International Europhysics Conference on High Energy Physics, 2007

Charmless Hadronic B Decays at *BABAR*

— July 20 —

J. P. Burke

UNIVERSITY OF LIVERPOOL

for the *BABAR* collaboration

Outline of talk

- Quick intro to charmless hadronic B decays, overview of *BABAR* detector, common analysis techniques
- Preliminary *BABAR* results:
  - New *previously unmeasured ($K^+K^-\pi^+$)/unstudied (the rest)*:

$B^+ \to K^+K^-\pi^+$ *Even number of kaons in final state*

$B^+ \to a_1(1260)\pi$ *$B \to AP$, rather than well covered $B \to PP, VP$*

$B \to b_1(1235)h^+$ *Also $B \to AP$, G-parity suppression*

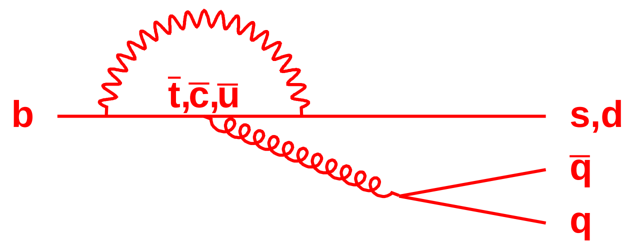
$B^+ \to \eta_X K^+$ *Possible η, η' excitations, no definitive theory*

  - Updated:

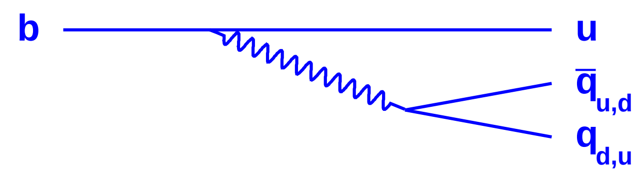
$B \to K\pi^0, \pi\pi^0$ *$B \to K\pi$ excellent probe for new physics*

$B \to h_1 h_2 (h_1 = \eta, \eta', \omega; h_2 = K^+, \pi^+, K^0)$, followed by summary

General overview of charmless hadronic B decays



often $\gtrsim$



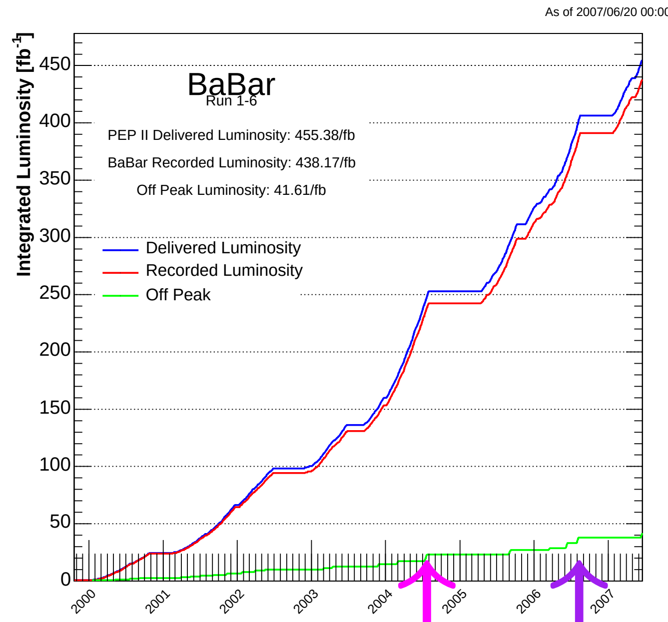
Penguin | CKM-suppressed tree

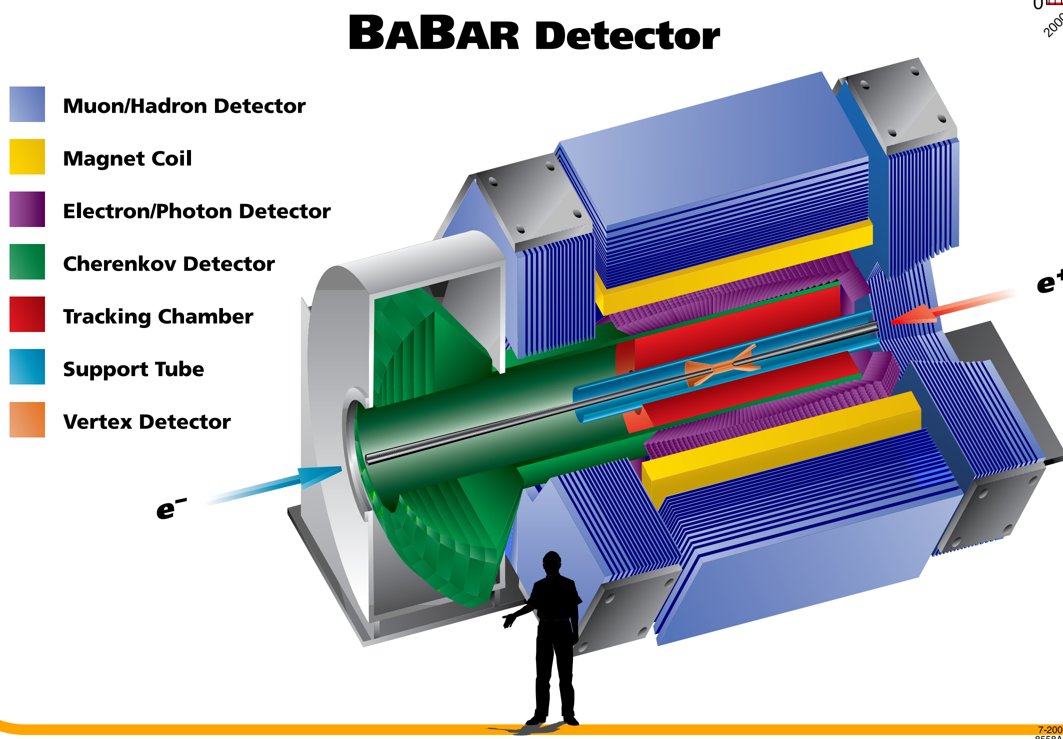
- Interfering SM amplitudes ... good place to look for direct CPV—see Nicolas Arnaud's talk
- Ideal environments to study loop processes (where new physics may enter)
- Extract CKM parameters—see talks by Mark Allen, Josh Thompson, Emmanuel Latour (c.f. $b \to c$ results to constrain NP)
- Use measured rates phenomenologically to test/develop theoretical models (factorization, pQCD, SU(3) flavour symmetry, ...)

