Search for Strangeonium and exotics in Photoproduction using CLAS

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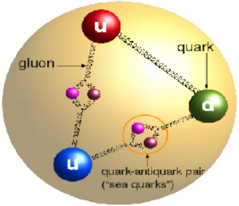
QCD, Standard Model and Hadronic Physics

Quantum chromodynamics (QCD) is theory of the strong interaction (color force).

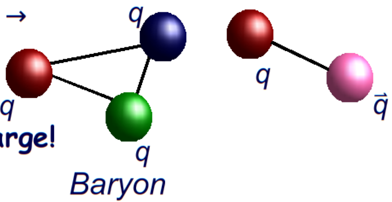
It describes the interactions of the quarks and gluons making up the hadron

QCD Picture

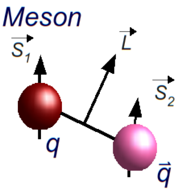


In Constituent Quark Model, →

Color charge!



Meson Spectroscopy



$$\vec{J} = \vec{L} + \vec{S}$$

$$P = (-1)^{L+1}$$

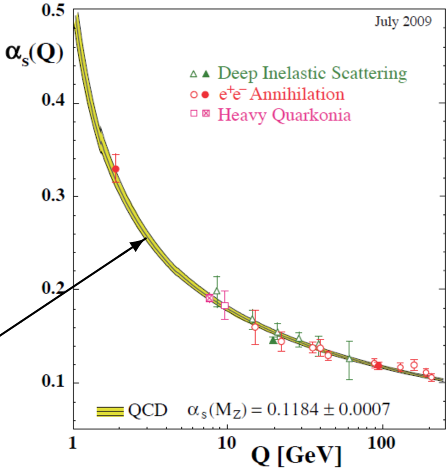
$$C = (-1)^{L+S}$$

$$J^{PC}\Big|_{allowed} = 0^{-+}, 0^{++}, 1^{--}, 1^{+-}, 1^{++}, 2^{--}, \ldots$$

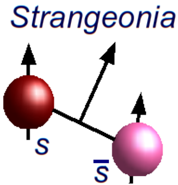
$$J^{PC}\Big|_{exotic} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots\ .$$

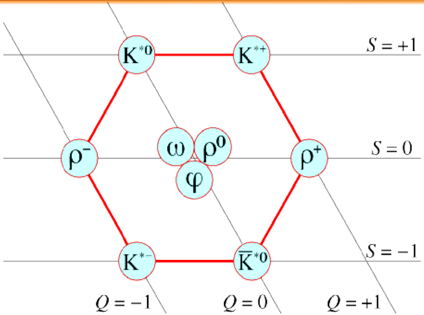
Quark Model and beyond

- Free quarks and gluons have not been observed in nature due to confinement.
- QCD predicts exotic hadrons beyond the naive quark model [hybrids, glueballs and multi-quark states]
- Mapping of the meson spectra will help us identify exotic unconventional mesons and decays, to further our insight into soft (Non-perturbative) QCD



Known Strangeonia





$\surd$ Of the 22 expected resonances, only 7 are well identified

$\eta - \eta'$	ϕ (1020)	h_1 (1387)
f_1 (1426)	f_2' (1525)	ϕ (1680)
ϕ_3 (1850)	..	..

Expected Strangeonia spectrum

			J^{PC}	Name	Mass (MeV)
n=1	L=0	S=0	0^{-+}	η, η'	548,958
		S=1	1^{--}	ϕ	1020
	L=1	S=0	1^{+-}	h_1'	1380
		S=1	0^{++}	f_0'	1500
			1^{++}	f_1'	1530
			2^{++}	f_2'	1525
	L=2	S=0	2^{-+}	η_2	1850
		S=1	1^{--}	ϕ_1	1850
			2^{--}	ϕ_2	1850
			3^{--}	ϕ_3	1854

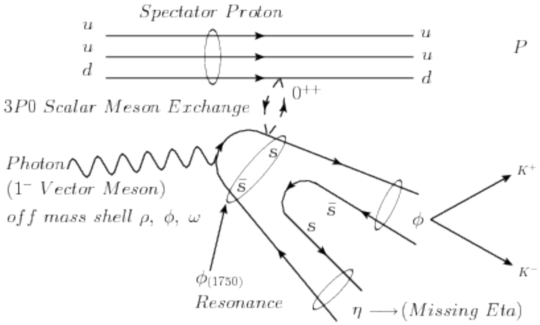
Orbital excitations of (I = 0, $s\bar{s}$) meson.

			J^{PC}	Name	Mass (MeV)
n=2	L=0	S=0	0^{-+}	η_s	1415
		S=1	1^{--}	ϕ	1680
	L=1	S=0	1^{+-}	h_1	1850
		S=1	0^{++}	f_0	2000
			1^{++}	f_1	1950
			2^{++}	f_2	2000
n=3	L=0	S=0	0^{-+}	η_s	1950
		S=1	1^{--}	ϕ	2050

Radial excitations of (I = 0, $s\bar{s}$) meson.

Photoproduction - VMD

- In hadronic interactions, photon beam can be regarded as a superposition of vector mesons (ρ, ω, ϕ) with an important $s\bar{s}$ component - Vector Meson Dominance (VMD).
- $\phi\eta$ channel is the signature decay mode for strangeonium ($s\bar{s}$) states. Interference with non-strange vectors is negligible in this channel.
- $\phi\pi^0$ is an exotic channel due to OZI suppression.



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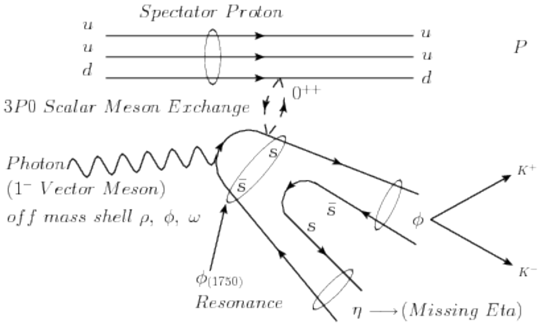

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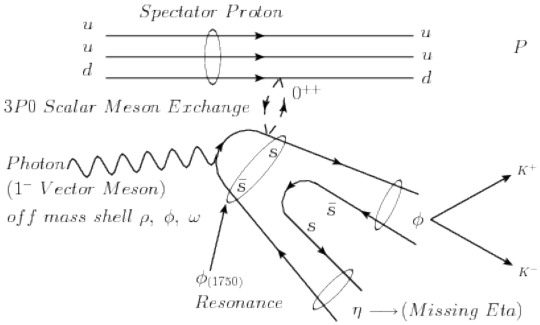


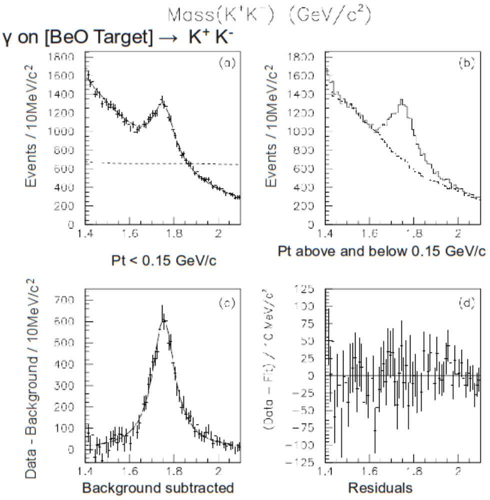
Strangeonia

- η has a significant *$n\bar{n}$* component to it, but $\phi\eta$ and $\phi\eta'$ decay modes can only originate from initial *$s\bar{s}$* states.
- “Due to the *OZI* rule, the observation of a state with a large branching fraction to $\eta\phi$, $\eta'\phi$ or $\phi\phi$ and small branches to nonstrange final states can serve as a “smoking gun" for an initial *$s\bar{s}$* state." - Barnes, Black & Page (Strong decays of Strange Quarkonia).

