Study of baryonic *B* meson decays at *BaBar*

David N. Brown
University of Louisville
For the *BaBar* Collaboration

Meeting of the Division of Particles and Fields
Of the American Physical Society
University of California, Santa Cruz
August 13-17, 2013

BABAR
™ and © Nelvana, All Rights Reserved

2013 DPF
UC SANTA CRUZ

UNIVERSITY OF LOUISVILLE

Studies of baryonic *B* meson decays at *BABAR*

This Talk

- Recent Results on baryonic *B* decays

$$\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$$

$$B^- \to \Sigma_c^{++} \bar{p} \pi^- \pi^-$$

$$\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}$$

$$\bar{B}^0 \to D^0 \Lambda \bar{\Lambda}$$

(charge conjugation implied throughout)

Physics Reach

- *B*-physics
  - *CP Violation &* Mixing, CKM matrix elements, hadronic, leptonic & semi-leptonic decays, penguin decays, etc
- Charm and charmonium
- Tau physics
- Initial state radiation (ISR)
- Bottomonium spectroscopy
- Two-photon physics
- Beyond the Standard Model
- More

Motivation – baryonic *B* Decays

- In general, *B* decays provide an important platform for understanding *CP*-Violation and the CKM mechanism
  - Does it contribute to baryon asymmetry?
- Baryonic modes involve strong interactions in hadronization and final state interaction – study fragmentation, QCD models, etc.
- Poorly understood details of baryonic *B* decays need study
- Measurements of rare modes improve our model constraints and can signal new physics

Baryonic *B* decay detailed motivation

- 6.8% of all *B* decays are baryonic*
- Fewer than 10% *of these* are accounted for via exclusive modes!
- **What about the rest?**

Hou and Soni (PRL **86**, 4247): for *B* baryonic decays, energy must be taken away by particles other than baryons

- Threshold enhancement in baryon anti-baryon invariant mass
- Suppression of two-body baryonic *B* decay modes
- $\mathcal{B}(\text{2-body}) < \mathcal{B}(\text{3-body}) < \mathcal{B}(\text{4-body})$

Relative effects of resonant substructure and fragmentation on branching fractions?

Examples for baryonic B-decays (PDG values)

B^0/B^- decay mode	branching fraction $[\times 10^{-4}]$
$\Lambda_c^+\overline{p}$	0.20 ± 0.04
$\Lambda_c^+\overline{p}\pi^-$	2.8 ± 0.8
$\Lambda_c^+\overline{p}\pi^0$	1.9 ± 0.5
$\Lambda_c^+\overline{\Lambda}_c^- K^-$	8.7 ± 3.5
$\Lambda_c^+\overline{p}\pi^+\pi^-\pi^-$	22 ± 7
$D^{*0}p\overline{p}$	1.0 ± 0.1
$D^{*+}p\overline{n}$	14 ± 4
$D^0\overline{p}\Lambda$	0.14 ± 0.03
$\Lambda\overline{p}$	< 0.003
$\Lambda\overline{p}\pi^-$	0.031 ± 0.003
$p\overline{p}\overline{K}^0$	0.027 ± 0.003
$p\overline{p}K^-$	0.055 ± 0.005

*ARGUS Collaboration, ZP **C56**, 1 (1992)

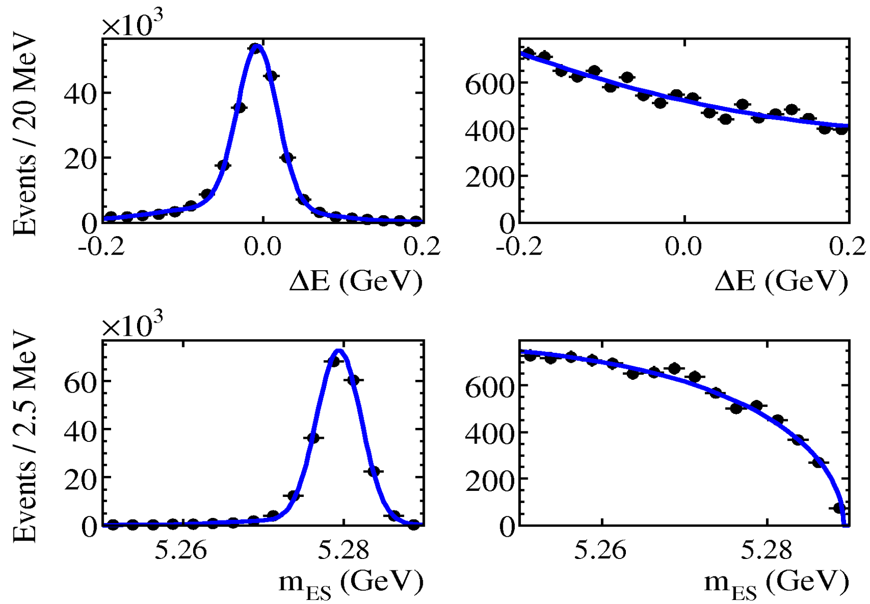
Kinematics of *B* Decays

- Fully reconstructed *B* mesons: two variables are commonly used (exploiting the precise knowledge of the beam energy):

$$\Delta E = E_{meas} - E_{beam}$$

$$m_{ES} = \sqrt{E_{beam}^2 - \mathbf{p}_{meas}^2}$$

Monte Carlo



Signal Background

- Dominant background: $q\bar{q}$ ($q = u, d, s, c$), exhibiting a jet-like topology ($B\bar{B}$ events are more "spherical").
- We separate/suppress the continuum background, combining several variables sensitive to the event shape.

$$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$$

Phys. Rev. **D 87** 092004 (2013)

$\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$

- There are many possible resonances – will this affect the total branching fraction?

$$\left(\Lambda_c^+ \pi^+\right) \Rightarrow \Sigma_c^{++}(2455), \Sigma_c^{++}(2520), \text{ etc.}$$

$$\left(\Lambda_c^+ \pi^-\right) \Rightarrow \Sigma_c^{0}(2455), \Sigma_c^{0}(2520), \text{ etc.}$$

$$\left(p\pi\right) \Rightarrow \text{ various } N, \Delta$$

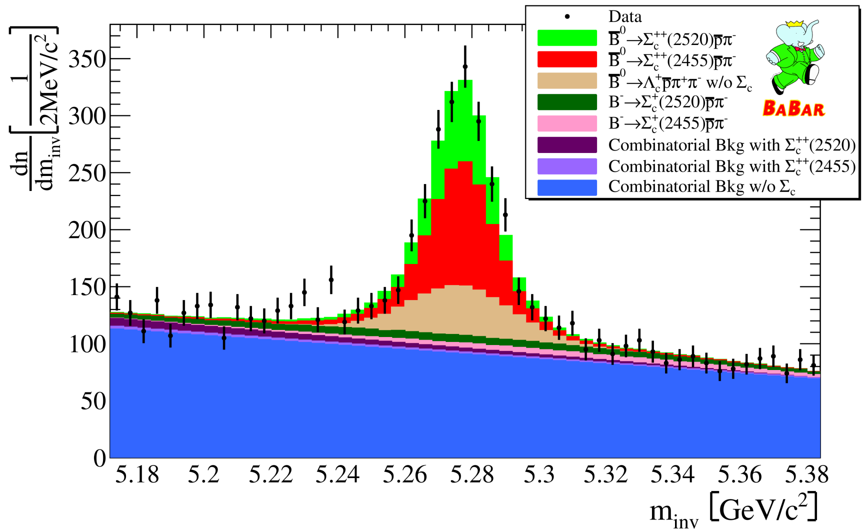
- Will a quark difference between Σ_c^0 and Σ_c^{++} affect possible threshold enhancement in $m\left(\Sigma_c \overline{p}\right)$?

