# Differential Cross Section of $\gamma p \to K^+\Sigma^0$ at the BGOOD Experiment

Johannes Groß, on behalf of the BGOOD collaboration

Physikalisches Institut
University of Bonn

*johgross@uni-bonn.de*

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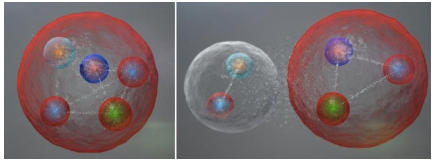
# Exotic Phenomena in the **Charmed** Sector*

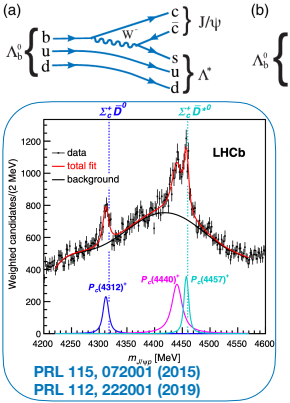
***Not** what we study at BGOOD!

PARTICLE PHYSICS 16 JULY 2015 | VOL 523 | NATURE | 267

## Forsaken pentaquark particle spotted at CERN

*Exotic subatomic species confirmed at Large Hadron Collider after earlier false sightings.*






- Pentaquark candidates at LHCb: Meson-baryon dynamically generated states in the charmed sector?
  eg Wu, Molina, Oset, and Zou, PRL 105, 232001 (2010)

# Overview

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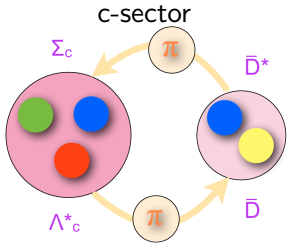
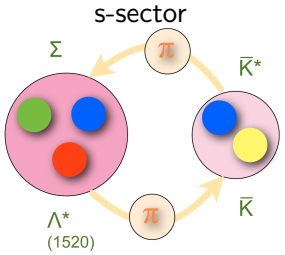
# Parallels in the Strange & Charmed Sectors

| | Charmed sector | | Strange sector | |
|---|---|---|---|---|
| | Meson | Baryons | Meson | Baryons |
| State(s) | $X(3872)$ | $P_c^*(4380/4457)$ | $f_1(1285)$ | $N^*(2030/2080)$ |
| $\pi$ exchange transition | $D^{*0}\bar{D}^0/D^0\bar{D}^{*0}$ | $\Lambda_c^*\bar{D}+\Sigma_c\bar{D}^*$ | $K^*\bar{K}/K\bar{K}^*$ | $\Lambda^*\bar{K}+\Sigma\bar{K}^*$ |
| Quantum numbers | $J^{PC}=1^{++}$ | $J^P=3/2^-$ | $J^{PC}=1^{++}$ | $J^P=3/2^-$ |

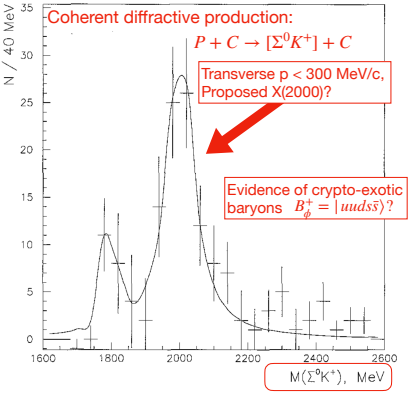


# Forward $\gamma p \to K^+\Sigma^0$ - Predictions

- At $W \sim 1900\,\text{MeV}$, many predictions:
  - $\phi N$ bound systems Gao, Huang, Liu, Ping, Wang & Z. Zhao, PRC, 95:055202, 2017
  - Molecular $K\Sigma$ states, $J^P = 1/2^-$ & $3/2^-$ consistent with $N^*(1875)$ & $N^*(2100)$ Huang, Zhu & Ping, PRD 97:094019, 2018.
  - A 3-hadron $K\bar{K}N$ molecule with $a_0(980)N$ & $f_0(980)N$ components Martínez Torre, Khemchandani, Meißner & Oset, EPJA 41:361, 2009.
- Limited data at forward $K^+$ angles

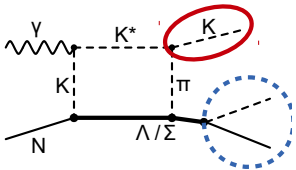
Previous SPHINX data, ZPC, 68:585 (1995)




Low transverse $p$ requires forward kinematics in photoproduction!

