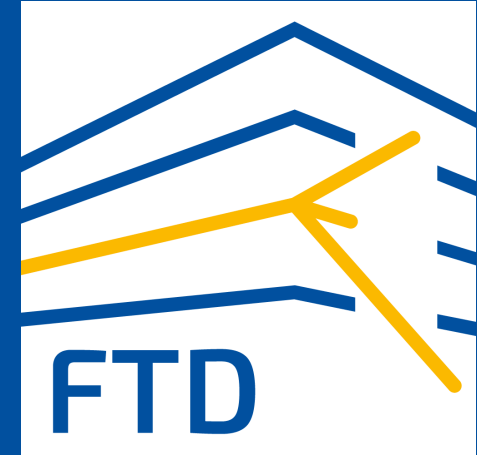




Studies of unconventional baryon structure in the light quark sector

with the **BGOOD** photoproduction experiment



Review: T.C. Jude, Prog. Part. Nucl. Phys. 147 (2026) 104224

Tom Jude, 8th September 2026



Molecular-like structure in the light sector?

- Molecular-like states, meson-baryon degrees of freedom in ChPt based calculations
- Improved success in describing N^* , Δ^* , Λ^* & Σ^* spectra
- Supported by electroproduction data (eg CLAS)
- Transition form factor measurements

Glozman & Riska, Phys. Rep. 268 (1996) 263, Garcia-Recio *et al.*, PLB 582 (2004) 49.
Lutz & Kolomeitsev, PLB 585 (2004) 243,

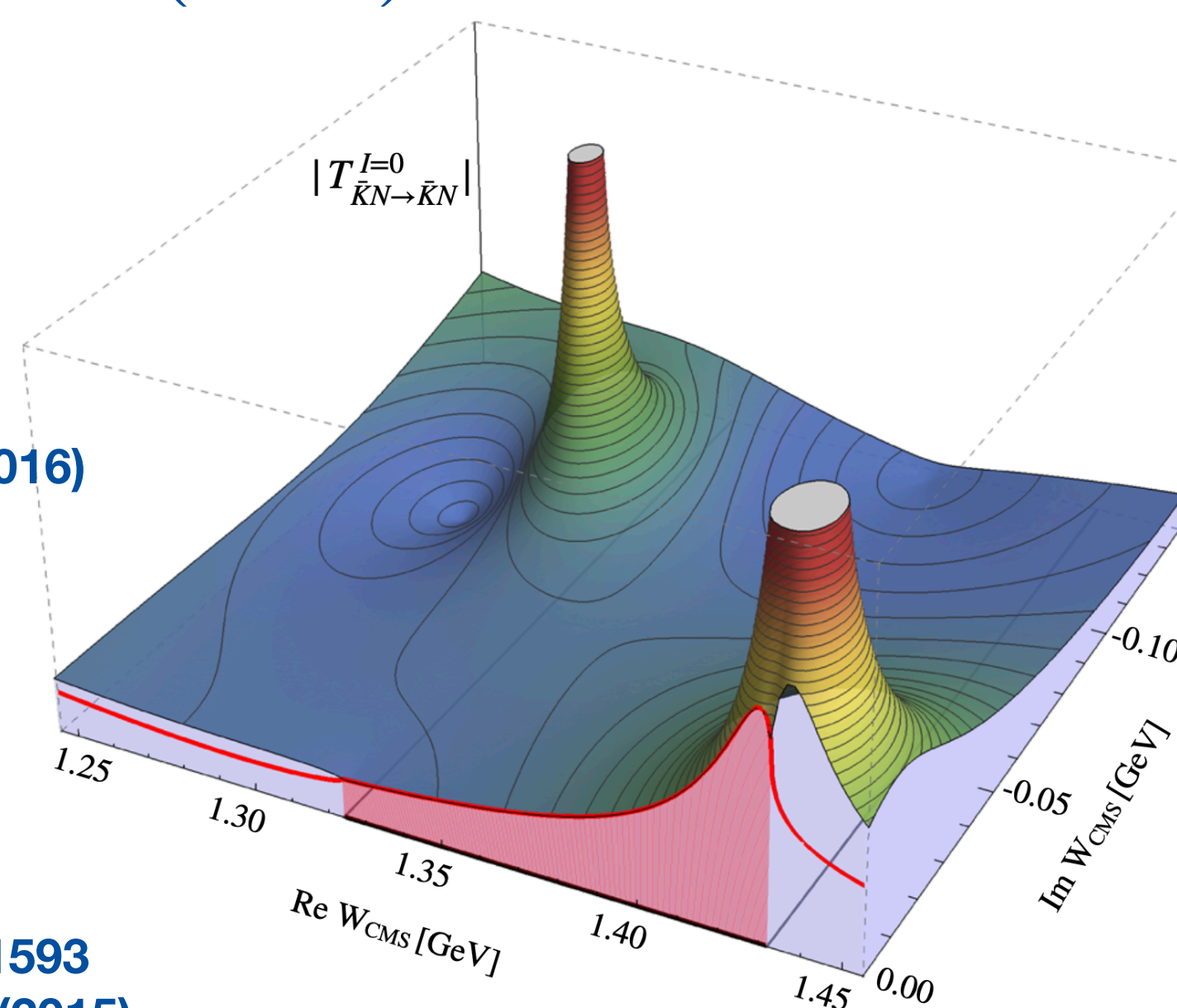
The $\Lambda(1405)$

- Dynamically generated, meson-baryon interactions?

D. Jido, *et al.* NPA 725:181 (2003).
Molina & Döring, PRD 94, 056010 (2016)

- 2-pole structure in χ PT based models

M. Mai, EPJ Spec. Top. (2021) 230, 1593
M. Mai, U.-G. Meißner, EPJA 51, 30 (2015)



$$\gamma^* N \rightarrow N(1440)$$

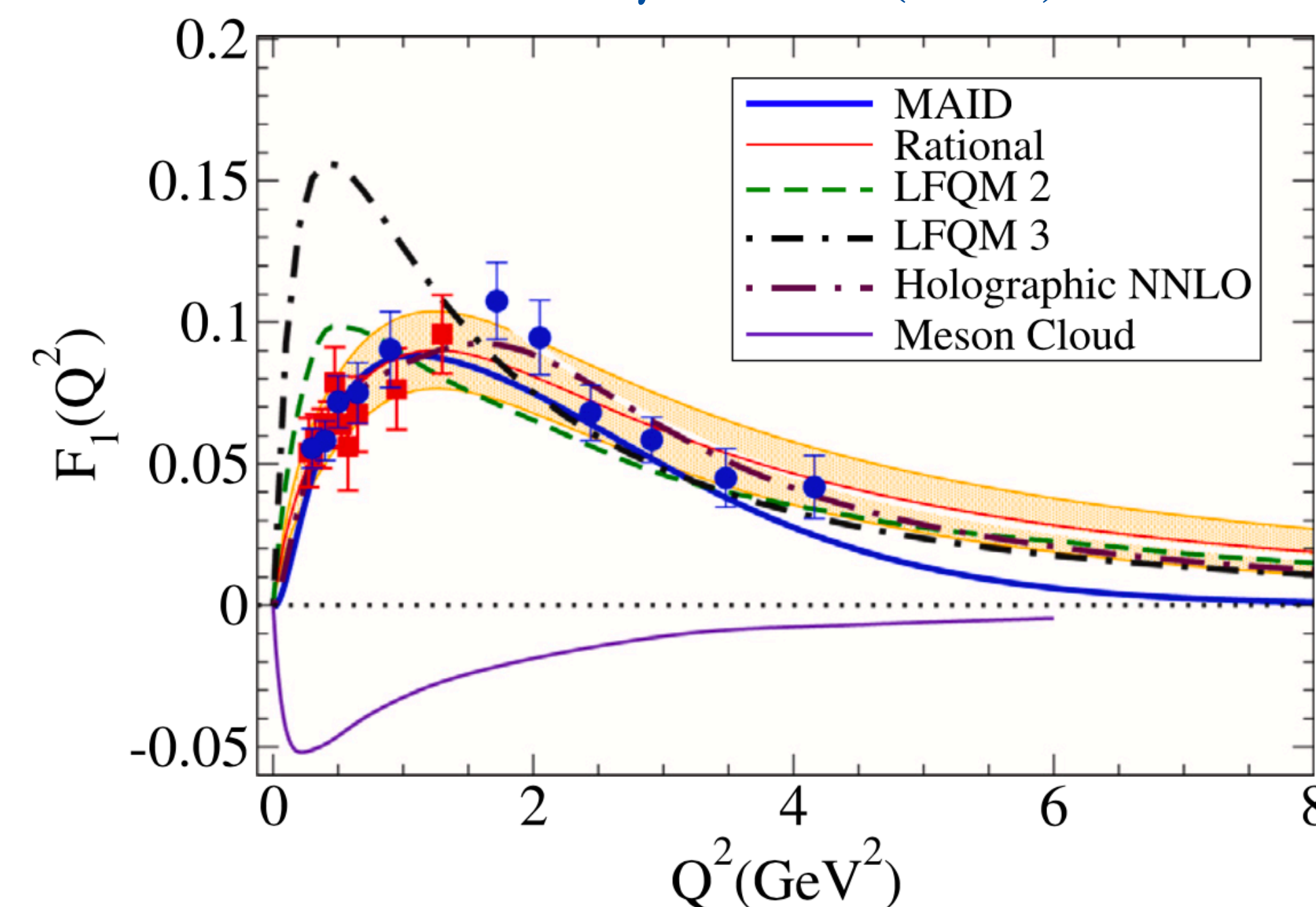
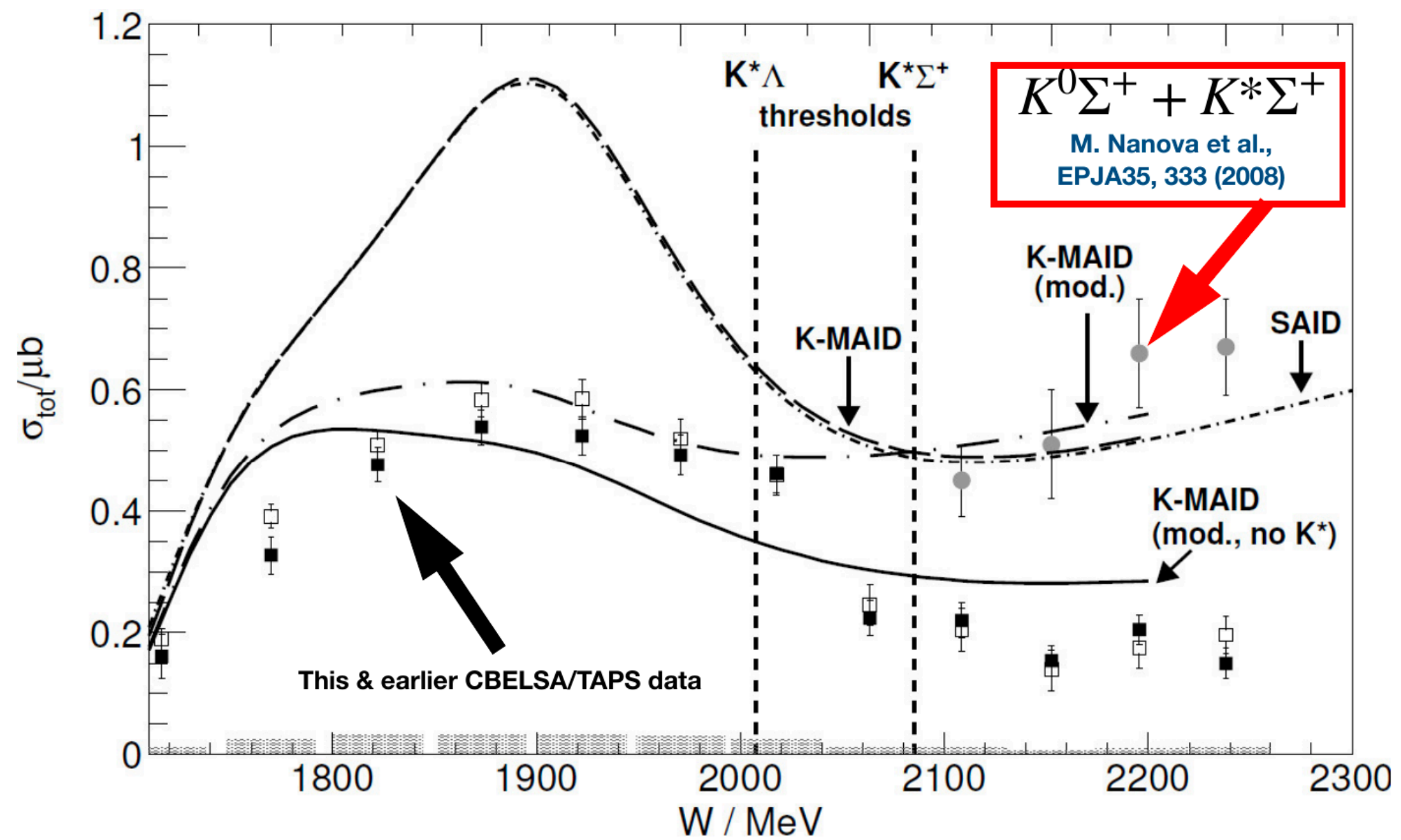


Figure from (and references in) G. Ramalho, M.T. Peña, PNP 136 (2024) 104097

Motivation: Cusp in $\gamma p \rightarrow K^0 \Sigma^+$ (CBELSA/TAPS)

- Cusp at $K^* Y$ thresholds, pronounced at forward angles
- K^{*0} rescattering to π^0 & K^0 ?

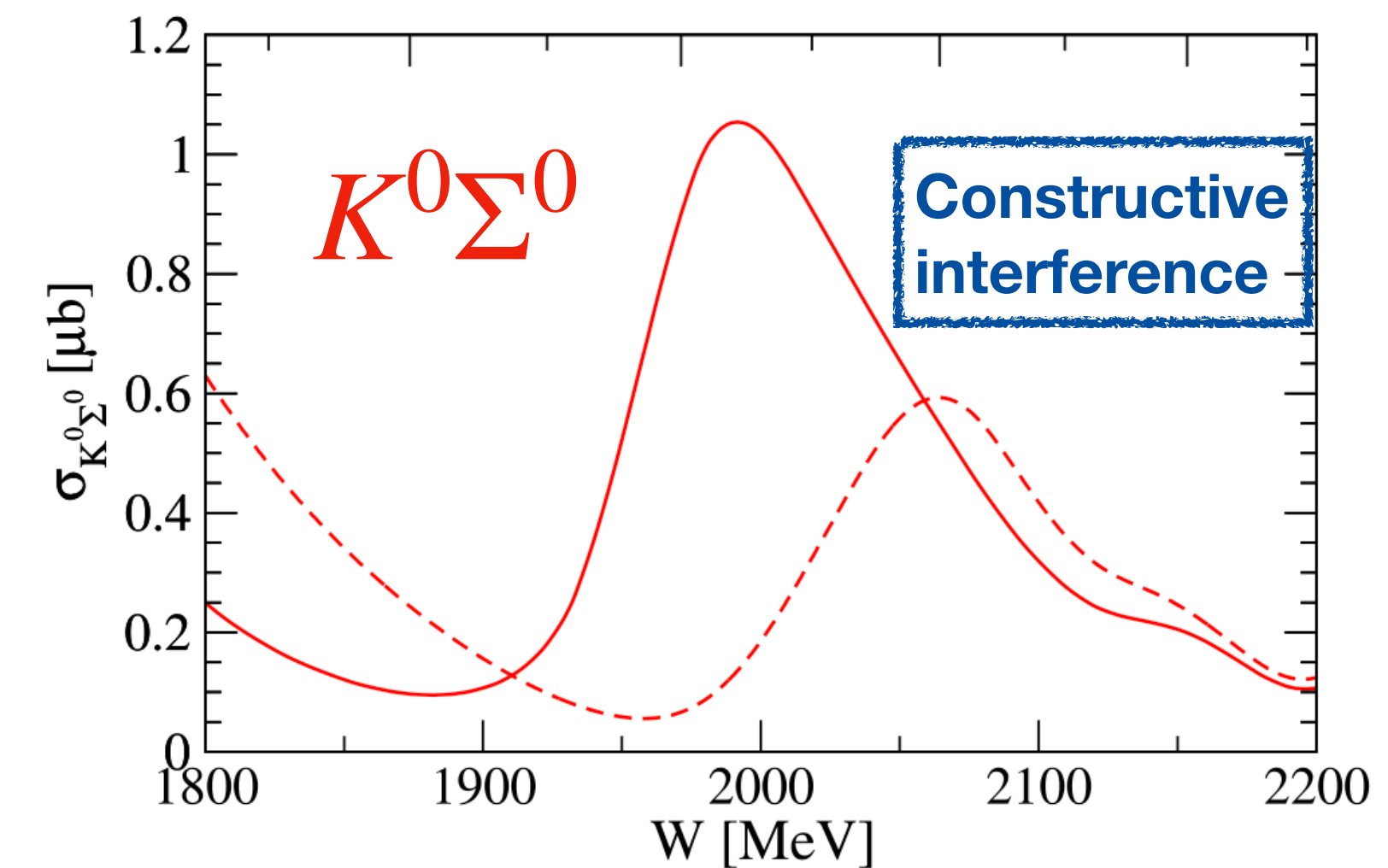
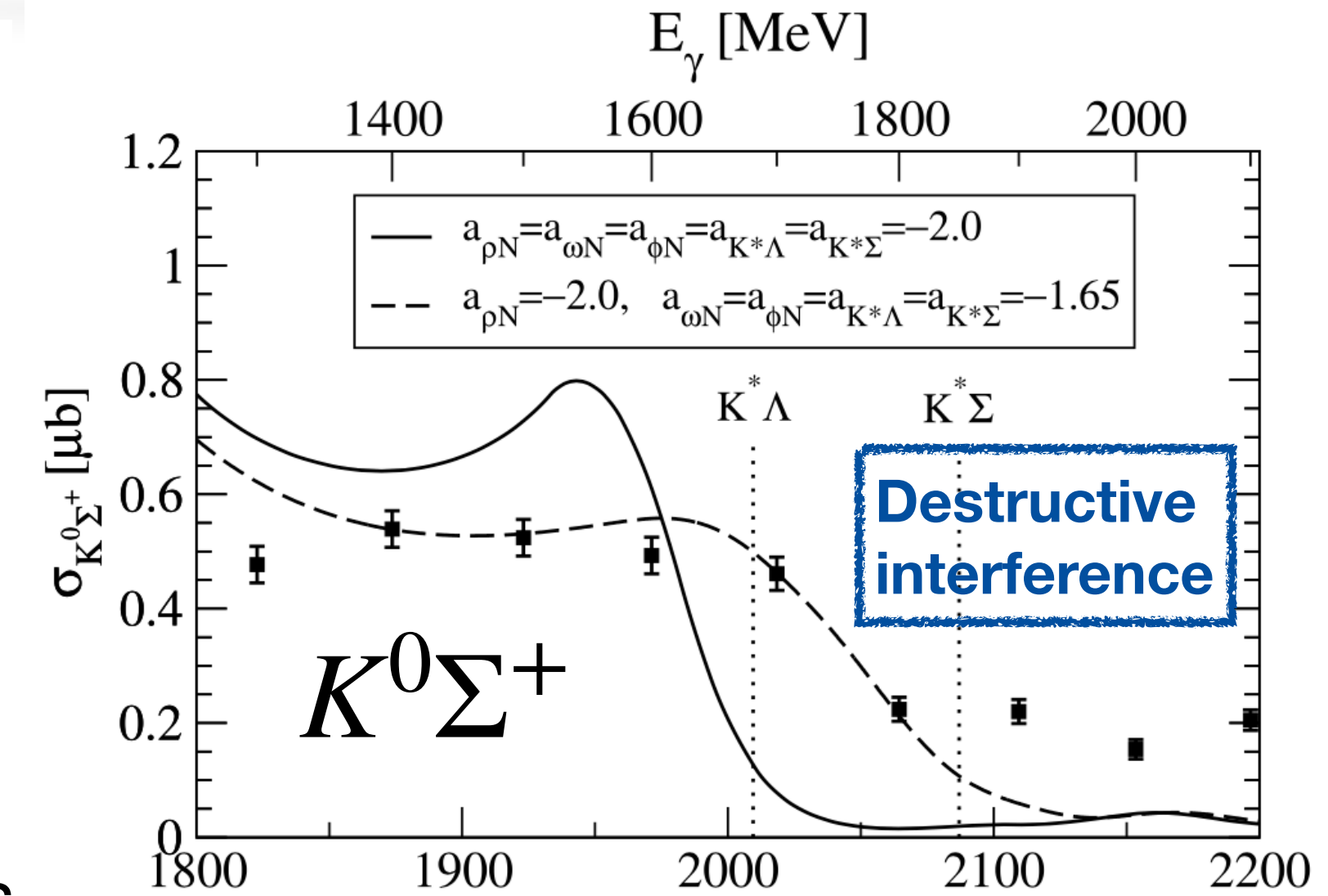
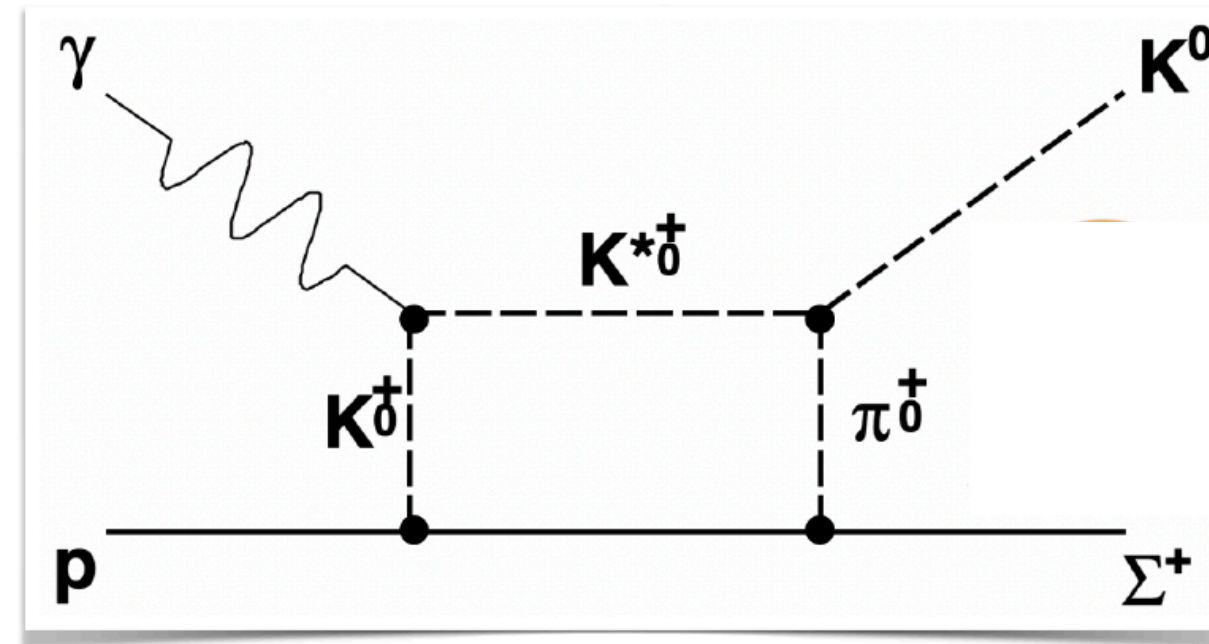
R. Ewald *et al.*, PLB 713 (2012) 180



- Coupled channel model
Ramos & Oset, PLB 727 (2013) 287
- Dynamically generated N^* s

Equivalent model
predicted P_c states

Wu *et al.*, PRL 105, 232001 (2010)



Molecular-like structure - experimental requirements

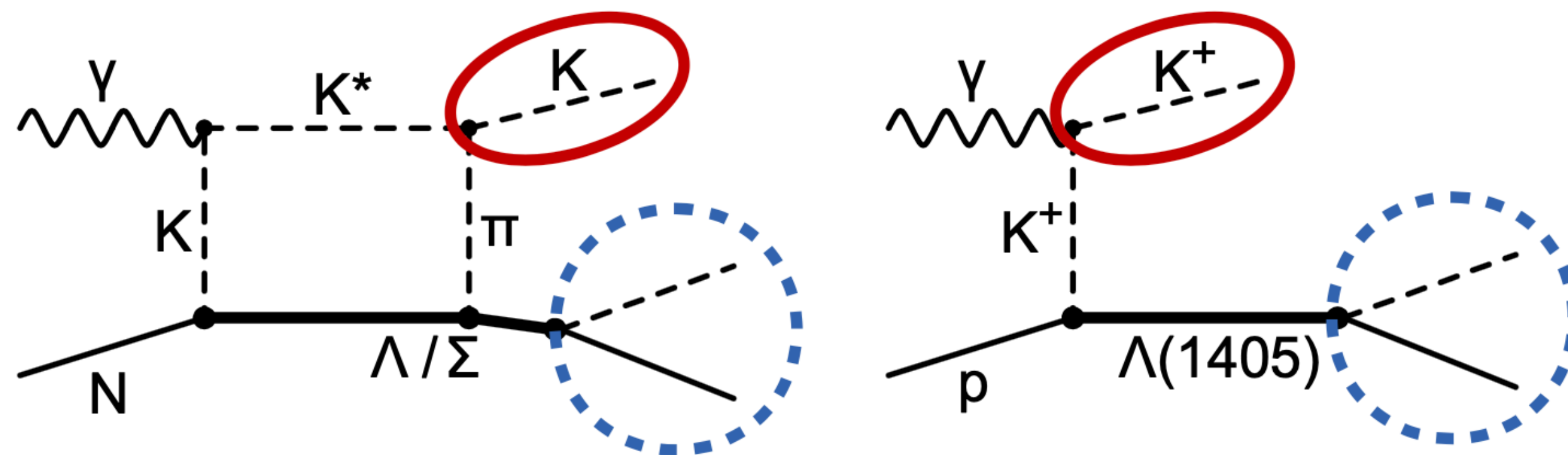
For strangeness photoproduction: $\gamma p \rightarrow K^+ Y$

- Charged particle identification at extremely forward angles
- Reaction dynamics at very low momentum exchange (low t)
- Reconstruction of complicated, mixed charge final states, eg $\gamma p \rightarrow K^+(\Lambda(1405) \rightarrow \pi^0 \Sigma^0 \rightarrow \pi^0 \gamma \Lambda \rightarrow 3\gamma p \pi^-)$

$$s = (P_\gamma + P_{\text{Target}})^2 = (P_{K^+} + P_Y)^2$$

$$t = (P_\gamma - P_{K^+})^2 = (P_Y - P_{\text{Target}})^2$$

$$u = (P_\gamma - P_Y)^2 = (P_{K^+} - P_{\text{Target}})^2$$

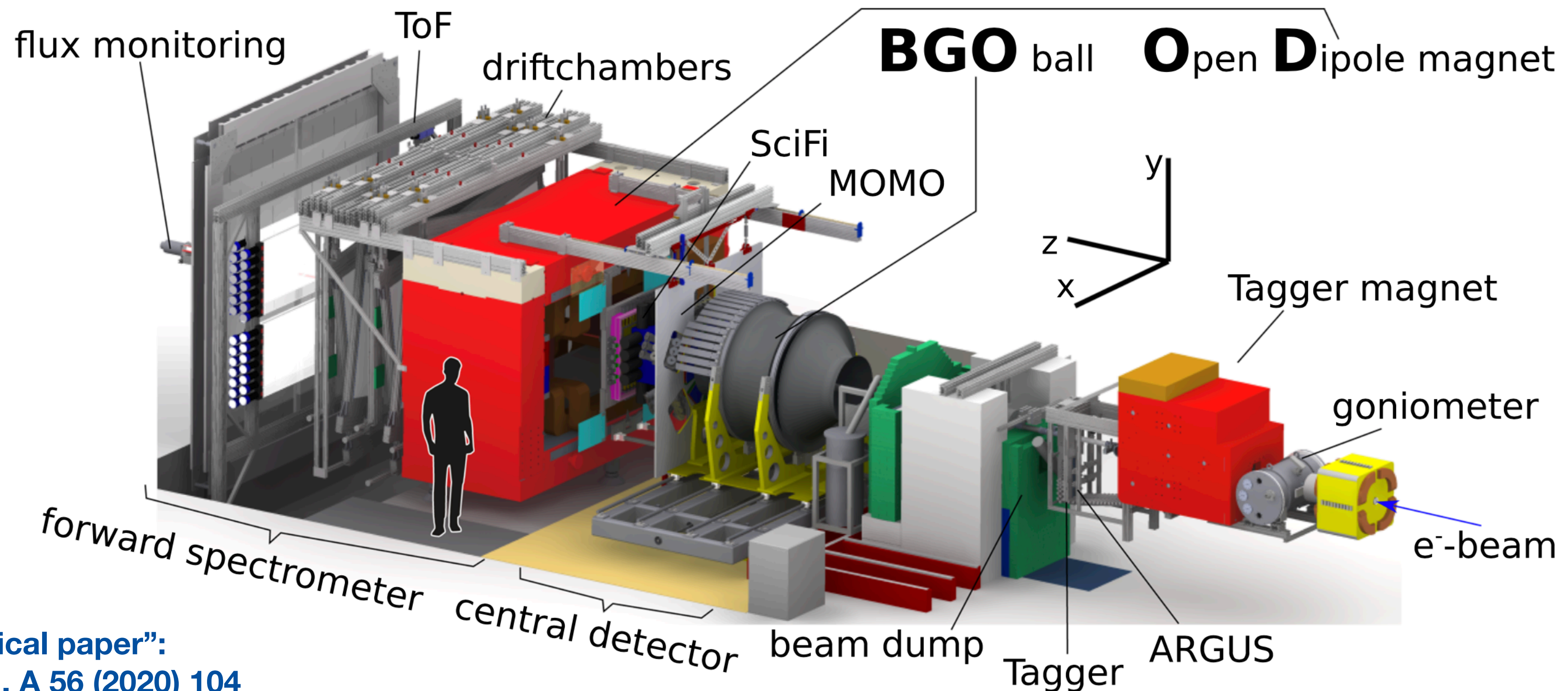


- **BGOOD** - Complementary to other facilities:
 - CBELSA-TAPS - 4π photon detection
 - CLAS - Charged particle identification

The BGOOD photoproduction experiment

- **ELSA** - 3 stage electron accelerator - quasi-continuous beams up to 3.2 GeV
- **BGOOD** - BGO calorimeter (central region) & Forward Spectrometer combination

Spokespersons:
T.C. Jude (Bonn)
P. Levi Sandri (Frascati)

