STUDY OF $K\bar{K}\pi$ AND STRANGEONIA STATES IN THE (1 - ~~3~~) GEV MASS RANGE ~2.2

Alessandra Filippi

INFN Torino, Italy

Workshop on Future Directions in Spectroscopy Analysis – JLAB, Nov 18-20, 2014

Outline

- Introduction: light mesons with open and hidden strangeness, and their decay to $K\bar{K}\pi$ final states
- Strangeonia: expected decay channels
- Conventional and exotic strangeonia: experimental status
- Overlapping (possibly exotic) states: the case of the 0^{-+} glueball
  - Pseudoscalars vs axial vectors in the 1-2 GeV mass region
- Open possibilities of observations in photoproduction reactions
- CLAS data and CLAS12 benchmark reactions studies
- Summary and Conclusions

Introduction: strange quarkonia

- 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 are known
  - Strangeonia: $s\bar{s}$
    - of 22 expected states below 2.1 GeV, only less than 10 are steadily established

- Many fundamental information still missing in the 1.2-2.5 GeV mass range

- Necessary to complete the meson spectrum scenario for the study of exotic states
  - Dominantly non $q\bar{q}$ states: glueballs, hybrids, multiquark systems
  - Featuring both exotic and non-exotic quantum numbers
    - Large possibility of strong mixing with conventional quarkonia
    - Overlap in the same mass region

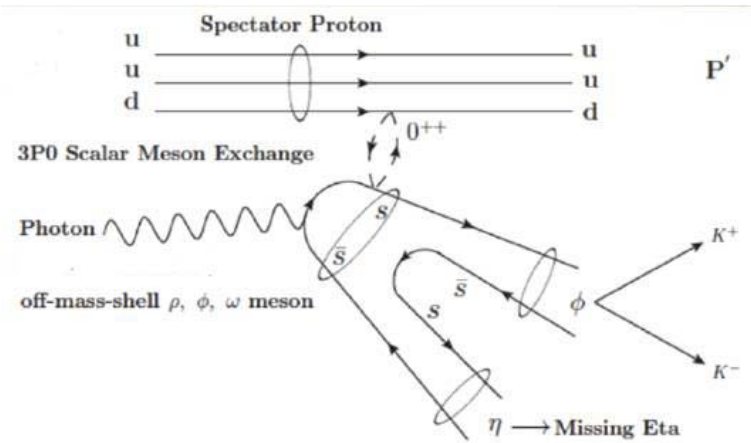
Strangeonia production processes

- Small $s\bar{s}$ production cross section
  - OZI suppressed processes
  - Most effective reactions studied so far:
    - Hadronic reactions:
      - Central production (CERN, Fermilab)
      - Strangeness exchange reactions: $K^- p \rightarrow \Lambda X$ (SLAC)
      - $\pi^- p$ peripheral collisions: low cross sections (BNL, CERN, …)
    - e^+e^- collisions: pure $J^{PC} = 1^{--}$ sector
      - Mixing between possible vector hybrids and quarkonia
    - Diffractive photoproduction: $\gamma\, p \rightarrow X\, p$
      - Excitation of C = -1 $s\bar{s}$ states: the photon beam can be seen as a superimposition of vector mesons, with meaningful $s\bar{s}$ coupling
      - Lack of intense enough beams (so far)

- Large production of open-strangeness pairs in OZI allowed processes
  - Decay modes are shared between open-flavor mesons and strangeonia: additional complication

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



$$|\eta\rangle = \frac{1}{\sqrt{2}}\left(|n\bar{n}\rangle_{I=0} - |s\bar{s}\rangle\right)$$

$$|\eta'\rangle = \frac{1}{\sqrt{2}}\left(|n\bar{n}\rangle_{I=0} + |s\bar{s}\rangle\right)$$

$$|n\bar{n}\rangle_{I=0} = \frac{1}{\sqrt{2}}\left(|u\bar{u}\rangle + |d\bar{d}\rangle\right)$$

- 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 $n\bar{n} \leftrightarrow G \leftrightarrow s\bar{s}$ mixing, especially in the scalar 0^{++}, **pseudoscalar 0^{-+}** and 2^{-+} sectors

STRANGEONIA STATES: EXPERIMENTAL STATUS

Vector strangeonia 1^{++}: present experimental status

- The strangeonium spectrum does not simply replicate the spectrum ~250 MeV higher in mass: several channel dependent couplings

- Only three really well established $s\bar{s}$ resonances:
  - $\phi(1020)$ (1^{--})
  - $\phi_3(1854)$ (1^{--})
  - + $f_2(1525)$ (tensor)

- Several controversial observations of other strange quarkonia states:
  - $h_1(1380)$ $(^1P_1, 1^{+-})$
  - $\phi(1680)$ $(2^3S_1, 1^{--})$
  - + several axial-vectors:
    - $f_1(1420)$, $f_1(1510)$, …

1^{++} expected excitations

State		Predicted Decay Width Theory MeV/c^2	Observed Decay Width Expt. MeV/c^2
$\phi(1680)$	2S	$\Gamma_{theory} = 378$ $\Gamma_{\phi\eta} = 44$	$\Gamma_{expt} = 150 \pm 50$
$\phi(2050)$	3S	$\Gamma_{theory} = 378$ $\Gamma_{\phi\eta} = 21$	Γ_{expt} = unknown
$\phi_3(1854)$	1D	$\Gamma_{theory} = 104$ $\Gamma_{\phi\eta} = 3$	$\Gamma_{expt} = 87^{+28}_{-23}$
$\phi_2(1850)$	1D	$\Gamma_{theory} = 214$ $\Gamma_{\phi\eta} = 53$	Γ_{expt} = unknown
$\phi(1850)$	1D	$\Gamma_{theory} = 652$ $\Gamma_{\phi\eta} = 29$	Γ_{expt} = unknown

T. Barnes et al., PR D68 054014 (2003)

Strangeonium hadroproduction

- **LASS @SLAC, 11 GeV/c K^- beam (1988)**

  $K^-p \rightarrow K^+K^-\Lambda$, $K^-p \rightarrow K^0_sK^\pm\Lambda$, $K^-p \rightarrow K^0_sK^0_s\Lambda$

  – **Favored** production of $s\bar{s}$ vs glueball

  – Observed states: linear orbital ladder up to 4^+ f'_4

  – **Good evidence for two $s\bar{s}$ axial vector mesons**
    - **1^{++}: m ~ 1530 MeV**
    - **1^{+-}: m ~ 1380 MeV $\Rightarrow$ $h_1(1380)$**
      - **Confirmed @ BNL-771 & Crystal Barrel**

  – No significant production of $f_1(1420)$ ($\Rightarrow$ K*K molecule)

