Search For New And Unusual Strangeonia In Photoproduction Using CLAS

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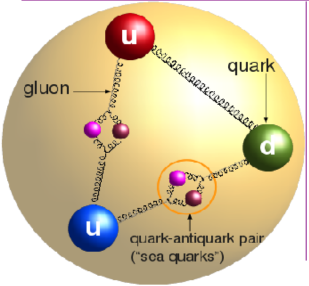
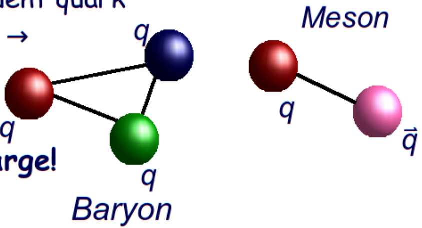
Quantum chromodynamics (QCD) is theory of the strong interaction (color force).

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

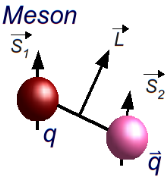
QCD Picture



In constituent quark Model, →



Color charge!



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

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

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

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

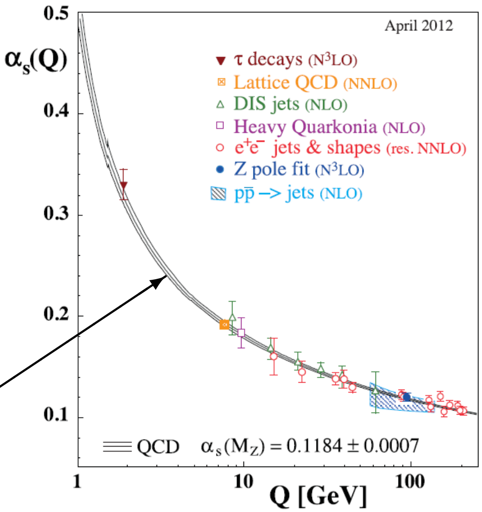
$$\mathrm{J}^{PC}\Big|_{exotic} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots\ .$$

Classify Mesons

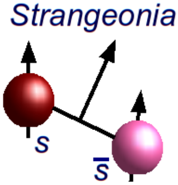
- Physical mesons are the linear superposition of allowed basis states
- Dominance of one of these basis states in this expansion, classifies that state as a quarkonia, exotic, hybrid, glueball, strangeonia ...

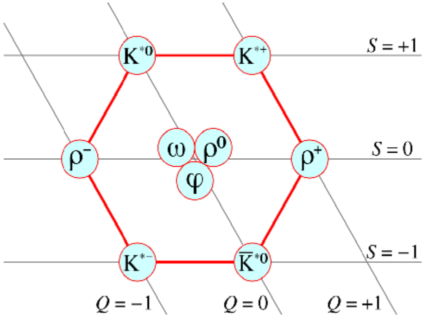
Usual Mesons	EXOTICA			
Quark Model Mesons	Gluonic Hybrids	Tetra-quarks	Glue-Balls	...
$q\bar{q}$	$q\bar{q}g$	$q\bar{q}q\bar{q}$	gg	$\ldots$

- 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



PDG, 2012





√ 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)	?	?

			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

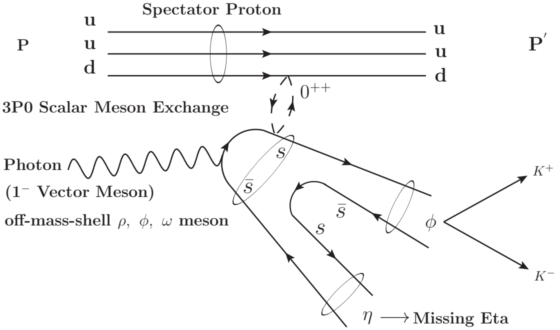
← Radial excitations of (I = 0, $s\bar{s}$) meson.

			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.

Tables from reference:
T. Barnes, N. Black and P. R. Page, Phys. Rev. D 68, 054014 (2003)

- 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).
- Study of diffractive photoproduction reaction $\gamma p \to Xp$, should lead to observation of many C=(-) $s\bar{s}$ states.
- $\phi\eta$ 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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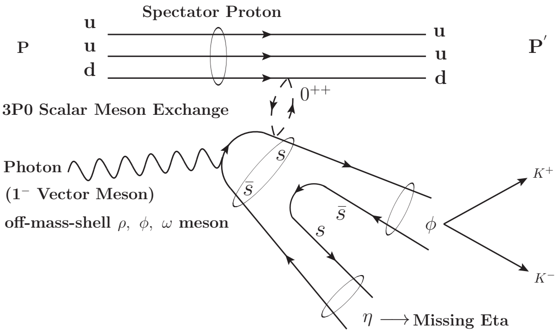

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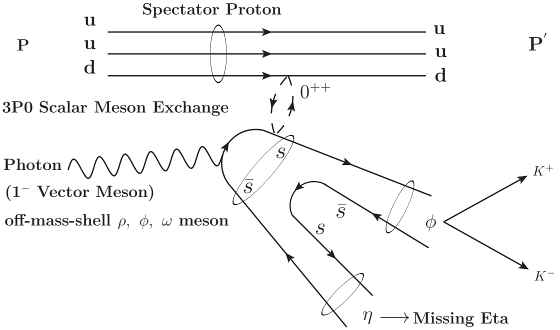

Photoproduction - VMD

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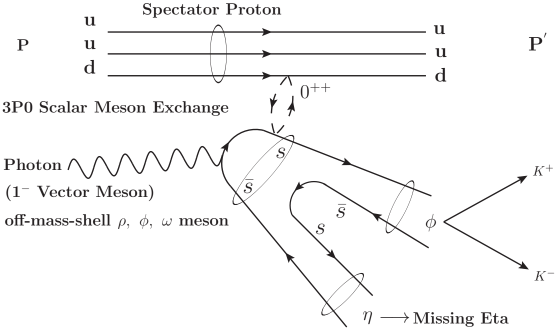


- η has a significant $n\bar{n}$ component to it, but $\phi\eta$ and $\phi\eta'$ decay modes can only originate from initial $s\bar{s}$ states.
- “Due to the *OZI* rule, the observation of a state with a large branching fraction to $\eta\phi$, $\eta'\phi$ or $\phi\phi$ and small branches to nonstrange 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.