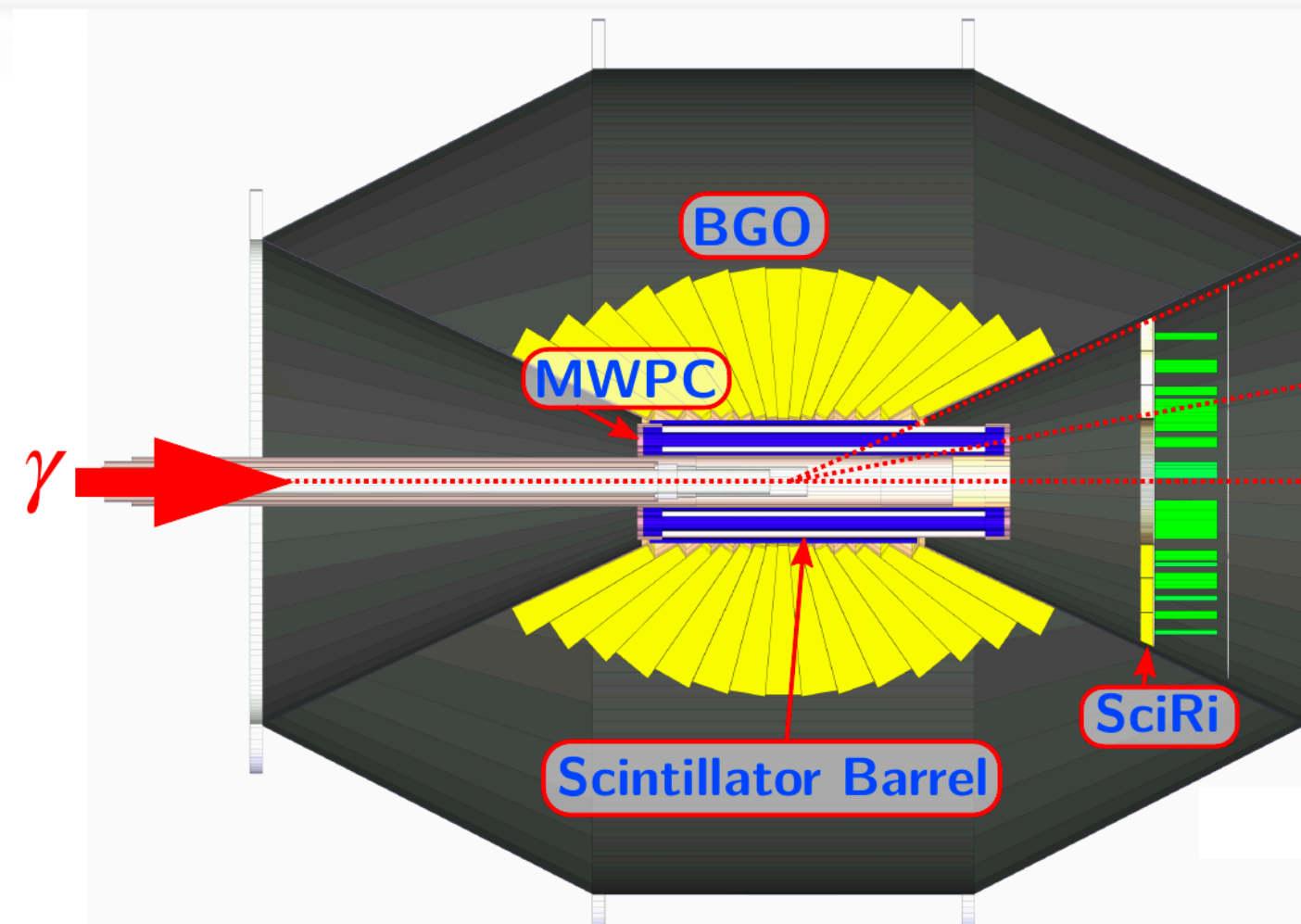


The "Technical paper":
Eur. Phys. J. A 56 (2020) 104

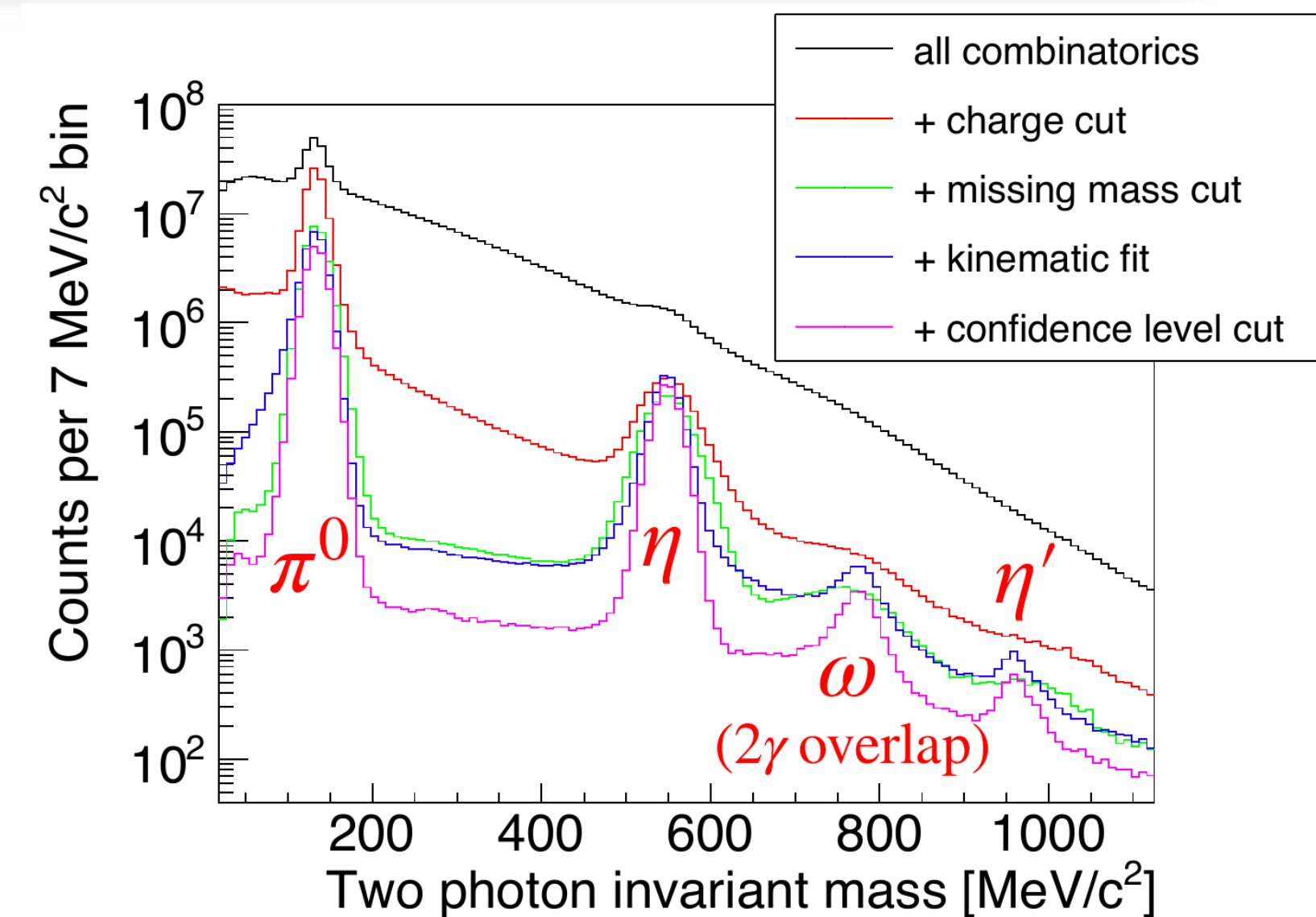
BGOOD - particle identification



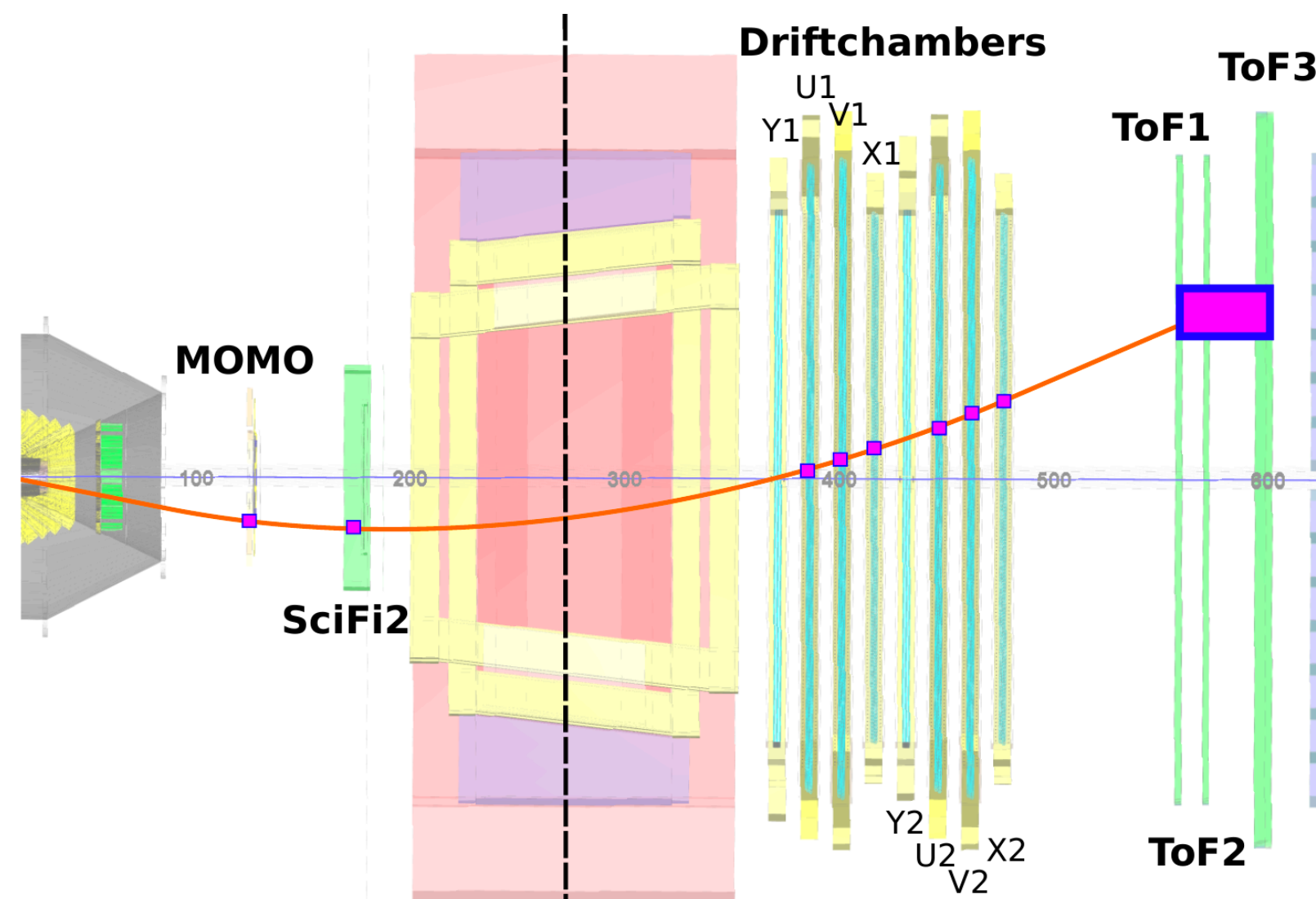
Central region



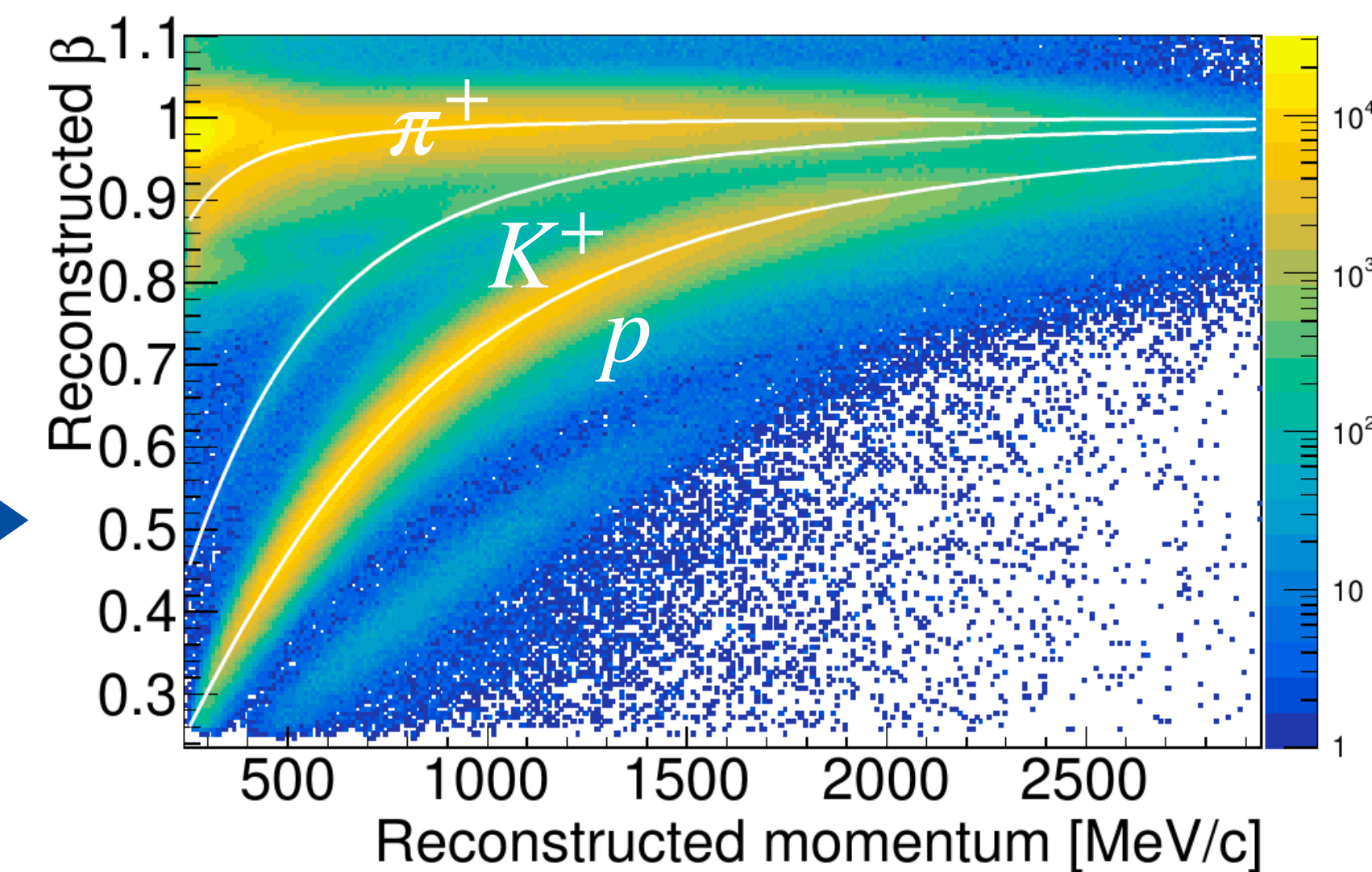
Neutral meson identification



Forward region



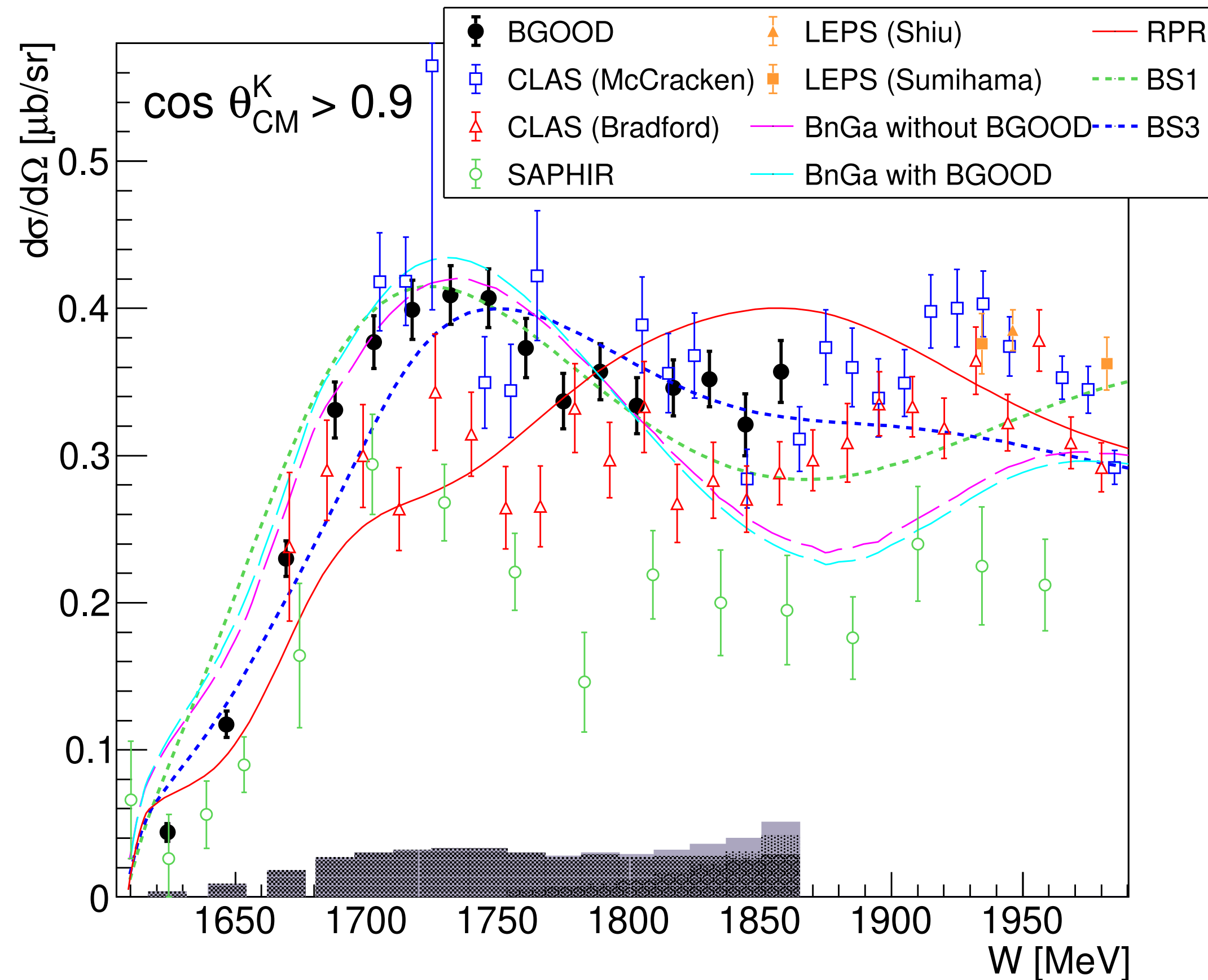
Charged particle identification



Forward $K^+ \Lambda$ and $K^+ \Lambda(1520)$ photoproduction

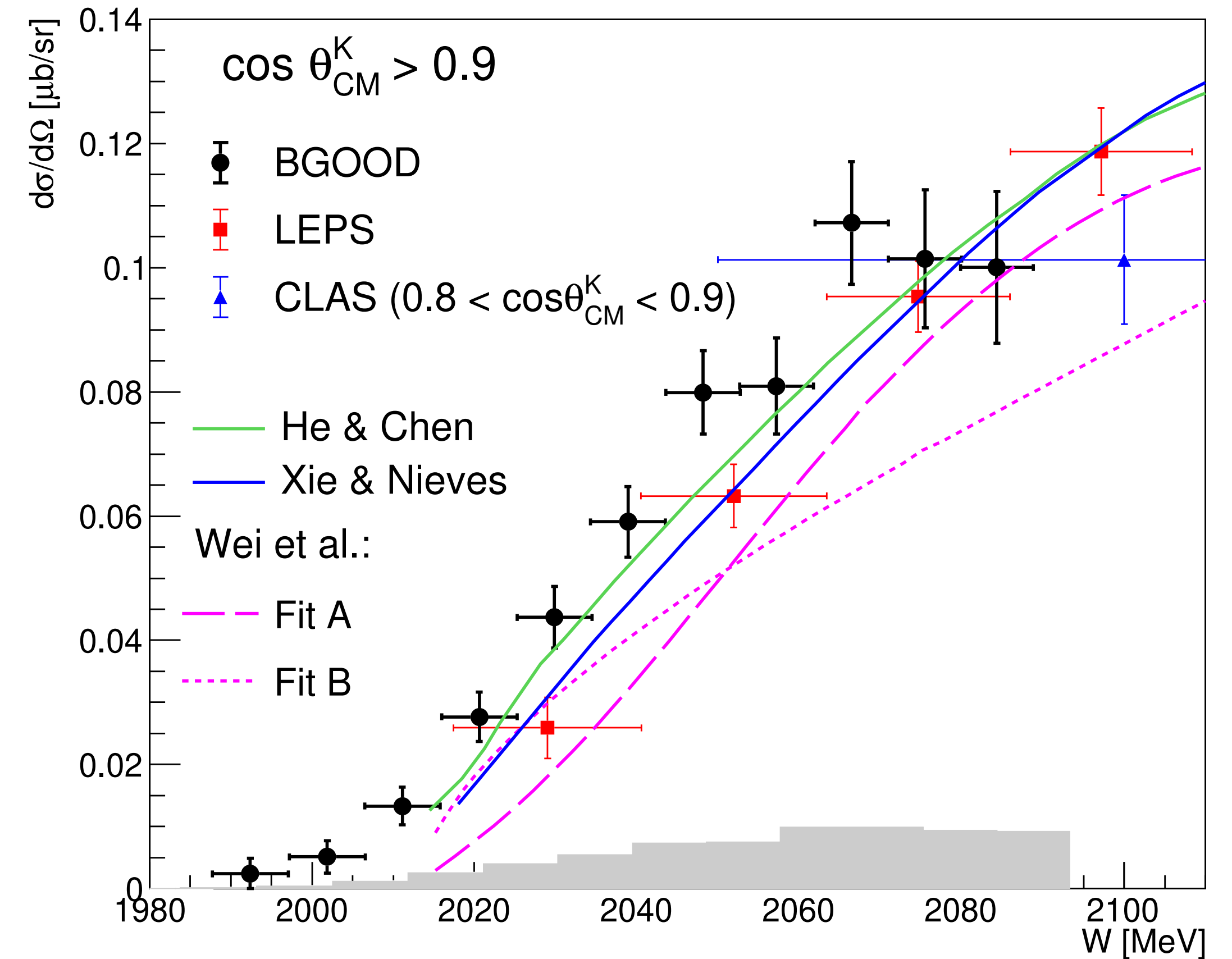
High statistical precision at forward angles & low t from threshold

$$\gamma p \rightarrow K^+ \Lambda$$



Eur. Phys. J. A (2021) 57:80

$$\gamma p \rightarrow K^+ \Lambda(1520)$$



E. Rosanowski, T.C Jude *et al.* Eur. Phys. J. A (2025) 61:147

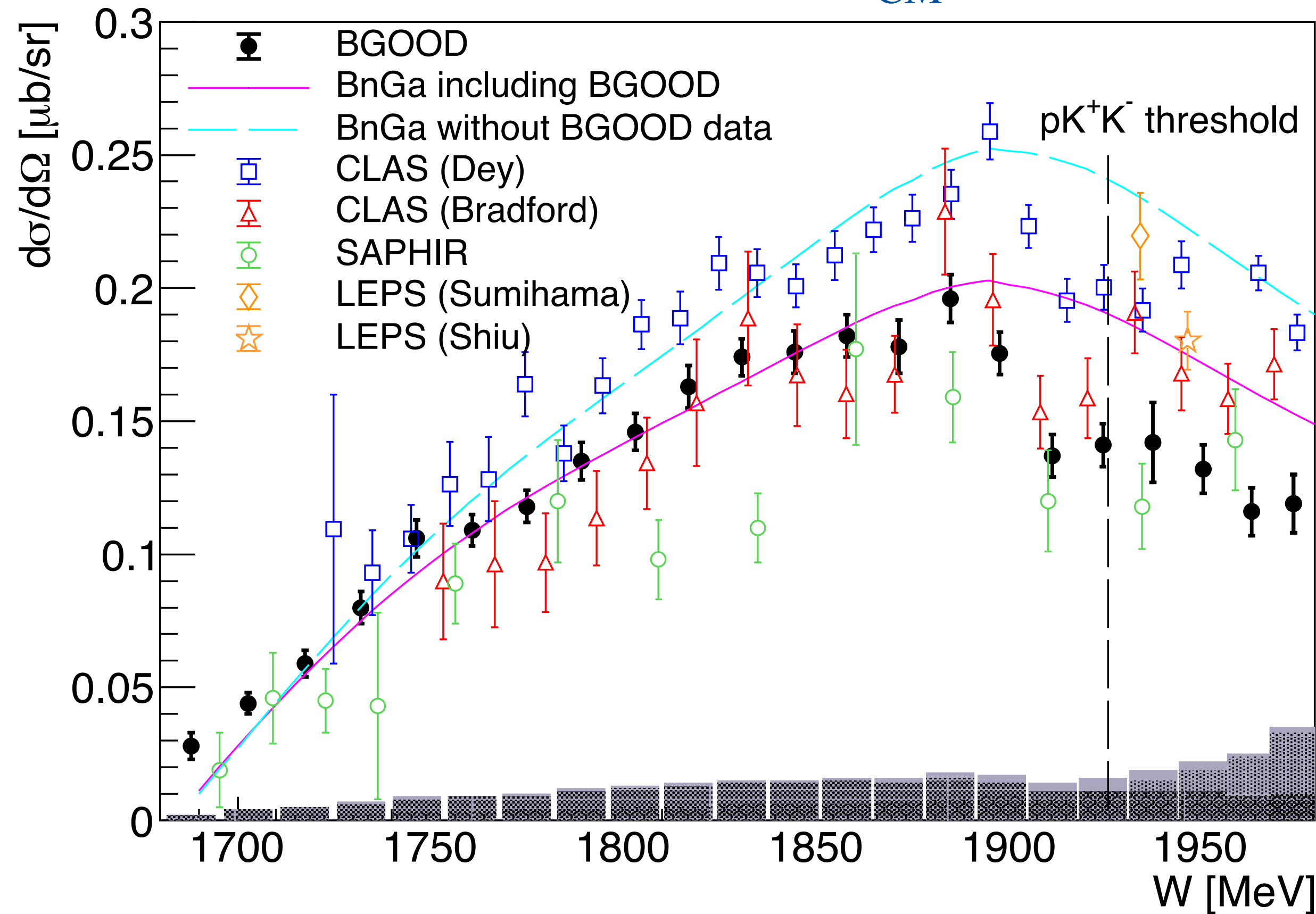
Forward $K^+\Sigma^0$ photoproduction

T.C. Jude *et al.*,
Phys. Lett. B 820 (2021) 136559



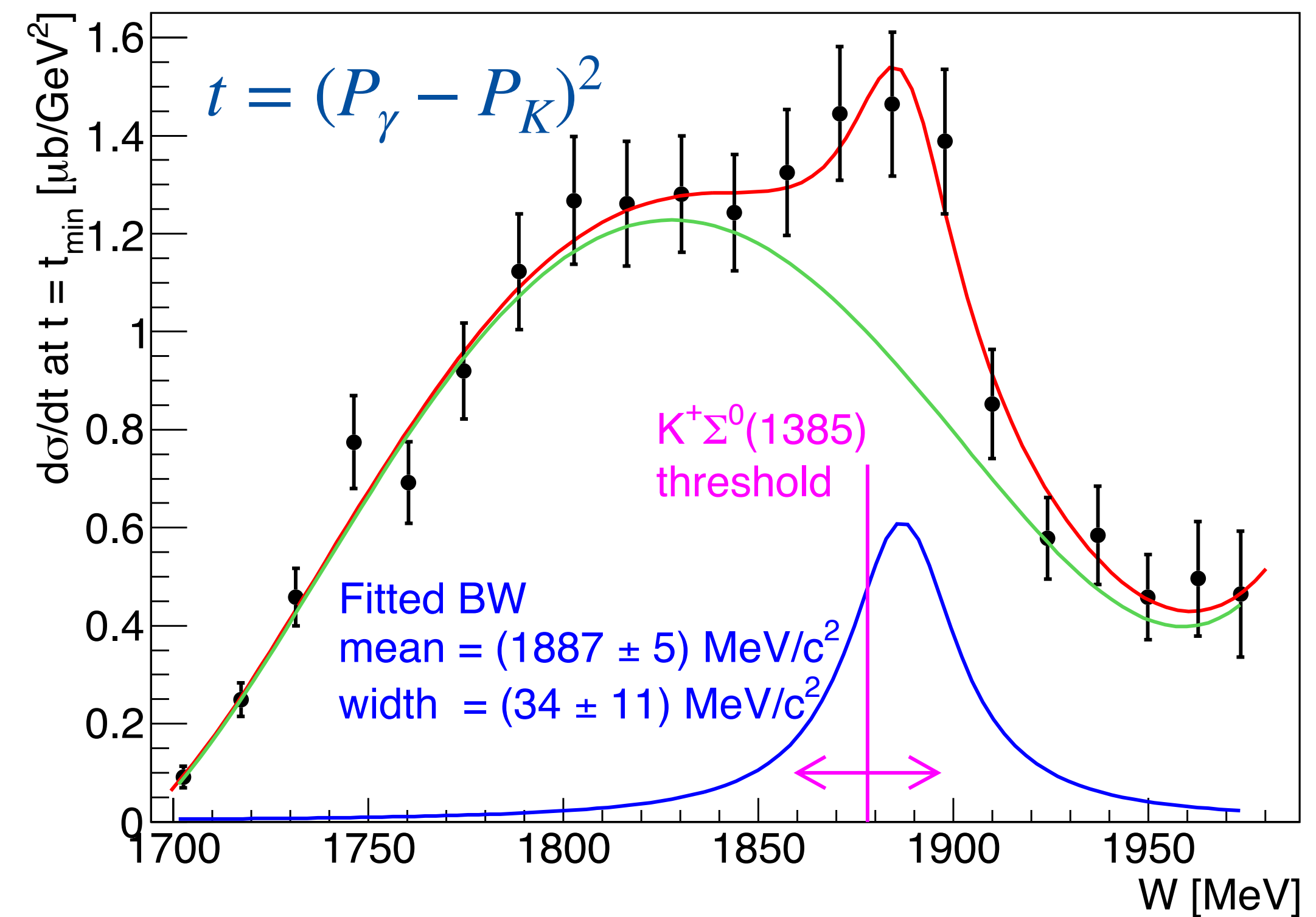
Cusp/peak resolved at $W \sim 1900$ MeV

$$\gamma p \rightarrow K^+\Sigma^0, \cos\theta_{\text{CM}}^K > 0.9$$



- A bound $K^+\Sigma(1385)$ system?
- Parallels to P_C states? $P_C(4382)$ at $\Sigma_C^*\bar{D}$ threshold

- Consistent with model calculations *P_C -like pentaquarks in a hidden strange sector, Huang et al., PRD 97, 094019 (2018)*

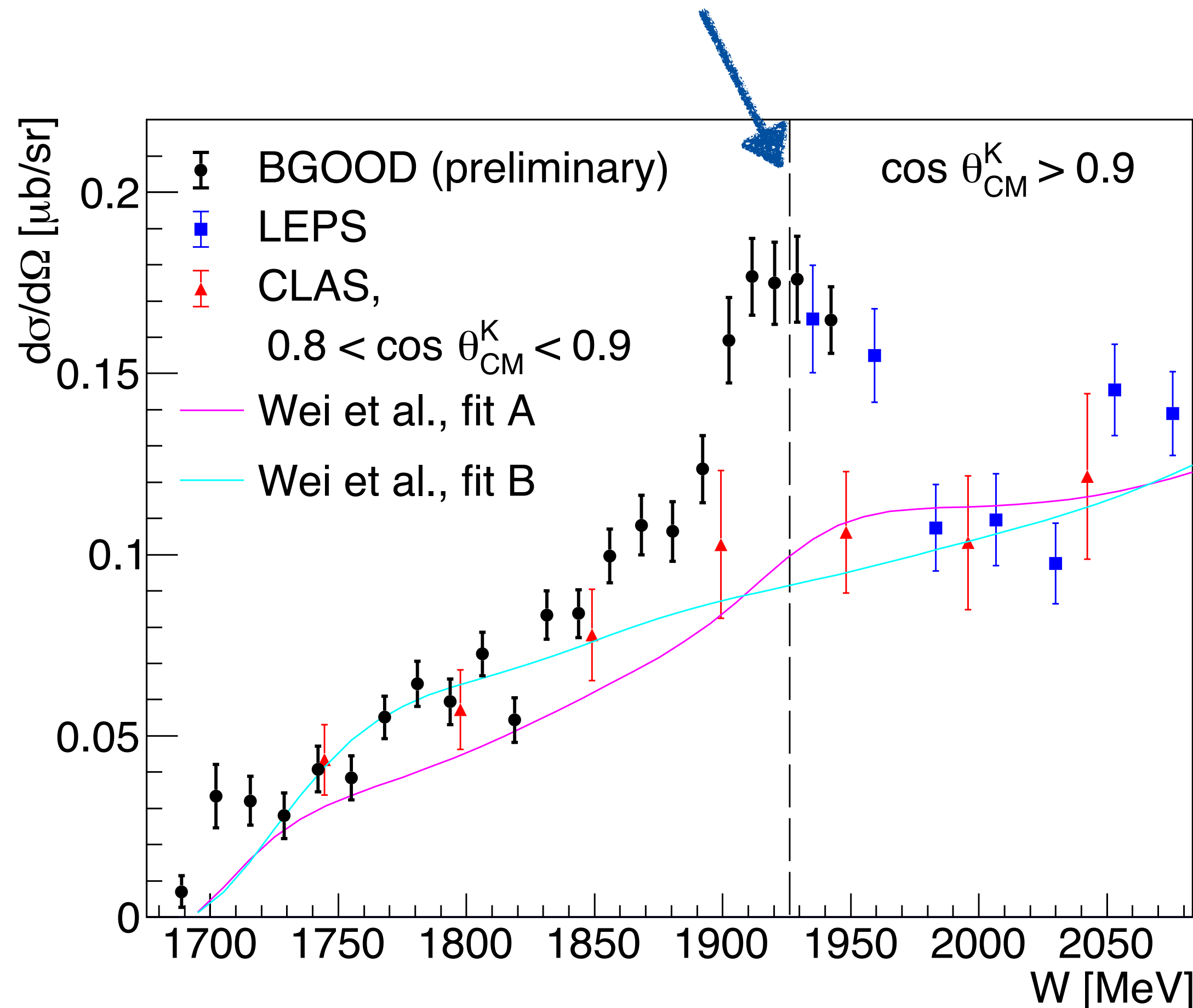


Forward $K^+\Sigma^-$ photoproduction

J. Gross, PhD thesis, Uni Bonn 2025



Structure consistent with proposed $K\bar{K}N$ bound state? Torres et al., EPJA 41 (2009) 361

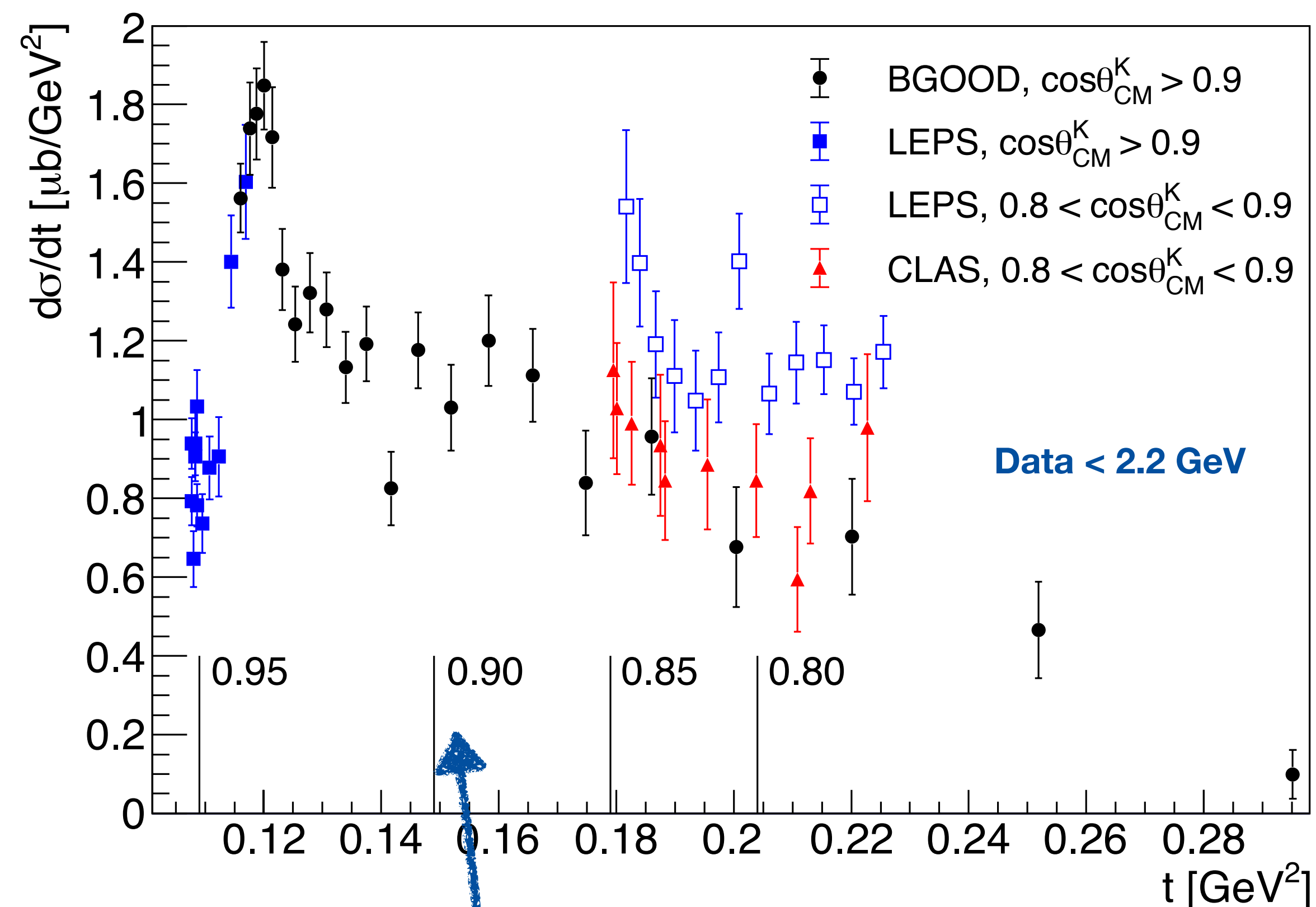


Wei, Wang & Huang, PRD 107, 114018 (2023) (& priv. comm.)

