b-Quark Hadrons - a Theoretical Laboratory for Color Magnetic Interaction

Marek Karliner

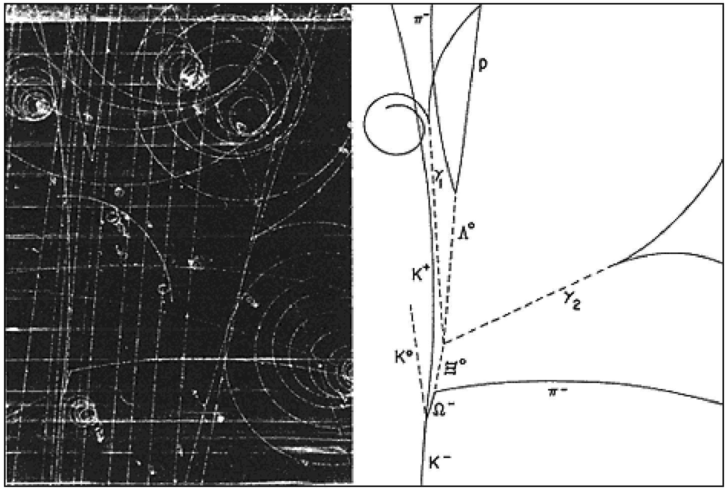
in collaboration with B. Keren-Zur, H.J. Lipkin and J. Rosner

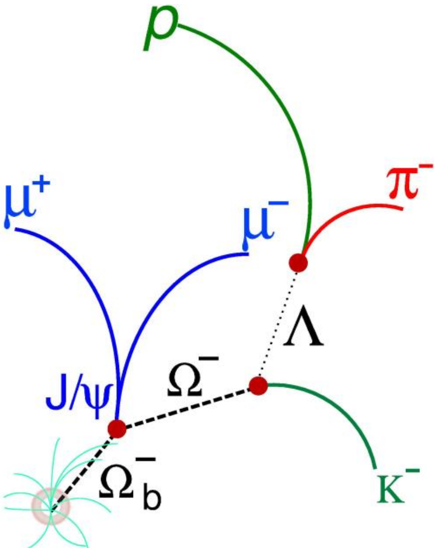
50 Cracow School of Theoretical Physics, Zakopane, June 9-19, 2010

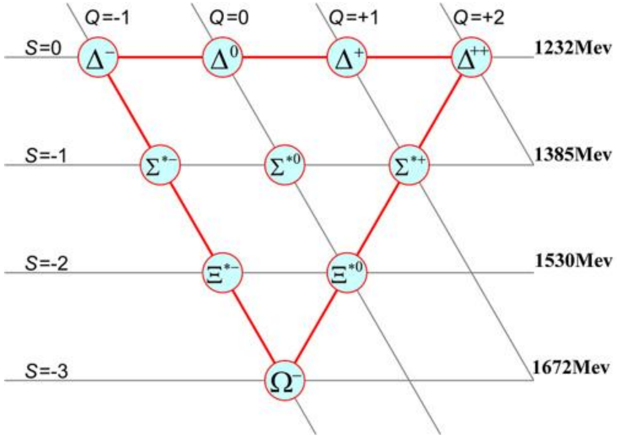
Outline

- a bit of history
- spin-spin interaction between quarks – “color magnetic”
- constituent quark masses – differences and ratios
- same constituent masses in mesons and baryons
- tests, applications and predictions

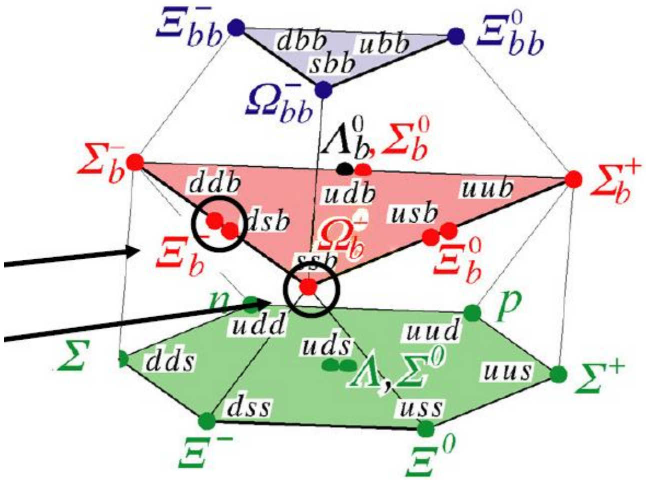
From Ω^- to Ω_b



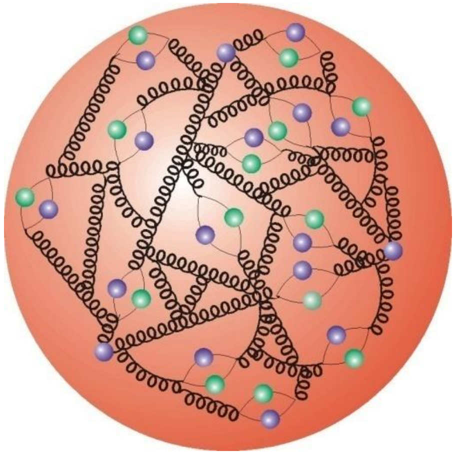




$J = 1/2$ b Baryons

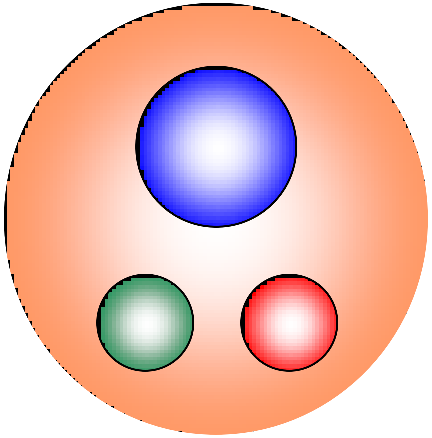


Constituent Quark Models (CQM)



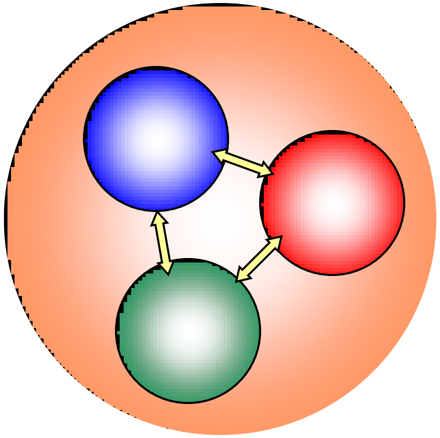
- QCD describes hadrons as valence quarks in a sea of gluons and q-qbar pairs.
- at low E, χSB
- → quark constituent mass
- hadron can be considered as a bound state of constituent quarks.
- Sakharov-Zeldovich formula:

$$M = \sum_i m_i$$



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

Color Hyperfine (HF) interaction



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

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

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

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

$$V^{HF(em)}{}_{ij} \propto \vec{\mu}_i \cdot \vec{\mu}_j = e^2 \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i m_j} \langle \psi | \delta(r_i - r_j) | \psi \rangle$$

  - 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 mass differences

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

$$M_{\Lambda_c} - M_{\Lambda} =$$

$$= \left(\cancel{m_u} + \cancel{m_d} + m_c + \cancel{V^{HF}}_{ud} + V^{HF}_{uc} + V^{HF}_{dc} \right) -$$

$$- \left(\cancel{m_u} + \cancel{m_d} + m_s + \cancel{V^{HF}}_{ud} + V^{HF}_{us} + V^{HF}_{ds} \right) =$$

