# CHARGED LNV/LFV AND NEW PHYSICS

# SEARCHES AT THE B FACTORIES

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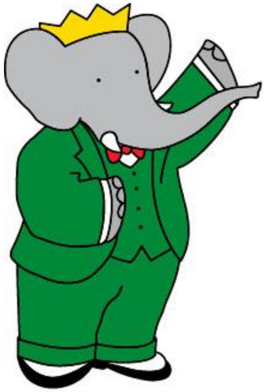


# Overview

- $B^+ \rightarrow K^-/\pi^- \, l^+ \, l^+$ ($ll = ee, \mu\mu$) (Babar) **NEW!**

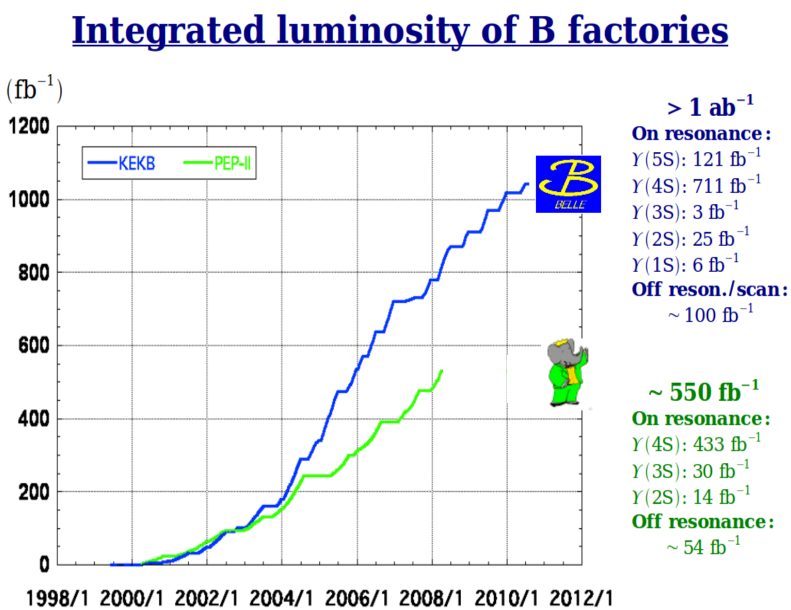
- $B^+ \rightarrow D^- \, l^+ \, l^+$ ($l = e, \mu$) (Belle, 2011)

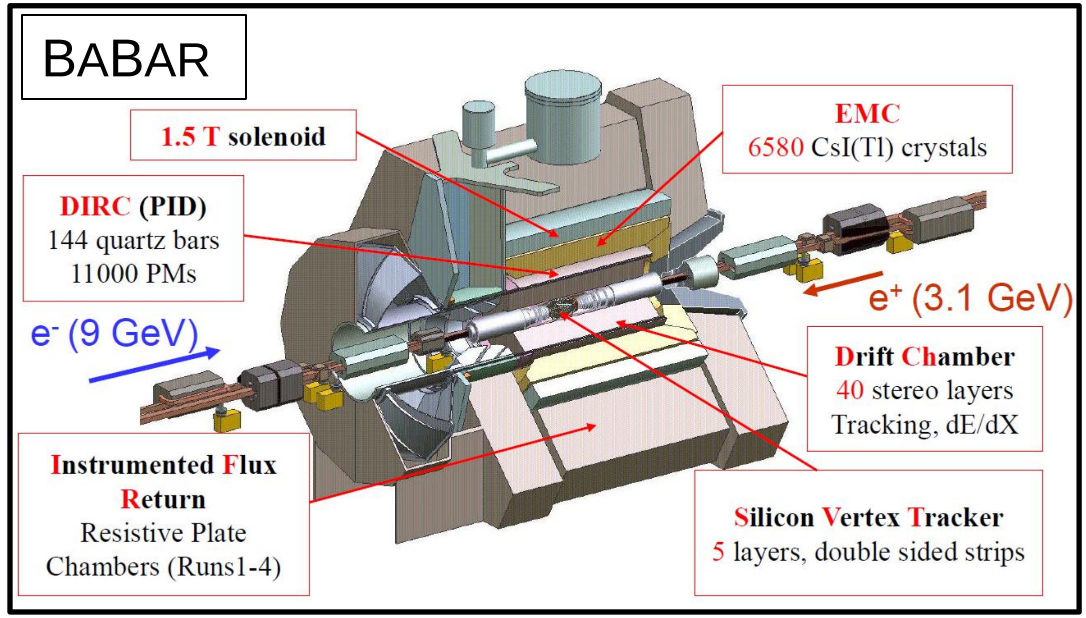
- $B^+ \rightarrow K^+/\pi^+ \, \tau^\pm \, (e,\mu)^\mp$ (Babar) **NEW!**

- Search for Dark Higgs (Babar) **NEW!**

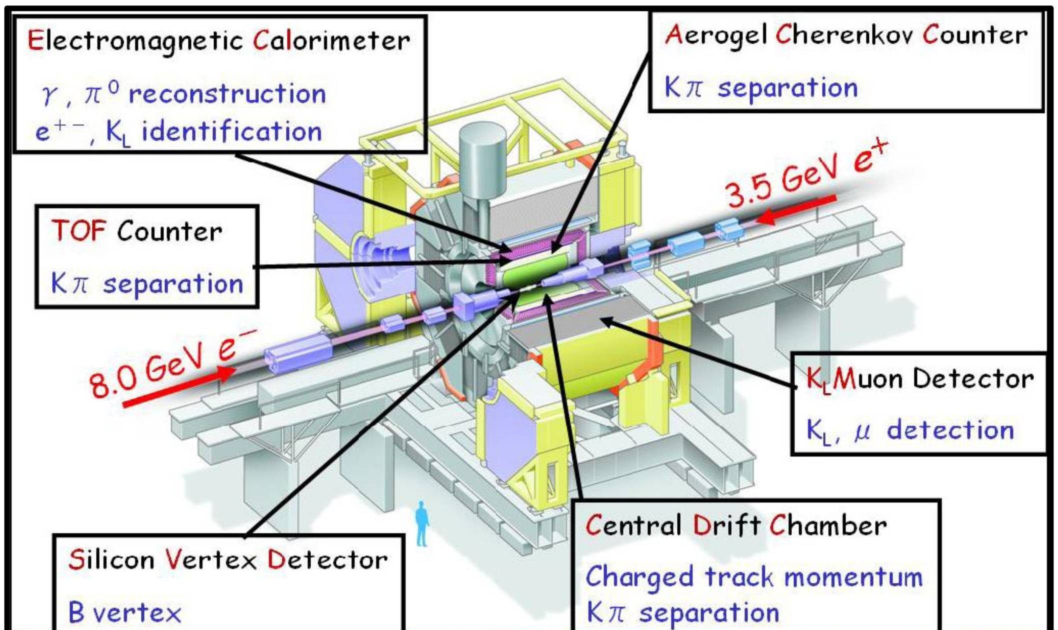
*** Charge conjugation assumed everywhere except as noted.**

# BABAR and Belle Detectors




Belle



# LEPTON NUMBER VIOLATION

## $B^+ \to h^- l^+ l^+$

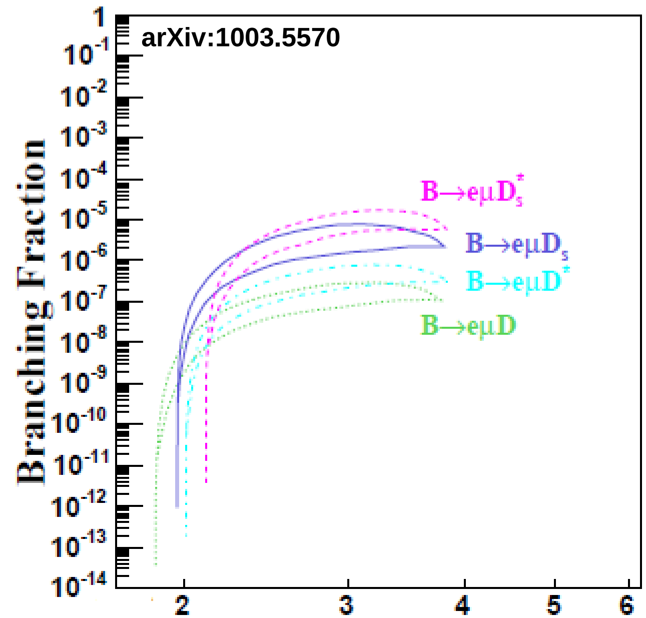
# Lepton number violation

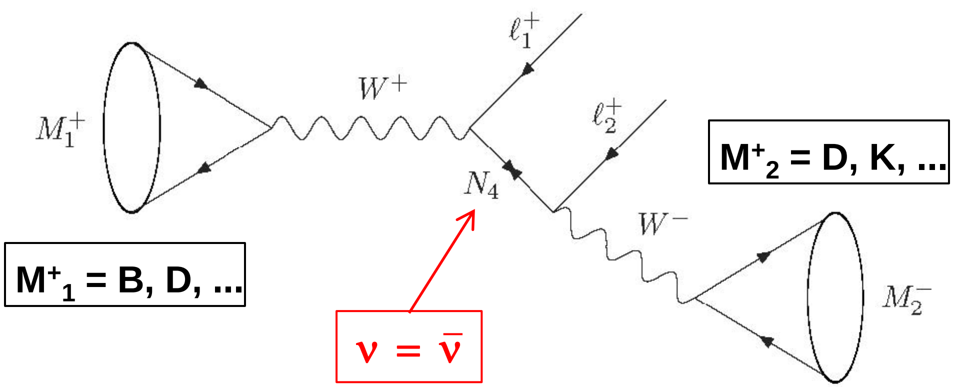
- Lepton number is conserved in the SM at low energies, but
  - Neutrinos have mass, so $L_e, L_\mu, L_\tau$ can be trivailly violated, but $\Sigma L$ is conserved
  - Chiral anomalies can violate $\Sigma L$

