Search for new phenomena at BaBar, Belle and LHCb

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On behalf of the BABAR, BELLE, LHCb collaborations

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Outline

- Dark photon (A') and dark Higgs boson (h') searches
  - BaBar: $e^+e^- \to \gamma A'$, $A' \to l^+l^-$ (l=e or μ) — PRL **113**, 201801 (2014)
  - Belle: $e^+e^- \to A'h'$, $h' \to A'A'$ inclusive and exclusive channels — PRL **114**, 211801 (2015)
- Search for long-lived particles
  → Identified thanks to their displaced vertices
  - BaBar: six exclusive 2-track final states e^+e^-, $\mu^+\mu^-$, $e^{\pm}\mu^{-/+}$, $\pi^+\pi^-$, K^+K^-, $\pi^{\pm}K^{-/+}$ — PRL **114**, 171801 (2015)
  - LHCb: pair-produced by the decay of a Standard Model (SM)-like Higgs boson and decaying into two jets — Eur. Phys. J. C**75** 152 (2015)
- Units with c=1 used in this talk

Context and motivation

- Standard Model (SM) complete since the discovery of the Higgs boson (LHC, 2012)
- Yet: many experimental and theorical reasons to look for new physics beyond the SM
  → All-out searches for the new particles predicted by SM extensions

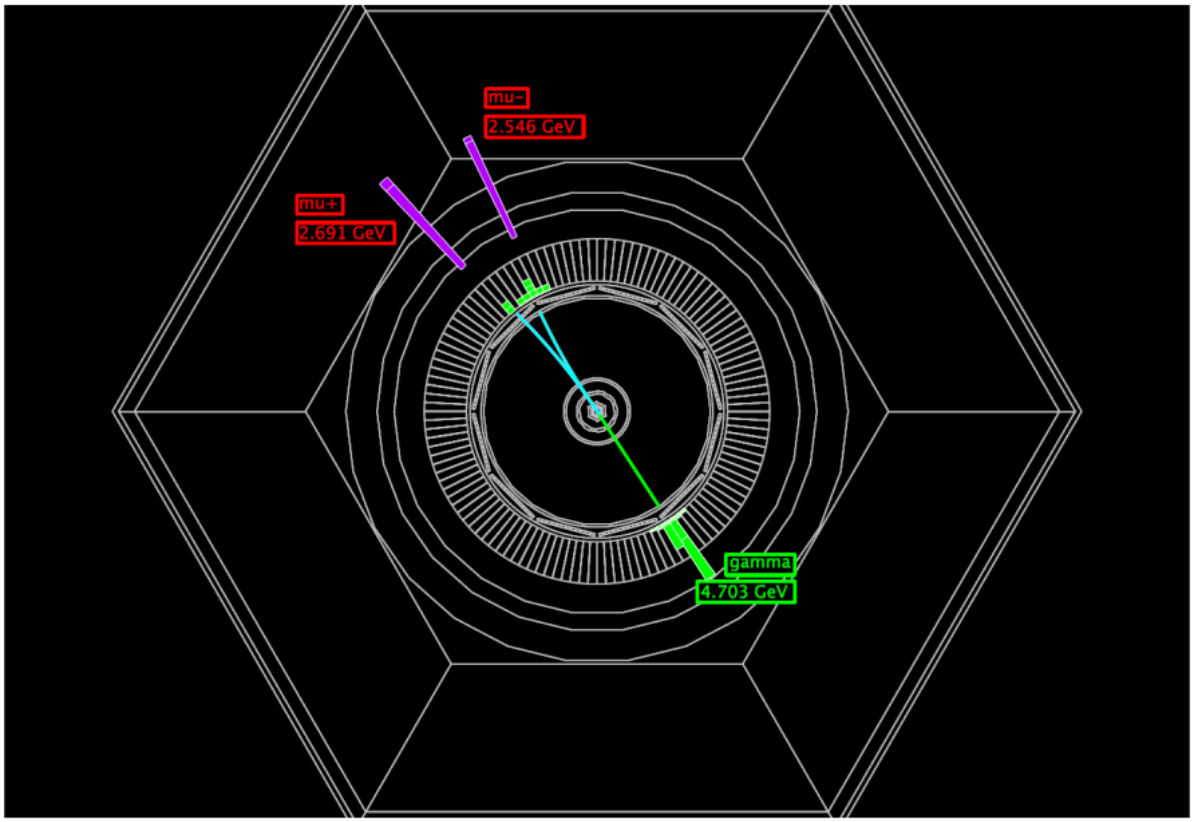
- Dark sector models B. Battel et al. (2009) R. Essig et al. (2013)
  - New hidden U(1) interaction mediated by a dark photon A'
    → Acts as a portal between dark (hidden) sector and SM
  - A' couples to the SM hypercharge via kinetic mixing – (small) mixing strength ε
  - Can mediate the annihilation of Weakly Interactive Massive Particles (WIMPs) into SM fermions: $\chi\chi \rightarrow A'A' \rightarrow (l^+l^-)\,(l^+l^-)$
  - Mass in the MeV to GeV range to account for recent astrophysical observations
  - Hidden U(1) group could be spontaneously broken
    → Dark Higgs boson(s) h'

