Hadron Spectroscopy at CLAS and CLAS12

Raffaella De Vita (Jefferson Lab)
for the CLAS Collaboration

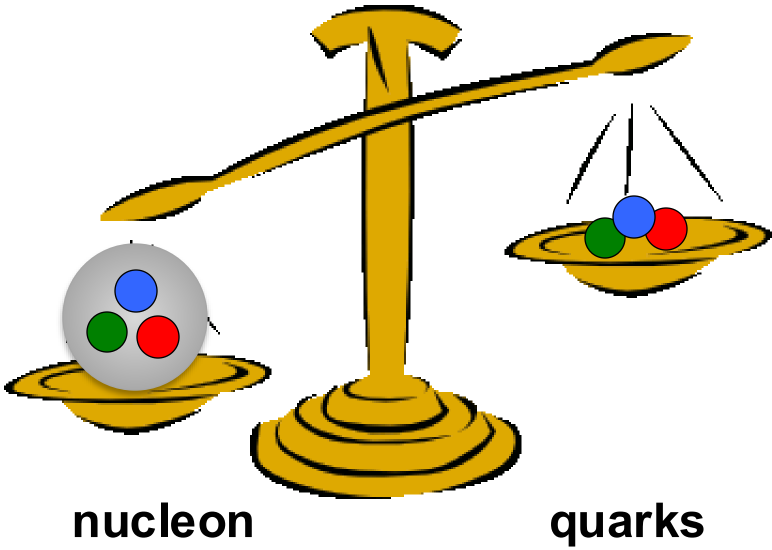
QCD and Spectroscopy

- Hadrons are one of the most relevant manifestations of the works of QCD

- Hadrons have an internal structure being made of quarks: known quark configurations are baryons, made of tree quarks and mesons, made of quark-antiquark pairs
- Quark masses account only for a small fraction of the nucleon mass: ~ 1%
  - $m_q \sim 10$ MeV
  - $m_N \sim 1000$ MeV

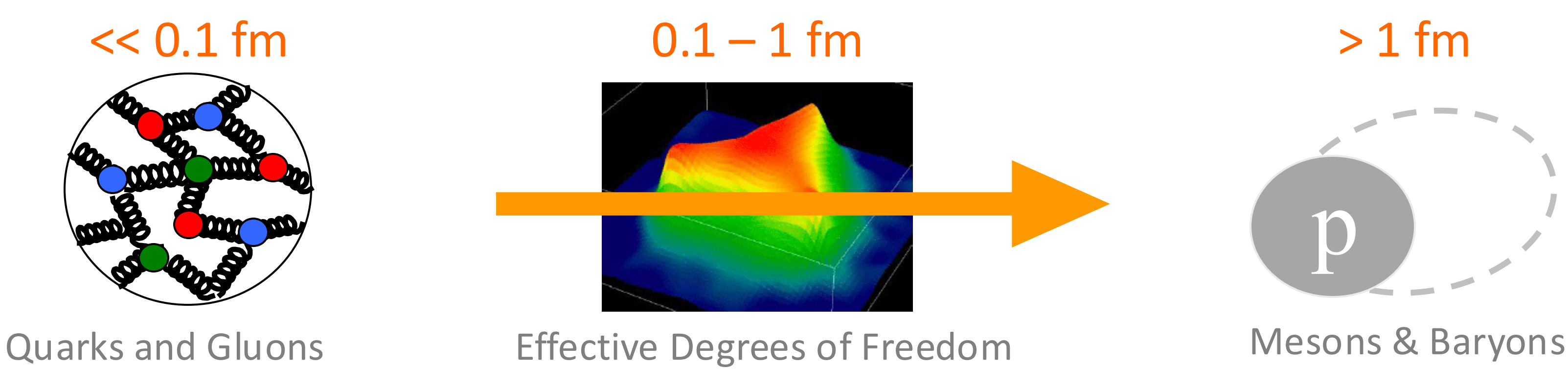
  while the remaining fraction is to to the force that binds the quarks: **QCD**

- Hadron spectroscopy is a “portal” to Quantum Chromo Dynamics



Spectroscopy at CLAS and CLAS12

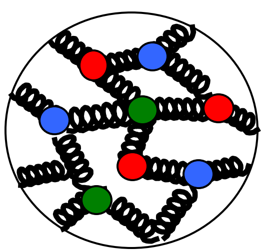
- Quark confinement and the role of the glue in meson and baryon spectroscopy:
  – What is the internal structure and what are the internal degrees of freedom of hadrons?
  – What is the role of gluons?
  – What is the origin of quark confinement?
  – Are 3-quarks and quark-antiquark the only possible configurations?



Spectroscopy at CLAS and CLAS12

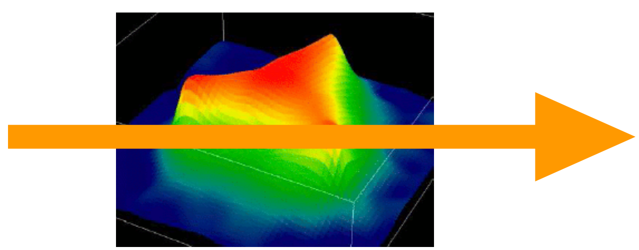
- Quark confinement and the role of the glue in meson and baryon spectroscopy:
  - Study of nucleon resonances in electroproduction
  - Hyperon spectroscopy and production of “very-strange” states
  - J/Psi photoproduction and LHCb pentaquark search
  - Real and quasi-real photoproduction of light-quark mesons

<< 0.1 fm



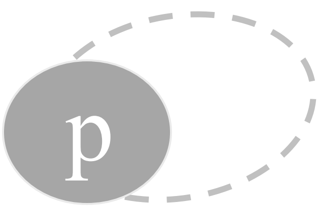
Quarks and Gluons

0.1 – 1 fm



Effective Degrees of Freedom

> 1 fm



Mesons & Baryons

Hadron spectroscopy

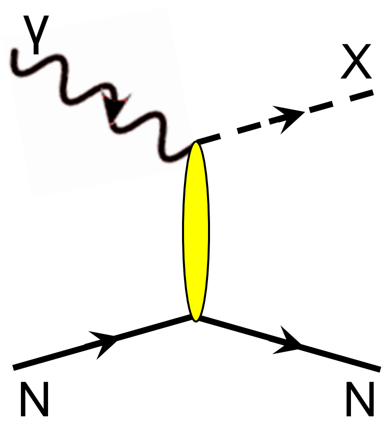
Objective:

Understand how quarks interact to form hadrons and what the role of gluons is

- Precise determination of the meson and baryon spectrum
- Study of poorly known states, e.g. , strangeness-rich resonances, …
- Search for unusual states as hybrids (qqg), tetraquarks (qqqq) and glueballs

Technique:

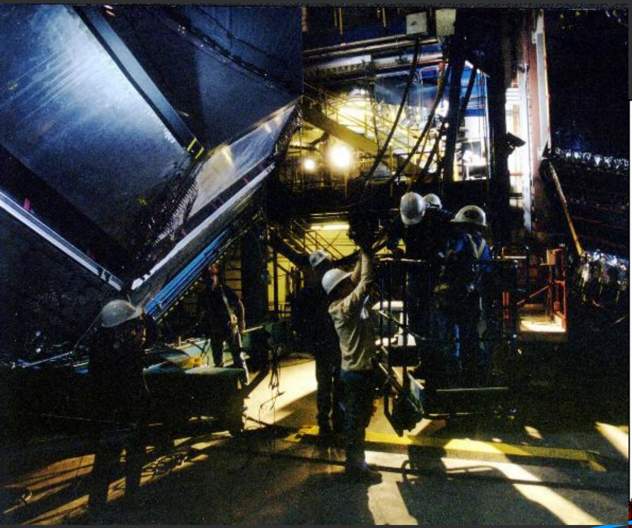
Use virtual or (quasi) real photon beams to produce the resonances and isolate the single states by detecting the decay products



- Use of S=1 probe provides complementary information to S=0 (pion beams) probes
- Measurement of the decay products and PWA to isolate single resonances
- Full determination of the initial state allows for the study of the production mechanism

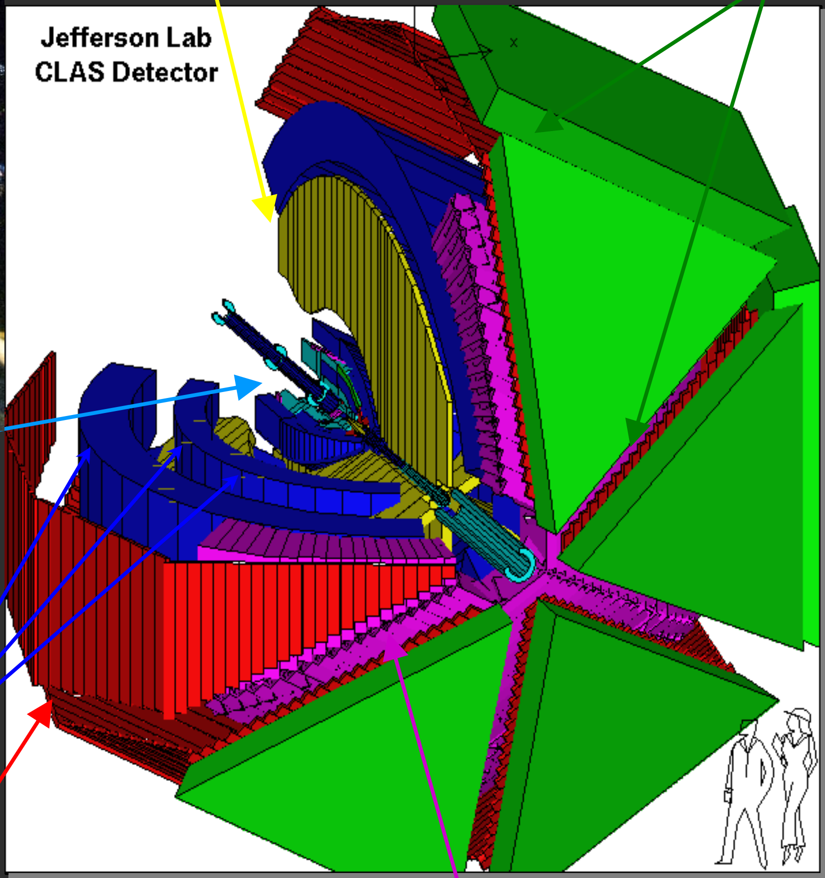
- High intensity photon beams and large acceptance detector are needed!!

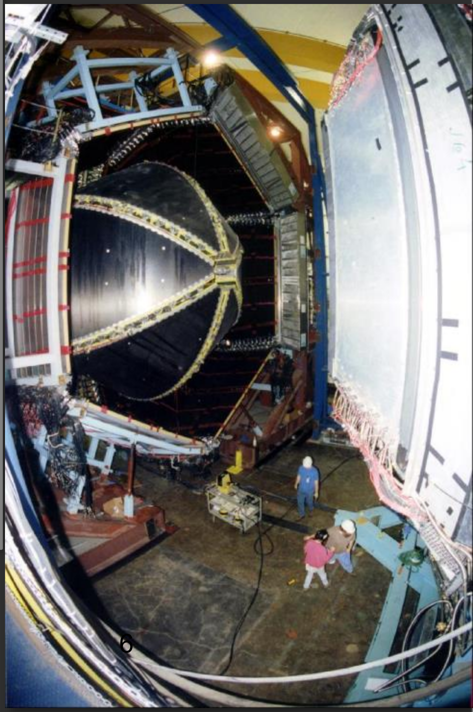
CEBAF Large Acceptance Spectrometer



Torus Magnet
6 Superconductive Coils

Electromagnetic Calorimeter
lead/plastic scintillator, 1296 PMTs





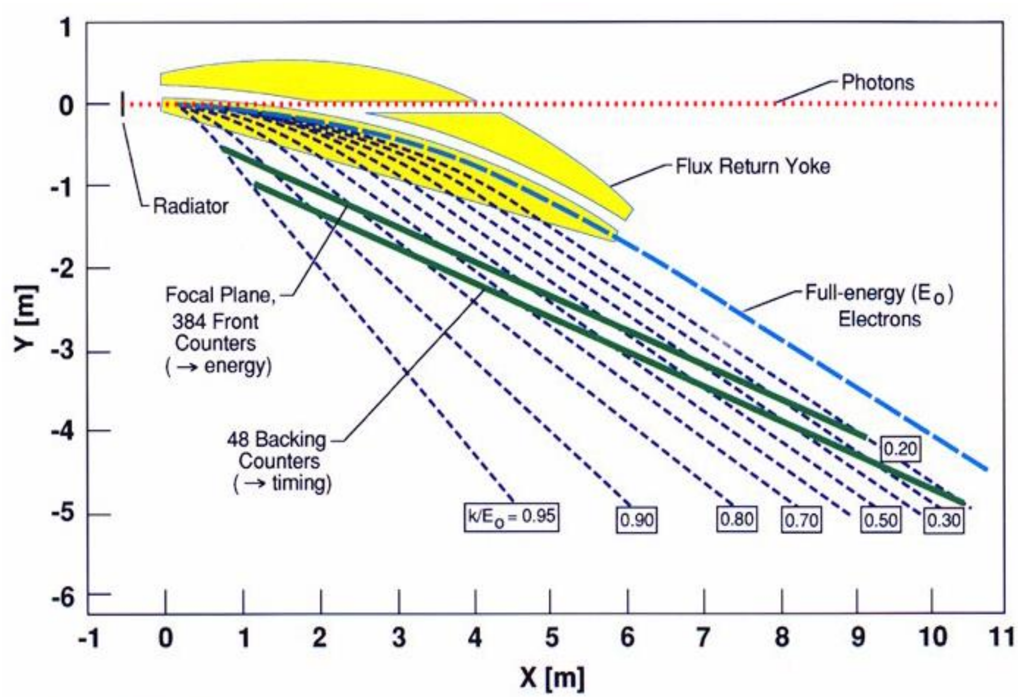
Target +
γ start counter
e mini-torus

Drift Chamber
35,000 cells

Time of Flight
Plastic Scintillator,
684 PMTs

Cherenkov Counter
e/π separation, 256 PMTs

Hall B Photon Tagger



- Photon beam produced from the primary electron beam via Bremsstrahlung
- Gold and diamond radiator for In/Coherent Bremsstrahlung
- Energy coverage: 0.2-0.95 E_0
- Efficiency ~ 80%
- Energy Resolution ~ 10^{-3}
- Timing Resolution ~100 ps

