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# Light-Front Approach for Strong & Weak Decays of Pentaquarks

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# Experimental observations for $\Theta^+$

Experiments	modes	$\Theta^+$ mass (MeV)	Width (MeV)
Spring-8	$\gamma n$ $K^-K^+n$	$1540 \pm 10 \pm 5$	$<25$
DIANA	$K^+Xe$ $K^0pXe$	$1539 \pm 2 \pm \text{“few”}$	$< 9$
CLAS	$\gamma d$ $K^-K^+np$	$1542 \pm 2 \pm 5$	$<21$
SAPHIR	$\gamma p$ $K_S K^+n$	$1540 \pm 4 \pm 2$	$<25$
ITEP	$\nu X$ $K^0pX$	$1533 \pm 5$	$<20$
CLAS	$\gamma p$ $\pi^+K^-K^+n$	$1555 \pm 1 \pm 10$	$26 \pm 7$
HERMES	$eD$ $pK_S X$	$1528 \pm 2.6 \pm 2.1$	$19 \pm 5 \pm 2$
ZEUS	$ep$ $pK_S X$	$1527 \pm 2$	$10 \pm 2$
SVD-2	$pA$ $pK_S X$	$1526 \pm 3 \pm 3$	$<24$
COSY-TOF	$pp$ $\Sigma^+pK^0$	$1530 \pm 5$	$<18 \pm 4$
JINR	$pC_3H_8$ $pK^0X$	$1545.1 \pm 12$	$<16.1 \pm 4.1$

PDG

$1539.2 \pm 1.6$

$0.9 \pm 0.3$

# Negative Votes of $\Theta^+$ Pentaquark State

null results from high-energy experiments:

- ❑ **NA49**
- ❑ **BES : in  $J/\psi$  and  $\Psi(2S)$  decays**
- ❑ **PHENIX**
- ❑ **HERA-B**
- ❑ **ALEPH, DELPHI**
- ❑ **BaBar**
- ❑ **Belle**
- ❑ **Fermilab: CDF, HyperCP, E690**

Evidence must be established beyond any doubt

# What do we learn from positive experiments:

- $\Theta^+$  observed by 10 groups.  $m \approx 1540$  MeV,  $\Gamma \sim 1$  MeV.

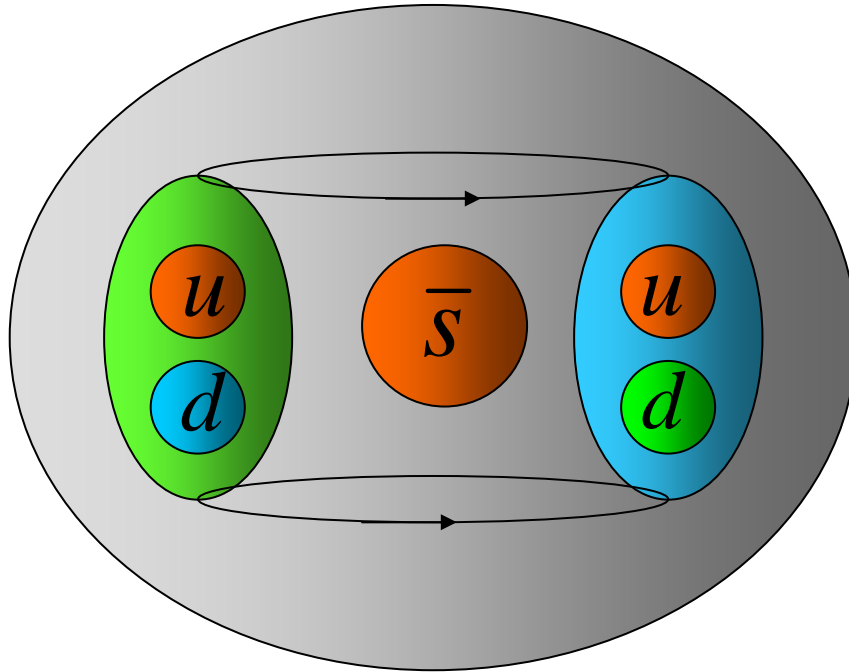
$$\Theta^+ (\bar{s}uudd) \rightarrow K^+ (\bar{s}u) n(udd), K^0 (\bar{s}d) p(uud)$$

