$B$-factory searches for forbidden/rare heavy flavour decays and dark photons

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on behalf of the $\text{B}A\text{BAR}$ and Belle Collaborations
Forbidden/rare heavy flavour decays

**definitions for this talk**

- **“forbidden”** = lepton and/or baryon number violating heavy flavour decays (LNV, BNV)
  - LN and BN conserved due to SM accidental symmetries
- **“rare”** = lepton flavour violating heavy flavour decays (LFV)
  - LF also SM accidental symmetry (conservation of each lepton flavour separately)
  - SM + neutrino mixing predicts minuscule charged LFV, not experimentally accessible
  - LNV always implies LFV
- **“heavy flavour”**: $b$ hadrons, $c$ hadrons, $\tau$ leptons
Introduction

Forbidden/rare heavy flavour decays

motivation

- why are these decays interesting? their detection would unveil New Physics, plus
  - no (or unmeasurably small) SM background, i.e., very precise SM predictions
  - many NP models naturally include possibly experimentally accessible signals
    - mainstream NP includes LFV (e.g. SUSY, LHT)
    - GUT, models with proton-decay NP include BNV
    - GUT, models with Majorana neutrinos NP include LNV
**Dark Photon**

- postulated member ($A'$) of hidden/dark sector of New Physics models
- may constitute *Dark Matter* and/or explain astrophysical anomalies
- may also explain the experiment vs. theory *discrepancy on the muon* $g-2$ anomaly
- may be produced in $e^+e^-$ collisions at $B$-factories energies
- kinetic mixing, i.e., photon-like coupling with smaller coupling constant $\alpha'$

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*If you only knew the power of the dark side.*
LNV/BNV/LFV on decays of $b$ hadrons
**Searches for LNV / LFV B mesons decays**

**B-factory searches summary**

- $B^0 \rightarrow \ell^+ \ell^-$, $\ell^+ \ell^- = e^+ \mu^-, e^+ \tau^-, \mu^+ \tau^-$
- $B^0 \rightarrow \pi^0 e^+ \mu^-$
- $B^+ \rightarrow X^- \ell^+ \ell'^+$, $X^- = \pi^-, K^-, \rho^-, K^{*-}, D^-$, $\ell^+ \ell'^+ = e^+ e^+, \mu^+ \mu^+, e^+ \mu^+$
- $B^+ \rightarrow X^0 \ell^+ \nu_h \rightarrow \ell'^+ \pi^-$, $X^0 = D^{*0}, \pi^0, \rho, \eta$, $\ell^+ \ell'^+ = e^+ e^+, \mu^+ \mu^+, e^+ \mu^+$

**Majorana neutrino mediation can produce two same-sign leptons**

![Diagram showing Majorana neutrino mediation producing two same-sign leptons.](image)
<table>
<thead>
<tr>
<th>basic analysis strategy for $B$ mesons decays at $B$-factories</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ require for $B$ candidate the expected $\left{ \begin{align*} m_{ES} &amp;= \sqrt{(\sqrt{s}/2)^2 - \left</td>
</tr>
<tr>
<td>▶ no true SM background events expected</td>
</tr>
<tr>
<td>▶ combinatorial / peaking background from mis-id. particles, momentum resolution</td>
</tr>
</tbody>
</table>
Searches for LNV / LFV $B$ mesons decays

- **$B$-factory searches for forbidden/rare heavy flavour decays and dark photons**

**LNV/BNV/LFV on decays of $b$ hadrons**

- **$B$AR PRD-RC 85, 071103 (2012)**
  - $B^+ \rightarrow X^- l^+ l'^+$, $X^- = \pi^-, K^-$, $l^+ l'^+ = e^+ e^+, \mu^+ \mu^+$

- **$B$AR PRD-RC 89, 011102 (2014)**
  - Extends previous search to other modes
  - $B^+ \rightarrow X^- l^+ l'^+$, $X^- = \pi^-, K^-, \rho^-, K^{*-}, D^-$, $l^+ l'^+ = e^+ e^+, \mu^+ \mu^+, e^+ \mu^+

- **$B$AR PRD 86, 012004 (2012)**
  - $B^+ \rightarrow h^+ \tau^\pm \ell^\mp$, with $\ell = e, \mu$

