Review of Experimental Aspects of Pentaquark Physics

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Based on work in collaboration with
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Outline

- Prehistory of exotics
- What we know about Θ^+
- Θ^+ - (non)observation
- Is N* = N(1710) ?
- How to search for alternatives ? Modified PWA
- Theoretical expectation
- Experimental evidences for N*
- Summary

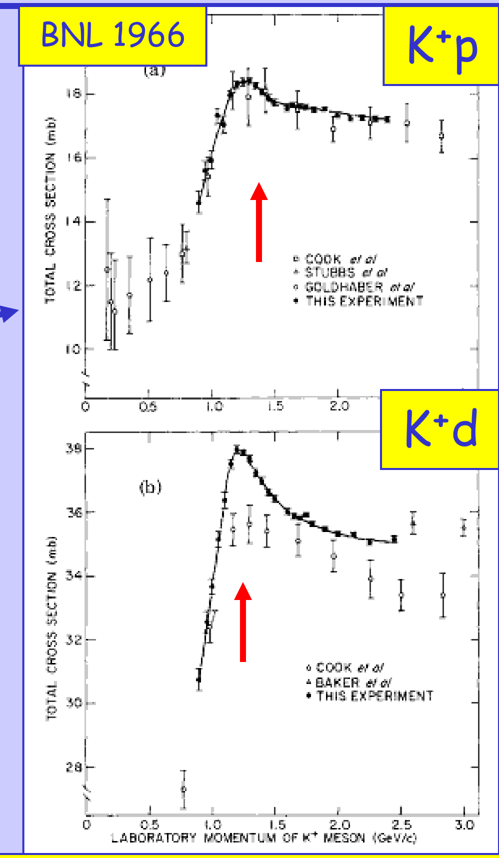
Prehistory of Exotics

- The problem of observing multiquark (exotic and/or `cryptoexotic') states is as old as quark themselves
- The first experimental results on search for baryon exotics in KN system

  [R. Cool *et al*, Phys Rev Lett **17**, 102 (1966)
  R. Abrams *et al*, Phys Rev Lett **19**, 259 (1967)
  J. Tyson *et al*, Phys Rev Lett **19**, 255 (1967)]

- were published soon after the invention of quarks

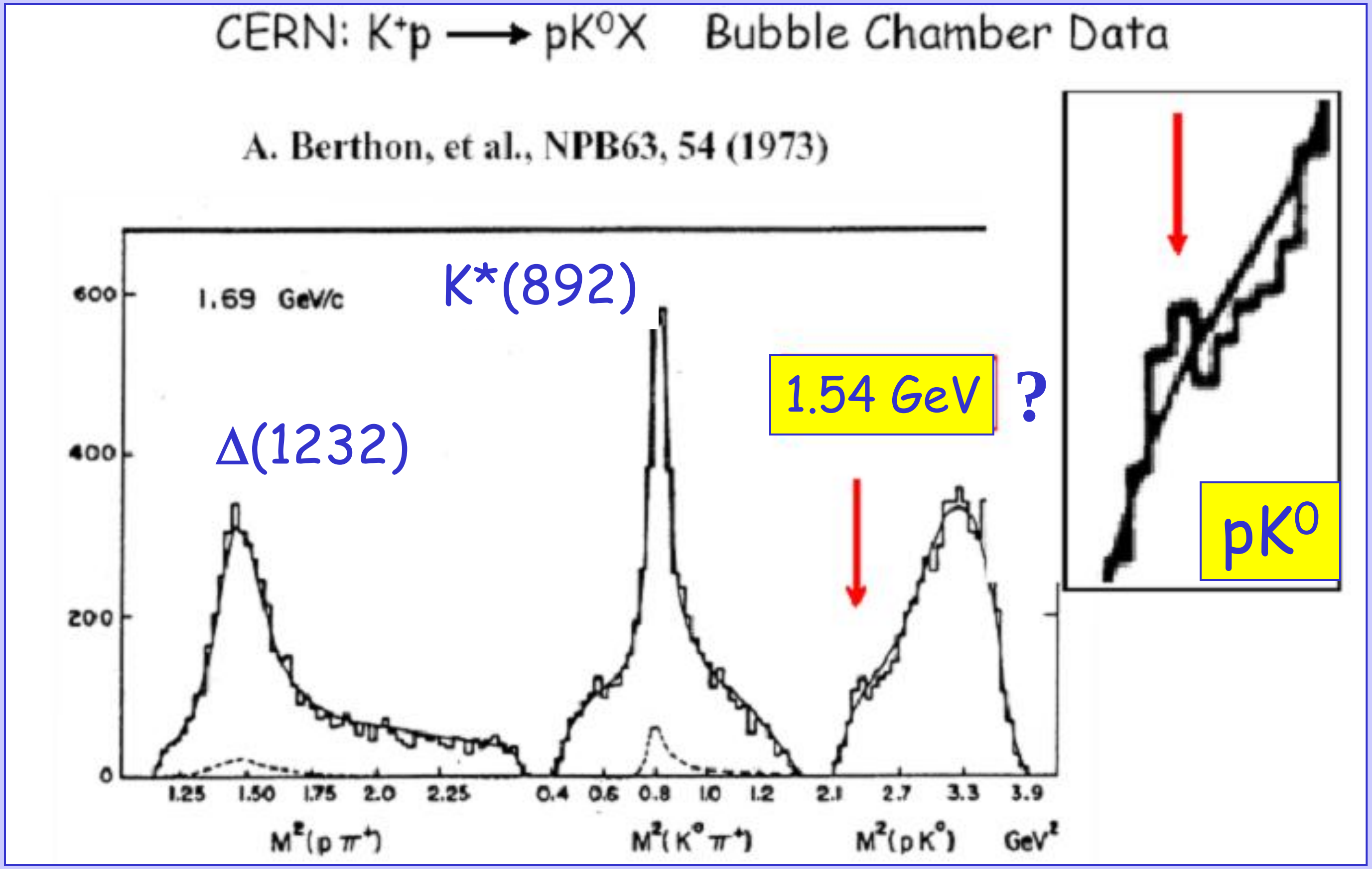
  [M. Gell-Mann, Phys Lett **8**, 214 (1964)
  G. Zweig, CERN preprints TH-401, TH-412, 1964



- Resonance peak found in K^+N at $M = 1910$ MeV, $\Gamma = 180$ MeV

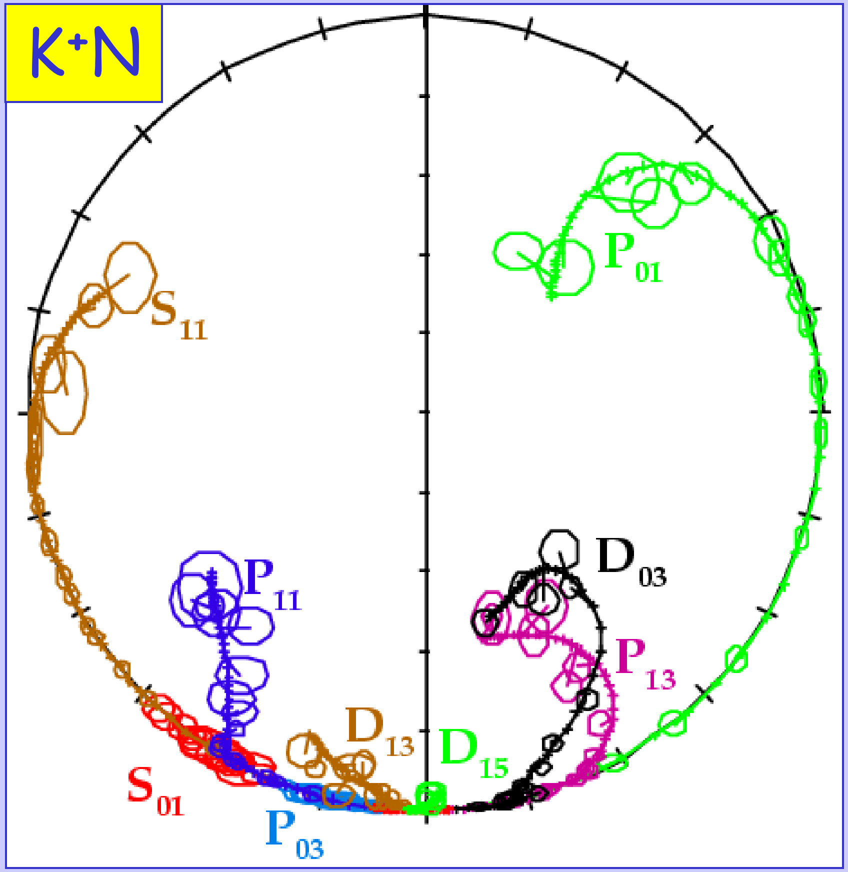
Unclaimed Θ^+ ?

[found by V. Burkert, Pentaquark 2003, Nov 2003]



Standard PWA for K^+N

[J. Hyslop, R. Arndt, D. Roper, R. Workman, Phys Rev D **46**, 961 (1992)]



T_{lab} = 0 [20] 1100 MeV

- Pole Positions:

I	Ampl	ReW (MeV)	-ImW (MeV)
0	P_{01}	1831	95
	D_{03}	1788	170
1	P_{13}	1811	118
	D_{15}	2074	253

- *All suggested resonances are too heavier than known Θ^+ to be its isospin partners*

Was Progress delayed by Prejudice ?

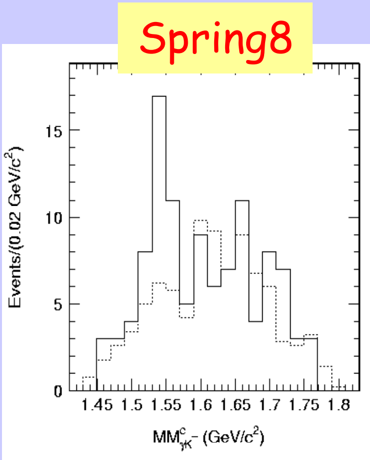
[PDG (M. Aguilar-Benitez *et al*) Phys Lett B **170**, 289 (1986)]

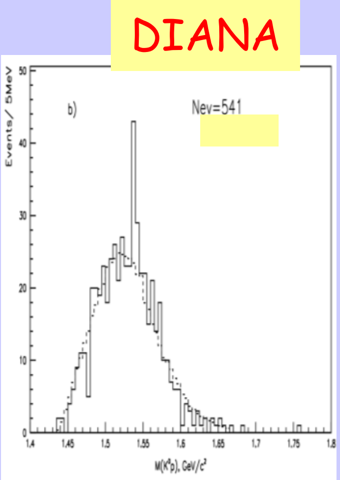
- "The evidence for strangeness +1 baryon resonances was reviewed in our 1976 edition [1], and more recently by Kelly [2] and by Oades [3]. Two new partial-wave analyses [4] have appeared since our 1984 edition. Both claim that the P_{13} and perhaps other waves resonate.
- However, the results permit no definite conclusion - the same story heard for 15 years. The standards of proof must simply be much more severe here than in a channel in which many resonances are already known to exist. 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."
- References:

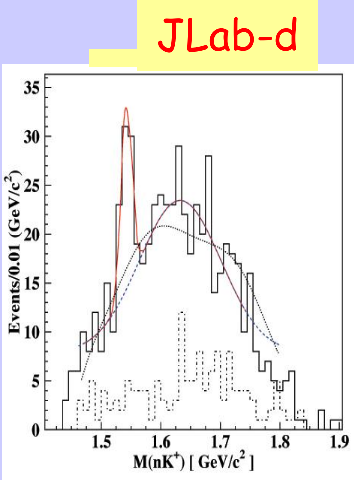
[1] Particle Data Group (T.G. Trippe *et al*.) Rev Mod Phys **48**, No 2, Part II (1976)
[2] R.L. Kelly, in *Proceedings of the Meeting on Exotic Resonances* (Hiroshima, 1978) edited by I. Endo *et al*.
[3] G.C. Oades, in *Low and Intermediate Energy Kaon-Nucleon Physics* (1981) edited by E. Ferrari and G. Violini
[4] K. Hashimoto, Phys Rev C **29**, 1377 (1984); **R.A. Arndt and L.D. Roper, Phys Rev D 31, 2230 (1985)**

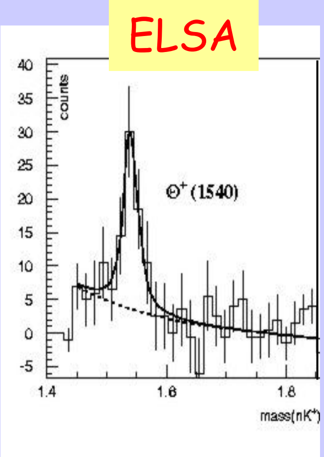
Was PDG right: 1986 + 15 = 2001±2 ?