Why study Strangeonia?

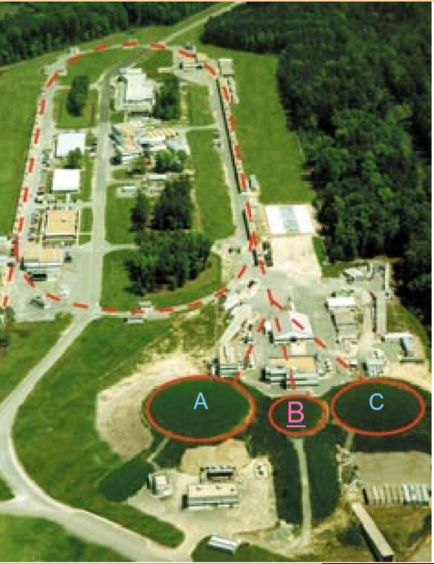
- Due to the intermediate mass of the strange quarks, study of the strangeonium states will serve as a bridge between short and large distance behavior of QCD confinement potential, a study of the transition from light quark sector to the HQET.

ϕ (1680) / X (1750)



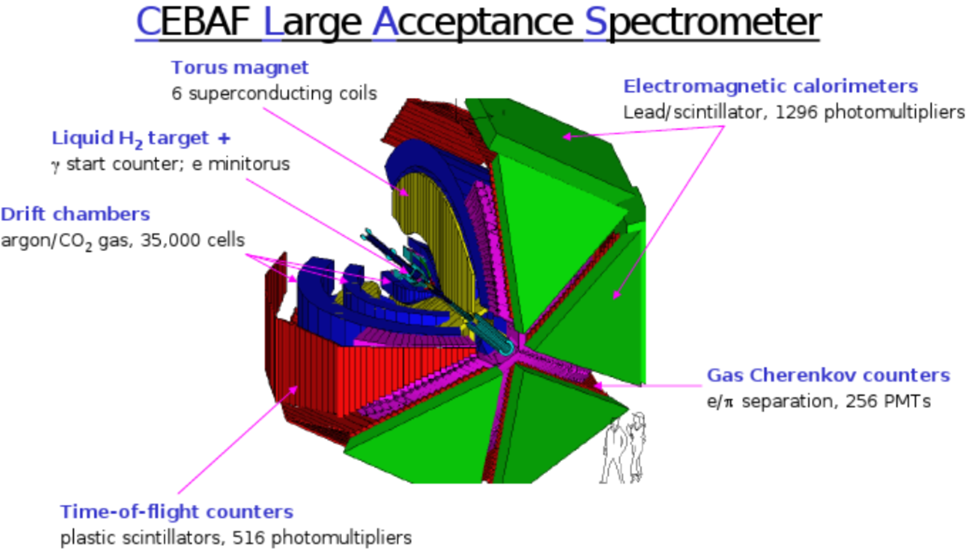
- e^+e^- production experiments observe the $\phi(1680)$
- $\phi(1750)$ is cited by PDG under $\phi(1680)$ with a note
- Focus experiment @ Fermilab has ~ 11,700 events for a resonance at $\phi(1750)$
- Exclusive $K^+ K^-$ events
- Cleanest way to look for this resonance is in the $\phi\eta$ decay

Jefferson Lab

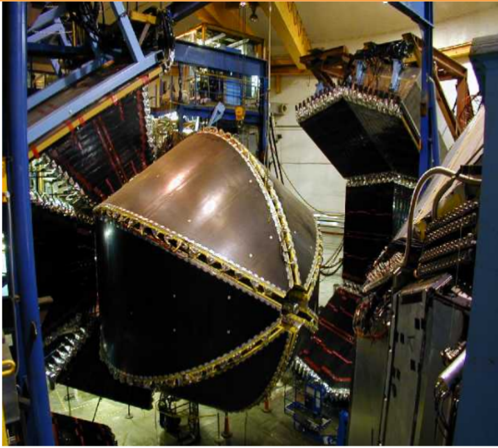


- **CEBAF**:
  Continuous **E**lectron **B**eam **A**ccelerator **F**acility,
  hosted at
  Thomas Jefferson National Accelerator Facility,
  Newport News, Virginia
- CEBAF delivers e^- beams to the 3 Halls, polarised upon request in 5 passes with e^- Energies up-to 6 GeV (1.2 x 5)
- Hall-B is the smallest experimental Hall with the largest detector "CLAS"
- Major upgrades at CEBAF and the Halls for the 12 GeV upgrade as well as addition of a new Hall-D which will house GLUEX created with meson spectroscopy as the primary purpose
- Plans for upgrade of CLAS to CLAS12 for the 12 GeV program at JLAB, with new detector components added and reusing the old where possible

CLAS subsystems



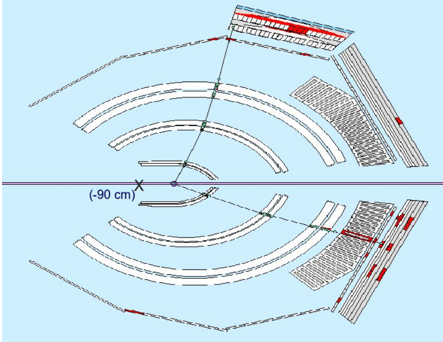
CLAS



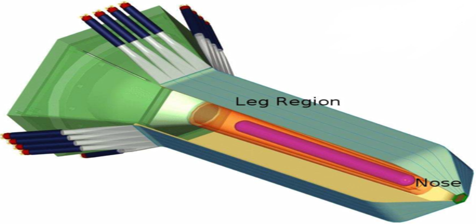
- Skeletal superconducting Toroidal Magnets for CLAS.
- CLAS detector during assembly.

g12 - HyCLAS

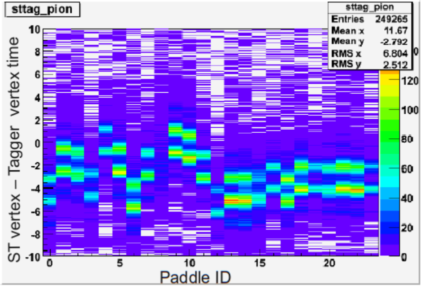
- 44.2 Days of beam-time over 70 days, 1^{st} April to 9^{th} June, 2008
- Beam current $\rightarrowtail$ 60-65 nA ; $E_e \rightarrowtail 5.71 GeV$; DAQ Rate $\rightarrowtail$ 8 KHz
- 26.2 billion triggers; Main Trigger $\rightarrowtail$ 2 prong or more with $E_\gamma \geq 4.4$ GeV, 3 prong with no MOR ...
- 126 TB of raw data
- 250 TB of reconstructed data
- 68 pb^{-1} of photo-production data
- Analysis over 95% of data available



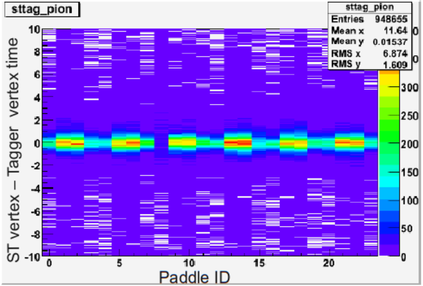
Start Counter



- Incorporates the independent sector based tracking of CLAS
- g12 pulled ST 90cm back from the center of CLAS to increase acceptance for low t, forward going particles
- ST crucial for picking the right photon and Particle ID

