Hyperon spectroscopy prospects with a polarized target

Workshop on Polarized Target Studies with Real Photons in Hall D

Farah Afzal for
Bonn (Y. Wunderlich, A. Thiel), FSU (V. Crede), JLab (M.M. Dalton) and Glasgow (P. Hurck, D.G. Glazier and K. Livingston)

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University of Bonn

Motivation - hyperon spectroscopy

- **Goal: Study excited states (Λ^*, Σ^*) and properties**
- More states expected than have been found so far!
  - → Do these states exist?
  - → Is SU(6)xO(3)-symmetry realized?
  - → At least 23 missing Σ^*
- What is the nature of the observed states, e.g. $\Lambda(1405)$ two-pole structure

PDG2021:"...the field is starved for data ...the established (Λ^*, Σ^*) resonances are the same ones that were listed in our 1984 edition ..."

→ High demand for data in strange baryon sector!

N	(D, L_N^P)	S	J^P	Octet Members					Singlets
0	$(56, 0_0^+)$	1/2	$1/2^+$	$N(939)$	****	$\Lambda(1116)$	$\Sigma(1193)$	$\Xi(1318)$	–
1	$(70, 1_1^-)$	1/2	$1/2^-$	$N(1535)$	****	$\Lambda(1670)$	$\Sigma(1620)$	$\Xi(1690)$	$\Lambda(1405)$
			$3/2^-$	$N(1520)$	****	$\Lambda(1690)$	$\Sigma(1670)$	$\Xi(1820)$	$\Lambda(1520)$
		3/2	$1/2^-$	$N(1650)$	****	$\Lambda(1800)$	$\Sigma(1750)$		–
			$3/2^-$	$N(1700)$	***				–
			$5/2^-$	$N(1675)$	****	$\Lambda(1830)$	$\Sigma(1775)$		–
2	$(56, 0_2^+)$	1/2	$1/2^+$	$N(1440)$	****	$\Lambda(1600)$	$\Sigma(1660)$		–
	$(70, 0_2^+)$	1/2	$1/2^+$	$N(1710)$	****	$\Lambda(1810)^{\dagger}$	$\Sigma(1770)^{\dagger}$		
		3/2	$3/2^+$						–
	$(56, 2_2^+)$	1/2	$3/2^+$	$N(1720)^{\dagger}$	****	$\Lambda(1890)^{\dagger}$	$\Sigma(1840)^{\dagger}$		–
			$5/2^+$	$N(1680)$	****	$\Lambda(1820)^{\dagger}$	$\Sigma(1915)^{\dagger}$		–
	$(70, 2_2^+)$	1/2	$3/2^+$						
			$5/2^+$	$N(1860)$	**				
		3/2	$1/2^+$	$N(1880)$	***			–	
			$3/2^+$	$N(1900)^{\dagger}$	****		$\Sigma(2080)^{\dagger}$		–
			$5/2^+$	$N(2000)$	**	$\Lambda(2110)^{\dagger}$	$\Sigma(2070)^{\dagger}$		–
			$7/2^+$	$N(1990)$	**	$\Lambda(2020)$	$\Sigma(2030)^{\dagger}$		–
	$(20, 1_2^+)$	1/2	$1/2^+$	$N(2100)^{\dagger}$	***				
			$3/2^+$	$N(2040)^{\dagger}$	*				
			$5/2^+$	–		–	–	–	
3	$(56, 1_3^-)$	1/2	$1/2^-$	$N(1895)^{\dagger}$	****				–
			$3/2^-$	$N(1875)^{\dagger}$	***		$\Sigma(1940)^{\dagger}$		–
	$(70, 1_3^-)$			5 x					
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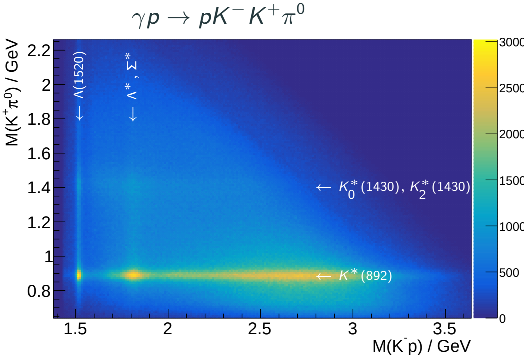
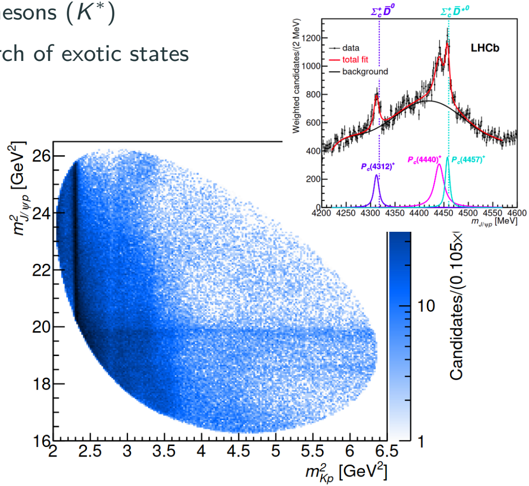
	$(20, 1_3^-)$	1/2		2 x					
	$(70, 2_3^-)$			6 x					
	$(56, 3_3^-)$	1/2		2 x					–
	$(70, 3_3^-)$	1/2	$7/2^-$	$N(2190)^{\dagger}$	****	$\Lambda(2100)^{\dagger}$			
		3/2	$9/2^-$	$N(2250)$	****				
	$(20, 3_3^-)$	1/2		2 x					
4			$9/2^+$	$N(2220)$	****	$\Lambda(2350)$			
5			$11/2^-$	$N(2600)$	***				