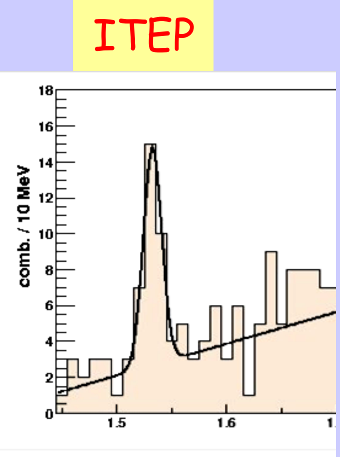
- There are over a dozen published evidences
- However…

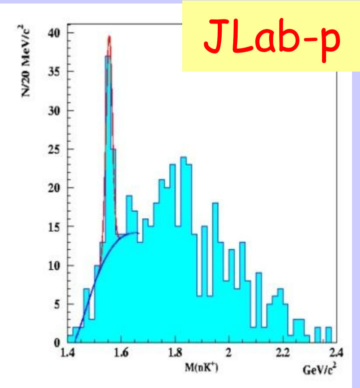








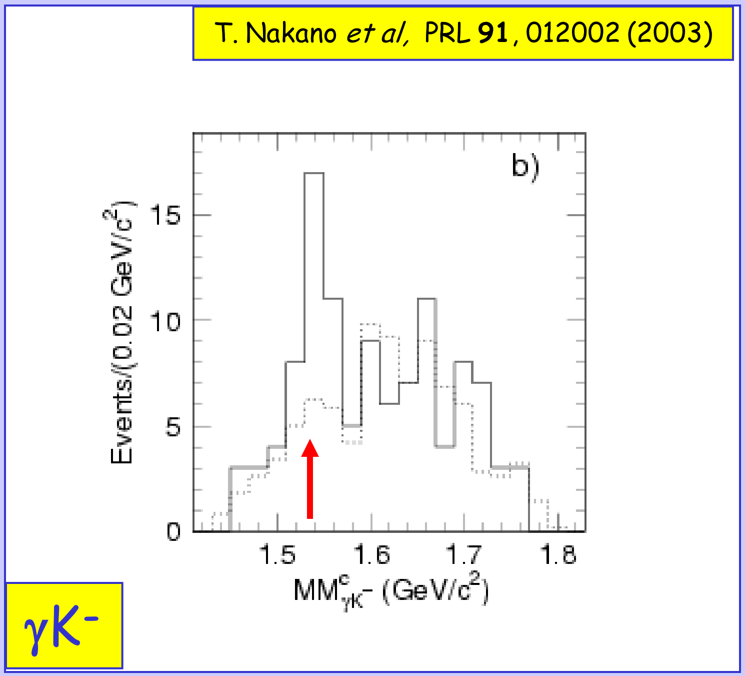




Θ^+ Evidences with EM Probe

- LEPS at Spring-8:

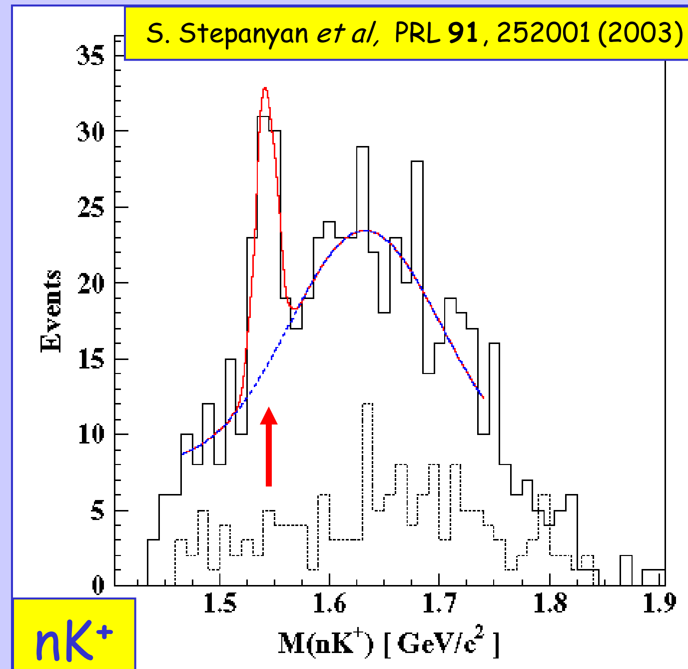
  $\gamma n(^{12}C) \rightarrow K^+K^-(n)$



- Strangeness = +1
- Significance ($N_s/\sqrt{N_b}$) = 4.6±1 σ

- CLAS at JLab:

  $\gamma d \rightarrow K^- p K^+(n)$

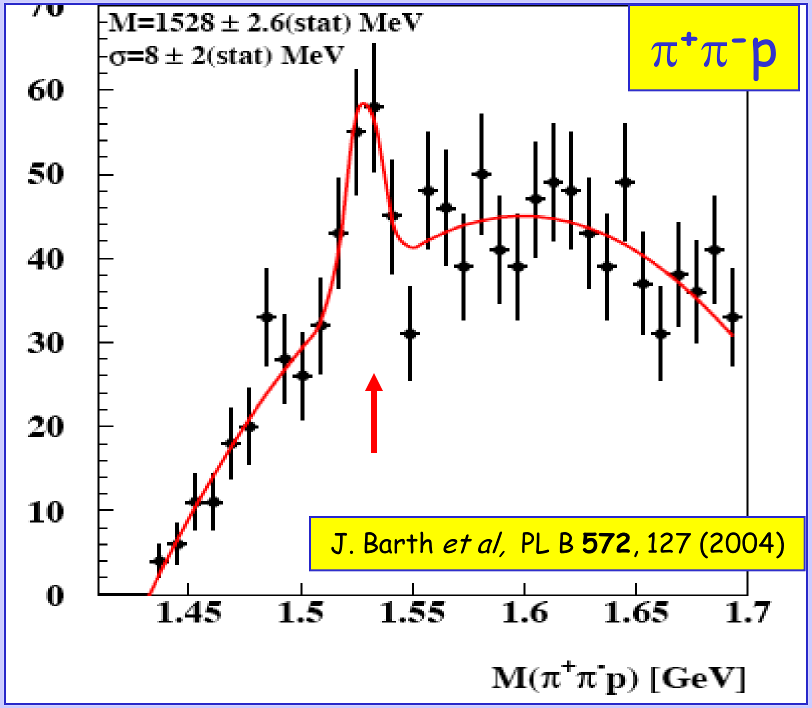


- Strangeness = +1
- Significance = 5.3±0.5 σ

Θ^+ Evidences with EM Probe

- SAPHIR at ELSA:

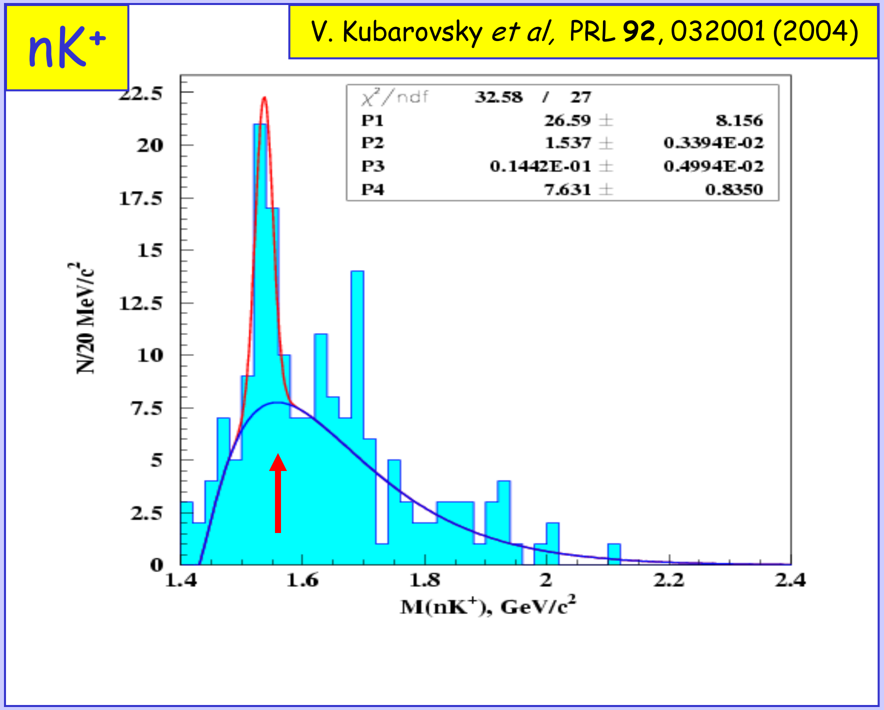
  $\gamma p \to K_s K^+ n$



  - Isospin = 0
  - Significance = 4.8 σ

- CLAS at JLab:

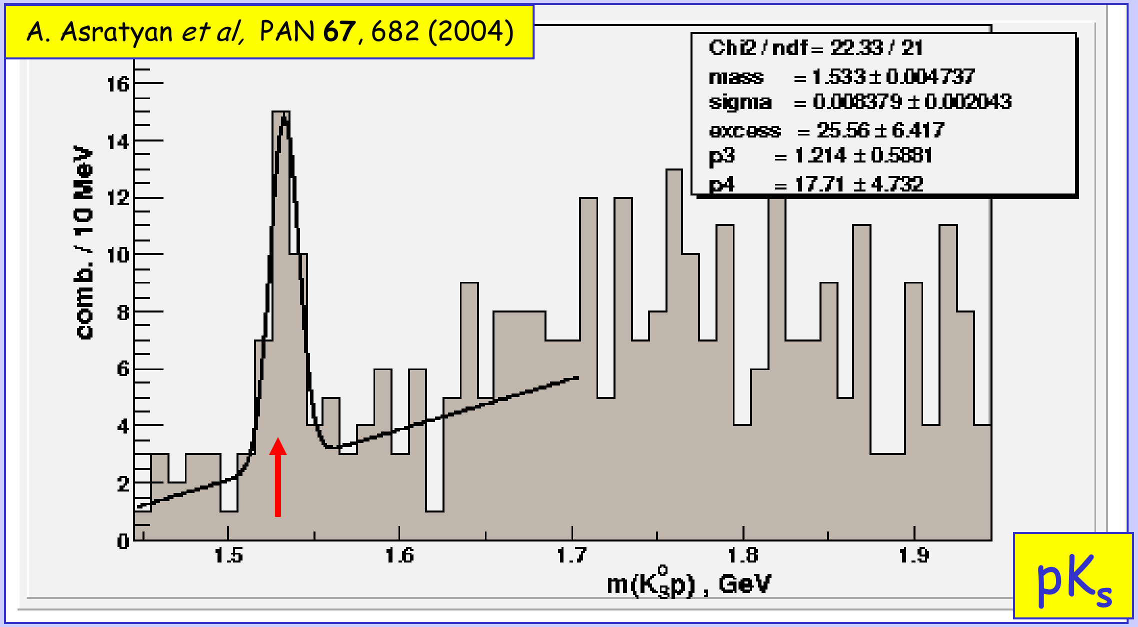
  $\gamma p \to K^- \pi^+ K^+ (n)$



  - Strangeness = +1
  - Significance = 7.8±1 σ

Θ^+ Evidences with Lepton Probe

- Reanalysis of Bubble Chamber Data from CERN and FNAL via ITEP: $\nu_\mu(\bar{\nu}_\mu)A \rightarrow pK_sX$

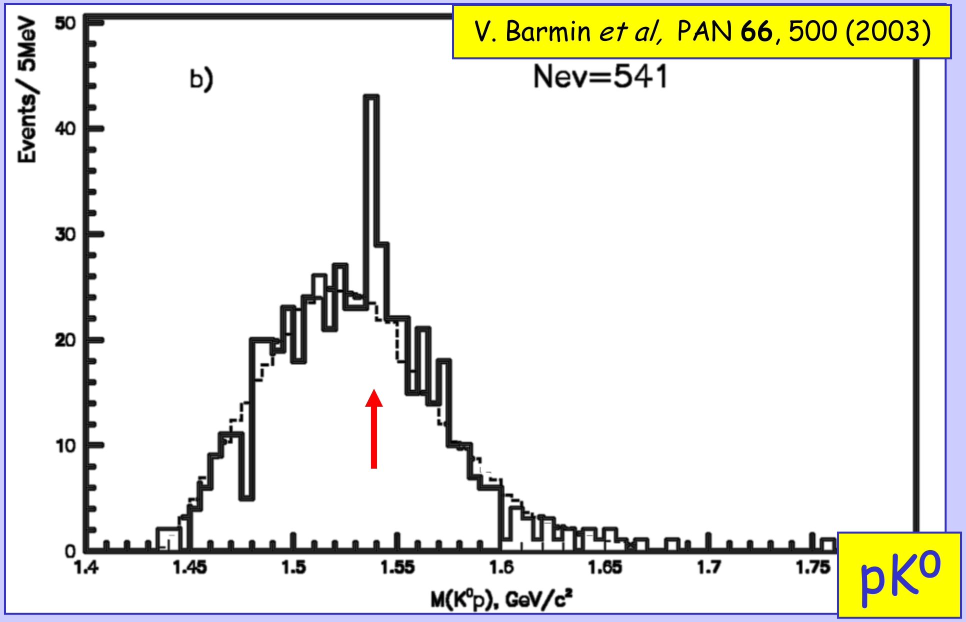


- Significance = 6.7 σ

Θ⁺ and Φ Evidences with Hadron Probes

- DIANA at ITEP:

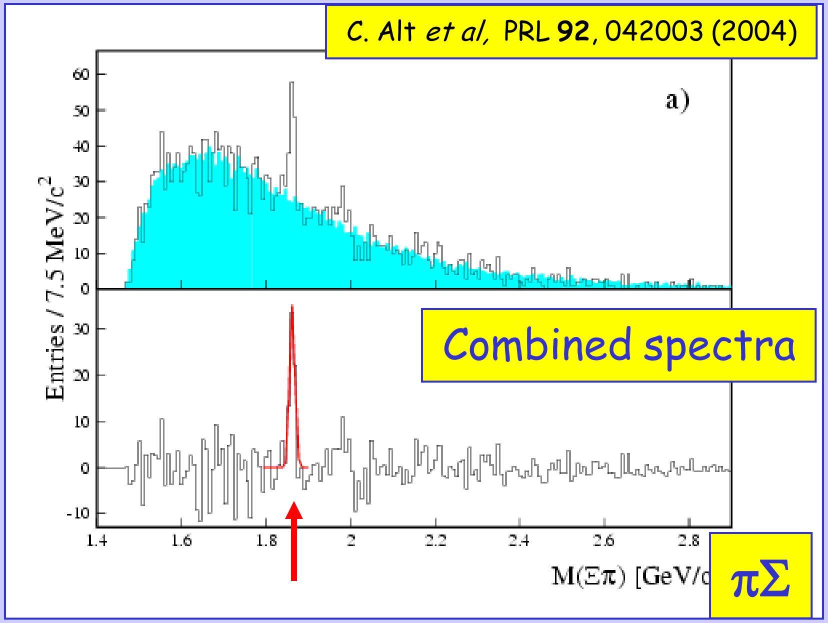
$K^+n(Xe) \to K_s p(X)$



- Γ< 9 MeV
- Significance = 4.4 σ

- NA49 at CERN:

$pp \to \Xi^-\pi^- + \Xi^-\pi^+ (X)$



- Significance = 4σ

Θ^+ and Φ - What is known

[PDG (S. Eidelman *et al*) Phys Lett B **592**, 1 (2004)]

	Experiment	Mass (MeV)	Width (MeV)
$\Theta(1540)^+$	LEPS	1540 ± 10	<25
	DIANA	1539 ± 2	< 9
	CLAS (d)	1542 ± 5	<21
	SAPHIR	$1540 \pm 4 \pm 2$	<25
	ITEP (ν)	1533 ± 5	<20
	CLAS (p)	1555 ± 10	<26
	PDG average	1539.2 ± 1.6	-
	GWU	1545	≤ 1
	LBNL	1540	0.9 ± 0.3
$\Phi(1860)$	NA49	1862 ± 2	<18

Only one pw P_{01} admits the effect near 1545 MeV and Γ < 1 – 2 MeV [R. Arndt, IS, R. Workman, Phys Rev C **68**, 042201 (2003)]

With additional assumption and unknown systematics [R. Cahn and G. Trilling, PRD **69**, 011501 (2004)]

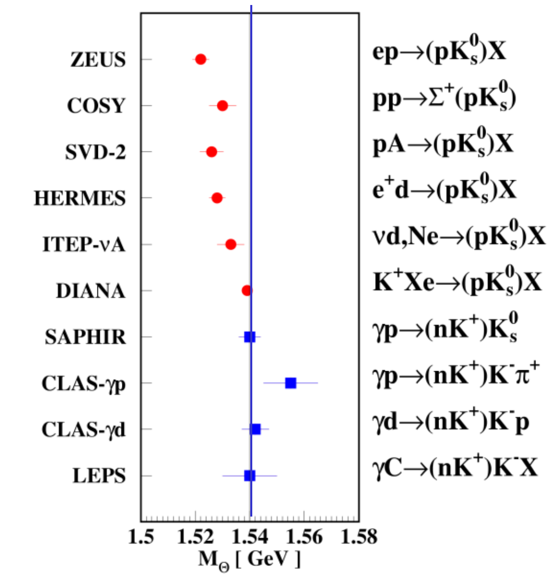
- The measured mass looks similar to expectation of the ChSA [D. Diakonov, V. Petrov, M. Polyakov, Z Phys A **359**, 305 (1997)]

Summary on Exotic Baryon Observation

- The measured mass looks similar to expectation of the ChSA
- The measured width is only upper limit
- Highest Significance (CLAS) = 7.8 σ
- Spin and Parity are not measured yet
- Production mechanisms are unknown
- Xsections are uncertain
- NA49 results yet to be confirmed
- Search for the other flavor partners is underway

- CLAS fans, please be patient, g10 and g11 data are coming soon

V. Kubarovsky *et al*, **hep-ex/0409025**



(Non)observation of Θ^+ (?)

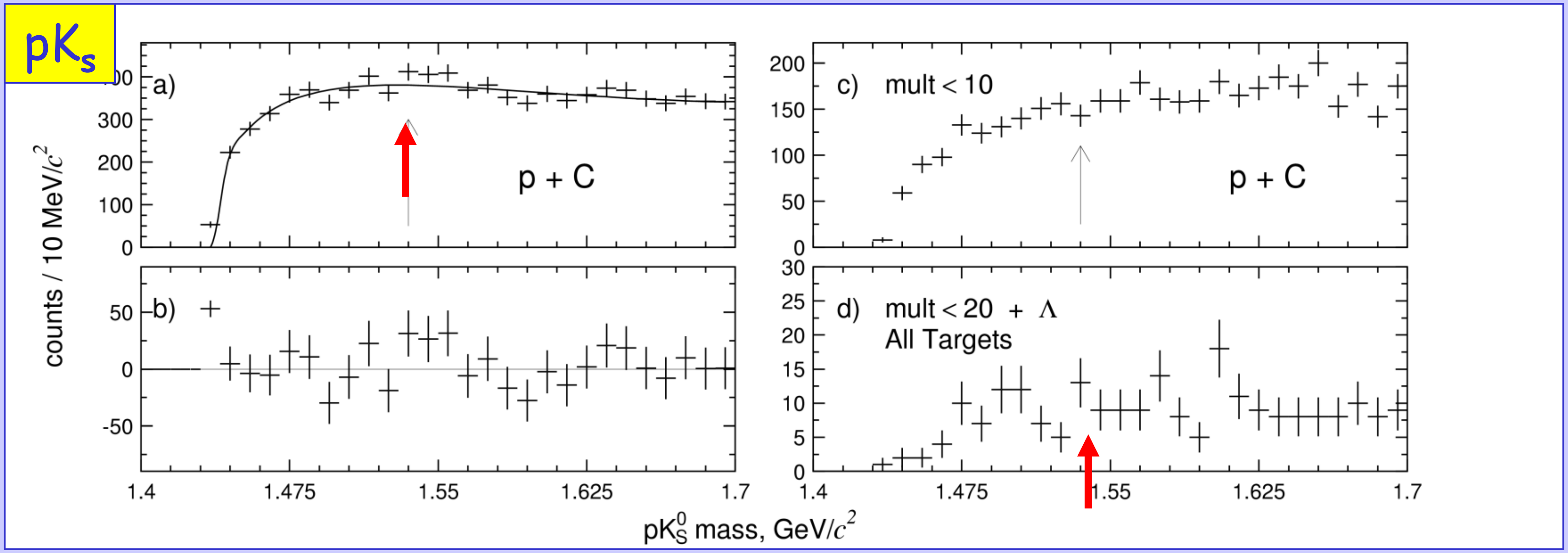
- What we can learn from published High Energy (non)observations of Θ^+ ?

- HERA-B in pA at $\sqrt{s}$ = 41.6 GeV
- PHENIX in dA at $\sqrt{s}$ = 200 GeV
- BES in e^+e^- at J/ψ and $\psi(2S)$
- BaBar in e^+e^-

- SPHINX in pC at 70 GeV
- HERMES in e^+d at 27.5 GeV

- **HERA-B** [K. Knoepfle *et al*, J Phys G **30**, S1363 (2004)]

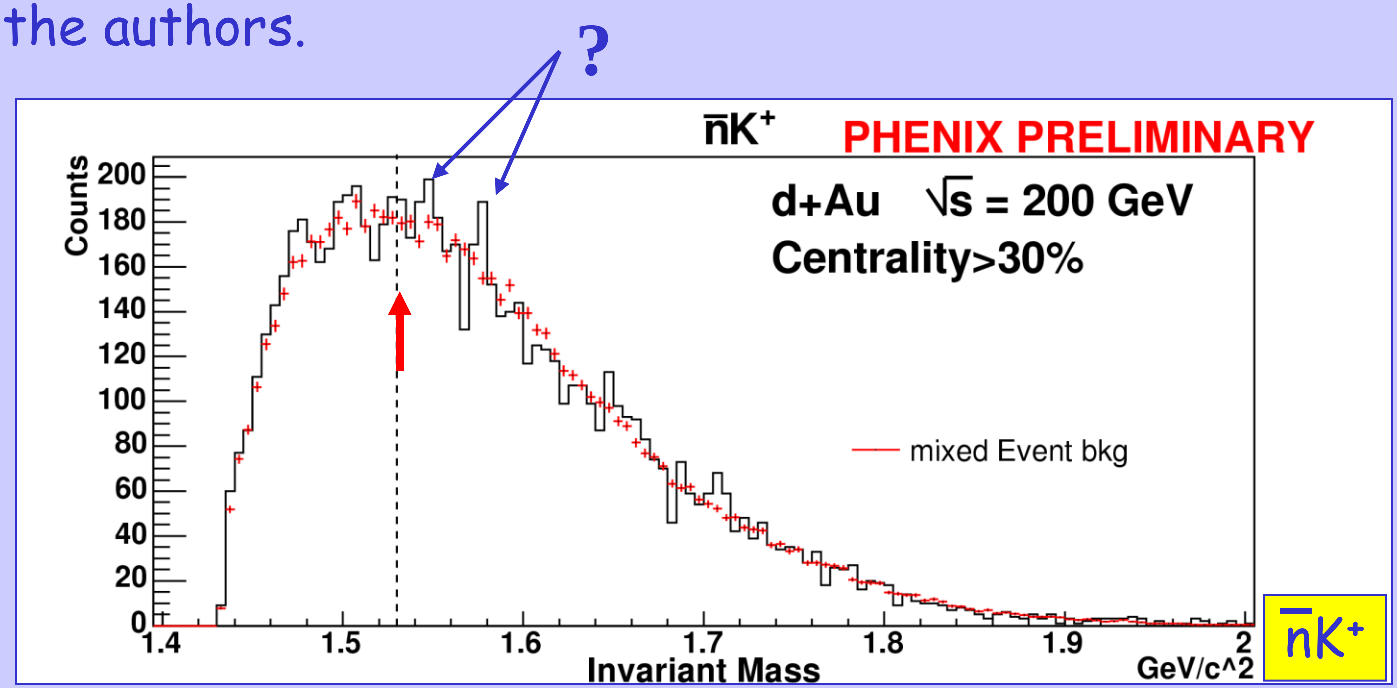
- Some features of data suggest a small Θ^+ signal with very large background. Special selection(s) may be needed



- Still hint at a possibility to extract a Θ^+

- **PHENIX** [C. Pinkenburg *et al*, J Phys G **30**, S1201 (2004)]

- The Quark Matter 2004 talk with `clear $\bar{\Theta}^-$ signal' transformed into the Proceedings text with `no signal' after a `small correction'. The situation is not clear even to the authors.



