Partial wave analysis for $K^+\Lambda$ *and* $K^+\Sigma^0$ *photoproduction*

Biplab Dey, Michael E. McCracken, Curtis A. Meyer

Carnegie Mellon University

May 17^{th}, 2011
NSTAR'11, Jefferson Lab

Outline

1. Introduction, "complete" experiments and polarizations
2. Normalization issues
3. Preliminary PWA results: the non-resonant part
4. Preliminary PWA results: the resonant part
5. Summary

Outline

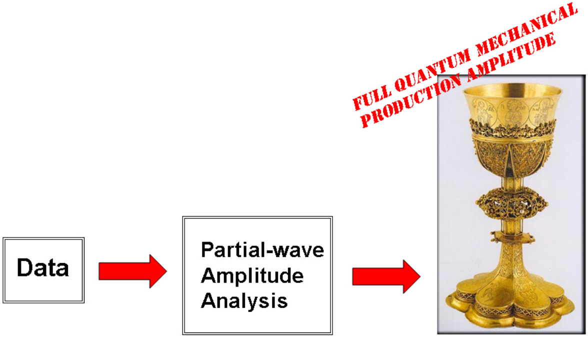
1. Introduction, “complete” experiments and polarizations
2. Normalization issues
3. Preliminary PWA results: the non-resonant part
4. Preliminary PWA results: the resonant part
5. Summary

Introduction

- Fundamental question in hadronic physics – what are the relevant degrees of freedom in low/medium energy QCD?

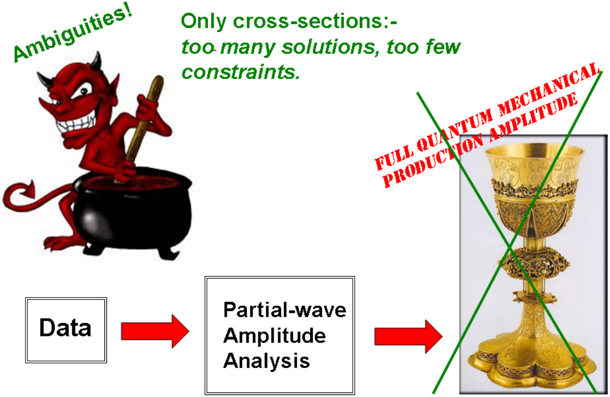
INTRODUCTION

- Fundamental question in hadronic physics – what are the relevant degrees of freedom in low/medium energy QCD?
- Can we figure out the complex production amplitudes?



Introduction

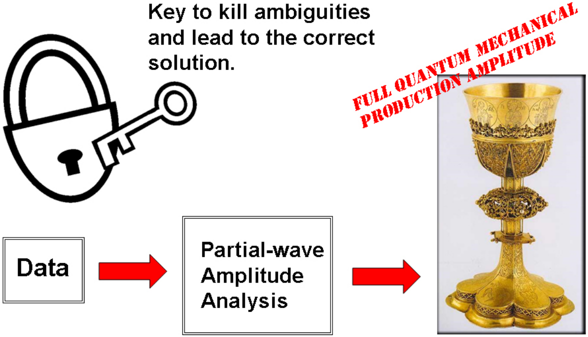
- Fundamental question in hadronic physics – what are the relevant degrees of freedom in low/medium energy QCD?
- Can we figure out the complex production amplitudes?



Introduction

- Fundamental question in hadronic physics – what are the relevant degrees of freedom in low/medium energy QCD?
- Can we figure out the complex production amplitudes?

Polarization data, “complete” experiments



Pseudoscalar-meson photoproduction

- 8 $(2 \times 2 \times 2)$ $\mathcal{A}_{m_\gamma m_i m_b}$ complex amplitudes tagged by m_γ (photon), m_i (initial target) and m_b (outgoing baryon) spin projections
- Parity invariance reduces the 8 $\mathcal{A}$'s to 4 *independent* L_i longitudinal basis amplitudes (a single spin-quantization axis along the longitudinal beam direction).