- **Belle PRD 84, 071106(R) (2011)**
  - $B^+ \rightarrow X^- l^+ l'^+$, $X^- = D^-$, $l^+ l'^+ = e^+ e^+, \mu^+ \mu^+, e^+ \mu^+$

- **Belle PRD 87, 071102 (2013)** search for Majorana neutrino $\nu_h \rightarrow \ell^\pm \pi^+$
  - $B^+ \rightarrow X^0 l^+ \nu_h(\rightarrow l'^+ \pi^-)$
  - $X^0 l^\pm \nu_h(\rightarrow l^+ \pi^-)$, $X^0 = D^{*0}, \pi^0, \rho, \eta$

- **$B$AR PRD 77 032007 (2008)**
  - $B^0 \rightarrow e\mu$

- **$B$AR PRD 77 091104 (2008)**
  - $B^0 \rightarrow e\tau$, $B^0 \rightarrow \mu\tau$

- **$B$AR PRL 99 051801 (2007)**
  - $B^0 \rightarrow \pi^0 e\mu$

- **$B$AR PRD 73 092001 (2006)**
  - $B^0 \rightarrow K^0 e\mu$, $B^0 \rightarrow K^{*0} e\mu$

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$B^+ \rightarrow X^- \ell^+ \ell'^+$,  \textit{BABAR} PRD-RC 85, 071103 (2012)

- $B^+ \rightarrow X^- \ell^+ \ell'^+$,  $X^- = \pi^-, K^-, \rho^-, K^{*-}, D^-$,  $\ell^+ \ell'^+ = e^+ e^+, \mu^+ \mu^+, e^+ \mu^+$
- reconstruct $B$ mass and energy, use BDT multivariate selector

$B^+ \rightarrow \pi^- e^+ \mu^+$:  $m$,  $\Delta E$,  BDT output

- no significant signal on signal (solid dark green) + bkg fits
analysis

- require $B_{\text{tag}}$ fully reconstructed in hadronic mode
- indirectly reconstruct tau mass using $B_{\text{tag}}$, $h$, $\ell$, $E_{\text{beam}}$
- $\tilde{p}_{\tau} = -\tilde{p}_{\text{tag}} - \tilde{p}_h - \tilde{p}_\ell$
- $E_\tau = E_{\text{beam}} - E_h - E_\ell$
- $m_\tau = \sqrt{E_\tau^2 - |\tilde{p}_\tau|^2}$

indirectly reconstructed $m_\tau$ distributions

- $B^+ \rightarrow h^+ \tau^\pm \ell^\mp$, $\text{BABAR}$ PRD 86, 012004 (2012)
B→(L, Λc+)l, BNV/LNV, BABAR PRD-RC D83, 091101 (2011)

- searches for: $B^0 \rightarrow \Lambda^+_c l^-$, $B^- \rightarrow \Lambda l^-$, $B^- \rightarrow \bar{\Lambda} l^-$

![Graphs showing $B \rightarrow \Lambda^+_c e^-$ and $B \rightarrow \Lambda^+_c \mu^-$ decay distributions](image_url)

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Searches for LFV $\Upsilon$ decays

- **$\textbf{B}a\textbf{B}a\textbf{R}$ PRL 104, 151802 (2010)**
  - $\Upsilon(2S, 3S) \rightarrow l^\pm l'^\mp$, $l^\pm l'^\mp = e^\pm \tau^\mp, \mu^\pm \tau^\mp$
- **$\textbf{B}a\textbf{B}a\textbf{R}$ preliminary, N. Tasneem, Lake Louise, Feb 2018**
  - $\Upsilon(3S) \rightarrow e^\pm \mu^\mp$
Search for Lepton Flavour Violating Decay in $\Upsilon(3S) \rightarrow e^{\pm} \mu^{\mp}$

