Search for dark photons and dark Higgs at *BABAR*

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On behalf of the *BABAR* Collaboration

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Outline

- Motivations;
- The BaBar experiment at SLAC;
- Particle IDentification at BaBar;
- Analysis strategy;
- Results and conclusions.

Motivations

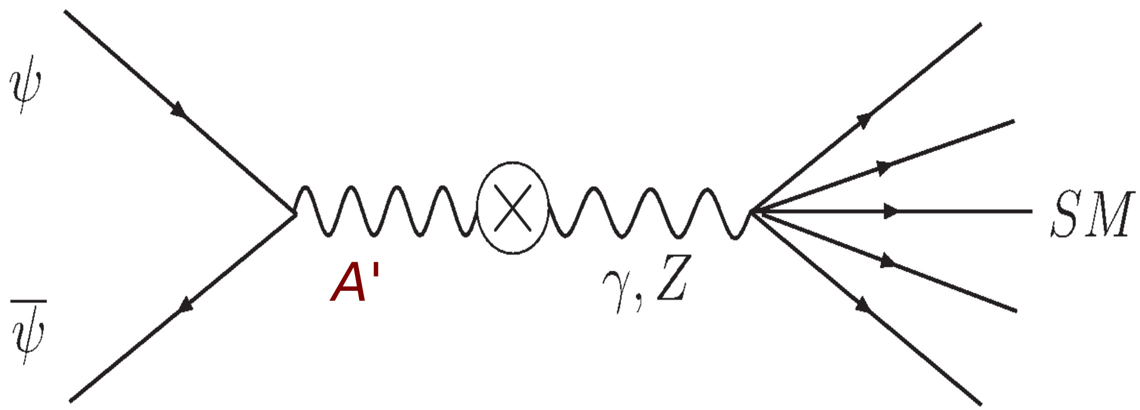
- Many independent observations confirm the existence of dark matter;
- In the last few years the efforts to experimentally detect dark matter signatures have flourished;
- Several fields are being investigated:
  - γ-ray astrophysics;
  - Detection of dark matter particles in underground laboratories;
  - Searches at colliders;
- A scenario in which dark matter is made of Weekly Interacting Massive Particles (WIMPs) seems to be preferred, as it can naturally provide the observed cosmological abundance.

Motivations

- The generic Lagrangian including the "dark sector" can be written as:

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{WIMP}} + \mathcal{L}_{\mathrm{mediator}}$$

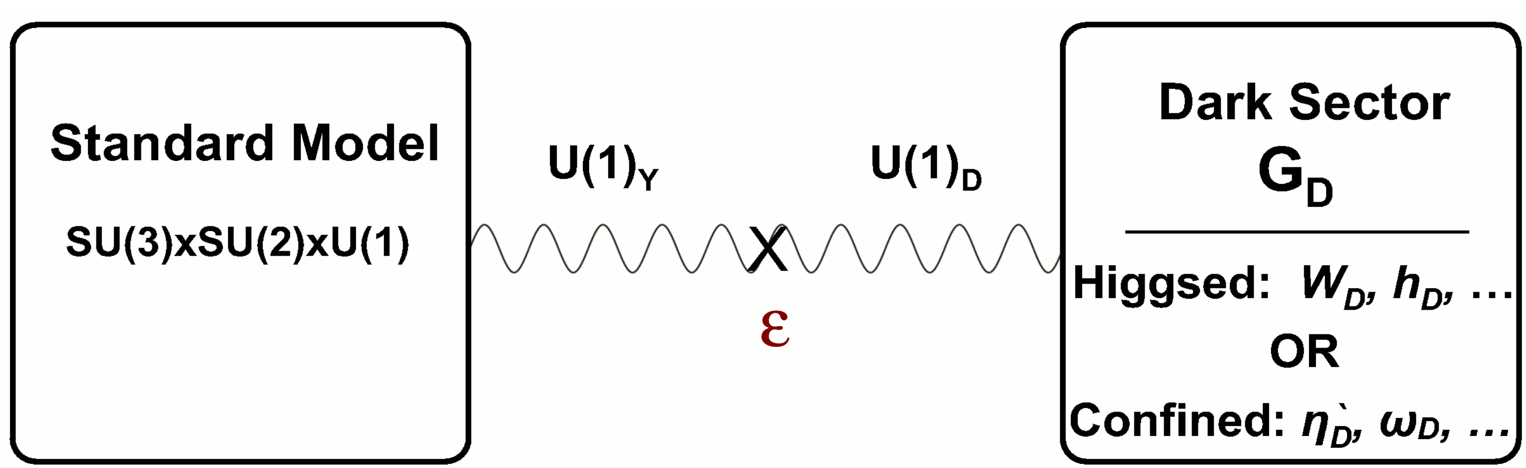
- The mediator between SM and WIMP can be a SM particle (gauge bosons, Higgs), or it can be another particle;
- Models of "secluded" $U(1)_D$ gauge fields that can have kinetic mixing with the SM hypercharge $U(1)_Y$ are particularly appealing for investigation at colliders;



see e. g. M. Pospelov, A. Ritz, M. Voloshin, PLB 662, 53 (2008)

Motivations

- WIMP particles can annihilate into the mediator particle A' (dark photon), which then couples to SM particles;
- Scenarios in which $m_{A'} \sim O(\text{GeV}) \ll m_{WIMP}$ naturally lead to an enhancement of the WIMP annihilation cross-section in the galaxy and of the leptonic branching fraction, consistent with the observations by PAMELA, ATIC, INTEGRAL and the possible signal from DAMA/LIBRA; see E. Guido's talk
- In the following we will consider a scenario in which the dark sector includes a Higgs' (h') state, responsible for spontaneous breaking of the $U(1)_D$ symmetry:

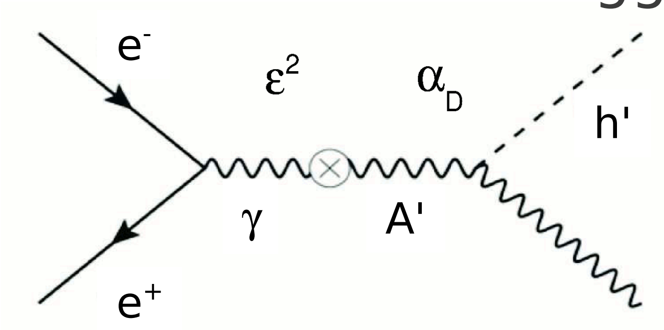


ε: strength of the kinetic mixing

Naturalness arguments predict $\varepsilon \sim 10^{-2} - 10^{-4}$

Motivations

- In most scenarios h' and A' are narrow states, thus the favored production mechanism is Higgs-strahlung:

