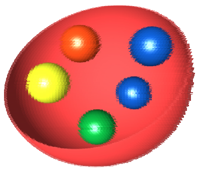

Pentaquarks

in Chiral Soliton Models

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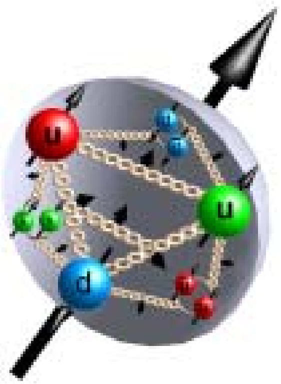
Feb.17-19, 2004, talk on Feb.18

at Yukawa Institute for Theoretical Physics, Kyoto Univ.

In Collaboration with B. Wu

Hep-ph/0312041, PRD
Hep-ph/0312326, PLB
Hep-ph/0311331

Search for Exotic Baryon States

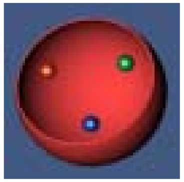


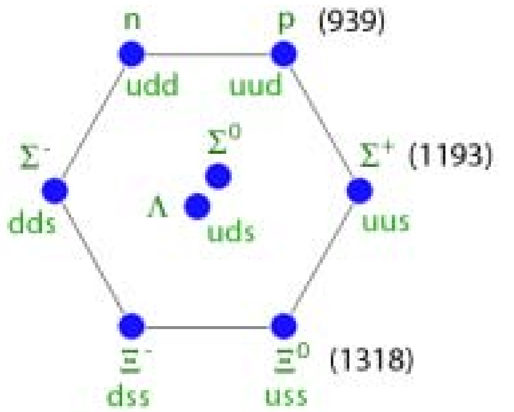
- Standard Quark Model
  - classifies hadrons as
    - mesons ($q\bar{q}$)
    - baryons (qqq)
  - also allows "non-standard" or exotic hadron states
    - multiquark mesons ($qq\bar{q}\bar{q}$)
    - multiquark baryons ($qqqq\bar{q}$)
      -> appear as baryon resonances
    - hybrid states ($q\bar{q}g$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

-> no convincing previous evidence for exotic baryon states.

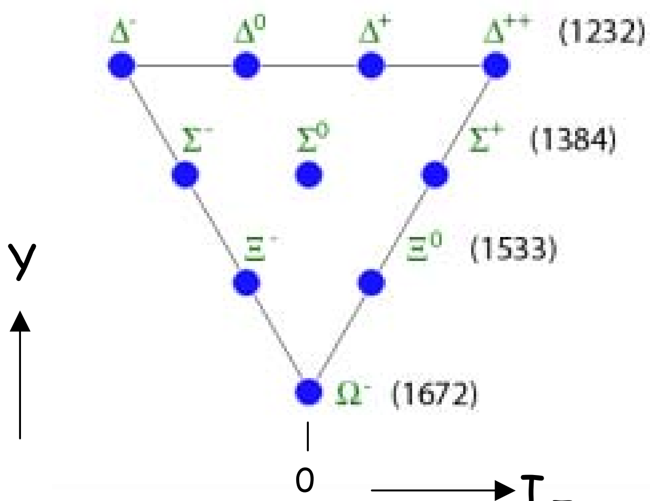
Baryon States

- All baryons observed before
  - classified as singlets, octets and decuplets of SU(3) flavor group
    -> constructed of 3 quarks only,
  - may have higher orbital angular momentum, resonances
  - have strangeness from S=-3 to S=0





baryon octet with $J^P=\frac{1}{2}^+$



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

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

Previous Searches for Exotic Baryons

- Ideally: kaon-nucleon (KN) scattering
- started in 1966 at BNL
  -> "*clear*" resonance peak found in K^+p at
  $M=1.91$ GeV and $\Gamma=180$ MeV
- searches: partial wave analyses in KN scattering
  - candidates: isoscalar $Z_0(1780)$ and $Z_0(1865)$
    -> give poor evidence (PDG)
- dropped from PDG listings after 1986
- reasons for failure:
  - KN (in)elastic scattering at p(K) corresponding to $1.74 \leq M_Z \leq 2.16$ GeV
  - resonance widths large: $70 \leq \Gamma_Z \leq 845$ MeV
  - MIT bag model predictions: $M_Z \geq 1.7$ GeV
- $\Lambda(1405)$: molecular meson-baryon state $uuds\bar{u}$?
  - interpretation problematic: could be uds
    -> ambiguity remains

R. Cool et al., PRL 17, 102 (1966)

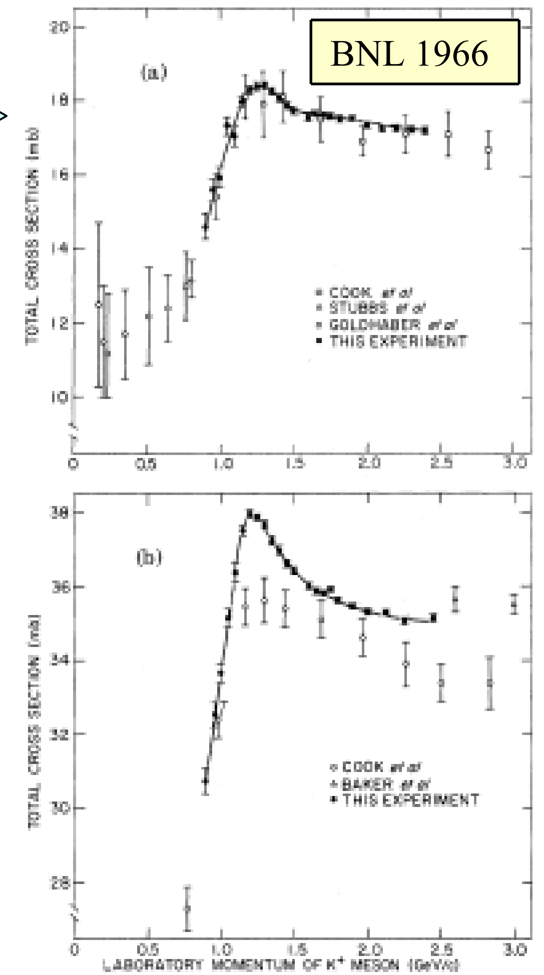
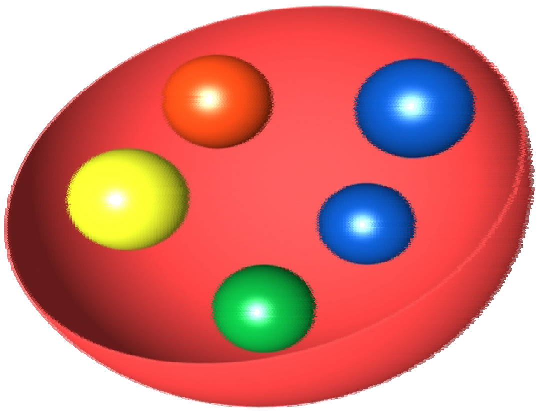


FIG. 1. The total cross section of K^+ mesons on (a) protons, (b) deuterons.

