EXOTIC HADRONS, LIGHT HIGGS AND DARK FORCES AT BaBar

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DPNC Seminar - October 2010
B-factories legacy

BEFORE B-FACTORIES

Confirm CKM mechanism as dominant source of CP-violation in meson decays

Still not enough to explain matter-antimatter asymmetry → New Physics

AND AFTER

Kobayashi and Maskawa were awarded the Nobel Prize 2008 "for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature."
Physics at BABAR

Upper limit on $\tau$ LFV decays

AND MUCH MORE...

More than 440 papers published by BABAR on many topics!
In this talk

Spectroscopy and exotic hadrons

Search for Light Higgs

Dark forces and dark matter
PEP-II delivered ~553 fb⁻¹

BABAR collected about
470 millions Υ(4S)
122 millions Υ(3S)
99 millions Υ(2S)
The BABAR detector

BABAR Detector

- Muon/Hadron Detector
- Magnet Coil
- Electron/Photon Detector
- Cherenkov Detector
- Tracking Chamber
- Support Tube
- Vertex Detector

$e^-$

$e^+$
Spectroscopy and exotic hadrons
Besides mesons and baryons, other “exotic” combinations of quarks and gluons could exist (i.e. are not forbidden by QCD). This include for example:

**Hybrid**
State with excited gluonic degree of freedom
Lattice predictions for lowest mass c̅c̅g ~ 4.2 GeV

**Glueball**
Bound state of gluons

**Tetraquark**
Four-quark bound states
Large number of states expected

**Pentaquark**
Five-quark bound states

**DD(*) molecule**
Loosely bound state of pair of mesons
Small number of states

**Hadrocharmonium**
Charmonium state embedded in a 'shell' of light quark

And many more...
Many new hadrons...

Since the last decade, many new states have been discovered at high-luminosity B-factories (BABAR, Belle), charm-factories (BES, CLEO) and hadronic colliders (CDF, D0). Among these new states, some were expected, but some were not.

Do we finally have observed exotic hadrons?

T. Barnes, S. Godfrey, and E.S. Swanson, Phys. Rev. D72, 054026 (2005).
Since the observation of the $X(3872)$, many new similar states have been reported.

### Well established*

<table>
<thead>
<tr>
<th>State</th>
<th>$J^P_C$</th>
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<tbody>
<tr>
<td>$X(3872)$</td>
<td>$1^{++}/2^+$</td>
<td></td>
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<tr>
<td>$X(3915)$</td>
<td>$0/2^+$</td>
<td></td>
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<tr>
<td>$G(3900)$</td>
<td>$1^-$</td>
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<td>$Y(4260)$</td>
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<td>$Y(4360)$</td>
<td>$1^-$</td>
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<td>$Y(4008)$</td>
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<td>$Z^+_1 (4050)$</td>
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<td>$Y(4140)$</td>
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<td>$X(4160)$</td>
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<td>$Z^+_2 (4250)$</td>
<td>$??^+$</td>
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<tr>
<td>$X(4350)$</td>
<td>$0,2^{++}$</td>
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<td>$Z^{±}(4430)$</td>
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<tr>
<td>$X(4630)$</td>
<td>$1^-$</td>
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<tr>
<td>$Y(4660)$</td>
<td>$1^-$</td>
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### Need confirmation

<table>
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<td>$Z^0 (4050)$</td>
<td>$??^+$</td>
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<tr>
<td>$Z^{±}(4250)$</td>
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<td>$Z^{±}(4430)$</td>
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</tr>
<tr>
<td>$X(4630)$</td>
<td>$1^-$</td>
<td></td>
</tr>
<tr>
<td>$Y(4660)$</td>
<td>$1^-$</td>
<td></td>
</tr>
</tbody>
</table>

*Well established: 2 experiments with at least 5$\sigma$ observation

References in appendix
**Discovered** by Belle in exclusive $B^+ \rightarrow K^+ \pi^+\pi^- J/\psi$ decay, existence now firmly established. Most possibilities for conventional charmonium ($\psi_2, \psi_3, h_c', \chi_{c1}'$) assignment ruled out by measurement of angular distribution or decay widths.
Mass very close to DD* threshold, molecular state?

Isosinglet, no \( X^\pm (3872) \) found

Branching fraction

**BABAR**: \( B(X \rightarrow \gamma \psi (2S))/B(X \rightarrow \gamma \ J/\psi) = 3.4 \pm 1.4 \)

Too large for molecule!