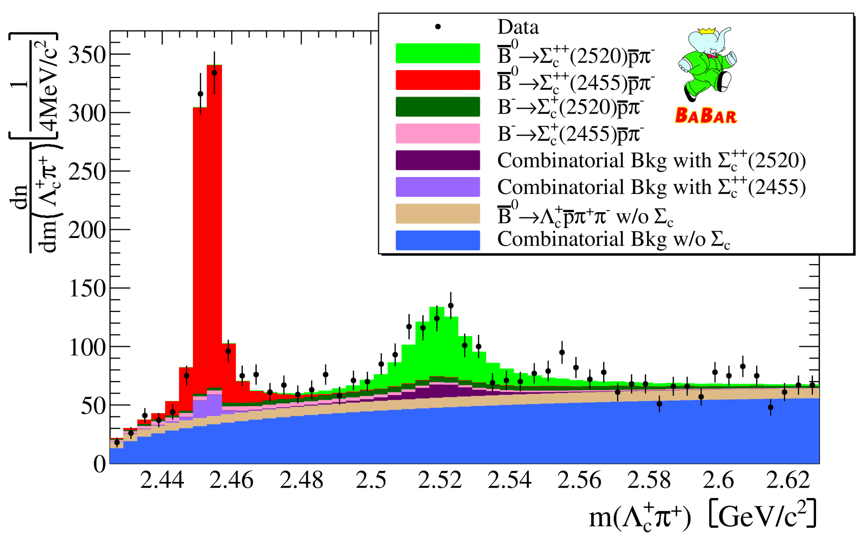
467×10^6 $B\overline{B}$ pairs in analysis

$\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$ Fits

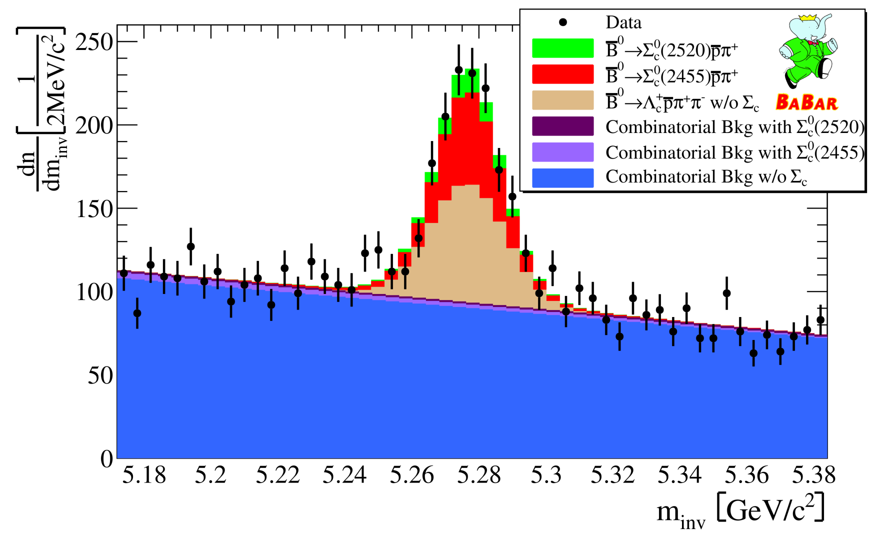
[PR **D87**, 092004 (2013)]

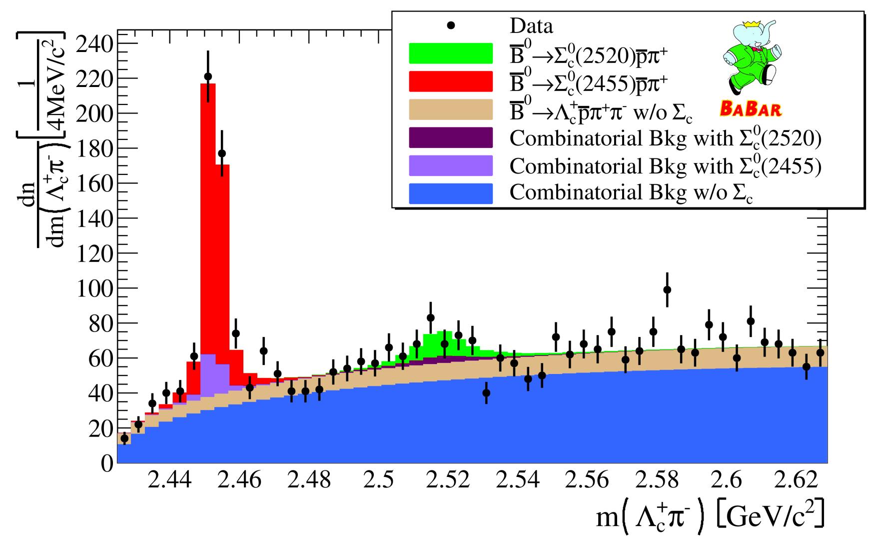
Charged sub-modes





Neutral sub-modes





$\overline{B}^0 \rightarrow \Lambda_c^+ \overline{p} \pi^+ \pi^-$ Results

Decay mode	fitted signal yield	branching fraction $[10^{-4}]$
$\overline{B}^0 \rightarrow \Sigma_c^{++}(2455)\overline{p}\pi^-$	723 ± 32	$2.13 \pm 0.10 \pm 0.10 \pm 0.55$
$\overline{B}^0 \rightarrow \Sigma_c^{0}(2455)\overline{p}\pi^+$	347 ± 24	$0.91 \pm 0.07 \pm 0.04 \pm 0.24$
$\overline{B}^0 \rightarrow \Sigma_c^{++}(2520)\overline{p}\pi^-$	458 ± 38	$1.15 \pm 0.10 \pm 0.05 \pm 0.30$
* $\overline{B}^0 \rightarrow \Sigma_c^{0}(2520)\overline{p}\pi^+$	87 ± 27	$0.22 \pm 0.07 \pm 0.01 \pm 0.06$
$(\overline{B}^0 \rightarrow \Lambda_c \overline{p}\pi^+\pi^-)_{\text{non}-\Sigma_C}$	2728 ± 132	$7.9 \pm 0.4 \pm 0.4 \pm 2.0$

uncertainties: statistical, systematic, and from $\mathcal{B}(\Lambda_c^+ \rightarrow pK^-\pi^+)$

