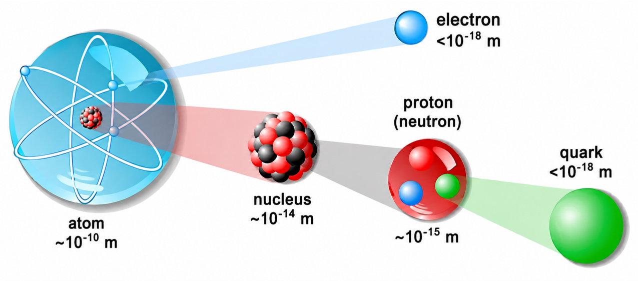
$\gamma n \rightarrow K^+\Sigma(1385)^-$ Photoproduction at Low Momentum Transfer at the BGOOD Experiment

Martin Ludwig

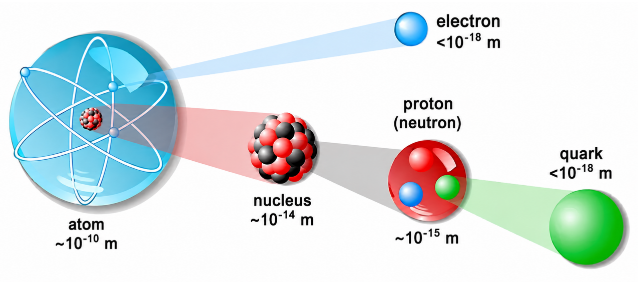
19.06.2026

Motivation

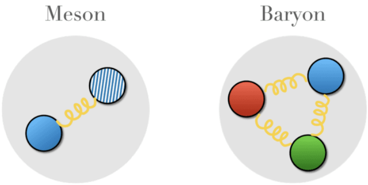


[adapted from https://curiousmatrix.com/what-is-the-smallest-thing-in-the-universe/]

Motivation



[adapted from https://curiousmatrix.com/what-is-the-smallest-thing-in-the-universe/]



[https://www.icvtank.com/newsinfo/593012.html]

Exotic Hadrons

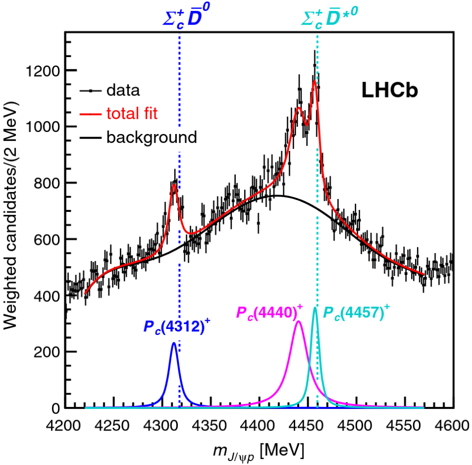


Figure: Discovery of the P_c pentaquark states in $\Lambda_b^0 \to J/\psi p K^-$ decays [Aaij et al. (LHCb), 2019]

Exotic Hadrons

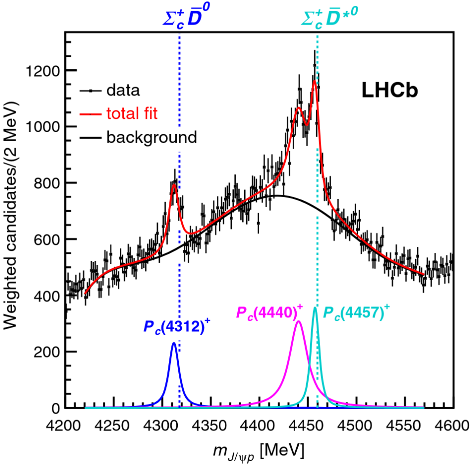
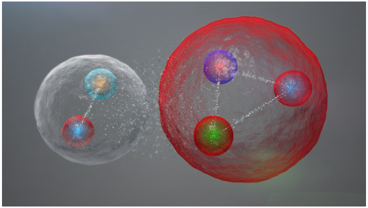


Figure: Discovery of the P_c pentaquark states in $\Lambda_b^0 \to J/\psi p K^-$ decays [Aaij et al. (LHCb), 2019]



