Heavy baryon spectrum new heavy exotics and isospin breaking

Marek Karliner

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

Hadron 2011, Munchen, June 17, 2011

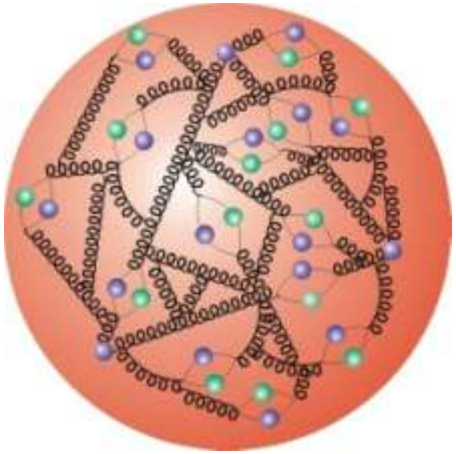
Outline

- spin-spin interaction between quarks – “color magnetic”
- same constituent quark masses in mesons and baryons
- known baryons + mesons ➔ predictions for
  new heavy baryons: magnetic moments & masses
- apps to heavy exotic QQqq mesons → predictions for Belle
- Belle 5/2001: two Z_b(I=1) exotic mesons ~@ B+B*, B*+B*

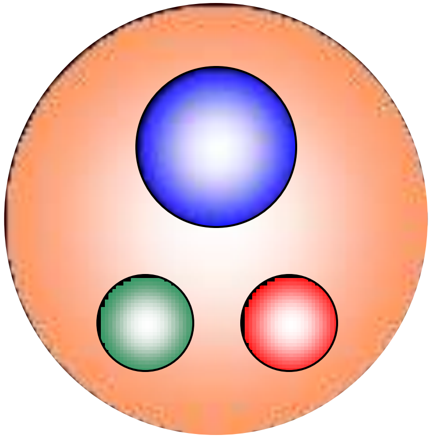
→ additional, more deeply bound states with I=0

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:



$$M = \sum_i m_i$$



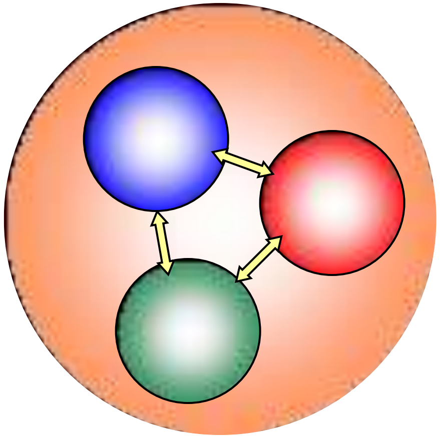
- the binding & kinetic energies "swallowed" by the constituent quarks masses.

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.

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

  - 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 ratios

- example II:

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

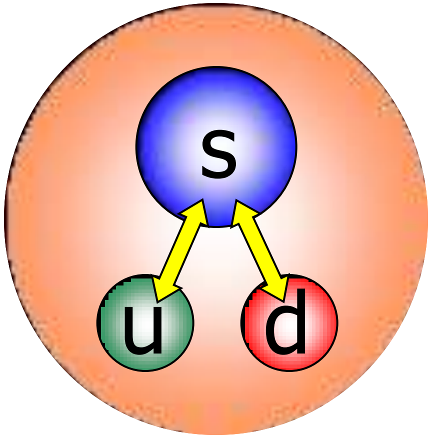
$$= 4 v_0 \frac{\left(\vec{\lambda}_u \cdot \vec{\lambda}_{\bar{s}}\right)}{m_u m_s} \langle \psi | \delta(r) | \psi \rangle$$

- extracting quark masses ratio:

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

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



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

- 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

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

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)

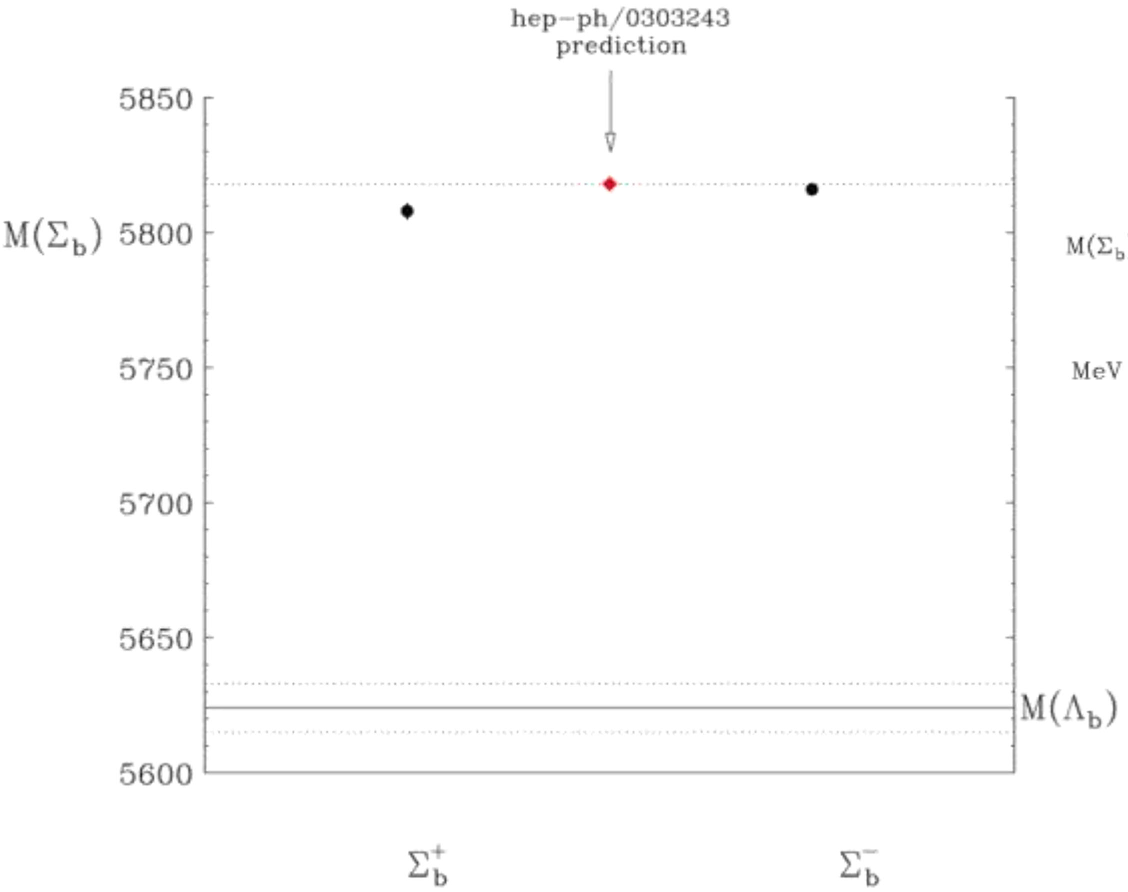
CDF obtained the masses of the Σ_b^- and Σ_b^+ from the decay $\Sigma_b \to \Lambda_b + \pi$ by measuring the corresponding mass differences

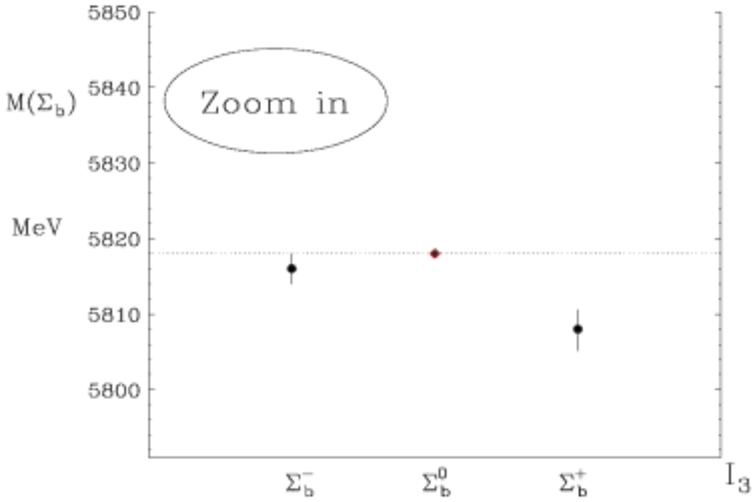
$$M(\Sigma_b^-) - M(\Lambda_b) = 195.5^{+1.0}_{-1.0}\,(\text{stat.}) \pm 0.1\,(\text{syst.})\ \text{MeV}$$

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

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

new result from CDF at Hadron 2011: **193 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

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

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

new result from CDF at
Hadron 2011: **20 MeV**

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

→

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

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

challenge to EXP !

