Hadronic Physics at $BABAR$

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Traditionally, main focus of Babar measurements is the electroweak sector:

- “Standard Model” CP violation in B mesons;
- angles and sides of the Unitarity Triangle

But the huge amount of data recorded ($\int \mathcal{L} \, dt = 477 \text{ fb}^{-1}$) allows a wealth of measurements related to hadronic physics:

- quark masses, form factors in hadronic, semileptonic and radiative $B$ and $D_{(s)}$ decays;
- spectroscopy of charm mesons, quarkonium, light mesons, charmed baryons;
- search for exotics;
- cross sections, form factors, vacuum polarization from $e^+e^- \rightarrow \text{hadrons}$
Outline

- Selection of a few recent results with broad range of involved hadronic models/parameters and very different experimental techniques:
  - hadronic $B$ decays (to charmless or charmonium states);
  - hadron production in $e^+e^-$ annihilation;
  - $D$ meson mixing;
  - charmed baryon properties

- Many more details (and more results) in the 13 parallel talks and in the “new states” plenary talk
Amplitude analysis of $B^\pm \rightarrow \phi K^{*\pm}$

- In Standard Model occurs through $b \rightarrow s$ penguin
- Three amplitudes contribute, corresponding to helicity $\lambda = -1, 0, +1$ of the vector mesons:

$$d^3\Gamma / d \cos \theta_1 d \cos \theta_2 d\Phi \propto \left| \sum_{\lambda=-1,0,+1} A_\lambda Y_1^\lambda (\theta_1, \Phi) Y_1^{-\lambda} (\pi - \theta_2, 0) \right|^2$$

- Weak interaction $V-A$ structure, helicity conservation in strong interactions, $s$-quark spin flip suppression in penguin decays
  \[ |A_0| \gg |A_+| \gg |A_-| \quad (A_\pm \equiv (A_\parallel \pm A_\perp) / \sqrt{2}) \]

- Models have been proposed which violate this:
  - within the SM: annihilation mechanism (Phys. Lett. B 601, 151), QCD rescattering (Phys. Rev. D 70, 054015);
  - New Physics: scalar interaction, SuSy particles in loop
Amplitude analysis of $B^\pm \to \phi K^{*\pm}$

- Both $K^*(892)^\pm \to K_S \pi^\pm$ and $K^*(892)^\pm \to K^\pm \pi^0$ are reconstructed
- 12 polarization-related quantities measured, including 6 $CP$-violating parameters:
  - $\mathcal{B}(B^\pm \to \phi K^{*\pm}) = (11.2 \pm 1.0 \pm 0.9) \times 10^{-6}$
  - $f_L \equiv |A_0|^2 / \Sigma |A_\lambda|^2 = 0.49 \pm 0.05 \pm 0.03 \Rightarrow |A_0|^2 \approx |A_+|^2 + |A_-|^2$
  - $f_\perp \equiv |A_\perp|^2 / \Sigma |A_\lambda|^2 = 0.21 \pm 0.05 \pm 0.03$
  - $\phi_\parallel - \pi \equiv \arg(A_||/A_0) - \pi = (-0.67 \pm 0.20 \pm 0.07) \text{ rad}$
  - $\phi_\perp - \pi \equiv \arg(A_\perp/A_0) - \pi = (-0.45 \pm 0.20 \pm 0.03) \text{ rad}$
  - no evidence of $CP$ violation
- Discrete ambiguity in the determination of $\phi_\parallel$, $\phi_\perp$:
  - $\phi_\perp \approx \phi_\parallel - \pi \Rightarrow A_\perp \approx -A_\parallel \Rightarrow |A_+|^2 << |A_-|^2$
  - $\phi_\perp \approx \phi_\parallel \Rightarrow A_\perp \approx A_\parallel \Rightarrow |A_+|^2 \gg |A_-|^2$
- The ambiguity is solved by studying interference of $S$ and $P$ waves in the $K\pi$ system: only $\phi_\perp \approx \phi_\parallel$ acceptable $\Rightarrow |A_0| \approx |A_+| >> |A_-|$