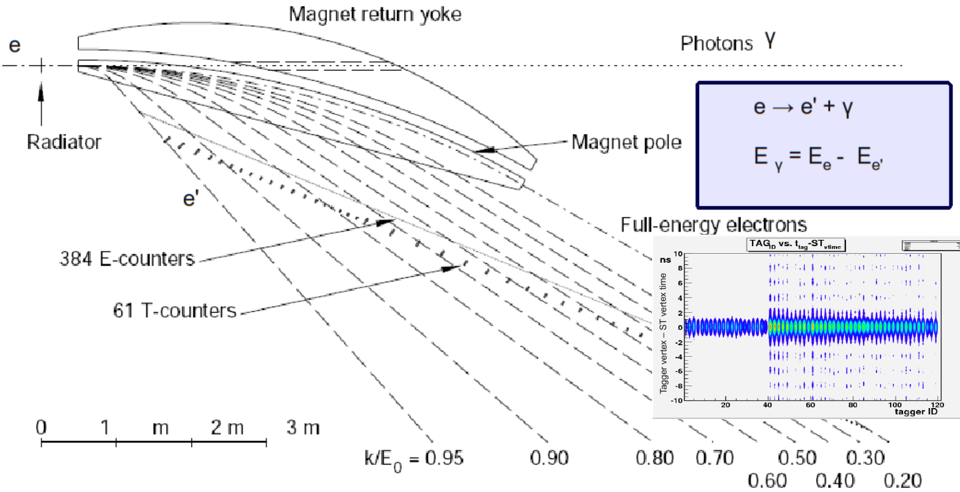


(a) Before



(b) After

Tagger



$$e \rightarrow e' + \gamma$$

$$E_\gamma = E_e - E_{e'}$$

Fig. 23. Hall B photon-tagging system.

Particle Identification

PART Bank

- *Proton*
- K^+
- K^-

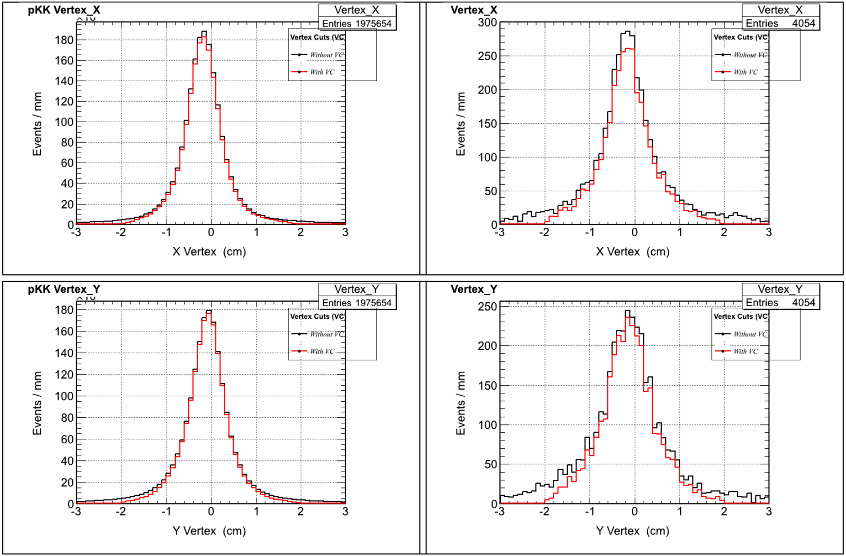
Meson ID

- ϕ – Invariant Mass reconstructed from K^+ & K^-
- To Identify ϕ, Select 1010 MeV $\leq$ IM(K^+ K^-) $\leq$ 1030 MeV
- η – Calculated from Missing Mass as "*Beam* $+$ *Target* $-$ *Proton* $-$ K^+ $-$ K^-"
- To identify η, Select 510 MeV $\leq$ MM $\leq$ 580 MeV

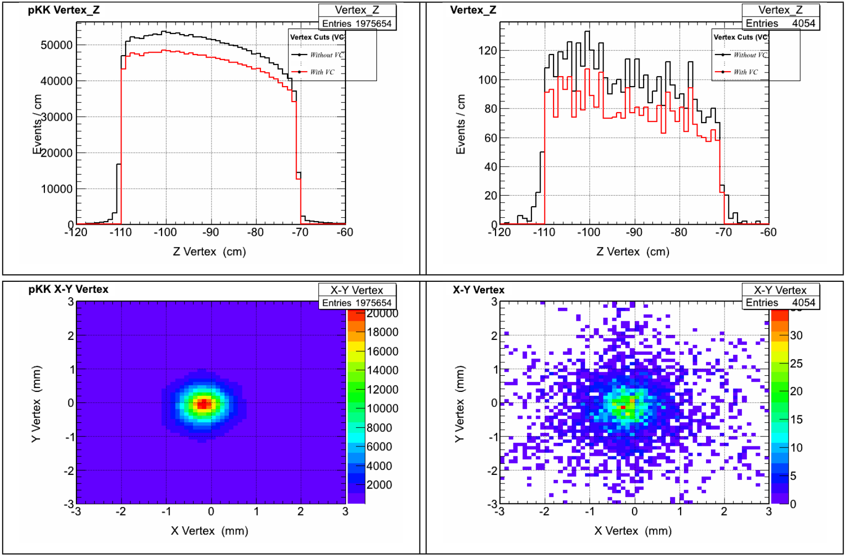
Cuts

- Event vertex time within 1.002 ns of the Start Counter vertex time
- All particles have the the difference between their measured and calculated beta (with PART bank PID) less than 0.05
- Event vertex is required to be within the Target

