Heavy quark spectroscopy and prediction of bottom baryon masses

Marek Karliner

BEACH’08, Columbia SC, June 23, 2008

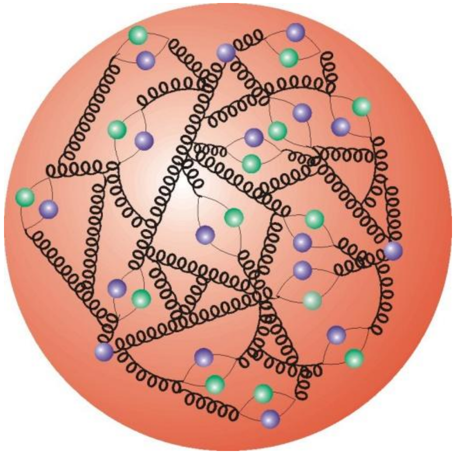
in collaboration with B. Keren-Zur, H.J. Lipkin and J. Rosner

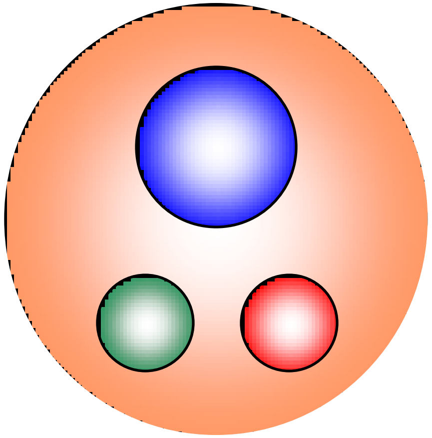
Constituent Quark Models (CQM)

- QCD describes hadrons as valence quarks in a sea of gluons and q-qbar pairs.
- at low E, χSB
- → quark constituent mass
- hadron can be considered as a bound state of constituent quarks.
- Sakharov-Zeldovich formula:

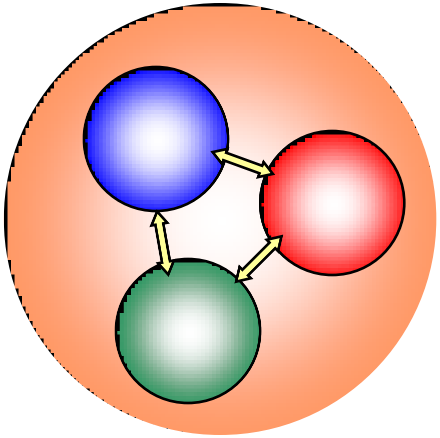
$$M = \sum_i m_i$$

- the binding & kinetic energies "swallowed" by the constituent quarks masses.





Color Hyperfine (HF) interaction



- 1st correction – color hyperfine (chromo-magnetic) interaction

$$M = \sum_i m_i + \sum_{i<j} V^{HF}{}_{ij}$$

$$V^{HF(QCD)}{}_{ij} = v_0 \left(\vec{\lambda}_i \cdot \vec{\lambda}_j\right) \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i m_j} \langle \psi | \delta(r_i - r_j) | \psi \rangle$$

  - A contact interaction
  - Analogous to the EM hyperfine interaction – a product of the magnetic moments.

$$V^{HF(em)}{}_{ij} \propto \vec{\mu}_i \cdot \vec{\mu}_j = e^2 \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i m_j}$$

  - In QCD, SU(3) generators take the place of the electric charge.

Constituent Quark Model: *caveat emptor*

- a low energy limit, phenomenological model
- still awaiting derivation from QCD
- far from providing a full explanation of the hadronic spectrum, but it provides excellent predictions for mass splittings and magnetic moments
- assumptions:
  - HF interaction considered as a perturbation
  - → does not change the wave function
  - same masses for quarks inside mesons and baryons.
  - no 3-body effects.

constituent quark masses

- example I:
  quark mass differences from baryon mass differences:

$$
\begin{aligned}
&M_{\Lambda_c} - M_{\Lambda} = \\
&= \left(\cancel{m_u} + \cancel{m_d} + m_c + \cancel{V^{HF}{}_{ud}} + V^{HF}{}_{uc} + V^{HF}{}_{dc}\right) - \\
&- \left(\cancel{m_u} + \cancel{m_d} + m_s + \cancel{V^{HF}{}_{ud}} + V^{HF}{}_{us} + V^{HF}{}_{ds}\right) = \\
&= m_c - m_s
\end{aligned}
$$

$$= 0$$

constituent quark masses

- example II:

$$M_{K^*} - M_K = v_0 \frac{\left(\vec{\lambda}_u \cdot \vec{\lambda}_{\bar{s}}\right)}{m_u m_s} \left[\left(\vec{\sigma}_u \cdot \vec{\sigma}_{\bar{s}}\right)_{K^*} - \left(\vec{\sigma}_u \cdot \vec{\sigma}_{\bar{s}}\right)_K \right] \left\langle \psi \middle| \delta(r) \middle| \psi \right\rangle$$

$$= 4 v_0 \frac{\left(\vec{\lambda}_u \cdot \vec{\lambda}_{\bar{s}}\right)}{m_u m_s} \left\langle \psi \middle| \delta(r) \middle| \psi \right\rangle$$

- extracting quark masses ratio:

$$\frac{M_{K^*} - M_K}{M_{D^*} - M_D} = \frac{4 v_0 \frac{\left(\vec{\lambda}_u \cdot \vec{\lambda}_{\bar{s}}\right)}{m_u m_s} \left\langle \psi \middle| \delta(r) \middle| \psi \right\rangle}{4 v_0 \frac{\left(\vec{\lambda}_u \cdot \vec{\lambda}_{\bar{c}}\right)}{m_u m_c} \left\langle \psi \middle| \delta(r) \middle| \psi \right\rangle} \approx \frac{m_c}{m_s}$$

quark mass difference is the same

in mesons and baryons

$$\langle m_i - m_j \rangle_{dBar} \approx \langle m_i - m_j \rangle_{dMes}$$

but depends on the spectator quark

→ **challenge to npQCD**

MK & Lipkin, hep-ph/0307243

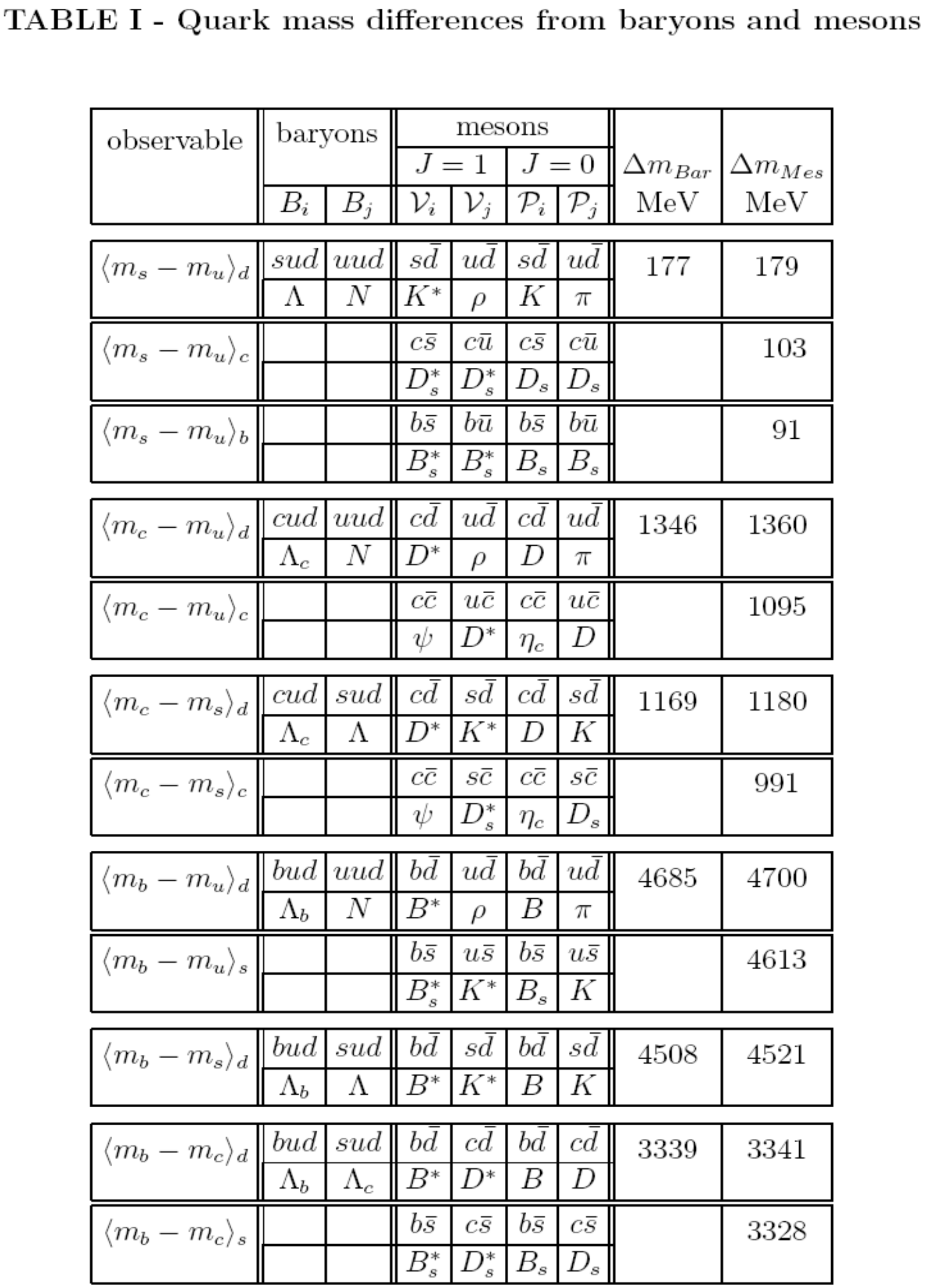
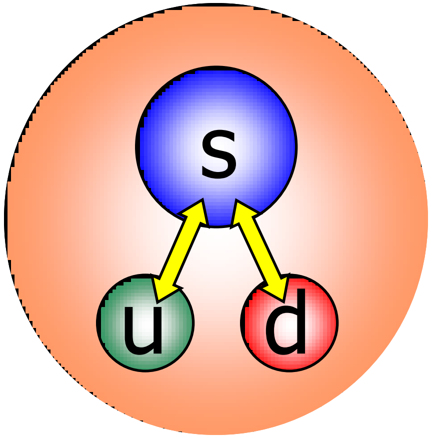