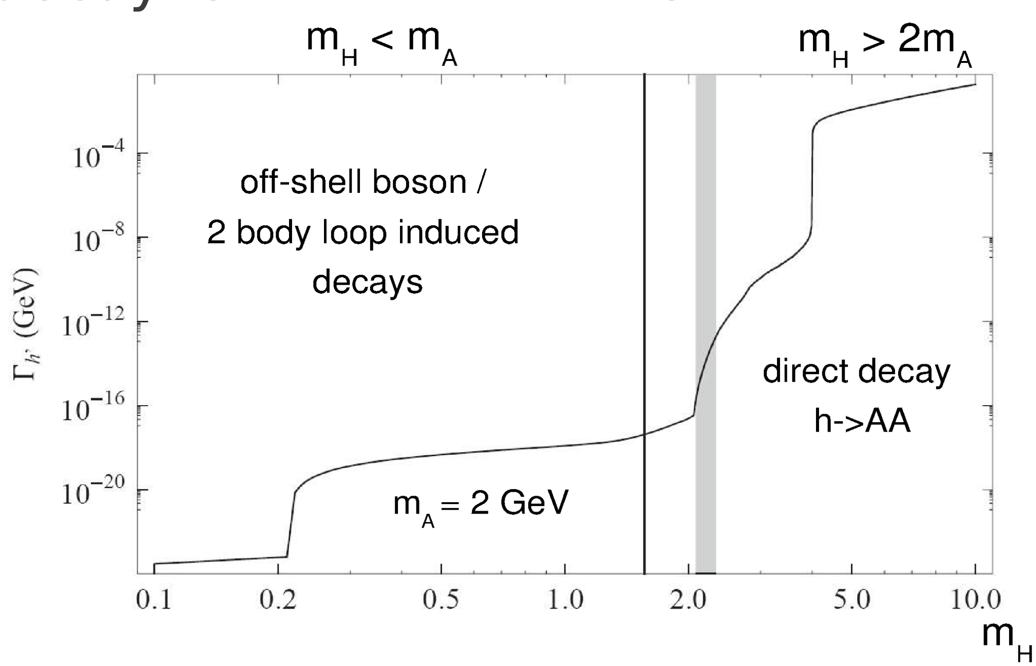


B. Batell, M. Pospelov, A. Ritz, PRD 79, 115008 (2009)
R. Essig, P. Shuster, N. Toro, PRD 80, 115003 (2009)

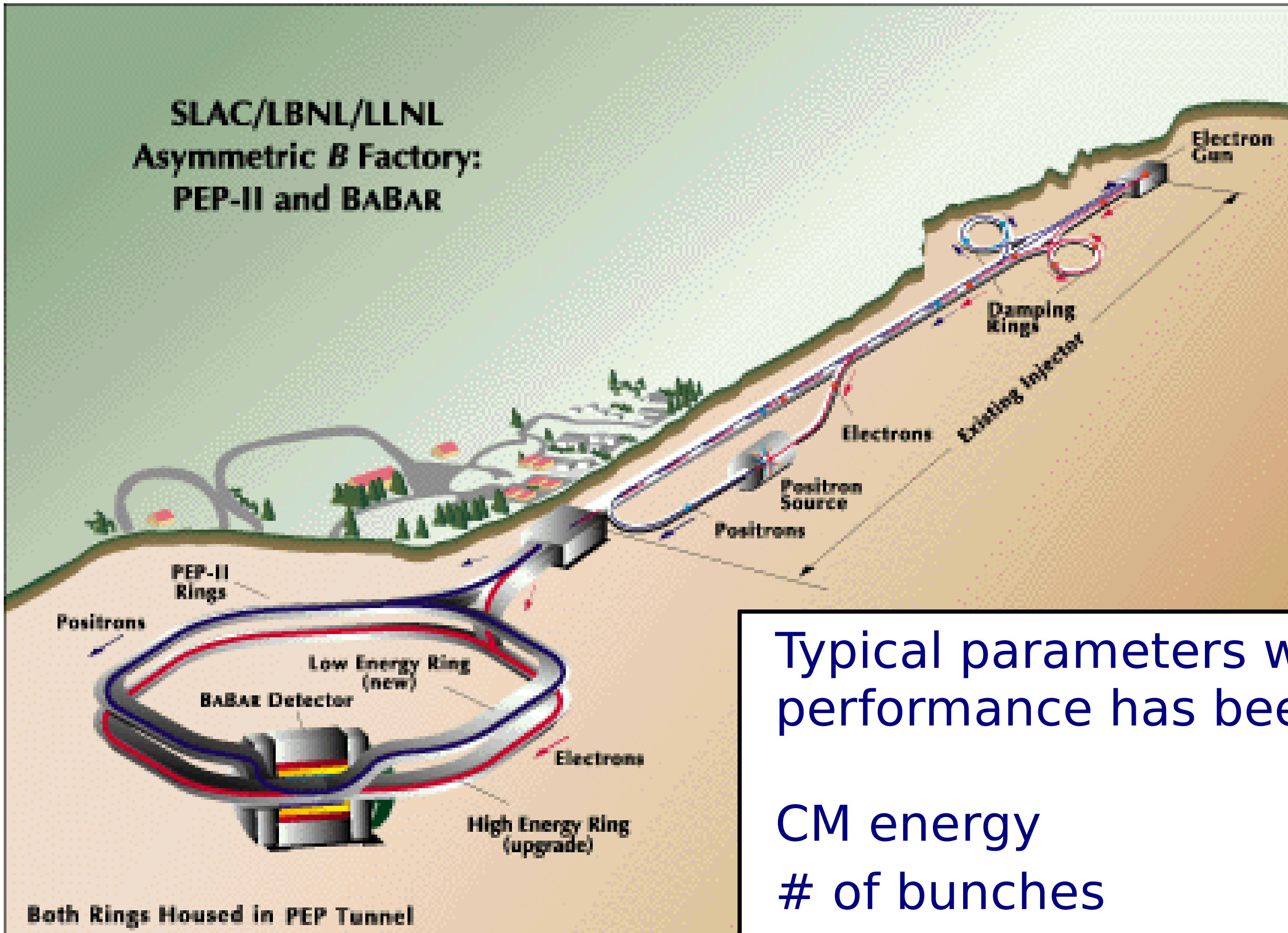
- The phenomenology then depends on the masses of h' and A':

  1) For $m_{h'} > m_{A'}$ the dominant decay is $h' \rightarrow A'A'^{(*)}$. The branching fraction of A' to leptons is always substantial, leading to a very clean 6 leptons final state;

  2) For $m_{h'} < m_{A'}$ the h' is long lived and generally escapes detection, so the signature is 2 leptons + missing energy;



