Differential cross sections and spin density matrix elements for $\gamma p \rightarrow \phi p$ from CLAS

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Outline

1. Introduction and Event Selection

2. Signal-background separation

3. Acceptance Calculation and $d\sigma/d\cos\theta_{c.m.}$

4. Spin Density Matrix Elements

5. Summary
OUTLINE

1. Introduction and Event Selection

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Introduction – $\phi(1020)$

- Belongs to the family of ground state vector mesons $V = \rho, \omega, \phi$.

- Almost pure $s\bar{s}$ state – OZI rule suppresses quark/meson exchanges during interaction with nucleons.

- Chief attraction – very “clean” system to study gluonic exchanges; gluonic structure of the Pomeron, for example.

- Around $\sqrt{s} \approx 2.1$ GeV, previous world data (LEPS, SAPHIR) saw a “bump” at $t \rightarrow |t|_{\text{min}}$ (forward-angle). Not expected from Pomeron exchange – interference with $K^+\Lambda(1520)$? Resonance contribution?
**Charged- and Neutral-Mode Topologies**

- \( \phi \) predominantly decays to two kaons. \( \phi \rightarrow K^+K^- \) is the "charged-mode" \((bf = 0.491)\) while \( \phi \rightarrow K^0_SK^0_L \) is the "neutral-mode" \((bf = 0.34)\).

- **Charged-mode**: kinematic fit to \( \gamma p \rightarrow \phi p \rightarrow K^+(K^-)p \).

- **Neutral-mode**: kinematic fit to \( \gamma p \rightarrow \phi p \rightarrow K^0_SK^0_Lp \rightarrow \pi^+\pi^-(K^0_L)p \)

- Event selection: 10% confidence level cut from kinematic fit, timing cuts for particle-identification.

- \( K^0_S \) selection cut (neutral-mode): \( 0.488 \text{ GeV} \leq M(\pi^+, \pi^-) \leq 0.508 \text{ GeV} \).
CHARGED-MODE AND $\phi p - K^{+}\Lambda(1520)$ OVERLAP

- Overlap with $\gamma p \rightarrow K^{+}\Lambda(1520) \rightarrow K^{+}K^{-}p$ between 2 and 2.2 GeV.

- Only for the charged-mode, therefore, need for the neutral-mode.
1 Introduction and Event Selection

2 Signal-background separation

3 Acceptance Calculation and \( \frac{d\sigma}{d \cos \theta_{c.m.}} \)

4 Spin Density Matrix Elements

5 Summary
Signal-background separation

**General set-up**

- Since the $\phi$ mass is so close to the $KK$ threshold, very few events on the low mass side. Therefore, side-band subtraction is difficult to perform.

- Previous analyses often used background “template shapes” ($\Lambda(1520)$, $f_0(980)$, $KK$ phase-space, etc.), but the scales of these “templates” were not constrained by any physics.

- **Our method:**
  - Use the mass-dependent Breit-Wigner width for the $\phi$ lineshape in the Voigtian signal function.
  - Background level shape/scale depends on location in phase-space, therefore perform individual background fits in localized regions of phase space.
  - Final output is a quality-factor (Q-value) for each event – probability of the event being a good signal (ref: arXiv:0809.2548). Much better/easier control over systematics.
**Charged-mode: \(K^+\Lambda(1520)\) cut**

- After all cuts and background removal, a \(M(p, K^-) = 1.52\) GeV “band” still visible, especially in mid-angles. Shown for \(2.08 \text{ GeV} \leq \sqrt{s} \leq 2.12\) GeV below:

- \(\phi p\) and \(K^+\Lambda(1520)\) seems to be somewhat strongly correlated in phase-space.

