

Diquarks, Tetraquarks, Pentaquarks

Exotic hadrons in QCD

R. Jaffe, Quark Matter 2004
in collaboration with F. Wilczek

Based in part on
hep-ph/0307341
hep-ph/0312369

Rigorous Approaches to QCD

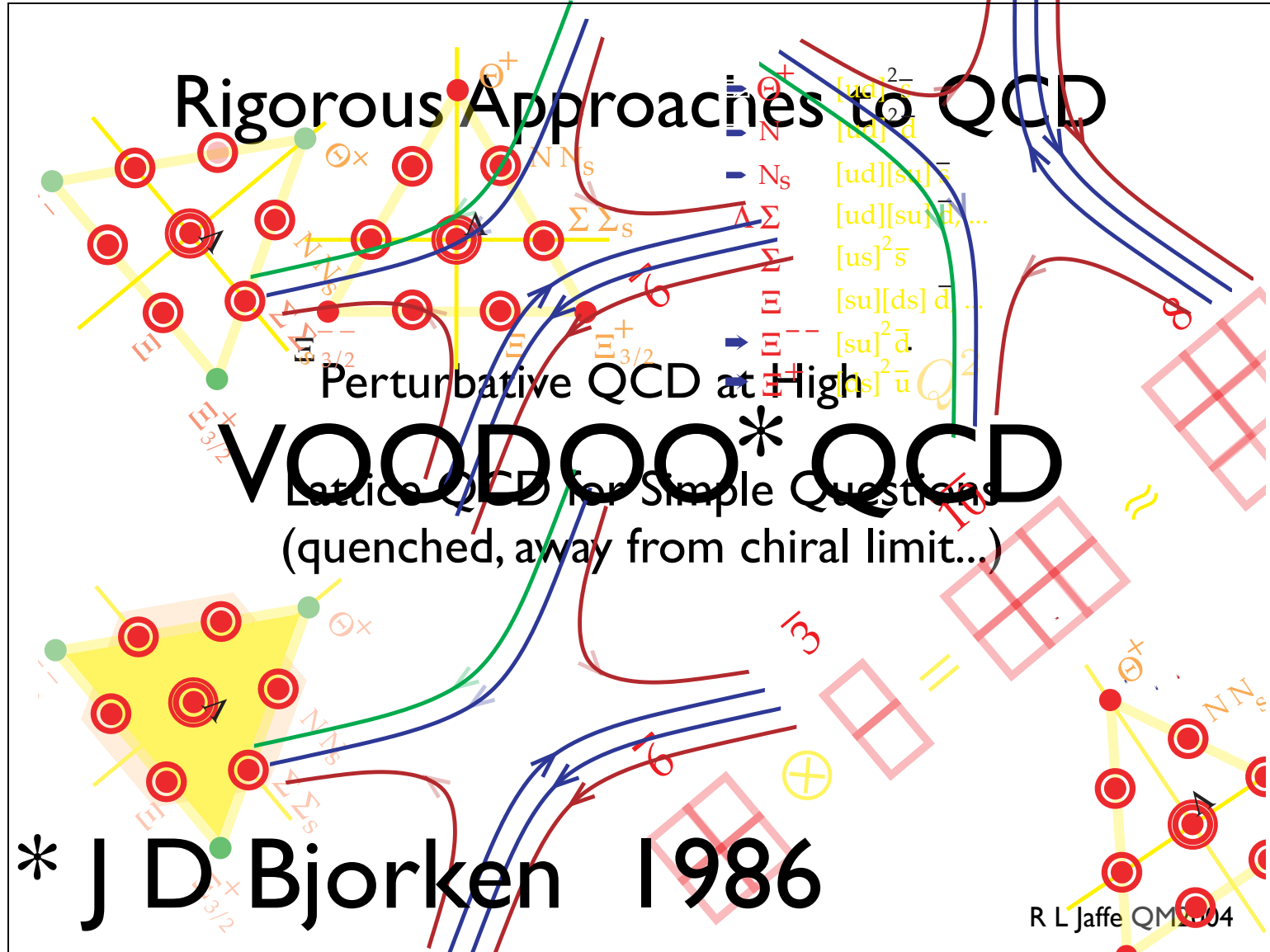
Perturbative QCD at High

VOODOO* QCD

Lattice QCD for Simple Questions
(quenched, away from chiral limit...)

* J D Bjorken 1986

R L Jaffe QM04



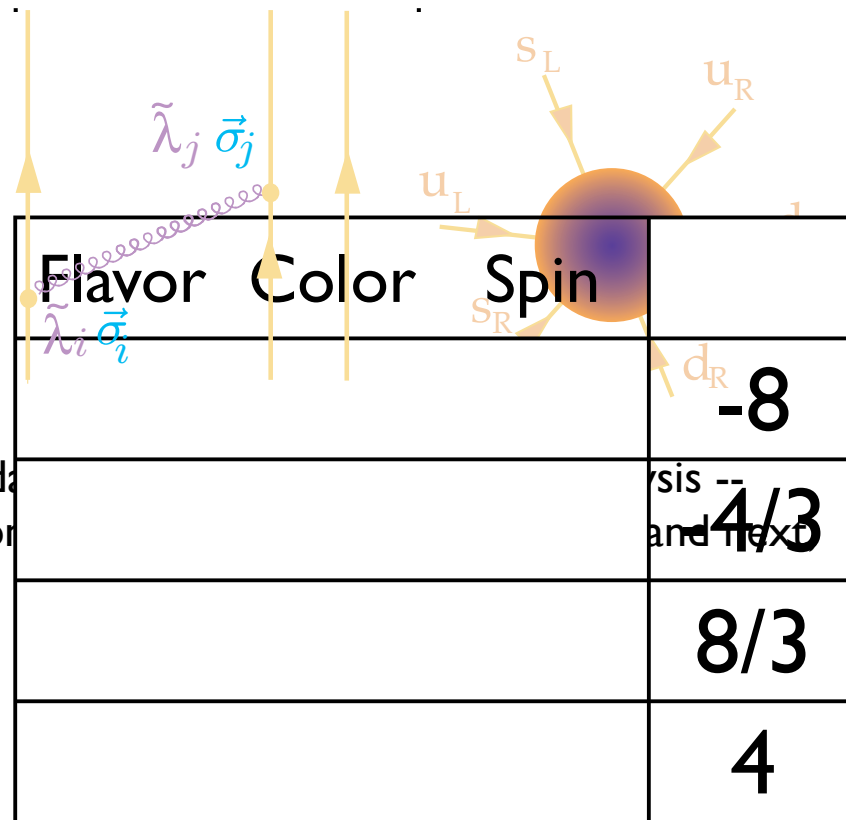
Basic idea

- Experimental discoveries of the past year.
- Continuing clarification of longstanding problems with scalar mesons
- Suggest diquark correlations in QCD^{*}

*

I'm will advocate a particular interpretation of the physics, and I must say up front that it is by no means established or universally accepted. (It does have the virtue of being readily falsifiable, so I expect that this talk will come to look either prescient or hopelessly misguided within a few years.) In fairness I will say a few words about the leading alternatives, and how they can be distinguished.