CLAS: Pereira et al., PLB 688 (2010) 289

LEPS: H. Kohri et al., PRL 97 (8 2006) 082003

- The same data differential with respect to t



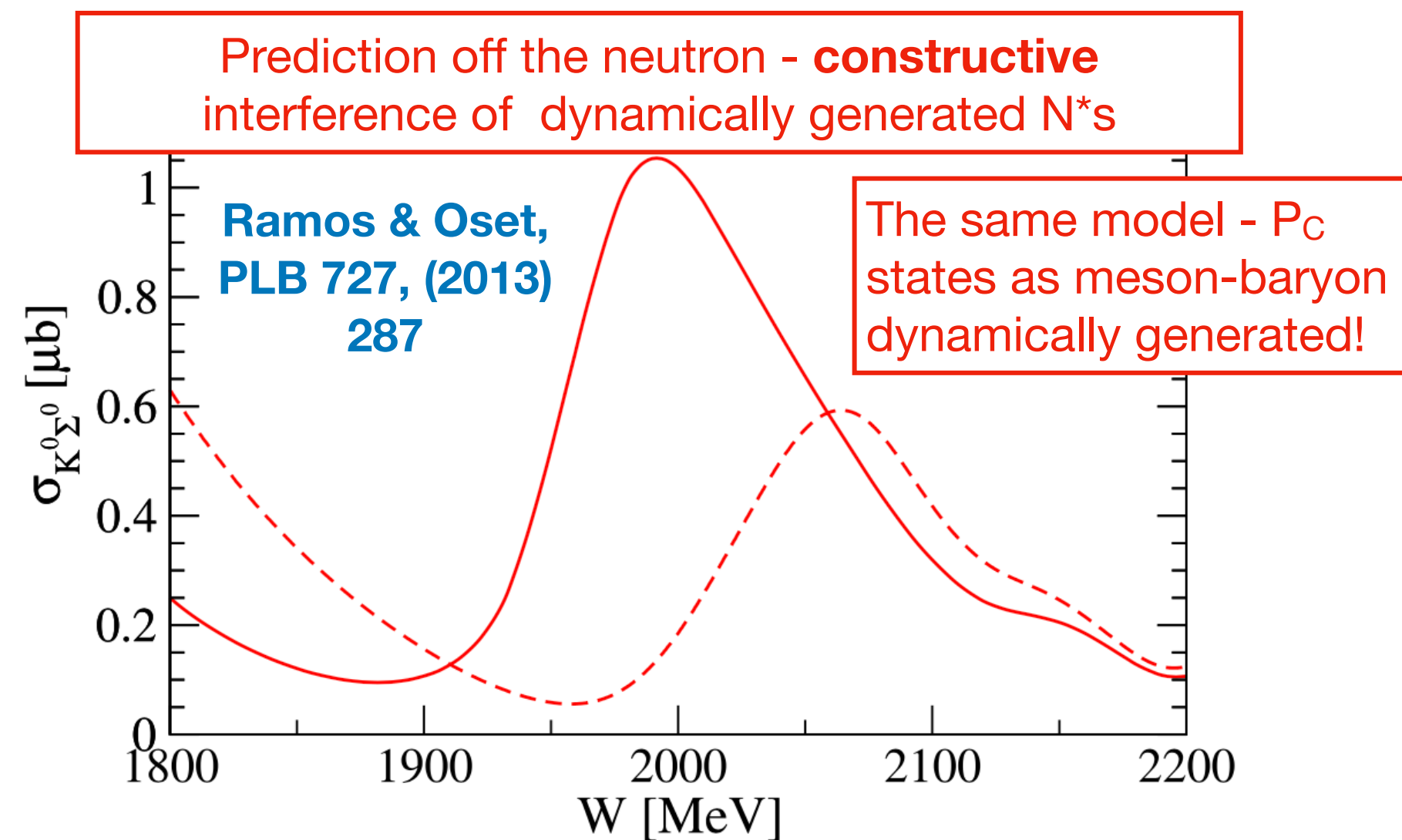
- Low t (with structure evident) only accessible for $\cos \theta_{\text{CM}}^K > 0.9$

$$\gamma n \rightarrow K^0 \Sigma^0$$

Predicted peak - *strange pentaquarks?*

- Dynamically generated meson-baryon states? - $\Lambda^* K - \Sigma K^*$

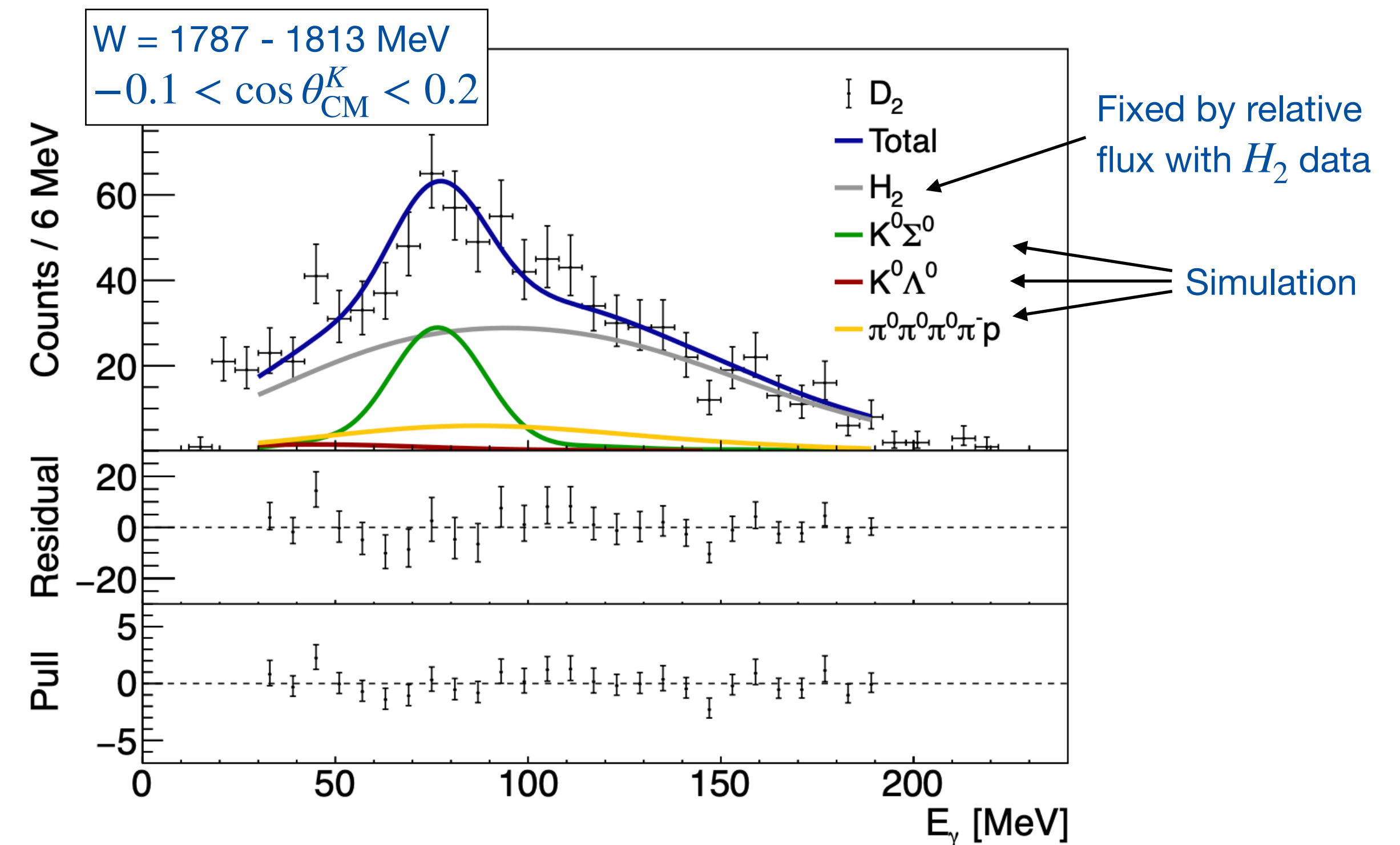
Integrated over all angles



- Kinematic fit & Identification via:

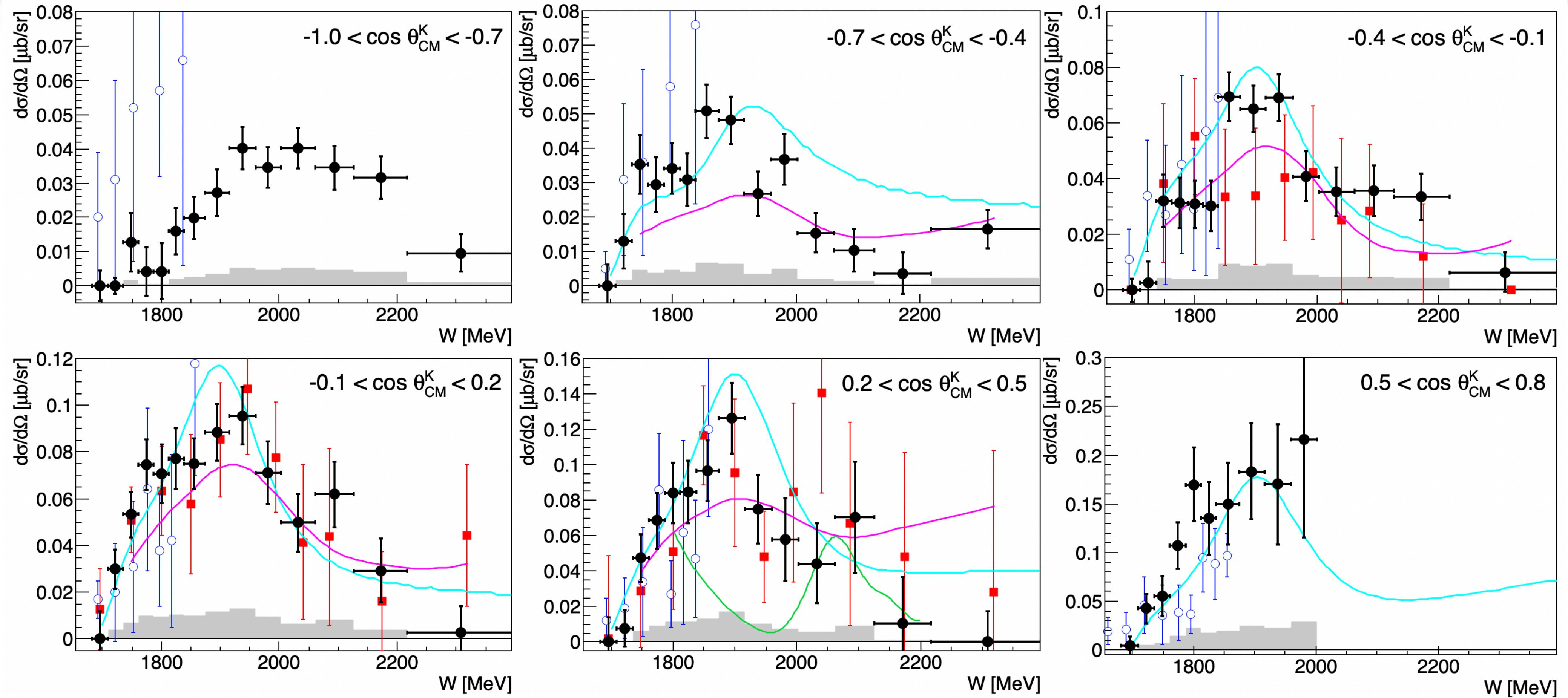
$$K^0 \rightarrow \pi^0 \pi^0 \quad \& \quad \Sigma^0 \rightarrow \gamma (\Lambda \rightarrow p \pi^-)$$

- Fitting to photon energy in the Σ rest frame (example):

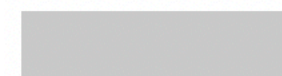


$\gamma n \rightarrow K^0 \Sigma^0$

K. Kohl, T.C. Jude, *et al.*, EPJA 59 (2023)
A. Sonnenschein, PhD thesis (in preparation)



BGOOD, Sonnenschein



BGOOD Sys. error, Sonnenschein



BGOOD, Kohl et al., EPJA 59 (2023) 254



A2, Akondi et al., EPJA 55 (2019) 202



Ramos & Oset, PLB 727 (2013) 287 (Total cross section at an arbitrary scale)



Kaon MAID, <http://www.kph.uni-mainz.de/MAID/>



BnGa PWA, <https://pwa.hiskp.uni-bonn.de>

A2 data at $\cos \theta_{\text{CM}}^K$ of -0.625,
-0.375, -0.125, 0.125, 0.375, 0.625

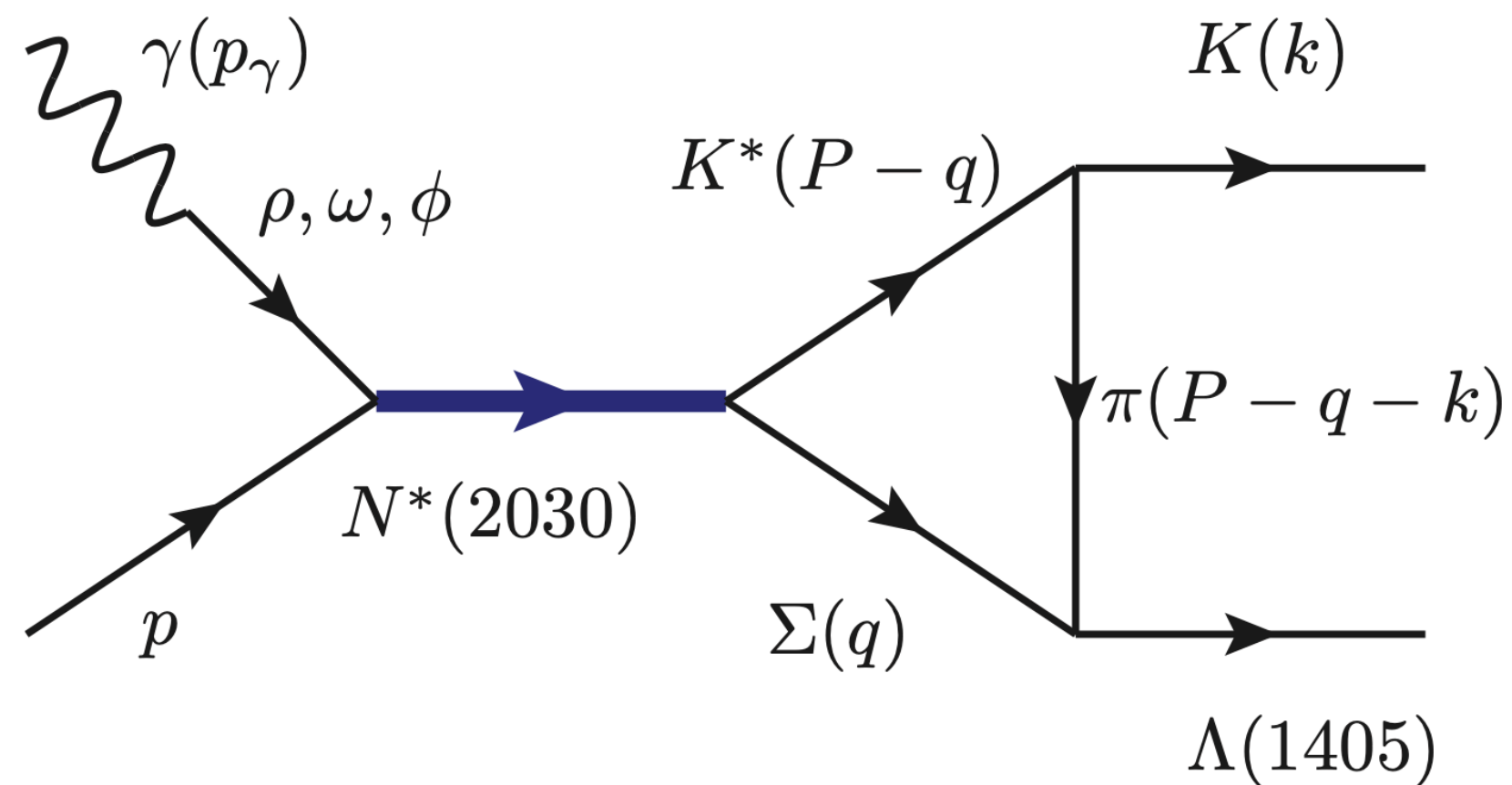
$\gamma p \rightarrow K^+ \Lambda(1405) \rightarrow K^+ (\Sigma^0 \pi^0)$

G. Scheluchin, T.C Jude *et al.*
PLB 833 (2022) 137375

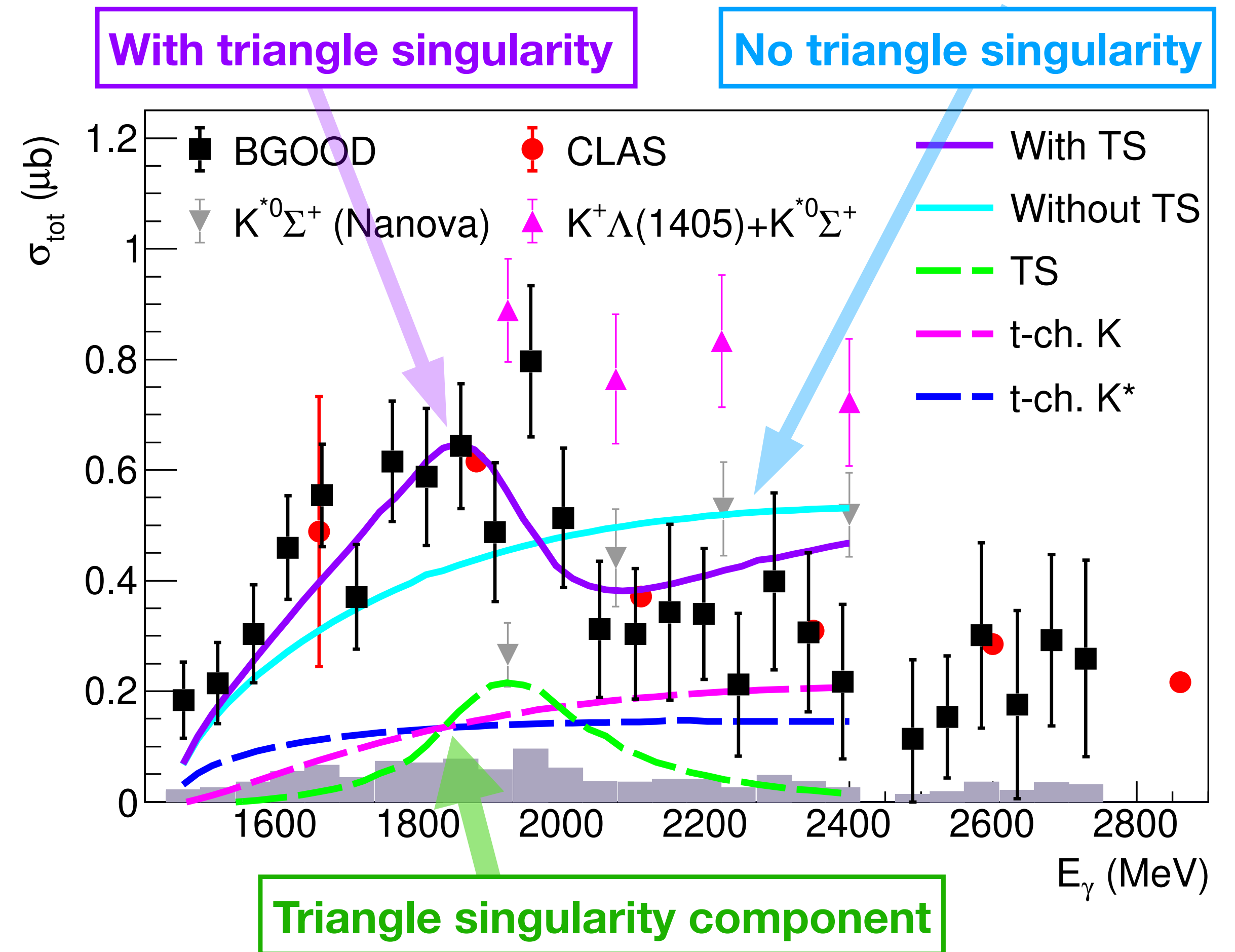


$\gamma p \rightarrow K^+ \Lambda(1405) \rightarrow K^+ \Sigma^0 \pi^0 \rightarrow K^+ 3\gamma p \pi^-$ & kinematic fit

- Proposed triangle singularity:
- The same dynamically generated $N^*(2030)$ proposed for cusp in $K^0 \Sigma^+$



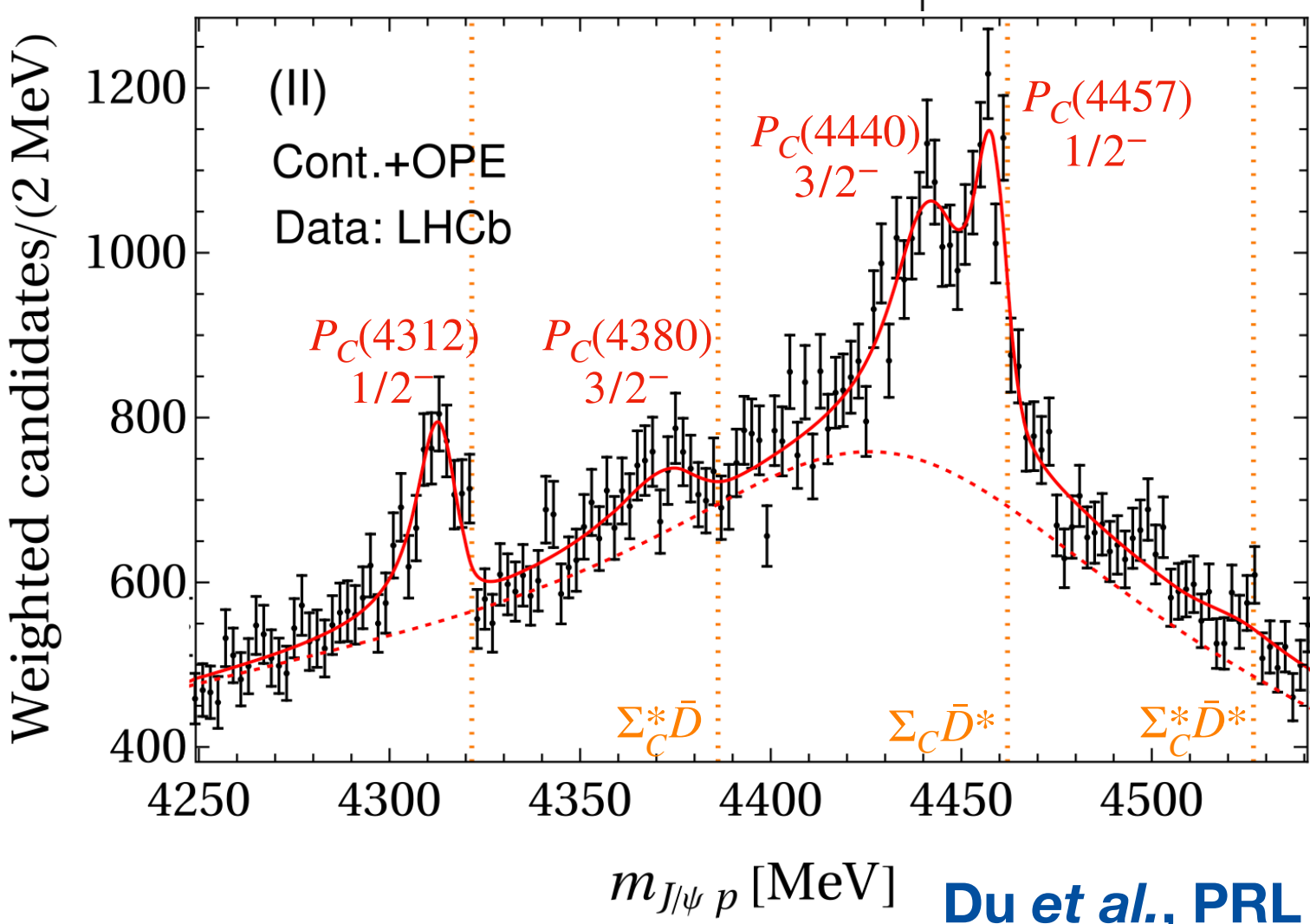
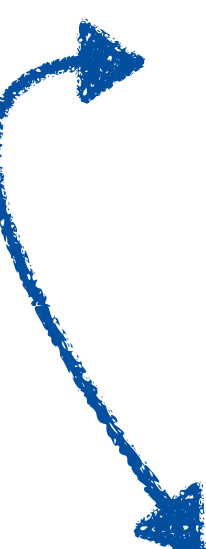
Wang *et al.*, PRC 95, 015205 (2017)



- Also - **Line shape measurements** A. J. C. Figueiredo, PhD thesis (in preparation), Uni Bonn

Strange pentaquarks? Equivalence to P_c states?

Charm sector		Strange sector	
Threshold	State	Threshold	Evidence
$\Sigma_c \bar{D}$	$P_c(4312)$	$\Sigma^0 K^+$ at 1687 MeV	$N(1535)$
$\Sigma_c^* \bar{D}$	$P_c(4382)$	$\Sigma^0(1385) K^+$ at 1879 MeV	Peak in $K^+ \Sigma^0$ at $t_{\min}$ TJ et al., Phys. Lett. B 820 (2021) 136559
-	-	$K^+ K^- N$ at 1926 MeV	Structure in $K^+ \Sigma^-$ at low t J. Gross, PhD thesis 2025, Uni Bonn
$\Sigma_c \bar{D}^*$	$P_c(4457)$	$\Sigma^0 K^{*+}$ at 2085 MeV	Cusp in $K^0 \Sigma^+$ CB/ELSA-TAPS R. Ewald et al., PLB 713 (2012) 180 (Tentative) peak in $K^0 \Sigma^0$ K. Kohl, TJ, et al., EPJA 59 (2023) Triangle singularity in $K^+ \Lambda(1405)$ G. Scheluchin, TJ et al. PLB 833 (2022) 137375



Resolve the nature of structures via polarisation observables at INSIGHT

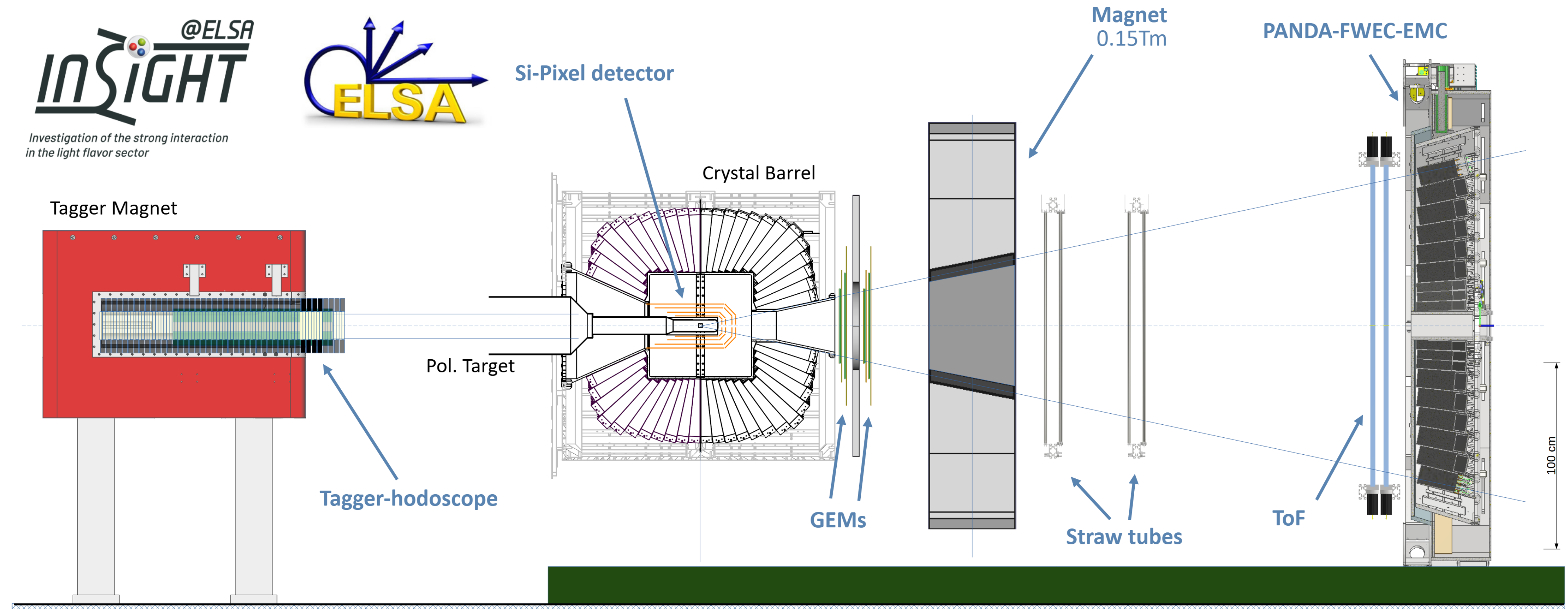


Investigation of the strong interaction in the light flavor sector

Du et al., PRL 124, 072001 (2020)

The Future: INSIGHT @ ELSA

Unique possibilities in understanding strange and non-strange baryon resonance spectra & their properties



- $\sim 4\pi$ solid angle: High resolution photon measurements, Precise charged particle detection
- Polarised beam & polarised target

Ulrike Thoma (spokesperson), Parallel session C, Thursday 15:00

The Future: INSIGHT @ ELSA

Polarisation observables for $K^+\Sigma^0$ at $\cos \theta_{\text{CM}}^K = 0.95$ (A bound $K\Sigma^*$ state?)