The experiment

PEP-II collider: $9\,\mathrm{GeV}\ e^-$, $3.1\,\mathrm{GeV}\ e^+$,

data taking commenced 1999





$\approx 232 \times 10^6\ B\overline{B}$ pairs

$(B^+ \to a_1(1260)\pi,$

$B^+ \to \overline{K}^{*0} K^+)$

$\approx 383 \times 10^6\ B\overline{B}$ pairs

(the rest)

Common analysis strategy

- Aim is to isolate very small signal from vast backgrounds
- Main background due to continuum events, $e^+e^- \to d\bar{d}, u\bar{u}, s\bar{s}, c\bar{c}$
- (# signal events):(# continuum events) enhanced using
  - Particle ID systems
  - Cutting on discriminating event variables
- Discriminating variables include
  - Kinematic: m_{ES}, ΔE—use beam and decay products' $(E, \vec{p})$
  - Event shape: B events isotropic, continuum events jet-like
  - Combine in Fisher discriminants, $\mathcal{F}$, and neural networks, $\mathcal{N}$
  - Resonance: invariant mass, helicity angle (related to spin)
- Signal parameters extracted using maximum likelihood (ML)
- Must also treat background from B events

$B^+ \to K^+K^-\pi^+$—*preliminary*

- Heavily suppressed $B^+ \to \overline{K}^{*0}K^+$ expected to occur via $b \to d$ penguin, no tree
- Search conducted with no significant signal observed:

$$\boxed{\begin{array}{l}\mathcal{B}(B^+ \to \overline{K}^{*0}(892)K^+) < 1.1 \times 10^{-6\ \dagger} \\ \mathcal{B}(B^+ \to \overline{K}^{*0}_0(1430)K^+) < 2.2 \times 10^{-6}\end{array}}$$

90% CL

arXiv:0706.1059 [hep-ex]

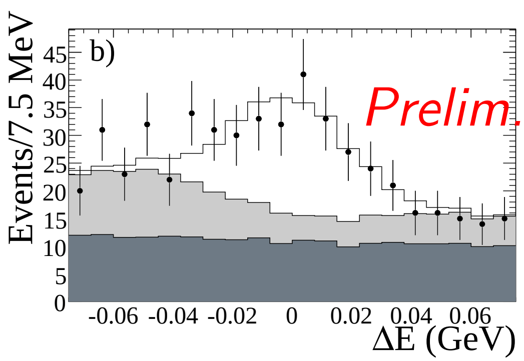
... in agreement with pQCDF and SU(3) predictions

†: assists in bounding $|\sin 2\beta(B^0 \to J/\psi\, K^0_S) - \sin 2\beta_{eff}(B^0 \to \phi K^0_S)| < 0.11$ (in SM)

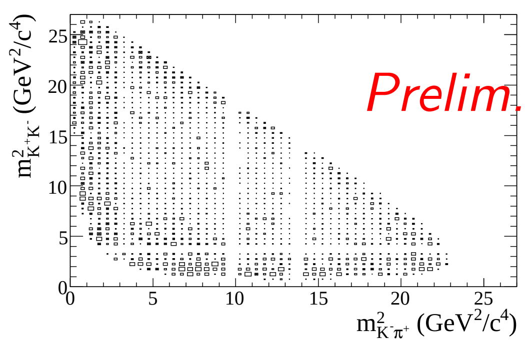
- $\mathcal{B}(B^+ \to \phi\pi^+) < 2.4 \times 10^{-7}$ (also $b \to d$ penguin, need *three* gluons or Z^0/γ from loop) arXiv:hep-ex/0605037
- Other (known, charmless) possible contributions to Dalitz plot include f_0's and non-resonant ... not expected to be very large
- Enough for a significant signal in the inclusive decay? ...

