B Meson Decays to Open Charm and Charmonium

Erich W. Varnes
Princeton University
for the
BABAR™ Collaboration

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Topics Covered

- Understanding charm multiplicity

  $\mathcal{B}(B \to \bar{D}^{(*)} D^{(*)} K)$

- Testing models of hadronic B decay

  $\mathcal{B}(B^0 \to D^0\pi^0)$, $\mathcal{B}(B^0 \to D^0\eta)$, and $\mathcal{B}(B^0 \to D^0\omega)$

  $\mathcal{B}(B^+ \to \chi_{c0} K^+)$

  $\mathcal{B}$ and polarization for $B^0 \to D_s^{(*)+} D^{*-}$

- Steps toward CP Violation beyond sin2β

  $B^+ \to D^0 K^+$

  $\mathcal{B}(B^0 \to D_s^{(*)+}\pi^-)$ and $\mathcal{B}(B^0 \to D_s^{(*)+} K^-)$

All of the above analyses represent new or newly updated results

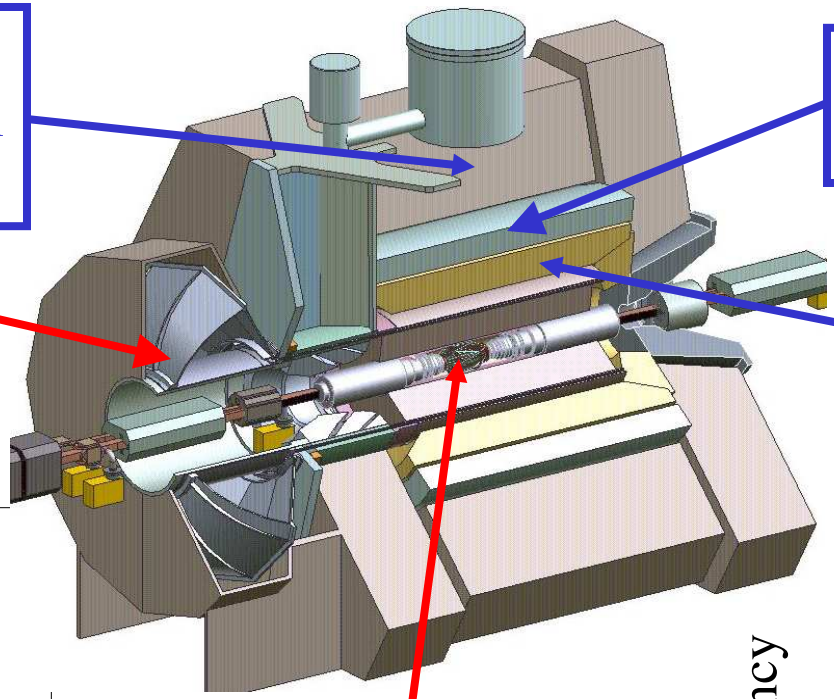
The BaBar Detector

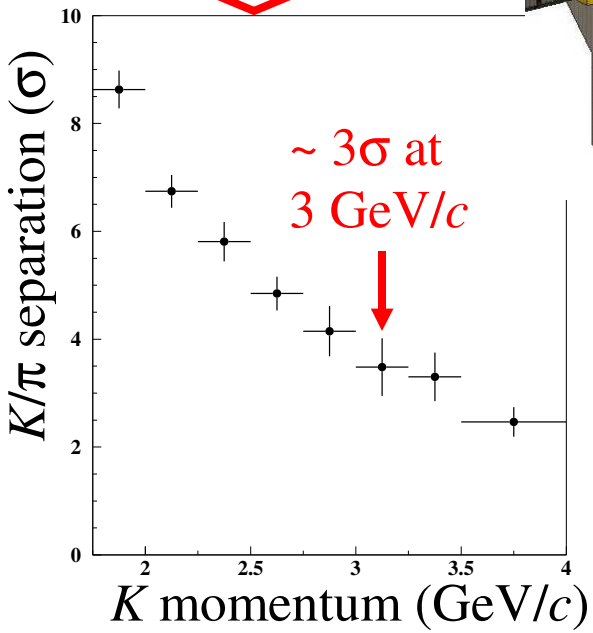
Flux return
Muon and neutral
hadron detection

CsI(Tl) EM
Calorimeter

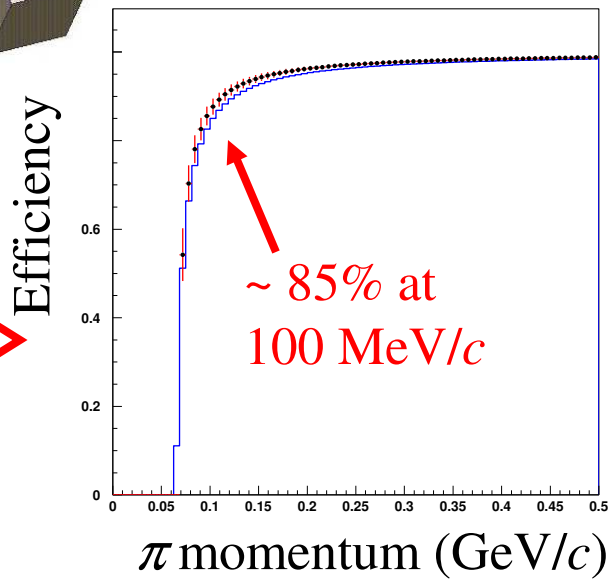
DIRC:
K/π separation

40-layer
He/isobutane
Drift Chamber



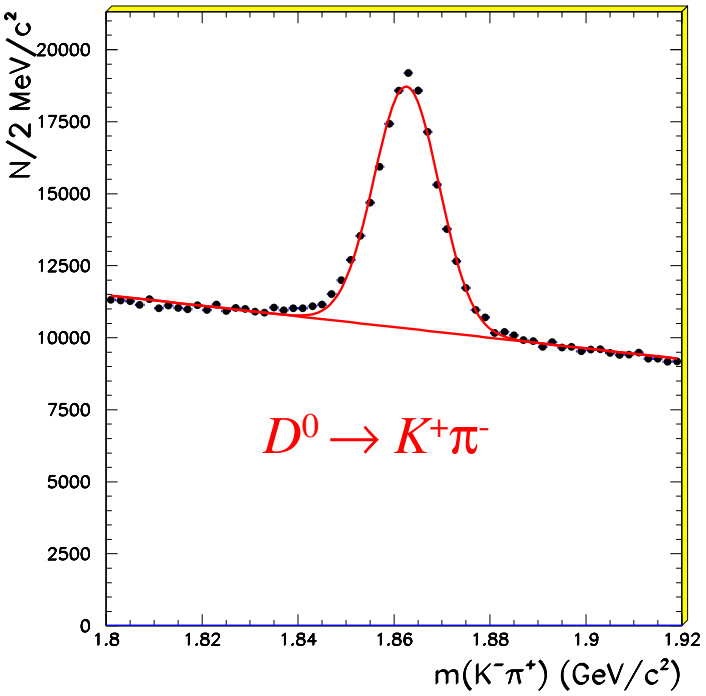


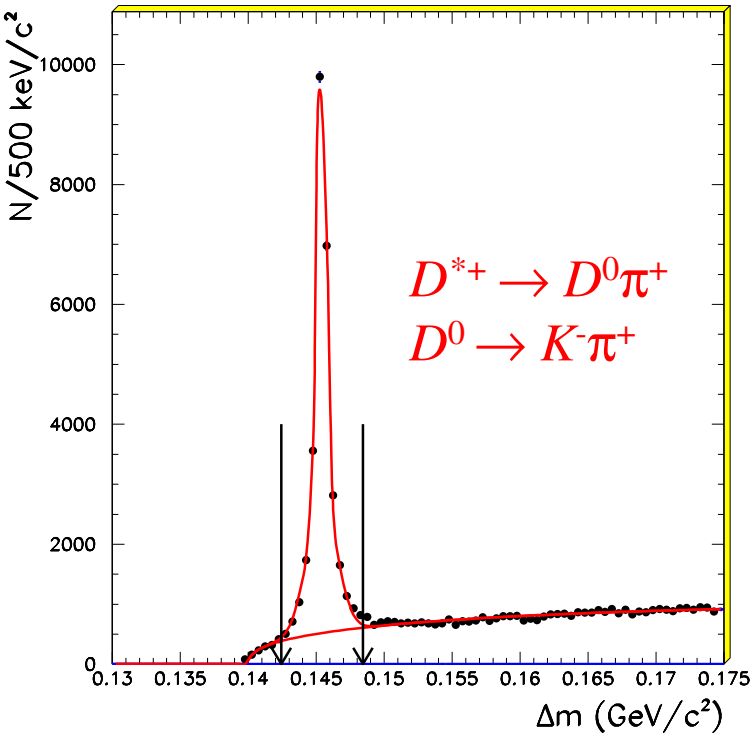
Five-layer
double-sided
Si tracker:
Slow π efficiency