Strong Correlations in QCD

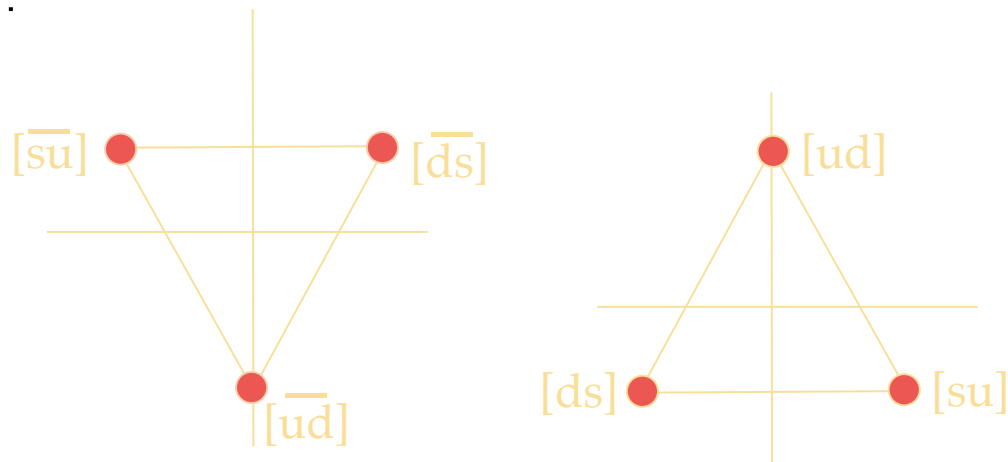


Both perturbative QCD -- standard
and instanton induced interactions

the flavor antisymmetric
color antisymmetric
spin singlet diquark

The Favored Diquark

$$QQ\bar{3}_f\bar{3}_c0_s \Rightarrow Q$$



Note: these are SMALL flavor representations

Supporting Role for Diquarks

- Certain regularities in baryon spectroscopy
 - Absence of $L = 1[20]$ of $SU(6)$
- Condensation in quark matter at high density
 - Q condenses in flavor antisymmetric channel generating color-flavor locked superconductivity
- Behavior of nucleon parton distributions in valence domain
 - Limiting behavior of spin dependent quark distributions

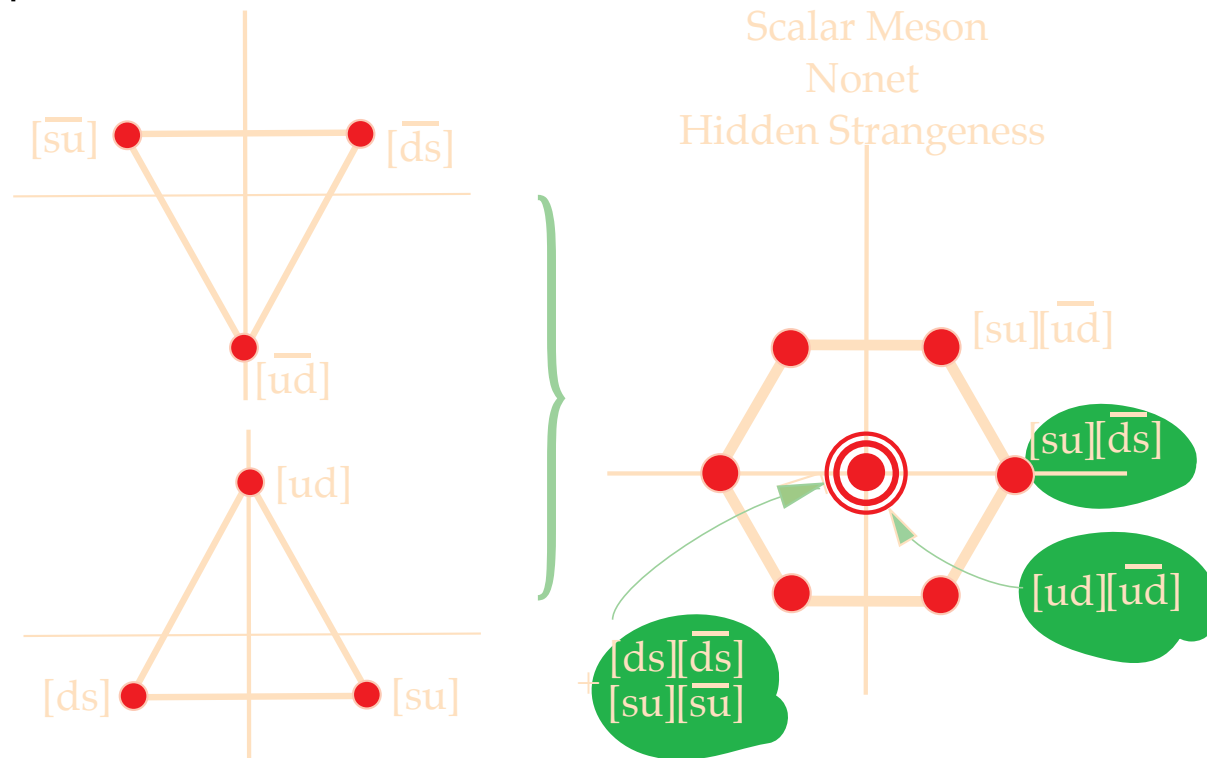
$$\lim_{x \rightarrow 1} \begin{cases} \Delta u/u = 1 \\ \Delta d/d = -1/3 \end{cases}$$

Interesting new data
from JLab nucl-ex/
030811 supports
diquark correlations!

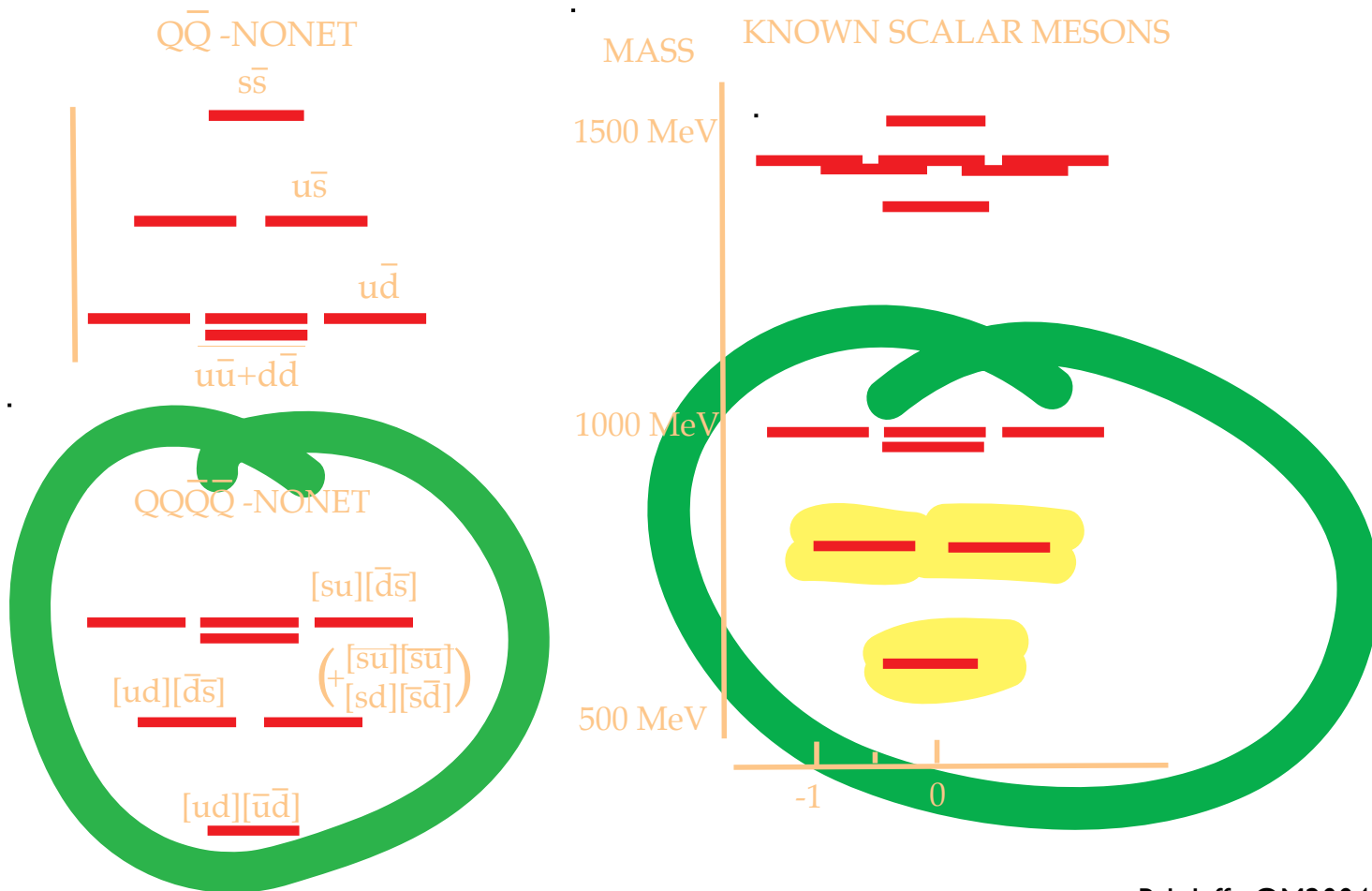
Immediate Exotic Consequences

- No exotic mesons $Q \otimes \bar{Q} \supset 1_f \oplus 8_f$
Just like $q \otimes \bar{q}$
- Scalar meson nonet made from $Q \otimes \bar{Q}$
Accumulating evidence over many years
- The ONLY prominent exotic baryons will be
 $Q \bar{3}_f \otimes Q \bar{3}_f \otimes \bar{q} \bar{3}_f \supset \bar{10}_f \oplus 8_f$
- Possibly stable charm and bottom analog exotics
 $([ud][ud]\bar{s}) \Rightarrow ([ud][ud]\bar{c}) \Rightarrow ([ud][ud]\bar{b})$

A Tetraquark Scalar Nonet !