TABLE I - Quark mass differences from baryons and mesons

observable	baryons		mesons				Δm_{Bar} MeV	Δm_{Mes} MeV
			$J=1$		$J=0$			
	B_i	B_j	$\mathcal{V}_i$	$\mathcal{V}_j$	$\mathcal{P}_i$	$\mathcal{P}_j$		
$\langle m_s - m_u \rangle_d$	sud	uud	$s\bar{d}$	$u\bar{d}$	$s\bar{d}$	$u\bar{d}$	177	179
	Λ	N	K^*	ρ	K	π		
$\langle m_s - m_u \rangle_c$			$c\bar{s}$	$c\bar{u}$	$c\bar{s}$	$c\bar{u}$		103
			D_s^*	D_s^*	D_s	D_s		
$\langle m_s - m_u \rangle_b$			$b\bar{s}$	$b\bar{u}$	$b\bar{s}$	$b\bar{u}$		91
			B_s^*	B_s^*	B_s	B_s		
$\langle m_c - m_u \rangle_d$	cud	uud	$c\bar{d}$	$u\bar{d}$	$c\bar{d}$	$u\bar{d}$	1346	1360
	Λ_c	N	D^*	ρ	D	π		
$\langle m_c - m_u \rangle_c$			$c\bar{c}$	$u\bar{c}$	$c\bar{c}$	$u\bar{c}$		1095
			ψ	D^*	η_c	D		
$\langle m_c - m_s \rangle_d$	cud	sud	$c\bar{d}$	$s\bar{d}$	$c\bar{d}$	$s\bar{d}$	1169	1180
	Λ_c	Λ	D^*	K^*	D	K		
$\langle m_c - m_s \rangle_c$			$c\bar{c}$	$s\bar{c}$	$c\bar{c}$	$s\bar{c}$		991
			ψ	D_s^*	η_c	D_s		
$\langle m_b - m_u \rangle_d$	bud	uud	$b\bar{d}$	$u\bar{d}$	$b\bar{d}$	$u\bar{d}$	4685	4700
	Λ_b	N	B^*	ρ	B	π		
$\langle m_b - m_u \rangle_s$			$b\bar{s}$	$u\bar{s}$	$b\bar{s}$	$u\bar{s}$		4613
			B_s^*	K^*	B_s	K		
$\langle m_b - m_s \rangle_d$	bud	sud	$b\bar{d}$	$s\bar{d}$	$b\bar{d}$	$s\bar{d}$	4508	4521
	Λ_b	Λ	B^*	K^*	B	K		
$\langle m_b - m_c \rangle_d$	bud	sud	$b\bar{d}$	$c\bar{d}$	$b\bar{d}$	$c\bar{d}$	3339	3341
	Λ_b	Λ_c	B^*	D^*	B	D		
$\langle m_b - m_c \rangle_s$			$b\bar{s}$	$c\bar{s}$	$b\bar{s}$	$c\bar{s}$		3328
			B_s^*	D_s^*	B_s	D_s		

color hyperfine splitting in baryons

- The Σ (uds) baryon HF splitting:
  - Σ*: total spin 3/2 -
    u and d at relative spin – 1
  - Σ : isospin – 1
    - Symmetric under exchange of u and d
    - u and d at relative spin – 1



$$\left(\vec{\sigma}_u \cdot \vec{\sigma}_d\right)_{\Sigma^*} = \left(\vec{\sigma}_u \cdot \vec{\sigma}_d\right)_{\Sigma}$$

- the ‘ud’ pair does not contribute to the HF splitting

$$M_{\Sigma^*} - M_{\Sigma} = 6v_0 \frac{\left(\vec{\lambda}_u \cdot \vec{\lambda}_s\right)}{m_u m_s} \langle \psi | \delta\left(r_{ij}\right) | \psi \rangle$$

Quark mass ratio from HF splittings in mesons and baryons

$$\left(\frac{m_c}{m_s}\right)_{Bar} = \frac{M_{\Sigma^*} - M_\Sigma}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 2.84 = \left(\frac{m_c}{m_s}\right)_{Mes} = \frac{M_{K^*} - M_K}{M_{D^*} - M_D} = 2.81$$

$$\left(\frac{m_c}{m_u}\right)_{Bar} = \frac{M_\Delta - M_p}{M_{\Sigma_c^*} - M_{\Sigma_c}} = 4.36 = \left(\frac{m_c}{m_u}\right)_{Mes} = \frac{M_\rho - M_\pi}{M_{D^*} - M_D} = 4.46$$

New type of mass relations with more heavy flavors

$$\left(\frac{\frac{1}{m_u^2} - \frac{1}{m_u m_c}}{\frac{1}{m_u^2} - \frac{1}{m_u m_s}}\right)_{Bar} = \frac{M_{\Sigma_c} - M_{\Lambda_c}}{M_\Sigma - M_\Lambda} = 2.16 \approx \left(\frac{\frac{1}{m_u^2} - \frac{1}{m_u m_c}}{\frac{1}{m_u^2} - \frac{1}{m_u m_s}}\right)_{Mes} = \frac{(M_\rho - M_\pi) - (M_{D^*} - M_D)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.10$$

Similar relation for bottom baryons → prediction for Σ_b mass

$$\frac{M_{\Sigma_b} - M_{\Lambda_b}}{M_\Sigma - M_\Lambda} = \frac{(M_\rho - M_\pi) - (M_{B^*} - M_B)}{(M_\rho - M_\pi) - (M_{K^*} - M_K)} = 2.51$$

→ $$\boxed{M_{\Sigma_b} - M_{\Lambda_b} = 194\,\mathrm{MeV}}$$

(MK & Lipkin, hep-ph/0307243)

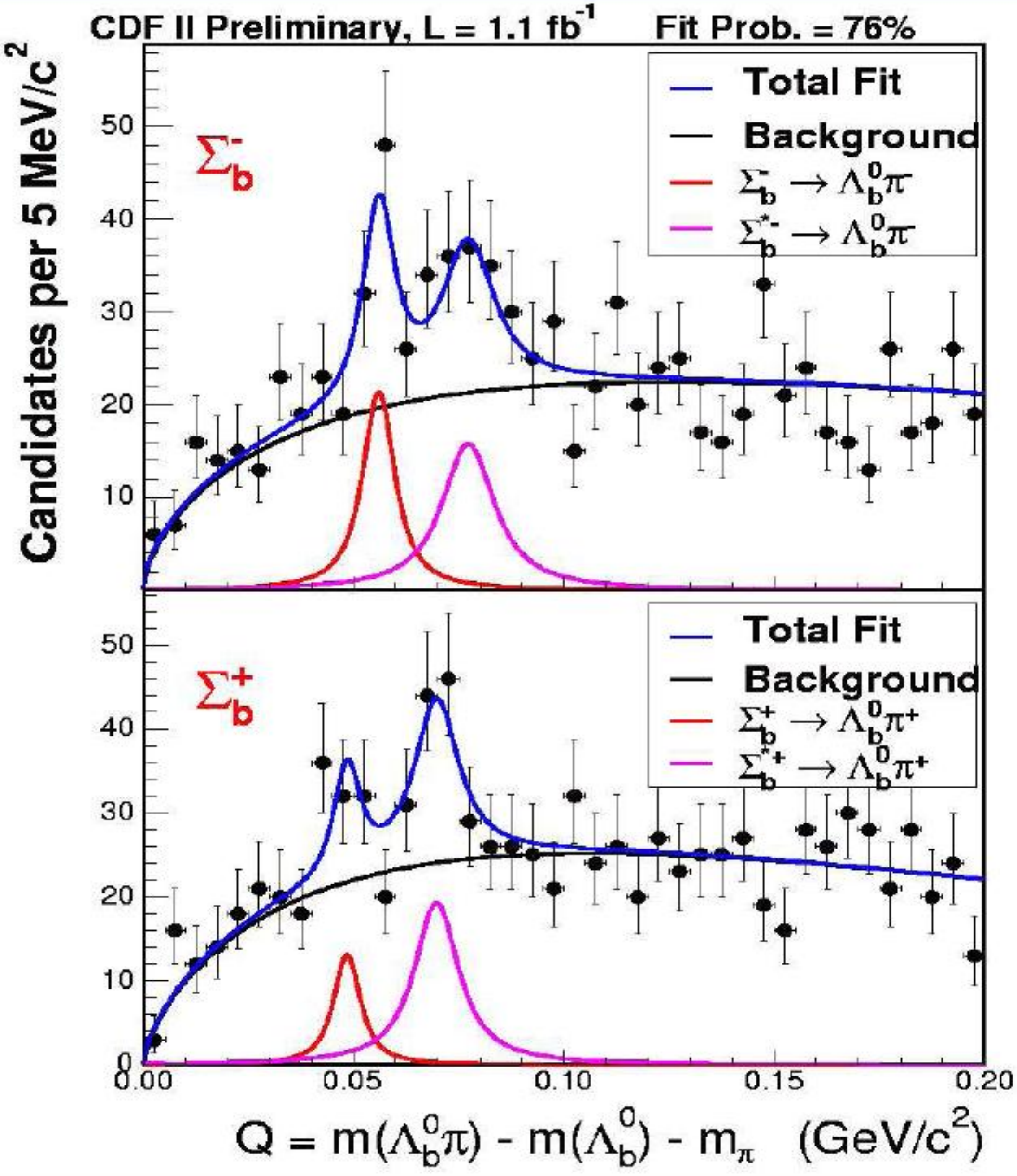
Observation of New Heavy Baryon Σ_b and Σ_b^*