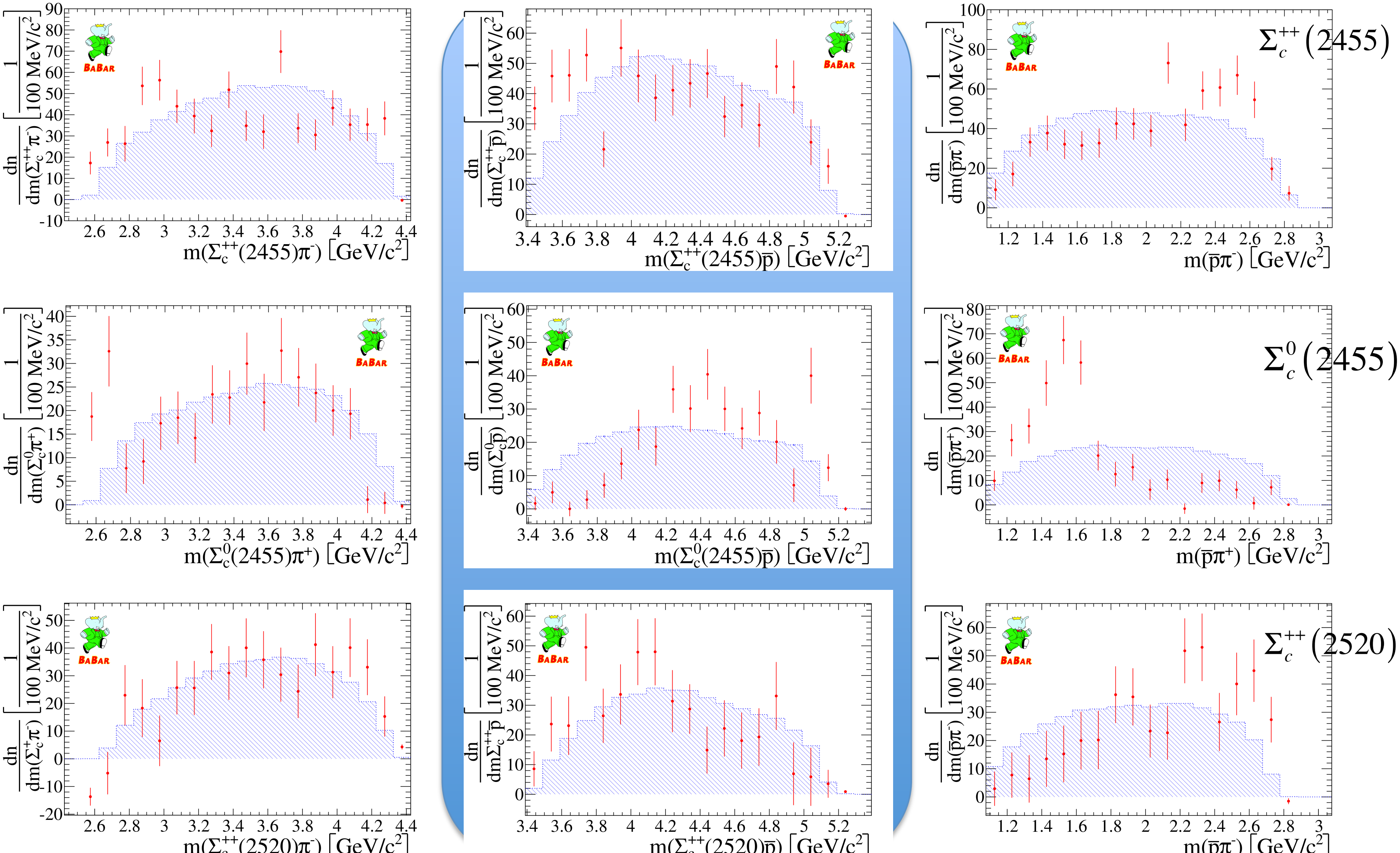
$$\boxed{\mathcal{B}(\overline{B}^0 \rightarrow \Lambda_c \overline{p}\pi^+\pi^-)_{\text{total}} = (12.3 \pm 0.5 \pm 0.7 \pm 3.2) \times 10^{-4}}$$

*First observation this mode

Phys. Rev. **D 87** 092004 (2013)

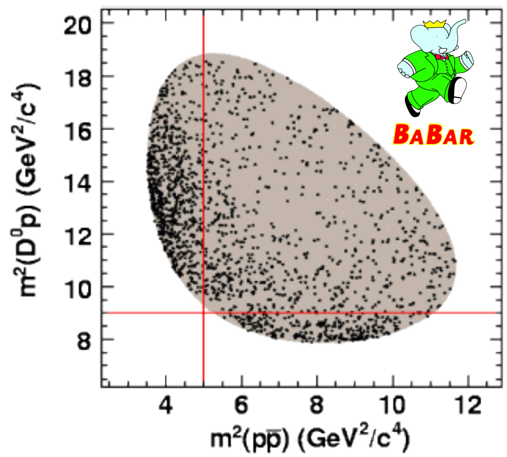
Resonant Substructure?

$\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-$

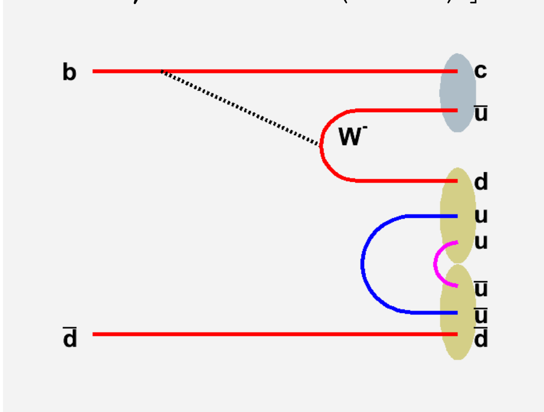


Threshold Enhancements

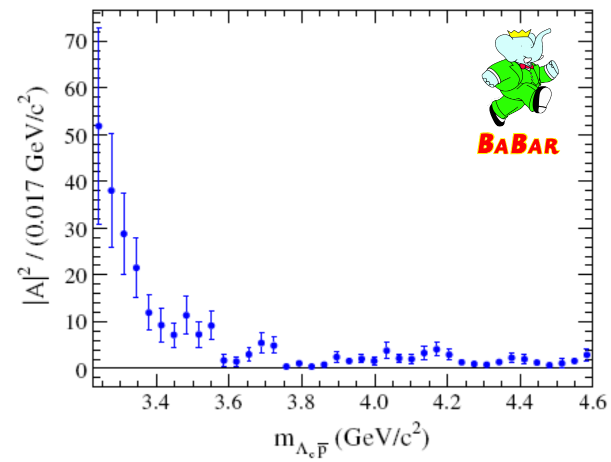
$\bar{B}^0 \to D^0 p\bar{p}$



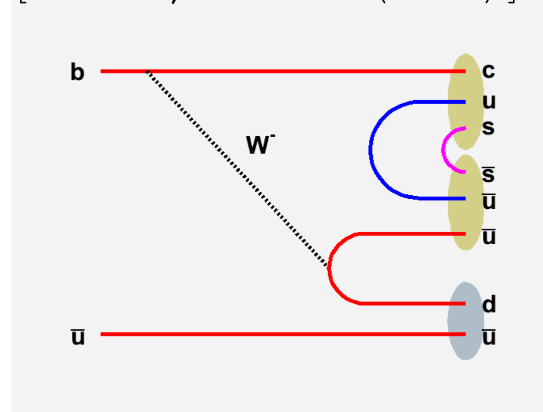
[PR **D85**, 092017 (2012)]