- Best illustration of the present uncertain status

- **BES** [J. Bai *et al,* Phys Rev D **70**, 012004 (2004)]

Analysis [Ya. Azimov, IS, Phys Rev C **70**, 035210 (2004)]

- Data need some (rather soft) dynamical suppression, say 1/5 in the probability
- Meanwhile, because of necessity to produce directly two more $q\bar{q}$ pairs (in exotic decays as compared with decays to canonical baryon-antibaryon pairs), some dynamical suppression should naturally arise.

  One or two order suppression might be quite natural

- Thus, the recent result of BES is only a starting point for investigating exotics in e^+e^--annihilation

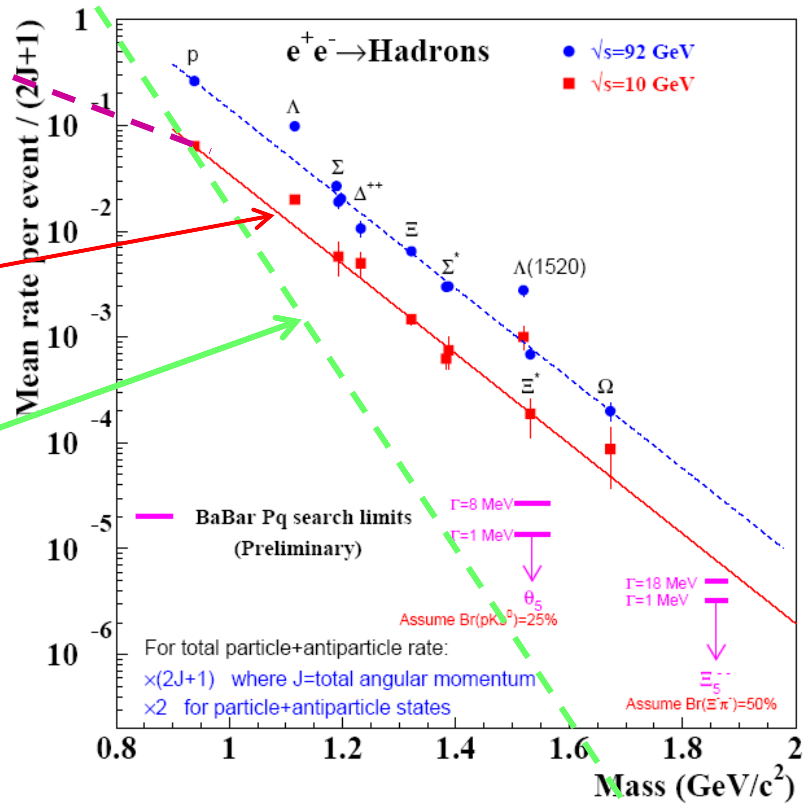
Hadron Production in e^+e^-

Analysis: V. Burkert, MENU 2004

Slope for p.s. mesons

Slope for baryons

Slope for Pentaquark??



Slope:

Pseudoscalar mesons:
~10^{-2}/GeV/c^2 (need to generate one qq 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.

Summary on Θ^+ (non)observation

- Different initial particles
- Different energies
- Different production mechanisms
- How to separate ?

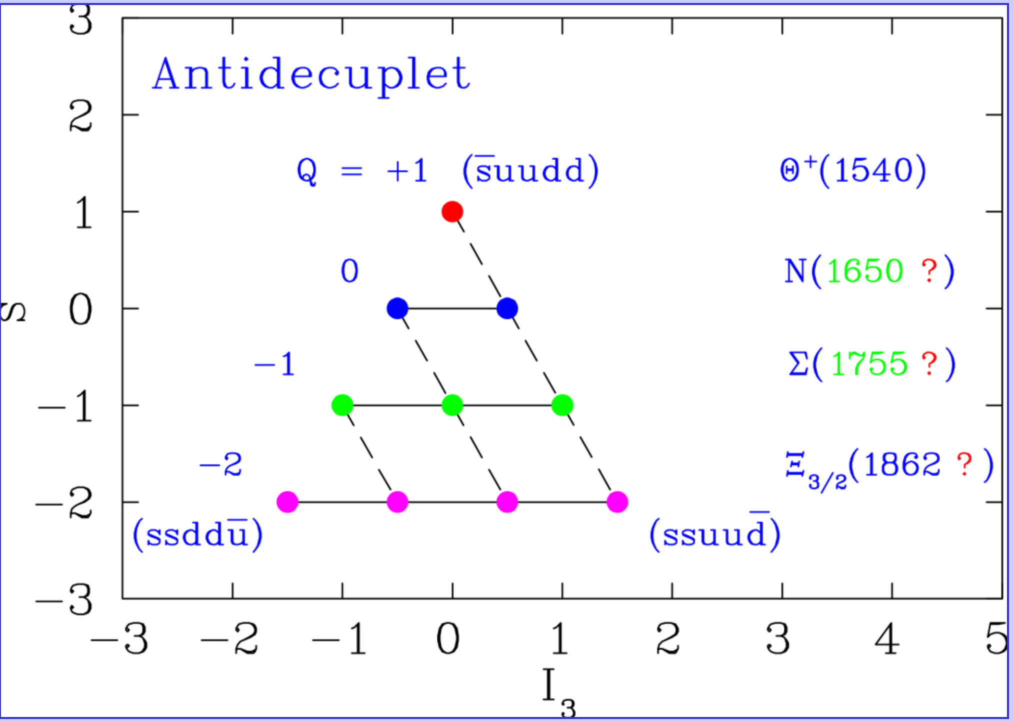
- Published `Null' Experiments do not really contradict the existence of pentaquarks; need to (im)prove their sensitivity

- If Θ^+ does not survive, `damned' questions revive:

- `Why are there no strongly bound exotic states…, like those of two quarks and two antiquarks or four quarks and one antiquark ?'
  [H. Lipkin, Phys Lett **45B**, 267 (1973)]

- `…either these states will be found by experimentalists or our confined, quark-gluon theory of hadrons is as yet lacking in some fundamental, dynamical ingredient which will forbid the existence of these states or elevate them to much higher masses.'
  [R. Jaffe and K. Johnson, Phys Lett **60B**, 201 (1976)]

Tentative unitary Antidecuplet with Θ



- GMO: $\delta m(\sigma) = (M_{\Xi} - M_{\Theta})/3 =$ 107 MeV at $\sigma = 67$ MeV [SAID] 180 MeV at $\sigma = 45$ MeV [Karlsruhe]
- Current δm corresponds to the GW SAID σ-term
- Mixing is able to shift GMO masses for N* and Σ*

SAID: [M. Pavan *et al,* hep-ph/0111066]
Karlsruhe: [G. Hoehler, Springer, 1983]

N(1710) – What was known

[PDG (S. Eidelman *et al*) Phys Lett B **592**, 1 (2004)]

	Ref	Mass (MeV)	Width (MeV)
ChSA	DPP	1710 (input)	~40
PWA	KH	1723± 9	120± 15
	CMU	1700±50	90± 30
	KSU	1717±28	480±230
	GW	no state !	

- It would be more natural for the same unitary multiplet (with Θ^+ and N*) to have comparable widths

Narrow Resonances in PWA

[R. Arndt, Ya. Azimov, M. Polyakov, IS, R. Workman, Phys Rev C **69**, 035208(2004)]

- Standard PWA reveals only wide resonances
- PWA (by construction) tends to miss resonances with $\Gamma < 30$ MeV
- We assume the existence of a Res and refit over the whole database
- Insertion of narrow resonances in PWA for

  elastic case: $e^{2i\delta} \Rightarrow e^{2i\delta_R} e^{2i\delta_B}$

  $e^{2i\delta_R} = (M_R - W + i\,\Gamma_R/2)/(M_R - W - i\,\Gamma_R/2)$

  inelastic case: $\eta\, e^{2i\delta} \Rightarrow \langle a|S|a\rangle = r_a\, A(W)\, e^{2i\delta_R} + (1 - r_a)\, B(W)$

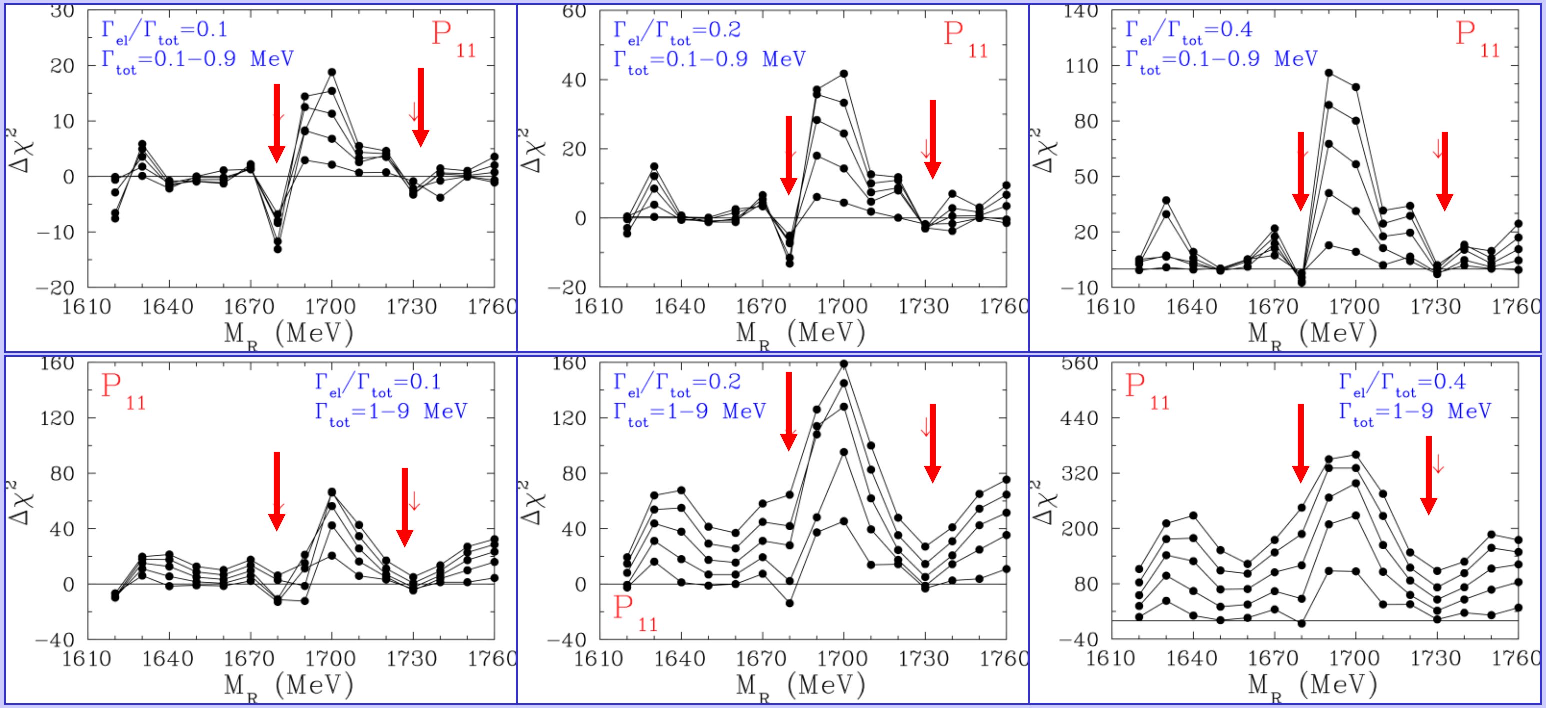
  $r_a = BR(R \rightarrow a)$ $\quad |A(M_R)| = 1$ $\quad \Sigma r_a = 1$

  $\eta \leq 1 \Rightarrow r_a\, |A(W)| + (1 - r_a)\, |B(W)| \leq 1$

- How does this insertion changes χ^2 ?
  (Will it decrease ?)

