# The BGOOD experiment at ELSA

## - multi-quark structures in the uds sector ?

Hartmut Schmieden
Physikalisches Institut
Universität Bonn

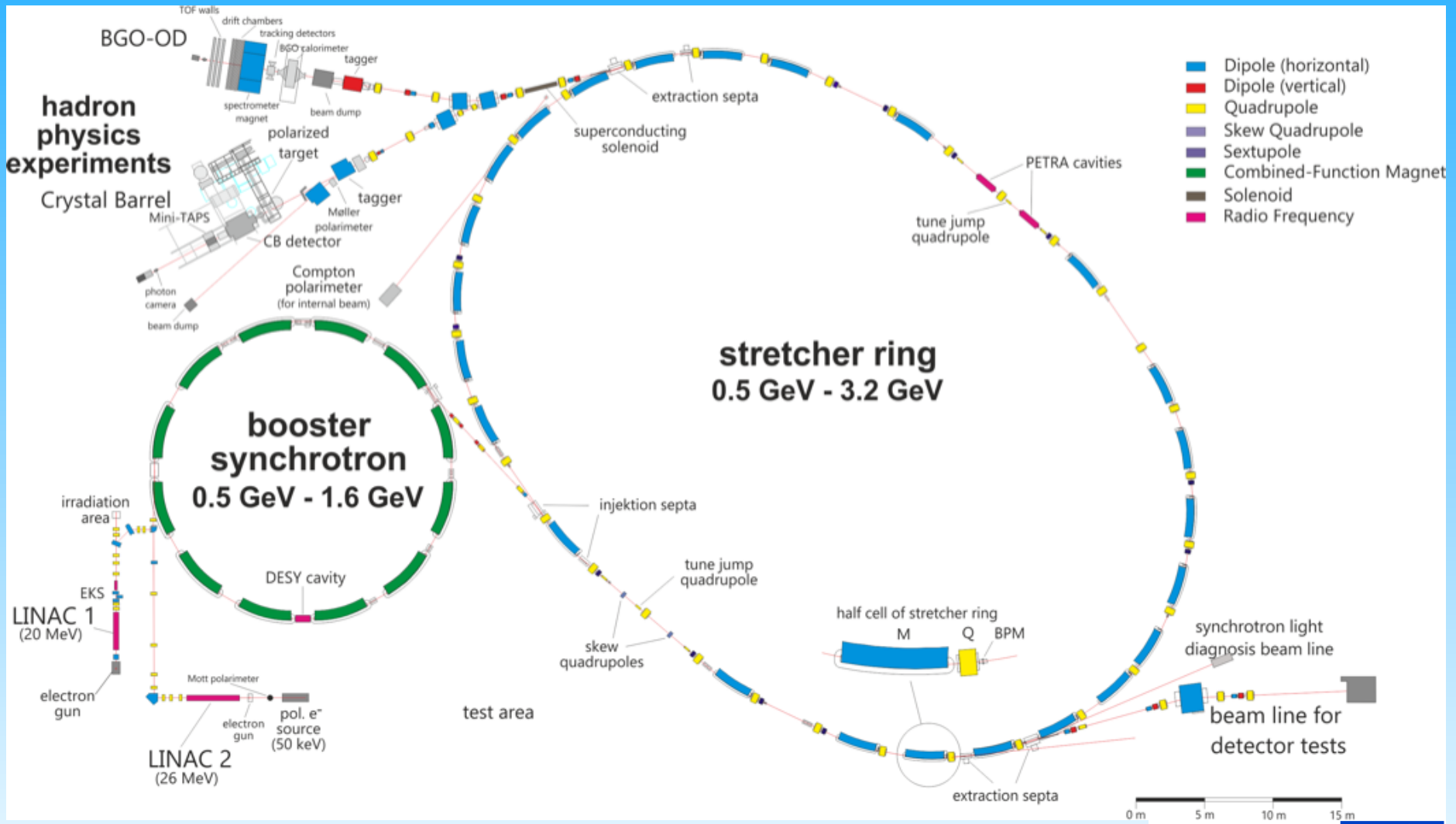
## Outline

- BGOOD experiment
- why? - physics case
- what? - (preliminary) results
- conclusions

supported by DFG
PN 50165297 and
PN 405882627

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

located at ELSA
electron accelerator
Physikalisches Institut
University of Bonn

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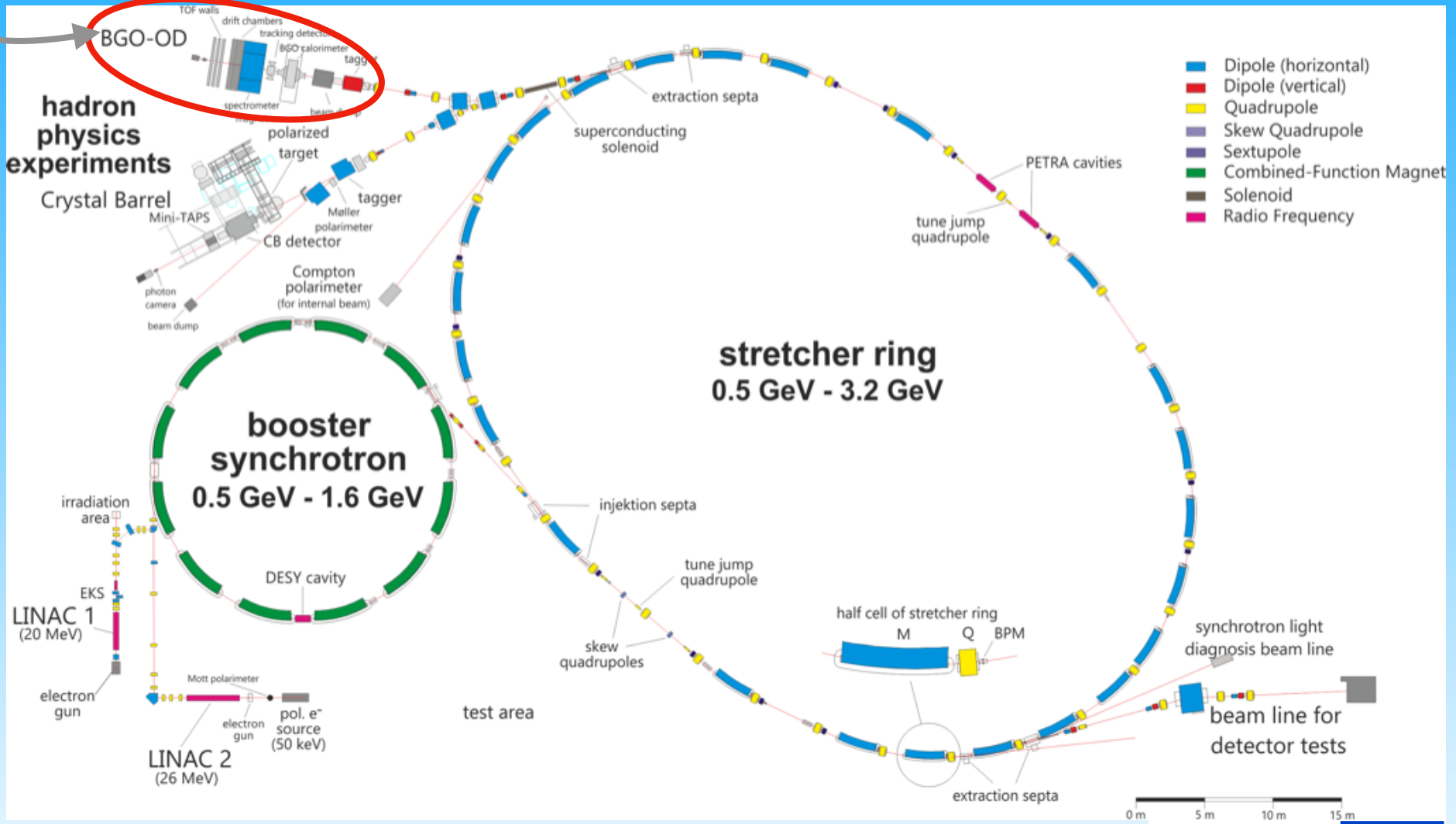


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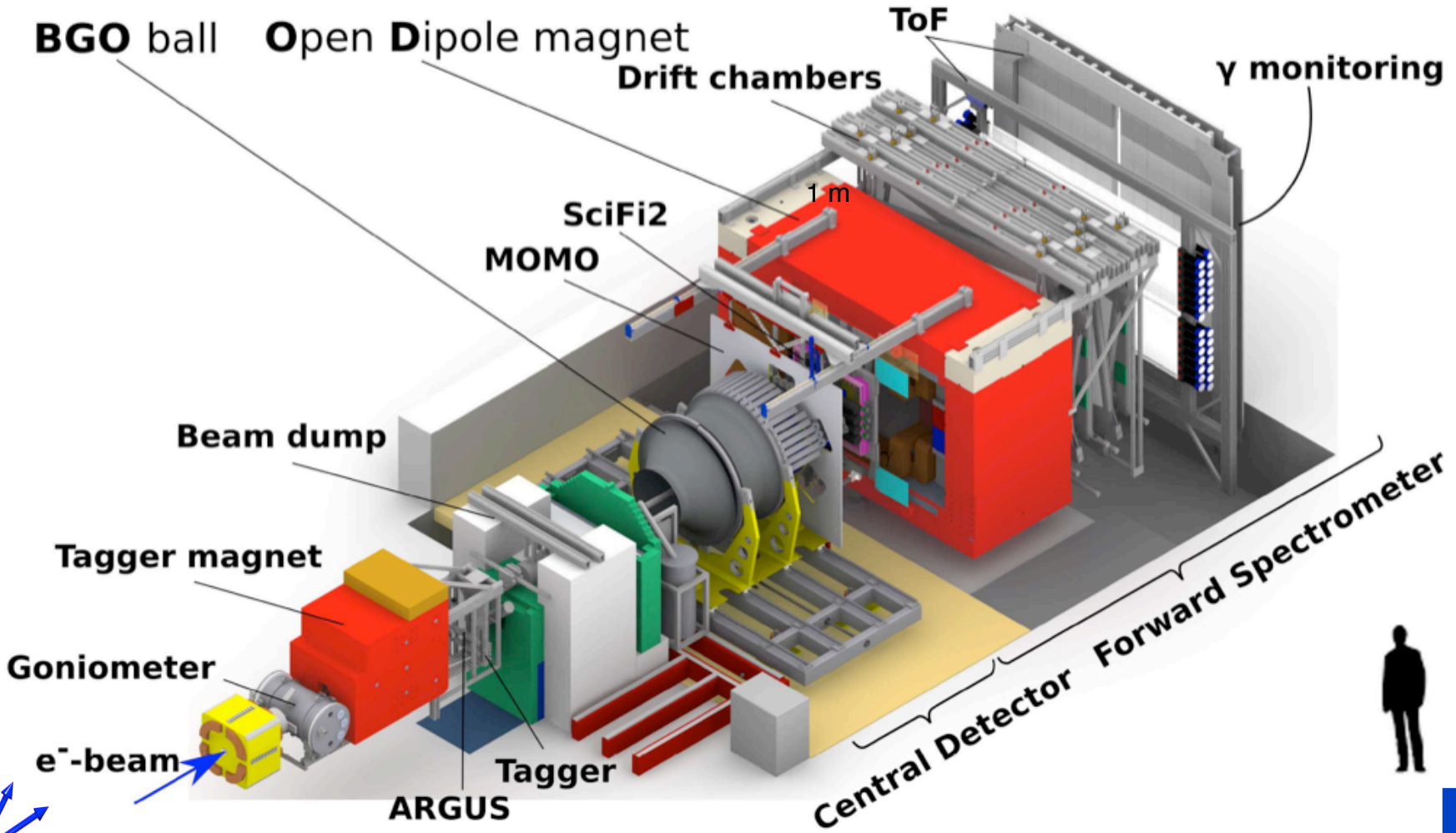
# BGOOD experiment

S. Alef et al. [BGOOD collab.], EPJ A 56 (2020) 104

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

- combination of BGO central calorimeter & forward spectrometer
- high momentum resolution, excellent neutral & charged particle id



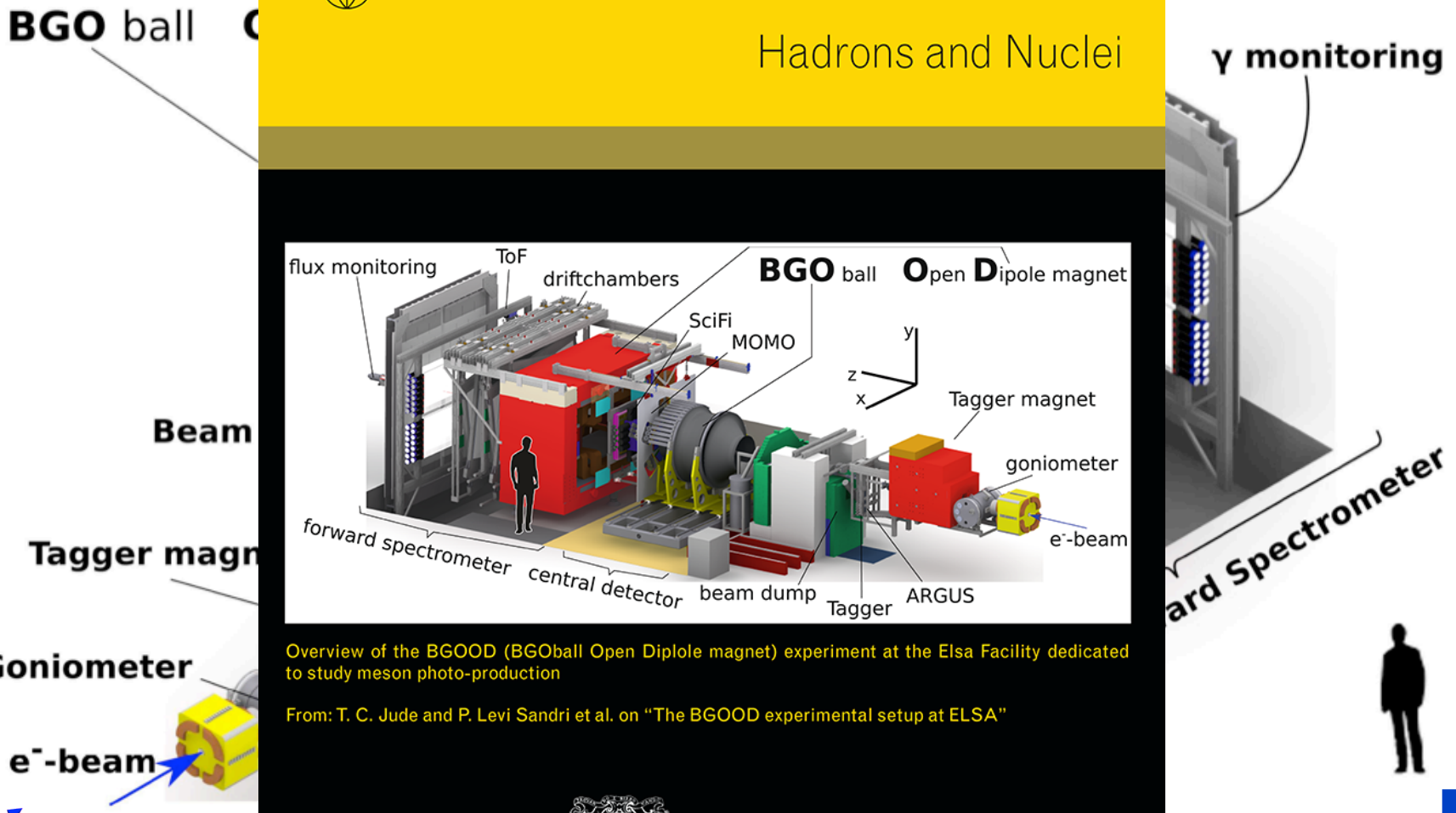
# BGOOD experiment

S. Alef et al. [BGOOD collab.], EPJ A 56 (2020) 104

Levi Sandri (Frascati) &
.Schmieden (Bonn)

- combination
- high moment

trometer
particle id




The European Physical Journal volume 56 · number 4 · april · 2020

EPJ A

Recognized by European Physical Society

Hadrons and Nuclei




Overview of the BGOOD (BGOball Open Diplole magnet) experiment at the Elsa Facility dedicated to study meson photo-production

From: T. C. Jude and P. Levi Sandri et al. on "The BGOOD experimental setup at ELSA"

Società Italiana di Fisica

Springer



ELSA

H. Schmi

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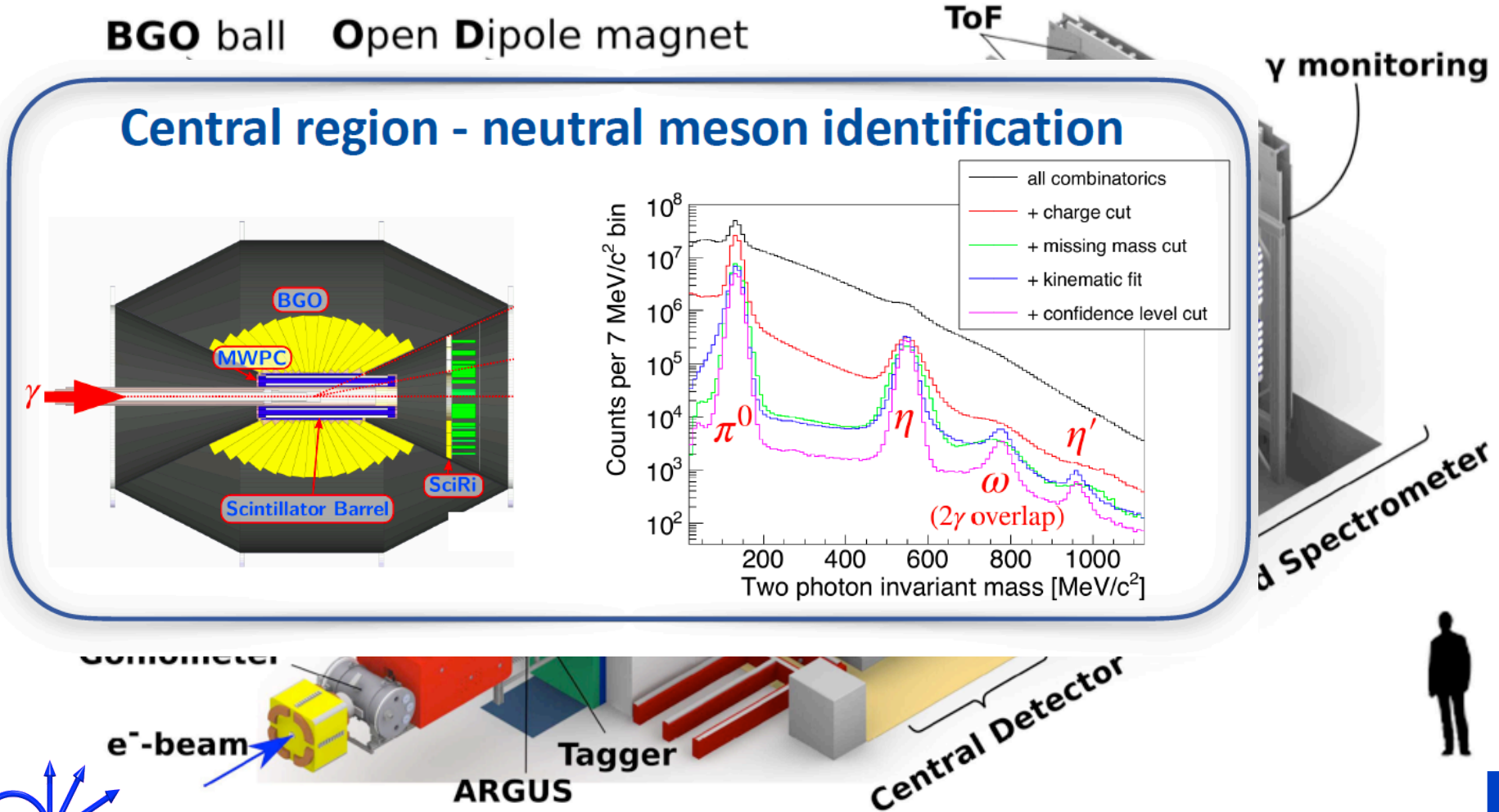