Bonn-Gatchina PWA

K. Nikonov,
A. Sarantsev, Priv. Comm.

“Standard” calculation

With $N^*(1896)\frac{3}{2}^-$,

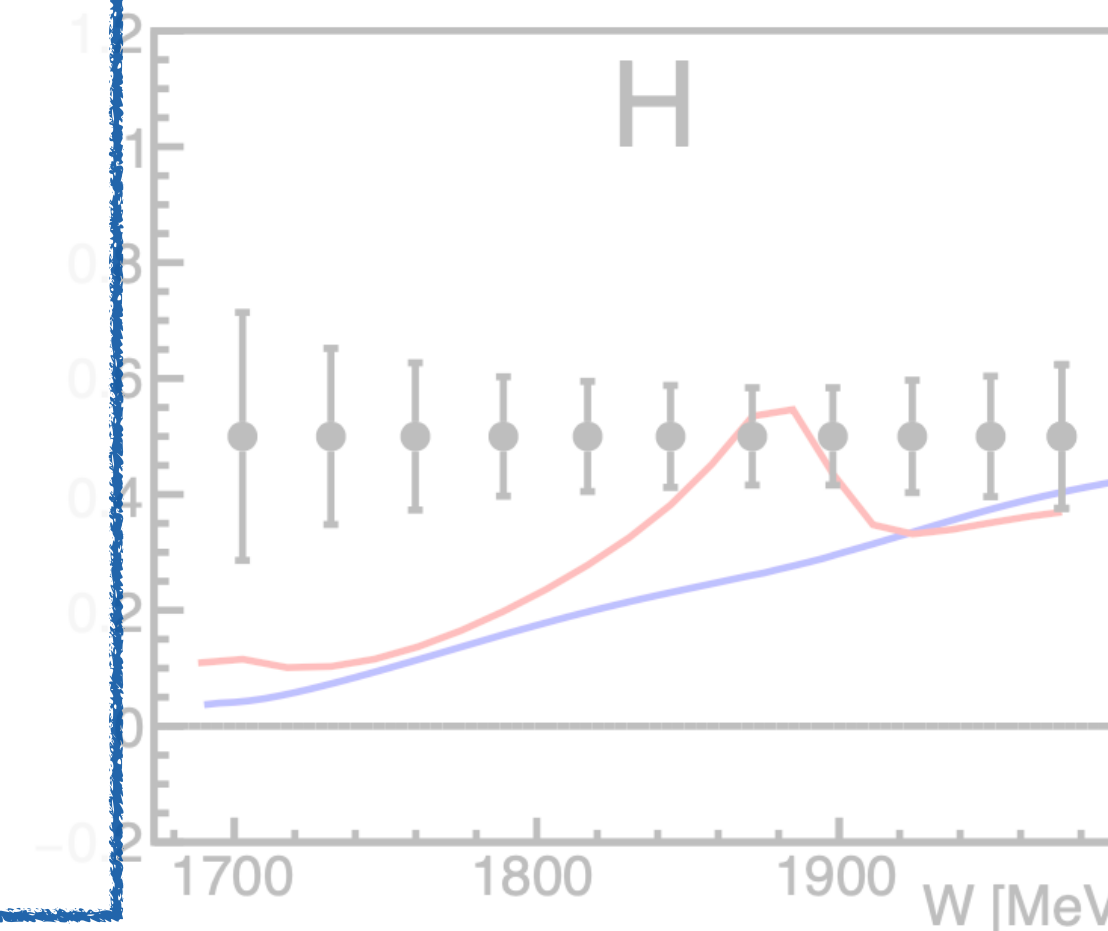
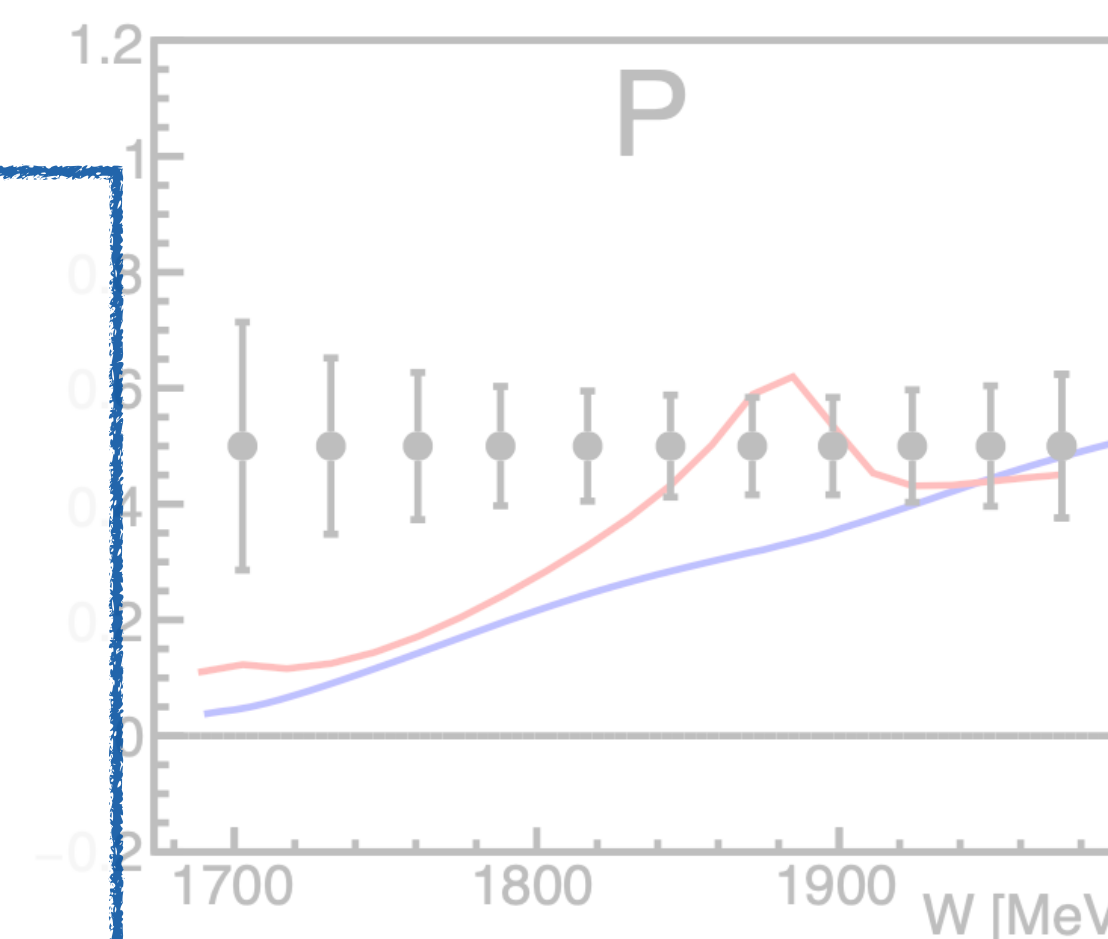
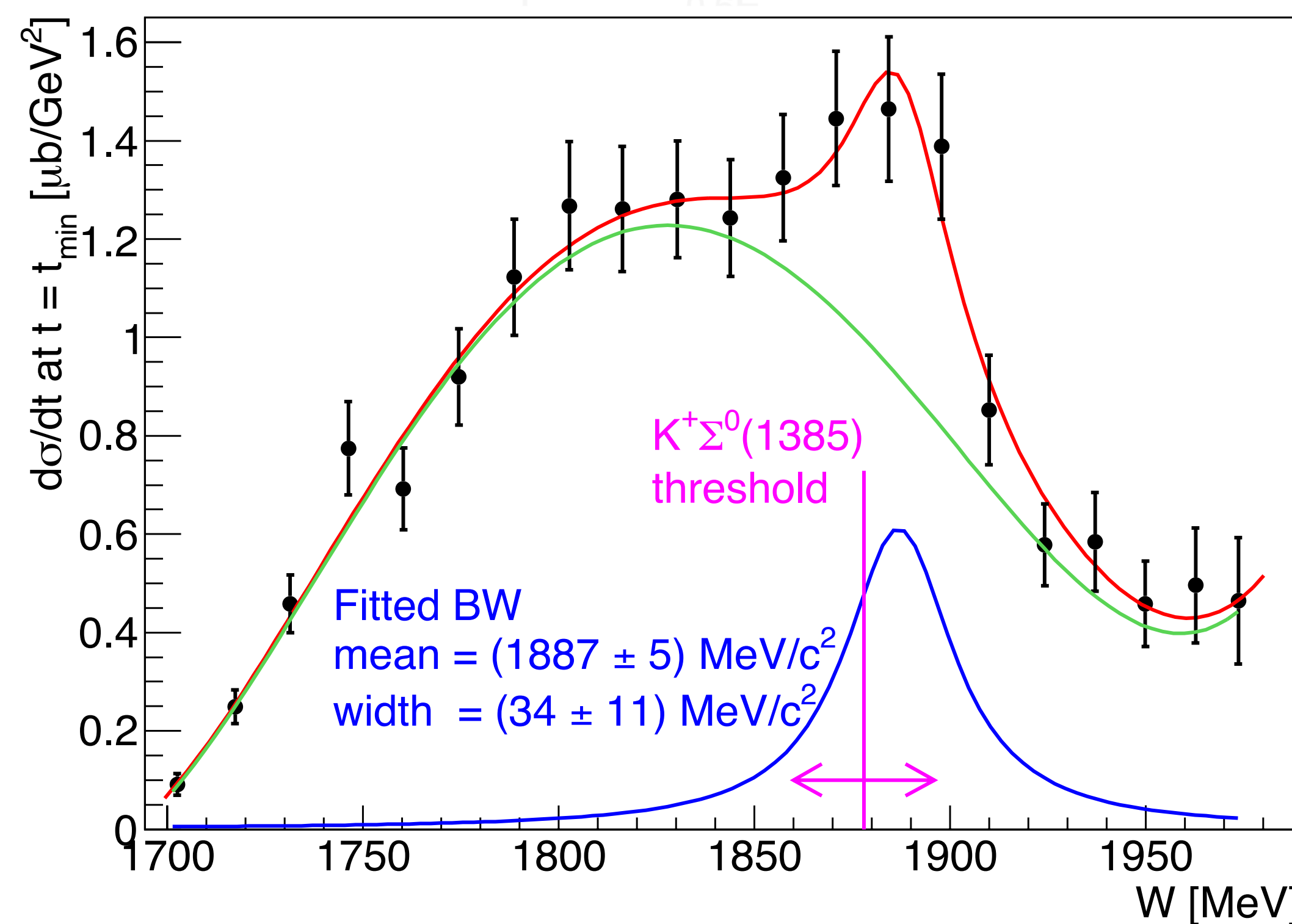
$\Gamma = 36$ MeV

Black circles - INSIGHT
precision over 2 years

GRAAL

A. Lleres et al, EPJA 31 (2007)

Differential cross section measured at BGOOD



The Future: INSIGHT @ ELSA

Polarisation observables for $K^+\Sigma^0$ at $\cos \theta_{\text{CM}}^K = 0.95$ (A bound $K\Sigma^*$ state?)

Bonn-Gatchina PWA

K. Nikonov,
A. Sarantsev, Priv. Comm.

“Standard” calculation

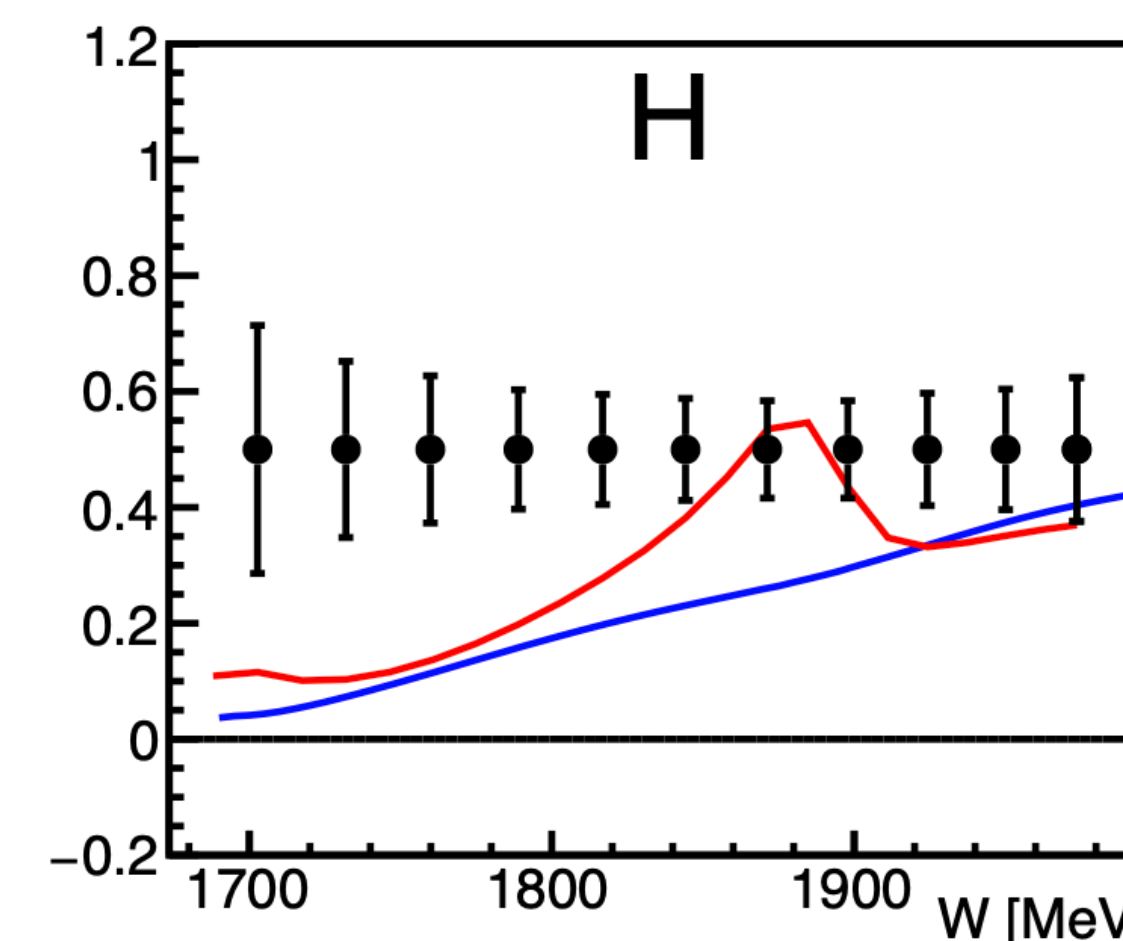
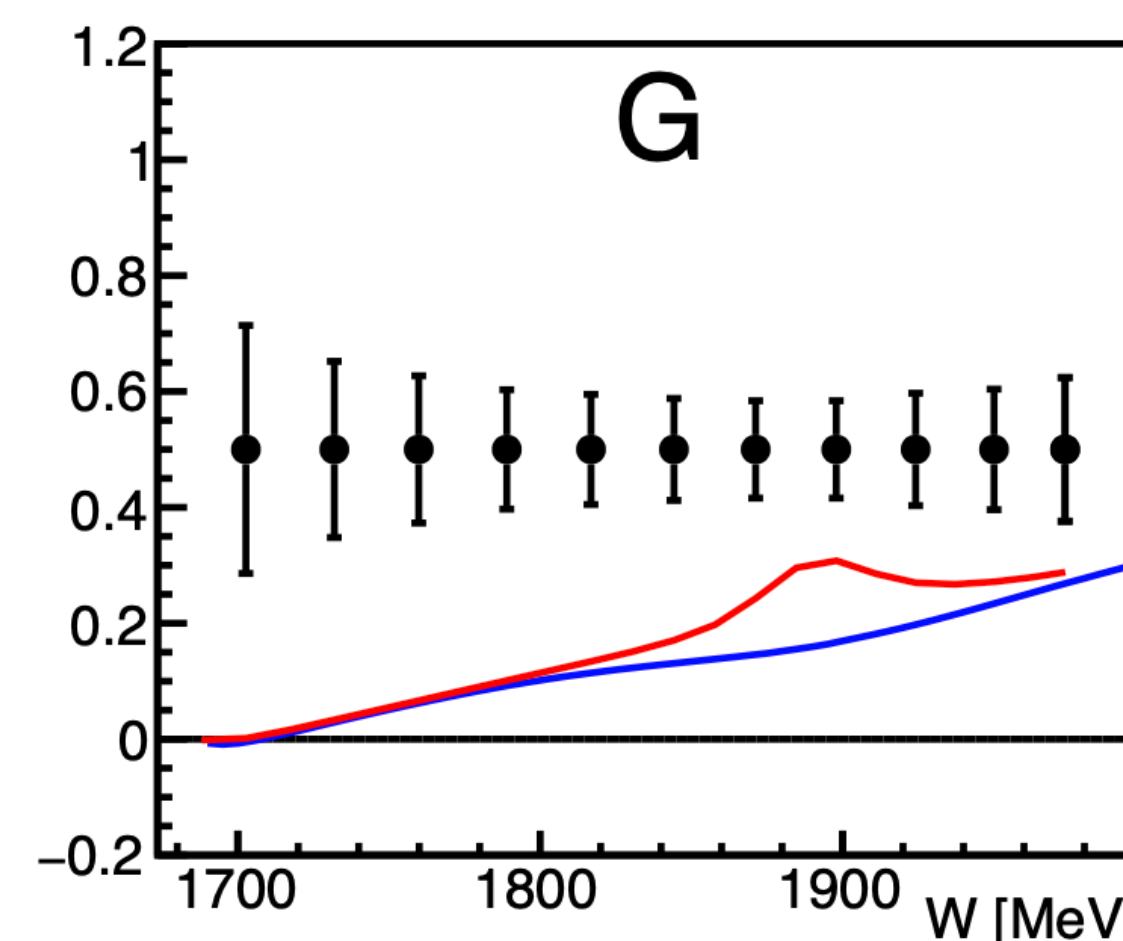
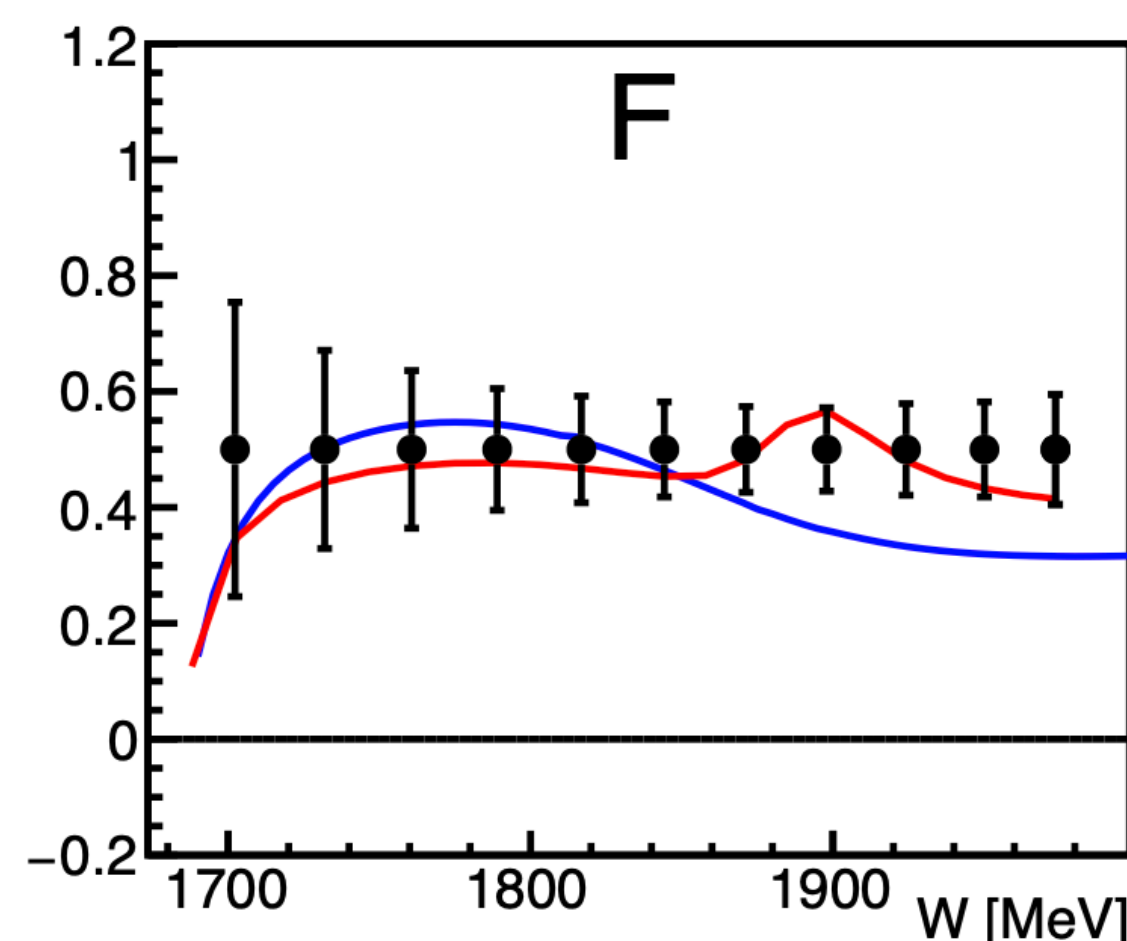
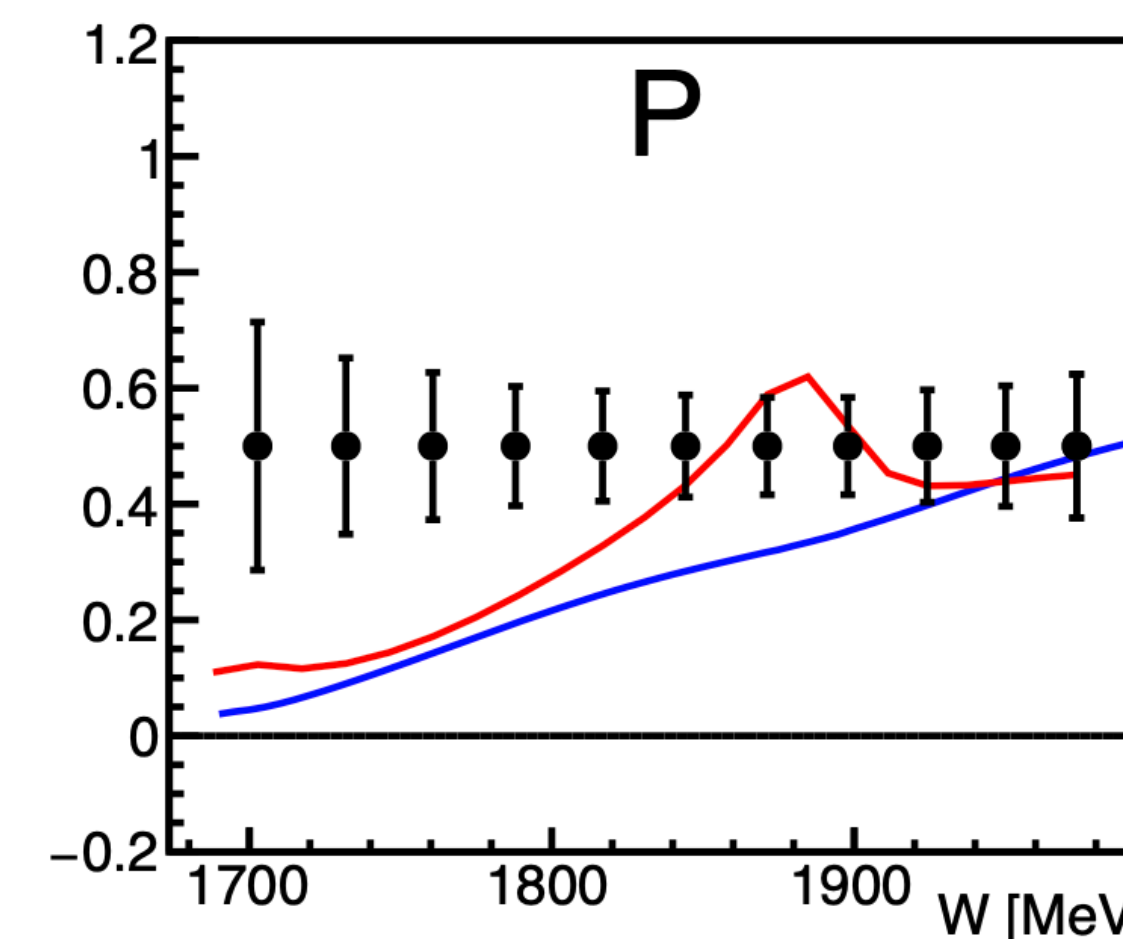
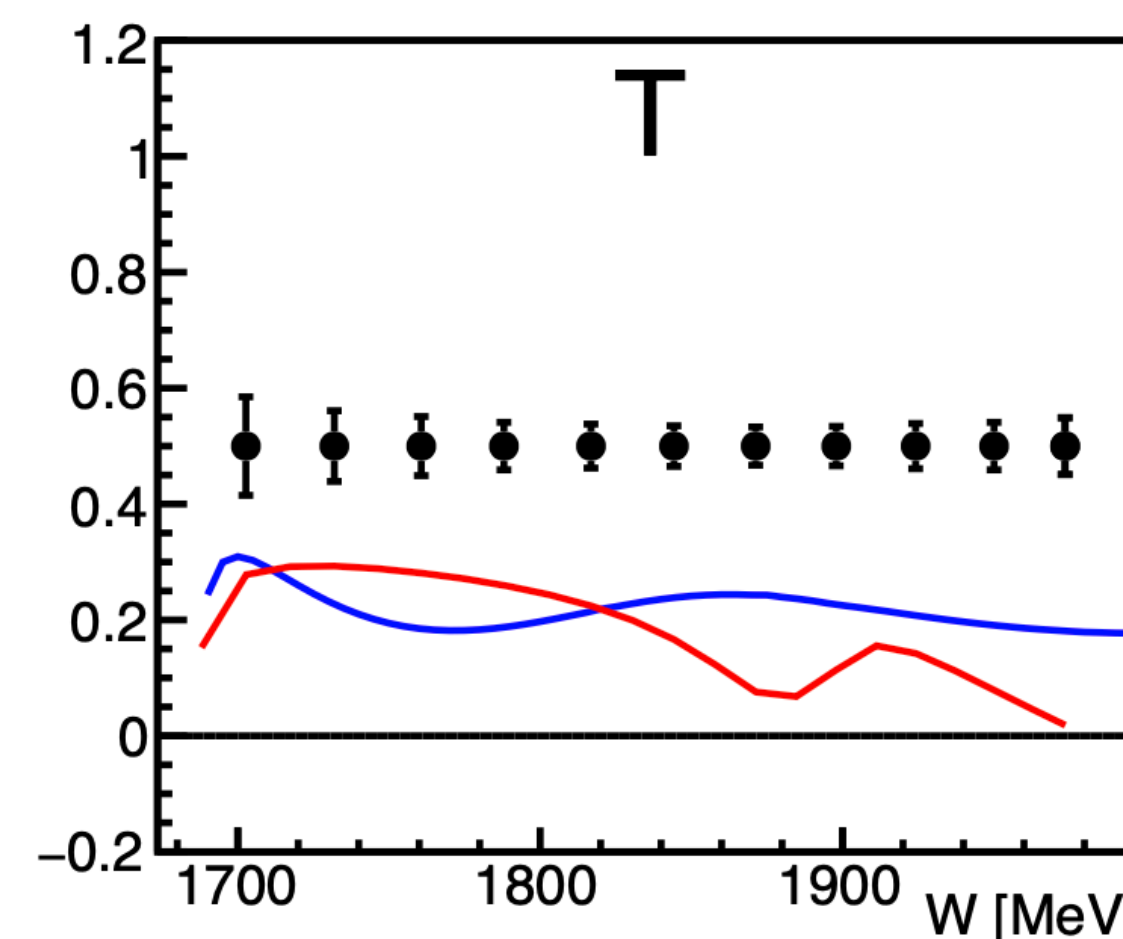
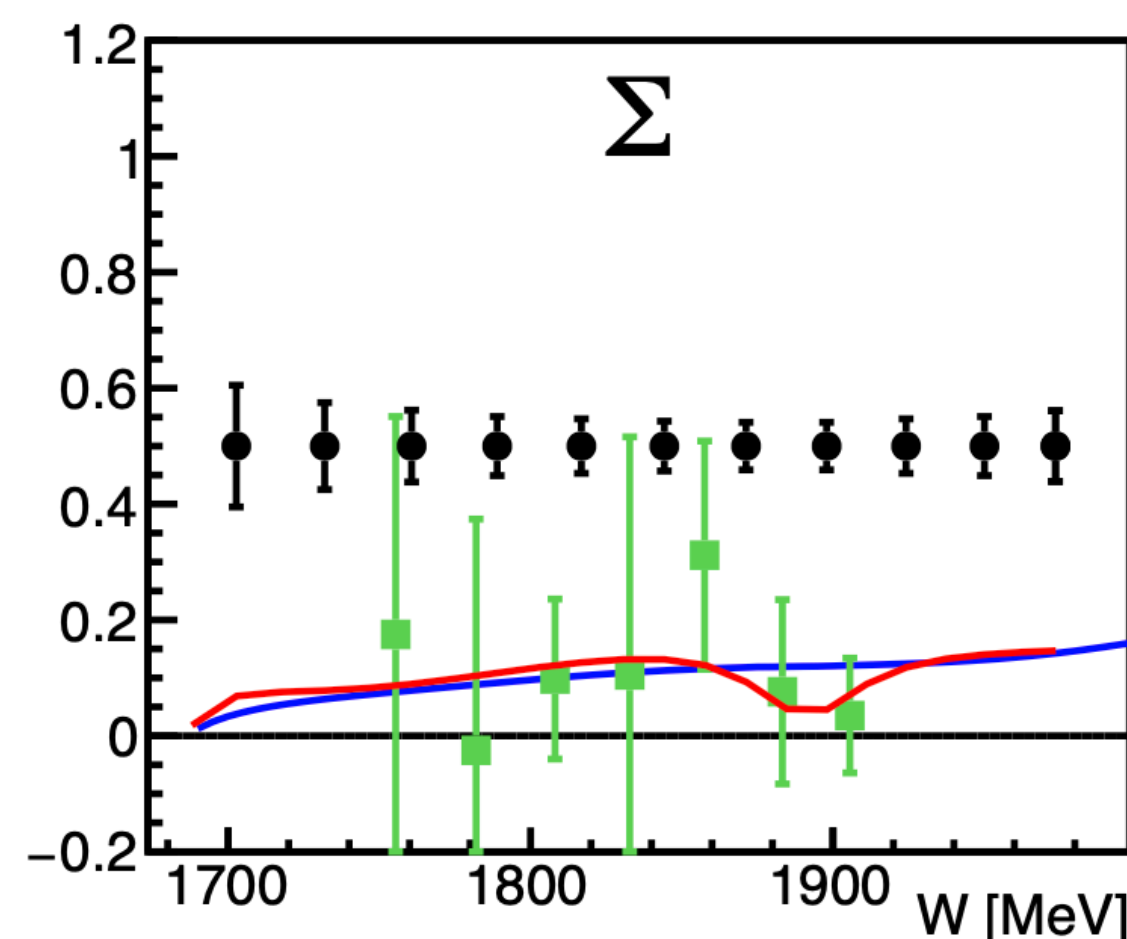
With $N^*(1896)\frac{3}{2}^-$,

$\Gamma = 36 \text{ MeV}$

Black circles - INSIGHT
precision over 2 years

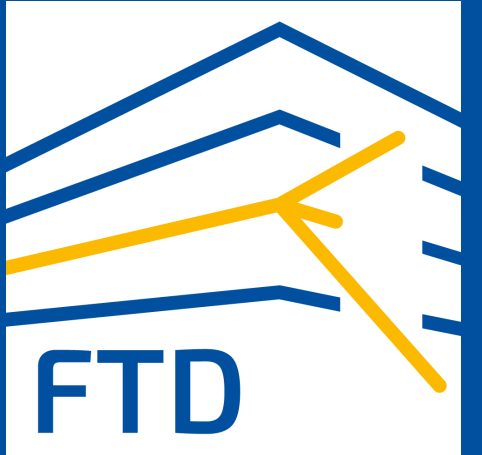
GRAAL

A. Lleres et al, EPJA 31 (2007)



Overview

UNIVERSITÄT **BONN**



- **Motivation**
- **The BGOOD experiment at ELSA, Bonn**
- **Exotic structure in associated strangeness photoproduction**
- **Coherent photoproduction off the deuteron**



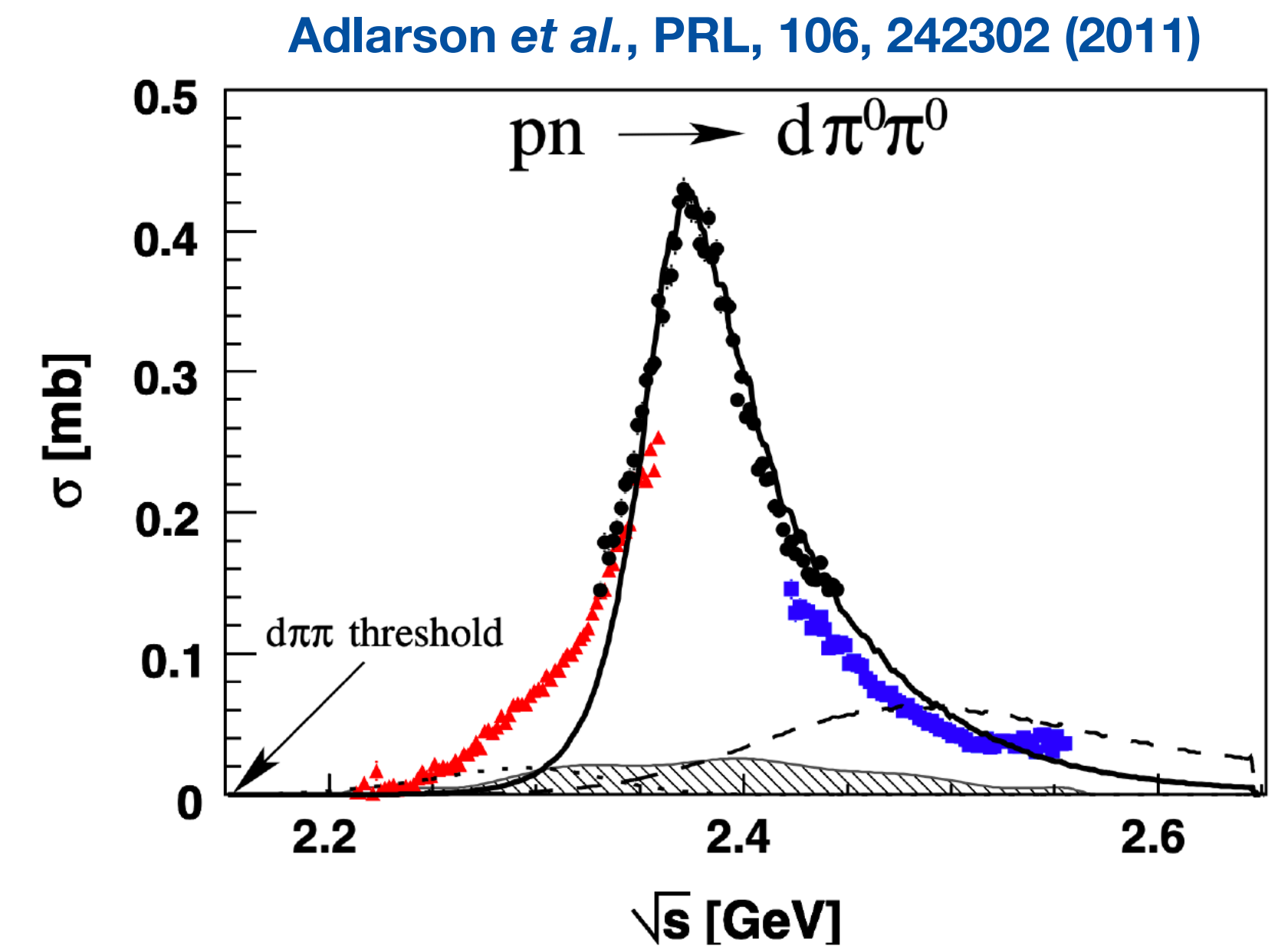
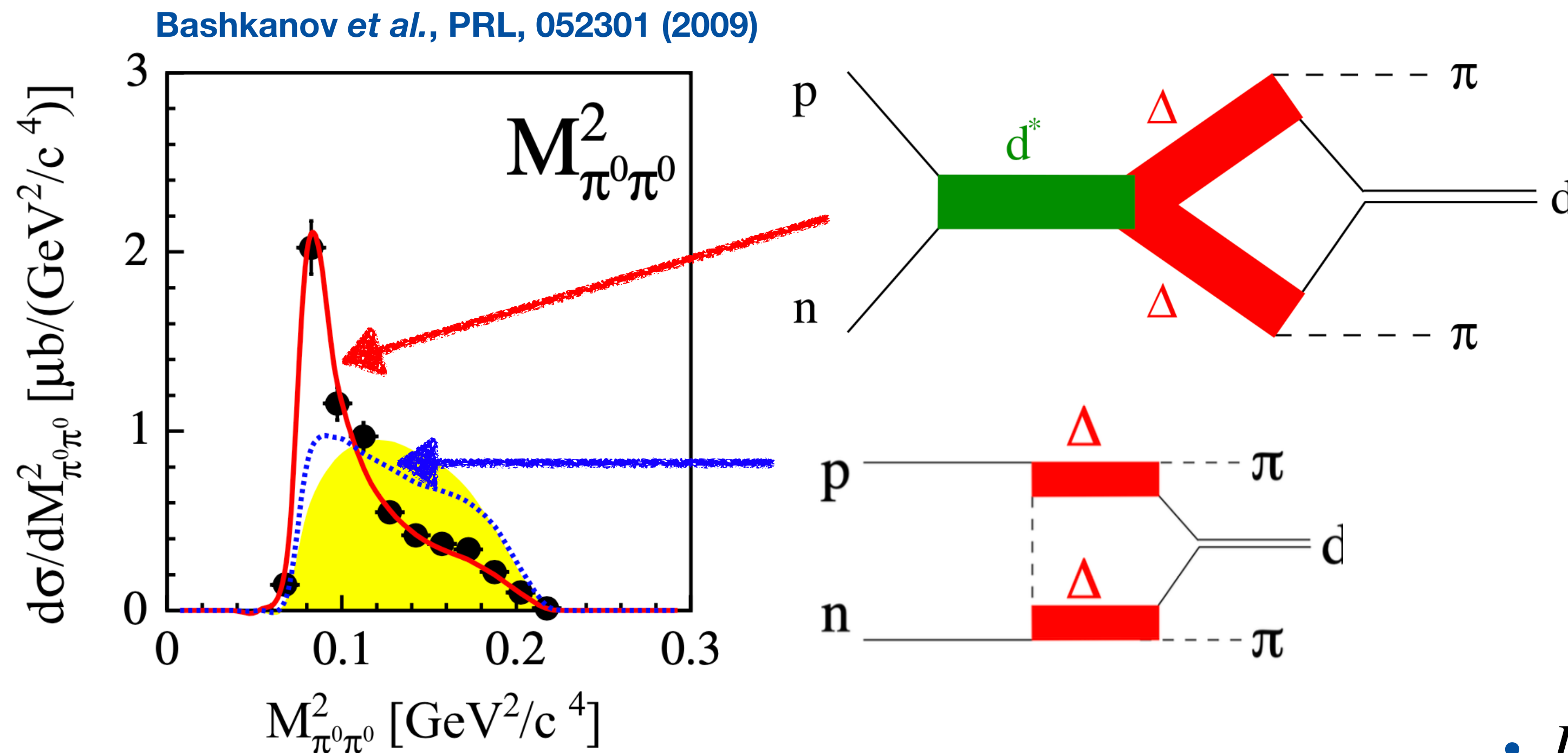
Tom Jude, 8th September 2026



