Physics with the new INSIGHT experiment @ELSA

UNIVERSITÄT BONN

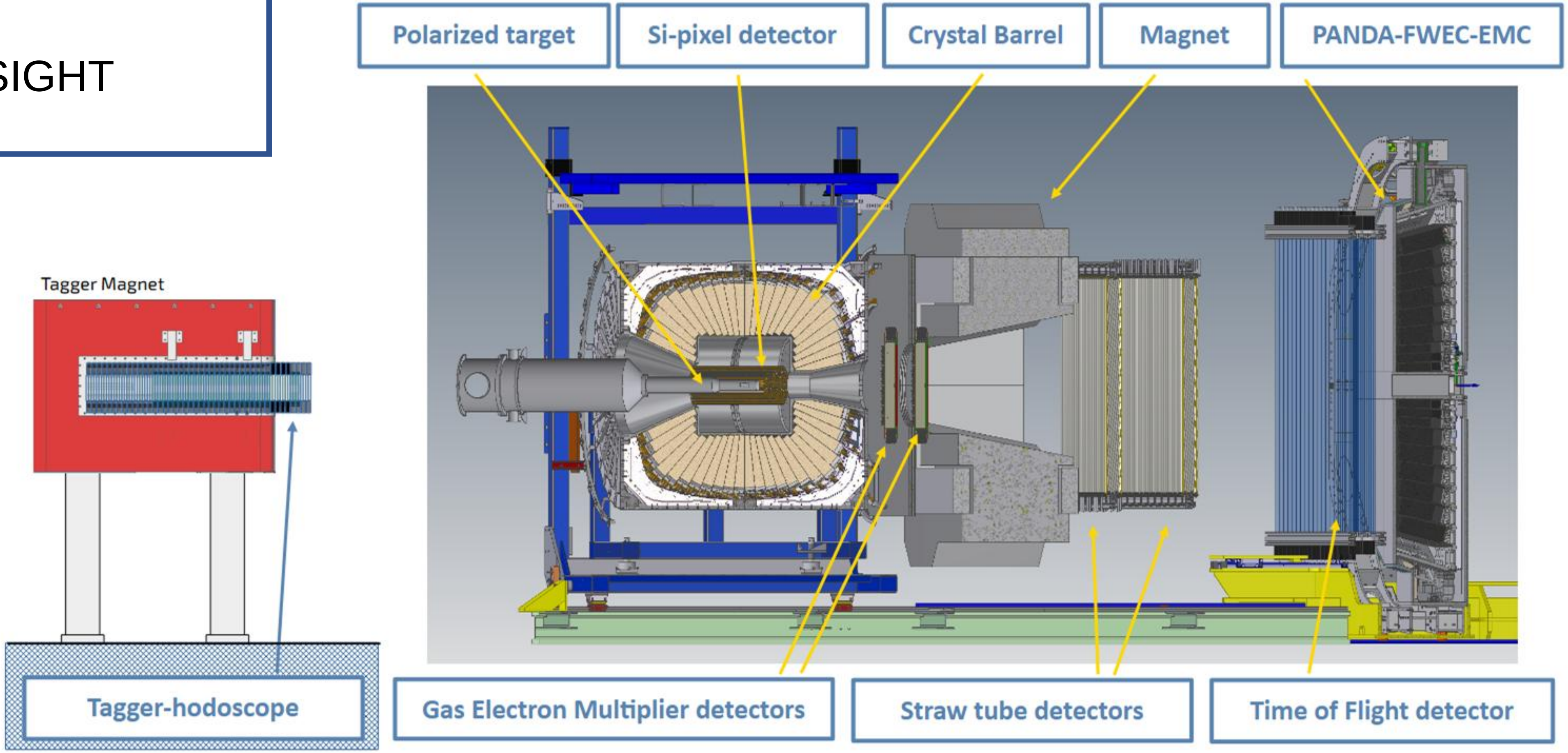
U.Thoma

Contents:

- Introduction
- Open questions
- The future with INSIGHT

INSIGHT @ELSA

Investigation of the strong interaction in the light flavor sector



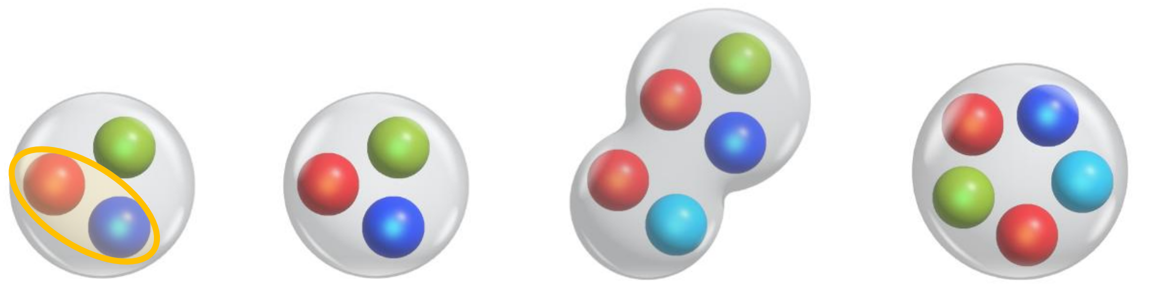
Introduction

QCD in the non-perturbative regime:

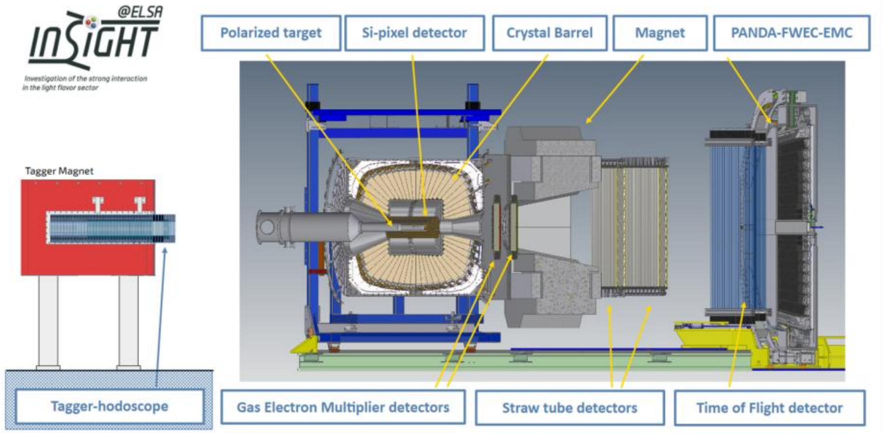
⇔ One of the worst understood areas of the standard model = a challenge!

⇔ How does QCD produce its massive bound states from almost massless quarks?

- What are the relevant degrees of freedom?
- Effective forces between them?



⇔ Nature of the complex bound states of QCD = ?



⇔ **Experimental spectrum of baryons and their properties**

⇔ **Search for exotic states**

Physics at ELSA - results on the baryon spectrum

Polarization as key to resolve the baryon spectrum

→ **huge impact on knowledge of resonances in the second and third resonance region based on data from ELSA + exp. worldwide**

	RPP 2010	BnGa-PWA	RPP'25 (2018-25)
N(1710)1/2+	***	****	****
N(1860)5/2+		*	**
N(1875)3/2−		***	***
N(1880)1/2+		***	***
N(1895)1/2−		****	****
N(1900)3/2+	**	****	****
N(2060)5/2−		***	***
N(2100)1/2+	*	***	***
N(2120)3/2−		***	***
Δ(1600)3/2+	***	***	****
Δ(1900)1/2−	*	***	***
Δ(1940)3/2−	*	**	**
Δ(2200)7/2−	*	***	***

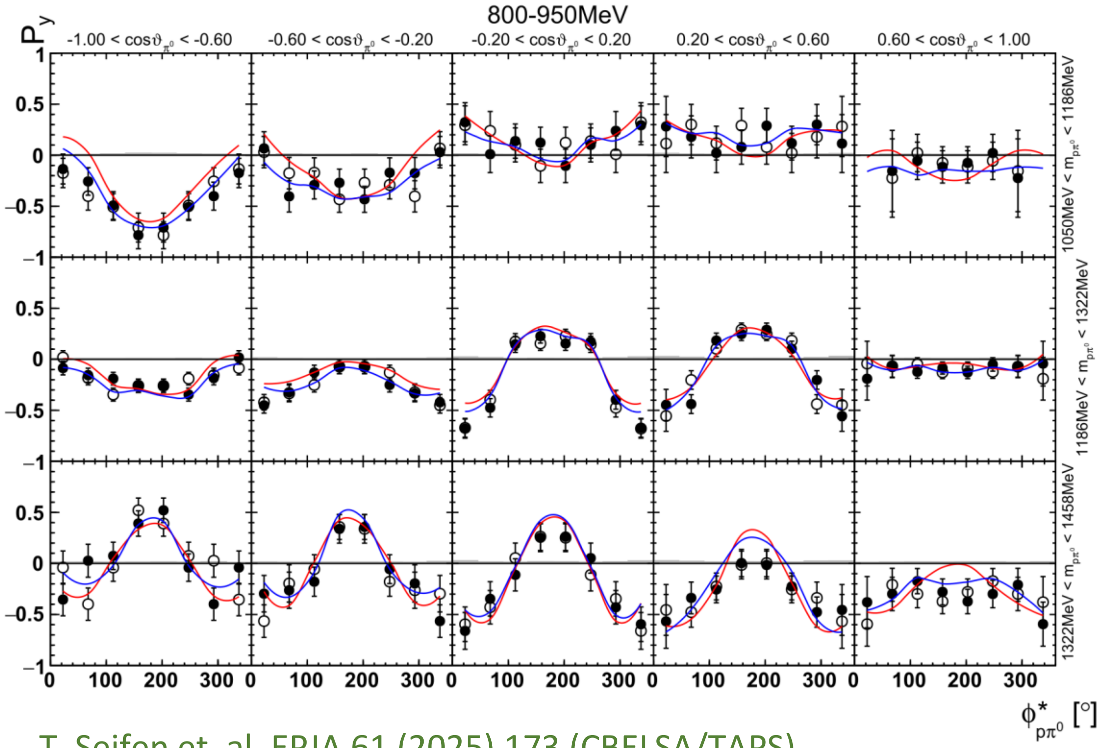
only examples shown

Up to 2.3 GeV:

- **6 new N*-resonances found** (25% of known N*-states)
- **7 N* + 2 Δ* new in the PDG summary tables** (30%)
- Many new resonance properties determined

$\gamma p \rightarrow p\, \pi^0 \pi^0$ (CBELSA/TAPS) **- Target asymmetry data**

(only a few bins shown)