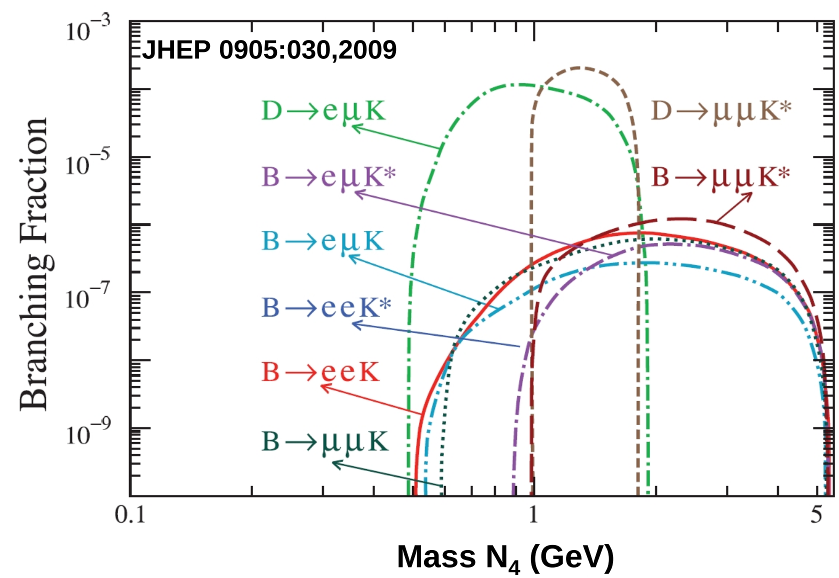
- Many theories beyond the SM predict LNV, e.g.
  - left-right symmetric gauge theories, SO(10) SUSY, R-parity violating models, ...

- Majorana neutrinos are an example via see-saw mechanism

- **Can probe existence of heavy Majorana neutrino in LNV processes $M_1^+ \rightarrow l^+ l^+ M_2^-$ at B-factories**

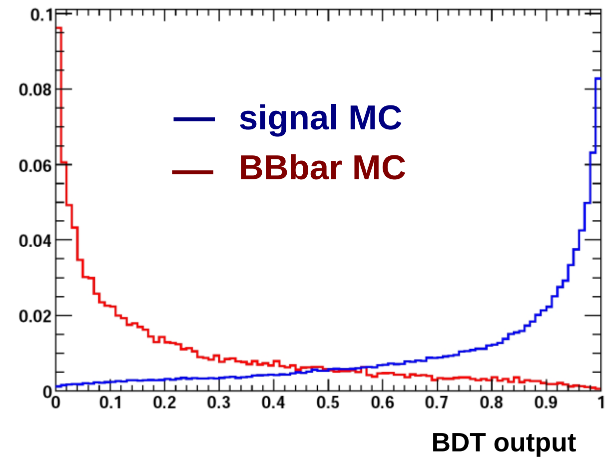


## Analysis overview

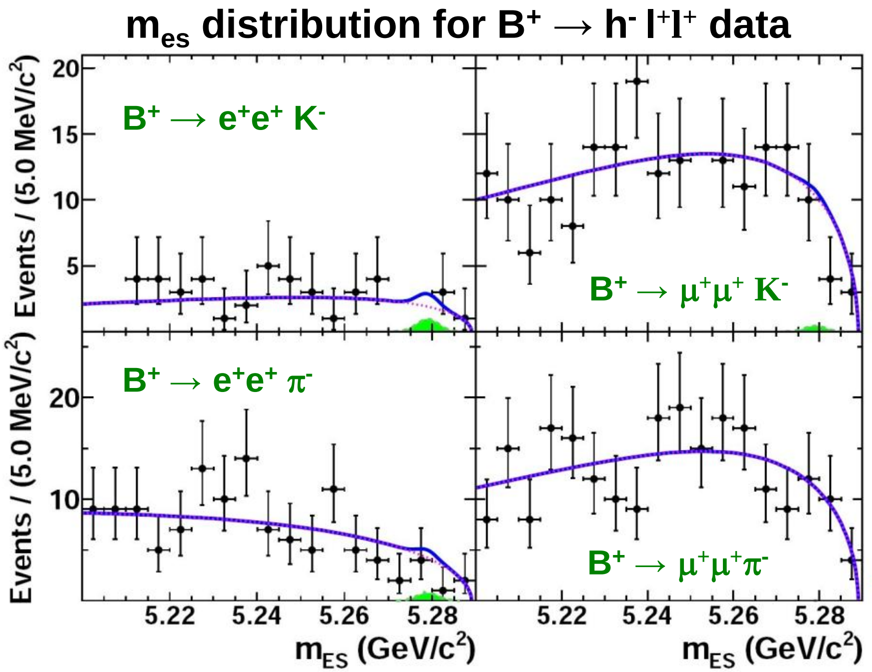
- Select two leptons and one hadron to form a B meson
- Apply particle identification for leptons and hadron
- Boosted Decision Trees (BDT) trained to suppress $e^+e^- \to c\bar{c}$ and $e^+e^- \to B\bar{B}$ background
- Combine BDT outputs in a likelihood ratio R




## Signal extraction

- Unbinned maximum likelihood fit for signal and combinatoric background
- Fit R and $m_{es} = (E^{*2}_{beam} - p_B^{*2})^{1/2}$
- Signal $m_{es}$ parameters taken from $B \to J/\psi\, h$ data

**No signal is observed**



**Upper limits (90% CL)**

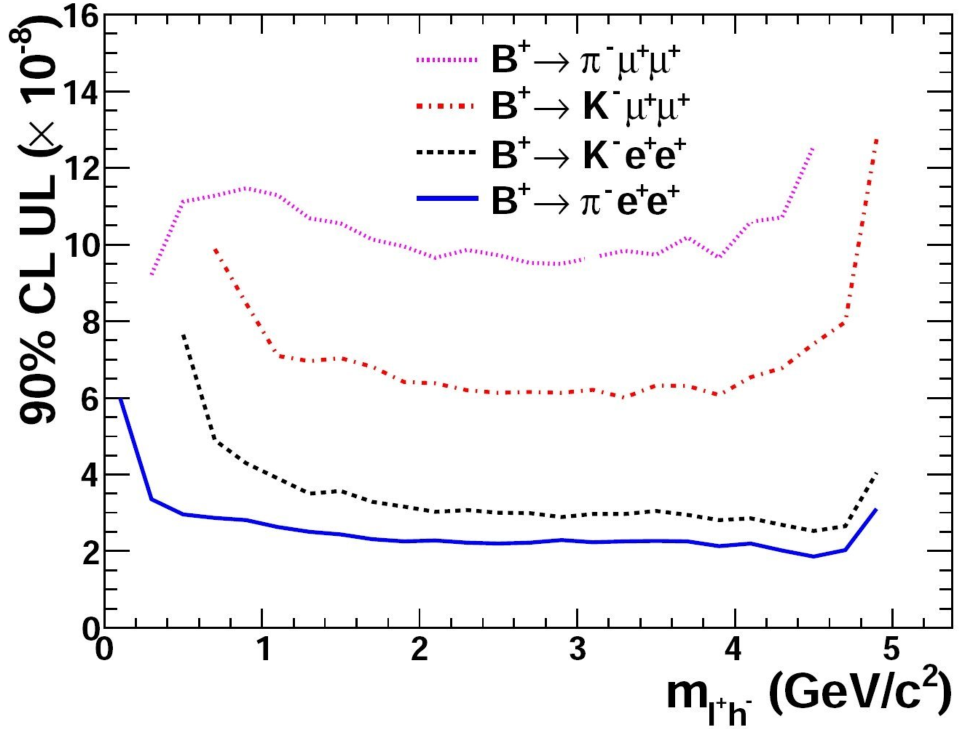
$BF(B^+ \to e^+e^+\pi^-) < 2.3 \times 10^{-8}$

