Productions and decays of charmed baryons

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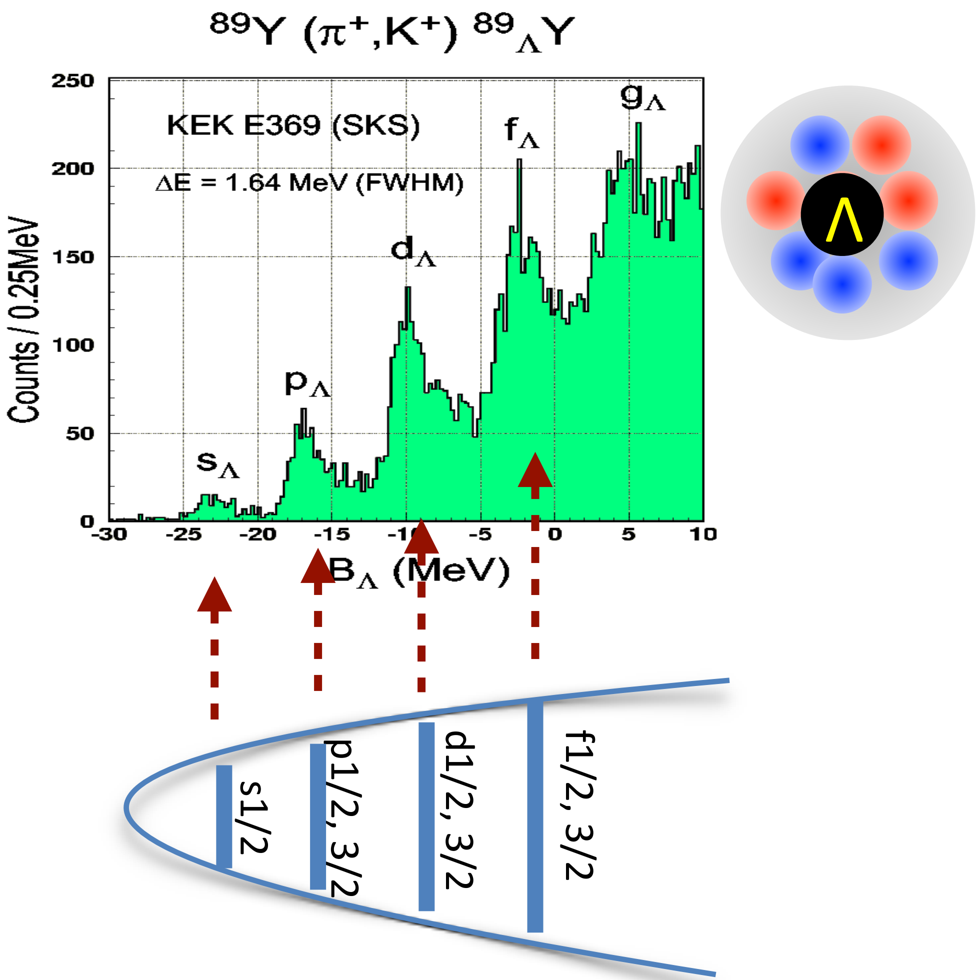
Workshop on J-PARC hadron physics
KEK Tokai Campus, March 2-4, 2016

- Introduction — Similarity to Hyp and HQ
- Production
- Pion emission decays

Similarities/differences — hyper nuclear physics

- Hyperon behaves differently from nucleons
- It goes into deep inside to see **shell structure** and shows up in **CSB**



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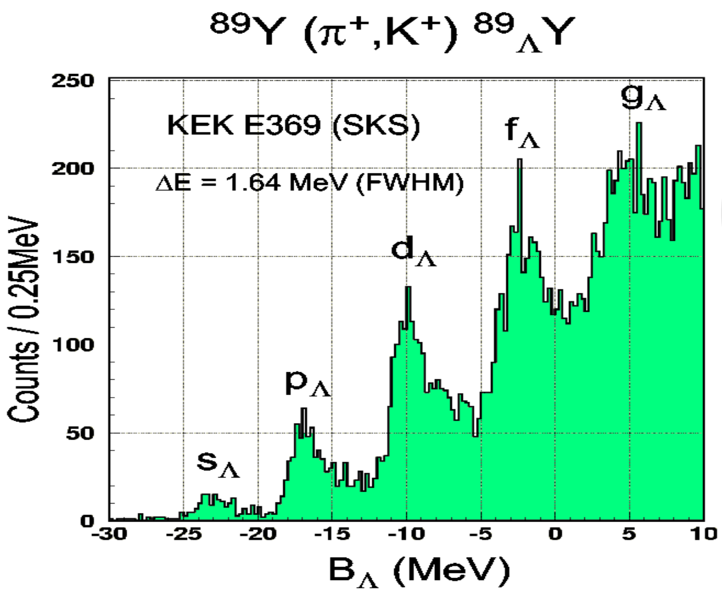

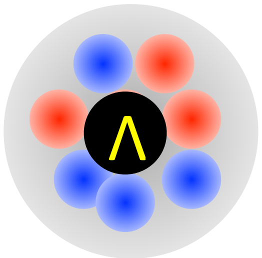

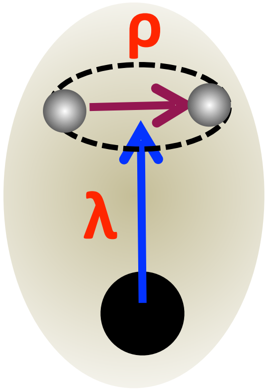

- Heavy quark changes motion of light quarks (few quarks)
- It resolves the motions of light quarks, **ρ** and **λ** modes

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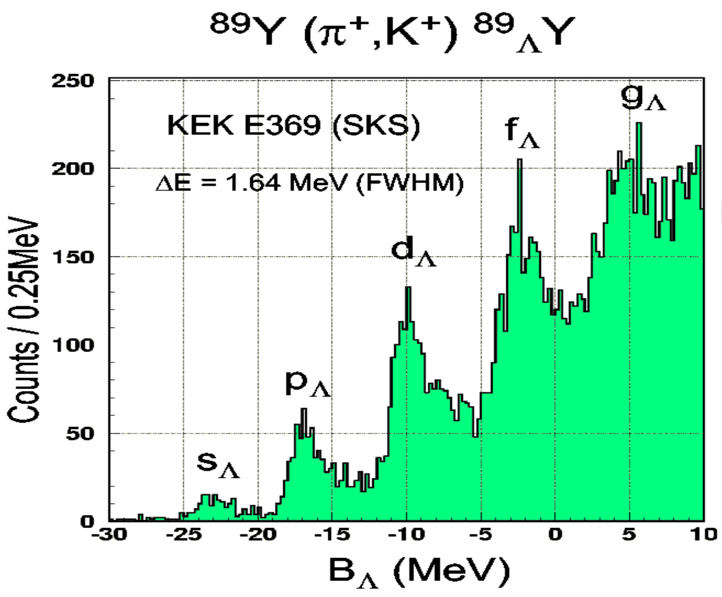
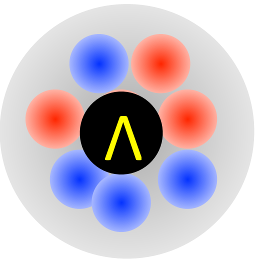
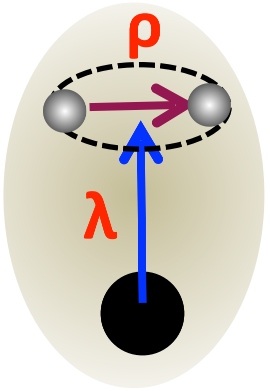