V. Crede

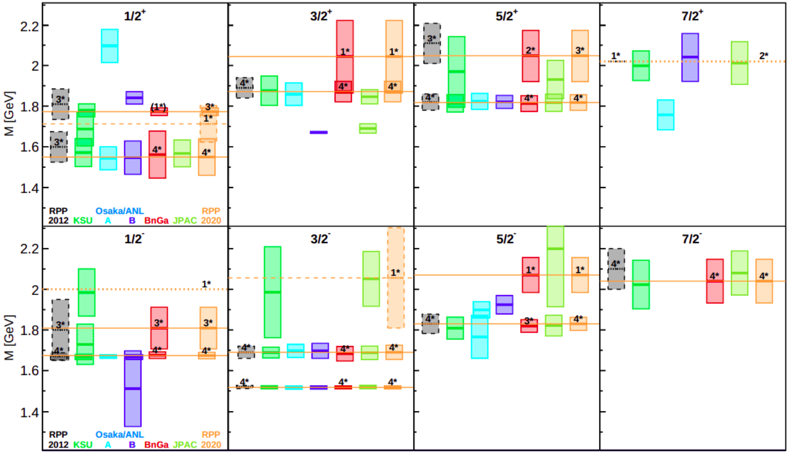
- Significant overlap of strange baryons and strange mesons (K^*)
- Knowledge of strange baryons important for the search of exotic states





R. Aaij et al. [LHCb], Phys. Rev. Lett. 122, no.22,222001 (2019)

Comparison of different PWA with PDG for Λ^* (I=0)



- Almost same data used by PWA groups
- Existing data does not constrain models well
- Several new possible states and a lot of 1^* resonances need confirmation
- Some 3^* or 4^* resonances not seen by all models
- Different resonance parameters

E. Klempt et al., Eur.Phys.J.A 56 (2020) 10, 261

Comparison of different PWA with PDG for Σ^* (I=1)