$BF(B^+ \to e^+e^+K^-) < 3.0 \times 10^{-8}$

$BF(B^+ \to \mu^+\mu^+\pi^-) < 10.7 \times 10^{-8}$

$BF(B^+ \to \mu^+\mu^+K^-) < 6.7 \times 10^{-8}$

Upper limit as a function of $l^+h^-$ mass ("Majorana neutrino mass")

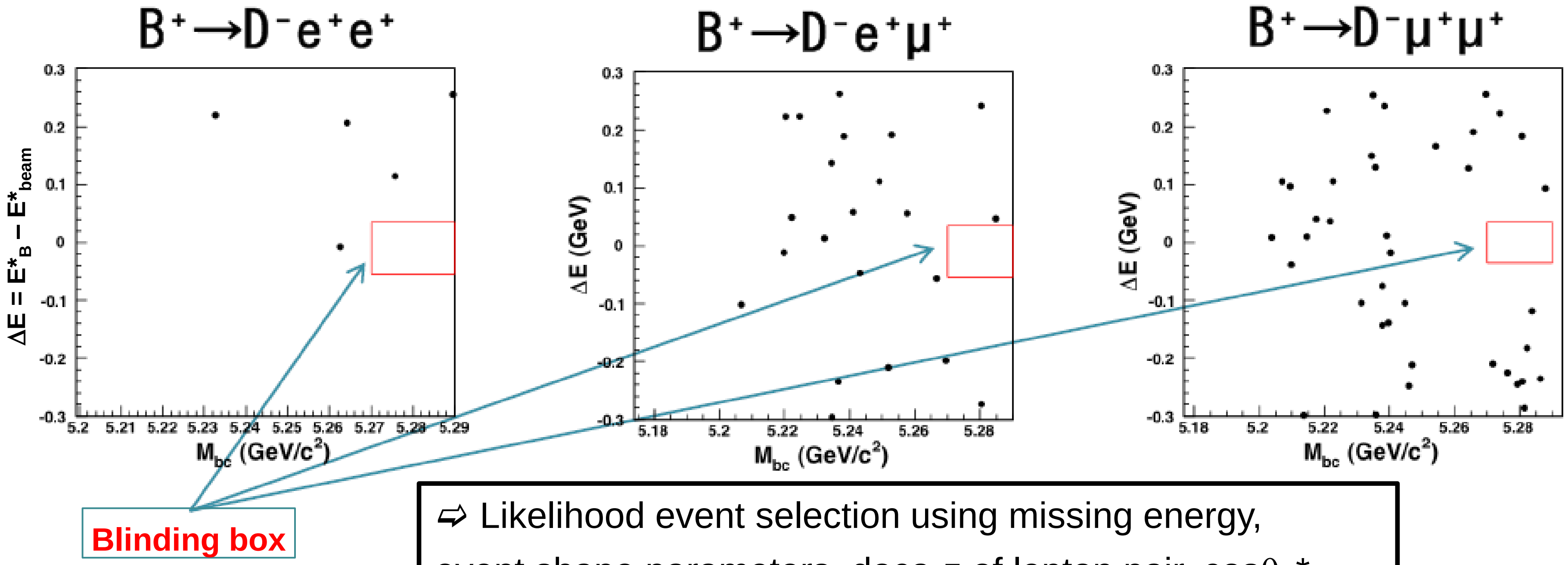



## Current limits for B decays

CLEO[1]: $BF(B^+ \to h^- l^+ l'^+) < (1.0 - 8.3) \times 10^{-6}$  $h = \pi, K^{(*)}, \rho$

LHCb[2]: $BF(B^+ \to X^- \mu^+ \mu^+) < 1.3 \times 10^{-8} - 2.6 \times 10^{-6}$  $X^- = D^{-(*)}, D_s^-, \pi^-, D^0\pi^-$; with 41 $pb^{-1}$

1. PRD 65, 111102 (2002)  2. arXiv:1201.5600




- Likelihood event selection using missing energy, event shape parameters, doca-z of lepton pair, $\cos\theta_B^*$
- Reconstructs $D^- \to K^+\pi^-\pi^-$
- Backgrounds from kinematic sidebands
- Cut and count in signal region (blinding box)

| Mode | $\epsilon$ [%] | $N_{obs}$ | $N_{exp}^{bkg}$ | U.L. $[10^{-6}]$ |
|---|---|---|---|---|
| $B^+ \to D^- e^+ e^+$ | 1.2 | 0 | 0.18±0.13 | $< 2.6$ |
| $B^+ \to D^- e^+ \mu^+$ | 1.3 | 0 | 0.83±0.29 | $< 1.8$ |
| $B^+ \to D^- \mu^+ \mu^+$ | 1.9 | 0 | 1.44±0.43 | $< 1.0$ |

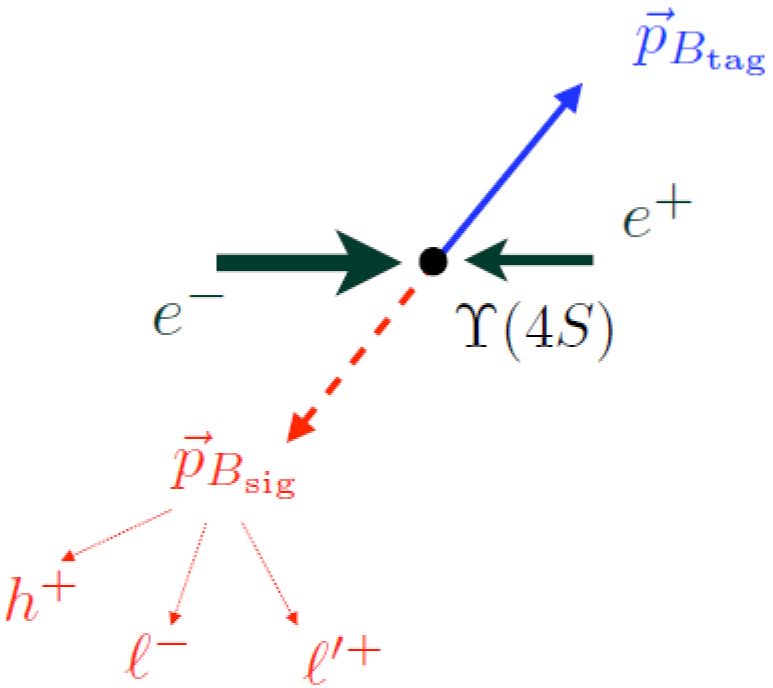
# LEPTON FLAVOR VIOLATION

## $B^+ \rightarrow K^+/\pi^+ \tau l$ $(l = e,\mu)$

## Study four channels

$B^+ \to \pi^+ \tau e$ $B^+ \to \pi^+ \tau \mu$

$B^+ \to K^+ \tau e$ $B^+ \to K^+ \tau \mu$




## Single-prong τ decays

$\tau \to e\nu\bar{\nu}$

$\tau \to \mu\nu\bar{\nu}$

$\tau \to \pi^+ (n\pi^0)\, \nu$

**Btag is fully reconstructed in hadronic final states**

- $B^- \to D^{(*)0} X^-$
- $X^- = n_1\pi^- + n_2K^- + n_3 K_S + n_4 \pi^0$

**Reconstruct tau mass using**

- tag B, beam energy and signal-side lepton, hadron
- $p_\tau = p_B - p_h - p_l$
- $E_\tau = E_{beam} - p_h - p_l$

**Charmonium di-lepton mass regions vetoed**

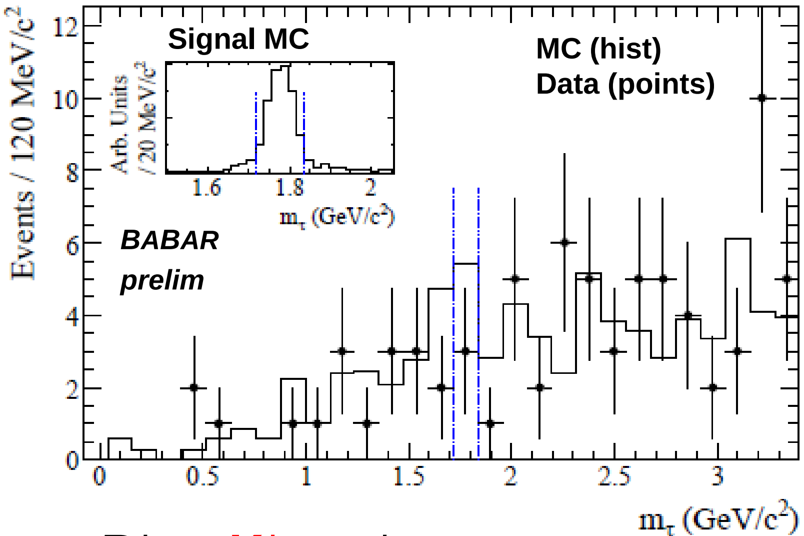
**Signal region is $M_\tau$ +/- 60 MeV**