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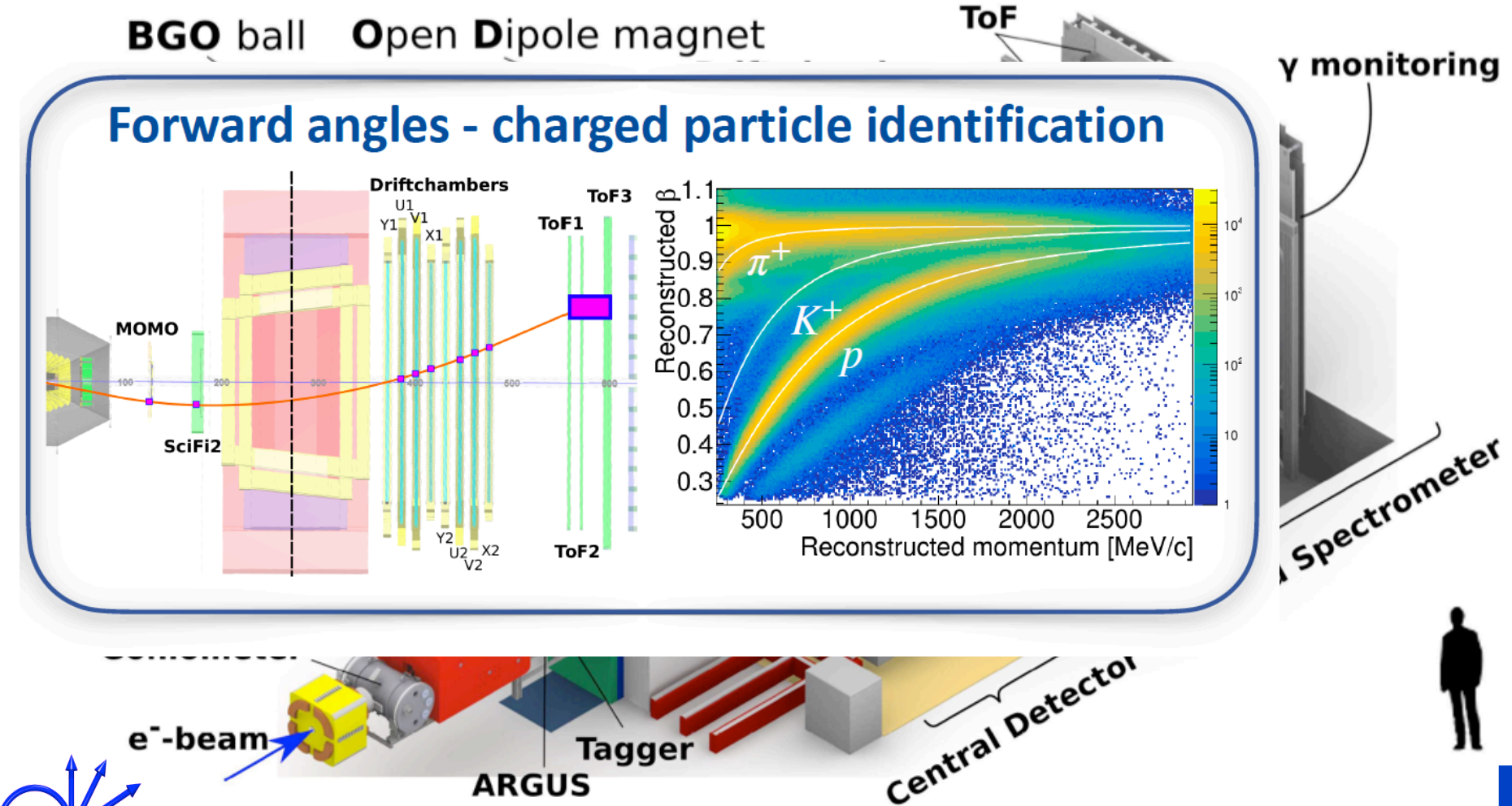
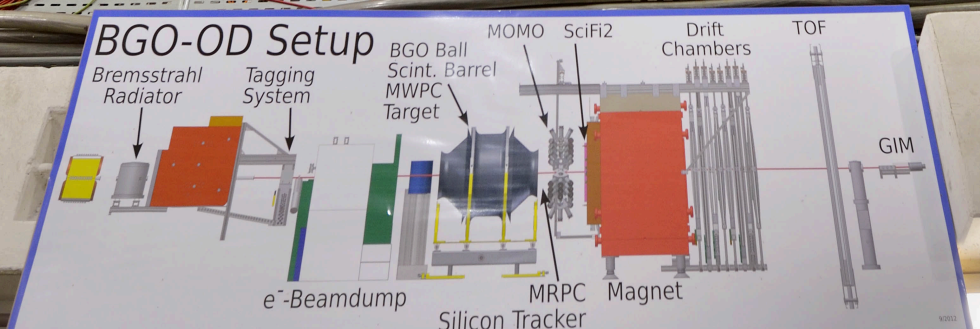
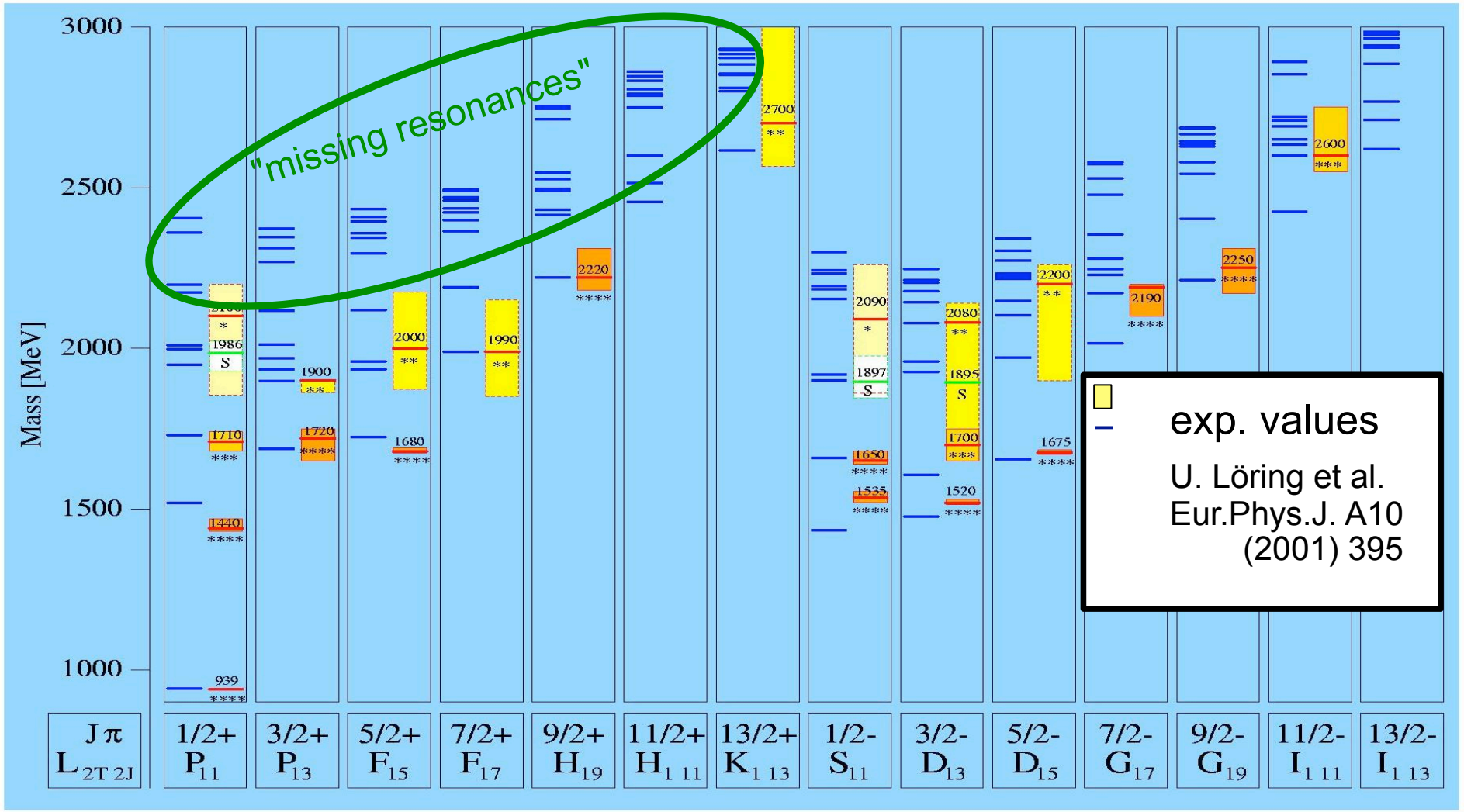


# BGO-OD experiment at ELSA



# why? - physics case

# Excited states: quark model



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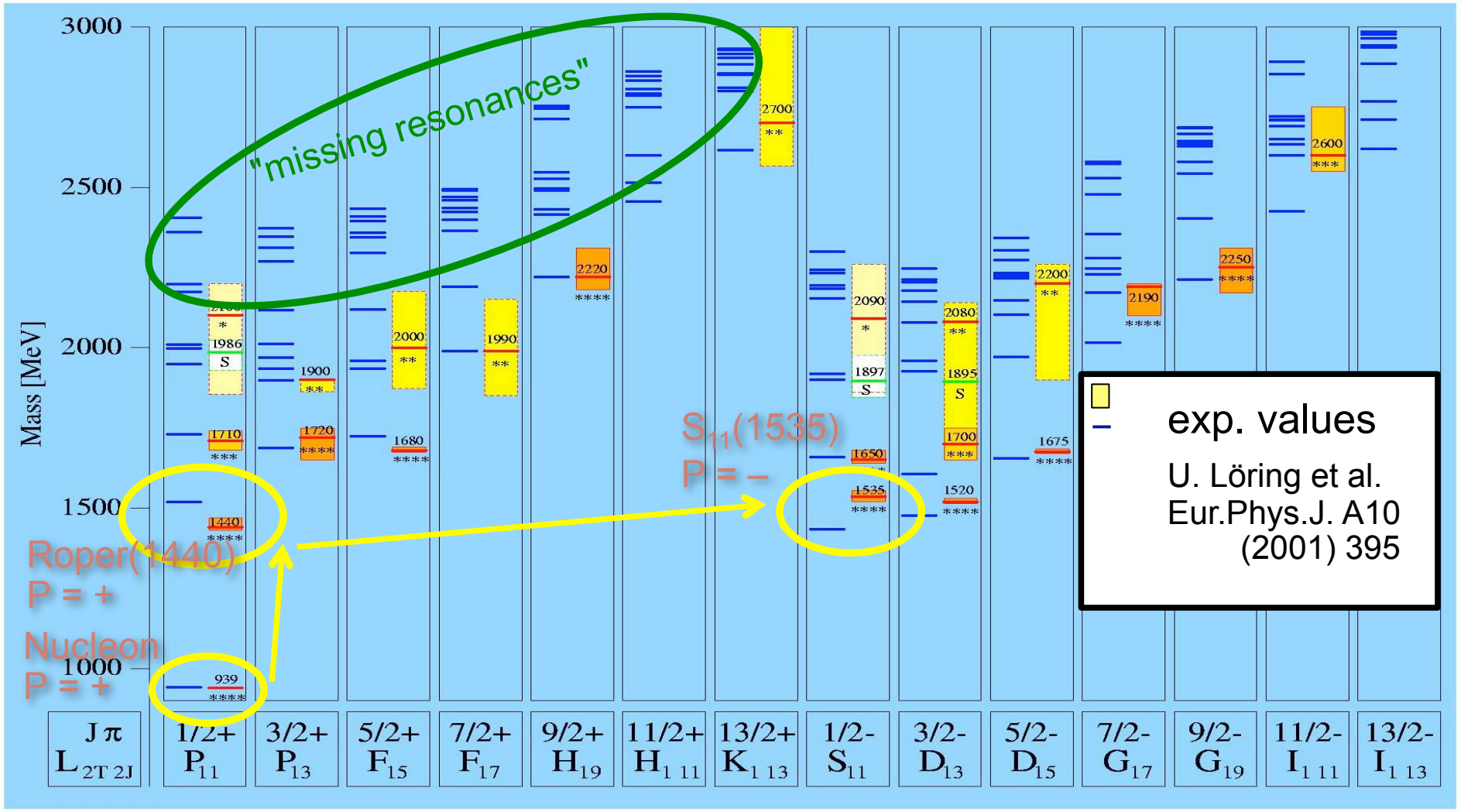
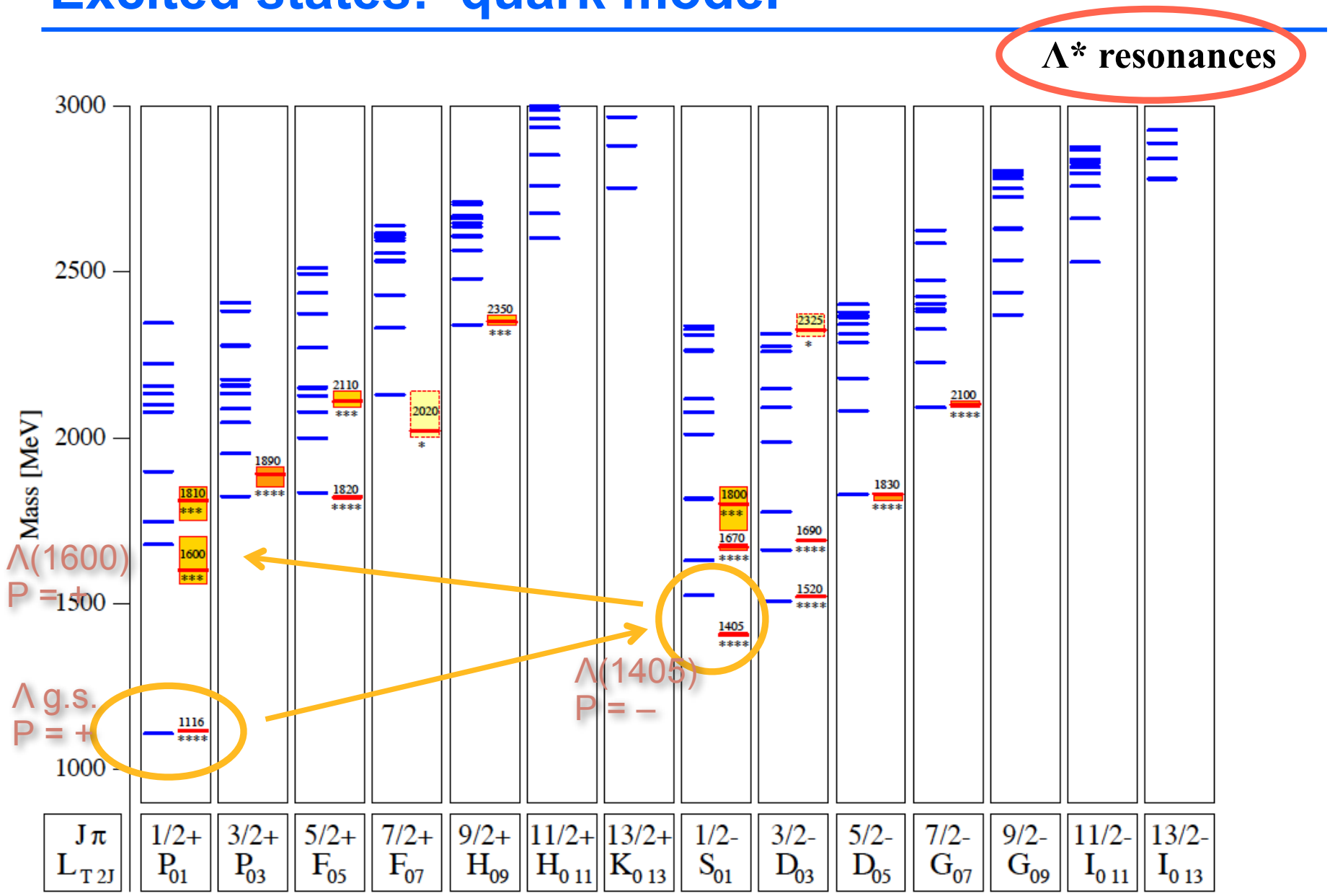



- parity pattern lowest states + → + → – !?!
- effective degrees of freedom ??

# Excited states: quark model

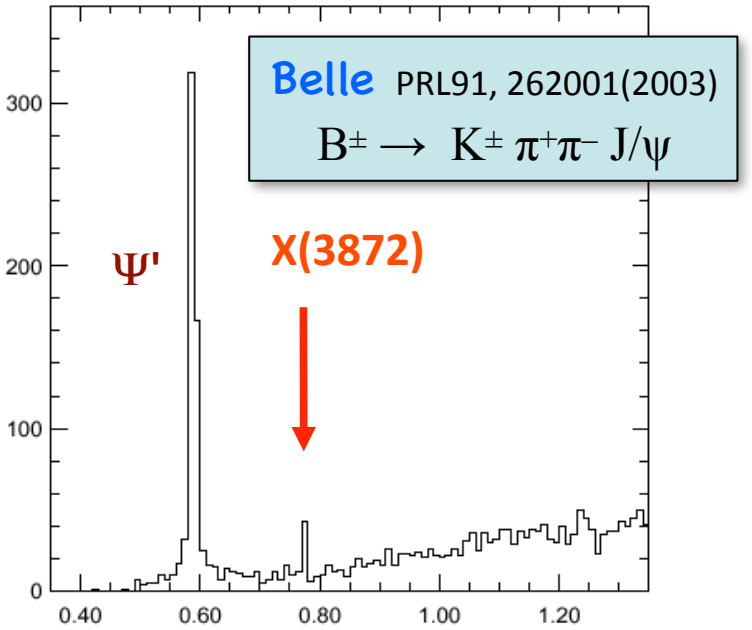



- parity pattern OK
- masses reversed ??

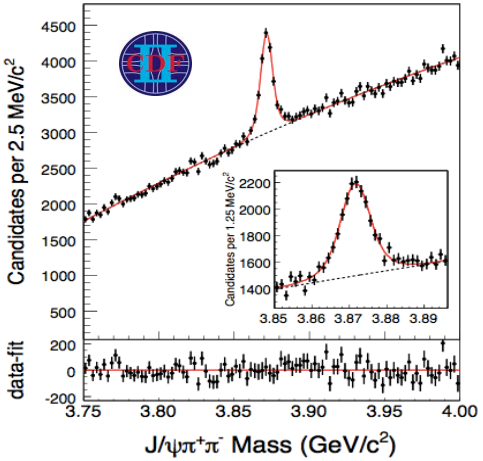
H. Schmieden

# context c-quark sector

## *X(3872)*

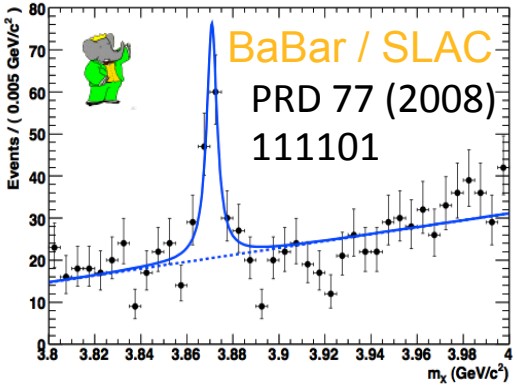



$M(\pi^{+}\pi^{-}l^{+}l^{-}) - M(l^{+}l^{-})$



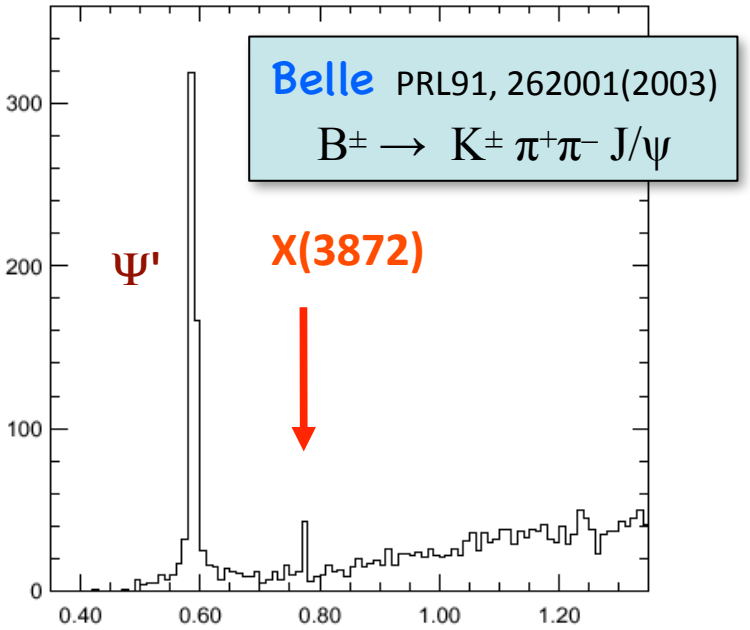

CDF / Tevatron

PRL 103 (2009) 152001

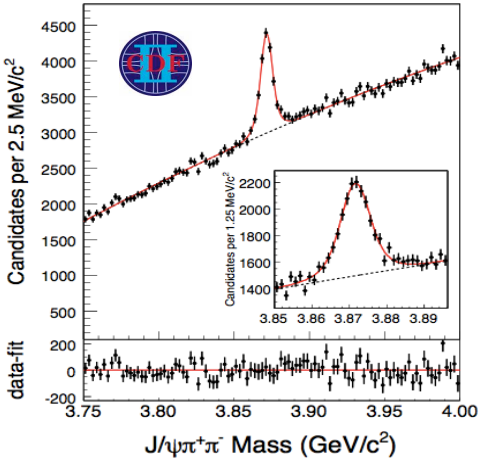


# context c-quark sector

## X(3872)




M(π+π-l+l-) - M(l+l-)