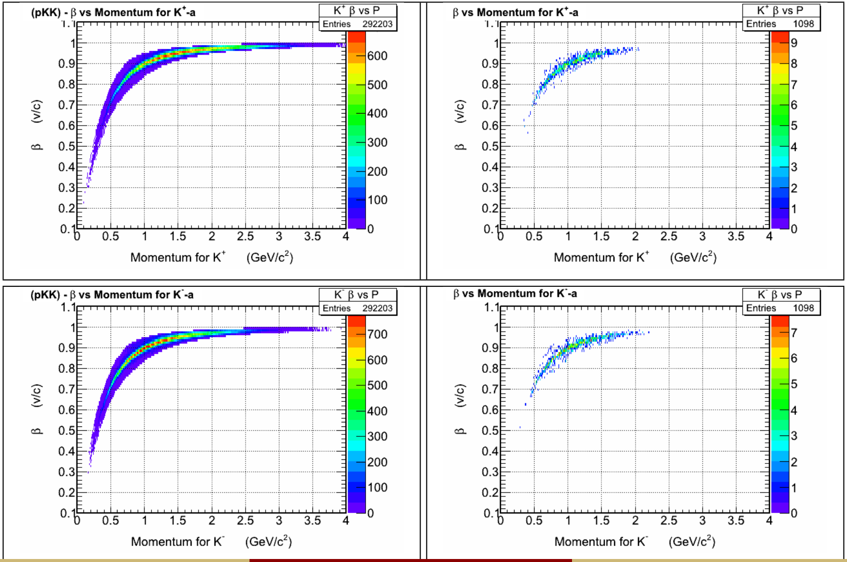
Particle Vertex 1



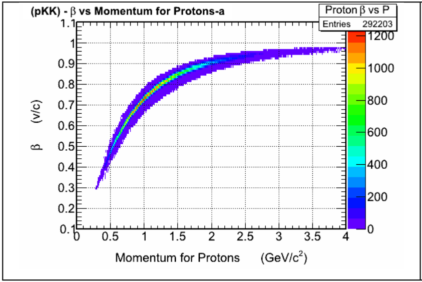
Particle Vertex 2

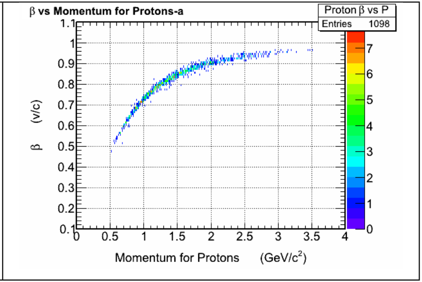


Particle Beta 1



Particle Beta 2

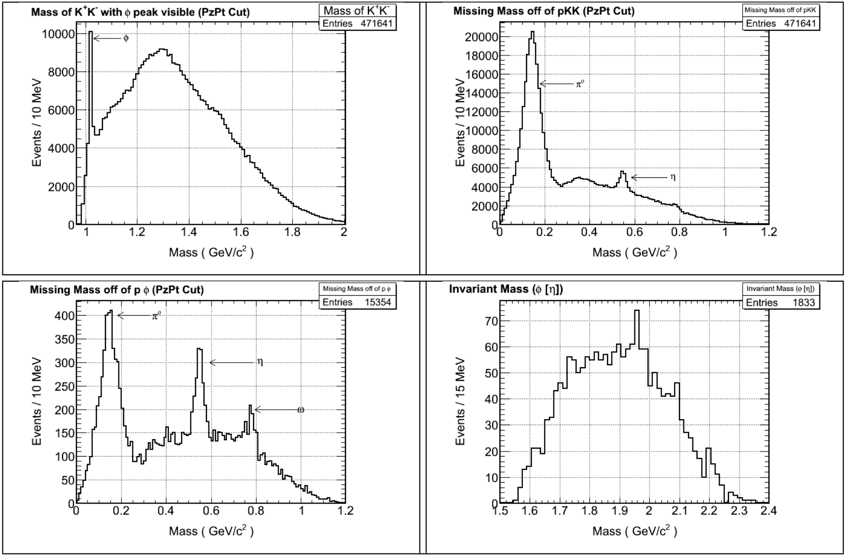




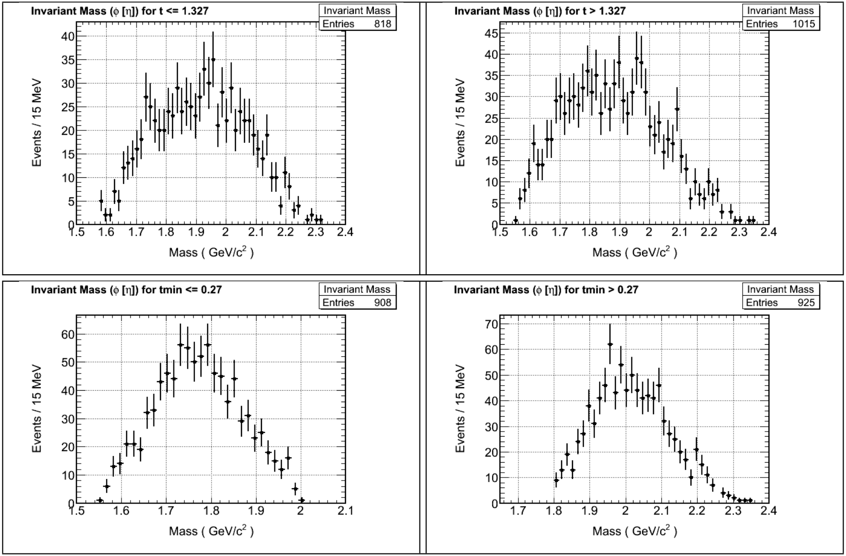
Observations

- Vertex and Timing Distributions look reasonable
- Beta for *Proton*, K^+ & K^- have no cross-contamination bands
- PID and Cuts employed work reasonably well

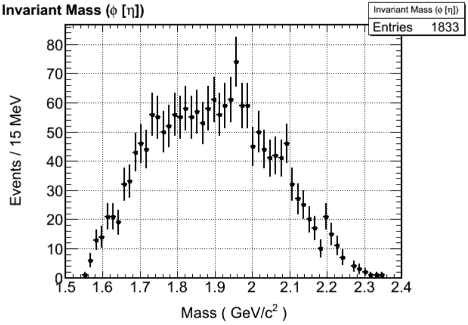
Selection of $KK \rightarrow \phi$ Data

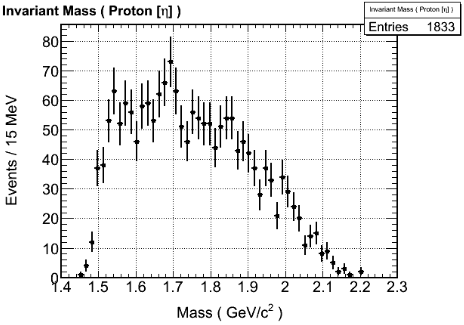


Momentum transfer dependence of $\phi - \eta$ data

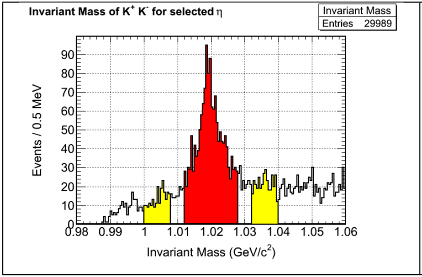


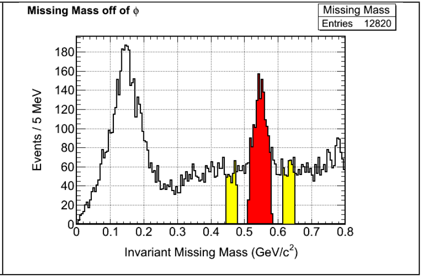
proton ϕ η Invariant Masses





ϕ & η Side-Bands

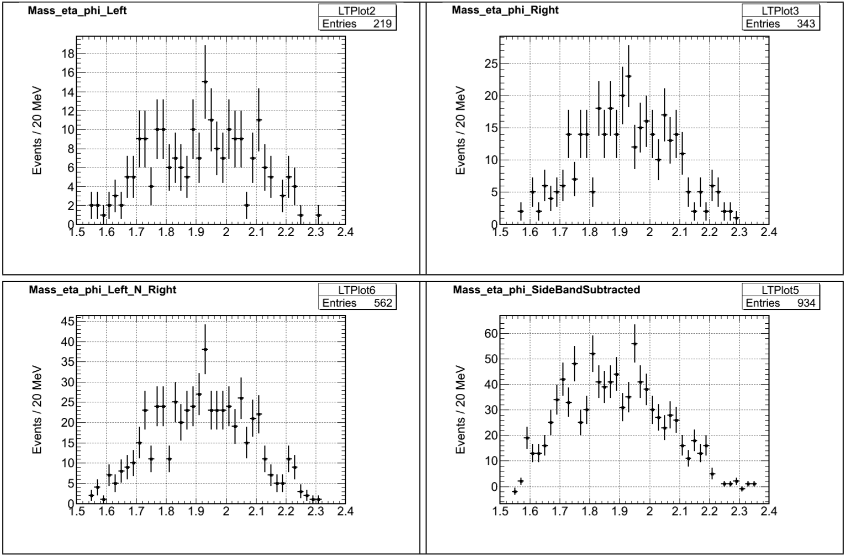




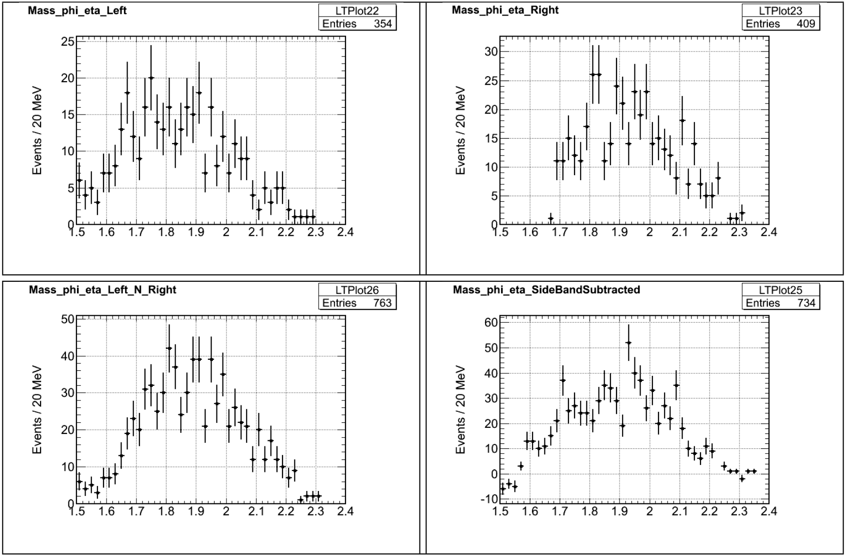
Side-Band Observations:

- ϕ width is 4 MeV and the peak is at 1020 MeV. .
- η width is 17 MeV and the peak is at 547 MeV.
- Signal region is chosen to be peak $\pm 2\sigma$.
- $\phi \rightarrow 1012 - 1028$ MeV, $\eta \rightarrow 513 - 581$ MeV
- Gap of 1σ is used between signal and sideband to minimize loss of ϕ's.
- Gap of 2σ is used between signal and sideband to minimize loss of η's.