**Background estimated from mass sidebands**

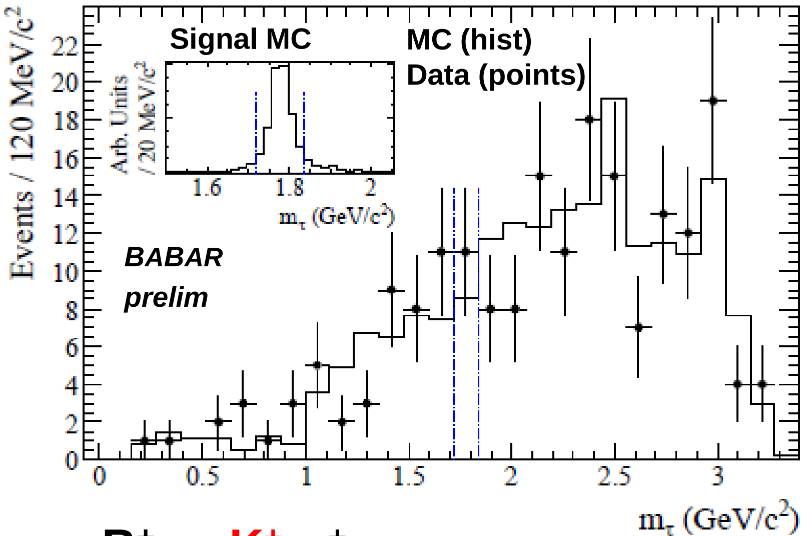
**D semileptonic backgrounds contribute more to $\tau^+$**

