

STRANGE MESON SPECTROSCOPY AT CLAS AND CLAS12



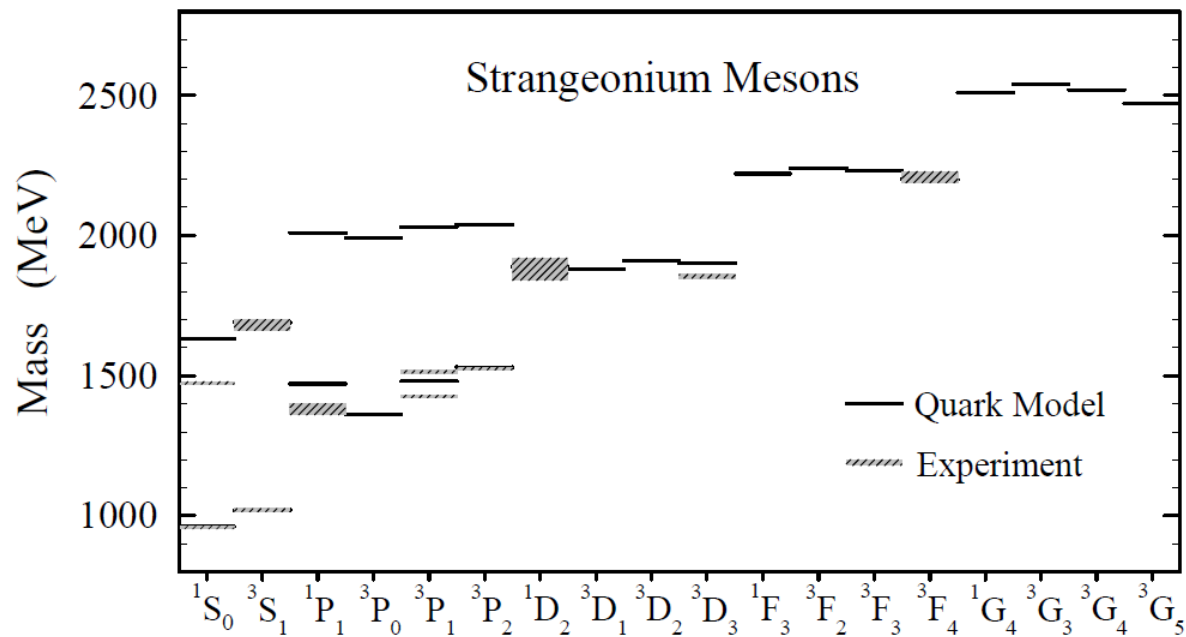
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Outline

- Introduction
 - Light mesons decaying to $K\bar{K}$ and $K\bar{K}\pi$: open vs hidden strangeness
 - Exotic strangeonia and expected channels
- Studies of photoproduction reactions by real photons: CLAS6
 - The $K\bar{K}$ system: K^+K^- and $K_S K_S$
 - The $K\bar{K}\pi$ and $K\pi\pi$ systems
 - The $\phi\eta$ system
- Studies of photoproduction reactions by virtual photons: CLAS12
- Summary and Conclusions

Introduction: strange quarkonia

- Light mesons (u,d,s) with at least one strange quark/antiquark in their valence component
 - **Kaonia/antikaonia**: dominant valence $n\bar{s}/s\bar{n}$ (n= u, d)
 - Of 22 expected states below 2.1 GeV, ~13 have been observed
 - **Strangeonia: $S\bar{S}$**
 - Of 22 expected states below 2.1 GeV, <10 are steadily established



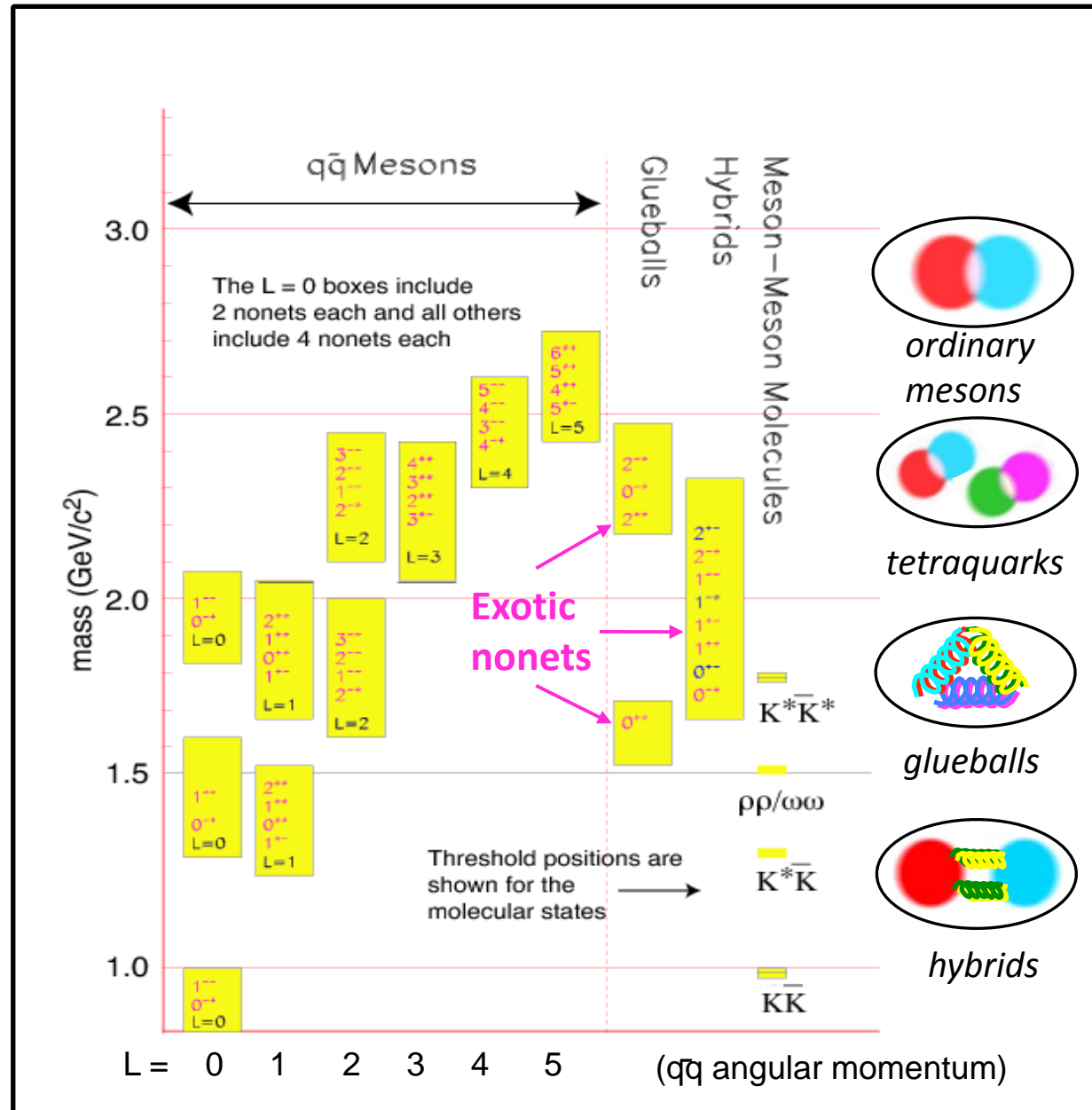
Godfrey, Napolitano, Rev. Mod. Phys. 71 (1999), 1411

- Strangeonium experimental signatures much less known (and clear) than charmonium
- Large probability of:
 - strong mixing with light mesons & other expected (but still unobserved) structures
 - Overlap of broad states
 - Decay channels shared

