



# Baryonic $B$ decays at *BABAR*

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on behalf of the *BABAR* collaboration



Bundesministerium  
für Bildung  
und Forschung



**BABAR**

# Why investigate $B$ decays into baryons?

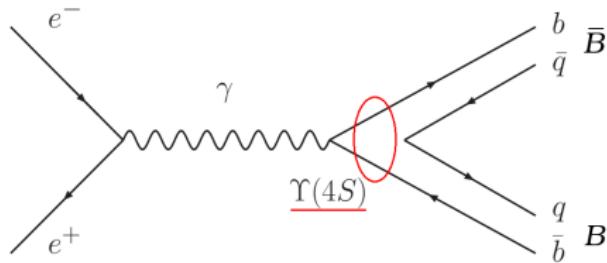
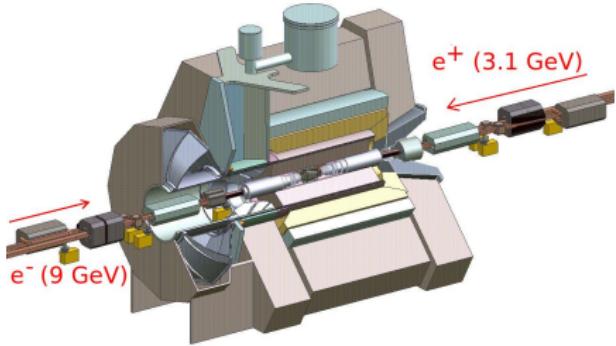
- ARGUS showed  $\mathcal{B}(B \rightarrow \text{baryons...}) = (6.8 \pm 0.6)\%$ <sup>1</sup>
  - only 1/5 explicitly known
- mechanisms of baryon production largely unknown
  - comparison of different decay modes might provide insight in the mechanisms
  - measurements needed as input for theory

<sup>1</sup> H. Albrecht et al., ARGUS Koll., Z. Phys. C 56 1 (1992)

# The *BABAR* experiment



- detector at the PEP-II  $e^+e^-$  asymmetric-energy  $B$  Factory at SLAC
- operated from 1999 to 2008
- $B$  production in the process  $e^+e^- \rightarrow \gamma(4S) \rightarrow B\bar{B}$
- in total  $\approx 470 \times 10^6 B\bar{B}$  pairs



$B \rightarrow D^{(*)} p\bar{p}$  m ·  $\pi$ , m = 0, 1, 2

Phys. Rev. D 85, 092017 (2012)

- measurement of 10  $B$  meson decays
- branching fraction results are averaged over different  $D^{(*)}$  decay modes

$$\bar{B}^0 \rightarrow D^0 p\bar{p} = (1.02 \pm 0.04_{\text{stat}} \pm 0.06_{\text{syst}}) \times 10^{-4}$$

$$\bar{B}^0 \rightarrow D^+ p\bar{p} \pi^- = (3.32 \pm 0.10_{\text{stat}} \pm 0.29_{\text{syst}}) \times 10^{-4}$$

$$\bar{B}^0 \rightarrow D^0 p\bar{p} \pi^- \pi^+ = (2.99 \pm 0.21_{\text{stat}} \pm 0.45_{\text{syst}}) \times 10^{-4}$$

...

- the high systematic uncertainty arises mainly from peaking background
- branching fractions indicate:

$$\mathcal{B}(B \rightarrow 3-body) < \mathcal{B}(B \rightarrow 5-body) < \mathcal{B}(B \rightarrow 4-body)$$

$$B \rightarrow \Lambda_c^+ \bar{p} \text{ m} \cdot \pi, \quad \text{m} = 0, 1, 2$$

$$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \text{ and } \bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^0 \text{ PRD78, 112003(2008) and PRD82, 031102R(2010)}$$

$$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} = (0.19 \pm 0.02_{\text{stat}} \pm 0.01_{\text{syst}} \pm 0.05_{\mathcal{B}(\Lambda_c^+)}) \times 10^{-4}$$

$$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^0 = (1.94 \pm 0.17_{\text{stat}} \pm 0.14_{\text{syst}} \pm 0.50_{\mathcal{B}(\Lambda_c^+)}) \times 10^{-4}$$

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

$$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^- \pi^+ = (12.25 \pm 0.47_{\text{stat}} \pm 0.73_{\text{syst}} \pm 3.19_{\mathcal{B}(\Lambda_c^+)}) \times 10^{-4}$$

$$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^- \pi^+ \text{ (excluding } \Sigma_c(2455, 2520)) = (7.84 \pm 0.44_{\text{stat}} \pm 0.39_{\text{syst}} \pm 2.04_{\mathcal{B}(\Lambda_c^+)}) \times 10^{-4}$$

- CLEO measured<sup>2</sup>  $\mathcal{B}(B^- \rightarrow \Lambda_c^+ \bar{p} \pi^- \pi^- \pi^+) = (23 \pm 7) \times 10^{-4}$
- branching fractions indicate a preference for high multiplicities