# Lepton Flavor Violation - $B^+ \to K^+ \tau\, l$ ($l = e,\mu$) - results

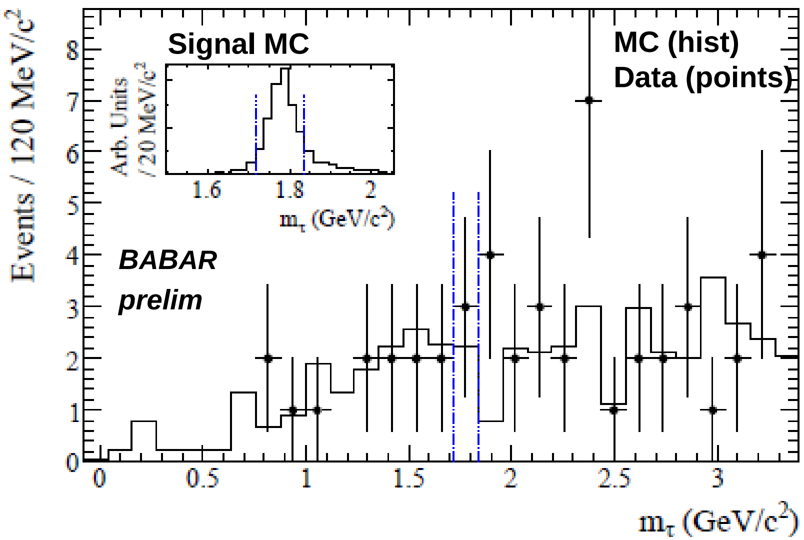
$B^+ \to K^+ \tau^- \mu^+$



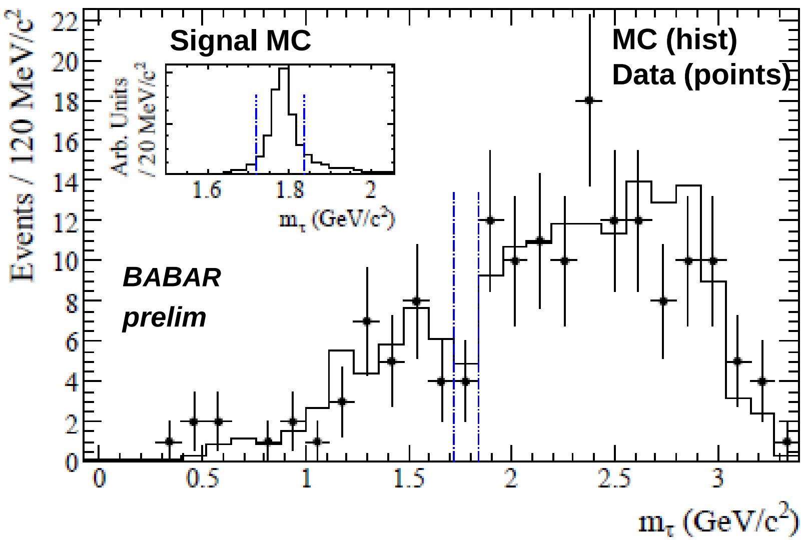

$B^+ \to K^+ \tau^+ \mu^-$



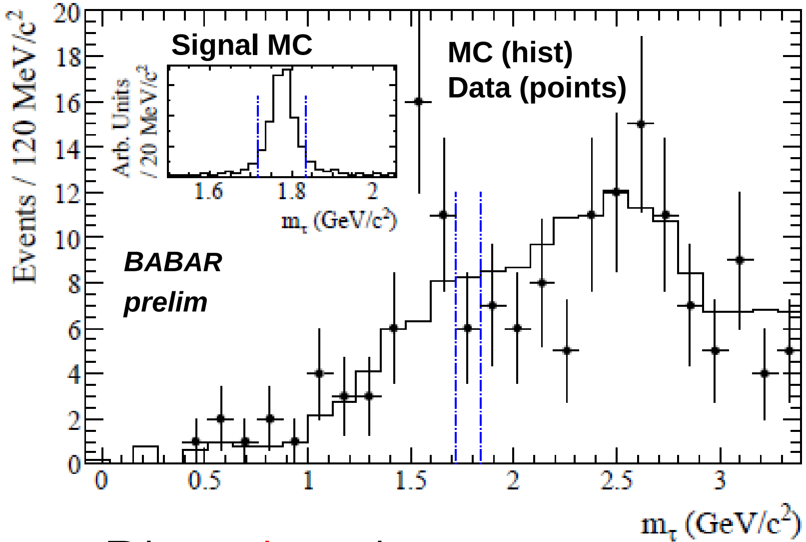

$B^+ \to K^+ \tau^- e^+$



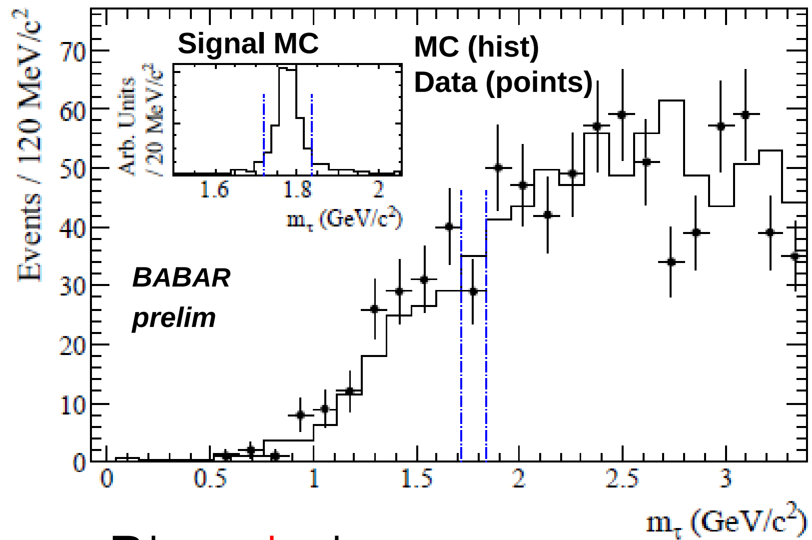

$B^+ \to K^+ \tau^+ e^-$



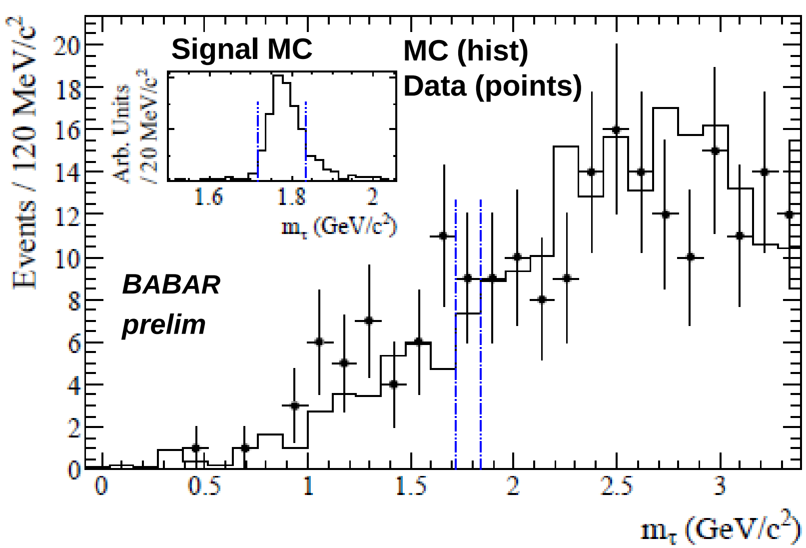
## $B^+ \to \pi^+ \tau^- \mu^+$



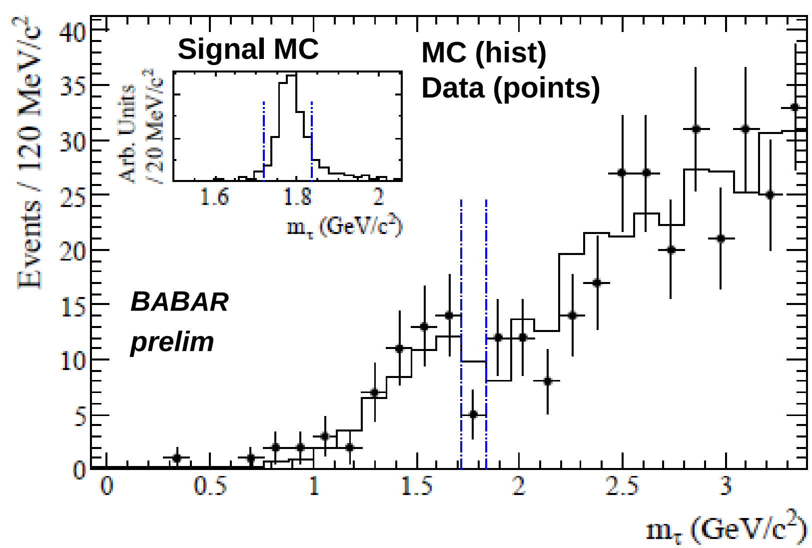

## $B^+ \to \pi^+ \tau^+ \mu^-$



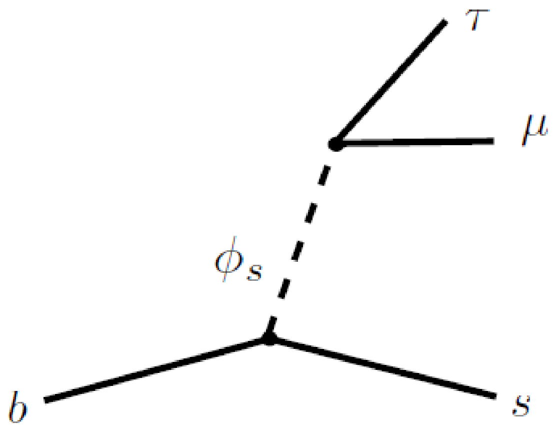

## $B^+ \to \pi^+ \tau^- e^+$




## $B^+ \to \pi^+ \tau^+ e^-$



$$\Delta\mathcal{L} = \Delta\mathcal{L}^{(6)}_{\tau\mu} = \sum_{j,\alpha,\beta} \frac{\mathcal{C}^{j}_{\alpha\beta}}{\Lambda^2} \left(\overline{\mu}\,\Gamma_j\,\tau\right)\left(\overline{q}^{\alpha}\,\Gamma_j\,q^{\beta}\right) + \mathrm{H.c.}\ ; \quad \Gamma_j = (S, P, V, A)$$




BF U.L. (90% CL) *

| | |
|---|---|
| $B^+ \to K^+\tau\mu$ | $< 4.8 \times 10^{-5}$ |
| $B^+ \to K^+\tau e$ | $< 3.0 \times 10^{-5}$ |
| $B^+ \to \pi^+\tau\mu$ | $< 7.2 \times 10^{-5}$ |
| $B^+ \to \pi^+\tau e$ | $< 7.5 \times 10^{-5}$ |

LFV Energy Scale from Prev. Results (90% CL)

| | |
|---|---|
| $\bar{b}d$ | 2.2 TeV $(B \to \pi\mu\tau)$ |
| $\bar{b}s$ | 2.6 TeV $(B \to K\mu\tau)$ |

**PRD 66, 053002 (2002)**

| LFV Energy Scale from BABAR Results (90% CL) | $B^+ \to K^+ \tau l$ | $B^+ \to \pi^+ \tau l$ |
|---|---|---|
| | **$\Lambda$ > 15 TeV** | **$\Lambda$ > 11 TeV** |

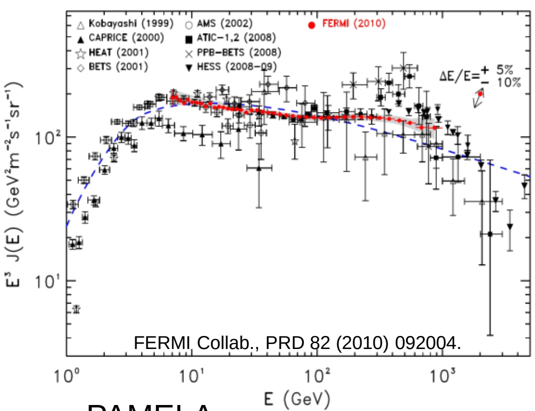
* Assumes $BF(B^+ \to h^+ \tau^- l^+) = BF(B^+ \to h^+ \tau^+ l^-)$

# DARK FORCES

Models introducing a **new 'dark' force** mediated by a **new gauge boson with a mass around a GeV** have been proposed to explain the observations of PAMELA, FERMI, DAMA/LIBRA, CREST,...

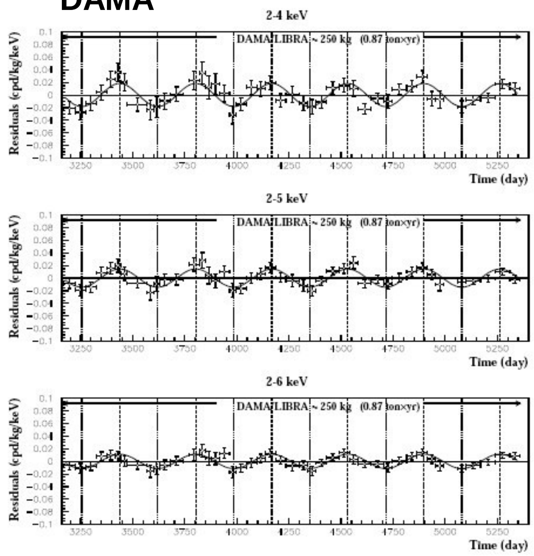
**WIMP-like dark matter** particles can **annihilate into pairs of dark bosons**, which subsequently decays to lepton pairs (protons are kinematically forbidden).

**FERMI**



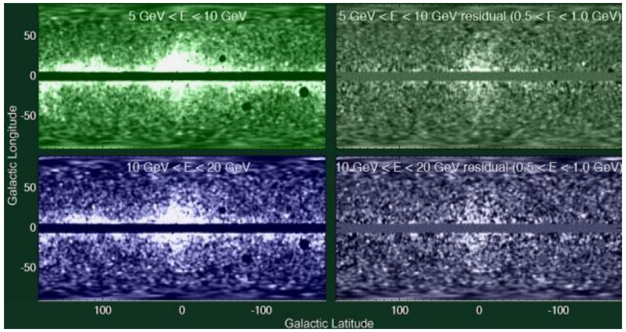

FERMI Collab., PRD 82 (2010) 092004.

**DAMA**



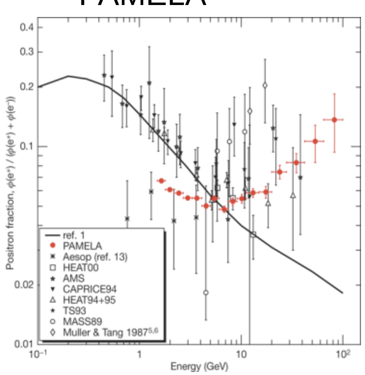

DAMA Collab., Eur. Phys. J. C (2010) 67

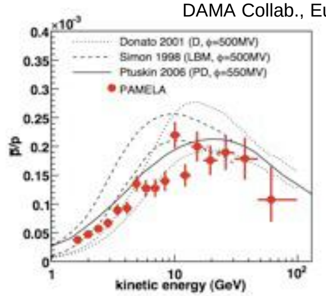
**FERMI HAZE**




Dobler *et al.*, Astrophys.J.717

PAMELA



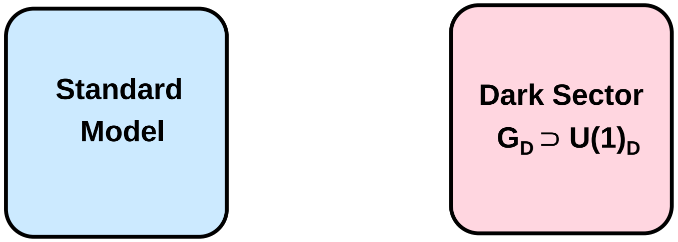




PAMELA Collab., Nature 458, 607 (2009);
PAMELA Collab., PRL 102 (2009) 051101.