B Meson Reconstruction, Step 1

- Begin by selecting intermediate mesons using either mass or mass difference:

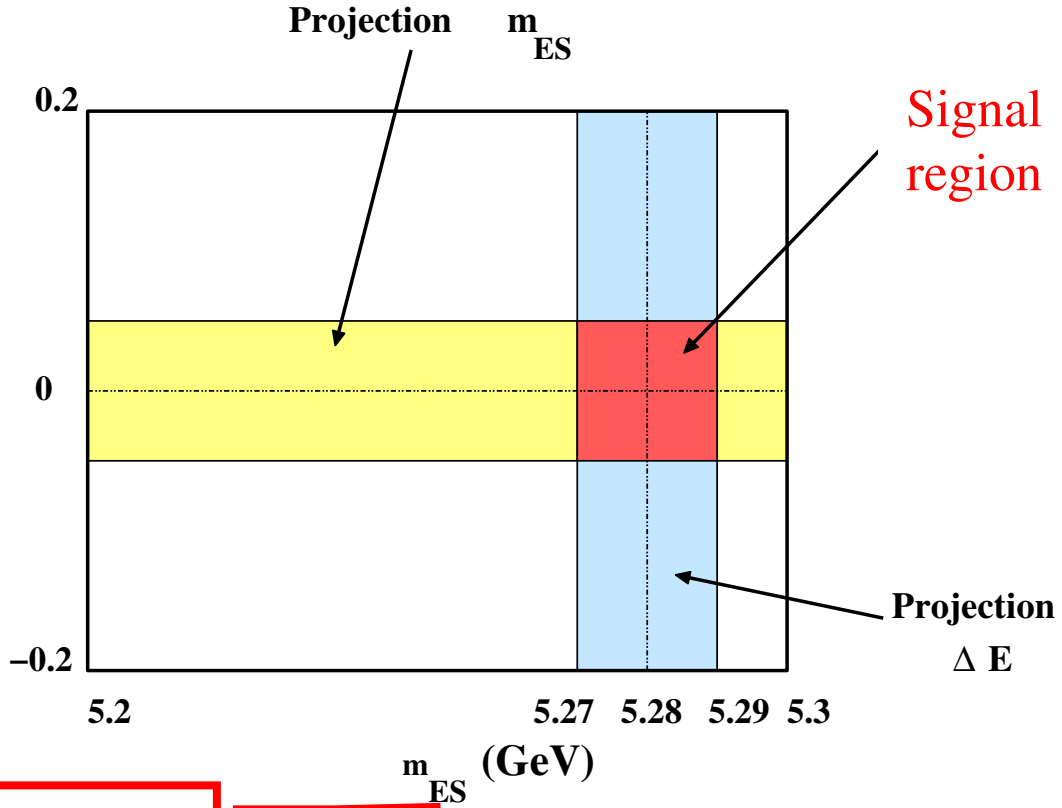




- After selection, candidates are constrained to nominal masses

B Meson Reconstruction, Step 2

Two variables distinguish true *B* candidates from background:



$\Delta E \equiv E_B^* - E_{\text{beam}}^*$

Resolution is mode-dependent

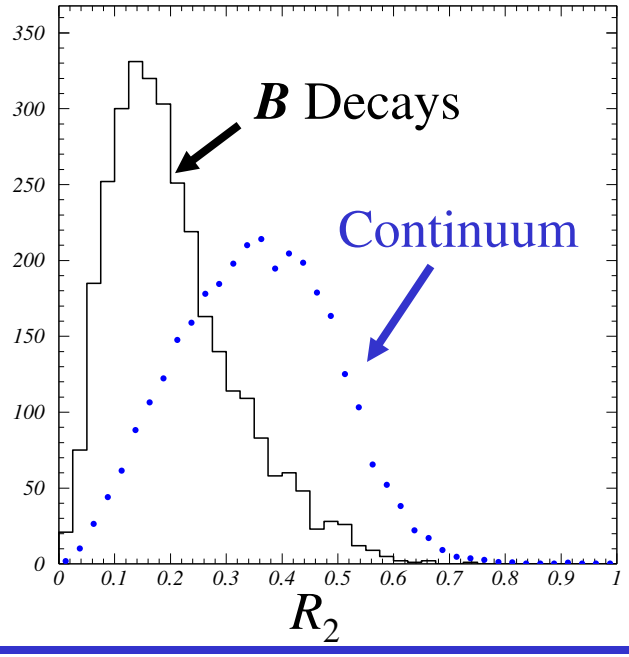
$m_{ES} \equiv \sqrt{E_{\text{beam}}^{*2} - p_B^{*2}}$

Resolution dominated by beam energy spread, and is ~3 MeV

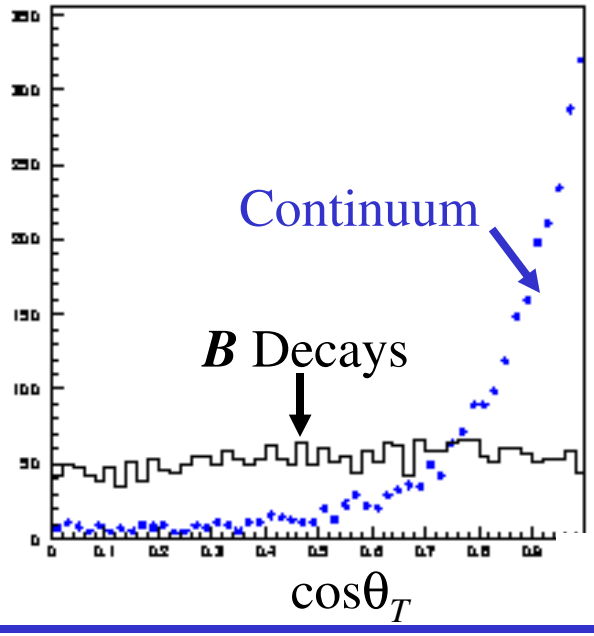
Continuum Background Suppression

- Need to separate "jetty" continuum from spherical $B\bar{B}$ events

Ratio of second-to-zeroth order Fox-Wolfram moments (R_2):



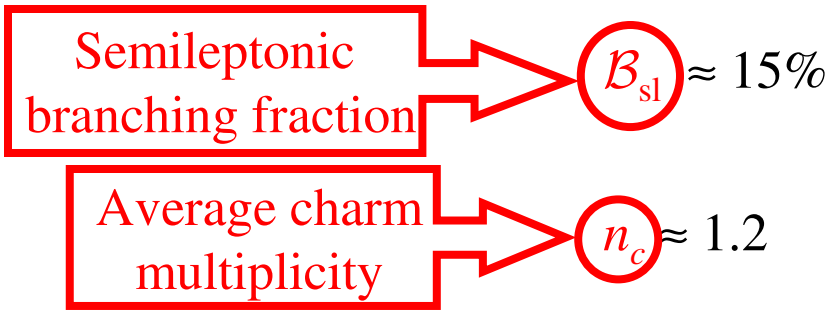
Angle of thrust axis of "rest of the event" w.r.t. ***B*** candidate direction (θ_T)



Analyses needing additional rejection combine several variables in Fisher discriminant

Charm Multiplicity

- The naïve parton model of ***B*** decay predicts:

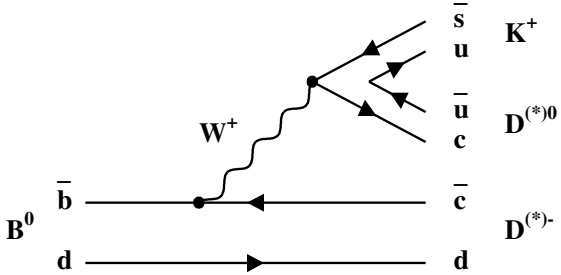


Observed values (PDG):
$\mathcal{B}_{sl} = (10.5 \pm 0.8)\%$
$n_c = 1.10 \pm 0.05$*
Assuming $b \to c\bar{c}s$ always produces $\boldsymbol{D_S X}$ or charmonium