- search in 27 fb$^{-1}$ $\Upsilon(3S)$ sample
  - $\Gamma_{\Upsilon(4S)} \approx 1000 \times \Gamma_{\Upsilon(3S)} \Rightarrow B[\Upsilon(3S) \rightarrow e\mu] \approx 1000 \times B[\Upsilon(4S) \rightarrow e\mu]$
- require 1 identified $e$ candidate + 1 identified $\mu$ candidate
- measured $p_e^*, p_{\mu}^*$ compatible with $\sqrt{s}/2$: $\sqrt{p_{e}^* + m_e^2} \approx \sqrt{s}/2$ $\sqrt{p_{\mu}^* + m_{\mu}^2} \approx \sqrt{s}/2$
- both tracks in EMC acceptance: $24^\circ < \theta_{\text{lab}} < 130^\circ$
- $e$ and $\mu$ tracks back-to-back, $\theta_{e\mu}^{\text{CM}} > 179^\circ$
- $\mu$ energy deposit in EMC $> 50$ MeV
- non-peaking background estimated with data (78 fb$^{-1}$ $\Upsilon(4S)$ sample)
- peaking background studied in simulated events vs. data inverting well simulated cuts
Search for Lepton Flavour Violating Decay in $\Upsilon(3S) \rightarrow e^{\pm} \mu^{\mp}$

Data vs. simulated signal (red) and expected backgrounds

- no selection but identified $e$ and $\mu$
- test on unblinded 3 fb$^{-1}$ of data
- MC signal normalization arbitrary, to be visible in the plot
Search for Lepton Flavour Violating Decay in $\Upsilon(3S) \rightarrow e^\pm \mu^\mp$

Mass distribution after all selection requirements

- red: simulated signal
- gray: estimated background
- points with errors: data

$B[\Upsilon(3S) \rightarrow e\mu] = (1.0 \pm 1.4 \text{ stat.} \pm 0.8 \text{ syst.}) \cdot 10^{-7}$

$B[\Upsilon(3S) \rightarrow e\mu] < 3.6 \cdot 10^{-7}$ 90% CL
Limits on BRs of LNV/BNV/LFV decays of $B$, $\Upsilon$ hadrons

90% or 95% CL upper limits on BRs of LNL, BNL, LFV decays of beauty hadrons

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B-factory searches for forbidden/rare heavy flavour decays and dark photons

LNV/BNV/LFV on decays of charm hadrons

1.28 GeV

charm

R/G/B

2/3

1/2
B-factory searches for forbidden/rare heavy flavour decays and dark photons

Searches for LNV / LFV charmed hadron decays

**BABAR PRD 84, 072006 (2011)**

- $X^+_c \rightarrow h^\pm \ell^\mp \ell'(\ell'^\pm)$, $X^+_c = D^+, D_s^+, \Lambda_c^+$, $h = \pi^-, K^-, \bar{p}$, $\ell'(\ell'^\pm) = e^+, \mu^+$
- LNV (and/or LFV): $\ell\ell'(\ell'^\pm) = e^\pm e^\pm, \mu^\pm \mu^\pm, e^\pm, \mu^\pm, e^\pm \mu^\mp$
- FCNC: $\ell\ell'(\ell'^\pm) = e^\pm e^\mp, \mu^\pm \mu^\mp$

**BABAR PRD 86, 032001 (2012)**

- search for $D^{*+} \rightarrow D^0 \pi^+$, $D^0 \rightarrow e^\pm \mu^\mp$
- (analysis also searches for FCNC decays $D^0 \rightarrow e^+ e^-, D^0 \rightarrow \mu^+ \mu^-$)
- require $p^*_D > 2.5$ GeV to select $e^+ e^- \rightarrow c\bar{c}$, removing $B$ decays

**$m_{D^0}$ and $\Delta m$ plots**

- $\Delta m = m(D^0 \pi^+) - m(D^0)$
- black: $D^0 \rightarrow e^+ \mu^-$
- blue: misid $D^0 \rightarrow \pi^+ \pi^-$
- red: misid $D^0 \rightarrow K^- \pi^+$

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**Searches for LNV / LFV charmed hadron decays (older)**

<table>
<thead>
<tr>
<th><strong>BABAR</strong> PRL 93 191801 (2004)</th>
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<td>$D^0 \rightarrow e\mu$</td>
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Limits on BRs of LNV/BNV/LFV decays of charm hadrons

90% or 95% CL upper limits on BRs of LNL, BNL, LFV decays of charm hadrons

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LNV/BNV/LFV tau decays

$1.777 \text{ GeV}^{-1}$

$\tau^{-1/2}$
- clean and powerful tool to search for New Physics
- $B$ factories are the best experimental facilities for these searches

