Strangeness spectroscopy with Photoproduction Experiments

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Outline

Motivation

Hyperon Spectroscopy at CBELSA/TAPS

Hyperon Spectroscopy at GlueX

Conclusion

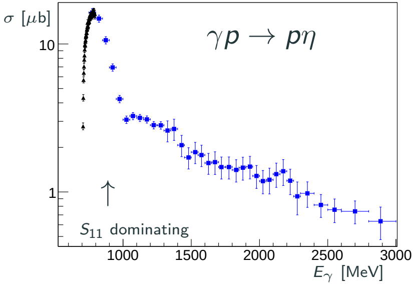
Motivation

Cross Section

Total cross section:

Sum of different partial waves

$\sigma_{tot} \sim |A_{1/2}(S_{11})|^2 + |A_{1/2}(P_{13})|^2 + |A_{3/2}(P_{13})|^2 + \cdots$



Cross Section

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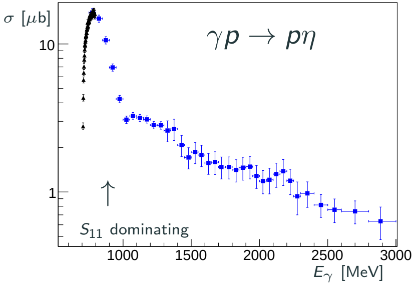
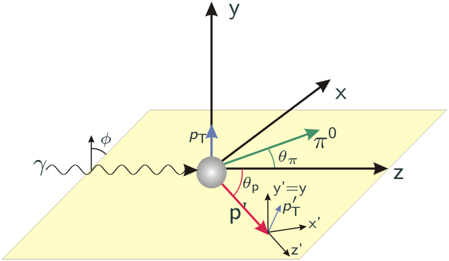


Polarization observables sensitive to interference terms:

$$\Sigma \sim A_{1/2}(S_{11}) \cdot A_{1/2}(P_{11}) + \cdots$$

Measurement of polarization observables necessary for a unique solution of the partial wave analysis and to identify small resonance contributions.

Polarization Observables



16 Polarization Observables in photoproduction of pseudoscalar mesons, e.g. a single π^0:

		Target			**Recoil**			**Target+Recoil**			
		–	–	–	x'	y'	z'	x'	x'	z'	z'
Photon		x	y	z	–	–	–	x	z	x	z
unpolarized	σ	–	T	–	–	P	–	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linearly pol.	Σ	H	(-P)	-G	$O_{x'}$	(-T)	$O_{z'}$	–	–	–	–
circularly pol.	–	F	–	-E	$-C_{x'}$	–	$-C_{z'}$	–	–	–	–

For other reactions see:

[A. Thiel et al., "Light Baryon Spectroscopy," Prog. Part. Nucl. Phys. **125**, 103949 (2022)]

Comparison between PDG values

- Until 2010: almost only results from pion nucleon scattering used in the PDG, only few pion photoproduction data used
- PWA groups include photoproduction data with different final states from several experiments
- Now: new values from the fits are entering the PDG

Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***	-			-		
$N(1520)$	$3/2^-$	****	****	****	****	**	****			- - - -		
$N(1535)$	$1/2^-$	****	****	****	***	*	****			- -		
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*- -	- -	- -		
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*	-		
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*	- - - -		
$N(1700)$	$3/2^-$	***	**	***	***	*	*	- -	-	-		
$N(1710)$	$1/2^+$	****	****	****	*-		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*-	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**	-	*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*-	**	*	*	-	-	- -	*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

[A. Thiel et al., PPNP **125**, 103949 (2022)]

Large improvement, but still a lot of work to be done!