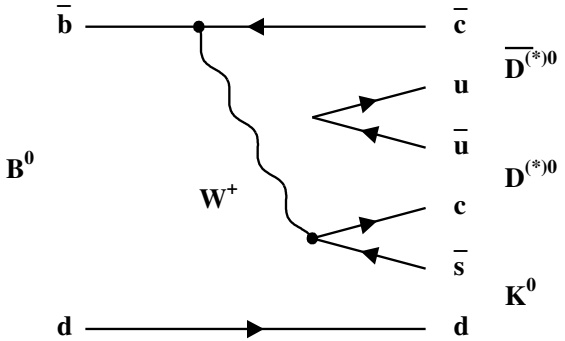
- Many modifications to model that lower $\mathcal{B}_{sl}$ predict higher n_c
  - "$\mathcal{B}_{sl}/n_c$ puzzle"
- Progress towards resolution has come on two fronts:
  1. Models that predict lower $\mathcal{B}_{sl}$
     - e.g. [Neubert & Sachradja, Nucl. Phys. **B483**, 339]
  2. Realization that other final states from $b \to c\bar{c}s$ may make significant contribution to n_c

B Decays to $\bar{D}^{(*)} D^{(*)} K$

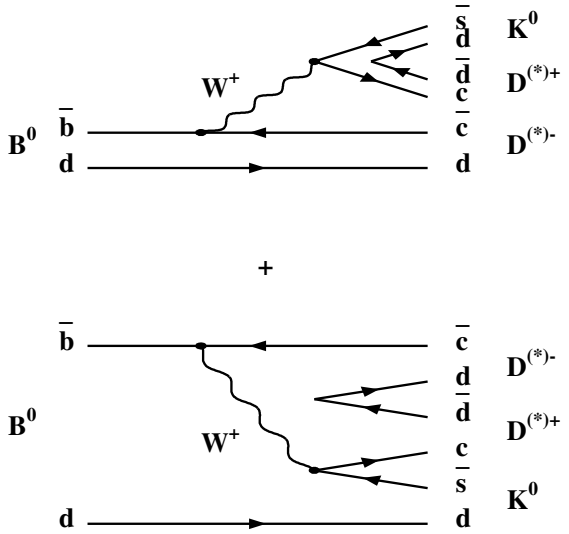
- Creation of quark pairs from vacuum leads to $\bar{D}^{(*)} D^{(*)} K$ final states:



4 modes



3 modes



3 modes

- Analogous diagrams for B^+ yield 12 modes
- All 22 modes are included in our analysis
- Meson decays used:

$D^{(*)+} \to D^0 \pi^+$

$D^{(*)0} \to D^0 \pi^0$

$D^{(*)0} \to D^0 \gamma$

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

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

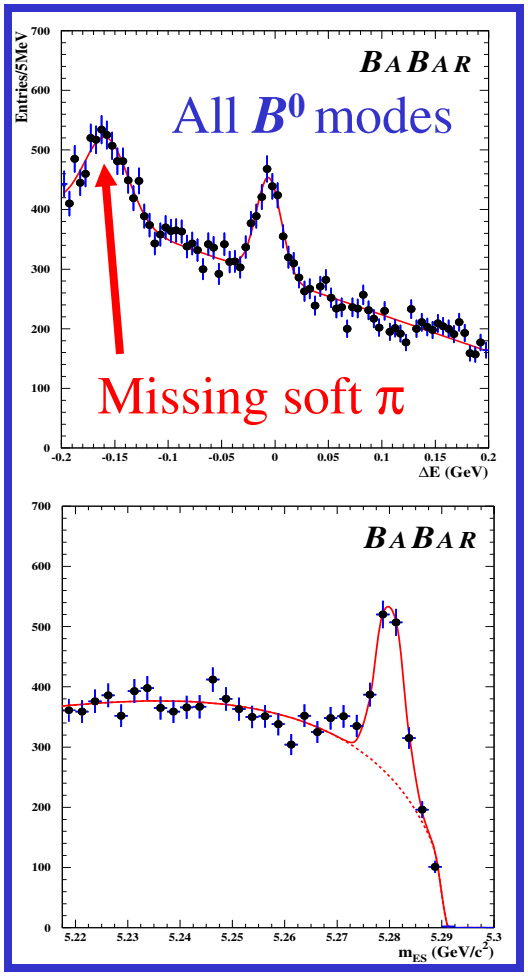
$D^0 \to K^- \pi^+ \pi^- \pi^+$

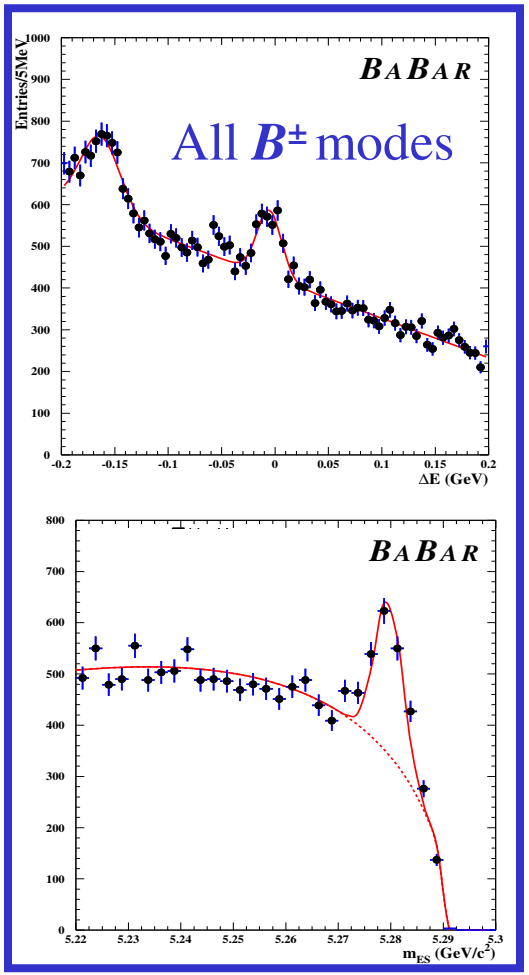
$D^+ \to K^- \pi^+ \pi^+$

$B \to \bar{D}^{(*)} D^{(*)} K$ Results (82 Million B Pairs)

ΔE

m_{ES}





Observed signals:

- 969 ± 65 B^+,
- 823 ± 57 B^0
- 11 of 22 B modes have >4σ signals
- $\mathcal{B}$ determined via Poisson max. likelihood fit

$$\mathcal{B}\left(B^0 \to \bar{D}^{(*)} D^{(*)} K\right) = \left[4.3 \pm 0.3(\text{stat.}) \pm 0.6(\text{syst.})\right]\%$$

$$\mathcal{B}\left(B^+ \to \bar{D}^{(*)} D^{(*)} K\right) = \left[3.5 \pm 0.3(\text{stat.}) \pm 0.5(\text{syst.})\right]\%$$

