Production of Tetraquark States in the e^+e^- Collisions

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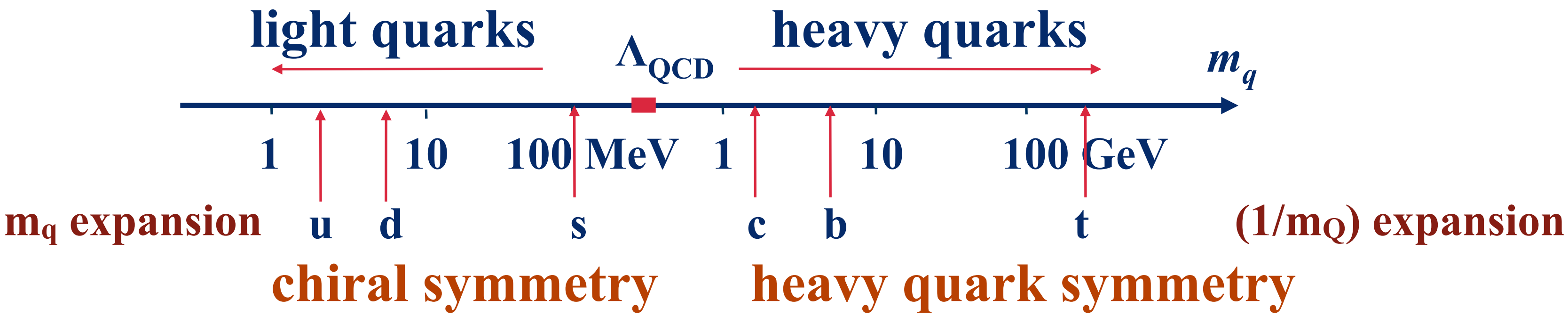
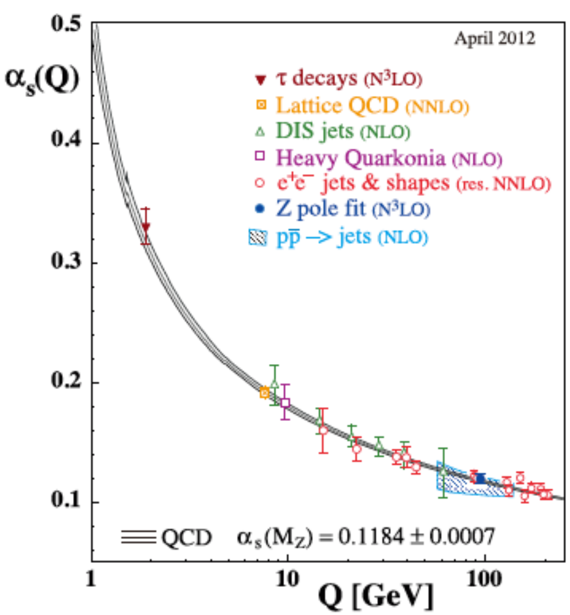
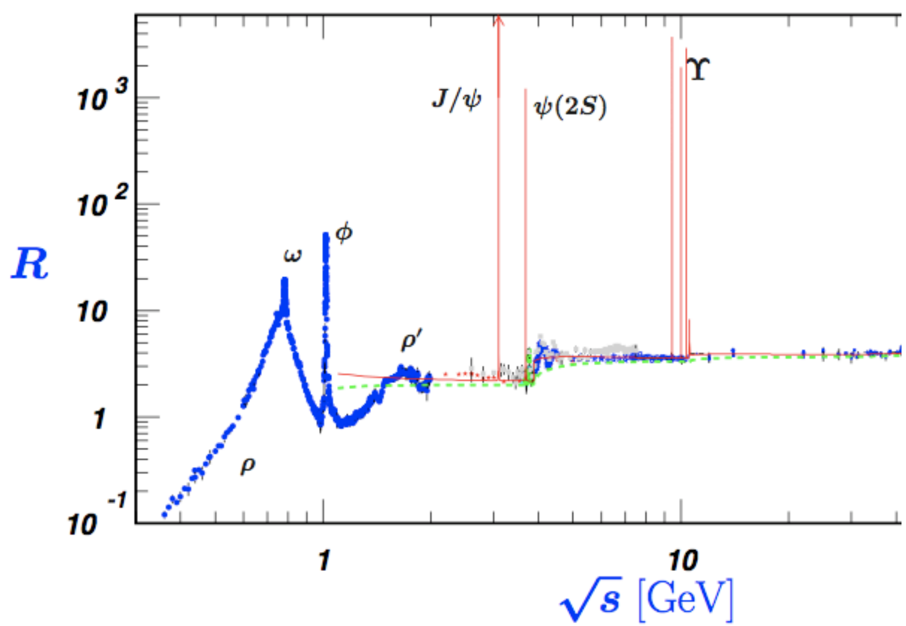
From Strangeness to Charm/Bottom

- $\Lambda_{QCD}(\sim 300\ \text{MeV}) \ll m_c(\sim 1.3\ \text{GeV}) \ll m_b(\sim 4.2\ \text{GeV})$

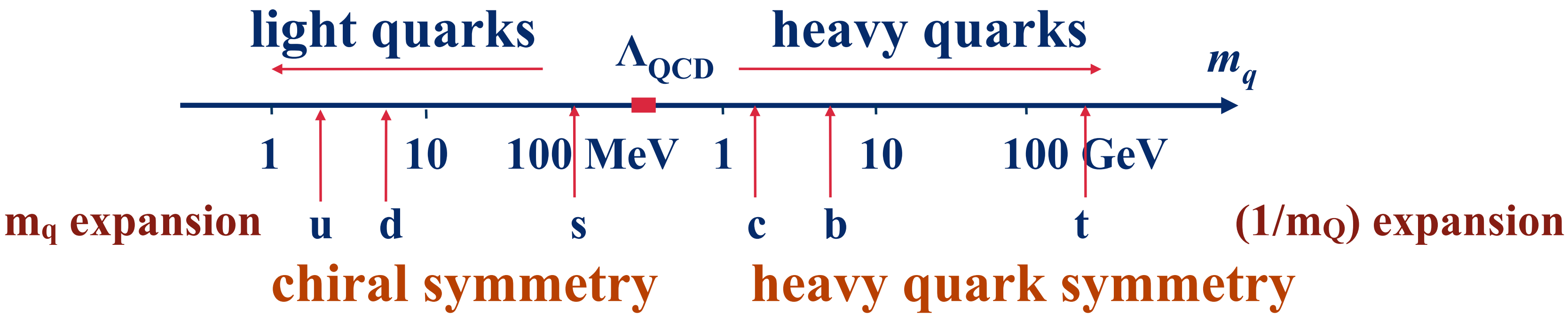






From Strangeness to Charm/Bottom

- $\Lambda_{QCD}(\sim 300\ \text{MeV}) \ll m_c(\sim 1.3\ \text{GeV}) \ll m_b(\sim 4.2\ \text{GeV})$



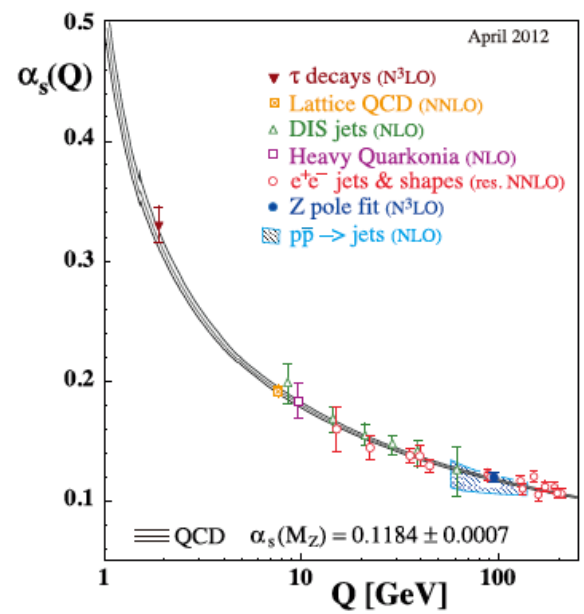
- LQ: Dynamically generated mass

  $m_q \sim \Lambda_{QCD} \sim 300$ MeV

  Strongly Correlated/ Non-perturbative

- HQ: Small $\alpha_s \sim v/c \sim 0.3$ for charm

  Perturbative/ Non-relativistic

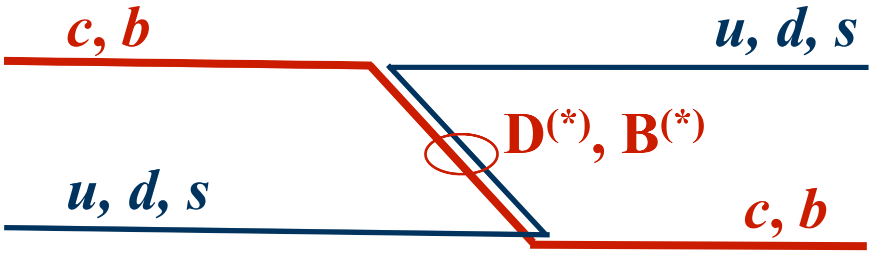


Dynamics of Heavy Quarks

Dynamics of Heavy Quarks

Several important properties of HQ interactions:

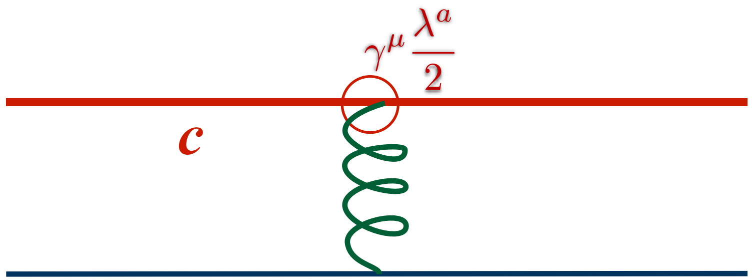
1. **<u>Heavy flavor exchanges are suppressed</u>**



The large masses of HQ mesons, m(D, B) ≫ m(π, K, ρ), make the HQ exchange forces suppressed by $O(1/m_Q)^2$. The interaction of the HQ hadrons is dominated by light hadron exchanges.

