Life and Death among the Hadrons

Θ Update on the Theta

Q Diquark correlations in QCD

R. L. Jaffe
DIS05
Madison
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Postmortem on the Theta

- The Θ is in trouble. It may survive, but it is not too early to look at the consequences of its demise should it occur

- Positive sightings of the Theta

Experiment	Reaction	State	Mode	Reference
LEPS(1)	$\gamma C_{12} \to K^+K^-X$	θ^+	K^+n	[4]
LEPS(2)	$\gamma d \to K^+K^-X$	θ^+	K^+n	[5]
CLAS(d)	$\gamma d \to K^+K^-(n)p$	θ^+	K^+n	[6]
CLAS(p)	$\gamma p \to K^+K^-\pi^+(n)$	θ^+	K^+n	[7]
SAPHIR	$\gamma p \to K^0_S K^+(n)$	θ^+	K^+n	[8]
COSY	$pp \to \Sigma^+ K^0_S p$	θ^+	$K^0_S p$	[9]
JINR	$p(C_3H_8) \to K^0_S pX$	θ^+	$K^0_S p$	[10]
SVD	$pA \to K^0_S pX$	θ^+	$K^0_S p$	[11]
DIANA	$K^+Xe \to K^0_S p(Xe)'$	θ^+	$K^0_S p$	[12]
νBC	$\nu A \to K^0_S pX$	θ^+	$K^0_S p$	[13]
NOMAD	$\nu A \to K^0_S pX$	θ^+	$K^0_S p$	[14]
HERMES	quasi-real photoproduction	θ^+	$K^0_S p$	[15]
ZEUS	$ep \to K^0_S pX$	θ^+	$K^0_S p$	[16]
NA49	$pp \to \Xi\pi X$	Ξ_5	$\Xi\pi$	[17]
H1	$ep \to (D^*p)X$	θ_c	D^*p	[18]

Dzierba, Meyer, Szczepaniak hep-ex/0412077

- Negative non-sightings of the Theta

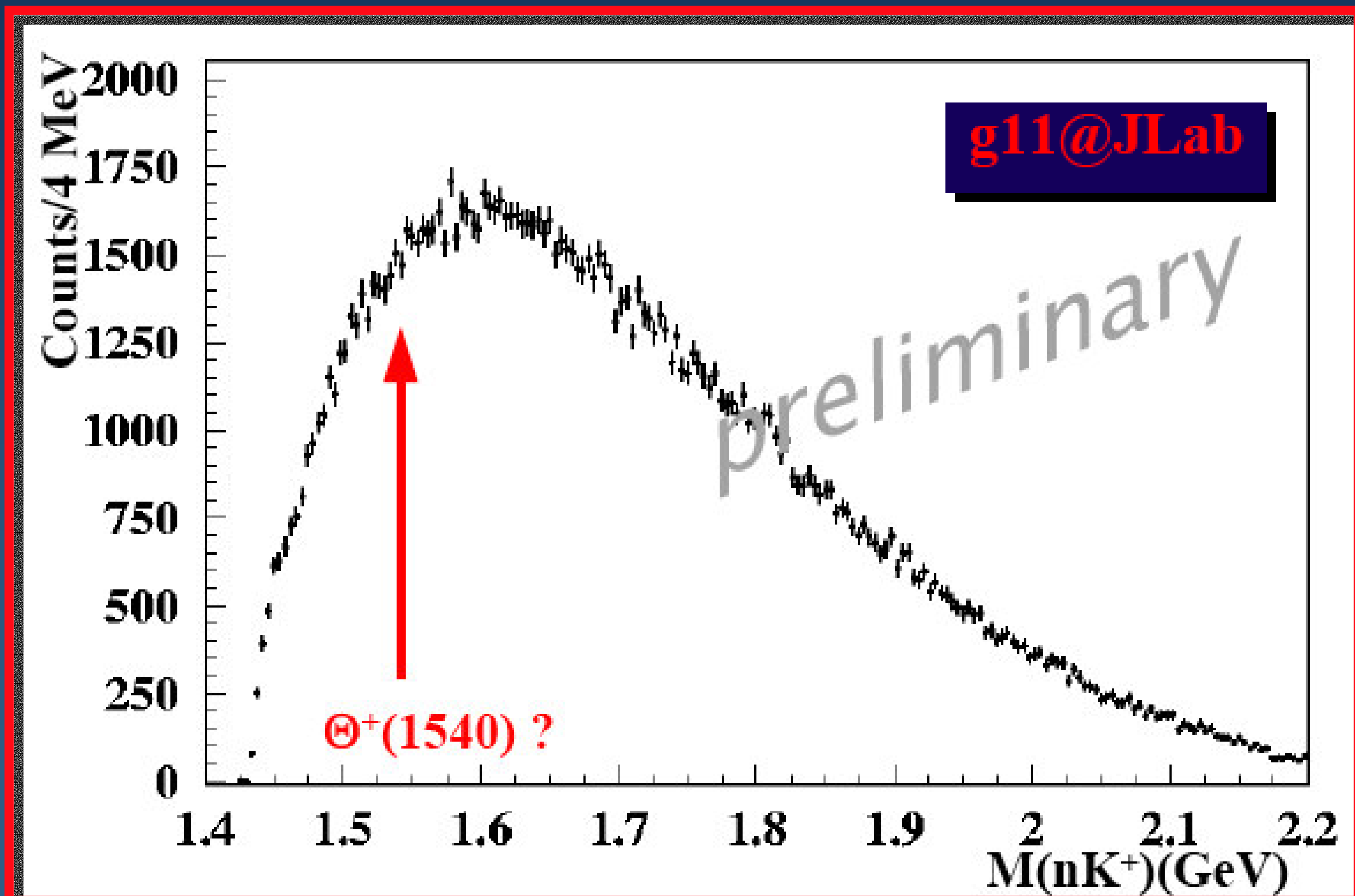
Experiment	Search Reaction	θ^+	Ξ_5	θ_c	Reference
ALEPH	Hadronic Z decays	$\Downarrow$	$\Downarrow$	$\Downarrow$	[19]
BaBar	$e^+e^- \to \Upsilon(4S)$	$\Downarrow$	$\Downarrow$	–	[20]
BELLE	$KN \to PX$	$\Downarrow$	–	$\Downarrow$	[21]
BES	$e^+e^- \to J/\psi(\psi(2S) \to \theta\bar{\theta}$	$\Downarrow$	–	$\Downarrow$	[22]
CDF	$p\bar{p} \to PX$	$\Downarrow$	$\Downarrow$	$\Downarrow$	[23]
COMPASS	$\mu^+(^6LiD) \to PX$	$\Downarrow$	$\Downarrow$	–	[24]
DELPHI	Hadronic Z decays	$\Downarrow$	–	–	[25]
E690	$pp \to PX$	$\Downarrow$	$\Downarrow$	–	[26]
FOCUS	$\gamma p \to PX$	$\Downarrow$	$\Downarrow$	$\Downarrow$	[27]
HERA-B	$pA \to PX$	$\Downarrow$	$\Downarrow$	–	[28]
HyperCP	$(\pi^+, K^+, p)Cu \to PX$	$\Downarrow$	–	–	[29]
LASS	$K^+p \to K^+n\pi^+$	$\Downarrow$	–	–	[30]
L3	$\gamma\gamma \to \theta\bar{\theta}$	$\Downarrow$	–	–	[25, 31]
PHENIX	$AuAu \to PX$	$\Downarrow$	–	–	[32]
SELEX	$(\pi, p, \Sigma)p \to PX$	$\Downarrow$	–	–	[33]
SPHINX	$pC(N) \to \theta^+C(N)$	$\Downarrow$	–	–	[34]
WA89	$\Sigma^-N \to PX$	–	$\Downarrow$	–	[36]
ZEUS	$ep \to PX$	$\Uparrow$	$\Downarrow$	$\Downarrow$	[16, 37, 38]