# Experimental Requirements

- Reaction dynamics at very low momentum exchange - charged particle identification at extremely forward angles
- High forward momentum resolution
- Reconstruction of complicated, mixed charge final states - eg $K^+\Lambda(1405) \rightarrow K^+(\pi^0\Sigma^0) \rightarrow K^+\pi^0\gamma p\pi^-$




**Ideally suited: BGOOD at the ELSA facility, Bonn**

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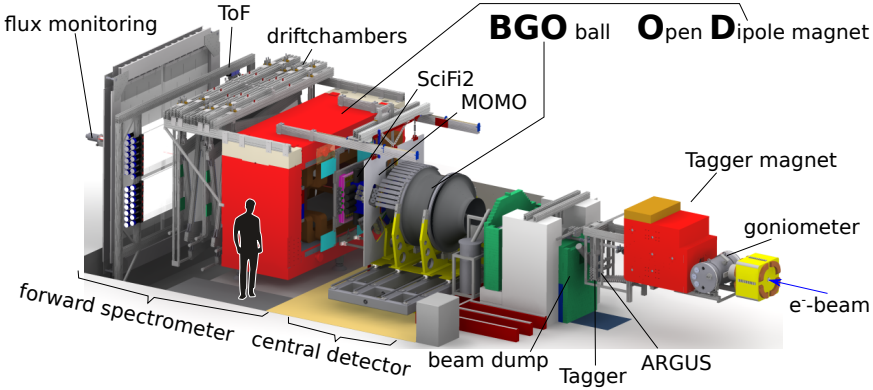
# The BGOOD Experiment at ELSA, Bonn

- Electron beam is tagged and converted to photon beam
- Central region: BGO calorimeter
- Forward region: Forward spectrometer



# The BGOOD Experiment, Eur. Phys. J. A 56:104 (2020)

Spokespersons: H. Schmieden (Bonn) & P. Levi Sandri (Frascati)


Eur. Phys. J. A (2020) 56:104
https://doi.org/10.1140/epja/s10050-020-00107-x

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article - Experimental Physics

## The BGOOD experimental setup at ELSA

**S. Alef[1], P. Bauer[1], D. Bayadilov[2,3], R. Beck[2], M. Becker[2], A. Bella[1], J. Bieling[2], S. Böse[2], A. Braghieri[4], K.-Th. Brinkmann[5], P. L. Cole[6], R. Di Salvo[7], D. Elsner[1], A. Fantini[7,8], O. Freyermuth[1], F. Frommberger[1], G. Gervino[9,10], F. Ghio[11,12], S. Goertz[1], A. Gridnev[3], E. Gutz[3], D. Hammann[1], J. Hannappel[1,19], W. Hillert[1,19], O. Jahn[1], R. Jahn[2], J. R. Johnstone[1], R. Joosten[2], T. C. Jude[1,a], H. Kalinowsky[2], V. Kleber[1,20], F. Klein[1], K. Kohl[1], K. Koop[2], N. Kozlenko[3], B. Krusche[13], A. Lapik[14], P. Levi Sandri[15,b], V. Lisin[14], I. Lopatin[3], G. Mandaglio[16,17], M. Manganaro[16,17,21], F. Messi[1,22], R. Messi[7,8], D. Moricciani[7], A. Mushkarenkov[14], V. Nedorezov[14], D. Novinskiy[3], P. Pedroni[4], A. Polonskiy[14], B.-E. Reitz[1], M. Romaniuk[7,18], T. Rostomyan[13], G. Scheluchin[1], H. Schmieden[1], A. Stugelev[3], V. Sumachev[3], V. Tarakanov[3], V. Vegna[1], D. Walther[2], H.-G. Zaunick[2,5], T. Zimmermann[1]**

