Quark masses, hyperfine interaction and exotic baryons[a]

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[a] hep-ph/0307243 and hep-ph/0307343

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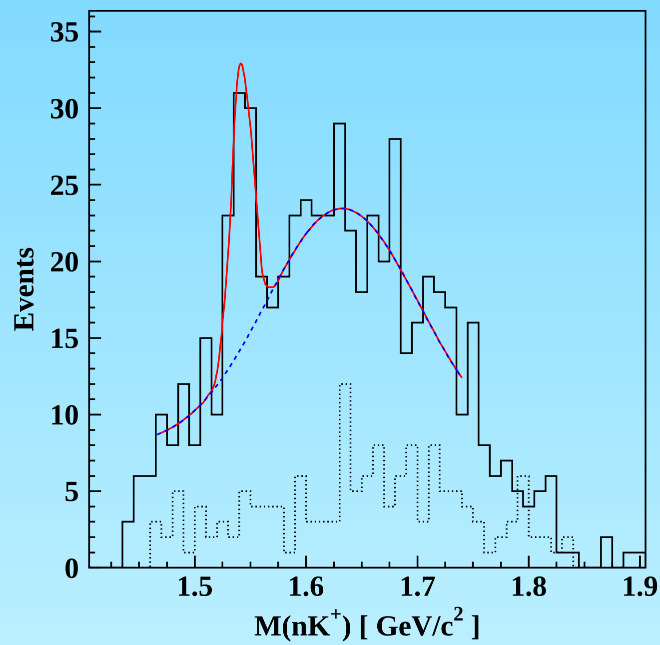

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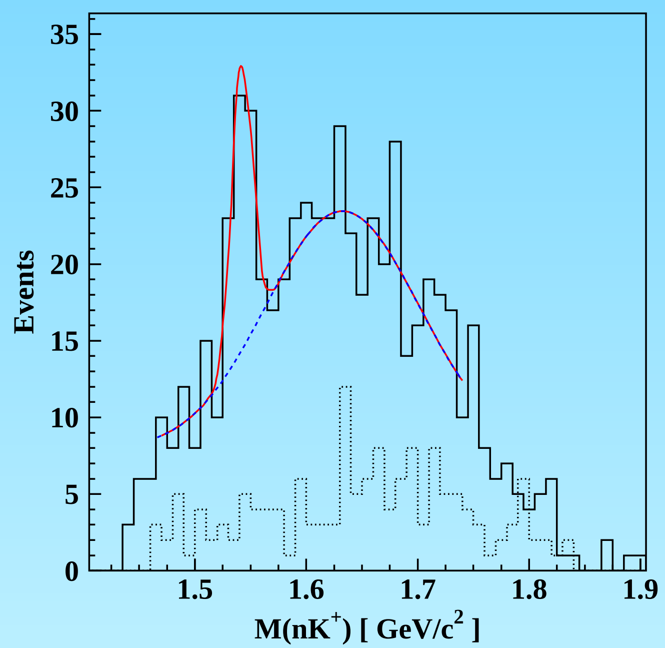

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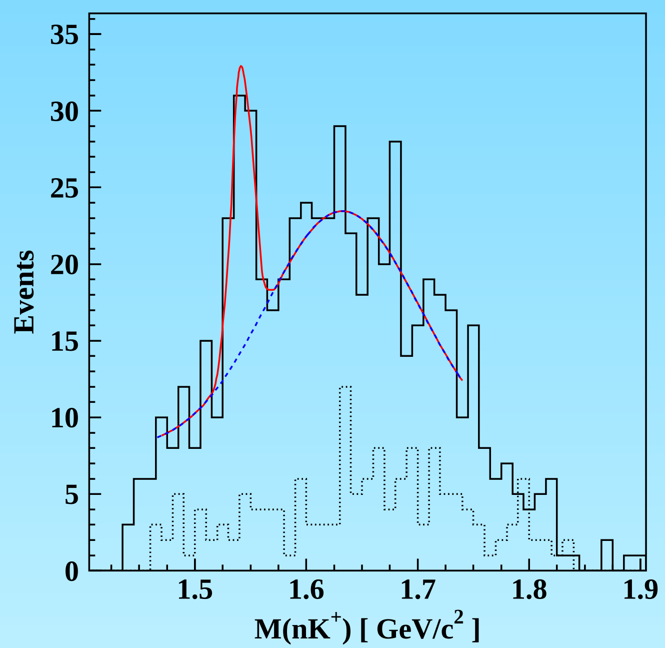

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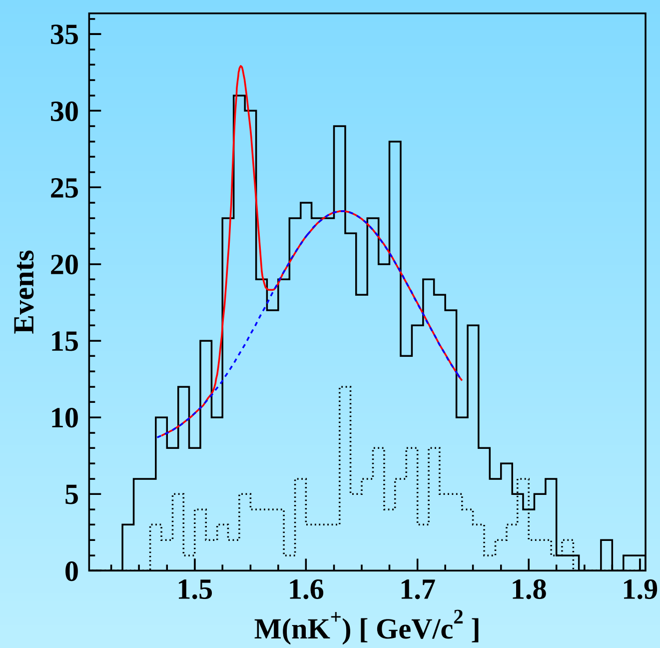

