FLAVOR PHYSICS & CP VIOLATION

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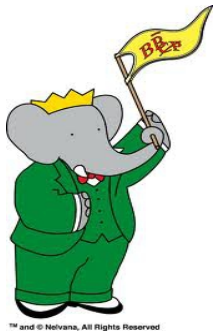
Baryonic B Decays

Marcello Rotondo

I.N.F.N. Padova
BaBar Collaboration

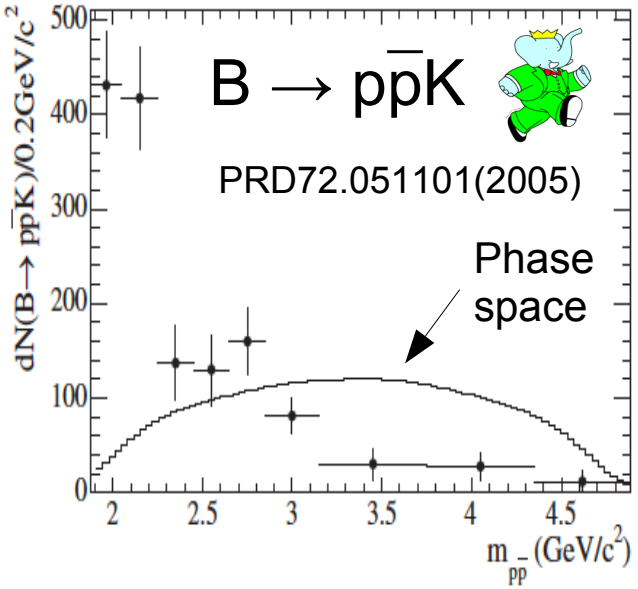


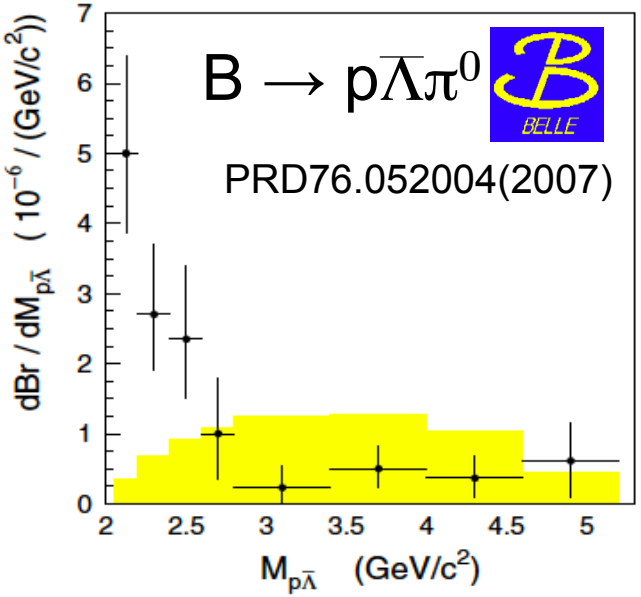
Baryonic B meson decays: why?

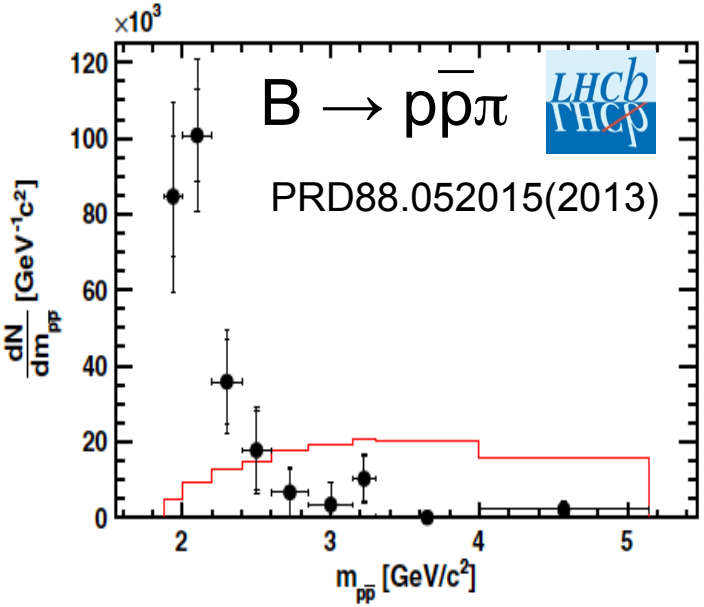
- The $B \to \mathcal{B}_1 \overline{\mathcal{B}}_2 + X$ has large branching fraction ($\mathcal{B}$ ≡ Baryon)
  - Inclusive measured BF:
    - $BF(B \to \mathcal{B} X) = (6.8 \pm 0.6)\ \%$ PDG2014
    - $BF(B \to \Lambda_c X) = (4.5 \pm 1.2)\ \%$
  - Only about 10% of all baryonic decays are exclusively know so far!
- The relatively high B meson mass allows big variety of baryons in the final state
  - Perturbative QCD cannot be applied:
    - Investigation of quark fragmentation at low q^2
    - Tests for phenomenological models

Baryonic B decays: threshold enhancement

- Near threshold enhancement observed in many baryonic B decays
  - The baryon pair in B→$\mathcal{B}1\overline{\mathcal{B}}2$+X decays are produced near the $\mathcal{B}1\overline{\mathcal{B}}2$ threshold







- Different models to describe threshold enhancement
  - Pole model: PRD66,014020 (2002)
  - Final-state interaction: PRC68,052201 (2003)
  - Glueball: PRD66,054004 (2002)
  - Bound state PLB567,273 (2003)

The enhancement is present also in baryon produced in e^+e^- collisions and Ψ decays

Example for Branching Fractions (PDG)

Charmed baryon modes (10^{-4})

$B^0 \to \bar{\Lambda}_c p$	0.2
$B^0 \to \bar{\Lambda}_c p\pi^0$	1.9
$B^+ \to \bar{\Lambda}_c p\pi^+$	2.8
$B^+ \to \bar{\Lambda}_c p\pi^+\pi^0$	18.0
$B^0 \to \bar{\Lambda}_c p\pi^+\pi^-$	11.7
$B^+ \to \bar{\Lambda}_c p\pi^+\pi^+\pi^2$	22.0
$B^+ \to \Sigma_c^0 p$	0.37
$B^+ \to \Sigma_c^0 p\pi^0$	4.4
$B^+ \to \Sigma_c^0 p\pi^-\pi^+$	4.4
$B^+ \to \Sigma_c^{--} p\pi^-\pi^+$	3.0

Non-charmed modes (10^{-6})

$B^0 \to p\bar{p}$	
$B^+ \to p\bar{p}\,\pi$	1.6
$B^+ \to p\bar{p}\,K$	5.9
$B^0 \to p\bar{p}\,K^0$	2.7
$B^+ \to p\bar{\Lambda}$	<0.3
$B^+ \to p\bar{\Lambda}\pi^0$	3.0
$B^0 \to p\bar{\Lambda}\pi^-$	3.1
$B^+ \to p\bar{\Lambda}\pi^+\pi^-$	5.9
$B^+ \to M\bar{\Lambda}\gamma$	2.4
$B^0 \to M\bar{\Lambda}\pi^+\gamma$	

Two-body decays are suppressed

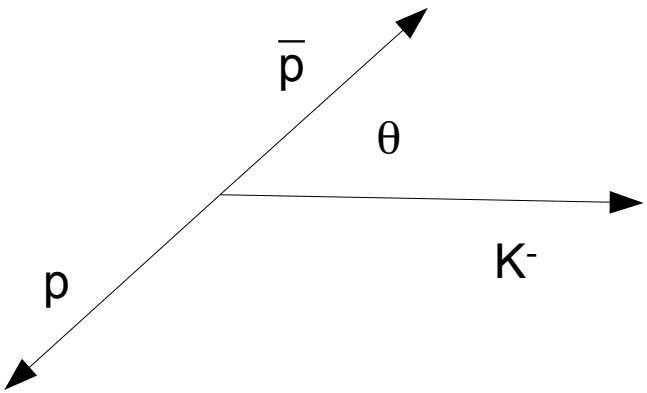
Charmed modes: modes with additional particles can have significant higher BF

Crucial if more resonant submodes exists with the same final state

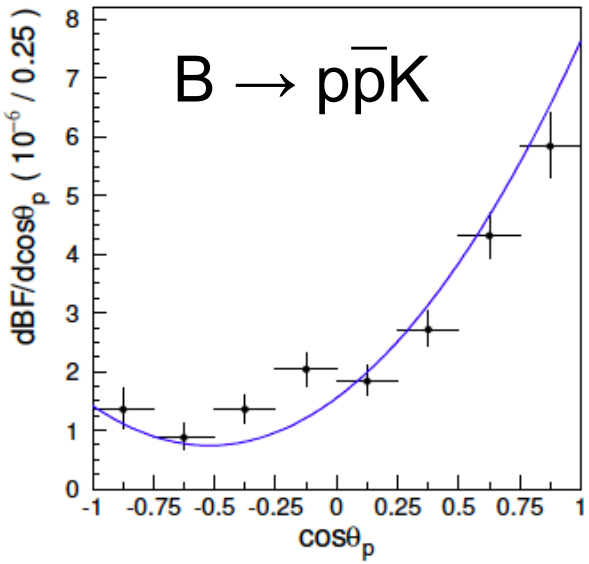
Non-charmed: hierarchy seems not visible for more than 2 particles

Baryonic B decays: known problems

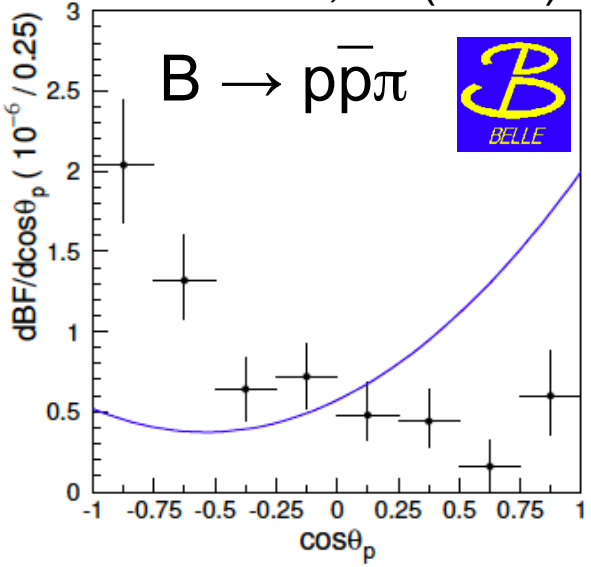
- Various models exist. First predictions from Hou and Soni PRL86, 4247(2001)
- The present models are not completely satisfactory, for example the short distance model for $B \to \mathcal{B}_1\bar{\mathcal{B}}_2 M$ decays by Geng-Hsiao (2006) explains very well the threshold enhancement and the multiplicity pattern...
  - but predicts wrong angular distribution in $B \to p\bar{p}\pi$