Dynamics of Heavy Quarks

2. Magnetic gluon coupling is suppressed



$$\bar{\Psi}\gamma^\mu \frac{\lambda^a}{2}\Psi A^a_\mu \sim \Psi^\dagger \frac{\lambda^a}{2}\Psi A^a_0 - \Psi^\dagger \sigma \frac{\lambda^a}{2}\Psi \cdot \frac{1}{m_Q}(\nabla \times A^a)$$

(Color Electric coupling) ≫ (Color Magnetic coupling)

HQ spin-flip amplitudes are suppressed by ($1/m_Q$).

⇨ Heavy Quark Spin Symmetry

Dynamics of Heavy Quarks

HQ spin symmetry $[S_Q, H] = O\left(\frac{1}{m_Q}\right)$

Q

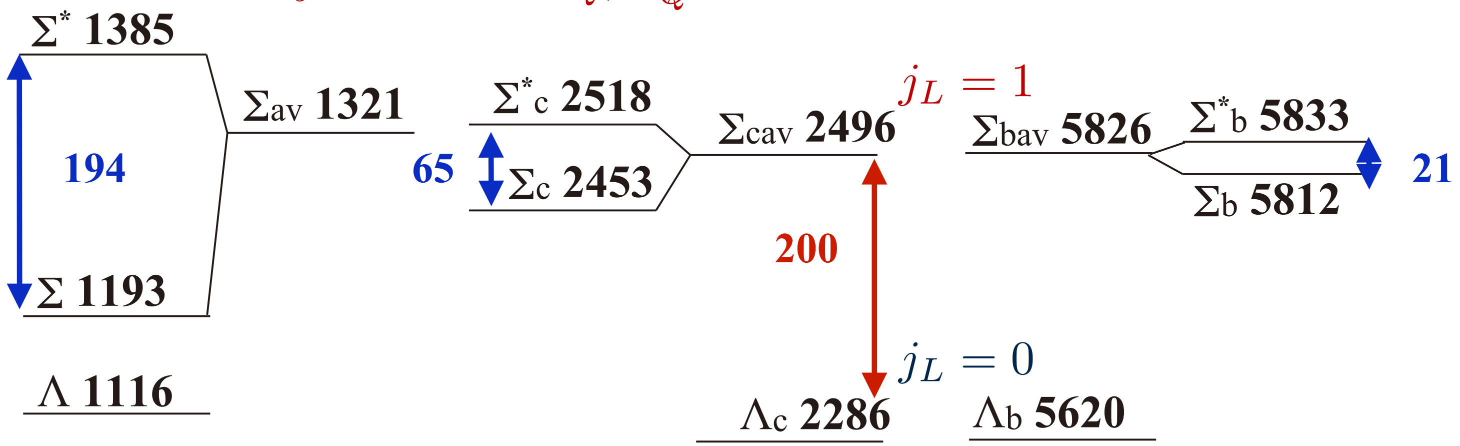
q

$\vec{J} = \vec{S}_Q + \vec{j}_L \qquad \vec{j}_L = \vec{S}_q + \vec{L}_q$

$J = j_L \pm \frac{1}{2}$ **states are degenerate in the HQ limit.**

$j_L = 0 \longrightarrow \Lambda_Q$

$j_L = 1 \longrightarrow \Sigma_Q, \Sigma_Q^*$



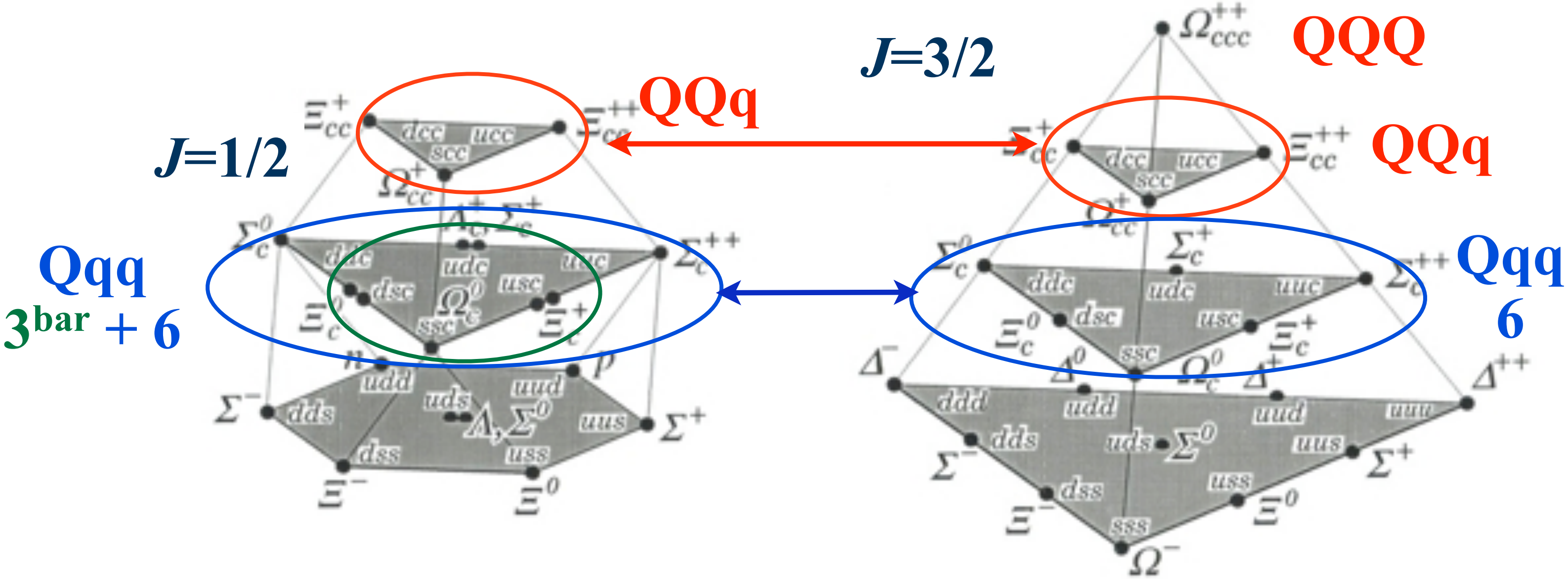
m_s (~0.1 GeV) ≪ m_c (~1.3 GeV) ≪ m_b (~4.2 GeV)

Dynamics of Heavy Quarks

- **Light Baryons: qqq color singlet (color antisymmetric)**
  SU(6) 56 dim. L=0, (8, S=1/2) + (10, S=3/2)
- **Heavy Baryons:** ***HQ spin symmetry***

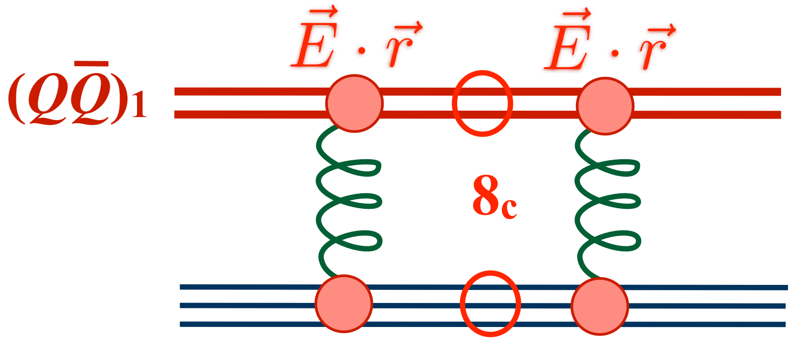
Qqq ⇒ (3^{bar}, J=1/2) + (6, J=1/2) + (6, J=3/2)

QQq ⇒ (3, J=1/2) + (3, J=3/2)