- Why is  $\Theta^{++} (\bar{s}uuud) \rightarrow K^+ (\bar{s}u) p(uud)$  not observed ?  
Easier to detect. Very similar to  $\Theta^+$ , only change one  $d \rightarrow u$ .
- $m_{\Theta} < 4m_u + m_s \approx 1900$  MeV. Why is  $\Theta^+$  anomalously light ?
- A width of order  $\geq 200$  MeV is expected as  $\Theta^+ \rightarrow K^+ n$  is OZI super-allowed (no gluon is needed). Why is  $\Theta^+$  so narrow ?
- **The most important message: quark-quark correlation (cluster structure) is an essential feature in multi-quark systems.**

Review: S.L. Zhu, hep-ph/0406204

M. Oka, hep-ph/0406211

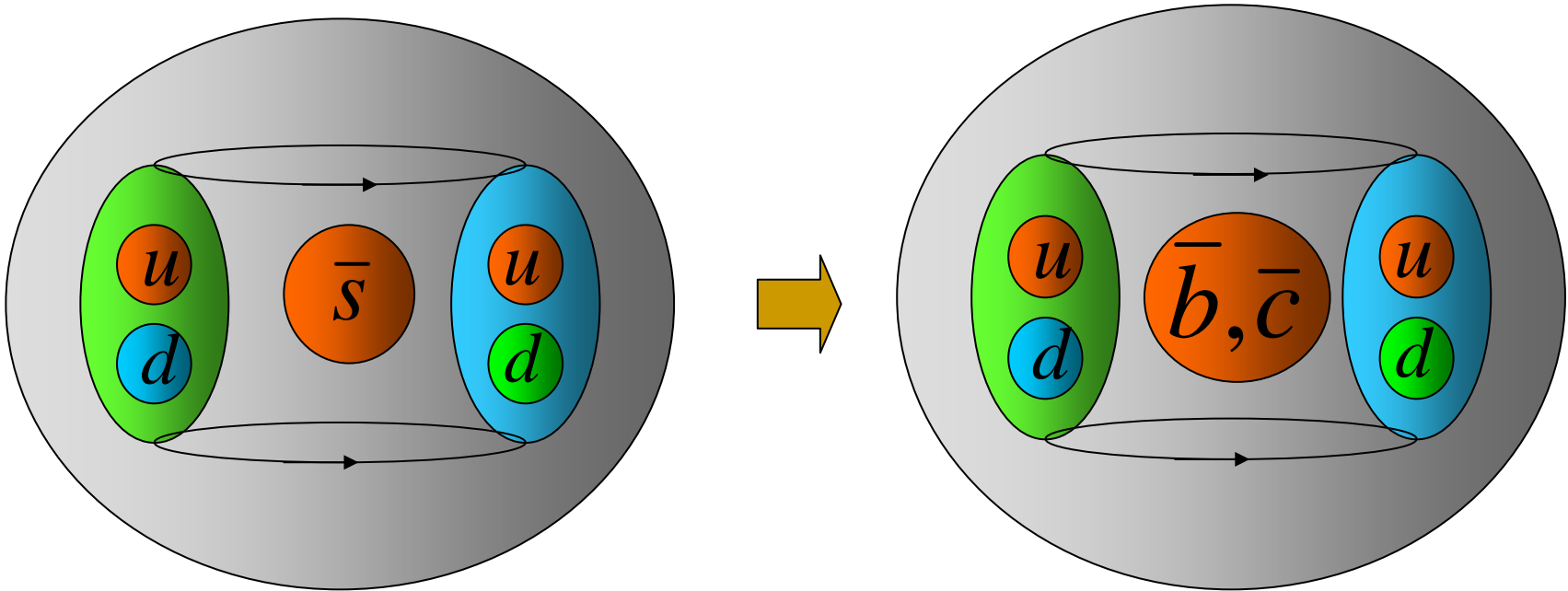
# $\Theta^+$ pentaquark in Jaffe-Wilczek model



Jaffe & Wilczek, PRL, 91, 232003 (2003)

- $ud$  quarks are correlated to form a composite **scalar diquark**.
- The anti-s quark is in a s-wave configuration, while the diquark pair is in a **p-wave** (orbital angular momentum=1) configuration.
- Spin=1/2. Parity =  $(-)^{1+1} = + \Rightarrow J^P = 1/2^+$ .