PLB659, 80 (2008)



$B^+ \to p\bar{p}K^+$ (Wei, 2008b)

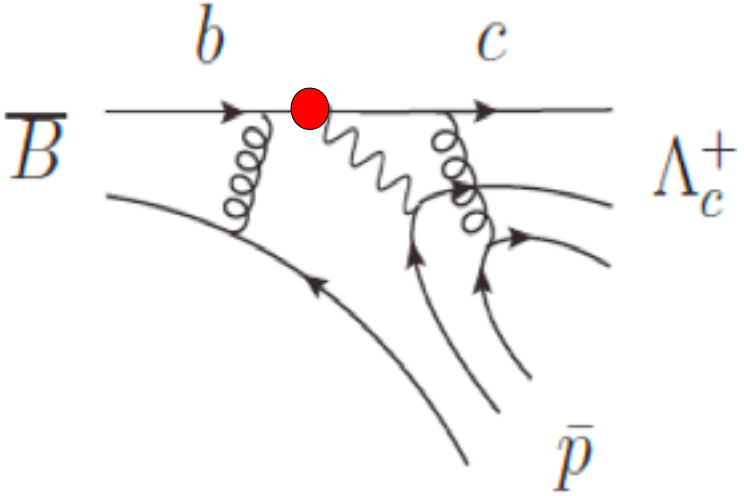


$B^+ \to p\bar{p}\pi^+$ (Wei, 2008b)

- Long interaction terms and re-scattering effects? Exotic states? Still an open issue that requires further development

Recent results on non-charmed baryonic B decays

Charmless two-body decays



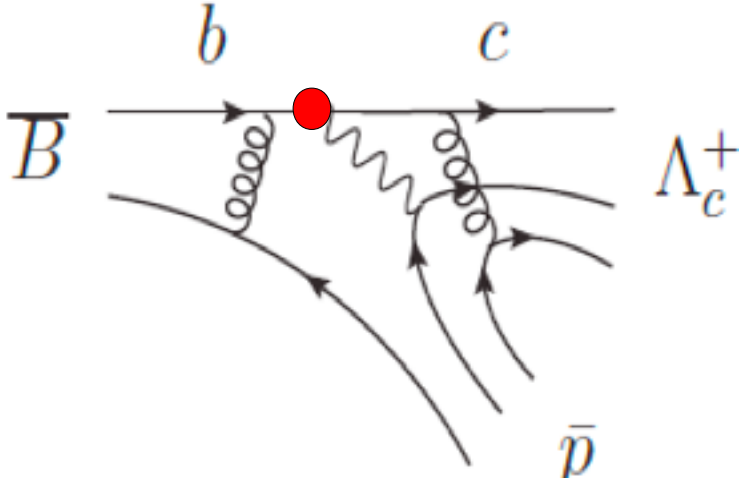
$BF(\overline{B}^0 \to \Lambda_c \overline{p}) = (2.0 \pm 0.4) \times 10^{-5}$

Dynamical suppression due to the emission of two hard gluons

Chen, Chua Hsiao 2009

$BF(B \to p\overline{p}) \sim 10^{-7}$ because of the suppression due to $|V_{ub}/V_{cb}|^2$

Charmless two-body decays



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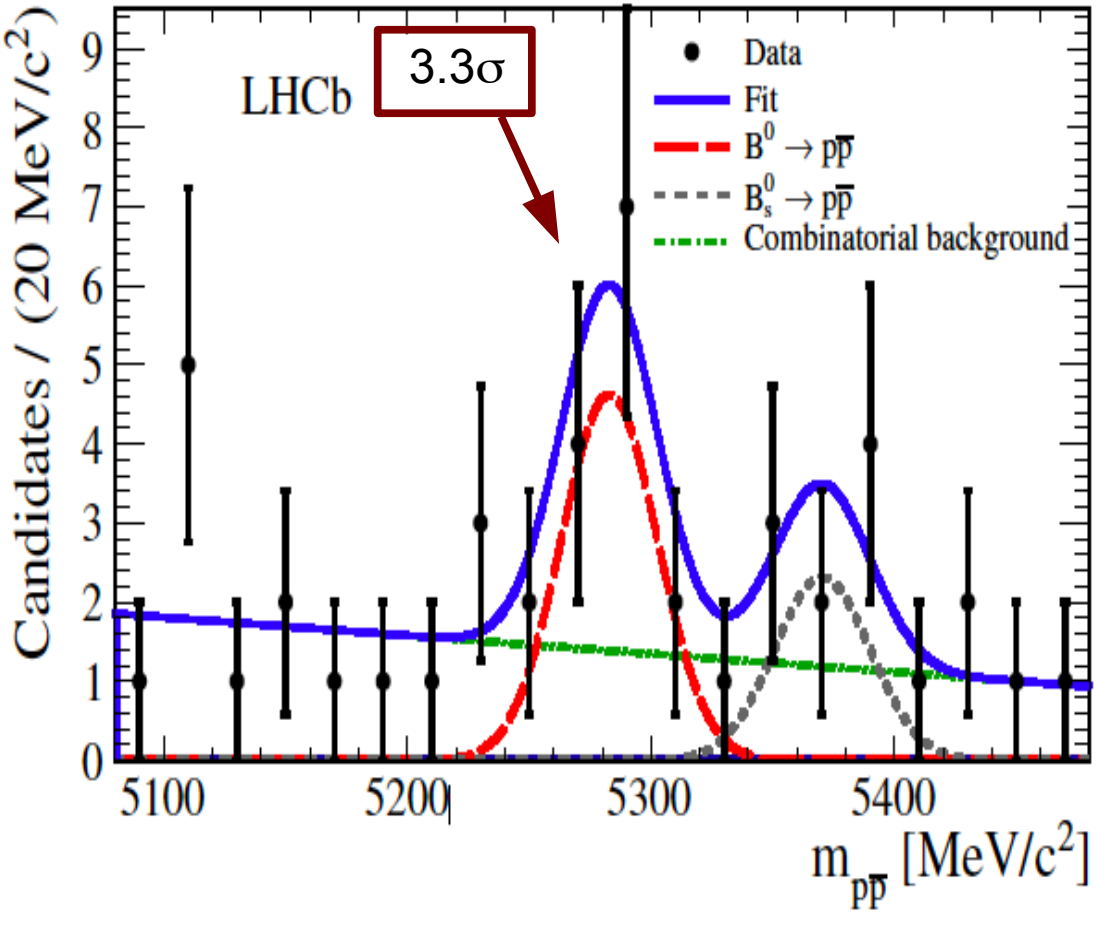


$$\mathcal{B}(B^0 \to p\bar{p}) = \left(1.47\,^{+0.62\,+0.35}_{-0.51\,-0.14}\right) \times 10^{-8}$$

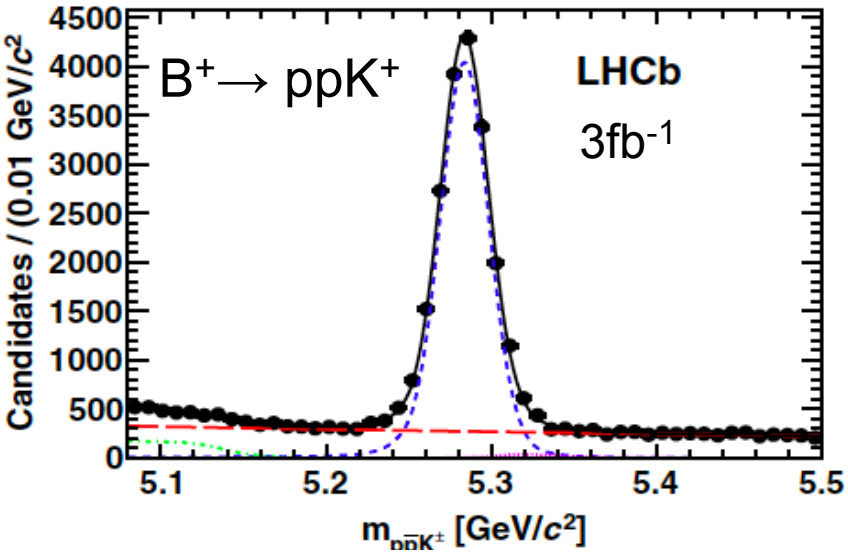
$$\mathcal{B}(B_s^0 \to p\bar{p}) = \left(2.84\,^{+2.03\,+0.85}_{-1.68\,-0.18}\right) \times 10^{-8}$$

- Incompatible with most of the old theoretical predictions
  - A recent calculation explains well the results Hsiao, Geng PRD91,077501(2015)
  - Predicts also BFs of many other channels accessible at LHCb!

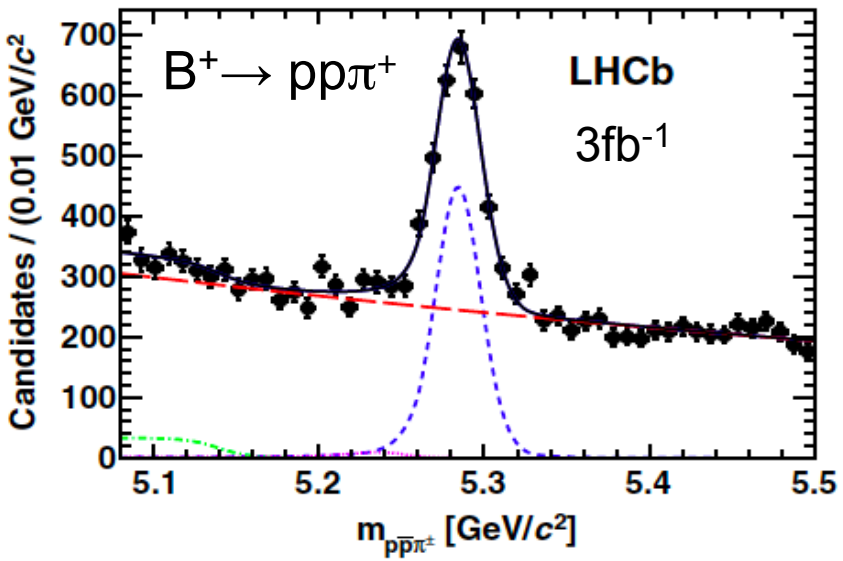
Study of $B^+ \to p\bar{p}K^+$ ($p\bar{p}\pi^+$)

- First charmless baryonic B decay (Belle, 2002): widely studied
- Huge clean sample: thanks to excellent VELO and RICH performances