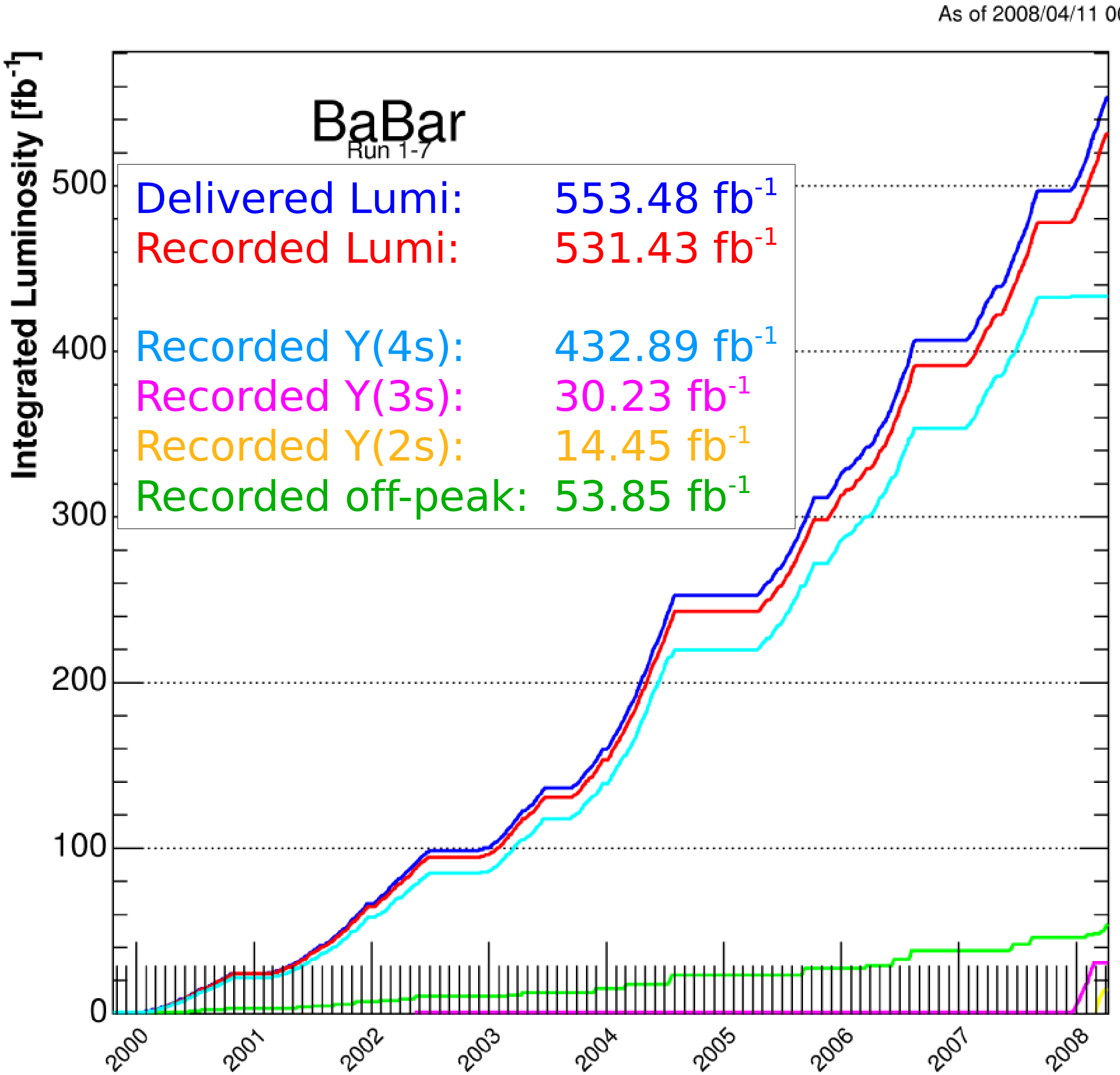
The PEP-II e^+e^- collider



Typical parameters when ultimate performance has been achieved:

CM energy	~10.58 GeV
# of bunches	~1700
e^+ energy/current	3.1 GeV / 2.5 A
e^- energy/current	9.0 GeV / 1.7 A
Record luminosity	1.2×10^{34} $cm^{-2}s^{-1}$

Data taking history



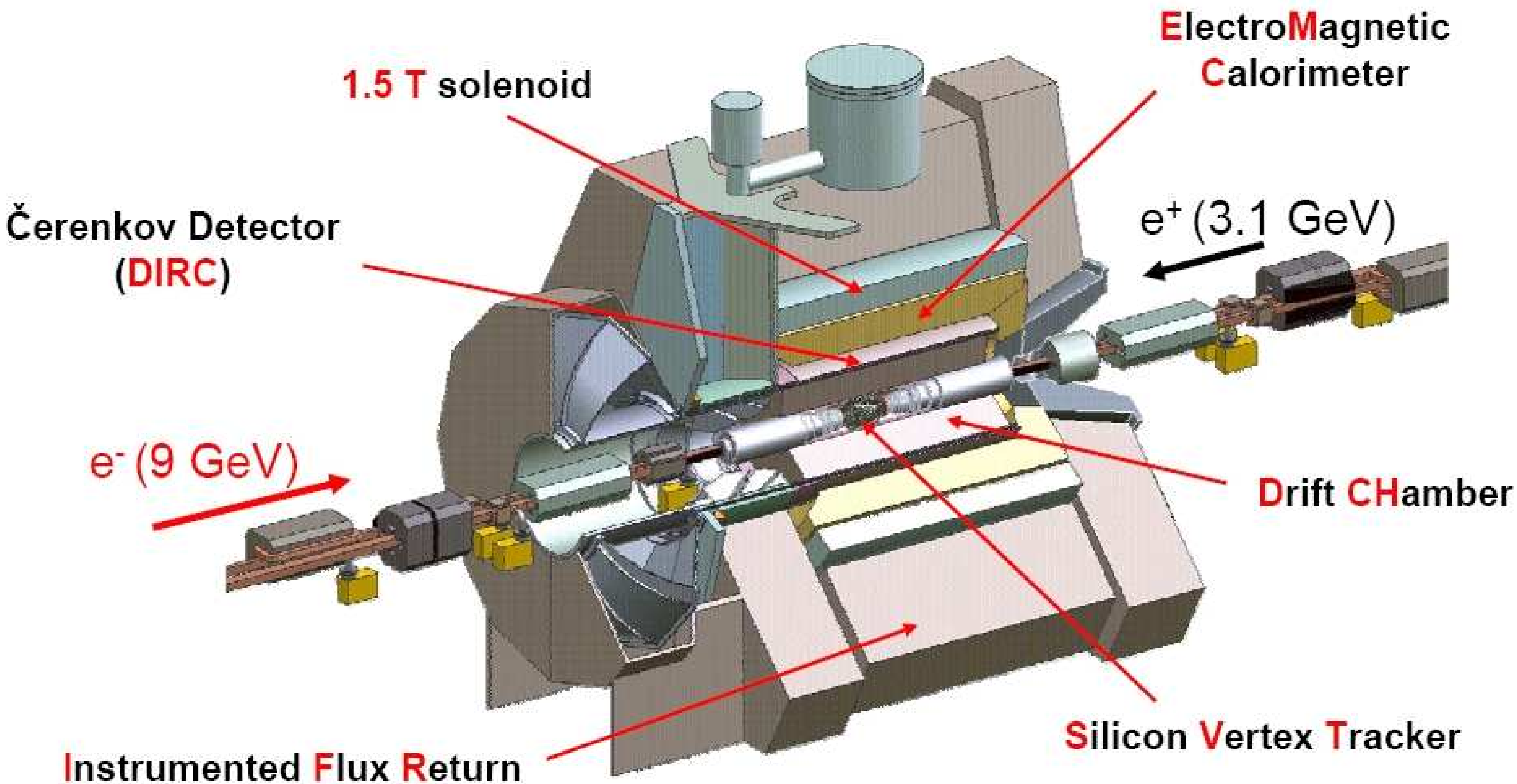
PEP-II and BaBar were operated from October 1999 to April 2008, most of the time as a B-factory (~467 million $B\bar{B}$ pairs recorded).