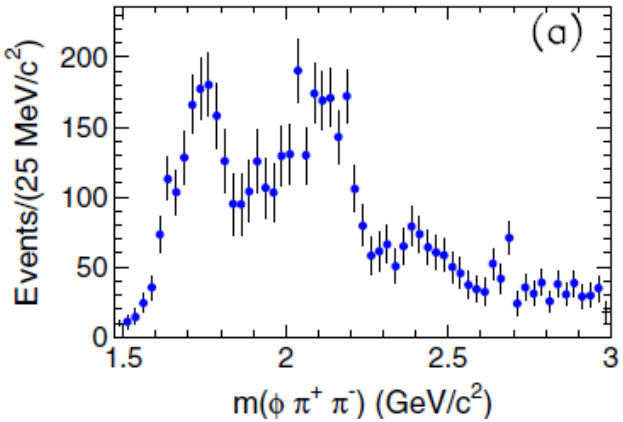
  – No evidence of $f_J(1710)$

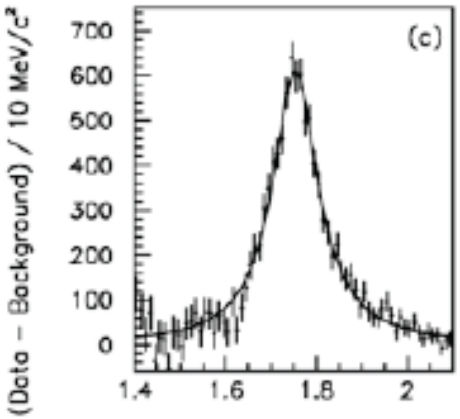
  – **Indications of $f_J(2200)$ $J^{PC} = 4^{++}$**
    - Superimposition of two narrow states? one could be strangeonium

The ϕ(1680) resonance

- Natural candidate for ϕ(1020) 2S excitation
- Observations in KK and KK*
  - Cited as evidence of ss nature, but not enough!
- contrasting observations in different production channels
  - **e^+e^-: low mass, KK* dominance**
    - DM1: $e^+e^- \to K^0_S K^0_L$
    - VEPP-2M & DM2: $e^+e^- \to K^+K^-$
    - DM2: $e^+e^- \to K\bar{K}\pi, \omega\pi^+\pi^-$
    - BaBar: $e^+e^- \to$ hadrons
    - BELLE: $e^+e^- \to K^+K^-\pi^+\pi^-(+\gamma_{ISR})$
      - **M = 1680 ± 20 MeV, Γ = 150 ± 50 MeV**
  - **photoproduction: high mass, KK dominance**
    - Omega (CERN), WA57, E401
      - Larger mass, ~ 1750 MeV
    - FOCUS: diffractive photoproduction of K^+K^-
      - Clear enhancement at large mass
      - **M = 1753 ± 3 MeV, Γ = 122.2 ± 63 MeV**
      - **No evidence of KK* decay**

BELLE, PR **D80**, 031101 (2009)





FOCUS, γ BeO $\to$ **K^+K^-** X
PL **B545**, 50 (2002)

HYBRIDS WITH STRANGENESS: THE C(1460) CASE

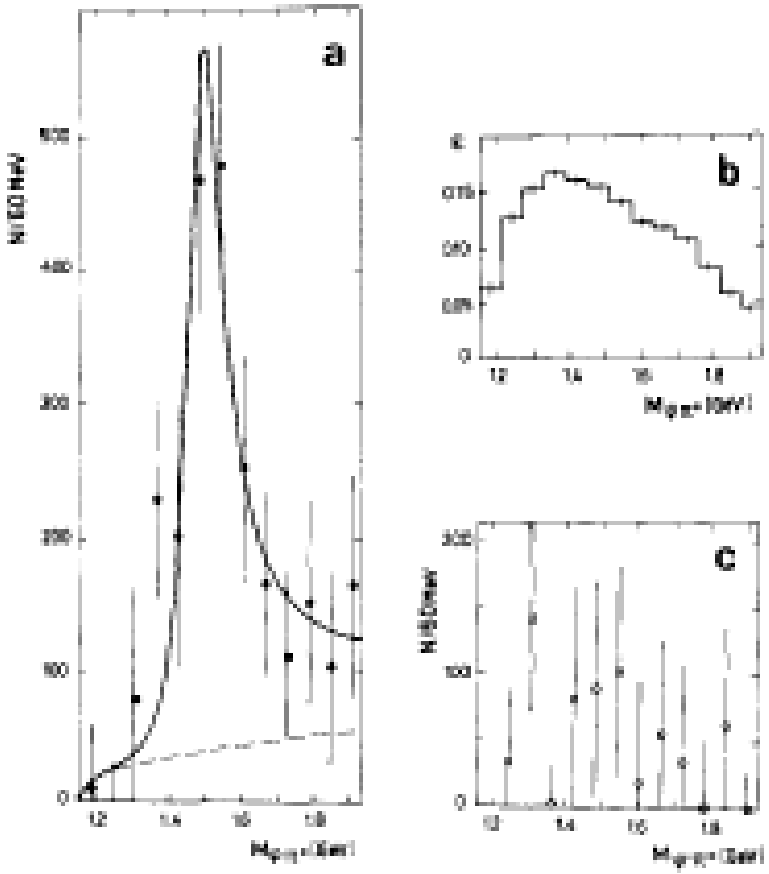
First (and only) strange hybrid observation

Lepton-F @Serpukhov, 32.5 GeV/c π^- beam (1987)

$\pi^- p \rightarrow \varphi \pi^0 n$

LEPTON-F, PL **B188**, 383 (1987)

- Resonance observed in the $\phi\pi^0$ channel: **C(1480)**
  - m = 1480 ± 40 MeV
  - Γ = 130 ± 60 MeV



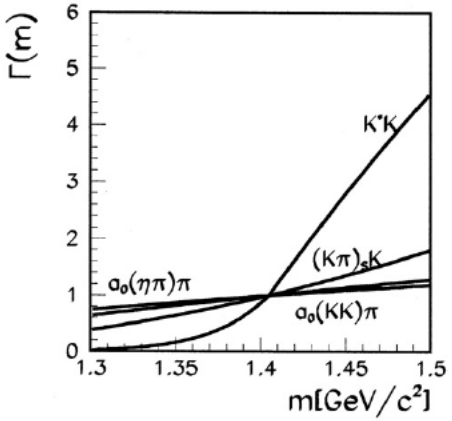
- Spin-parity assignment: $J^{PC} = 1^{--}$
- Isovector state
- Suggested to be an exotic candidate
- Quite large cross-section at 32.5 GeV/c: 40 ± 15 nb
- *Needs confirmation!*

THE 2^1S_0 $s\bar{s}$ STATE AND THE CASE OF THE 0^{-+} GLUEBALL - $\eta(1440)$

2S pseudoscalar strangeonium

- **$^3P_0$ model**: strong decays occur through the production of a $q\bar{q}$ 0^{++} pair in the intermediate state, which decays in two mesons
  - Experimental evidence: spin 1 $q\bar{q}$

- **2S pseudoscalar $s\bar{s}$ states**
  - Assumption: η-η' flavor mixing does not occur for the radially excited $s\bar{s}$ states
    - **the only open strangeness allowed decay mode for is KK* (P-wave decay)**
  - Problem: mass close to KK* threshold
    - Mass dependent width and distortions due to thresholds opening (KK*, $\eta\pi\pi$)
    - Overlap with other signals sharing the same decay mode in a rather problematic region: **η(1440)**
      - is this the lightest glueball?

