Doubly Heavy Baryons

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J.H., T.Mehen, PRD 73, 054003 (2006)

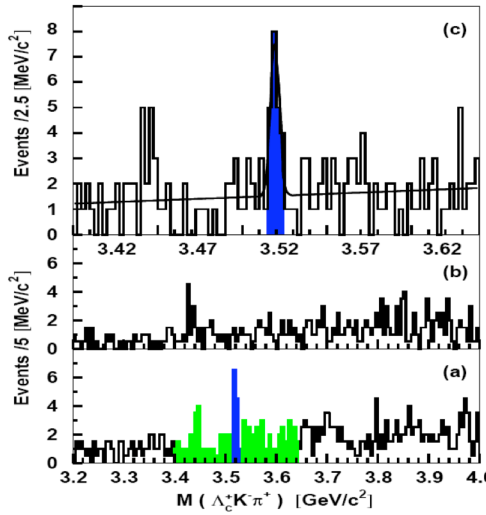
Outline:

- Motivation
- Heavy Quark-Diquark Symmetry
- Chiral Lagrangian of Doubly Heavy Baryons and Heavy Mesons
- Predictions for Doubly Charm Baryon
- Other Related Work
- Chiral Lagrangian for Doubly Heavy Baryon Semileptonic Decay
- Summary

Motivation

SELEX

PRL 89, 112001 (2002)
PLB 628, 18 (2005)



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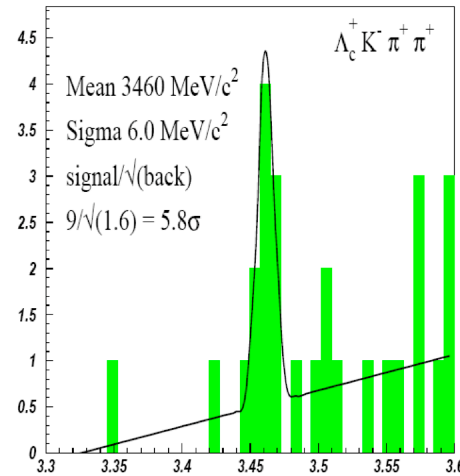

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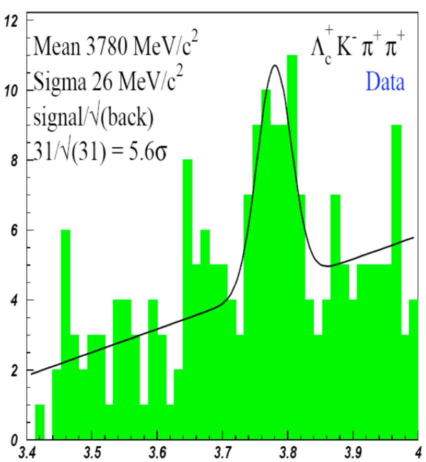

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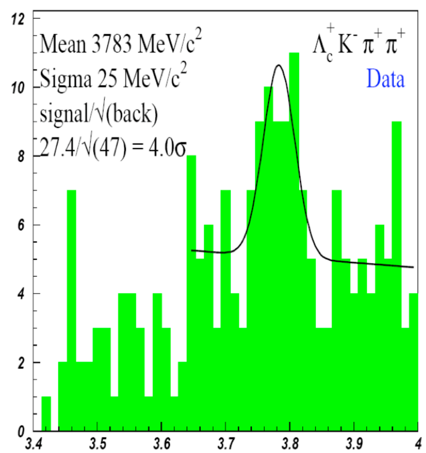

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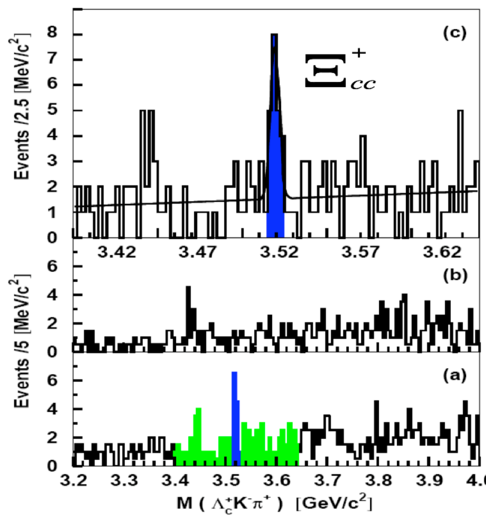

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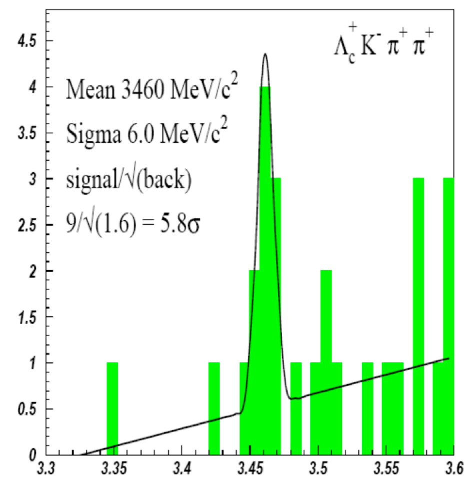