Dzierba, Meyer, Szczepaniak hep-ex/0412077

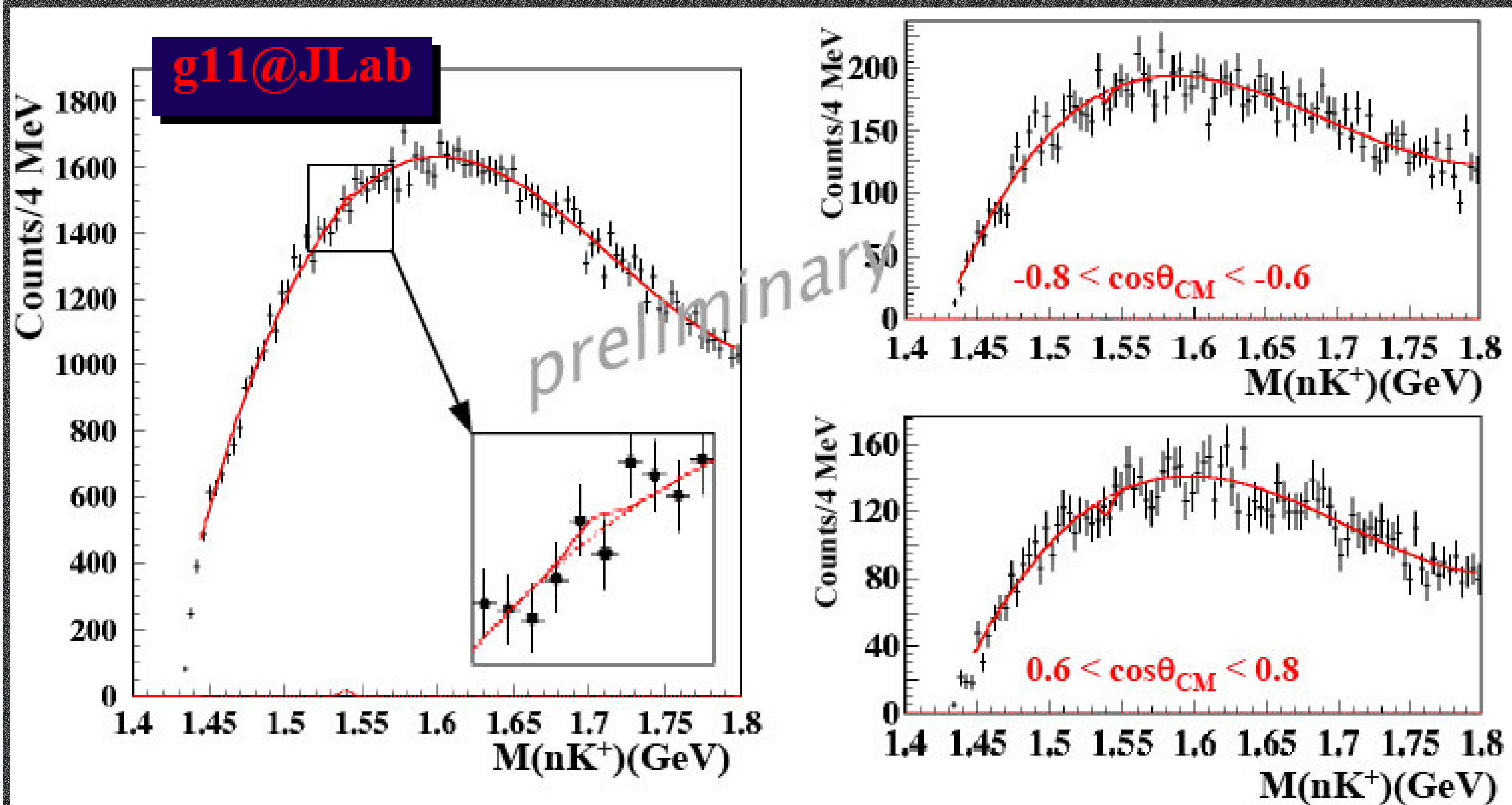
- Very recent results -- first of a second generation
- Reported by R. De Vita for CLAS at APS Tampa 4/17/05

$$\gamma\, p \rightarrow \Theta^+\, \overline{K}^0$$

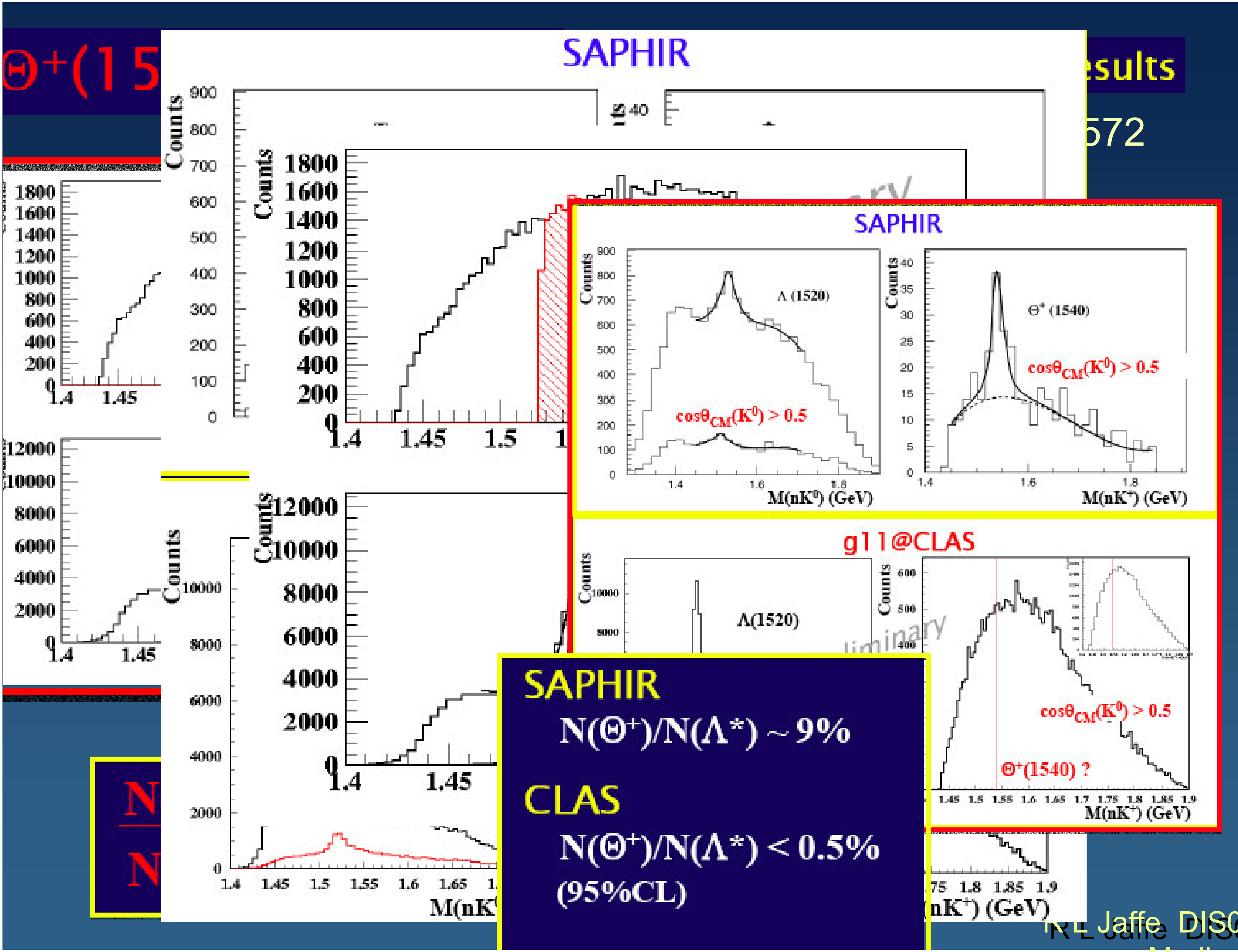
$$\Theta^+ \rightarrow K^+ n \text{ and } \overline{K}^0 \rightarrow \pi^+\pi^-$$



