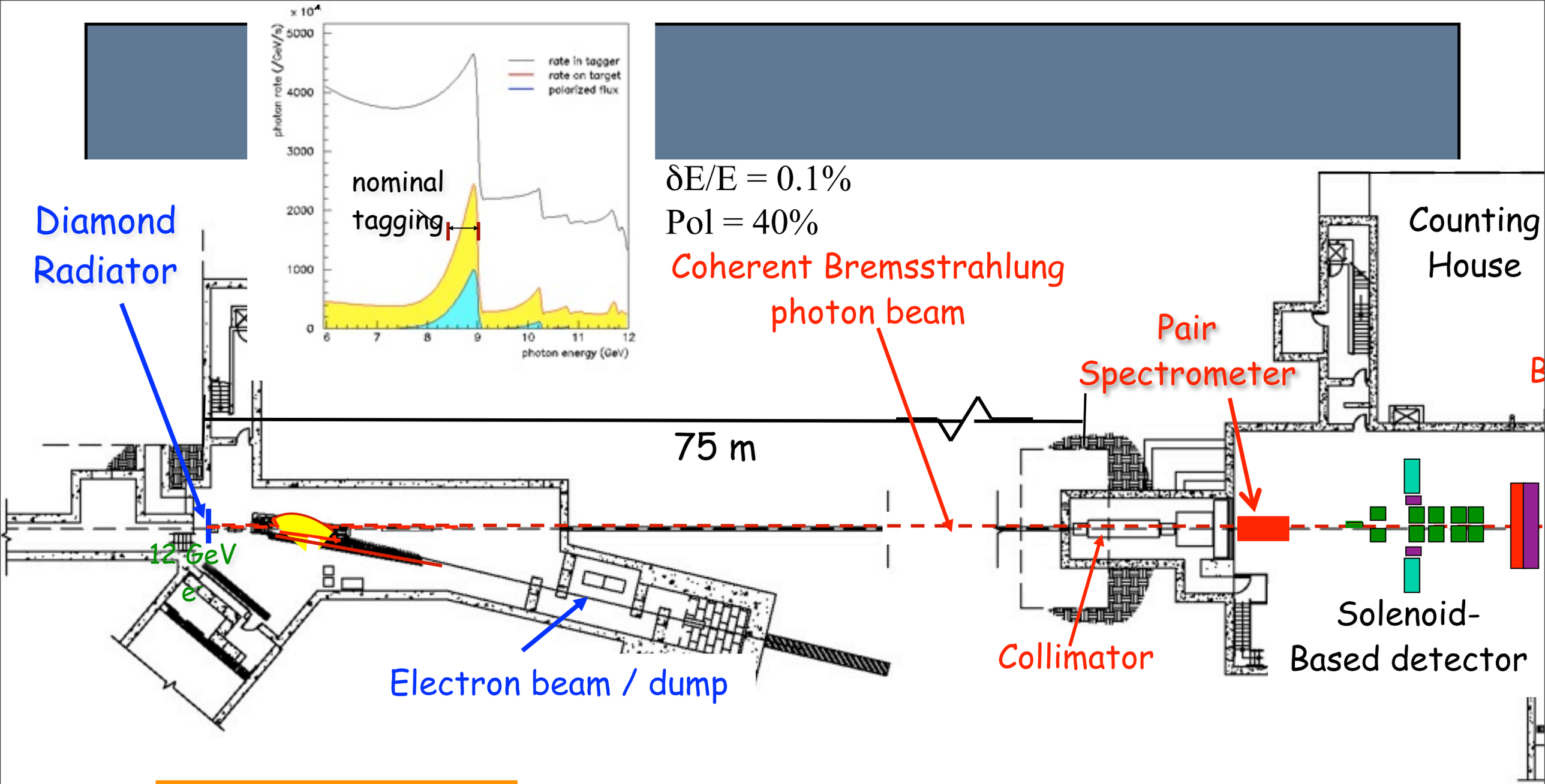
- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance

Hermetic detection of charged and neutral particles in solenoid magnet

Initial Flux 10^7 γ/s
18,000 FADCs
4,000 pipeline TDCs
20 KHz L1 trigger
300 MB/s to tape



Tagger Spectrometer (Upstream)



Tagger Area

Radiation $e^- Z \rightarrow \gamma e^- Z$

Collimator Cave

Selection $\theta < 25\mu r$
polarized photons

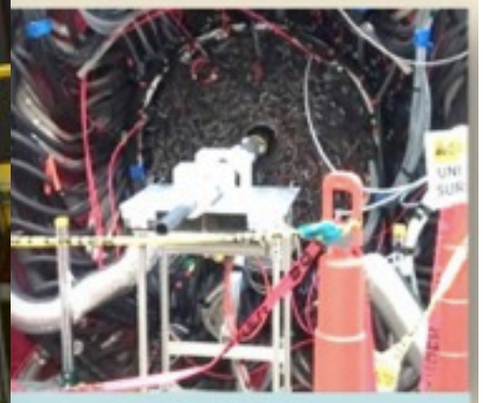
Experimental Hall D

Target,
Spectrometer

BCAL (UR)

FCAL (IU)

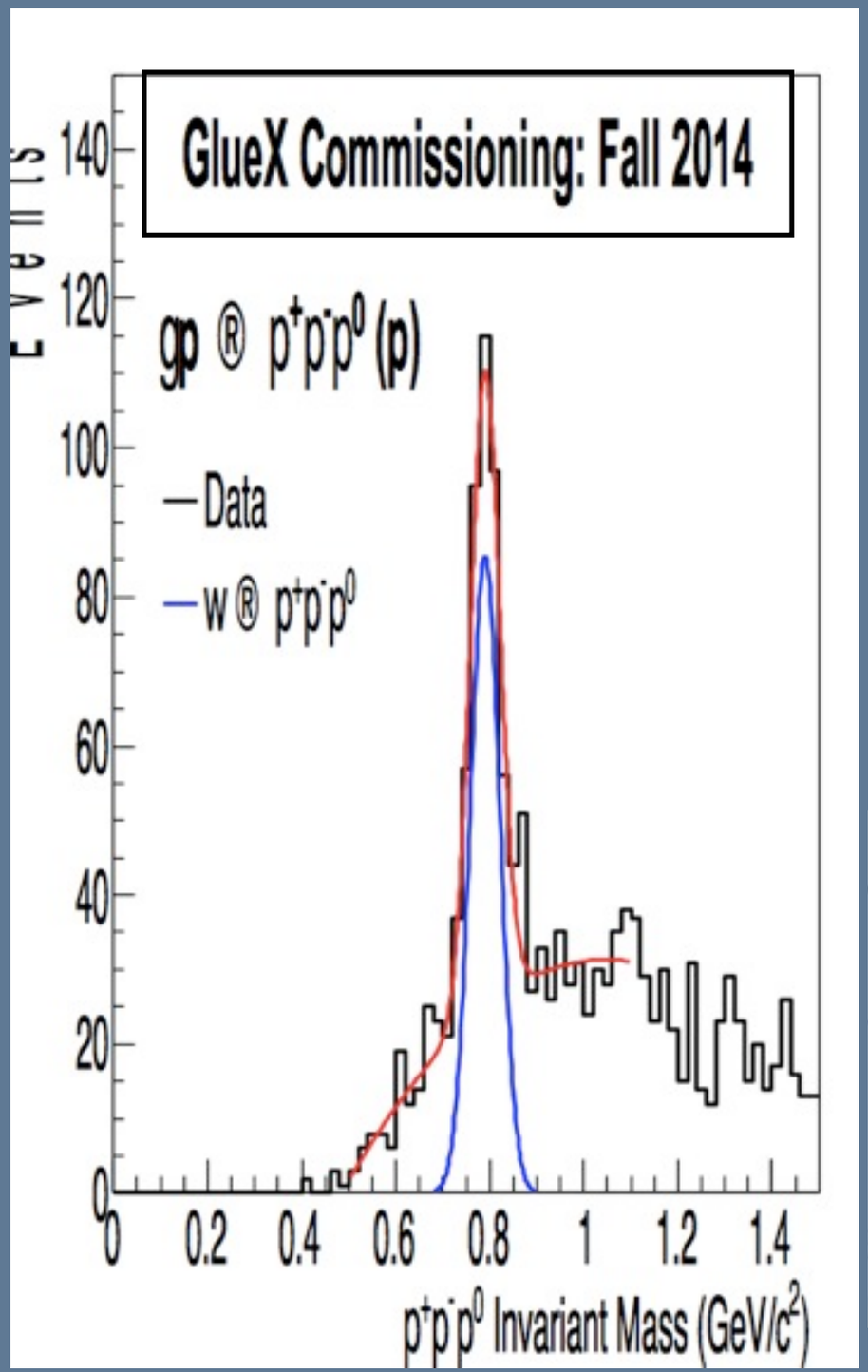
TOF (FSU)

