Ideas for heavy baryon at ILC

Kiyoshi Tanida

Japan Atomic Energy Agency

@ILCハドロン物理検討会

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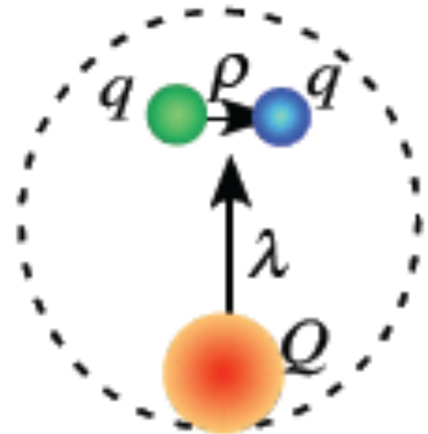
Introduction – Heavy quark baryons

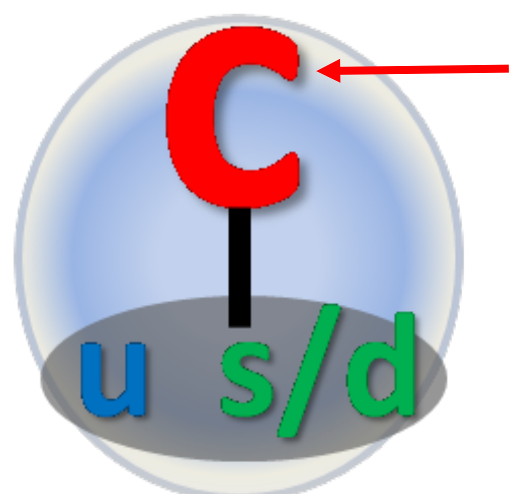
- Heavy quark in Baryon
  - Bare quark ≒ constituent quark
  - Makes a "static core", light quarks play around
    → Diquark correlation enhanced?
  - New symmetry – heavy quark symmetry
    → Hyperfine doublet for heavy quark spin.



Nucleon

Indistinguishable pairs

Charmed baryon



Light di-quark with inert charm?

HQ baryonの状況

- Charm baryon は全部で20～30個くらい知られている。
  - Λ_c/Σ_c、Ξ_cが10個ずつくらい
  - 最近LHCbがΩ_c共鳴を5個一気に見つけて、Ω_cは7つ。
- Bottom baryonは全部で10個程度
- Heavy quark (c,b)が2つ以上入ったバリオンはまだ見つかっていない。
- 励起エネルギー　< 400 MeV程度までは、クォークモデル（λモードのL=1励起）で良く理解できるが、それ以上の励起状態はうまく分類できていない
  - QMで複数の予想。そのどれでもなさそうに見えるものも。
  - エキゾチック状態はあるか？
  - スピン・パリティーの測定は必須だが、ほとんど決まっていない。

例: $\Lambda_c(2880)$

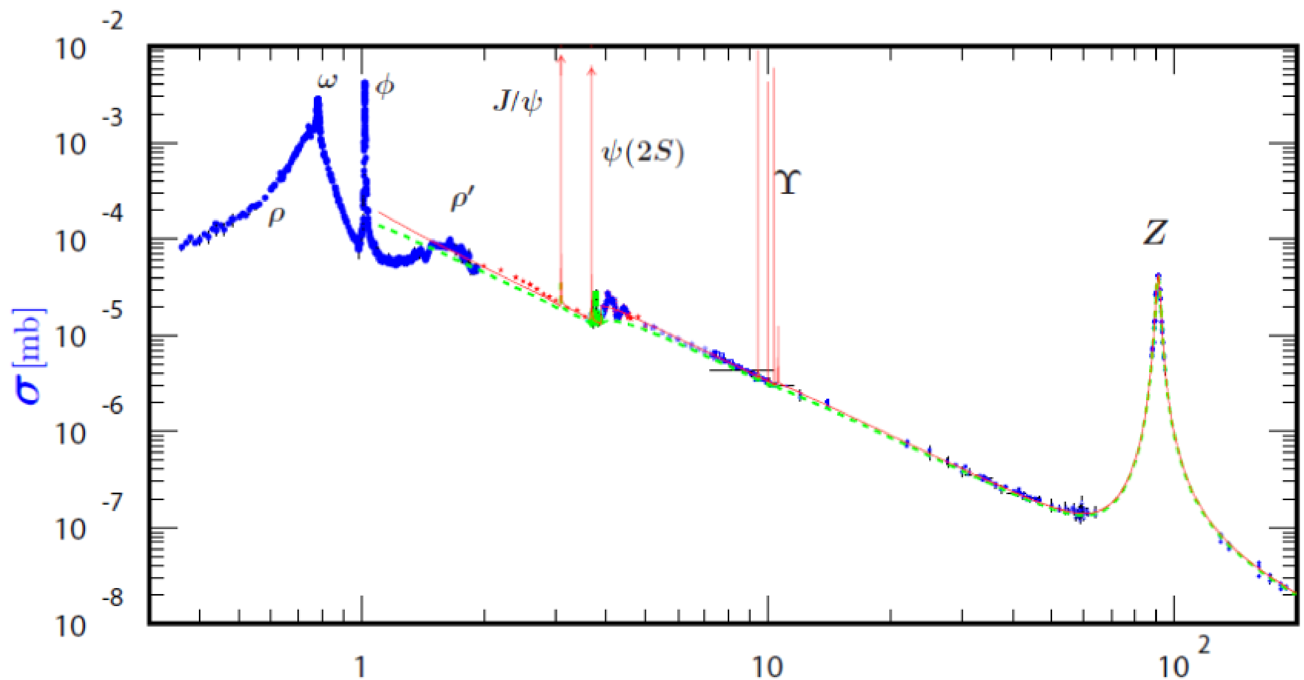
- Ex>400 MeVのHQバリオンで、唯一J^Pが決まっている例
  - 5/2$^+$ [Belle, PRL98 (2007) 262001]
- Quark Modelでは、5/2$^+$ならばL=2
  - つまり2$^+$のBrown-muck＋spin 1/2 (c) → 5/2$^+$, 3/2$^+$のダブレット
- すると、$\Lambda_c(2880) \to \Sigma_c\pi$, $\Sigma_c^*\pi$の分岐比をうまく説明できない

$$R = \frac{\Gamma(\Lambda_c^* \to \Sigma_c^* \pi)}{\Gamma(\Lambda_c^* \to \Sigma_c\ \pi)} = 0.225 \pm 0.062 \pm 0.025$$

  - 5/2$^+$ -> 3/2$^+$の崩壊はP波が可能なので、5/2$^+$->1/2$^+$の崩壊(F波)より圧倒的に大きくなくてはいけない。
    [Nagahiro et al., PRD 95.014023]
- 分岐比を説明するには、Brown-muck j^Pは3$^+$が必要
  - 今度はQMでの解釈が困難。