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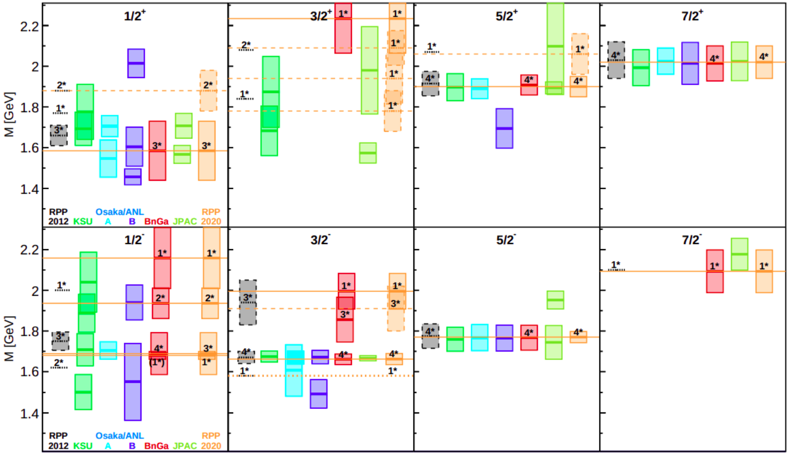

E. Klempt et al., Eur.Phys.J.A 56 (2020) 10, 261

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Different production mechanisms to study hyperons

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Electromagnetic beam:

- Electroproduction: $e^- N \rightarrow e^- K\Lambda^*/\Sigma^*$ (CLAS-12 (JLab))
- Photoproduction: $\gamma N \rightarrow K\Lambda^*/\Sigma^*$ (A2 (MAMI), CBELSA/TAPS (ELSA), GlueX, CLAS-6 (JLab))

Hadron beam:

- π-induced production: HADES (GSI)
- K-induced production: KLF in Hall D (JLab), J-PARC

Proposed project will give complementary data to KLF program!

Photoproduction of hyperons - Overview of different experiments

Experiment	Photon energy /GeV	Experimental tools	planned/past physics program
A2	Up to 1.6	Polarized photon beams Polarized target Recoil polarimeter	Focus on Λ, Σ ground state
CBELSA/TAPS	Up to 3.2	Polarized photon beams Polarized target	Large interest in studying Λ^*, Σ^* Focus on threshold region
CLAS-6	Up to 6.0	Polarized photon beams Polarized target	Had a dedicated program to measure pol. observables (Up to **2.2 GeV!**) Focused mainly on Λ, Σ ground states
GlueX	Up to 12	Polarized photon beams **Polarized target?**	Study of cross section, beam asymmetry and SDMEs (e.g. $\Lambda(1520)$)

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A2

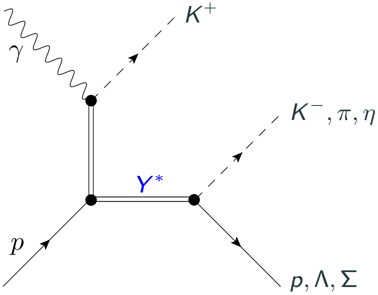
CBELSA/TAPS

GlueX

V. Crede

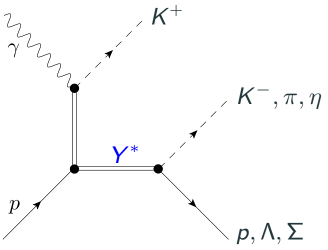
GlueX is only (photoproduction) experiment that can access high-mass Λ^*, Σ^* states!

All states can be accessed by GlueX!



Final State	Sensitive to	Important because
$K^+ \; pK^-$	Λ^*, Σ^*	high statistics
$K^+ \; \Sigma^0\pi^0$	Λ^*	isospin filter
$K^+ \; \Lambda\eta$	Λ^*	$\Lambda(1670)\frac{1}{2}^-$, $\Lambda(1670)\frac{3}{2}^+$?
$K^+ \; \Lambda\pi$	Σ^*	isospin filter
$K^+ \; \Sigma\eta$	Σ^*	$\Sigma(1750)\frac{1}{2}^-$
$(K^+ \; \Sigma(1385)\pi)$	Λ^*, Σ^*	high mass resonances
$(K^+ \; pK^{*-})$	Λ^*, Σ^*	