**Belle**: \( B(X \rightarrow \gamma \psi (2S))/B(X \rightarrow \gamma \ J/\psi) < 2.1 @ 90\% \text{ CL} \)

Compatible for molecule

Quantum numbers

**Belle**: \( 1^{++} \) favored (no \( \rho-\omega \) interference)

**CDF**: \( 1^{++} \) or \( 2^{-} \)

**BABAR**: \( 2^{-} \) favored \( \rightarrow \eta_{c2}(1D) \) ?

Other possibilities

tetraquark, charmonium-molecule mix, hybrid

No conclusive answer about its nature
Several Y states produced in Initial State Radiation (ISR)

Quantum number $1^-$ but only $Y(4660)$ is close to a predicted $1^- \bar{c}\bar{c}$ state.

No dominant open charm decay, as expected for charmonium, DD* molecule.

Non-trivial dipion distribution, $f_0(980)$ contribution?
The $Z^\pm(4430)$

Belle $B^+ \rightarrow Z^- K$, $Z^- \rightarrow \psi(2S)\pi^-$

\[ K^*(892) \quad K^*(1430) \]

Belle $B^+ \rightarrow Z^- K$, $Z^- \rightarrow \psi(2S)\pi^-$

M = 4433 ± 4 ± 3 MeV
\[ \Gamma = 45^{+18}_{-13}^{+30}_{-13} \text{ MeV} \]
\[ \chi^2/\text{dof} = 80.2/94 \quad (6.5\sigma) \]

Clearly exotic state: tetraquark (c\overline{c}d\overline{u})

Observation from Belle (K* veto analysis)

Non confirmation from BABAR
The Z±(4430)

Belle DP analysis result

\[ M = 4443^{+15}_{-12}^{+19}_{-13} \text{ MeV} \]
\[ \Gamma = 107^{+86}_{-43}^{+74}_{-56} \text{ MeV} \]
Significance 6.4\(\sigma\)

\[ \text{BF}(B^+ \rightarrow Z^- K, Z^+ \rightarrow \psi(2S)\pi^-) \times 10^{-5} \]

3.2^{+1.8}_{-0.9}^{+5.3}_{-1.6} Belle

1.9 \pm 0.8 (< 3.1) BABAR

No more contradiction, but confirmation of Z±(4430) needed
**Other states**

- **$Z_1^+(4050)$ and $Z_2^+(4250)$**
  - **Belle** $B^+ \rightarrow K\pi\chi_{c1}$

- **X(4160)**
  - **Belle** $X(4160) \rightarrow D^{*}\bar{D}^{*}$

- **Y(4140)**
  - **CDF** $B \rightarrow J/\psi \phi K$

- **X(4350)**
  - **Belle** $X(4350) \rightarrow J/\psi \phi$

All these states need confirmation
Summary

<table>
<thead>
<tr>
<th>State</th>
<th>M (MeV)</th>
<th>Γ (MeV)</th>
<th>JPC</th>
<th>Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(3872)</td>
<td>3871.52 ± 0.20</td>
<td>1.3 ± 0.6</td>
<td>1++/2-++</td>
<td>$\eta_{c2}(1D)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DD* molecule tetraquark, charmonium-molecule mix, hybrid</td>
</tr>
<tr>
<td>X(3915)</td>
<td>3915.6 ± 3.1</td>
<td>28 ± 10</td>
<td>0, 22++</td>
<td>$\omega J/\psi$</td>
</tr>
<tr>
<td>X(3940)</td>
<td>3942.9 ± 3.7</td>
<td>37 ± 27</td>
<td>1-++</td>
<td>DD*</td>
</tr>
<tr>
<td>G(3900)</td>
<td>3943 ± 21</td>
<td>52 ± 11</td>
<td>1--</td>
<td>DD</td>
</tr>
<tr>
<td>Y(4008)</td>
<td>4008.12 ± 0.49</td>
<td>226 ± 97</td>
<td>1--</td>
<td>$\pi^+\pi^- J/\psi$</td>
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<tr>
<td>Z(4050)</td>
<td>4051.1 ± 0.4</td>
<td>89 ± 85</td>
<td>?</td>
<td>$\pi^+\chi_{c1}(1P)$</td>
</tr>
<tr>
<td>Y(4140)</td>
<td>4143 ± 3.1</td>
<td>117 ± 6.2</td>
<td>1-?</td>
<td>$\phi J/\psi$</td>
</tr>
<tr>
<td>X(4160)</td>
<td>4156 ± 29</td>
<td>130 ± 11</td>
<td>1-?</td>
<td>DD</td>
</tr>
<tr>
<td>Z(4250)</td>
<td>4248 ± 14.5</td>
<td>177 ± 31</td>
<td>?</td>
<td>$\pi^+\chi_{c1}(1P)$</td>
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<tr>
<td>Y(4260)</td>
<td>4263 ± 5</td>
<td>108 ± 14</td>
<td>1--</td>
<td>$\pi^+\pi^- J/\psi$</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td>$\pi^0\pi^0 J/\psi$</td>
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<tr>
<td>X(4350)</td>
<td>4350.6 ± 4.6</td>
<td>13.3 ± 10</td>
<td>0, 22++</td>
<td>$\phi J/\psi$</td>
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<td>Y(4360)</td>
<td>4353 ± 11</td>
<td>96 ± 42</td>
<td>1--</td>
<td>$\pi^+\pi^- f_0(2S)$</td>
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<td>Z(4430)</td>
<td>4443 ± 24.1</td>
<td>107 ± 14</td>
<td>?</td>
<td>$\pi^+\psi(2S)$</td>
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<td>X(4630)</td>
<td>4634 ± 6</td>
<td>92 ± 41</td>
<td>1--</td>
<td>$\Lambda_c^+ \Lambda_c^-$</td>
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<tr>
<td>Y(4660)</td>
<td>4664 ± 12</td>
<td>48 ± 15</td>
<td>1--</td>
<td>$\pi^+\pi^- f_0(2S)$</td>
</tr>
</tbody>
</table>