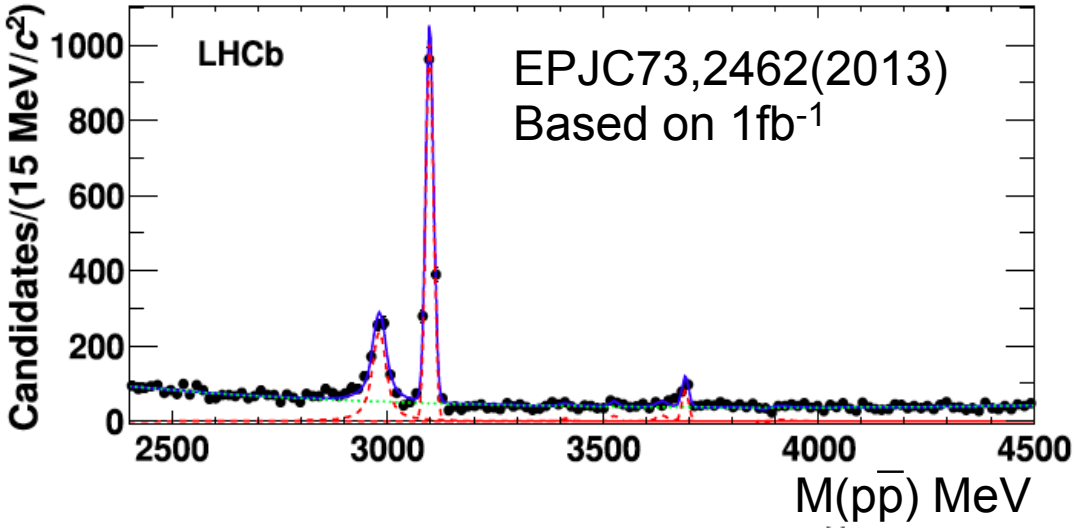
N = 18721 ± 142



N = 1988 ± 74



PRL113, 141801 (2014)



$$\frac{\mathcal{B}(B^+ \to p\bar{p}K^+)_{\text{total}}}{\mathcal{B}(B^+ \to J/\psi K^+ \to p\bar{p}K^+)} = 4.91 \pm 0.19\ (\text{stat}) \pm 0.14\ (\text{syst})$$

$$\frac{\mathcal{B}(B^+ \to p\bar{p}K^+)_{M_{p\bar{p}}<2.85\ \text{GeV}/c^2}}{\mathcal{B}(B^+ \to J/\psi K^+ \to p\bar{p}K^+)} = 2.02 \pm 0.10\ (\text{stat}) \pm 0.08\ (\text{syst})$$

CP violation in $B^+ \to p\bar{p}K^+$

PRL113,141801(2014)

- Three-body decays are a laboratory to study strong phase of interfering amplitudes
  - In $B^+ \to h^+h^-h^+$ decays a CP asymmetry appears at low (h^+h^-) masses
  - What happens for $p\bar{p}$ case?

$$A_{\rm raw} = \frac{N(B^- \to p\bar{p}h^-) - N(B^+ \to p\bar{p}h^+)}{N(B^- \to p\bar{p}h^-) + N(B^+ \to p\bar{p}h^+)}$$

$$A_{CP} = A_{\rm raw}^{\rm acc} - A_{\rm P}(B^\pm) - A_{\rm det}(K^\pm)$$

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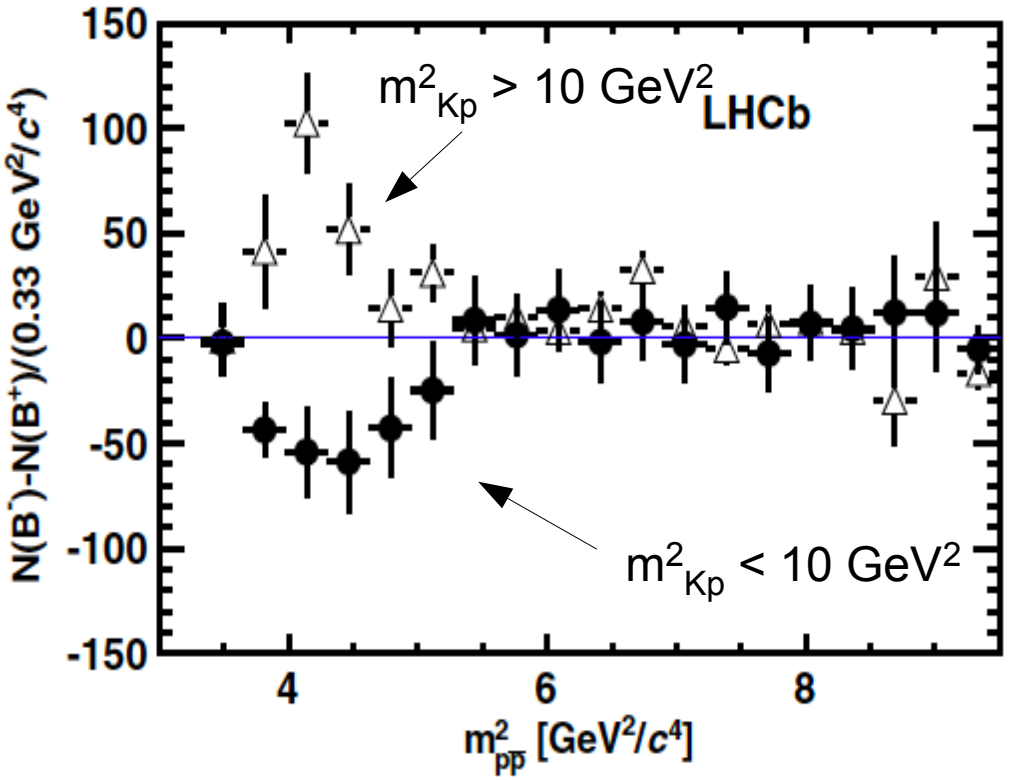


- Clear pattern close to the threshold
  - $m(p\bar{p})<2.85$ GeV

$$A_{CP}(m^2_{Kp} < 10GeV^2) = -0.036 \pm 0.023 \pm 0.004$$
$$A_{CP}(m^2_{Kp} > 10GeV^2) = 0.096 \pm 0.024 \pm 0.004$$

4.2σ

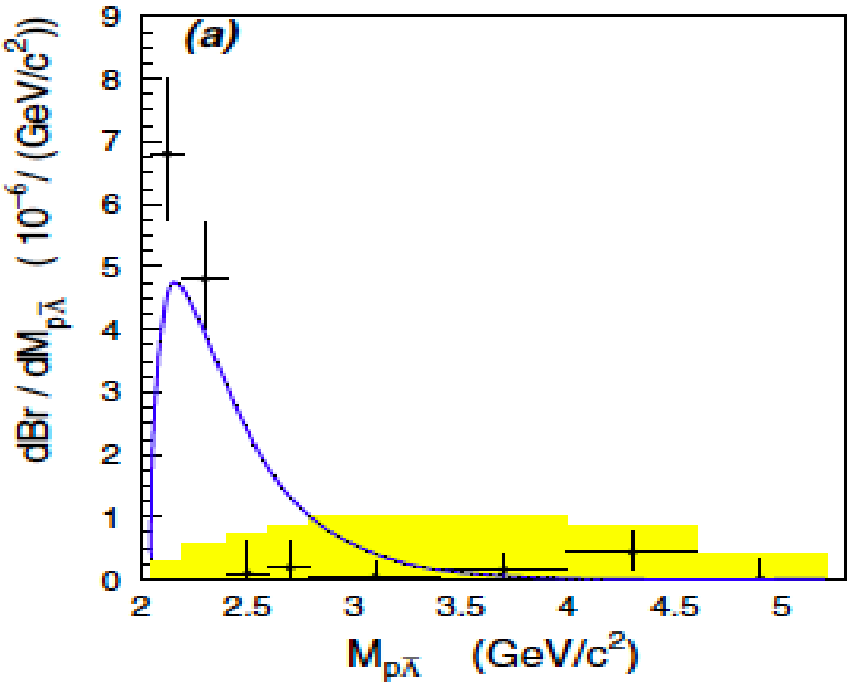
- Similar to $B^+ \to h^+h^-h^+$: strong phase difference could involve specific mechanism
  - Interference between long-range $p\bar{p}$-waves with different angular momenta M.Suzuki JPG34,283(2007)

Study of radiative $\bar{B} \to \Lambda\bar{p}\pi^+\gamma$ decay

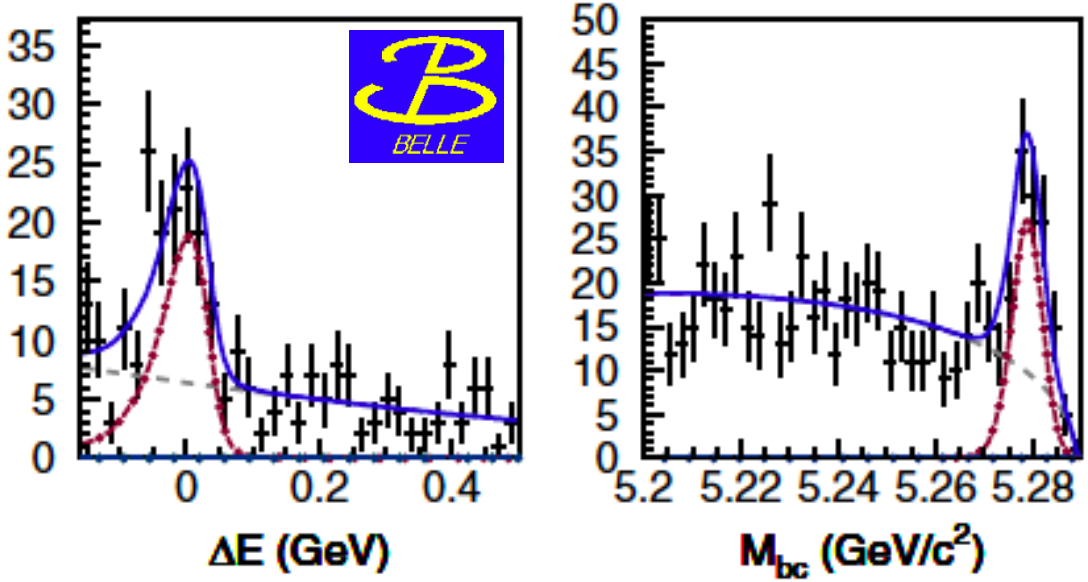
- $BF(B \to \Lambda\bar{p}) << BF(B \to \Lambda\bar{p}\pi^0)$
  - Following the well known multiplicity pattern

- $BF(B \to \Lambda\bar{p}) < 0.3 \cdot 10^{-6}$
- $BF(B \to \Lambda\bar{p}\pi^0) = (3.0\pm0.7)\cdot 10^{-6}$

- Radiative baryonic B decays well established
  - $BF(B \to \Lambda\bar{p}\gamma)=(2.5\pm0.5)\cdot10^{-6}$
  - Usual enhancement close to the $\mathcal{B}1\bar{\mathcal{B}}2$ mass-threshold



