Hadron spectroscopy with CLAS and CLAS12

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Why hadron spectroscopy?

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

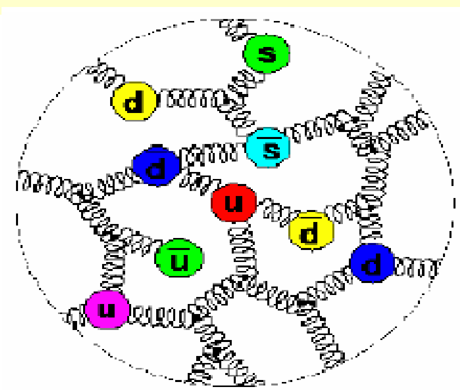
Perturbative | **Transition** | **Non- Perturbative**

High energy
Small distance

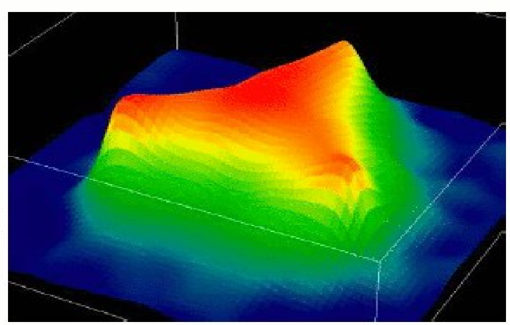
Asymptotic freedom

Low energy
Large distance

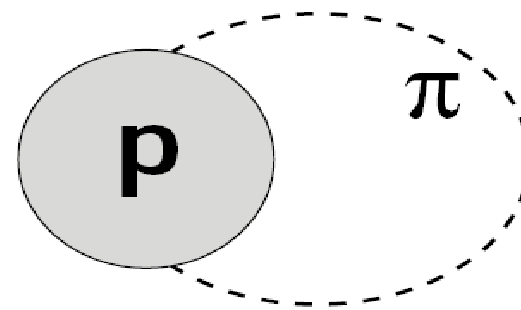
Confinement



pQCD



Effective degrees of freedom (models)

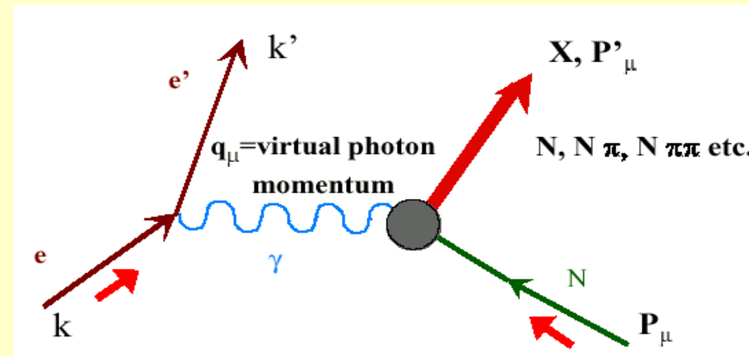


Mesons & Baryons

The tool: electromagnetic interaction

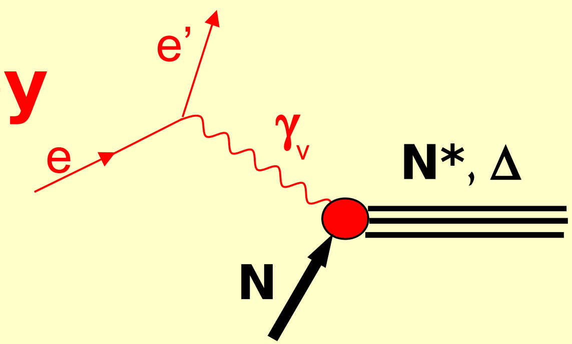
- weaker than strong interactions
- therefore calculable perturbatively
- based on the well-known QED

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



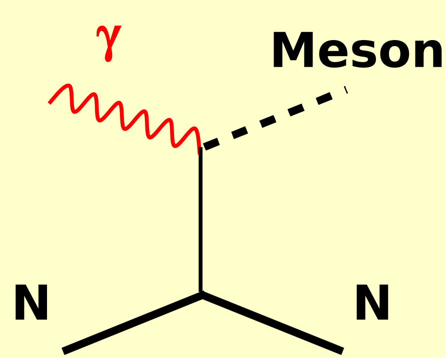
The scattering is normally analyzed in term of the One-Photon-Exchange approximation (OPE)

Baryon spectroscopy



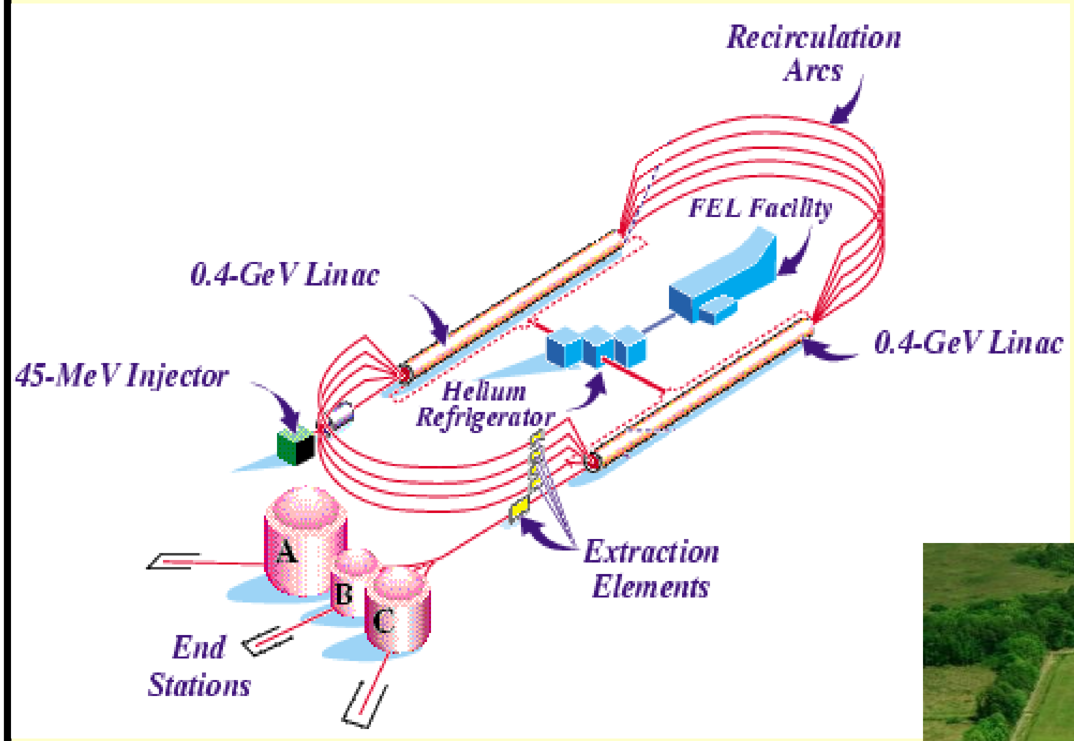
- Direct γ_v - *qqq* system coupling
- Establish the excitation spectrum
- Access to strong interaction dynamics (Q^2 evolution of resonance form factors)

Meson spectroscopy

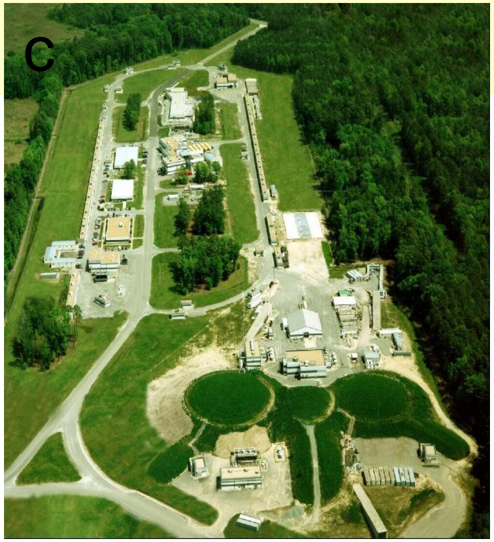


- $q\bar{q}$ system → easier to study
- Indirect coupling to initial particle
- Access to gluonic degrees of freedom

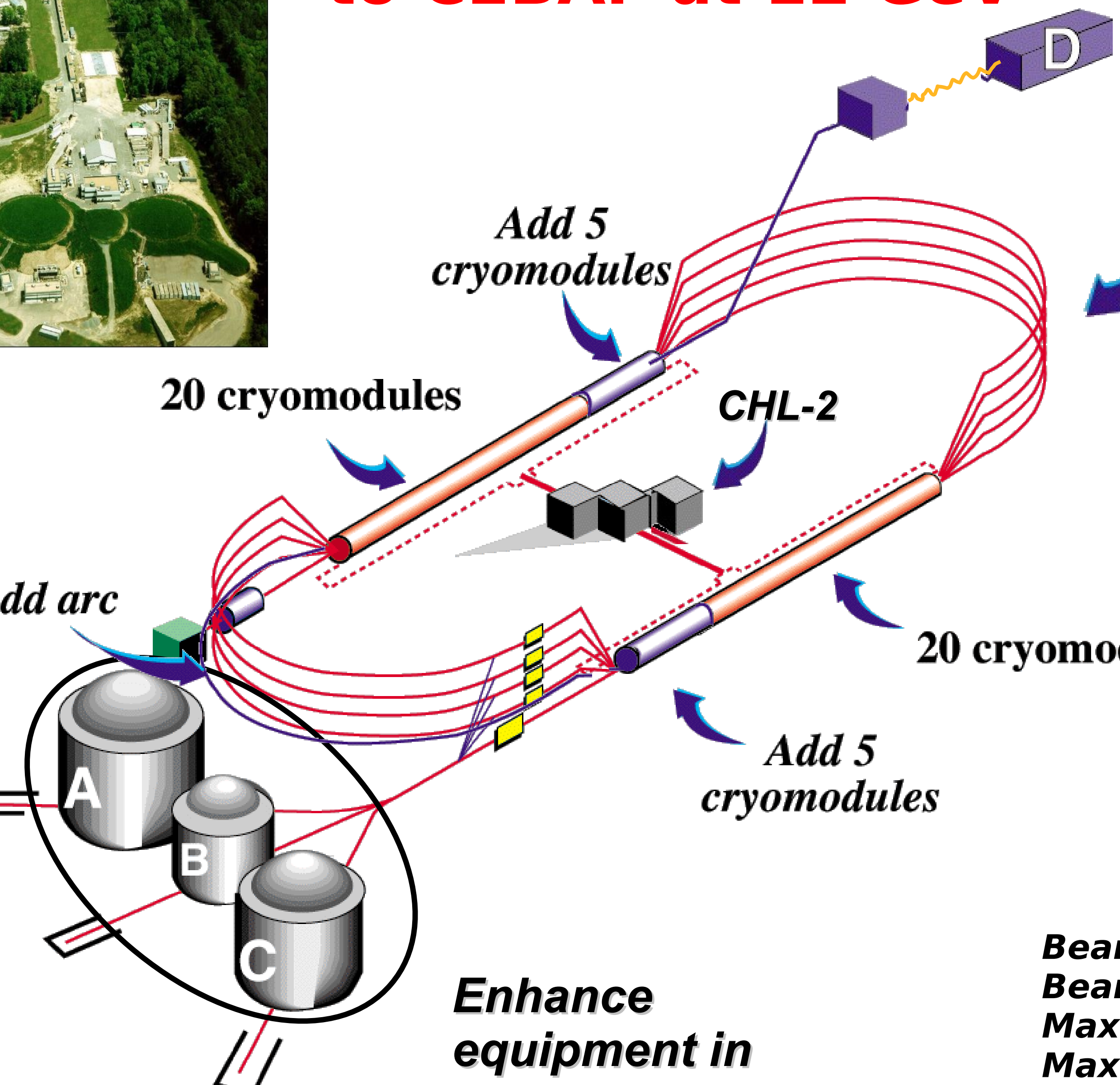
Jefferson Lab (now)



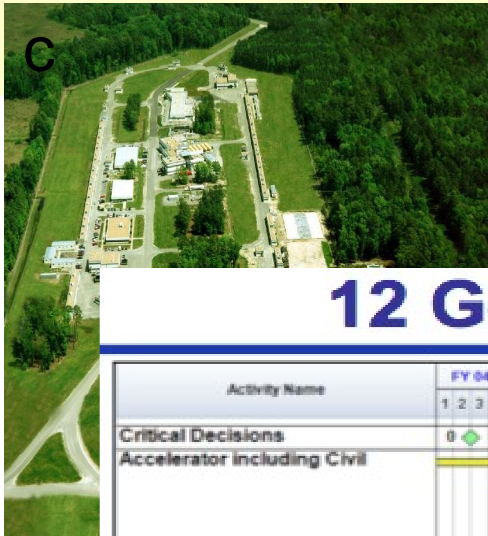
E_{max}	~ 6 GeV
I_{max}	~ 200 μA
Duty Factor	~ 100%
σ_E/E	~ 2.5 10^{-5}
Beam P	~ 80%
E_γ	~ 0.8-5.7 GeV



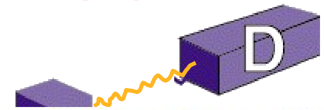
From CEBAF at 6 GeV to CEBAF at 12 GeV



Beam Power: *1MW*
Beam Current: *90 μA*
Max Pass energy: *2.2 GeV*
Max Enery Hall A-C: *10.9 GeV*
Max Energy Hall D: *12 GeV*

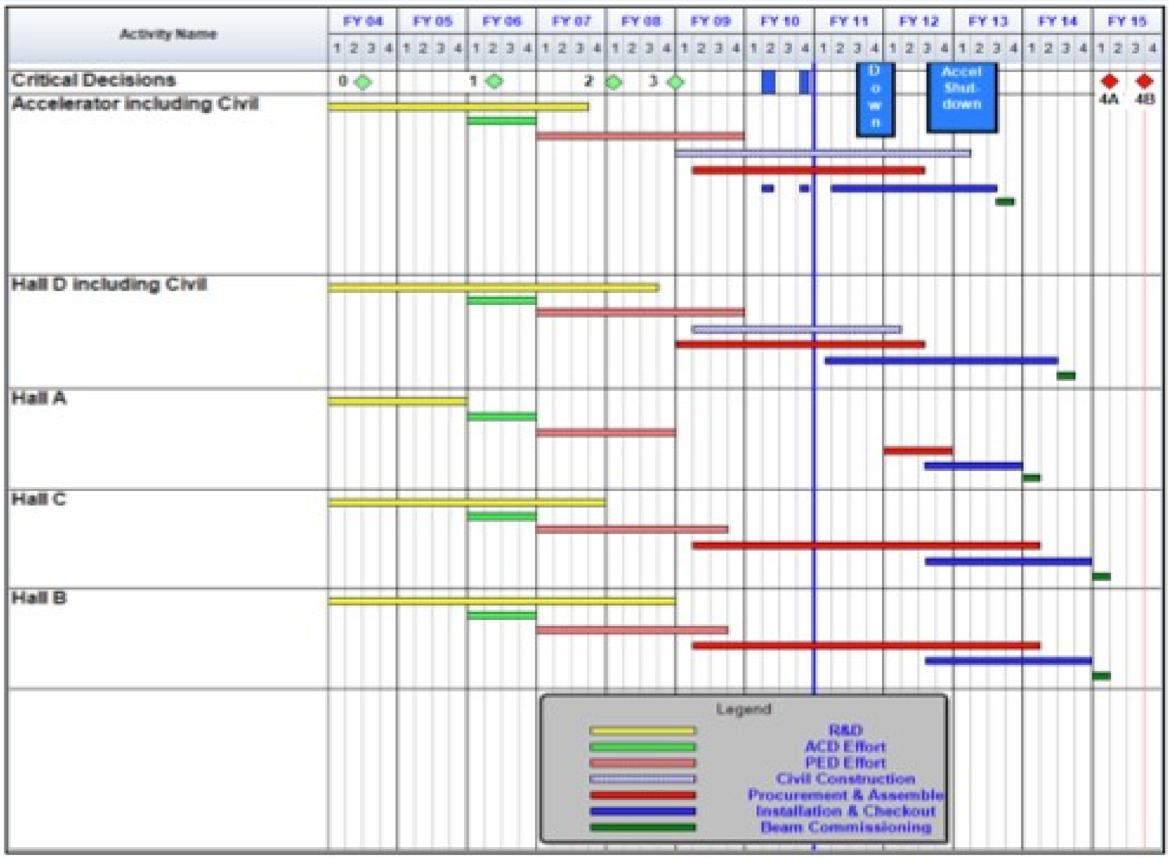


From CEBAF at 6 GeV to CEBAF at 12 GeV



add Hall D
(and beam

12 GeV Upgrade Project Schedule



Two short parasitic installation periods in FY10

6-month installation May-Oct 2011

12-month installation May 2012-May 2013

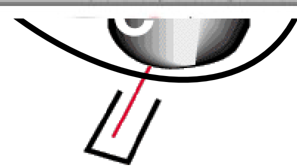
Hall D commissioning start April 2014

Hall A commissioning start October 2013

Halls B & C commissioning start October 2014

Project Completior

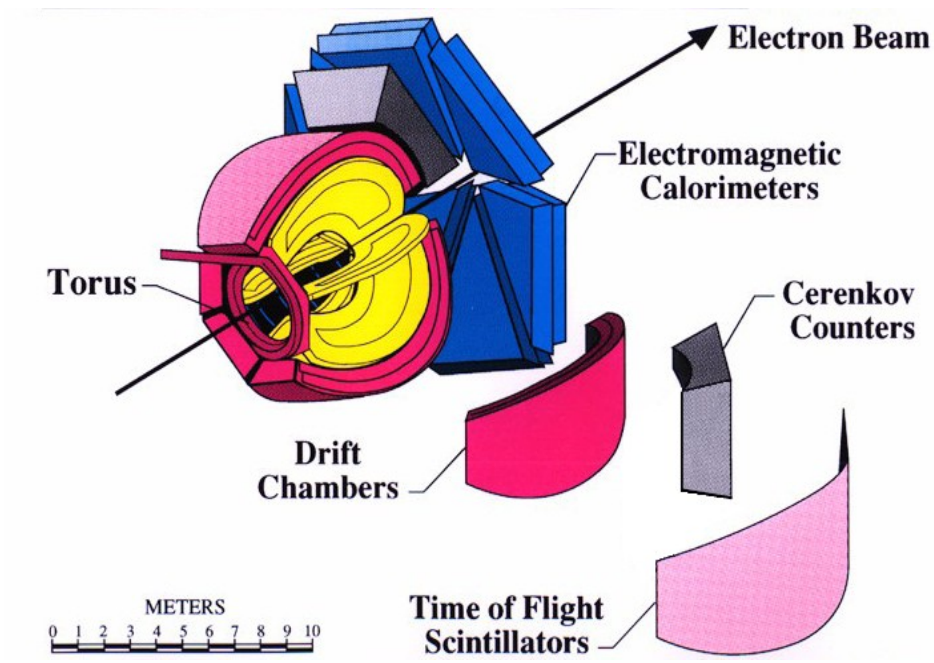
HallA Oct 13
HallD Apr 14
HallB Oct 14

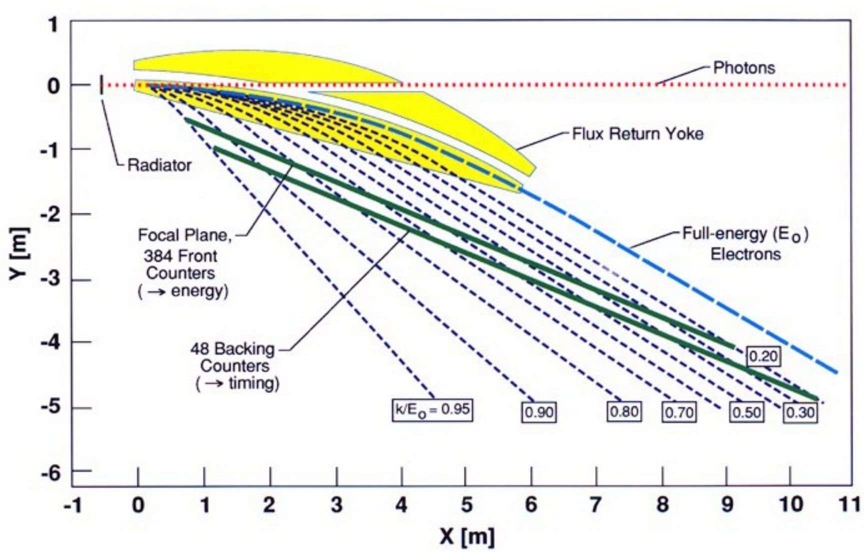


Enhance equipment in existing halls

Beam Current: 90 μA
Max Pass energy: 2.2 GeV
Max Enery Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV

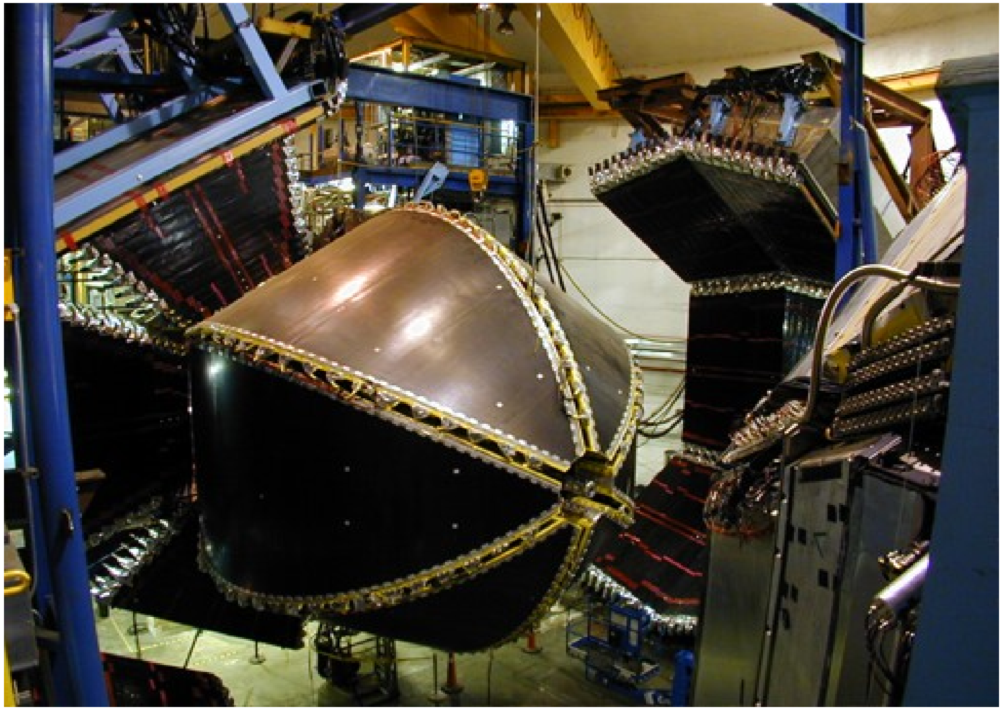
The CEBAF Large Acceptance Spectrometer CLAS



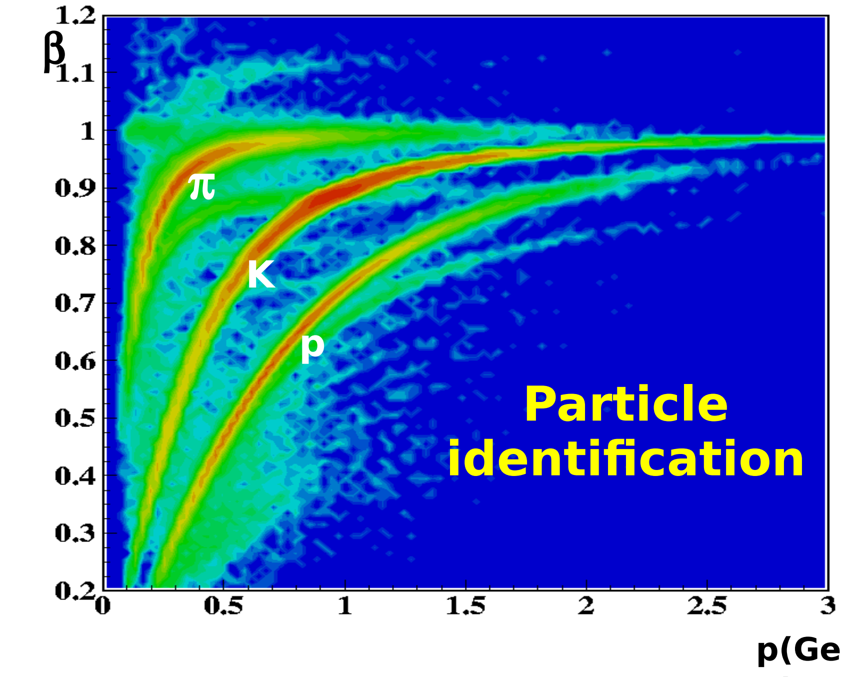


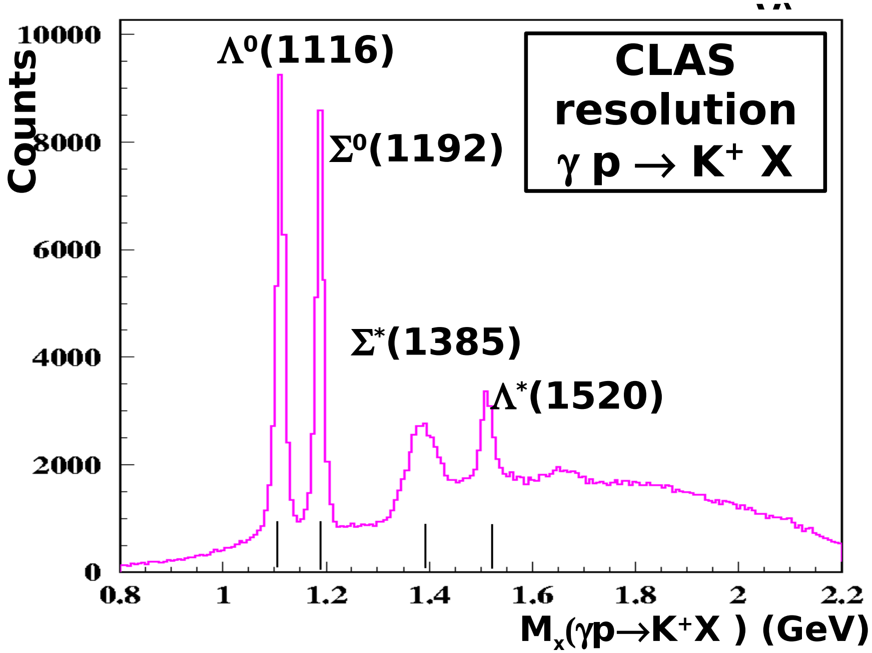
Performance

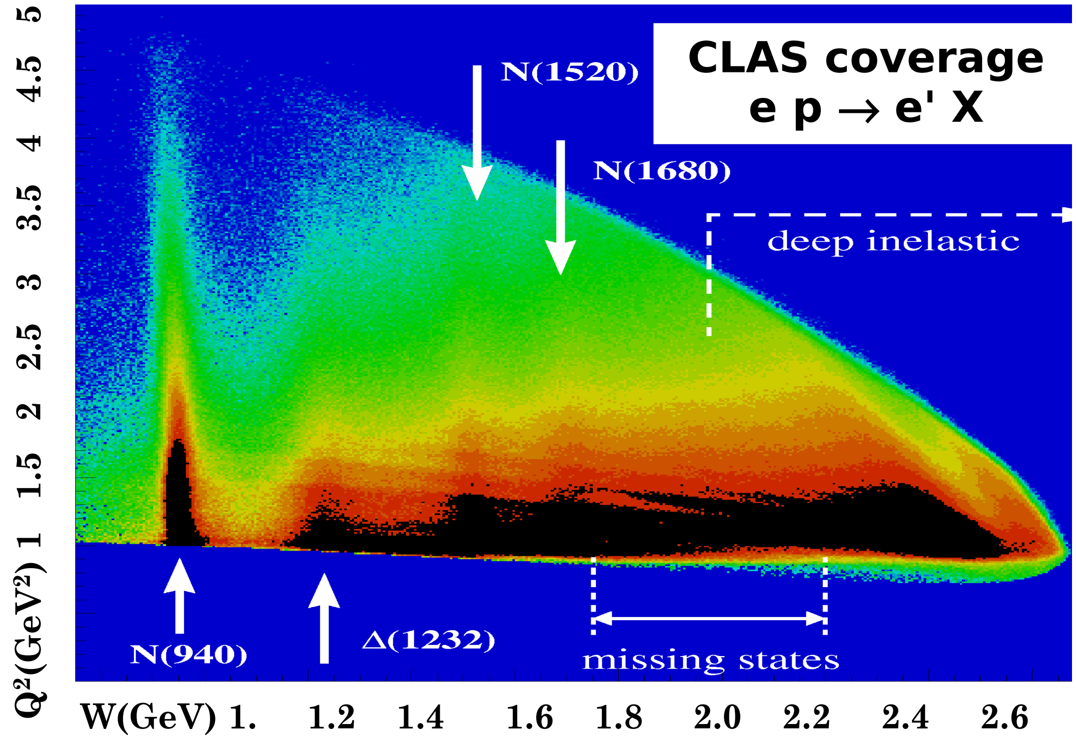
- $L = 10^{34}\ cm^{-2}\ s^{-1}$
- $\int B\, dl = 2.5$ T m
- $\Delta p/p \sim 0.5$-1 %
- 4π acceptance
- Best suited for multiparticle final states
- Bremsstrahlung Photon Tagger ($\Delta E_\gamma/E_\gamma \sim 10^{-3}$)

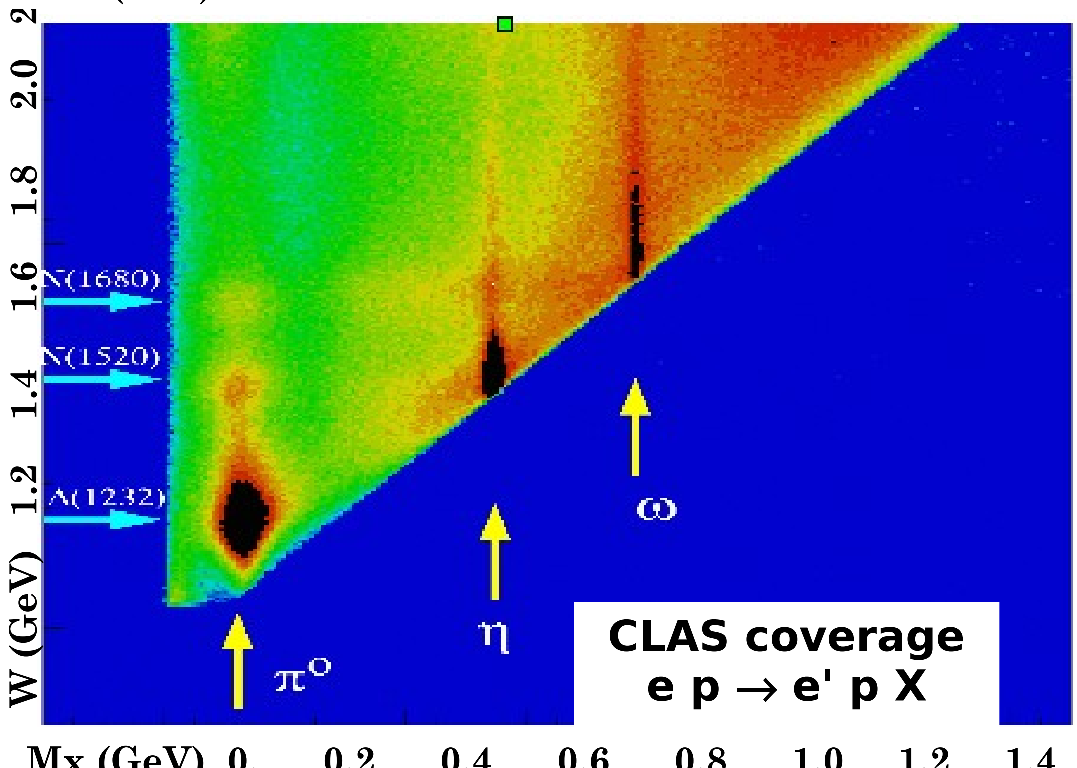


Hadron detection efficiency and kinematic coverage





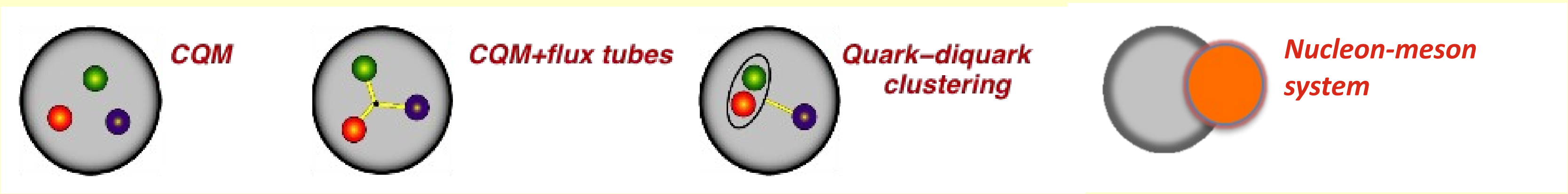




Why do we study excited baryons?

Hadron physics major goal:
to understand the structure of the nucleon and its excited states

- **The N* spectrum reflects the underlying degrees of freedom of the nucleon**



Two main components in JLab N* program

- **Transition amplitudes of prominent resonances**
- **Search of new states**

- **Exclusive electro and photoproduction**
- **precise measurements of cross sections**
- **polarization observables**
- **Q^2 evolution**
- **simultaneous analysis of many different channels**

Electroproduction data and analyses from CLAS

Reaction	W (GeV)	Q^2 (GeV^2)	Observable	Physics extracted
$ep \to ep\pi^0$	1.1 - 1.4	0.4 - 1.8; 3 - 6	$\sigma_T+\varepsilon_L\sigma_L$, σ_{TT}, σ_{LT}; $d\sigma/d\Omega$	Δ (G_M, R_{EM}, R_{SM})
$\vec{e}p \to ep\pi^0$	1.1 - 1.4	0.4 - 0.65	$\sigma_{LT'}$	Δ (G_M, R_{EM}, R_{SM})
$\vec{e}\vec{p} \to ep\pi^0$	1.1 - 1.4; 1.1 - 1.7	0.5 - 1.5; 0.19 - 0.77	A_t , A_{et}	Comparison to models
$ep \to en\pi^+$	1.1 - 1.6	0.25 - 0.65	$\sigma_T+\varepsilon_L\sigma_L$, σ_{TT}, σ_{LT}	$P_{11}(1440)$ ($A_{1/2}$, $S_{1/2}$), $D_{13}(1520)$ ($A_{1/2}$, $A_{3/2}$, $S_{1/2}$), S_{11} (1535) ($A_{1/2}$, $S_{1/2}$)
$\vec{e}p \to en\pi^+$	1.3 - 1.5; 1.15 - 1.7	0.4 - 0.65; 1.72 - 4.16	$\sigma_{LT'}$; $\sigma_T+\varepsilon_L\sigma_L$, σ_{TT}, σ_{LT} , $\sigma_{LT'}$	$P_{11}(1440)$ ($A_{1/2}$, $S_{1/2}$), $D_{13}(1520)$ ($A_{1/2}$, $A_{3/2}$, $S_{1/2}$), S_{11} (1535) ($A_{1/2}$, $S_{1/2}$)
$\vec{e}\vec{p} \to en\pi^+$	1.12 - 1.84	0.35 - 1.5	$(A_1 + \eta A_2)/(1+\varepsilon R)$	Comparison to models
$ep \to ep\eta$	1.5 - 1.86	0.25 - 1.5	σ, $d\sigma/d\Omega$ → Legendre coeff. in $\sigma_T+\varepsilon_L\sigma_L$, σ_{TT}, σ_{LT}	S_{11} (1535) ($A_{1/2}$, $S_{1/2}$)
$ep \to ep\eta$	1.5 - 2.3	0.13 - 3.3	σ, $d\sigma/d\Omega$ → Legendre coeff. in $\sigma_T+\varepsilon_L\sigma_L$, σ_{TT}, σ_{LT} + σ_{TT}/σ, σ_{LT}/σ	S_{11} (1535) ($A_{1/2}$, $S_{1/2}$) + further PWA
$e\,p \to ep\pi^+\pi^-$	1.4 - 2.1; 1.3 - 1.57	0.5 - 1.5; 0.2 - 0.6	Simultaneous fit of $d\sigma/d\theta$ and $d\sigma/dM$	$P_{11}(1440)$, $D_{13}(1520)$, $P_{13}(1720)$, $D_{33}(1700)$
$\vec{e}\,p \to eK^+\vec{\Lambda}$	1.6 - 2.15	0.3 - 1.5	Λ transferred pol. $P'_{x'}$, $P'_{z'}$	Comparison to models
$ep \to eK^+\Lambda$, $K^+\Sigma^0$	1.6 - 2.4	0.5 - 2.8	σ_T , σ_L, σ_{TT}, σ_{LT}	Comparison to models
$\vec{e}\,p \to eK^+\Lambda$	1.65 - 2.05	0.65, 1	$\sigma_{LT'}$	Comparison to models