T. Seifen et. al. EPJA 61 (2025) 173 (CBELSA/TAPS)

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N(1895)1/2−		****	****
N(1900)3/2+	**	****	****
N(2060)5/2−		***	***
N(2100)1/2+	*	***	***
N(2120)3/2−		***	***
Δ(1600)3/2+	***	***	****
Δ(1900)1/2−	*	***	***
Δ(1940)3/2−	*	**	**
Δ(2200)7/2−	*	***	***

only examples shown

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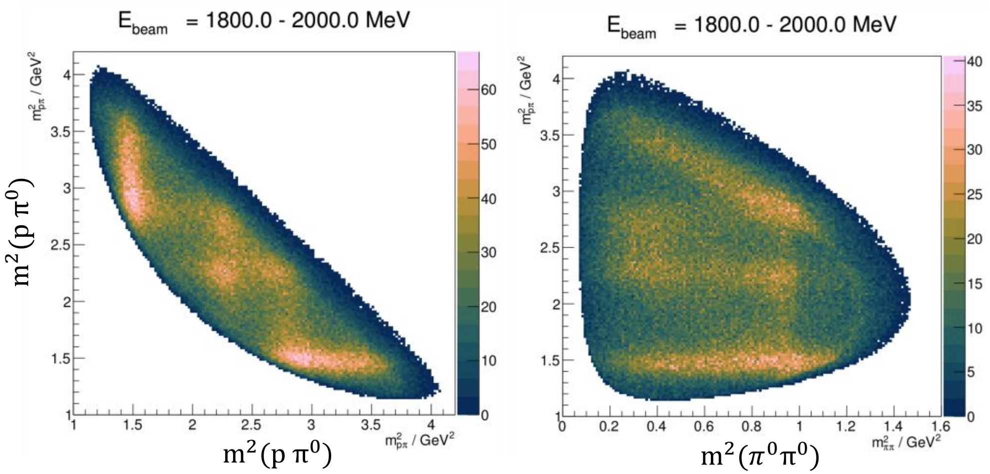
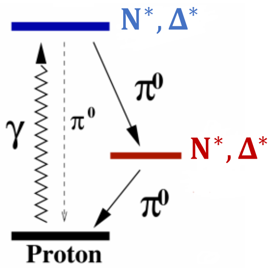


$$\gamma p \rightarrow N^*, \Delta^* \rightarrow \Delta(1232)\pi^0 \rightarrow p\,\pi^0\pi^0$$
$$\rightarrow N(1520)\pi^0 \rightarrow p\,\pi^0\pi^0$$
$$\rightarrow N(1680)\pi^0 \rightarrow p\,\pi^0\pi^0$$
$$\rightarrow \ldots..$$
$$\rightarrow p\,f_0(980) \rightarrow p\,\pi^0\pi^0$$



Clear observation of cascading decays

⇔ **Important: polarisation observables:**

$T, P, H, \Sigma, P_x, P_y, P_x^s, P_y^s, P_x^c, P_y^c, I_s, I_c$

(published, in prep.)

Physics at ELSA - results on the baryon spectrum

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N(1900)3/2+	**	****	****
N(2060)5/2−		***	***
N(2100)1/2+	*	***	***
N(2120)3/2−		***	***
Δ(1600)3/2+	***	***	****
Δ(1900)1/2−	*	***	***
Δ(1940)3/2−	*	**	**
Δ(2200)7/2−	*	***	***

only examples shown

Up to 2.3 GeV:

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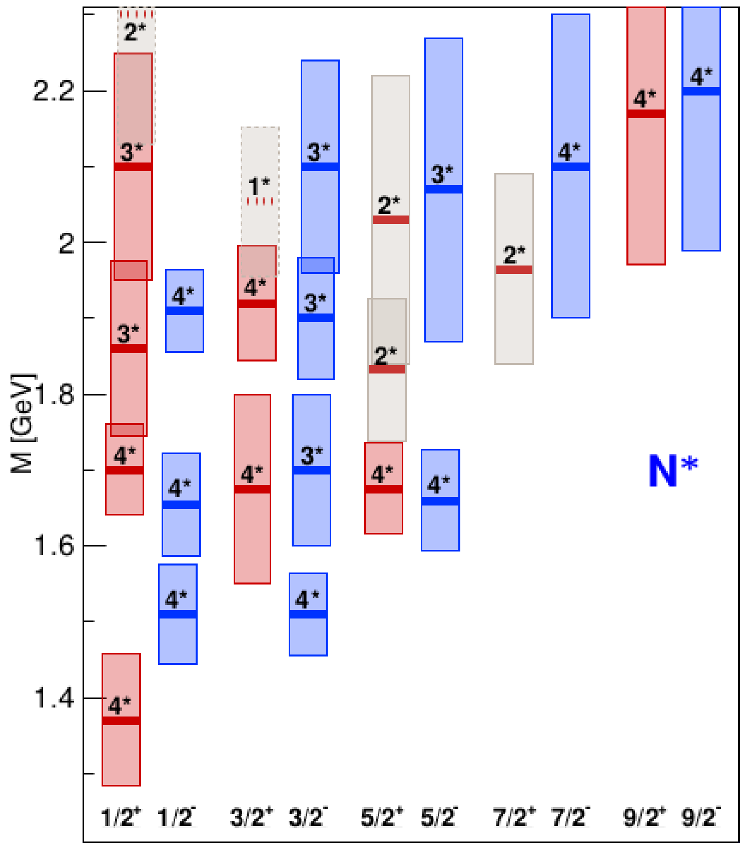
N^*-pole positions:



N^*, Δ^* -parity doublets occur (but not for all states)

⇔ **Not expected by present lattice calculations or constituent quark models**

⇔ **Not yet understood**

Excited baryon spectrum – open questions

Open questions (examples)**:**

⇔ **Do all the expected qqq-SU(6)xO(3)-states exist?**

- **Existing but experimentally not found yet?**

  ⇔ pol. photoproduction off the neutron (isospin dependence)

  ⇔ multi-meson photoproduction, further final states

  continuation of the successful N^*, Δ^*-program

⇔ **Certain resonances have parity partners other‘s don‘t** ⇔ **Why?**

- **Needs to be explained by theory**

  ⇔ effective degrees of freedom / effective forces

  ⇔ meson-baryon or 3q or …..

… also relates to the first point …

➔ **Clarify the systematics in the spectrum !**

(SU(6): u ↑↓ d ↑↓ **s** ↑↓)

⇔ **strange baryons of large interest**

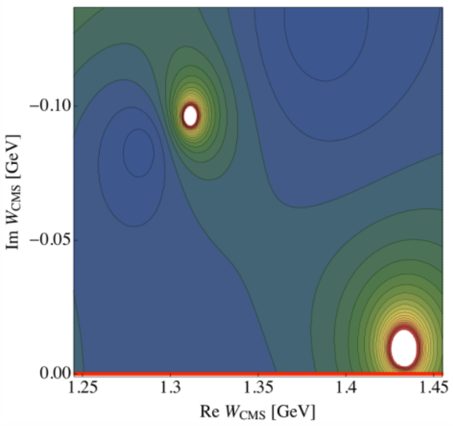
- since decades: progress hampered by the lack of high quality data not even the first excitation band completely know

⇔ **multiquark states? molecules? 2 pole-structures?**

- **$\Lambda(1405)$: 2 pole structure**

  chiral unitary approach

  ↔ meson-baryon interaction



M. Mai EPJST (2021) 230:1593

$(m,\Gamma)=(1325\pm16, 180^{+24}_{-36})$MeV

$(m,\Gamma)=(1429^{+8}_{-7}, 24^{+4}_{-6})$MeV

Excited baryon spectrum – open questions

(D, L_N^P)	S	J^P	Singlet	Octet N	Octet Λ	Octet Σ	Decuplet Δ	Decuplet Σ
$(56, 0_0^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$		$N(939)$	$\Lambda(1116)$	$\Sigma(1193)$		
	$\frac{3}{2}$	$\frac{3}{2}^+$					$\Delta(1232)$	$\Sigma(1385)$
$(70, 1_1^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$	$\Lambda(1405)$	$N(1535)$	$\Lambda(1670)$	$\Sigma(1620)$	$\Delta(1620)$	$\Sigma(1900)\dagger$
		$\frac{3}{2}^-$	$\Lambda(1520)$	$N(1520)$	$\Lambda(1690)$	$\Sigma(1670)$	$\Delta(1700)$	$\Sigma(1910)\dagger$
	$\frac{3}{2}$	$\frac{1}{2}^-$		$N(1650)$	$\Lambda(1800)$	$\Sigma(1750)$		
		$\frac{3}{2}^-$		$N(1700)$	-	-		
		$\frac{5}{2}^-$		$N(1675)$	$\Lambda(1830)$	$\Sigma(1775)$		
$(56, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$		$N(1440)$	$\Lambda(1600)$	$\Sigma(1660)$		
	$\frac{3}{2}$	$\frac{3}{2}^+$					$\Delta(1600)$	$\Sigma(1780)$
$(70, 0_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	$\Lambda(1710)$	$N(1710)$	$\Lambda(1810)$	$\Sigma(1880)$	$\Delta(1750)$	-
	$\frac{3}{2}$	$\frac{3}{2}^+$		-	-	-		
$(56, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$		$N(1720)$	$\Lambda(1890)$	$\Sigma(1940)$		
	$\frac{1}{2}$	$\frac{5}{2}^+$		$N(1680)$	$\Lambda(1820)$	$\Sigma(1915)$		
	$\frac{3}{2}$	$\frac{1}{2}^+$					$\Delta(1910)$	
	$\frac{3}{2}$	$\frac{3}{2}^+$					$\Delta(1920)$	$\Sigma(2080)$
	$\frac{3}{2}$	$\frac{5}{2}^+$					$\Delta(1905)$	$\Sigma(2070)$
	$\frac{3}{2}$	$\frac{7}{2}^+$					$\Delta(1950)$	$\Sigma(2030)$
$(70, 2_2^+)$	$\frac{1}{2}$	$\frac{3}{2}^+$	$\Lambda(2070)$	-	-	-	-	-
		$\frac{5}{2}^+$	$\Lambda(2110)$	$N(1860)$	-	-	$\Delta(2000)$	-
	$\frac{3}{2}$	$\frac{1}{2}^+$		$N(1880)$	-	-		
		$\frac{3}{2}^+$		$N(1900)$	-	-		
		$\frac{5}{2}^+$		$N(2000)$	-	-		
		$\frac{7}{2}^+$		$N(1990)$	$\Lambda(2085)$	-		
$(20, 1_2^+)$	$\frac{1}{2}$	$\frac{1}{2}^+$	-	-	-	-		
		$\frac{3}{2}^+$	-	-	-	-		
		$\frac{5}{2}^+$	-					
$(56, 1_3^-)$	$\frac{1}{2}$	$\frac{1}{2}^-$		$N(1895)$	$\Lambda(2000)$	$\Sigma(1900)\dagger$		
		$\frac{3}{2}^-$		$N(1875)$	$\Lambda(2050)$	$\Sigma(1910)\dagger$		
	$\frac{3}{2}$	$\frac{1}{2}^-$					$\Delta(1900)$	$\Sigma(2110)\dagger$
		$\frac{3}{2}^-$					$\Delta(1940)$	$\Sigma(2010)\dagger$
		$\frac{5}{2}^-$					$\Delta(1930)$	-
$(70, 3_3^-)$	$\frac{1}{2}$	$\frac{5}{2}^-$	$\Lambda(2080)$	$N(2060)$	-	-	-	-
		$\frac{7}{2}^-$	$\Lambda(2100)$	$N(2190)$	-	$\Sigma(2100)$	$\Delta(2200)$	-