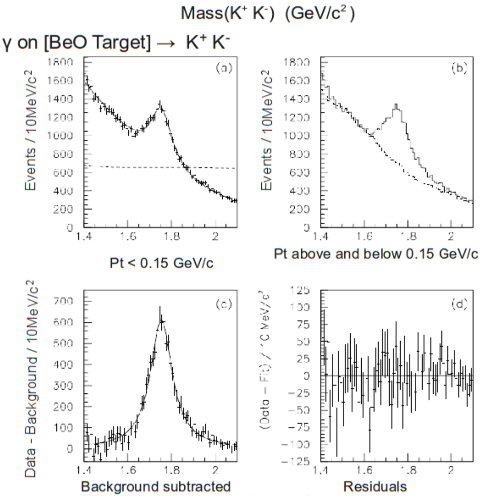


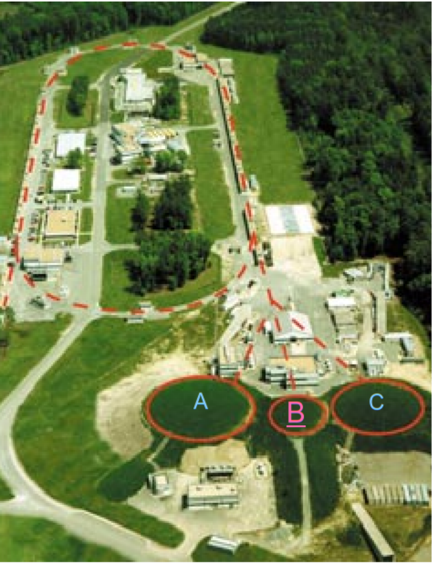
Image from reference:
J. M. Link et al., [FOCUS Collaboration], Phys. Lett. B 545, 50 (2002)

- 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

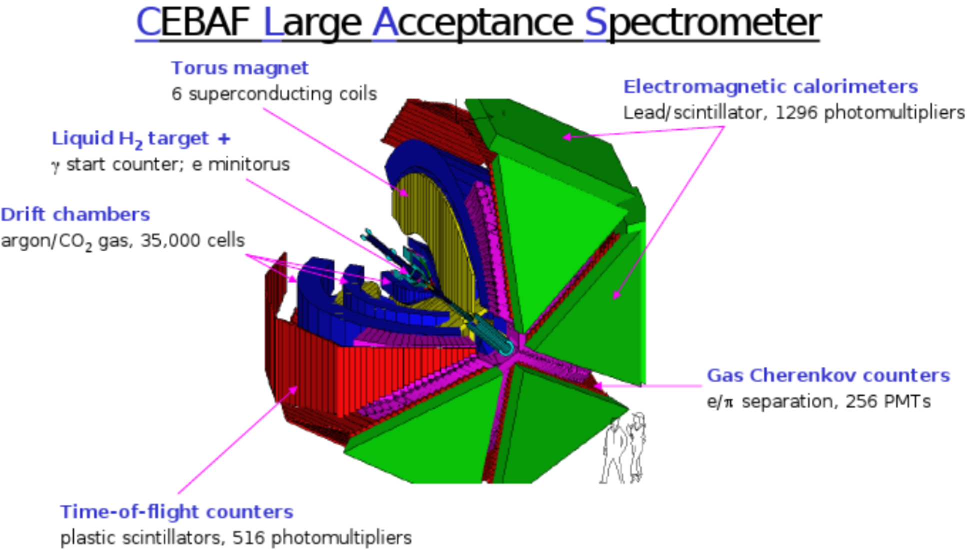
Final State $\gamma + p \rightarrowtail p + \phi + [\eta]$

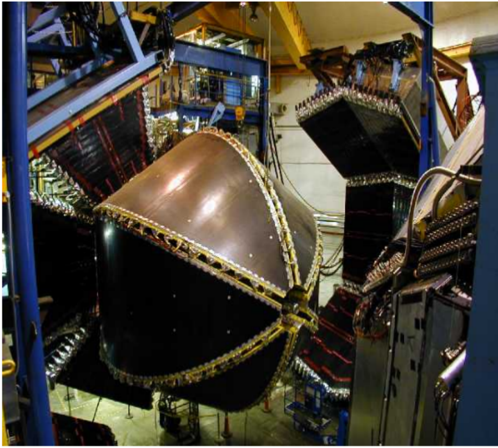
State		Decay Width Theory MeV/c^2	Decay Width Expt. MeV/c^2
$\phi(1680)$	2S	$\Gamma_{theory} = 378$ $\Gamma_{\phi\eta} = 44$	$\Gamma_{expt} = 150 \pm 50$
$\phi(2050)$	3S	$\Gamma_{theory} = 378$ $\Gamma_{\phi\eta} = 21$	Γ_{expt} = unknown
$h_1(1850)$	2P	$\Gamma_{theory} = 193$ $\Gamma_{\phi\eta} = 33$	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
$h_3(2200)$	1F	$\Gamma_{theory} = 249$ $\Gamma_{\phi\eta} = 5$	Γ_{expt} = unknown

Theoretical predictions for the strangeonium states expected to be observed in the $\phi\ \eta$ invariant mass distribution from the reference - T. Barnes, N. Black and P. R. Page, Phys. Rev. D 68, 054014 (2003).



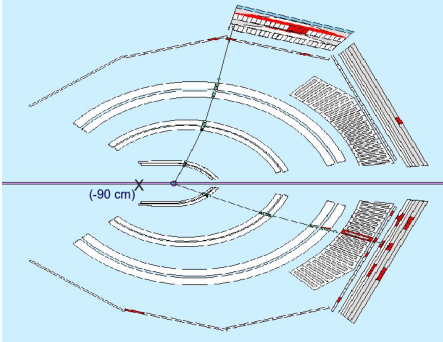
- **CEBAF**:
  Continuous **E**lectron **B**eam **A**ccelerator **F**acility,
  hosted at
  Thomas Jefferson National Accelerator Facility,
  Newport News, Virginia
- CEBAF delivers e^- beams to the 3 Halls, polarised upon request in 5 passes with e^- Energies up-to 6 GeV (1.2 x 5)
- Hall-B is the smallest 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

