Maximum Likelihood Analysis of $B^+ \longrightarrow \rho^+\rho^0$ at the BaBar Detector

Katharine Schofield

THE UNIVERSITY
of LIVERPOOL

Overview

- The BaBar Experiment
- Motivation for analysis
  - Theoretical Overview
- Analysis Method
- Results
- Systematics
- Conclusion

The BaBar Detector

🟧 Silicon Vertex Tracker (SVT)
Tracking & dE/dx

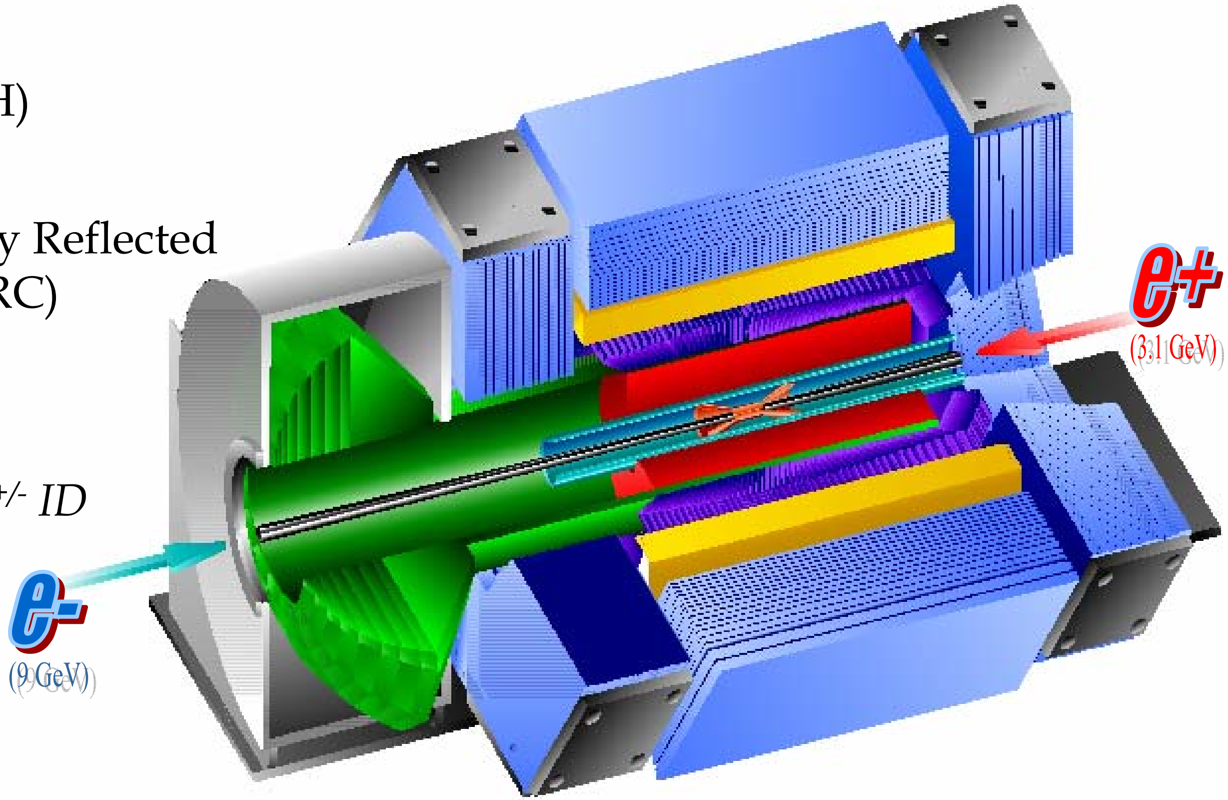
🟥 Drift Chamber (DCH)
Tracking & dE/dx

🟩 Detector of Internally Reflected Cerenkov Light (DIRC)
K/π Separation

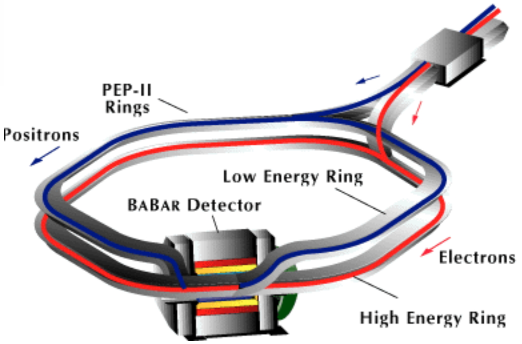
🟪 Electromagnetic Calorimeter (EMC)
π^0/γ *reconstruction,* $e^{+/-}$ *ID*

🟨 1.5T Solenoid Magnet

▤ Instrumented Flux Return (IFR)
$\mu^{+/-}$, K_L *ID*



- Centre of Mass Energy 10.58 GeV
- Boost $\beta\gamma = 0.56$
- >360 million BB pairs



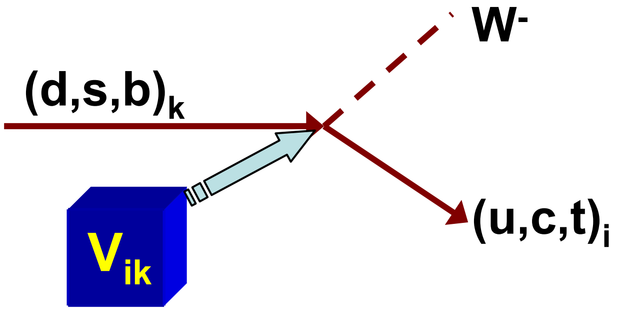
BABAR

PEP-II
ASYMMETRIC B FACTORY
SLAC/LBL/LLNL

Motivation and brief overview of theory

The Unitarity Triangle

- Fermions of different flavours can communicate via flavour changing weak interactions
- Modeled by 3×3 CKM matrix – 3 mixing angles, 1 phase