**typical LFV tau decay search at $B$-factory**

- neutrinoless tau decay facilitates reconstruction
- reconstruct tau from final state particles, e.g., $\mu \gamma$, $e^- e^+ e^-$, $e^- h$, $e^- h^+ h^-$
- compute energy-constrained invariant mass of tau candidate $m_{EC}$
  - constraint: in center-of-mass frame, $E^* = \frac{\sqrt{s}}{2}$
- compute energy of tau candidate in CM, $E^*$, and $\Delta E = E^* - \frac{\sqrt{s}}{2}$
- fit for signal on $m_{EC} - \Delta E$ plane
- LFV tau decay candidates peak on both $m_{EC}$ and $\Delta E$
Most recent LFV searches results from the $B$-Factories

- BaBar $\tau \rightarrow 3$ leptons, PRD 81 111101 (2010)
- Belle $\tau \rightarrow 3$ leptons, PLB 687 139 (2010)
- Belle $\tau \rightarrow \ell K^0_S$, $\tau \rightarrow \ell K^0_S K^0_S$, PLB 692 4 (2010)
- Belle $\tau \rightarrow \ell V$, PLB 699 251 (2011)
- Belle $\tau \rightarrow \ell hh'$, PLB 719 346 (2013)
HFLAV collects limits on BRs of Tau LFV/LNV/BNV decays

90% CL upper limits on $\tau$ LFV decays

- ATLAS
- BaBar
- Belle
- CLEO
- LHCb
HFLAV combined limits on BRs of Tau LFV/LNV/BNV decays

90% CL upper limits on $\tau$ LFV decays

- $e^- \gamma$
- $\mu^- \gamma$
- $e^- \pi^0$
- $\mu^- \pi^0$
- $e^- K^0_S$
- $\mu^- K^0_S$
- $e^- \eta$
- $\mu^- \eta$
- $e^- \eta'$ $(958)$
- $\mu^- \eta'$ $(958)$
- $e^- \rho^0$
- $\mu^- \rho^0$
- $e^- \omega$
- $\mu^- \omega$
- $e^- K^*(892)^0$
- $\mu^- K^*(892)^0$
- $e^- K^*(892)^0$
- $\mu^- K^*(892)^0$
- $e^- \phi$
- $\mu^- \phi$
- $e^- e^+$
- $e^- \mu^+$
- $\mu^- e^+$
- $\mu^- \mu^+$

● BaBar  ● Belle  ● LHCb  ● HFLAV combination

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Belle II expected limits on BRs of Tau LFV/LNV/BNV decays

branching fraction 90% CL upper limits

(plot from M. Barret, FPCP 2015)
Dark photon searches
Dark Photon models

- Vector boson ($A'$) belonging to hidden-sector accounting for dark matter
- Coupling (loose) to SM matter via kinetic mixing with photon, $\Delta \mathcal{L} = -\frac{1}{2} \epsilon F_{\mu\nu} F'_{\mu\nu}$
- Mass of order GeV
- $A'$ may be invisible, decaying into lighter dark-matter particles that escape detection
  - Long-lived & feebly interacting, or decaying into lighter dark-matter particles that escape detection
  - Spoiling limits obtained assuming it must decay into ordinary matter particles
- $A'$ may also decay to ordinary matter
  - Kinetic mixing predicts relative branching fractions to available decay modes
- In some models, dark photon can couple preferentially to some flavours
  - Muonic dark force
### Most recent or important Dark Photon searches

#### Search for dark photon decaying to electrons or muons
- **BABAR** PRL 113 201801 (2014)  
  \[ e^+ e^- \rightarrow A' \gamma, \quad A' \rightarrow e^+ e^-, \mu^+ \mu^- \]  
  \((514 \text{ fb}^{-1})\)

#### Search for dark photon decaying to invisible
- **BABAR** PRL 119 131804 (2017)  
  \[ e^+ e^- \rightarrow A' \gamma, \quad A' \rightarrow \text{invisible} \]  
  \((53 \text{ fb}^{-1})\)
  - relies on special single-photon trigger

#### Search for dark photon in \(\eta\) decays and decaying to \(\pi^+ \pi^-\)
- **Belle** PRD 94 092006 (2016)  
  \[ D^0 \rightarrow K_S \eta, \quad \eta \rightarrow A' \gamma, \quad A' \rightarrow \pi^+ \pi^- \]  
  \((977 \text{ fb}^{-1})\)

