Recent results from the BaBar experiment

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OUTLINE

Introduction
  • PEP-II and the BaBar detector at SLAC
  • B factories physics program

Mixing-induced CP violation in semileptonic B-meson decays
Amplitude analysis of $B^+ \rightarrow K_S \pi^+ \pi^0$  BABAR preliminary

New Physics in “rare” B decays
  • Branching fractions and CP violation results in $B \rightarrow X_s \gamma$
  • and $B \rightarrow X_s l^+ l^−$ decays  PRL 112, 211802 (2014)

Search for dark matter
  • Antideuteron production at BaBar  PRD 89, 111102 (2014)
  • Search of dark photon in $e^+ e^- \rightarrow \gamma A', A' \rightarrow e^+ e^-, \mu^+ \mu^-$  BABAR preliminary
  • $e^+ e^- \rightarrow \text{hadrons and } (g-2)_\mu$  @ BABAR
  • $e^+ e^- \rightarrow K_S K_L, e^+ e^- \rightarrow K_S K_S \pi^+ \pi^-, e^+ e^- \rightarrow K_S K_L \pi^+ \pi^-$, and $e^+ e^- \rightarrow K_S K_S K^+ K^-$  PRD 89, 092002 (2014)
B factories: the physics program

- **Measurements of CP asymmetries**
  - Established in B meson in 2001 with time dependent CP asymmetries
  - Direct CP violation measured in 2004

- Precise measurement of the CKM matrix parameters

- Search of new CP violation sources in B, D, and τ decays

- Search of New Physics (NP) in rare decays, such as $B \rightarrow X_{s,d} \gamma$, $B \rightarrow X_{s,d} l^+l^-$, $B \rightarrow K^{(*)}\nu\nu$, $B \rightarrow \tau\nu$, $B \rightarrow D^{(*)}\tau\nu$, ...

- Observation of time reversal violation

- Search for physics behind the standard model
  - Complementary approach with respect to the direct searches
  - Looking from the difference with respect to expectation from the standard model

- Systematic exploration of beauty, charm, and tau physics
  - Discovery of several bottomonium (including $\eta_b$) and bottomonium-like states
  - Discovery of unexpected states in harmed mesons and charmonium-like spectra

- Search for Lepton Flavor Violation (LFV) in τ and B decays

- Precise measurement of the hadronic contributions to the muon (g-2)

- Search for low mass NP particles (light CP-odd Higgs, dark photon)

- ...

The PEPII asymmetric collider and the BABAR detector

Asymmetric $e^+e^-$ collider at the $Y(4S)$ resonance:
- 9 GeV ($e^-$) x 3.1 GeV ($e^+$)

General purpose of the detector: excellent performances in tracking, and particle identification

- Instrumented Flux Return
  - RPCs/LSTs (muons/neutral hadrons)
- 1.5 T superconducting solenoid
- EMC
  - 6580 CsI(Tl) crystals
- DIRC (PID)
  - 144 quartz bars, 11000 PMs
- Silicon Vertex Tracker
  - 5 layers, double sided strips
- Drift Chamber
  - 40 layers
The BABAR dataset

BABAR collected about 531 fb\(^{-1}\) of e\(^{+}\)e\(^{-}\) collisions around the Y(4S) resonance
CP violation in mixing

A neutral B meson can transform to its antiparticles through the weak interaction (via a “box” diagram), and the evolution is governed by the Schroedinger equation:

\[
-\frac{i}{\hbar} \frac{\partial}{\partial t} \left( \begin{array}{c} |B^0> \\ |\bar{B}^0> \end{array} \right) = \mathcal{H} \left( \begin{array}{c} |B^0> \\ |\bar{B}^0> \end{array} \right)
\]

effective Hamiltonian: 
\[\mathcal{H} = \mathcal{M} + i \Gamma/2\]

The two eigenstates of \(\mathcal{H}\) (mass eigenstates) are expressed in terms of \(B^0\) and \(\bar{B}^0\) (flavor eigenstates), as:

\[
|B_L\rangle = p|B^0\rangle + q|\bar{B}^0\rangle \\
|B_H\rangle = p|B^0\rangle - q|\bar{B}^0\rangle
\]

CP violation in mixing if \(\mathcal{P}(B^0 \rightarrow \bar{B}^0) \neq \mathcal{P}(\bar{B}^0 \rightarrow B^0) \Rightarrow |q/p|^2 \neq 1\). The mixing probabilities are:

\[
\mathcal{P}(B^0 \rightarrow \bar{B}^0 \rightarrow f)(t) \propto |q/p|^2[\cosh(\Delta \Gamma t/2) - \cos(\Delta mt)]
\]

\[
\mathcal{P}(\bar{B}^0 \rightarrow B^0 \rightarrow f)(t) \propto |p/q|^2[\cosh(\Delta \Gamma t/2) - \cos(\Delta mt)]
\]

\[
A_{CP} = \frac{\mathcal{P}(\bar{B}^0 \rightarrow B^0)(t) - \mathcal{P}(B^0 \rightarrow \bar{B}^0)(t)}{\mathcal{P}(\bar{B}^0 \rightarrow B^0)(t) + \mathcal{P}(B^0 \rightarrow \bar{B}^0)(t)} = \frac{1 - |q/p|^4}{1 + |q/p|^4} \approx 2(1 - |q/p|)
\]