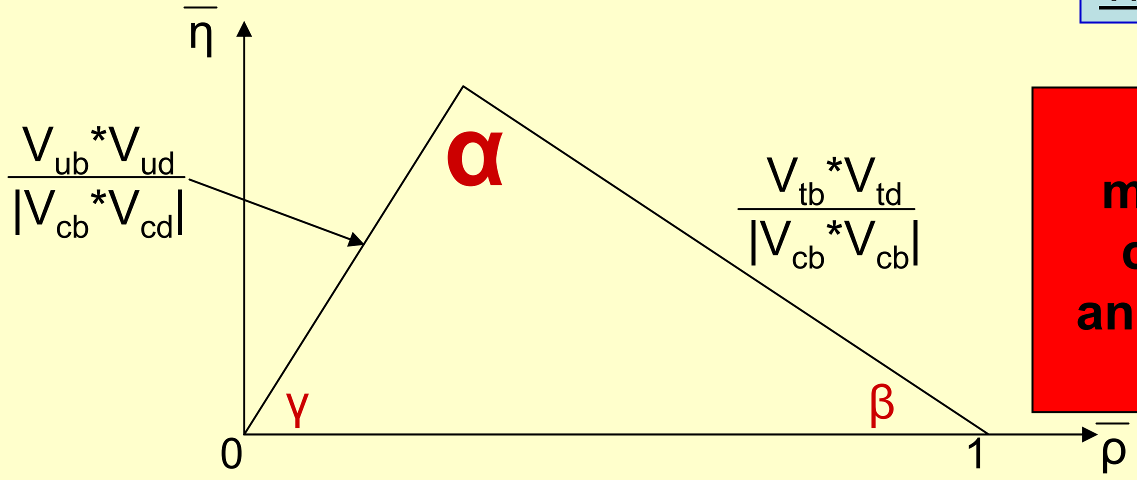


$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \underbrace{\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}}_{V_{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Unitarity condition:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

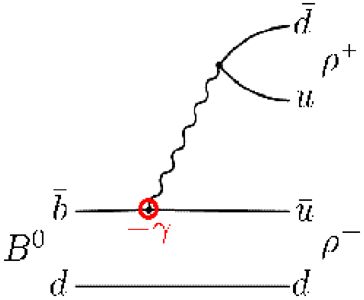
The Unitarity Triangle

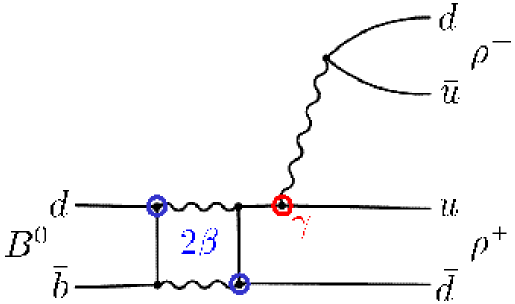


BaBar measurements constrain the angles and sides of the UT

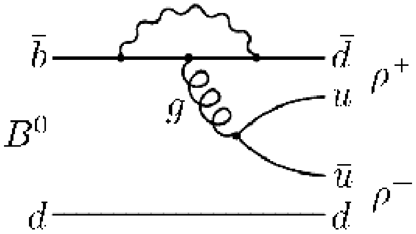
Motivations

- $B \rightarrow \rho^+\rho^-$ decays involve transitions of the type $b \rightarrow uud$
  - Access to CKM angle α (=180 - β - γ) from dominant tree diagrams





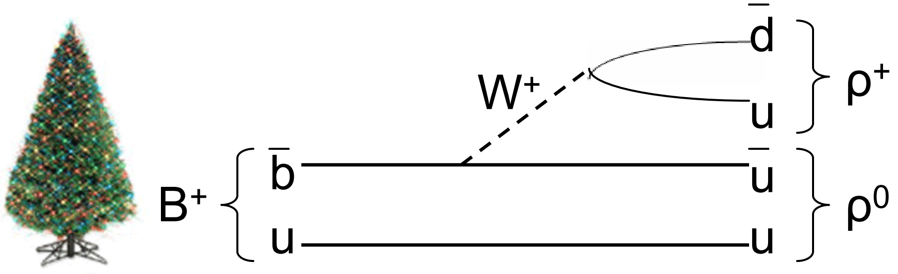
  - BUT gluonic penguin amplitudes also interfere → actually we measure $2\alpha_{eff}$
  - Define $\kappa = 2(\alpha_{eff}-\alpha)$ – difference due to penguin loops



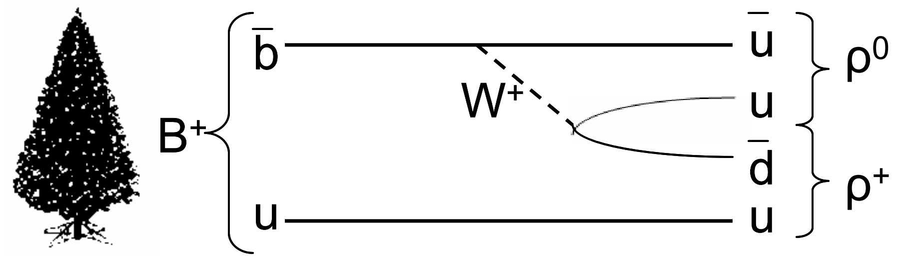
  - However, we can disentangle these penguin contributions – hence measure α – using the other $B \rightarrow \rho\rho$ modes via an *Isospin Analysis…*