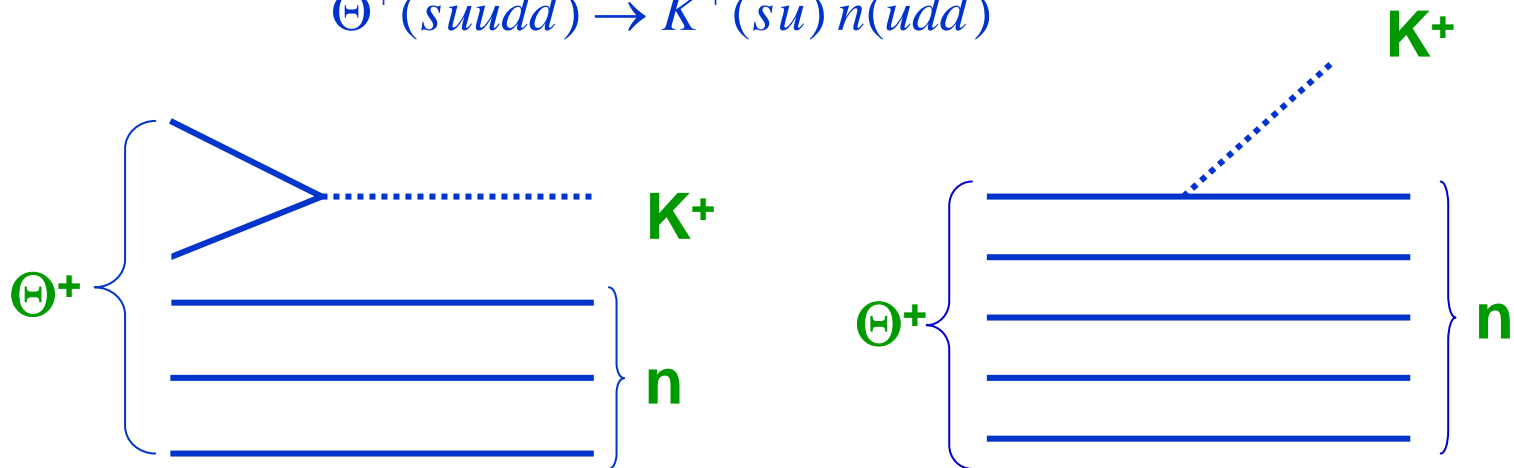
# Heavy pentaquark



- Replacing anti-quark in light pentaquark by heavy anti-charm or anti-bottom quarks.

