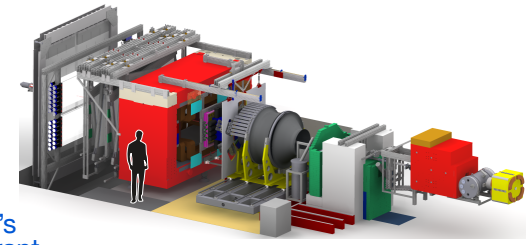
The BGOOD experiment at ELSA

- multi-quark structures in the uds sector ?

Hartmut Schmieden
Physikalisches Institut
Universität Bonn

Outline

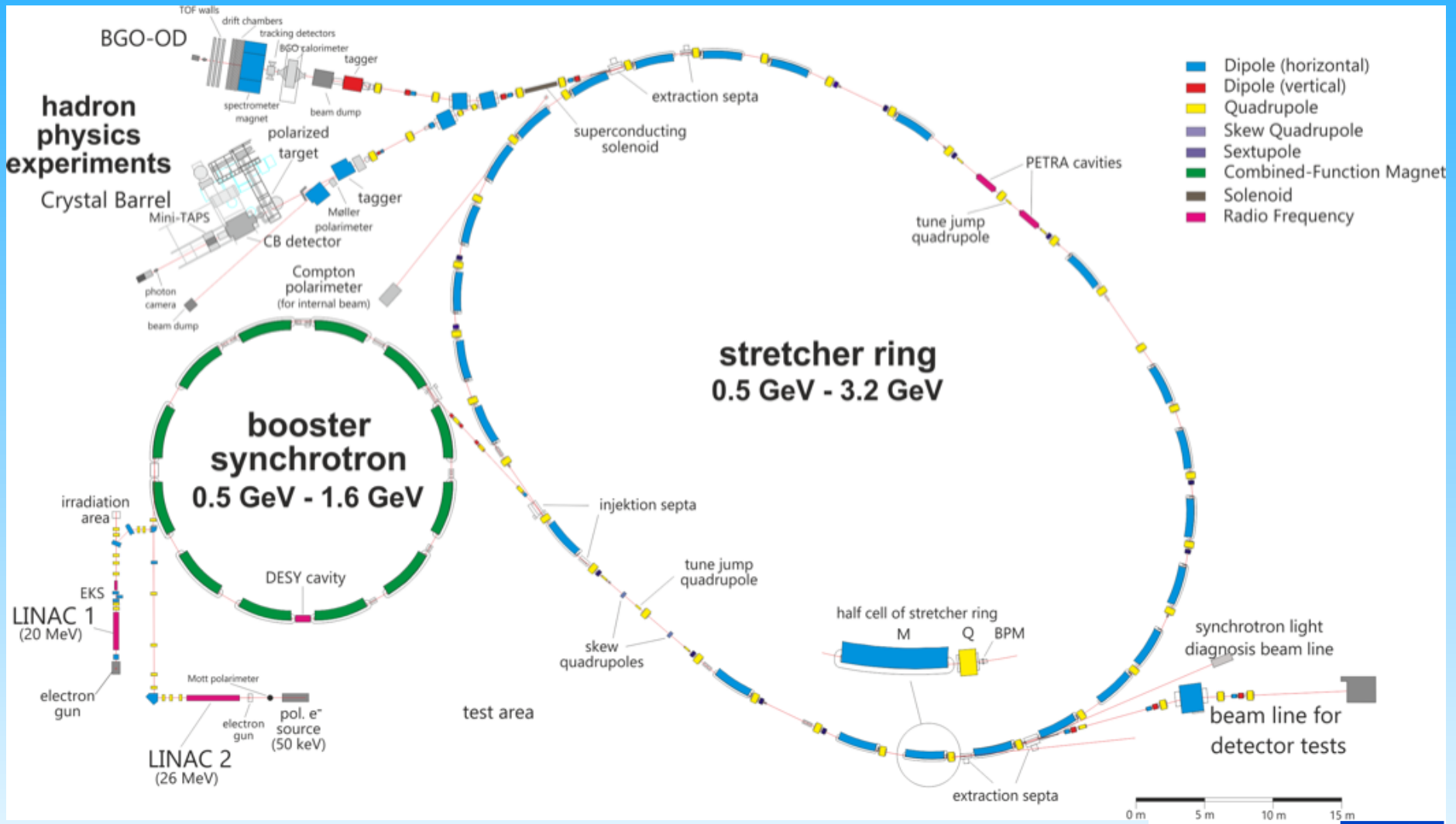
- BGOOD experiment
- physics case
- selected results
- conclusions



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
Universität Bonn



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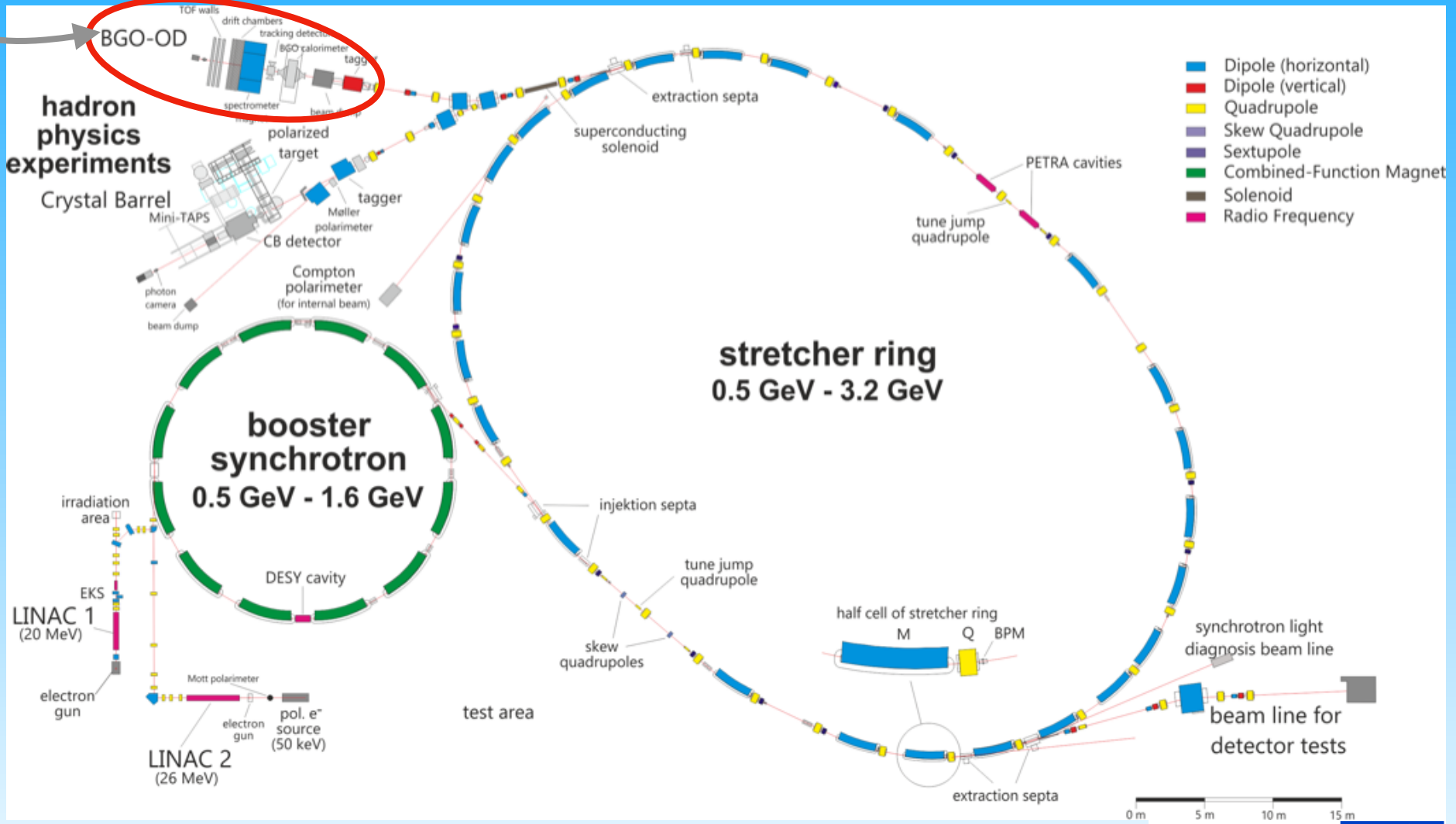

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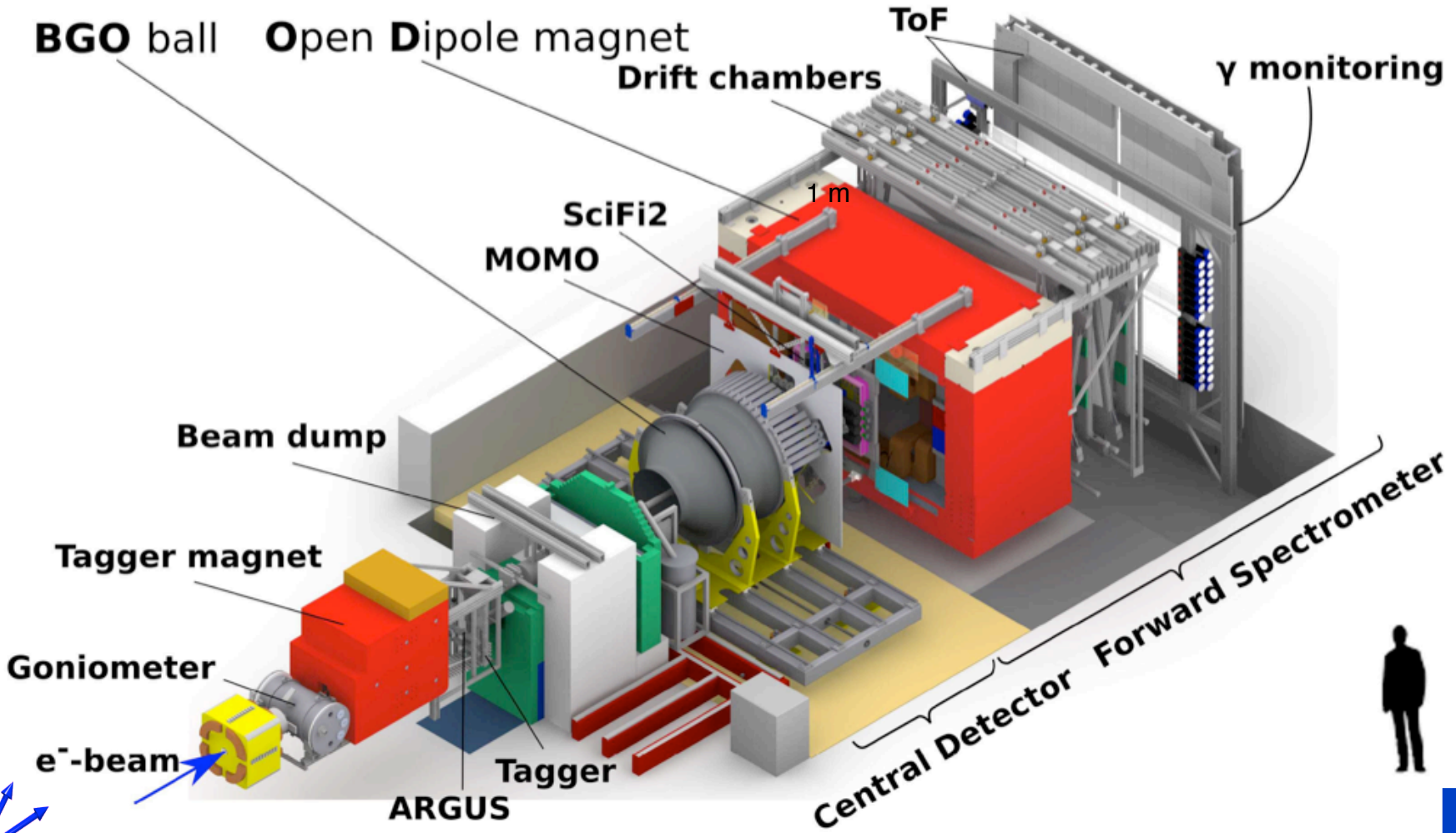
BGOOD experiment

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



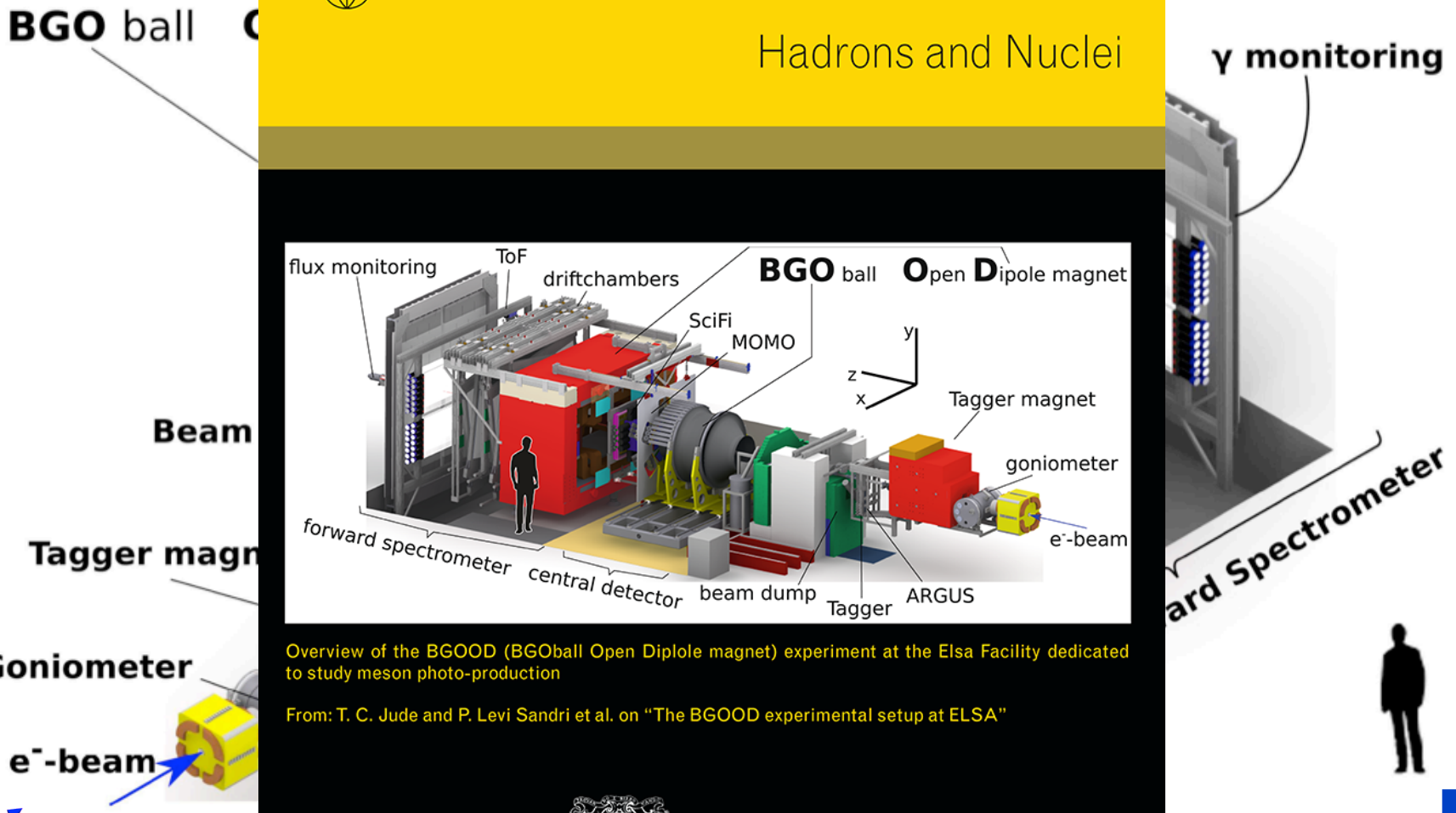
BGOOD experiment

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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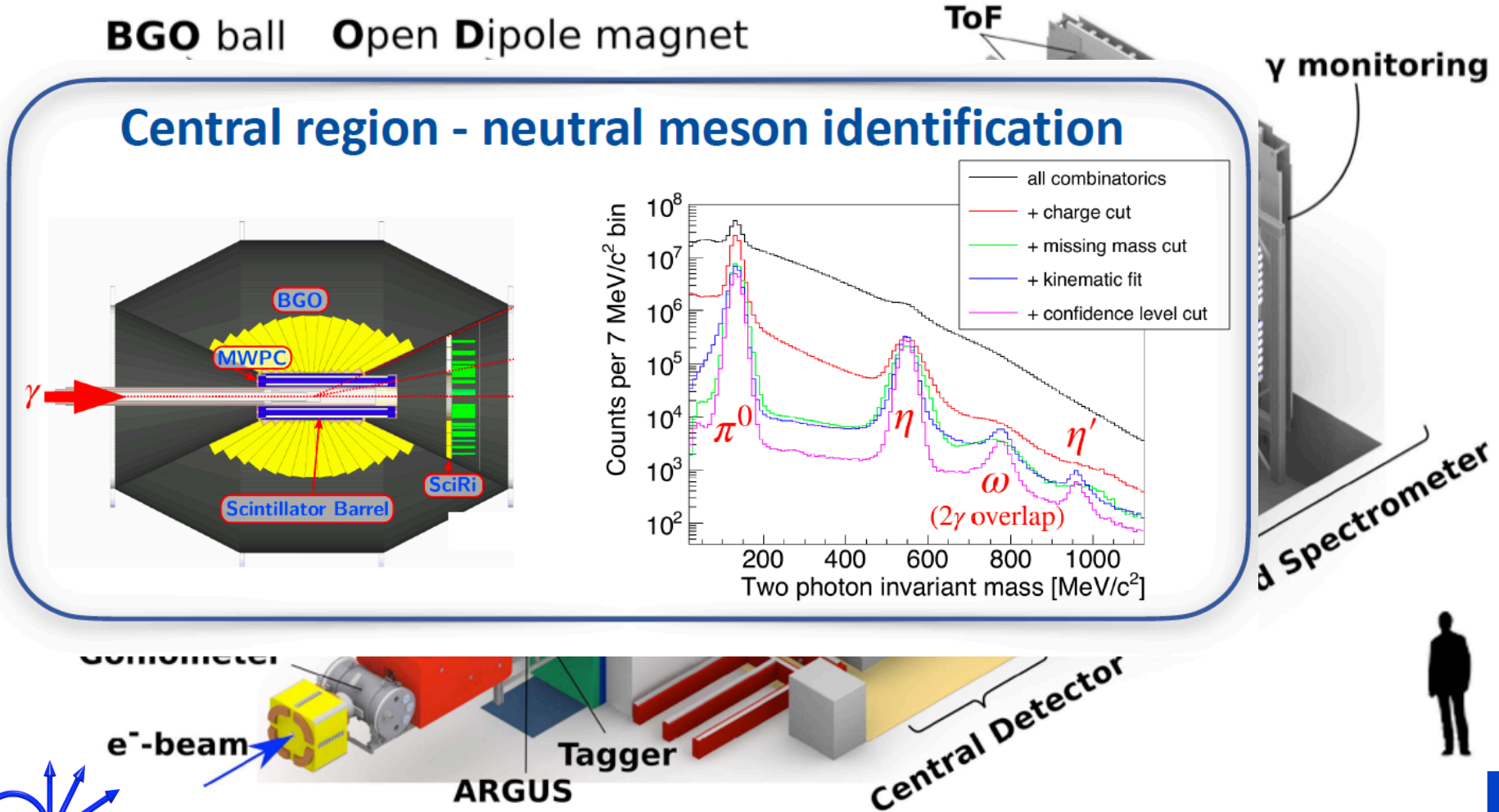

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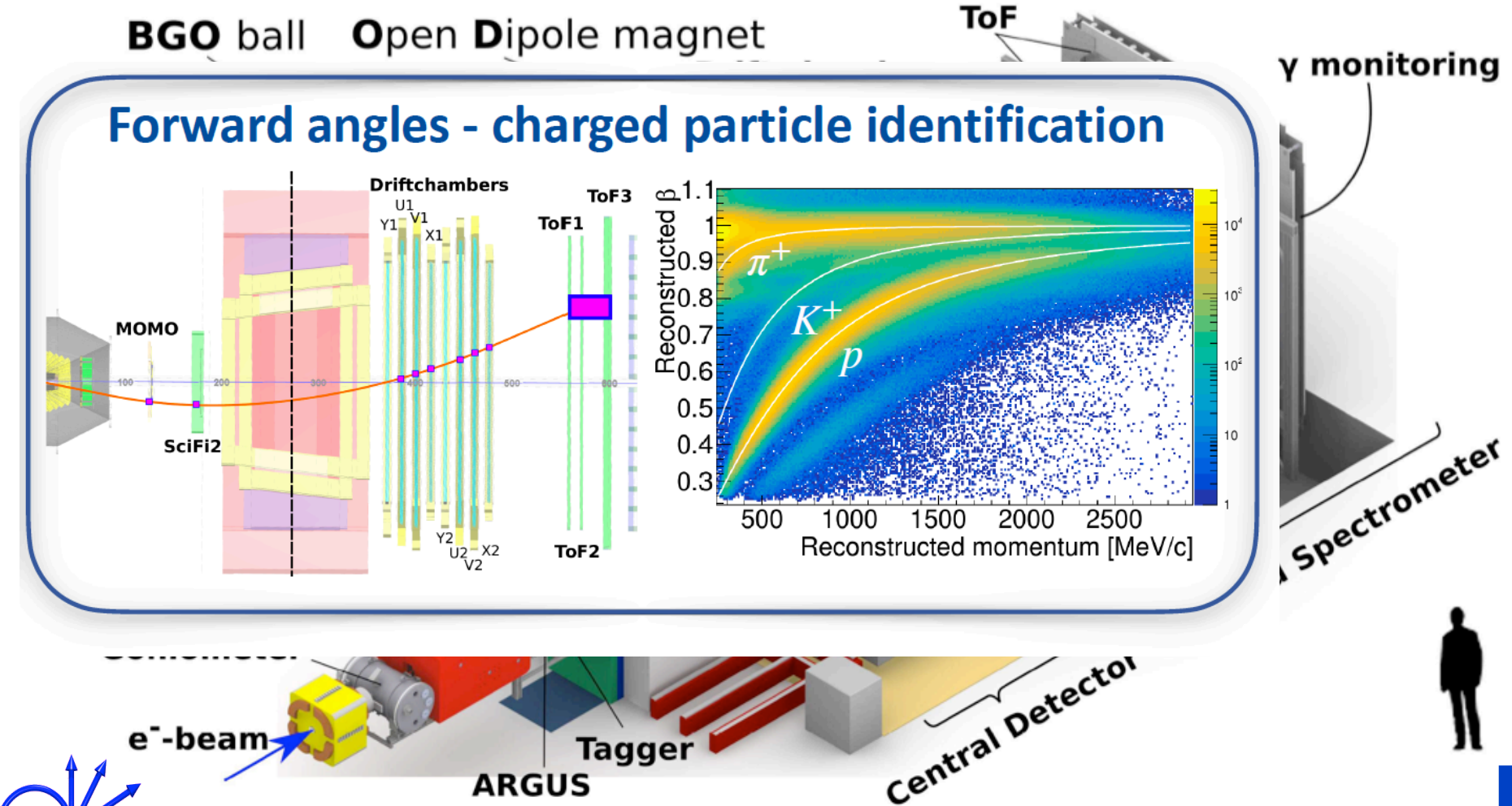
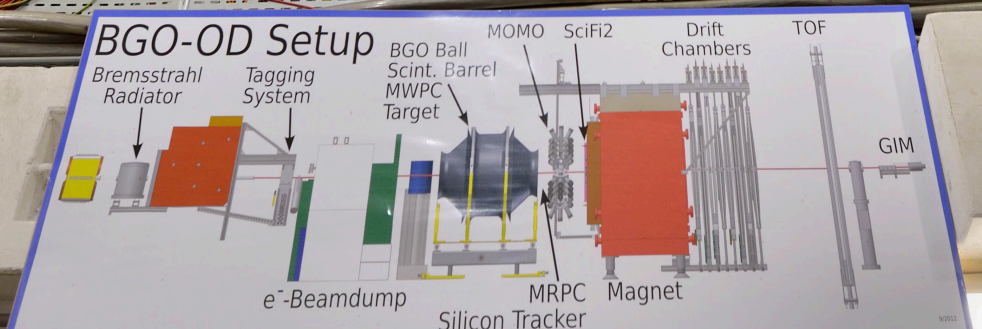