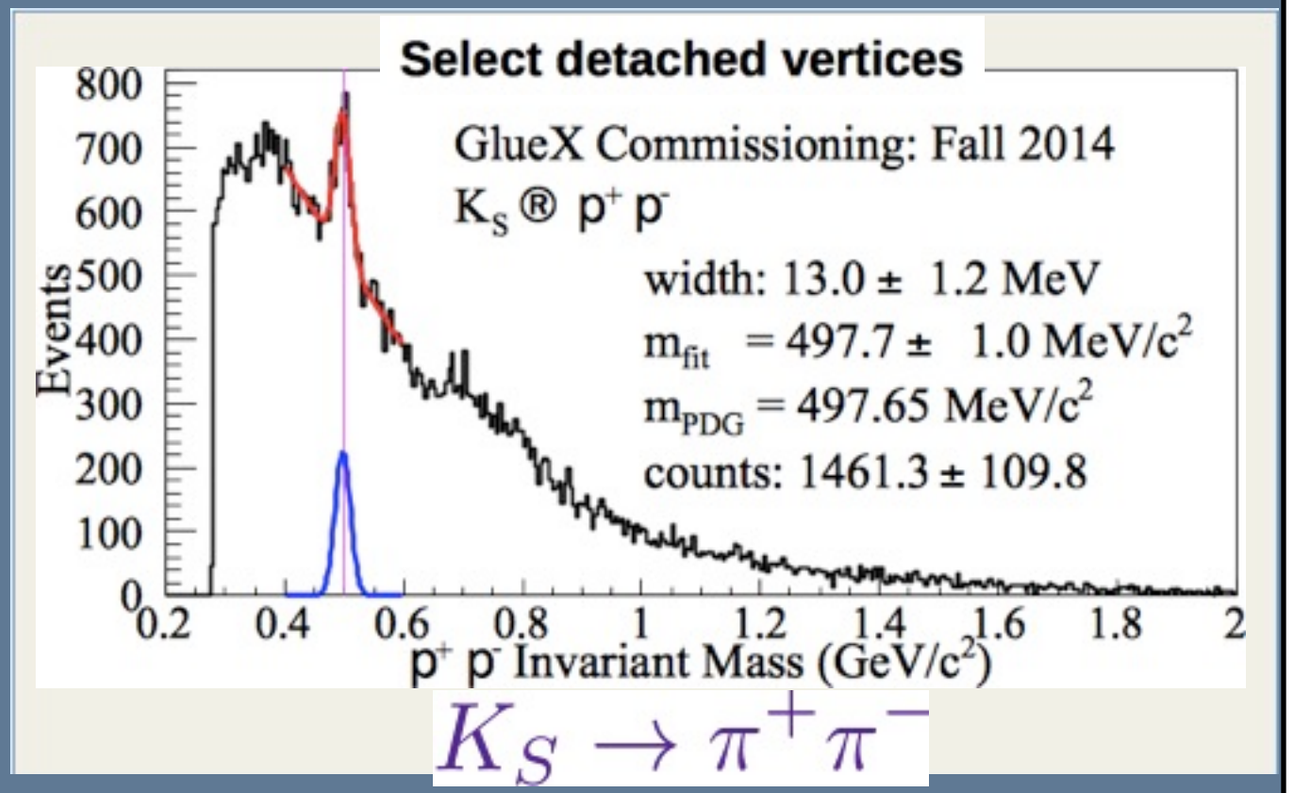


CDC (CMU)

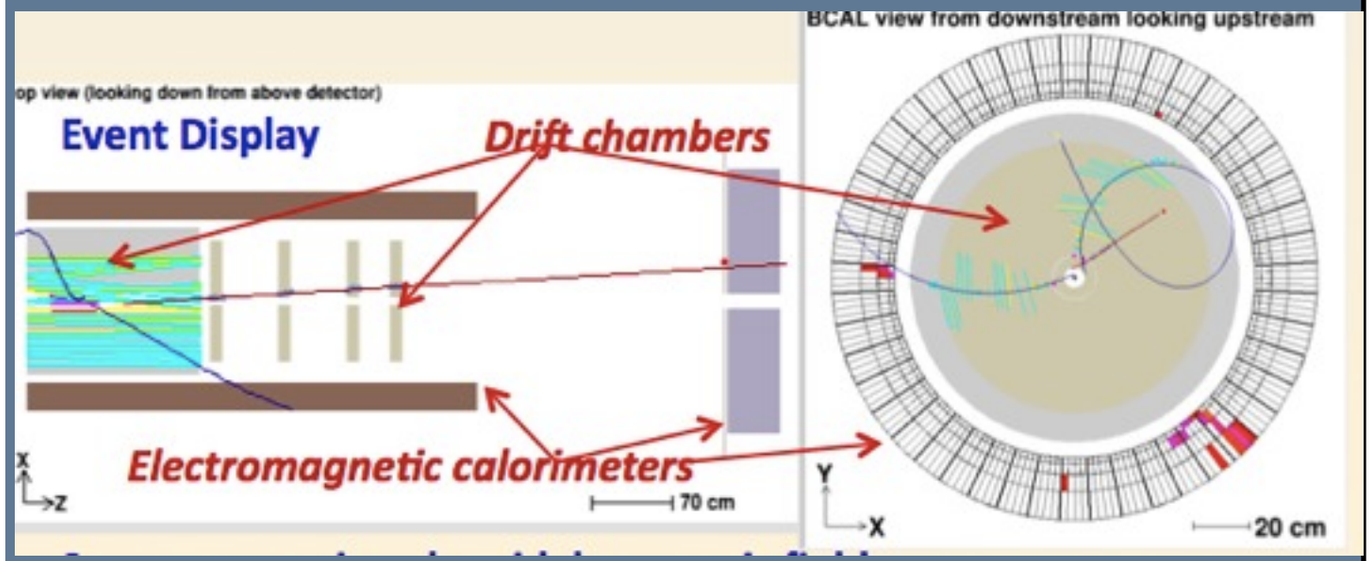
- **GlueX**
  - GlueX will study the spectrum of mesons up to M ~ 2.8 GeV with a linearly polarized photon beam, a large acceptance (neutrals and charged final particles) spectrometer, and search for mesons with sensitivities of a few percent of the total cross section.
- **GlueX status**
  - Civil construction of accelerator is completed.
  - Hall D experimental equipment is mostly completed.
  - Most GlueX systems are installed.
  - Hall D is being commissioned (2014-2015).
  - First “physics” beam expected for 2016.