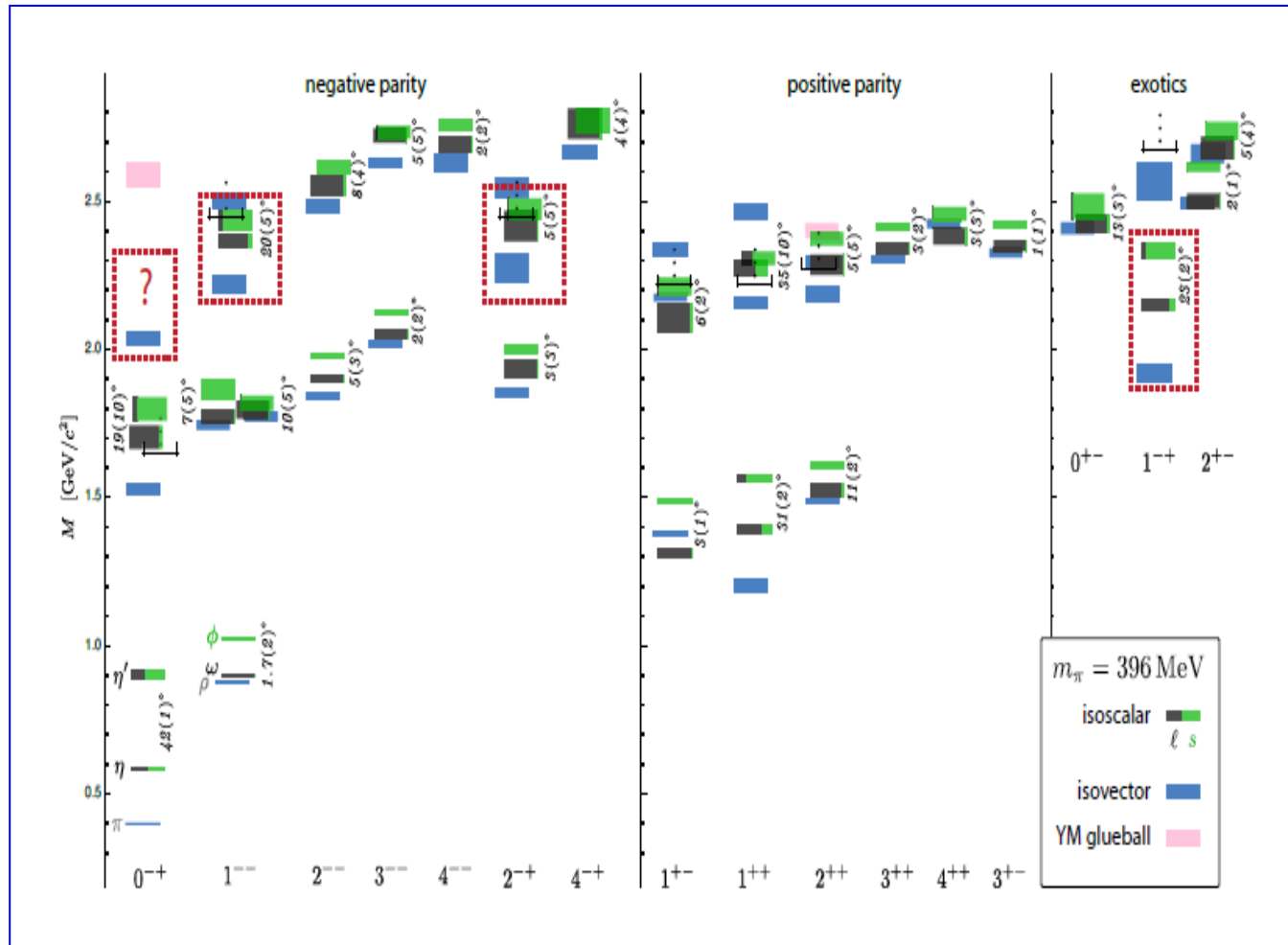
The meson spectrum + gluons: exotics

- The meson spectrum bears also the information about gluons, which bind quarks
- Which is the expected signature of gluonic degrees of freedom ?
 - Observation of extra states possibly with quantum numbers not allowed by CQM
- New states with gluonic content:
 - Glueballs (ggg)
 - Hybrids (q \bar{q} g)
 - Multiquark/molecular states

EXOTICS



LQCD expectations for the meson spectrum

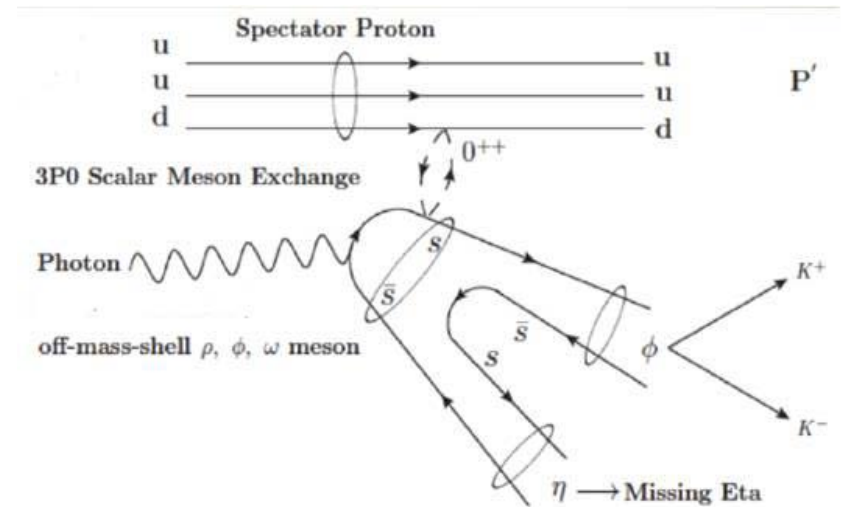


Remarkable agreement of most recent LQCD calculation with the expected meson spectrum
 BUT: the lightest exotic of the spectrum now expected at **1600 MeV (1^-+)** and **2 GeV (0^++)**

Strangeonia decay patterns

- **Smoking gun** decay modes for $s\bar{s}$ states: $\eta\phi$, $\eta'\phi$, $\phi\phi$

- $\eta\phi$: identification of $C = -1$ $s\bar{s}$ candidates
- Small branching fraction to non-strange final states

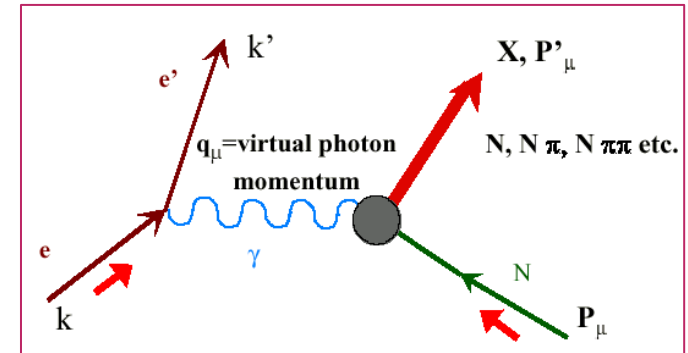


- Other relevant channel for $s\bar{s}$ and exotics ($q\bar{q}g$, $q\bar{q}q\bar{q}$): $\phi\pi^0$
- **Decays to open-strangeness final states do not uniquely identify strangeonia:** $K\bar{K}$, $K\bar{K}^*$ ($K\bar{K}\pi$), $K^*\bar{K}^*$ (+c.c.)
 - Decay channels shared by:
 - Light quark iso-singlet mesons
 - Exotic states
 - Experimental evidences of significant $n\bar{n} \leftrightarrow$ gluons $\leftrightarrow s\bar{s}$ mixing, especially in the scalar 0^{++} , pseudoscalar 0^{-+} and 2^{-+} sectors

OPEN/HIDDEN STRANGENESS IN PHOTOPRODUCTION REACTIONS

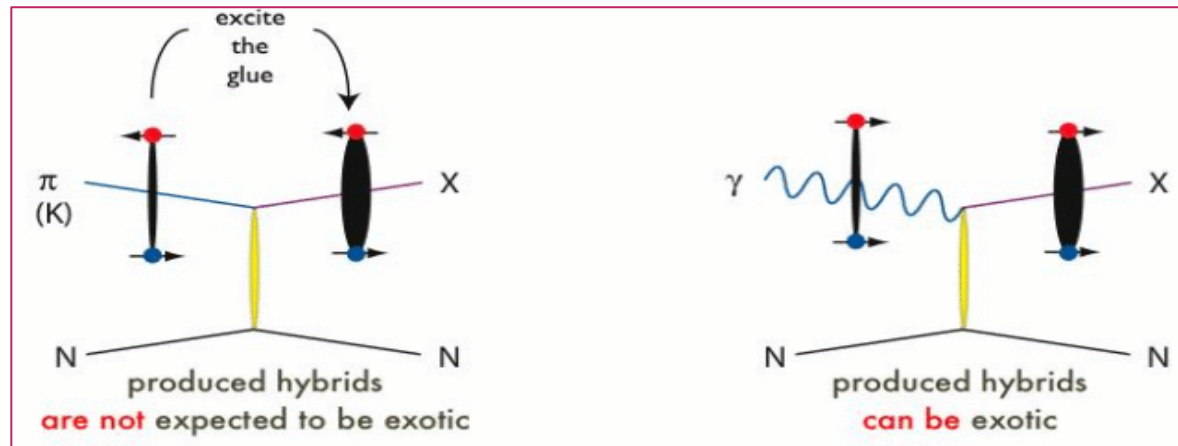
Meson spectroscopy with e.m. probes

- The electromagnetic interaction is weaker than the strong one and can be calculated perturbatively with high precision (based on well-known QED)
 - Scattering: one-photon exchange approximation



- Meson photoproduction: **high probability of spin-1 meson production from photons**