Motivation - the $d^*(2380)$ dibaryon

- Low mass enhancement in $\pi\pi$ invariant mass - seen in the 1960s - ($d + p \rightarrow {}^3\text{He} + 2\pi$)
- Described via intermediate $d^*(2380)$ in CELSIUS-WASA data:

Booth, Abashian & Crowe,
PRL, 7 (1961) 35



- $IJ^P = 03^+$, observed in multiple final states

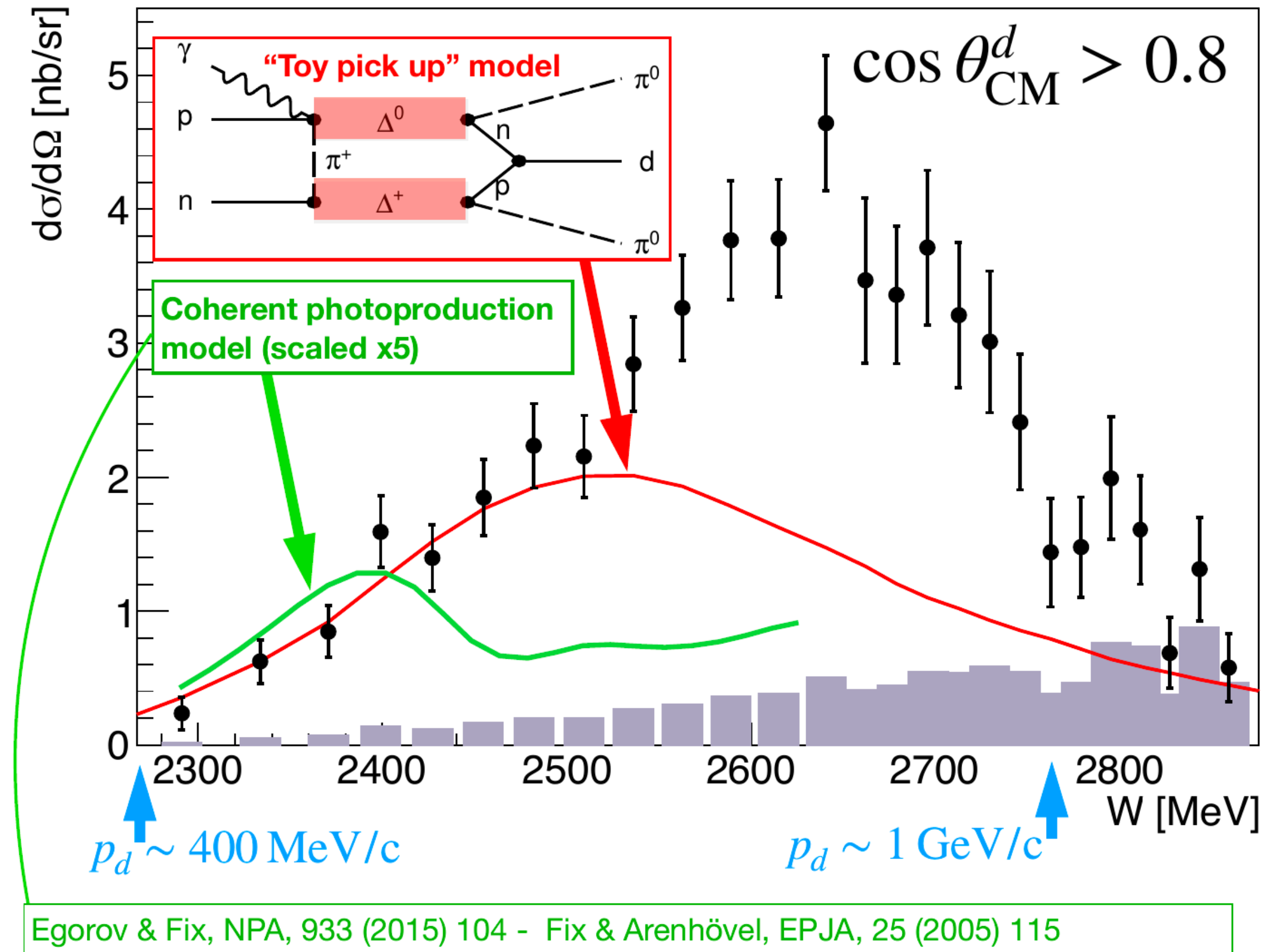
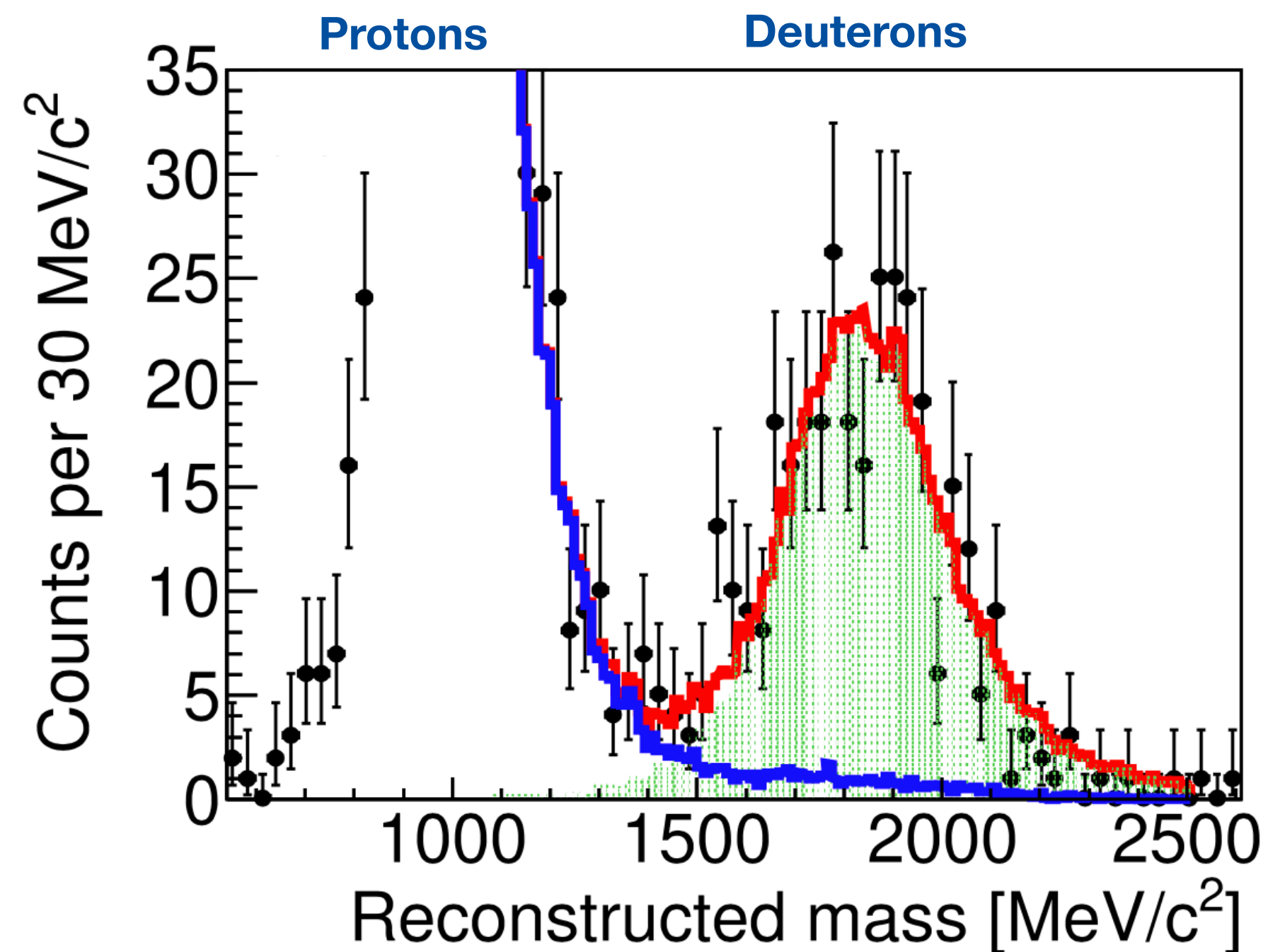
- Alternative descriptions via π exchange & triangle type mechanisms [R. Molina et al 2023 Chinese Phys. C 47 041001](#)

$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD

T.C. Jude *et al.*, PLB 832 (2022) 137277



- Deuterons identified in the Forward Spectrometer
- Unexpected! $p_d > 400$ MeV/c (Fermi momentum ~ 80 MeV/c)



- Differential cross section not described by coherent photoproduction model or "Toy pick up model"

$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD

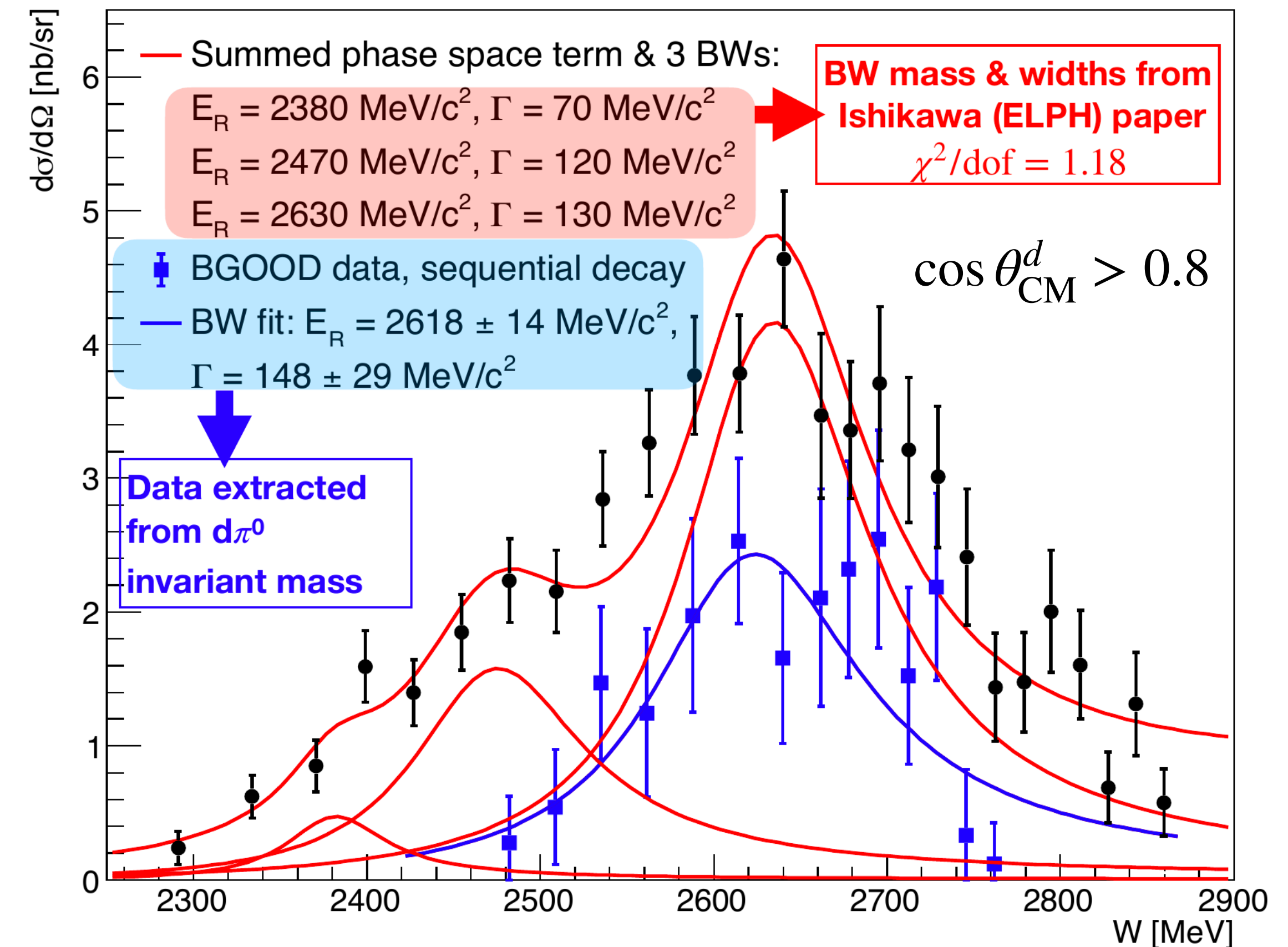
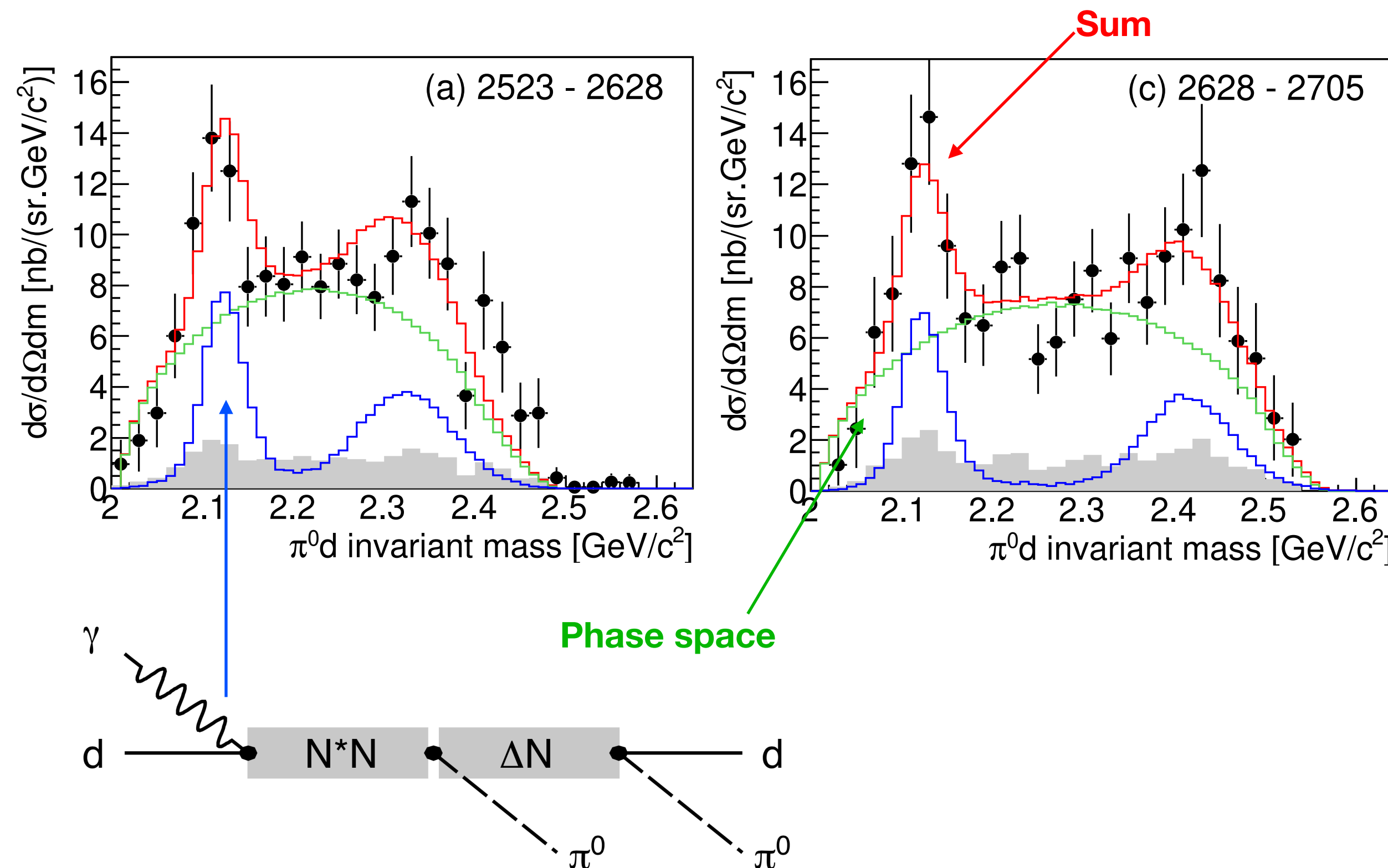
T.C. Jude *et al.*, PLB 832 (2022) 137277



- Propose sequential decay for πd invariant mass distributions
- Fit yields “dibaryon” mass 2114 MeV/c², width ~ 20 MeV/c² (exp resolution)

- Distribution consistent with 3 isoscalar & 1 isovector dibaryon (but not conclusive)

Dyson & Xuong PRL 13 (1964) 815 - Dibaryon sextet



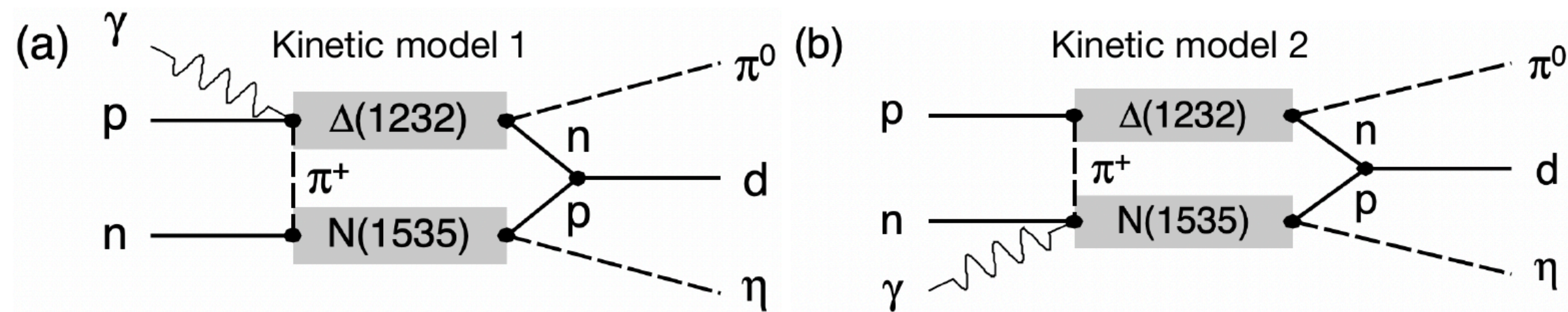
ELPH paper: Ishikawa *et al.*, PLB 789 (2019) 413

$\gamma d \rightarrow \pi^0 \eta d$ at BGOOD

A.J. Clara Figueiredo, T.C. Jude, *et al.*
arXiv:2405.09392 (2024). Submitted to PLB



- Distribution described by toy model of π rescattering:



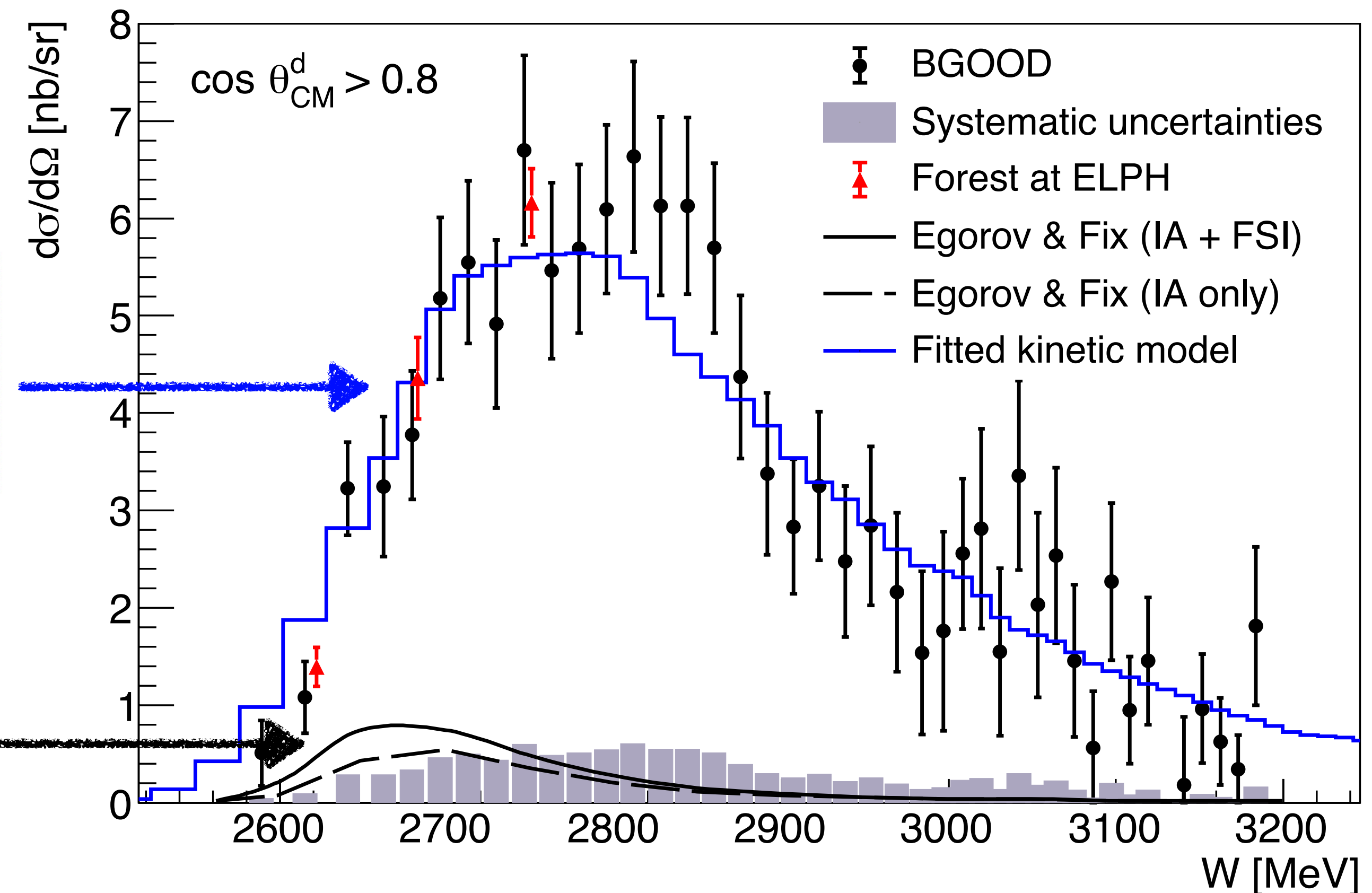
- Quantitative models including final states interactions however an order of magnitude smaller

M. Egorov & A. Fix, PRC 88 (2013) 5, 054611,
A. Fix (Private comm.) 2024

- Also - $\pi^0 \pi^0 \pi^0 d$ & $\pi^+ \pi^- d$

Preliminary - R. Volk, Masters thesis, Uni Bonn (2024)

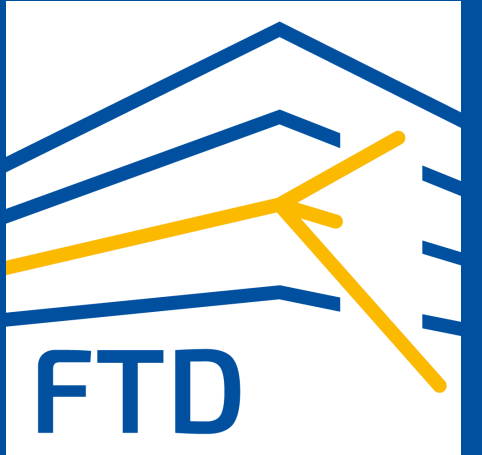
Preliminary - K. Kohl



Forest at ELPH: Ishikawa et al., PRC 105, 045201 (2022)

Summary

UNIVERSITÄT **BONN**



- **BGOOD** - photoproduction at low t
- **Equivalent structure to P_C states?**
 - $K^+\Sigma^0, K^+\Sigma^-, K^+\Lambda(1405), K^0\Sigma^0$
- **Coherent photoproduction off the deuteron**
 - **Intermediate dibaryons?**
 - **π rescattering mechanisms?**
- **INSIGHT - the future at ELSA**

Ulrike Thoma, Parallel session C, Thursday 15:00

Tom Jude, 8th September 2026

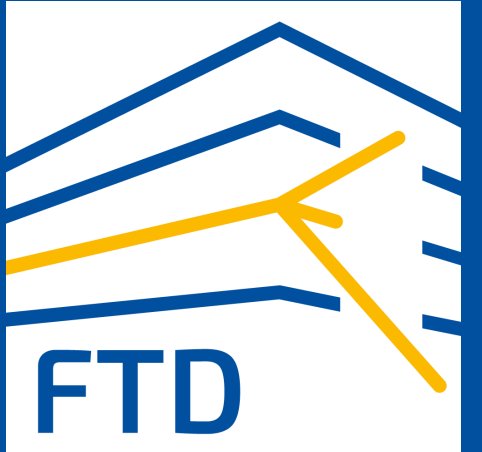


Review: T.C. Jude,
Prog. Part. Nucl. Phys. 147 (2026) 104224



Extra slides

UNIVERSITÄT **BONN**

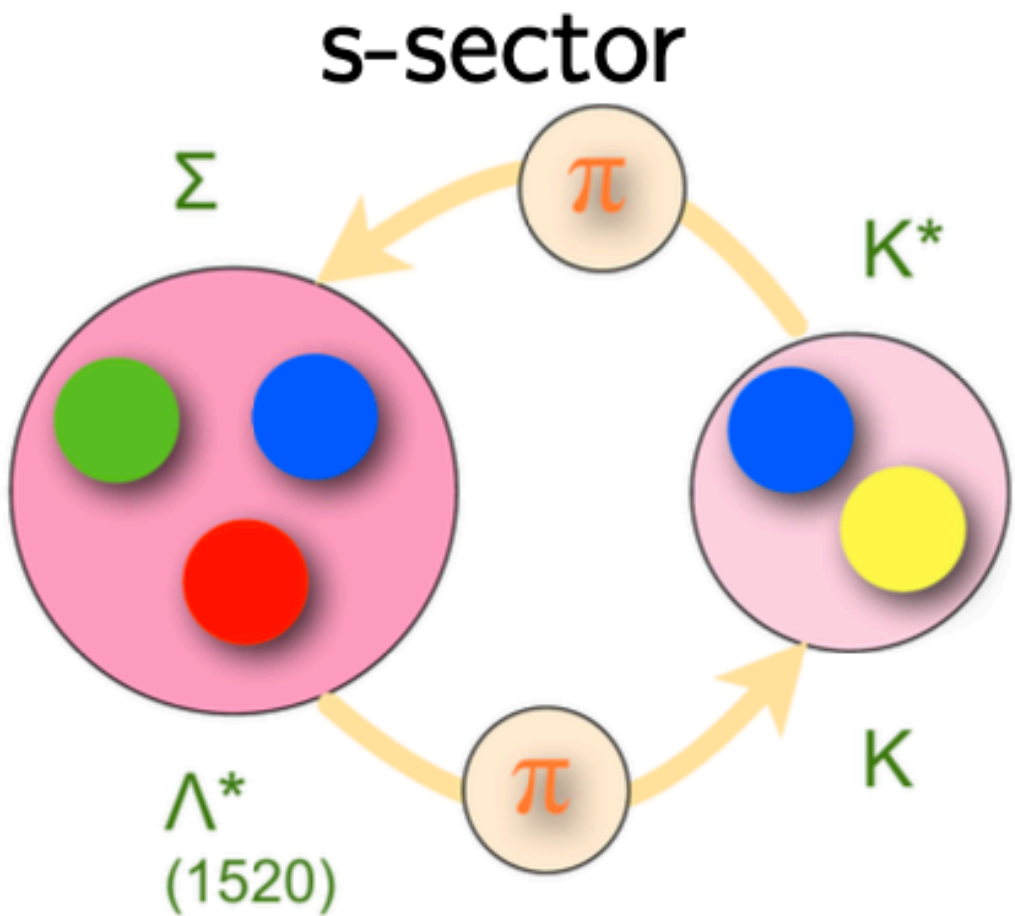
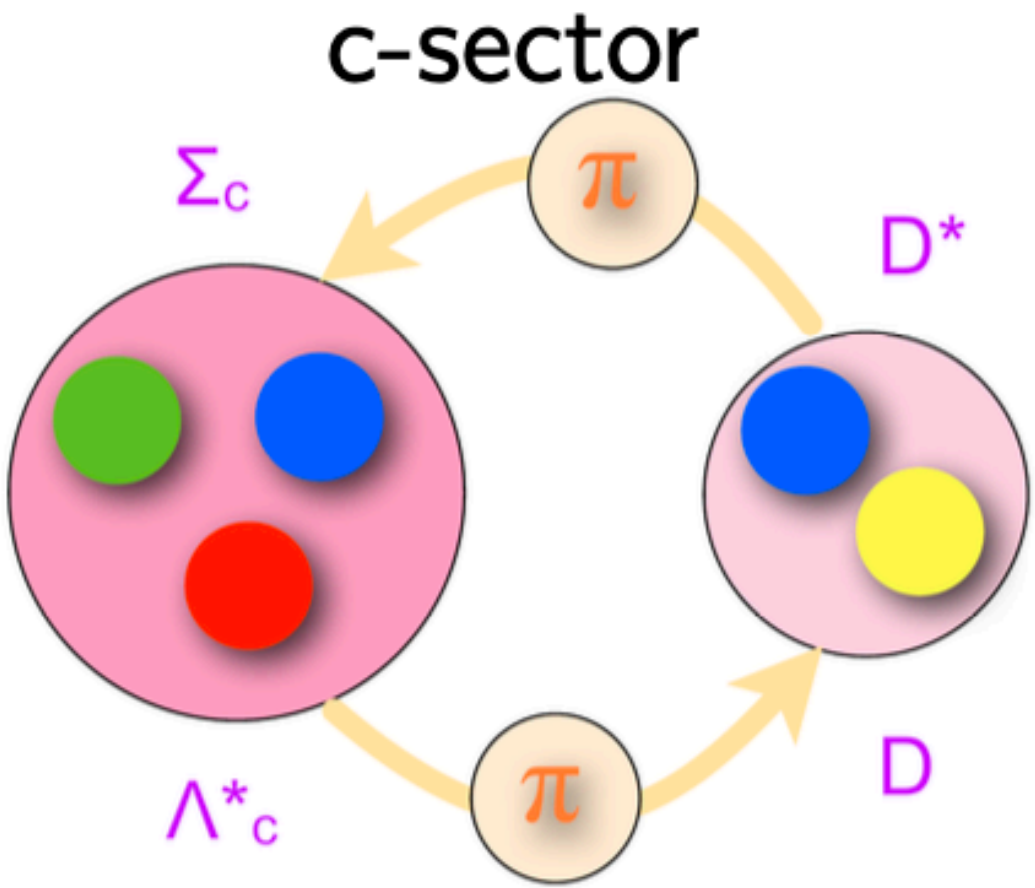


Tom Jude, 8th September 2026

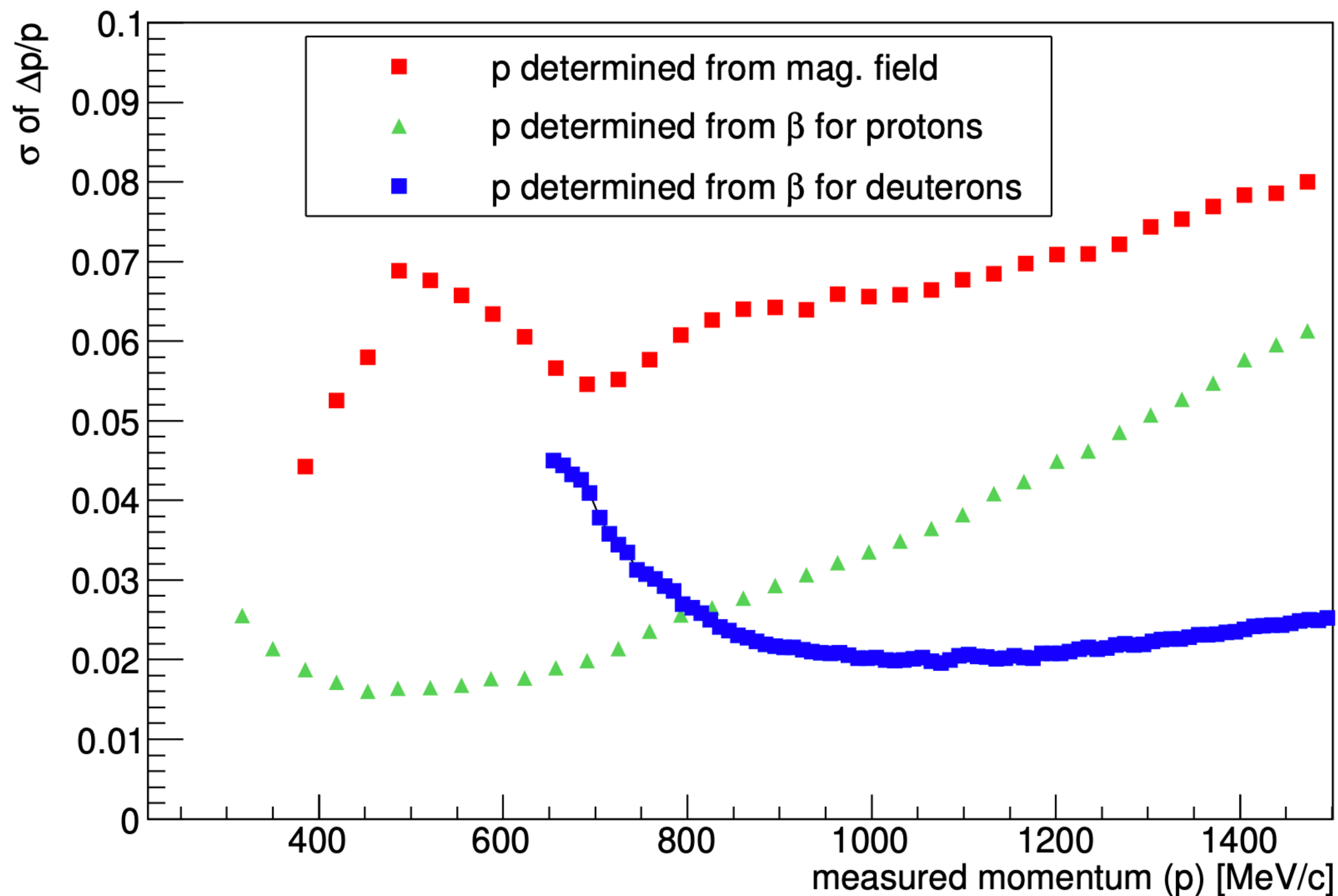


Parallels between the charm & light sectors?