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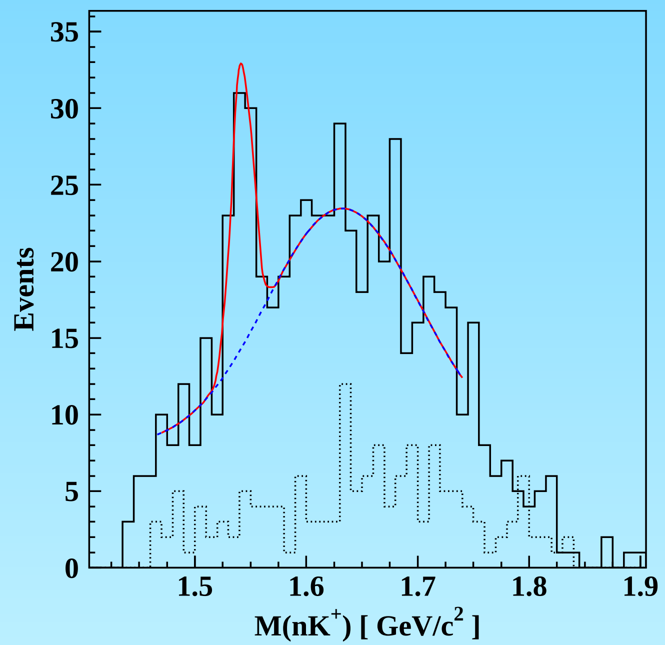

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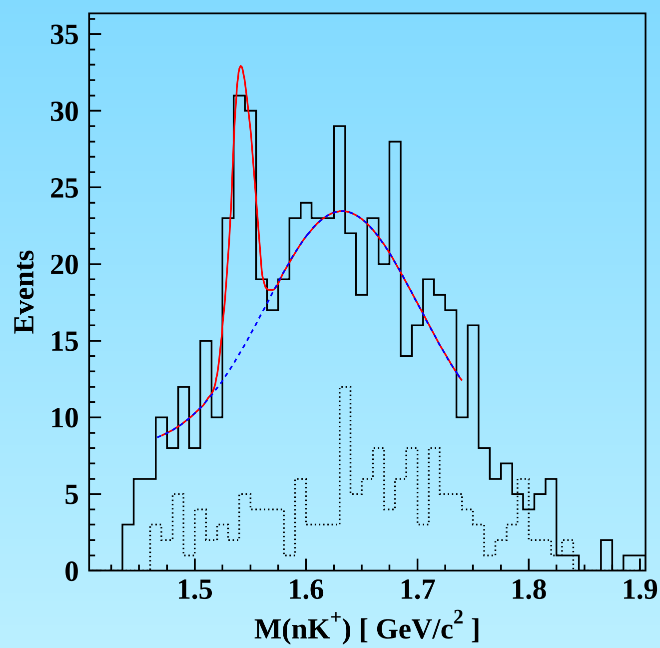

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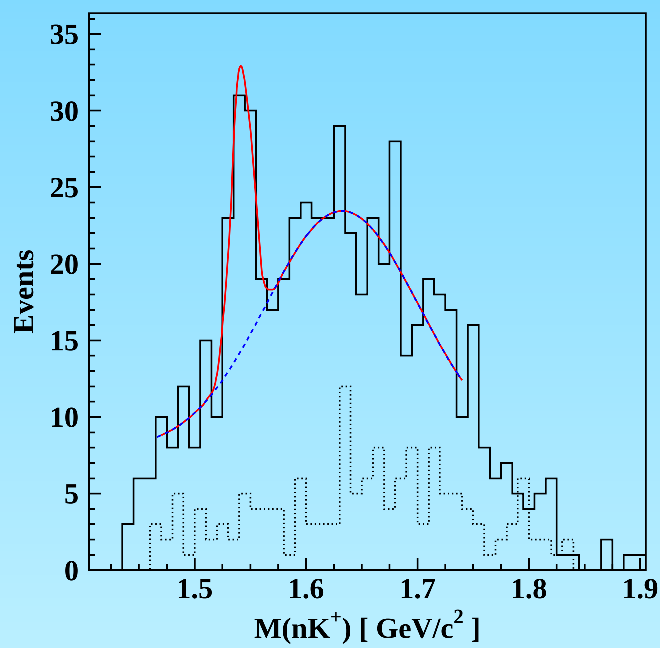

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re-analysis of old KN data: $\Gamma_{\Theta^+} \lesssim 1$ MeV (Nussinov, Arndt et al.)

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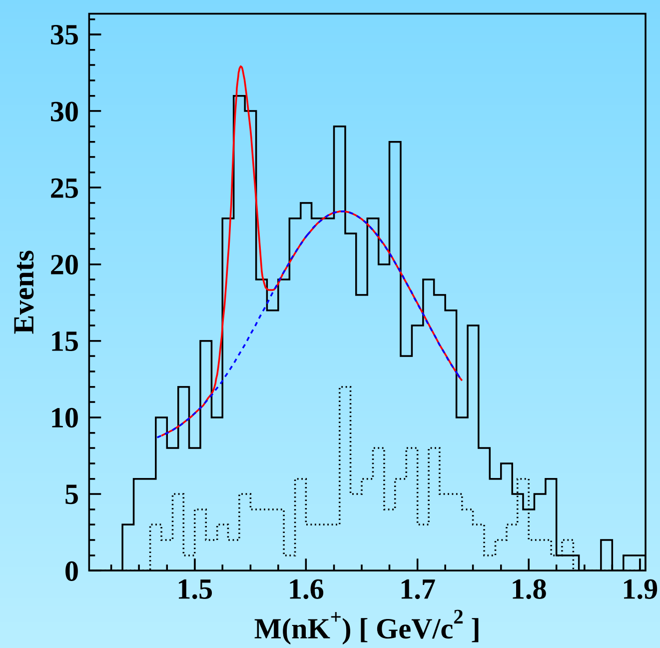