Coupled channel effect (E. Eichten et al., PRD 21 (1980) 203)

Hybrid
J/ψ $f_0(980)$ bound state
DD* molecule
Tetraquark (c̅c̅s̅s̅)

DD* molecule
Tetraquark (c̅c̅ud̅)

ψ(2S) $f_0(980)$ bound state
Tetraquark (c̅c̅s̅s̅)

Still no clear idea about their nature
Non-observation of the bottomonium ground state was an annoying thorn in the side of quarkonium spectroscopy. Finally, after 30 years of work, the observation of the bottomonium ground state was an interesting discovery.

First measurement of $\eta_b$ by BABAR in radiative $Y(3S)$ and $Y(2S)$ decays, followed by CLEO.

Measured parameters:

- $BF (Y(3,2S)\rightarrow \gamma \eta_b) \times 10^{-4}$: $5.1 \pm 0.7 \pm 3.9 \pm 1.5$
- $Y(1S) - \eta_b(1S)$ mass splitting: $69.3 \pm 2.8$ MeV

Hyperfine mass splitting predictions (MeV):

- Potential models: $36-100$ ($36-87$ recent models)
- pNRQCD: $60.3 \pm 5.5 \pm 3.8 \pm 2.1$
- Lattice QCD: $40-71$

Confirmation from independent experiment or other decay channel desirable, as well as observation of $\eta_b(2S)$.
**Glueball:** isoscalar meson made of gluons, expected to be produced in gluon-rich environment such as radiative $J/\psi$ decays.

**Glueball lattice QCD spectrum**

Tensor ground state expected close to 2.2 – 2.5 GeV

1) C. Morningstar and M. Peardon, PRD 60 (1999) 034509
Search for glueball - Initial state radiation

**Initial State Radiation:**
Radiation of photon(s) by incoming electron(s)
→ Reduce center of mass energy

\[ \sqrt{s'} < \sqrt{s} \]

Production of many resonances, even with nominal \( \sqrt{s} \) fixed

Select \( J/\psi \) in ISR events

![Graphs showing \( J/\psi \) decay modes](image-url)
Search for glueball - Results

No sign of glueball

Upper limit $\text{BF}(J/\psi \rightarrow \gamma \xi) \times \text{BF}(\xi \rightarrow KK) @ 90\% \text{ CL}$

- $K^+K^- : < 1.4 \times 3.3 \times 10^{-5}$ depending on spin/helicity for $\xi$
- $K_S K_S : < 1.1 \times 2.6 \times 10^{-5}$ depending on spin/helicity for $\xi$

Below branching fractions reported by Mark III

arXiv:1007.3526 to be published in PRL
Search for light Higgs

Light exotic particles could be discovered at BABAR
NMSSM and Light CP-odd Higgs

Light CP-odd Higgs in NMSSM

- NMSSM proposed to solve the “μ problem” and reduce amount of fine tuning
- Add one CP-odd Higgs, one CP-even Higgs and one neutralino to MSSM content
- A light CP-odd Higgs $A^0$ with mass lower than $2m_b$ is not excluded by LEP constraints
- Could explain the excess of $b\bar{b}$ events seen at LEP at $\sim 114$ GeV if $h_1 \rightarrow A^0 A^0$ is dominant
- Radiative $\Upsilon(nS)$ decays offer an ideal environment to search for light

Radiative $\Upsilon(nS)$ decays

- $\Upsilon(nS) \rightarrow \gamma A^0$ is a two-body decay
  - $A^0 \rightarrow l^+ l^-$ ($l=e,\mu,\tau$) decays, full/partial final state
  - invisible decay $A^0 \rightarrow \chi_1 \chi_1$ if $m_{A^0} > 2m_{\chi_1}$
- Mixing $\eta_b - A^0$ could lead to huge enhancement.