- New long-lived neutral particles in the GeV scale predicted by several models

- Fixed target experiments and B-Factories are ideal for such searches
  - Clean environment, high luminosity

- LHCb has a unique coverage for particles with relatively small mass and lifetime
  - Transverse mometum trigger requirements lower than for ATLAS and CMS

Dark photon and dark Higgs boson searches

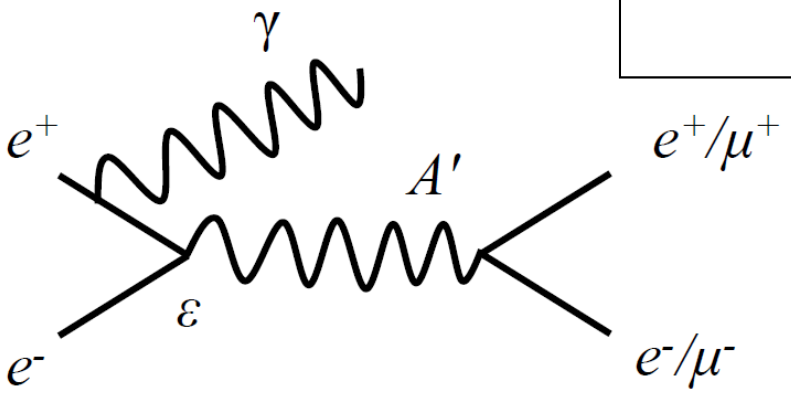


BaBar Monte-Carlo event showing a dark sector particle decaying into a $\mu^+\mu^-$ pair in a radiative event