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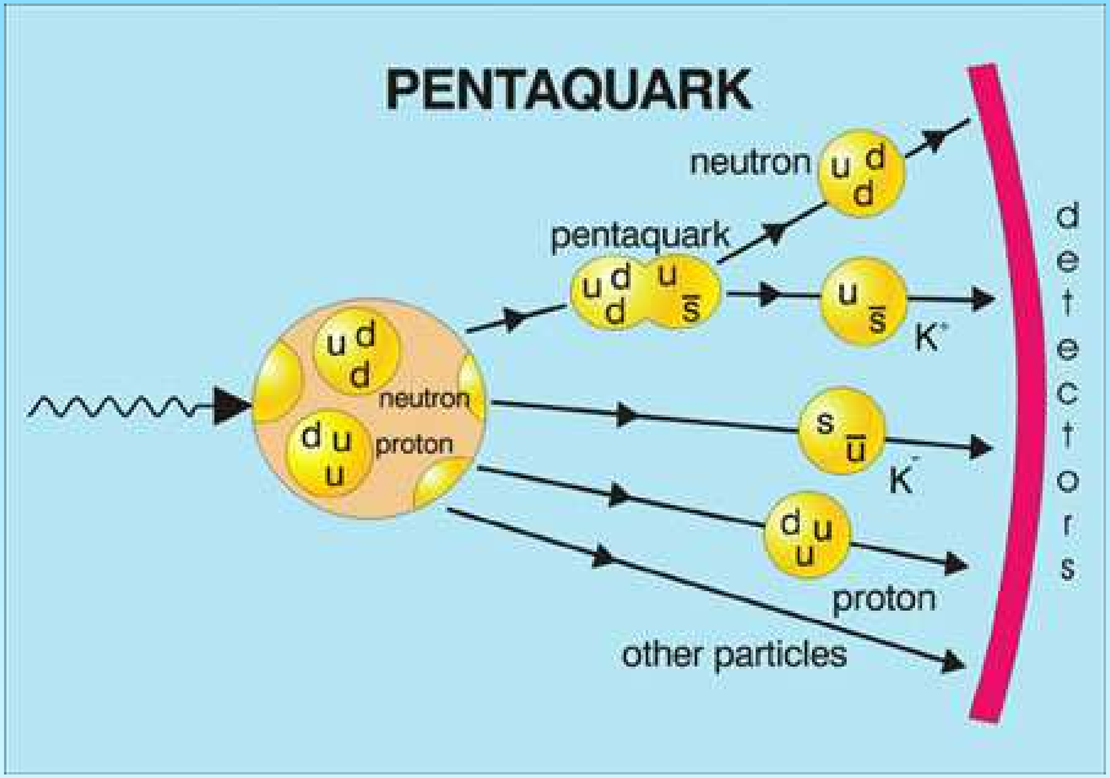
but analysis indirect: no exp. coverage of relevant energy

Most precise experiment so far:

CLAS Collaboration at JLab

$$\gamma d \to p \underbrace{n K^+}_{\Theta^+} K^-$$



1984 Review of Particle Properties:

For notation, see key at front of Listings.

Baryons

$\Delta(2950)$, $\Delta(\sim3000)$, Z's, $Z_0(1780)$

$\Delta(2950)$ K_{315} Status: **

```
126  DELTA(2950, JP=15/2+) I=3/2   K3 15
------ --------- --------- --------- --------- --------- --------- --------
              126  DELTA(2950) MASS  (MEV)
M       2850.0    100.0           HENDRY    78 MPWA    PI N TO PI N     12/79
M       2990.0    100.0           HOEHLER   79 IPWA    PI N TO PI N     12/79
------ --------- --------- --------- --------- --------- --------- --------
              126  DELTA(2950) WIDTH  (MEV)
W        700.0    200.0           HENDRY    78 MPWA    PI N TO PI N     12/79
W        330.0    100.0           HOEHLER   79 IPWA    PI N TO PI N     12/79
------ --------- --------- --------- --------- --------- --------- --------
              126  DELTA(2950) PARTIAL DECAY MODES
                                                    DECAY MASSES
P1     DELTA(2950) INTO N PI                       938+ 140
------ --------- --------- --------- --------- --------- --------- --------
              126  DELTA(2950) BRANCHING RATIOS
R1     DELTA(2950) INTO (N PI)/TOTAL                  (P1)
R1         0.03      0.01         HENDRY    78 MPWA    PI N TO PI N     12/79
R1         0.04      0.02         HOEHLER   79 IPWA    PI N TO PI N     12/79
****** ********* ********* ********* ********* ********* ********* ********
                     REFERENCES FOR DELTA(2950)
HENDRY   78 PRL 41 222        A W HENDRY                      (IND+LBL)IJP
         *** THE ANALYSIS AND RESULTS ARE DISCUSSED MORE FULLY IN HENDRY 81.
HOEHLER  79 HANDBOOK OF PI-N SCATTERING, PHYSIK DATEN VOL.12-1
                              +KAISER,KOCH,PIETARINEN          (KARL)IJP
   ALSO 80  TORONTO CONF 3    R KOCH                           (KARL)IJP
HENDRY   81 ANP 136 1         A W HENDRY                        (IND)
****** ********* ********* ********* ********* ********* ********* ********
****** ********* ********* ********* ********* ********* ********* ********
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~3000 MEV REGION – FORMATION EXPERIMENTS

```
              127  DELTA(~3000) I=3/2

               WE LIST HERE MISCELLANEOUS HIGH-MASS CANDIDATES FOR
               ISOSPIN-3/2 RESONANCES FOUND IN PARTIAL-WAVE ANALYSES.
               SO FAR, NO ANALYSIS OF THIS REGION HAS USED ALL THE
               AVAILABLE DATA OR INCORPORATED ANALYTICITY CONSTRAINTS.

    OUR 1982 EDITION ALSO HAD A DELTA(2850) AND A DELTA (3230).
    NOTHING HAS BEEN HEARD FROM THEM IN 10 YEARS, AND UNDER THE
    AUTHORITY GRANTED UNTO US BY THE STATUTE OF LIMITATIONS, WE
    DECLARE THEM TO BE DEAD.  THE EVIDENCE FOR THEM WAS DEDUCED FROM
    TOTAL-CROSS-SECTION AND 180-DEG-ELASTIC-CROSS-SECTION MEASUREMENTS.
    PLACED IN THE MAIN BARYON TABLE IN THE ANYTHING-GOES 1960'S, THEY
    REMAINED THERE DUE TO INATTENTION UNTIL THIS EDITION.
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NOTE ON THE S = +1 BARYON SYSTEM

The evidence for strangeness +1 baryon resonances was thoroughly reviewed in our 1976 edition,[1] and has been reviewed more recently by Kelly[2] and by Oades.[3] One new partial-wave analysis[4] has been published since our 1982 edition. As usual, the results permit no definite conclusion — the same story heard for 15 years. The general feeling, supported by the prejudice against baryons not make up of three quarks, is that the suggestive counterclockwise movement in the Argand diagram of some of the partial waves is not real evidence for true Breit-Wigner resonances. But until the dynamics of the KN system is better understood, the possibility that Z* resonances exist will not be finally laid to rest.