This web page summarizes the results of the search for new heavy baryons Σ_b and Σ_b^* based upon $1fb^{-1}$ of data. The results have been approved as of September 21, 2006. The ratio of likelihoods of the null-hypothesis (no $\Sigma_b^{(*)\pm}$ signal) and the hypothesis of four $\Sigma_b^{(*)\pm}$ states is 2.6×10^{-19}. Using the fully reconstructed decay mode

$$\Sigma_b^{(*)\pm} \rightarrow \Lambda_b^0 \pi^\pm; \quad \Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-; \quad \Lambda_c^+ \rightarrow p K^- \pi^+$$

we measure:

- $m(\Sigma_b^+) = 5808^{+2.0}_{-2.3}(\text{stat.}) \pm 1.7(\text{syst.})\ \text{MeV}/c^2$
- $m(\Sigma_b^-) = 5816^{+1.0}_{-1.0}(\text{stat.}) \pm 1.7(\text{syst.})\ \text{MeV}/c^2$
- $m(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8}(\text{stat.}) \pm 1.7(\text{syst.})\ \text{MeV}/c^2$
- $m(\Sigma_b^{*-}) = 5837^{+2.1}_{-1.9}(\text{stat.}) \pm 1.7(\text{syst.})\ \text{MeV}/c^2$

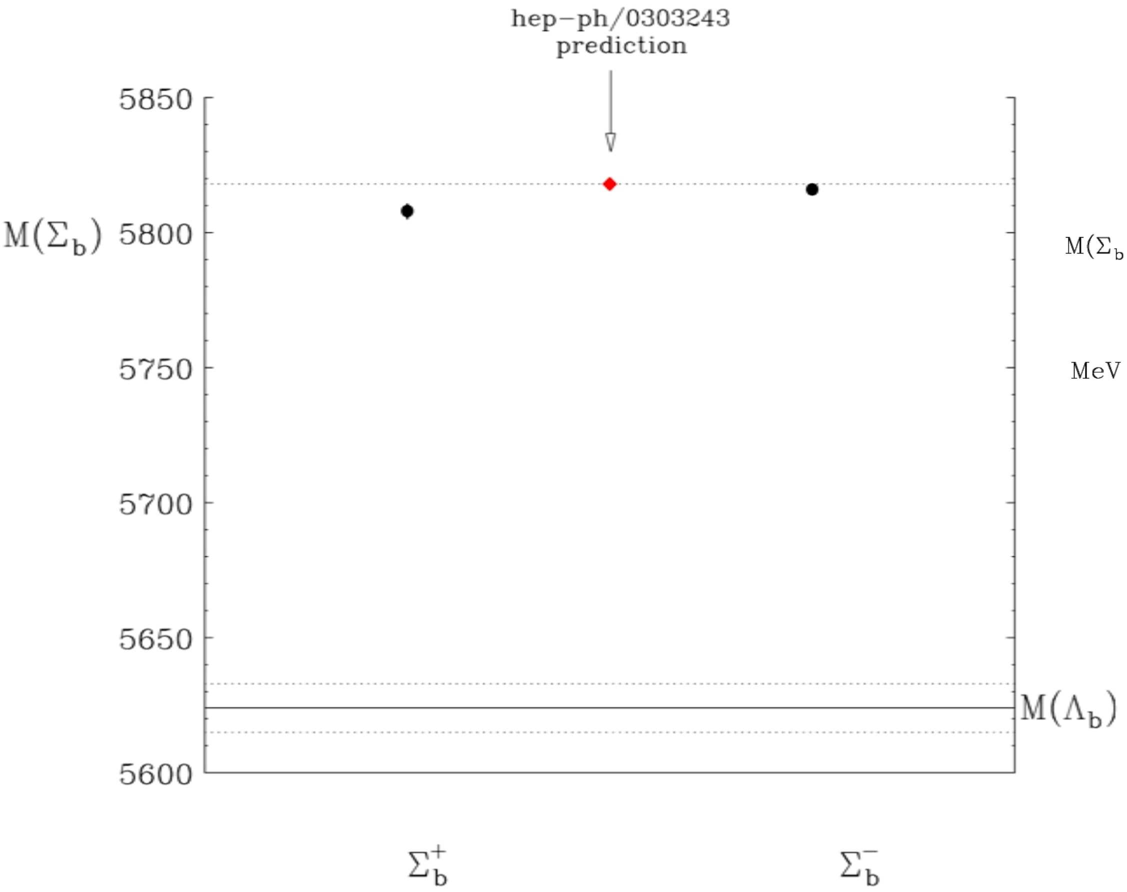

CDF II Preliminary, L = 1.1 fb^{-1}
Fit Prob. = 76%
Candidates per 5 MeV/c^2
Σ_b^-
Total Fit
Background
$\Sigma_b^- \rightarrow \Lambda_b^0\pi^-$
$\Sigma_b^{*-} \rightarrow \Lambda_b^0\pi^-$
Σ_b^+
Total Fit
Background
$\Sigma_b^+ \rightarrow \Lambda_b^0\pi^+$
$\Sigma_b^{*+} \rightarrow \Lambda_b^0\pi^+$
0
10
20
30
40
50
0.00
0.05
0.10
0.15
0.20
$Q = m(\Lambda_b^0\pi) - m(\Lambda_b^0) - m_\pi$ (GeV/c^2)

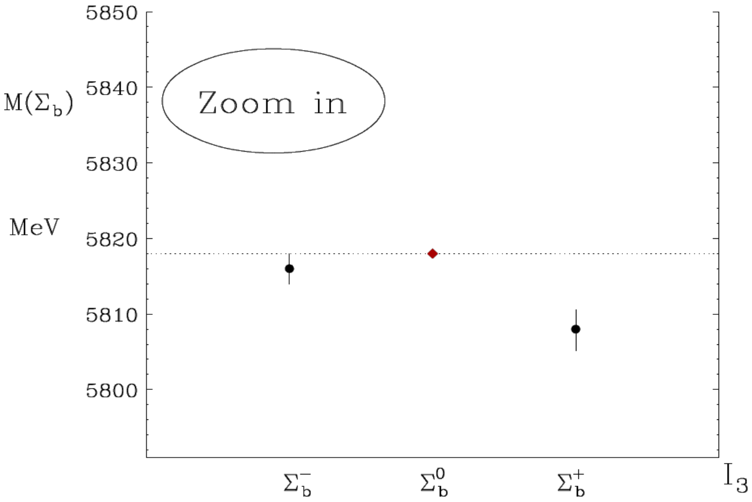
CDF obtained the masses of the Σ_b^- and Σ_b^+ from the decay $\Sigma_b \to \Lambda_b + \pi$ by measuring the corresponding mass differences

$$M(\Sigma_b^-) - M(\Lambda_b) = 195.5^{+1.0}_{-1.0}\,(\text{stat.}) \pm 0.1\,(\text{syst.})\ \text{MeV}$$

$$M(\Sigma_b^+) - M(\Lambda_b) = 188.0^{+2.0}_{-2.3}\,(\text{stat.}) \pm 0.1\,(\text{syst.})\ \text{MeV}$$

with isospin-averaged mass difference $M(\Sigma_b) - M(\Lambda_b) = \boxed{192\ \text{MeV.}}$





can rederive without assuming HF ~ 1/m_q

a weaker assumption of same flavor dependence suffices

$$\frac{V_{hyp}(q_i\bar{q}_j)}{V_{hyp}(q_i\bar{q}_k)} = \frac{V_{hyp}(q_iq_j)}{V_{hyp}(q_iq_k)}$$

$$\frac{M_{\Sigma_b} - M_{\Lambda_b}}{(M_\rho - M_\pi) - (M_{B^*} - M_B)} = \frac{M_{\Sigma_c} - M_{\Lambda_c}}{(M_\rho - M_\pi) - (M_{D^*} - M_D)} = \frac{M_\Sigma - M_\Lambda}{(M_\rho - M_\pi) - (M_{K^*} - M_K)}$$

$$0.32 \approx 0.33 \approx 0.325$$

also prediction for spin splitting between Σ_b^* and Σ_b

$$M(\Sigma_b^*) - M(\Sigma_b) = \frac{M(B^*) - M(B)}{M(K^*) - M(K)} \cdot [M(\Sigma^*) - M(\Sigma)] = \boxed{22\,\mathrm{MeV}}$$