Makes invisible to visible

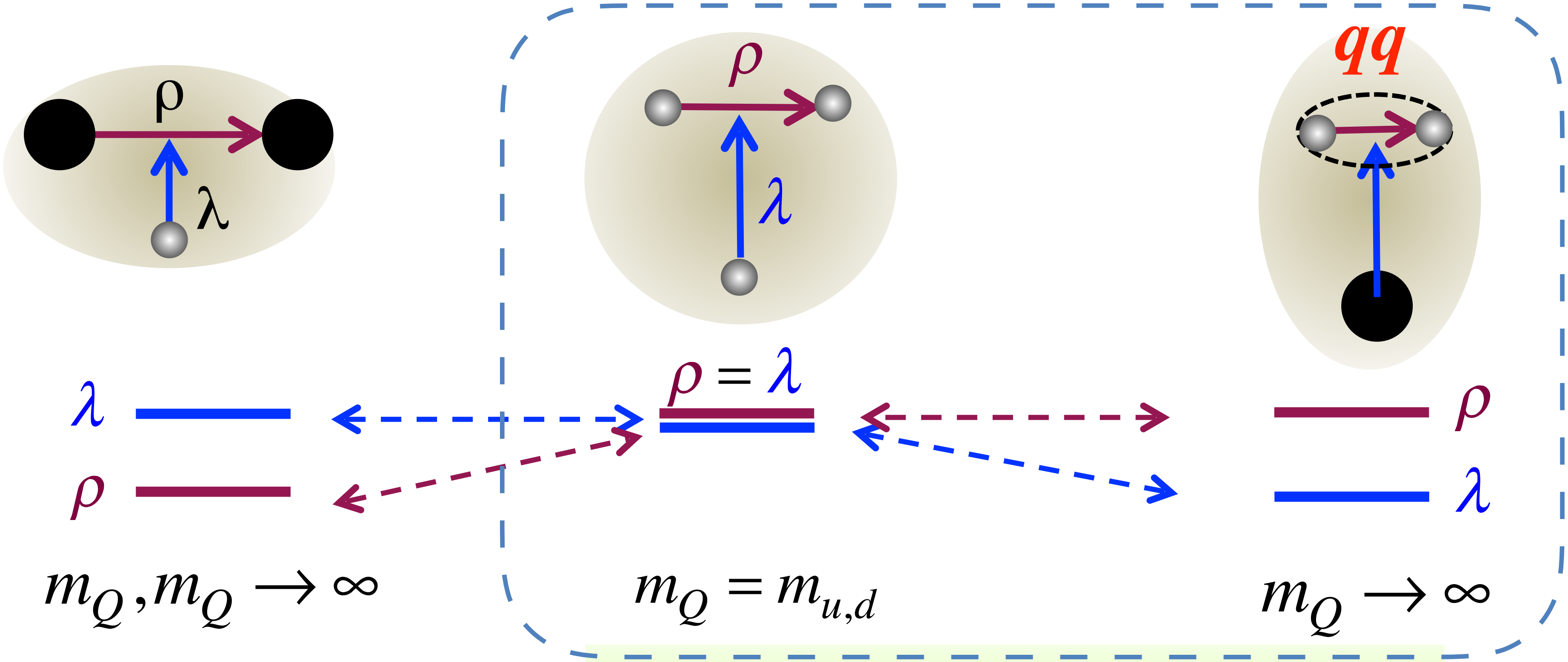


- Heavy quark changes motion of light quarks (few quarks)
- It resolves the motions of light quarks, **ρ** and **λ** modes

A heavy quark distinguish the fundamental modes

λ and ρ Place to look at qq dynamics

Isotope-shift: Copley-Isgur-Karl, PRD20, 768 (1979)



Smooth change in m_Q is useful

Productions

- How much $\left\{\begin{array}{l}\text{charm}\\\text{excited states}\end{array}\right.$ are produced

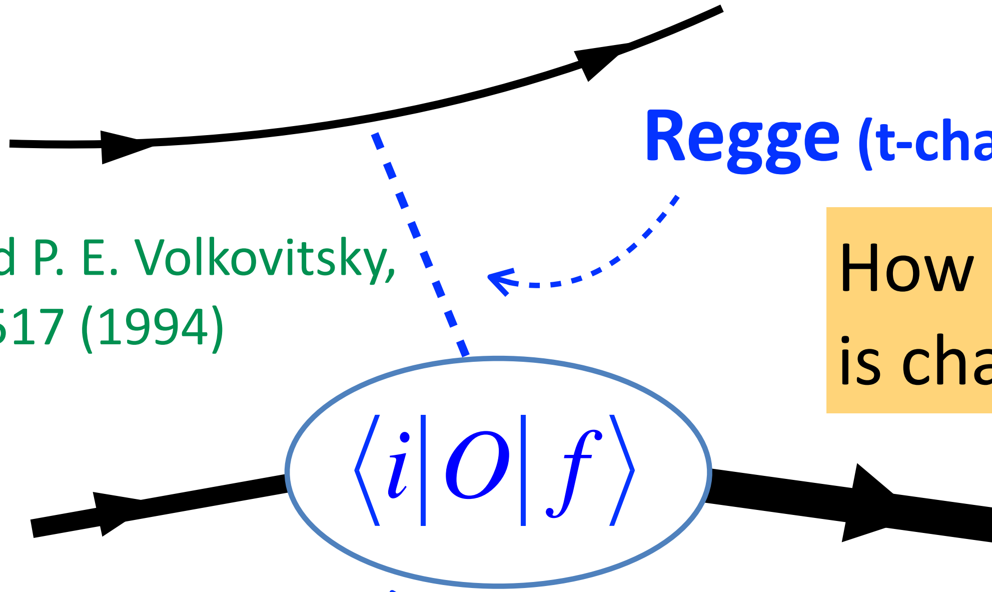
- Can we study structure?

Productions

$$\pi + N \quad \rightarrow \quad D^* + \Lambda_c$$

Productions

$$\pi + N \rightarrow D^* + \Lambda_c$$



Regge (t-channel) model

A. B. Kaidalov and P. E. Volkovitsky,
B. Z. Phys. C 63, 517 (1994)

How much
is charm produced?

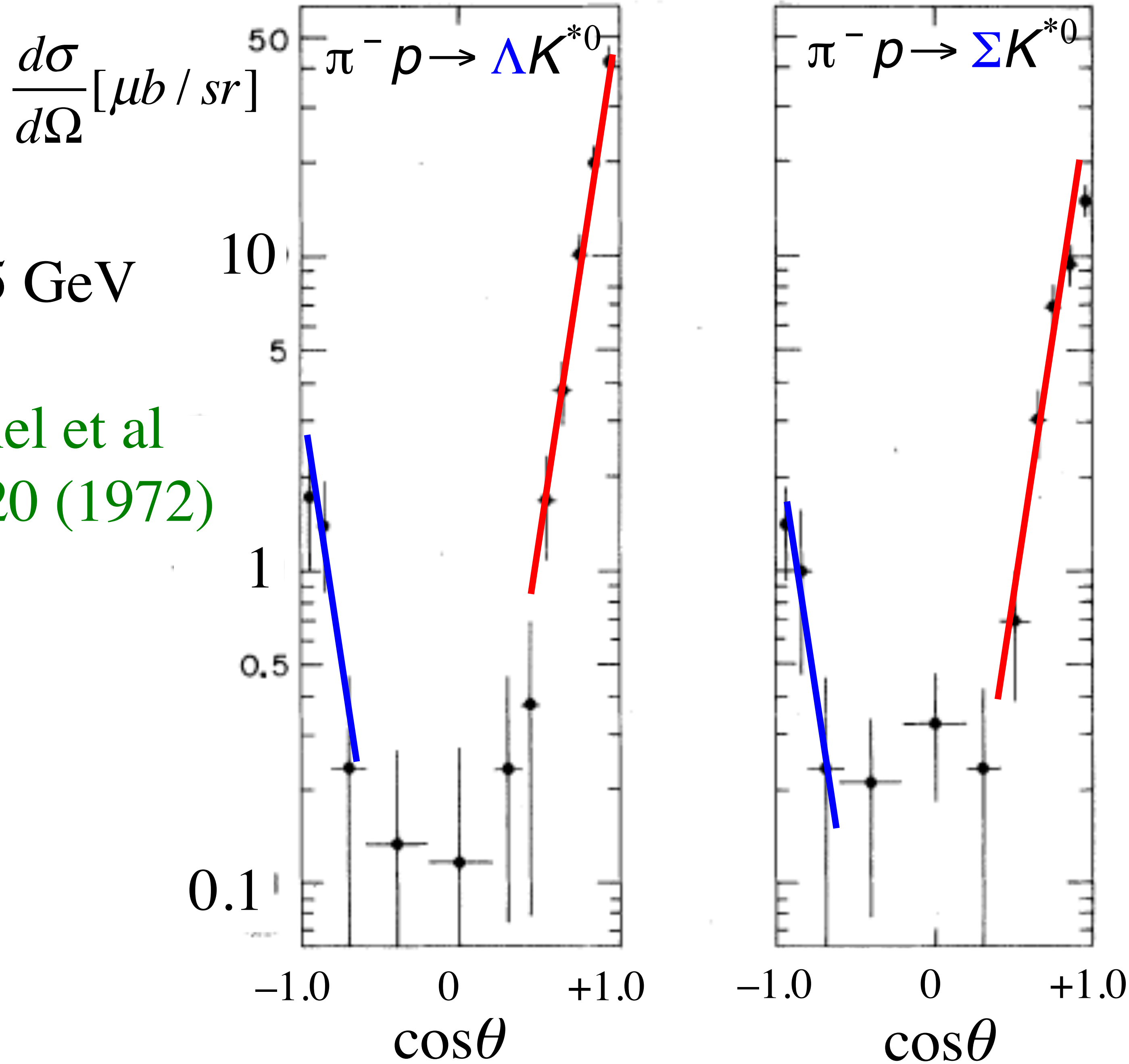
Quark model

Kim, Kim, Noumi, Shirotori, Hosaka
PTEP 2014 (2014) 10, 103D01,
PRD92 (2015) 9, 094021

How are they related to
internal structure of Λ_c*?