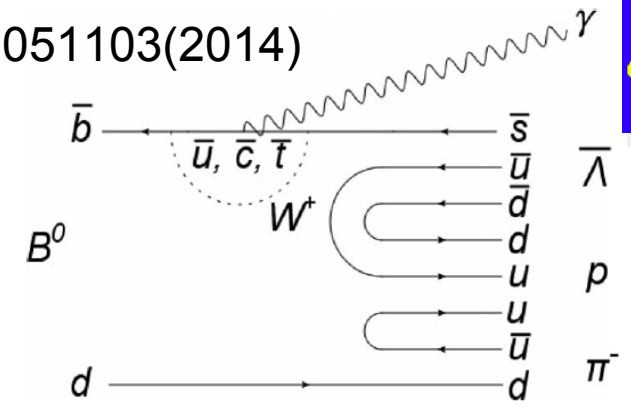
PRD76,052004(2007)



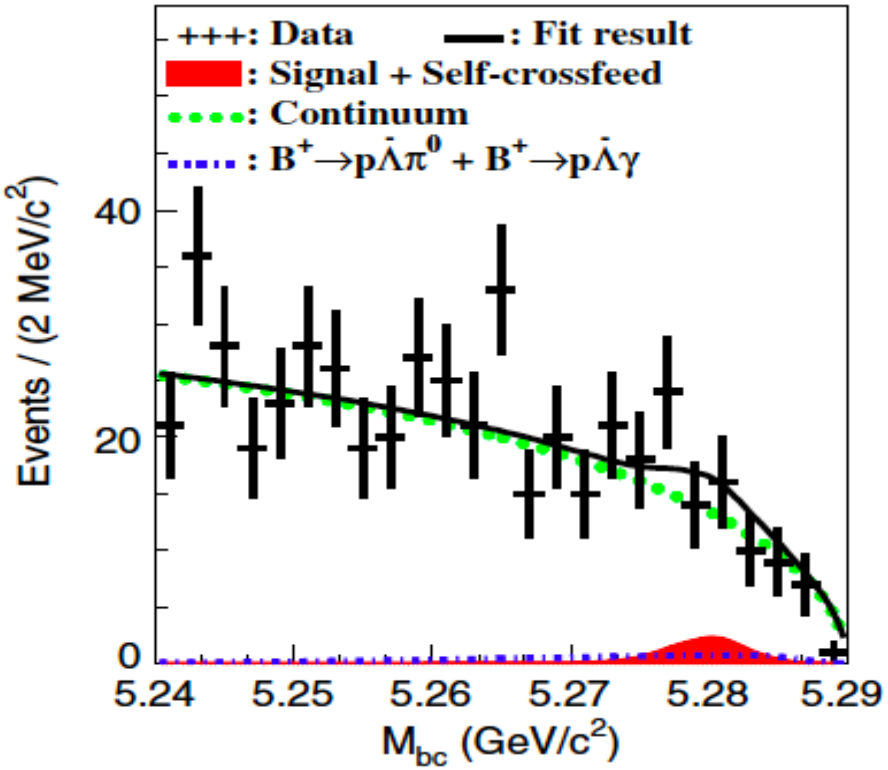
- With higher multiplicity we expect "naturally" a similar/higher rate
  - $BF(B \to \Lambda\bar{p}\pi\gamma) > BF(B \to \Lambda\bar{p}\gamma)$

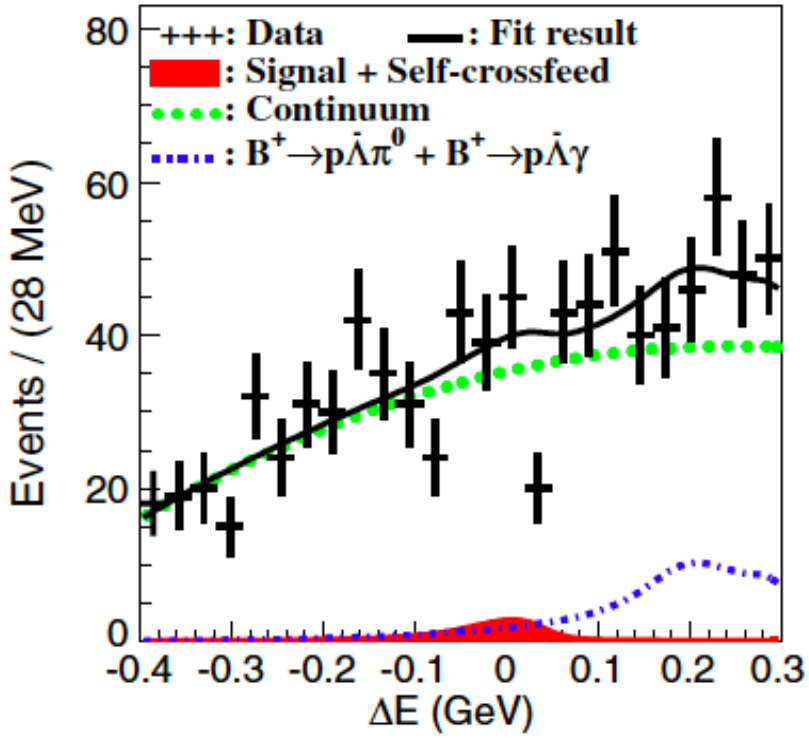
Search for $B \to \Lambda \bar{p} \pi^+ \gamma$

PRD89,051103(2014)



- With the full dataset 772 x 10^6 $B\bar{B}$
- $\Lambda \to p\pi$ and E^*_γ>1.7 GeV





$$\mathcal{B}(\bar{B}^0 \to \Lambda \bar{p} \pi^+ \gamma) < 6.48 \times 10^{-7} @ 90\% CL \sim \frac{1}{4} \mathcal{B}(\bar{B}^0 \to \Lambda \bar{p} \gamma)$$

The hierarchy observed in baryonic B decays is not observed in the radiative decays

Recent results on charmed baryonic B decays

Study of $\overline{B} \to \Lambda_c^+ \overline{p} K^- K^+$

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

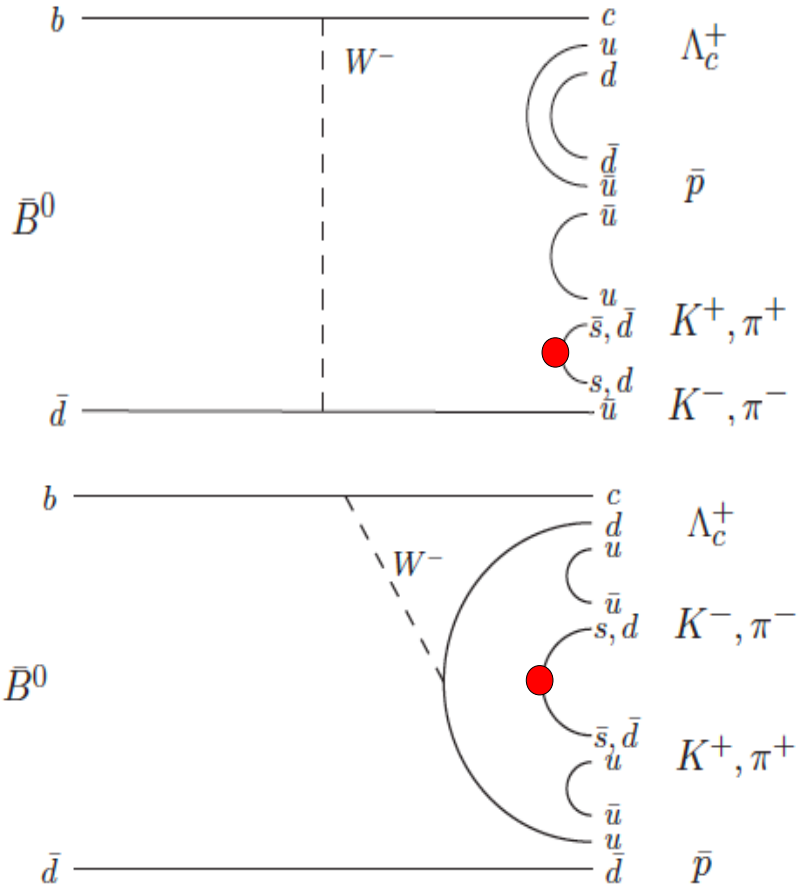
$$\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+) = (1.17 \pm 0.23) \times 10^{-3}$$

PRD75,011101 (2007)

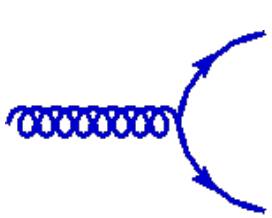
PRD87,092004 (2013)

- But for the $\pi^-\pi^+$ mode there are more resonant sub-channels
  - Σ_c^{++} , Σ_c^0, ...

$$\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+)_{\text{non-res}} \lesssim$$
$$50\% \cdot \mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+) = 6 \cdot 10^{-4}$$



- We expect a further suppression for the $s\bar{s}$

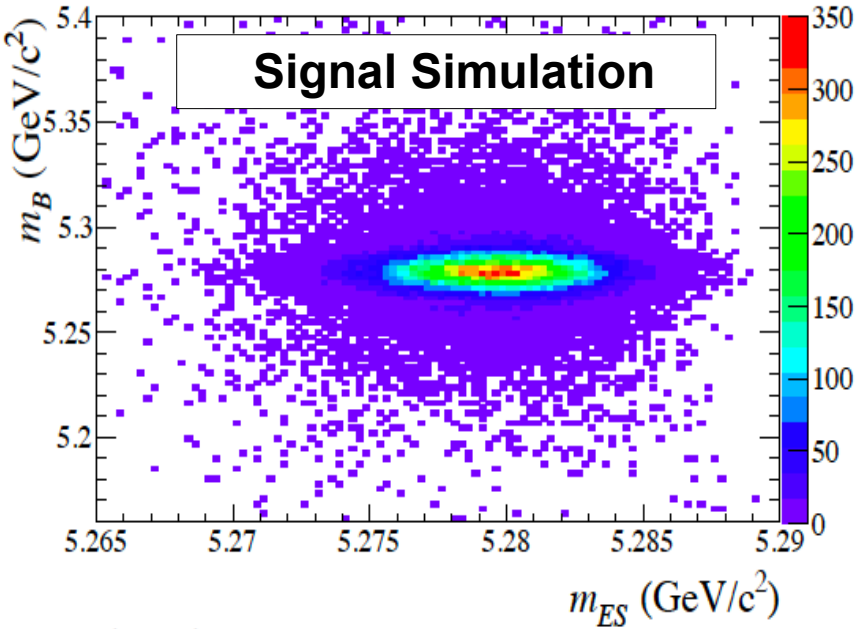


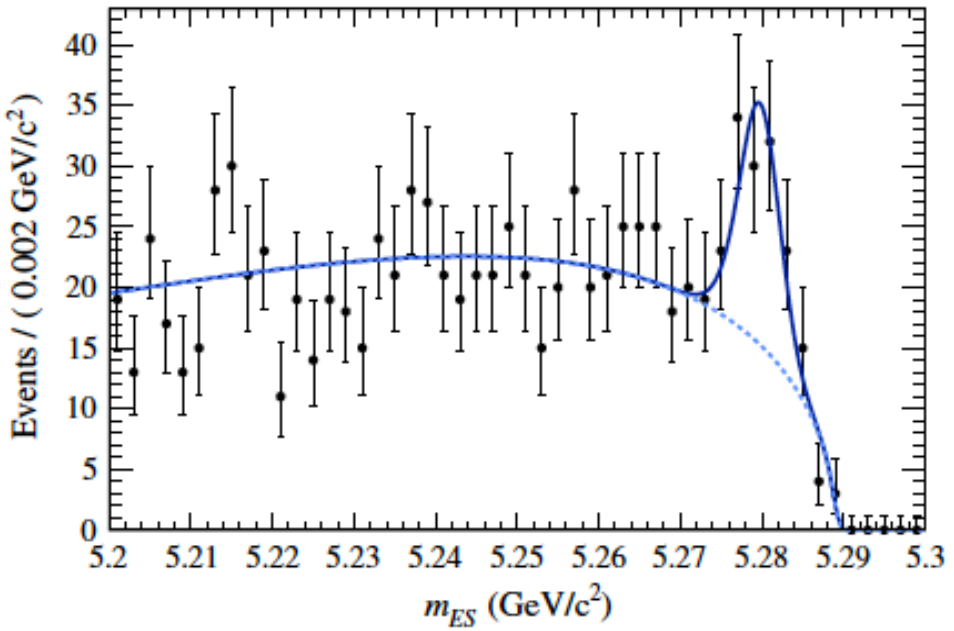
$s\bar{s}/d\bar{d}$ suppression factor 1/3

