Pentaquarks

or

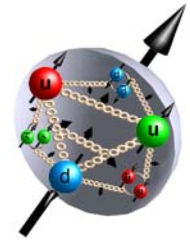
The Search for Exotic Baryons

Physics 390 – Fall 2006

5 April 2006

Supported by NSF–0244842

Search for Exotic Baryons

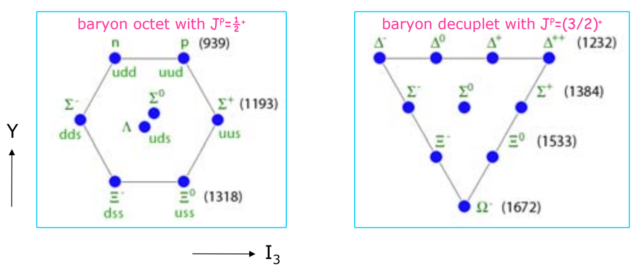


- Standard Quark Model
  - classifies hadrons as
    - mesons ($q\bar{q}$)
    - baryons (qqq)
      -> surrounded by pion cloud
      or $q\bar{q}$ vacuum polarization
  - also allows "non-standard" (or exotic) hadron states
    - multiquark mesons ($qq\bar{q}\bar{q}$)
    - multiquark baryons ($qqqq\bar{q}$)
      -> appear as baryon resonances
    - hybrid states ($q\bar{q}g$ or $qqqg$)
    - dibaryons ($qqqqqq$)
    - glueballs

→ no convincing evidence far for exotic states until 2003

Families of Baryons

- All baryons observed so far
  - classified as singlets, octets and decuplets of SU(3) flavor group
    -> constructed of 3 quarks only
  - have strangeness from S=-3 to S=0

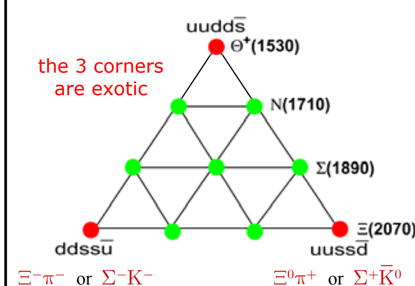


- Exotic Baryons with S=+1 cannot be formed of by 3 quarks only → belong to higher SU(3) multiplet

Anti-decuplet predicted in Chiral Soliton Model

D. Diakonov et al., Z. Phys. A 359, 305 (1997)

- all baryons are rotational excitations of a rigid object
  - Rotational excitations include: $8 \oplus 10 \oplus \overline{10} \oplus 27$
- reproduces mass splittings witin 1% of
  - baryon octet ($J^P=\frac{1}{2}^+$) and decuplet ($J^P=3/2^+$)
- only one free parameter



masses are counterintuitive
- $m(\Theta^+) < m(N)$ w/ nucleon q.n.

=> in naïve QPM:
expect strange baryons are heavier than non-strange in given multiplet
- $m(\Theta^+) = m(\Xi) - 540$ MeV
  Θ^+ has 4 light + 1 s quark
  Ξ^- has 3 light + 2 s quarks

=> in naïve QPM:
expect $\Delta m = 150$ MeV

First Experimental Evidence

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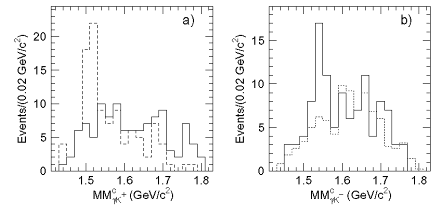
Experimental Evidence from Japan

T. Nakano et al., PRL 91, 012002-1 (2003)

- LEPS collaboration at Spring-8:
- exclusive $\gamma n\,(^{12}\mathrm{C}) \to K^+K^-n$ versus $\gamma p \to K^+K^-p$



a) solid histogram: spectrum of K^-n invariant mass (no reson. expected)
dashed histogram: spectrum of K^-p invariant mass ($\Lambda(1520)$ expected)

b) solid histogram: spectrum of K^+n invariant mass (Θ^+ expected?)
dashed histogram: spectrum of K^+p invariant mass (no reson. expected)

Conclusion by authors:
M = 1540 ±10 MeV, $\Gamma < 25$ MeV, $\sigma(= N_s/\sqrt{N_b})$ = 4.6±1

