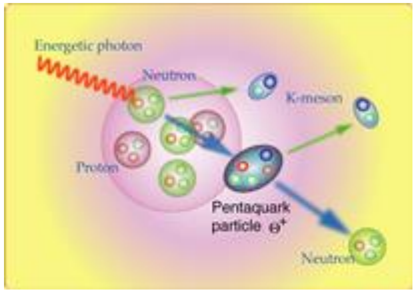
Hadron Physics at RHIC

Su Houng Lee
Yonsei Univ., Korea

1. Introduction for Exotics
2. Hadron production in HIC
3. Exotics from RHIC



Thanks to: Former collegues and students
Present students: Y. Park, Y. Sarac, Y. Heo, K. Kim
Post doc: K. Ohnishi

Introduction for Exotics

Definition of Exotics

1. Hadrons that can not be explained by quark-antiquark, or 3 quarks

Exotics	$udud\bar{s}$, $ud\bar{c}\bar{s}$, $ud\bar{c}\bar{c}$
Non Exotics	$udus\bar{s}$, $udus\bar{u}$, $uc\bar{u}\bar{c}$

2. That are bound by strong interaction

3. Reasons for its search are similar to that for superheavy Element in low energy nuclear Physics

   → Understand QCD → sQGP

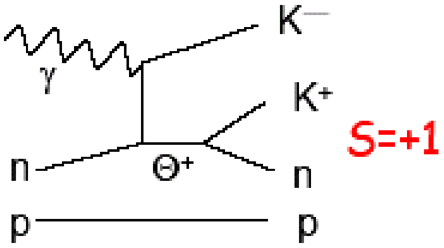
Experiment - First claim

1. LEPS coll., Nakano et.al. PRL 91 012002 (2003)

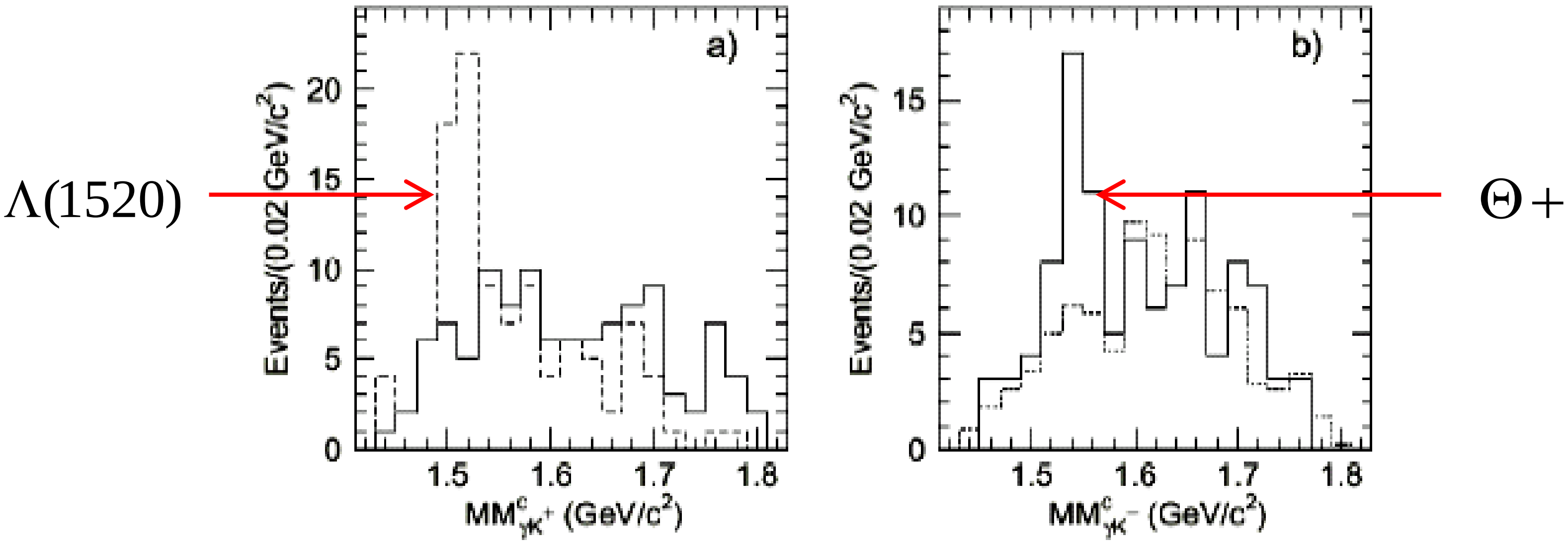
$$\gamma n\,(p) \rightarrow \Theta^{+} K^{-}\,(p)$$

$$\Theta^{+} \rightarrow K^{+} n$$

"Exotic"



Mass= 1.54 GeV , width <25 MeV , quark content= $uudd\bar{s}$



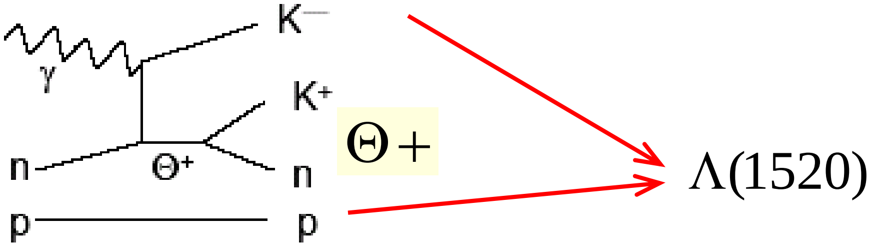
Experiment - Recent claim

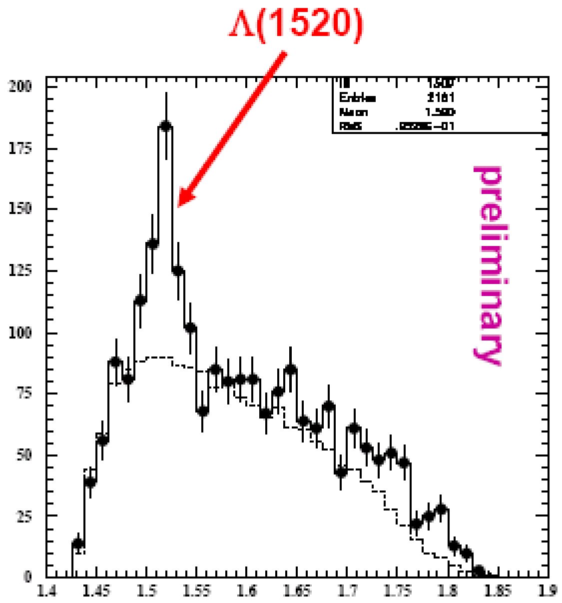
In Carbon target $\sigma(\Lambda(1520)) >> (\Theta^+(1540))$, but