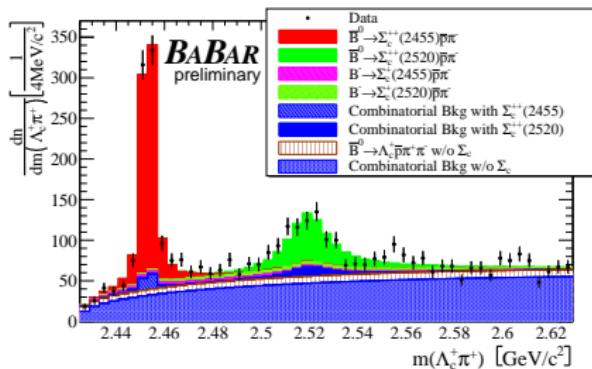
$$\mathcal{B}(B \rightarrow 2 - body) < \mathcal{B}(B \rightarrow 3 - body) < \mathcal{B}(B \rightarrow 4 - body) < \mathcal{B}(B \rightarrow 5 - body)$$

<sup>2</sup>Phys. Rev. D66, 091101R(2002)

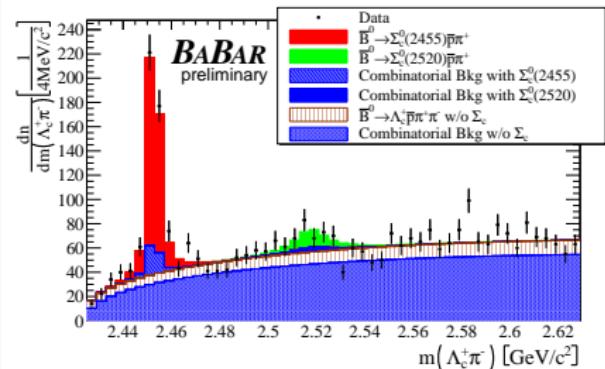
# Resonant decays in $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^- \pi^+$

preliminary

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



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

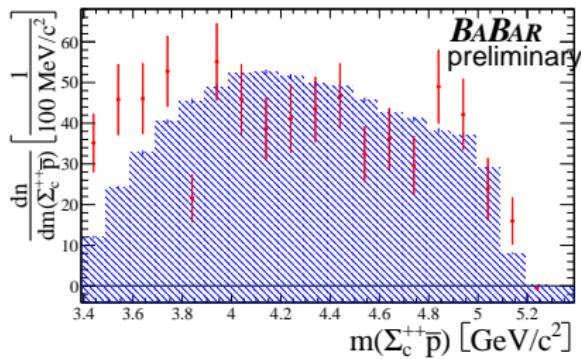


Mode	$\mathcal{B}(\bar{B}^0) [10^{-5}]$
$\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$	$(21.31 \pm 0.97_{\text{stat}} \pm 0.98_{\text{sys}} \pm 5.54)_{\mathcal{B}(\Lambda_c^+)}$
$\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$	$(9.06 \pm 0.65_{\text{stat}} \pm 0.42_{\text{sys}} \pm 2.36)_{\mathcal{B}(\Lambda_c^+)}$
$\bar{B}^0 \rightarrow \Sigma_c(2520)^{++} \bar{p} \pi^-$	$(11.52 \pm 0.97_{\text{stat}} \pm 0.54_{\text{sys}} \pm 2.99)_{\mathcal{B}(\Lambda_c^+)}$
$\bar{B}^0 \rightarrow \Sigma_c(2520)^0 \bar{p} \pi^+$	$(2.21 \pm 0.69_{\text{stat}} \pm 0.10_{\text{sys}} \pm 0.57)_{\mathcal{B}(\Lambda_c^+)}$

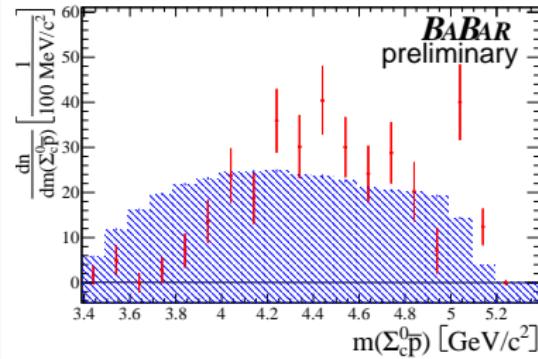
# $\Sigma_c^{++}$ vs. $\Sigma_c^0$ for $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$

- $\mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c(2520) \bar{p} \pi) < \mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c(2455) \bar{p} \pi)$  due to angular momentum
- $\Sigma_c^0$  modes suppressed compared to  $\Sigma_c^{++} \rightarrow$  different decay dynamics?