Pseudoscalar-meson photoproduction

- 8 $(2 \times 2 \times 2)$ $\mathcal{A}_{m_\gamma m_i m_b}$ complex amplitudes tagged by m_γ (photon), m_i (initial target) and m_b (outgoing baryon) spin projections

- Parity invariance reduces the 8 $\mathcal{A}$'s to 4 *independent* L_i longitudinal basis amplitudes (a single spin-quantization axis along the longitudinal beam direction).

- Density matrix: $\rho = \frac{1}{2}(1 + \vec{P} \cdot \vec{\sigma}) \equiv \frac{P^\mu \sigma_\mu}{2}$, with $P_0 = 1$ and $\sigma_0 = \mathbb{I}$.

- Intensity profile has 64 $(4 \times 4 \times 4)$ terms on expansion:

$$\mathcal{I} = \mathcal{I}_0 \left(\frac{\mathrm{Tr}[\rho^b \mathcal{A} \rho^i \rho^\gamma \mathcal{A}^\dagger]}{\mathrm{Tr}[\mathcal{A}\mathcal{A}^\dagger]/8} \right) = \mathcal{I}_0 \left(\sum_{lmn \in \{0,1,2,3\}} P_l^\gamma P_m^i P_n^b \; T_{lmn} \right)$$

The T_{lmn} elements and polarizations

- $T_{lmn} \equiv \frac{\mathrm{Tr}[\sigma_n^b \mathcal{A} \sigma_m^i \sigma_l^\gamma \mathcal{A}^\dagger]}{\mathrm{Tr}[\mathcal{A}\mathcal{A}^\dagger]}$ elements are the polarization observables.

- Parity on T_{lmn}: reshuffle the ordering of (lmn).
- Parity transform: out of 64 terms, 32 get killed and remaining 16 terms occur twice.
- Simply read off T_{lmn} from the table → compactness of notation and derivation!
- 15 independent polarization observables. FROST and g8 from CLAS will give many of these.

The T_{lmn} elements (lmn)

Type	Observable	Definition	Parity flip
Unpolarized	1	(000)	(122)
Single-pol.	P	(002)	(120)
"	Σ	(100)	(022)
"	T	(020)	(102)
Beam-target	E	(330)	(212)
"	F	(310)	-(232)
"	G	-(230)	(312)
"	H	-(210)	-(332)
Beam-recoil	C_x	(301)	(223)
"	C_z	(303)	-(221)
"	O_x	-(201)	(323)
"	O_z	-(203)	-(321)
Target-recoil	T_x	(011)	(133)
"	T_z	(013)	-(131)
"	L_x	(031)	-(113)
"	L_z	(033)	(111)

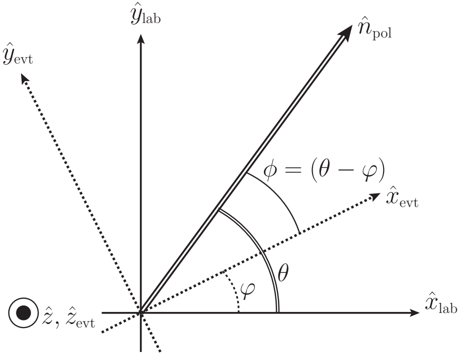
Sign issues - I

- Photon polarization $\vec{P}^{\gamma}$:

$$P_z^{\gamma} = P_C^{\gamma}(circular)$$
$$P_x^{\gamma} = -P_L^{\gamma}\cos(2\phi)(linear)$$
$$P_y^{\gamma} = -P_L^{\gamma}\sin(2\phi)(linear)$$

- Linear case: $\phi = (\theta - \varphi)$
  - Theory/PWA: ϕ
  - Experimentalists: φ
  - $\theta = 0$ "para" and $\theta = 90^{\circ}$ "perp" settings.

Looking "into" the beam-dirn. ($\hat{z}$):



- While showing intensity profile, clarify whether azimuthal angle is ϕ or φ.
- Intensity profile for "para"/"perp" will carry totally different signs. Can lead to sign ambiguities.