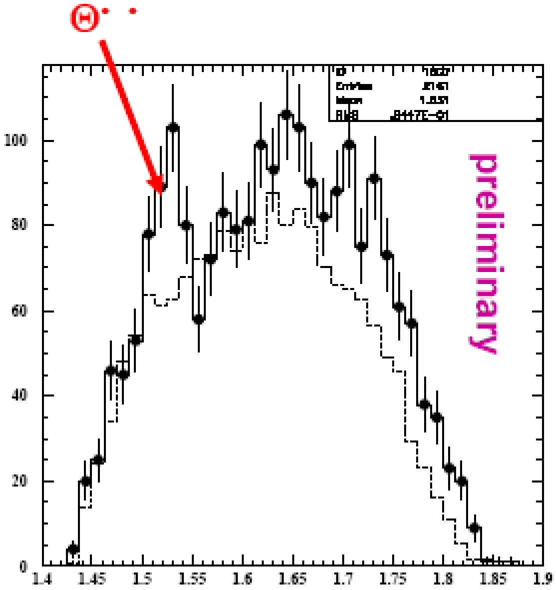
$\gamma n\,(p) \rightarrow \Theta^+ K^-\ (p)$

$\Theta^+ \rightarrow K^+ n$

"Exotic"







Positive results

Negative results

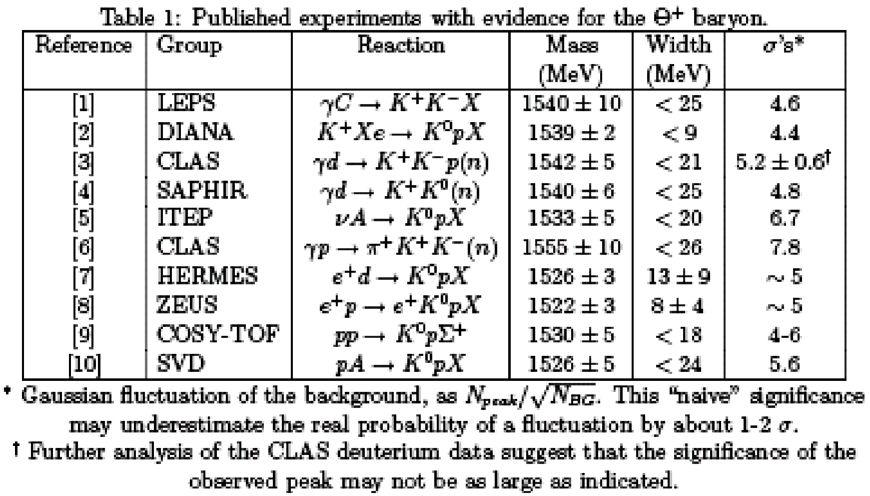


Table 1: Published experiments with evidence for the Θ^+ baryon.

Reference	Group	Reaction	Mass (MeV)	Width (MeV)	σ's*
[1]	LEPS	$\gamma C \rightarrow K^+K^-X$	1540 ± 10	< 25	4.6
[2]	DIANA	$K^+Xe \rightarrow K^0pX$	1539 ± 2	< 9	4.4
[3]	CLAS	$\gamma d \rightarrow K^+K^-p(n)$	1542 ± 5	< 21	$5.2 \pm 0.6^\dagger$
[4]	SAPHIR	$\gamma d \rightarrow K^+K^0(n)$	1540 ± 6	< 25	4.8
[5]	ITEP	$\nu A \rightarrow K^0pX$	1533 ± 5	< 20	6.7
[6]	CLAS	$\gamma p \rightarrow \pi^+K^+K^-(n)$	1555 ± 10	< 26	7.8
[7]	HERMES	$e^+d \rightarrow K^0pX$	1526 ± 3	13 ± 9	~ 5
[8]	ZEUS	$e^+p \rightarrow e^+K^0pX$	1522 ± 3	8 ± 4	~ 5
[9]	COSY-TOF	$pp \rightarrow K^0p\Sigma^+$	1530 ± 5	< 18	4-6
[10]	SVD	$pA \rightarrow K^0pX$	1526 ± 5	< 24	5.6

* Gaussian fluctuation of the background, as $N_{peak}/\sqrt{N_{BG}}$. This "naive" significance may underestimate the real probability of a fluctuation by about 1-2 σ.

† Further analysis of the CLAS deuterium data suggest that the significance of the observed peak may not be as large as indicated.

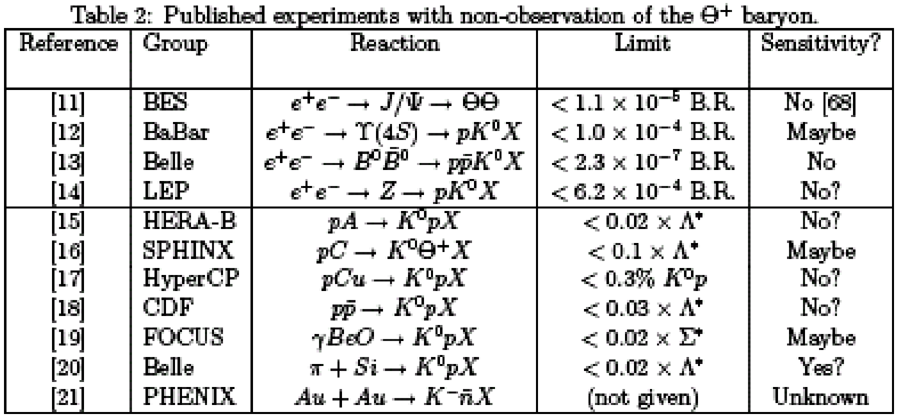


Table 2: Published experiments with non-observation of the Θ^+ baryon.

Reference	Group	Reaction	Limit	Sensitivity?
[11]	BES	$e^+e^- \rightarrow J/\Psi \rightarrow \Theta\Theta$	$< 1.1 \times 10^{-5}$ B.R.	No [68]
[12]	BaBar	$e^+e^- \rightarrow \Upsilon(4S) \rightarrow pK^0X$	$< 1.0 \times 10^{-4}$ B.R.	Maybe
[13]	Belle	$e^+e^- \rightarrow B^0\bar{B}^0 \rightarrow p\bar{p}K^0X$	$< 2.3 \times 10^{-7}$ B.R.	No
[14]	LEP	$e^+e^- \rightarrow Z \rightarrow pK^0X$	$< 6.2 \times 10^{-4}$ B.R.	No?
[15]	HERA-B	$pA \rightarrow K^0pX$	$< 0.02 \times \Lambda^*$	No?
[16]	SPHINX	$pC \rightarrow K^0\Theta^+X$	$< 0.1 \times \Lambda^*$	Maybe
[17]	HyperCP	$pCu \rightarrow K^0pX$	$< 0.3\%\ K^0p$	No?
[18]	CDF	$p\bar{p} \rightarrow K^0pX$	$< 0.03 \times \Lambda^*$	No?
[19]	FOCUS	$\gamma BeO \rightarrow K^0pX$	$< 0.02 \times \Sigma^*$	Maybe
[20]	Belle	$\pi + Si \rightarrow K^0pX$	$< 0.02 \times \Lambda^*$	Yes?
[21]	PHENIX	$Au + Au \rightarrow K^-\bar{n}X$	(not given)	Unknown

Recent CLAS experiments find no Θ+ in γ+d or γ+p

→ Give up, more experiment or theoretical guideline?