$B^- \to \Lambda_c^+ \bar{p} \pi^-$



[PR **D78**, 112003 (2008)]

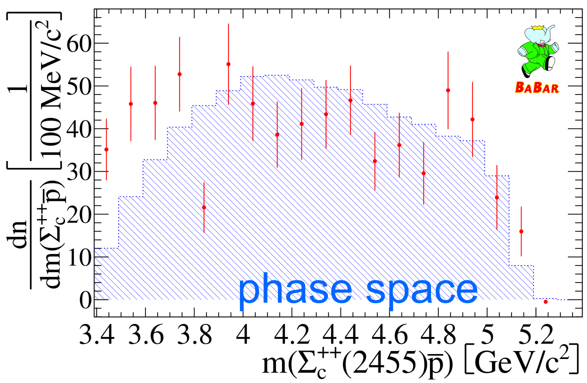


Both involve "meson pole"

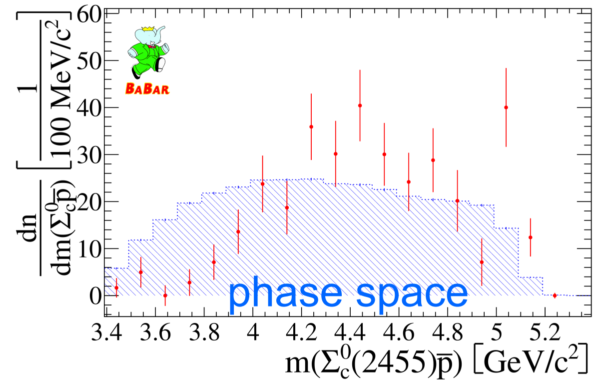
Previous measurements from 3-body modes

More on Threshold Enhancements

$\bar{B}^0 \to \Sigma_c^{++}\bar{p}\pi^-$

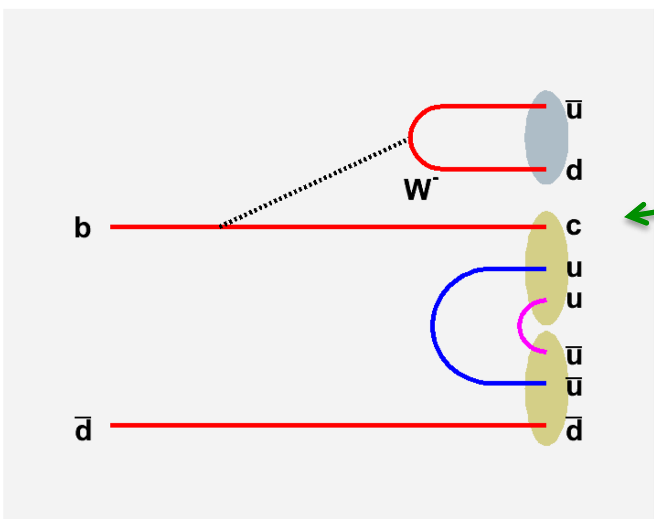


$\bar{B}^0 \to \Sigma_c^{0}\bar{p}\pi^+$



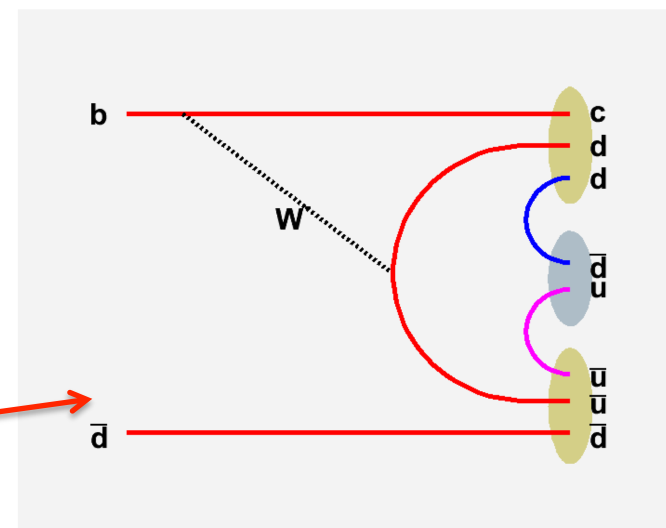
Different diagrams for charged and neutral Sigma

- Difference in both threshold behavior and overall production rate.



Meson Pole

No Meson Pole



Phys. Rev. **D 87** 092004 (2013)

$$B^- \to \Sigma_c^{++}(2455)\,\bar{p}\,\pi^-\pi^-$$

Phys. Rev. **D86** 091102 (2012)

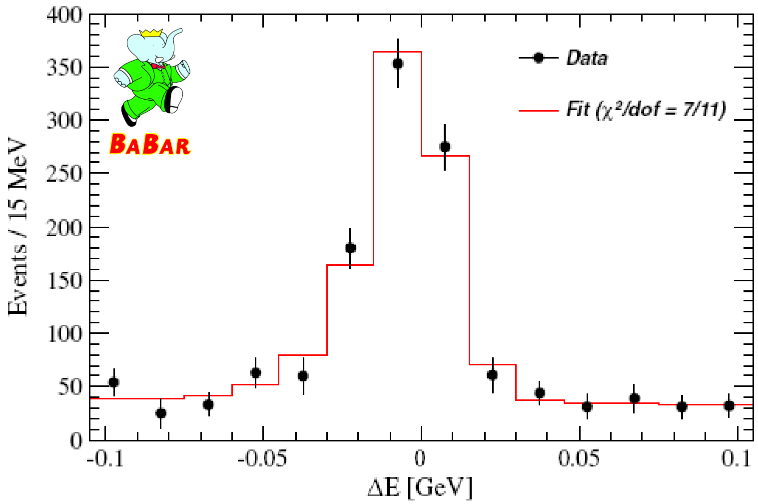
$B^- \to \Sigma_c^{++}(2455)\,\overline{p}\,\pi^-\pi^-$

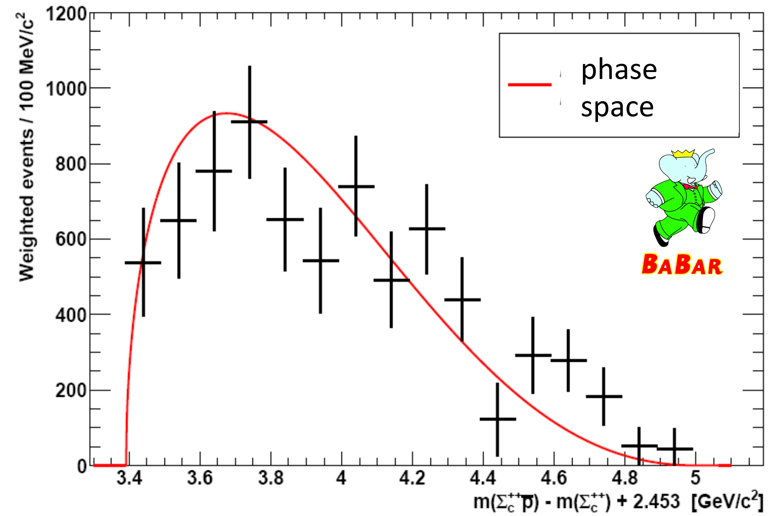
PR**D 86** 091102 (2012)

- Four-body mode, similar to $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$
  - Both are 4-body modes. Similar branching fraction?
  - Fewer resonant substructures available. Suppress production?