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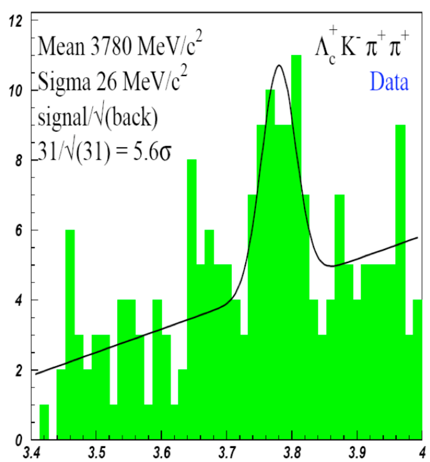

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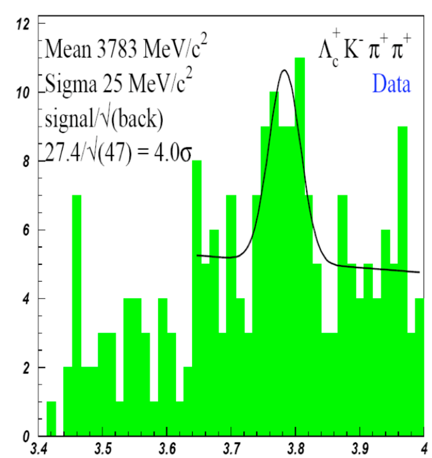

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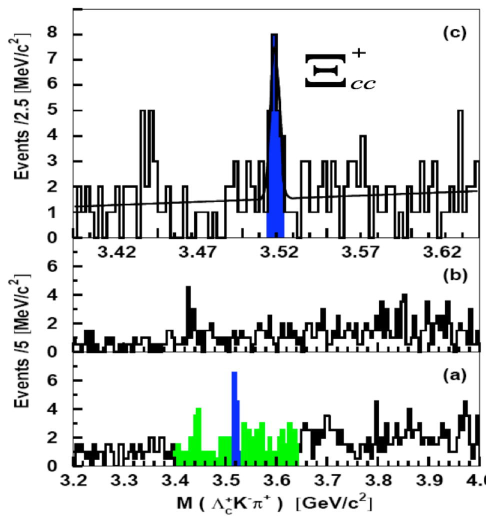

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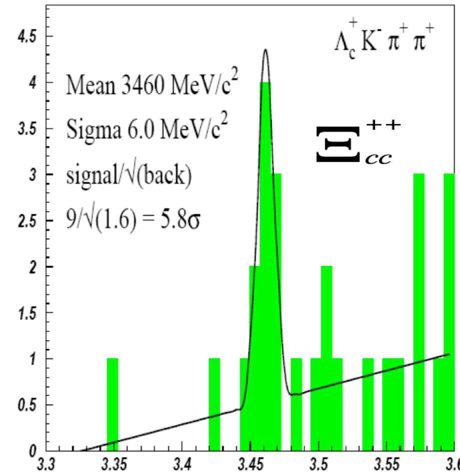

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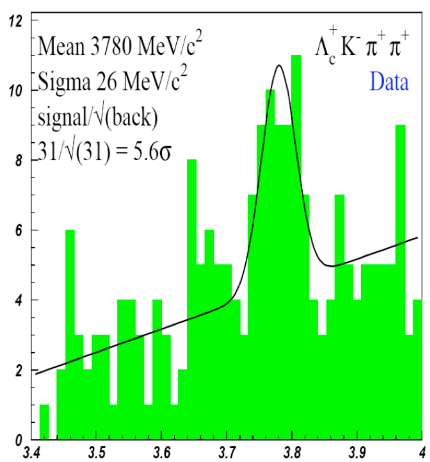

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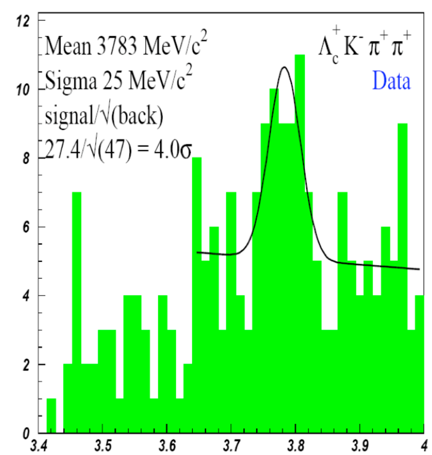

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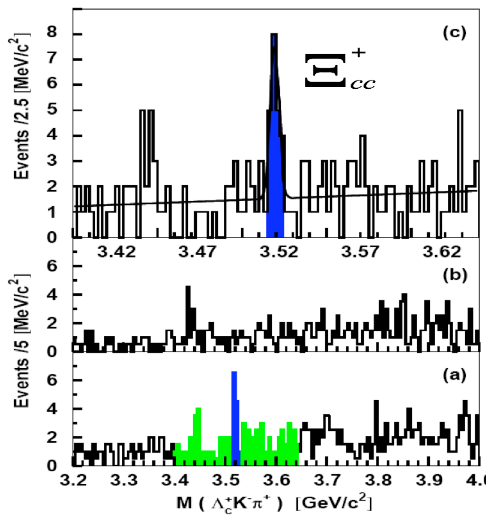

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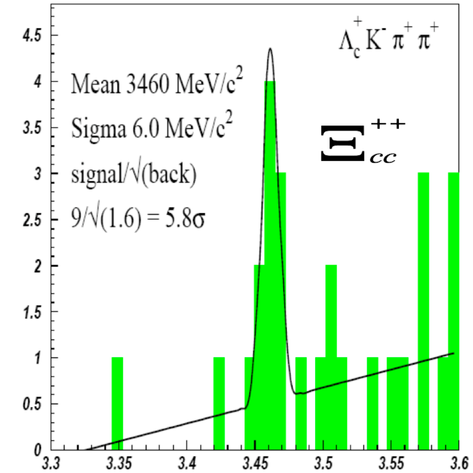