First look: ω's and K_s's





$K_S \to \pi^+\pi^-$



Hall B: CLAS12

Forward Detector:

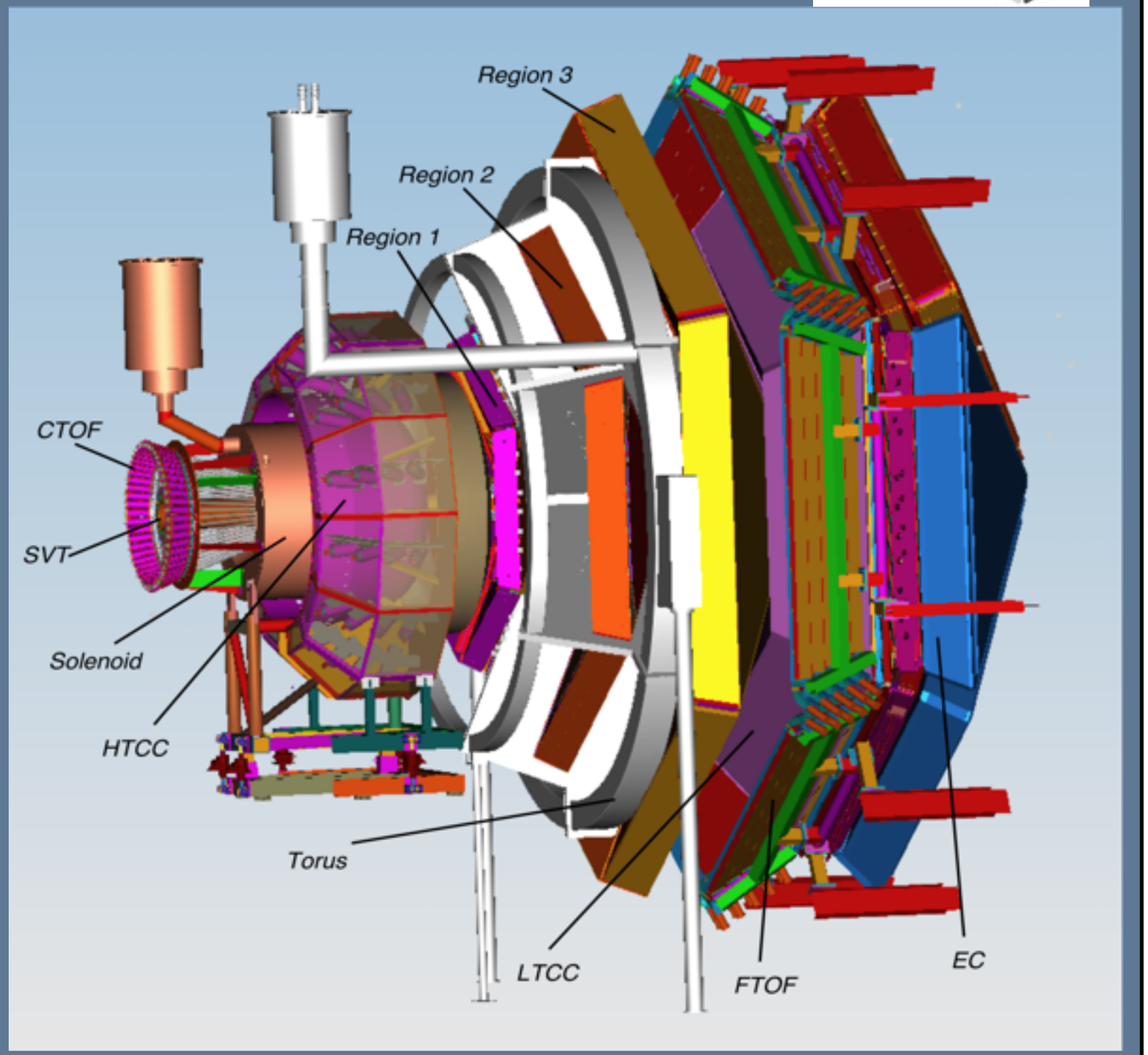
- *TORUS magnet*
- *Forward SVT tracker*
- *HT Cherenkov Counter*
- *Drift chamber system*
- *LT Cherenkov Counter*
- *Forward ToF System*
- *Preshower calorimeter*
- *E.M. calorimeter (EC)*