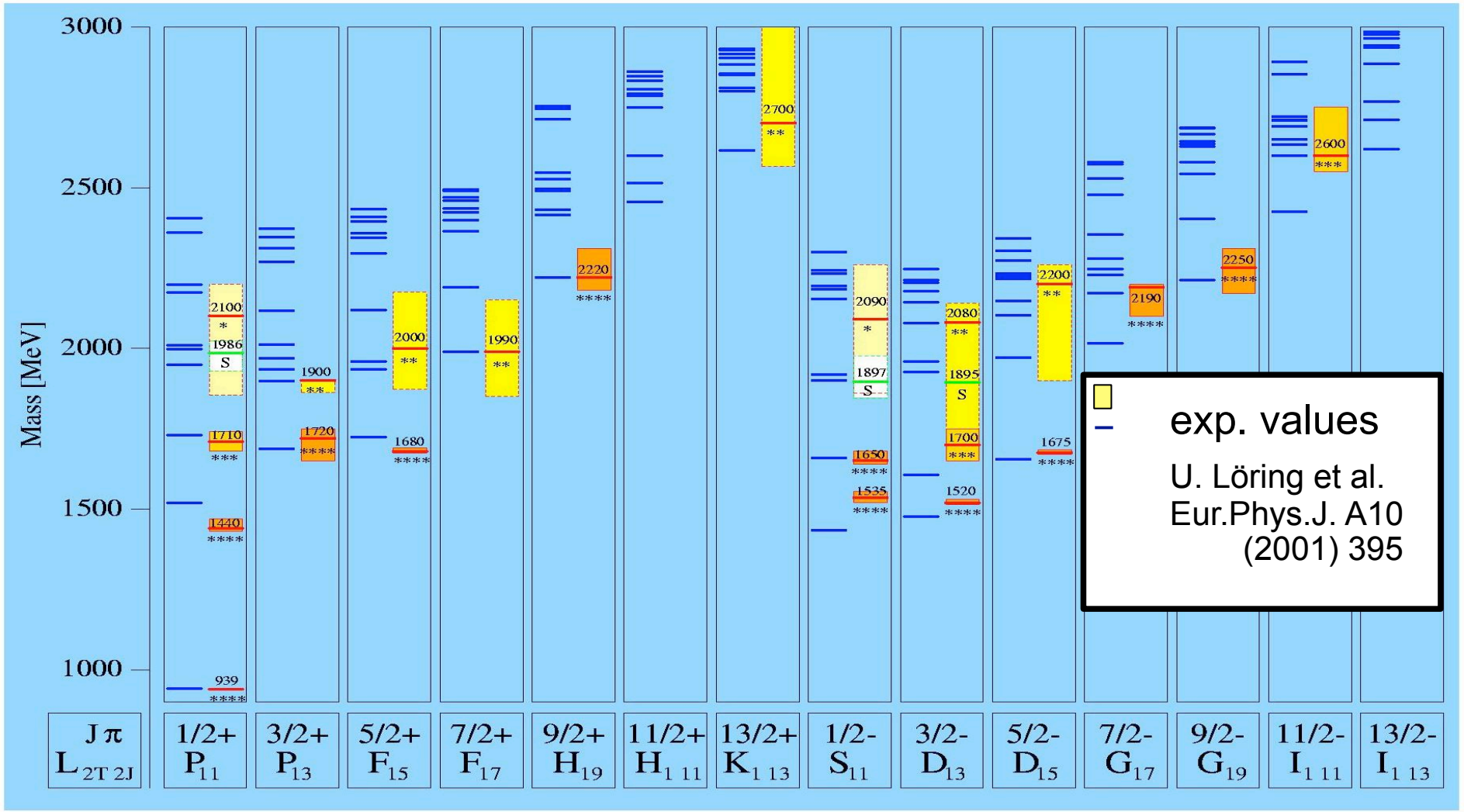
BGOOD experiment at ELSA



BGOOD

physics case

Excited states: quark model



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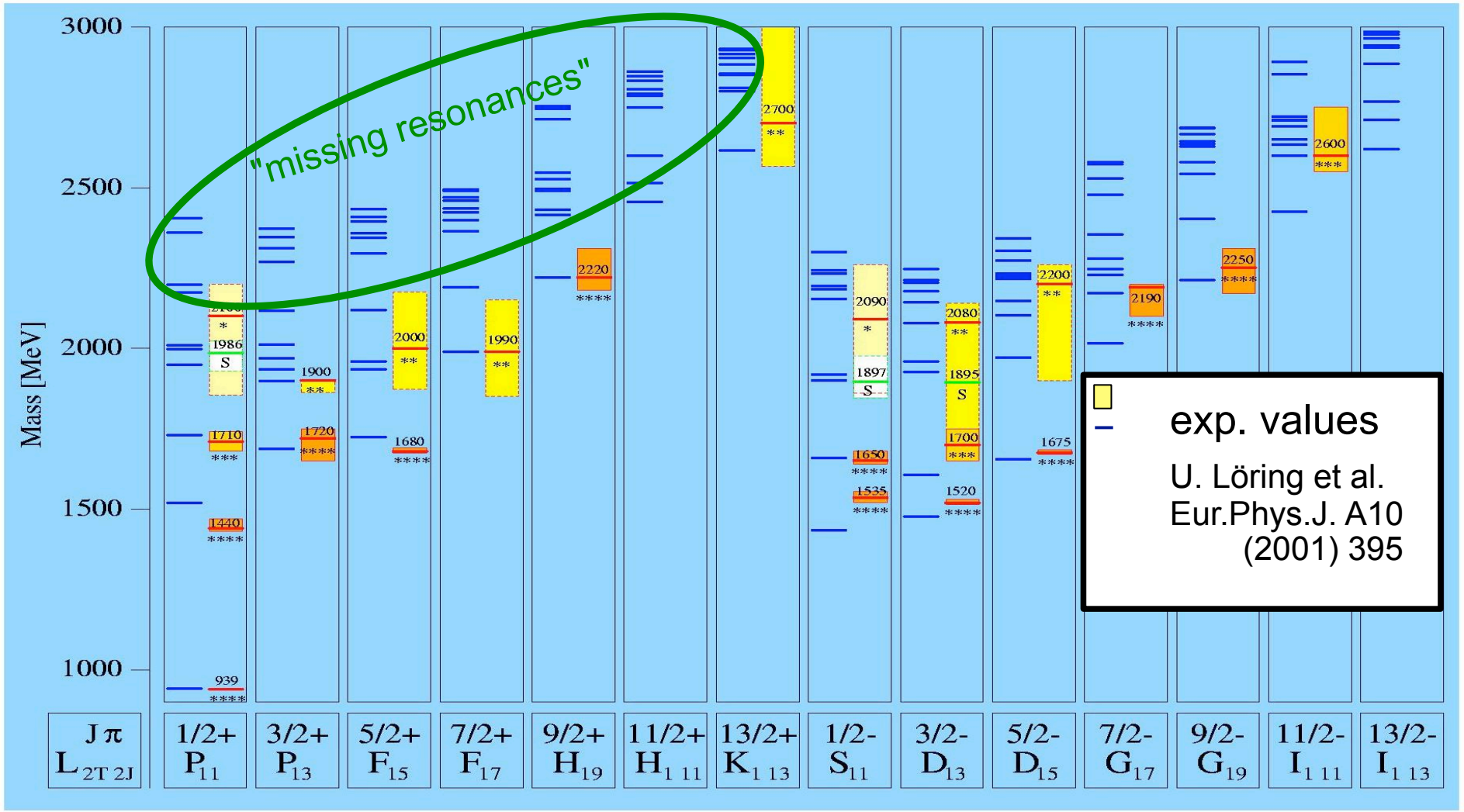

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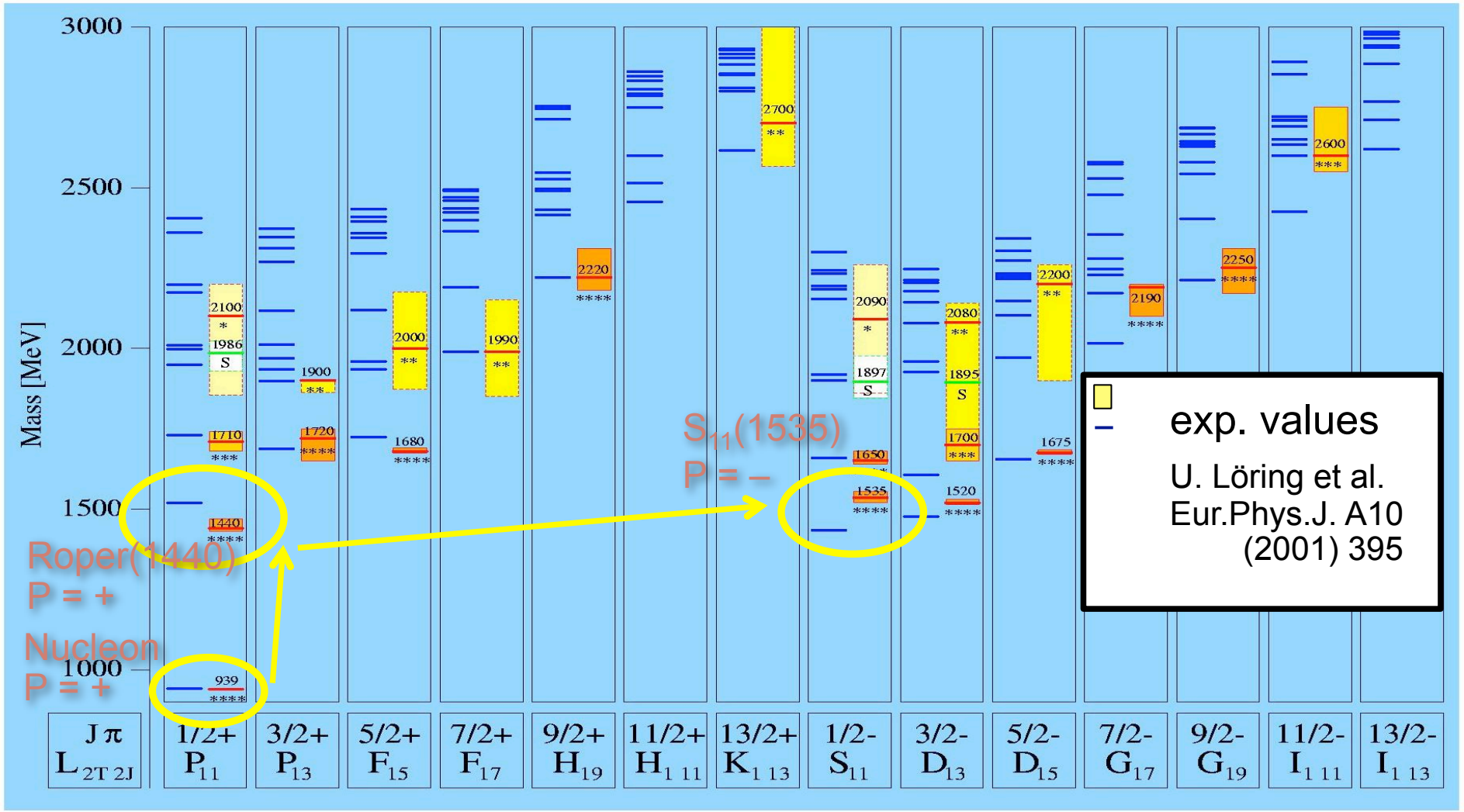

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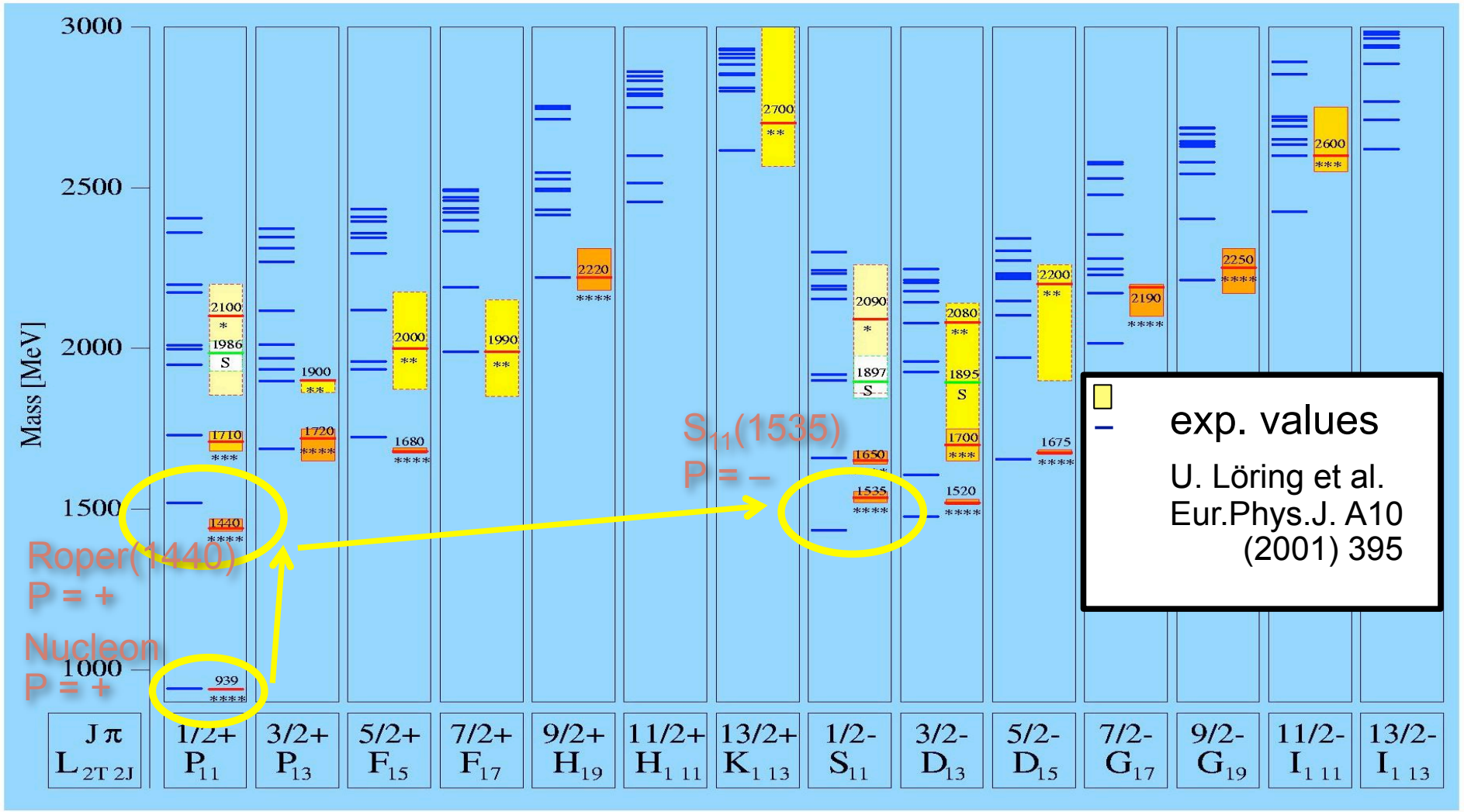
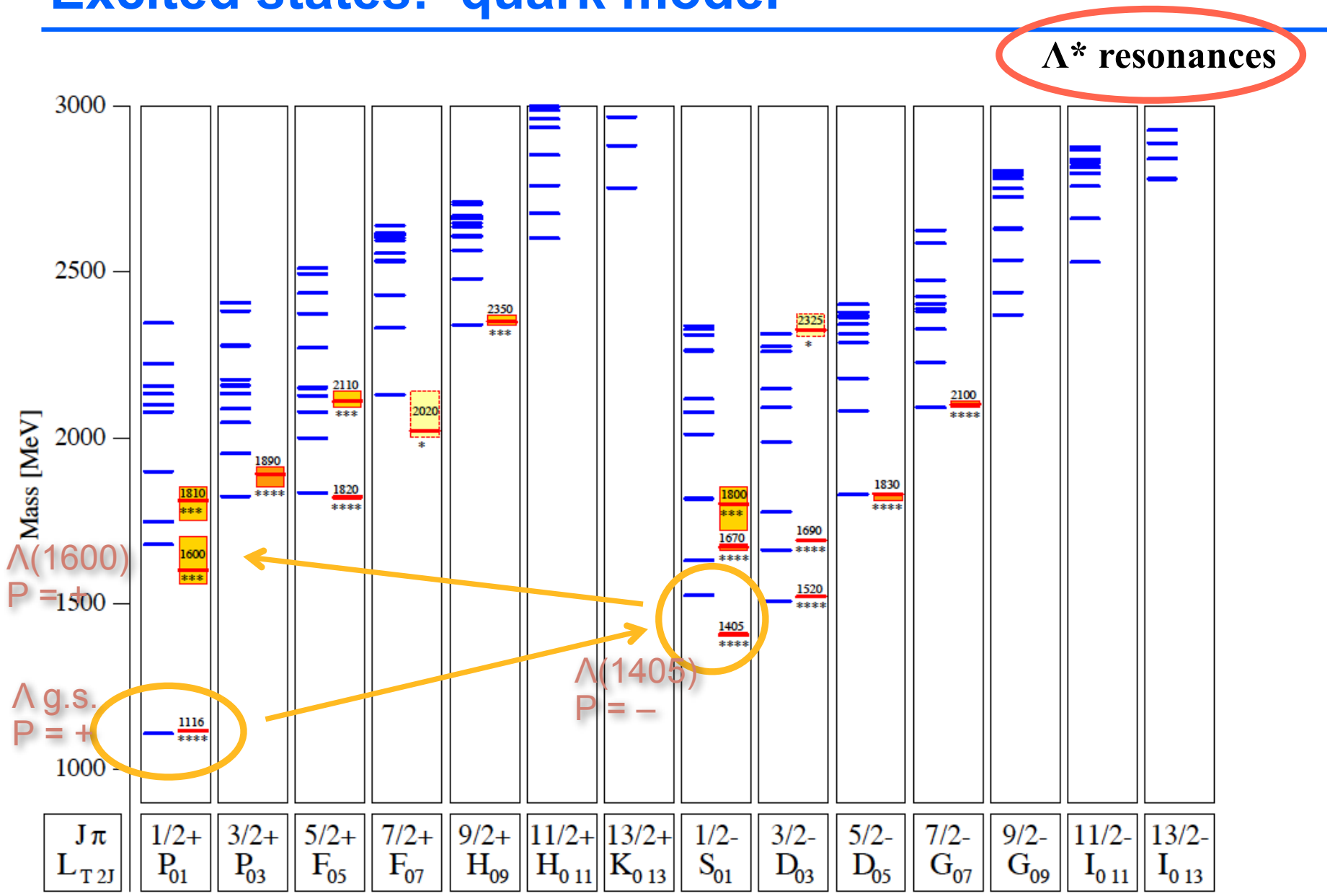


- parity pattern lowest states + → + → – !?!
- effective degrees of freedom ??

Excited states: quark model

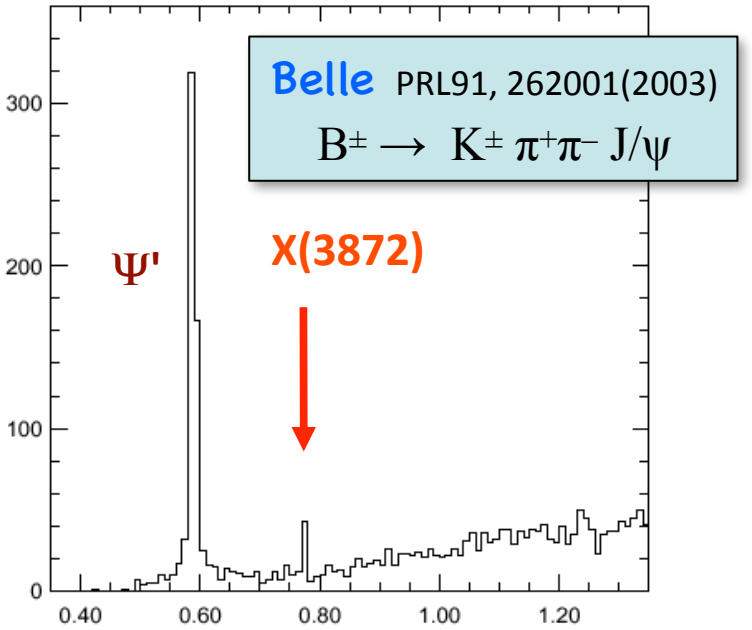


- parity pattern OK
- masses reversed ??

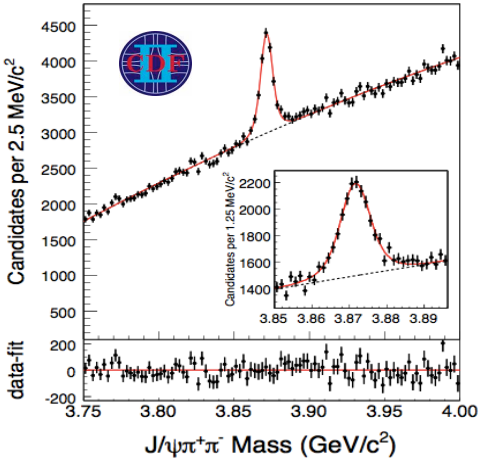
H. Schmieden

context c-quark sector

X(3872)

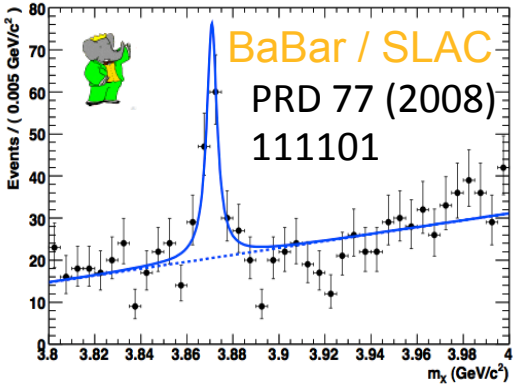


$M(\pi^{+}\pi^{-}l^{+}l^{-}) - M(l^{+}l^{-})$



CDF / Tevatron

PRL 103 (2009) 152001



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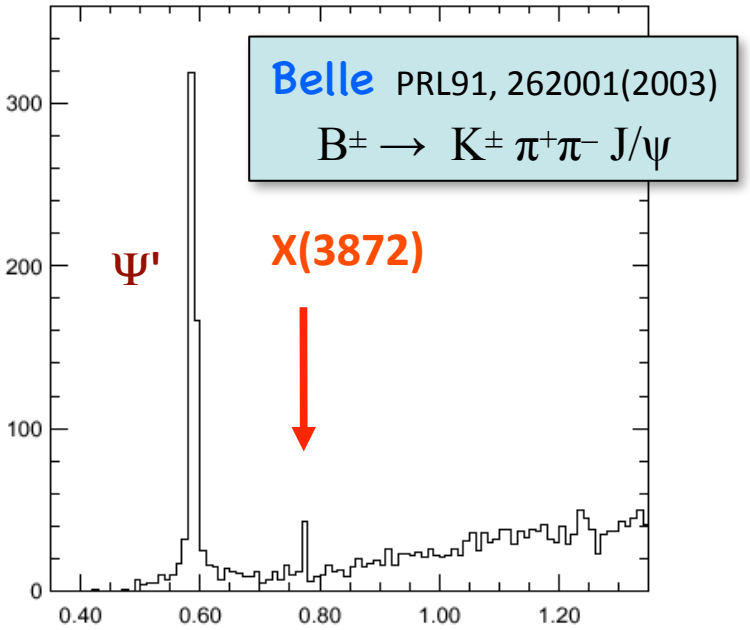
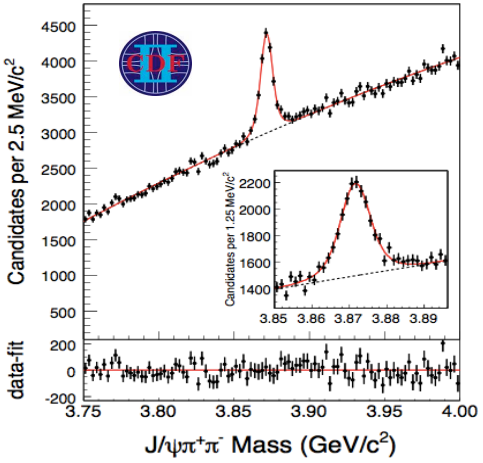


M(π+π-l+l-) - M(l+l-)



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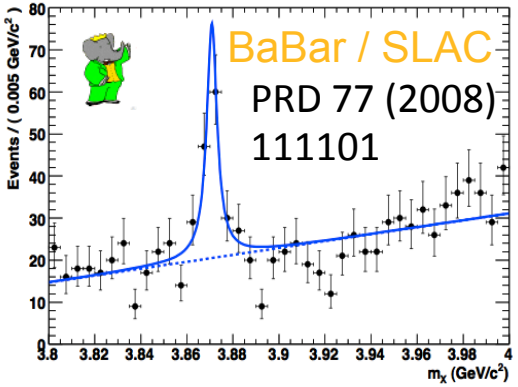