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

# Hidden sector and dark forces

- New dark sector with a $U(1)_D$ gauge group
- New gauge boson: **dark photon A' with O(GeV) mass**

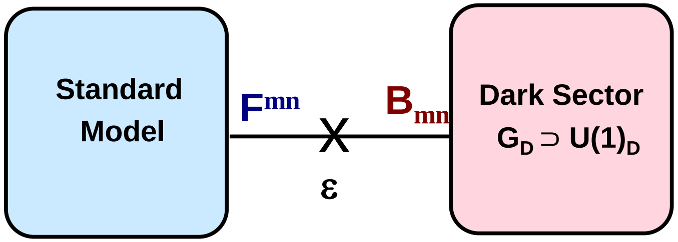


# Hidden sector and dark forces

- New dark sector with a $U(1)_D$ gauge group
- New gauge boson: **dark photon A' with O(GeV) mass**
- Interaction with the SM is via **kinetic mixing**

$$\varepsilon F^{mn} B_{mn}$$

with a **mixing strength $\varepsilon$.**




$$\Delta L_{mix} = \varepsilon F^{mn} B_{mn}$$

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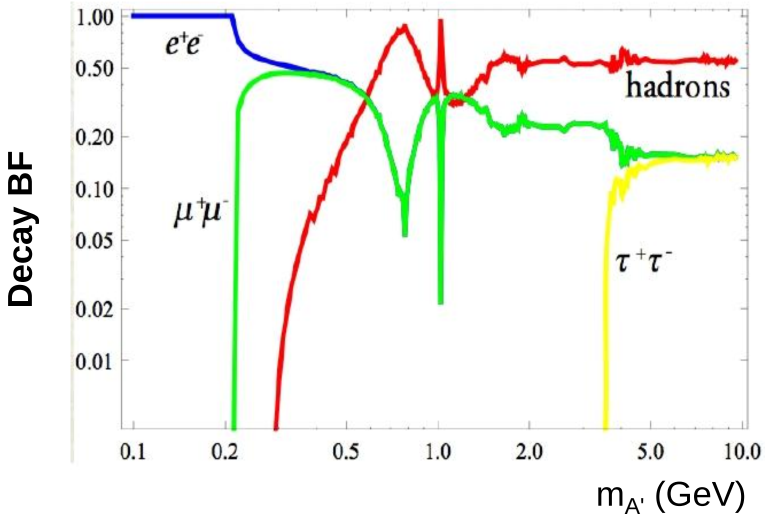
- ⇨ The dark photon acquires a charge $\varepsilon e$, and the **coupling of the dark photon to SM fermions** is characterized by $\alpha' = \alpha\,\varepsilon^2$

***PRD 79, 115008, 2009***

**dark photon branching fraction**



- New dark sector with a $U(1)_D$ gauge group
- New gauge boson: **dark photon A' with O(GeV) mass**

- Interaction with the SM is via **kinetic mixing**

  $$\varepsilon F^{mn} B_{mn}$$

  with a **mixing strength $\varepsilon$.**

- The dark photon acquires a charge $\varepsilon e$, and the **coupling of the dark photon to SM fermions** is characterized by $\alpha' = \alpha\,\varepsilon^2$.

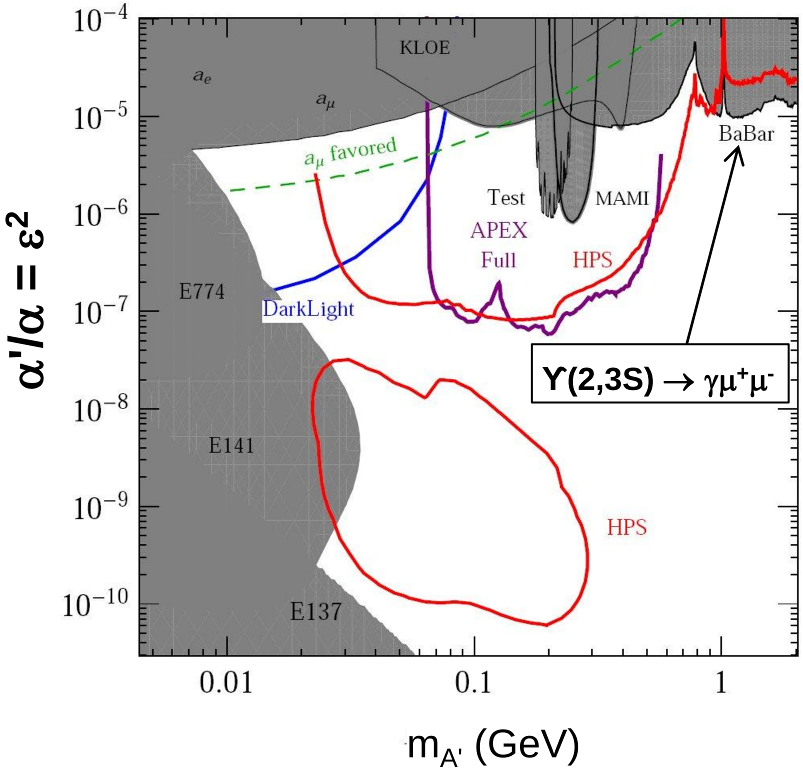
- A dark photon can be readily produced in

  $$e^+e^- \rightarrow \gamma A', A' \rightarrow f\bar{f}$$

  The limits on $e^+e^- \rightarrow \Upsilon(2S,3S) \rightarrow \gamma\mu^+\mu^-$ can be reinterpreted as limits on dark photon production.

*J.D. Bjorken et al., PRD 80 (2009) 075018*

**Constraints on $\alpha'/\alpha = \varepsilon^2$**



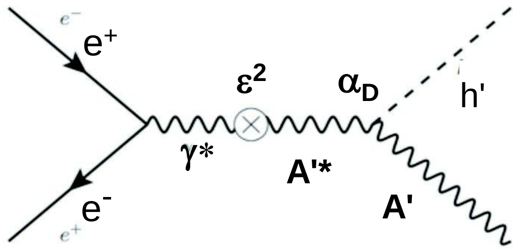
*B. Batell et al., PRD 79 (2009) 115008*
*R. Essig et al., PRD 80 (2009) 015003*

- Dark boson mass is generated via the Higgs mechanism, **adding a dark Higgs boson (h') to the theory.**
- A **minimal scenario** has a **single dark photon and a single dark Higgs boson**. Very well motivated theoretically.
- The **dark Higgs mass** could be at **the GeV scale.**
- The **Higgs'-strahlung process**

$$e^+e^- \rightarrow A'^* \rightarrow h' A' \,,\ h' \rightarrow A' A'$$

is very interesting, as it is **only suppressed by $\varepsilon^2$** and is expected to have a **very small background.**