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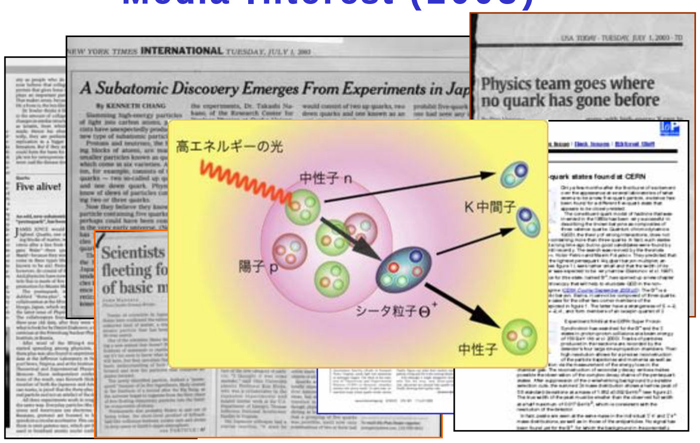
Media Interest (2003)



- The reason? In part, because the idea is simple to explain.

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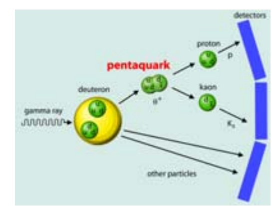
What is a Pentaquark

- Minimum quark content is 4 quarks and 1 antiquark
- "Exotic" pentaquarks are those where the antiquark has a different flavor than the other 4 quarks $(qqqq\bar{Q})$
- Quantum numbers cannot be defined by 3 quarks alone.



Example: $uuds\bar{s}$, non-exotic

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 - 1/3 = **1**

Strangeness = 0 + 0 + 0 − 1 + 1 = **0**

Example: $uudd\bar{s}$, exotic

Baryon number = 1/3 + 1/3 + 1/3 + 1/3 − 1/3 = **1**

Strangeness = 0 + 0 + 0 + 0 + 1 = **+1**

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Quarks are confined inside Colorless Hadrons

Mystery remains:
Of the many possibilities for combining quarks with color into colorless hadrons, only two configurations were found, until now…

Particle Data Group 1986 reviewing evidence for *exotic baryons states*

"…The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

PDG dropped the discussion on pentaquark searches after 1988

Why is it important to search for Pentaquarks?

- QCD does not prohibit $q^4\bar{q}$ states
  - The width is expected to be large due to "fall-apart":
    - $M(\Theta^+) - M(p + K_s) \approx 100$ MeV above threshold: expect $\Gamma > 175$ MeV unless suppressed by phase space, symmetry or special dynamics
  - Are pentaquarks too broad so be seen in experiments?
- **If it does exist** (with a narrow width) naïve quark models cannot explain it
  - Is the "fall-apart" model too simplisic?
- **If it does not exist** then do we understand why non-perturbative solutions of QCD do not allow it?
  - Can lattice calculations tell us why?
  - it should have far-reaching consequences for understanding the structure of matter

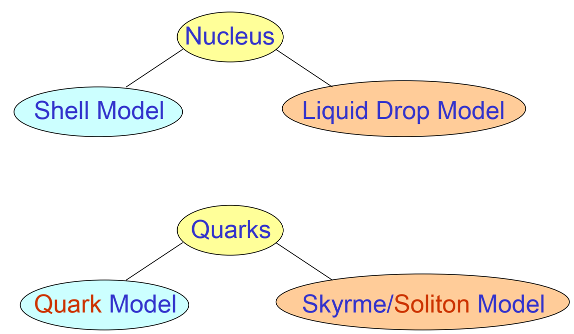
Pentaquark in naïve Quark Model

	u	d	s
Current mass	4 MeV	7 MeV	150 MeV
Constituent mass	350 MeV	350 MeV	470 MeV

The spontaneous breakdown of the chiral symmetry would produce nonzero constituent mass and the massless pseudoscaler Goldstone bosons

- Pentaquark mass = **4*350+470=1870** MeV
- In addition there is some penalty for p-wave (in case of positive parity)
- So the pentaquark mass must be about 2 GeV in any constituent quark model
- The predicted width is wide (>175 MeV) due to the allowed decay to the baryon and meson with mass well above the threshold
- The ground state has **negative** parity.

