Baryon-like Spectroscopy

from strange baryons to exotic pentaquarks

Outline

- intro: set the stage
- baryon spectroscopy
- context heavy quarks
- recent results
- summary

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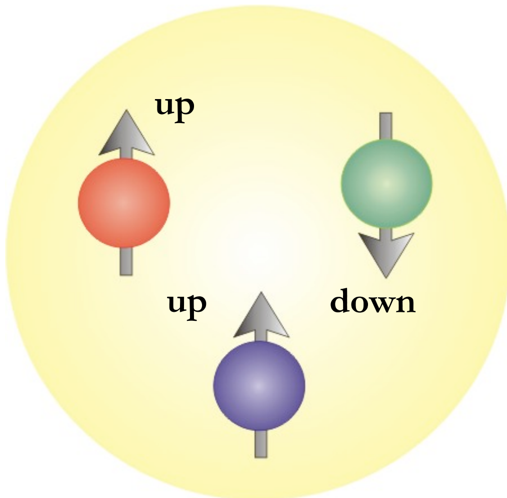
Baryon Structure – Basics

what is a baryon ?

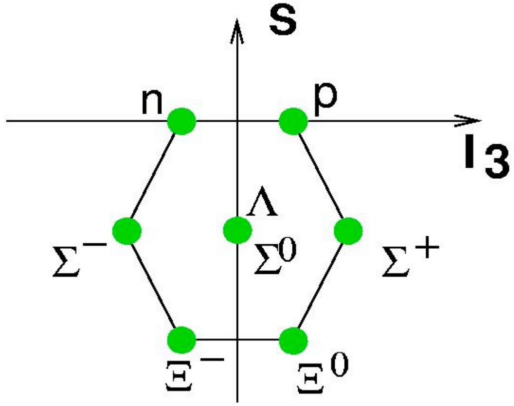
- from ancient Greek βαρυς → weighty, heavy
- analogue meson → medium weight & lepton → lightweight
- matter particle with
- quark constituents: 3 quarks or 3 anti-quarks
- interactions: gravitation, electromagnetic, weak, strong
- fermion
- SM: conserved baryon number
- most abundant: proton, neutron → nucleon
- internal color forces → gluon exchange
- asymptotic freedom: inter-quark forces → 0 @ distance → 0
- external interactions: strong Yukawa forces

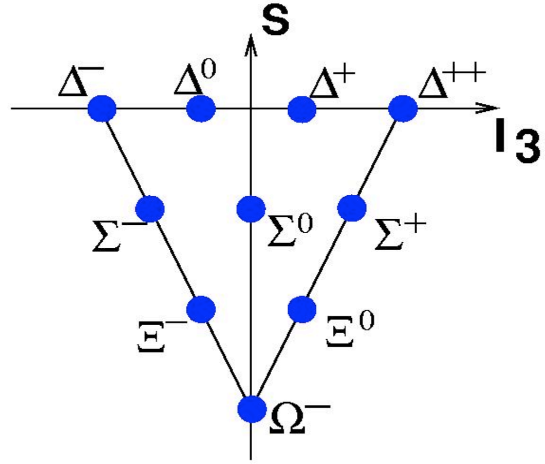
⇨ residual of strong color interactions

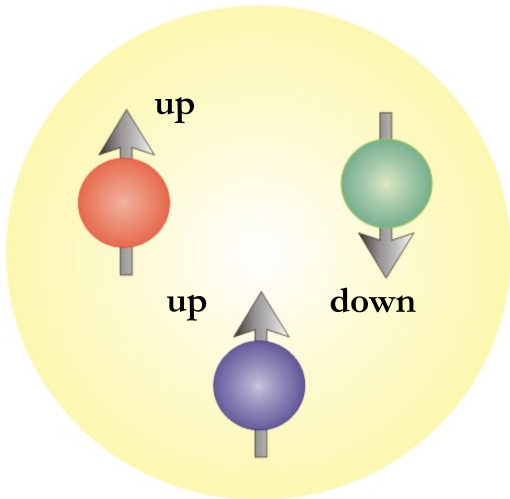
Baryon Structure – Basics



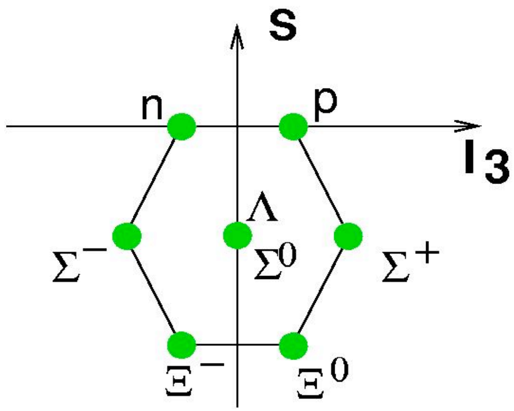
Baryon Structure – Basics

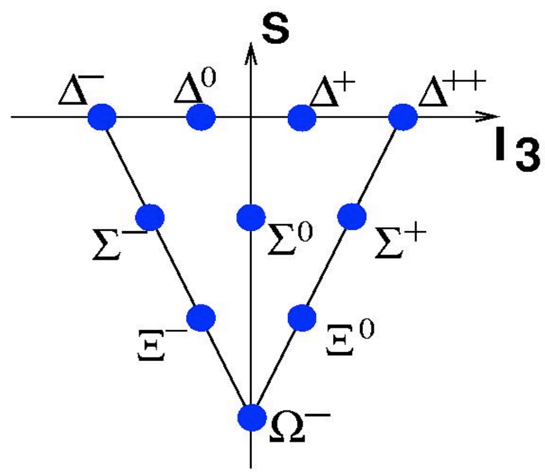


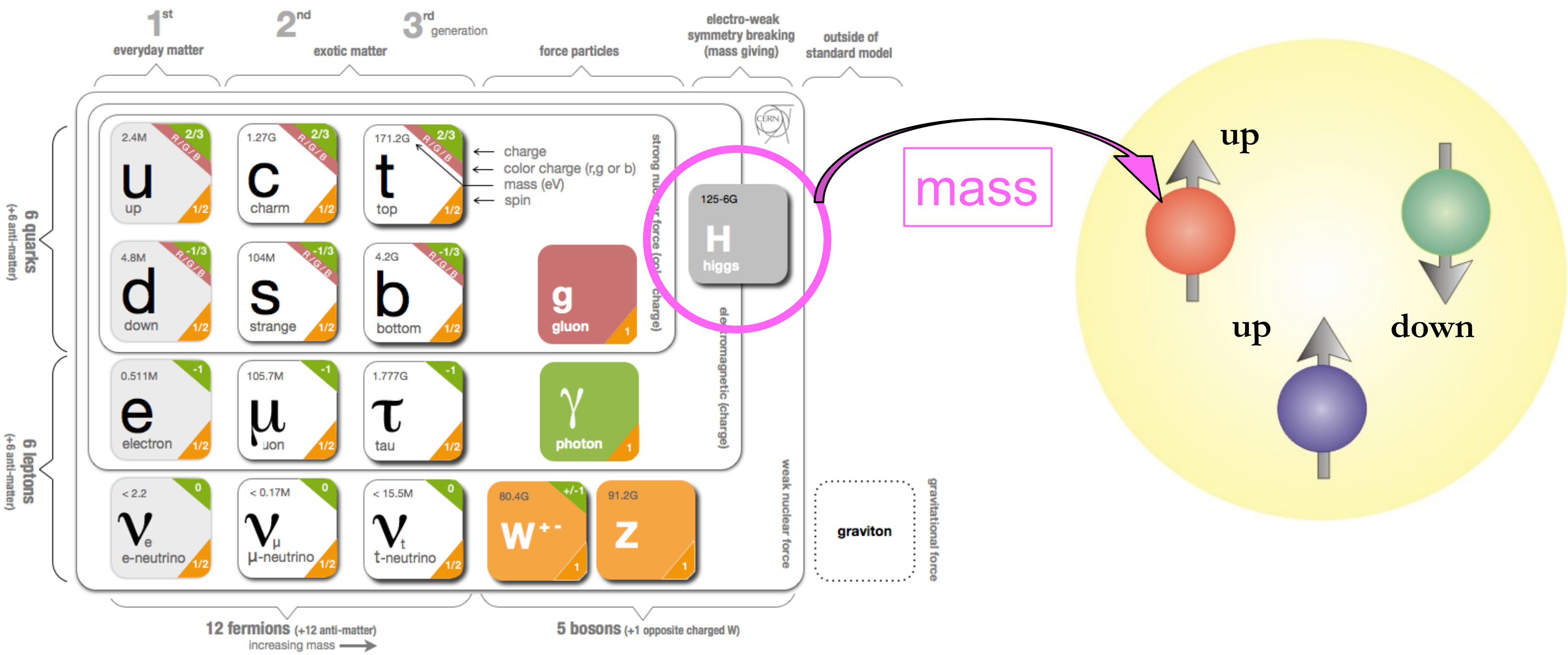




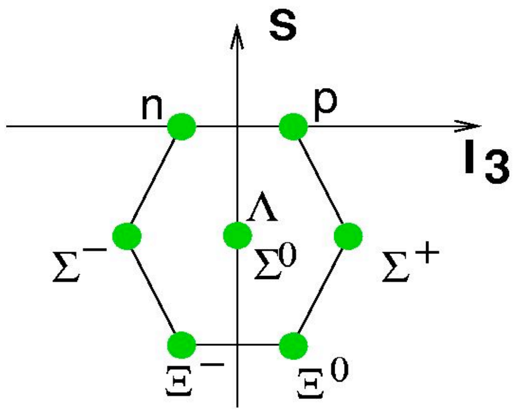
Baryon Structure – Basics

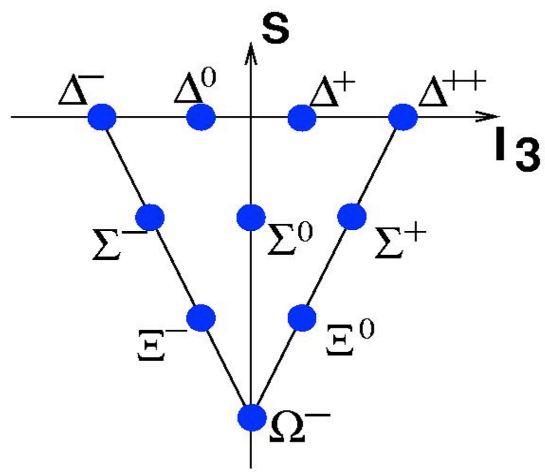


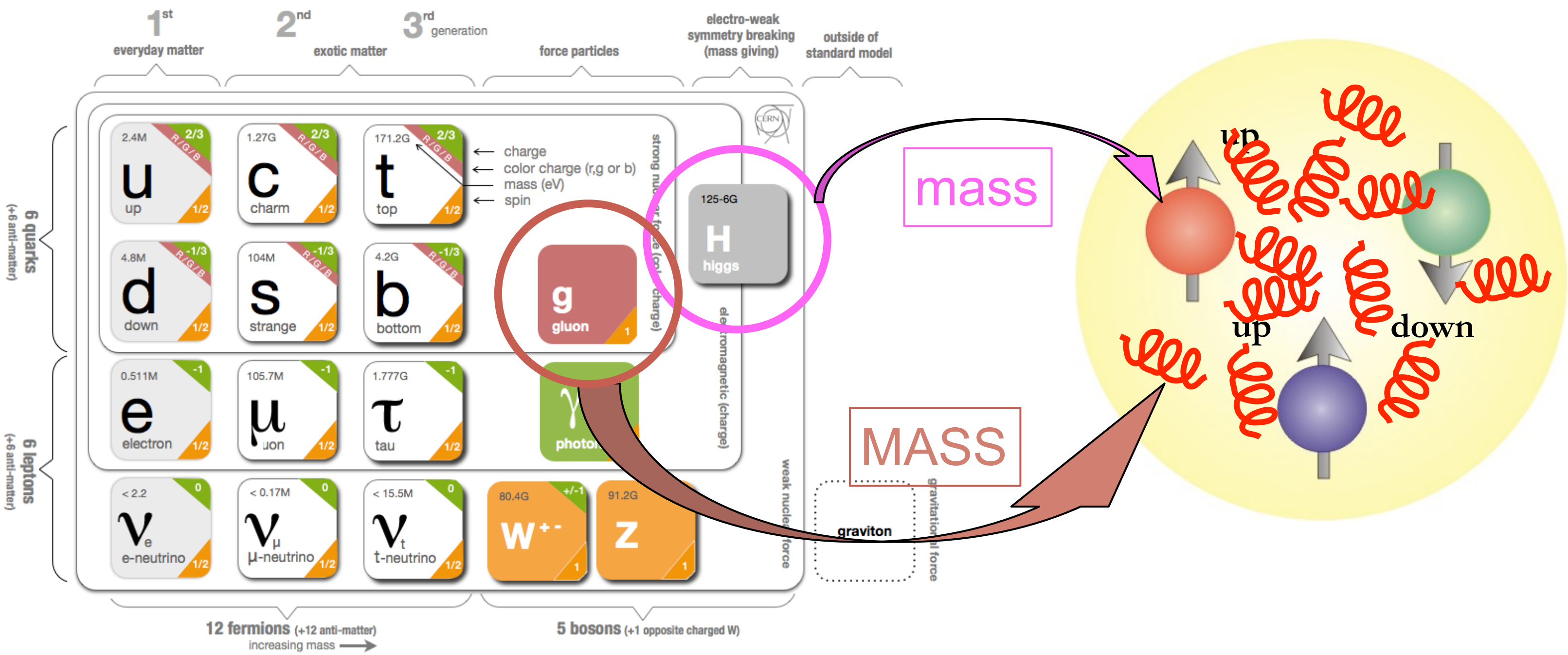




Baryon Structure – Basics







Baryon Structure – Basics

- fit of the quarkonia spectra obtained with

strong coupling

$$V_{QCD} = -\frac{4}{3}\frac{\alpha_S}{r} + k\,r$$

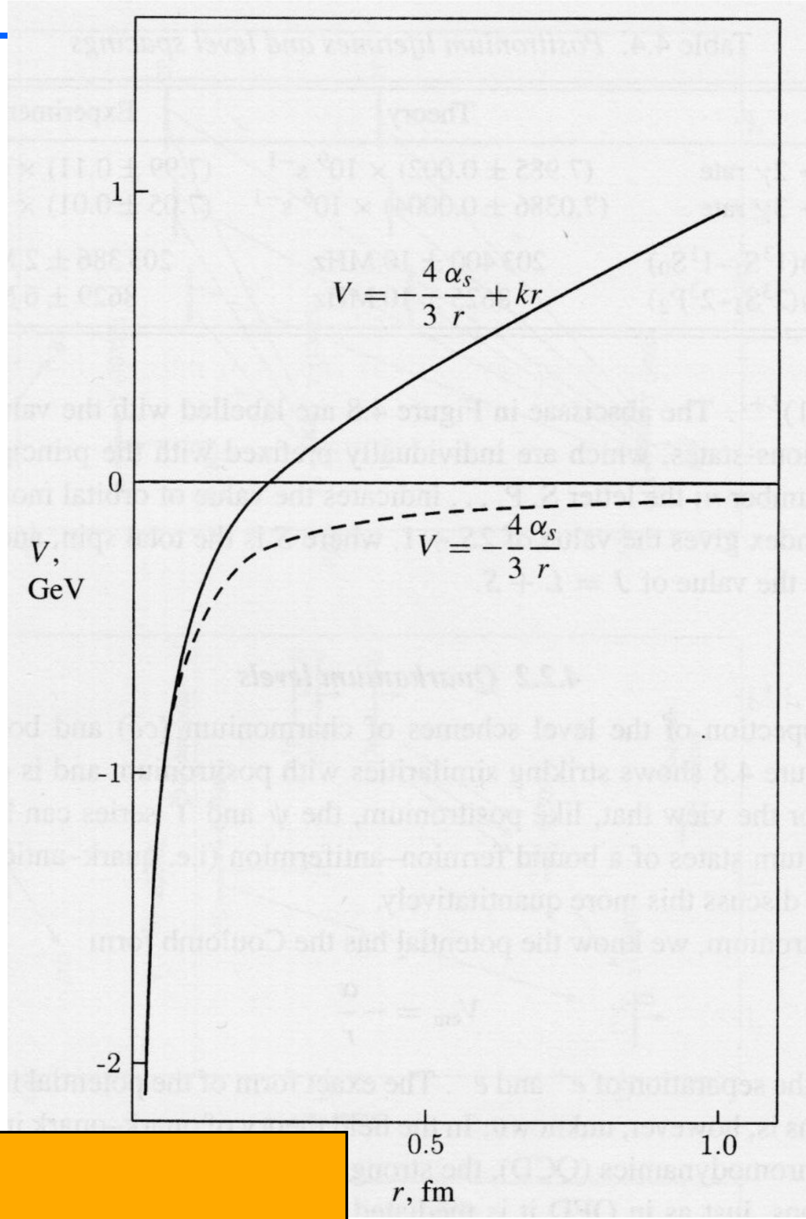
linear confinement

- <u>best fit values</u> (charmonium & bottomonium)

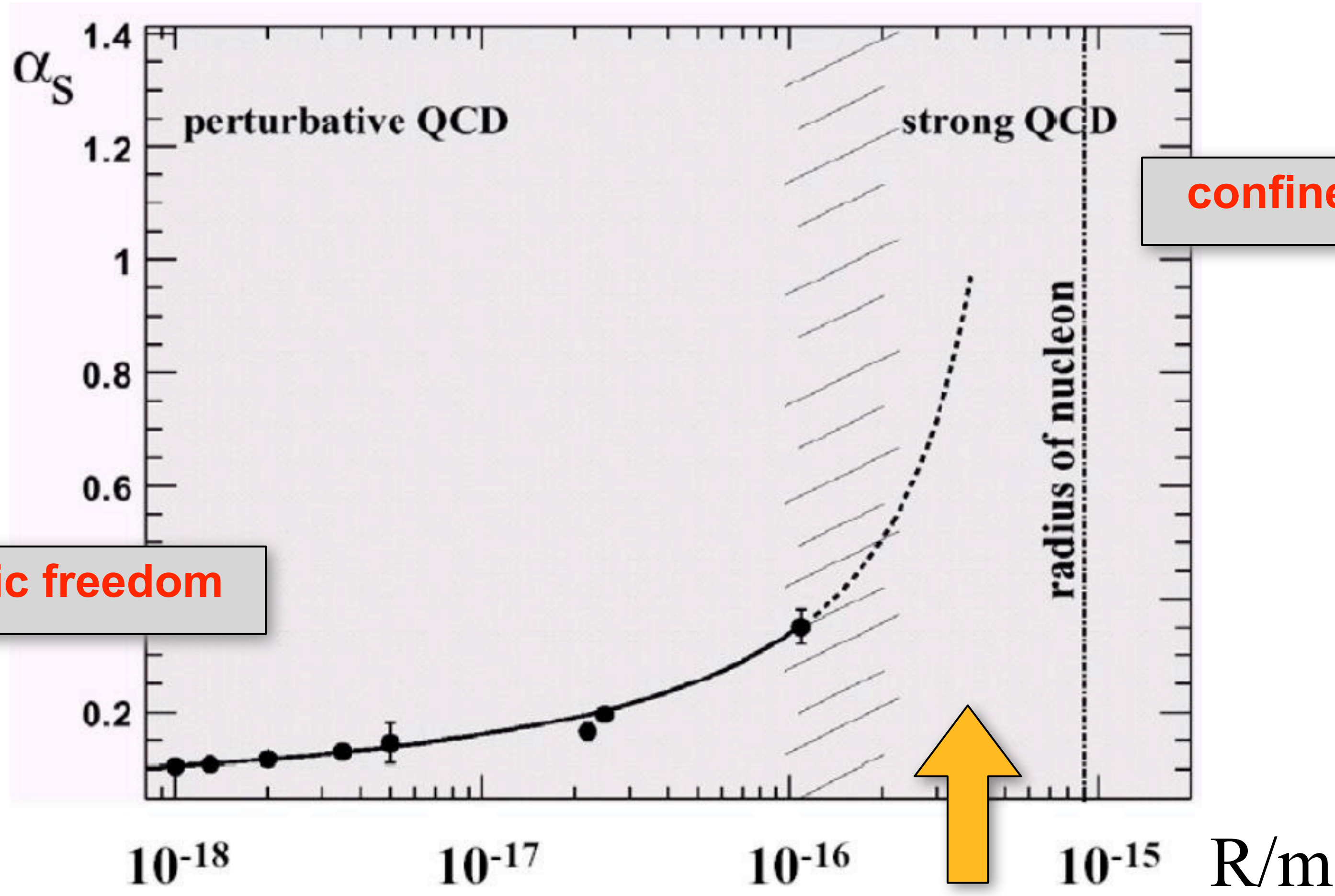
$\alpha_S \approx 0.2$
$k \approx 1\ \mathrm{GeV\,fm^{-1}}$

F =

exercise



Running Coupling



confinement

asymptotic freedom

Lion's Den

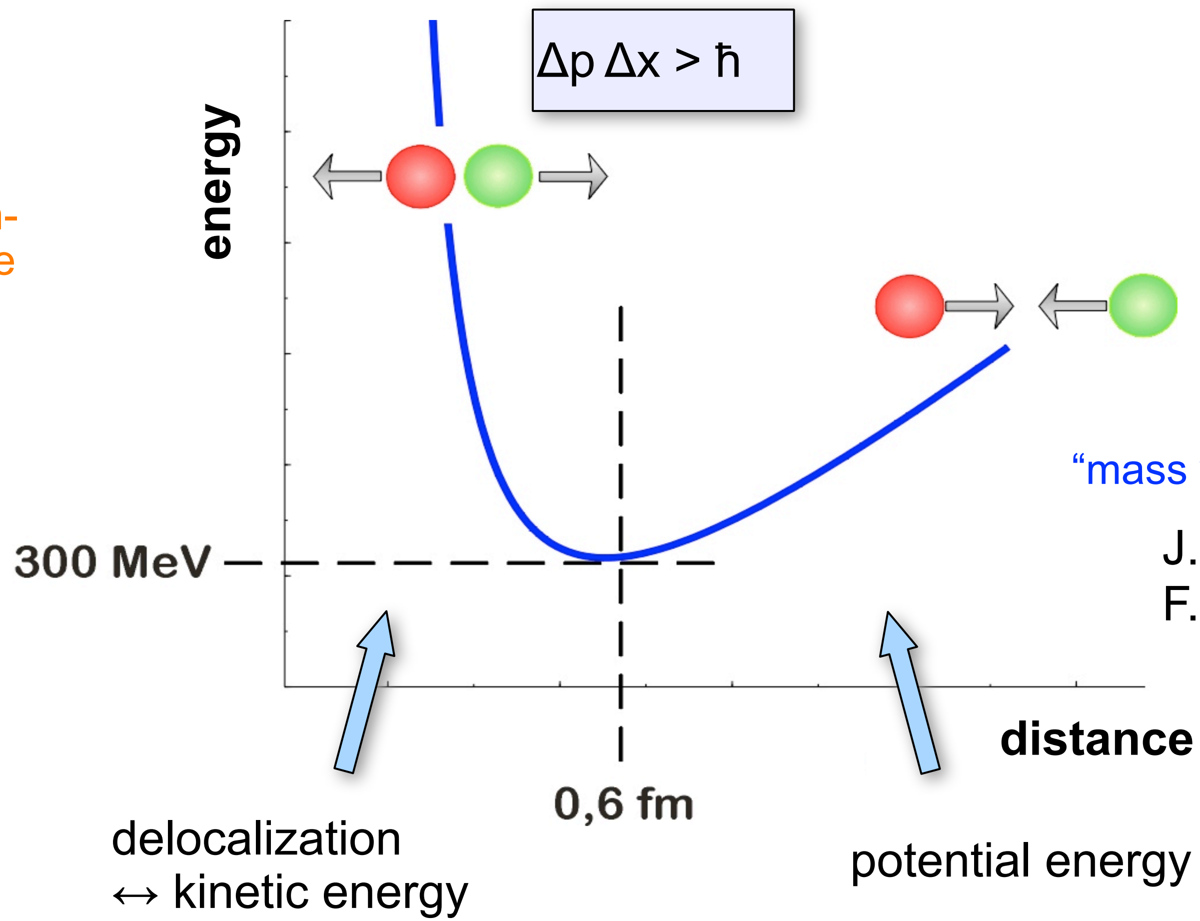
QFT w/o perturbative expansion

Confinement & Nucleon Mass

$G^{a}_{\mu\nu} G_{a}^{\mu\nu} \neq 0$

trace anomaly ↕ scale non-invariance

$m = E/c^2$



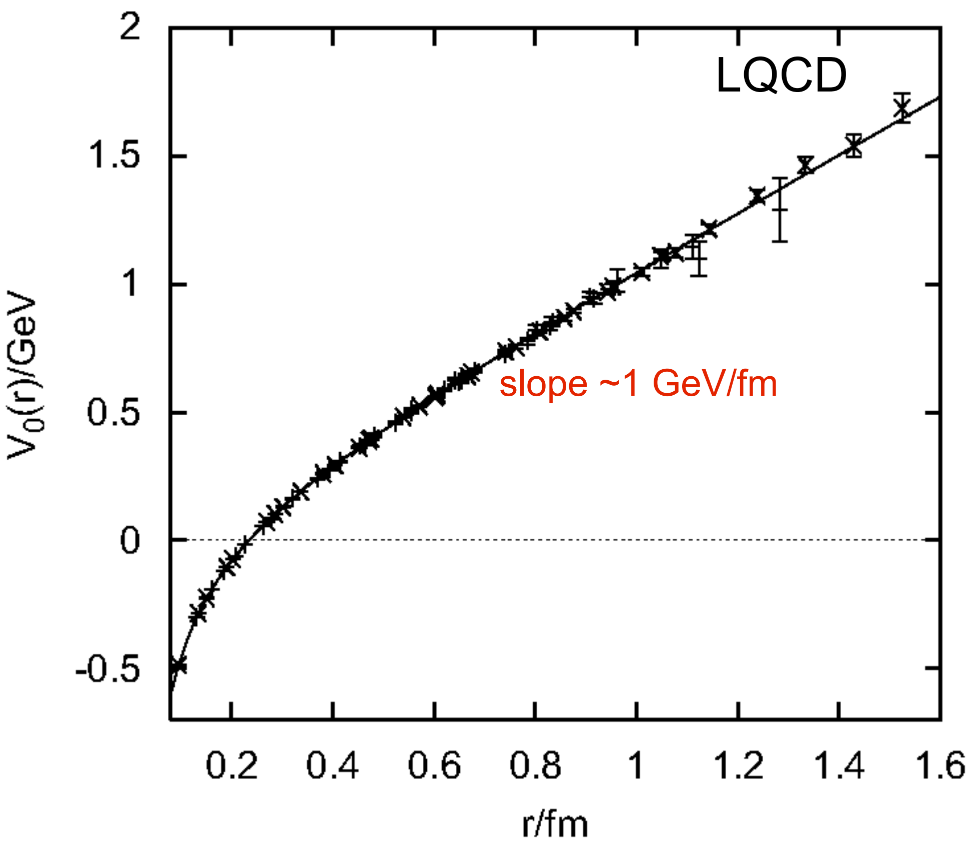
$E_{pot} \sim r$

"mass without mass"

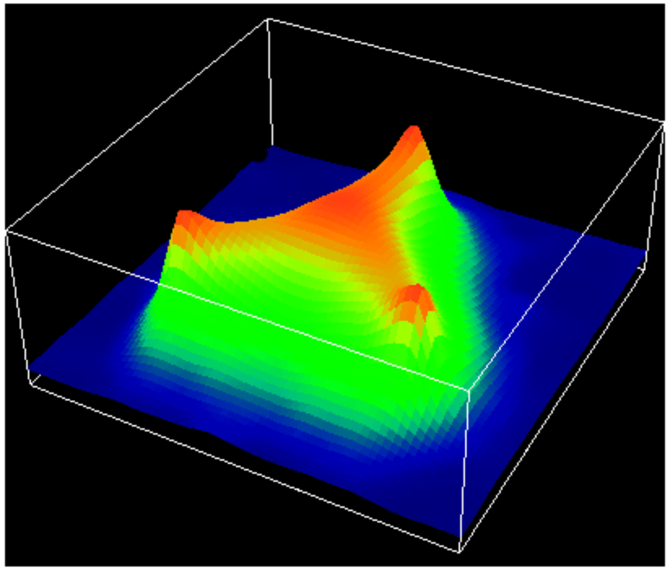
J. Wheeler
F. Wilczek

Hadronic Structure

ground states



G.S. Bali,
Phys. Rep. 343 (2001) 1



Energy density distribution
inside nucleon in LQCD simulation
(F. Wilczek, Physics today 11/99 & 1/00)