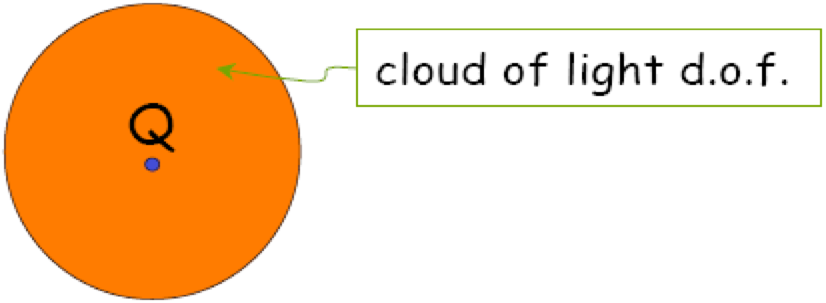
to be compared with $\boxed{21\ \mathrm{MeV}}$ from the isospin-average of CDF measurements

$$M(\Sigma_b^{*-}) = 5837^{+2.1}_{-1.9}\,(\mathrm{stat.}) \pm 1.7\,(\mathrm{syst.})\ \ \mathrm{MeV}$$

$$M(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8}\,(\mathrm{stat.}) \pm 1.7\,(\mathrm{syst.})\ \ \mathrm{MeV}$$

Effective meson-baryon supersymmetry

- meson: Q qbar baryon: Q qq
- in both cases: valence quark coupled to light quark "brown muck" color antitriplet, either a light antiquark (S=1/2) or a light diquark (S=0,S=1)



- Effective supersymmetry: $T^S_{LS}|\mathcal{M}(\bar{q}Q_i)\rangle \quad \equiv \quad |\mathcal{B}([qq]_S Q_i)\rangle$
- m($\mathcal{B}$) – m($\mathcal{M}$) independent of quark flavor (u,s,c,b) !

- need to first cancel the HF interaction contribution to meson masses:

$$\tilde{M}(V_i) \equiv \frac{3M_{\mathcal{V}_i} + M_{\mathcal{P}_i}}{4}$$

- for spin-zero diquarks:

$$\begin{array}{ccccccc} M(N) - \tilde{M}(\rho) & = & M(\Lambda) - \tilde{M}(K^*) & = & M(\Lambda_c) - \tilde{M}(D^*) & = & M(\Lambda_b) - \tilde{M}(B^*) \\ 323 \text{ MeV} & \approx & 321 \text{ MeV} & \approx & 312 \text{ MeV} & \approx & 310 \text{ MeV} \end{array}$$

- for spin-one diquarks need to also cancel HF contribution to baryon masses:

$$\tilde{M}(\Sigma_i) \equiv \frac{2M_{\Sigma_i^*} + M_{\Sigma_i}}{3}; \qquad \tilde{M}(\Delta) \equiv \frac{2M_{\Delta} + M_N}{3}$$

$$\begin{array}{ccccccc} \tilde{M}(\Delta) - \tilde{M}(\rho) & = & \tilde{M}(\Sigma) - \tilde{M}(K^*) & = & \tilde{M}(\Sigma_c) - \tilde{M}(D^*) & = & \tilde{M}(\Sigma_b) - \tilde{M}(B^*) \\ 517.56 \text{ MeV} & \approx & 526.43 \text{ MeV} & \approx & 523.95 \text{ MeV} & \approx & 512.45 \text{ MeV} \end{array}$$

Magnetic moments of heavy baryons

- In Λ, Λ_c and Λ_b light q coupled to spin zero
- → mag. moments determined by s,c,b moments
- quark mag. moments proportional to their chromomagnetic moments

DGG: $\mu_\Lambda = -\frac{\mu_p}{3} \cdot \frac{M_{\Sigma^*} - M_\Sigma}{M_\Delta - M_N} = -0.61\,\mathrm{n.m.}$ (=EXP)

→

$$\mu_{\Lambda_c} = -2\mu_\Lambda \cdot \frac{M_{\Sigma_c^*} - M_{\Sigma_c}}{M_{\Sigma^*} - M_\Sigma} = 0.43\,\mathrm{n.m.}$$

$$\mu_{\Lambda_b} = \mu_\Lambda \cdot \frac{M_{\Sigma_b^*} - M_{\Sigma_b}}{M_{\Sigma^*} - M_\Sigma} = -0.067\,\mathrm{n.m.}$$

challenge to EXP !

Testing confining potentials through meson/baryon HF splitting ratio

B. Keren-Zur, hep-ph/0703011 & Ann. Phys

- from constituent quarks model can derive:

$$\frac{M_{K^*}-M_K}{M_{\Sigma^*}-M_\Sigma}=\frac{4}{3}\frac{\langle\psi|\delta(\vec{r}_u-\vec{r}_{\bar{s}})|\psi\rangle_{meson}}{\langle\psi|\delta(\vec{r}_u-\vec{r}_s)|\psi\rangle_{baryon}}$$

- depends only on the confinement potential and quark mass ratio
- can be used to test different confinement potentials

Testing confining potentials through meson/baryon HF splitting ratio

- 3 measurements (Q = s,c,b)

- 5 potentials:
  - Harmonic oscillator
  - Coulomb interaction
  - Linear potential
  - Linear + Coulomb
  - Logarithmic

baryon/meson HF splitting ratio

- K meson HF splitting

$$M_{K^*} - M_K = 4v_0 \frac{\left(\vec{\lambda}_u \cdot \vec{\lambda}_{\bar{s}}\right)}{m_u m_s} \langle \psi | \delta(r_{us}) | \psi \rangle$$

- The Σ (uds) baryon HF splitting:

$$M_{\Sigma^*} - M_\Sigma = 6v_0 \frac{\left(\vec{\lambda}_u \cdot \vec{\lambda}_s\right)}{m_u m_s} \langle \psi | \delta(r_{us}) | \psi \rangle$$

- Using the relation:

$$\left(\vec{\lambda}_u \cdot \vec{\lambda}_s\right)_{meson} = 2\left(\vec{\lambda}_u \cdot \vec{\lambda}_s\right)_{baryon}$$