	Charmed-sector		Strange-sector	
	Meson	Baryons	Meson	Baryons
State(s)	$X(3872)$	$P_c^*(4380/4457)$	$f_1(1285)$	$N^*(2030/2080)$
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 numbers	$J^{PC} = 1^{++}$	$J^P = 3/2^-$	$J^{PC} = 1^{++}$	$J^P = 3/2^-$
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 thresh.	$J/\psi\omega$	$\chi_{c1}p$	$\phi f_0(500)$	ϕp



Forward spectrometer momentum resolution

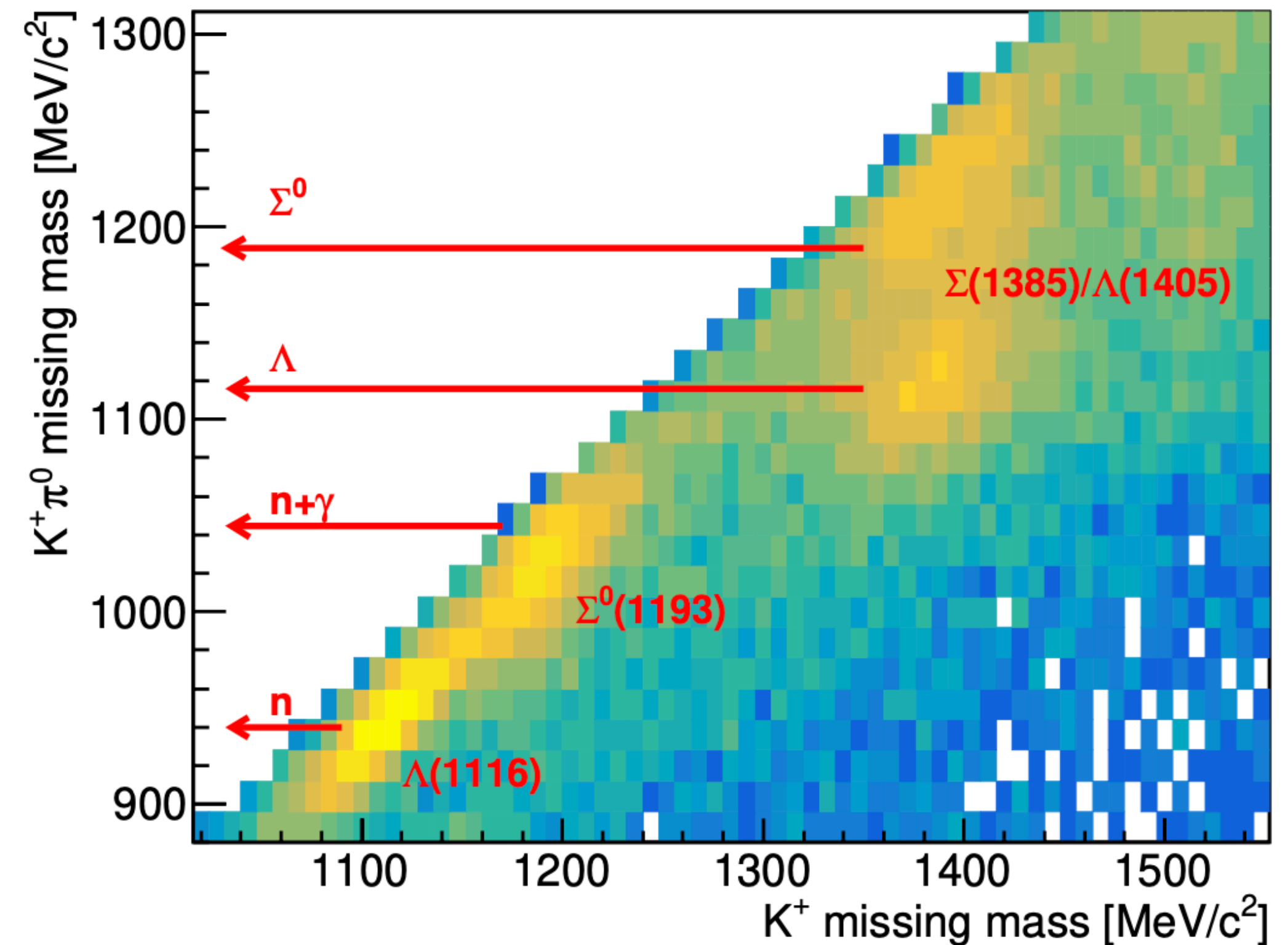
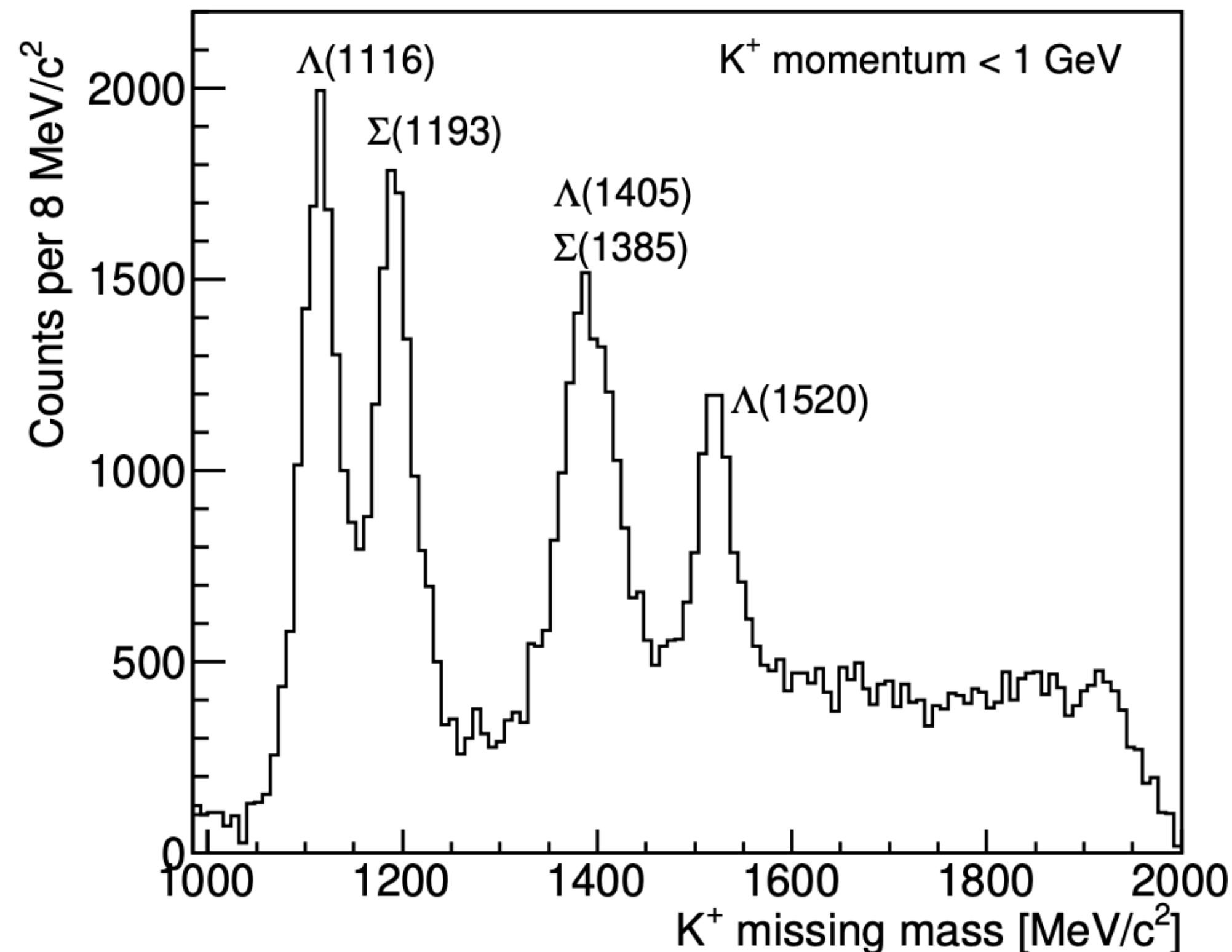


Identification of open strangeness final states

- K^+ identified in the forward spectrometer, $\cos \theta_{CM}^K > 0.9$
- The study of Y^* in an extremely low momentum transfer region

“Missing Mass”

$$P_{\text{Beam}} + P_{\text{Target}} = P_{K^+} + P_X$$



Identification of open strangeness final states

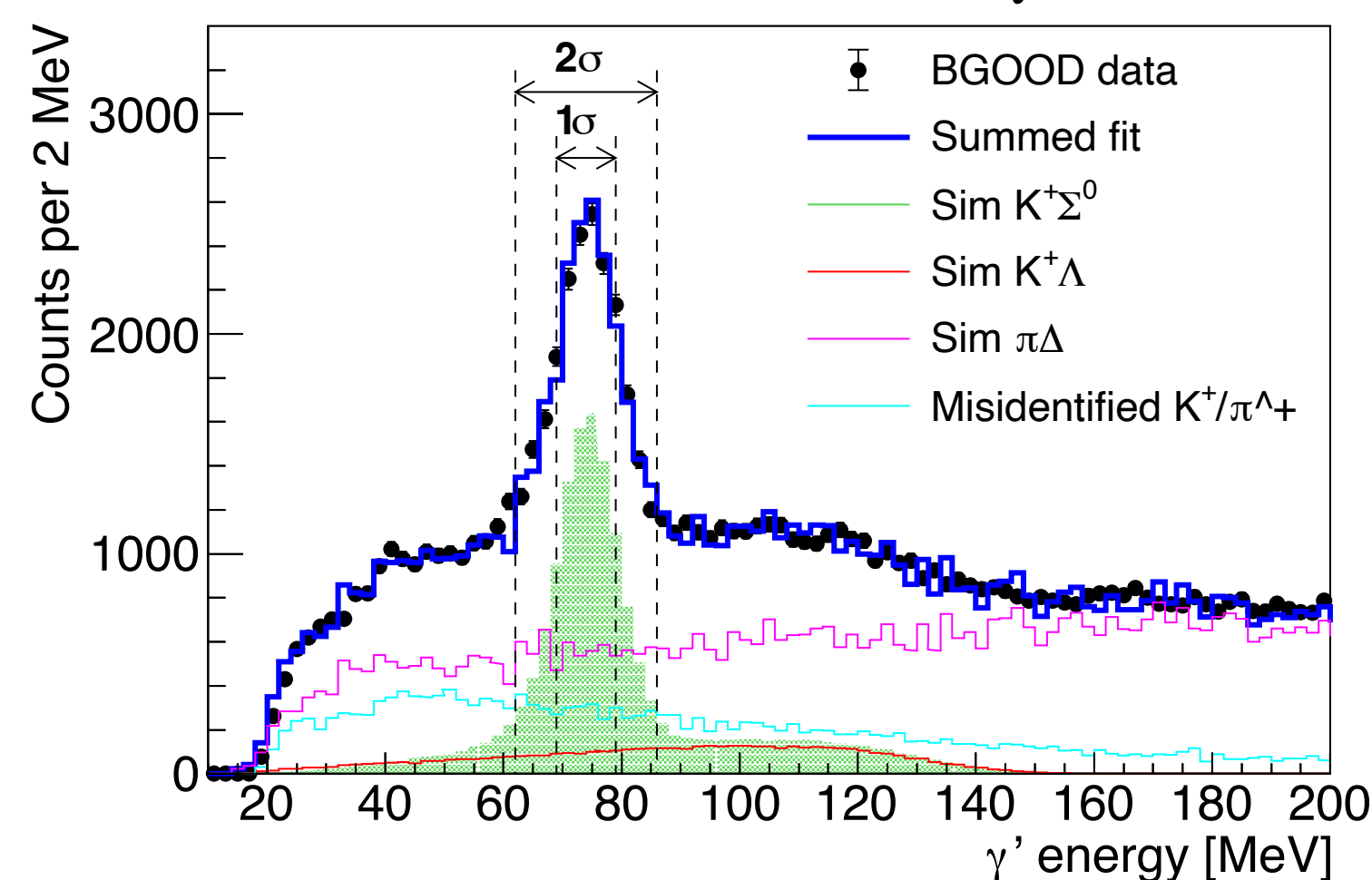
Examples of signal / background separation

E. Rosanowski, T.C Jude *et al.*
Eur. Phys. J. A (2025) 61:147

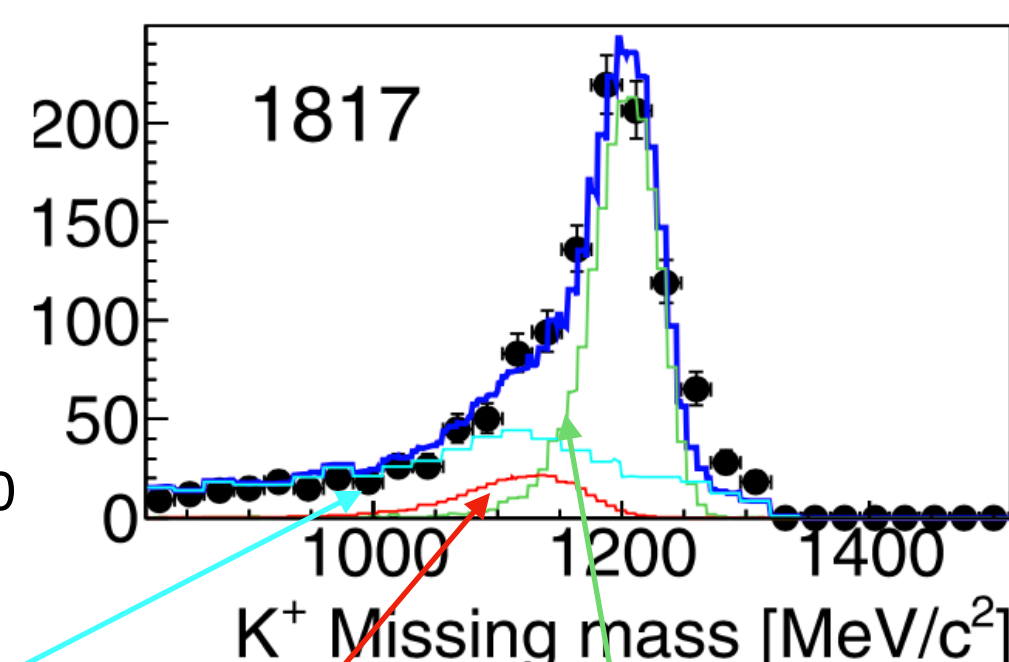
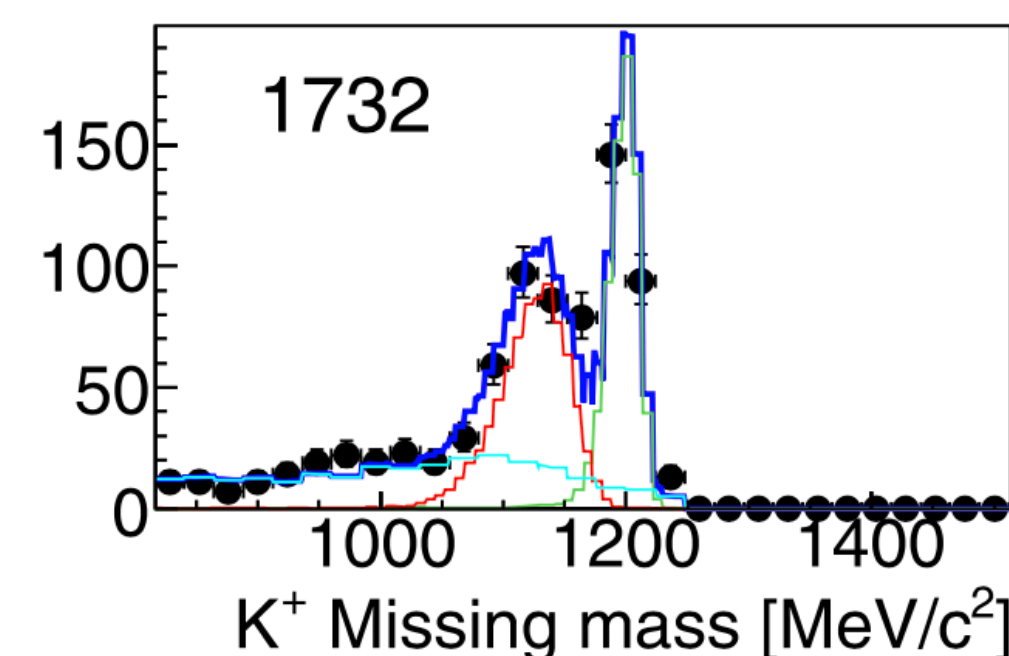
$$\gamma p \rightarrow K^+ \Sigma^0$$

T.C. Jude *et al.*,
Phys. Lett. B 820 (2021) 136559

$$\Lambda \leftarrow \Sigma^0 \rightarrow \gamma$$



e^+/π^+ modelled from real e^-/π^- signal



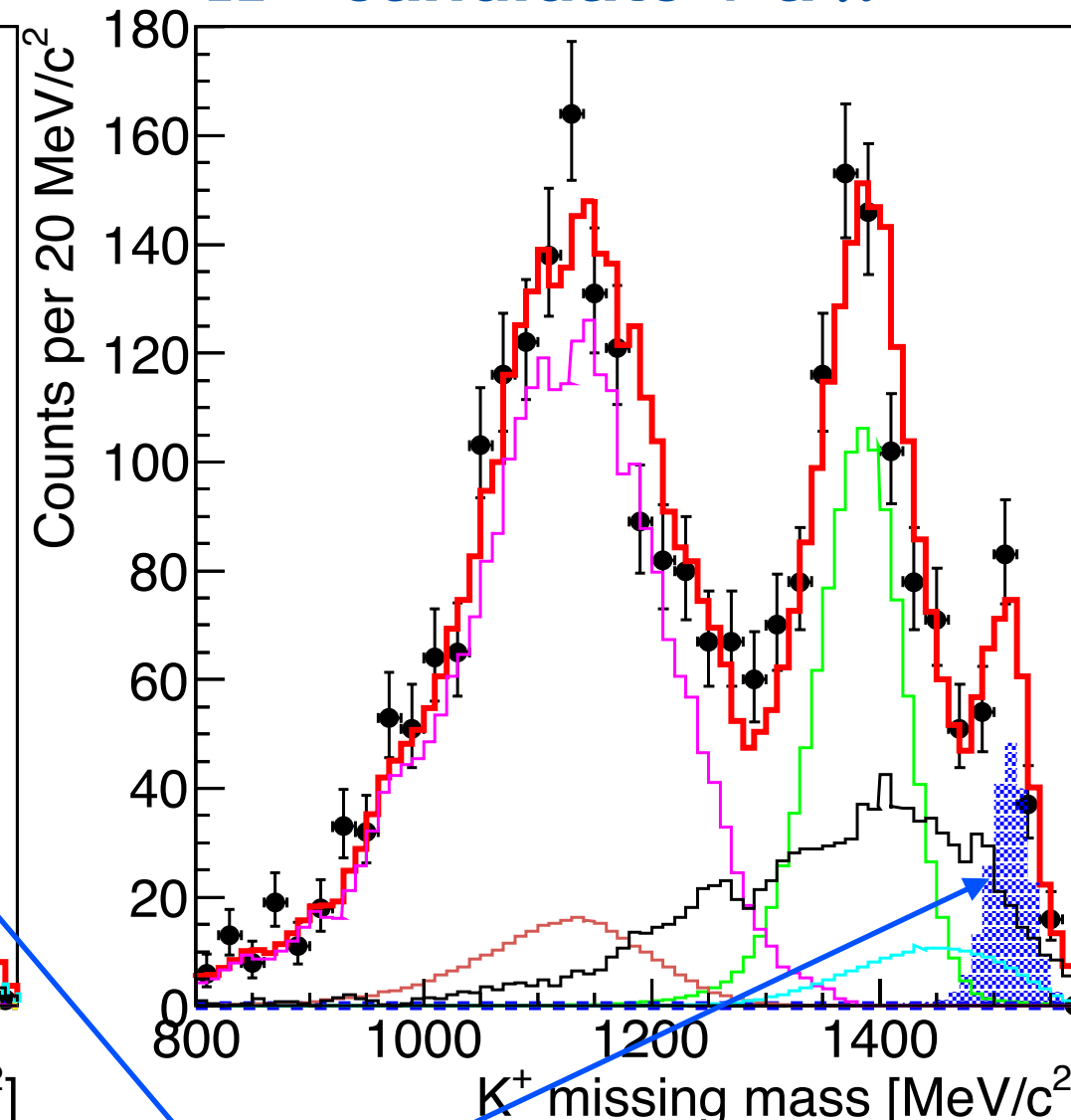
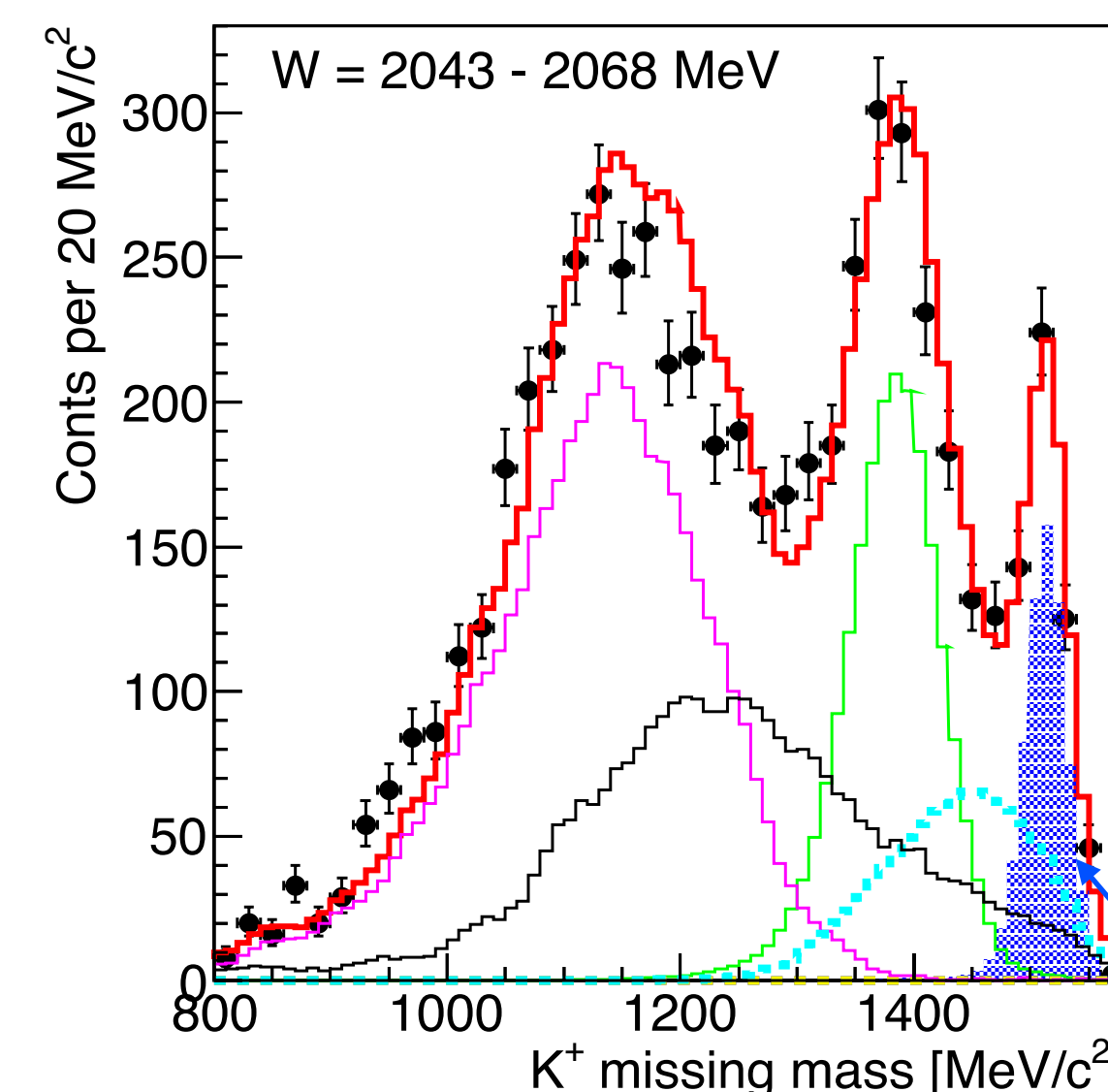
Sim $K^+ \Lambda$

Sim $K^+ \Sigma^0$

$$\gamma p \rightarrow K^+ \Lambda(1520)$$

Just a forward K^+ candidate

K^+ candidate + a π^0



— Total fit
— $K^+ \Lambda$
— $K^{*+} \Lambda$
— $\Delta^0 \pi^+$ background
— $K^+ \Lambda(1520)$
— $K^+ \Sigma^0(1385)$
— e^+/π^+ background

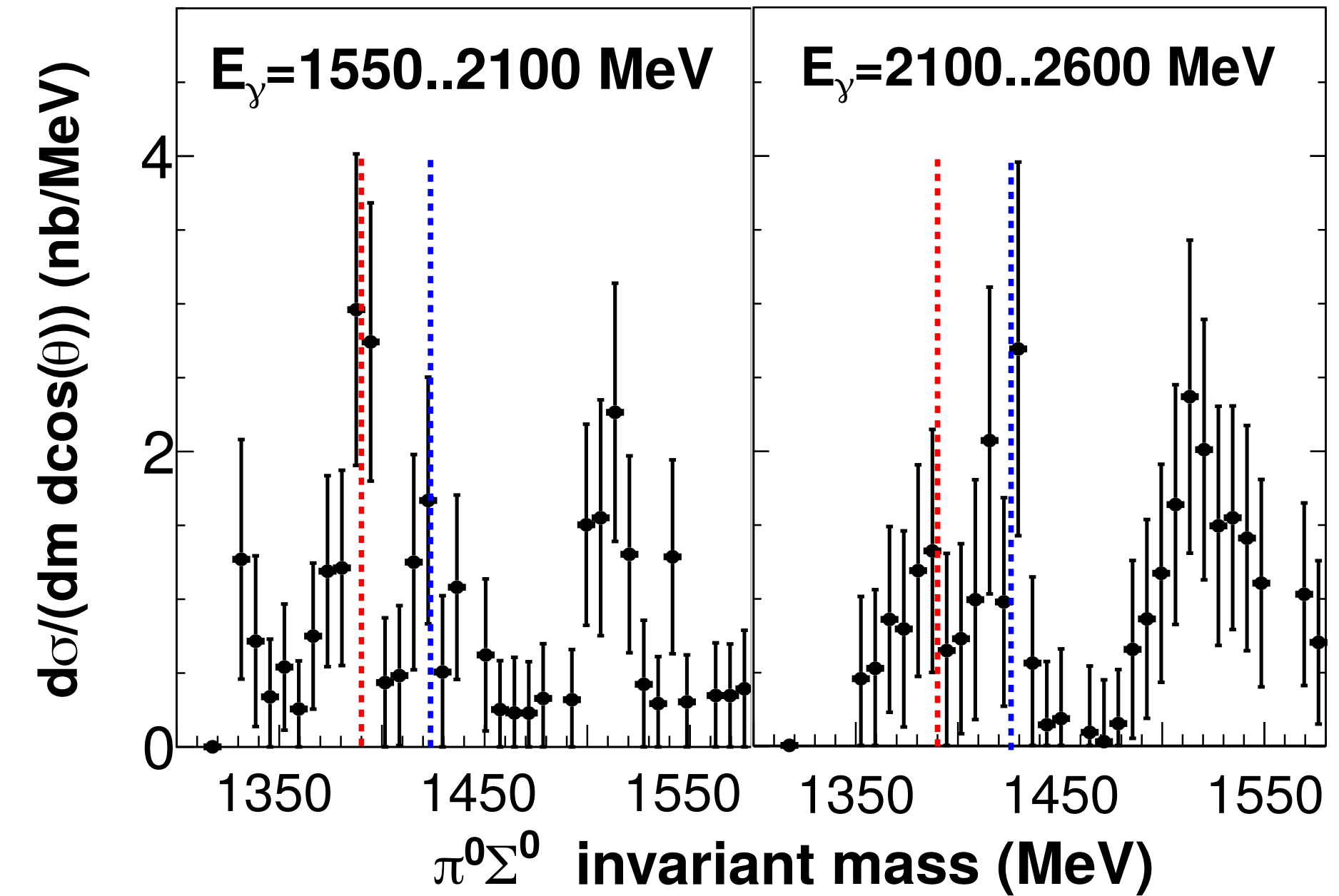
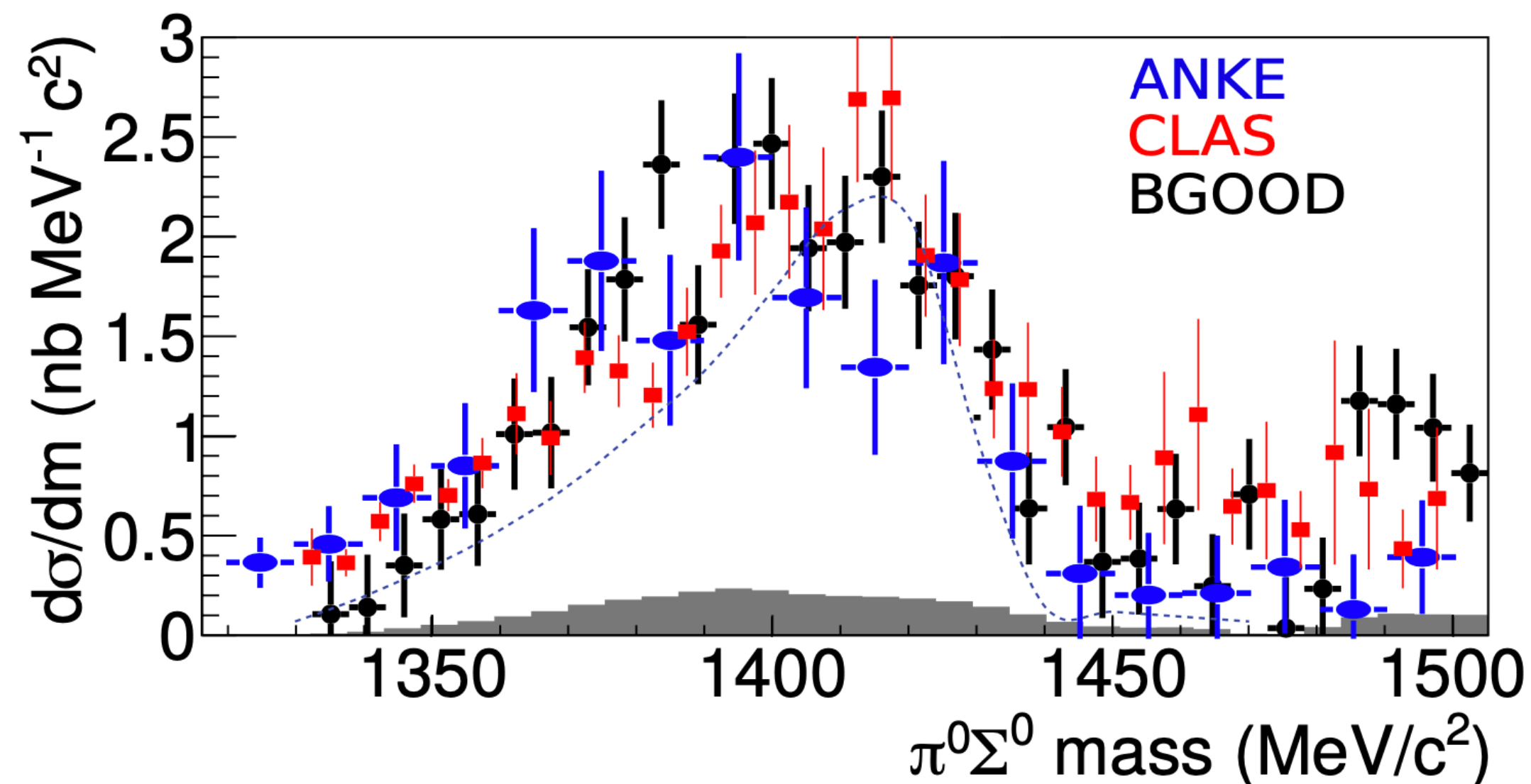
$\gamma p \rightarrow K^+ \Lambda(1405) \rightarrow K^+ (\Sigma^0 \pi^0)$

G. Scheluchin, T.C Jude *et al.*
PLB 833 (2022) 137375



$\Lambda(1405)$ line shape measurements

- 2 peak structure at 1395 & 1425 MeV/c²?
- Similar to proposed 2-pole structure
Oller & Meißner, PLB 500, 263 (2001)
- Integrated over all $\cos \theta_{\text{CM}}^K$:
- At forward K^+ angles: $\cos \theta_{\text{CM}}^K > 0.86$:



- Relative amplitudes of “poles” appear to vary
- Further data & analysis underway