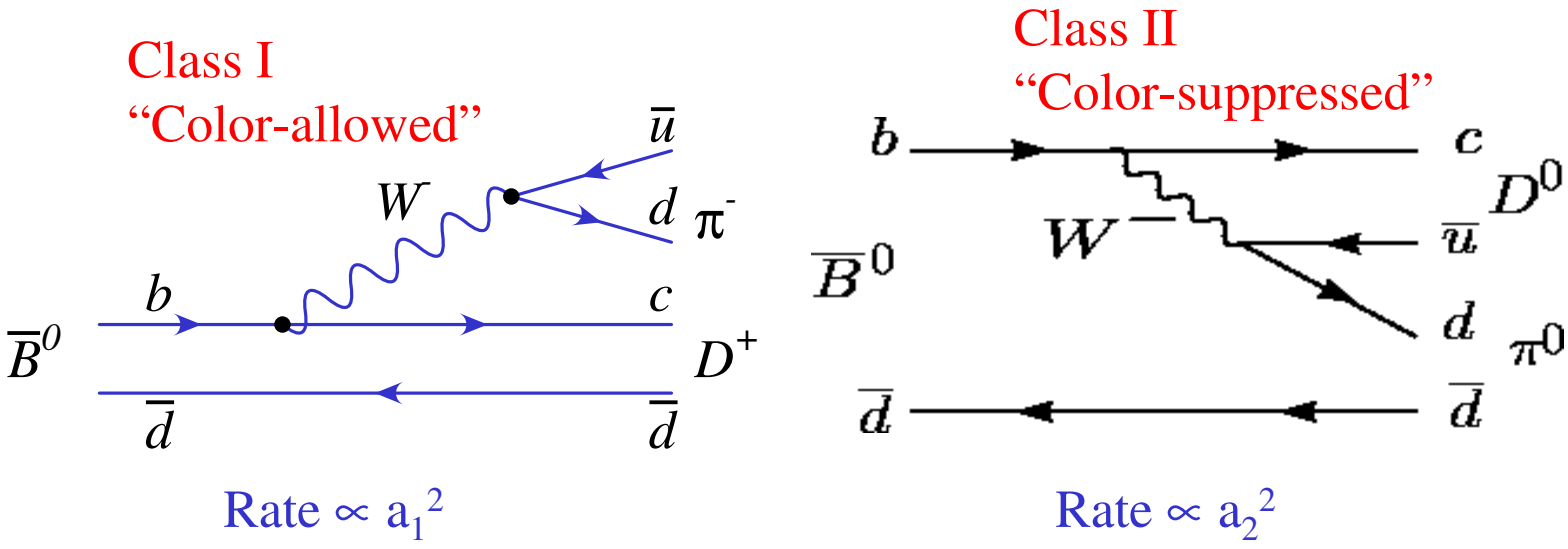
Systematic Uncertainties

Values in red are common to all analyses

Source	Magnitude
Tracking efficiency	0.8% per track (Drift Chamber hits required) 1.2% per track otherwise
K_S reconstruction	2.5% per K_S
π^0 reconstruction	5.1% per π^0
γ identification	5.1% per γ
$K^{\pm}$ identification	2.5% per $K^{\pm}$
Vertexing	1.3 to 5.7 %
ΔE resolution	2 to 5%
Monte Carlo statistics	2 to 10%
Intermediate $\mathcal{B}$	2 to 5%
Number of B mesons in sample	1.1%
Decay model	5%

"Color Suppressed" *B* Decays

- One model of ***B*** decay ("factorization") assumes light meson hadronizes independently of charmed meson in decay
  - Decay rates predicted by diagram class:



Rate $\propto a_1^2$ Rate $\propto a_2^2$

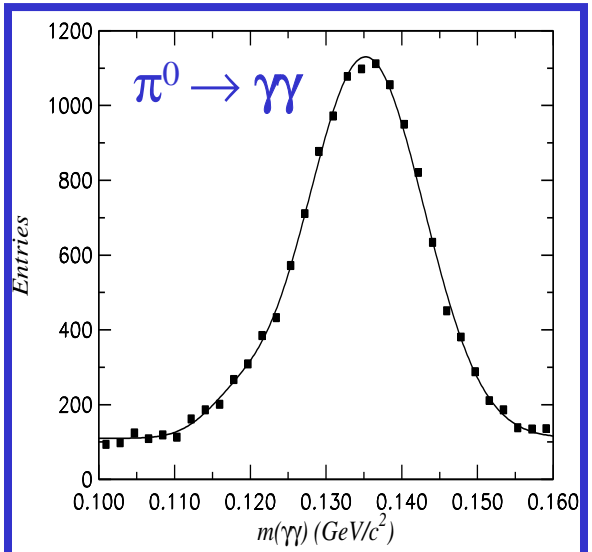
a_1 and a_2 are assumed to be process-independent parameters

- This model predicts $\mathcal{B}(B \to D^0\pi^0)$, $\mathcal{B}(B \to D^0\eta)$, and $\mathcal{B}(B \to D^0\omega)$ are $(0.3 - 0.7) \times 10^{-4}$

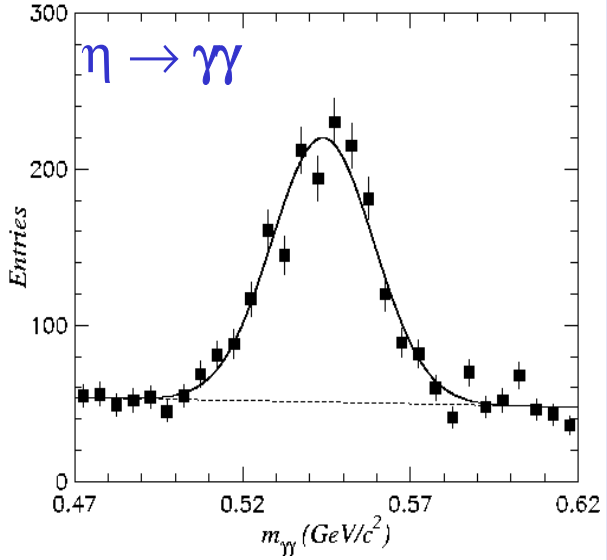
[M. Neubert and B. Stech in Heavy Flavours, 2nd ed. (hep-ph/9705292)]

Candidate Selection

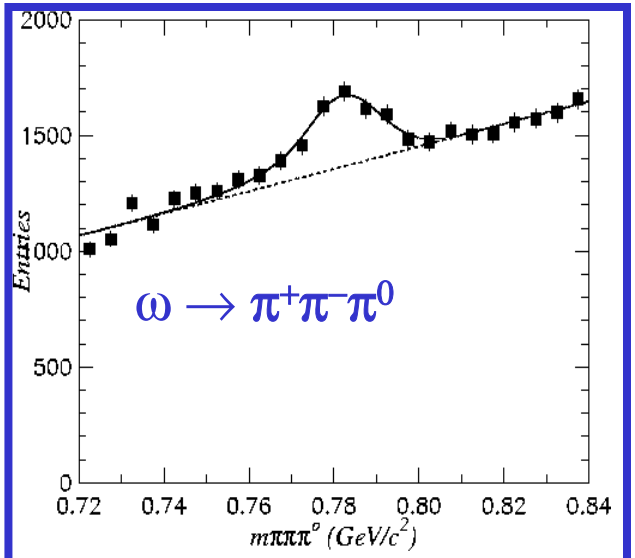
- Charm meson decays reconstructed: $D^0 \to K^-\pi^+$, $K^-\pi^+\pi^0$, or $K^-\pi^+\pi^-\pi^+$
- Light mesons:



Veto $D^0\pi^0$ candidates if adding a soft $\pi^\pm$ yields a good $D^0\rho^\pm$



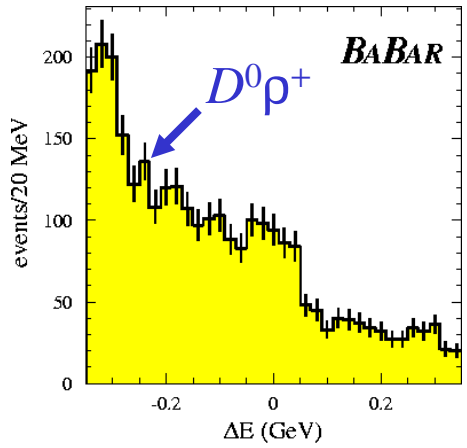
For $D^0\eta$ and $D^0\omega$, cut applied on B polar angle in $\Upsilon(4S)$ frame

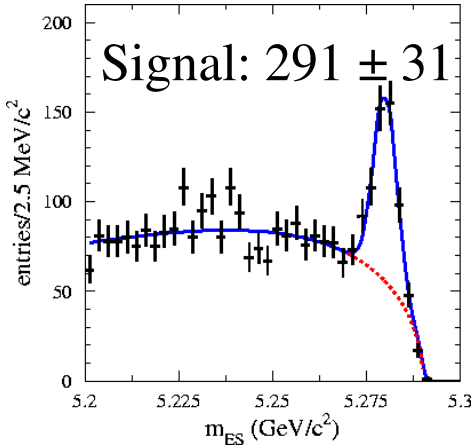


Vector nature of ω exploited by applying cuts on pion angular distributions

Results (49 Million *B* Pairs)

