Strangeness photoproduction at extremely forward angles at the BGO-OD experiment

Tom Jude
On behalf of the BGO-OD Collaboration

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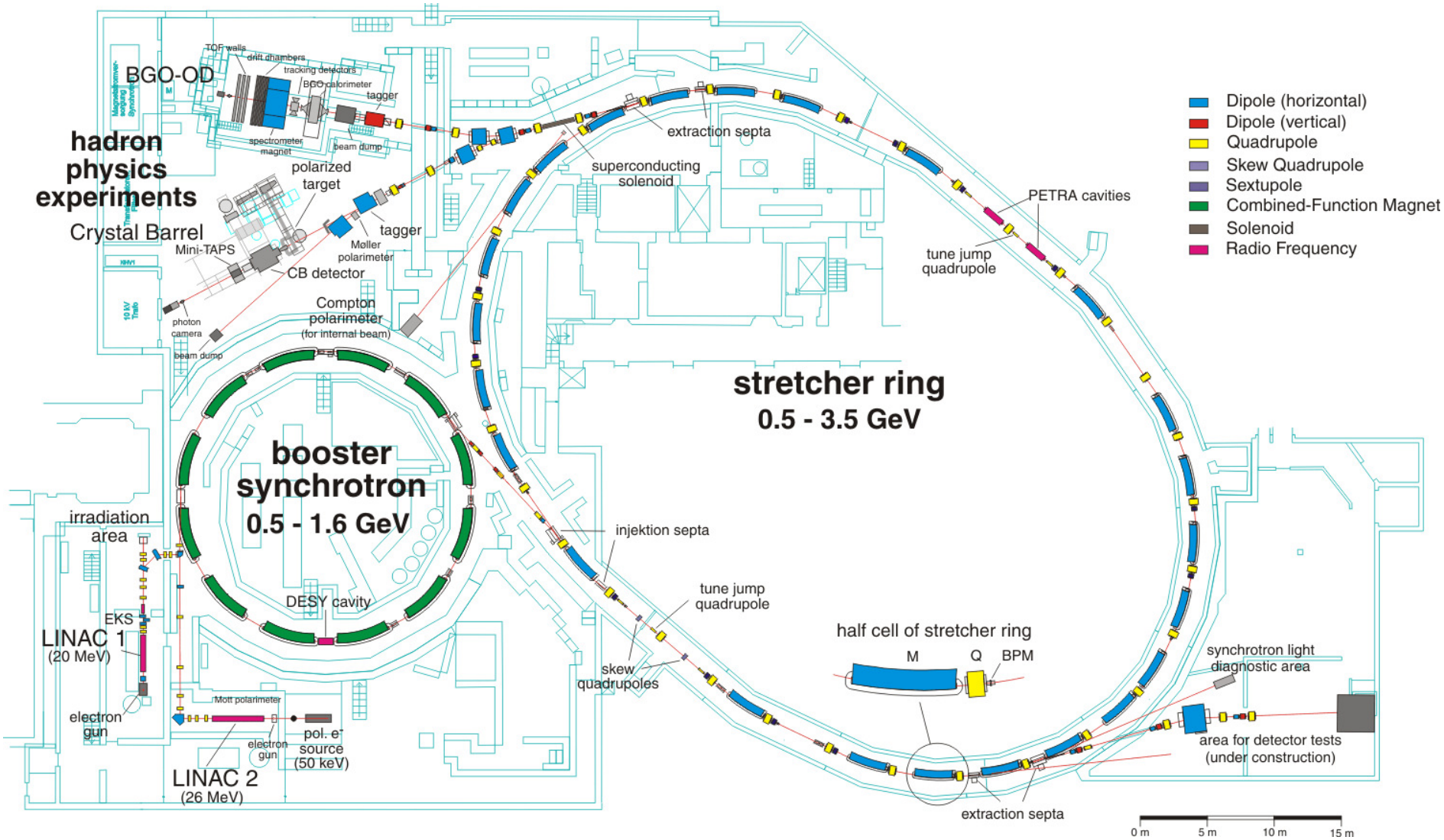
Strangeness photoproduction at extremely forward angles at the BGO-OD experiment

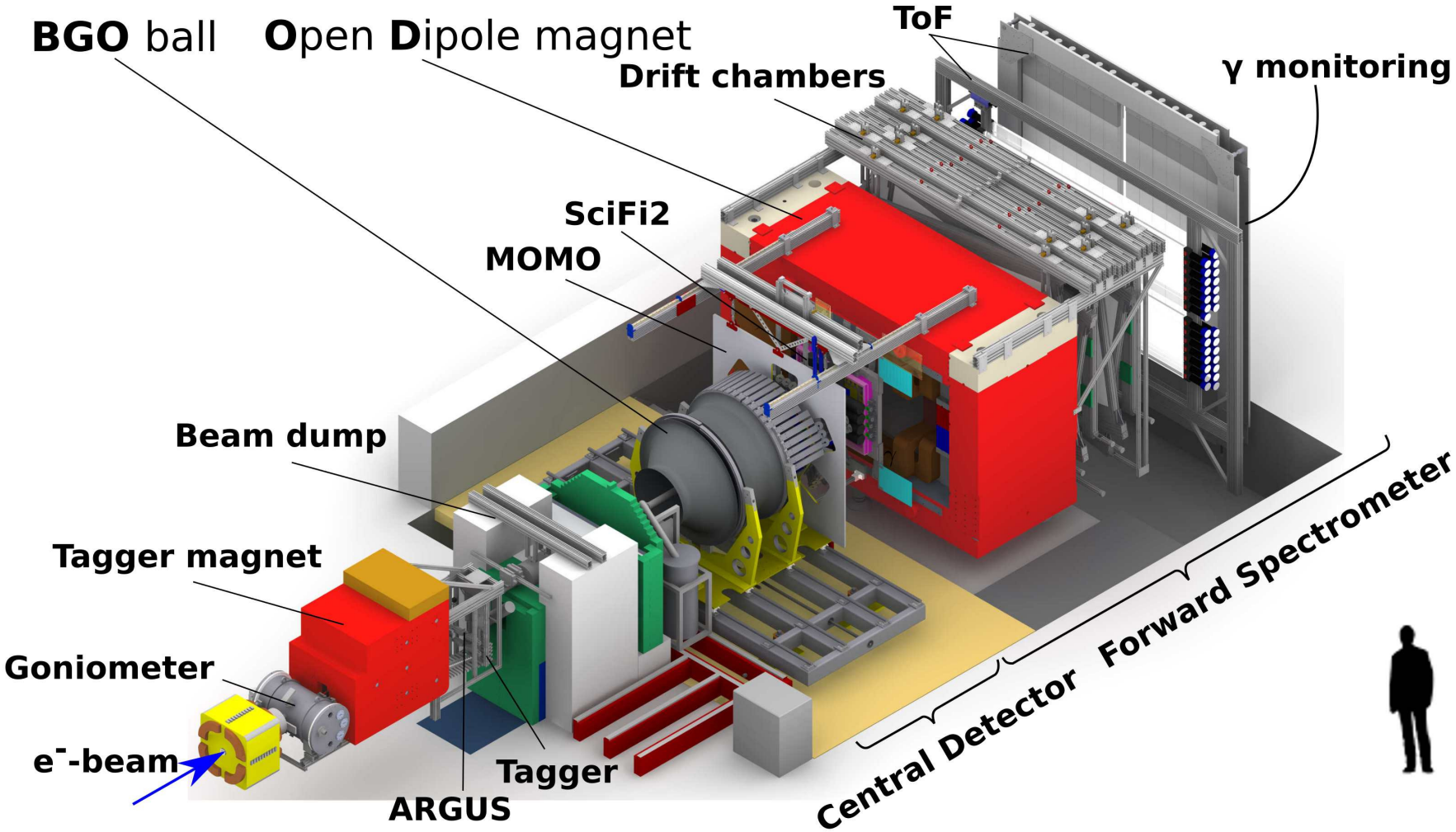
- The BGO-OD experiment at ELSA, Bonn
- Motivation: Hadron structure - parallels in strange & charmed quark sectors?
- Strangeness photoproduction - first results:
  1. $\Lambda(1405)$ & access to higher lying hyperons
  2. Extreme forward cross sections for $K^+\Lambda$ & $K^+\Sigma^0$ photoproduction
  3. K^0 photoproduction off proton & neutron (deuterium) targets
  4. Future opportunities - Y-N interaction & hypernuclei studies
- Summary

The Electron Stretcher Accelerator (ELSA)



The BGO-OD experiment at ELSA

- BGO calorimeter (central region) & Forward Spectrometer combination
- High momentum resolution, excellent charged & neutral particle ID



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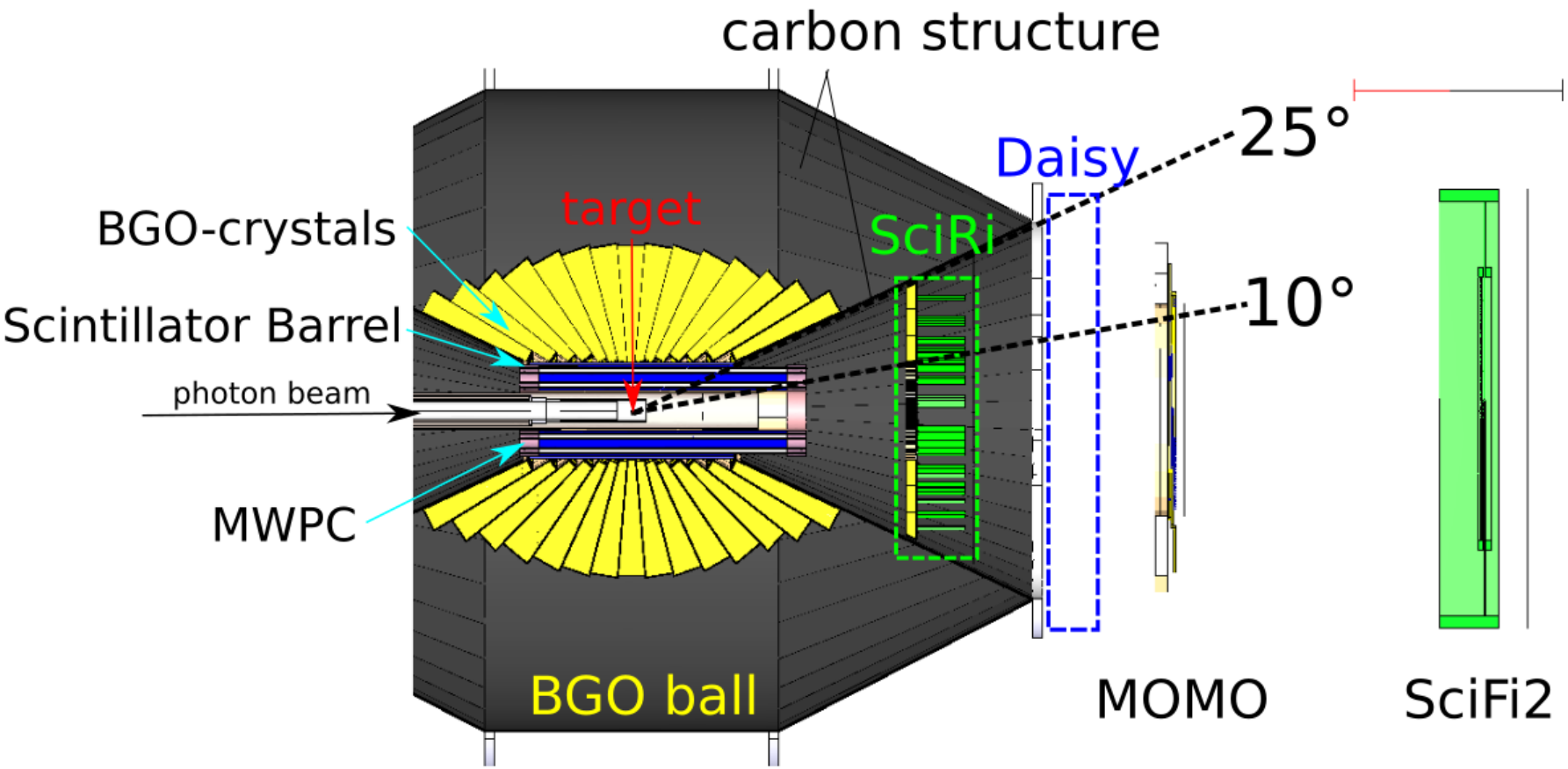

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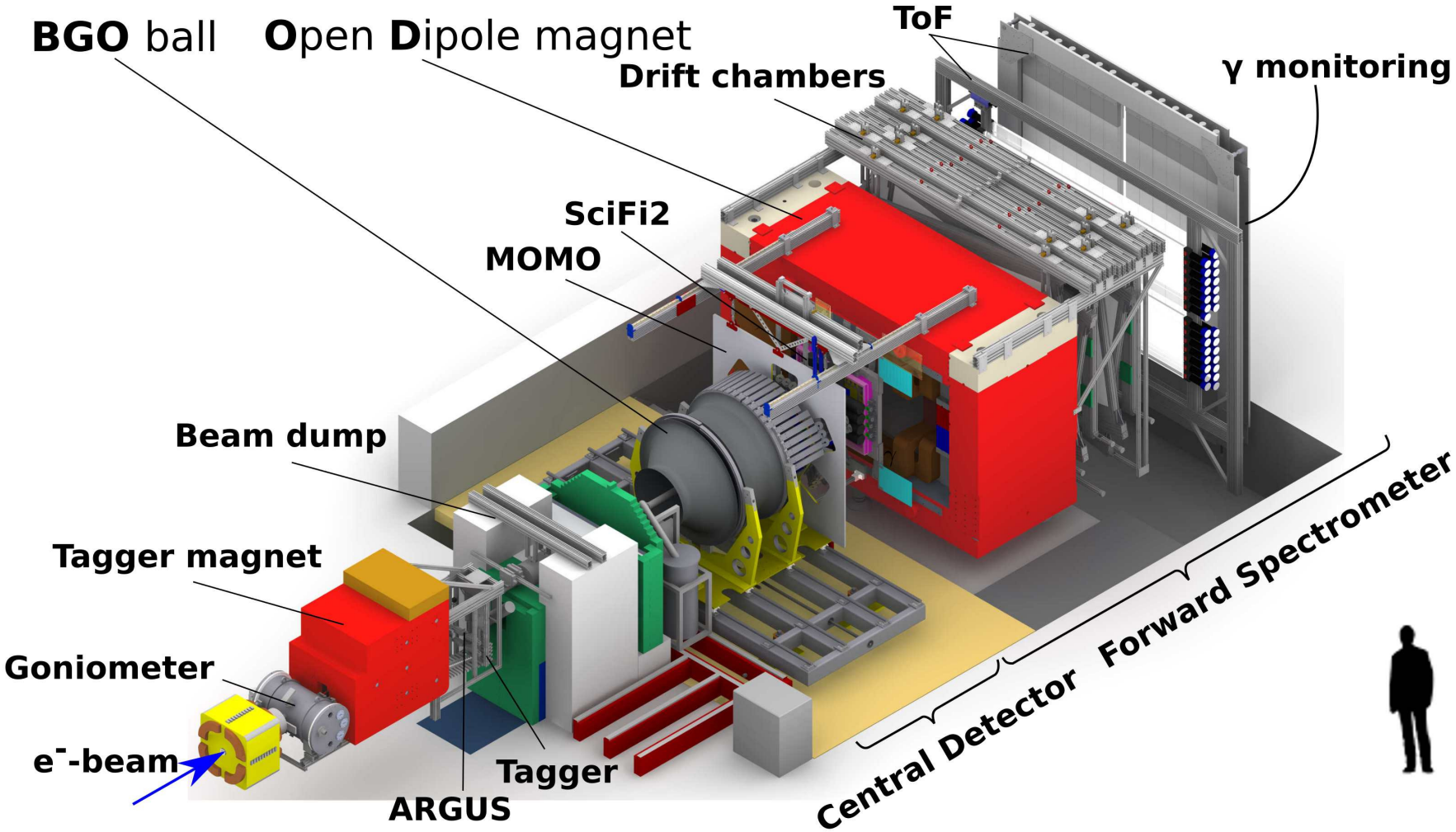
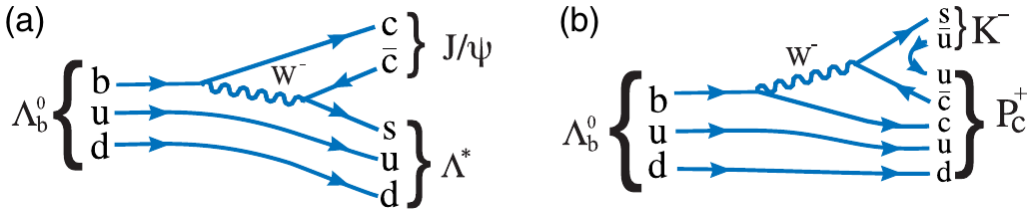


Motivation - Exotic phenomena in the charmed sector

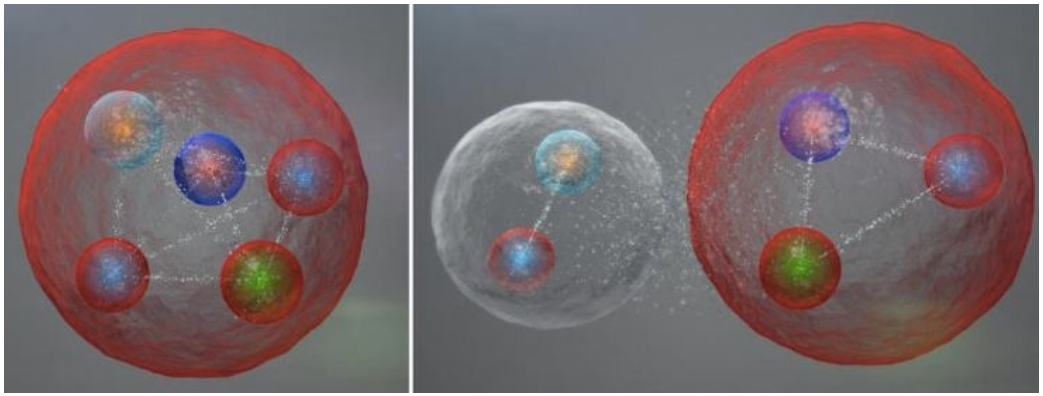
Pentaquark candidates observed at LHCb - $P_c(4450)^+$ & $P_c(4380)^+$

R. Aaij et al, PRL 115, 072001 (2015)



Meson-baryon dynamically generated states in the charmed sector - J.-J. Wu, R. Molina, E. Oset, and B.S. Zou, Phys. Rev. Lett. 105, 232001 (2010)

Forsaken pentaquark particle spotted at CERN

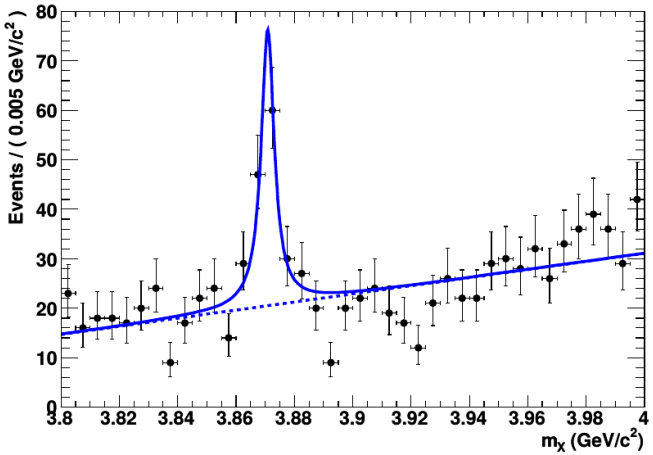


Nature 523, 267 (2015)

$X(3872)$ - a molecular $D^0\bar{D}^{0*}$ state?