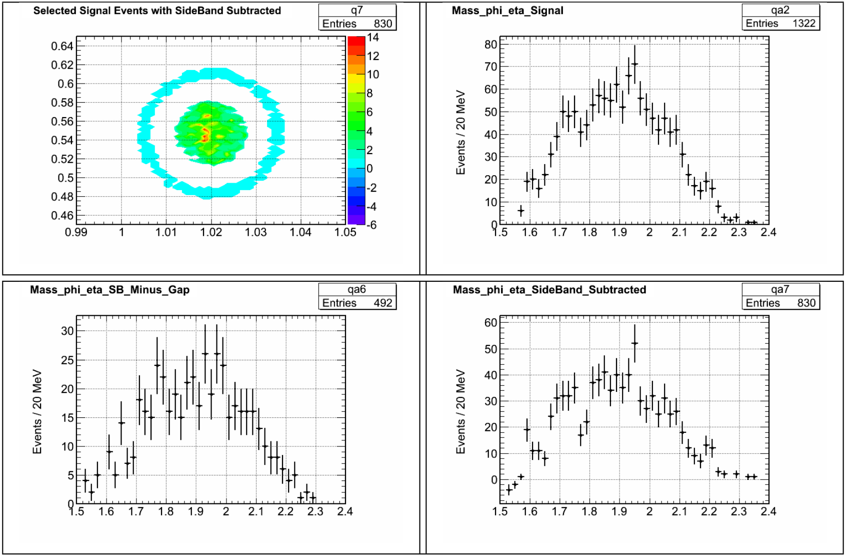
ϕ SBS


Mass_eta_phi_Left
LTPlot2
Entries 219
Events / 20 MeV
Mass_eta_phi_Right
LTPlot3
Entries 343
Events / 20 MeV
Mass_eta_phi_Left_N_Right
LTPlot6
Entries 562
Events / 20 MeV
Mass_eta_phi_SideBandSubtracted
LTPlot5
Entries 934
Events / 20 MeV

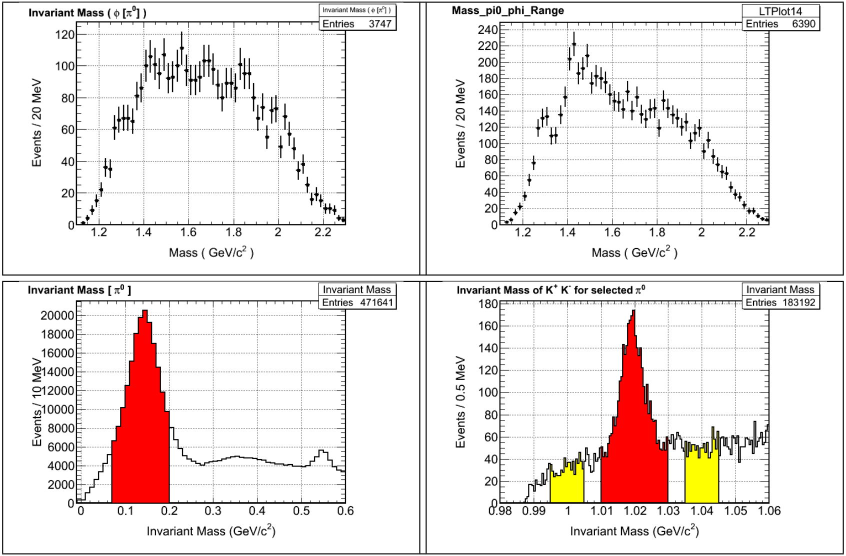
η SBS


Mass_phi_eta_Left
LTPlot22
Entries 354
Events / 20 MeV
Mass_phi_eta_Right
LTPlot23
Entries 409
Events / 20 MeV
Mass_phi_eta_Left_N_Right
LTPlot26
Entries 763
Events / 20 MeV
Mass_phi_eta_SideBandSubtracted
LTPlot25
Entries 734
Events / 20 MeV

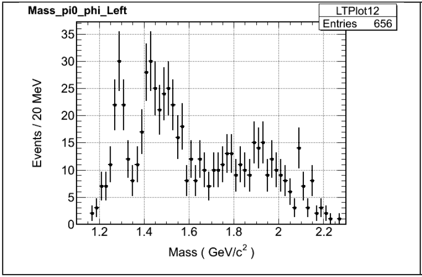
$\phi - \eta$ SBS

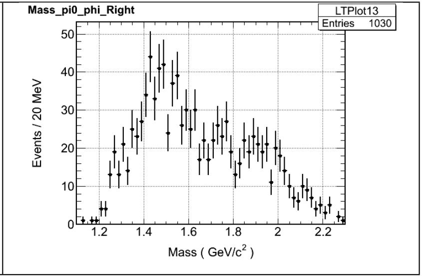

Selected Signal Events with SideBand Subtracted
q7
Entries 830
Mass_phi_eta_Signal
qa2
Entries 1322
Events / 20 MeV
Mass_phi_eta_SB_Minus_Gap
qa6
Entries 492
Events / 20 MeV
Mass_phi_eta_SideBand_Subtracted
qa7
Entries 830
Events / 20 MeV

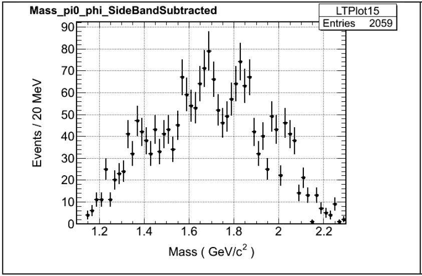
ϕ π^0 SB

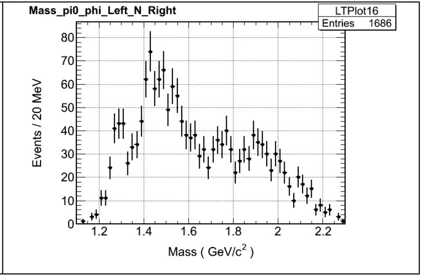

Invariant Mass (φ [π0])
Invariant Mass (φ [π0])
Entries 3747
Events / 20 MeV
Mass (GeV/c2)
Mass_pi0_phi_Range
LTPlot14
Entries 6390
Events / 20 MeV
Mass (GeV/c2)
Invariant Mass [π0]
Invariant Mass
Entries 471641
Events / 10 MeV
Invariant Mass (GeV/c2)
Invariant Mass of K+ K- for selected π0
Invariant Mass
Entries 183192
Events / 0.5 MeV
Invariant Mass (GeV/c2)