© CERN

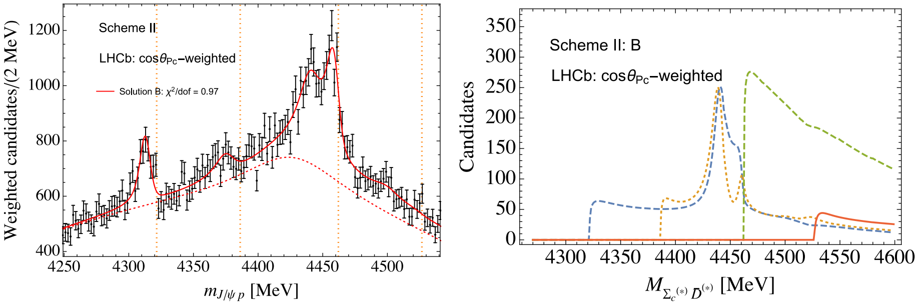


Figure: Fit to the LHCb data obtained from coupled channel analysis (left), along with the corresponding line shapes of the constituents (right) [Du et al., 2021]

Exotic Hadrons

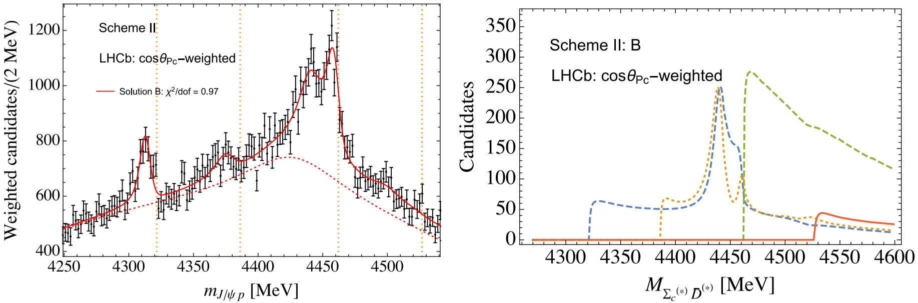
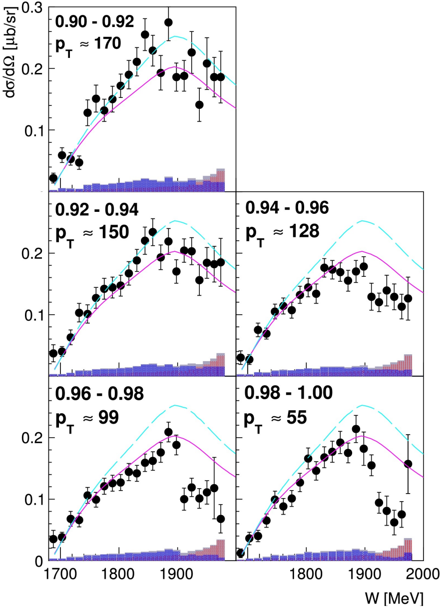


Figure: Fit to the LHCb data obtained from coupled channel analysis (left), along with the corresponding line shapes of the constituents (right) [Du et al., 2021]

Similar states in *uds* sector?

- replace c by s quarks $\to \Sigma^{(*)} K^{(*)}$ molecules?
- should have an impact on $K^+\Sigma(1385)^-$ production

Exotic Hadrons in the *uds* Sector?



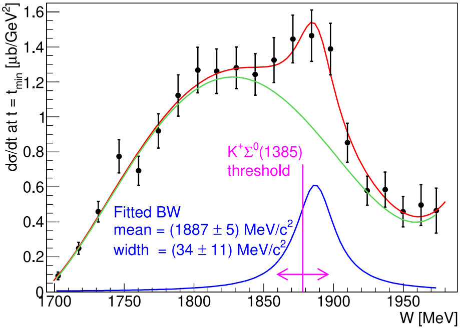


Figure: Differential cross section for $\gamma p \to K^+\Sigma^0$
[Jude et al. (BGOOD), 2021]

$K^+\Sigma(1385)^-$ Photoproduction: Sparse Data Situation

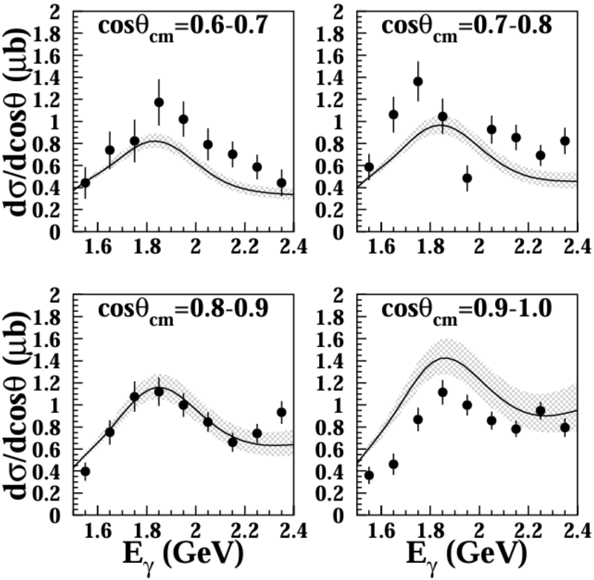


Figure: $\gamma n \to K^+\Sigma(1385)^-$ differential cross section [Hicks et al. (LEPS), 2009]