Dynamics of Heavy Quarks

3. **Pure HQ hadrons have attractive interaction with matter.**

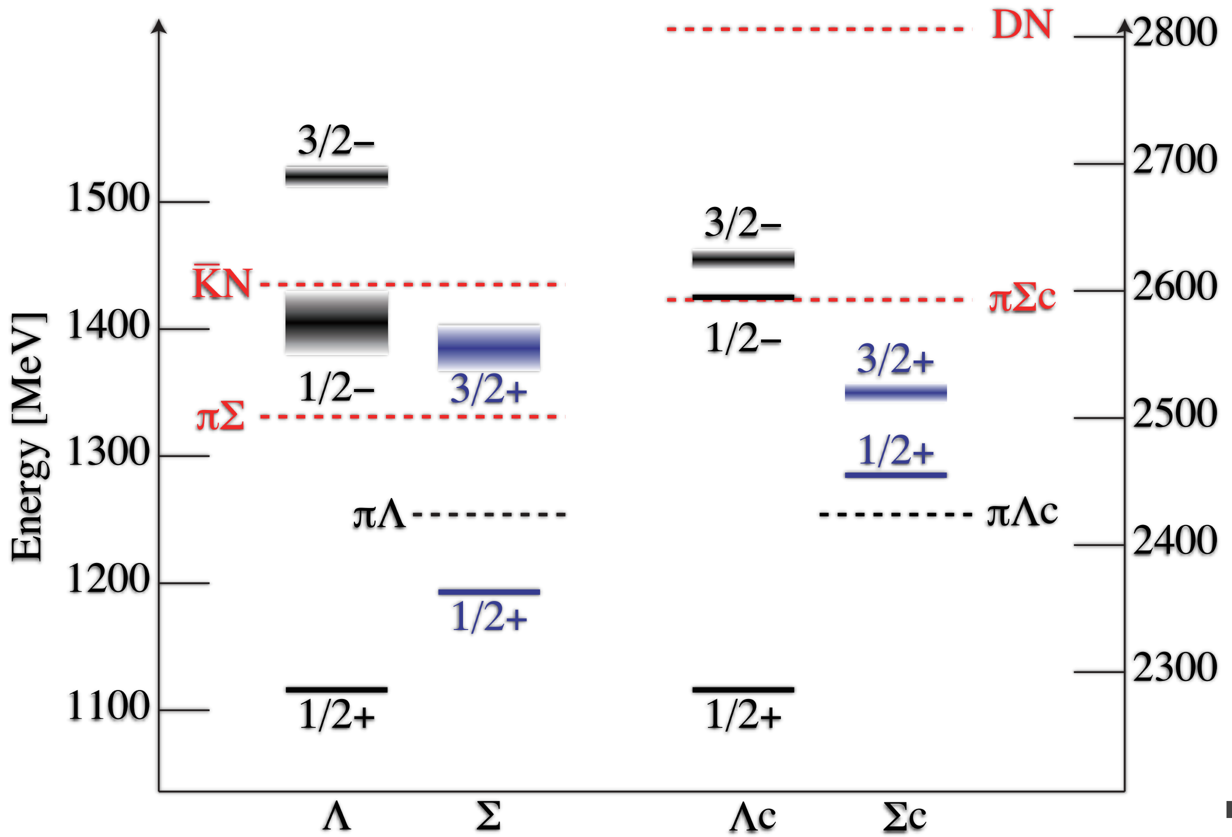


Color-van-der-Waals force ~ second order perturbation ~ is (weakly) attractive. $V \sim -\frac{\alpha_s^2}{R^5}$

Heavy Baryon Spectroscopy

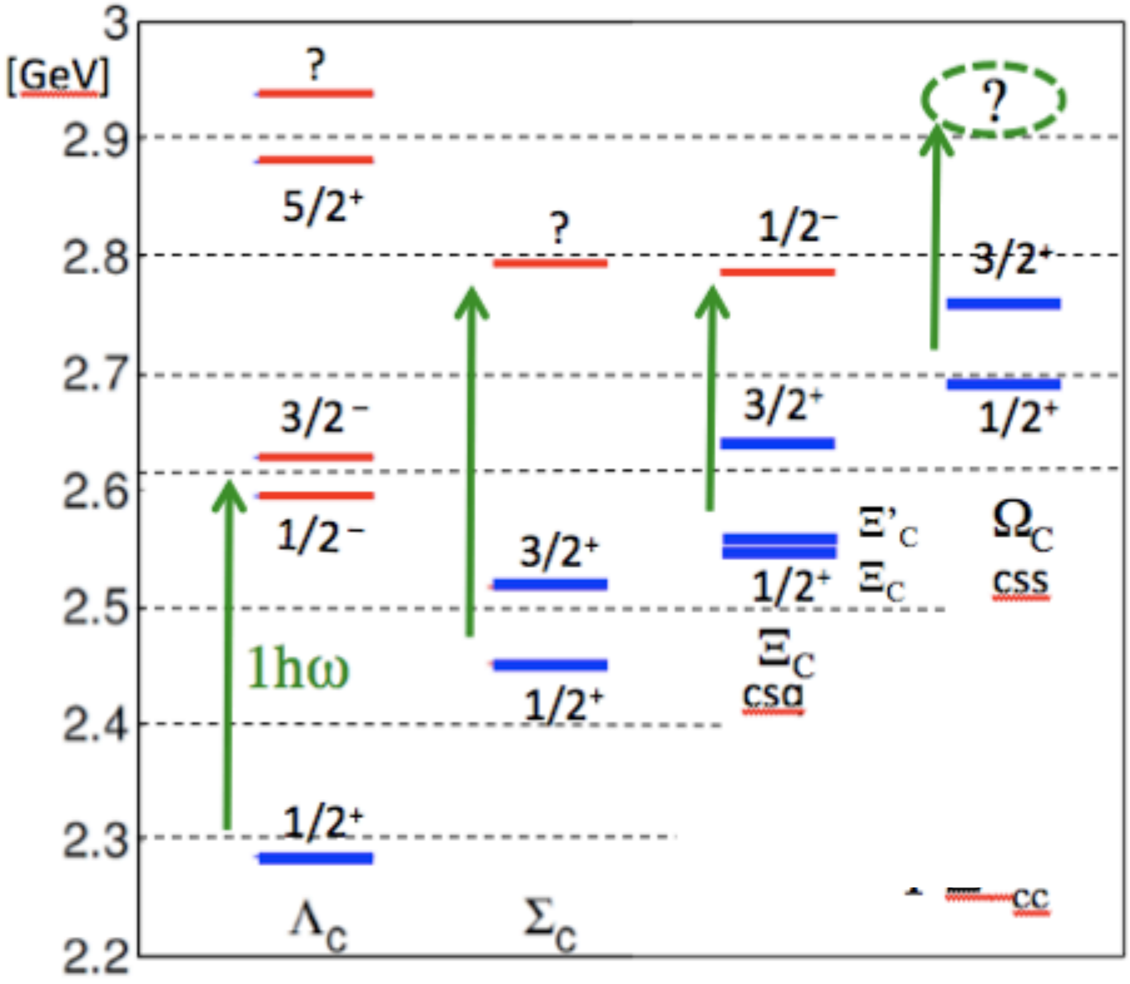
Heavy Baryon Spectroscopy

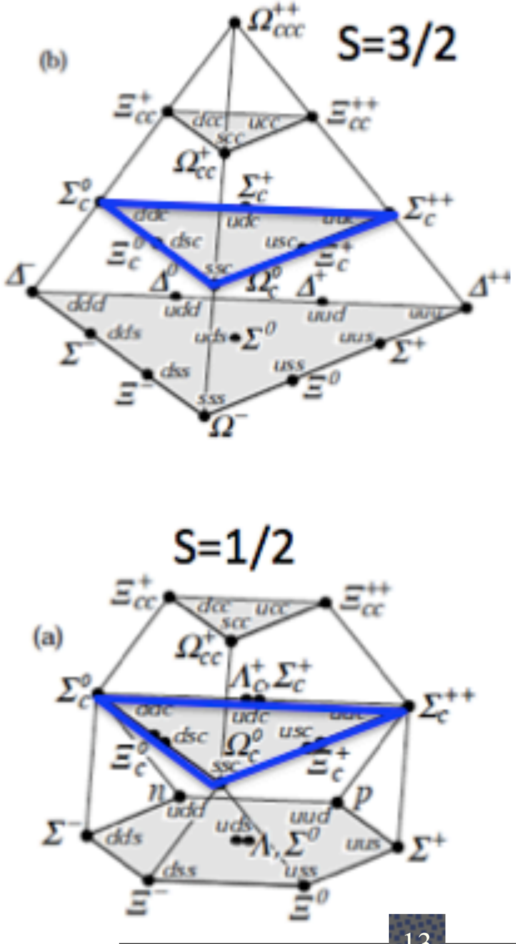
Heavy baryon spectrum looks simpler.
The higher thresholds make the heavy baryon excited states narrower. → No or small overlapping