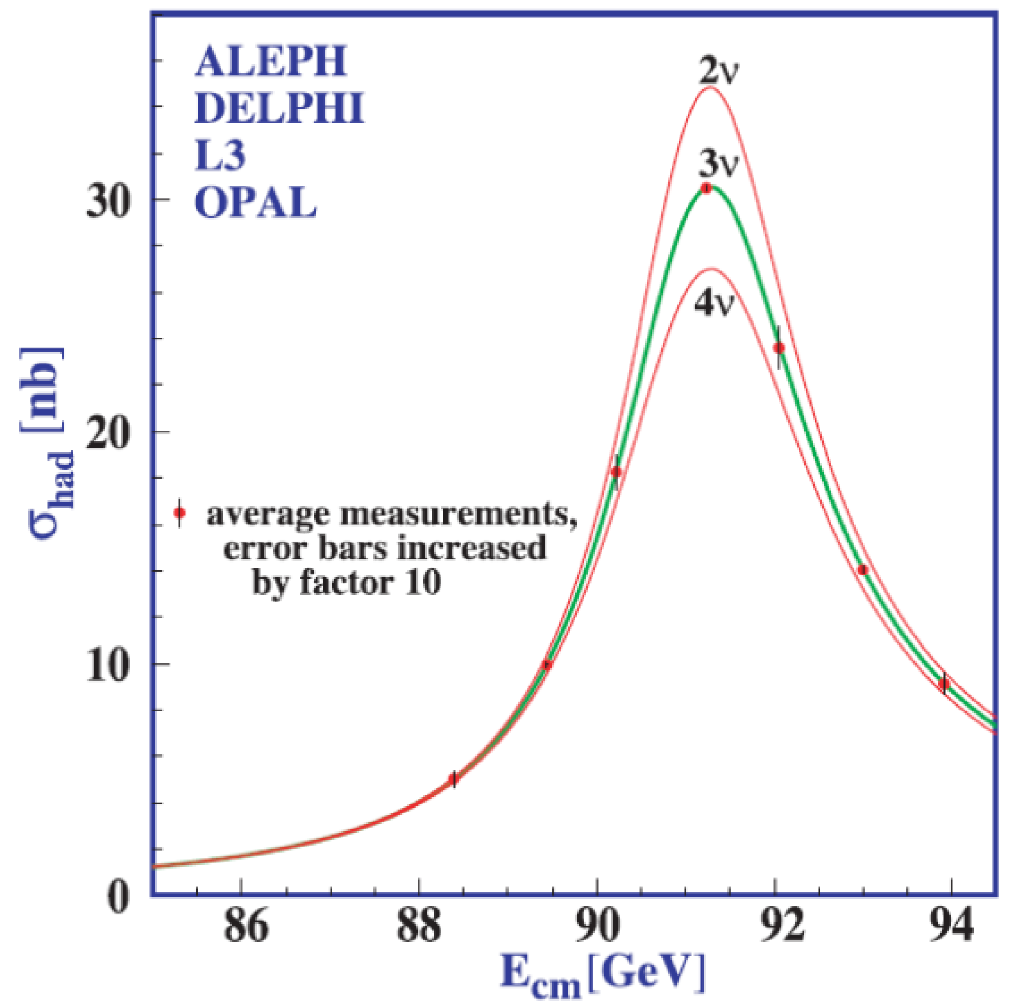
High energy e^+e^- collider

- Necessary for beauty baryons
  - Comparison with charm baryons
  - Finding heavy quark symmetry partners
- Statistics is the first issue
  - High luminosity x high cross section
- Best energy?
  - On Z mass
  - Large cross section



Statistics@√s=M_Z

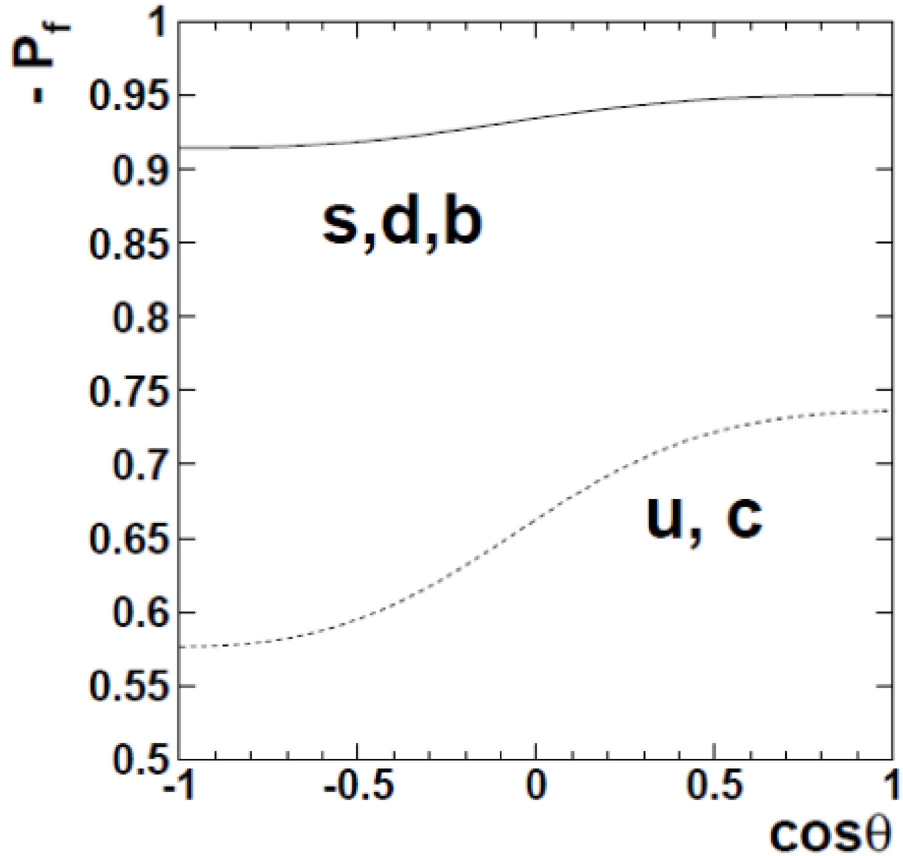
- Λ_b multiplicity: 3.1±1.6 per 100 hadron production events → Cross section: ~ 1nb
- For integrated luminosity of 1 ab^{-1} → 10^9 events
- 10^5 reconstructed events
- Similar level as Ξ_c at Belle
  - Enough statistics
  - Chance for exotics
  - Smaller statistics than LHC



Merit?

- So, what is good for ILC compared to LHC?
  1. Smaller backgrounds
     - Good for excited states
  2. Polarization
     - Produced b is > 90% polarized
     - Charm is also ~60% polarized

- Physics with polarization is possible.