- More detail



g11@JLab
Counts/4 MeV
M(nK+)(GeV)
preliminary
-0.8 < cosθ_CM < -0.6
0.6 < cosθ_CM < 0.8


SAPHIR
SAPHIR
Λ (1520)
Θ+ (1540)
cosθCM(K0) > 0.5
M(nK0) (GeV)
M(nK+) (GeV)
g11@CLAS
Λ(1520)
Θ+(1540) ?
SAPHIR
N(Θ+)/N(Λ*) ~ 9%
CLAS
N(Θ+)/N(Λ*) < 0.5%
(95%CL)

Implication

- SU(3) Chiral Soliton Models (Diakonov, Petrov, Polyakov)
  - Strong prediction asserted: M=1540 MeV, Γ = 15 MeV
  - Apparently the model is unreliable, why?

? Perhaps baryons are not chiral solitons in the first place

? Truncation of chiral effective lagrangian?

$$\mathcal{L} = f_\pi^2 \partial_\mu U \partial^\mu U^\dagger + \mathcal{L}_6 + \mathcal{L}_8 + \mathcal{L}_{10} + \ldots$$

Dynamical balance

No justification to ignore

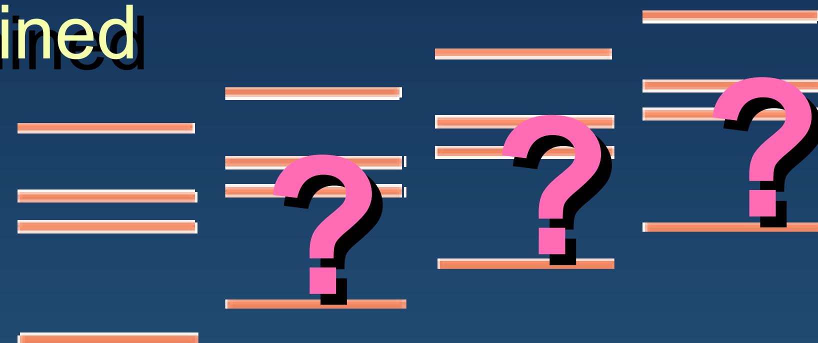
? Adiabatic (rigid) excitation?

Assume that rotational excitations neither deform soliton nor mix with radial excitations. No separation of scales.

? Perturbative implimentation of SU(3) violation?

Implications

- Quark models, Large N_c (a la Jenkins/Manohar),
  - No prediction because absolute mass scale of $q^4\bar{q}$ could not be determined



  - Never could accommodate narrow width
  - Absence of Theta limits the strength of the correlation (diquark) that has other important spectroscopic and dynamical implications

Lessons

- There really are no (light, narrow) exotics in QCD
- Phenomenological models should not be taken very quantitatively, especially for overall scale (eg. mass of lightest state in $qqqq\bar{q}$ sector, or lightest glueball)
- Lattice QCD has not yet progressed to the stage that it can be decisive
- Comments do not apply to heavy quark (c and b) exotics, where different issues apply. See (e.g.) Stewart, Wessling & Wise, hep-ph/0402076. Not covered here/ lack of time.
- A happy accident: the saga of the Theta has reminded us of the importance of diquark correlations in QCD

Diquarks correlations in QCD

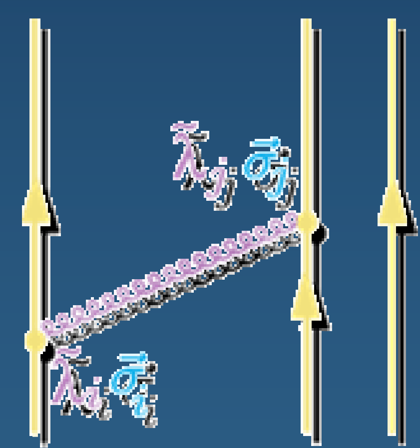
- Color, flavor, spin antisymmetric diquark dominates
- Phenomenological evidence for diquark correlations
- Defining diquarks
- Spectroscopic consequences
  - Exotics in general
  - Pentaquarks and related states
- Diquarks in deep inelastic processes ?
- Spectroscopy in color non-singlet sectors!
- Conclusions

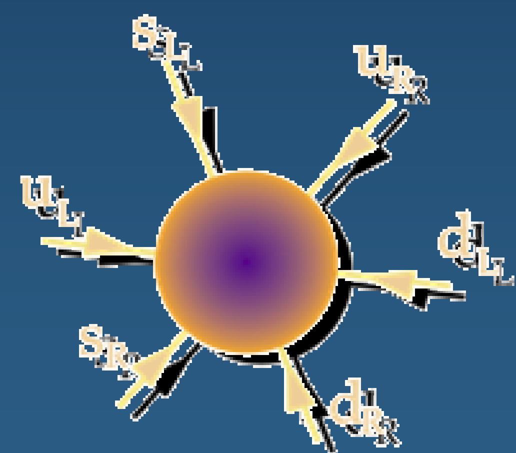
Q Correlations and classification

- Confinement
- Chiral symmetry breaking
- QQ correlations ?

$$Q\overline{Q}\;\; 1_f\, 1_c\, 0_s$$

$$QQ\;\; \bar{3}_f\, \bar{3}_c\, 0_s$$





- Color, flavor, spin antisymmetry

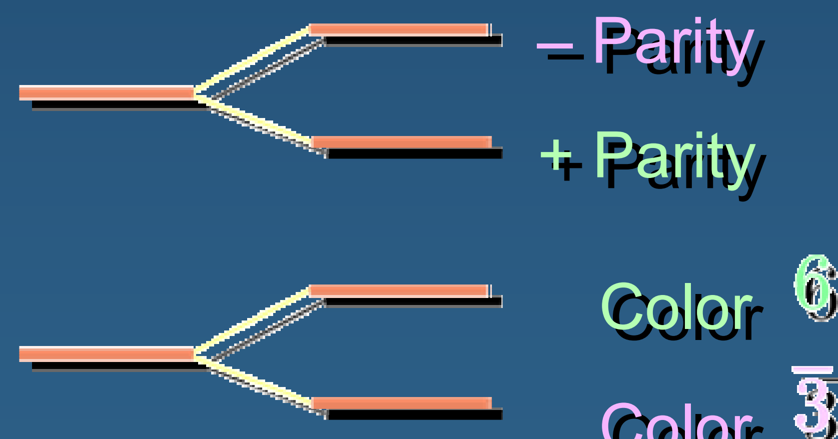
$\mathcal{Q}$ Classification $\qquad \overline{Q}_c \Gamma Q$

Spins and Parities	(Flavor, Color)	Operators	Single mode survival
0^+	$(\overline{\mathbf{3}}, \overline{\mathbf{3}})$ → [illegible]	$\overline{q}_C\gamma_5 q,\ \overline{q}_C\gamma^0\gamma_5 q$	yes
1^+	[illegible] $(\mathbf{6}, \overline{\mathbf{3}})$ →	$\overline{q}_C\vec{\gamma}q,\ \overline{q}_C\sigma^{0i}q$	yes
0^-	[illegible] $(\mathbf{6}, \mathbf{3})$	$\overline{q}_C q,\ \overline{q}_C\gamma^0 q$	[illegible]
1^-	$(\overline{\mathbf{3}}, \mathbf{3})$ [illegible]	$\overline{q}_C\vec{\gamma}\gamma_5 q,\ \overline{q}_C\sigma^{ij}q$	[illegible]