N.A. Törnqvist, Phys. Lett. B590, 209 (2004)

Close to $D^0\bar{D}^{0*}$ threshold, favouring DD^* decay



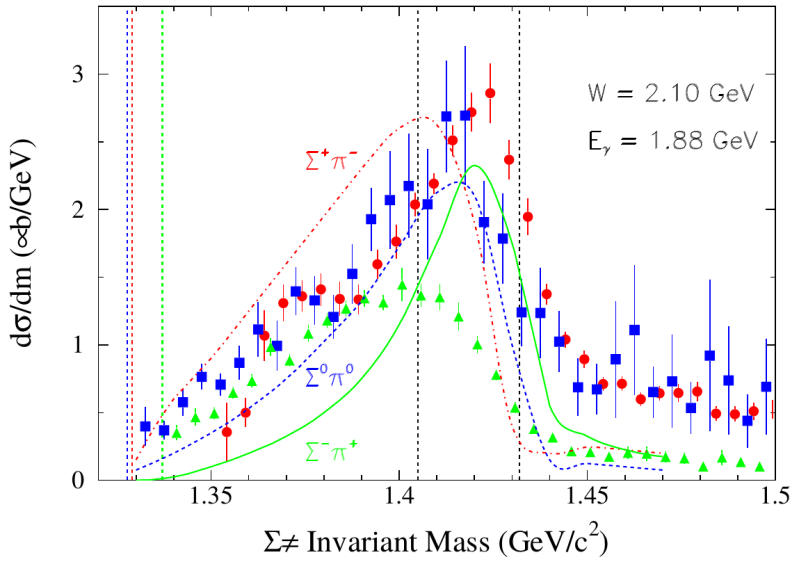
B. Aubert et al (BARBAR Collaboration), Phys. Rev. D77 111101 (2008)

J^{PC} verified: 1^{++} R. Aaij *et al.* (LHCb Collaboration), PRL 110, 222001 (2013)

X(3872) discovery - most cited paper from Belle, PRL91, 262001 (2003)

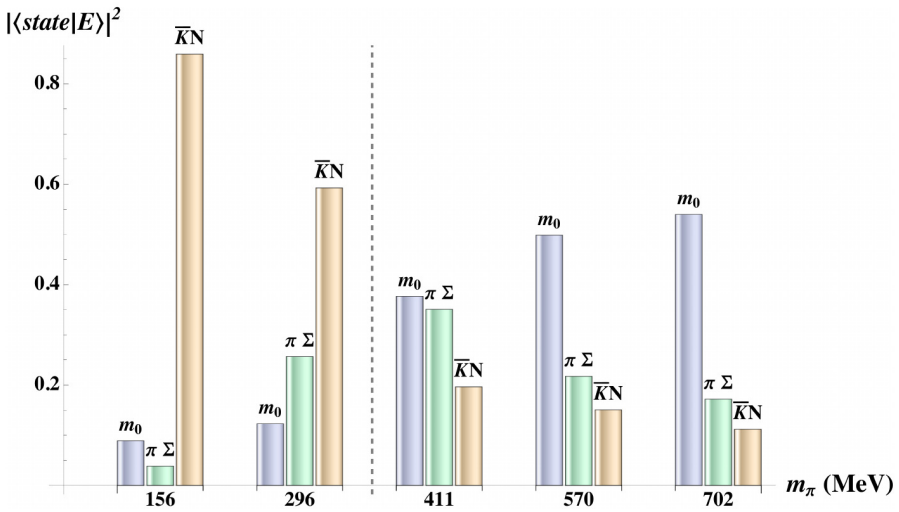
Motivation - Structure of the Λ(1405)

- Between the $\pi\Sigma$ & $\bar{K}N$ thresholds
- Line shape (invariant mass) depends upon the $\pi\Sigma$ decay mode
- Distorted by interference of Isospin 0 & 1 amplitudes J.C. Nacher *et al.*, Nucl. Phys. A 725, 181 (2003)



K. Moriya *et al.* (CLAS Collaboration) Phys. Rev. **C 87**, 035206 (2013)

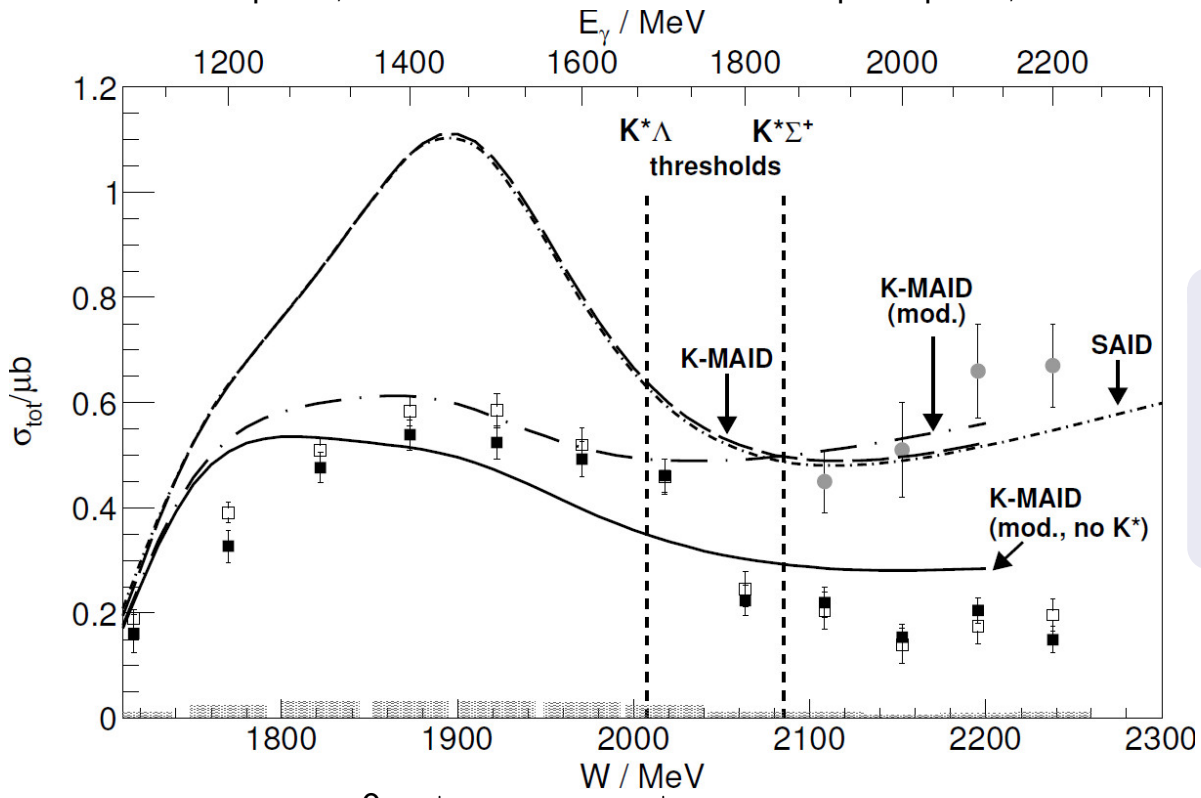
- Λ(1405) - dynamically generated by meson-baryon interactions? J.C. Nacher, E. Oset, H. Toki, A. Ramos, U.G. Meissner, Nucl. Phys. A 725 (2003) 181
- LQCD calculations: J.M.M Hall et al., Phys. Rev. Lett. 114 (2015) 132002



Motivation - Cusp structure in $\gamma p \to K^0\Sigma^+$ cross section

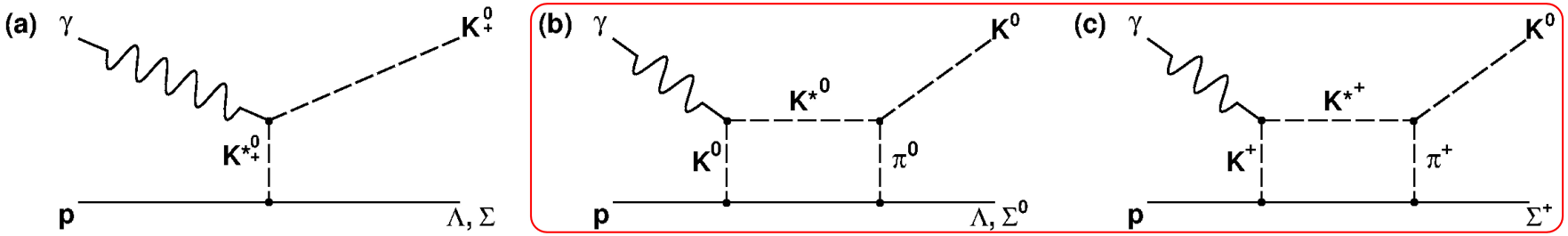
R. Ewald *et al.*,Phys. Lett. B 713 (2012) 180 (CBELSA/TAPS Collaboration).

This data: Full squares, Previous CBELSA-TAPS data: open squares, Previous SAPHIR data: triangles (references therein)



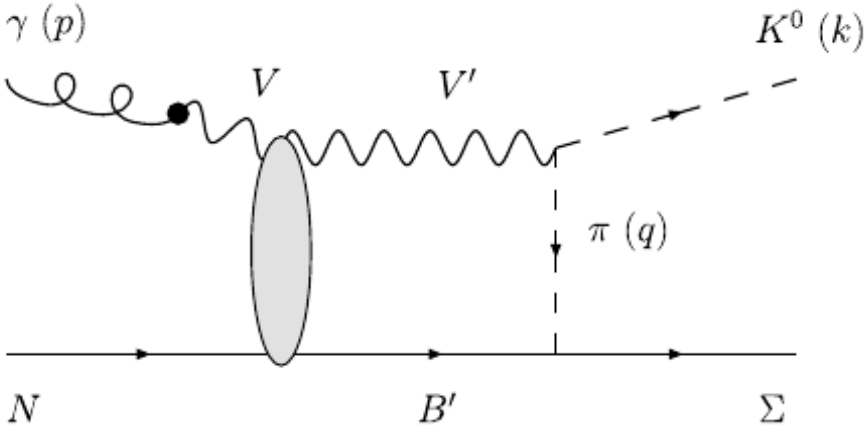
- Cusp-like structure due to K^{*0} subthreshold production rescattering to π^0 & K^0?

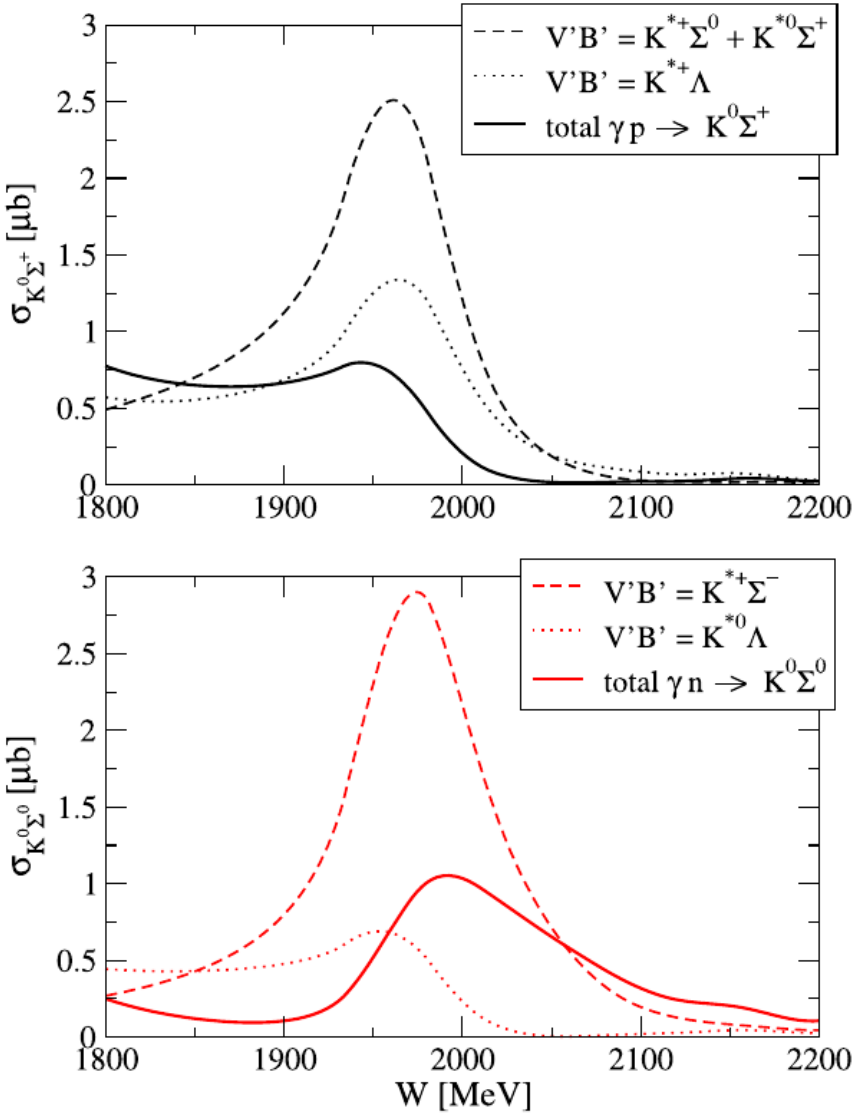
Grey points - $K^0\Sigma^+ + K^*\Sigma^+$ M. Nanova et al., EPJ A35, 333 (2008)



Motivation - K^0 photoproduction off the neutron

A. Ramos and E. Oset, Phys. Lett. **B 727**, (2013) 287 *The role of vector-baryon channels and resonances in the $\gamma p \to K^0\Sigma^+$ and $\gamma n \to K^0\Sigma^0$ reactions near the $K^*\Lambda$ threshold*



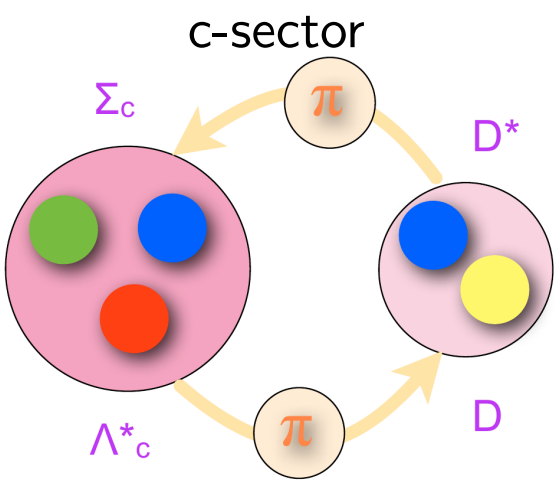


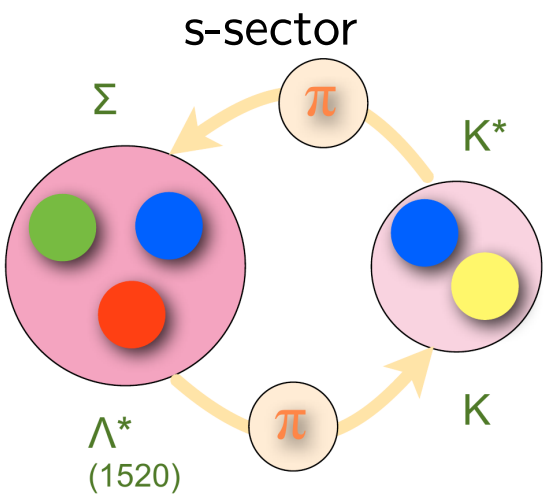
- $K^0\Lambda$ Complementary to $K^+\Lambda$ - relate hadronic coupling constants
- Limited available data, K. Tsukada et al, Phys. Rev. C 78, 014001 (2008)

Motivation - Parallels between charmed and strange sectors

Table and figures from H. Schmieden, private communication

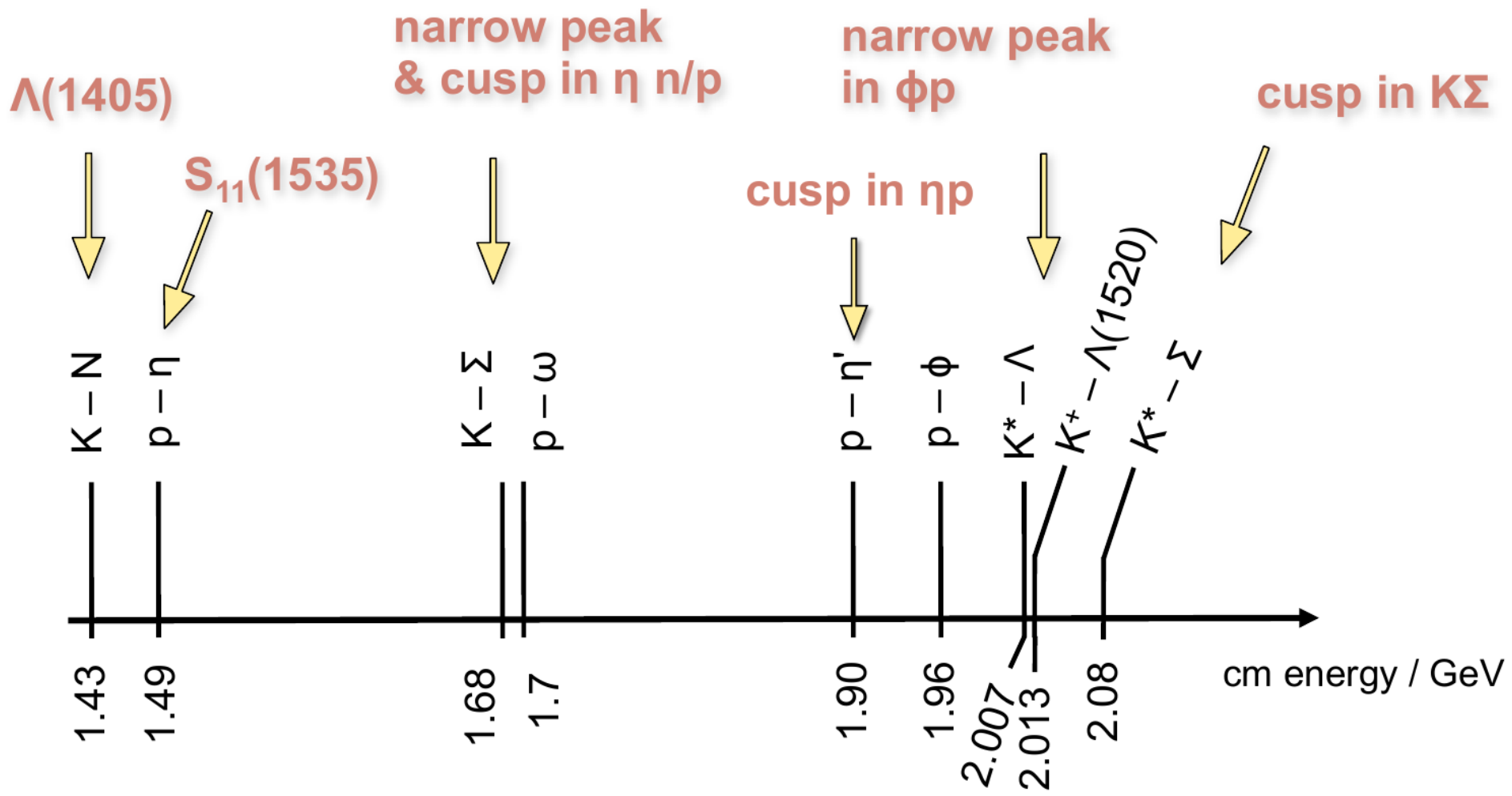
	c-sector		s-sector	
	meson	baryon(s)	meson	baryon(s)
state(s)	$X(3872)$	$P_c^*(4380/4450)$	$f_1(1420)$	$N^*(2030/2080)$
π-exchange transition	$D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$	$\Lambda_c^*\bar{D} + \Sigma_c\bar{D}^*$	$K^*\bar{K} + K\bar{K}^*$	$\Lambda^*\bar{K} + \Sigma\bar{K}^*$
quantum nos.	$J^{PC} = 1^{++}$	$J^P = (3/2)^-$	$J^{PC} = 1^{++}$	$J^P = (3/2)^-$
3-body threshold	$D^0\bar{D}^0\pi^0$	$\Sigma_c^+\bar{D}^0\pi^0$	$K\bar{K}\pi$	$\Sigma\bar{K}\pi^0$
closed flavour channel	$J/\psi\ \omega$	$\chi_{c1}p$	$\phi f_0(500)$	ϕp





Motivation - Threshold dynamics

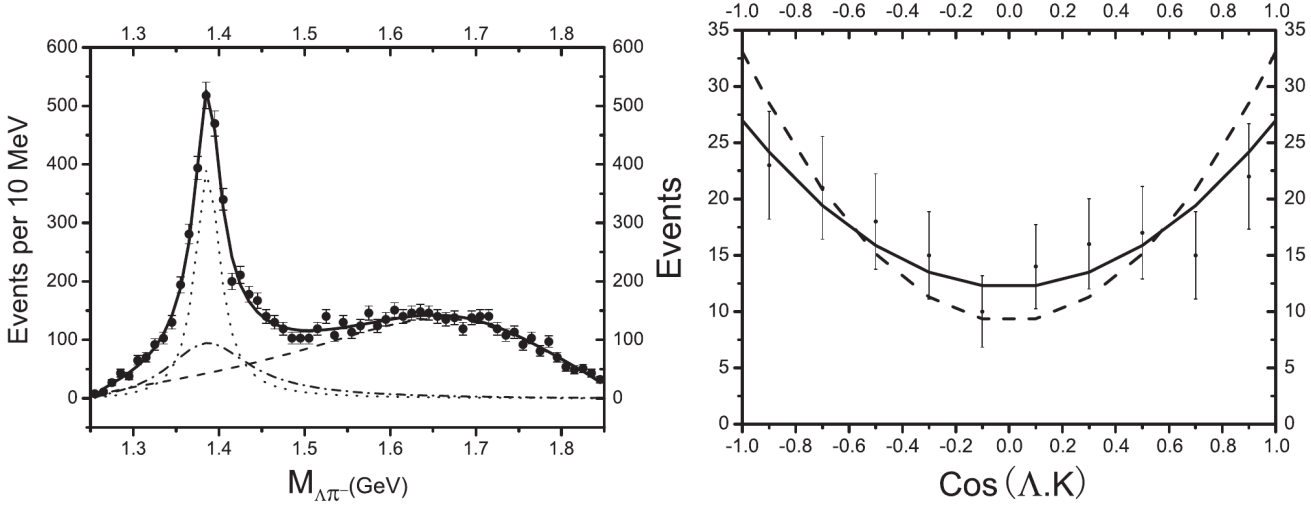
Figure from H. Schmieden, private communication



Λ^* and Σ^* spectra

- Very limited succss with constituent quark models
- Models including meson-baryon interactions as degrees of freedom - more successful, L.Ya. Glozman and D.O. Riska, Physics Reports 268 (1996) 263, C. Garcia-Recio et al., Phys. Lett. B 582 (2004) 49, M.F.M. Lutz, E.E. Kolomeitsev, Phys. Lett. B 585 (2004) 243.
- Hadronic molecules - predict new Y^* states, eg Σ^* ($J^P = 1/2^-$) close to $\Sigma(1385)$: Jia-Jun Wu et al., Phys. Rev. D 80 (2009) 017503

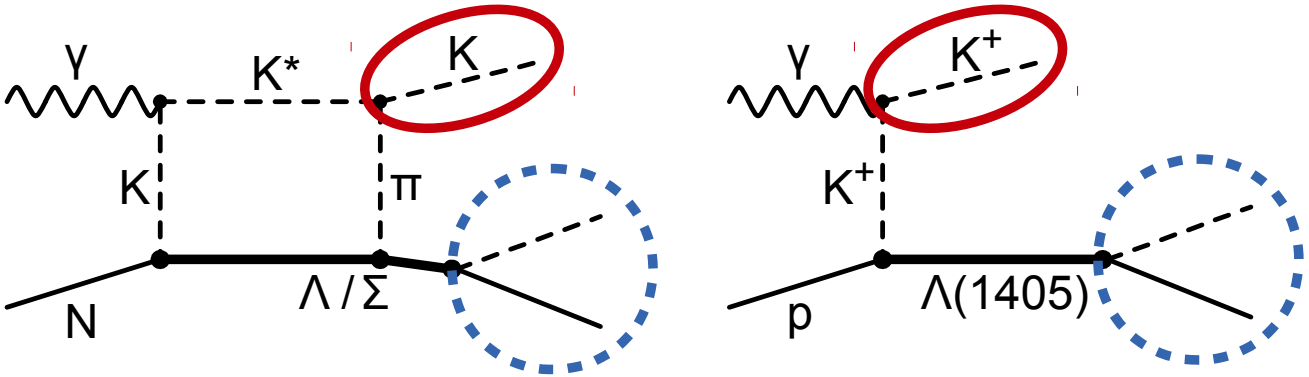
$$K^- p \to \Lambda \pi^+ \pi^-$$



- 26 PDG Σ^* states - 16 are listed as existence poor to fair. C. Patrignani *et al.*

Experimental requirements

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

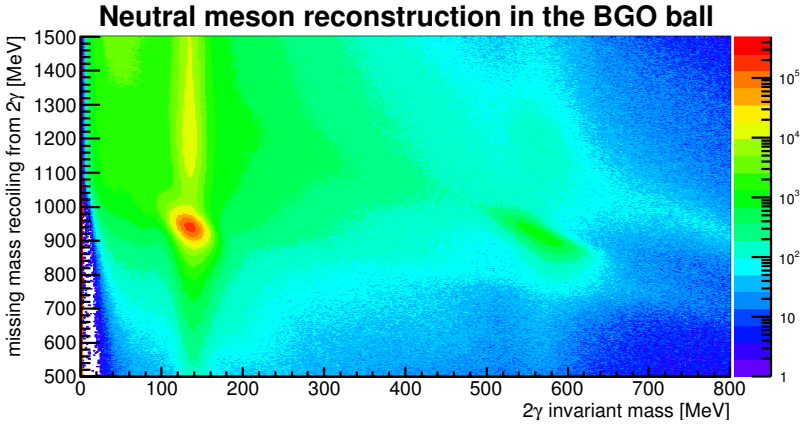


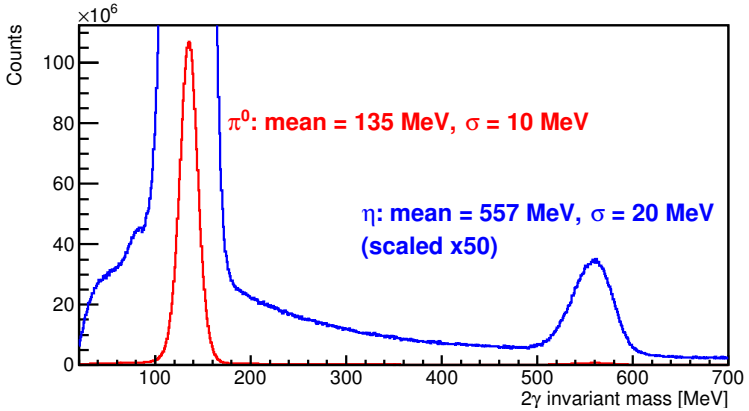
- Unique & complementary to existing facilities (eg CBELSA-TAPS neutral particle reconstruction, CLAS charged particle reconstruction).