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:

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

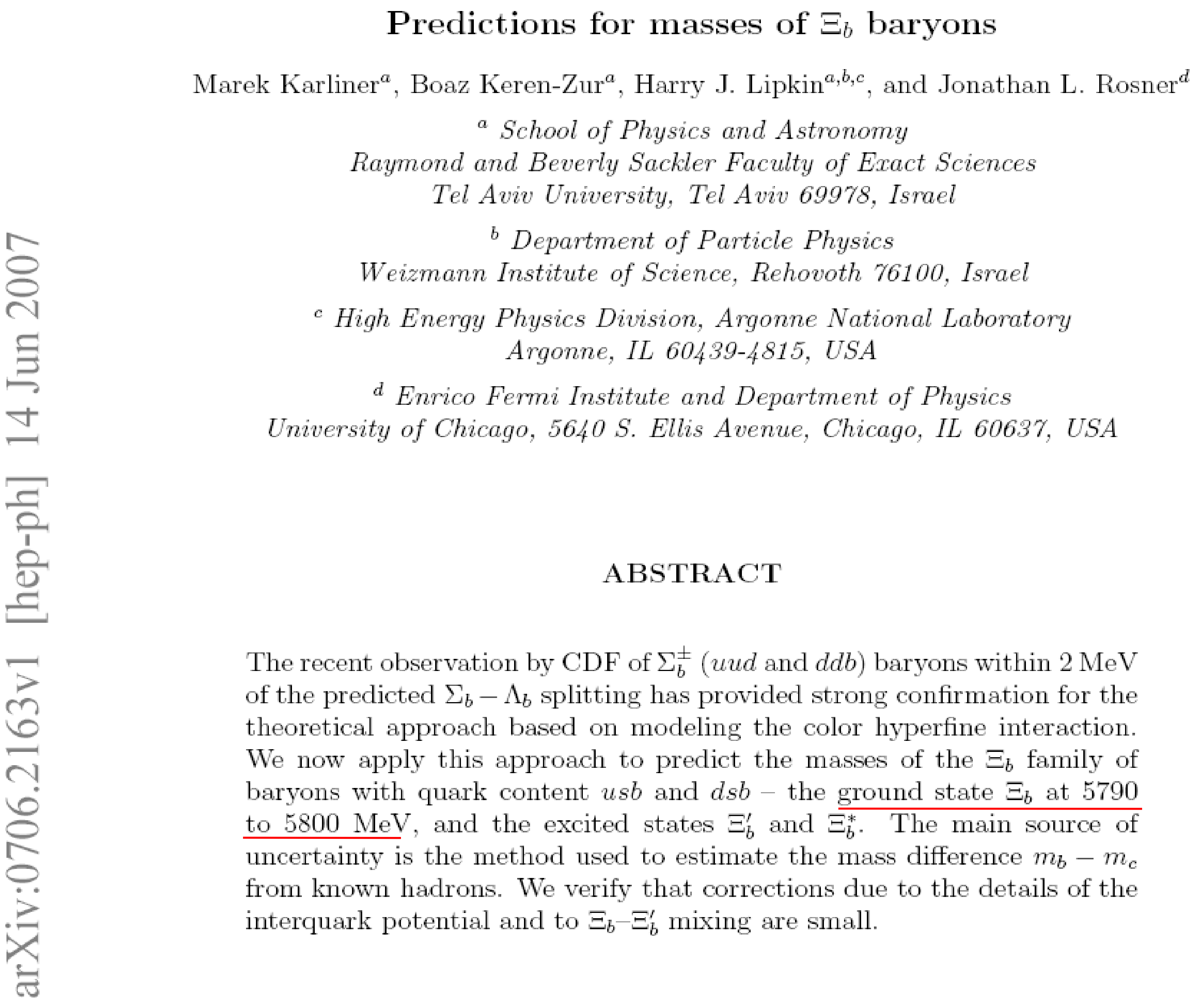
several options for obtaining $m_b - m_c$ from data:

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

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

- 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:

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



Predictions for masses of Ξ_b baryons

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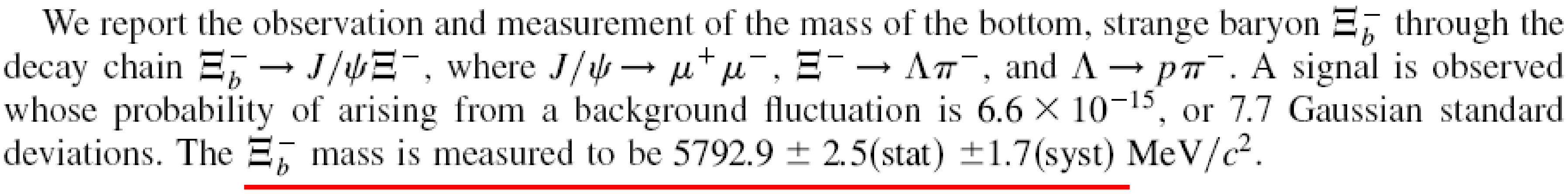
ABSTRACT

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

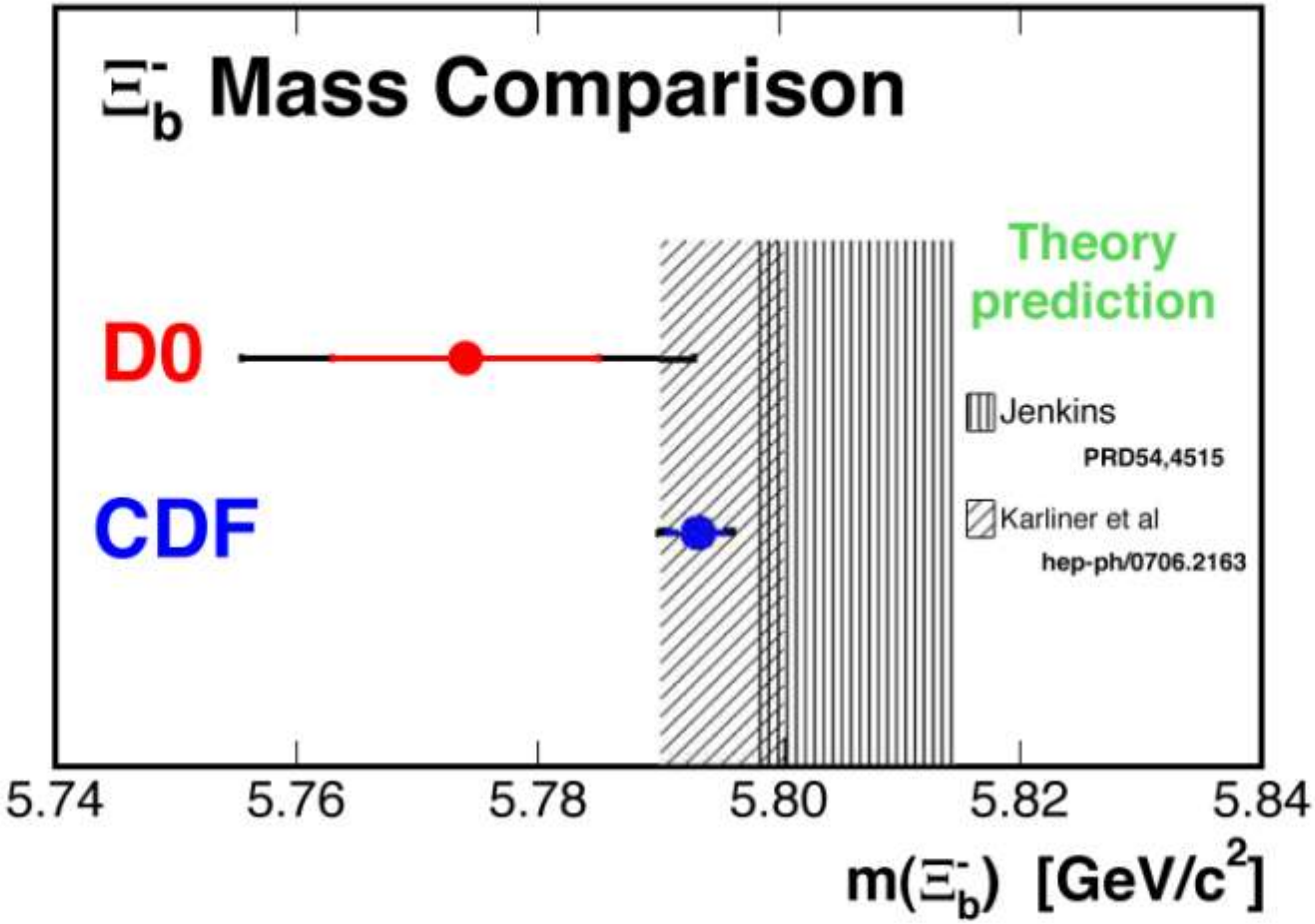
Observation and Mass Measurement of the Baryon Ξ_b^-

(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
D0
CDF
Theory prediction
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]

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

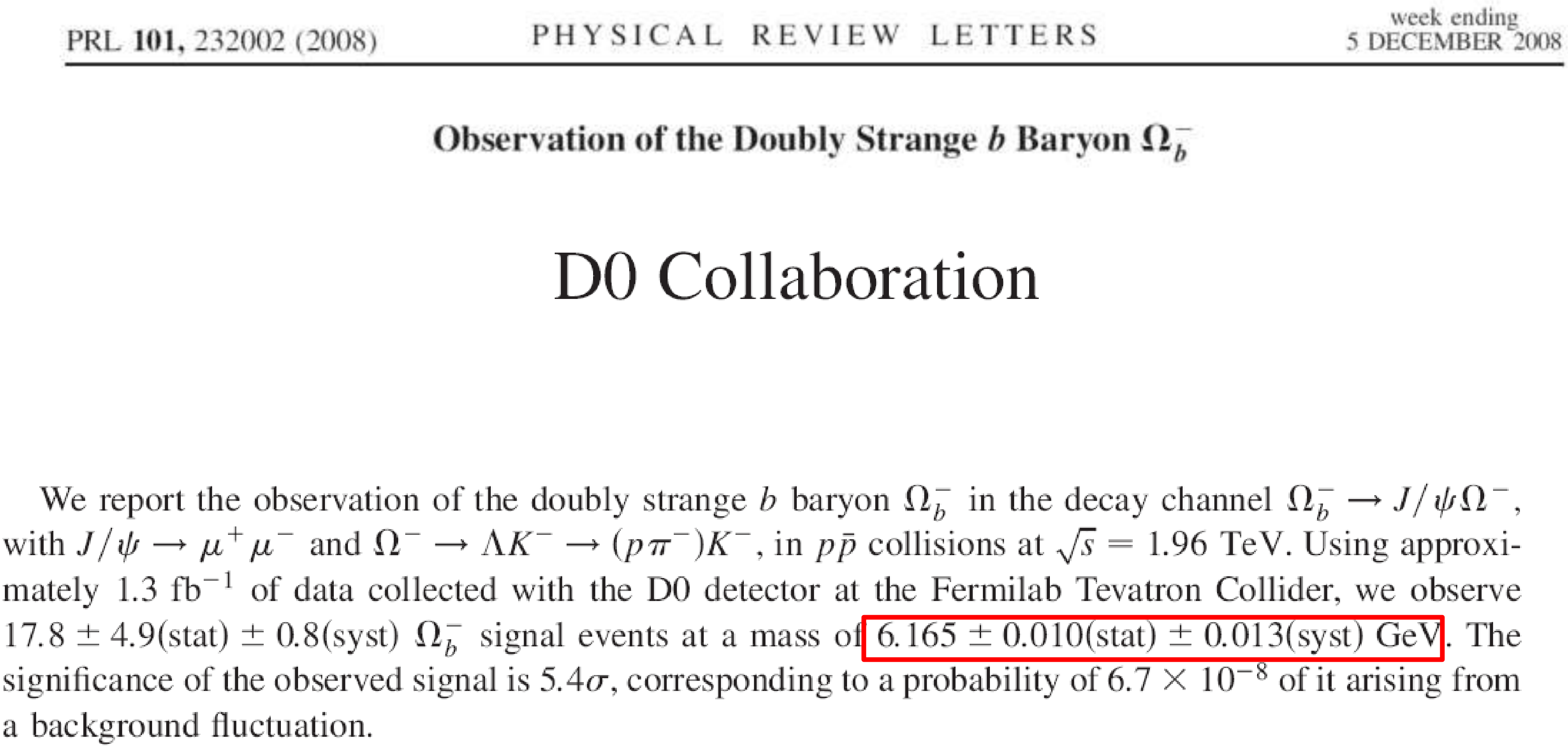
This gives the following mass predictions:

$\Omega_b = 6052.1 \pm 5.6$ 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)**



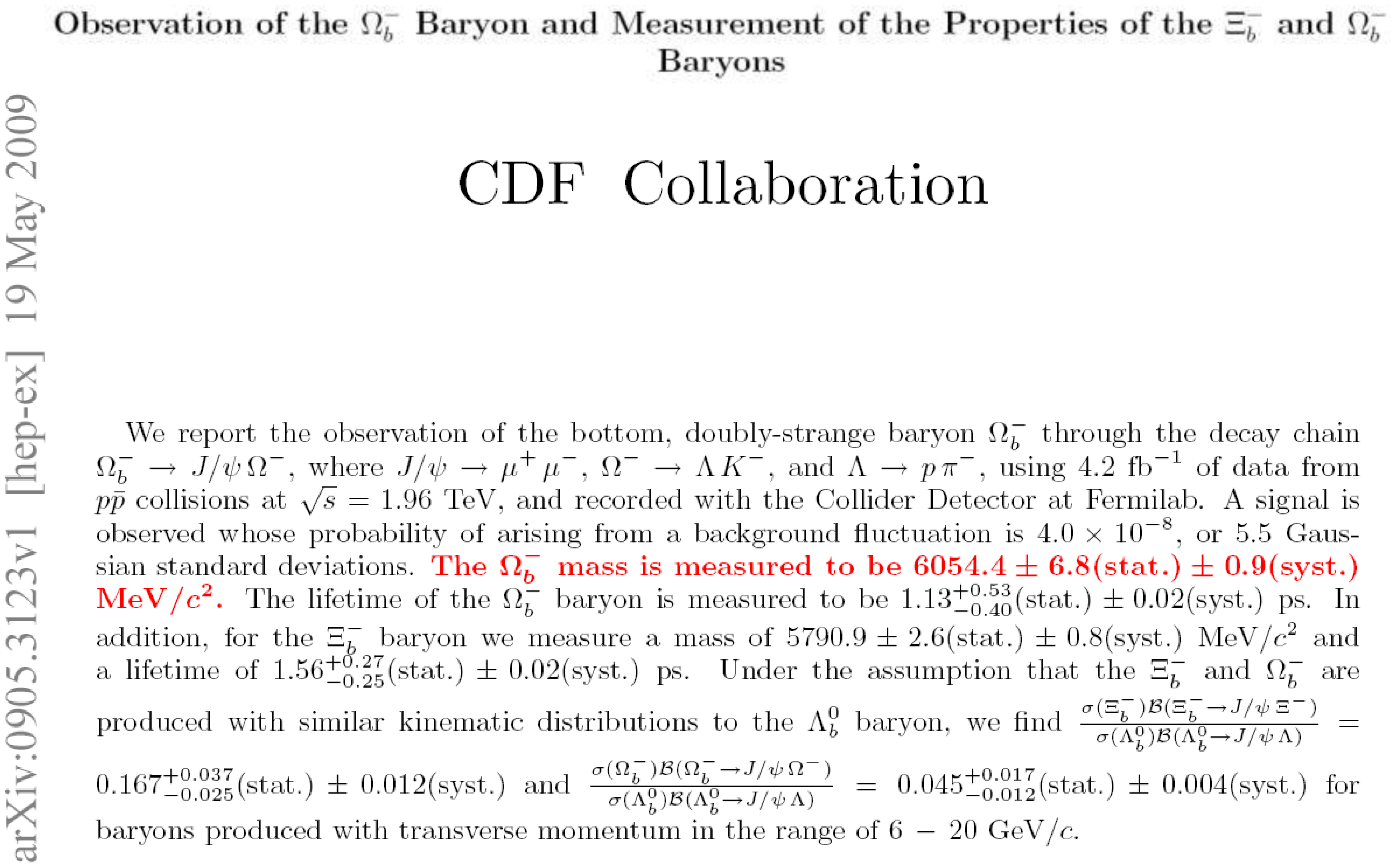
PRL **101,** 232002 (2008) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2008

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 $6.165 \pm 0.010(\text{stat}) \pm 0.013(\text{syst})$ 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.

M.K. @DIS’09:
“D0: Ω_b=6165 +/- 10 (stat) +/- 13(syst.) --- wrong”

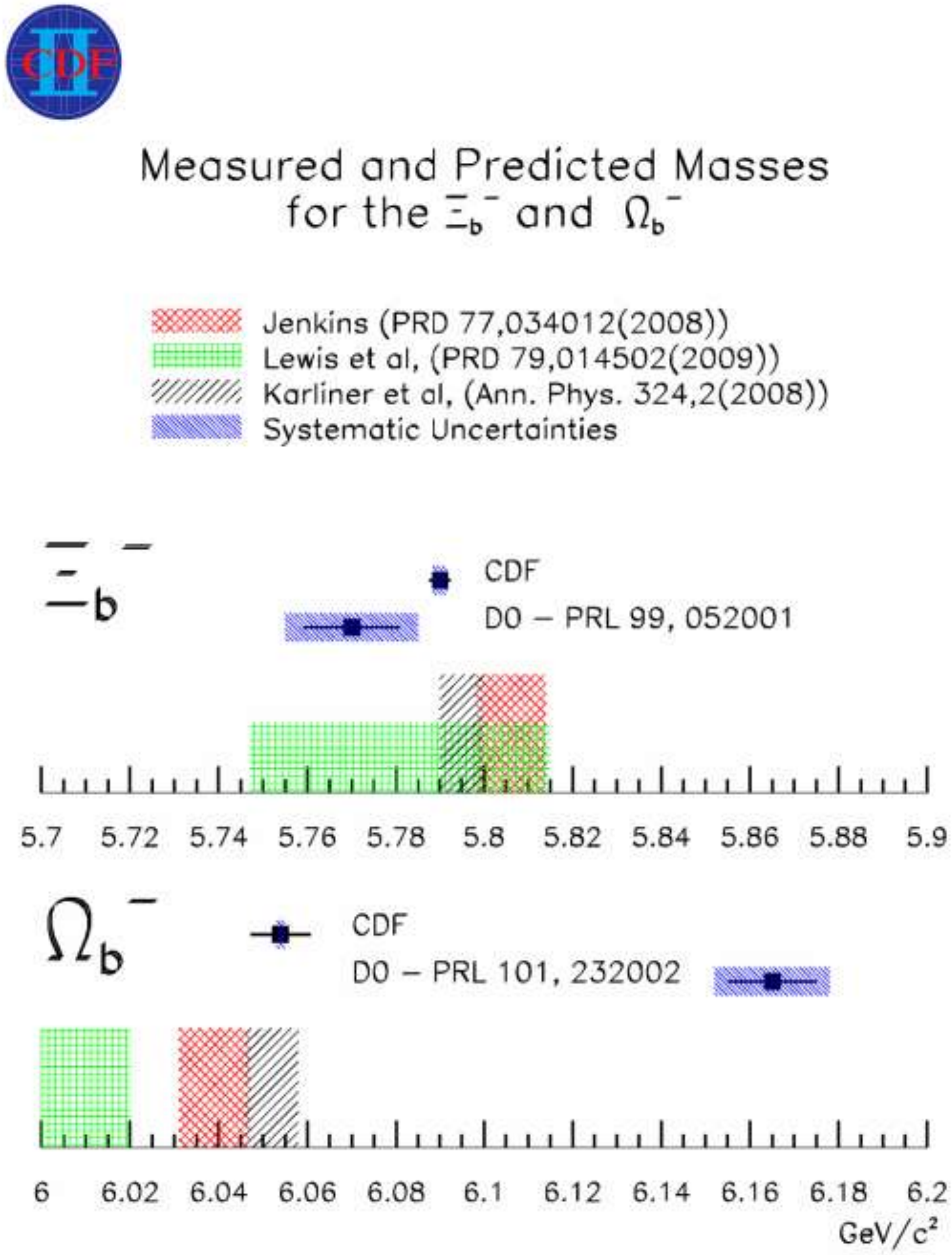


Observation of the Ω_b^- Baryon and Measurement of the Properties of the Ξ_b^- and Ω_b^- Baryons