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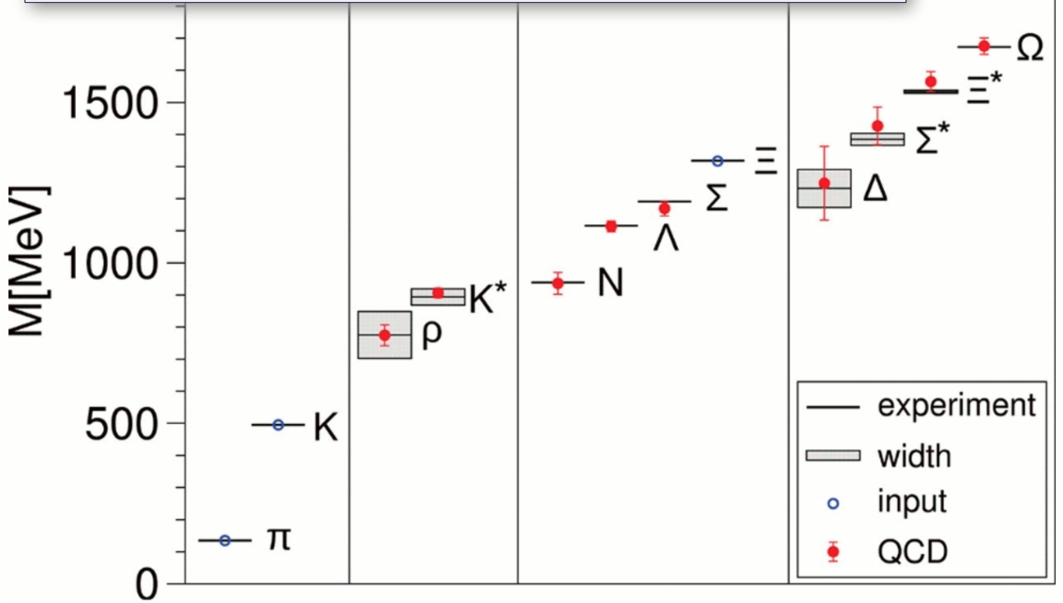
Hadronic Structure – L(attice)QCD

ground states

top 10 science achievements 2008

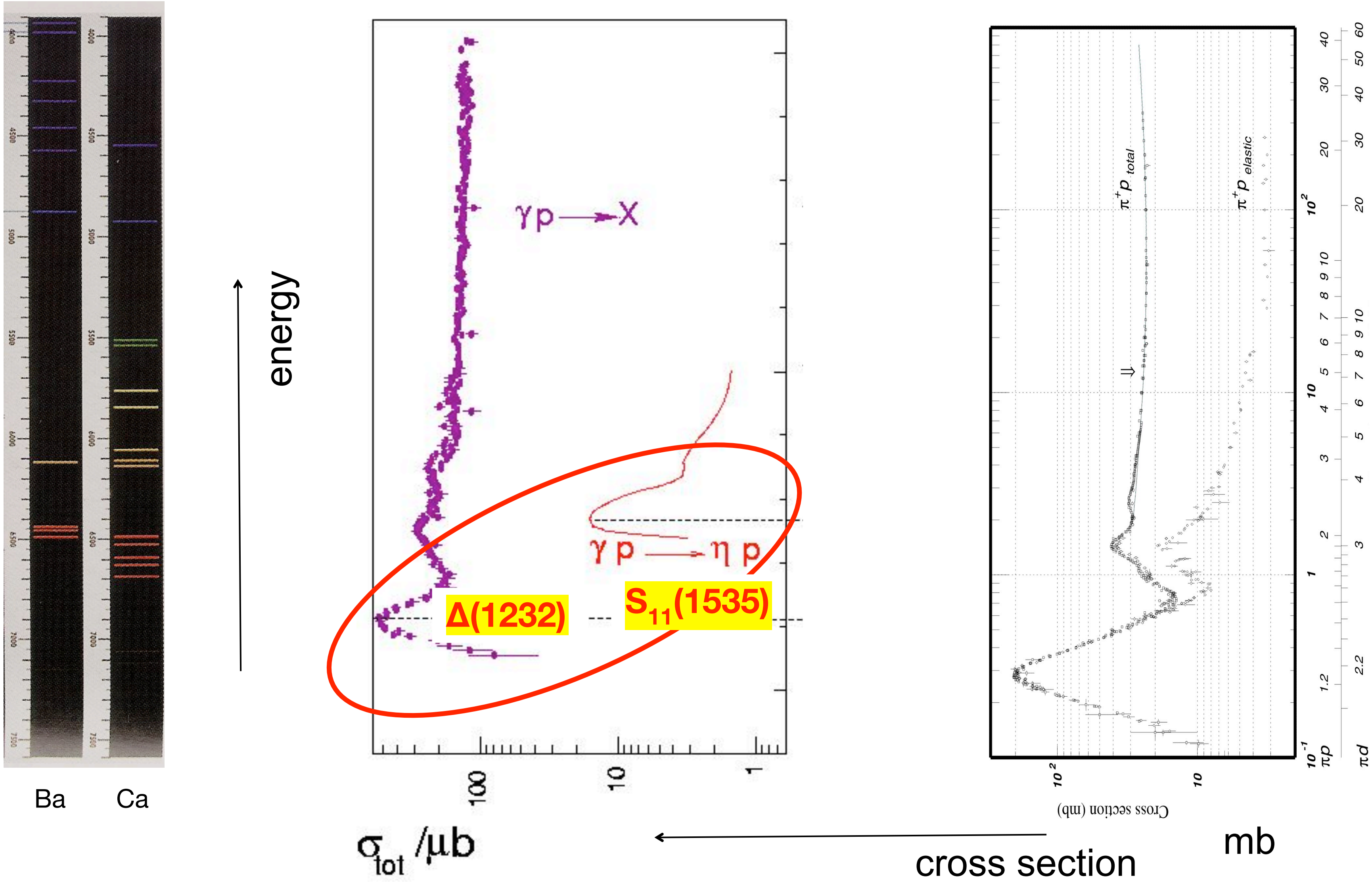


S. Dürr et al. (BMW-collaboration),
Science 322 (2008) 1224

- "unquenched" calculation
- realistic quark masses

Hadronic Structure

excited states – spectroscopy



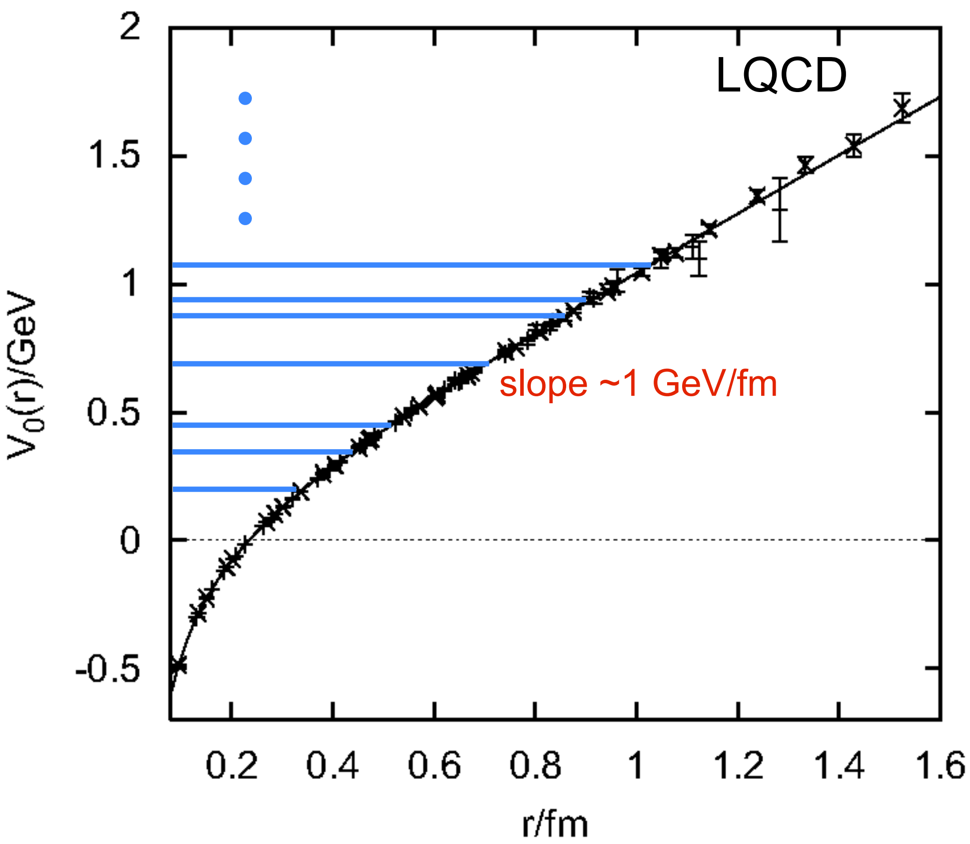
atom

nucleon

Physics Motivation

hadronic resonances

models: excitation in mutual potential



G.S. Bali,
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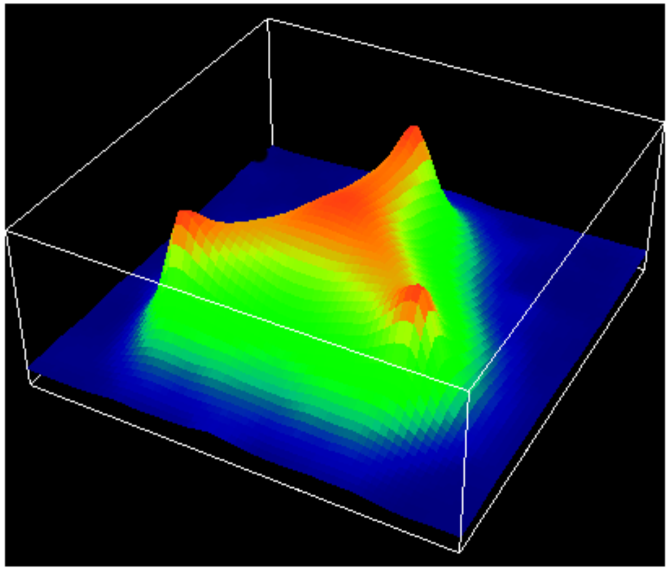

Energy density distribution
inside nucleon in LQCD simulation
(F. Wilczek, Physics today 11/99 & 1/00)

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The enignmatic: Discovery Δ(1232) resonance

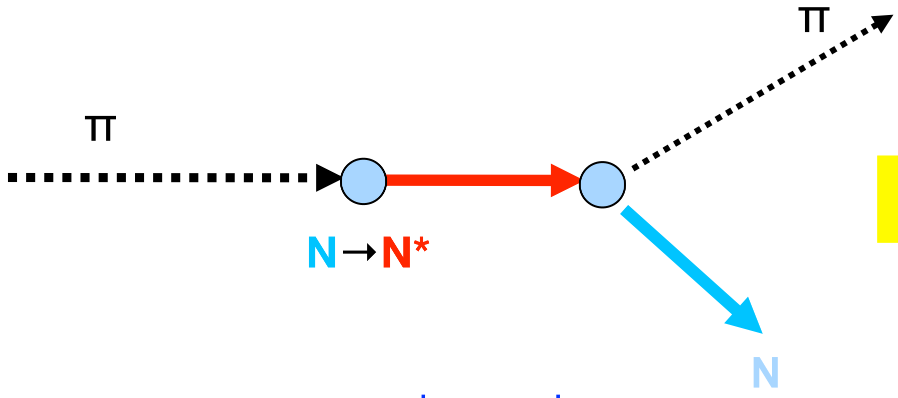
- weak decays → typ. track lengths of centimeters - meters
  → observable in emulsions & bubble chambers
  → lifetimes typ. $10^{-10} - 10^{-7}$ s
- strong interactions → lifetime order of ~ 10^{-20} s

  → unobservable track !
- but: width of decaying state via uncertainty relation

  $$\Delta E \, \Delta t \approx \hbar$$
- accelerator beams: production / formation of resonance states
- detection of resonance decay (chain)

⇨ example: Δ(1232) resonance in π N “elastic“ scattering

π–N elastic scattering



invariant mass

$$M = \sqrt{p_\mu p^\mu} = \sqrt{(p_\pi + p_N)^2}$$

resonance decay via meson emission

⇓

<u>elastic channel:</u>

π + N → π + N

⇓

resonance mass

first baryonic resonance observed

H.L. Anderson, E. Fermi, A. Long, and D.E. Nagle, Phys. Rev. 85 (1952) 936

Total Cross Sections of Positive Pions in Hydrogen*

H. L. Anderson, E. Fermi, E. A. Long,† and D. E. Nagle
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 21, 1952)

In a previous letter,[1] measurements of the total cross sections of negative pions in hydrogen were reported. In the present letter, we report on similar experiments with positive pions.

The experimental method and the equipment used in this measurement was essentially the same as that used in the case of negative pions. The main difference was in the intensity, which for the positives was much less than for the negatives, the more so the higher the energy. This is due to the fact that the positive pions which escape out of the fringing field of the cyclotron magnet are those which are emitted in the backward direction with respect to the proton beam, whereas the negative pions are those emitted in the forward direction. The difficulty of the low intensity was in part compensated by the fact that the cross section for positive pions turned out to be appreciably larger than for negative pions. The results obtained thus far are summarized in Table I.

In Fig. 1 the total cross sections of positive and negative pions are collected. It is quite apparent that the cross section of the positive particles is much larger than that of the negative particles, at least in the energy range from 80 to 150 Mev.

In this letter and in the two preceding ones,[1,2] the three processes: (1) scattering of positive pions, (2) scattering of negative pions with exchange of charge, and (3) scattering of negative pions without exchange of charge have been investigated. It appears that over a rather wide range of energies, from about 80 to 150 Mev, the cross section for process (1) is the largest, for process (2) is intermediate, and for process (3) is the smallest. Furthermore, the cross sections of both positive and negative pions increase rather rapidly with the energy. Whether the cross sections level off at a high value or go through a maximum, as might be expected if there should be a resonance, is impossible to determine from our present experimental evidence.

Brueckner[3] has recently pointed out that the existence of a broad resonance level with spin 3/2 and isotopic spin 3/2 would give an approximate understanding of the ratios of the cross sections for the three processes (1), (2), and (3). We might point out in this connection that the experimental results obtained to date are also compatible with the more general assumption that in the energy interval in question the dominant interaction responsible for the scattering is through one or more intermediate states of isotopic spin 3/2, regardless of the spin. On this assumption, one finds that the ratio of the cross sections for the three

Table I. Total cross sections of positive pions in hydrogen.

Energy (Mev)	Cross section (10^{-27} cm^2)
56±8	20±10
82±7	50±13
118±6	91± 6
136±6	152±14

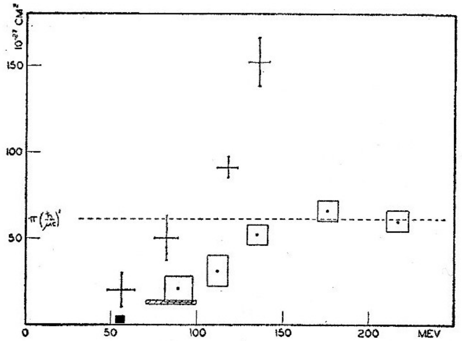


Fig. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

processes should be (9:2:1), a set of values which is compatible with the experimental observations. It is more difficult, at present, to say anything specific as to the nature of the intermediate state or states. If there were one state of spin 3/2, the angular distribution for all three processes should be of the type $1+3\cos^2\theta$. If the dominant effect were due to a state of spin 1/2, the angular distribution should be isotropic. If states of higher spin or a mixture of several states were involved, more complicated angular distributions would be expected. We intend to explore further the angular distribution in an attempt to decide among the various possibilities.

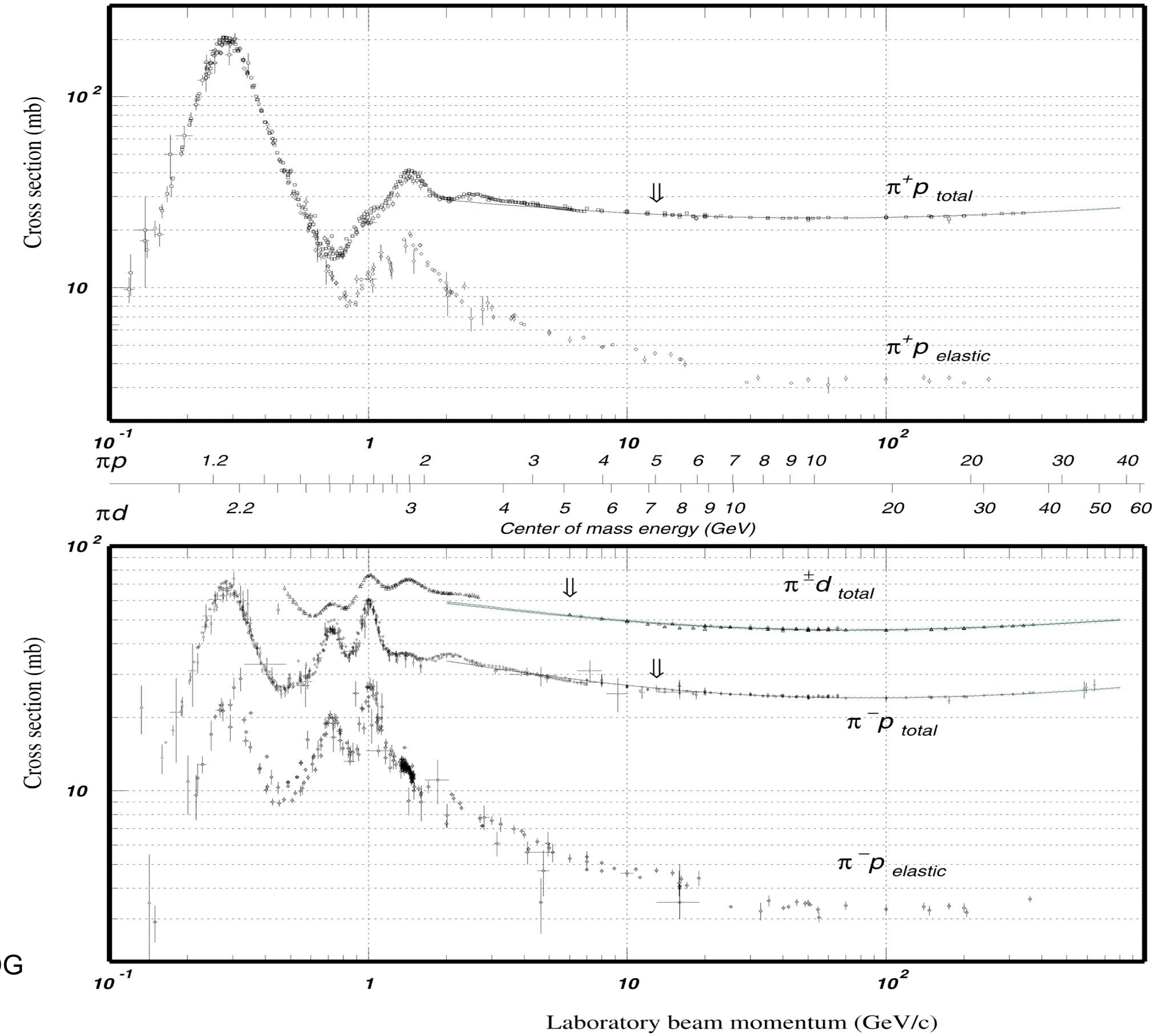
Besides the angular distribution, another important factor is the energy dependence. Here the theoretical expectation is that, if there is only one dominant intermediate state of spin 3/2 and isotopic spin 3/2, the total cross section of negative pions should at all points be less than $(8/3)\pi\lambda\!\!\!^{-2}$. Apparently, the experimental cross section above 150 Mev is larger than this limit, which indicates that other states contribute appreciably at these energies. Naturally, if a single state were dominant, one could expect that the cross sections would go through a maximum at an energy not far from the energy of the state involved. Unfortunately, we have not been able to push our measurements to sufficiently high energies to check on this point.

Also very interesting is the behavior of the cross sections at low energies. Here the energy dependence should be approximately proportional to the 4th power of the velocity if only states of spin 1/2 and 3/2 and even parity are involved and if the pion is pseudoscalar. The experimental observations in this and other laboratories seem to be compatible with this assumption, but the cross section at low energy is so small that a precise measurement becomes difficult.

* Research sponsored by the ONR and AEC.
† Institute for the Study of Metals, University of Chicago.
[1] Anderson, Fermi, Long, Martin, and Nagle, Phys. Rev., this issue.
[2] Fermi, Anderson, Lundby, Nagle, and Yodh, preceding Letter, this issue, Phys. Rev.
[3] K. A. Brueckner (private communication).

experimental results

$\pi^{\pm}$ scattering



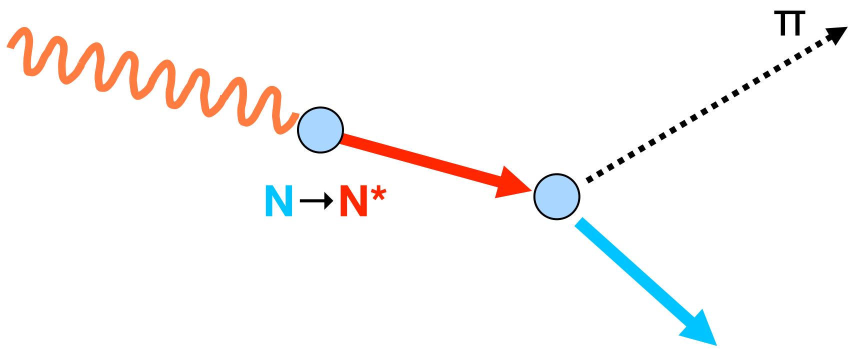
isospin invariance !

taken from PDG

Meson photoproduction

modern experiments mainly use photoproduction of resonances

photon induced



Order in the Particle Zoo

- discovery of vast amount of particles
- mesons of different spins, e.g. π's (spin 0) & ρ's (spin 1)
- ... and charge states, e.g. $\pi^{0,\pm}$, $K^{0,\pm}$
- baryons of different spins, e.g. p (spin 1/2), Δ(1232) (spin 3/2), $\Sigma^{(*)}$-hyperons (spin 1/2 and 3/2)
- ... and charge states, e.g. Δ^{++}, Δ^{+}, Δ^{0}, Δ^{-}
- quantum numbers determined
- sheer number ↔ mesons & baryons not elementary objects
- ordering scheme? ↔ quark hypothesis by Gell-Mann & Zweig (1964)
- quarks as elementary constituents?

Flavor Symmetry

extension

2 flavors **u, d** (isospin, SU(2)) ⇒ 3 flavors **u, d, s** (SU(3)),
standard model: 6 flavors u, d, s, c, b, t

⇒ fundamental representation $\varphi = \begin{pmatrix} u \\ d \\ s \end{pmatrix}$

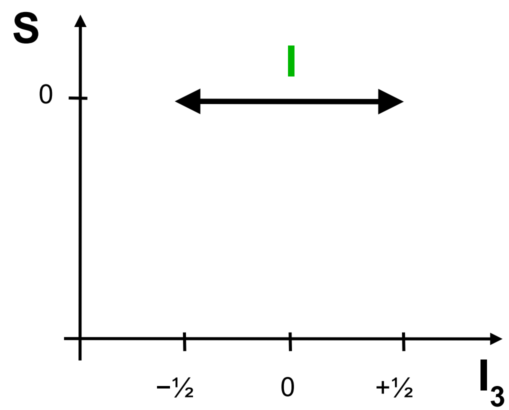
with $\varphi' = U \varphi$ ⇔ invariance under iso/flavor-rotations

⇕

rotation matrix $U \equiv \exp\{ \frac{1}{2} i \theta \, \vec{\mathbf{n}} \cdot \vec{\boldsymbol{\lambda}} \}$

⇑ 3^2-1 = 8 traceless 3x3 matrices,
analogous to σ_i in SU(2)

⇒ 3 basic doublets: u ↔ d **I**



Flavor Symmetry

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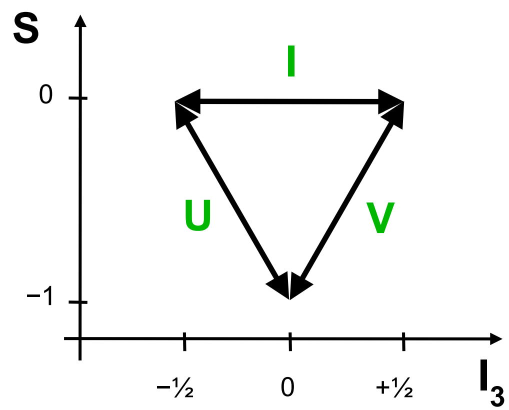
3^2-1 = 8 traceless 3x3 matrices,
analogous to σ_i in SU(2)

⇨ 3 basic doublets:

u ↔ d	**I**
d ↔ s	**U**
s ↔ u	**V**

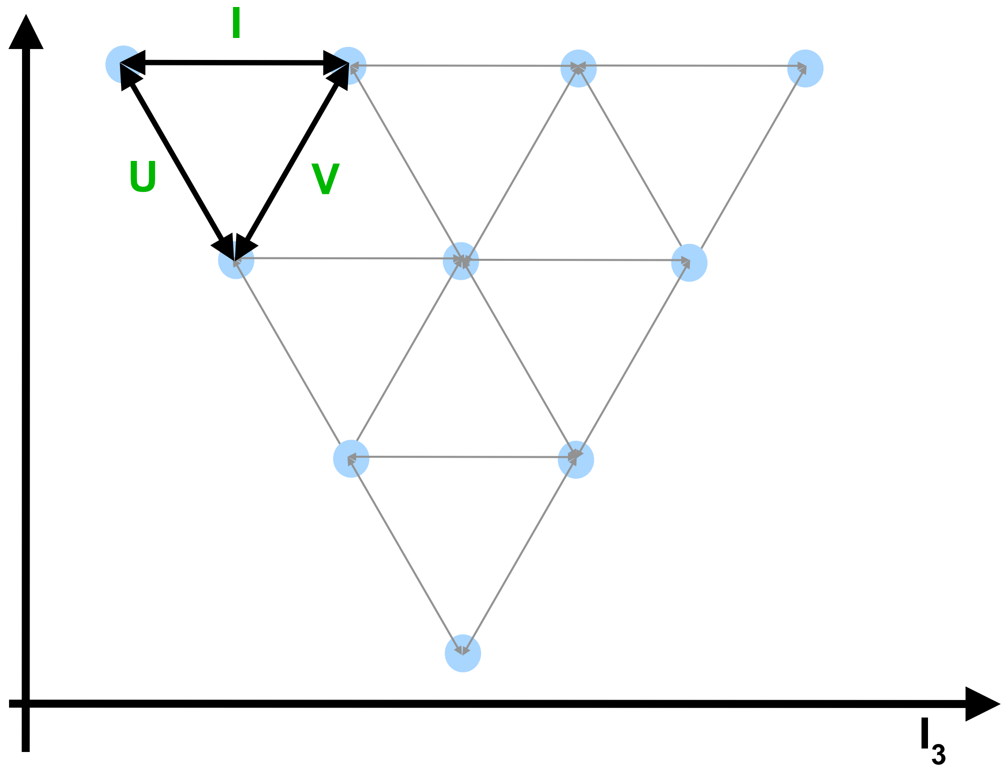


Flavor Symmetry: Decuplet

Baryons: qqq states w/ 3 possible flavors

Y = B+S

(hypercharge)



decuplet

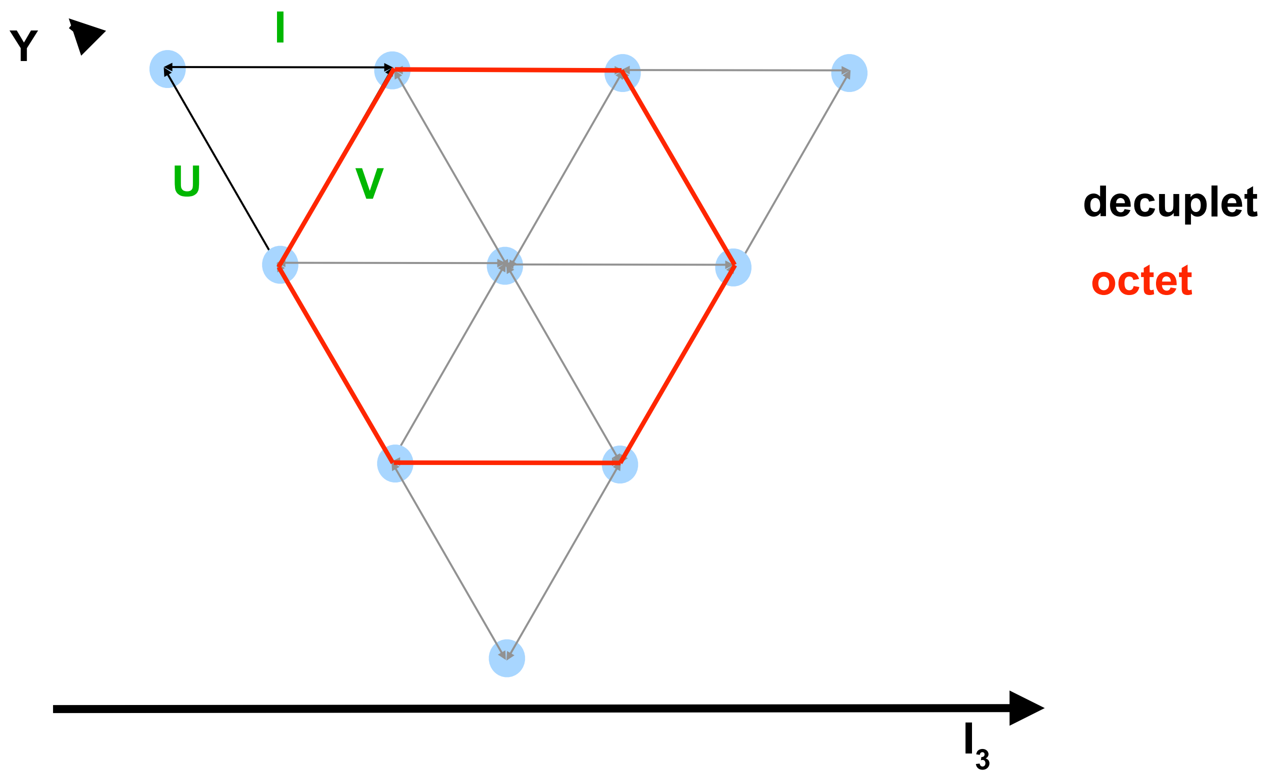
$$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A$$

combinations of u, d, s quarks

symmetry under interchange of any two (equal-mass) quarks

Flavor Symmetry: Decuplet

Baryons: qqq states w/ 3 possible flavors



$$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A$$

combinations of u, d, s quarks

symmetry under simultaneous interchange of flavor & spin

Baryon Decuplet

Baryon decuplet $J^P = (3/2)^+$

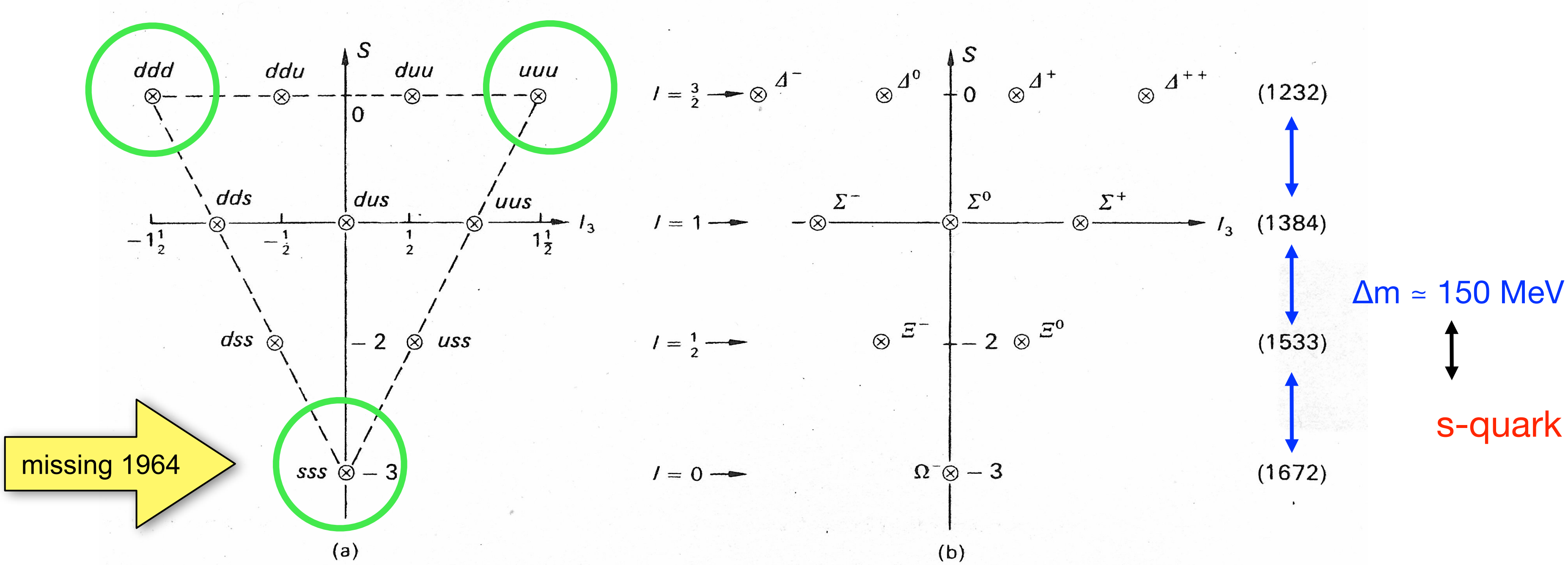


Figure 5.1 (a) Quark label assignments in the baryon decuplet. (b) The observed decuplet of baryon states of spin-parity $\frac{3}{2}^+$. The mean mass of each isospin multiplet is given in brackets.

corner states uuu, ddd, sss symmetric under interchange of quarks
⇔ symmetry of *all* decuplet states

$$M = M_0 + M_1 Y + M_2[I(I+1) - Y^2/4]$$

coefficients determined from mass spectrum

Gell-Mann-Okubo mass formula

with Y = B+S "hypercharge"

Discovery of the Ω^- Baryon

It has been pointed out[1] that among the multitude of resonances which have been discovered recently, the $N_{3/2}^*(1238)$, $Y_1^*(1385)$, and $\Xi_{1/2}^*(1532)$ can be arranged as a decuplet with one member still missing. Figure 1 illustrates the position of the nine known resonant states and the postulated tenth particle plotted as a function of mass and the third component of isotopic spin. As can be seen from Fig. 1, this particle (which we call Ω^-, following Gell-Mann[1]) is predicted to be a negatively charged isotopic singlet with strangeness minus three.[2] The spin and parity should be the same as those of the $N_{3/2}^*$, namely, $3/2^+$. The 10-dimensional representation of the group SU_3 can be identified with just such a decuplet. Consequently, the existence of the Ω^- has been cited as a crucial test of the theory of unitary symmetry of strong interactions.[3,4] The mass is predicted[5] by the Gell-Mann–Okubo mass formula to be about 1680 MeV/c^2. We wish to report the observation of an event which we believe to be an example of the production and decay of such a particle.