Photoproduction data and analyses from CLAS

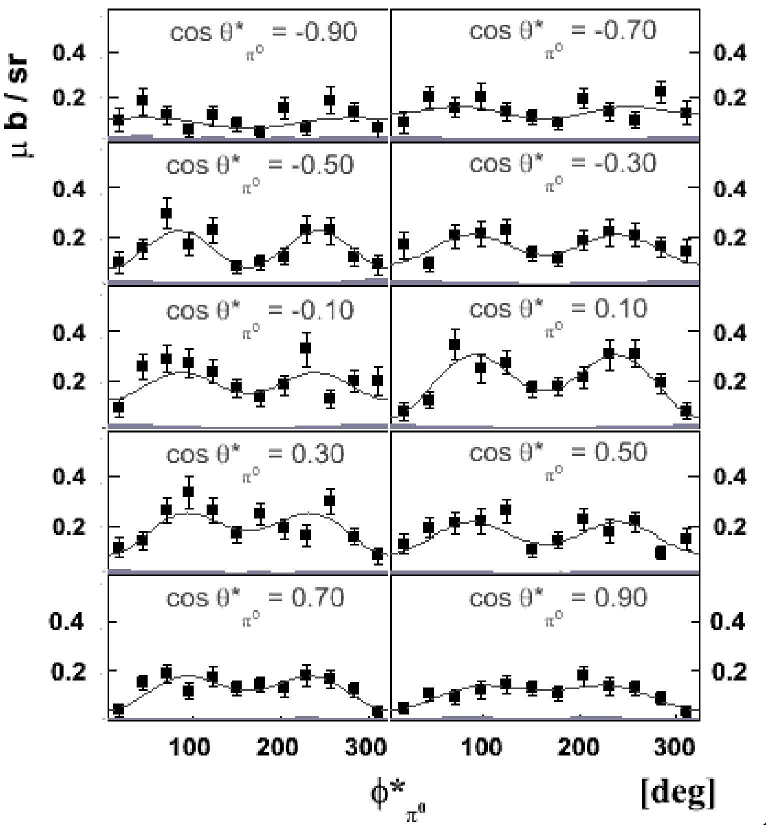
Reaction	W (GeV)	Q^2 (GeV^2)	Observable	Physics extracted
$ep \to ep\pi^0$	1.1 - 1.4	0.4 - 1.8; 3 - 6	$\sigma_T+\epsilon_L\sigma_L$, σ_{TT}, σ_{LT}; $d\sigma/d\Omega$	Δ (G_M, R_{EM}, R_{SM})
$\vec{e}p \to ep\pi^0$	1.1 - 1.4	0.4 - 0.65	[illegible]	[illegible]
$\vec{e}\vec{p} \to ep\pi^0$				
$ep \to en\pi^+$				
$\vec{e}p \to en\pi^+$				
$\vec{e}\vec{p} \to en\pi^+$				
$ep \to ep\eta$				
$ep \to ep\eta$				
$e\,p \to ep\pi^+\pi^-$				
$\vec{e}p \to eK^+\vec{\Lambda}$				
$ep \to eK^+\Lambda$, $K^+\Sigma^0$				
$\vec{e}p \to eK^+\Lambda$				

completed   scheduled for future run

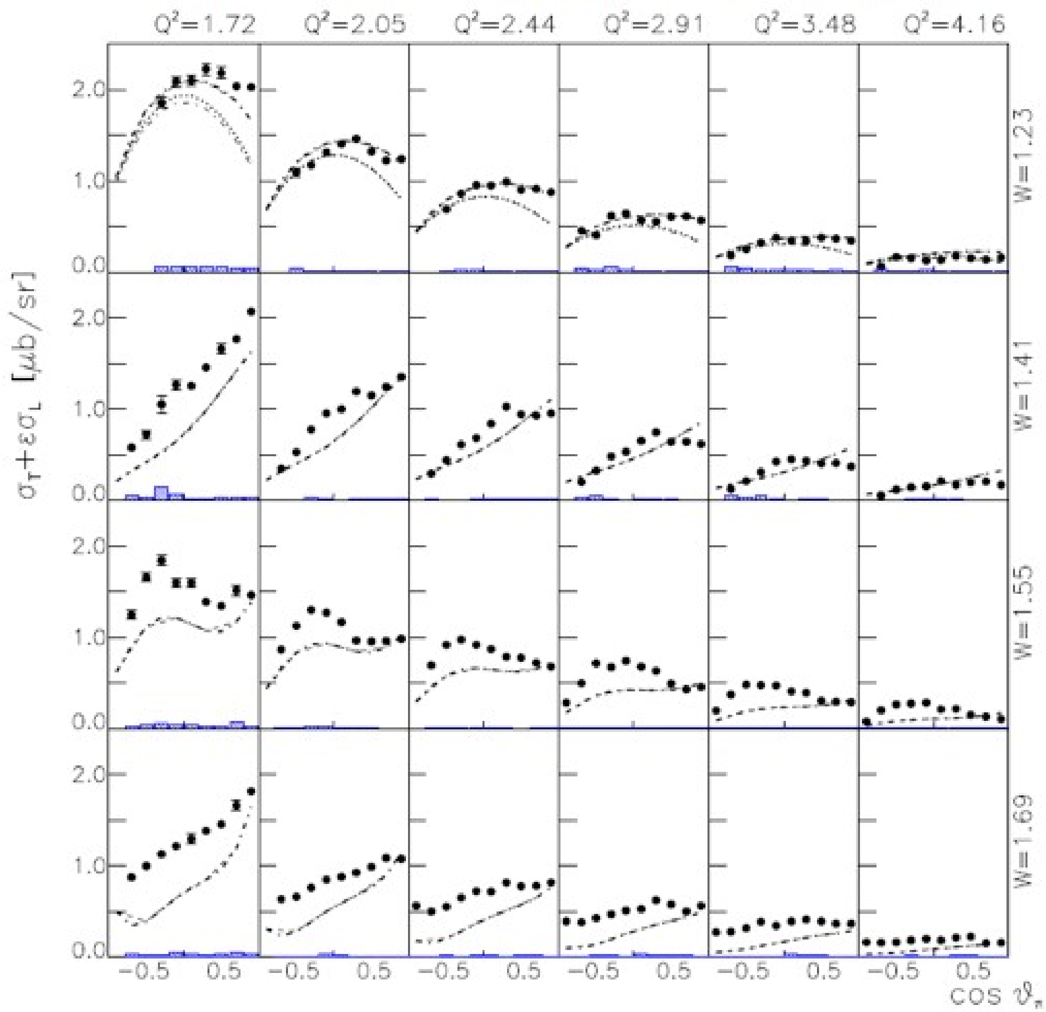
Reaction	Diff cr-s	Lin. beam	Circ. beam	Long. Target	Trans. Target	Recoil Polar.	Run Group	Status/Schedule
$\gamma_p \to p\pi^0$	completed						G1	*PRC76 025211, 2007*
$\gamma_p \to n\pi^+$	completed						G1	*arXiv:0903.1110 [hep-ex]*
$\gamma_p \to p\eta$	completed						G1, G11	*PRL89 222002, 2002 / Upcoming paper*
$\gamma_p \to p\eta'$	completed						G1, G11	*PRL96 062001, 2006 / Upcoming paper*
$\gamma_p \to K^+\Lambda$, $K^+\Sigma$ $K^+\Lambda(1520)$	completed		completed			completed	G1, G11	*PRC69 042201, 2004; PRC73, 035202, 2006; PRC75 035205, 2007 / Analysis*
$\gamma_p \to K^{0*}\Sigma^+$	completed		completed				G1	*PRC75 042201, 2007*
$\gamma_p \to p\pi^-\pi^+$	completed		completed				G1	*PRL95 162003, 2006, Analysis*
$\gamma_p \to p\omega$, $p\rho^0$, $n\rho^+$, $K^+\Lambda$, $K^+\Sigma$	completed	completed	completed				G8	*2005 / Analysis*
$\gamma_p \to p\omega$	completed					completed	G11	*2004 / Upcoming paper*
$\gamma_n \to K^0\Lambda$, $K^0\Sigma$, $K^+\Sigma^-$, $K^-\Sigma^+$, $K^+\Sigma^-(1385)$	completed	completed	completed			completed	G13	*2007 / Analysis*
$\gamma_p \to p\pi^0$, $n\pi^+$, $p\eta$		completed	completed	completed	scheduled		*G9-FROST*	*2007 / Analysis, 2010*
$\gamma_p \to K^+\Lambda$, $K^+\Sigma$		completed	completed	completed	scheduled	completed	*G9-FROST*	*2007 / Analysis 2010*
$\gamma_p \to p\pi^-\pi^+$		completed	completed	completed	scheduled		*G9-FROST*	2007 / *Analysis 2010*
$\gamma_n \to K^0\Lambda$, $K^0\Sigma$, $K^+\Sigma^-$, $K^-\Sigma^+$	scheduled	scheduled	scheduled	scheduled	scheduled	scheduled	*G14-HDIce*	*2011*
$\gamma_n \to p\pi^-$, $n\pi^+\pi^-$	scheduled	scheduled	scheduled	scheduled	scheduled		*G14-HDIce*	*2011*

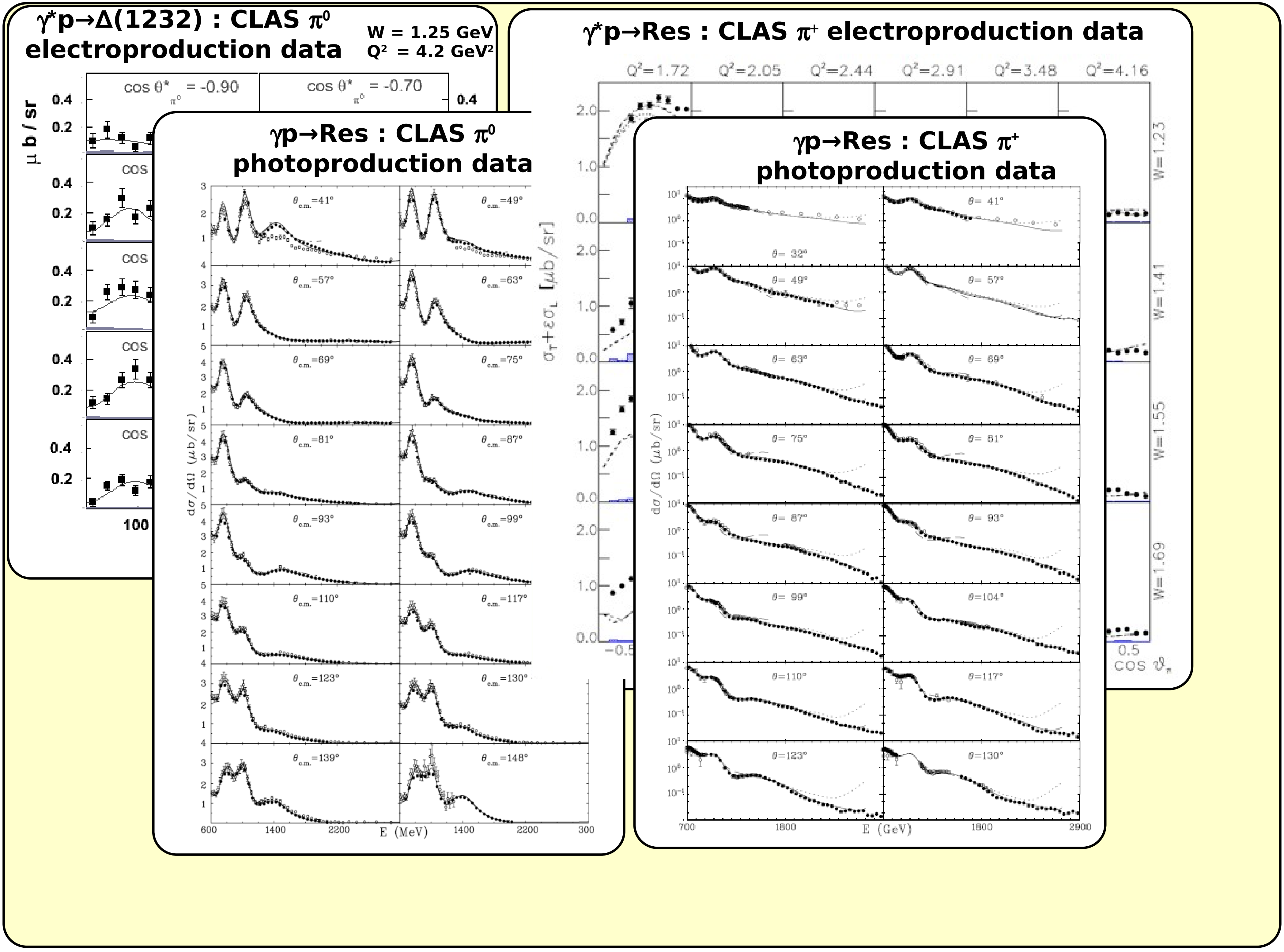
$\gamma^* p \rightarrow \Delta(1232)$: CLAS π^0 electroproduction data

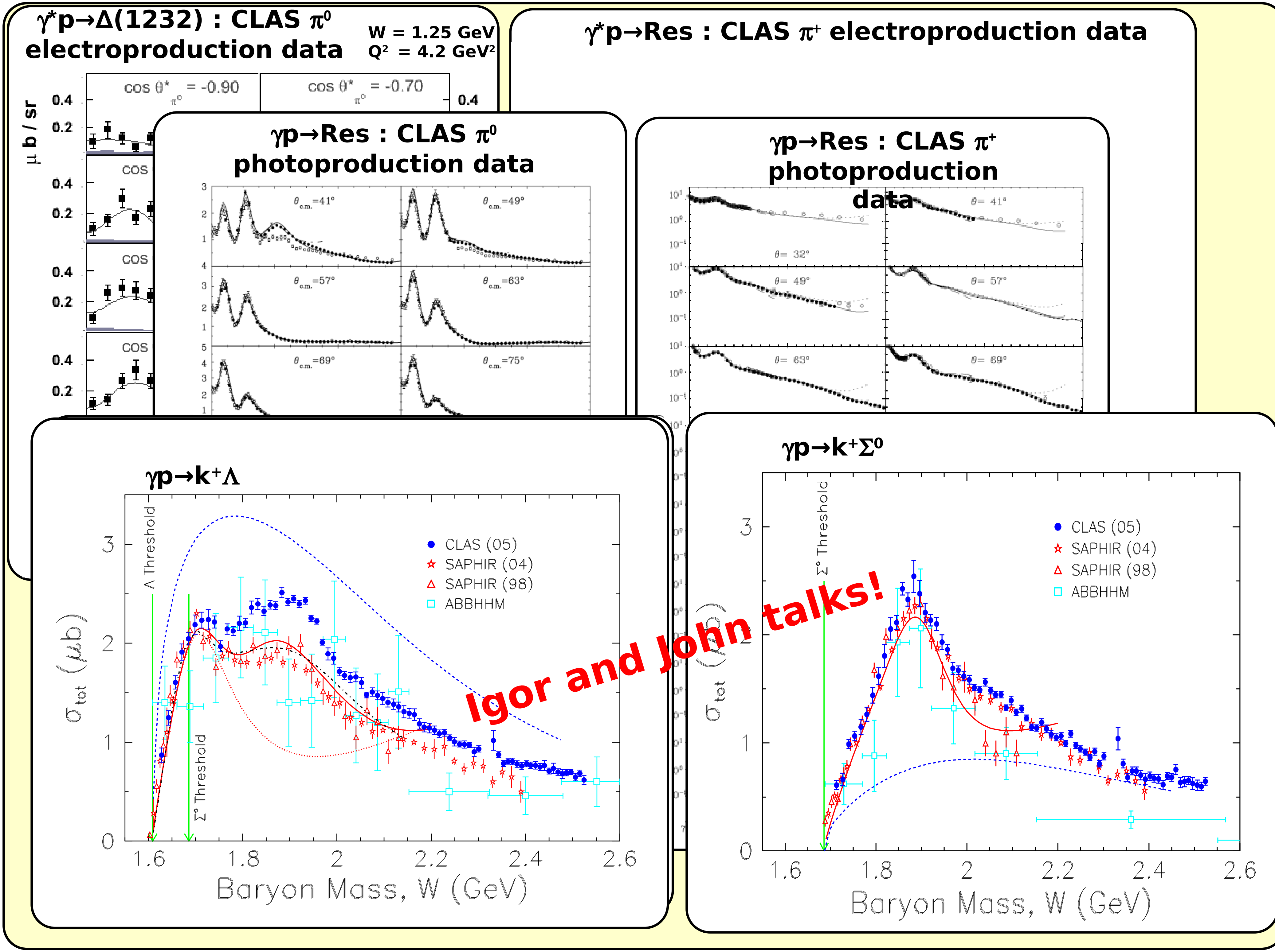
W = 1.25 GeV
Q^2 = 4.2 GeV^2



$\gamma^* p \rightarrow$ Res : CLAS π^+ electroproduction data



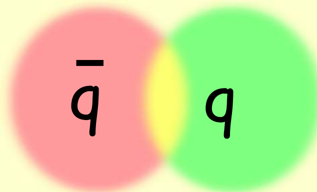

γ*p→Δ(1232) : CLAS π⁰ electroproduction data
W = 1.25 GeV
Q² = 4.2 GeV²
cos θ*π⁰ = -0.90
cos θ*π⁰ = -0.70
μ b / sr
γp→Res : CLAS π⁰ photoproduction data
dσ/dΩ (μb/sr)
E (MeV)
γ*p→Res : CLAS π⁺ electroproduction data
Q²=1.72
Q²=2.05
Q²=2.44
Q²=2.91
Q²=3.48
Q²=4.16
σT+εσL [μb/sr]
W=1.23
W=1.41
W=1.55
W=1.69
cos ϑπ
γp→Res : CLAS π⁺ photoproduction data
dσ/dΩ (μb/sr)
E (GeV)



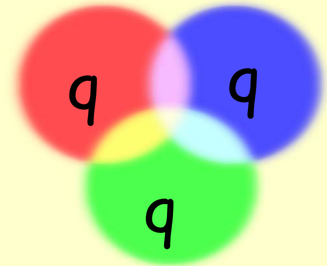
γ*p→Δ(1232) : CLAS π0 electroproduction data
W = 1.25 GeV
Q2 = 4.2 GeV2
μ b / sr
cos θ*π0 = -0.90
cos θ*π0 = -0.70
γ*p→Res : CLAS π+ electroproduction data
γp→Res : CLAS π0 photoproduction data
θc.m.=41°
θc.m.=49°
θc.m.=57°
θc.m.=63°
θc.m.=69°
θc.m.=75°
γp→Res : CLAS π+ photoproduction data
θ= 32°
θ= 41°
θ= 49°
θ= 57°
θ= 63°
θ= 69°
γp→k+Λ
Λ Threshold
Σ° Threshold
CLAS (05)
SAPHIR (04)
SAPHIR (98)
ABBHHM
σtot (μb)
Baryon Mass, W (GeV)
γp→k+Σ0
Σ° Threshold
CLAS (05)
SAPHIR (04)
SAPHIR (98)
ABBHHM
σtot (μb)
Baryon Mass, W (GeV)
Igor and John talks!