$B^+ \rightarrow \rho^+\rho^0$

- Leading diagrams for $B^+ \rightarrow \rho^+\rho^0$ – Tree diagrams dominate:



- Colour allowed tree diagram



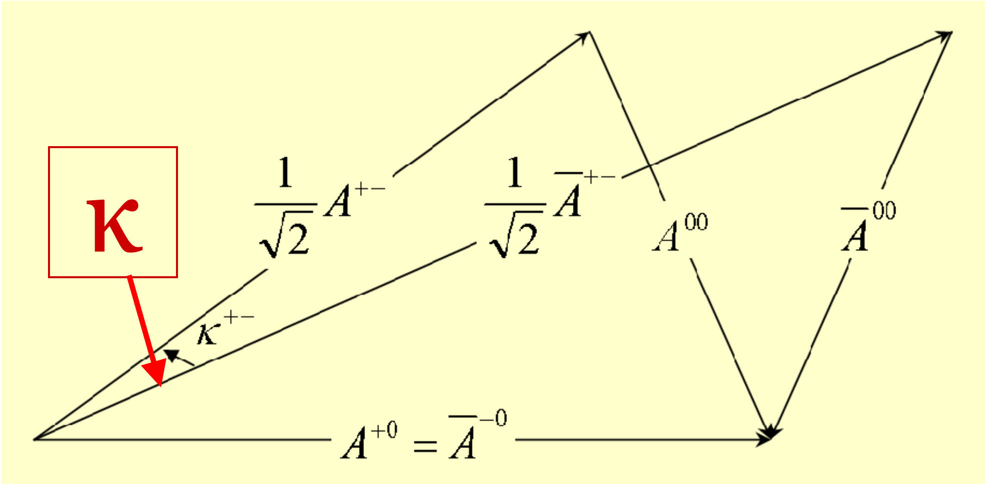
- Colour suppressed tree diagram

- No gluonic penguins in $B^+ \rightarrow \rho^+\rho^0$
- $B^0 \rightarrow \rho^0\rho^0$ is gluonic penguin only and constrained to be small
- By using all three ($\rho^+\rho^-$, $\rho^+\rho^0$ and $\rho^0\rho^0$), we can measure the penguin contribution κ

Isospin Analysis

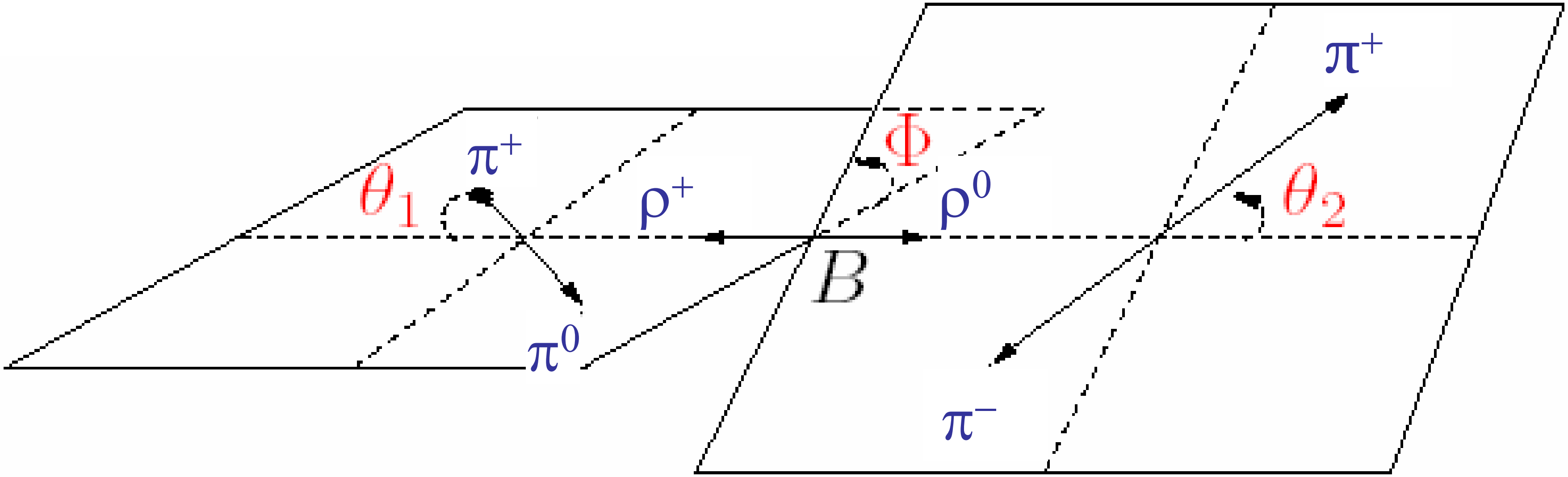
- Isospin Analysis disentangles penguin contributions to using SU(2) symmetry relations between the B→ρρ modes
- Need 5 rates:
  - $B(B^{\pm}\to\rho^{\pm}\rho^{0})$, $B(B^{0}\to\rho^{+}\rho^{-})$, $B(\overline{B}^{0}\to\rho^{+}\rho^{-})$, $B(B^{0}\to\rho^{0}\rho^{0})$, $B(\overline{B}^{0}\to\rho^{0}\rho^{0})$
- Construct triangles representing the complex amplitudes

$$A^{+-} = A(B^0 \to \rho^+\rho^-),\ \bar{A}^{+-} = A(\overline{B}^0 \to \rho^+\rho^-),$$
$$A^{+0} = A(B^+ \to \rho^+\rho^0) = \bar{A}^{-0} = A(B^- \to \rho^-\rho^0),$$
$$A^{00} = A(B^0 \to \rho^0\rho^0),\ \bar{A}^{00} = A(\overline{B}^0 \to \rho^0\rho^0).$$