$\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$  ( $s_{\text{P} \text{lot}}$ )

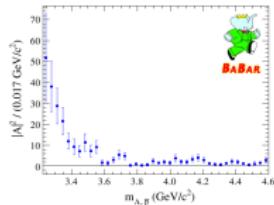


$\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$  ( $s_{\text{P} \text{lot}}$ )



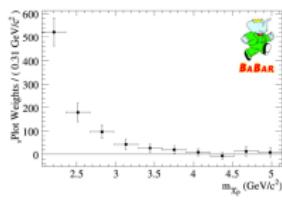
- agreement between  $m(\Sigma_c^{++} \bar{p})$  and  $m(\Sigma_c^0 \bar{p})$  above  $4.2 \text{ GeV}/c^2$
- possible threshold enhancement in  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$

# Threshold enhancements in other baryonic $B$ decays



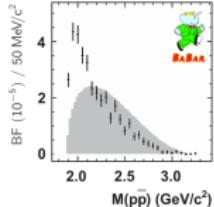
$$B^- \rightarrow \Lambda_c^+ \bar{p} \pi^-$$

PRD78, 112003(2008)



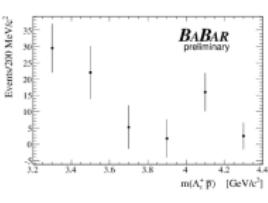
$$\bar{B}^0 \rightarrow \Lambda p \pi^-$$

PRD 79, 112009 (2009)



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

PRD 85, 092017 (2012)



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

PRD 80, 051105(R) (2009)

PoS(EPS-HEP 2009) 215

- the baryon-antibaryon enhancements seems to be a common feature for  $B$  decays to baryons
  - possible explanations come from
    - pole models
    - phenomenological models (M. Suzuki)
- Why no enhancement in  $m(\Sigma_c^0 \bar{p})$ ?
- no possible meson pole

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

preliminary

- CLEO measured  $\mathcal{B}(B^- \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^- \pi^-) = (2.3 \pm 0.7) \times 10^{-3}$  (largest known baryonic branching fraction)<sup>3</sup>
- *BABAR* and Belle measurement of  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$  showed significant contributions from resonant sub-modes  
→ How large is the  $\Sigma_c(2455)^{++}$  contribution to  $B^- \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^- \pi^-$ ?

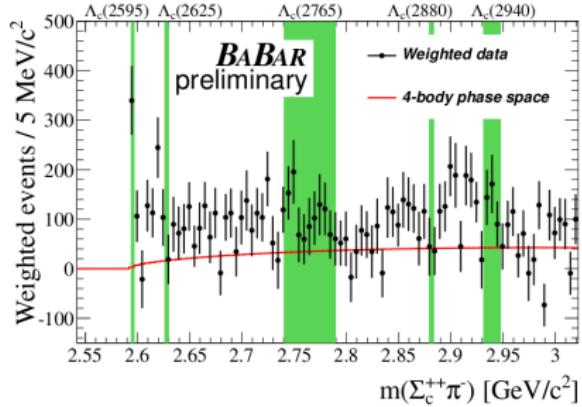
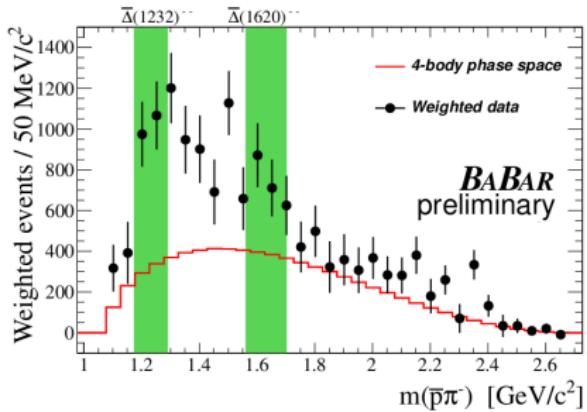
$$\mathcal{B}(B^- \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^- \pi^-) = (2.98 \pm 0.16_{\text{stat}} \pm 0.15_{\text{sys}} \pm 0.77_{\Lambda_c^+}) \times 10^{-4}$$

- 
- comparison with  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$  shows preference for higher multiplicities
    - $\mathcal{B}(\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-) = (2.13 \pm 0.10_{\text{stat}} \pm 0.10_{\text{sys}} \pm 0.6_{\Lambda_c^+}) \times 10^{-4}$

<sup>3</sup>Phys. Rev. D66, 091101R(2002)

# Resonant sub-modes of $B^- \rightarrow \Sigma_c(2455)^{++} \bar{p}\pi^-\pi^-$

- efficiency corrected and sideband subtracted 2-body masses
- shaded regions represent a width of one  $\Gamma$  centered around the average mass