Summary of Scalar Meson Data



Experimental Discoveries

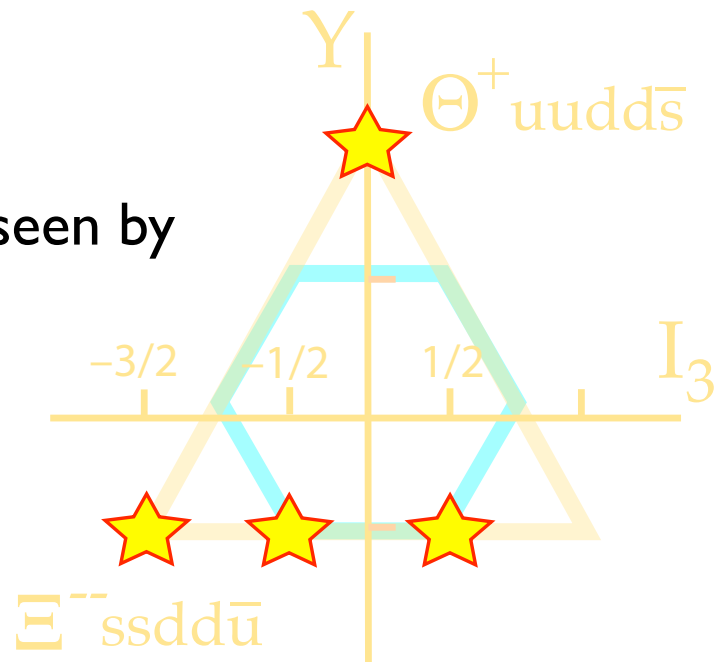
$$\Xi^+(1540)$$

One manifestly exotic baryon seen by many experiments.

$$\Xi^{--}(1860) \quad **$$

$$\Xi^0(1860) \quad **$$

$$\Xi^-(1855) \quad *$$

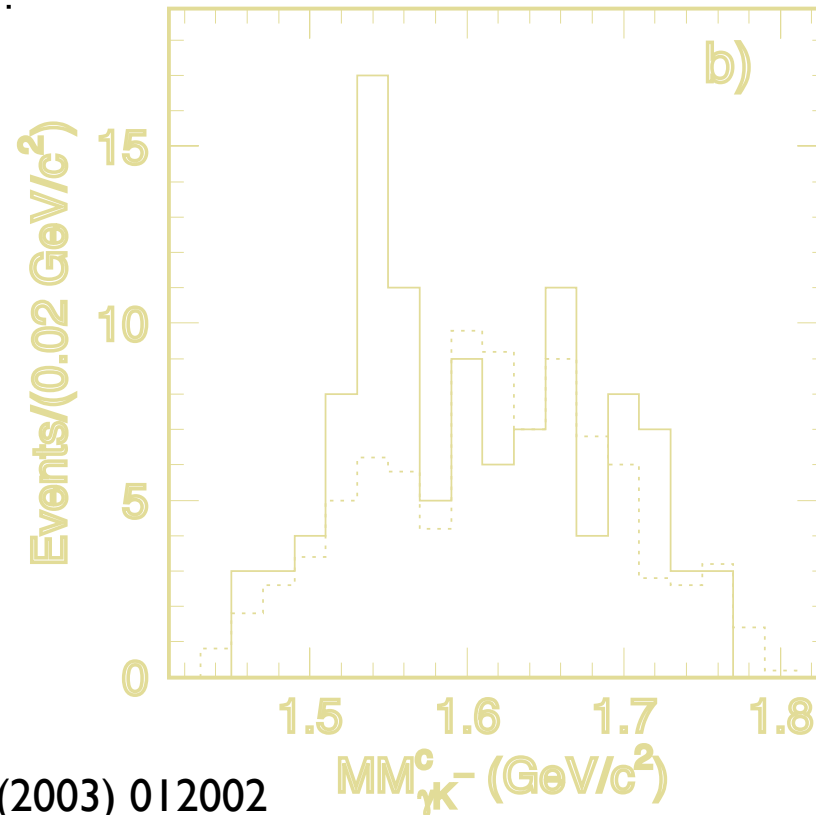


Another exotic and two non-exotic partners seen by one experiment.