# Pentaquark strong decays

$$\Theta^+ (\bar{s}uudd) \rightarrow K^+ (\bar{s}u) n(udd)$$



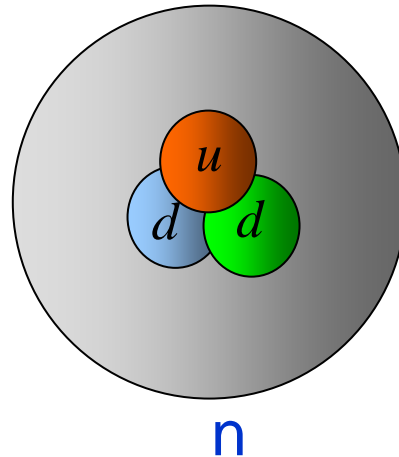
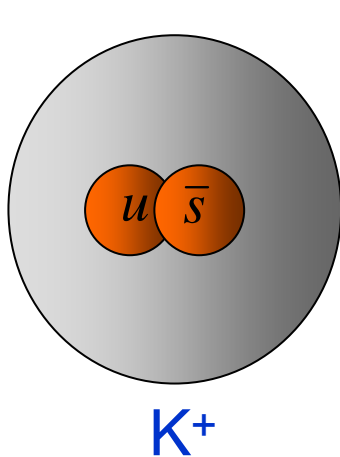
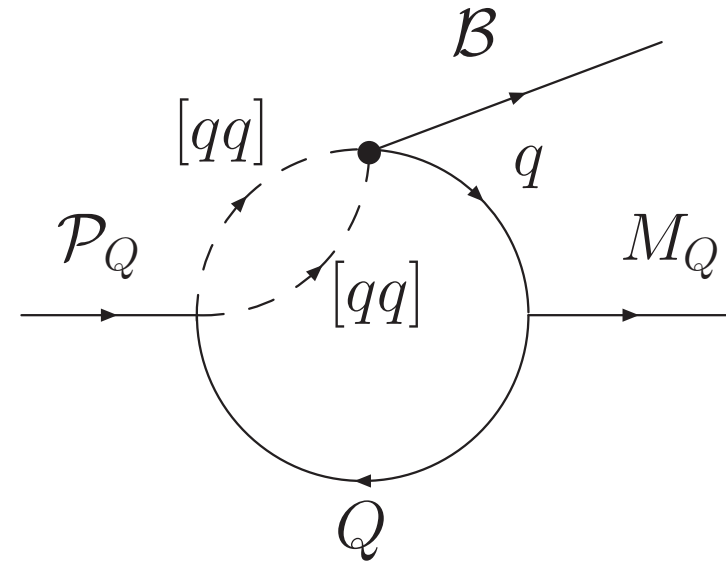
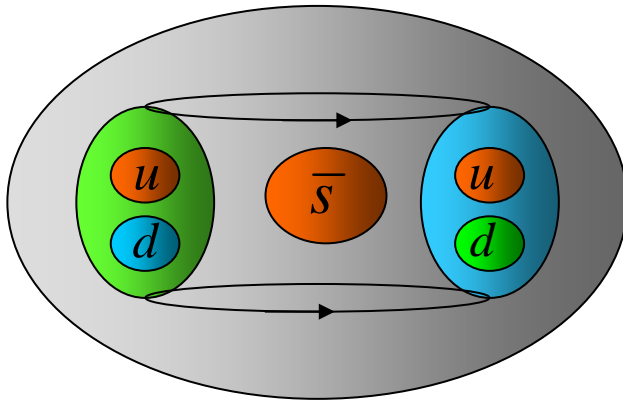
fall-apart decay (OZI super-allowed)

emission

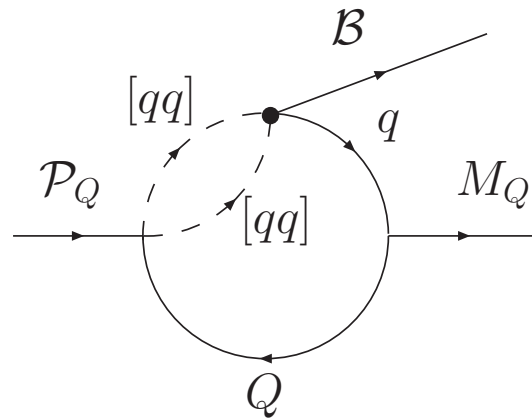
Since  $\Theta^+$  is above KN threshold, its strong decay is generally dominated by the fall-apart process which cannot occur in ordinary baryon decay. Quark correlation is needed in order to suppress fall-apart mechanism.

(In infinite momentum frame, no quark production & annihilation  $\Rightarrow$  emission only  $\Rightarrow$  suppression due to transition between  $\Theta^+$  and 5-quark component of nucleon )

# Strong decay in Jaffe-Wilczek model



The decay width is narrow due to the breaking of diquarks and the transformation of the p-wave into s-wave configurations



- Pentaquark vertex function has been worked out in light-front approach [HYC, Chua, Hwang, hep-ph/0403232]
- For even parity pentaquark: the antiquark has a Gaussian distribution. Use the Melosh transform to project the antiquark spin in the hadron rest frame.
- Diquark has a Gaussian  $\times$  (momentum) $_m$ :  $p$ -wave distribution.
- Combine antiquark and diquark angular momentum to form a spin  $\frac{1}{2}$  pentaquark state.
- (Pseudo-)scalar meson vertex functions are known (CCH, PRD 2004).

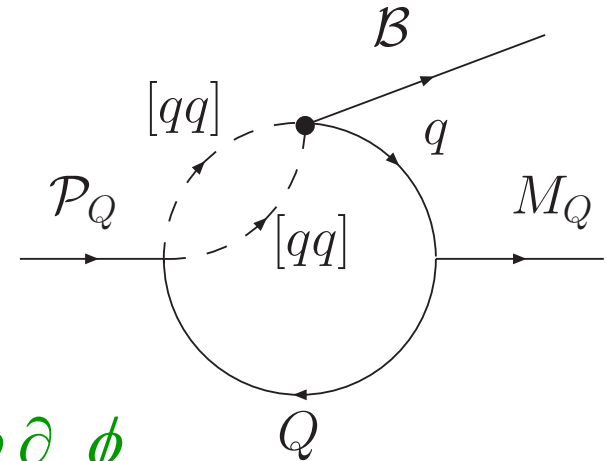
# Modelling the $[qq][qq] \mathcal{B}q$ sub-process