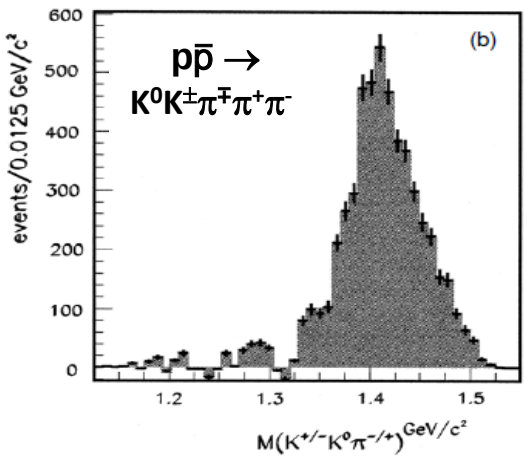


States decaying into $K\bar{K}\pi$ in the 1.3-1.5 GeV mass region

- Long-standing problem: superimposition of several pseudoscalar+axial states: **"E/ι" region**

- **Pseudoscalar states 0^{-+}:** all of them decay in $K\bar{K}\pi$ (direct), $K^*\bar{K}$, $a_0(980)\pi$
  - **η(1275)**
    - Can be the first radial excitation of the η
  - **η(1440)**, likely to be splitted in two states
    - **η(1405)**
      - **Gluonium? not observed in γγ collisions**
    - **η(1475)**

OBELIX, PL **B462**, 453 (1998)



- **Axial states 1^{++}:**
  - $f_1(1285)$ – does not decay in KK^*
  - $f_1(1420)$
    - Arguments favoring its interpretation as **hybrid $q\bar{q}g$**, or four-quark state, or $K^*\bar{K}$ molecule
  - $f_1(1510)$
    - Not well established
  - Isovector $a_1(1420)$

$\eta(1440)$: $\eta(1405) \oplus \eta(1475)$

- >20 years of observations (very few recent results!) in different reactions
- Low statistics experiments identify usually only one η (and DM2 reports opposite decay modes)
- **Central hadroproduction: no observation**

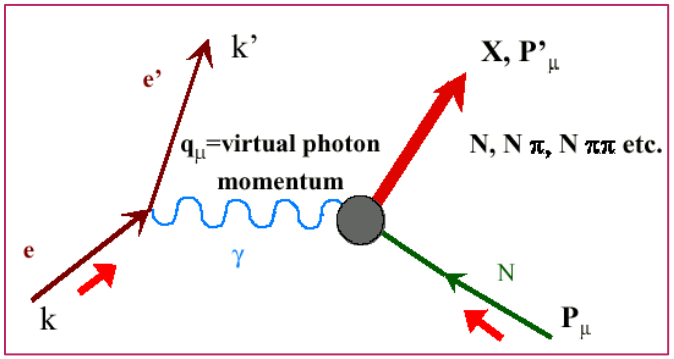
- **$\eta(1405)$: gluonium candidate**
  - **Dominant decay: $a_0(980)\pi$, direct $\eta\pi\pi$, $K\bar{K}\pi$**
  - **Not observed in $\gamma\gamma$ collisions**
  - **Large production in gluon-rich environments**
    - J/ψ radiative decays
    - Peripheral hadroproduction (BNL E769, E852)
    - $p\bar{p}$ annihilation at rest in LH_2 target (S-wave enhancement)
  - Estimated glue content: ~78% (Li, EPJ C28, 335 (2003))
  - **Contrary to LQCD expectations**: lightest pseudoscalar glueball expected above 2 GeV

- **$\eta(1475)$: $s\bar{s}$ 2S excitation? (first η' radial excitation)**
  - **Dominant decay: $\bar{K}K^*$ + c.c.**
  - Observed in $\gamma\gamma$ collisions by L3
  - **Not observed in $\eta\pi\pi$**
  - If $\eta(1475)$ is the 2S $s\bar{s}$: no available slot for $\eta(1405)$ in the CQM
  - The width matches with the value expected in $^3P_0$ model for the radially excited $s\bar{s}$ state
  - Flaw: **lack of observations in K^-p**

OPEN/HIDDEN STRANGENESS IN PHOTOPRODUCTION REACTIONS

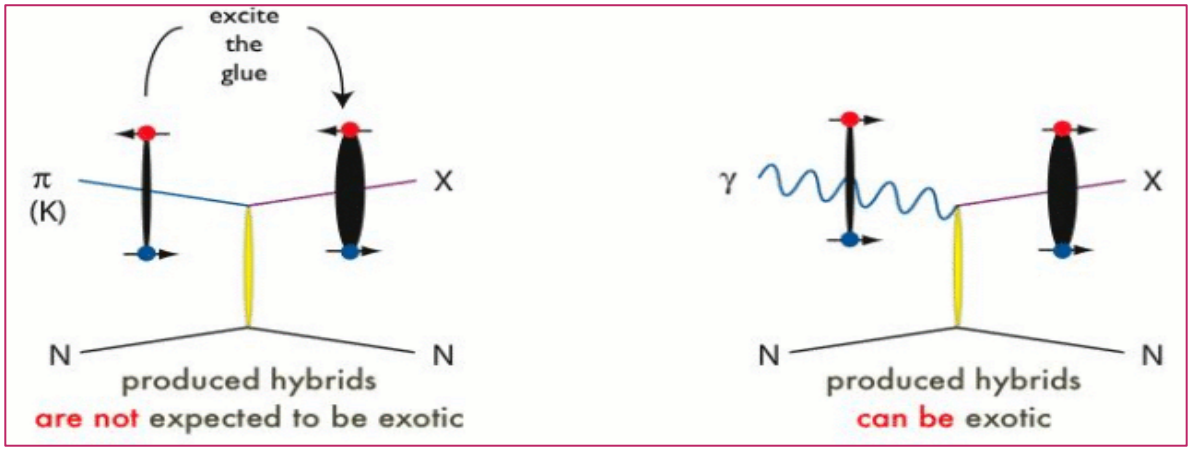
Meson spectroscopy with e.m. probes

- 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**

π (K)N: Need spin-flip for exotic quantum number



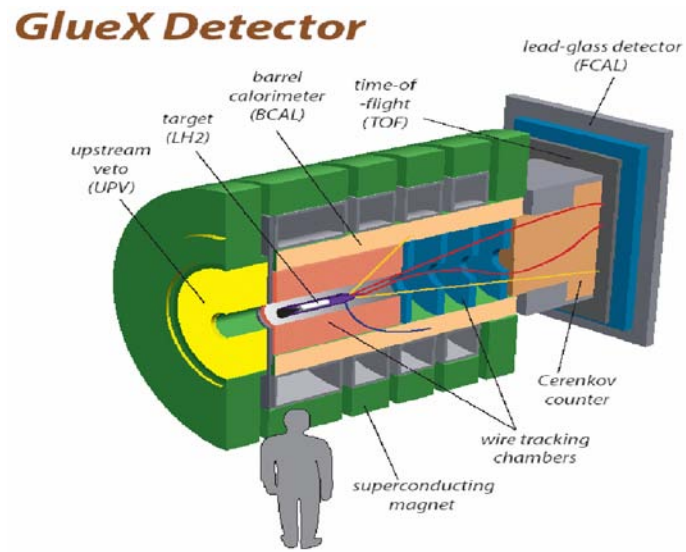
γN: No spin-flip for exotic quantum number