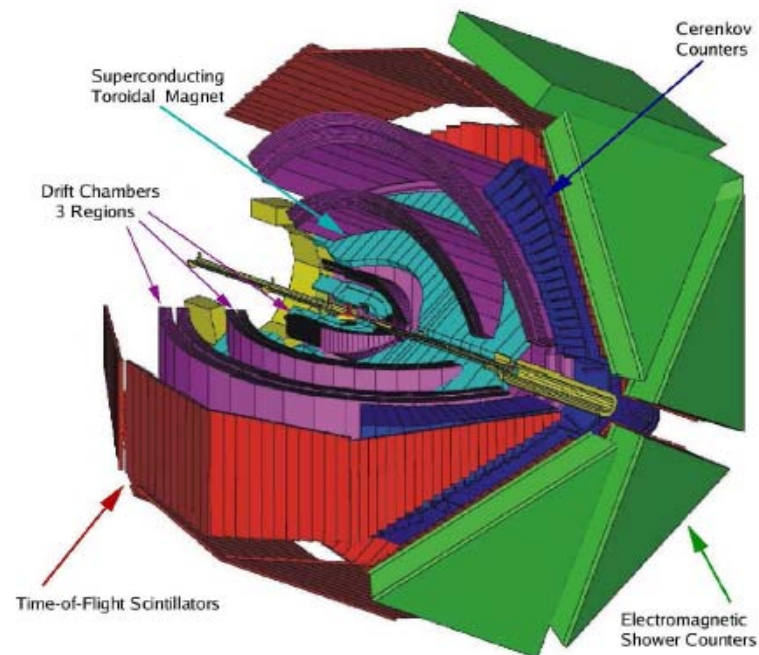
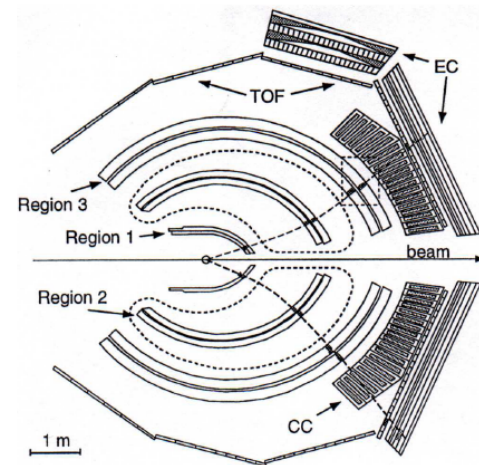
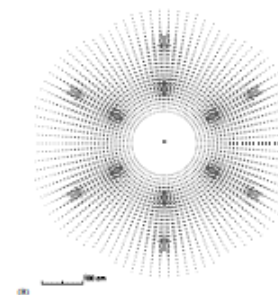
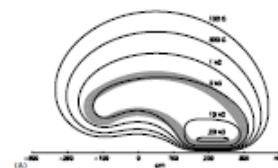
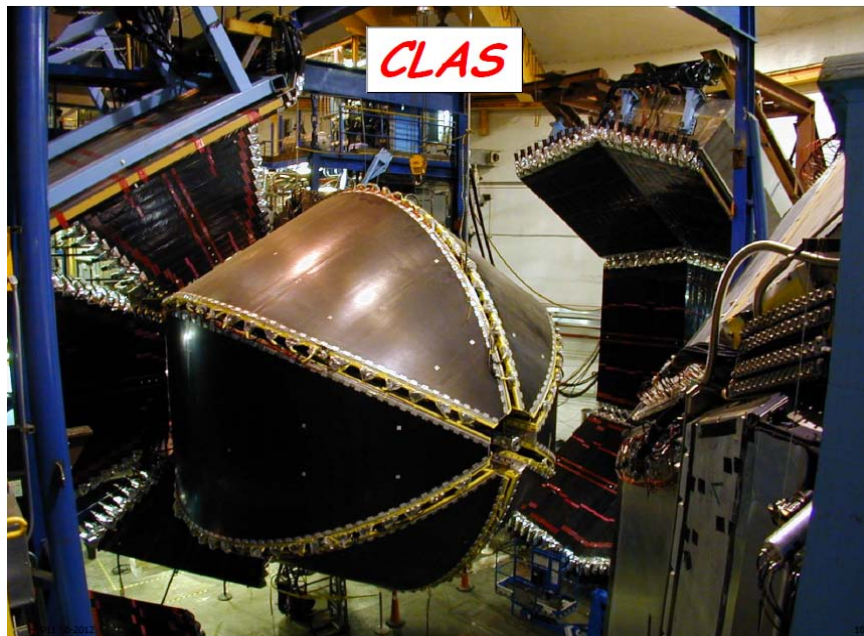
$\pi(K)N$:
Need spin-flip
for exotic
quantum
number



γN :
No spin-flip for
exotic quantum
number

- Expected production rate for exotics and conventional mesons: comparable
- $\bar{s}s$ coupling to the photon relatively large (beam spin vector)**

CLAS @ 6 GeV



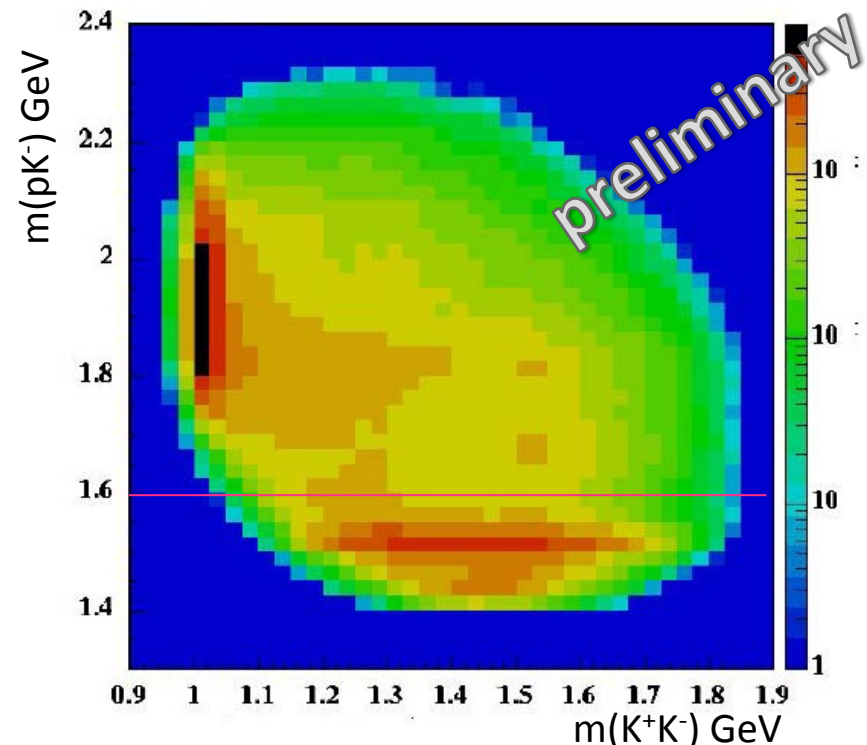
The K^+K^- system: $\gamma p \rightarrow pK^+K^-$

S. Lombardo, UConn, 2016

Physics case: investigation of light meson resonance spectrum

- $\phi(1020)$ main decay mode
- possible sub-threshold decay of $f_0(980)$ and $a_0(980)$ scalars
- issues: σ production? Other scalars? $f_0(980)$ coupling to $\pi\pi/K\bar{K}$?

- CLAS6 g11 data set:
 - $E_\gamma = (3-3.8)$ GeV
 - $-t: (0.6-1.3)$ GeV²
 - p and K^+ detected in CLAS, K^- reconstructed by missing mass
 - π/K misidentification: 10-15%
- Low mass region selected
 - $m_{pK^-} > 1.6$ GeV
 - Baryonic resonance contributions ($\Lambda(1520)$) removed, no overlap



The K^+K^- system: $\gamma p \rightarrow pK^+K^-$

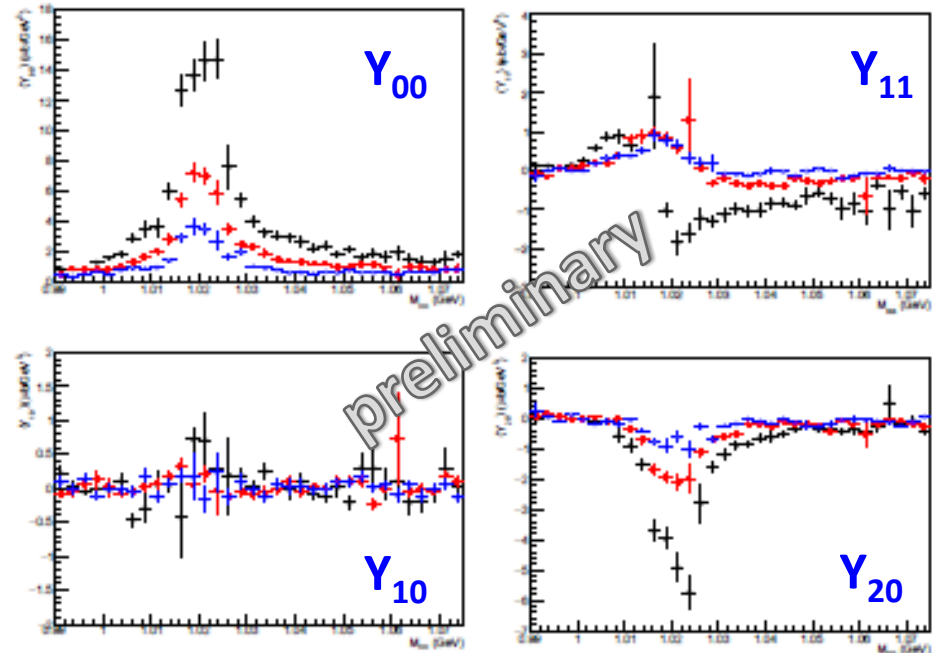
S. Lombardo, 2016

- Study of S-P wave interplay in the $K\bar{K}$ system
 - Cross-sections extraction in each partial wave through likelihood fits