- coarse E_γ bins
- threshold at $E_\gamma = 1412\,\text{MeV}$ not covered

Experimental Setup

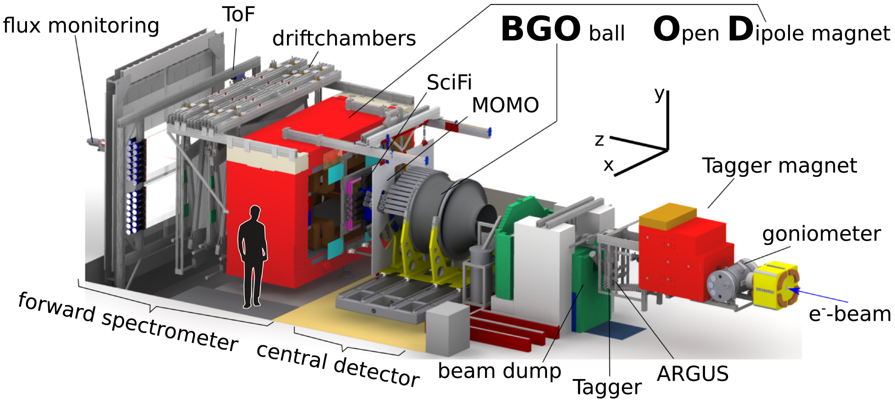


Figure: BGOOD experiment at ELSA [Alef et al. (BGOOD), 2020]

Experimental Setup

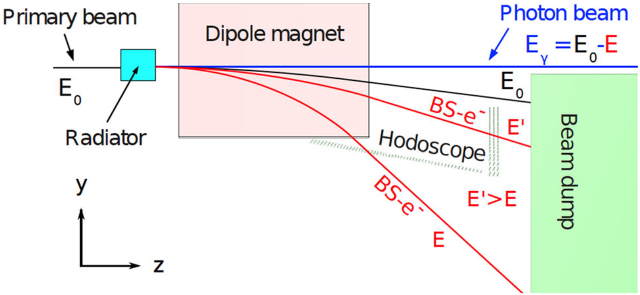
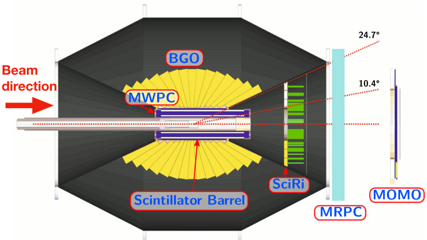


Figure: Photon Tagging

Experimental Setup



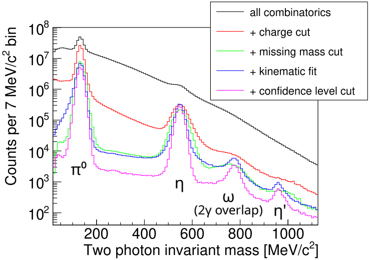
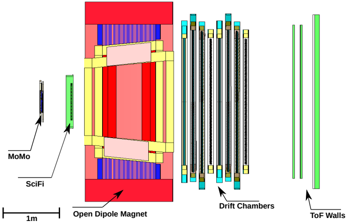


Figure: Neutral meson reconstruction in the BGO ball



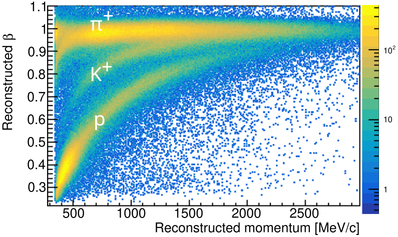


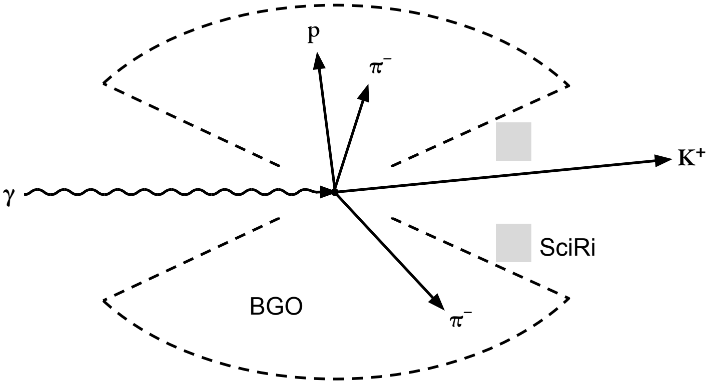
Figure: Charged particle identification in the FS

