Rare $B \to$ baryon decays

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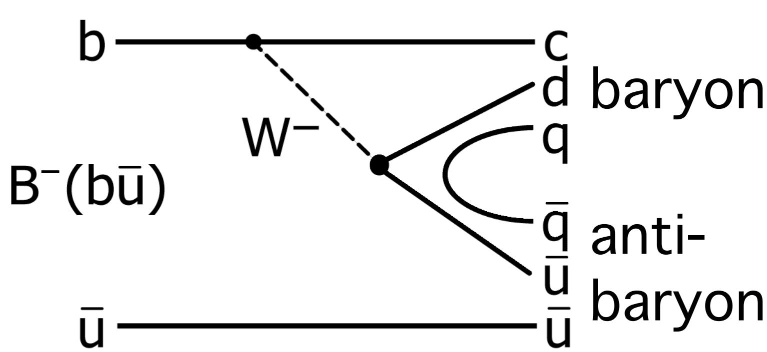
EPS 2003

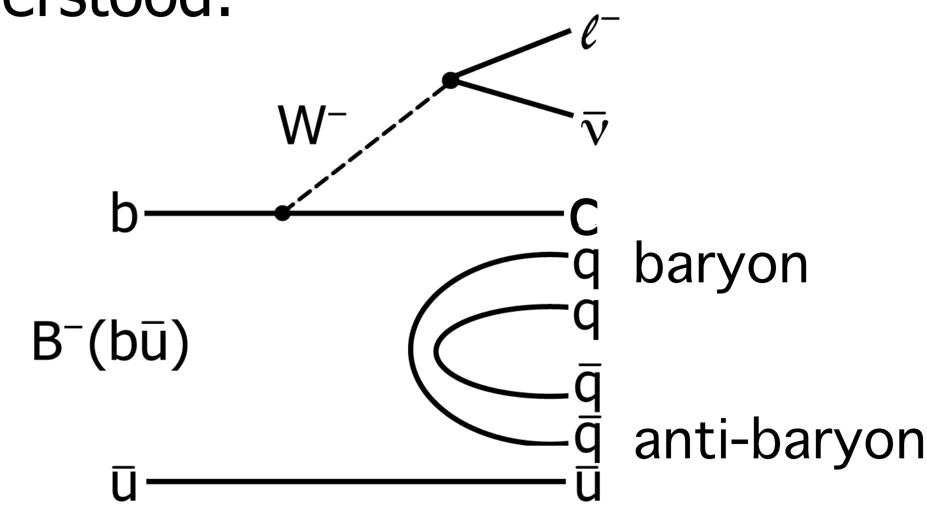
- Motivation
  - Baryon production in B decays
- Semileptonic B decays to $e\bar{p}$ final states
  - $B \to \bar{p} e^- \bar{\nu}_e X$ (Abstract: 141)
- Baryon-containing radiative penguin decays: $B \to X_s(\text{baryons}) \gamma$ (Abstract: 121)
  - $B^- \to \Lambda \bar{p} \gamma$
  - $B^- \to \Sigma^0 \bar{p} \gamma$
- Conclusions

Baryon production in B decay

Mechanism for baryon production in B decay not completely understood:



Internal W Emission



External W Emission

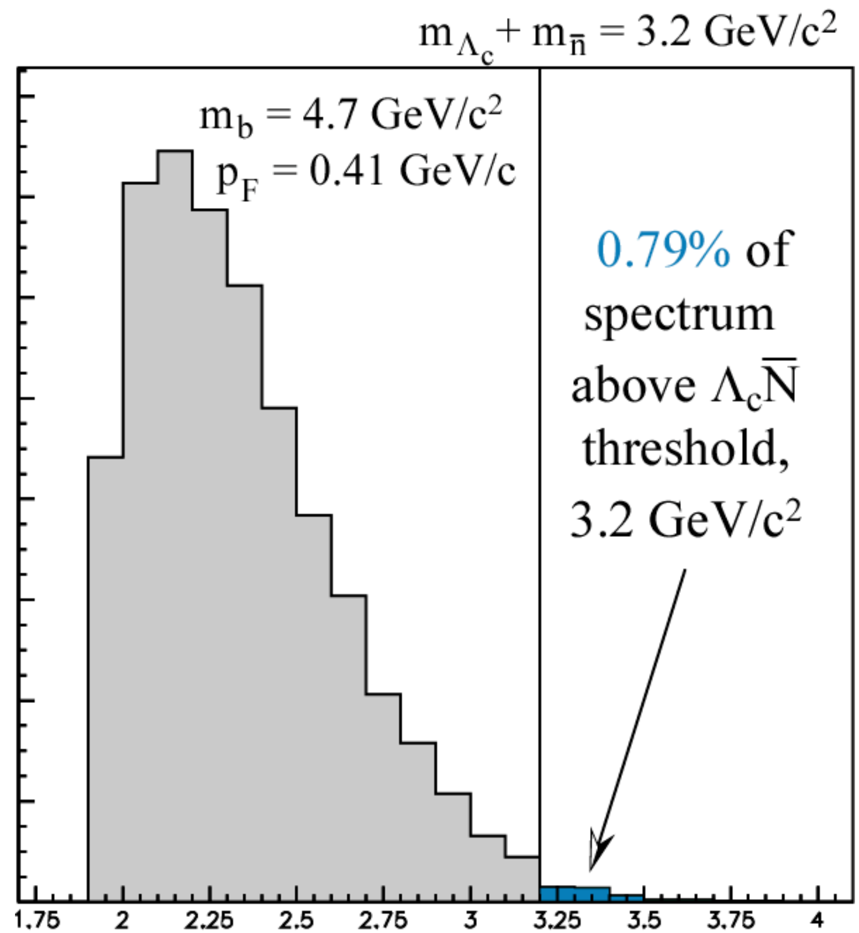
If mechanism is
Internal W Emission
then b □ s□ and b □ cl□ final states will NOT contain baryons.

If mechanism is
External W Emission
then b □ s□and b □ cl□ final states MAY contain baryons.

Why $B \to \bar{p} e^- \bar{\nu}_e X$?

- Semileptonic B decays distinguish between internal and external W emission
- There is *no positive evidence* for baryons in semileptonic B decays:
  - $B^- \to \Lambda_c e^-$ anything $< 3.2 \times 10^{-3}$ [1]
  - $B^- \to \Lambda_c^+ \bar{p} e^- \bar{\nu}_e < 1.7 \times 10^{-3}$ [2]
  - $B^- \to \bar{p} e^- \bar{\nu}_e X < 1.6 \times 10^{-3}$ [3]

- BUT, kinematic argument against baryon production in $b \to c l \nu$



$c\bar{q}_{spectator}$ mass distribution

[1] = PDG 2000

[2] = CLEO II, limit using full reconstruction on $\Lambda_c \to pK^-\pi^+$

[3] = ARGUS

Why $B \to X_s(\text{baryon})\gamma$?

Search for exclusive modes:

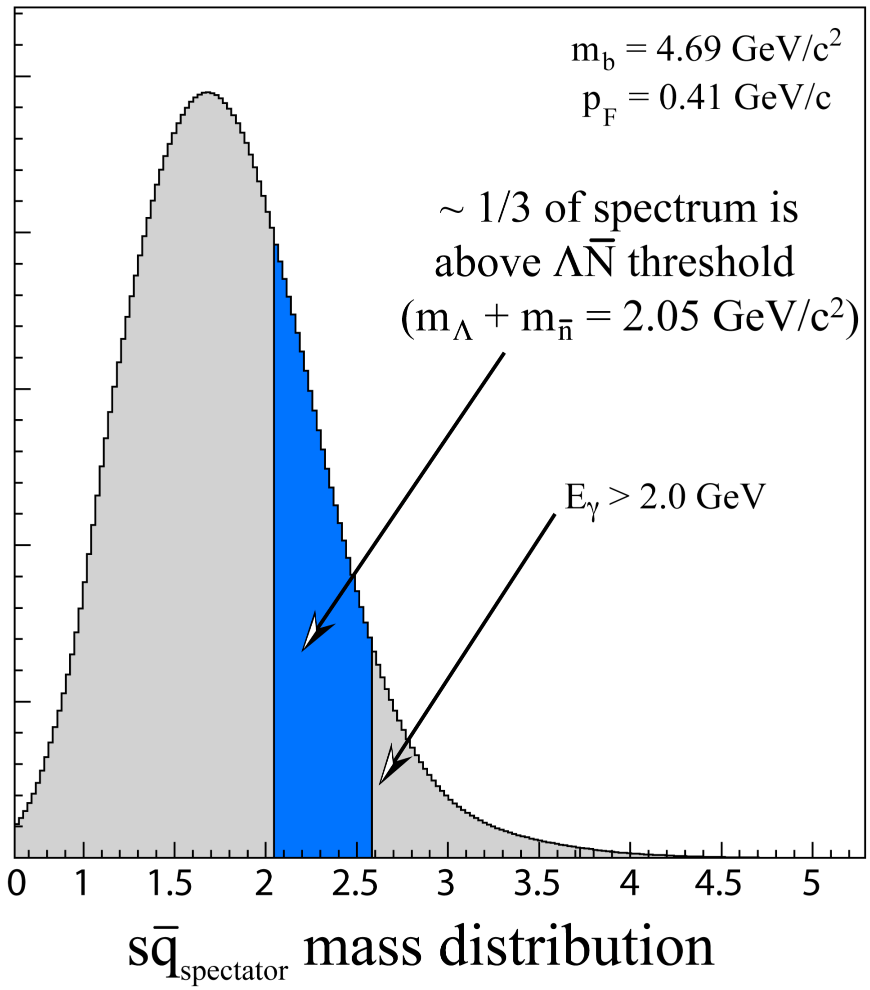
$B^- \to \Lambda \bar{p} \gamma$ with some sensitivity to
$B^- \to \Sigma^0 (\Sigma^0 \to \Lambda\gamma) \bar{p} \gamma$