BGO-OD at the ELSA facility, Bonn (Germany)

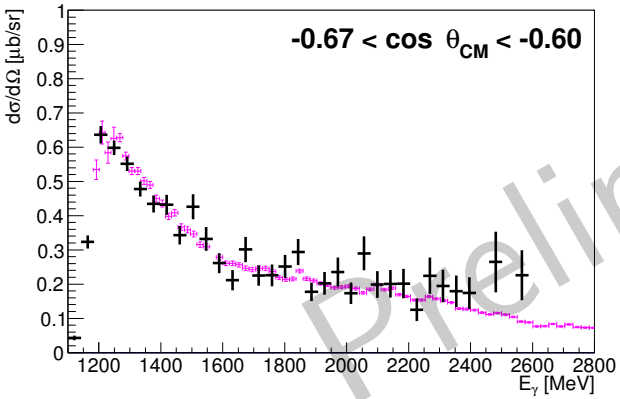
Detector performance - central region

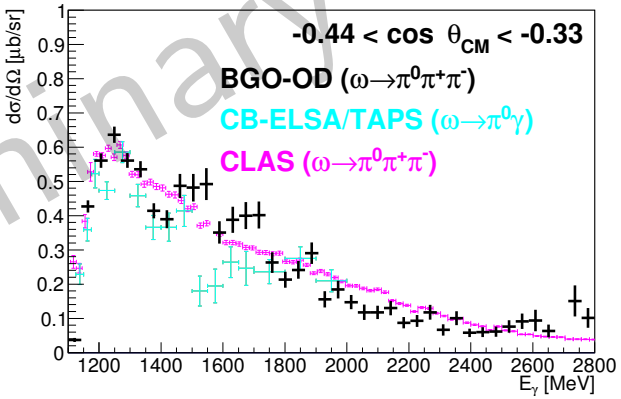
- 1st large data set taken in 2017. Neutral meson reconstruction (IH_2 target):





- Demonstration (1 of many bench marks) - $\gamma p \to \omega p$ $d\sigma/d\Omega$ via the mixed charge decay, $\omega \to \pi^0\pi^+\pi^-$ (G. Scheluchin)



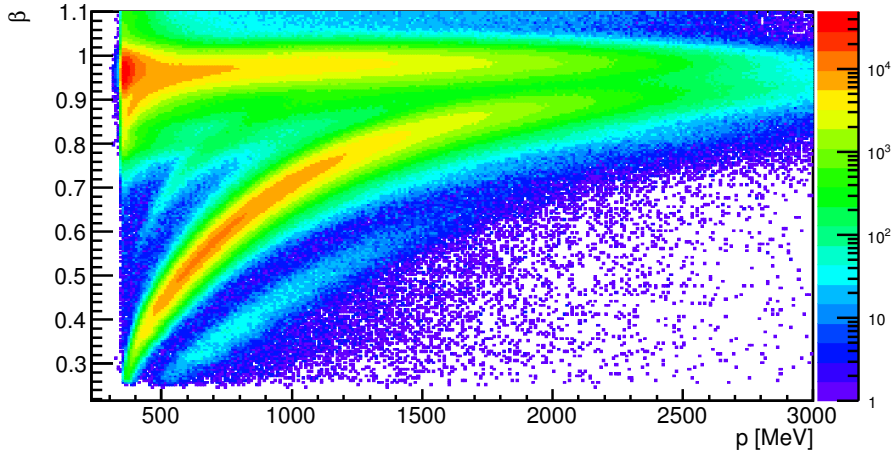


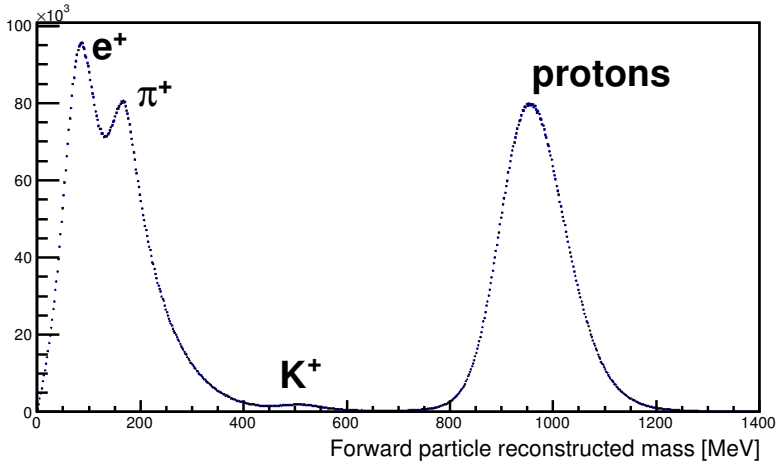
F. Dietz *et al.* (CB-ELSA/TAPS), Eur. Phys. J. **A 51**, 6 (2015)

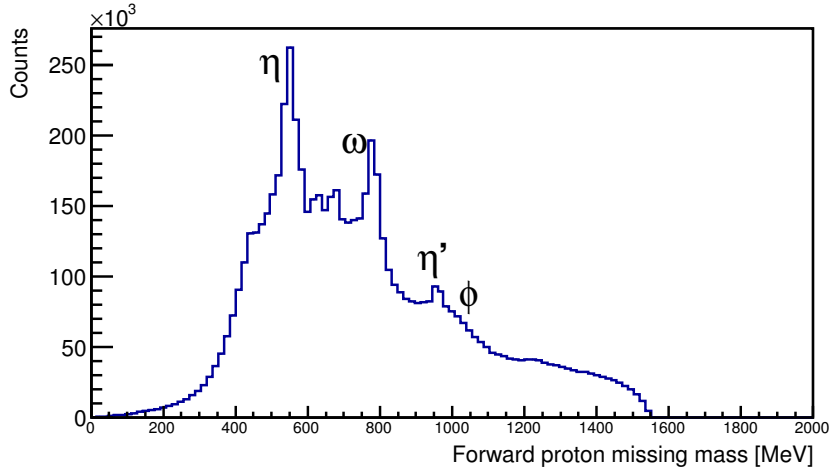
M. Williams *et al.* (CLAS), Phys. Rev. **C 80**, 065208 (2009)

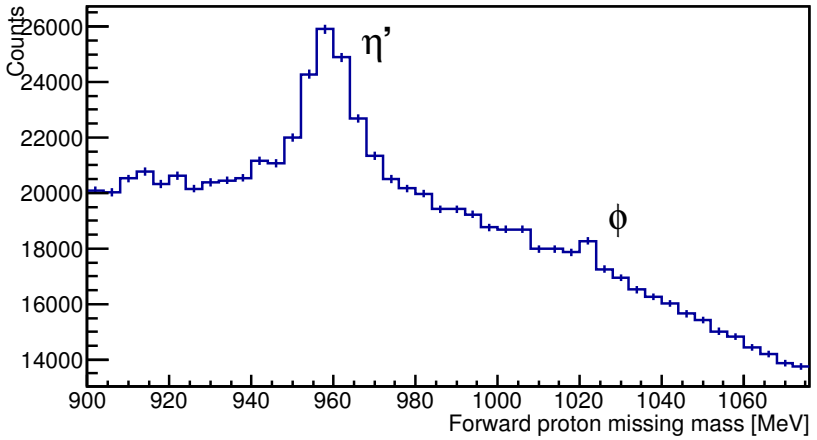
Detector performance - forward spectrometer

- Top - Particle identification in the Forward Spectrometer
- Bottom - "Missing mass" from forward proton (raw counts)









Strangeness photoproduction at extremely forward angles at the BGO-OD experiment

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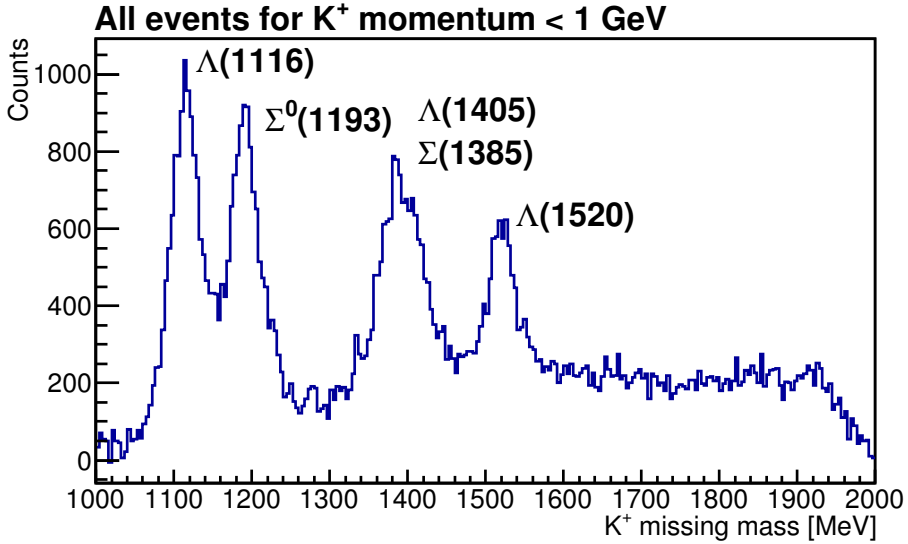
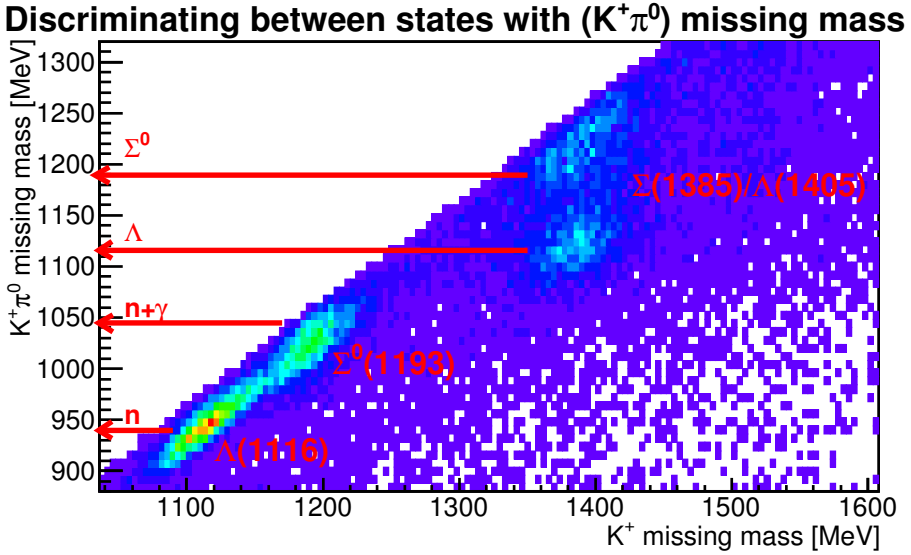
- Motivation: Hadron structure - parallels in strange & charmed quark sectors?
- Strangeness photoproduction - first results:
  1. $\Lambda(1405)$ & access to higher lying hyperons
  2. Extreme forward cross sections for $K^+\Lambda$ & $K^+\Sigma^0$ photoproduction
  3. K^0 photoproduction off proton & neutron (deuterium) targets
  4. Future opportunities - Y-N interaction & hypernuclei studies
- Outlook and conclusions

Mass recoiling from K^+ in the forward spectrometer

- The study of Y^* states in an extremely low momentum transfer region





Identify Y^* states from $K^+\pi^0$ recoiling mass

- $K^+\Lambda \rightarrow K^+\pi^0 n$ (Missing neutron mass from $K^+\pi^0$ system)
- $K^+\Lambda(1405) \rightarrow K^+\pi^0\Sigma^0$ (Missing Σ^0 mass from $K^+\pi^0$ system)
- $K^+\Sigma(1385) \rightarrow K^+\pi^0\Lambda$ (Missing Λ mass from $K^+\pi^0$ system)

Goal - $\Lambda(1405)$ lineshape at low momentum transfer region

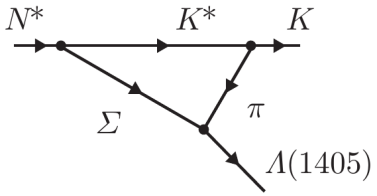
$\Lambda(1405)$ over a broad kinematic range

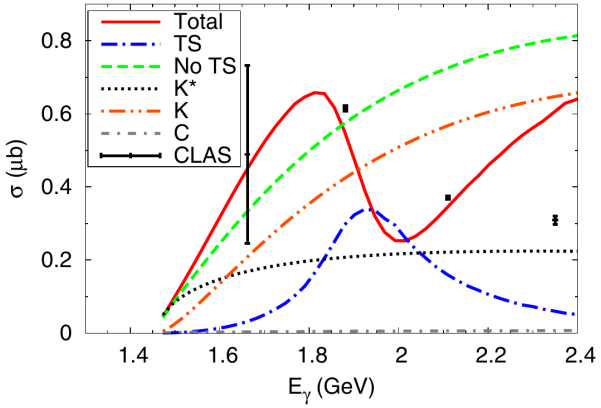
G. Scheluchin

Complements CLAS data - K. Moriya et al., Phys. Rev. **C** **88**, 045201 (2013)

Triangle singularity can describe peak at $W = 2110$ MeV & $\cos\theta = 0$:

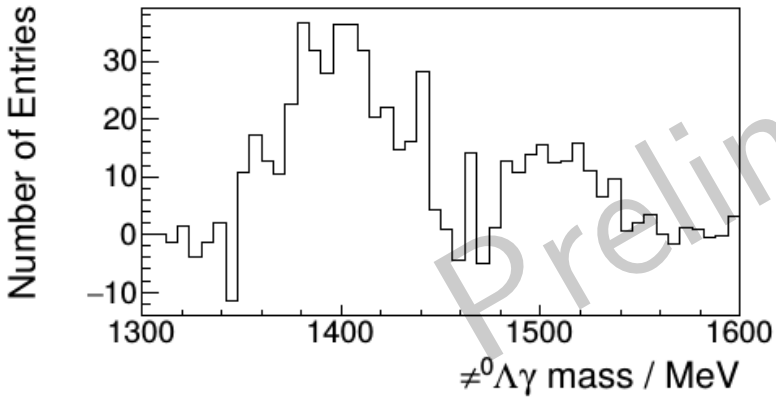
- Full $K^+\Lambda(1405)$ & $K^+\Lambda(1520)$ reconstruction
- $K^+\Lambda(1405) \to K^+\pi^0\Sigma^0 \to K^+\gamma\gamma\gamma\pi^- p$



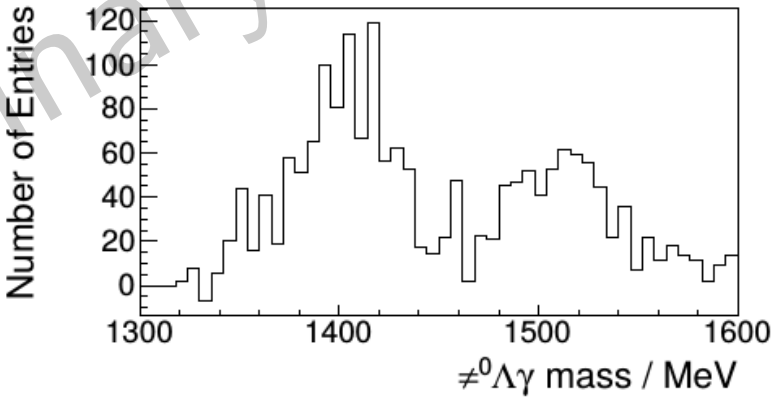


E. Wang et al., Phys. Rev. **C** **95**, 015205 (2017)

$\theta^{c.m.}_{K^+} = 0..45°$



$\theta^{c.m.}_{K^+} = 45..90°$



Preliminary

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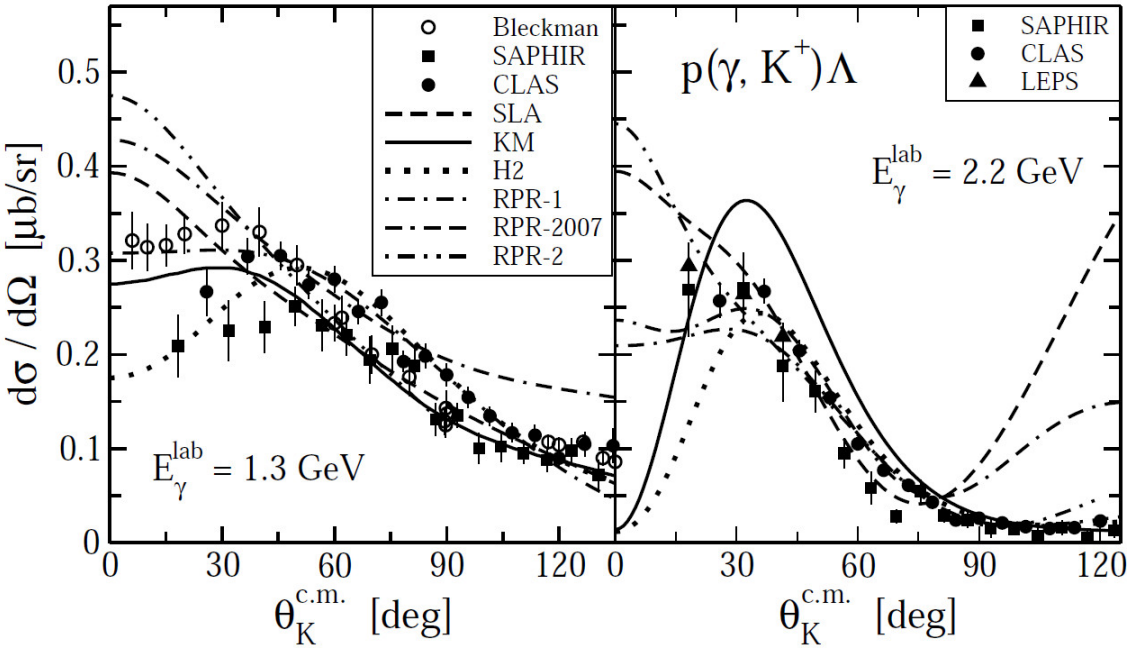
$K^+\Lambda$ at forward angles - motivation

Not only Y^* states at forward angles important - ground state hyperon photoproduction at low t virtually unconstrained by data!