The BNL 80-in. hydrogen bubble chamber was exposed to a mass-separated beam of 5.0-BeV/c K^- mesons at the Brookhaven AGS. About 100 000 pictures were taken containing a total K^- track

VOLUME 12, NUMBER 8 PHYSICAL REVIEW LETTERS 24 FEBRUARY 1964

OBSERVATION OF A HYPERON WITH STRANGENESS MINUS THREE*

V. E. Barnes, P. L. Connolly, D. J. Crennell, B. B. Culwick, W. C. Delaney, W. B. Fowler, P. E. Hagerty,† E. L. Hart, N. Horwitz,† P. V. C. Hough, J. E. Jensen, J. K. Kopp, K. W. Lai, J. Leitner,† J. L. Lloyd, G. W. London,‡ T. W. Morris, Y. Oren, R. B. Palmer, A. G. Prodell, D. Radojičić, D. C. Rahm, C. R. Richardson, N. P. Samios, J. R. Sanford, R. P. Shutt, J. R. Smith, D. L. Stonehill, R. C. Strand, A. M. Thorndike, M. S. Webster, W. J. Willis, and S. S. Yamamoto
Brookhaven National Laboratory, Upton, New York

(Received 11 February 1964)

length of ~10^6 feet. These pictures have been partially analyzed to search for the more characteristic decay modes of the Ω^-.

The event in question is shown in Fig. 2, and the pertinent measured quantities are given in Table I. Our interpretation of this event is

$$K^- + p \to \Omega^- + K^+ + K^0$$
$$\quad \Omega^- \to \Xi^0 + \pi^-$$
$$\quad\quad \Xi^0 \to \Lambda^0 + \pi^0$$
$$\quad\quad\quad \pi^0 \to \gamma_1 + \gamma_2$$
$$\quad\quad\quad\quad \gamma_2 \to e^+ + e^-$$
$$\quad\quad\quad\quad \gamma_1 \to e^+ + e^-$$
$$\quad\quad\quad \Lambda^0 \to \pi^- + p. \qquad (1)$$

V. E. Barnes et al.

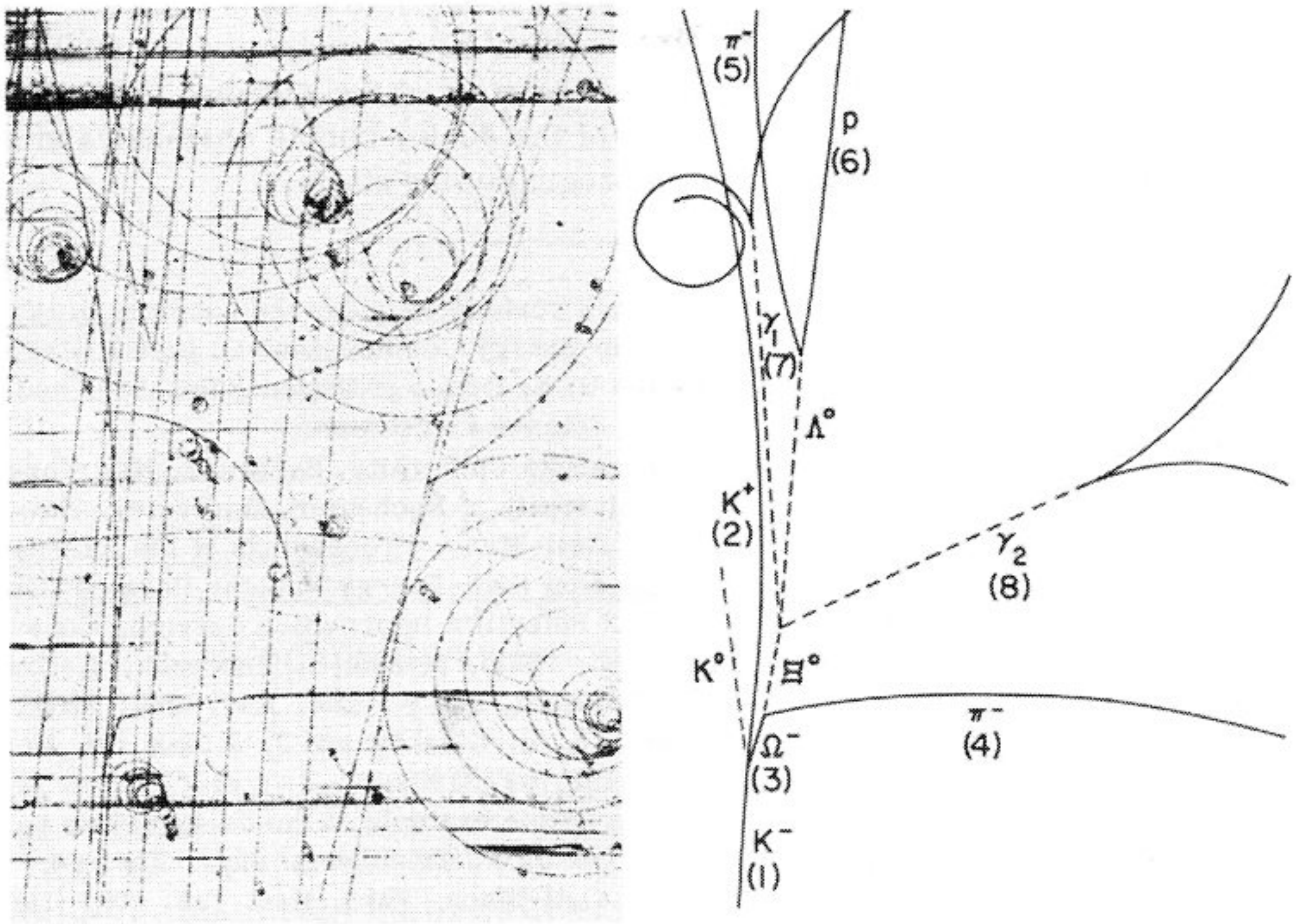


FIG. 2. Photograph and line diagram of event showing decay of Ω^-.

The proper lifetime of particle 3 was calculated to be 0.7×10^{-10} sec; consequently we may assume that it decayed by a weak interaction with $\Delta S=1$ into a system with strangeness minus two. Since a particle with $S=-1$ would decay very rapidly into $Y+\pi$, we may conclude that particle 3 has strangeness minus three. The missing mass at the production vertex is calculated to be 500 $\pm$ 25 MeV/c^2, in good agreement with the K^0 assumed in Reaction (1). Production of the event by an incoming π^- is excluded by the missing mass calculated at the production vertex, and would not alter the interpretation of the decay chain starting with track 3.

In view of the properties of charge ($Q=-1$), strangeness ($S=-3$), and mass ($M=1686\pm12$ MeV/c^2) established for particle 3, we feel justified in identifying it with the sought-for Ω^-. Of course, it is expected that the Ω^- will have other observable decay modes, and we are continuing to search for them. We defer a detailed discussion of the mass of the Ω^- until we have analyzed further examples and have a better understanding of the systematic errors.

The observation of a particle with this mass and strangeness eliminates the possibility which has been put forward[6] that interactions with $\Delta S=4$ proceed with the rates typical of the strong interactions, since in that case the Ω^- would decay very rapidly into $n+K^0+\pi^-$.

We wish to acknowledge the excellent cooperation of the staff of the AGS and the untiring efforts of the 80-in. bubble chamber and scanning and programming staffs.

---

*Work performed under the auspices of the U. S. Atomic Energy Commission and partially supported by the U. S. Office of National Research and the National Science Foundation.

†Syracuse University, Syracuse, New York.

‡University of Rochester, Rochester, New York.

[1]M. Gell-Mann, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 805; R. Behrends, J. Dreitlein, C. Fronsdal, and W. Lee, Rev. Mod. Phys. 34, 1 (1962); S. L. Glashow and J. J. Sakurai, Nuovo Cimento 25, 337 (1962).

[2]A possible example of the decay of this particle was observed by Y. Eisenberg, Phys. Rev. 96, 541 (1954).

[3]M. Gell-Mann, Phys. Rev. 125, 1067 (1962); Y. Ne'eman, Nucl. Phys. 26, 222 (1961).

[4]See, however, R. J. Oakes and C. N. Yang, Phys. Rev. Letters 11, 174 (1963).

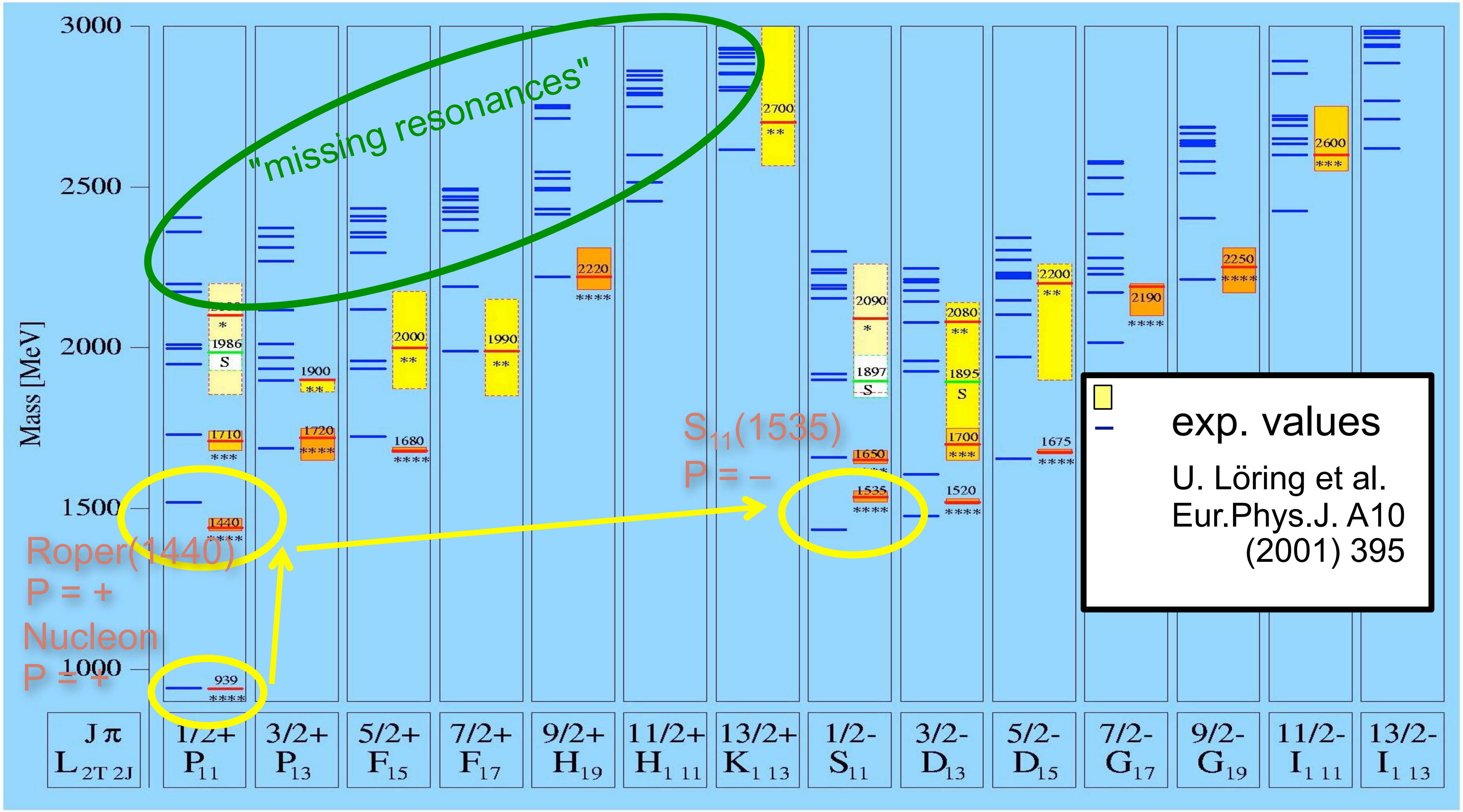
[5]M. Gell-Mann, Synchrotron Laboratory, California Institute of Technology, Internal Report No. CTSL-20, 1961 (unpublished); S. Okubo, Progr. Theoret. Phys. (Kyoto) 27, 949 (1962).

[6]G. Racah, Nucl. Phys. 1, 302 (1956); H. J. Lipkin, Phys. Letters 1, 68 (1962).

now: Excitated States

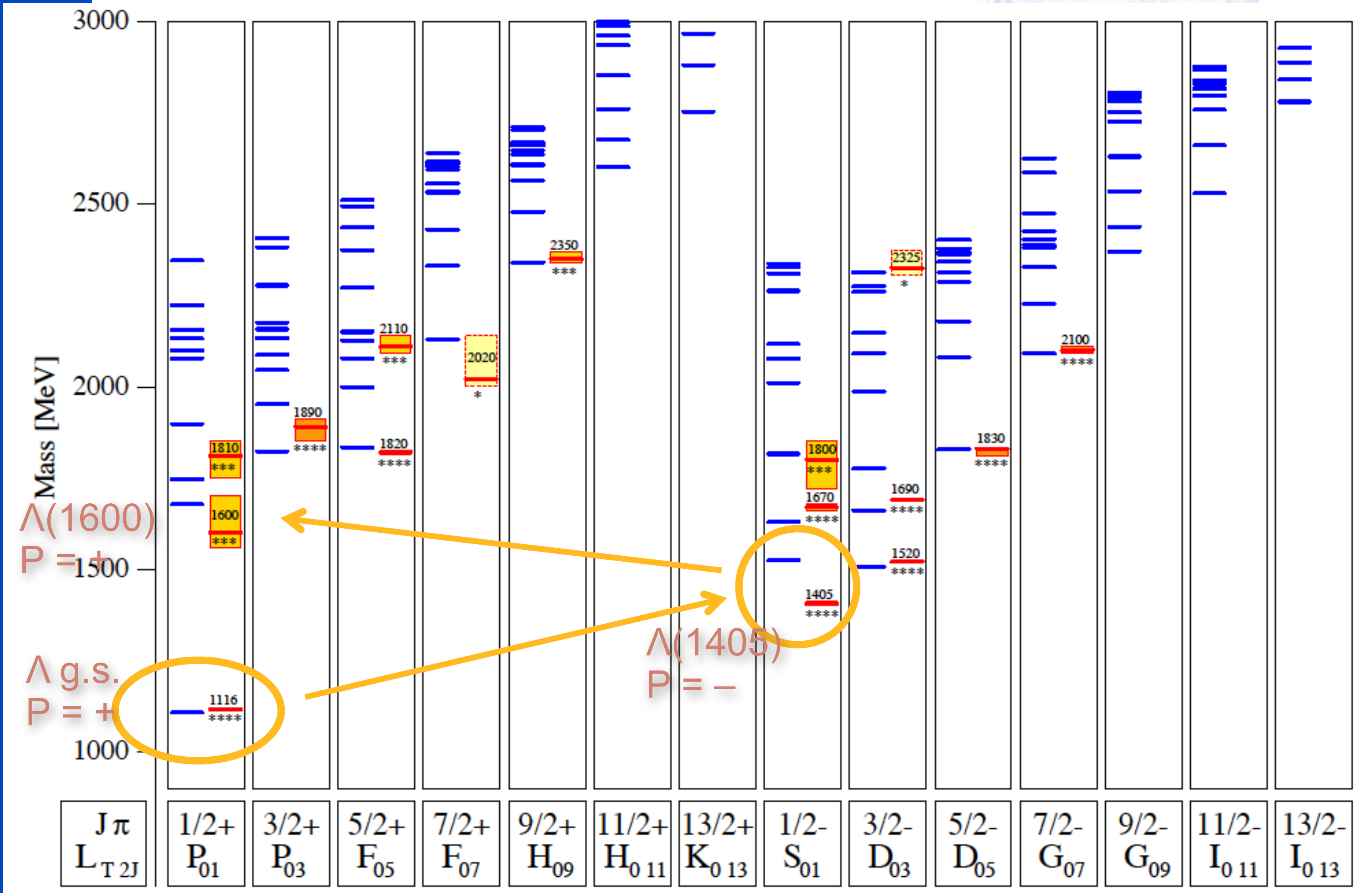
Excited states: Quark Model

N* resonances



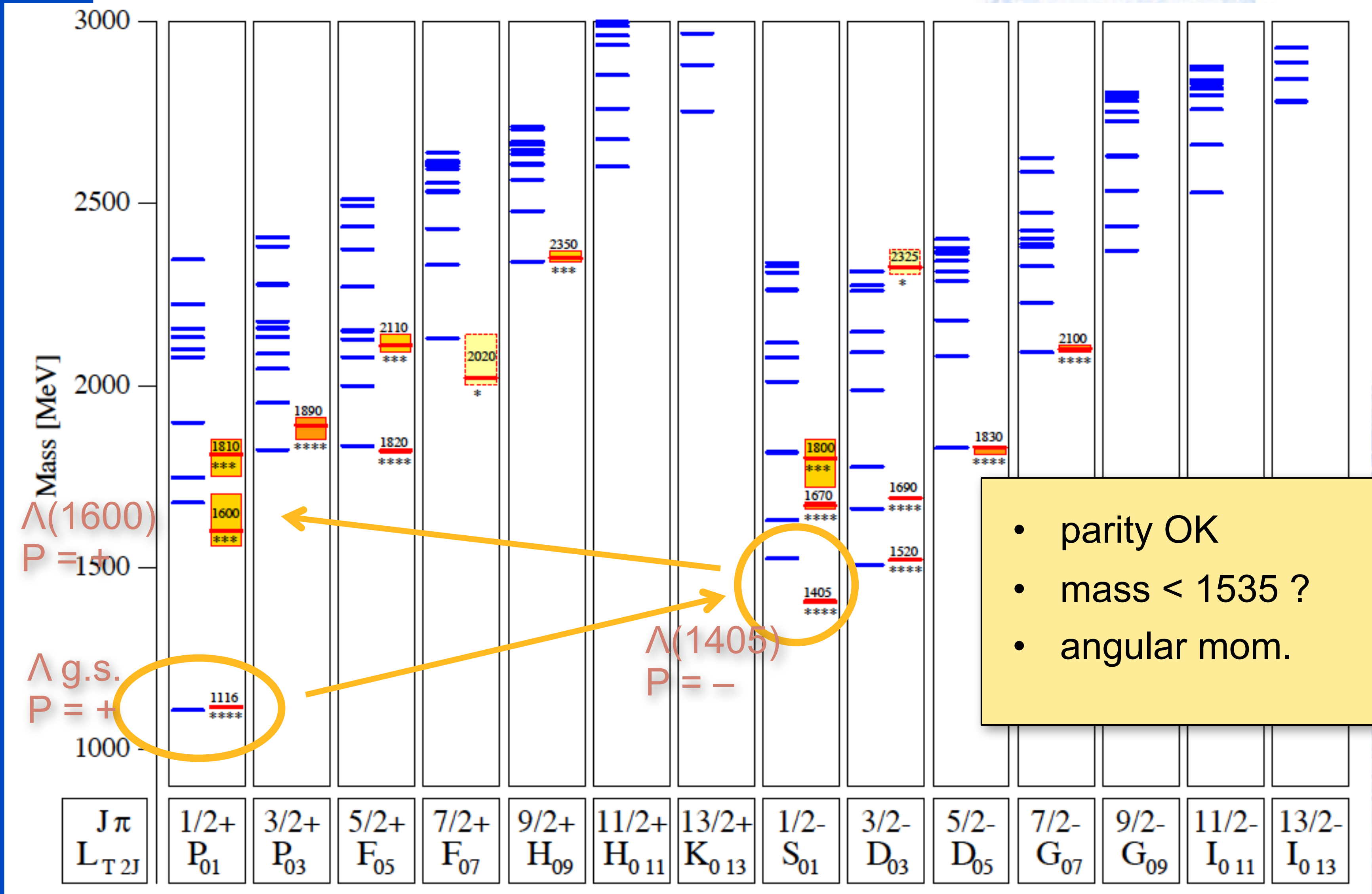
- parity pattern + → + → – !?!
- effective degrees of freedom ??

Λ hyperons: Quark Model



Metsch, Löring, Petry, EPJ A10 (2001)

Λ hyperons: Quark Model



- parity OK
- mass < 1535 ?
- angular mom.

Metsch, Löring, Petry, EPJ A10 (2001)

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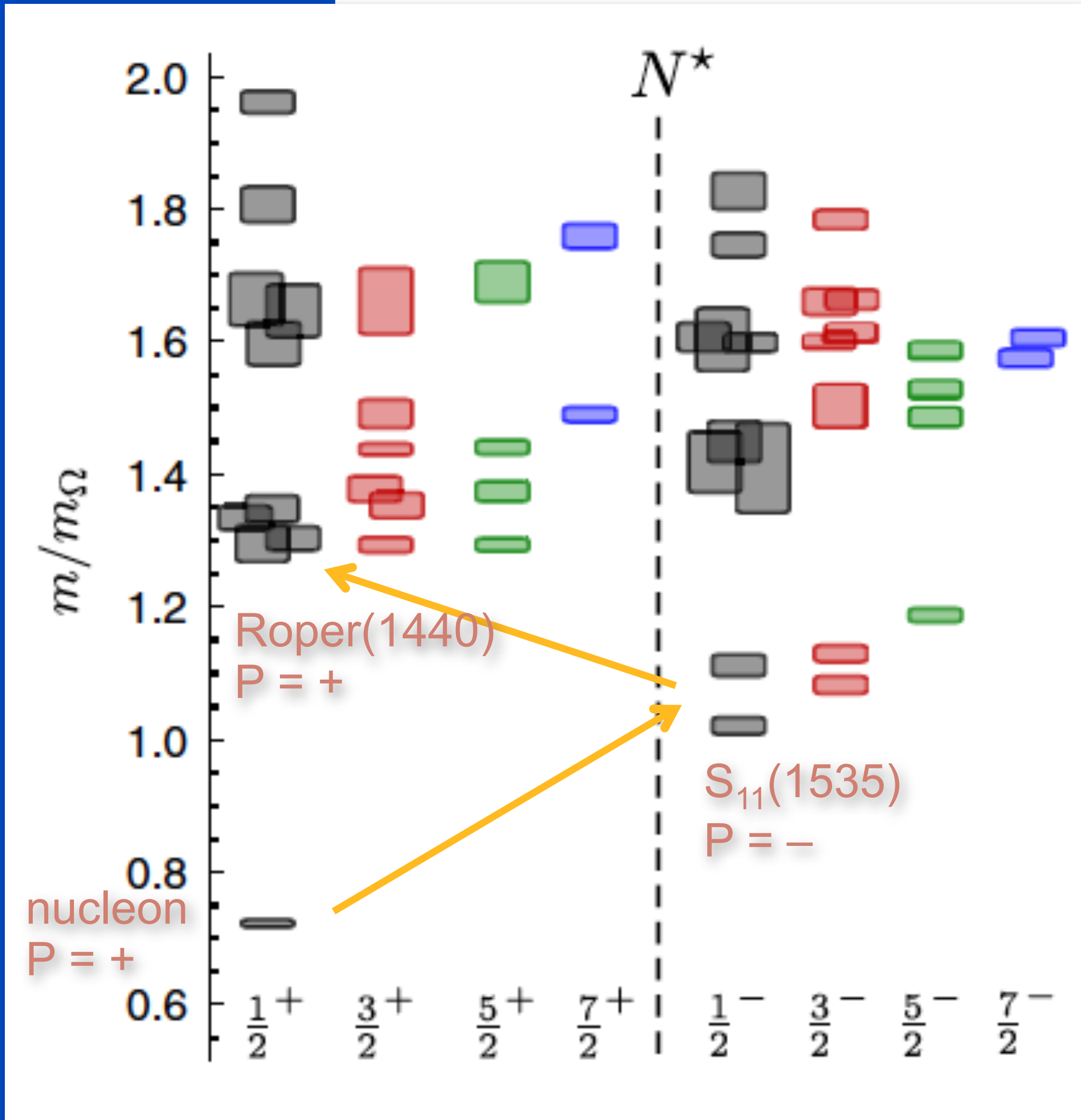
Excited states: LQCD

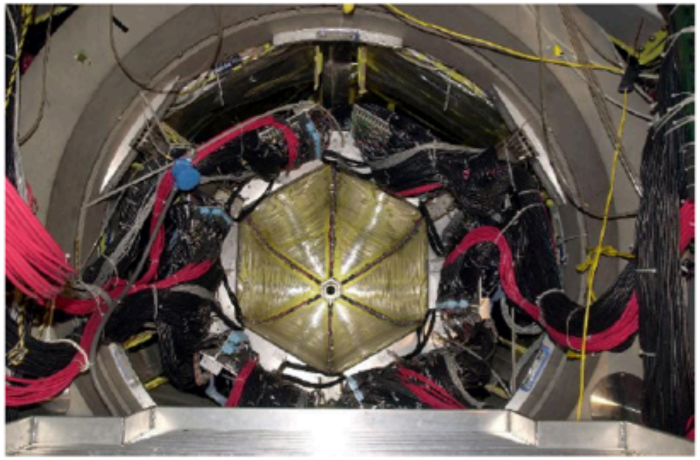


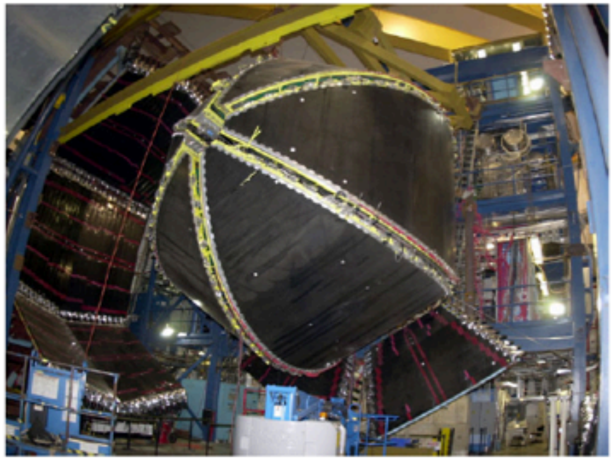
- m_π = 396 MeV
- reproduces q-models
- wrong parity pattern
- but: no decays !