Modified πN PWA

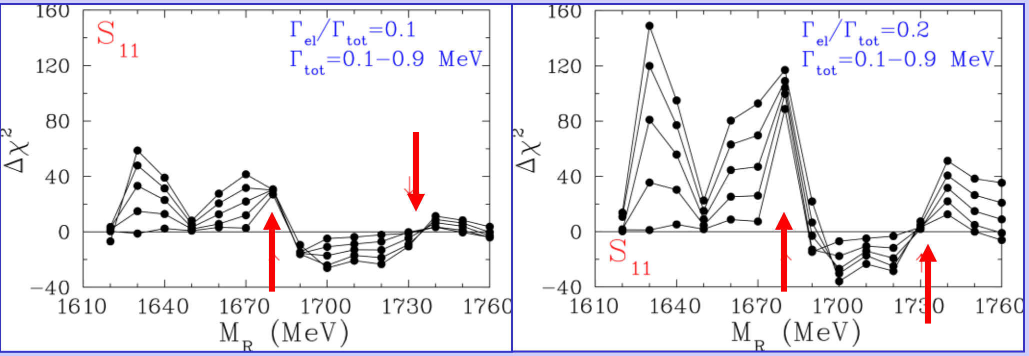
- $\Delta\chi^2$ due to insertion of a resonance into P_{11} ($J^P = 1/2^+$)



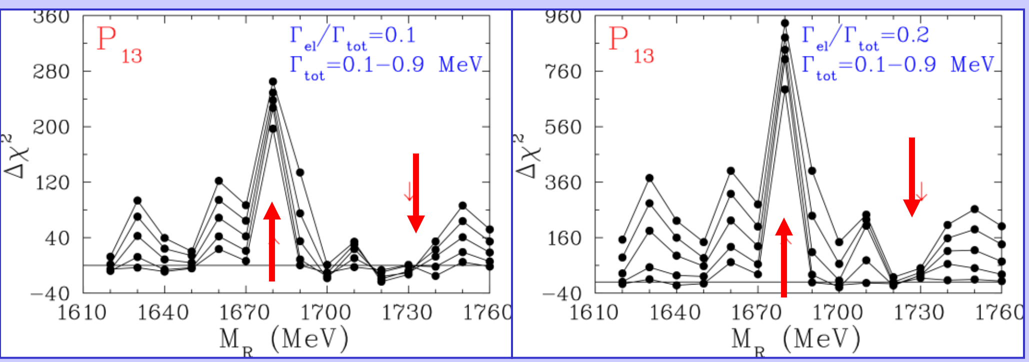
- At $|M_R - W| \gg \Gamma_R$, Res contributes ~ $\Gamma_{el}/(M_R - W)$
- Two candidates: M_R = 1680 MeV 1730 MeV

Γ_{el} < 0.5 MeV < 0.3 MeV

Check other Partial Waves



- $\Delta\chi^2$ due to insertion of a Res into S_{11} ($J^P = 1/2^-$)



- $\Delta\chi^2$ due to insertion of a Res into P_{13} ($J^P = 3/2^+$)

Conclusion from Modified πN PWA

- 1680 MeV – only one partial wave (P_{11}) reveals the effect: support to the resonance, $\Gamma_{\pi N} < 0.5$ MeV

- 1730 MeV – P_{11} may also reveal a resonance with $\Gamma_{\pi N} < 0.3$ MeV but differently: resonance is still possible, if accompanied by different corrections

- Other partial waves, P_{13} and S_{11} (less probable), could show effect, if accompanied by different corrections

For example, thresholds: Nω(1720), Nρ(1710) ?, KΣ(1685)

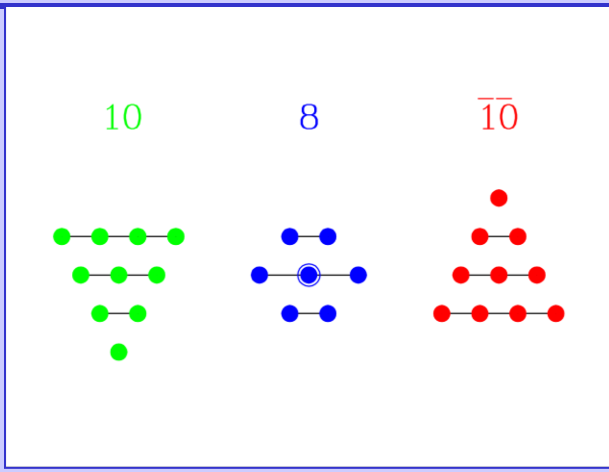
Theoretical Analysis

- Theoretical analysis is rather uncertain but nevertheless may be used for orientation
- Structure of hadron mixing due to violation of $SU(3)_F$
  - $10 \leftrightarrow 8$ for Σ, Ξ (no partners for Λ, N, Δ)
  - $\overline{10} \leftrightarrow 8$ for Σ, N (no partners for Λ, Θ, Ξ)
  - $\overline{10} \leftrightarrow 10$ for Σ (no partners for Δ, N, Θ, Ξ)

    Only higher orders in octet violation
  - Mixing shifts GMO masses of Θ partners

    may essentially influence decay widths
  - What are mixing with higher multiplets, such as 27 and/or 35?

Mixing



- Mixing is possible only for states with the same strangeness and isospin
- Mixing acts differently for different members of the $\overline{10}$

- $\Theta \to KN$ no mixing in the init state, $\overline{10}$-8 mixing is efficient in the fin state
- $N^* \to \pi\Delta$ no mixing in the fin state, $\overline{10}$-8 mixing is possible in the init state
- Mixing does not shift masses of Θ and $\Xi_{3/2}$,
  is able to shift GMO masses for

N^*: 1650 MeV → 1650-1690 MeV
Σ^*: 1755 MeV → 1760-1810 MeV

[D. Diakonov, V. Petrov, Phys Rev D **69**, 094011 (2004)]

Θ^+ Flavor Partner, $N^*(J^P = \frac{1}{2}^+)$

- If $\Gamma_\Theta \leq 1$ MeV, then expected structure for decays of the Θ-partner N^* looks as follows:

  - $\Gamma(N^* \to \pi\Delta)$ ~ 6 MeV [forbidden for $\overline{10}$, open due to $\overline{10}$-8 mixing]
  - $\Gamma(N^* \to \eta N)$ ~ 0.5 – 2 MeV
  - $\Gamma(N^* \to K\Lambda)$ ~ 0.5 – 1.5 MeV
  - $\Gamma(N^* \to \pi N)$ ~ 0.3 - 0.5 MeV [non-trivial cancellation due to mixing is required]
  - $\Gamma(N^* \to \pi\pi N)$ [out of $\pi\Delta$] ?
  - $\Gamma(N^* \to K\Sigma)$ is small ?

  - $\Gamma(N^* \to \text{all})$ ~ 10 MeV [$\Gamma_{\pi N}/\Gamma_{tot} \leq 10$ %]

    Ratio of modes πN and ηN is sensitive to the mixing

Σ^* (again, recall $\Gamma_\Theta \leq 1$ MeV)

- The most uncertain member of the $\overline{10}$, for both mass and width

- Most decay modes may be essentially influenced by mixing in either initial and/or final states

- Estimates of partial widths are not very reliable, but at the level of `handwaving'

  $\Gamma(\Sigma^* \rightarrow all) \leq 30$ MeV

$\Xi_{3/2}$ (again, recall $\Gamma_\Theta \leq 1$ MeV)

- Kinematically possible decays:
  $\Xi_{3/2} \to \pi\Xi(1530)$ forbidden by $SU(3)_F$
  ($\overline{10} \to 8+10$) could be allowed by (small !)
  mixing 10-8 for $\Xi(1530)$,
  and/or mixing of $\Xi_{3/2}$ with 27, 35, …
  $\Gamma(\Xi_{3/2} \to \pi\Xi)$ practically independent of mixing
  $\Gamma(\Xi_{3/2} \to K\Sigma)$ essentially depends on the final state mixing

- Estimates give general bound
  $\Gamma(\Xi_{3/2} \to \text{all}) \leq 5$ MeV

- Both Γ_{tot} and ratio of modes $\pi\Xi$ and $K\bar{\Sigma}$
  are highly sensitive to the mixing

Experimental Evidences for N*

- GRAAL in $\gamma n \to \eta n$, $K^0\Lambda$, and $K^+\Sigma^-$
- STAR in $AuAu \to \Lambda K_s$
- COSY-TOF in $pp \to \Lambda K^+ p$
- JLab Hall A in $H(e,e'\pi^+)X^0$

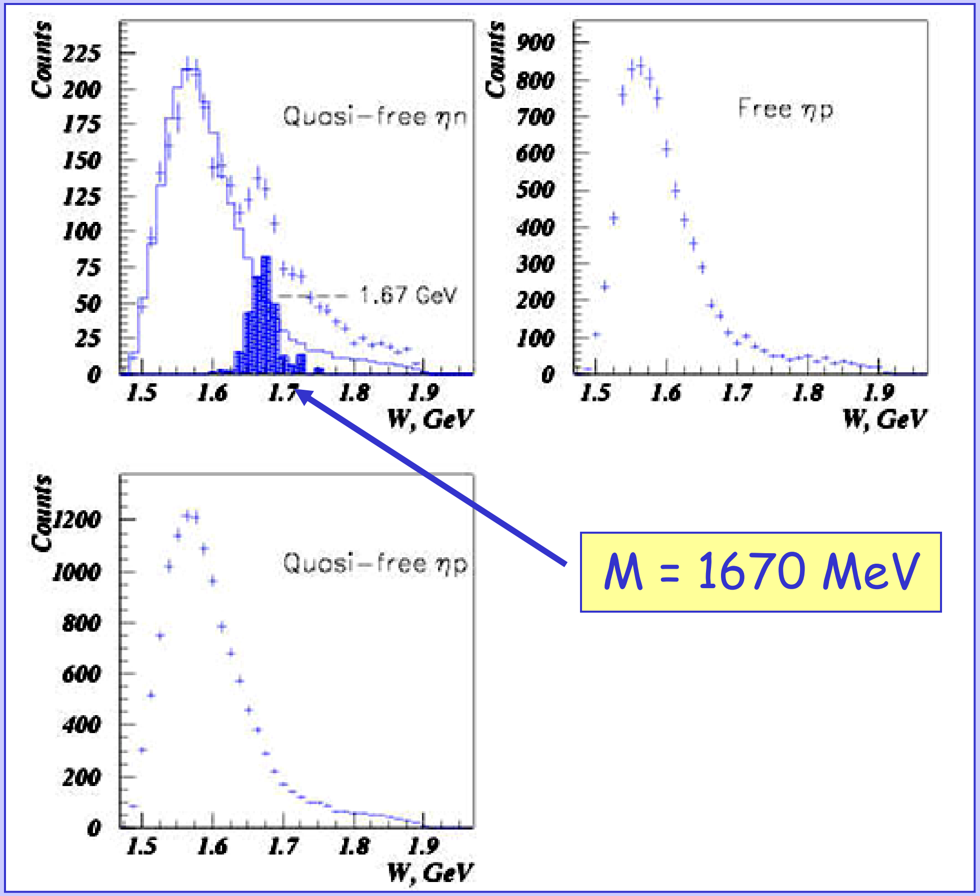
GRAAL [V. Kuznetsov, hep-ex/0409032, NSTAR 2004, March 2004]