Angular Analysis

- The final state contains 2 vector mesons
  - Both Longitudinal and Transverse components
- Perform analysis as function of 2 helicity angles $\theta_{\rho+}$ (=θ_1) and $\theta_{\rho0}$ (= θ_2)
  - Integrate over angle φ between the decay planes



Differential decay rate:

$$\frac{1}{\Gamma}\frac{d^2\Gamma}{d\cos\theta_1 d\cos\theta_2} \propto \frac{1}{4}\underbrace{(1-f_L)\sin^2\theta_1\sin^2\theta_2}_{\text{transverse}} + \underbrace{\overset{\text{“polarization”}}{f_L}\cos^2\theta_1\cos^2\theta_2}_{\text{longitudinal}}$$

Data Sample

- 210.5 fb^{-1} ($231.8*10^6$ BB pairs) taken on the Y(4S) resonance
- 21.6 fb^{-1} taken 40MeV below Y(4S) resonance for studying backgrounds
  - In this data sample we expect:
    - ~400 Signal events ($\varepsilon_{long} = 8.4\%$, $\varepsilon_{tran} = 18.6\%$)
    - ~65000 Continuum (qq) events ($\varepsilon = 0.03\%$)
    - ~9000 B-background events

- We measure:
  - Fraction of longitudinally polarized events f_L
  - Branching Fraction *B*,
  - Charge Asymmetry A_{CP}

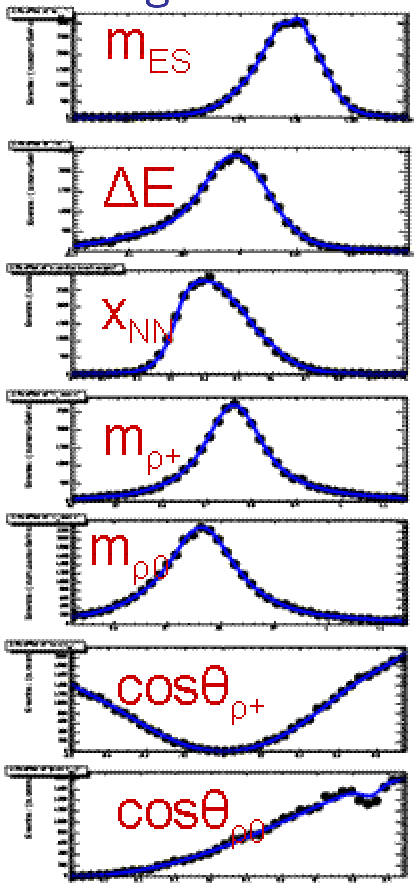
$$A_{CP} = \frac{N(B^+\rightarrow\rho^+\rho^0) - N(B^-\rightarrow\rho^-\rho^0)}{N(B^+\rightarrow\rho^+\rho^0) + N(B^-\rightarrow\rho^-\rho^0)}$$

Event Selection

- Discriminating Variables:
- Kinematic selection:
  - $m_{ES} = (E_{beam}{}^2 - p_B{}^2)^{1/2}$ *Beam energy constrained B mass*
  - $\Delta E = E_B - E_{CM}/2$ *Difference between reconstructed B energy and known value*
- Background Rejection:
  - Neural Net *Discriminate signal and backgrounds using event shape variables*
- Properties of ρ mesons:
  - $m_{\rho+}$, $m_{\rho 0}$ *Masses*
  - $\cos\theta_{\rho+}$, $|\cos\theta_{\rho 0}|$ *Helicity angles*

- Challenges:
  - Reconstructing π^0s
  - Reconstructing soft π's
  - Backgrounds from B decays
  - ρ resonance is broad (width = 150MeV)

Signal PDFs:



Extended Unbinned Maximum Likelihood Fit

- Build ML fit with 7 variables: m_{ES}, ΔE, x_{NN}, $m_{\rho+}$, $m_{\rho0}$, $\cos\theta_{\rho+}$, $|\cos\theta_{\rho0}|$

Likelihood Function:

$$\mathcal{L} = e^{-N'} \prod_{i=1}^{N} \left(\underbrace{N_S P_{S,i}(f_L)}_{\text{Signal}} + \underbrace{N_C P_{C,i}}_{\text{Continuum}} + \sum_{\text{bdf B } j} \underbrace{N_j P_{j,i}}_{\text{B-Backgrounds\&SxF}} \right)$$

- N_S, N_C, Nj are the numbers of events in each category; $P_{S,i}$, $P_{C,i}$, $P_{j,i}$ are the PDFs

Components modelled in the likelihood function:

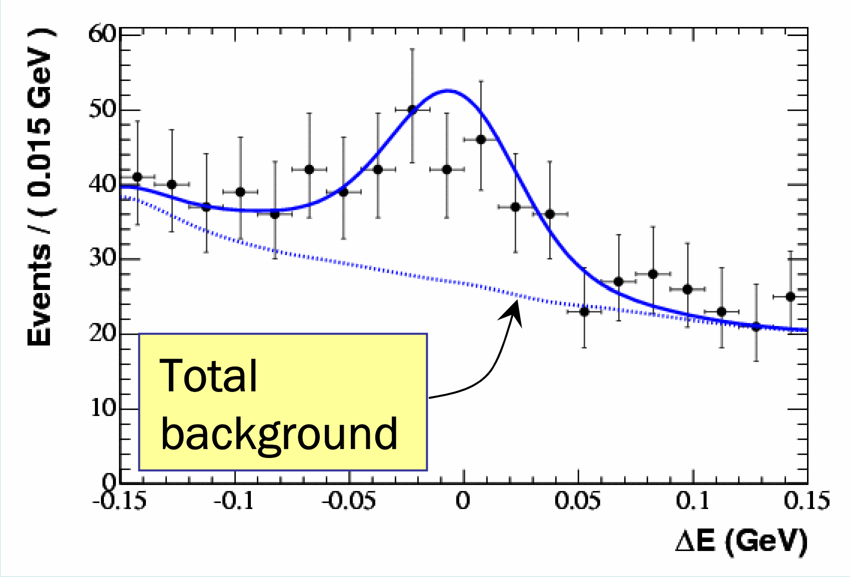
- Correctly reconstructed Signal (longitudinal and transverse)
- Continuum background from qq
- B-Background modes (16 in total)
- Mis-reconstructed signal

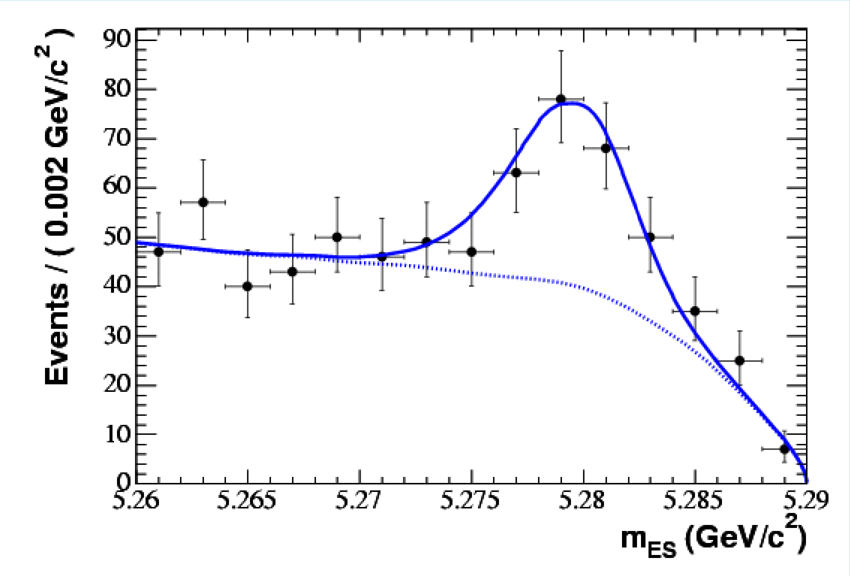
Fit Results

Fit results:

- N_{signal} = 358 ± 48
- Polarization, f_L = 0.95 ± 0.04
- Charge Asymmetry, A_{CP} = 0.10 ± 0.14

Projection of signal-enriched sample:





Systematics

- Corrections and systematics on the signal yield and polarisation fraction:

Source	N_{Sig} (events)		f_L (%)	
	Size	Syst. Err	Size	Syst Err
Amount of mis-reconstructed signal	-	29	-	0.7
Model of signal and B-backgrounds	-47	23.5	+1.4	0.7
B backgrounds yields	-	11	-	0.6
NN/helicity correlation in qq	+22	11	+0.1	0.05
Additional B backgrounds	-	8	-	0.5
Statistical uncertainty on signal PDF shapes	-	15	-	1.5
Uncertainty in continuum model for NN PDF	-	33	-	4.8
Total	-25	55	+1.5	5.2

- Corrections and systematics on the Branching Fraction:

Source	Correction (%)	Uncertainty (%)
Measurement of N_{Sig}	-	15
Number of BB pairs	-	1.1
π^0 Reconstruction	-2.54	3
Track Reconstruction	-1.5	3.9
Particle Identification	-	1.1
Total	-4.04	16

- Systematics on the Charge Asymmetry A_{CP}:

Source	Uncertainty (%)
Particle Identification	4
Track reconstruction	0.45
Asymmetry in B-backgrounds	8.5
Total	9

Conclusion

- We have measured (preliminary!):
  - Branching Fraction, *B* = (17.2±2.5(stat.)±2.8(syst.)).10^{-6}
  - Longitudinal Polarization, f_L = 0.96±0.04±0.05
  - Charge Asymmetry, A_{CP} = 0.10±0.14±0.09
- $B^+ \rightarrow \rho^+ \rho^0$ is almost 100% longitudinally polarized, as seen in previous measurements
- Measured *B* is smaller than previous measurements (but still consistent)
  - In better agreement with the isospin hypothesis
  - Improves our understanding of the penguin pollution uncertainty on α

Backup Slides

Previous Measurements

Belle analysis (*Phys. Rev. Lett.* **91**, 221801) with $78\,\mathrm{fb}^{-1}$:

- $\mathcal{B} = \left(31.7 \pm 7.1(\mathrm{stat})^{+3.8}_{-6.7}(\mathrm{syst})\right) \times 10^{-6}$,
- $f_L = 0.95 \pm 0.11(\mathrm{stat}) \pm 0.02(\mathrm{syst})$,
- $\mathcal{A}_{\mathcal{CP}} = 0.00 \pm 0.22(\mathrm{stat}) \pm 0.03(\mathrm{syst})$.