Theory : prediction (Diakanov, Petrov, Polyakov 97)

1. SU(3) soliton

$$L_{Kin}(U^2) + L_{Skyrme}(U^4) + L_{W-Z}$$

$$U(x,t) = R(t)\begin{pmatrix} \exp(i\pi\cdot r) & 0 \\ 0 & 1 \end{pmatrix} R^{\dagger}(t)$$

where $R(t)$ has 8 angles

I=J Hedghog

2. Quantizing the 8 angles, the Hamiltonian becomes

$$H^{Rot} = \frac{1}{2I_1}\sum_{A=1}^{3}\hat{J}'^2_A + \frac{1}{2I_2}\sum_{A=4}^{7}\hat{J}'^2_A$$

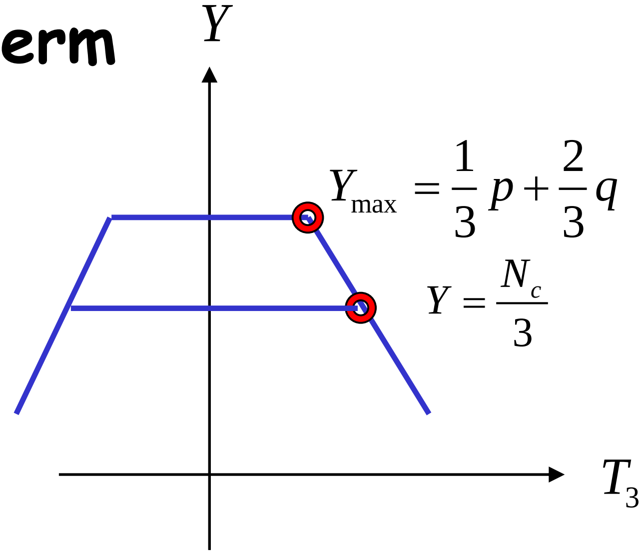
$$E_{10} - E_8 = \frac{3}{2I_1}, \quad E_{\overline{10}} - E_8 = \frac{3}{2I_2}$$

3. With constraint coming from WZ term

$$J'_8 = -\frac{N_c B}{2\sqrt{3}}$$

1. only SU(3) representations containing Y=1 are allowed
2. moreover, the number of states 2I+1 at S=0 or Y= $N_c/3$ must determine the spin of the representation through 2J+1 because I=J in the SU(2) soliton

→ one spin state for given representation



4. Diakanov Petrov Polyakov applied it to Anti-decuplet

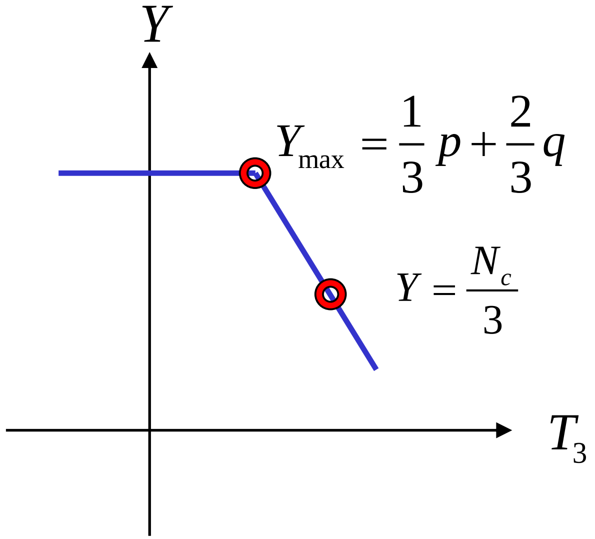
$\overline{10}$ **which predicted M_Θ= 1540, Γ_Θ=30 MeV**

Theory: why it can be wrong (T. Cohen)

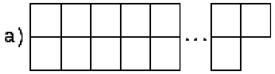
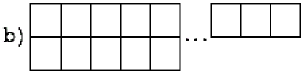
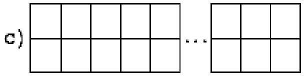
1. Soliton picture is valid at large N_c:

Semi-classical quantization is valid for slow rotation: ie. Valid for describing excitations of order 1/N_c, so that it does not mix and breakdown with vibrational modes of order 1

2. Lowest representation $SU(3)_f$ (p,q) at large N_c



Quantization constraint requires $Y_{\max} = \frac{p}{3} + \frac{2q}{3} \geq \frac{N_c}{3}$

1. Octet $(1, \frac{N_c - 1}{2})$ 
2. Decuplet $(3, \frac{N_c - 3}{2})$ 
3. Anti decuplet $(0, \frac{N_c + 3}{2})$ 

(lowest representation containing s=1)

$$Y = \frac{N_c B}{3} + S$$

3. Mass splitting in large N$_c$:

$$H^{Rot} = \frac{1}{2I_1}\sum_{A=1}^{3}\hat{J}'^2_A + \frac{1}{2I_2}\sum_{A=4}^{7}\hat{J}'^2_A$$

$$E_{10} - E_8 = \frac{3}{2I_1} = O(\frac{1}{N_c}),$$

$$E_{\overline{10}} - E_8 = \frac{3+N_c}{4I_2} = O(1)$$

Anit decuplet octet mass splitting is mixes with vibrational mode and inconsistent with original assumption and has undetermined correction of same order

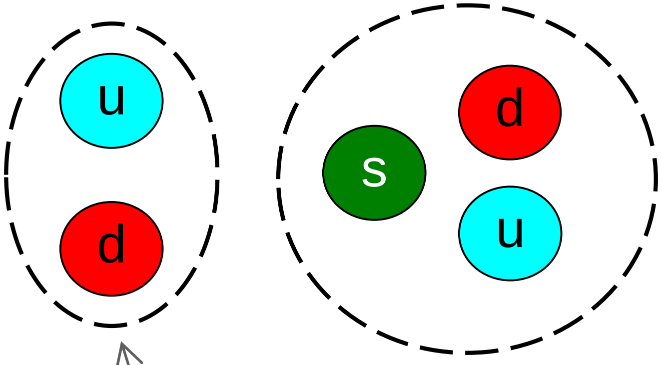
→ Rotation is too fast and may couple to vibrational modes, which might be important to excite q qbar mode, hence describing anti decuplet state with naive soliton quantization might be wrong