Beyond the quark model: hybrids and exotics

Quarks are confined inside colorless hadrons
they combine to 'neutralize' color force

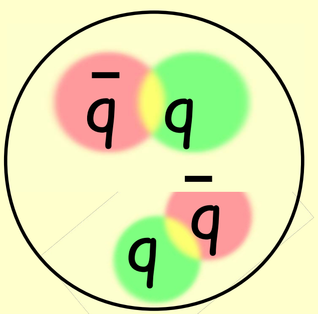


mesons

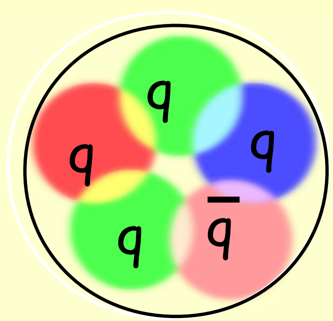


baryons

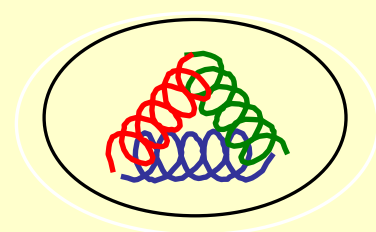
Other quark-gluon configuration can give colorless objects



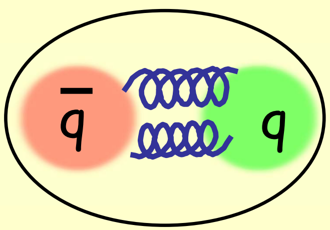
molecules



pentaquarks



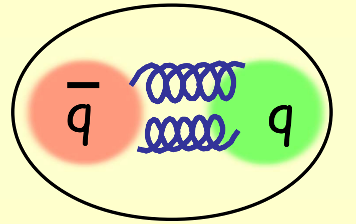
glueball mesons



hybrid mesons

QCD does not prohibit such states
but not yet unambiguously observed

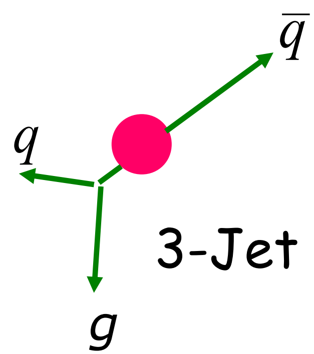
Meson spectroscopy with photons at JLab



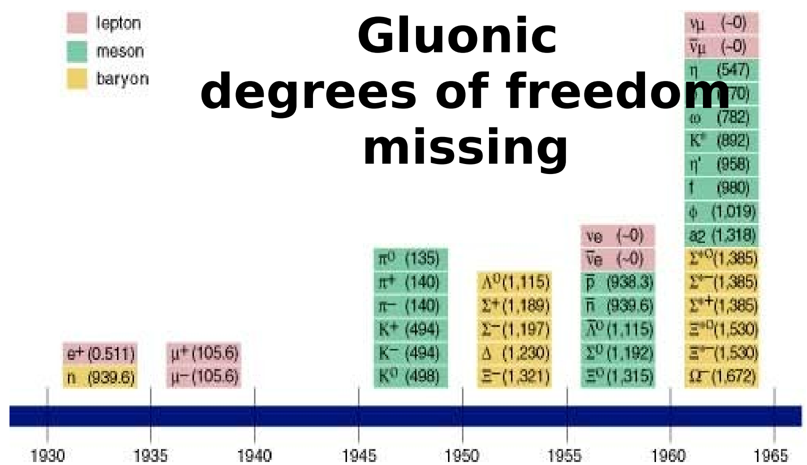
hybrid mesons

✯ **Understanding gluonic excitations of mesons and the origin of confinement**

Gluon jets observed at high energy



Gluonic degrees of freedom missing

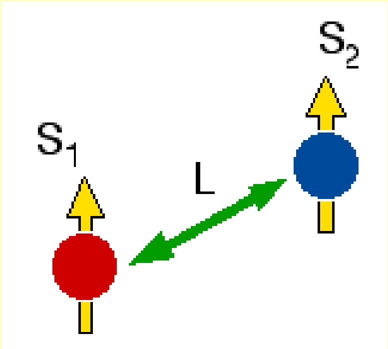


Spectroscopy

one of the most important issue in hadron physics and main motivation for the JLab 12 GeV upgrade (GlueX program in Hall-D)

Meson spectroscopy with photons at JLab

Search for mesons with 'exotic' quantum numbers (not compatible with quark-model)

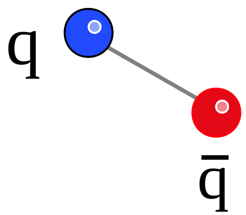


$S = S_1 + S_2$ $J = L + S$ $P = (-1)^{L+1}$ $C = (-1)^{L+S}$

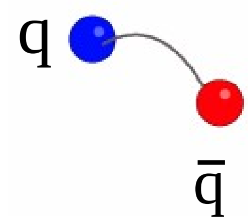
Not-allowed: $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-} \ldots$

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

Normal meson:
flux tube in ground state
m=0
$CP = (-1)^{S+1}$

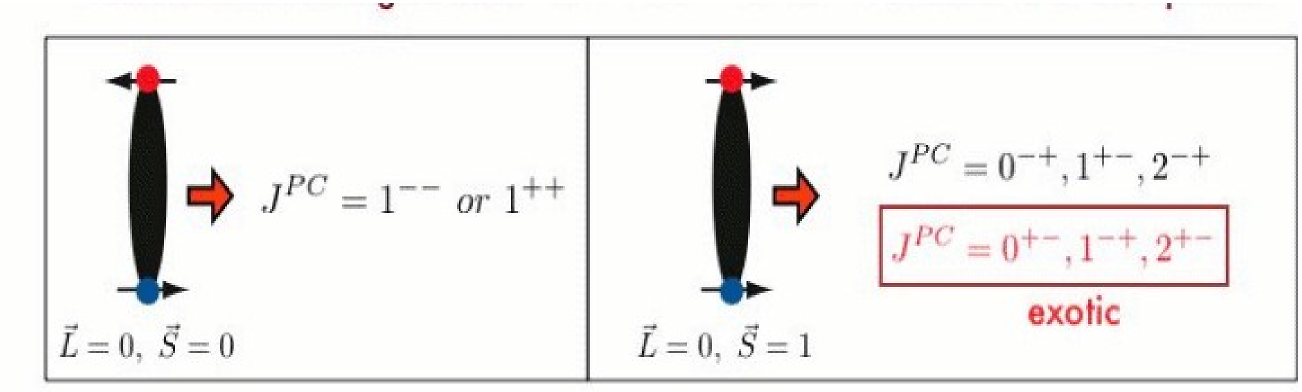


Hybrid meson:
flux tube in excited state
m=1
$CP = (-1)^{S}$



Flux tube J^{PC} 1^{-+}, 1^{+-}

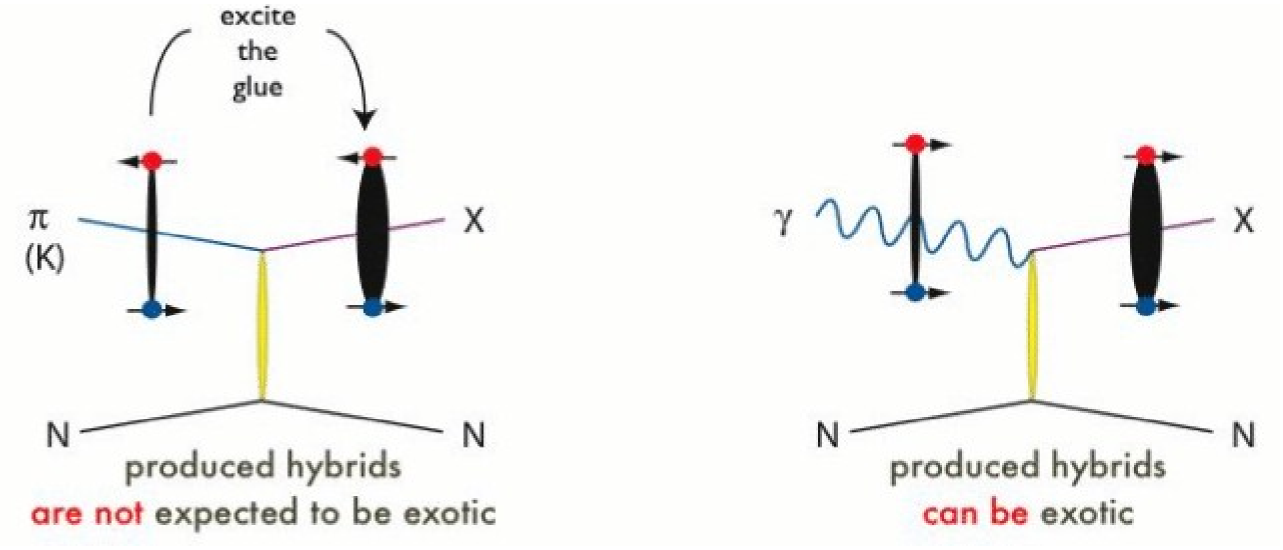
Combine excited glue quantum number with those of the quarks



Meson spectroscopy with photons at JLab

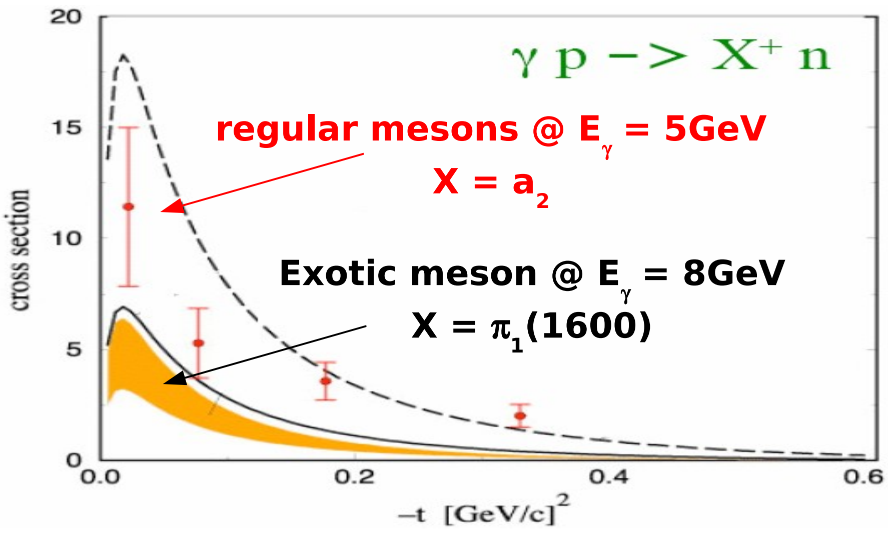
Why photoproduction?

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



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

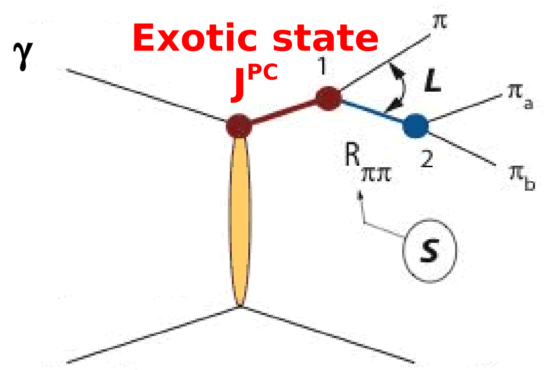
Few data (so far) but expected similar production rate as regular mesons



Partial Wave Analysis

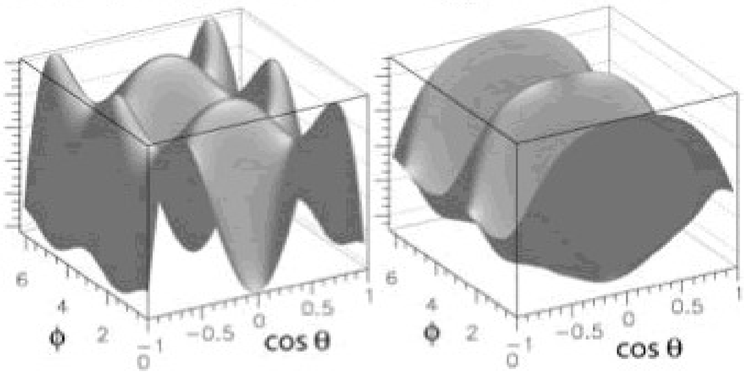
1) the isobar model

e.g. 3π system



(a) resonance: X decay — $X(2^{-+}) \to f_2(1275)\pi$

(b) isobar: $R_{\pi\pi}$ decay — $f_2(1275) \to \pi\pi$



Does the PWA work with photo-production data?

Use the PWA machinery on CLAS data

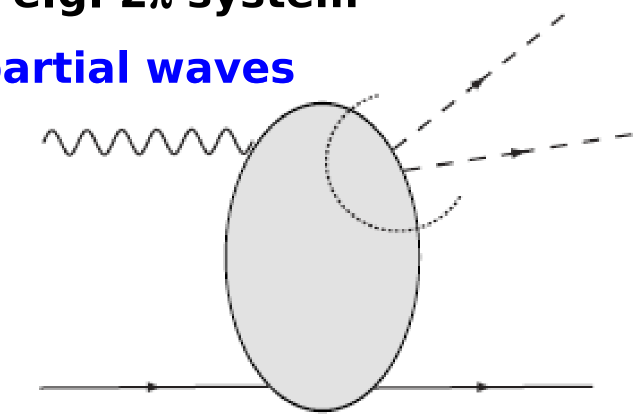
2) Moments+Dispersion relations

e.g. 2π system

1) Moments of the angular distribution in term of partial waves

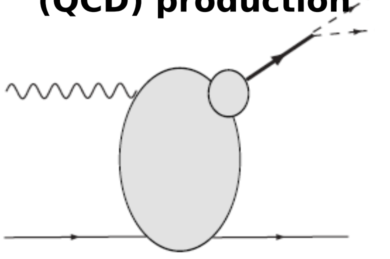
$$\langle Y_{\lambda\mu}\rangle(E_\gamma, t, M) = \frac{1}{\sqrt{4\pi}} \int d\Omega_\pi \frac{d\sigma}{dt dM d\Omega_\pi} Y_{\lambda\mu}(\Omega_\pi)$$

$$\langle Y_{00}\rangle = N\left[|S|^2 + |P_-|^2 + |P_0|^2 + |P_+|^2 + |D_-|^2 + |D_0|^2 + |D_+|^2 + |F_-|^2 + |F_0|^2 + |F_+|^2\right]$$

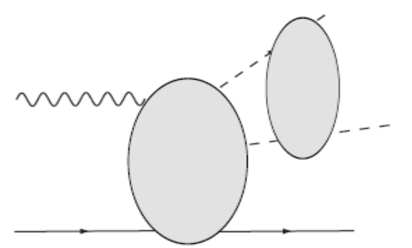


2) Parametrize partial waves in term of known ππ phase shift and unknown coefficients using Dispersion Relations

3) Derive partial wave cross sections to compare with models



Short range (QCD) production



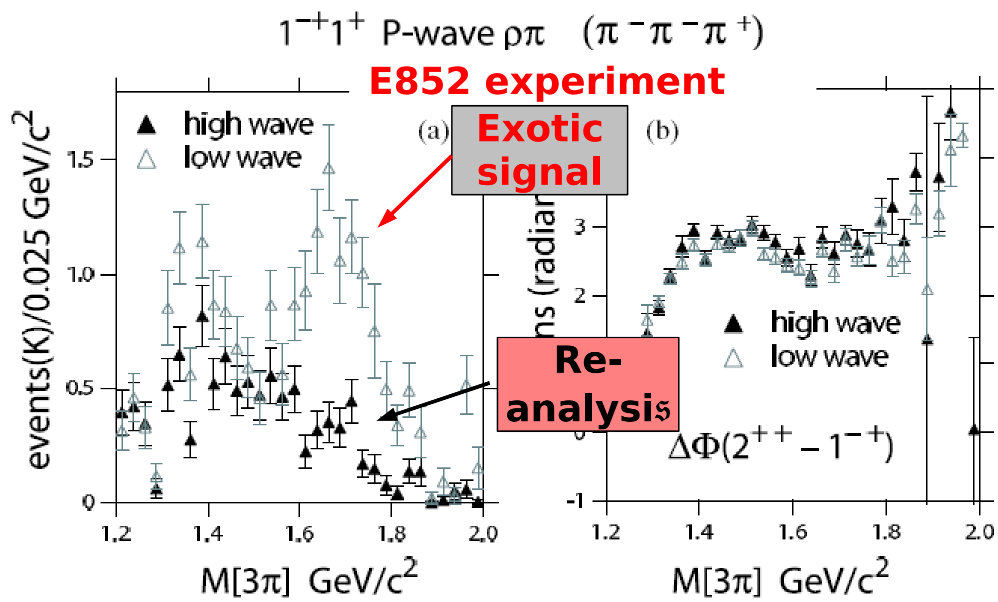
Meson formation

Partial Wave Analysis with CLAS

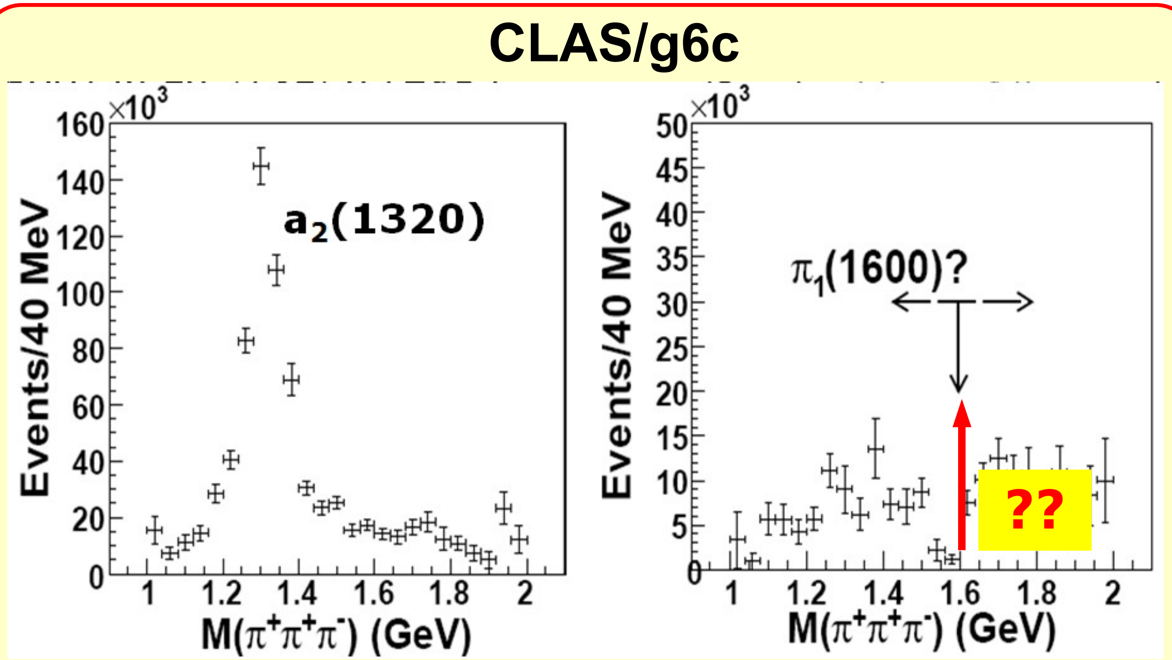
Isobar Model

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

- 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
- Simple final state with low background



M.Nozar et al Phys.Rev.Lett.102:102002,2009



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

No-evidence of exotic 1^{-+} state $\pi_1(1600)$

- Relevance of baryon resonance background

PWA in CLAS is feasible!