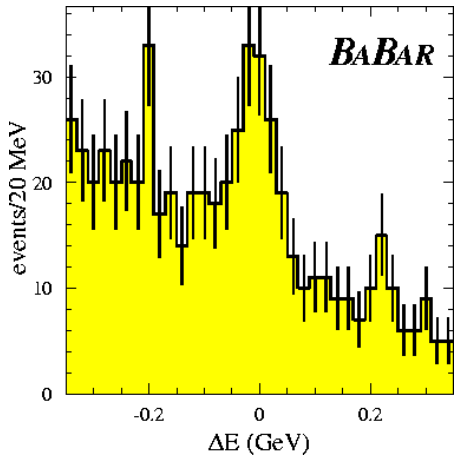
$D^0\pi^0$

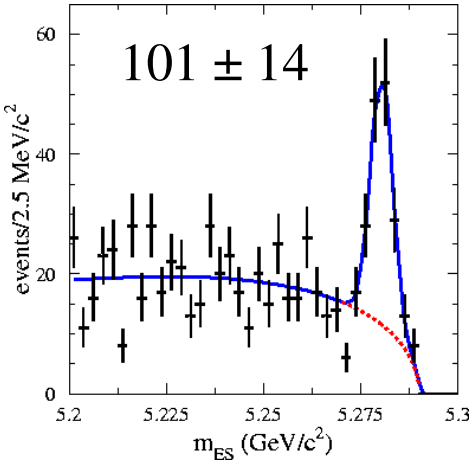




$\mathcal{B} = (2.9 \pm 0.3 \pm 0.4) \times 10^{-4}$

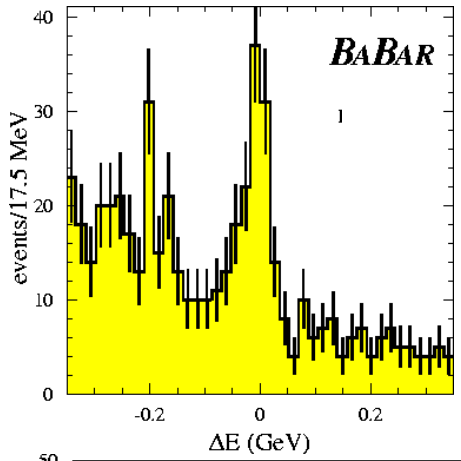
$D^0\eta$

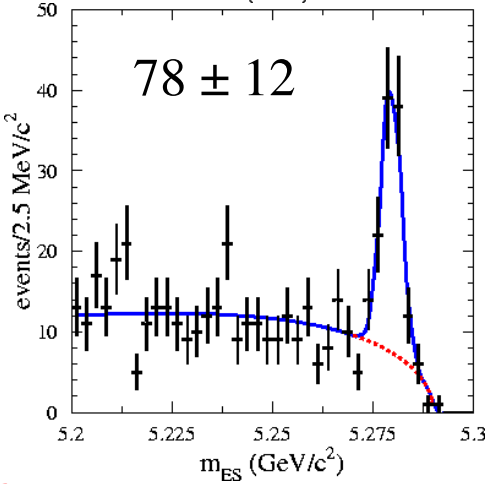




$\mathcal{B} = (2.4 \pm 0.4 \pm 0.3) \times 10^{-4}$

$D^0\omega$





$\mathcal{B} = (2.5 \pm 0.4 \pm 0.3) \times 10^{-4}$

Rates are more than twice the naïve factorization prediction

$B^+ \to \chi_{c0} K^+$

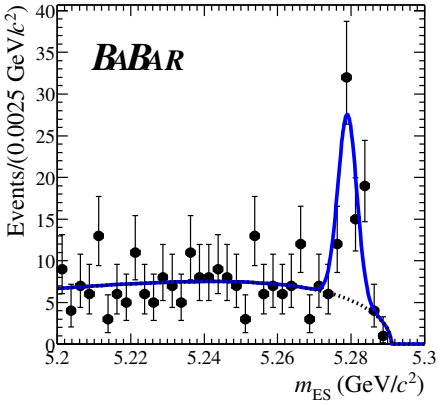
- If $B \to \chi_{c0} X$ proceeds only through color-singlet operator, $B \to \chi_{c0} K$ is disallowed [Kühn and Rückl, Phys. Lett. **B135**, 477 (1984)]
- But decay can proceed via color-octet mechanism (i.e., soft gluon interaction) [Bodwin *et al.*, Phys. Rev. **D46**, 3703 (1999)]

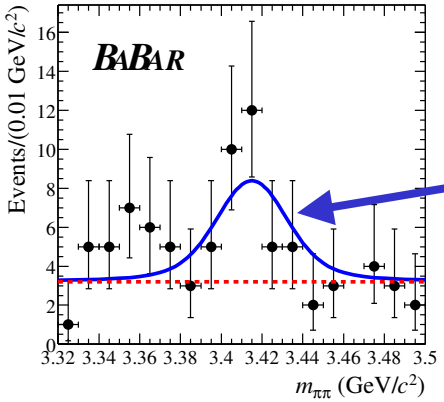
If color-octet production dominates $B \to (c\bar{c})K$,
$\mathcal{B}(B \to \chi_{c0} K) \approx \mathcal{B}(B \to \chi_{c1} K) = (1.0 \pm 0.4) \times 10^{-3}$

- We reconstruct χ_{c0} decays to $\pi^+\pi^-$ and K^+K^-
- 11-variable Fisher discriminant used to reduce background
- Special care needed to address backgrounds from B mesons decaying to same final-state particles without an intermediate χ_{c0}
  - These backgrounds peak in both m_{ES} and ΔE
  - MC studies predict small contribution after D^0 and ϕ resonances vetoed
  - Signal cross-checked using two-dimensional fit to m_{ES} and χ_{c0} candidate mass

Preliminary Results (76 Million *B* Pairs)

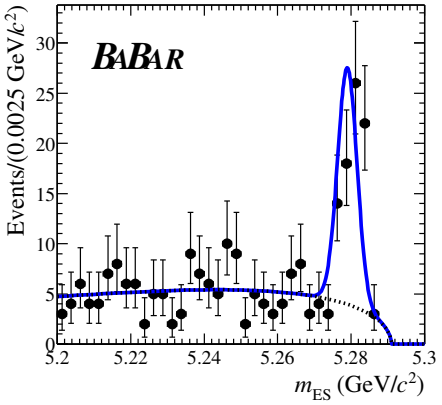
$\chi_{c0} \to \pi^+\pi^-$

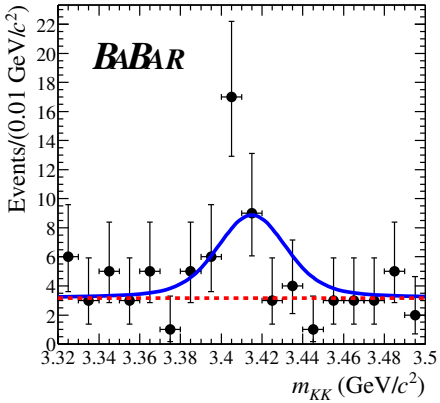




χ_{c0} mass and width fixed to expected values

$\chi_{c0} \to K^+K^-$





$\mathcal{B}(B^+ \to \chi_{c0}K^+) = [2.4 \pm 0.7\ (\text{stat.} \oplus \text{syst.})] \times 10^{-4}$

$\Rightarrow$ Color octet mechanism is important, but not dominant

Study of $B^0 \to D_S^{(*)+} D^{*-}$

- Rate of $B \to D_S^{(*)+} D^{*-}$, and polarization of $B \to D_S^{*+} D^{*-}$ are predicted in factorization model
- From [M. Neubert and B. Stech in Heavy Flavours, 2nd ed. (hep-ph/9705292)]

$$\mathcal{B}(B^0 \to D_S^+ D^{*-}) = (0.58 - 0.70)\%$$
$$\mathcal{B}(B^0 \to D_S^{*+} D^{*-}) = (2.32 - 2.45)\%$$
$$\text{For } D_S^{*+} D^{*-}, \ \frac{\Gamma_L}{\Gamma} = 52\%$$

- Analysis uses partial reconstruction to maximize statistics:
  - No attempt made to reconstruct D^0
  - B candidate "missing mass" should equal D^0 mass
- Meson decays considered:

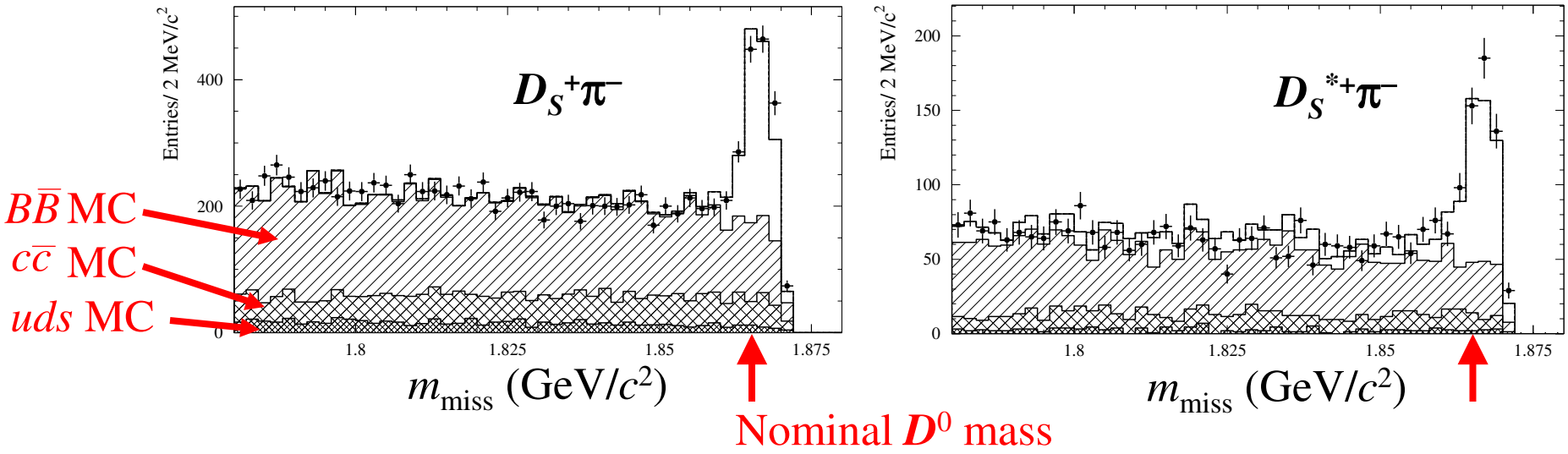
$$D_S^+ \to \phi\pi^+$$
$$\to K_S K^+$$
$$\to \bar{K}^{*0} K^+$$