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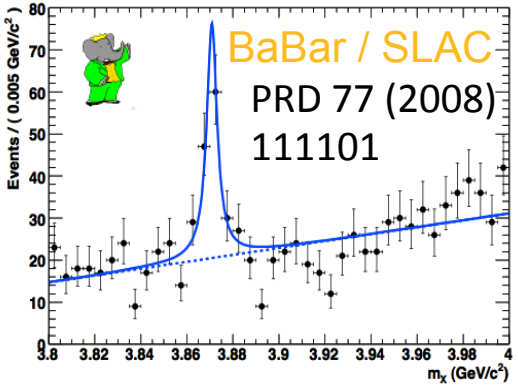
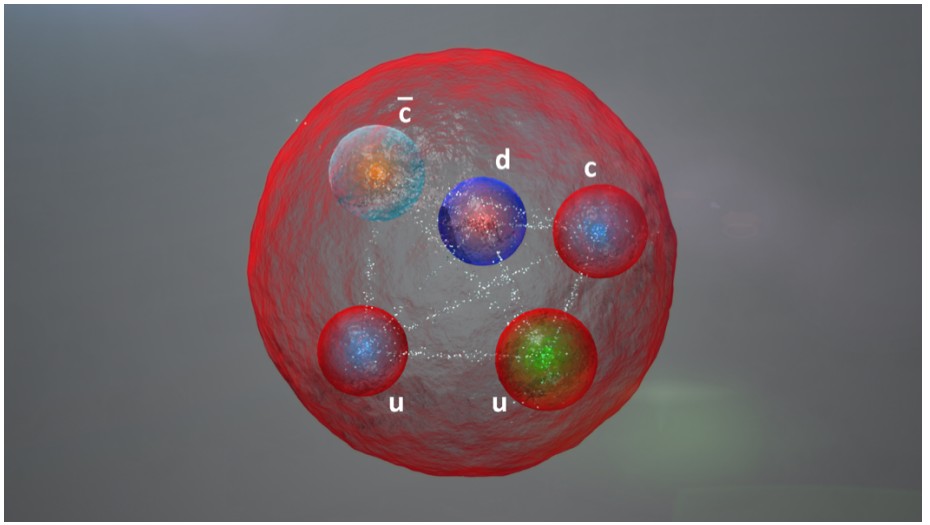


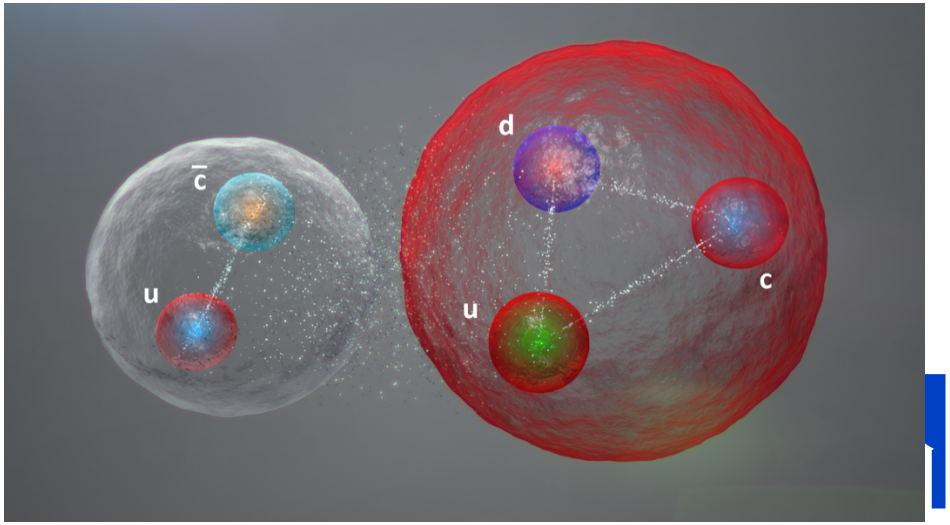


PARTICLE PHYSICS

**Forsaken pentaquark particle spotted at CERN**

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



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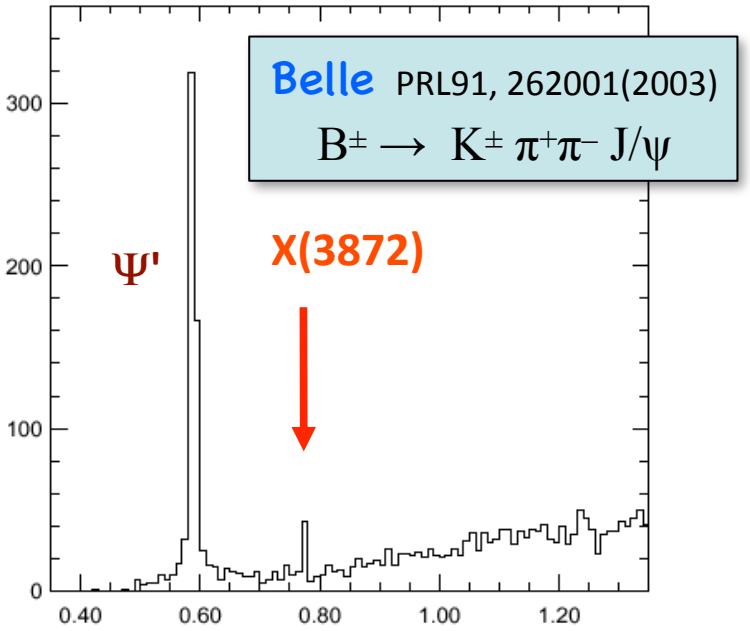


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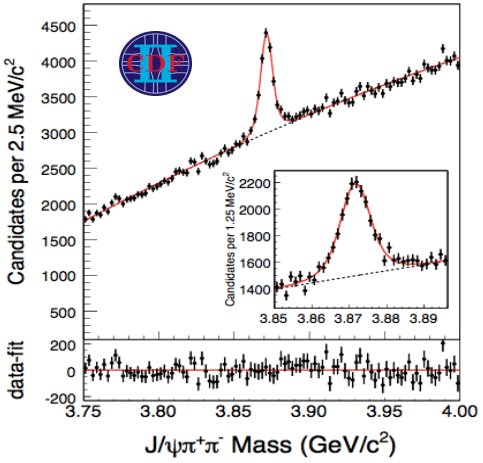


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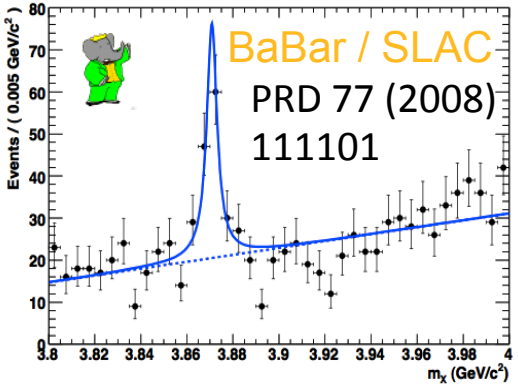



BaBar / SLAC

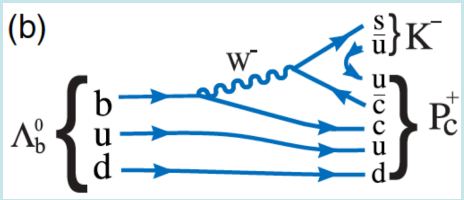
PRD 77 (2008) 111101

## $P_c^+(4380, 4450)$

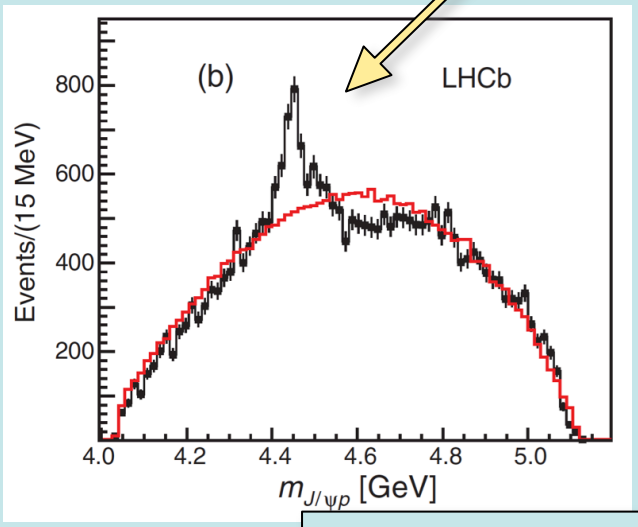

PARTICLE PHYSICS

**Forsaken pentaquark**

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




p J/ψ




PB / VB hidden c predicted from meson-baryon interactions:
Oset, Zou et al., PRL 105 (2010)

"new $N^*_{cc}$ states are simply brothers or sisters of the well known N*(1535) and Λ*(1405) ... and many other dynamically generated states ..."

# context c-quark sector

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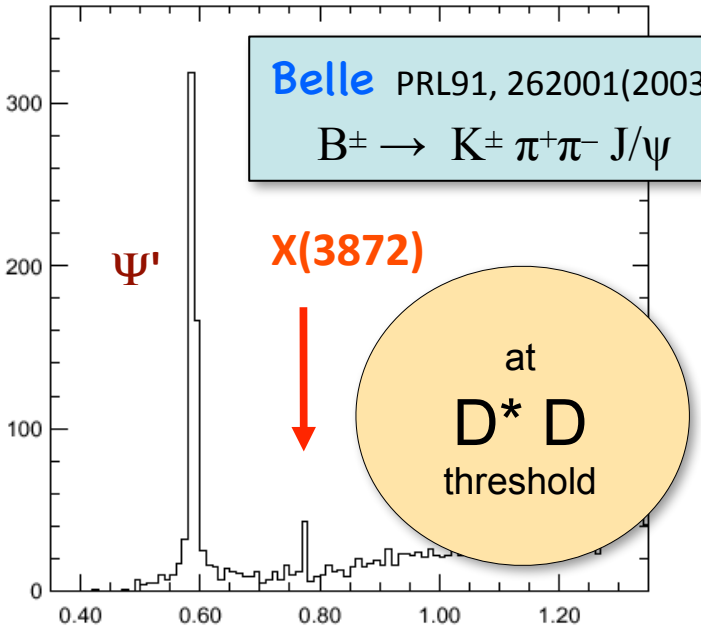


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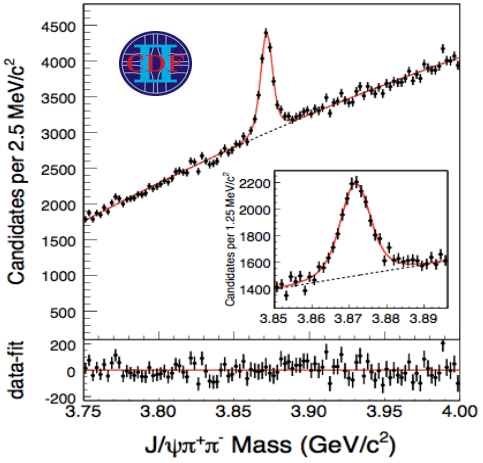


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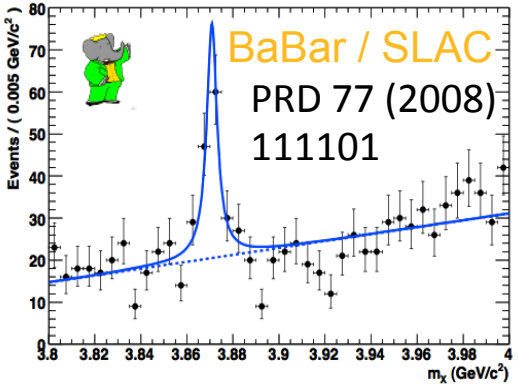


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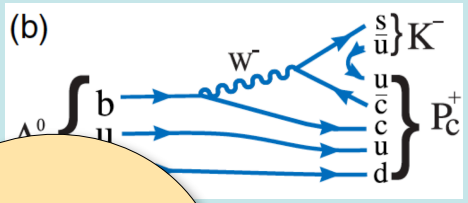
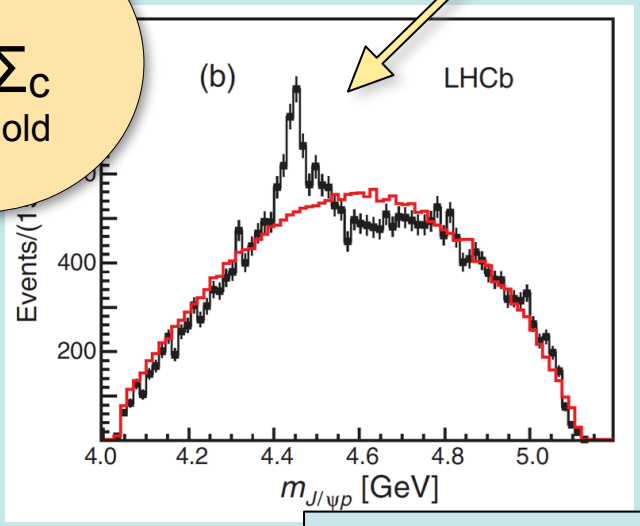



p J/ψ

at
D* Σc
threshold

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# parallels between c and s sector ?

| | c-sector | | s-sector | |
|---|---|---|---|---|
| | meson | baryon(s) | meson | baryon(s) |
| state(s) | $X(3872)$ | $P_c^*(4380/4450)$ | $f_1(1420)$ | $N^*(2030/2080)$ |
| $\pi$-exchange transition | $D^{*0}\bar{D}^0 + D^0\bar{D}^{*0}$ | $\Lambda_c^*\bar{D} + \Sigma_c\bar{D}^*$ | $K^*\bar{K} + K\bar{K}^*$ | $\Lambda^*\bar{K} + \Sigma\bar{K}^*$ |
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| 3-body threshold | $D^0\bar{D}^0\pi^0$ | $\Sigma_c^+\bar{D}^0\pi^0$ | $K\bar{K}\pi$ | $\Sigma\bar{K}\pi^0$ |
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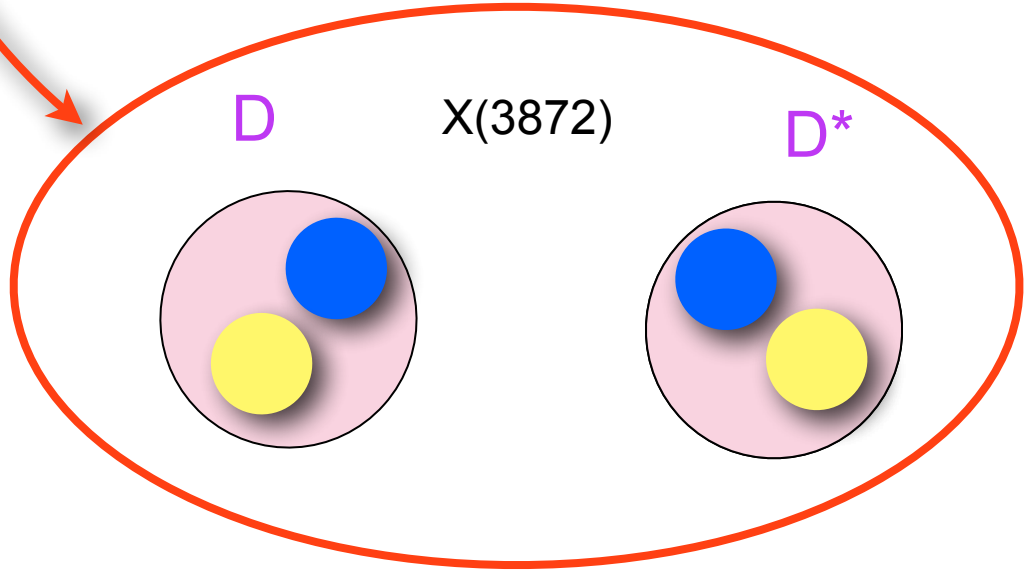

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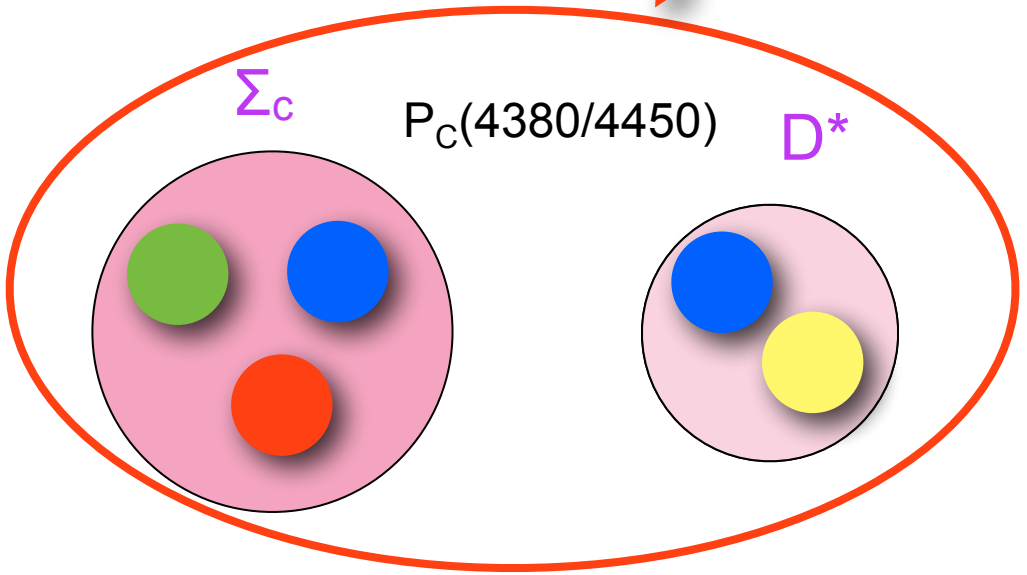
$\bar{3} \leftrightarrow \bar{3}$

$\bar{q} \rightarrow [qq]$



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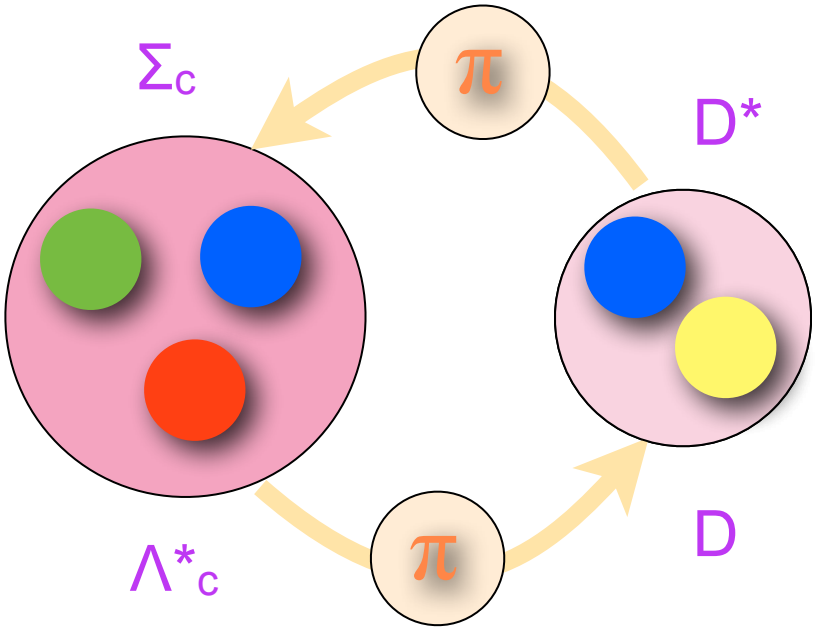