Central Detector:

- *SOLENOID magnet*
- *Barrel Silicon Tracker*
- *Central Time-of-Flight*

Proposed upgrades:

- *Micromegas (CD)*
- *Neutron detector (CD)*
- *RICH detector (FD)*
- *Forward Tagger (FD)*



Meson Spectroscopy
with low Q2 electron scattering in CLAS12

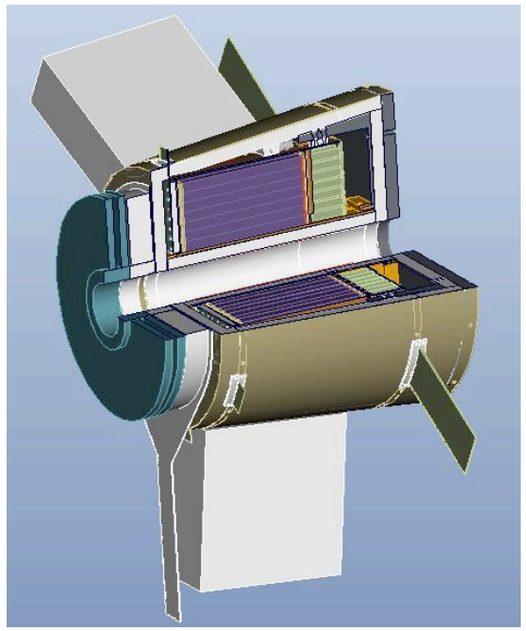
M.Battaglieri, R.Devita, D.Glazier, C.Salgado, S.Stepanyan, D.Weygand

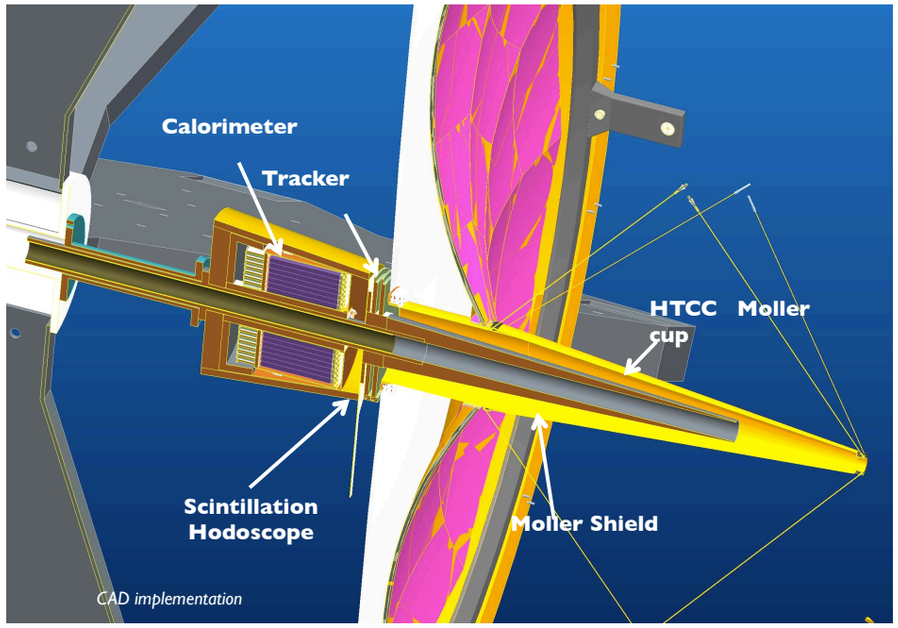
Electro-production a very Low -Q^2

Experiments using unpolarized leptons are equivalent in the small Q^2 limit to those using partially linearly polarized photons {Dombey 69}