arXiv:0905.3123v1 [hep-ex] 19 May 2009

CDF Collaboration

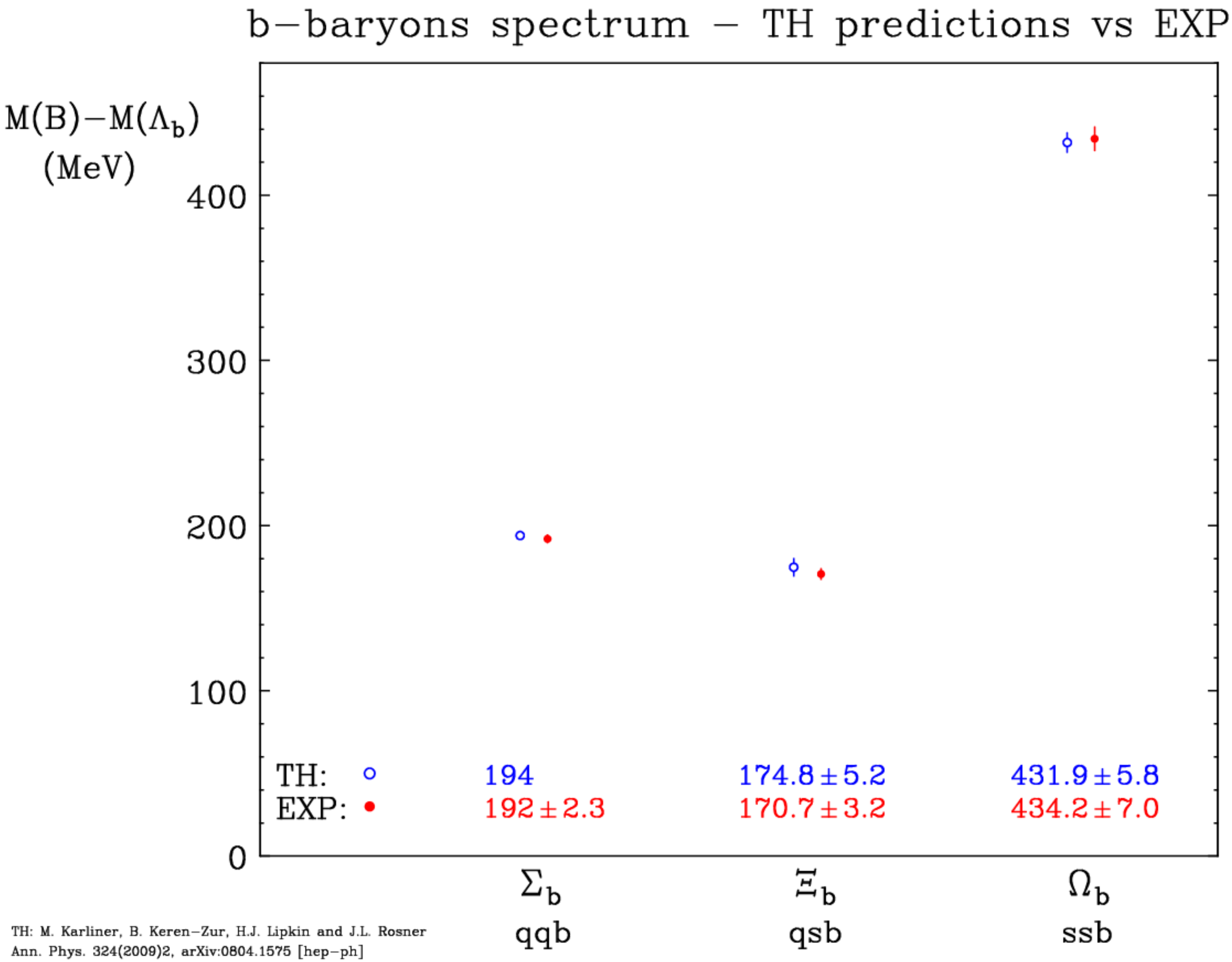
We report the observation of the bottom, doubly-strange baryon Ω_b^- through the decay chain $\Omega_b^- \to J/\psi\, \Omega^-$, where $J/\psi \to \mu^+ \mu^-$, $\Omega^- \to \Lambda K^-$, and $\Lambda \to p \pi^-$, using 4.2 fb^{-1} of data from $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV, and recorded 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^-

▨ Jenkins (PRD 77,034012(2008))
▨ Lewis et al, (PRD 79,014502(2009))
▨ Karliner et al, (Ann. Phys. 324,2(2008))
▨ Systematic Uncertainties

Fermilab Seminar – May, 2009



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

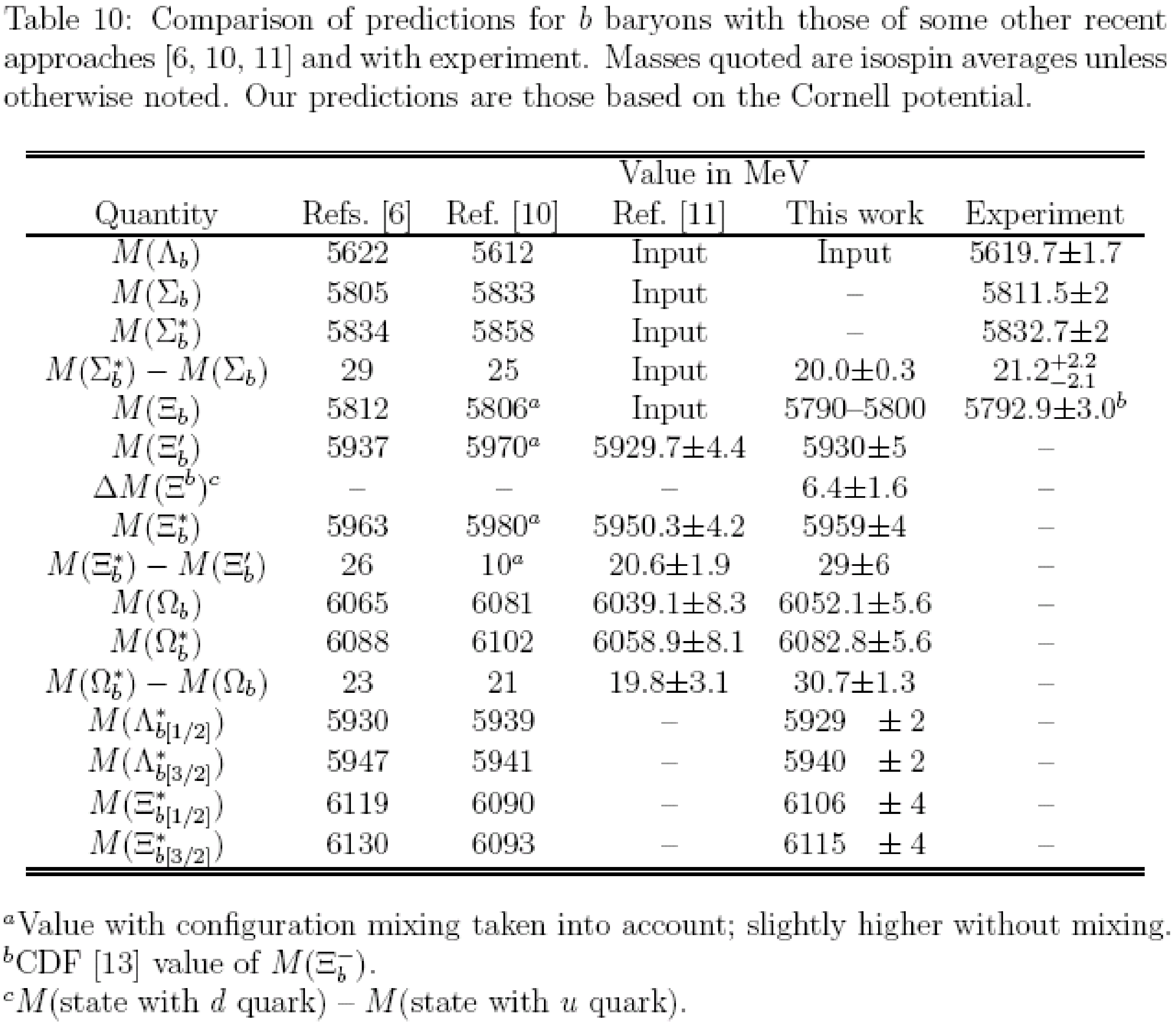


Table 10: Comparison of predictions for b baryons with those of some other recent approaches [6, 10, 11] and with experiment. Masses quoted are isospin averages unless otherwise noted. Our predictions are those based on the Cornell potential.

	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

until 5/2011:

leading tetraquark candidate: X(3872)

Seen in $B \to K \pi^+ \pi^- J/\psi(1S)$

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 $\bar{\mathbf{6}}\mathbf{6}$ color configuration
which has much stronger binding than $\bar{\mathbf{3}}\mathbf{3}$

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

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

so $bbq \to J/\psi\ J/\psi\ (ssq) \to J/\psi\ J/\psi\ \Xi$

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

and $bb\overline{qq}$

With all final state hadrons coming from the same vertex

Unique signature but v. low rate.
Challenge & opportunity for LHCb !

2008: Belle reported anomalously large BR (2 orders of mag.)