#### Search for muonic dark force
- **BABAR** PRD 94 011102 (2016)  
  \((514 \text{ fb}^{-1})\)
  - final state 4 muons

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Experimental constraints on Dark Photon decaying to visible states

plot from PRL 113 201801 (2014)
Experimental constraints on Dark Photon in $\eta \rightarrow U'\gamma$, $U' \rightarrow \pi^+\pi^-$

$m(\pi^+\pi^-)$ of $U'$ data candidates

limits on $U'$ mass and coupling

- plots from PRD 94 092006 (2016)
- $\alpha_{U'} = \epsilon^2/(4\pi)$ in terms of $\epsilon$ of previous dark photon plots
Experimental constraints on Dark Muonic Force

plot from PRD 94 011102 (2016)
Experimental constraints on Dark Photon decaying to invisible

\[ \gamma \rightarrow \text{invisible} \]

\[ (g-2)_{\mu} \pm 5\sigma \]

\[ (g-2)_{e} \]

\[ K \rightarrow \pi \nu \nu \]

\[ B A B A R 2017 \]

\[ \text{BABAR plot from PRL 119 131804 (2017)} \]
Belle II sensitivity for Dark Photon to invisible

- Belle II has
  - dedicated single-photon trigger for searches
  - more hermetic electromagnetic calorimeter w.r.t. BABAR (non projective)
- Chris Hearty estimated the Belle II sensitivity for Dark Photon to invisible (U.S. Cosmic Visions: New Ideas in Dark Matter, March 2017)

Reach masses of 9.1–9.5 GeV/c² with lower trigger threshold (vs 8 GeV/c² for BaBar)

Better calorimeter hermeticity to suppress $e^+e^- \rightarrow \gamma \gamma$
Many present and future facilities other than $B$-factories effective on Dark Photon searches, e.g., LHCb, SHiP, ...
Conclusions
Summary and conclusions

- No evidence of New Physics on B-factories searches for
  - LNV, BNV and LFV decays of B mesons, charmed hadrons, tau
  - Dark photons
- B-factories are
  - Best location for tau LFV, LNV and BNV searches
  - Competitive for dark photon searches
  - Competitive for B meson, charm hadron LFV, LNV and BNV searches
- Belle II will significantly improve experimental reach on
  - Tau LFV, LNV and BNV searches
  - Dark photon searches
- LHCb competitive on
  - Bottom and charm hadron LFV, LNV and BNV searches
  - Dark photon searches

SM rules still what is rare or forbidden
Backup Slides
B-factory searches for forbidden/rare heavy flavour decays and dark photons

The BABAR experiment

BABAR detector at PEP-II, SLAC National Accelerator Laboratory

BABAR detector

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

BABAR main focus: study of CP violation in B mesons

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**BabAR** searches for forbidden/rare heavy flavour decays and dark photons

**The BabAR experiment**

**BabAR: CM energy, collected luminosity**

**Center-of-mass energies**

\[ \Upsilon(nS) \text{ resonances (CUSB)} \]
\[ \Gamma(1S, 2S, 3S) \sim 20-50 \text{ keV} \]
\[ \text{beam energy spread} \sim 5 \text{ MeV} \]

**Data samples (large and clean)**

<table>
<thead>
<tr>
<th>( \Upsilon )</th>
<th>Events</th>
<th>( \mathcal{L} ) (fb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Upsilon(4S) \rightarrow B \bar{B} )</td>
<td>( 471 \cdot 10^6 )</td>
<td>424</td>
</tr>
<tr>
<td>( \Upsilon(3S) \rightarrow \text{visible} )</td>
<td>( 121 \cdot 10^6 )</td>
<td>28</td>
</tr>
<tr>
<td>( \Upsilon(2S) \rightarrow \text{visible} )</td>
<td>( 99 \cdot 10^6 )</td>
<td>14</td>
</tr>
<tr>
<td>off-peak</td>
<td></td>
<td>48</td>
</tr>
<tr>
<td>single-( \gamma ) trigger</td>
<td></td>
<td>53</td>
</tr>
</tbody>
</table>

**Integrated luminosity over time**

Data-taking ended in April 2008.