⇐ **First excitation band**

Λ^*, Σ^*:

Not known

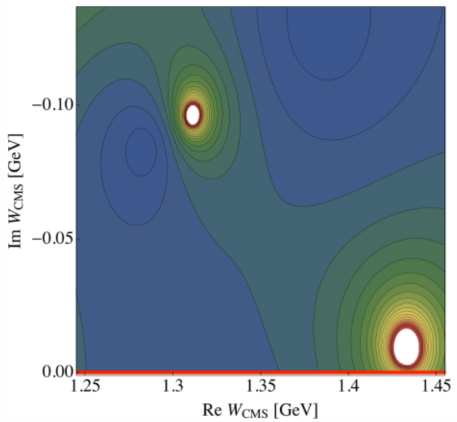
$1^*, 2^*$ only

N^*, Δ^*:

Not known

$1^*, 2^*$ only

- **$\Lambda(1405)$: 2 pole structure**
  chiral unitary approach
  ↔ meson-baryon interaction



M. Mai EPJST (2021) 230:1593

$(m,\Gamma)=(1325\pm16, 180^{+24}_{-36})$MeV

$(m,\Gamma)=(1429^{+8}_{-7}, 24^{+4}_{-6})$MeV

$\Lambda(1325)$: Singlet dominant

$\Lambda(1405)$: Octet dominat

⇔ **Destroys the symmety of the 3-Quark -model**

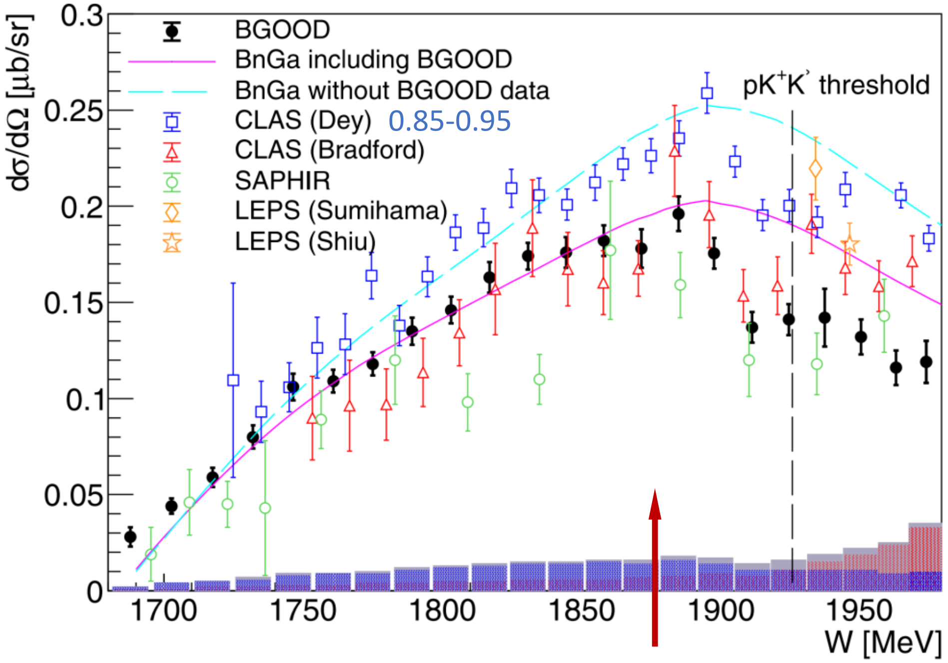
Important: Investigate the full SU(6)
u ↑↓, d ↑↓, s ↑↓ space !

(INSIGHT: up to $m(\Lambda, \Sigma)$=2 GeV)

Physics at ELSA - Interesting observations @BGOOD

Interesting observations, e.g.:

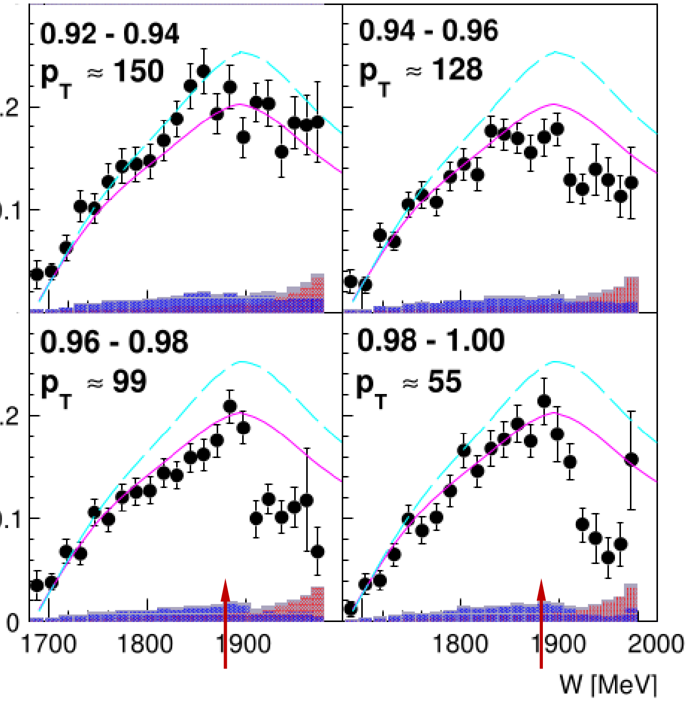
BGOOD: $\gamma p \rightarrow K^+ \Sigma^0$, $\cos(\Theta)_K > 0.9$



T. Jude et al.,PLB 820 (2021) 136559

Σ(1385) K

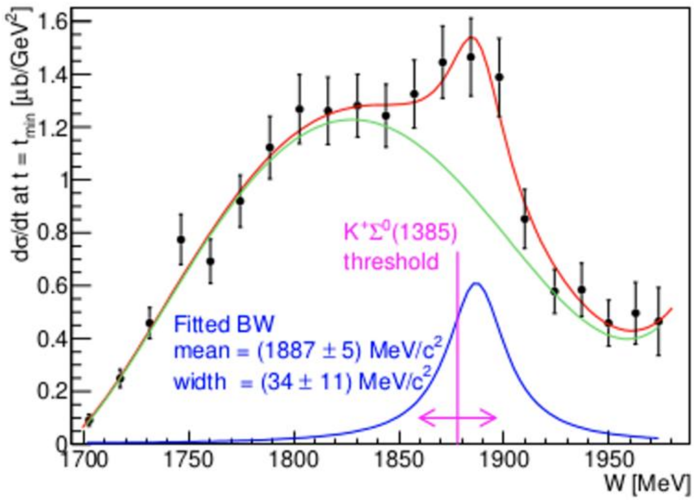
$\gamma p \rightarrow K^+ \Sigma^0$



Σ(1385) K

Extrapolated to

$t_{min}, \quad \cos(\Theta^K) = 1$



Forward angles indicate „low momentum exchange" production ⇔ molecular structures?

Good understanding of the data needed ⇔ Contributing amplitudes? ⇔ Polarization

INSIGHT covers forward angles down to 1° ⇔ K- detection!

Excited baryon spectrum – open questions

Open questions (examples)**:**

⇔ **Do all the expected qqq-SU(6)xO(3)-states exist?**

- **Existing but experimentally not found yet?**
  - ⇔ pol. photoproduction off the neutron (isospin dependence)
  - ⇔ multi-meson photoproduction, further final states

⇔ **Gain a complete picture of the N^*, Δ^*-baryon spectrum**

⇔ **Certain resonances have parity partners other's don't** ⇔ **Why?**

- **Needs to be explained by theory**
  - ⇔ effective degrees of freedom / effective forces
  - ⇔ meson-baryon or 3q or …..

… also relates to the first point …

➔ **Clarify the systematics in the spectrum !**

(SU(6): u ↑↓ d ↑↓ **s** ↑↓)

⇔ **strange baryons of large interest**

⇔ not even the first excitation band completely know
since decades: progress hampered by the lack of high quality data

⇔ **multiquark states? molecules? 2 pole-structures?**

A new experiment at ELSA:

INSIGHT @ELSA

Investigation of the strong interaction in the light flavor sector

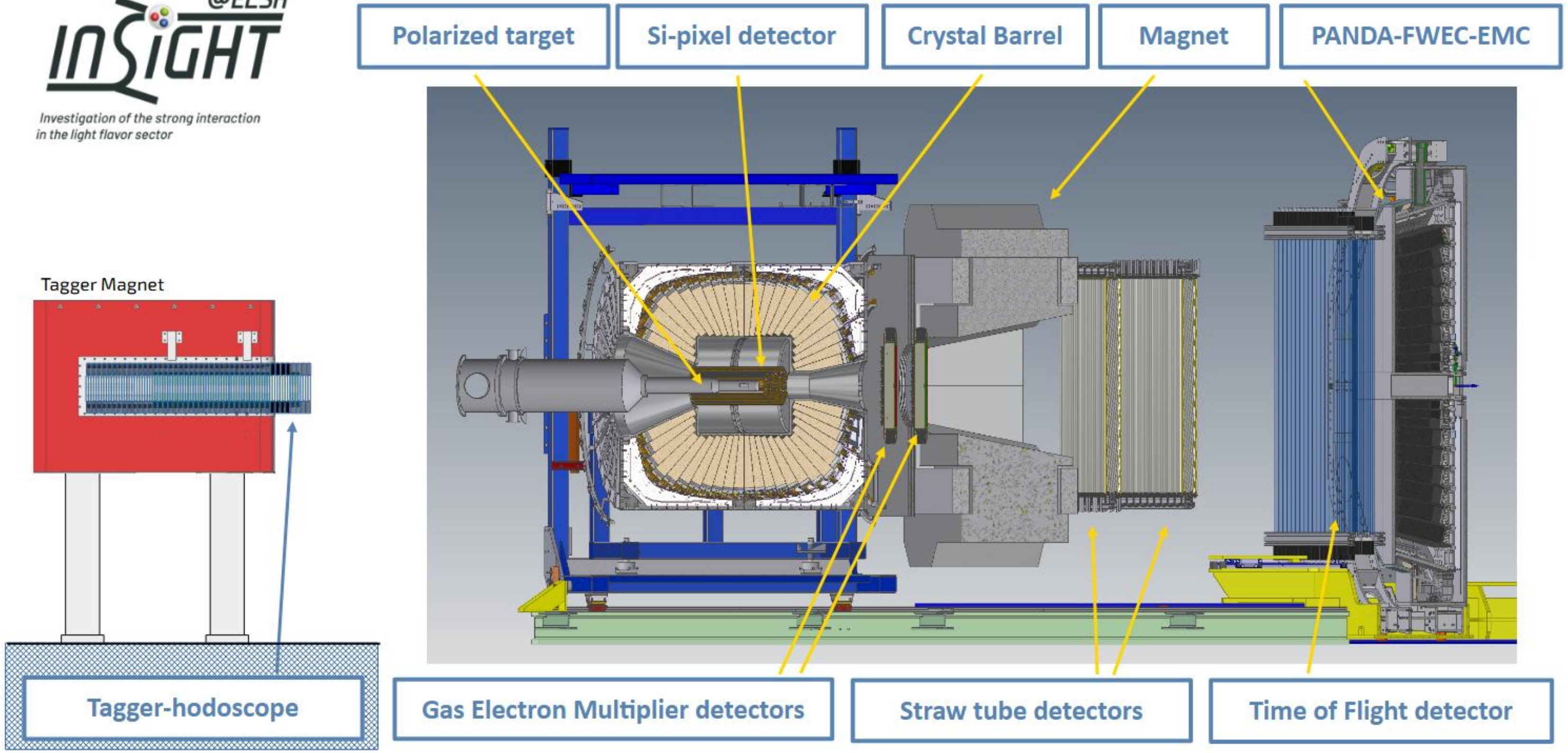
Physics at ELSA - the future

A new experiment ⇔ integral part of the new Cluster of Excellence „Color meets Flavor“:

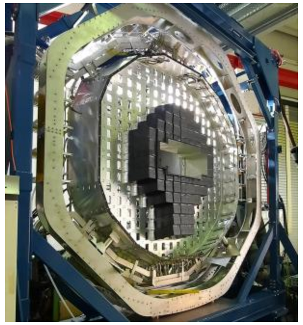
color meets flavor

UNIVERSITÄT BONN · technische universität dortmund · Universität Siegen · JÜLICH Forschungszentrum

INSIGHT @ELSA
Investigation of the strong interaction in the light flavor sector



Arrival of the PANDA-FWEC in Bonn:



at the FTD

➡ **Over almost the entire 4π-solid angle:**
- **High resolution photon measurements**
- **Precise charged particle detection**

Polarized beam and polarized target

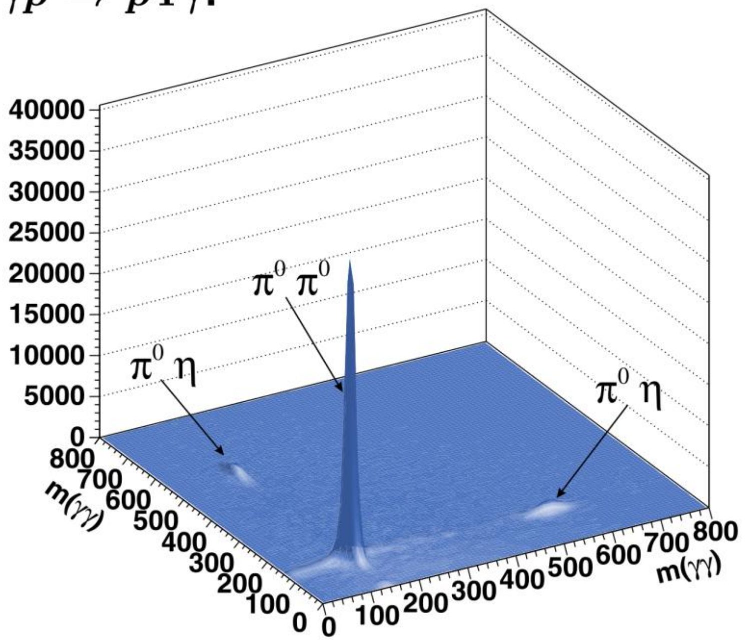
➡ **unique possiblilities!**

Performance: Photon-Measurements and vertex resolutions

- **Photons from measurements:**

Crystal Barrel:

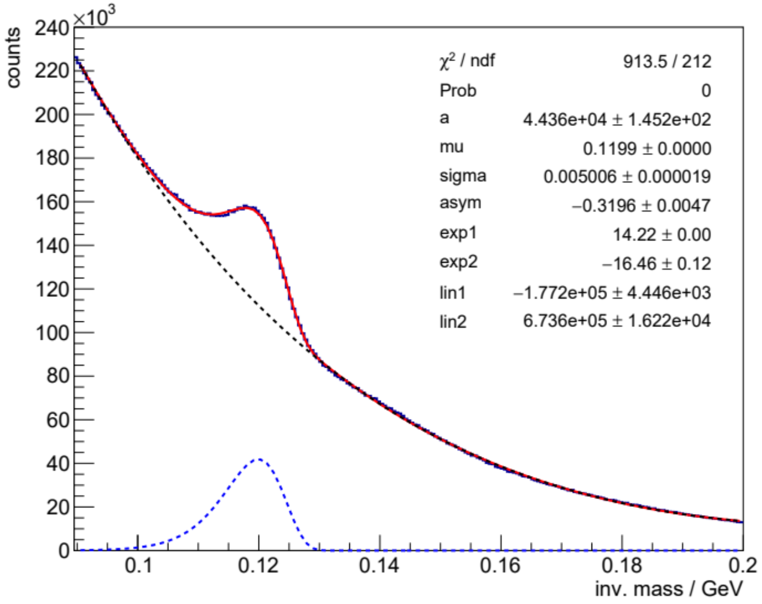
$\gamma p \rightarrow p4\gamma$:



$\sigma(\pi^0) \approx 7\ \text{MeV}$

+ excellent signal to background ratio

PANDA-FWEC @COSY testbeam



$\sigma(\pi^0) \approx 5\ \text{MeV}$

+ further improvements to be expected

Pixel detector: Measurement of charged particle trajectories in the central region

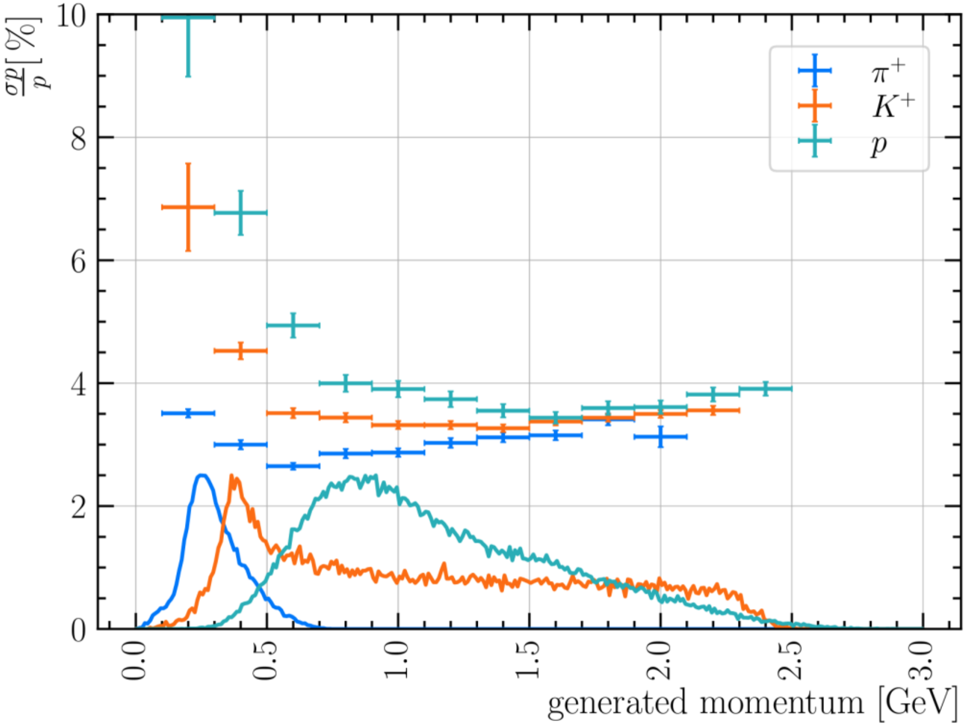
- Vertex resolution (simulations with polarized target):

- $\Delta z, \Delta r \approx 150 - 500 \mu m$ (energy and angle dependent)

Forward tracking - Simulations

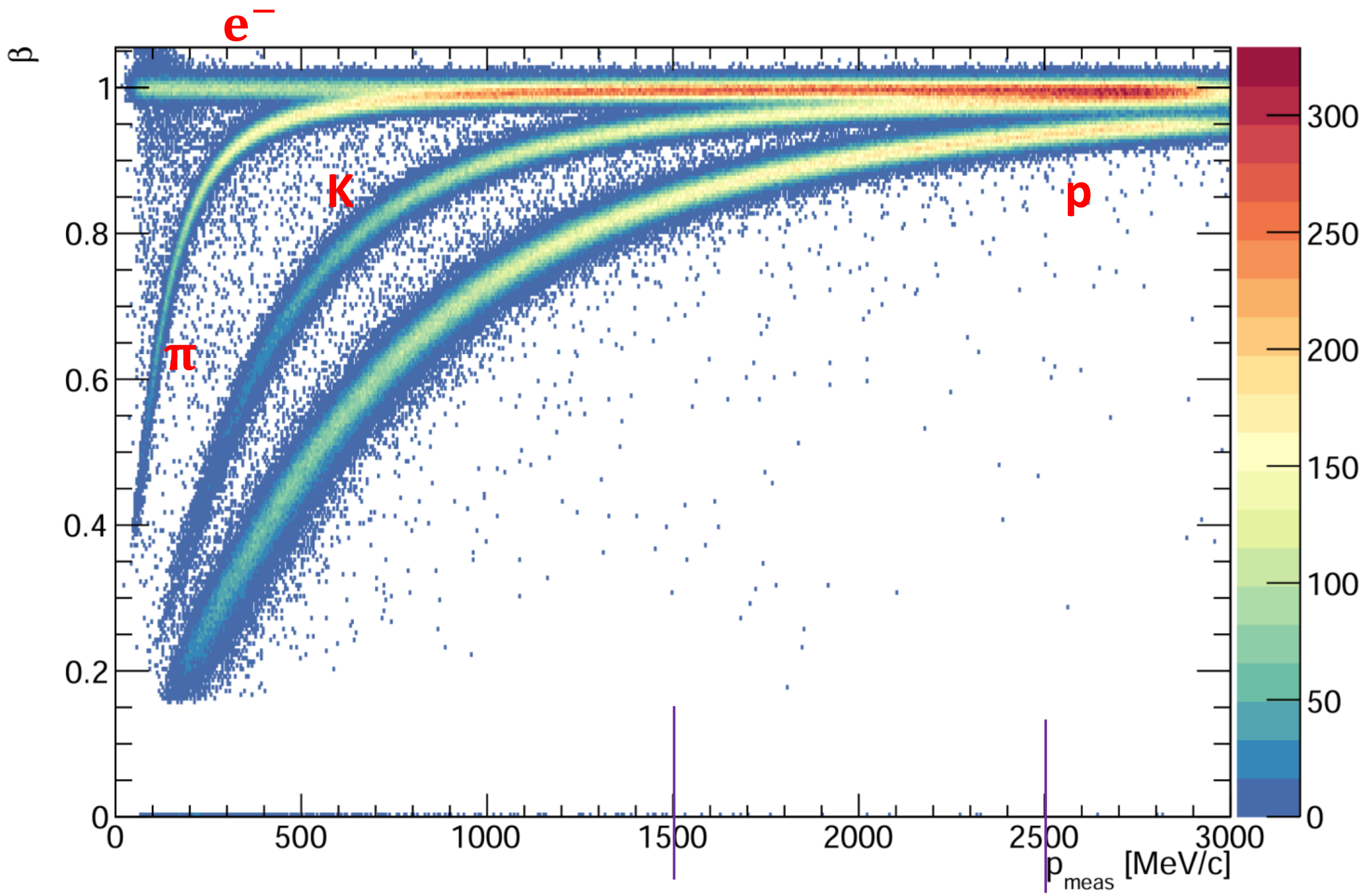
Simulating tracking:

$$\gamma p \rightarrow K^+\Lambda^* \rightarrow K^+\Sigma^0\pi^0 \rightarrow K^+ p\pi^-\gamma\pi^0$$