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

Photoproduction experiments today: JLAB

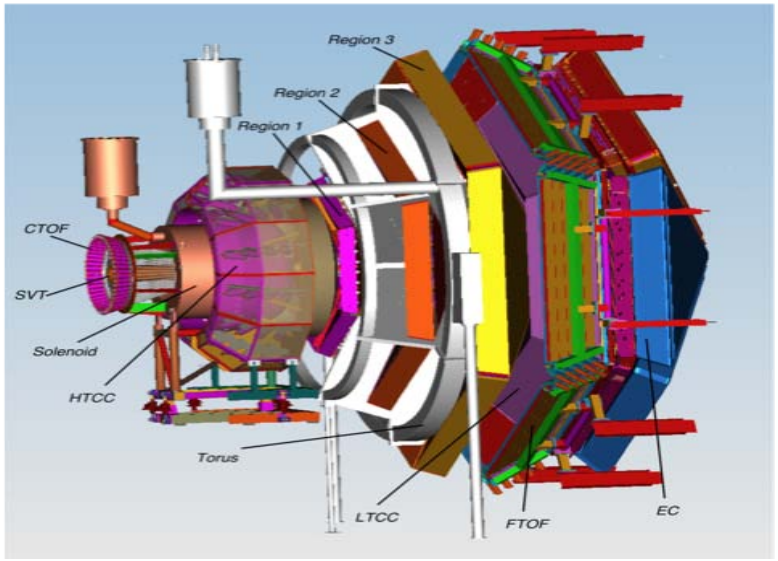
- High intensity real and virtual photon beams
- Able to measure exclusively the production reactions and the decays of the emitted particles
- Requirements:
  - Good acceptance, momentum resolution, particle id capabilities

Hall-D - GlueX Detector



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

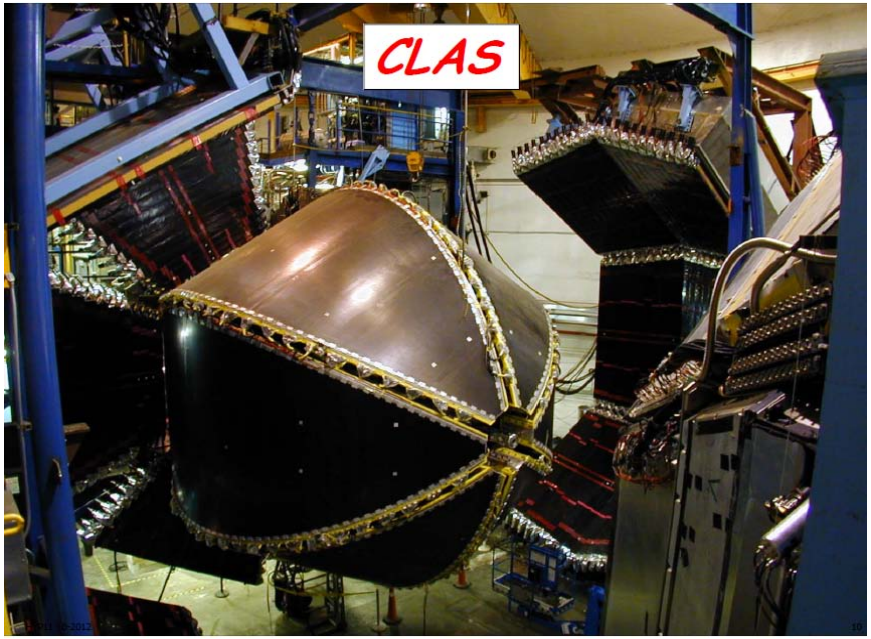
Hall-B - CLAS12 Detector

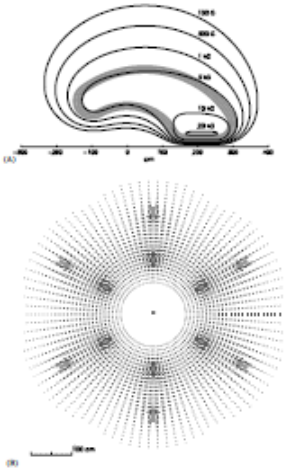


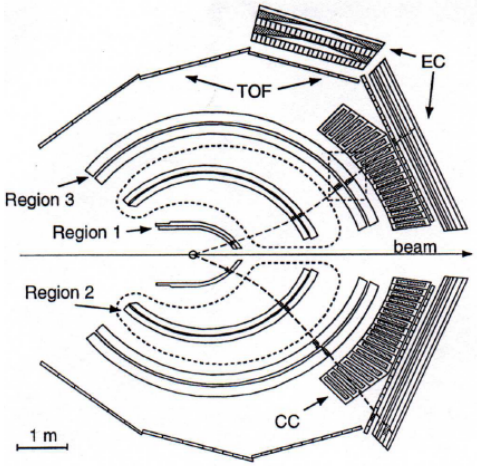
- Good resolution
- Good pID
- Resonable hermeticity
- NON-Uniform acceptance