Determination of parity

- Spin is rather easy to determine from e.g., decay angle distribution, but parity is difficult
- Why?
  - For the case J → 1/2 + 0 (e.g., Y → $\Lambda+\pi$), different parity gives exactly the same decay distribution
  - E.g., for J=3/2, the decay is either P-wave (λ=1) or D-wave (λ=2) (for parity conserving case), so the problem is to determine λ.
  - However…

Example distribution

3/2 → 1/2 + 0

- λ=1 (P-wave)

  J_z=3/2 → J_z'=1/2: m=ΔJ_z=1

  $$W(\theta,\varphi) \propto |Y_{11}|^2 \propto \sin^2\theta$$

  J_z=1/2 → J_z'=1/2, -1/2: m=ΔJ_z=0,1 (weight by C-G coefficient)

  $$W(\theta,\varphi) \propto \frac{2}{3}|Y_{10}|^2 + \frac{1}{3}|Y_{11}|^2 \propto 3\cos^2\theta + 1$$

- λ=2 (D-wave)

  J_z=3/2 → J_z'=±1/2: m=ΔJ_z=1,2

  $$W(\theta,\varphi) \propto \frac{1}{5}|Y_{21}|^2 + \frac{4}{5}|Y_{22}|^2 \propto \sin^2\theta$$

  J_z=1/2 → J_z'=±1/2: m=ΔJ_z=0,1

  $$W(\theta,\varphi) \propto \frac{2}{5}|Y_{20}|^2 + \frac{3}{5}|Y_{21}|^2 \propto 3\cos^2\theta + 1$$

Generally, λ cannot be distinguished

Determination of parity

- Spin is rather easy to determine from e.g., decay angle distribution, but parity is difficult
- Why?
  - For the case J → 1/2 + 0 (e.g., Y → $\Lambda+\pi$), different parity gives exactly the same decay distribution
  - E.g., for J=3/2, the decay is either P-wave (λ=1) or D-wave (λ=2) (for parity conserving case), so the problem is to determine λ.

- One more information is necessary
  → Polarization is most powerful
  - Model independent

Example: Spin 1/2 case

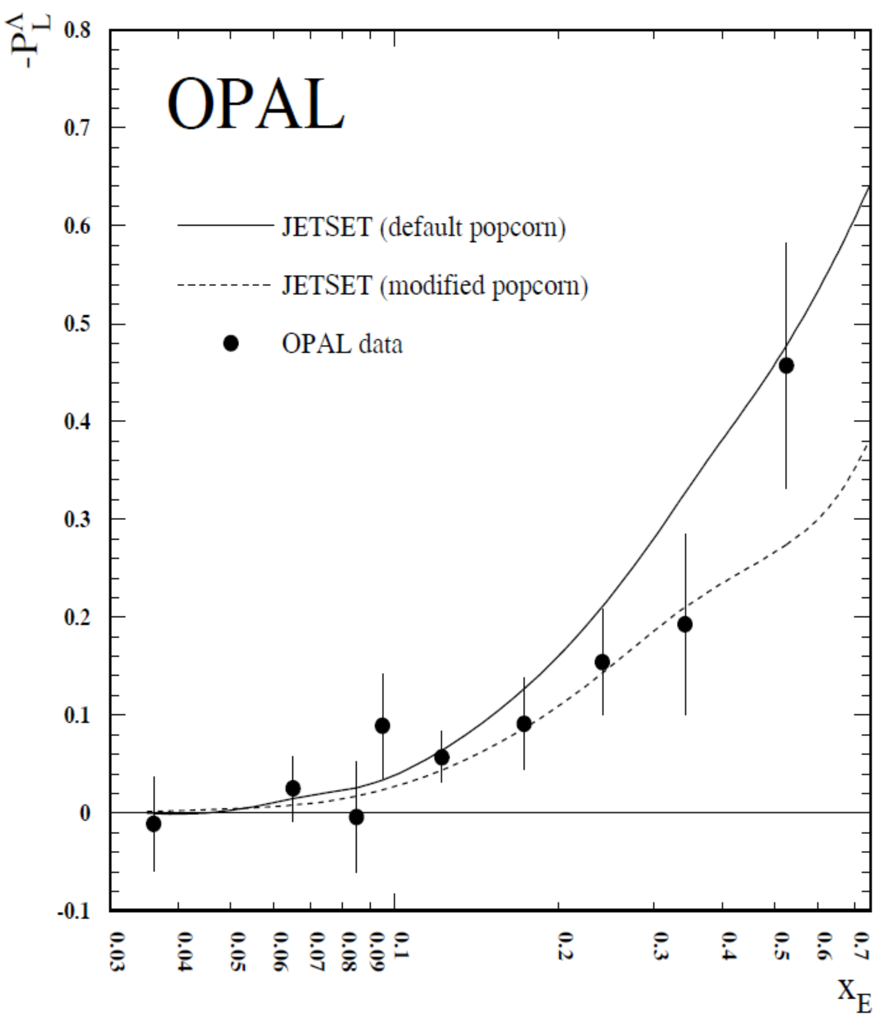
- Ex: $\Sigma_c \rightarrow \Lambda_c + \pi$ ($1/2^? \rightarrow 1/2^+ + 0^-$)
  - S-wave decay (P= −):
    $\overrightarrow{P_{\Lambda_c}} = \overrightarrow{P_{\Sigma_c}}$, independent of decay angle
  - P-wave decay (P=+):
    $\overrightarrow{P_{\Lambda_c}} = P_{\Sigma_c} \cdot \hat{n}(2\theta)$, depends on decay angle
    (note: $\langle \overrightarrow{P_{\Lambda_c}} \rangle = 0$ for this case, so feed down correction to Λ_c polarization is straightforward)
- In case of Σ_c, $P_{\Sigma c} = -\frac{1}{3} P_c \sim 0.2$ is expected from QM
  - $\delta P < 0.01 \rightarrow$ determination of Σ_c parity is possible!
  - Higher excited states, too.

Spin structure study from polarization

- Helicity PDF: Δq, Δg
  → distribution of (longitudinally) polarized parton in a baryon.
- Analog in fragmentation: polarization transfer
  – Polarized quark → polarized baryon
  – Also reflects quark helicity structure
  – The fragmentation polarization transfer factor is equal to the fraction of spin carried by the f-flavor-quark divided by the average number of quark of flavor f in the hyperon
  – First suggested by Augustin and Renard in 1979
- Longitudinal polarization in weak decays
  – Quark polarization: reliably calculable
  – Baryon polarization: measurable