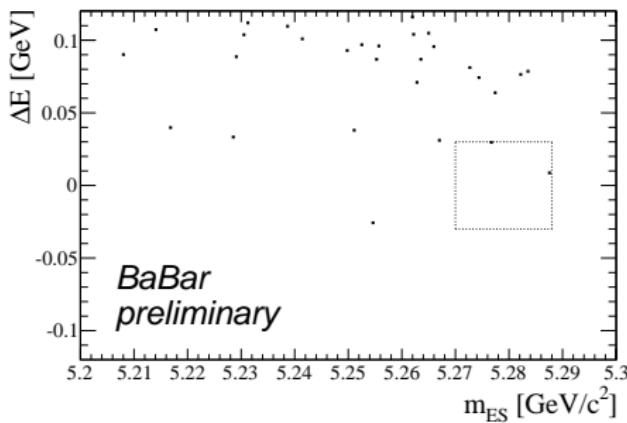


- deviation from phase space in  $m(\bar{p}\pi^-)$  compatible with  $\bar{\Delta}^{--}(1232, 1600, 1620)$
- in  $m(\Sigma_c^{++}\pi^-)$  the  $\Lambda_c(2595)^+$  is apparent

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

preliminary

- $B \rightarrow D p \bar{p}$   $m \cdot \pi$  and  $B \rightarrow \Lambda_c^+ \bar{p}$   $m \cdot \pi$  results indicate that a small phase space favors baryon production
- $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} p \bar{p}$  could be enhanced



- after event selection 2 events remain in signal region
- assuming 0 events background we determine an upper limit

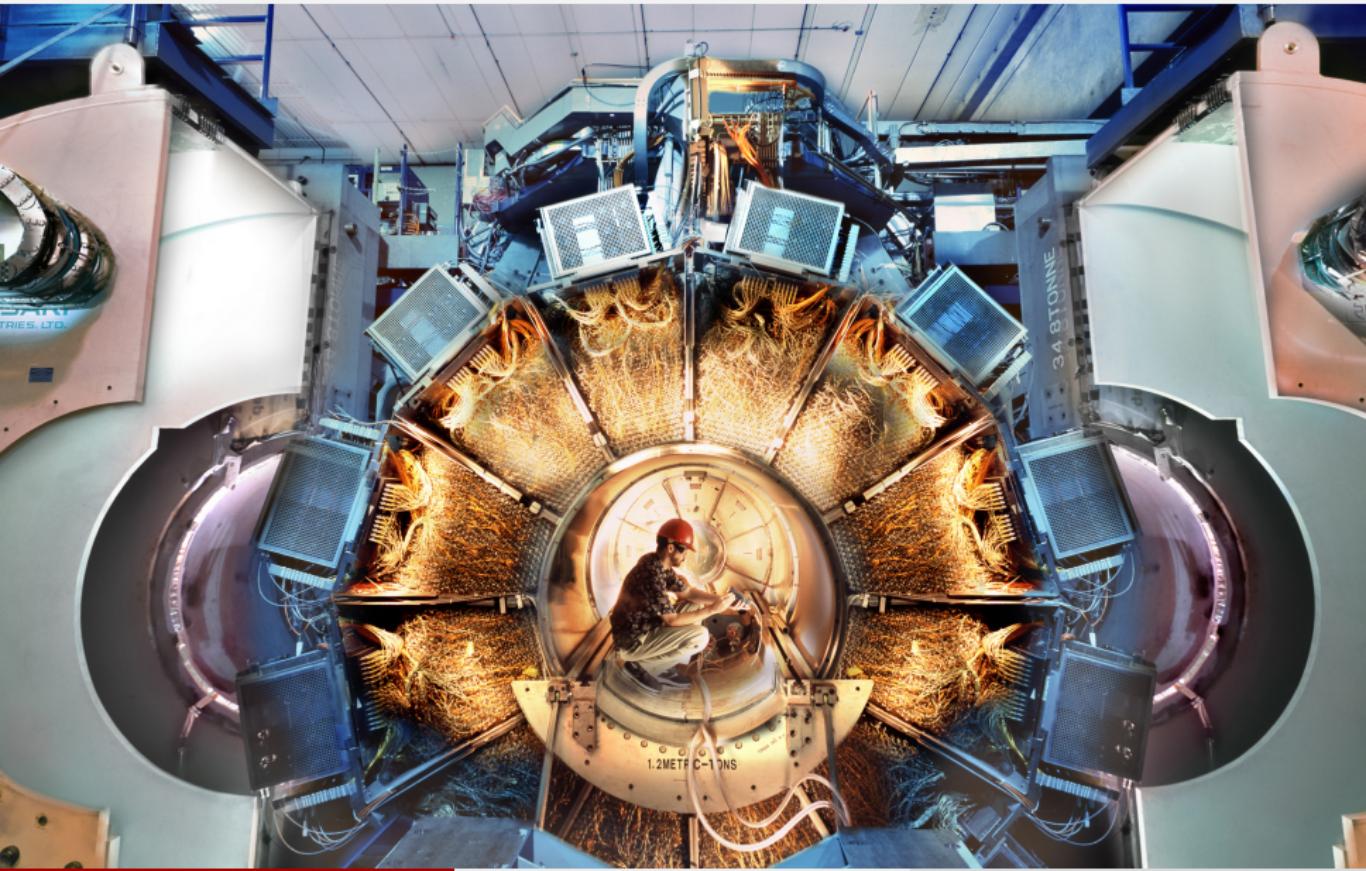
$$\mathcal{B}(\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} p \bar{p}) < 6.2 \times 10^{-6} @ CL = 90\%$$

# Summary

- measurements show some interesting features of baryonic  $B$  decays
  - higher multiplicities (smaller phase space) preferred for charmed baryon production
  - resonant sub-modes have a substantial impact on the total branching fraction
- in  $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^- \pi^+$  the  $\Sigma_c^0$  modes are suppressed compared to the  $\Sigma_c^{++}$  modes and show different dynamics

Theoretical explanations would be appreciated!