- Apply \(|M(p, K^-) - 1.52\) GeV\| \(\leq 15\) MeV cut for \(\Lambda(1520)\) removal.
**CHARGED-MODE: FINAL RESULTS**

- $\sqrt{s} = 2.095$ GeV
  - $\cos \theta_{c.m.} < -0.33$
  - $|\cos \theta_{c.m.}| < 0.33$
  - $\cos \theta_{c.m.} > 0.33$

- $\sqrt{s} = 2.355$ GeV
  - $\cos \theta_{c.m.} < -0.33$
  - $|\cos \theta_{c.m.}| < 0.33$
  - $\cos \theta_{c.m.} > 0.33$

- $\sqrt{s} = 2.695$ GeV
  - $\cos \theta_{c.m.} < -0.33$
  - $|\cos \theta_{c.m.}| < 0.33$
  - $\cos \theta_{c.m.} > 0.33$
NEUTRAL-MODE: FINAL RESULTS

- $\sqrt{s} = 2.105$ GeV

- $\sqrt{s} = 2.405$ GeV

- $\sqrt{s} = 2.645$ GeV
Final $\phi$ data yields and binning

- Charged-mode: $\sim 0.475$ million $\phi$ events. $\sqrt{s} = 10$-MeV-wide energy bins.

- Neutral-mode: $\sim 0.101$ million $\phi$ events. $\sqrt{s} \approx 30$-MeV-wide energy bins.

- Angular binning is always 0.1 in the center-of-mass production angle, $\cos \theta_{c.m.}$. 
Acceptance Calculation and $d\sigma / d\cos\theta^\Phi_{c.m.}$

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Acceptance Calculation

100 million flat phase-space “Raw” Monte Carlo events generated for each topology and passed thru GSIM to give a set of “Accepted” (Acc) Monte Carlo events.

Acc. MC underwent same set of analysis cuts as actual Data.

Expand the scattering amplitude using a large number (almost complete basis) of s-channel $J^P$ waves:

$$\mathcal{M}(\sqrt{s}, \cos \theta_{c.m.}) \sim \sum_{J^P} a^{J^P}_{MP,LS} A^{\gamma p \rightarrow J^P \rightarrow \phi p, MP, LS}(\sqrt{s}, \cos \theta_{c.m.})$$

Perform a unbinned extended maximum likelihood partial-wave analysis (PWA) fit independently in each $\sqrt{s}$-bin (see PRC 80, 065208 (2009) for more details).
Sample fit quality check

Charged-mode, center-of-mass production-angle:

\[ \sqrt{s} = 2.155 \text{ GeV} \]

- PWA-fit weighted Monte Carlo matched the Data in all distributions for both modes.
Acceptance Calculation and $d\sigma / d\cos\theta_{c.m.}$

Acceptance from PWA-fit results

- PWA-fit-weighted acceptance is: $\eta_{wtd.} = \left( \sum_{i}^{N_{acc}} I_i \right) / \left( \sum_{j}^{N_{raw}} I_j \right)$ where

$$I_i = \sum_{m_{coh.}} \sum_{m_{incoh.}} |M_{m_{coh.},m_{incoh.}}|^2.$$ 

- Note that this PWA-fit result is not to be interpreted as physics (in terms of resonances). We have simply expanded the production amplitude in a semi-complete basis of $s$-channel $J^P$ waves in order to best fit the data.

- Applied in previous CLAS $\omega p$ (PRC 80, 06528 (2009)), $\eta p/\eta' p$ (PRC 80, 045213, (2009)), $K^+\Lambda$ (PRC 81, 025201 (2010)) and $K^+\Sigma^0$ (PRC 82, 025202 (2010)) analyses, with excellent results.
Acceptance Calculation and $d\sigma/d\cos\theta^\phi_{\text{c.m.}}$

**Differential cross sections**

Backward-angles

- $-0.55 < \cos\theta^\phi_{\text{c.m.}} < -0.45$

![Graph](attachment:image.png)

- ○ Charged-mode
- ▲ Neutral-mode

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (GeV)</th>
<th>2</th>
<th>2.1</th>
<th>2.2</th>
<th>2.3</th>
<th>2.4</th>
<th>2.5</th>
<th>2.6</th>
<th>2.7</th>
<th>2.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d\sigma/dt$ (µb/GeV$^2$)</td>
<td>0.3</td>
<td>0.2</td>
<td>0.1</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Differential cross sections

Mid-angles

$0.05 < \cos \theta_{c.m.} < 0.15$

- Charged-mode
- Neutral-mode
Differential cross sections

Forward-angles

\[ 0.85 < \cos \theta_{\text{c.m.}} < 0.95 \]

\[ \frac{d\sigma}{d\cos \theta_{\text{c.m.}}} \]
Yield extraction is complicated since $\phi$ is so close to $KK$ threshold. Physics model in MC could also make a difference, since forward-angle “bump” around $\sqrt{s} \sim 2.1$ GeV shows that simple diffractive Pomeron phenomenology is no longer valid.
**Comparison with Daresbury ’84 and CLAS ’00**

- $E_\gamma$ bin-widths were 1 GeV (Daresbury-84) and 600 MeV (CLAS-00). Systematics of background subtraction/yield extraction in older $\phi$ results seem questionable.