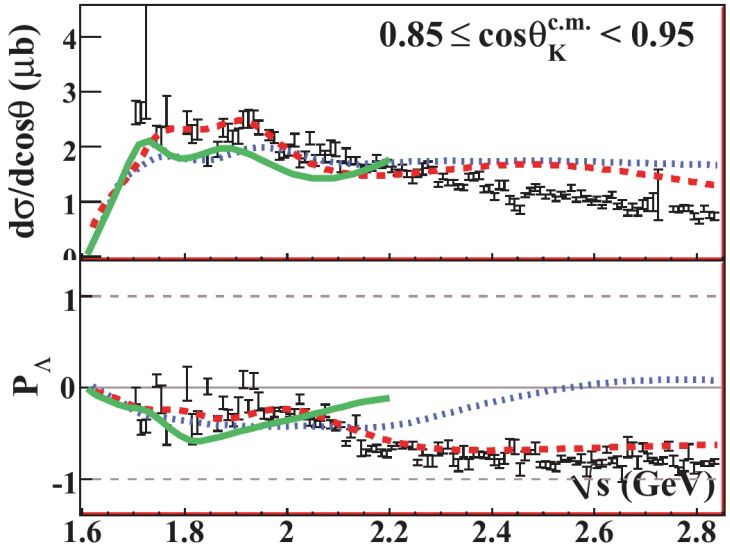


Bydzovsky and D. Skoupil, arXiv:1211.2684v1 (2012) Proceedings of SNP12

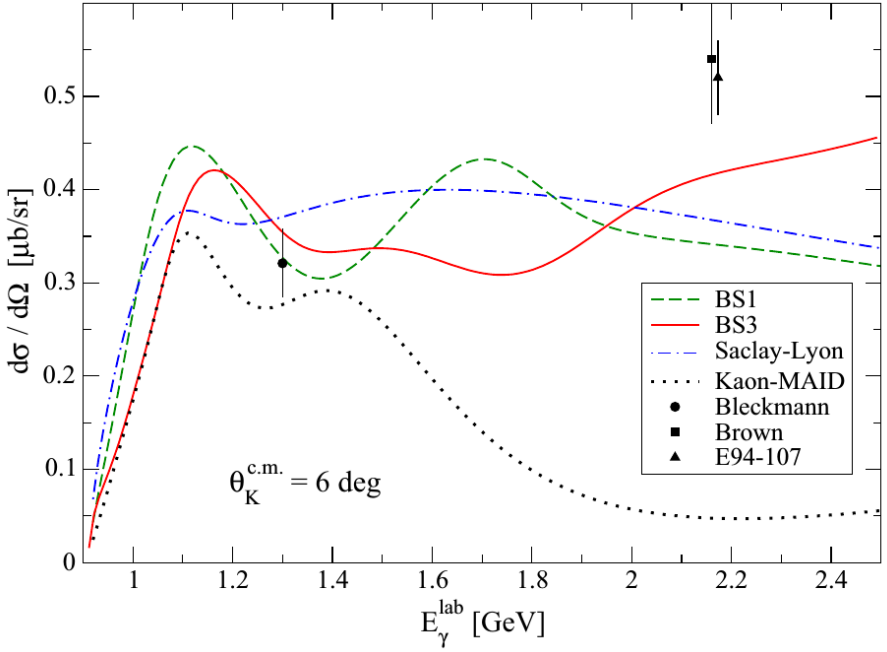
Crucial constraint for hypernuclei electroproduction!
- eg Saclay Leon model for $p(e, e'K^+)\Lambda$

T. Mizutani, C. Fayard, G.-H. Lamot & B. Saghai, Phys. Rev. **C 58**, 75 (1998)

$K^+\Lambda$ at forward angles - motivation



M. E. McCracken, *et. al* (CLAS Collaboration), Phys. Rev. **C 81, 025201 (2010)**



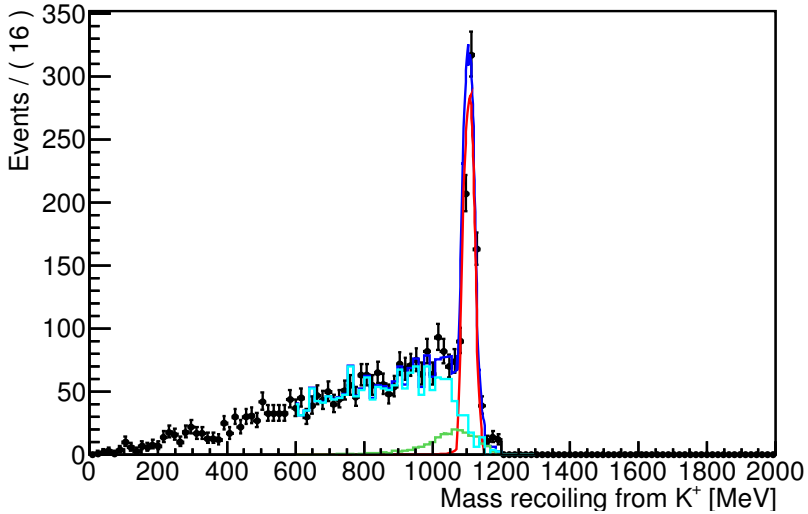
D. Skoupil, P. Bydzovsky, Phys. Rev. **C97**, 025202 (2018)

At BGO-OD

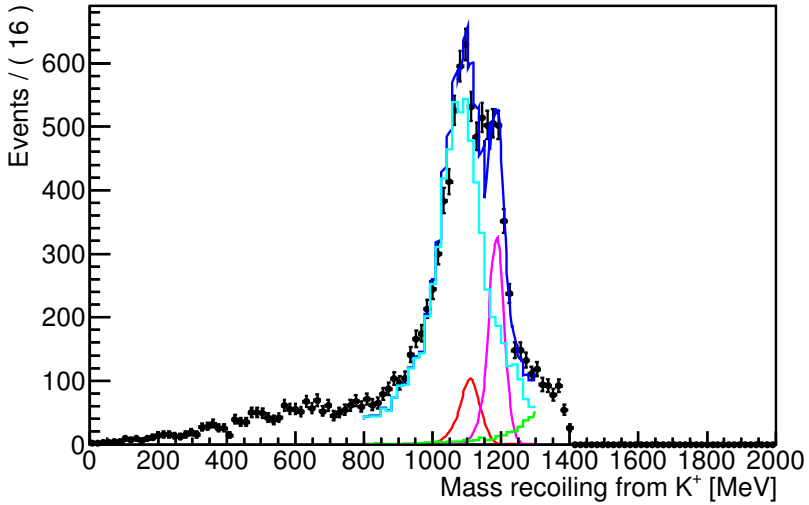
- Forward CM polar angle range approx. 3-26^0, $0.9 < \cos\theta_{cm}^{K^+} < 1.0$
- Unprecedented $\theta_{cm}^{K^+}$ resolution ($< 1^0$)
- P_Λ - recoil Λ polarisation accessed by angular distribution of $\Lambda \to \pi^0 n$ & $\pi^- p$

Extracting $K^+\Lambda$ & $K^+\Sigma^0$ signal from background

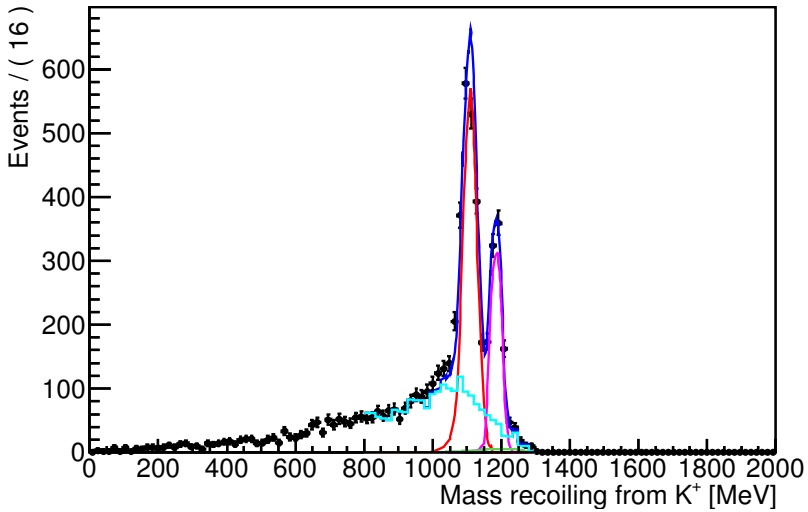
W = 1600 - 1700 MeV



W = 1800 - 1900 MeV



W = 1700 - 1800 MeV

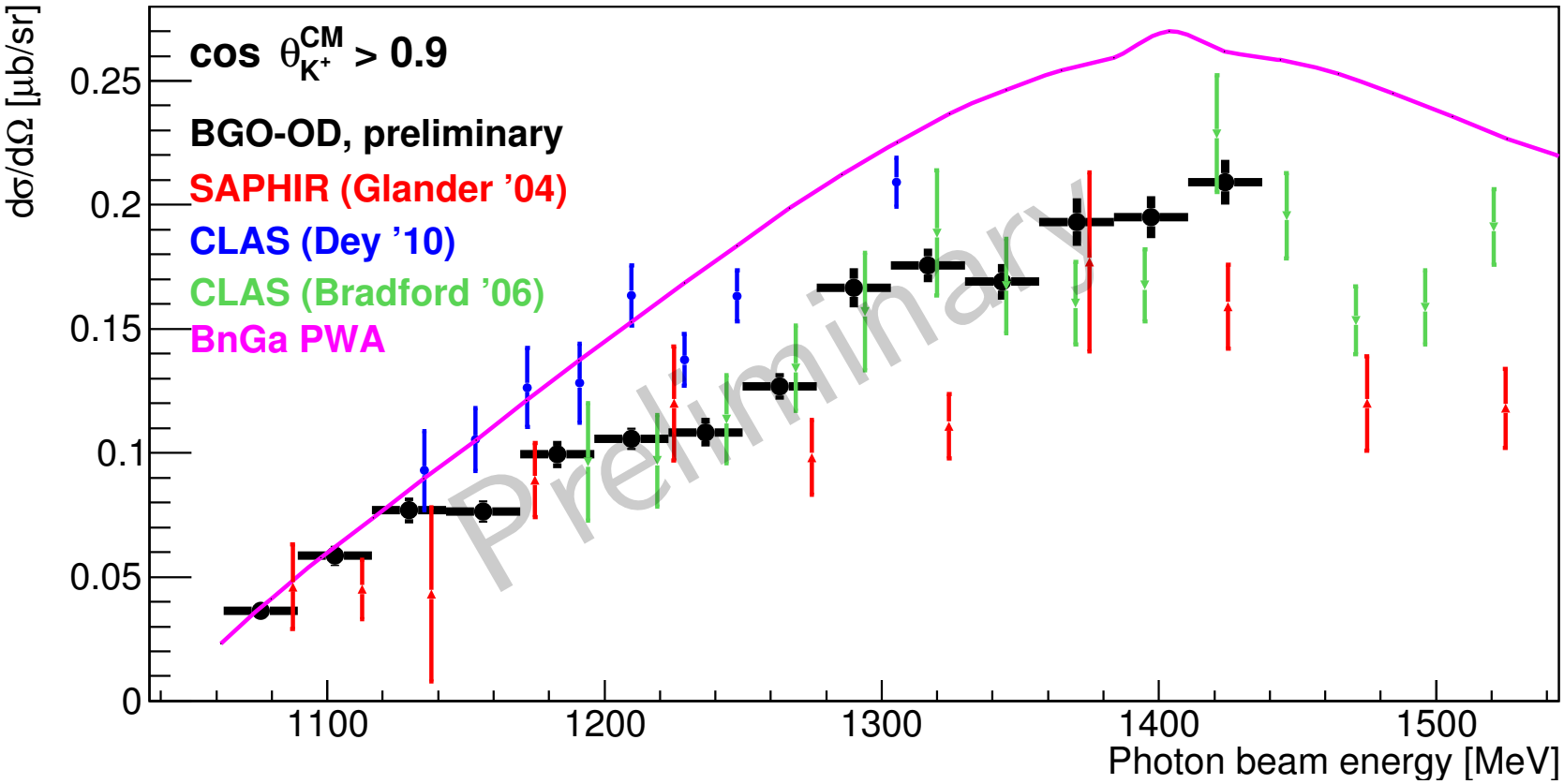


Fitting with *RooFit* https://root.cern.ch/roofit

- Signal
- Simulated $K^+\Lambda$ events
- Simulated $K^+\Sigma^0$ events
- Background from pair production in the beam

Preliminary forward $K^+\Sigma^0$ differential cross sections

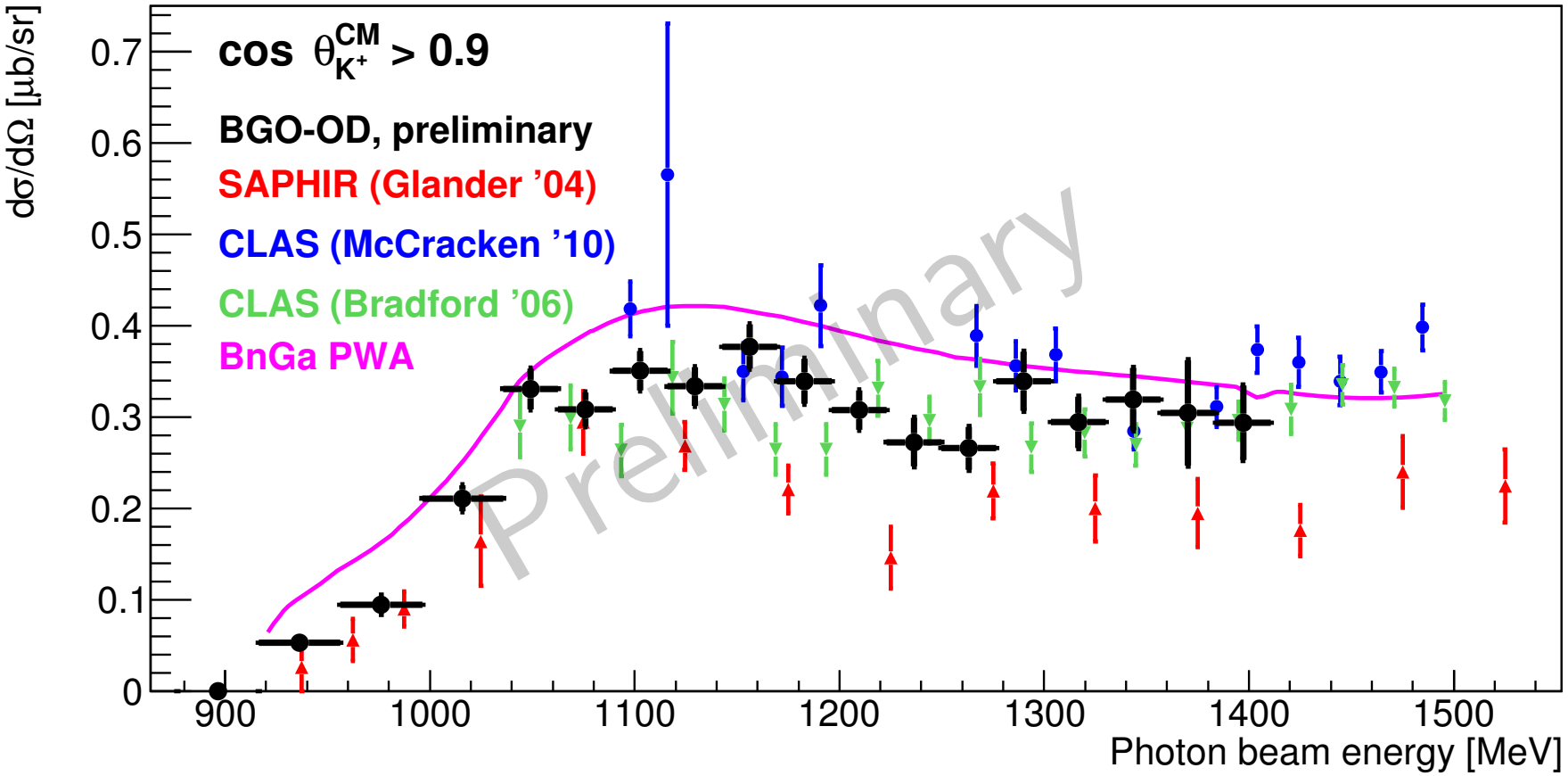
- Test of systematics for forward K^+ detection
- Highest statistics data set (& only 75% of available data)
- Work in progress - binning into fine polar angle intervals (3^0 centre of mass)



R. Bradford *et al.*, Phys. Rev. C73, 035202 (2006), B.Dey *et al.*, Phys.Rev. C82, 025202 (2010), K.H. Glander *et al.*, Eur. Phys. J. A19, 251 (2004), CLAS data in $\cos\theta^{CM}_{K^+}$ 0.85 to 0.95 interval

Preliminary forward $K^+\Lambda$ differential cross sections

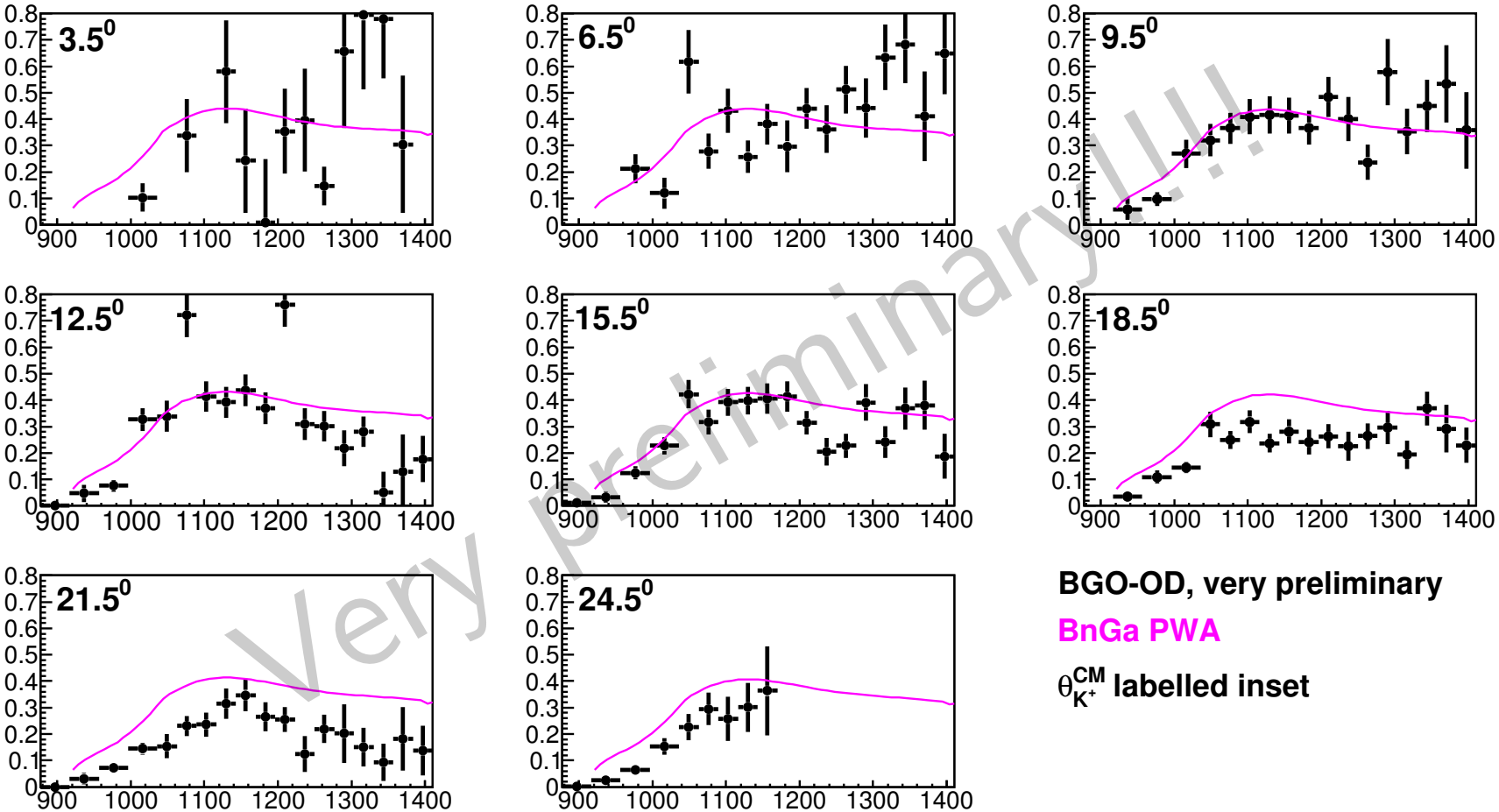
- Highest statistics data set - distinguish discrepancies in existing data
- Ongoing analysis - statistical error to be reduced by 1/2



R. Bradford *et al.*, Phys. Rev. C73, 035202 (2006), M.E.McCracken *et al.*, Phys.Rev. C81, 025201 (2010), K.H. Glander *et al.*, Eur. Phys. J. A19, 251 (2004), CLAS data in $\cos\theta^{CM}_{K^+}$ 0.85 to 0.95 interval

Preliminary forward $K^+\Lambda$ differential cross sections

- X-axis: E_γ, 900 - 1400 MeV. Y-axis: $d\sigma/d\Omega$, 0 - 0.8 [μb/sr]
- Unprecedented polar angle resolution
- Ongoing analysis - statistical error to be reduced by 1/2



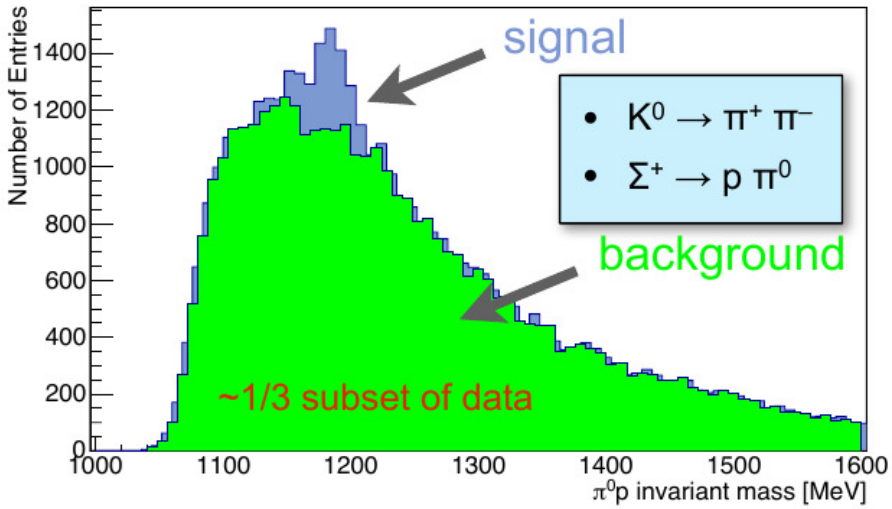
Strangeness photoproduction at extremely forward angles at the BGO-OD experiment

- BGO-OD experiment at ELSA, Bonn
- Motivation: Hadron structure - parallels in strange & charmed quark sectors?
- Strangeness photoproduction - first results:
  1. $\Lambda(1405)$ & access to higher lying hyperons
  2. Extreme forward cross sections for $K^+\Lambda$ & $K^+\Sigma^0$ photoproduction
  3. K^0 photoproduction off proton & neutron (deuterium) targets
  4. Future opportunities - Y-N interaction & hypernuclei studies
- Outlook and conclusions