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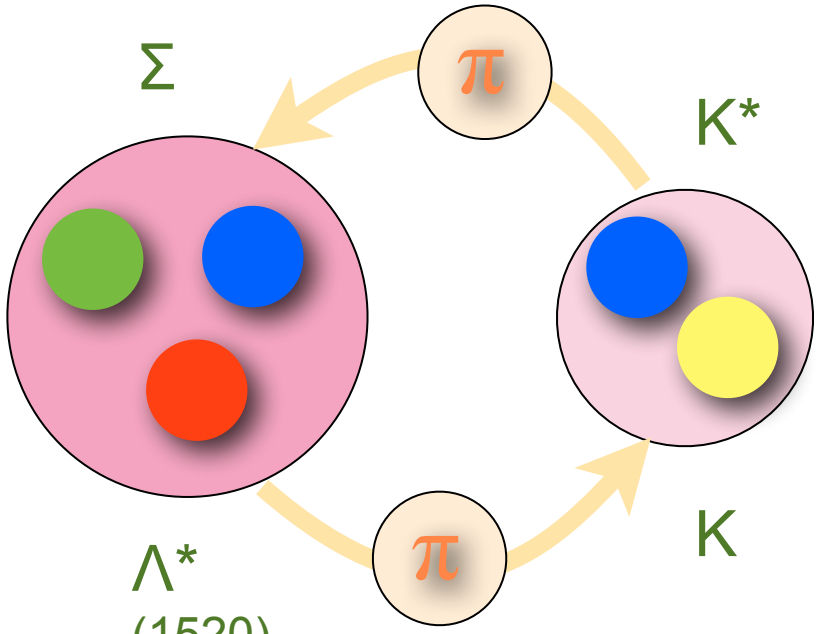
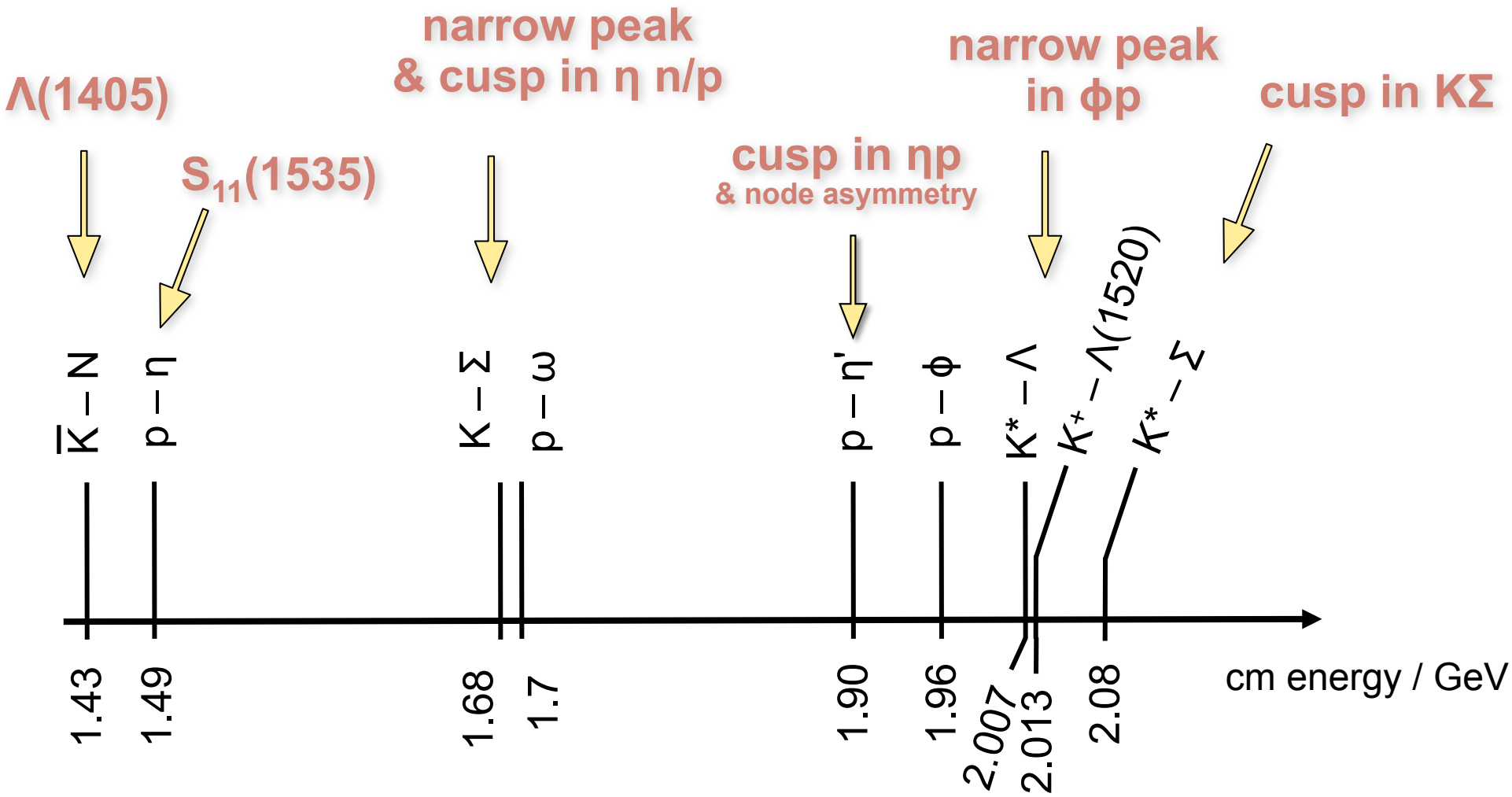


# uds sector ?

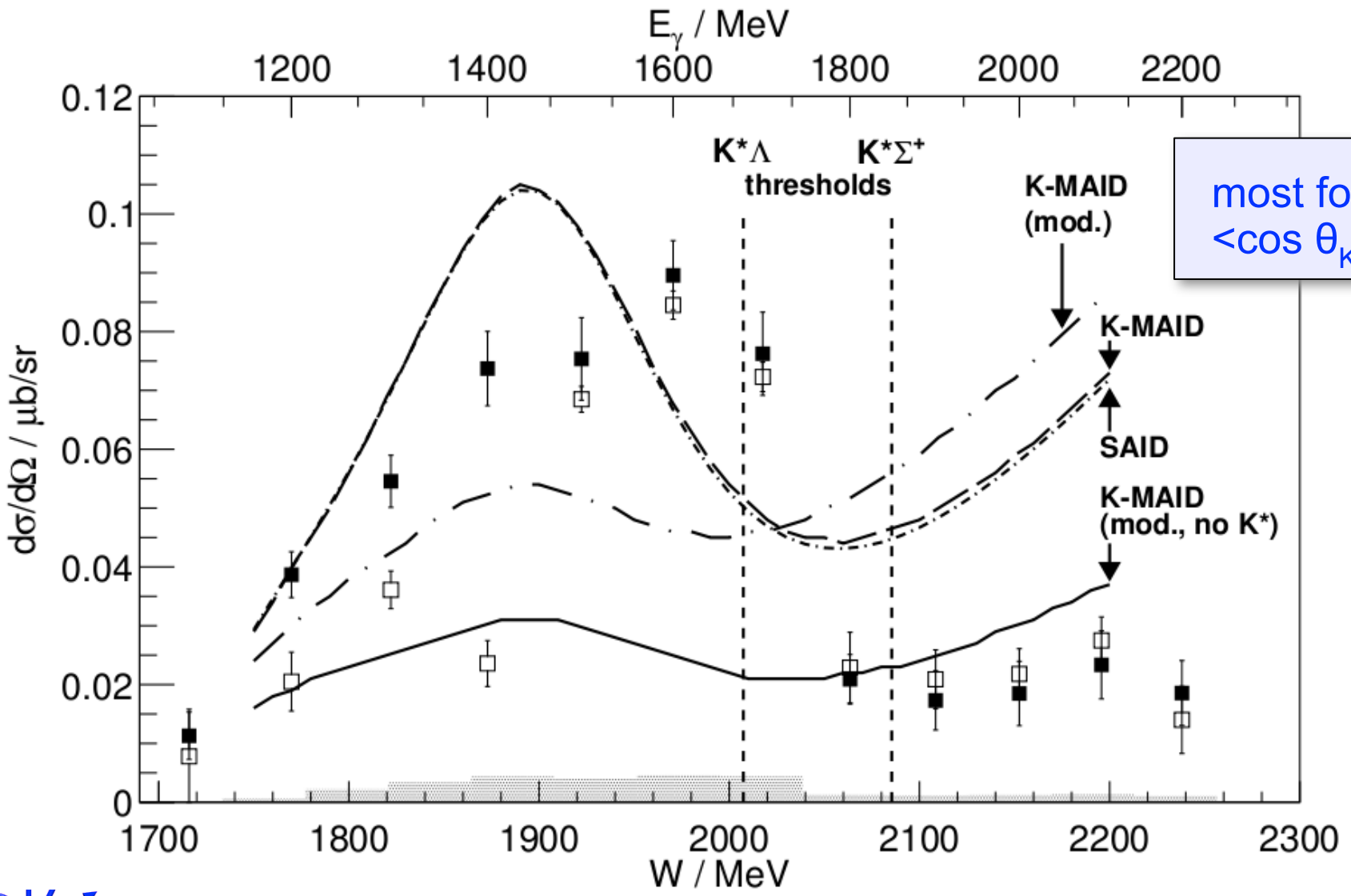
what? - (preliminary) results of BGOOD

# uds sector – threshold dynamics



# $\gamma + p \rightarrow K^0 + \Sigma^+$ anomaly @ K* threshold

R. Ewald et al. (CB/TAPS), PLB 713 (2012)




most forward bin
$\langle \cos \theta_K^{cm} \rangle = 0.83$

# γ + p -> K⁰ + Σ⁺ anomaly @ K* threshold

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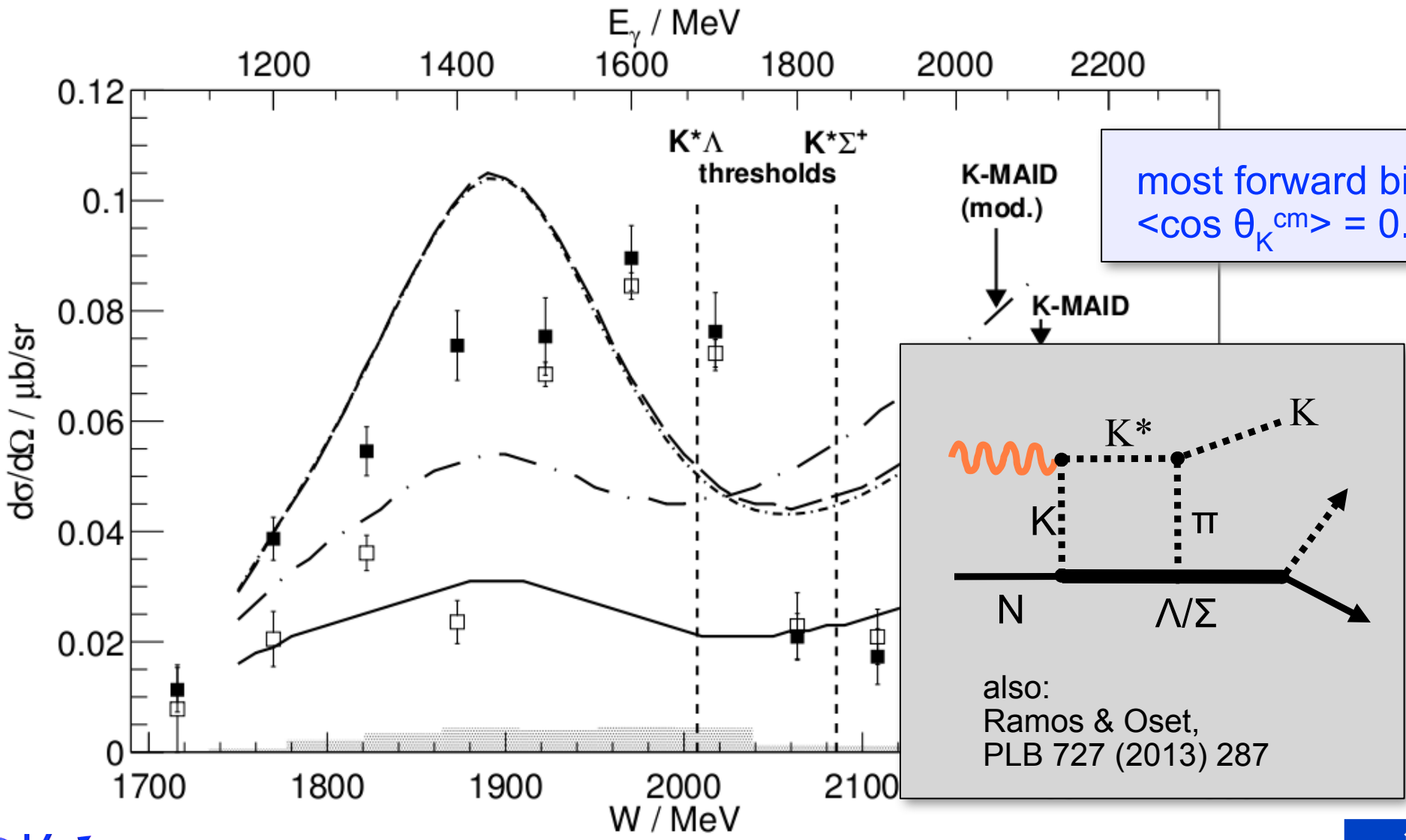


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also:
Ramos & Oset,
PLB 727 (2013) 287

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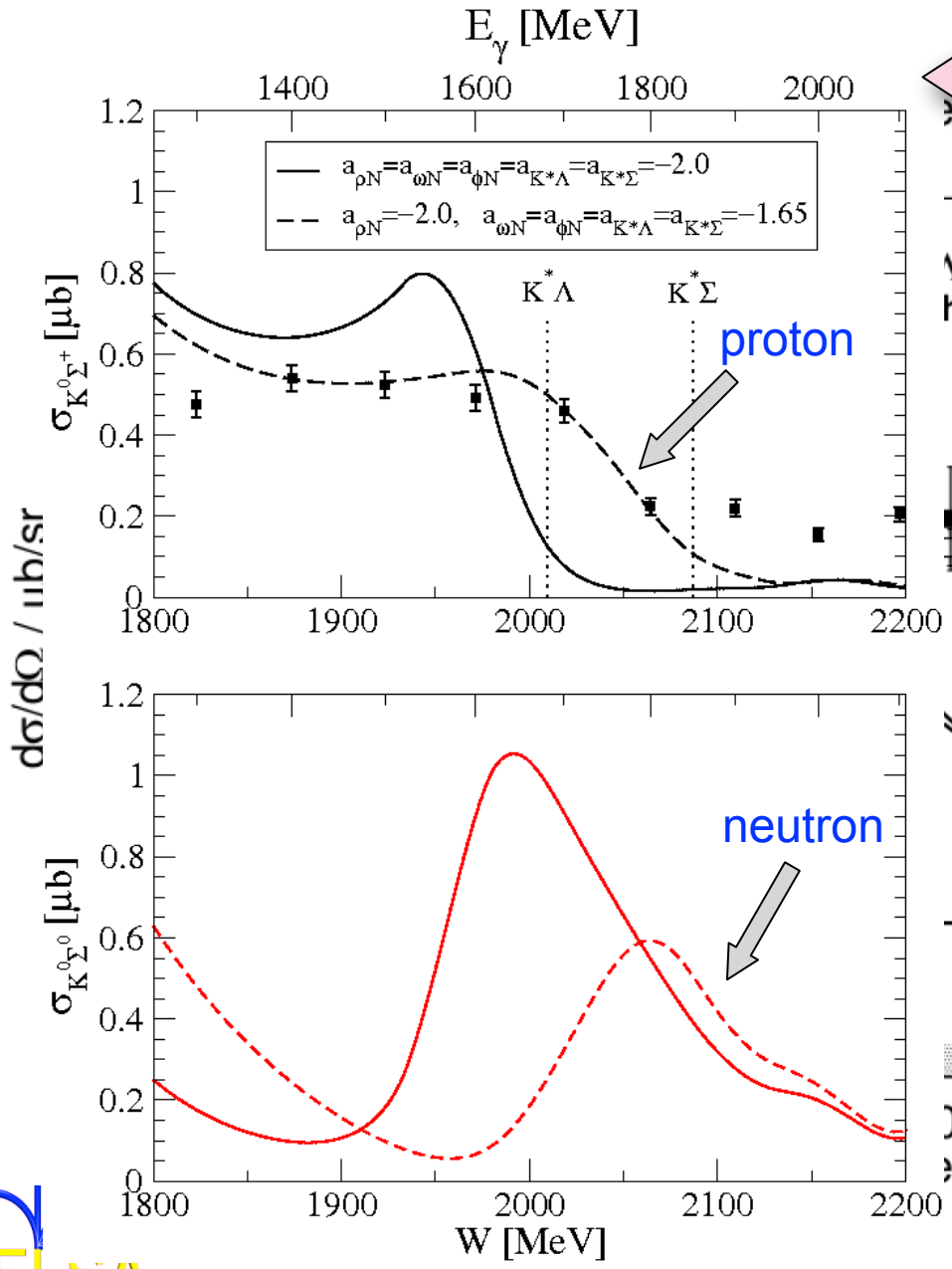
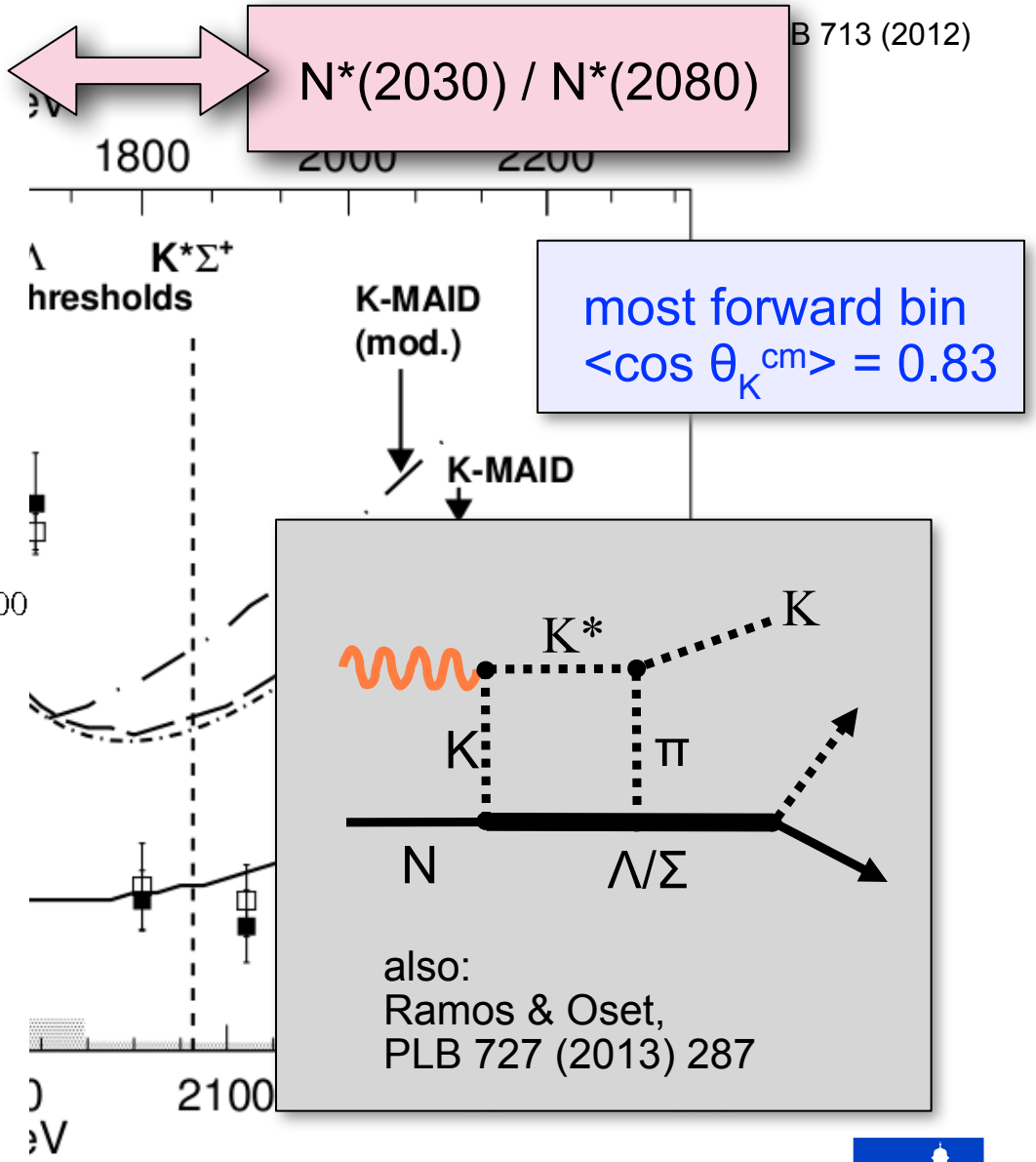
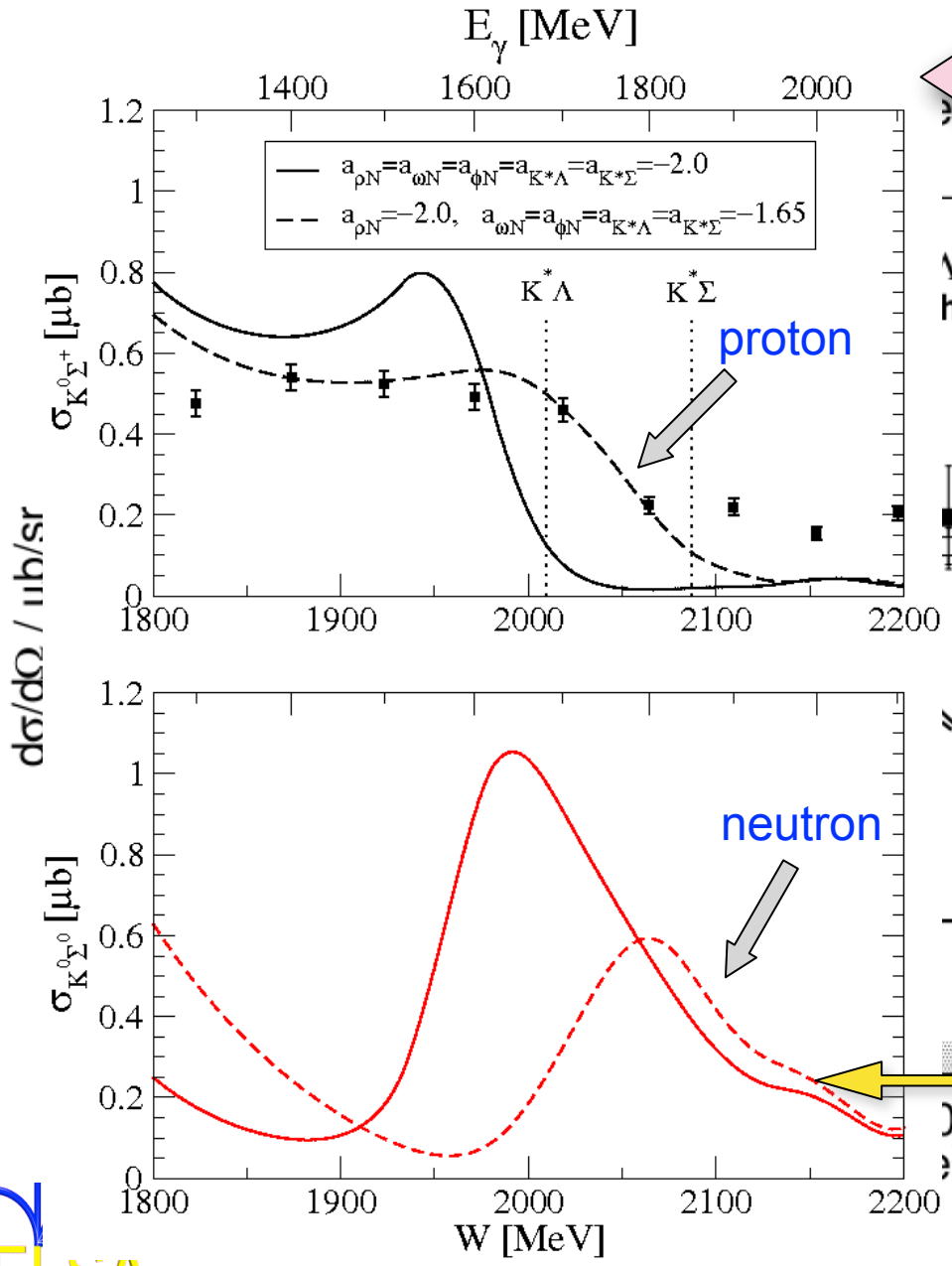
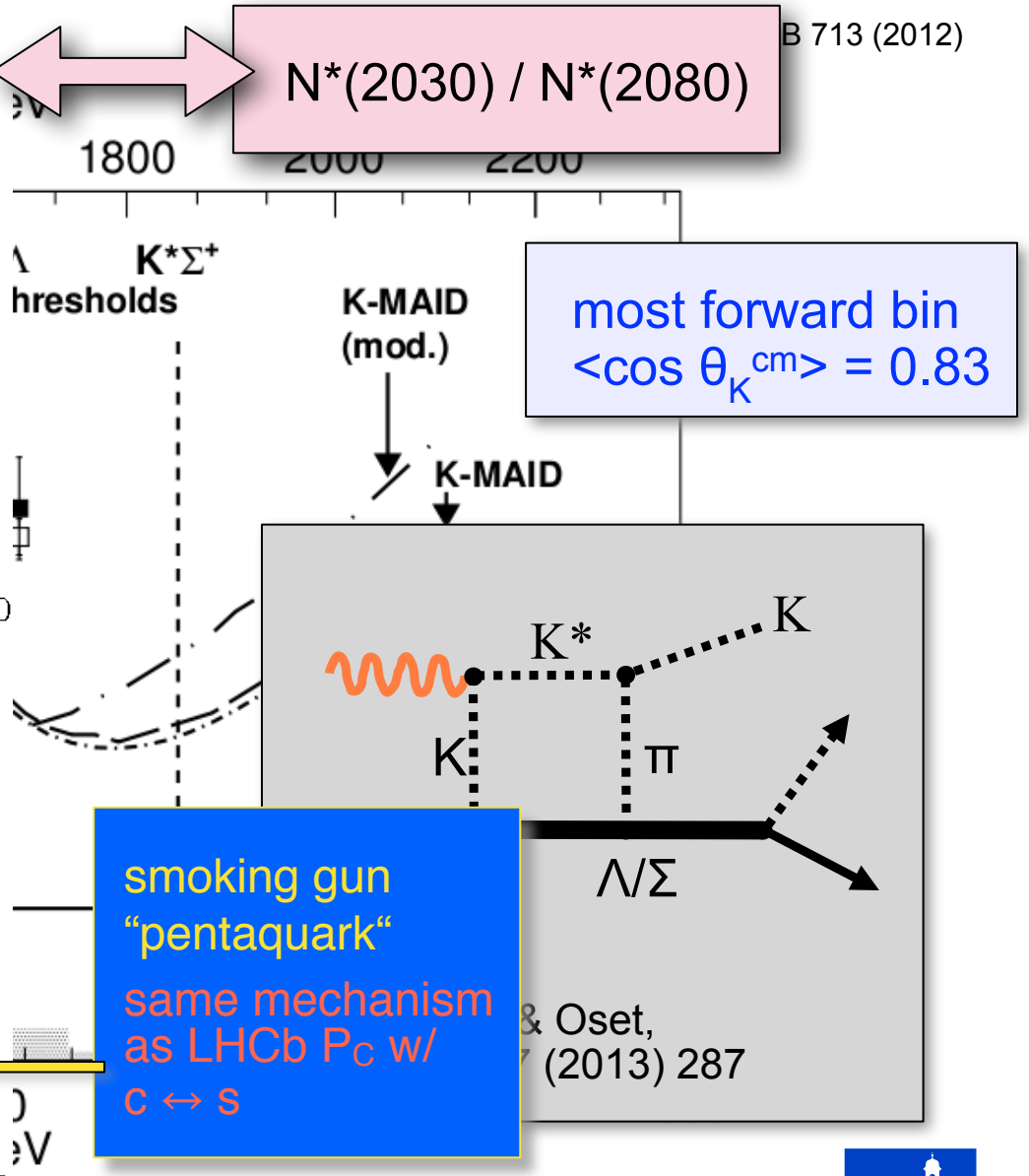