PARTICLE PHYSICS

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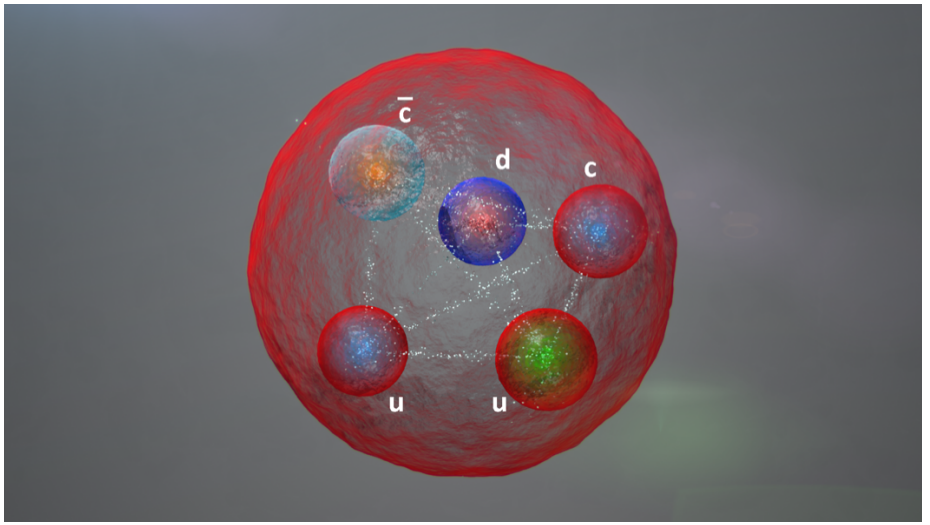

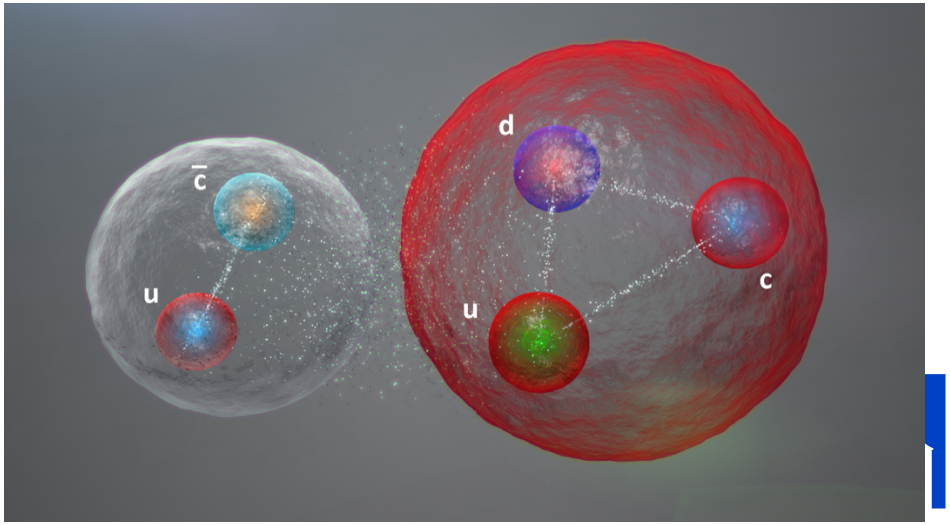

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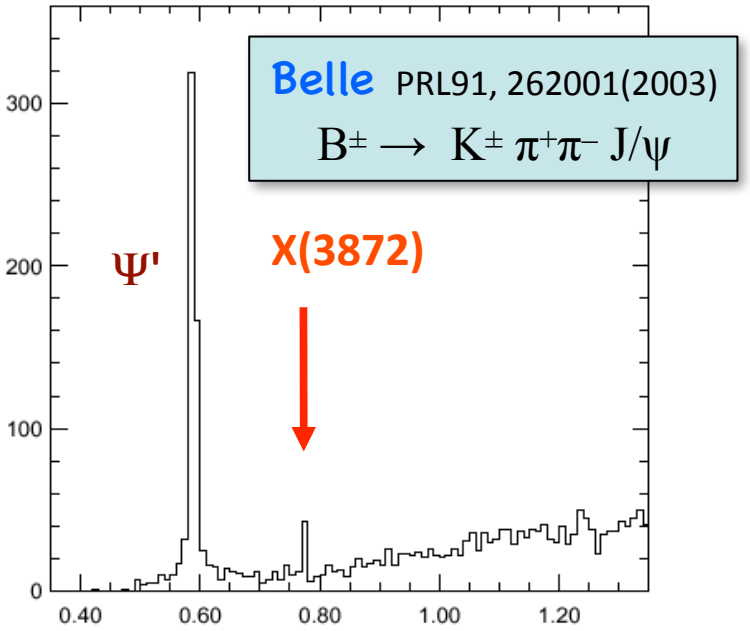

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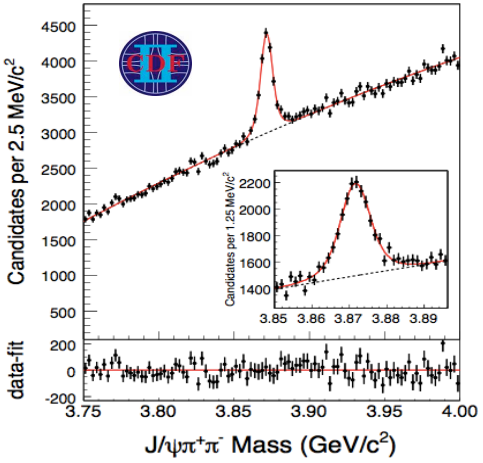

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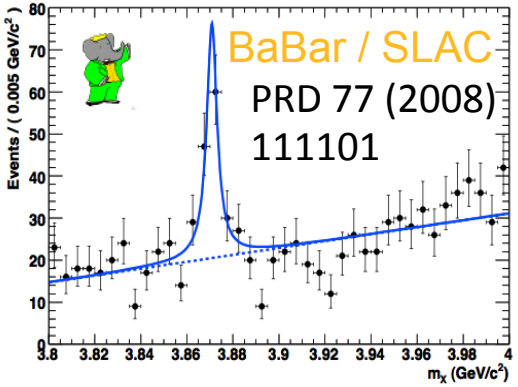

BaBar / SLAC

PRD 77 (2008) 111101

$P_c^+(4380, 4450)$

PARTICLE PHYSICS

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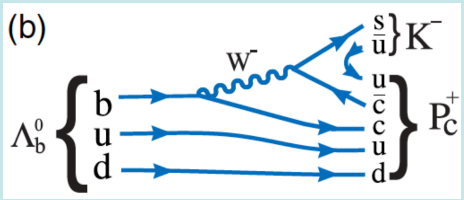
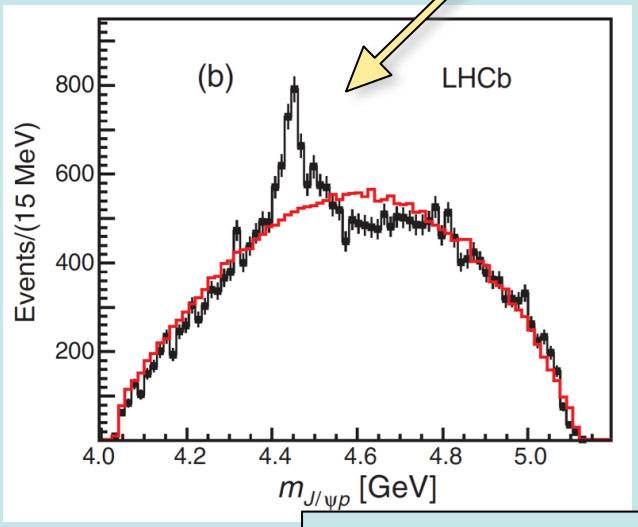
R. Aaij et al., PRL 115 (2015) 072001



p J/ψ



PB / VB hidden c predicted from meson-baryon interactions:
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"new N^*_{cc} states are simply brothers or sisters of the well known N*(1535) and Λ*(1405) ... and many other dynamically generated states ..."

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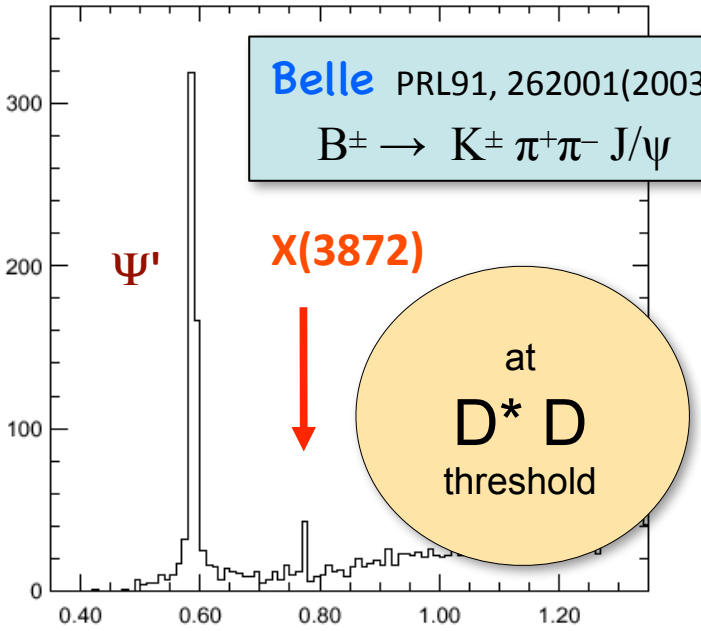

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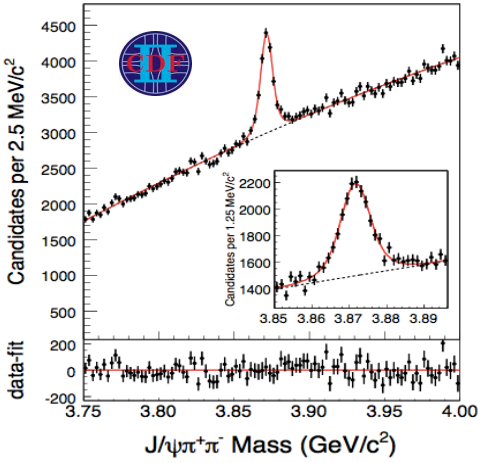

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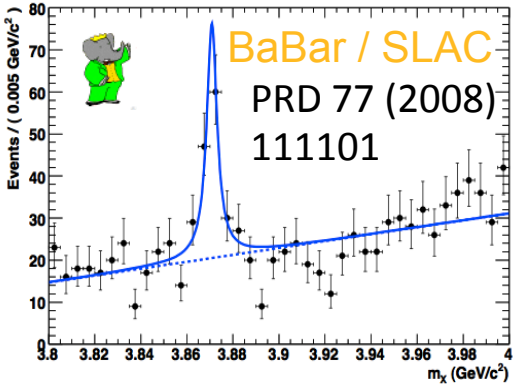

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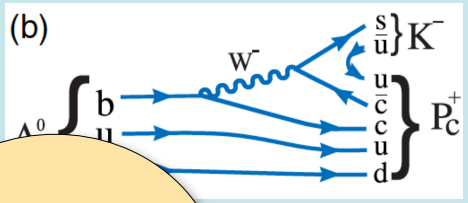
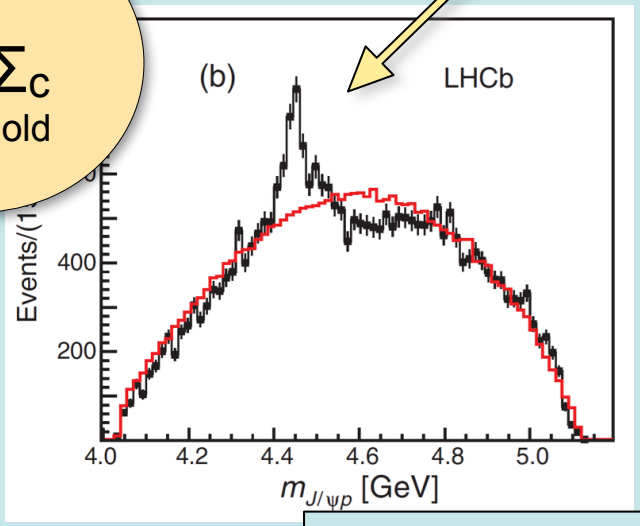


p J/ψ

at
D* Σc
threshold



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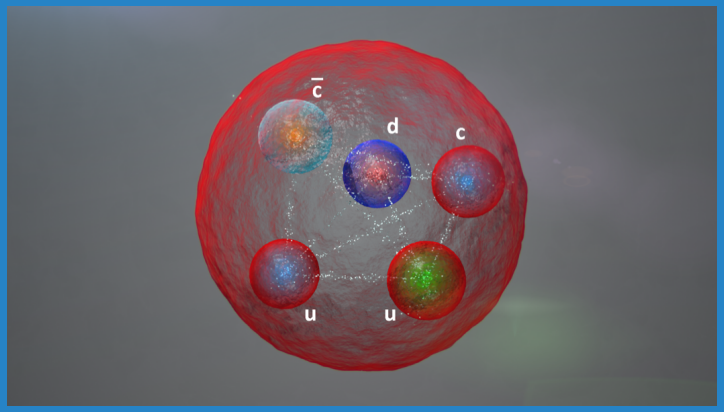
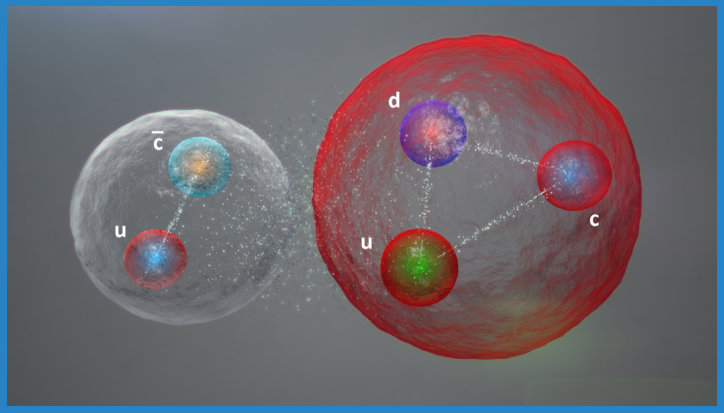


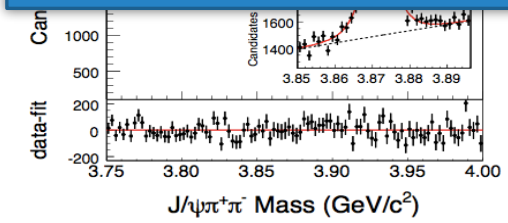


- 5-quark structures definitely observed
- (hidden) c-quark sector
- similar 4-quark states in meson sector
- structure/binding mechanism under debate

→ paradigm change in hadron physics

→ general feature of structure formation in QCD ?

→ similiar structures in (hidden) s-quark sector ??



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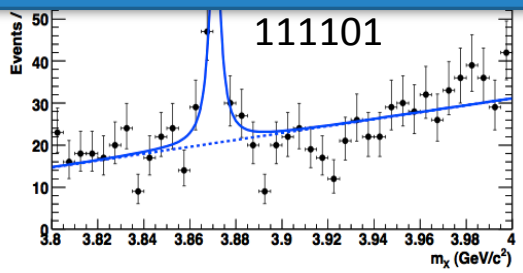

111101

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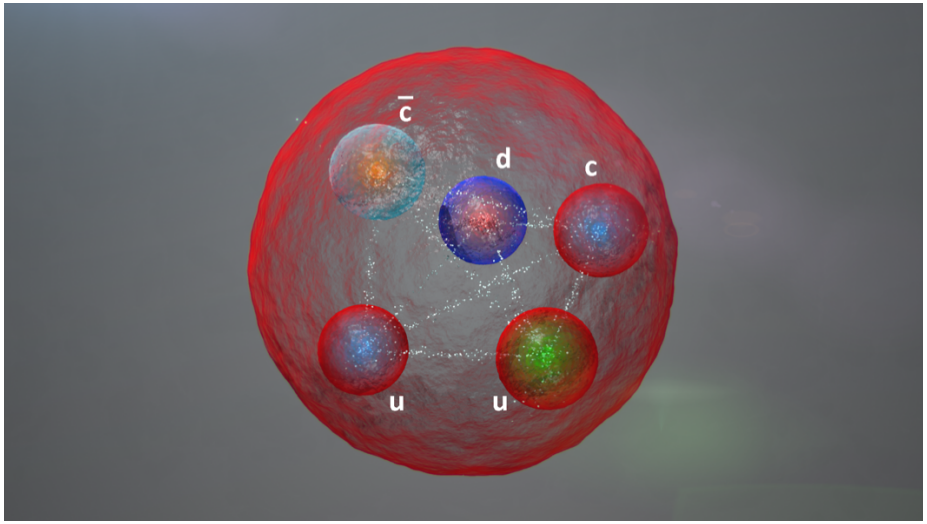
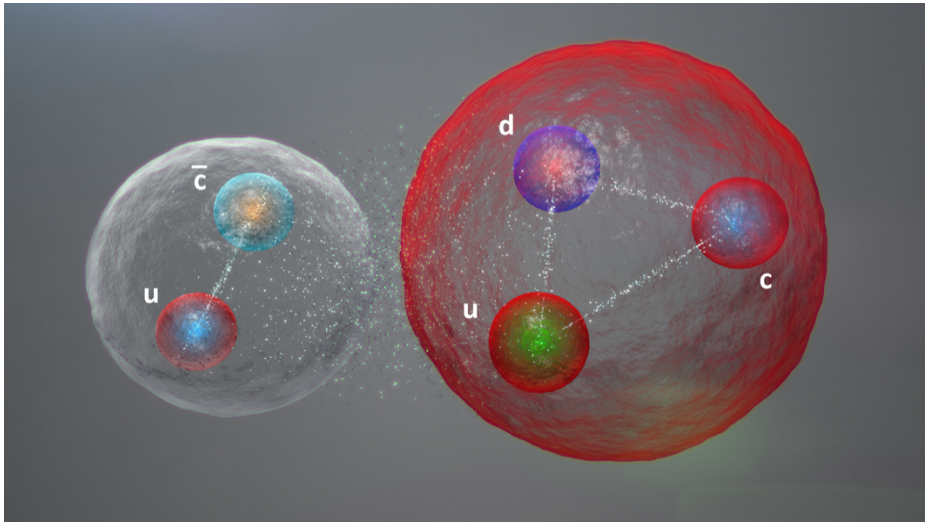
Parallels in s-quark sector ?





$D^{(*)}\ \Sigma_c$ thresholds

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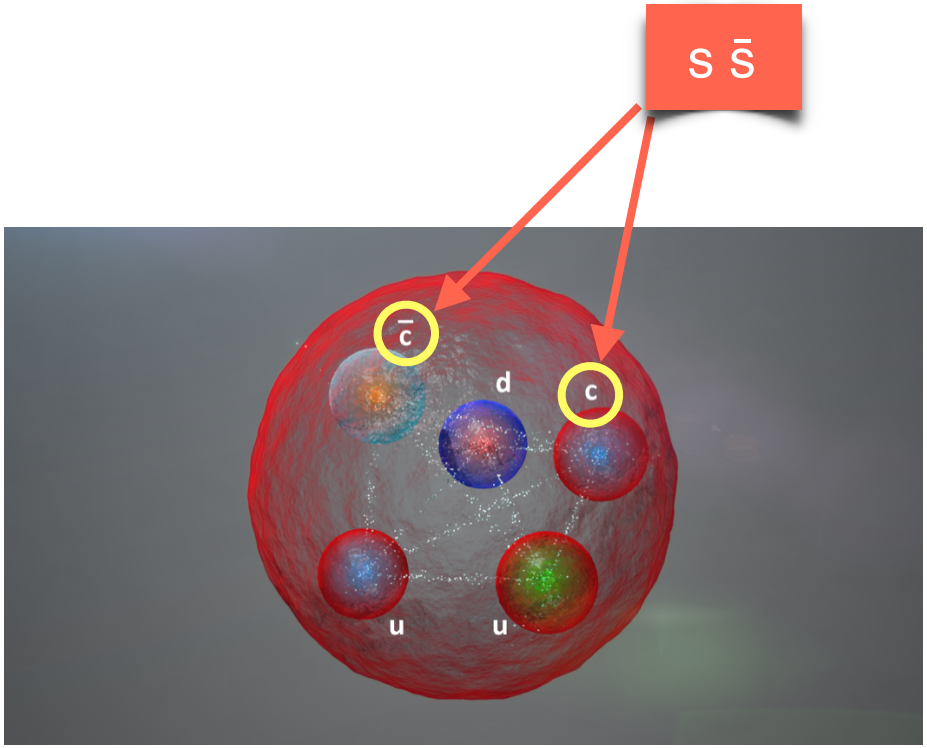

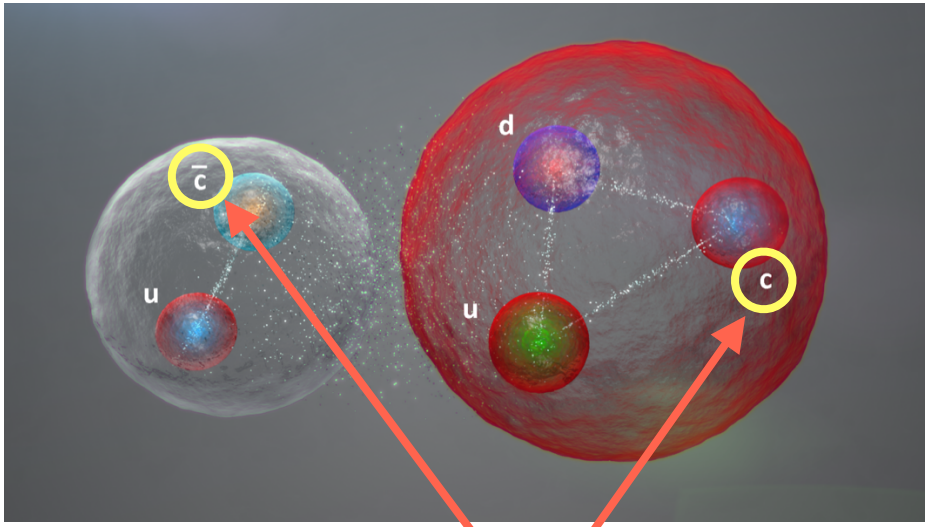

$D^{(*)}\ \Sigma_c$ thresholds

$K^{(*)}\ \Sigma$ thresholds

parallels between c and s sector ?

	c-sector		s-sector	
	meson	baryon(s)	meson	baryon(s)
state(s)	$X(3872)$	$P_c^*(4380/4450)$	$f_1(1420)$	$N^*(2030/2080)$
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

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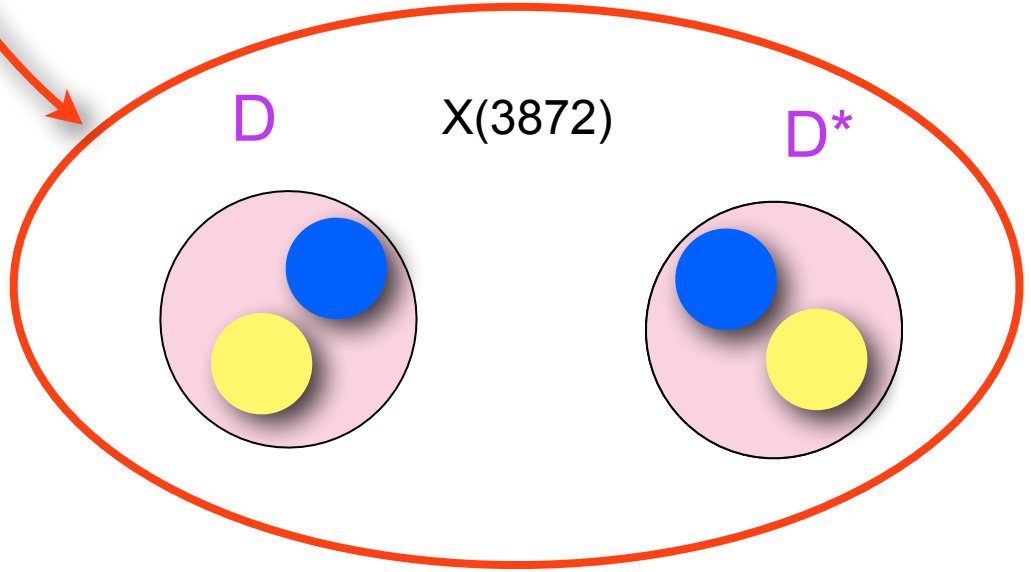

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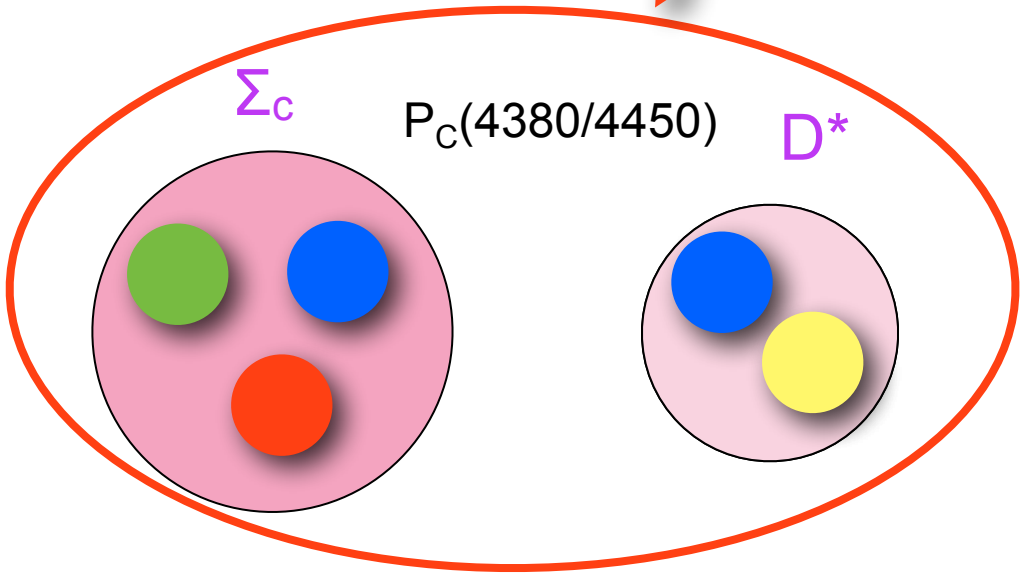
$\bar{3} \leftrightarrow \bar{3}$

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



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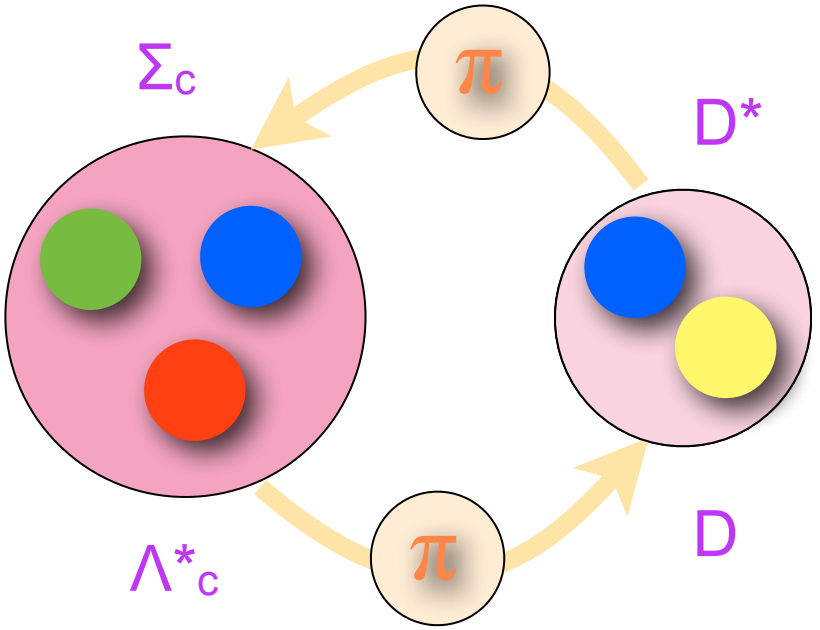
quantum nos.	$J^{PC} = 1^{++}$	$J^P = (3/2)^-$	$J^{PC} = 1^{++}$	$J^P = (3/2)^-$
3-body threshold	$D^0\bar{D}^0\pi^0$	$\Sigma_c^+\bar{D}^0\pi^0$	$K\bar{K}\pi$	$\Sigma\bar{K}\pi^0$
closed flavour channel	$J/\psi\,\omega$	$\chi_{c1}p$	$\phi f_0(500)$	ϕp



parallels between c and s sector ?