Polarization observables of interest



Photoproduction of two pseudo-scalars: W. Roberts, T. Oed, Phys.Rev.C 71 (2005) 055201

- Considering spins of initial and final state particles, $N = 2 \times 2 \times 2 = 8$ Amplitudes needed
- $N^2 = 8^2 = 64$ observables can be defined using polarization of beam, target and recoil baryon
- Minimal complete set consists of $2N = 16$ (1 unpol. cross section + 15 polarization observables)
  → P. Kroenert, Y. Wunderlich, F. Afzal, A. Thiel, Phys.Rev.C 103 (2021) 1, 014607

$$I(\Phi, \Omega_{Y^*}) = \frac{d\sigma}{dt}[1 - p_T \boldsymbol{I^s} \sin 2\Phi - p_T \boldsymbol{I^c} (\widehat{=} \boldsymbol{\Sigma}) \cos 2\Phi + p_\odot \boldsymbol{I^\odot} \qquad \text{lin.+ circ. pol. beam}$$

$$- p_T p_z \boldsymbol{P_z^s} (\widehat{=} \boldsymbol{G}) \sin 2\Phi - p_T p_z \boldsymbol{P_z^c} \cos 2\Phi + p_\odot p_z \boldsymbol{P_z^\odot} (\widehat{=} \boldsymbol{E}) + p_z \boldsymbol{P_z}] \qquad + \text{long. pol. target}$$

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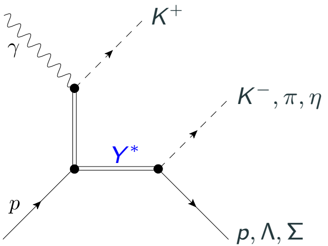

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$$+ p_{x'} \boldsymbol{P_{x'}} + p_{y'} \boldsymbol{P_{y'}} + p_{z'} \boldsymbol{P_{z'}} + p_\odot(p_{x'} \boldsymbol{P_{x'}^\odot} + p_{y'} \boldsymbol{P_{y'}^\odot} + p_{z'} \boldsymbol{P_{z'}^\odot}) \qquad + \text{recoil pol. } (p_{x'} = \alpha_- \cos\theta_{x'}$$

$$+ p_T(p_{x'} \boldsymbol{P_{x'}^s} + p_{y'} \boldsymbol{P_{y'}^s} + p_{z'} \boldsymbol{P_{z'}^s}) \sin 2\Phi + p_T(p_{x'} \boldsymbol{P_{x'}^c} + p_{y'} \boldsymbol{P_{y'}^c} + p_{z'} \boldsymbol{P_{z'}^c}) \cos 2\Phi$$

$$+ p_z(p_{x'} \boldsymbol{O_{zx'}} + p_{y'} \boldsymbol{O_{zy'}} + p_{z'} \boldsymbol{O_{zz'}}) + p_\odot p_z(p_{x'} \boldsymbol{O_{zx'}^\odot} + p_{y'} \boldsymbol{O_{zy'}^\odot} + p_{z'} \boldsymbol{O_{zz'}^\odot})$$

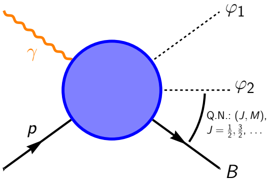
$$+ p_T p_z(p_{x'} \boldsymbol{O_{zx'}^s} + p_{y'} \boldsymbol{O_{zy'}^s} + p_{z'} \boldsymbol{O_{zz'}^s}) \sin 2\Phi + p_T p_z(p_{x'} \boldsymbol{O_{zx'}^c} + p_{y'} \boldsymbol{O_{zy'}^c} + p_{z'} \boldsymbol{O_{zz'}^c}) \cos 2\Phi$$

Moment-analysis formalism for the meson-baryon subsystem

$\gamma(\lambda_\gamma, p_\gamma) + N(\lambda_1, p_N) \longrightarrow \varphi_1(k_1) + \varphi_2(k_2) + B(\lambda_2, k_B)$