Heavy Baryon Spectroscopy

Many *"missing"* resonances

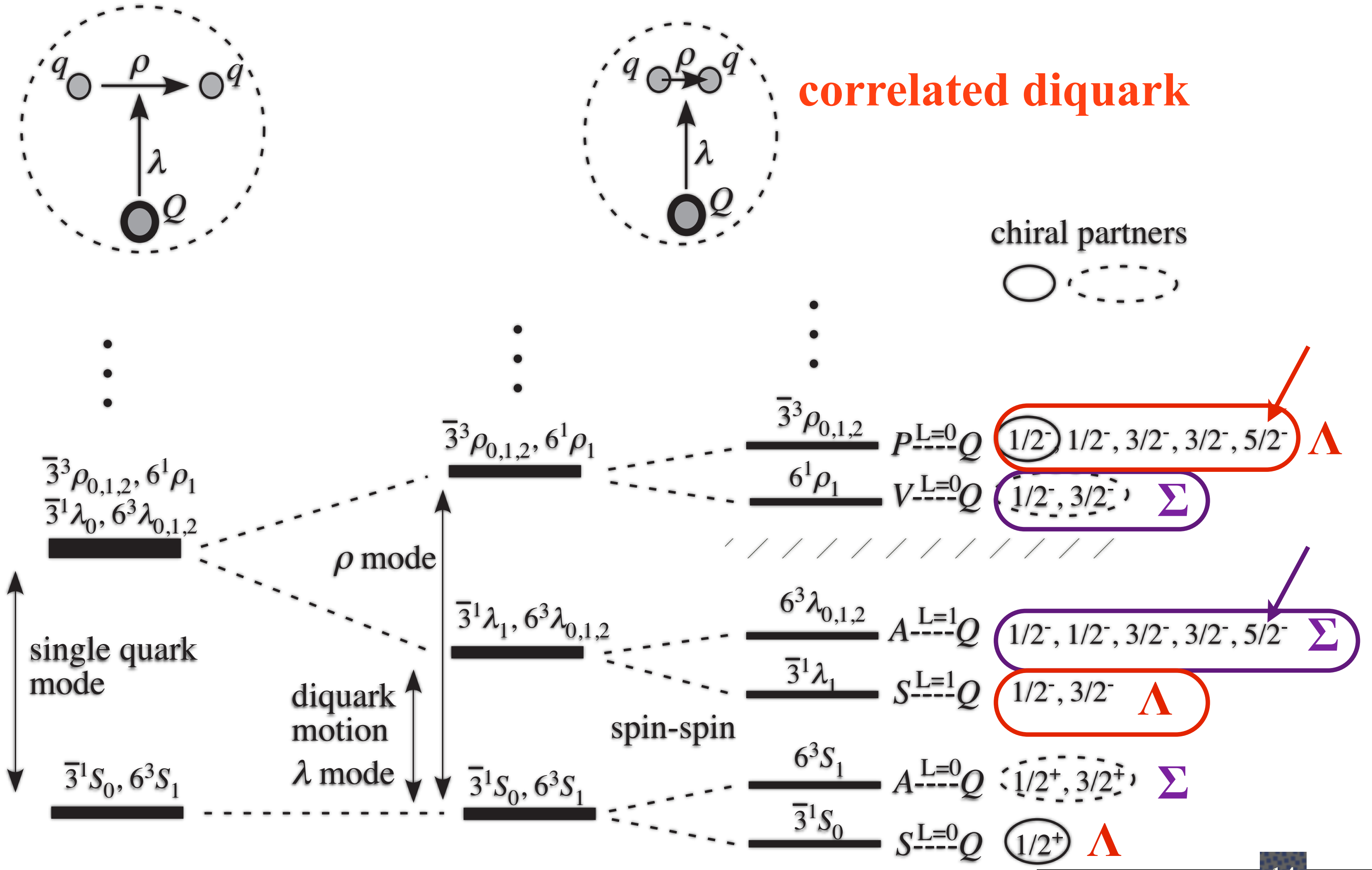




Heavy Baryon Spectroscopy

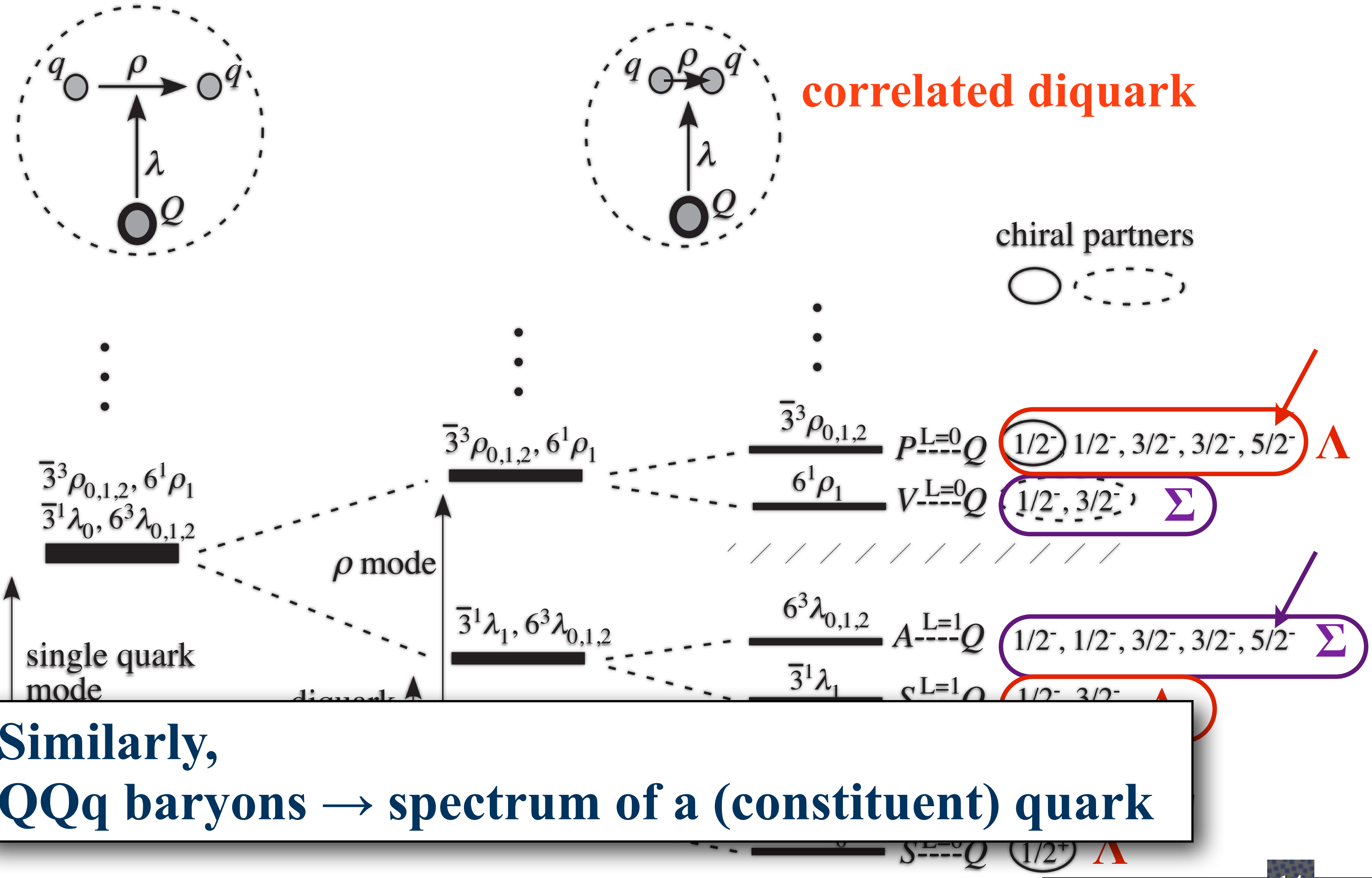
Two kinds of excitation modes

correlated diquark



Heavy Baryon Spectroscopy

Two kinds of excitation modes



Similarly,
QQq baryons → spectrum of a (constituent) quark

Diquarks in QCD

- QCD predicts attraction in the channels:
  PS meson q-q^{bar} : color 1, spin-parity 0^-, flavor 1+8
  S *good* diquark qq: color 3^{bar}, spin-parity 0^+, flavor 3^{bar}

$$U = [\bar{d}\bar{s}]_{C=3,J=0,F=3}, \quad D = [\bar{s}\bar{u}]_{3,0,3}, \quad S = [\bar{u}\bar{d}]_{3,0,3}$$

- diquark "meson" d d^{bar} (tetra-quark)

- di-diquark "baryon" d-d-q (pentaquark)

- tri-diquark "dibaryon" d^3 (6 quarks)
  color 1, flavor 1, 0^{++} H dibaryon

$$H = [\bar{U}\bar{D}\bar{S}]_A = [uuddss]$$

- diquark matter: color superconductivity
  U^{bar}+D^{bar}+S^{bar} condensates:
  color-flavor locking (CFL)
  S^{bar}: 2SC (U^{bar}: uSC D^{bar}: dSC)