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

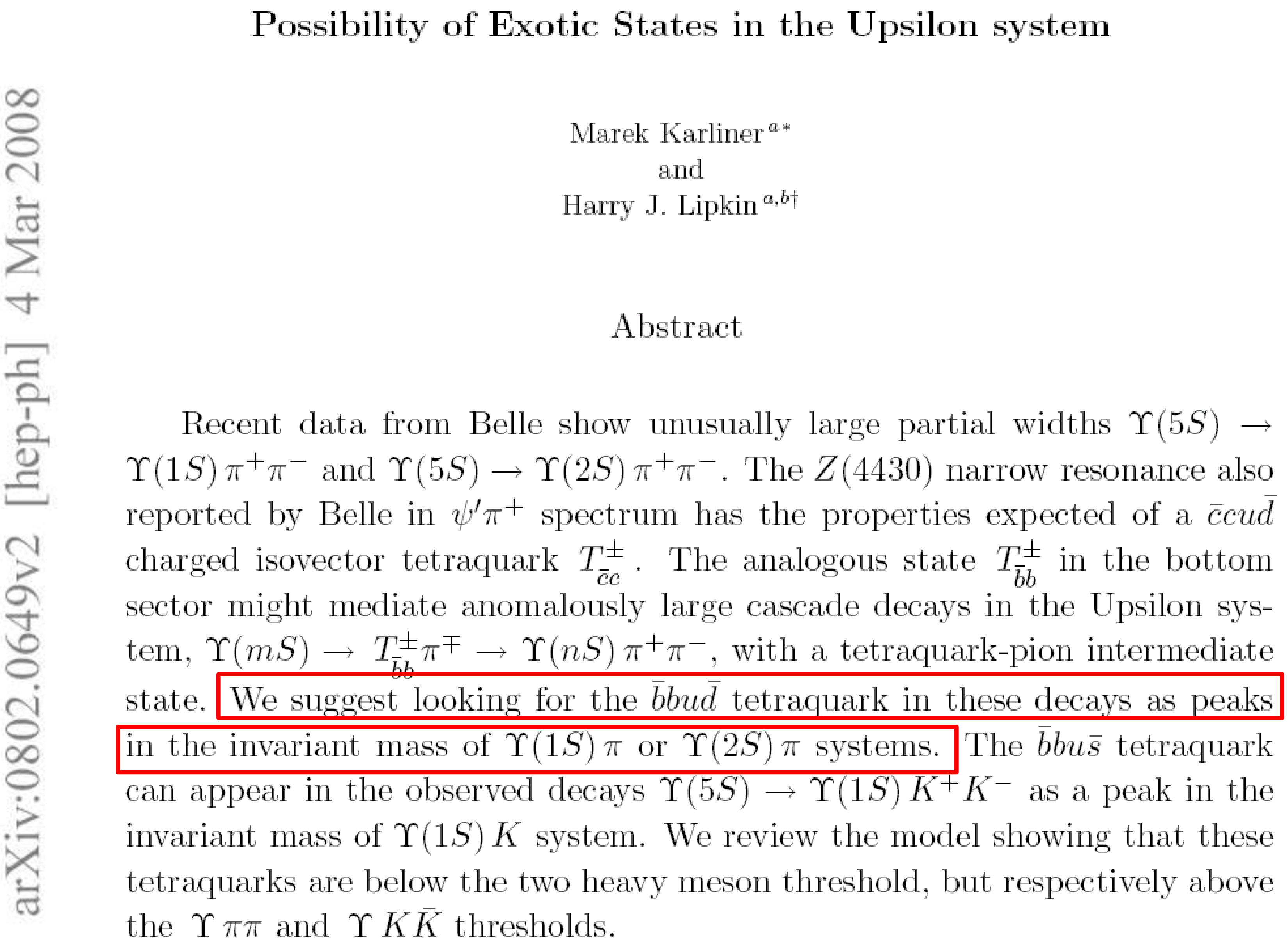
$$\Upsilon(5S) \rightarrow \Upsilon(2S)\,\pi^+\pi^-$$

0802.0649 [hep-ph], Lipkin & M.K.:

Enhancement due to mediation by $\bar{b}bu\bar{d}$ tetraquark T_bb:

B B*-bar ≈ (b-bar b u dbar)

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

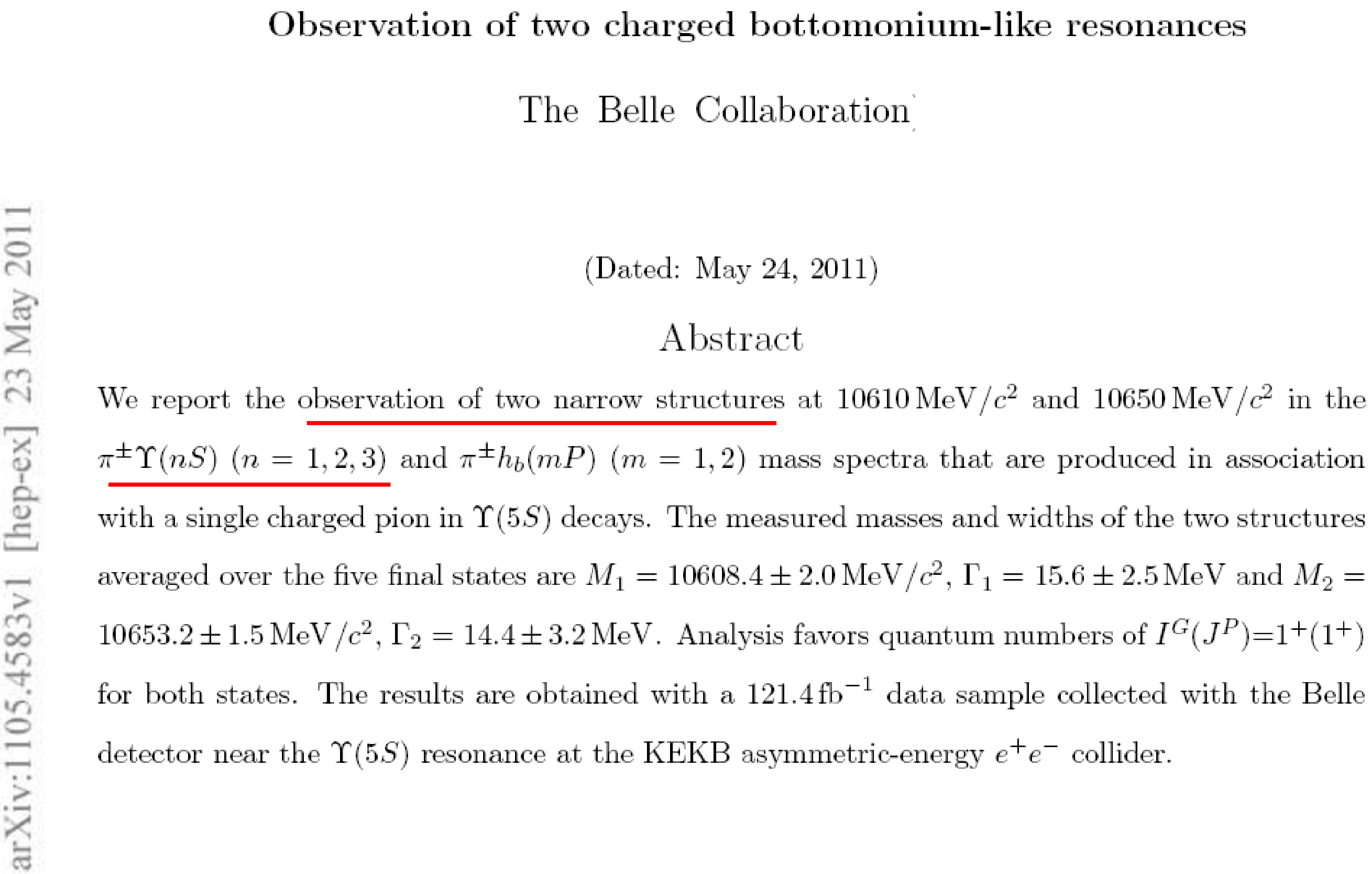


Possibility of Exotic States in the Upsilon system

Marek Karliner[a*]
and
Harry J. Lipkin[a,b†]

Abstract

Recent data from Belle show unusually large partial widths $\Upsilon(5S) \to \Upsilon(1S)\,\pi^+\pi^-$ and $\Upsilon(5S) \to \Upsilon(2S)\,\pi^+\pi^-$. The $Z(4430)$ narrow resonance also reported by Belle in $\psi'\pi^+$ spectrum has the properties expected of a $\bar c c u \bar d$ charged isovector tetraquark $T^{\pm}_{\bar c c}$. The analogous state $T^{\pm}_{\bar b b}$ in the bottom sector might mediate anomalously large cascade decays in the Upsilon system, $\Upsilon(mS) \to T^{\pm}_{\bar b b}\pi^{\mp} \to \Upsilon(nS)\,\pi^+\pi^-$, with a tetraquark-pion intermediate state. We suggest looking for the $\bar b b u \bar d$ tetraquark in these decays as peaks in the invariant mass of $\Upsilon(1S)\,\pi$ or $\Upsilon(2S)\,\pi$ systems. The $\bar b b u \bar s$ tetraquark can appear in the observed decays $\Upsilon(5S) \to \Upsilon(1S)\,K^+K^-$ as a peak in the invariant mass of $\Upsilon(1S)\,K$ system. We review the model showing that these tetraquarks are below the two heavy meson threshold, but respectively above the $\Upsilon\,\pi\pi$ and $\Upsilon\,K\bar K$ thresholds.