Two BaBar results presented:

1. Mixing induced CP-violation in \(B^0 \rightarrow D^{*+}l^-\nu\) decays (PRL 111, 159901 (2013))

2. Study of CP asymmetry with inclusive dilepton
CP violation using $B^0 \to D^* l\nu$ and current experimental results

New pioneering approach from BABAR based on $\mathcal{L} \approx 426$ fb$^{-1}$:

- "Reco" first $B$: partial reconstruction of $B^0 \to D^* - l^+ \nu_e$
- "Tag" second $B$: using charged kaons ($K_T$)

Precise BaBar measurement of CP asymmetry using $B^0 \to D^* l\nu$ decays:

$$A_{CP} = (0.06 \pm 0.17^{+0.38}_{-0.32})\%$$

Competitive and complementary to similar measurements at hadron collider

$$A_{CP}(B^0) = (2.3 \pm 2.6) \times 10^{-3}$$
Mixing-induced CP violation with inclusive dilepton events

- Updated measurement of $A_{CP}$ using $471 \times 10^6$ $B \bar{B}$ pairs
- Use the charge of lepton from semileptonic decays to identify the flavor of the $B$ meson
  - mixing: leptons with same charge
- Four lepton combination allowed: $\ell_1 \ell_2 = \{ee, e\mu, \mu e, \mu\mu\}$, times four charge combinations
- Time-integrated signal yields for events with $\ell$ originating from direct semileptonic $B$ decays:

$$N_{\ell_1 \ell_2}^{\pm \pm} = \frac{1}{2} N_{\ell_1 \ell_2}^0 (1 \pm a_{\ell_1} \pm a_{\ell_2} \pm A_{CP}) \chi_0^{\ell_1 \ell_2},$$

$$N_{\ell_1 \ell_2}^{\pm \mp} = \frac{1}{2} N_{\ell_1 \ell_2}^0 (1 \pm a_{\ell_1} \mp a_{\ell_2})(1 - \chi_0^{\ell_1 \ell_2} + r_B).$$

$a_\ell$: charge asymmetry of the detection efficiency
$r_B$: $B^+/B^0$ event ratio
$\chi_d$: mixing probability
$N_{\ell_1 \ell_2}^0$: neutral B signal yield

- Single-electron sample to constraint $a_\ell$: $a_{\text{single}} = f(A_{CP}, a_\ell)$
- Use of 16+1 observables in a $\chi^2$ fit to extract $A_{CP}$, 4 $B^0$ yields $N_{\ell_1 \ell_2}^{\ell_1 \ell_2}$, 4 efficiency asymmetries $a_{ij}$, and 4 effective mixing probabilities $\chi^{\ell_1 \ell_2}$
- Multivariate classifier to suppress backgrounds. The final sample includes:
  - 2.5% continuum background
  - 35% (8%) $B\bar{B}$ background in same (opposite)-sign sample
$A_{CP} = (-3.9 \pm 3.5 \pm 1.9) \cdot 10^{-3}$

- $A_{CP}$ results consistent among different BaBar subsamples
- One of the most precise measurements

$A_{CP}(B^0) = (0.3 \pm 2.3) \cdot 10^{-3}$

- Competitive and complementary to similar measurement at hadron collider
- $A_{CP}(B^0) = (0.3 \pm 2.3) \cdot 10^{-3}$ taking into account the new BaBar $\mu\mu$ preliminary (supersedes old BaBar $\mu\mu$)
- Consistent with the Standard Model

Chih-hsiang Cheng, CKM 2014
CP violation effects in $B^+ \rightarrow K_S \pi^+ \pi^0$

- $B^+ \rightarrow K_S \pi^+ \pi^0$ channel is the only $B \rightarrow K\pi\pi$ channel which had not been studied yet
  - Inclusive branching fraction upper limit from CLEO

- More sensitivity to direct CP violation in $B^+ \rightarrow K^{*+} \pi^0$ can shed light onto “$K\pi$ puzzle” in the $K^{*}\pi$ system
  - Previous measurement of $A_{CP}(K^{*+} \pi^0)$ from final state $B^+ \rightarrow K^+ \pi^0 \pi^0$ by BABAR
  - $\Delta A_{CP} = A_{CP}(K^{+} \pi^0) - A_{CP}(K^{+} \pi^-)$ was expected to be zero, but experimentally $A_{CP}(K^{+} \pi^0) = 0.040 \pm 0.021$ and $A_{CP}(K^{+} \pi^-) = -0.082 \pm 0.006$

- Relative phase between the two $K^{*}\pi$ intermediate states can be used to measure the CKM angle $\gamma$
  - Similar method used to measuring $\gamma$ from $B^0 \rightarrow K^+ \pi^- \pi^0$ and $B^0 \rightarrow K_S \pi^+ \pi^-$
  - Method used isospin triangle formalism for the amplitudes in $K^{*}\pi$

\[
A_{3/2} = A(K^{*0} \pi^+) + \sqrt{2} A(K^{*+} \pi^0) \\
\Phi_{3/2} = -\frac{1}{2} \text{Arg}(A_{3/2}/A_{3/2})
\]
Amplitude analysis of $B^+ \rightarrow K_S \pi^+ \pi^0$: Dalitz plot