[1] Rheinische Friedrich-Wilhelms-Universität Bonn, Physikalisches Institut, Nußallee 12, 53115 Bonn, Germany
[2] Rheinische Friedrich-Wilhelms-Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik, Nußallee 14-16, 53115 Bonn, Germany
[3] Petersburg Nuclear Physics Institute, Gatchina, Leningrad District 188300, Russia
[4] INFN sezione di Pavia, Via Agostino Bassi, 6, 27100 Pavia, Italy
[5] Justus-Liebig-Universität Gießen, II. Physikalisches Institut, Heinrich-Buff-Ring 16, 35392 Gießen, Germany
[6] Department of Physics, Lamar University, Beaumont, TX 77710, USA
[7] INFN Roma "Tor Vergata", Via della Ricerca Scientifica 1, 00133 Rome, Italy
[8] Dipartimento di Fisica, Università di Roma "Tor Vergata", Via della Ricerca Scientifica 1, 00133 Rome, Italy
[9] INFN sezione di Torino, Via PGiuria 1, 10125 Turin, Italy
[10] Dipartimento di Fisica,, Università di Torino, via P. Giuria 1, 10125 Turin, Italy
[11] INFN sezione di Roma La Sapienza, P.le Aldo Moro 2, 00185 Rome, Italy
[12] Istituto Superiore di Sanità, Viale Regina Elena 299, 00161 Rome, Italy
[13] Institut für Physik, Klingelbergstrasse 82, 4056 Basel, Switzerland
[14] Russian Academy of Sciences Institute for Nuclear Research, Prospekt 60-letiya Oktyabrya 7a, Moscow 117312, Russia
[15] INFN - Laboratori Nazionali di Frascati, Via E. Fermi 54, 00044 Frascati, Italy
[16] INFN sezione Catania, 95129 Catania, Italy
[17] Dipartimento MIFT, Università degli Studi di Messina, Via F. S. D'Alcontres 31, 98166 Messina, Italy
[18] Institute for Nuclear Research of NASU, 03028 Kiev, Ukraine
[19] *Present Address:* DESY Research Centre, Hamburg, Germany
[20] *Present Address:* Forschungszentrum Jülich, Jülich, Germany
[21] *Present Address:* University of Rijeka, Rijeka, Croatia
[22] *Present Address:* Lund University & ESS, Lund, Sweden

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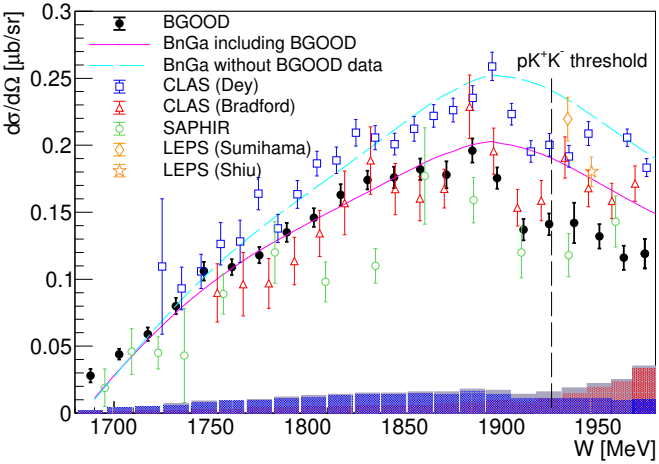
# Differential Cross Section of $\gamma p \to K^+\Sigma^0$

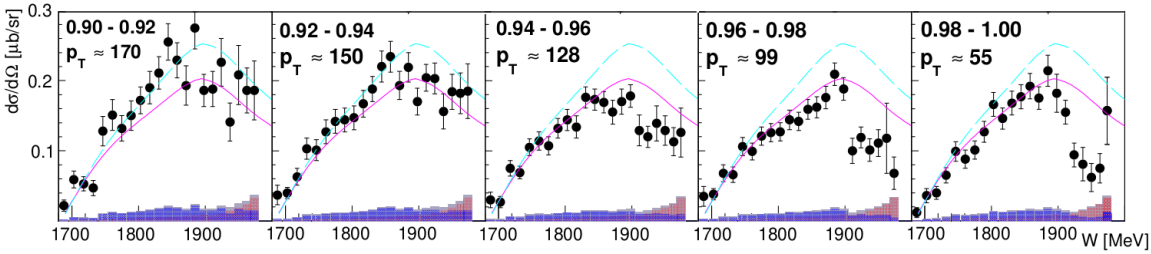
- BGOOD paper: T.C. Jude et al., Phys. Lett. B 820 (2021) 136559