467×10^6 $B\overline{B}$ pairs in analysis

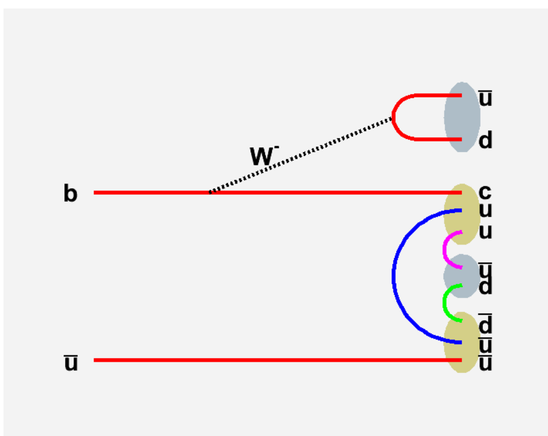
$B^- \to \Sigma_c^{++}(2455)\bar{p}\pi^-\pi^-$ Results





no threshold enhancement.

$$\mathcal{B}(B^- \to \Sigma_c(2455)^{++}\bar{p}\pi^-\pi^-) = (2.98 \pm 0.16_{\text{stat}} \pm 0.15_{\text{sys}} \pm 0.77_{\mathcal{B}(\Lambda_c^+)}) \times 10^{-4}$$



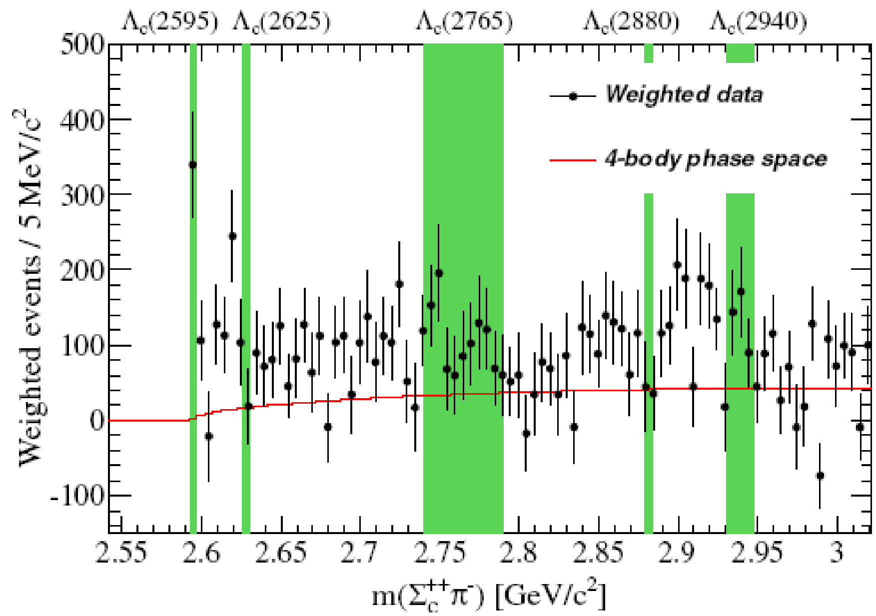
Compare:

$$\mathcal{B}\left(\bar{B}^0 \to \Lambda_c^+\bar{p}\pi^+\pi^-\right) = 12.3\times10^{-4}$$

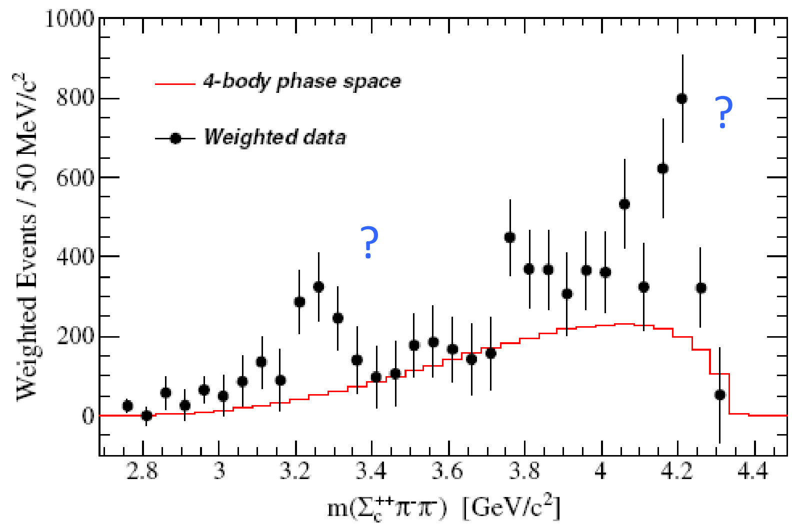
$$\mathcal{B}\left(\bar{B}^0 \to \Sigma_c^{++}(2455)\bar{p}\pi^-\right) = 2.13\times10^{-4}$$

$B^- \rightarrow \Sigma_c^{++} \bar{p} \pi^- \pi^-$ Resonances

Look for known $\Sigma_c^{++}\pi^-$ resonances



$\Sigma_c^{++}\pi^-\pi^-$ invariant mass shows structures not yet understood



$$\overline{B}^0 \to \Lambda_c^+ \overline{p}\, p\, \overline{p}$$

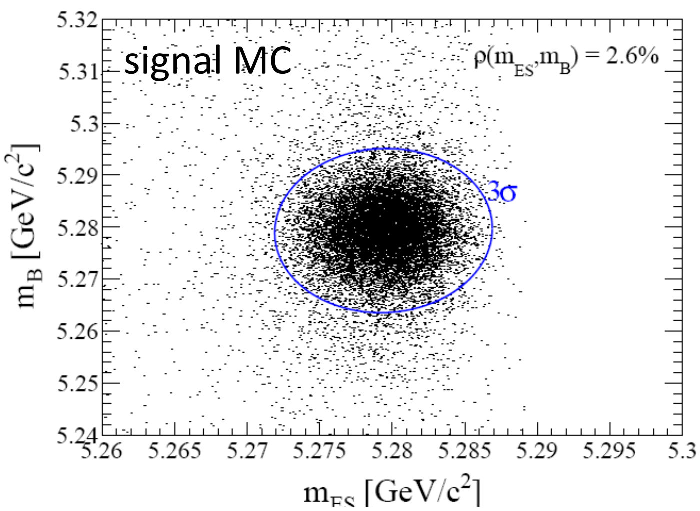
New Result! To be submitted to Phys. Rev. **D**