NMSSM and Light CP-odd Higgs

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- Radiative $Y(nS)$ decays offer an ideal environment to search for light

Lepton universality

- In the SM, decay width $Y(nS) \rightarrow l^+l^-$ independent of lepton type, except for small mass effects, and one expects
  \[ R_{ll'} = \frac{\Gamma^{(em)}(nS \rightarrow ll)}{\Gamma^{(em)}(nS \rightarrow l'l')} \approx 1 \quad R_{\mu\mu} \sim 0.992 \]
- New Physics (2HDM(II), NMSSM, Little Higgs, ...) can induce deviations from SM. The effect is often larger if one lepton is a $\tau$.

In NMSSM scenario, a light CP-odd Higgs could mediate

- $Y(1S) \rightarrow \gamma A^0, A^0 \rightarrow l^+l^-$
- $Y(1S) \rightarrow \gamma \eta_b, \eta_b \rightarrow A^0 \rightarrow l^+l^-$

Diagram showing $R_{ll'}$ vs. $m_{A^0}$ with resonant and non-resonant contributions.

Axion-like particles and dark matter

- Motivated by the positron excess reported by PAMELA\(^1\) (confirmed by FERMI\(^2\))
- Dark matter is a TeV-scale particle \(\psi\) annihilating into a light pseudoscalar “axion” and a scalar with subsequent decay scalar \(\rightarrow\) axion axion
- Several phenomenological constraints on the axion mass and decay channels: absence of antiprotons, \(\pi^0\) and \(\gamma\) production, annihilation cross-sections,...

Explicit model

- Light pseudoscalar \(a\) and scalar \(s\) with
  \[ m_a \sim O(500 \text{ MeV}) \quad \text{and} \quad m_s \sim O(10 \text{ GeV}) \]
  - Dominant decay \(\psi\bar{\psi} \rightarrow sa, s \rightarrow aa\)

Predictions

Mass axion between 360 and 800 MeV
Decay axion \(\rightarrow\mu\mu\) dominant

\[
BF(Y \rightarrow \gamma \text{ axion } ) \approx 3 \times 10^{-6} \sin^4 \beta \left( 1 \text{ TeV} / f_a \right)^2 \quad f_a: \text{ axion decay constant of } O(\text{TeV})
\]

General considerations on light Higgs searches

Two-body decay: photon energy is related to Higgs (recoil) mass

General strategy

- Event selection (improve purity of signal)
- Scan di-lepton mass (fully reconstructed final state) or photon energy spectrum for bumps
- Derive Higgs characteristics or upper limits

Results from CLEO on $BF(Y(1S) \rightarrow \gamma A^0) \times BF(A^0 \rightarrow l^+l^-)$

Upper limits @ 90% CL

- $A^0 \rightarrow \mu^+\mu^- \; 10^{-6} \sim 10^{-5}$ \quad $m_{A^0} \; 0.2 \sim 3.57 \text{ GeV}$
- $A^0 \rightarrow \tau^+\tau^- \; 10^{-5} \sim 10^{-4}$ \quad $m_{A^0} \; 4.0 \sim 9.5 \text{ GeV}$
- $A^0 \rightarrow \text{invisible} \; 10^{-5} \sim 10^{-3}$ \quad $m_{A^0} \; 0 \sim 8.4 \text{ GeV}$
Event selection

- Fully reconstructed, 2 tracks and a photon with \( E_{\gamma}^* > 0.2 \text{ GeV} \)
- Particle Id, one or two tracks must be identified as muon(s)
- Energy and beam spot constraints for \( Y(2,3S) \) candidate
- Muon pair and photon must be back-to-back in the CM frame

Major backgrounds

- **QED:** \( e^+e^- \rightarrow \gamma \mu^+\mu^- \)
- \( \rho^0 \) production in ISR: \( e^+e^- \rightarrow \gamma \rho^0 \rightarrow \gamma \pi^+\pi^- \)
  - Suppress by requiring both tracks identified as \( \mu \) in the range
    \( 0.5 < m_{A_0} < 1.05 \text{ GeV} \)
- \( Y(1S) \) production in ISR: \( e^+e^- \rightarrow \gamma Y(1S) \)
- \( Y(1S) \) in \( Y(2,3S) \) decays: \( Y(2,3S) \rightarrow \gamma_2 \chi_b(1,2P), \chi_b(1,2P) \rightarrow \gamma_1 Y(1S) \)
  - Reject events with a secondary photon \( E_{\gamma}^* > 0.1 \) (0.08) GeV for \( 2S \) (1S)