In the last months special runs were taken at the Υ(3s) and Υ(2s) resonances.

Throughout the whole period, runs at CM energies away from the Υ's have been taken, to study the continuum $e^+e^- \rightarrow q\bar{q}$ (q = u, d, s, c, (b)) background.

All data are used for the analysis presented in the following.

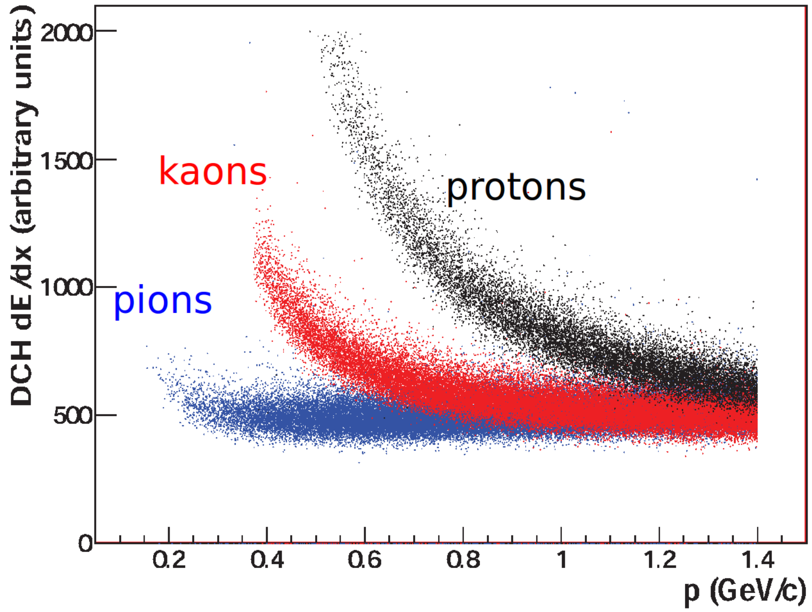
The BaBar detector

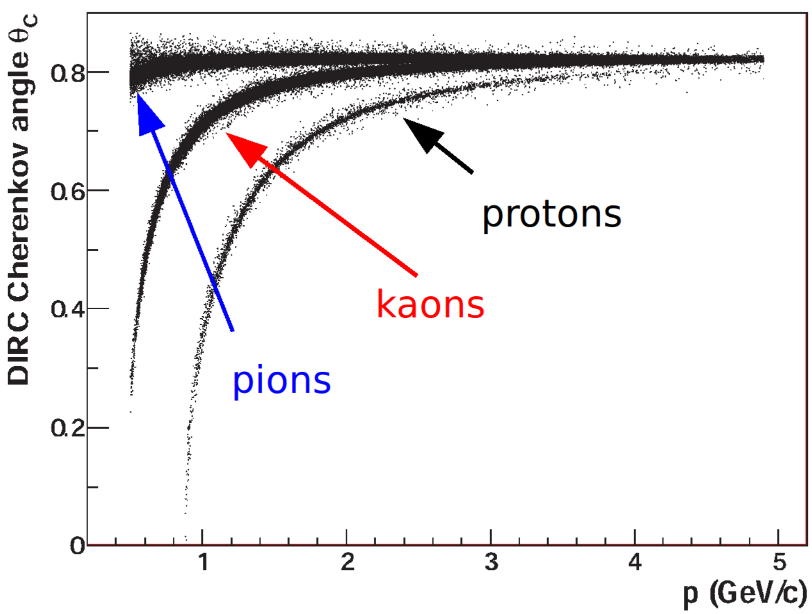


BaBar PID capabilities

Particle IDentification is a key task for the physics of BaBar. The discrimination among the different flavors relies on:

- Measurement of dE/dx in the SVT and DCH;
- Measurement of the Cherenkov angle θ_C in the DIRC;
- Measurement of the energy (and shower shape) deposited in the calorimeter;
- Measurement of the distance travelled through the IFR.





PID algorithms

μ identification: heavily relies on the information from the IFR. Combining this with input from all the other detectors in Bagged Decision Trees (BDTs) substantially helps reducing π contamination and compensating for the loss of efficiency of RPC's.

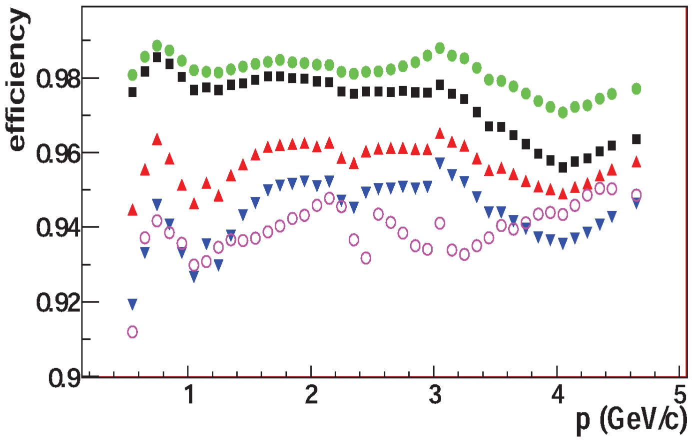
e, π, K, p discrimination: several binary discriminators (based on BDTs) combined in an exhaustive matrix, are used in a selector based on Error Correcting Output Code (ECOC). This exploits basically all the PID information available (36 inputs), and reaches the ultimate PID performance, improving over selectors based on Likelihood Ratios and Neural Networks.