Evidence for the

$\Theta^+(1540)$

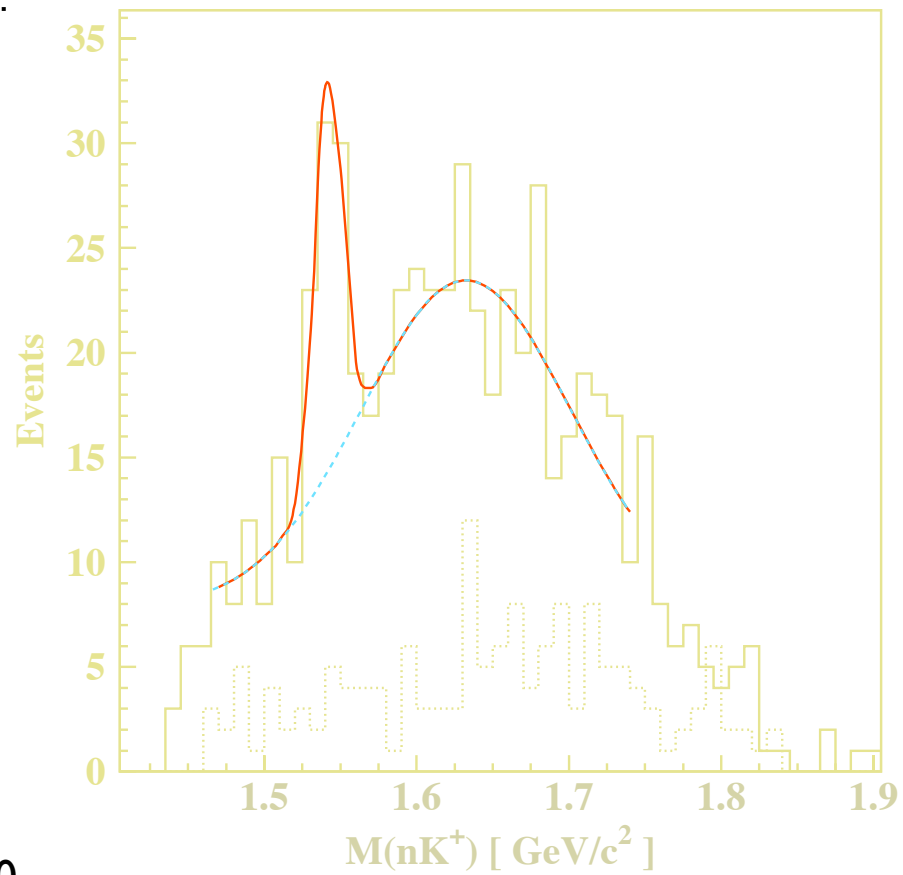
SPRing-8



CLAS PRL 91 (2003) 012002
hep-ex/0301020

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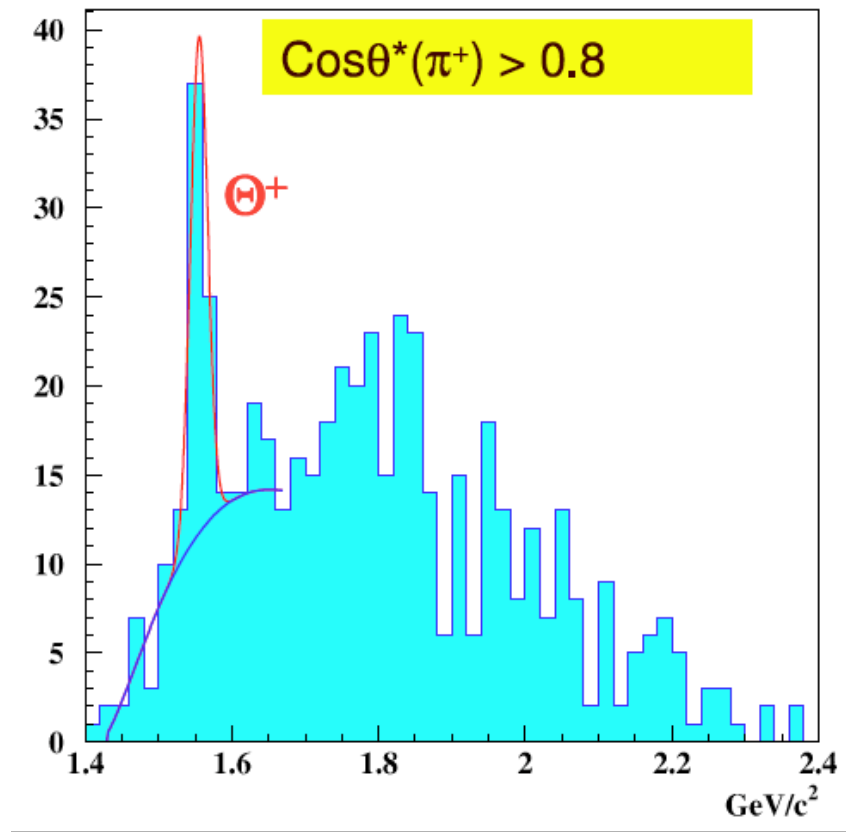
CLAS @ JLab I $\square D \rightarrow K^+ K^- p n$



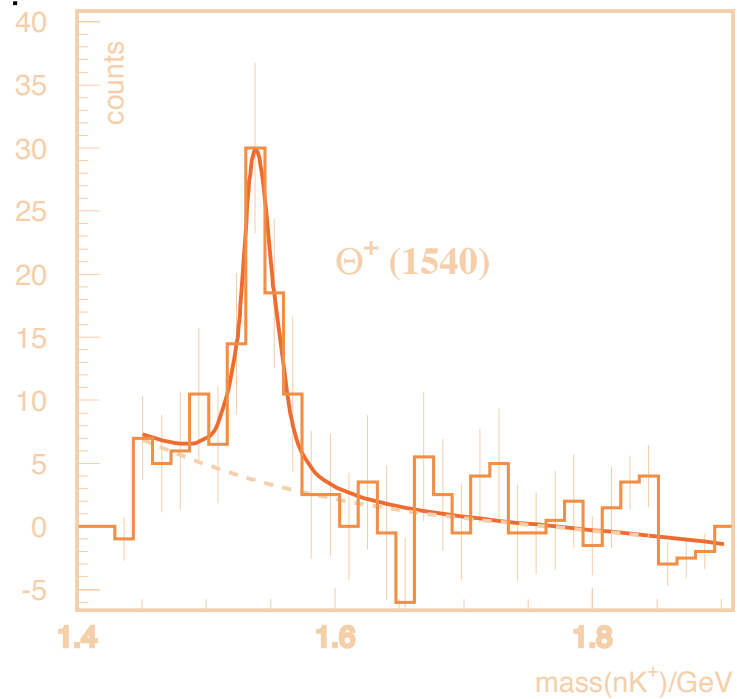
hep-ex/0304040

R L Jaffe QM2004

CLAS @ JLab II $\square D \rightarrow K^+ K^- p n$



SAPHIR @ BONN $\pi^+ p \rightarrow \pi^+ \pi^- K^+ n$

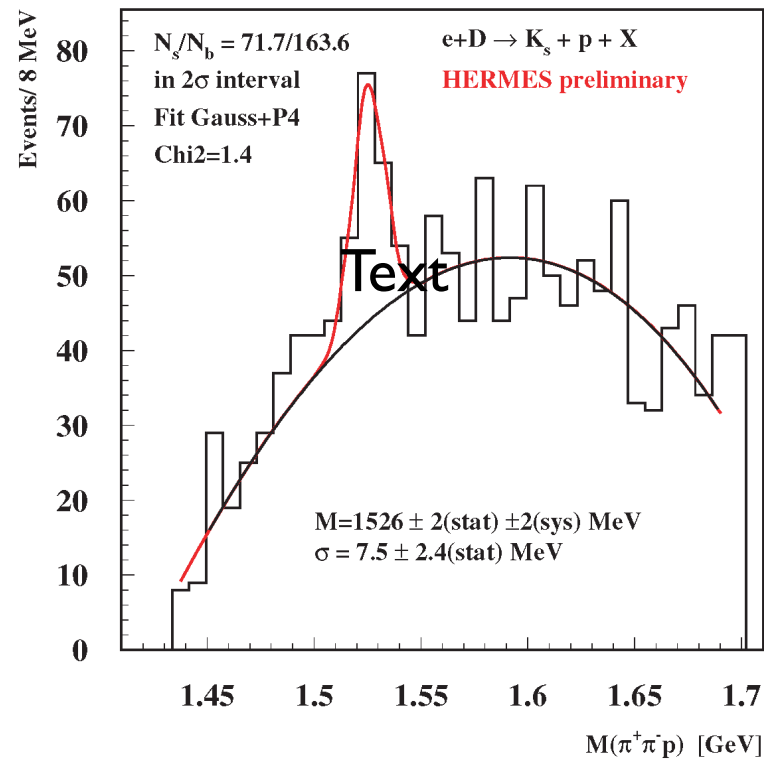


SAPHIR PL B572 (2003) 127
Jlab Pentaquark Workshop

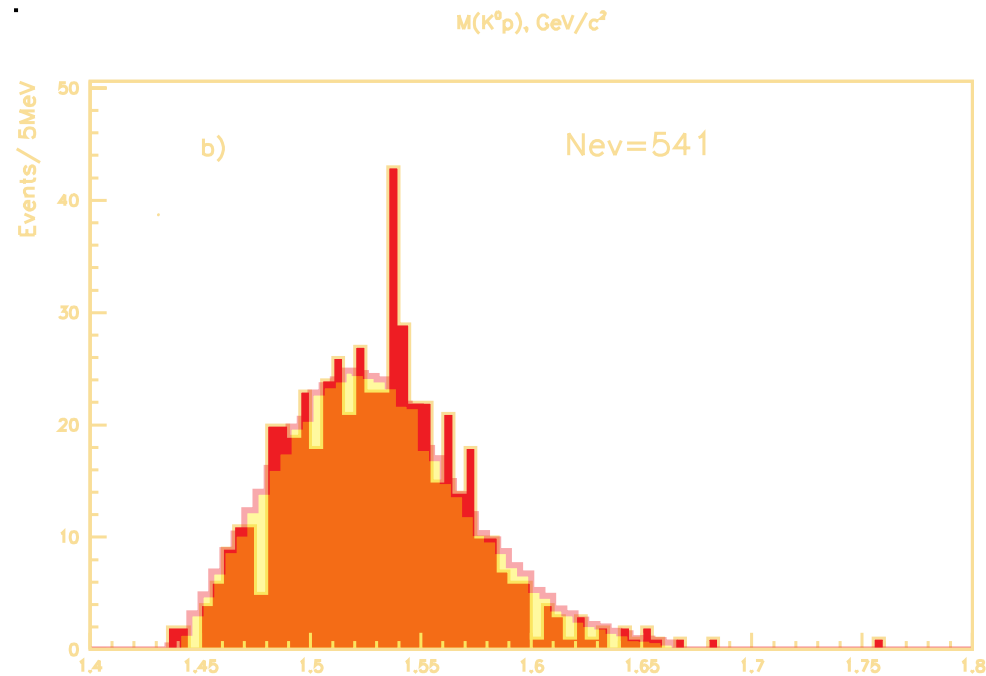
SAPHIR (ELSE)