- **3-body Dalitz plot** analysis in the plane $m(K_S \pi^0)^2$ vs. $m(K_S \pi^+)^2$
- Intermediate resonances appear as structures in the Dalitz plot, described by their mass, width and spin
- **Isobar model** used to parametrize the resonances:

$$A = A \left( m_{K_S\pi^+}^2, m_{\pi^+\pi^0}^2 \right) = \sum_j c_j F_j \left( m_{K_S\pi^+}^2, m_{\pi^+\pi^0}^2 \right)$$

$$\bar{A} = \bar{A} \left( m_{K_S\pi^-}^2, m_{\pi^-\pi^0}^2 \right) = \sum_j \bar{c}_j \bar{F}_j \left( m_{K_S\pi^-}^2, m_{\pi^-\pi^0}^2 \right)$$

- complex coefficients for a given decay mode $j$
- describes dynamic of the decay amplitudes

- **Candidates $K_S$ reconstructed from $\pi^+\pi^-$ decay, and $\pi^0 \rightarrow \gamma\gamma$**
- Large B background from $D^0$ decays → apply **veto around $D^0$ mass** in $K_S\pi^0$ invariant mass
- Difficulty: account for large correlation between kinematic and Dalitz plot (DP) variables for signal events
  - STRATEGY: **subdivide the DP into regions described by different PDFs and/or parameters**

Fit to about 32000 candidate events in data returns a signal yield of $1014 \pm 63$
signal events and 31000 background events
B⁺ → K_Sπ⁺π⁰: fit to combined B⁺ and B⁻ candidates

First measurement of inclusive K₀π⁺π⁰ and K₀⁺*(1430) π⁰ branching fraction:

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>B (10⁻⁶)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K⁰π⁺π⁰</td>
<td>45.9 ± 2.6 ± 3.0 ± 8.6</td>
</tr>
<tr>
<td>BABAR preliminary</td>
<td></td>
</tr>
<tr>
<td>K⁺*(892)π⁺</td>
<td>14.6 ± 2.4 ± 1.3 ± 0.5</td>
</tr>
<tr>
<td>K⁺*(892)π⁰</td>
<td>9.2 ± 1.3 ± 0.6 ± 0.5</td>
</tr>
<tr>
<td>K⁰*(1430)π⁺</td>
<td>50.0 ± 4.8 ± 6.0 ± 4.0</td>
</tr>
<tr>
<td>K⁰*(1430)π⁰</td>
<td>17.2 ± 2.4 ± 1.5 ± 1.8</td>
</tr>
<tr>
<td>ρ⁺(770)K⁰</td>
<td>9.4 ± 1.6 ± 1.0 ± 2.6</td>
</tr>
</tbody>
</table>

- First uncertainty is statistical, second is systematic, and third due to the signal model
- Destructive interference: the sum of the resonance BFs is higher than the inclusive one
B$^+\rightarrow$K$_S$$\pi^+\pi^0$: CP violation results

- Compute inclusive and exclusive CP asymmetry ($A_{CP}$)
- Parameterization of the coefficients $c_j$:
  \[ c_j = (x_j + \Delta x_j) + i (y_j + \Delta y_j) \]
  \[ \bar{c}_j = (x_j - \Delta x_j) + i (y_j - \Delta y_j) \]

  \[ A_{CP,j} = \frac{|\bar{c}_j|^2 - |c_j|^2}{|\bar{c}_j|^2 + |c_j|^2} \]

  Evidence of direct CP violation in $B^+\rightarrow K^{*-}\pi^0$

  - First evidence of direct CP violation in $B^+\rightarrow K^{*-}\pi^0$
  - $3.4\sigma$ significance estimated including statistical, systematic and model uncertainties
  - $A_{CP}$ for $B^+\rightarrow K^{*0}\pi^+$ consistent with zero CP asymmetry

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$A_{CP}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{*0}\pi^+\pi^0$</td>
<td>$0.07 \pm 0.05 \pm 0.03 \pm 0.04$</td>
</tr>
<tr>
<td>$K^{*0}(892)\pi^+$</td>
<td>$-0.12 \pm 0.21 \pm 0.08 \pm 0.11$</td>
</tr>
<tr>
<td>$K^{*-}(892)\pi^0$</td>
<td>$-0.52 \pm 0.14 \pm 0.04 \pm 0.04$</td>
</tr>
<tr>
<td>$K_0^{*0}(1430)\pi^+$</td>
<td>$0.14 \pm 0.10 \pm 0.04 \pm 0.14$</td>
</tr>
<tr>
<td>$K_0^{*-}(1430)\pi^0$</td>
<td>$0.26 \pm 0.12 \pm 0.08 \pm 0.12$</td>
</tr>
<tr>
<td>$\rho^+(770)K^0$</td>
<td>$0.21 \pm 0.19 \pm 0.07 \pm 0.30$</td>
</tr>
</tbody>
</table>