Using still 4 double layers of straws in the simulation
↔ 6 double layers presently planned

Simulating different particles separately:

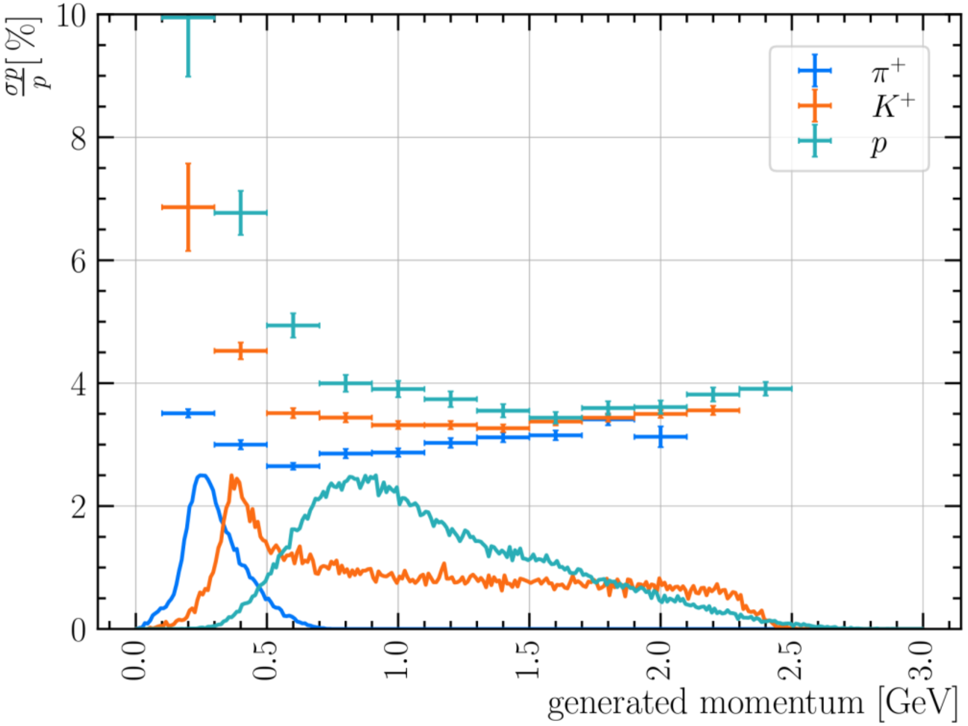


TOF @ 360cm , σ = 100 ps

Forward tracking - Simulations

Simulating tracking:

$$\gamma p \to K^+\Lambda^* \to K^+\Sigma^0\pi^0 \to K^+\,p\pi^-\gamma\pi^0$$



Using still 4 double layers of straws in the simulation
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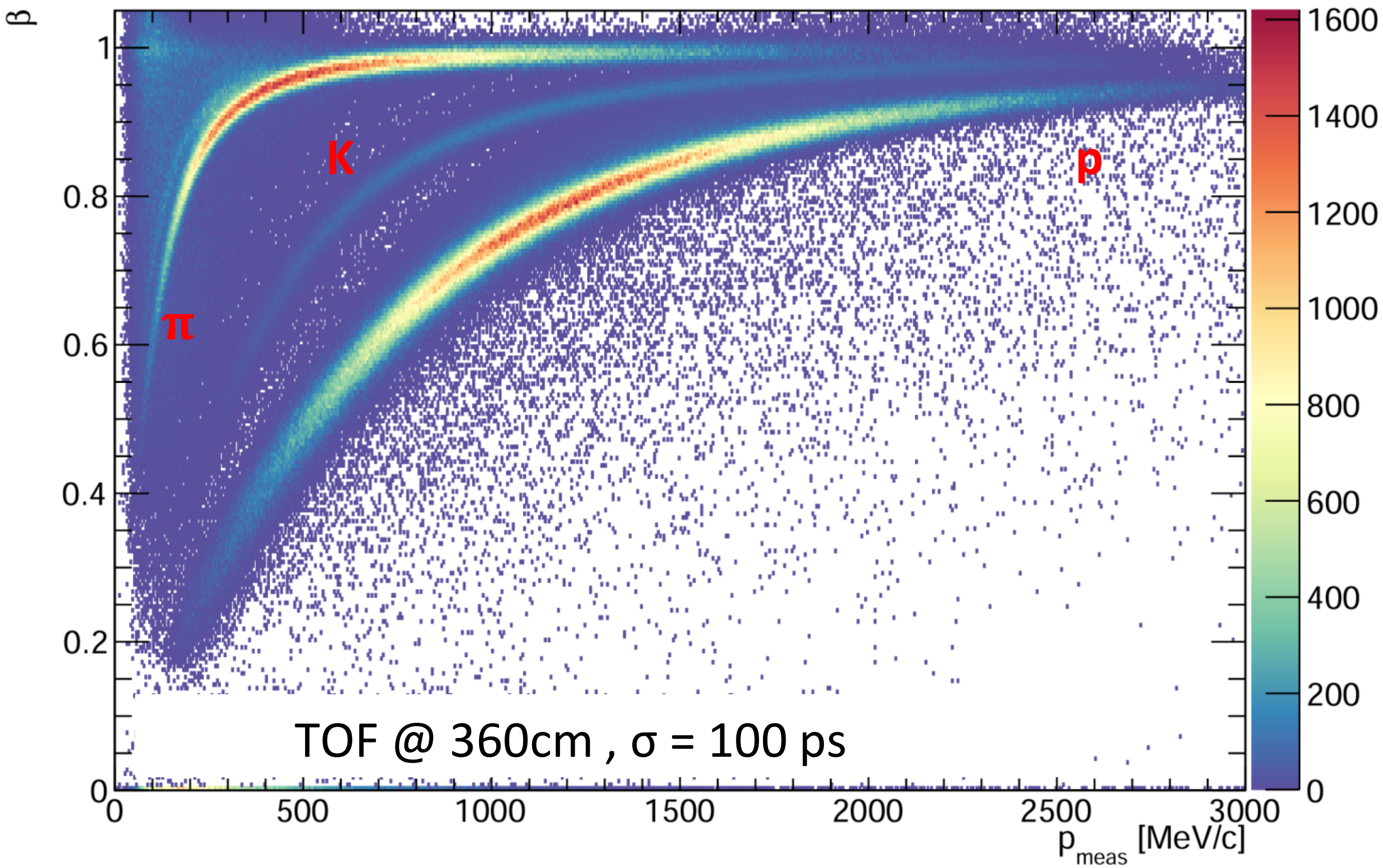
$\gamma p \to K^+\Lambda^* \to K^+\Sigma^0\pi^0 \to K^+\,p\pi^-\gamma\pi^0$ with background and pol. target



Strange baryons @INSIGHT

@ELSA, e.g.:

$\gamma p \to K^+\Lambda^* \to K^+\Sigma^0\pi^0$

isospin selective

$\to K^+\Lambda\gamma\pi^0$

$\to K^+(p\pi^-)\gamma\pi^0$

$\gamma p \to K^+\Sigma^{*0} \to K^+\Lambda\pi^0$

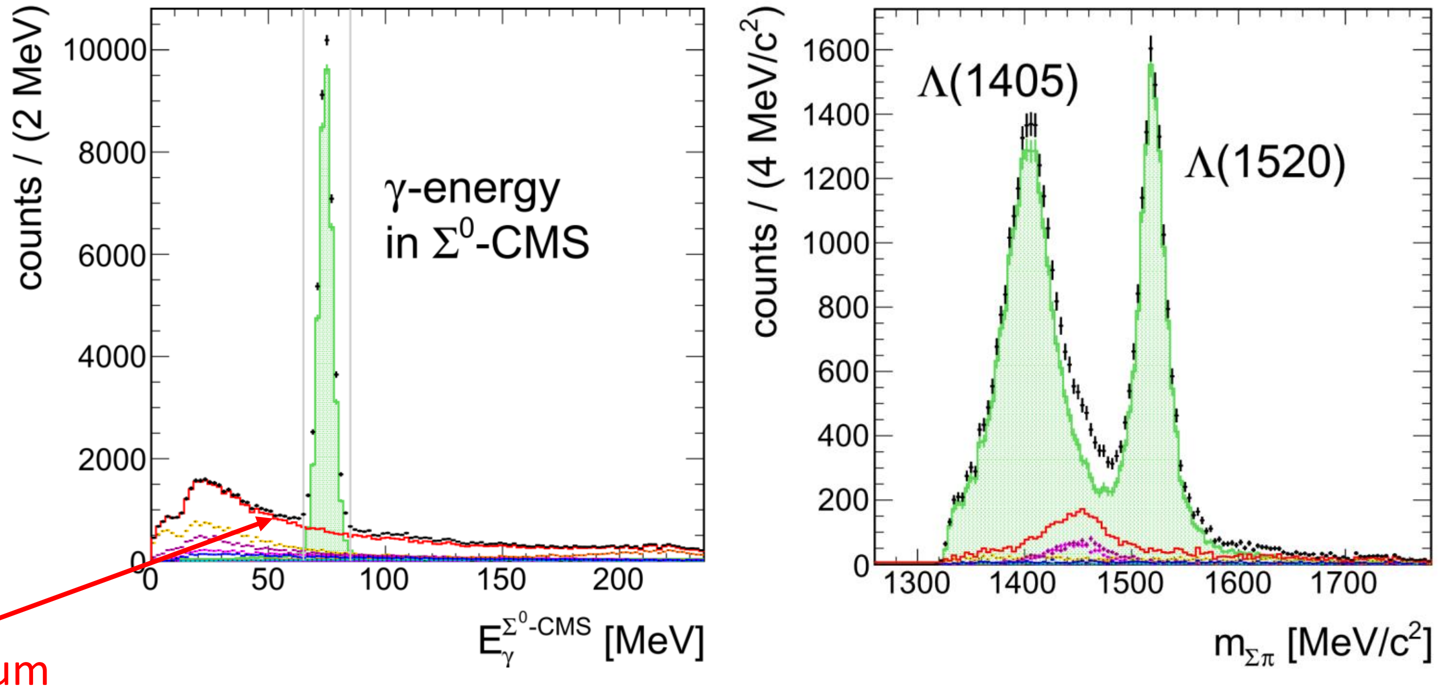
isospin selective

$\to K^+(p\pi^-)\pi^0$

How well can we measure strange baryons?