Preliminary identification of $K^0\Sigma^+$ with BGO-OD

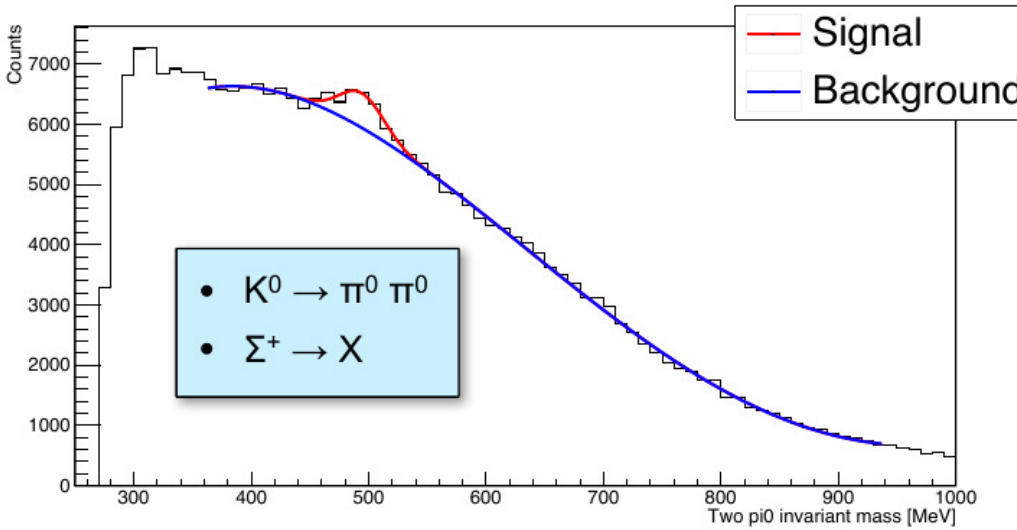
- Study the Cusp-like structure in the cross section. K^{*0} subthreshold production rescattering to π^0 & K^0?
- Access $\gamma p \to K^0\Sigma^+$ via different decay modes at BGO-OD
- Reduction of background & improved momentum resolution acheivable with the MWPC (analysis underway)

work of B.-E. Reitz



w/ kinematic fit

work of S. Alef



prior to kinematic fit

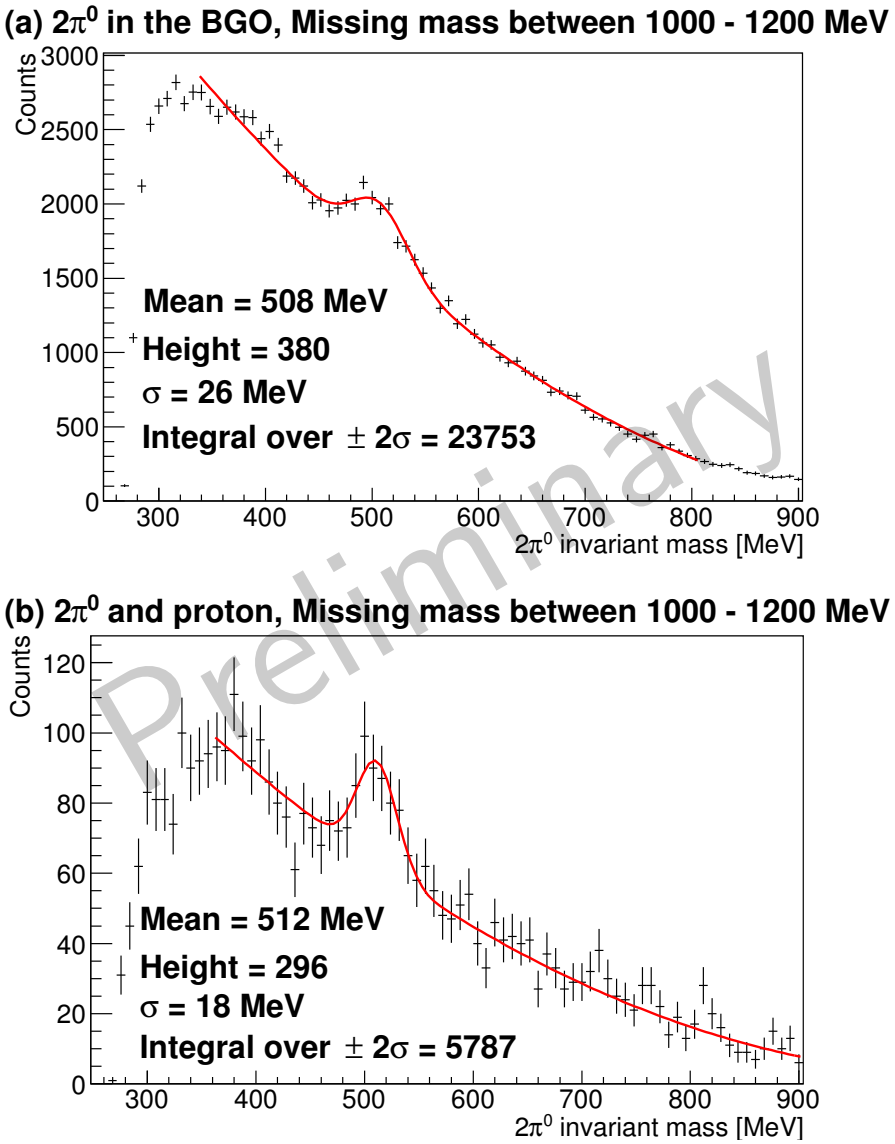
Test beam time data (Deuterium target), 2 days

Peak predicted from coherent interference of dynamically generated resonances

A. Ramos and E. Oset, Phys. Lett. **B 727**, (2013) 287

- $K^0 \to 2\pi^0$ reconstructed in the BGO
- Total neutral particles < 6
- Total charged particles < 3

- $K^0 \to 2\pi^0$ reconstructed in the BGO
- Proton in the Forward spectrometer & select missing π^0 mass from $\Sigma^+ \to p\pi^0$
- Total neutral particles < 6
- Total charged particles < 3



Strangeness photoproduction at extremely forward angles at the BGO-OD experiment

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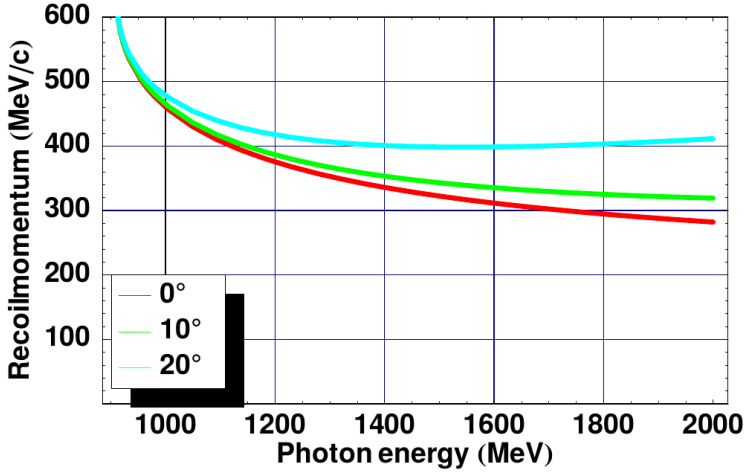
- Outlook and conclusions

Future opportunities: Hypernuclei production

- Hypernuclei photoproduction, eg $\gamma +^{12} C \rightarrow K^+ +^{12}_{\Lambda} B$ - natural laboratory to probe the $Y - N$ interaction
- Forward K^+, coherent production, leaving the Λ within the Fermi surface of the residual nuclei



P. Achenbach, arXiv:1101.4395 (2008)

Opportunities for first real photon beam photoproduction?

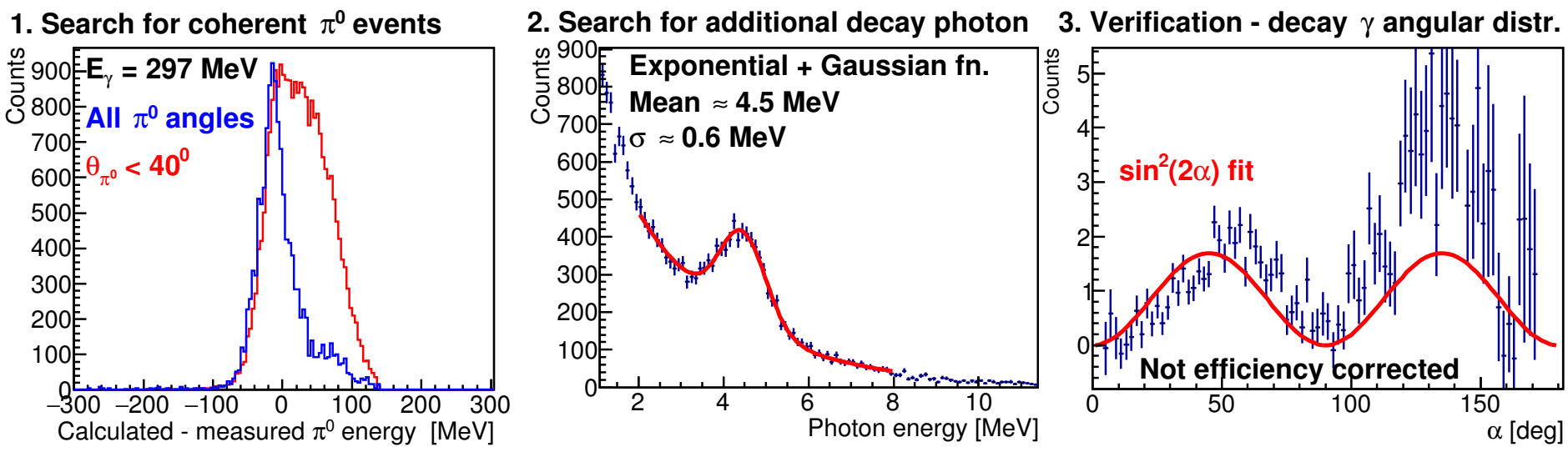
In conversation with P. Achenbach & J. Pochodzalla, 2018

- Mesic decay ($\Lambda \rightarrow \pi N$) identification in BGO - favour light nuclei
- Identify specific states, eg $\gamma +^{12} C \rightarrow \pi^0 +^{12} C^* \rightarrow \pi^0 +^{12} C + \gamma'$ (4.4 MeV)
- Can use "sensitive" targets that are spoiled by intense e^- beams (eg Li)
- Hypernuclei lifetime measurements, angular K^+ distributions, differential cross sections...

Future opportunities: Hypernuclei production

Coherent pion production ("non-strange" example)

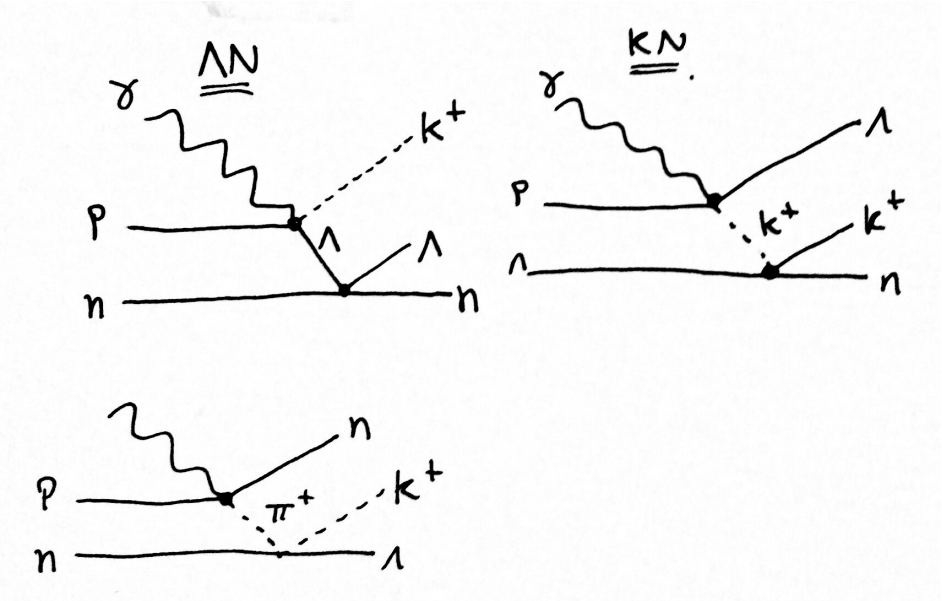
- Method similar to C.M. Tarbert, D.P. Watts *et. al* (A2 Collaboration) Phys Rev. Lett. 100 (2008) 13
- $\gamma +^{12} C \rightarrow \pi^0 +^{12} C^* \rightarrow \pi^0 +^{12} C + \gamma'$ (4.4 MeV)
- E2 transition, $J^\pi : 2^+ \rightarrow 0^+$, $\sin^2(2\alpha)$ distr. between nuclear recoil & γ'
- $\sim$ 2 hours of commissing data with BGO-OD:



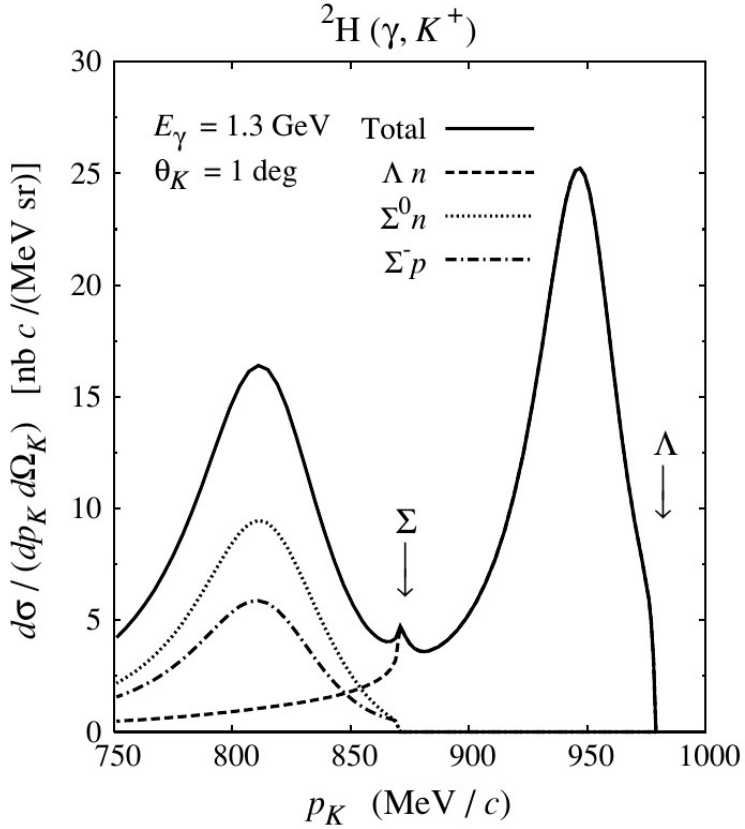
Future opportunities: Y-N studies with deuterium targets

Data being taken this very moment!

- Final state interactions for $\gamma d \to K^+\Lambda + (n)$
- KN, YN & pion mediated
- $\theta_K < 30^0$ - FSI dominated by Y-N



Models of YN forces - cusps at ΣN & YN thresholds

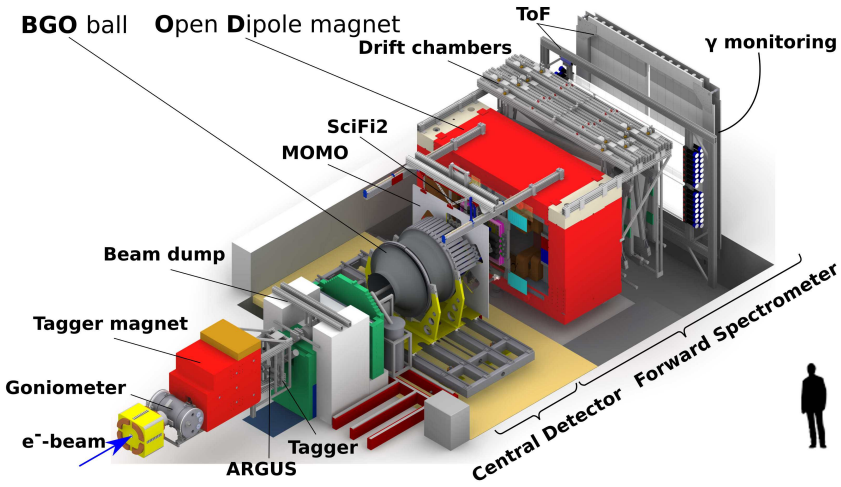


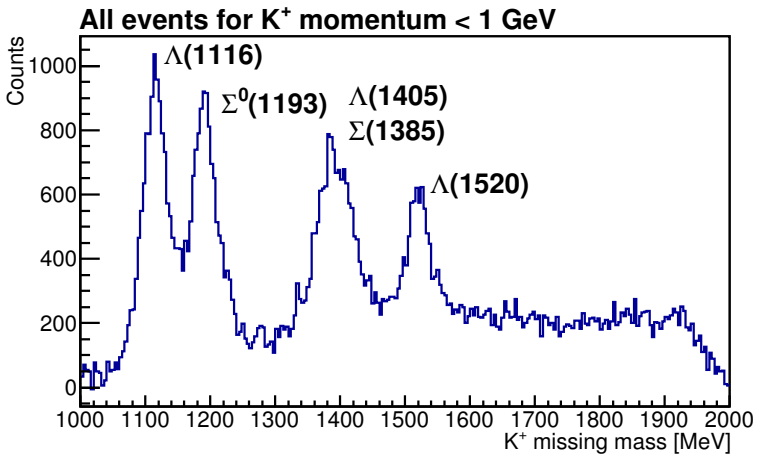
K. Miyagawa, T. Mart, C. Bennhold, W. Glöckle, Phys. Rev. **C74** (2006) 034002

Cross section & pol. obs. sensitive to YN interactions at these cusps!

Summary

- Hadrons - molecular-like structure?
- BGO-OD - strangeness photoproduction - extreme forward angles
- Low momentum transfer region
- 1st preliminary results - K^+Y at forward angles
- $\Lambda(1405)$, K^0 off protons & neutrons - analyses ongoing
- Deuterium target - data being taken now!
- Y-N interaction study opportunities - deuterium, hypernuclei...

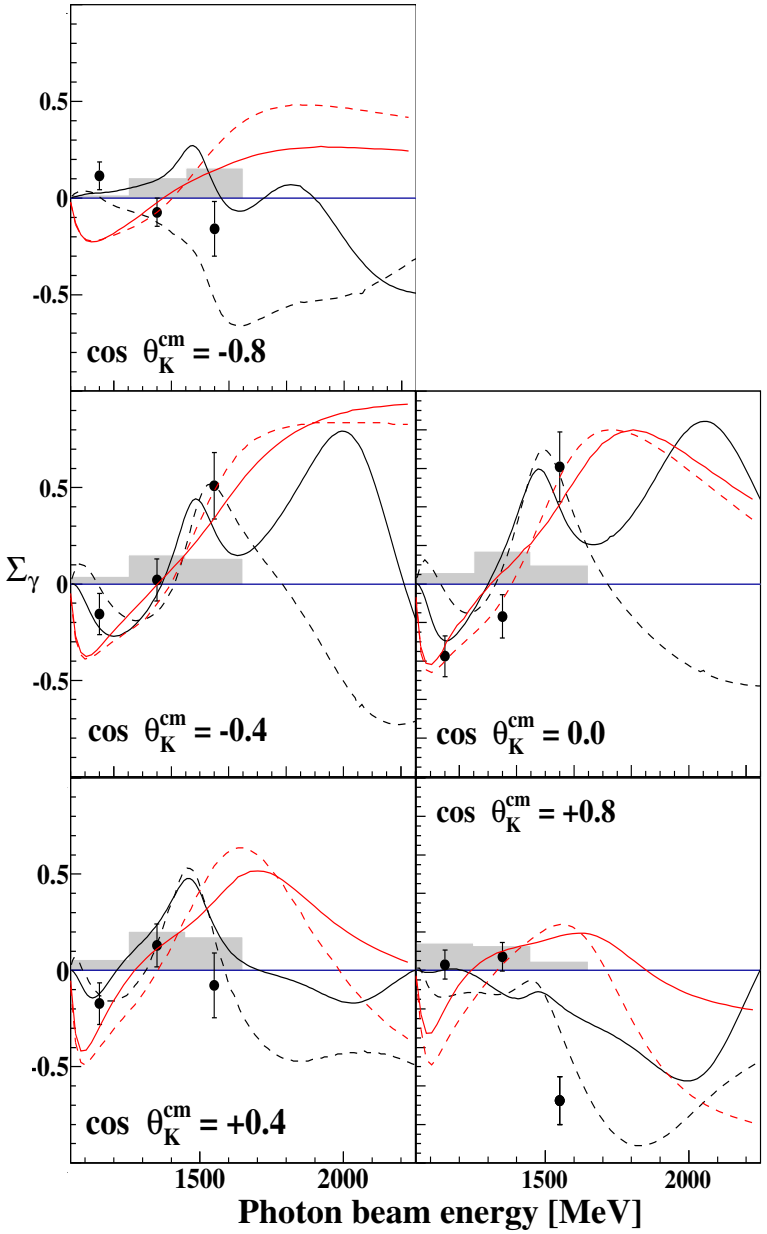




Extra slides

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

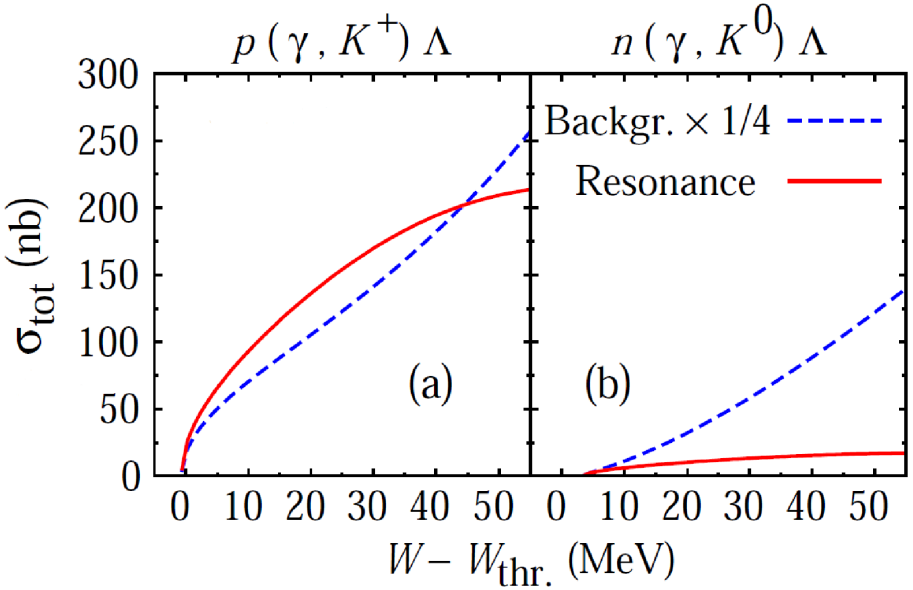
- The 1st beam asymmetry measurement
  R. Ewald *et.al*, PLB 738 (2014) 268
  (CBELSA/TAPS Collaboration)