R L Jaffe QM2004

HERMES



DIANA @ ITEP $K_S p$ in Xe

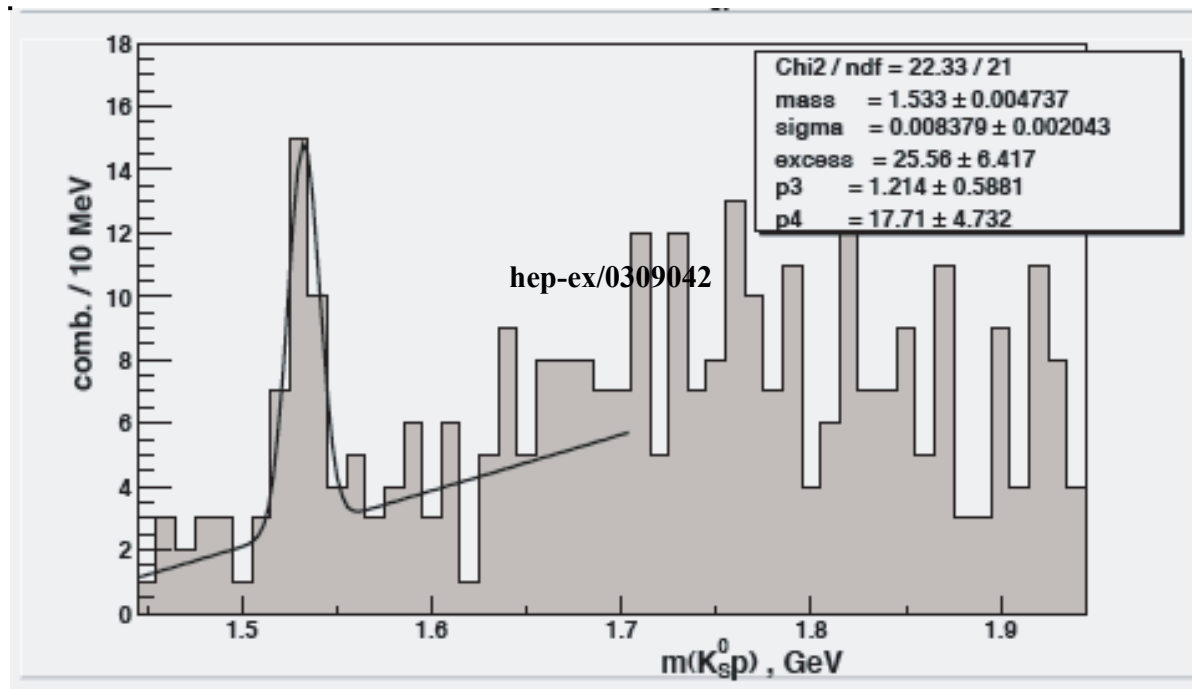


hep-ex/0304040
Jlab Pentaquark Workshop

DIANA (ITEP)

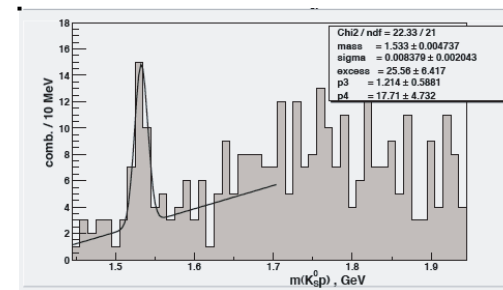
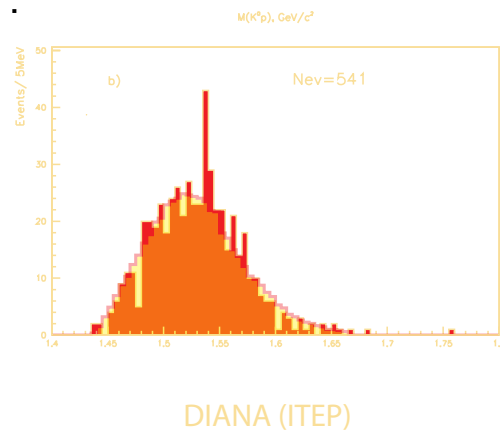
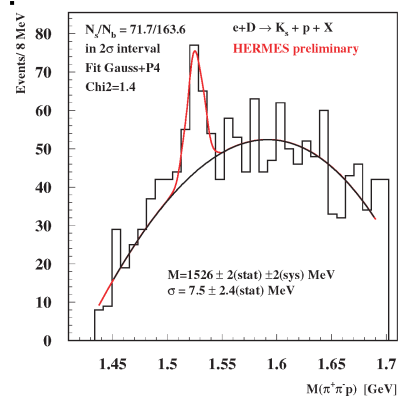
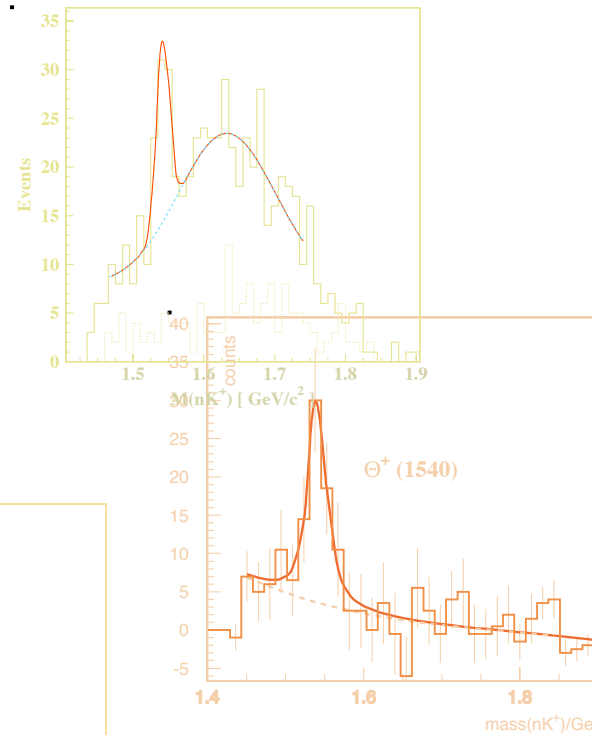
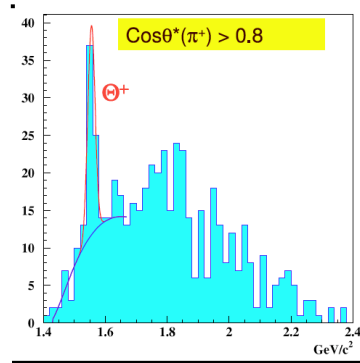
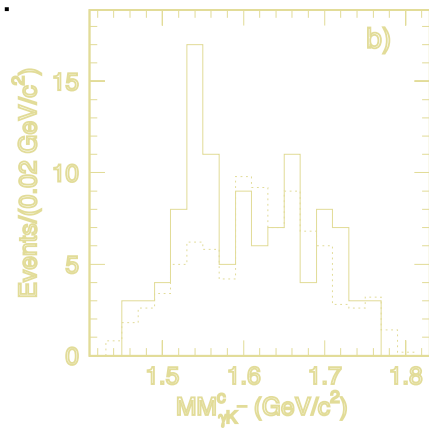
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Neutrino Bubble Chamber Compendium