**Signal efficiency:** \( \sim 25\% - 55\% \) (as fcn of \( m_R \))
Event selection

- Leptonic decays for both $\tau$: $ee$, $e\mu$ and $\mu\mu$ modes
- Partially reconstructed, 2 tracks of opposite charge and a photon with $E_\gamma > 0.1$ GeV
- Eight discriminating variables:
  - $E_{\text{tot}}$, $P_T$, missing mass/angle, angle photon-lepton plane, angle track-track or track-photon, angle tracks
- Optimization in 5 overlapping regions (reduce discontinuities in efficiency)

Major backgrounds

- QED: $e^+e^- \rightarrow \gamma \tau^+\tau^-$
- Higher order QED, such as $e^+e^- \rightarrow e^+e^- e^+e^-$, $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$
- $\Upsilon(1S)$ in $\Upsilon(2,3S)$ decays: $\Upsilon(2,3S) \rightarrow \gamma_2 \chi_b(1,2P)$, $\chi_b(1,2P) \rightarrow \gamma_1 \Upsilon(1S)$

Signal efficiency: $\sim$ 10%-14% ($ee$), 22%-26% ($e\mu$), 12%-20% ($\mu\mu$) (as fcn of $E_\gamma$)
Event selection

- Invisible $A^0$ decay, only one single photon with $E^*_\gamma > 2.2$ GeV
- No charged tracks
- Additional discriminating variables: $\cos(\theta^*_\gamma)$, extra neutral energy, photon quality
- Optimization in 2 regions (trigger performances)
  - low $E^*_\gamma$: $2.2 < E^*_\gamma < 3.7$ GeV
  - high $E^*_\gamma$: $3.2 < E^*_\gamma < 5.5$ GeV

Major backgrounds

- QED: $e^+e^- \rightarrow \gamma\gamma$ and $e^+e^- \rightarrow \gamma\gamma\gamma$
- Radiative Bhabha: $e^+e^- \rightarrow e^+e^-\gamma$
- Two-photon: $e^+e^- \rightarrow e^+e^-\gamma + X$

Signal efficiency: $\sim 10\%$ ($E^*_\gamma > 3$ GeV), $\sim 20\%$ ($E^*_\gamma < 3$ GeV)

Trigger: special single photon trigger designed for this kind of analysis
Fit procedure

- Extended unbinned maximum likelihood fit in 1951 intervals of reduced mass $m_r = (m_{\mu\mu}^2 - 4^2 m_{\mu}^2)^{1/2}$ from 0.212 – 9.3 GeV
- Signal
  - Sum of two Crystal-Ball functions (Gauss + power-law tail)
- Peaking background, $\phi, J/\psi, \psi(2S), \Upsilon(1S)$
  - Sum of two Crystal-Ball functions
  - $J/\psi$ and $\psi(2S)$ veto

- Continuum background
  - tanh for $m_{A_0} < 0.23$ GeV, Chebychev polynomial above

Distribution of results

No significant outliers, agrees with a standard normal distribution for **null hypothesis**
**Fit procedure**

- Simultaneous binned ML fit to all modes to determine background parameters (no signal)
- Fit signal yield fixing some background parameters in the range 0.2 – 4.5 GeV
- Signal
  - Crystal-Ball functions
- $\Upsilon(3S) \rightarrow \gamma \chi_{bJ}(2P), \chi_{bJ}(2P) \rightarrow \gamma_1 \Upsilon(1S,2S)$ background,
  - Crystal-Ball functions
- Continuum background $^1$
  - $(p(1-x)/E_\gamma^{q_s} + s/E_\gamma^5) F(x)$ with $x = 2E_\gamma / m_{3S}$.