- Measured electron scattering at very low forward angles
- low-Q^2 virtual photon ⇔ real photon (well known technique from high energy experiments)
- detection of the scattered electron allows to determine the photon energy and linear polarization
- polarization is essential to isolate the exchange production mechanisms
- high luminosity allows the use of thin (gas)- targets

The Forward Tagger for CLAS12





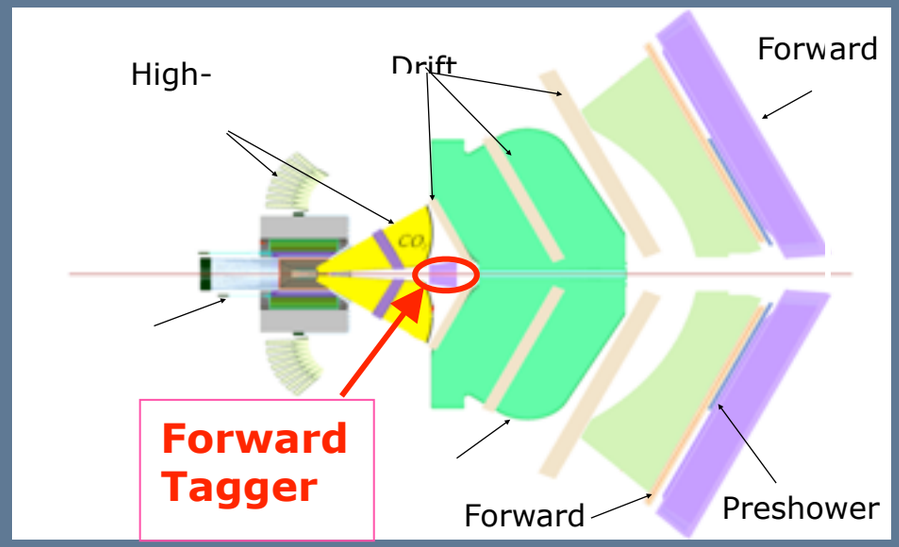
FT-Cal: $PbWO_4$ calorimeter
electron energy/momentum
Photon energy (ν=E-E')
Polarization $\varepsilon^{-1} \approx 1 + \nu^2/2EE'$

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

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

Quasi-real photons will be "tagged" by detection of scattered electrons at low forward angles

- electron beam on target, scattered electrons at small angles are detected by the forward detector



- CLAS12+Forward Tagger Detector
- CLAS12 will study the spectrum of mesons up to M ~ 2.8 GeV with a virtual photon beam, a large acceptance (neutrals and charged final particles) spectrometer, and search for mesons with sensitivities of a few percent of the total cross section.
- **CLAS12 (FWD)** status
  - Civil construction of accelerator is completed.
  - CLAS12 experimental equipment is being completed.
  - The Forward Tagger Detector is planned for installation in 2016
  - Hall B commissioning by the end of 2016.
  - First “physics” beam expected for 2017.

Conclusions

Meson Spectroscopy together with LQCD calculations promise to provide a window to detailed studies of **strong interactions** at intermediate energies

High-statistics experiments : (GlueX/CLAS12 - Compass - Panda)

Two Meson Spectroscopy programs at Jefferson Lab

- **CLAS12** using a beam of "quasi-real" photons
- **GlueX** using a linearly polarized real photon beam

Analysis progress :

- **Theory:** improve models - include more "constraints" in PWA
- **Computing:** increase computer efficiency - Parallel computing - vectorization of existing code (GPU, Xeon Phi). Faster / user friendly.
- **Algorithms:** Minimization/Optimization (Genetic Algorithms,...)

For improving the understanding of the meson spectrum we will need to analyze data from different beams (production mechanisms), different channels (coupled channel analysis) and consider an improvement in our analysis tools accordingly with the expected high statics experiments (better resolutions).

Thank you for listening!