- Method: moments analysis

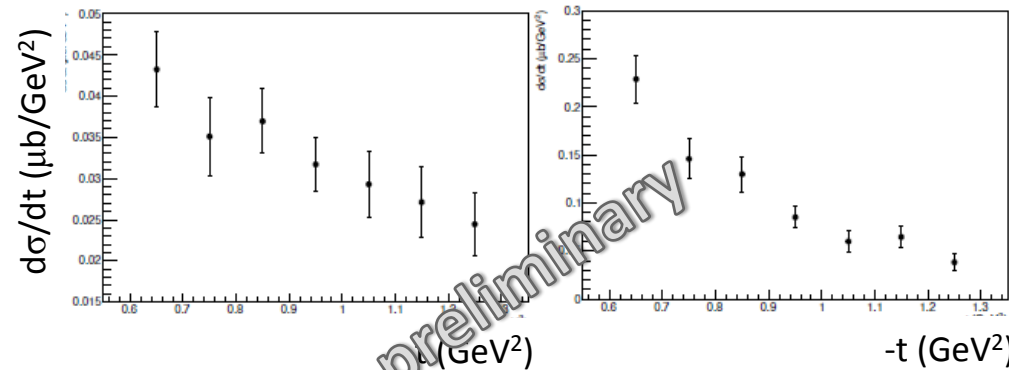
$$\langle Y_{LM} \rangle = 4\pi \int d\Omega_K \frac{d\sigma}{dt dM_{KK} d\Omega_K} Y_{LM}(\Omega_K)$$

- Moments can be expressed as bilinear combination of partial waves, depending on L, M and photon and proton helicities
- Amplitude parameterizations:
 - S wave: ρ, ω exchange in t-channel
 - P-wave: Pomeron exchange



S-wave diff. cross section

P-wave diff. cross section



The $K_S K_S$ system: $\gamma p \rightarrow p K_S K_S$

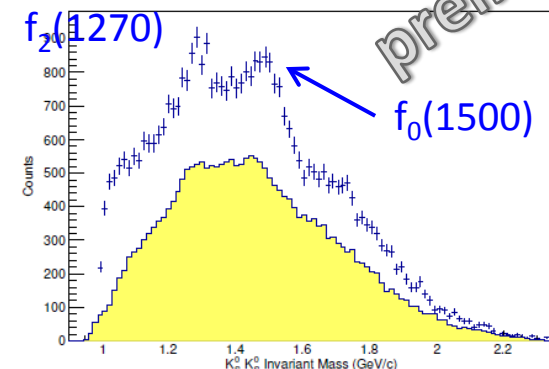
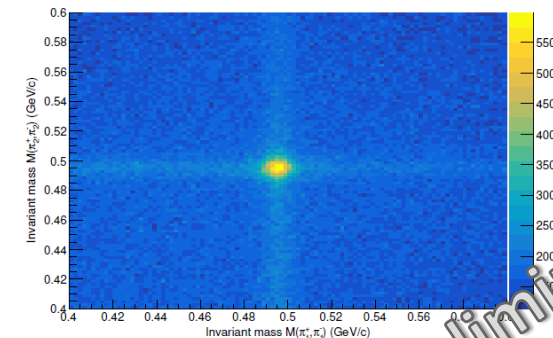
S. Chandavar, UOhio, 2017

arXiv: 1712.02184

Physics case: search for a scalar glueball in its kaonic decay

- $K_S K_S$ system: $J^{PC} = (\text{even})^{++}$
- light scalar sector: several candidates, too many states for the nonet
 - $f_0(600)$, $f_0(980)$, $f_0(1370)$, **$f_0(1500)$** , $f_0(1700)$, ...
- no study yet in photoproduction reactions

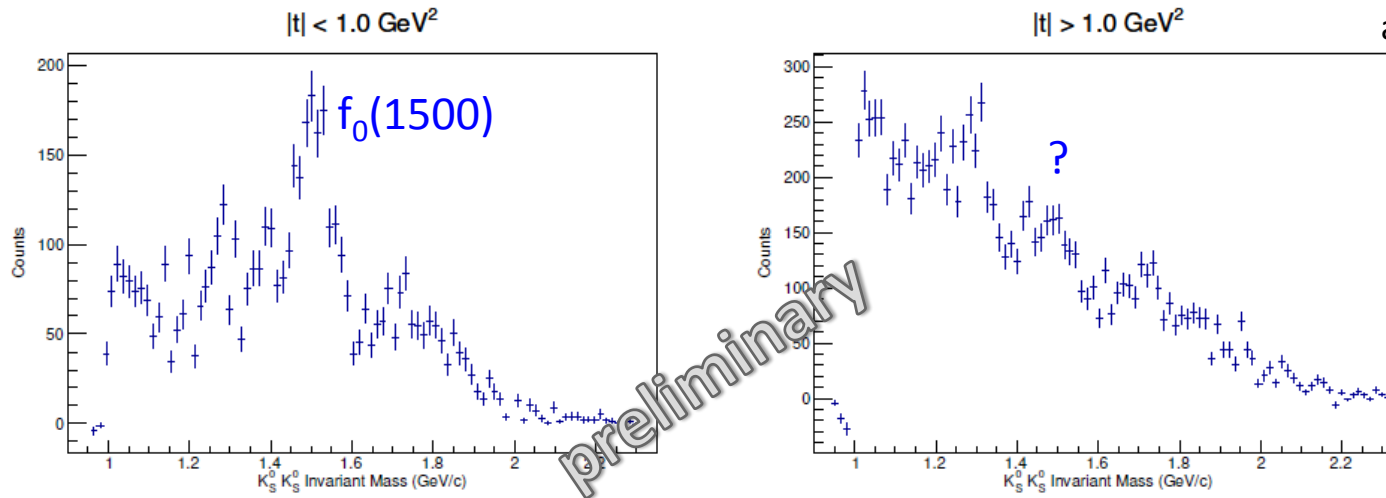
- CLAS6 g12 data set:
 - $E_\gamma = (2.7\text{-}3) \ \&\& \ (3.1\text{-}5.1) \text{ GeV}$
 - 4π detected in CLAS, p reconstructed by missing mass
 - High correlation between K_S pairs
- Selection in t ranges
 - Low t : resonance production in t -channel
 - Wider t range for s -channel production



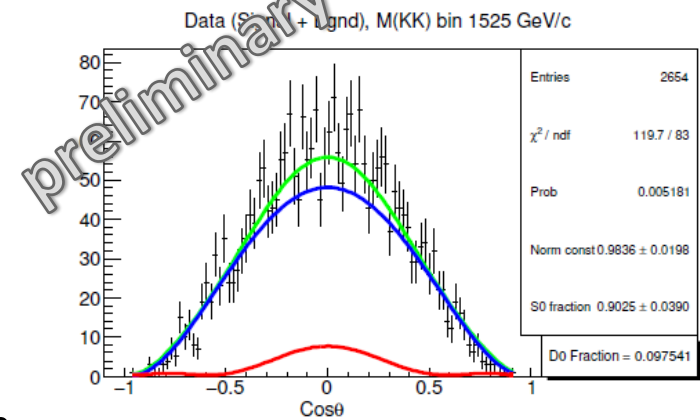
The $K_S K_S$ system: $\gamma p \rightarrow p K_S K_S$

S. Chandavar, UOhio, 2017

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- Clean signal of $f_0(1500)$ for $|t| < 1 \text{ GeV}^2$, no indication for $|t| > 1 \text{ GeV}^2$
 - t-channel process
 - Good glueball candidate??
- Low acceptance at fw/bw angle: no PW analysis possible
- Angular analysis of Gottfried-Jackson distributions, comparison with simulations
 - S-wave dominance, small D-wave contribution above 1550 MeV



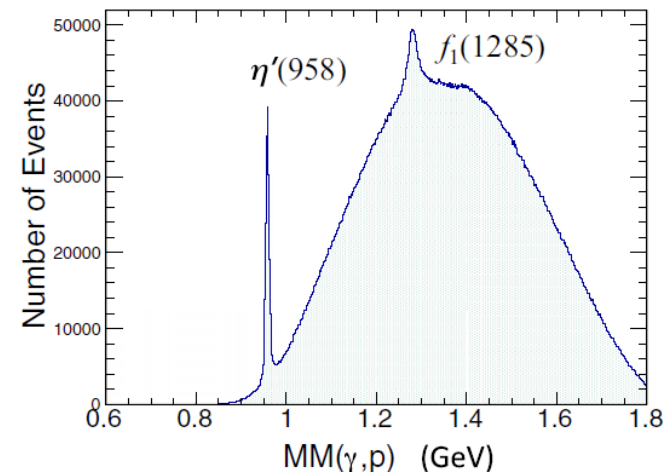
The $K\bar{K}\pi$ system: $\gamma p \rightarrow p K^0 K^\pm \pi^\mp$