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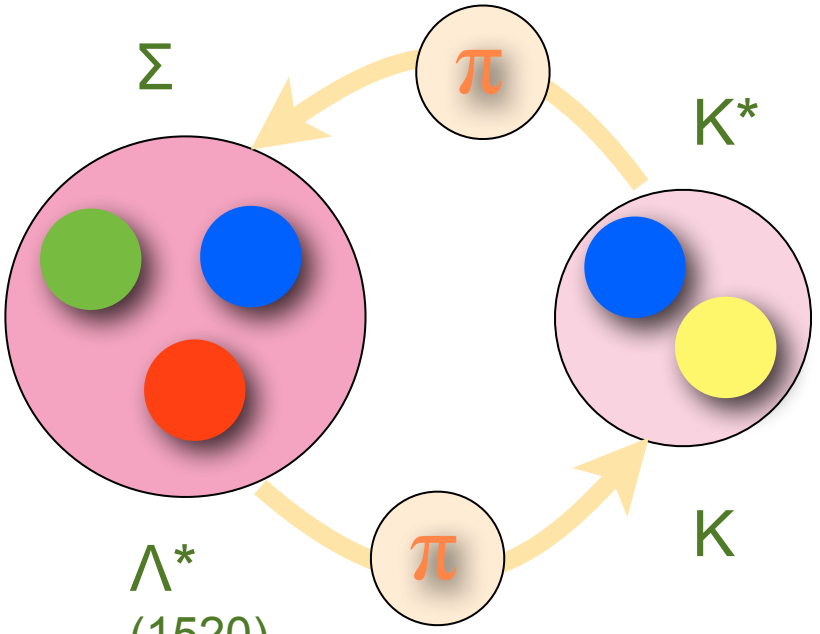
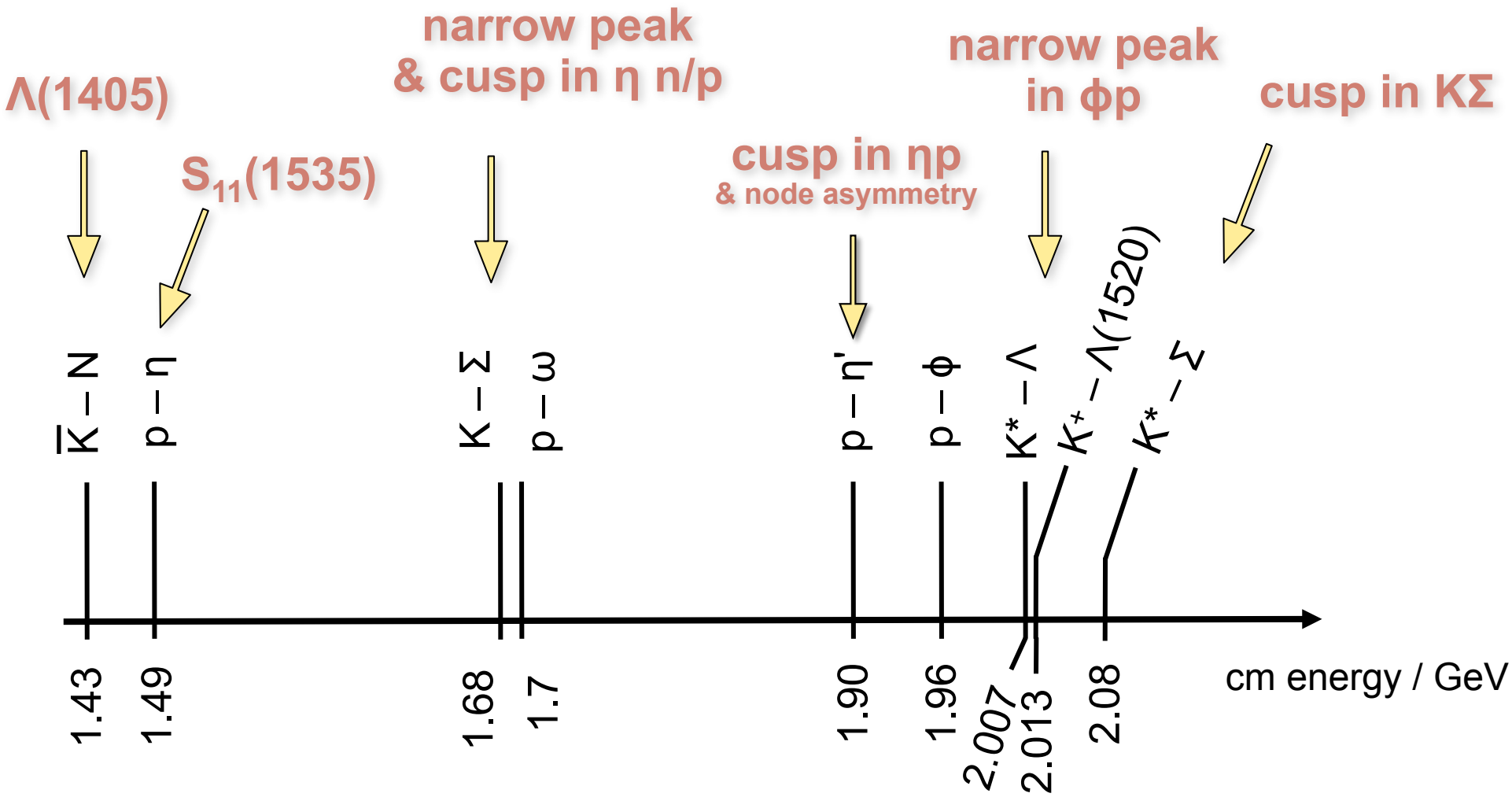


uds sector ?

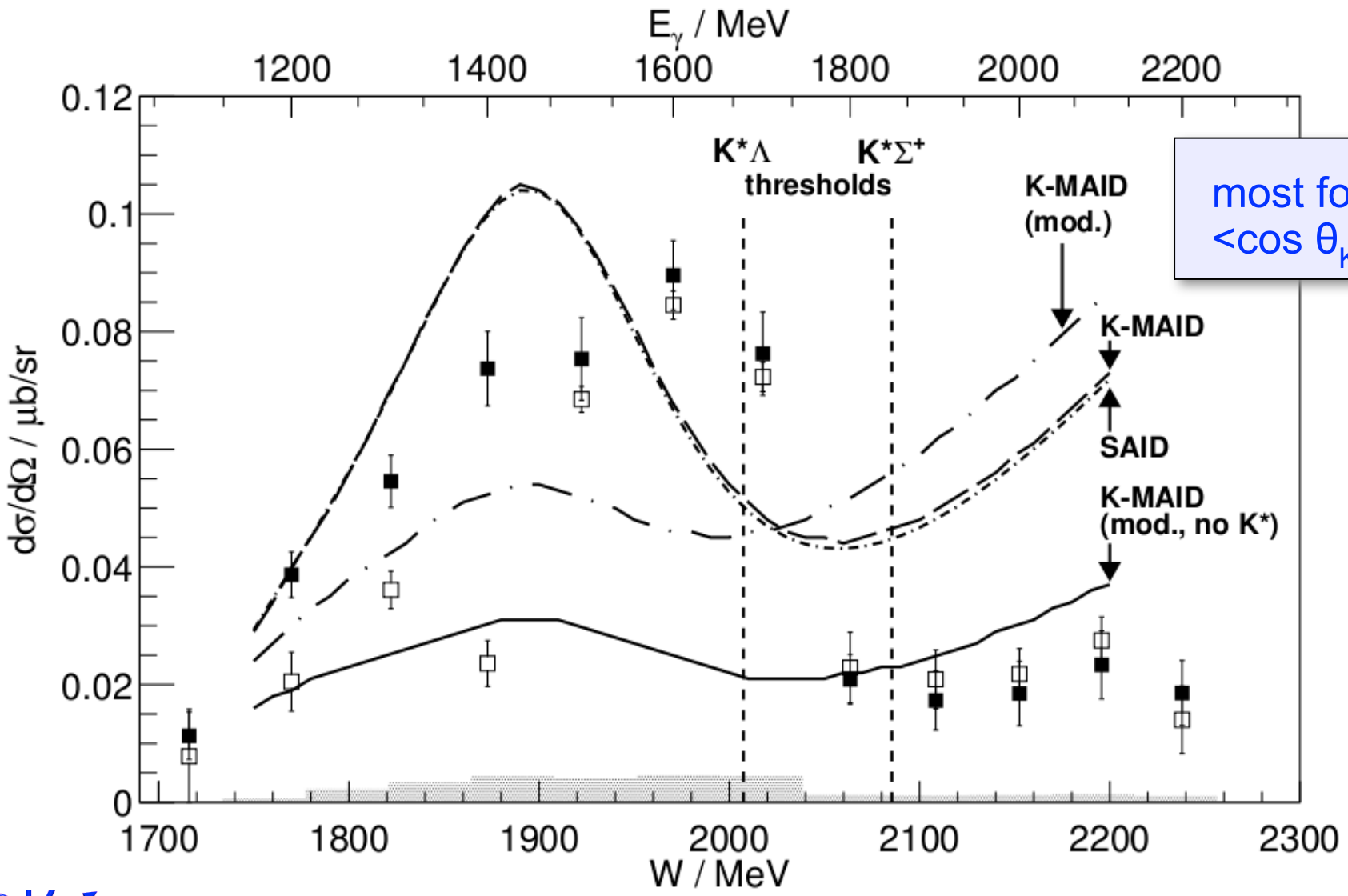
selected results of BGOOD

uds sector – threshold dynamics



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

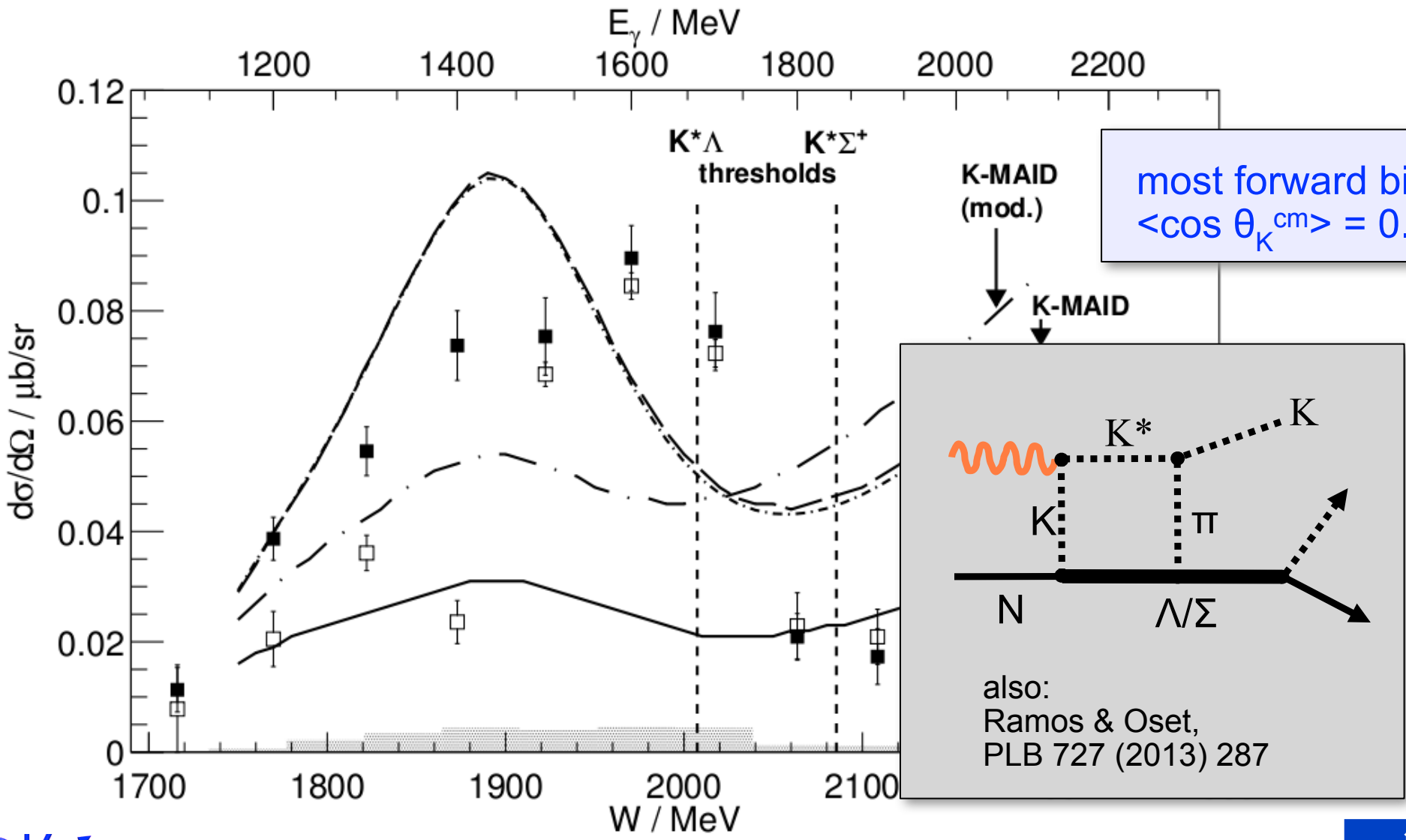
R. Ewald et al. (CB/TAPS), PLB 713 (2012)



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

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

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



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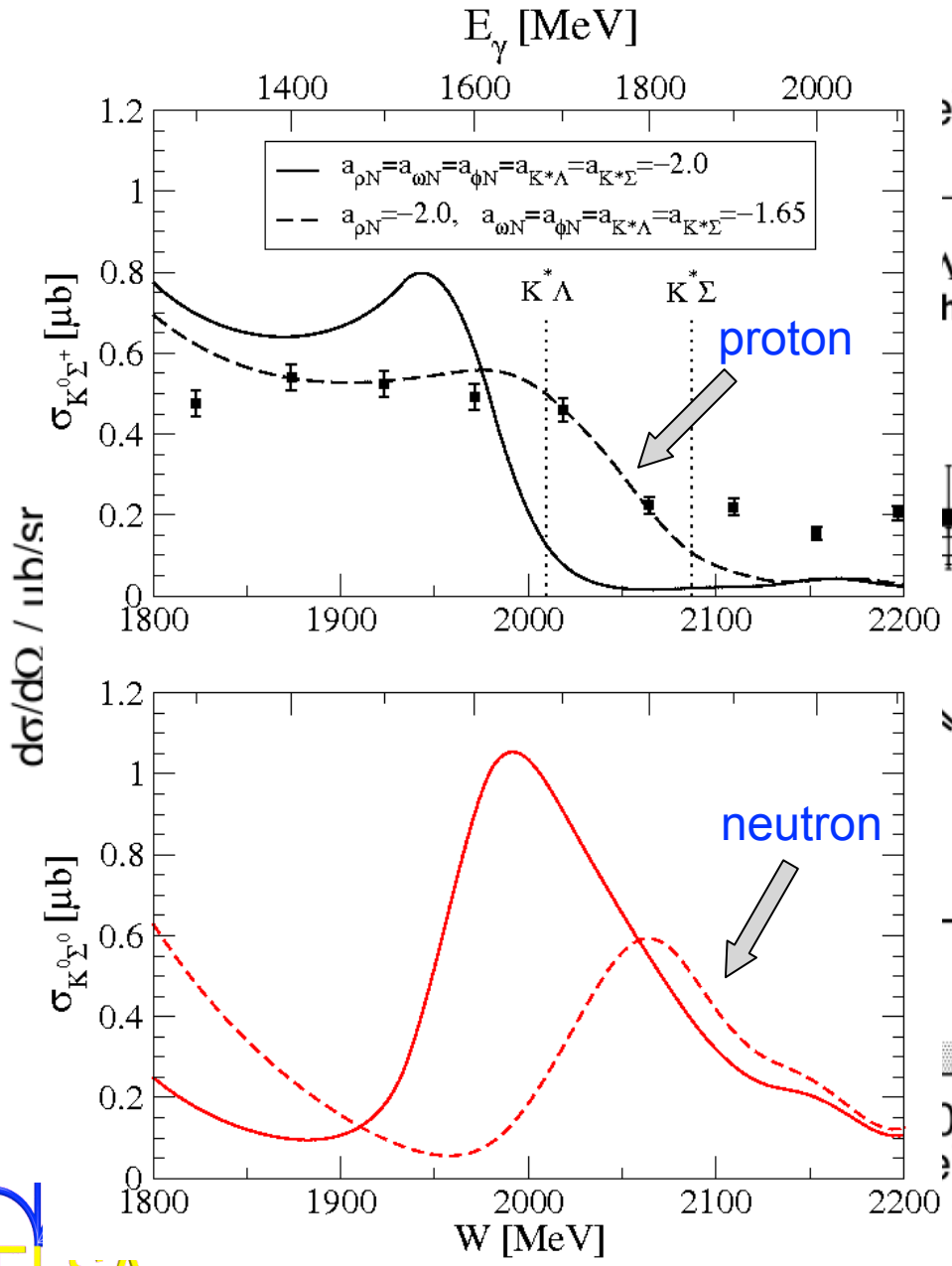

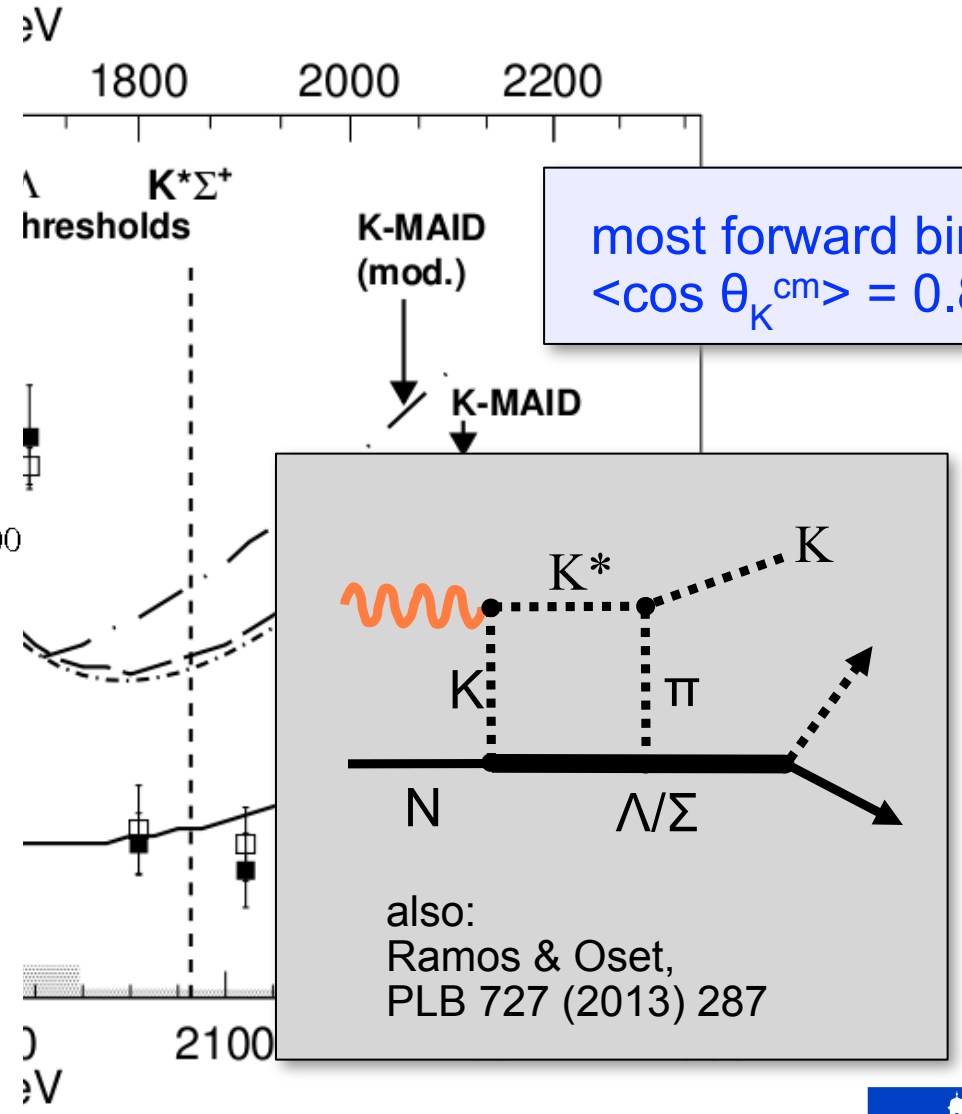

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also:
Ramos & Oset,
PLB 727 (2013) 287