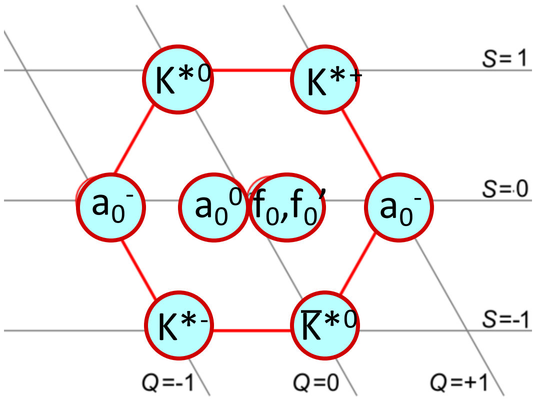
✱ Maximum photon energy of 5.7 GeV
- W_{max} ~ 3.4 GeV

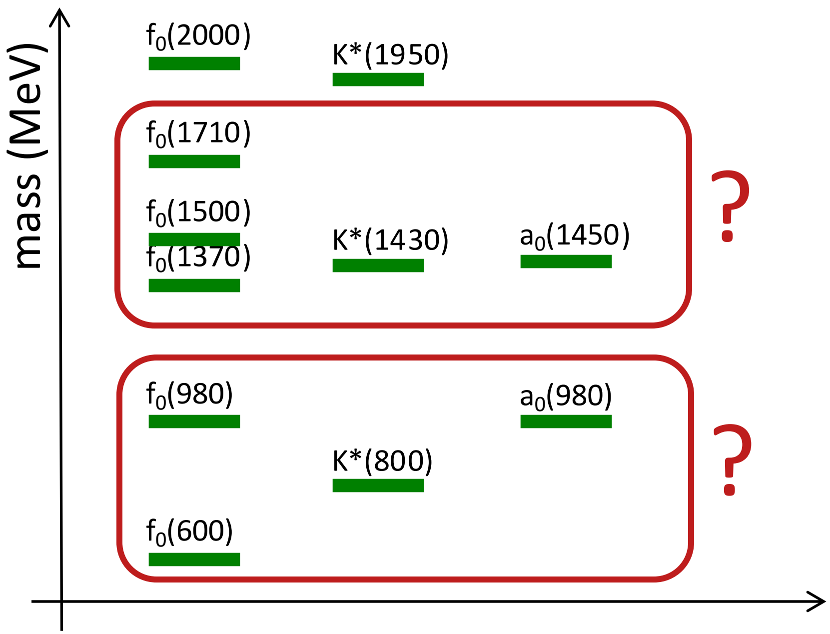
✱ Beam intensity 10^7 γ/s

Scalar mesons and the $f_0(980)$

Scalars are fundamental states because they represent the Higgs sector of strong interaction:

- same quantum numbers of the QCD vacuum
- responsible for chiral symmetry breaking





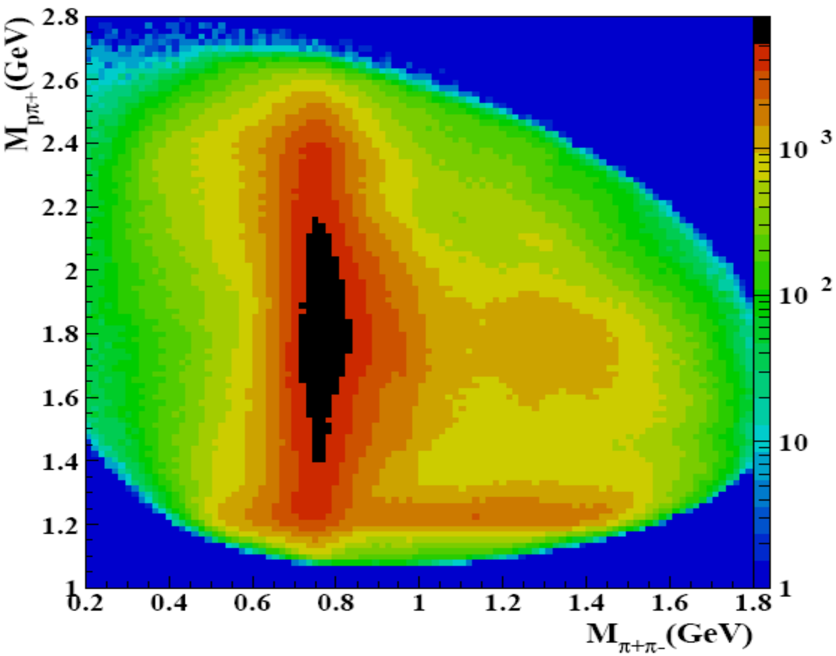
The $f_0(980)$ is one of the lowest mass scalar and isosinglet candidate of the first nonet:

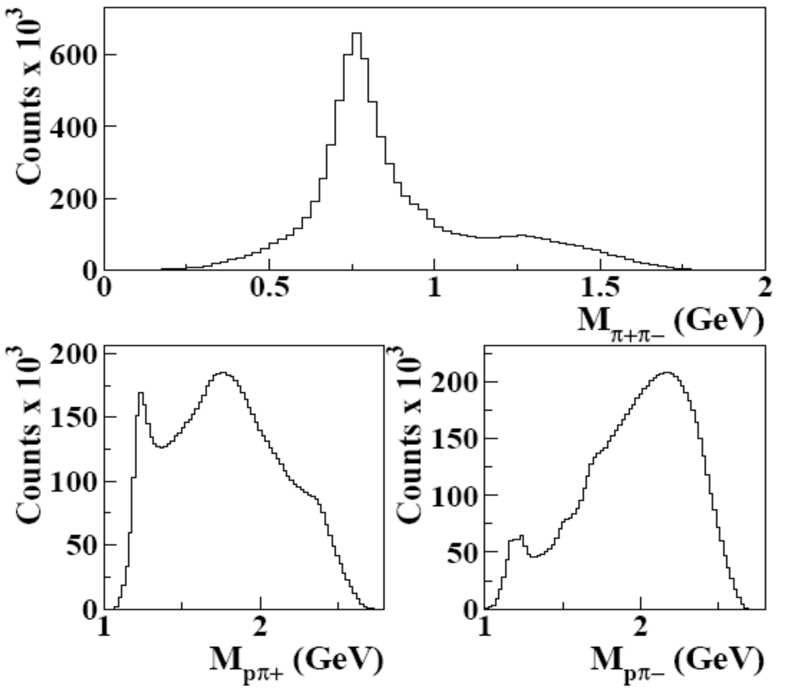
➔ Unusual mass hierarchy of the multiplet ($f_0(980)$ almost degenerate with $a_0(980)$) and decays led to propose these states as tetraquarks

The $f_0(980)$ at CLAS

Study of $\pi^+\pi^-$ production on the proton and of scalar meson production

- Bremsstrahlung photon beam: 1.6-3.8 GeV
- 40 cm long liquid hydrogen target
- ~$7\cdot10^9$ triggers
- Integrated Luminosity ~ 80 pb^{-1}



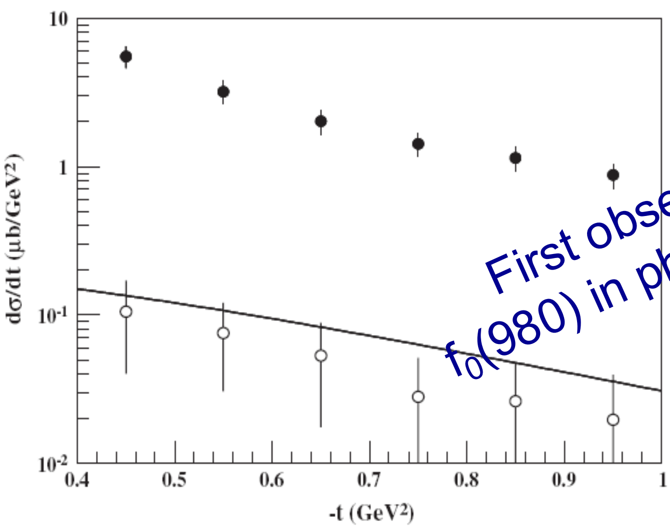


- Proton and π^+ detected in CLAS
- Reaction $\gamma p \to p\pi^+\pi^-$ isolated via missing mass
- Analysis focused on high energy (3.0-3.8 GeV) and low –t (0.4-1.0 GeV^2) region

The $f_0(980)$ at CLAS

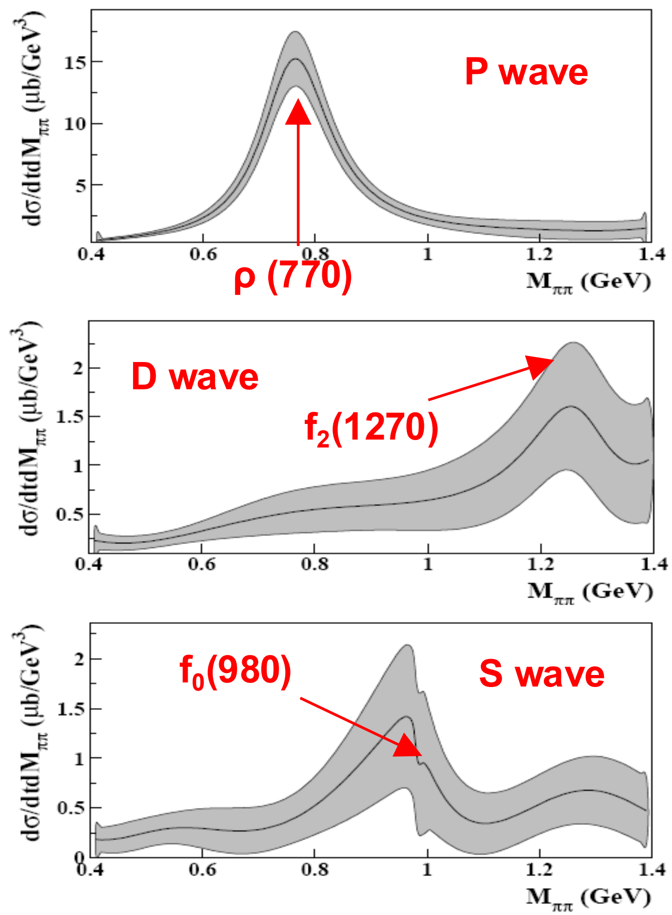
$\gamma p \rightarrow p\pi^+\pi^-$

- $M(\pi^+\pi^-)$ spectrum below 1.5 GeV:
    - P-wave: ρ meson
    - D-wave: $f_2(1270)$
    - S-wave: σ, $f_0(980)$ and $f_0(1370)$
- Moments of the 2-pion angular distribution extracted via likelihood fit of data
- Partial Wave fitted to experimental moments
- **Known states well reproduced, e.g. $\rho(770)$**



First observation of $f_0(980)$ in photoproduction

3.4 GeV < E_g < 3.6 GeV
0.5 GeV^2 < -t < 0.6 GeV^2



M. Battaglieri et al. (CLAS Collaboration), PRL 102, 102001

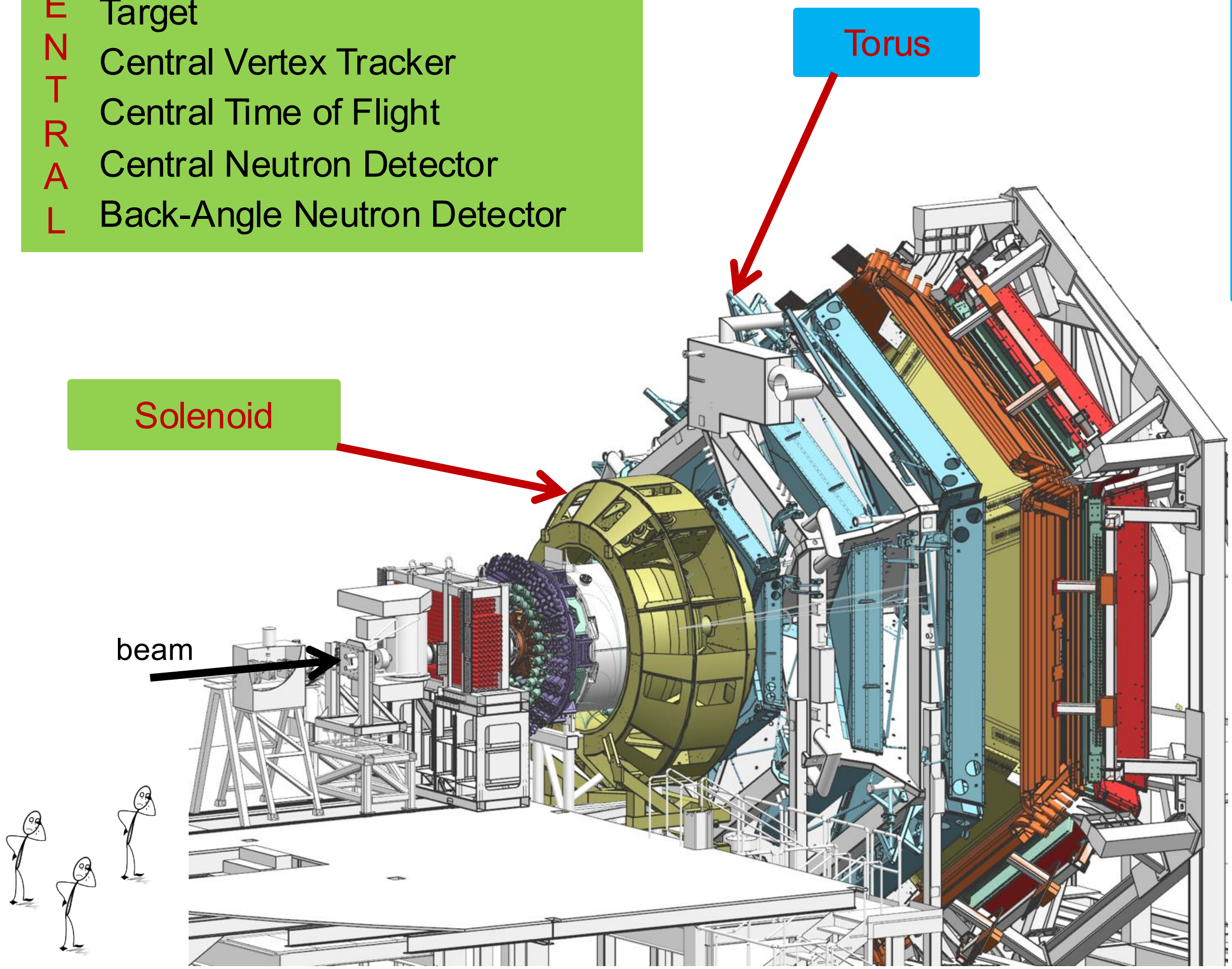
CLAS12

C E N T R A L

- Beamline
- Target
- Central Vertex Tracker
- Central Time of Flight
- Central Neutron Detector
- Back-Angle Neutron Detector