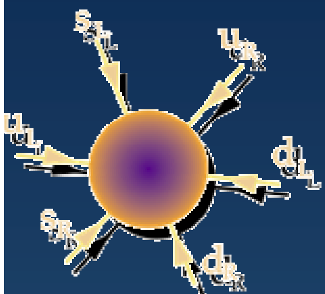
Fermi statistics

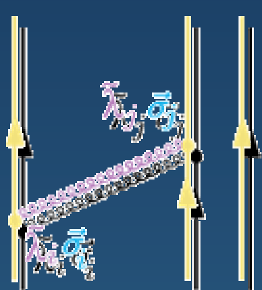
Leaves only two diquarks in the low energy spectrum

$$|\{qq\}\ \overline{\mathbf{3}}_c(A)\ \overline{\mathbf{3}}_f(A)\ 0^+(A)\rangle$$
$$|\{qq\}\ \overline{\mathbf{3}}_c(A)\ \mathbf{6}_f(S)\ 1^+(S)\rangle$$



Diquarks

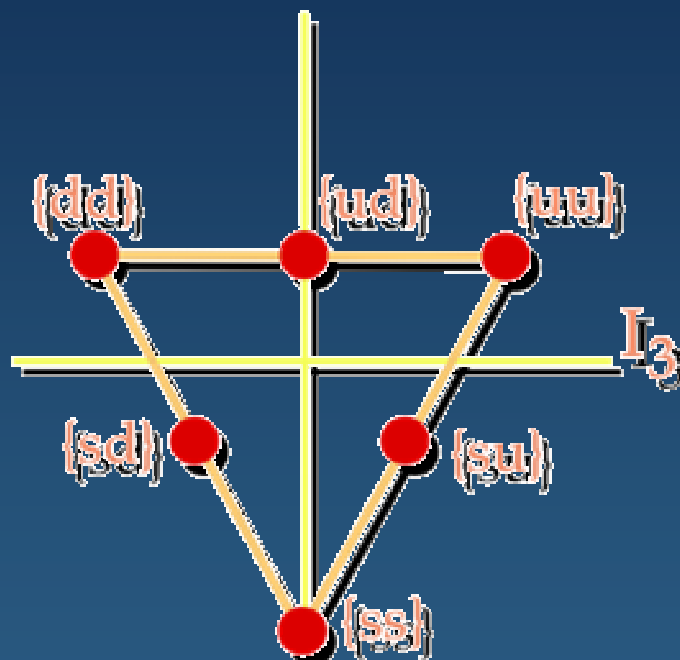




"Bad"

$$\{q_1, q_2\} \Leftrightarrow Q$$

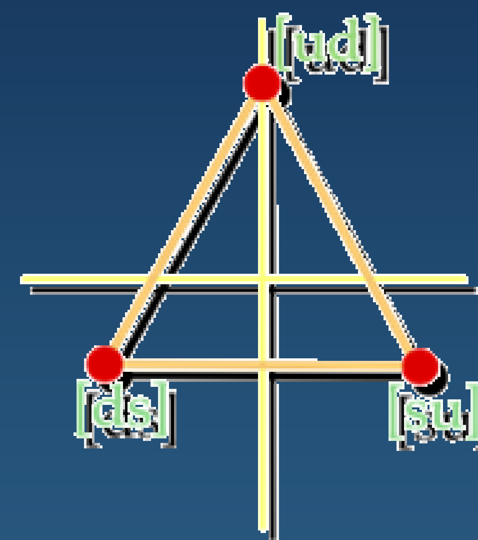
{qq} Symmetric 6



"Good"

$$[q_1, q_2] \Leftrightarrow Q$$

[qq]
Antisymmetric $\bar{3}$



Flavor	Color	Spin	ΔE
$\bar{3}$ (A)	$\bar{3}$ (A)	0 (A)	-8
6 (S)	$\bar{3}$ (A)	1 (S)	8/3

Phenomenological evidence for diquarks

Long history in QCD, but never in the mainstream (D. Lichtenberg)

- Certain regularities in spectroscopy
  - Absence of $L = 2$ $[20]$ of $SU(6)$
  - Systematic analysis of baryon and meson resonances.
    More later -- A. Selem & F. Wilczek in preparation
- Condensation in quark matter at high density
  - Q condenses in flavor antisymmetric channel generating color-flavor locked superconductivity
- $\Delta I = 1/2$ rule in nonleptonic weak decays
  - Q dominance gives good description of non-perturbative effects.
  - Systematic study by Neubert, Stech & collaborators in late 1980's.