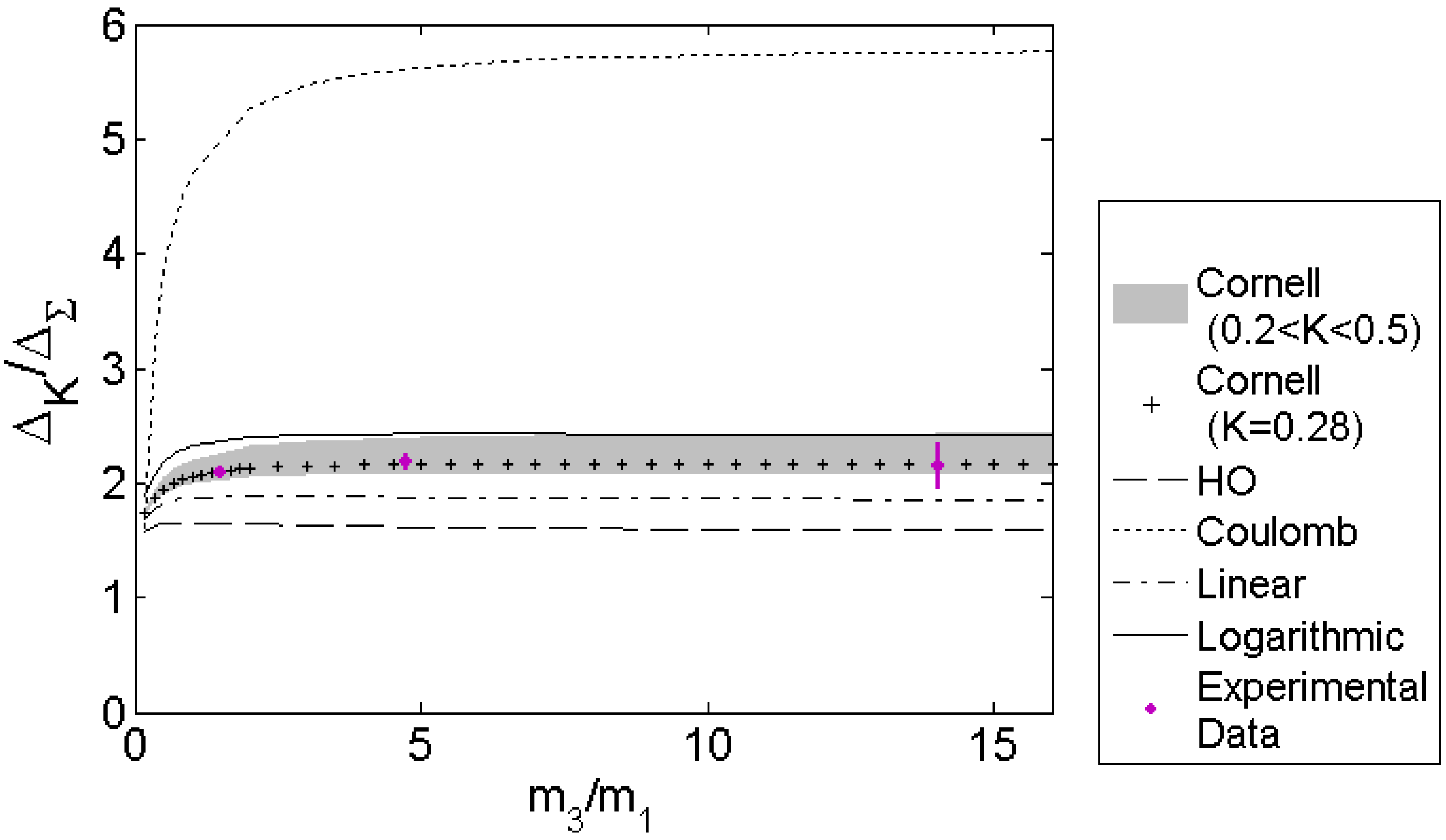
$$\boxed{\frac{M_{K^*} - M_K}{M_{\Sigma^*} - M_\Sigma} = \frac{4}{3} \frac{\langle \psi | \delta(r_{us}) | \psi \rangle_{meson}}{\langle \psi | \delta(r_{us}) | \psi \rangle_{baryon}}}$$

baryon/meson HF splitting ratio

$$\boxed{\frac{M_{K^*}-M_K}{M_{\Sigma^*}-M_\Sigma}=\frac{4}{3}\frac{\langle\psi|\delta(r_{us})|\psi\rangle_{meson}}{\langle\psi|\delta(r_{us})|\psi\rangle_{baryon}}}$$

- similar quark content, so can cancel out the HF coupling constant (v_0).
- confinement potential coupling constant and quark mass scale also cancel out
- depends only on the shape of the potential and the ratio of the quark masses.

Hyperfine splitting ratio from potential models vs experiment



hyperfine splitting ratio from potential models vs experiment

	Δ_K/Δ_Σ	$\Delta_D/\Delta_{\Sigma_c}$	$\Delta_B/\Delta_{\Sigma_b}$
M_3/M_1	1.33	4.75	14
EXP	2.08 ± 0.01	2.18 ± 0.08	2.15 ± 0.20
Harmonic	1.65	1.62	1.59
Coulomb	5.07±0.08	5.62±0.02	5.75±0.01
Linear	1.88±0.06	1.88±0.08	1.86±0.09
Cornell (K=0.28)	2.10±0.05	2.16±0.07	2.17±0.08
Log	2.38 ± 0.02	2.43 ± 0.02	2.43 ± 0.01

Predicting the mass of $\Xi_{\mathbf{Q}}$ baryons

$\Xi_{\mathbf{Q}}$: Qsd or Qsu. (sd), (sd) in spin-0

→ $\Xi_{\mathbf{Q}}$ mass given by

$$\Xi_q = m_q + m_s + m_u - \frac{3v\langle\delta(r_{us})\rangle}{m_u m_s}$$

Can obtain (bsd) mass from (csd) + shift in HF:

$$\Xi_b \;=\; \Xi_c + (m_b - m_c) - \frac{3v}{m_u m_s}\left(\langle\delta(r_{us})\rangle_{\Xi_b} - \langle\delta(r_{us})\rangle_{\Xi_c}\right)$$

several options for obtaining $m_b - m_c$ from data:

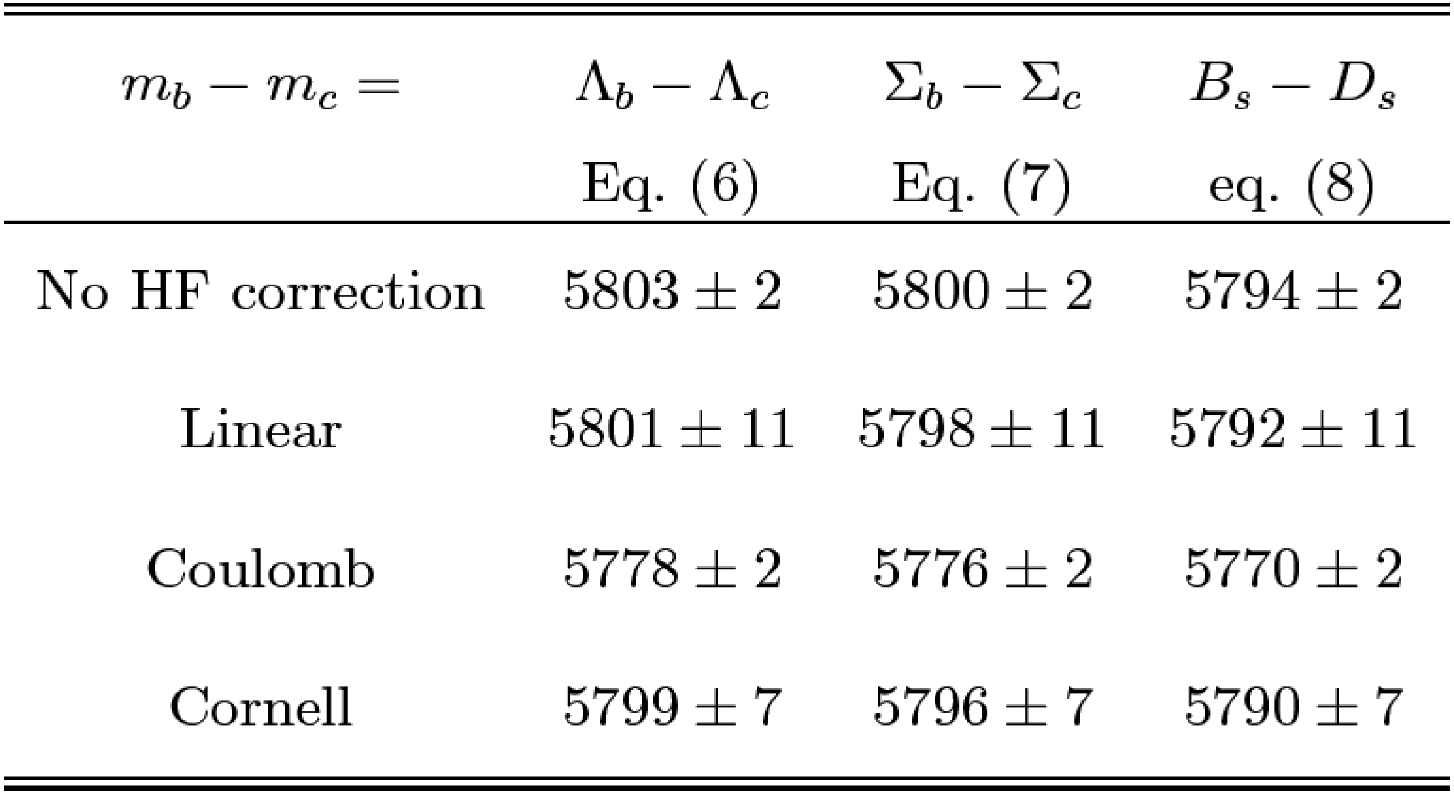
$$m_b - m_c = \Lambda_b - \Lambda_c = 3333.2 \pm 1.2 \quad \text{MeV}$$

$$m_b - m_c = \left(\frac{2\Sigma_b^* + \Sigma_b + \Lambda_b}{4} - \frac{2\Sigma_c^* + \Sigma_c + \Lambda_c}{4} \right) = 3330.4 \pm 1.8 \quad \text{MeV}$$

- The Ξ_Q (Qsq) baryons contain an s quark
- Q mass differences depend on the spectator
- optimal estimate from mesons which contain both s and Q:

$$m_b - m_c = \left(\frac{3B_s^* + B_s}{4} - \frac{3D_s^* + D_s}{4} \right) = 3324.6 \pm 1.4 \quad \text{MeV}$$