γn→ηn

Quasi-free ηn

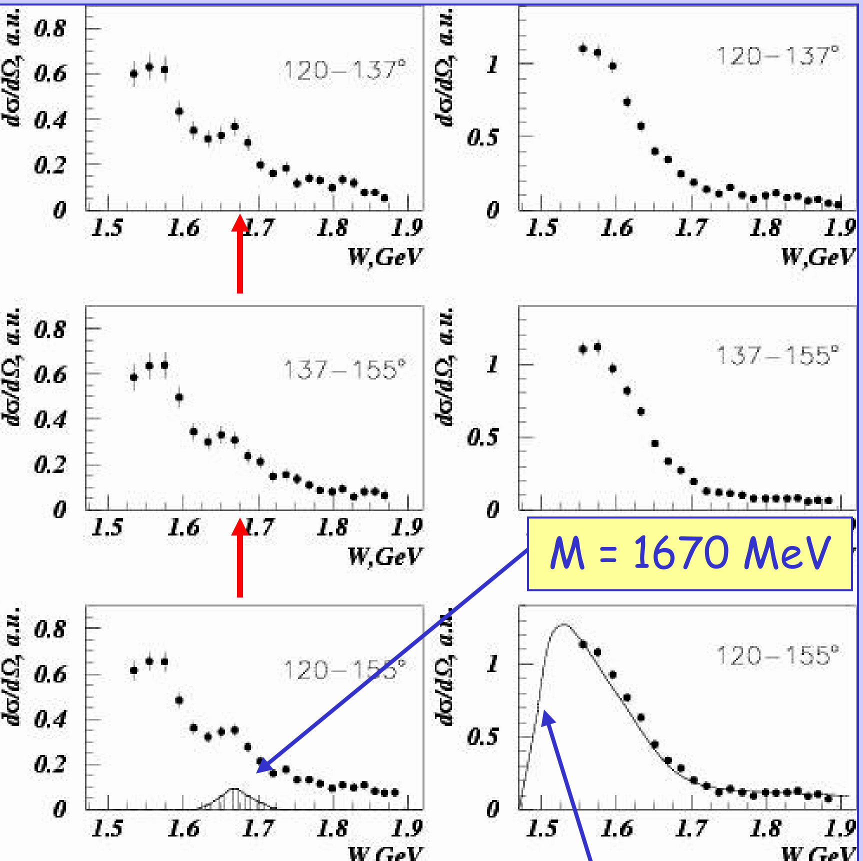
Free ηp

Quasi-free ηp

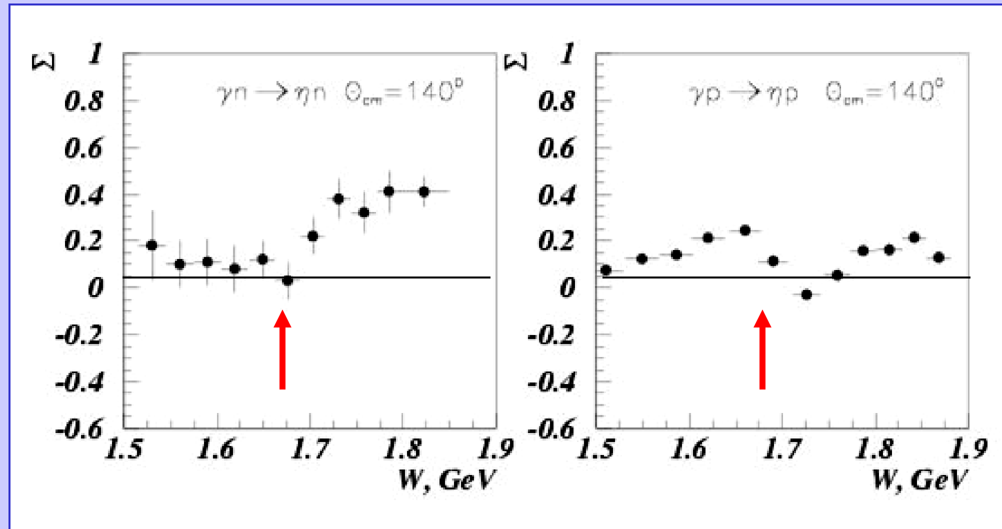


dσ/dΩ and Σ for γn→ηn vs γp→ηp

γn→ηn γp→ηp



$\vec{\gamma}$n→ηn $\vec{\gamma}$p→ηp



M = 1670 MeV

θ = 140°

GW SAID PWA

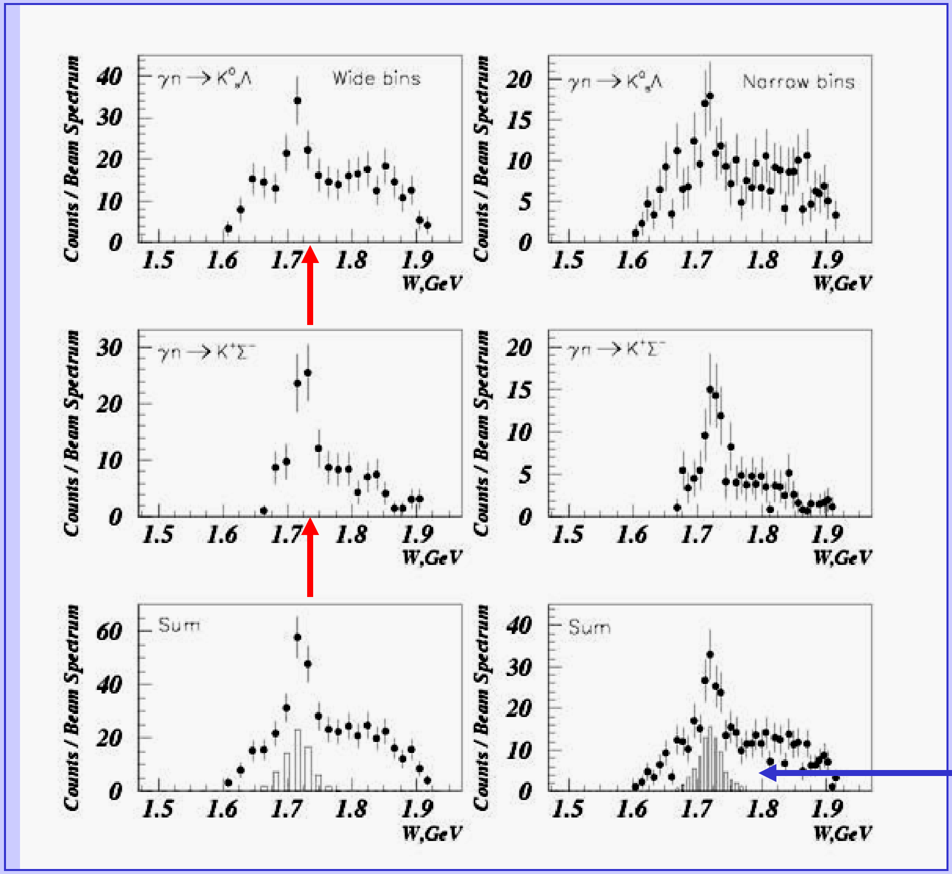
GRAAL [V. Kuznetsov, Trento 2004, Feb 2004]