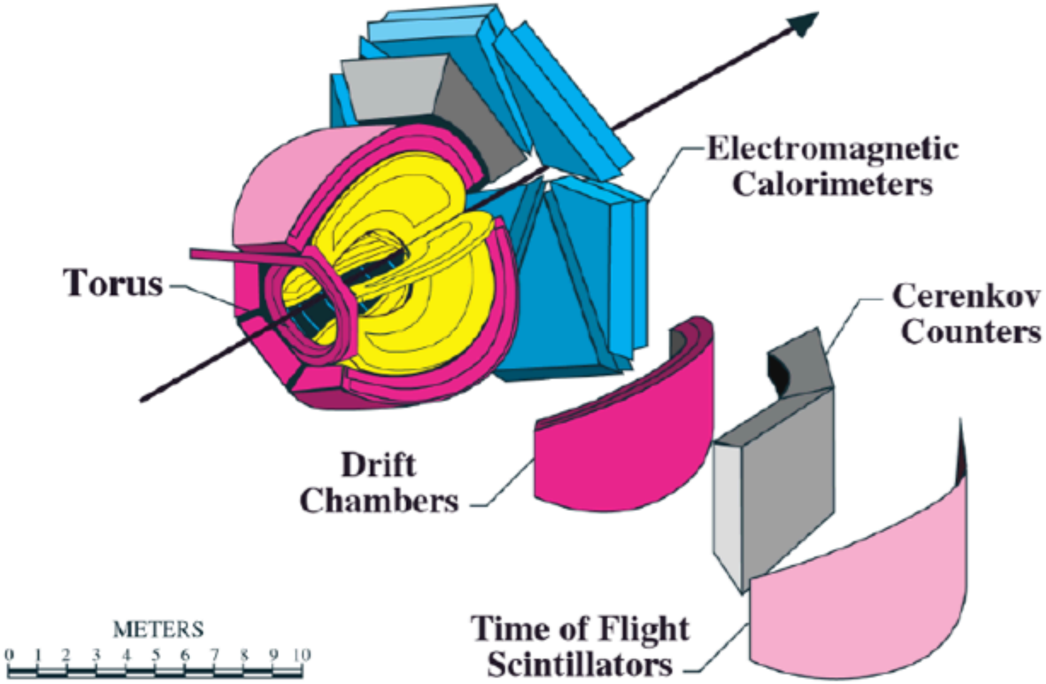
R.G. Edwards et al.,
Phys. Rev. D84 (2011) 074508

Nucleon Excitations: Experimental Status

CLAS @ JLab







courtesy: V. Credé

CLAS @ JLab

✓ - *data acquired* ✔ - *analyzed/published*

(✓ = blue, data acquired; ✔ = red, analyzed/published)

γp→X

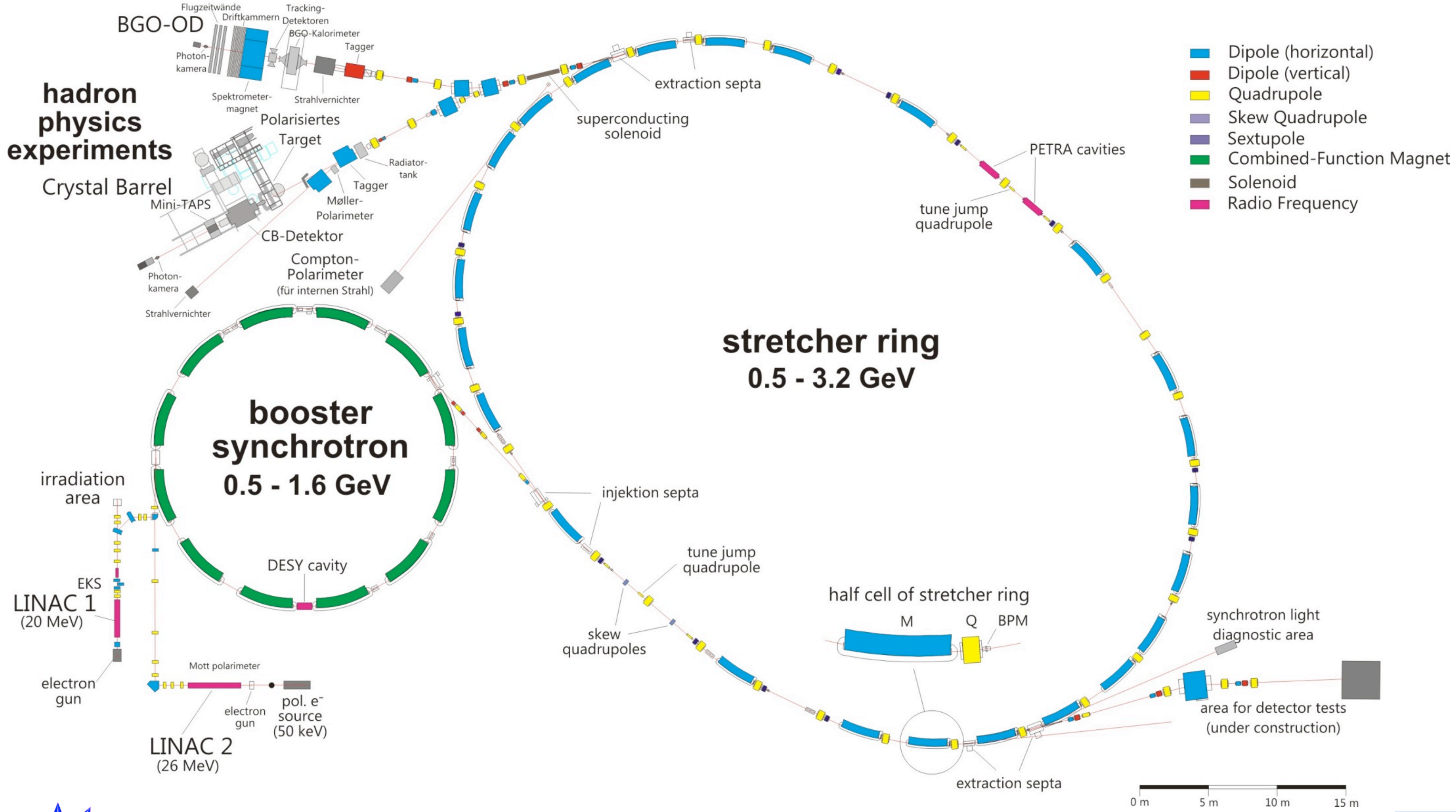
Observable	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^0$	✔	✔	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓		✔	✓	✓	✓								
$p\eta$	✔	✓	✓		✔	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$K^+\Lambda$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$K^+\Sigma^0$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$p\omega/\phi$	✔	✓	✓		✓	✓	✓	✓	✔ SDME							
$K^{+*}\Lambda$	✔			✔					SDME							
$K^{0*}\Sigma^+$	✔	✓									✓	✓	SDME			

γn→X

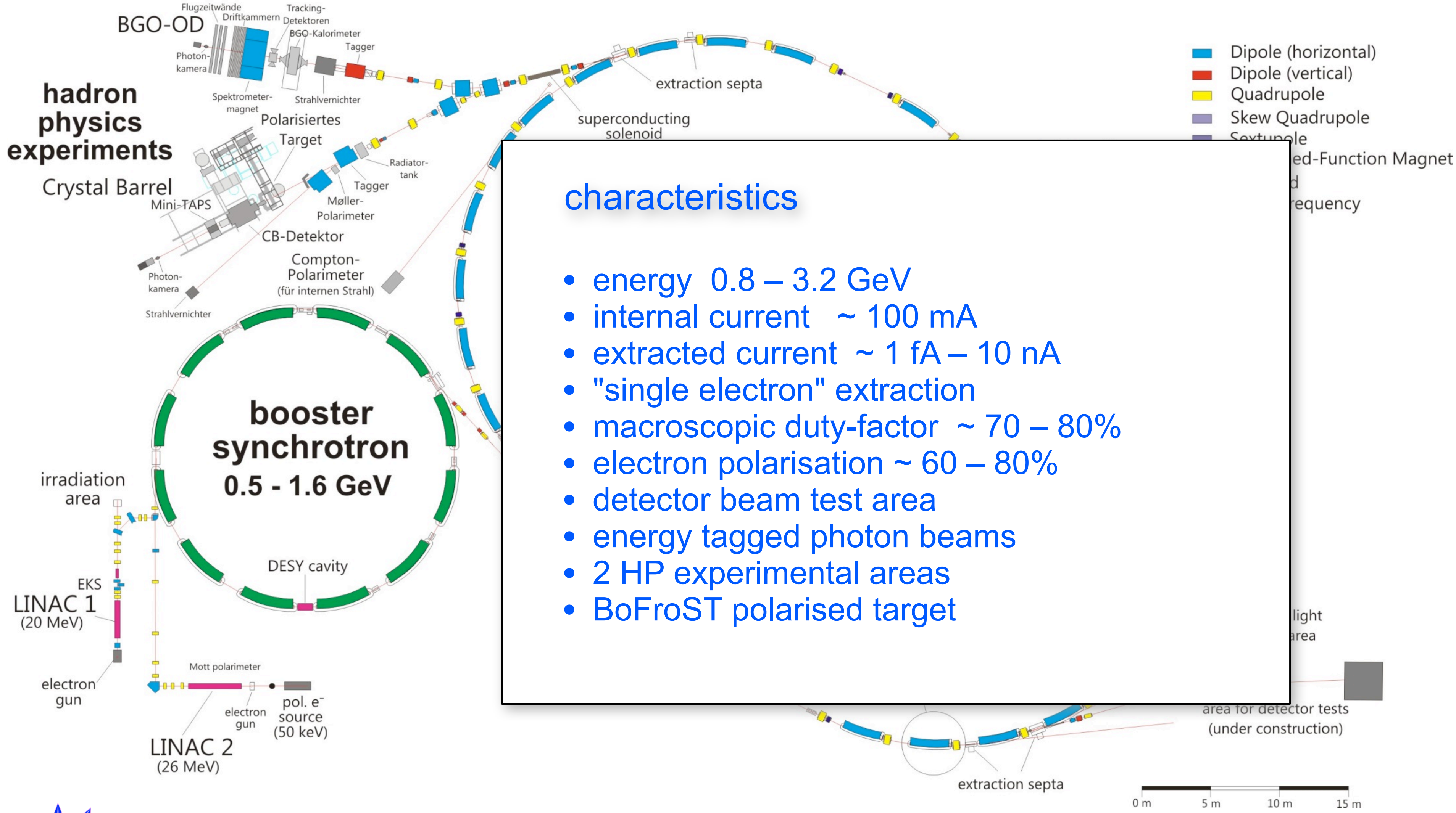
Observable	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^-$	✔	✔			✔	✓	✓									
$p\rho^-$	✓	✓			✓	✓	✓									
$K^-\Sigma^+$	✔	✓			✓	✓	✓									
$K^0\Lambda$	✔	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

courtesy: V. Burkert

ELSA accelerator @ Bonn



ELSA accelerator @ Bonn



characteristics

- energy 0.8 – 3.2 GeV
- internal current ~ 100 mA
- extracted current ~ 1 fA – 10 nA
- "single electron" extraction
- macroscopic duty-factor ~ 70 – 80%
- electron polarisation ~ 60 – 80%
- detector beam test area
- energy tagged photon beams
- 2 HP experimental areas
- BoFroST polarised target

ELSA

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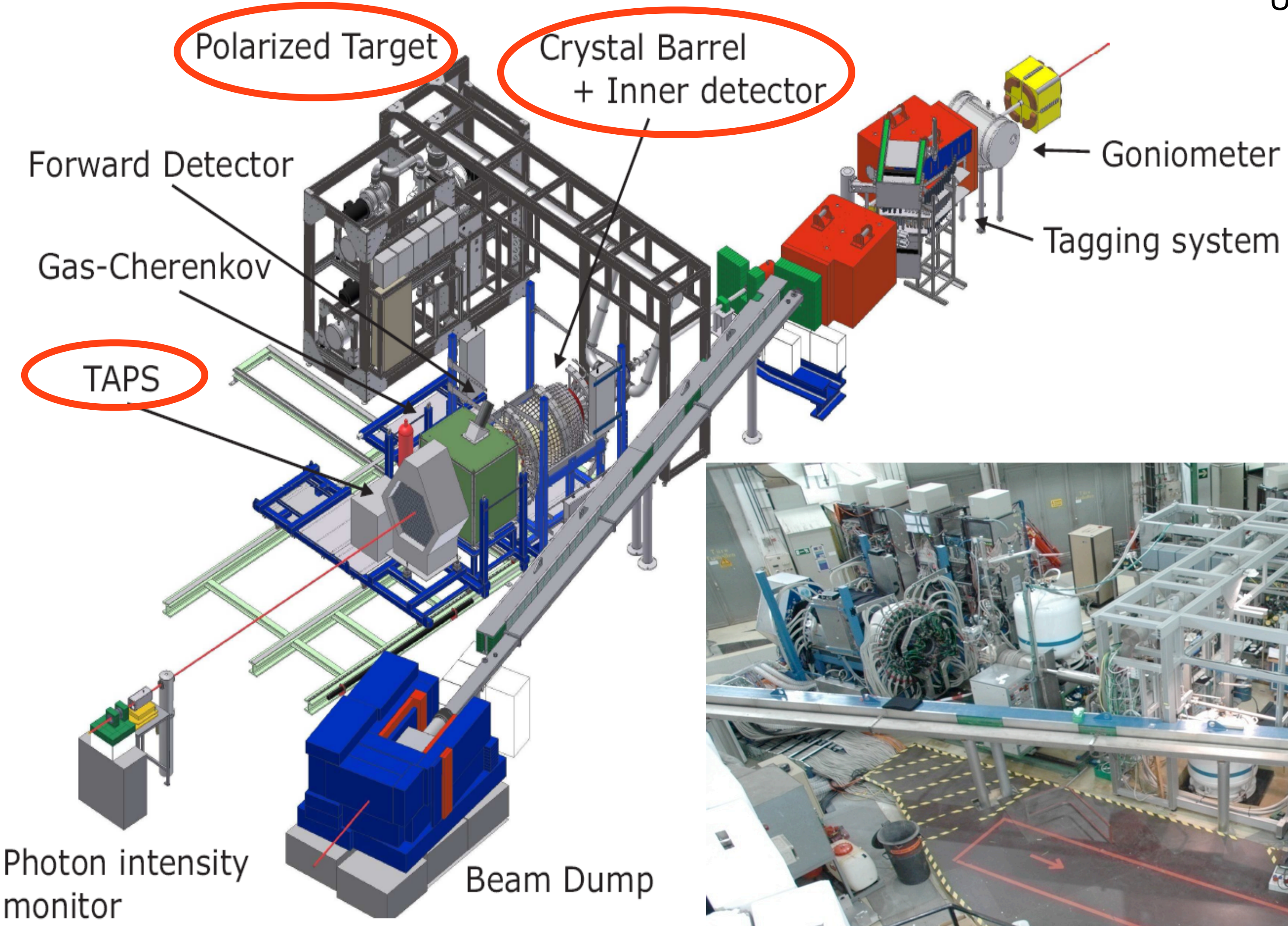
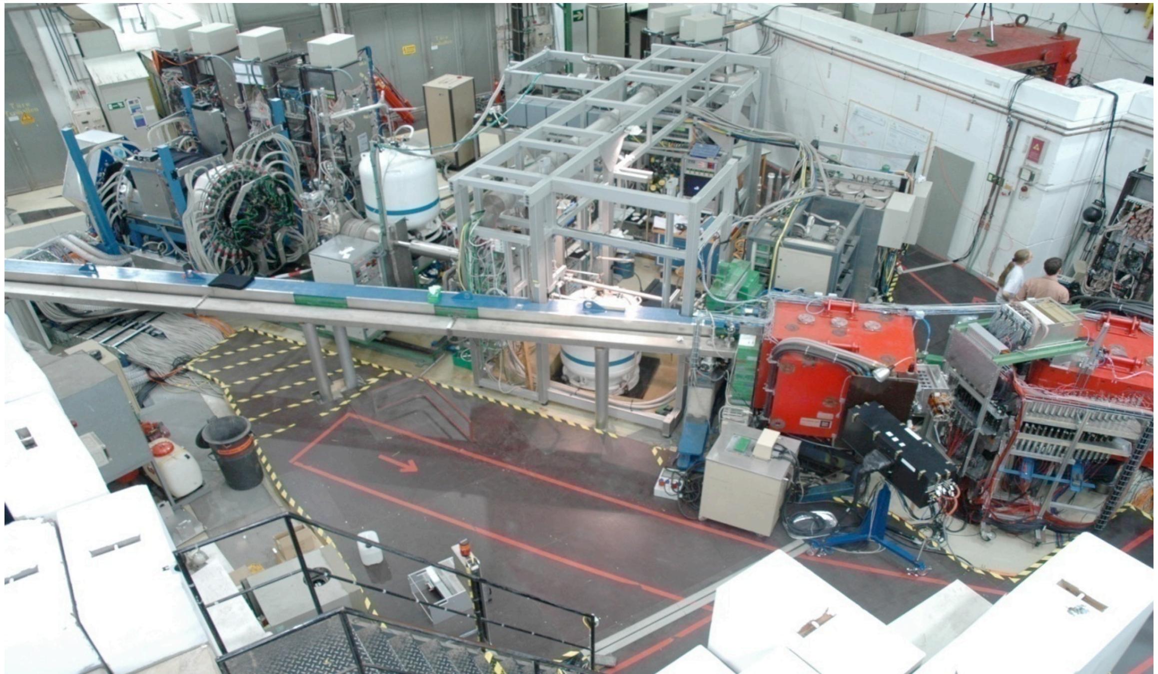
CBELSA/TAPS experiment

spokespersons: B. Krusche (Basel)
U. Thoma (Bonn)





ELSA

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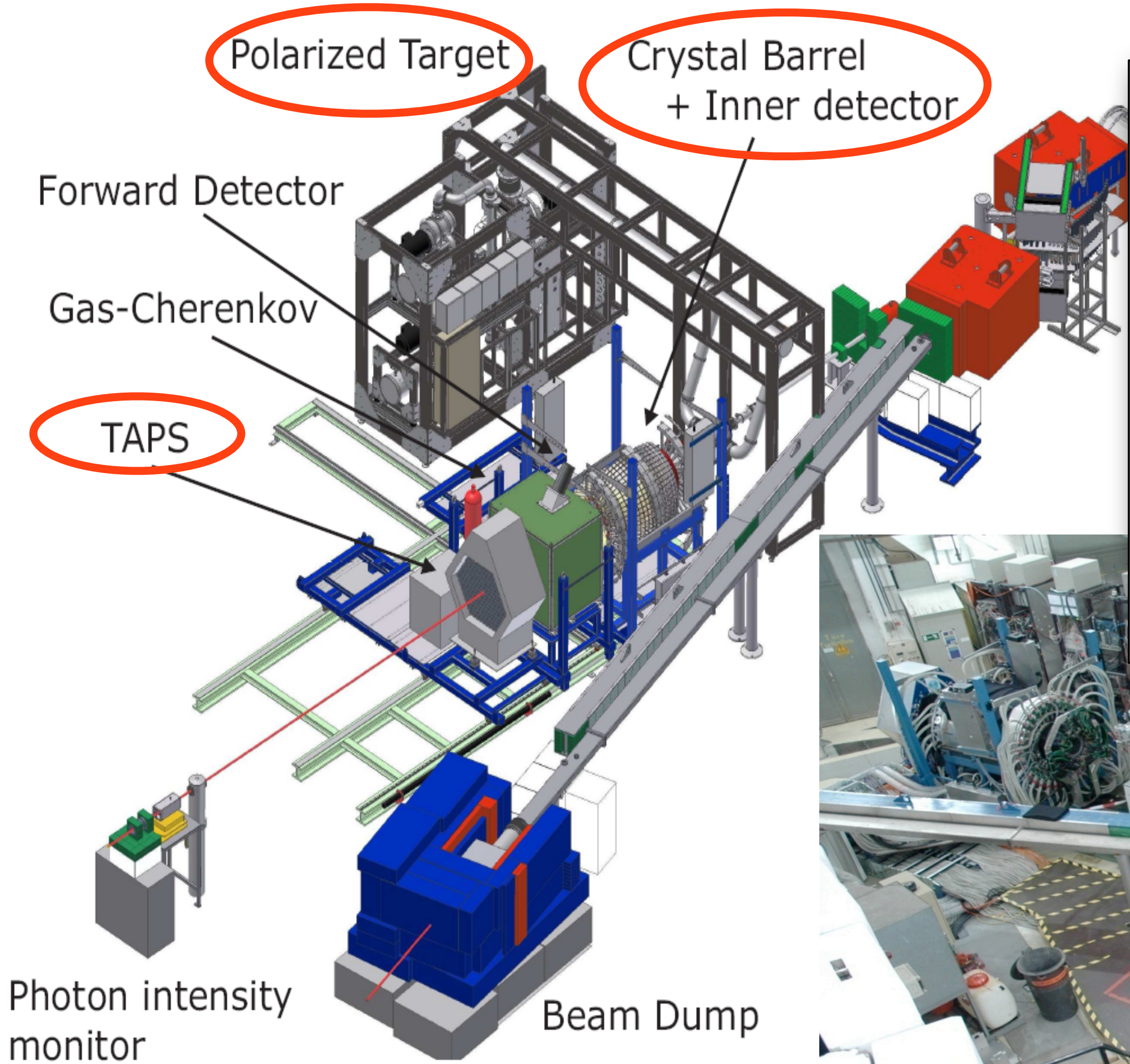
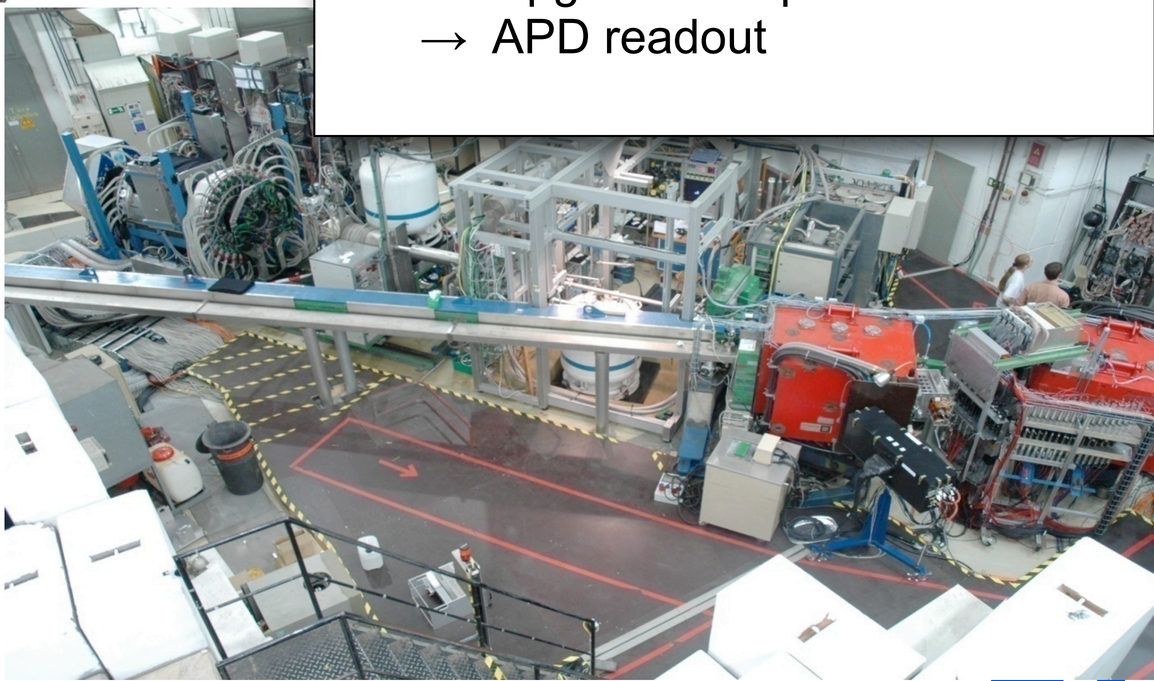


- lin./circ. polarised beam
  & long./transv. polarised target
- central calorimeter combined
  with forward calorimeter
- ideal for multi photon final states
- CB upgrade completed
  → APD readout

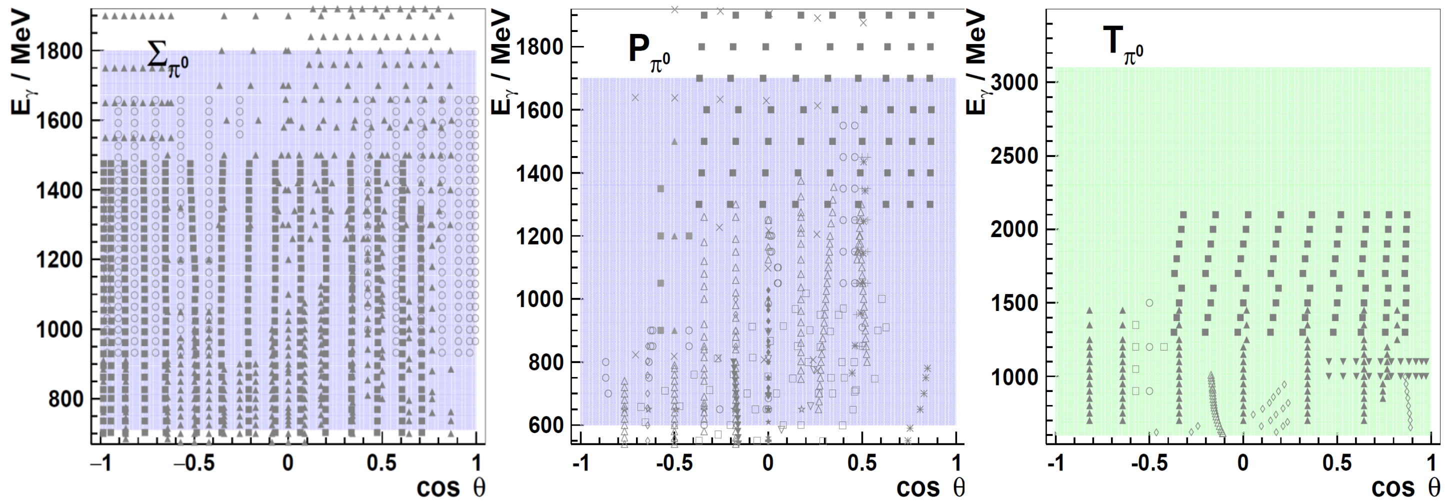


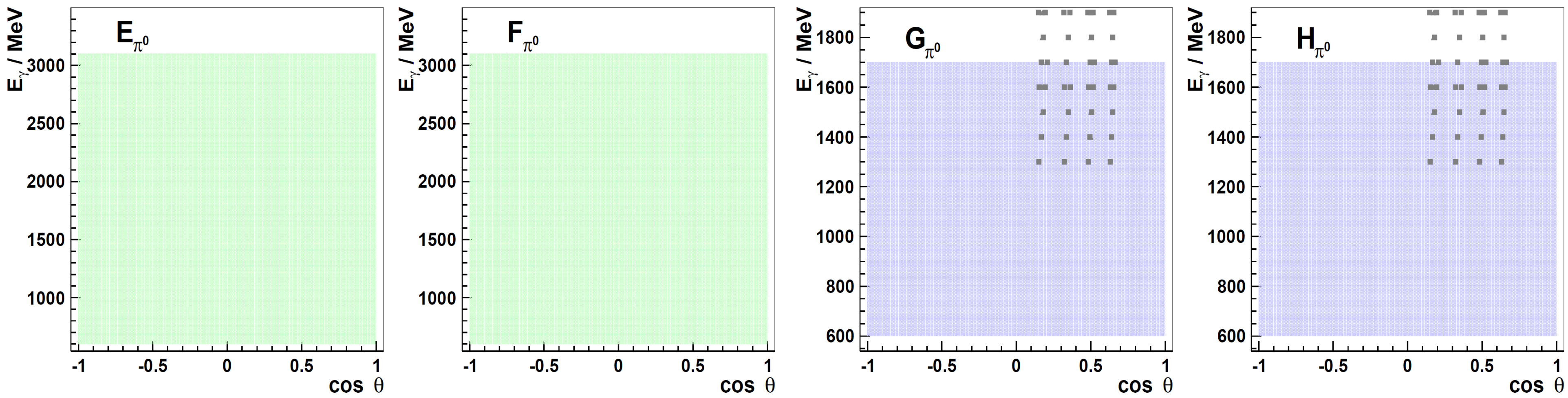
ELSA

Overview measurements

$$\vec{\gamma}\ \vec{p} \rightarrow p\,\pi^0$$

data base **before**
CBELSA/TAPS

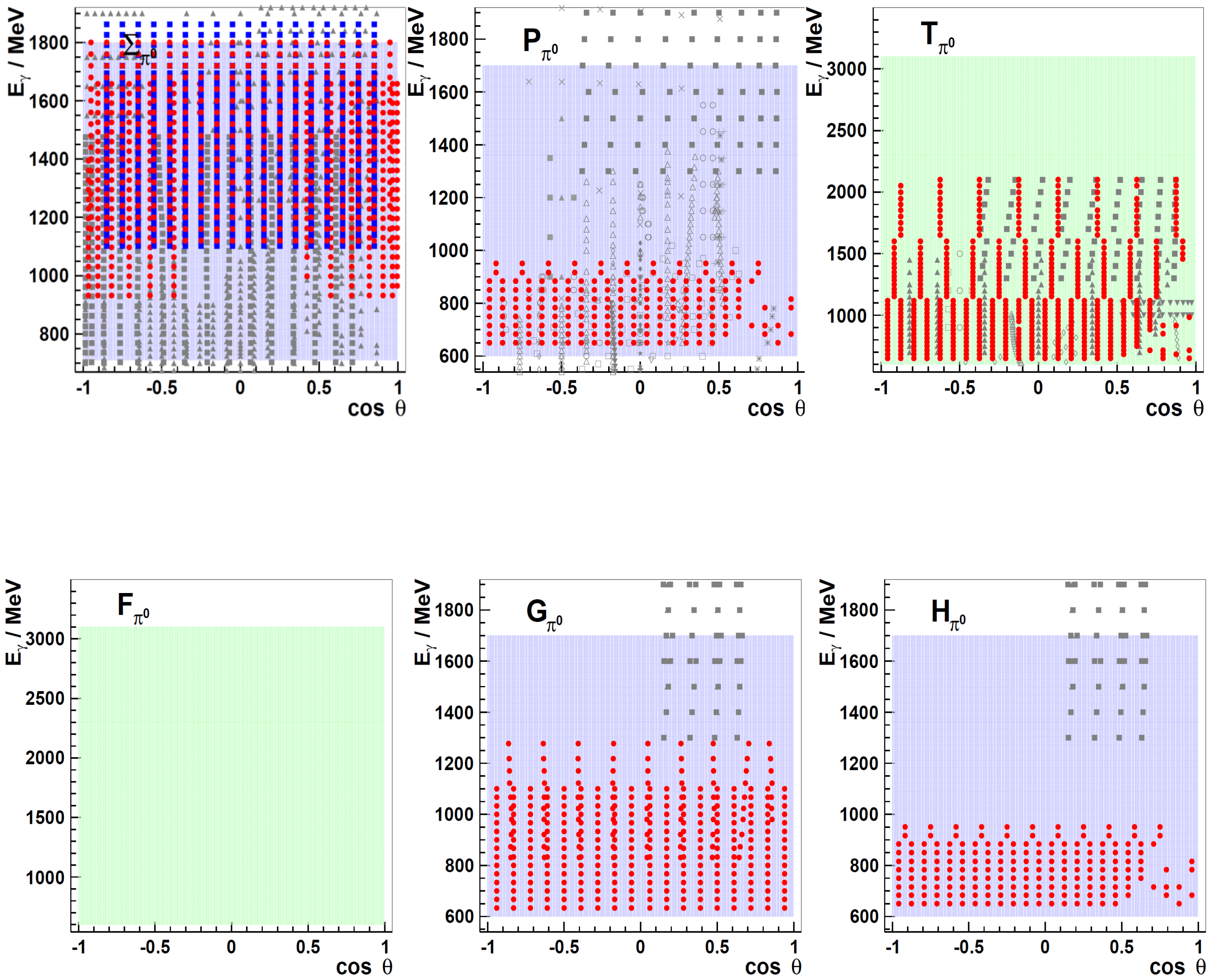




Overview measurements

$$\vec{\gamma}\ \vec{p} \rightarrow p\,\pi^0$$

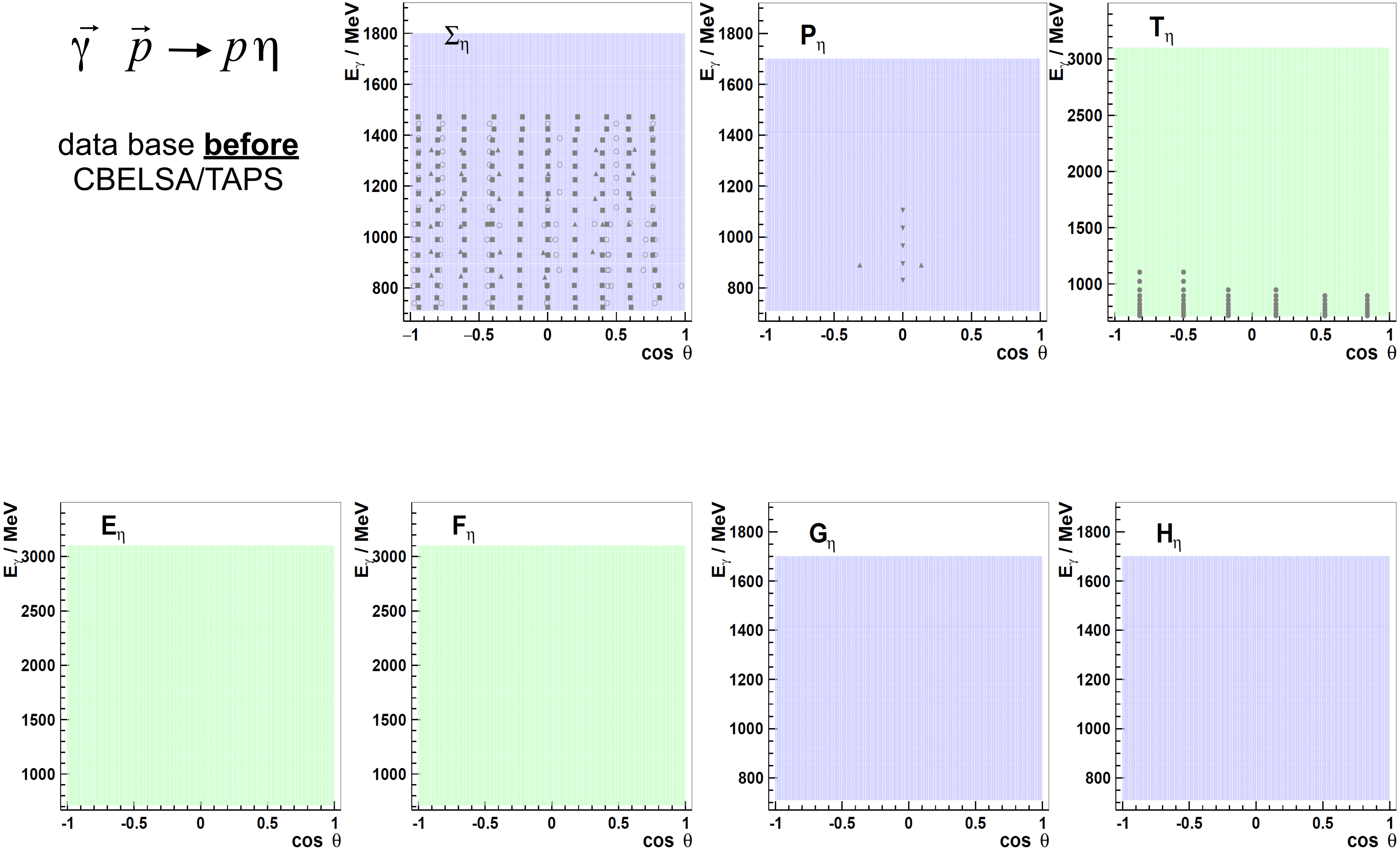
- data base **after** CBELSA/TAPS
- JLab