Summary of Ξ_b mass predictions



$m_b - m_c =$	$\Lambda_b - \Lambda_c$ Eq. (6)	$\Sigma_b - \Sigma_c$ Eq. (7)	$B_s - D_s$ eq. (8)
No HF correction	5803 ± 2	5800 ± 2	5794 ± 2
Linear	5801 ± 11	5798 ± 11	5792 ± 11
Coulomb	5778 ± 2	5776 ± 2	5770 ± 2
Cornell	5799 ± 7	5796 ± 7	5790 ± 7

Predictions for masses of Ξ_b baryons

Marek Karliner[a], Boaz Keren-Zur[a], Harry J. Lipkin[a,b,c], and Jonathan L. Rosner[d]

[a] *School of Physics and Astronomy*
Raymond and Beverly Sackler Faculty of Exact Sciences
Tel Aviv University, Tel Aviv 69978, Israel

[b] *Department of Particle Physics*
Weizmann Institute of Science, Rehovoth 76100, Israel

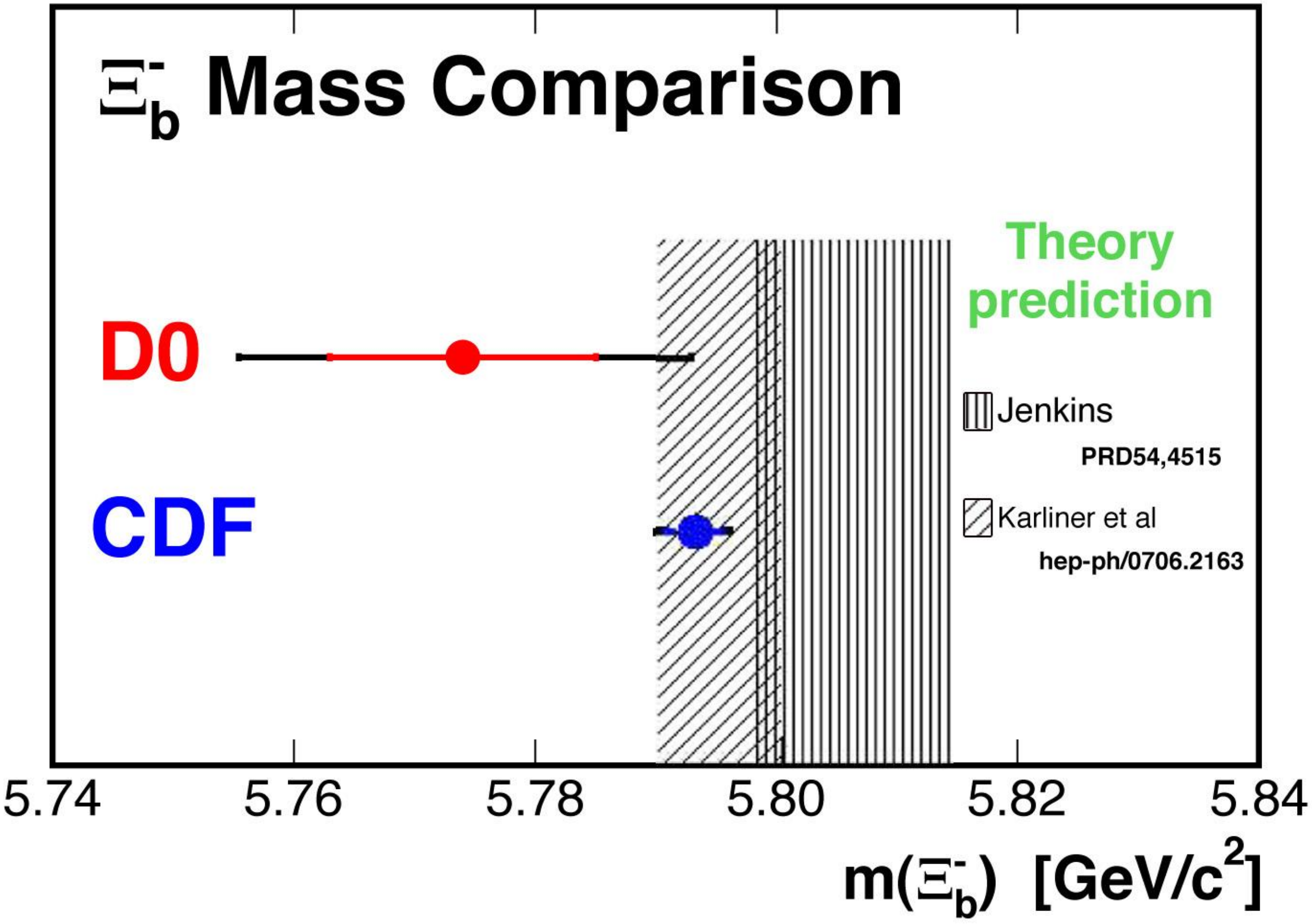
[c] *High Energy Physics Division, Argonne National Laboratory*
Argonne, IL 60439-4815, USA

[d] *Enrico Fermi Institute and Department of Physics*
University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637, USA

ABSTRACT

The recent observation by CDF of $\Sigma_b^{\pm}$ (uud and ddb) baryons within 2 MeV of the predicted $\Sigma_b - \Lambda_b$ splitting has provided strong confirmation for the theoretical approach based on modeling the color hyperfine interaction. We now apply this approach to predict the masses of the Ξ_b family of baryons with quark content usb and dsb – the ground state Ξ_b at 5790 to 5800 MeV, and the excited states Ξ_b' and Ξ_b^*. The main source of uncertainty is the method used to estimate the mass difference $m_b - m_c$ from known hadrons. We verify that corrections due to the details of the interquark potential and to Ξ_b–Ξ_b' mixing are small.

Ξ_b masses


Ξ_b^- Mass Comparison
Theory prediction
D0
CDF
Jenkins
PRD54,4515
Karliner et al
hep-ph/0706.2163
5.74
5.76
5.78
5.80
5.82
5.84
$m(\Xi_b^-)$ [GeV/c^2]

Ξ_b^*, Ξ_b' mass prediction

Ξ_b' : bsd with (sd) in S=1; total spin = 1/2

Ξ_b^* : bsd with (sd) in S=1; total spin = 3/2

spin-averaged mass of these two states

$$\frac{2\Xi_q^* + \Xi_q'}{3} = m_q + m_s + m_u + \frac{v\langle\delta(r_{us})\rangle}{m_u m_s}$$

so that

$$\frac{2\Xi_b^* + \Xi_b'}{3} = \frac{2\Xi_c^* + \Xi_c'}{3} + (m_b - m_c) + \frac{2\Xi_c^* + \Xi_c' - 3\Xi_c}{12}\left(\frac{\langle\delta(r_{us})\rangle_{\Xi_b}}{\langle\delta(r_{us})\rangle_{\Xi_c}} - 1\right)$$

Ξ_b^*, Ξ_b' mass prediction

$$(2\Xi_b^* + \Xi_b')/3$$

$m_b - m_c =$	$\Lambda_b - \Lambda_c$	$\Sigma_b - \Sigma_c$	$B_s - D_s$
	Eq. (6)	Eq. (7)	Eq. (8)
No HF correction	5956 ± 3	5954 ± 3	5948 ± 3
Linear	5957 ± 4	5954 ± 4	5948 ± 4
Coulomb	5965 ± 3	5962 ± 3	5956 ± 3
Cornell	5958 ± 3	5955 ± 3	5949 ± 3

difference between the spin averaged mass $(2\Xi_b^* + \Xi_b')/3$ and Ξ_b is roughly $150 - 160$ MeV.

Ξ_b^*, Ξ_b' mass prediction

- $\Xi_b^* - \Xi_b'$ mass difference more difficult to predict
- small due to the large m_b: $\Xi_q^* - \Xi_q' = 3v\left(\frac{\langle\delta(r_{qs})\rangle}{m_q m_s} + \frac{\langle\delta(r_{qu})\rangle}{m_q m_u}\right)$

	$\Xi_b^* - \Xi_b'$
No HF correction	24 ± 2
Linear	28 ± 6
Coulomb	36 ± 7
Cornell	29 ± 6

using

$$\frac{m_s}{m_u} = 1.5 \pm 0.1, \ \frac{m_b}{m_c} = 2.95 \pm 0.2.$$

Predictions for other bottom baryons

with B.Keren-Zur, H.J. Lipkin and J.L. Rosner

Ω_b mass prediction

$$\begin{aligned}\frac{2\Omega_b^*+\Omega_b}{3} &= \frac{2\Omega_c^*+\Omega_c}{3}+(m_b-m_c)\\ &= \frac{2\Omega_c^*+\Omega_c}{3}+\frac{3B_s^*+B_s}{4}-\frac{3D_s^*+D_s}{4}\\ &= 6068.6\pm 2.6\ \mathrm{MeV}\end{aligned}$$

wavefunction correction $\approx +2$ MeV.

HF splitting: m_b/m_c taken to be 3.0 ± 0.5.

$$\Omega_b^*-\Omega_b = (\Omega_c^*-\Omega_c)\frac{m_c}{m_b} = 23.6\pm 4.0\ \mathrm{MeV}$$

Ω_b mass prediction

This gives the following mass predictions:

$$\boxed{\Omega_b^* = 6076.5 \pm 2.9 \text{ MeV}; \quad \Omega_b = 6052.9 \pm 3.7 \text{ MeV}}$$

Wavefunction corrections give a factor of 1.28, and a splitting of 30 ± 6 MeV.