5-dimensional phase-space: $(s, t, m^2_{\varphi_2 B} = (k_2 + k_B)^2, \Omega_{\varphi_2 B} \equiv (\theta_{\varphi_2}, \phi_{\varphi_2}))$

$$I(\Omega_{\varphi_2 B}, \Phi) = \kappa_B \sum_{\lambda_\gamma, \lambda'_\gamma, \lambda_1, \lambda_2} \mathcal{A}_{\lambda_\gamma;\lambda_1\lambda_2}(\Omega_{\varphi_2 B}) \rho^\gamma_{\lambda_\gamma, \lambda'_\gamma}(\Phi) \mathcal{A}^*_{\lambda'_\gamma;\lambda_1\lambda_2}(\Omega_{\varphi_2 B})$$



Y. Wunderlich

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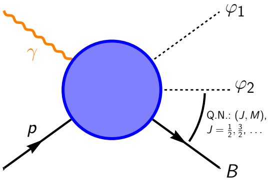

Y. Wunderlich

$$I(\Omega_{\varphi_2 B}, \Phi) = \kappa_B \sum_{\lambda_\gamma, \lambda'_\gamma, \lambda_1, \lambda_2} \mathcal{A}_{\lambda_\gamma;\lambda_1\lambda_2}(\Omega_{\varphi_2 B}) \rho^\gamma_{\lambda_\gamma, \lambda'_\gamma}(\Phi) \mathcal{A}^*_{\lambda'_\gamma;\lambda_1\lambda_2}(\Omega_{\varphi_2 B})$$

Partial-wave expansion of the baryonic helicity amplitude $\mathcal{A}_{\lambda_\gamma;\lambda_1\lambda_2}$:

$$I(\Omega_{\varphi_2 B}, \Phi) = I^0(\Omega_{\varphi_2 B}, \Phi) + \boldsymbol{P}_\gamma(\Phi) \cdot \boldsymbol{I}(\Omega_{\varphi_2 B}, \Phi),$$

$$I^0(\Omega_{\varphi_2 B}, \Phi) = \sum_{\tilde{J}, \tilde{M}, \tilde{N}} H^0(\tilde{J}, \tilde{M}, \tilde{N})\, D^{\tilde{J}}_{\tilde{M}, \tilde{N}}(\Omega_{\varphi_2 B}), \qquad \boldsymbol{I}(\Omega_{\varphi_2 B}, \Phi) = \sum_{\tilde{J}, \tilde{M}, \tilde{N}} \boldsymbol{H}(\tilde{J}, \tilde{M}, \tilde{N})\, D^{\tilde{J}}_{\tilde{M}, \tilde{N}}(\Omega_{\varphi_2 B}).$$

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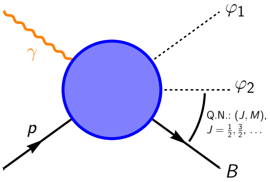

Y. Wunderlich

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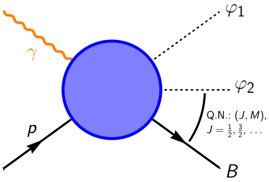

Y. Wunderlich

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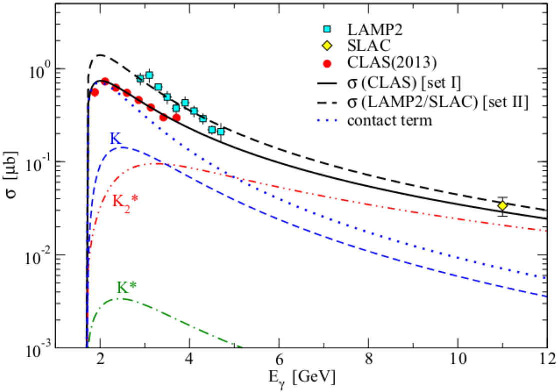
$$\rho^{(0), JJ'}_{MM'}(\tilde{J}, \tilde{M}) = \frac{\kappa_B}{2} \sum_{\lambda_\gamma, \lambda_1, \lambda_2} C^{J-\lambda_2}_{J'-\lambda_2, \tilde{J}\tilde{M}} \mathcal{T}^{(J)}_{\lambda_\gamma, M; \lambda_1\lambda_2} \mathcal{T}^{*(J')}_{\lambda_\gamma, M'; \lambda_1\lambda_2}$$