$B^+ \to K^+K^-\pi^+$—*preliminary*

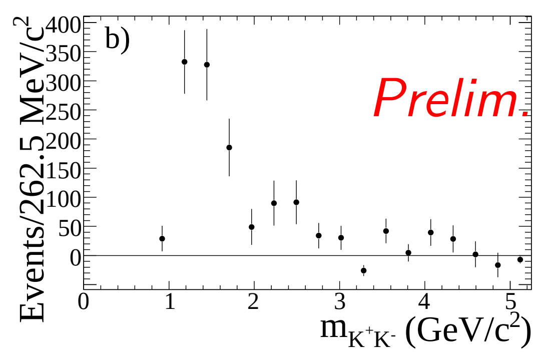
- ML technique applied to full Dalitz plot using m_{ES}, ΔE, $\mathcal{N}$
- Good sized (429 events) signal observed:
  $\boxed{\mathcal{B}(B^+ \to K^+K^-\pi^+) = (5.0 \pm 0.5 \pm 0.5) \times 10^{-6}}$ 9.6σ
- Dominated by broad structure in K^+K^- spectrum $\sim 1.5\,\mathrm{GeV}/c^2$
- Similar structure seen in DP analyses of $B^+ \to K^+K^-K^+$, $B^0 \to K^+K^-K^0$ (not in $K^\pm K^0$ spectrum, not in D decays)—dubbed $X_0(1550)$ by *BABAR*, $f_X(1500)$ by Belle



ΔE proj. plot



DP $_s\mathcal{P}lot$



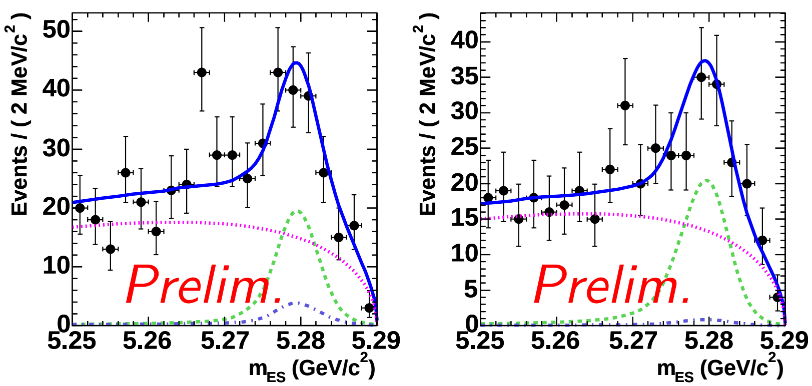
$m_{K^+K^-}$ $_s\mathcal{P}lot$

$B^+ \to a_1(1260)\pi$—*preliminary*

- First evidence of $B^+ \to a_1^+(1260)\pi^0$ and $B^+ \to a_1^0(1260)\pi^+$ ($b \to u\bar{u}d$ tree + penguin), final state $\pi^+\pi^-\pi^+\pi^0$
- ML using m_{ES}, ΔE, $\mathcal{F}$, invariant mass of reconstructed a_1, helicity angle; results consistent with factorization predictions
- With $\mathcal{B}(a_1^+(1260) \to 3\pi^\pm) = \frac{1}{2}$, $\mathcal{B}(a_1^0(1260) \to \pi^+\pi^-\pi^0) = 1$:

$$\mathcal{B}(B^+ \to a_1^+(1260)\pi^0) = (26.4 \pm 5.4 \pm 4.1) \times 10^{-6} \quad 4.2\sigma$$

$$\mathcal{B}(B^+ \to a_1^0(1260)\pi^+) = (20.4 \pm 4.7 \pm 3.4) \times 10^{-6} \quad 3.8\sigma$$



$\longleftarrow$ Projection plots of m_{ES} (likelihood cut applied)

- Helpful for measurement of UT angle α from $\rho\pi$

$B \to b_1(1235)h^+$—*preliminary*

- Recent searches of $B \to A\pi$ have revealed rather large $\mathcal{B}$'s, e.g. $\mathcal{B}(B^0 \to a_1^\pm(1260)\pi^\mp) = (33.2 \pm 3.8 \pm 3.0) \times 10^{-6}$ PRL 97, 051802, and $B^+ \to a_1(1260)\pi$ as shown on previous slide
- Two types of axial-vector mesons, A:
  - a_1 is the $I^G = 1^-$ member of the $J^{PC} = 1^{++}$ $^3P_1$ nonet ($\uparrow\uparrow$)
  - b_1 is the $I^G = 1^+$ member of the $J^{PC} = 1^{+-}$ $^1P_1$ nonet ($\uparrow\downarrow$)
- K_{1A} (K_{1B}) member of $^3P_1$ ($^1P_1$) nonet, K_{1A} and K_{1B} mix to give physical $K_1(1270)$ and $K_1(1400)$
- Mixing angle θ known (within a few $^\circ$'s) up to twofold ambiguity symmetric about $\frac{\pi}{4}$ (32° and 58°)
- From naïve factorization (for non-G-parity-suppressed modes)
  - hep-ph/0602243 v4: $\mathcal{B}(B \to b_1 h^+) \approx 4 - 30 \times 10^{-6}$ with $\theta = 32^\circ$, $\mathcal{B}(B \to b_1 h^+) \approx 4 - 20 \times 10^{-7}$ with $\theta = 58^\circ$
  - arXiv:0705.1181 [hep-ph]: $\mathcal{B}_{32^\circ}(B \to b_1 h^+) \approx 18 - 36 \times 10^{-6}$

$B \to b_1(1235)h^+$—*preliminary*

- $b \to u\bar{u}q_d$ $(q_d = d, s)$ tree (K Cabibbo suppressed wrt π) + penguin (π suppressed wrt K)
- b_1 reco'd as $b_1 \to \omega(\to \pi^+\pi^-\pi^0(\to \gamma\gamma))\pi$
- ML: m_{ES}, ΔE, $\mathcal{F}$, invariant masses of reconstructed b_1 and ω
- First observations of $B \to b_1(1235)h^+$ decays:

$\mathcal{B}(B^+ \to b_1^0(1235)\pi^+) = (6.6 \pm 1.7 \pm 1.0) \times 10^{-6}$	4.0σ	$b\pi \Rightarrow \theta$
$\mathcal{B}(B^+ \to b_1^0(1235)K^+) = (8.8 \pm 1.7 \pm 1.0) \times 10^{-6}$	5.3σ	$= 32°$;
$\mathcal{B}(B^0 \to b_1^\mp(1235)\pi^\pm) = (10.9 \pm 1.2 \pm 0.9) \times 10^{-6}$ †	8.9σ	$\ldots$ bK in
$\mathcal{B}(B^0 \to b_1^-(1235)K^+) = (7.4 \pm 1.0 \pm 1.0) \times 10^{-6}$	6.1σ	between

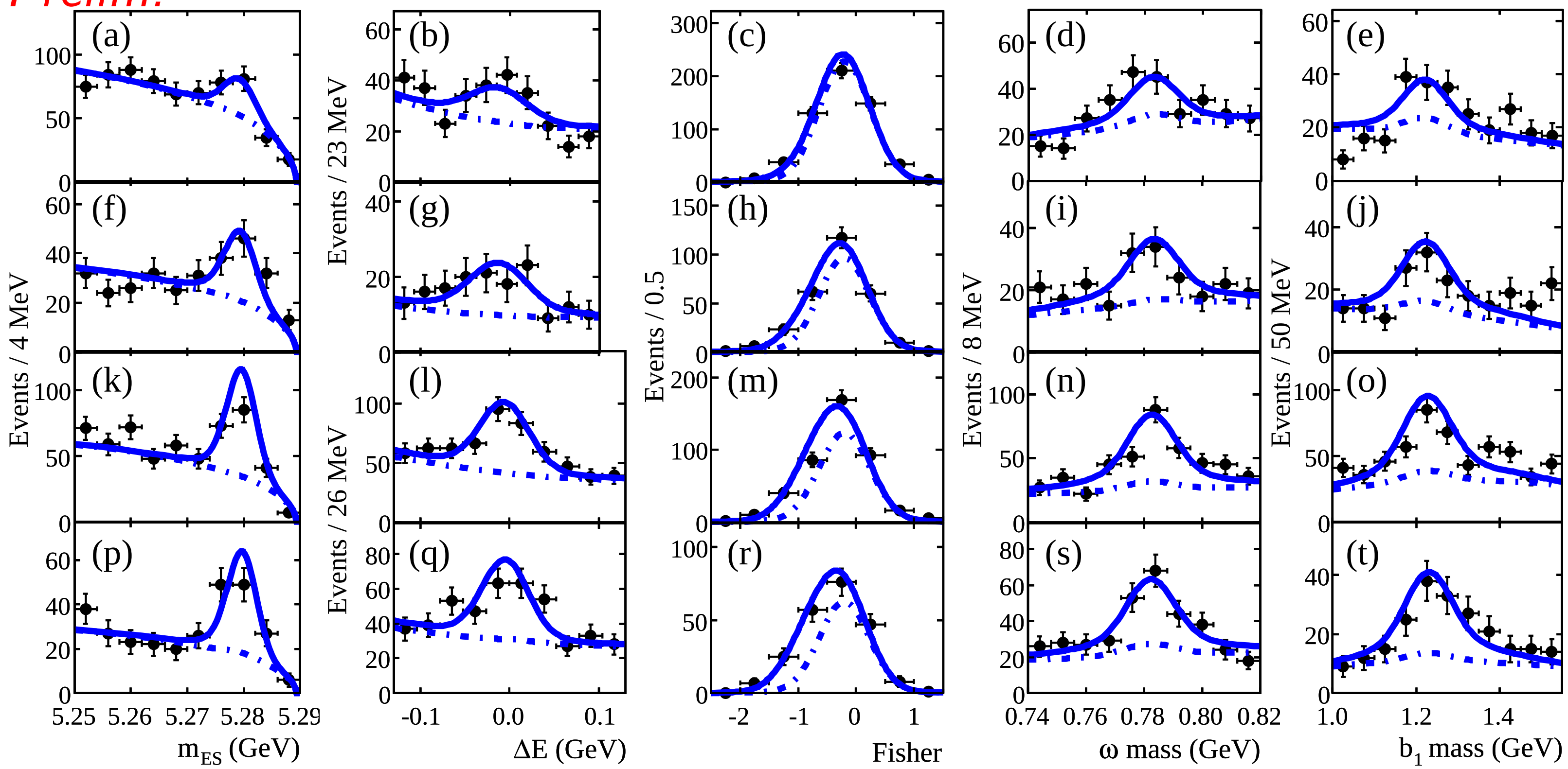
†: Asymmetry measurement: $b_1^+\pi^-$ heavily suppressed ($(0 \pm 10)\%$) wrt $b_1^-\pi^+$—follows (in SM) from b_1 decay const. ~ 0 (a prediction of G-parity suppression)

Best agreement: hep-ph/0602243 ($32°$), but b_1K $\mathcal{B}$'s smaller than predicted

$B \to b_1(1235)h^+$—*preliminary*

Top row: $B^+ \to b_1^0(1235)\pi^+$; second row: $B^+ \to b_1^0(1235)K^+$;

Prelim.