- Highest statistics to date for $\cos\theta^K_{\mathrm{CM}} > 0.9$ (CLAS data in $\cos\theta^K_{\mathrm{CM}}$ 0.85 to 0.95)
- Resolve discrepancies in world data set & reveals "cusp" at $W \sim 1900\,\mathrm{MeV}$

R. Bradford *et al.* (CLAS), PRC 73, 035202 (2006),
B.Dey *et al.* (CLAS), PRC 82, 025202 (2010),
CLAS data in $\cos\theta^K_{\mathrm{CM}}$ 0.85 to 0.95 interval,
K.H. Glander *et al.* (SAPHIR), EPJA 19, 251 (2004),
BnGa PWA - without BGOOD/with BGOOD

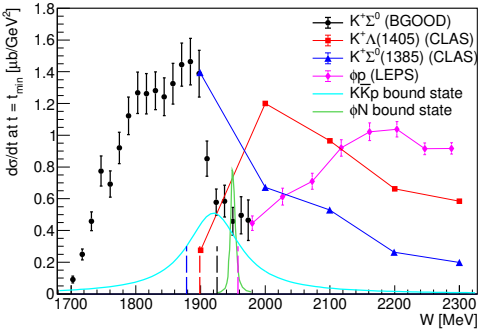
# Differential Cross Section of $\gamma p \to K^+\Sigma^0$




- Cusp increases quickly with $\cos\theta^K_{\mathrm{CM}}$ and $K^+$ transverse momentum ($p_T$) (labelled left, inset)

# Differential Cross Section of $\gamma p \to K^+\Sigma^0$

Data extrapolated to $t_{\min}$ & $\cos\theta^K_{\mathrm{CM}} = 1$




CLAS data extrapolated from: K. Moriya. PhD thesis, Carnegie Mellon University, 2010.
https://www.jlab.org/Hall-B/general/thesis/Moriya thesis.pdf.
LEPS: Mibe et al. PRL.95:182001,2005.
$K\bar{K}p$ bound state: Mart et al., EPJA, 41:361, 2009.
$\phi N$ bound state: Gao, et al, PRC, 95:055202, 2017.

## The Cusp is....

- in the same kinematic regime to the $X(2000)$ proposed by SPHINX
- at predicted $K\bar{K}p$ and $\phi p$ bound states
- 20 MeV above predicted bound $\Sigma(1385)K$ state

## Channel thresholds:

- A "smooth" transition between $K^+\Sigma^0$ & $p\phi$
- Similar behaviour of $K^+\Sigma^0(1385)$

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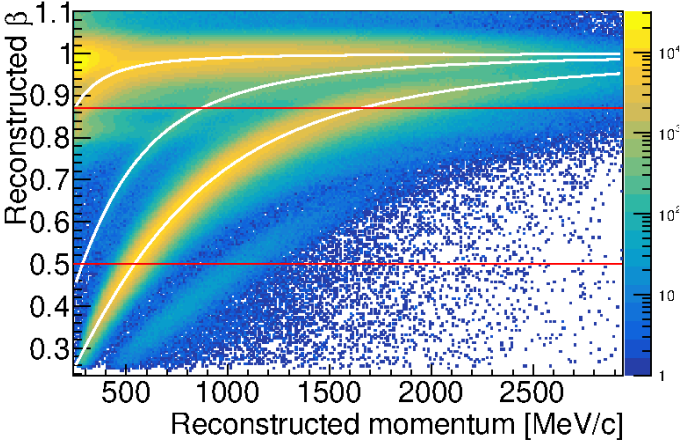
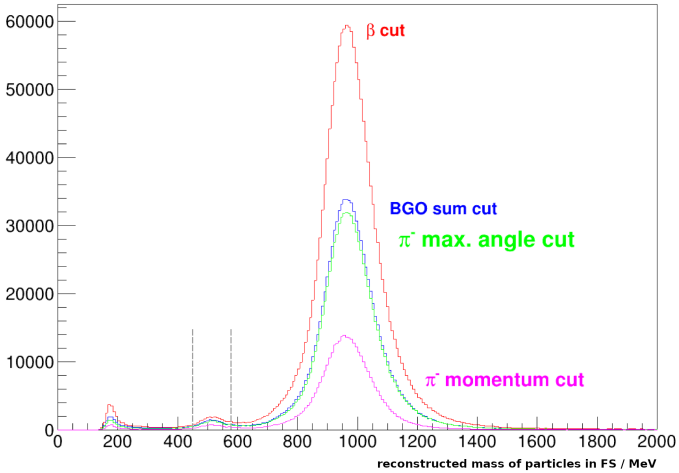
# Differential Cross Section of $\gamma n \to K^+\Sigma^-$