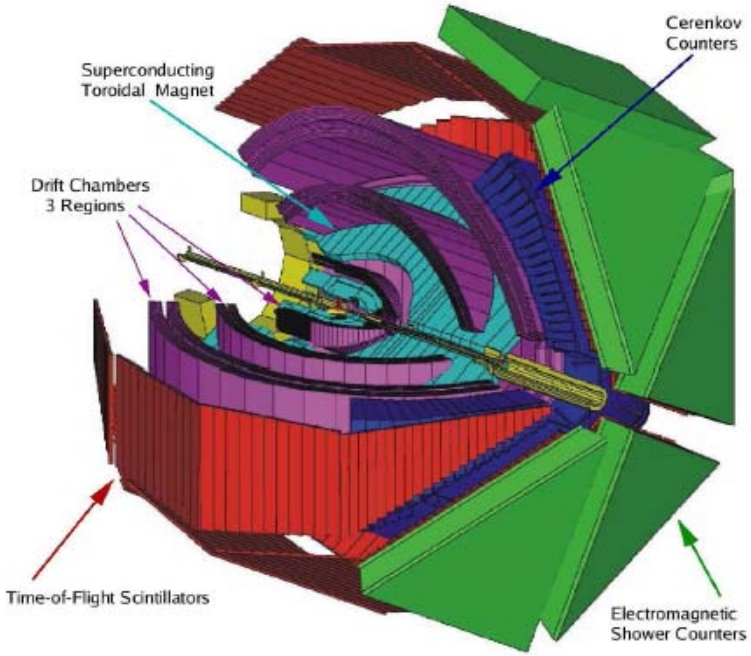
STRANGEONIA PHOTOPRODUCTION WITH CLAS: EXPLORATORY SEARCHES

CLAS @ 6 GeV

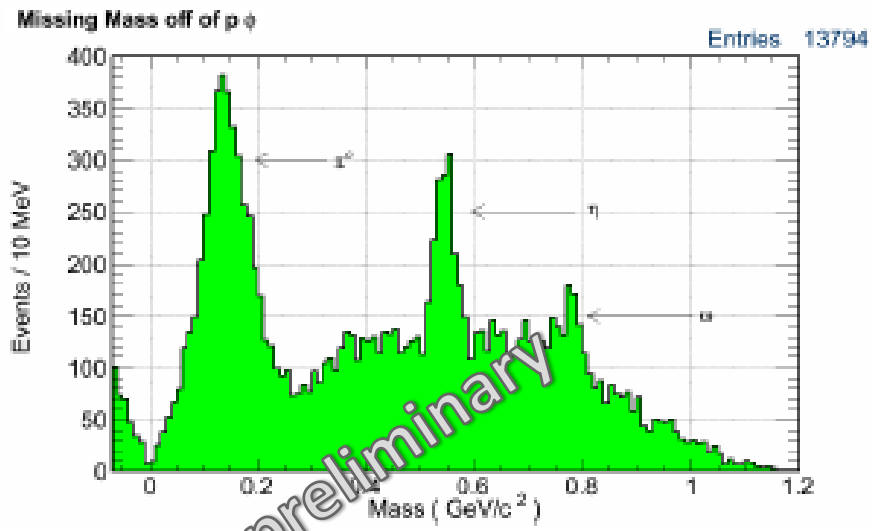

CLAS

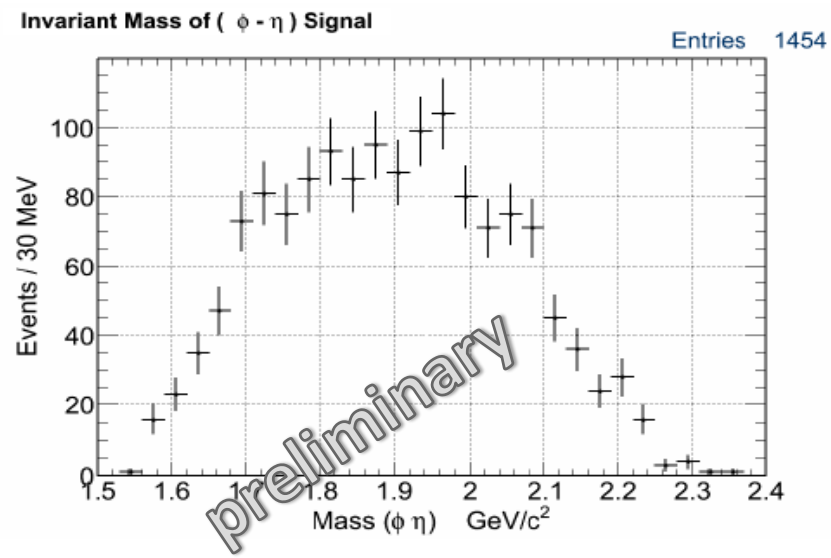


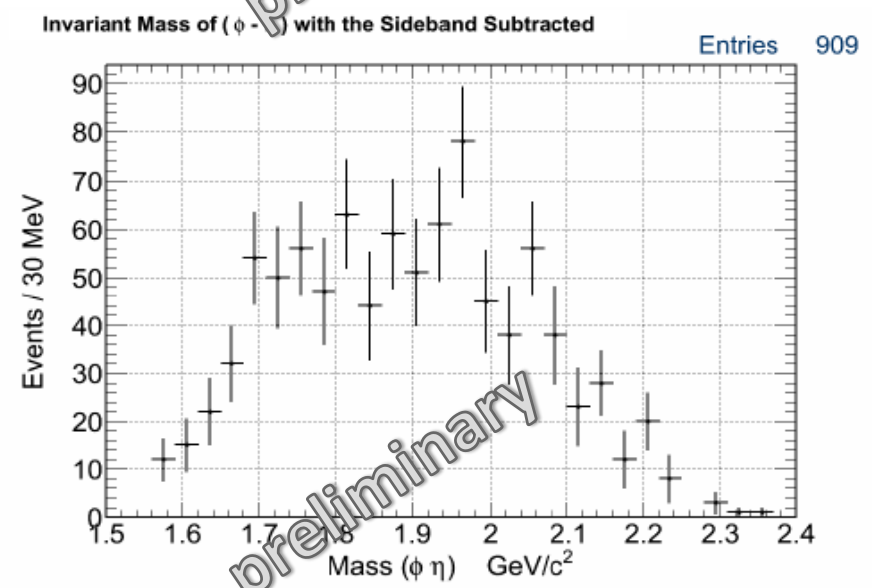

EC
TOF
Region 3
Region 1
beam
Region 2
CC
1 m


Cerenkov
Counters
Superconducting
Toroidal Magnet
Drift Chambers
3 Regions
Time-of-Flight Scintillators
Electromagnetic
Shower Counters

The $\eta\phi$ decay channel: preliminary observations with CLAS6 data

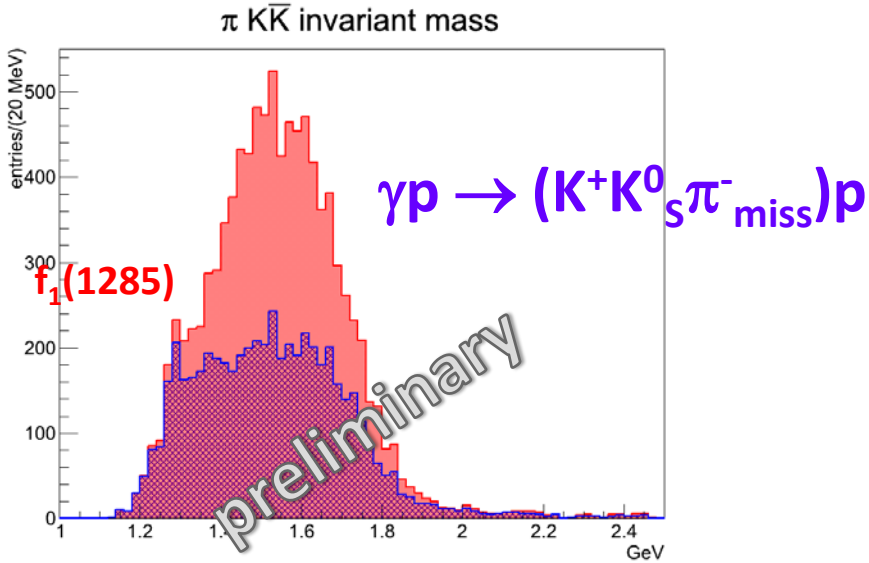


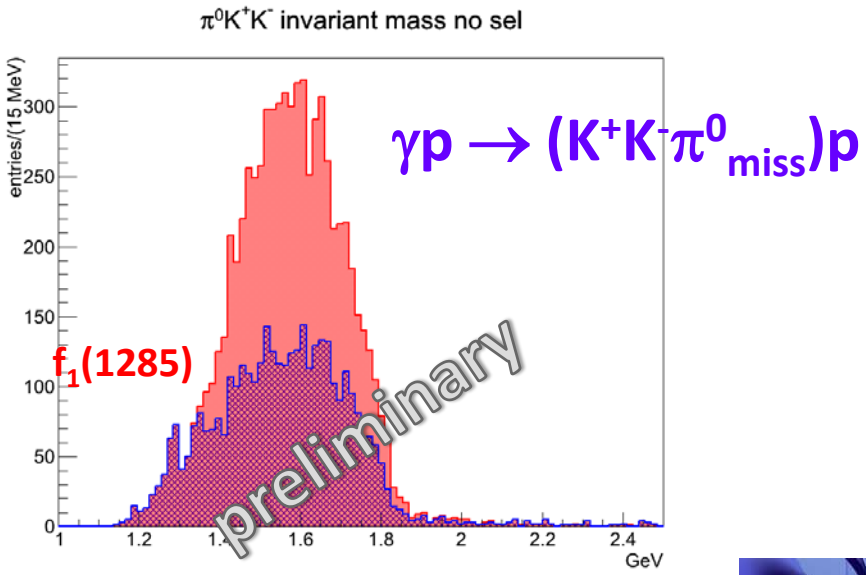




- g12 dataset analysis (M. Saini, FSU, 2012):
  - $\gamma p \rightarrow pK^+K^-\eta_{miss}$ (photons up to 5.45 GeV/c)
- Largest sample collected for final state (909 events)
- A few hints of possible signals emerge in i.m. spectrum