- CLAS-2000 backward-angle rise confirmed by CLAS-2010: non-negligible $g_{\phi NN}$ for $u$-channel exchange at high $\sqrt{s}$. 
Pomeron slope

- Fit to the form: \( \frac{d\sigma}{dt} \propto \exp(-B\phi |t - t_0|) \).

- Above \( \sqrt{s} \sim 2.3 \text{ GeV} \), in the purely diffractive regime, the Pomeron slope \( B\phi \approx 3 \text{ GeV}^{-2} \) and almost constant in this energy range.

- Below \( \sqrt{s} \sim 2.2 \text{ GeV} \), in the \( \phi\)-\( \Lambda(1520) \) overlap region, it is not a simple Pomeron phenomenology any longer.
The $\sqrt{s} \approx 2.1$ GeV “structure”

- Kiswandhi et al. (PLB 691, 214 (2010)): $3/2^-$ resonance around 2100 MeV.

- Ozaki et al. (PRC 80, 035201 (2009)): $K\Lambda(1520)$ and $\phi p$ channels couple:
The $\sqrt{s} \approx 2.1$ GeV “structure” (contd.)

\[ \gamma p \rightarrow K^+\Lambda(1520): \]

- “Structures” also visible in $K^+\Lambda(1520)$ channel around $\sqrt{s} \sim 2.1$ GeV as well.

- Full $\phi p-K^+\Lambda(1520)$ coupled-channel analysis required to decipher the underlying physics.

- Also look at the $\Lambda(1520) \rightarrow \Sigma\pi$ mode, which doesn’t share the same final states as $\phi p$ charged-mode.

Work of R. De Vita et al.
$R_{\phi/\omega}$ AND FLAVOR-INDEPENDENCE


- $R_{\phi/\omega}$ is generally small (OZI-suppression).

- In the diffractive limit where Pomeron dominates, $R_{\phi/\omega} \sim \mathcal{O}(1)$. Qualitatively agrees with Donnachie-Landshoff model: quark-quark-Pomeron coupling $\sim \beta_u \beta_s \bar{u}' \gamma_{\mu} u$. Couplings $\beta$ almost flavor-independent.

$R_{\phi/\omega}$ as a function of $(\cos \theta_{c.m.}, \sqrt{s})$:

(CLAS $\omega$: PRC 80, 065208 (2009))
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Spin Density Matrix Elements (SDME’s)

- With unpolarized beam and target, $\rho_{0m'}^0$ only accessible.
- Spin quantitation axis as the beam dirn. $\hat{z}_{CM}$ (Adair frame).
- $\phi$ rest frame decay angles: $\theta_{Ad}$ and $\varphi_{Ad}$.

Conventional Schilling’s method: fit to an $\phi \rightarrow KK$ decay angular intensity distribution:

$$I(\sqrt{s}, \cos \theta_{c.m.}) \sim \frac{1}{2} (1 - \rho_{00}^0) + \frac{1}{2} (3\rho_{00}^0 - 1) \cos^2 \theta_{Ad} - \rho_{1-1}^0 \sin^2 \theta_{Ad} \cos 2\varphi_{Ad}$$

$$-\sqrt{2} \text{Re} \rho_{10}^0 \sin 2\theta_{Ad} \cos \varphi_{Ad}$$

Equivalently, direct construction of the $\phi$ density matrix using PWA fit results:

$$\rho_{mm'}^0 = \frac{\sum A^m A^{m'*}}{\sum |A^m|^2 + |A^{m'}|^2}$$

where $m, m'$ are $\phi$ spin-projections and incoherent sum is over the spins of $\gamma, p,$ and $p'$. 
**SDME results (charged-mode)**

Adair frame:

- **Backward-angles**
- **Mid-angles**
- **Forward-angles**

$\cos \theta^\phi_{c.m.} = -0.5$

$\cos \theta^\phi_{c.m.} = 0.1$

$\cos \theta^\phi_{c.m.} = 0.9$

- $\sqrt{s} = 10$-MeV-wide energy bins.
SDME: COMPARISON BETWEEN $\phi$ AND $\omega$ RESULTS

- Adair frame $\rho^0_{00}$: “hump” followed by a “dip” for both channels.