$$\phi \to K^+ K^-$$
$$\bar{K}^{*0} \to K^- \pi^+$$
$$K_S \to \pi^+ \pi^-$$

$$D_S^{*+} \to D_S^+ \gamma$$

Preliminary Results (23 Million *B* Pairs)

- Observed missing mass distributions:



- Part of the "signal" peak is due to feed-across from other channel
  - rate estimated using Monte Carlo

Results:

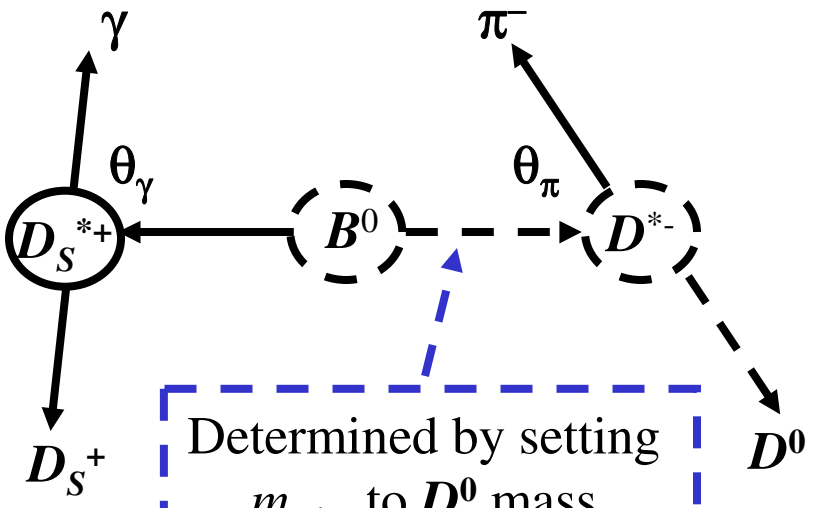
$$\mathcal{B}\left(B^0 \to D_S^+ D^{*-}\right) = \left[1.03 \pm 0.14(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.26(\text{meson } \mathcal{B})\right]\%$$

$$\mathcal{B}\left(B^0 \to D_S^{*+} D^{*-}\right) = \left[1.97 \pm 0.15(\text{stat.}) \pm 0.30(\text{syst.}) \pm 0.49(\text{meson } \mathcal{B})\right]\%$$

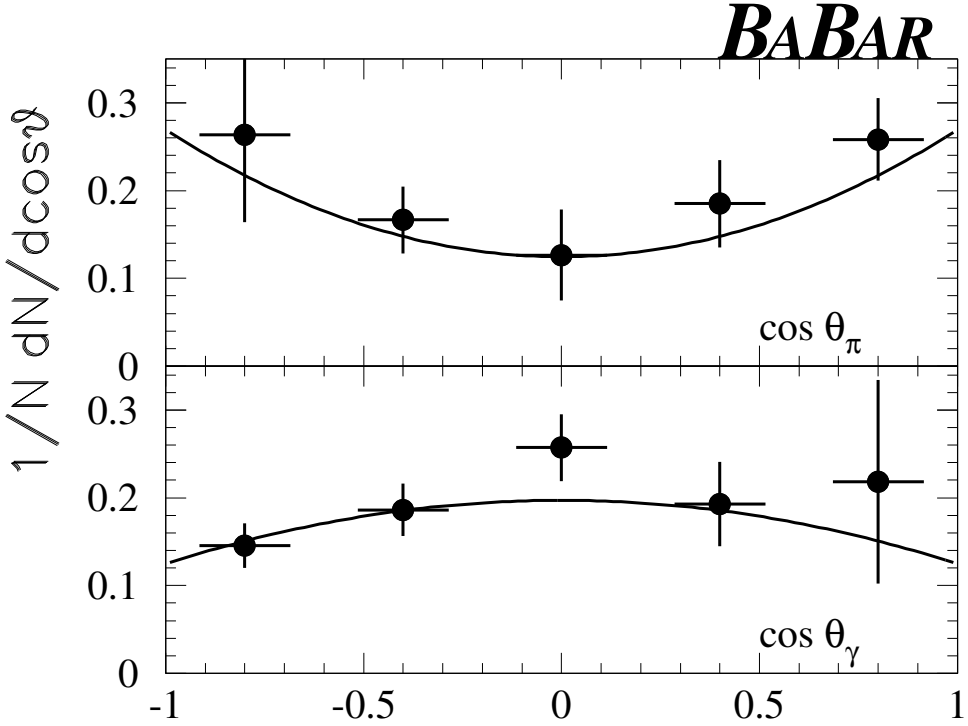
Preliminary Polarization Measurement

- To reduce background systematics, only cleanest mode, $D_S^+ \to \phi\pi^+$, is used

Polarization measured via distributions of θ_γ and θ_π



Background-subtracted acceptance-corrected data:



Result: $\frac{\Gamma_L}{\Gamma} = [51.9 \pm 5.0 \pm 2.8]\%$

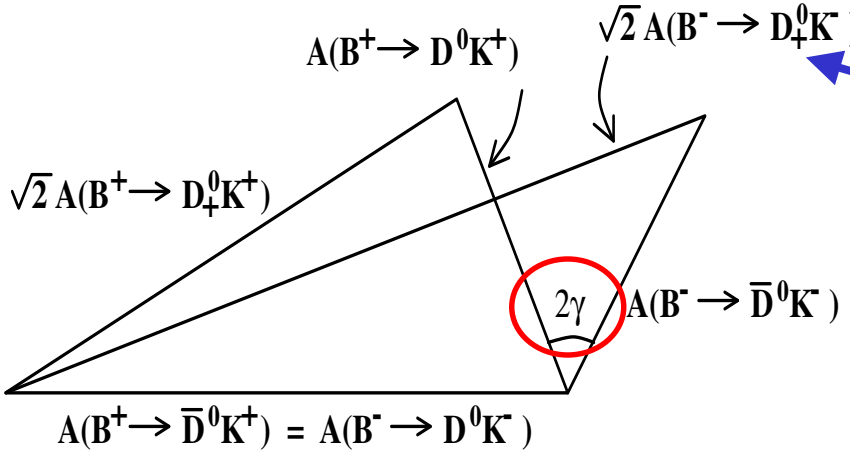
CP Violation beyond sin2β

- BaBar and Belle have shown that sin2β agrees well with Standard Model expectation
  - No sign yet of CP violation outside CKM matrix
- But maybe the agreement is just fortuitous…?
  - Need to overconstrain the unitarity triangle
- Measurement of the other angles is the next big step for the B Factories

Decays to open charm final states offer prospects for measuring γ

Study of $B^- \to D^0 K^-$ Decays

- In principle, these modes allow clean measurement of γ
- Simplest scheme [M. Gronau and D. Wyler, Phys. Lett **B265**, 172 (1991)]:



$D_\pm$ are CP eigenstates:

$$D_\pm = \frac{1}{\sqrt{2}}\left(D^0 \pm \bar{D}^0\right)$$

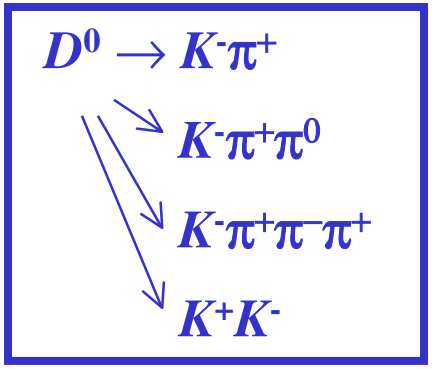
- This particular measurement is experimentally challenging, but variations on it offer hope
- In addition, one can look for a direct CP asymmetry, i.e.:

Select via CP-eigenstate decays, e.g. K^+K^-

$$A_{CP} = \frac{\mathcal{B}\left(B^- \to D_{CP}^0 K^-\right) - \mathcal{B}\left(B^+ \to D_{CP}^0 K^+\right)}{\mathcal{B}\left(B^- \to D_{CP}^0 K^-\right) + \mathcal{B}\left(B^+ \to D_{CP}^0 K^+\right)}$$

Candidate Selection

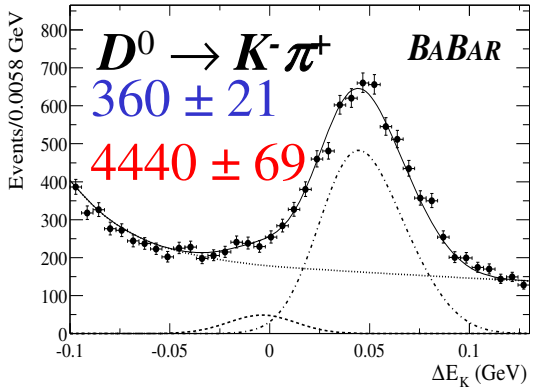
- Meson decays considered:

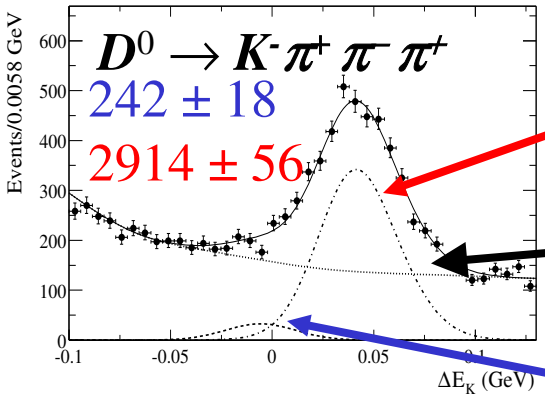


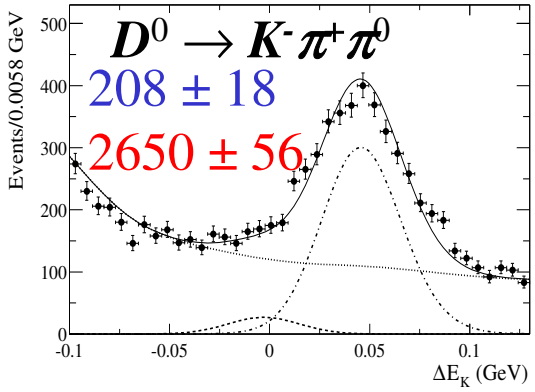
- Isolating $B^- \to D^0K^-$ is complicated by kinematic similarity to more common $B^- \to D^0\pi^-$
  - Both have same m_{ES} distribution
- Signal extracted using unbinned max. likelihood fit to ΔE, m_{ES}, and K ID probability
  - Continuum background shapes determined from off-resonance data
  - B meson background shapes estimated from Monte Carlo
  - Signal shapes measured in data control samples
- To reduce systematics, we measure the ratio $\dfrac{\mathcal{B}\left(B^- \to D^0K^-\right)}{\mathcal{B}\left(B^- \to D^0\pi^-\right)}$

Preliminary Result for $\mathcal{B}$ (58 Million B Pairs)

ΔE distributions for data, with fit superimposed:







$D^0\pi^-$

Background

D^0K^-

Numbers are:
- Fitted D^0K^- yield
- Fitted $D^0\pi^-$ yield

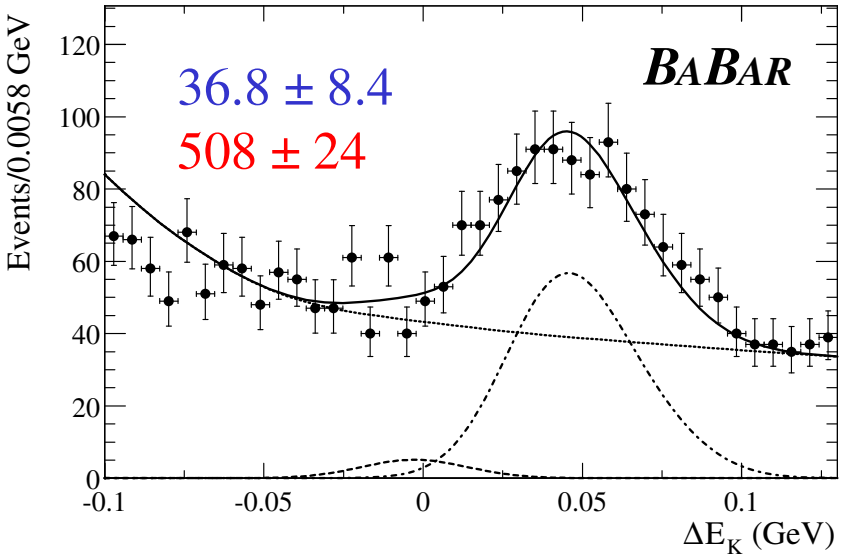
Summing non-CP modes, $\dfrac{\mathcal{B}\left(B^- \to D^0K^-\right)}{\mathcal{B}\left(B^- \to D^0\pi^-\right)} = \left[8.31 \pm 0.35(\text{stat.}) \pm 0.20(\text{syst.})\right]\%$

Preliminary Result for A_{CP} (81 Million B Pairs)

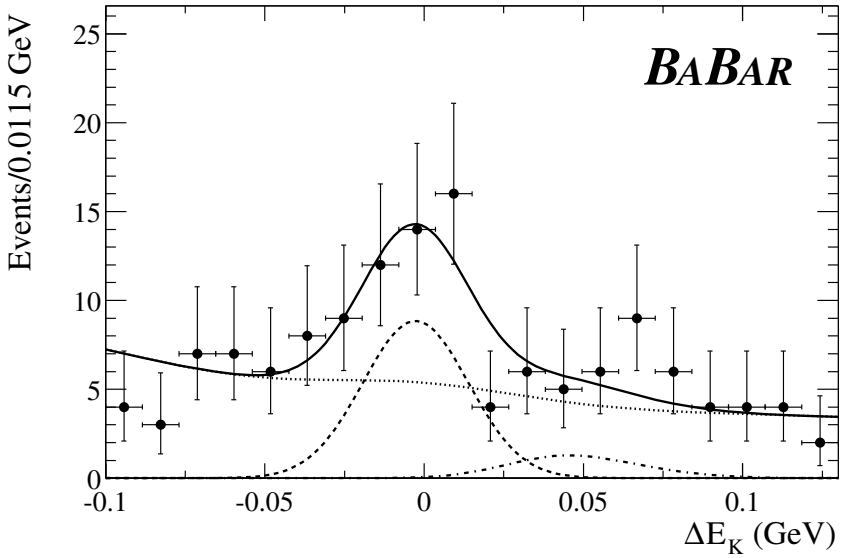
- Applying kaon ID and m_{ES} selections highlights the $B^- \to D^0 K^-$ signal:

$D_{CP}{}^0 \to K^+K^-$ candidates

Standard selection



With cuts on K ID and m_{ES}



$$15.3 \pm 5.6\ B^+$$
$$21.7 \pm 5.6\ B^- \Rightarrow A_{CP} = 0.17 \pm 0.23^{+0.09}_{-0.08}$$

Towards a Measurement of sin(2β+γ)

- Another way to measure γ is to find the time-dependent asymmetry in $B \to D^{(*)}\pi$

Amplitude ∝ sin(2β+γ)

- But asymmetry arises from interference between Cabibbo-allowed $\bar{B}^0 \to D^{(*)+}\pi^-$ and doubly Cabibbo-suppressed $B^0 \to D^{(*)+}\pi^-$

$\to$ asymmetry is small ($\mathcal{O}(2\%)$) and $\propto \dfrac{A\left(B^0 \to D^{(*)+}\pi^-\right)}{A\left(\bar{B}^0 \to D^{(*)+}\pi^-\right)} \equiv \lambda_{D^{(*)}\pi}$

- So, we need to know $\lambda_{D(*)\pi}$
- Can exploit $SU(3)$ relation
  - In naïve factorization model:

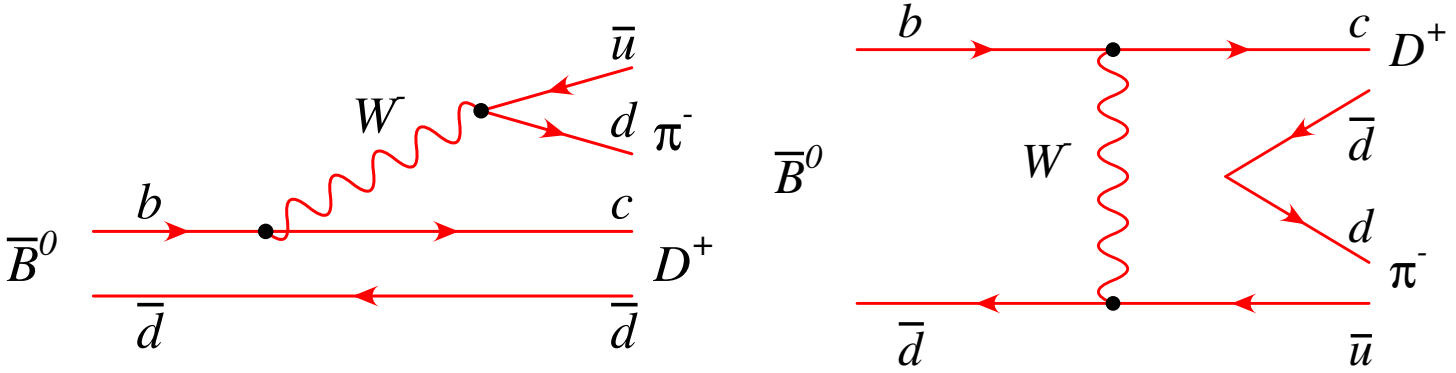
Need to measure this rate!

$$\lambda_{D^{(*)}\pi} = \frac{\mathcal{A}\left(B^0 \to D_s^{(*)+}\pi^-\right)}{\mathcal{A}\left(\bar{B}^0 \to D^{(*)+}\pi^-\right)} \bullet \cos\theta_c \bullet \frac{f_{D^{(*)}}}{f_{D_s^{(*)}}}$$

SU(3) symmetry breaking: 1.1 ± 0.1

How Reliable is $SU(3)$ Relation?

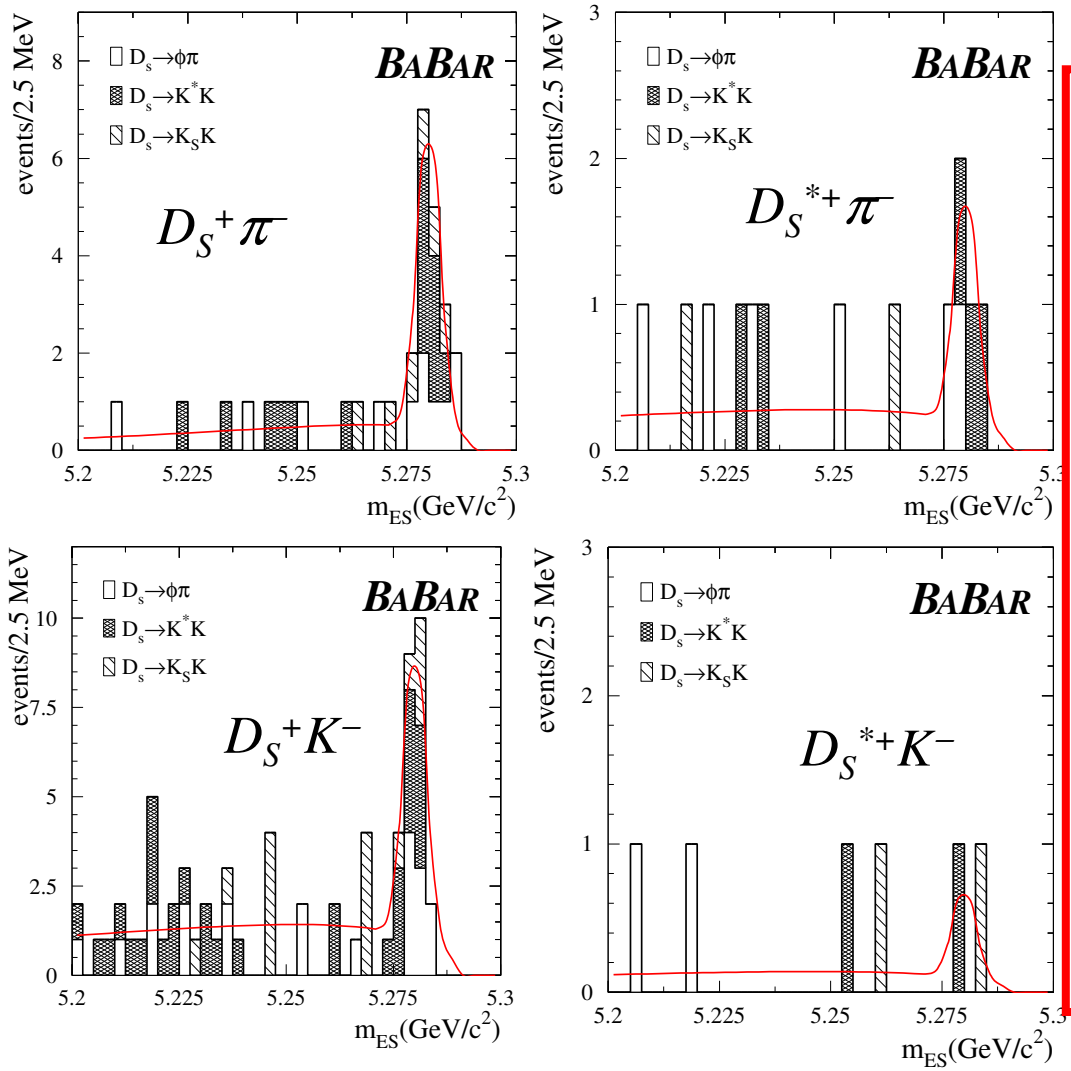
- Usual caveats about factorization apply!
- Also, a fundamental difference between $\bar{B}^0 \to D^{(*)+}\pi^-$ and $\bar{B}^0 \to D_S^{(*)+}\pi^-$
  - former proceeds though both emission and W-exchange diagrams:



  - SU(3) relation holds only if W-exchange is small
- Can study this by measuring $\mathcal{B}(\bar{B}^0 \to D_S^{(*)+}K^-)$, which has only W-exchange diagram
  - No such ***B*** decays have been previously observed

Ratio $\dfrac{\mathcal{B}\left(\bar{B}^0 \to D_S^{(*)+}K^-\right)}{\mathcal{B}\left(\bar{B}^0 \to D^{(*)+}\pi^-\right)}$ provides estimate of W-exchange magnitude

Results (84 Million *B* Pairs)



Results:

$\mathcal{B}(B^0 \to D_S^+ \pi^-) =$
$[3.2 \pm 0.9 \pm 1.0] \times 10^{-5}$
3.3σ significance

$\mathcal{B}(B^0 \to D_S^+ K^-) =$
$[3.2 \pm 1.0 \pm 1.0] \times 10^{-5}$
3.5σ significance

$\mathcal{B}(B^0 \to D_S^{*+} \pi) < 4.1 \times 10^{-5}$

$\mathcal{B}(B^0 \to D_S^{*+} K^-) < 2.5 \times 10^{-5}$

@90% C.L.

Implications for sin(2β+γ)

- The small branching fractions for $B^0 \to D_S^{(*)+} K^-$ imply that *W*-exchange diagram is a minor correction (~10^{-2})
- Using this, and the measured $\mathcal{B}(B^0 \to D_S^{(*)+} K^-)$ one finds

$$\lambda_{D^{(*)}\pi} = 0.020 \pm 0.005 \text{ (stat. } \oplus \text{ syst.)}$$

…but only if factorization is a good approximation!

- How can one tell? Measure other similar ratios, see if a consistent picture emerges

The road to γ is still a long one, but the initial steps are encouraging

Summary

- ***B*** decays to open charm and charmonium provide an excellent laboratory for the study of hadronic ***B*** decays
- With a sample of over 80 million ***B*** pairs, BaBar is able to test models of ***B*** decay in more modes and with greater precision than ever before
- The results presented here show that:
  - $\bar{D}^{(*)}D^{(*)}K$ is an important contributor to n_c
  - The simplest factorization models do not correctly predict all color-suppressed decay rates
- In addition, this sample allows us to take steps toward measuring the CKM angle γ

With the expected increase in data rate in the next few years, BaBar will continue to improve our understanding of non-perturbative QCD and CP violation