- We use a local operator

$$H_{\text{eff}} = \frac{g_{1\text{eff}}}{M} \overline{\mathcal{B}} \gamma_5 q^c \phi \phi + i \frac{g_{2\text{eff}}}{M^2} \overline{\mathcal{B}} \gamma^\mu \gamma_5 q^c \phi \partial_\mu \phi$$

to model the  $[qq][qq] \mathcal{B}q$  sub-process with  $M \sim O(m_{[qq]}, m_{\mathcal{B}})$ .

- Need to bring two diquarks close together local operators
- Only the second term contributes to even parity pentaquark decays
- The coupling  $g_2/M^2$  is determined from  $\Gamma(\Theta)$ .



# Decay matrix elements and form factors

- The pentaquark matrix element:

$$M(\mathcal{P} \rightarrow M\mathcal{B}) = \frac{g_{2\text{eff}}}{M^2} \bar{u} \langle M | i\gamma^\mu \gamma_5 q^c \phi \partial_\mu \phi | \mathcal{P} \rangle$$

- The transition matrix elements:

$$\langle P(8) | \mathcal{O}_{\text{eff}} | \mathcal{P}(\overline{10}) \rangle = f(q^2) i\gamma_5 u,$$

$$\langle P_Q(3) | \mathcal{O}_{\text{eff}} | \mathcal{P}_Q(\overline{6}) \rangle = f_Q(q^2) i\gamma_5 u,$$

$$\langle S_Q(3) | \mathcal{O}_{\text{eff}} | \mathcal{P}_Q(\overline{6}) \rangle = -g_Q(q^2) u.$$

- Dimension-2 form factors:  $f, f_Q, g_Q$ .