Overview measurements

$\vec{\gamma}\ \ \vec{p} \rightarrow p\eta$

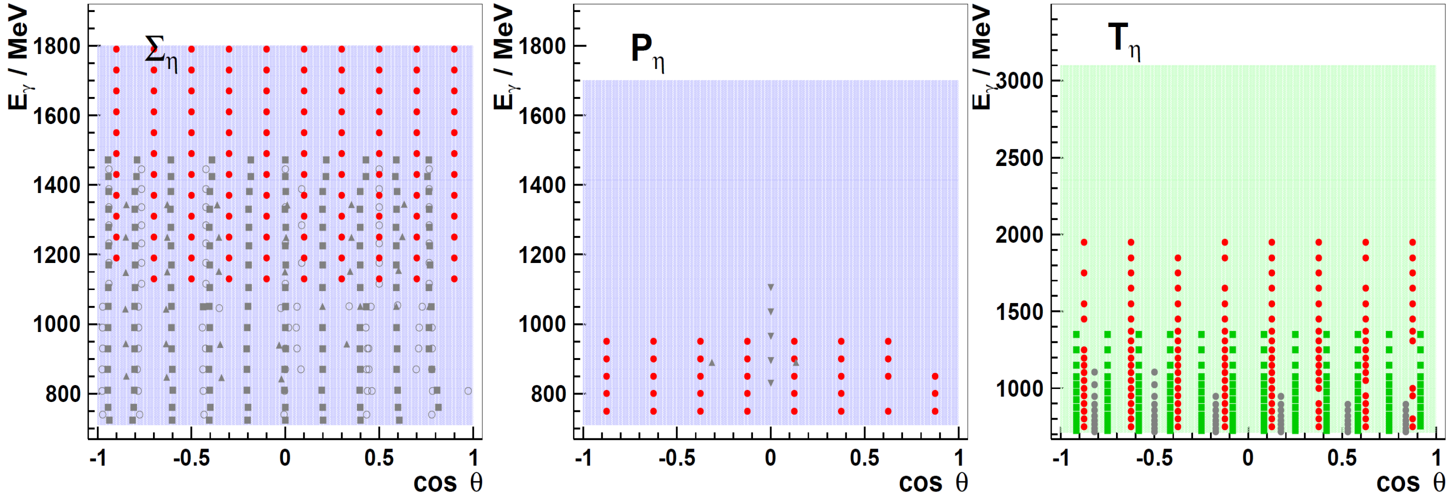
data base **before**
CBELSA/TAPS

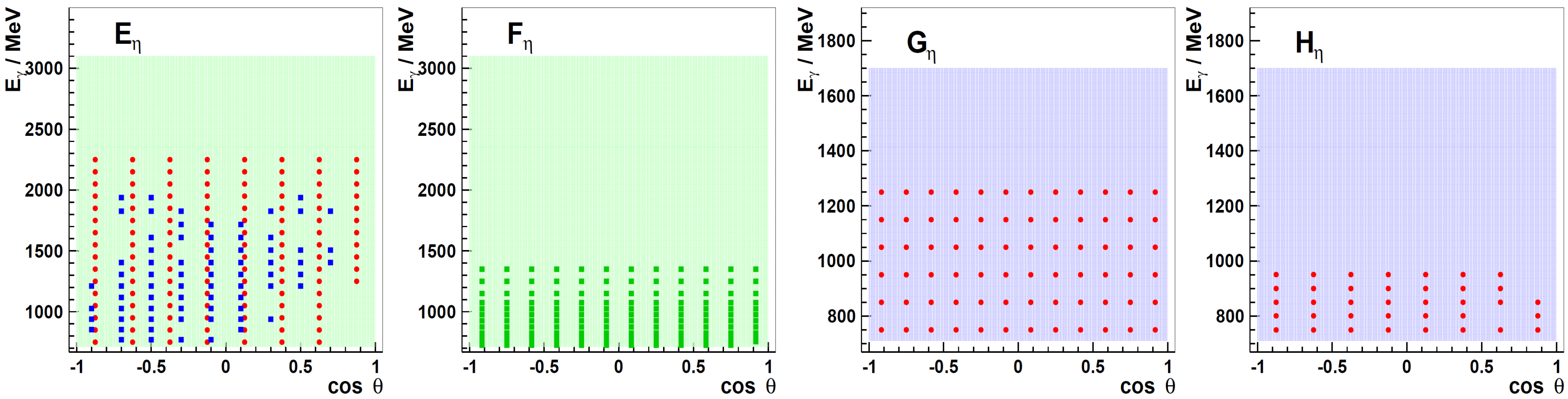


Overview measurements

$$\vec{\gamma}\ \ \vec{p} \rightarrow p\eta$$

- data base **after** CBELSA/TAPS
- JLab
- MAMI





Nucleon excitation spectrum

State	PDG 2010	BnGa PWA	PDG 2012	SAID PWA
N(1860) 5/2+		*	**	
N(1875) 3/2-		***	***	
N(1880) 1/2+		**	**	
N(1895) 1/2-		**	**	
N(1900) 3/2+	**	***	***	no evidence
N(2060) 5/2-		***	**	
N(2150) 3/2-		**	**	
Δ(1940) 3/2-	*	*	**	no evidence

- inclusion of CLAS, MAMI, ELSA data
- confirmation of known resonances w/ improved parameters
- observation of new states

ELSA

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Nucleon excitation spectrum

- N* spectrum $\rightarrow$ endeavor since over 50 years
- breakthrough meson photoproduction
- single & double polarisation observables
- identification of "missing" states

  - ... some at least, but total number ??
  - low lying states ??

La "Belle" Révolution 2003

c-sector

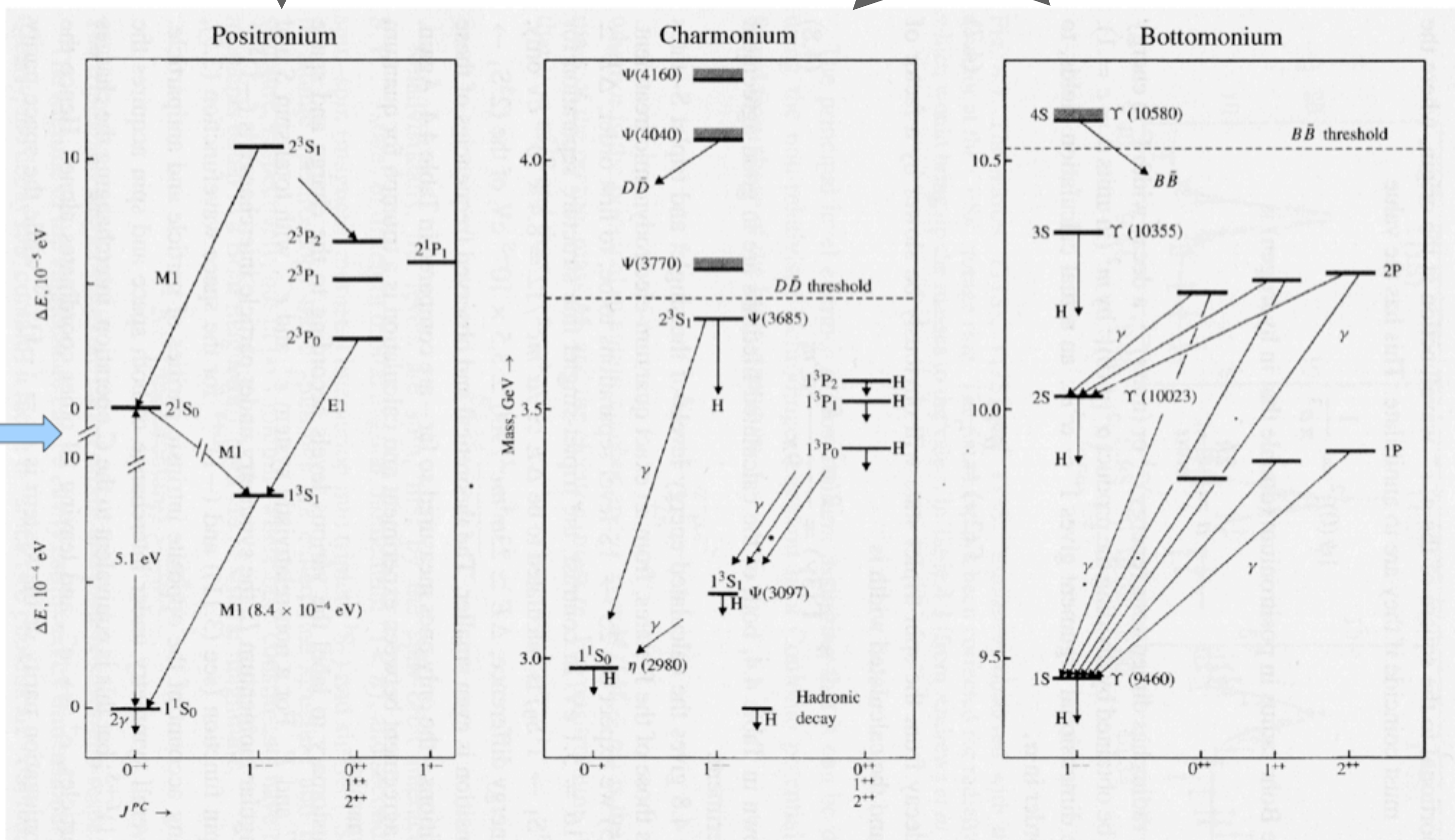
heavy quark meson sector

positronium

heavy quarks

textbook: Perkins

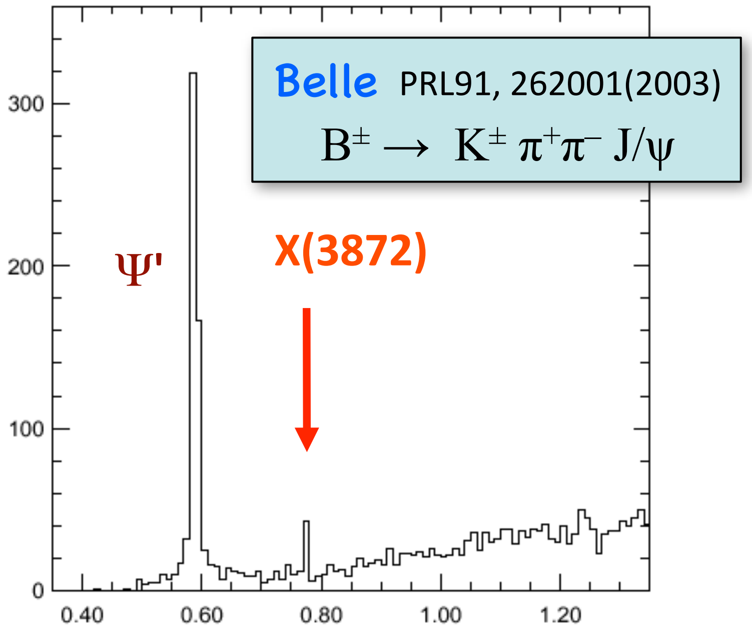
scale change



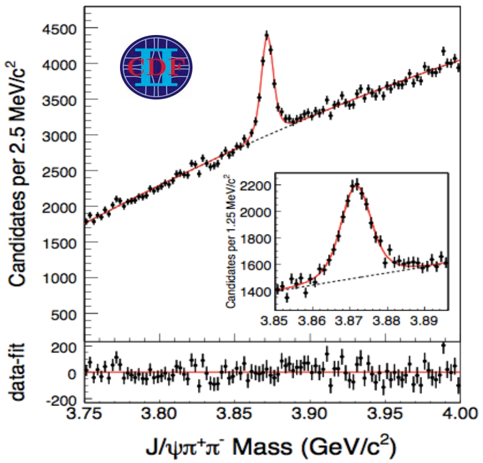
La "Belle" Révolution 2003

c-sector

X(3872)

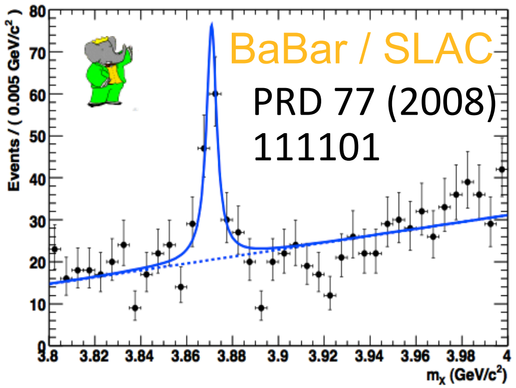


$M(\pi^{+}\pi^{-}l^{+}l^{-}) - M(l^{+}l^{-})$

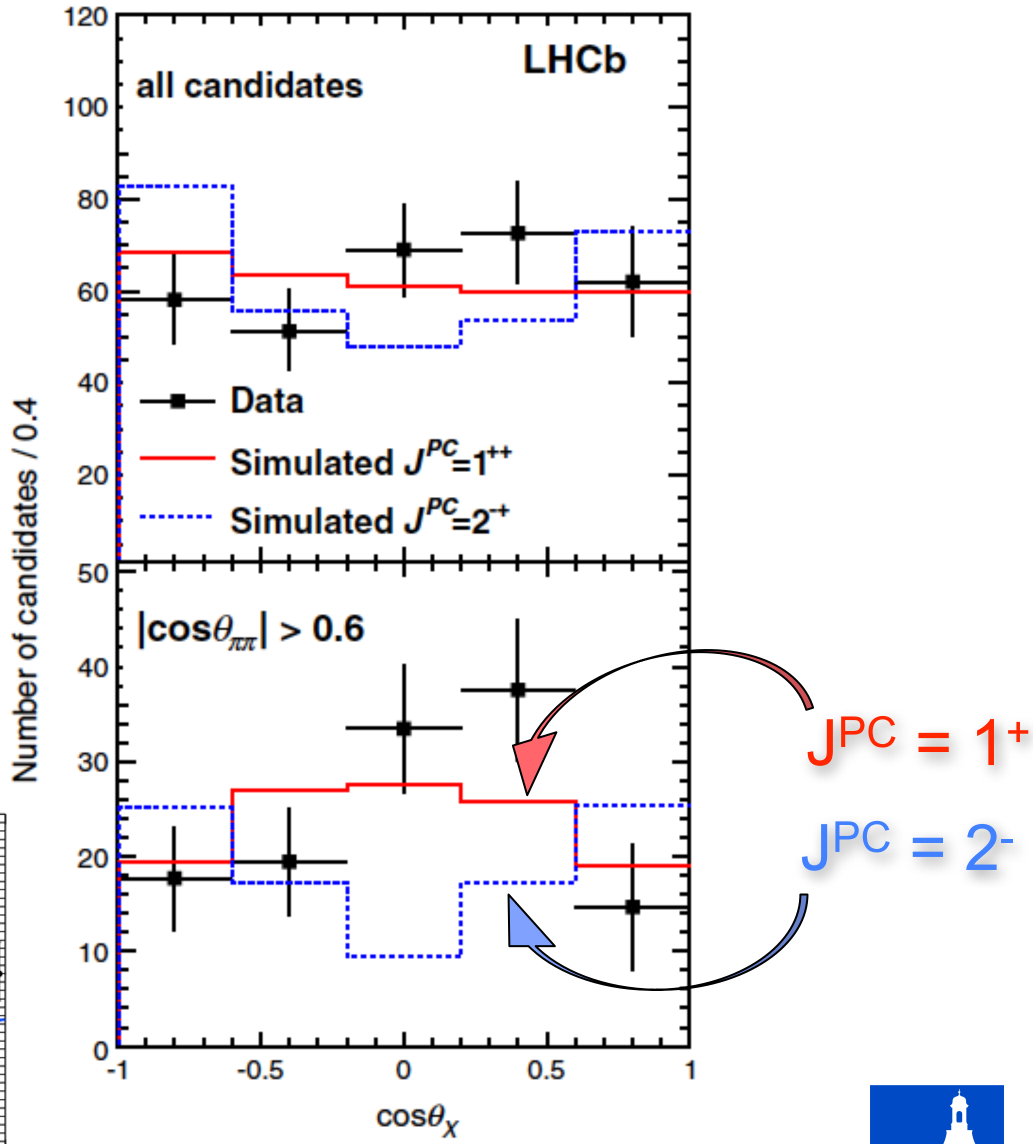


CDF / Tevatron

PRL 103 (2009) 152001



PRL 110 (2013)



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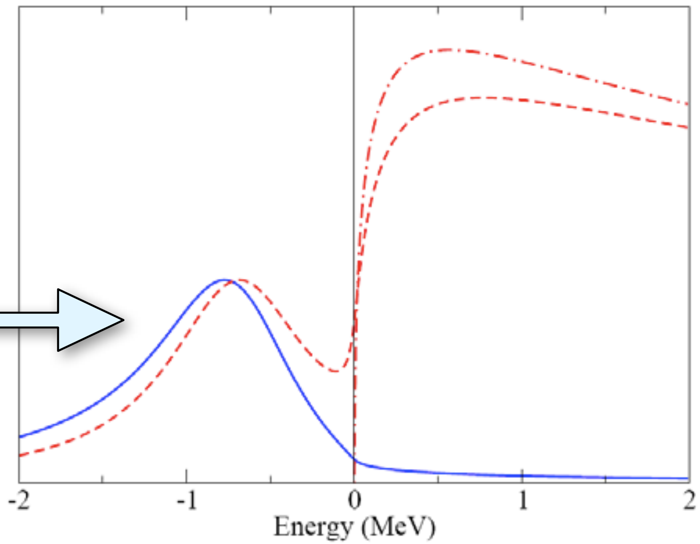
X(3872)

	M(X(3872)), MeV/c²	Γ(X(3872)), MeV/c²
$B \to XK$	$3871.46 \pm 0.37 \pm 0.07$	<2.3 @ 90% C.L. (2003)
$B \to XK$	$3871.4 \pm 0.6 \pm 0.1$	<3.3 @ 90% C.L. (2008)
$X \to J/\psi \pi^+ \pi^-$	$3871.61 \pm 0.16 \pm 0.19$	1.34 (fixed from first two)
average	**3871.50 ± 0.19**	
$M(D^0)+M(D^{*0})$	3871.81 ± 0.36	

"molecule"

possible bound state of D^0 D^{*0}

$J^P = 0^-$ 1^-



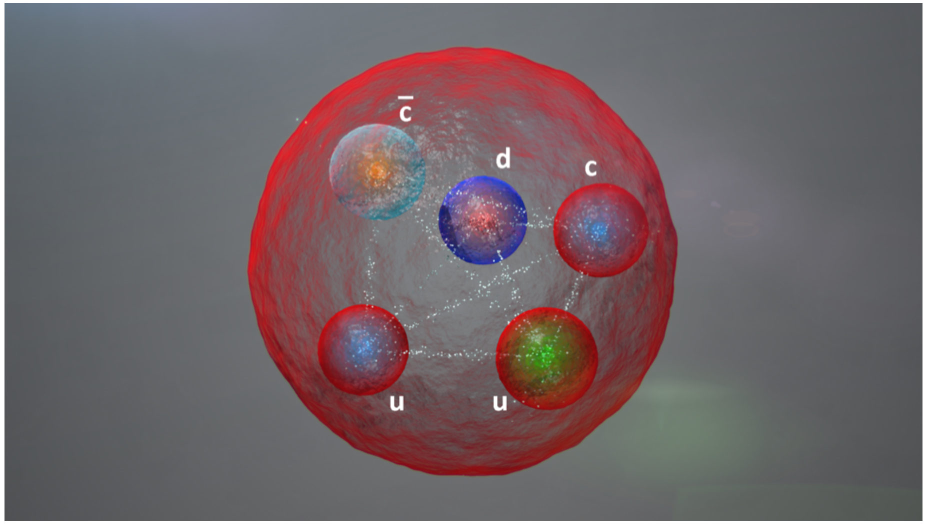
Hidden charm *baryon* sector

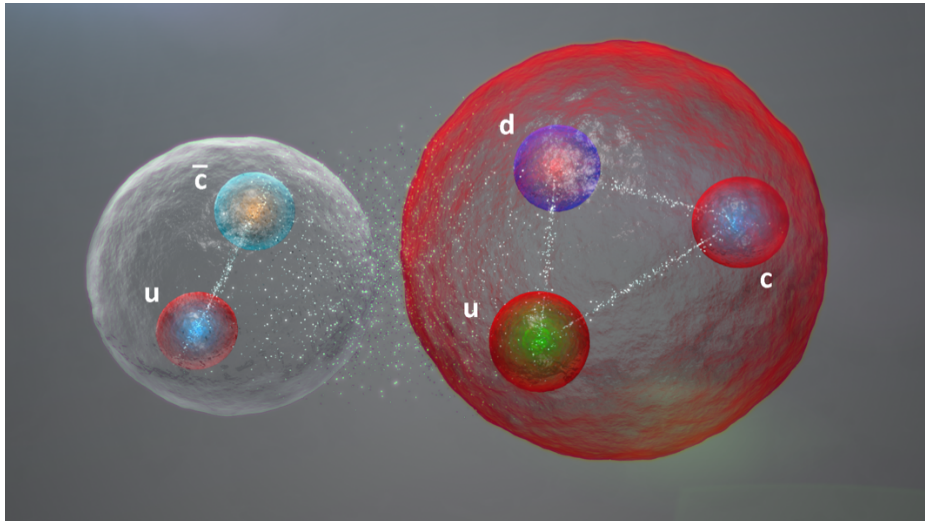
LHCb 2015

PARTICLE PHYSICS

Forsaken pentaquark particle spotted at CERN

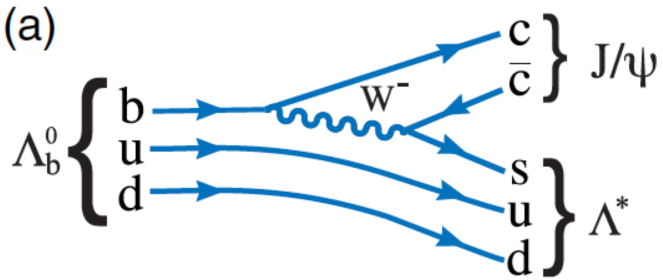
Exotic subatomic species confirmed at Large Hadron Collider after earlier false sightings.

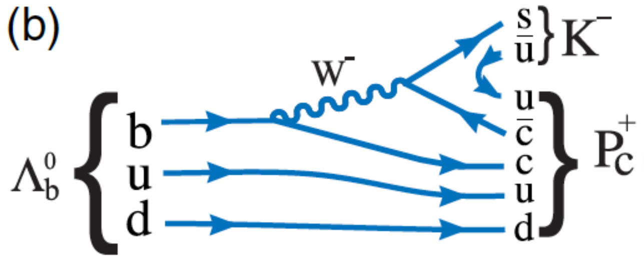




LHCb: $P_c^+(4380, 4450)$

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

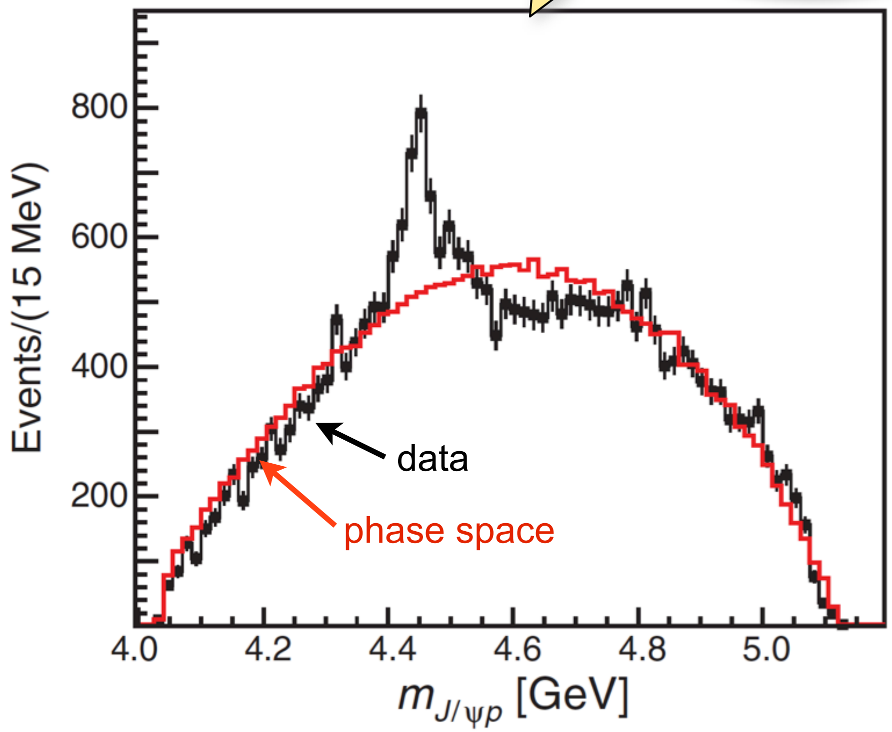




p J/ψ

$J^P = 3/2^-, 5/2^+$

D* Σ_c ?



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 ..."

$\chi_{c1}p$ threshold dynamics?