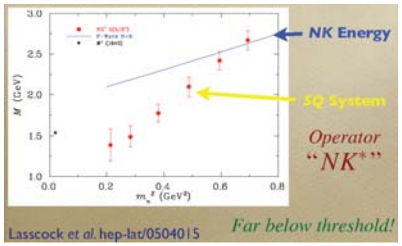
Models: An Analogy



Describe various, not mutually exclusive aspects of nucleus/quarks

Pentaquarks on the Lattice

- It is only known method to derive hadronic properties from first principles
- Several lattice studies performed to see if Θ^+ can be predicted from QCD
- Some studies did not find a pentaquark resonance, only scattering states of weakly-interacting kaons and nucleons → not mature yet (2 more years?)
- Main problem: disentangling KN scattering states from genuine resonances
- Very time consuming: V-dependence, light quarks, small lattice spacing …



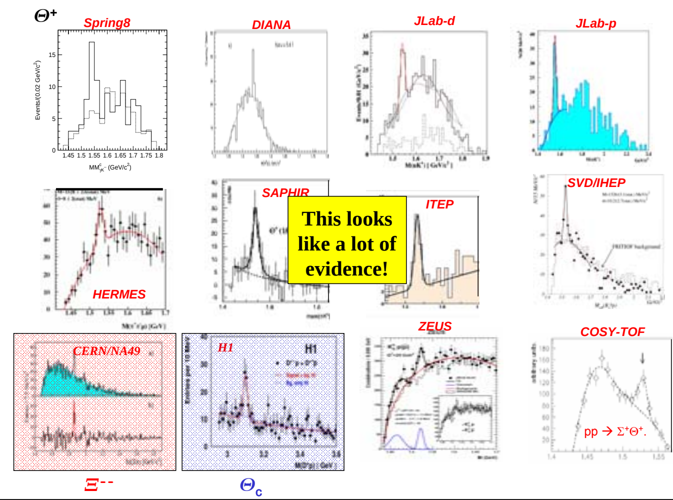
Possible signal for $J^P=3/2^+$?

(in χSM $J^P=½^+$)

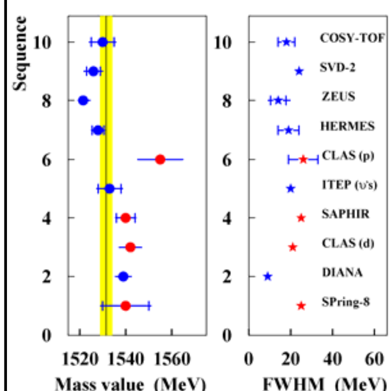
Binding Mechanism: ~500 MeV

Note: N. Ishii et al. get different results!?

The initial Evidence for Pentaquarks



The Θ^+ Mass



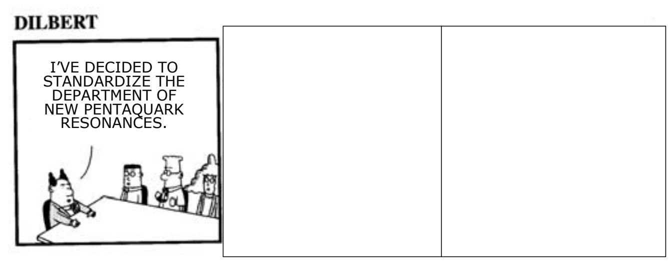
Decay channel:

nK^+ pK_s^0

World Average:
1532.5±2.4 MeV

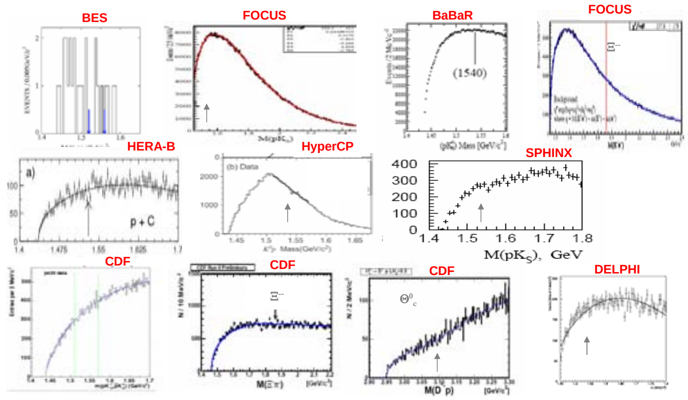
- $m(pK_s^0) < m(nK^+)$
- Could be due to different background shapes and interference effects
- Or it may indicate a serious concern about the existence of the Θ^+ baryon
- Observation of peak in two decay channels in same experiment → would be convincing!