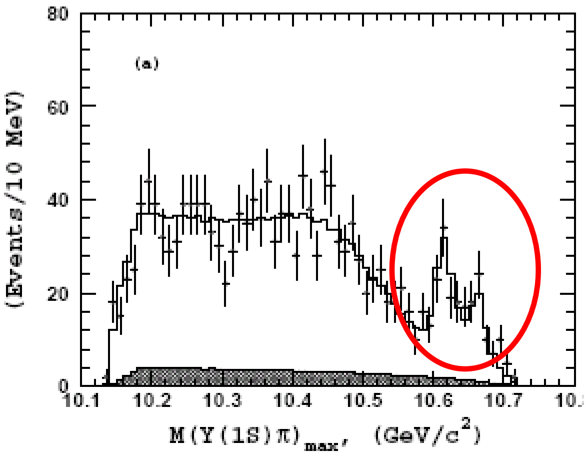
Observation of two charged bottomonium-like resonances

The Belle Collaboration

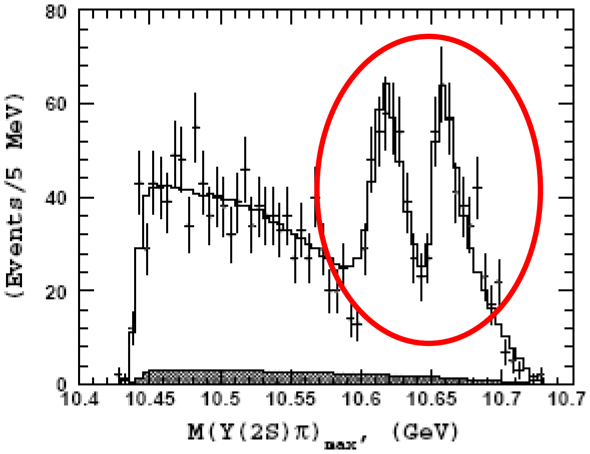
(Dated: May 24, 2011)

Abstract

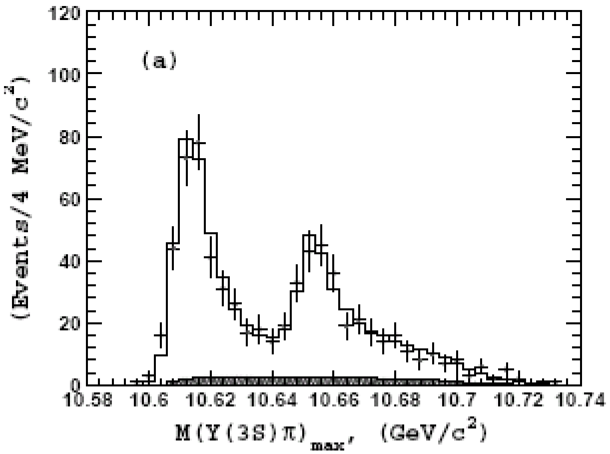
We report the observation of two narrow structures at 10610 MeV/c^2 and 10650 MeV/c^2 in the $\pi^{\pm}\Upsilon(nS)$ $(n = 1, 2, 3)$ and $\pi^{\pm}h_b(mP)$ $(m = 1, 2)$ mass spectra that are produced in association with a single charged pion in $\Upsilon(5S)$ decays. The measured masses and widths of the two structures averaged over the five final states are $M_1 = 10608.4 \pm 2.0\,\mathrm{MeV}/c^2$, $\Gamma_1 = 15.6 \pm 2.5\,\mathrm{MeV}$ and $M_2 = 10653.2 \pm 1.5\,\mathrm{MeV}/c^2$, $\Gamma_2 = 14.4 \pm 3.2\,\mathrm{MeV}$. Analysis favors quantum numbers of $I^G(J^P)$=$1^+(1^+)$ for both states. The results are obtained with a $121.4\,\mathrm{fb}^{-1}$ data sample collected with the Belle detector near the $\Upsilon(5S)$ resonance at the KEKB asymmetric-energy e^+e^- collider.



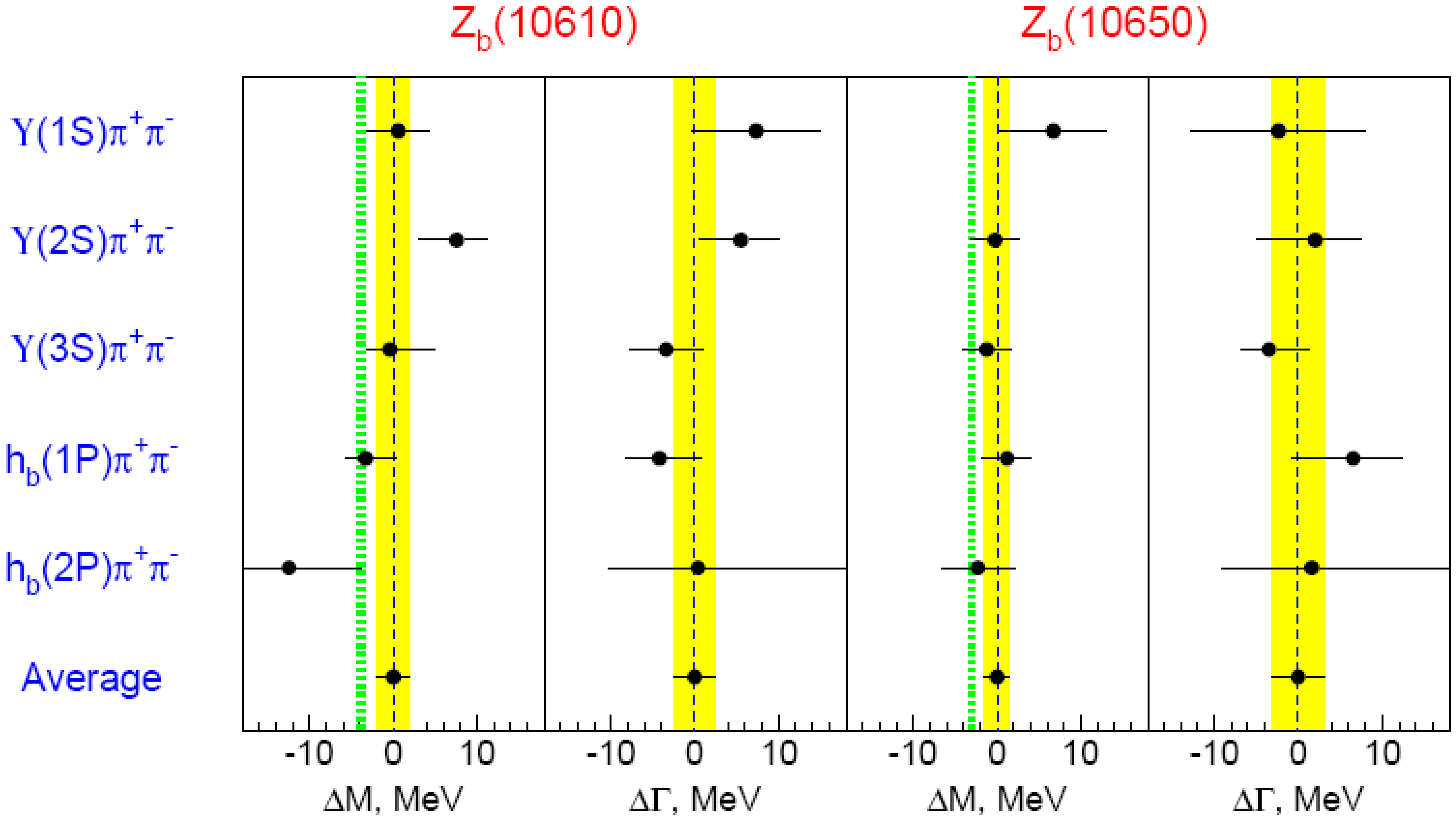
$$\Upsilon(3S)\pi^+$$



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



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



Comparison of $Z_b(10610)$ and $Z_b(10650)$ parameters obtained from different decay channels. The vertical dotted lines indicate $B^*\overline{B}$ and $B^*\overline{B}^*$ thresholds.

$$J^P = 1^+ \text{ for both } Z_b(10610) \text{ and } Z_b(10650)$$

Alternative (complementary ?) desc. as "molecule"

Tornqvist, Z. Phys. C61,525 (1993):

Heavy-light Qq mesons have I=1/2

→ they couple to pions

→ deuteron-like meson-meson bound states, "deusons" via pion exchange:

$D\bar{D}$* (I=0) at threshold ←→ X(3872) !

S-wave → $J^P = 1^+$

I=1 attraction x3 weaker than I=0 → no I=1

What about B B-bar* analogue ?...

B B* vs D D*:

-- same attractive potential

-- much heavier, so smaller kinetic energy

→ expect $B\bar{B}^*$ and $B^*\bar{B}^*$ I=1 states near threshold

→ $Z_b(10610)$ and $Z_b(10650)$ seen by Belle !!!

I=0 binding much stronger

→I=0 states expected 20-30 MeV below threshold

EXP signature:

Z_b(I=0) → Υ(ns) π+ π-

Z_b(I=0) → B B-bar γ via EM B* → B γ, E(γ)=46 MeV

→ LHCb!

$\Sigma_b^+\Sigma_b^-$ dibaryon ?

Σ_b heavier, with I=1 → stronger binding via π

→ deuteron-like J=1, I=0 bound state: “beautron”

exp. signature:

(Σ_b Σ_b) → Λ_b Λ_b π π

Γ(Σ_b) = 4.3+-3 MeV, Γ(Σ_b) = 9.2+-3 MeV

- +

so might be visible

should be seen in lattice QCD

Summary

- consitituent quark model with color HF interaction

  → Σ_b, Ξ_b, Ω_b masses predicted to ≤ 3MeV
- challenge for theory: derivation from QCD
- prediction: $\mu_{\Lambda_c} = 0.43\,\mathrm{n.m.} \quad \mu_{\Lambda_b} = -0.067\,\mathrm{n.m.}$
- QQqq tetraquarks: new color structures,

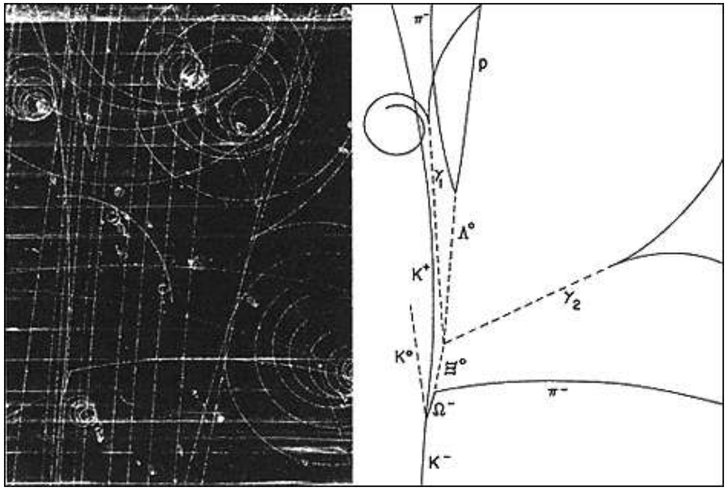
  unique exp. signatures
- prediction for $\Upsilon(nS)\,\pi^+$ peaks → just seen by Belle