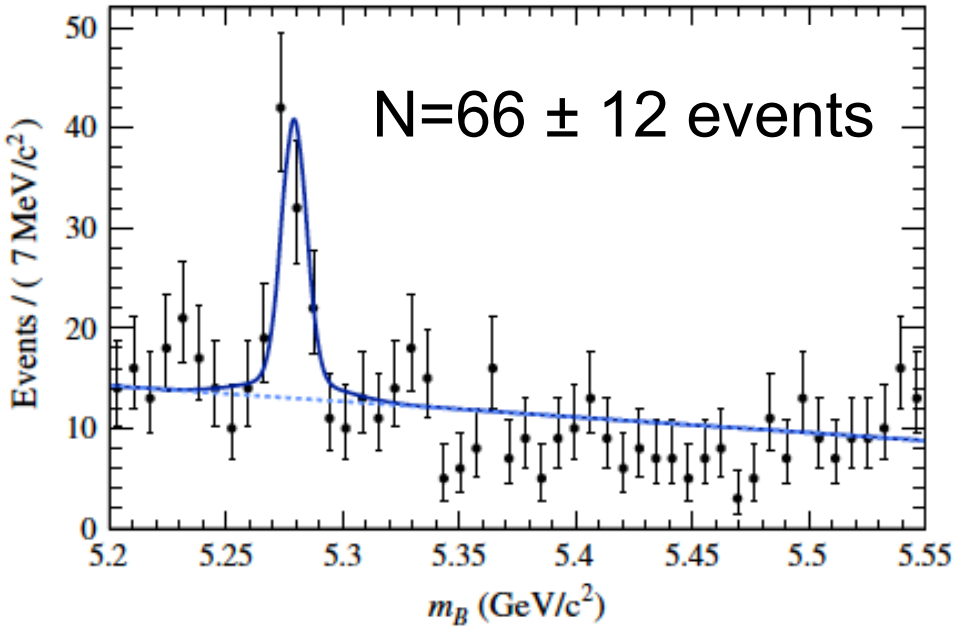
$\overline{B} \to \Lambda_c^+ \bar{p} K^2 K^+$: signal yield

PRD91,031102(2015)

- Full statistics $471 \cdot 10^6$ BB
- $\Lambda_c \to pK\pi$
- Signal extracted with a fit to the energy-substituted mass m_{ES} and the invariant mass m_B







- Significance (statistical only):

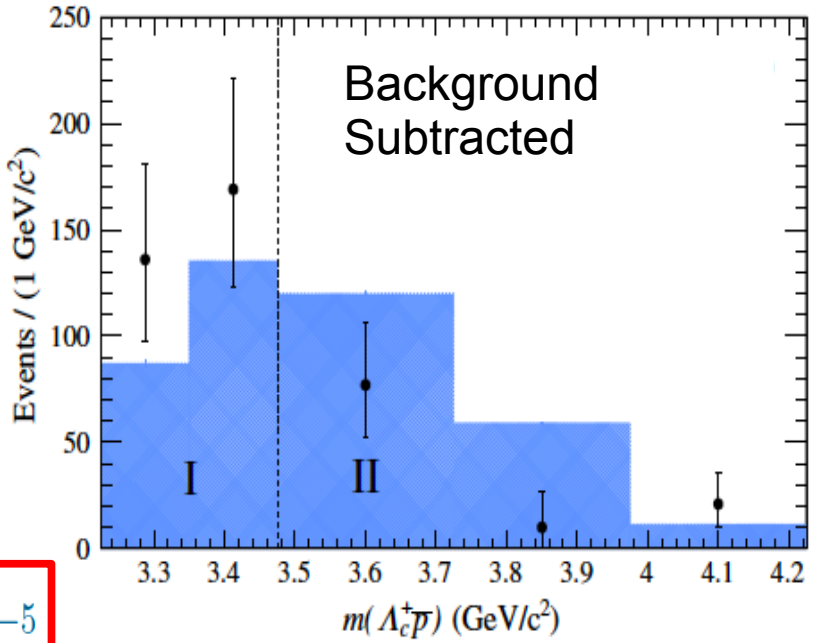
$$S = \sqrt{-2\log\left(L_0/L_{\text{sig}}\right)} = 5.4\,\sigma$$

$\overline{B} \to \Lambda_c^+ \overline{p} K^- K^+$: results

PRD91,031102(2015)

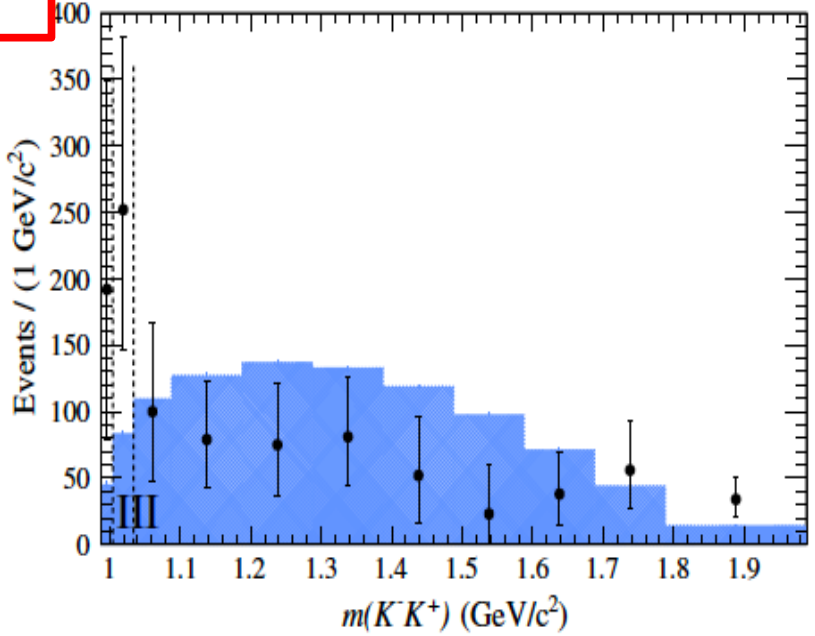
- Threshold enhancement not significant
  - consistent with small enhancement observed in $B \to \Lambda_c \overline{p}\pi\pi$
- Efficiency determined in 2 different regions of $M(\Lambda_c \overline{p})$ to account for a possible enhancement in the invariant $\mathcal{B}1\overline{\mathcal{B}}2$ mass

$$\mathcal{B}\left(\overline{B}^0 \to \Lambda_c^+ \overline{p} K^- K^+\right) = \left(2.5 \pm 0.4_{(\text{stat})} \pm 0.2_{(\text{syst})} \pm 0.6_{\left(\Lambda_c^+\right)}\right) \times 10^{-5}$$



- Hint for resonance in the KK invariant mass

$$\mathcal{B}\left(\overline{B}^0 \to \Lambda_c^+ \overline{p}\phi\right) < 1.2 \times 10^{-5}$$



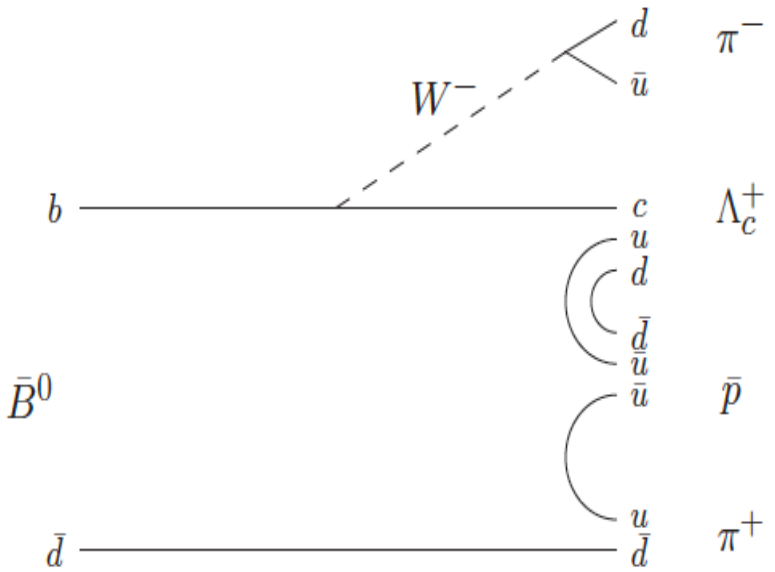
- No evidence for other resonances

$\overline{B} \to \Lambda_c^+ \overline{p} K^- K^+$: interpretation

PRD91,031102(2015)

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

$$\frac{\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} K^- K^+)}{\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+)_{\text{non-res}}} \gtrsim \frac{2.5 \cdot 10^{-5}}{6 \cdot 10^{-4}} = \frac{1}{24} < \frac{1}{3}$$



External W emission

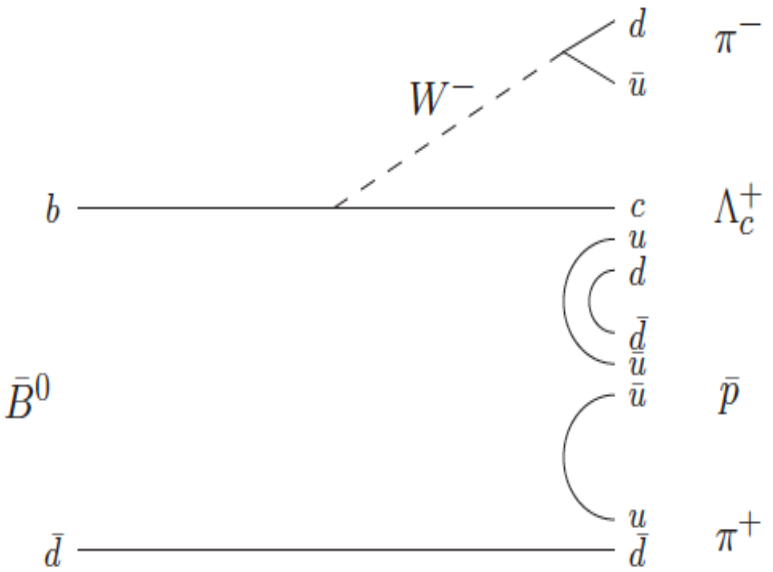
- Simple expectation from $s\bar{s}$ suppression perhaps does not hold because
  - $\overline{B} \to \Lambda_c^+ \overline{p} \pi^- \pi^+$ can have contributions not possible for $\overline{B} \to \Lambda_c^+ \overline{p} K^- K^+$
  - More careful study of all possibile resonant submodes in are needed!