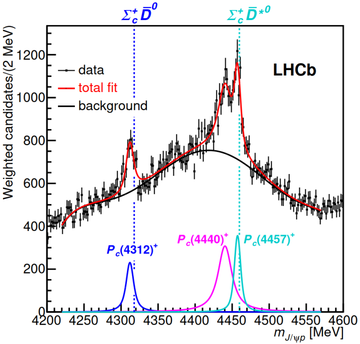
Hyperons in the PDG

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Sigma\pi$	Other channels
$\Lambda(1116)$	$1/2^+$	****			$N\pi$ (weak decay)
$\Lambda(1380)$	$1/2^-$	**	**	**	
$\Lambda(1405)$	$1/2^-$	****	****	****	
$\Lambda(1520)$	$3/2^-$	****	****	****	$\Lambda\pi\pi, \Lambda\gamma, \Sigma\pi\pi$
$\Lambda(1600)$	$1/2^+$	****	***	****	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1670)$	$1/2^-$	****	****	****	$\Lambda\eta$
$\Lambda(1690)$	$3/2^-$	****	****	***	$\Lambda\pi\pi, \Sigma(1385)\pi$
$\Lambda(1710)$	$1/2^+$	*	*	*	
$\Lambda(1800)$	$1/2^-$	***	***	**	$\Lambda\pi\pi, N\overline{K}^*$
$\Lambda(1810)$	$1/2^+$	***	**	**	$N\overline{K}^*$
$\Lambda(1820)$	$5/2^+$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1830)$	$5/2^-$	****	****	****	$\Sigma(1385)\pi$
$\Lambda(1890)$	$3/2^+$	****	****	**	$\Sigma(1385)\pi, N\overline{K}^*$
$\Lambda(2000)$	$1/2^-$	*	*	*	
$\Lambda(2050)$	$3/2^-$	*	*	*	
$\Lambda(2070)$	$3/2^+$	*	*	*	
$\Lambda(2080)$	$5/2^-$	*	*	*	
$\Lambda(2085)$	$7/2^+$	**	**	*	
$\Lambda(2100)$	$7/2^-$	****	****	**	$N\overline{K}^*$
$\Lambda(2110)$	$5/2^+$	***	**	**	$N\overline{K}^*$
$\Lambda(2325)$	$3/2^-$	*	*		
$\Lambda(2350)$	$9/2^+$	***	***	*	
$\Lambda(2585)$		*	*		

Particle	J^P	Overall status	Status as seen in — $N\overline{K}$	$\Lambda\pi$	$\Sigma\pi$	Other channels
$\Sigma(1193)$	$1/2^+$	****				$N\pi$ (weak decay)
$\Sigma(1385)$	$3/2^+$	****		****	****	$\Lambda\gamma$
$\Sigma(1580)$	$3/2^-$	*	*	*	*	
$\Sigma(1620)$	$1/2^-$	*	*	*	*	
$\Sigma(1660)$	$1/2^+$	***	***	***	***	
$\Sigma(1670)$	$3/2^-$	****	****	****	****	
$\Sigma(1750)$	$1/2^-$	***	***	**	***	$\Sigma\eta$
$\Sigma(1775)$	$5/2^-$	****	****	****	**	
$\Sigma(1780)$	$3/2^+$	*	*	*	*	
$\Sigma(1880)$	$1/2^+$	**	**	*		
$\Sigma(1900)$	$1/2^-$	**	**	*	**	
$\Sigma(1910)$	$3/2^-$	***	*	*	**	
$\Sigma(1915)$	$5/2^+$	****	***	***	***	
$\Sigma(1940)$	$3/2^+$	*	*		*	
$\Sigma(2010)$	$3/2^-$	*	*	*		
$\Sigma(2030)$	$7/2^+$	****	****	****	**	$\Delta(1232)\overline{K}, N\overline{K}^*, \Sigma(1385)\pi$
$\Sigma(2070)$	$5/2^+$	*	*		*	
$\Sigma(2080)$	$3/2^+$	*		*		
$\Sigma(2100)$	$7/2^-$	*	*	*	*	
$\Sigma(2110)$	$1/2^-$	*	*	*	*	
$\Sigma(2230)$	$3/2^+$	*	*	*	*	
$\Sigma(2250)$		**	**	*	*	
$\Sigma(2455)$		*	*			
$\Sigma(2620)$		*	*			
$\Sigma(3000)$		*	*	*		
$\Sigma(3170)$		*				

Mostly unknown states for masses $M > 2000$ MeV

Data on pentaquarks by LHCb:



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

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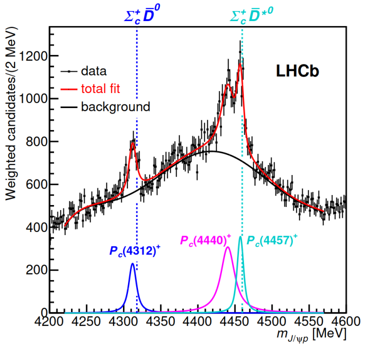