- Clean; easiest of baryon modes to reconstruct
- Largest fraction above threshold

Relevance for $b \to s\gamma$

- Previous $b \to s\gamma$ measurement less sensitive to $B \to$ baryon γ
- Could shift $\langle E_\gamma \rangle$ down by as much as 56 MeV (1.7σ)

NOTE: Only interested in photons with $E_\gamma > 2.0$ GeV
$\Rightarrow 2.05 < M_{s\bar{q}} < 2.6$ GeV



Experimental technique: $B^{-} \rightarrow \bar{p} e^{-} \bar{\nu}_e X$

Technique: Study angular distribution between electrons and antiprotons to search for semileptonic baryon decays from B mesons.

Partially reconstruct the decay $B \rightarrow \bar{p} e^{-} \bar{\nu}_e X$:

- Identify hadronic events with an
  e^{-} (0.6 GeV < p_e < 1.5 GeV) and
  $\bar{p}$ (0.2 GeV < $p_{\bar{p}}$ < 1.5 GeV)
  emerging promptly from the B
- Examine angular distributions between e^{-} and $\bar{p}$

  $\theta \equiv$ the angle between the electron and the antiproton

⇒ Use the difference between the signal and background shapes in $\cos(\theta)$ to fit for the amount of signal

$e^-/\bar{p}$ angular distributions

Signal events: $\cos(\theta) = -1$

Sources of background:

Uncorrelated background

- $e/\bar{p}$ combinations where e and $\bar{p}$ are from opposite B's
- Flat distribution