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Hadron 07 - Frascati, October 10, 2007
$B \rightarrow \eta_c \ K^*, \ \eta_c \ \gamma \ K^{(*)}$

- $B$ decays to singlet states of charmonium much less known than decays to triplet ($J/\psi$, $\psi(2S)$, $\chi_{c1}$)
- NRQCD predicts $B$ decays to $P$ states of charmonium to occur at similar rates (Phys. Rev. D 51, 125):
  - indeed $\mathcal{B}(B \rightarrow \chi_{c1} \ K) \sim \mathcal{B}(B \rightarrow \chi_{c0} \ K) \sim 10^{-4}$;
  - but $B \rightarrow \chi_{c2} \ K$, $B \rightarrow h_c \ K$ as yet unobserved: current limit $< 10^{-5}$
- Search for $B^0 \rightarrow \eta_c \ K^{*0}$, $B^0 \rightarrow h_c \ K^{*0}$, $B^\pm \rightarrow h_c \ K^\pm$,
  with $\eta_c \rightarrow K_S K^+ \pi^-$, $K^+ K^- \pi^0$ and $h_c \rightarrow \eta_c \ \gamma$:
  - $\mathcal{B}(B^0 \rightarrow \eta_c \ K^{*0}) = (6.1 \pm 0.8 \pm 1.1) \times 10^{-4}$
    (factor 2 improvement over WA);
  - no signal for $h_c$:
    $\mathcal{B}(B^\pm \rightarrow h_c \ K^{\pm}) \cdot \mathcal{B}(h_c \rightarrow \eta_c \ \gamma) < 5.2 \times 10^{-5}$ (90% C.L.)
    $\mathcal{B}(B^0 \rightarrow h_c \ K^{*0}) \cdot \mathcal{B}(h_c \rightarrow \eta_c \ \gamma) < 2.4 \times 10^{-4}$ (90% C.L.)

0707.2843 [hep-ex]
More on charmless hadronic $B$ decays in Heavy Meson Spectroscopy session:

– G. Mohanty (12/10)
Hadron production in $e^+e^-$ annihilations

- $\sigma(e^+e^- \rightarrow \text{hadrons}) \sim 3 \text{ nb}$ ($\sigma(e^+e^- \rightarrow b \bar{b}) \sim 1 \text{ nb}$) $\Rightarrow$ huge amount of data with $\mathcal{L} \sim 500 \text{ fb}^{-1}$

- Only some quantum numbers and helicity values are allowed in final state

- Non-perturbative quantities:
  - $e^+e^- \rightarrow h\bar{h}$ $\Rightarrow$ form factor;
  - $e^+e^- \rightarrow \gamma P$ $\Rightarrow$ transition form factor

- Broad $e^+e^-$ energy range available via radiative return (Initial State Radiation, or ISR):
  - invariant mass spectrum up to 4-5 GeV in the same experiment $\Rightarrow$ same conditions, same analysis tools, same systematic errors;
  - high acceptance and high transverse momentum of hadrons
Correlated baryon-antibaryon production

- Baryon production in $e^+e^-$ interactions:
  - **primary correlation**: a diquark-antidiquark pair is produced in the interaction $\Rightarrow$ the baryons resulting from hadronization share two flavors and have large rapidity gap $|\Delta y|$
  - **local correlation**: a baryon-antibaryon pair is produced “locally” in the hadronization cascade from the initial quark or antiquark $\Rightarrow$ small $|\Delta y|$

- Experimentally, $|\Delta y|$ peaks at low values $\Rightarrow$ no evidence for primary production
  - Several generators, with very different production models, are tuned to data for observed baryons and accompanying mesons distributions