# Thank you for your attention!



# $\mathcal{B}(B \rightarrow baryons \dots)$

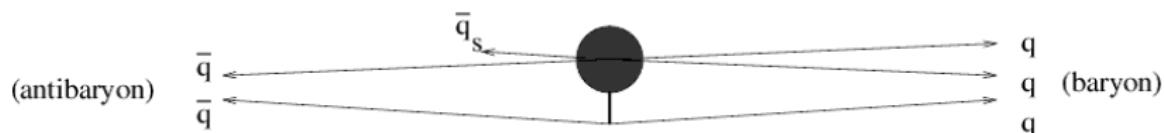
- measured by the ARGUS experiment<sup>4</sup>
- determine number of events with:
  - a reconstructed proton
  - a reconstructed  $\Lambda$
  - the combination  $p\bar{p}$  and  $\Lambda p$
  - various lepton-baryon and lepton-baryon-anti baryon combinations
- ⇒ *12 equations with 5 unknowns*
- determine all 5 unknowns by a fit

$$\Rightarrow \mathcal{B}(B \rightarrow baryons \dots) = (6.8 \pm 0.5_{\text{stat}} \pm 0.3_{\text{syst}})\%$$

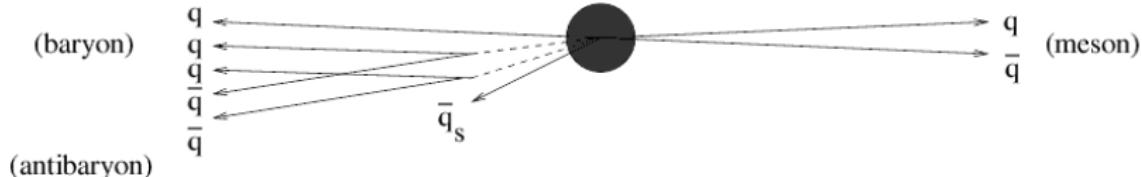
<sup>4</sup>H. Albrecht et al., ARGUS Koll., Z. Phys. C 56 1 (1992)

# Theoretical/Phenomenological explanation

- branching fraction results suggest that:
  - 2-body modes are strongly suppressed
  - two-body baryonic  $B$  decays are suppressed
- phenomenological explanation given by:
  - Mahiko Suzuki arXiv:hep-ph/0609133v3



- the gluon has to be highly off mass shell  $\rightarrow$  suppressed



- the gluon is close to the mass shell

## $_s\mathcal{P}$ lot formalism

- invented for the separation of different event species ( $N_s$ )
- define fit function  $f$  with components for each species
- fit the distribution in a set of variables  $\vec{y}$
- calculate a weight for each event  $e$  for species  $n$

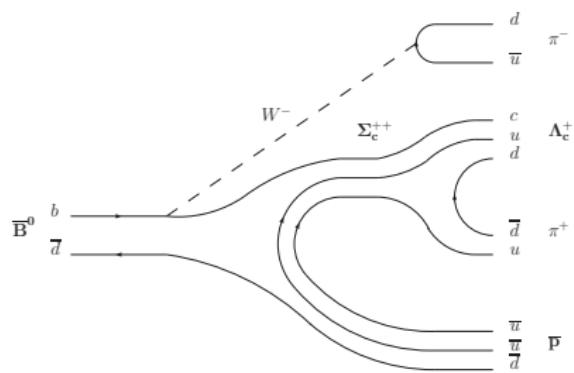
$${}_s\mathcal{P}_n(\vec{y}_e) = \frac{\sum_{j=1}^{N_s} \mathbf{V}_{nj} f_j(\vec{y}_e)}{\sum_{k=1}^{N_s} N_k f_k(\vec{y}_e)}$$

- $\mathbf{V}$  is the covariance matrix for the yields of the different species
- weights can be used to plot every distribution (not correlated with  $\vec{y}$ ) for each species

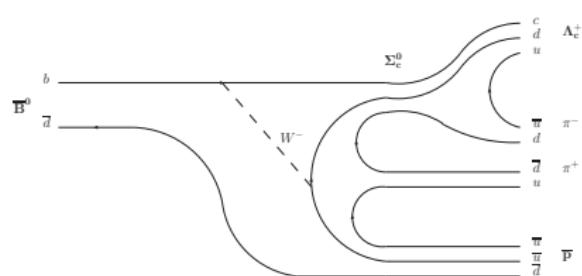
# Possible explanation for the $\Sigma_c^0$ suppression