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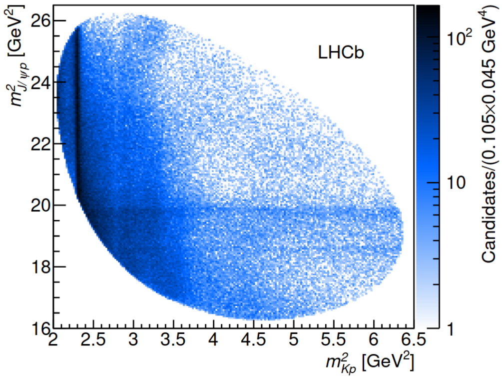
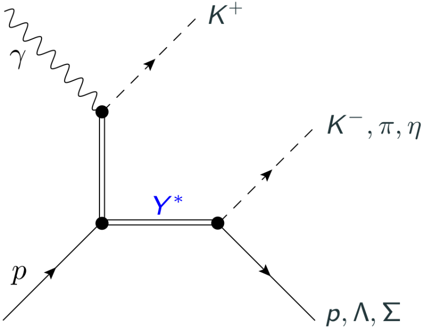


Source: R. Aaij *et al.* [LHCb], PRL **122**, no.22, 222001 (2019)

Horizontal lines: Pentaquarks

Vertical lines: Strange Baryon Resonances

Reactions

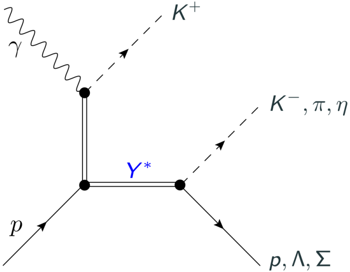


Photoproduction of Hyperons via t-channel exchange

Possible final states

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



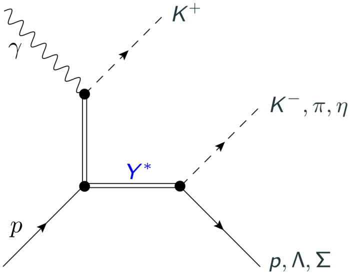
Photoproduction of two pseudo-scalars: Roberts, Oed (2005)

- 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

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

lin. & circ. pol. beam

Polarization Observables of Interest



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$$- p_T p_z \boldsymbol{P_z^s} (\boldsymbol{\hat{=}G}) \sin 2\Phi - p_T p_z \boldsymbol{P_z^c} \cos 2\Phi + p_\odot p_z \boldsymbol{P_z^\odot} (\boldsymbol{\hat{=}E}) + p_z \boldsymbol{P_z}]$$

& long. pol. target

Polarization Observables of Interest

For a linearly and circularly polarized beam, on a longitudinally polarized target and measurement of the recoil polarization (self-analyzing decay):

$$
\begin{aligned}
I(\Phi, \Omega_{Y^*}) = \frac{d\sigma}{dt}[1 &- p_T \boldsymbol{I^s} \sin 2\Phi - p_T \boldsymbol{I^c (\widehat{=}\Sigma)} \cos 2\Phi + p_\odot \boldsymbol{I^\odot} \\
&- p_T p_z \boldsymbol{P_z^s (\widehat{=}G)} \sin 2\Phi - p_T p_z \boldsymbol{P_z^c} \cos 2\Phi + p_\odot p_z \boldsymbol{P_z^\odot (\widehat{=}E)} + p_z \boldsymbol{P_z}] \\
&+ p_{x'} \boldsymbol{P_{x'}} + p_{y'} \boldsymbol{P_{y'}} + p_{z'} \boldsymbol{P_{z'}} + p_\odot (p_{x'} \boldsymbol{P_{x'}^\odot} + p_{y'} \boldsymbol{P_{y'}^\odot} + p_{z'} \boldsymbol{P_{z'}^\odot}) \\
&+ p_T (p_{x'} \boldsymbol{P_{x'}^s} + p_{y'} \boldsymbol{P_{y'}^s} + p_{z'} \boldsymbol{P_{z'}^s}) \sin 2\Phi + p_T (p_{x'} \boldsymbol{P_{x'}^c} + p_{y'} \boldsymbol{P_{y'}^c} + p_{z'} \boldsymbol{P_{z'}^c}) \cos 2\Phi \\
&+ p_z (p_{x'} \boldsymbol{O_{zx'}} + p_{y'} \boldsymbol{O_{zy'}} + p_{z'} \boldsymbol{O_{zz'}}) + p_\odot p_z (p_{x'} \boldsymbol{O_{zx'}^\odot} + p_{y'} \boldsymbol{O_{zy'}^\odot} + p_{z'} \boldsymbol{O_{zz'}^\odot}) \\
&+ p_T p_z (p_{x'} \boldsymbol{O_{zx'}^s} + p_{y'} \boldsymbol{O_{zy'}^s} + p_{z'} \boldsymbol{O_{zz'}^s}) \sin 2\Phi \\
&+ p_T p_z (p_{x'} \boldsymbol{O_{zx'}^c} + p_{y'} \boldsymbol{O_{zy'}^c} + p_{z'} \boldsymbol{O_{zz'}^c}) \cos 2\Phi
\end{aligned}
$$