Sign issues - II

- CMU follows the *asymmetry definitions* in Fasano-Tabakin-Saghai (FTS) PRC 46, 2430 (1992).
- Caveat: FTS *density matrix* definitions for O_x, O_z, G and H (linear pol. photon) have incorrect signs.
- CMU $\leftrightarrow$ SAID/MAID : flip signs of H, E, C_x, C_z, O_x, O_z and L_x.
- CMU $\leftrightarrow$ EBAC : flip signs of E.
- To avoid sign issues, need to mention:
  - Which convention (CMU/SAID/EBAC) is being followed.
  - Which angle, ϕ or φ, is being shown in the intensity profile.

Sign issues - II

- CMU follows the *asymmetry definitions* in Fasano-Tabakin-Saghai (FTS) PRC 46, 2430 (1992).
- Caveat: FTS *density matrix* definitions for O_x, O_z, G and H (linear pol. photon) have incorrect signs.
- CMU $\leftrightarrow$ SAID/MAID : flip signs of H, E, C_x, C_z, O_x, O_z and L_x.
- CMU $\leftrightarrow$ EBAC : flip signs of E.
- To avoid sign issues, need to mention:
  - Which convention (CMU/SAID/EBAC) is being followed.
  - Which angle, ϕ or φ, is being shown in the intensity profile.

Ref: B. Dey *et al*, arXiv:1010.4978 [hep-ph] (to be published in PRC)

Outline

The new CLAS "g11a" photoproduction results

- High-statistics ($\sim$ 20 billion triggers), precision (very well calibrated) experiment, originally for pentaquark search.
- Very fine $\Delta(\sqrt{s}) = 10$ MeV binning, wide kinematic coverage, till $\sqrt{s} = 2.84$ GeV
- First world dataset to "bridge" the low-energy regime ($\sqrt{s} \leq 2.3$ GeV) where most of the world data resides, and the older high-energy ($\sqrt{s} \geq 3$ GeV) data from SLAC/DESY/CEA *et al.*
- Generally good to excellent agreement with lower energy LEPS/GRAAL data.

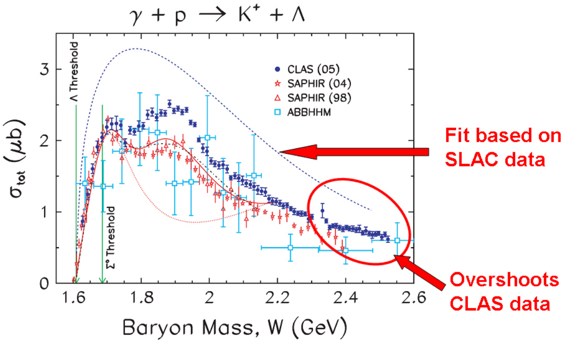
The new CLAS "g11a" photoproduction results

- High-statistics ($\sim$ 20 billion triggers), precision (very well calibrated) experiment, originally for pentaquark search.
- Very fine $\Delta(\sqrt{s}) = 10$ MeV binning, wide kinematic coverage, till $\sqrt{s} = 2.84$ GeV
- First world dataset to "bridge" the low-energy regime ($\sqrt{s} \leq 2.3$ GeV) where most of the world data resides, and the older high-energy ($\sqrt{s} \geq 3$ GeV) data from SLAC/DESY/CEA *et al.*
- Generally good to excellent agreement with lower energy LEPS/GRAAL data.
- ...however, normalization discrepancy with the old SLAC/DESY/CEA high-energy data.

The first signs...

- Regge-based model fit to SLAC-Boyarski-1969 $E_\gamma = 5, 8, 11, 16$ GeV data clearly overshoots 2006 CLAS g1c results.

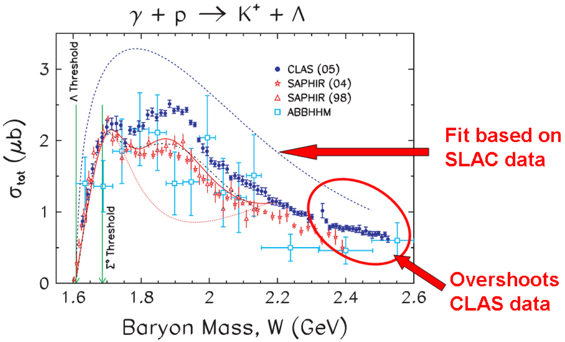
CLAS "g1c", PRC 73, 035202 (2006):



The first signs...