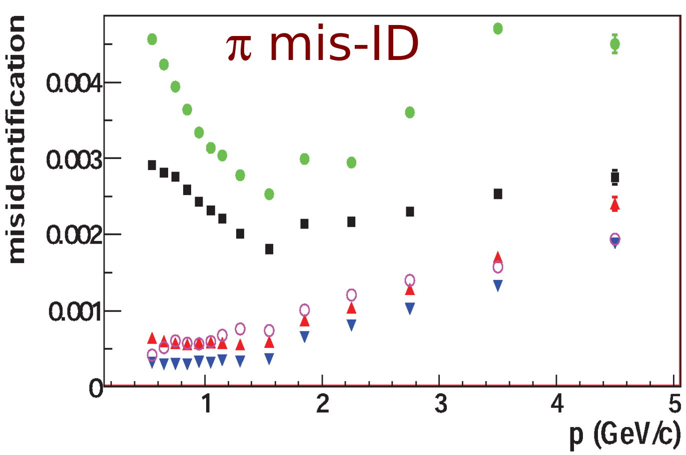
Class	t_1	t_2	t_3	t_4	t_5	t_6	t_7
K	1	1	1	1	1	1	1
π	-1	1	-1	1	-1	1	-1
proton	1	-1	-1	1	1	-1	-1
e	1	1	1	-1	-1	-1	-1

Exhaustive matrix used in ECOC based selectors

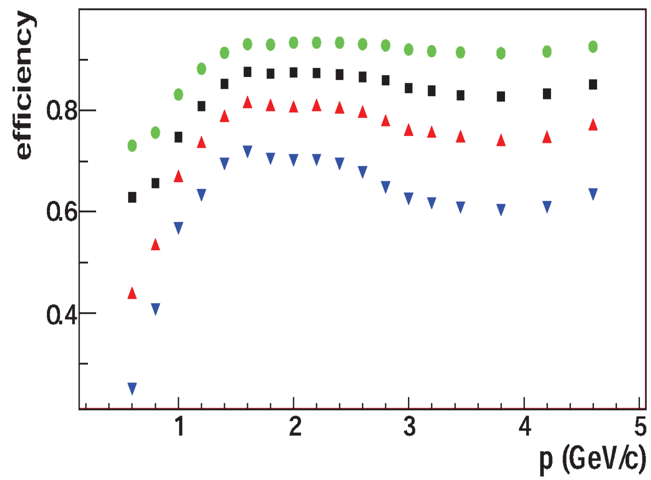
PID performance

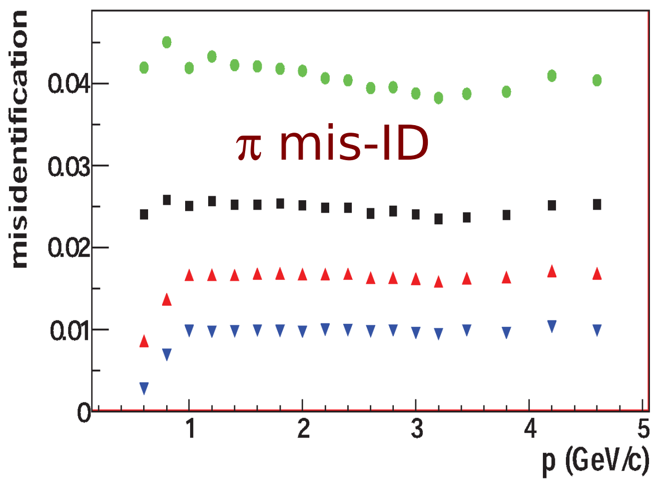
electrons



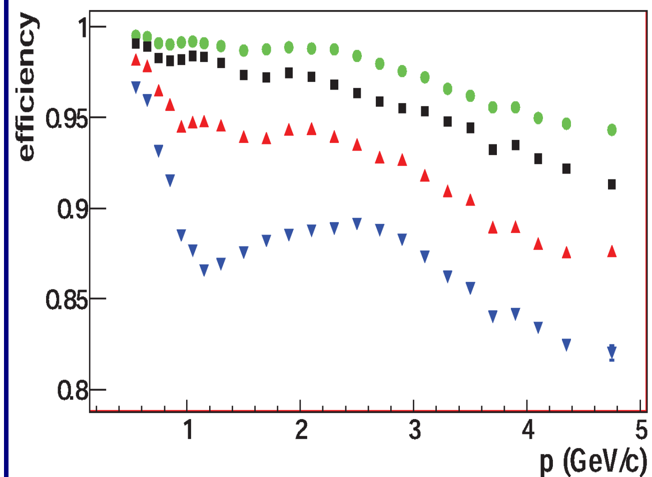


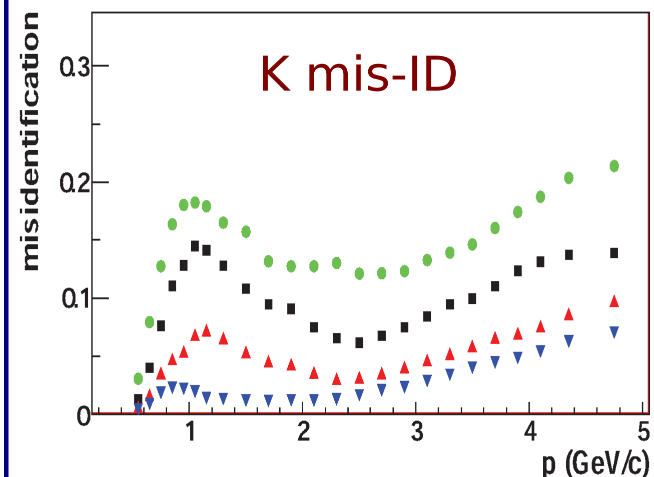
muons





pions





Different colors correspond to different “tightness” of the selectors.

For this analysis, we use pretty loose selectors, in order to maximize the selection efficiency.

Analysis strategy

BaBar Collaboration, J.P. Lees et al., PRL 108 211801 (2012)

- We search for the dark photon A' and dark Higgs h' if the full BaBar dataset (521 fb^{-1}), through the Higgs-strahlung production;
- We assume $m_{h'} > 2m_{A'}$ so h' dominantly decays to pair of dark photons on mass shell:

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

- We search for h' and A' in the mass ranges:

$$0.8 < m_{h'} < 10 \text{ GeV} \quad \text{and} \quad 0.25 < m_{A'} < 3.0 \text{ GeV}$$

- For these masses and mixing strength $\varepsilon \gtrsim 10^{-4}$, the decays of h' and A' are considered to be prompt (i.e. their decay length is $\lesssim$ than the detector resolution).