Diquarks in QCD

		J^π	color	flavor
Pseudoscalar	$\epsilon_{abc}(u_a^T C d_b)$	0^-	$\bar{3}$	$\bar{3}$ $(I=0)$
Scalar (S)	$\epsilon_{abc}(u_a^T C \gamma^5 d_b)$ ***good***	0^+	$\bar{3}$	$\bar{3}$ $(I=0)$
Vector	$\epsilon_{abc}(u_a^T C \gamma^\mu \gamma^5 d_b)$	1^-	$\bar{3}$	$\bar{3}$ $(I=0)$
Axial V. (A)	$\epsilon_{abc}(u_a^T C \gamma^\mu d_b)$ ***bad***	1^+	$\bar{3}$	6 $(I=1)$
	$\epsilon_{abc}(u_a^T C \sigma^{\mu\nu} d_b)$	$1^+, 1^-$	$\bar{3}$	6 $(I=1)$
Color 6 only in Exotic Hadrons	$(u_a^T C d_b) + (a \leftrightarrow b)$	0^-	6	6 $(I=1)$
	$(u_a^T C \gamma^5 d_b) + (a \leftrightarrow b)$	0^+	6	6 $(I=1)$
	$(u_a^T C \gamma^\mu \gamma^5 d_b) + (a \leftrightarrow b)$	1^-	6	6 $(I=1)$
	$(u_a^T C \gamma^\mu d_b) + (a \leftrightarrow b)$	1^+	6	$\bar{3}$ $(I=0)$
	$(u_a^T C \sigma^{\mu\nu} d_b) + (a \leftrightarrow b)$	$1^+, 1^-$	6	$\bar{3}$ $(I=0)$

Diquarks in QCD

- **Diquarks in some lattice calculations**
  - **Hess, Karsch, Laermann, Wetzorke, PR D58, 111502 (1998)**
    from the correlators in the Landau gauge
    m_q~342 MeV, M(S)~694 MeV, M(A) ~ 810 MeV
  - **Alexandrou, de Forcrand, Lucini, PRL 97, 222002 (2006)**
    gauge invariant calculation inside a Qqq system
    M(A)- M(S) ~ 100-150 MeV, R(S) ~ 1 fm
    M(PS)- M(S) ~ 600 MeV
  - **Babich, et al., PR D76, 074021 (2007)**
    diquark correlation and effective mass in the Landau gauge
    M(S)- 2m_q ~ -200 MeV, M(A)-M(S) ~162 MeV

Double Charm Exotics
Tetraquark T_{cc}

Exotic Multiquark Heavy Hadrons

- **New Exotic Multiquark states discovered at the B factories.**
  - X(3872): D-D* molecule with cc^{bar} component
  - Y(4260): $cc^{bar}g$ hybrid meson candidate
  - Z_c(3900), Z_c(4430): charged charmonium-like tetraquarks
  - Z_b(10610), Z_b(10650): bottom siblings

- **Prediction of Double charm meson i.e. c-c-q^{bar}-q^{bar} based on the diquark correlations**

  S. H. Lee, S. Yasui, W. Liu, C. M. Ko, Eur. Phys. J. C54, 259-265 (2008),
  S. H. Lee, S. Yasui , Eur. Phys. J. C64, 283-295 (2009).

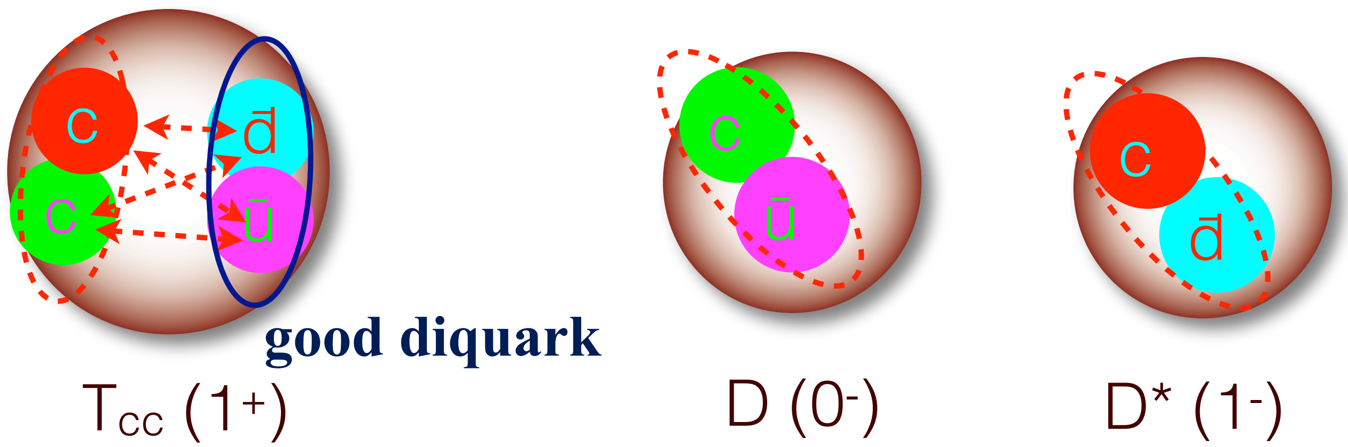
- **Various studies have been made.**

  S. Zouzou, B. Silvestre-Brac, C. Gignoux, J.M. Richard, Z. Phys. C30 (1986)457
  H.J. Lipkin, Phys. Lett. B172 (1986) 242, and so on.

T_{cc} spectrum

- **Double charm meson** **T_{cc} ($c^{bar}c^{bar}ud$, 1^+, I=0)**

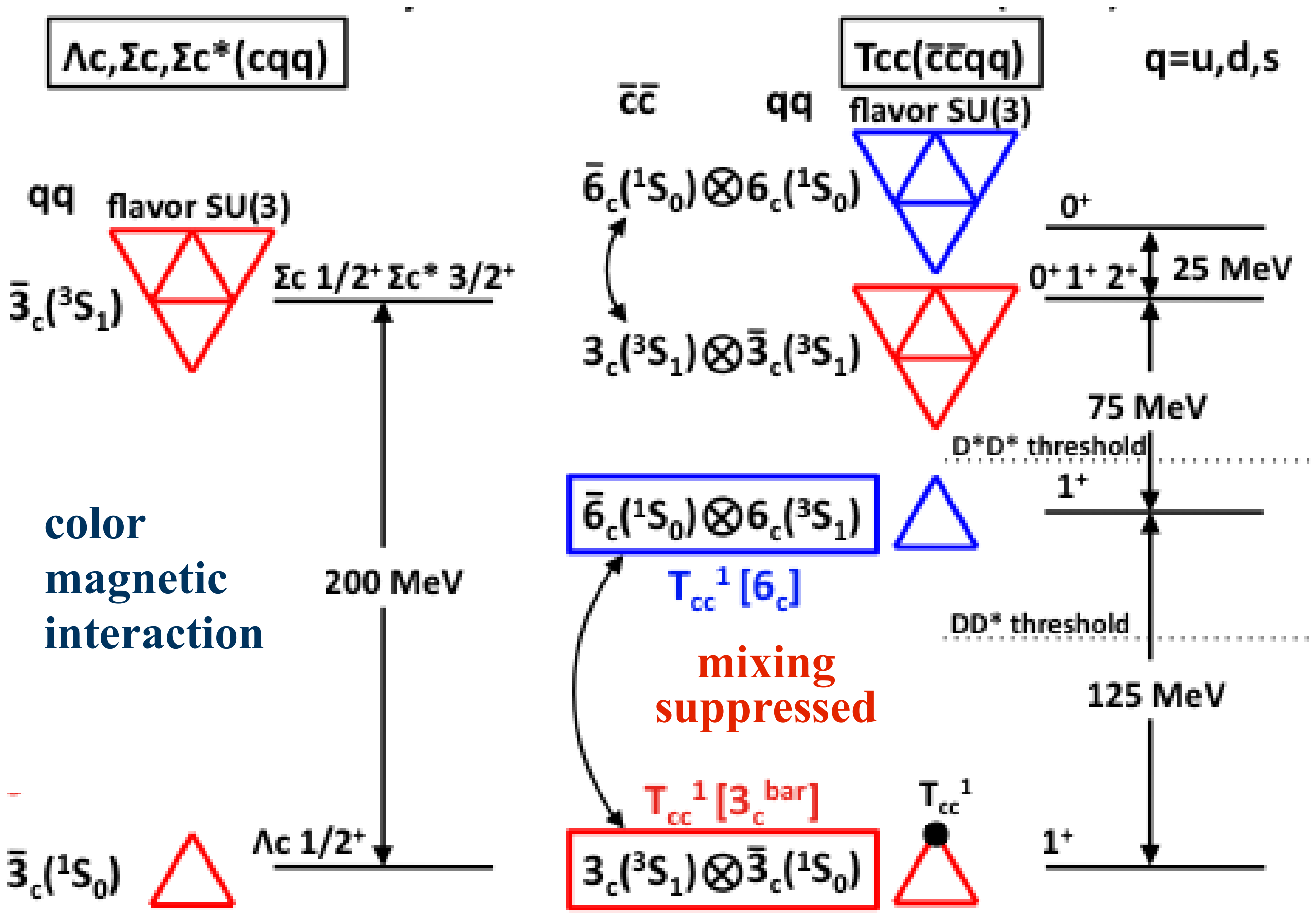
  - stable against strong decay if M(Tcc) < M(D)+M(D*)