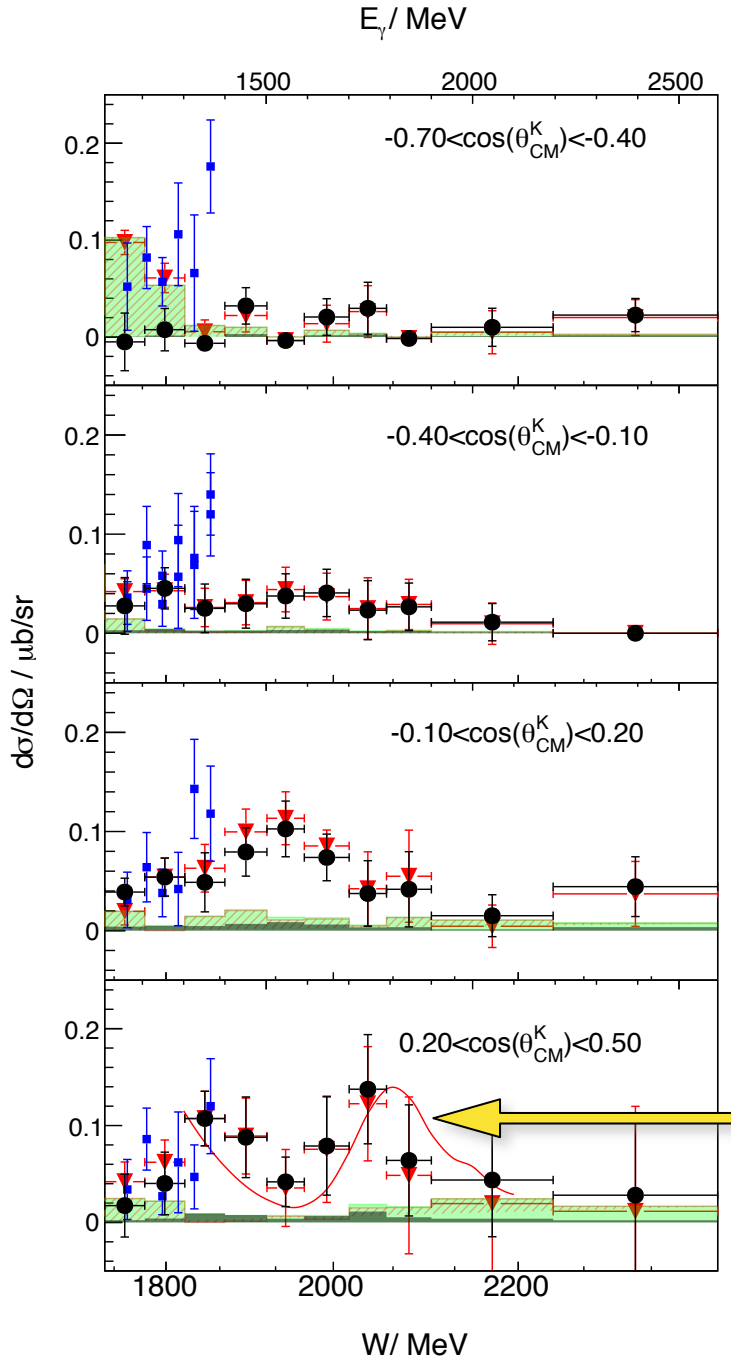
# γ + p -> K⁰ + Σ⁺ anomaly @ K* threshold



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

PhD thesis K. Kohl (Bonn 2021)
arXiv:2108.13319




data:

C. Akondi et al. [MAMI-A2]
EPJ A 55 (2019) 202

BGOOD simulated bg fit

BGOOD real bg fit

smoking gun "pentaquark"

same mechanism as LHCb $P_c$ w/ c ↔ s

see also:
"The molecular nature of some exotic hadrons"
Ramos, Feijoo, Llorens, Montaña
Few Body Sys. 61 (2020) 4, 34
arXiv:2009.04367 (2020)

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

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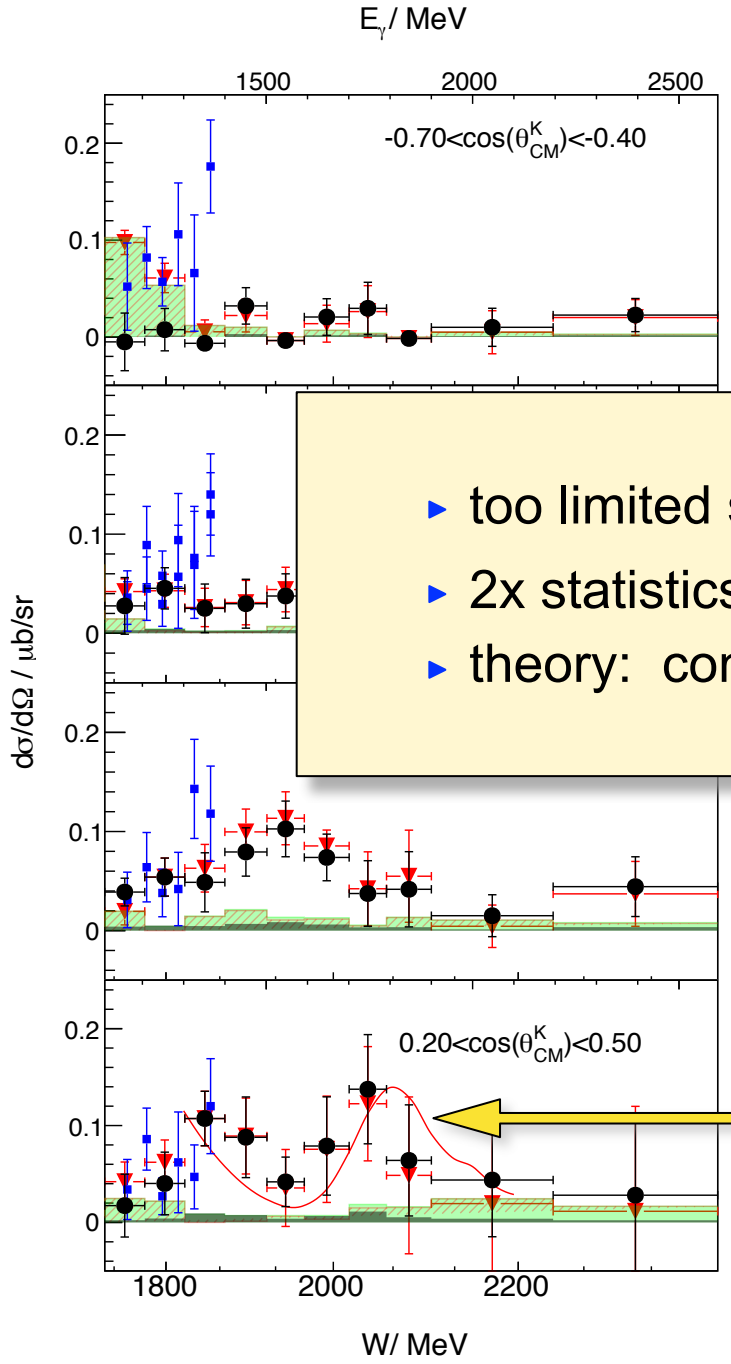


data:

- too limited statistics 😕
- 2x statistics on disc 😀
- theory: compare differential cross sections

smoking gun "pentaquark"

same mechanism as LHCb $P_C$ w/ $c \leftrightarrow s$

see also:
"The molecular nature of some exotic hadrons"
Ramos, Feijoo, Llorens, Montaña
Few Body Sys. 61 (2020) 4, 34
arXiv:2009.04367 (2020)

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# Λ(1405)

**Historic remark**

→ Λ(1405) predicted by Dalitz & Tuan as composed of Kaon-Nucleon
R.H. Dalitz & S.F. Tuan, PRL 2 (1959) 425

→ discovered 1961 in Kp → $\Sigma\pi\pi\pi$
M.H. Alston et al., PRL 4 (1961) 698

→ probably first “exotic“ hadron

ttle the decades-long
-quark state or mere
ne first interpretation.

yon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the *archetype* of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan.

# Λ(1405)

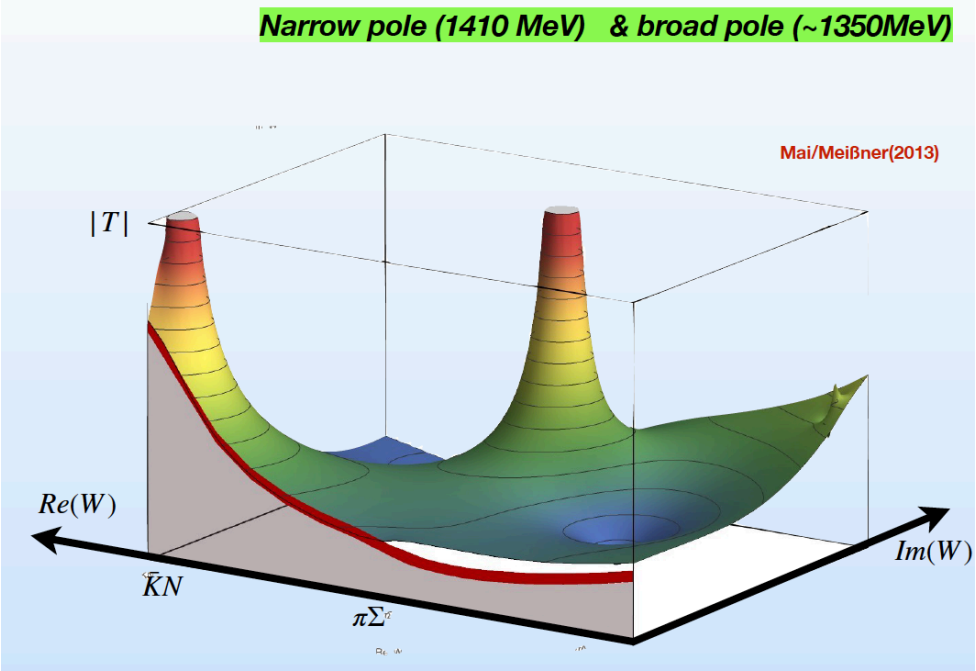
## PDG 2010

The clean $\Lambda_c$ spectrum has in fact been taken to settle the decades-long discussion about the nature of the $\Lambda(1405)$ – true 3-quark state or mere $\bar{K}N$ threshold effect? – unambiguously in favor of the first interpretation.

## PDG 2016

The $\Lambda(1405)$ resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the *archetype* of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan.