Work in progress:

- **Ξ_b isospin splitting**
- **Λ_b and Ξ_b orbital excitations**
- **Ξ_{bc} (bcu)**
- **Ξ_{cc} (ccu)**

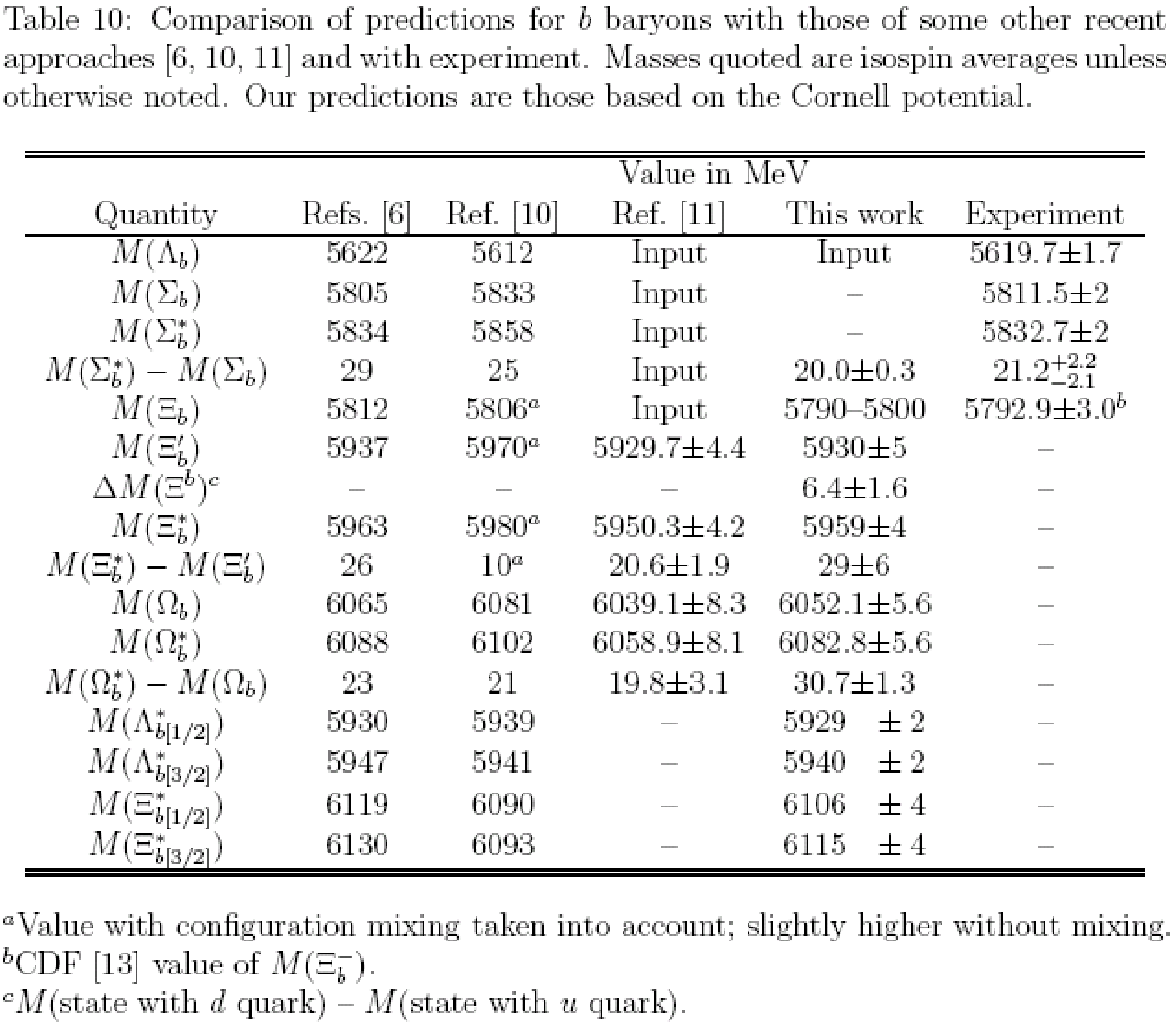


Table 10: Comparison of predictions for b baryons with those of some other recent approaches [6, 10, 11] and with experiment. Masses quoted are isospin averages unless otherwise noted. Our predictions are those based on the Cornell potential.

	Value in MeV				
Quantity	Refs. [6]	Ref. [10]	Ref. [11]	This work	Experiment
$M(\Lambda_b)$	5622	5612	Input	Input	5619.7±1.7
$M(\Sigma_b)$	5805	5833	Input	–	5811.5±2
$M(\Sigma_b^*)$	5834	5858	Input	–	5832.7±2
$M(\Sigma_b^*) - M(\Sigma_b)$	29	25	Input	20.0±0.3	$21.2^{+2.2}_{-2.1}$
$M(\Xi_b)$	5812	5806[a]	Input	5790–5800	5792.9±3.0[b]
$M(\Xi_b')$	5937	5970[a]	5929.7±4.4	5930±5	–
$\Delta M(\Xi^b)$[c]	–	–	–	6.4±1.6	–
$M(\Xi_b^*)$	5963	5980[a]	5950.3±4.2	5959±4	–
$M(\Xi_b^*) - M(\Xi_b')$	26	10[a]	20.6±1.9	29±6	–
$M(\Omega_b)$	6065	6081	6039.1±8.3	6052.1±5.6	–
$M(\Omega_b^*)$	6088	6102	6058.9±8.1	6082.8±5.6	–
$M(\Omega_b^*) - M(\Omega_b)$	23	21	19.8±3.1	30.7±1.3	–
$M(\Lambda^*_{b[1/2]})$	5930	5939	–	5929 ± 2	–
$M(\Lambda^*_{b[3/2]})$	5947	5941	–	5940 ± 2	–
$M(\Xi^*_{b[1/2]})$	6119	6090	–	6106 ± 4	–
$M(\Xi^*_{b[3/2]})$	6130	6093	–	6115 ± 4	–

[a] Value with configuration mixing taken into account; slightly higher without mixing.

[b] CDF [13] value of $M(\Xi_b^-)$.

[c] M(state with d quark) – M(state with u quark).

Recent data from Belle: anomalously large (2 orders of mag.)

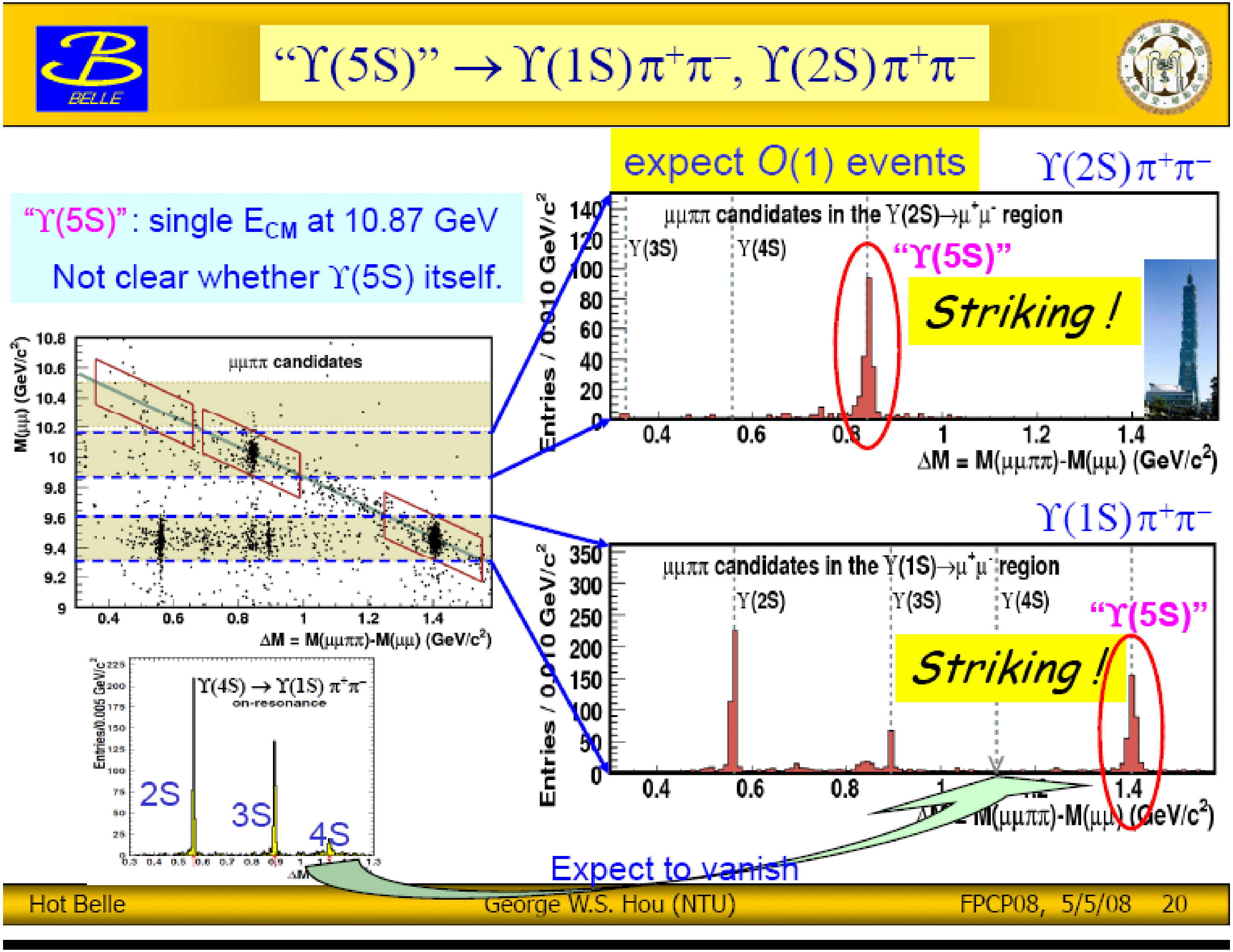
$$\Upsilon(5S) \to \Upsilon(1S)\,\pi^+\pi^-$$