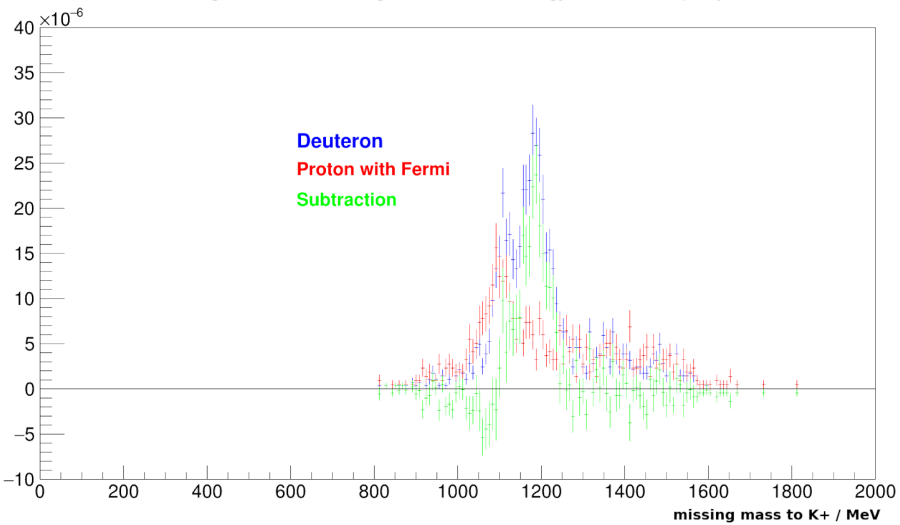

- Ongoing PhD work:
  $\gamma n \to K^+\Sigma^- \to K^+(\pi^- n)$
- $K^+$ is identified in FS via $p$ and $\beta$ measurement. $\beta$ cut is applied
- $\pi^-$ candidate is required in BGO as a charged particle track
- $n$ is not required

# Differential Cross Section of $\gamma n \to K^+\Sigma^-$



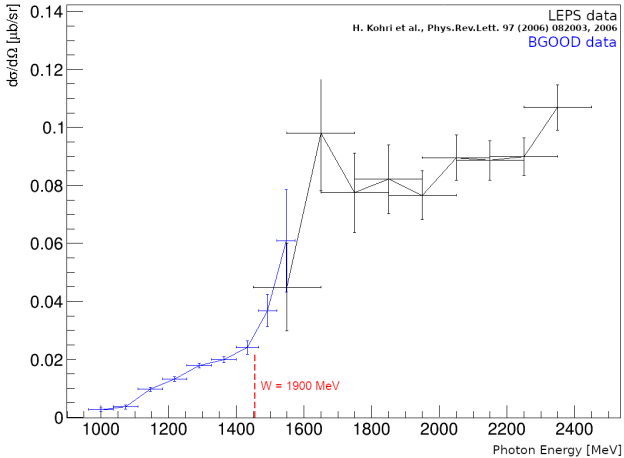

- Constraints on $\pi^-$:
  - Cut on maximum energy deposition in BGO
  - Cut on maximum allowed $\pi^-$ angle and momentum in the $\Sigma^-$ frame
- Apply $2\sigma$ cut
- Reduce $K^+$ signal by 50%, reduce $p$ background by 66%

# Differential Cross Section of $\gamma n \to K^+\Sigma^-$




- Measure missing mass to $K^+$
- Background stemming from $p$ is measured at hydrogen target, corrected for Fermi motion, subtracted