ϕ π^0 SBS

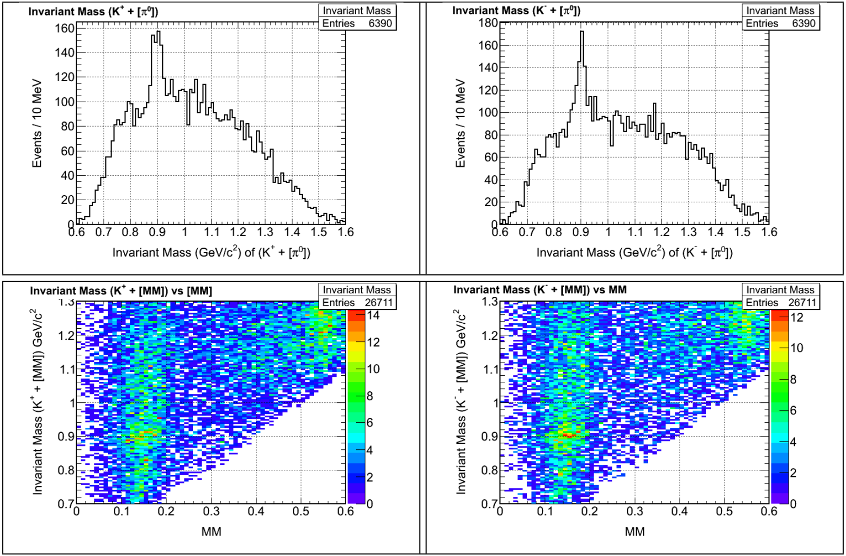

Mass_pi0_phi_Left
LTPlot12
Entries 656
Events / 20 MeV
Mass (GeV/c^2)


Mass_pi0_phi_Right
LTPlot13
Entries 1030
Events / 20 MeV
Mass (GeV/c^2)

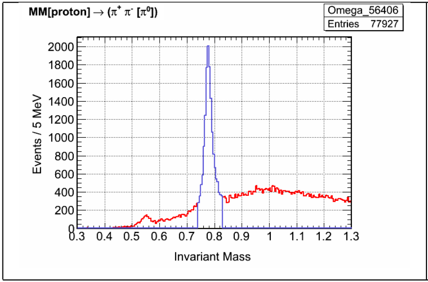

Mass_pi0_phi_SideBandSubtracted
LTPlot15
Entries 2059
Events / 20 MeV
Mass (GeV/c^2)

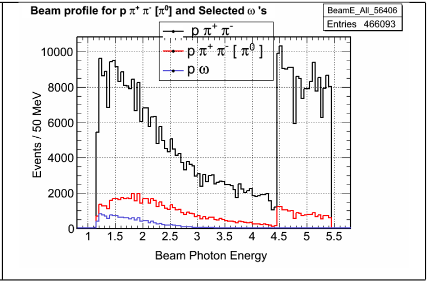

Mass_pi0_phi_Left_N_Right
LTPlot16
Entries 1686
Events / 20 MeV
Mass (GeV/c^2)

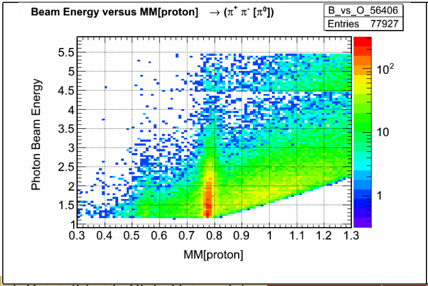
Check for K^{*+}


Invariant Mass (K+ + [π0])
Invariant Mass
Entries 6390
Events / 10 MeV
Invariant Mass (GeV/c2) of (K+ + [π0])
Invariant Mass (K- + [π0])
Invariant Mass
Entries 6390
Events / 10 MeV
Invariant Mass (GeV/c2) of (K- + [π0])
Invariant Mass (K+ + [MM]) vs [MM]
Invariant Mass
Entries 26711
Invariant Mass (K+ + [MM]) GeV/c2
MM
Invariant Mass (K- + [MM]) vs MM
Invariant Mass
Entries 26711
Invariant Mass (K- + [MM]) GeV/c2
MM

ω - yield for 40-80 nA Beam Current

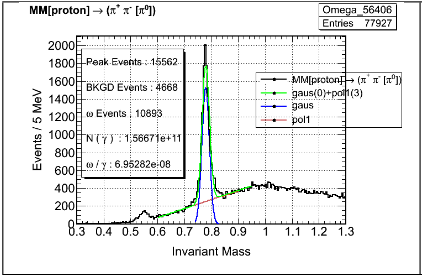


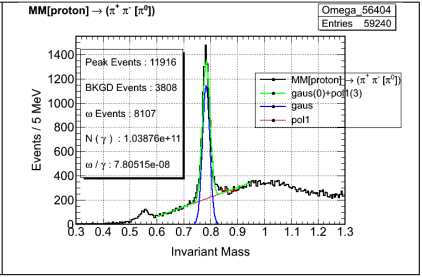


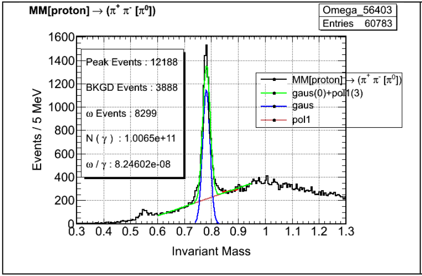


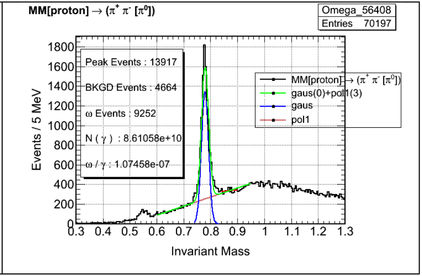
Beam Current : 40 nA	
Photons	1.5667e+11
Omegas	10893
Yield/Photon	6.953e-08
Run Number	56406