References

1. Particle Data Group, Rev. Mod. Phys. **48**, S188 (1976).
2. R.L. Kelly, in *Proceedings of the Meeting on Exotic Resonances* (Hiroshima, 1978), ed. I. Endo et al.
3. G.C. Oades, in *Low and Intermediate Energy Kaon-Nucleon Physics* (1981), ed. E. Ferrari and G. Violini.
4. K. Nakajima et al., Phys. Lett. **112B**, 80 (1982).

A beautiful prediction from Skyrme model:

Praszałowicz('87), Diakonov, Petrov & Polyakov('97): $m_{\Theta^+} \approx 1530$ MeV,

$\Gamma_{\Theta^+} < 15$ MeV, $J^P = \frac{1}{2}^+$, $I = 0$

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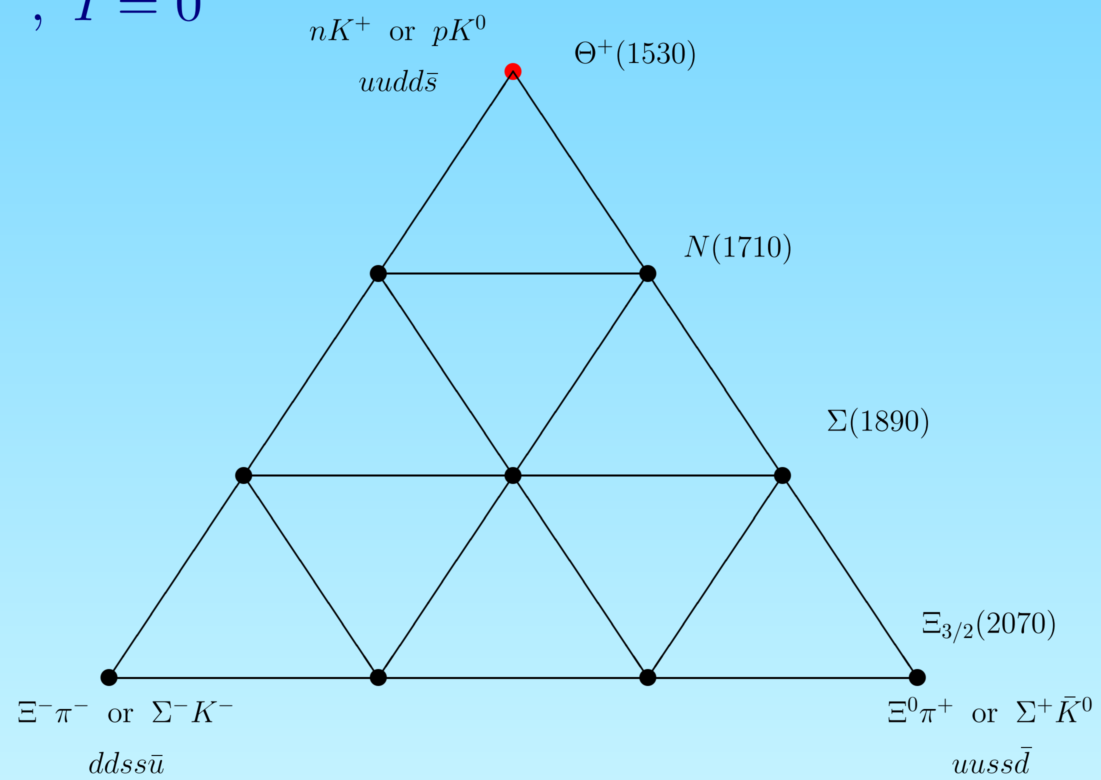

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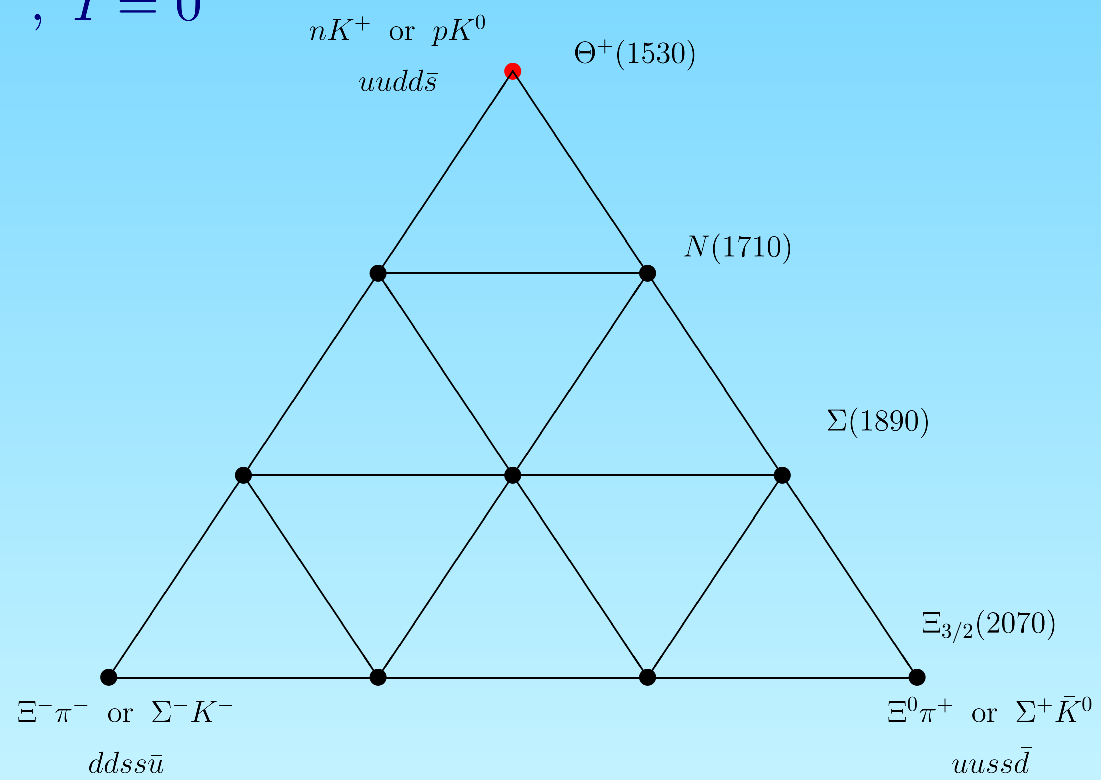