- $\Sigma_c^0$  modes suppressed compared to  $\Sigma_c^{++}$ 
  - the  $\Sigma_c^{++}$  can be produced by both, internal and external Feynman diagrams
  - for the  $\Sigma_c^0$  modes only internal Feynman diagrams possible

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



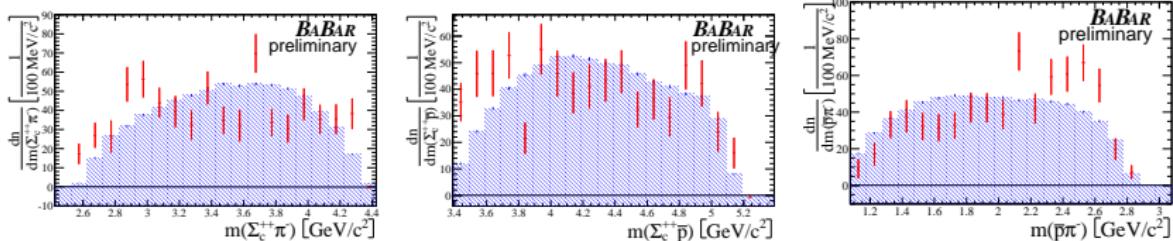
$$\bar{B}^0 \rightarrow \Sigma_c^0 \bar{p} \pi^+ \text{ and } \bar{B}^0 \rightarrow \Sigma_c^{++} \bar{p} \pi^-$$



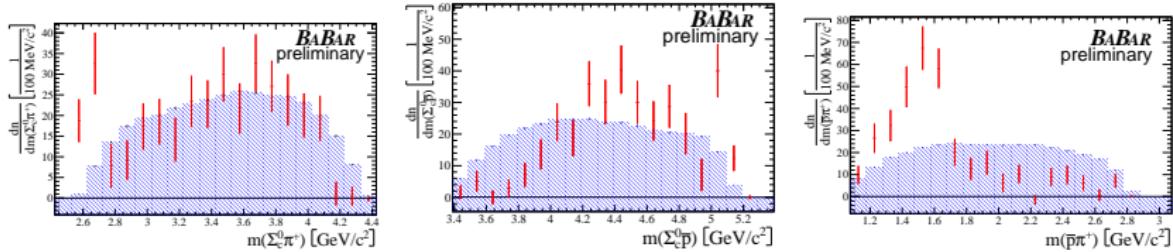
- the external graph can be rearranged into an initial meson-meson state
- for the internal graph only a baryon anti-baryon configuration is possible  
→ enhancement in the  $m(\bar{p} \pi^+)$  distribution?

# 2-body masses for $\bar{B}^0 \rightarrow \Sigma_c \bar{p} \pi$

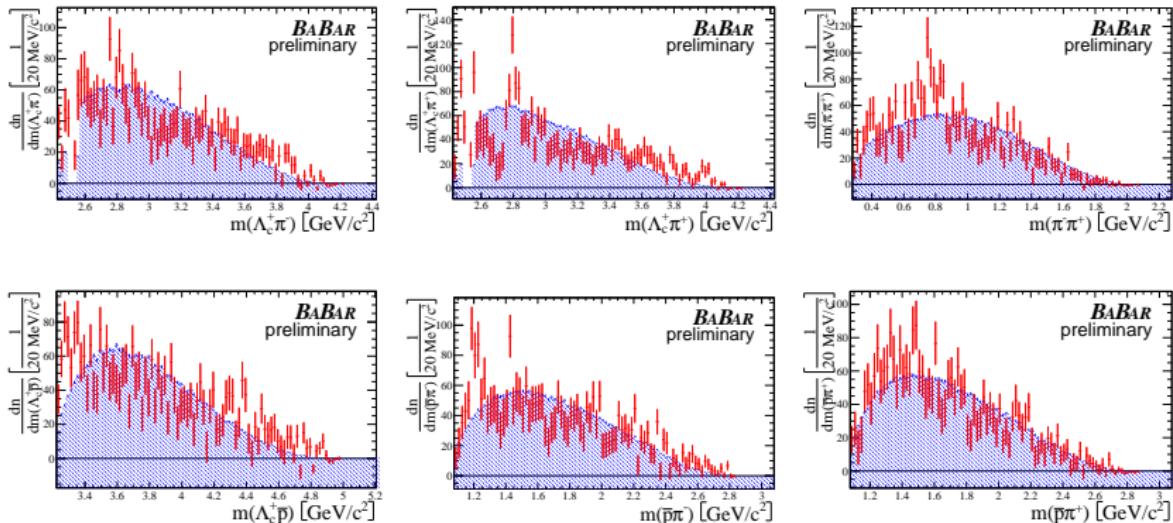
$s\mathcal{P}$ lot distributions for  $\bar{B}^0 \rightarrow \Sigma_c(2455)^{++} \bar{p} \pi^-$