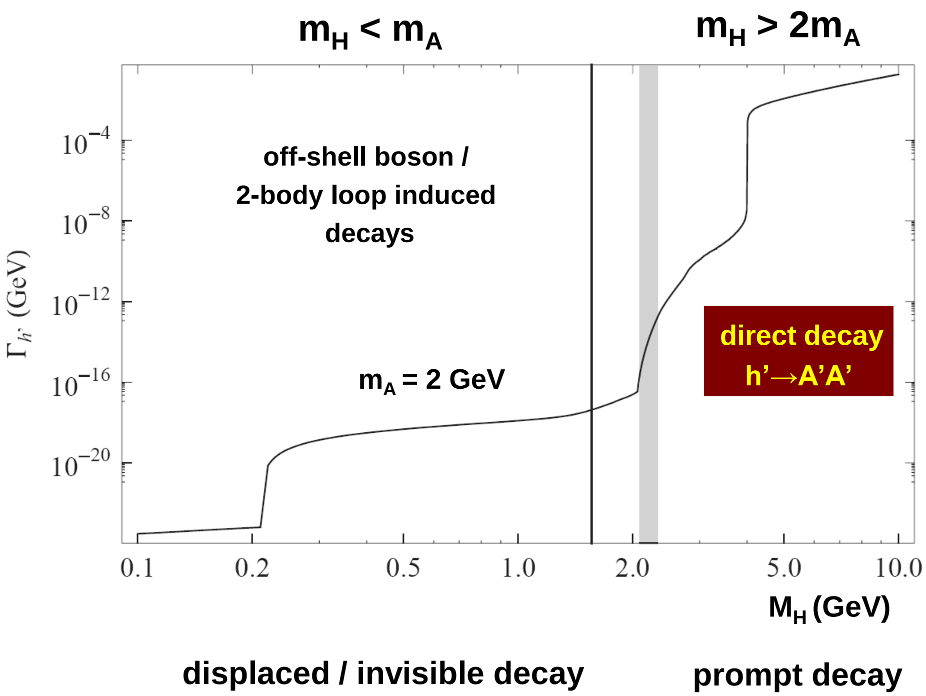
$\sigma \sim \varepsilon^2 \alpha_D$




$\alpha_D = g_D^2 / 4\pi$

$g_D$ is the dark sector gauge coupling

**Higgs decay topology**



**Fully reconstructed**

$e^+e^- \to h' A', h' \to A' A'$

with $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

**Partially reconstructed**

$e^+e^- \to h' A_1' , h' \to A_2' A_3'$

with $A'_{1,2} \to e^+e^-, \mu^+\mu^-, A'_3 \to X$

**Fully reconstructed signal**

- Three dark photons fully reconstructed

**Modes included**

- $e^+e^- \to (l^+l^-) (l^+l^-) (l^+l^-)$ $l=e,\mu$
- $e^+e^- \to (l^+l^-) (l^+l^-) (\pi^+\pi^-)$
- $e^+e^- \to (l^+l^-) (\pi^+\pi^-) (\pi^+\pi^-)$

**Selection**

- 6 tracks with an invariant mass $m_{tot} > 0.95 \sqrt{s}$
- apply lepton particle identification
- cosine helicity angle of $A' \to e^+e^-$ candidates < 0.9
- three dark photon candidates have similar mass

**Partially reconstructed signal**

- In the high mass region ($m_A$ > 1.2 GeV), the decay of the dark photon is dominated by $A' \to q\bar{q}$
- Reconstruct 2 A' decaying to leptons and 1 A' to $q\bar{q}$
- Reconstruct four-momentum $P_3 = P_{ee} - P_1 - P_2$

**Modes included**

- $e^+e^- \to (l^+l^-) (\mu^+\mu^-) + X$ where X is not $l^+l^-$ / $\pi^+\pi^-$

**Selection**

- 4 or more tracks
- apply particle identification for $A' \to l^+l^-$ decays
- cosine helicity angle of $A' \to e^+e^-$ candidates < 0.9
- three dark photon candidates have similar mass

# Dark Higgs boson - mass spectrum

*BABAR* arXiv:1202.1313, submitted to PRL

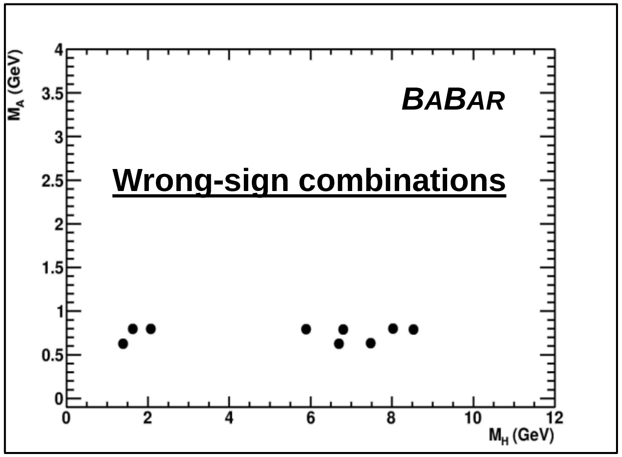
- **Six events** are selected from the full *BABAR* dataset (517 $fb^{-1}$)

- **Three entries for each event**, corresponding to the three possible assignments of the $h \rightarrow A'A'$ decay

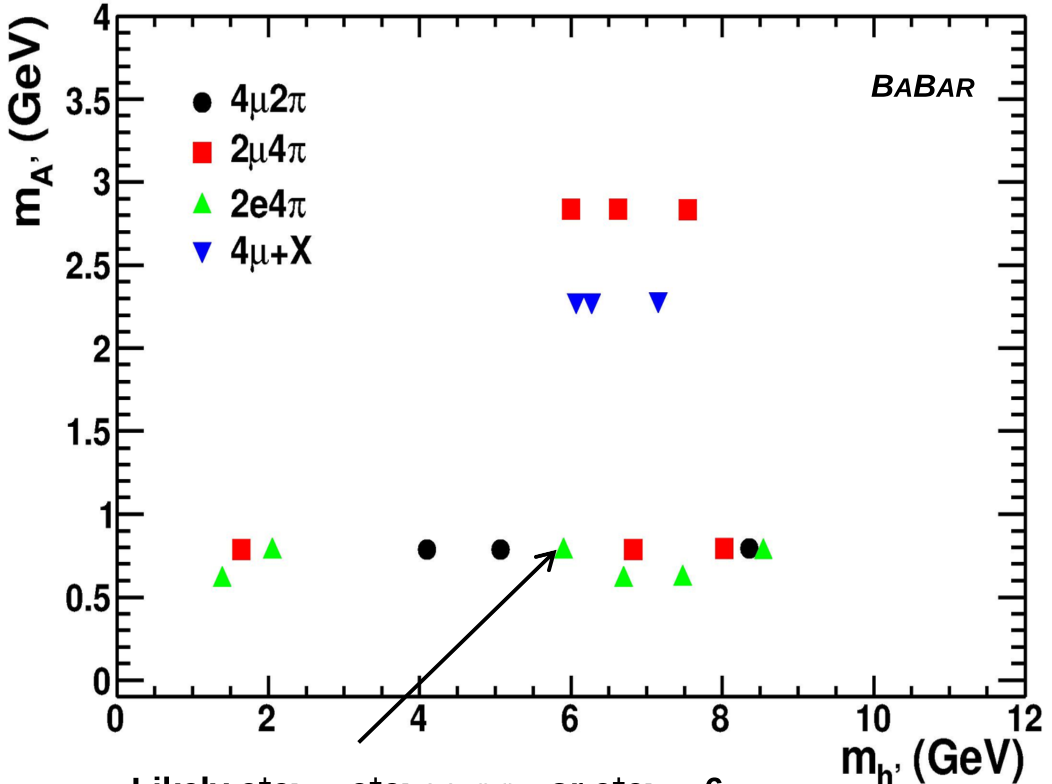
- **Estimate background from**
  - **wrong-sign combinations**, e.g.

    $e^+e^- \rightarrow (e^+e^+)\ (e^-e^-)\ (\mu^+\mu^-)$

  - **sidebands from final sample**
  - rate for 6 leptons ~ 100x rate for $4\pi$+2l above 1.5 GeV