First uncertainty is statistical, second is systematic, and third due to the signal model.
New Physics in “rare” B decays

Branching fractions and CP violation results in
B → X_sγ and B → X_s l^+l^- decays
Search for indirect New Physics effects

- $B \rightarrow X_s \gamma$ and $B \rightarrow X_s l^+l^-$ are FCNC processes forbidden at tree level in the SM, but happen at loop level
  - $A_{CP}^{SM}$ predicted to be very small
  - The general effective Hamiltonian that governs the inclusive $b \rightarrow s \gamma$ decays in the SM is:

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \sum_q V_{qb} V_{qsd} \sum_i C_i(\mu) O_i$$

$q = u, c, t$  

Rev. Mod. Phys. 68, 1125 (1996)

- $C_7$ and $C_8$ Wilson coefficients
- $C_7^{\text{eff}}, C_9^{\text{eff}}$ and $C_{10}^{\text{eff}}$ Wilson coefficients

SM prediction @NNLO:

$\mathcal{B}(B \rightarrow X_s \gamma)_{SM} = (3.15 \pm 0.23) \times 10^{-4}$

$\mathcal{B}(X_s l^+l^-)_{SM} = (4.6 \pm 0.8) \times 10^{-6}$

- New Physics (NP) add new loops with new particles, and can contribute at the same level of the SM
  - modifies the SM values of the Wilson coefficients and may introduce new terms
  - measurable changes of BF and CP asymmetry expected
- The measurement of BF and CP asymmetry can add constraints in several NP models, in particular the Two-Higgs Doublet Model (2HDM)
- Indirect studies complementary to direct search at LHC
B \rightarrow X_s \gamma: semi-inclusive A_{CP} results

- BF measurements obtained in bins of photon energy
  - BABAR lep-tag (X_{s+d}): (3.32\pm0.16\pm0.31\pm0.02) \times 10^{-4} \ [PRL 109, 191801 (2012)]
  - BABAR sum-excl (X_s): (3.52\pm0.20\pm0.51\pm0.04) \times 10^{-4} \ [PRD 86, 052012 (2012)]
  - BABAR hadron-tag (X_{s+d}): (3.90\pm0.91\pm0.64\pm0.04) \times 10^{-4} \ [PRD 77, 051103 (2012)]

- Results extrapolated to E_\gamma>1.6 \text{ GeV} and extrapolated:
  \[ \mathcal{B}(B \rightarrow X_s \gamma) = (3.40 \pm 0.21) \times 10^{-4} \]

- For the sum of exclusive decays, the CP asymmetry is decided by:
  \[ A_{CP}(X_s \gamma) = \frac{\Gamma(\bar{B} \rightarrow X_s \gamma) - \Gamma(B \rightarrow X_s \gamma)}{\Gamma(\bar{B} \rightarrow X_s \gamma) + \Gamma(B \rightarrow X_s \gamma)} \]

- SM predictions: -0.6% < A_{CP}(X_s \gamma) < 2.8%
  - Present word average: A_{CP}(X_s \gamma) = 0.8 \pm 2.9%

- Recent BABAR analysis measures A_{CP}(X_s \gamma) by using about 470 million of BB events and a sum of 16 exclusive modes
  \[ A_{CP} = (1.7 \pm 1.9_{\text{stat}} \pm 1.0_{\text{syst}})\% \]

- Good agreement with SM
- Significantly lower uncertainties than previous measurements

\textbf{arXiv:1406.0534}
B → X_sγ: ΔA_{CP} results

- The difference between the charged and neutral B decays depends on C_7 and C_8 Wilson coefficients (PRL 106, 41801 (2011)):

\[ ΔA_{CP}(X_sγ) = A_{CP}(B^+ → X_s^+γ) - A_{CP}(B^0 → X_s^0γ) ≈ 0.12 \frac{\tilde{λ}_{78}}{m_b} \text{Im} \frac{C_8^{\text{eff}}}{C_7^{\text{eff}}} \]

17 MeV < \tilde{λ}_{78} < 190 MeV
M. Benzke et al., PRL 106, 141801 (2011)

- C_7 and C_8 are real in the SM → ΔA_{CP} = 0
- From simultaneous fits to charged and neutral B samples, BABAR measure:

\[ ΔA_{CP}(X_sγ) = (5.0 ± 3.9_{\text{stat}} ± 1.5_{\text{syst}})\% \]

- Set 90% CL on Im(C_8/C_7) for any value of \tilde{λ}_{78} in the allowed range

This is the first ΔA_{CP}(X_sγ) measurement and the first constraint in the ratio of Wilson coefficients C_8/C_7 for new physics in this process.
Recent BABAR analysis uses sum of 20 exclusive modes of $B \rightarrow X_s l^+ l^-$, with $l=e, \mu$