CLAS Collaboration, PRC93, 065202 (2016)

Physics case: superimposition of several axial/scalar states in the 1.3-1.5 GeV mass range with decay in $K\bar{K}\pi$

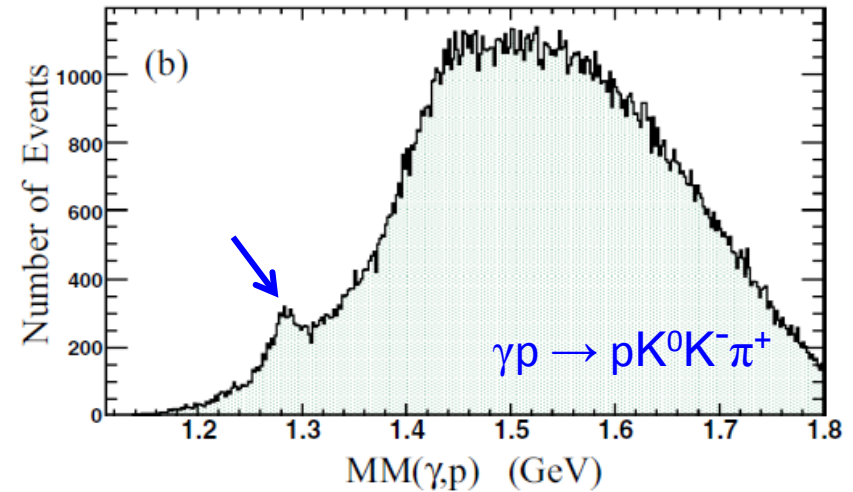
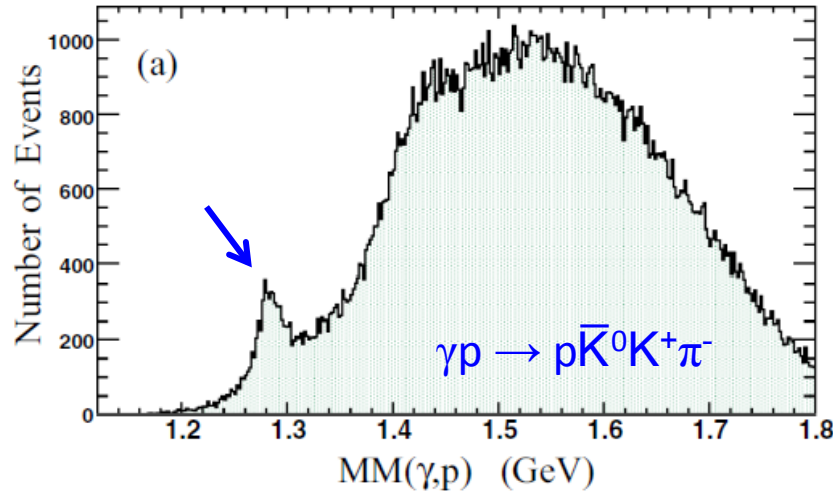
- $J^P = (\text{odd})^+$ or $J^P = (\text{even})^-$
- η -like pseudoscalars 0^{-+} : all of them decay to $K\bar{K}\pi$, K^*K , $a_0(980)\pi$
- axial states 1^{++} :
 - $f_1(1285)$: not seen in K^*K
 - $f_1(1420)$: favored candidate as hybrid $q\bar{q}g$, or $4q$ state, or K^*K molecule
 - other: $f_1(1510)$, isovector $a_1(1420)$...

- CLAS6 g11a data set:
 - $E_\gamma = (3-3.8)$ GeV
 - p , K^\pm , π^\mp detected in CLAS, K^0 from missing mass
 - Kaon identification by TOF
 - Study of the $p\pi^+\pi^-\eta$ and $p\pi^+\pi^-\gamma$ channels on the same sample

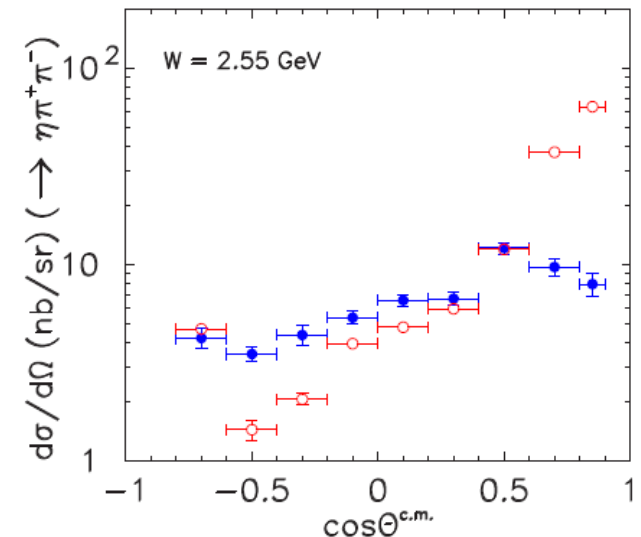


The $K\bar{K}\pi$ system: $\gamma p \rightarrow p K^0 K^\pm \pi^\mp$

CLAS Collaboration, PRC93, 065202 (2016)

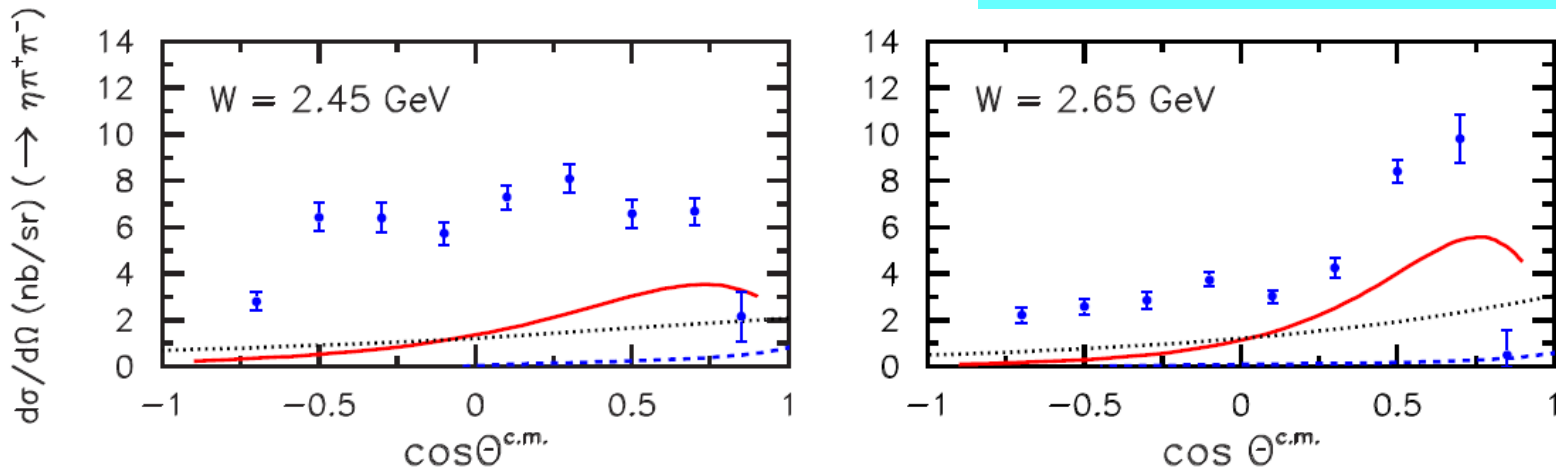


- No evidence found for higher mass $\eta(1405)$, $\eta(1470)$, $f_1(1420)$, $f_1(1510)$
- First observation in photoproduction at ~ 1280 MeV, studied in $\pi^+ \pi^- \eta$
 - $M = (1281.0 \pm 0.8) \text{ MeV}$
 - $\Gamma = (18.4 \pm 1.4) \text{ MeV}$
 - More compatible with $f_1(1285)$ than $\eta(1295)$
 - Differential cross sections: flatter trend as compared to $\eta'(958)$



The $K\bar{K}\pi$ system: $\gamma p \rightarrow p K^0 K^\pm \pi^\mp$

CLAS Collaboration, PRC93, 065202 (2016)