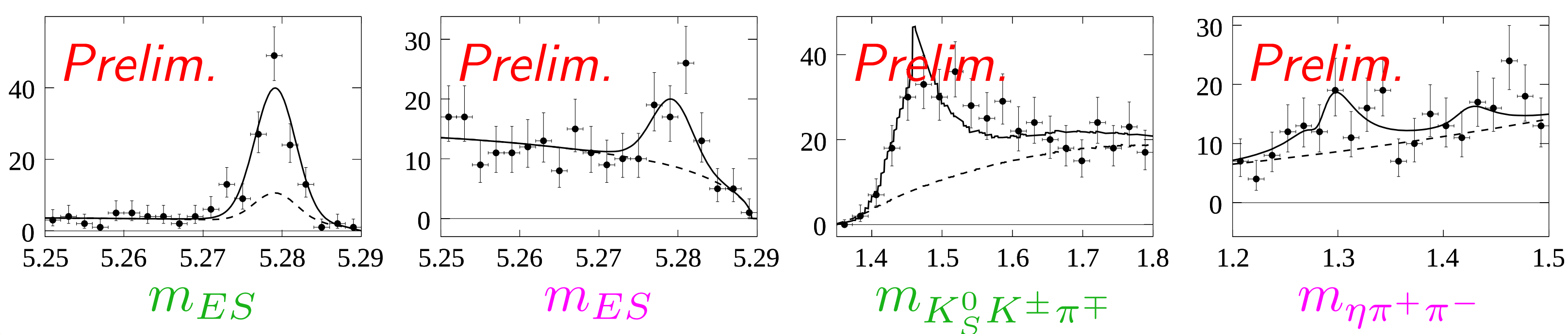
third row: $B^0 \to b_1^{\mp}(1235)\pi^{\pm}$; bottom row: $B^0 \to b_1^-(1235)K^+$

$B^+ \to (\eta_X)_{1.2-1.8\,\mathrm{GeV}/c^2} K^+$—*preliminary*

- B decays to a kaon and excited states of η, η' ($b \to s$ penguin)
- Cands. for such excited $J^P = 0^-$ states $\eta(1295)$, $\eta(1405)$, $\eta(1475)$
- Dynamics of these quasi-2-body decays is a difficult theoretical problem . . . why is $\mathcal{B}(B^+ \to \eta' K^+)$ so large?
- Explanation thought to be in SM, but large uncertainties (higher-order corrections/charming-penguin contributions to factorization, SCET, exotic gluonium states . . . ?)
- η_X's reco'd through decays to $K^0_S K^\pm \pi^\mp$ (via $K^* \overline{K}$) and $\eta\pi^+\pi^-$ in invariant mass ranges $1.2 - 1.8$, $1.2 - 1.5\,\mathrm{GeV}/c^2$
- Spectra here not well known J. Phys. G33, 1 (July 2006)—p591
- $f_1(1285)$ and $f_1(1420)$ ($J^P = 1^+$), and $\phi(1680)$ ($J^P = 1^-$), also found in these spectra—these states are also considered

$B^+ \to (\eta_X)_{1.2-1.8\,\mathrm{GeV}/c^2} K^+$—*preliminary*

- Two ML fits to m_{ES}, ΔE, $\mathcal{F}$, invariant η_X mass, helicity angle
- First fit simultaneously extracts $\mathcal{B}$'s for $B^+ \to \eta_X(\to K^0_S K^\pm \pi^\mp) K^+$, where $\boxed{\eta_X = \eta(1405), f_1(1420), \eta(1475), \phi(1680)}$
- Second fit simultaneously extracts $\mathcal{B}$'s for $B^+ \to \eta_X(\to \eta\pi^+\pi^-) K^+$, where $\boxed{\eta_X = f_1(1285), \eta(1295), \eta(1405), f_1(1420)}$
- m_{ES}, ΔE and $\mathcal{F}$ discriminate signal versus background
- Invariant η_X mass and helicity angle discriminate between signal hypotheses (different masses, widths, spins)



$B^+ \to (\eta_X)_{1.2-1.8\,\mathrm{GeV}/c^2} K^+$—*preliminary*

$\mathcal{B}(\eta_X \to K^* \overline{K})\times$

$\mathcal{B}(B^+ \to \eta(1475)K^+) = (13.8 \pm 1.8 \pm 1.0) \times 10^{-6}$ †	7.5σ †
$\mathcal{B}(B^+ \to \eta(1405)K^+) < 1.2 \times 10^{-6}$	90% CL
$\mathcal{B}(B^+ \to f_1(1420)K^+) < 4.1 \times 10^{-6}$	90% CL
$\mathcal{B}(B^+ \to \phi(1680)K^+) < 3.4 \times 10^{-6}$	90% CL

†: $\boxed{\text{only if}}$ only S-wave contributions are signal, phase-space $K^* K K$

$\mathcal{B}(\eta_X \to \eta\pi\pi)\times$

$\mathcal{B}(B^+ \to \eta(1295)K^+) = (2.9 \pm 0.8 \pm 0.2) \times 10^{-6}$	3.5σ
$\mathcal{B}(B^+ \to \eta(1405)K^+) < 1.3 \times 10^{-6}$	90% CL
$\mathcal{B}(B^+ \to f_1(1285)K^+) < 0.8 \times 10^{-6}$	90% CL
$\mathcal{B}(B^+ \to f_1(1420)K^+) < 2.9 \times 10^{-6}$	90% CL

- Same mechanism at work as for $B^+ \to \eta' K^+$?