Past measurements (1) -- LEP

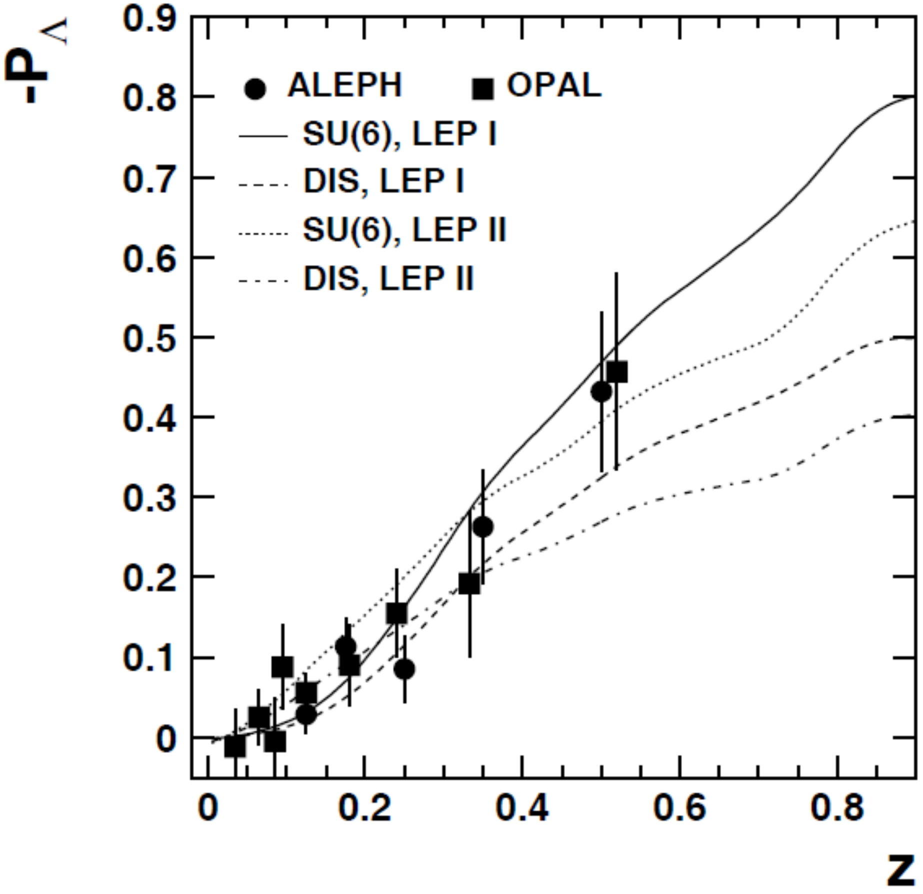
- OPAL and ALEPH measured Λ polarization in Z^0 decay
  - $Z^0 \rightarrow$ s: polarized by -0.94
  - Contamination by ss-bar pair creation during fragmentation
    $\rightarrow$ treated in simulation, with sizable uncertainty
  - Consistent with quark model within the uncertainty



Another analysis

- By Liu and Liang (arXiv:hep-ph/0005172v1)
  - Quark model (SU(6)) vs DIS + Hyperon-β + $SU_f(3)$
  - QM is favored, but uncertainty in pair creation is not taken into account

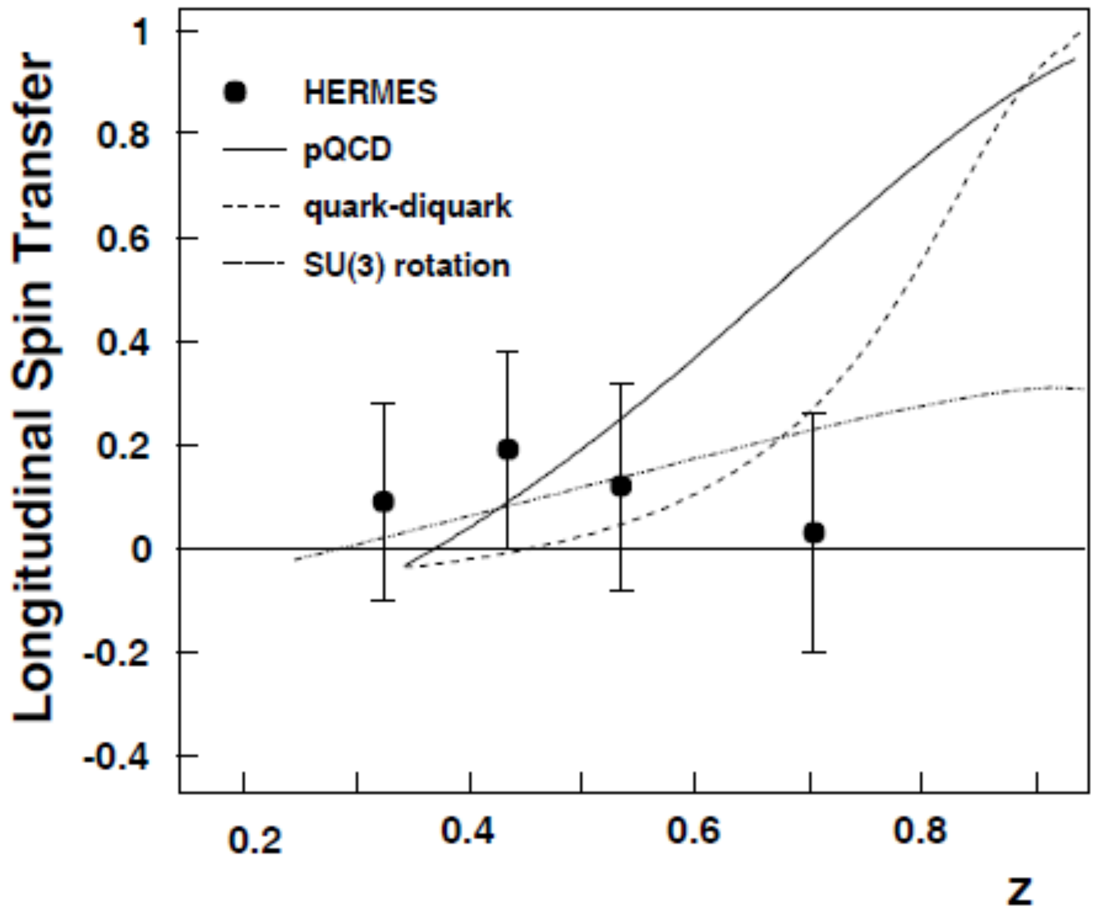
	Λ		
		$SU(6)$	DIS
ΔU	$\frac{1}{3}(\Sigma - D)$	0	-0.17
ΔD	$\frac{1}{3}(\Sigma - D)$	0	-0.17
ΔS	$\frac{1}{3}(\Sigma + 2D)$	1	0.62



Past measurements (2) -- DIS

- Example in HERMES: polarization transfer from beam positron to Λ. [PRD 74 (2006) 072004]
- Initially, u&d quarks dominate, and the result is not unexpected

Interpretation is limited by fragmentation uncertainty



So, what can we do?