OK, we've seen a Peak…



So how do we decide if it is a resonance?

Non-evidence for Pentaquarks



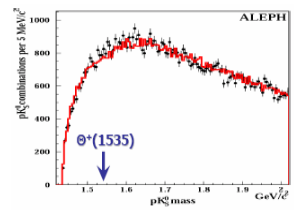
Null Results $\Theta^+(1540)$

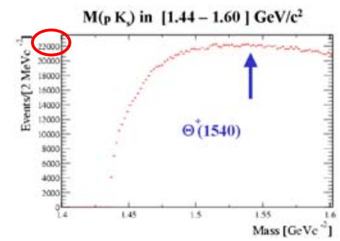
ALEPH:

- e^+/e^- collider (LEP 1)
- Pentaquark search in hadronic Z decays
- 3.5 million hadronic Z decays
- σ_{mass} < 5 MeV/c^2

BaBar:

- e^+/e^- collider at SLAC ($\sqrt{s}$ = 10.58 GeV)
- Pentaquark search at or just below Υ(4S)
- Integrated luminosity of 123 fb^{-1}
- σ_{mass} in the range of [2,8] MeV/c^2





Typical Criticism

- It is a kinematic reflection
- It is not statistically significant ("statistical fluctuations")
- It is due to "ghost tracks"
- It is fake in exclusive reactions
- In inclusive reactions it is not a Θ^+ but a Σ^{*+}
- It is not seen in high statistics experiments

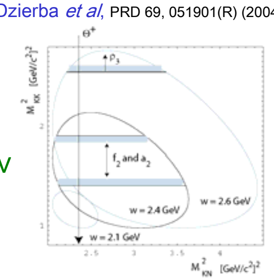
  ⟶ it must be wrong!

Kinematic Reflections

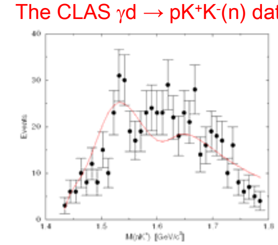
A. Dzierba *et al*, PRD 69, 051901(R) (2004).

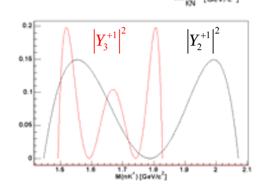
- Low energy experiments:
  - Produce a spin-2 or spin-3 resonance that decays into K^+K^-
  - Have non-uniform populations of |m|=0,1,2,…

Produces a broad enhancement near 1.5 GeV



The CLAS $\gamma d \rightarrow pK^+K^-(n)$ data

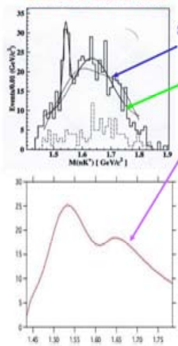




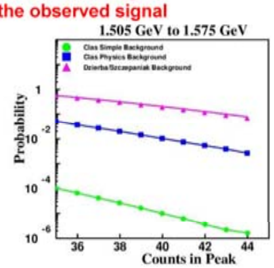
Statistical Fluctuations

You need to understand your background to claim a new discovery!

CLAS Published



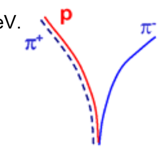
Chance of the Background Fluctuating into the observed signal

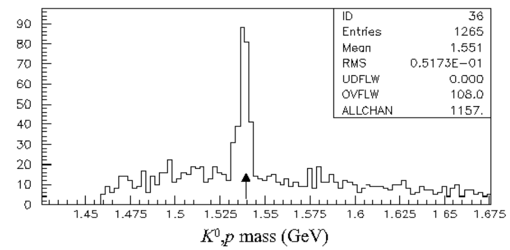


Ghost Tracks

M. Longo *et al*, PRD 69, 051901(R) (2004).

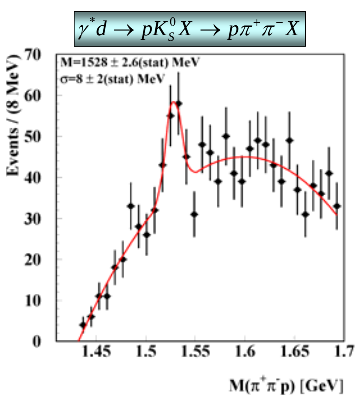
- Ghost tracks from a $\Lambda \rightarrow p\pi^-$ can produce a peak near 1.54 GeV. The positive track is used twice – as a p and a π^+
- misinterpret the p as a π^+
- assume that the $\pi^+\pi^-$ pair came from a K_s
- the resulting pK_s pair produces a narrow peak





What about HERMES?