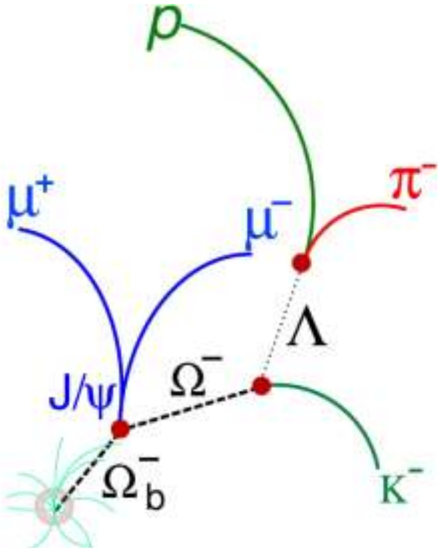
- → new I=0 exotic states below threshold:

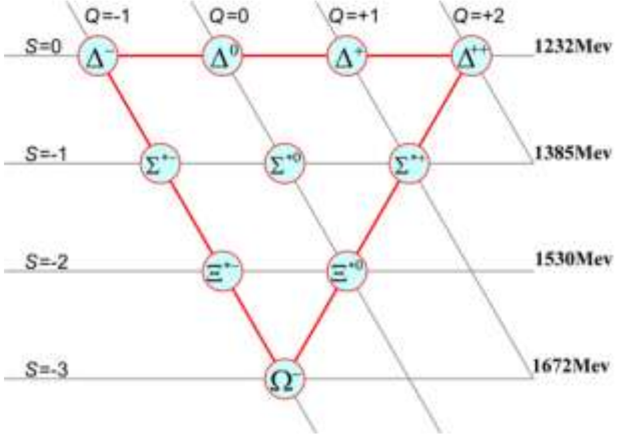
  BB*,B*B*, **Σ_b Σ_b , …**

Backup slides

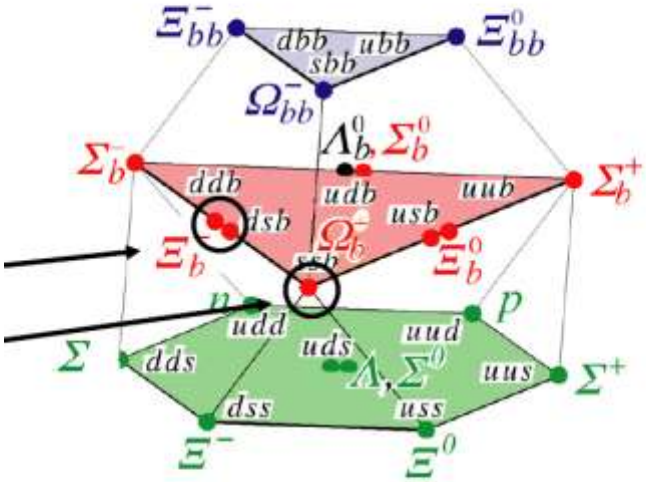
From Ω^- to Ω_b







J =1/2 b Baryons



constituent quark mass differences

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

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

$$= 0$$

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

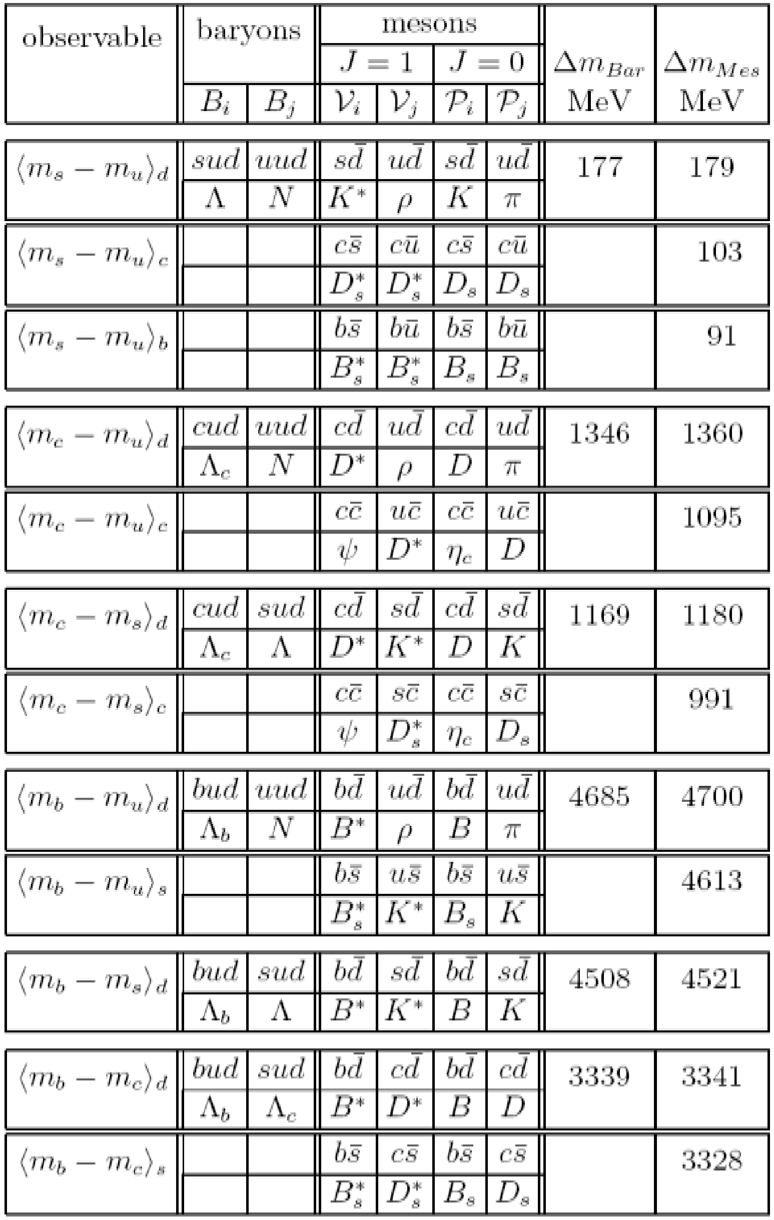
"how much you weigh depends

on *who your neighbors are"*

→ challenge to npQCD

MK & Lipkin, hep-ph/0307243

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		

Testing confining potentials through meson/baryon HF splitting ratio

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

- from constituent quarks model can derive:

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

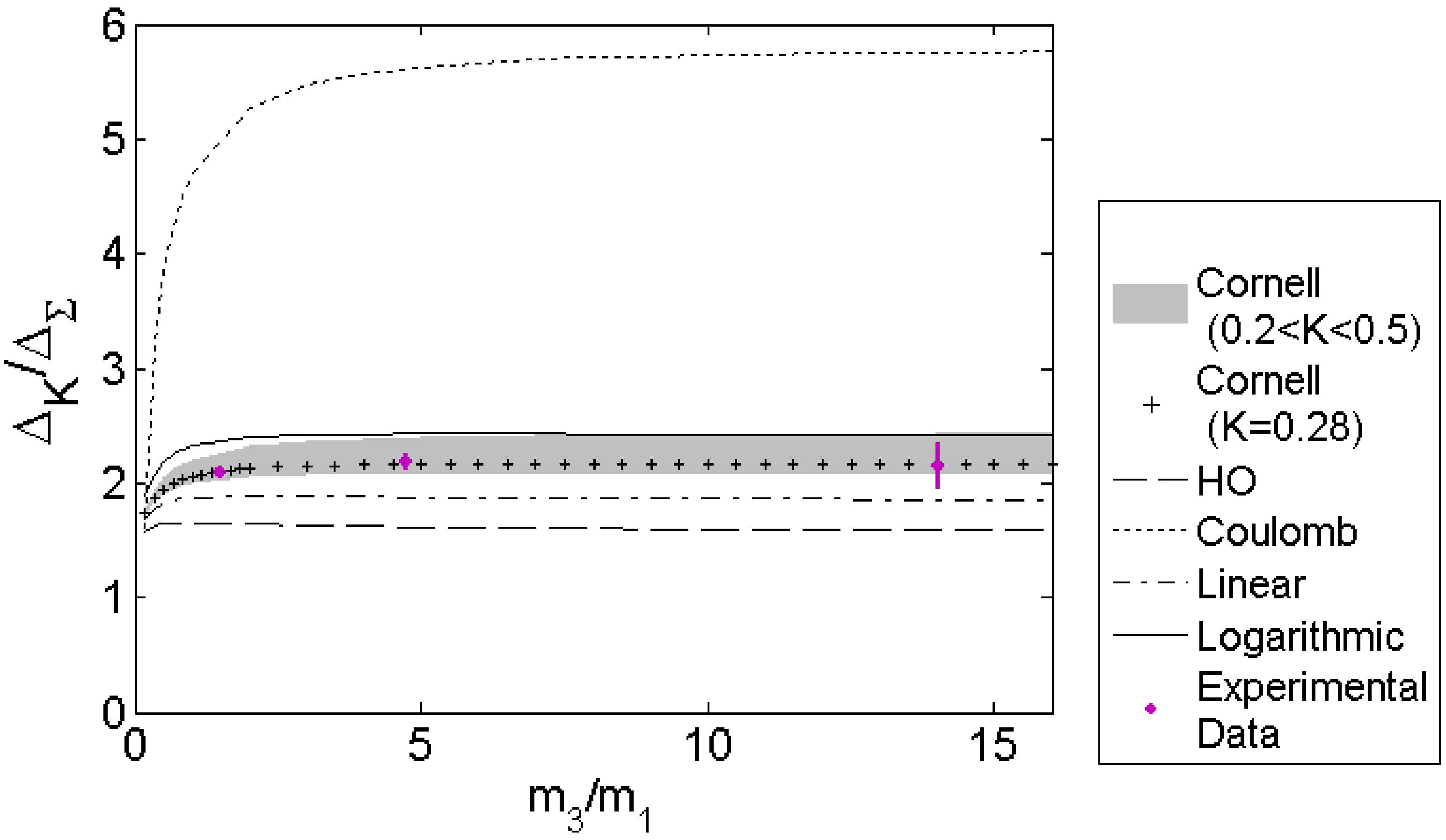
- depends only on the confinement potential and quark mass ratio
- can be used to test different confinement potentials