$$= m_c - m_s$$

$$= 0$$

difference of effective quark

masses is the same in

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

"how much you weigh depends

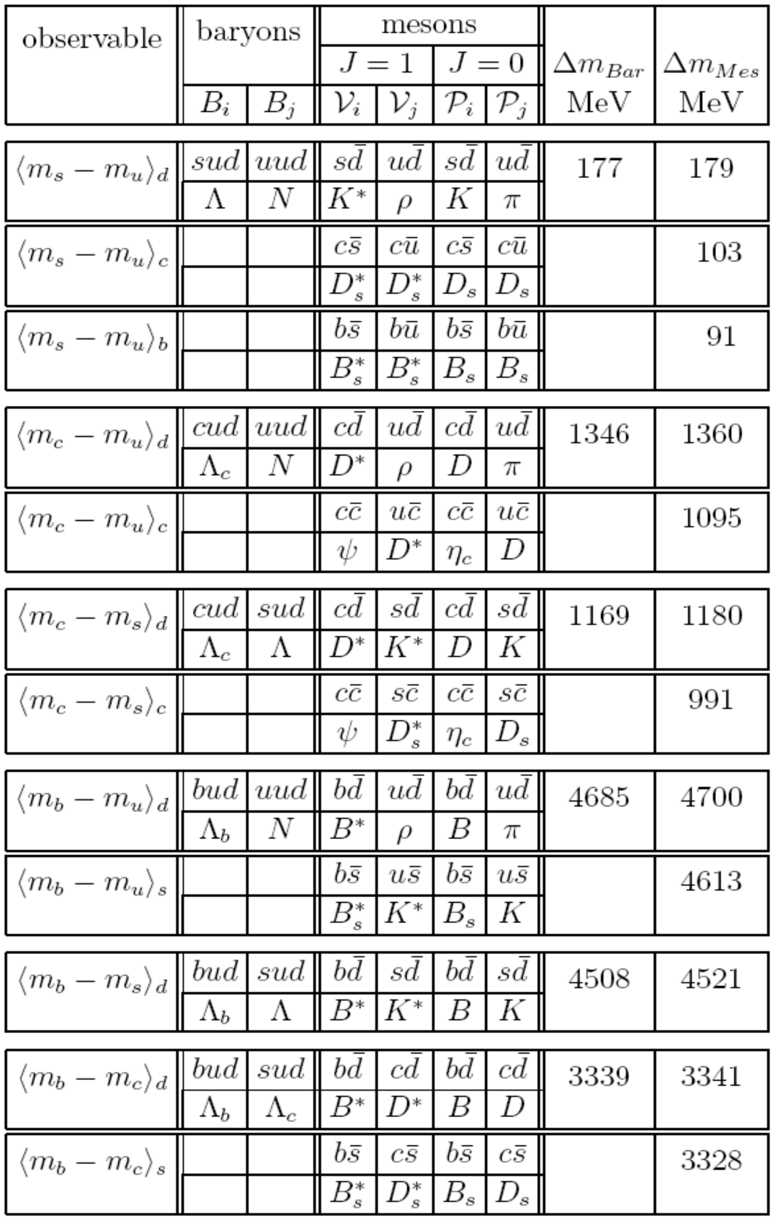
on *who your neighbors are"*

→ challenge to npQCD

MK & Lipkin, hep-ph/0307243

M. Karliner b-quark hadrons

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		

constituent quark mass ratios

- example II:

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

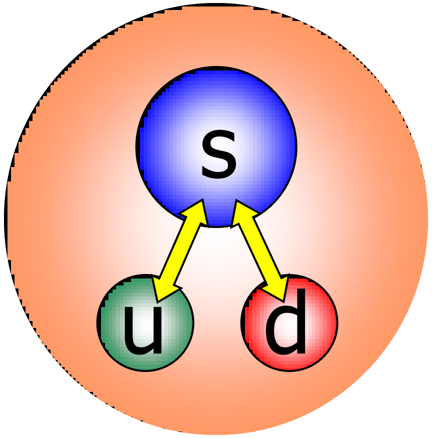
$$= 4v_0 \frac{\left(\vec{\lambda}_u \cdot \vec{\lambda}_{\bar{s}}\right)}{m_u m_s} \langle\psi|\delta(r)|\psi\rangle$$

- extracting quark masses ratio:

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

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



$$\left\langle \vec{\sigma}_u \cdot \vec{\sigma}_d \right\rangle_{\Sigma^*} = \left\langle \vec{\sigma}_u \cdot \vec{\sigma}_d \right\rangle_{\Sigma}$$

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

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

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

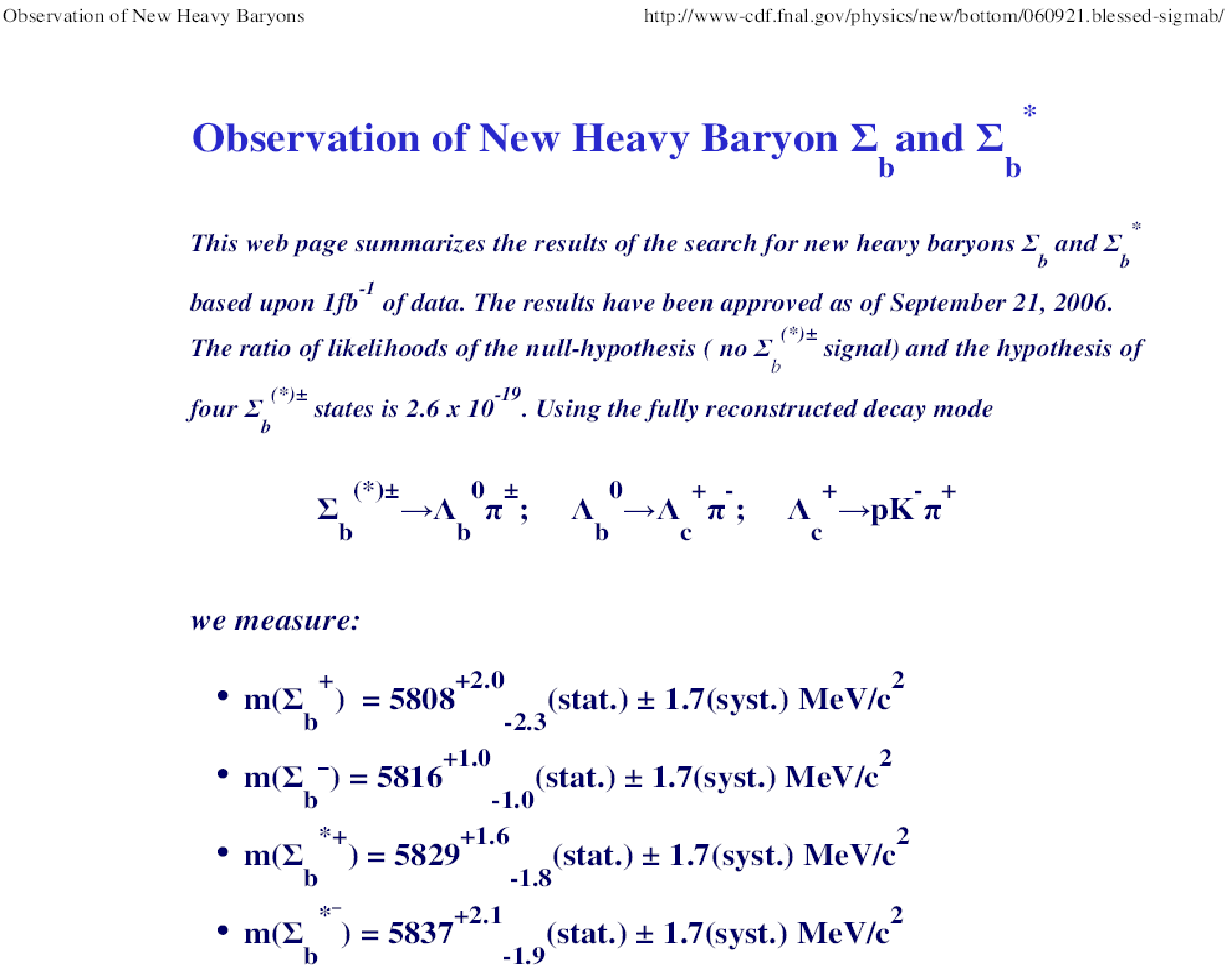
$$\left(\frac{\dfrac{1}{m_u^2} - \dfrac{1}{m_u m_c}}{\dfrac{1}{m_u^2} - \dfrac{1}{m_u m_s}}\right)_{Bar} = \frac{M_{\Sigma_c} - M_{\Lambda_c}}{M_{\Sigma} - M_{\Lambda}} = 2.16 \approx \left(\frac{\dfrac{1}{m_u^2} - \dfrac{1}{m_u m_c}}{\dfrac{1}{m_u^2} - \dfrac{1}{m_u m_s}}\right)_{Mes} = \frac{(M_{\rho}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

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 Baryons http://www-cdf.fnal.gov/physics/new/bottom/060921.blessed-sigmab/

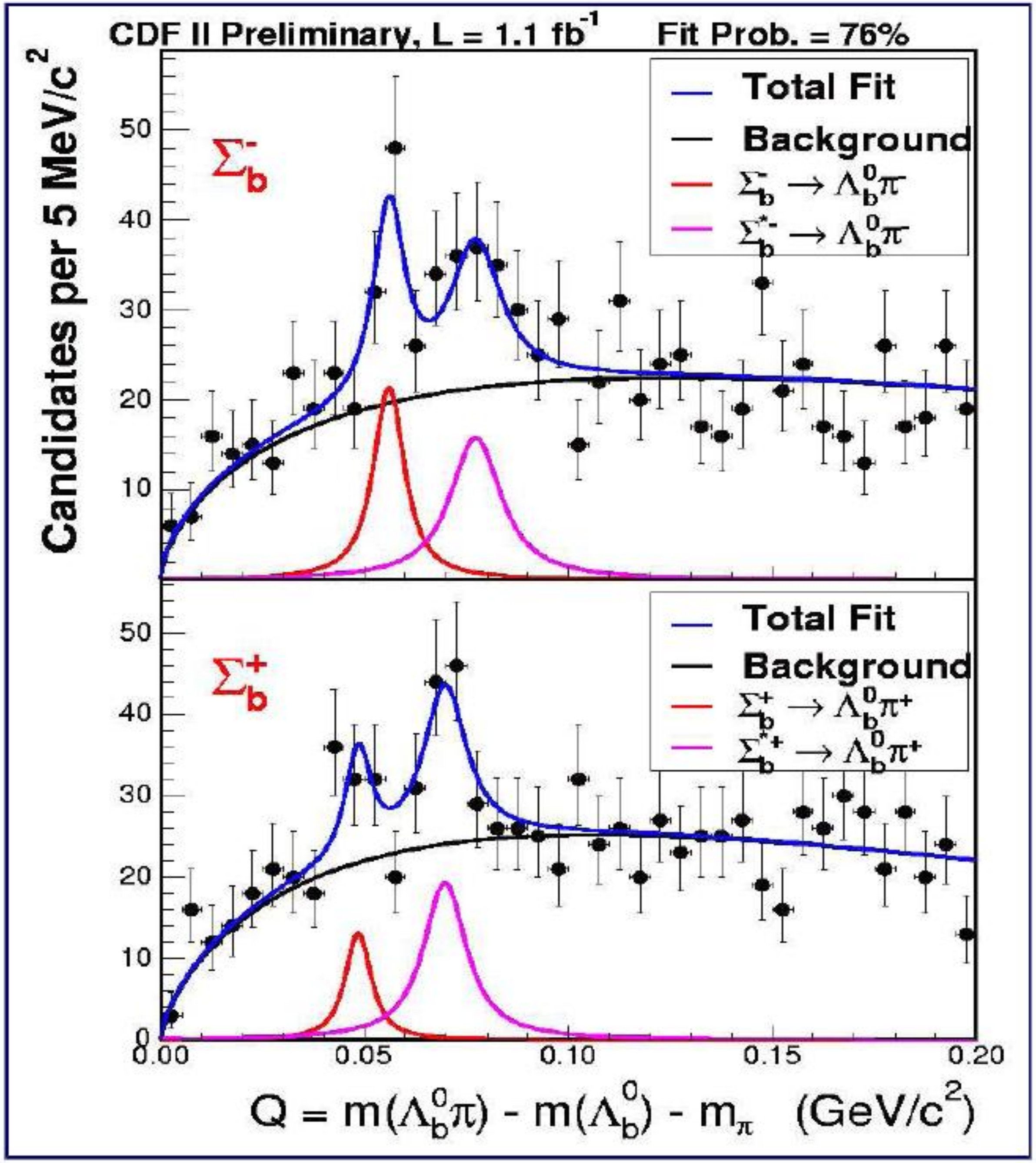
Observation of New Heavy Baryon Σ_b and Σ_b^*