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The BABAR search
search for

\[ e^- e^+ \rightarrow \gamma A', \; A' \rightarrow \text{invisible (e.g. } \chi \bar{\chi}) \]

i.e. one single photon and nothing else

- reconstruct \( A' \) mass, \( M^2_{A'} = s - 2\sqrt{s}E^*_\gamma \)
- scan \( M^2_{A'} \) distribution, fitting bumps over smooth background, compute significance

\[ \sigma \propto \alpha' \alpha = \epsilon^2 \alpha^2 \]

[\( A' \) decay width \( \Gamma_{A'} \) expected \( \ll \) experimental resolution on \( M_{A'} \)]
**Babar** collected \( \sim 53 \, \text{fb}^{-1} \) of data with dedicated single photon triggers during its last year of data taking, mostly collected at the \( \Upsilon(3S) \) and \( \Upsilon(2S) \) peaks.

### Hardware trigger
- \( \geq 1 \) EMC cluster with \( E_{\text{LAB}} > 800 \, \text{MeV} \)
- 52.9 fb\(^{-1}\) data sample

### Software triggers
- **high energy photon trigger line**
  - \( E^*_{\gamma} > 2 \, \text{GeV} \)
  - no track from interaction region (SVT [+DCH])
  - active on full 52.9 fb\(^{-1}\) data sample
- **low energy photon trigger line**
  - \( E^*_{\gamma} > 1 \, \text{GeV} \)
  - no track from interaction region (SVT [+DCH])
  - active on 35.9 fb\(^{-1}\) out of the total 52.9 fb\(^{-1}\) data sample
## Low-mass and high-mass pre-selections

**Low-mass** \(-4 < M_{A'}^2 < 36 \text{ GeV}^2\)

- approximately \(0 < M_{A'} < 5.5 \text{ GeV}\)
- background:
  - \(e^+e^- \rightarrow \gamma\gamma\) with lost \(\gamma\)
  - peaking at \(M_{A'} = 0\)
  - low tail away from \(M_{A'} = 0\)
- \(E_{\gamma}^* > 3 \text{ GeV}\)
- \(|\cos \theta_{\gamma}^*| < 0.6\) against radiative Bhabha
- no track from interaction region
- no DCH-only track with \(p^* > 1 \text{ GeV}\)

**High-mass** \(24 < M_{A'}^2 < 69 \text{ GeV}^2\)

- approximately \(5.5 < M_{A'} < 8.0 \text{ GeV}\)
- background:
  - \(e^+e^- \rightarrow e^+e^-\gamma\) with lost \(e^+e^-\)
  - tail of \(e^+e^- \rightarrow \gamma\gamma\)
  - large but smooth background
- \(E_{\gamma}^* > 1.5 \text{ GeV}\)
- \(|\cos \theta_{\gamma}^*| < 0.6\) against radiative Bhabha
- no track from interaction region
- no DCH-only track with \(p^* > 0.1 \text{ GeV}\)
### Boosted Decision Tree (BTD) discriminant

#### 12 input variables

- fired vs. expected EMC crystals
- two transverse moments of EMC shower
- total EMC energy other than most energetic photon
- CM energy and polar angle of 2nd most energetic EMC cluster
- azimuthal angle difference $\Delta\phi_{12}$ between the highest and second-highest energy EMC clusters (the $e^+e^- \rightarrow \gamma\gamma$ events with partial energy deposit in the EMC tend to peak at $\Delta\phi_{12} \sim \pi$)
- distance of missing momentum from EMC crystal edges in $\theta$ and $\phi$
- angle $\Delta\phi_{NH}$ between the primary photon and the IFR cluster closest to the missing momentum direction ($e^+e^- \rightarrow \gamma\gamma$ events peak at $\cos \Delta\phi_{NH} \sim -1$)
- variable measuring how close is missing momentum to uninstrumented IFR regions
- $\cos \theta^*$ (discriminates between signal and background distributions)

- background sample: 25k (3 fb$^{-1}$) of $\Upsilon(3S)$ data
- signal sample: 25k simulated $e^+e^- \rightarrow A'\gamma$, $A' \rightarrow$ invisible, uniform mass distribution
- BDT trained separately in low-mass and high-mass regions
B-factory searches for forbidden/rare heavy flavour decays and dark photons

The \textit{BaBar} search

\textbf{BDT response}

\textbf{Low-mass selection}

\textbf{High-mass selection}


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### Tight, loose and background selection regions