$\overline{B} \to \Lambda_c^+ \overline{p} K^2K^+$: interpretation

PRD91,031102(2015)

- Comparing $\overline{B} \to \Lambda_c^+ \overline{p} \pi^-\pi^+$ to $\overline{B} \to \Lambda_c^+ \overline{p} K^2K^+$

$$\frac{\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} K^- K^+)}{\mathcal{B}(\overline{B}^0 \to \Lambda_c^+ \overline{p} \pi^- \pi^+)_{\text{non-res}}} \gtrsim \frac{2.5 \cdot 10^{-5}}{6 \cdot 10^{-4}} = \frac{1}{24} < \frac{1}{3}$$



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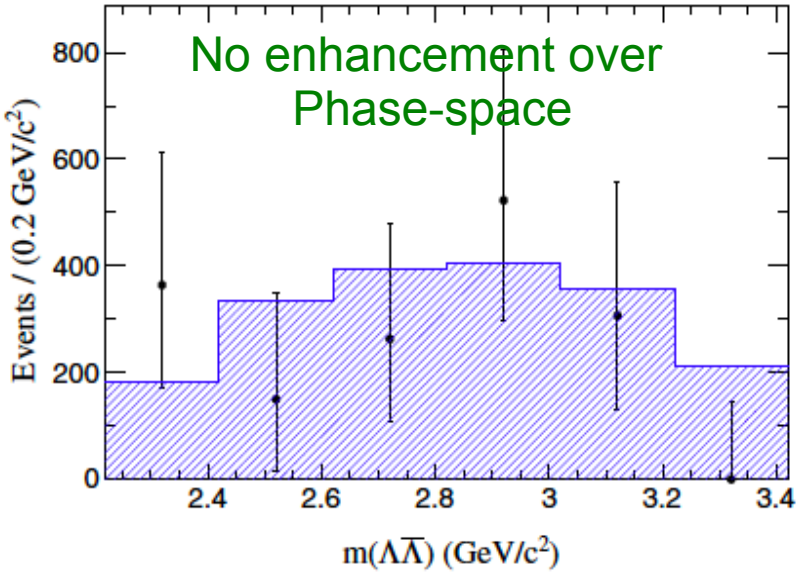
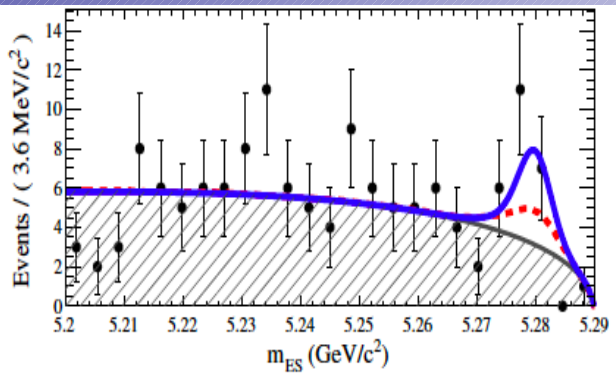
- Simple expectation from $s\bar{s}$-suppression in the fragmentation holds in other cases:
  - $B^0 \to D^0 \Lambda\overline{\Lambda}$ / $B^0 \to D^0 p\overline{p}$

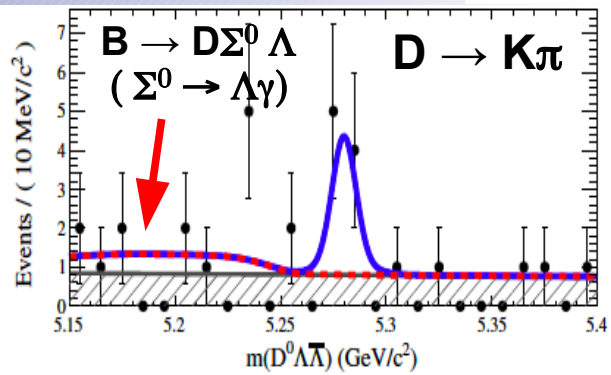
Study of $B^0 \to D^0 \Lambda\bar{\Lambda}$

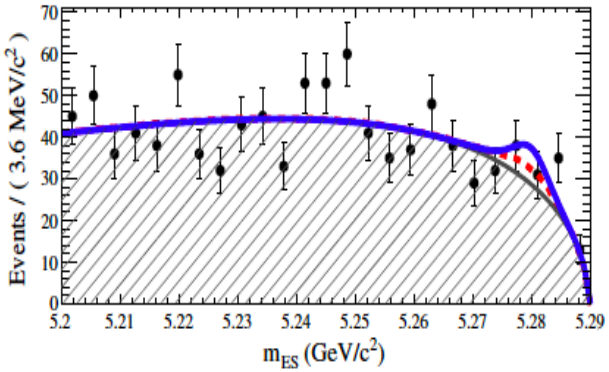
PRD89,112002(2014)

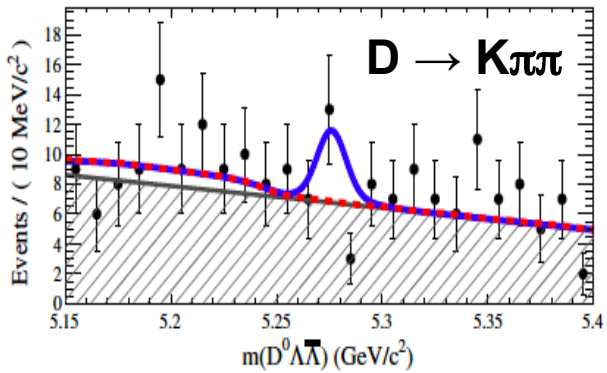
- $B^0 \to D^0 \Lambda\bar{\Lambda}$
  - $\Lambda \to p\pi$
  - $D \to K\pi, K\pi\pi\pi, K\pi\pi$
- 2D fit on m_{ES} and m_B, simultaneous for the three different D^0 decay modes
- Include also the contribution from $B \to D\Sigma^0\Lambda$ $(\Sigma^0 \to \Lambda\gamma)$

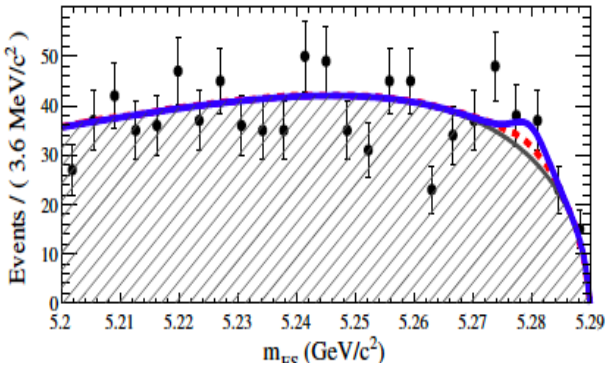


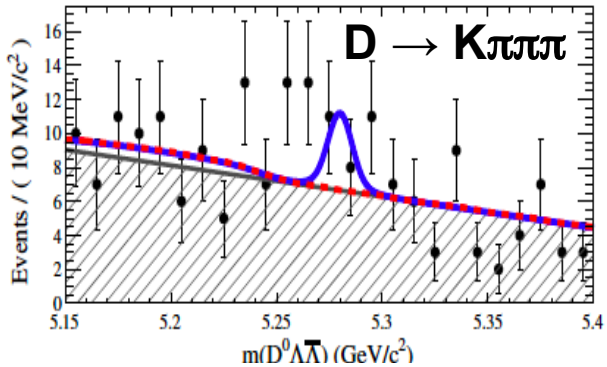












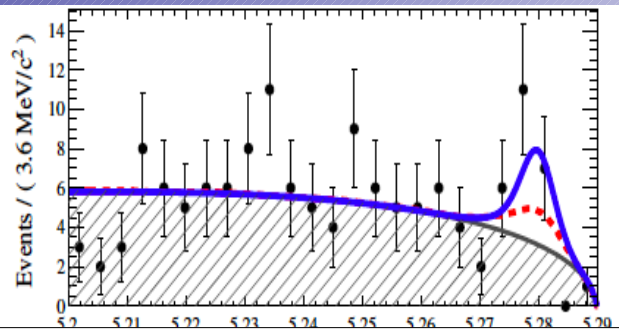
$$\mathcal{B}(\bar{B}^0 \to D^0 \Lambda\bar{\Lambda}) = (9.8^{+2.9}_{-2.6} \pm 1.9) \times 10^{-6}$$

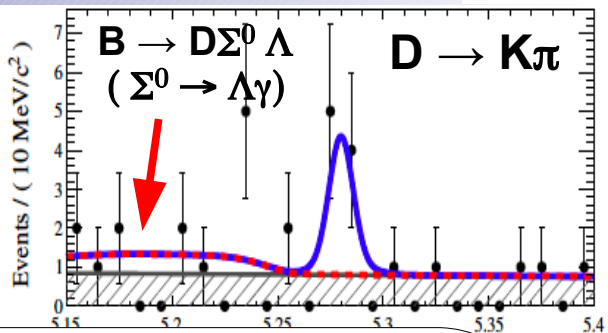
$$\mathcal{B}(\bar{B}^0 \to D^0 \Sigma^0 \bar{\Lambda} + \bar{B}^0 \to D^0 \Lambda \bar{\Sigma}^0) < 3.1 \times 10^{-5}$$

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

PRD89,112002(2014)

- $B^0 \to D^0 \Lambda\bar{\Lambda}$
  - $\Lambda \to p\pi$
  - $D \to K\pi, K\pi\pi\pi, K\pi\pi$

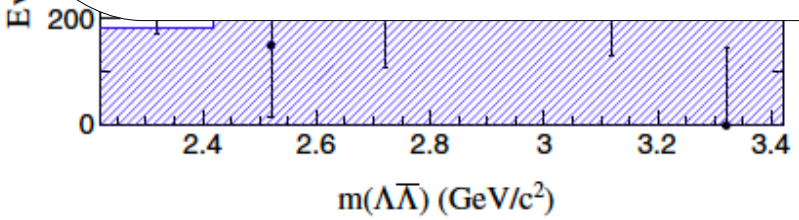




- Result consistent with Belle and with the theoretical expectations
- A simple model of hadronization with ss-suppresson holds in this case

$$\frac{\mathcal{B}(\bar{B}^0 \to D^0 \Lambda\bar{\Lambda})}{\mathcal{B}(\bar{B}^0 \to D^0 p\bar{p})} = 0.087 \pm 0.032$$

Expectation is 1/12 = 0.083



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Study of $\overline{B} \to \Lambda_c^+ \overline{p} p \overline{p}$

PRD89,071102 (2014)

- This decay is related to $\overline{B} \to \Lambda_c^+ \overline{p} \pi^- \pi^+$
- The allowed phased space is smaller ~1/1500
  - Large deviations are expected because hadronization can be enhanced in the phase region where $p\overline{p}$ have an invariant mass close to threshold
  - Possible resonances are absent: suppression?