- However, CLEO reported a 3.5-fold excess of events with both $\Lambda_c^+$ and $\bar{\Lambda}_c^-$ at $\sqrt{s} = 10.6$ GeV/$c^2$ with respect to expectations from local correlation
  - Given the energy and masses, the two charmed baryons must be leading hadrons from $e^+e^- \rightarrow c\bar{c}$ process
Correlated baryon-antibaryon production

- \( \Lambda_c \) reconstructed in \( \Lambda_c^+ \rightarrow p K^- \pi^+, p K_S \)
  - \( Y(4S) \) decays rejected by \( p^* > 2.3 \text{ GeV/c} \)
- \( N(\Lambda_c^+ \Lambda_c^-) = 649 \pm 31 \)
  - if production uncorrelated \( \Rightarrow \) 155 events expected
  - \( \Rightarrow \) 4.2-fold excess, consistent with CLEO

- Additional tracks:
  - low multiplicity: \( \langle N_{\text{tracks}} \rangle = 2.6 \pm 0.2 \);
  - mostly pions;
  - no evidence for \( e^+e^- \rightarrow \Lambda_c^+ \Lambda_c^- \)

- Missing mass distribution:
  - low-peaking \( \Rightarrow \) suppressed \( n\bar{n} \) production

- Four-baryon events: \( N_{4\text{-bar}} = 13 \pm 8 \)

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**Measurements with Initial State Radiation**

- Why extending measurements of hadronic cross sections at low $\sqrt{s}$?
  - hadronic contributions to $\alpha_\mu = g_\mu - 2$ and $\alpha_{\text{QED}}$ are calculated from hadronic cross section (in particular, $\alpha_\mu^\text{had}$ sensitive to $\sqrt{s} < 2$ GeV contribution);
  - form factors (e.g. proton form factors from $e^+e^- \rightarrow p\bar{p}$);
  - light meson spectroscopy;
  - charmonium and bottomonium spectroscopy.

- **Technique:**
  - detection of ISR photon can either be required or not;
  - specific identified final set of particles;
  - kinematic fits
$e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0$

- Precision measurement important for $\alpha_\mu$, $\alpha_{\text{QED}}$
  - currently 8% at peak;
  - improved accuracy over existing measurements
- Events selected requiring $\gamma_{\text{ISR}}$
- Several structures seen:
  - $\omega\pi^0$, $a_1(1260)\pi$, $\rho^+\rho^-$, $f_0(980)\rho^0$

Charmonium region:
- first measurement of
  $$B(J/\psi \rightarrow \pi^+\pi^-\pi^0\pi^0) = (5.74 \pm 0.74) \times 10^{-3}$$
**Λ form factor**

- $e^+e^- \rightarrow \Lambda \overline{\Lambda} \gamma_{\text{ISR}}$ events selected requiring $\gamma_{\text{ISR}}$
- Production cross session as function of $m(\Lambda \overline{\Lambda})$:
  \[
  \sigma_{\Lambda \overline{\Lambda}}(m) = \frac{4\pi\alpha^2}{3m^2} \left[ |G_M(m)|^2 + \frac{1}{2\tau} |G_E(m)|^2 \right] \\
  \left\{ \begin{array}{l}
  \tau = m^2 / 4m^2_{\Lambda} \\
  \beta = \sqrt{1-1/\tau}
  \end{array} \right. \\
  \frac{2\tau + 1}{2\tau} |F(m)|^2 \text{ effective form factor}
  
- Both $\Lambda$ reconstructed in $\Lambda \rightarrow p \pi^-$, with at least one proton identified
- Different angular distributions for $E$ and $M$ contributions
  - statistics too low to conclude on $|G_E|/|G_M|
- Also analyzed $e^+e^- \rightarrow \Sigma^0 \overline{\Sigma^0} \gamma_{\text{ISR}}$, $e^+e^- \rightarrow \Lambda \overline{\Sigma^0} \gamma_{\text{ISR}}$ ($\Sigma^0 \rightarrow \Lambda \gamma$)
  - limited statistic