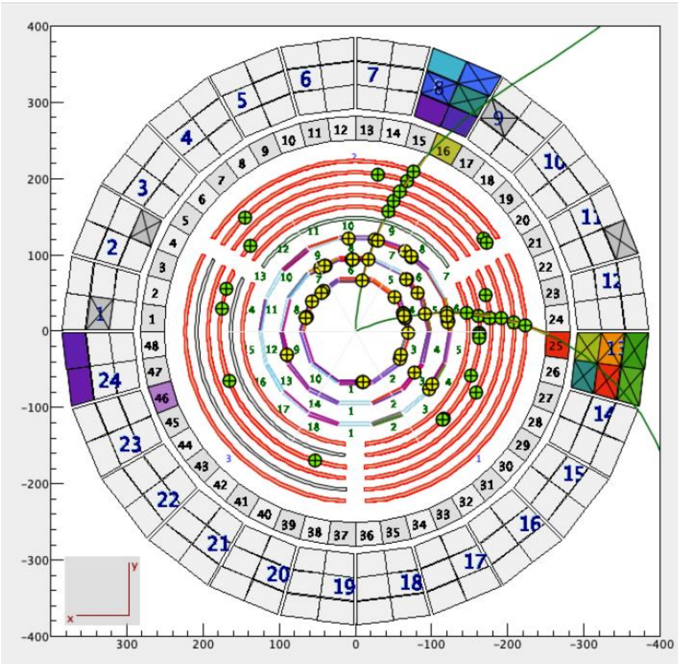
F O R W A R D

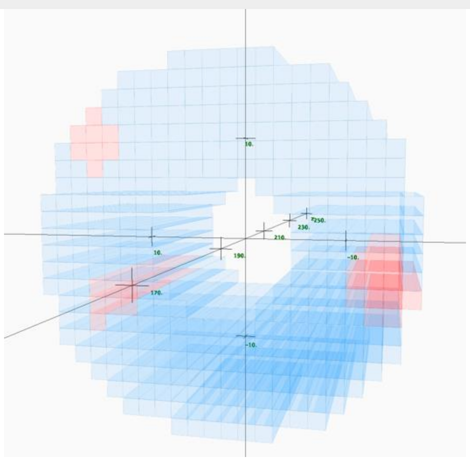
- High Threshold Cherenkov
- Forward Tagger
- Drift Chambers
- Low Threshold Cherenkov
- Ring Imaging Cherenkov
- Forward Time of Flight
- EM Calorimeter

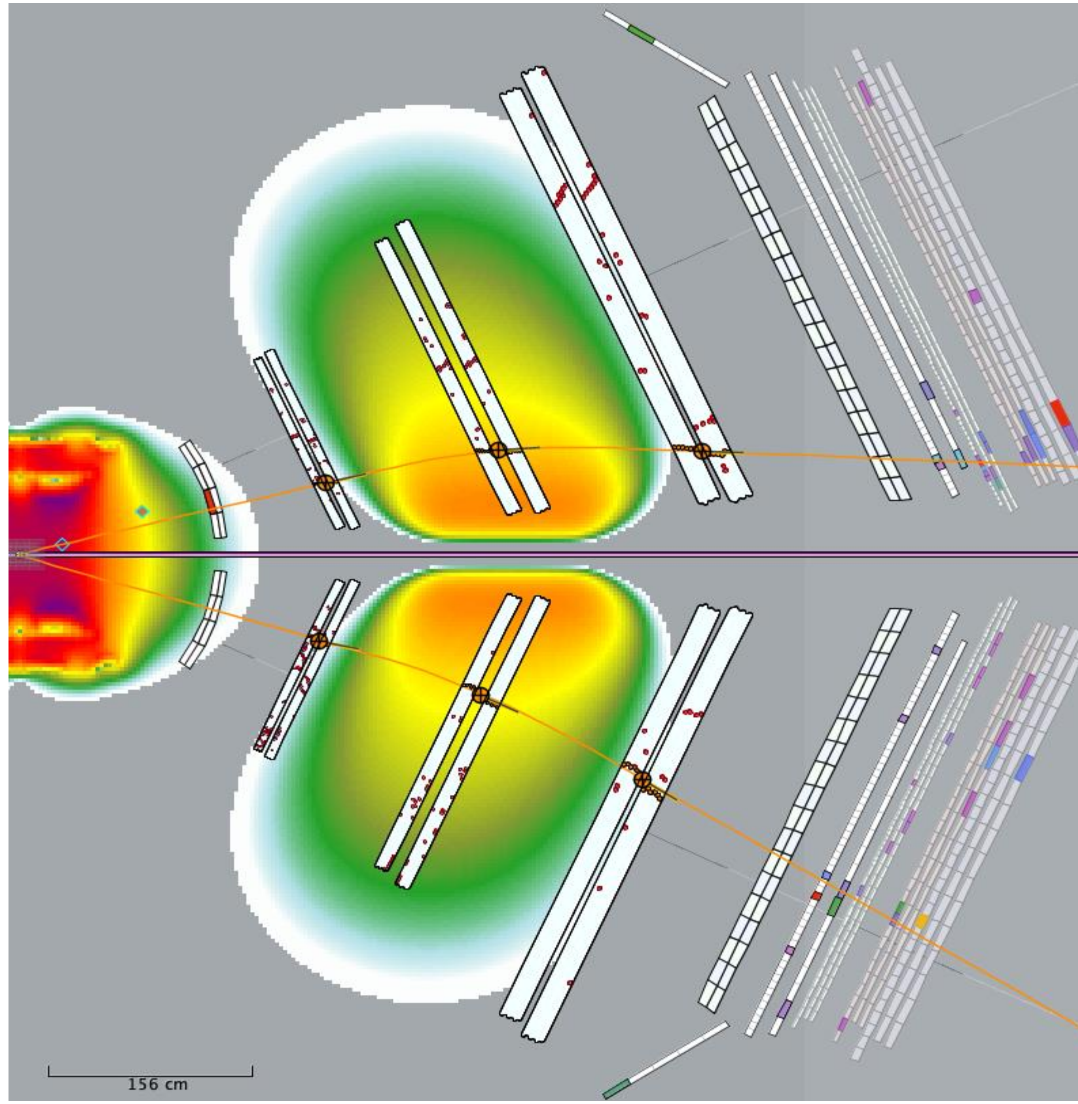


	Forward	Central
Angular coverage	5° – 35°	35° – 135°
Momentum resolution	dp/p < 1%	dp/p < 5%
θ resolution	1 mrad	5 – 10 mrad
ϕ resolution	1 mrad/sinθ	5 mrad/sinθ