#### Tight selection region, $R_T$
- BDT cut, FoM$_1 = \frac{\epsilon_S}{\max(N_{BKG}, 2.3)}$
- maximal suppression of peaking bkg
- appropriate for low-mass $A'$
- $-0.4 < \cos \theta^{\gamma^*} < 0.6$
  
  $(e^+ e^- \rightarrow \gamma \gamma$ photons in EMC barrel)

#### Loose selection region, $R_L$
- BDT cut, FoM$_2 = \frac{\epsilon_S}{\sqrt{N_{BKG}}}$
- appropriate for high-mass $A'$
- smooth background

#### Background selection region, $R_B$
- select background using BDT output
  (use to fit background shape on data)

### Define 9 + 4 non-overlapping data samples

#### 9 low-mass ($0.0 < M_{A'} < 5.5$ GeV) samples
- $\{R_{L'}, R_T, R_B\} \times \{2S, 3S, 4S\} = 9$ samples
- $R_{L'} = R_L$, but excluding $R_T$

#### 4 high-mass ($5.5 < M_{A'} < 8.0$ GeV) samples
- $\{R_L, R_B\} \times \{2S, 3S\} = 4$ samples
Selection of signal and background samples

**tight optimization (FoM₁ / Rₜ)***

- bkg at low $M'_A$:  
  - $e^+ e^- \rightarrow \gamma \gamma$ with lost $\gamma$  
  - peaking bkg at $M_A' = 0$  
  - low tail away from $M_A' = 0$  

- FoM₁ = $\frac{\epsilon_S}{\max(N_{BKG}, 2.3)}$  
  - maximal suppression of peaking bkg  
  - poor $S/B$ separation fitting $M_A'$ peak

**loose optimization (FoM₂ / Rₜ)***

- bkg at high $M'_A$:  
  - $e^+ e^- \rightarrow e^+ e^- \gamma$ with lost $e^+ e^-$  
  - tail of $e^+ e^- \rightarrow \gamma \gamma$  
  - $N_{BKG} \gg 1$ but smooth  

- FoM₂ = $\frac{\epsilon_S}{\sqrt{N_{BKG}}}$

**Pure background selection (R_B)**

- select pure bkg (for simultaneous fits)
Crystal Ball for $e^+e^- \rightarrow A'\gamma$, from simulation (parameters depend on $M_{A'}$)

Correct simulated resolution using real data sample $e^+e^- \rightarrow \gamma\gamma$, where one photon converts to $e^+e^-$ in detector material

Example signal+background fit
B-factory searches for forbidden/rare heavy flavour decays and dark photons

The B\textit{a}B\textit{a}R search

**Background PDF**

- low-mass region: second-order polynomial + Crystal Ball for $e^+e^- \rightarrow \gamma\gamma$
- high-mass region: sum of exponentiated polynomials

**Example low-mass background fit**

- Pull vs. $M_\gamma^2$ (GeV$^2$)
- $\chi^2$/df = 29.7/38

**Example high-mass background fit**

- Pull vs. $M_\gamma^2$ (GeV$^2$)
- $\chi^2$/df = 67.3/89

Alberto Lusiani, SNS – Beauty 2018, La Biodola, 6-11 May 2018
Fits and signal yield significance

**fit**
- simultaneous unbinned extended maximum likelihood fit on all 9+4 samples
- signal normalization fixed to zero on 2 background data samples
- fit bkg shape on bkg region, float just bkg normalization on tight/loose signal regions
- scan total of 166 $M_{A'}^2$ values (spaced by about half the resolution)

**signal significance**
- local significance from likelihood-ratio test
  \[ \sigma = \sqrt{2 \ln \left( \frac{L_{\text{max}}}{L_0} \right)} \]
- local maximum of 3.1 $\sigma$ at $M_{A'} = 6.21$ GeV
- overall global significance 2.6 $\sigma$
  (estimated look-elsewhere effect with parametrized simulations)
- compute upper limits
  (both bayesian and frequentist)
Constraints on Dark Photon theory model

- significant improvement over previous searches
- rule out entire region preferred by possible muon \((g-2)\) anomaly
- search can be re-interpreted to constrain models with invisible narrow resonance

\(A'\)-mass-dependent limit on \(\epsilon^2\)

constraints on mass and coupling

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