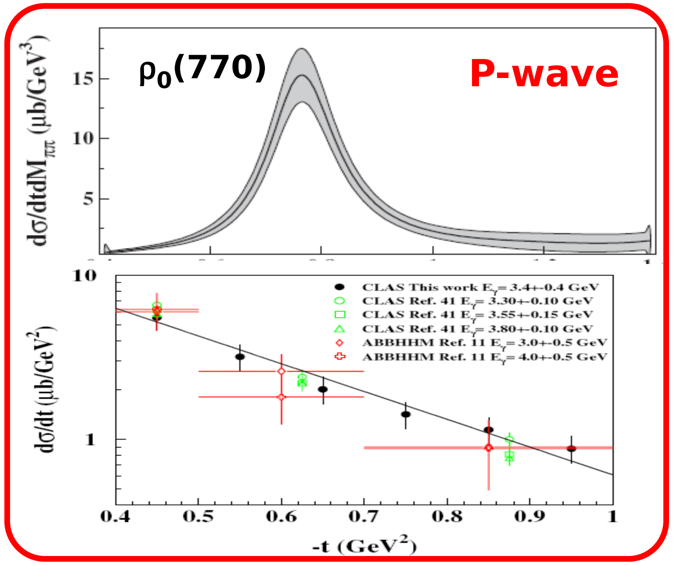
Partial Wave Analysis with CLAS

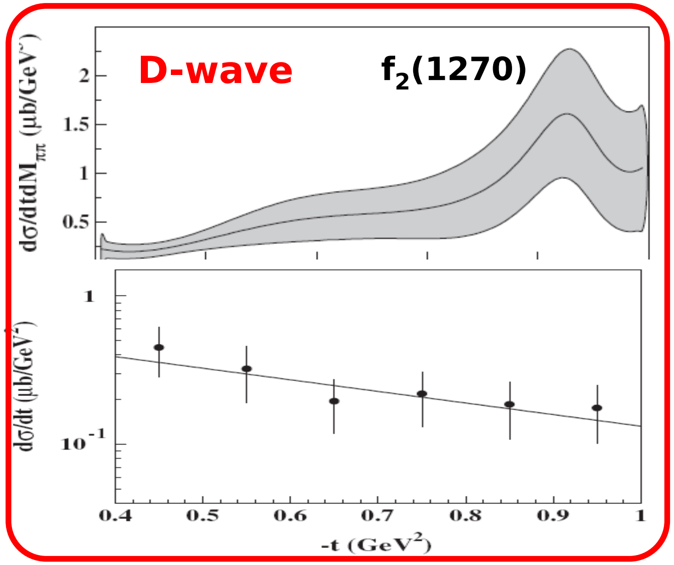
Moments + Dispersion relations

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

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

P-wave: ρ meson
D-wave: $f_2(1270)$
S-wave: σ, $f_0(980)$ and $f_0(1320)$

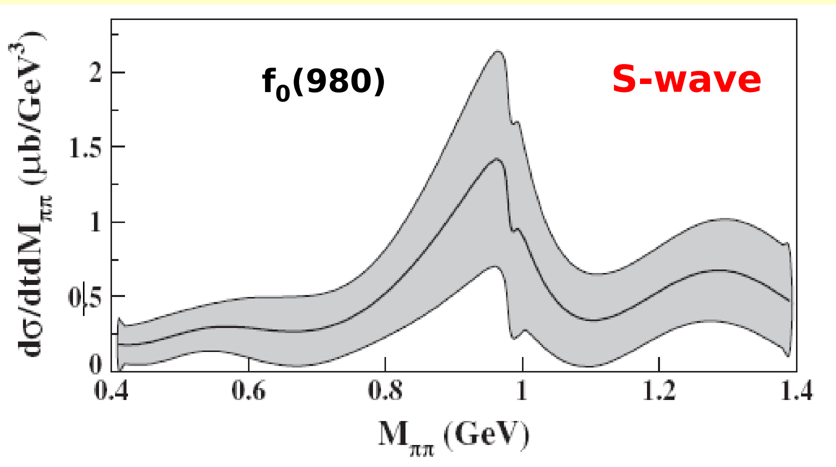




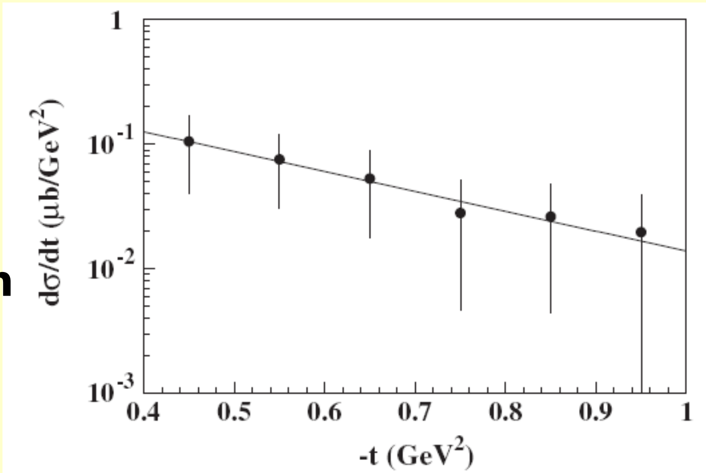
Known states are well reproduced, ρ(770)

PWA in CLAS is feasible!

MB ,De Vita A. Szczpaniak et al. **Phys.Rev.Lett. 102:102001,2009**
MB ,De Vita A. Szczpaniak et al **Phys.Rev. D80:072005,2009**



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

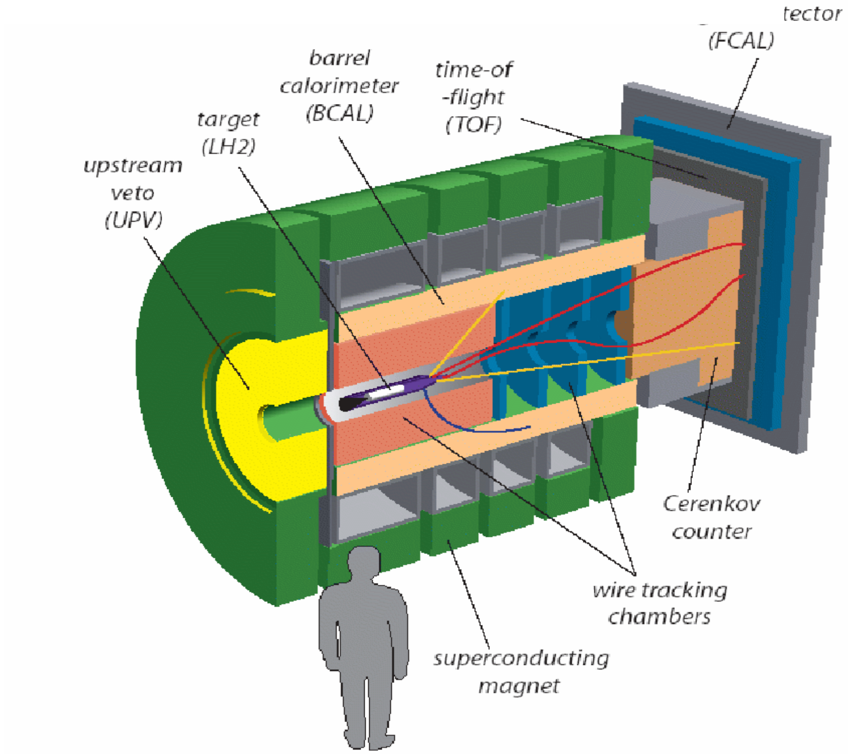


Meson spectroscopy with photons at JLab-12GeV

✯ The Detector

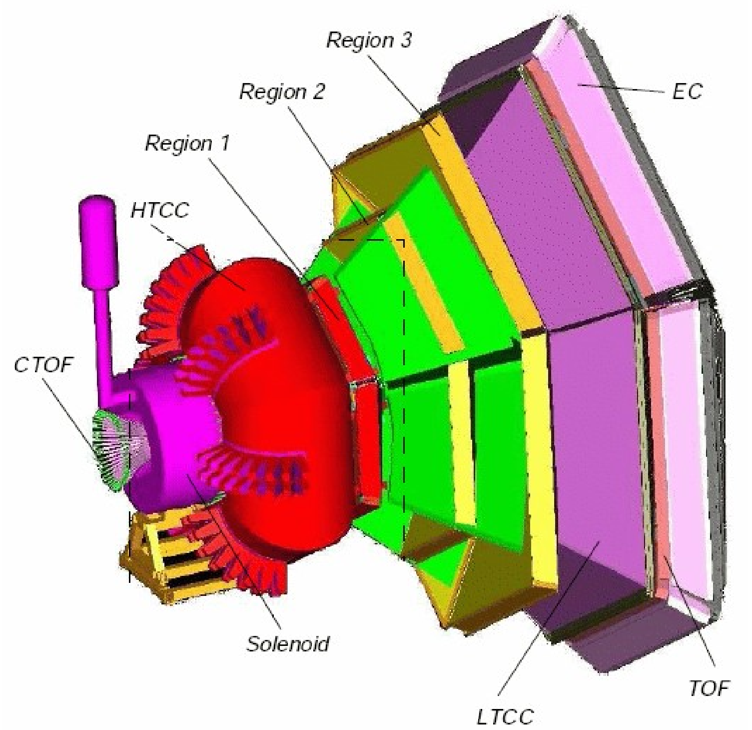
- Determination of J^{PC} of meson states requires Partial Wave Analysis
- Decay and Production of exclusive reactions
- Good acceptance, energy resolution, particle Id

Hall-D - GlueX Detector



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

Hall-B - CLAS12 Detector

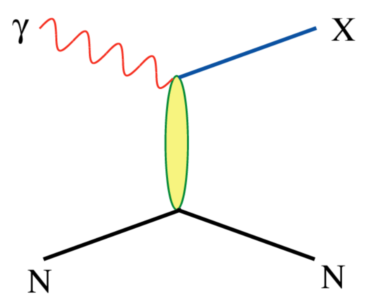


- Good resolution
- Good pID
- Reasonable hermeticity
- Un-uniform acceptance

Meson spectroscopy with photons at JLab-12GeV

The photon beam requirements

- 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



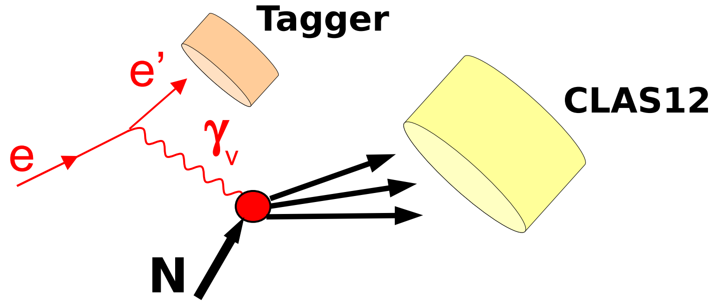
- Essential to isolate production mechanisms (M)
- Polarization acts as a J^{PC} filter if M is known
- Linear polarization separates natural and unnatural parity exchange

- With a 12 GeV electron beam only few choices:
  1) Bremsstrahlung
  2) Quasi-real electro-production

Hall-D and Hall-B will host real photon beams!

Photoproduction in CLAS12

Quasi-real electroproduction at Low Q^2

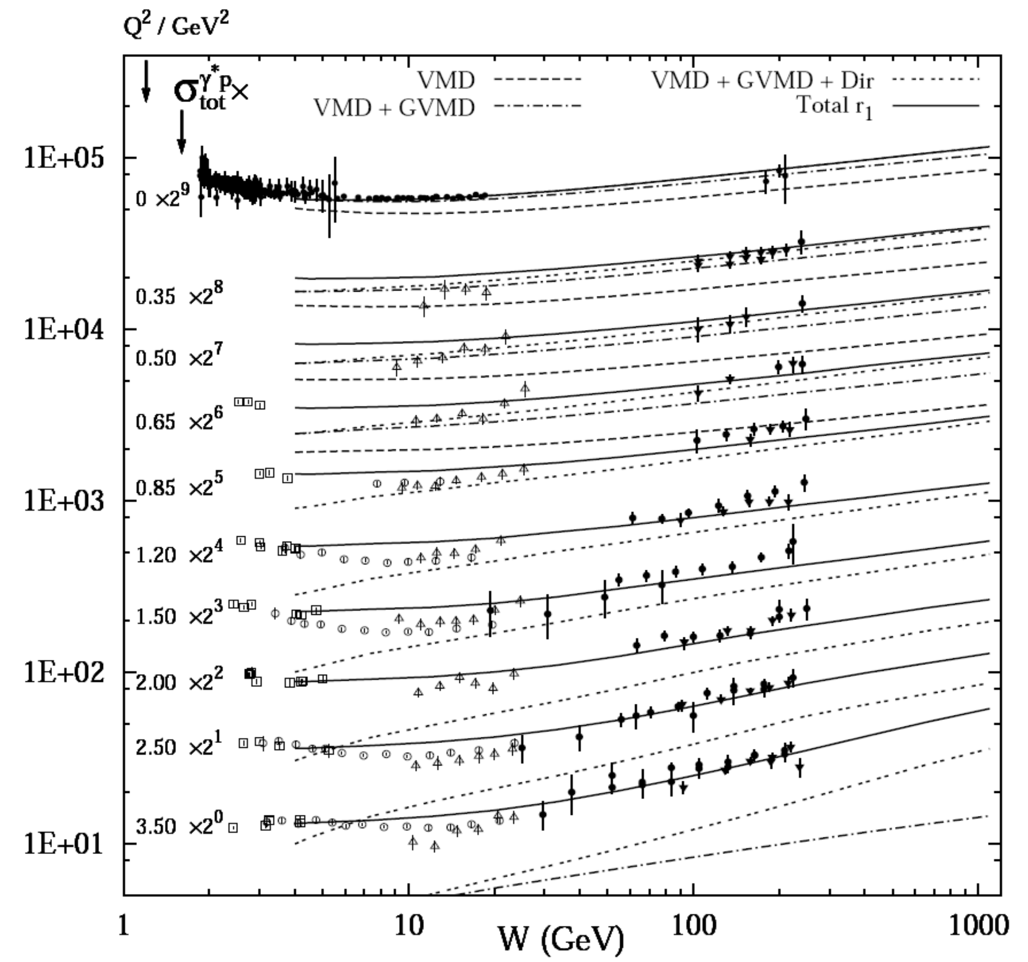


- **Electron scattering at "0" degrees (2^o - 5^o)**
  low Q2 virtual photon ⇔ real photon
- **Photon tagged by detecting the scattered electron at low angles**
  High energy photons $7 < E_\gamma < 10.5$ GeV
- **Quasi-real photons are linearly polarized**
  Polarization ~ 65% - 20% (individual)
- **High Luminosity (unique opportunity to run thin gas target!)**
  Equivalent photon flux $N_\gamma \sim 5\ 10^7$ on 40cm H_2 ($L=10^{35}\ cm^{-2}s^{-1}$)

Complementary to Hall-D (GLUEX)
Exploits the unique PID&resolution of CLAS12

Q^2 dependence of the Xsec

Studies at large W (~100GeV) show a smooth transition between Q^2=0 and $Q^2 \neq 0$



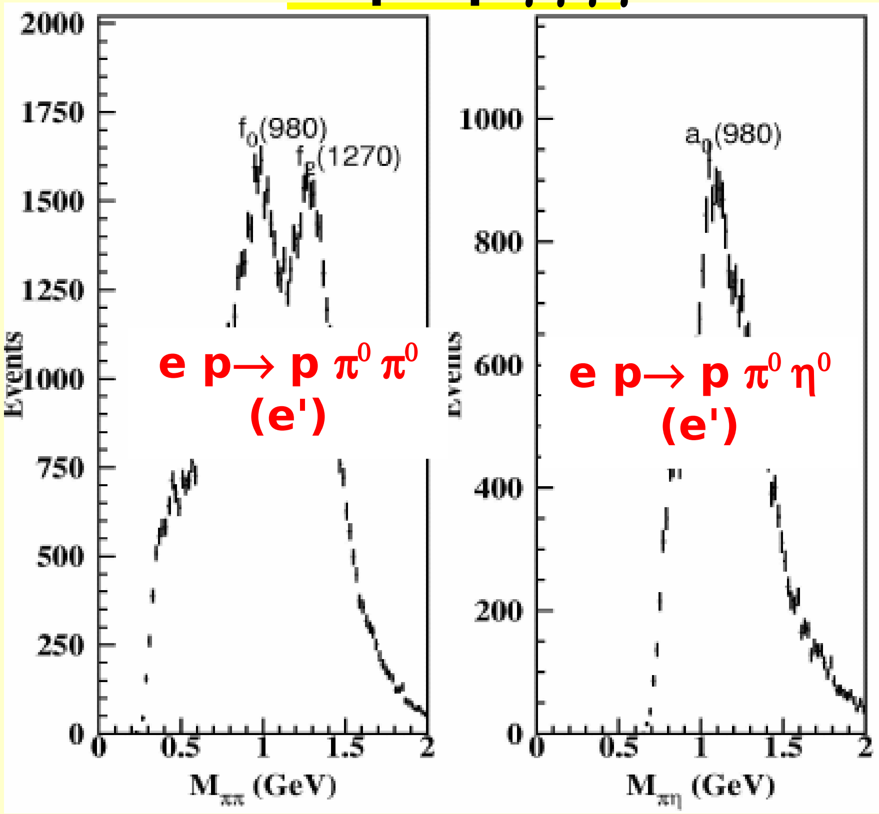
Well known technique used in hep

$Q^2 < W^2$

COMPASS: <1 GeV² <Q²> ~ 10⁻¹ GeV²
ZEUS: 10⁻⁷ – 0.02 GeV² <Q²> ~5 10⁻⁵ GeV²
H1: <2 GeV²

Tested in CLAS

e p→ p γγγγ X



Bright meson peaks show up
The technique works!