hep-ex/0309042, M. Kubantsev
Jlab Pentaquark Workshop

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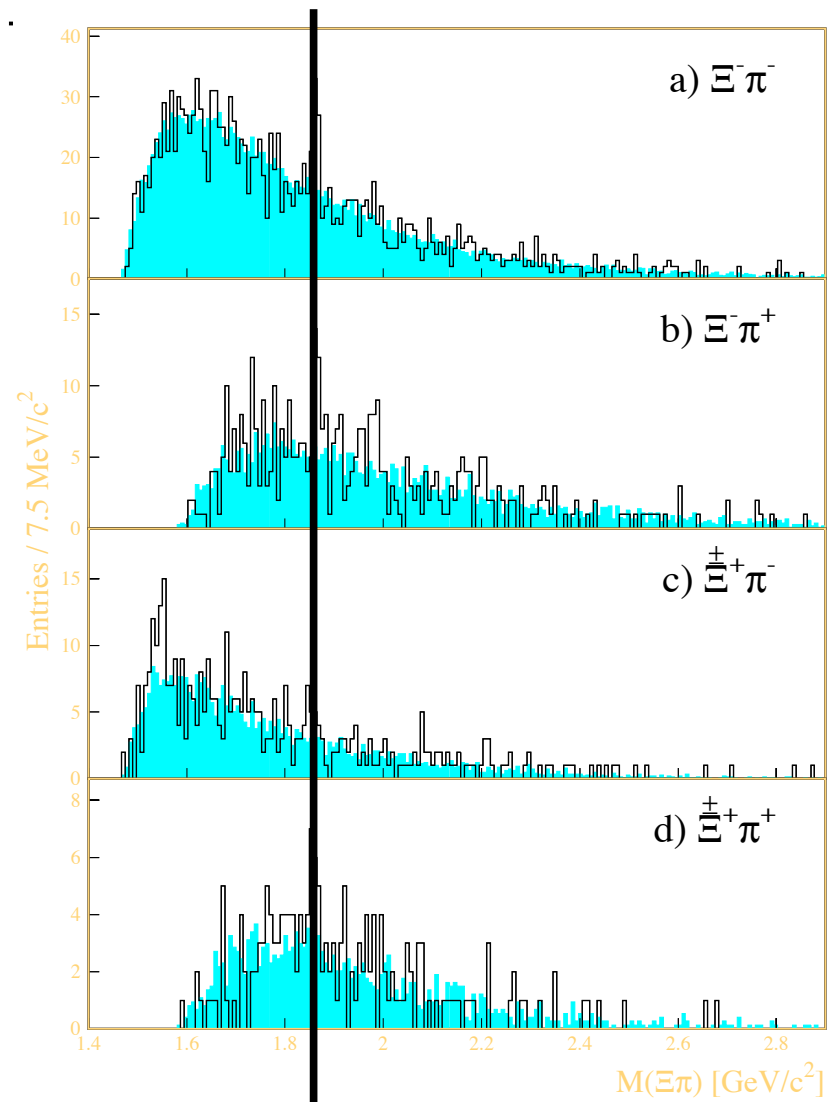