**Distribution of results**

No significant outliers, agrees with a standard normal distribution for **null hypothesis**

---

**Y(3S)→γA⁰, A⁰→invisible**  -  **Signal extraction**

**Fit procedure**

- Extended unbinned maximum likelihood fit of missing mass squared $m^2_X \equiv m^2_{Y(3S)} - 2E^*_{\gamma} m_{Y(3S)}$
  - low $E^*_{\gamma}$ \(0 < m_{A^0} < 6\) GeV
  - high $E^*_{\gamma}$ \(6 < m_{A^0} < 7.8\) GeV
  - Step size 25 MeV ($E^*_{\gamma} < 3$ GeV), 100 MeV ($E^*_{\gamma} > 3$ GeV)
  - Resolution $\sigma(m^2_X) \ 0.7 - 1.5$ GeV²

- **Signal**
  - Crystal-Ball function

- **QED: e⁺e⁻ → γγ**
  - Shape and yield fixed using data

- **Radiative Bhabha and two-photon**
  - Exponential function (continuum)

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No statistically significant signal

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$m_{A^0} = 5.2$ GeV (low $E^*_{\gamma}$)

$m_{A^0} = 7.275$ GeV (high $E^*_{\gamma}$)
Y(3S,2S) → γA⁰, A⁰ → µ⁺µ⁻  -  Results

\[ \tan \beta = 10, \mu = 150 \text{ GeV}, M_{1,2,3} = 100,200,300 \text{ GeV} \]

Combined

F2B, UL (10⁻⁶)
UL (0.26-8.3) x 10⁻⁶
@ 90% CL

BR(Y → γA⁰)

\[ A⁰ = \cos \theta_A A_{MSSM} + \sin \theta_A A_S \]

0 < m_A⁰ < 2m_τ
2m_τ < m_A⁰ < 7.5 GeV
7.5 < m_A⁰ < 8.8 GeV
8.8 < m_A⁰ < 9.2 GeV

Light CP-odd Higgs clearly disfavored
$Y(3S, 2S) \rightarrow \gamma A^0, A^0 \rightarrow \mu^+ \mu^-$ - Results

Severe constraints on axion-like particle

"Favored region" for axion-like particle
Upper limits (90% CL)

\[ \text{BF}(Y(3S) \rightarrow \gamma A^0) \times \text{BF}(A^0 \rightarrow \tau^+ \tau^-) < (1.5 - 16) \times 10^{-5} \]
\[ \text{BF}(\eta_b \rightarrow \tau^+ \tau^-) < 8\% \]

No evidence of light CP-odd Higgs
\[ \Upsilon(3S) \rightarrow \gamma A^0, \quad A^0 \rightarrow \text{invisible} \]

- **Result**

**Upper limits (90% CL)**

\[ \text{BF}(\Upsilon(3S) \rightarrow \gamma A^0) \times \text{BF}(A^0 \rightarrow \text{invisible}) < (0.7 - 31) \times 10^{-6} \]

Very light Higgs also disfavored

**Preliminary, arXiv:0808.0017**
Analysis strategy

- Measure ratio \( R_{\tau\mu}(Y(1S)) = \frac{\Gamma(Y(1S)\rightarrow\tau^+\tau^-)}{\Gamma(Y(1S)\rightarrow\mu^+\mu^-)} \)
- Tag \( Y(1S) \) mesons using the transition \( Y(3S)\rightarrow\pi^+\pi^- Y(1S) \)
- Fully reconstruct the \( Y(1S)\rightarrow\mu^+\mu^- \) final state, cut on track quality and particle identification for muons
- Select all one-track \( \tau \) decays (no lepton id)
- Multivariate classifier (BDT) to improve \( \tau^+\tau^- \) purity
  variables: event shape, \( \pi^+\pi^- \) mass/angle, \( \pi/\tau \)-daughter angle,...
- Reconstruct signal using the \( \mu^+\mu^- \) and \( \pi^+\pi^- \) recoil masses
  \( M^\text{recoil}_{\pi\pi} = (s + M^2_{\pi\pi} - 2sE^*_{\pi\pi})^{1/2} \)
  \( M_{\mu\mu} = \text{Mass } \mu^+\mu^- \text{ pair} \)

Signal efficiency: \( \varepsilon_{\mu\mu} \sim 45\% \) and \( \varepsilon_{\tau\tau} \sim 17\% \)
Fit procedure

- Extended unbinned maximum likelihood fit
  - muon sample: 2-dim likelihood on $M_{\text{recoil}}^{\pi\pi}$ and $M_{\mu\mu}$
  - tau sample: 1-dim likelihood on $M_{\text{recoil}}^{\pi\pi}$
- Simultaneous fit on both datasets to extract $N_{\text{tot}}$ and $R_{\tau\mu}$
  - Signal PDF fixed from MC
  - Bkg PDF floating (a few fixed from validation sample)

Systematic studies / checks

- Extensive studies on trigger, efficiencies, particle id, selection, PDF, final state radiation, ...
- Repeat analysis using only tau leptonic decays $\rightarrow$ consistent results