- Regge-based model fit to SLAC-Boyarski-1969 $E_\gamma = 5, 8, 11, 16$ GeV data clearly overshoots 2006 CLAS g1c results.

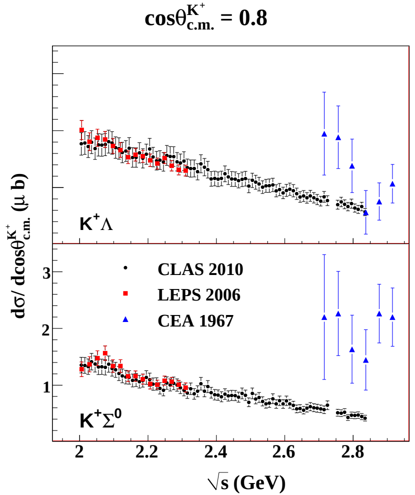
CLAS "g1c", PRC 73, 035202 (2006):



- However, this is a projection from a fit, not a direct comparison.

Direct comparison possible with g11a

- With higher energy g11a data, a direct comparison is possible.
- Shown, comparison between, **CLAS-2010**, LEPS-2006 and CEA-1967 at a particular forward-angle bin.
- Generally, older SLAC/DESY/CEA results are mutually consistent and overshoot CLAS at high-energy, forward-angles.
- CLAS and LEPS are in excellent agreement!

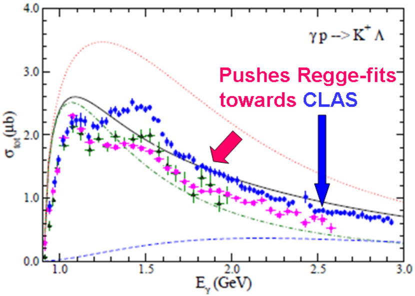


RECENT YU *et al* WORK

- Yu *et al* (2011): extension of the original GLV (NPA 627, 645 (1997)) Regge model.
- Claim: can reconcile CLAS and SLAC, but tensor-meson ($a2$, $f2$, $K2$) exchanges are *required*.
- Does not include latest CLAS $g11a$ results, only CLAS-2006 ($g1c$).
- Most of the extra tensor-couplings are model-dependent.

Yu *et al.* (nucl-th/1104.3672)

add $K^*2(1430)$ exchange:

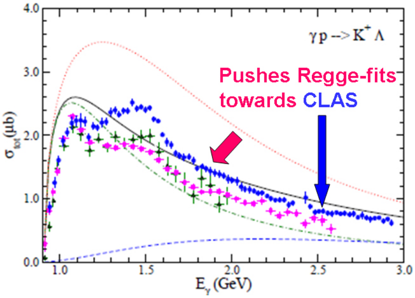


Recent Yu *et al* work

- Yu *et al* (2011): extension of the original GLV (NPA 627, 645 (1997)) Regge model.
- Claim: can reconcile CLAS and SLAC, but tensor-meson ($a2$, $f2$, $K2$) exchanges are *required*.
- Does not include latest CLAS $g11a$ results, only CLAS-2006 ($g1c$).
- Most of the extra tensor-couplings are model-dependent.