Theory: Quark model of a pentaquark

Karlinear, Lipkin model

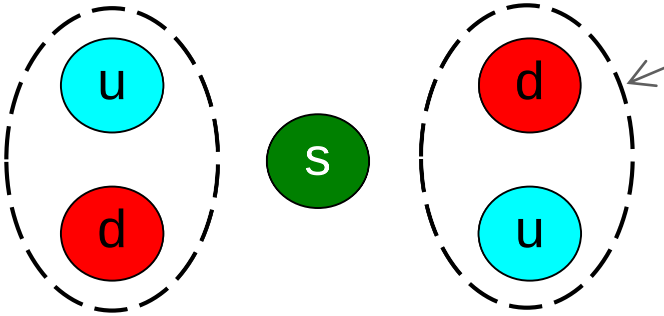
diquark: C=$\bar{3}$,F=3,S=0

triquark: C=$\bar{3}$,F=$\bar{6}$,S=1/2



Strong diquark correlation

Jaffe, Wilczek model

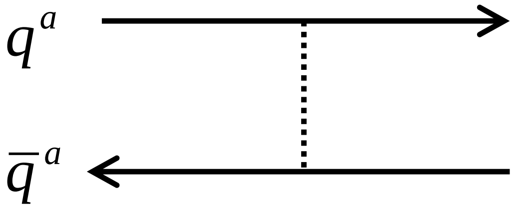


2 diquark: C=$\bar{3}$,F=3,S=0

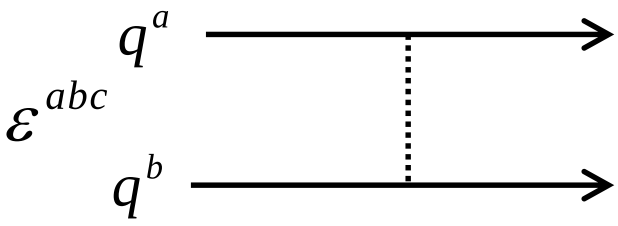
relative p wave

Color Spin Interaction in QCD

1. In QCD q-q are also attractive if in color anti-triplet channel.



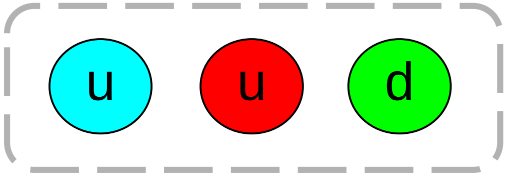
$$\frac{C_M}{m_i m_k}\sum S_i \cdot S_k$$



$$\frac{C_B}{m_i m_k}\sum S_i \cdot S_k$$

In perturbative QCD, $2C_B=C_M$ This term is called color spin interaction

Color spin interaction explains hadron spectrum



Nucleon

$$\frac{C_B}{m_i m_k}\left[s_u \cdot s_u + s_u \cdot s_d + s_u \cdot s_d\right]$$

$$= \frac{C_B}{m_q^2}\frac{1}{2}\left[\left(s_u + s_u + s_d\right)^2 - s_u^2 - s_u^2 - s_d^2\right]$$

Baryon Mass difference

Mass Difference	$M_\Delta - M_N$	$M_\Sigma - M_\Lambda$	$M_{\Sigma_c} - M_{\Lambda_c}$
Formula	$\frac{3C_B}{2m_c^2}$	$\frac{C_B}{m_u^2}(1 - \frac{m_u}{m_s})$	$\frac{C_B}{m_u^2}(1 - \frac{m_u}{m_c})$
Fit	290 MeV	77 MeV	154 MeV
Experiment	290 MeV	75 MeV	170 MeV

Meson Mass difference

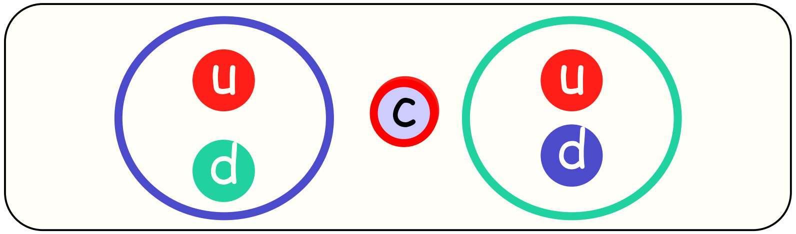
Mass Difference	$M_\rho - M_\pi$	$M_{K^*} - M_K$	$M_{D^*} - M_D$
Formula	$\frac{C_M}{m_u^2}$	$\frac{C_M}{m_u m_s}$	$\frac{C_M}{m_u m_c}$
Fit	635 MeV	381 MeV	127 MeV
Experiment	635 MeV	397 MeV	137 MeV

Works very well with $3C_B = C_M$ = constant

$$m_u = m_d = 300 \text{ MeV}, \quad m_s = 500 \text{ MeV}, \quad m_c = 1500 \text{ MeV}$$

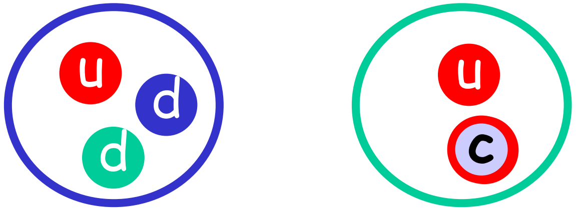
Why there should be a heavy pentaquark

1. For a charmed Pentaquark



$$-\frac{3C_B}{4m_u^2} \qquad -\frac{3C_B}{4m_u^2} \quad = \quad -290\ \text{MeV}$$

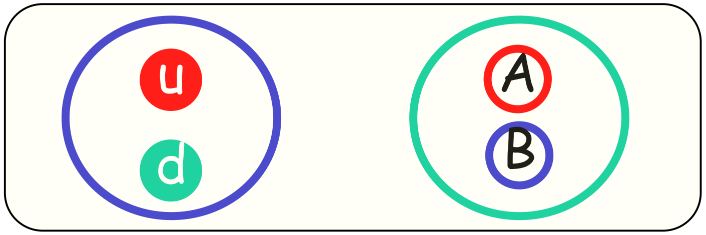
3. If recombined into a D-meson and a Nucleon



$$-\frac{3C_B}{4m_u^2} \qquad -\frac{3C_M}{4m_u m_c} \quad = \quad -240\ \text{MeV}$$

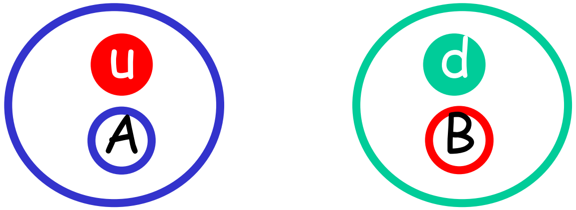
Other possible states - Tetraquark

1. For a Tetraquark



$$-\frac{3C_B}{4m_u^2} - \frac{3C_B}{4m_A m_B} = E_{\text{tetraquark}}$$

2. For the meson and meson



$$-\frac{3C_M}{4m_u m_A} - \frac{3C_M}{4m_u m_B} = E_{\text{2-meson}}$$

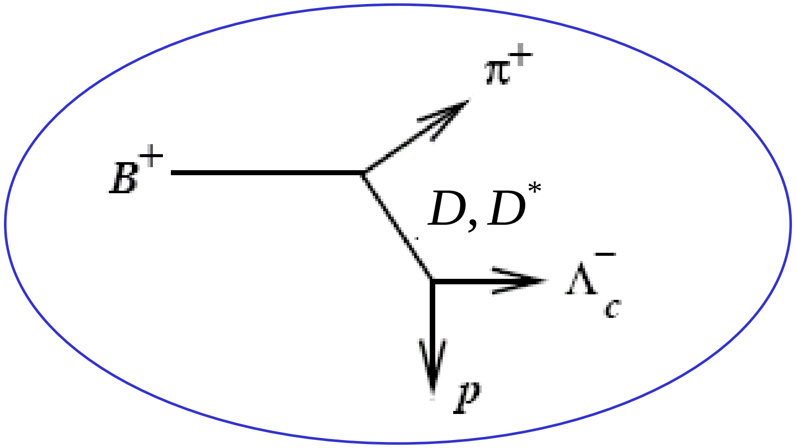
A	B	$E_{\text{tetraquark}}$-E_{2meson}
u	u	663 MeV
u	s	530
s	s	374
u	c	397
s	c	218
c	c	39
b	b	-88