Additional observables accessible with a transversely polarized target.

Extraction of the Amplitudes

Complete Experiment: Model-independent extraction of all amplitudes without discrete ambiguities

$\rightarrow$ 16 Observables needed for two meson photoproduction!

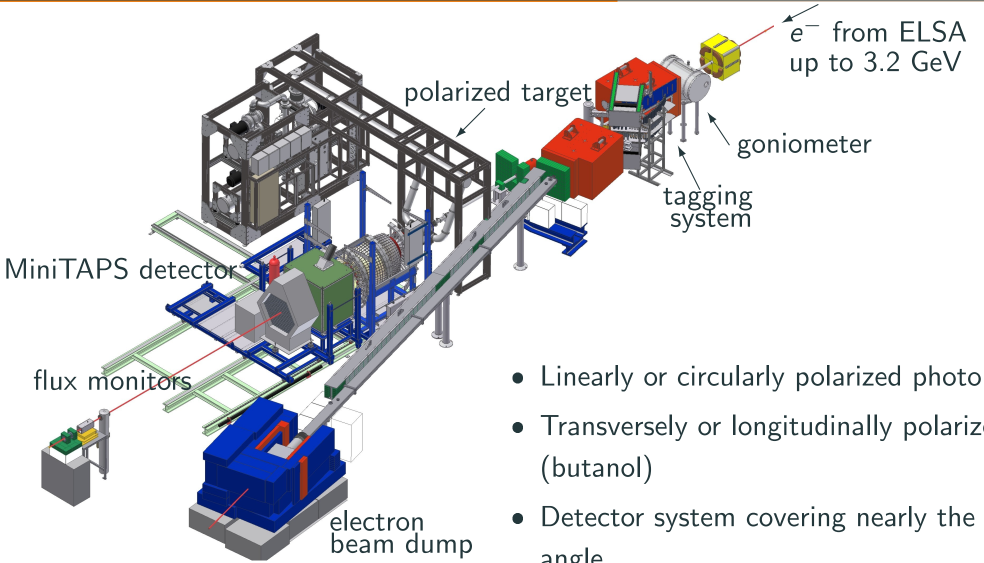
P. Kroenert, et al. Phys. Rev. C **103**, no.1, 014607 (2021)

Two possibilities to extract amplitudes from the observables:

- Extract observables and provide them as input to different partial wave analysis groups
  Contact with different groups initiated
- Direct extraction of the amplitudes from the fit
  Framework currently being developed in Bonn

Hyperon Spectroscopy at CBELSA/TAPS

The CBELSA/TAPS Experiment



- Linearly or circularly polarized photons
- Transversely or longitudinally polarized target (butanol)
- Detector system covering nearly the full solid angle