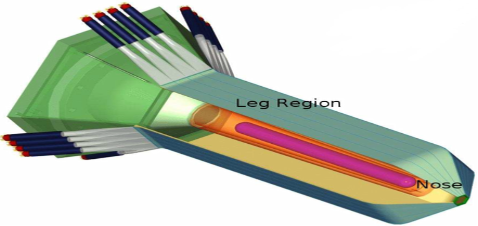

CEBAF Large Acceptance Spectrometer
Torus magnet
6 superconducting coils
Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers
Liquid H2 target +
γ start counter; e minitorus
Drift chambers
argon/CO2 gas, 35,000 cells
Gas Cherenkov counters
e/π separation, 256 PMTs
Time-of-flight counters
plastic scintillators, 516 photomultipliers



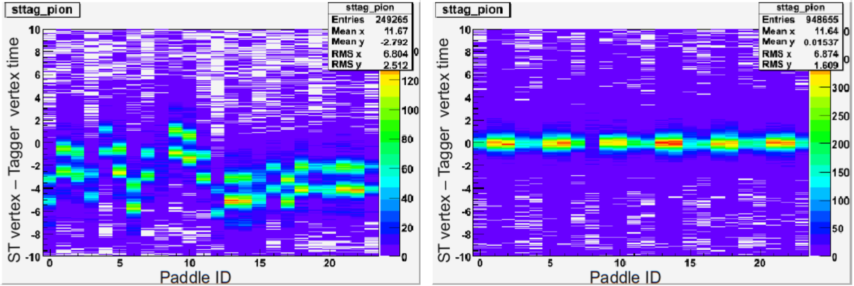
- Skeletal superconducting Toroidal Magnets for CLAS.
- CLAS detector during assembly.

- 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

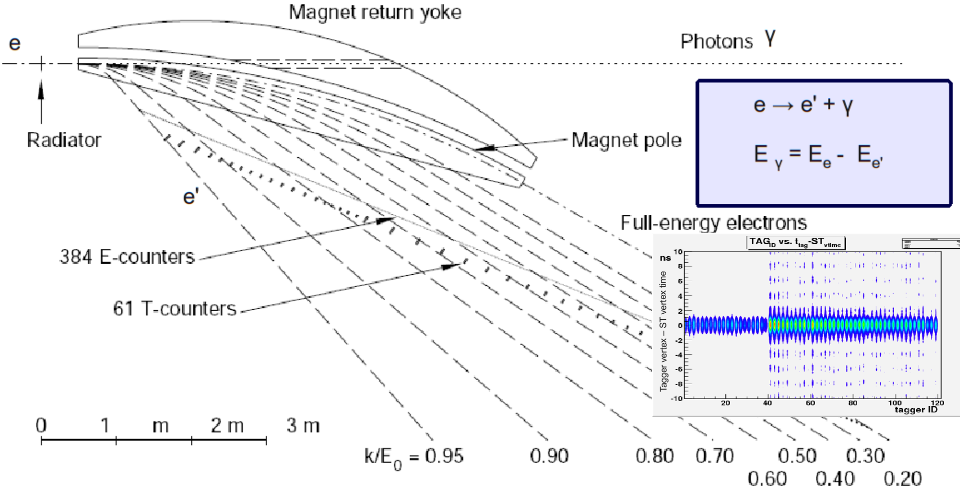




- Incorporates the independent sector based tracking of CLAS
- g12 pulled ST 90cm back from the center of CLAS to increase acceptance for low t, forward going particles
- ST crucial for picking the right photon and Particle ID



(a) Before (b) After



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

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

Fig. 23. Hall B photon-tagging system.

$$\gamma \; + \; p \; \rightarrowtail \; p \; + \; \phi \; + \; [\eta]$$

- Select 3 charged tracks identified as - *Proton*, K^+, K^-
- Apply Energy-Momentum conservation to all the known four-vectors
- Calculate the missing mass four-vector and hence the invariant mass of the missing particle
- Select - η - in this missing mass distribution
- Add four-vectors for K^+K^- to get their invariant mass and hence identify the - ϕ - meson
- Reconstruct the invariant mass for ($\phi\eta$) using the above selected ϕ & η mesons