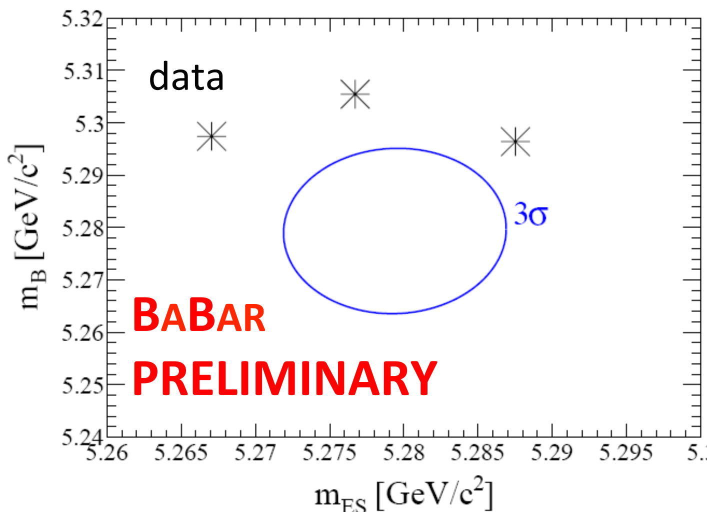
$\overline{B}^0 \to \Lambda_c^+ \overline{p} p \overline{p}$

471×10^6 $B\overline{B}$ pairs in analysis

Small phase space is available to this decay, with available kinetic energy ~1/10 of $\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^+ \pi^-$

But in baryonic decays, smaller phase space not suppressed?





$$\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} p \overline{p}) \cdot \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{5\,\%} < 2.8 \cdot 10^{-6} \quad @\ 90\%\ CL$$

Compare:

$$\mathcal{B}(\overline{B}^0 \to \Lambda_c \overline{p} \pi^+ \pi^-)_{\text{total}} = (12.3 \pm 0.5 \pm 0.7 \pm 3.2) \times 10^{-4}$$

less than half is non-resonant 4-body

Note:

$\mathcal{B}(\Lambda_c \to p K \pi) \sim 5\%$

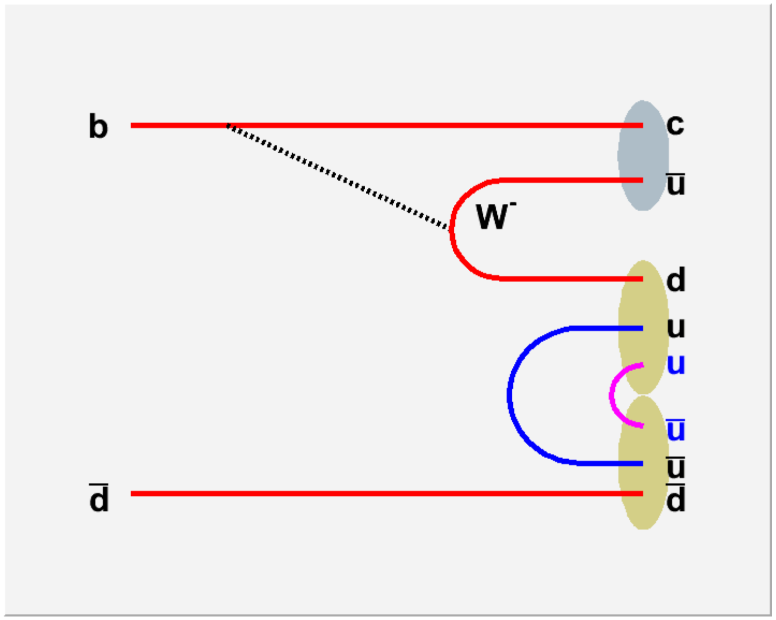
$$\bar{B}^0 \to D^0 \Lambda \bar{\Lambda}$$

New Result! To be submitted to Phys. Rev. **D**

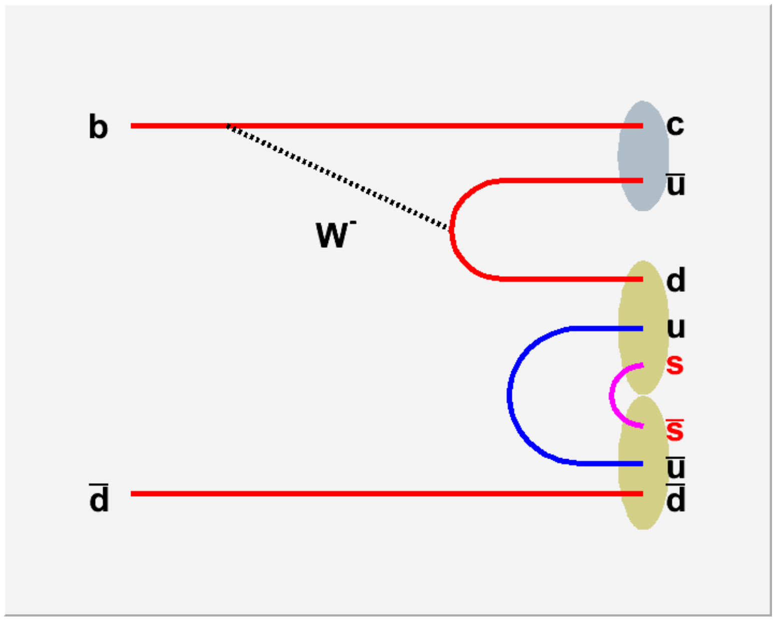
$\bar{B}^0 \to D^0 \Lambda \bar{\Lambda}$

PRELIMINARY!

$\bar{B}^0 \to D^0 p\bar{p}$



$\bar{B}^0 \to D^0 \Lambda\bar{\Lambda}$



$\mathcal{B}\left(\bar{B}^0 \to D^0 p\bar{p}\right) = (1.13 \pm 0.10) \times 10^{-4}$