One example (simulations):

$\Leftrightarrow$ $K^+\Lambda(1405)$ $(0.5\mu b)$ **and** $K^+\Lambda(1520)$ $(0.7\mu b)$



sum

Simulated background channels:

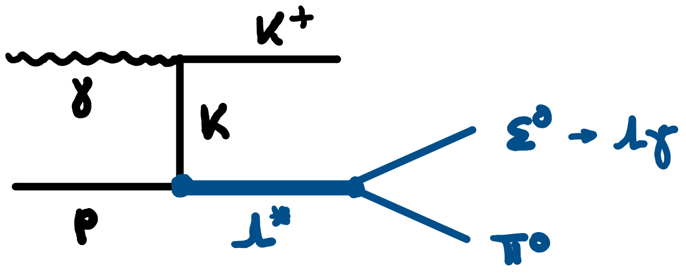
- $K^+\Sigma(1385)$: $0.8\mu b$
- $K^0\Sigma^+$: $0.6\mu b$
- $K^+\Sigma^0$: $1.8\mu b$
- $p\pi^0\eta$: $3.5\mu b$
- $p\pi^+\pi^-\pi^0$: $9\mu b$
- $K^+\Sigma(1385)\pi^0$: $0.4\mu b$
- $K^+\Sigma^+\pi^-$: $1\mu b$
- $K^+\Lambda\pi^0$: $1\mu b$

@ELSA: Advantage of polarization experiments

Several PWA groups have re-analysed the exisiting data (KN-scatt.) on strange baryon resonances

Almost the same data included in the fit, but quite different solutions

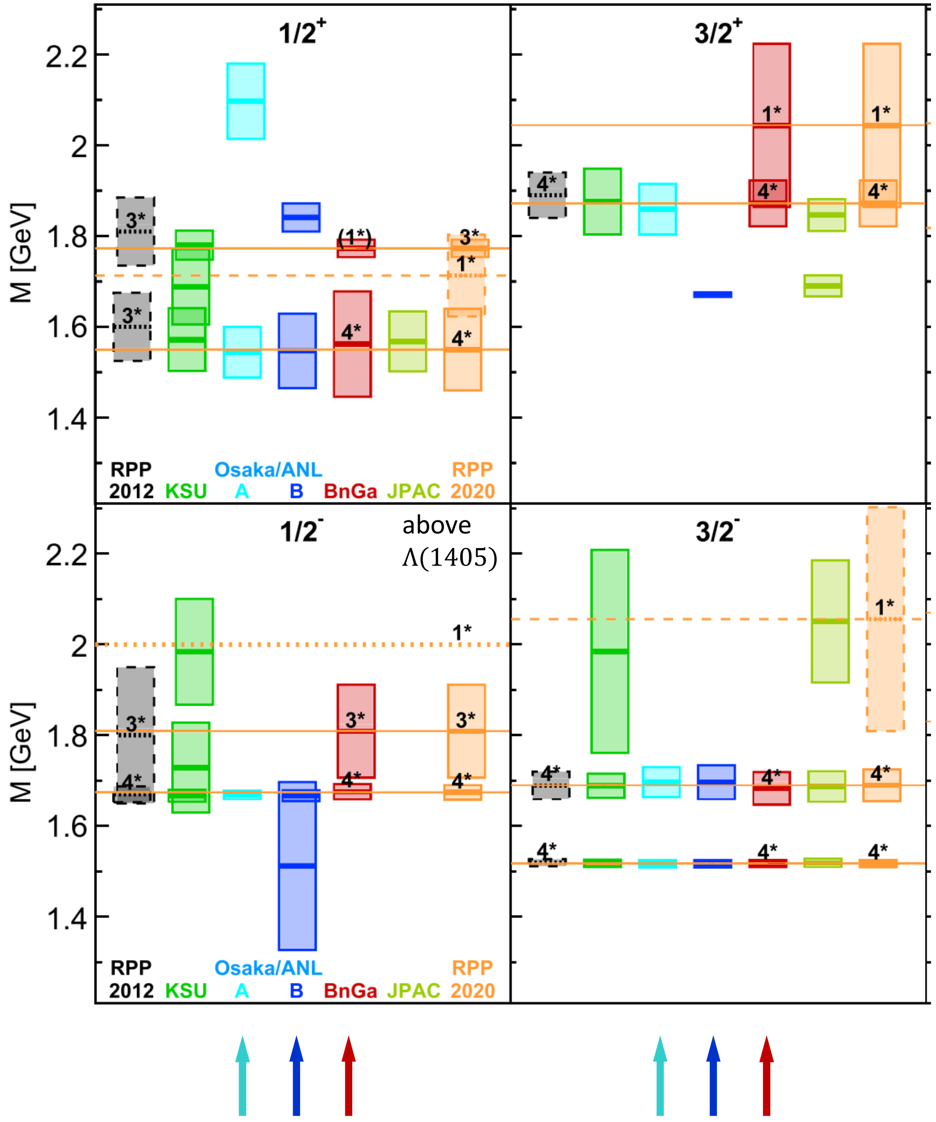
Use a PWA-solution toy model
⇔ calculation based on t-channel K-exchange only



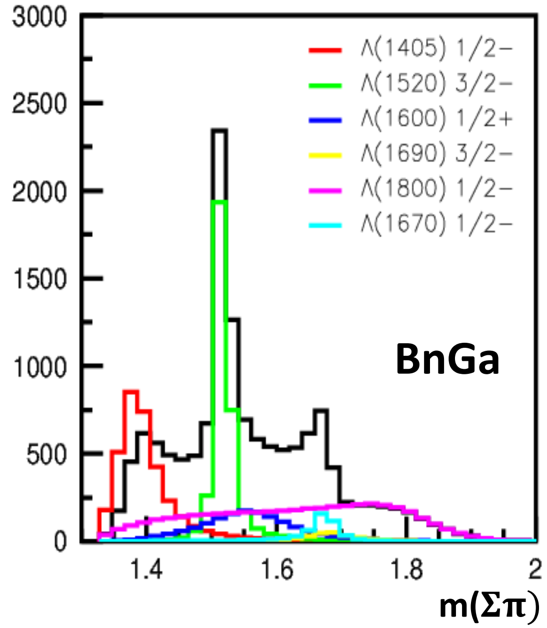
Resonances based on
ANL/Osaka- and BnGa-PWA

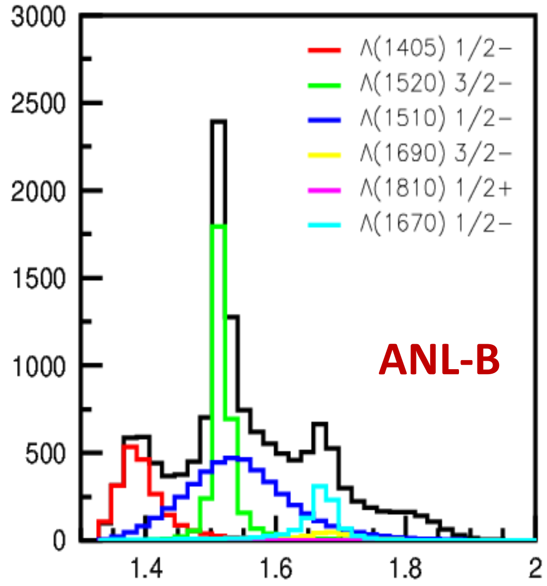
Use resonance properties and $pK\Lambda^*$ couplings from BnGa
⇔ Predict solution
⇔ Fit to BnGa-"data" with ANL/Osaka pole positions

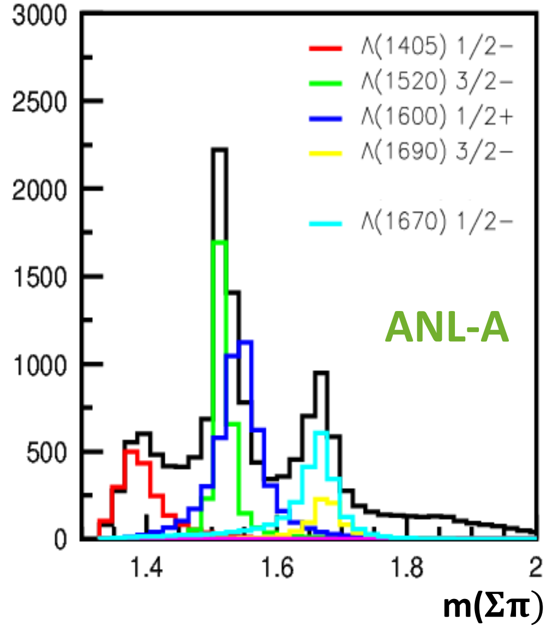
(only J=1/2, 3/2, P=+/- shown)



Strange baryons ⇔ Predictions for $\gamma p \rightarrow \Lambda^{*} K^{+} \rightarrow \Sigma^{0} \pi^{0} K^{+}$