**Signal candidates**

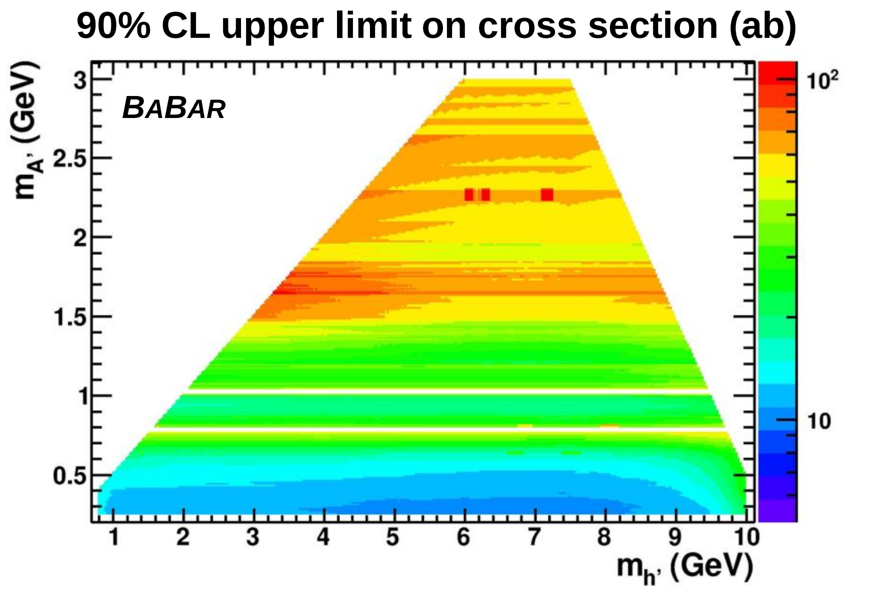



**Likely $e^+e^- \rightarrow e^+e^-\ \rho\rho,\omega\omega$ or $e^+e^- \rightarrow 6\pi$**

**No events with 6 leptons, consistent with the pure background hypothesis**

**Limit on the cross section $e^+e^- \rightarrow h' A'$, $h' \rightarrow A' A'$ in the regime $m_H > 2\, m_A$**

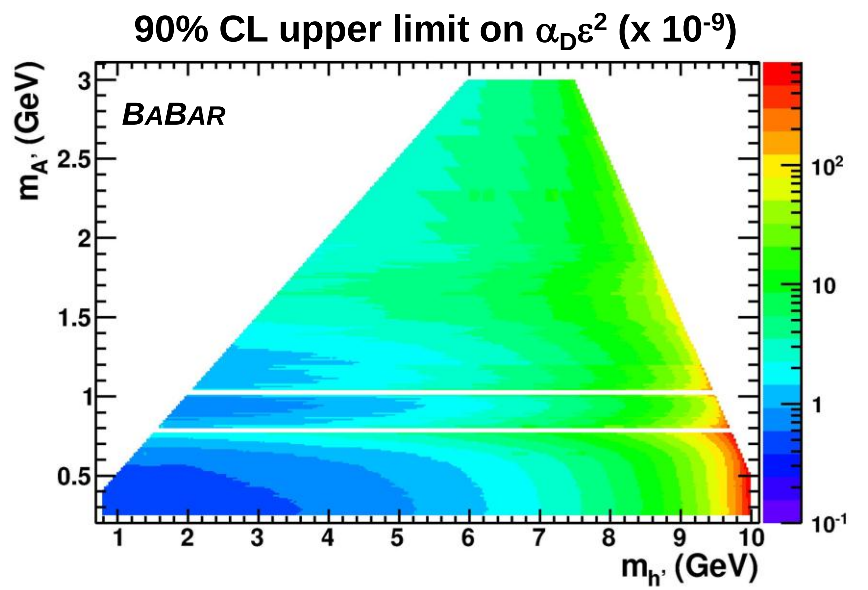
- Scan the $m_h$ vs $m_A$ plane, Bayesian limit with uniform prior in cross-section
- Conservative approach, treat every event as signal candidate (hot spots in bi-dimensional plot)
- **Cross section limits from 10 to ~100 ab**




**Extract limits[1] on the product $\alpha_D \varepsilon^2$**

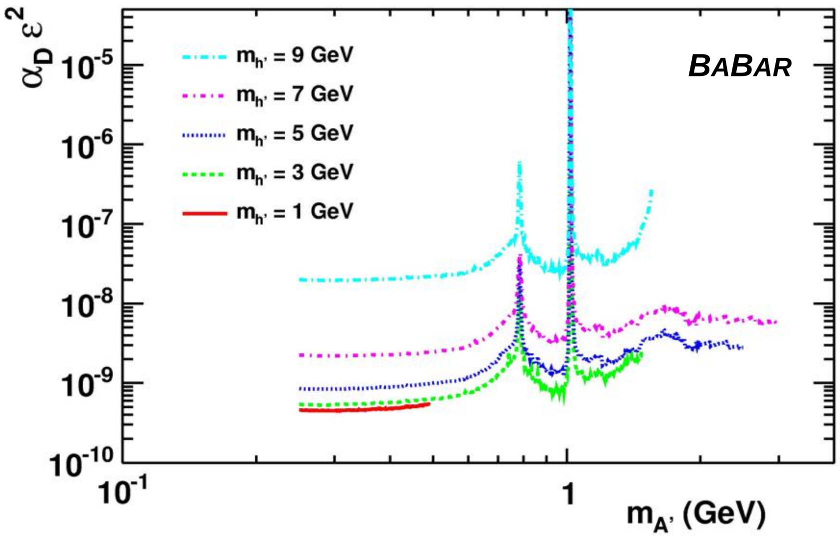
- **Limits on couplings down to a few x $10^{-10}$**

**$\alpha_D = g_D^2 / 4\pi$**
**$g_D$ is the dark sector gauge coupling**

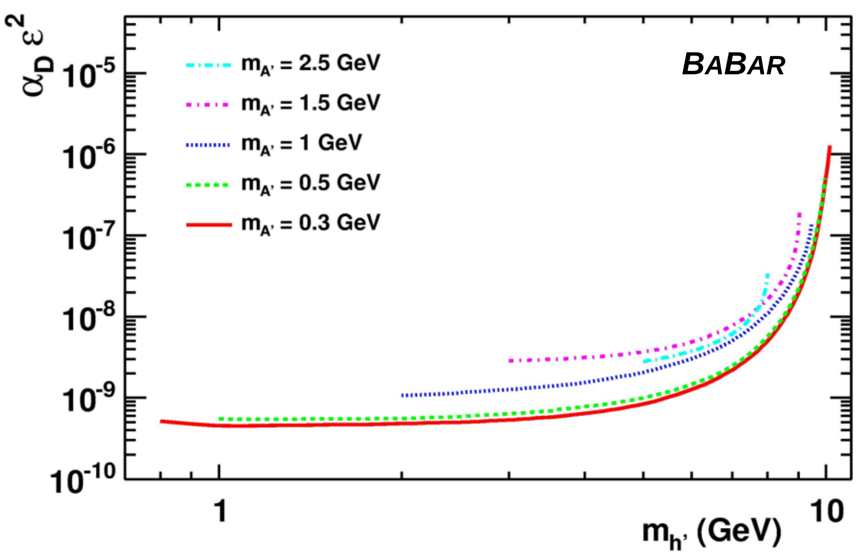



*1. B. Batell, M. Pospelov and A. Ritz, Phys.Rev.D79:115008,2009.*

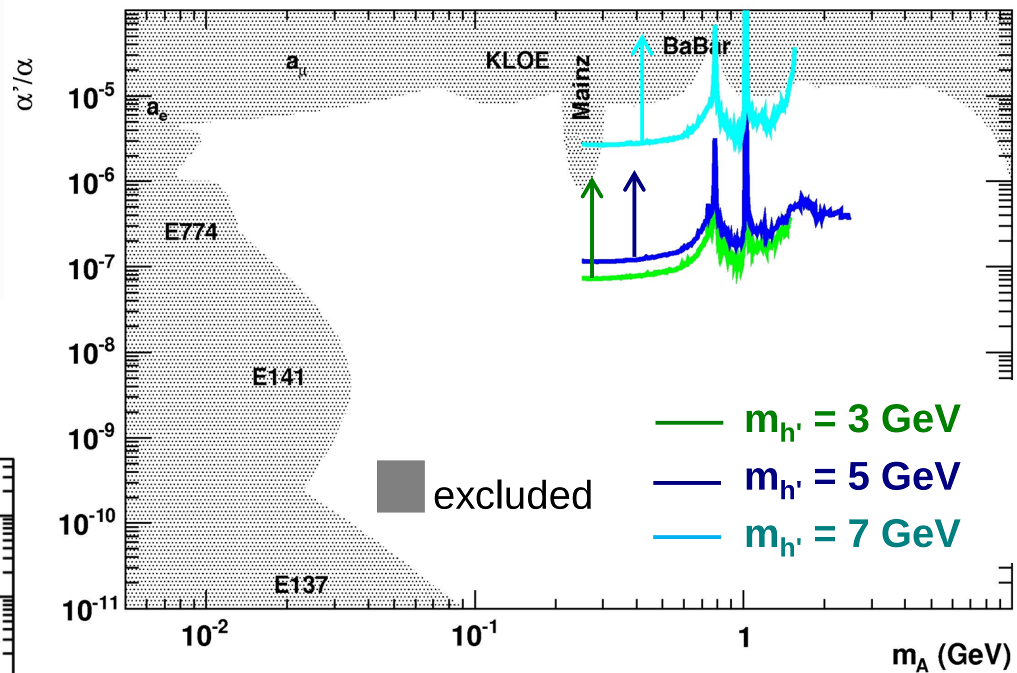
**90% CL upper limit on $\alpha_D\varepsilon^2$ vs $m_{A'}$**




**90% CL upper limit on $\alpha_D\varepsilon^2$ vs $m_{h'}$**




**Limit on $\varepsilon^2 = \alpha'/\alpha$ for various Higgs mass (assuming $\alpha_D$=$\alpha_{em}$)**




**Substantial improvement over existing limits for $m_{h'}$ < 5 - 7 GeV if light dark Higgs boson exists**

# Summary

- The B-Factories are well-suited to the study of Lepton Number Violation and Lepton Flavor Violation in a wide variety of initial and final states
- Large datasets of B, D and tau decays, excellent lepton identification and kinematic handles from fully reconstructed decays and/or hermiticity have helped in setting LFV and LNV limits approaching $10^{-8}$, competitive (at least for the moment) with LHCb, and complementary to dedicated experiments
- In the little-to-no backgrounds regime currently seen in many of the searches, the ~50-75 $ab^{-1}$ luminosities projected for the future Belle-II and Super-B "super" flavor factories will allow additional sensitivity up to two orders of magnitude beyond the current limits