$p_{\pi,\,\mathrm{Lab}} = 4.5$ GeV

D.J. Krennel et al
PRD6, 1220 (1972)

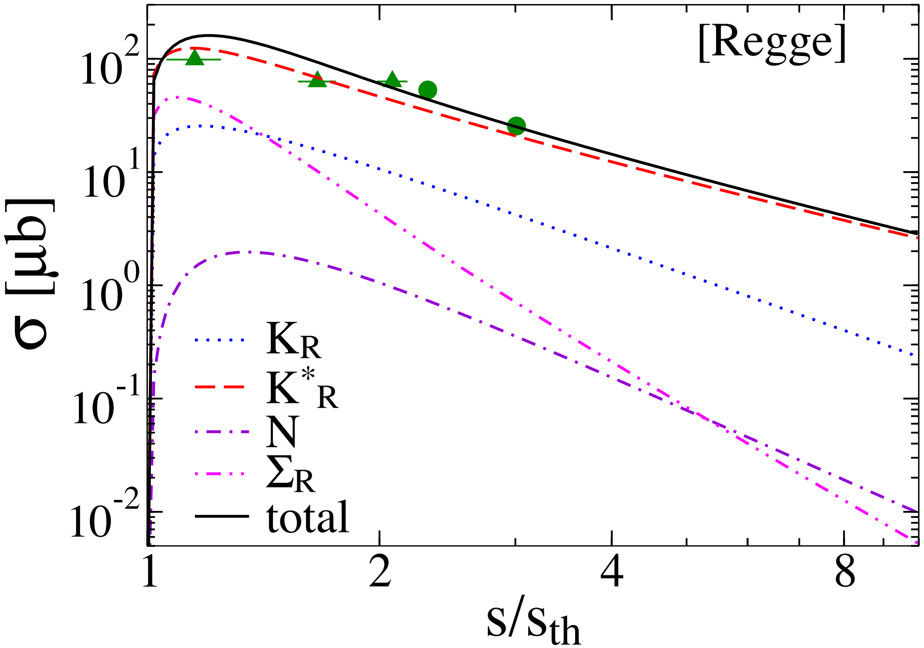


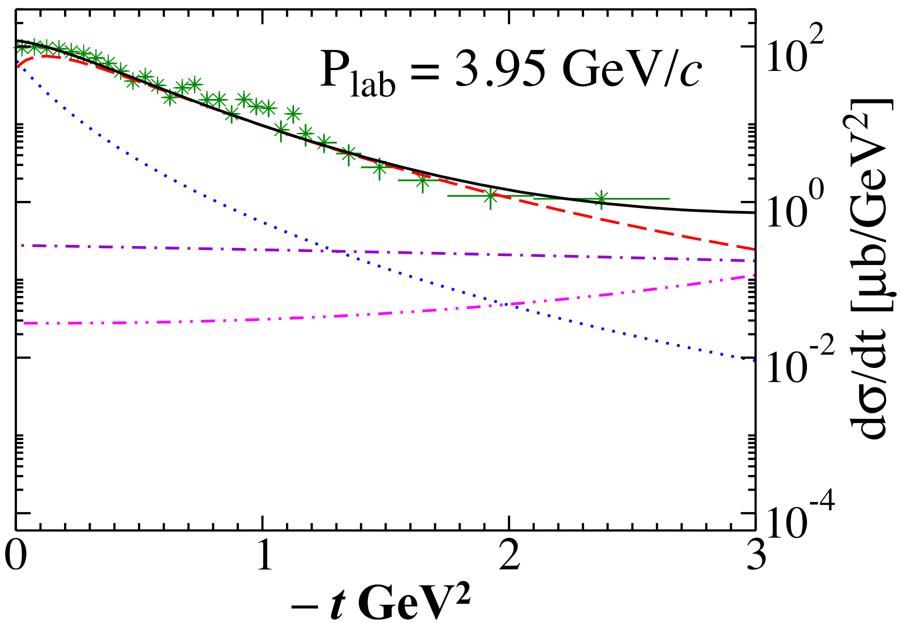
How much is charm produced?

Regge model description

Kim Hosaka Kim Noumi, arXiv:1509.03567

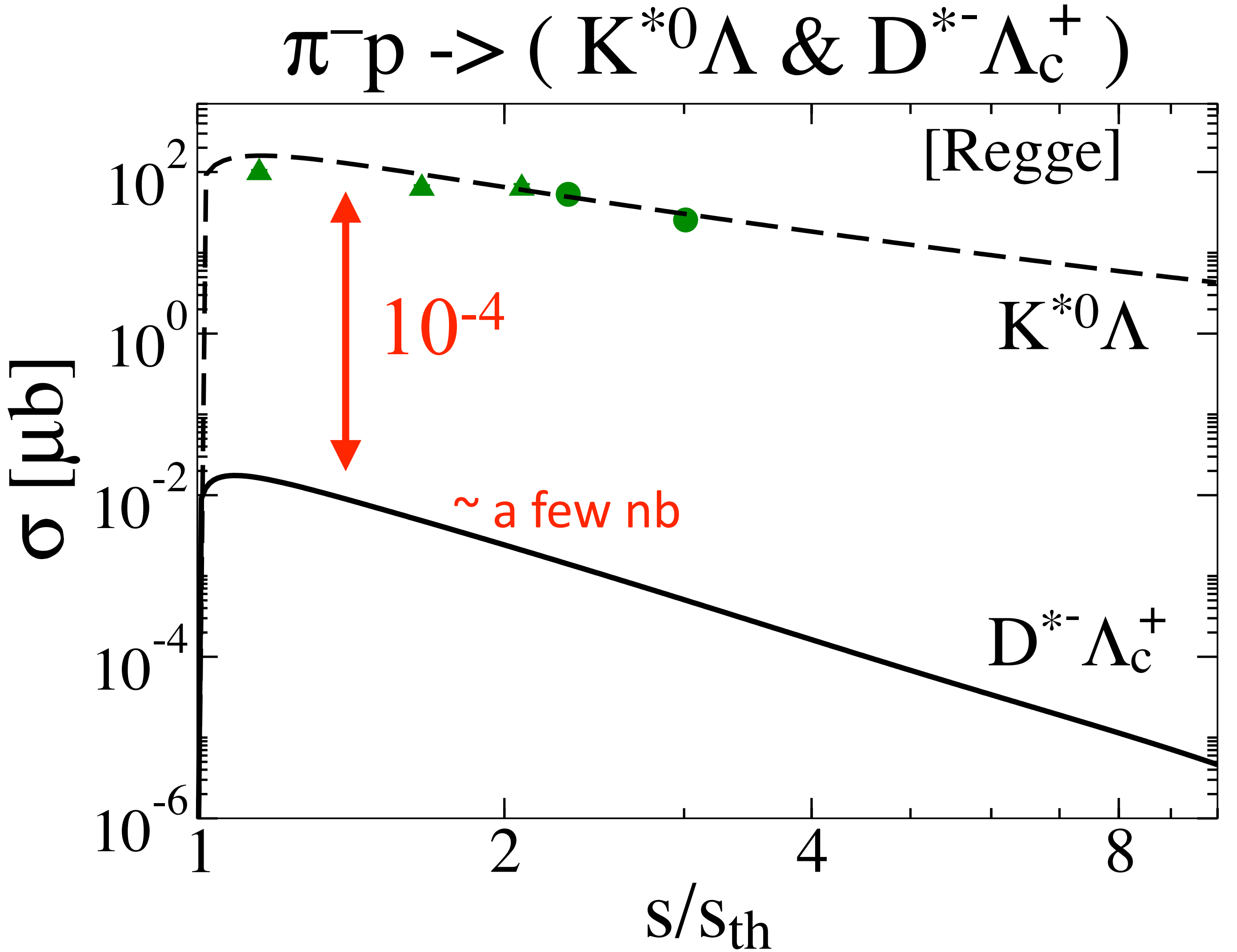
$$\pi^- + N \rightarrow K^{*0} + \Lambda$$





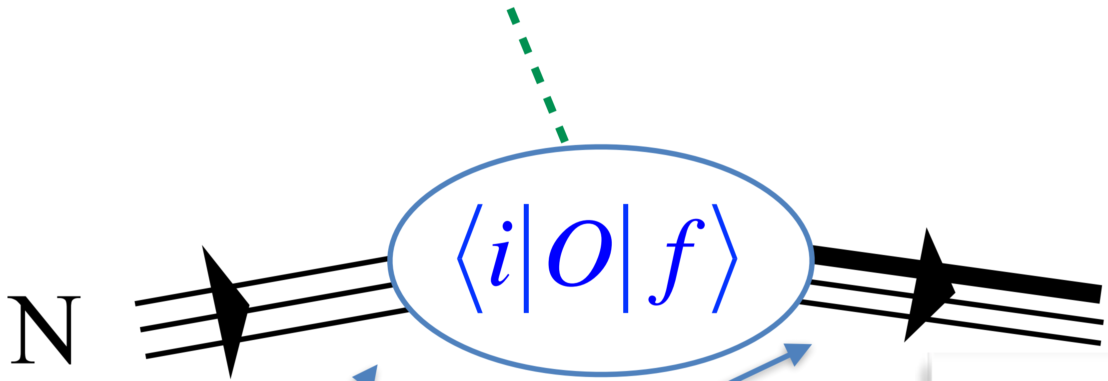
- Vector-Reggeon dominance with some pseudoscalar
- Energy dependence is also well produced

Prediction to the charm production



How are they related to internal structure?