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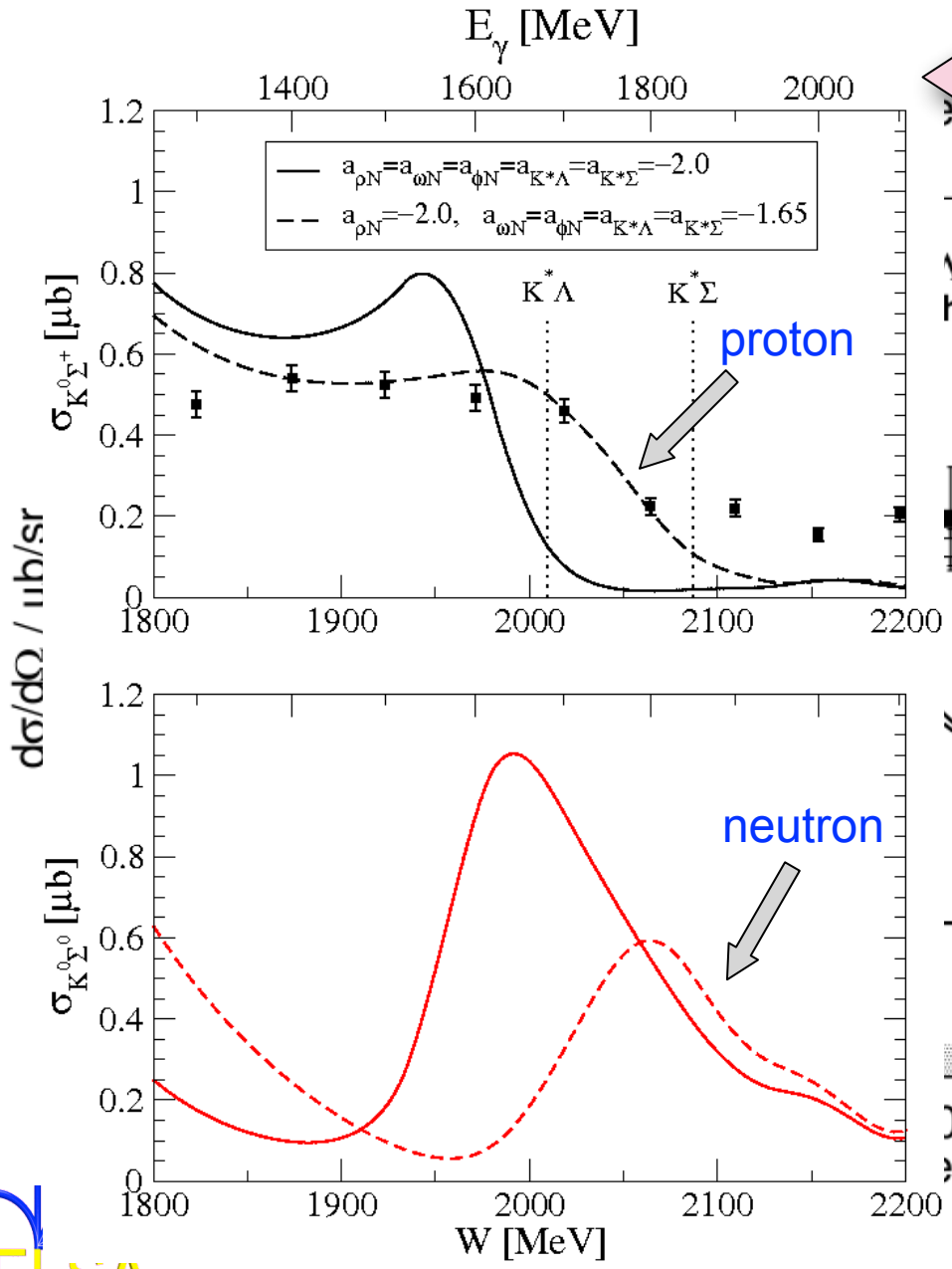

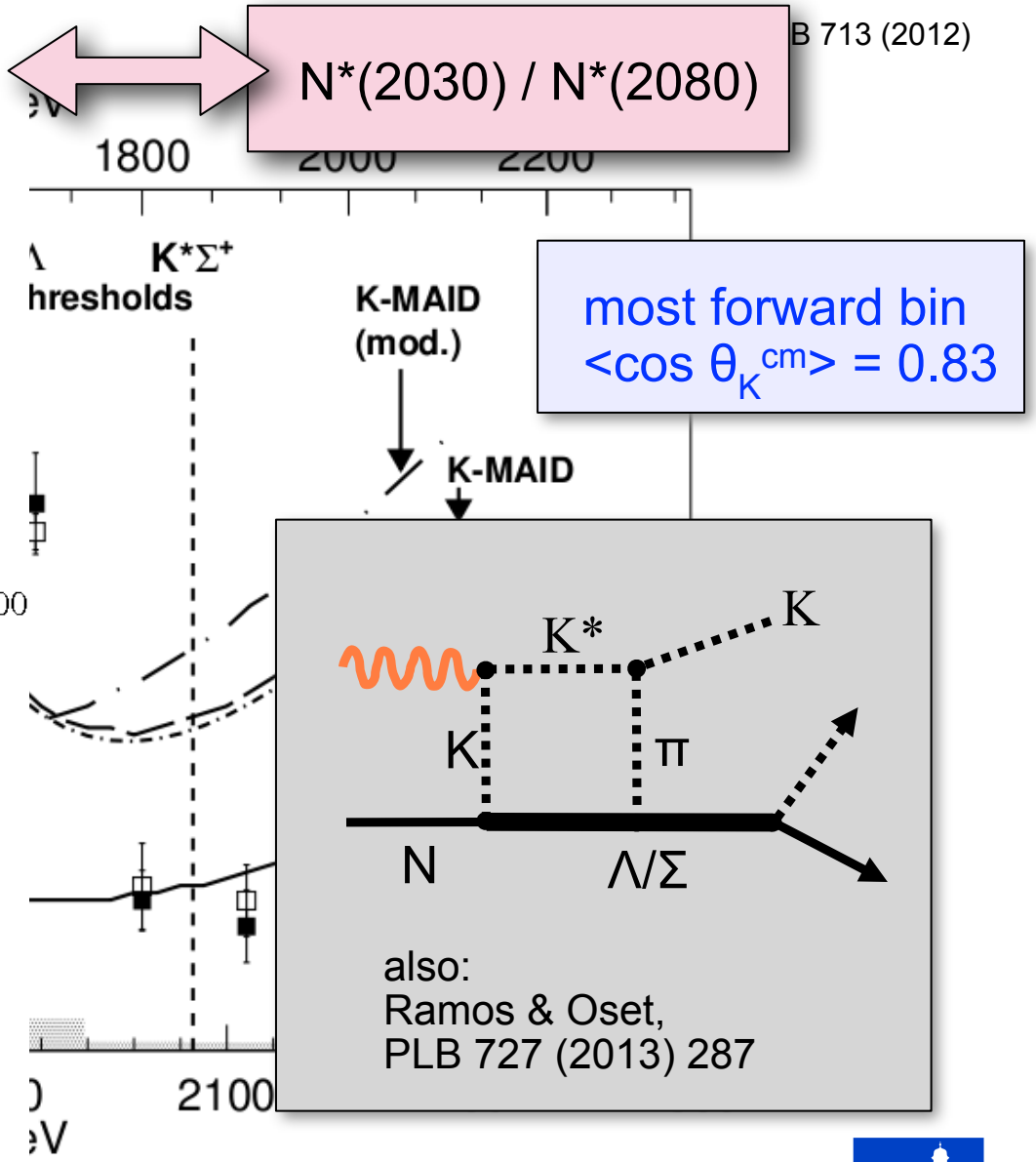

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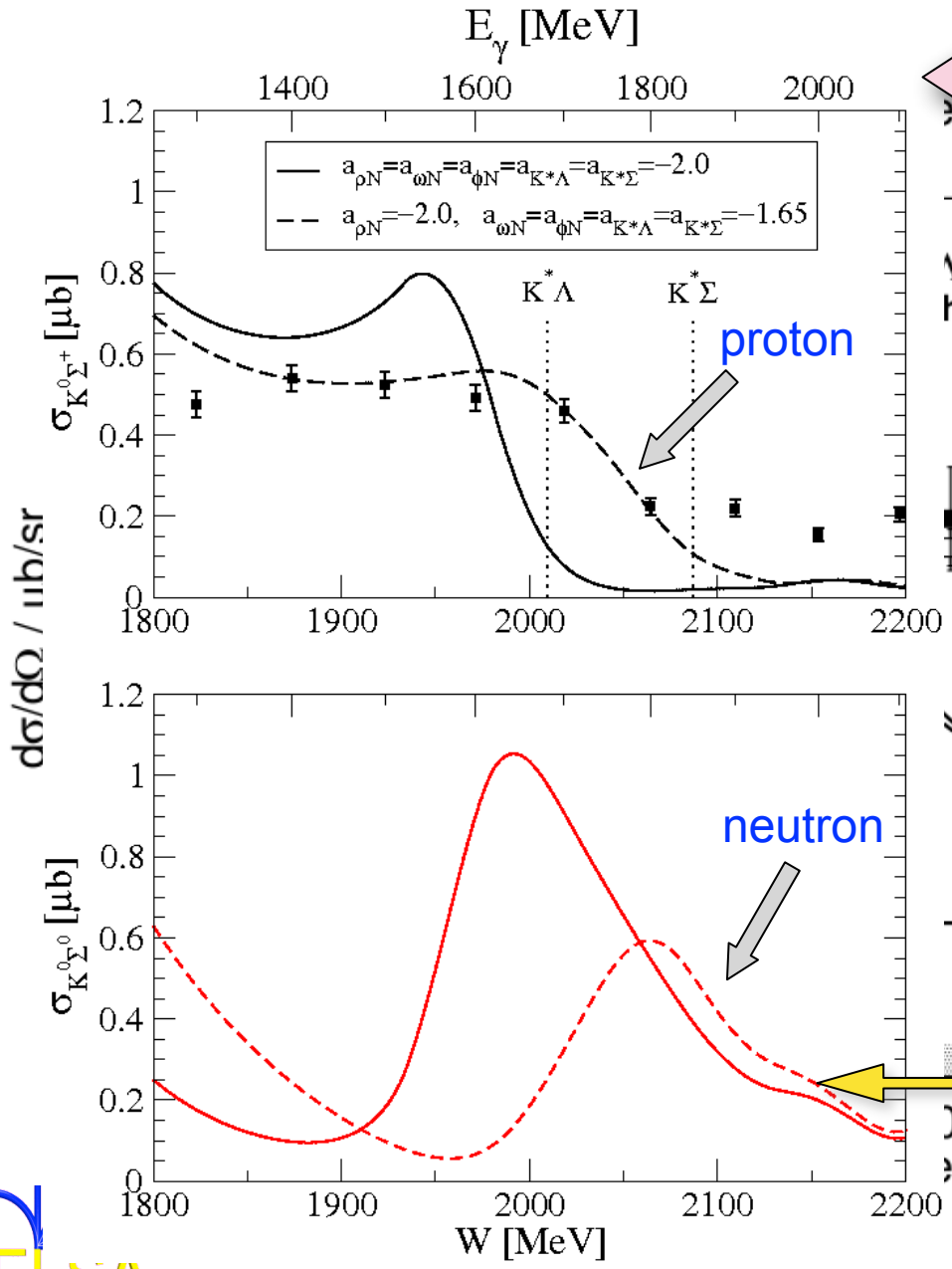
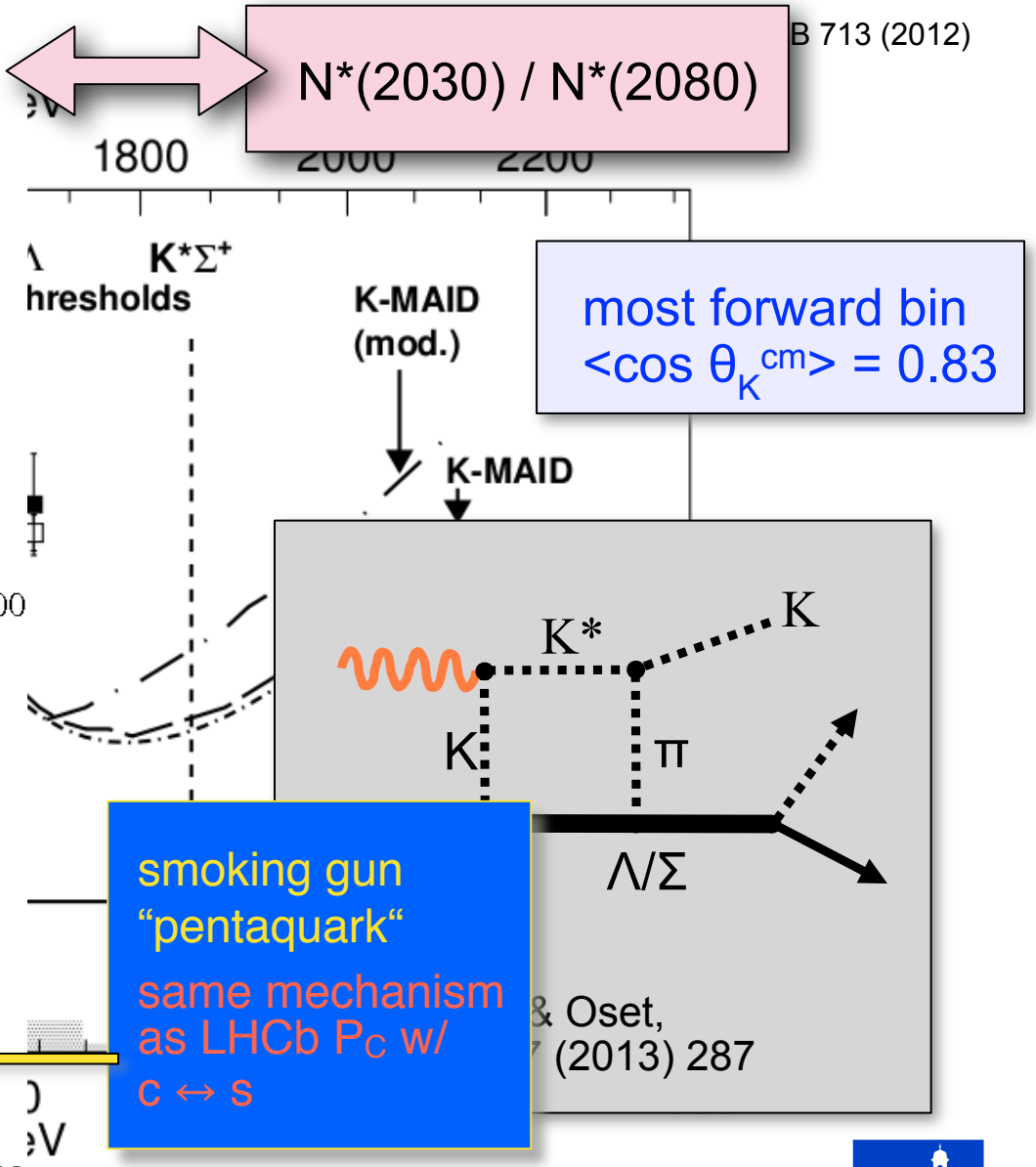
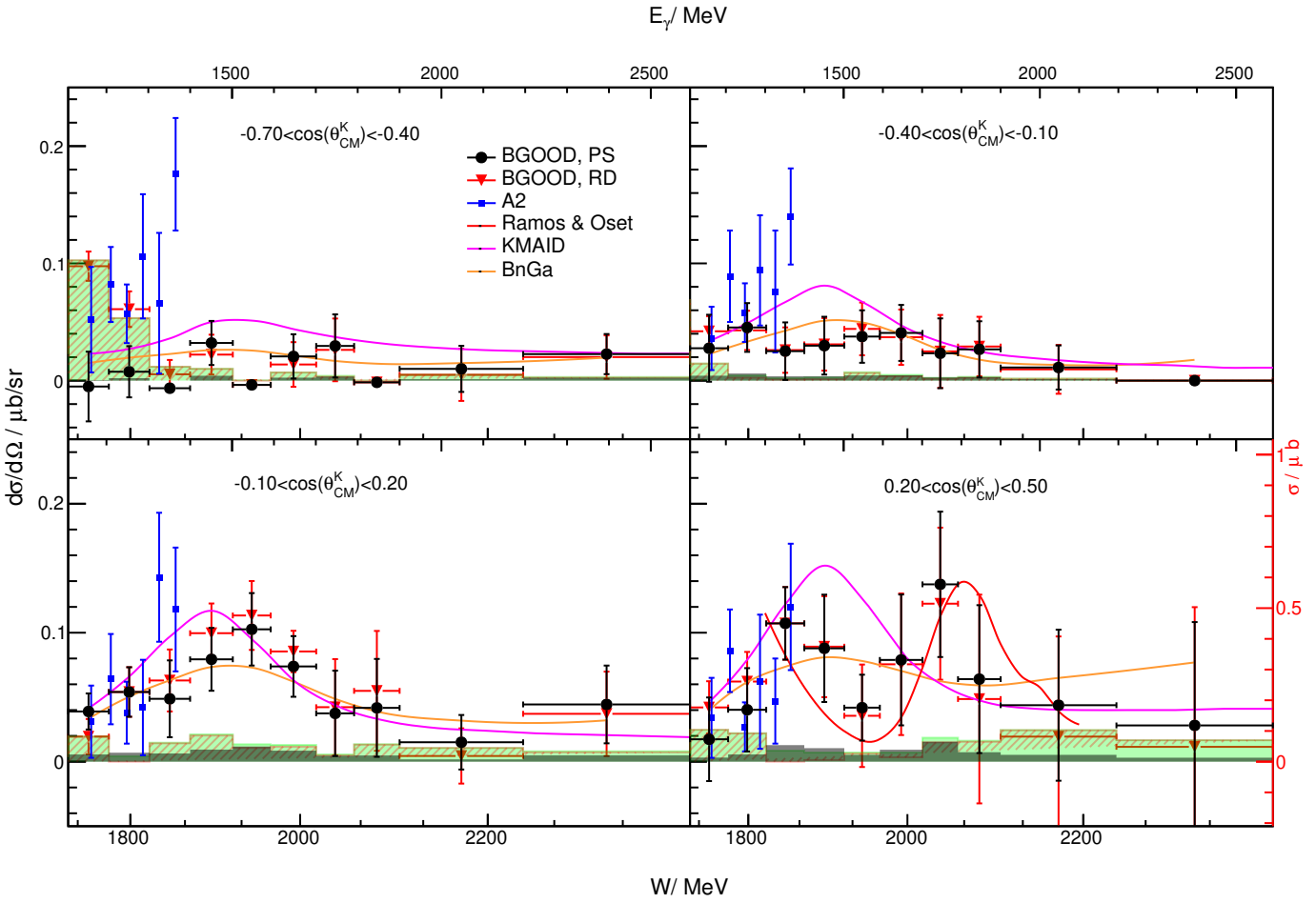




$\gamma\, n \rightarrow K^0\, \Sigma^0$



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

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

BGOOD simulated bg fit

BGOOD real bg fit

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

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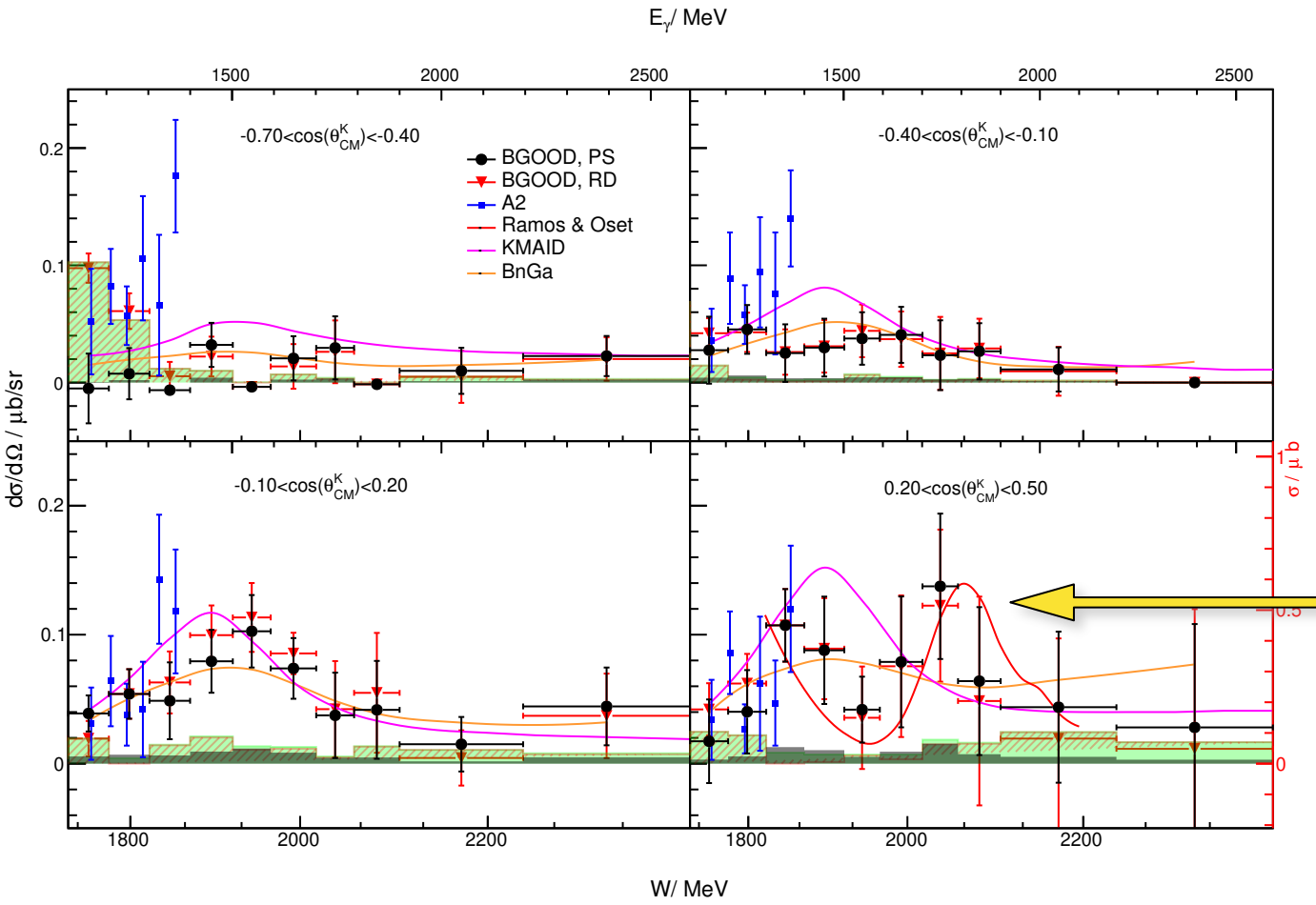

see also:
"The molecular nature of some exotic hadrons"
Ramos, Feijoo, Llorens, Montaña
Few Body Sys. 61 (2020) 4, 34
arXiv:2009.04367 (2020)

smoking gun "pentaquark"

same mechanism as LHCb P_C w/ c ↔ s

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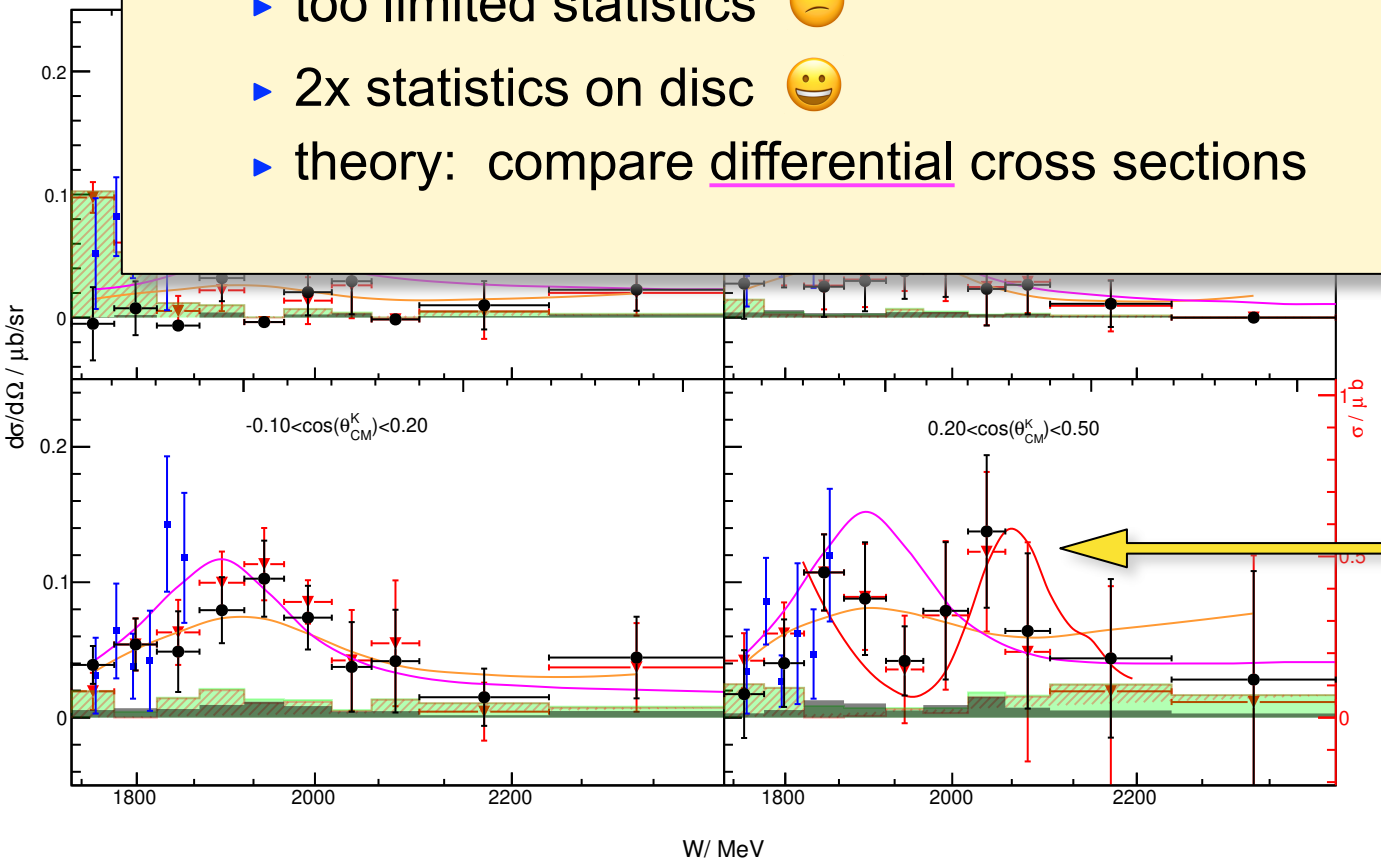
EPJ A 55 (2019) 202