K^0 photoproduction off the neutron

- T. Mart, Phys. Rev. C 83, 048203 (2011)
- Complimentary to $\gamma p \to K^+\Lambda$ measurements: relate hadronic coupling constant - predictions of $n(\gamma, K^0)\Lambda$ cross section

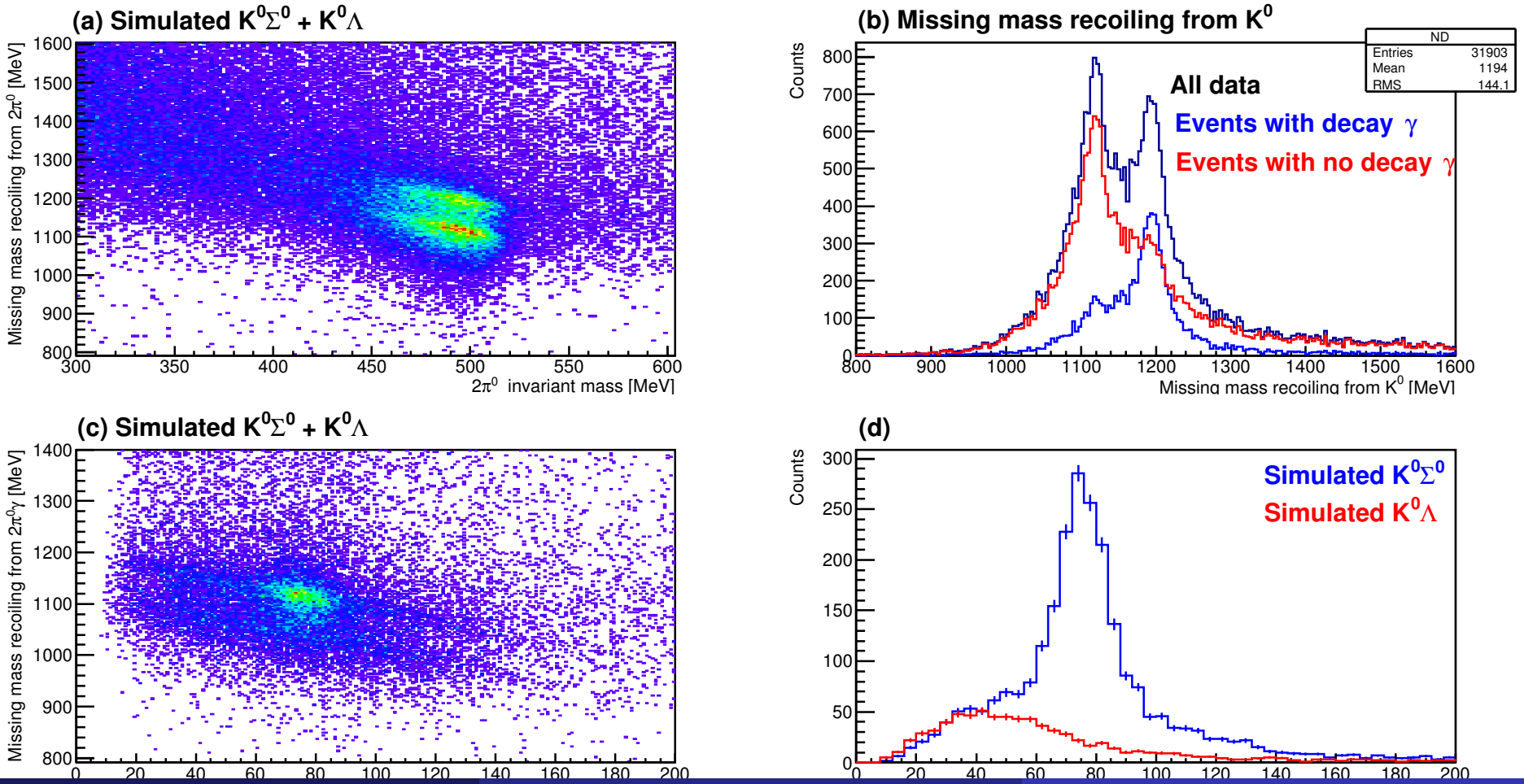
$$
\begin{aligned}
g_{K^+\Lambda_p} &= g_{K^0\Lambda_n} \\
g_{K^+\Sigma^0_p} &= -g_{K^0\Sigma^0_n} \\
g^{V,T}_{K^{*+}\Lambda_p} &= g^{V,T}_{K^{*0}\Lambda_n}
\end{aligned}
$$



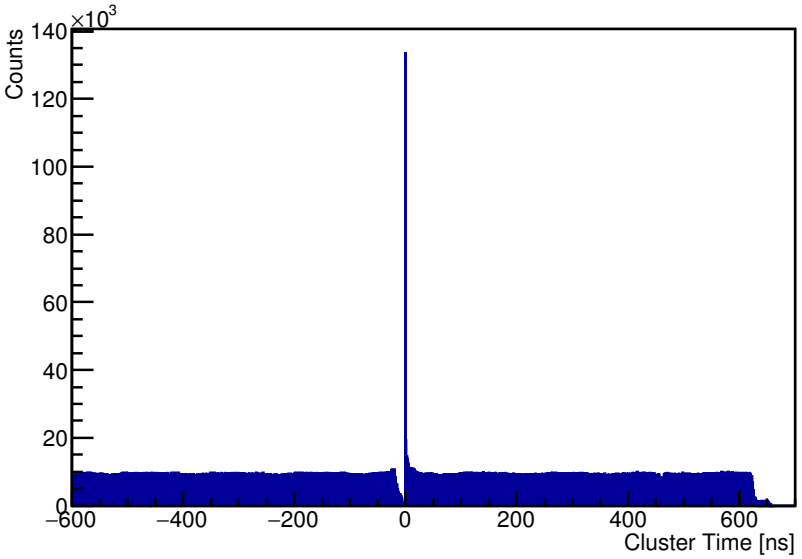
- BGO-OD - 1st differential cross section measurement to $E_\gamma = 3$ GeV & polarisation observables
- Higher statistics - K^0 identification via both main decay modes

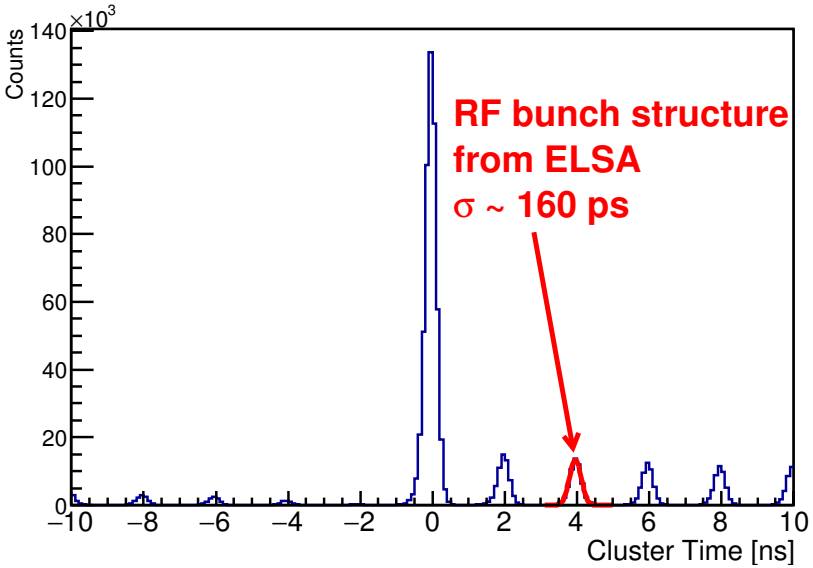
Separating $K^0\Lambda$ and $K^0\Sigma^0$ final states

- Simulated data to demonstrate separation of channels
- Identify the decay: $\Sigma^0 \to \Lambda\gamma$



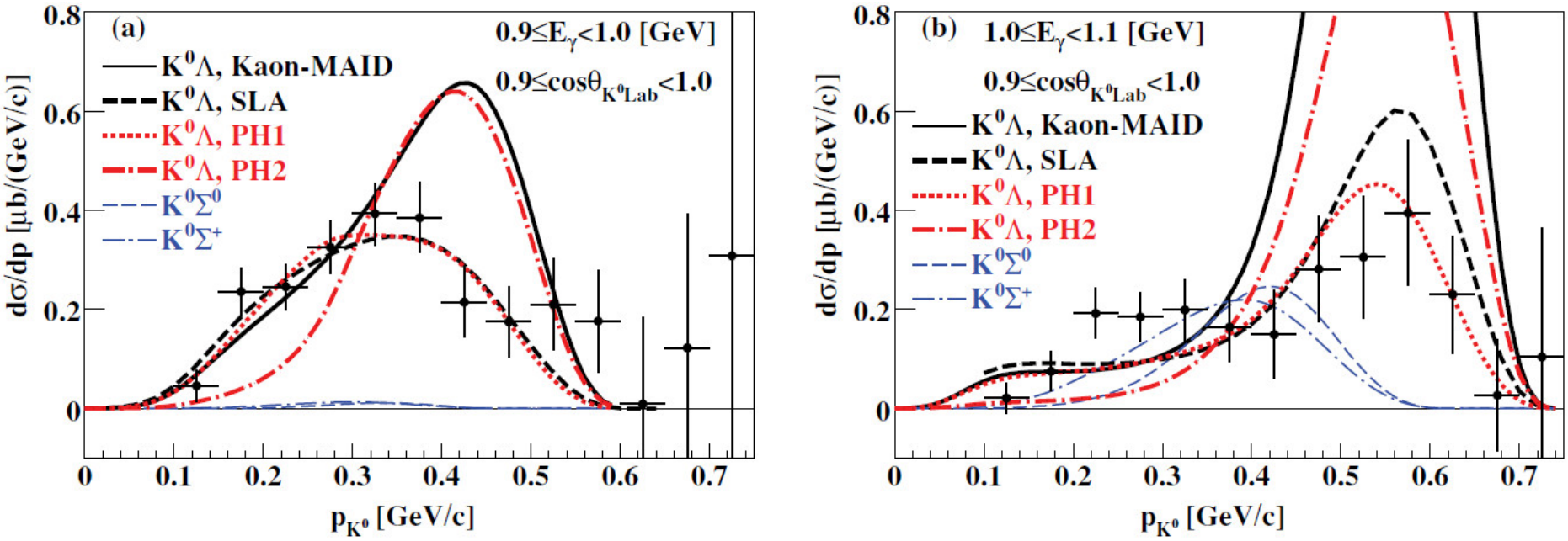
Tagger timing





K^0 photoproduction off the neutron

- No K^0 t-channel exchange (but still K^*) - s channel resonances more prominent
- Complementary to $K^+\Lambda$ - relate hadronic coupling constants
- K. Tsukada et al, Phys. Rev. C 78, 014001 (2008)

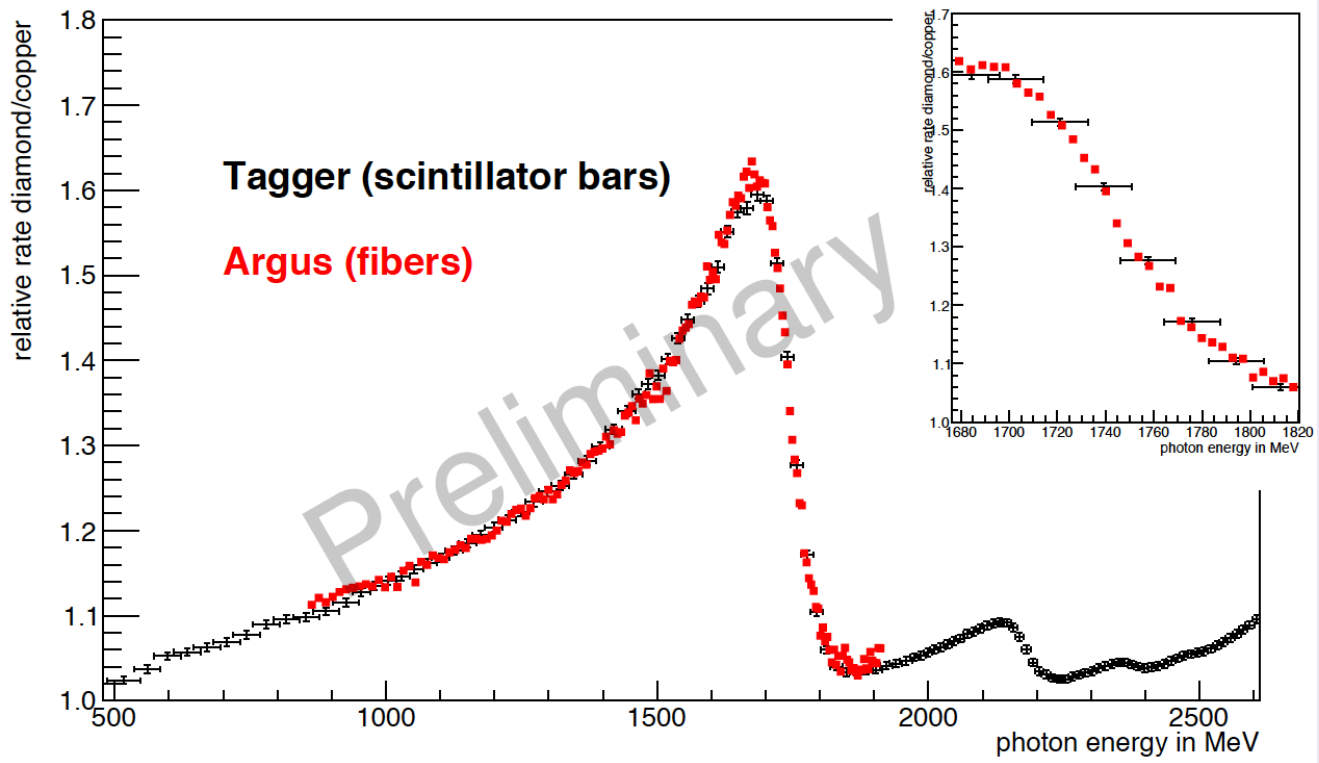


Incident photon beam parameters

- Energy tagged γ beam $\leq$ 3 GeV, 250 ps time resolution
- Current $\leq$2 nA, 10 nA upgrade planned
- Circularly and linearly polarised γ beams available

Coherent bremsstrahlung using a diamond radiator

30% polarisation at 1.8 GeV with an incident electron energy of 3.2 GeV

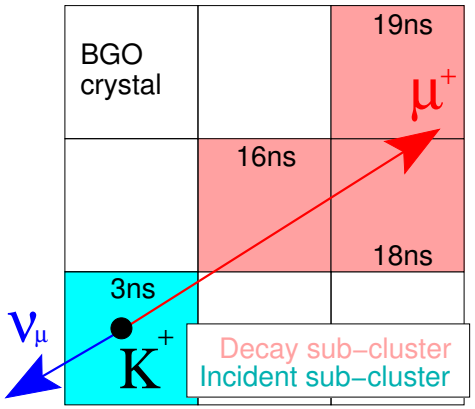


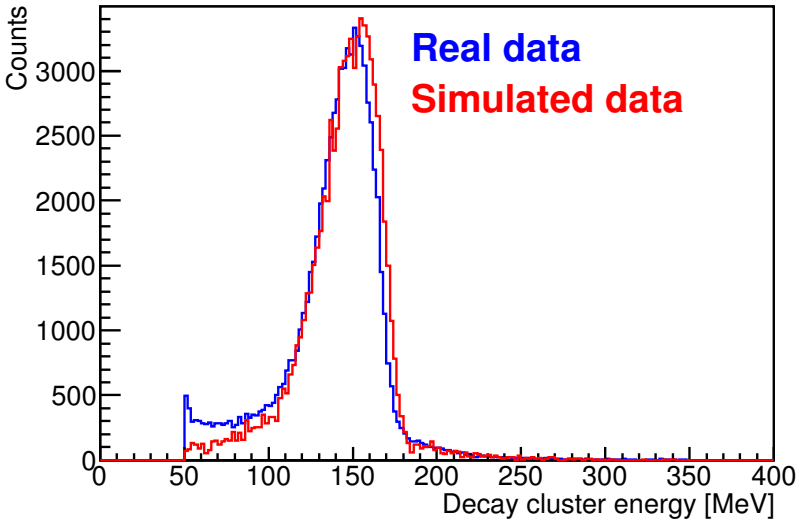
K^+ identification in the BGO

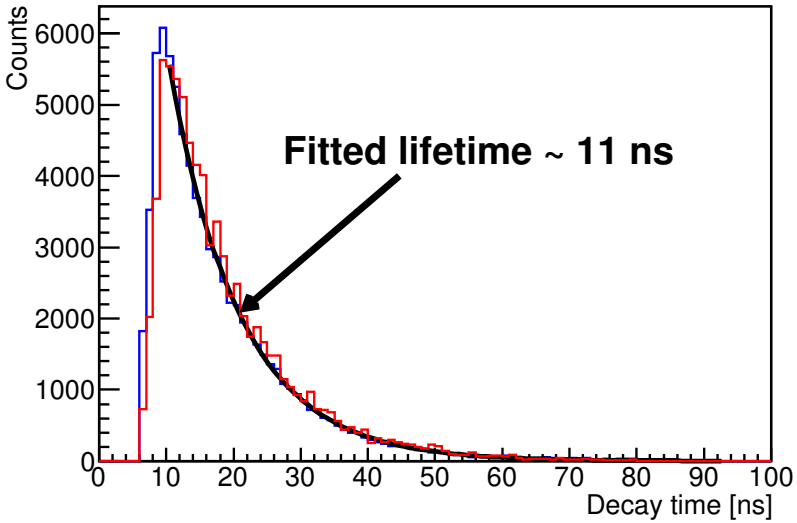
- Time delayed, K^+ weak decay within the crystals of the BGO ball
- T.C Jude, D.I. Glazier, D.P. Watts, *et al*, PLB, 735 (2014) 112

Lifetime 12 ns,
2 main decay modes:

$$K^+ \rightarrow \mu^+ \nu_\mu$$
$$K^+ \rightarrow \pi^+ \pi^0$$



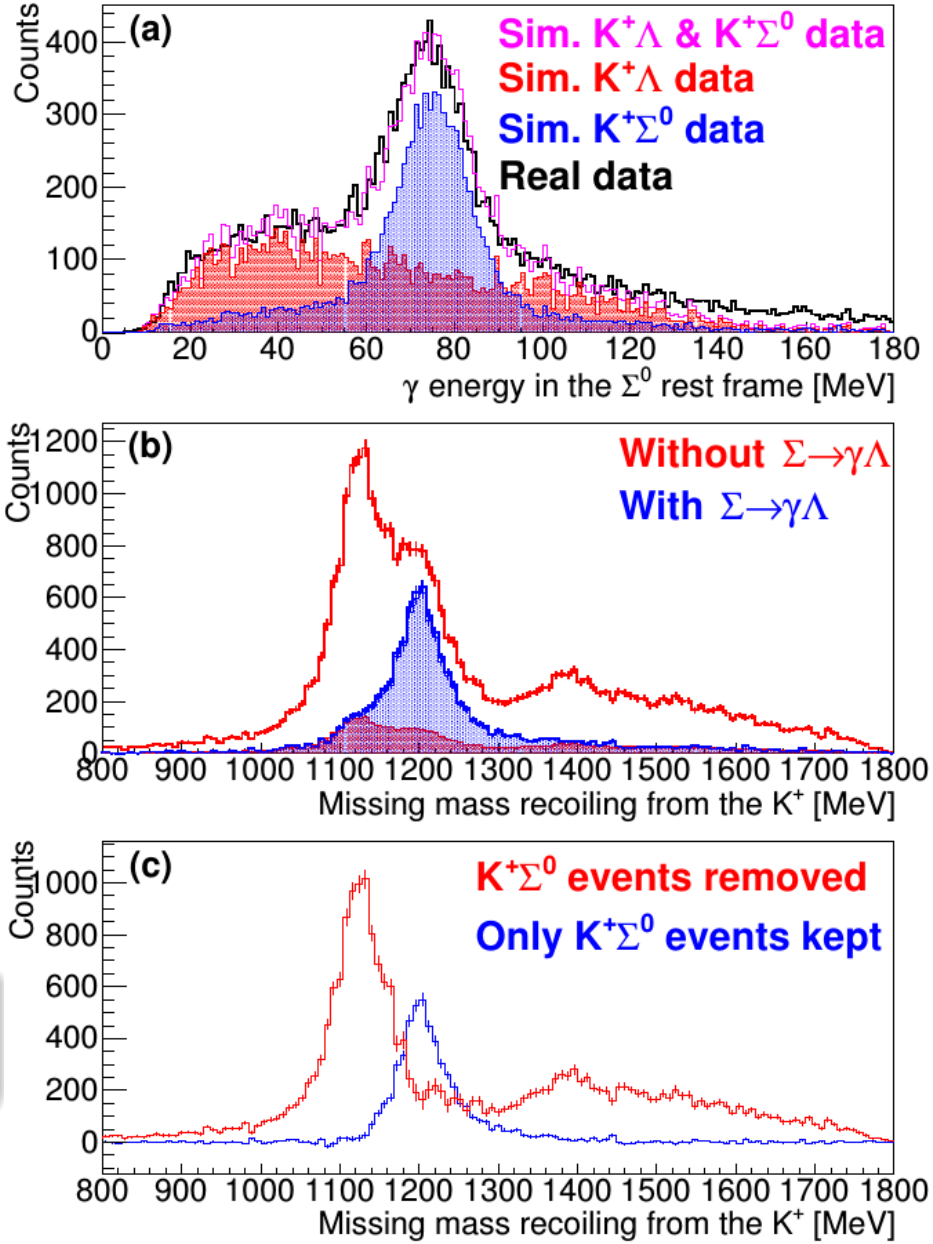




Identifying the $\Sigma^0 \to \Lambda\gamma$ decay ($\Gamma = 100\%$)

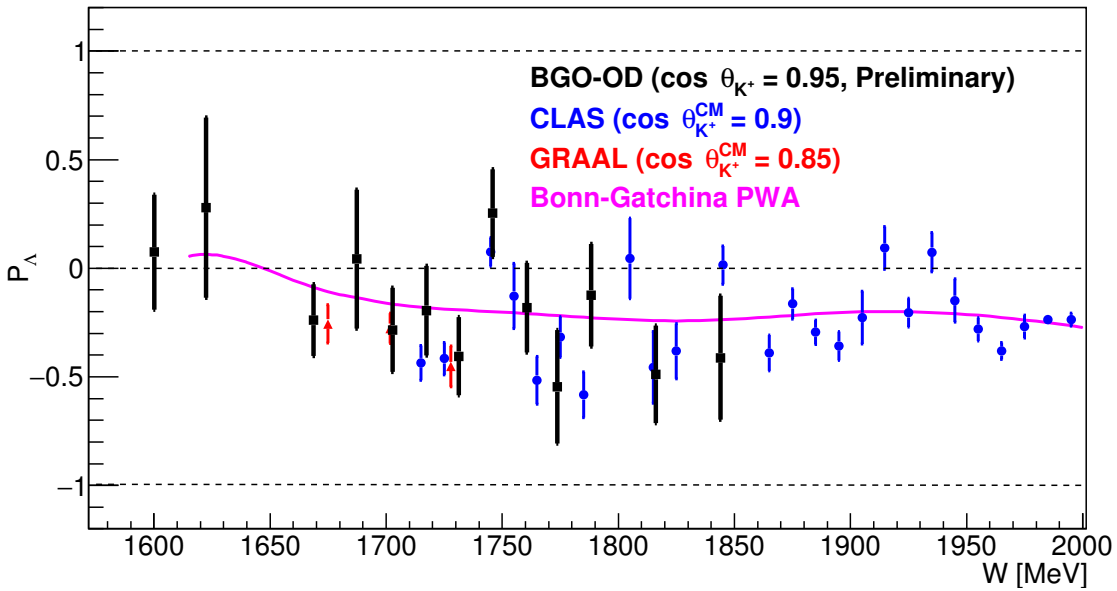
- Boost all neutral particles in the BGO into missing hyperon rest frame
- If $K^+\Sigma^0$:
- γ energy (Σ^0 rest frame) = $M_{\Sigma^0} - M_\Lambda = 77$ MeV
- Efficiency scale events with/without ID to separate missing mass spectrum

Photon detection in the BGO to separate different K^+Y^* states!