Pentaquark States

- Predictions of pentaquark states with both strange and charm (by Lipkin et al.),

  no evidence found in experimental searches for more than ten years.



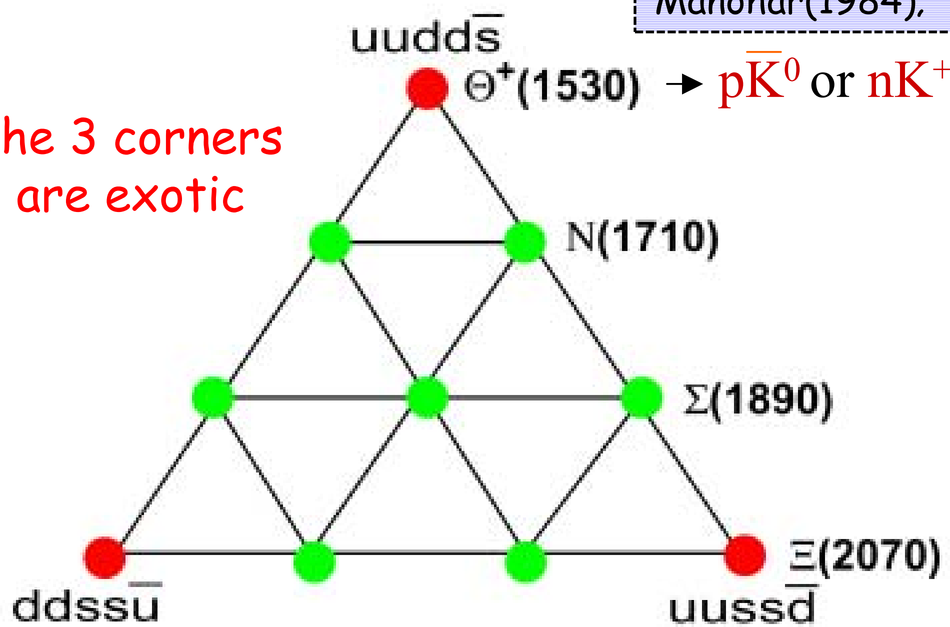
Prediction in Chiral Soliton Model

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

- all baryons are rotational excitations of a rigid object
- reproduces mass splittings witin 1% of
  - baryon octet ($J^P=\frac{1}{2}^+$) and decuplet ($J^P=3/2^+$)
- predicts new anti-decuplet (among many N_c≙🕓 artifacts)
- "only one" free parameter

Based on older predictions:
Manohar(1984); Chemtob (1984); Praszalowicz (1987)

the 3 corners are exotic



$\Xi^-\pi^-$ or Σ^-K^- $\Xi^0\pi^+$ or $\Sigma^{\overline{+}}K^0$

Identifying $P_{11}(1710)$ as member of anti-decuplet:

prediction for Θ^+:

$M=1.53$ GeV, $\Gamma \leq 15$ MeV

I=0 S=+1 $J^P=\frac{1}{2}^+$

with $-$

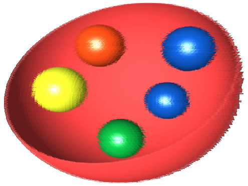
$\Theta^+ \rightarrow K_0\, p$ or $K^+ n$

Nothing is “Exotic” in the Chiral Solition Picture

- **Baryons are “solitons” in the chiral fields.**
- **No baryon is “exotic” except that it has different quantum numbers compared to other baryons.**

"Exotic"-baryon (Pentaquark) Defination

H.Gao and B.-Q. Ma



Mod. Phys. Lett. A 14 (1999) 2313

- **A pentaquark $qqqq\bar{q}$ state can be clearly distinguished from the conventional qqq-baryon state or their hybrids if the flavor of $\bar{q}$ is different from any of the other four quarks:**

minimal Fock state of pentaquark

- **Possible existence of $uudd\bar{s}$ and $uuud\bar{s}$ states are suggested.**