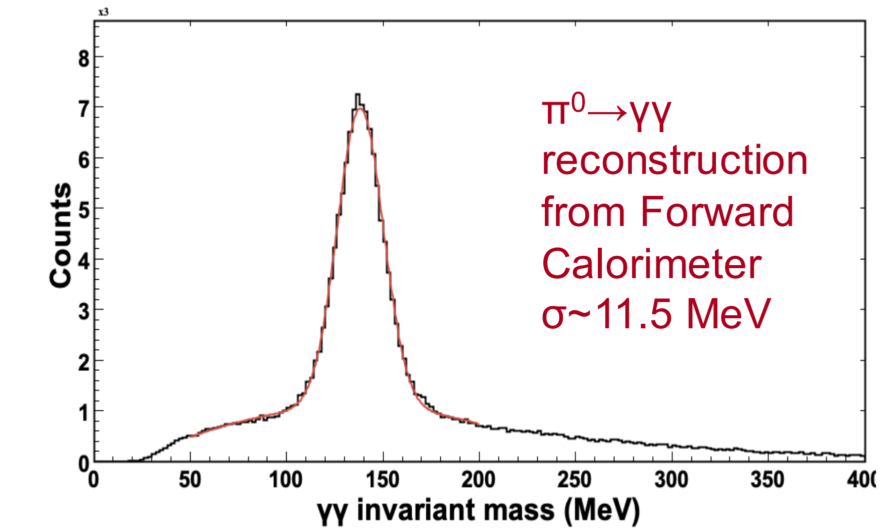
CLAS12 Event Display

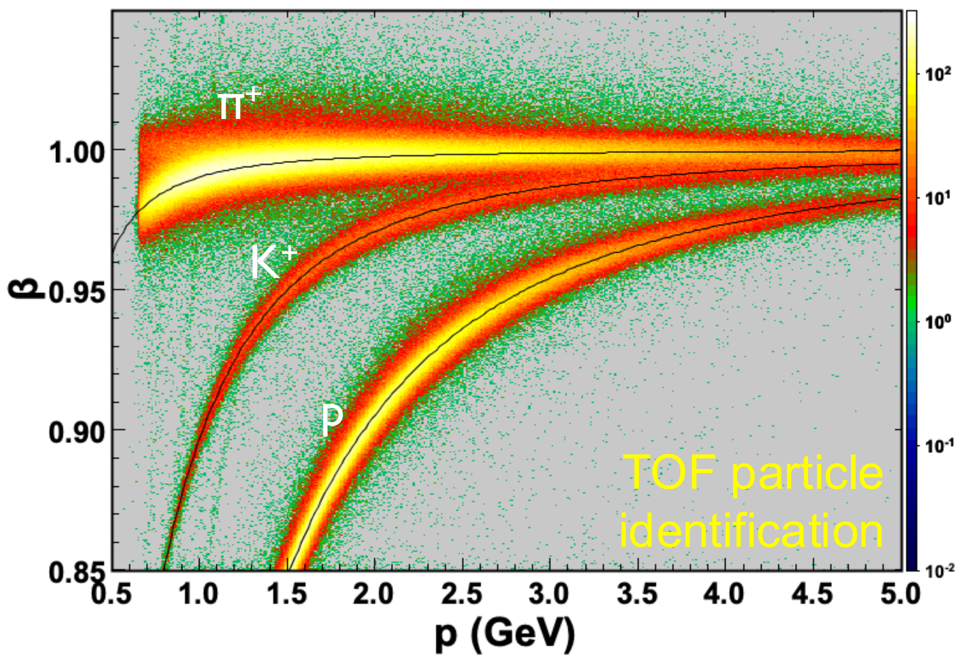


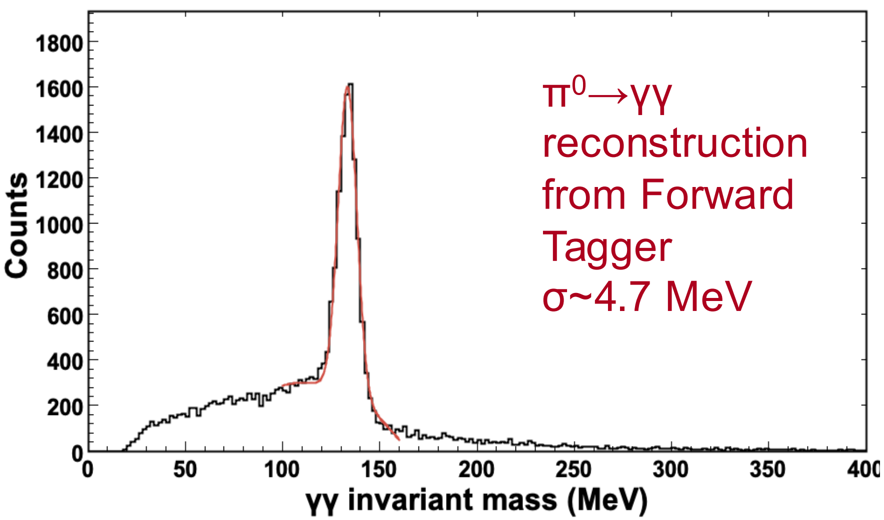


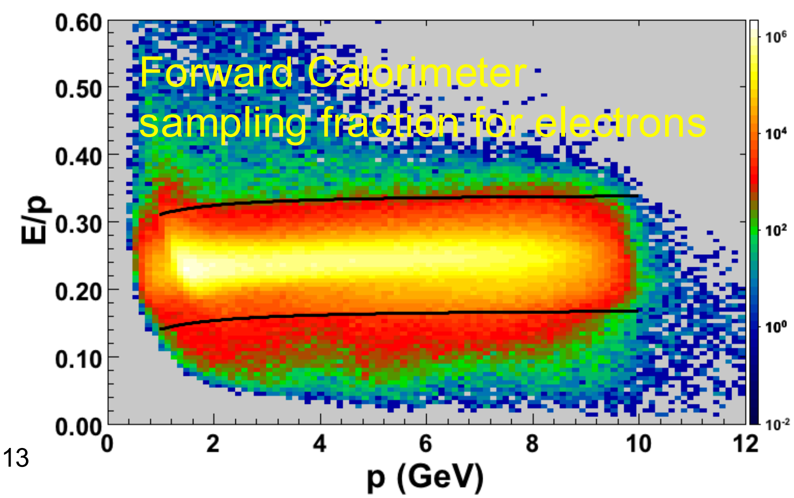


Event reconstruction

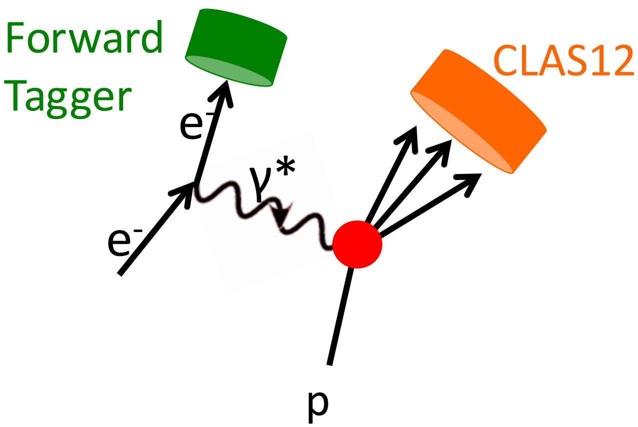








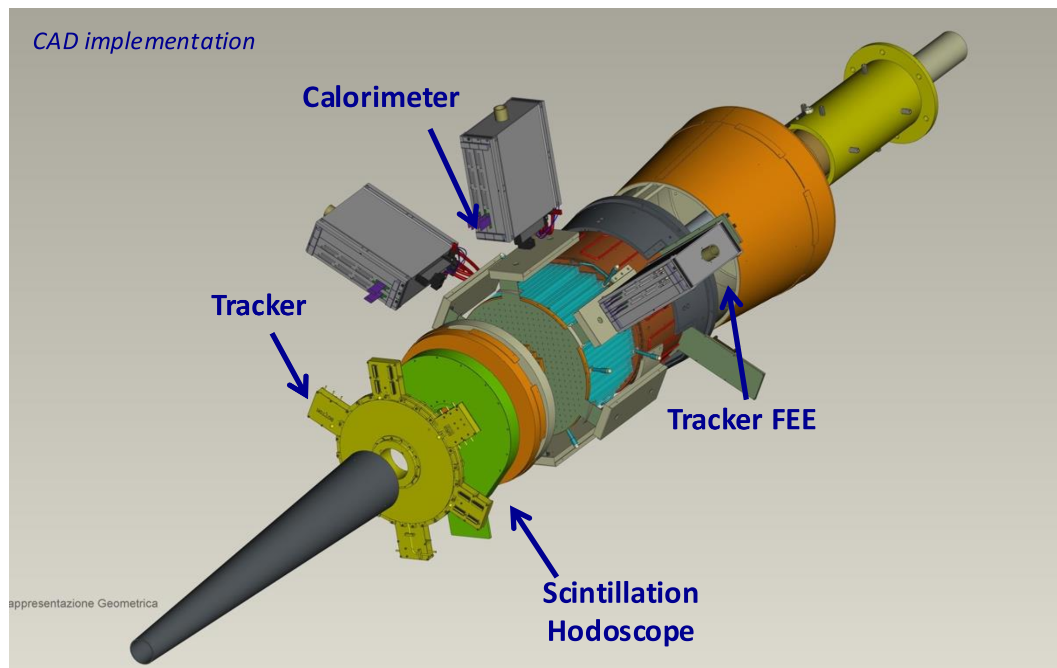
Quasi-real photoproduction



- Detection of multiparticle final state from meson decay in the large acceptance spectrometer CLAS12
- Detection of the scattered electron for the tagging of the quasi-real photon in the CLAS12 Forward Tagger
- High-intensity and high-polarization tagged "photon" beam; degree of polarization can be determined event-by-event from the electron kinematics

MesonEx:

- Detailed mapping of the meson spectrum up to masses of 2.5 GeV
- Search for rare or poorly known states (strangeness-rich, scalars, …)
- Search states with unconventional quark-gluon configurations



MesonEx status

- Approximately 35% of expected data available for analysis after major improvements to event reconstruction
- Focus on charged decay products (better resolution)
- First extract two pseudoscalar ($\pi^+\pi^-$, K^+K^-)
- Fourier analysis of angular distributions, i.e. extract moments
  - more general expansion than just partial waves
  - check acceptance corrections
  - check distortions from backgrounds
  - model independent formalism
  - already applied to CLAS di-meson photoproduction data
- Extract partial waves from moments or directly fit partial waves
- Expand to vector-pseudoscalar final states

arXiv.org > hep-ph > arXiv:1906.04841

Search...

Help | Advanc

High Energy Physics - Phenomenology

Moments of angular distribution and beam asymmetries in $\eta\pi^0$ photoproduction at GlueX

V. Mathieu, M. Albaladejo, C. Fernández-Ramírez, A. W. Jackura, M. Mikhasenko, A. Pilloni, A. P. Szczepaniak (JPAC collaboration)

(Submitted on 11 Jun 2019)

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

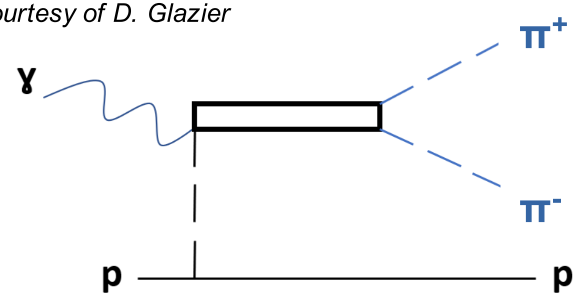
Moments relate directly to partial wave amplitudes

$$\begin{aligned}
H^0(11) &= H^1(11) + 2\sqrt{\frac{2}{5}}\,\mathrm{Re}(P_1^{(+)} D_2^{(+)*}) \ , \\
H^1(11) &= \frac{2}{15}\left[3\sqrt{5}\,\mathrm{Re}(P_0^{(+)} D_1^{(+)*}) - \sqrt{15}\,\mathrm{Re}(P_1^{(+)} D_0^{(+)*}) + 5\sqrt{3}\,\mathrm{Re}(S_0^{(+)} P_1^{(+)*})\right] \ , \\
H^0(20) &= H^1(20) - \frac{2}{35}\left[7|P_1^{(+)}|^2 - 5|D_1^{(+)}|^2 + 10|D_2^{(+)}|^2\right] \ , \\
H^1(20) &= \frac{4}{35}\left[7|P_0^{(+)}|^2 + 5|D_0^{(+)}|^2 + 7\sqrt{5}\,\mathrm{Re}(S_0^{(+)} D_0^{(+)*})\right] \ , \\
H^0(21) &= H^1(21) + \frac{2}{7}\sqrt{6}\,\mathrm{Re}(D_1^{(+)} D_2^{(+)*}) \ , \\
H^1(21) &= \frac{2}{35}\left[7\sqrt{5}\,\mathrm{Re}(S_0^{(+)} D_1^{(+)*}) + 7\sqrt{3}\,\mathrm{Re}(P_0^{(+)} P_1^{(+)*}) + 5\,\mathrm{Re}(D_0^{(+)} D_1^{(+)*})\right] \ ,
\end{aligned}$$

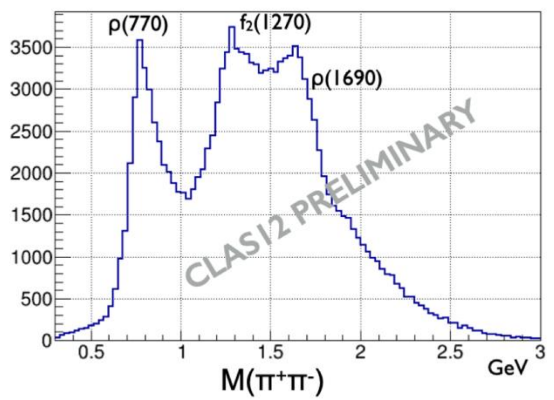
Analysis carried out by a team involving several institutions and collaborators (Glasgow, INFN, Jlab, York, …)

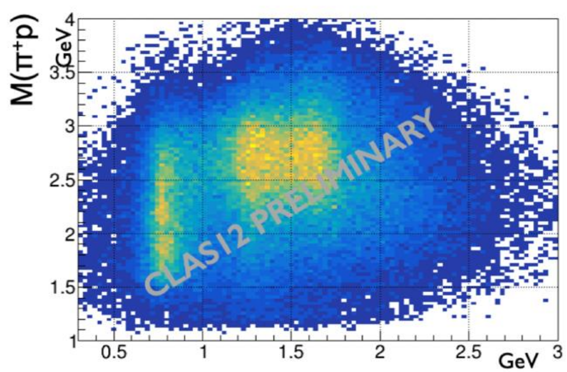
MesonEx: $\pi^+\pi^-$ p preliminary data

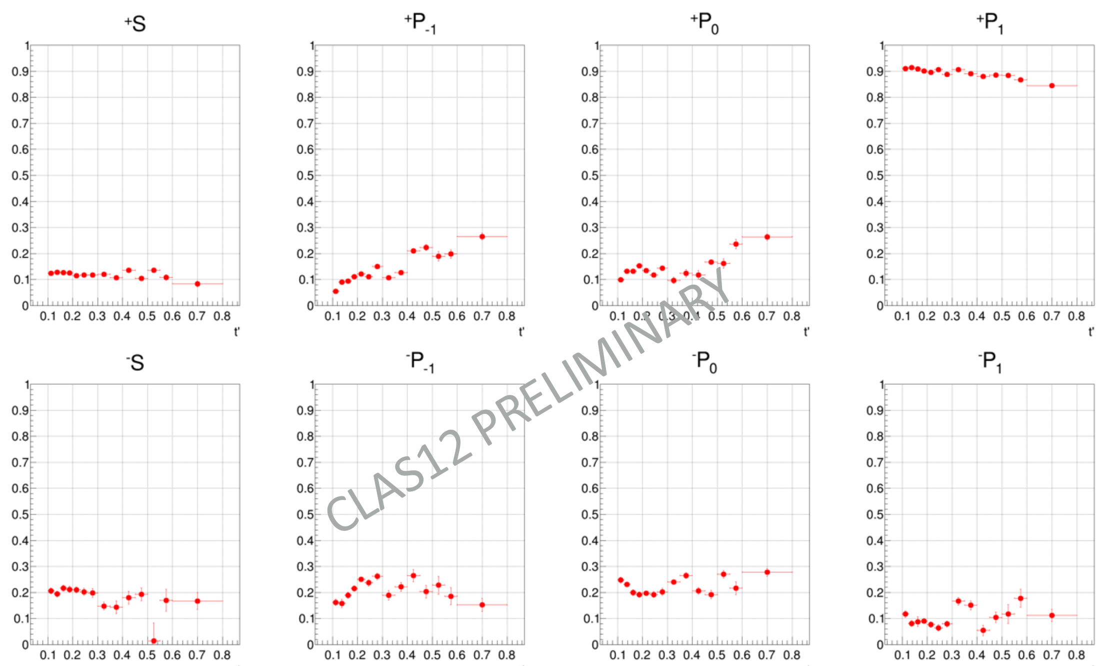
Courtesy of D. Glazier



- 10.6 GeV electron beam on LH2 target
- Detection of fully exclusive final state:
  - Low acceptance for mpp<1.1 GeV
- Need to account for baryon contribution
- Analysis tools, including PWA, are ready
- Preliminary results in good agreement with expectations from S-channel helicity conservation and pomeron exchange