Diquark regularities in DIS

- Baryo… low fro…

  …n since 1960's

  …nt JLab results

  …ucl-ex/0308011

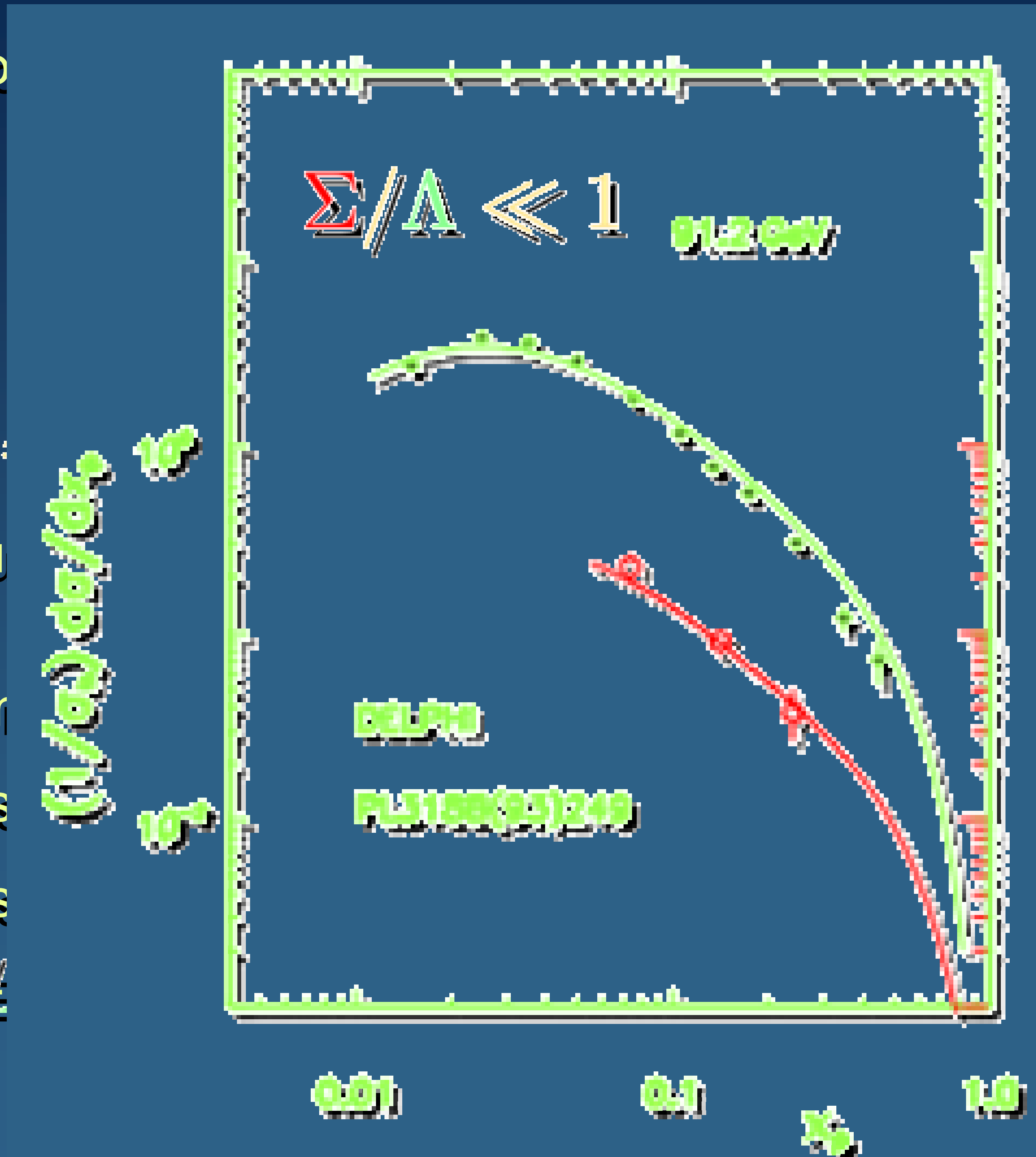
- Regu… …adrons

  Fragr…

  ratios…

  meas…

  a… Σ/Λ…



Characterizing diquarks

- Formally define color antitriplet diquarks in the presence of an infinitely heavy spectator quark (or Polyakov line)

Good diquark, non-strange	$[u,d]Q$	mass $\mathcal{M}_A$
Good diquark, strange	$[u,s]Q$	mass $\mathcal{M}_A + \Delta_A$
Bad diquark, non-strange	$\{u,d\}Q$	mass $\mathcal{M}_S$
Bad diquark, strange	$\{u,s\}Q$	mass $\mathcal{M}_S + \Delta_S$
Bad diquark, doubly strange	$\{s,s\}Q$	mass $\mathcal{M}_S + \Delta_{SS}$

- Awaiting lattice calculations, estimate from charm and strange systems:

$$[M_S - M_A]|_Q = \frac{1}{3}\left(2M(\Sigma_Q^*) + M(\Sigma_Q)\right) - M(\Lambda_Q)$$

$$[M_S - M_A]|_s = 205 \text{ MeV}$$
$$[M_S - M_A]|_c = 212 \text{ MeV}$$

- Other estimates from charm sector

Good - bad mass difference decreases with quark mass.

$$M\{u,s\}|_{\mathcal{C}} - M[u,s]|_{\mathcal{C}} = 152\ \text{MeV}$$

$$\Rightarrow \Delta_S - \Delta_A|_{\mathcal{C}} = -60\ \text{MeV}$$

Diquark -- heavy quark spin interaction decreases with heavy quark mass and with light quark mass

$$K(s,\{u,d\}) = 64\ \text{MeV}$$
$$K(c,\{u,d\}) = 21\ \text{MeV}$$

- Conclude: charm baryon masses allow estimate of diquark masses in a heavy quark background. Correlation is ~ 200 MeV. Not huge, but important

Spectroscopic consequences

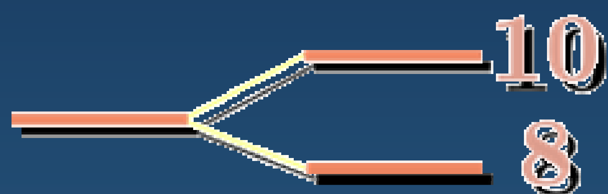
- Most important: Diquark correlations explain the total (so far) absence of exotics in the light quark spectrum.
- Next: Diquark correlations "explain" supernumerary nonet of light scalar mesons as dominantly $QQ\bar{Q}\bar{Q}$ states
- Qualitative regularities in the meson and baryon spectra
- Suggest possible exotics in the heavy quark spectrum.

Q Spectra

- Baryons

$Q \times q \quad \bar{3} \times 3 \Rightarrow 8 \oplus 1$

$Q \times q \quad 6 \times 3 \Rightarrow 8 \oplus 10$



Fermi statistics kills the singlet and allows only one octet which is a mixture of good and bad diquark except for Σ Λ and

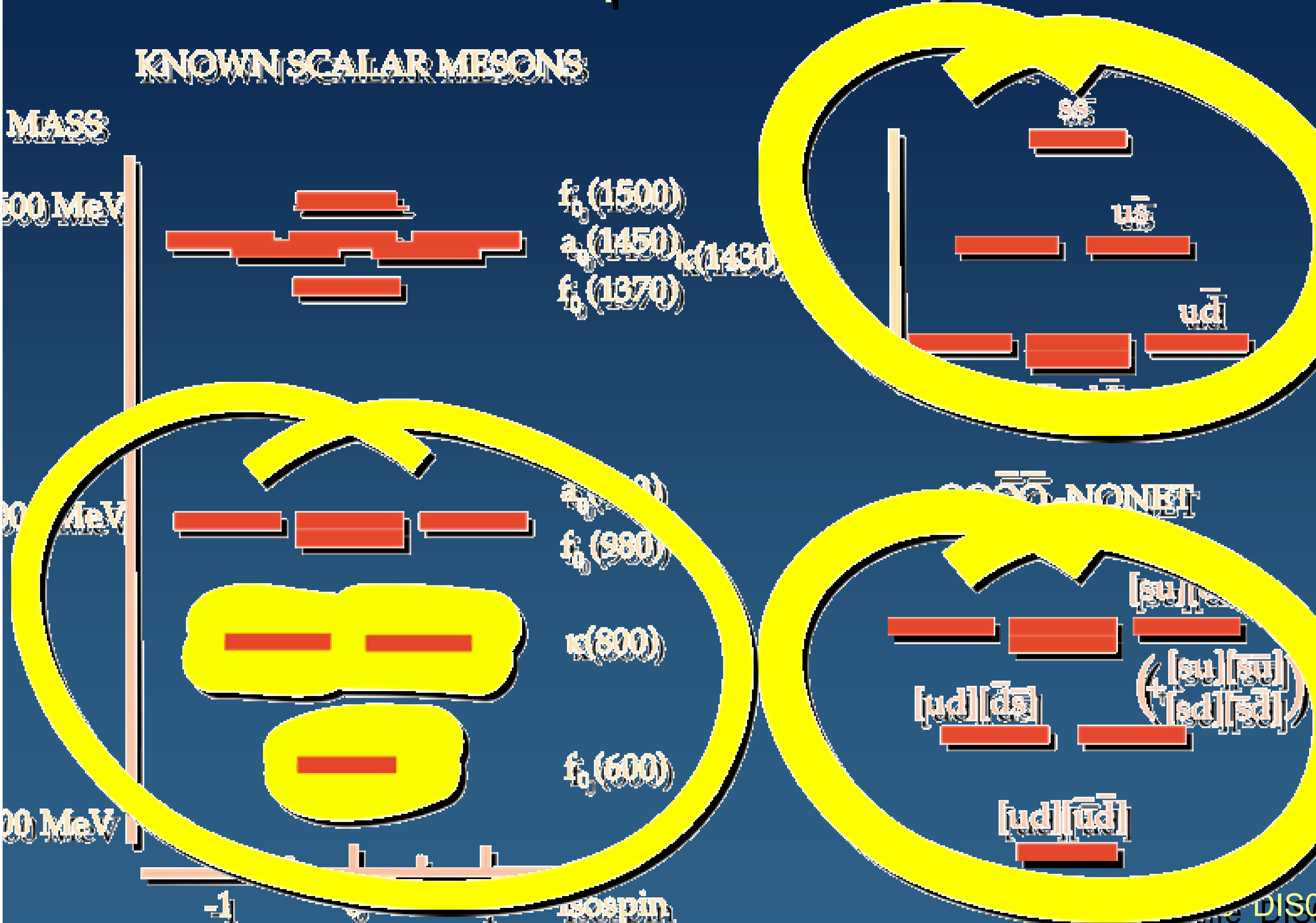
- $Q\bar{Q}$ Mesons

$Q \times \bar{Q} \quad \bar{3} \times 3 \Rightarrow 8 \oplus 1$

No Exotics !