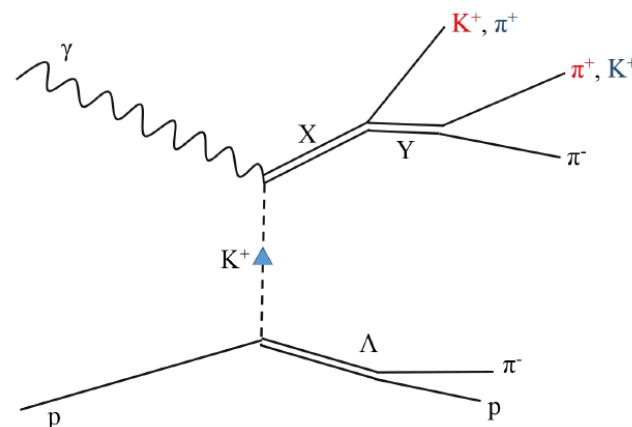
- Poor match of the differential cross sections with expectations from t-channel models
 - s-channel substantial contribution?
 - Dynamically produced state via s-channel involving N^* excitations or KK^* molecular interactions?
 - Larger support for $f_1(1285)$ identification
- First determination of the relative branching ratio: $\Gamma(K\bar{K}\pi)/\Gamma(\eta\pi\pi) = 0.216 \pm 0.032$
 - Consistent with PDG value : 0.171 ± 0.013
 - Not known for $\eta(1295)$

The $K\pi\pi$ system: $\gamma p \rightarrow \Lambda K^+ \pi^+ \pi^-$

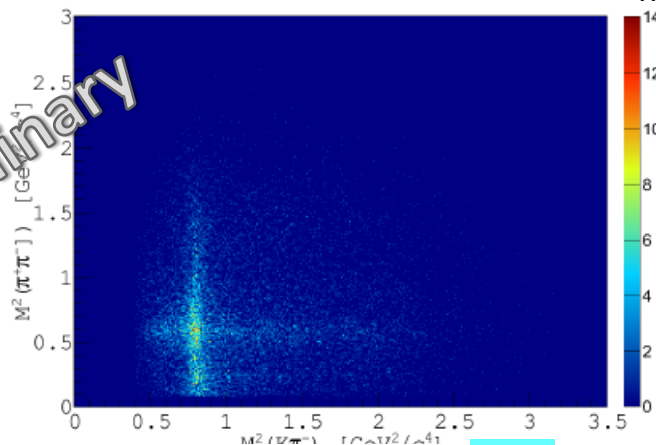
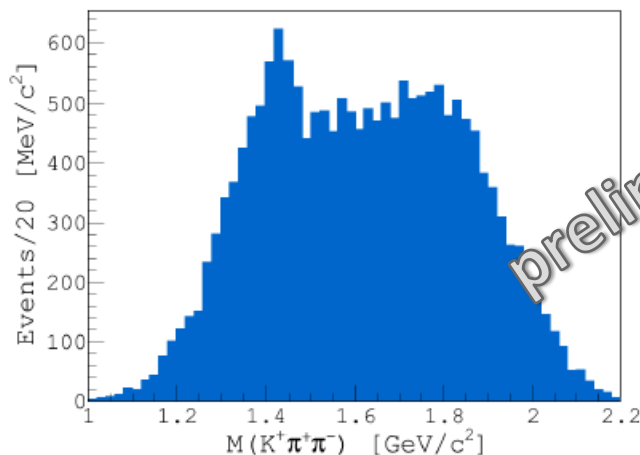
Physics case: search for excited strange mesons

- Low mass region (1-1.5 GeV) extensively studied in past diffractive experiments: $K_1(1270)$, $K_1(1400)$, $K^*(1410)$
- Little is known in the (1.5-2) GeV mass range: $K(1630)$, $K_1(1650)$
- None of these states ever observed in photoproduction (peripheral production: low momentum transfer events)

- CLAS6 g12 data set:
 - $E_\gamma = (4.40-5.45)$ GeV
 - Selection of $pK^+\pi^+\pi^-\pi^-$ exclusive final state
 - $\Lambda \rightarrow \pi^- p$ selection by invariant mass
 - Background from $\Sigma^-(1385) \rightarrow \Lambda \pi^-$ decay removed
 - Background from π/K misidentification removed



The $K\pi\pi$ system: $\gamma p \rightarrow \Lambda K^+ \pi^+ \pi^-$



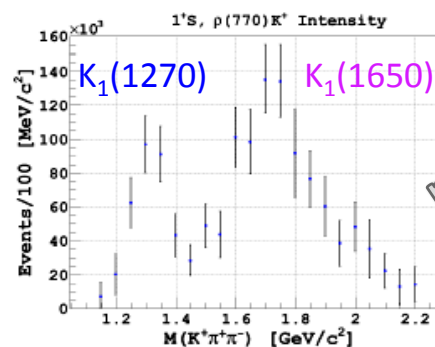
Partial wave analysis 16K evts

– 1^+S :

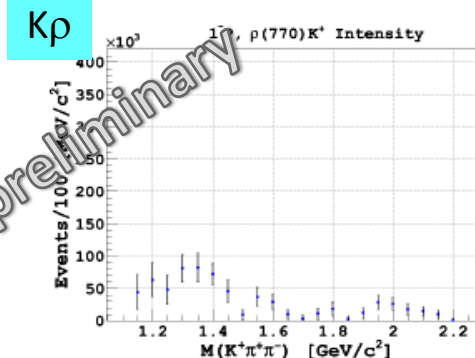
- $K\rho$: observation of $K_1(1270)$ and $K_1(1650)$
- $K^*\pi$: observation of $K_1(1400)$

– 1^-P :

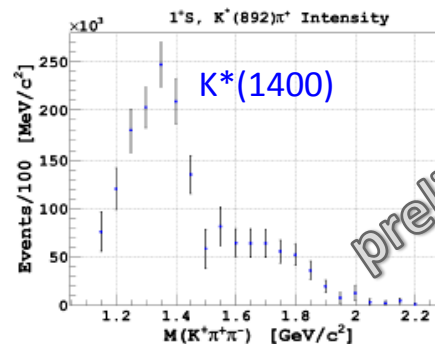
- $K\rho$: observation of $K^*(1650)$?
- $K^*\pi$: observation of $K^*(1410)$



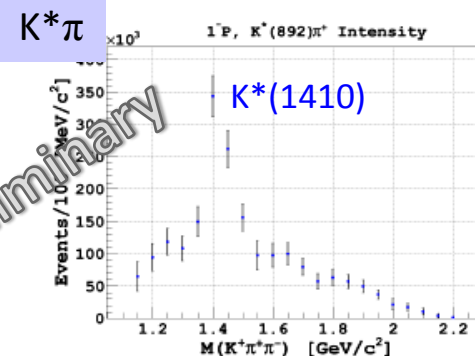
(a) The $1^+ S, \rho(770) K^+$ wave intensity.



(a) The $1^+ P, \rho(770) K^+$ wave intensity.



(b) The $1^+ S, K^*(892) \pi^+$ wave intensity.

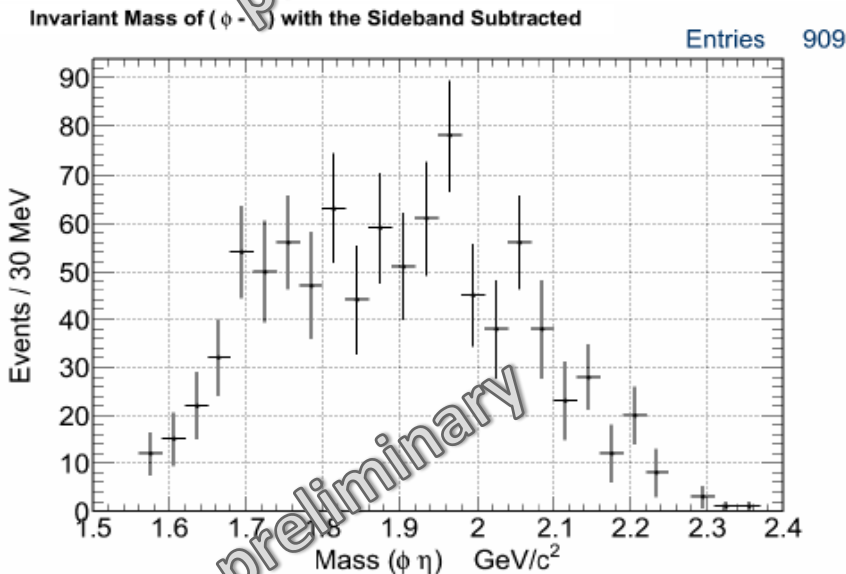
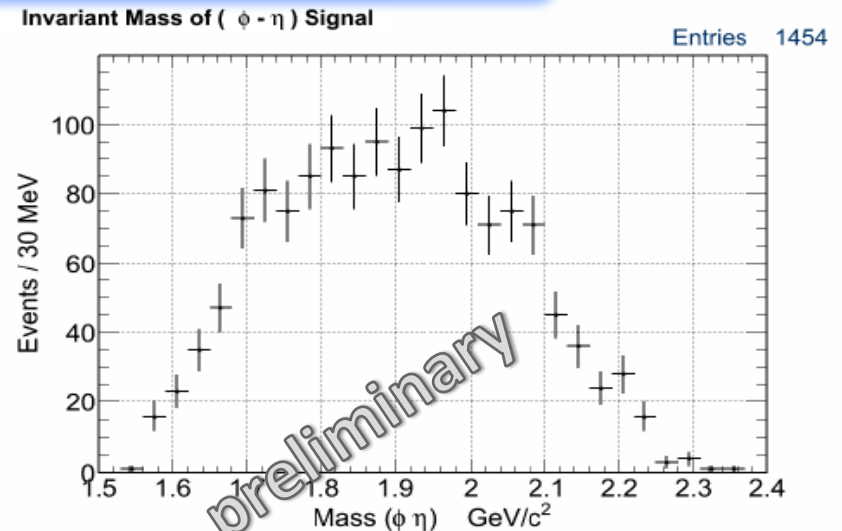
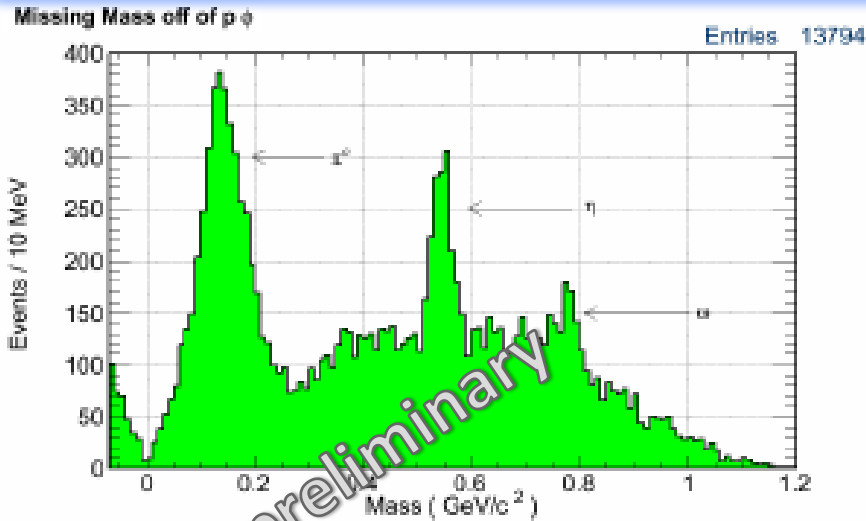