DD^-

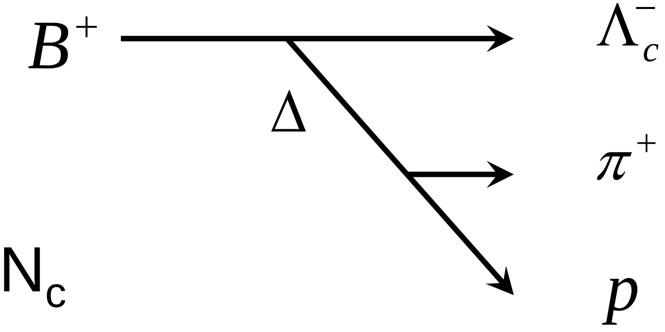
BB^-

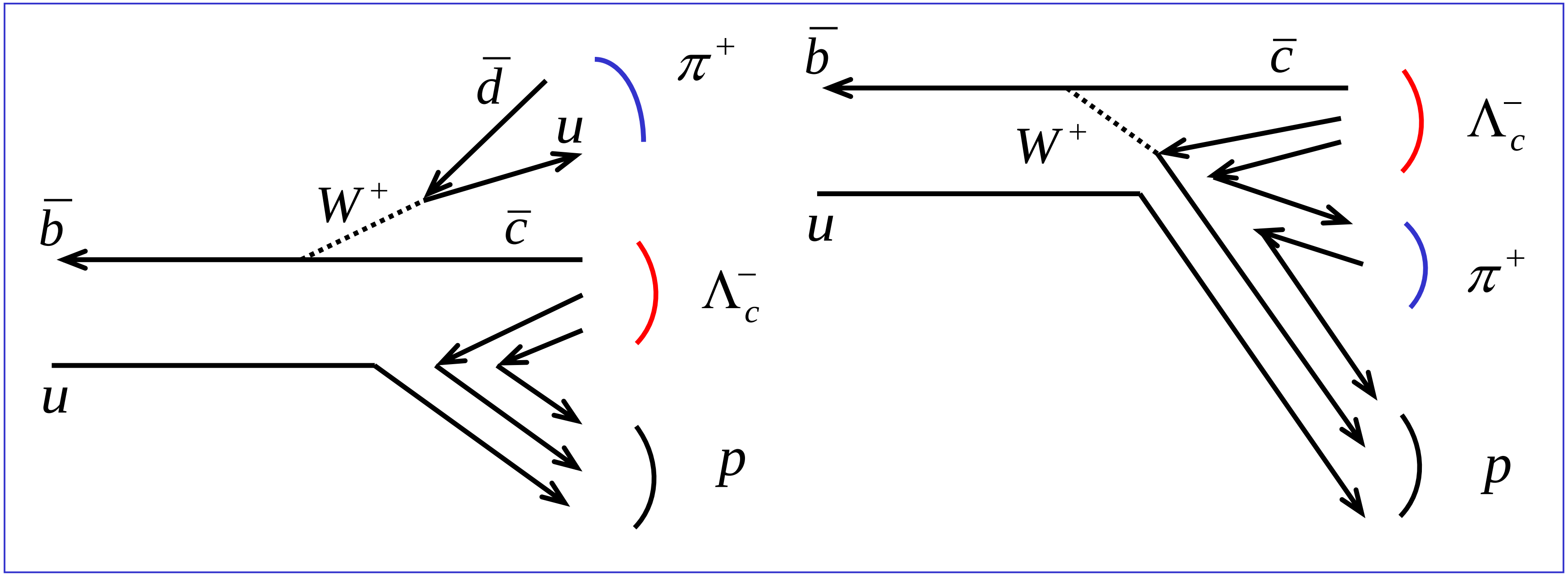
Where to search: Baryonic decay mode of B^+

$B^+ \to \Lambda_c^- p \pi^+$ decay in hadronic language

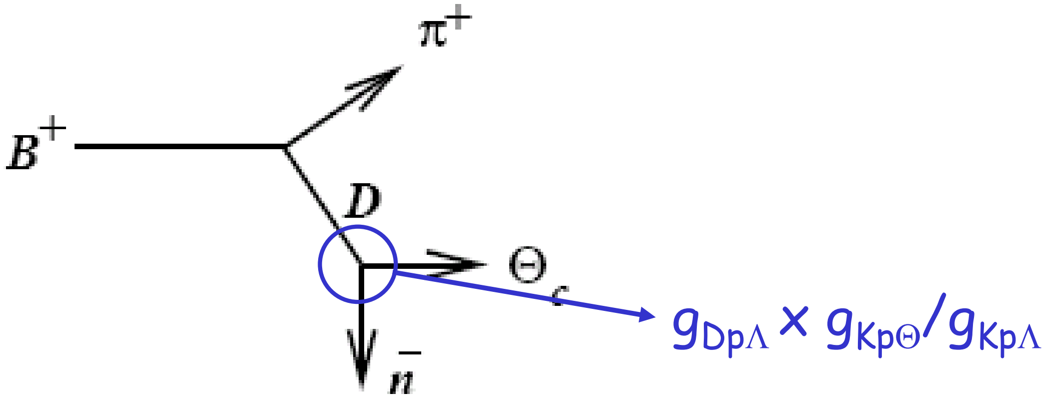


Larger By N_c

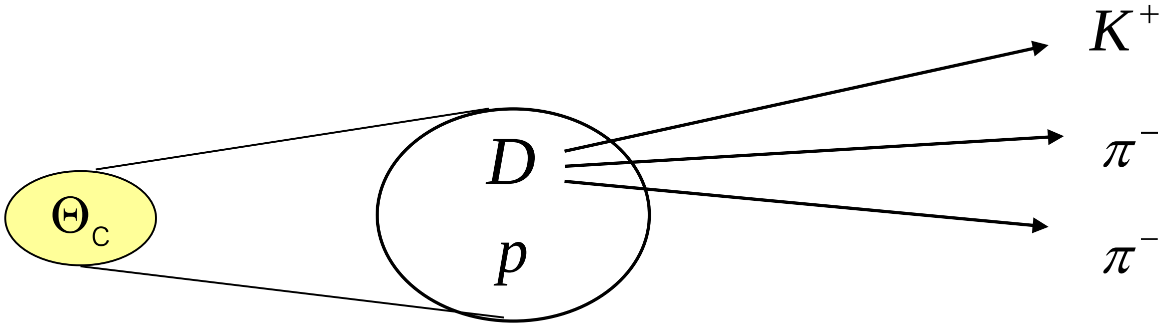




Pentaquark decay mode of B^+



Using pevious fit, we find the branching ratio to be $14.4\text{x}10^{-7}$



Weak decay Branching ratio is 0.092

lower limit in B-factory

$$(10^9)(14.4\times10^{-7})(0.092)(0.7)^4 = 32 \text{ events}$$

Can search for it in Belle S.H.Lee. Y. Kown. Y. Kwon , PRL (06)