Lightest multiplet is 0^{++} nonet

Scalar mesons: a supernumerary nonet



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Q Spectra

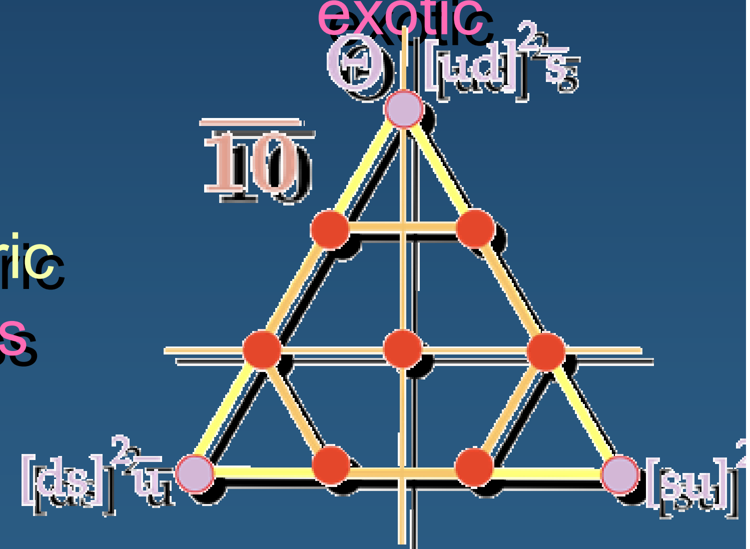
- $Q^2 q$ Pentaquarks

$Q^2 \times q \quad \bar{3} \times \bar{3} \times \bar{3} \Rightarrow 1 \oplus 8 \oplus 8 \oplus \overline{10}$

$1 \oplus 8$ Negative parity, non-exotic, s-wave

$8 \oplus \overline{10}$ Positive parity, possibly exotic, p-wave

Only possible exotic



Exotic requires diquarks in an antisymmetric space state (bose statistics) -- heavier, less stable

- Q^3 Dibaryons

Only s-wave is the SU(3)- singlet

Made heavier by Pauli blocking

$$H = \mathcal{S}\{[u,d][d,s][s,u]\}$$

Q Spectra Summary

- Generically, no exotics among light (u,d,s)
- Marginal cases:

Pentaquark $(q^4\bar{q})$ $\overline{\mathbf{10}}$

Dibaryon (q^6) $\mathbf{1}$

- Scalar mesons:

$Q\overline{Q}$ Ground state is a nonet of 0^{++} mesons resembling known light nonet.

- Heavy quark exotics should be explored more thoroughly

In Deep Inelastic Processes

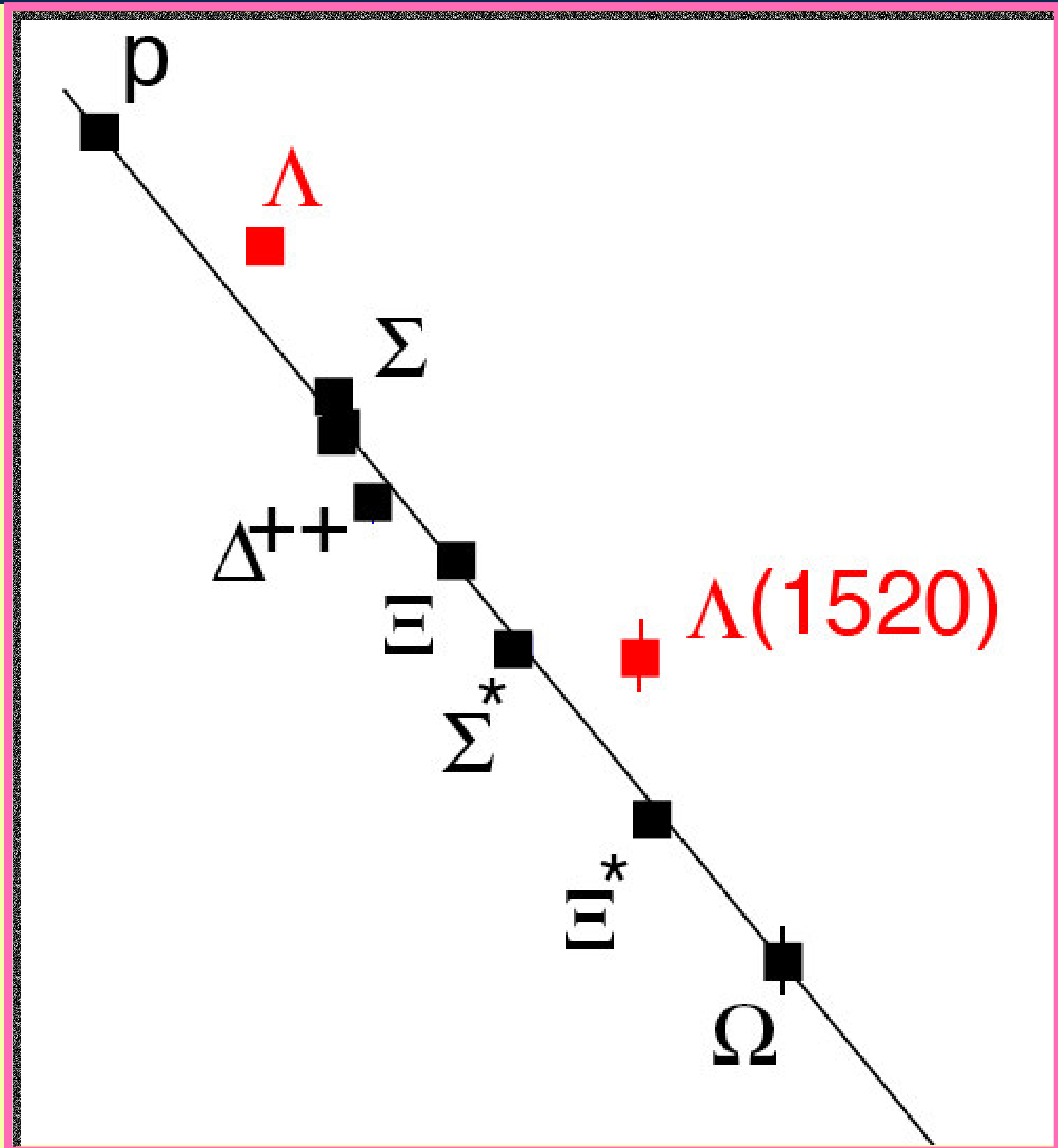
- Structure function regularities, especially as $x \to 1$

- Fragmentation functions

  - If diquarks are strongly correlated, baryon fragmentation functions should not be dramatically smaller than meson f.f.
  - Data on two particular baryons...

  $\Lambda(1116, 1/2^+)$ Good [u,d] diquark in s-wave

  $\Lambda(1520, 3/2^-)$ Good [u,d] diquark in p-wave



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Limits on diquarks from higher twist...