BABAR analysis by LBL (BAD 483, *Phys. Rev. Lett.* **91**, 171802) with $81.9\,\mathrm{fb}^{-1}$:

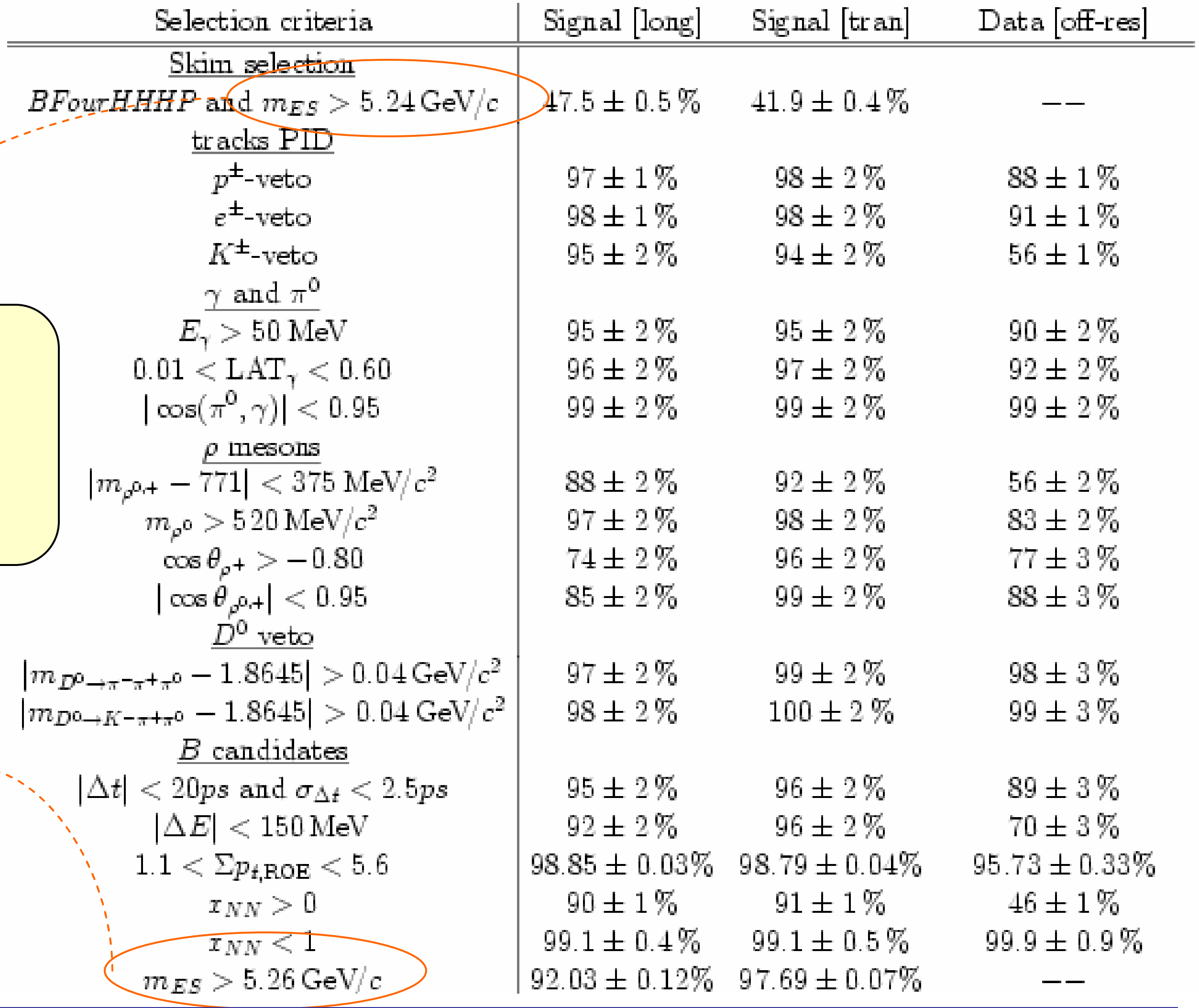
- $\mathcal{B} = (22.5^{+5.7}_{-5.4}(\mathrm{stat}) \pm 5.8(\mathrm{syst})) \times 10^{-6}$,
- $f_L = 0.97^{+0.03}_{-0.07}(\mathrm{stat}) \pm 0.04(\mathrm{syst})$,
- $\mathcal{A}_{\mathcal{CP}} = -0.19 \pm 0.23(\mathrm{stat}) \pm 0.03(\mathrm{syst})$,

BABAR analysis by Saclay (BAD 692, unpublished) with $81.9\,\mathrm{fb}^{-1}$:

- $\mathcal{B} = (17.9^{+3.3}_{-3.2}(\mathrm{stat}) \pm 2.4(\mathrm{syst})) \times 10^{-6}$,
- $f_L = 0.87^{+0.06}_{-0.07}(\mathrm{stat}) \pm 0.05(\mathrm{syst})$,
- $\mathcal{A}_{\mathcal{CP}} = -0.02 \pm 0.09(\mathrm{stat}) \pm 0.04(\mathrm{syst})$.