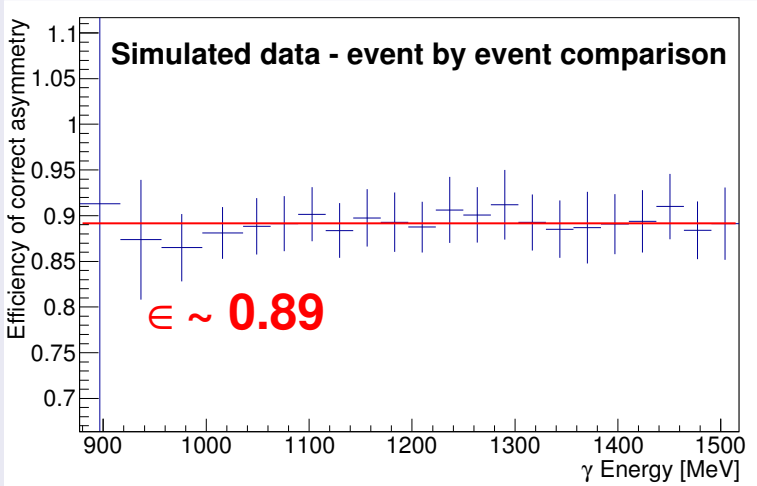


$K^+\Lambda$ Recoil Polarisation at forward angles

- Up-down asymmetry between decay proton/neutron direction in Λ rest frame & normal to the reaction plane
- $\Lambda \rightarrow \pi^0 n$ identified in the BGO
- $P_\Lambda = \frac{2}{\alpha}\frac{N_{up} - N_{down}}{N_{up} + N_{down}}$, $\alpha = 0.642$ (Λ decay parameter)



"Dilution" - spatial resolutions/particle miss ID



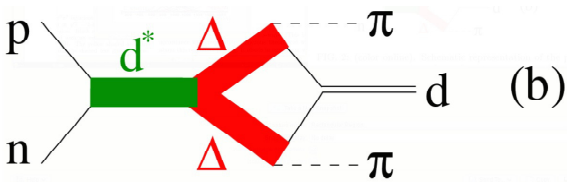
M.E.McCracken *et al.* (CLAS), Phys.Rev. C81, 025201 (2010). A. Lleres *et al.* (GRAAL), Eur. Phys. J. **A 31**, 79 (2007)

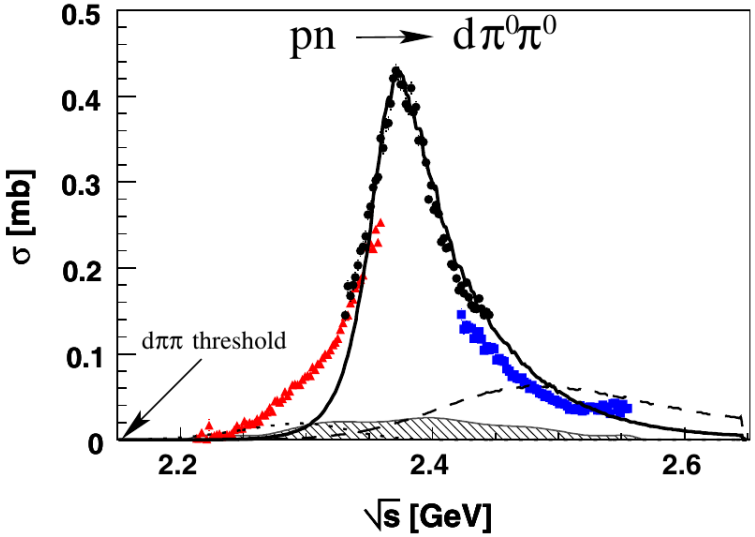
$d^*(2380)$ dibaryon, $\Gamma \approx 70$ MeV, $J^P = 3^+$

- Decay branching ratios determined

  M. Bashkanov, H. Clement, T. Skorodko, Eur. Phys. J. **A 51**, 87 (2015)

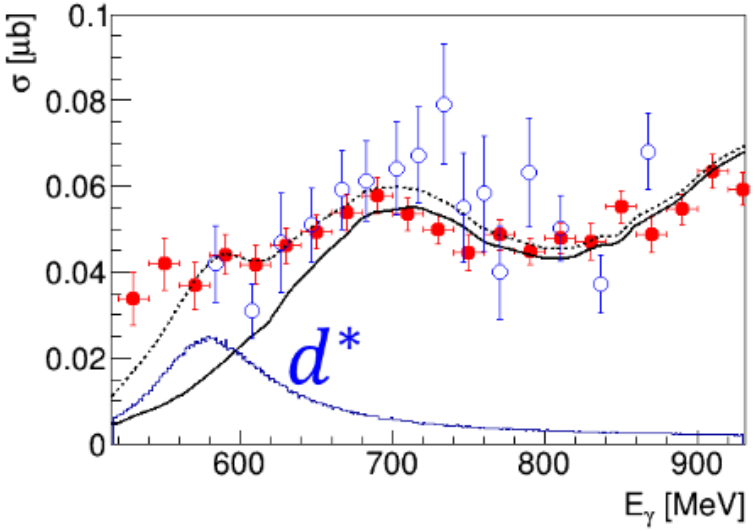
- Hexaquark/molecule/dominated by diquark components?
  $M_{d^*} = M_{\Delta\Delta} - 80$ MeV





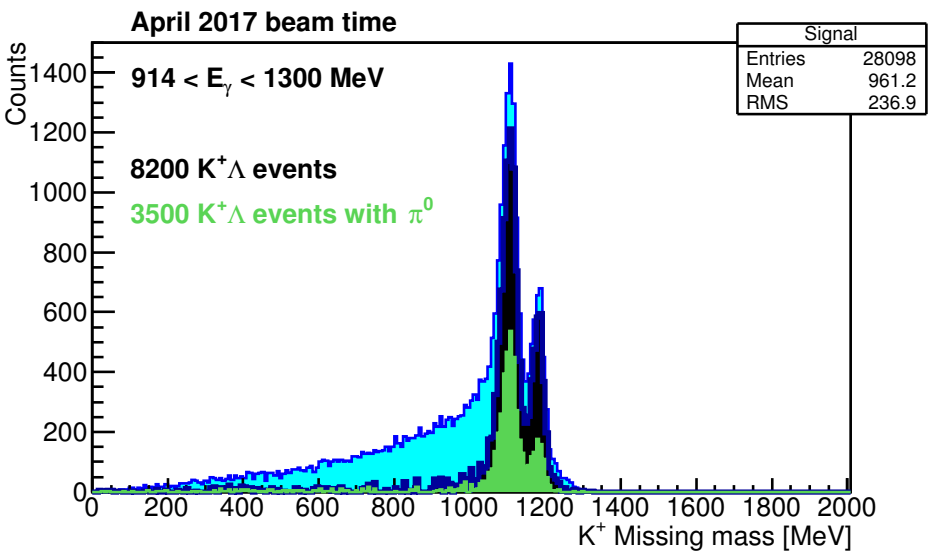
P. Adlarson *et al.*, (WASA-at-COSY Collaboration), PRL **106**, 242302 (2011)

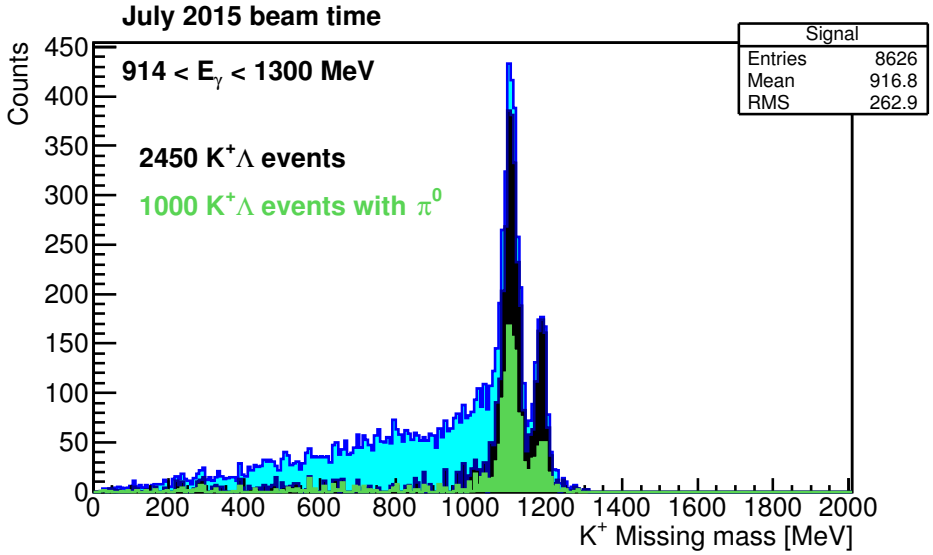
$\gamma d \to p\pi^0\pi^0$



solid (dashed) lines - Conventional background (with $d^*(2380)$ contribution),M. Egorov and A. Fix, Nucl. Phys. **A933**, 104 (2015)
M. Guenther, Master thesis, Basel (2015), T Ishikawa *et al.*, Phys. Lett **B 772**, 398 (2017)

High statistics new dataset





- 3^0 bins in $\theta^{K^+}_{CM}$, 6-7 bins in angle
- 25 bins in energy
- $\sim$ 10% statistical error - consistent with PAC proposal (& higher than other datasets at more backward angles)
- Small bug found in track-tagger correlations, will increase yield by $\sim$ 1.5

$\gamma p \rightarrow K^+\Sigma^0$ with no initial particle Identification

Preliminary analysis , 25 days data, (G. Scheluchin, PhD thesis work)

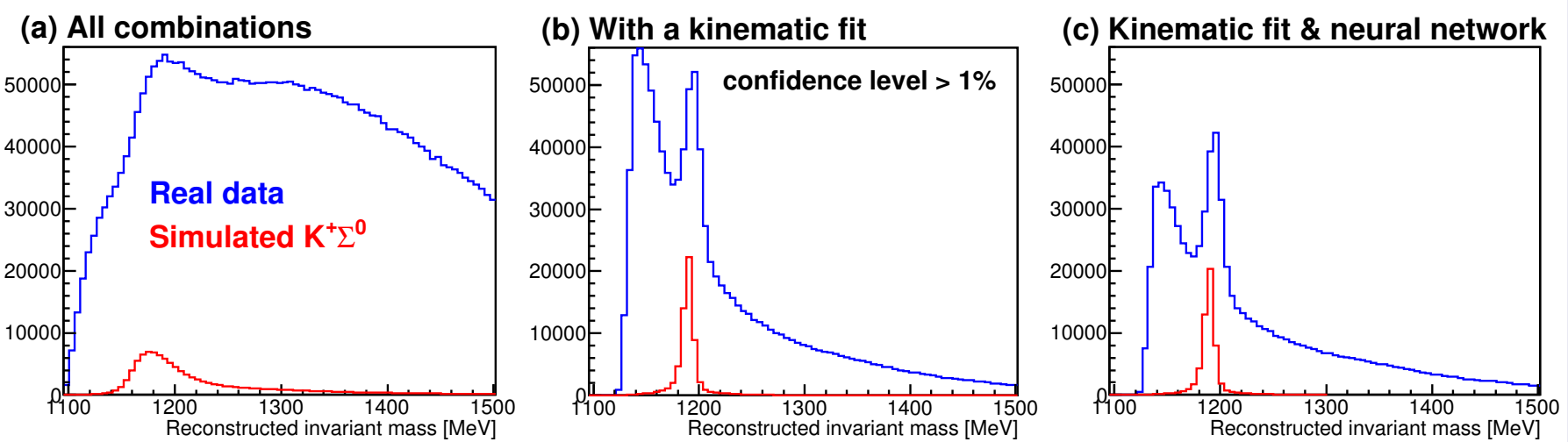
- K^+ & $\Lambda \rightarrow p\pi^-$ over large acceptance region ($1^0 < \theta < 155^0$)
- Σ^0 decay photon in the BGO ($\Sigma^0 \rightarrow \Lambda\gamma$)
- Technique used for higher lying Y* states (eg $\Lambda(1405) \rightarrow \pi^0\Sigma^0$)

Reconstructing the Σ^0 invariant mass

(a) Momentum conservation & K^+ "missing mass" cut

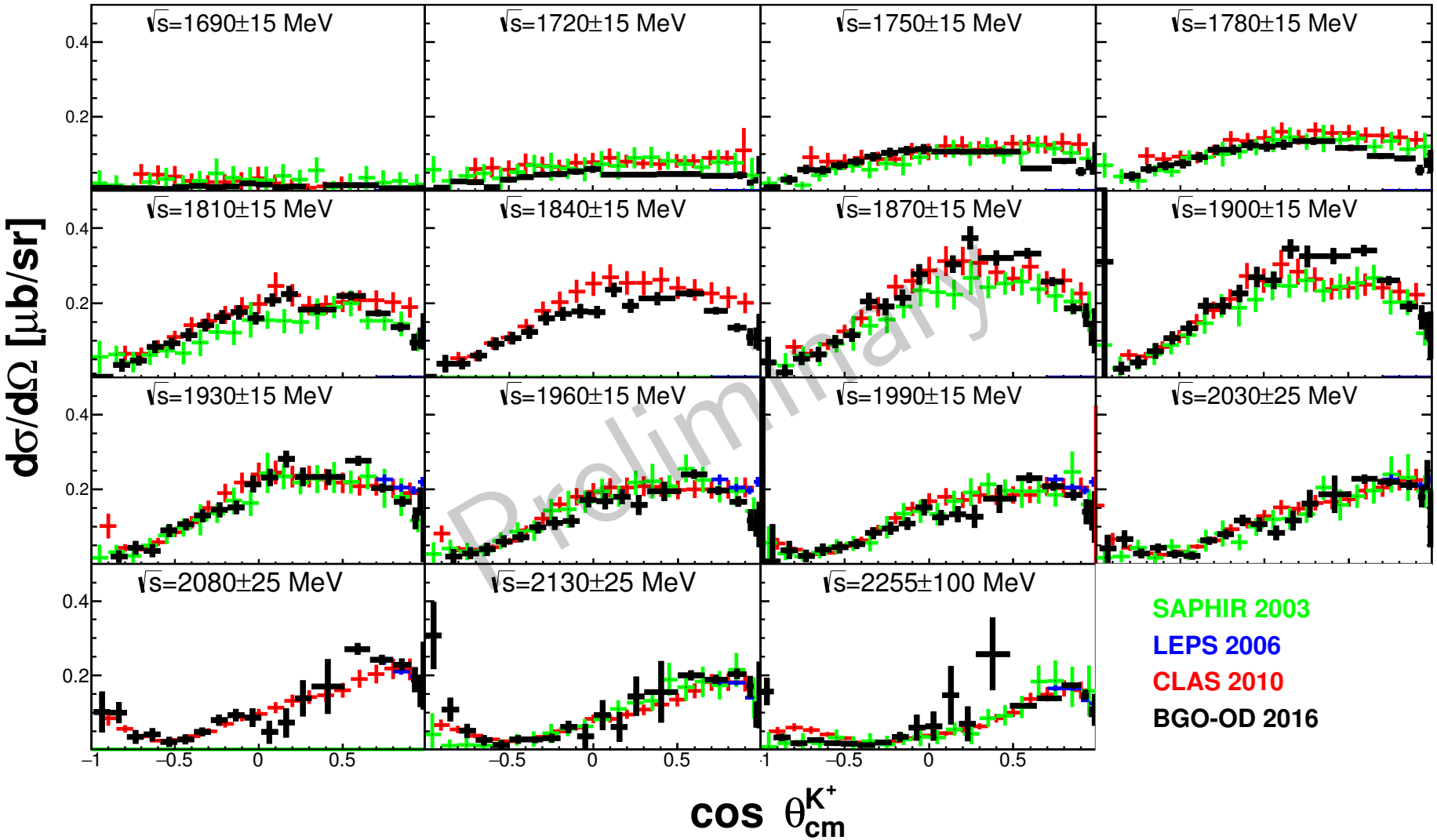
(b) Kinematic fit & confidence level cut

(c) Neural network to suppress background



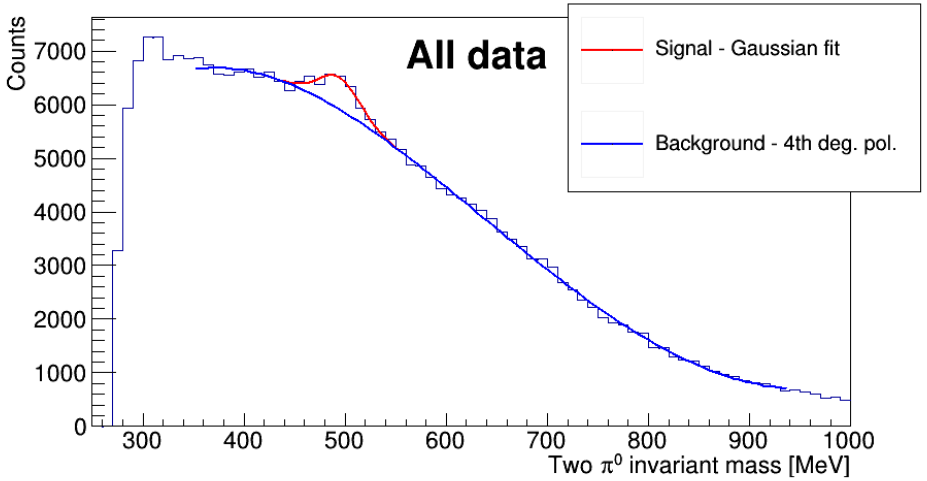
$\gamma p \rightarrow K^+\Sigma^0$ with no initial particle Identification

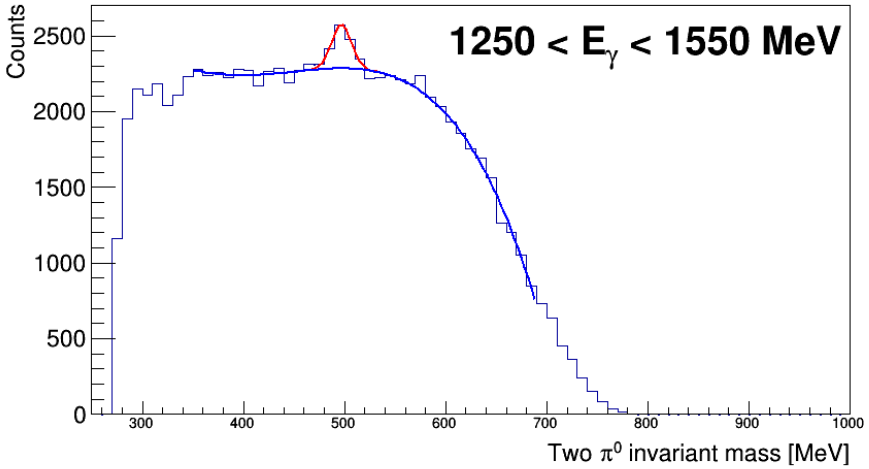
BGO-OD (preliminary), CLAS: B. Dey, *et al.*, Phys. Rev. **C82** 025202 (2010)
SAPHIR: K.-H. Glander *et al.*, Eur. Phys. J. **A19** 251 (2004), LEPS: M. Sumihama *et al.*, Phys. Rev. **C73** 035214 (2006)