The ($K\bar{K}\pi$) invariant mass system

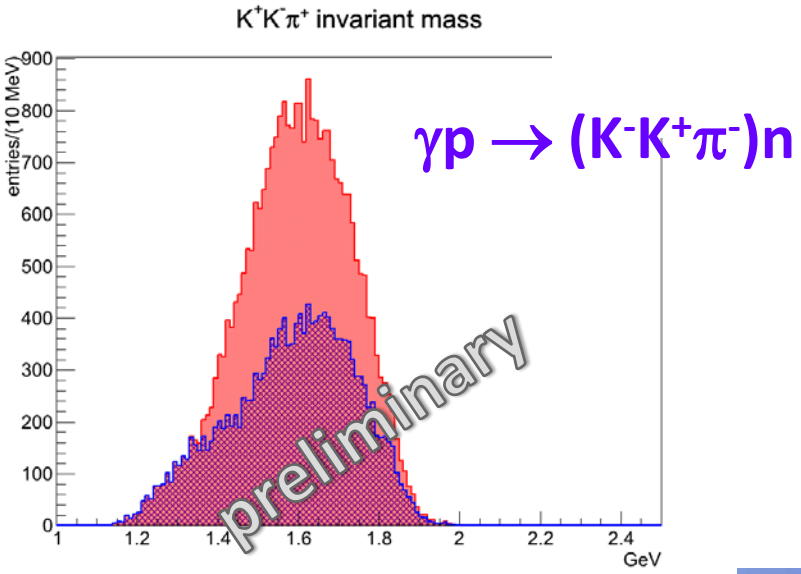




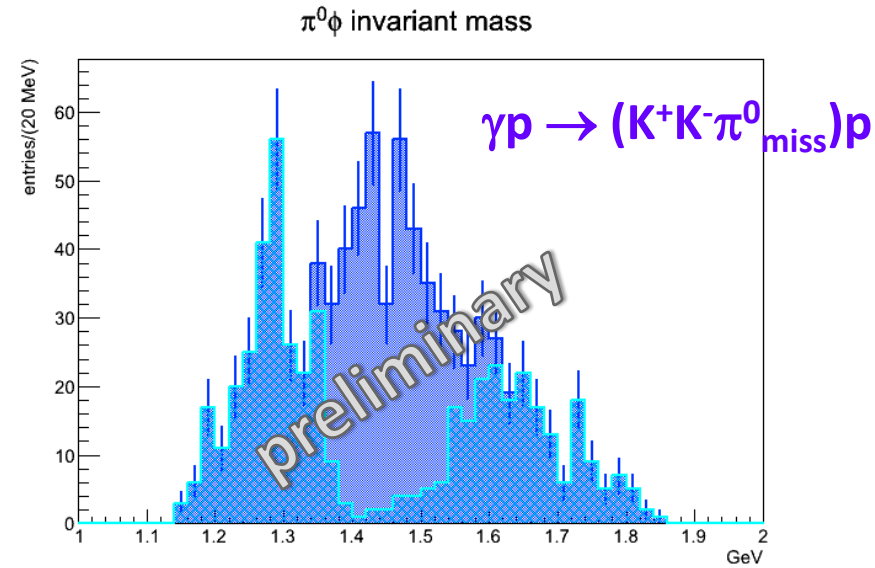
Blue: **No K* in the data**
Events within ±1 .5σ from the peak central value are excluded

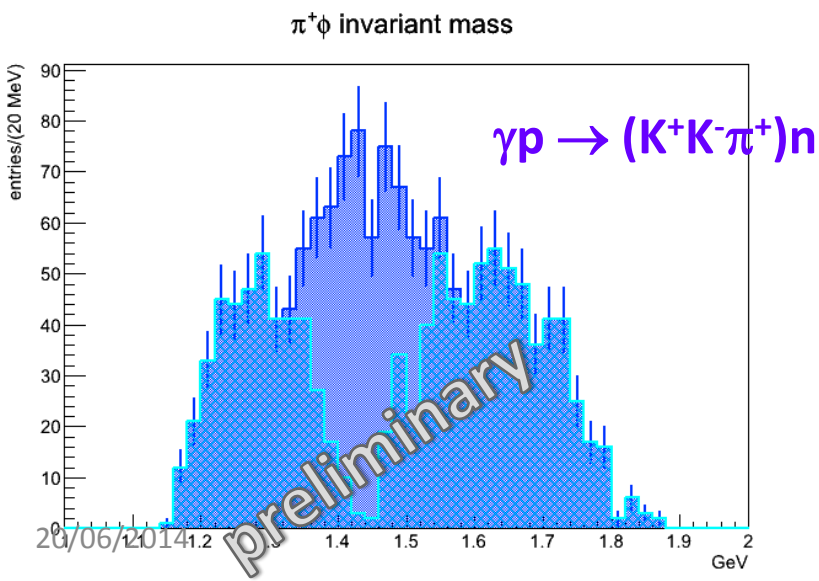
Signals of $f_1(1285)$: its decay in K*K has never been seen (anti-cut)

No signal for an isovector structure



The ($\varphi\pi$) invariant mass system





- **Cyan histogram: no K* in the sample**
- Hole at about 1450 MeV (where the C(1480) had been observed)
- Clean signal of $f_1(1285)/b_1(1235)$
  - Γ f_1: 25 MeV narrow
  - Γ b_1: ~140 MeV
- Signal of $\phi(1680)$?