Updated measurements—preliminary

- $B^0 \to K^0\pi^0$ $\mathcal{B}$ updated: $\underline{(10.34 \pm 0.66 \pm 0.58) \times 10^{-6}}$
  - $K^0 \to K^0_S$ used for updated time-dependent CP asymmetry measurements, including $\sin 2\beta_{eff}$—see Josh Thompson's talk
- $B \to h\pi^0$ $\mathcal{B}$'s updated—these modes can be used to constrain α, see Mark Allen's talk
  - $\mathcal{B}(B^0 \to \pi^0\pi^0) = \underline{(1.47 \pm 0.25 \pm 0.12) \times 10^{-6}}$
  - $\mathcal{B}(B^+ \to \pi^+\pi^0) = \underline{(5.02 \pm 0.46 \pm 0.29) \times 10^{-6}}$
  - $\mathcal{B}(B^+ \to K^+\pi^0) = \underline{(13.6 \pm 0.6 \pm 0.7) \times 10^{-6}}$

Lipkin ratio consistent with 1:

$$R_L = \frac{2\Gamma(B^+ \to K^+\pi^0) + 2\Gamma(B^0 \to K^0\pi^0)}{\Gamma(B^+ \to K^0\pi^+) + \Gamma(B^0 \to K^+\pi^-)} = 1 + \mathcal{O}\left(\frac{P_{EW} + T}{P}\right)^2 = \boxed{1.11 \pm 0.07}$$

Updated measurements

- $B \to h_1 h_2$ ($h_1 = \eta, \eta', \omega$; $h_2 = K^+, \pi^+, K^0$):

$$\begin{aligned}
\mathcal{B}(B^+ \to \eta\pi^+) &= (5.0 \pm 0.5 \pm 0.3) \times 10^{-6} \\
\mathcal{B}(B^+ \to \eta K^+) &= (3.7 \pm 0.4 \pm 0.1) \times 10^{-6} \\
\mathcal{B}(B^+ \to \eta'\pi^+) &= (3.9 \pm 0.7 \pm 0.3) \times 10^{-6} \\
\mathcal{B}(B^+ \to \eta' K^+) &= (70.0 \pm 1.5 \pm 2.8) \times 10^{-6} \\
\mathcal{B}(B^0 \to \eta' K^0) &= (66.6 \pm 2.6 \pm 2.8) \times 10^{-6} \\
\mathcal{B}(B^+ \to \omega\pi^+) &= (6.7 \pm 0.5 \pm 0.4) \times 10^{-6} \\
\mathcal{B}(B^+ \to \omega K^+) &= (6.3 \pm 0.5 \pm 0.3) \times 10^{-6} \\
\mathcal{B}(B^0 \to \omega K^0) &= (5.6 \pm 0.8 \pm 0.3) \times 10^{-6}
\end{aligned}$$

- See Nicolas Arnaud's talk for asymmetry measurements

- Further charmless results presented by Silvano Tosi: $B \to p\bar{p}h$, $B \to \phi K^*$

Summary

- $B^+ \to K^+K^-\pi^+$: first observation of charmless 3-body B meson decay to final state with even number of kaons
- $B \to Ah$ (A = axial-vector mesons b_1, a_1; $h = K$, π): first observation of three modes, evidence of a further three modes
- First observation of G-parity suppression in B decays ($B^0 \to b_1^+(1235)\,\pi^-$)
- Excess of events that could be $B^+ \to \eta(1475)K^+$, $B^+ \to \eta(1295)$ K^+ ... are these η, η' excitations?
- Value of Lipkin ratio updated
- Several previous results updated with greater precision
- New/improved limits placed on numerous modes

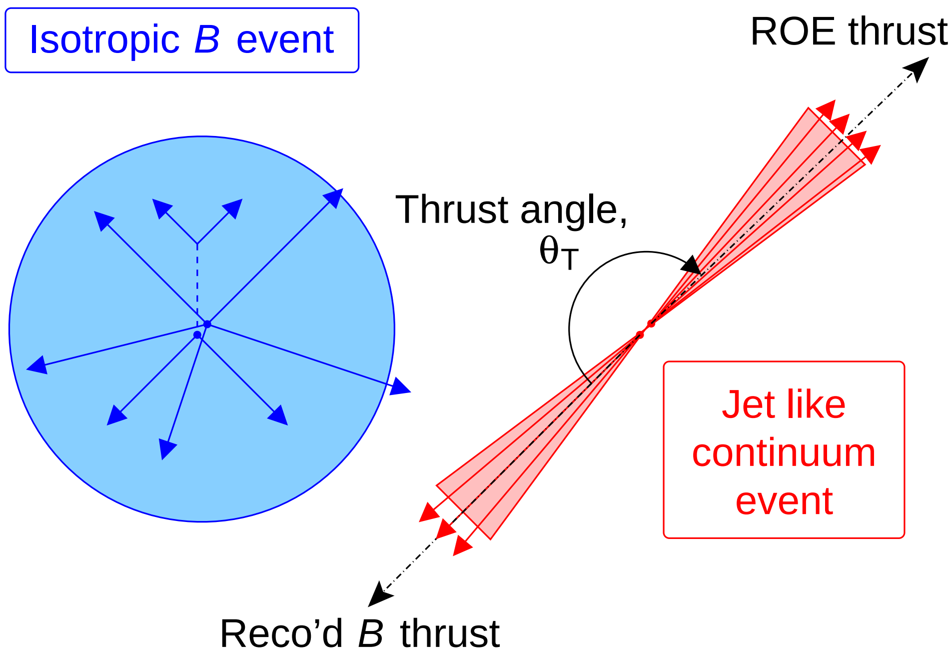
Backup slides . . .