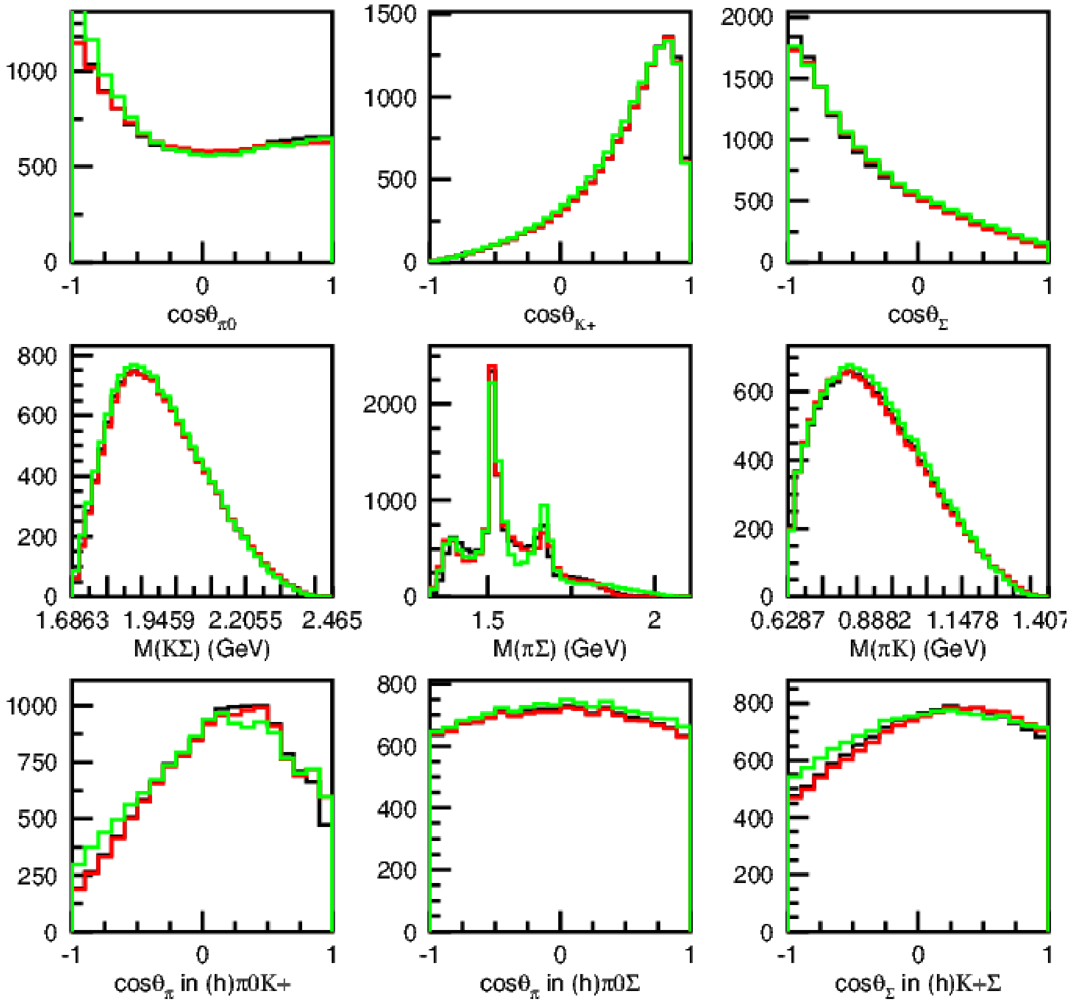
BnGa
Λ(1600)1/2+
Λ(1800)1/2-

ANL-B
Λ(1510)1/2-
Λ(1600)1/2+
Λ(1810)1/2+

ANL-A
Λ(1600)1/2+
Λ(2100)1/2+

+ different resonance parameters

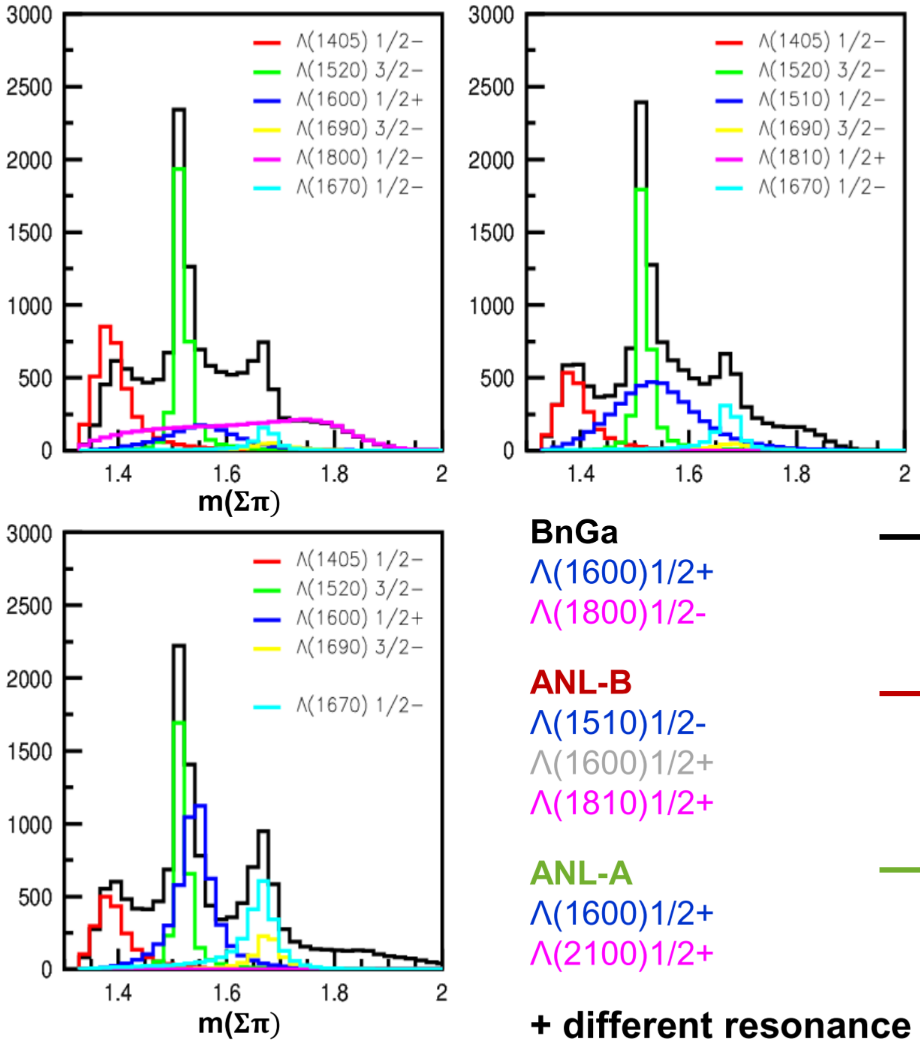
differential cross sections



=> Almost identical distributions

Polarized target – strange baryons ⇔ sensitivity studies

@ELSA INSIGHT
Investigation of the strong interaction in the light flavor sector



Measurement with polarized target:
(1600h + 20% carbon)

BnGa
Λ(1600)1/2+
Λ(1800)1/2-

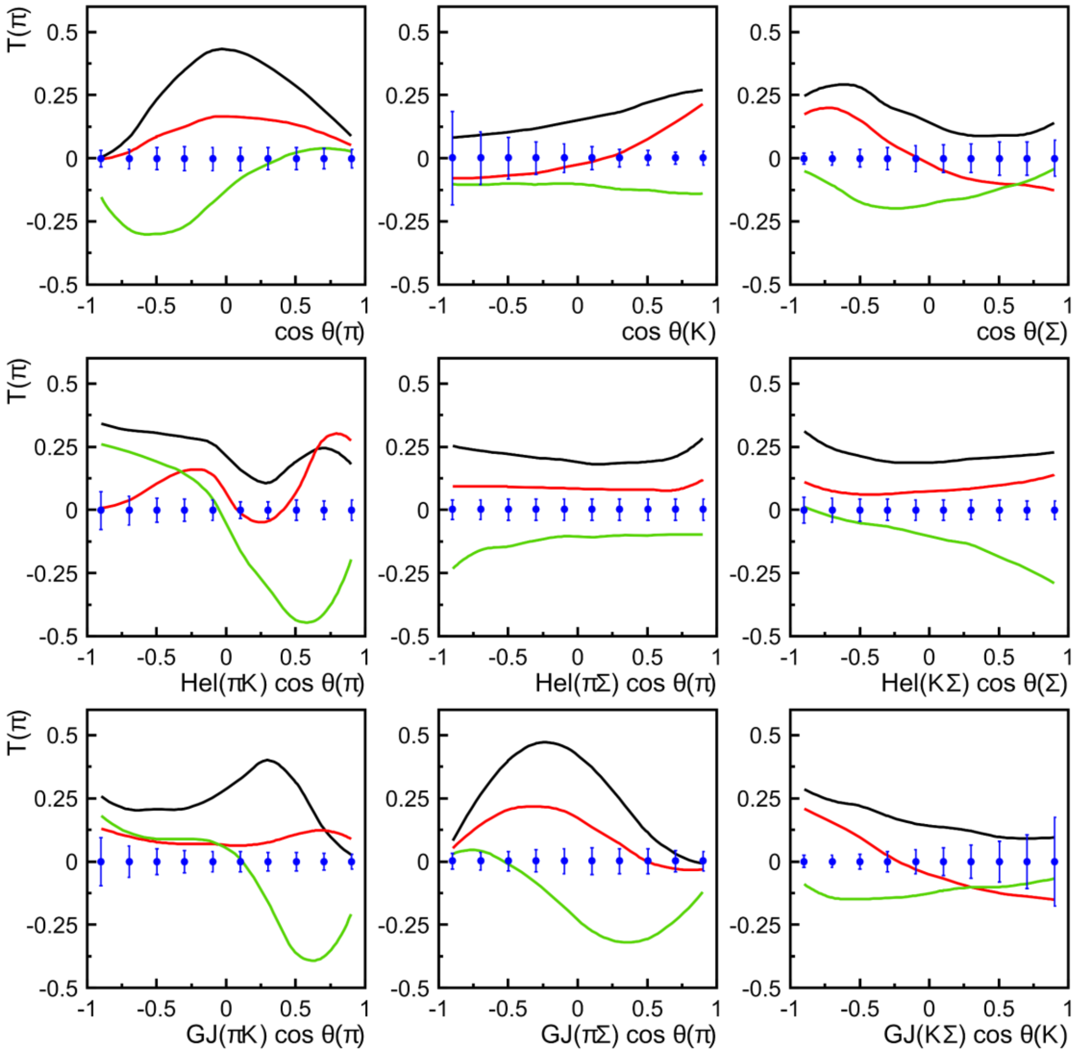
ANL-B
Λ(1510)1/2-
Λ(1600)1/2+
Λ(1810)1/2+

ANL-A
Λ(1600)1/2+
Λ(2100)1/2+

+ different resonance parameters

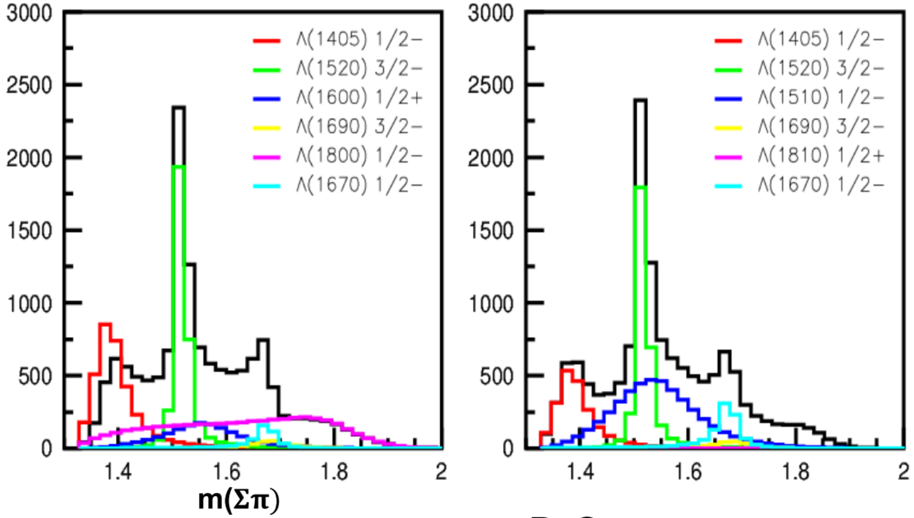
Target asymmetry
(transv. pol.)