Result

$$R_{\tau\mu}(Y(1S)) = 1.005 \pm 0.013 \text{ (stat)} \pm 0.022 \text{ (syst)}$$

SM: $R_{\tau\mu}(Y(1S)) = 0.992$  
CLEO$^1$: $R_{\tau\mu}(Y(1S)) = 1.02 \pm 0.02 \pm 0.05$

No significant deviation from SM predictions

Dark matter and
dark forces
Existence of dark matter is well established, it constitutes about 23% of the mass-energy density of the observable universe.
A few anomalies

FERMI\(^1\)

Excess of electrons / positrons
Few / no antiprotons
Large annihilation cross section

FERMI HAZE\(^2\)

INTEGRAL\(^3\)

PAMELA\(^4\)

Dark matter with a new GeV-scale force?

1) FERMI Collab., PRL 102, 181101 (2009)
3) G. Weidenspointner et al., Astron. Astrophys. 450, 1013 (2006);
4) PAMELA Collab., PRL 102 (2009) 051101
Dark matter and Dark Force:

TeV-scale Dark matter particle and a new force with a force-carrier $\phi$ having a mass around the GeV. Dark matter annihilate into a pair of $\phi$ bosons, and each boson into an $e^+e^-$ pair. This naturally explain the previous anomalies:

- Hard lepton spectrum from boosted $\phi$

- No antiprotons, kinematically suppressed

- Sommerfeld enhancement boosts the thermal cross-section to levels needed to explain the observations

Inelastic dark matter

TeV-scale dark matter has an excited state a few MeV above the ground state. Enhance sensitivity of DAMA and decreases sensitivity of CDMS/XENON.

Can explain the positive observation from DAMA and null observations from CDMS/XENON

The idea of a hidden sector interacting weakly with the standard model has a rich history (e.g. axions). Recent astrophysical anomalies can be naturally by introducing a new ‘dark’ force(s) mediated by a new dark gauge boson(s) with a mass around a GeV (regardless of the detailed structure at the TeV-scale). The dark gauge boson(s) couples to the SM gauge bosons via kinetic mixing (other portals are possible, like higgs mixing).

\[ \mathcal{L}_{\text{int}} = \varepsilon F_{\mu \nu} B_{\mu \nu} \]

**G\text{D}** group can be
- Abelian: One dark photon \( A_D \)
- Non-abelian: Many dark bosons \( W_D \)

Thanks to their large integrated luminosity, B factories offer an ideal environment to probe this new sector.
The idea of a hidden sector interacting weakly with the standard model has a rich history (e.g. axions). Recent astrophysical anomalies can be naturally by introducing a new ‘dark’ force(s) mediated by a new dark gauge boson(s) with a mass around a GeV (regardless of the detailed structure at the TeV-scale). The dark gauge boson(s) couples to the SM gauge bosons via kinetic mixing (other portals are possible, like higgs mixing).

Re-interpret the upper limit on light Higgs search in $Y(ns) \rightarrow \gamma A^0$ decays*

Limit on $\varepsilon$ between $10^{-3} - 10^{-2}$

* As limit on $\varepsilon$ scales with luminosity$^{1/4}$, little improvement by analyzing all data
Search for $e^+e^- \rightarrow W_D W_D$, $W_D \rightarrow e^+e^-$ with $l=e, \mu$

Very clean mode, especially for 4 muons

Require 2 dilepton resonances with similar masses

Cut and count analysis with background estimated from sidebands

Use full BABAR dataset (540 fb$^{-1}$)

Extract upper limit on production cross-section and mixing $\varepsilon$

\[
\sigma(e^+e^- \rightarrow W'W')_{\text{low}} = N_c \frac{4\pi \varepsilon^2 \alpha_D \alpha}{3} \frac{E_{\text{cm}}^2}{E_{\text{cm}}^2} \sqrt{1 - \frac{4m_{W'}^2}{E_{\text{cm}}^2}} \left(1 + \frac{2m_{W'}^2}{E_{\text{cm}}^2}\right)
\]

\[
\sigma(e^+e^- \rightarrow W'W')_{\text{high}} = N_c \frac{4\pi \varepsilon^2 \alpha_D \alpha}{3} \frac{E_{\text{cm}}^4}{m_A^4} \sqrt{1 - \frac{4m_{W'}^2}{E_{\text{cm}}^2}} \left(1 + \frac{2m_{W'}^2}{E_{\text{cm}}^2}\right)
\]

$m_A < E_{\text{cm}}$

$m_A > E_{\text{cm}}$
No signal, limit on $\varepsilon$ between $10^{-4} - 10^{-3}$

Note: on-going analysis with initial state radiation will improve these limits
Since the dark sector is spontaneously broken at about a GeV, it is reasonable to expect that there is a dark Higgs boson at this scale too\(^1\). Therefore, we can have dark Higgs'-strahlung, analogous to Higgs-strahlung in the Standard Model, as an interesting channel of production. In non-abelian scenarios, a confined dark sector with dark quarks is also possible, resulting in dark mesons and dark baryons (dark "QCD").