Future Perspectives: Strangeness Measurements at Bonn

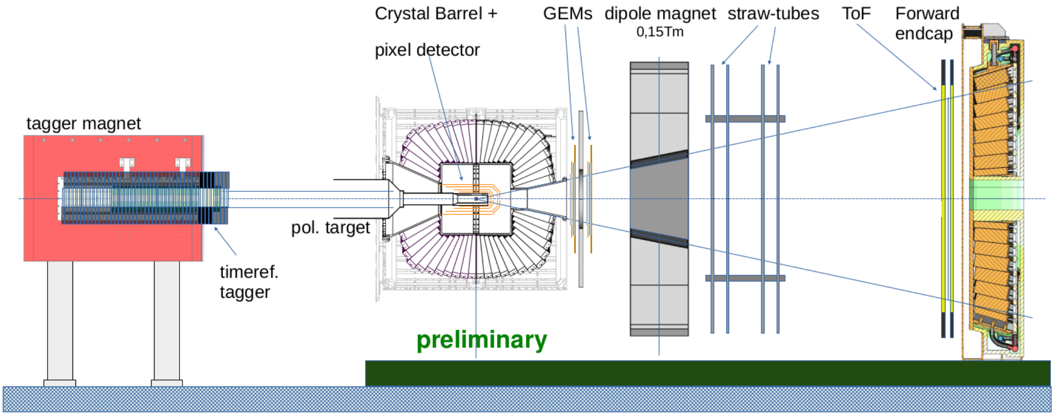
Up to now mostly measurements of non-strange baryons (N^*, Δ^*)
$\rightarrow$ Extension to the strange sector (Λ^*, Σ^*) planned

- Strangeness measurements with a polarized beam and a polarized target possible!
- Precise mapping of Hyperons with masses up to ~ 2 GeV and extraction of quantum numbers
- Investigation of two-pole structure of $\Lambda(1405)$ possible

Planned Setup for CBELSA++

Major Experimental Upgrade!

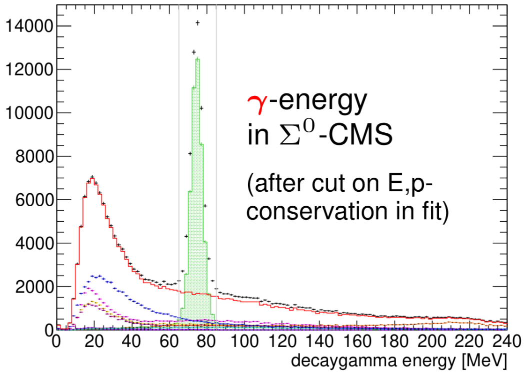
Additional forward spectrometer including large-scale forward calorimeter



Anticipated Impact

Simulation of reaction $\gamma p \rightarrow K^+\Sigma^0\pi^0$ with $\Sigma^0 \rightarrow \gamma\Lambda$

Selection of Σ^0 via decay photon energy



Included BG channels:

$K\Sigma(1385)$

$K^0\Sigma^+$

$K^+\Sigma^0$

$p\pi^0\eta$

$p\pi^+\pi^-\pi^0$

$K^+\Sigma(1385)\pi^0$

$K^+\Sigma^+\pi^-$

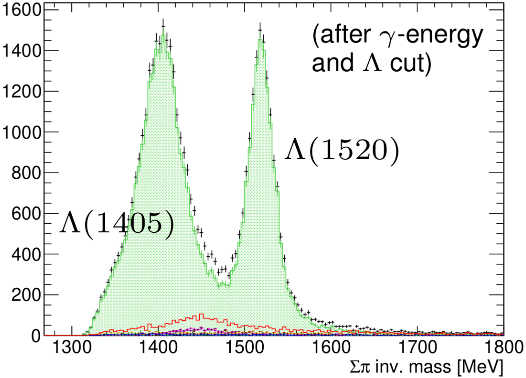
$K^+\Lambda\pi^0$

Sum

Anticipated Impact

Simulation of reaction $\gamma p \rightarrow K^+\Sigma^0\pi^0$ with $\Sigma^0 \rightarrow \gamma\Lambda$

Clear Signal of $\Lambda(1405)$ and $\Lambda(1520)$ visible, higher mass states not included yet