$s\mathcal{P}$ lot distributions for  $\bar{B}^0 \rightarrow \Sigma_c(2455)^0 \bar{p} \pi^+$

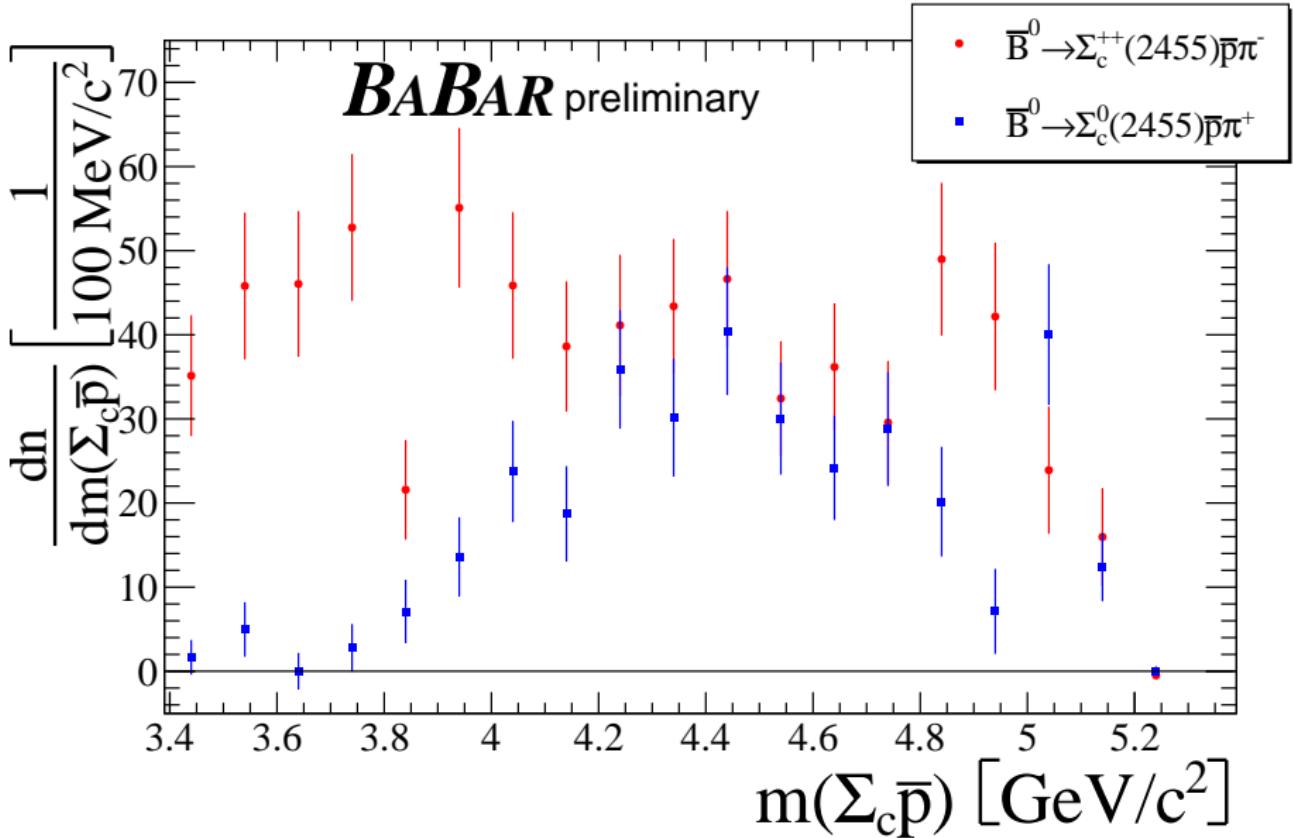


# 2-body masses for $\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^+ \pi^-$ non- $\Sigma_c$



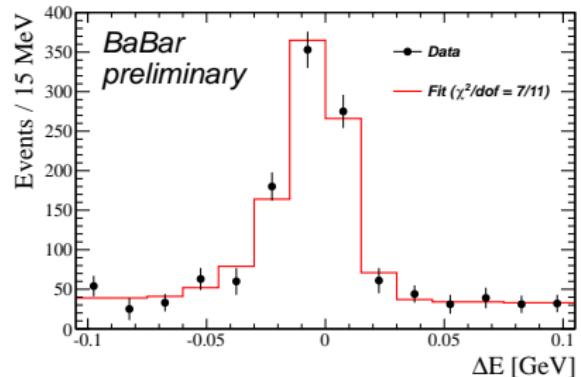
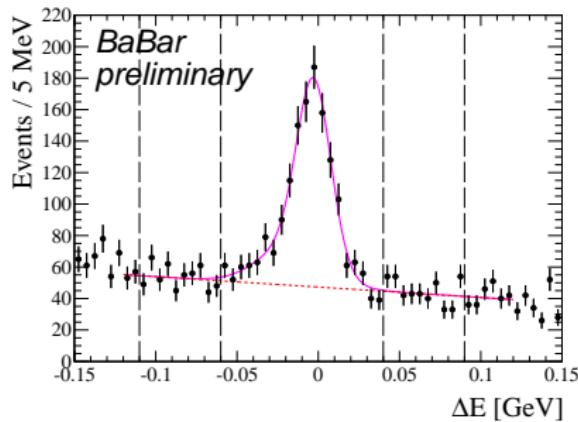
- clear contributions from  $\Sigma_c(2800)^{++}$ ,  $\Sigma_c(2800)^0$  not as conclusive
- $m(\pi^- \pi^+)$  could contain  $\rho(770)$  and  $f_2(1270)$
- in  $m(\bar{p}\pi^-)$  structure around  $\approx 1.2 \text{ GeV}/c^2$  could point to  $\bar{\Delta}^{--}$