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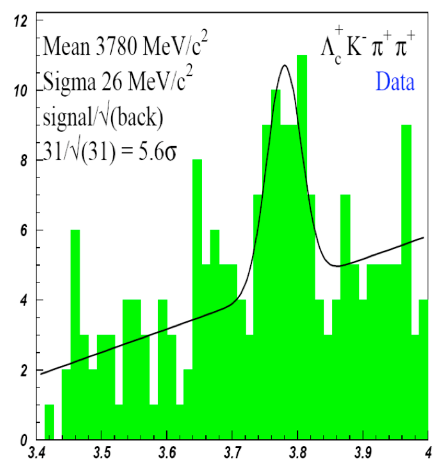

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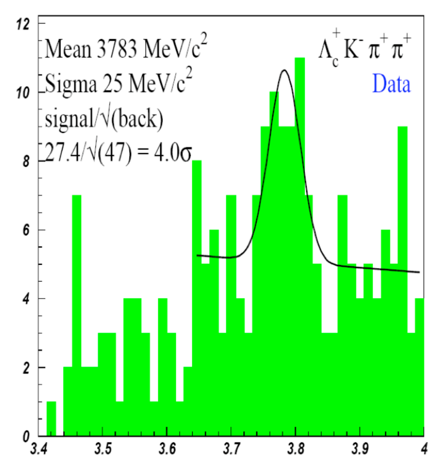
Ξ_{cc}^{*++}



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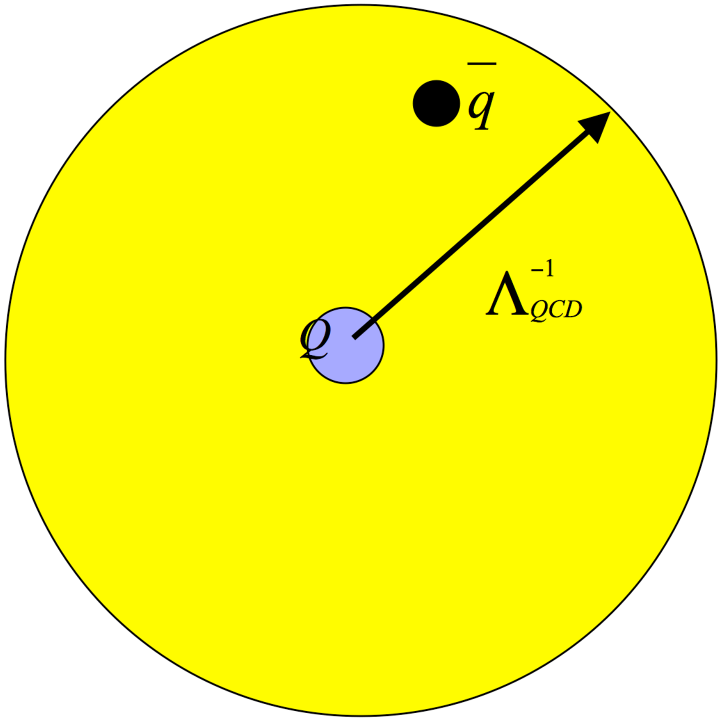

Heavy Quark Symmetry

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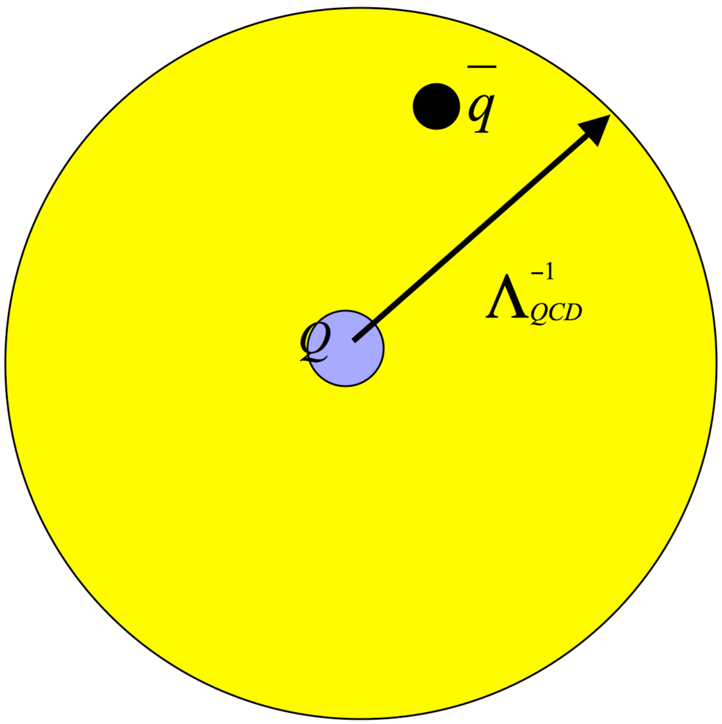