Particle Identification

PART Bank

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

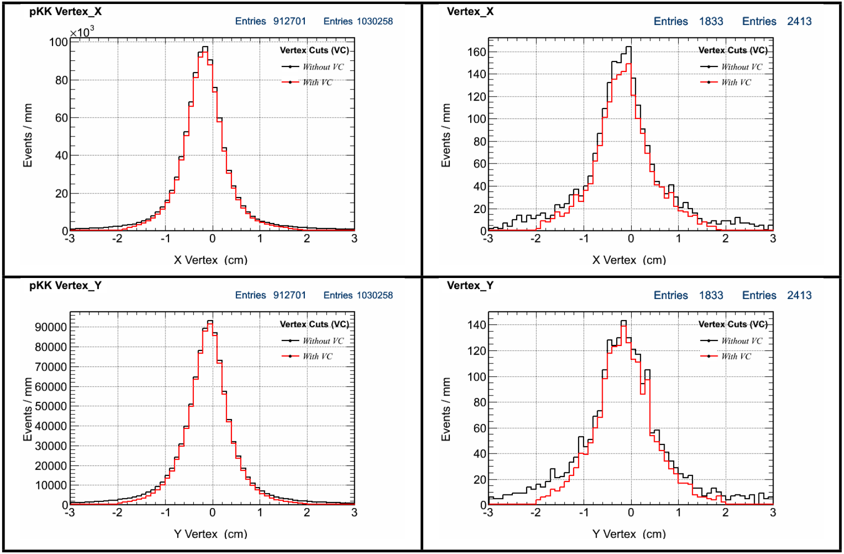
Meson ID

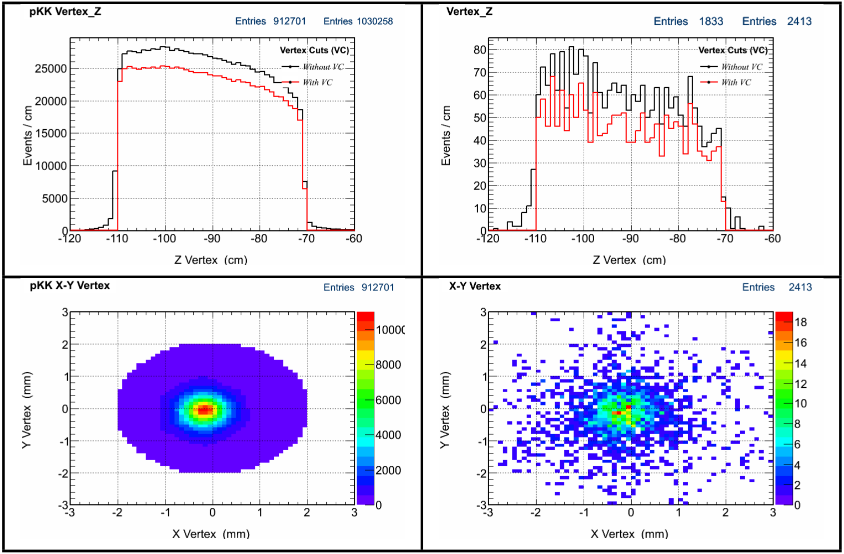
- ϕ – Invariant Mass reconstructed from K^+ & K^-
- To Identify ϕ, Select $1010\text{ MeV} \leq \text{IM}(K^+\,K^-) \leq 1030\text{ MeV}$
- η – Calculated from Missing Mass as "$Beam + Target - Proton - K^+ - K^-$"
- To identify η, Select $510\text{ MeV} \leq \text{MM} \leq 580\text{ MeV}$

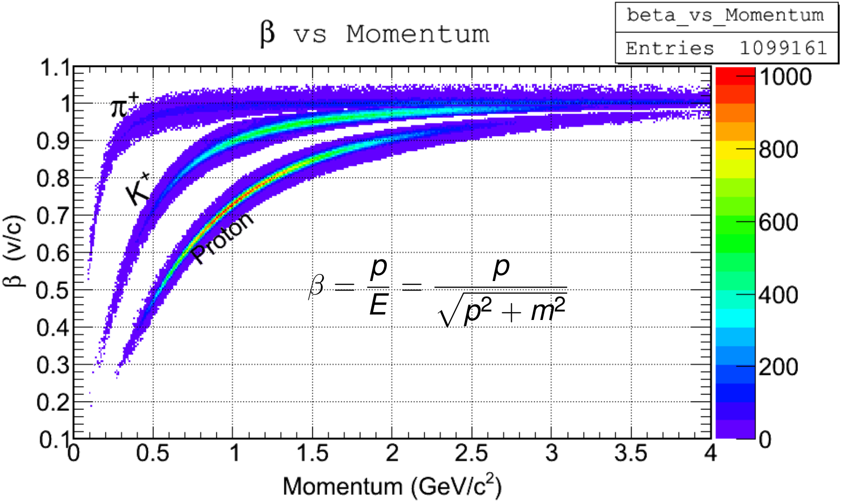
Cuts

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

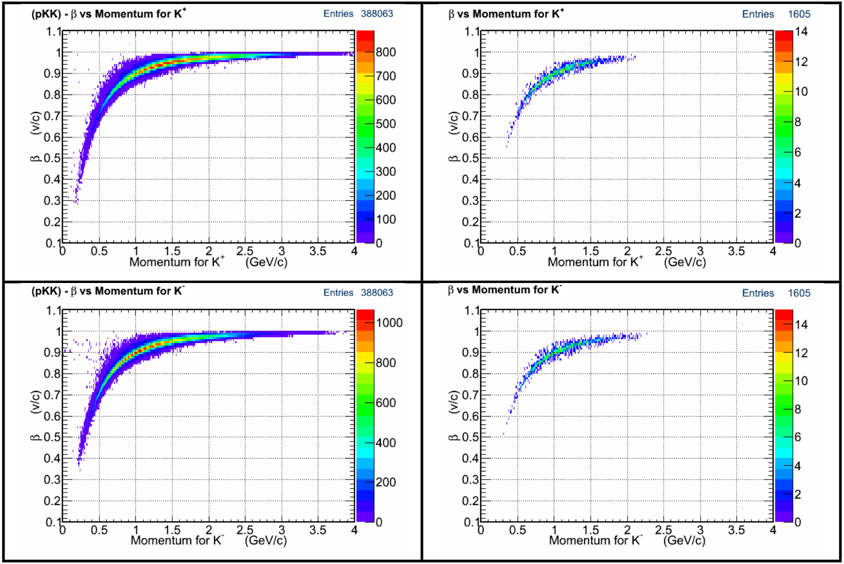
Particle Vertex 1

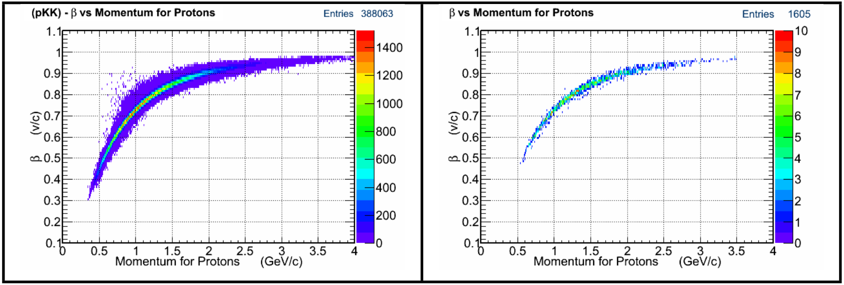



pKK Vertex_Z
Entries 912701
Entries 1030258
Vertex Cuts (VC)
Without VC
With VC
Events / cm
Z Vertex (cm)
Vertex_Z
Entries 1833
Entries 2413
Vertex Cuts (VC)
Without VC
With VC
Events / cm
Z Vertex (cm)
pKK X-Y Vertex
Entries 912701
Y Vertex (mm)
X Vertex (mm)
X-Y Vertex
Entries 2413
Y Vertex (mm)
X Vertex (mm)


β vs Momentum
beta_vs_Momentum
Entries 1099161
β (v/c)
Momentum (GeV/c²)
π⁺
K⁺
Proton
$\beta = \frac{p}{E} = \frac{p}{\sqrt{p^2 + m^2}}$
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.5
1
1.5
2
2.5
3
3.5
4
1000
800
600
400
200
0