Decay Chain

$\gamma n \rightarrow K^+\Sigma(1385)^-$

- $\rightarrow \Lambda\pi^-$ (87.0 %)
  - $\rightarrow p\pi^-$ (63.9 %)
  - $\rightarrow n\pi^0$ (35.8 %)
    - $\rightarrow \gamma\gamma$ (98.8 %)
- $\rightarrow (\Sigma\pi)^-$ (11.7 %)

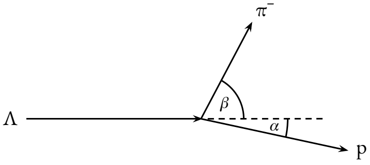
Event Selection: Charged Λ Decay



- require K^+ in FS and three charged particles in BGO or SciRi
- recalculate p/π momenta from momentum conservation

The Correct Particle Assignment

Issue: difficult to distinguish p and π in central detector
Idea: use angle between reconstructed Λ and p/π candidates to determine correct assignment



$$\cos\alpha = \frac{\boldsymbol{p}_\Lambda \cdot \boldsymbol{p}_p}{|\boldsymbol{p}_\Lambda||\boldsymbol{p}_p|}$$

$$= \frac{m_\pi^2 - m_p^2 - m_\Lambda^2 + 2E_\Lambda E_p}{2\sqrt{E_\Lambda^2 - m_\Lambda^2}\sqrt{E_p^2 - m_p^2}}$$

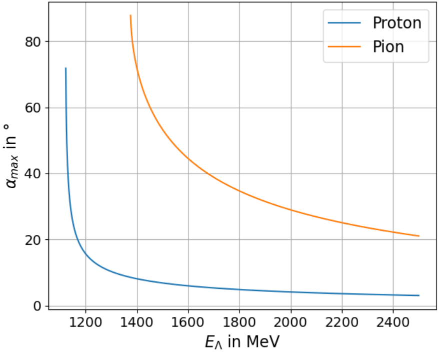


Figure: Maximum allowed angle $\alpha_{\max}$ as a function of energy E_Λ

Identification of the Σ(1385)

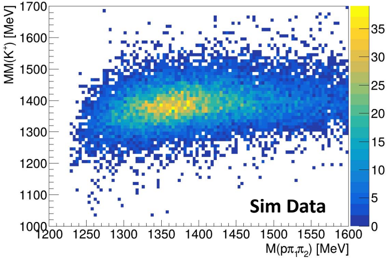


Figure: K^+ missing mass vs $p\pi\pi$ invariant mass

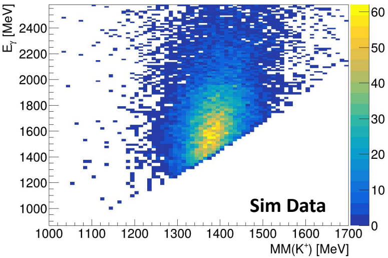
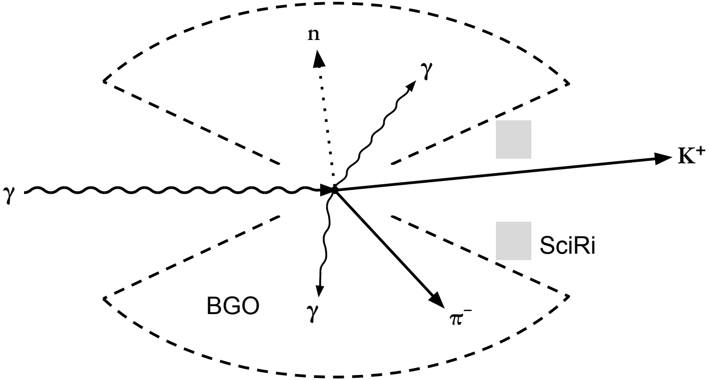


Figure: Beam energy vs K^+ missing mass

Event Selection: Neutral Λ Decay



- require K^+ in FS, two or three neutral particles in BGO, and one charged particle in BGO or SciRi
- reconstruct π^0 from its 2γ decay, 105 MeV $<$ M($\gamma\gamma$) $<$ 165 MeV