Analysis strategy

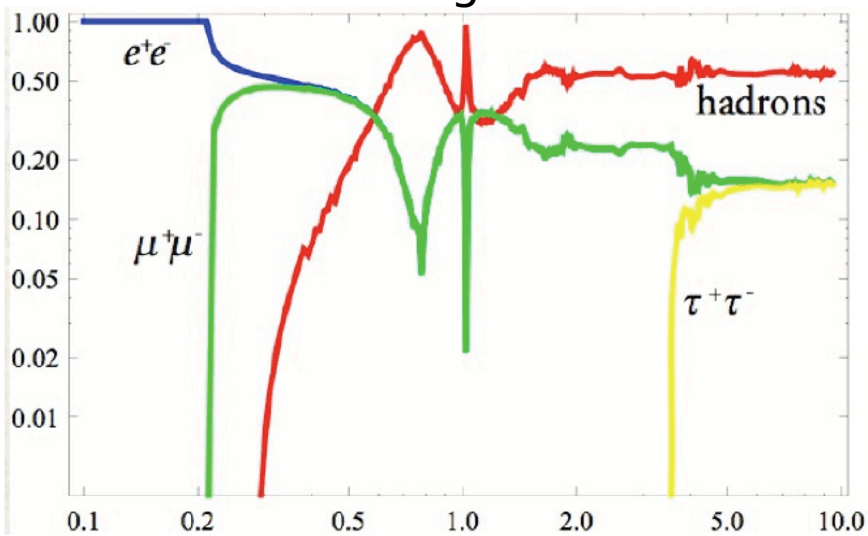
We consider the following final states:

1) "Exclusive" modes: $3(l^+l^-)$, $2(l^+l^-)\,\pi^+\pi^-$, $l^+l^-\,2(\pi^+\pi^-)$.

Signal candidates are selected looking (in the following order) for a match in the final states:

6μ, $4\mu 2e$, $2\mu 4e$, $6e$, $4\mu 2\pi$, $2\mu 2e 2\pi$, $4e 2\pi$, $2\mu 4\pi$, $2e 4\pi$.

A' branching fractions



$m_{A'}$ (GeV)

2) "Inclusive" modes (for $m_{A'} > 1.2$ GeV):

$4\mu + X$, $2\mu 2e + X$.

This order is chosen to minimize the cross-feed between channels and the loss of efficiency due to misclassification.

Other possible combinations are not considered due to their higher background.

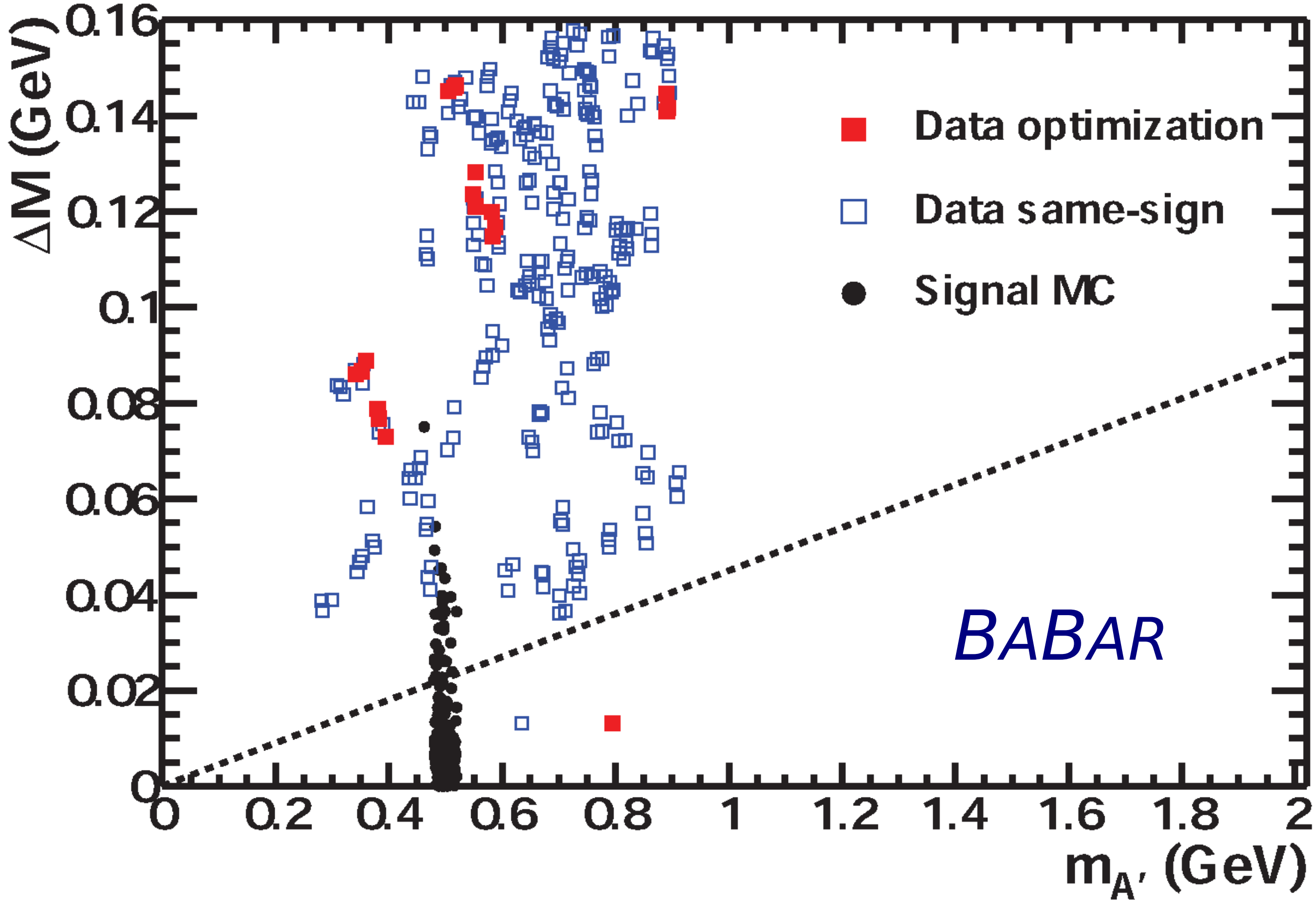
Event Selection

~10% of the data are used to optimize the selection. These are then discarded from the analysis.

- Exclusive modes:
  - The event contains exactly 6 tracks, which account for > 95% of the CM energy;
  - The tracks are constrained to originate from same vertex, fit probability > 10^{-5};
  - The largest mass difference between the A' candidates ΔM must be less than 10-240 MeV (depending on final state);
- Inclusive modes:
  - Fit probability of the four tracks > 10^{-5};
  - The masses of the A' candidates must be compatible within uncertainties. The knowledge of the beam energy allows us to constrain the mass of X, which must be compatible with A'.

Event Selection

Example of ΔM vs $m_{A'}$ for the signal point with $m_{h'}$ = 3.0 GeV, $m_{A'}$ = 0.5 GeV, in the 2e4π final state (MadGraph is used to generate our signal sample).



Signal events peak at ΔM ~0, whereas background is much broader.