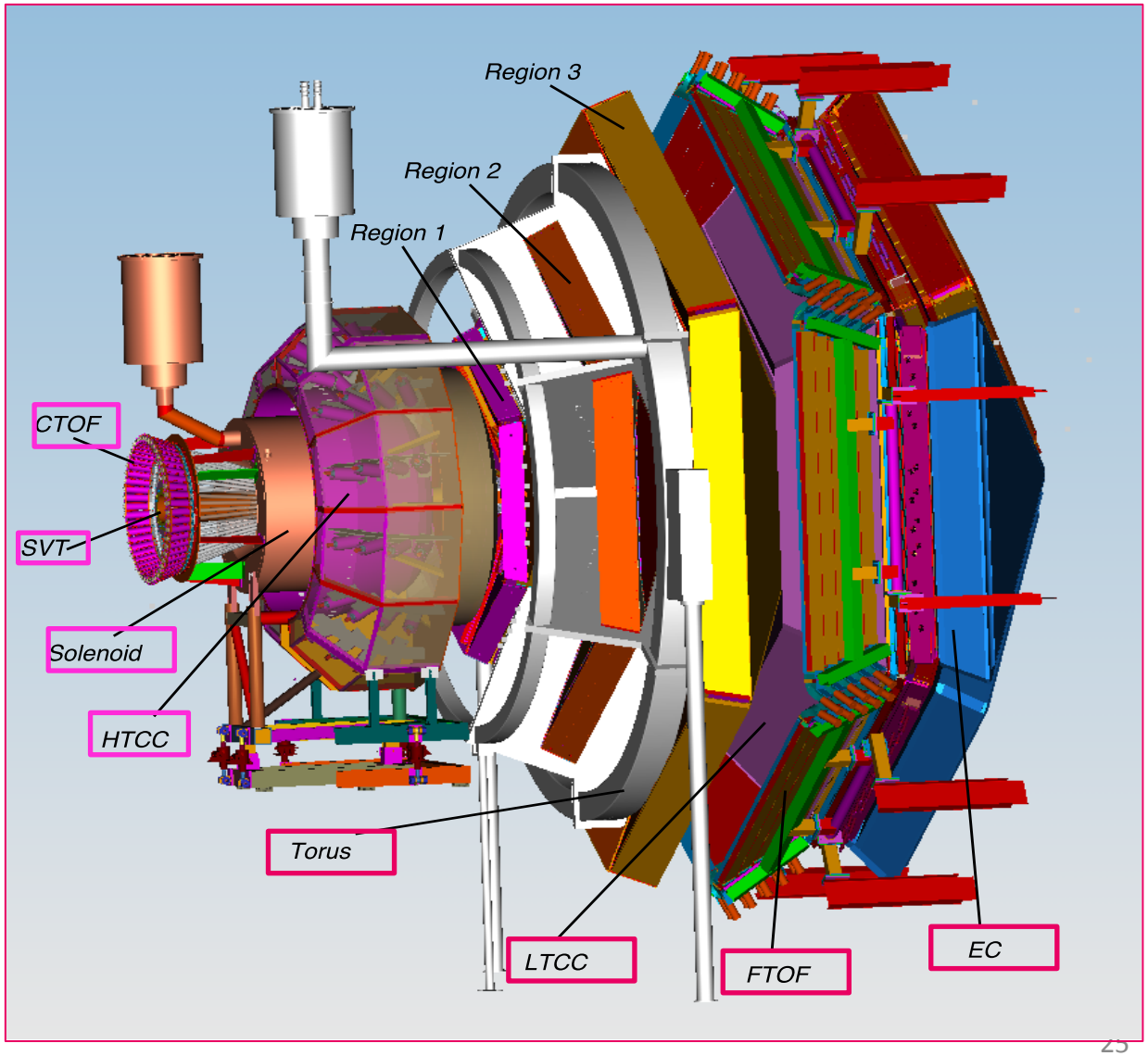
OUTLOOK: CLAS12 PERFORMANCE AND POTENTIALITIES

The CLAS12 Experiment

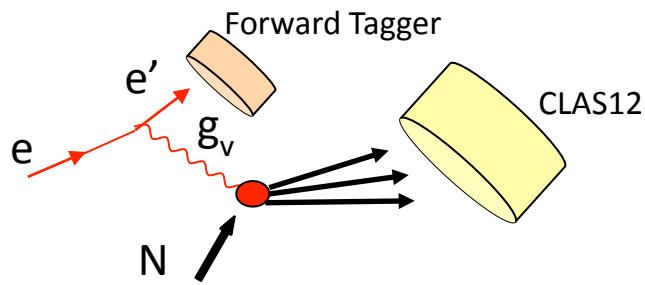
- **Forward detector**
  - Torus Magnet
  - Forward SVT tracker
  - HT Cherenkov counter
  - Drift chamber system
  - LT Cherenkov counter
  - Forward TOF system
  - Preshower calorimeter
  - EM calorimeter (EC)

- **Central detector**
  - Solenoid magnet
  - Barrel silicon tracker
  - Central TOF

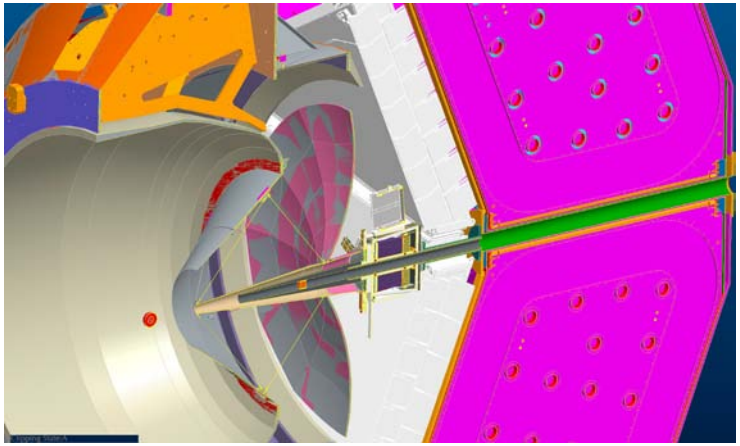
- **Proposed add-ons**
  - Micromegas (CD)
  - Neutron Detector (CD)
  - RICH Detector (FD)
  - Forward tagger (FD)



Low Q^2 quasi-real photoproduction



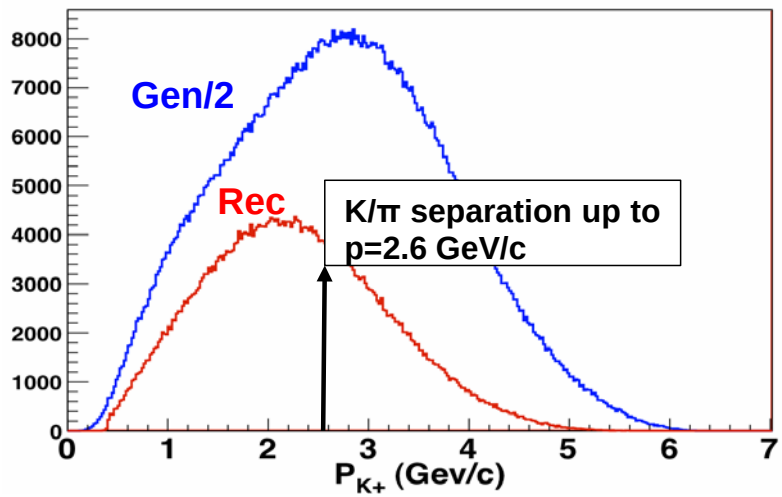
$E_{scattered}$	0.5 - 4.5 GeV
θ	2.5^o - 4.5^o
ϕ	0° - 360°
ν	6.5 - 10.5 GeV
Q^2	0.01 - 0.3 GeV^2 ($< Q^2 >$ 0.1 GeV^2)
W	3.6 - 4.5 GeV