Correlated background

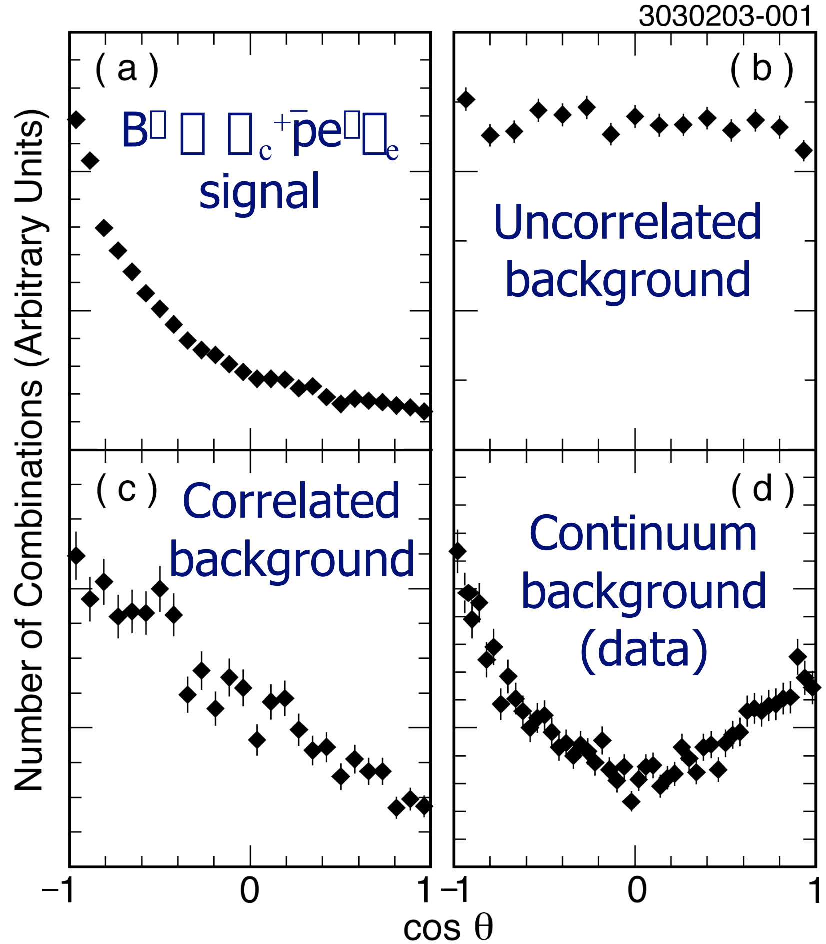
- Non-prompt $e/\bar{p}$ combinations from the same B but not from signal, i.e. $B^+ \to \Lambda_c^- X$, $\Lambda_c^- \to \bar{\Lambda} e^- X$, $\bar{\Lambda} \to \bar{p} X$
- Peaked near $\cos(\theta) \approx -1$, but less sharply than signal.

Continuum background

- Background due to non-$B\bar{B}$ sources, ($e^+e^- \to q\bar{q}$, where q = u, d, s, c)

Fake $e/\bar{p}$ background

- Misidentified e^- or $\bar{p}$

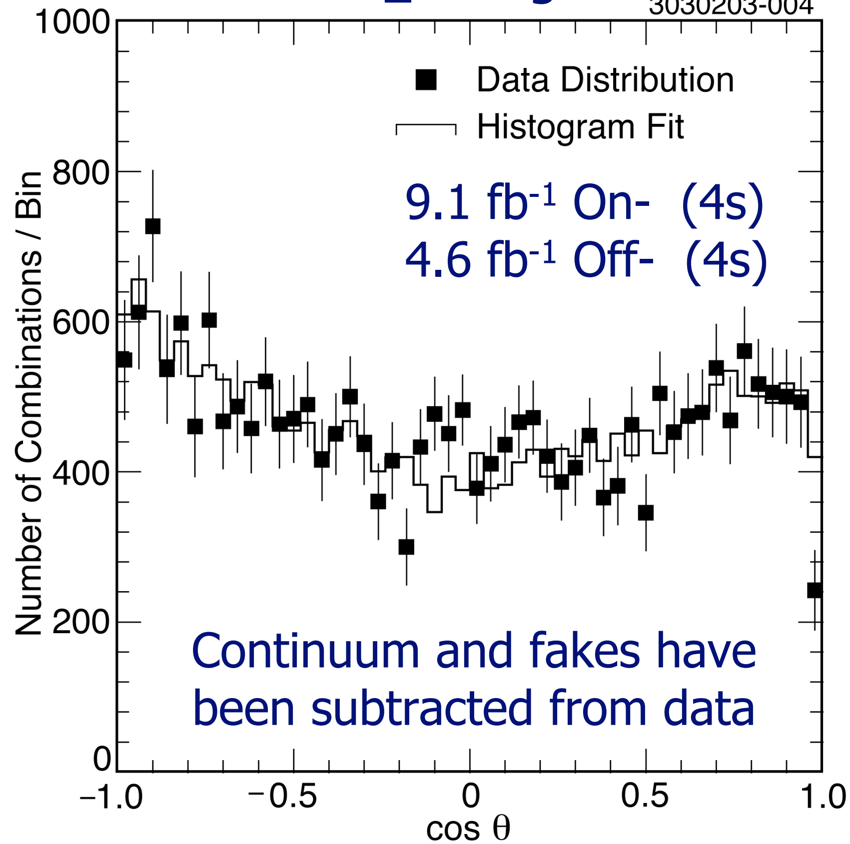


Yield: $B^- \to \bar{p} e^- \bar{\nu}_e X$

Partially reconstruct the decay
$B \to \bar{p} e^- \bar{\nu} X$

- Obtain cos(θ) distribution for sample
- Subtract fake e^- and $\bar{p}$ backgrounds using data distributions
- Subtract continuum background using Off-Υ(4s) data
- Using MC generated shapes for uncorrelated and correlated backgrounds, fit to a sum of these components to get signal yield

$b \to c$ signal



N_{signal} = 834 ± 634 (stat.) ± 380 (syst.)