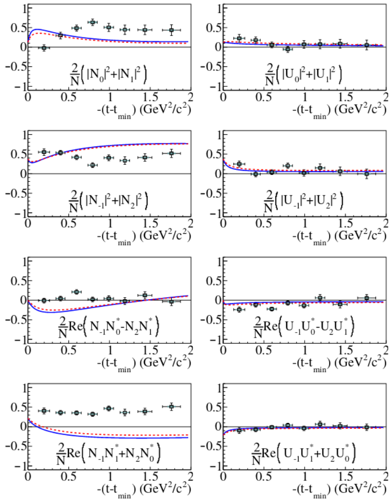
$$\rho^{\alpha, JJ'}_{MM'}(\tilde{J}, \tilde{M}) = \frac{\kappa_B}{2} \sum_{\lambda_\gamma, \lambda'_\gamma, \lambda_1, \lambda_2} C^{J-\lambda_2}_{J'-\lambda_2, \tilde{J}\tilde{M}} \mathcal{T}^{(J)}_{\lambda_\gamma, M; \lambda_1\lambda_2} \sigma^{\alpha}_{\lambda_\gamma, \lambda'_\gamma} \mathcal{T}^{*(J')}_{\lambda'_\gamma, M'; \lambda_1\lambda_2}.$$

Different exchanges in t channel process

$\gamma p \to K^+ \Lambda(1520)$



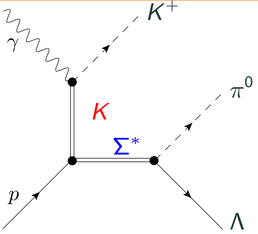
B.-G. Yu and K.-J. Kong, Phys. Rev. C 96, 025208

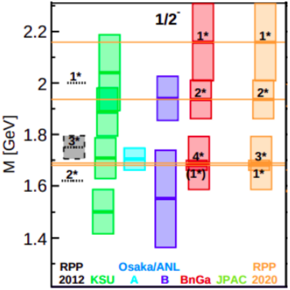


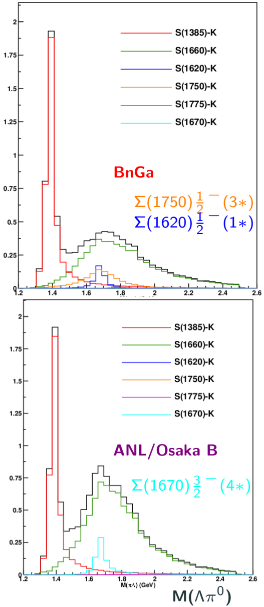
GlueX: Phys.Rev.C 105 (2022) 3, 035201

P. Hurck

Studies for polarization observables with toy models







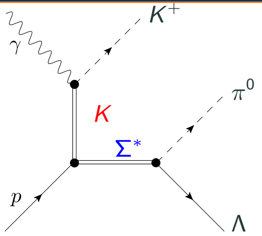
BnGa Toy model:

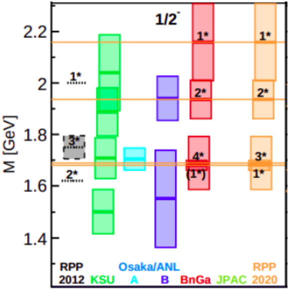
- Only K exchange is considered in t-channel
- Couplings $NK\Sigma^*$ taken from BnGa solution (based on KN data)
- Resonance parameters also taken from BnGa solution
  $\rightarrow$ Phasespace MC weighted with predicted BnGa toy model solution