- Problem: Λ can be produced from u/d quark
  → Uncertainty for dilution
- This problem does not appear in heavier quarks

↓

Proposed measurement:
Polarization of charmed/bottom baryons, especially Λ_c/Λ_b

Polarization measurements

- Using decay asymmetries in $\Lambda_b \rightarrow \Lambda_c + \pi^-$ ($\Lambda_c \rightarrow \Lambda + \pi^+$)
  - $W(\theta)=1+P\alpha\cos\theta$
  - Examples:
    $\Lambda_b \rightarrow \Lambda + J/\psi$: $\alpha = 0.18 \pm 0.13$, BR～0.03%(?)
    $\Lambda_c \rightarrow \Lambda + \pi$: $\alpha = -0.91 \pm 0.15$, BR～2%
    $\Lambda_c \rightarrow \Lambda + e,\mu + \nu$: $\alpha = -0.86 \pm 0.04$, BR～3% each
  - Can be better determined ← Should be measured first
- δP~0.01 would be possible with 10^5 reconstructed events

Comparison with model calculation

- To what extent can we distinguish models?
  - In QM, $P_{\Lambda b}=P_b\sim-0.9$
  - $\delta P_{\Lambda b}\sim0.01$ gives $\delta\Delta C\sim0.01$
  - Easy to distinguish $\Delta C\sim1$ and $\Delta C\sim0.6$

	Λ		
		$SU(6)$	DIS
ΔU	$\frac{1}{3}(\Sigma - D)$	0	-0.17
ΔD	$\frac{1}{3}(\Sigma - D)$	0	-0.17
ΔS	$\frac{1}{3}(\Sigma + 2D)$	1	0.62

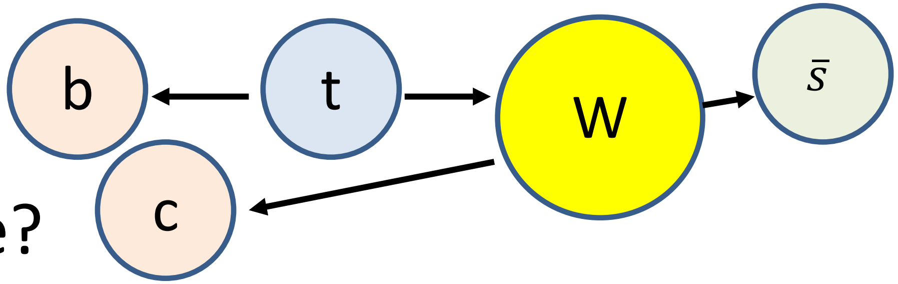
- Theoretically, heavy quark symmetry supports QM
- Note: contributions from higher resonances, such as Σ_b, should be taken into account.
  - Such contributions (on yields) are measurable
  - Polarizations of such excited baryons should be modeled, too.

Yet another possibility

- Polarization can be measured for excited baryons
  - Can be used to study baryon structure
- For example, Λ_c(2593) may be
  1. A three quark state of spin-0 diquark + c with relative L=1 (QM + Heavy quark symmetry)
  2. A bound state of DN (Hyodo et al.)
  3. ...
  - If 1. is the case, $\mathrm{P} = -\frac{1}{3} P_c$
  - If 2., $\mathrm{P} = 0$
- Would be a powerful tool to identify exotic baryons

Double HQ baryon from top

- In ILC energy, top can be also produced
- Top itself does not make a baryon, but…
- Top decay: $t \rightarrow b + W \rightarrow b + c + \bar{s}$
  → Two heavy quarks are produced (spatially) nearby



- How near in momentum space?
  - When b and c are going to the same direction
    $p_b \sim 67$ GeV/c, $p_c \sim 19$ GeV/c: $y_b \sim y_c \sim 3.4$
- There is a chance to stick and make Ξ_{bc}

Summary

- Rich possibility in ILC
- $\sqrt{s}=m_Z$ is the best energy for b-baryon spectroscopy
  - Up to $O(10^5)$ reconstructed events expected
  - Very high polarization.
- Polarization transfer from longitudinally polarized quark to baryon ⇔ helicity contribution of quark in baryon
- Baryon polarization can be further used for other studies
  - Parity determination
  - Exotic search
- Chance for Ξ_{bc} in top decay?

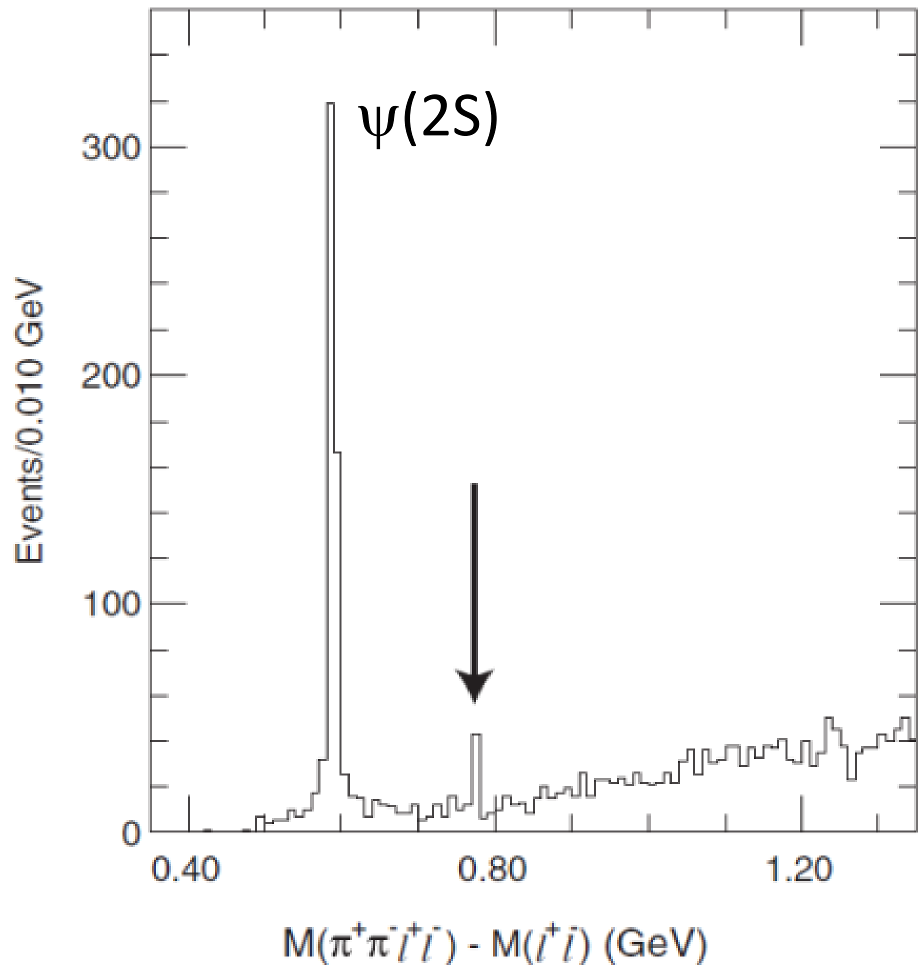
Backup

エキゾチックハドロン

- 単純なクォーク模型で記述できないハドロン
  - Non-$q\bar{q}$ メソン、Non-qqq バリオン
- 閉じ込めはカラー白色だけを要求。必ずしも上の組み合わせ以外でもいい。
- どんなものがありえる？
  - ハドロンの束縛（分子）状態：MM、MB、・・・
  - クォークの数が違う：$qq\bar{q}\bar{q}$、$qqqq\bar{q}$、・・・
  - グルーオン自由度：$q\bar{q}g$、グルーボール、・・・
- 20世紀中には、確実なものは2例だけ。
  - $J^{PC}=1^{-+}$のメソンは$q\bar{q}$で書けない。
  - 候補は沢山
- 最近、チャームやボトムで新発見が相次いでいる