Dark Higgs search

**Dark Higgs**

**Off-shell boson / 2 body loop induced decays**

\[ m_H < 2m_A \]

\[ m_H > 2m_A \]

**Direct decay**

\[ h \rightarrow A'A' \]

Invisible \( h_D \) decay

2 leptons final state

Prompt \( h_D \) decay

6 leptons final state

**And searches in**

meson decays: \( \pi^0/\eta \rightarrow \gamma A' \)

\( B \) decays : \( B^0 \rightarrow 4l \) and \( B^0 \rightarrow K(*)4l \)

**Interesting results to come**
Y(1S)→invisible decays

“Generic” Dark Matter model and Y(1S) decays

- Minimal model introducing a dark matter particle $\chi$ and a new scalar or gauge boson $U$ to serve as a s-channel annihilation mediator ($m_U > 2m_\chi$).

- Could increase the invisible decay width of the $Y(1S)$ predicted by SM$^1$ by orders of magnitude.

- Rate estimates are fairly model independent, based on cosmological observations and assuming time-reversal symmetry.

Rate predictions

\[
\begin{align*}
\text{BF}(Y(1S) \rightarrow \chi\chi) & \sim 4.2 \times 10^{-4} \text{ (s-wave)} \\
\text{BF}(Y(1S) \rightarrow \chi\chi) & \sim 1.8 \times 10^{-3} \text{ (p-wave)} \\
\text{BF}(Y(1S) \rightarrow \nu\nu) & \sim 9.9 \times 10^{-6}
\end{align*}
\]

Large increase from SM predictions

1) PLB 441 (1998) 419.
Analysis strategy

- Tag $Y(1S)$ mesons in $Y(3S)\rightarrow \pi^+\pi^- Y(1S)$ transition using the $\pi^+\pi^-$ pair
- Dipion recoil mass $M_{\text{rec}}$ should peak at $Y(1S)$ mass, $M_{\text{rec}} = (s + M^2_{\pi\pi} - 2sE^*_{\pi\pi})^{1/2}$
- Estimate peaking background from MC, use $Y(1S,2S)\rightarrow l^+l^-$ with one or two reconstructed leptons to check and correct simulations
- Blind analysis, optimize analysis using sidebands and MC

Event selection

- Two low-momentum oppositely-charged tracks
- Little extra activity
- Multivariate classifier (Random Forest) to improve signal purity:

Backgrounds

- Non-peaking background: suppressed by a factor > 1000
- Peaking background: $Y(3S)\rightarrow l^+l^-$ decays
Y(1S) → invisible - Results

Fit procedure

- Extended unbinned maximum likelihood fit of recoil mass $M_{\text{rec}}$
- Signal and peaking background
  - Crystal-Ball function
- Non-peaking background
  - $1^{\text{st}}$ order polynomial

Signal efficiency $\sim 18\%$

Results

Yield (fit) $2326 \pm 105$
Background $2444 \pm 123$
Signal $-118 \pm 105 \pm 124$

Upper limit (90% CL)

$\text{BF}(Y(1S) \rightarrow \text{invisible}) < 3.0 \times 10^{-4}$

Previous measurements $\text{BF}(Y(1S) \rightarrow \text{invisible})$

CLEO: $\text{BF} < 3.9 \times 10^{-3}$ @ 90% CL PRD 75 (2007) 031104
Belle: $\text{BF} < 2.5 \times 10^{-3}$ @ 90% CL PRL 98 (2007) 132001

No evidence of dark matter contribution in invisible Y(1S) decays
**Conclusion**

**BABAR** has a very rich physics program and has published more than 440 papers. There is still an active analysis program and many more results are expected.

Many tests of SM predictions, confirmed CKM mechanism as dominant source of CP-violation in meson decays.

No unambiguous sign of New Physics so far, but searches continues.

A super-B factory (SuperB / Belle II) would be a perfect complement to LHC for probing physics at the TeV-scale.

**The End**
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X(3915)

X(3940) / X(4160)

Y(4008) / Y(4260)

Z₁⁺(4050) / Z₂⁺(4250)
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**Z*(4430)**

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**Yb(10580)**

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