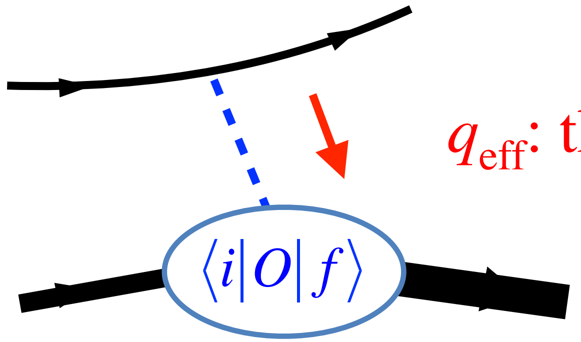
PTEP 2014 (2014) 10, 103D01



Various Yc

Λ_c^+	****
$\Lambda_c(2595)^+$	***
$\Lambda_c(2625)^+$	***
$\Lambda_c(2765)^+$	*
$\Lambda_c(2880)^+$	***
$\Lambda_c(2940)^+$	***
$\Sigma_c(2455)$	****
$\Sigma_c(2520)$	***
$\Sigma_c(2800)$	***

Quark model wave functions
(Harmonic oscillator)



q_{eff}: the momentum transfer ~ Large

GS $\quad \left\langle B_c(\text{S-wave})\middle|\vec{e}_\perp\cdot\vec{\sigma}e^{i\vec{q}_{eff}\cdot\vec{x}}\middle|N(\text{S-wave})\right\rangle_{radial} \sim 1\times\exp\left(-\frac{q_{eff}^2}{4A^2}\right)$

Excited states

$$\left\langle B_c(P\text{-wave})\middle|\vec{e}_\perp\cdot\vec{\sigma}e^{i\vec{q}_{eff}\cdot\vec{x}}\middle|N(\text{S-wave})\right\rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^1\times\exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

$$\left\langle B_c(D\text{-wave})\middle|\vec{e}_\perp\cdot\vec{\sigma}e^{i\vec{q}_{eff}\cdot\vec{x}}\middle|N(\text{S-wave})\right\rangle_{radial} \sim \left(\frac{q_{eff}}{A}\right)^2\times\exp\left(-\frac{q_{eff}^2}{4A^2}\right)$$

Transitions to excited states are not suppressed!

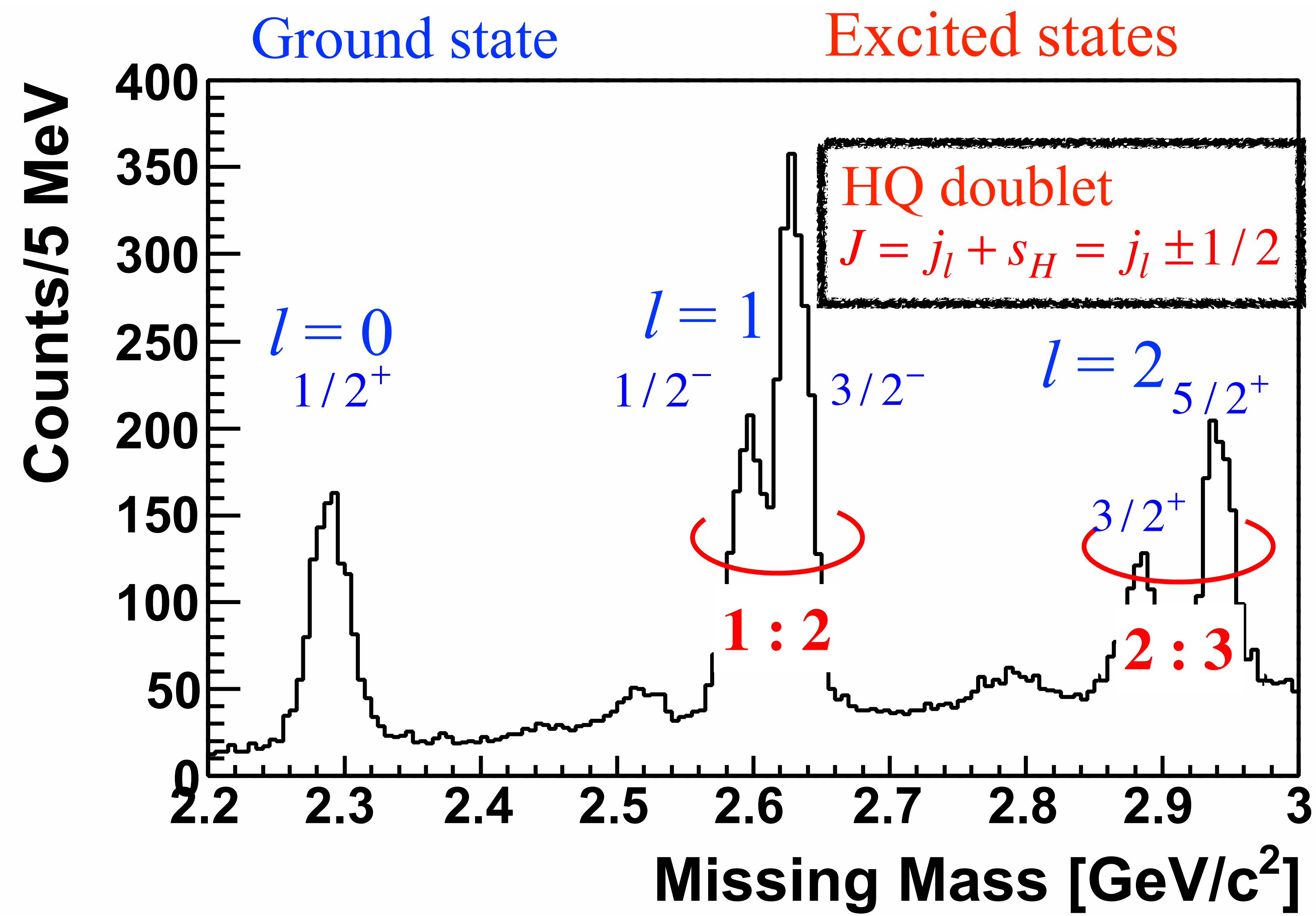
Charm $k_\pi^{CM} = 2.71$ [GeV] , $k_\pi^{Lab} = 16$ [GeV]

$l=0$	$\Lambda_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{1}{2}^+)$	$\Sigma_c(\frac{3}{2}^+)$					
	1.00	0.02	0.16					
$l=1$	$\Lambda_c(\frac{1}{2}^-)$	$\Lambda_c(\frac{3}{2}^-)$	$\Sigma_c(\frac{1}{2}^-)$	$\Sigma_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{1}{2}^-)$	$\Sigma'_c(\frac{3}{2}^-)$	$\Sigma'_c(\frac{5}{2}^-)$	
	0.90	1.70	0.02	0.03	0.04	0.19	0.18	
$l=2$	$\Lambda_c(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+-)$	$\Sigma_c(\frac{3}{2}^+)$	$\Sigma_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{1}{2}^+)$	$\Sigma'_c(\frac{3}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$	$\Sigma'_c(\frac{5}{2}^+)$
	0.50	0.88	0.02	0.02	0.01	0.03	0.07	0.07

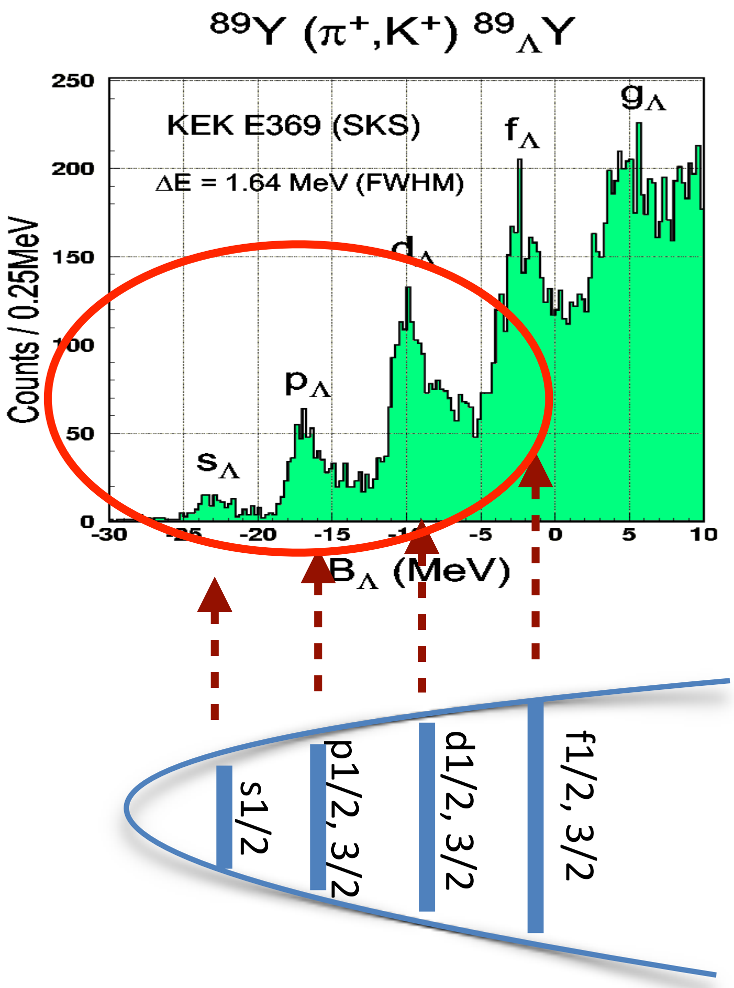
Strange $k_\pi^{CM} = 1.59$ [GeV], $k_\pi^{Lab} = 5.8$ [GeV]