β Vs Momentum Distributions





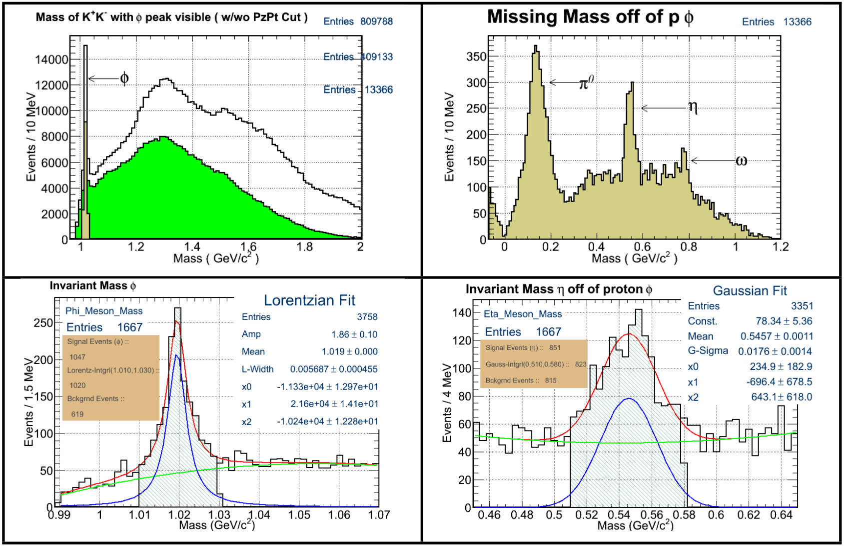
Observations

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

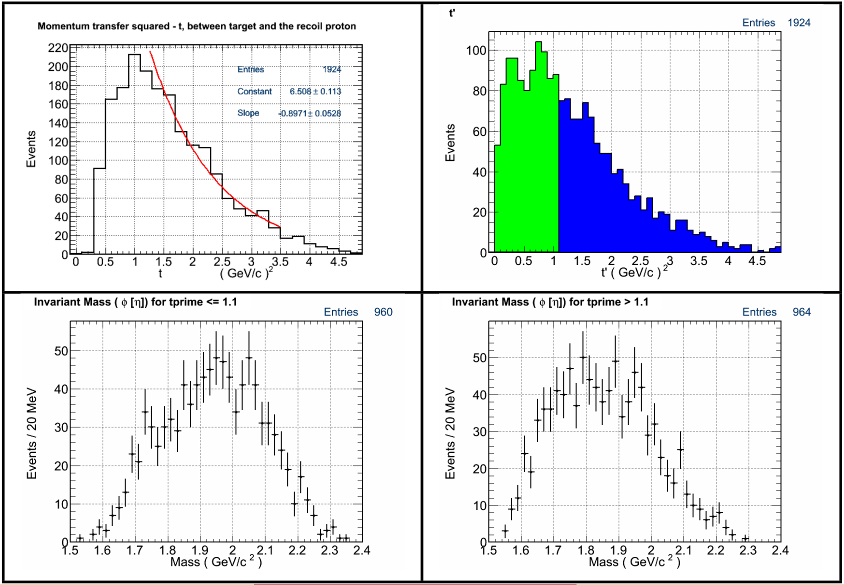
$$\gamma \; + \; \textit{proton} \; \rightarrowtail \; \textit{proton} \; + \; \phi \; + \; \eta$$

$$\gamma \; + \; \textit{proton} \; \rightarrowtail \; \textit{proton} \; + \; K^{+} \; + \; K^{-} \; + \; [\eta]$$

Selection Plots - $\phi\ \eta$

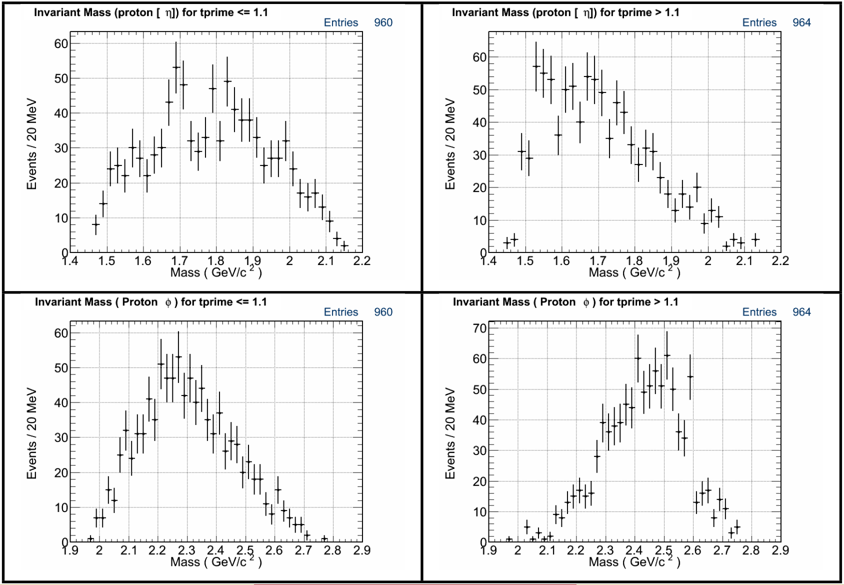


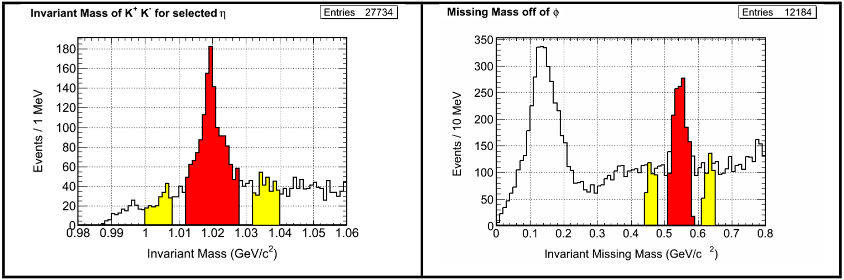
$$\text{Mandelstam's} \quad t \;=\; |\,P^{\mu}_{\gamma} \;-\; P^{\mu}_{X}\,|^{2} \;=\; |\,P^{\mu}_{\text{target}} \;-\; P^{\mu}_{\text{recoil}}\,|^{2}$$



Selection Based On Kinematics

$$t' = t - t_{min}, \text{ where } t_{min} = \text{Excess Momentum Transfer Squared}$$
$$\text{Over The Minimum Required For Resonance Production}$$