# Λ(1405) 2-pole structure in χPT




taken from Maxim Mai's talk at NSTAR 2019 (Baryon ChPT)

Oller/Meißner (2001)

- *Relativistic re-summation of chiral potential*
- *Two-poles on II Riemann Sheet* → **Now part of PDG**

Kaiser/Siegel/Weise (1995) Oset/Ramos (1998)

- *Lippmann-Schwinger equation for $K^-p$,Σπ,Λπ*
- *Potential from Chiral Lagrangian*

*"Thus, a potential derived from chiral dynamics with interaction ranges commensurate with the meson-baryon system necessarily produces a quasi-bound state or resonance below or near the $K^-p$ threshold"*

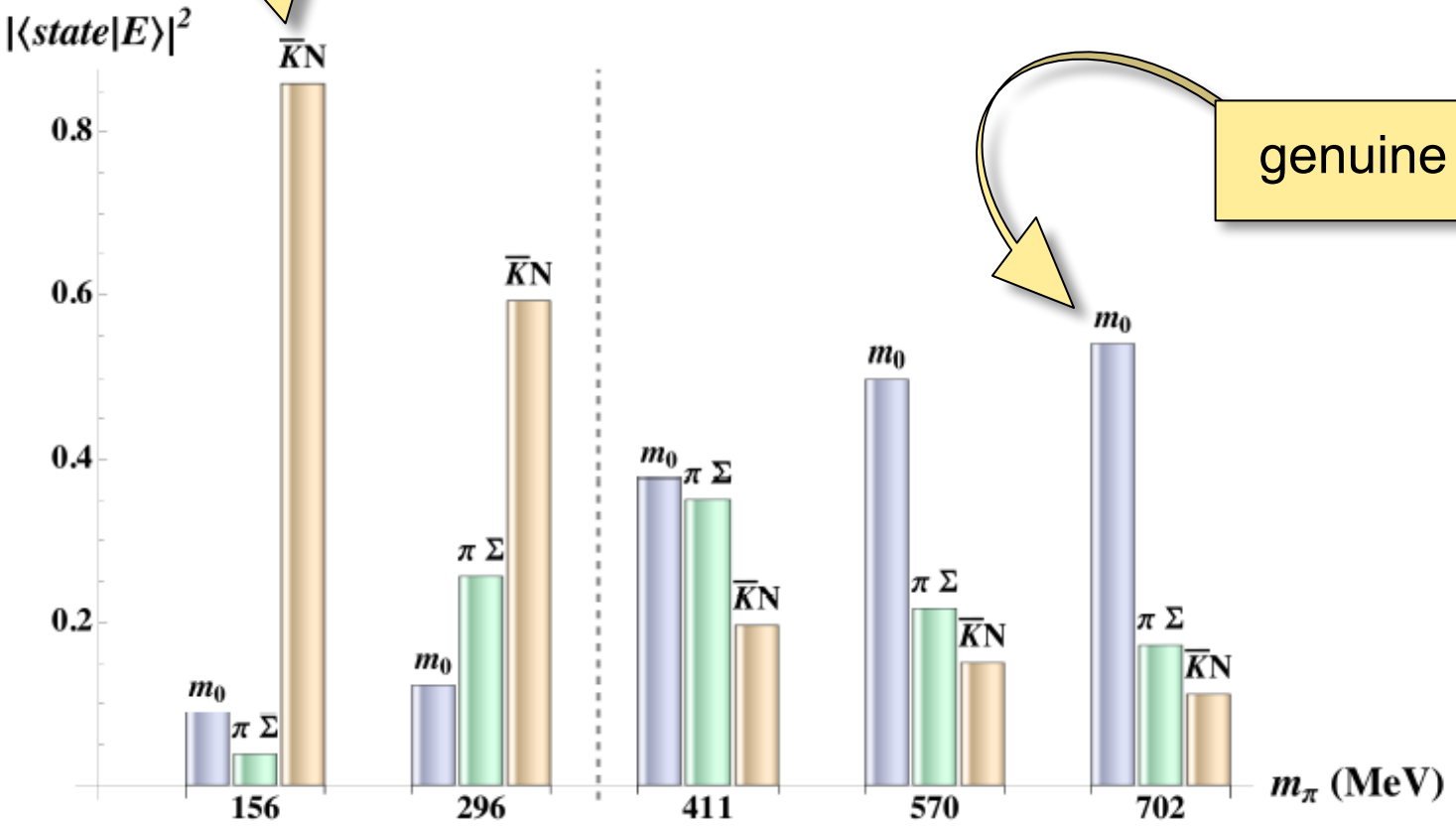
# Λ(1405) Lattice QCD

J.M.M. Hall et al. [Adelaide group],
Phys. Rev. Lett. 114 (2015) 132002

UχPT see also:
R. Molina & M. Döring,
PR D94 (2016) 056010
& 079901

"molecule" as dominating Fock component

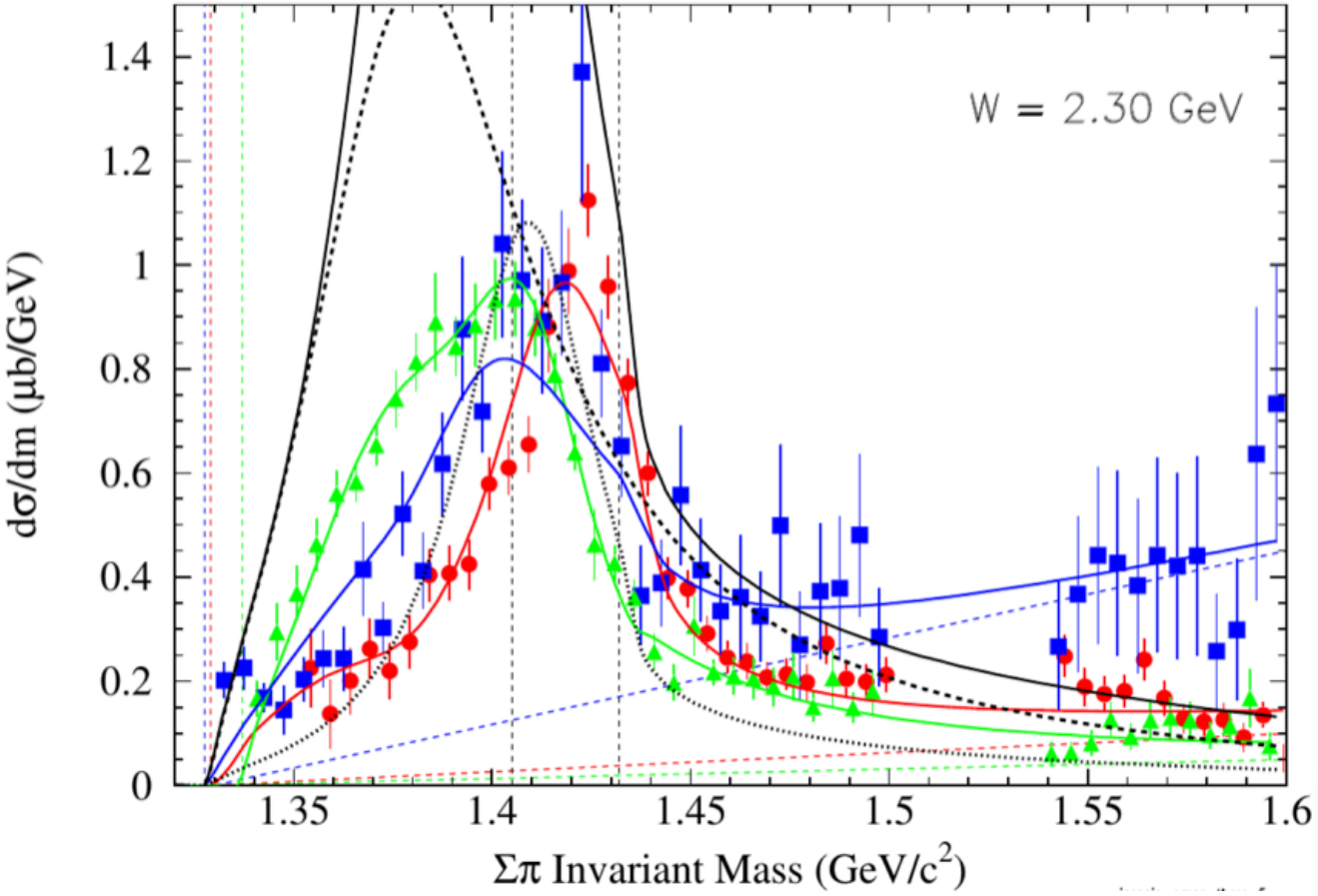
genuine 3q



# $K^+ \Lambda(1405)$ experimental status

## Λ(1405) photoproduction – line shape

$\Lambda(1405) \rightarrow \Sigma^0\pi^0$
$\Sigma^+\pi^-$
$\Sigma^-\pi^+$




- two pole structure predicted & confirmed
- different line shapes in $(\Sigma\pi)^0$ channels confirmed

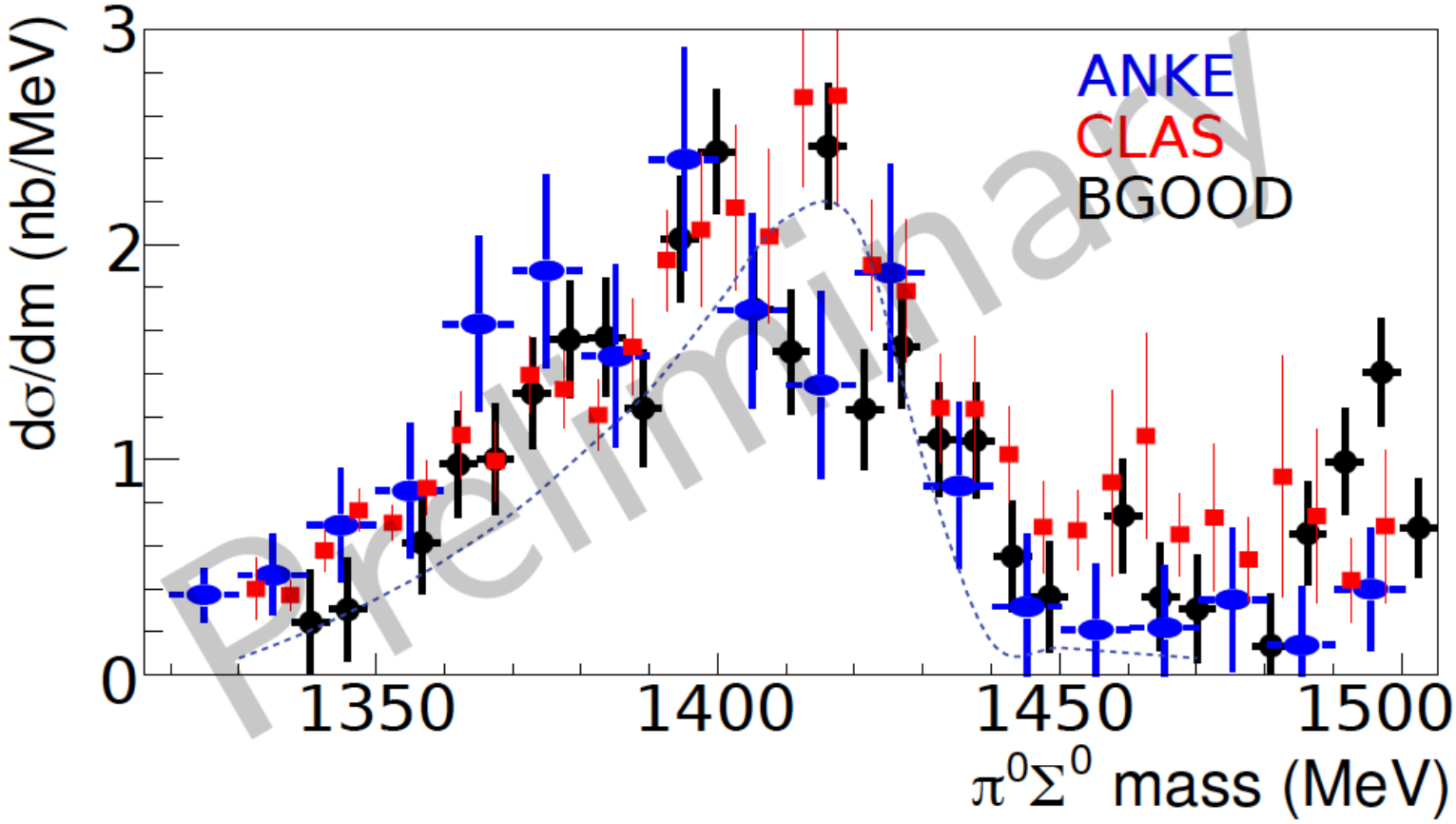
2-poles structure should be visible in pure I=0 channel $\Sigma^0\pi^0$

R.A.Schumacher et al. Nucl.Phys.A. 914,51–59 (2013)
K. Moriya et al., Phys. Rev. **C 88**, 045201 (2013)
theory: J.A. Oller & U.-G. Meißner, PLB 500 (2001) 263

# $K^+$ Λ(1405)

## Λ(1405) photoproduction – line shape

G. Scheluchin *et al.* [BGOOD collab.]
arXiv:2108.12235 (2021)

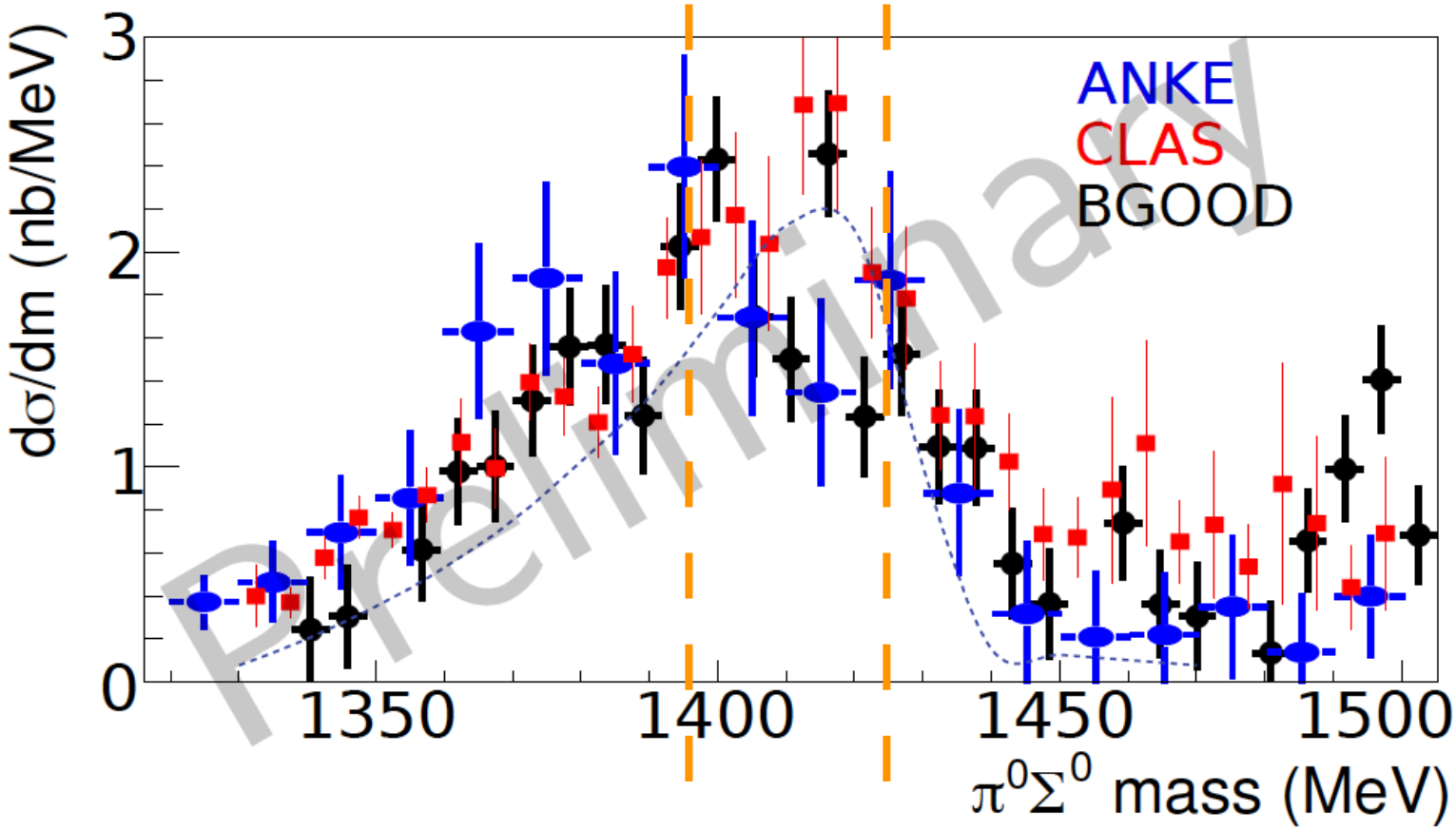


# $K^+ \Lambda(1405)$

## Λ(1405) photoproduction – line shape

G. Scheluchin *et al.* [BGOOD collab.]
arXiv:2108.12235 (2021)

double peak strukture
@ 1395 / 1425 MeV ??



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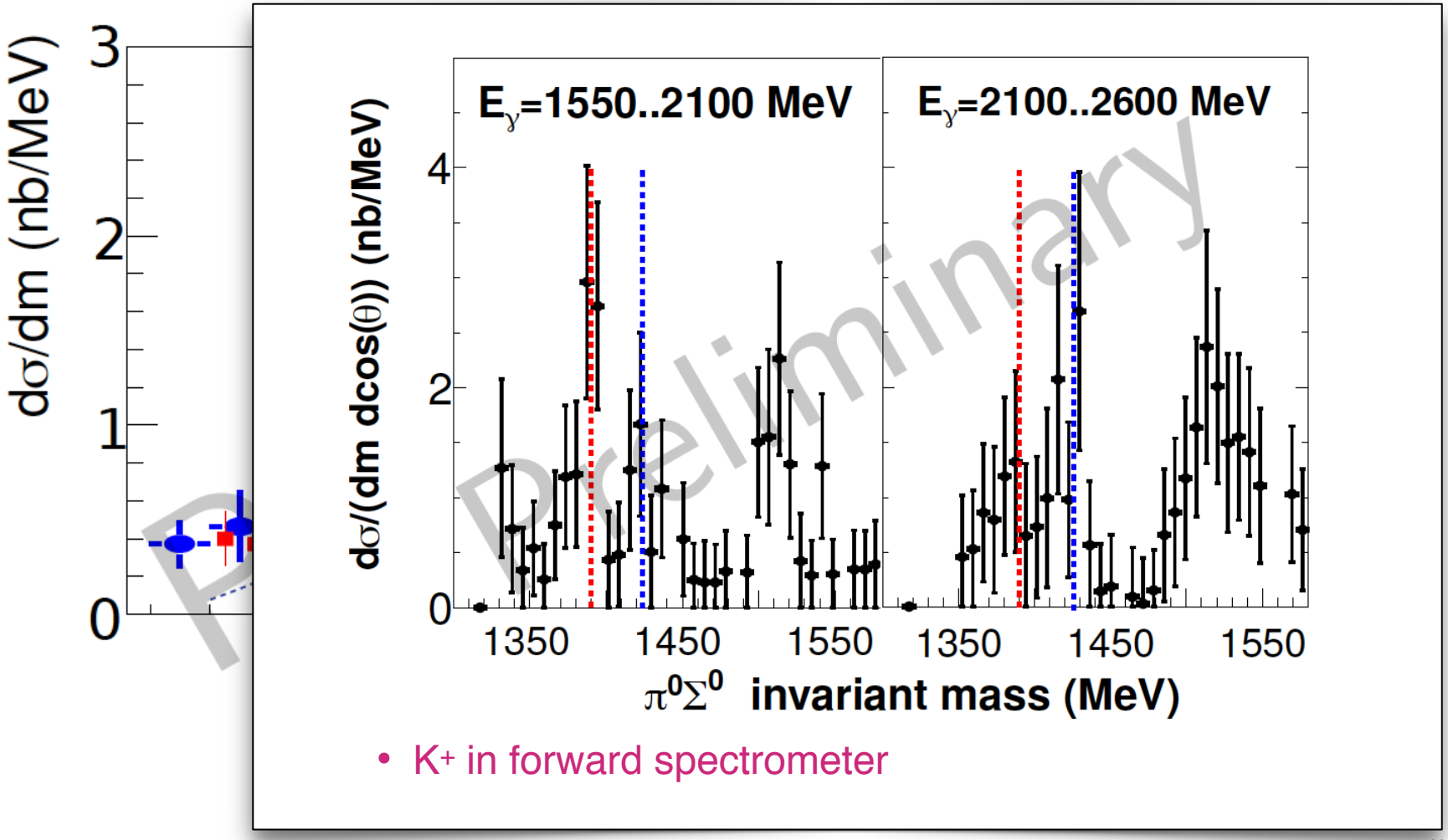
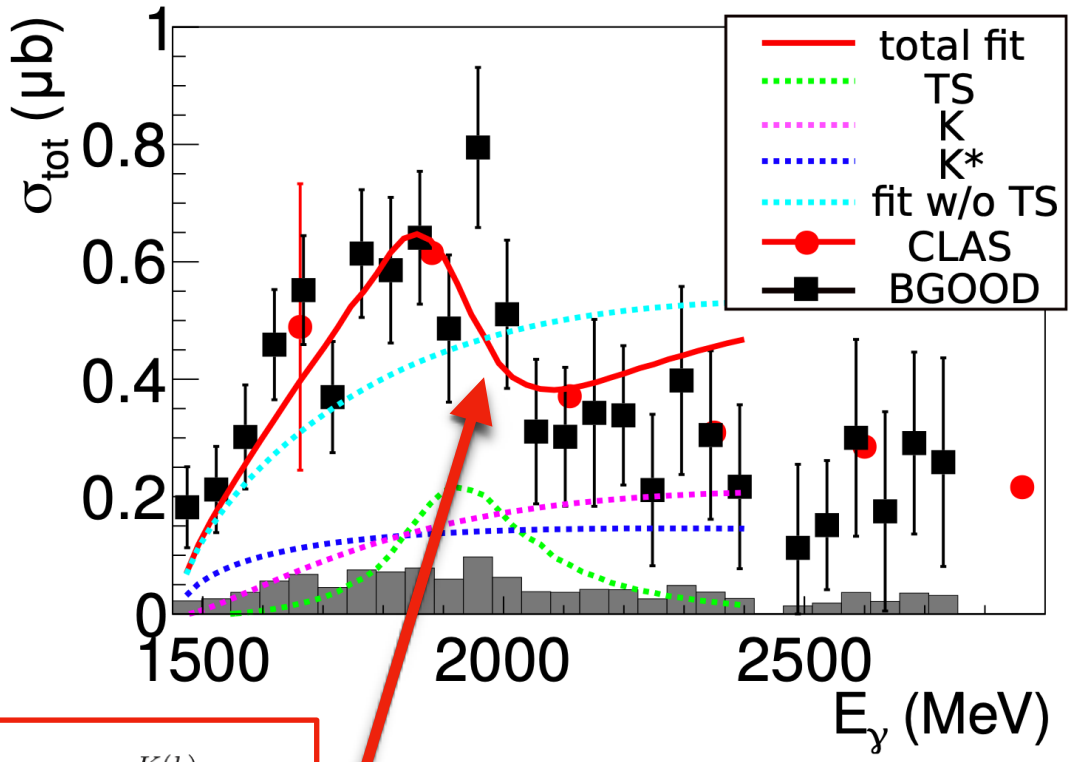