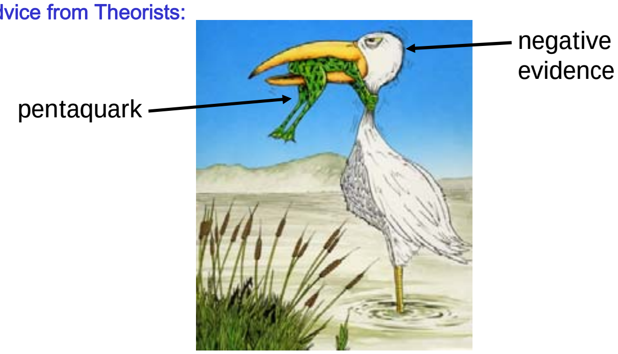
Inclusive quasi-real photo production with 27.6 GeV e+ on deuterium



- Excellent hadron identification RICH: **π:** 1-15 GeV **p:** 4–9 GeV
- Unbinned fit with 3rd order polynomial plus Gaussian
- Peak is observed at 1528 ± 2.6(*stat*) ± 2.1(*syst*) MeV in pK_S invariant mass distribution
- Width, $\sigma = 8$ MeV, is observably larger than experimental resolution
- Statistical significance is 3.7σ
- No known positively charged strange baryon in this mass region
- No strangeness tagging
- Three models of background were studied

Pentaquark Situation (April 2005)

- Dedicated, high-statistics experiments are key
- Advice from Theorists:

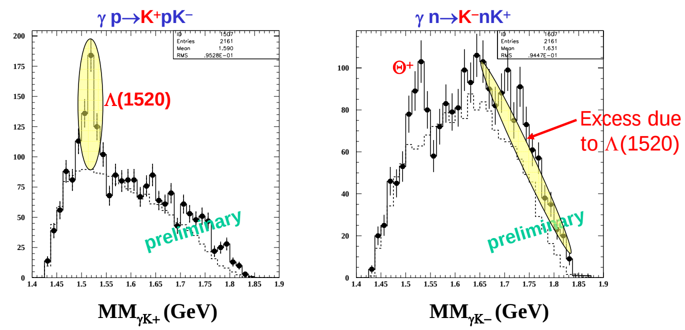


Don't give up too easily...

LEPS Search for Θ^+ in $\gamma d \to K^+K^-n(p)$

- The proton is a spectator (undetected)
- Fermi motion is corrected to get the missing mass spectra
- Background is estimated by mixed events

• Dedicated experiment
• Aimed at 4x stat. of 2003



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Conclusions of LEPS group

- LEPS high statistics experiment has reconfirmed the peak, very unlikely to be due to statistical fluctuations.
- The preliminary study shows no indication that the peak is generated by kinematical reflections, detector acceptance, Fermi-motion correction, nor cuts.
- "existence ranges from very likely to certain, but further confirmation is desirable" - "three-star" definition by PDG.

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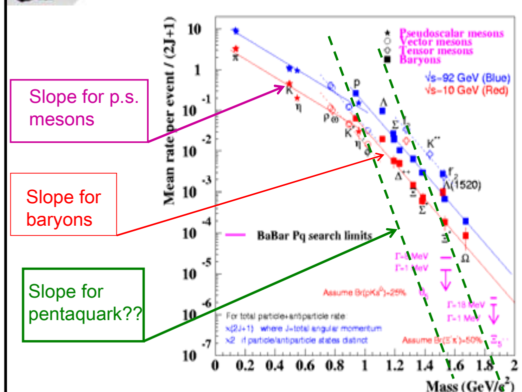
Hadron production in e^+e^-



Slope:

Pseudoscalar mesons: ~10^{-2}/GeV/c^2 (need to generate one $q\bar{q}$ pair)

Baryons: ~10^{-4} /GeV/c^2 (need to generate two pairs)

Pentaquarks: ~10^{-8}/GeV/c^2 (?) (need to generate 4 pairs)

→ Pentaquark production in direct e^+e^- collisions likely requires orders of magnitudes higher rates than available.