(b) The $1^- P, K^*(892) \pi^+$ wave intensity.

The $\eta\phi$ decay channel: $\gamma p \rightarrow p K^+ K^- \eta$

Physics case: search for a 1^+ strangeonium hybrid

M. Saini, FSU, 2012



- g12 dataset analysis:
 - $\gamma p \rightarrow p K^+ K^- \eta_{\text{miss}}$
 - real photons up to 5.45 GeV/c
- Largest sample collected for final state (909 events)

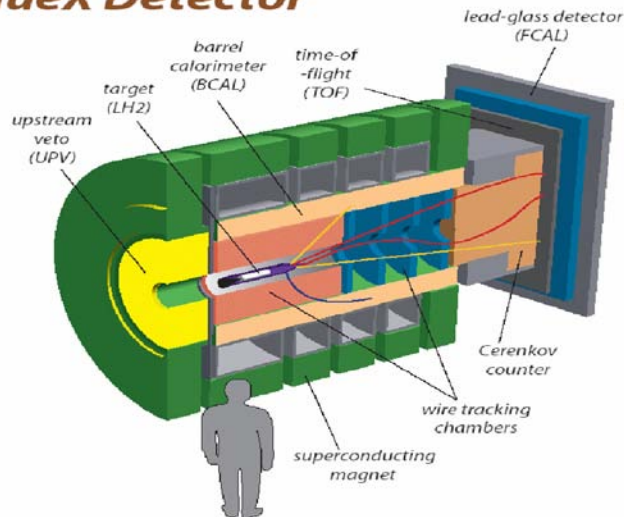
STRANGE MESON SPECTROSCOPY WITH VIRTUAL PHOTONS IN CLAS12

Photoproduction experiments at JLAB today

- High intensity real and virtual photon beams
- Able to measure exclusively the production reactions and the decays of the emitted particles
- Requirements:
 - Good acceptance, momentum resolution, particle id capabilities

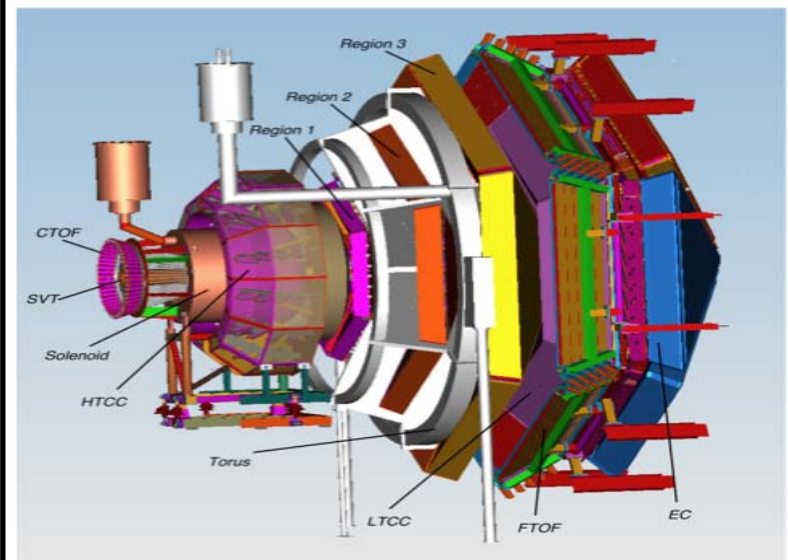
Hall-D - GlueX Detector

GlueX Detector



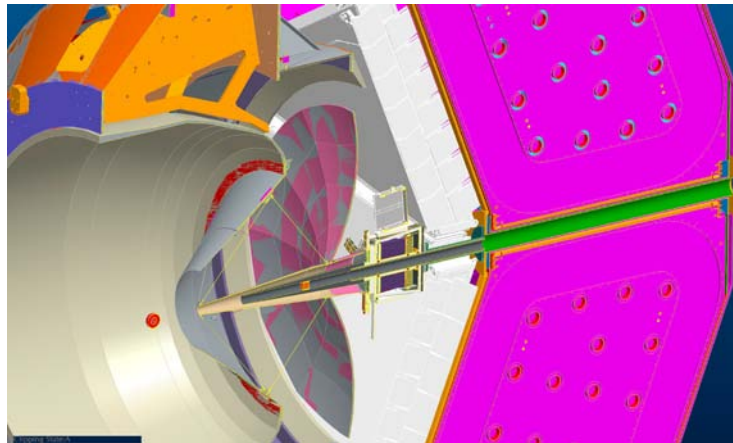
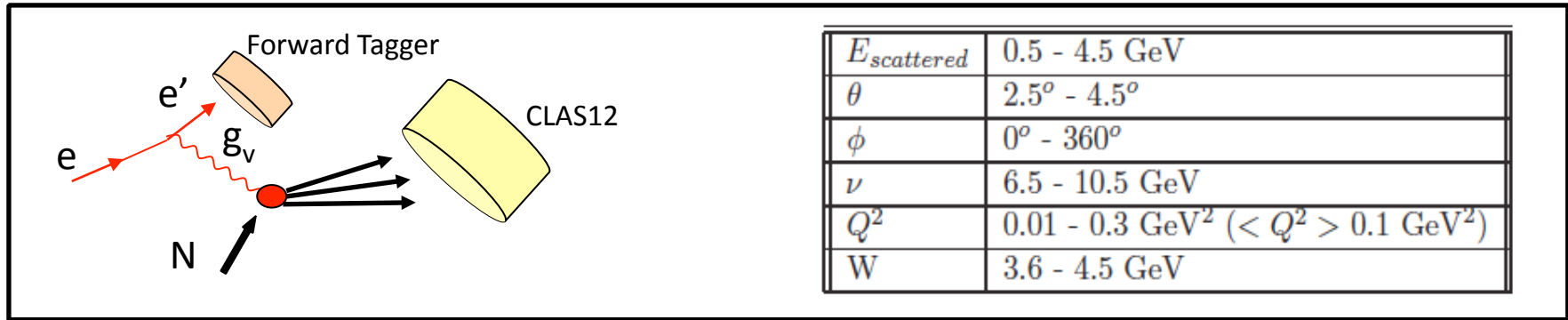
- Good hermeticity
- Uniform acceptance
- Limited resolution
- Limited pID

Hall-B - CLAS12 Detector



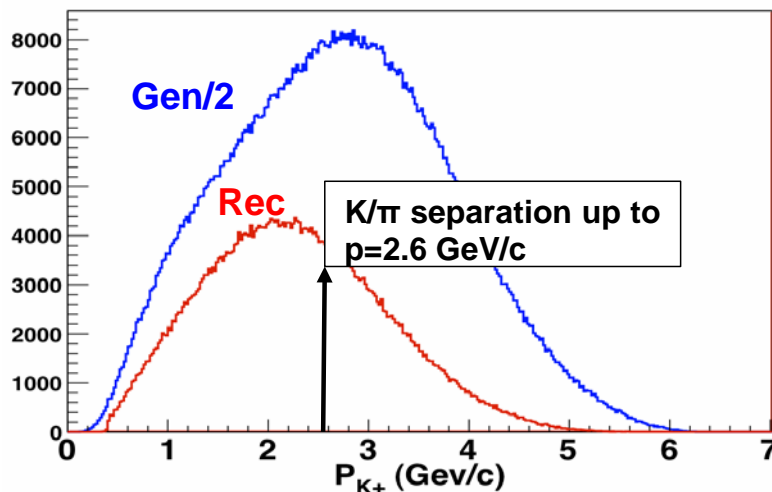
- Good resolution
- Good pID
- Resonable hermeticity
- NON-Uniform acceptance