This web page summarizes the results of the search for new heavy baryons Σ_b *and* Σ_b^* *based upon* $1 fb^{-1}$ *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*

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

we measure:

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

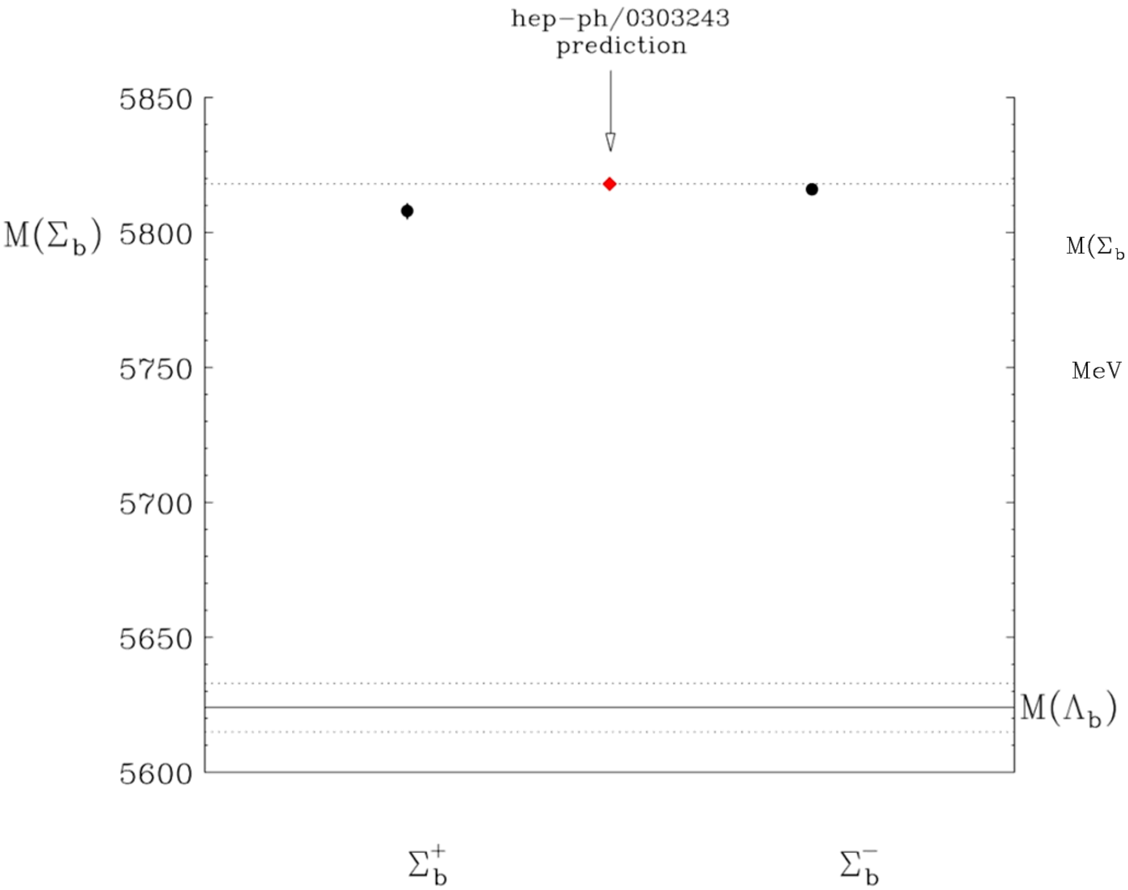

CDF II Preliminary, L = 1.1 fb^{-1}
Fit Prob. = 76%
Candidates per 5 MeV/c^2
Σ_b^-
Total Fit
Background
$\Sigma_b^- \to \Lambda_b^0\pi^-$
$\Sigma_b^{*-} \to \Lambda_b^0\pi^-$
Σ_b^+
$\Sigma_b^+ \to \Lambda_b^0\pi^+$
$\Sigma_b^{*+} \to \Lambda_b^0\pi^+$
0
10
20
30
40
50
0.00
0.05
0.10
0.15
0.20
Q = m($\Lambda_b^0\pi$)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

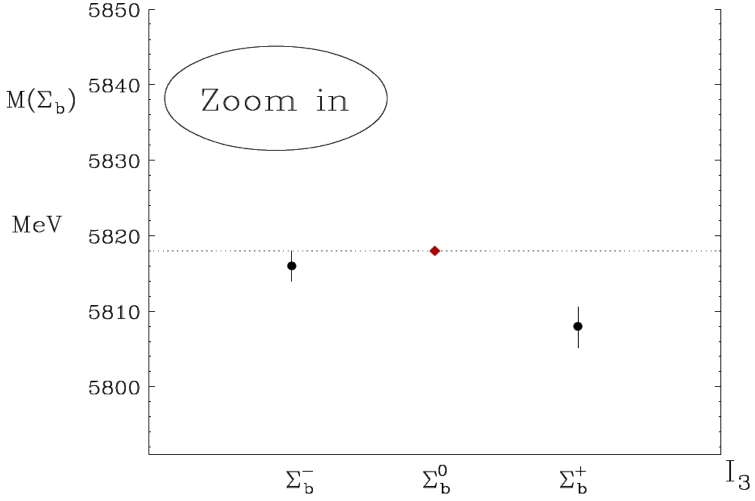
CDF obtained the masses of the Σ_b^- and Σ_b^+ from the decay $\Sigma_b \to \Lambda_b + \pi$ by measuring the corresponding mass differences

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

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

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





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

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

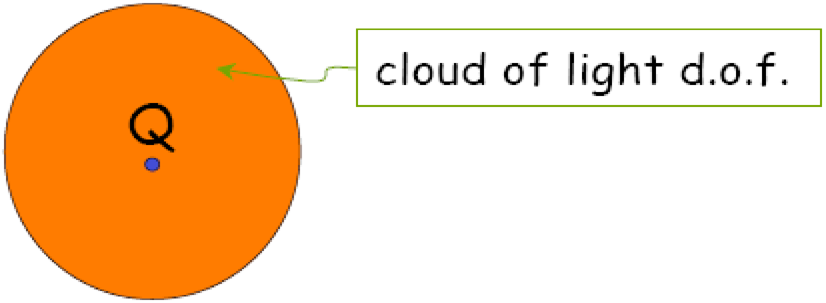
$$M(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8}\,(\mathrm{stat.}) \pm 1.7\,(\mathrm{syst.})\ \ \mathrm{MeV}$$

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: $T_{LS}^{S}|\mathcal{M}(\bar{q}Q_i)\rangle \quad \equiv \quad |\mathcal{B}([qq]_S Q_i)\rangle$
- 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)

→

$$\boxed{\begin{aligned} \mu_{\Lambda_c} &= -2\mu_\Lambda \cdot \frac{M_{\Sigma_c^*} - M_{\Sigma_c}}{M_{\Sigma^*} - M_\Sigma} = 0.43\,\mathrm{n.m.} \\ \mu_{\Lambda_b} &= \mu_\Lambda \cdot \frac{M_{\Sigma_b^*} - M_{\Sigma_b}}{M_{\Sigma^*} - M_\Sigma} = -0.067\,\mathrm{n.m.} \end{aligned}}$$

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:

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

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

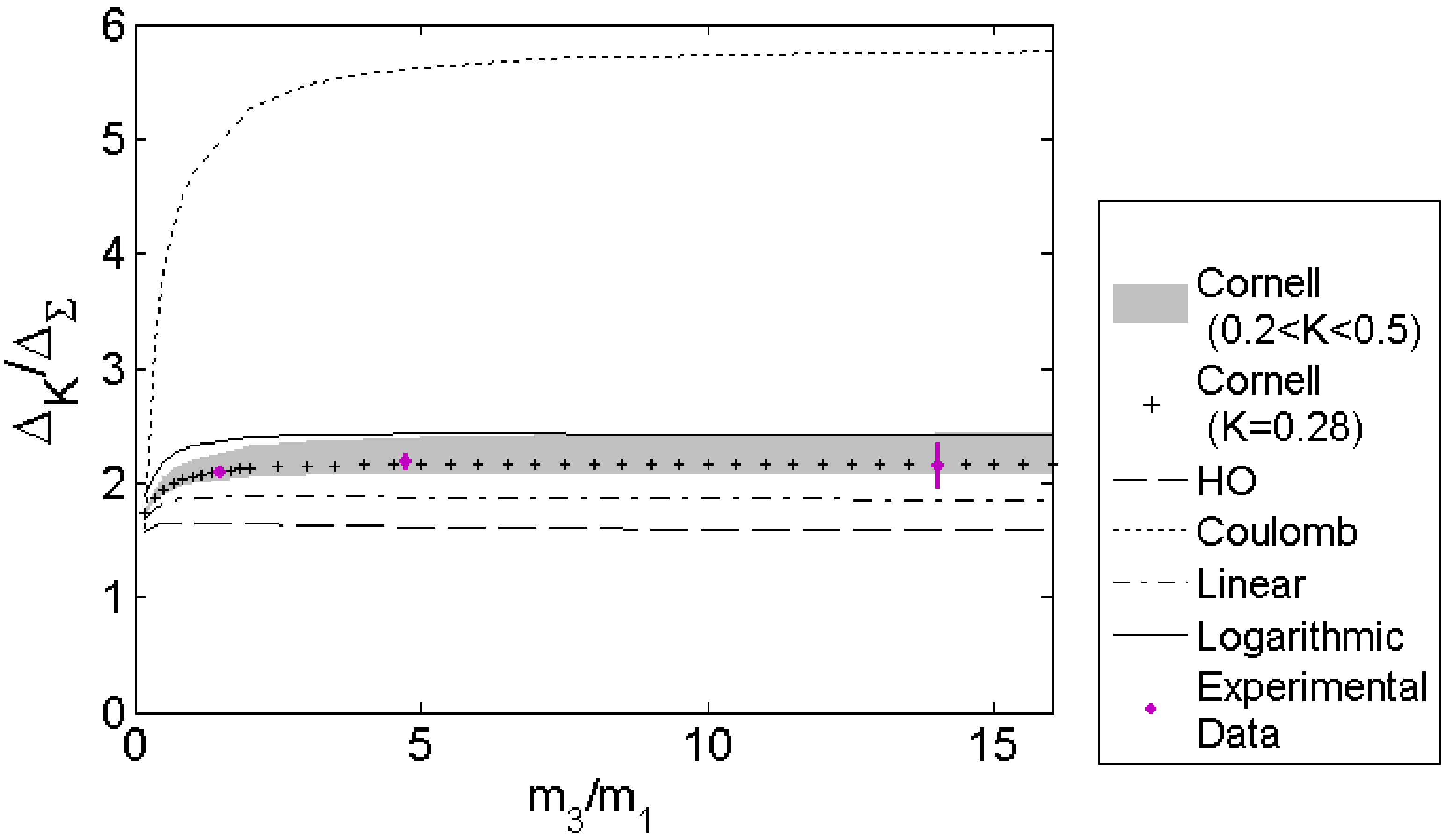
baryon/meson HF splitting ratio

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

- 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 Ξ_Q baryons

Ξ_Q : Qsd or Qsu. (sd), (sd) in spin-0

→ Ξ_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:

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

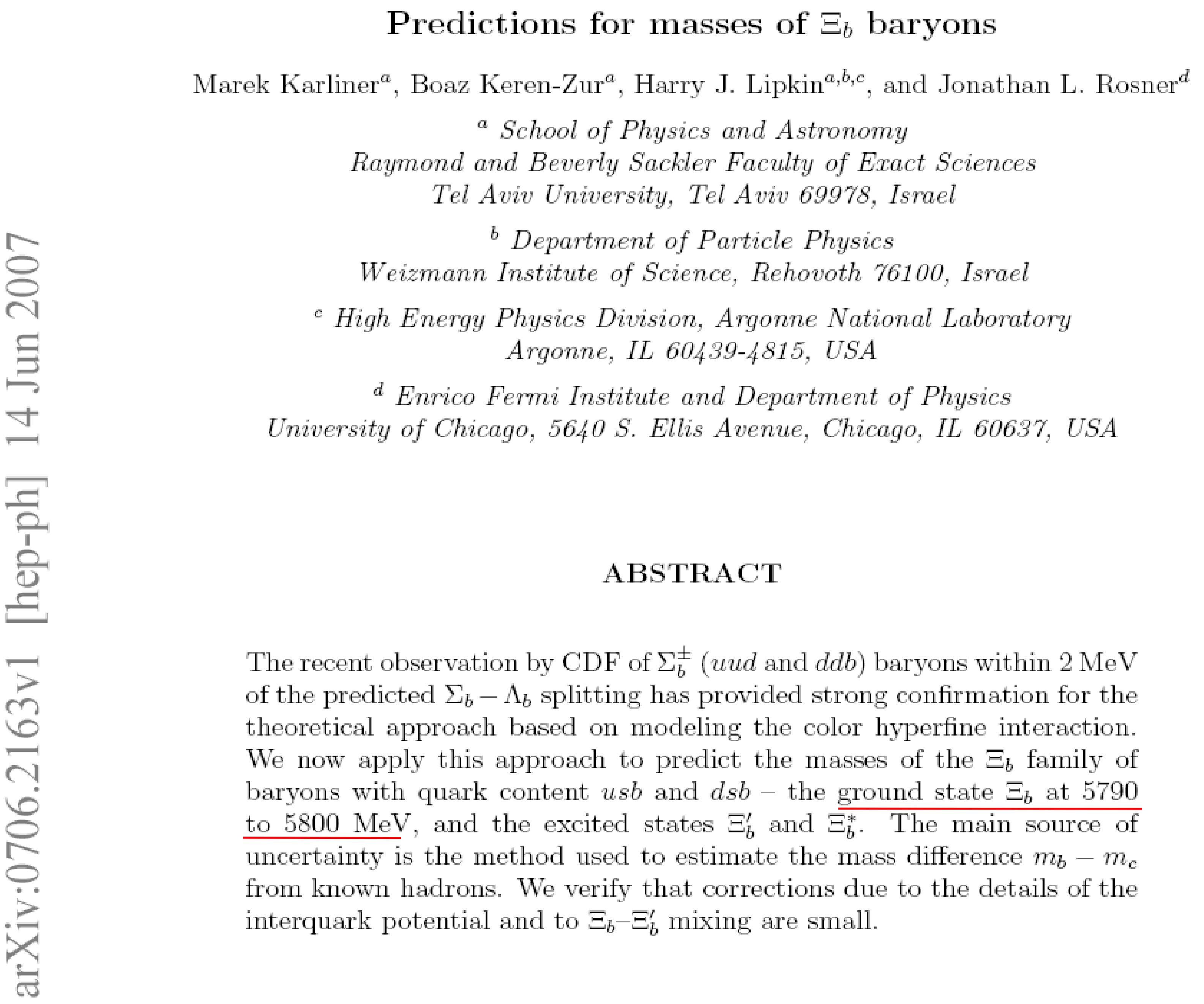
$$m_b - m_c = \left(\frac{2\Sigma_b^* + \Sigma_b + \Lambda_b}{4} - \frac{2\Sigma_c^* + \Sigma_c + \Lambda_c}{4} \right) = 3330.4 \pm 1.8 \quad \text{MeV}$$

- 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

$m_b - m_c =$	$\Lambda_b - \Lambda_c$	$\Sigma_b - \Sigma_c$	$B_s - D_s$
	Eq. (6)	Eq. (7)	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

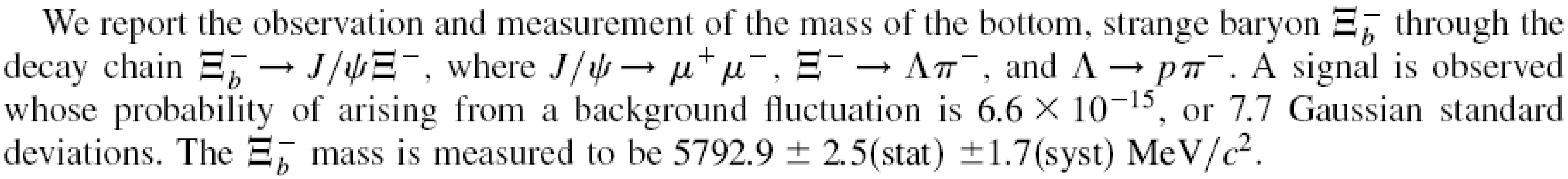
ABSTRACT

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.