- **Spin dependent force between the HQ and light quark is weak.**

T_{cc} spectrum

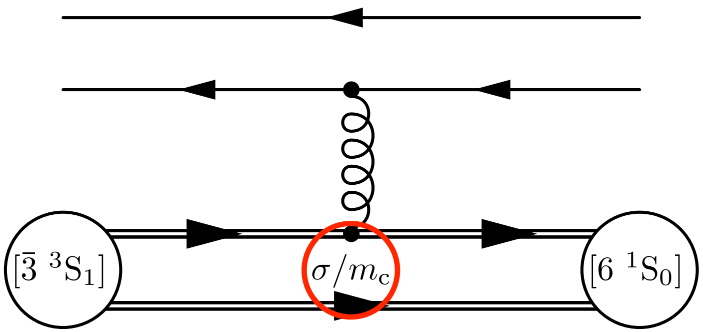
- **Double charm meson T_{cc} ($c^{bar}c^{bar}ud$, 1^+, $I=0$) spectrum**



Hyodo, Liu, Oka, Sudoh, Yasui

T_{cc} spectrum

- **The lowest two states, $T_{cc}[3, {}^3S_1]$, $T_{cc}[6, {}^1S_0]$, have $I(J^P) = 0(1^+)$, and in principle mix with each other.**
  However, the mixing is suppressed in the HQ limit as $\sim 1/m_Q$.

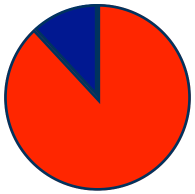


charm spin flip
mixing probability $\sim 1/m_c^2$

- **Dynamical 4-quark calculation:**

  J. Vijande, A. Valcarce, PRC80, 035204

  - Fraction: $\bar{3}$ (0.881) *v.s.* 6 (0.119) for the ground state.



$T_{cc}[3, {}^3S_1]$ and $T_{cc}[6, {}^1S_0]$ are well separated.

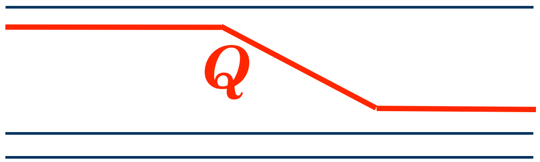
Production of T_{cc} in e^+e^- collisions

How can we produce them?

- **Charm (bottom) hadrons can be produced analogously to the *strangeness* hadron production**

flavor transfer, *ex.* (K$^-$, π)

□ **(D, π), (D, N) etc.**

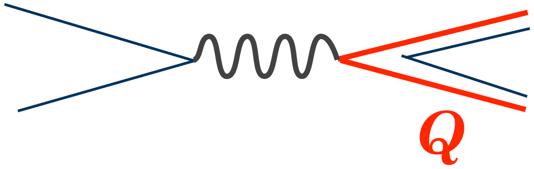


pair creation in hadronic reactions, *ex.* (π, K)

□ **(π, D$^{(*)}$), (p^{bar}, D$^{(*)}$) etc.**

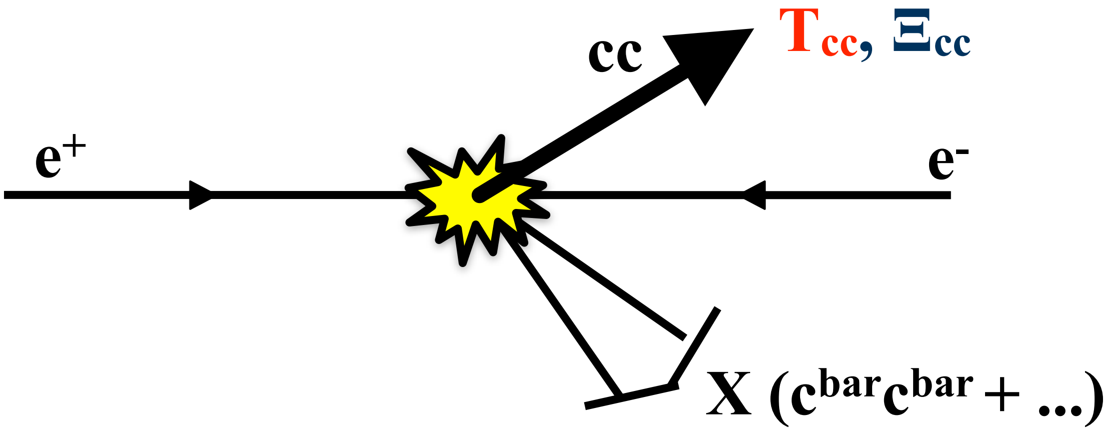
pair creation at high energy

□ **(e$^+$e$^-$, QQ^{bar}), (qq^{bar}, QQ^{bar})**



Production in $e^+ e^-$ collisions

- e+ e- collisions at Belle (KEKB; B-factory)
  Double-charm productions ($J/\psi+\eta_c$, ...) have been observed.
  K. Abe, et al, Belle Collaboration, Phys. Rev. Lett. 89, 142001 (2002)
- Recombination of the charm quarks and antiquarks will produce double charmed mesons (T_{cc}'s) and baryons (Ξ_{cc}).



- Calculate the cross sections of double charmed hadrons.

Cross section

- **Production of doubly charmed tetraquarks with exotic color configurations in electron-positron collisions,**
  T. Hyodo, Y.-R. Liu, M. Oka, K. Sudoh, S. Yasui
  Physics Letters B721 (2013) 56-60,
  and in preparation.

- **Formalism: NRQCD (factorization and expansion in v_Q)**
  hard process
  $e^+e^- \rightarrow cc\ [J^P]$ calculated perturbatively
  soft process
  representing the formation of T_{cc} as a matrix element

Cross section

- **NRQCD** G.T. Bodwin, E. Braaten, G.P. Lepage, Phys. Rev. D51, 1125 (1995)
  A. Petrelli, *et al*, Nucl. Phys. B514, 245 (1998)

  Effective field theory in terms of HQ velocity = p/m_c.

  Coefficients are computed by perturbative QCD in α_s.

  Matrix element of NRQCD operator : nonperturbative

$$\sigma \sim \sum_k \underbrace{f_k(\alpha_s)}_{\text{hard}} \underbrace{\left|\langle H|\mathcal{O}_k(v)|0\rangle\right|^2}_{\text{soft}}$$

- **NRQCD is applied to the double-charm productions**

  E. Braaten, J. Lee, Phys. Rev. D67, 054007 (2003).
  K.Y. Liu, Z.G. He, K.T. Chao, Phys. Lett. B557, 45 (2003), ...

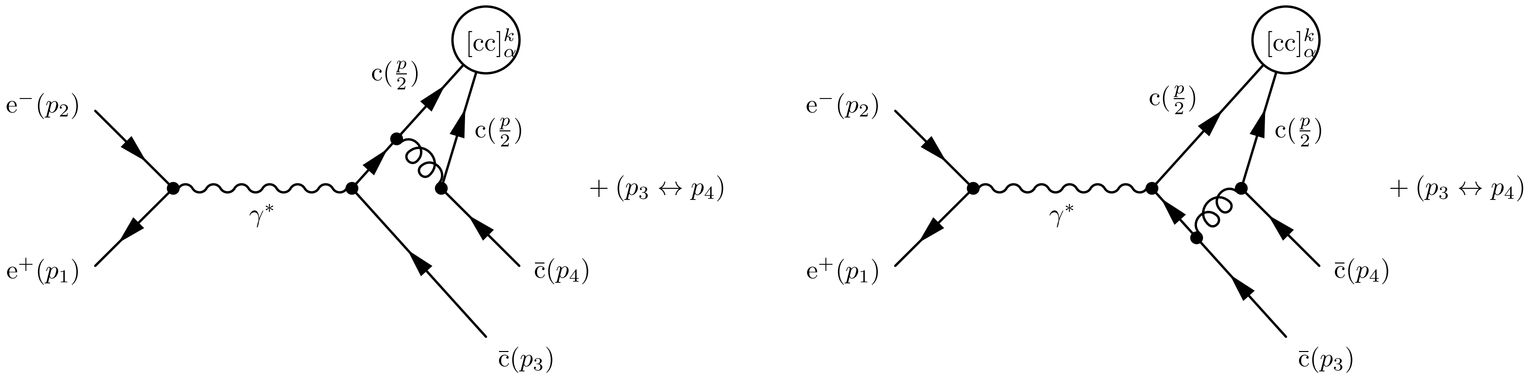
Cross section

Cross section

$$d\sigma_\alpha(e^+e^- \to T_{cc}[\alpha] + X) = \sum_k \underline{d\hat{\sigma}(e^+e^- \to [cc]^k_\alpha + \bar{c} + \bar{c})} \underline{\left|\langle T_{cc} + X | [cc]^k_\alpha | 0\rangle\right|^2}$$

Hard part: leading order in α_s by pQCD calculation

cc with color-spin projection



Soft part can be factorized: leading order in v → a number.