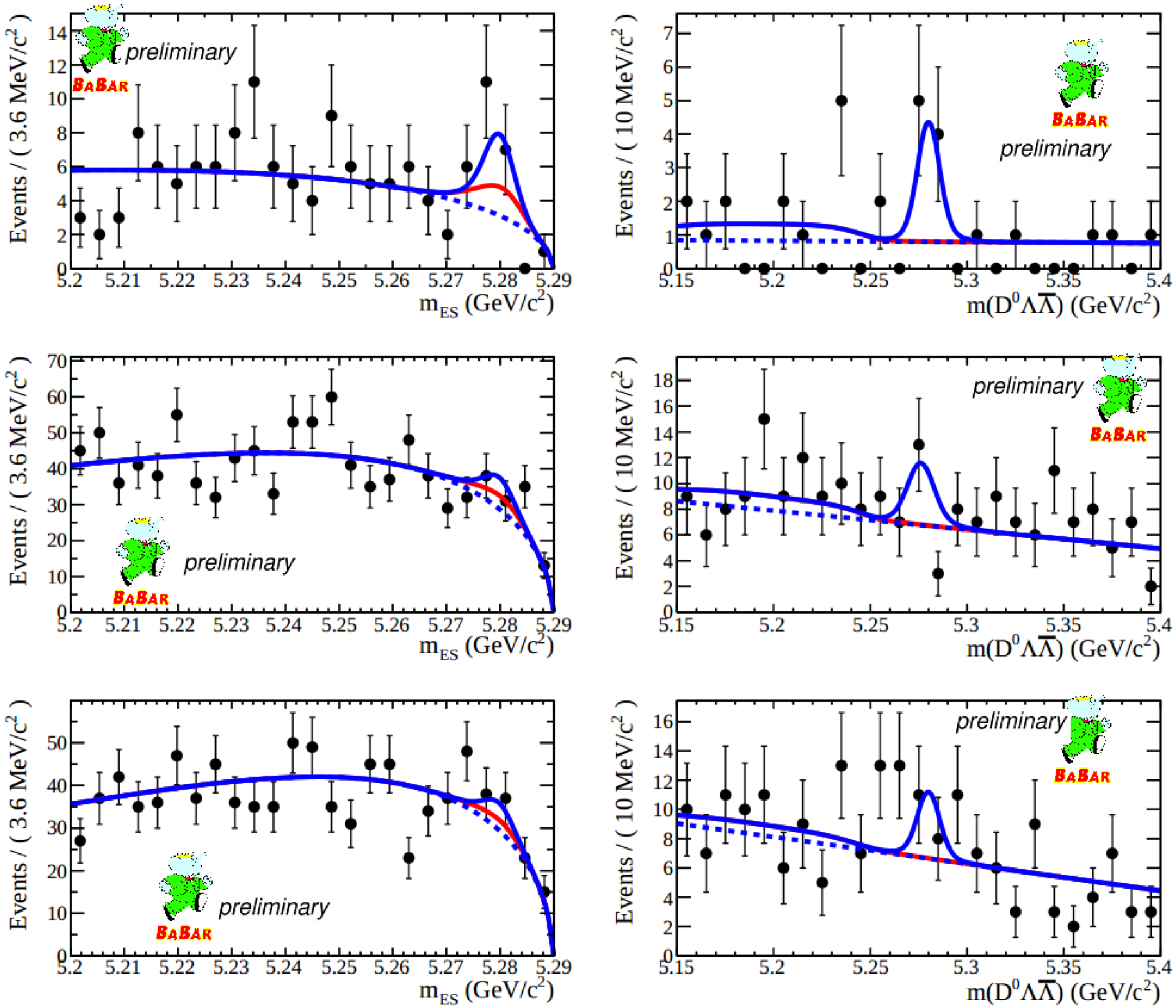
[PR **D74**, 051101 (2006)]

$471 \times 10^6 \; B\bar{B}$ pairs in analysis

Expect suppression ~1/3 for *s* quark vs. *u*
Also suppression ~1/4 due to possible final states

$\Lambda\bar{\Lambda}, \quad \Lambda\bar{\Sigma}^0, \quad \Sigma^0\bar{\Lambda}, \quad \Sigma^0\bar{\Sigma}^0$

$\bar{B}^0 \to D^0 \Lambda \bar{\Lambda}$ Fits



simultaneous fit to $D^0 \to K^- \pi^+$

$D^0 \to K^- \pi^+ \pi^0$

$D^0 \to K^- \pi^+ \pi^+ \pi^-$

$\bar{B}^0 \to D^0 \Lambda \bar{\Lambda}$ Results

BABAR PRELIMINARY!

evidence at 3.4σ

$$\boxed{\mathcal{B}(\bar{B}^0 \to D^0 \Lambda \bar{\Lambda}) = (9.8^{+2.9}_{-2.6} \pm 1.9_{\rm syst}) \times 10^{-6}}$$

Belle: $\mathcal{B}\left(\bar{B}^0 \to D^0 \Lambda \bar{\Lambda}\right) = \left(10.5^{+5.7}_{-4.4} \pm 0.14\right) \times 10^{-6}$ [PR **D79**, 052006 (2009)]

Theory: $\mathcal{B}\left(\bar{B}^0 \to D^0 \Lambda \bar{\Lambda}\right) = \left(2.3 \pm 0.8\right) \times 10^{-6}$ [IJModP **A24**, 3638 (2009)]

$$\frac{D^0 \Sigma^0 \bar{\Lambda} + D^0 \bar{\Sigma}^0 \Lambda}{D^0 \Lambda \bar{\Lambda}} = 1.5 \pm 0.9$$ consistent with 2

$$\mathcal{B}(\bar{B}^0 \to D^0 p \bar{p}) = (1.04 \pm 0.07) \cdot 10^{-4}$$ Belle, BABAR average

$$\frac{D^0 \Lambda \bar{\Lambda}}{D^0 p \bar{p}} = \frac{1}{10.6 \pm 3.7}$$ consistent with $\frac{1}{12}$