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Media Interest (2005)

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And More ….

➢ R.L. Jaffe (MIT) at DIS 05 Madison:

Life and Death among the Hadrons

"May it rest in peace"

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New CLAS Result

• Dedicated experiment
• Aimed at 10x stat. of 2003

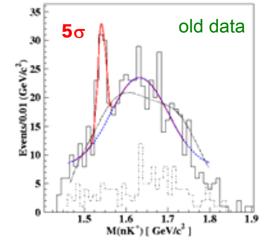
$\gamma d \to p K^- n K^+$

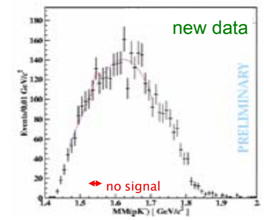
➢ The new high-statistics data show no signal
⇒ Set upper limit on cross section

$\gamma n \to K^- \Theta^+$

σ_{Θ^+} < 5 nb (95% CL)
model dependent

➢ In previous result the background is underestimated. New estimate of the original data gives a significance of ~3σ, possibly due to a fluctuation.





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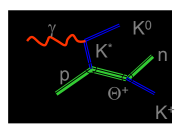
Impact on Θ⁺ production mechanism

➢ The CLAS result puts a very stringent limit on a possible production mechanism of the Θ⁺, e.g. it implies a very small coupling to K*.



➢ But: "Null-result from CLAS does not lead immediately to the absence of Θ⁺."

Nam, Hosaka and Kim, hep-ph/0505134

Lipkin and Karliner, hep-ph/0506084

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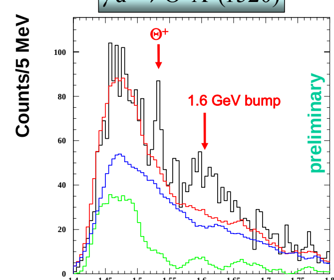
LEPS: pK⁻ missing mass spectrum

$\gamma d \to \Theta^+ \Lambda^*(1520)$



MMd(γ,pK⁻) GeV/c²

sidebands
Λ* from LH_2
sum

Excesses are seen at 1.53 GeV and at 1.6 GeV above the background level.

1.53-GeV peak: $\frac{S}{\sqrt{S+B}} \sim 5$?

mostly from p_{nK} ~ 0.42 GeV
outside CLAS acceptance …

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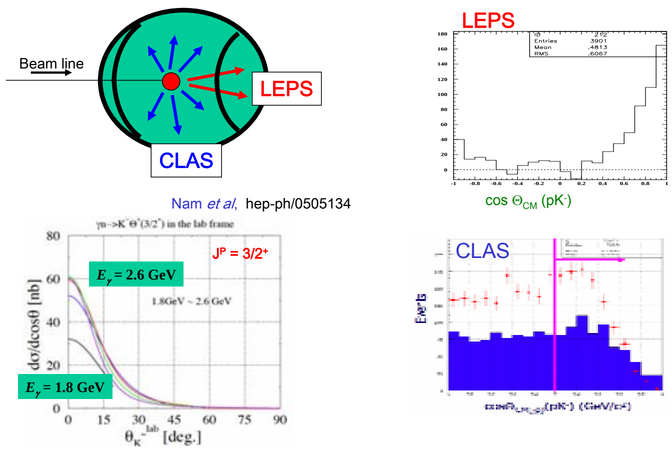
LEPS vs. CLAS



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Status: Pentaquark-2005 (Oct 20-22 JLab, VA)