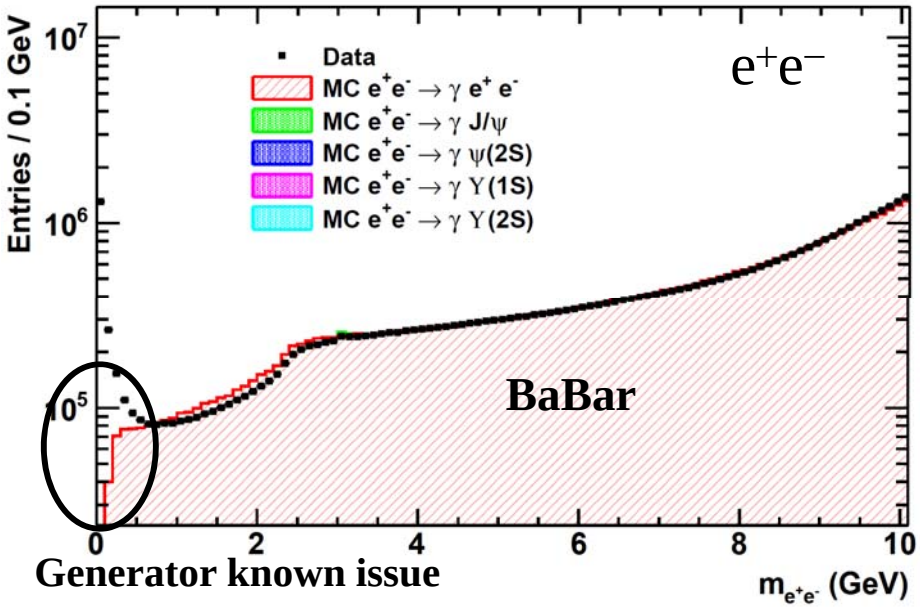
Dark photon search at BaBar

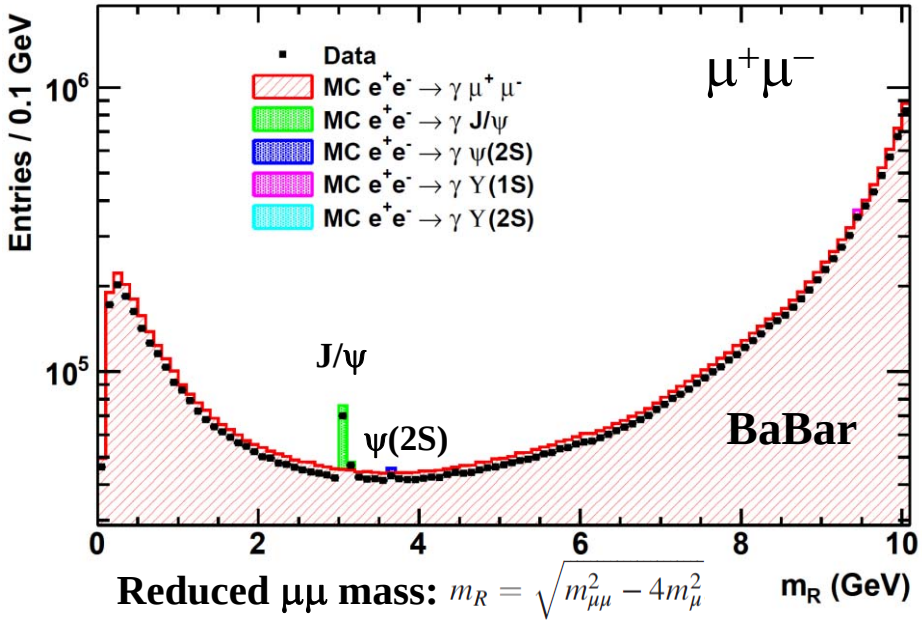
514 fb^{-1}: Υ(4S), Υ(3S), Υ(2S)

- Look for narrow resonance in radiative events with two leptons in the final state
- E(γ) > 200 MeV; 1 e or 2 μ identified
- Kinematic + geometric fits



- Converted photon events removed by a multivariate analysis
- Typical signal efficiencies: 15% (e^+e^-), 35% ($\mu^+\mu^-$)
- 5% of the data used to optimize the selection criteria and validate the fitting procedure
  → Discarded from the final sample





Fit procedure

- Simulated signal events generated by MADGRAPH for 35 different mass hypothesis
  - Resolution estimated by Gaussian fits; interpolated to other masses

  → Typical values: 1.5-8 MeV
- Series of independent maximum likelihood fits over sliding windows
  - Mass step ~half the mass resolution
  - Fit range > 20 × mass resolution
  - Non-parametric kernel probability density function (pdf) for signal

    → Shape interpolated between the simulated masses
- Background
  - Radiative Bhaba or dimuon
  - Peaking contributions included where appropriate – J/ψ, ψ(2S), ϒ(1S) and ϒ(2S)
- Resonant regions excluded from the search
  - Within ± 5 × (the experiental mass resolution of the resonance, 5-10 MeV)
- Scanned A' mass ranges for the ϒ(4S) dataset
  - e^+e^-: $0.02 < m_{A'} < 10.2$ GeV (5704 fits)
  - $\mu^+\mu^-$: $0.212 < m_{A'} < 10.2$ GeV (5370 fits)