$l=0$	$\Lambda(\frac{1}{2}^+)$	$\Sigma(\frac{1}{2}^+)$	$\Sigma(\frac{3}{2}^+)$					
	1.00	0.067	0.44					
$l=1$	$\Lambda(\frac{1}{2}^-)$	$\Lambda(\frac{3}{2}^-)$	$\Sigma(\frac{1}{2}^-)$	$\Sigma(\frac{3}{2}^-)$	$\Sigma'(\frac{1}{2}^-)$	$\Sigma'(\frac{3}{2}^-)$	$\Sigma'(\frac{5}{2}^-)$	
	0.11	0.23	0.007	0.01	0.01	0.07	0.067	
$l=2$	$\Lambda(\frac{3}{2}^+)$	$\Lambda_c(\frac{5}{2}^+-)$	$\Sigma(\frac{3}{2}^+)$	$\Sigma(\frac{5}{2}^+)$	$\Sigma'(\frac{1}{2}^+)$	$\Sigma'(\frac{3}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$	$\Sigma'(\frac{5}{2}^+)$
	0.13	0.20	0.007	0.01	0.004	0.02	0.038	0.04

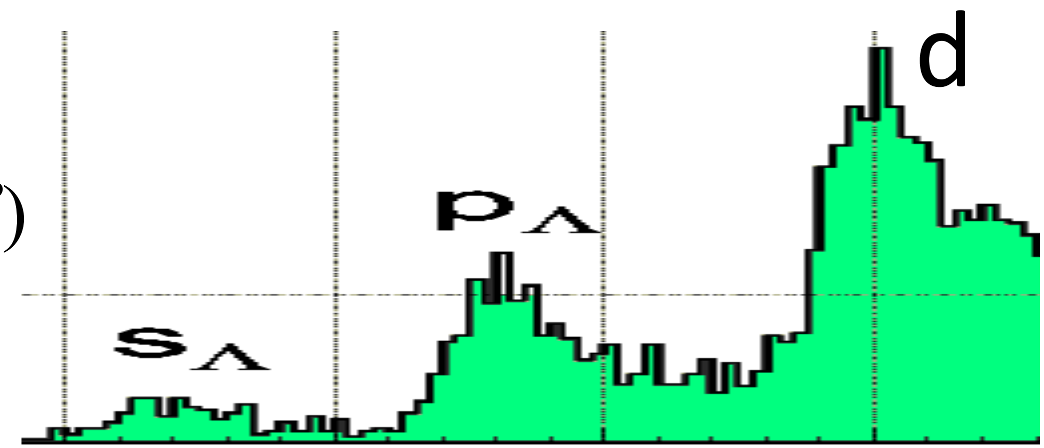
Charm production spectrum



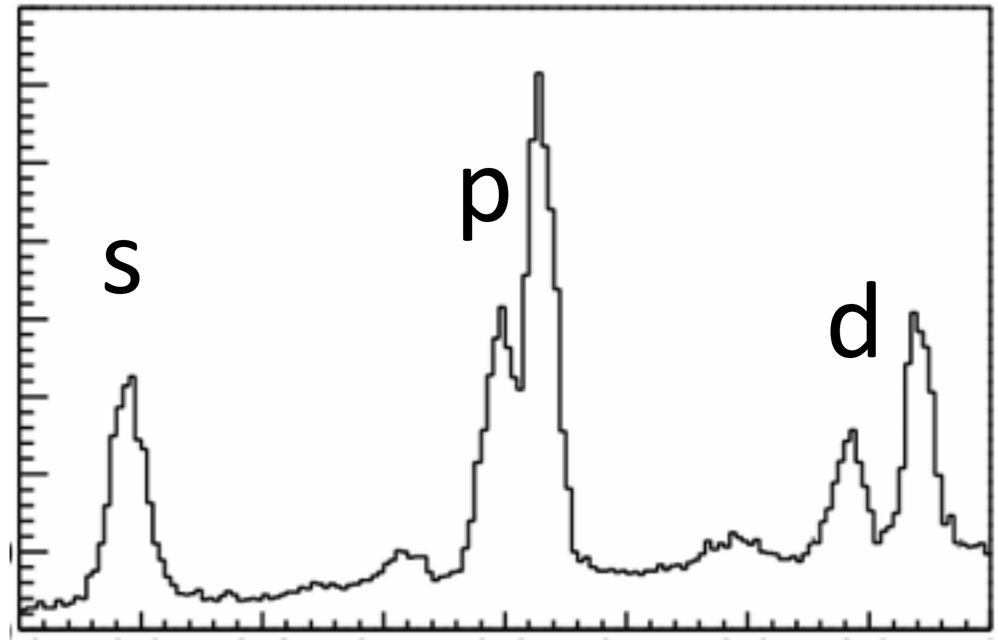
Coming back to this again



$$\pi^+ + {}^{89}\mathrm{Y} \\ \rightarrow \mathrm{K}^+ + {}^{89}{}_{\Lambda}\mathrm{Y}(J^P)$$



$$\pi + p \rightarrow D^* + B_c{}^*(J^P)$$



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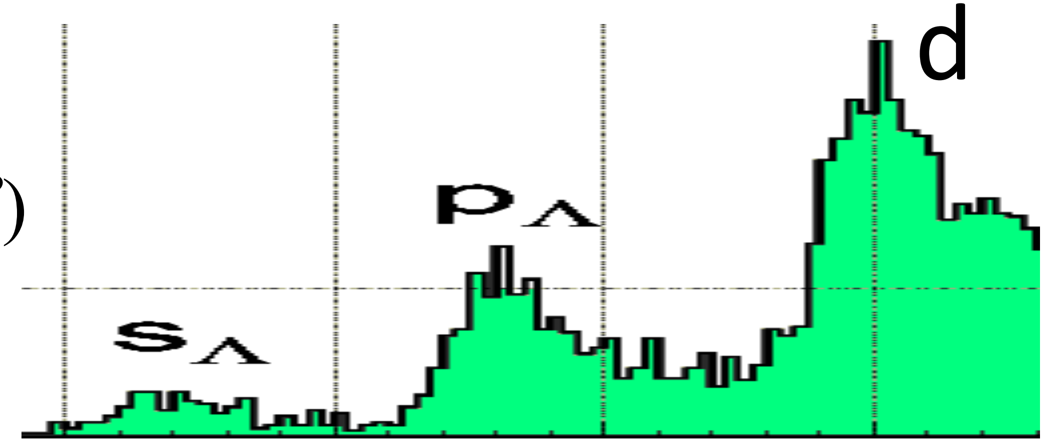

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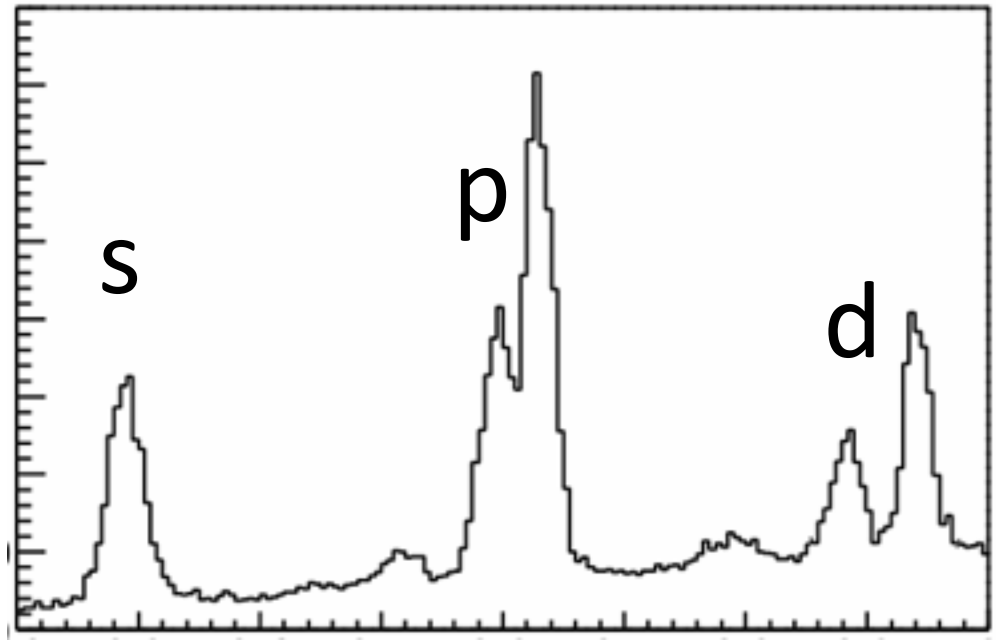