Suggestion for search of pentaquark uudd$\bar{s}$ state in physics process

H.Gao and B.-Q. Ma ***Mod. Phys. Lett. A 14 (1999) 2313***

- Suggested: $\gamma^* n \rightarrow \mathrm{K}^- \, \Theta^+$

  missing mass method to construct Θ^+

- SPring8 and CLAS experiments: sub-process

  $\gamma \, n \rightarrow \mathrm{K}^- \, (\mathrm{K}^+ \mathrm{n})$

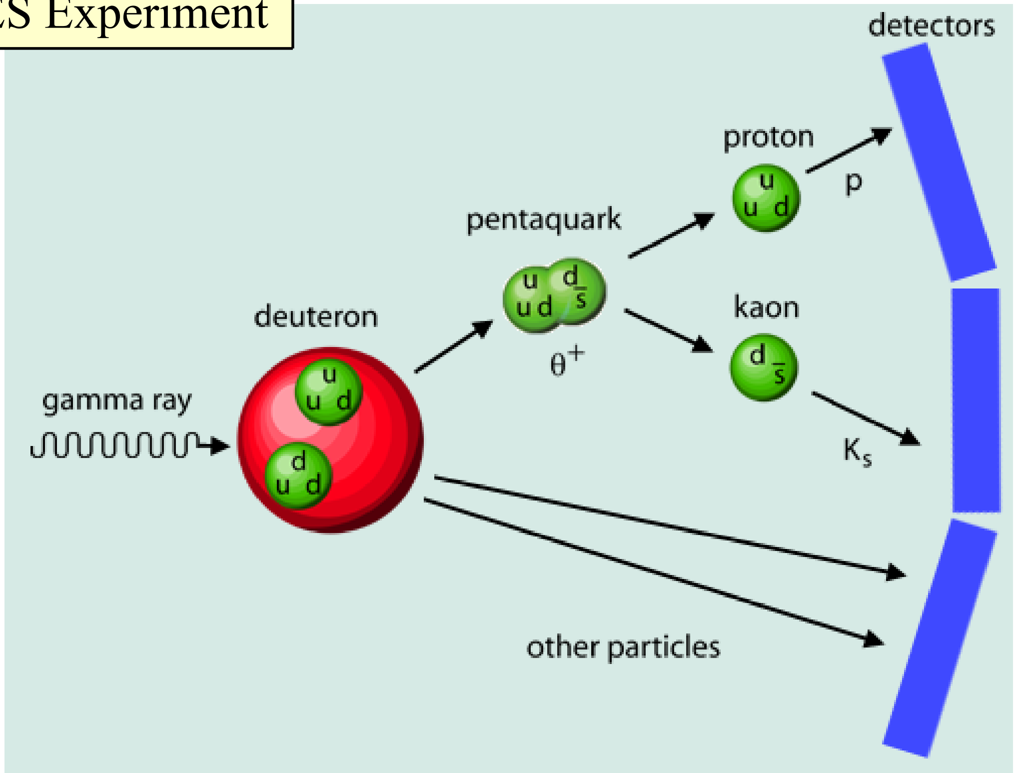
  an additional K^+ is detected to reduce background for the missing mass spectrum and real photon is used instead of virtual photon.

What is a Pentaquark

A pentaquark is a hadron that is composed of 4 valence quarks and one valence antiquark. It has strangeness S=+1 and is tightly bound by the strong hadronic force.

-> constitutes a new form of matter

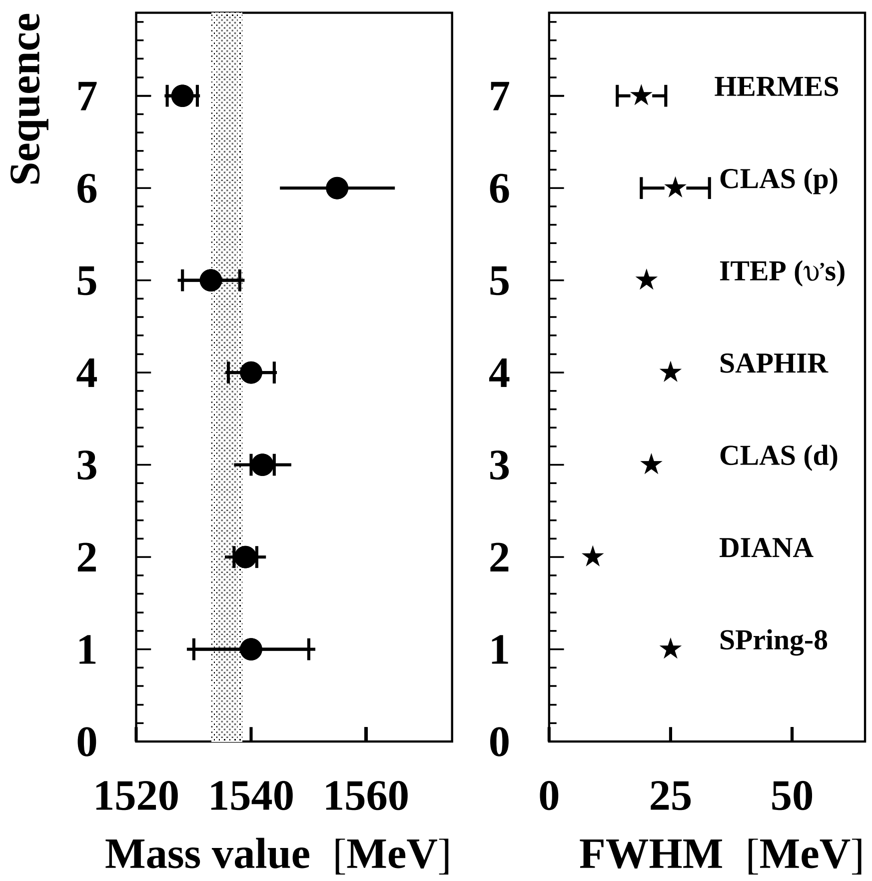
HERMES Experiment



Decay Mode:

$\Theta^+ \rightarrow K_s\, p$ or $K^+ n$

Summary of recent experiments



world-average:

$M(\Theta^{+})$: 1535.8±2.7 MeV

Summary of recent Evidence for

Experiments	Results Mass (MeV)	 Width (Mev)	 $\sigma(=N_s/\sqrt{N_b})$
SPring8	$1540 \pm 10 \pm 5$	$\Gamma < 25$	4.6 ± 1
DIANA	$1539 \pm 2 \pm$ "few"	$\Gamma < 8$	4.4
CLAS	$1542 \pm 2 \pm 5$	FWhM = 21	5.3 ± 0.5
SAPHIR	$1540 \pm 4 \pm 2$	$\Gamma < 25$	4.8
ITEP (ν)	1533 ± 5	$\Gamma < 20$	6.7
HERMES	$1526 \pm 2 \pm 2$	$\Gamma < 13$	5.6 ± 0.5
KN elastic		Γ ❾ few MeV !	
One theory (χQSM)	1530 MeV I=0 S=+1	$\Gamma < 15$ MeV $J^P = \frac{1}{2}^+$	