Identification of the $\Sigma(1385)$

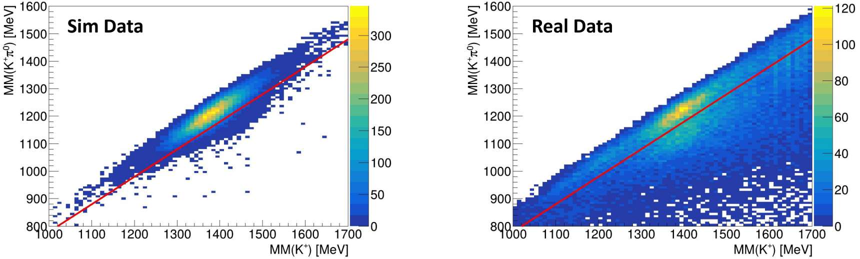


Figure: $K^+\pi^0$ missing mass vs K^+ missing mass

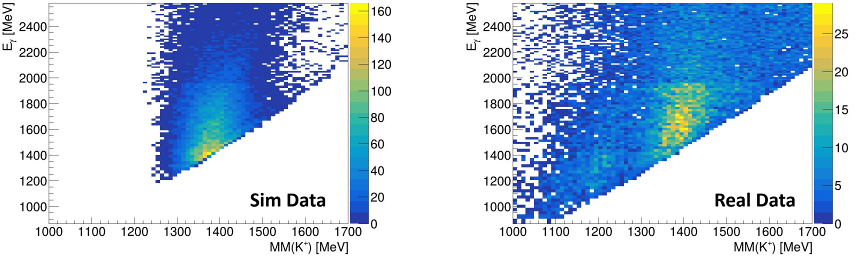


Figure: Beam energy vs K^+ missing mass

π^- Momentum Cut

Use π^- direction $\hat{\boldsymbol{u}}$ for further cut:

$$p_{\text{init}} = p_{K^+} + p_{\pi^0} + p_{\pi^-} + p_n$$

$$\iff (\underbrace{p_{\text{init}} - p_{K^+} - p_{\pi^0}}_{=: p_X} - p_{\pi^-})^2 = m_n^2$$

$$\iff p_X \cdot p_{\pi^-} = \frac{1}{2}\left(m_n^2 - m_{\pi^-}^2 - p_X^2\right)$$

Inserting $p_{\pi^-} = (E_\pi, p\hat{\boldsymbol{u}})$, with $p = |\boldsymbol{p}_{\pi^-}|$ and $E_\pi = \sqrt{m_{\pi^-}^2 + p^2}$:

$$E_\pi E_X - p \underbrace{\hat{\boldsymbol{u}} \cdot \boldsymbol{p}_X}_{=: A} = \underbrace{\frac{1}{2}\left(m_n^2 - m_{\pi^-}^2 - p_X^2\right)}_{=: B}$$

$$\iff \left(m_{\pi^-}^2 + p^2\right) E_X^2 = (Ap + B)^2$$

π^- Momentum Cut

This leads to a quadratic equation in p:

$$\underbrace{\left(A^2 - E_X^2\right)}_{:=a} p^2 + \underbrace{2AB}_{:=b} p + \underbrace{B^2 - m_{\pi^-}^2 E_X^2}_{:=c} = 0$$

A real solution for p exists only if the discriminant is non-negative:

$$D = b^2 - 4ac \overset{!}{\geq} 0$$

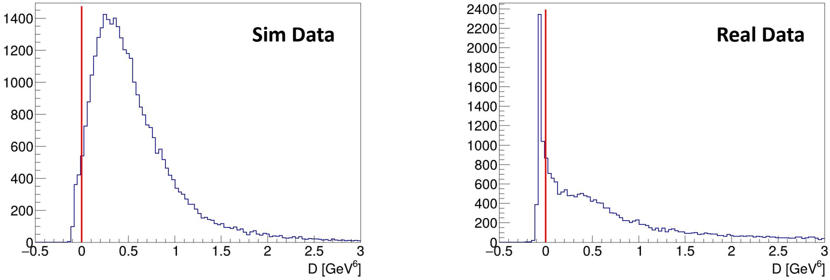


Figure: Pion-momentum discriminant

Identification of the $\Sigma(1385)$

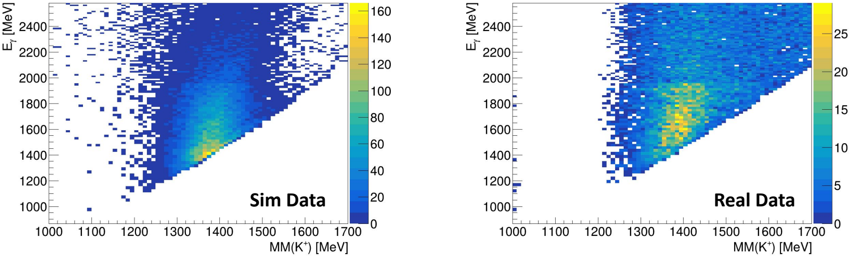


Figure: Beam energy vs K^+ missing mass

Fitting Background Contributions

Background contributions include:

- reactions off the proton → estimated from hydrogen target
- $K^+\Lambda\pi^-$ production
- $K^{*0}\Lambda$ production

} → modeled with simulation

- π^+ misidentified as K^+ → modeled by requiring a K^-

$\Longrightarrow$ template fits of the MM(K^+) spectra to extract signal yield

Fitting Background Contributions

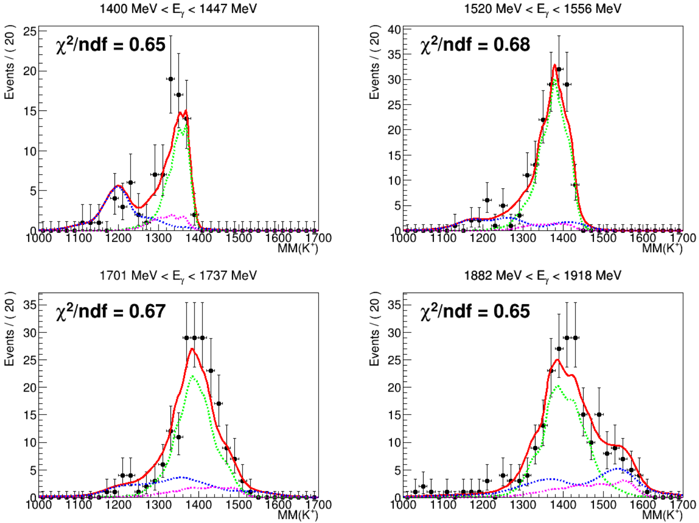


Figure: Example fitting results for charged Λ decay mode: red = total fit, green = signal, blue = reactions off the proton, magenta = $K^+\Lambda\pi^-$ background

Differential Cross Section

$$\frac{\mathrm{d}\sigma(\theta, E_\gamma)}{\mathrm{d}\Omega} = \frac{N(\theta, E_\gamma)}{\varepsilon(\theta, E_\gamma) \cdot N_\gamma(E_\gamma) \cdot n_d \cdot d \cdot \Delta\Omega}$$

Differential Cross Section

$$\frac{\mathrm{d}\sigma(\theta, E_\gamma)}{\mathrm{d}\Omega} = \frac{N(\theta, E_\gamma)}{\varepsilon(\theta, E_\gamma) \cdot N_\gamma(E_\gamma) \cdot n_d \cdot d \cdot \Delta\Omega}$$

solid angle element

$$\Delta\Omega = 2\pi \cdot [\cos\theta]_{\theta_1}^{\theta_2}$$

$$\stackrel{\cos\theta \geq 0.9}{=} 0.2\pi$$

Differential Cross Section

$$\frac{\mathrm{d}\sigma(\theta, E_\gamma)}{\mathrm{d}\Omega} = \frac{N(\theta, E_\gamma)}{\varepsilon(\theta, E_\gamma) \cdot N_\gamma(E_\gamma) \cdot n_d \cdot d \cdot \Delta\Omega}$$

solid angle element

$$\Delta\Omega = 2\pi \cdot [\cos\theta]_{\theta_1}^{\theta_2} \overset{\cos\theta \geq 0.9}{=} 0.2\pi$$

target length

$$d = 11.1\,\mathrm{cm}$$

Differential Cross Section

$$\frac{\mathrm{d}\sigma(\theta, E_\gamma)}{\mathrm{d}\Omega} = \frac{N(\theta, E_\gamma)}{\varepsilon(\theta, E_\gamma) \cdot N_\gamma(E_\gamma) \cdot n_d \cdot d \cdot \Delta\Omega}$$

solid angle element

$$\Delta\Omega = 2\pi \cdot [\cos\theta]_{\theta_1}^{\theta_2} \overset{\cos\theta > 0.9}{=} 0.2\pi$$

target length

$d = 11.1\,\mathrm{cm}$

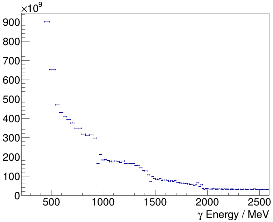
deuteron number density

$n_d = 5.053 \times 10^{22}\,\mathrm{cm}^{-3}$

Differential Cross Section

$$\frac{\mathrm{d}\sigma(\theta, E_\gamma)}{\mathrm{d}\Omega} = \frac{N(\theta, E_\gamma)}{\varepsilon(\theta, E_\gamma) \cdot N_\gamma(E_\gamma) \cdot n_d \cdot d \cdot \Delta\Omega}$$