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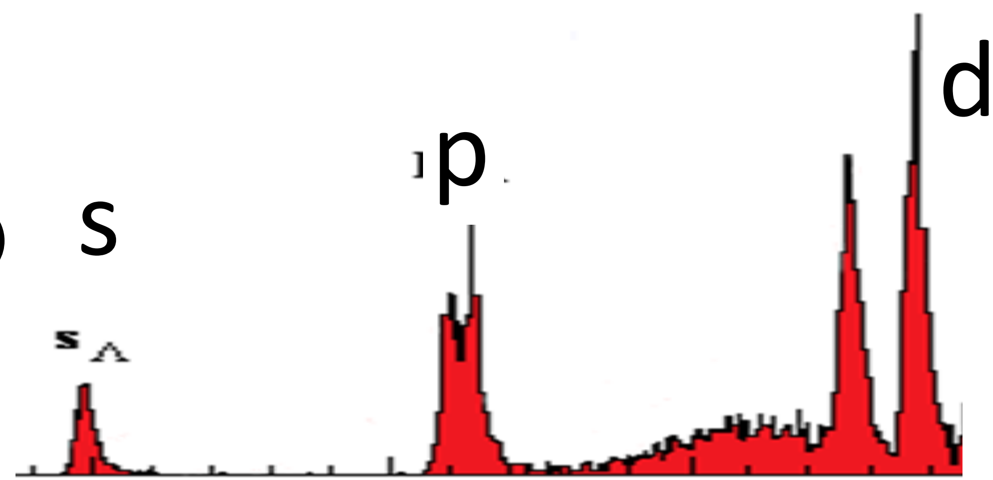
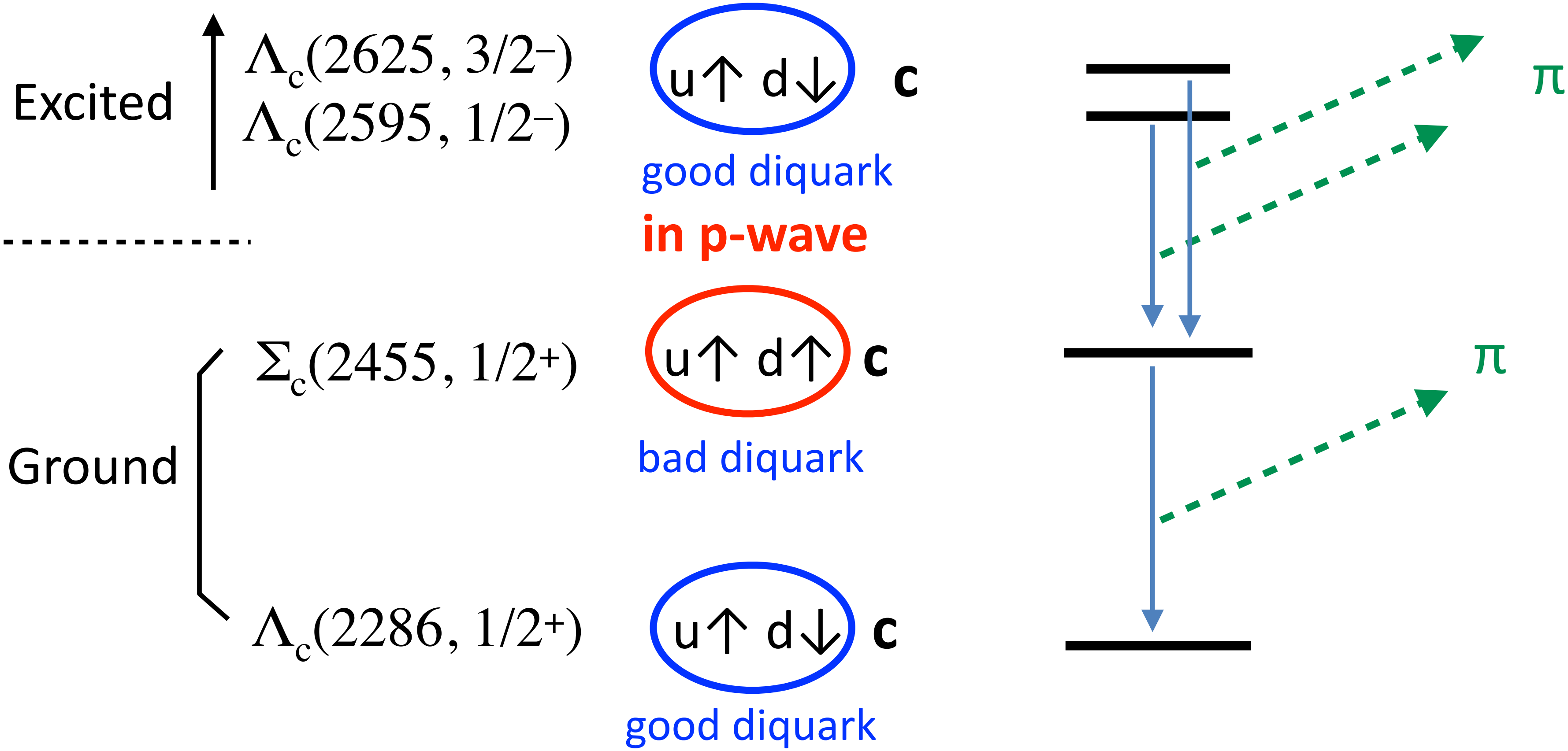


Decays —Pion emission—

On going, Nagahiro, Yasui, …



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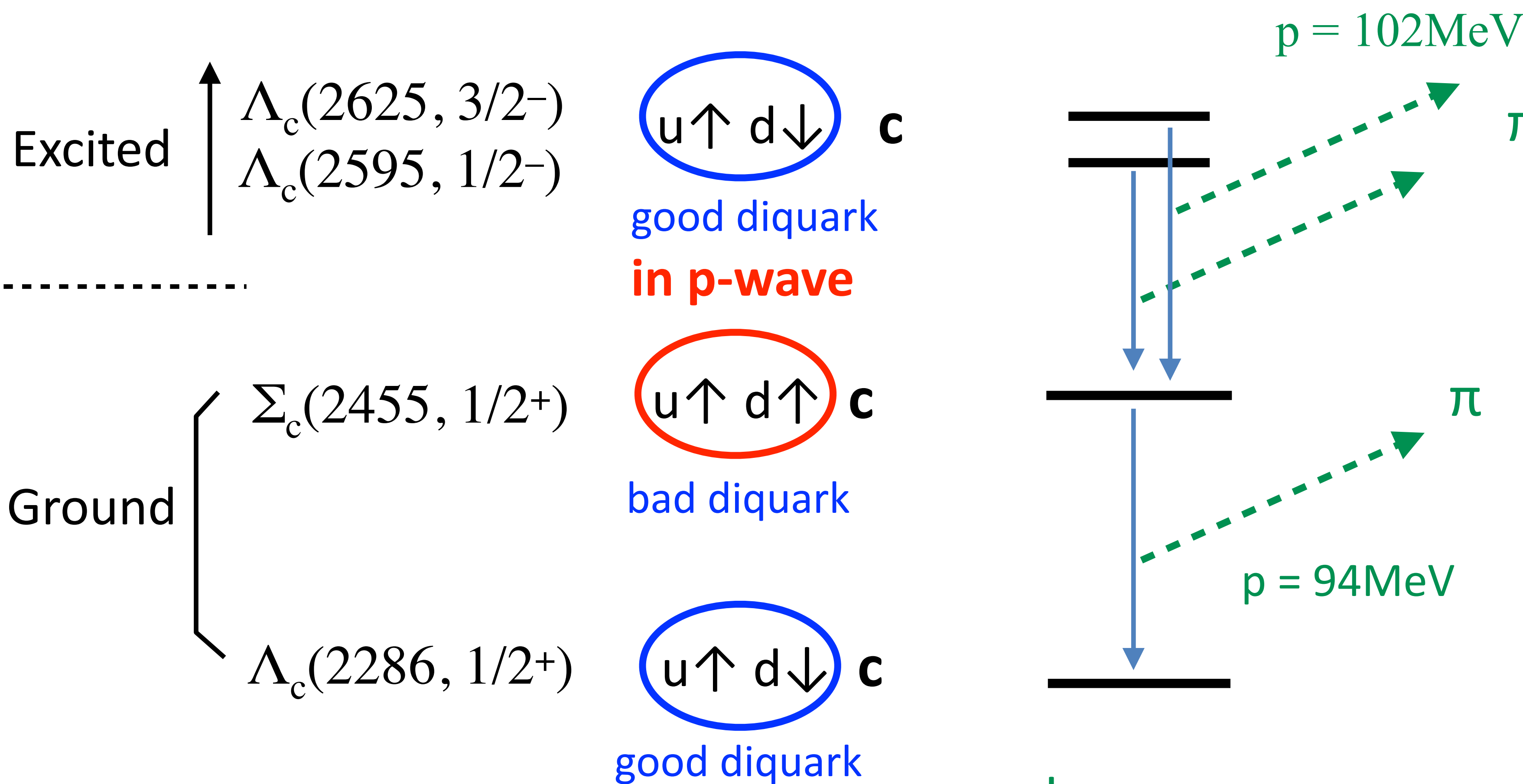