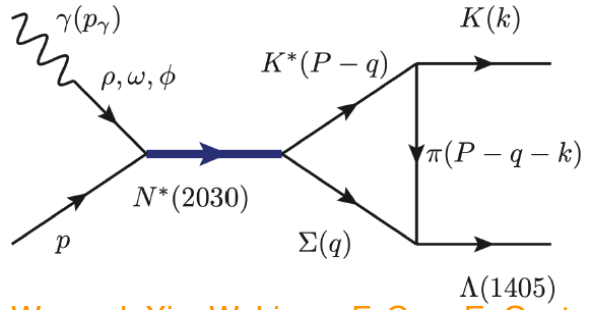

- $K^+$ in forward spectrometer

# $K^+ \Lambda(1405)$

## $K^+ \Lambda(1405)$ photoproduction – total x-sec

G. Scheluchin *et al.* [BGOOD collab.]
arXiv:2108.12235 (2021)

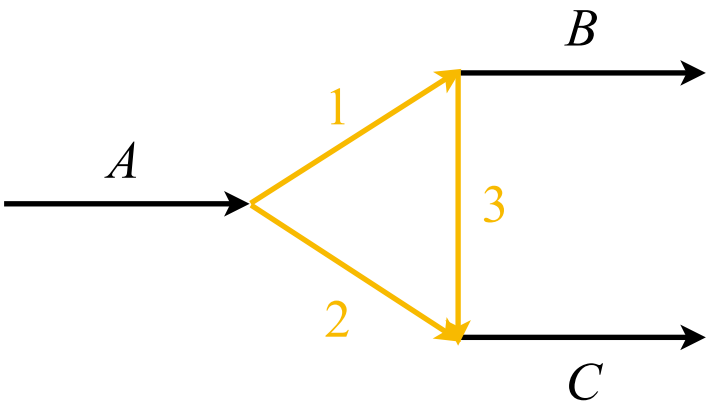



E. Wang, J. Xie, W. Liang, F. Guo, E. Oset,
PR C 95 (2017) 015205

cusp: triangle meachanism significant

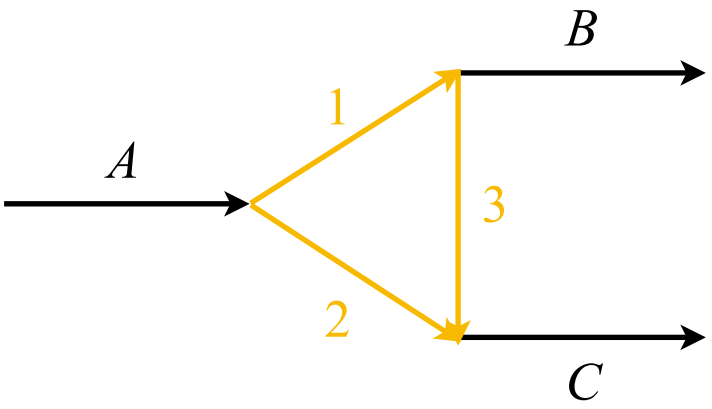
# triangle singularity




Coleman-Norton theorem,
Il Nuovo Cimento 38 (1965) 438:
1, 2, 3 must be nearly on mass shell

can mimic resonance

# triangle singularity

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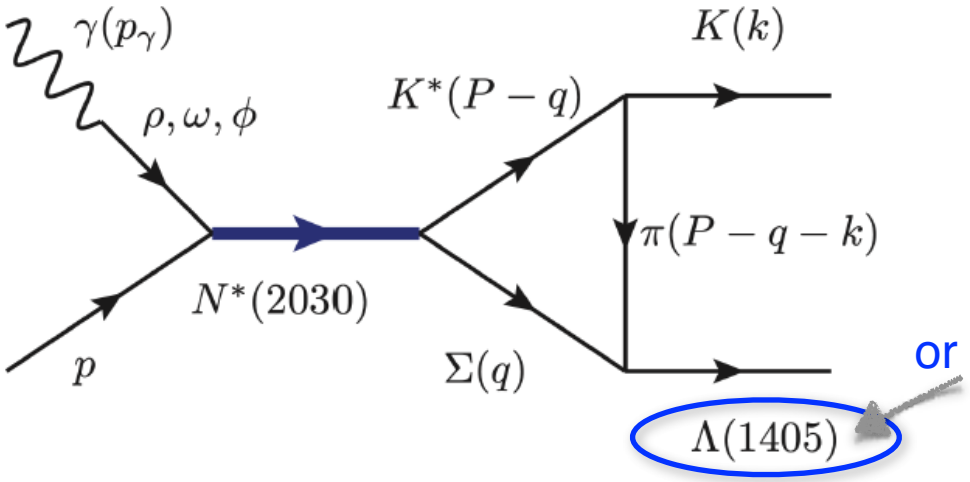
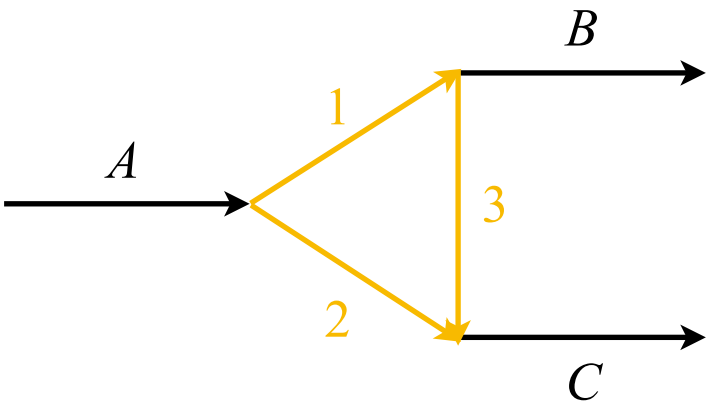



or drive (dynamically generated) resonance

E. Wang, J. Xie, W. Liang, F. Guo, E. Oset,
PR C 95 (2017) 015205

# triangle singularity

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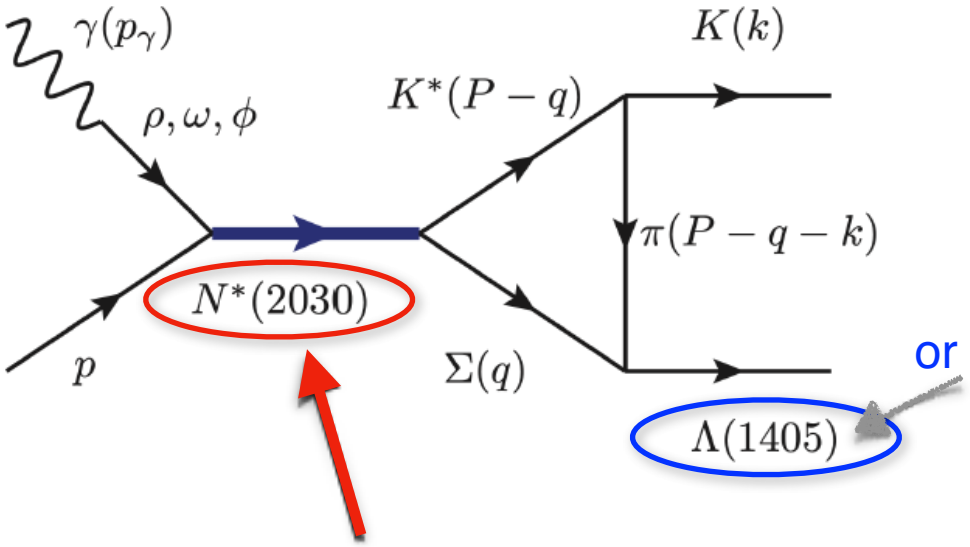


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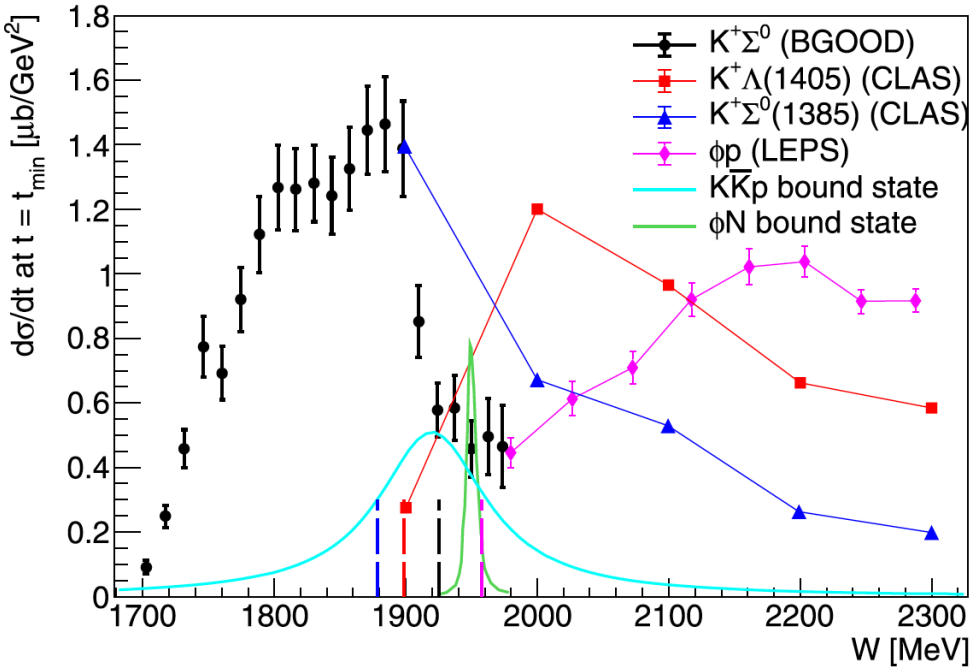
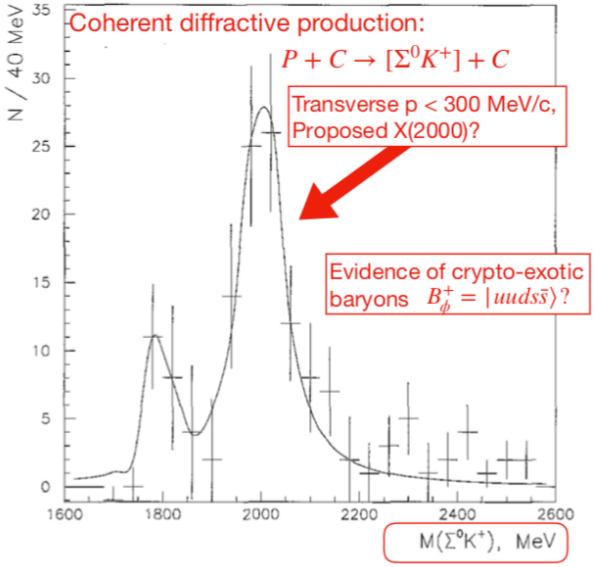
E. Wang, J. Xie, W. Liang, F. Guo, E. Oset,
PR C 95 (2017) 015205

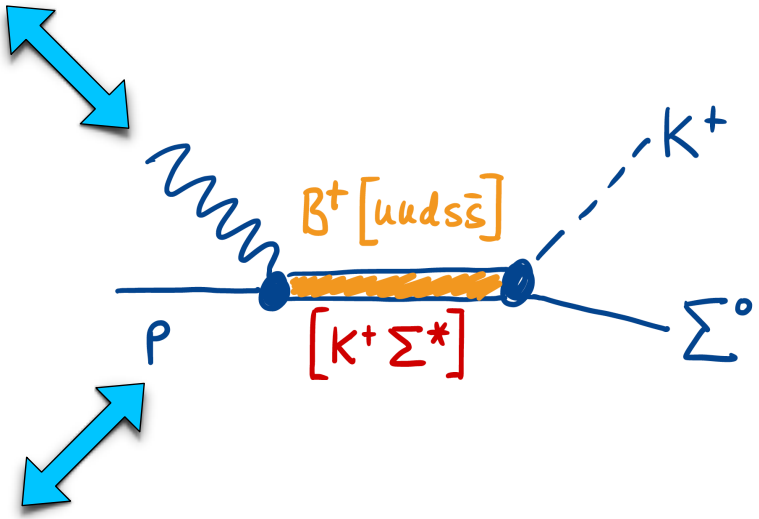
$K^*\Sigma$ suspect in $K^0\Sigma^0$ channel

# $\gamma\, p \to K^+\, \Sigma^0$ photoproduction



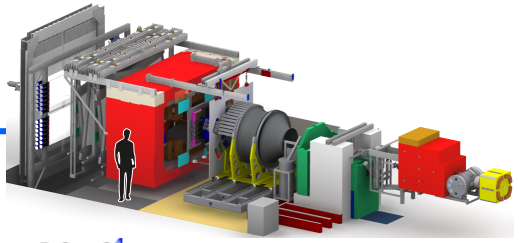

T. Jude *et al.* [BGOOD collab.]
Phys. Lett B 820 (2021) 136559




S.V. Golovkin *et al.* [SPHINX collab.]
Z. Phys. C 68 (1995) 585

# BGOOD collaboration




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[5], 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
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[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 P.Giuria 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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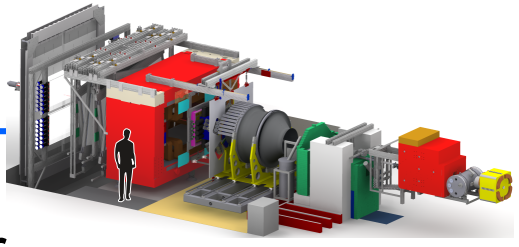
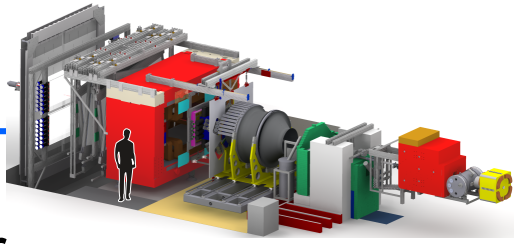
# Conclusions



- multi-quark objects established in (hidden) c sector
- plausible parallels in (hidden) s sector
- BGOOD ideally suited to pursue this: thresholds & low t
- $K^+ \Lambda(1405)$
  - line shape in I = 0: double peak ??
  - photoproduction cross section: triangle driven !!
  - indication of LHCb analogous $K^*\Sigma$ „multi-quark“ state ??
- also appearing in $K^0 \Sigma^0$ ?? – similar in $K^+\Sigma$ ??
- not shown: $K^+\Lambda$ & non-strange channels
- BGOOD debut results
  - overlap regions: on par with best to-date measurements
  - unique regions: qualitatively new effects
  - more to come …

# Conclusions



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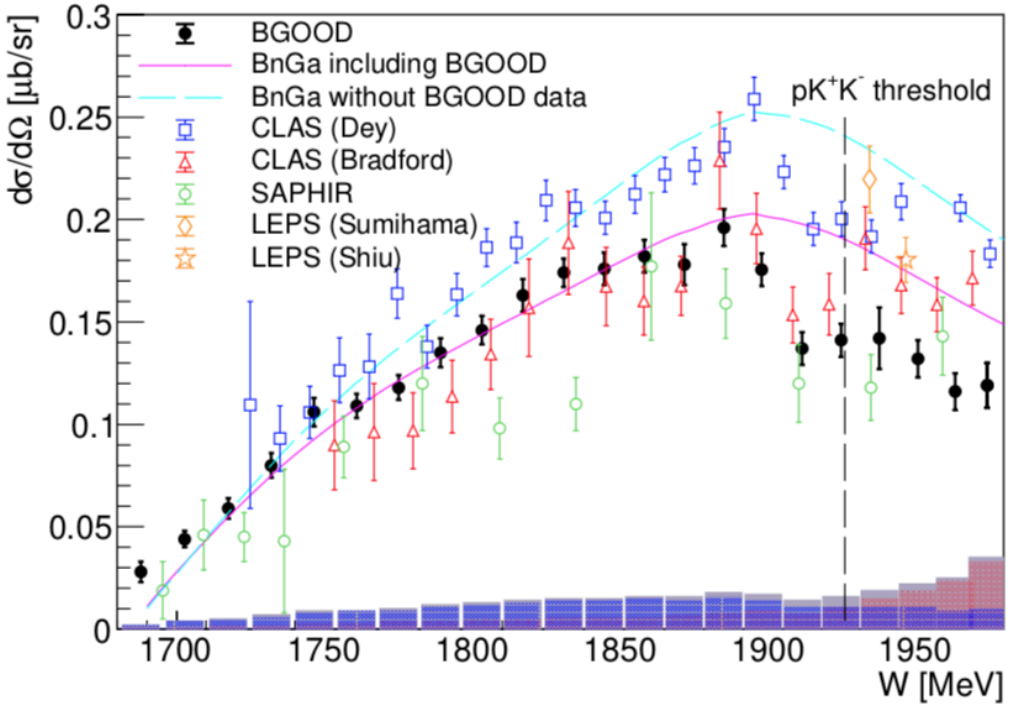
  - more to come …

THANKS for your attention

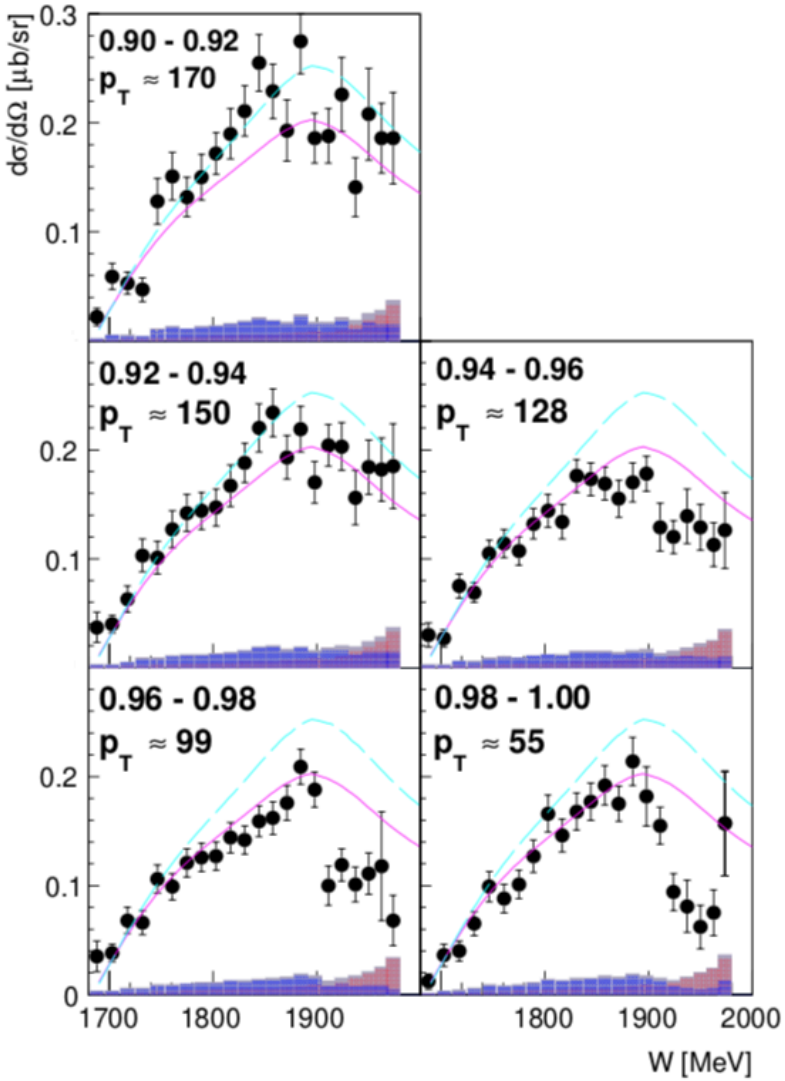
# BACKUP

# $\gamma p \to K^+ \Sigma^0$ photoproduction

T. Jude *et al.* [BGOOD collab.]
Phys. Lett B 820 (2021) 136559




Bradford *et al.* (CLAS), PRC 73, 035202 (2006), Dey *et al.* (CLAS), PRC 82, 025202 (2010), Glander *et al.* (SAPHIR), EPJA 19, 251 (2004), BnGa PWA - without BGOOD/with BGOOD



# Status N* spectroscopy

- missing resonances ?
- relevant degrees of freedom ?

- 3 const. quarks unlikely
- quark – diquark ??
- meson d.o.f. ?

e.g.