- Reconstruct 10 hadronic $X_s$ final states with one kaons, and up to two charged and one neutral pion ($m_{X_s} < 1.8$ GeV)
- These exclusive modes represent 70% of the inclusive rate with $m_{X_s} < 1.8$ GeV, accounting for $K^0_L$ modes, $K^0_S \rightarrow \pi^0 \pi^0$, and $\pi^0$ Dalitz decays
- Missing modes and those with $m_{X_s} > 1.8$ GeV estimated using MC (JETSET fragmentation and theory predictions)

- Measure the total BF and the partial BFs in 5 bins of $q^2=m_{ll}$ and 4 bins of $m_{X_s}$
- 14 “self-tagging” modes used for CP asymmetry measurements
  - require a charge $K$ in the final state in order to determine the charge of the b quark
B→X_s l^+ l^- RESULTS

- Over the full q^2 range BABAR measures a direct CP asymmetry of

\[ \mathcal{A}_{CP}(B\to X_s l^+ l^-) = 0.04 \pm 0.11 \pm 0.11 \]

- Consistent with zero as expected in the SM
- The direct CP asymmetry measured in 5 bins of q^2 is also consistent with zero

General consistency with SM prediction

PRL 112, 211802 (2014)
Searches for Dark Matter @ BABAR
Anti-deuteron production @ BABAR

Dark matter annihilation to quark and gluons could be a source of primary anti-deuteron
- Anti-deuteron as probe of dark matter
- Large production uncertainties (e.g. "coalescence model"), estimated at 90%
- Uncertainties also in the expected spectra

Using the full data set, BABAR has made improved measurements of anti-deuteron
production in Y(nS) (i.e. via gluons) and in $e^+e^-\rightarrow qq$ near $\sqrt{s}\sim 10.6$ GeV

- Key element is the measurement of energy loss ($dE/dx$) in the tracking system
- Deuterons well-separated from protons up to 1.5 GeV/c: $0.5<p_{LAB}<1.5$ GeV/c

![Graph showing data and fit](image1)

- Fit to $dE/dx$ normalized residual distribution:

\[
\frac{dE}{dx} - \frac{dE}{dx} \text{ (deuteron)} \bigg/ \sigma_{dE/dx}
\]
Anti-deuteron production: RESULTS

- Fireball function to model the deuteron production spectra (NP B24, 93 (1970)):
  \[ P(E) = \alpha v^2(E) e^{-\beta E} = \frac{E^2 - m_d^2}{E^2} e^{-\beta E} \]

<table>
<thead>
<tr>
<th>Process</th>
<th>Rate</th>
</tr>
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<tbody>
<tr>
<td>( B(\Upsilon(3S) \rightarrow \bar{d}X) )</td>
<td>( (2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5} )</td>
</tr>
<tr>
<td>( B(\Upsilon(2S) \rightarrow \bar{d}X) )</td>
<td>( (2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5} )</td>
</tr>
<tr>
<td>( B(\Upsilon(1S) \rightarrow \bar{d}X) )</td>
<td>( (2.81 \pm 0.49^{+0.20}_{-0.24}) \times 10^{-5} )</td>
</tr>
<tr>
<td>( \sigma(e^+e^- \rightarrow \bar{d}X) ) [( \sqrt{s} \approx 10.58 \text{ GeV} )]</td>
<td>( (9.63 \pm 0.41^{+1.17}_{-1.01}) \text{ fb} )</td>
</tr>
<tr>
<td>( \frac{\sigma(e^+e^- \rightarrow \bar{d}X)}{\sigma(e^+e^- \rightarrow \text{Hadrons})} )</td>
<td>( (3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6} )</td>
</tr>
</tbody>
</table>

- Good agreement with CLEO results on the \( \Upsilon(2S) \) and \( \Upsilon(1S) \) (PRD 75, 012009 (2007)):
  - \( B(\Upsilon(2S) \rightarrow dX)^\text{CLEO} = (3.37\pm0.50\pm0.25) \times 10^{-5} \)
  - \( B(\Upsilon(1S) \rightarrow dX)^\text{CLEO} = (2.86\pm0.19\pm0.21) \times 10^{-5} \)

- No significant evidence of anti-deuteron production in \( \Upsilon(4S) \) decays
- \( \bar{d} \) production in continuum (qq) is much smaller than in \( \Upsilon \) (gg) decays
Search of dark photon in $e^+e^-\rightarrow\gamma A', A'\rightarrow e^+e^-, \mu^+\mu^-$

- Dark matter particles feebly interact with ordinary matter
- Possibility: new U(1)' gauge group with corresponding dark photon $A'$
  - Could couple the SM hypercharge via kinetic mixing with a mixing strength $\varepsilon$
  - Effective interaction between dark photon and electromagnetic current: $\varepsilon e A'_\mu j^{\mu EM}$
  - The dark photon would mediate the annihilation of dark matter into SM fermions

**Search for dark photon in $e^+e^-\rightarrow\gamma A', A'\rightarrow e^+e^-, \mu^+\mu^-$ using the full dataset**
- Measure the cross section from 20 MeV to 10.2 GeV
- Background from QED $e^+e^-\rightarrow l^+l^-\gamma$
- Train a neutral network to remove $e^+e^-\rightarrow\gamma\gamma, \gamma\rightarrow e^+e^-$ events with a conversion in the beam pipe/detector material