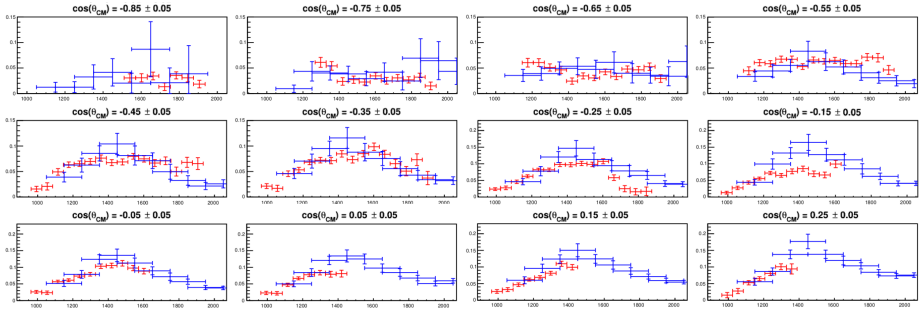
# Differential Cross Section of $\gamma n \to K^+\Sigma^-$




- Preliminary DCS for $\cos(\theta_{CM}) > 0.9$
- Energy binning of $\sim$ 50MeV, data leading up nicely to LEPS data
- Need more statistics to resolve smaller-scale structures
- More statistics is coming!

# Differential Cross Section of $\gamma n \to K^+\Sigma^-$

- Preliminary DCS also measured for central region:
  From $\cos(\theta_{CM}) = -0.85$ to $\cos(\theta_{CM}) = 0.35$
- Utilizing weak $K^+$ decay in BGO: Observing two time-delayed clusters
- Our data (red) mostly matches with CLAS data (blue), fine energy binning possible



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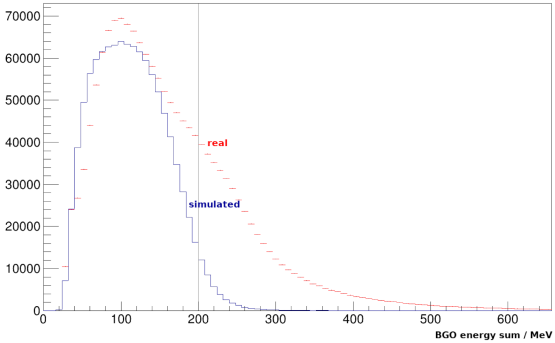
# Summary & Outlook

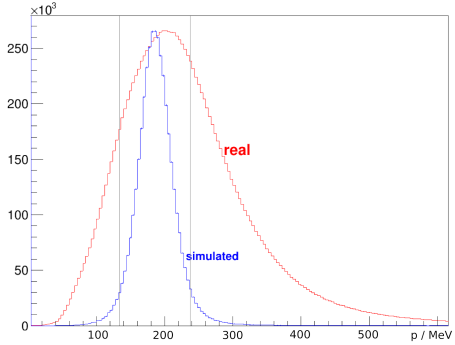
- For $\gamma p \to K^+\Sigma^0$: T.C. Jude et al., Phys. Lett. B 820 (2021) 136559
  - DCS has been measured from threshold to $W = 1970$MeV, using the extreme forward angular acceptance of BGOOD
  - Cusp-like structure at $W = 1900$MeV has been resolved, previously regarded as a peak
  - Indication of re-scattering effects close to open and hidden strange thresholds in an energy region where multiple predictions of hadronic bound states exist
- For $\gamma n \to K^+\Sigma^-$: PhD thesis of J.Groß, preliminary data
  - Preliminary DCS measurement at forward angles up to $W = 1970$MeV
  - Energy binning of $\sim 50$MeV, smooth transition between our data and LEPS data
  - Need more statistics for resolution of smaller-scale structures
- More data has already been taken, calibration and analysis ongoing!

Thank you for your attention!