$$\left|\langle T_{cc} + X | [cc]^k_\alpha | 0\rangle\right|^2 \Big|_{k=\mathrm{LO}} = \begin{cases} h_3 & \text{for } \alpha = [\bar{\mathbf{3}}, {}^3S_1] \\ h_6 & \text{for } \alpha = [\mathbf{6}, {}^1S_0] \end{cases}$$

Cross section

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$$d\sigma_\alpha(e^+e^- \to T_{cc}[\alpha] + X) = \sum_k \underline{d\hat{\sigma}(e^+e^- \to [cc]^k_\alpha + \bar{c} + \bar{c})} \underline{\left|\langle T_{cc} + X|[cc]^k_\alpha|0\rangle\right|^2}$$

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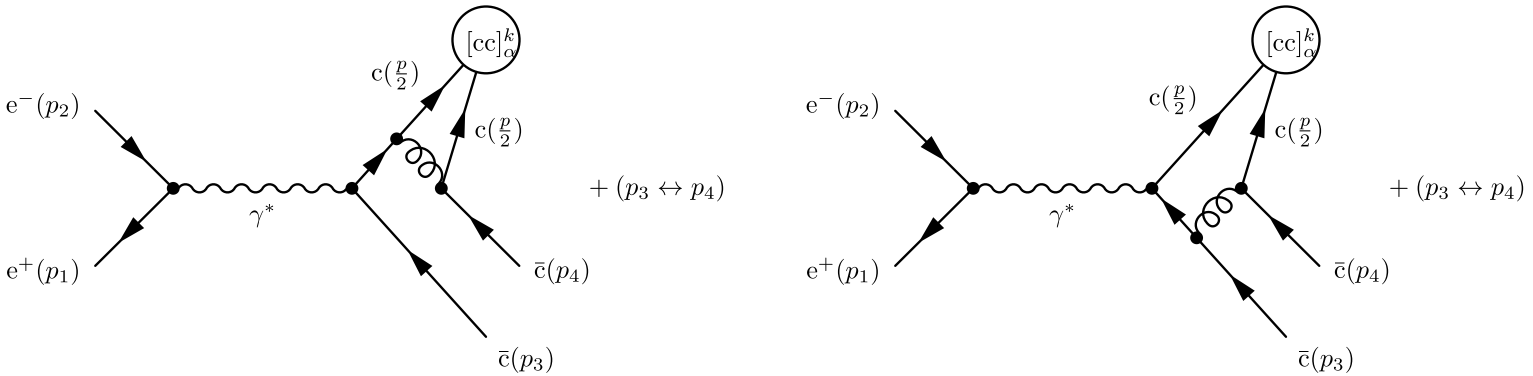

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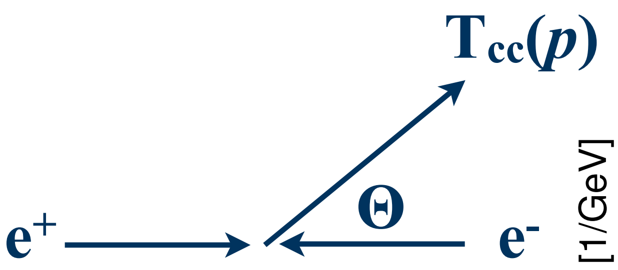
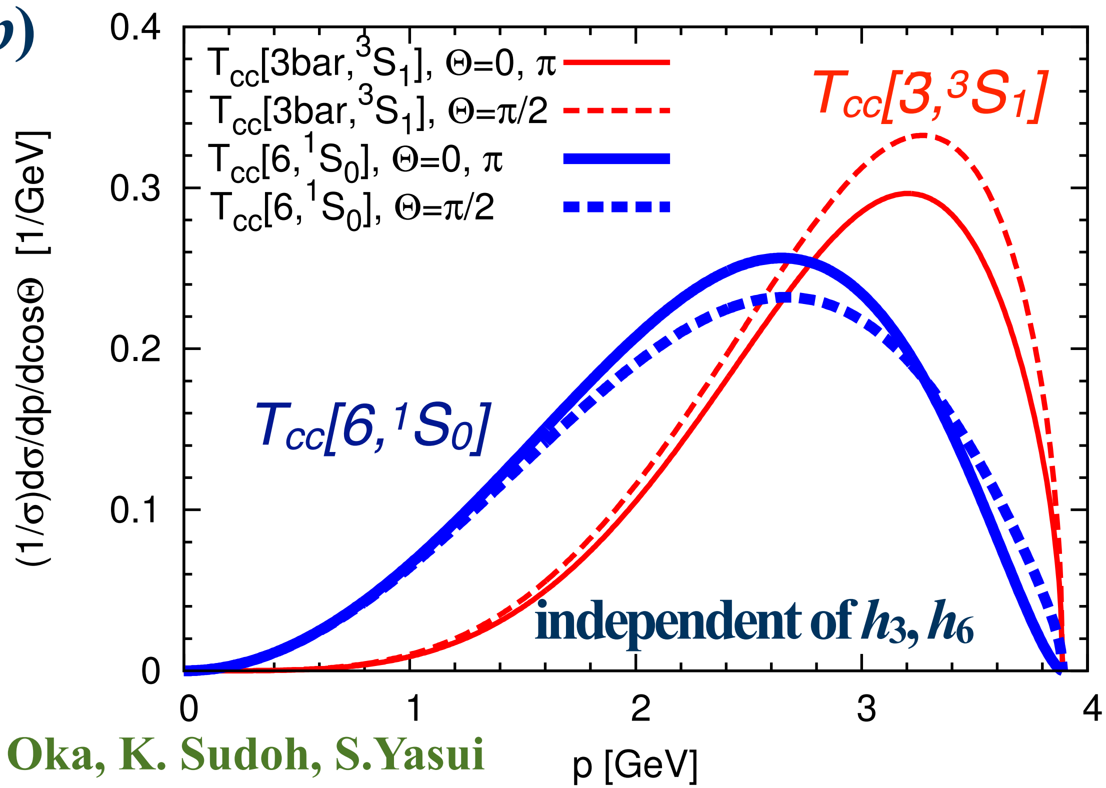
→ cancel when normalized by the total cross section dσ/σ

Cross section

- **Normalized differential cross sections** $\frac{1}{\sigma}\frac{d\sigma_\alpha}{dp\, d\cos\Theta}$



$m_c = 1.8$ GeV
$\alpha_s = 0.212$
$s^{1/2} = 10.6$ GeV



T. Hyodo, Y.R. Liu, M. Oka, K. Sudoh, S.Yasui

- **Momentum distribution depends on the color configurations.**

Cross section

- **For absolute value, we need nonperturbative matrix elements.**
  Charmonium case: $c\bar{c}$ wave function at origin.

  G.T. Bodwin, E. Braaten, G.P. Lepage, Phys. Rev. D51, 1125 (1995)
  A. Petrelli, *et al*, Nucl. Phys. B514, 245 (1998)

$$\left|\langle J/\psi|\bar{c}c|0\rangle\right|^2 \sim \frac{1}{4\pi}|R_{\bar{c}c}(x=0)|^2$$

- **Constituent quark model for T_{cc} with harmonic confinement.**

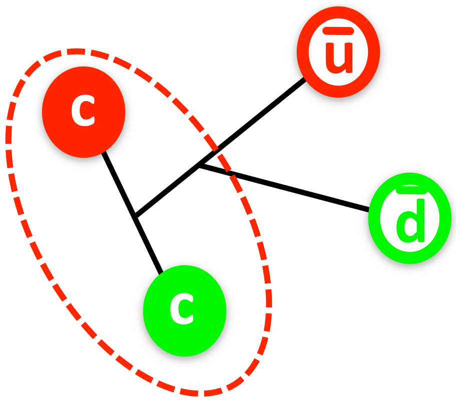
$$V = \sum_{i<j}\left(-\frac{3}{16}\right)\vec{\lambda}_i\cdot\vec{\lambda}_j\frac{k}{2}|\vec{r}_i-\vec{r}_j|^2$$

$T_{cc}[\bar{3}]$

$$h_3 = \frac{1}{4\pi}|R_{cc}^{\bar{\mathbf{3}}_c(^3S_1)}(0)|^2$$

$$\sim 0.089\ \mathrm{GeV}^3$$

$$\sigma(T_{cc}[\bar{3}]) = 13.8\ \mathrm{fb}$$



ref: Ξ_{cc} production with NRQCD formalism
- Ma, Si, PLB568, 135 (2003), - Jian, et al., arXiv:1208.3051

Cross section

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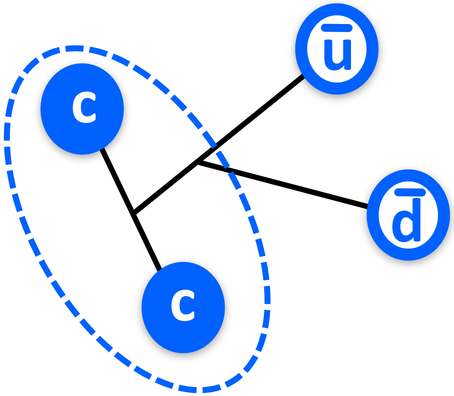
  $$V = \sum_{i<j}\left(-\frac{3}{16}\right)\vec{\lambda}_i\cdot\vec{\lambda}_j\frac{k}{2}|\vec{r}_i-\vec{r}_j|^2$$