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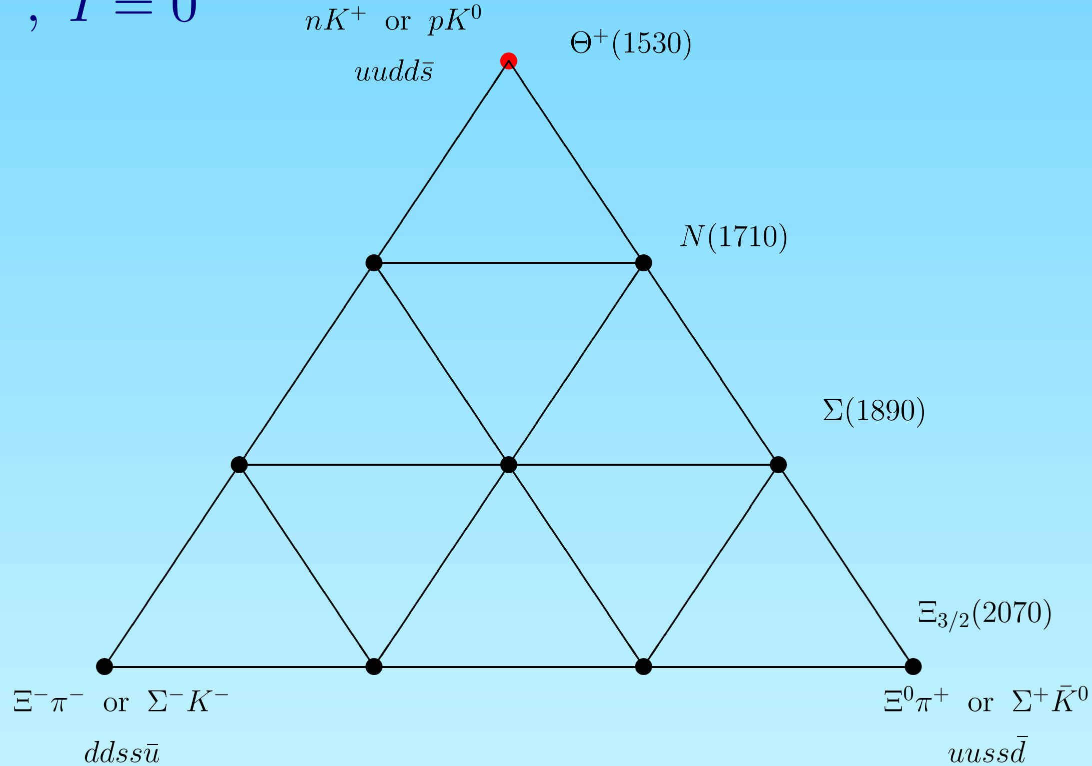

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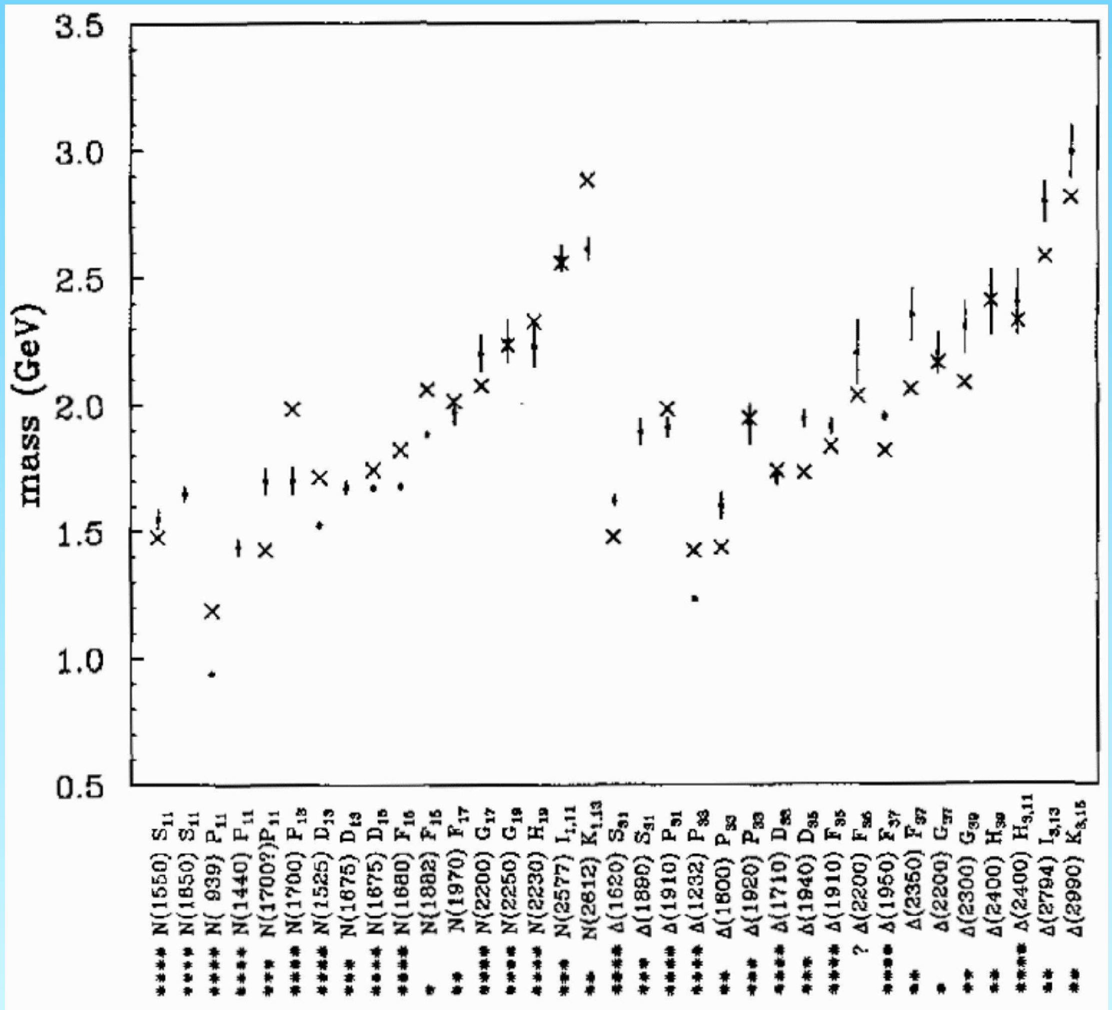
for $S < 0$, simple: $\Longleftrightarrow$ counting s-quarks.