# FFs (form factors)

- FFs are fitted to the form

$$F(q^2) = \frac{F(0)}{1 - (q^2 / \Lambda_1^2) + (q^2 / \Lambda_2^2)^2}$$

in spacelike region and then extrapolated to timelike region

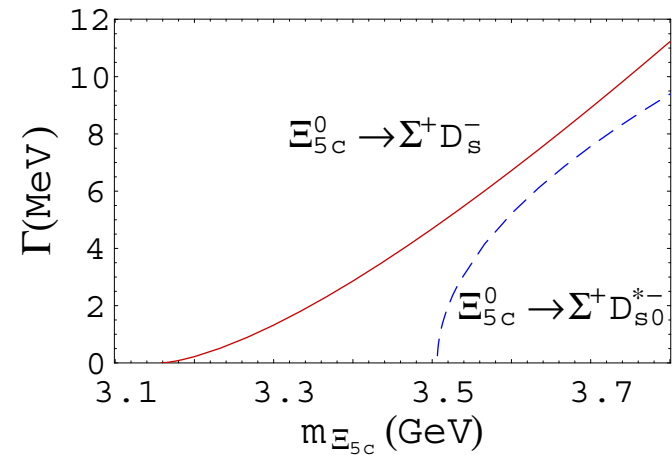
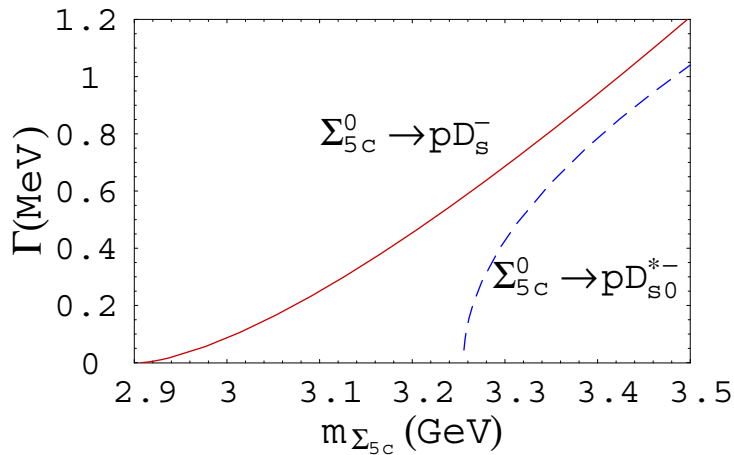
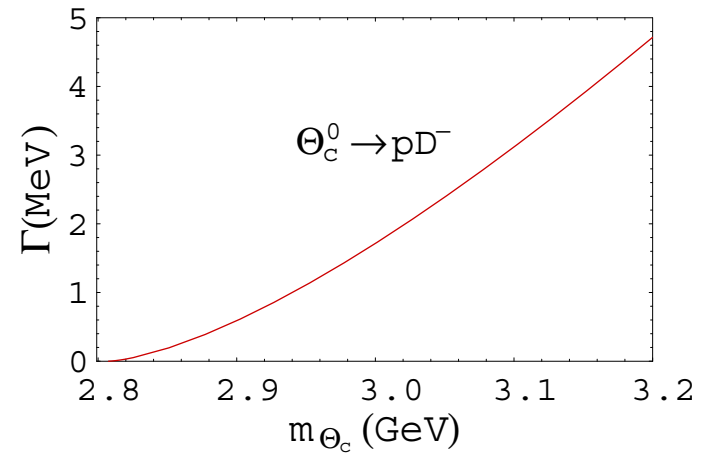
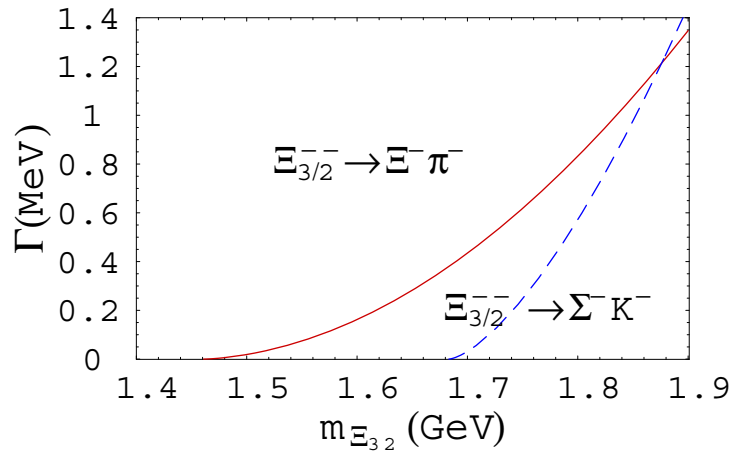
- FFs in units of  $\text{GeV}^2$ ,  $\Lambda_{1,2}$  in units of  $\text{GeV}$ .

$F^{\mathcal{P} \rightarrow M}$	F(0)	$\Lambda_1$	$\Lambda_2$	$F^{\mathcal{P} \rightarrow M}$	F(0)	$\Lambda_1$	$\Lambda_2$
$f^{\Theta \rightarrow K}$	0.077	2.18		$f^{\Sigma 5c \rightarrow Ds}$	0.045	2.25	2.40
$f^{\Xi 3/2 \rightarrow \pi}$	0.065	2.59		$g^{\Sigma 5c \rightarrow Ds0}$	0.024	2.64	2.32
$f^{\Xi 3/2 \rightarrow K}$	0.085	2.56		$f^{\Xi 5c \rightarrow Ds}$	0.084	2.16	2.55
$f^{\Theta c \rightarrow D}$	0.081	2.06	2.39	$g^{\Xi 5c \rightarrow Ds0}$	0.045	2.97	2.23

# Determining $g_2$ from $\Theta$ width.

- Take  $\Gamma(\Theta) \approx 1$  MeV (from K-d scattering data analysis).  
 $f^{\Theta \rightarrow K}(m_N^2) = 0.095 \text{ GeV}^2 \Rightarrow g_2/M^2 \approx 10.2 \text{ GeV}^{-2}$ .  
Taking  $M \sim 1 \text{ GeV} \Rightarrow g_2 \approx 10.2$  similar to  $g_{\pi NN} \approx 14$ .
- Narrowness of  $\Theta$  width arises from bringing the two diquarks in a p-wave configuration close together to form a final state baryon in s-wave configuration.
- Apply this  $g_2$  to those decays involving similar  $[qq][qq] \mathcal{B}q$  sub-process.