ω - yield fits

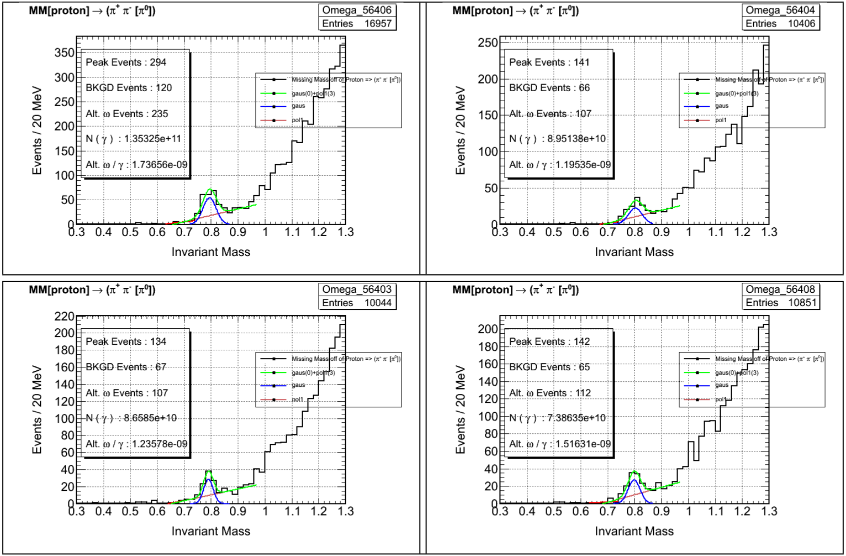




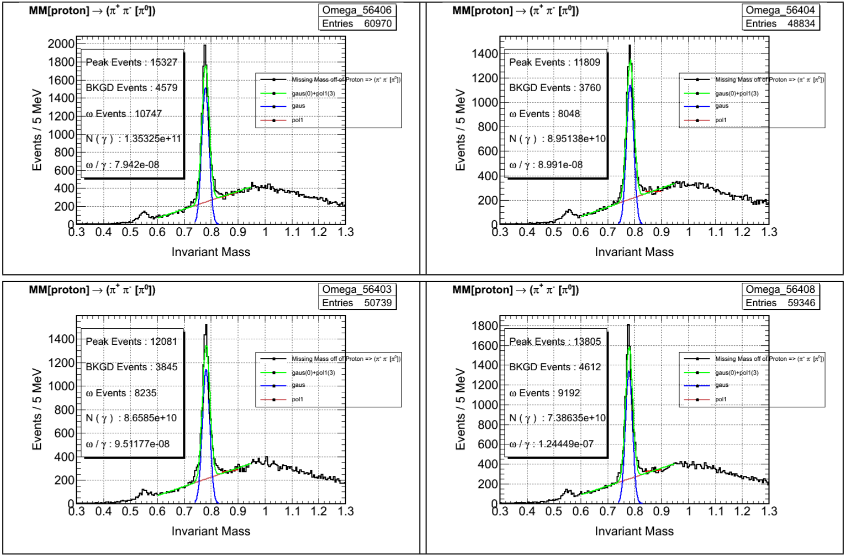




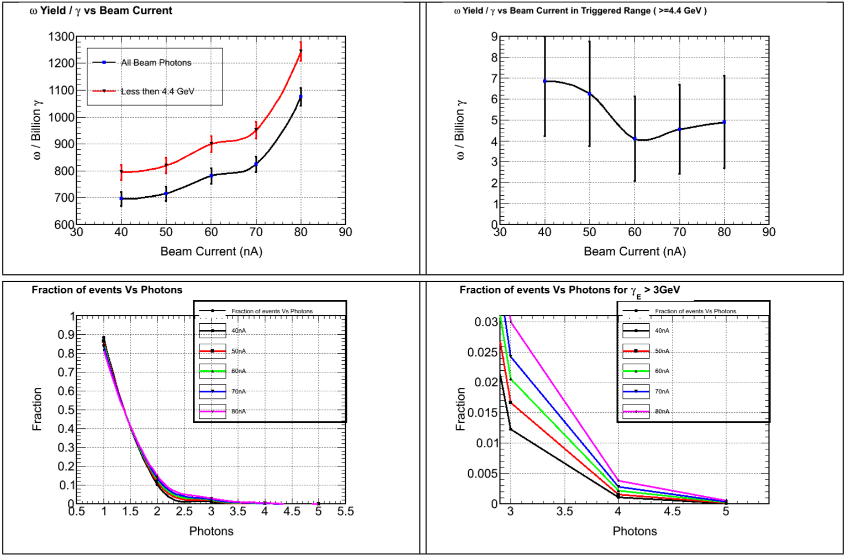
ω - yield fits for $\gamma \geq 4.4$ GeV



ω - yield fits for γ < 4.4 GeV



ω - yield plots



g12 Cross Section Cheat Sheet

Number of Interactions (N_i) $\propto$ Number of Target Particles (N_t)

Number of Interactions (N_i) $\propto$ Number of Beam Photons (N_b)

$\therefore \quad N_i = \sigma * N_t * N_b$

where σ is the Cross-Section/Area or interaction probability

Number of Beam Photons calculated using gflux for Beam Energy Range (A-B) GeV

Number of Target Particles (N_t) = Proton Density of LH2 * Volume of Target

Proton Density = 2 * N_A * Density / Molar Mass
" = $2 * 6.022 * 10^{23} * 0.0708/2.016\ cm^{-3}$
" = $0.423 * 10^{23}\ cm^{-3}$

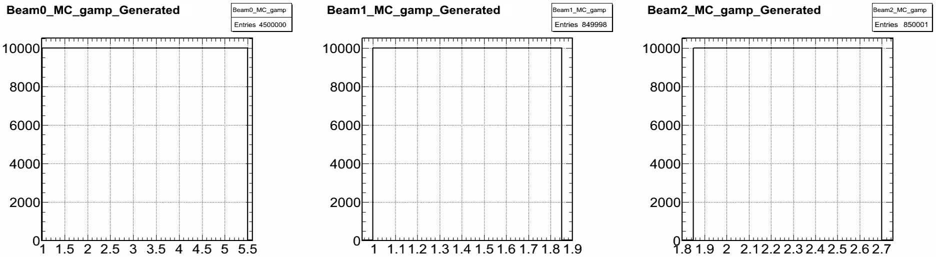
Target Volume = Area * Length = 0.1257 * 40 = 5.0265 cm^3

$$\sigma = \frac{N_E\ w}{2\ N_B\ N_A\ \rho\ L_T} \tag{1}$$

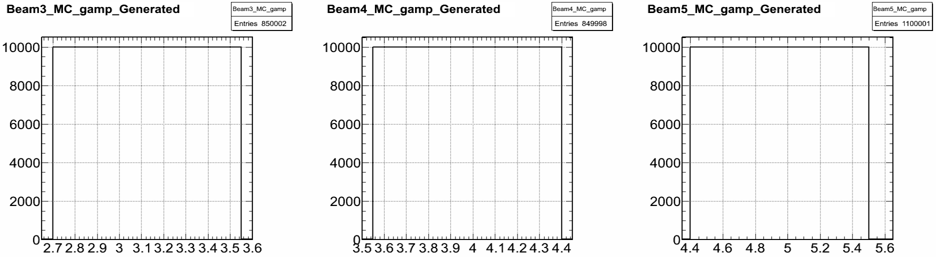
where,

$\rho = 0.0708 gm.cm^{-3}$, $L_T = 40 cm$, $N_B = 5.782 * 10^{11}$,
$N_A = 6.022 * 10^{23}$, $w = 2.016$, $N_E = N_{Events}\ /\ Acceptance.$