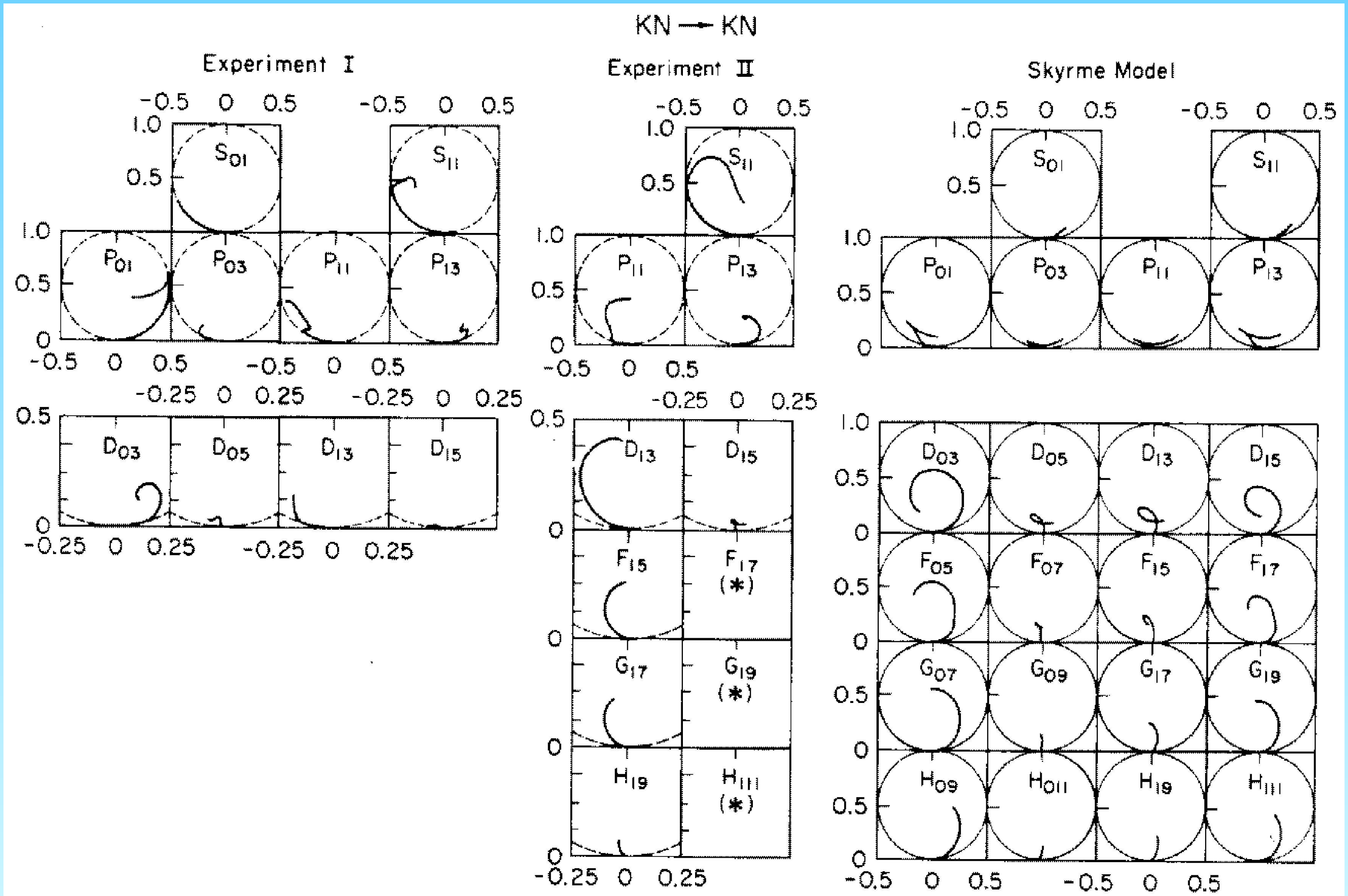
for $S > 0$: $\Delta\langle \#s + \#\bar{s} \rangle = \frac{1}{3}$

Skyrme model sometimes does very well. . .



N and Δ spectrum from the Skyrme Model (Karliner & Mattis, 1984)

But sometimes predicts too many exotics



πN, KN, $\bar{K}N$ Scattering, Skyrme Model vs. Experiment (Karliner & Mattis, 1986)

Itzhaki, Klebanov, Ouyang & Rastelli: WZ normalization ?