W = 2.2-2.3 GeV

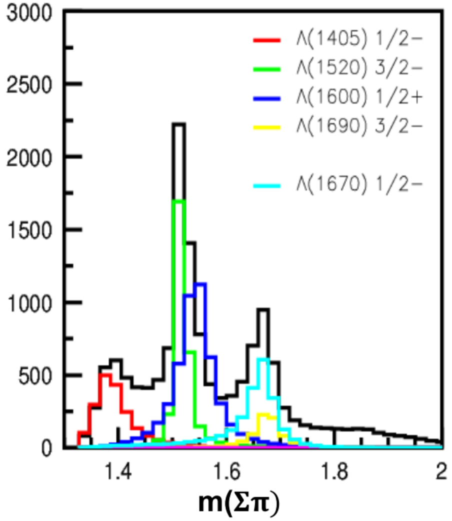


Target pol. 70%, dilution factor 0.7, Acceptance from fast simulation
PWA-distribution normalised to Λ(1520)-cross section at W=2.1 GeV (0.8μb)

Polarized target – strange baryons ⇔ sensitivity studies



Measurement with polarized target:
(1600h + 20% carbon)



BnGa
Λ(1600)1/2+
Λ(1800)1/2-

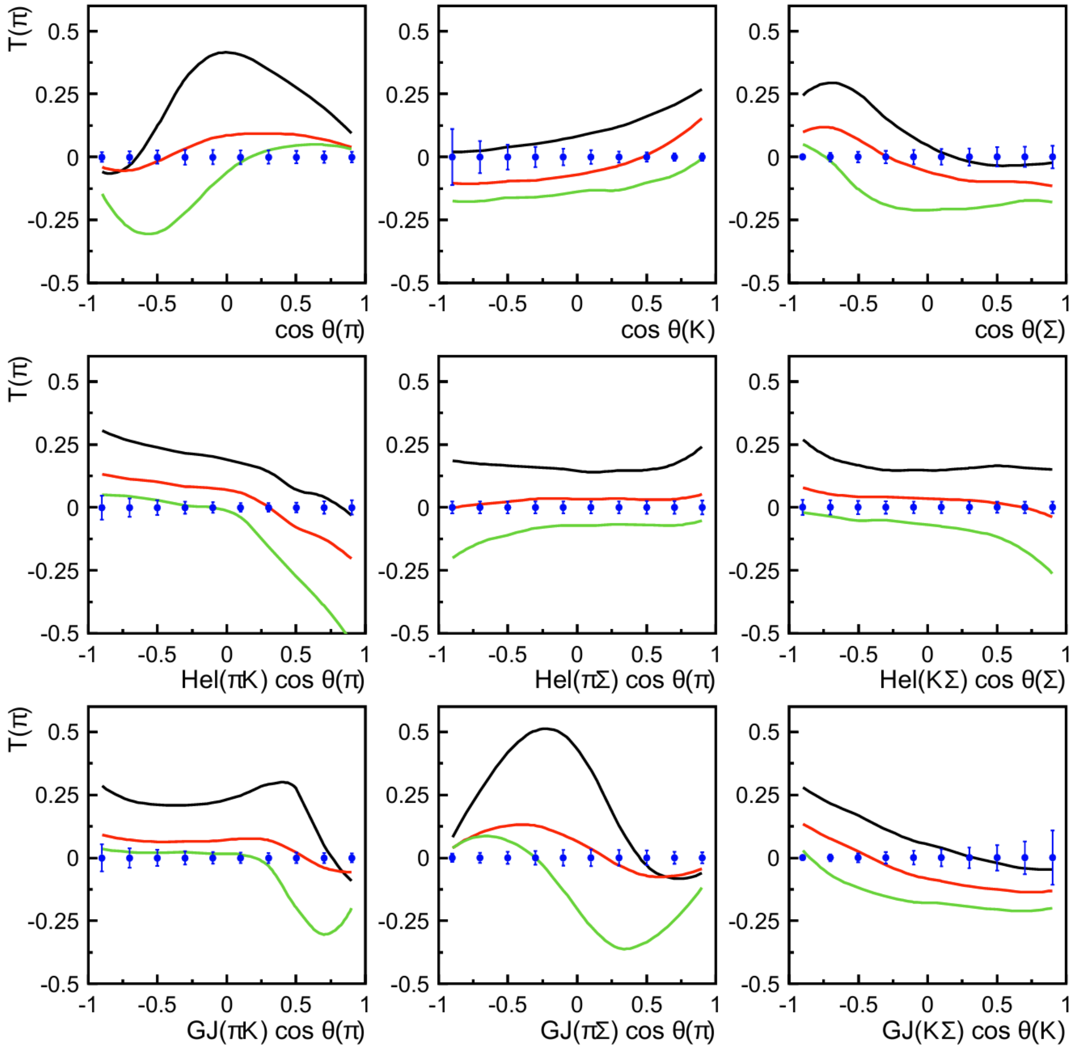
ANL-B
Λ(1510)1/2-
Λ(1600)1/2+
Λ(1810)1/2+

ANL-A
Λ(1600)1/2+
Λ(2100)1/2+

+ different resonance parameters

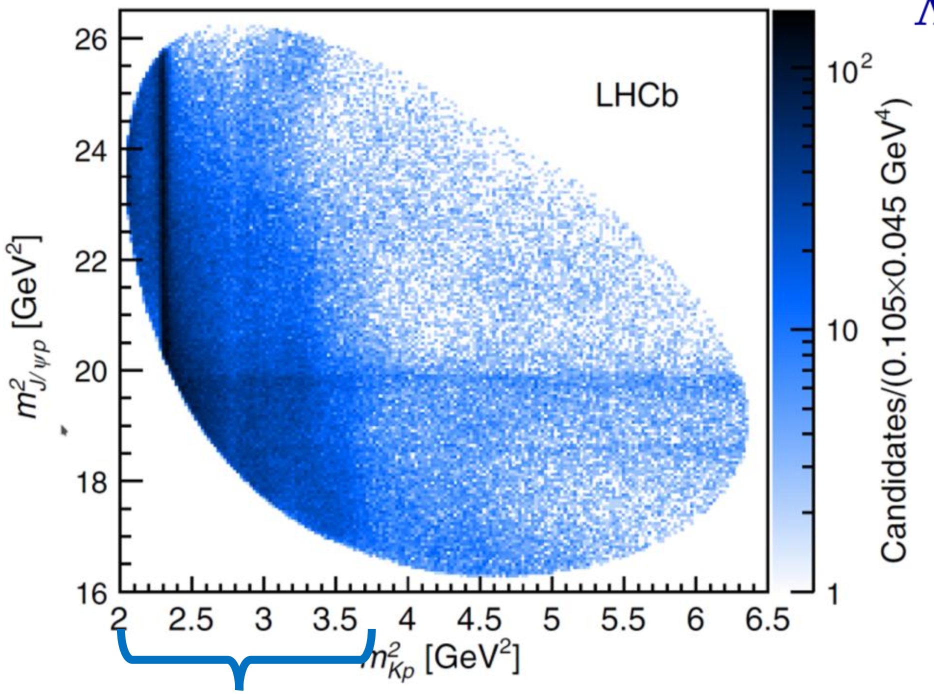
Target asymmetry
(transv. pol.)

Cut on m(Σπ) =1.5-1.7 GeV

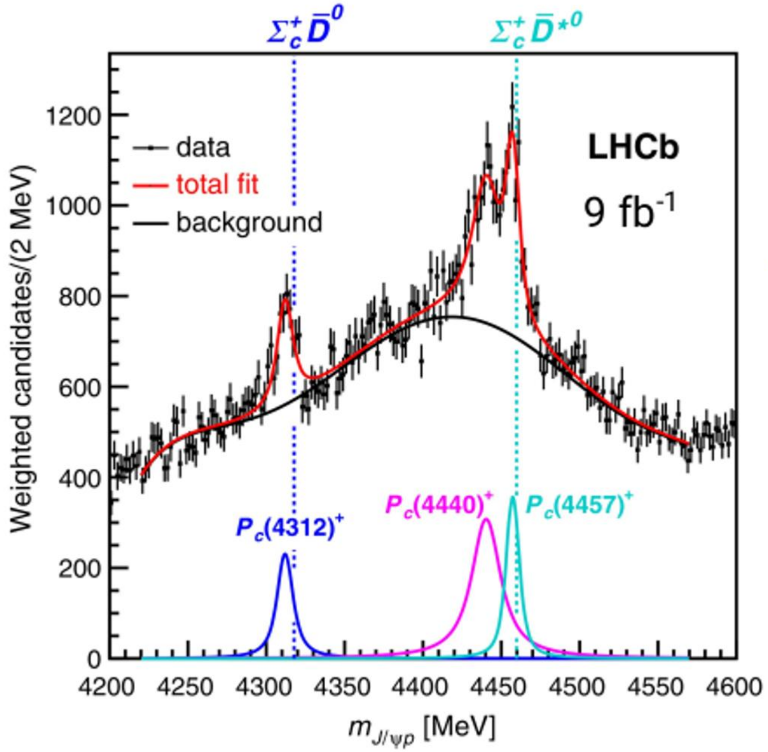


Target pol. 70%, dilution factor 0.7, Acceptance from fast simulation
PWA-distribution normalised to Λ(1520)-cross section at W=2.1 GeV (0.8μb)

LHCb – data $\Lambda_b^0 \to J/\Psi p K^-$ ⇔ strange baryon resonances



$\Lambda_b^0 \to J/\Psi p K^-$



Contribution of strange baryon resonances

For determination of pentaquark properties:

⇔ Strange baryon resonances and their properties important!

Polarisation experiments to avoid ambiguities!

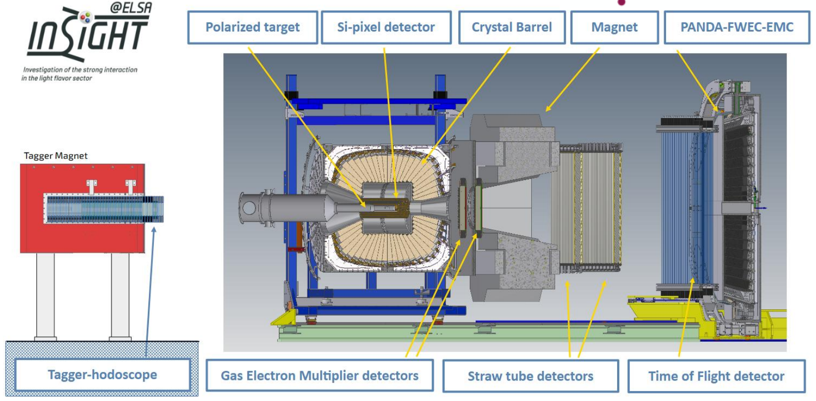
⇔ Common analysis of ELSA- and LHCb-data ⇔ large advantage

INSIGHT@ELSA - Summary

Non-strange baryons:

Gain a complete picture of the N^*, Δ^*- baryon spectrum:

- **Polarized photoproduction off the polarized proton and neutron!**
- **Multi-meson photoproduction**



Strange baryons: (Λ^*, Σ^*):

„… the field is starved for data“ (PDG‘2024)

Established resonances remained the same for more than 30 years!

Interesting exception: Two pole structure of the (1405)

⬄ Not even all states of the first excitation band known!

- spectrum and properties of Λ^*, Σ^*

- multi-quark states? molecules? 2-pole structures?

Combined PWA of LHCb and INSIGHT data: large potential

- **Heavy hadron spectroscopy**
- **New phenomena in rare decays**