L.Ya. Glozman and D.O. Riska,
Phys. Rep. 268 (1996) 263

C. Garcia-Recio et al., PLB 582 (2004) 49

M. Lutz, E. Kolomeitsev, PLB 585 (2004) 243

| | | PDG status in | |
|---|---|---|---|
| state | $J^P$ | 2010 | 2020(Nγ) |
| N(1860) | $5/2^+$ | * | * |
| N(1875) | $3/2^-$ | | ** |
| N(1880) | $1/2^+$ | | ** |
| N(1895) | $1/2^-$ | | **** |
| N(1900) | $3/2^+$ | **** | **** |
| N(1990) | $7/2^+$ | ** | ** |
| N(2000) | $5/2^+$ | ** | ** |
| N(2060) | $5/2^-$ | | *** |
| N(2100) | $1/2^+$ | * | ** |
| N(2120) | $3/2^-$ | | *** |
| N(2190) | $7/2^-$ | **** | ** |
| N(2220) | $9/2^+$ | **** | ** |
| N(2250) | $9/2^-$ | **** | ** |

- inclusion of CLAS, GRAAL, MAMI, ELSA data
- confirmation of known resonances w/ improved parameters
- observation of few (!) new states

# compact size vs. “molecule“

„Hadronic molecules"
Guo, Hanhart, Meißner, Wang, Zhao, Zou
Rev. Mod. Phys. 90 (2018) 1, 015004
arXiv:1705.00141

salient features “molecule“

- Weinberg’s compositeness criterion: $\lambda = 0$ (pure molecule) …. 1 (compact)

$$a = -2\frac{1-\lambda^2}{2-\lambda^2}\left(\frac{1}{\gamma}\right) + \mathcal{O}\left(\frac{1}{\beta}\right)$$

scattering length ↔ interaction probability, i.e. x-sec

$$r = -\frac{\lambda^2}{1-\lambda^2}\left(\frac{1}{\gamma}\right) + \mathcal{O}\left(\frac{1}{\beta}\right)$$

effective range ↔ distance between constituents

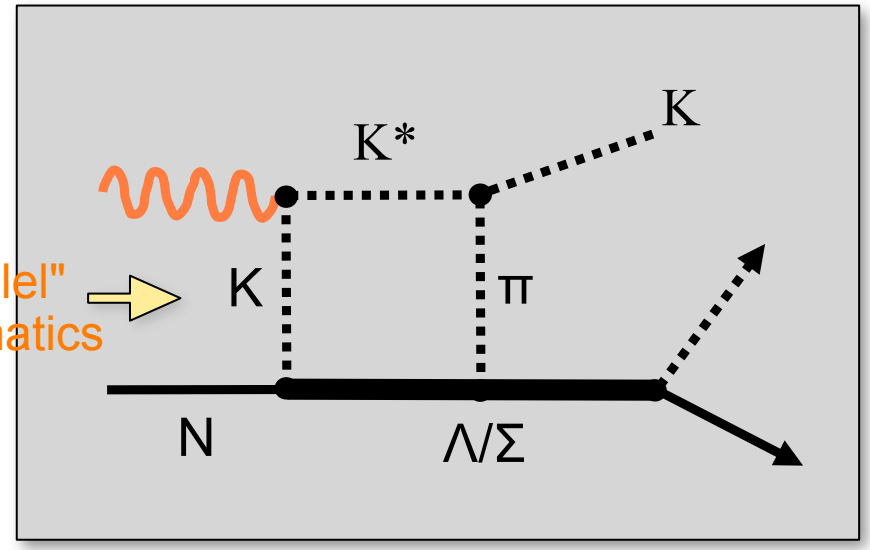
- $\gamma$ ↔ momentum scale constituents:
- $\beta$ ↔ momentum scale through forces, e.g. deuteron $1/\beta \sim 1/M_\pi \sim 1.4$ fm
- molecule natural near thresholds

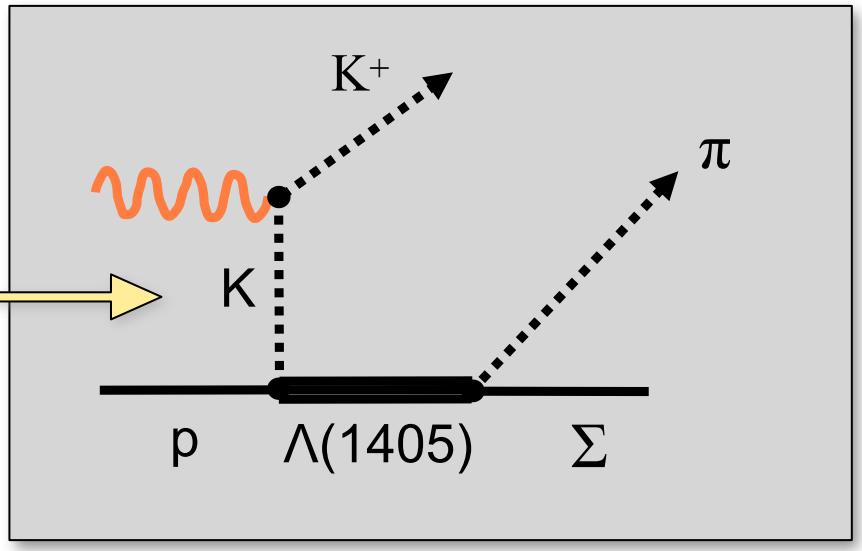
$$\gamma = \sqrt{2\mu E_B} \rightarrow \frac{1}{\gamma} \sim R$$

reduced mass, binding energy

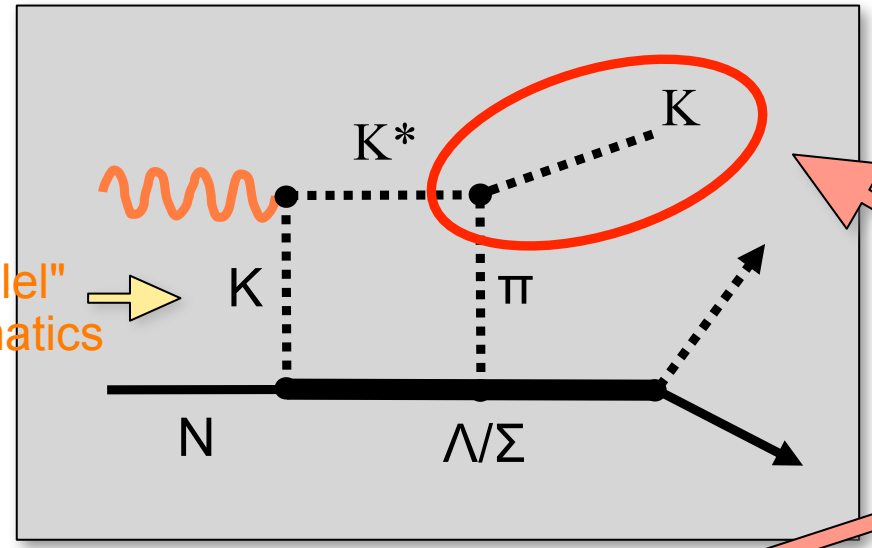
composite size

# t-channel Kinematics



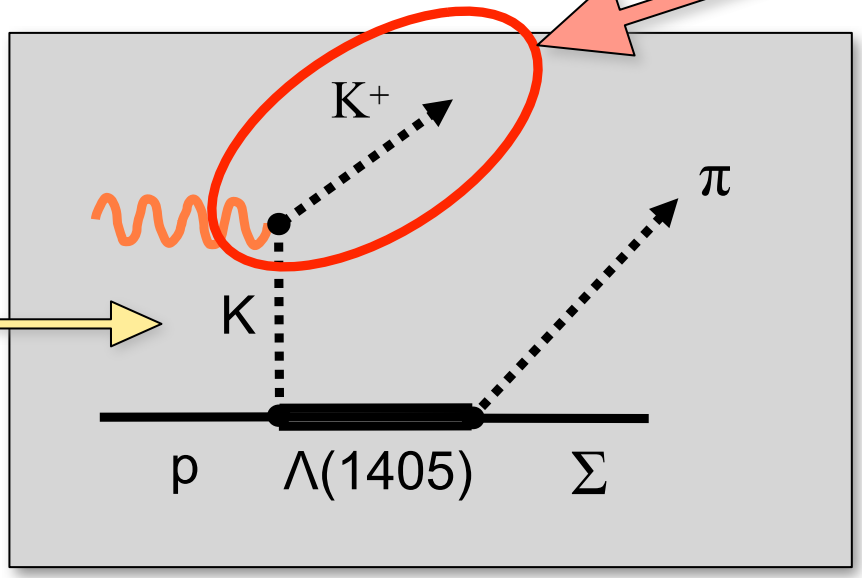



# t-channel Kinematics



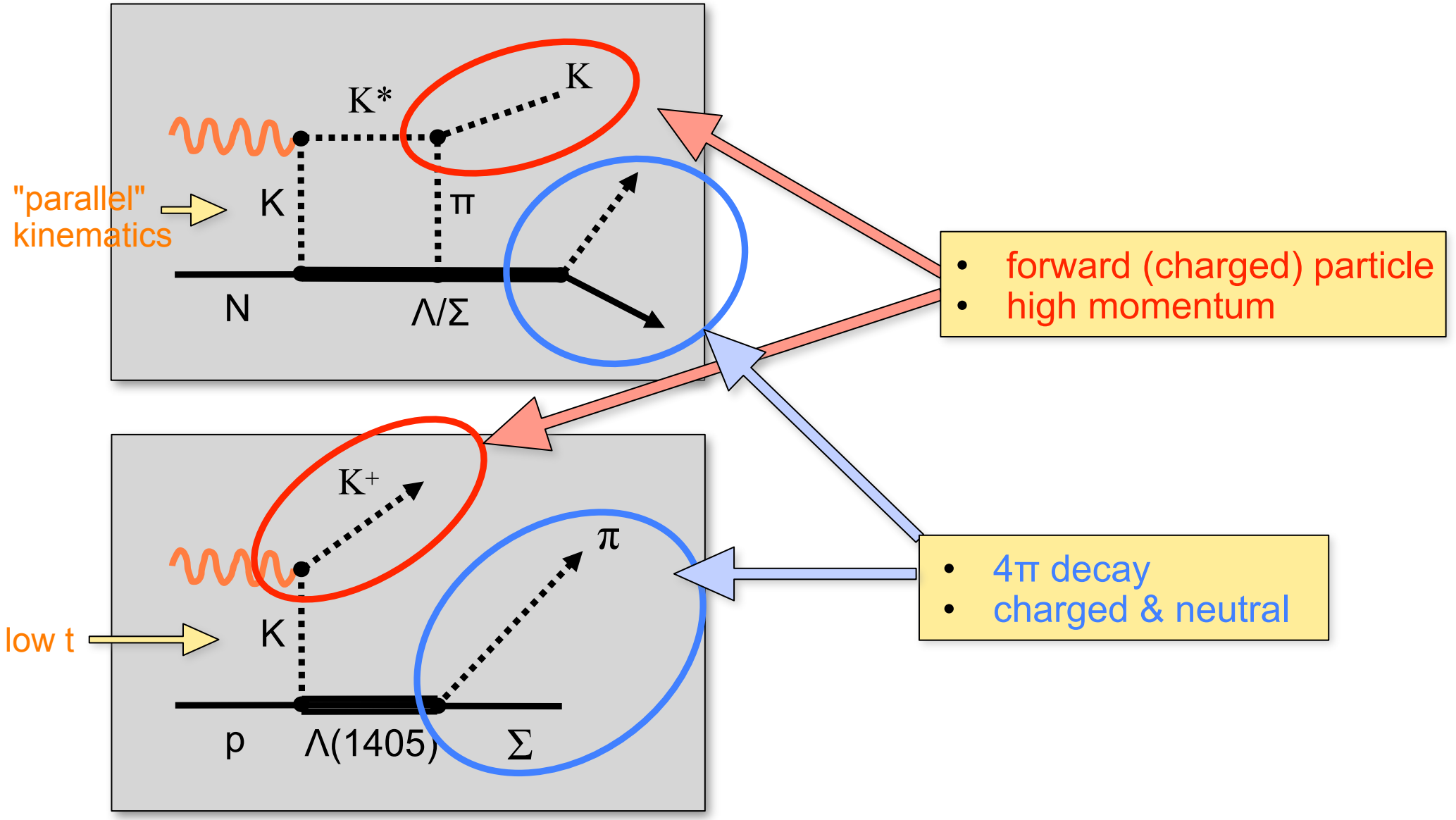

"parallel" kinematics

- forward (charged) particle
- high momentum

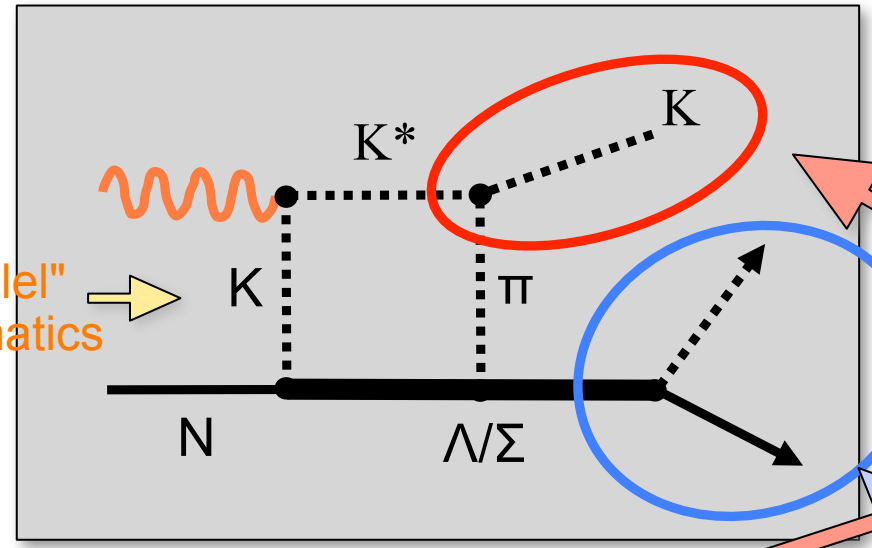



low t

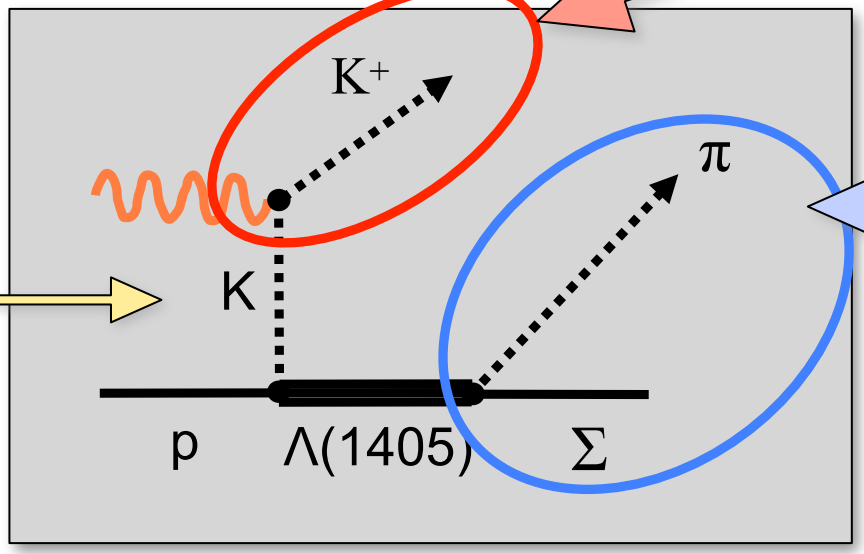
# t-channel Kinematics



# t-channel Kinematics




"parallel" kinematics




low t

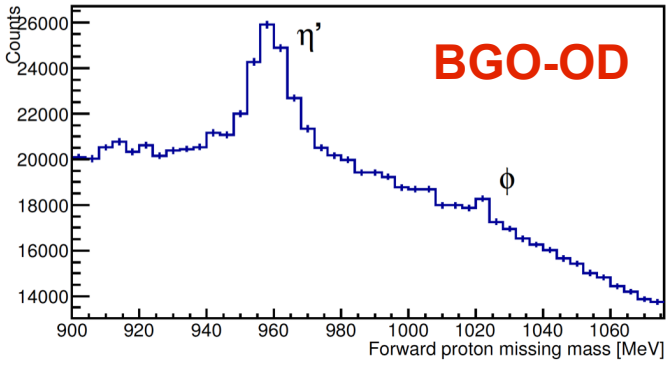
BGOOD !

- forward (charged) particle
- high momentum

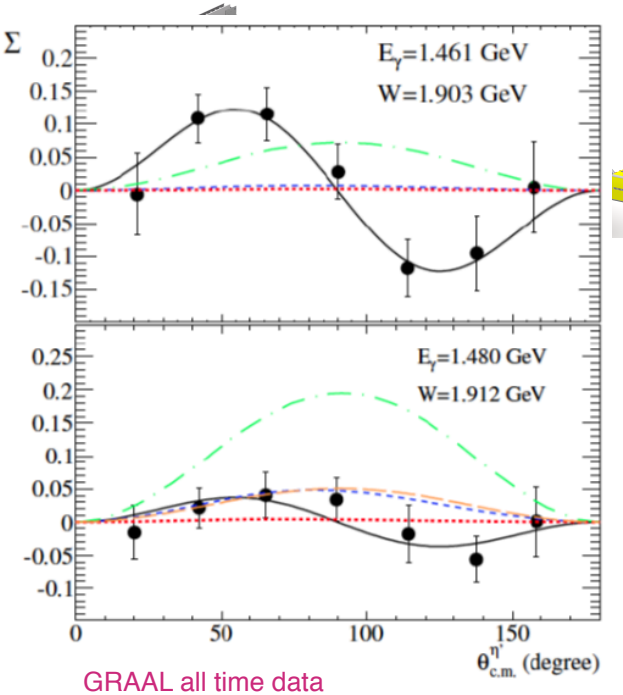
- 4π decay
- charged & neutral

# next …

- $\eta' p$ threshold → nodal structure in beam asymmetry
  → associated with sharp $\Gamma \sim 2$ MeV (!) resonance



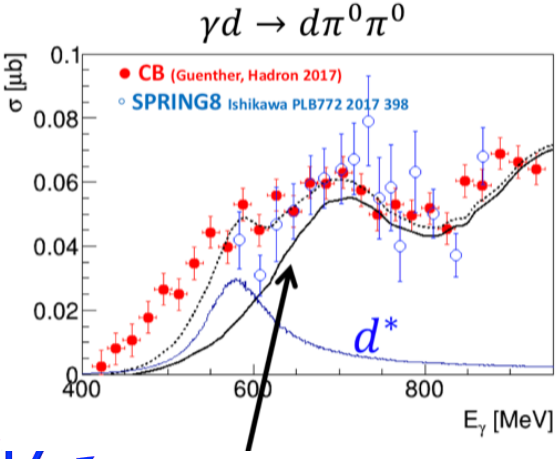

$\Theta_{lab} \lesssim 10^{o} \leftrightarrow$
$\Delta E_{thresh} \lesssim 30$ MeV




GRAAL all time data
P. Levi Sandri *et al.*, EPJ A 51 (2015) 77

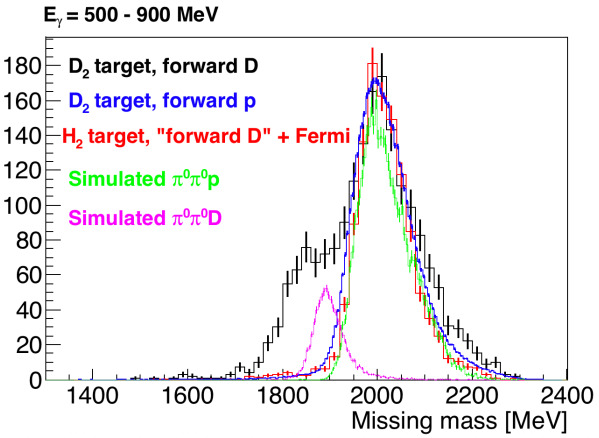
- $d^*$ suspected *hexaquark* state
  → coherent $2\pi^0$ photoproduction off deuteron

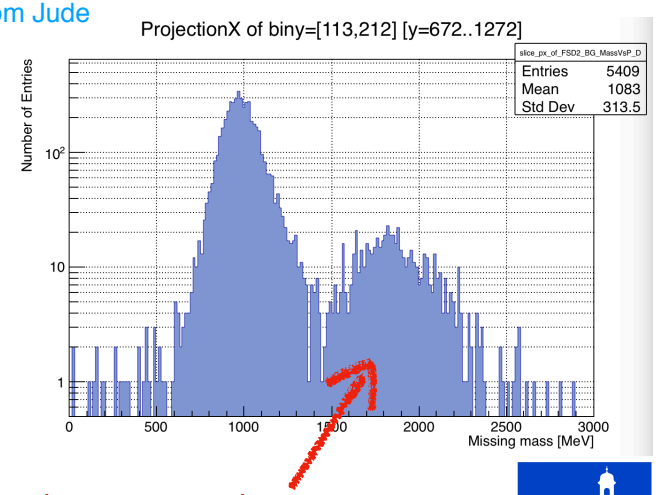
Figure from D. Watts (Crystal Ball), NSTAR 2017




conventional background
Egorov & Fix, NP A933 (2015) 104

work of Tom Jude




1st coherent deuteron reaction
@ BGOOD