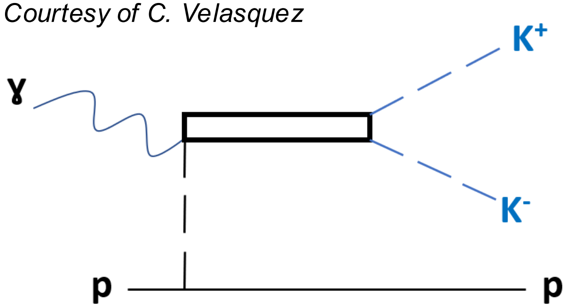


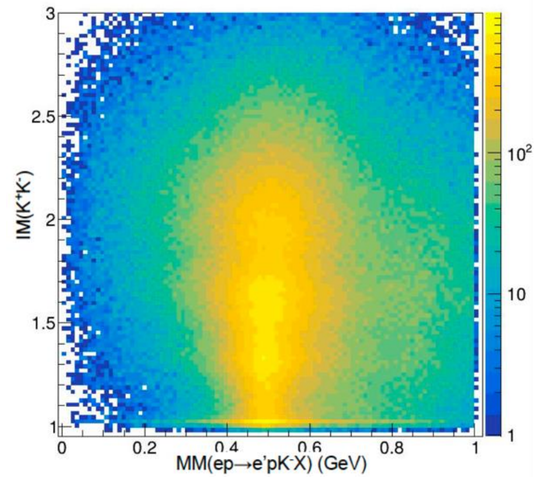




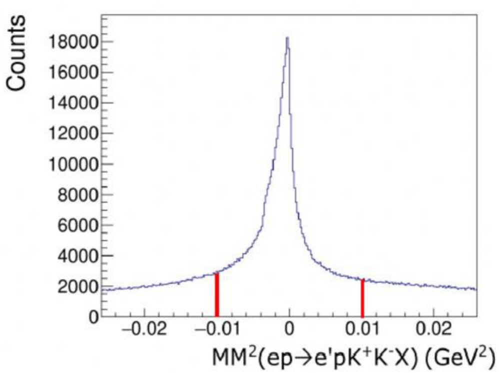
MesonEx: K^+K^- p preliminary data

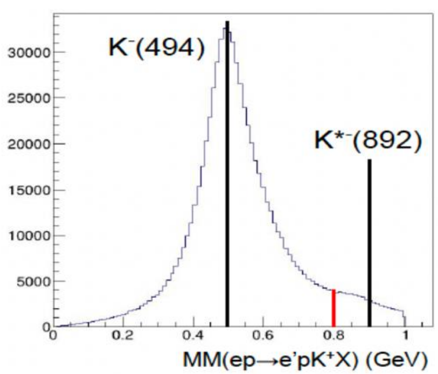
Courtesy of C. Velasquez

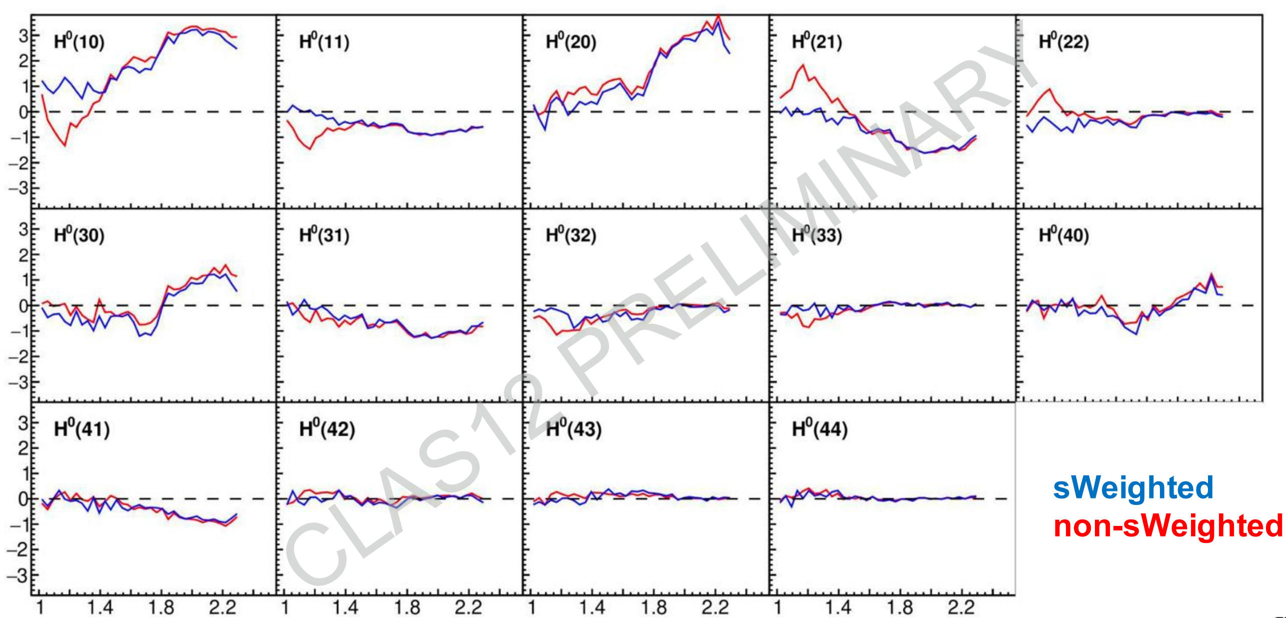




- Analysis developed using 1/2 of the available statistics
- Kaon identification based on Time-of-Flight technique
- Pion contamination highly suppressed by detecting the fully exclusive final state … still to be accounted for



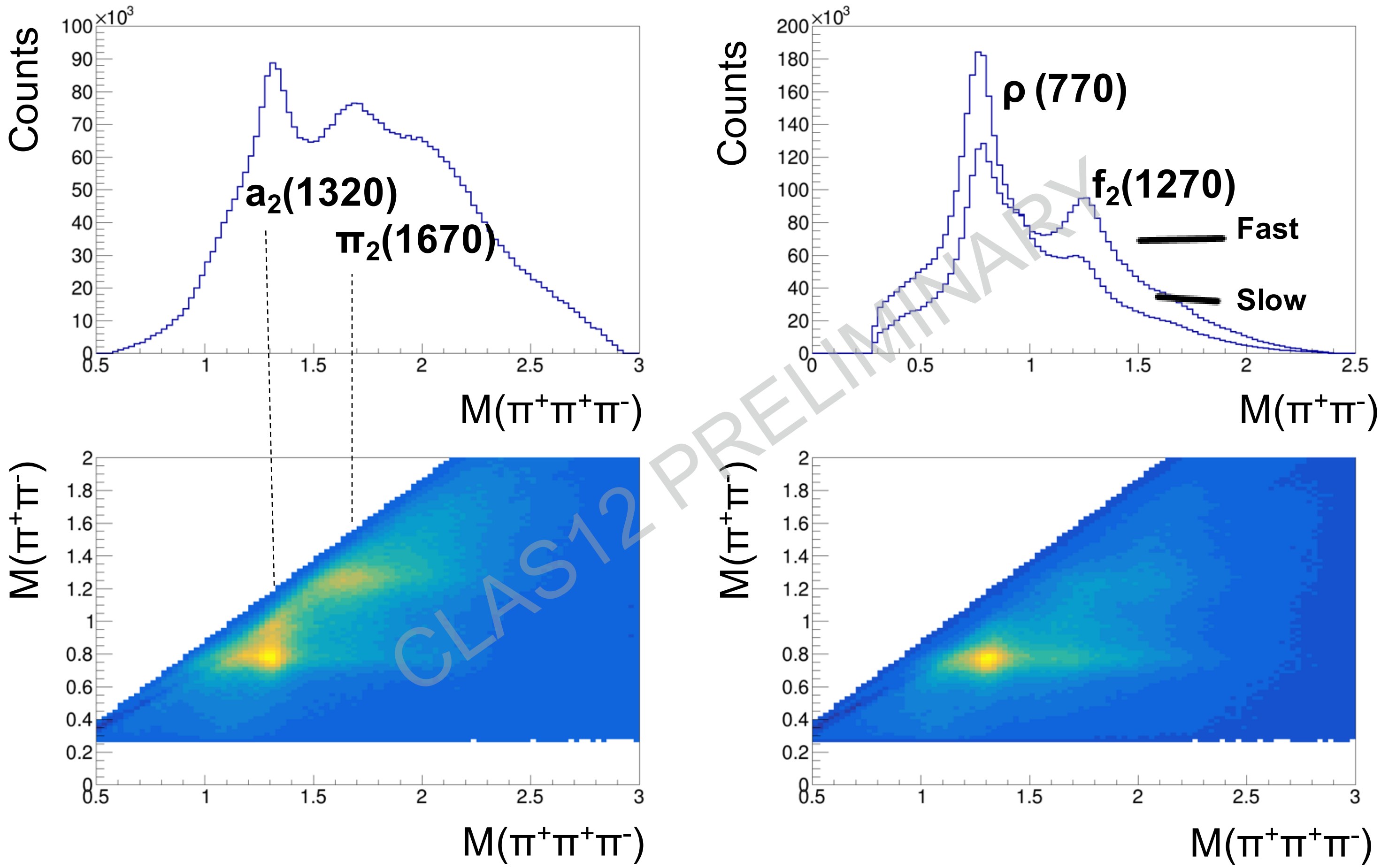




CLAS12 $\pi^+\pi^+\pi^- n$ preliminary data

Courtesy of D. Glazier

- Preliminary analysis of 3 pion channel from the 10.6 GeV data
- Candidate for search of the exotic $\pi_1(1600)$
- Spectrum richness already accessible with a fraction of the expected data



Why studying the Λ(1405)

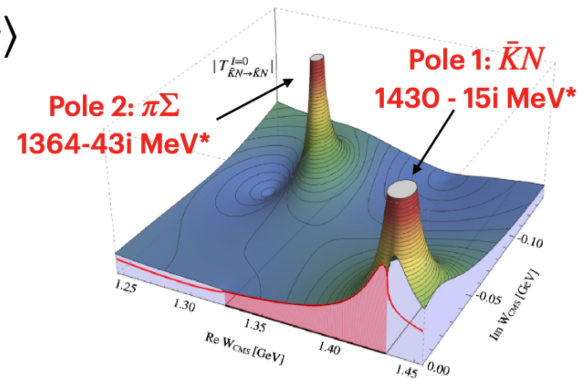
Description of the Λ(1405) as hadron molecular state

Courtesy of Tatsuhiro Ishige

$$|\Lambda(1405)\rangle = |\text{meson}\rangle \otimes |\text{baryon}\rangle \otimes |s\ wave\rangle$$

$0\left(\frac{1}{2}^-\right)$ couples to

$\pi : 1\,(0^-)$	$\Sigma : 1\left(\frac{1}{2}^+\right)$
$\bar{K} : \frac{1}{2}\,(1^-)$	$N : \frac{1}{2}\left(\frac{1}{2}^+\right)$
$\eta : 0\,(0^-)$	$\Lambda : 0\left(\frac{1}{2}^+\right)$
$K : \frac{1}{2}\,(0^-)$	$\Xi : \frac{1}{2}\left(\frac{1}{2}^+\right)$



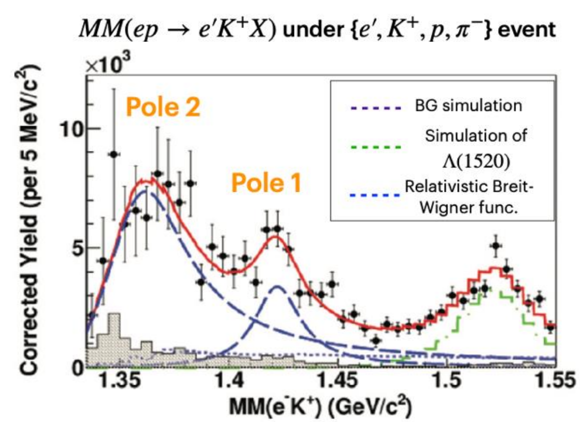
M. Mai, Eur. Phys. J. Spec. Top. (2021) 230:1593-1607

* S. Navas et al. (Particle Data Group), "83. Pole Structure of the Λ(1405) Region", Phys. Rev. D 110, 030001 (2024)

Expect two states in one resonance!

Previous CLAS results

- Position of poles, line shape, and photoproduction cross section measurement
- Study of Q^2 dependence not possible due to limited statistics
  - Now possible with CLAS12



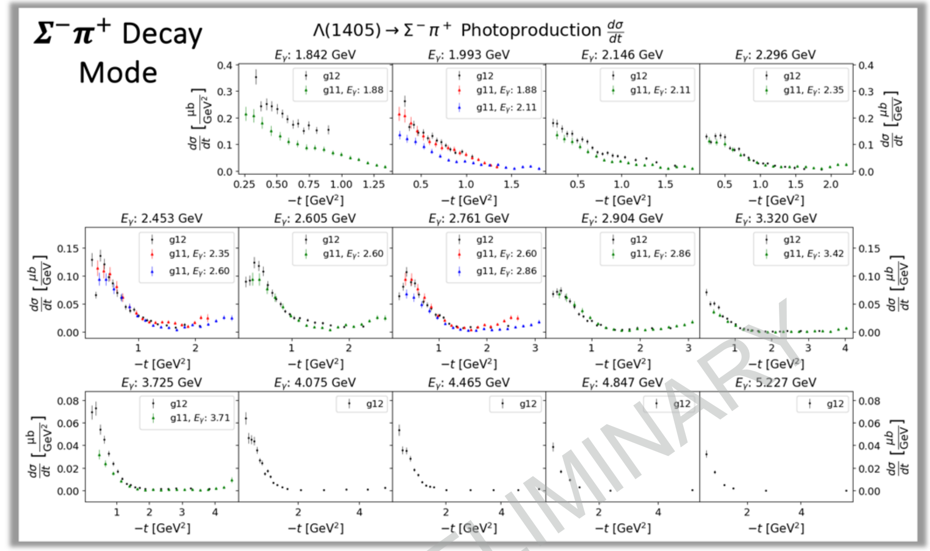
* H. Lu et al., Phys. Rev. C 88, 045202 (2013)