BGOOD simulated bg fit

BGOOD real bg fit

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



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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 → Σππ
M.H. Alston et al., PRL 4 (1961) 698

→ probably first "exotic" hadron

ttle the decades-long
-quark state or mere
e 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 Λ_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

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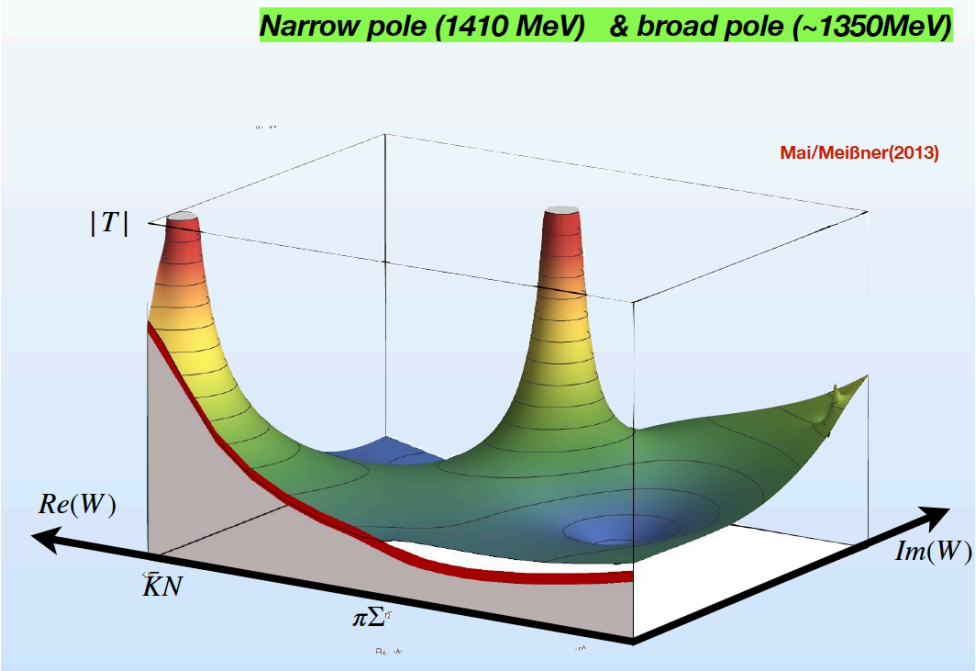
Λ(1405) 2-pole structure in χPT



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"

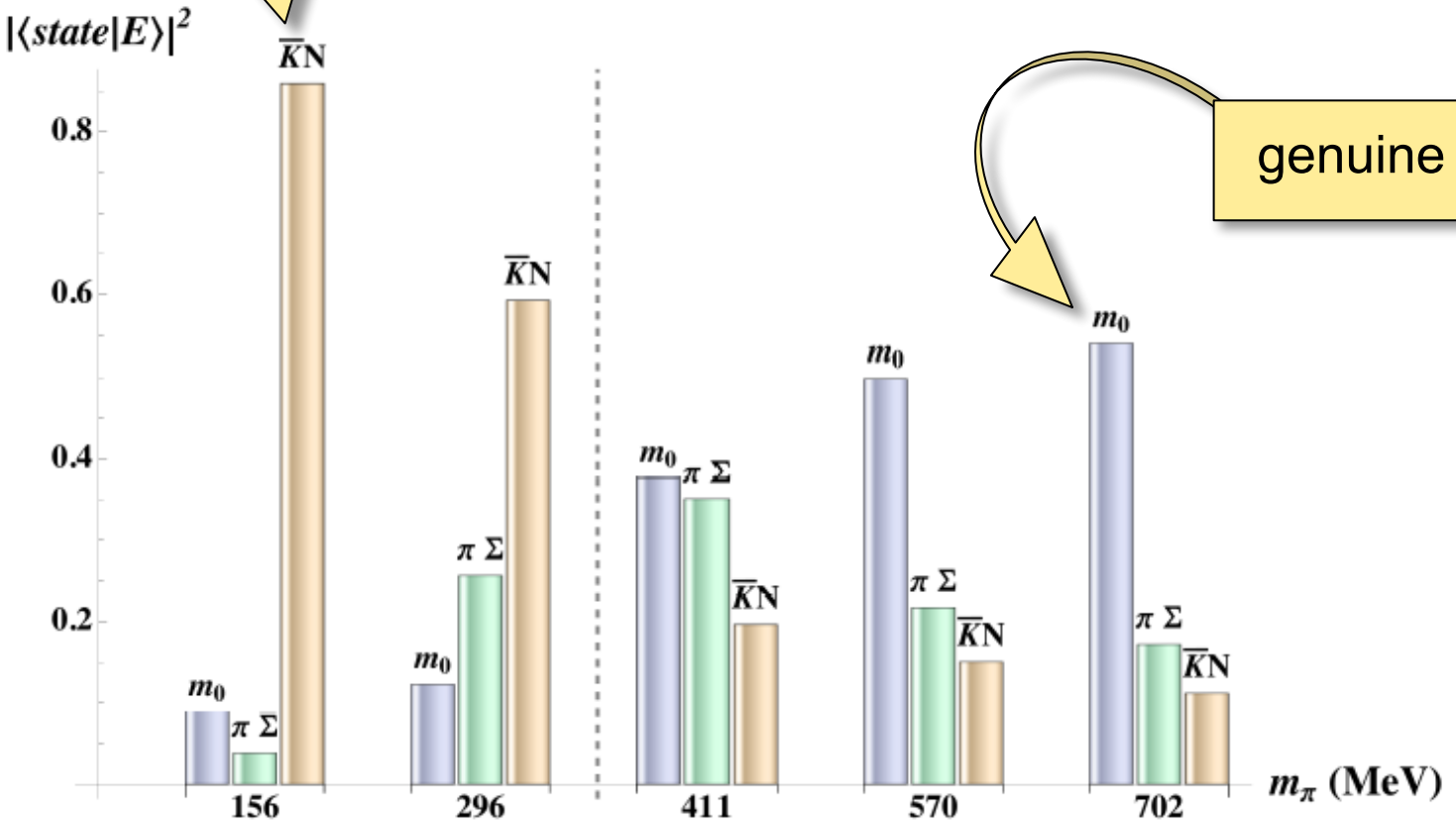
Λ(1405) Lattice QCD

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

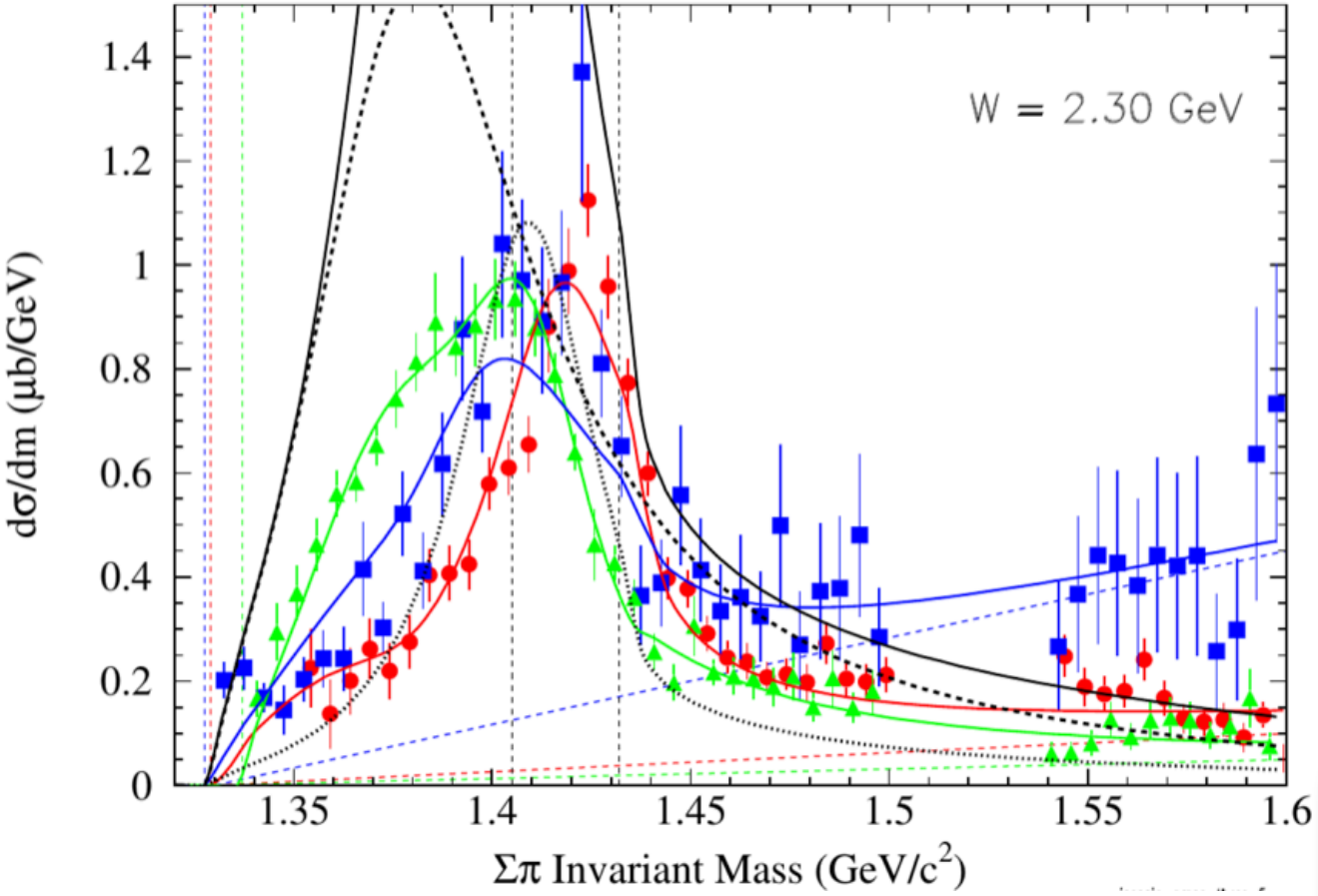
genuine 3q



$K^+ \Lambda(1405)$ 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

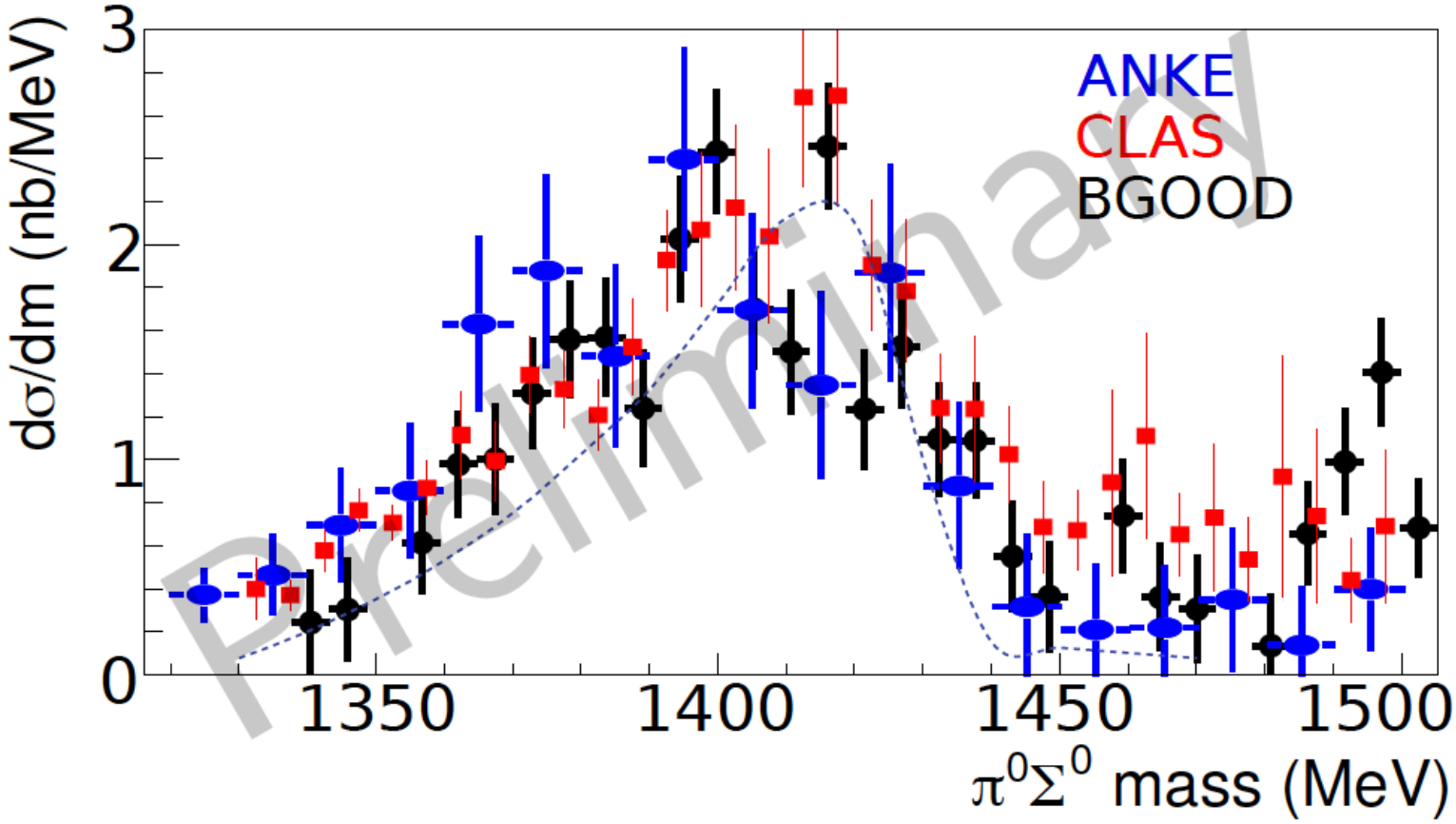
2-poles structure should be visible in pure I=0 channel $\Sigma^0\pi^0$

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.]
Phys. Lett B 833 (2022) 137375



$K^+ \Lambda(1405)$

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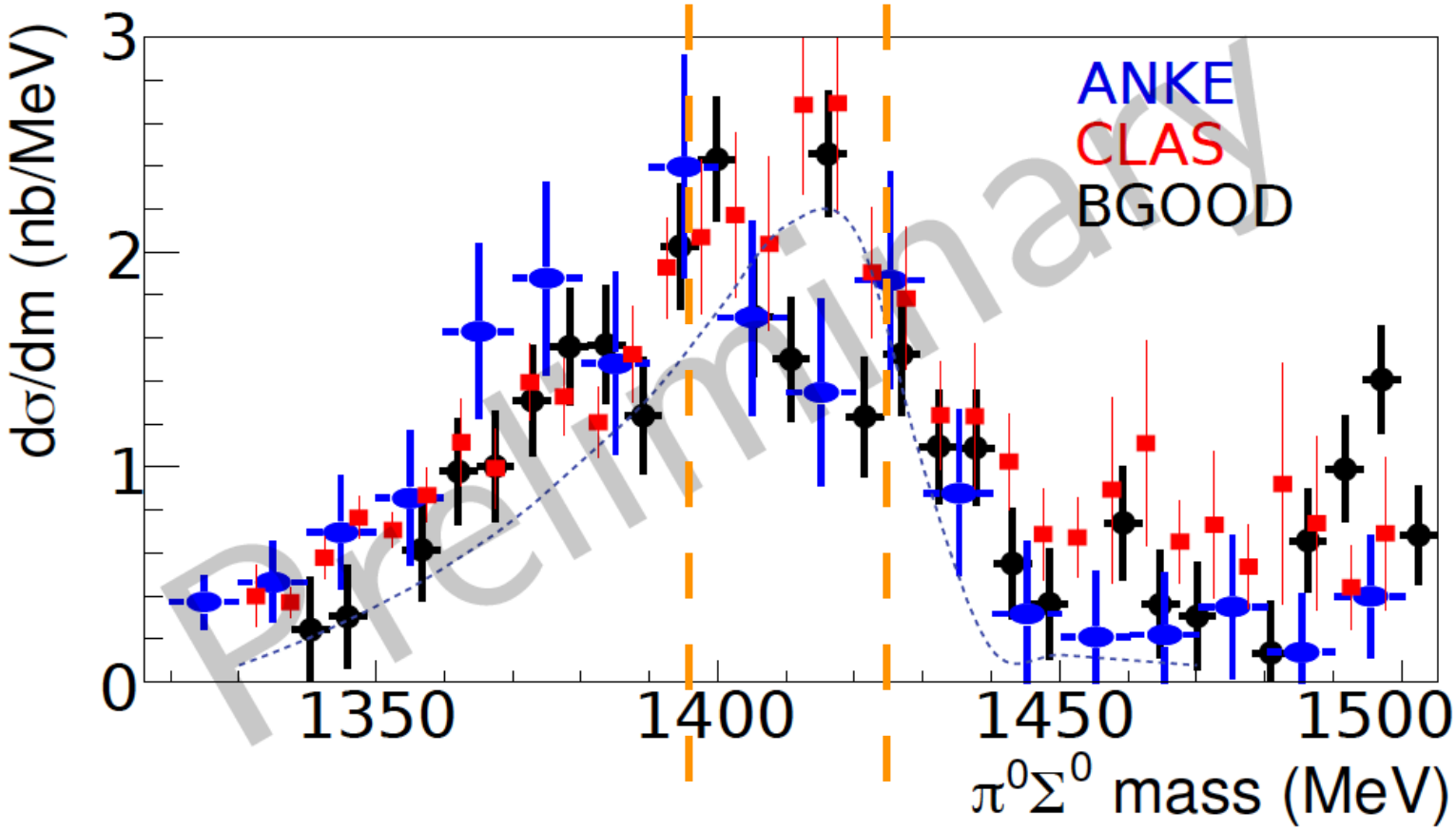
double peak strukture
@ 1395 / 1425 MeV ??



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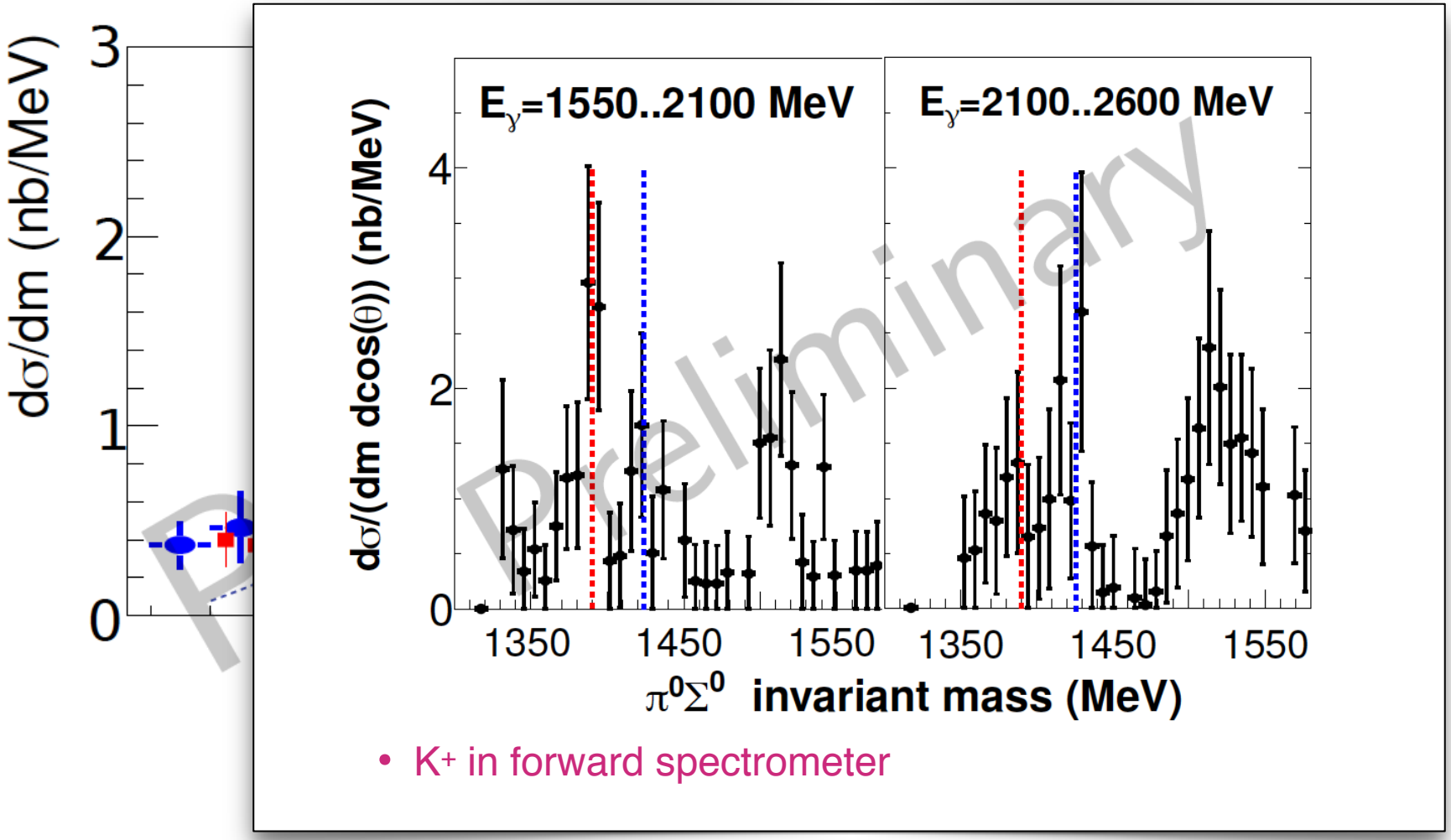
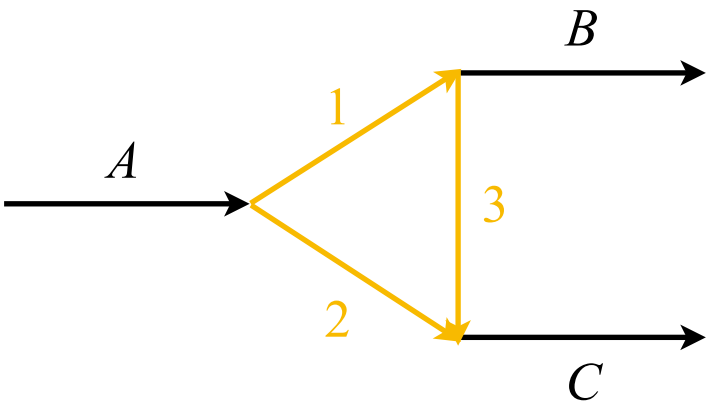


- K^+ in forward spectrometer

photoproduction mechanism – triangle singularity



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

can mimic resonance

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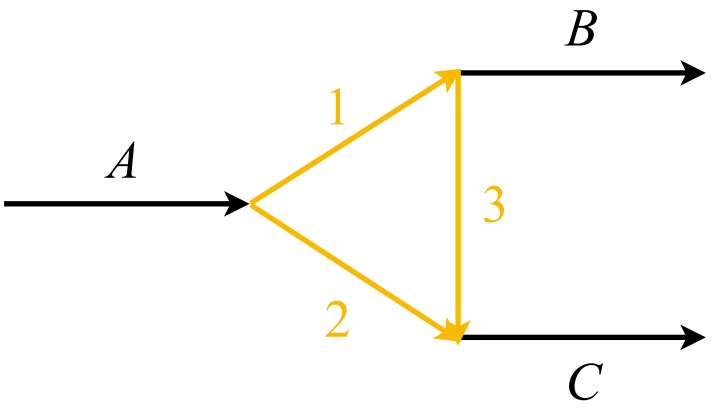