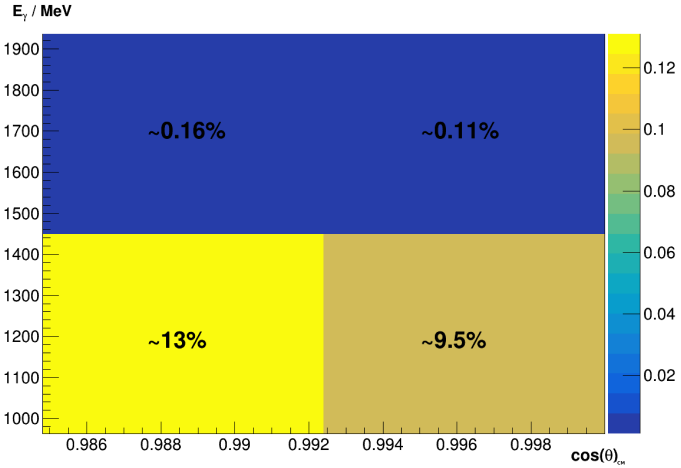
# Differential Cross Section of $\gamma n \to K^+\Sigma^-$

- Constraints on $\pi^-$:
  - Maximum deposited energy sum in BGO
  - $\pi^-$ is boosted in $\Sigma^-$ frame: Maximum allowed momentum and angle



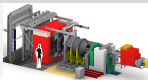



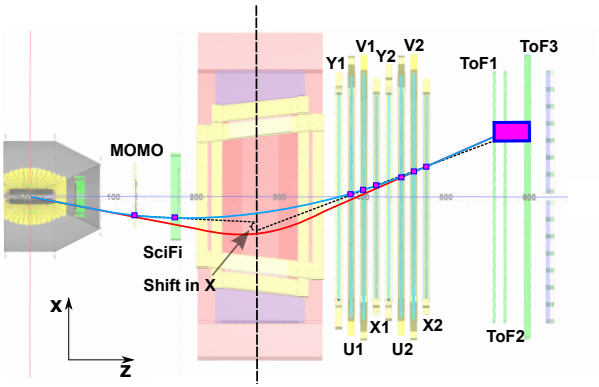
# Differential Cross Section of $\gamma n \rightarrow K^+\Sigma^-$

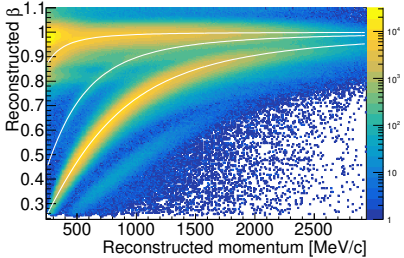


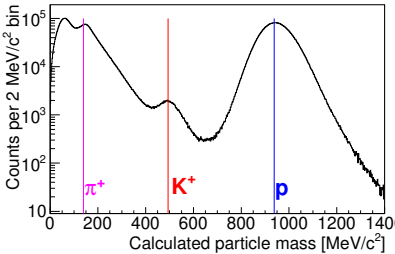

- Reconstruction efficiency determined using simulated model of BGOOD within Geant4, including magnetic field and trigger
- Reliable detection efficiency for up to $\sim$ 1500MeV

# BGOOD - Forward Region





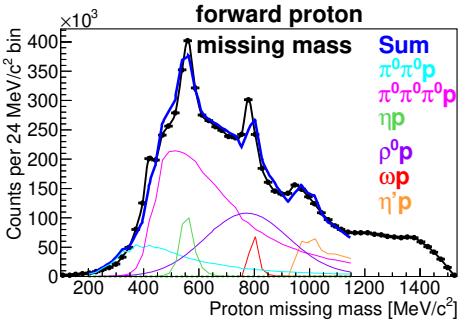



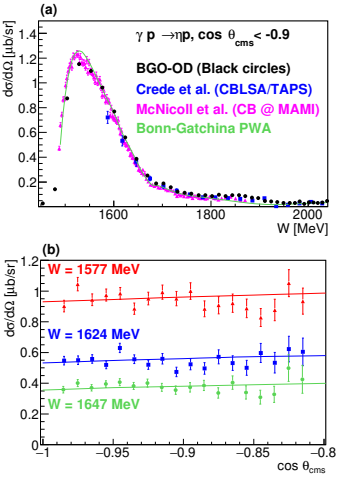




- Charged particle ID & momentum reconstruction
- $1^\circ < \theta_{\mathrm{Lab}} < 12^\circ$, $\Delta\theta_{\mathrm{Lab}} \sim 0.5^\circ$
- $\Delta p/p \sim 3\,\%$ (at max field strength)

# BGOOD - Forward region

- Accurate knowledge of detector & trigger efficiencies, momentum & $\beta$ resolution
- Right: $\gamma p \to \eta p$ (proton in F.S) - excellent agreement with existing data