	Group	Signal	Backgr.	Significance publ.	Significance $s/\sqrt{b+s}$	Comments
Θ^+	SPring8	19	17	4.6σ	3.2σ	
	SPring8	56	162	?	3.8σ	
	~~SAPHIR~~	~~55~~	~~56~~	~~4.8σ~~	~~5.2σ~~	New CLAS-p
	DIANA	29	44	4.4σ	3.4σ	
	~~CLAS(d)**~~	~~43~~	~~54~~	~~5.2σ~~	~~4.4σ~~	New CLAS-d
	CLAS(p)	41	35	7.8σ	4.7σ	
	ν	18	9	6.7σ	3.5σ	
	HERMES	51	150	3.4-4.3σ	3.6σ	
	COSY	57	95	4-6σ	4.7σ	
	ZEUS	230	1080	4.6σ	6.4σ	
	SVD	41	87	5.6σ	3.6σ	
Ξ^{--}	~~NA49~~	~~38~~	~~43~~	~~4.2σ~~	~~4.2σ~~	? HERA-B, CDF
Θ_c	~~H1~~	~~50.6~~	~~51.7~~	~~5-6σ~~	~~5.0σ~~	? ZEUS
	SPring8	200	285		5.0σ	$\Lambda^*(nK^+)$
	STAR	2,250	150,000		5.5σ	Θ^{++} candidate
	SVD-2	370	2000		7.5σ	Improved analysis

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Conclusions: Experiment (P. Stoler)

- The situation cannot be put into *any neat package.*
- New very high quality exclusive experiments from CLAS have repeated earlier experiments by SAPHIR and CLAS, and contradicted earlier positive observations.
- The new CLAS results do not exclude a state of <1 MeV width.
- There have been new positive reports from LEPS, SVD-2 and STAR.
- Beyond that there is a lot of overwhelming negative evidence which appear to push the observed pentaquark signals into narrower corners.

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Conclusions: Theory (M. Karliner)

- The pentaquark is not in good health, but it is still alive…
- Crucial open questions:
  - why do some experiments see it and other not
  - maybe does not exist (pessimistic view)
  - what is production mechanism (optimistic view)
  - if Θ^+ exists, why is it so narrow
  - why is cross section forward (LEPS, ZEUS)
  - is there an energy & Q^2 dependence
- Gold plated experiment: K^+ on nucleus at low momentum
- Ball is in experimental court!

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Prognosis

- Analysis is continuing at Spring8, JLab, COSY, HERMES, H1, ZEUS, SVD-2, STAR, PHENIX
- New measurements planned at SPring8 (March 2006), JLab 2006)
- H1, ZEUS, HERMES high luminosity run until July 2007
- Higher statistics data from STAR, PHENIX
- Limited additional statistics from B-factories, Fermilab and CERN
- Focus moved from bump hunting to more quantitative estimations of cross sections or upper limits

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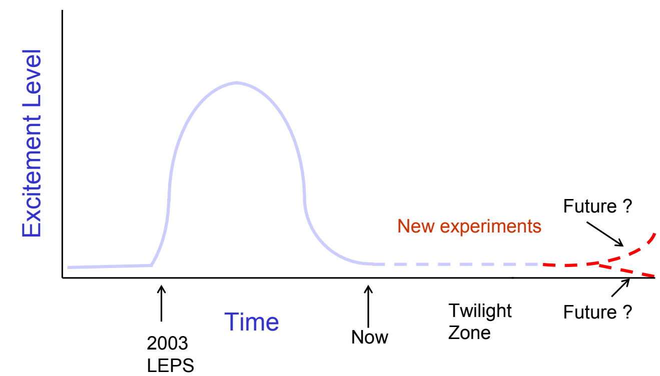
Pentaquark Vital Signs



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Quote about Pentaquarks by a distinguished American

"…the reports of my death are exaggerated."

…Mark Twain

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What will happen to this entry in PDG?

Citation: S. Eidelman *et al.* (Particle Data Group), Phys. Lett. B 592, 1 (2004) (URL: http://pdg.lbl.gov)

EXOTIC BARYONS

Minimum quark content: $\Theta^+ = uudd\bar{s}$, $\Phi^{--} = ssdd\bar{u}$, $\Phi^+ = ssuu\bar{d}$.

$\Theta(1540)^+$ $I(J^P) = 0(?^?)$

It is difficult to deny a place in the Summary Tables for a state that six experiments claim to have seen. Nevertheless, we believe it reasonable to have some reservations about the existence of this state on the basis of the present evidence.

Mass $m = 1539.2 \pm 1.6$ MeV
Full width $\Gamma = 0.90 \pm 0.30$ MeV

NK is the only strong decay mode allowed for a strangeness $S=+1$ resonance of this mass.

$\Theta(1540)^+$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
KN	100%	270

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