ϵ = (17.1 ± 0.1)%

Upper limit: BF($B^- \to \bar{p} e^- \bar{\nu}_e X$) < 5.9×10^{-4}

Implications for $B \to Xe\nu$

CLEO $B \to Xe\nu$ measurement:

BF($B \to Xe\nu$) = (10.49 ± 0.17 ± 0.43)% [1]

Limit on $B \to \bar{p}e^{-}\bar{\nu}_e X$:

BF($B^{-} \to \bar{p}e^{-}\bar{\nu}_e X$) < 5.9×10^{-4}

BF($B \to$ baryon):

BF($B \to p/\bar{p}$ anything) = (8.0 ± 0.4)% [2]

[1] CLEO (1996)
[2] PDG 2000

Limit on $B \to \bar{p}e^{-}\bar{\nu}_e X$ is a limit on $e\bar{p}$ final states ONLY.

Want limit on $B \to$ baryon $e\nu$ ⇒ factor of 2 for neutrons:

⇒ Upper limit on BF($B \to$ baryon $e\nu$): ($2 \times (5.9 \times 10^{-4})$) ~ 10^{-3}

BF($B \to$ baryon $e\nu$) < 1% of BF($B \to Xe\nu$)

⇒ $(B \to \text{baryon})_{\text{external W}}$ < 1% of $B \to X$

⇒ External W emission* does not contribute significantly to baryonic decays of B mesons

* Baryon production at lower vertex via external W emission

Experimental technique: $B^- \to \Lambda \bar{p} \gamma$

Fully reconstruct events: $B^- \to \Lambda(\Lambda \to p\pi^-)\bar{p}\gamma$

Background sources:

- $B\bar{B}$ - negligible (smaller than continuum by a factor of 60!)
- Continuum ($e^+e^- \to q\bar{q}$, $q\bar{q} = u\bar{u}, d\bar{d}, s\bar{s}, c\bar{c}$)

After shape variable cuts are applied to remove continuum:

Real Λ	94.7%
Real γ	95.5%
Real $\bar{p}$	80.5%

ISR*	34.2%
π^0	32.2%
η	19.6%
Other	8.8%

For remaining events, feed shape variables into neural net, cut on net output

Obtain signal and background yields in ΔE, M_B signal box

- $|\Delta E| \leq 0.084$ GeV
- $5.272 \leq M_B \leq 5.288$ GeV/c^2

*ISR = Initial State Radiation

ΔE and M_B (beam-constrained mass)

(4s) ~ 20 MeV above $B\bar{B}$ threshold.

⇒ Energy of each candidate B (E_{cand}) is same as beam energy (E_{beam})

Reconstruct B meson candidate, impose the constraint $E_{cand} = E_{beam}$ to form the following standard reconstruction variables:

Beam-constrained mass, M_B

$$M_B = \sqrt{E_{beam}^2 - p_{cand}^2}$$

Resolution: σ_M ~ 2-4 MeV

~ 10× better than the resolution obtained without the constraint

Energy Difference, ΔE

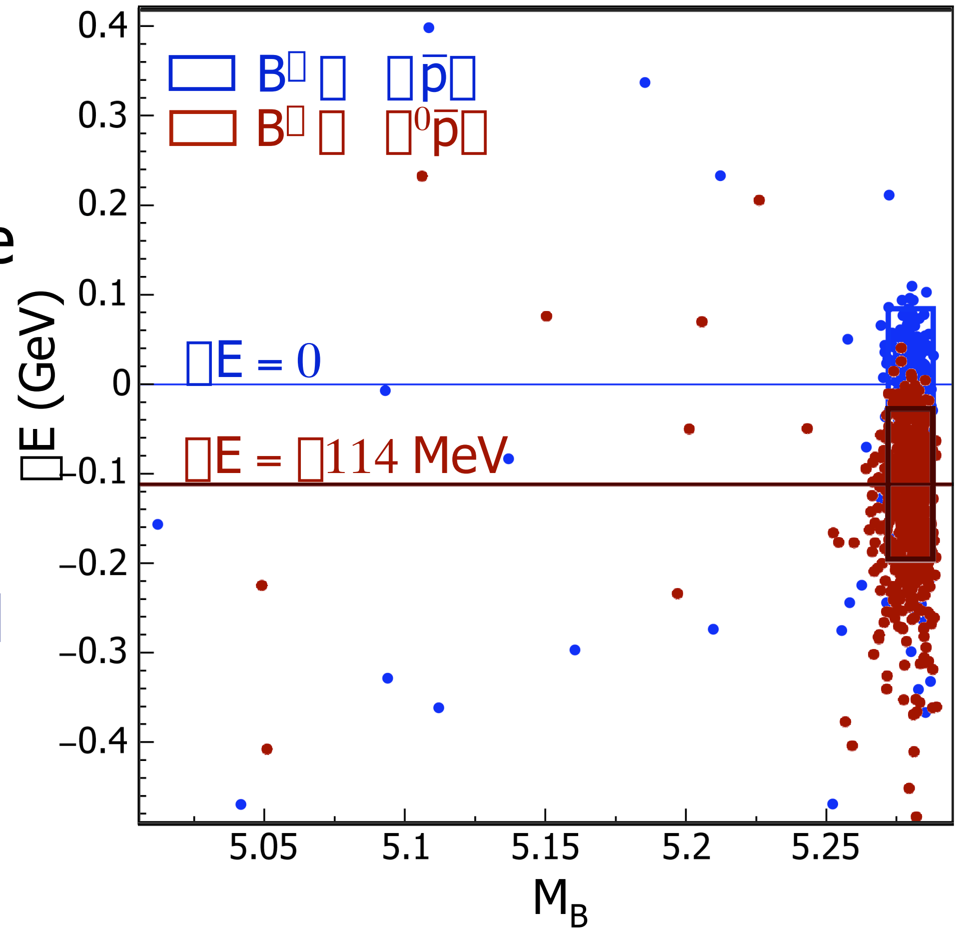
$$\Delta E = E_{cand} - E_{beam} \approx 0$$

Resolution: σ_E ~ 20-60 MeV

To find $B\bar{B}$ events, look at M_B distributions for events with ΔE ~ 0

Experimental technique: B□ □ □⁰p̄□

- Reconstructing B□ □ □⁰ (□⁰ □ □□)p̄□ not feasible because of low efficiency and high fake rate
- Instead, preserve all features of B□□ □p̄□ analysis and slide the □E□M_B signal box to □□E
  - The soft □ is not included in □p̄□, so □E will be shifted by the energy of the □ for □⁰p̄□