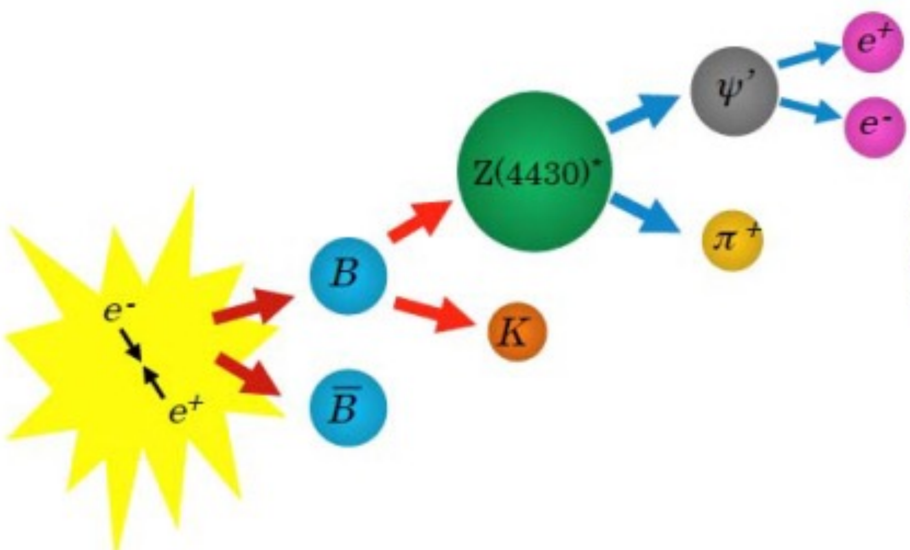
X(3872)

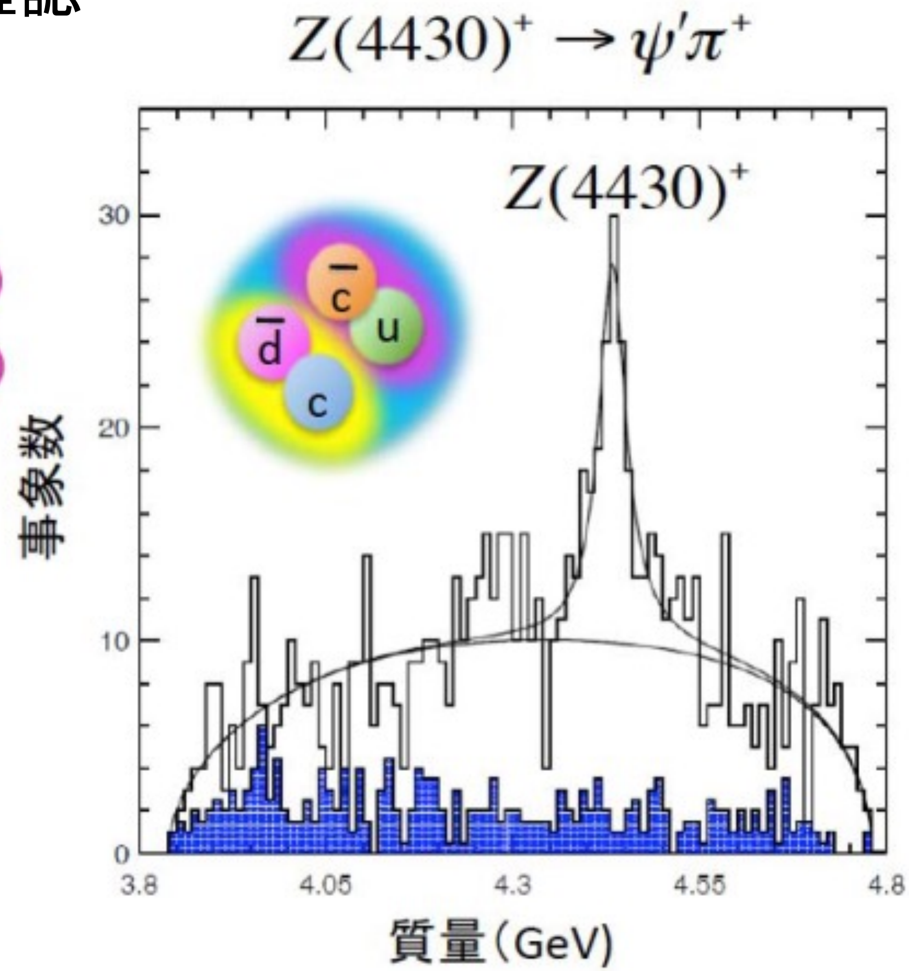
- 通常、$D\overline{D}$より重いチャーモニウムは広い幅を持つ
- が、この粒子の幅は狭い（<1.2 MeV）
- ちょうど$D^*\overline{D}$の真上 (3±200 keV)
- Belleが発見、他の多くの実験でも観測
- J^{PC}は1^{++}と決定（LHCbによる）
- $D^*\overline{D}$の分子的状態と$c\bar{c}$チャーモニウムの混合状態という説が有力