Guo, Meißner et al., PRD92 (2015) 071502

ELSA

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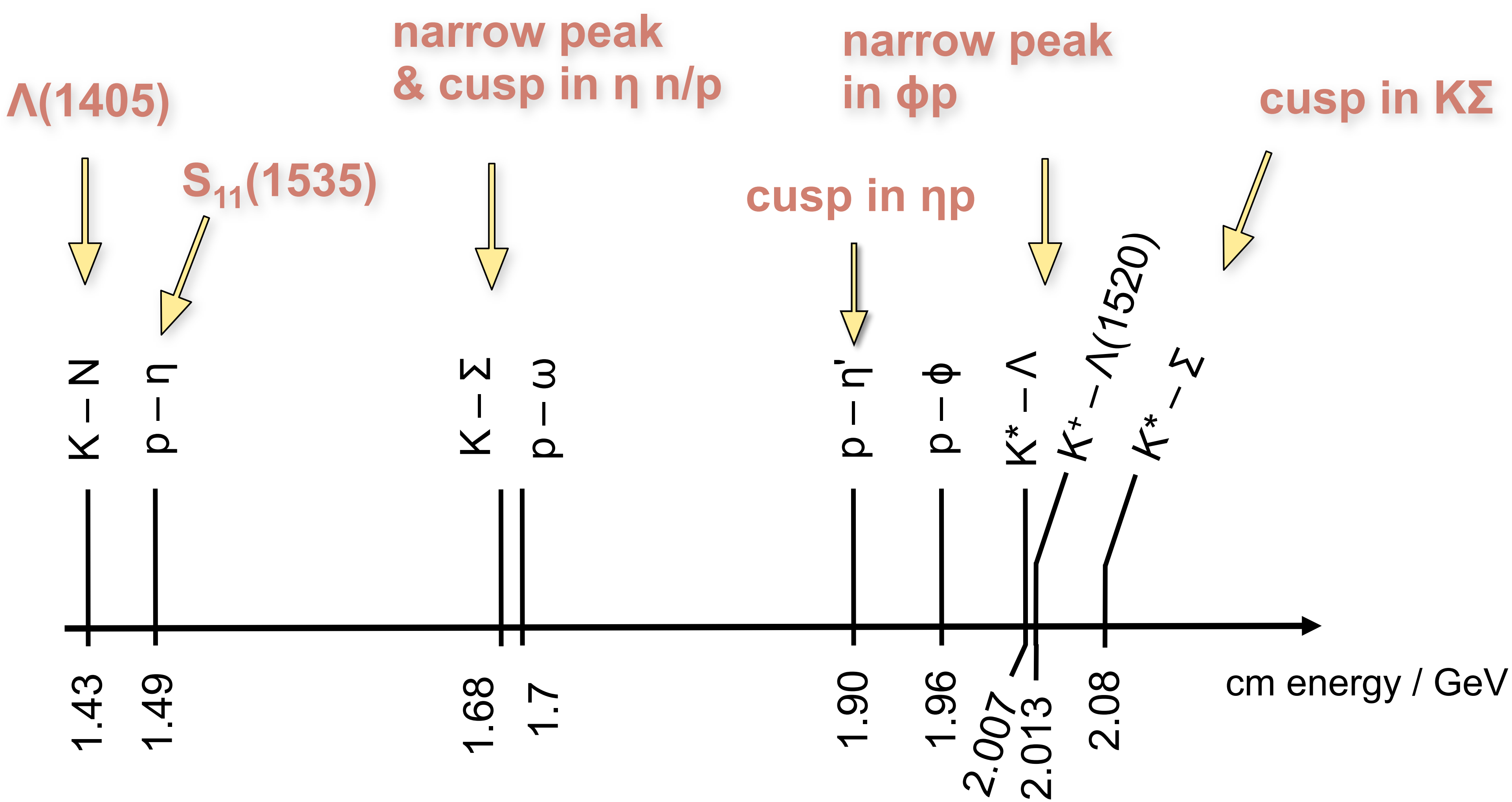
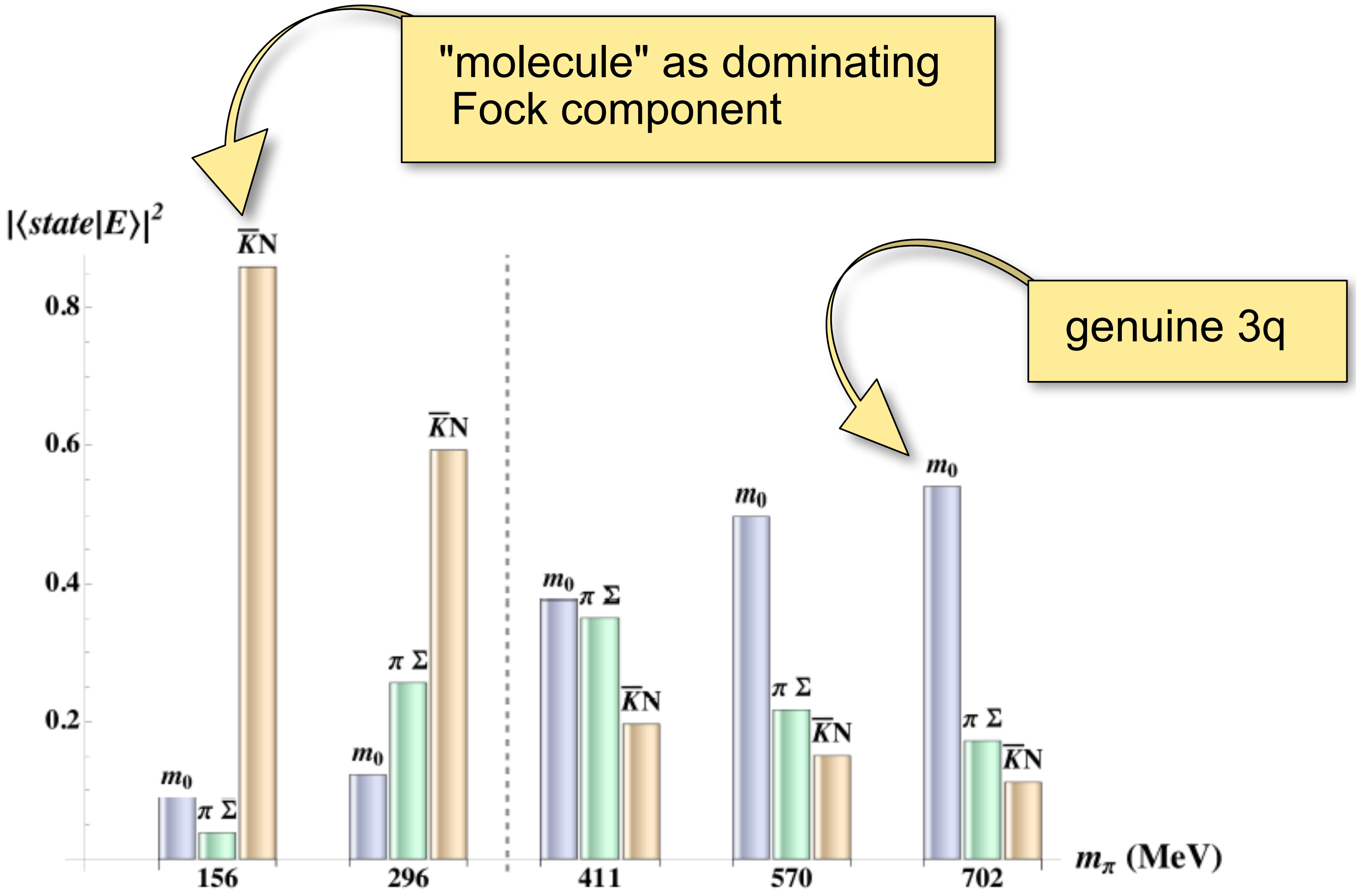
uds sector ?

uds sector – threshold dynamics



Λ(1405)

L-QCD



J.M.M. Hall et al. [Adelaide group], Phys. Rev. Lett. 114 (2015) 132002
arXiv::1411.3402v2 (2015)

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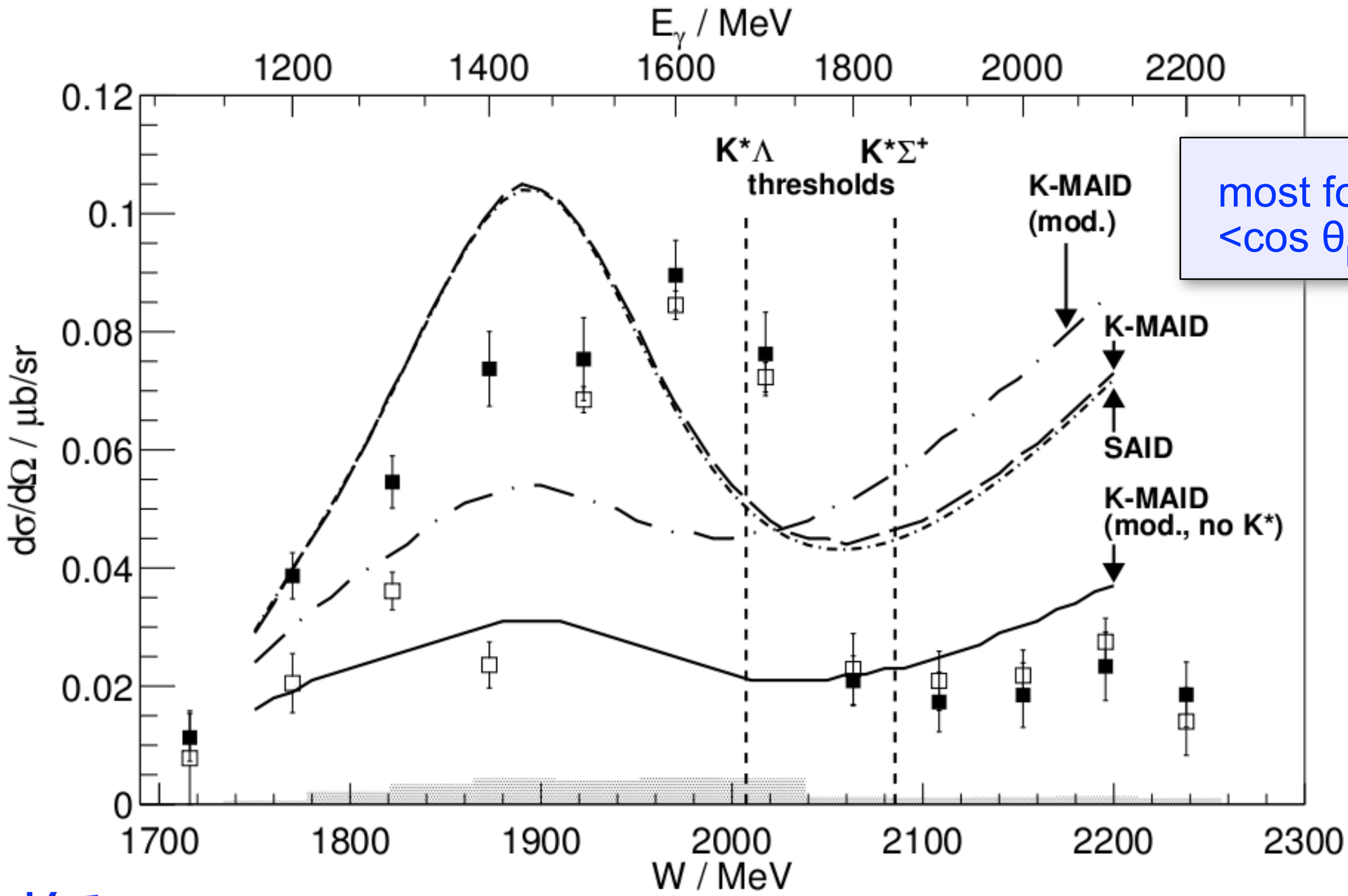
$\gamma + p \rightarrow K^0 + \Sigma^+$ anomaly @ K^* threshold

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



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

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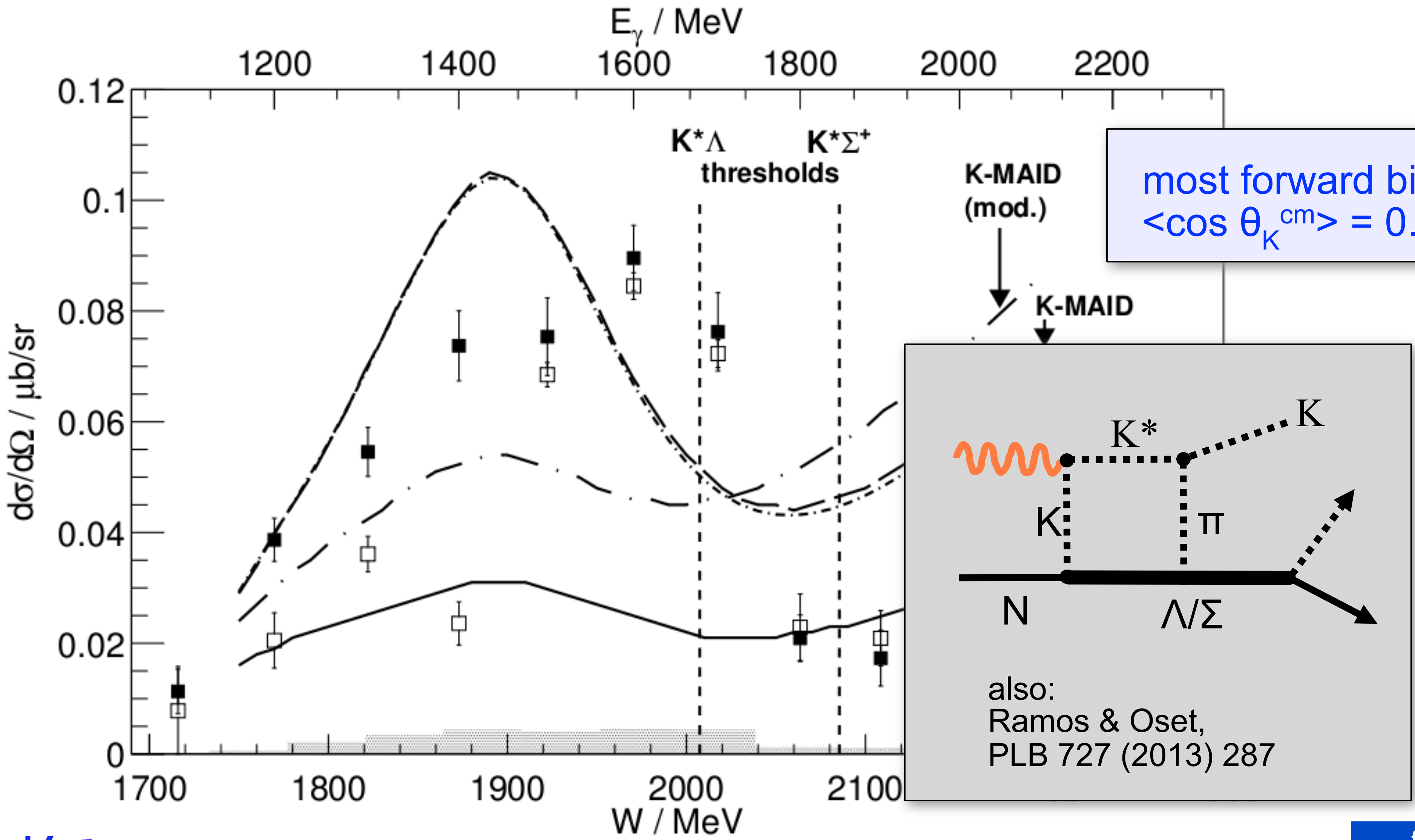

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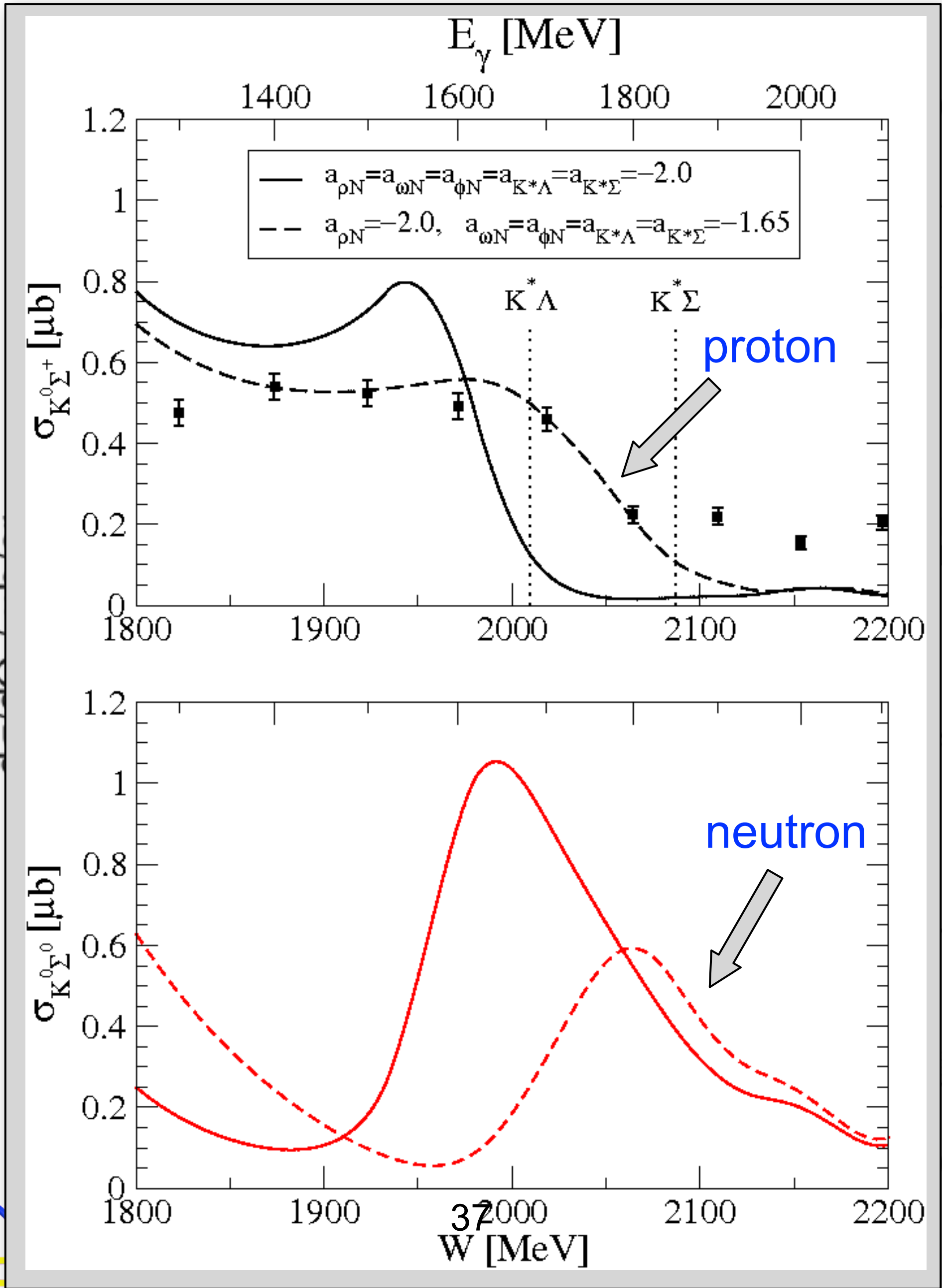
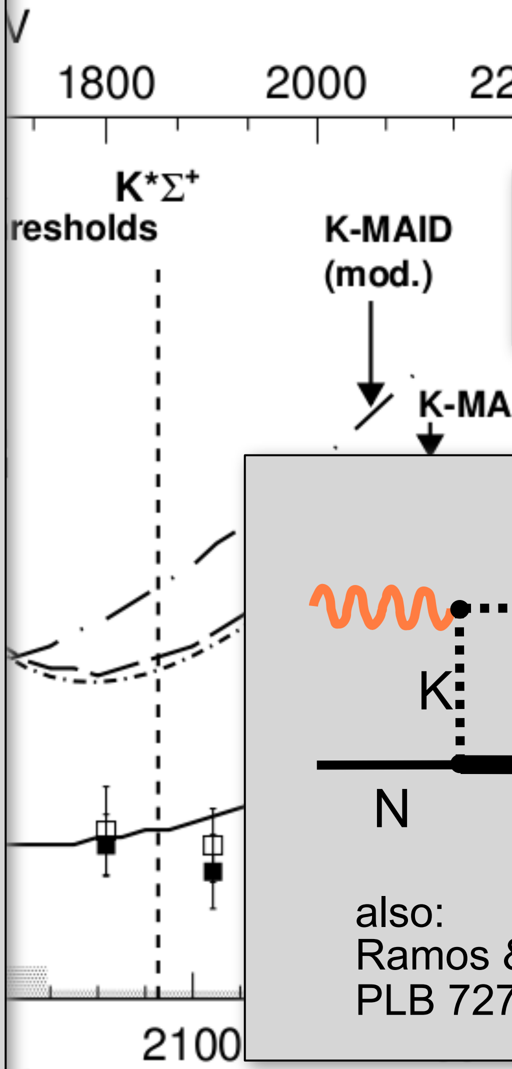


R. Ewald et al. (CB/TAPS), PLB 713 (2012)



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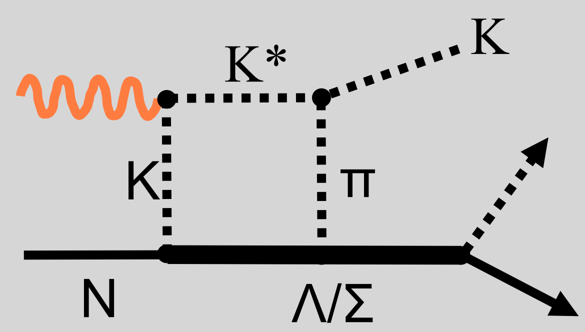

also:
Ramos & Oset,
PLB 727 (2013) 287

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uds sector ?

→ parallels between c and s sectors

	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

uds sector ?

parallels between c and s sectors

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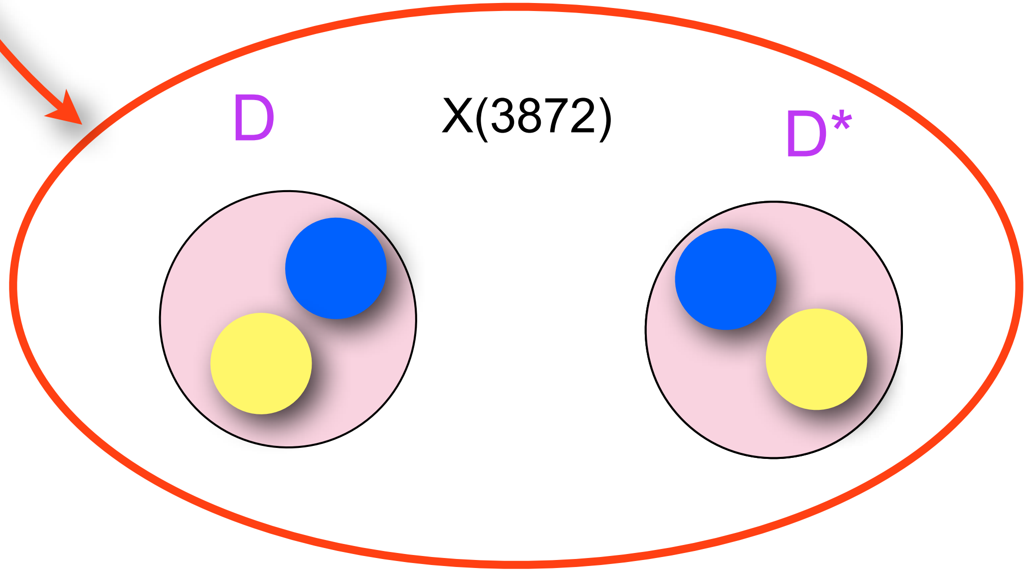

uds sector ?

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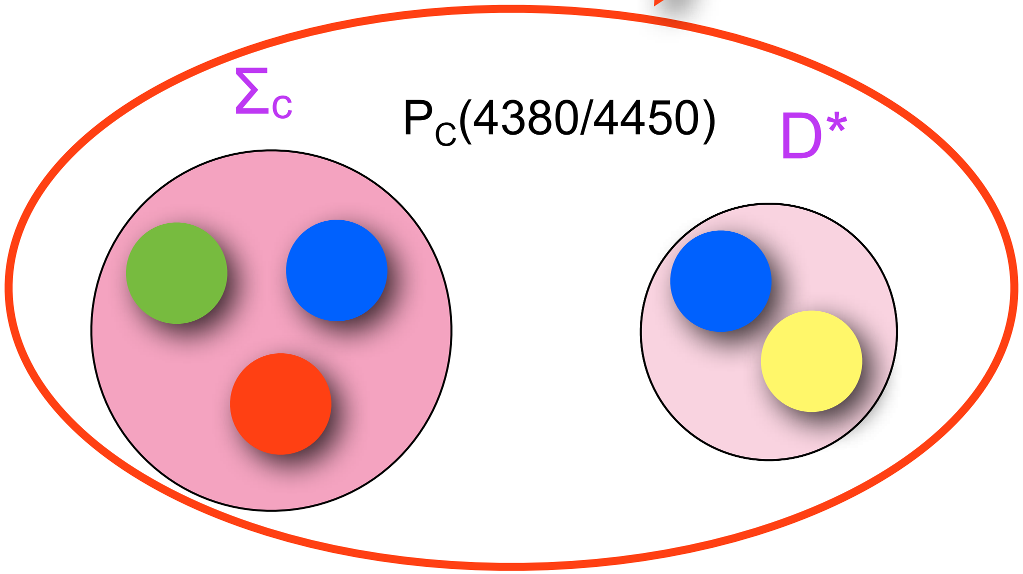
$\bar{3} \leftrightarrow \bar{3}$

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



uds sector ?

parallels between c and s sectors

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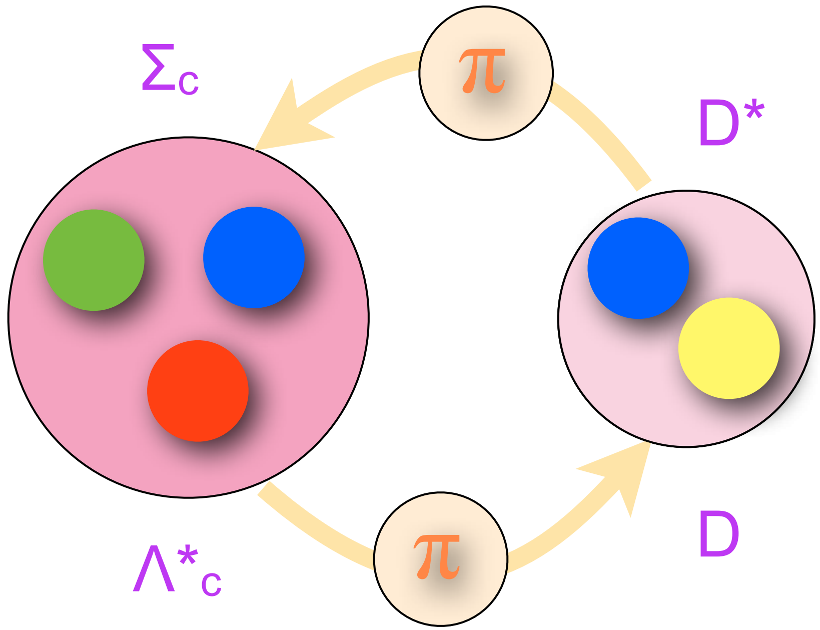
3-body threshold	$D^0\bar{D}^0\pi^0$	$\Sigma_c^+\bar{D}^0\pi^0$	$K\bar{K}\pi$	$\Sigma\bar{K}\pi^0$
closed flavour channel	$J/\psi\ \omega$	$\chi_{c1}p$	$\phi f_0(500)$	ϕp



uds sector ?

parallels between c and s sectors

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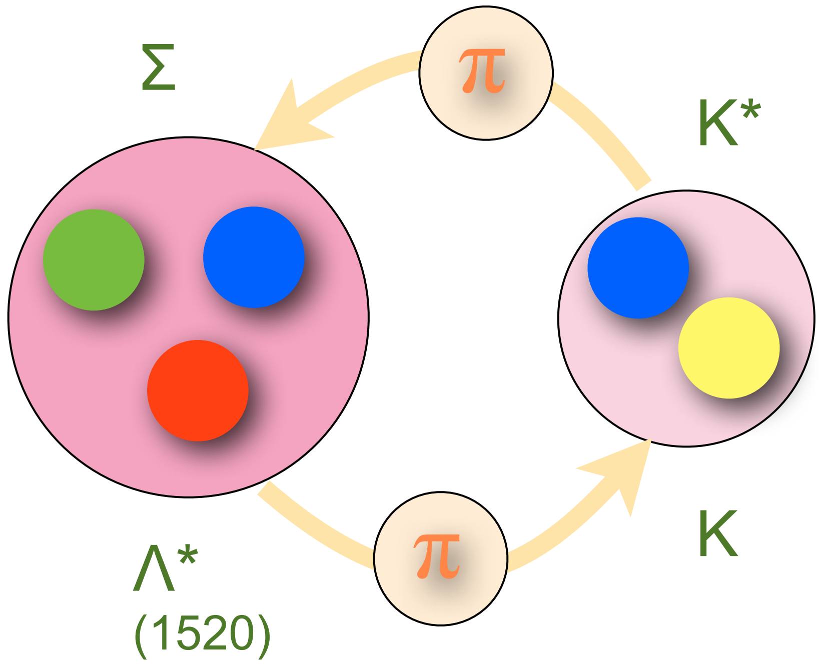
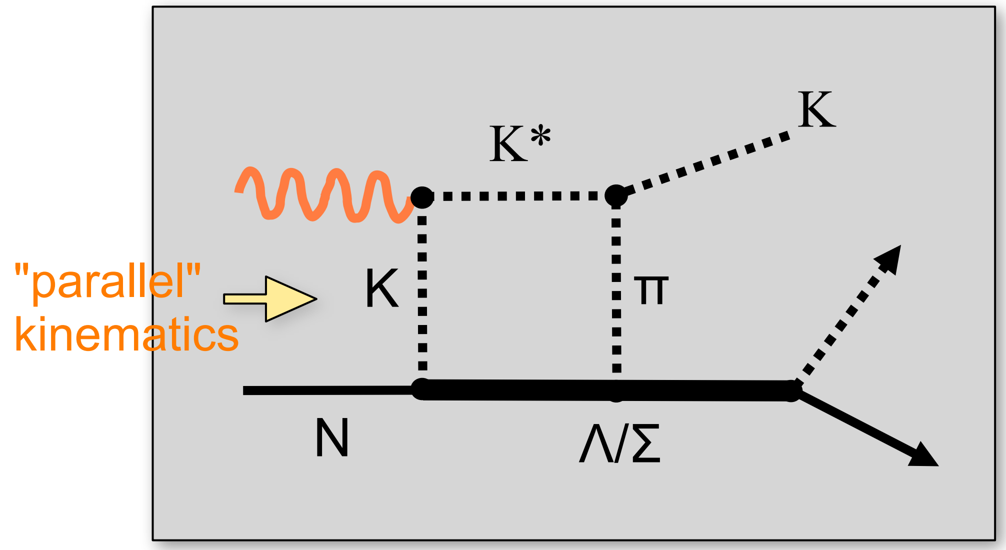
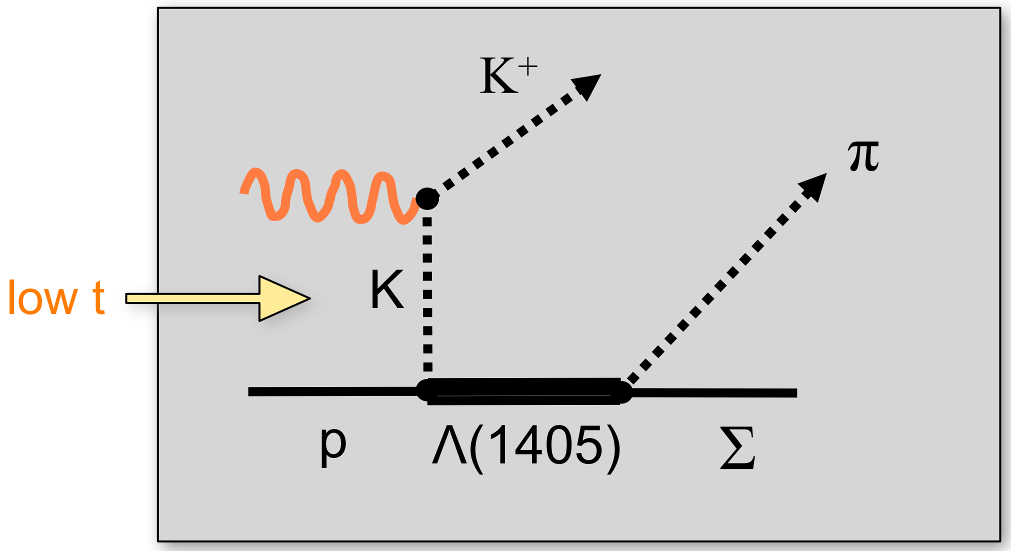
quantum nos.	$J^{PC} = 1^{++}$	$J^P = (3/2)^-$	$J^{PC} = 1^{++}$	$J^P = (3/2)^-$
3-body threshold	$D^0\bar{D}^0\pi^0$	$\Sigma_c^+\bar{D}^0\pi^0$	$K\bar{K}\pi$	$\Sigma\bar{K}\pi^0$
closed flavour channel	$J/\psi\ \omega$	$\chi_{c1}p$	$\phi f_0(500)$	ϕp