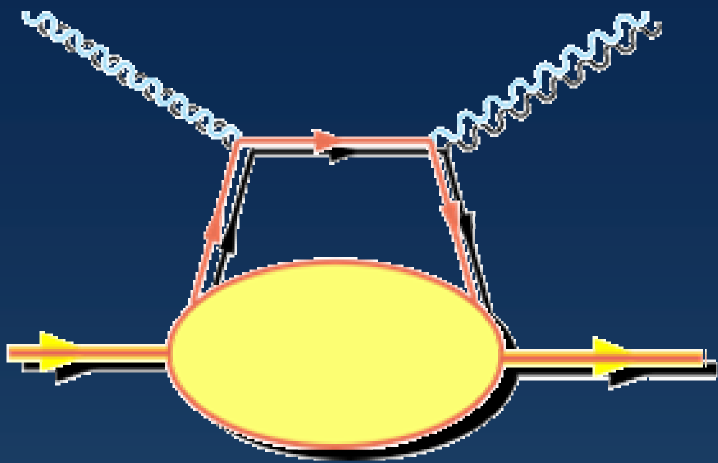
A. Vainshteyn & RLJ
(unpublished)

"But aren't strong correlations in QCD ruled out by the absence of large twist-four corrections to DIS?"

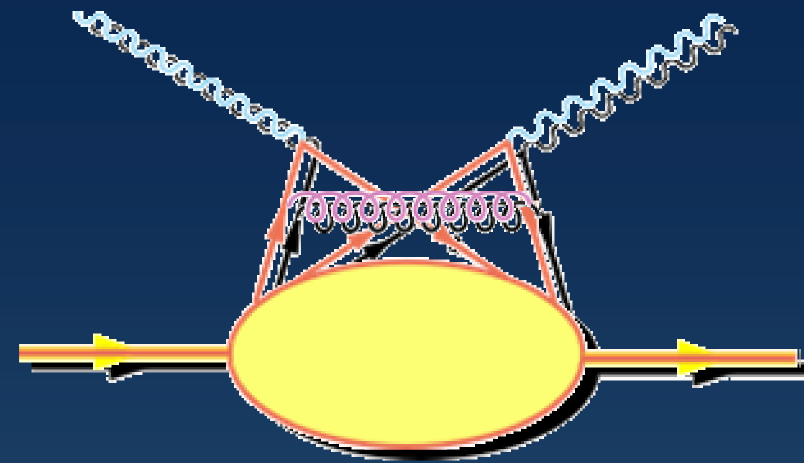
"How pointlike can diquarks be?"

$1/Q^2$ corrections to DIS are known to be small, and limit non-perturbative scales in QCD beyond Λ

These limits constrain diquarks because twist-four operators include ones sensitive to diquark correlations...



Leading twist



Twist four -- diquark operator

However: "Good" diquark is spinless and does not contribute at twist four !

$$\mathcal{S}\left\{\bar{\psi}\gamma^{\mu}\psi\ \bar{\psi}\gamma^{\nu}\psi\right\} - \text{Traces}$$

Dimension-6, spin-2 $\Rightarrow$ twist-4, but only if quarks are coupled to maximum spin.

QCD spectroscopy in color non-singlet sectors

- The "Θ affair" suggests that correlations in QCD can be studied by studying color non-singlet light quark systems neutralized by heavy quark spectator.
- Study correlations in QCD by studying color non-singlet spectroscopy!

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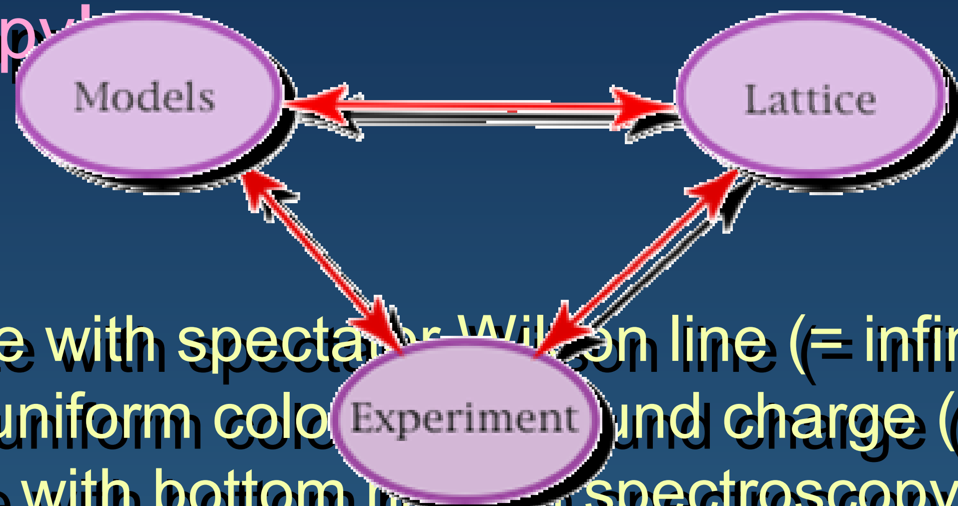
- Study correlations in QCD by studying color non-singlet spectroscopy!



- Neutralize with spectator Wilson line (= infinitely heavy quark)
- (Or with uniform color background charge (how?))
- Compare with bottom hadron spectroscopy
- And with phenomenological models

Mesons	$q^{3_c}\overline{Q}$	Tetraquark mesons	$[qq\bar{q}]^{3_c}\overline{Q}$
Baryons	$[qq]^{\bar{3}_c}Q$	Pentaquark baryons	$[qqqq]^{3_c}\overline{Q}$