low energy

cf: p(Δ->πN)=229 MeV

Decays —Pion emission—

On going, Nagahiro, Yasui, …

Excited

$\Lambda_c(2625, 3/2^-)$

$\Lambda_c(2595, 1/2^-)$

u↑ d↓ c

good diquark

in p-wave

Ground

$\Sigma_c(2455, 1/2^+)$

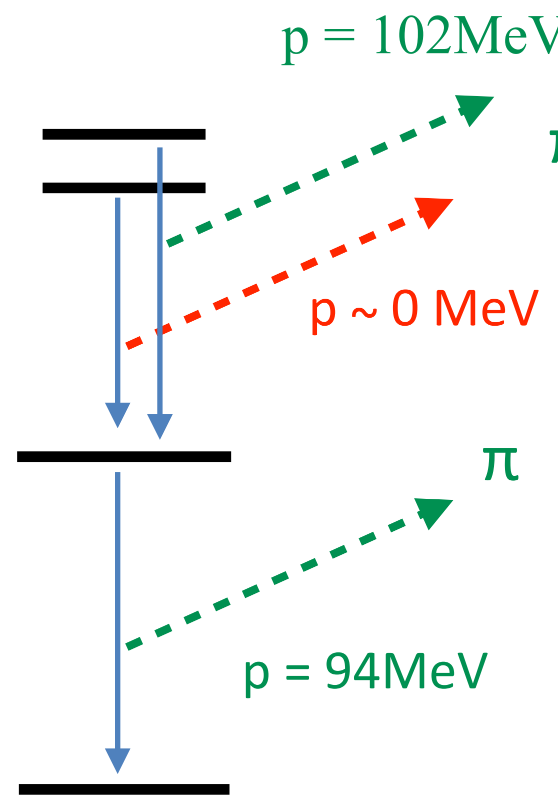
u↑ d↑ c

bad diquark

$\Lambda_c(2286, 1/2^+)$

u↑ d↓ c

good diquark

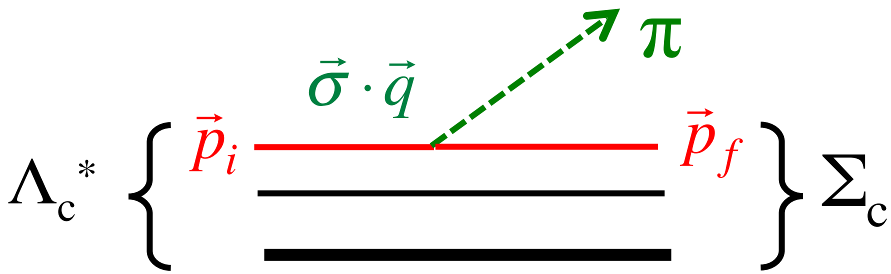


Extremely low energy

Decays —Pion emission—

On going, Nagahiro, Yasui, …

- Place to look at the ***two independent*** operators



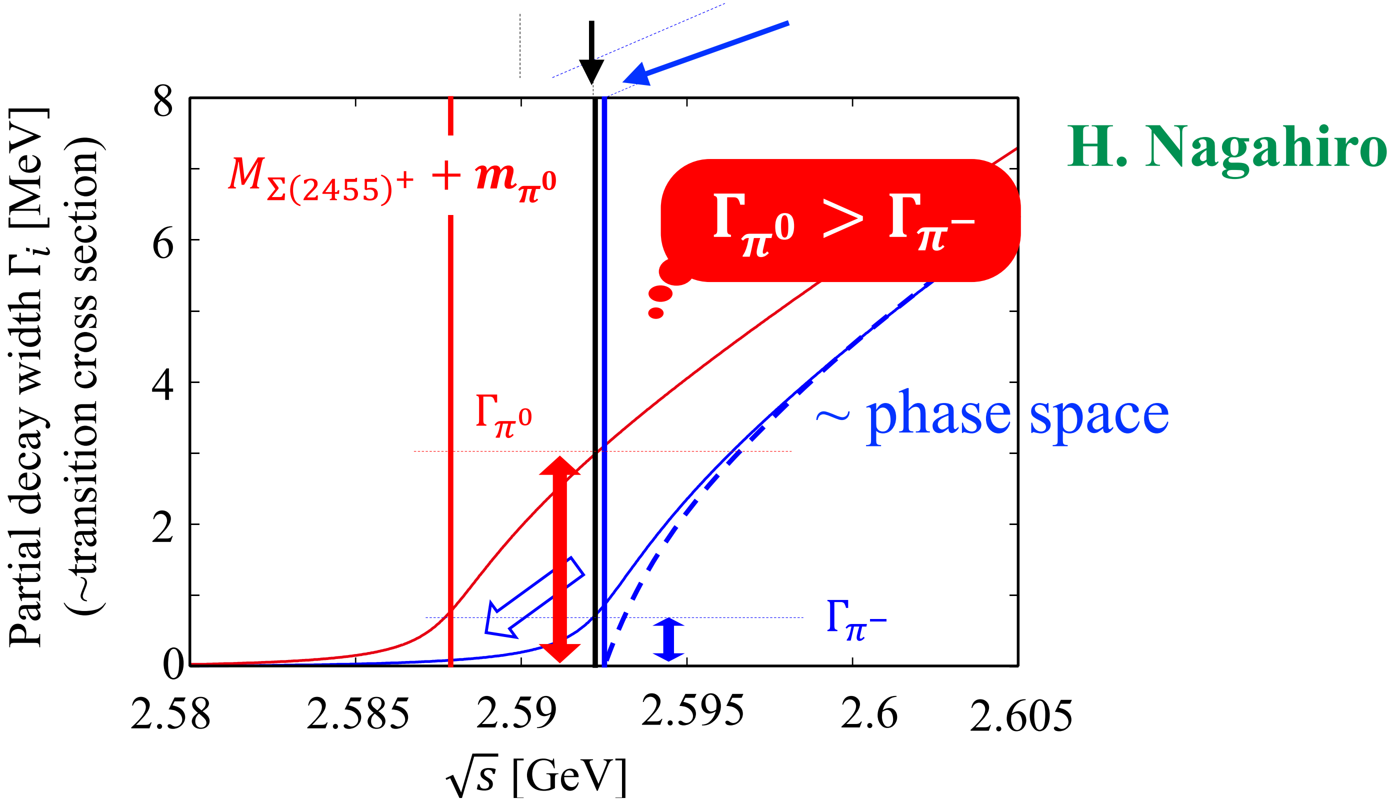
$\vec{\sigma}\cdot\vec{p}_i,\ \vec{\sigma}\cdot\vec{p}_f$

$\bar{q}\gamma_5 q\phi_\pi,\ \bar{q}\gamma^\mu\gamma_5 q\partial_\mu\phi_\pi$

$\Lambda_c(2595, 1/2^-) \rightarrow \Sigma_c(2455, 1/2^+)$

Isospin breaking right on the threshold

$M_{\Lambda(2595)} < M_{\Sigma(2455)^{++}} + m_{\pi^-} \Rightarrow \Gamma_{\pi^-} = 0\ ?$