  → Lower upper mass bounds for ϒ(2S) and ϒ(3S) samples – 9.6 and 10 GeV

Results

- Cross sections $\sigma(e^+e^- \to \gamma A', A' \to l^+l^-)$ extracted by dividing the fitted signal yields by the product of the reconstruction efficiency times the integrated luminosity

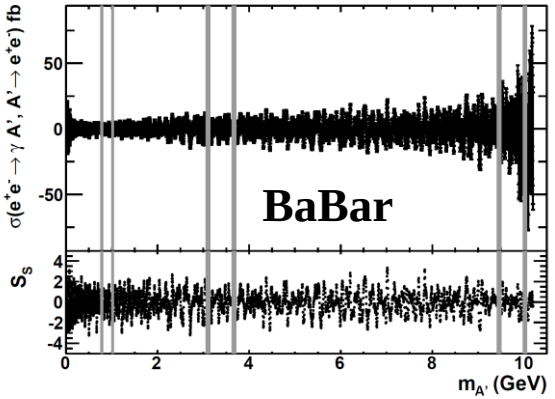
- Statistical significance S computed by comparing the likelihood values for the nominal fit (L) and the null hypothesis (L_0)

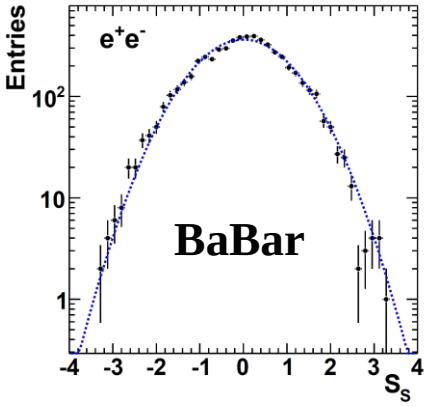
$$\mathcal{S} = \sqrt{2\log(\mathcal{L}/L_0)},$$

- Largest fluctuations
  - e^+e^-: 3.4σ @ $m_{A'}$ = 7.02 GeV
  - $\mu^+\mu^-$: 2.9σ @ $m_{A'}$ = 6.09 GeV

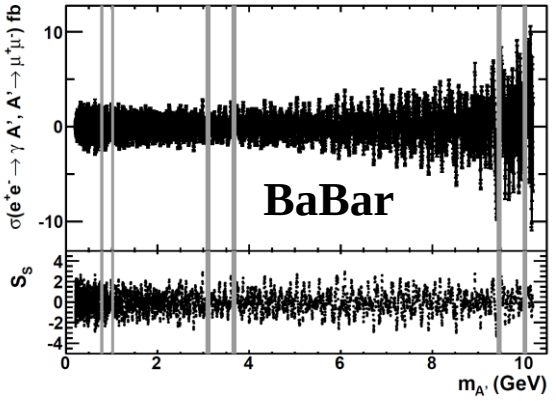
  → p-values consistent with the null hypothesis including trial factors: 0.57 and 0.94 respectively

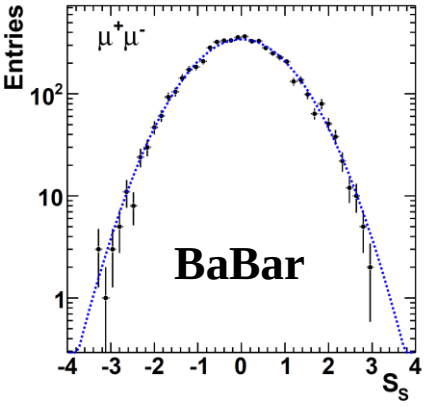
- No signal found at 214 MeV
  - Mass of the event excess reported by HyperCP