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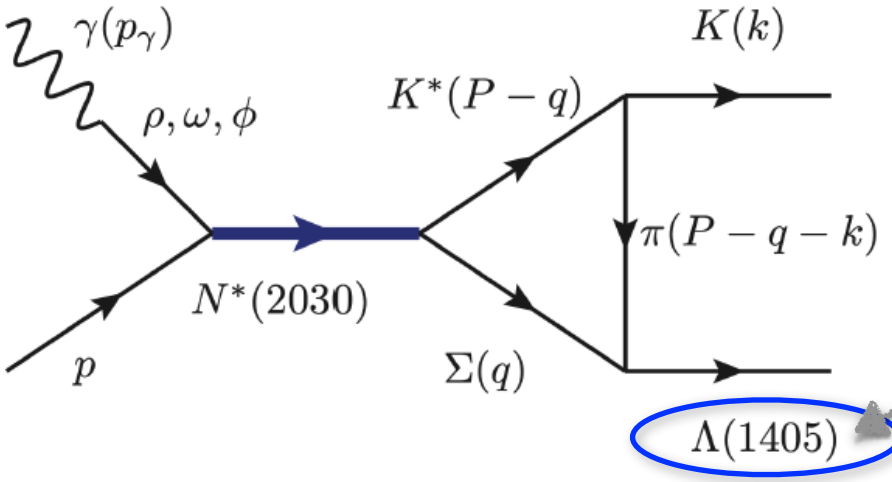
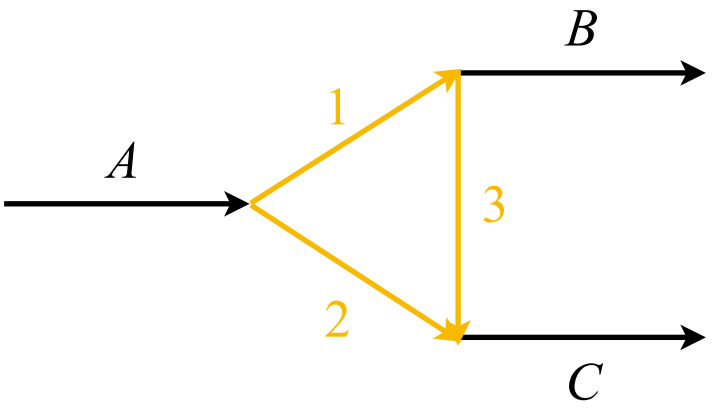


or drive (dynamically generated) resonance

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

photoproduction mechanism – triangle singularity



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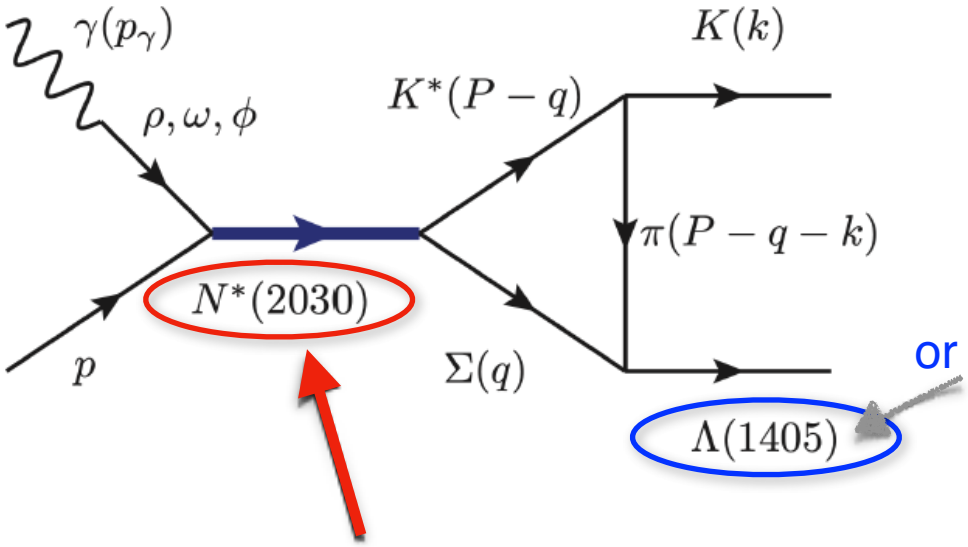

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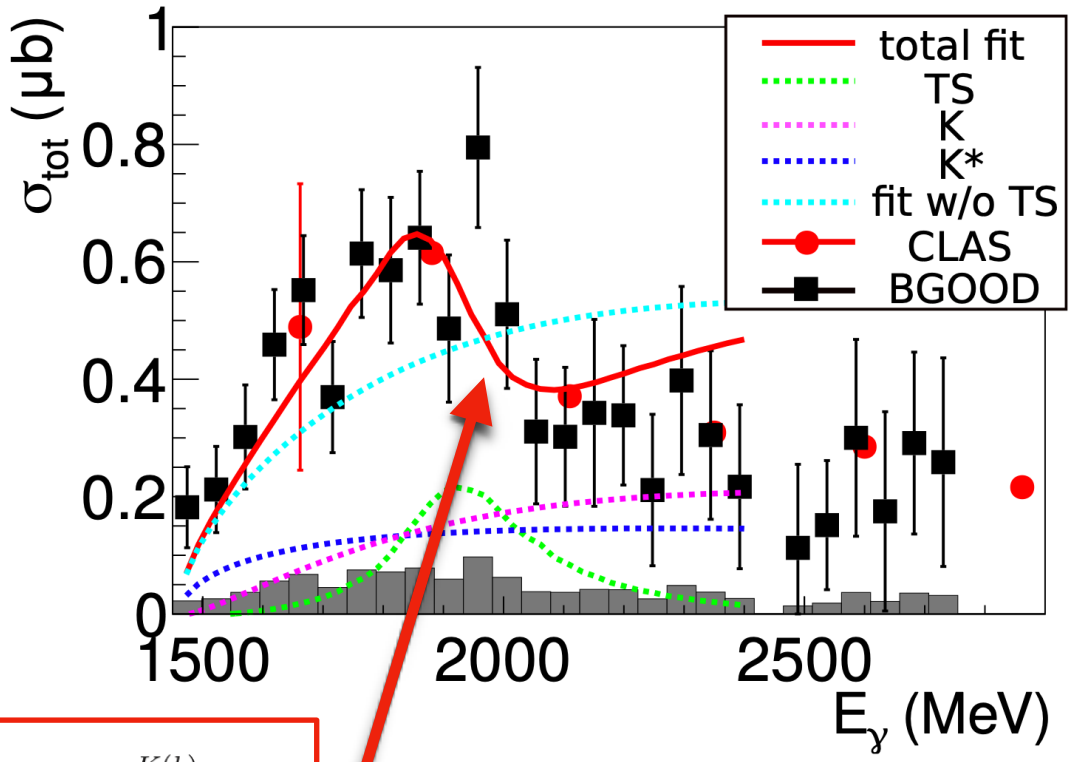
E. Wang, J. Xie, W. Liang, F. Guo, E. Oset,
PR C 95 (2017) 015205

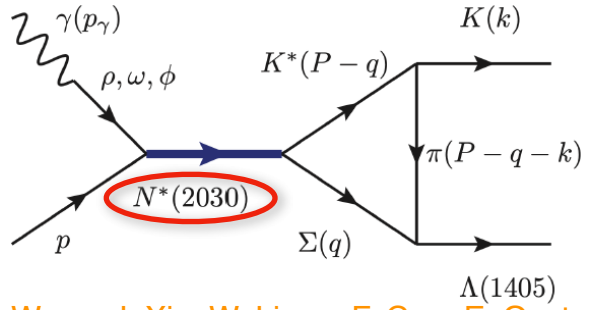
$K^*\Sigma$ suspect in $K^0\Sigma^0$ channel

$K^+ \Lambda(1405)$ – photoproduction mechanism

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

G. Scheluchin *et al.* [BGOOD collab.]
Phys. Lett B 833 (2022) 137375



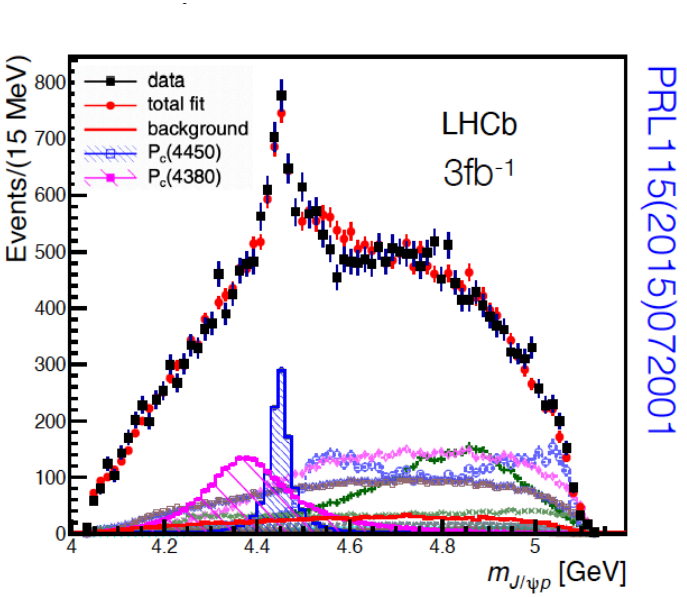


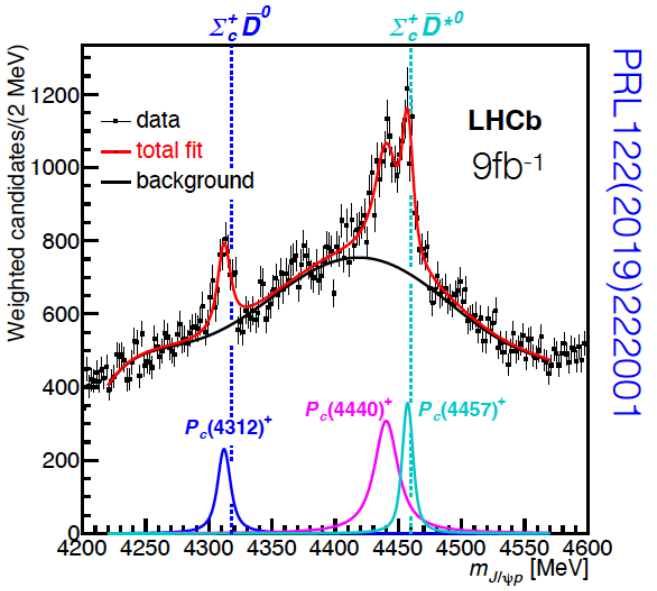
E. Wang, J. Xie, W. Liang, F. Guo, E. Oset,
PR C 95 (2017) 015205

cusp: triangle meachanism significant

Multi-quark states

taken from Jinlin Fu's talk
@ HaSP general meeting (Munich 22)





pentaquark candidates:

$P_\psi^N(4450)^+$

$P_\psi^N(4380)^+$

Fine structures $P_\psi^N(4440)^+$, $P_\psi^N(4457)^+$

New pentaquark state $P_\psi^N(4312)^+$

Not sensitive to broad state $P_\psi^N(4380)^+$

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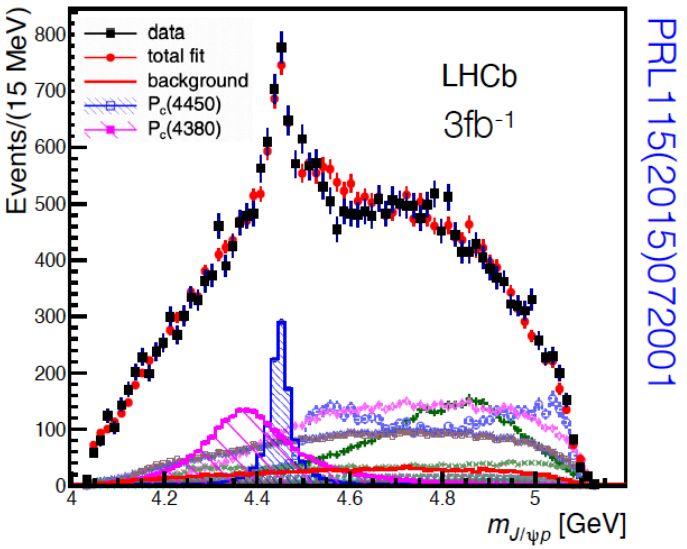

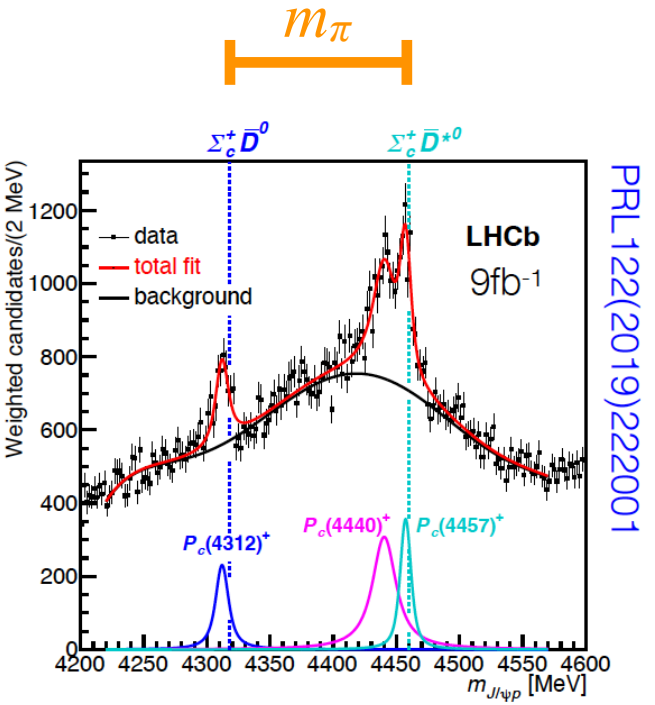

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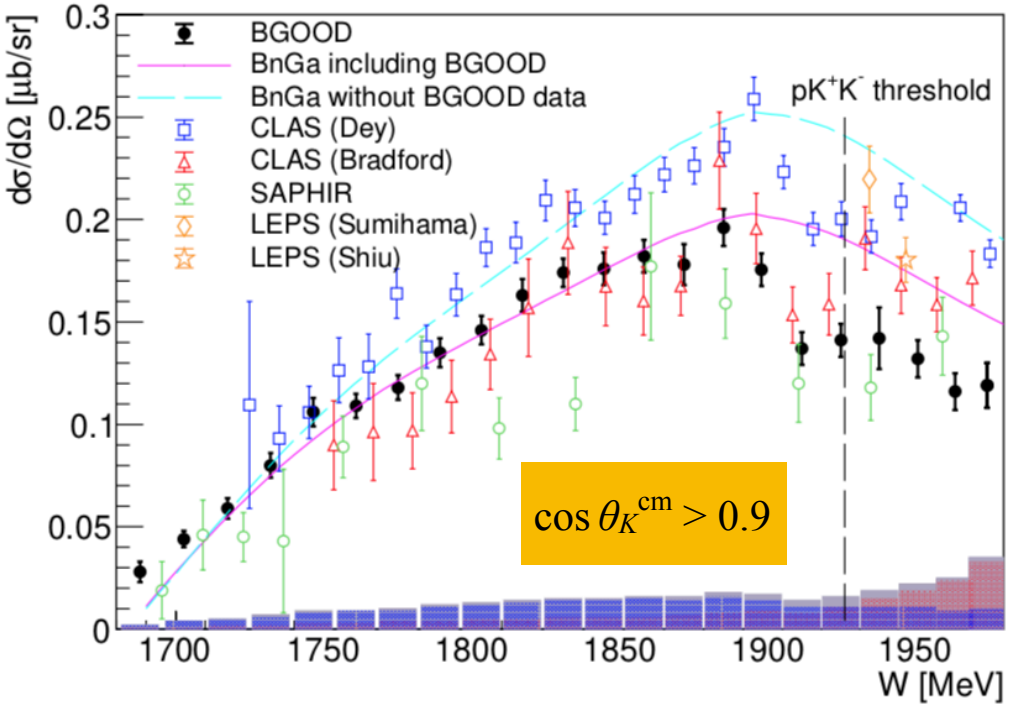
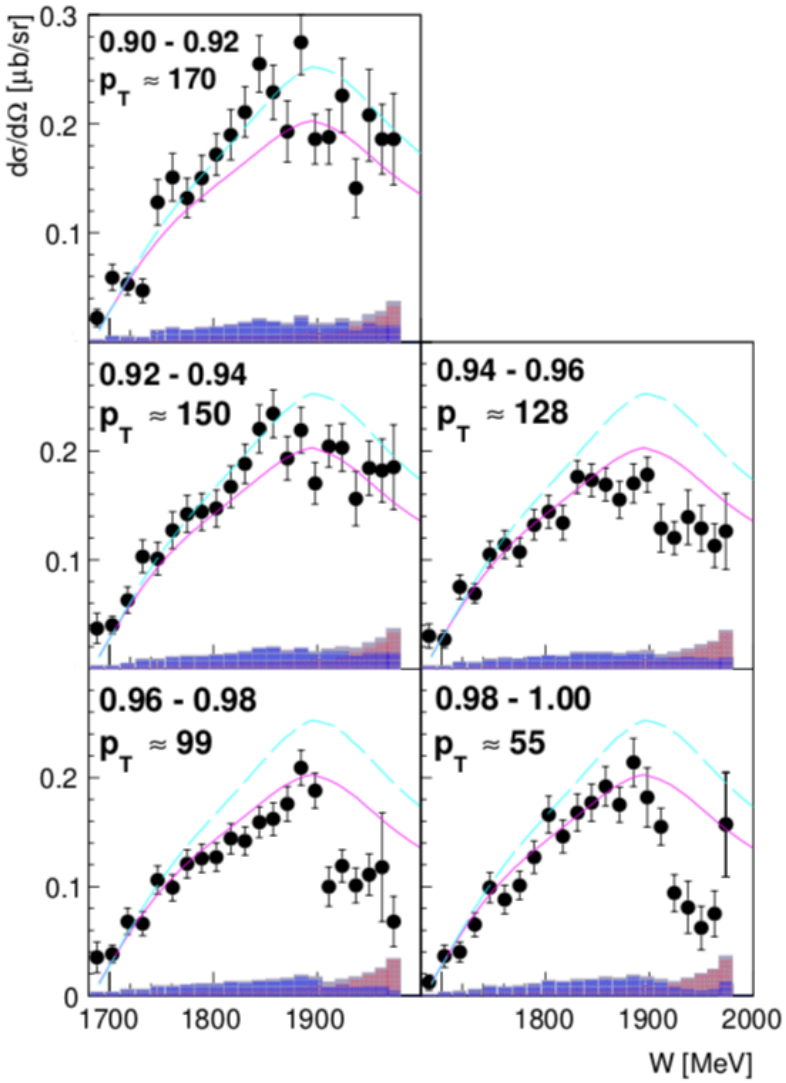
$\gamma p \to K^+ \Sigma^0$ photoproduction

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





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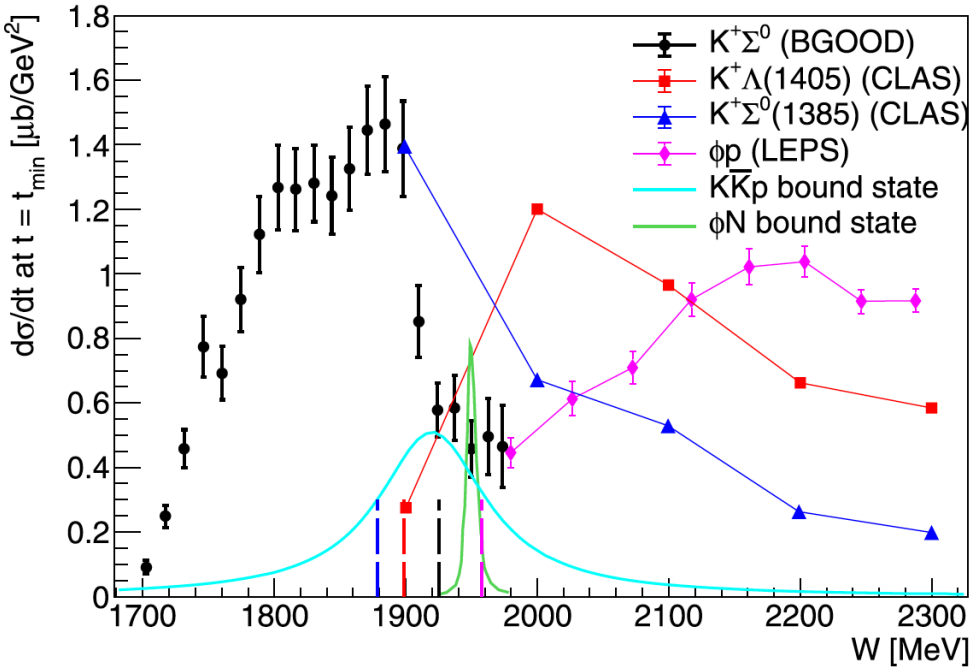

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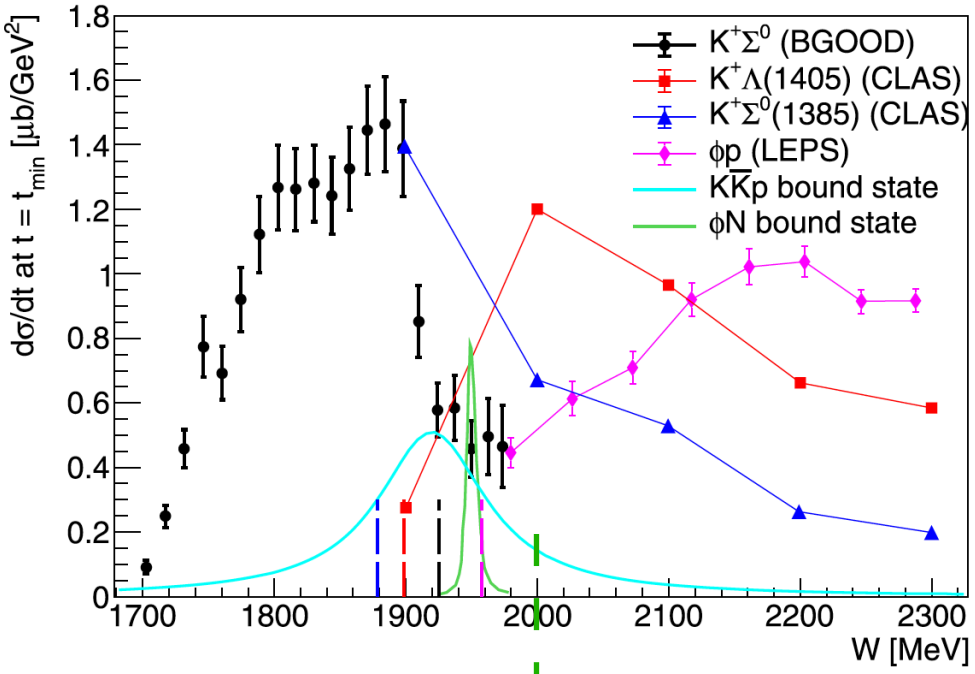