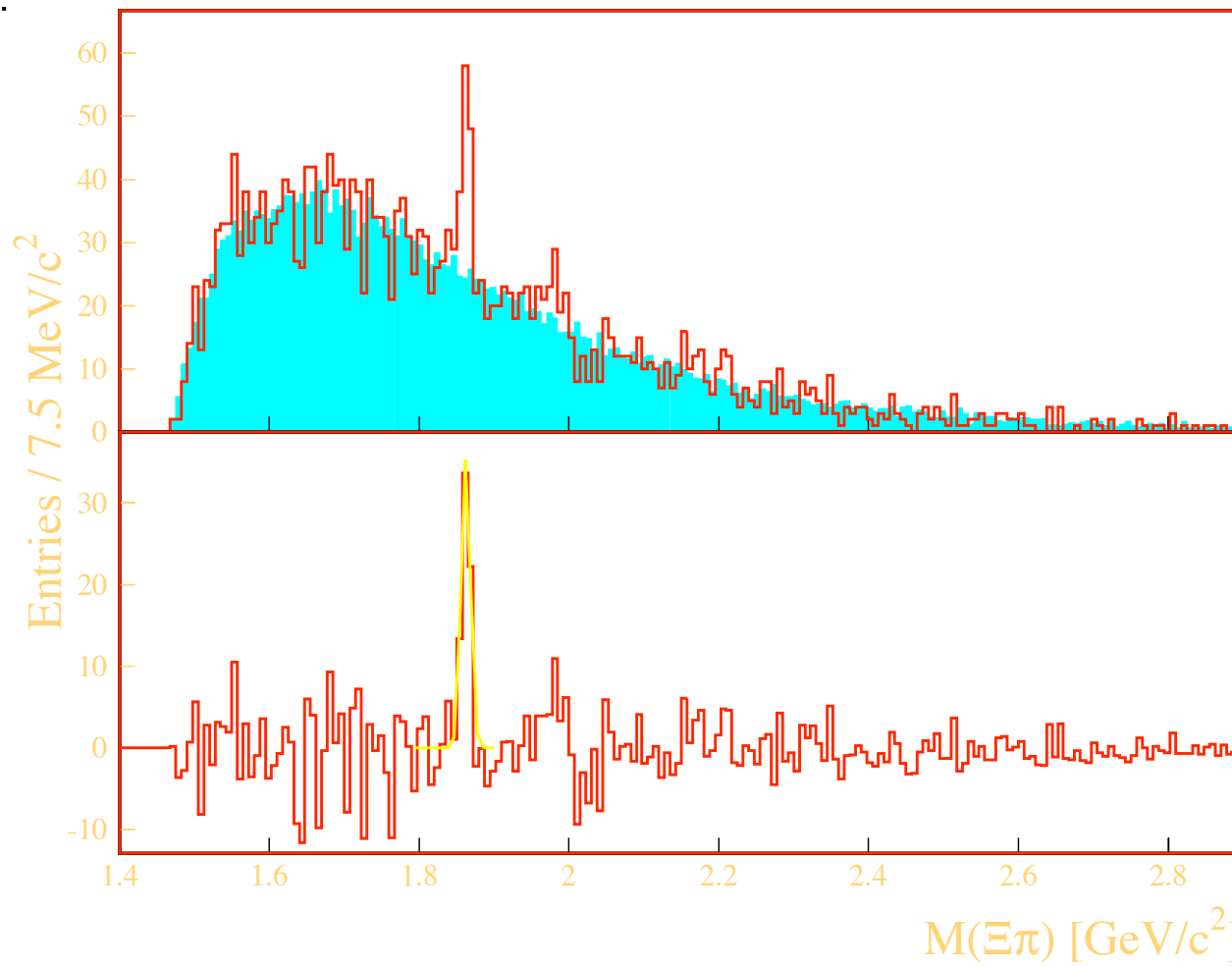
Evidence for the

$\square^{--}(1860)$ ★★

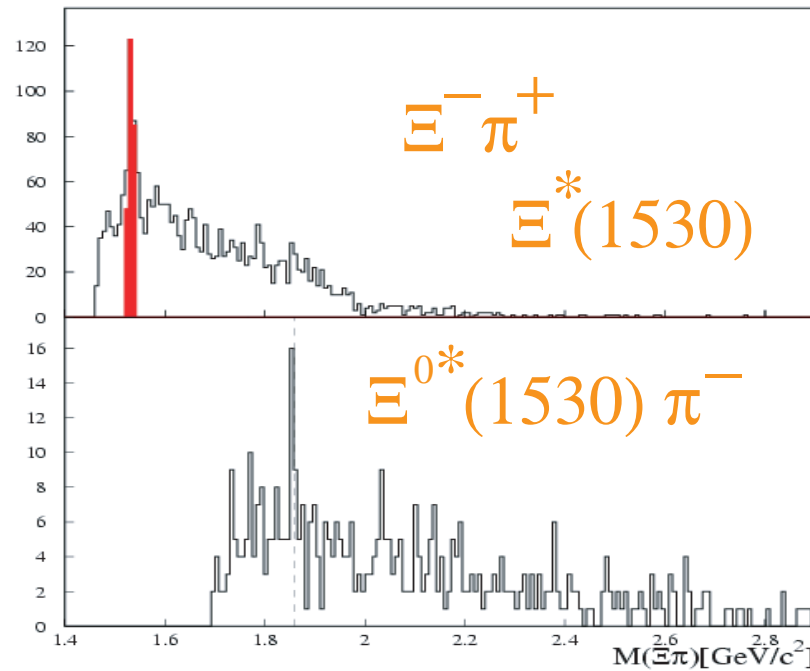
$\square^0(1860)$ ★★

$\square^-(1855)$ ★



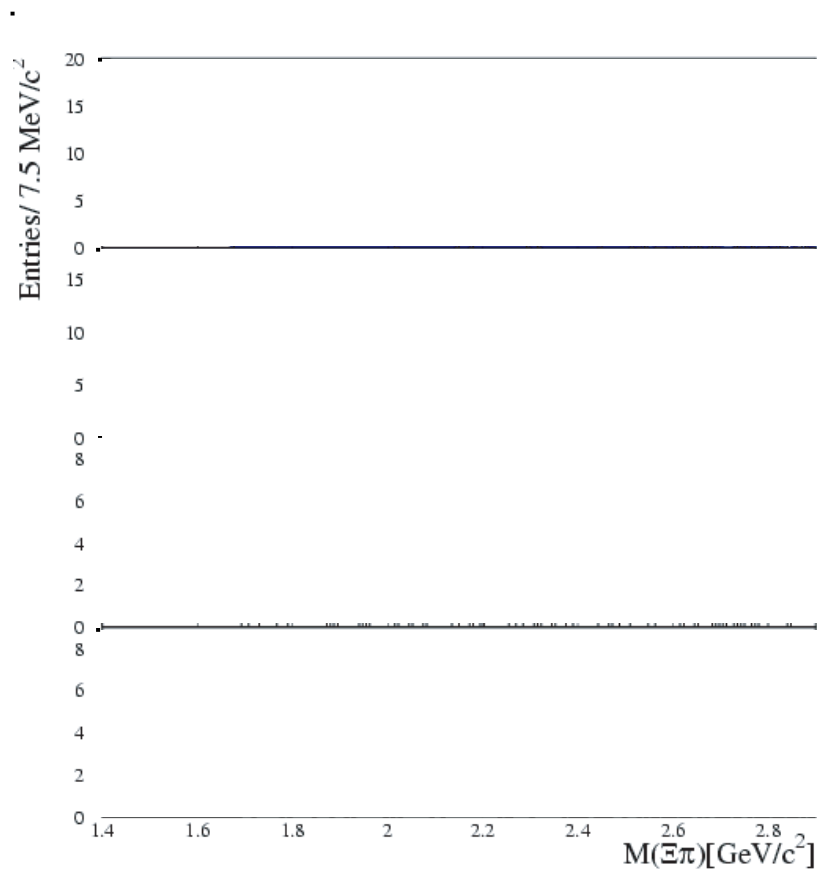


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NA49 Evidence for $\Xi_{1/2}^- \rightarrow \Xi^{0*}(1530)\pi^-$

Very preliminary --- additional data also shows signal



Evidence for



but none for



Upper figures show uncut data. Lower include cuts on pion momentum &c.

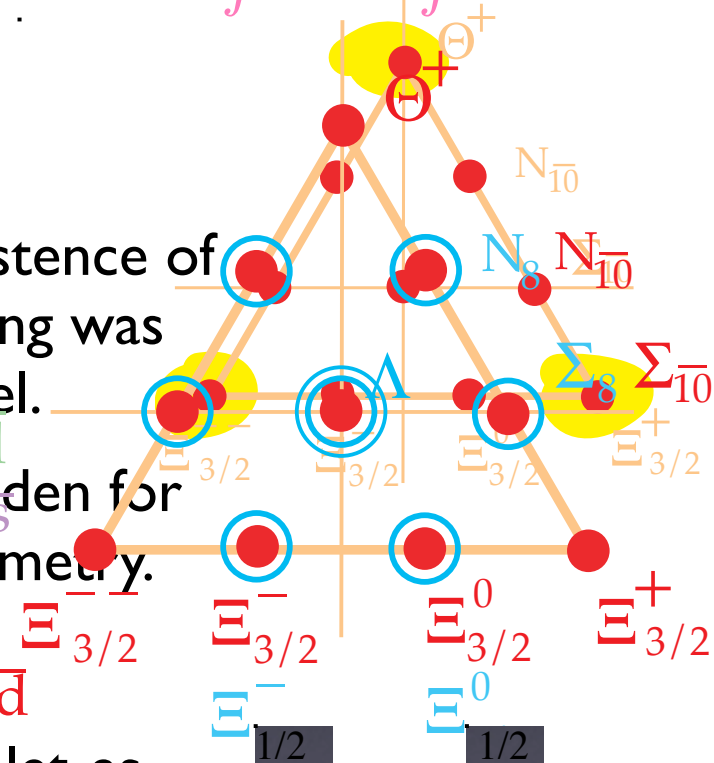
Implications of Data $\supset \overline{10}_f \oplus 8_f$

- Θ^+ (1540) establishes existence of antidecuplet
- Ξ^{--} (1860) confirms existence of antidecuplet & small splitting was predicted by diquark model.
- Ξ (1330) ~~Ξ^*~~ π forbidden for antidecuplet by SU(3) symmetry.

Evidence for octet nearly degenerate with antidecuplet, as predicted by diquark dynamics.

Ideally Mixed
Quark Content

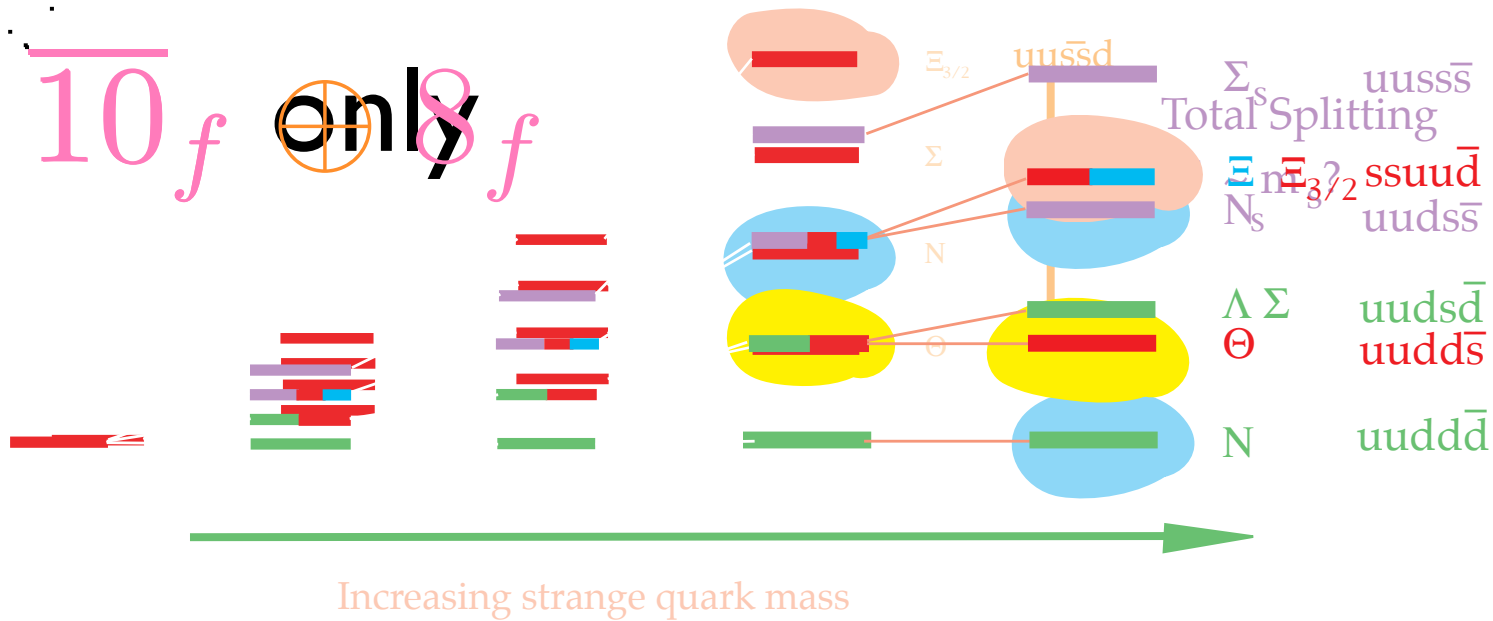
Octet and Antidecuplet



SU(3) Mass Splittings

$\overline{10}_f$ versus $\overline{10}_f \oplus 8_f$

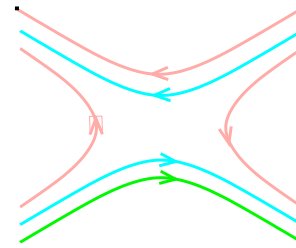
Note that $\Xi - \Theta$ is larger across the multiplet -- smaller splittings



Other dynamical approaches

- Chiral Soliton (Skyrme) Model

$$8^{1/2^+} \quad 10^{3/2^+} \quad \overline{10}^{1/2^+} \quad 27^{3/2^+} \quad 35^{3/2^+}$$



- Traditional (uncorrelated) Quark Model



- Diquark-Triquark Model (Karlner/Lipkin)



- KN Bound State (potential theory)
- More every day!