This analysis: based on BAD692, with improvements to the model, performed on the Run1-4 dataset

Event Selection and Efficiencies



Selection criteria	Signal [long]	Signal [tran]	Data [off-res]
Skim selection			
$BFourHHHP$ and $m_{ES} > 5.24\,\mathrm{GeV}/c$	$47.5 \pm 0.5\,\%$	$41.9 \pm 0.4\,\%$	$--$
tracks PID			
$p^{\pm}$-veto	$97 \pm 1\,\%$	$98 \pm 2\,\%$	$88 \pm 1\,\%$
$e^{\pm}$-veto	$98 \pm 1\,\%$	$98 \pm 2\,\%$	$91 \pm 1\,\%$
$K^{\pm}$-veto	$95 \pm 2\,\%$	$94 \pm 2\,\%$	$56 \pm 1\,\%$
γ and π^0			
$E_\gamma > 50$ MeV	$95 \pm 2\,\%$	$95 \pm 2\,\%$	$90 \pm 2\,\%$
$0.01 < \mathrm{LAT}_\gamma < 0.60$	$96 \pm 2\,\%$	$97 \pm 2\,\%$	$92 \pm 2\,\%$
$\lvert\cos(\pi^0, \gamma)\rvert < 0.95$	$99 \pm 2\,\%$	$99 \pm 2\,\%$	$99 \pm 2\,\%$
ρ mesons			
$\lvert m_{\rho^+} - 771\rvert < 375\,\mathrm{MeV}/c^2$	$88 \pm 2\,\%$	$92 \pm 2\,\%$	$56 \pm 2\,\%$
$m_{\rho^0} > 520\,\mathrm{MeV}/c^2$	$97 \pm 2\,\%$	$98 \pm 2\,\%$	$83 \pm 2\,\%$
$\cos\theta_{\rho^+} > -0.80$	$74 \pm 2\,\%$	$96 \pm 2\,\%$	$77 \pm 3\,\%$
$\lvert\cos\theta_{\rho^+}\rvert < 0.95$	$85 \pm 2\,\%$	$99 \pm 2\,\%$	$88 \pm 3\,\%$
D^0 veto			
$\lvert m_{D^0\to\pi^-\pi^+\pi^0} - 1.8645\rvert > 0.04\,\mathrm{GeV}/c^2$	$97 \pm 2\,\%$	$99 \pm 2\,\%$	$98 \pm 3\,\%$
$\lvert m_{D^0\to K^-\pi^+\pi^0} - 1.8645\rvert > 0.04\,\mathrm{GeV}/c^2$	$98 \pm 2\,\%$	$100 \pm 2\,\%$	$99 \pm 3\,\%$
B candidates			
$\lvert\Delta t\rvert < 20ps$ and $\sigma_{\Delta t} < 2.5ps$	$95 \pm 2\,\%$	$96 \pm 2\,\%$	$89 \pm 3\,\%$
$\lvert\Delta E\rvert < 150\,\mathrm{MeV}$	$92 \pm 2\,\%$	$96 \pm 2\,\%$	$70 \pm 3\,\%$
$1.1 < \Sigma p_{t,\mathrm{ROE}} < 5.6$	$98.85 \pm 0.03\%$	$98.79 \pm 0.04\%$	$95.73 \pm 0.33\%$
$x_{NN} > 0$	$90 \pm 1\,\%$	$91 \pm 1\,\%$	$46 \pm 1\,\%$
$x_{NN} < 1$	$99.1 \pm 0.4\,\%$	$99.1 \pm 0.5\,\%$	$99.9 \pm 0.9\,\%$
$m_{ES} > 5.26\,\mathrm{GeV}/c$	$92.03 \pm 0.12\%$	$97.69 \pm 0.07\%$	$--$