More on $e^+e^-$ hadron production in **Light Meson Spectroscopy** session:

- **D. Muller**: quasi-two-body $e^+e^- \rightarrow X \ Y \text{ at } 10.6 \text{ GeV (12/10);}$
- **W. Wang**: inclusive and exclusive $e^+e^- \rightarrow \text{hadrons in ISR (12/10);}$
- **S. Serednyakov**: exclusive $e^+e^- \rightarrow \text{baryons or charmed mesons in ISR (12/10);}$
Contributions to $D$-mixing

- Like in the case of the $B$ meson system, initially produced $D^0$, $\bar{D}^0$ flavour eigenstates evolve in time as two $D_1$, $D_2$ mass eigenstates:
  - $|D_{1,2}\rangle = p |D^0\rangle \pm q |\bar{D}^0\rangle$;
  - $\Delta M = m_1 - m_2$; $\Delta \Gamma = \Gamma_1 - \Gamma_2$; $\Gamma = (\Gamma_1 + \Gamma_2) / 2$; $x \equiv \Delta M / \Gamma$; $y \equiv \Delta \Gamma / 2\Gamma$

- But unlike for $B$, the heaviest quark in the box loop is $b$ (instead of $t$) and vertices are strongly CKM-suppressed.

  - short distance contribution (electroweak sector): GIM cancellation, destructive interference between LO and NLO $\Rightarrow x_{SD} \sim 10^{-6}$, $y_{SD} \sim 10^{-8}$;
  - long distance contribution (QCD): real states contribute to $x$ and $y$, virtual states to $x$ only; $x$ more model-dependent, $y$ more sensitive to quark-hadron duality $\Rightarrow x_{LD} \sim y_{LD} \sim 10^{-3} - 10^{-2}$
**D-mixing results**

- At *BABAR*, the *D* sample is produced in $e^+e^- \rightarrow c \bar{c}$ events ($\sigma \sim 1.3$ nb)
  - $D^{*+} \rightarrow D^0 \pi^+$, $D^{*-} \rightarrow \bar{D}^0 \pi^-$ decays are used to tag the $D^0$ flavour

- $D \rightarrow K \pi$: fit “wrong sign” ($D^0 \rightarrow K^+ \pi^-$) decay time distribution:
  - $x' \equiv x \cos \delta_{K\pi} + y \sin \delta_{K\pi}$
  - $y' \equiv y \cos \delta_{K\pi} - x \sin \delta_{K\pi}$
  - $x'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
  - $y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$
  - $\Rightarrow 3.9 \sigma$ away from no mixing

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*PRL 98:211802, 2007*
D-mixing results

- Lifetime ratio in $D^0 \rightarrow h^+ h^-$ ($h = K, \pi$):
  - $D$-mixing affects the decay time to $CP$ eigenstates: the distributions can be fitted with effective lifetimes;
  - difference from $D^0 \rightarrow K^- \pi^+$ lifetime is evidence for $D$ mixing
  - fit distributions for all modes simultaneously
  $\Rightarrow$ 3.0 $\sigma$ away from no mixing

- Analysis of $D^0 \rightarrow K^- \pi^+ \pi^0$ Dalitz plot:
  - amplitudes extracted from time-independent Dalitz plot analysis of “right sign” sample;
  - “wrong sign” decay time distribution varies across Dalitz plot: fit with proper amplitudes and phases
  $\Rightarrow$ no mixing excluded at 99% C.L.
More on $D$ mixing in Heavy Meson Spectroscopy session:
   – R. Andreassen (9/10)
Measurement of the $\Xi(1530)^0$ spin