A. J. Clara Figueiredo, PhD thesis (in preparation)

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

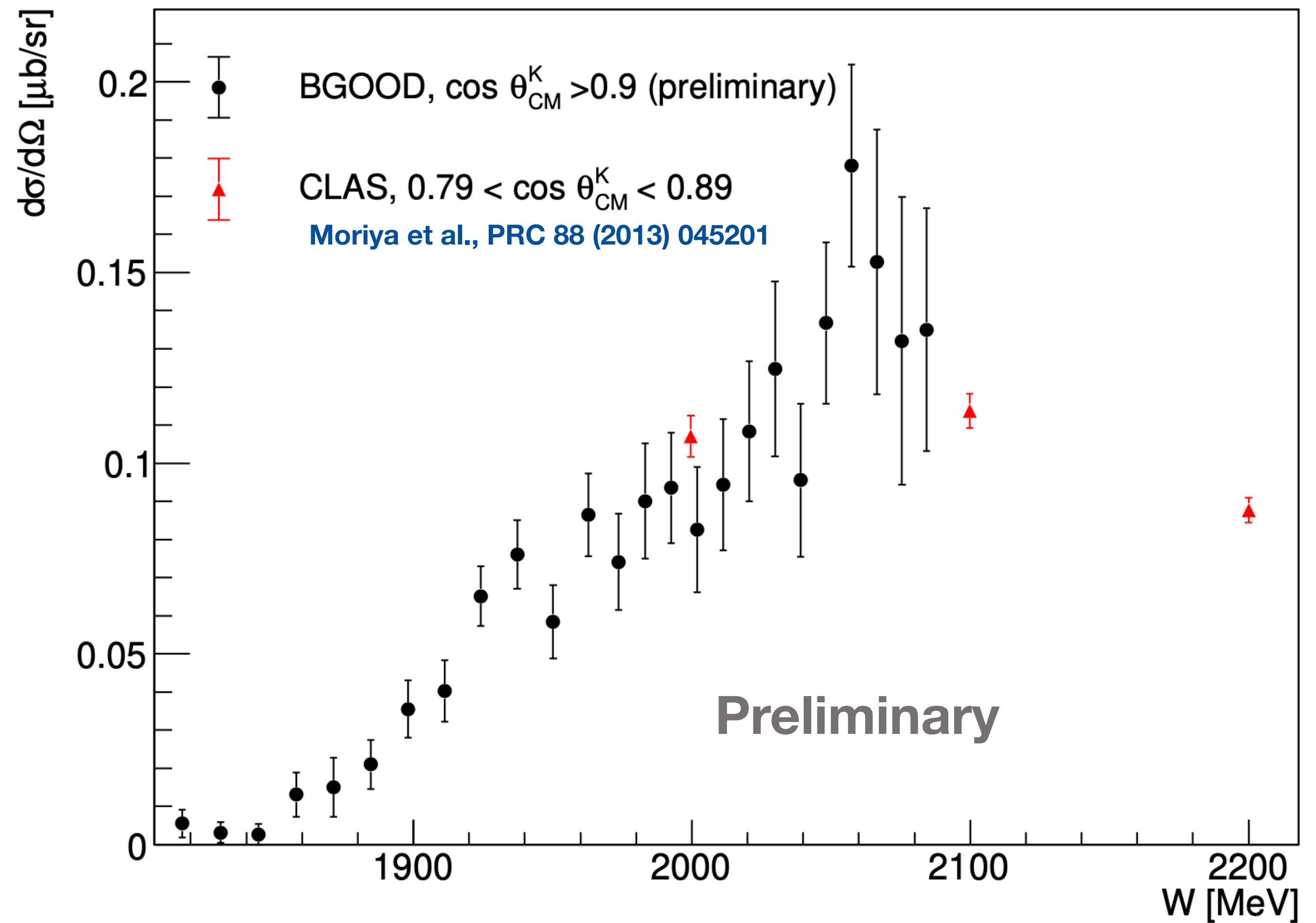
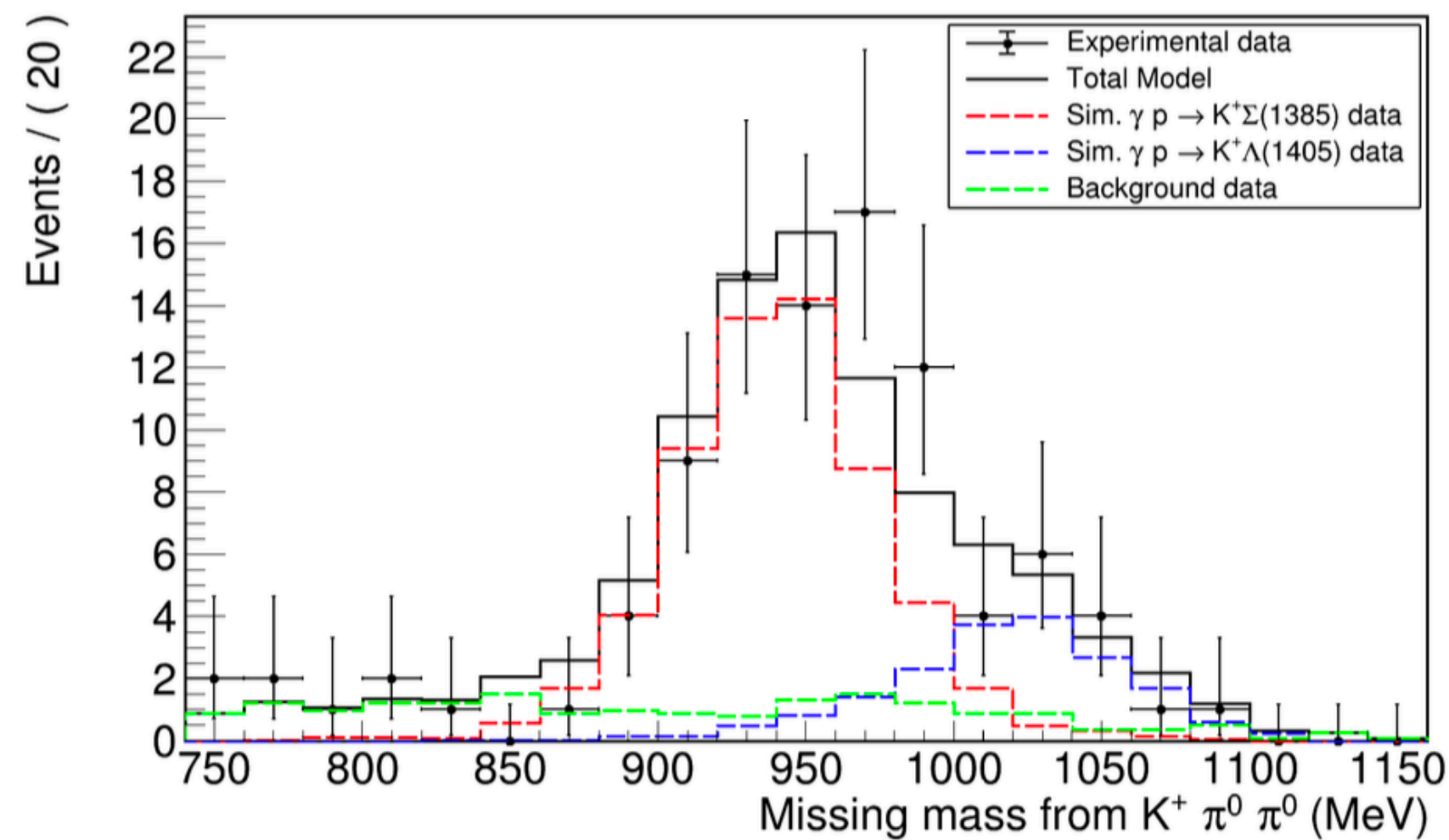
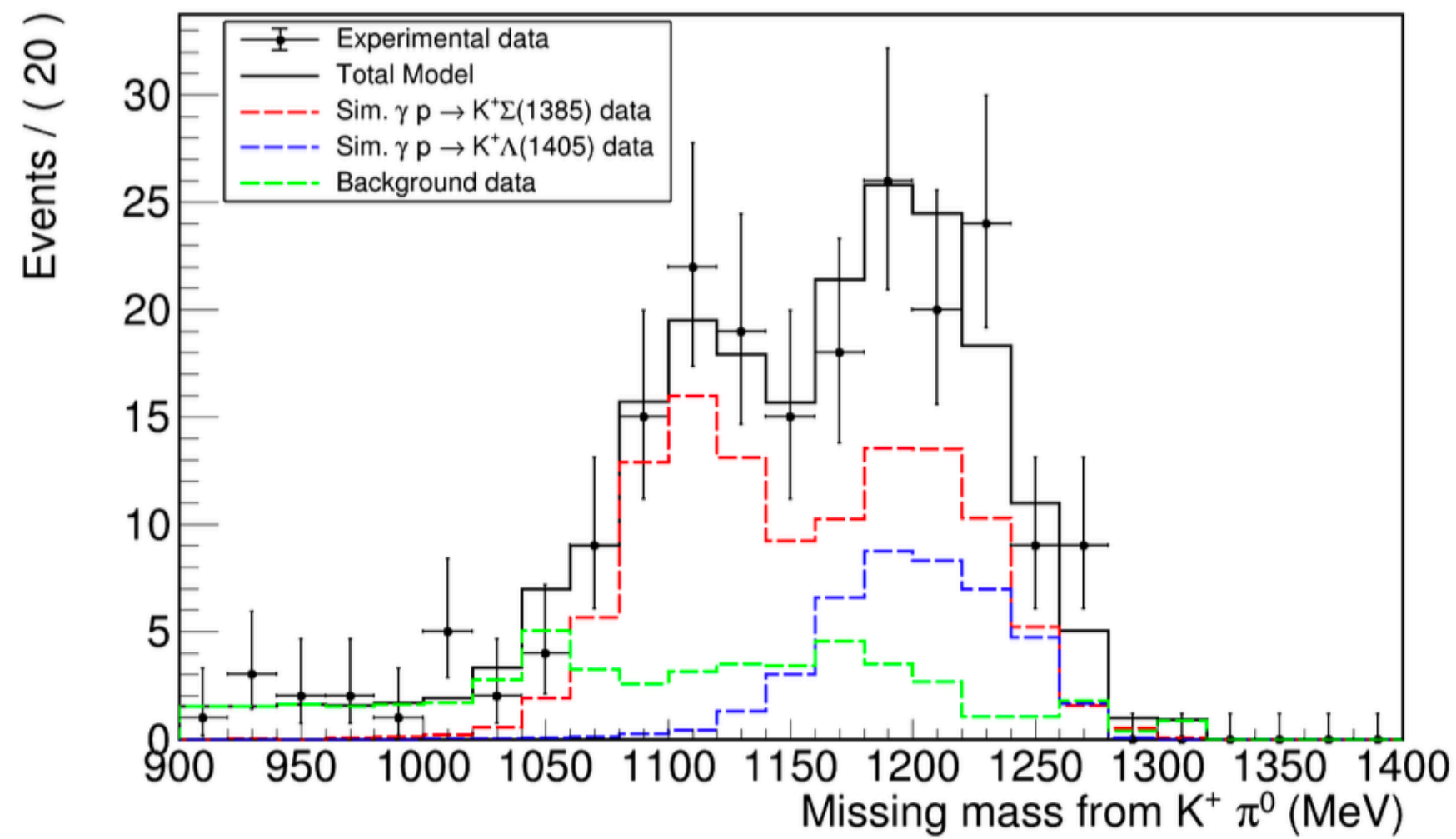
M. Jena, Masters thesis, Uni Bonn 2024

A. J. C. Figueiredo, PhD thesis (in preparation), Uni Bonn

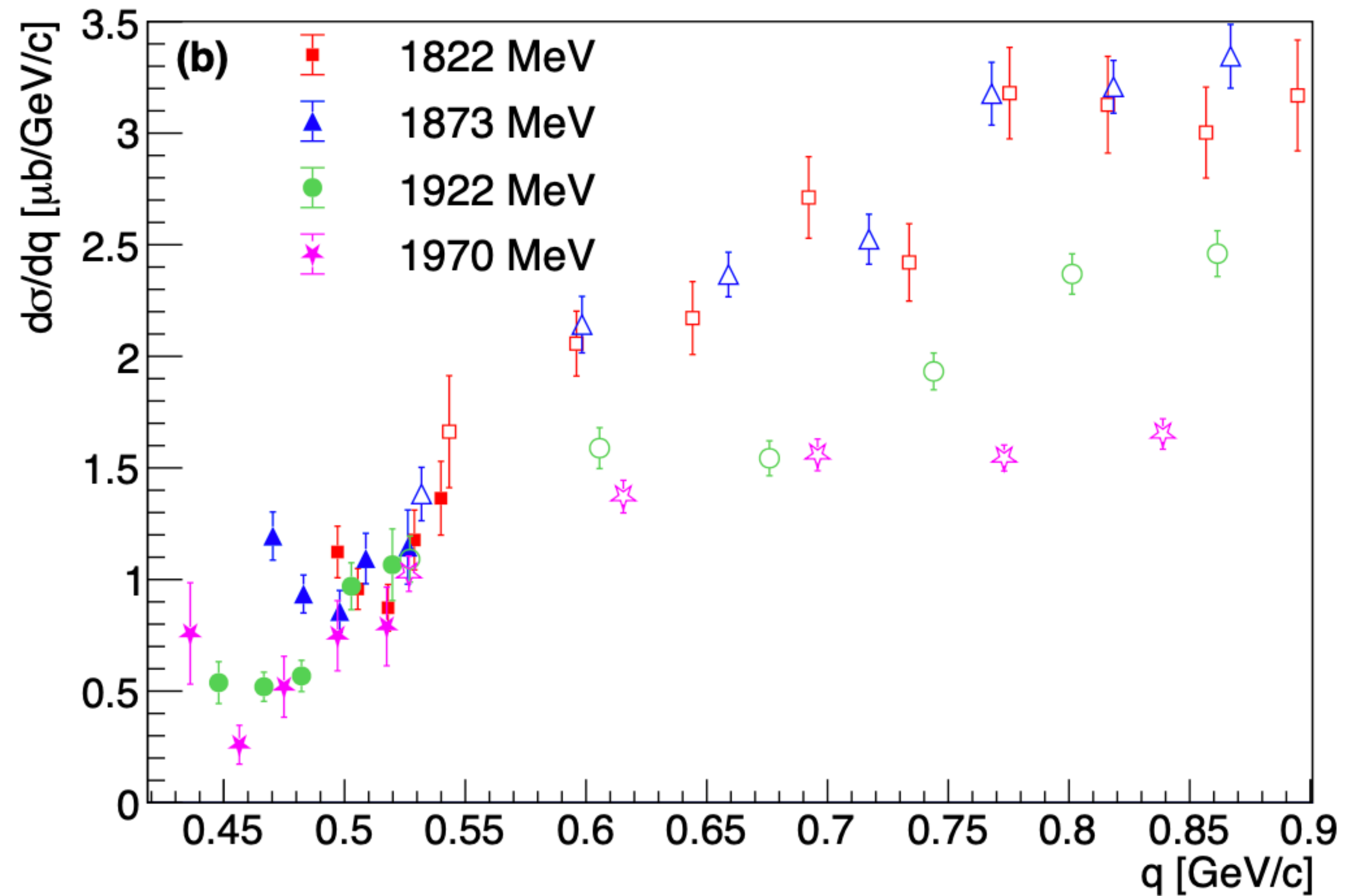
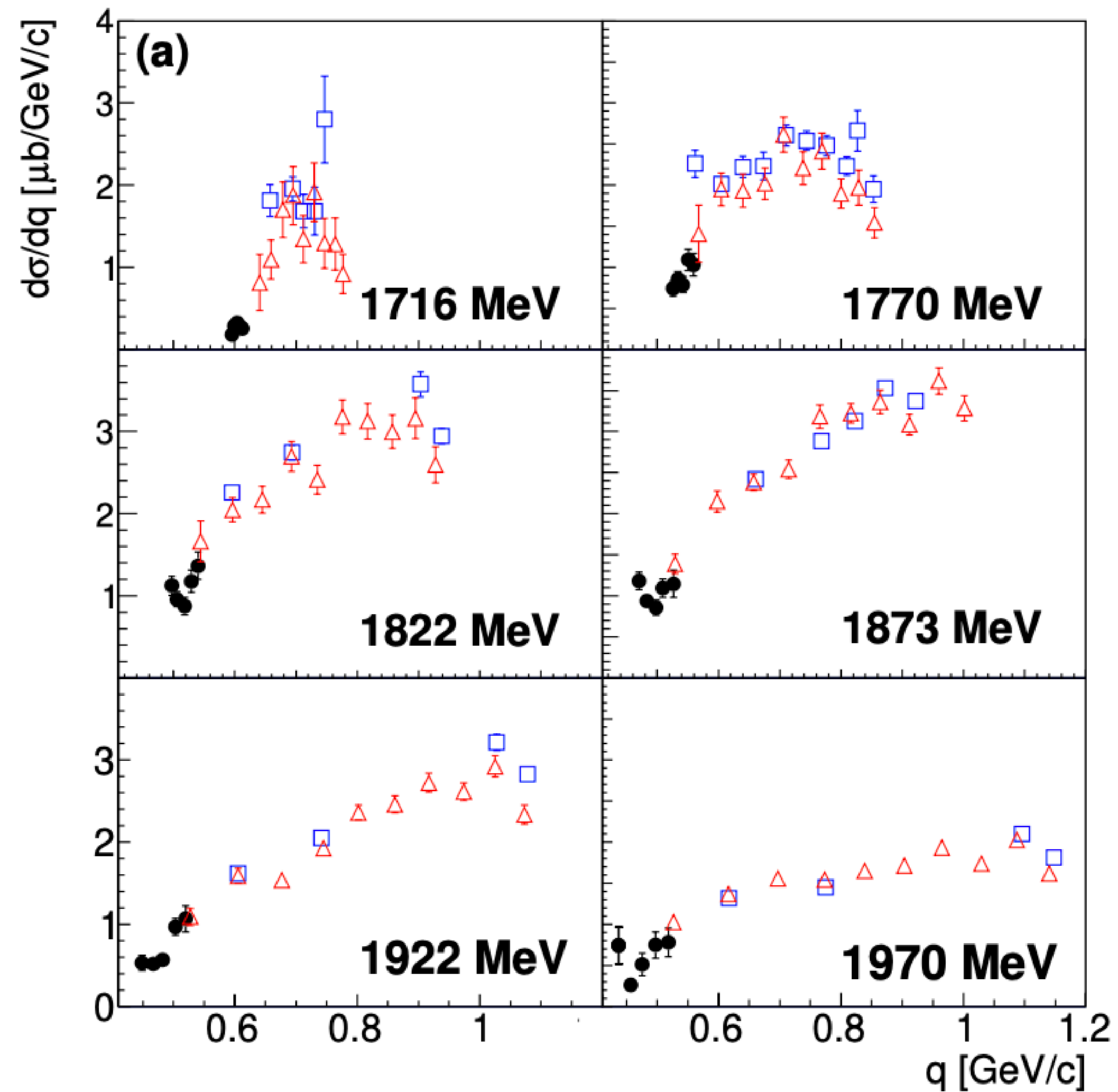


- Example separation of $\Sigma^0(1385)$ and $\Lambda(1405)$

- First data at threshold & forward angles



$K^+\Sigma^0$ - Additional slide



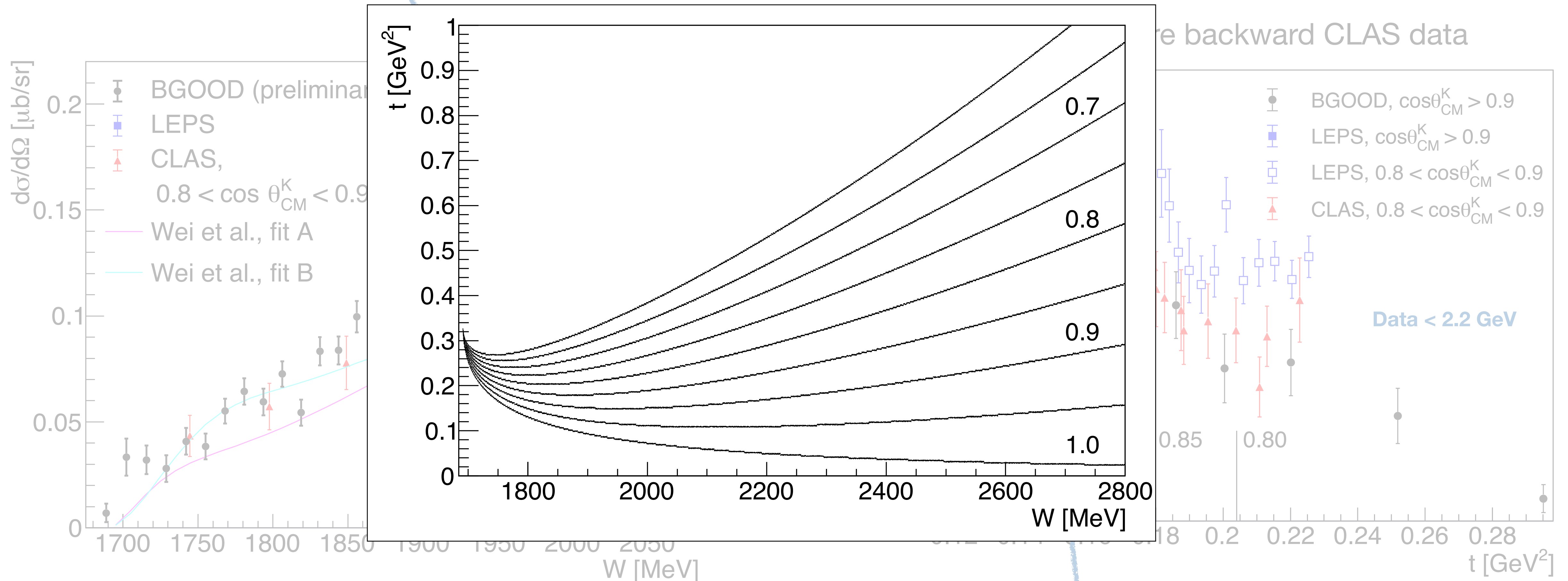
Forward $K^+\Sigma^-$ photoproduction

J. Gross, PhD thesis 2025



Structure close to K^+K^-p threshold?

- The same data differential with t



Wei, Wang & Huang, PRD 107, 114018 (2023) (& priv. comm.)

CLAS: Pereira et al., PLB 688 (2010) 289

LEPS: H. Kohri et al., PRL 97 (8 2006) 082003

- Low t (with structure evident) only accessible for $\cos\theta_{\text{CM}}^K > 0.9$

Forward $K^+\Sigma^-(1385)$

M. Ludwig, Masters thesis (in preparation)

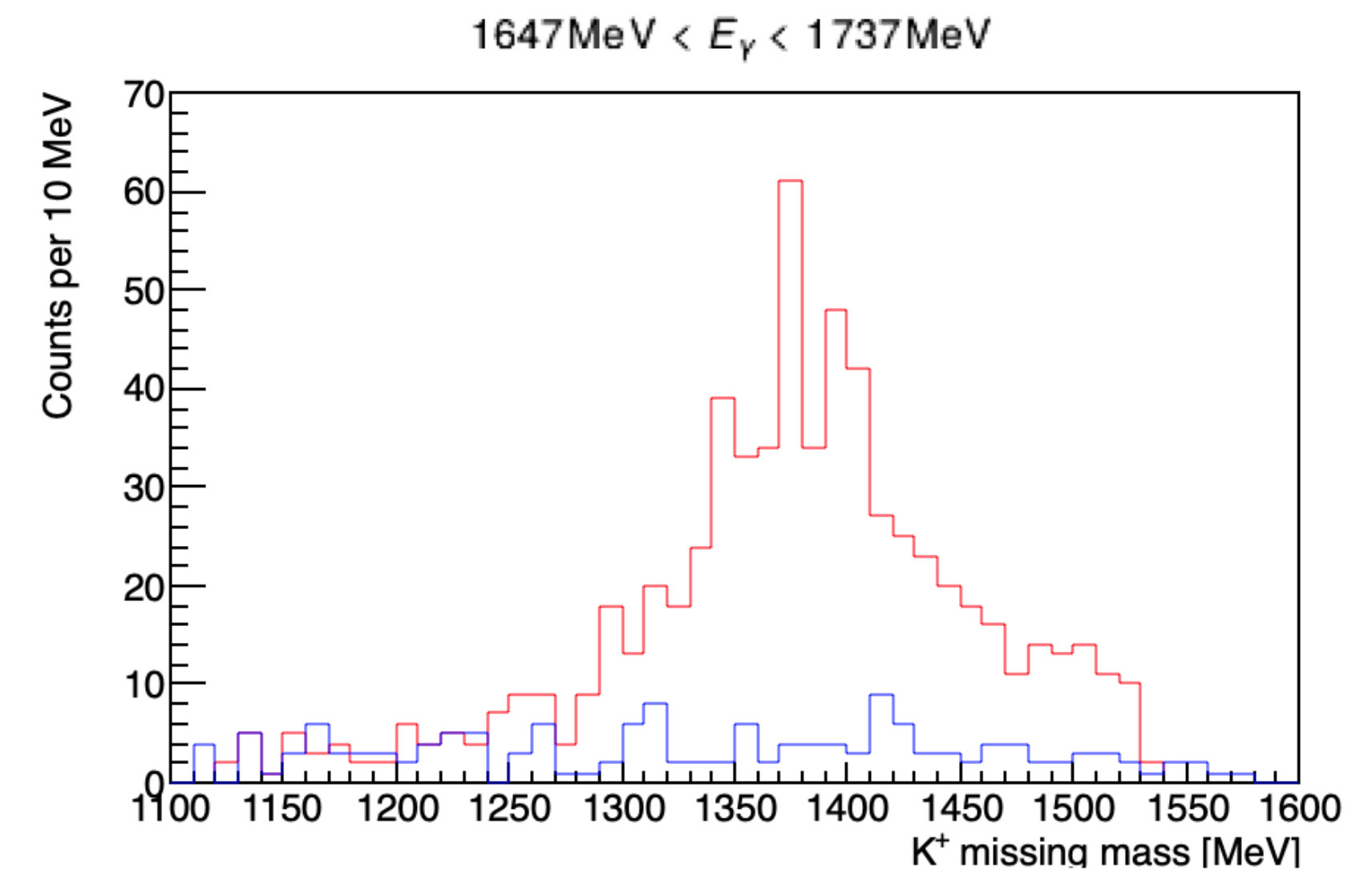
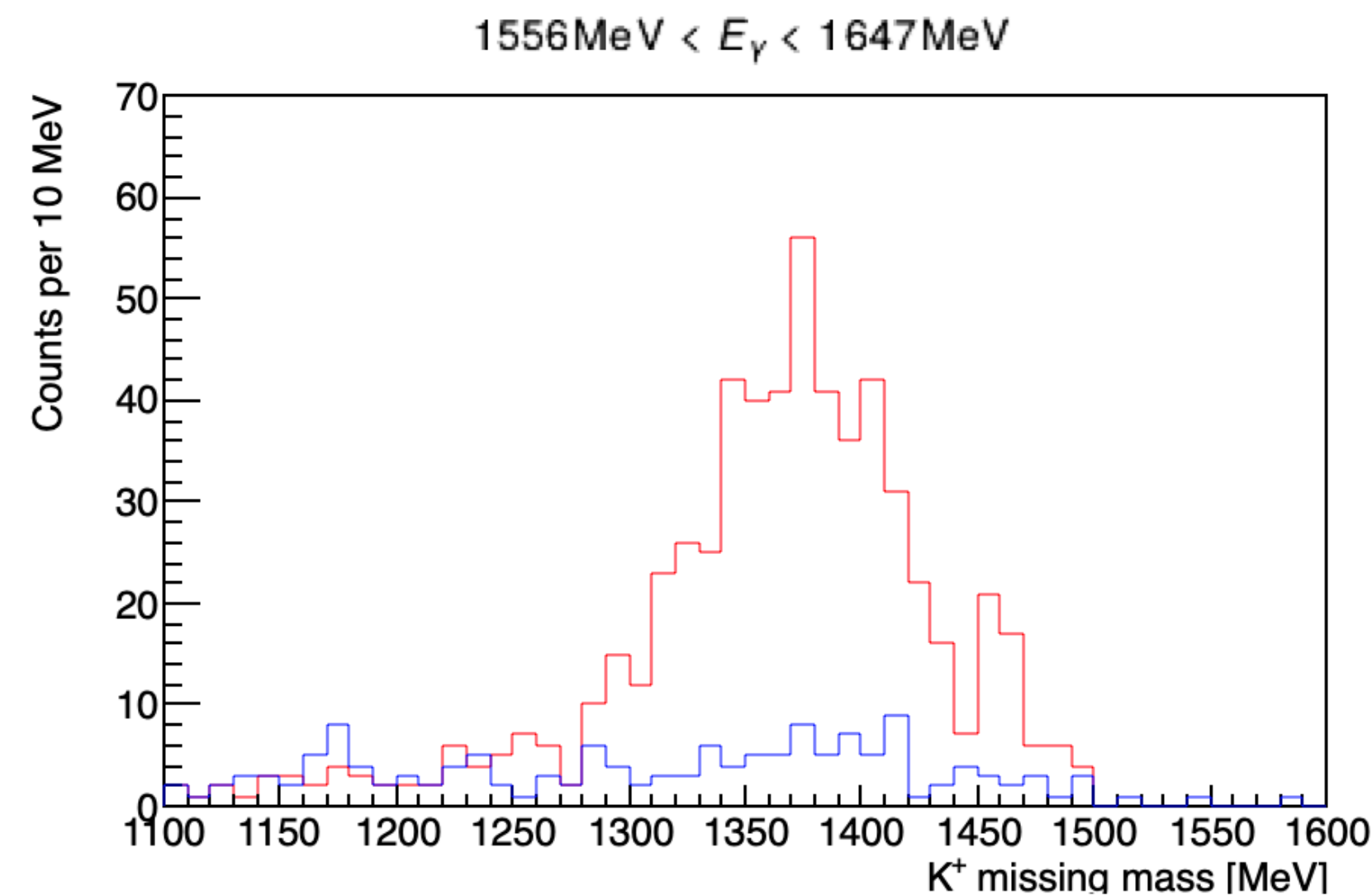
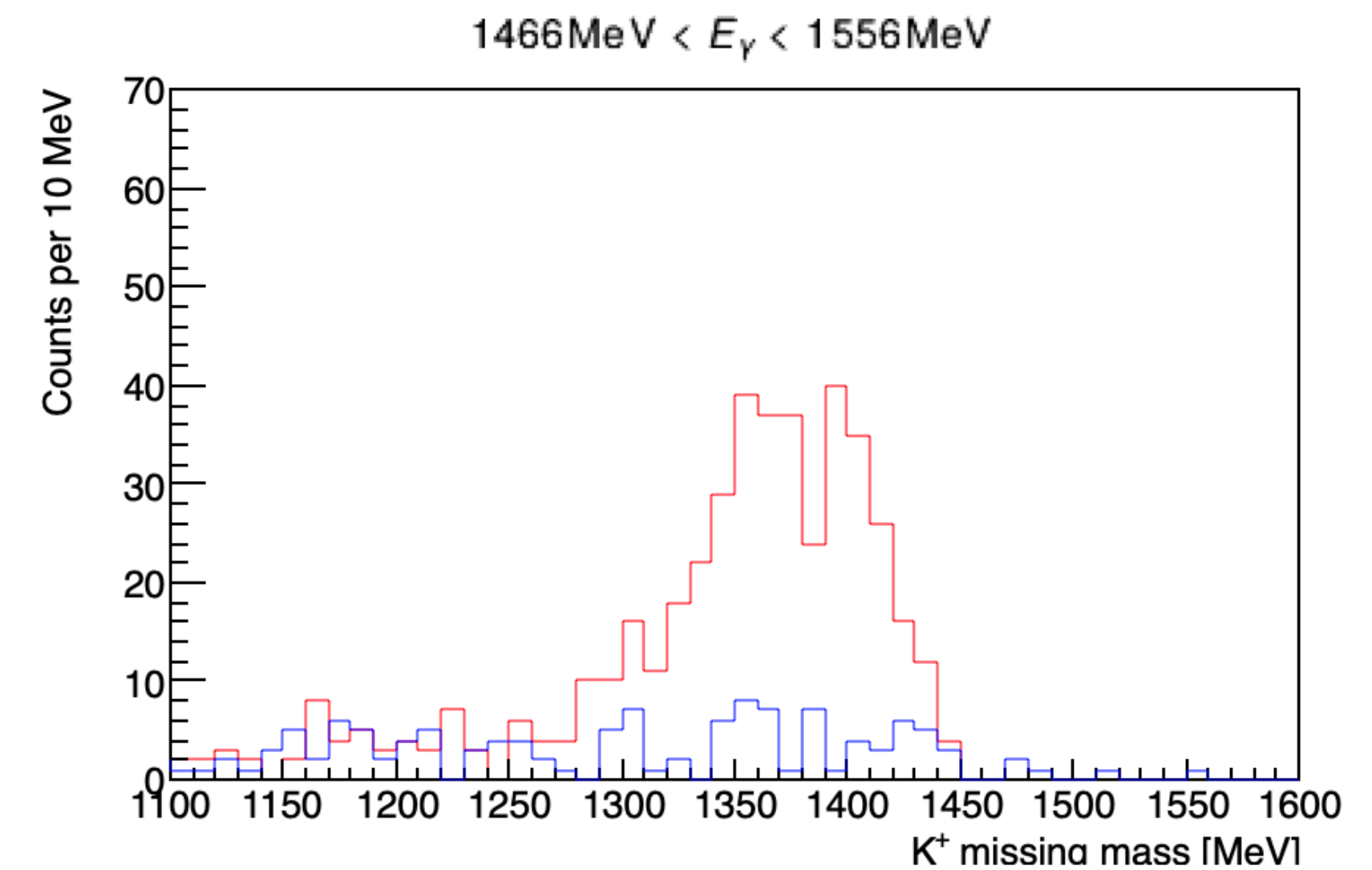
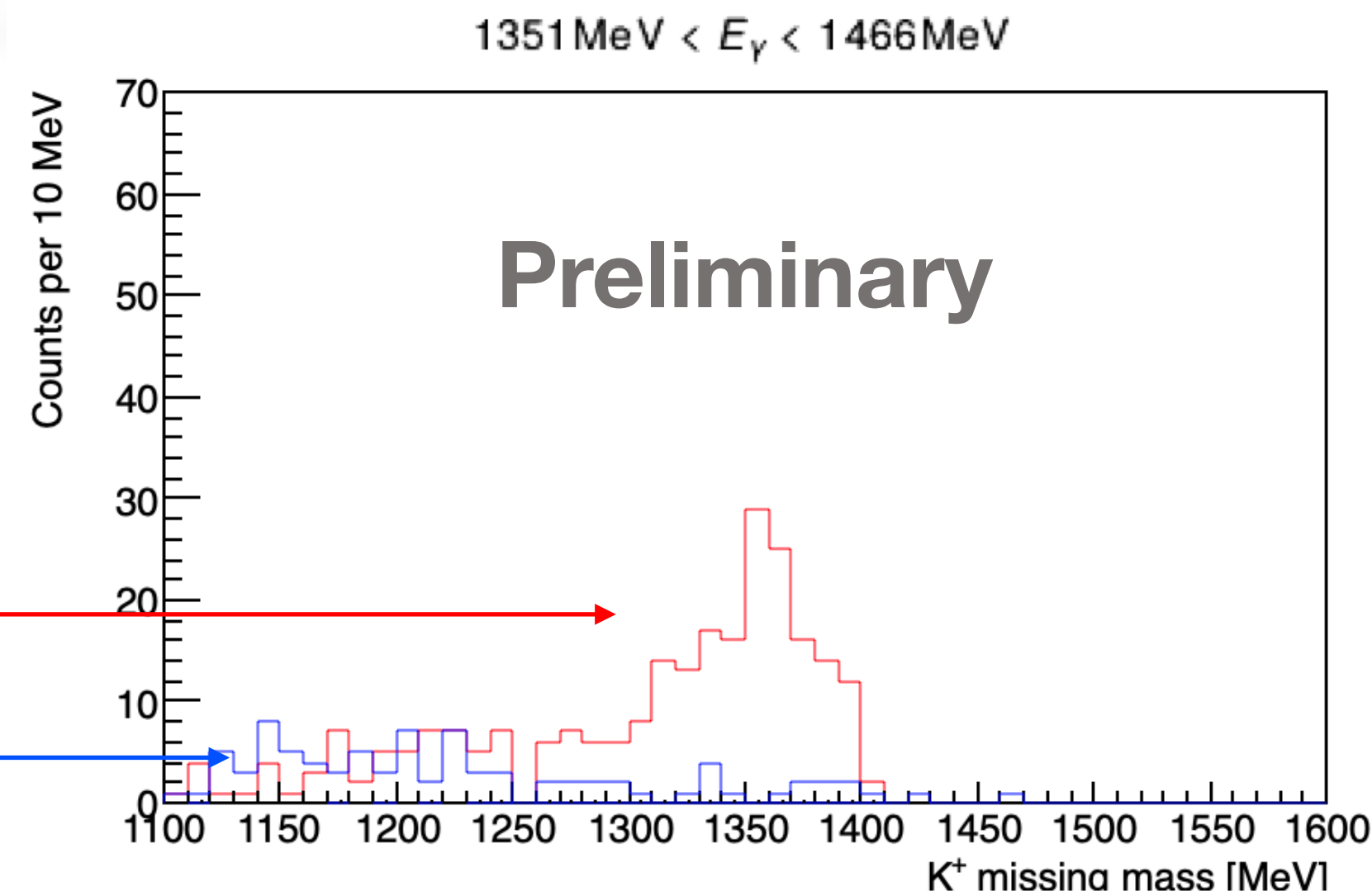