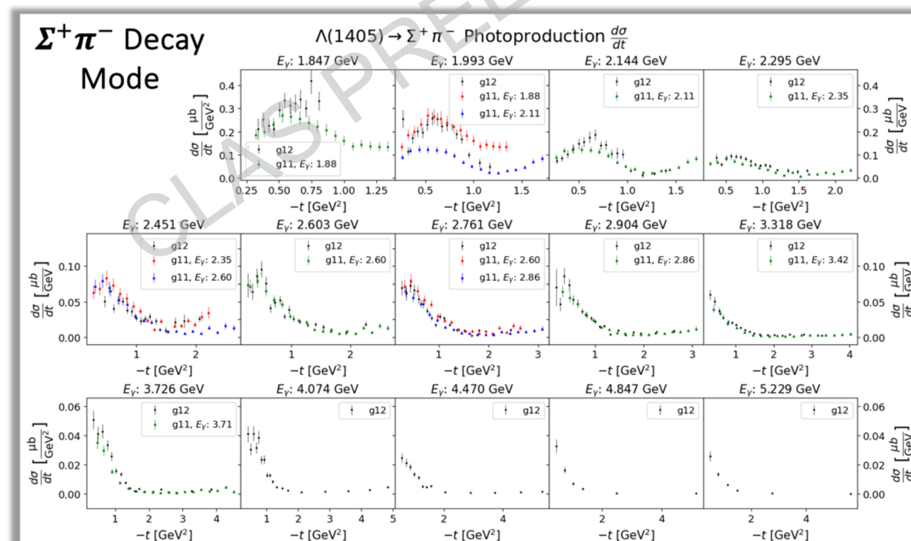
New Λ(1405) analysis of CLAS data

Courtesy of Trevor Reed

Differential cross-section measurements for Λ(1405) photoproduction
(E_{max} = 5.7 GeV)

- **CLAS Results**: Black
- **Published Results from Another (CLAS) Experiment**: Green, Red, Blue





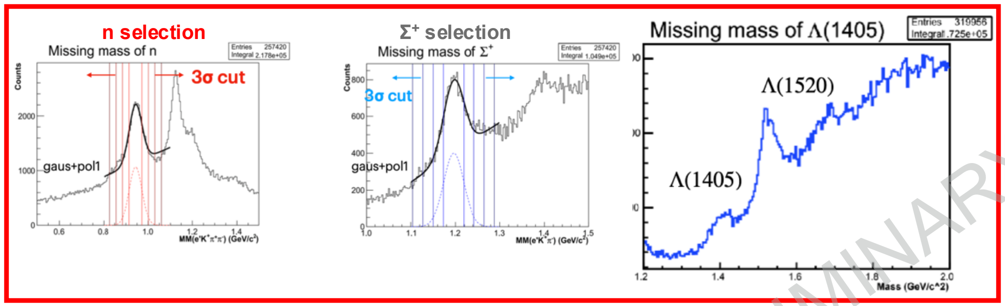
- Results in good agreement with prior CLAS photoproduction measurements (E_{max} = 3.8 GeV)
- Extended energy range over previous measurement
- Currently under review

Λ(1405) at CLAS12

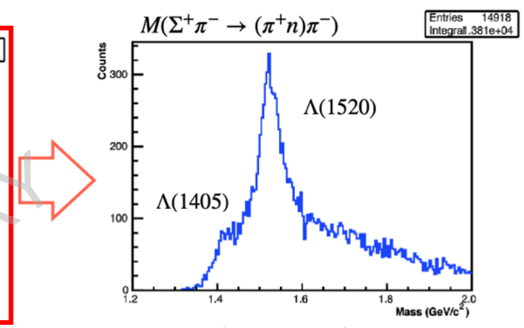
Courtesy of Tatsuhiro Ishige

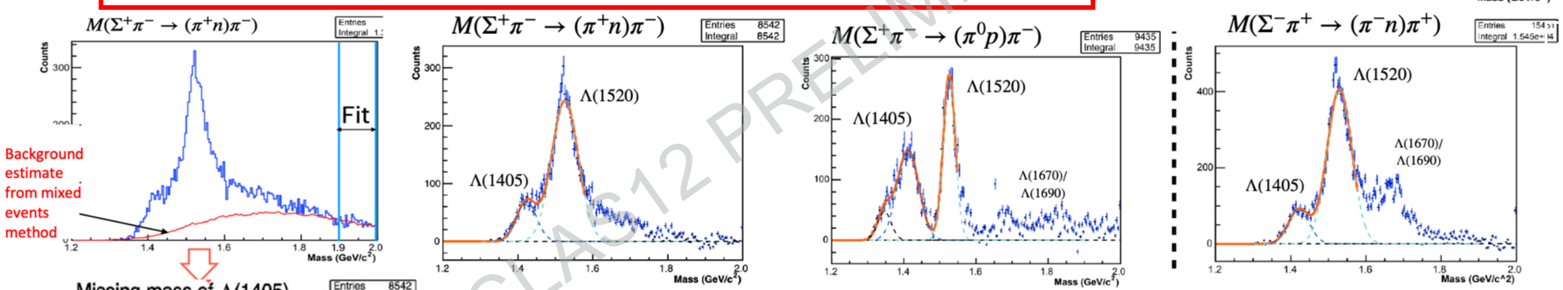
Search for the Λ(1405) in the reaction ep → e'K⁺(X) by missing mass technique, RG-K data (E_{beam} = 7.5 GeV and 6.5 GeV)

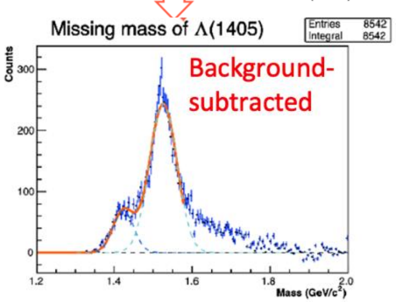
By missing mass technique



By invariant mass reconstruction







Fitting results

	Λ(1405) yield [Counts]	Λ(1405) sigma [MeV]
$M(\Sigma^+\pi^- \to (\pi^+ n)\pi^-)$	1100	33
$M(\Sigma^+\pi^- \to (\pi^0 p)\pi^-)$	3300	30
$M(\Sigma^-\pi^+ \to (\pi^- n)\pi^+)$	1500	27

- Consistent with the rough estimation at the order-of-magnitude level
  - ✦ Result: ~6000 , Rough estimation: ~2800
- Two-pole structure in $M(\Sigma^+\pi^- \to (\pi^0 p)\pi^-)$

- Analysis of resonance poles coupling as a function of Q^2
- High statistics using Spring24 RG-K statistics ~ 5x statistics shown in this preliminary study.

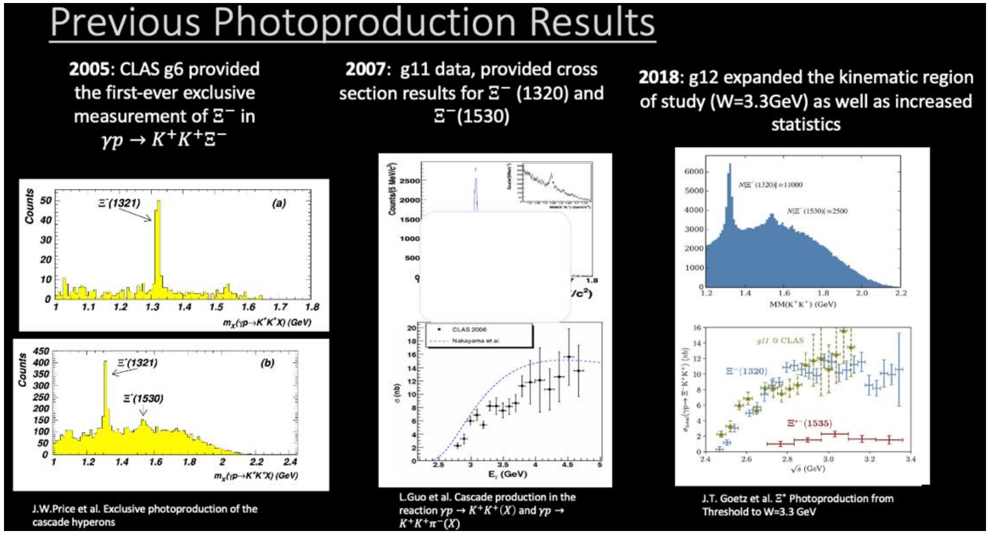
Search for missing Cascades

- Number of excited Ξ's predicted from SU(3) symmetry greater than the number of states seen experimentally
- Incomplete knowledge of quantum numbers
- Production mechanism still unclear

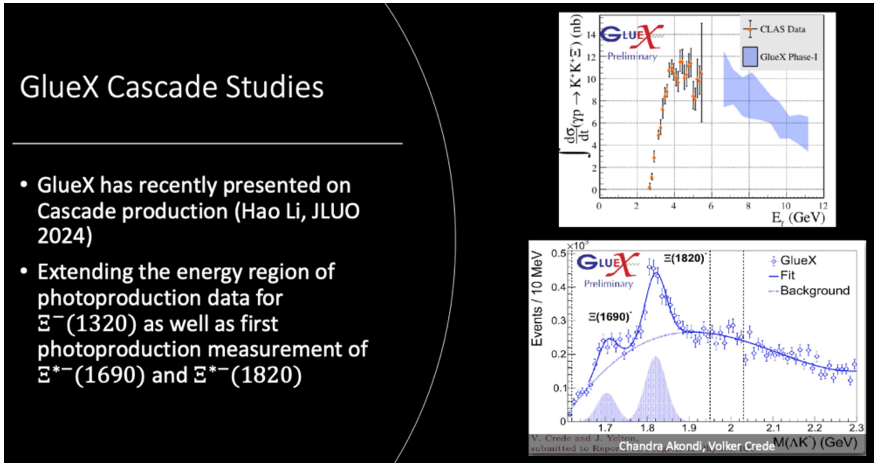
Particle	J^P	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
Ξ(1318)	1/2+	****					Decays weakly
Ξ(1530)	3/2+	****	****				
Ξ(1620)		**	**				
Ξ(1690)		***	**	***	**		
Ξ(1820)	3/2−	***	**	***	**	**	
Ξ(1950)		***	**	**		*	
Ξ(2030)		***		**	***		
Ξ(2120)		*		*			
Ξ(2250)		**					3-body decays
Ξ(2370)		**					3-body decays
Ξ(2500)		*		*	*		3-body decays

**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, *etc.* are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

State	PDG rating	Width (MeV)	J^P
Ξ(1320)	****		$\frac{1}{2}^+$
Ξ(1530)	****	9.5	$\frac{3}{2}^+$
Ξ(1690)	***	< 30	$\frac{1}{2}^-?$
Ξ(1820)	***	24	$\frac{3}{2}^-$
Ξ(1950)	***	60	?
Ξ(2030)	***	20	$\frac{5}{2}^?$



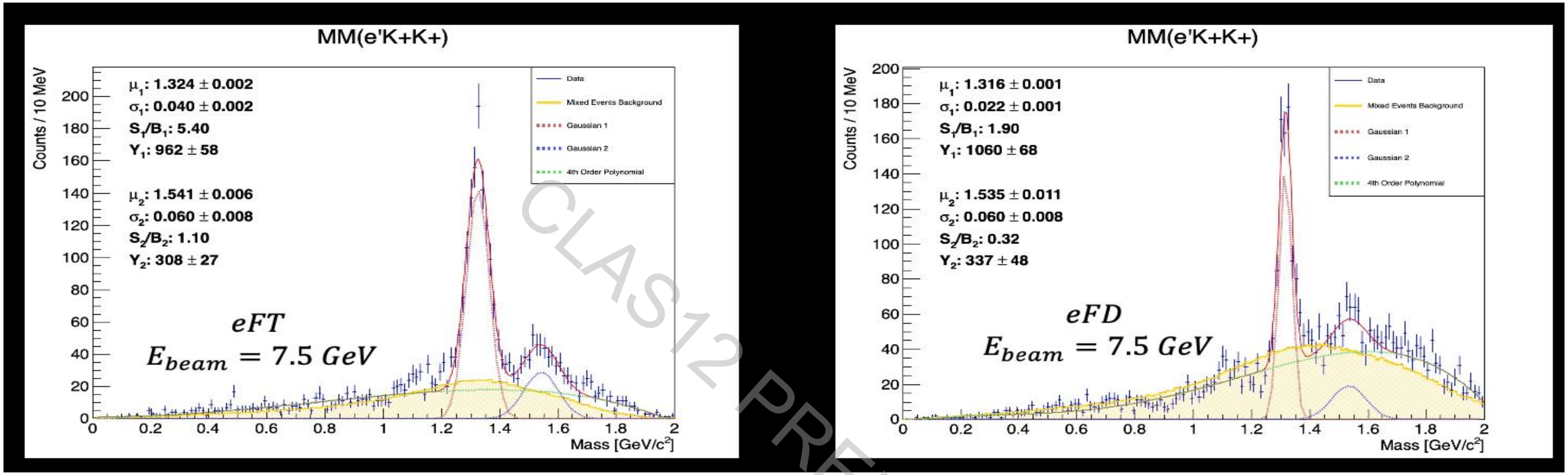
Courtesy of Bianca Gualtieri



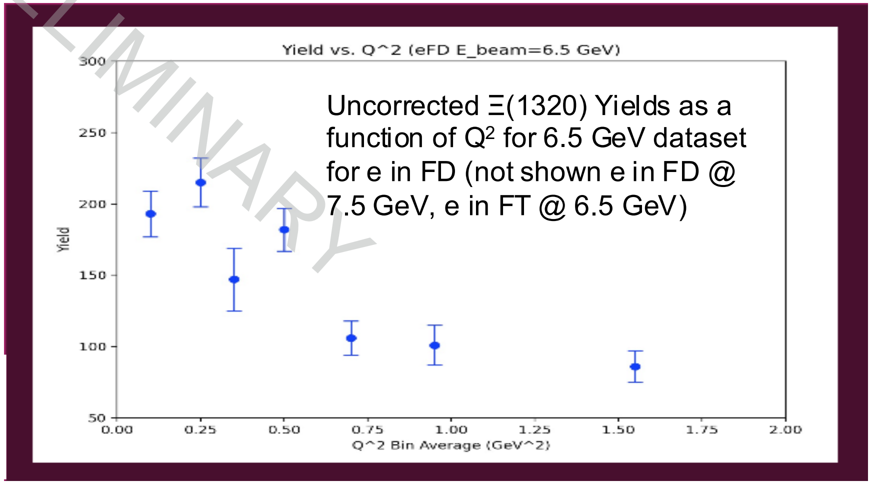
Search for excited Cascades in the exclusive reaction: $ep \rightarrow e'K^+K^-(\Xi^-)$