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$K^0\Sigma^+$

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$K^+\Sigma(1385)\pi^0$

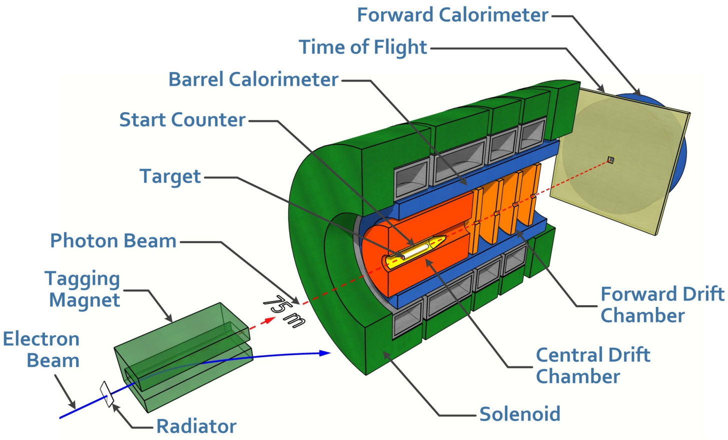
$K^+\Sigma^+\pi^-$

$K^+\Lambda\pi^0$

Sum

Hyperon Spectroscopy at GlueX

The GlueX experiment at JLab



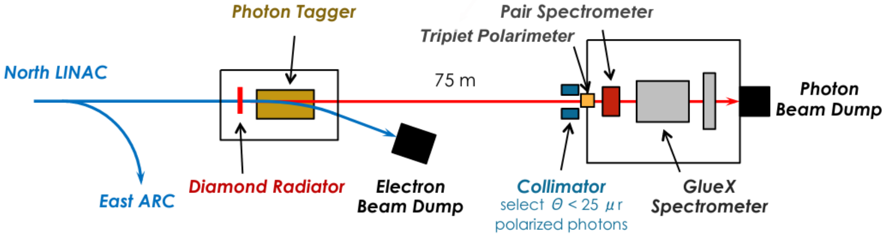
[S. Adhikari, et al. Nucl.Instrum.Meth.A 987 (2021) 164807]

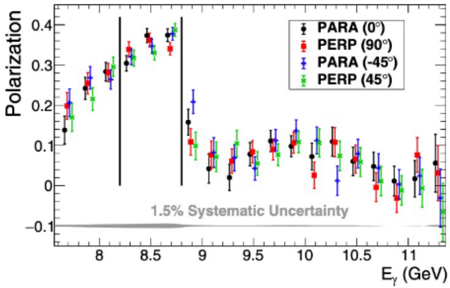
GlueX Phase I:
Data taking finished

GlueX Phase II:
Ring-imaging Cherenkov (DIRC) detector added

Recent update:
Upgrade of FCAL
$PbWO_4$ insert

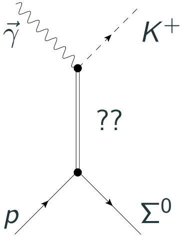
Beam Polarization





- Linearly polarized photons to shed light onto the exchange mechanism
- Coherent bremsstrahlung off a diamond crystal
- Polarization degree determined by a triplet polarimeter

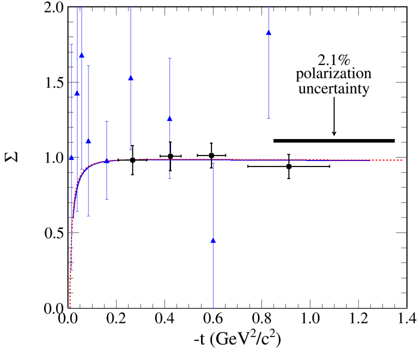
Measurements of the Beam Asymmetry Σ



Beam asymmetry Σ sensitive to the exchange mechanism:

- $\Sigma > 0$: natural exchange favored
- $\Sigma < 0$: unnatural exchange favored

$\gamma p \to \Sigma^0 K^+$

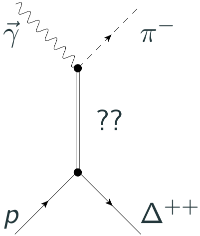


blue: SLAC
black: GlueX

Results for strangeness production show dominance of natural exchange $\to$ Kaons

[S. Adhikari et al. Phys. Rev. C **101**, 6, 065206 (2020)]

Measurements of the Beam Asymmetry Σ



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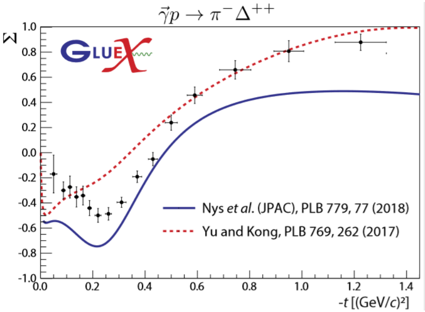


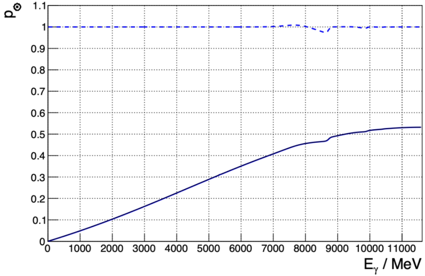
[S. Adhikari, et al. Phys.Rev.C 103 (2021) 2, L022201]

Analysis of Σ hints at different particles in the t-channel

Interesting for hyperon production?