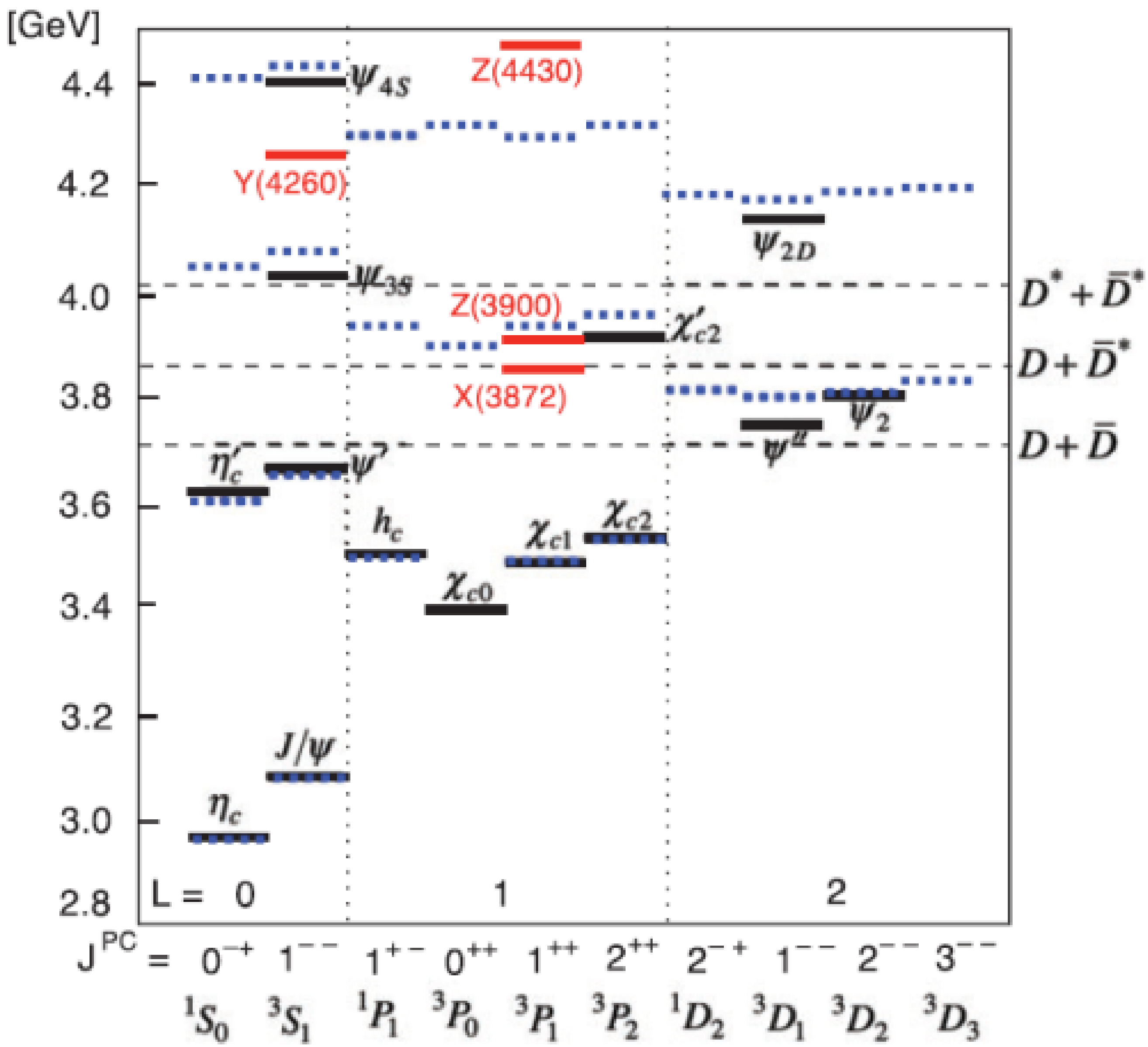
Z(4430)$^+$

- 電荷を持つチャーモニウム！
  - 最低でも $c\bar{c}u\bar{d}$ という構成が必要
  - Belleが発見、LHCbによる確認



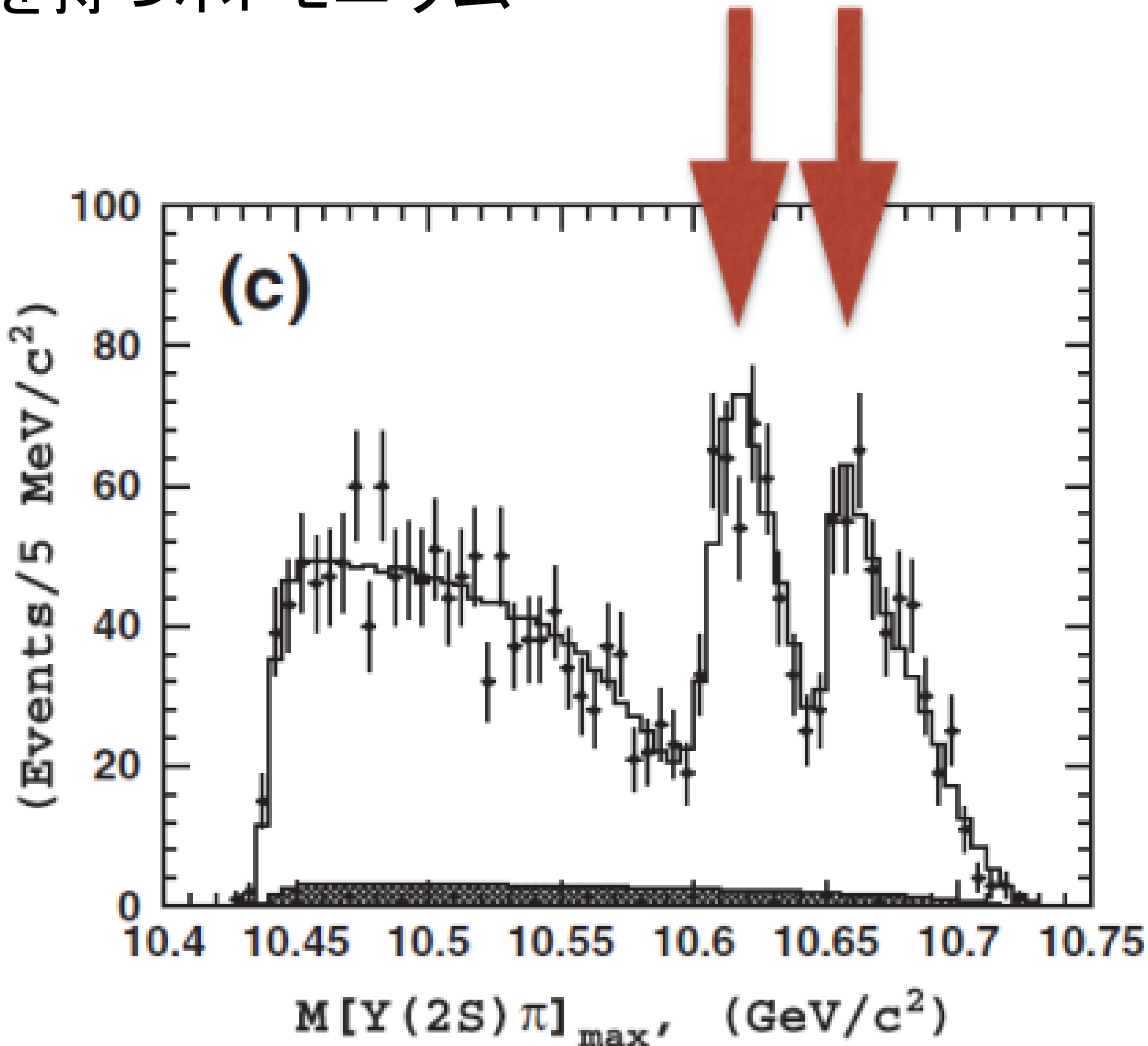


エキゾチックなチャーモニウム



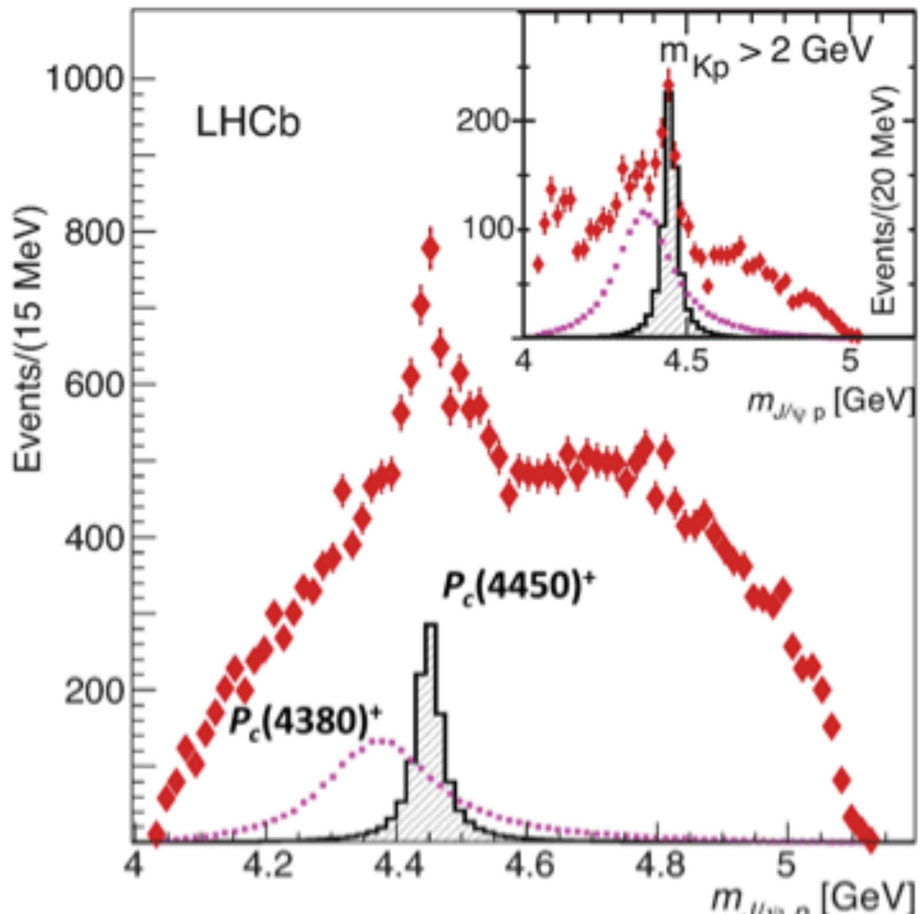
ボトムでも

- $Z_b(10610)$、$Z_b(10650)$の発見（Belle）
  - 電荷を持つボトモニウム



バリオンでは

- ペンタクウォークP_cの発見（LHCb）
  - $\Lambda_b \to J/\psi\ p\ K^-$ で、$J/\psi\ p$の不変質量にピーク
  - $P_c(4450)$ははっきり見えるが、$P_c(4380)$はピークには見えない
- どんな状態？
  議論はこれから



フレーバーハドロン物理？

- 強い相互作用はフレーバーによらないはず。
- なのにチャーム、ボトムでエキゾチックハドロンの新発見が相次ぐのはなぜ？
  → QCDはエネルギーによって、多様な顔を見せる
- 重いクォークでエキゾチックができやすい（見えやすい）理由として：
  – 単純に質量が大きく、運動エネルギーが小さい
  – 相互作用が弱く、崩壊幅が狭くなりやすい
    OZI rule, Heavy quark symmetry
  – ・・・

OZI rule

- 重いクォーク-反クォーク対は消えにくい
  - もちろん、逆に生成しにくい
- 例: φ メソンは1040 MeVの質量を持ち、同じ量子数（$J^P=1^-$）のω(780)より260MeVも重い
  - 幅はωの半分しかない
  - しかも崩壊モードは$K\bar{K}$がメイン（Q=50 MeV）
  - ω/φ → 3π の部分幅は大体10倍違う
  - φが$s\bar{s}$の構造を持つとして理解されている
- J/ψやΥではさらにこの傾向が顕著
  - η_cやη_bはこれほど細くないが、それでも10-30 MeV程度

Heavy Quark Symmetry

- 重いクォークのスピンは、近似的に保存量になる

$$\mathcal{L}_{\rm HQ} = \bar{Q}(i\not{D} - m_{\rm Q})Q$$

$$Q_v(x) = e^{im_Q v\cdot x}\frac{1+\not{v}}{2}Q(x)$$

$$\mathcal{L}_{\rm HQET} = \bar{Q}_v v\cdot iDQ_v + \bar{Q}_v\frac{(iD_\perp)^2}{2m_Q}Q_v - c(\mu)g_s\bar{Q}_v\frac{\sigma_{\mu\nu}G^{\mu\nu}}{4m_Q}Q_v + \mathcal{O}(1/m_Q^2)$$

- $J = j + S_Q$なので、残り部分の角運動量 j も保存
  - Brown-muck
  - $J = j \pm 1/2$ という2重項ができる
    → Hyperfine splittingのようなもの。Heavy quark doublet
- 重いクォークのスピンが反転するような崩壊は起きにくい
  - h_cはJ/ψに壊れず、η_cに壊れる