Model	<p style="text-align: center;"> ρ Absence of Charm & other Normal Scalarity of Bottom Prominent Antidecuplets, Pentaanalogs, States & the Missing 10, 27, $\Theta^{3/2+}$ </p>									
	↓	↓	↓	↓	↓	↓	↓	↓	↓	↓
Diquarks	✓	✓	✓	✓	✓	+	?	✓	X	✓
Skyrme	*	✓	*	*	X	+	?	X	✓	X
Triquark (KL)	✓	✓	X	X	✓	±	?	X	X	✓
Traditional QM	✓	X	✓	✓	✓	-	X	?	✓	X
KN Bound	✓	X	*	*	X	±	X	X	✓	?

* Not applicable -- outside context of model

Thoughts for QM2004?

- Can you search for pentaquark signals in heavy ion collisions? STAR, Phenix?

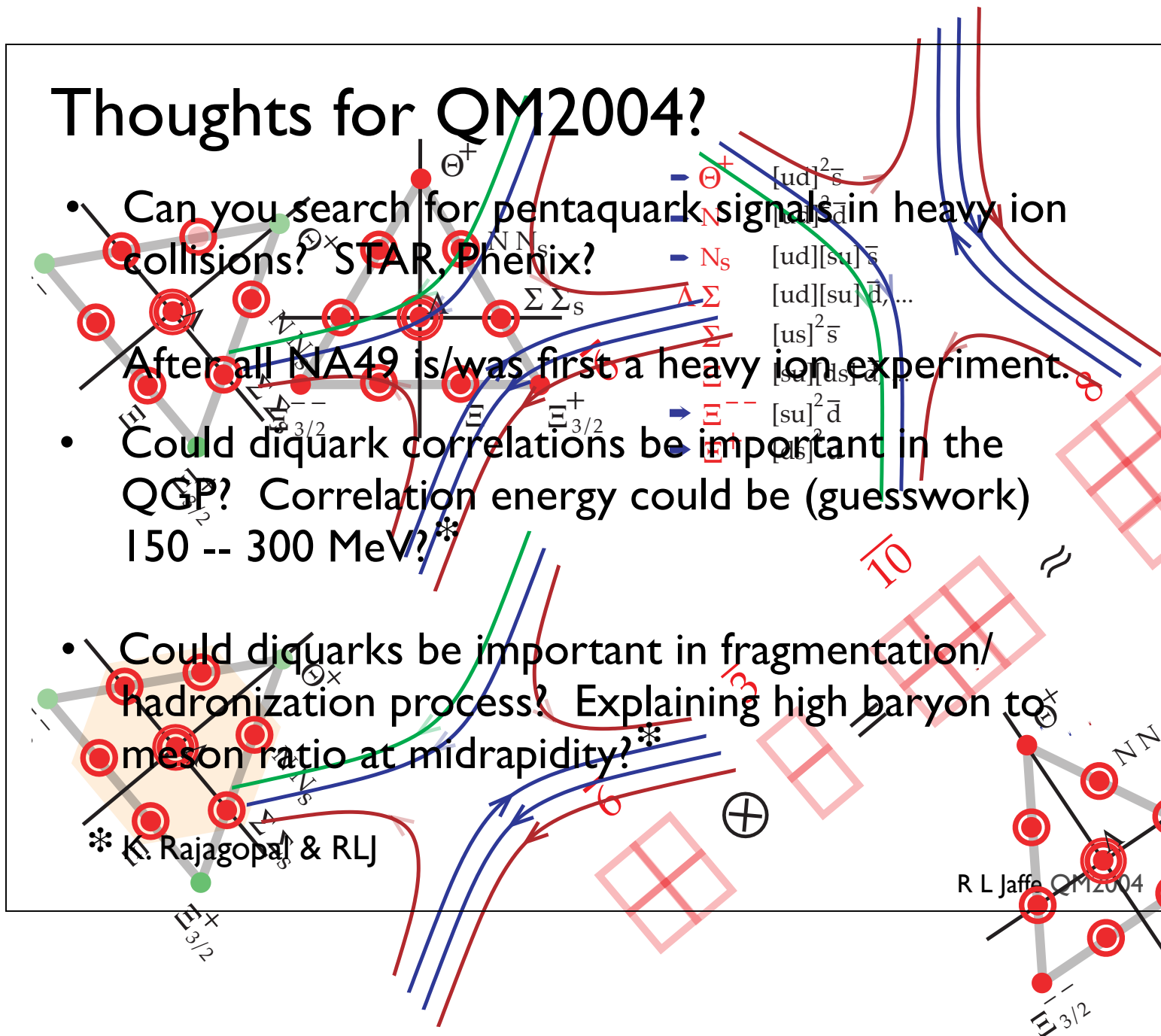
After all NA49 is/was first a heavy ion experiment.

- Could diquark correlations be important in the QGP? Correlation energy could be (guesswork) 150 -- 300 MeV?*

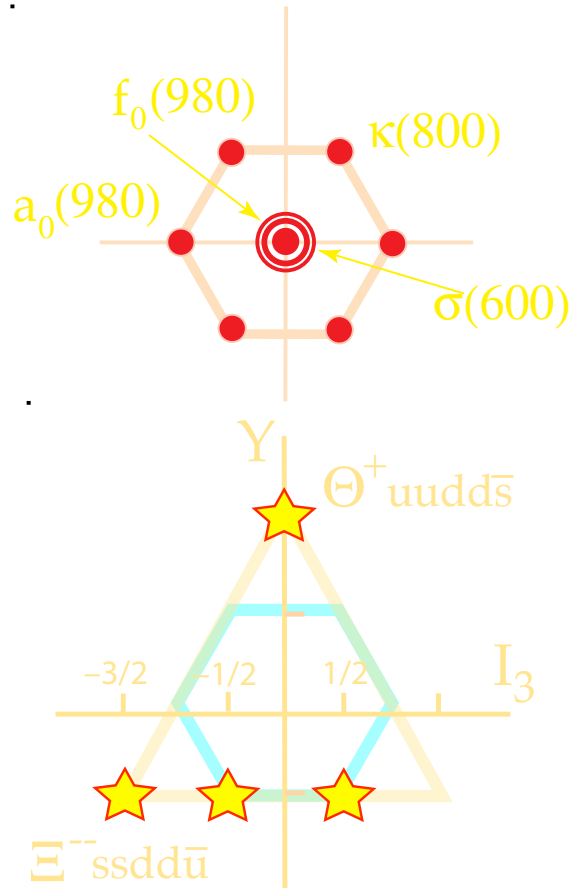
- Could diquarks be important in fragmentation/hadronization process? Explaining high baryon to meson ratio at midrapidity?*

* K. Rajagopal & RLJ

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Diquarks, Tetraquarks, Pentaquarks



What's next?

- Confirmation (or not)?
- Crucial dynamical tests
 - Parity
 - Octet plus decuplet?
 - $27_f^{3/2}$ $35_f^{3/2+}$ as predicted by Skyrme model?
 - Spin 3/2 partners?
- Charm and bottom pentaquarks ?
- Lattice tests of spectrum and wavefunctions!