**arXiv:1406.2980**

- Fit the $m_{e^+e^-}$ and $m_{\mu^+\mu^-}$ spectra locally
- Significance estimates as:
  $$S_S = \sqrt{2\log(L/L_0)}$$

- Largest significance (3.4$\sigma$ near $m_{A'}=7.02$ GeV for $e^+e^-$ final state) consistent with null hypothesis
Search of dark photon in $e^+ e^- \rightarrow \gamma A', A' \rightarrow e^+ e^-, \mu^+ \mu^-$. Implications

Converting the results into 90% confidence level (CL) upper limits on the mixing strength $\varepsilon$ between photon and dark photon as a function of the dark photon mass:

Upper limit for $\varepsilon$ are set at level of $10^{-4} - 10^{-3}$

- Supersede and extend BABAR2009 constraints based on a search for light CP-odd Higgs boson [PRL 103, 081803 (2009)] with a smaller dataset
- Further constraints the range of parameter space favored by interpretations of the discrepancies between the calculated and the measured $(g-2)_\mu$

Only $15 \text{ MeV/c}^2 \leq m_{A'} \leq 30 \text{ MeV/c}^2$ remains
$e^+e^- \rightarrow \text{hadrons and } (g-2)_\mu \text{ @ BABAR}$
e⁺e⁻ → hadrons and (g-2)μ

Processes involving initial state radiation (ISR) allowed very precise measurements of the σ(e⁺e⁻→hadrons) as a function of the CM energy from threshold to several GeV

- used for the calculation of \( a_\mu = (g_\mu - 2)/2 \)
- \( a_\mu (\text{meas.}) = 116592080 \pm 63 \times 10^{-11} \) (E821 @ BNL PRD 73, 072003 (2006))
- \( a_\mu (\text{SM}) = 116591828 \pm 49 \times 10^{-11} \) (H. Hagiwara et al., J. Phys. G 38, 085003 (2011))

\[ a_\mu (\text{SM}) = a_\mu (\text{QED}) + a_\mu (\text{weak}) + a_\mu (\text{had}) \]

- Not calculable using perturbative approach
- Dispersion relation:

\[ a_\mu (\text{had}) = \frac{\alpha^2}{3\pi^2} \int_{\text{threshold}}^{\infty} R(s) \frac{K(s)}{s} ds \]

\[ R(s) = \frac{\sigma_{\text{tot}}(e^+e^- \rightarrow \text{hadrons})}{\sigma_{\text{tot}}(e^+e^- \rightarrow \mu^+\mu^-)} \]

- Low-energy region dominates the determination of \( a_\mu \)
- 70% from two pion final state (dominated by the ρ(770) resonance)
BABAR’s ISR measurements

- With $\gamma_{\text{ISR}}: \sqrt{s'} = [s(1-x)]^{1/2}$ where $x = 2E_{\gamma'}/\sqrt{s}$ in the CM frame
- $E_{\gamma'} > 3 \text{GeV}$
- Continuous measurement from threshold to 3-5 GeV in single data set
  - reduced systematics w.r.t multiple data sets taken in different energy scan

Final state(s)

- $\pi^+\pi^-$
- $K^+K^-$
- $\pi^+\pi^-\pi^0$
- $K^+K^-\eta, K^+K^-\pi^0, K_S^0K^{\mp}\pi^\mp$
- $\pi^+\pi^-\pi^+\pi^-$
- $K^+K^-\pi^+\pi^-\pi^0, 2(K^+K^-)$
- $\Lambda\bar{\Lambda}, \Lambda\Sigma^0, \Sigma\bar{\Sigma}^0$
- $2(\pi^+\pi^-)\pi^0, 2(\pi^+\pi^-)\eta, K^+K^-\pi^+\pi^-\pi^0$
- $K^+K^-\pi^+\pi^-\eta$
- $\phi\eta$
- $3(\pi^+\pi^-), 2(\pi^+\pi^-)\pi^0, K^+K^-2(\pi^+\pi^-)$
- $p\bar{p}$

- $K_S^0K_L^0, K_S^0K_L^0\pi^+\pi^-, K_S^0K_S^0\pi^+\pi^- K_S^0K_S^0K^+K^-$
- $K_S^0K^{\pm}\pi^\mp\pi^0, K_S^0K^{\pm}\pi^\mp\eta, \pi^+\pi^- 2\pi^0$

Publication

- PRD 88 032013 (2013)
- PRD 70 072004 (2004)
- PRD 77 092002 (2008)
- PRD 85 112009 (2012)
- PRD 86 012008 (2012)
- PRD 76 092006 (2007)
- PRD 76 0922005 (2007)
- PRD 74 111103 (2006)
- PRD 73 052003 (2006)
- PRD 87 092005 (2013)
- PRD 88 072009 (2013)
- PRD 89 092002 (2014)

In progress
$e^+e^- \rightarrow K_SK_L$

- Events with $K_SK_L$ mass near $\phi$ resonance are selected by the requirement of detected $K_S$ ($K_S \rightarrow \pi^+\pi^-$) and $\gamma_{ISR}$, and the condition that the missing mass is close to the $K_L$ mass.
- $\phi$-meson used to measure the $K_S$ detection efficiency.
- Total cross section measured up to 2.2 GeV.
- Most precise measurement above 1.4 GeV.