Yu *et al.* (nucl-th/1104.3672)

add $K^*2(1430)$ exchange:



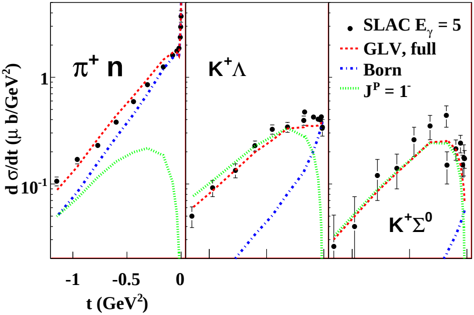
- However, include CLAS-$g11a$: *simply can not fit the SLAC/DESY/CEA and CLAS/LEPS datasets in a single Regge-based fit*

Effect on couplings

- Most authors agree on $g_{\pi NN} \approx 13$, but wide uncertainties on the rest of the couplings ($g_{\rho NN}$, $\kappa_{\rho NN}$, etc.).
- Kaon-sector: g_{KpY}, $g_{K^* pY}$, $\kappa_{K^* pY}$ even more poorly known.
- In the GLV-model, the *$t \to 0$ shape* fixes the strength-ratio between the Born π^+ (K^+) and vector ρ (K^*) exchanges for $\pi^+ n$ ($K^+ Y$).

At $t \to 0$:

- Rise for $\pi^+ n$
- Plateau for $K^+\Lambda$
- Drop-off for $K^+\Sigma^0$



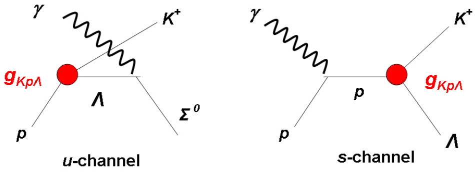
Couplings ...

- Unfortunately, CLAS forward-angle beam-dump hole does not allow $t \rightarrow 0$ measurements.
- We take the SLAC forward-angle shape as "plausible" and take the following as guidance:
  - $K^+\Lambda$ and $K^+\Sigma^0$ should not show a peak at high $\sqrt{s}$ and $t \rightarrow 0$.
  - The non-resonant model extrapolated to near-thrshold should not grossly overestimate the CLAS cross-sections.
- Enforcing $|g_{Kp\Lambda}| \leq 10$ seems to satisfy both above conditions.
- This is an extra unwanted ambiguity that remains to be resolved!

Outline

FORMALISM

- Non-resonant t- and u-channel Reggeized amplitudes mostly follows the Ghent Regge-plus-resonance (RPR) formalism.
- Couple $K^+\Lambda$ and $K^+\Sigma^0$ channels, *eg.* same $g_{Kp\Lambda}$ for the Born terms:



- Channel-coupling leads to much better self-consistency.
- Fit to $\sqrt{s} \geq 2.6$ GeV and $|\cos\theta^K_{c.m.}| > 0.5$ to fix the non-resonant couplings.
- Simple Regge model (no form-factors!): $\Lambda(1115)$, $\Sigma(1192)$ exchanges in the u-channel, K^+ and $K^*(892)$ exchanges in the t-channel

Non-resonant results

- No local "dips" in the non-resonant regime for KY: strongly degenerate Regge trajectories should be a good starting point. Constant or rotating phases.
- Our preliminary couplings with all rotating phases for the trajectories:

	$g_{Kp\Lambda}$	$g_{Kp\Sigma}$	$g_{K^*p\Lambda}$	$\kappa_{K^*p\Lambda}$	$g_{K^*p\Sigma}$	$\kappa_{K^*p\Sigma}$
GLV	-11.5	4.5	-23	2.5	-25	-1
This work	-9.5	5.6	-14.5	1.7	-14.5	-1.3

- All-rotating is just one possibility. All combinations have to be checked.

NON-RESONANT RESULTS

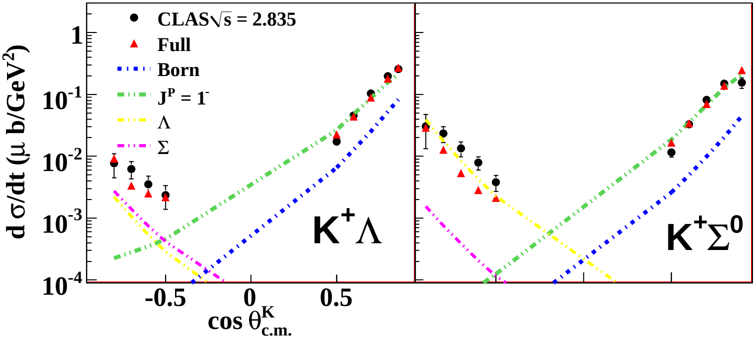
- No local "dips" in the non-resonant regime for KY: strongly degenerate Regge trajectories should be a good starting point. Constant or rotating phases.
- Our preliminary couplings with all rotating phases for the trajectories:

	$g_{Kp\Lambda}$	$g_{Kp\Sigma}$	$g_{K^*p\Lambda}$	$\kappa_{K^*p\Lambda}$	$g_{K^*p\Sigma}$	$\kappa_{K^*p\Sigma}$
GLV	-11.5	4.5	-23	2.5	-25	-1
This work	-9.5	5.6	-14.5	1.7	-14.5	-1.3

- All-rotating is just one possibility. All combinations have to be checked.
- However, our (CLAS) $g_{Kp\Lambda}$, $g_{Kp\Sigma}$, $g_{K^*p\Lambda}$ and $g_{K^*p\Sigma}$ are definitely going to be smaller than what GLV (SLAC) saw.

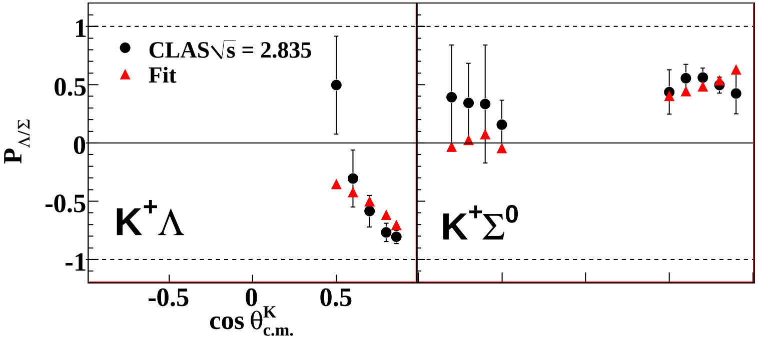
NON-RESONANT RESULTS: $d\sigma/dt$

From fits to high energy, forward- and backward-angle regime only:



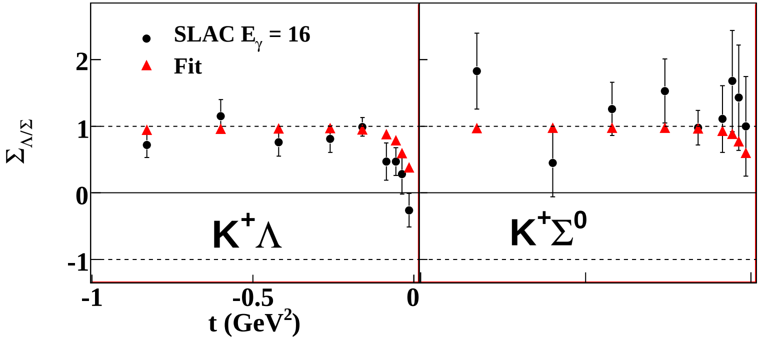
Non-resonant results: recoil polarization

From fits to high energy, forward- and backward-angle regime only:



Non-resonant results: beam asymmetry

From fits to high energy, forward- and backward-angle regime only:

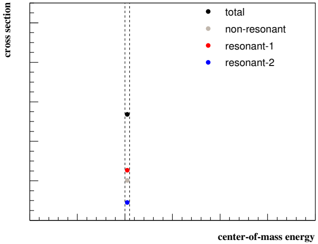


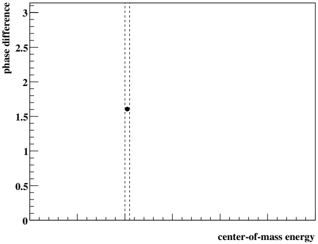
Outline

Adding s-channel resonances

- The non-resonant part is "fixed" by fits at high energy. Add s-channel J^P waves in the resonance regime as in RPR (Ghent group).
- J^P waves constructed using the Rarita-Schwinger covariant formalism, loosely follows Bonn-Gatchina work (Anisovich *et al*)
- For overlapping resonances, Breit-Wigner (propagator) shapes not valid.
- *Mass-indepenent* technique: if the $\sqrt{s}$-binning is fine enough, the propagator function ($\sim R(\sqrt{s})\exp(i\phi(\sqrt{s}))$) is approximately a constant *within* a bin.
- Extract the strength $R(\sqrt{s})$ and phase $\phi(\sqrt{s})$ from individual fits in each $\sqrt{s}$-bin.