PRL **99,** 052002 (2007) PHYSICAL REVIEW LETTERS week ending 3 AUGUST 2007

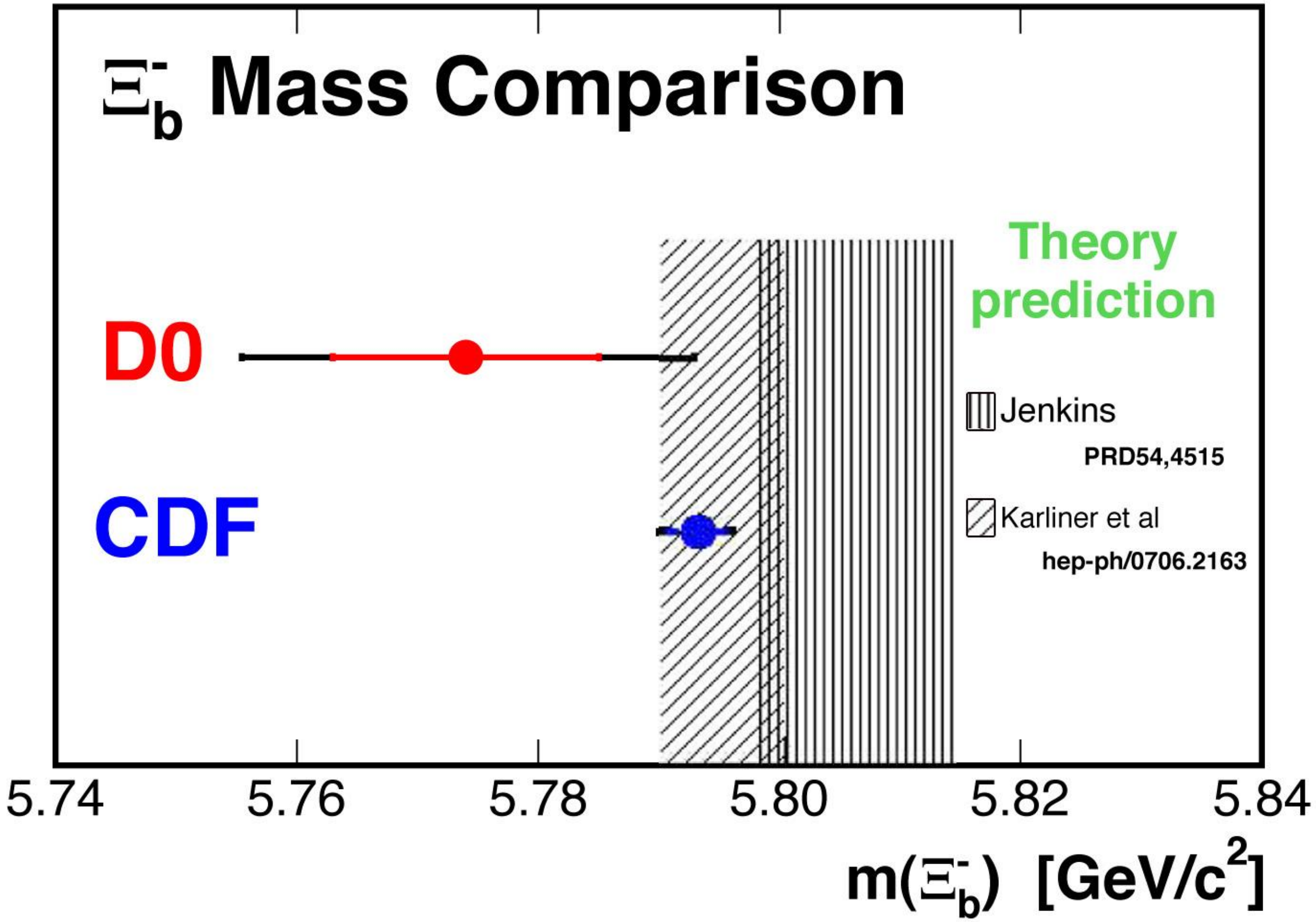
Observation and Mass Measurement of the Baryon Ξ_b^-

(CDF Collaboration)



We report the observation and measurement of the mass of the bottom, strange baryon Ξ_b^- through the decay chain $\Xi_b^- \to J/\psi \Xi^-$, where $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda\pi^-$, and $\Lambda \to p\pi^-$. A signal is observed whose probability of arising from a background fluctuation is 6.6×10^{-15}, or 7.7 Gaussian standard deviations. The Ξ_b^- mass is measured to be $5792.9 \pm 2.5(\text{stat}) \pm 1.7(\text{syst})\ \text{MeV}/c^2$.

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

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

$m_b - m_c =$	$\Lambda_b - \Lambda_c$ Eq. (6)	$\Sigma_b - \Sigma_c$ Eq. (7)	$B_s - D_s$ 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

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

wavefunction correction $\approx +2$ MeV.

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

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

Ω_b mass prediction

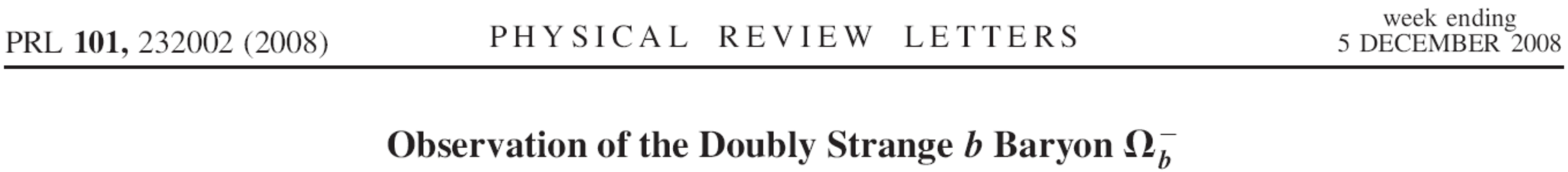
This gives the following mass predictions:

$\Omega_b = 6052.1 \pm 5.6$ MeV $\Omega_b^* = 6082.8 \pm 5.6$ MeV

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

Work in progress:

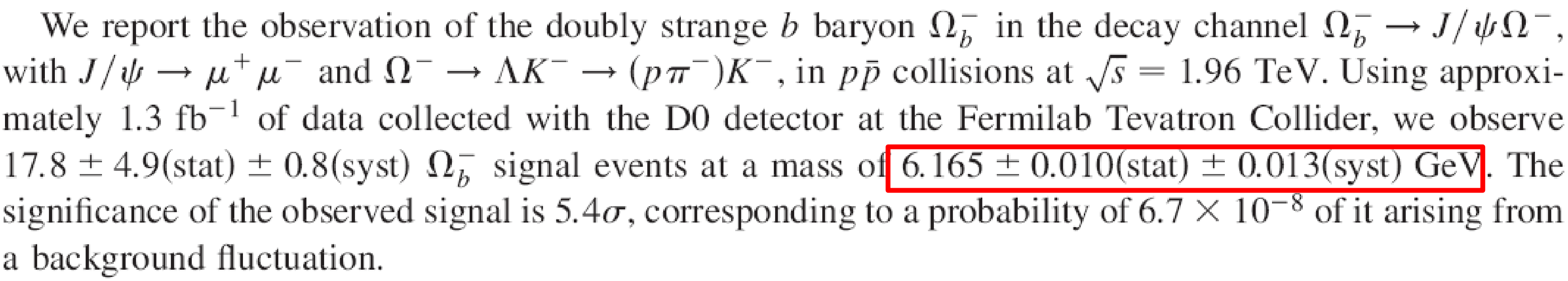
- **Ξ_b isospin splitting**
- **Λ_b and Ξ_b orbital excitations**
- **Ξ_{bc} (bcu)**
- **Ξ_{cc} (ccu)**



PRL **101,** 232002 (2008) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2008

Observation of the Doubly Strange b Baryon Ω_b^-

D0 Collaboration



We report the observation of the doubly strange b baryon Ω_b^- in the decay channel $\Omega_b^- \to J/\psi\Omega^-$, with $J/\psi \to \mu^+\mu^-$ and $\Omega^- \to \Lambda K^- \to (p\pi^-)K^-$, in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. Using approximately 1.3 fb^{-1} of data collected with the D0 detector at the Fermilab Tevatron Collider, we observe $17.8 \pm 4.9(\text{stat}) \pm 0.8(\text{syst})$ Ω_b^- signal events at a mass of $\boxed{6.165 \pm 0.010(\text{stat}) \pm 0.013(\text{syst})\ \text{GeV}}$. The significance of the observed signal is 5.4σ, corresponding to a probability of 6.7×10^{-8} of it arising from a background fluctuation.

Ω_b mass prediction

This gives the following mass predictions:

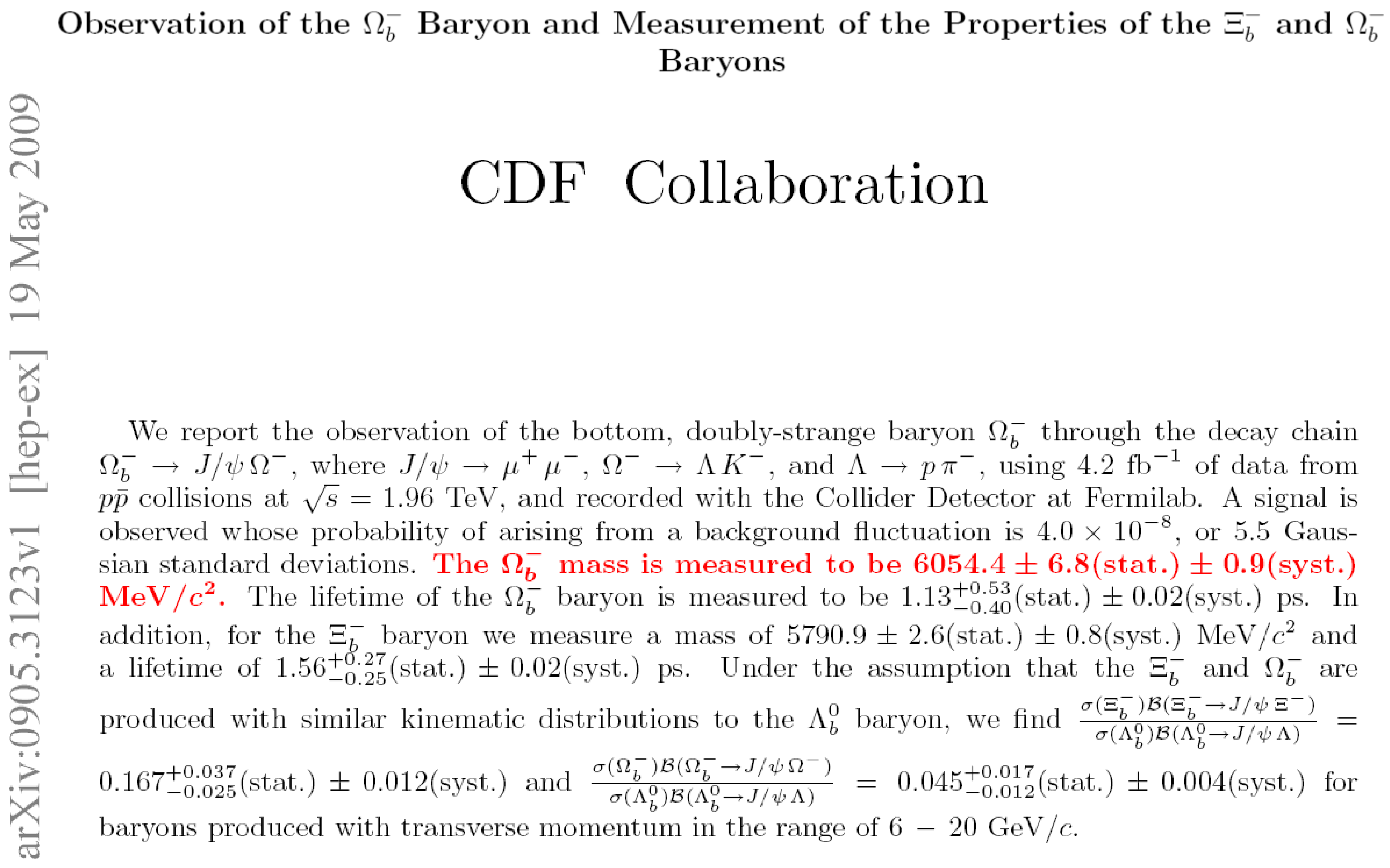
$\Omega_b = 6052.1 \pm 5.6$ MeV $\Omega_b^* = 6082.8 \pm 5.6$ MeV

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

"D0: Ω_b=6165 +/- 10 (stat) +/- 13(syst.)
either wrong or we don't understand something"
M.K. @DIS'09

Work in progress:

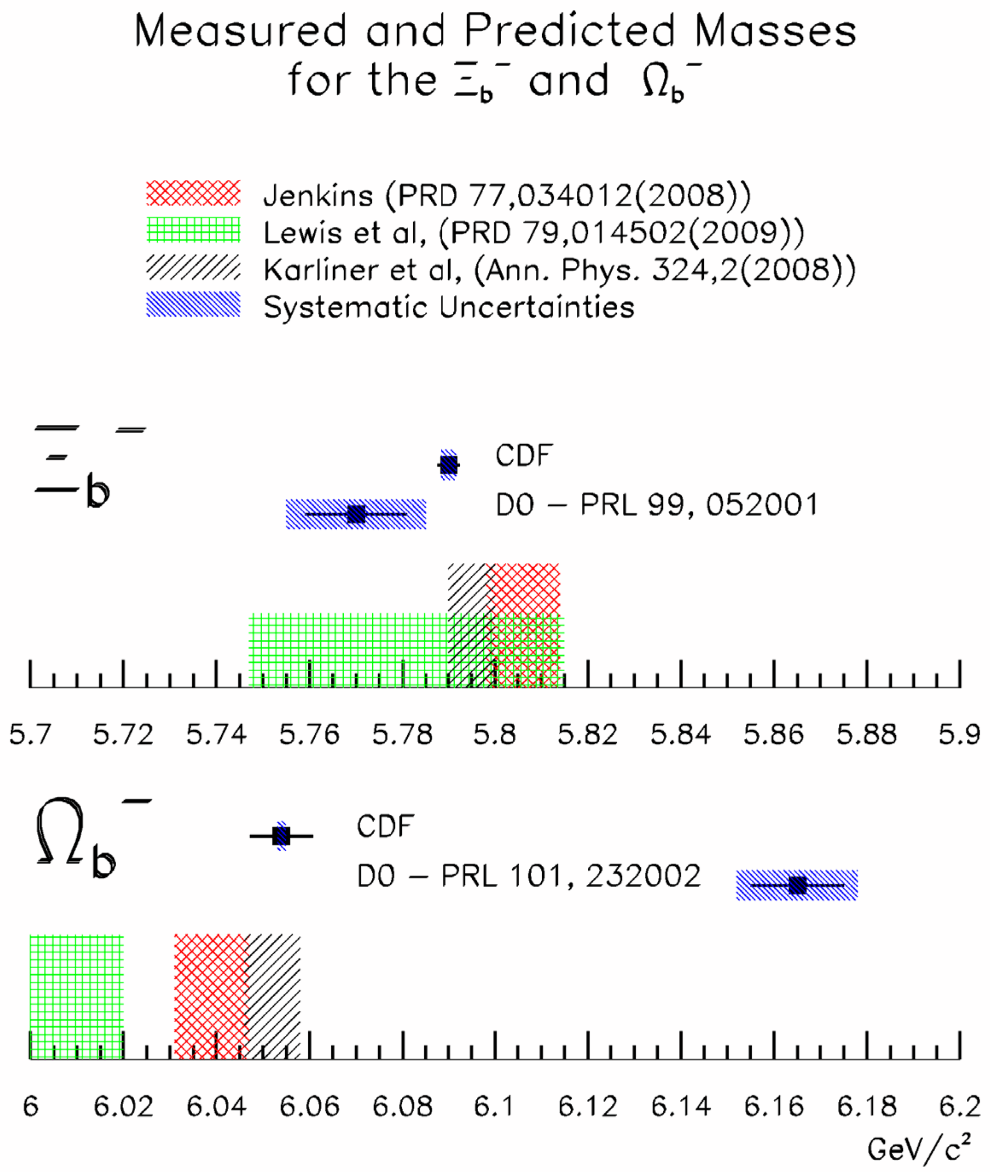
- **Ξ_b isospin splitting**
- **Λ_b and Ξ_b orbital excitations**
- **Ξ_{bc} (bcu)**
- **Ξ_{cc} (ccu)**



Observation of the Ω_b^- Baryon and Measurement of the Properties of the Ξ_b^- and Ω_b^- Baryons