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PRD89,071102 (2014)

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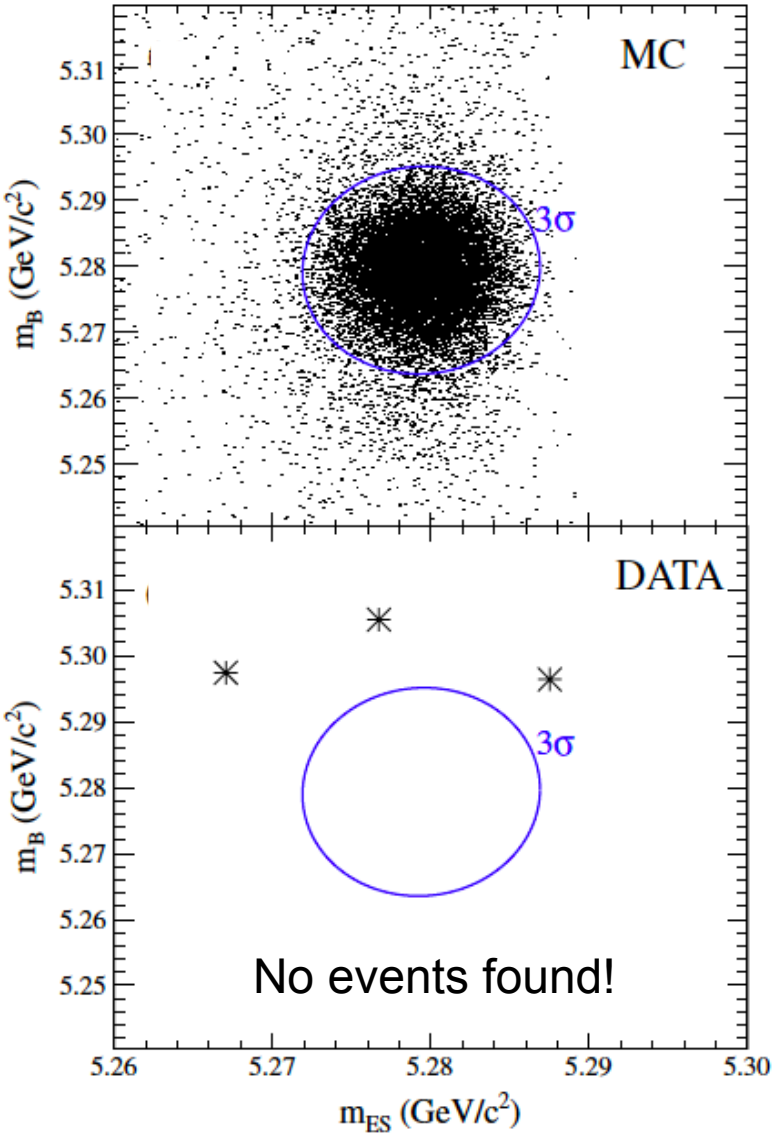
$$\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p}) \times \frac{\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+)}{0.050} < 2.8 \times 10^{-6} \text{ at } 90\% \text{ C.L.},$$

$$\frac{\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} p \bar{p})}{\mathcal{B}(\bar{B}^0 \to \Lambda_c^+ \bar{p} \pi^+ \pi^-)_{\text{non-res}}} \lesssim \frac{1}{220}$$



The enhancement over the phase space suppression is smaller than 6.8

Summary I

Charmed baryon modes (10^{-4})

$B^0 \to \bar{\Lambda}_c p$	0.2
$B^0 \to \bar{\Lambda}_c p\pi^0$	1.9
$B^+ \to \bar{\Lambda}_c p\pi^+$	2.8
$B^+ \to \bar{\Lambda}_c p\pi^+\pi^0$	18.0
$B^0 \to \bar{\Lambda}_c p\pi^+\pi^-$	11.7
$B^+ \to \bar{\Lambda}_c p\pi^+\pi^+\pi^2$	22.0
$B^+ \to \Sigma_c^0 p$	0.37
$B^+ \to \Sigma_c^0 p\pi^0$	4.4
$B^+ \to \Sigma_c^0 p\pi^-\pi^+$	4.4
$B^+ \to \Sigma_c^{++} p\pi^-\pi^+$	3.0
$B^0 \to \bar{\Lambda}_c p K^+ K^-$	**0.25**
$B^0 \to \bar{\Lambda}_c p\bar{p}p$	**<0.028**

Non-charmed modes (10^{-6})

$B^0 \to p\bar{p}$	**0.015**
$B^+ \to p\bar{p}\,\pi$	1.6
$B^+ \to p\bar{p}\,K$	5.9
$B^0 \to p\bar{p}\,K^0$	2.7
$B^+ \to p\bar{\Lambda}$	<0.3
$B^+ \to p\bar{\Lambda}\pi^0$	3.0
$B^0 \to p\bar{\Lambda}\pi^-$	3.1
$B^+ \to p\bar{\Lambda}\pi^+\pi^-$	5.9
$B^+ \to p\bar{\Lambda}\gamma$	2.4
$B^0 \to p\bar{\Lambda}\pi^+\gamma$	**<0.65**

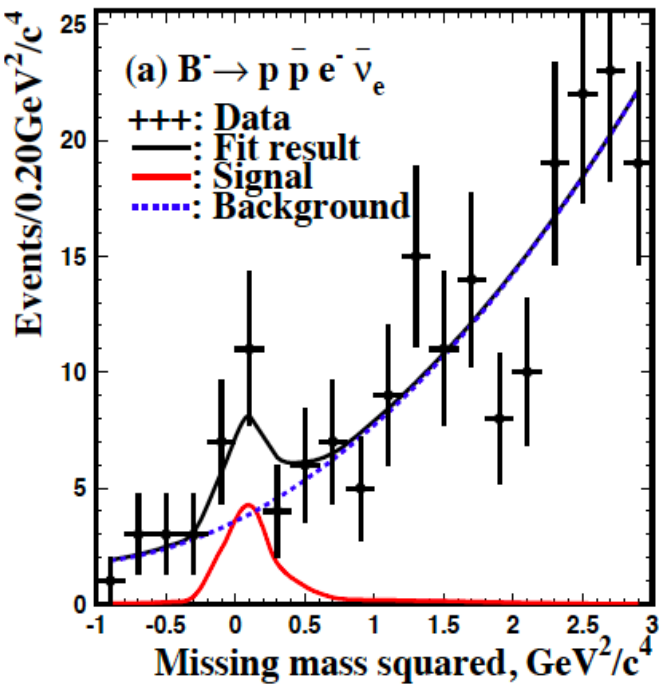
Summary II

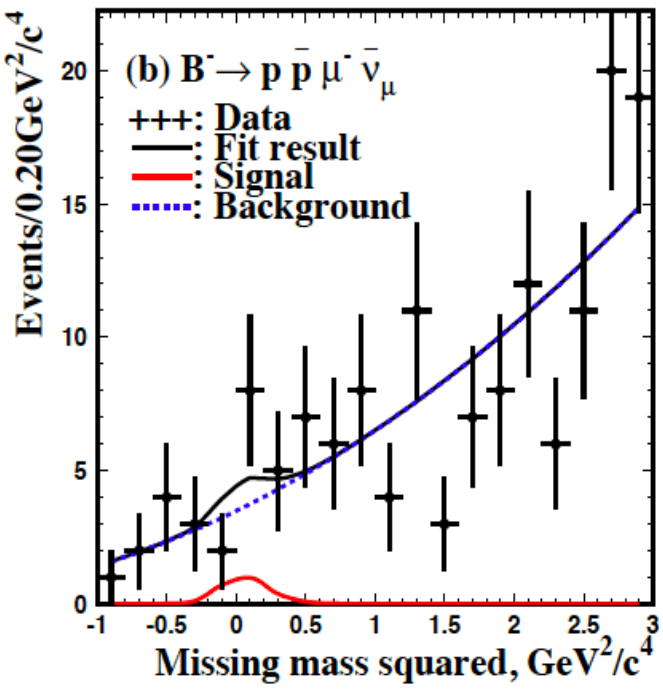
- LHCb has evidence of $B \to p\bar{p}$: BF lower than CKM suppression expectation
  - Study of other rare 2-body baryonic decays would be desirable, only accessible at LHCb due to their small BFs
- LHCb shows a first evidence of CP violation in $B \to p\bar{p}K$
  - CP should be enhanced in $B \to p\bar{p}K^*$
- Belle search of $B^0 \to p\bar{\Lambda}\pi^+\gamma$ shows that multiplicity hierarchy predicted by short-range models is violated in this case
- BaBar shows that $B^0 \to \bar{\Lambda}_c pK^+K^-$ suppression is beyond the $s\bar{s}$ -contribution
- The $B^0 \to \bar{\Lambda}_c p\bar{p}p$ from BaBar shows that a significantly enhanced decay rate due to dynamic effects related to the threshold enhancement is not present

BACKUP

Evidence for semileptonic B→pp̄ lν

- Only external W diagram contributes
  - Help to understand the relative weights with other diagrams
  - Geng,Hsiao PLB704,495(2011) predicts BF=(1.04 ± 0.38)x10^{-4}
- Data sample 772 MBB
  - Use hadronic tagged B to reduce combinatorics
  - Good identification of protons and lepton
  - Neutrino from the recoil mass