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

Hyperfine splitting ratio from potential models vs experiment

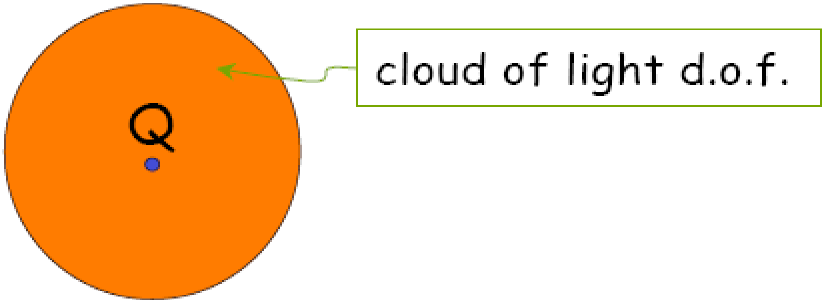


Effective meson-baryon supersymmetry

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

- 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:

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

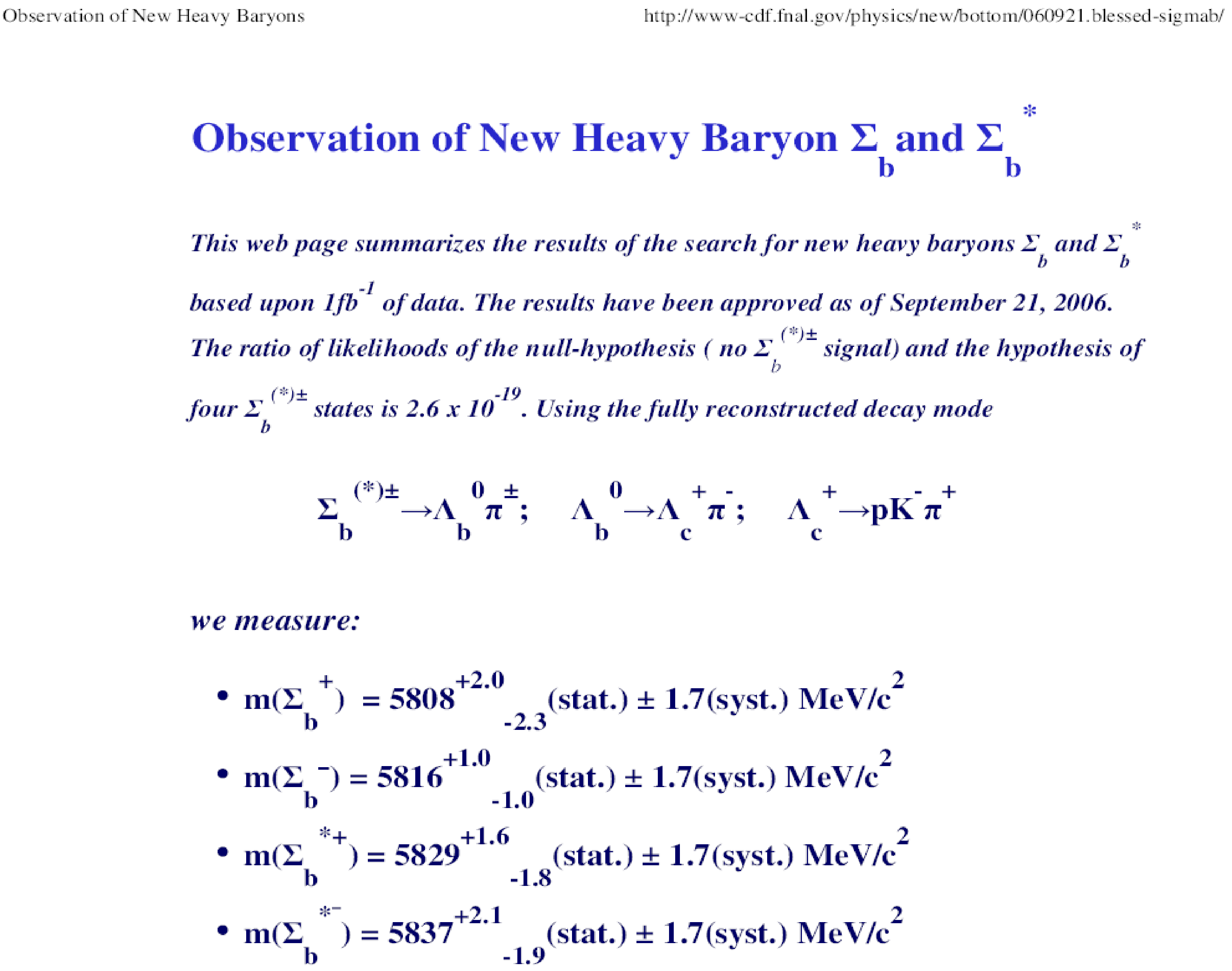
- for spin-zero diquarks:

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

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

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

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



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

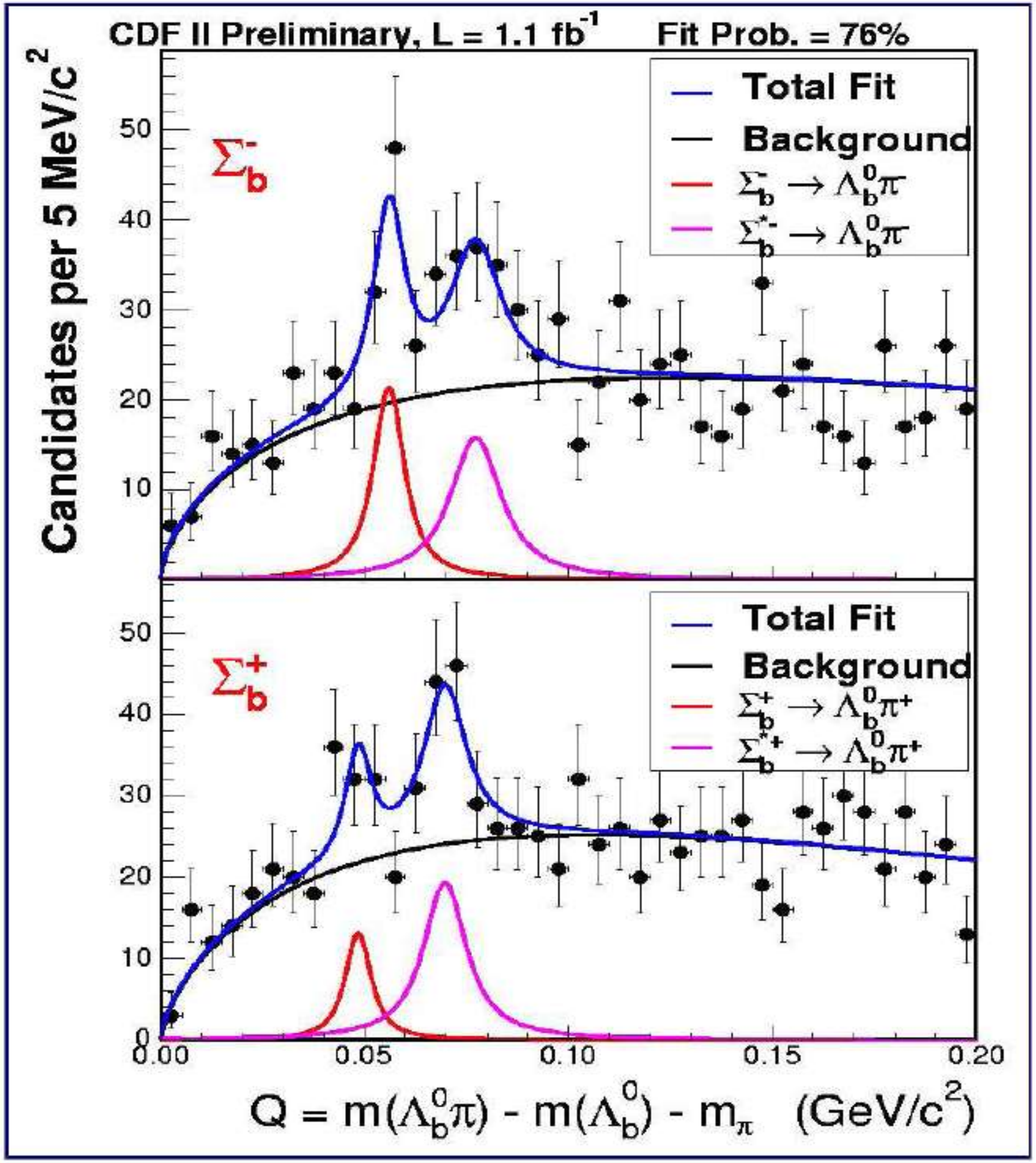
Observation of New Heavy Baryon Σ_b and Σ_b^*

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

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

we measure:

- $m(\Sigma_b^+) = 5808^{+2.0}_{-2.3}$(stat.) ± 1.7(syst.) MeV/c^2
- $m(\Sigma_b^-) = 5816^{+1.0}_{-1.0}$(stat.) ± 1.7(syst.) MeV/c^2
- $m(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8}$(stat.) ± 1.7(syst.) MeV/c^2
- $m(\Sigma_b^{*-}) = 5837^{+2.1}_{-1.9}$(stat.) ± 1.7(syst.) 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
$Q = m(\Lambda_b^0\pi) - m(\Lambda_b^0) - m_\pi$ (GeV/c^2)

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