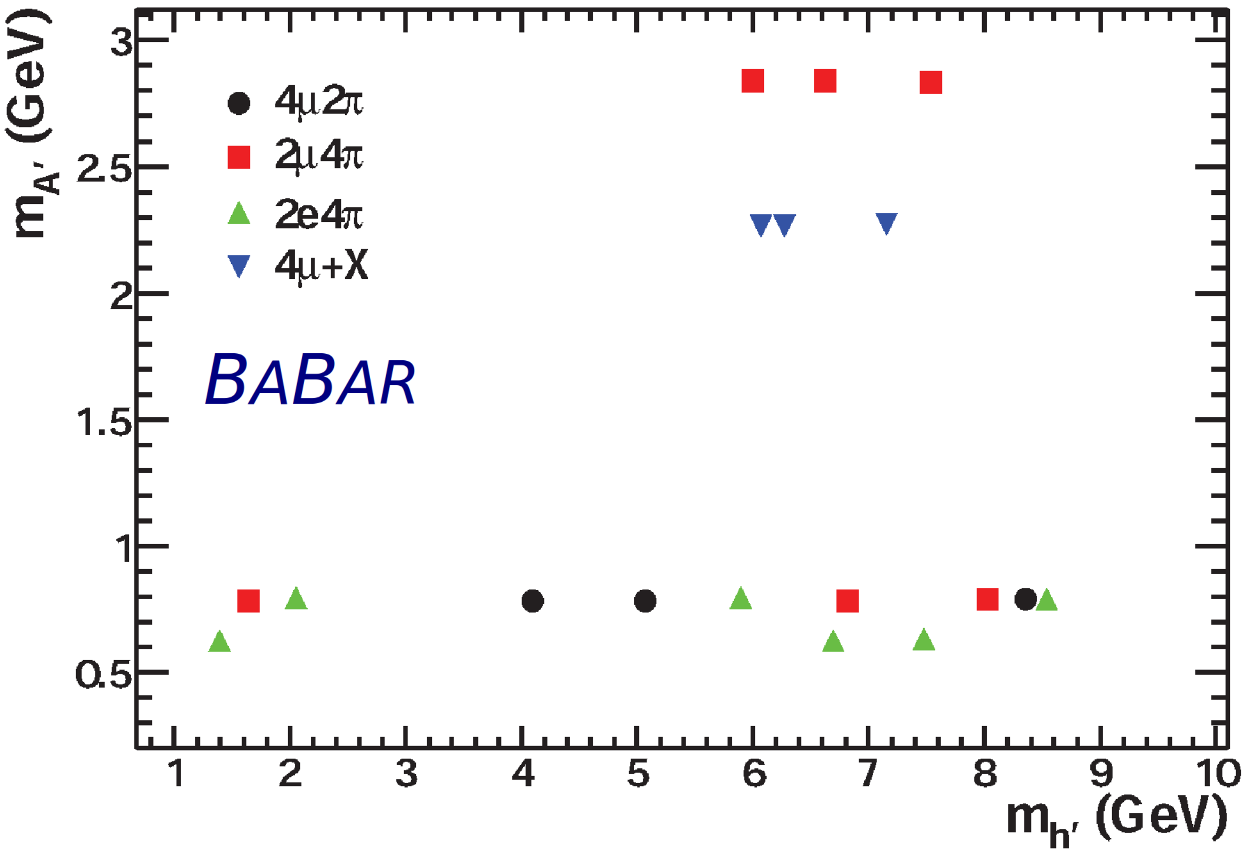
In order to have more data statistics to estimate the combinatorial background, we also consider same sign ($l^{\pm}l^{\pm}$) combinations.

Observed Events

We observe 6 events in the full dataset:

Selection	# events
$4\mu2\pi$	1
$2\mu4\pi$	2
$2e4\pi$	2
$4\mu + X$	1

No 6 lepton events observed!



For each event three h' → A'A' combinations are possible.

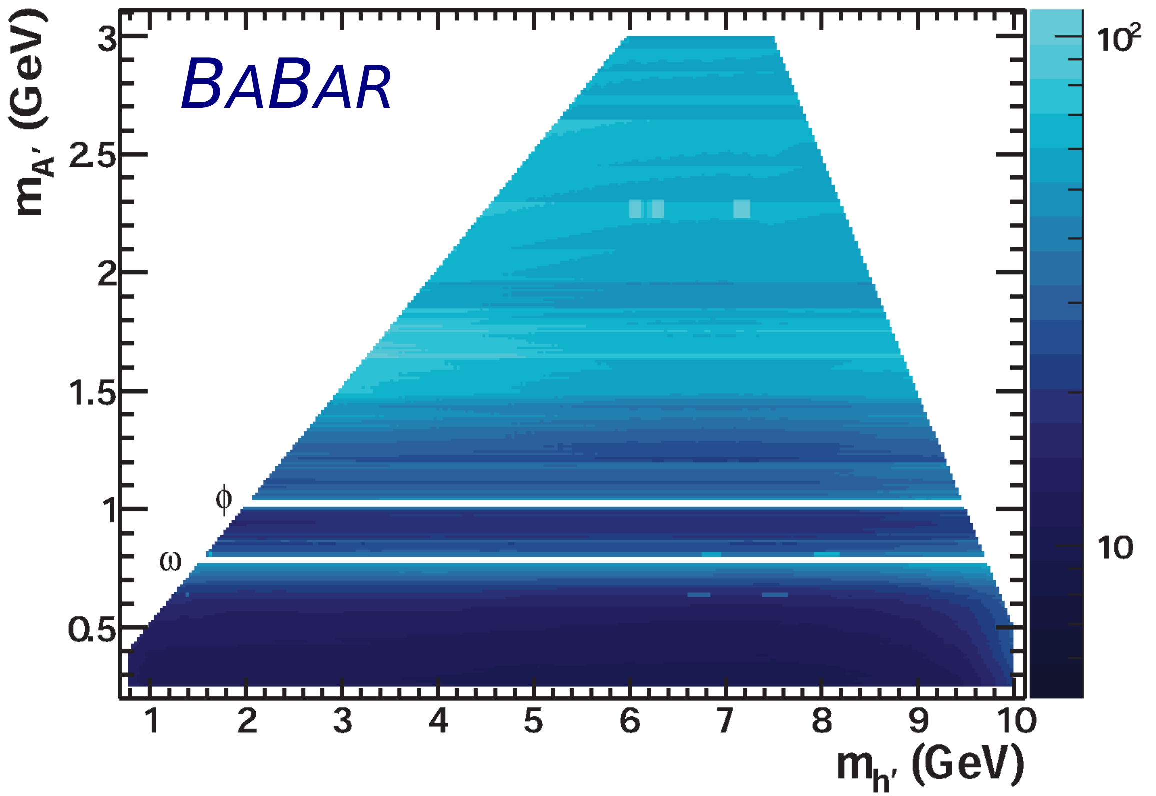
The band at $m_{A'} \sim 0.7$-0.8 GeV is consistent with ρ and ω decays.

The observed number of events agrees well with our estimates of the combinatorial background.