さらなる発見は？

- むしろまだ始まったばかり
- どこに何が潜んでいるかわからない楽しみ
- 発見されたエキゾチックハドロンの本質についてもこれからの議論
  - 本当に共鳴状態なのか、すらはっきりしていない

ハドロン物理の大航海時代

Ex: comparison of Ξ_c and Λ_c/Σ_c

J^p	Λ_c^+	Ξ_c	ΔM(Mev/c²)	Note
$1/2^+$	$\Lambda_c(2286)^+$	$\Xi_c(2470)$	181	
$1/2^+$	$\Sigma_c(2455)$	$\Xi'_c(2580)$	125	
$3/2^+$	$\Sigma^*_c(2520)$	$\Xi^*_c(2645)$	125	
$1/2^-$	$\Lambda_c(2595)^+$	$\Xi_c(2790)$	194	Λ(1405) like
$3/2^-$	$\Lambda_c(2625)^+$	$\Xi_c(2815)$	188	Λ(1520) like
??	$\Lambda_c(2765)^{+?}$	$\Xi_c(2980)$??	215	
??	$\Sigma_c(2800)$	$\Xi_c(3055)$??	255	
$5/2^+$	$\Lambda_c(2880)^+$	$\Xi_c(3080)$??	200	
??	$\Lambda_c(2940)^+$	$\Xi_c(3123)$??	180	

- Which corresponds to which??
  → Measurements allow systematic discussions

Analog state of $\Lambda_c(2880)$?

- Mass difference of low-lying Ξ_c and Λ_c ~ 200 MeV
  → $\Xi_c(3080)$ is the analog of $\Lambda_c(2880)$??
- Branching ratio for $\Lambda_c(2880)$ [Belle, PRL98 (2007) 262001]
  $$B(\Lambda_c^* \to \Sigma_c^* \pi)/B(\Lambda_c^* \to \Sigma_c\ \pi) = 0.225 \pm 0.062 \pm 0.025$$
- The ratio is much larger for $\Xi_c(3080)$ [Belle, PRD**94**, 032002 (2016)]
  $$B(\Xi_c(3080)^+ \to \Sigma_c^{*++} K^-)/B(\Sigma_c^{++} K^-) = 1.27 \pm 0.27 \pm 0.01$$
  - Must be similar (or even smaller for phase space) for analog states if HQS holds.
  - They are not analog?

Analog state of $\Lambda_c(2880)$? (cont.)

$B(\Xi_c \to \Sigma_c^{*++}K^-)/B(\Sigma_c^{++}K^-)$ is small for $\Xi_c(3055)$

→ This may be the analog state of $\Lambda_c(2880)$

Belle, PRD 89, 052003