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$m_Q \gg \Lambda_{QCD}$

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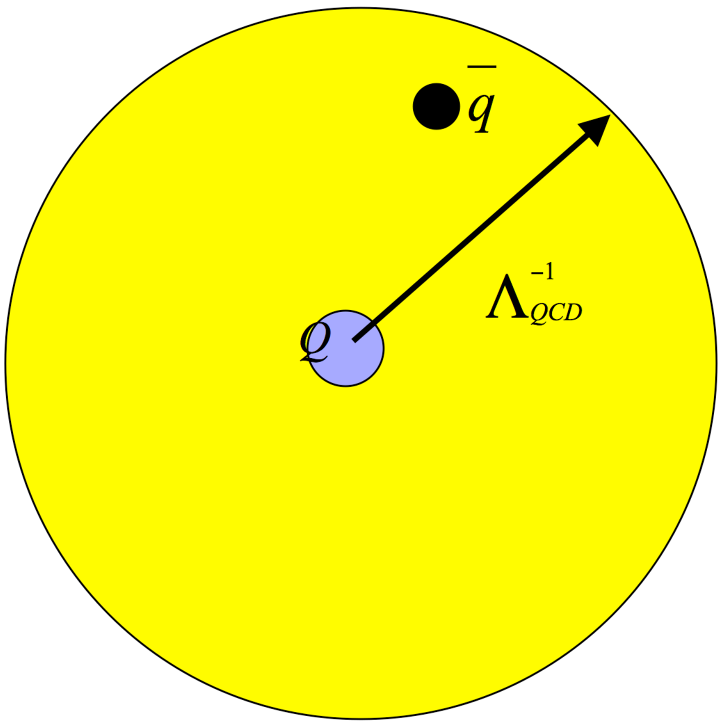

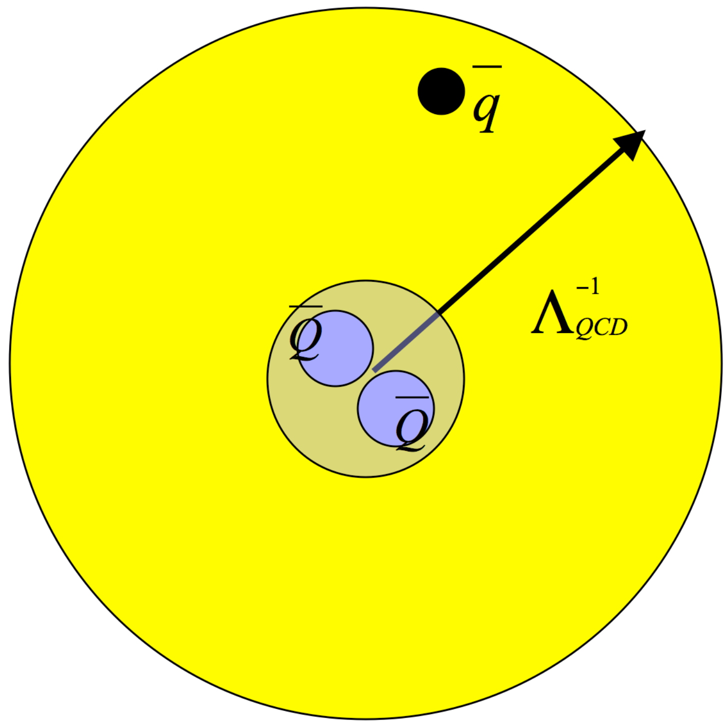

Heavy Quark Symmetry

Heavy Quark-Diquark Symmetry

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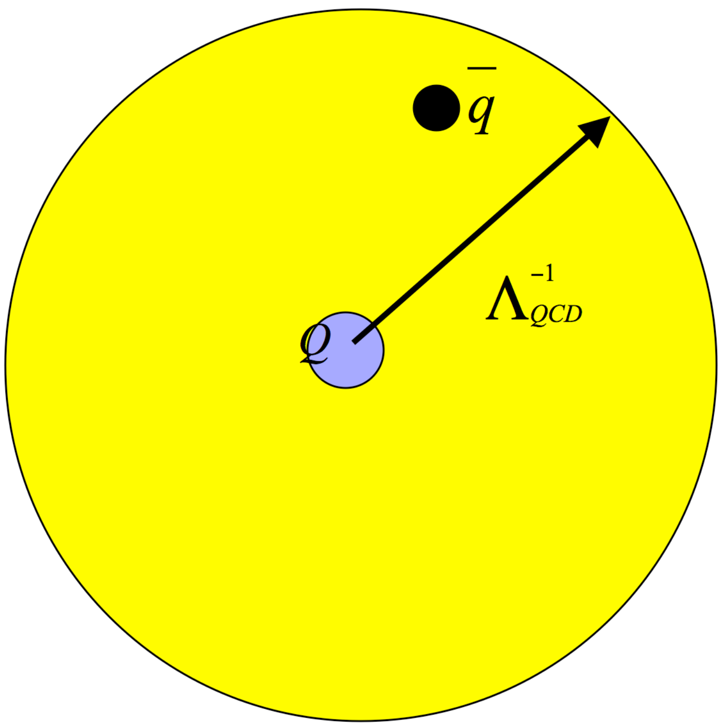