Possible Polarization Measurements

- Elliptically polarized beam: linearly and circularly at the same time!



For information about this method see

[F. Afzal *et al.* Phys. Rev. Lett. **132**, no.12, 121902 (2024)]

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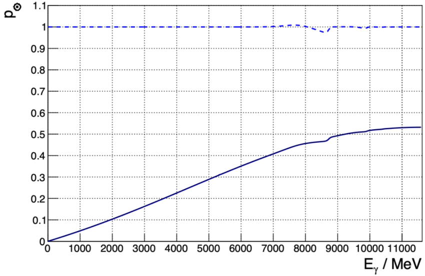
- Elliptically polarized beam: linearly and circularly at the same time!

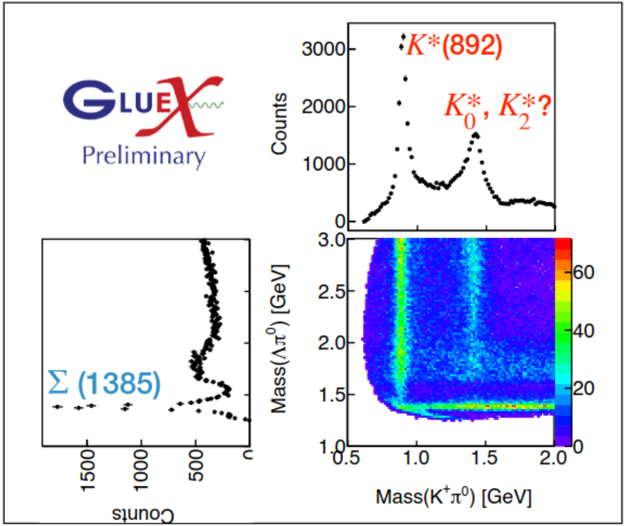


For information about this method see

[F. Afzal *et al.* Phys. Rev. Lett. **132**, no.12, 121902 (2024)]

- Polarized target (Proposed for GDH measurement) currently being developed
  - Butanol target
  - Longitudinally polarized

Dalitz Plot for Hyperons

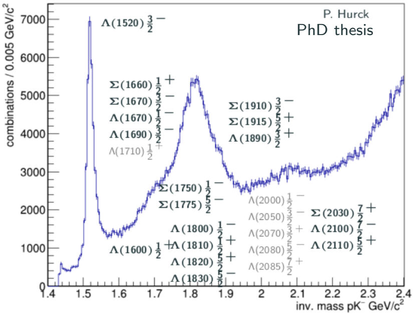


Source: Hao Li, this workshop

Multiple Hyperons directly visible in the data

Various final states accessible e.g. pK^+K^-, $K^+\Sigma\pi$, $K^+\Lambda\pi$, $K^+\Sigma\eta$, $K^+\Lambda\eta$,...

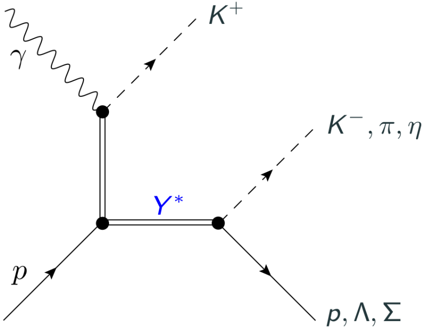
Only Spring 2017!



Conclusion

Complementary Measurement between GlueX and CBELSA++

- Large amount of data on hyperons with a polarized photon beam available at GlueX!
- Various different exchange particles possible (K, K^* ...)
- Polarized target may be available in the future



- GlueX can probe the high-mass states
- CBELSA++ can focus on precision spectroscopy of the low-mass states

$\rightarrow$ Only the combination of both experiments can cover the whole mass range!

Conclusion and Outlook

- New era of experiments allows precise measurements of (polarization) observables for Meson and Baryon Spectroscopy
- New polarization data will help to understand the resonance spectra and will provide an experimental basis for comparison with constituent quark models, lattice QCD or other methods
- New experiment at ELSA currently being developed, which will shed light onto the strange sector.
- LoI for polarization measurements at GlueX currently being written

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Thank you for your attention.