Forward Tagger

Calorimeter + tracking device + veto

Electron energy/momentum

Photon energy (ν=E-E')

Polarization $\varepsilon^{-1} \sim 1 + \nu^2/2EE'$

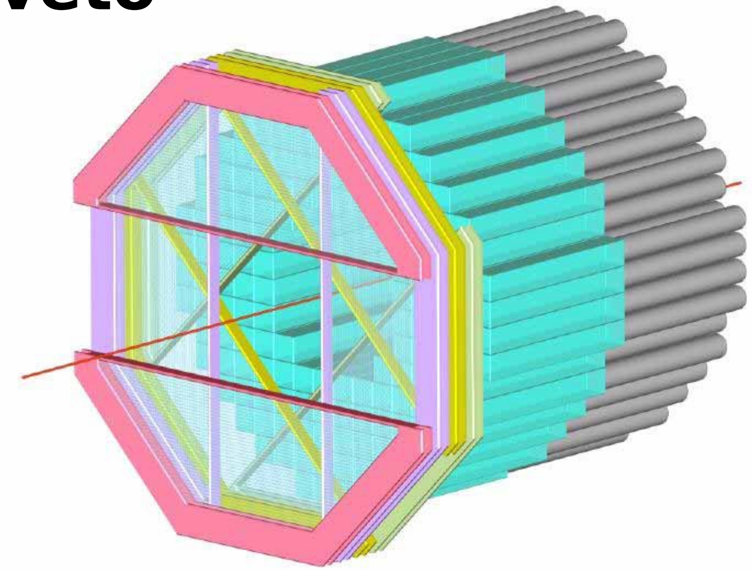
$\delta\nu / \nu = \delta E'/(E-E')$

Electron angles

$Q^2 = 4\ E\ E'\ \sin^2 \vartheta/2$

φ polarization plane

Veto for photons

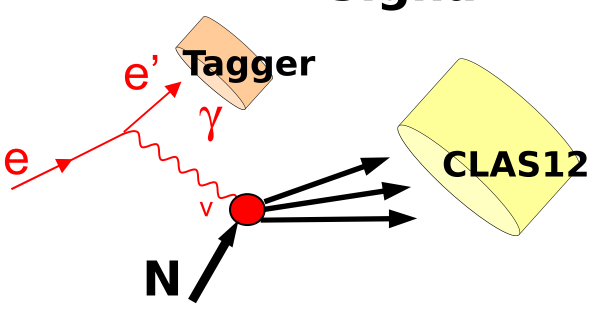


Rates in the forward tagger

$L_e \sim 10^{35}\ cm^{-2}\ s^{-1}$ ($N_\gamma \sim 0.5\ 10^8\ \gamma/s$)

Inelastic electro-production

Signal

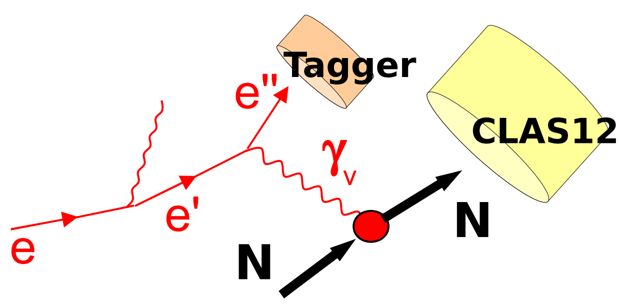


R ~10kHz

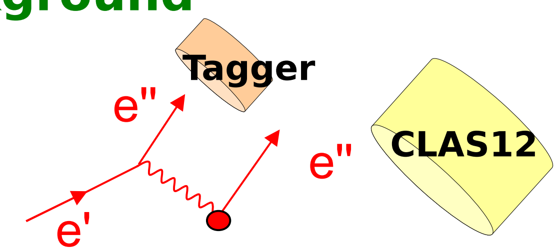
Elastic radiative tail

Moeller scattering

Background



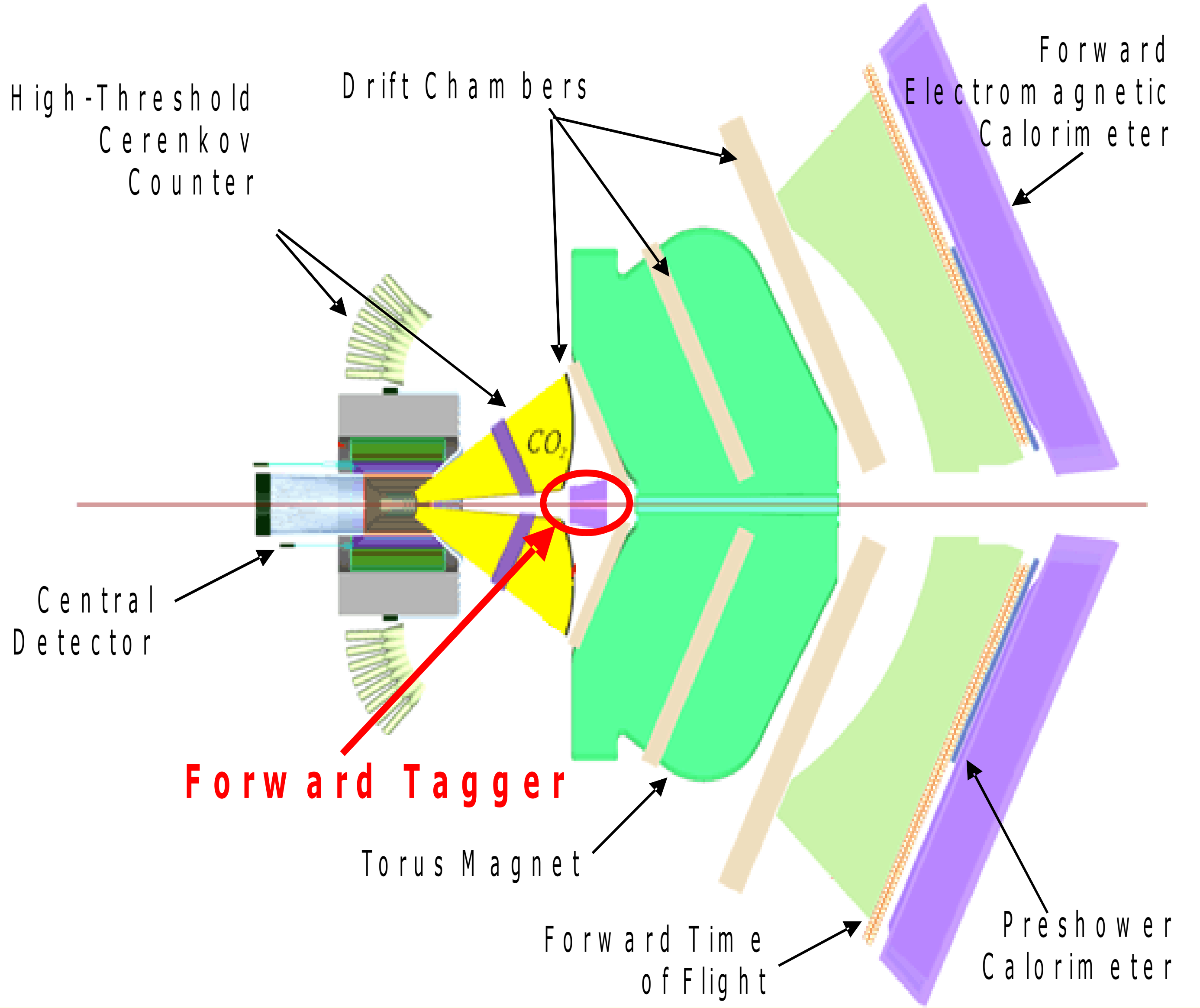
R ~100kHz



R ~10MHz

The Forward Tagger in CLAS12

- **Compatible with standard electron runs (HTCC)**
- **Photon detector for leading DVCS experiments**
- **Extend the CLAS12 coverage for neutral from 5° to 2°**



photons and electrons can run in parallel!

Photoproduction in CLAS12

Photon beam requirement

- High Luminosity
- Tagger (initial photon energy) is required to add 'production' information to decay
- Linear polarization simplifies the PWA

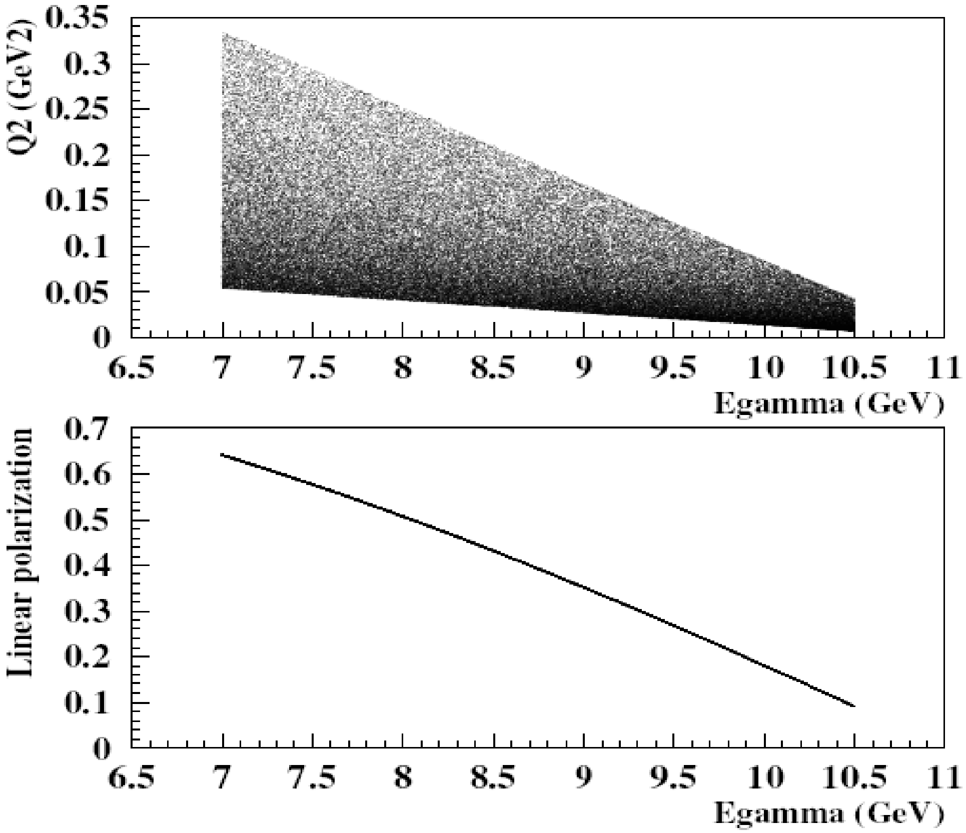
Quasi-real electroproduction at Low Q^2

Electron kinematics:

- E=0.5-4 GeV
- θ=2-5 deg

⇓

- Q^2=0.007-0.33 GeV^2
- E_g=7-10.5 GeV
- Photon Polarization: 10-65%



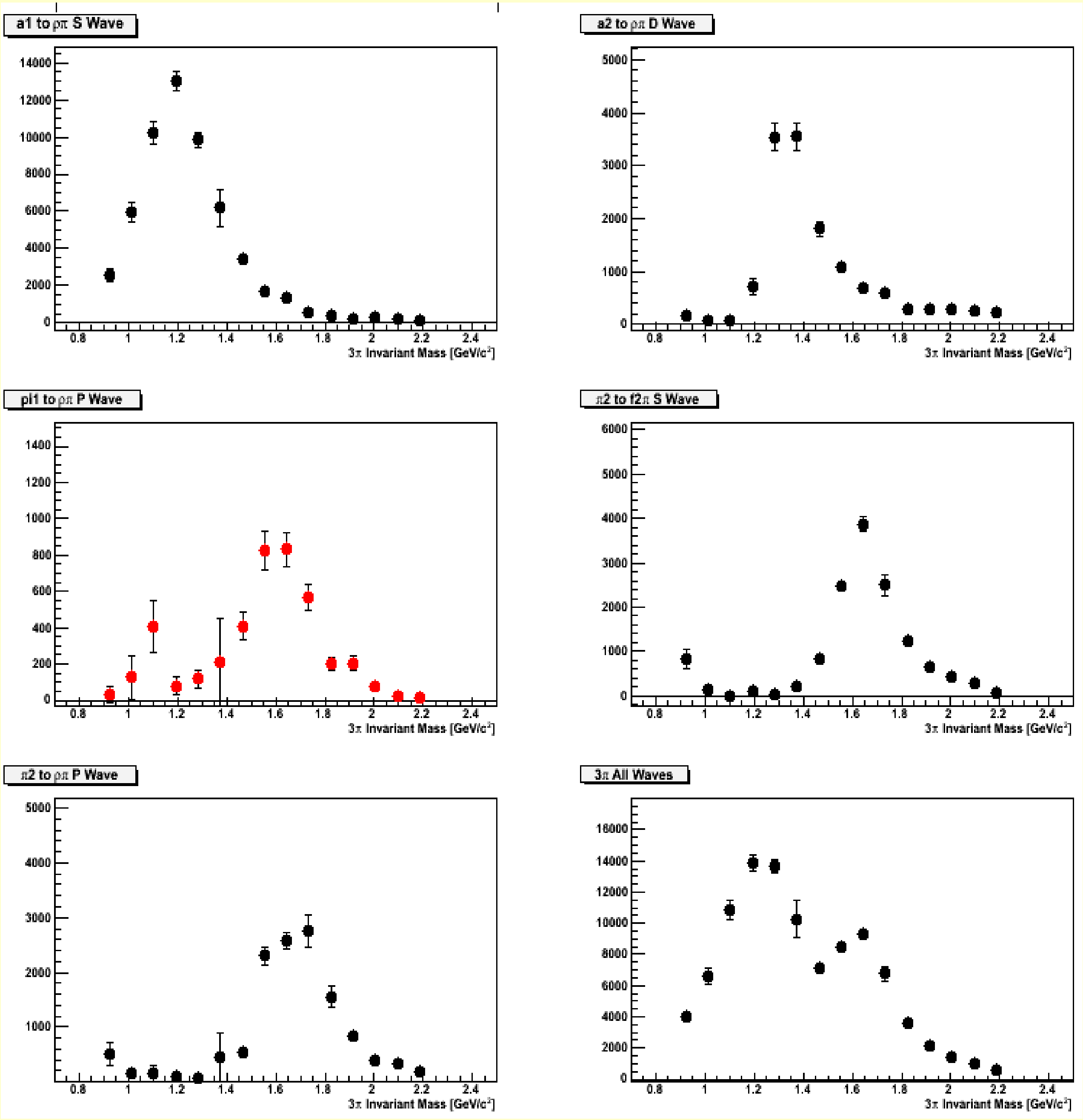
Partial Wave Analysis in CLAS12

IU-Edinburgh-INFN-JLab

Benchmark channel:

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

- The process is described as sum of 8 isobar channels:
  - a2 $\rightarrow \rho \pi$ (D-wave)
  - a1 $\rightarrow \rho \pi$ (S-wave)
  - a2 $\rightarrow \rho \pi$ (D-wave)
  - pi2 $\rightarrow \rho \pi$ (P-wave)
  - pi2 $\rightarrow \rho \pi$ (F-wave)
  - pi2 $\rightarrow$ f2 π(S-wave)
  - pi2 $\rightarrow$ f2 π (D-wave)
  - pi1 $\rightarrow \rho \pi$ (P-wave) (exotic)
- Amplitudes calculated by A.Szczepaniak
- CLAS12 acceptance projected and fitted

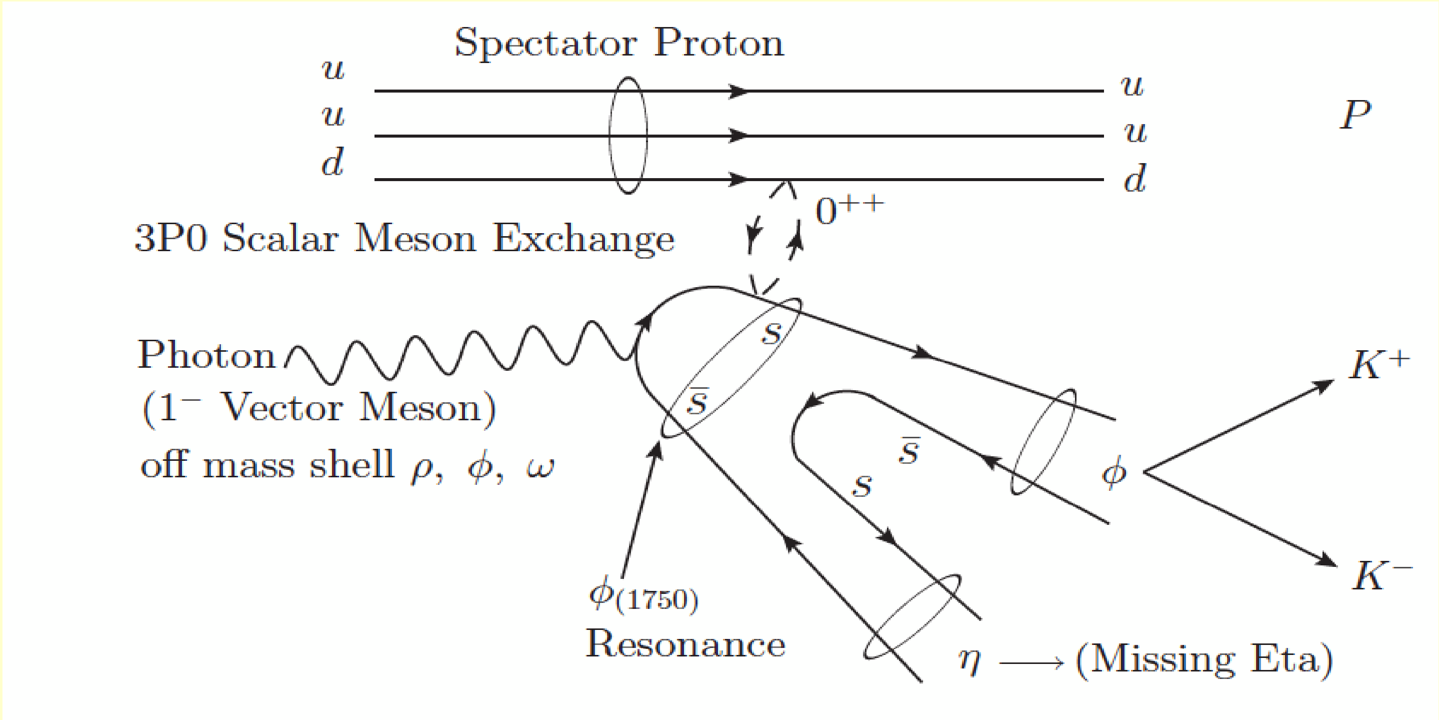


PWA in CLAS12 is feasible !