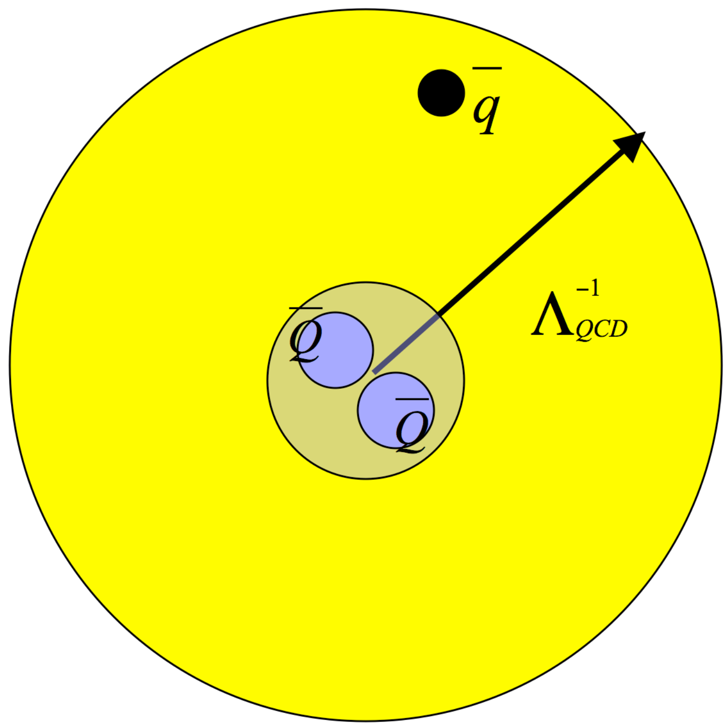

HQET Lagrangian

(Savage, Wise, Fleming, Mehen)

$$\mathcal{L} = h^\dagger\Big(iD_0 - \frac{\vec{D}^2}{2m_Q}\Big)h + \vec{V}^\dagger\cdot\Big(iD_0 + \delta - \frac{\vec{D}^2}{4m_Q}\Big)\vec{V} + \frac{g_s}{2m_Q}h^\dagger\vec{\sigma}\cdot\vec{B}^a\frac{\lambda^a}{2}h + \frac{ig_s}{2m_Q}\vec{V}^\dagger\cdot\vec{B}^a\frac{\lambda^a}{2}\times\vec{V}.$$

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$$\vec{\Sigma}_{\mu\nu} = \begin{pmatrix} \vec{\sigma}_{\alpha\beta} & 0 \\ 0 & \vec{\mathcal{T}}_{jk} \end{pmatrix} \qquad (\mathcal{T}^i)_{jk} = -i\epsilon_{ijk}$$

Chiral Lagrangian with Heavy Quark-Diquark Symmetry

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- Chiral corrections

$$\delta m_{\Xi_{cc}^*} - \delta m_{\Xi_{cc}} - \frac{3}{4}(\delta m_{D^*} - \delta m_D) = \begin{cases} 3.9\,\mathrm{MeV} & \mu = 500\,\mathrm{MeV} \\ 5.3\,\mathrm{MeV} & \mu = 1000\,\mathrm{MeV} \\ 6.1\,\mathrm{MeV} & \mu = 1500\,\mathrm{MeV} \end{cases}$$

Electromagnetic Decay

$$\mathcal{L} = \frac{e\beta}{2}\,\mathrm{Tr}[\mathcal{H}_a^\dagger \mathcal{H}_b \vec{\sigma}\cdot\vec{B} Q_{ab}] + \frac{e}{2m_Q} Q'\,\mathrm{Tr}[\mathcal{H}_a^\dagger \vec{\Sigma}'\cdot\vec{B}\mathcal{H}_b]$$

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$$\Gamma[P_a^* \to P_a\gamma] = \frac{\alpha}{3}\left(\beta Q_{aa} + \frac{Q'}{m_Q}\right)^2 \frac{m_P}{m_{P^*}} E_\gamma^3$$

$$\Gamma[\Xi_a^* \to \Xi_a\gamma] = \frac{4\alpha}{9}\left(\beta Q_{aa} - \frac{Q'}{m_Q}\right)^2 \frac{m_\Xi}{m_{\Xi^*}} E_\gamma^3$$

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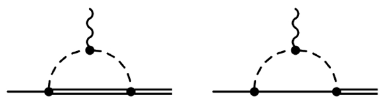
TABLE I. Predictions for the electromagnetic widths of the Ξ_{cc}^{*+} and Ξ_{cc}^{*++}. The fits are explained in the text.

Fit	β^{-1} (MeV)	m_c (MeV)	$\Gamma[\Xi_{cc}^{*++}]$ (keV)	$\Gamma[\Xi_{cc}^{*+}]$ (keV)
QM 1	379	1863	$3.3\left(\frac{E_\gamma}{80\text{ MeV}}\right)^3$	$2.6\left(\frac{E_\gamma}{80\text{ MeV}}\right)^3$
QM 2	356	1500	$3.4\left(\frac{E_\gamma}{80\text{ MeV}}\right)^3$	$3.2\left(\frac{E_\gamma}{80\text{ MeV}}\right)^3$
χPT 1	272	1432	$2.3\left(\frac{E_\gamma}{80\text{ MeV}}\right)^3$	$3.5\left(\frac{E_\gamma}{80\text{ MeV}}\right)^3$
χPT 2	276	1500	$2.3\left(\frac{E_\gamma}{80\text{ MeV}}\right)^3$	$3.3\left(\frac{E_\gamma}{80\text{ MeV}}\right)^3$



Excited States

- P-wave excited diquark

$$\Xi_{cc}^{\mathcal{P}} \quad J^P = \frac{1}{2}^+ \qquad\qquad \Xi_{cc}^{\mathcal{P}*} \quad J^P = \frac{3}{2}^+$$

$$\Gamma[\Xi_{cc}^{\mathcal{P}*} \to \Xi_{cc}^{*}\pi] = \lambda_{3/2}^2 111 \text{ MeV}$$

$$\Gamma[\Xi_{cc}^{\mathcal{P}} \to \Xi_{cc}\pi] = \lambda_{1/2}^2 111 \text{ MeV}$$