Very preliminary: $\gamma n \to K^0\Lambda$, $K^+\Sigma^-$

$\gamma n \to K^0\Lambda$

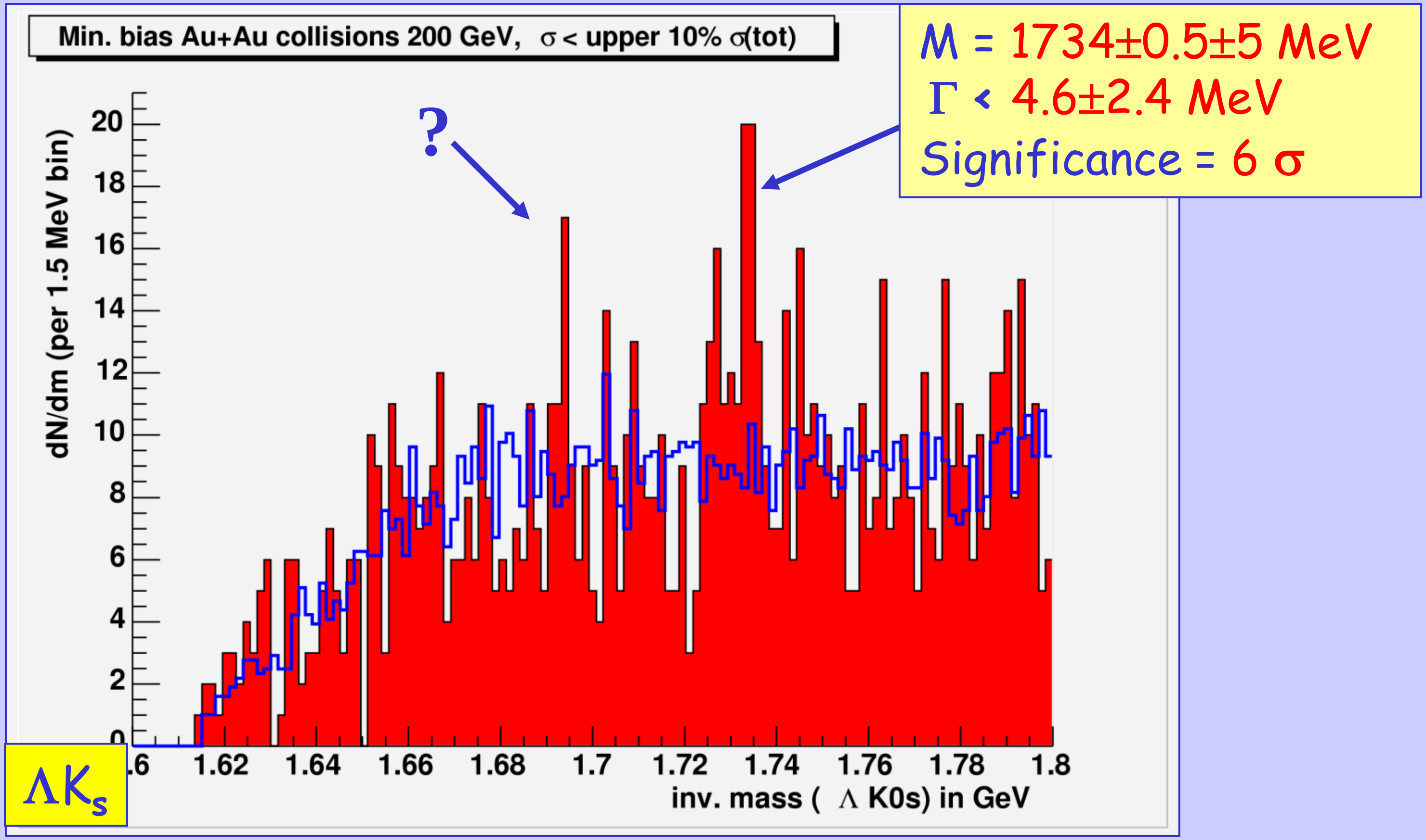
$\gamma n \to K^+\Sigma^-$

Sum

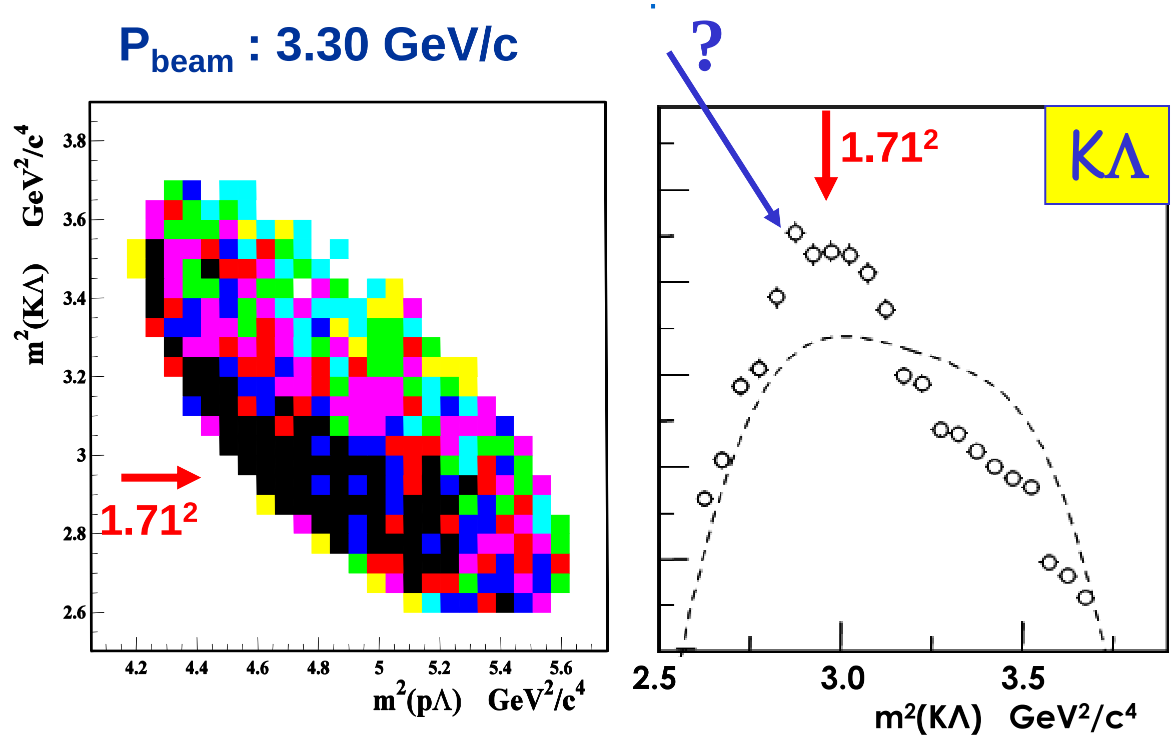


M = 1720 MeV

STAR [S. Kabana, hep-ex/0406032, Jamaica 2004]
AuAu→ΛK_s



COSY-TOF [W. Eyrich, Pentaquark 2004, July 2004]
Very preliminary: pp→ΛK⁺p

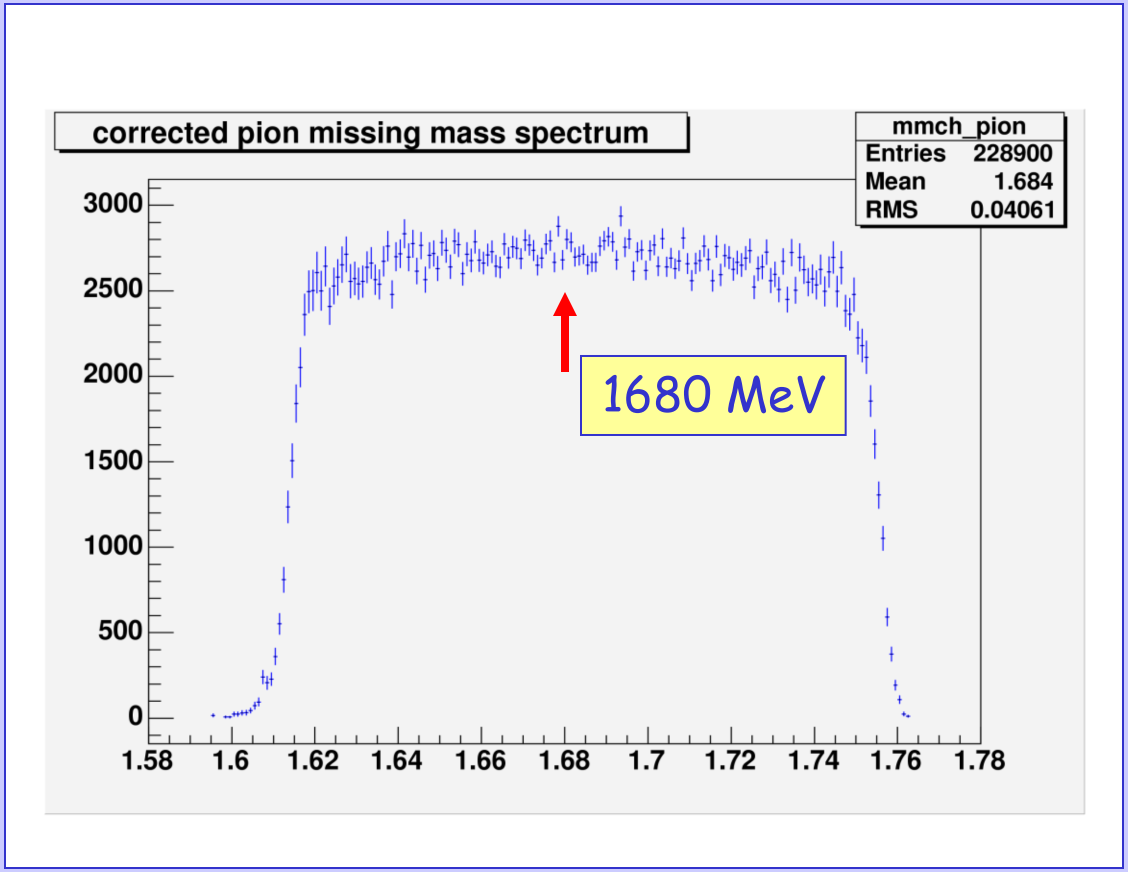


N*(1710) contributes strongly

Influence of pΛ-FSI

In progress: Investigation of Dalitz plots → **width**

JLab Hall A [B. Wojtsekhowski, E-04-012]
Very preliminary: $H(e,e'\pi^+)X^0$



- E_0 = 5 GeV
  $\theta_{e'}$ = 6^0
  θ_π = 0^0 $\Delta\Theta = \pm 2^0$
  σ_{MM} = 1.3 MeV

- Signal 1680 MeV (if any) is small (agrees with expectation)

Summary

- Narrowness of Θ^+ required reanalysis of all its flavor partners. We did it for `N(1710)' using modified πN PWA
- If Θ^+ is indeed a narrow state with $\Gamma_\Theta \leq 1$ MeV, then other members of the flavor $\overline{10}$ are, most probably, narrow as well

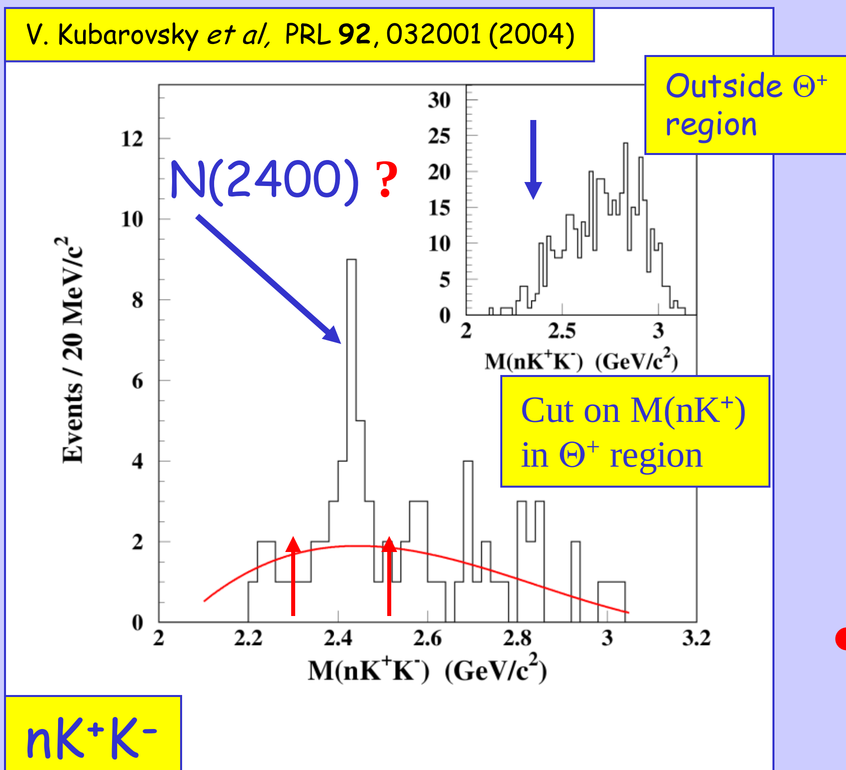
  Their properties are sensitive to the structure of mixing which can be rather complicated
- Studies of the $\overline{10}$ (and other non-qqq baryons) promise to be very interesting and exciting, though may appear not easy
- Direct precise measurements are necessary !!

Backup

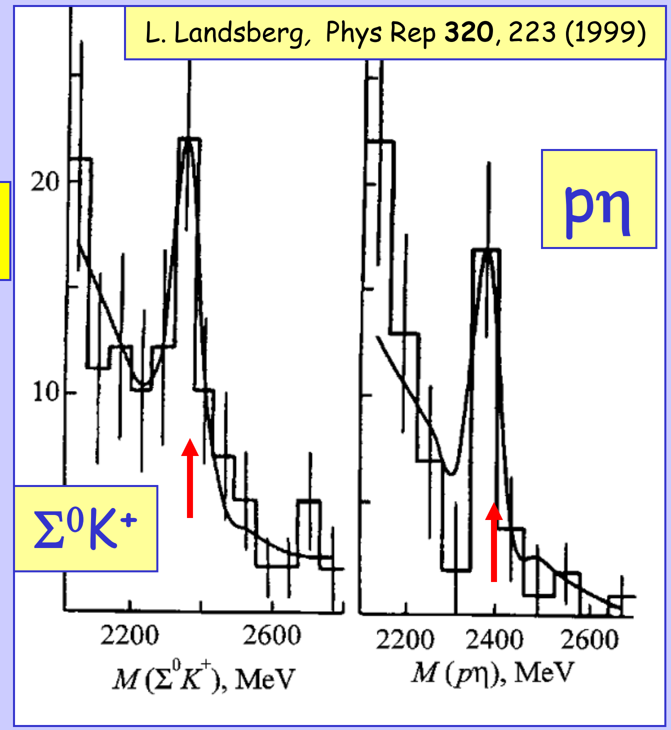
Possible Mechanism of Θ^+ Production, N(2400)

[Ya. Azimov, IS, Phys Rev C **70**, 035210 (2004)]

- CLAS at JLab: $\gamma p \to \pi^+ n(2400) \to \pi^+ K^- \Theta^+$



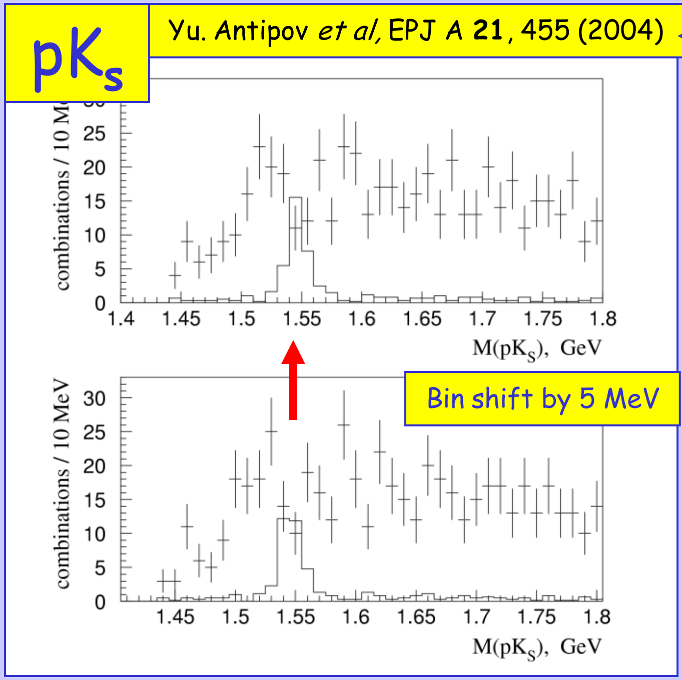
- SPHINX at IHEP: $pN \to Nn(2400) \to \Sigma^0 K^+$, $p\eta$



- No πN PWA has seen an N(2400) at $\pi^- p \to K^- \Theta^+$ with $\Gamma_{tot} \geq$ 100 MeV and BR($R \to a$) $\geq$ 5% [G. Hoehler, Springer, 1983]

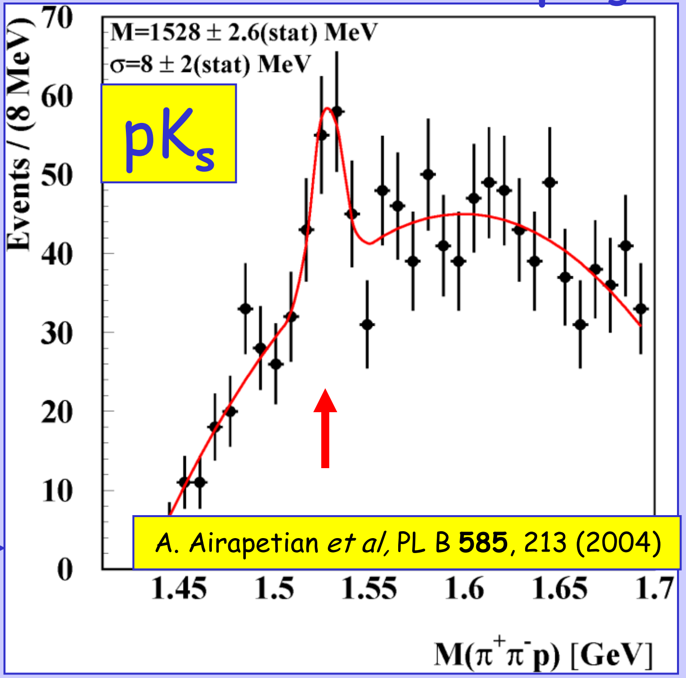
• SPHINX vs HERMES
[found by A. Dolgolenko]

• SPHINX at IHEP: $pC(N) \to pK_sK_sN$



• Significance = 3.8 σ

• HERMES at DESY: $e^+d \to pK_sX$



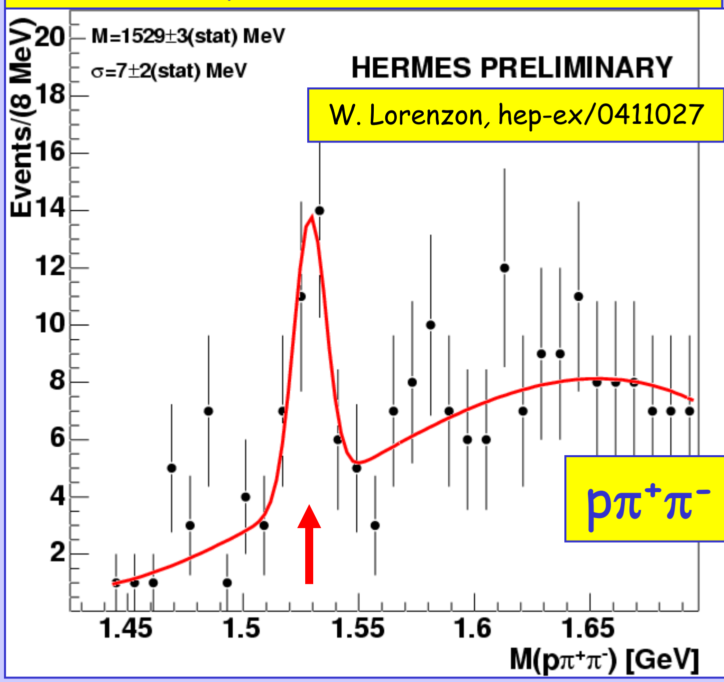
• Significance = 5.6±0.5 σ

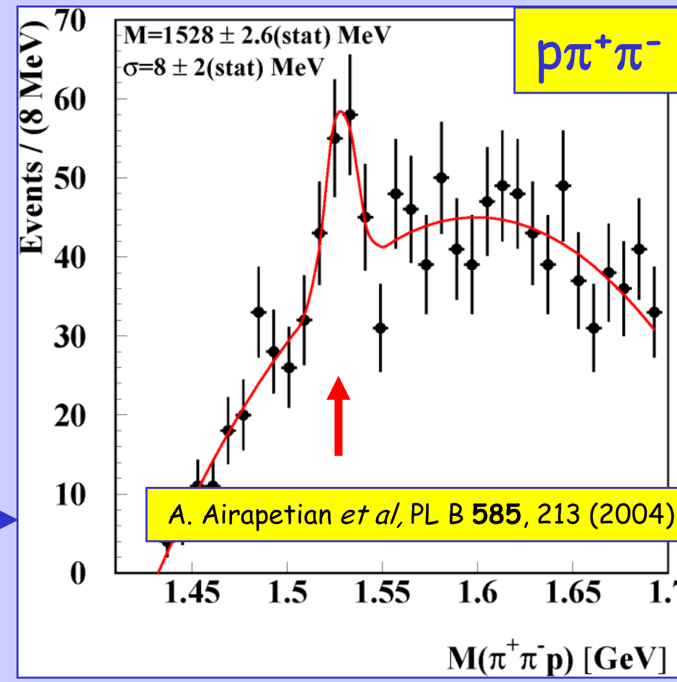
• HERMES vs HERMES

[W. Lorenzon, Pentaquark 2004, July 2004]