Meson spectroscopy: φη and φπ channels

Exploiting the CLAS12 uniqueness: looking for strangeonia ($s\bar{s}$)

Good resolution and kaon ID required



- **Intermediate mass of s quarks links long to short distance QCD potential**
- ***Due to the OZI rule, observation of a state with a large BR in φη, φπ and φφ and small BR in nonstrange final states can serve as smoking gun for an initial $s\bar{s}$ state*** **(Barnes, Blak and Pages)**

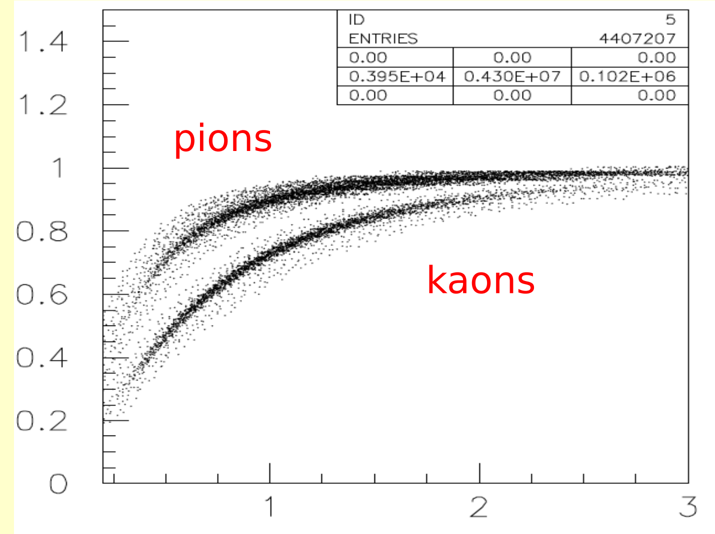
Search for strangeonia in CLAS

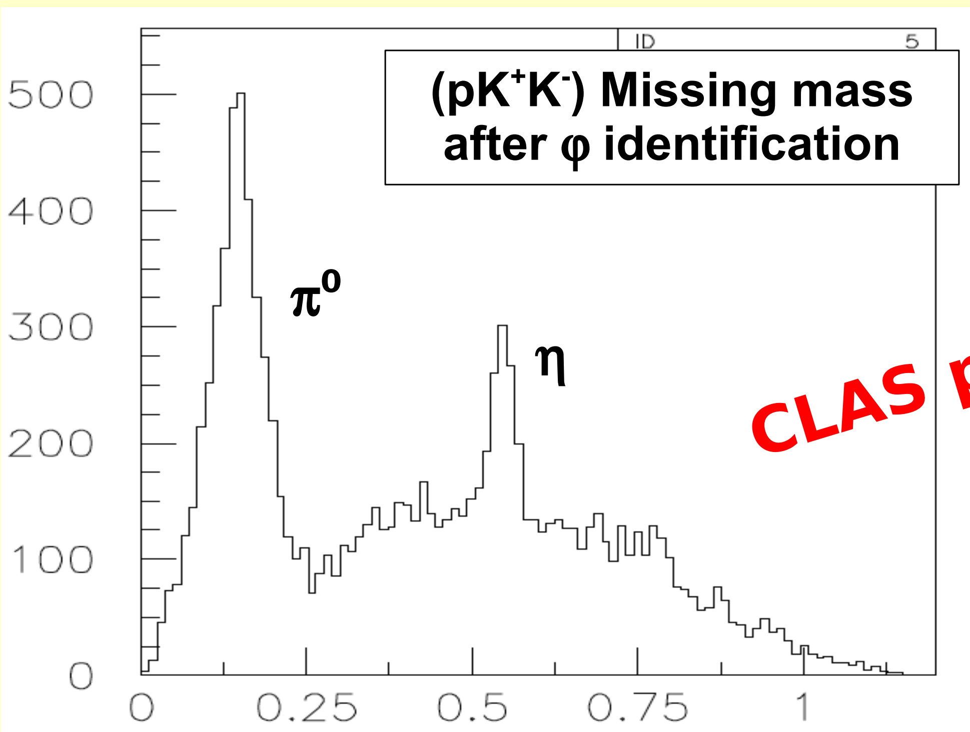
G12 Experiment:

Search of new forms of hadronic matter in photoproduction on the proton

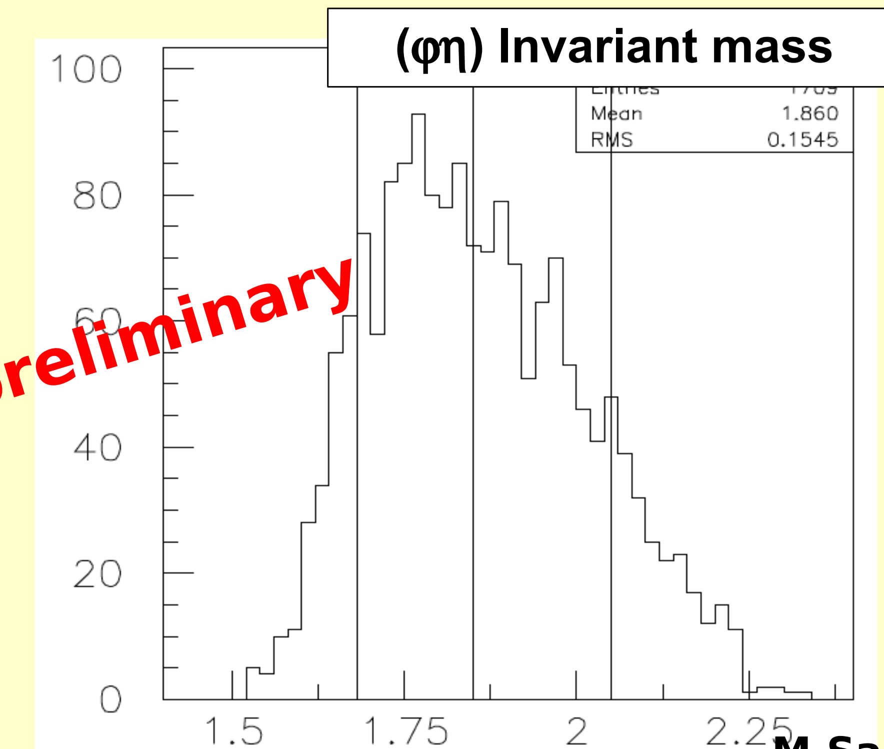
- Data tacking completed in 2008
- Photon energy up to 5.5 GeV
- More than 26 billions triggers
- Data analyses and PWA in progress

$$\gamma\, p \rightarrow\; p\, \varphi\, \eta/\pi^0 \rightarrow\; p\, K^+K^-\, (\eta/\pi^0)$$





CLAS preliminary



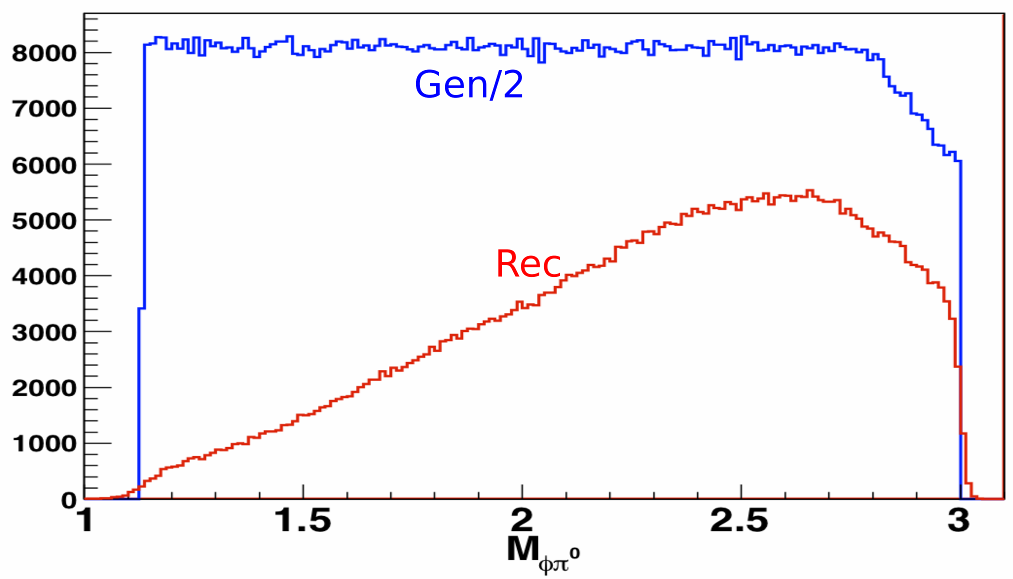
M.Saini

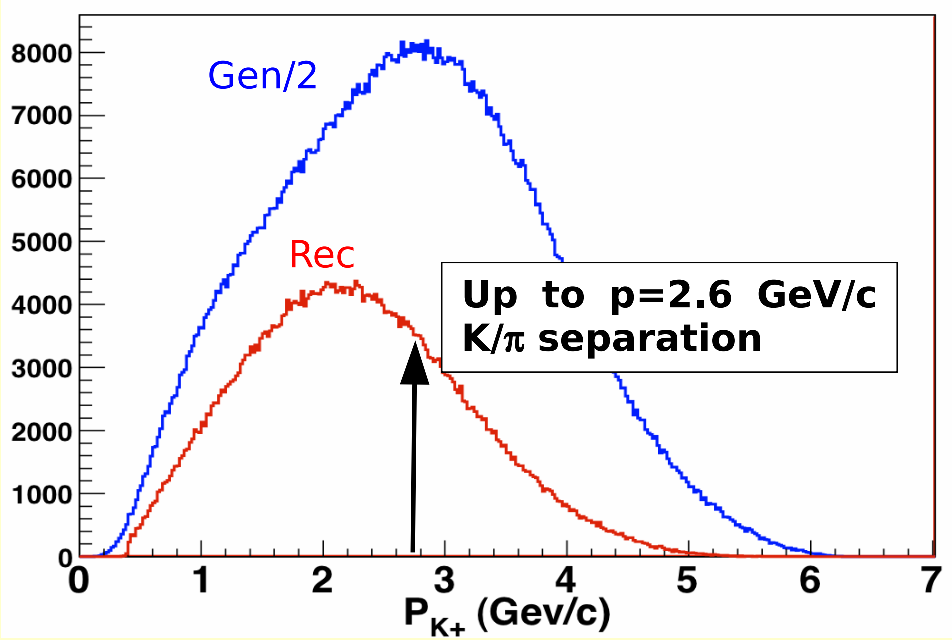
Search for strangeonia in CLAS12

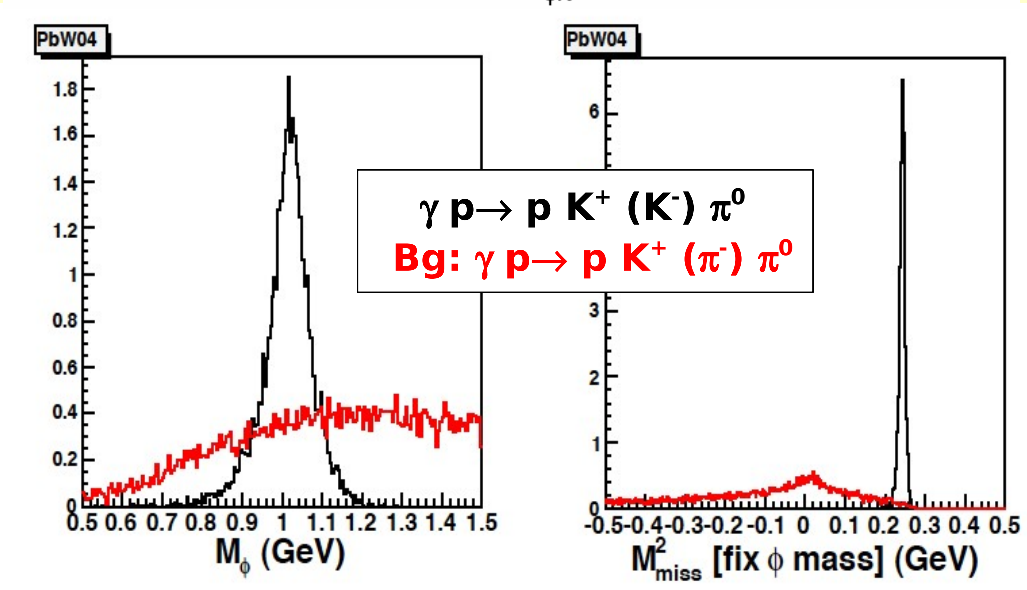
CLAS12 simulations

$\gamma\, p \rightarrow p\, C(M=1480, \Gamma=130\ MeV) \rightarrow p\, \varphi\, \pi^0 \rightarrow p\, K^+(K^-)\, \gamma\gamma$

- **Unusual BR in $\varphi\pi$ (OZI suppressed)**
- **$J^{PC}=1^{--}$ $\sigma \sim 10nb$**
- **Tetra-quarks or hybrid**
- **CLAS12 acceptance ~ 10%**
- **High-p K id relies on kin-fit**
- **K/π separation for p>2.6 GeV/c highly desirable!**







Conclusions

Jefferson Lab is providing new, precise and abundant data on hadron spectroscopy

CLAS

Baryon spectrum

- **Many different exclusive reactions w/wo polarization**
- **Coupled channel analysis are on progress**
  1) to map the $N \rightarrow N^*$ transition form factors
  2) to look for missing resonances

Meson spectrum investigated in photoproduction

- **PWA (IM and Moments + Dispersion relations) feasible**

CLAS12

- **An extension of this program to CLAS12 has been proposed**
- **Low-Q2 electroproduction is a complementary technique to the Hall-D coherent Bremsstrahlung**
- **Particle Id and good resolution are unique for CLAS12**

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

Back up slides

Partial Wave Analysis

- The development of robust PWA techniques is a crucial step for the succesful completion of any meson spectroscopy program

- Advancements in detectors, beam and experimental techniques are leading to a high precision and high statistics data sets

Are the prently available PWA tools adequate for the new data that are and will be produced?

Workshop on Hadron Spectroscopy
INT - Seattle, November 9-13 2009
Organizers: M. Battaglieri, C. Munoz Camacho, RDV, J. Miller, A.P. Szczepaniak

- ~ 40 participants from the theoretical and experimental community
- address open issues in experimental techniques, pwa, and theoretical interpretation
- interest from the theory community to work with experimentalists to develop more sophisticated analysis approaches, going beyond the isobar model
- white paper being written

Next meeting:

Workshop on Amplitude Analysis in Hadron Spectroscopy
ECT* - Trento, January 24-28 2011
Organizers: C. Hanhart, M. Pennington, E. Santopinto, A.P. Szczepaniak (coordinator), U. Wiedner

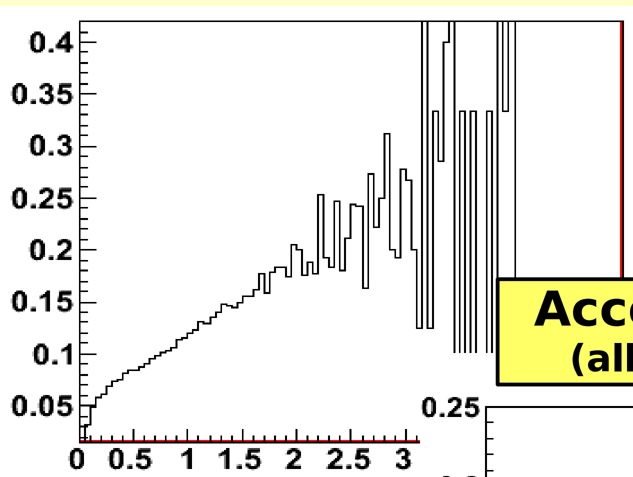
Physics channels simulation: 3π

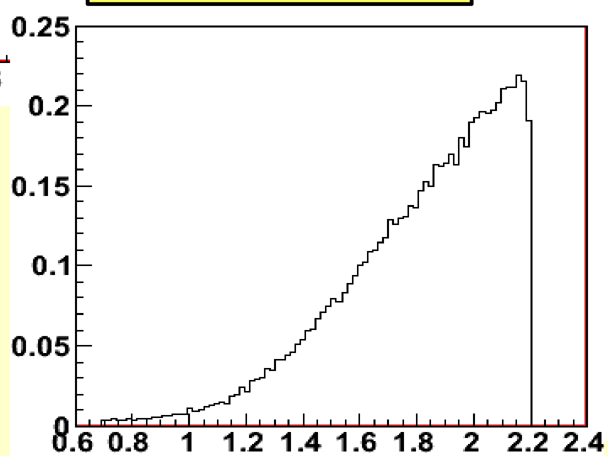
Acceptance and resolution studies

- Determine CLAS12 acceptance
- Determine resolution for exclusive channel selection and mass reconstruction

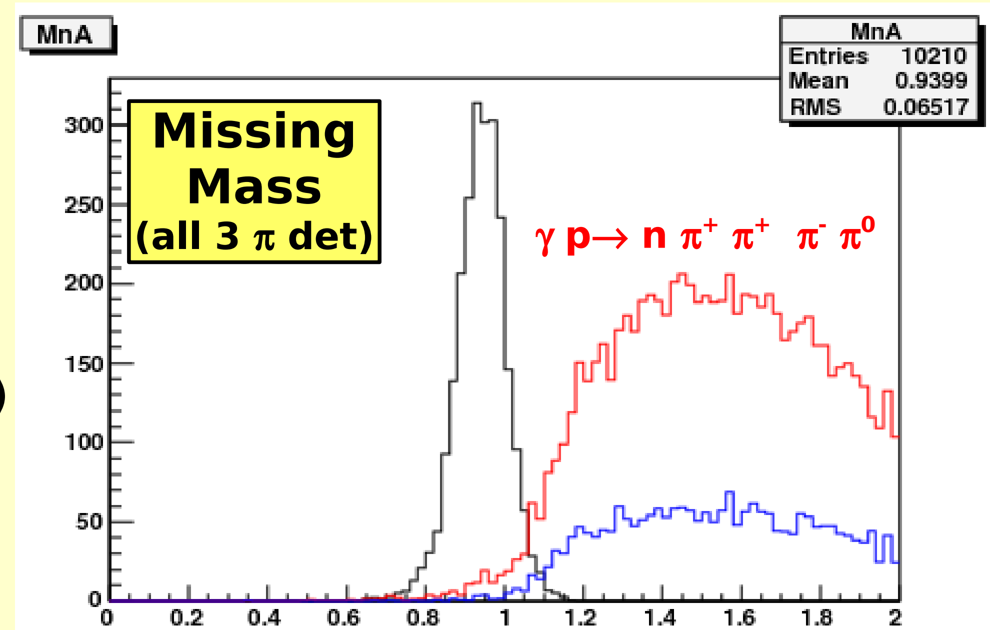
$\gamma\, p \rightarrow n\, Res$ (M=1.6 GeV, Γ=150 MeV)