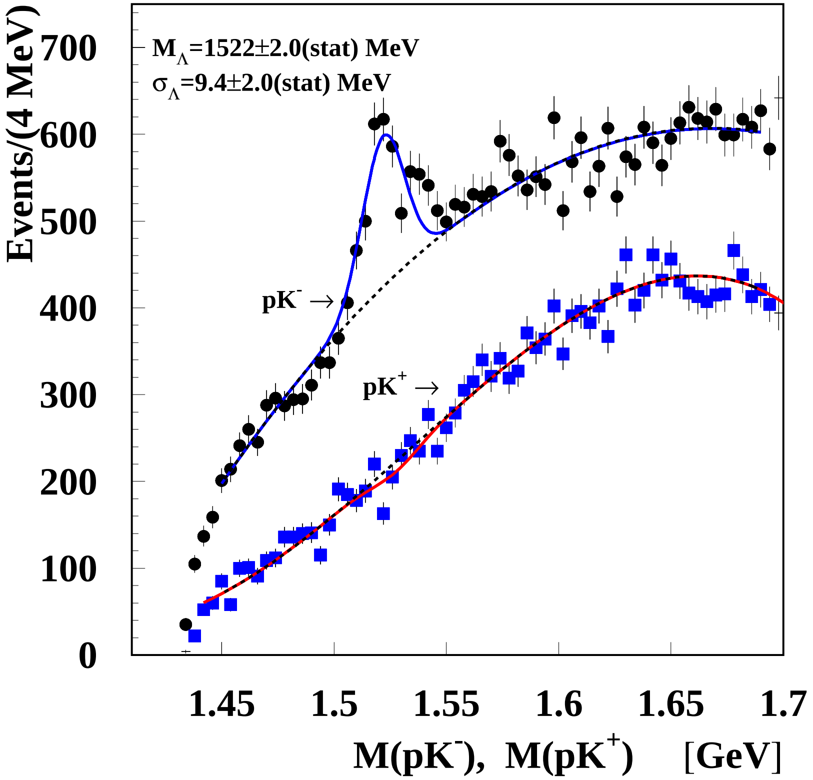
Next:

- Determine width, other quantum numbers (parity!).

no evidence for $\Theta^{++} \rightarrow K^{+}p$ in HERMES

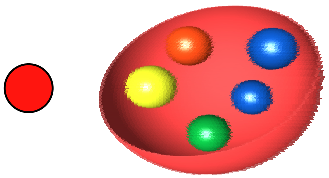
Suggesting Θ+ Being Isosinglet

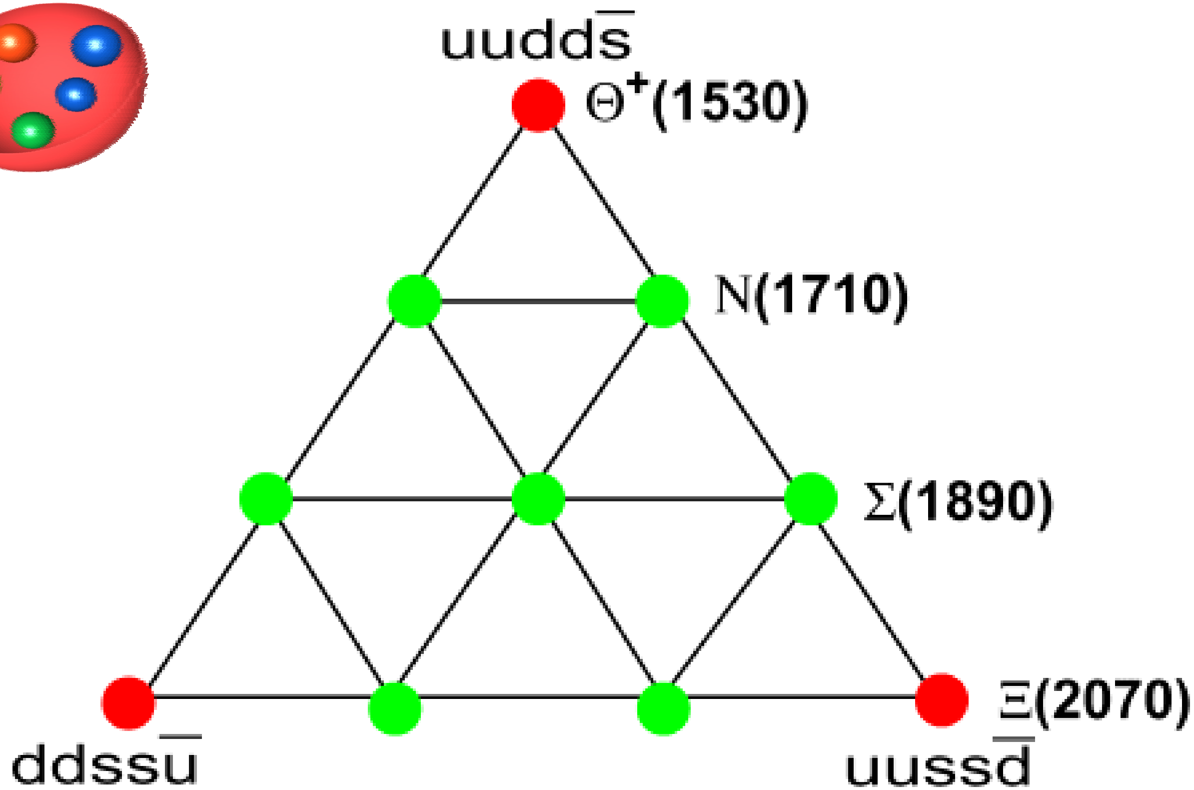
I=0



Pentaquark States from Theory:

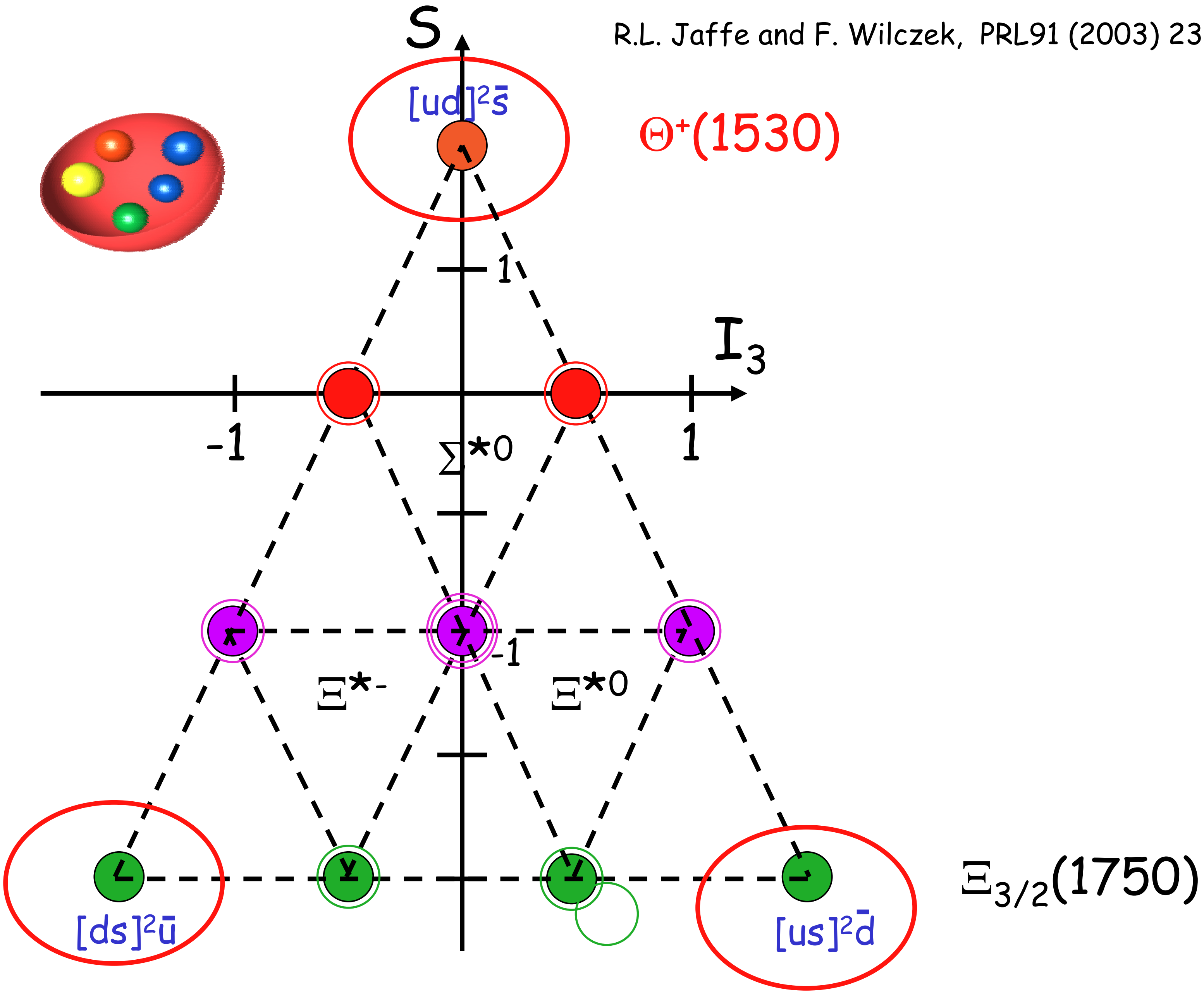
anti-decuplet in chiral soliton models-1st version





Prediction of Diquark model

R.L. Jaffe and F. Wilczek, PRL91 (2003) 232003

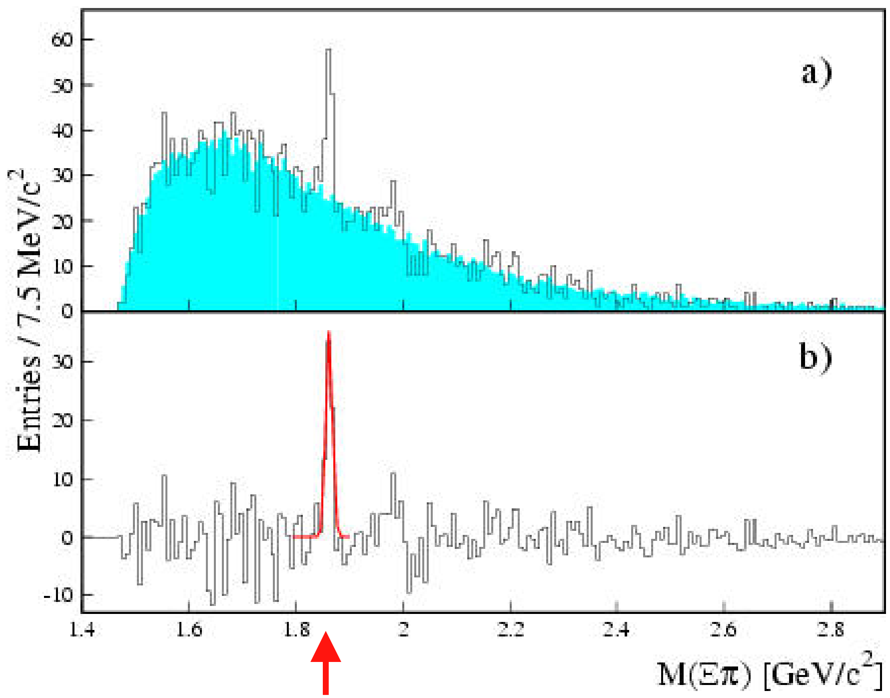


Evidence for New Pentaquark?

- NA49 at CERN
  $\sqrt{s}$ = 17,2 GeV

$pp \rightarrow \Xi^{*--} X, \quad \Xi^{*0} X,$
$\quad \rightarrow \Xi^- \pi^- \quad \rightarrow \Xi^- \pi^+$