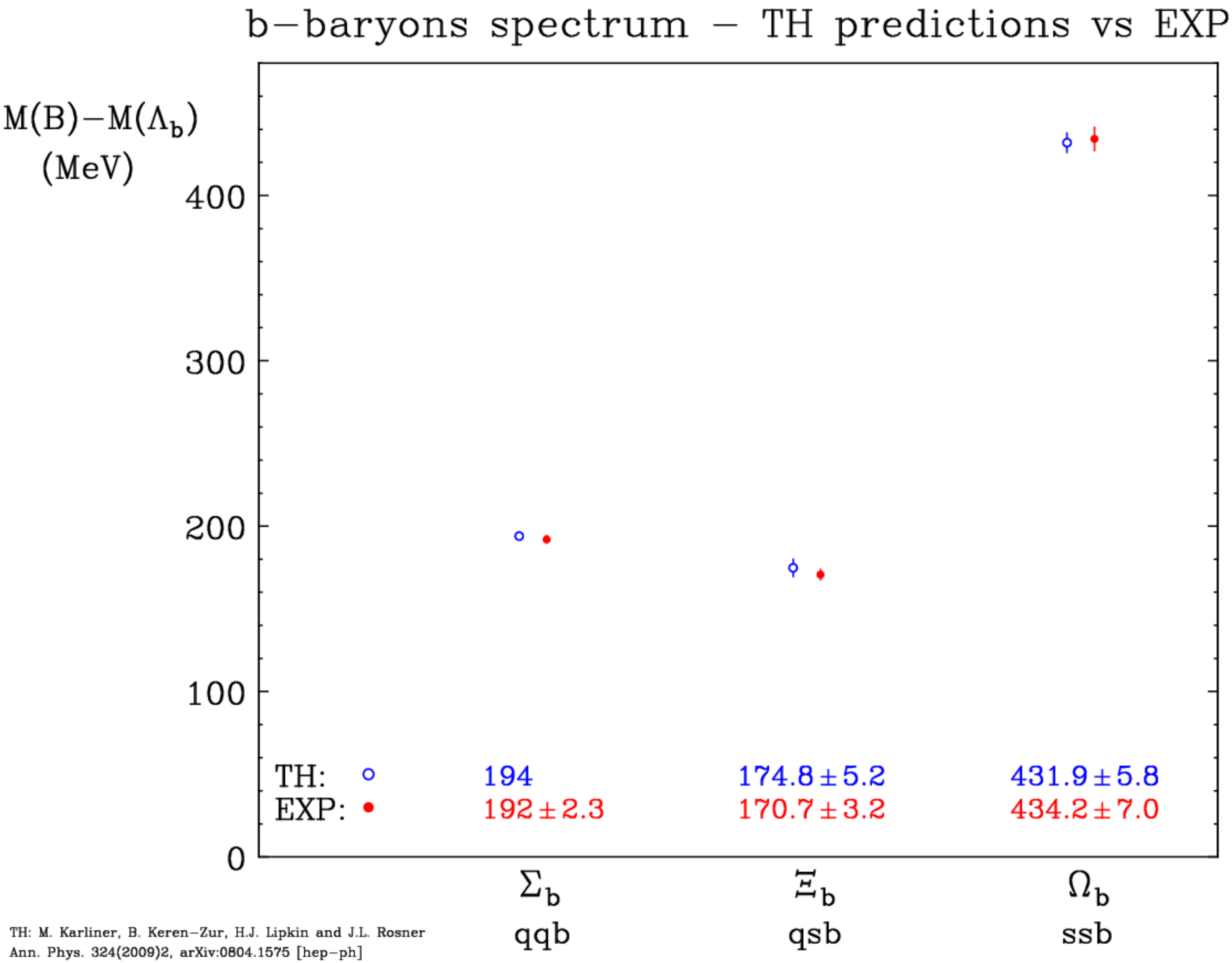
CDF Collaboration

We report the observation of the bottom, doubly-strange baryon Ω_b^- through the decay chain $\Omega_b^- \to J/\psi\,\Omega^-$, where $J/\psi \to \mu^+\mu^-$, $\Omega^- \to \Lambda K^-$, and $\Lambda \to p\pi^-$, using 4.2 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, and recorded with the Collider Detector at Fermilab. A signal is observed whose probability of arising from a background fluctuation is 4.0×10^{-8}, or 5.5 Gaussian standard deviations. **The Ω_b^- mass is measured to be $6054.4 \pm 6.8(\mathrm{stat.}) \pm 0.9(\mathrm{syst.})$ MeV/c^2.** The lifetime of the Ω_b^- baryon is measured to be $1.13^{+0.53}_{-0.40}(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})$ ps. In addition, for the Ξ_b^- baryon we measure a mass of $5790.9 \pm 2.6(\mathrm{stat.}) \pm 0.8(\mathrm{syst.})$ MeV/c^2 and a lifetime of $1.56^{+0.27}_{-0.25}(\mathrm{stat.}) \pm 0.02(\mathrm{syst.})$ ps. Under the assumption that the Ξ_b^- and Ω_b^- are produced with similar kinematic distributions to the Λ_b^0 baryon, we find $\frac{\sigma(\Xi_b^-)\mathcal{B}(\Xi_b^- \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = 0.167^{+0.037}_{-0.025}(\mathrm{stat.}) \pm 0.012(\mathrm{syst.})$ and $\frac{\sigma(\Omega_b^-)\mathcal{B}(\Omega_b^- \to J/\psi\,\Omega^-)}{\sigma(\Lambda_b^0)\mathcal{B}(\Lambda_b^0 \to J/\psi\,\Lambda)} = 0.045^{+0.017}_{-0.012}(\mathrm{stat.}) \pm 0.004(\mathrm{syst.})$ for baryons produced with transverse momentum in the range of $6 - 20$ GeV/c.



Measured and Predicted Masses for the Ξ_b^- and Ω_b^-

Fermilab Seminar – May, 2009


b−baryons spectrum − TH predictions vs EXP

TH: M. Karliner, B. Keren−Zur, H.J. Lipkin and J.L. Rosner
Ann. Phys. 324(2009)2, arXiv:0804.1575 [hep−ph]

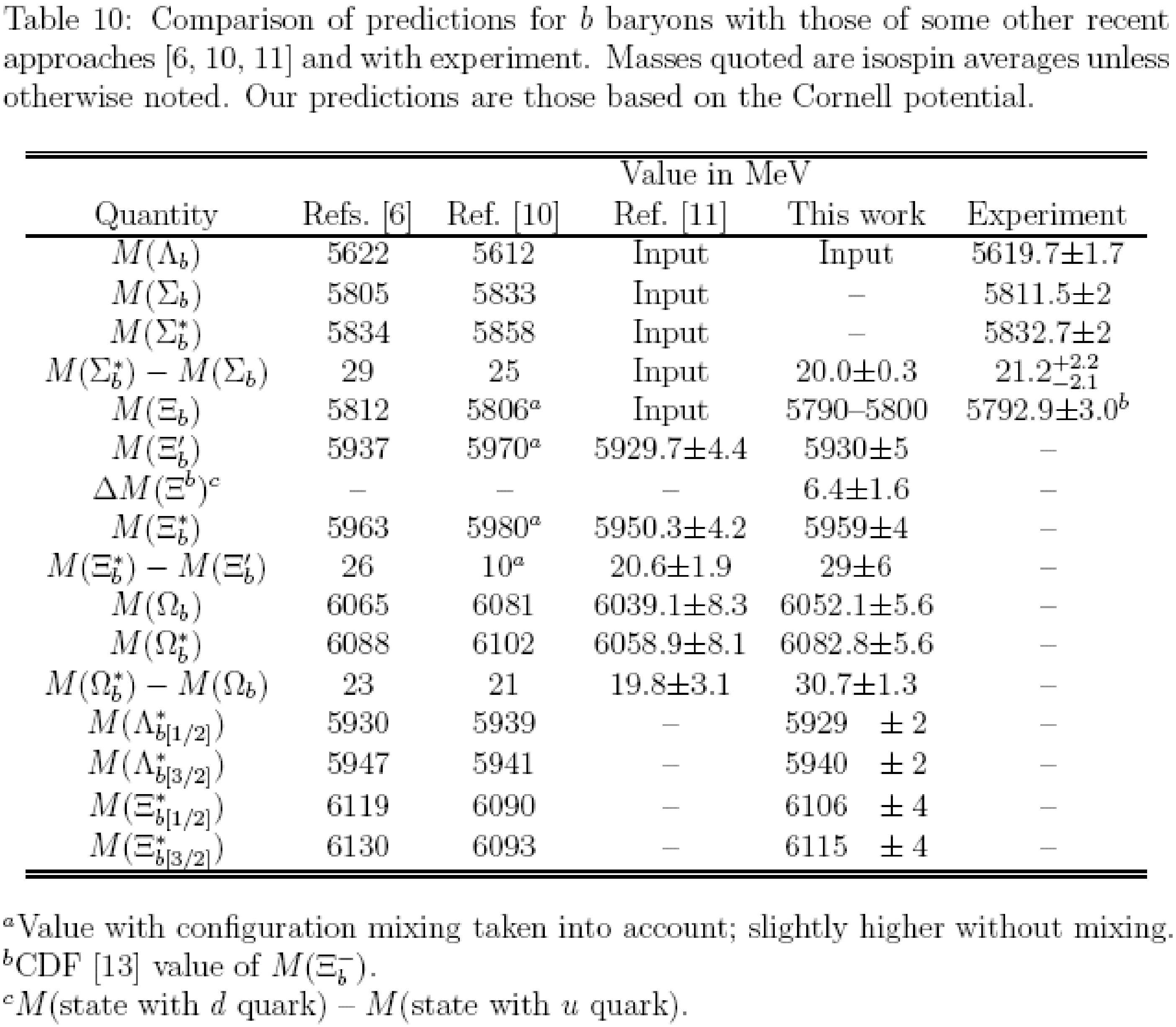


Table 10: Comparison of predictions for b baryons with those of some other recent approaches [6, 10, 11] and with experiment. Masses quoted are isospin averages unless otherwise noted. Our predictions are those based on the Cornell potential.

	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).

Diquarks and antiquarks in exotics: a ménage à trois and a ménage à quatre

- a menage a trois is very different from an ordinary family…
- similarly, exotic hadrons with *both* q-q and q-qbar pairs have important color-space correlations that are completely absent in ordinary mesons and baryons.
- when both present, need to keep in mind that q-qbar interaction is much stronger than q-q interaction

→color structures that are totally different from those in normal hadrons

→unusual experimental properties of
(Q Q qbar qbar) and (Q Qbar q qbar) tetraquarks

leading tetraquark candidate: X(3872)
Seen in $B \rightarrow K \pi^+ \pi^- J/\psi(1S)$
With very high stats by Belle, BaBar and CDF
M[X(3872)] = M(D) + M(D*)
= 1865 + 2007 *to within 1 MeV!*

→b-quark analogue(s)?

TH: for sufficiently heavy Q-s, tetraquarks might be below two meson threshold:
(b qbar bbar q) below B Bbar
(b qbar cbar q) below B Dbar

crucial difference vs. ordinary mesons:
$(Qq)\,(\bar{Q}\bar{q})$ can form a $\mathbf{\bar{6}6}$ color configuration
which has much stronger binding than $\mathbf{\bar{3}3}$

some of these states have exotic electric charge, e.g.
$bd\bar{c}\bar{u}$ → $J/\psi\pi^-\pi^-$

their decays have striking experimental signatures:
monoenergetic photons and/or pions, e.g.
$bq\bar{c}\bar{q}$ with I=0 above $B_c\pi$ threshold can
decay into $B_c\pi$ via isospin violation,

or electromagnetically into $B_c\gamma$

both very narrow!