$\rightarrow n\, \pi^+ \pi^+ \pi^-$



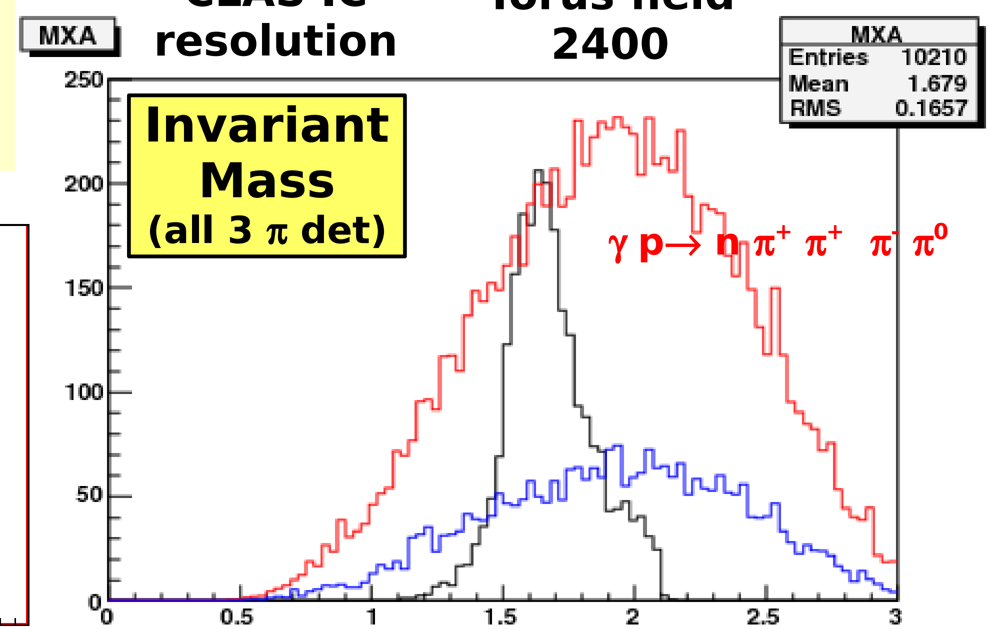


Acceptance (all 3 π det)



CLAS IC resolution

Torus field 2400



Edinburgh-INFN

The detector: CLAS12

- Determination of J^{PC} of meson states requires Partial Wave Analysis
- Decay and Production of exclusive reactions
- Good acceptance, energy resolution, particle Id

Hermetic charged/neutral particles detector

Forward Detector

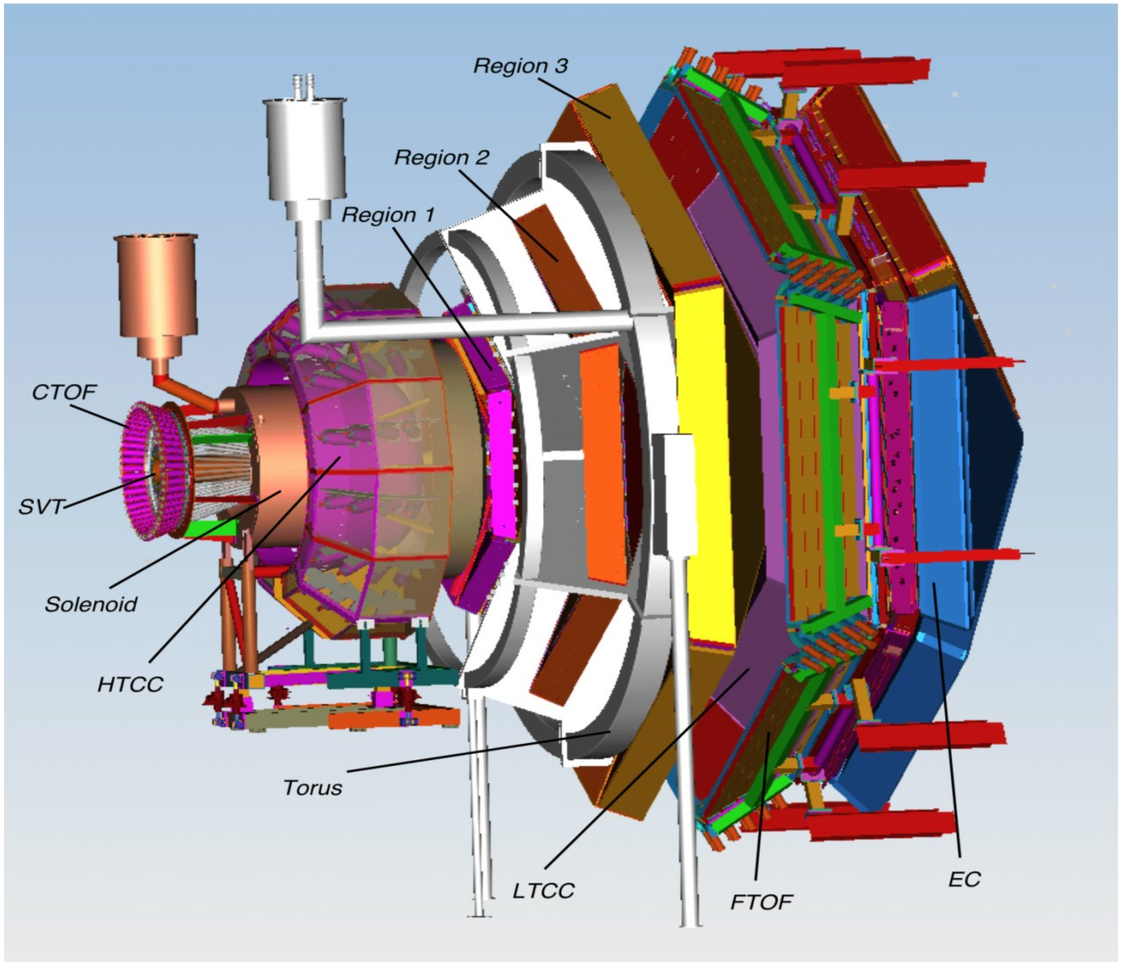
- TORUS Magnet
- Forward SVT tracker
- HT Cerenkov Counter
- LT Cerenkov Counter
- Forward TOF System
- Preshower calorimeter
- E.M. Calorimeter

Central Detector

- SOLENOID magnet
- Barrel silicon tracker
- Central TOF

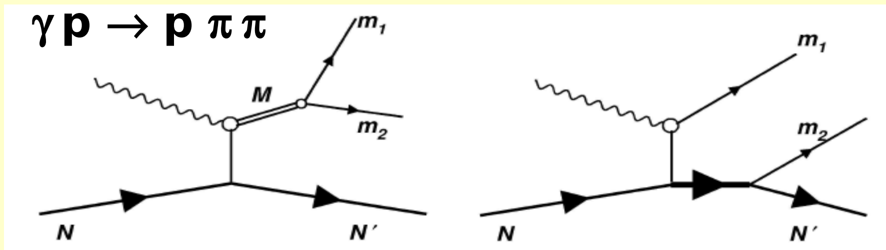
Proposed updates

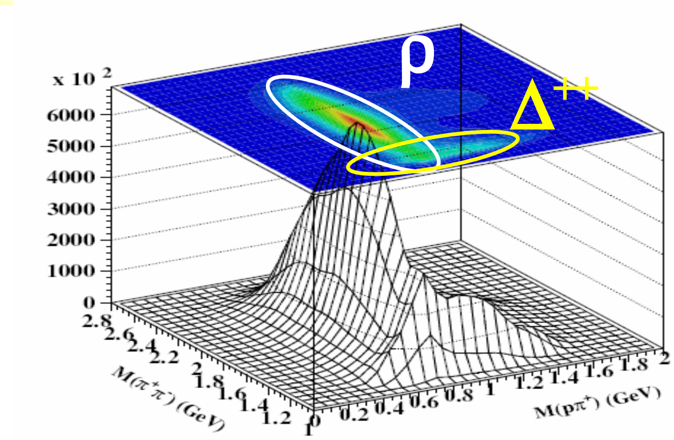
- Micromegas (CD)
- Neutron detector (CD)
- Forward Tagger



Coherent meson production on nuclei

☆ **Eliminate *s-channel* resonance background**





☆ **Simplify PWA: S=I=0 target acts as spin and parity filter for final state mesons**

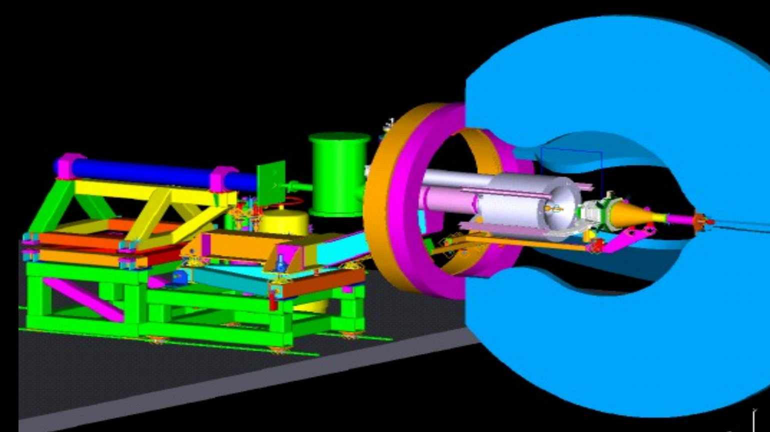
☆ **Production cross section expected ~ $e^{-bt} |A\, F_A(t)|^2 \to$ low $-t$ kinematic**

Detection of recoiling nucleus:
- **low $-t$ (p~0.2-0.5 GeV)**
- **thin (gas) target (~10^{-3} g/cm^2)**

Photon beam:
- **small size**
- **high flux**

quasi-real photoproduction Hall-B

- Radial TPC with 7atm. He4 Target
- Solenoid for forward-focusing of Moeller electrons and bending of recoil nucleus in the TPC
- PbWO4 calorimeter for improved photon acceptance at forward angles



EG6: Meson spectroscopy in coherent ^{4}He photoproduction

Calorimeter options

- Radiation hardness
- light yield (cooling?)
- timing
- temperature dependence
- Magnetic field effect
- light read-out (APD/SiPM)

Homogeneous (crystals)

EM shower: ionization energy of charged particles (electrons)

Longitudinal size:
Radiation lenght X_0 (e loses 1-1/e E)
~ 180 A/Z^2 (gr/cm^2)

Transverse size:
Moliere Radius R_M (90% of shower)
~ 7 A/Z (gr/cm^2)

- **PbWO**
  Fast, rad hard, few light, well known
- **LSO/LYSO**
  Quite fast (8x), more light (100x)
  poorly known
- **LaBr**
  Fast, a lot of light (600x), expensive

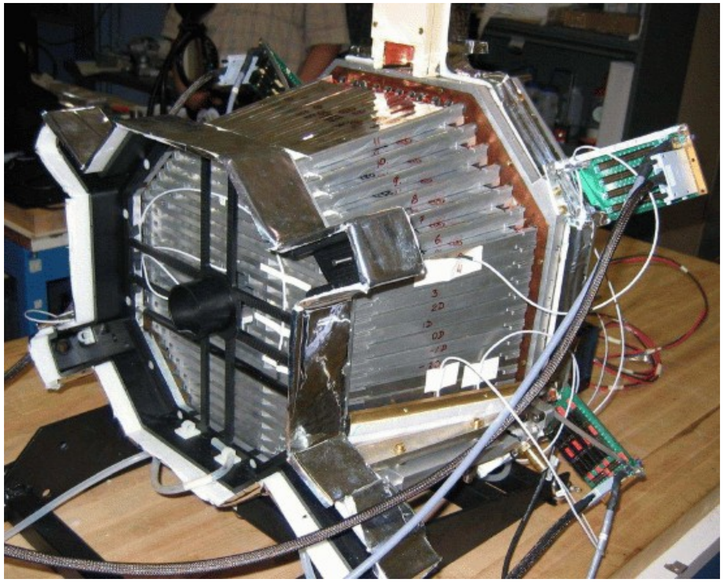
PbWO4

τ_{Decay}	~ 6.5 ns
R_M	~ 2.1 cm
ρ	~ 8.3 g/cm^3
X_0	~ 0.9 cm

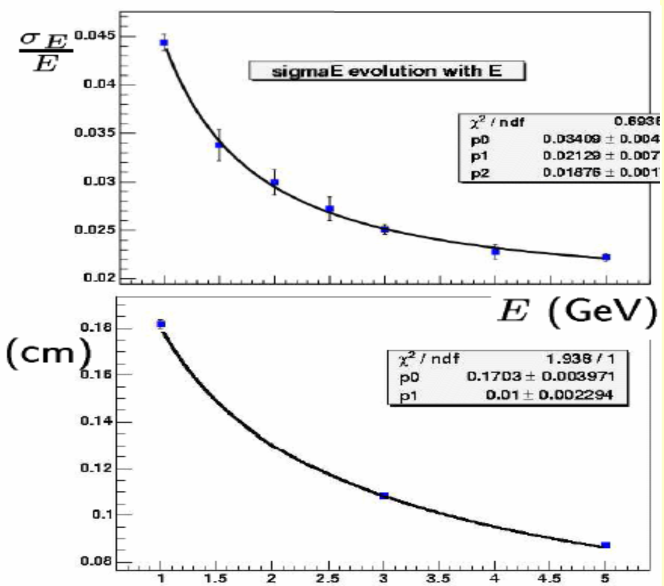
light yield 0.3% (LY NaI(Tl))

CMS(LHC)	ECAL
ALICE (LHC)	PHOS
CLAS (JLab)	IC
PANDA (GSI)	EMC

CLAS Inner Calorimeter



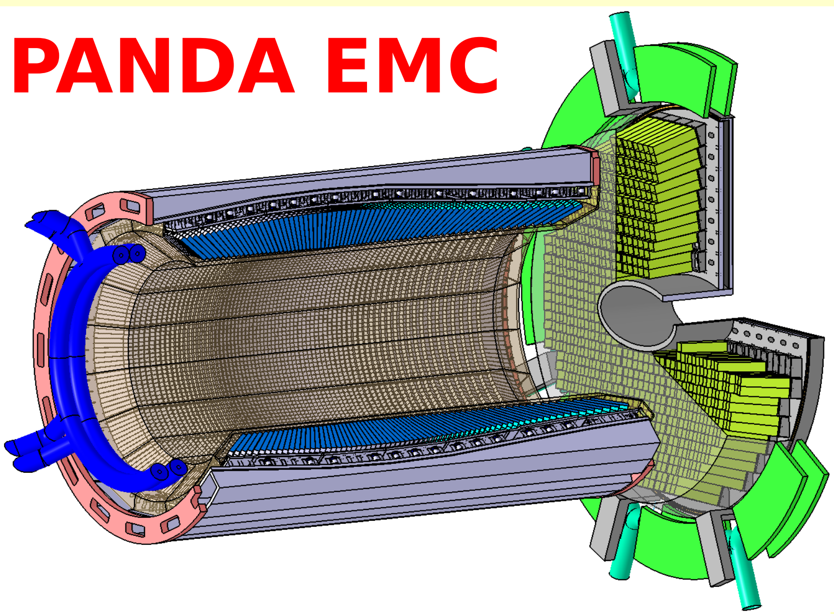
- 424 PbWO4 crystals
- L = 16 cm = 17 X_0
- Front size 1.3x1.3 cm^2
- Back size 1.6x1.6 cm^2
- Controlled Temperature (0.1 ^{0}C)
- APD readout



$$\frac{\sigma_E}{E} = \frac{0.02}{E} \oplus \frac{0.03}{\sqrt{E}} \oplus 0.024$$

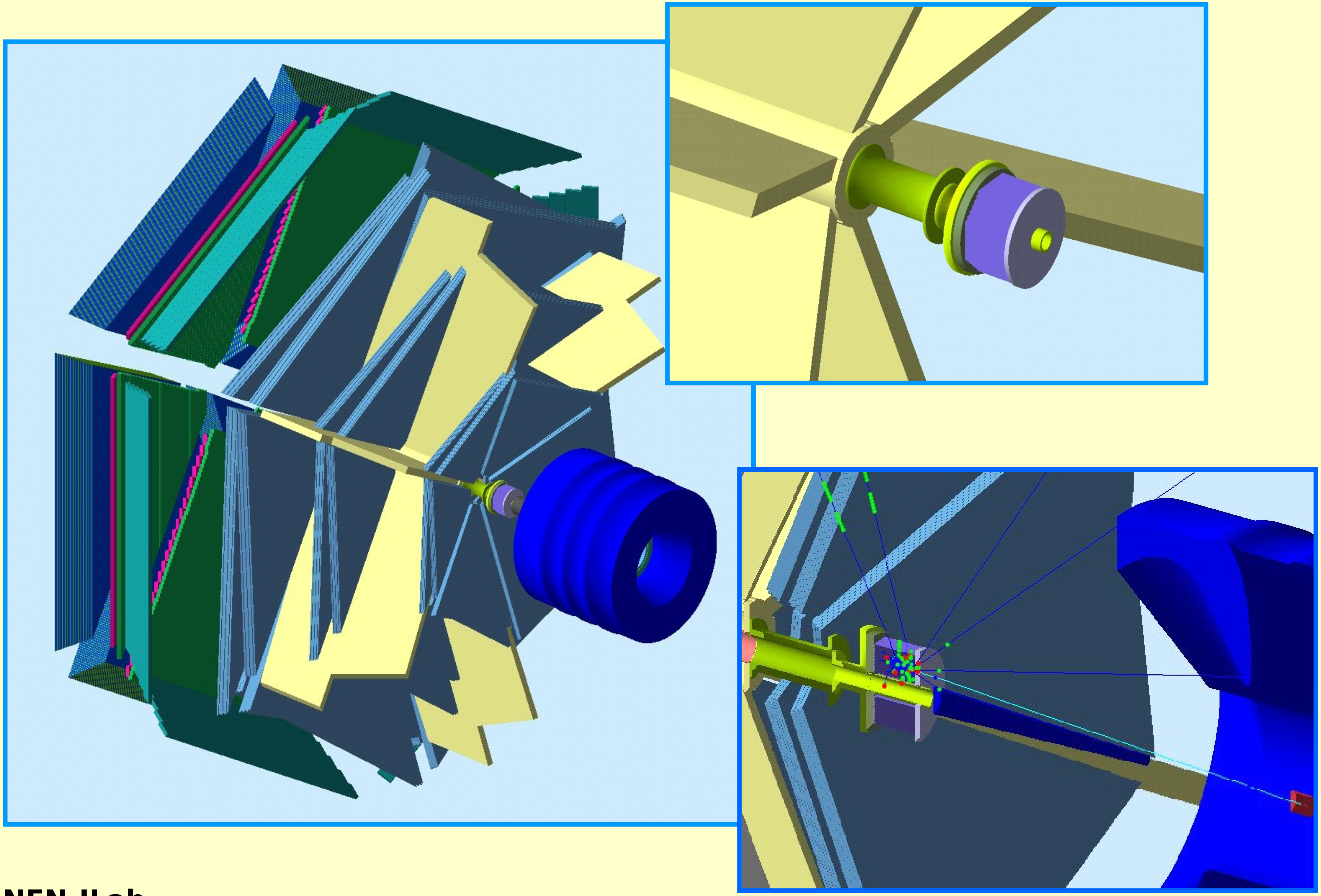
$$\sigma_x = \frac{0.2}{\sqrt{E}} \text{ (cm)}$$

PANDA EMC



- 16k PbWO-II crystals
- Size = 2 x 2 x 20 cm3 (23 X_0)
- LY = 20 phe/MeV (80 phe/MeV @ -25^{0}C)
- APD readout
- Resolution ($2/\sqrt{E} \oplus 1$)%

GEANT4 Simulations



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