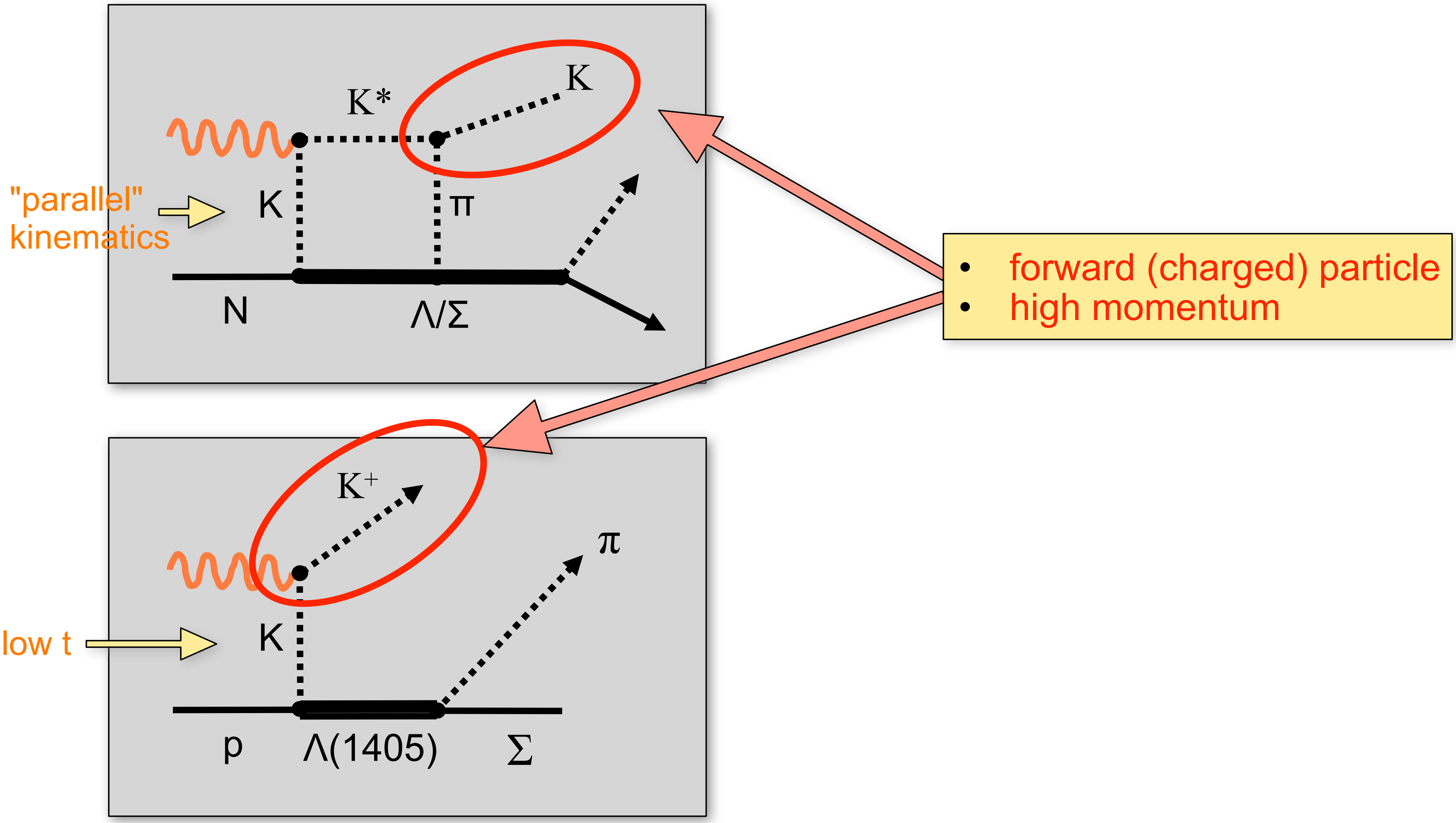


t-channel Kinematics

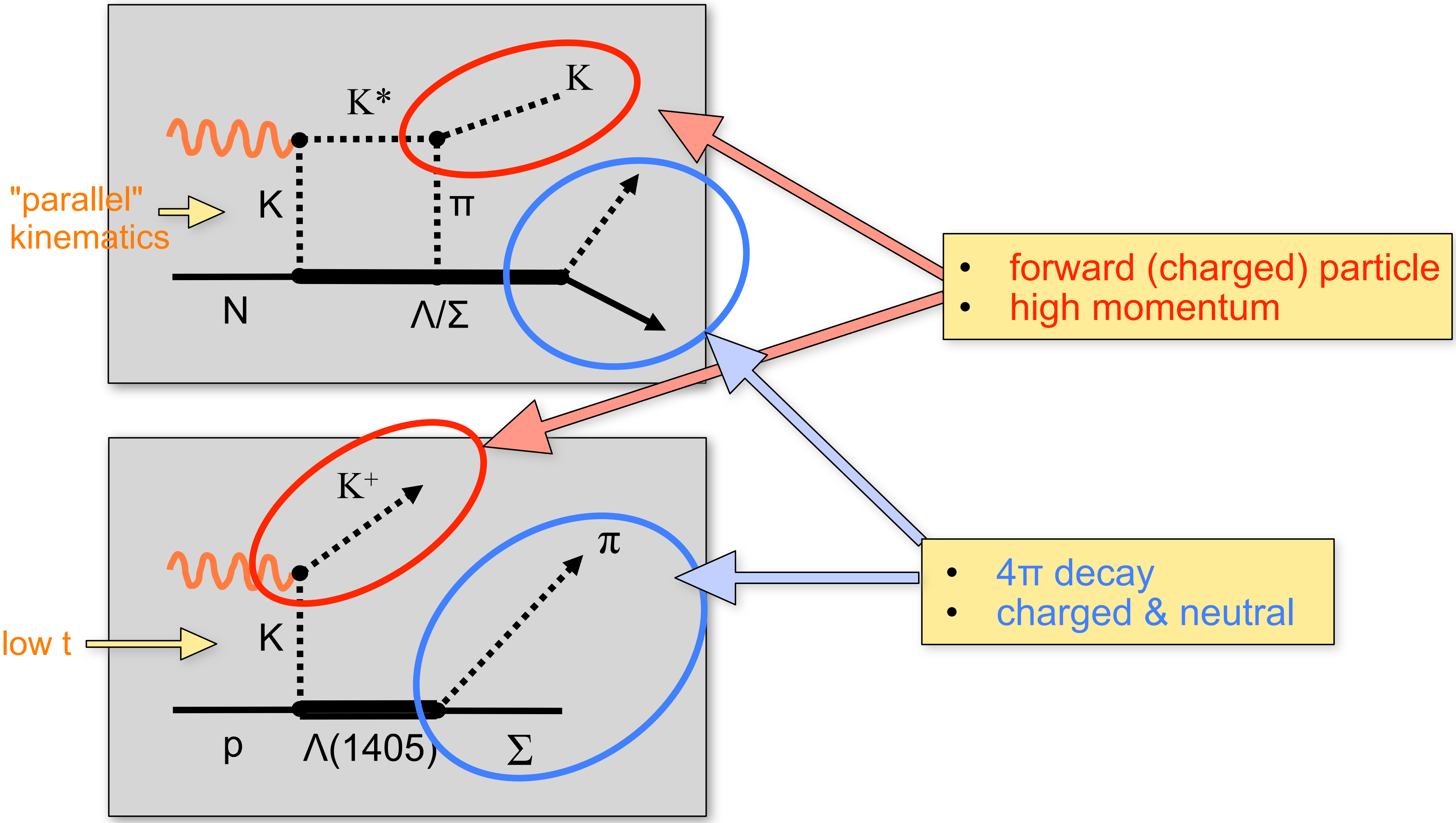




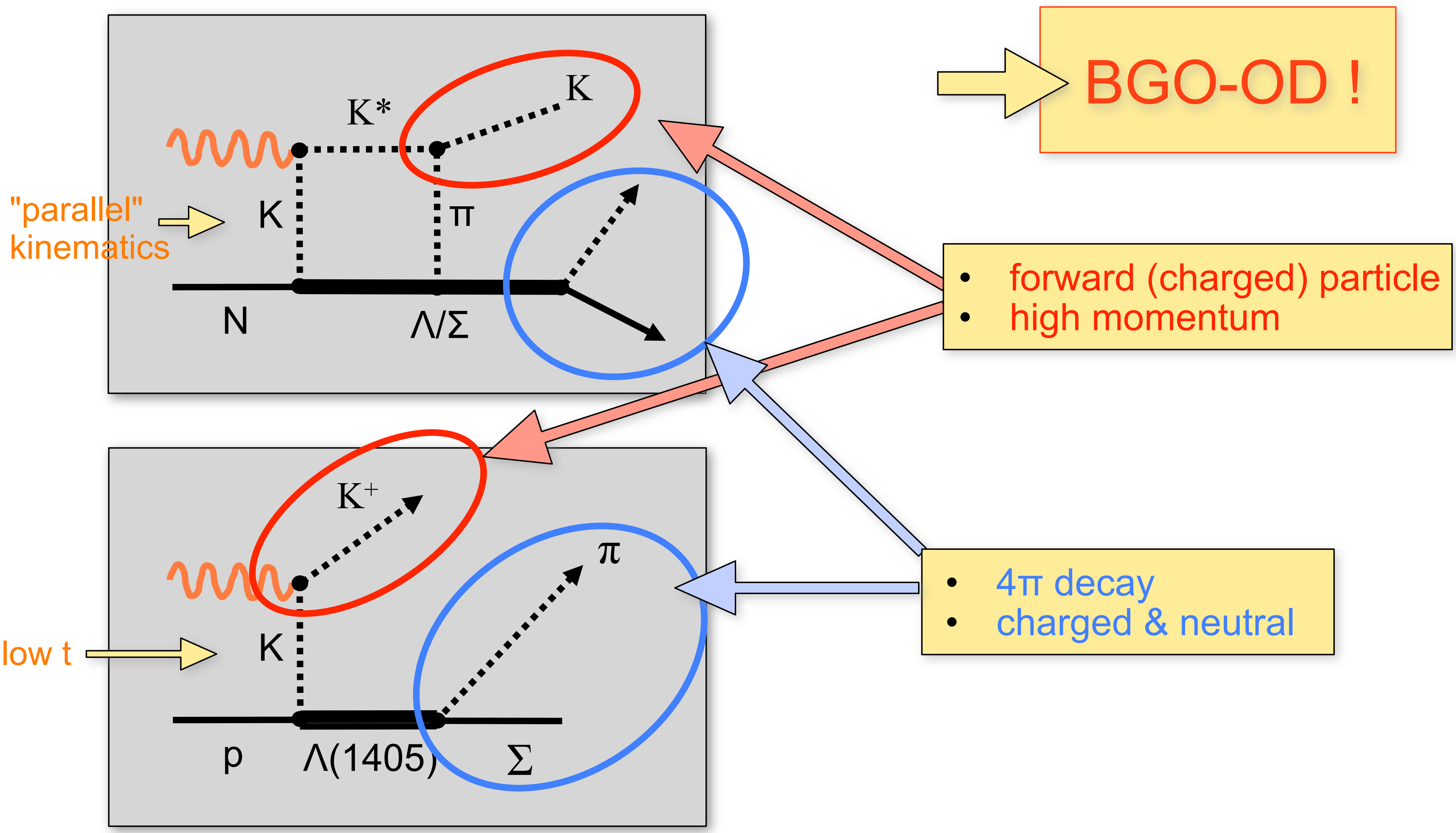
t-channel Kinematics



t-channel Kinematics



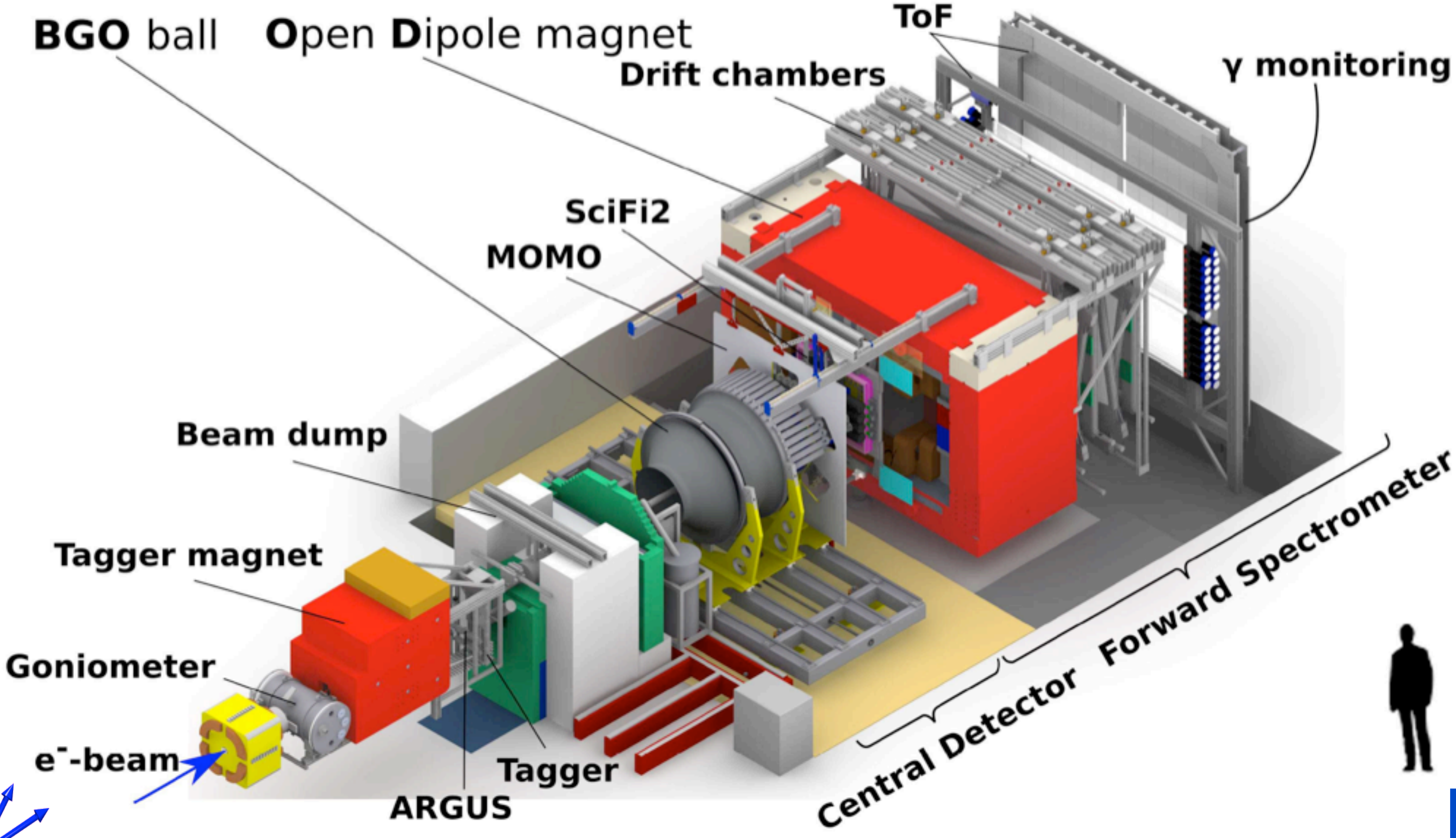
t-channel Kinematics



BGO-OD experiment

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

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



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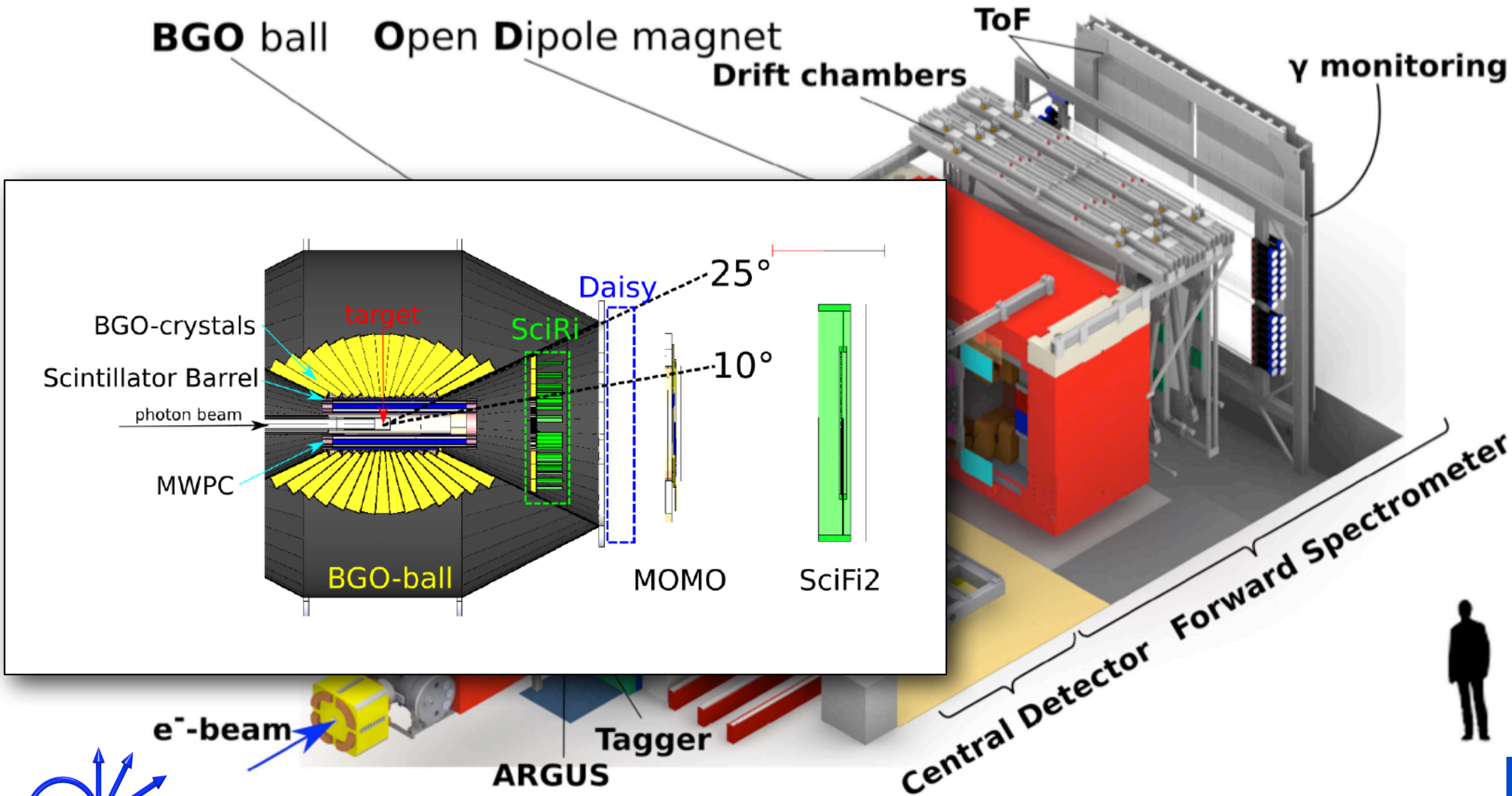

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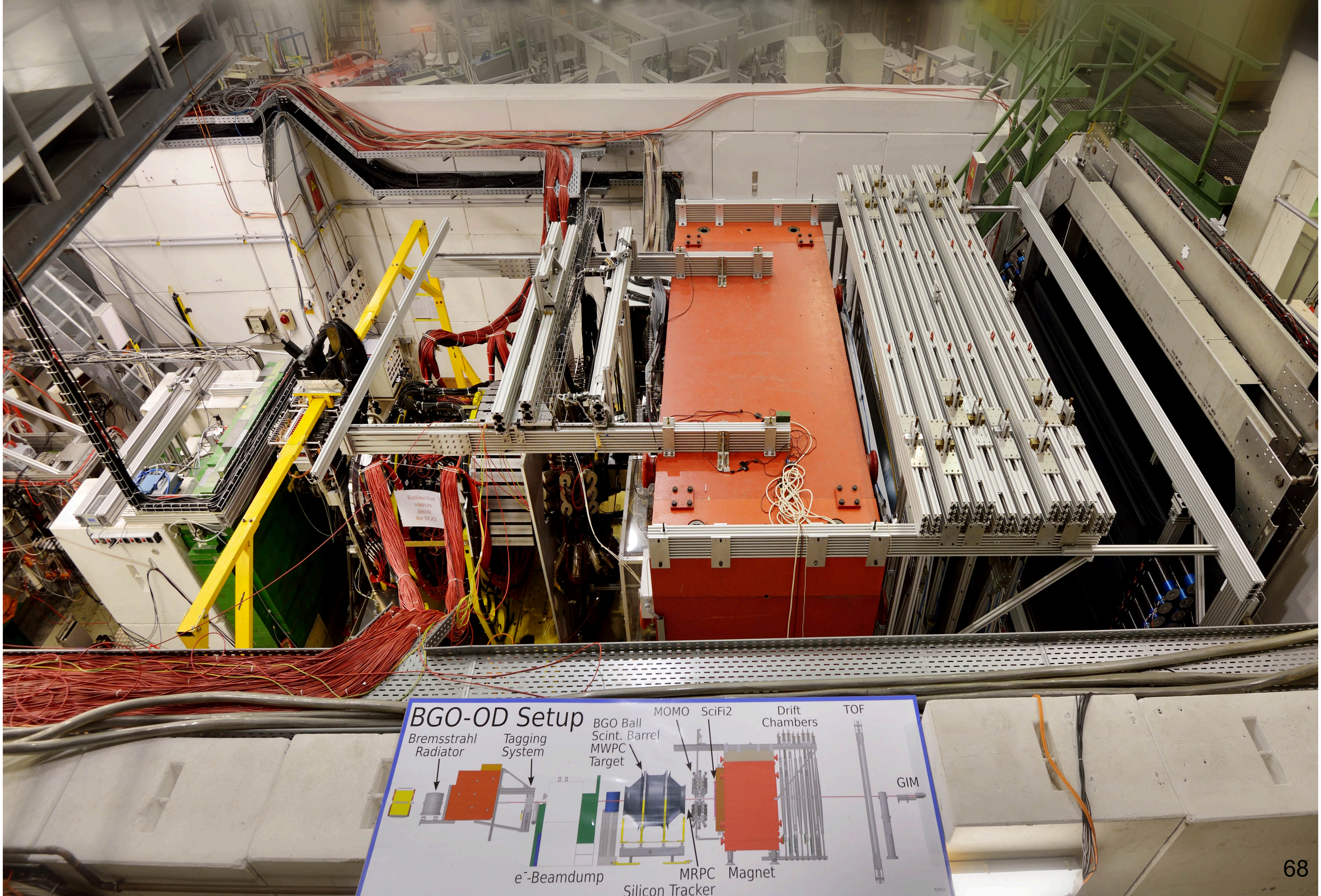
BGO-OD experiment at ELSA



First Results from BGO-OD

all preliminary

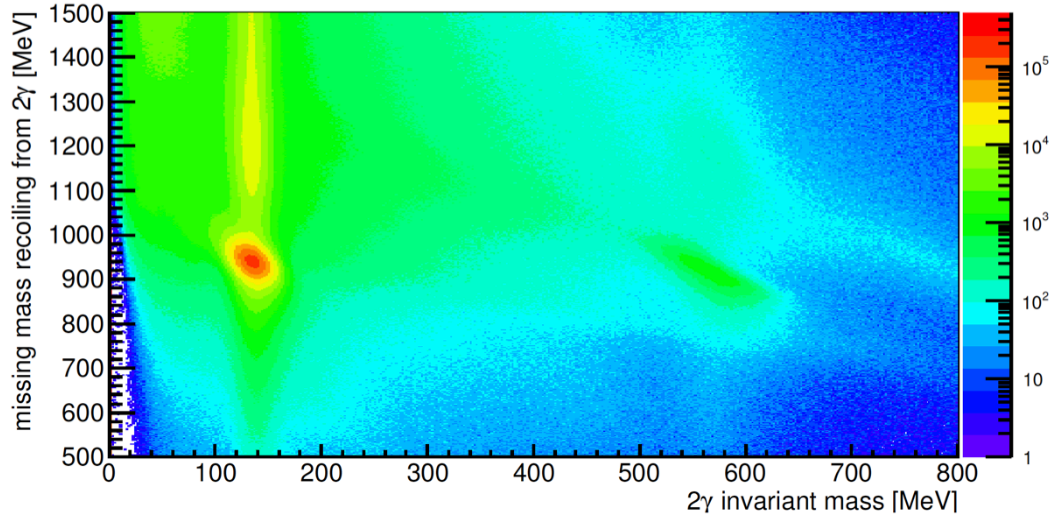
Particle ID & event reconstruction

central

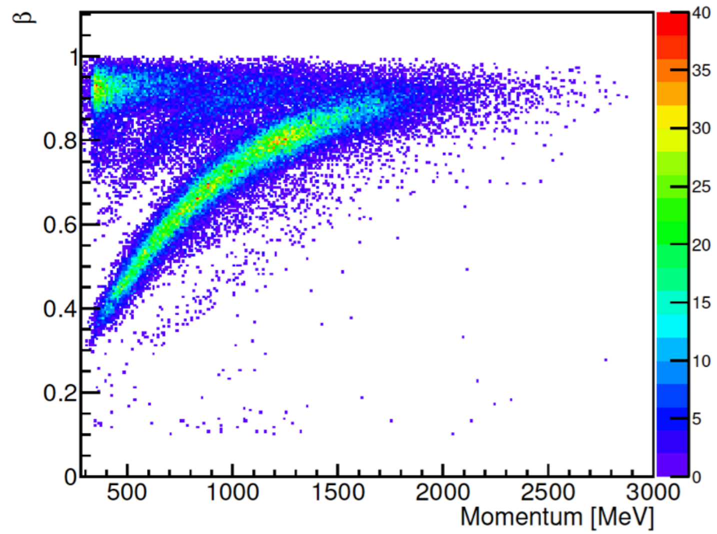
forward

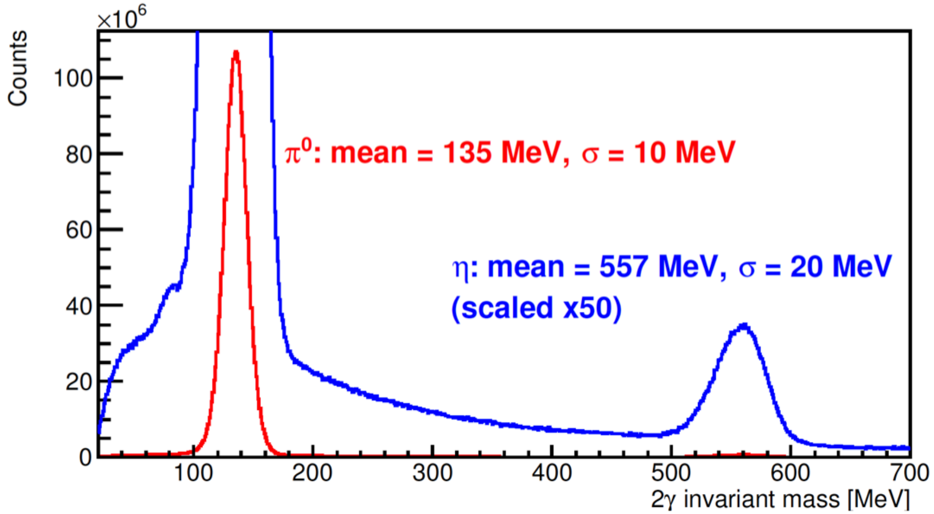
few days of data

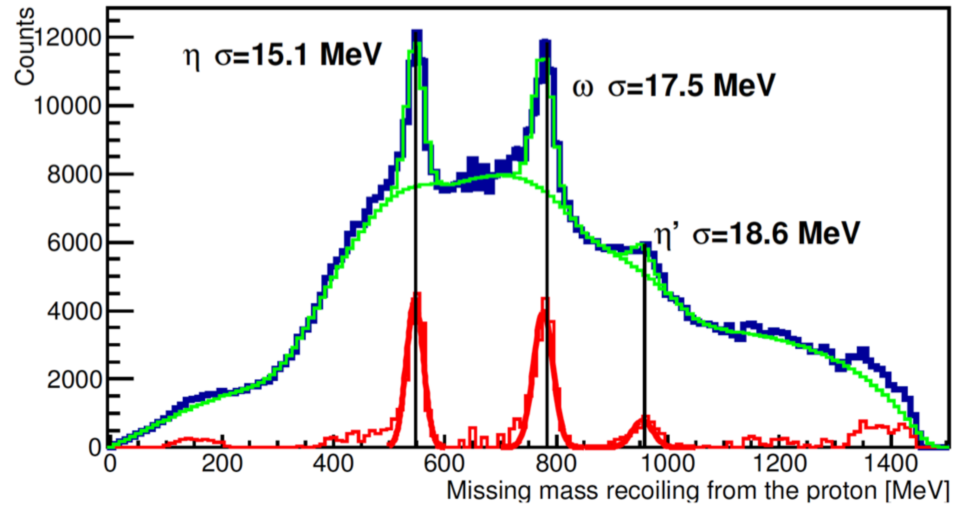
BGO 2γ reconstruction



OD pos. charged particles







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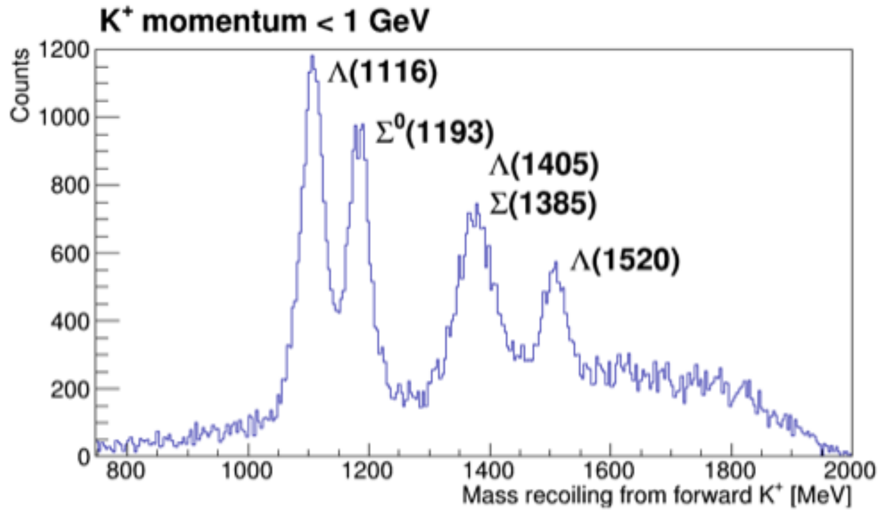
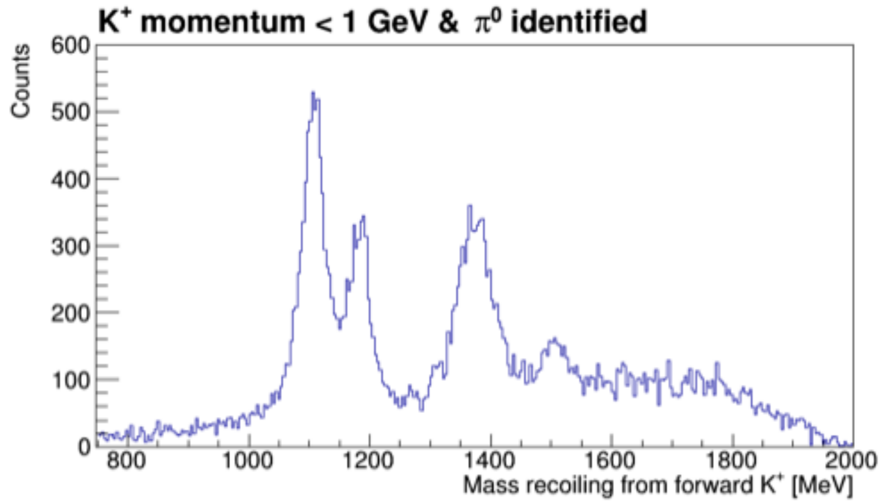
First Results from $\gamma + p \rightarrow K^+ + X$