Cross-section Upper Limits

- We scan the ($m_{h'}$, $m_{A'}$) space at steps of 10 MeV along each axis, defining the signal region as [m_X – $5\sigma_{mX}$; m_X + $3\sigma_{mX}$], X = h', A'
- We conservatively assume that each event is a potential signal event;
- The signal efficiency (including acceptance, trigger and selection efficiency, and branching fractions) is determined in several signal points and interpolated across the plane.

90% CL Bayesian cross-section upper limit (ab)



BF(A' → l^+l^-) = 1/(2+R)

BF(A' → had.) = R/(2+R)

R = BF(e^+e^- → had.)/BF(e^+e^- → $\mu^+\mu^-$)

Systematic uncertainties

- The dominant systematic uncertainty comes from the interpolation procedure of the signal efficiency (ranging from 1 to 8%);

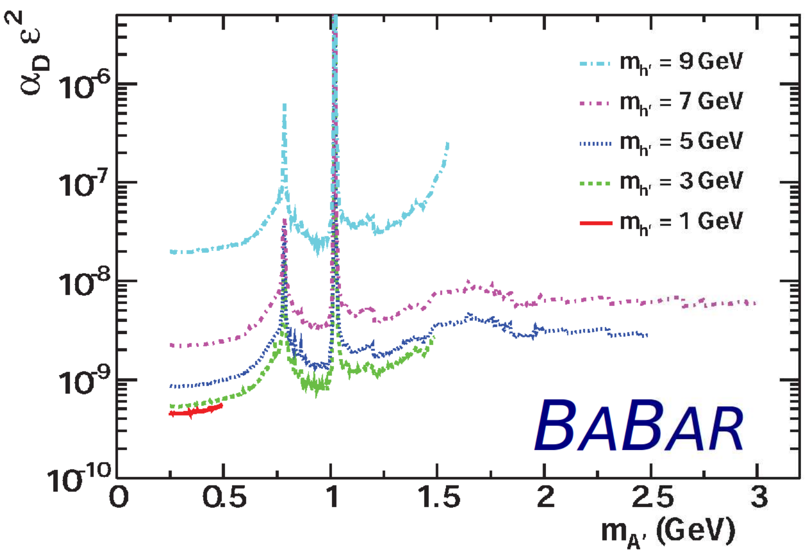
- Other significant uncertainties:

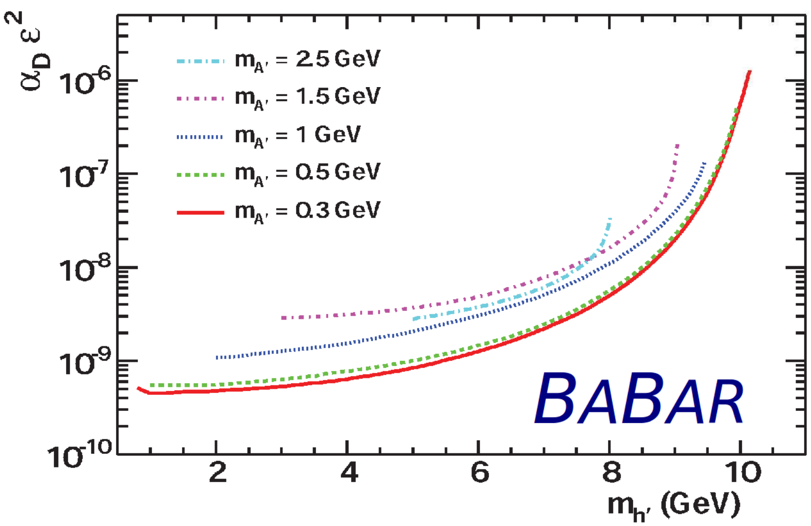
Source	**Uncertainty (%)**
Branching Fractions	0.3 - 4
Modeling of A' → hadrons	4
PID	1.5 – 4.5
Tracking efficiency	1.2
Luminosity	0.6
MC statistics	0.5 – 2.4

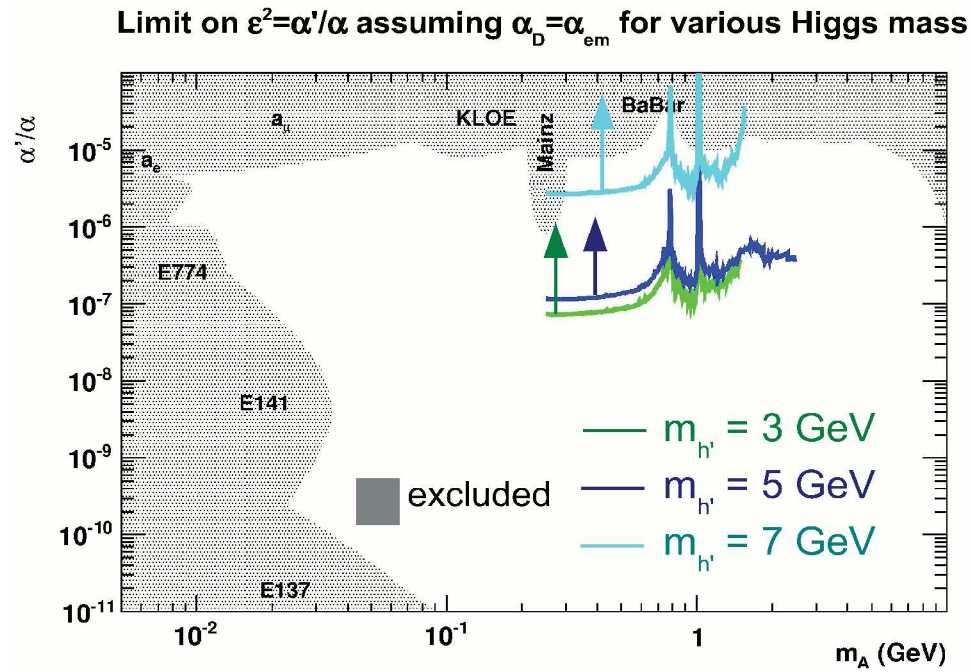
- Overall the systematics are small and have little impact on the final results.

$\alpha_D \varepsilon^2$ limits

We translate the cross-section UL's into upper limits on the product $\alpha_D \varepsilon^2$, where $\alpha_D = g^2_D/4\pi$. g_D: dark sector gauge coupling.







We obtain limits of 10^{-10} – 10^{-8} in wide ranges of the A' and h' masses. If we assume $\alpha_D = \alpha$, we have upper limits on ε in the range 10^{-4} – 10^{-3}, an order of magnitude tighter than previous limits.

Conclusions

- After more than four years from the end of data-taking, BaBar continues to exploit its rich dataset;
- We searched for a dark Higgs and a dark photon through Higgs-strahlung production;
- The number of events that we observe is consistent with the expected backgrounds, and the limits on cross-sections and kinetic mixing ε extend those of previous searches;
- More searches are ongoing and new results will come out soon!