Hadron Production in HIC

Success of statistical model

P. Braun-Munzinger, J. Stachel (95 …)

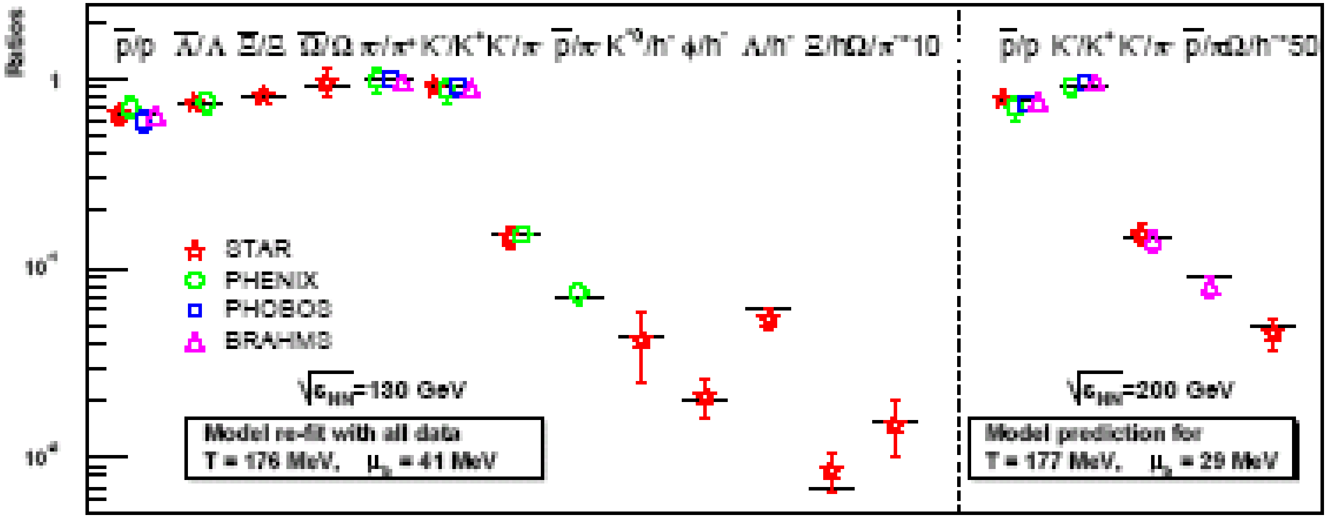


Figure 1. Fit of particle ratios for Au-Au collisions measured at RHIC energies. The measurements are the symbols, the thermal model values are the lines [6, 10]

Recent Star data - I

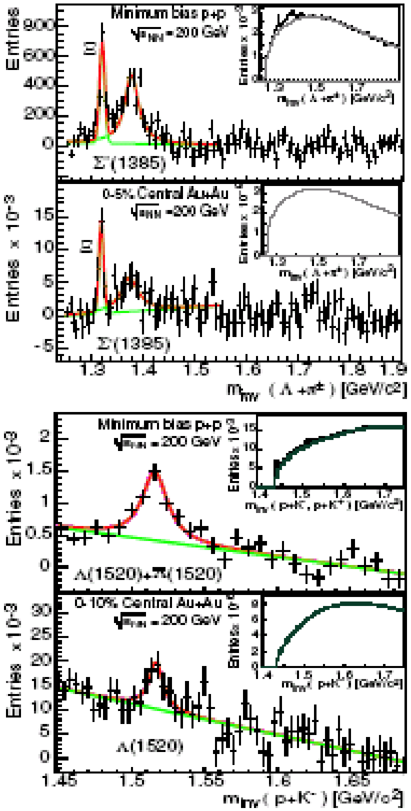


FIG. 1: Invariant mass distributions of $\Sigma^* \to \Lambda + \pi^\pm$ and $\Lambda^* \to p + K^-$ in $p+p$ and $Au+Au$ collisions at $\sqrt{s_{NN}}$ = 200 GeV before (inset) and after mixed-event background subtraction.

Fig. 2. The dashed curves represent an exponential fit to the data [17]. The inverse slopes (T) and the yields at mid-rapidity (dN/dy) as obtained from the fit are listed

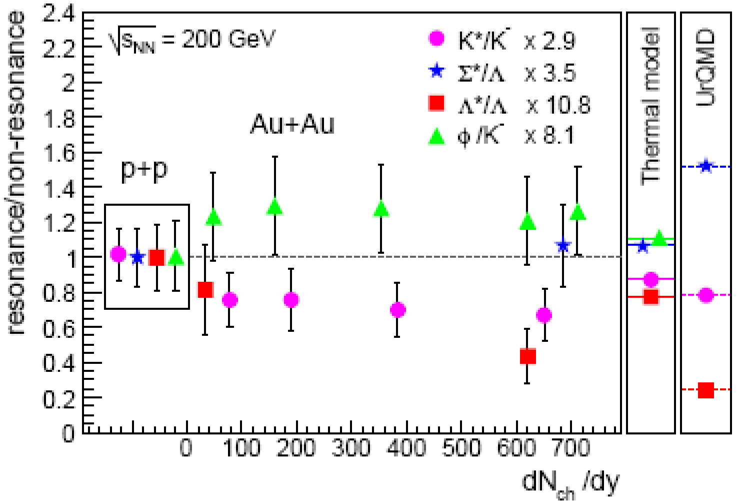
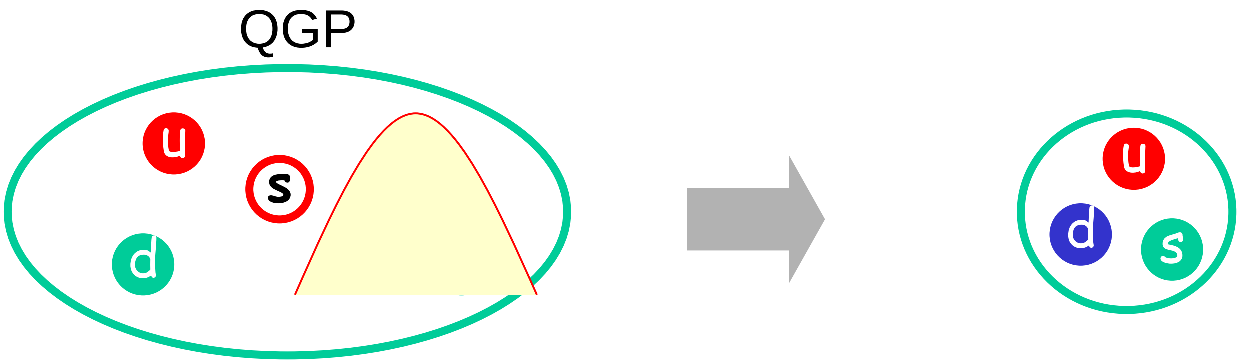