photon flux



solid angle element

$$\Delta\Omega = 2\pi \cdot [\cos\theta]_{\theta_1}^{\theta_2} \overset{\cos\theta \geq 0.9}{=} 0.2\pi$$

target length

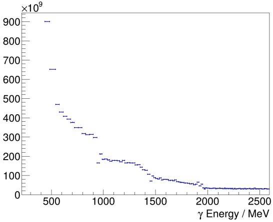
$$d = 11.1\,\mathrm{cm}$$

deuteron number density

$$n_d = 5.053 \times 10^{22}\,\mathrm{cm}^{-3}$$

$$\frac{\mathrm{d}\sigma(\theta, E_\gamma)}{\mathrm{d}\Omega} = \frac{N(\theta, E_\gamma)}{\varepsilon(\theta, E_\gamma) \cdot N_\gamma(E_\gamma) \cdot n_d \cdot d \cdot \Delta\Omega}$$

photon flux

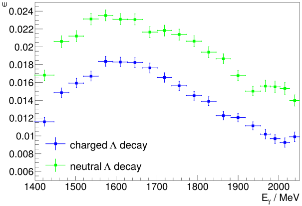


solid angle element

$$\Delta\Omega = 2\pi \cdot [\cos\theta]_{\theta_1}^{\theta_2}$$

$$\overset{\cos\theta \geq 0.9}{=} 0.2\pi$$

reconstruction efficiency



target length

$d = 11.1\,\mathrm{cm}$

deuteron number density

$n_d = 5.053 \times 10^{22}\,\mathrm{cm}^{-3}$

Systematic Error Estimation

Source	Error (%)
beam spot alignment	4.0
beam energy calibration	1.0
photon flux	4.0
SciFi efficiency	3.0
MOMO efficiency	1.0
driftchamber efficiency	1.0
ToF wall efficiency	1.5
forward track geometric selection	1.0
track time selection	2.0
modelling hardware triggers	1.0
target wall contribution	2.0
target length	1.7
K^+ selection	?
π^0 selection	?
fitting uncertainties	?
summed in quadrature	> 7.7

Differential Cross Section

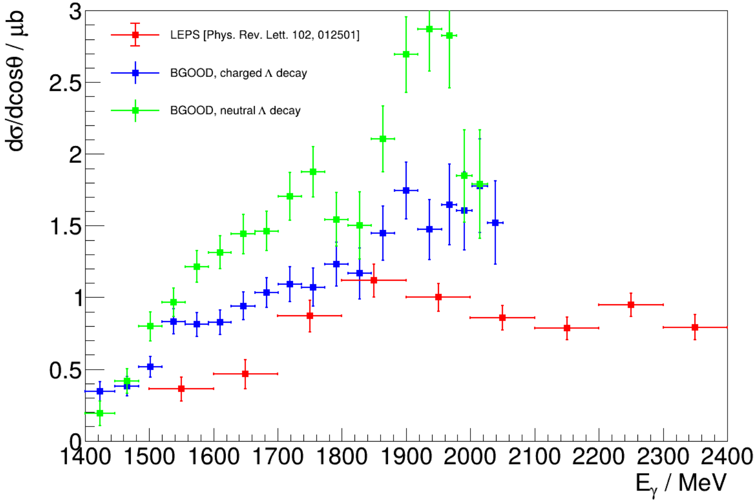


Figure: Preliminary $\gamma n \to K^+\Sigma(1385)^-$ differential cross section for $\cos\theta_{CM}^{K^+} > 0.9$

Summary

- $\gamma n \to K^+\Sigma(1385)^-$ could provide evidence for the existence of light hadronic molecules
- BGOOD experiment ideally suited to study this reaction, identification via both Λ decay channels works
- first high-resolution cross section measurement from threshold, further studies necessary to understand discrepancy
- outlook: more data on disk, INSIGHT experiment

References

R. Aaij et al. [LHCb Collaboration] (2019)
Observation of a Narrow Pentaquark State, $P_c(4312)^+$, and of the Two-Peak Structure of the $P_c(4450)^+$
Phys. Rev. Lett. 122, 222001

M.-L. Du et al. (2021)
Revisiting the nature of the P_c pentaquarks
J. High Energy Phys. 157, 094019

T. C. Jude et al. [BGOOD Collaboration] (2021)
Observation of a cusp-like structure in the $\gamma p \to K^+\Sigma^0$ cross section at forward angles and low momentum transfer
Phys. Lett. B 820, 136559