- Position of the “dip” in $\cos \theta_{c.m.}$ is different for the two vector mesons.

![Graph showing $\rho^0_{00}$ vs. $\cos \theta_{c.m.}$ for $\omega$ and $\phi$ with $\sqrt{s}$ values of 2.575 GeV and 2.705 GeV respectively.]

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Dip'' = 2.575 GeV
$\omega$ $\sqrt{s}$ = 2.705 GeV
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**SDME: Comparison between \( \phi \) and \( \omega \) Results**

- Adair frame \( \rho_{00}^0 \): “hump” followed by a “dip” for both channels.

- Position of the “dip” in \( \cos \theta_{c.m.} \) is different for the two vector mesons.

- Present theory models don’t describe this dip very well – shown on the right for the \( \omega \) case. Room for improvement.

- \( \rho_{00}^0 \) (Adair frame)

- \( \omega \sqrt{s} = 2.575 \text{ GeV} \)
- \( \phi \sqrt{s} = 2.705 \text{ GeV} \)

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**Oh-Titov-Lee background model**

- \( \rho_{00}^0 \)
- \( \omega \sqrt{s} = 2.575 \text{ GeV} \)
- \( \phi \sqrt{s} = 2.705 \text{ GeV} \)

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**CLAS \( \omega \) PWA, Williams et al.** (PRC 60, 065209 (2009))

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**SCHC violation**

- Naively, Pomeron \((0^{++} \text{ exchange})\) should conserve \(t\)-channel helicity (TCHC). Instead, experimentally, TCHC is broken and \(s\)-channel helicity is seen to be conserved (SCHC).

- Phenomenological explanation by Gilman *et al.* (PLB 31, 387 (1970)). However, no *fundamental reason* for SCHC.

- New CLAS results show \(\rho_{00}^0 \neq 0\): both TCHC and SCHC violation at all angles (both \(\phi\) and \(\omega\) channels, in fact).

![Graph showing \(\cos \theta_{c.m.} = 0.7\)]
Previous SDME measurements: highly statistics limited, wide energy bins.

Often averaged over angular variables in Schilling’s intensity expression, without proper acceptance correction.

Latest forward-angle LEPS results (Chang PRC 82, 015205 (2010)) incorporates several improvements and are in overall good agreement with us.
Neutral-mode SDME’s also extracted in exactly similar way as for the charged-mode.

Some local differences visible around $\sqrt{s} \sim 2.1$ GeV region.

Further studies to be done on the charged-mode “structures” before finalizing results.
OUTLINE

1 INTRODUCTION AND EVENT SELECTION

2 SIGNAL-BACKGROUND SEPARATION

3 ACCEPTANCE CALCULATION AND $d\sigma/d\cos\theta_{c.m}$. 

4 SPIN DENSITY MATRIX ELEMENTS

5 SUMMARY
**SUMMARY**

- **First ever extensive world data** for the $\phi$ channel. Corresponding $\omega$ results already published by the CLAS Collaboration.

- Detailed $d\sigma/dt$ and $\rho_{mm'}^0$: coverage from near threshold to $\sqrt{s} = 2.84$ GeV and $-0.85 \leq \cos \theta_{c.m.} \leq 0.95$.

- Access to both charged- and neutral-modes results is a very useful tool.

- “Structure” around $\sqrt{s} \sim 2.1$ GeV needs careful study. Present results will provide detailed information towards this.

- *Lots* of interesting features visible in the new data — SCHC violation, finite value of $g_{\phi NN}$, Pomeron slope etc.