Search for missing Cascades

Courtesy of Bianca Gualtieri



- RG-K 2018 data at 6.5 and 7.5 GeV
- Clear evidence for Ξ(1530)
- Cross section analysis in progress



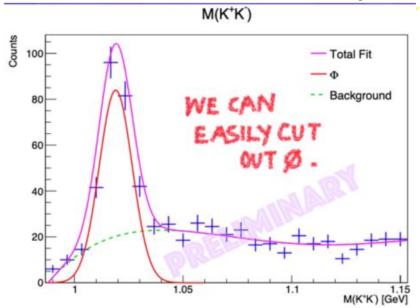
Search for excited Cascades in the exclusive reaction: $ep \rightarrow e'K^+K^-(\Xi^-)$

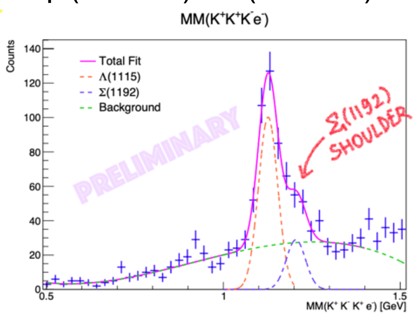
Search for missing Cascades

Search for the Ξ(1690) in the reactions: ep → e'$K^+K^+K^-(\Lambda)$ and ep → e'$K^+K^+\pi^-(\Xi^0)$ (missing mass technique) RG-A data (E_{beam} = 10.2 GeV)

ep → e'$K^+K^+K^-(\Lambda)$ channel: $\Xi(1690)^- \rightarrow K^-(\Lambda)$

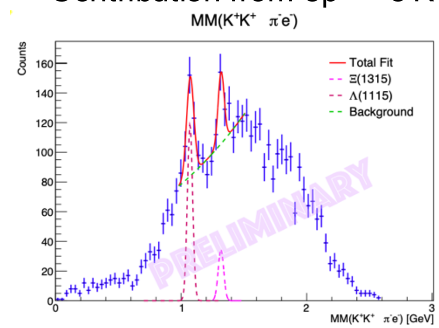
- Detecting 3 kaons
- Contamination from ep → e' φ (→$K^+ K^-$) N*(→ Λ K^+)





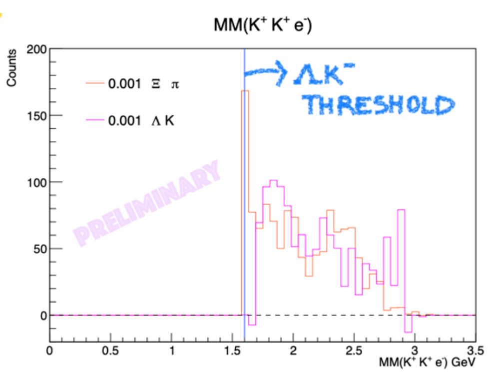
ep → e'$K^+K^+\pi^-(\Xi^0)$ channel: $\Xi(1690)^- \rightarrow \pi^-(\Xi^0)$

- Detecting 2 kaons and a pion
- Contribution from ep → e'K^+Y* (→ K^+ Ξ^-(→ Λ π^-))



Background-subtracted yields

- Efficiency corrected



- First analysis to search for the Ξ(1690) in electroproduction
- Analysis to be done 6x more statistics
- Goal is to extract J^P and branching ratios

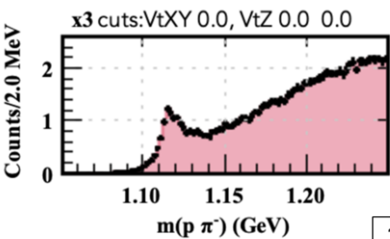
Courtesy of Asli Acar

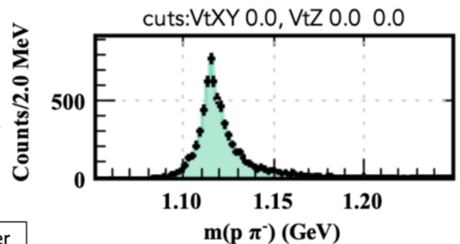
Strangeness Production Studies with Λ's

Courtesy of Veronique Ziegler

Λ Skim

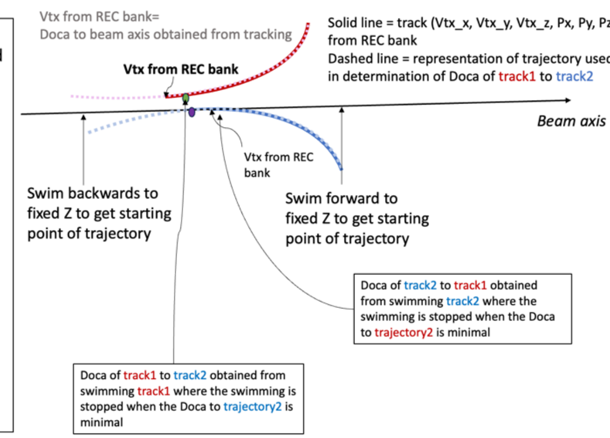
- Using displaced vertex reconstruction

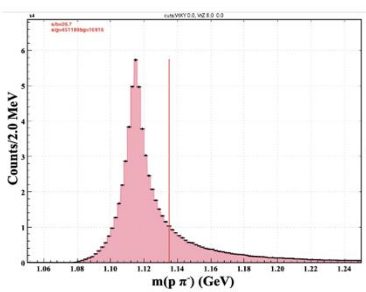


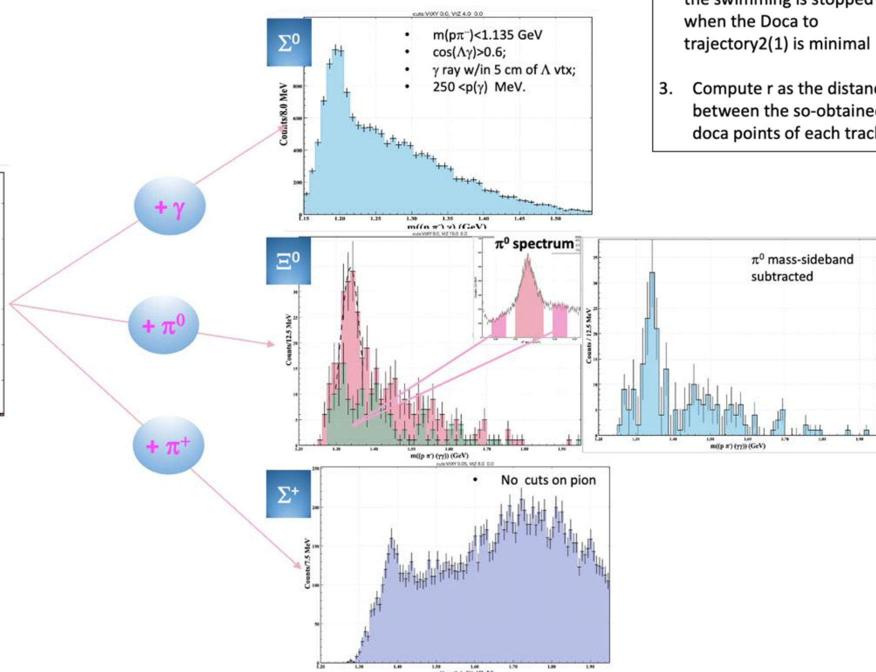


~ no loss in number of signal events

1. For each track
   1. Swim backwards to fixed Z to get starting point of trajectory
   2. Swim forward to fixed Z to get starting point of trajectory
2. Compute Doca of track2(1) to track1(2) obtained from swimming track2(1) where the swimming is stopped when the Doca to trajectory2(1) is minimal
3. Compute r as the distance between the so-obtained doca points of each track





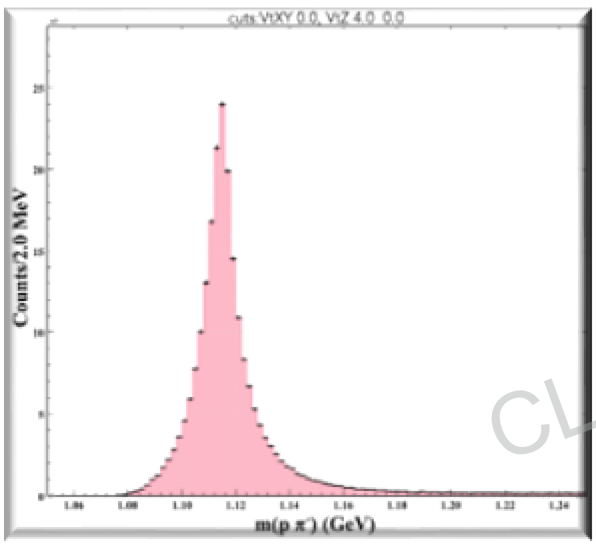


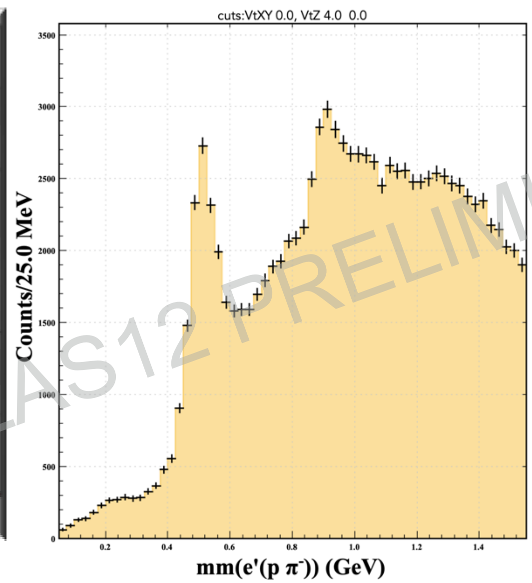
Polarization observables with Λ's

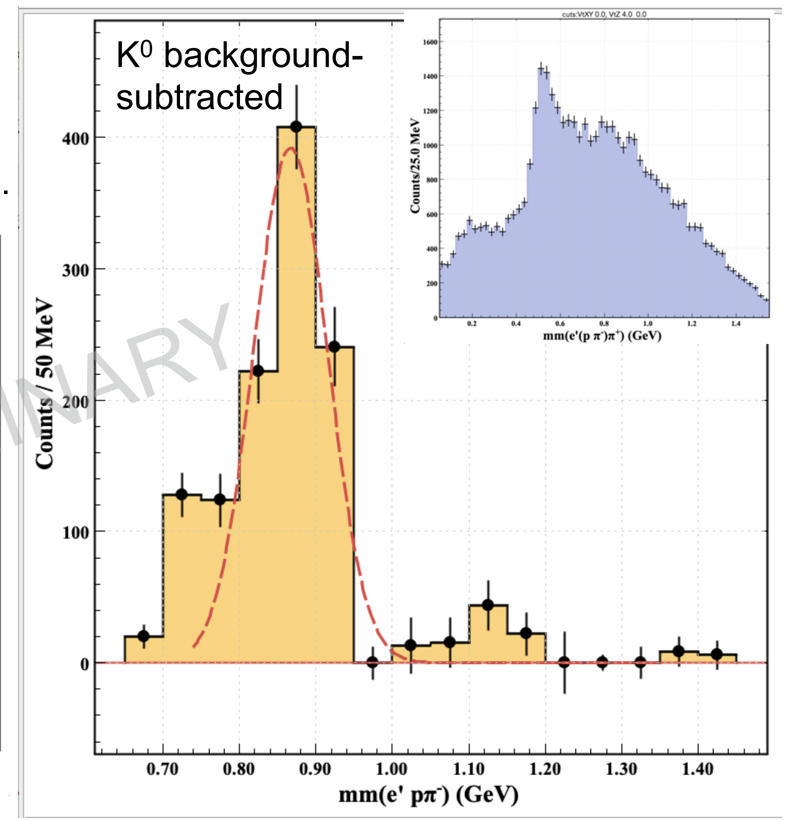
Courtesy of Veronique Ziegler

First observation of the reaction ep→e'ΛK*(892)$^+$ in electroproduction using RGK Pass-2 Fall-18 Data

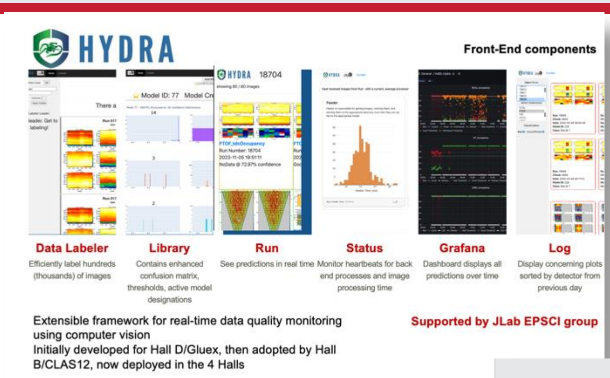
- Clean Λ spectrum ➔ reduces background in extraction of physics observables from misreconstructed Λ candidates
- Studies of beam-recoil spin transfer in electro-produced K$^+$Λ final states from unpolarized proton target have shown that the Λ polarization is predominantly in the direction of the spin of the virtual photon.
- For the **electro-produced K^{*+}Λ** final state, the spin of the u-quark is the same as for K$^+$Λ → test hypothesis that the **Λ spin direction should flip**.