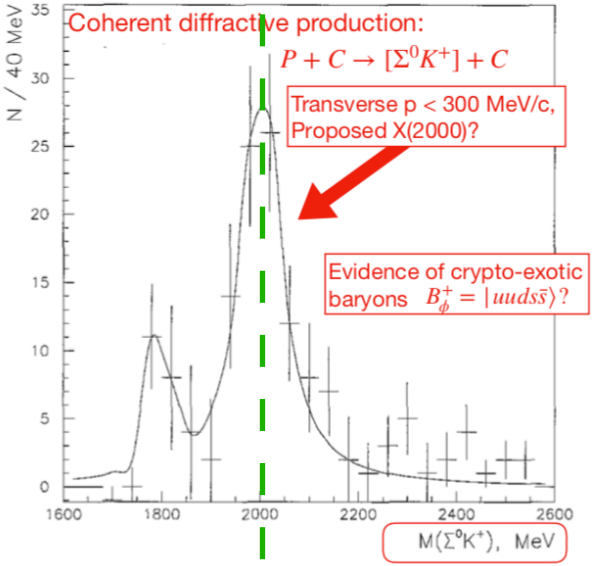

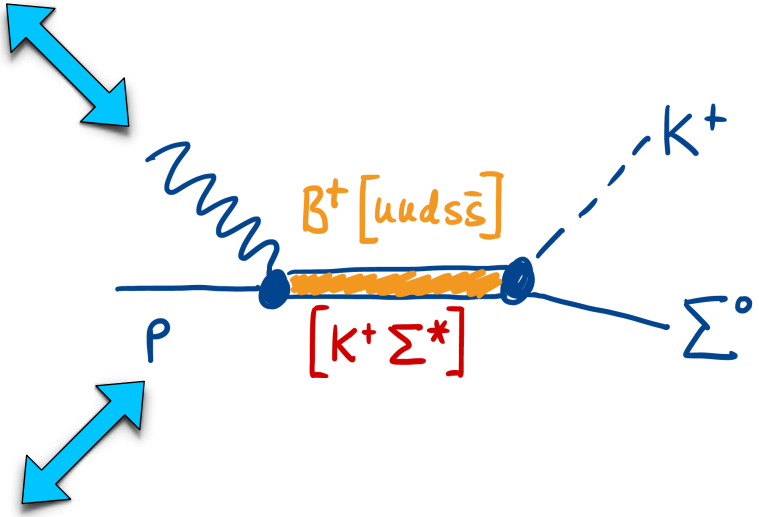

S.V. Golovkin *et al.* [SPHINX collab.]
Z. Phys. C 68 (1995) 585

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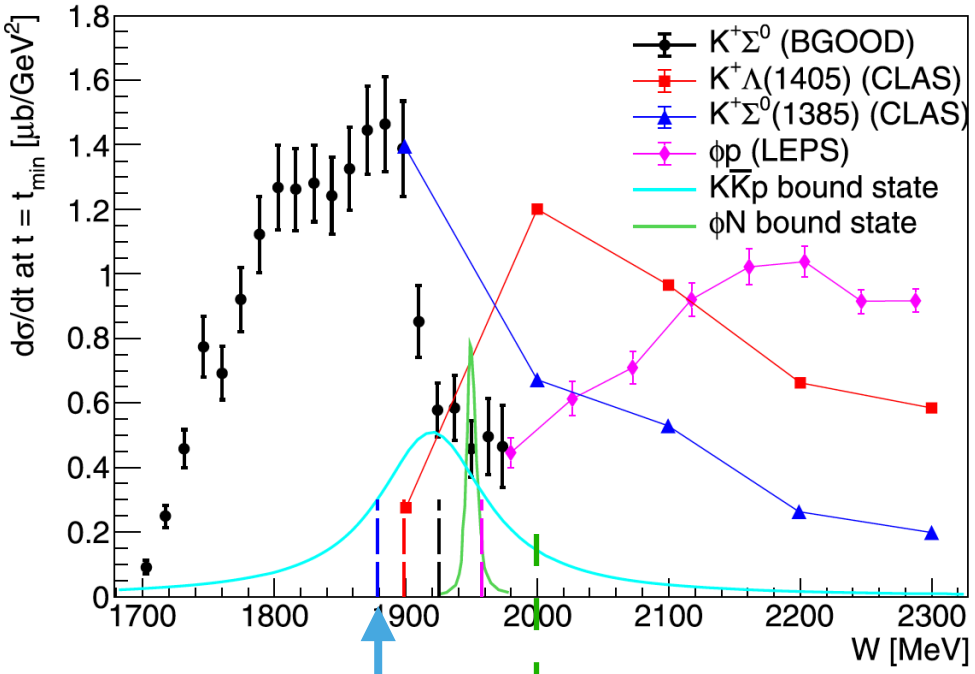
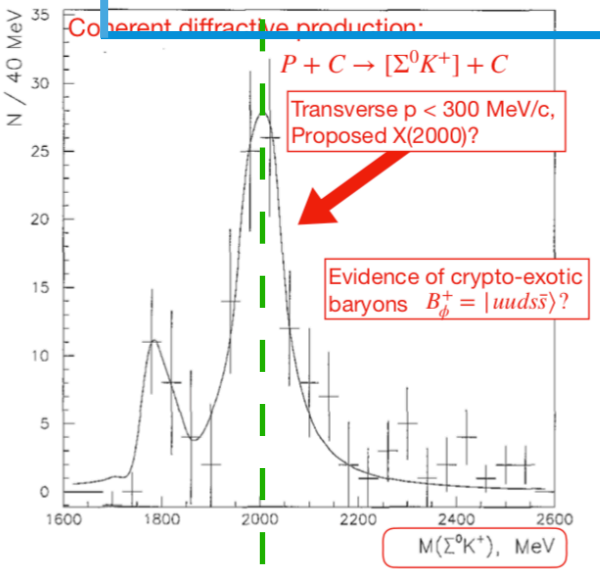
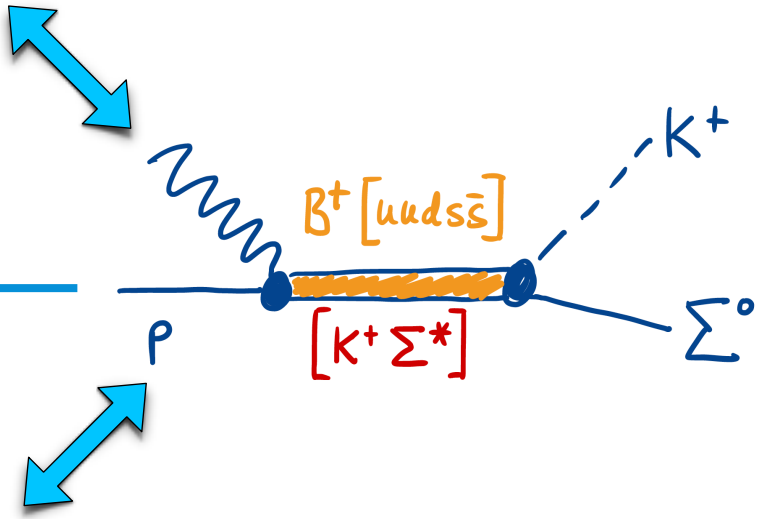






S.V. Golovkin *et al.* [SPHINX collab.]
Z. Phys. C 68 (1995) 585

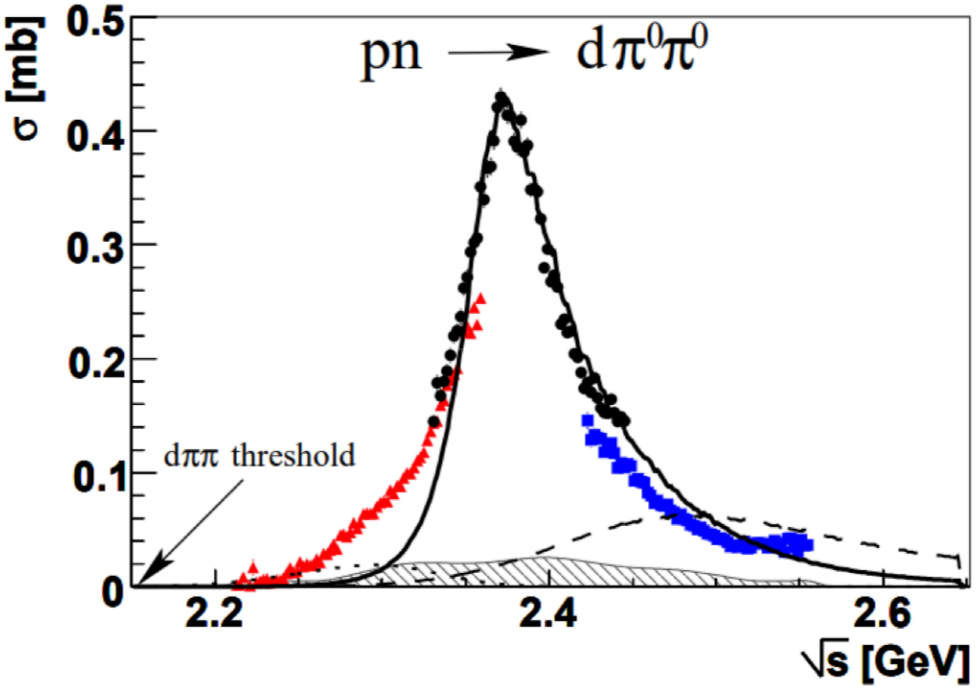
from penta to hexa ...

→ Dibaryons ?

from penta to hexa ...

Dibaryons ?

- early SU(6) predictions – NN, NΔ & ΔΔ type dibaryon candidates
  Dyson & Xuong, PRL 13 (1964) 815
- 3-body calculations NΔ & ΔΔ in good agreement
  Gal & Garcilazo, NPA 928 (2014) 73



d(2380)*
observed in pn fusion reaction
at WASA experiment at COSY

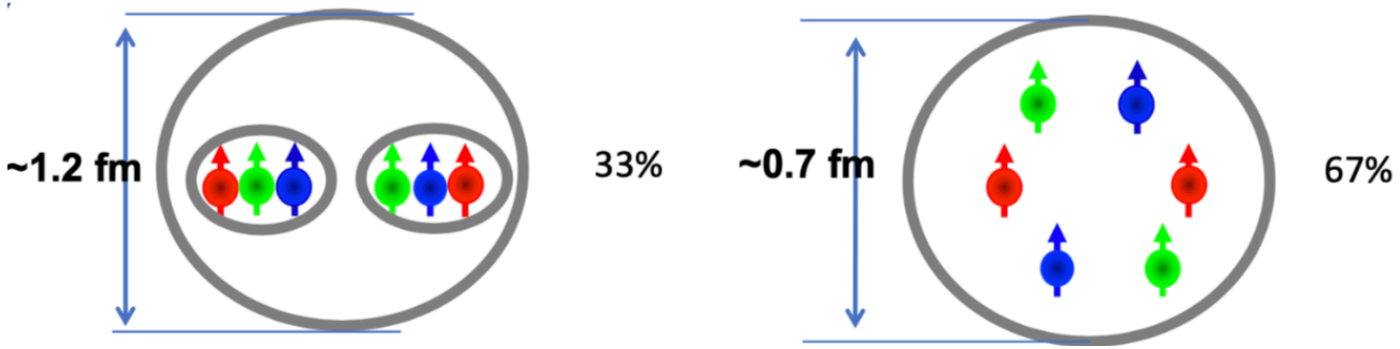
P. Adlarson et al. [WASA@COSY],
PRL 106 (2011) 242302

- $(I)\ J^P = (0)\ 3^+$
- ΔΔ type object ?
- meanwhile observed in multiple final states in pn reactions

Dibaryons ?

- Microscopic χ quark models:
  - 2/3 hidden color (compact) configuration
  - 1/3 molecular component

    Huang et al., Chin. Phys. C7 (2015) 071001



- *d*(2380)* in the centre of neutron stars

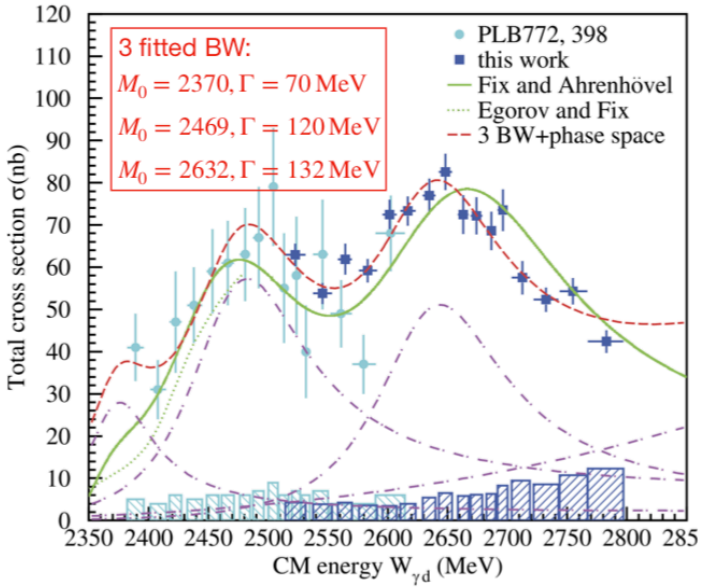
  Vidana et al., PLB 781 (2018) 112

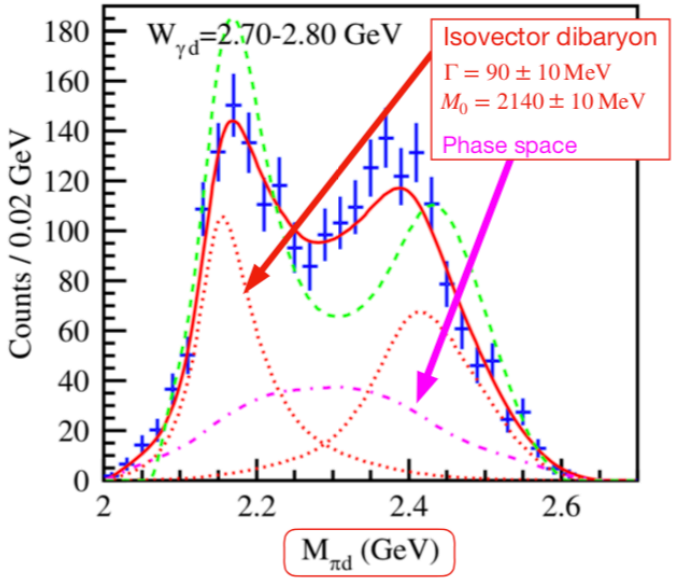
- Dark matter ?? – *d*(2380)* BEC formed in early universe ?

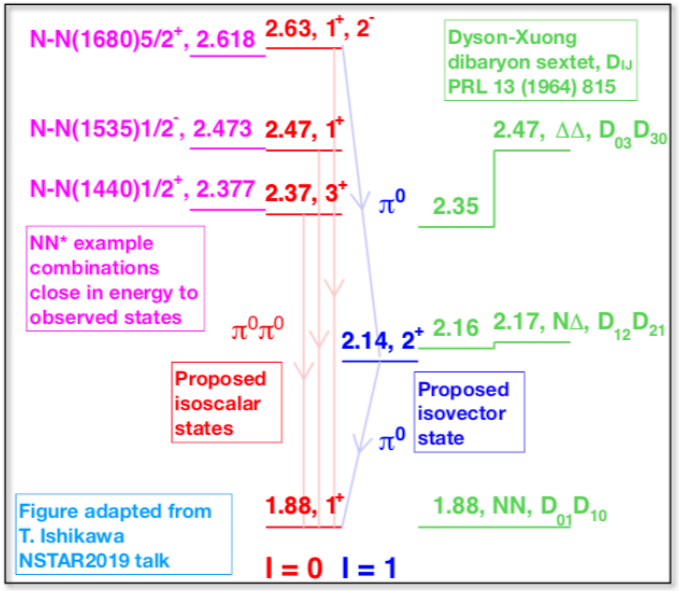
  Bashkanov and Watts, J. Phys. G 47 (2020) 03LT01

Dibaryons ?

- coherent photoproduction $\gamma\, d \rightarrow \pi\, \pi\, d$
  challenging: minimal momentum transfer to target deuteron, nbarn x-sec & large qf background
- previous data from ELPH
  Takatsuku Ishikawa et al., PLB 789 (2019) 413

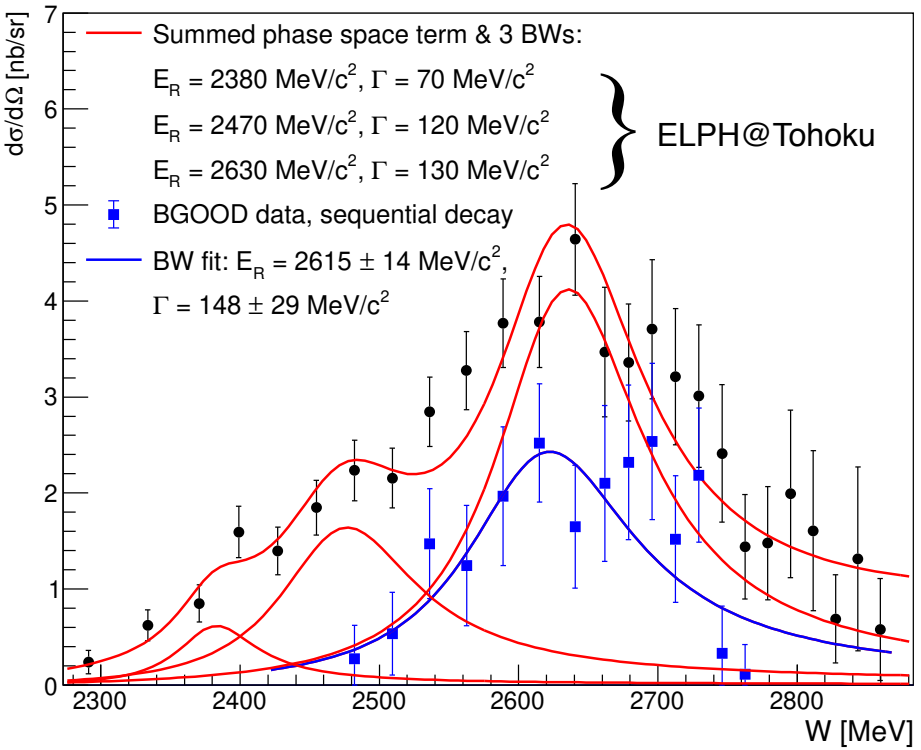


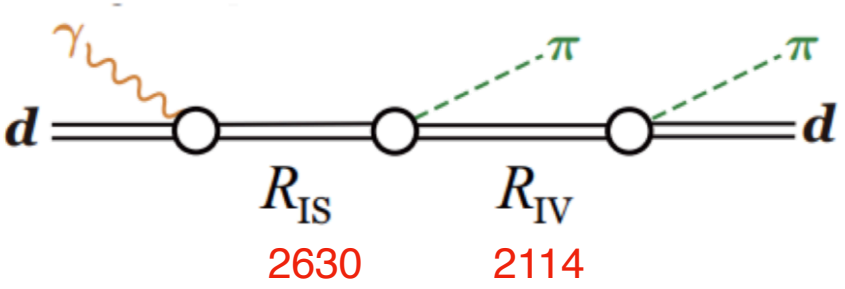


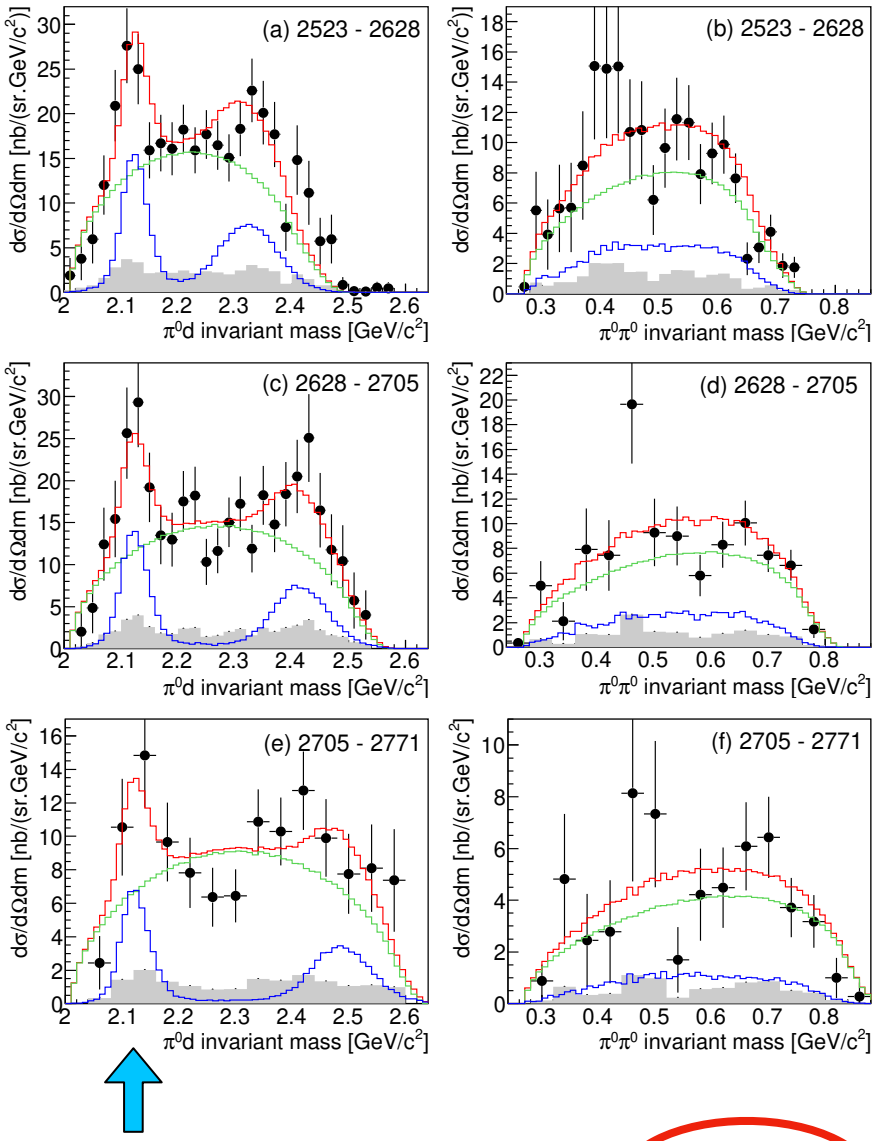


$\gamma\, d \rightarrow d\, \pi^0\, \pi^0$ coherent photoproduction @BGOOD

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





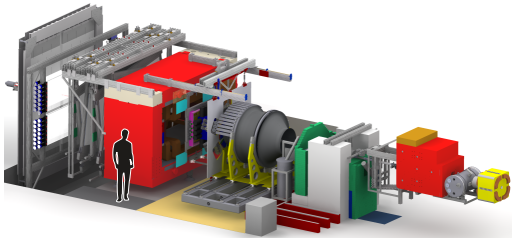


$\pi^0 d$ isovector state: 2114 MeV, Γ≃ 20 MeV

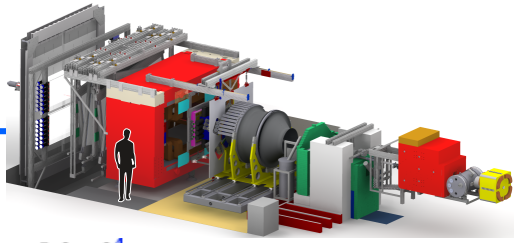
Conclusions

- multi-quark effects in uds sector observed w/ BGOOD experiment
- forward acceptance ↔ meson-baryon dynamics
  @ thresholds & low t / p_T
- Λ(1405) line shape in agreement w/ molecular $\bar{K}N$ structure
- possible [K*-Σ] configuration N*(2030) in $K^0\Sigma^0$ and $K^+\Lambda(1405)$ photoproduction (triangle singularity)
- possible [K-Σ*(1385)] configuration in $K^+\Sigma^0$
- possible dibaryon transitions in coherent $2\pi^0$ d
- hadronic structure formation from basic QCD d.o.f. ?

⇨ a lot remains to be done, but:
meson-baryon & baryon-baryon interactions at thresholds
do play a significant role in uds similar to c sector



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]

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ELSA

universitätbonn

BACKUP

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

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

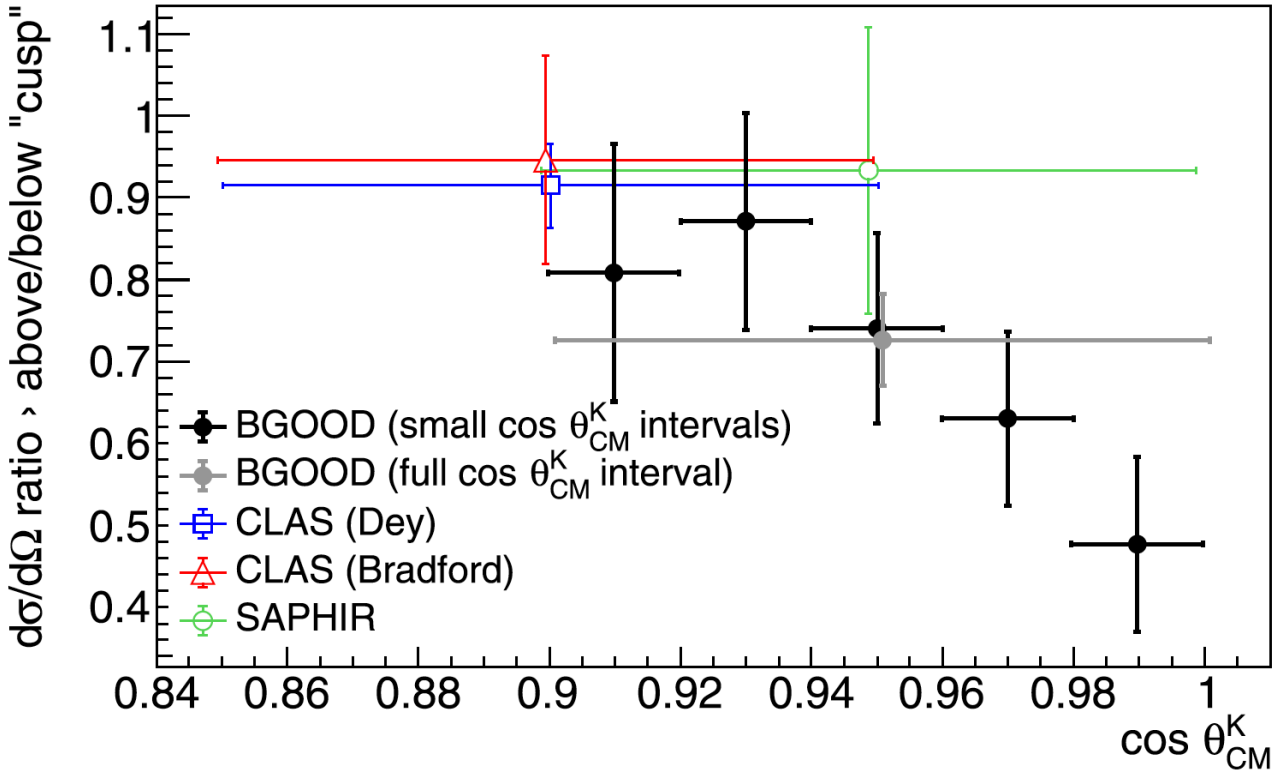

Fig. 7. The ratio of the differential cross section from $W = 1924$ to 1974 MeV compared to $W = 1831$ to 1885 MeV (above and below the cusp-like structure). The data are the average of the differential cross section over these intervals, weighted by the statistical and systematic error. The vertical error bars are the statistical uncertainties, the horizontal error bars are the interval in $\cos\theta^K_{\mathrm{CM}}$ for the given dataset.

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