Unique signal for $b\bar{b}q\bar{q}$ and bbq
double bottom baryons and bb tetratqaurks

- $b \rightarrow c\,\bar{c}\,s \rightarrow J/\psi\ s$

so bbq → $J/\psi\ J/\psi\ (ssq) \rightarrow J/\psi\ J/\psi\ \Xi$

similarly $b\bar{b}q\bar{q} \rightarrow J/\psi\ J/\psi\ (s\bar{s}q\bar{q}) \rightarrow J/\psi\ J/\psi\ K\ K$

and $bb\bar{q}\bar{q}$

With all final state hadrons coming from the same vertex

Unique signature but v. low rate - is there enough data?

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

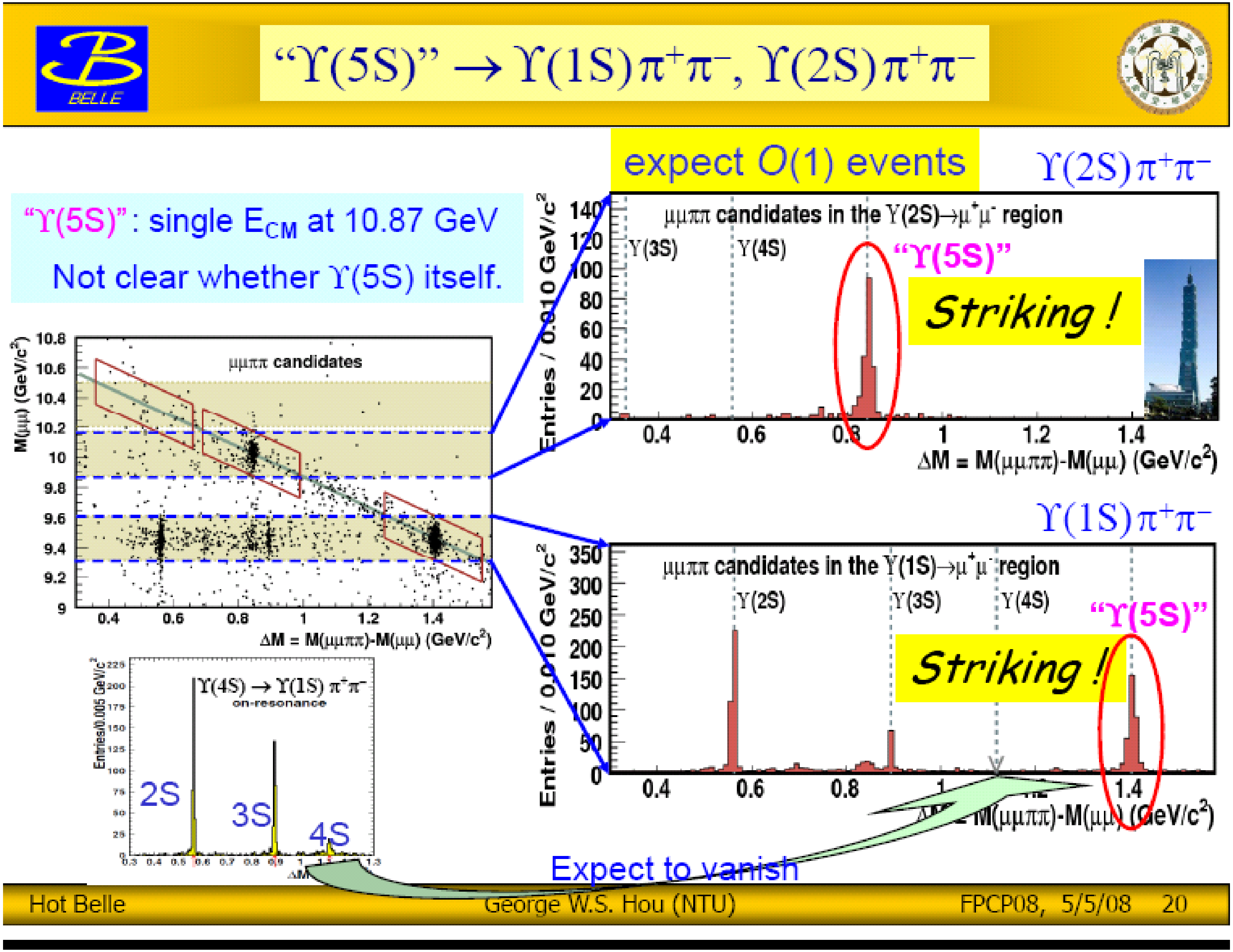
$$\Upsilon(5S) \to \Upsilon(1S)\,\pi^+\pi^-$$

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

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 $J/\psi\pi^{\pm}$



"$\Upsilon(5S)$" → $\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(2S)\pi^+\pi^-$

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

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

expect *O*(1) events

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

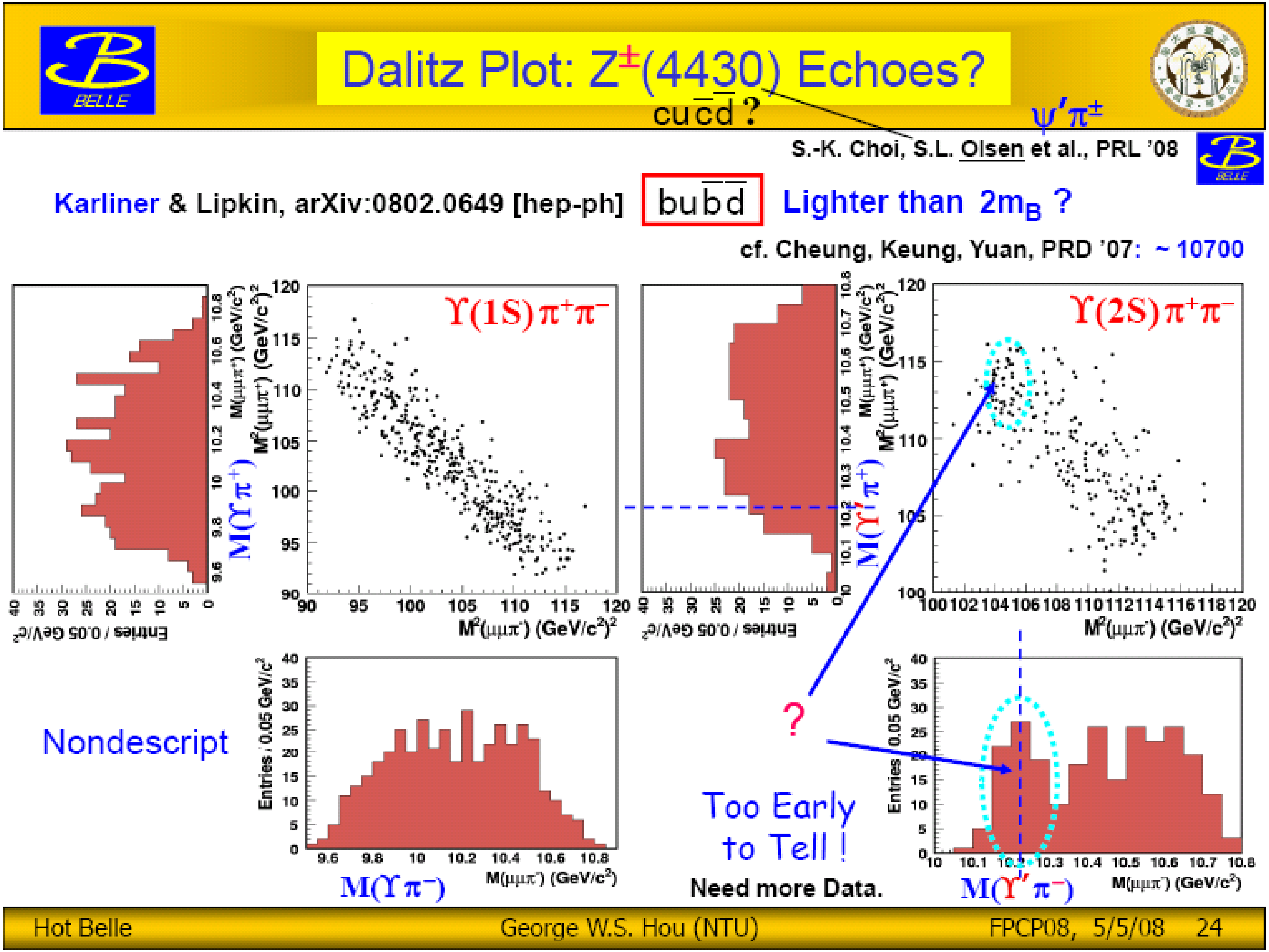
Striking !

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

Striking !

Expect to vanish

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



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] $bu\bar{b}\bar{d}$ **Lighter than $2m_B$?**

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

Nondescript

Too Early to Tell !

Need more Data.

Hot Belle George W.S. Hou (NTU) FPCP08, 5/5/08 24

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?
- η_b : BaBar & CLEO. $\Upsilon(1S)$ - η_b too large. Mixing ?

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, Ω_b mass predictions: better than 3 MeV
- $\Upsilon(1S)$ - η_b : too large ?

Backup slides

can rederive without assuming HF ~ 1/m_q

a weaker assumption of same flavor dependence suffices

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

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

$$0.32 \approx 0.33 \approx 0.325$$

In Jewish mysticism, the KABALA, one can uncover the secret meaning of Hebrew words by computing their numerical value from their constituent letters, e.g.

ALEPH =1, BET=2, GIMEL=3, etc.,

and comparing with other words' numerical values.

In a famous incident, Viki Weisskopf, attempting to mock this scheme, challenged an expert to explain 137= $1/\alpha$.

He was astonished and humbled when told that 137 is the numerical value of no other but the word KABALA itself:

(5+30+2+100)