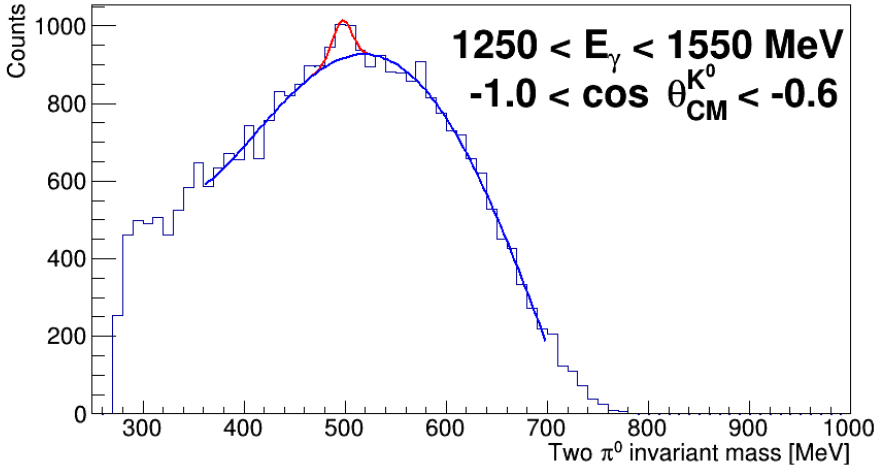


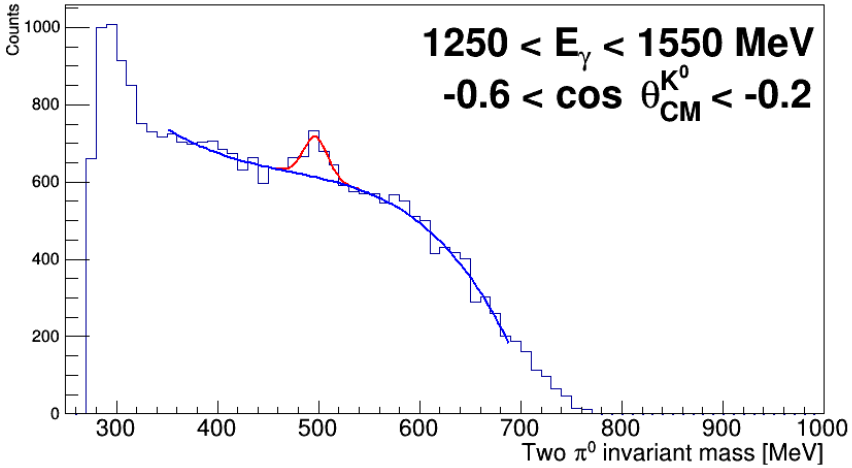
Preliminary identification of $K^0\Sigma^+$ with BGO-OD

Analysis by S. Alef





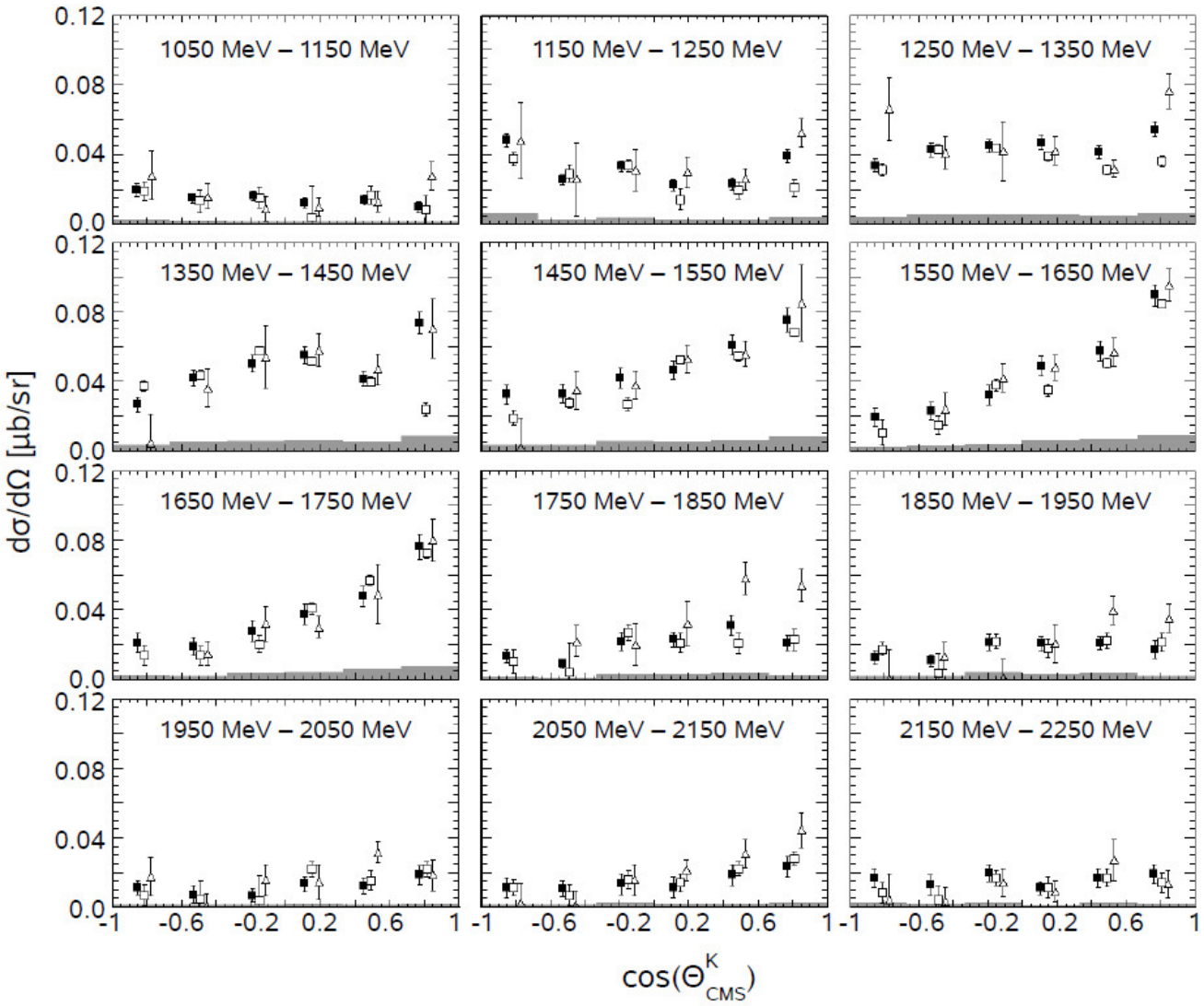




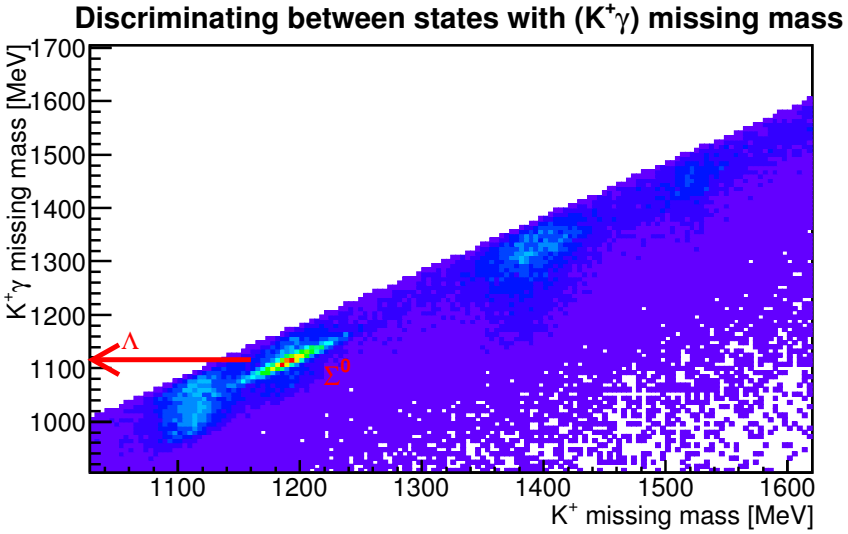
Previous $\gamma p \rightarrow K^0\Sigma^+$ measurements

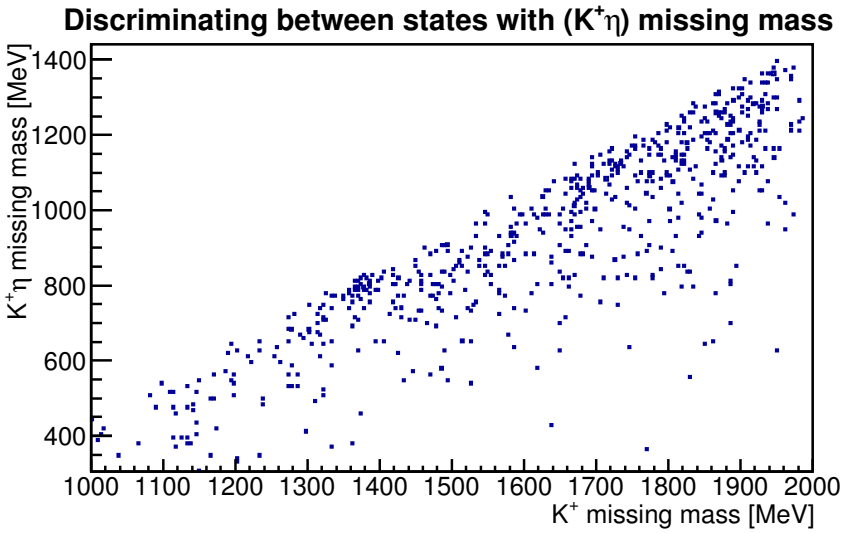
R. Ewald *et al.*,Phys. Lett. B 713 (2012) 180 (CBELSA/TAPS Collaboration).

This data: Full squares, Previous CBELSA-TAPS data: open squares, Previous SAPHIR data: triangles (references therein)



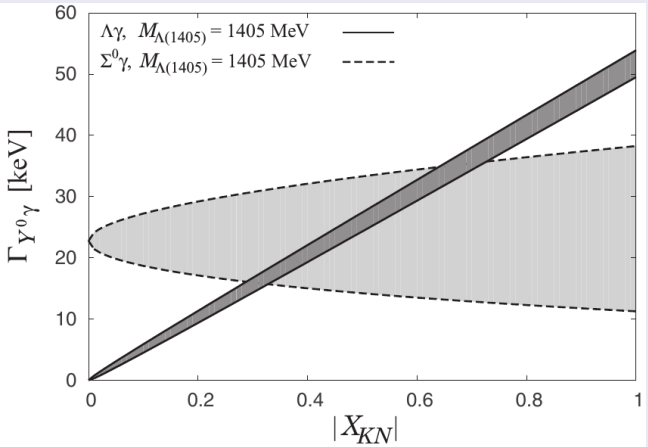
Access to rare Y^* decays





$\Lambda(1405) \to \Lambda\gamma$

$\Gamma_{\gamma\Lambda}$ indication of compositeness:



T. Sekihara, S. Kumano, Phys. Rev **C89**, 025202 (2014)

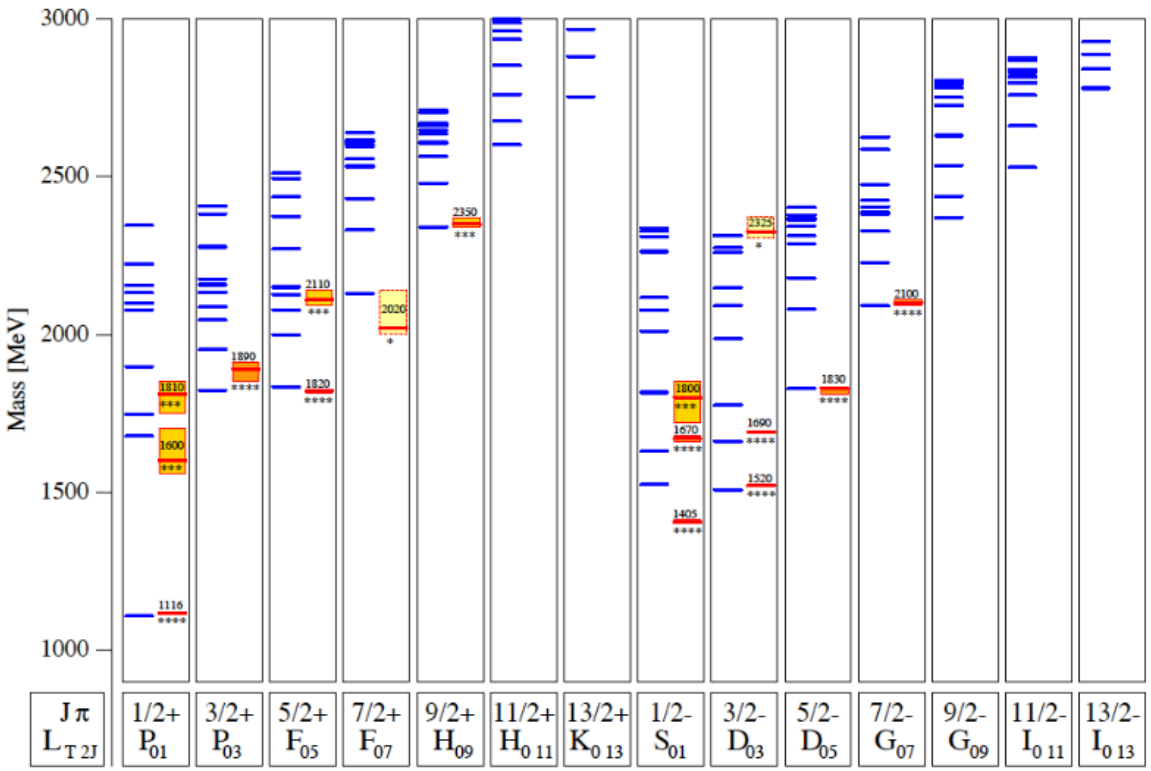
$K^+\eta$ recoiling mass

eg, $\Lambda(1670)1/2^+$ (PDG ****)
Width 25 - 50 MeV
$\Gamma_{\Lambda\eta} = 10 - 25\%$ (never observed)

Many poorly known Σ^* and Λ^* states

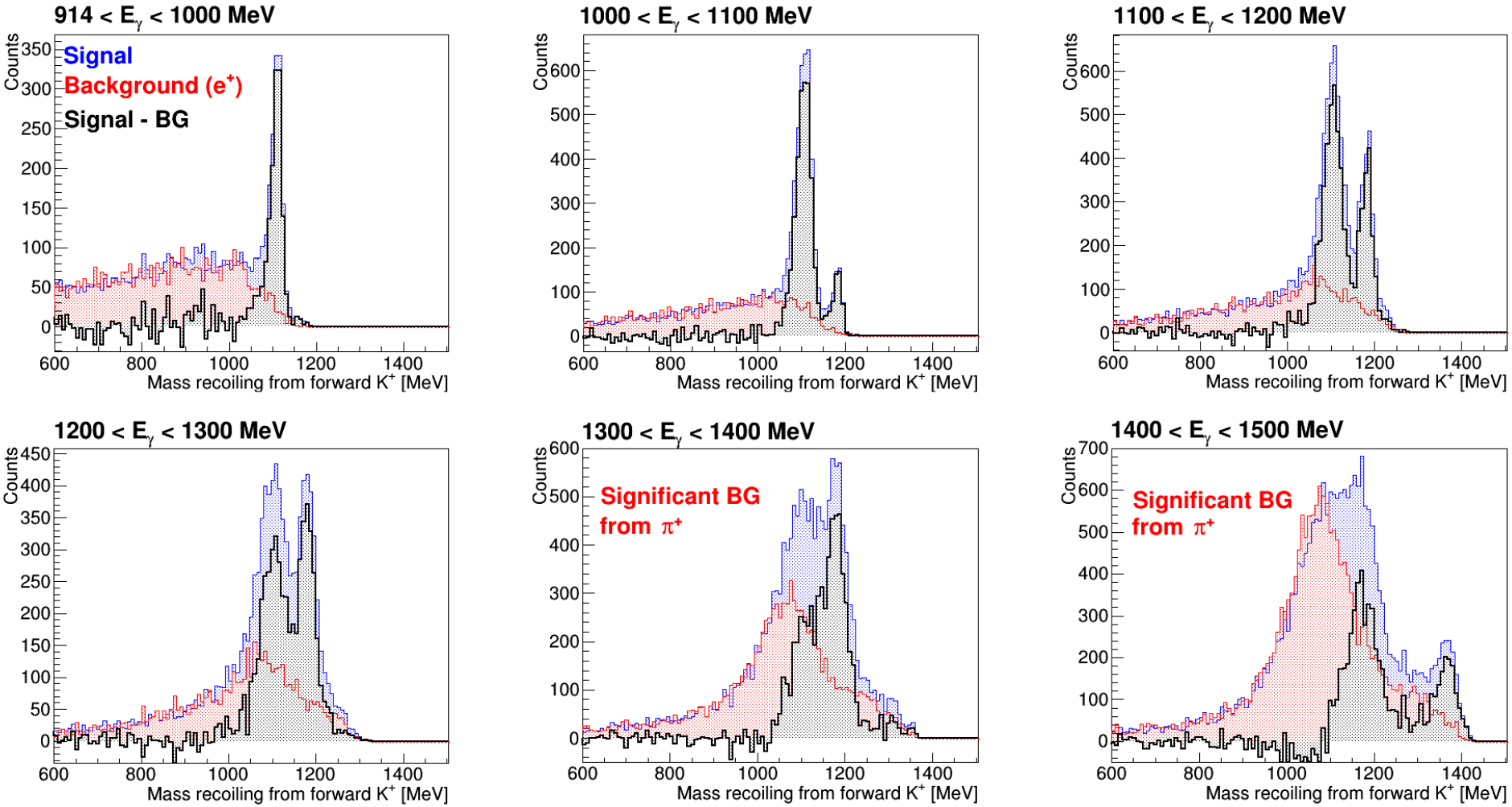
Motivation - Λ hyperons in a constituent quark model

- Parity ordering of 3 lowest states agrees with CQM model, but Λ(1405) mass too low (compared to $N^*(1535)$)
- Y* spectrum - limited success with constituent quark models
- Models including meson-baryon interactions as degrees of freedom - more successful, L.Ya. Glozman and D.O. Riska, Physics Reports 268 (1996) 263, C. Garcia-Recio et al., Phys. Lett. B 582 (2004) 49, M.F.M. Lutz, E.E. Kolomeitsev, Phys. Lett. B 585 (2004) 243.



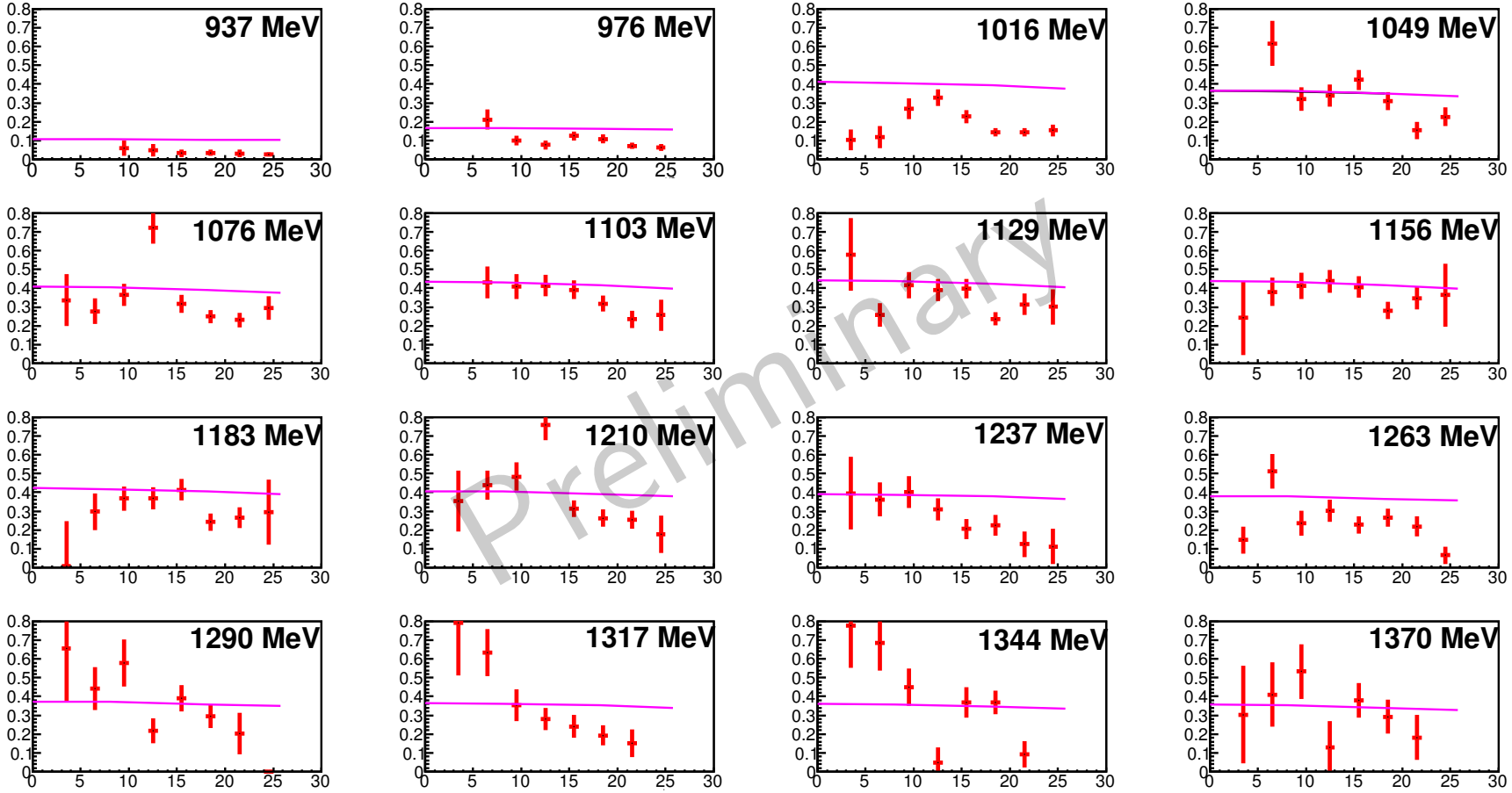
High statistics new dataset

- Unprecedented angular resolution - 3^0 bins in $\theta_{CM}^{K^+}$
- Fit to background: e^+e^- from the beam, misidentifed π^+ at higher energy



Preliminary forward $K^+\Lambda$ differential cross sections

- X-axis: $\theta_{K^+}^{CM}$, 0 - 30^0. Y-axis: dσ/dΩ, 0 - 0.8 [μb/sr]
- Magenta line - BnGa PWA, Beam energy labelled inset
- π^0 identification required - x4 stats anticipated without this



Future opportunities in K^+Y studies: Y-N interaction

- Forward kinematics ideal for BGO-OD
- Increase OD magnetic field to improve momentum resolution
- Difficult measurement but very important and not possible anywhere else!

Right hand side plots:

K. Miyagawa, T. Mart, C. Bennhold, W. Glöckle, Phys. Rev. **C74** (2006) 034002