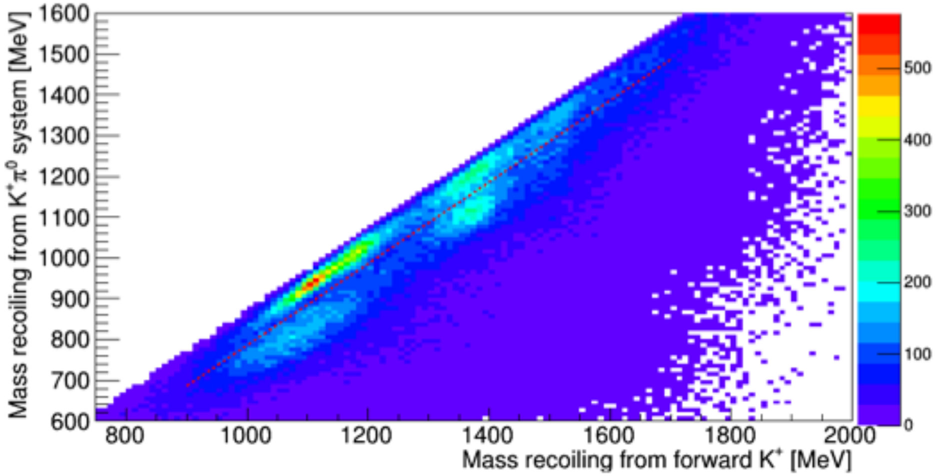
forward K^+ in spectrometer

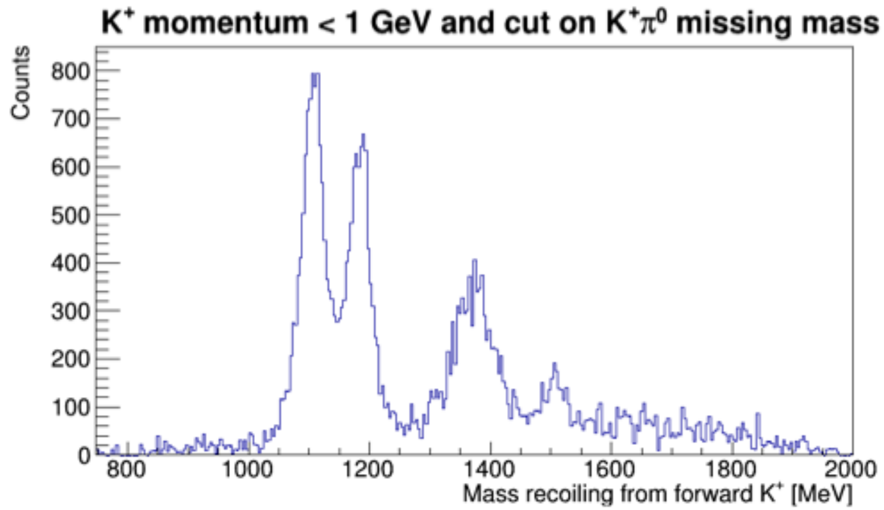
work of T. Jude

all data









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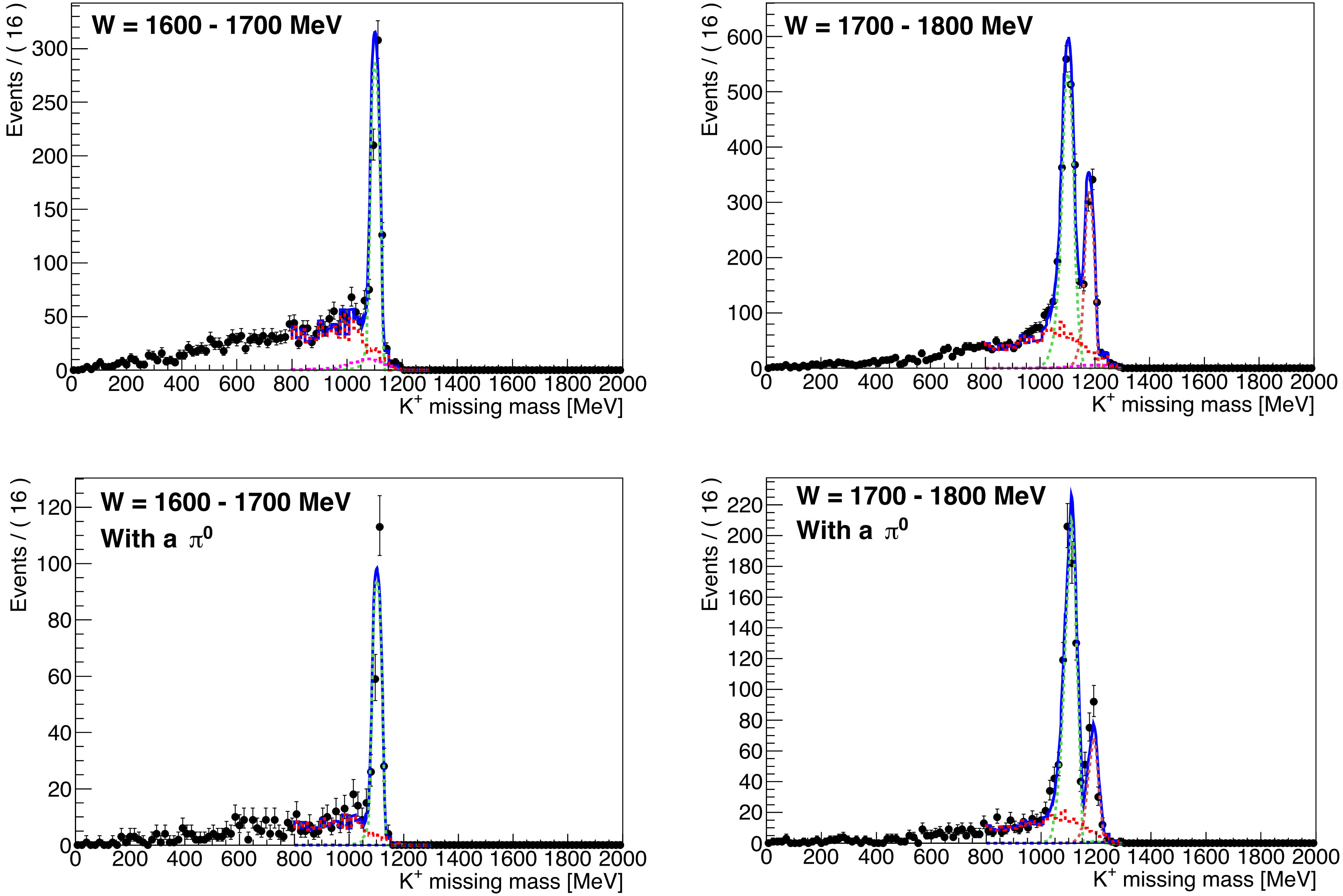
γ + p → K^+ + Λ(1116) @ forward angles

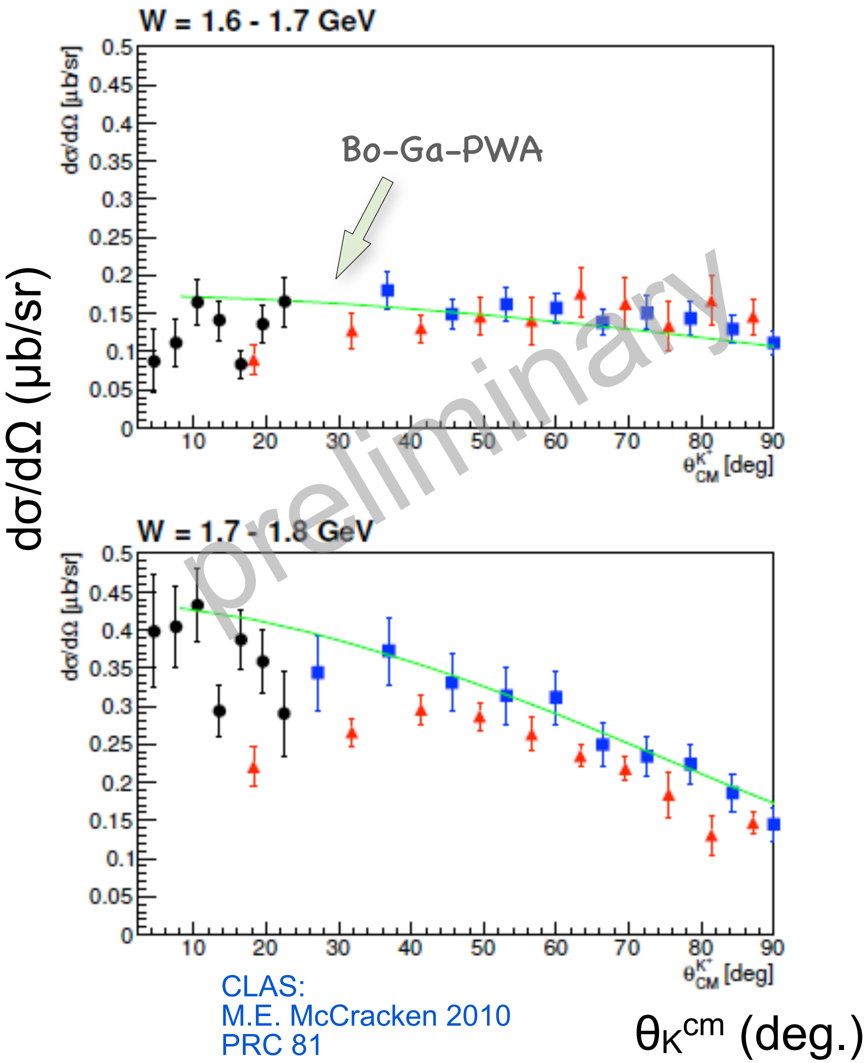
work of T. Jude

~1/3 subset of data



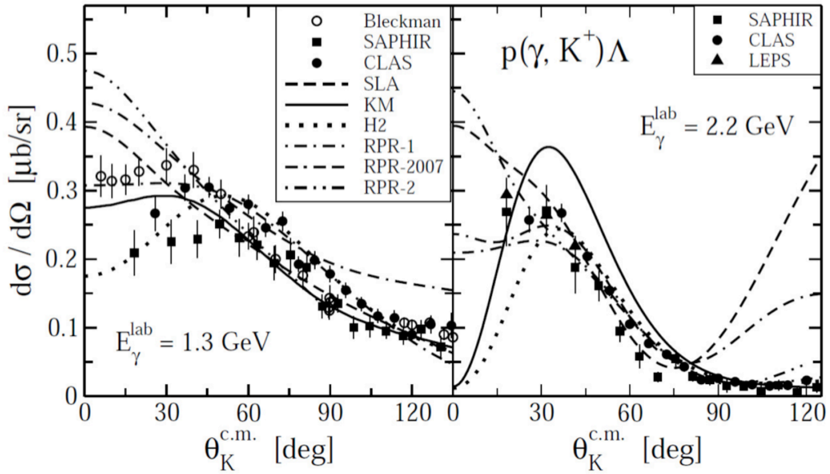
$\gamma + p \rightarrow K^+ + \Lambda(1116)$ @ forward angles

work of Th. Zimmermann & T. Jude



CLAS:
M.E. McCracken 2010
PRC 81

SAPHIR:
K.H. Glander 2004
EPJA 19



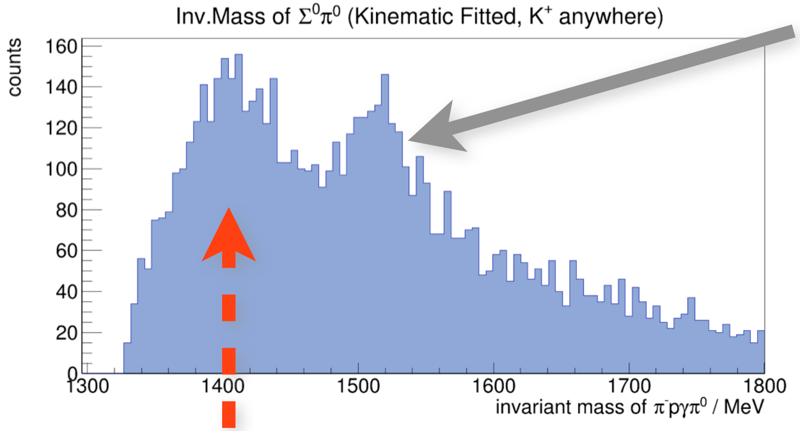
Bydzovsky and Skoupil, arXiv:1211.2684
Proceedings SNP12

→ important constraint for hypernuclei production

10x event statistics available

$\Lambda(1405)$: initial tests – *very preliminary*

first results: $K^+\Lambda(1405)$



$\Lambda(1520) \rightarrow \Sigma\pi$ [42%]
$\Lambda\pi\pi$ [10%]

work of G. Scheluchin

~1/3 subset of data

- production at small t possible
- inaccessible to previous expts

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

$\Downarrow$

$(\pi\Sigma)^0$

isospin forbidden for $\Sigma(1385)$

$\Downarrow$

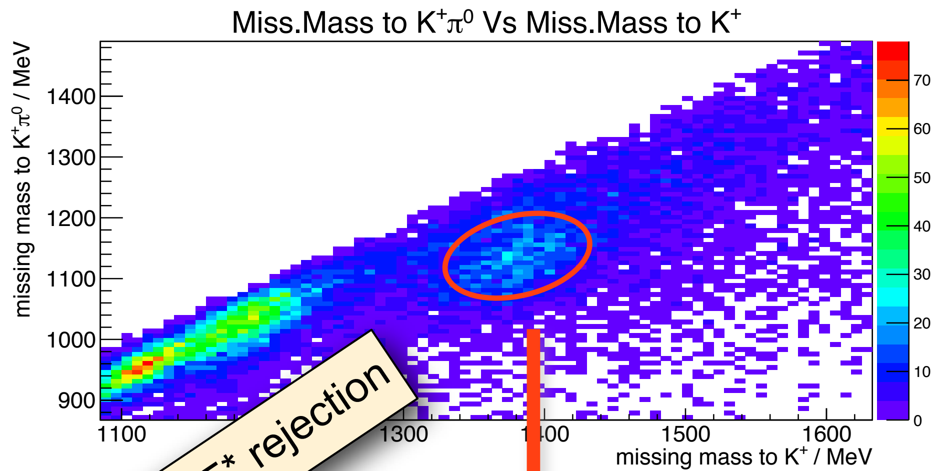
$\pi^0 \Sigma^0(1192)$

$\Downarrow$

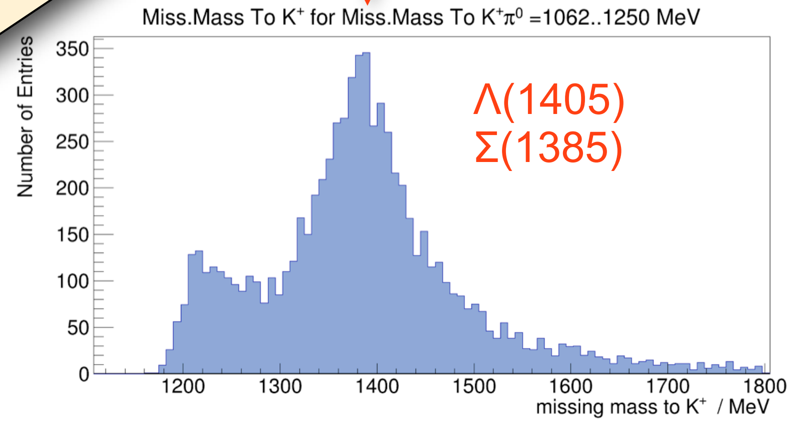
$\Lambda(1116) + \gamma$

$\Downarrow$

$\pi^- p$

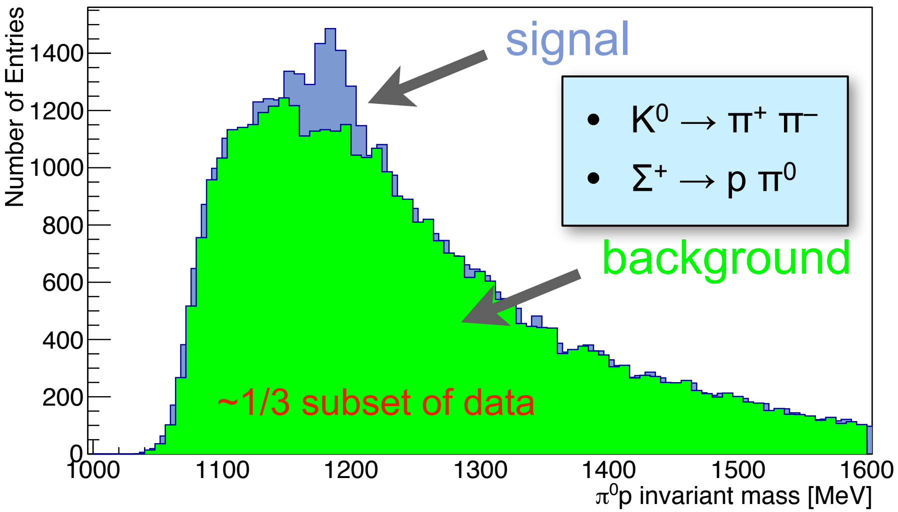


no explicit Σ^* rejection



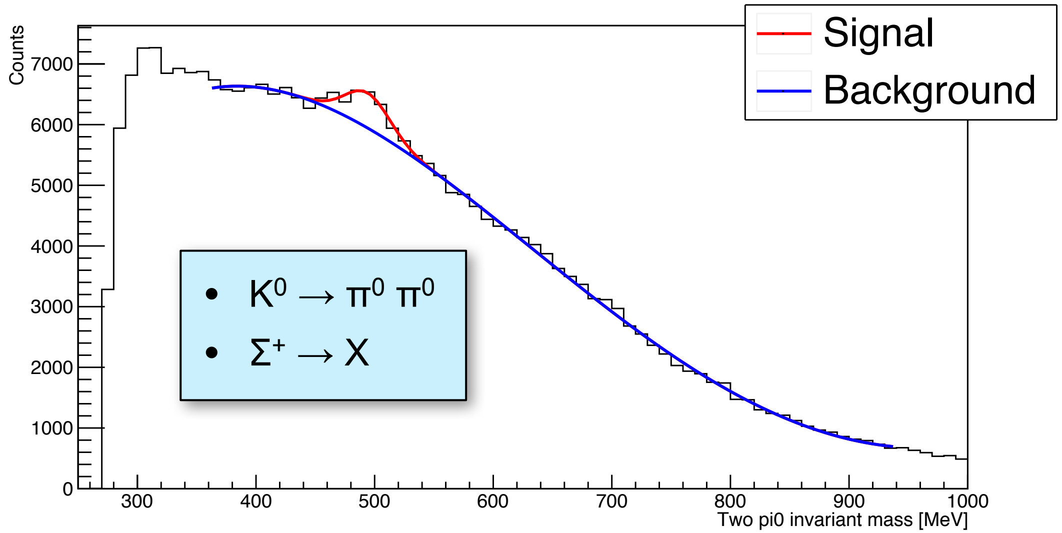
K^0 from *proton* target

work of B.-E. Reitz



w/ kinematic fit

work of S. Alef



prior to kinematic fit

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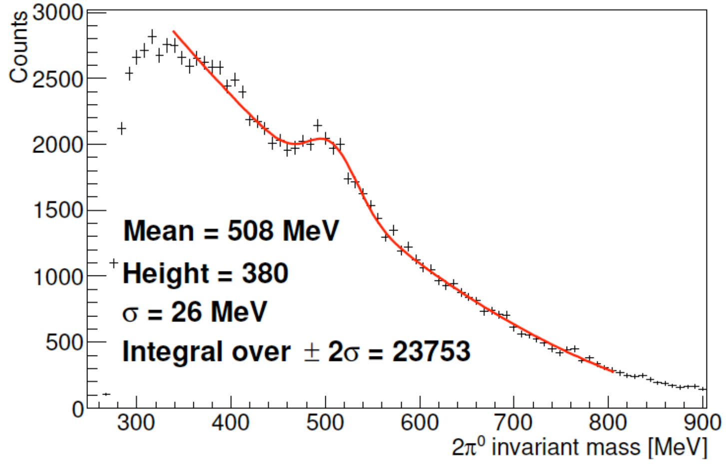
K^0 from *neutron* target

2 day test beam

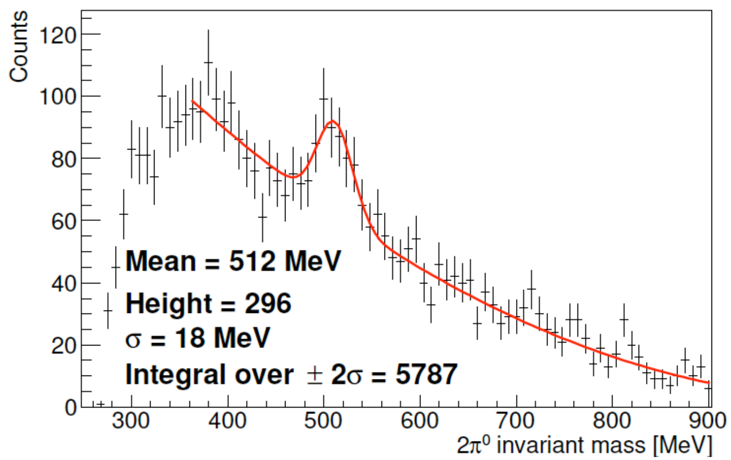
work of T. Jude

- $K^0 \rightarrow 2\pi^0$ in BGO
- n(neutral) < 6
- n(charged) < 3



in addition:

- p from $\Sigma^0 \rightarrow p\,\pi^-$ in forward spectrometer



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Summary

- Baryon Spectrum long standing problem
- new insights through meson photoproduction,
- in particular w/ (single & double) polarisation
- "exotics" in charm sector
- uds sector → parallels ??
- threshold dynamics
- low-t experiments

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Tutorial issues

1. Estimate lifetime of $\Delta(1232)$ from Γ = 110 MeV
2. Estimate strong coupling constant α_s from
   - $\Sigma^0(1385) \rightarrow \Lambda(1116)\,\pi^0$ width Γ = 36 MeV
   - $\Sigma^0(1193) \rightarrow \Lambda(1116)\,\gamma$ lifetime $\tau = 10^{-19}$ s
   - particle lifetime is ~ $1/(c.c.)^2$ of interaction
3. Size & internal momenta of composite objects:
   - Hydrogen atom (size ↔ binding energy?)
   - Nucleus R ~ 2 fm
4. Confinement & Nucleon Mass ?
   - delocalisation ↔ potential energy ?
   - energy minimum ?
   - size / total energy ?
5. Decuplet: Symmetry ? ↔ Quark Hypothesis

estimate of strong coupling α_s

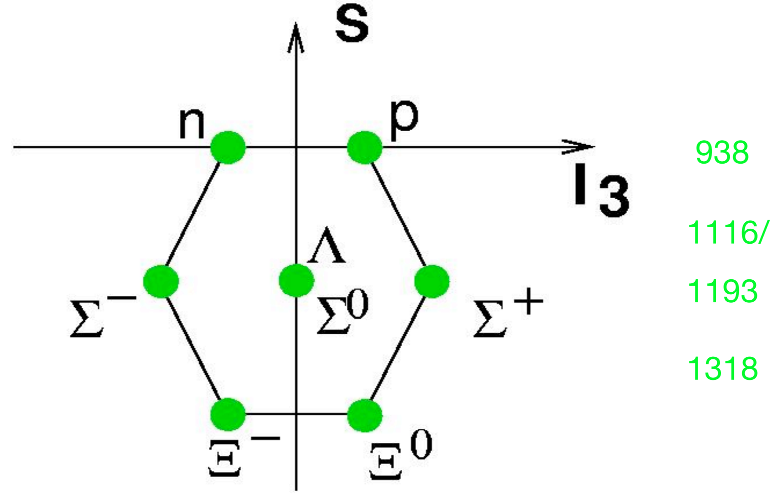
compare strong and electromagnetic decay of Σ baryons

$\Sigma^0(1385) \rightarrow \Lambda(1116) + \pi^0$ $\Gamma = 36$ MeV $\leftrightarrow \tau = 2 \times 10^{-23}$s

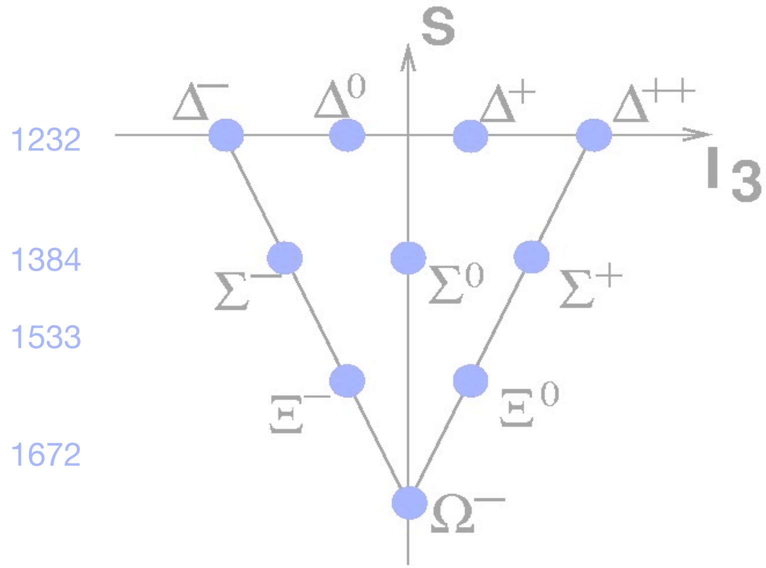
$\Sigma^0(1192) \rightarrow \Lambda(1116) + \gamma$ $\tau = 0.7 \times 10^{-19}$s

$$\Rightarrow \quad \frac{\alpha_s}{\alpha} \simeq 60 \qquad \Rightarrow \alpha_s \simeq 0.5$$

Baryon octet & decuplet



octet



decuplet

decuplet: wf. symmetric in spin, flavor and space *separately*

octet: symmetry under *simultaneous* interchange of flavor and spin

Statistics problem & Color quantum number

nucleon

⇩

3 quarks	J = ½ or 3/2	⇦	baryons
quark-antiquark	J = 0 or 1	⇦	mesons

⇧

pion

p = uud
n = ddu
Δ^{++} = uuu ⇦ π^+p resonance (Fermi 1951)
Δ(1232)

statistics problem

forbidden by Fermi statistics

J = 3/2	quark spins all aligned
uuu	three identical quarks
L = 0	spatial symmetric ground state

also: no hadrons observed with fractional charges, e.g. uu → Q = +4/3

both problems resolved by concept of **color**

quarks have three primary colors, Red, Green, Blue

$\Delta^{++} = u_R\, u_G\, u_B$ with *non-identical* constituents

$p = u_R\, u_G\, d_B \oplus u_B\, u_R\, d_R \oplus \ldots$

anti-quarks carry anti-colors, anti-Red, anti-Green, anti-Blue: $\bar{R}, \bar{G}, \bar{B}$

all observed hadrons are **colorless**, i.e. white :

confinement

invariant under rotations in color space

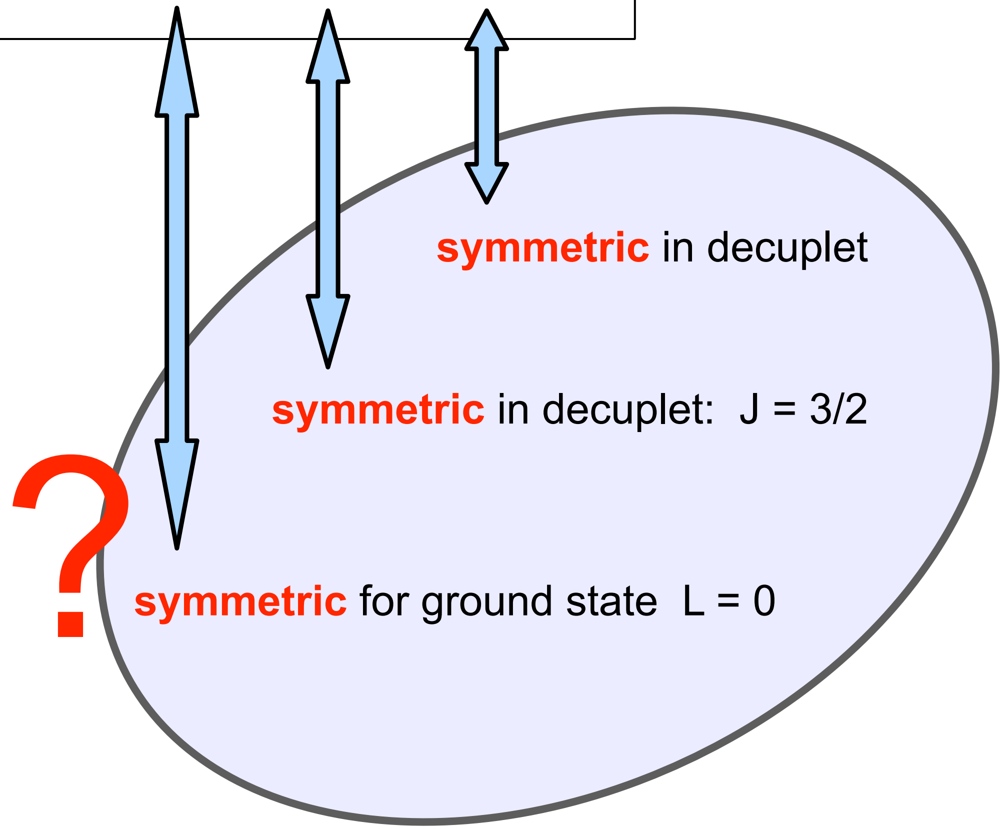
antisymm.

equal mixture of R, G, B
equal mixture of $\bar{R}, \bar{G}, \bar{B}$
equal mixture of complementary colors, $\bar{R}R$, $\bar{G}G$, $\bar{B}B$

only combination $\bar{R}R + \bar{G}G + \bar{B}B$ unchanged by rotations: **color singlet**

combinations other than qqq, $\bar{q}\bar{q}\bar{q}$, $q\bar{q}$ are colored ↔ don't exist in nature baryons are fermions ⇔ wave function antisymmetric

$$| \, qqq >_A \quad = \quad | \, \text{color} >_A \quad \text{x} \quad | \, \text{space, spin, flavor} >_S$$



Baryon wave functions

color wavefunction $3 \otimes 3 \otimes 3 \to$ antisymmetric

decuplet: spin-flavor-space parts of wavefunction separately are manifestly symmetric

octet: spin-flavor-space part must be symmetric through $\to$ suitable combination of MS–MS