First let us look at

$\Lambda_c(2625, 3/2^-)$
$\Lambda_c(2595, 1/2^-)$

u↑ d↓ **c**

good diquark

in p-wave

$\Sigma_c(2520, 3/2^+)$
$\Sigma_c(2455, 1/2^+)$

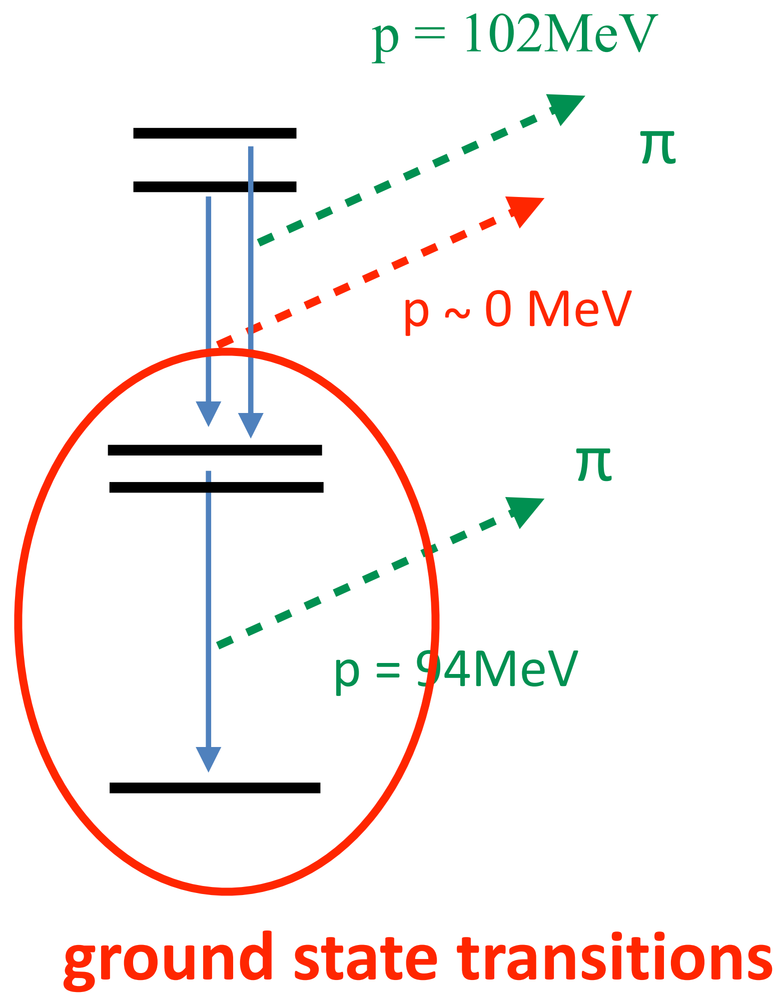
u↑ d↑ **c**

bad diquark

$\Lambda_c(2286, 1/2^+)$

u↑ d↓ **c**

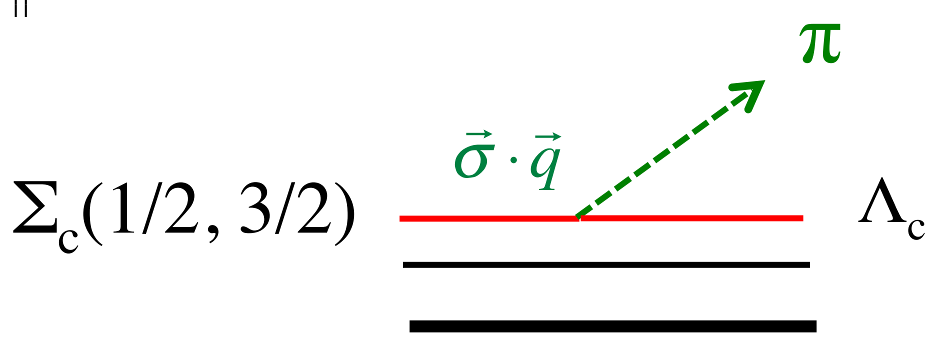
good diquark



Preliminary results

Ground (1/2, 3/2$^+$) –> Ground (1/2$^+$)

$B_i J^P$ (MeV)	$\Gamma^{\text{full}}_{\text{exp}}(\Gamma_i)$ (MeV)	q (MeV)	$\Gamma_{\text{th}}(\Sigma_c(J^+)^{++} \to \Lambda_c^{gs}(1/2^+;2286)^+\pi^+)$ (MeV)
$\Sigma_c(2455)\ 1/2^+$ (2453.98) ($\omega_\pi = 0$ limit)	$\boxed{2.26\ (2.26)}$ (2.26)	89	$\boxed{4.27\text{–}4.33}$
$\Sigma_c(2520)\ 3/2^+$ (2517.9) ($\omega_\pi = 0$ limit)	$\boxed{14.9\ (14.9)}$	176	$\boxed{30.0\text{–}31.2}$



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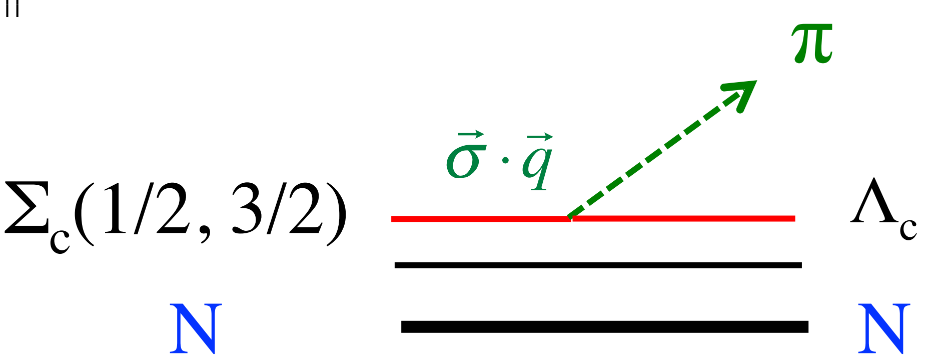
$$\boxed{g_A{}^q = 1 \ \longrightarrow\ g_A{}^N = 5/3}$$



First let us look at

Excite —> ground transitions

$\Lambda_c(2625, 3/2^-)$
$\Lambda_c(2595, 1/2^-)$

u↑ d↓ **c**

good diquark
in p-wave

$\Sigma_c(2520, 3/2^+)$
$\Sigma_c(2455, 1/2^+)$

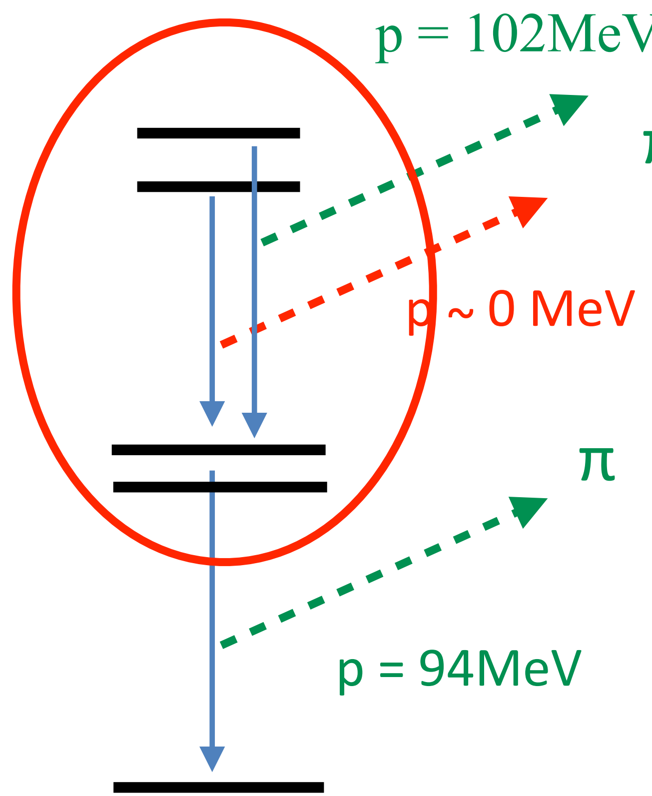
u↑ d↑ **c**

bad diquark

$\Lambda_c(2286, 1/2^+)$

u↑ d↓ **c**

good diquark



Preliminary results

P-wave excitation –> Ground ($1/2^+$)

$B_i J^P$ (MeV)	$\Gamma^{\rm full}_{\rm exp}$ (Γ_i) (MeV)	q (MeV/c)	$\Gamma_{\rm th}(\Lambda_c^*(J^-)^+ \to \Sigma_c^{gs}(2455; 1/2^+)^{++}\pi^-)$						
			λ-mode		ρ-mode				
			doublet		singlet	doublet		doublet	
			$1/2^-$	$3/2^-$	$1/2^-$	$1/2^-$	$3/2^-$	$3/2^-$	$5/2^-$
$\Lambda_c(2595)$ $1/2^-$ (2592.25)	$\boxed{2.6}$ (0.624)	π^- π^0 total	0.15-0.29 1.23–2.36 $\boxed{1.38\text{–}2.66}$		0	0.65–1.20 5.29–9.69 $\boxed{5.94\text{–}10.89}$			
$\Lambda_c(2625)$ $(3/2^-)$ (2628.11)	$\boxed{< 0.97}$ (0.0485)	101	5.4 –10.7	$\boxed{0.024 \\ -0.039}$	0	24.0 –45.1	$\boxed{0.013 \\ -0.019}$	0.023 –0.034	0.010 –0.015
				x 3			x 3		
$\Lambda_c(2765)$?$^?$ (2766.6)	50 (not seen)	263	20.4–46.7	2.6–3.9	0	107.8–224.0	1.4–1.9	2.5–3.4	1.1–1.5

Summary

- Heavy quarks identify and disentangle different modes of baryons, ρ and λ modes
- Productions are useful for structure study

    A similar feature with hyper nuclei
- Charm baryons could be abundantly produced
- Decays are useful to further understand the structure and fundamental nature of hadron physics = QCD