- **Full partial-wave analysis** on both $\phi$ and $\omega$ currently underway. CLAS $\Lambda(1520)$ results from the same dataset soon to be available as well for coupled-channel analysis.
**Event-selection: Timing cuts**

- 2-D calculated mass cut on \( p, K^+ \) (charged-mode)

![Graph showing mass distribution](image1)

- 2-D \( \Delta \)time-of-flight \( (\text{tof}_{\text{meas}} - \text{tof}_{\text{calc}}) \) cut on \( p, \pi^+ \) (neutral-mode)

![Graph showing timing cut](image2)
**Event-selection contd.**

- $K_S^0$ selection cut (neutral-mode): $0.488 \text{ GeV} \leq M(\pi^+,\pi^-) \leq 0.508 \text{ GeV}$.

![Graph showing the acceptance and rejection of events based on missing mass and invariant mass distributions.](image-url)
**LINESHAPE**

- φ width is $\Gamma_0 \approx 4$ MeV, however, its mass being so close to the $KK$ threshold ($\approx 0.99$ GeV) leads to a *unsymmetric lineshape*.

- All previous world data relied on a Gaussian φ lineshape for yield extraction fits.

- We’ve tried to employ a better approximation by taking a mass-dependent width:

  $$\Gamma(m) = \Gamma_0 \left( \frac{q}{q_0} \right)^{2L+1} \left( \frac{m_0}{m} \right) \left( \frac{B_0}{B} \right)$$

- $L = 1$ for $P$-wave $\phi \rightarrow KK$ decay.

- Break-up momentum $q(m) = \sqrt{m^2 - m_K^2}/2$ for a φ mass $m$.

- Barrier-factor $B_{L=1} = \frac{2z}{1 + z}$ with $z = q/d$, $d \sim 1$ fm ($\approx 0.1973$ GeV).

- Subscript 0 denotes evaluation at the φ mean mass $m_0 = 1.01946$ GeV.

- Final *signal-function* in background fits: *Voigtian* with Breit-Wigner width taken as $\Gamma(m)$. 

FIG. 1. (a) Missing mass distribution for the $p(γ, K^+ K^-)X$ reaction in $KK$ mode. (b) Missing mass distribution for the $p(γ, K^0 p)X$ reaction in $Kp$ mode. (c) and (d) are the $K^+ K^-$ invariant mass distributions after the cut on the missing mass for $KK$ and $Kp$ modes, respectively. The hatched histograms are the simulated background.
**SAPHIR BACKGROUND SEPARATION**

**Fig. 3.** $\Phi$ separation from the background in the $K^+K^-$ mass spectrum.

**Fig. 4.** Contributions of phase space, $\Lambda(1520)$ and $\Phi$ production to the $K^+K^-$ mass spectrum for photon energies between 2.1 and 2.4 GeV.
Anciant background separation
**Fit Quality Checks**

### Charged-mode

\[ \sqrt{s} = 2.155 \text{ GeV} \]

- Data
- Acc MC (unweighted)
- Acc MC (weighted)

\[ \cos \theta_{\text{c.m.}} \]

\[ \cos \theta_{\text{Adair}} \]

\[ \cos^{-1} \]

- 0
- 0.5
- 1

\[ \phi \text{ c.m.} \]

\[ K \text{ Adair} \]

\[ \sqrt{s} = 2.155 \text{ GeV} \]

Data
Acc MC (unweighted)
Acc MC (weighted)

\[ = 2.155 \text{ GeV} \]

\[ s \]

\[ K \text{ Adair} \]

Data
Acc MC (unweighted)
Acc MC (weighted)

\[ = 2.155 \text{ GeV} \]

\[ s \]
Neutral-mode

$\sqrt{s} = 2.135$ GeV

Data
Acc MC (unweighted)
Acc MC (weighted)

$\cos^0_{c.m.}$

$\phi$

$\cos^{-1} \theta$

$\phi$

$\cos^{-1} \theta$

Data
Acc MC (unweighted)
Acc MC (weighted)

$\sqrt{s} = 2.135$ GeV

$\cos^K_{\text{Adair}}$
Comparison between PWA and Schilling’s methods

\[ \cos \theta_{\text{c.m.}} \]

\[ \sqrt{s} = 2.105 \text{ GeV} \]

\[ \sqrt{s} = 2.325 \text{ GeV} \]

\[ \sqrt{s} = 2.615 \text{ GeV} \]