Low Q^2 quasi-real photoproduction

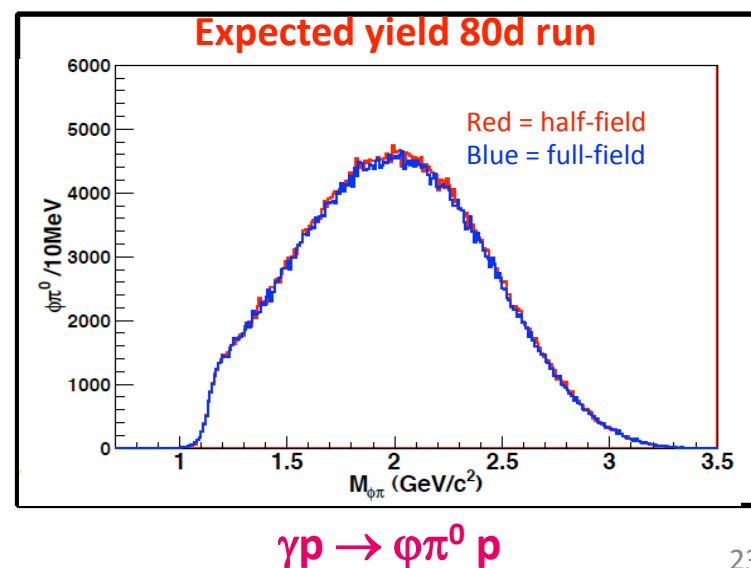
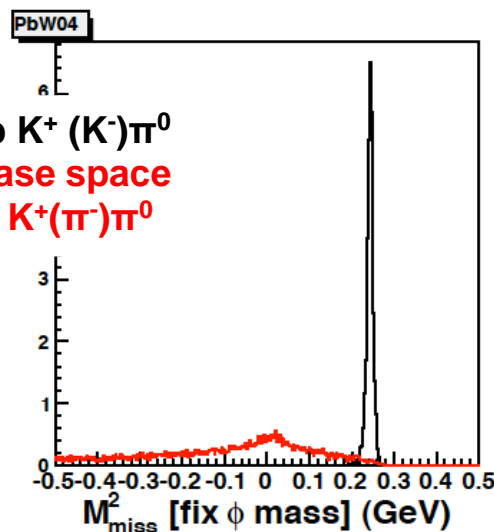
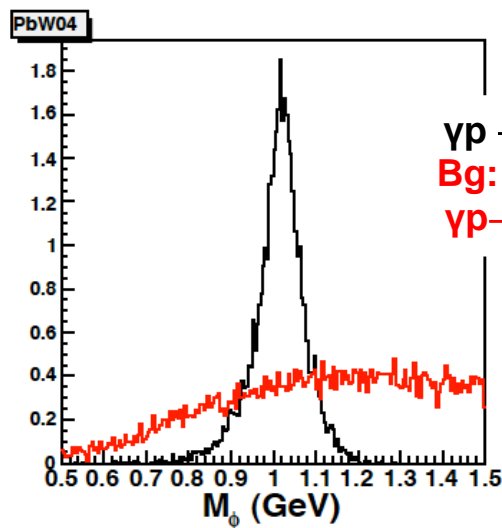


- Electron scattering at “0” deg (2.5° - 4.5°)
 - Low Q^2 virtual photon \Rightarrow quasi real
- Photon tagging: detection of electron at small angles
 - High energy photons: 6.5 - 10.5 GeV
 - To be accomplished by a “Forward Tagger”
- Quasi real photons: linearly polarized
 - Polarization: 70%-10%, measured event by event
- High luminosity: $N_\gamma \sim 5 \times 10^8$, $L \sim 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ on 5 cm LH_2 target
 - Thin targets can be used

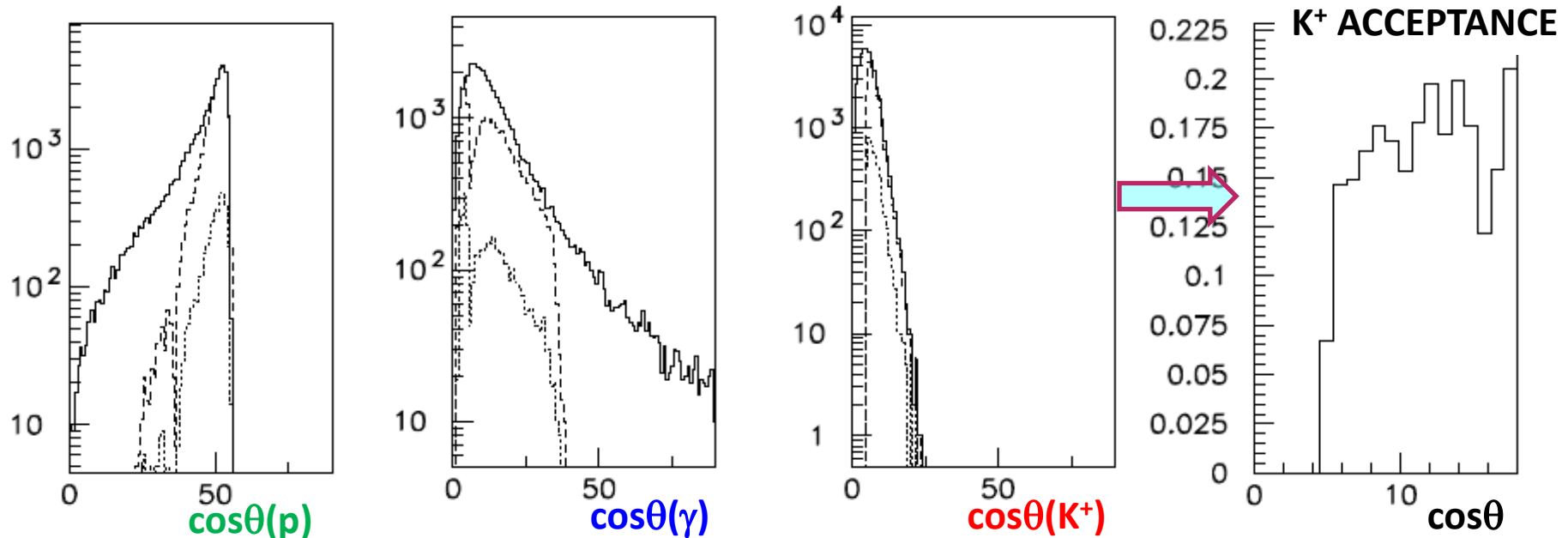
Search for strange hybrids with CLAS12: $\gamma p \rightarrow p \phi \pi^0$



- Production cross section: 10 nb
- CLAS12 acceptance: $\sim 10\%$
- Good π/K separation power required for momenta up to 2.6 GeV/c
- Simulation: **good background rejection capabilities using kin. fit and pid** of CLAS12
- Expected events in 80 data taking days @ full luminosity: ~ 3000 evts/mass bin
- Expected trigger rate: < 10 kHz



Search for strange hybrids with CLAS12: $\gamma p \rightarrow p \phi \eta$



- Acceptance evaluation of $\gamma p \rightarrow p \phi(1850) \rightarrow p \eta \phi \rightarrow p K^+(K^-)_{\text{miss}} \gamma \gamma$ events with CLAS12 (lab emission angle distribution)
 - Good acceptance for neutrals, sizeably increased by FT calorimeter: overall acceptance $> 10\%$
- Expected cross section for strangeonia production: $O(10 \text{ nb})$
 - About half of $\text{BR}(K^+ K^-)$

Summary and Conclusions

- Light meson spectrum with open and hidden strangeness still to be fully understood
 - Many observations in different reactions
 - Many confirmations, many disagreements
 - Too many states observed to be arranged in available CQM slots
 - Too few ordinary states (radial excitations) observed where expected

- Photoproduction reactions can be studied now with intense beams at new generation experiments. Expected to be an efficient source of:
 - $s\bar{s}$ pairs, due to the spin vector nature of the photon beam
 - Open and hidden strangeness (strangeonia) mesons
 - spin-1 hybrid states

- Photoproduction: ideal place to study benchmark decay channels
 - Promising outlook for smoking-gun decay channels: $\eta\phi$, $\eta'\phi$, $\phi\phi$, $\phi\pi$
 - $\text{BR}(\eta\phi)/\text{BR}(K^+K^-) = 0.5$
 - Limited outcome from other spectroscopy experiments in the last decade