![Graph showing $\sigma (nb)$ vs. $E_{c.m.}$ (GeV)]

Difference indicates substantial interference between the isovector and isoscalar amplitudes in this energy range:

$$\sigma(e^+e^- \rightarrow K^+K^-) \sim |A_{l=1} + A_{l=0}|^2,$$

$$\sigma(e^+e^- \rightarrow K_SK_L) \sim |A_{l=1} - A_{l=0}|^2,$$

Simultaneous fit to $K_SK_L$, $K^+K^-$, $\pi^+\pi^0$ (pure isovector) and $\pi^+\pi^0\pi^0$ (pure isoscalar) is needed to extract the isoscalar and isovector components, together with resonance parameters.
$e^+e^- \rightarrow K_S K_S \pi^+\pi^-$, $e^+e^- \rightarrow K_S K_L \pi^+\pi^-$, and $e^+e^- \rightarrow K_S K_S K^+K^-$

First cross section measurements for these processes

Intermediate states:
- $K^*(892)^+K^*(892)^-$ dominant
- $K^*(892)^+K_2^*(1430)^+$ for $K_S K_L \pi^+\pi^-$
- $\phi\pi^+\pi^-$ for $K_S K_L \pi^+\pi^-$
- $K_S K_S p^0$ for $K_S K_S \pi^+\pi^-$

- $\phi(1020)K_S K_S$ is the dominant intermediate state
- Signal from $f_2'(1525)\phi(1020)$ intermediate state

- First measurements of $K_S K_L \pi^+\pi^-$, $K_S K_S \pi^+\pi^-$, and $K_S K_S K^+K^-$ cross sections
- $J/\psi \rightarrow K_S K_L \pi^+\pi^-$, $K_S K_S \pi^+\pi^-$, and $K_S K_S K^+K^-$ decays observed for the first time

PRD 89, 092002 (2014)
1. Search for CP violation in $B^0$-$B^0$ mixing using partial reconstruction of $B^0 \rightarrow D^{*}X L^+\nu_l$ and kaon tag, PRL 111, 101802 (2013)
3. Search for a low-mass scalar Higgs boson decays to tau pair in a single-photon decays of $\Upsilon(1S)$, PRD 88, 071102(R) (2013)
4. Measurement of the $B^+ \rightarrow \omega l^+\nu$ branching fraction with semileptonically tagged B mesons, PRD 88, 072006 (2013)
5. Measurement of the $e^+e^- \rightarrow p\bar{p}$ cross section in the energy range from 3.0 to 6.5 GeV, PRD 88, 072009 (2013)
7. Measurement of an access of $\bar{B} \rightarrow D^{(*)}\tau^+\bar{\nu}_\tau$ decays and implications for charged Higgs bosons, PDR 88, 072012 (2013)
8. Search for lepton-number violating $B^+ \rightarrow XL^+l^+$ decays, PRD 89, 011102(R) (2014)
9. Evidence for the decay $B^0 \rightarrow \omega\omega$ and search for $B^0 \rightarrow \omega\phi$, PRD 89, 051101(R) (2014)
10. Search for the decay $B^0 \rightarrow \Lambda_c^+[\bar{p}\bar{p}\bar{p}]$, PRD 89, 071102(R) (2014)
11. Cross sections for the reactions $e^+e^- \rightarrow K_S K_L$, $e^+e^- \rightarrow K_S K_L \pi^+\pi^-$, $e^+e^- \rightarrow K_S K_S \pi^+\pi^-$, and $e^+e^- \rightarrow K_S K_S K^+K^-$ from events with initial-state radiation, PRD 89, 092002 (2014)
13. Evidence for the baryonic decay $\bar{B}^0 \rightarrow D^0\Lambda\bar{\Lambda}$, PRD 89, 112002 (2014)
14. Dalitz plot analysis of $\eta_c \rightarrow K^+K^-\eta$ and $\eta_c \rightarrow K^+K^-\pi^0$ in two-photon interactions, PRD 89, 112004 (2014)
15. Antideuteron production in $\Upsilon(nS)$ decays and $e^+e^- \rightarrow q\bar{q}$ at $\sqrt{s} \approx 10.58$ GeV, PRD 89, 111102(R) (2014)
16. Study of the reaction $e^+e^- \rightarrow \psi(2S)\pi^+\pi^-$ via initial-state radiation at BABAR, PRD 89, 111103(R) (2014)
Conclusions

- Several years after the end of the data taking period, BaBar still produces interesting physics results.