C. Alt et al., hep-ex/0310014



1,862 ± 0,002 GeV

χSM: $M(\Xi^{*--})$ = 2070 MeV

$[q_i q_j]^2 q$: $M(\Xi^{*--})$ = 1750 MeV

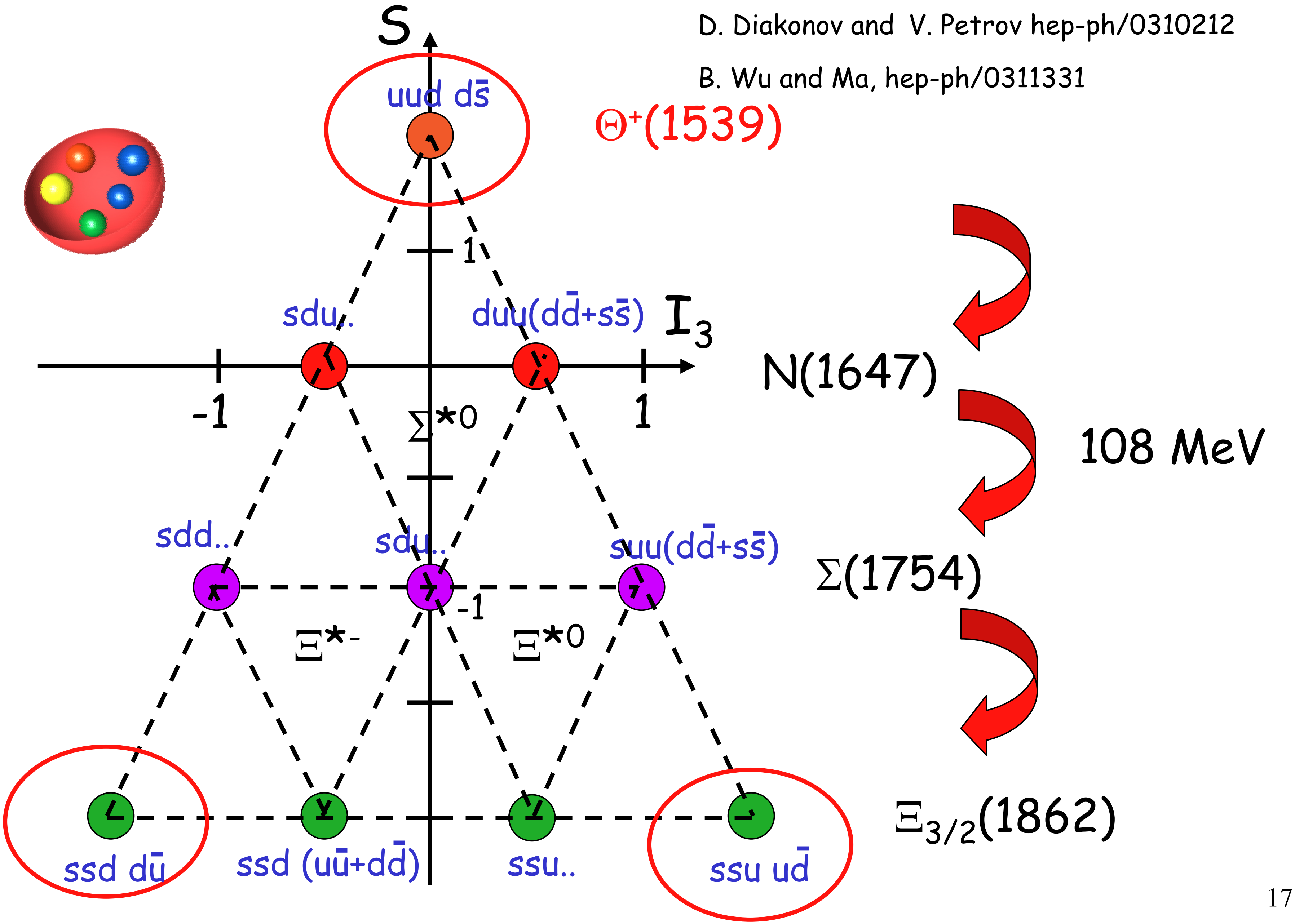
But: It is not what theory predicted !

D. Diakonov et al., hep-ph/0310212

Anti-Decuplet in Chiral Soliton Model - Version 2

D. Diakonov and V. Petrov hep-ph/0310212

B. Wu and Ma, hep-ph/0311331



Where are the missing members of antidecuplet?

- For baryons with spin ½ and + parity, there is no N around, and a weak evidence for Σ(1770),

  1. so Diakonov and Petro (hep-ph/0310212) suggeted a missing N around 1650-1690 MeV;

  2. the position of N(1710) is not at M=1710 MeV, but some where around M=1650 to 1690 MeV, suggested by Arndt et al(nucl-th/0312126) .

- We noticed (hep-ph/9311331) that there are candidates of N(1650) and Σ(1750) with spin ½ and negative (–) parity, in PDG

  This may suggest a negative parity for antidecuplet members in the chiral soliton model:

  parity in chiral solition has two parts: quantized part with positive parity and classical part with unknown parity;

  the collective coordinate quantization can not inevitably fix the parity of the corresponding baryons.

The width formula and the widths in the case of negative parity

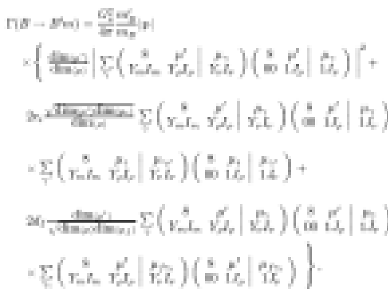


Table 1. The widths of baryons in the anti-decuplet

Mode	Observation (MeV)	$J^P = \frac{1}{2}^-$ (MeV)
$\Theta^+ \to KN$	< 25	25(input)
$N(1650) \to N\pi$	$80 \sim 171$	9
$N(1650) \to N\eta$	$4 \sim 19$	10
$N(1650) \to \Lambda K$	$4 \sim 21$	2.4
$\Sigma(1750) \to N\overline{K}$	$6 \sim 64$	8.6
$\Sigma(1750) \to \Sigma\pi$	<12.8	11.6
$\Sigma(1750) \to \Sigma\eta$	$9 \sim 88$	5
$\Sigma(1750) \to \Lambda\pi$	seen	3.3
$\Xi_{3/2} \to \Xi\pi$	$<18(?)$	11
$\Xi_{3/2} \to \Sigma\overline{K}$		36

decay width is excellent for S(1750), but poor for N(1650) , possible solution:

SU(3) breaking for baryons with strangeness,

or there is a missing N resonance around 1650 with narrow width.

Theories of positive parity for Θ^+

- Chiral Soliton Models (old version)

  Diakonov-Petrov-Polyakov, ZPA359(1997)305

- Analysis in Quark Model

  Stancu-Riska, PLB575(2003)242

- Diquark Cluster Model

  Jaffe-Wilczek, PRL91(2003)232003

- Diquark-Triquark Model

  Karliner-Lipkin, PLB575(2003)249

Theories of negative parity for Θ^+

- **Naive Quark Model**

  Jaffe (1976)

- **Some Quark Models**

  Capstick-Page-Roberts, PLB570(2003)185

  Huang-Zhang-Yu-Zhou, hep-ph/0310040

- **QCD Sum Rules**

  Zhu, PRL91(2003)232002, Sugiyama-Doi-Oka, hep-ph/0309271

- **Lattice QCD**

  Sasaki, hep-ph/0310014, Csikor et al, hep-ph/0309090,

  but we heard difference voices from this conference

Where is the answer? Experiment!