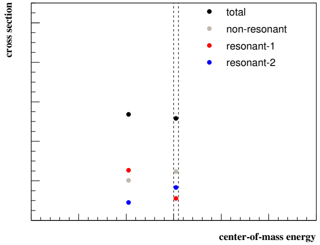
Mass-independent PWA Method (Toy-example)

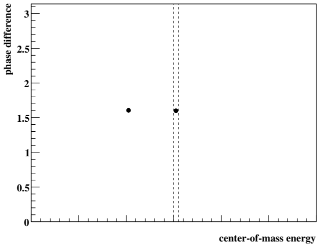




- Select a $\sqrt{s}$-bin and allow the fit to find the optimal physics for this small energy range
-
-

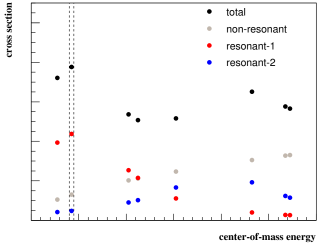
Mass-independent PWA Method (Toy-example)

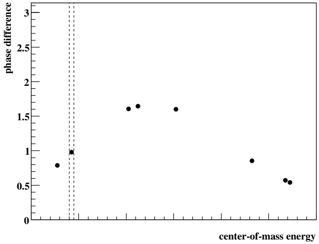




- Select a $\sqrt{s}$-bin and allow the fit to find the optimal physics for this small energy range
- Repeat this process over the entire energy range – all fits are *independent*
-

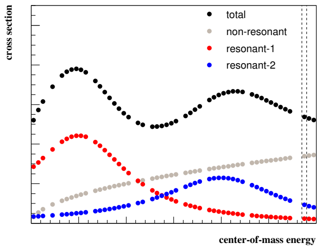
Mass-independent PWA Method (Toy-example)

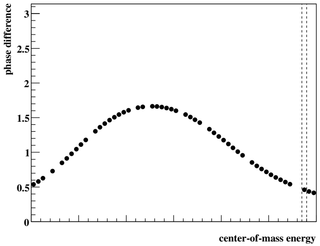




- Select a $\sqrt{s}$-bin and allow the fit to find the optimal physics for this small energy range
- Repeat this process over the entire energy range – all fits are *independent*
-

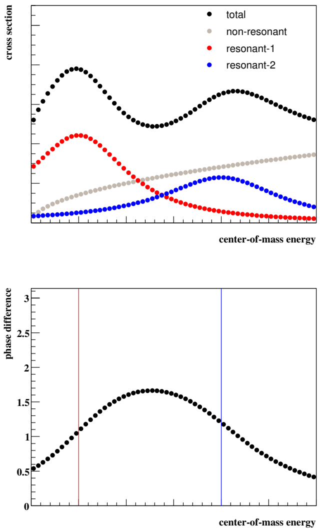
Mass-independent PWA Method (Toy-example)





- Select a $\sqrt{s}$-bin and allow the fit to find the optimal physics for this small energy range
- Repeat this process over the entire energy range – all fits are *independent*
-

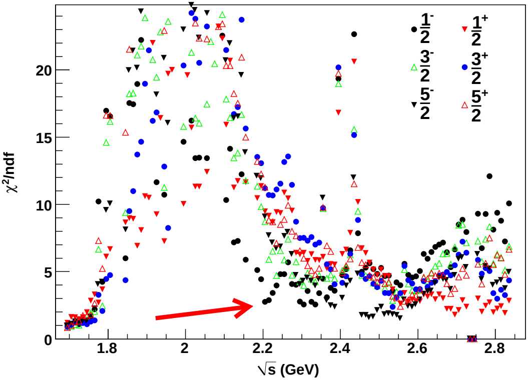
Mass-independent PWA Method (Toy-example)



- Select a $\sqrt{s}$-bin and allow the fit to find the optimal physics for this small energy range
- Repeat this process over the entire energy range – all fits are *independent*
- If the data contains resonances, we should be able to extract them without enforcing resonance masses and biasing the result.