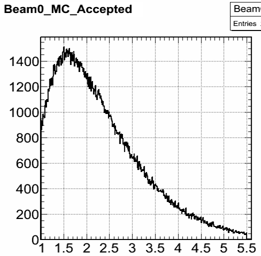
Simulated ρ Events

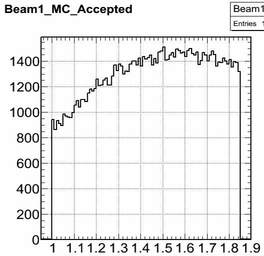


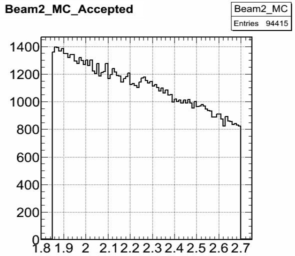
Accepted t-slope $\approx$ 7.1

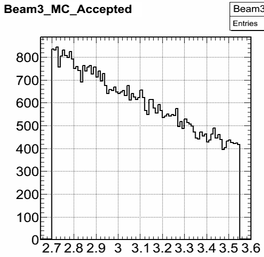


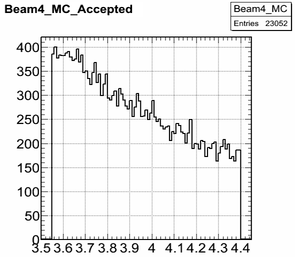
Accepted ρ Events

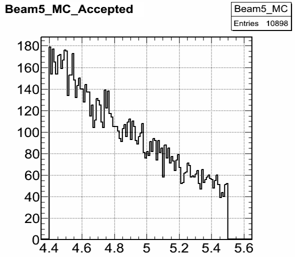




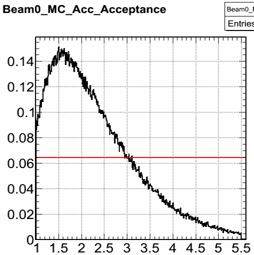


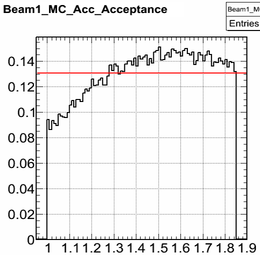


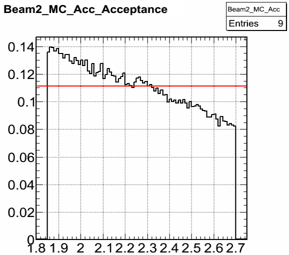


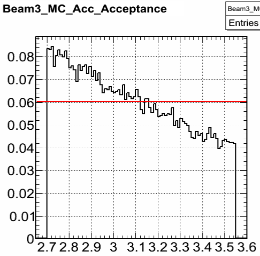


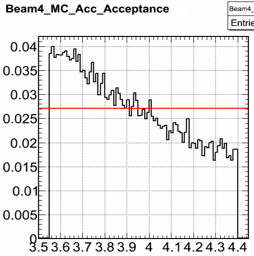
Acceptance for ρ

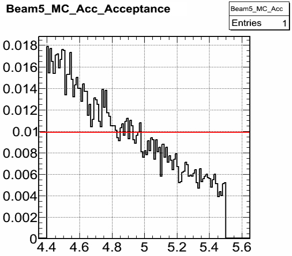




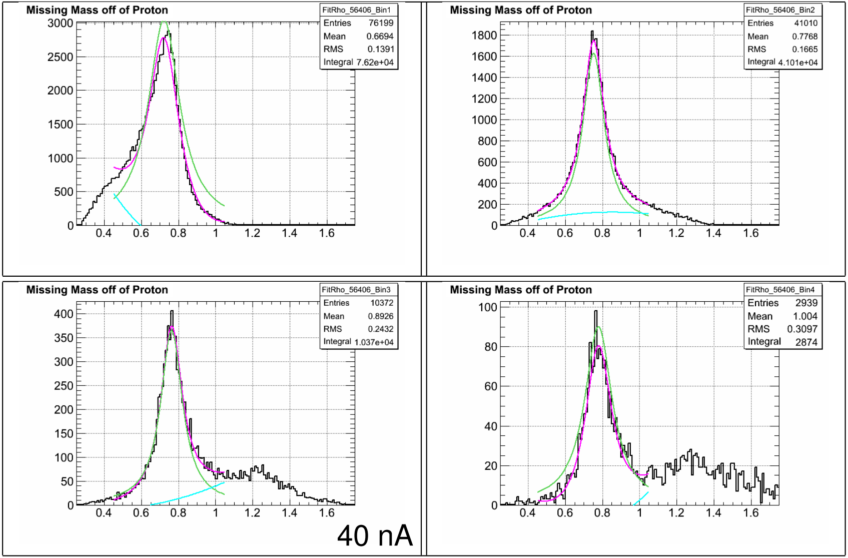




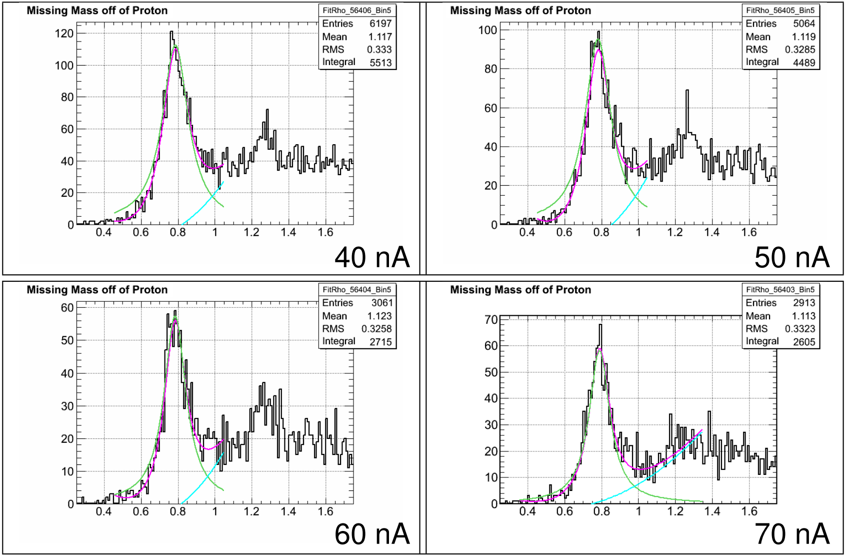




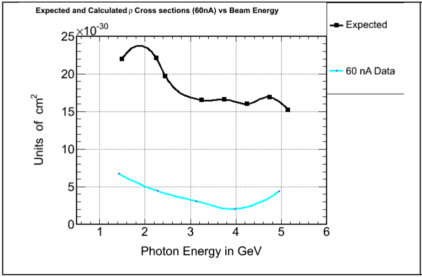
ρ - yield for 40-80 nA Beam Current

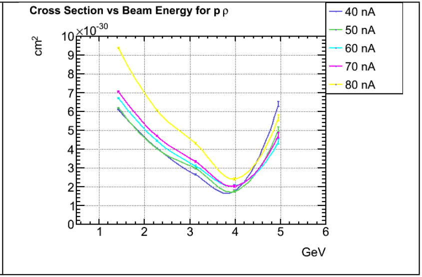


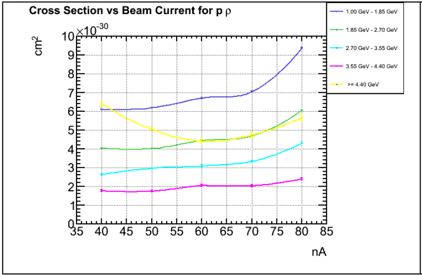
ρ - events in triggered range for 40 - 70 nA

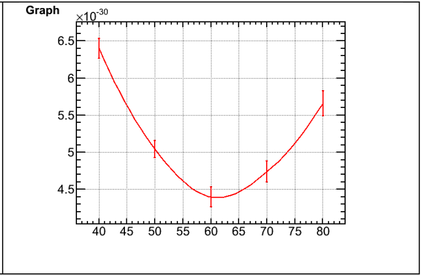


Expected and Calculated ρ Cross Sections

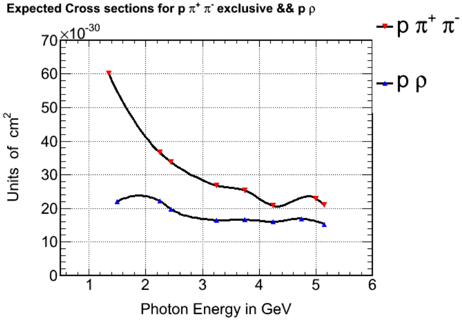


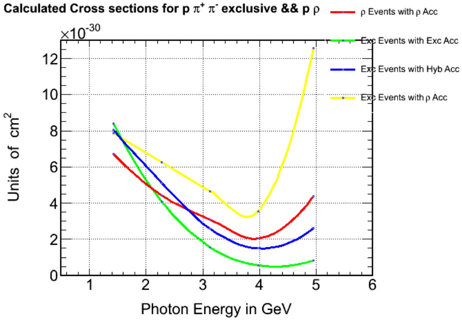






$p\ \pi^+\ \pi^-$ & ρ Cross Section as a function of Beam Energy for 60 nA





Summary for yield analysis

- Unless gflux numbers were off by orders of Magnitude earlier, ***which we have verified they are not***, any gflux fix cannot account for more than 25% difference in Yield/Cross Sections
- Any error in this study related to counting ρ's had erred on the side of over-counting, so the Cross Sections you saw were the most optimistic ones given our anomaly
- Reason for this yield anomaly has to come from the data reconstruction or the MC acceptance or the trigger inefficiency
- The fix made to gflux data for g12 increased the number of good intervals and hence the number of good photons by $\approx$ 20%, and It didn't change the total number of photons
- The new Cross Section values should now be lowered by $\approx$ 20% as the study only took good intervals into account for counting the number of photons and never threw any event out based on such intervals
- The most optimistic Cross Section was obtained for ρ events for which g12 was off by a factor of $\sim$ 3 at low energies and $\sim$ 4 in the triggered energy range for production Beam Current of 60nA

Summary for My analysis

- Complete final skimmed dataset is available for analysis
- We have taken a preliminary look at the preferred signature decay mode for strangeonia
- Moments and PWA analysis for $\phi - \eta$ channel is in progress
- We are trying approaches like side-band subtractions and kinematic fitter to get a better handle on our observations
- Monte Carlo simulations have been done and detector acceptance for different decays are being studied concurrently
- More decay channels for strangeonia like KK^*, K^*K^* and $\phi\,\eta \;\rightarrow\; K^+K^-\pi^+\pi^-[\pi^0]$ are being incorporated
- I have scattered pieces of literature written down and intend to collate them into parts of my thesis
- Finish writing (and more) by the end of this semester