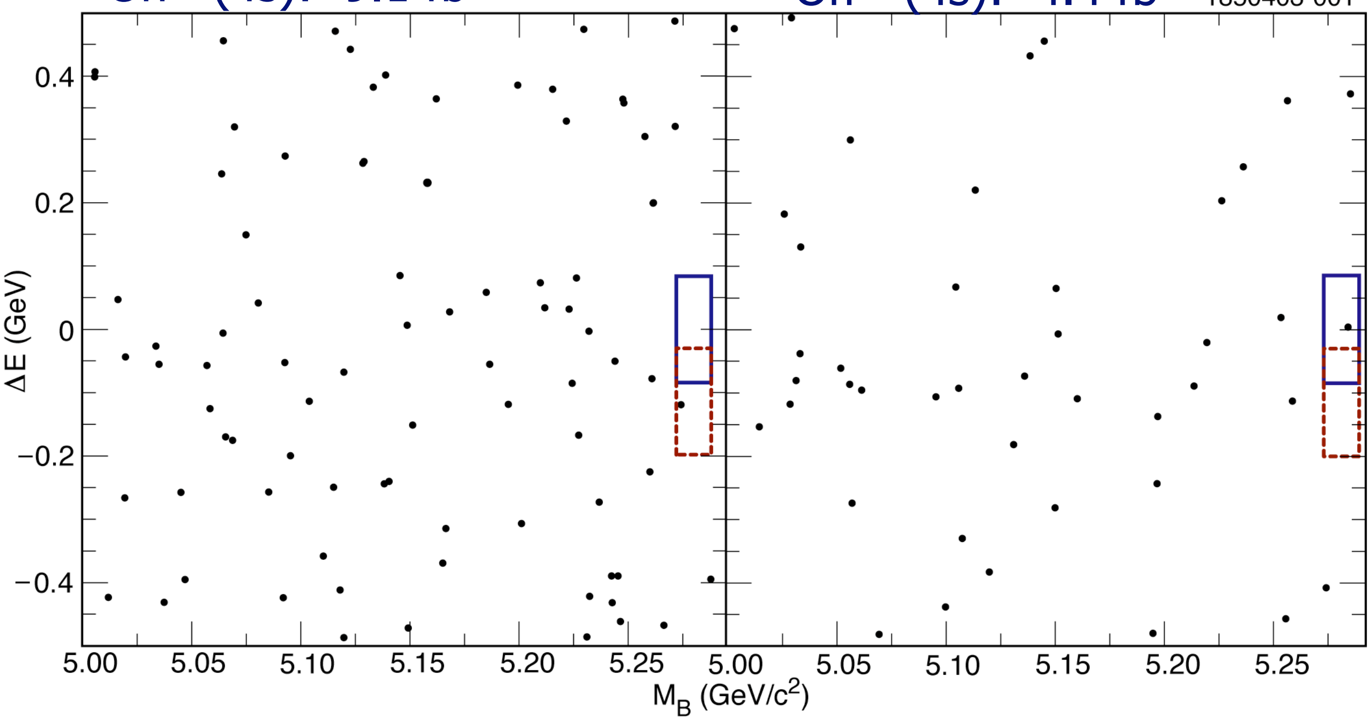
□E = □114 MeV

□(B□ □ □⁰p̄□)$_{max}$ = 0.42 □ □(B□□ □p̄□)$_{max}$

Yield: $B^- \to \Lambda\bar{p}\gamma$ and $B^- \to \Sigma^0\bar{p}\gamma$

CLEO II + II.V: (9.7×10^6 $B\bar{B}$ events)

On Υ(4s): 9.1 fb^{-1} Off Υ(4s): 4.4 fb^{-1}



$B^- \to \Lambda\bar{p}\gamma$

On Υ(4s): 0 events
Off Υ(4s): 1 event
(Expect 0.6 events)

$B^- \to \Sigma^0\bar{p}\gamma$

On Υ(4s): 1 events
Off Υ(4s): 0 event
(Expect 0.2 events)

<u>ΔE vs. M_B signal box:</u>

$5.272 < M_B < 5.288$ GeV

$|\Delta E| < 0.084$ GeV

ΔE shifted by -114 MeV for $\Sigma^0\bar{p}\gamma$

Upper Limit: $B^{-} \rightarrow \Lambda(\Sigma^0)\bar{p}\gamma$

Efficiency:

Use efficiencies calculated from a signal sample of unpolarized Λ's and using a P^3/M phase space factor (p-wave system) for the $\Lambda\bar{p}$ ($\Sigma^0\bar{p}$) mass distribution:

$$\varepsilon_{1.5\ \mathrm{GeV}} = 10.5\%$$

$$\varepsilon_{2.0\ \mathrm{GeV}} = 12.4\%$$

Systematic errors:

Combined systematic error on the efficiency: $\sigma = 8.4\%$

Increase upper limit on BF by 1.28σ

Conservative 90% CL upper limits (including syst. error):

$[Br(B^- \rightarrow \Lambda\bar{p}\gamma) + 0.3\, Br(B^- \rightarrow \Sigma^0\bar{p}\gamma)]_{1.5\ \mathrm{GeV}} < 3.9 \times 10^{-6}$

$[Br(B^- \rightarrow \Lambda\bar{p}\gamma) + 0.3\, Br(B^- \rightarrow \Sigma^0\bar{p}\gamma)]_{2.0\ \mathrm{GeV}} < 3.3 \times 10^{-6}$

$[Br(B^- \rightarrow \Sigma^0\bar{p}\gamma) + 0.4\, Br(B^- \rightarrow \Lambda\bar{p}\gamma)]_{1.5\ \mathrm{GeV}} < 7.9 \times 10^{-6}$

$[Br(B^- \rightarrow \Sigma^0\bar{p}\gamma) + 0.4\, Br(B^- \rightarrow \Lambda\bar{p}\gamma)]_{2.0\ \mathrm{GeV}} < 6.4 \times 10^{-6}$

Upper Limit on B □ X_s(baryon)□

- What we HAVE is a limit on BF(B□ □ □^{0}p̄□ + B□ □ □p̄□)
- What we WANT is limit on BF(B □ X_s□, X_s containing baryons)
  - Extrapolate from our measured exclusive baryon modes
  - We can use either B□ □ □p̄□ or B□ □ □^{0}p̄□ to get this limit, but using B□ □ □^{0}p̄□ relies on fewer theoretical assumptions.