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- Constituent Quark Model:

$$M = \sum_i m_i - \underbrace{\sum_{i>j} V(\vec{\lambda}_i \cdot \vec{\lambda}_j) \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i \cdot m_j}}_{\text{hyperfine interaction}}$$

m_i : effective quark mass, $\vec{\lambda}$: $SU(3)_c$ generators, $\vec{\sigma}$: Pauli spin operators

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$\Longrightarrow$ color-spin $SU(6)$ algebra:

symmetric	in color × spin	$\longleftrightarrow$	attractive
antisymmetric	in color × spin	$\longleftrightarrow$	repulsive

effective quark masses from baryons and mesons

$m_s - m_u$ and m_s/m_u:
same values from baryon and meson masses,
with hyperfine interaction properly isolated
(Sakharov & Zeldovich, DGG):

$$\langle m_s - m_u \rangle_{Bar} = M_{sud} - M_{uud} = M_\Lambda - M_N = 177\,\mathrm{MeV}$$

$$\langle m_s - m_u \rangle_{Mes} = \frac{3(M_{\mathcal{V}_{s\bar d}} - M_{\mathcal{V}_{u\bar d}}) + (M_{\mathcal{P}_{s\bar d}} - M_{\mathcal{P}_{u\bar d}})}{4} = \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi}{4} = 179\,\mathrm{MeV}$$

$$\left(\frac{m_s}{m_u}\right)_{Bar} = \frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} = 1.53 \approx \left(\frac{m_s}{m_u}\right)_{Mes} = \frac{M_\rho - M_\pi}{M_{K^*} - M_K} = 1.61$$

$\mathcal{V}$ and $\mathcal{P}$: vector and pseudoscalar mesons

Generalization to other flavors

for vector and pseudoscalar mesons containing q_i or q_j and a spectator x:

$$|\mathcal{V}_i\rangle = |q_i \bar{x}\rangle^{J=1}, \qquad |\mathcal{V}_j\rangle = |q_j \bar{x}\rangle^{J=1},$$
$$|\mathcal{P}_i\rangle = |q_i \bar{x}\rangle^{J=0}, \qquad |\mathcal{P}_j\rangle = |q_j \bar{x}\rangle^{J=0},$$

$$\langle m_{q_i} - m_{q_j}\rangle_{xMes} = \frac{3(M_{\mathcal{V}_i} - M_{\mathcal{V}_j}) + (M_{\mathcal{P}_i} - M_{\mathcal{P}_j})}{4}$$

(does not work for $\bar{s}$ because no light $\mathcal{P}$ – anomaly)

baryons: only N and $I = 0$ udq: Λ, Λ_c and Λ_b

where hyperfine for u and d only $\longrightarrow$ drops out of all mass diffs:

for $|B_i\rangle = |q_i ud\rangle$, $|B_j\rangle = |q_j ud\rangle$,

$$\langle m_{q_i} - m_{q_j}\rangle_{dBar} = M_{q_i ud} - M_{q_j ud} = M_{B_i} - M_{B_j}$$

TABLE I - Quark mass differences from baryons and mesons

observable	baryons		mesons				Δm_{Bar}	Δm_{Mes}
			$J=1$		$J=0$			
	B_i	B_j	$\mathcal{V}_i$	$\mathcal{V}_j$	$\mathcal{P}_i$	$\mathcal{P}_j$	MeV	MeV
$\langle m_s - m_u \rangle_d$	sud	uud	$s\bar{d}$	$u\bar{d}$	$s\bar{d}$	$u\bar{d}$	177	179
	Λ	N	K^*	ρ	K	π		
$\langle m_s - m_u \rangle_c$			$c\bar{s}$	$c\bar{u}$	$c\bar{s}$	$c\bar{u}$		103
			D_s^*	D_s^*	D_s	D_s		
$\langle m_s - m_u \rangle_b$			$b\bar{s}$	$b\bar{u}$	$b\bar{s}$	$b\bar{u}$		91
			B_s^*	B_s^*	B_s	B_s		
$\langle m_c - m_u \rangle_d$	cud	uud	$c\bar{d}$	$u\bar{d}$	$c\bar{d}$	$u\bar{d}$	1346	1360
	Λ_c	N	D^*	ρ	D	π		
$\langle m_c - m_u \rangle_c$			$c\bar{c}$	$u\bar{c}$	$c\bar{c}$	$u\bar{c}$		1095
			ψ	D^*	η_c	D		
$\langle m_c - m_s \rangle_d$	cud	sud	$c\bar{d}$	$s\bar{d}$	$c\bar{d}$	$s\bar{d}$	1169	1180
	Λ_c	Λ	D^*	K^*	D	K		
$\langle m_c - m_s \rangle_c$			$c\bar{c}$	$s\bar{c}$	$c\bar{c}$	$s\bar{c}$		991
			ψ	D_s^*	η_c	D_s		
$\langle m_b - m_u \rangle_d$	bud	uud	$b\bar{d}$	$u\bar{d}$	$b\bar{d}$	$u\bar{d}$	4685	4700
	Λ_b	N	B^*	ρ	B	π		
$\langle m_b - m_u \rangle_s$			$b\bar{s}$	$u\bar{s}$	$b\bar{s}$	$u\bar{s}$		4613
			B_s^*	K^*	B_s	K		
$\langle m_b - m_s \rangle_d$	bud	sud	$b\bar{d}$	$s\bar{d}$	$b\bar{d}$	$s\bar{d}$	4508	4521
	Λ_b	Λ	B^*	K^*	B	K		
$\langle m_b - m_c \rangle_d$	bud	sud	$b\bar{d}$	$c\bar{d}$	$b\bar{d}$	$c\bar{d}$	3339	3341
	Λ_b	Λ_c	B^*	D^*	B	D		
$\langle m_b - m_c \rangle_s$			$b\bar{s}$	$c\bar{s}$	$b\bar{s}$	$c\bar{s}$		3328
			B_s^*	D_s^*	B_s	D_s		

m_c/m_s, m_c/m_u from mesons and baryons

extract m_c/m_s and m_c/m_u same way as m_s/m_u,
isolating $1/m_q$ terms from mass differences

$$\begin{array}{llcl} \text{mesons:} & M(1^-) & - & M(0^-) \\ \text{baryons:} & M(\frac{3}{2}^+) & - & M(\frac{1}{2}^+) \end{array}$$

m_c/m_s, m_c/m_u from mesons and baryons

extract m_c/m_s and m_c/m_u same way as m_s/m_u,
isolating $1/m_q$ terms from mass differences

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$\Longrightarrow$ same values from mesons and baryons $\pm 2\%$:

$$\left(\frac{m_c}{m_s}\right)_{Bar} = \frac{M_{\Sigma^*} - M_\Sigma}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 2.84 = \left(\frac{m_c}{m_s}\right)_{Mes} = \frac{M_{K^*} - M_K}{M_{D^*} - M_D} = 2.81$$

$$\left(\frac{m_c}{m_u}\right)_{Bar} = \frac{M_\Delta - M_p}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 4.36 = \left(\frac{m_c}{m_u}\right)_{Mes} = \frac{M_\rho - M_\pi}{M_{D^*} - M_D} = 4.46$$

4-th flavor $\longrightarrow$ new relations between meson and baryon masses:

$$\left(\frac{m_c - m_u}{m_s - m_u} \cdot \frac{m_s}{m_c}\right)_{Bar} = \frac{M_{\Sigma_c} - M_{\Lambda_c}}{M_{\Sigma} - M_{\Lambda}} = 2.16$$

$$\left(\frac{m_c - m_u}{m_s - m_u} \cdot \frac{m_s}{m_c}\right)_{Mes} = \frac{(M_\rho - M_\pi) - (M_{D^*} - M_D)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.10$$

meson and baryon relations agree to $\pm 3\%$.