$\bar{B}^0 \rightarrow \Lambda_c^+ \bar{p} \pi^- \pi^+$  -  $m(\Sigma_c^{++})$  vs.  $m(\Sigma_c^0)$

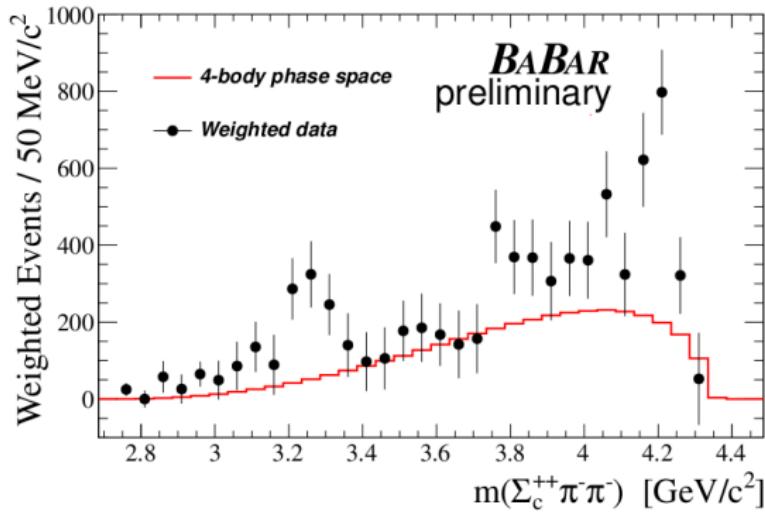


# $B^- \rightarrow \Sigma_c(2455)^{++} \bar{p}\pi^-\pi^-$ signal extraction

- main problem: rejection of  $B^- \rightarrow \Lambda_c^+ \bar{p}\pi^+\pi^-\pi^-$  decays
- divide  $\Delta E$  signal region  $(-105, 105)$  MeV into 14 equal slices  $i$
- plot each slice in  $\Delta M = m(\Lambda_c^+\pi^+) - m(\Lambda_c^+)_\text{PDG}$  and fit the number of  $\Sigma_c$  candidates  $N_i$
- fill another  $\Delta E$  plot with the  $N_i$



# $m(\Sigma_c^{++}\pi^-\pi^-)$ and $m(\Sigma_c^{++}\bar{p})$



- unexplained structures at  $3.25 \text{ GeV}/c^2$ ,  $3.80 \text{ GeV}/c^2$ , and  $4.20 \text{ GeV}/c^2$
- no indication of a threshold enhancement in  $m(\Sigma_c^{++}\bar{p})$

$B$ decay	$\mathcal{B} \pm \sigma_{\text{stat}} \pm \sigma_{\text{syst}} (10^{-4})$
$\bar{B}^0 \rightarrow D^0 p\bar{p}$	$1.02 \pm 0.04 \pm 0.06$
$\bar{B}^0 \rightarrow D^{*0} p\bar{p}$	$0.97 \pm 0.07 \pm 0.09$
$\bar{B}^0 \rightarrow D^+ p\bar{p}\pi^-$	$3.32 \pm 0.10 \pm 0.29$
$\bar{B}^0 \rightarrow D^{*+} p\bar{p}\pi^-$	$4.55 \pm 0.16 \pm 0.39$
$B^- \rightarrow D^0 p\bar{p}\pi^-$	$3.72 \pm 0.11 \pm 0.25$
$B^- \rightarrow D^{*0} p\bar{p}\pi^-$	$3.73 \pm 0.17 \pm 0.27$
$\bar{B}^0 \rightarrow D^0 p\bar{p}\pi^-\pi^+$	$2.99 \pm 0.21 \pm 0.45$
$\bar{B}^0 \rightarrow D^{*0} p\bar{p}\pi^-\pi^+$	$1.91 \pm 0.36 \pm 0.29$
$B^- \rightarrow D^+ p\bar{p}\pi^-\pi^-$	$1.66 \pm 0.13 \pm 0.27$
$B^- \rightarrow D^{*+} p\bar{p}\pi^-\pi^-$	$1.86 \pm 0.16 \pm 0.19$