- From $K^-p \rightarrow \Xi(1530)^0,\pi^0,\pi^+$ data $\Rightarrow J^P(\Xi(1530)^0) = 3/2^+$ or $J^P = 5/2^-$
- $\Xi(1530)^0$ seen as resonant $\Xi^-\pi^+$ structure in $\Lambda_c^+ \rightarrow \Xi^-\pi^+K^+$ decays

Angular distribution:

$$\frac{dN}{d\cos \theta_{\Xi^-}} = N \sum_{l=0}^{l_{\text{max}}} \langle P_l \rangle P_l(\cos \theta_{\Xi^-}) , \quad l_{\text{max}} = 2J - 1$$

- In any mass interval, the number of event has contributions from relevant $l$: by weighting each event with $P_l(\cos \theta_{\Xi})$, only $P_2$ contribution survives $\Rightarrow J^P(\Xi(1530)^0) = 3/2^+$
And more…

- Heavy meson spectroscopy: quarkonium, charmed mesons and baryons:
  - A. G. Mokhtar: charmonium spectroscopy (*Quarkonia States*, 8/10);
  - V. Poireau: charm spectroscopy (*Heavy Meson Spectroscopy*, 9/10);
  - K. Mishra: charm Dalitz plot analyses (*Heavy Meson Spectroscopy*, 9/10)

- Semileptonic, leptonic and radiative penguins $B$ decays:
  - M. Mazur: semileptonic decays (*Heavy Meson Spectroscopy*, 9/10);
  - E. Salvati: leptonic decays (*Heavy Meson Spectroscopy*, 12/10);
  - M. Lu: radiative penguins decays (*Heavy Meson Spectroscopy*, 12/10);
  - K. Tackman: determination of non-perturbative parameters (*Heavy Meson Spectroscopy*, 12/10)

- Angles of the Unitarity Triangle from hadronic $B$ decays:
  - S. Emery: UT angles (*Heavy Meson Spectroscopy*, 12/10)
Back-up slides
The BABAR data sample

Maximum instantaneous luminosity:
\[ \mathcal{L}_{\text{max}} = 1.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \]

Total integrated luminosity:
\[ \int \mathcal{L} \, dt = 477 \text{ fb}^{-1} \quad (45 \text{ fb}^{-1} \text{ off-peak}) \]
Reconstruction of $B$ decays

- A $B$-\$B$ meson pair is produced in the decay of the $\Upsilon(4S)$ formed in $e^+e^-$ annihilation.
- Final products of the $B$ decays are reconstructed and identified in the detector.
- A $B$ candidate is reconstructed through a given decay chain.

- After continuum background reduction, $B$-decay events are selected by means of a pair of nearly uncorrelated variables, such as:
  \[
  m_{ES} = \sqrt{\left(\frac{s}{2} + \mathbf{p}_Y \cdot \mathbf{p}_B\right)^2 / E_Y - \mathbf{p}_B^2}
  \]
  \[
  \Delta E = \frac{(E_YE_B - \mathbf{p}_Y \cdot \mathbf{p}_B - s/2)}{\sqrt{s}}
  \]
e^{+}e^{-} \rightarrow K^{+}K^{-}\pi^{+}\pi^{-}, K^{+}K^{-}\pi^{0}\pi^{0}, K^{+}K^{-}K^{+}K^{-}

- Several intermediate states observed:
  - $K^{+}K^{-}\pi^{+}\pi^{-}$: $K^{*0}K\pi$, $\phi\pi\pi$, $\phi f_{0}(980)$;
  - $K^{+}K^{-}\pi^{0}\pi^{0}$: $K^{*\pm}K\pi^{0}$, $\phi\pi^{0}\pi^{0}$, $\phi f_{0}(980)$;
  - $K^{+}K^{-}K^{+}K^{-}$: $\phi K^{+}K^{-}$

- Search for $Y(4260) \rightarrow \phi \pi \pi$ (large rate if glueball): no evidence

- Structure in $K K \pi \pi$ consistent with new state at 2.175 GeV/c^{2}