- Only a few topics are covered in this talk:
  - 4 published and 4 preliminary results
  - About 38 analysis on tracks for publication
  - 8 new analysis started this year
  - 539 paper so far

STAY TUNED
AND
THANKS FOR YOUR ATTENTION
The Cabibbo-Kobayashi-Maskawa (CKM) matrix

\[
V_{\text{CKM}} = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\]

- The origin of the CKM matrix is the difference between mass eigenstates and quark-flavour (or weak interaction) eigenstates
- Describes the quark mixing in weak charged transitions
- Unitary and complex 3x3 matrix
- \( V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \)
- Wolfenstein parameterization to highlight the hierarchy (O^3)

\[
V_{\text{CKM}} = \begin{pmatrix}
1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1 - \lambda^2/2 & A\lambda^2 \\
A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\]

- Unitary constrain:
  - 4 independent parameters:
    - 3 angles (quantify the mixing) and 1 complex phase (mechanism for introducing CP)
    - Interfering amplitudes can give CP violating asymmetries
    - The CKM is the only source of CP violation in the SM

- Measurements at B factories can over-constrain the Unitarity Triangle
- New Physics would be revealed in discrepancies among measurements

B\(^0\)\(\rightarrow\pi^+\pi^-\), \(\rho^+\rho^-\)

- Diagram showing the Dalitz plot for \(B^0\)\(\rightarrow\bar{D}^0\pi^+\pi^-\)
Mixing-induced CP violation in semileptonic B-meson decays

New pioneering approach from BABAR based on $\mathcal{L} \approx 426$ fb$^{-1}$:
- “Reco” first B: partial reconstruction of $B^0 \rightarrow D^*-l^+\nu_e$
- “Tag” second B: using charged kaons

Partial reconstruction of $B^0 \rightarrow D^*-l^+\nu_e$
- Use only $l$ and low momentum $\pi_s$ from the $D^* \rightarrow D^0\pi_s$ decay to reduce background dilution from $B^+B^-$ or from light quark events
- $l$ and $\pi_s$ originated from a common vertex and constrained to the beam-spot in the plane transverse to the beam axis
- reject BB events by combining $p_l$, $p_{\pi_s}$ and Prob(Vtx)
- limited phase space available for the $D^*$ decay $\Rightarrow$ get $D^*$ momentum from $\pi_s$

Neutrino missing mass: $M^2_{\nu} = (P_B - P_{D^*} - P_l)$
- the signal fraction is determined by fitting the missing mass distribution in the interval [-10,2.5] GeV$^2$/c$^4$ with the sum of all the background contributions
- continuum contribution fixed to the expectation from off-peak events
- $(5.945 \pm 0.007) \times 10^6$ peaking events
Mixing-induced CP violation in semileptonic B-meson decays

We distinguish $K_T$ from $K_R$ using:
- proper-time difference $\Delta t = \Delta Z/(\beta \gamma c)$ (in the Lab. frame)
- kinematics: looking at the angle between $\theta_{IK}$ between the lepton and the kaon (in the $Y(4S)$ frame)

“Tag”
- “mixed” or “unmixed” event by exploit the charge of $K_T$
- Oscillation when $K_T$ and $l$ have same electric charge
  - but also when $K_T$ comes from Cabibbo-suppressed decays, and for Cabibbo-favored $K_R$
Mixing-induced CP violation in $B^0 \to D^* l \nu$ decays

New pioneering approach from BABAR based on $\mathcal{L} \approx 426$ fb$^{-1}$:

- “Reco” first $B$: partial reconstruction of $B^0 \to D^* l^+ \nu_e$
- “Tag” second $B$: using charged kaons ($K_T$)

Oscillation when $K_T$ and $l$ have same electric charge; same charge also when $K_T$ comes from Cabibbo-suppressed decays (unmixed events), and for Cabibbo-favored $K_R$

- Discrimination between $K_R$ and $K_T$ using the proper-time difference and kinematic variables

Observed asymmetry for mixed events:

$$A_T = \frac{N(\ell^+ K_T^+) - N(\ell^- K_T^-)}{N(\ell^+ K_T^+) + N(\ell^- K_T^-)} \simeq A_{r\ell} + A_K + A_{CP}$$

$A_T$ charge asym. in $K$ reco.

$A_R = \frac{N(\ell^+ K_R^+) - N(\ell^- K_R^-)}{N(\ell^+ K_R^+) + N(\ell^- K_R^-)} \simeq A_{r\ell} + A_K + A_{CP} \cdot \chi_d$

$A_R$ charge asym. in $B^0$ reco.

Kaons from reco side have a tiny contribution from mixing:

Single lepton asymmetry:

$$A_{\ell} \simeq A_{r\ell} + A_{CP} \cdot \chi_d$$

$A_{\ell}$ mixing $B^0$ probability

- Large number of events and very complicate fit with more than 100 free parameters ⇒ 5D binned fit ($\Delta t$, $\sigma(\Delta t)$, $\cos(\theta_{IK})$, $M_\nu$, $p_K$) to separate signal from background, and tag from reco kaons
- Low systematic uncertainties w.r.t. dilepton analysis
CP violation results using \( B^0 \rightarrow D^{*} l \nu \)

- Well consistent with, and more precise (30%) than, the results from dilepton measurements at B factories
- Competitive and complementary to similar measurements at hadron collider
- No deviation from SM expectation

\[ \Delta t = \frac{Z_{\text{rec}} - Z_{\text{tag}}}{\beta \gamma c} \]

*Fit projection for \( \Delta t \) for the continuum-subtracted data*