FIG. 4: Resonance to stable particle ratios of Σ^*/Λ, ϕ/K^-, K^*/K^- and Λ^*/Λ for $p+p$ and $Au+Au$ collisions at $\sqrt{s_{NN}}$ = 200 GeV. The ratios are normalized to unity in $p+p$ collisions. The quadratic sum of statistical and systematic uncertainties are included in the error bars. Thermal and UrQMD model predictions are presented in the two right plot sections [13].

$$\left.(\Lambda^*(1520)/\Lambda)_{Au-Au}\middle/(\Lambda^*(1520)/\Lambda)_{p-p}\right. < 1$$

Theoretical Explanation – Muller, Kanada-En’yo

Quark Coalescence model = Statitical model + overlap integral



$$W = \int \prod_i dx_i dk_i F(x,k) \, |\langle \Lambda | \varphi_i \rangle|^2$$

$$\langle \Lambda | \varphi \rangle = \exp(-x^2/b^2 - k^2 b^2)$$

$$\langle \Lambda^* | \varphi \rangle = k^2 \exp(-x^2/b^2 - k^2 b^2)$$

$$F(x,k) = \prod_i \exp[-\frac{x_{i,x}^2}{2a^2} - \frac{k_i^2}{2mT}]$$

$$(\Lambda^*(1520)/\Lambda)_{Au-Au} \Big/ (\Lambda^*(1520)/\Lambda)_{p-p} < 1$$

$$\varphi_i = \exp[ik_i x_i + \ldots]$$

assuming $(\Lambda^*(1520)/\Lambda)_{p-p} = 1$

Statistical model = quark coalescence + overlap

Explicit example $$W^n = \int \prod_i dx_i dk_i F(x,k) |\langle \mathrm{H}^n | \varphi_i \rangle|^2$$

$$F(x,k) = \exp[-\frac{k_1^2}{2mT} - \frac{k_2^2}{2mT}]$$

$$|\langle \mathrm{H}^n | \varphi_i \rangle|^2 = (k_1 - k_2)^n \exp[-\frac{(x_1 - x_2)^2}{b^2} - b^2 (k_1 - k_2)^2 ..]$$

$$W^n = \exp[-\frac{P^2}{2MT}] \times \int drdk\, k^n \exp[-\frac{r^2}{b^2} - (b^2 + \frac{1}{mT}) k^2]$$

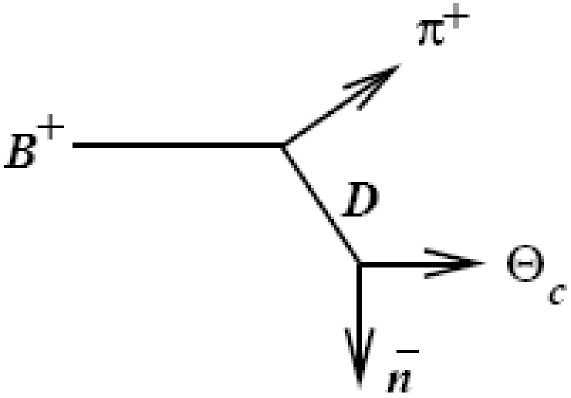
$$W^n / W = \frac{1}{(1 + \frac{1}{mTb^2})^{n/2}}$$

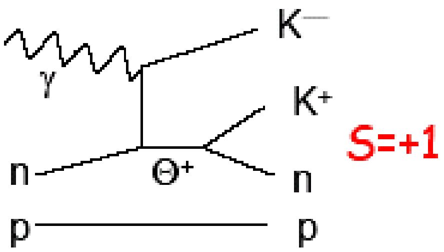
Exotic production in HIC will follow statistical model

modified only by the wave function overlap integral and hadronic phase

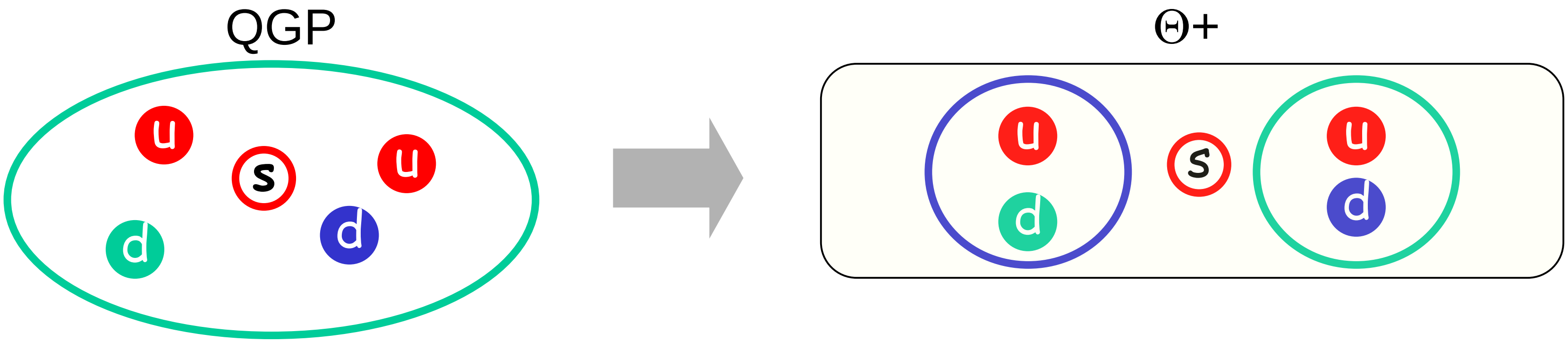
Exotic particle production: elementary vs HIC

Exotic particle production from elementary processes





Exotic particle production from Heavy Ion collision



Example

Θ+(1540) production in Au+Au at RHIC in central rapidity region

Statistical model

J. Randrup, PRC 68 (2003) 031903, N_{Θ} =1

Coalescence model

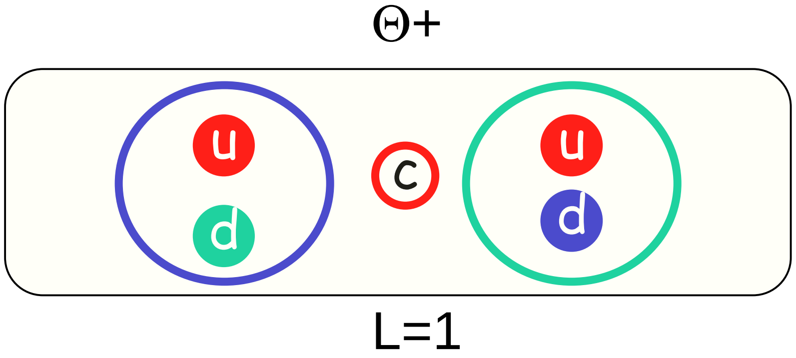
Chen, Greco, Ko, Lee, Liu, PLB 601 (2004) 34, N_{Θ} =0.2