- **Many suggestions on detecting the parity**

  Oh-Kim-Lee, hep-ph/0310019

  Zhao, hep-ph/0310350

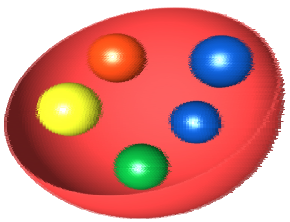
  Liu-Ko-Kubarovsky, nucl-th/0310087

  Nakayama-Tsushima, hep-ph/0311112

  Thomas-Hicks-Hosaka, hep-ph/0312083 ……

- **Measurement of parity is crucial to test theories**

Predictions of New Pentaquarks -27-plet



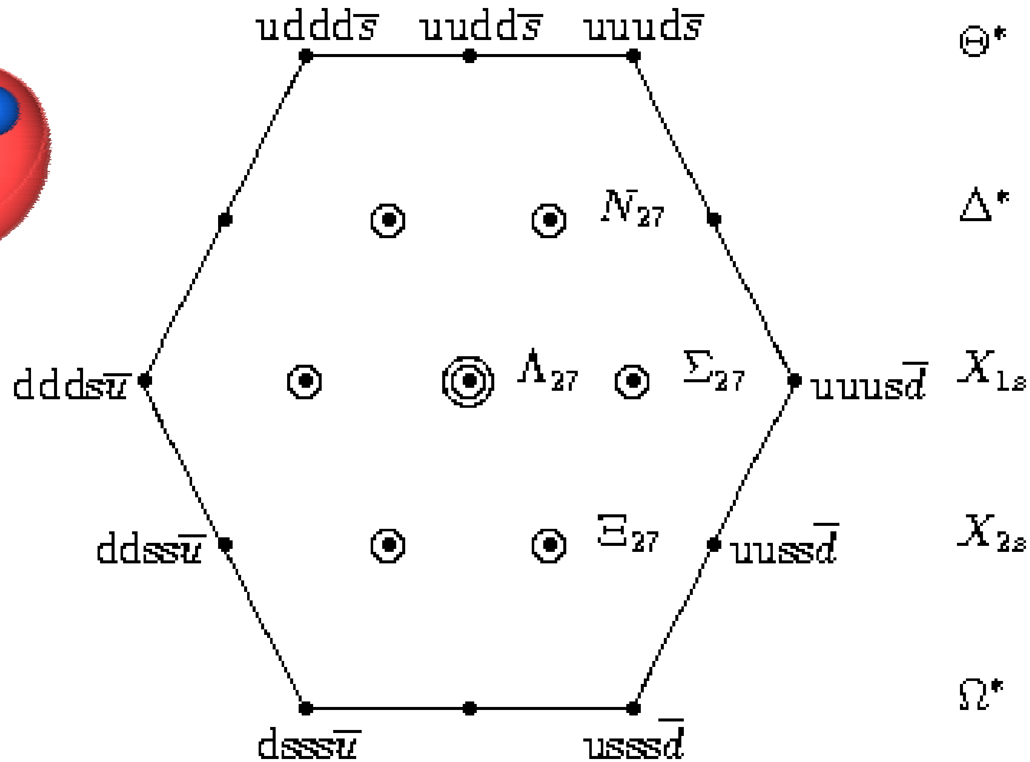


Figure from Wu & Ma, hep-ph/0312041, PRD

The mass splitting of the 27-plet from chiral solitons

Table 1. The masses (GeV) of baryons in the {27} multiplet

	$\langle B\|H'\|B\rangle$	method I	method II	candidate	$I(J^{PC})$	PDG
Δ^*	$\frac{13}{112}\alpha+\beta-\frac{65}{224}\gamma$	1.62	1.64	$\Delta(1600)$	$\frac{3}{2}(\frac{3}{2}^+)$	1.55 to 1.70
N_{27}	$\frac{1}{28}\alpha+\beta-\frac{5}{56}\gamma$	1.73	1.73	N(1720)	$\frac{1}{2}(\frac{3}{2}^+)$	1.65 to 1.75
Σ_{27}	$-\frac{1}{56}\alpha+\frac{5}{112}\gamma$	1.79	1.80	$\Sigma(1840)$	$1(\frac{3}{2}^+)$	1.72 to 1.93
Ξ_{27}	$-\frac{17}{112}\alpha-\beta+\frac{85}{224}\gamma$	1.95	1.96	$\Xi(1950)$	$\frac{1}{2}(\frac{3}{2}^+)(?^?)$	1.95 ± 0.015
Λ_{27}	$-\frac{1}{14}\alpha+\frac{5}{28}\gamma$	1.86	1.86	$\Lambda(1890)$	$0(\frac{3}{2}^+)$	1.85 to 1.91
Θ^*	$\frac{\alpha}{7}+2\beta-\frac{5}{14}\gamma$	1.61	1.60	?	$1(\frac{3}{2}^+)?(?^?)$	?
X_{1s}	$\frac{5}{56}\alpha-\frac{25}{112}\gamma$	1.64	1.68	?	$2(\frac{3}{2}^+)?(?^?)$	?
X_{2s}	$-\frac{1}{14}\alpha-\beta+\frac{5}{28}\gamma$	1.84	1.87	?	$\frac{3}{2}(\frac{3}{2}^+)?(?^?)$	?
Ω^*	$-\frac{13}{56}\alpha-2\beta-\frac{65}{112}\gamma$	2.06	2.07	?	$1(\frac{3}{2}^+)?(?^?)$	?