4-th flavor $\longrightarrow$ new relations between meson and baryon masses:

$$\left(\frac{m_c - m_u}{m_s - m_u} \cdot \frac{m_s}{m_c}\right)_{Bar} = \frac{M_{\Sigma_c} - M_{\Lambda_c}}{M_\Sigma - M_\Lambda} = 2.16$$

$$\left(\frac{m_c - m_u}{m_s - m_u} \cdot \frac{m_s}{m_c}\right)_{Mes} = \frac{(M_\rho - M_\pi) - (M_{D^*} - M_D)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.10$$

meson and baryon relations agree to $\pm 3\%$.

Similarly, for Λ_b and yet unmeasured Σ_b:

$$\frac{M_{\Sigma_b} - M_{\Lambda_b}}{M_\Sigma - M_\Lambda} = \frac{(M_\rho - M_\pi) - (M_{B^*} - M_B)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.51$$

$$\Longrightarrow M_{\Sigma_b} - M_{\Lambda_b} = 194\,\mathrm{MeV} \longrightarrow M_{\Sigma_b} = 5818\,\mathrm{MeV}$$

effective m_q depends on the neighbors:

- effective $m_s - m_u$ strongly dependent on "spectator" quarks:

$$\langle m_s - m_u \rangle_{dMes} = \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi}{4} = 179\,\mathrm{MeV}$$

vs.

$$\langle m_s - m_u \rangle_{cMes} = \frac{3(M_{D_s^*} - M_{D^*}) + M_{D_s} - M_D}{4} = 103\,\mathrm{MeV}$$

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quark double mass differences – theory vs. experiment

observable	Experiment					Theoretical prediction with V_{eff} MeV
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$\langle m_s - m_u \rangle$	d	179	c	103	76	51
$\langle m_c - m_u \rangle$	d	1360	c	1095	265	202
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- can improve on log potential with generalized

$$V_{eff} = \frac{V_o}{2n}\left[\left(\frac{r}{r_o}\right)^n - \left(\frac{r}{r_o}\right)^{-n}\right], \qquad n > 0$$

(for $n = 0$ get back the log potential)

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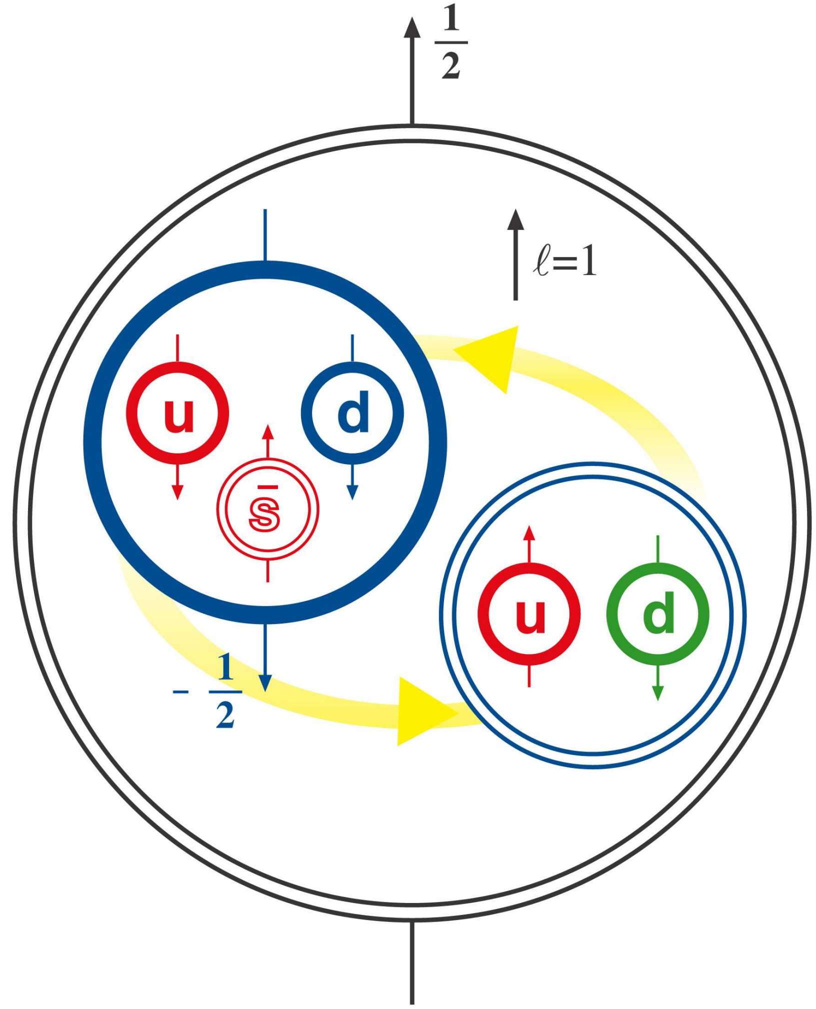
diquark-triquark configuration:



diquark – triquark configuration of the *uudds̄* pentaquark

Θ^+ properties from diquark-triquark

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- $m_{\Theta^+} \approx 1592 \pm 50$ MeV vs. 1542 ± 5 MeV (EXP). but...

analogous triquark-diquark configuration predicts

$m_{\Xi^{--}} = 1720 \pm 50$ MeV vs NA49 1862 ± 2 MeV

generic for all correlated quark configurations

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$\Longrightarrow$ look for protons coming out of charm/bottom decay vertex