# $\mathcal{P}$ $\mathcal{BM}$ strong decays



# $\mathcal{P}$ $\mathcal{B}M$ strong decays

- Smallness of  $\Gamma(\Theta)$  is due to diquark configuration
- $\Gamma(\Xi_{3/2} \rightarrow \Xi^- \pi^-) / \Gamma(\Theta \rightarrow p K^0) \approx 2.2$
- $\Gamma(\Theta_c \rightarrow p D^-) \approx 3.1 \text{ MeV} \Rightarrow \Gamma(\Theta_c \rightarrow p D^{*-}) \approx 3 \Gamma(\Theta_c \rightarrow p D^-) \approx 9 \text{ MeV}$   
 $\Rightarrow \Gamma(\Theta_c) \approx 20 \text{ MeV}$  [  $\Gamma(\Theta_c) \approx 12 \pm 3 \text{ MeV}$  from H1 collaboration ]
- $\Gamma(\mathcal{P}_c \rightarrow \mathcal{B} D_{s0}^*) \approx \Gamma(\mathcal{P}_c \rightarrow \mathcal{B} D_s)$  for even parity  $\mathcal{P}_c$ .  
Recall that  $\mathcal{P}_c(1/2^+)$ ,  $\mathcal{B}(1/2^+)$ ,  
 $D_s(0^-)$ ,  $D_{s0}^*(0^+)$  ( $m=2317 \text{ MeV}$  lighter than expected).  
 $\mathcal{P}_c \rightarrow \mathcal{B} D_s$ : final state in p-wave configuration, suppressed  
 $\mathcal{P}_c \rightarrow \mathcal{B} D_{s0}^*$ : final state in s-wave configuration, unsuppressed .  
Provide useful information on pentaquark parity.

# Heavy charmed and bottom pentaquarks

$\Theta_c = uuddc$ ,  $\Theta_b = uuddb$ , differ from  $\Theta$  by the replacement of  $s \rightarrow c$  or  $b$

In Jaffe-Wilczek model, there are parity-even  $\bar{6}_f$  and parity-odd  $3_f$  heavy-flavor pentaquarks.

Whether heavy pentaquark is above or below strong decay threshold is controversial

H1 expt: a narrow resonance in  $D^{*-}p$  and  $D^{*+}\bar{p}$  mass distributions

$$m=3099\pm 3\pm 5 \text{ MeV}, \quad \text{width}=12\pm 3 \text{ MeV}$$

can be identified with spin  $1/2$   $\Theta_c^0$  or spin  $3/2$   $\Theta_c^{*0}$

However, there are null results from ZEUS, ALEPH, FOCUS, CDF

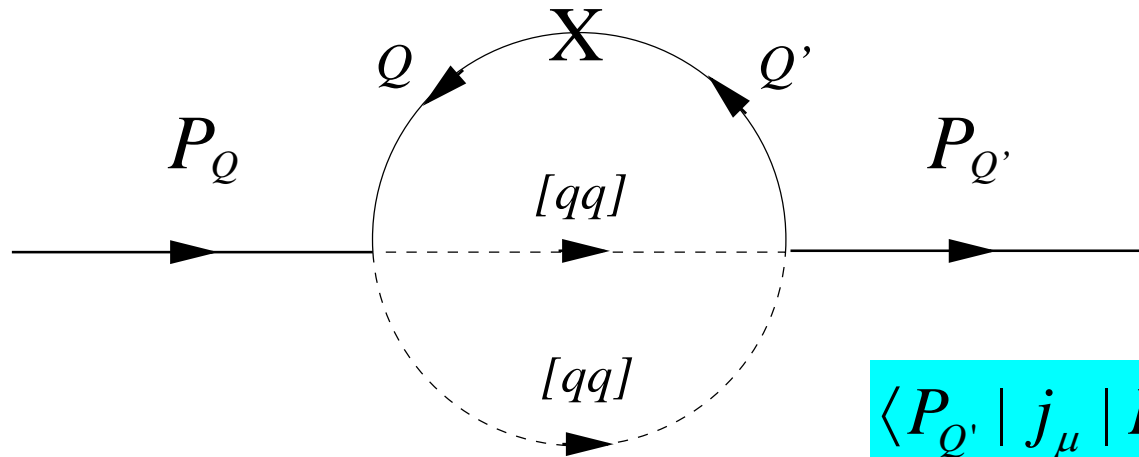
Triplet heavy pentaquarks are believed to be below strong decay threshold

# Search for heavy pentaquarks (if below threshold) through weak decays

HYC, Chua, Hwang (hep-ph/0403232)

- $P_b \rightarrow P_c \pi$ ,  $P_b \rightarrow P_c \rho$ ,  $\Theta_c \rightarrow \Theta \pi$ ,  $\Theta_c \rightarrow \Theta \rho$  weak transitions are the dominant ones.
- We use the relativistic light-front approach to calculate the pentaquark to pentaquark weak transition form factors
- This is the *first* calculation involving dynamics in transition.