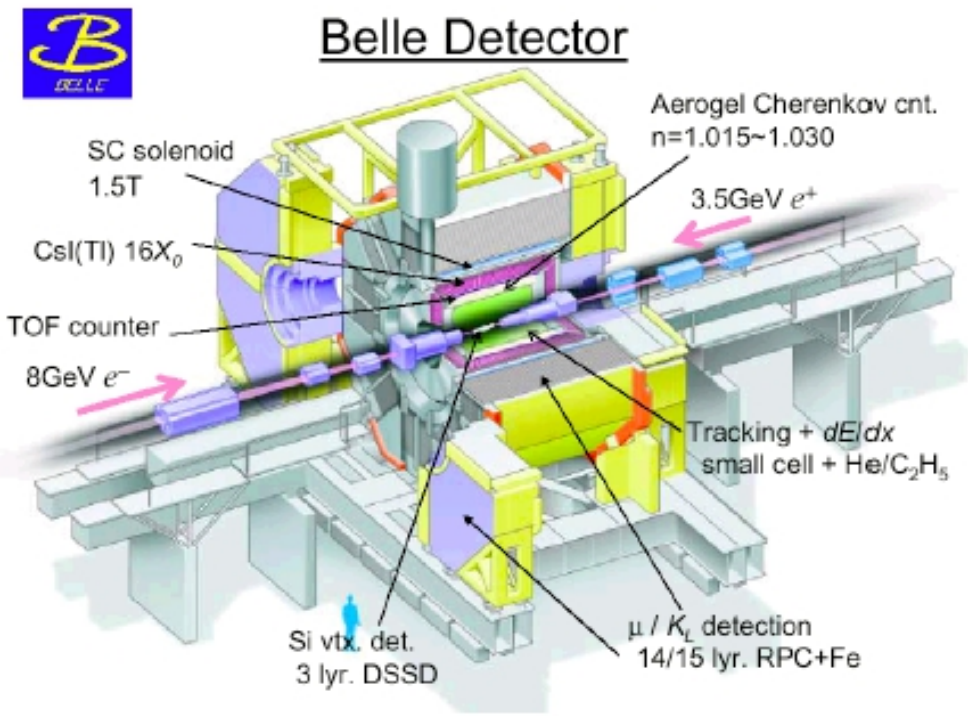




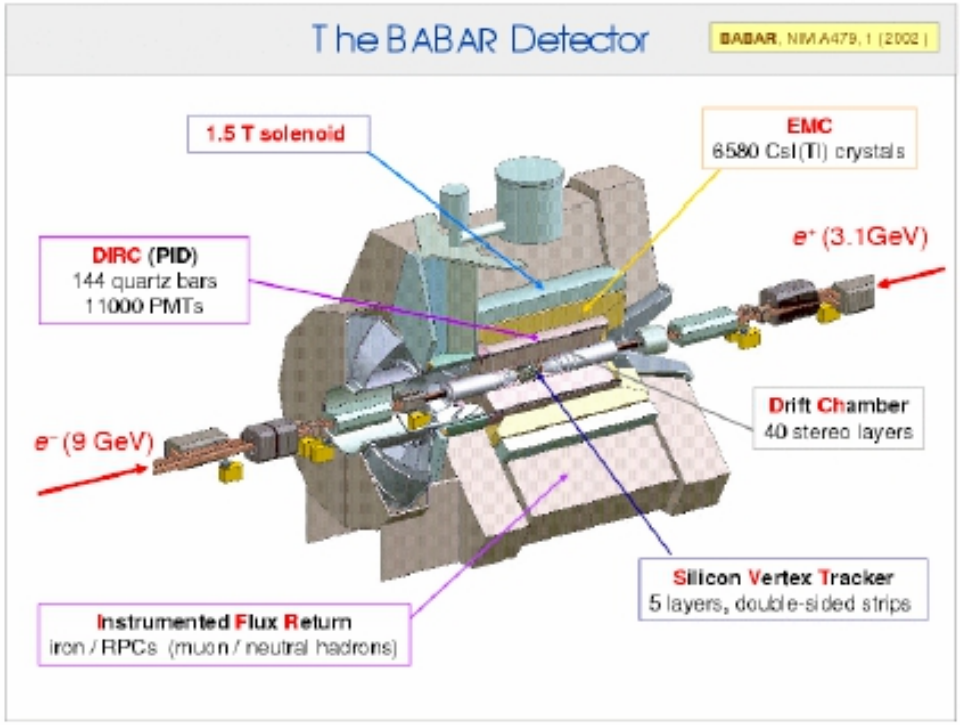
Mode	$\mathcal{B}$ (10^{-6})	U.L. (10^{-6})
$B^- \to p\bar{p}e^-\bar{\nu}_e$	$8.2\ ^{+3.7}_{-3.2} \pm 0.6$	13.8
$B^- \to p\bar{p}\mu^-\bar{\nu}_\mu$	$3.1\ ^{+3.1}_{-2.4} \pm 0.7$	8.5
Combined sample	$5.8\ ^{+2.4}_{-2.1} \pm 0.9$	9.6

Further investigate of theoretical modeling of Baryonic Form-Factor in B Decays are needed!

Experiments: B-Factories

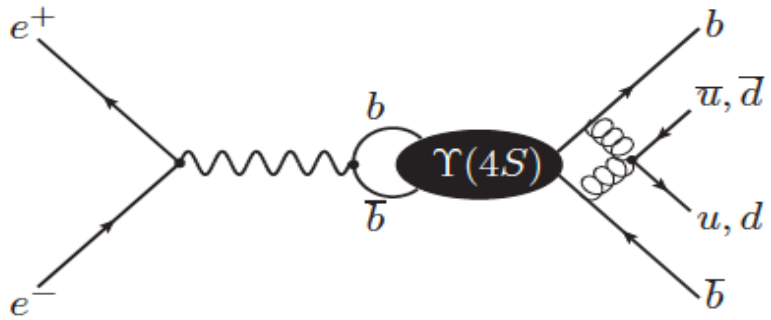


@KEK Japan: 1999-2009



@ PEPII - SLAC: 1999-2008

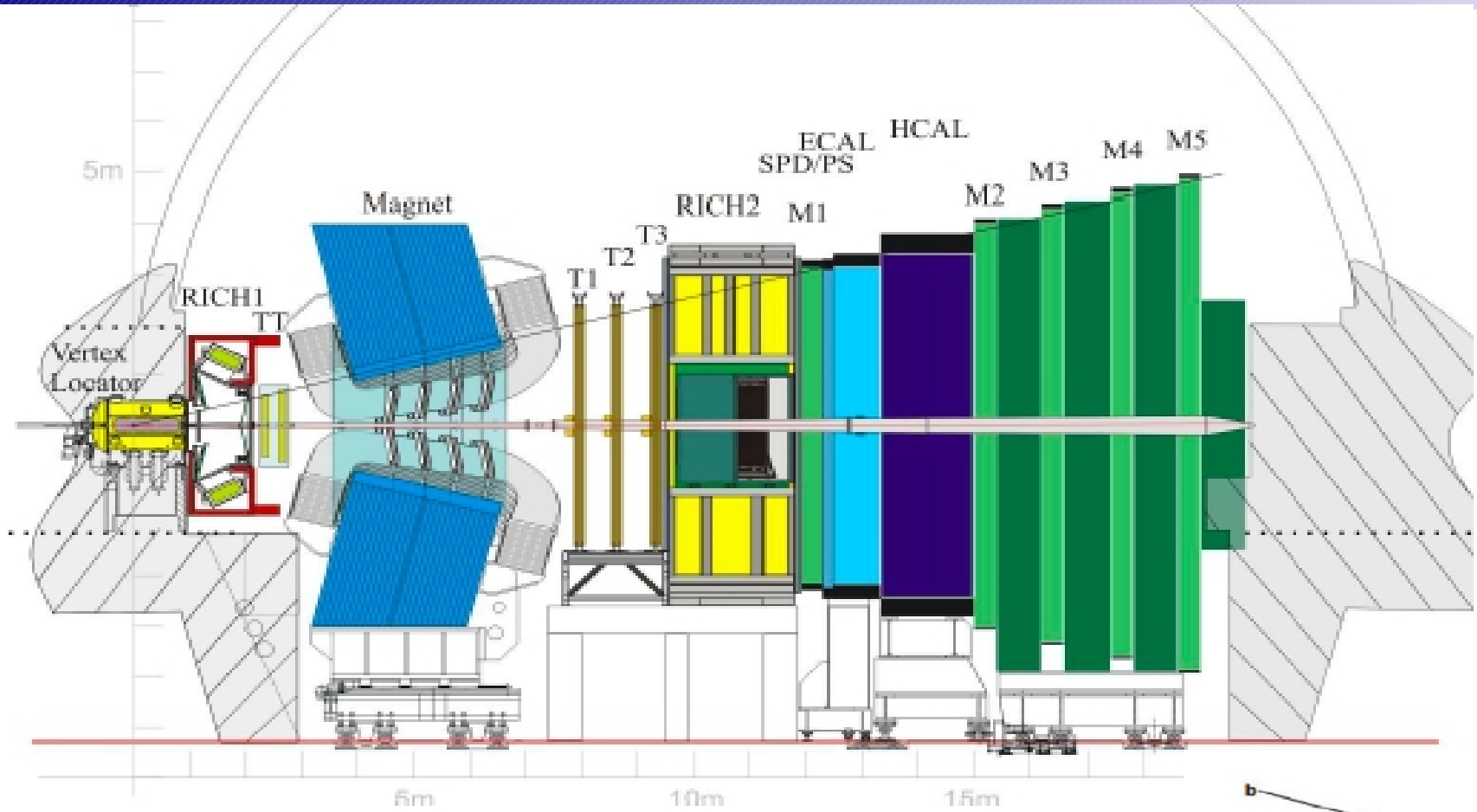
$$e^+e^- \to \Upsilon(4S) \to B\overline{B}$$



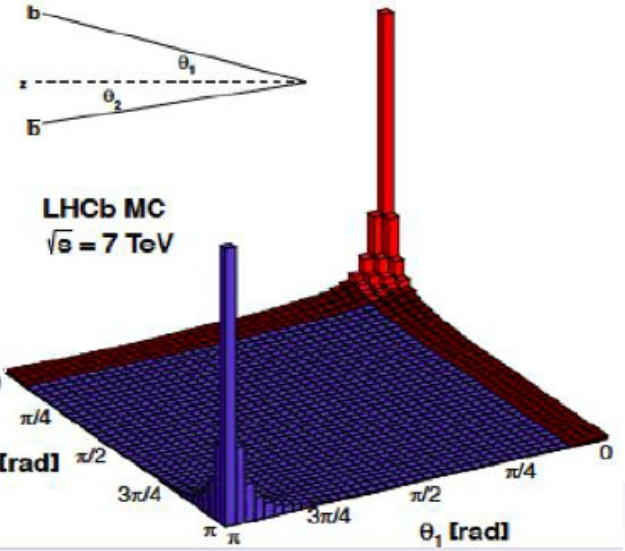
B-Factories: hermetic detectors, low background, Excellent PID, access (mainly) at $B^{0/+}$

About (771 + 467)x10^6 e^+e^- BB events in the Belle+BaBar data

Experiments: LHCb



@ LHC - CERN



LHCb: forward spectrometer for flavor physics
Excellent tracking and vertexing capabilities.
Excellent PID performances
Access to all hadrons with b-quarks