Grey bands indicate mass regions excluded from the fits



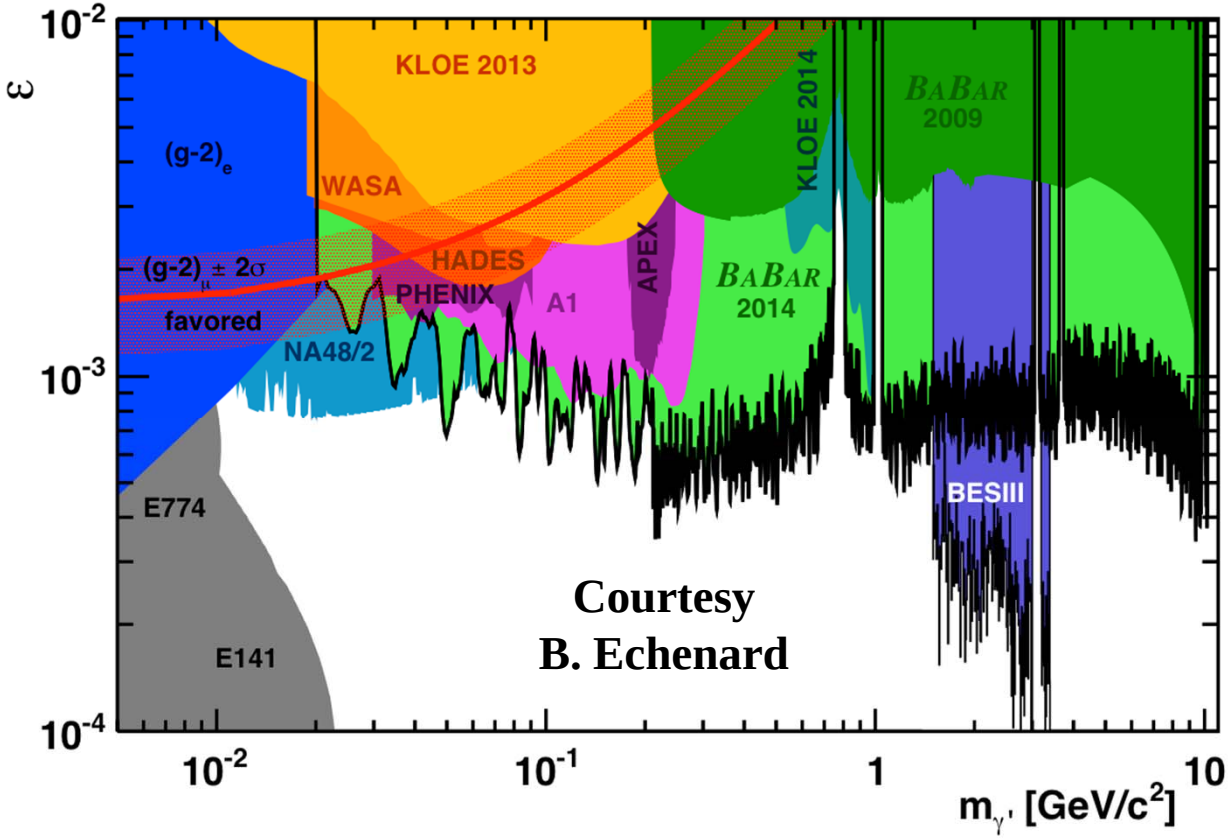


Constraints on physics model

- $\sigma(e^+e^- \to \gamma A')$ extracted using theoretical predictions for BF($A' \to l^+l^-$) and combining the results of the dielectron and dimuon channels

- No signal observed ⇒ Bayesien 90% C.L. upper limits in the 1-10 fb range

- Finally, results translated into 90% C.L. upper limits on ε (the mixing strength between the photon and the dark photon) as a function of $m_{A'}$



- Previous constraints significantly improved

- Parameter space range favored by the $(g-2)_\mu$ interpretation constrained further: only the region 15÷30 MeV still allowed
  → Later excluded by NA48/2 for $A' \to e^+e^-$ (not for $\mu^+\mu^-$)