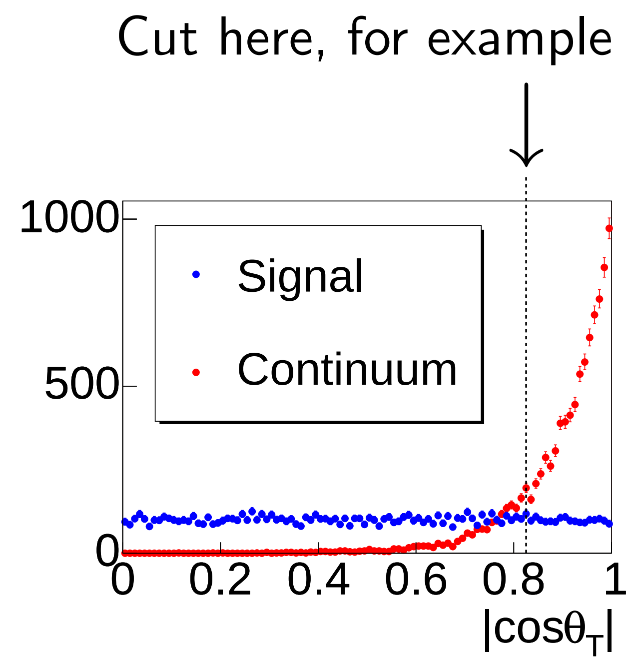
Reminder of some winter conference results

- $\mathcal{B}(B^+ \to \rho^+ K^0) = \underline{(8.0 \pm 1.4 \pm 0.6) \times 10^{-6}}$ 7.9σ
  - First observation of this pure penguin mode hep-ex/0702043— useful for determining UT angle γ using U-spin and charmless $B^+ \to M^+ M^0$ decays Phys. Lett. B635, 330
- $\mathcal{B}(B^0 \to K_1^+(1270)\pi^-) = \underline{(12.0 \pm 3.1 \pm 9.3)[< 25.2] \times 10^{-6}}$ 2.3σ
  $\mathcal{B}(B^0 \to K_1^+(1400)\pi^-) = \underline{(16.7 \pm 2.6 \pm 5.0)[< 21.8] \times 10^{-6}}$ 3.0σ
  - Needed to pin down penguin amplitudes in order to extract α from $B^0 \to a_1^\pm(1260)\pi^\mp$

Topological variables

- $B\overline{B}$ pairs produced almost at rest in CM frame; $q\overline{q}$ pairs from continuum have considerable KE



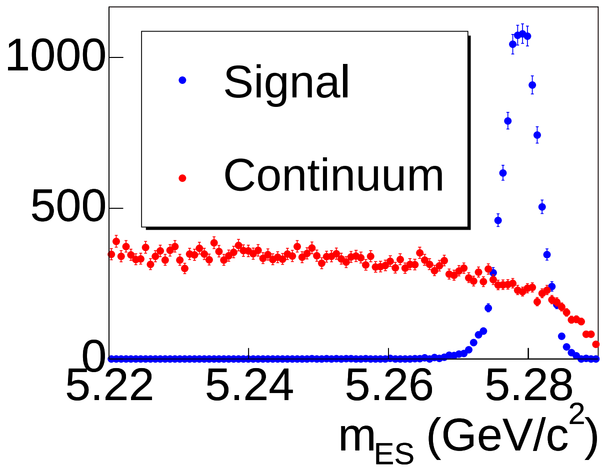


- Can combine variables in Fisher discriminants, $\mathcal{F}$, and neural networks, $\mathcal{N}$

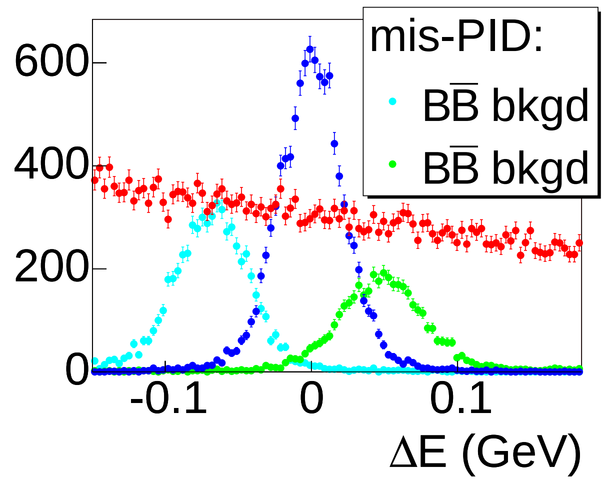
Kinematic variables

- Want to optimise resolution, take full advantage of available info, minimise correlations, allow for asymmetric nature of collider:

$$m_{ES} = \sqrt{E^{*2}_{beam} - \vec{p}^{\,*2}_{B}}$$



$$\Delta E = E^*_B - E^*_{beam}$$

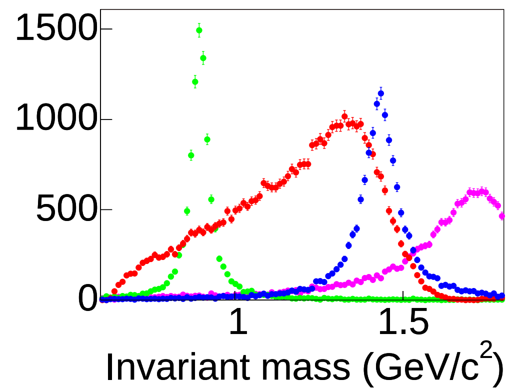


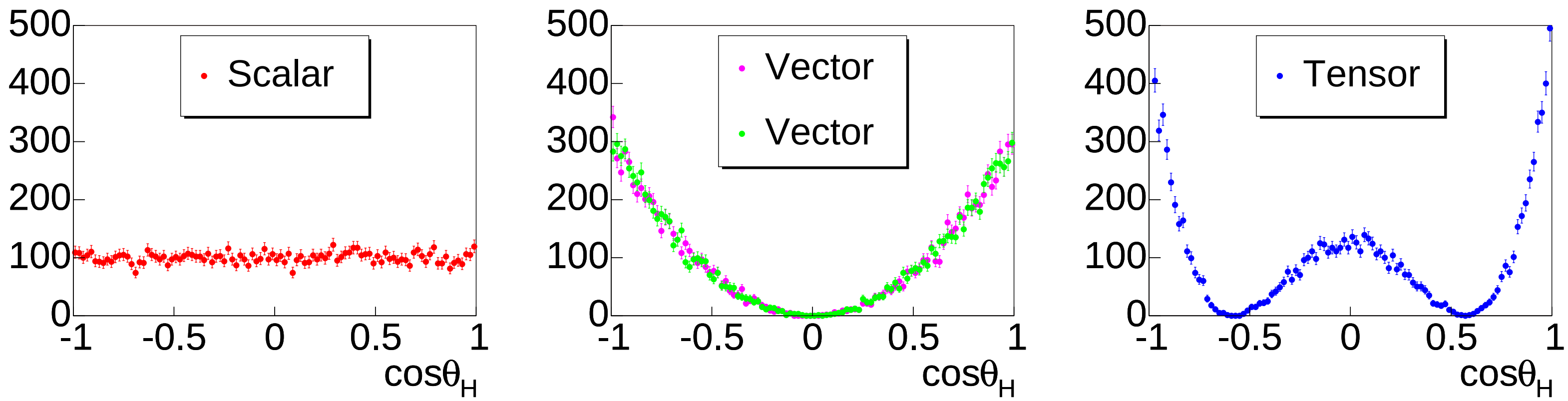
- E^*_{beam} is expected energy of reco'd candidate using beam's *4-momentum* and detected decay products' *3-momenta* (in lab)

- ΔE has inferior resolution but since uses detected decay products' mass hypotheses is sensitive to particle mis-ID

Resonance variables

- For decays via intermediate state(s) can utilise resonance invariant mass and helicity angle, θ_H





- Definition of θ_H depends on # of resonance daughters
- E.g., for two daughters, it's the polar angle in the resonance's rest frame of one of its daughters where the polar axis is anti-parallel to the receding B frame

The maximum likelihood (ML) method

- Probability density functions (PDFs), with parameters $\vec{\theta}$, are used to describe distributions of event variables $\vec{x}$ (e.g. m_{ES}, ΔE, $\mathcal{F}$, $\ldots$) for various species (e.g. signal, continuum background)
- ML technique used to determine values of $\vec{\theta}$ that maximise the probability of obtaining the observed measurements according to the pre-determined PDF forms (e.g. Gaussian)
- For the *extended* ML, the values of $\vec{n}$ are also extracted where $\vec{n}$ are the yields for each of our species
- The probability to maximise is given by the extended likelihood function . . .

The extended likelihood function

- The normal likelihood is the product of the PDFs for each individual candidate i (of which there are N), $\prod P(\vec{x}_i;\vec{\theta})$
- The extended likelihood function is given by $\mathcal{L}(\vec{n},\vec{\theta}) =$ Poisson factor $\times$ normal likelihood function
- Omitting constants the function to maximise is

$$\mathcal{L}'(\vec{n},\vec{\theta}) = \exp\left(-\sum_{k=1}^{M} n_k\right)\prod_{i=1}^{N}\left(\sum_{j=1}^{M} n_j \left(\prod_{l=1}^{V}\mathcal{P}_j^l(x_i^l;\vec{\theta})\right)\right)$$

- The PDF $P(\vec{x}_i;\vec{\theta})$, for a given measurement i, is the sum of the PDFs for each hypothesis (of which there are M)
- The PDF for each hypothesis, $\mathcal{P}_j$, is the product of the individual PDFs, $\mathcal{P}^l$, for each of the V discriminating event variables (assuming negligible correlation, which must be shown)

${}_s\mathcal{P}lots$

- Used to reconstruct a variable distribution for a particular species (e.g. signal) from the PDFs of other (fit) variables, $\mathcal{P}$
- sWeight for species of interest assigned to each event:

$$\frac{\sum_{j=1}^{N_S} \mathbf{V}_{nj}\mathcal{P}_j}{\sum_{k=1}^{N_S} N_k\mathcal{P}_k}$$

- N_S is # of species, $\mathbf{V}$ is the covariant matrix from the fit, N_k is the yield for species k returned from the fit, subscript n refers to the species of interest
- Summing the sWeights over all events gives the species yield
- Bin each sWeighted event to reproduce (e.g. signal) distribution —i.e. signal ${}_s\mathcal{P}lot$—of that variable (weight only the variable that we're ${}_s\mathcal{P}lot$ting)

Dalitz plot analyses

- Note, *amplitude*-level Dalitz plot analyses are beginning to dominate charmless 3-body decays as datasets $\uparrow$ (but none here!) (see Josh Thompson's presentation for a discussion of the $B^0 \to K^+K^-K^0$ DP analysis)
- Structure in the DP gives info on resonance masses, widths, spins, relative phases, interference
- Model each contribution to the DP as a separate amplitude with a complex coefficient (*isobar* model)