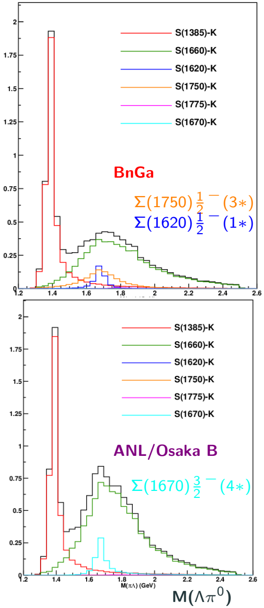
ANL/Osaka Toy model:

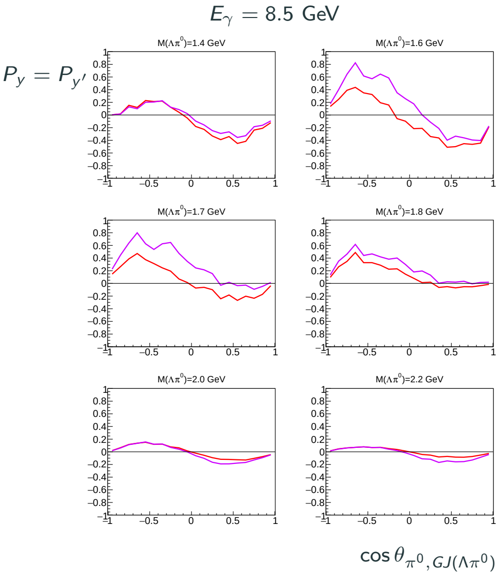
- ANL/Osaka pole positions used to fit BnGa data