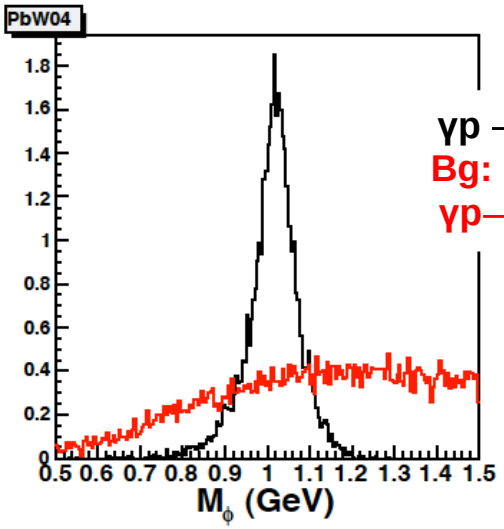
- Electron scattering at "0" deg (2.5°-4.5°)
  - **Low Q^2 virtual photon ⇒ quasi real**
- Photon tagging: detection of electron at small angles
  - High energy photons: 6.5 - 10.5 GeV
  - To be accomplished by a "Forward Tagger"

- **Quasi real photons: linearly polarized**
  - Polarization: 70%-10%, measured event by event
- **High luminosity**: $N_\gamma \sim 5\times10^8$, $L \sim 10^{35}$ $cm^{-2}s^{-1}$ on 5 cm LH_2 target
  - Thin targets can be used

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



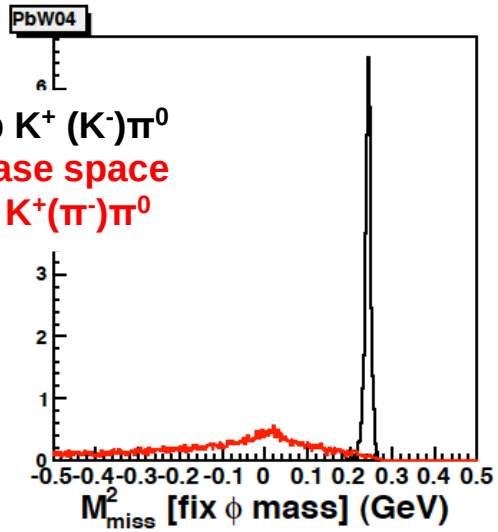
- Production cross section: 10 nb
- CLAS12 acceptance: ~10%
- Good π/K separation power required for momenta up to 2.6 GeV/c
- Simulation: **good background rejection capabilities using kin. fit and pid** of CLAS12
- Expected events in 80 data taking days @ full luminosity: ~ 3000 evts/mass bin
- Expected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

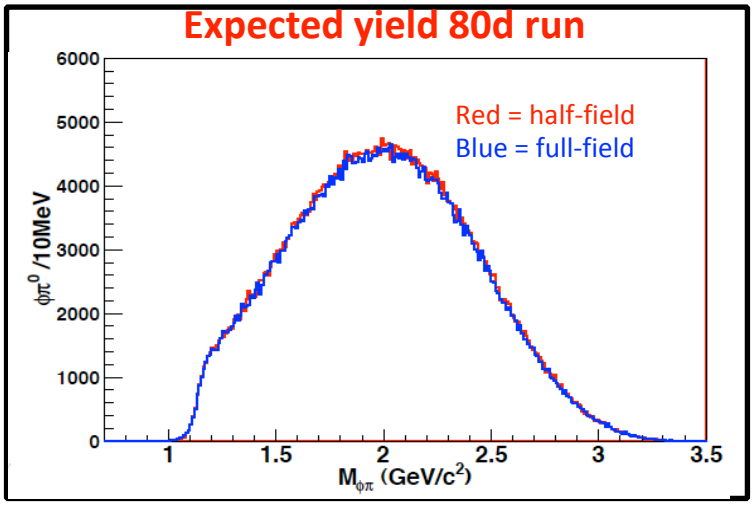


$\gamma p \rightarrow p\, K^+ (K^-)\pi^0$

Bg: phase space

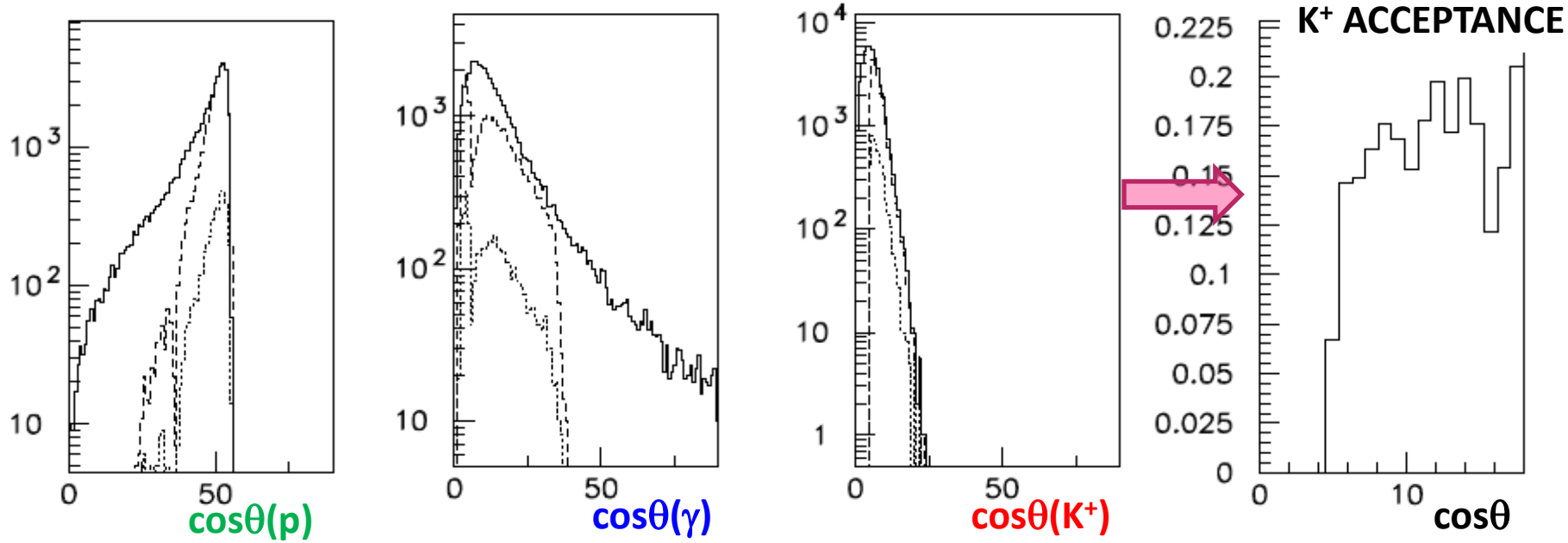
$\gamma p \rightarrow p\, K^+(\pi^-)\pi^0$





$\gamma p \rightarrow \varphi\pi^0\, p$

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



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

Summary and Conclusions

- Light meson spectrum with open and hidden strangeness still to be fully understood
  - Many observations in different reactions
  - Many confirmations and many disagreements
  - Too many states observed to be arranged in available CQM slots
    - Exotica? Glueballs? Hybrids?
  - 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: $\eta\phi$, $\eta'\phi$, $\phi\phi$, $\phi\pi$:
    - $BR(\eta\phi)/BR(K^+K^-) = 0.5$
  - Limited outcome from other spectroscopy experiments in the last decade