- Clean identification of

- $\Sigma^-(1385) \rightarrow \pi^-\Lambda$

Deuterium data

Hydrogen (background) data

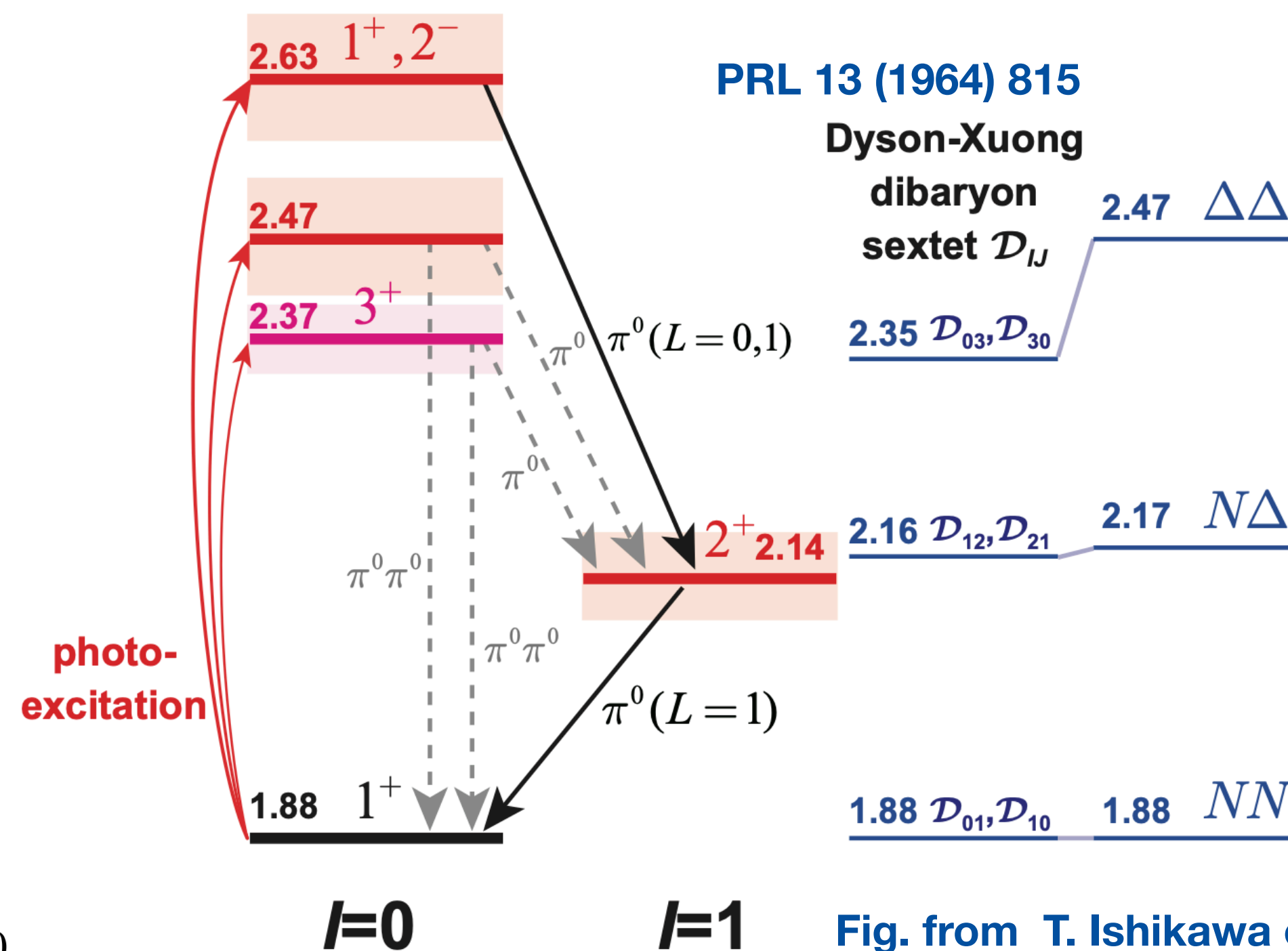
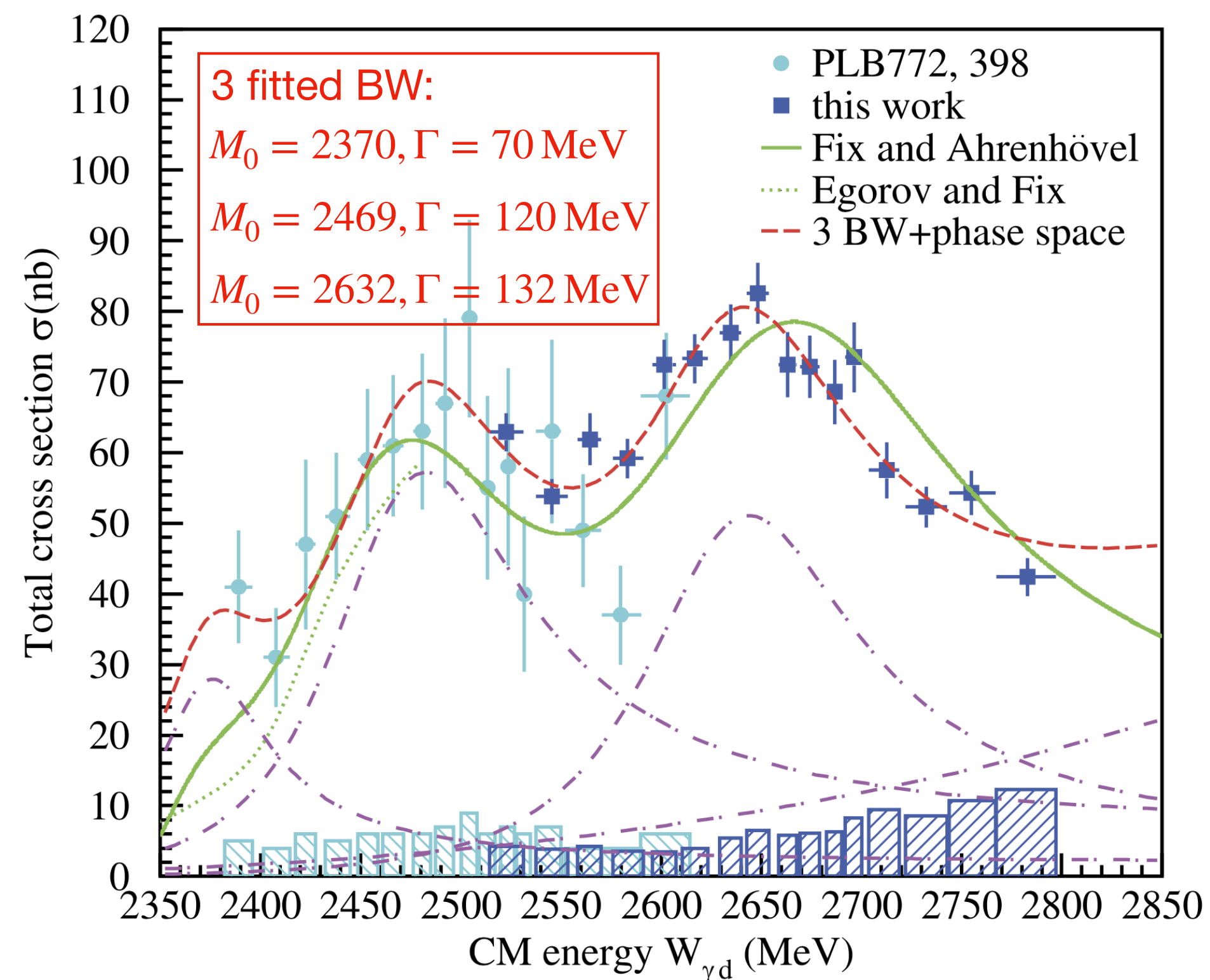


Evidence of a dibaryon spectrum in photoproduction

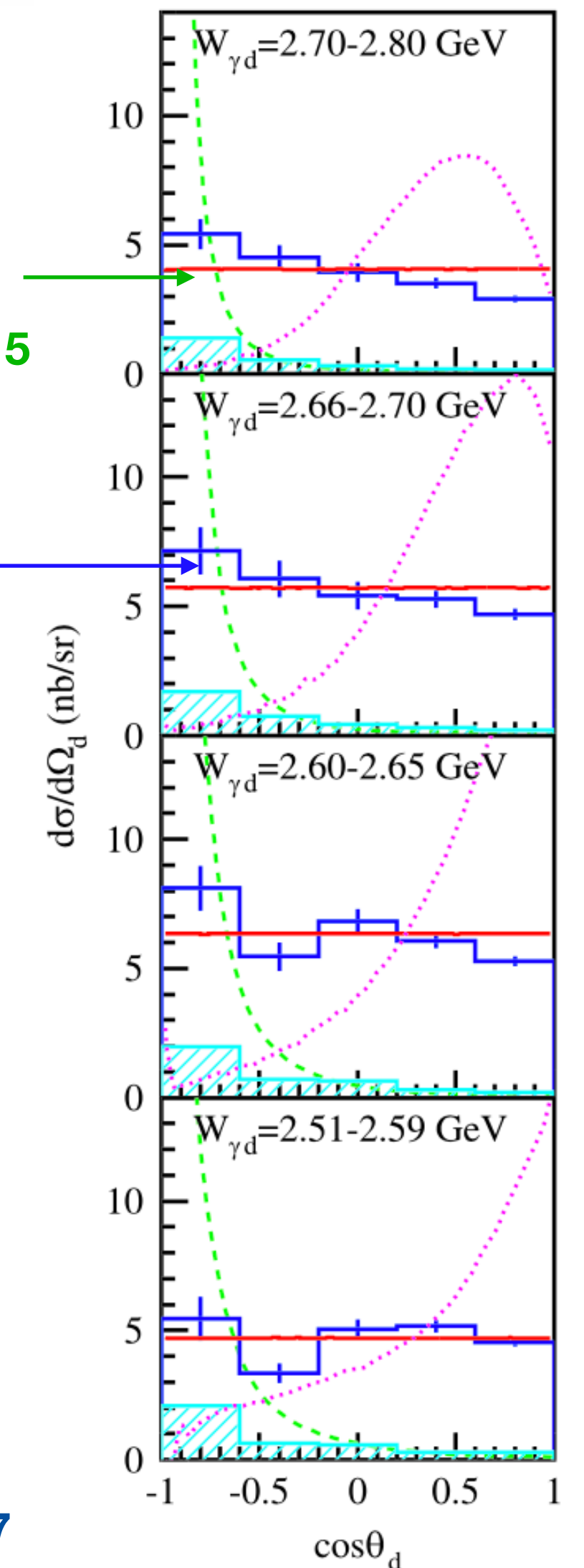
- $\gamma d \rightarrow \pi^0 \pi^0 d$ measured with the **FOREST** detector at **ELPH**

Evidence of 3 isoscalar & 1 isovector dibaryon:

Quasi-free coalescence model
Egorov & Fix, NPA 933 (2015) 104 —
Fix & Arenhövel, EPJA 25 (2005) 115



**Fig. from T. Ishikawa et al.,
EPJA Web Conf., 241 (2020) 01007**



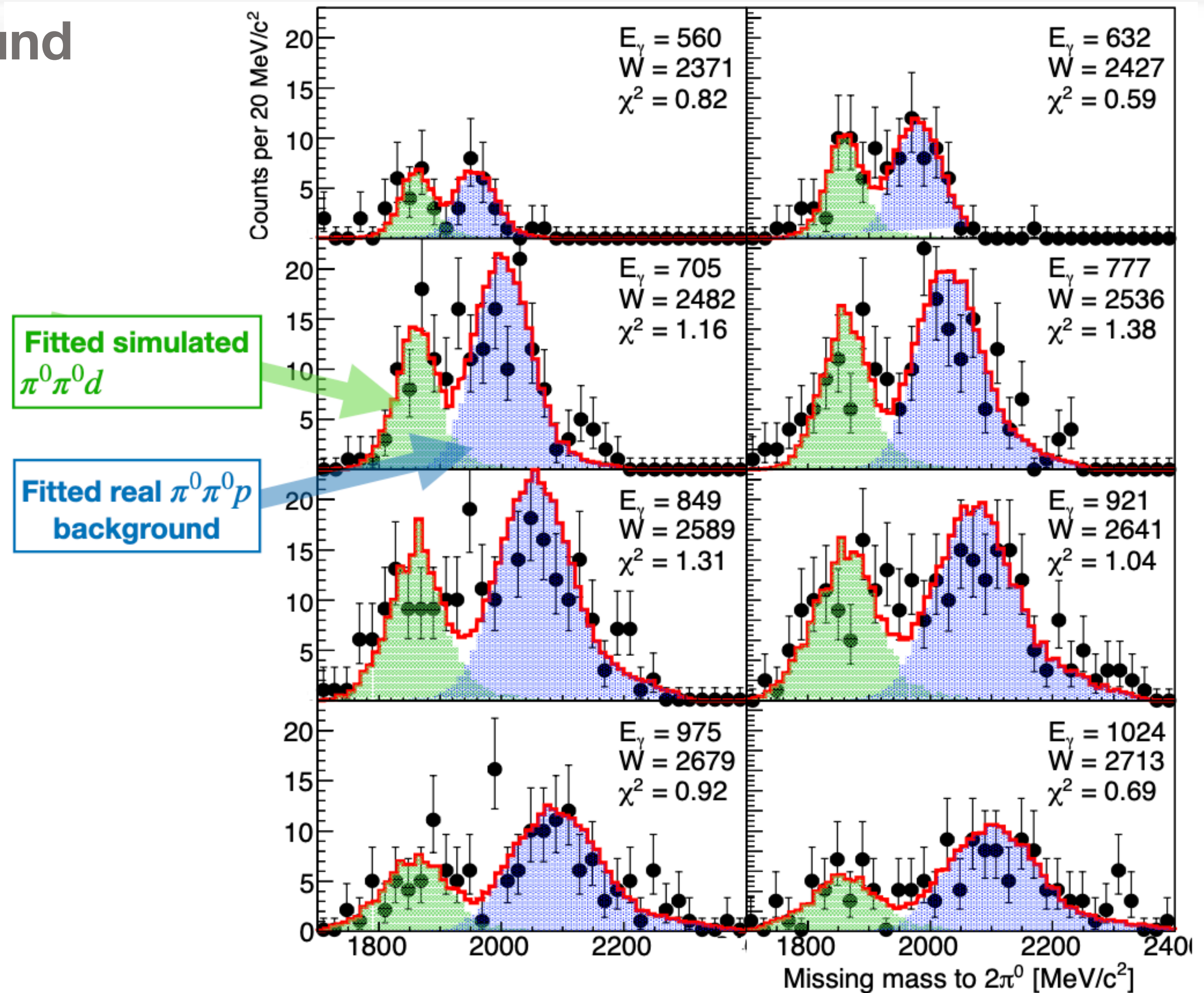
$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD

T.C. Jude *et al.*, PLB 832 (2022) 137277
arXiv:2202.08594



Separating signal & background

- Forward deuterons
- $\pi^0 \rightarrow \gamma\gamma$ in the BGO Rugby Ball
- Fit to the $2\pi^0$ missing mass:



$\gamma d \rightarrow \pi^0 \pi^0 d$ at BGOOD

T.C. Jude *et al.*, PLB 832 (2022) 137277
arXiv:2202.08594

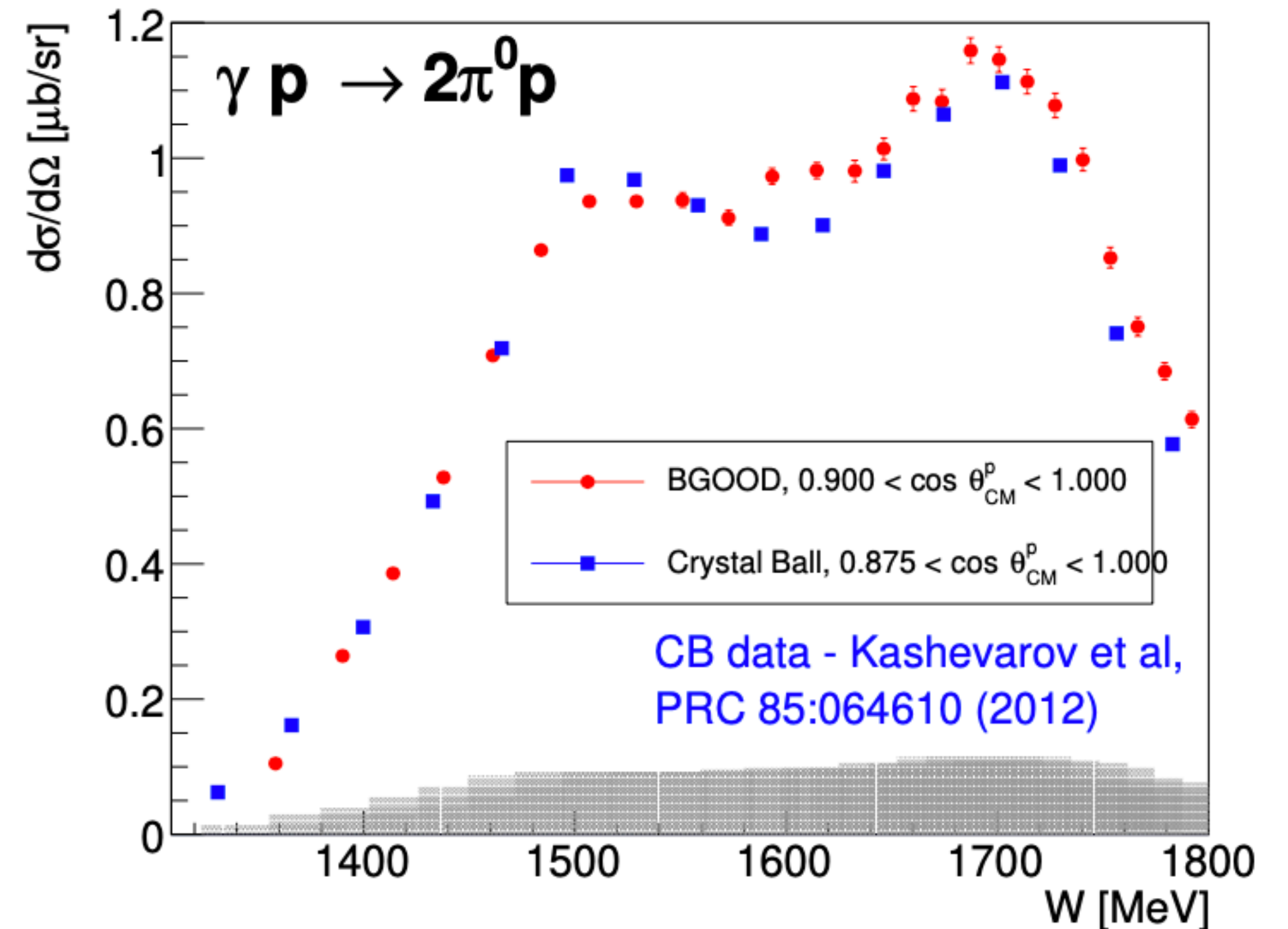
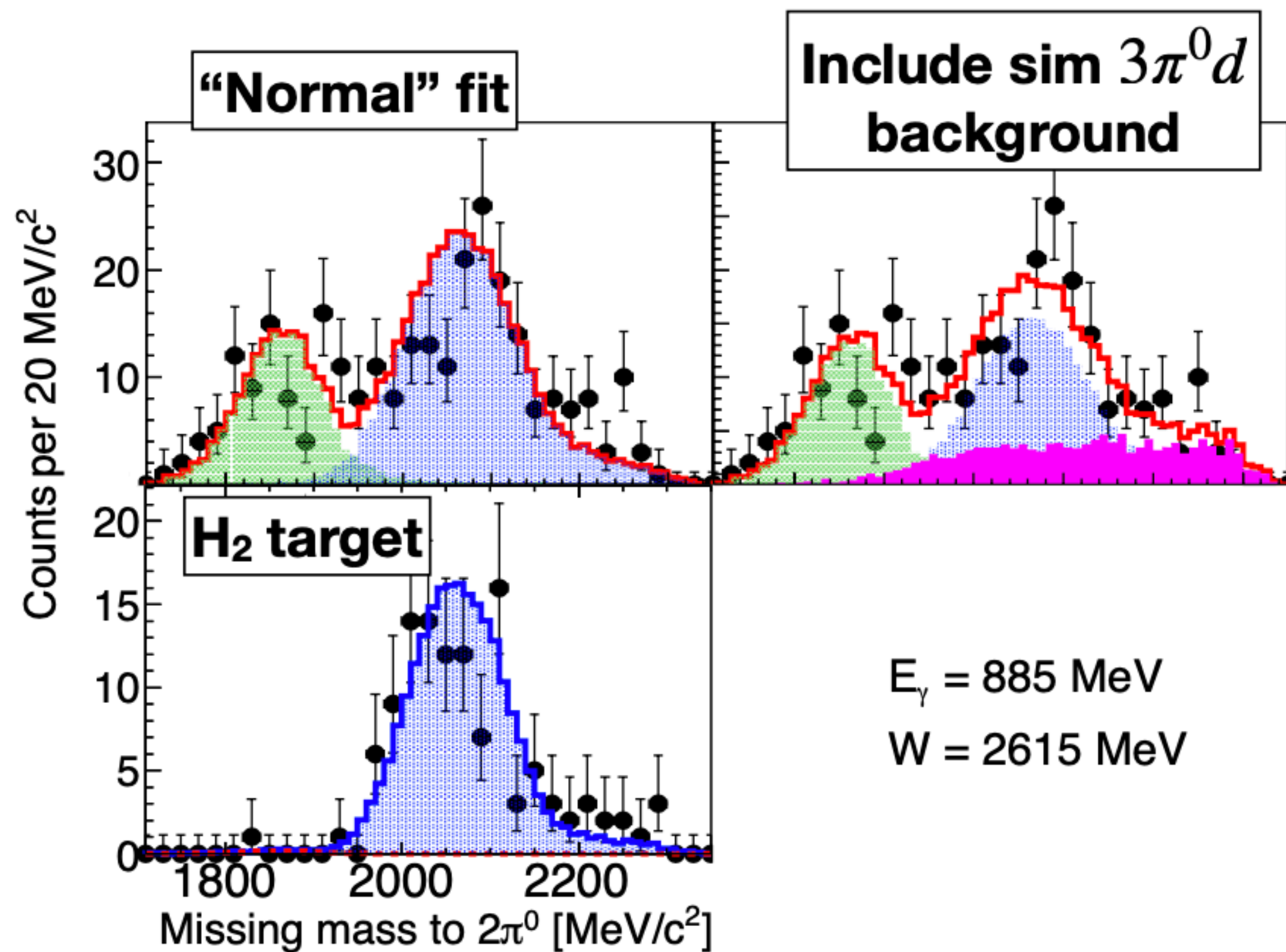


Systematic studies

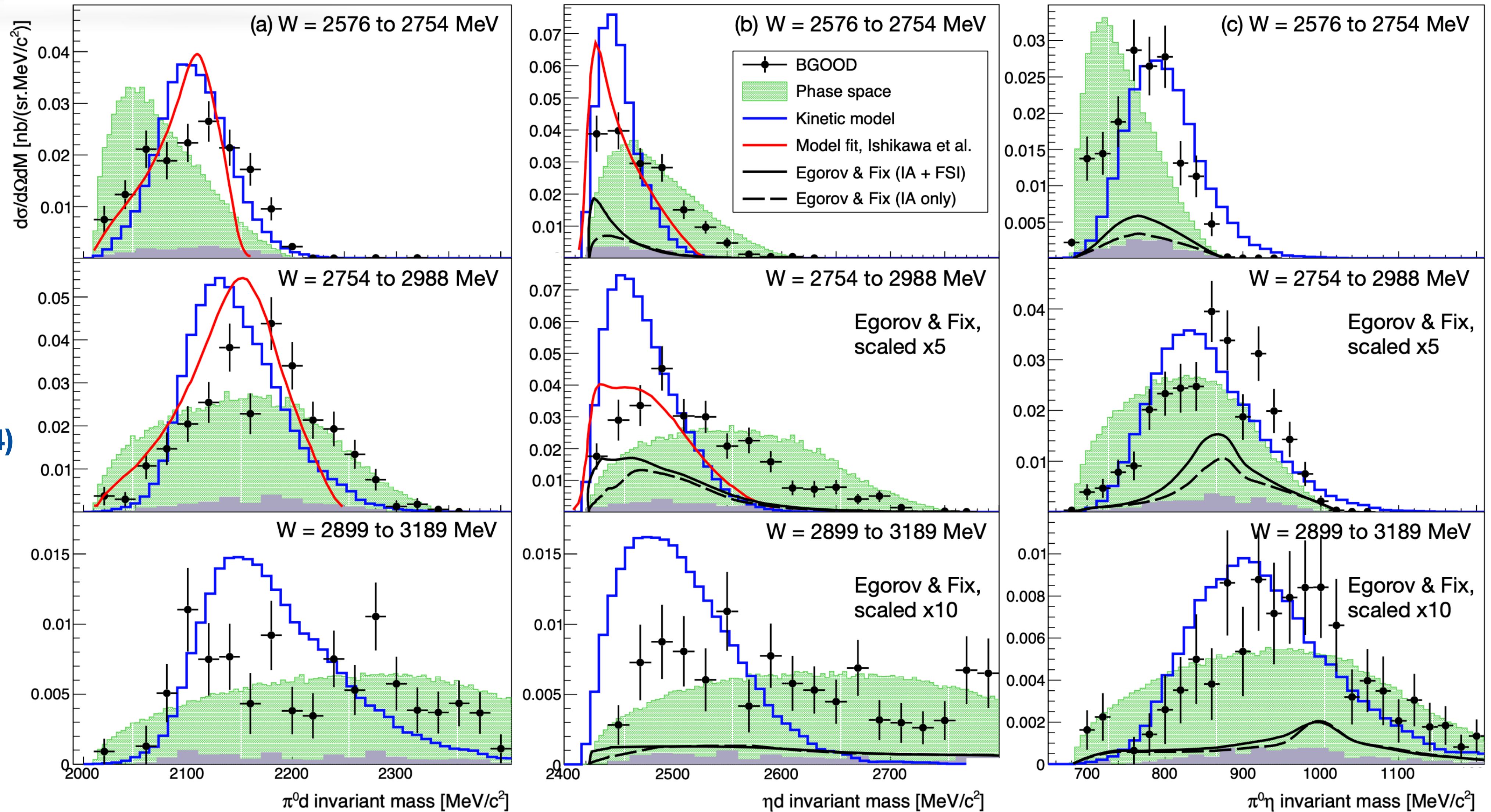
- Understood signal / background contributions:

- Good agreement to a similarly measured channel:

(Understood discrepancy at 1600 MeV due to ηp background)



$\gamma d \rightarrow \pi^0 \eta d$ at BGOOD Invariant mass distributions

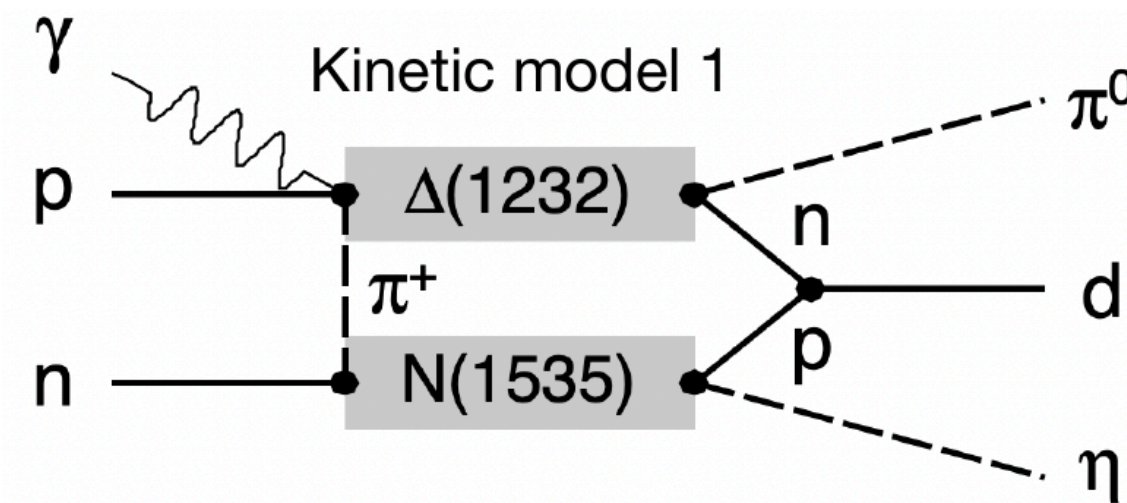


A.J. Clara Figueiredo,
T.C. Jude, *et al.*
arXiv:2405.09392 (2024)

Even more coherent reactions at BGOOD!

Preliminary measurement of $\pi^0\pi^0\pi^0d$

- Similarities between all three coherent final states
- Similar mechanisms?

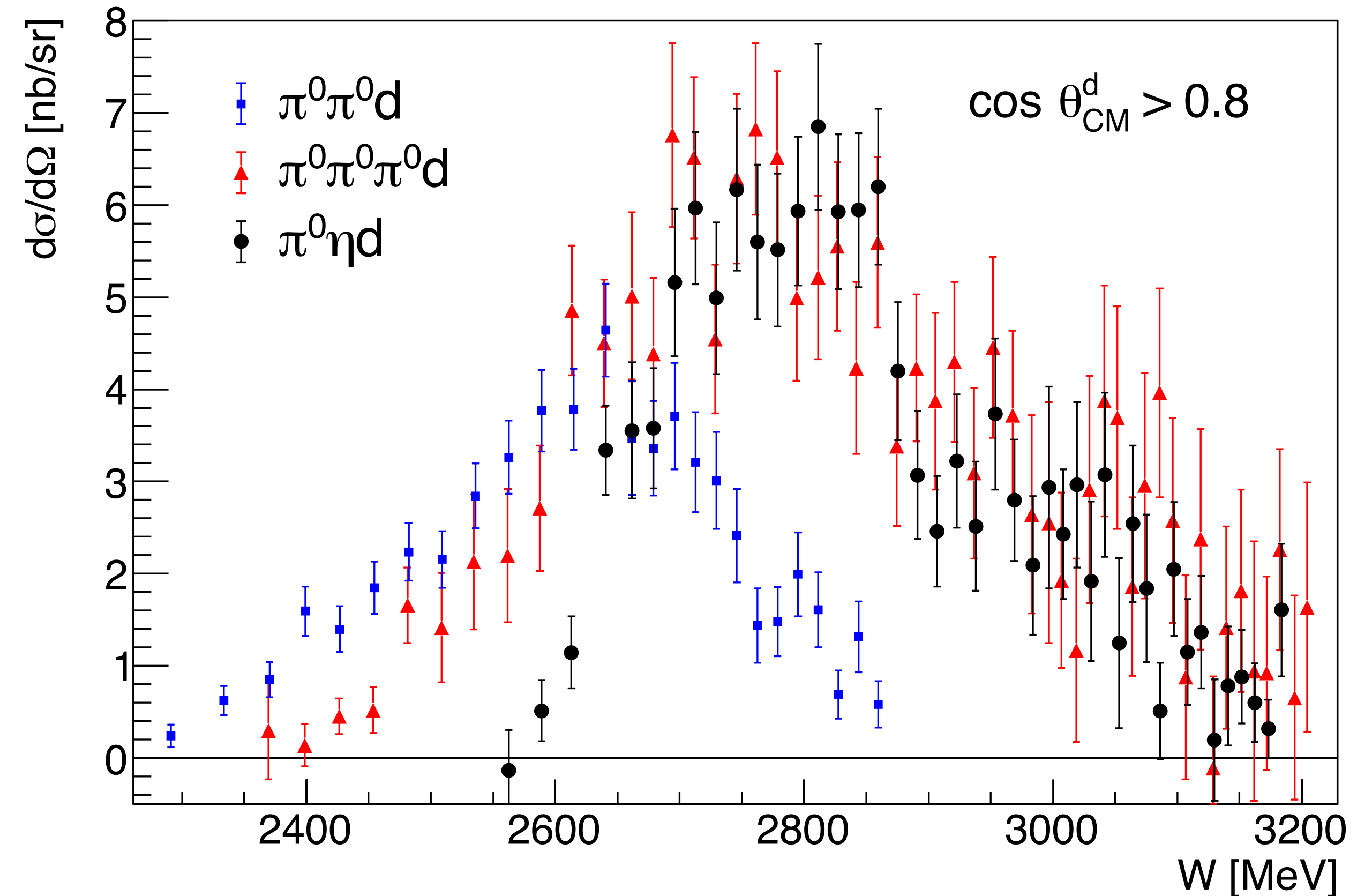


- Could be accounted for by branching ratios?

$$N(1535) \rightarrow \pi N, \Gamma_i/\Gamma = 32 - 53 \%$$

$$N(1535) \rightarrow \pi\pi N, \Gamma_i/\Gamma = 4 - 31 \%$$

$$N(1535) \rightarrow \pi\eta N, \Gamma_i/\Gamma = 30 - 55 \%$$



$\pi^0\pi^0\pi^0d$ data preliminary - R. Volk, Masters thesis, Uni Bonn (2024)

Forward $\gamma d \rightarrow \pi^+ \pi^- d$