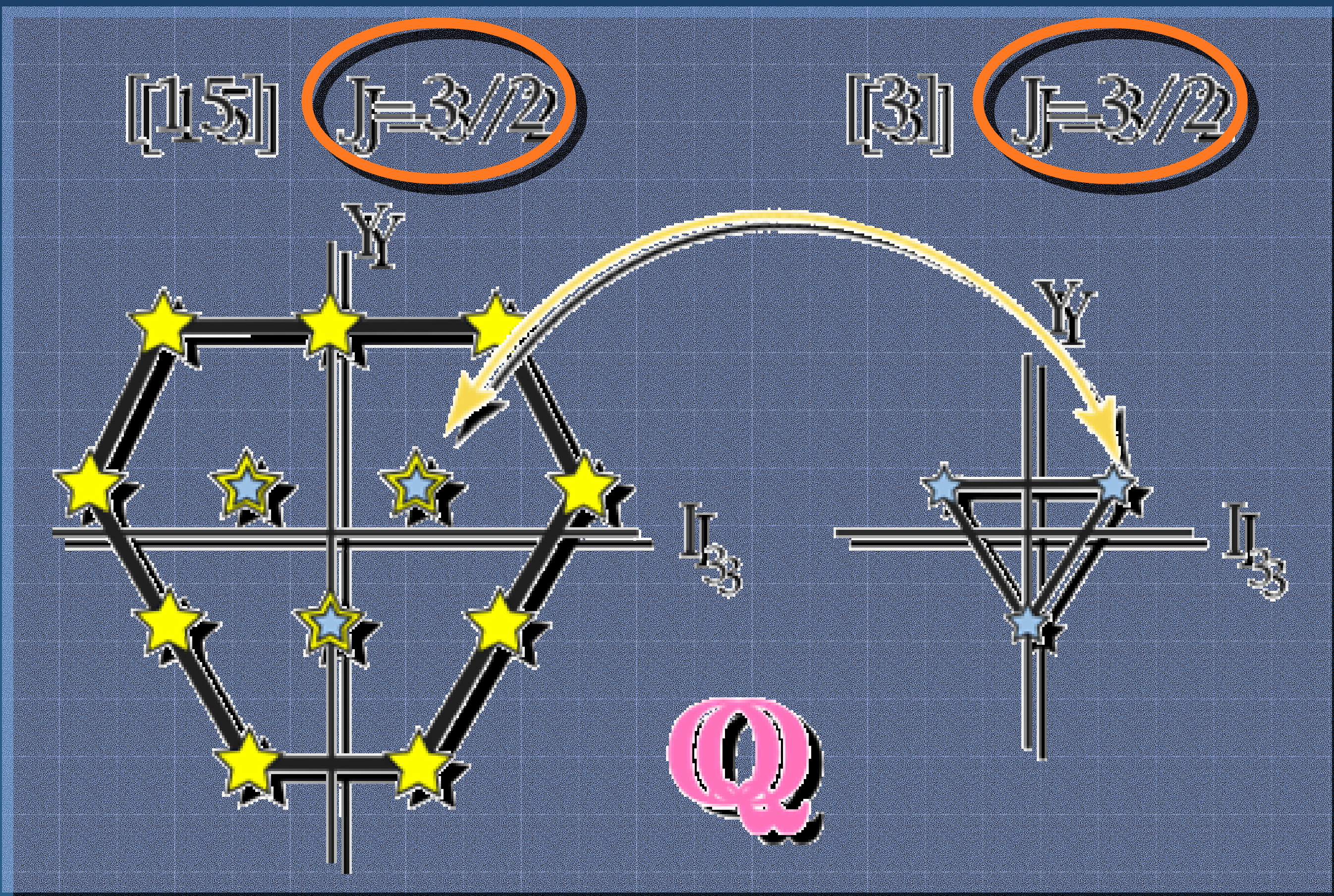
Even color sextet light quark states

Example: Classification of $[qq\bar{q}]^{3_c}$ ground state $[qq\bar{q}]^{3_c}$

Total J=3/2 states with $[qq]^{\bar{3}_c}$

(Ignore $[qq]^{6_c}$ for simplicity -- dynamics?)

$3\times3\times\bar{3}=\bar{3}\times(3\times3)\Rightarrow 3_Q^{(\frac{3}{2},\frac{1}{2})}\oplus\bar{3}_Q^{(\frac{1}{2})}\oplus\bar{6}_Q^{(\frac{3}{2})}\oplus 15_Q^{(\frac{1}{2})}\oplus 15_Q^{(\frac{3}{2},\frac{1}{2})}$



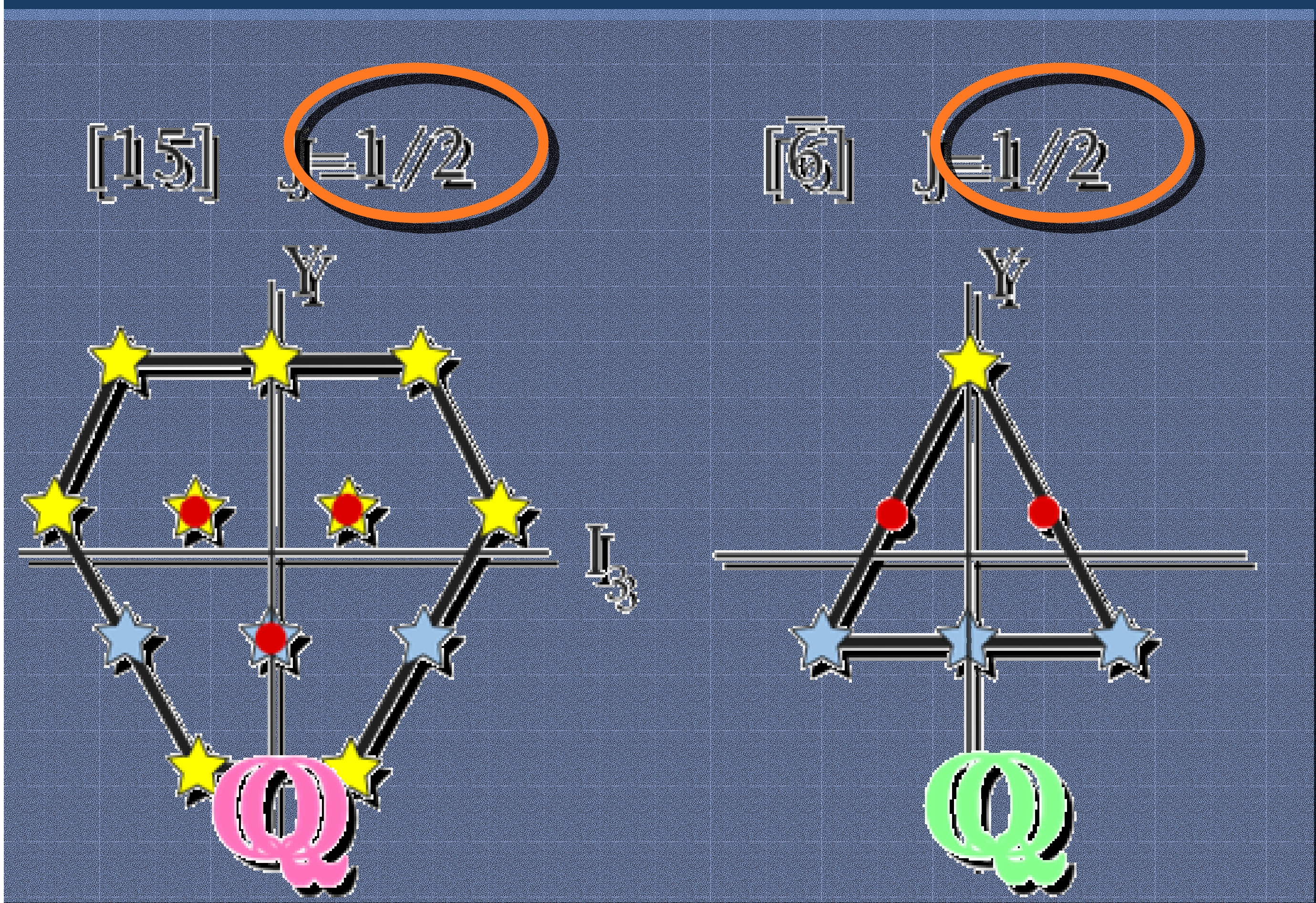
"Exotics" with unique SU(3) assignments.

"Exotics" mixed by SU(3) violating interactions.

$[qq\bar{q}]^{3_c}$ Total J=1/2 states with $[qq]^{\bar{3}_c}$

(Ignore $[qq]^{6_c}$ for simplicity -- dynamics?)

$$3\times 3\times \bar{3} \Rightarrow 3_Q^{(\frac{1}{2})} \oplus \bar{3}_Q^{(\frac{3}{2},\frac{1}{2})} \oplus \bar{6}_Q^{(\frac{1}{2})} \oplus 15_Q^{(\frac{3}{2},\frac{1}{2})}$$



- "Exotics" with unique SU(3) assignments.
- "Exotics" mixed by SU(3) violating interactions.
- Non-exotics, mix with single quark states.

Color triplet $[qq\bar{q}]^{\bar{3}_c}\bar{Q}$ spectroscopy

Spin	Isospin	Strangeness	SU(3)
3/2	1	+1	[15]
3/2	3/2	0	[15]
3/2	1/2	0	[15] + [3] + [6]*
3/2	1	-1	[15] + [6]*
3/2	0	-1	[15] + [3]
3/2	1/2	-2	[15]
3/2	0	+1	[6]*

1/2	1	+1	[15]
1/2	3/2	0	[15]
1/2	1	-1	[15] + [6]
1/2	1/2	-2	[15]
1/2	0	+1	[6]

* This representation only occurs when qq are coupled to 6

Conclusions

- The Theta may have died*
  - CSM takes a hit
- Quark model, large N_c and other phenomenological models remain as limited as before.
- Jury is still out on heavy quark analogues

*Resurrection?

- The "Theta affair" re-focused attention on diquarks
- Lots of phenomenological evidence for diquarks
- Important spectroscopic consequences, especially <u>absence of exotics</u> and <u>scalar mesons</u>
- Role in DIS --- qualitative --- fragmentation functions and higher twist
- A systematic study of correlations in QCD: light quark spectroscopy in the color non-singlet sectors