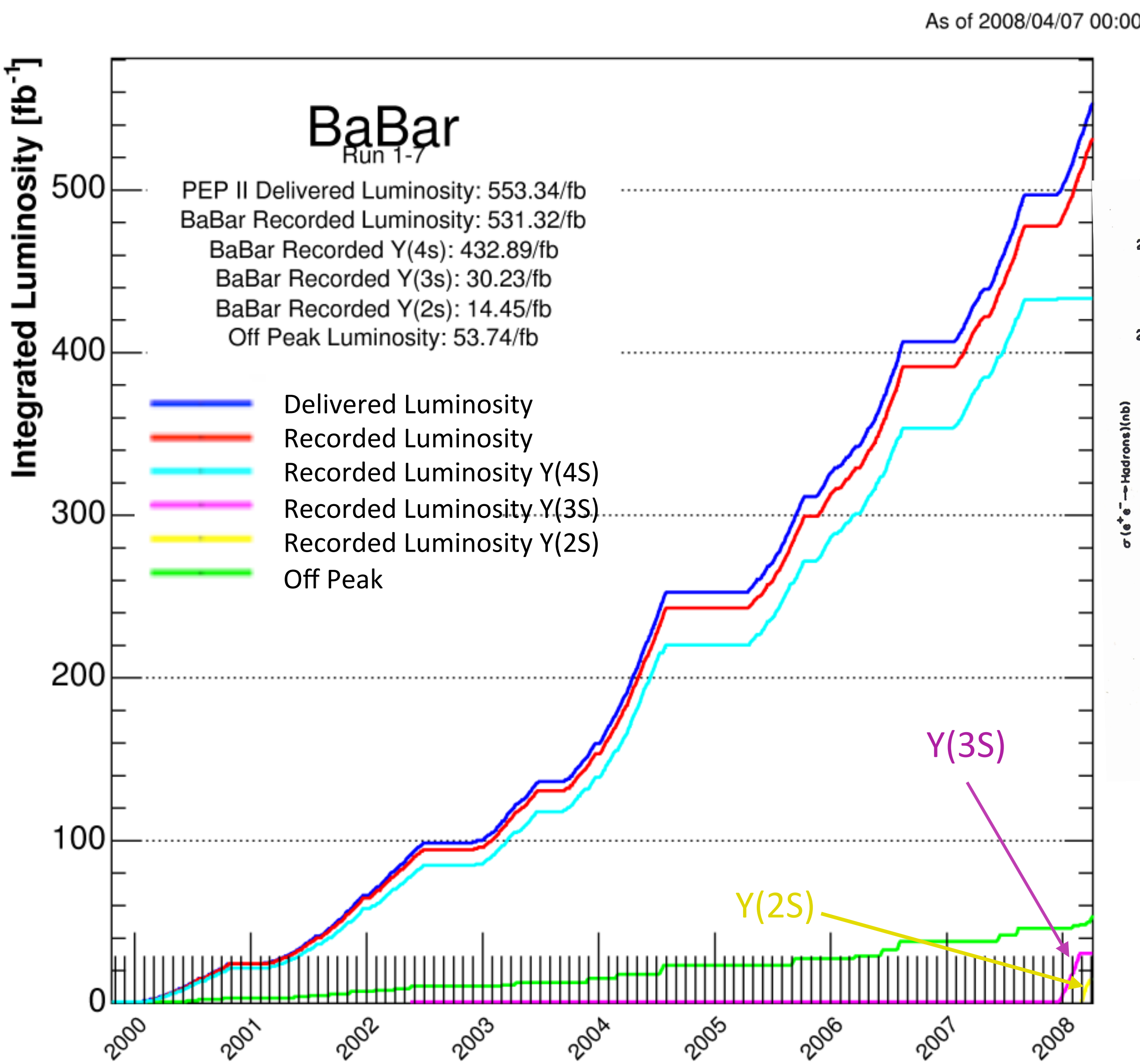
Summary & Conclusions

- *BABAR* continues producing interesting and competitive results.
  - new analyses improve understanding of baryon production in *B* decays, but still ~90% of all channels unknown
  - Resonant substructure appears to increase baryonic *B* decay branching fractions – not only having extra particles in the final state.
  - hadronisation is similar to (jet) fragmentation (e.g. s quark suppression)
  - baryon-antibaryon threshold enhancement is qualitatively understood (no quantitative theory)
    no general “baryon-antibaryon condensate” (see 4-baryon decay)

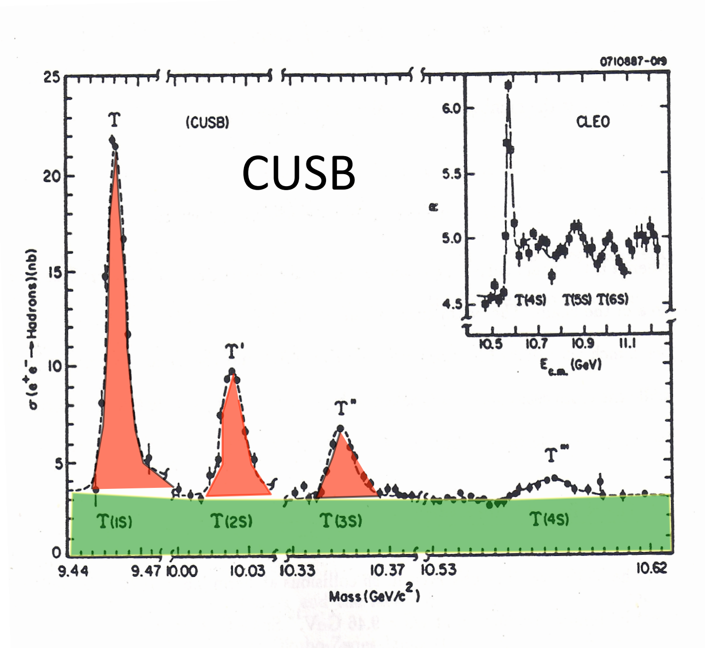
Thank You!

Back Up Slides

The *BaBar* Running Era

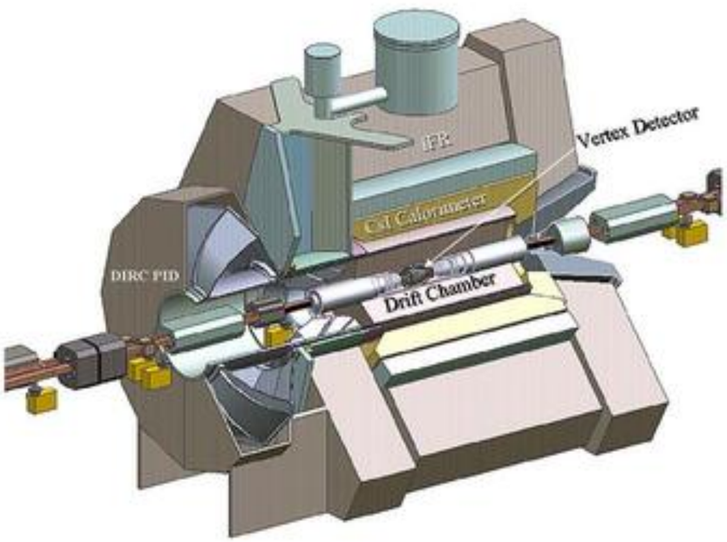


7 Runs over the course of 9 years



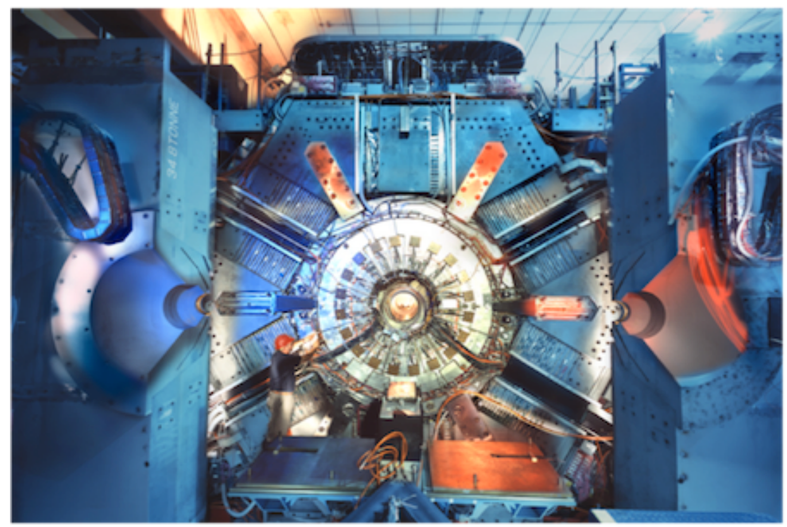
- First collisions with BaBar May 26, 1999
- Final data taken 12:43 p.m., April 7, 2008

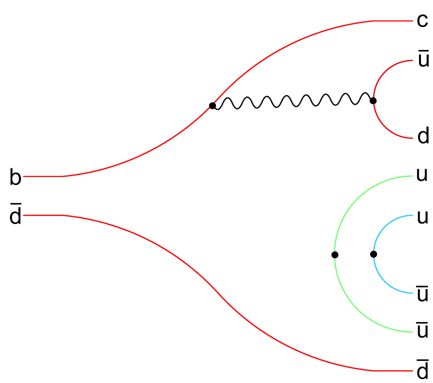
The *BABAR* Experiment at SLAC



- Asymmetric-energy beams for boost
- Modern/state of the art detector
- 5 cylindrical subdetectors with a 40-layer drift chamber
- Excellent electromagnetic calorimetry
- Multiple measurements for particle identification
- Excellent momentum resolution

- Primarily designed for study of *CP*-violation in *B* meson decays
- Quality and general-purpose design make it suitable for a large variety of studies




c
$\bar{u}$
d
b
$\bar{d}$
u
u
$\bar{u}$
$\bar{u}$
$\bar{d}$