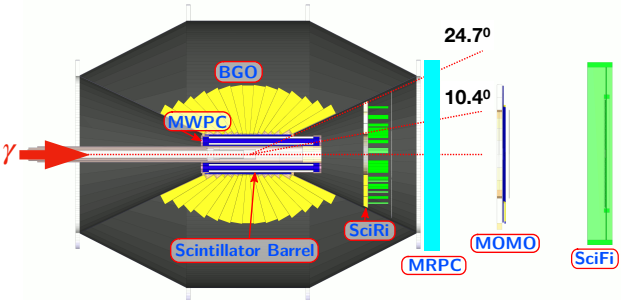


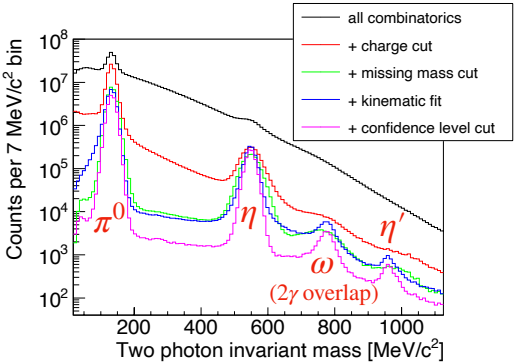

BnGa: Anisovich *et al.*, EPJA **25**, 427 (2005), McNicoll *et al.*, PRC **82** 035208 (2010), Crede *et al.*, PRC **80**, 055202 (2009)

# BGOOD - Central Region

- BGO crystals as calorimeter
- Charged & neutral particle ID
- Excellent time resolution ($\sim$ 2 ns) per BGO crystal

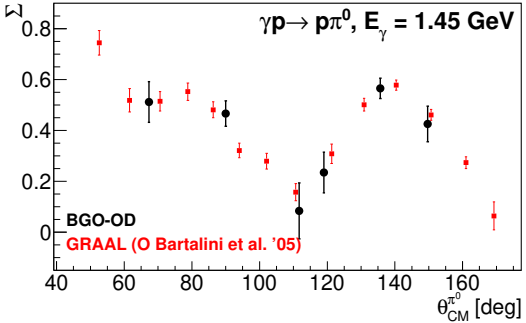


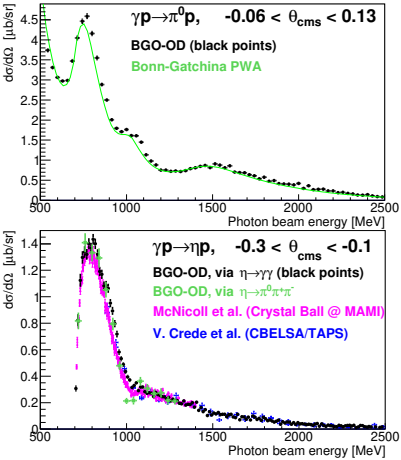

- Clean reconstruction of neutral meson decays:



# BGOOD - Central region

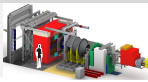
- Accurate neutral meson photoproduction cross sections
- $\gamma$ flux well understood ($\sim 4\%$)
- BGOOD - both neutral & mixed charged identification
- Well understood degree of linear polarisation



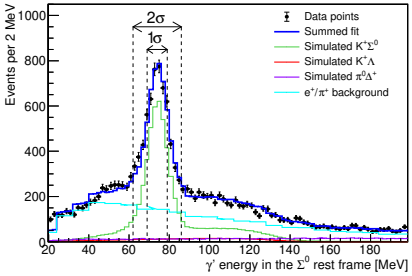




Bartalini *et al.*, EPJA **26**, 399 (2005), BnGa: Anisovich *et al.*, EPJA **25**, 427 (2005), McNicoll *et al.*, PRC **82** 035208 (2010), Crede *et al.*, PRC **80**, 055202 (2009)

# $\gamma p \to K^+\Sigma^0$ arXiv:2006.12437 (2020).



- After identifying forward $K^+$, boost all $\gamma$ in the BGO into the $\Sigma^0$ rest frame
- 74 MeV decay energy, select $1\sigma$ or $2\sigma$ events:




- Missing mass recoiling from forward $K^+$ after $\Sigma^0$ decay photon identification