- Radially excited diquark

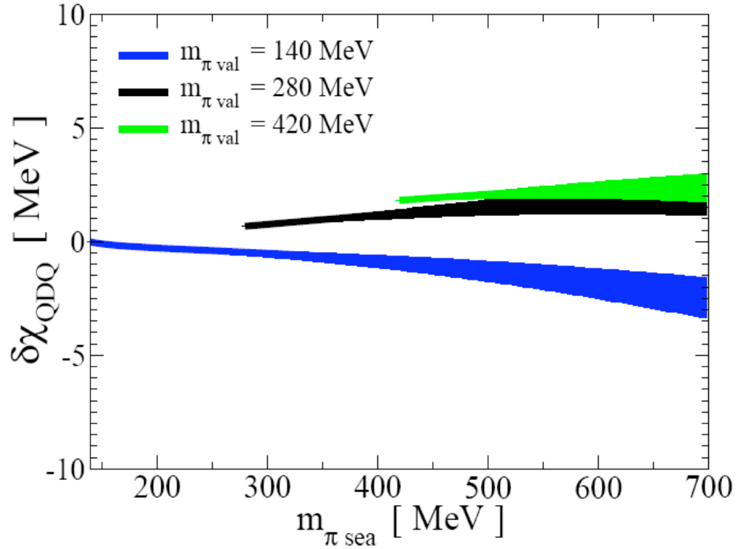
$$\Xi_{cc}'^{*} \quad J^P = \frac{3}{2}^- \qquad\qquad \Xi_{cc}' \quad J^P = \frac{1}{2}^-$$

$$\frac{\Gamma[\Xi_{cc}'^{*} \to \Xi_{cc}^{*}\pi]}{\Gamma[\Xi_{cc}'^{*} \to \Xi_{cc}\pi]} = 0.56 \qquad \frac{\Gamma[\Xi_{cc}' \to \Xi_{cc}^{*}\pi]}{\Gamma[\Xi_{cc}' \to \Xi_{cc}\pi]} = 2.3$$

In Quenched and Partially Quenched ChiPT

T.M., B.Tiburzi, PRD 74, 054505

- Partially quenched corrections to Quark-diquark symmetry prediction for hyperfine splittings



$$\delta\chi_{QDQ} = \left[M_{\Xi^*}^{(3/2)} - M_{\Xi}^{(3/2)} - \frac{3}{4}\left(M_{P^*}^{(3/2)} - M_{P}^{(3/2)}\right)\right]_{\mathrm{PQ}\chi\mathrm{PT}} - \left[M_{\Xi^*}^{(3/2)} - M_{\Xi}^{(3/2)} - \frac{3}{4}\left(M_{P^*}^{(3/2)} - M_{P}^{(3/2)}\right)\right]_{\chi\mathrm{PT}}$$

Diquark Effective Action from vNRQCD

S. Fleming, T.Mehen, PRD 73, 034502

- vNRQCD Lagrangian (Luke, Manohar, Rothstein)

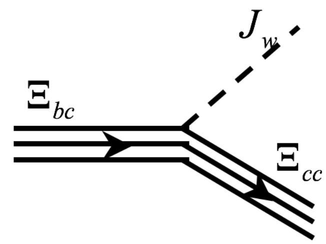
$$\mathcal{L} = \sum_{\mathbf{p}} \chi_{\mathbf{p}}^\dagger \left(iD^0 - \frac{(\mathbf{p} - i\mathbf{D})^2}{2m_Q} + \frac{g}{2m_Q}\boldsymbol{\sigma}\cdot\mathbf{B} \right)\chi_{\mathbf{p}}$$
$$-\frac{1}{2}\sum_{\mathbf{p},\mathbf{q}} \frac{g_s^2}{(\mathbf{p}-\mathbf{q})^2}\chi_{\mathbf{q}}^\dagger \bar{T}^A \chi_{\mathbf{p}} \chi_{-\mathbf{q}}^\dagger \bar{T}^A \chi_{-\mathbf{p}} + \ldots .$$

- Hubbard-Stratonovich trans. Integrate out χ

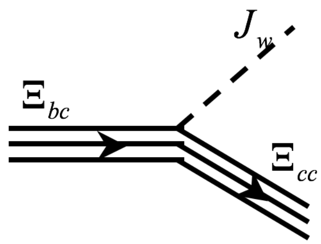
$$\mathcal{L}_{\mathbf{T}} = \int d^3\mathbf{r}\, \mathbf{T}_{\mathbf{r}}^\dagger \left(iD_0 + \frac{\boldsymbol{\nabla}_{\mathbf{r}}^2}{m_Q} - V^{(3)}(r) \right)\mathbf{T}_{\mathbf{r}} + \frac{g}{2m_Q}\int d^3\mathbf{r}\, i\, \mathbf{T}_{\mathbf{r}}^\dagger \cdot \mathbf{B}\times\mathbf{T}_{\mathbf{r}}$$
$$= \sum_n \mathbf{T}_n^\dagger (iD_0 + \delta_n)\mathbf{T}_n + \frac{g}{2m_Q} i \sum_n \mathbf{T}_n^\dagger \cdot \mathbf{B}\times\mathbf{T}_n$$

$$\mathbf{T}_{\mathbf{r}}^i = \sum_n \mathbf{T}_n^i \phi_n(\mathbf{r}) \qquad \left(-\frac{\boldsymbol{\nabla}_{\mathbf{r}}^2}{m_Q} + V^{(3)}(r) \right)\phi_n(\mathbf{r}) = -\delta_n \phi_n(\mathbf{r})$$