$$\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-$$

0802.0649 [hep-ph], Lipkin & M.K.:
might be mediated by $\bar{b}bu\bar{d}$ tetraquark
below $B\bar{B}$ threshold:

$$\Upsilon(mS) \to T^{\pm}_{\bar{b}b}\pi^{\mp} \to \Upsilon(nS)\,\pi^+\pi^-$$

analogous to Z(4430)? Seen in $\psi'\pi^{\pm}$ but not in $J/\psi\pi^{\pm}$



“$\Upsilon(5S)$” $\rightarrow \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$

“$\Upsilon(5S)$”: single E_{CM} at 10.87 GeV

Not clear whether $\Upsilon(5S)$ itself.

expect *O*(1) events

$\Upsilon(2S)\pi^+\pi^-$

Striking !

$\Upsilon(1S)\pi^+\pi^-$

Striking !

Expect to vanish

Hot Belle George W.S. Hou (NTU) FPCP08, 5/5/08 20

- E and p conservation in Υ(5S) → Υ(mS)ππ:

  plot of M_inv[Υ(mS)π]^2 vs. E_π linear

  modulo Υ(5S), Υ(mS) width

- Look for peaks in M_inv of Υ(mS)π

- Isospin:

  Υ(mS)π+ vs. π- = Υ(mS)π- vs. π+

  modulo statistics

Dalitz Plot: $Z^{\pm}(4430)$ Echoes?

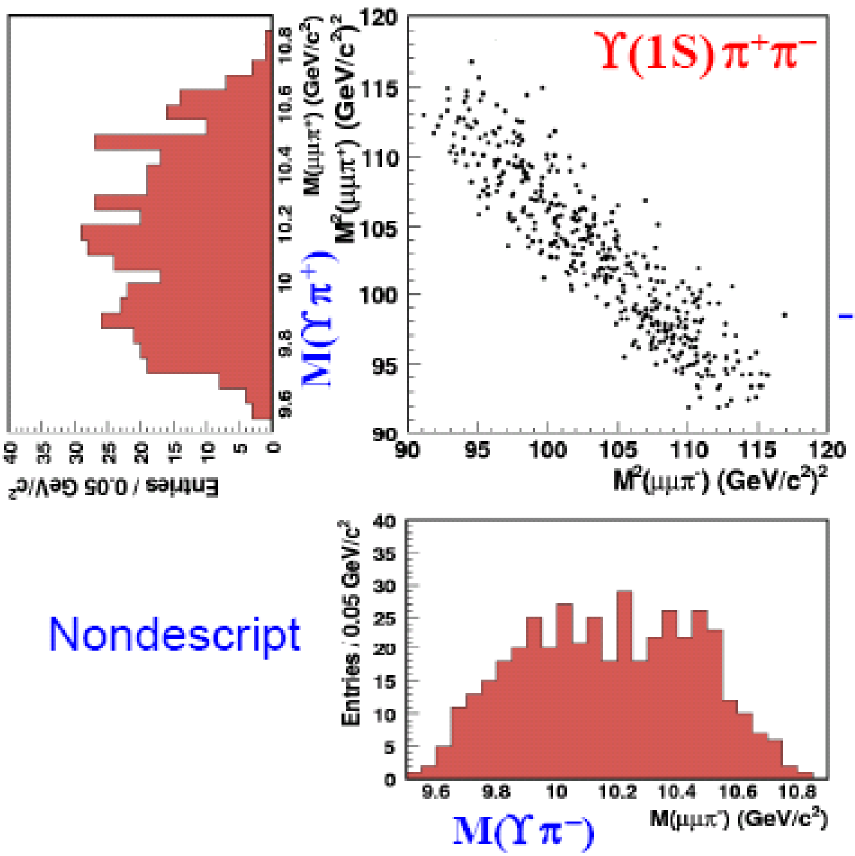
$cu\bar{c}\bar{d}$?

$\psi'\pi^{\pm}$

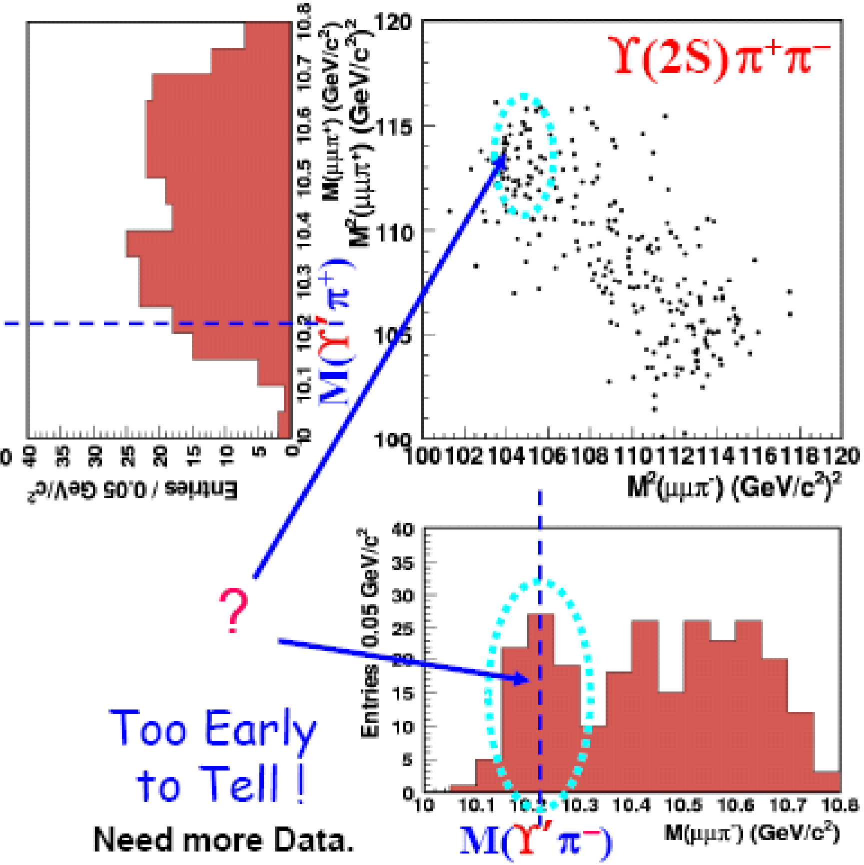
S.-K. Choi, S.L. Olsen et al., PRL '08

Karliner & Lipkin, arXiv:0802.0649 [hep-ph] $\boxed{bu\bar{b}\bar{d}}$ **Lighter than $2m_B$?**

cf. Cheung, Keung, Yuan, PRD '07: ~ 10700



Nondescript



Too Early to Tell !

Need more Data.

Open questions

- need to understand the XYZ states in the charm sector and their counterparts in the bottom sector
- replacing charmed quark by bottom quark makes the binding stronger
- excellent challenge for EXP and TH
- general question of exotics in QCD
- ccu, ccd and bbu, bbd:
  SELEX ccq data - isospin breaking much too large?

Summary

- Consitituent quark model with color HF interaction gives highly accurate predictions for heavy baryon masses
- a challenge for theory: derivation from QCD
- constituent quark masses depend on the spectator quarks
- $M_{\Sigma_b} - M_{\Lambda_b} = 194\,\mathrm{MeV}$ vs 192 in EXP (CDF)
- $M(\Sigma_b^*) - M(\Sigma_b) =$ 22 MeV vs 21 MeV in EXP (CDF)
- $\mu_{\Lambda_c} = 0.43\,\mathrm{n.m.}$ $\mu_{\Lambda_b} = -0.067\,\mathrm{n.m.}$
- meson-baryon effective supersymmetry
- meson/baryon HF splitting confirms Cornell potential
- Ξ_b mass prediction: 5795+-5 MeV vs $5793 \pm 2.4 \pm 1.7$ MeV
- puzzle in Υ(5S) decays: $\bar{b}bu\bar{d}$ candidates?