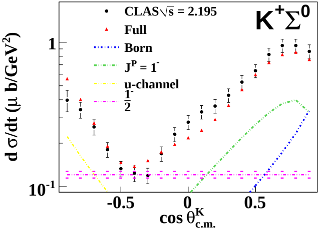
Preliminary $K^+\Sigma^0$ single s-channel scans

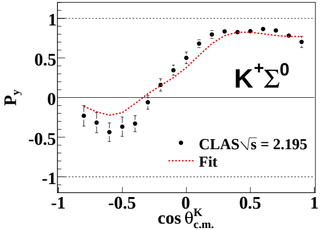
- Non-resonant model plus a single s-channel wave for $K^+\Sigma^0$



- Indication of a $\frac{1}{2}^-$ wave at around 2200 MeV.

$K^+\Sigma^0$ single s-channel scans (cntd.)





- Possible $\frac{1}{2}^-$ candidate could be $S_{31}(2150)$: one star PDG state also appearing in Capstick/Roberts work with a strong coupling to $K\Sigma$
- Single-channel scans are just the beginning, to get an idea of what the relevant waves might be.
- CLAS $K^+\Sigma^0$ data show broad structure between 2.1 and 2.2 GeV in the backward-angles.
- With more waves, we have seen phase-motion: multiple (overlapping) states present here.

Outline

Summary and further work

- Sign issues for polarization observables resolved. FTS *density matrix* expressions will require negative signs for O_x, O_z, G and H.

Summary and further work

- Sign issues for polarization observables resolved. FTS *density matrix* expressions will require negative signs for O_x, O_z, G and H.
- Normalization discrepancy between CLAS and SLAC datasets remains an outstanding issue that needs to be resolved.

Summary and further work

- Sign issues for polarization observables resolved. FTS *density matrix* expressions will require negative signs for O_x, O_z, G and H.
- Normalization discrepancy between CLAS and SLAC datasets remains an outstanding issue that needs to be resolved.
- The Regge-model for non-resonant processes works both at forward- (t-) and backward-angles (u-channel).

Summary and further work

- Sign issues for polarization observables resolved. FTS *density matrix* expressions will require negative signs for O_x, O_z, G and H.
- Normalization discrepancy between CLAS and SLAC datasets remains an outstanding issue that needs to be resolved.
- The Regge-model for non-resonant processes works both at forward- (t-) and backward-angles (u-channel).
- *Mass-independent* PWA is a powerful technique that reduces model-dependence.

Summary and further work

- Sign issues for polarization observables resolved. FTS *density matrix* expressions will require negative signs for O_x, O_z, G and H.
- Normalization discrepancy between CLAS and SLAC datasets remains an outstanding issue that needs to be resolved.
- The Regge-model for non-resonant processes works both at forward- (t-) and backward-angles (u-channel).
- *Mass-independent* PWA is a powerful technique that reduces model-dependence.
- This is very much an ongoing work. Detailed studies on the systematics and robustness of our PWA against ambiguities are underway.

Summary and further work

- Sign issues for polarization observables resolved. FTS *density matrix* expressions will require negative signs for O_x, O_z, G and H.
- Normalization discrepancy between CLAS and SLAC datasets remains an outstanding issue that needs to be resolved.
- The Regge-model for non-resonant processes works both at forward- (t-) and backward-angles (u-channel).
- *Mass-independent* PWA is a powerful technique that reduces model-dependence.
- This is very much an ongoing work. Detailed studies on the systematics and robustness of our PWA against ambiguities are underway.
- Stay tuned for results!