# Light-Front Approach for Heavy Pentaquark Transitions



$$\langle P_{Q'} | j_\mu | P_Q \rangle \otimes \langle \pi(\rho) | j^\mu | 0 \rangle$$

- We have experience in calculating s,p-wave systems, a systematic study of transition involving s,p-wave mesons (ISGW, 1989).
- Need to handle a three body system (better than handle a five body system, thanks to the diquark pic.) need proper treatment of spin, so called melosh transform.

# Heavy Quark Symmetry

- In HQ limit, heavy-to-heavy pentaquark transition can be described by one IW function  $\zeta(v \cdot v')$  and two IW functions  $\xi_{1,2}(v \cdot v')$  in the anti-triplet anti-triplet and sextet sextet transitions, respectively
- At zero recoil,  $\zeta(v \cdot v'=1) = \xi_1(1) = 1$  (robust),  $\xi_2(1) = 1/2$  [large- $N_c$  (Chow 95), QM (HYC 97)].
- At zero recoil (maximal  $q^2$ ):

$$f_1 = g_1 = 1, \quad f_{2,3} = g_{2,3} = 0, \quad (3 \rightarrow 3)$$

$$f_1 = \frac{1}{3} \left( 1 + \frac{M'}{M} + \frac{M}{M'} \right), \quad f_2 = f_1 + \frac{1}{3},$$

$$f_3 = \frac{1}{3} \left( \frac{M'}{M} - \frac{M}{M'} \right), \quad g_1 = -\frac{1}{3}, \quad g_{2,3} = 0 \quad (\bar{6} \rightarrow \bar{6})$$

# Heavy pentaquark decay rates

Mode	$\Sigma_{5b}^{\prime+} \rightarrow \Sigma_{5c}^{\prime0} \pi^+$	$\Theta_b^+ \rightarrow \Theta_c^0 \pi^+$	$\Theta_c^0 \rightarrow \Theta^+ \pi^-$
$\Gamma(10^{10} \text{ s}^{-1})$	0.23	0.14	22.10
Mode	$\Sigma_{5b}^{\prime+} \rightarrow \Sigma_{5c}^{\prime0} \rho^+$	$\Theta_b^+ \rightarrow \Theta_c^0 \rho^+$	$\Theta_c^0 \rightarrow \Theta^+ \rho^-$
$\Gamma(10^{10} \text{ s}^{-1})$	0.34	0.19	28.98

- Assuming  $\tau(\Theta_b) \approx \tau(\Lambda_b) \approx 1.2 \times 10^{-12} \text{ s}$  and  $\tau(\Theta_c) \approx \tau(\Lambda_c) \approx 2 \times 10^{-13} \text{ s}$  for the weakly decaying  $\Theta_b$  and  $\Theta_c$ , we find  $B(\Theta_b \rightarrow \Theta_c \pi^+) \approx 1 \times 10^{-3}$  and  $B(\Theta_c \rightarrow \Theta \pi^-) \approx 4\%$ , consistent with the intuitive estimate made in (Leibovich, Ligeti, Stewart, Wise, hep-ph/0312319).
- These heavy pentaquarks are searchable through weak decays.

# Conclusions

- $\Theta^+$  pentaquark is the *first* exotic particle we are searching for over 30 years. There are some evidences for other exotic pentaquarks ( $\Xi_{3/2}$ ,  $\Theta_c$  ...).
- The important message: Quark-quark correlation is essential.
- Fall-apart strong decays of pentaquarks are studied in JW model. Narrowness of widths is ascribed to quark correlation
- If its mass is above (below) threshold, a heavy pentaquark is searchable through strong (weak, EM) decays.
- We did the *first* dynamical calculation on heavy pentaquark weak transitions.