The widths of the 27-plet baryons

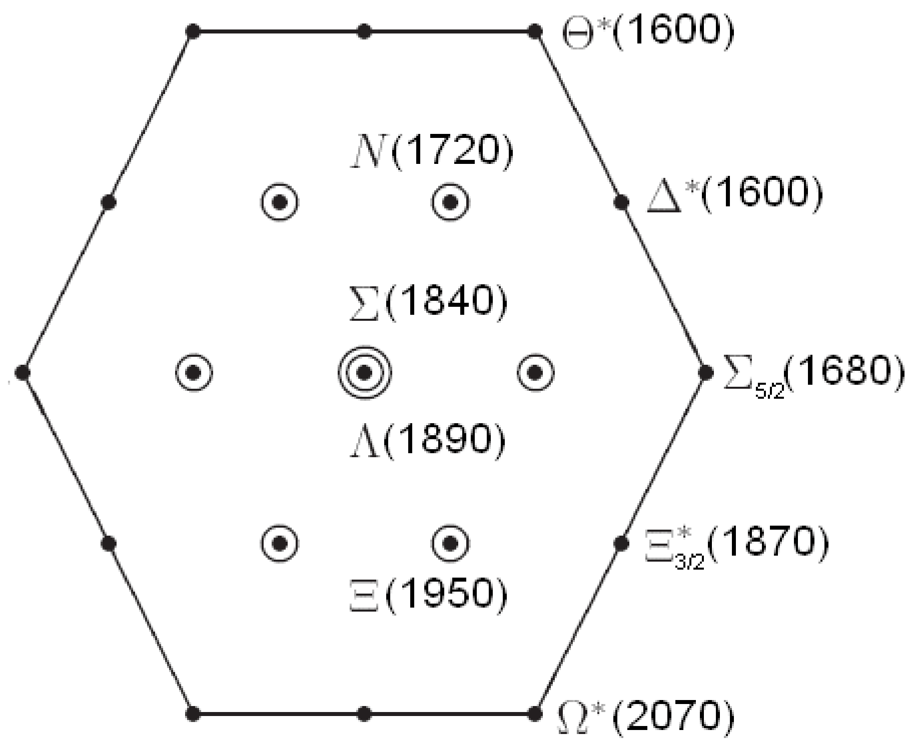
Table 2. The widths (MeV) of baryons in the 27-plet

	PDG estimation	modes	branching ratios	Γ_i from data	width $\leq$calculation
$\Delta(1600)$	250 to 450	$N\pi$	10 to 25%	25 to 113	130
N(1720)	100 to 200	$N\pi$	10 to 20%	10 to 40	19
		$N\eta$	$(4.0 \pm 1.0)\%$	3 to 10	66
		ΛK	1 to 15%	1 to 30	18
		ΣK			0.39
$\Sigma(1840)$	65 to 120	$N\overline{K}$	0.37 ± 0.13	11 to 60	50
		$\Lambda\pi$			0
$\Lambda(1890)$	60 to 200	$N\overline{K}$	20 to 35%	12 to 70	46
		$\Sigma\pi$	3 to 10%	2 to 30	5
$\Xi(1950)$	60 ± 20	$\Lambda\overline{K}$	seen		90
		$\Sigma\overline{K}$	pssible seen		6.5
		$\Xi\pi$	seen		8.3
Θ^*	?	KN	?	?	79
X_{1s}	?	$\Sigma\pi$	?	?	96
X_{2s}	?	$\Xi\pi$	?	?	58
		$\Sigma\overline{K}$	?	?	36
Ω^*	?	$\Xi\overline{K}$	?	?	107

SU(3) Symmetric Case

The picture of the 27-plet baryons:

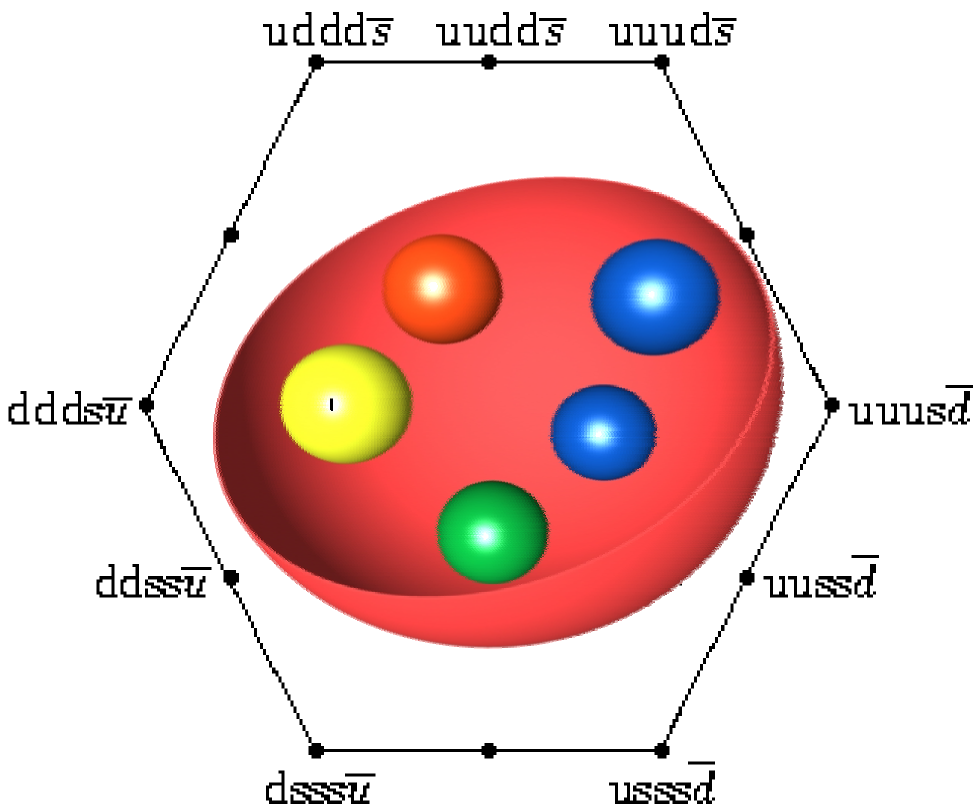
non-exotic members are well established



We suggest that the quantum numbers of Ξ(1950) is JP=(3/2)+

Many new pentaquarks

to be discovered



Θ^*

Δ^*

X_{1s}

X_{2s}

Ω^*

Predictions of Θ^*

- **Walliser-Kopeliovich, hep-ph/0304058**
  mass=1650/1690 MeV

- **Borisyuk-Faber-Kobushkin, hep-ph/0307370**
  mass=1595 MeV, width=80 MeV

- **Wu-Ma, hep-ph/0312326 (PLB)**
  mass=1600 MeV, width less than 43 MeV

Conclusions

- The discovery of pentaquark Θ^+ opens a new window to understand the basic structure of matter.
- Measurement of the parity of Θ^+ is crucial to test different theories
- There are new pentaquark states waiting for discovery