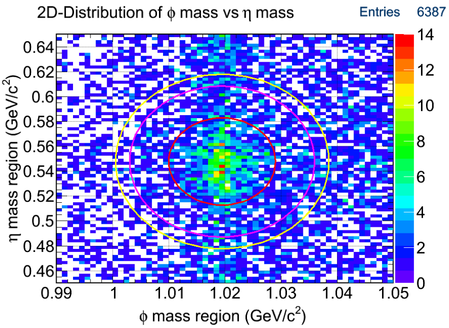


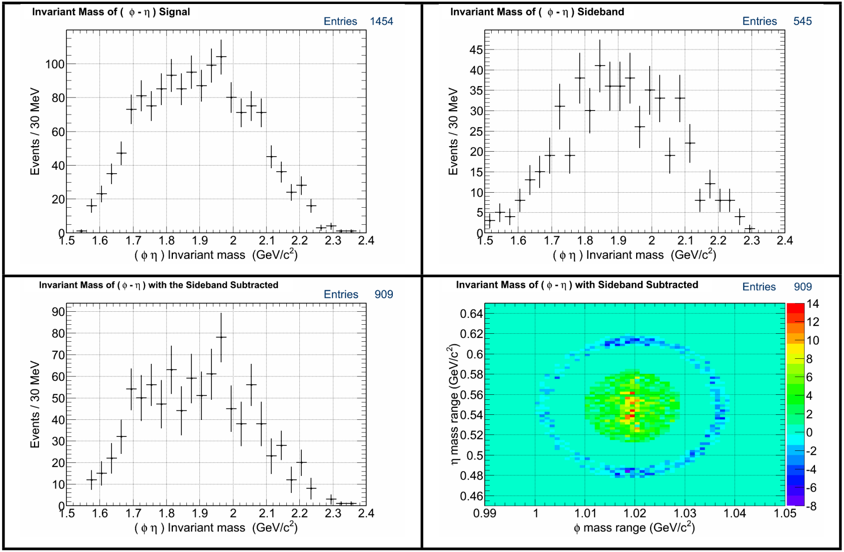
Side-Band Observations:

- 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.

$$\left(\frac{x - \phi_{mass}}{\frac{\phi \quad mass \quad range}{2}}\right)^2 + \left(\frac{y - \eta_{mass}}{\frac{\eta \quad mass \quad range}{2}}\right)^2 = 1$$

ϕ mass	1.0195 GeV/c^2
ϕ mass range selected	0.0019 GeV/c^2
ϕ sideband mass gap selected	$\sqrt{3}\times$ 0.0019 GeV/c^2
ϕ sideband mass range selected	$2\times$ 0.0019 GeV/c^2
η mass	0.5478 GeV/c^2
η mass range selected	0.070 GeV/c^2
η sideband mass gap selected	$\sqrt{3}\times$ 0.070 GeV/c^2
η sideband mass range selected	$2\times$ 0.070 GeV/c^2





Invariant Mass of (φ - η) Signal
Entries 1454
Events / 30 MeV
(φ η) Invariant mass (GeV/c²)
Invariant Mass of (φ - η) Sideband
Entries 545
Events / 30 MeV
(φ η) Invariant mass (GeV/c²)
Invariant Mass of (φ - η) with the Sideband Subtracted
Entries 909
Events / 30 MeV
(φ η) Invariant mass (GeV/c²)
Invariant Mass of (φ - η) with Sideband Subtracted
Entries 909
η mass range (GeV/c²)
φ mass range (GeV/c²)

$$\frac{N_{target}}{V} = 2 \times N_{avogadro} \times \frac{\rho_{target}}{A_{H_2}}$$

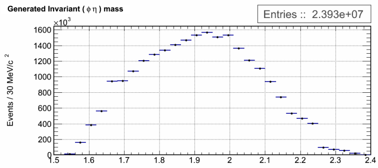
$$\frac{N_{observed}}{Acceptance} = \sigma \times N_{incident} \times N_{target}$$

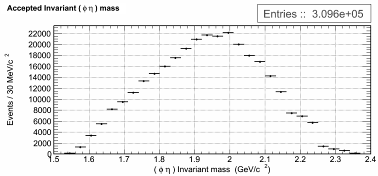
$$\sigma = \frac{N_{observed} \times A_{H_2}}{2 \times N_{incident} \times N_{avogadro} \times \rho_{target} \times L_{target} \times Acceptance}$$

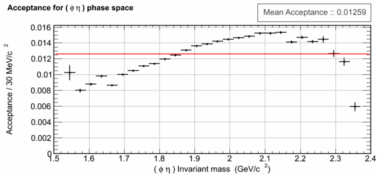
where,

N_{target}	is	the number of target protons that on average lie in the path of the incoming beam photons,
$N_{observed}$	is	the number of observed events in the experiment, aka the yield,
ρ_{target}	is	the density of the LH_2 used in the experiment,
$N_{incident}$	is	the integrated flux (total number) of the incoming beam photons that were incident on the target to achieve the observed yield,
L_{target}	is	the length of the target cell,
Acceptance	is	derived from the simulations of the reaction phase space for the experiment and represents the corrections due to the finite acceptance of the detector.