Hadronic regeneration or dissociation is not so large

Exotics from RHIC

1. RHIC (STAR)
   FAIR (GSI)

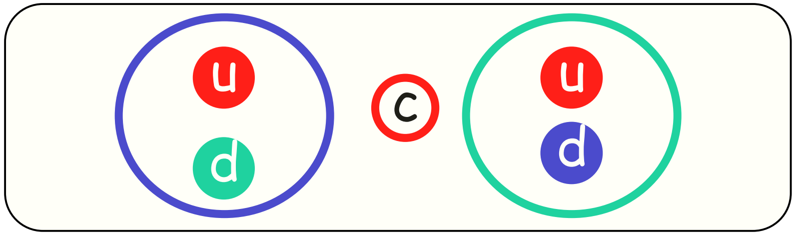
Possible Decay mode of charmed Pentaquark



exotic	Decay mode	Final states	Branching ratio
udus$\underline{c}$	uds(Λ) +u$\underline{c}$($\underline{D}^0$)	$\Lambda + k^0 \pi^0 (k^+ \pi^-)$ $\Lambda + k^0 \pi^- \pi^+$	2.3 % (3.8 %) 5.97 %
	uud(p) +s$\underline{c}$ (Ds-)	$P + k^0 \pi^-$ $P + k^+ \pi^- \pi^-$	2.82 % 9.2 %
udud$\underline{c}$	udu (p)+d$\underline{c}$ (D-)	$P + k^0 \pi^-$ $P + k^+ \pi^- \pi^-$	2.82 % 9.2 %
	udd (n)+u$\underline{c}$ ($\underline{D}^0$)	$n + k^0 \pi^0 (k^+ \pi^-)$ $n + k^0 \pi^- \pi^+$	2.3 % (3.8 %) 5.97 %

Rough estimate of events at RHIC

Θ+



Final state	Decay mode	Final states	Branching ratio
udud$\underline{c}$	udu (p)+d$\underline{c}$ (D-) p + $k^0 \pi^-$	P + $k^+ \pi^- \pi^-$	2.82 % 9.2 %
	udd (n)+u$\underline{c}$ ($\underline{D}^0$)	n + $k^0 \pi^0$ ($k^+ \pi^-$) n + $k^0 \pi^- \pi^+$	2.3 % (3.8 %) 5.97 %

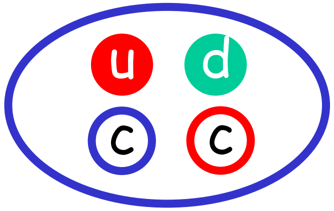
Central collision (0-10%)

$dN_{c\underline{c}}/dy$ = 2.2 (phenix)

$$dN_{\Theta c}/dy = dN_D/dy \times \exp[-m_p/T] \times \text{Branching ratio}$$

$$= 2.2 \times \frac{1}{148} \times 0.03 = 0.00045$$

Possible Decay mode of Tetra-quark



exotic	Decay mode	Final states	Branching ratio
us$\underline{cc}$	u$\underline{c}$ ($\underline{D}^0$)+s$\underline{c}$ (Ds-)	$\underline{D}^0$ (k^0 π^0 , k^+ π^- k^0 π^- π^+) Ds-($\underline{k^0}$$k^-$, k^-k^+ π^-)	3.6 % (4.4 %)
ud$\underline{cc}$	d$\underline{c}$ (D-)+u$\underline{c}$ ($\underline{D}^0$)	D- (k^0 π^{-l} k^+ π^- π^-) + $\underline{D}^0$ (k^0 π^0 , k^+ π^- k^0 π^- π^+)	

Who can do it :   STAR collaboration?

PRL 94, 062301 (2005)   PHYSICAL REVIEW LETTERS   week ending
18 FEBRUARY 2005

Open Charm Yields in d + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

$$D^0 \to k^- \pi^+$$

$$D^+ \to \overline{k}^0 \pi^+$$

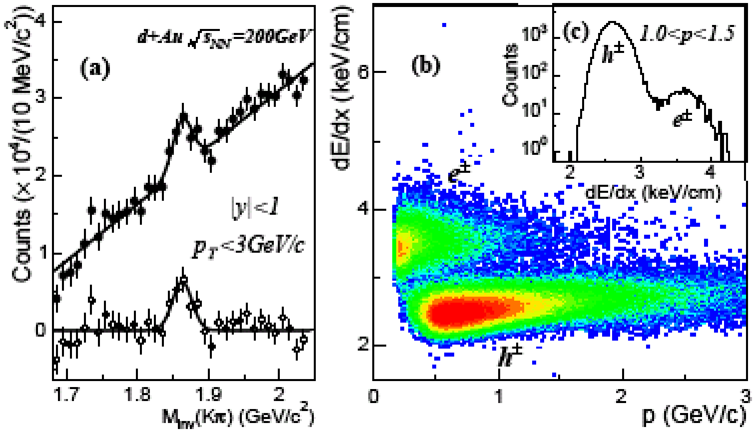


FIG. 1: (a) Invariant mass distributions of kaon-pion pairs from d+Au collisions. The solid circles depict the signal after mixed-event background subtraction, the open circles after subtraction of the residual background using a linear parametrization. (b) dE/dx in the TPC vs. particle momentum (p) with a TOF cut of $|1/\beta - 1| \leq 0.03$. Insert: projection on the dE/dx axis for particle momenta $1 < p < 1.5$ GeV/c.

Who can do it :   FAIR ?

Summary

1. **While controvery exist over light pentaquark, Many Theories consistently predict bound heavy pentaquark**

2. **Quark model also predict metastable tetraquark**

3. **RHIC can be a very useful exotic factory**

   → If found the first exotic ever, will tell us about QCD and dense matter → color superconductivity

References

- Experiments
- T. Nakano , Phys. Rev. Lett. 91 (03) 012002.
- K.~H.~Hicks, Prog. Part. Nucl. Phys. 55 (05) 647.

- Skyrme model controversy
- T.D.Cohen, Phys. Lett. B 581 (04) 175
- H. Walliser and H. Weigel, Eur. Phys. J. A 26 (05) 361.
- D.Diakonov, V.Petrov and M.V.Polyakov, Z. Phys.A 359 (97) 305

- Theory
- H. J. Lipkin, Phys. Lett. B 195 (87) 484.
- Fl. Stancu, Phys. Rev. D 58 (98) 111501.
- D. O. Riska, N. N. Scoccola, Phys. Lett. B 299 (93) 338.
- Y.Oh, B.Y. Park, D.P. Min, Phys. Lett. B 331 (94) 362. Phys. Rev. D 50 (94) 3350.
- R.L.Jaffe, F.Wilczek, Phys. Rev.Lett. 91(2003) 232003.

- present work
- H. Kim, Y. Oh, S.H.Lee, PLB 595 (04) 293:
- Y. Sarac, H.Kim, S.H.Lee, PRD 73 (06) 014009
- S.H.Lee, Y. Kown, Y. Kown, PRL 96 (06) 102001