- To obtain upper limit on B □ X_s(baryon)□, need to know

$$R_{\Box^0 \bar{p}\Box} \equiv \frac{Br(B \;\Box\; X_s\Box, X_s \text{ containing baryons})}{Br(B^{\Box} \;\Box\; \Box^0 \bar{p}\Box) + 0.4\, Br(B^{\Box} \;\Box\; \Box \bar{p}\Box)}$$

For $E_{\Box}$ > 1.5 GeV: $R_{\Box\bar{p}\Box}$ = 12; For $E_{\Box}$ > 2.0 GeV: $R_{\Box\bar{p}\Box}$ = 6

- Limits on b □ s□ decays to baryons:

BF(B □ X_s□, X_s containing baryons)$_{1.5\text{ GeV}}$ ≤ 9.5 x 10^{-5}

BF(B □ X_s□, X_s containing baryons)$_{2.0\text{ GeV}}$ ≤ 3.8 x 10^{-5}

Implications for $b \to s\gamma$

Recent CLEO $b \to s\gamma$ measurements:

$BF(b \to s\gamma)_{2.0\ \mathrm{GeV}} = (2.94 \pm 0.41 \pm 0.26) \times 10^{-4}$

$\langle E_\gamma \rangle_{2.0\ \mathrm{GeV}} = 2.346 \pm 0.032 \pm 0.011$ GeV

$\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2_{2.0\ \mathrm{GeV}} = 0.0226 \pm 0.0066 \pm 0.0020\ \mathrm{GeV}^2$

Limit on $b \to s\gamma$ from baryons (obtained from the $\Lambda^0 \bar{p} \gamma$ search):

$BF(B \to X_s\gamma$, X_s containing baryons) $\leq 3.8 \times 10^{-5}$ (13%)

Efficiency for $b \to s\gamma$ decays to baryons ≈ 1/2 that for $b \to s\gamma$ to mesons only

Branching Fraction

43%

⇒ Upper limit on correction to $BF(b \to s\gamma)$: (1/2 × 13%) = 6.5%

Mean Photon Energy

47%

$\langle E_\gamma \rangle_{baryons} \approx 2.10$ GeV (250 MeV lower than our published number)

⇒ Upper limit on correction to $\langle E_\gamma \rangle$: (1/2 × 13% × 250 MeV) = 16 MeV

Variance in Photon Energy

Estimate the effect of photons missed due to baryons by placing them at 2.1 GeV

⇒ Upper limit on correction to $\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2_{2.0\ \mathrm{GeV}}$: 0.0025 GeV^2

36%

Conclusions

To be published in PRD

$B \to X_s\gamma$ (X_s containing baryons)

All upper limits at 90% C.L. using 9.7×10^6 $B\bar{B}$'s:

$[BF(B^- \to \Lambda\bar{p}\gamma) + 0.3\ BF(B^- \to \Sigma^0\bar{p}\gamma)]_{E_\gamma>2.0} < 3.3 \times 10^{-6}$

$[BF(B^- \to \Sigma^0\bar{p}\gamma) + 0.4\ BF(B^- \to \Lambda\bar{p}\gamma)]_{E_\gamma>2.0} < 6.4 \times 10^{-6}$

$BF(B \to X_s\gamma,\ X_s \text{ containing baryons})_{E_\gamma>2.0} < 3.8 \times 10^{-5}$

- Corrections to $(b \to s\gamma)$ BF, $\langle E_\gamma\rangle_{2.0\ GeV}$, and $\langle E_\gamma^2\rangle - \langle E_\gamma\rangle^2_{2.0\ GeV}$ are less than half the combined stat. ⊕ syst. errors quoted.

To be published in PRD

$B \to \bar{p}e^-\bar{\nu}_e X$

Upper limits at 90% C.L. using 9.7×10^6 $B\bar{B}$'s:

$BF(B \to \bar{p}e^-\bar{\nu}_e X) < 5.9 \times 10^{-4}$

- External W emission is NOT the dominant mechanism for baryon production in B decays.