Cross Section

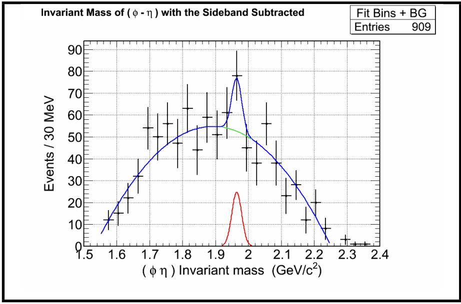


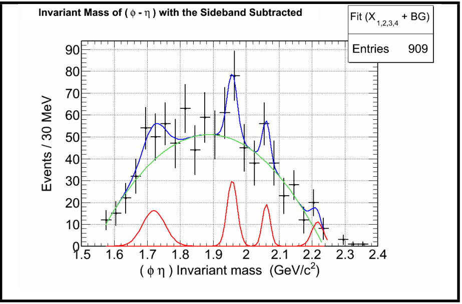




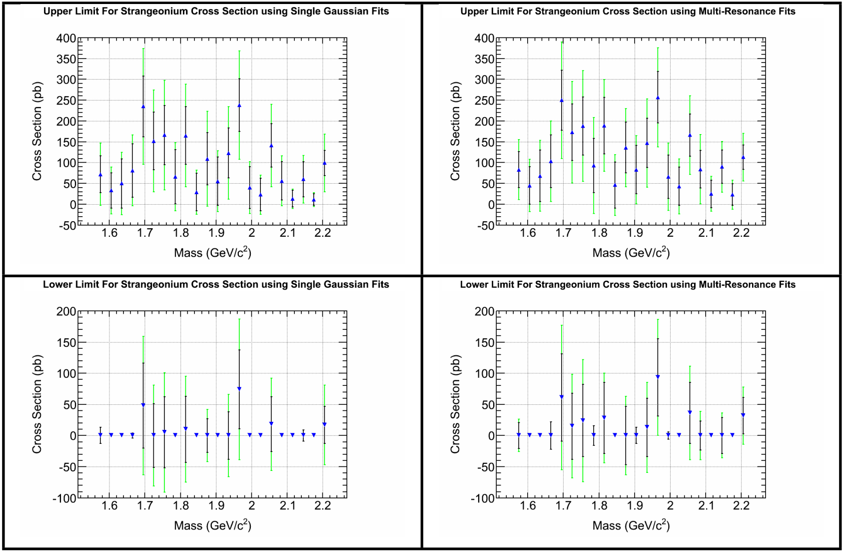
Yield of $\phi\ \eta$ events	909
Detector Corrected Yield of $\phi\ \eta$ events	1303
Scale factor for the branching ratio	2.0619 (48.5%)
Branching Ratio Corrected Yield of $\phi\ \eta$ events	2686
E_γ Flux	2.1781×10^{13}
Generated phase space MC Events	23930000
Accepted MC Events	309650
Overall phase space MC ($\phi\ \eta$) Acceptance	1.259%
ρ_{target}	$0.0708\ \frac{gm}{cm^3}$
A_{H_2}	2.016
$N_{Avogadro}$	6.022×10^{23}
L_{target}	40 cm
$\sigma_{X \to \phi\eta}$	4.04 nano-barns
Corrected $\sigma_{X \to \phi\eta}$	5.79 nano-barns
Statistical error on $\sigma_{X \to \phi\eta}$	0.287 nano-barns
Systematic error on $\sigma_{X \to \phi\eta}$	1.158 nano-barns

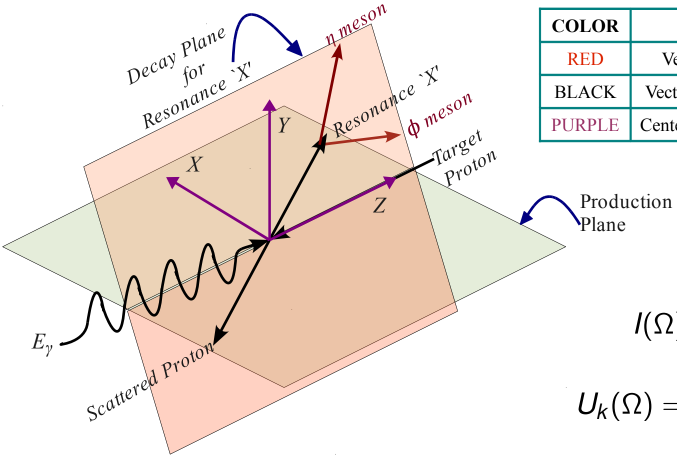
- Establishing discovery requires rejecting the background only hypothesis
- Particle Phyics Experiments - 3σ signal significance $\rightarrowtail$ evidence, 5σ signal significance $\rightarrowtail$ discovery
- FeldmanCousins method - a frequentist approach - use relative frequency of an event - Perform multiple experiments and number of positive results determines probability of that result
- It uses only the observed number of events and the estimated background count to calculate the confidence limits
- The fixed-unknown-true value of the cross section being measured will lie within the confidence interval in 90% of the repeats of the same experiment.





Strangeonium Cross Section Confidence Limits





COLOR	ATTRIBUTE
RED	Vectors In Decay Plane
BLACK	Vectors In Production Plane
PURPLE	Center of Mass Frame's Axes

$$I(\Omega) = \sum_k \left| U_k(\Omega) \right|^2$$

$$U_k(\Omega) = \sum_{lm} V_{lmk} A_{lm}(\Omega)$$

$$A_{lm}(\Omega) = \sqrt{\frac{2l+1}{4\pi}} D^{l}_{m0}{}^{*}(\phi, \theta, 0) = Y^m_l(\Omega)$$

$$\hat{\epsilon} = \hat{P} e^{i\pi J_y}$$

$$|\bar{p}\epsilon PJM\rangle = \theta(m)\ \{\ |\bar{p}PJM\rangle + \epsilon P(-1)^{J\text{-}M}\ |\bar{p}PJ - M\rangle\ \}$$

where,

$$\theta(m) = \frac{1}{\sqrt{2}} \textit{ for } m > 0\ ;\quad \theta(m) = \frac{1}{2} \textit{ for } m = 0;$$
$$\theta(m) = 0 \quad \textit{for } m < 0.$$

Reflectivity (ϵ) / Naturality (N) for a particle, in this case, by definition is:

$$\epsilon = N = P(-1^J)$$

hence the following holds true,

$$\text{Natural parity exchange } \epsilon = 1; \qquad J^P = 0^+, 1^-, 2^+, \ldots$$
$$\text{Unnatural parity exchange } \epsilon = \text{-}1; \qquad J^P = 0^-, 1^+, 2^-, \ldots$$

As an added advantage, states of different reflectivities / naturalities do not interfere.

$$^{\epsilon}U_k(\Omega) = \sum_{lm} {}_{\epsilon}V_{lmk} \sqrt{\frac{2l+1}{4\pi}}\ {}^{\epsilon}D^{l}_{m0}{}^{*}(\phi,\theta,0)$$

$$I(\Omega) = \sum_{\epsilon k} \left|{}^{\epsilon}U_k(\Omega)\right|^2 = \left|{}^{+}U_1(\Omega)\right|^2 + \left|{}^{-}U_1(\Omega)\right|^2 + \left|{}^{+}U_2(\Omega)\right|^2 + \left|{}^{-}U_2(\Omega)\right|^2$$

$$\mathcal{M} = \sum_{\alpha,\phi} \underbrace{\langle K^+K^-\ \eta\ p|\ \hat{T}_d^{\phi\rightarrow K^+K^-}\ |\phi\ \eta\ p\rangle\ \langle\phi\ \eta\ p|\ \hat{T}_d^{X\rightarrow\phi\eta}\ |X_\alpha\ p\rangle}_{Decay-A_\alpha(\tau)} \underbrace{\langle X_\alpha\ p|\ \hat{T}_p\ |\gamma p\rangle}_{Production-V_\alpha}$$