Studies for polarization observables with toy models



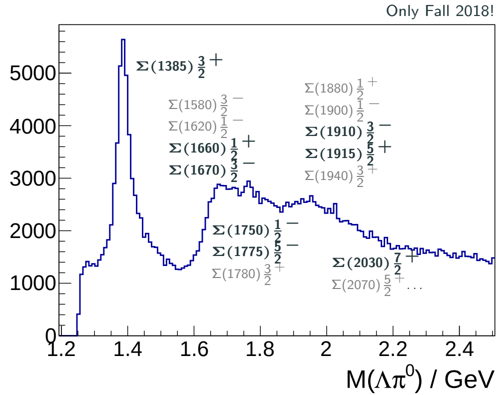


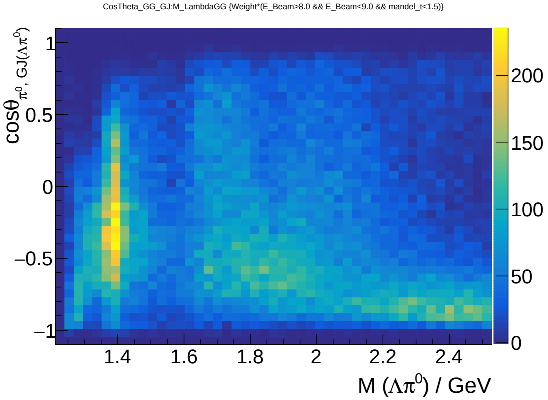




Data quality - Final state $K^+\Lambda\pi^0$

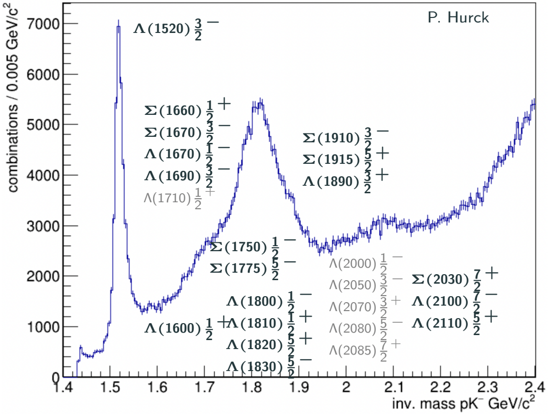
Isospin filter for Σ^*



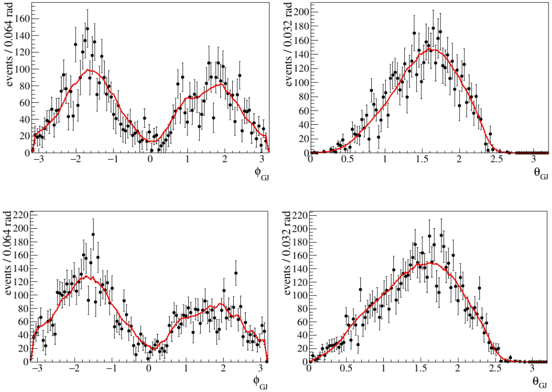


Data quality - Final state K^+pK^-

Only Spring 2017!



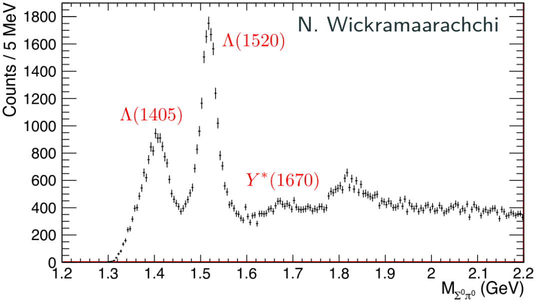
$M(pK^-) \approx 1.52$ GeV, $E_\gamma = 8.5$ GeV, 2 diff. t bins



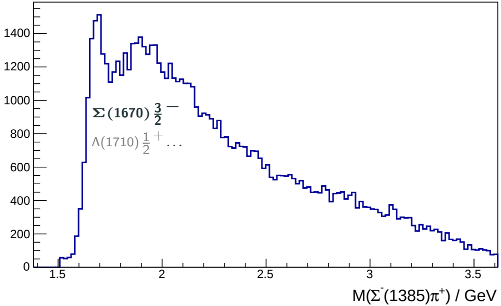
Data quality - Final state $K^+ \Sigma^0\pi^0$ and $K^+ \Sigma(1385)\pi$

- Isospin filter for Λ^* with $K^+\Sigma^0\pi^0$ final state
- Several Λ^* and Σ^* are expected to decay to $\Sigma(1385)\pi$

Only Spring 2017!



Only Spring 2018!



Measurement parameters

Measurement with

- Elliptically polarized photon beam:
  → lin. polarization degree: 38% (coh. peak)
  → circ. polarization degree: 70% (coh. peak)
- FROST target design:
- Longitudinally polarized target: $p_z \approx 90\%$
- Material: Butanol (C_4H_9OH)
  → requires additional measurement with a carbon target for subtraction of unpolarized
  → dilution factor: $50 - 80\%$ (depends on applied cuts)

- Approximately, amount of data of GlueX-Phase I and II combined, would give good good statistics for $K^+\Lambda\pi^0$ and K^+pK^- final states over large mass range
- Needs to be studied in detail!

Summary

- High demand for data in the strange baryon sector
  → Important tests for quark model and lattice QCD predictions
  → Many potentially new or 1^* resonances need confirmation!
- Different facilities will investigate hyperon spectrum, e.g.
  with $\boldsymbol{K_L}$ **beam** in Hall D → Expected to make high impact in finding missing states
  It is planned to measure unpolarized cross section and recoil polarization observable
  One missing piece: **No measurement with a polarized target planned!**
- GlueX experiment with photon beam can provide essential contribution for this missing piece:
  → Measurement with a high-intensity photon beam (ellipt. polarized) and a longitudinally polarized target
  → Polarization observables crucial for sensitivity to not-dominantly contributing resonances!
  → data shows clear signals with good statistics for known resonances, $K^+\Lambda\pi^0$ and K^+pK^- final states look promising
  → **Need a polarized target for measurements!**

Many thanks to Andrey Sarantsev, Kirill Nikonov and Vincent Mathieu!