Semileptonic Decay



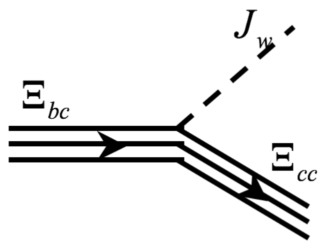
Semileptonic Decay



- Quark current $\bar{c}\gamma^{\mu}(1-\gamma^{5})b$

$$c^{+}(\delta^{\mu 0}-\delta^{\mu i}\sigma^{i})b$$

Semileptonic Decay

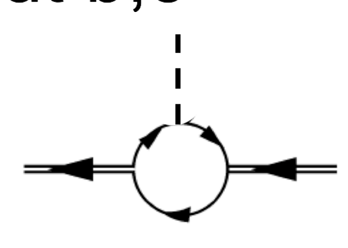


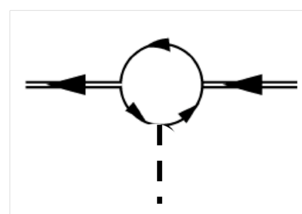
- Quark current $\bar{c}\gamma^{\mu}(1-\gamma^{5})b$

$$c^{+}(\delta^{\mu 0}-\delta^{\mu i}\sigma^{i})b$$

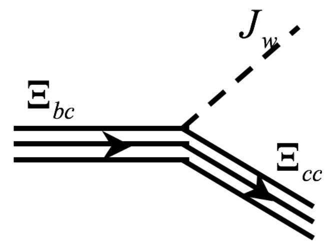
- Integrate out b,c

S. Fleming, T.Mehen, PRD 73, 034502





Semileptonic Decay



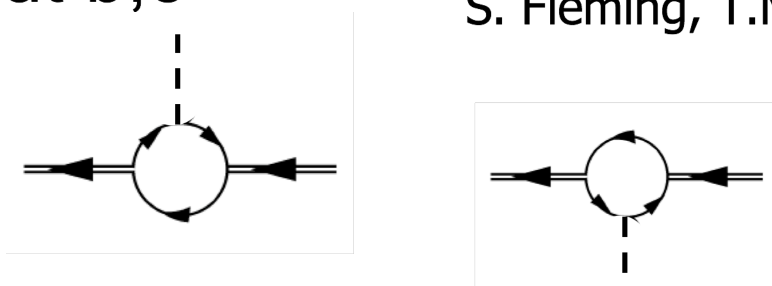
- Quark current $\bar{c}\gamma^{\mu}(1-\gamma^{5})b$

$$\Downarrow$$

$$c^{+}(\delta^{\mu 0}-\delta^{\mu i}\sigma^{i})b$$

- Integrate out b,c

S. Fleming, T.Mehen, PRD 73, 034502



- Effective Lagrangian of diquark coupled to weak current

$$L \propto J_{w}{}^{0}T_{cc}^{+i}T_{bc}{}^{i}-iJ_{w}{}^{i}T_{cc}^{+j}\varepsilon_{ijk}T_{bc}{}^{k}-J_{w}{}^{i}T_{cc}^{+i}T_{bc}^{'}$$

Semileptonic Decay

$$T_{a,i\beta} = \sqrt{2}\left(\Xi^*_{a,i\beta} + \frac{1}{\sqrt{3}}\Xi_{a,\gamma}\sigma^i_{\gamma\beta}\right) \qquad T' = \sqrt{2}\Xi'$$

- Reproduce zero recoil Cascade bc to cascade cc transition matrix elements.

$$\Xi_{bc} \to \Xi_{cc} \qquad \eta\,\bar{u}_{cc}\left(2\gamma^\mu - \frac{4}{3}\gamma^\mu\gamma_5\right)u_{bc}$$

$$\Xi'_{bc} \to \Xi_{cc} \qquad \frac{-2}{\sqrt{3}}\eta\,\bar{u}_{cc}\left(-\gamma^\mu\gamma_5\right)u_{bc}$$

$$\Xi_{bc} \to \Xi^*_{cc} \qquad \frac{-2}{\sqrt{3}}\eta\,\bar{u}^\mu_{cc}u_{bc}$$

$$\Xi'_{bc} \to \Xi^*_{cc} \qquad -2\eta\,\bar{u}^\mu_{cc}u_{bc}$$

$$\Xi^*_{bc} \to \Xi_{cc} \qquad \frac{-2}{\sqrt{3}}\eta\,\bar{u}_{cc}u^\mu_{bc}$$

$$\Xi^*_{bc} \to \Xi^*_{cc} \qquad -2\eta\,\bar{u}^\lambda_{cc}\left(\gamma^\mu - \gamma^\mu\gamma_5\right)u_{bc\,\lambda}$$

J. Flynn, J. Nieves, arXiv:0706.2805

Semileptonic Decay

$$L \propto J_w^{\ 0} T_{cc}^{+\,i} T_{bc}^{\ i} - i J_w^{\ i} T_{cc}^{+\,j} \varepsilon_{ijk} T_{bc}^{\ k} - J_w^{\ i} T_{cc}^{+\,i} T_{bc}^{'}$$

$$T_{a,i\beta} = \sqrt{2}\left(\Xi^{*}_{a,i\beta} + \frac{1}{\sqrt{3}}\Xi_{a,\gamma}\sigma^{i}_{\gamma\beta}\right) \qquad T^{'} = \sqrt{2}\Xi^{'}$$

- Reproduce zero recoil Cascade bc to cascade cc transition matrix elements.