$$I(\tau) \propto \sum_k \left|\sum_\alpha V_{k\alpha}A_\alpha(\tau)\right|^2$$

$$\alpha\ \forall\ \{J, P, C, M, L, l, (w, \Gamma)\}$$

where,

J	=	Total angular momentum of resonance ‘X’
P	=	Parity of the resonance ‘X’
C	=	Charge conjugation parity for the resonance ‘X’
M	=	Z-projection of the total angular momentum
L	=	Angular momentum between the ϕ and the η meson
l	=	Angular momentum between the decay products of ϕ
(w, Γ)	=	Mass and width parameter for the Breit-Wigner

$$\mathcal{L} \propto \left[\frac{\bar{n}^n}{n!}e^{-n}\right]\prod_i^n\left[\frac{I(\tau_i)}{\int I(\tau)\eta(\tau)pqd\tau}\right]$$

$$\bar{n} \propto \int I(\tau)\eta(\tau)pq(d\tau)$$

$$\begin{aligned} ln\mathcal{L} &\propto \sum_i^n ln(I(\tau_i)) - \int I(\tau)\eta(\tau)pqd\tau \\ &\propto \sum_{k\epsilon\alpha\alpha'} ln(\ {}^\epsilon V_{\alpha k}\ {}^\epsilon V^*_{\alpha' k}\ {}^\epsilon A_\alpha(\tau_i)\ {}^\epsilon A^*_{\alpha'}(\tau_i)) - \eta_X(\sum_{k\epsilon\alpha\alpha'}\ {}^\epsilon V_{\alpha k}\ {}^\epsilon V^*_{\alpha' k}\ {}^\epsilon\psi^a_{\alpha\alpha'}) \end{aligned}$$

$$\eta_X = \frac{\text{MC Events Accepted}}{\text{Raw MC Events Generated}}$$

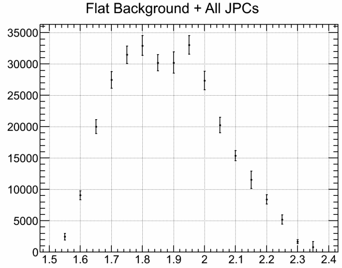
$${}^\epsilon\psi^a_{\alpha\alpha'} = \frac{1}{N_a}\sum_i^{N_a}\ {}^\epsilon A_\alpha(\tau_i)\ {}^\epsilon A^*_{\alpha'}(\tau_i)$$

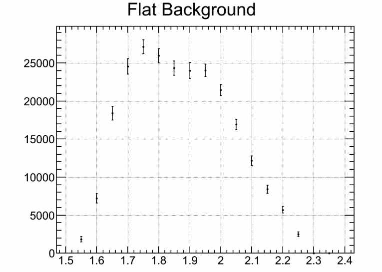
$$N = \sum_{k\epsilon\alpha\alpha'}\ {}^\epsilon V_{\alpha k}\ {}^\epsilon V^*_{\alpha' k}\ {}^\epsilon\psi^r_{\alpha\alpha'}$$

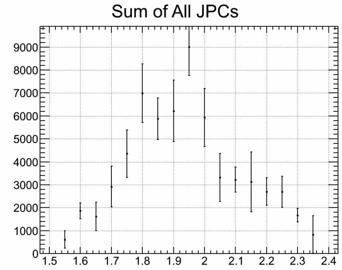
where,

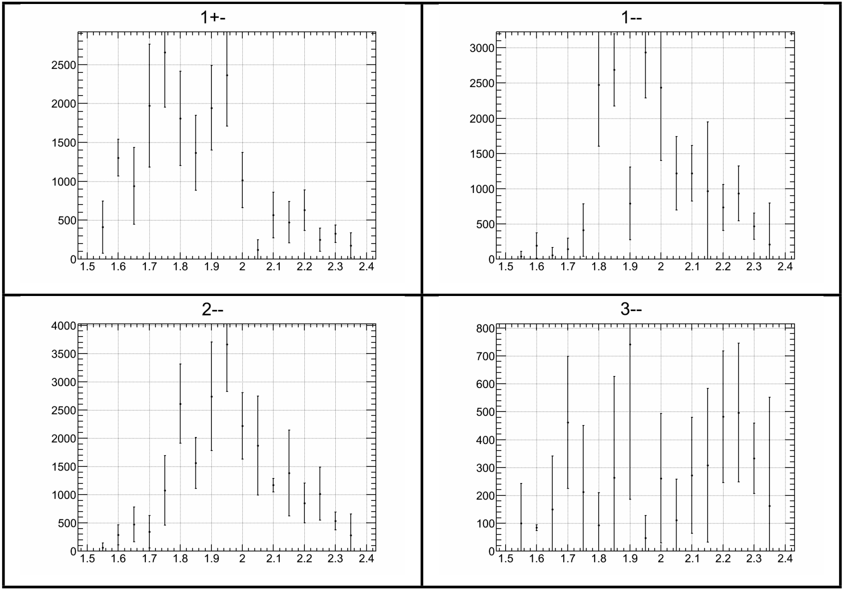
$\mathcal{L}$	*is*	the likelihood function,
n	*is*	the number of events observed,
$\bar{n}$	*is*	the average number of events observed if the experiment was ran multiple times,
$\eta(\tau)$	*is*	the finite experimental acceptance as determined by the Monte Carlo simulations,
$pqd\tau$	*is*	the lorentz invariant phase space element for the involved kinematics,
${}^\epsilon\psi^a_{\alpha\alpha'}$	*is*	the normalization integral calculated from phase space MC simulation for N_a accepted events.

+ve Helicity	-ve Helicity
$1+-1+D$	$1+-1-D$
$1--1+P$	$1--1-P$
$1+-1+S$	$1+-1-S$
$2--1+F$	$2--1-F$
$2--1+P$	$2--1-P$
$3--1+F$	$3--1-F$








1+-
0
500
1000
1500
2000
2500
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
2.3
2.4
1--
0
500
1000
1500
2000
2500
3000
2--
0
500
1000
1500
2000
2500
3000
3500
4000
3--
0
100
200
300
400
500
600
700
800