K. Hicks et al. [LEPS Collaboration] (2009)
Cross Sections and Beam Asymmetry for $K^+\Sigma^{*-}$ Photoproduction from the Deuteron at $E_\gamma = 1.5 - 2.4\,\mathrm{GeV}$
Phys. Rev. Lett. 102, 012501

S. Alef et al. [BGOOD Collaboration] (2020)
The BGOOD experimental setup at ELSA
Eur. Phys. J. A 56

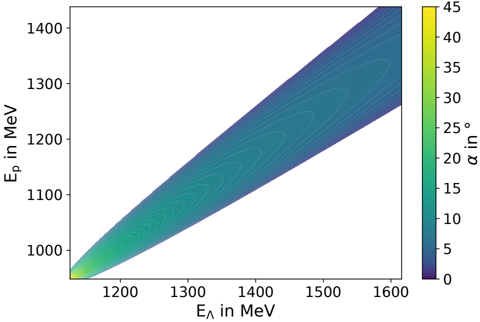
Backup I: Momentum Recalculation

In practice, we can only measure the direction of the charged particles: unit vectors $\hat{\boldsymbol{p}}^1$, $\hat{\boldsymbol{p}}^2$, $\hat{\boldsymbol{p}}^3$. Momentum conservation implies:

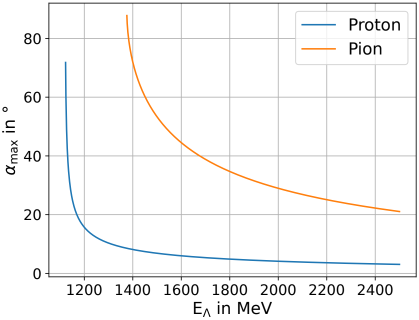
$$\begin{aligned} p_x^{K^+} + A \cdot \hat{p}_x^1 + B \cdot \hat{p}_x^2 + C \cdot \hat{p}_x^3 &= 0 \\ p_y^{K^+} + A \cdot \hat{p}_y^1 + B \cdot \hat{p}_y^2 + C \cdot \hat{p}_y^3 &= 0 \\ p_z^{K^+} + A \cdot \hat{p}_z^1 + B \cdot \hat{p}_z^2 + C \cdot \hat{p}_z^3 &= E_\gamma \end{aligned}$$

$\Longrightarrow$ solve equation system to find 3-momenta, check that $A, B, C > 0$
try all combinations to assign $\boldsymbol{p}^1, \boldsymbol{p}^2, \boldsymbol{p}^3$ to p, π_1^-, π_2^-

$$\cos\alpha = \frac{m_\pi^2 - m_p^2 - m_\Lambda^2 + 2E_\Lambda E_p}{2\sqrt{E_\Lambda^2 - m_\Lambda^2}\sqrt{E_p^2 - m_p^2}}$$



(a) α as a function of E_Λ and E_p. The uncoloured regions are kinematically forbidden.



(b) Maximum allowed angle $\alpha_{\max}$ as a function of E_Λ.

Backup III: Kernel Density Estimation (KDE)

given: some observed data $x_1, x_2, ..., x_n$
sought: underlying pdf

$$\hat{f}_h(x) = \frac{1}{nh} \sum_{i=1}^{n} K\left(\frac{x - x_i}{h}\right)$$

kernel has to satisfy $K(x) \geq 0$, $\int_{-\infty}^{\infty} K(x)\,\mathrm{d}x = 1$ and $K(x) = K(-x)$

example: Gaussian kernel $K(x) = \frac{1}{\sqrt{2\pi}} \exp(-\frac{x^2}{2})$

$\frac{1}{h} K\left(\frac{x-x_i}{h}\right)$ corresponds to a scaled kernel centered at x_i
bandwidth h controls how wide/narrow the kernel is

Backup III: Kernel Density Estimation (KDE)

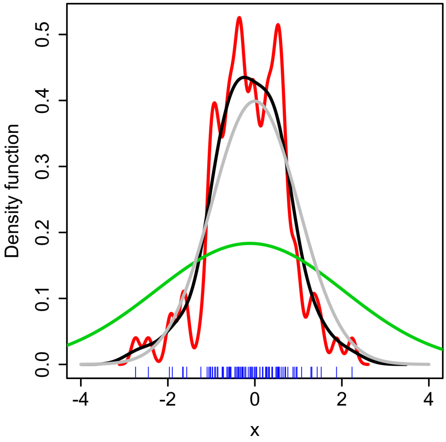


Figure: Example KDE. Grey = true density (standard normal), Red = h too small, Black = optimal h, Green = h too large. Taken from `https://commons.wikimedia.org/w/index.php?curid=73892711`