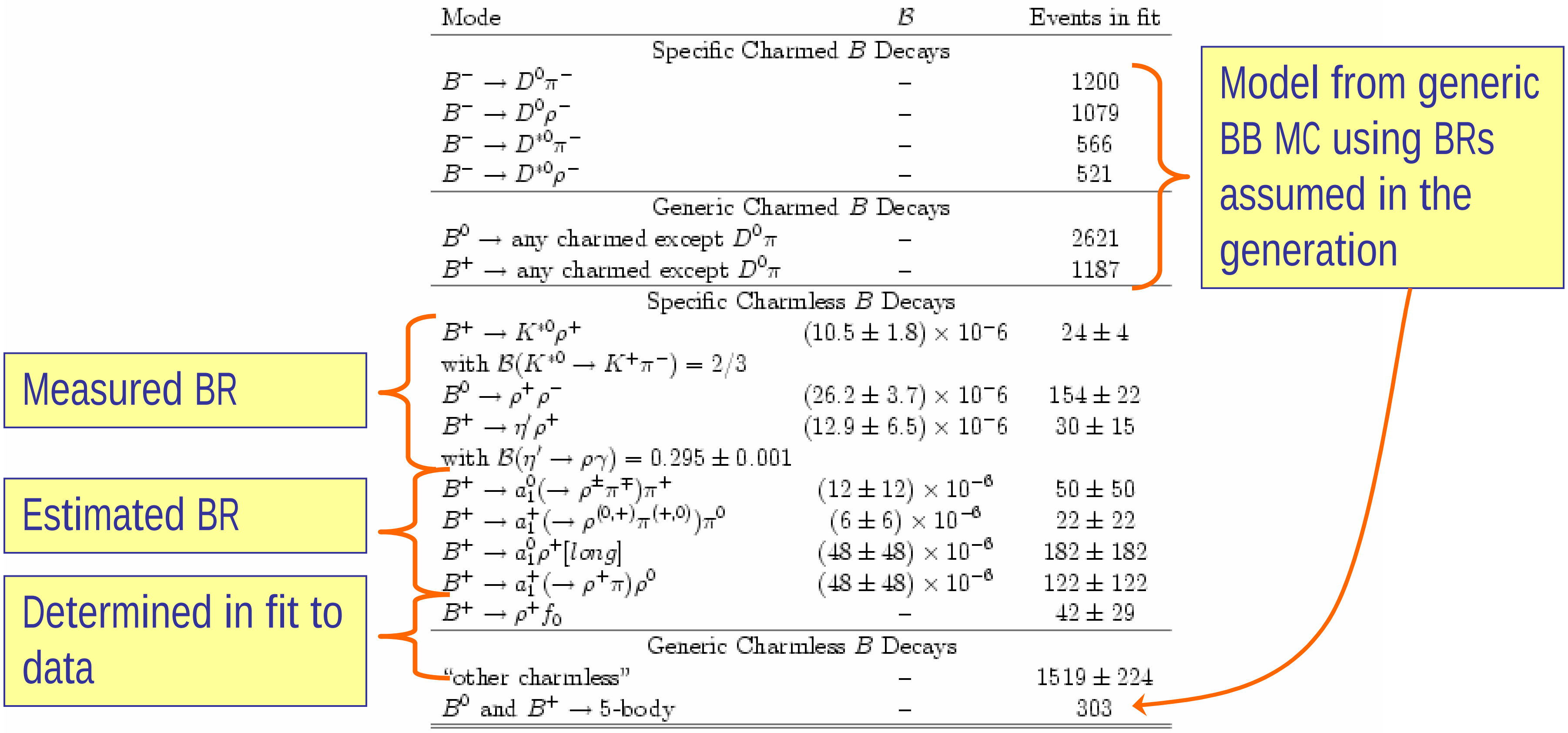
m_{ES} cut was tightened to expedite the fitting process

Multiple B Candidates: select event with reconstructed π⁰ mass closest to PDG π⁰ mass

TOTAL EFF'S	Signal (Lg)	Signal (Tr)	SxF (Lg)	SxF (Tr)	Data (Off-res)
	8.4%	18.6%	4.6%	3.0%	0.03%

B-Backgrounds

- Most peaking backgrounds are suppressed by the D-veto
- 16 B-Backgrounds are modeled in the fit
- All KEYS PDFs



Mode	$\mathcal{B}$	Events in fit
Specific Charmed B Decays		
$B^- \to D^0\pi^-$	–	1200
$B^- \to D^0\rho^-$	–	1079
$B^- \to D^{*0}\pi^-$	–	566
$B^- \to D^{*0}\rho^-$	–	521
Generic Charmed B Decays		
$B^0 \to$ any charmed except $D^0\pi$	–	2621
$B^+ \to$ any charmed except $D^0\pi$	–	1187
Specific Charmless B Decays		
$B^+ \to K^{*0}\rho^+$	$(10.5 \pm 1.8) \times 10^{-6}$	24 ± 4
with $\mathcal{B}(K^{*0} \to K^+\pi^-) = 2/3$		
$B^0 \to \rho^+\rho^-$	$(26.2 \pm 3.7) \times 10^{-6}$	154 ± 22
$B^+ \to \eta'\rho^+$	$(12.9 \pm 6.5) \times 10^{-6}$	30 ± 15
with $\mathcal{B}(\eta' \to \rho\gamma) = 0.295 \pm 0.001$		
$B^+ \to a_1^0(\to \rho^\pm\pi^\mp)\pi^+$	$(12 \pm 12) \times 10^{-6}$	50 ± 50
$B^+ \to a_1^+(\to \rho^{(0,+)}\pi^{(+,0)})\pi^0$	$(6 \pm 6) \times 10^{-6}$	22 ± 22
$B^+ \to a_1^0\rho^+[long]$	$(48 \pm 48) \times 10^{-6}$	182 ± 182
$B^+ \to a_1^+(\to \rho^+\pi)\rho^0$	$(48 \pm 48) \times 10^{-6}$	122 ± 122
$B^+ \to \rho^+ f_0$	–	42 ± 29
Generic Charmless B Decays		
"other charmless"	–	1519 ± 224
B^0 and $B^+ \to$ 5-body	–	303

Model from generic BB MC using BRs assumed in the generation

Measured BR

Estimated BR

Determined in fit to data

Signal & qq Continuum Model

KEYS = non-parametric PDF

G = Gaussian

BG = Bifurcated Gaussian

Pn = n^{th} order polynomial

PDF parametrizations:

Variable	Signal	qq Continuum
m_{ES}	KEYS	Argus
ΔE	G+G	P2
x_{NN}	KEYS	G+BG
$\cos\theta_{\rho+}$	P6	2D Model
$\lvert\cos\theta_{\rho 0}\rvert$	P6+G	
$m_{\rho+}$	G+G+G	
$m_{\rho 0}$	G+G+G	