$e^+d \to pK_sX$

Θ^+ Mass spectrum with additional π





- Signal/Background= 2:1
- Signal/Background= 1:3

- **BES** [J. Bai *et al*, Phys Rev D **70**, 012004 (2004)]
  Analysis [Ya. Azimov, IS, Phys Rev C **70**, 035210 (2004)]

- No double- or single-Θ production seen in decays of J/ψ and $\psi(2S) \rightarrow K_S p K^- n$ + ch.conj.

- Double Θ (take branching into account: $Br(\Theta \to K^+ n) = 1/2$ and $Br(\Theta \to K_S p) = 1/4$)

- $Br(J/\psi \to \Theta\bar{\Theta}) < 0.44 \times 10^{-4}$

  Compare:

  $J/\psi \to \Sigma(1530)\bar{\Sigma}(1530)$ kinematically similar, but not studied

  $Br(J/\psi \to \Lambda\bar{\Lambda}) < (13.0 \pm 1.2) \times 10^{-4}$

  $\Theta\bar{\Theta}$ vs. $\Lambda\bar{\Lambda}$ - 2 more quark pairs, much smaller phase space

  ($M_{J/\psi}$ = 3097 MeV, $M_{th}(\Theta\bar{\Theta})$ = 3080 MeV)

- $Br(\psi(2S) \to \Theta\bar{\Theta}) < 0.34 \times 10^{-4}$

  Compare:

  $Br(\psi(2S) \to \Lambda\bar{\Lambda}) = (1.81 \pm 0.34) \times 10^{-4}$

• Single Θ (again, recall branchings)

– The most stringent boundaries

$Br(J/\psi \to K^0 p\bar{\Theta})$ < 0.44×10^{-4}

$Br(\psi(2S) \to K^0 p\bar{\Theta})$ < 0.24×10^{-4}

Compare:

$Br(J/\psi \to K^- p\bar{\Lambda})$ = $(8.9 \pm 1.6) \times 10^{-4}$

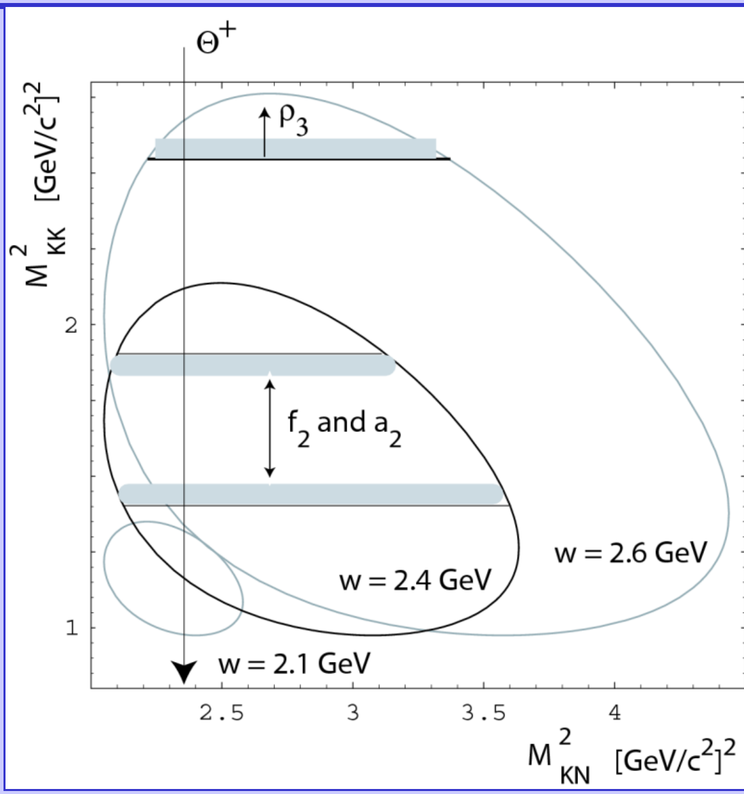
$Br(\psi(2S) \to \pi^0 p\bar{p})$ = $(1.4 \pm 0.5) \times 10^{-4}$

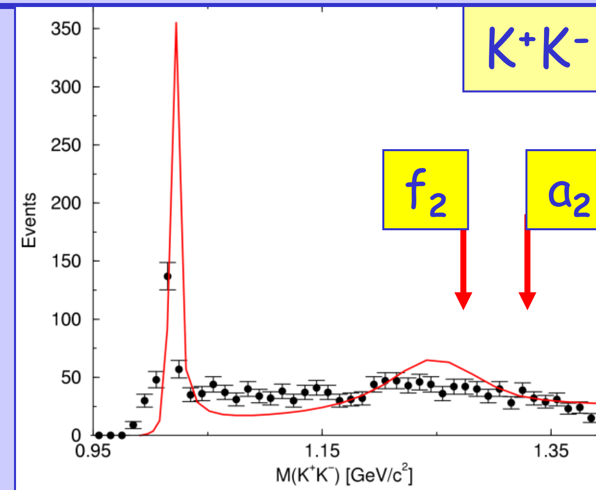
• Summary on Θ^+ Nonobservation at BES

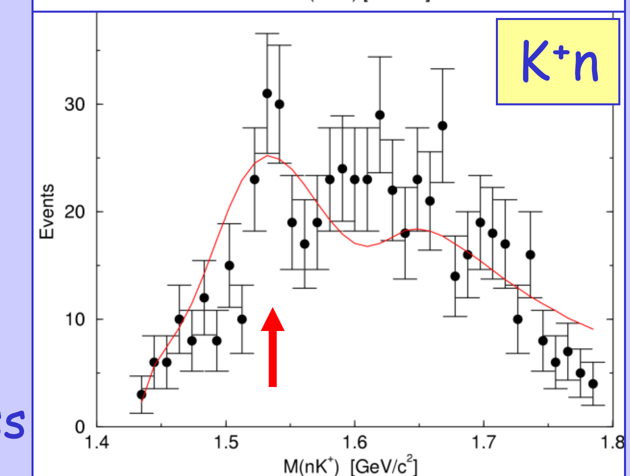
- Data need some (rather soft) dynamical suppression, say 1/5 in the probability
- Meanwhile, because of necessity to produce directly two more $q\bar{q}$ pairs (in exotic decays as compared with decays to canonical baryon-antibaryon pairs), some dynamical suppression should naturally arise.
  One or two order suppression might be quite natural
- Thus, the recent result of BES is only a starting point for investigating exotics in e^+e^--annihilation

Kinematic Reflections

[A. Dzierba *et al*, Phys Rev D **69**, 051901 (2004)







- Kinematic reflections due to $f_2(1275)$ and $a_2(1320)$ can generate a narrow enhancement in K^+n eff. mass
- Fluctuations of the broad peak could result in a false narrow structure

Kinematic Reflections

[K. Hicks, V. Burkert, A. Kudryavtsev, IS, S. Stepanyan, hep-ph/0411265]

- There are considerable model assumptions that paper by Dzierba *et al* have made
- The exchange particle in this model is the pion (and its higher-mass partners on the Regge trajectory line)

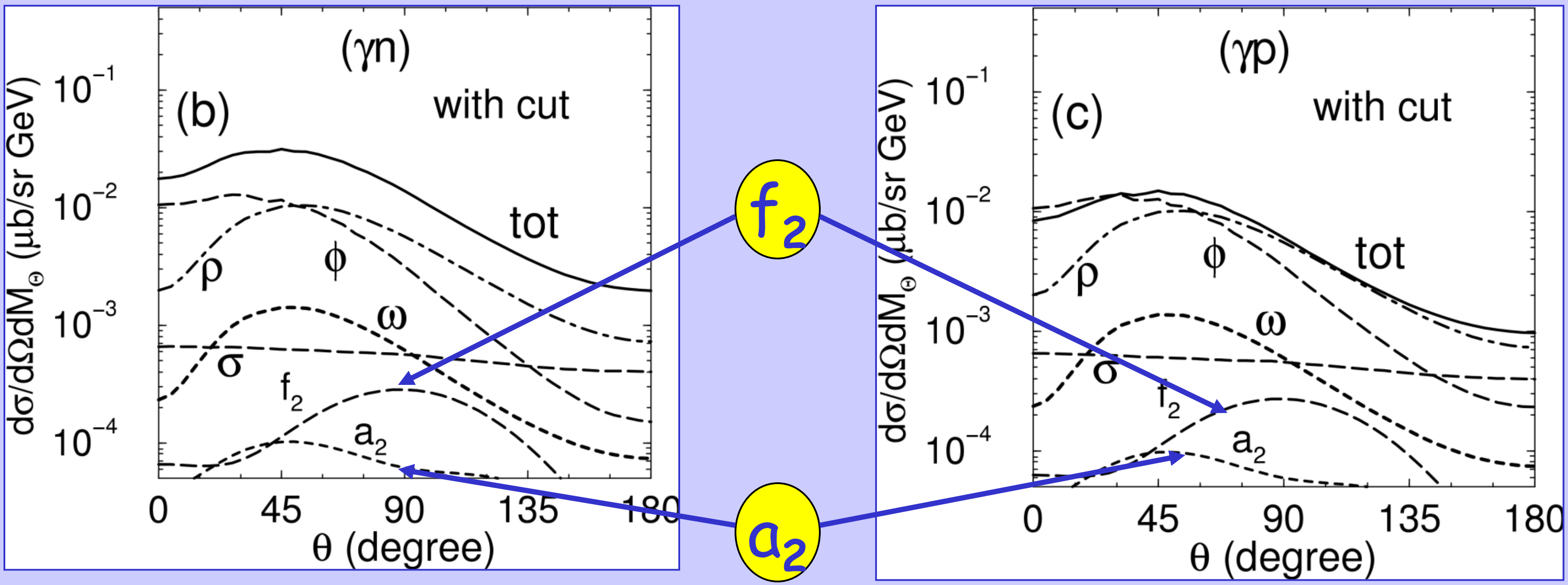
  However, the π^0 exchange contributions are absent indeed, in either reggeized or non-reggeized versions of the model, thus diminishing the corresponding cross sections
- Calculations of kinematic reflections should be due to calculations that have had parameters fixed from on previous data, rather than fit to the spectrum where kinematic reflections are suspected

  We believe it is fair to question Dzierba *et al* for their method to fit the nK^+ spectrum rather than the K^+K^- spectrum to obtain the unknown resonance parameters

Kinematic Reflections

[A. Titov *et al*, nucl-th/0410098]

$\gamma n \to nK^+K^-$ $\gamma p \to pK^+K^-$



- The contributions from the tensor mesons, f_2(1275) and a_2 (1320), at E_γ = 2 GeV are found to be very small

Lattice

- The lattice gauge theory is the only QCD based approach which pretends to do hadron spectroscopy computations directly from the first principles
- However as far as we know, in the current lattice literature there exist three various statements:

i) The Θ^+ has $J^P=1/2^+$ (1 group)
ii) The Θ^+ has $J^P=1/2^-$ (5 groups)
iii) The Θ^+ does not exist at all (2 groups)

- Therefore, it is worth of referencing