$\Xi_{bc} \to \Xi_{cc}$	$\eta\, \bar{u}_{cc}\left(2\gamma^{\mu} - \frac{4}{3}\gamma^{\mu}\gamma_5\right) u_{bc}$
$\Xi'_{bc} \to \Xi_{cc}$	$\frac{-2}{\sqrt{3}}\eta\, \bar{u}_{cc}\left(-\gamma^{\mu}\gamma_5\right) u_{bc}$
$\Xi_{bc} \to \Xi^{*}_{cc}$	$\frac{-2}{\sqrt{3}}\eta\, \bar{u}^{\mu}_{cc} u_{bc}$
$\Xi'_{bc} \to \Xi^{*}_{cc}$	$-2\eta\, \bar{u}^{\mu}_{cc} u_{bc}$
$\Xi^{*}_{bc} \to \Xi_{cc}$	$\frac{-2}{\sqrt{3}}\eta\, \bar{u}_{cc} u^{\mu}_{bc}$
$\Xi^{*}_{bc} \to \Xi^{*}_{cc}$	$-2\eta\, \bar{u}^{\lambda}_{cc}\left(\gamma^{\mu} - \gamma^{\mu}\gamma_5\right) u_{bc\,\lambda}$

J. Flynn, J. Nieves, arXiv:0706.2805

Summary

- Chiral Lagrangian of doubly heavy baryons and heavy mesons with quark-diquark symmetry

- Predictions:
  Chiral mass correciton,
  em decays,
  strong decays of excited states

- In progress:
  Chiral Lagrangian of doubly heavy baryon semileptonic decay
  Chiral correction

Electromagnetic couplings

$$\mathcal{L}_{em} = \frac{e}{2m_Q} Q' h^\dagger \vec{\sigma} \cdot \vec{B} h - \frac{ie}{m_Q} Q' \vec{V}^\dagger \cdot \vec{B} \times \vec{V}$$

$$= \frac{e}{2m_Q} Q' \mathcal{Q}^\dagger_\mu \vec{\Sigma}'_{\mu\nu} \cdot \vec{B} \mathcal{Q}_\nu,$$

$$\vec{\Sigma}'_{\mu\nu} = \begin{pmatrix} \vec{\sigma}_{\alpha\beta} & 0 \\ 0 & -2\vec{\mathcal{T}}_{jk} \end{pmatrix}$$

Electromagnetic couplings

$$\mathcal{L}_{em} = \frac{e}{2m_Q} Q' h^\dagger \vec{\sigma} \cdot \vec{B} h - \frac{ie}{m_Q} Q' \vec{V}^\dagger \cdot \vec{B} \times \vec{V}$$

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$$\mathcal{L} = \frac{e\beta}{2} \mathrm{Tr}[H_a^\dagger H_b \vec{\sigma} \cdot \vec{B} Q_{ab}] + \frac{e}{2m_Q} Q' \mathrm{Tr}[H_a^\dagger \vec{\sigma} \cdot \vec{B} H_a]$$

⇩

Electromagnetic couplings

$$\mathcal{L}_{em} = \frac{e}{2m_Q} Q' h^\dagger \vec{\sigma} \cdot \vec{B} h - \frac{ie}{m_Q} Q' \vec{V}^\dagger \cdot \vec{B} \times \vec{V}$$

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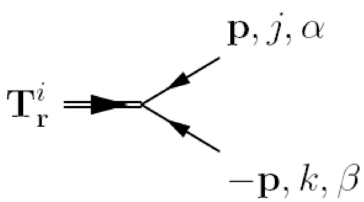
⇓

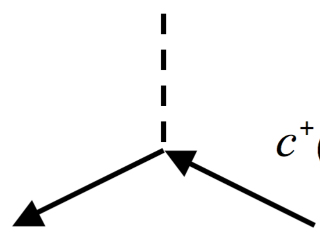
$$\mathcal{L} = \frac{e\beta}{2} \mathrm{Tr}[\mathcal{H}_a^\dagger \mathcal{H}_b \vec{\sigma} \cdot \vec{B} Q_{ab}] + \frac{e}{2m_Q} Q' \,\mathrm{Tr}[\mathcal{H}_a^\dagger \vec{\Sigma}' \cdot \vec{B} \mathcal{H}_b]$$

Coupled to Weak Current

	S	J^P	I	S^{π}_{hh}	
Ξ_{cc}	0	$\frac{1}{2}^+$	$\frac{1}{2}$	1^+	ccl
Ξ^*_{cc}	0	$\frac{3}{2}^+$	$\frac{1}{2}$	1^+	ccl
Ξ'_{bc}	0	$\frac{1}{2}^+$	$\frac{1}{2}$	0^+	bcl
Ξ_{bc}	0	$\frac{1}{2}^+$	$\frac{1}{2}$	1^+	bcl
Ξ^*_{bc}	0	$\frac{3}{2}^+$	$\frac{1}{2}$	1^+	bcl



$$-ie^{-i\mathbf{p}\,\mathbf{r}}\,V^{(3)}(r)\,\frac{\epsilon_{ijk}}{2}\,(\sigma\epsilon)_{\alpha\beta}$$



$$c^{+}(\delta^{\mu 0}-\delta^{\mu i}\sigma^{i})b$$