$T_{cc}[6]$

$$h_6 = \frac{1}{4\pi}|R_{cc}^{\mathbf{6}_c(^1S_0)}(0)|^2$$
$$\sim 0.053\ \mathrm{GeV}^3$$



$\boldsymbol{\sigma}(T_{cc}[6]) = 4.1\ \mathrm{fb}$

ref: Ξ_{cc} production with NRQCD formalism
- Ma, Si, PLB568, 135 (2003), - Jian, et al., arXiv:1208.3051

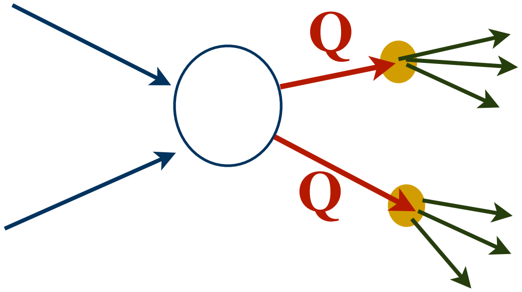
Cross section

- **The present treatment assumes that the light quarks are supplied by the vacuum to form T_{cc} without a further factor.**
- **The ratio of Ξ_{cc}/T_{cc} productions is about unity.**

Fragmentation to T_{cc}

Fragmentation of heavy quark

- HARD processes $e^+ + e^- \rightarrow QQ^{bar}, Q^2Q^{bar2}, \ldots$ are followed by SOFT hadronization
  $Q \rightarrow Qq^{bar}$, Qqq hadrons
  $QQ \rightarrow QQq, QQq^{bar}q^{bar}$
- In high energy processes, the hard vertex with heavy quarks and the soft hadronization processes are "factorized".



- Productions with the common hard parts:
  D/B (Qq^{bar}) and Λ_Q, Σ_Q (Qqq)
  Ds/Bs (Qs^{bar}) and Ξ_Q (Qqs)
  Ξ_{QQ} (QQq) and T_{QQ} ($QQq^{bar}q^{bar}$)

Experimental data

- **High energy production of *b* quark fragmented into B mesons and b-Baryons, eventually decaying via the weak interaction. Fragmentation probabilities of B_u, B_d, B_s, Λ_b productions are measured at LEP (Z decay), CDF (pp^{bar}), and LHCb (pp).**
- **Recent results**
  LHCb results (PR D85 (2012) 032008)
  $f_s/(f_u+f_d) = 0.134 \pm 0.004 \pm 0.001$
  $f_B/(f_u+f_d) = (0.40 \pm 0.10) \times (1 - 0.031\, p_T(\mathrm{GeV}))$
  $f_{u,\, d,\, s,\, B}$: probability of b-quark fragmentation into B^-(bu), B^0(bd), B_s(bs), and Λ_b(bud)
- **Note that the preceding strong decays are not "measured", so that the data include not only B and Λ_b, but also B^* and $\Sigma_b^{(*)}$.**
  $f_u + f_d = B + B^* +$ (some excited states)
  $f_B = \Lambda_b + \Sigma_b + \Sigma_b^* +$ (some excited states)

LEP, CDF and LHCb

- **Lifetime and production rate of beauty baryons from Z decays, DELPHI Collaboration, Z. Phys. C68 (1995) 375.**
- **Measurement of the b baryon lifetime and branching fractions in Z decays, The ALEPH Collaboration, Eur. Phys. J C2 (1998) 197.**
  $f_B = 0.101 \pm 0.040$
- **Measurement of b-Quark Fragmentation Fractions in pp^{bar} collisions at $s^{1/2} = 1.8$ TeV, CDF Collaboration, Phys. Rev. Lett. 84 (2000) 1663.**
  $f_B /(f_u+f_d) = (0.090 \pm 0.029)/(0.750 \pm 0.046) = 0.118 \pm 0.042$
- **Measurement of ratios of fragmentation functions for bottom hadrons in pp^{bar} collisions at $s^{1/2} = 1.96$ TeV, CDF Collaboration, Phys. Rev. D77 (2008) 072003.**
  $f_B/(f_u+f_d) = 0.281 \pm 0.10$
- **Measurement of b hadron production in 7 TeV pp collisions, The LHCb Collaboration, Phys. Rev. D85 (2012) 032008.**
  $f_B/(f_u+f_d) = (0.40 \pm 0.10) \times (1 - 0.031\ p_T(\text{GeV}))$

Estimate the ratio by counting

- Assume
  (1) The leading HQ is picking up light quarks and forms a hadron.
  (2) The light quarks are created as a quark-antiquark pair.
  (3) The "probability" of creating a quark-antiquark pair is universal to all the processes.
  (4) The hadrons are produced only when the HQ meets a light (anti-)quark with the *right* quantum numbers.
  (5) The "sticking probability" is determined by the (valence) quark wave function (@ R=0) of the hadron.
- More intuitively,
  $q\bar{q}$ can be created in the color singlet, spin singlet 0^+ state.
  The pairs $u\bar{u}$ and $d\bar{d}$ are created with the same probability, while $s\bar{s}$ may be partially suppressed.

Estimate the ratio by counting

- Suppose the probability of creating a uu^{bar} pair is η_u.
  Then
  u^{bar} $(R^{bar}, \downarrow) \rightarrow (1/6)\eta_u$.

  For a $Q(R, \uparrow)$ to form a 0^- Qq^{bar} (B_u) meson is then calculated so as to combine into color singlet and spin singlet
  $\rightarrow (1/3)(1/2)(1/6)\ \eta_u = (1/36)\ \eta_u$

- Similarly,
  Vector Qq^{bar} 1^- $(B_u^*) \rightarrow (1/3)(3/2)(1/6)\ \eta_u = (1/12)\ \eta_u$

  Same for B_d, and in total the probability of producing
  $B + B^* \rightarrow (8/36)\eta_q = (2/9)\eta_q$ (assuming $\eta_q = \eta_u = \eta_d$)

Estimate the ratio by counting

- **Baryons**

  Λ_b (1/108) $(\eta_q)^2$

  Σ_b (1/36) $(\eta_q)^2$

  Σ_b^* (1/18) $(\eta_q)^2$

  in total $\Lambda_b + \Sigma_b + \Sigma_b^* = (5/54)\ (\eta_q)^2$

- **The ratio of (Baryon)/(Meson) = (5/12) η_q = 0.42 η_q**

- **Exp data ~ 0.3-0.4 $\Rightarrow$ η_q = 0.7~1.0**

Estimate the ratio by counting

- **T_{QQ} and Ξ_{QQ}**

  Ξ_{QQ} (1/2) $\rightarrow$ (1/3)(2/3)(1/6) η_q = (1/27) η_q

  Ξ^*_{QQ} (3/2) $\rightarrow$ (1/3)(4/3)(1/6) η_q = (2/27) η_q

  T_{QQ} (1^+, 3^{bar}) $\rightarrow$ (1/108) $(\eta_q)^2$

  T_{QQ} (1^+, 6) $\rightarrow$ (1/72) $(\eta_q)^2$

- **$(T_{QQ})/(\Xi_{QQ})$**

  3^{bar} 1/2 = (1/4) η_q = 0.15 ~ 0.25

  6 1/2 = (3/8) η_q = 0.2 ~ 0.38

- **$T_{QQ}(6)/T_{QQ}(3^{bar})$ = 1.5 (indep. of η_q)**

- **This is a primitive model, but gives some guidance on what happens at the production of exotic hadrons.**

Conclusion

- New flavor-hadron physics will be open by the high-momentum proton beam line of J-PARC and other new experimental facilities: Charmed baryons, Charmed deuteron/ nucleus, Heavy exotics, i.e. T_{cc}.
- The charmed baryon spectroscopy may clarify the light-diquark correlations and their spectrum. Lattice QCD may help to make quantitative predictions on diquark correlations.
- T_{cc} production in the e^+e^- collisions has been predicted. We have compared it with the Ξ_{cc} production by introducing the light quark production probability.
- $T_{cc}(6_c)$ provides a new possibility to explore the colored force in hadrons. We compare the production of $T_{cc}(6_c)$ to $T_{cc}(3_c)$ and point out that the momentum dependence may distinguish them.

Extra slides

Decay modes

- **Decay of T_{cc}**
  weak decay through $c \to s$: $T_{cc} \to DK\pi$
  radiative decay : $T_{cc} \to D^0 D^+ \gamma$
- **Belle group is analyzing (T. Iijima, private communication)**
  exclusive mode (cross section is small)
  $e^+ e^- \to D^- D^{0bar} T_{cc}$ (missing mass)
  inclusive mode (large cross section, but resonance only)
  $e^+ e^- \to T_{cc} + X \to D^{*0} D^+ + X$ (invariant mass)