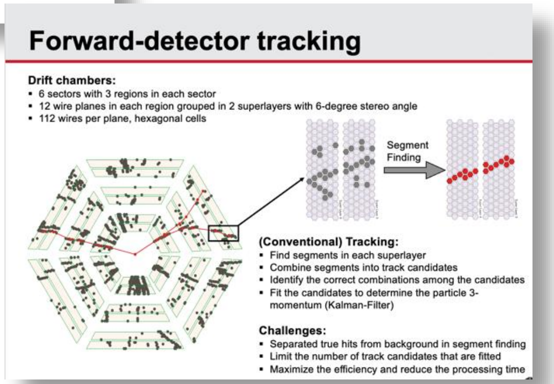


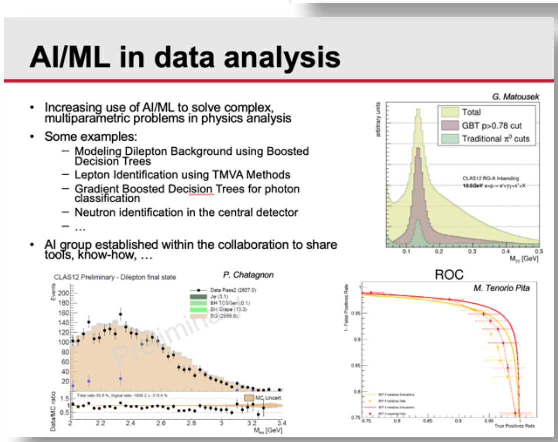


What AI/ML can do for spectroscopy



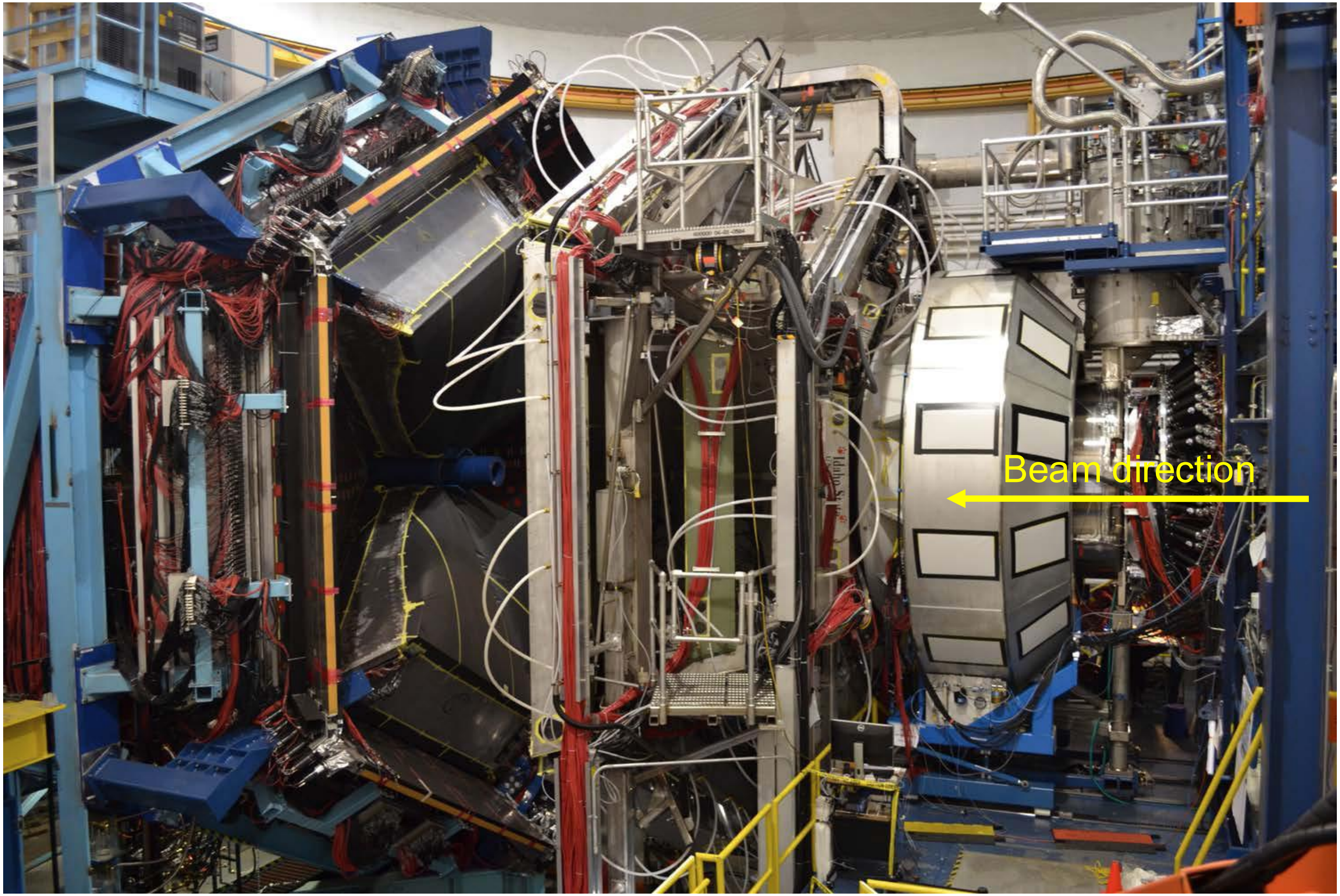
- Data Quality Assurance
- High reconstruction efficiency for multiparticle final states
- Good PID
- Background rejection
- MC for detector response
- Amplitude analyses
- …





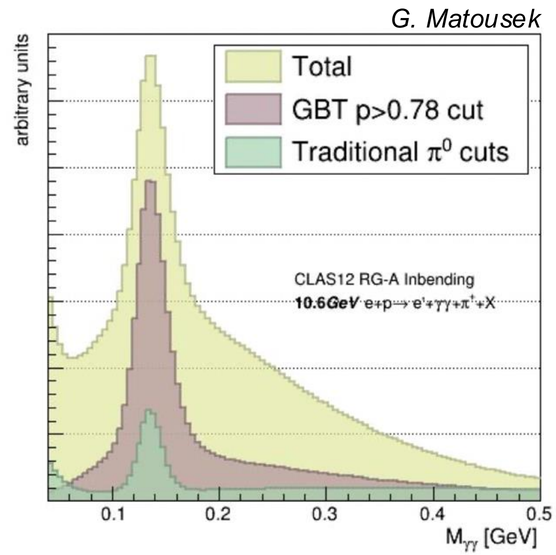
Backup

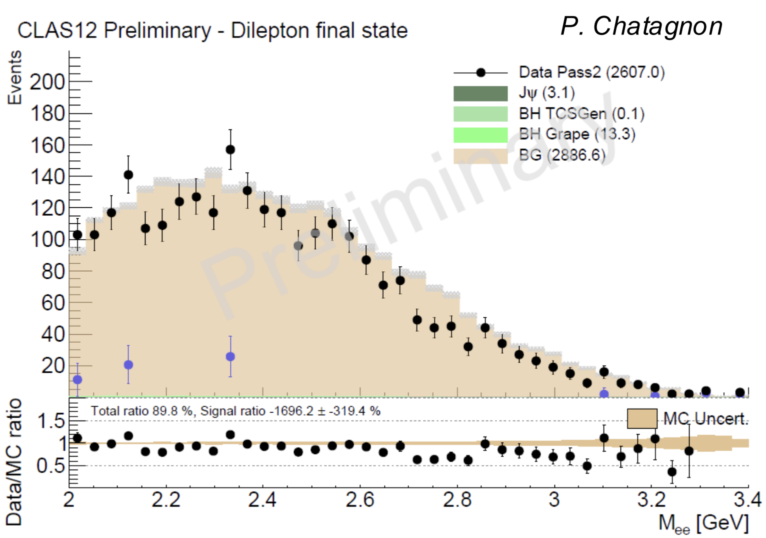
CLAS12 in Hall B

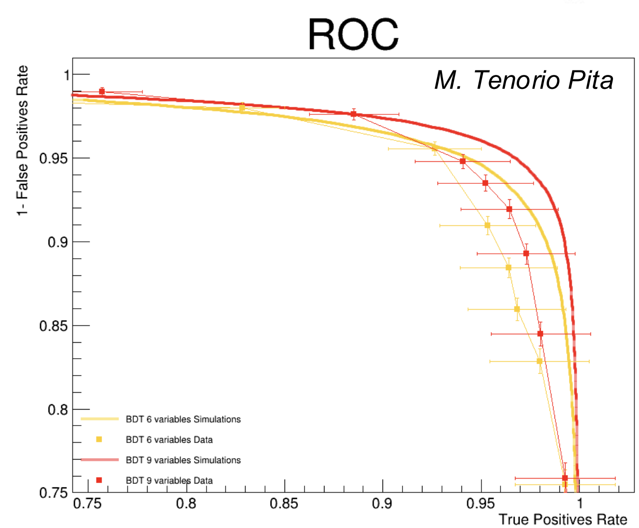


AI/ML in data analysis

- Increasing use of AI/ML to solve complex, multiparametric problems in physics analysis
- Some examples:
  - Modeling Dilepton Background using Boosted Decision Trees
  - Lepton Identification using TMVA Methods
  - Gradient Boosted Decision Trees for photon classification
  - Neutron identification in the central detector
  - …
- AI group established within the collaboration to share tools, know-how, …







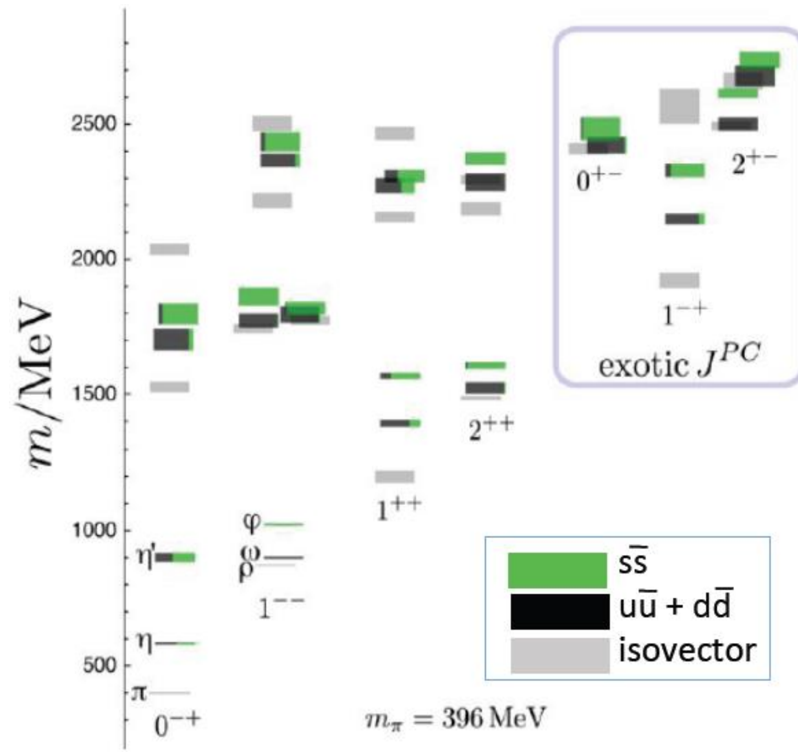
Meson spectroscopy at CLAS12

Predictions of the light quark meson spectrum now available from lattice QCD:

- Spectrum includes meson state with large gluonic content (hybrids) with both regular and exotic quantum numbers
- Experimental signature: a multiplet of gluonic mesons with exotic J^{PC}, i.e. non quark-antiquark
- Searches in progress at several facilities, world-wide

CLAS12 uses quasi-real photo-production to investigate the light quark meson spectrum and search for hybrid meson states

Meson Spectrum in LQCD

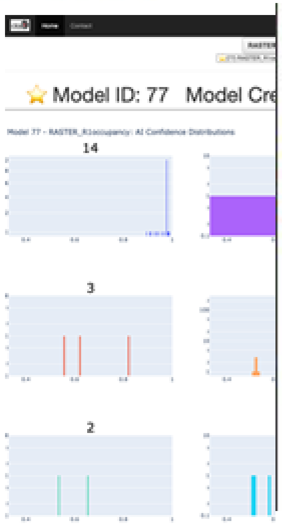


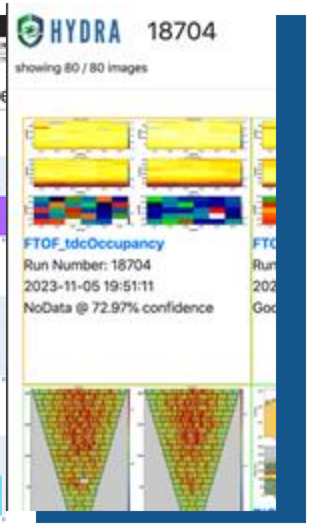
Dudek, Edwards, Guo and Thomas, PRD 88, 094505 (2013)

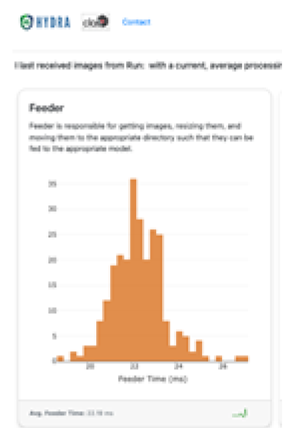
AI/ML for data monitoring

HYDRA

Front-End components







Data Labeler	Library	Run	Status	Grafana	Log
Efficiently label hundreds (thousands) of images	Contains enhanced confusion matrix, thresholds, active model designations	See predictions in real time	Monitor heartbeats for back end processes and image processing time	Dashboard displays all predictions over time	Display concerning plots sorted by detector from previous day

Extensible framework for real-time data quality monitoring using computer vision
Initially developed for Hall D/Gluex, then adopted by Hall B/CLAS12, now deployed in the 4 Halls

Supported by JLab EPSCI group