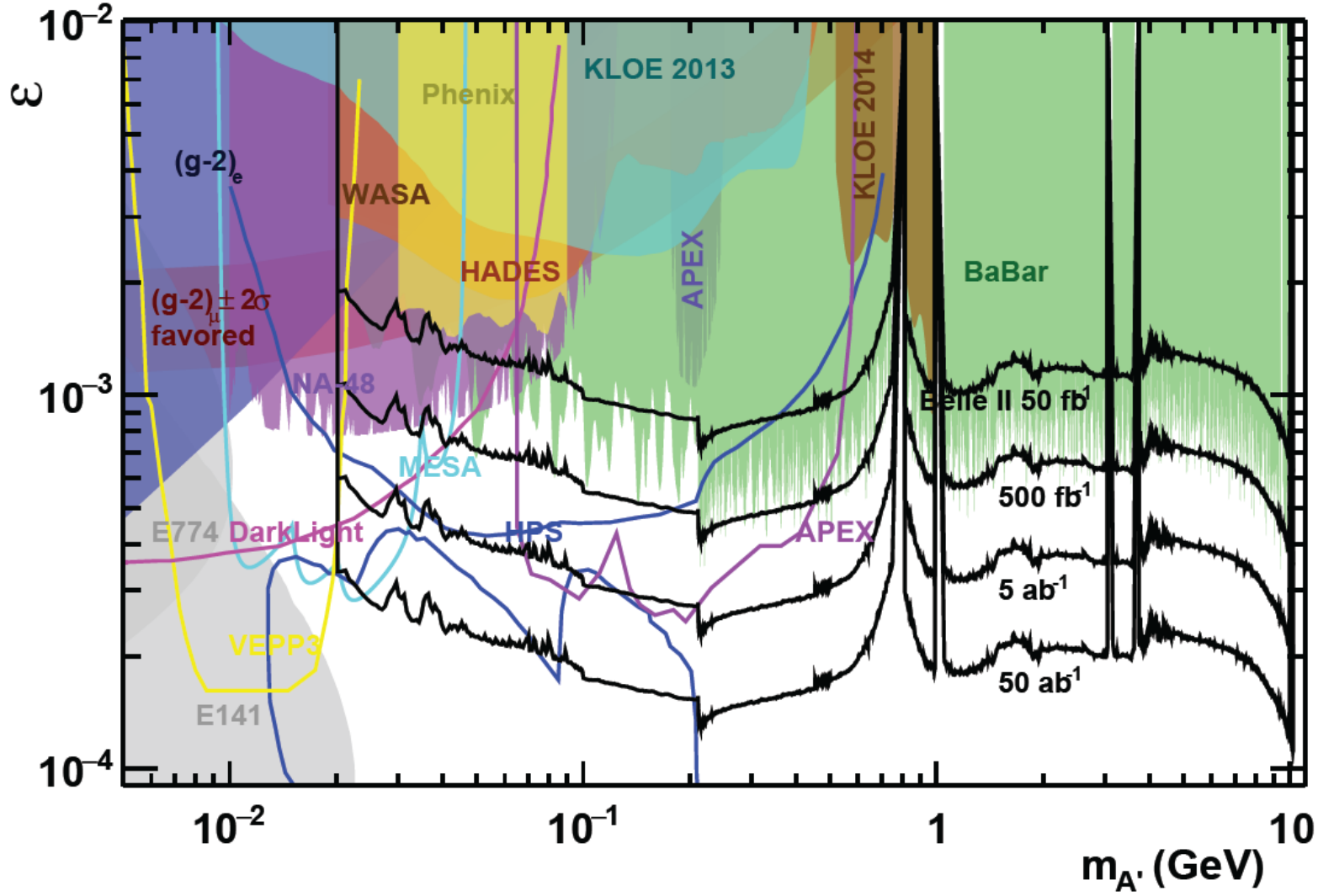
- New results from BES-III as well

Belle-2 prospect for this radiative decay

- $e^+e^- \to \gamma A'$, $A' \to e^+e^-$ or $\mu^+\mu^-$

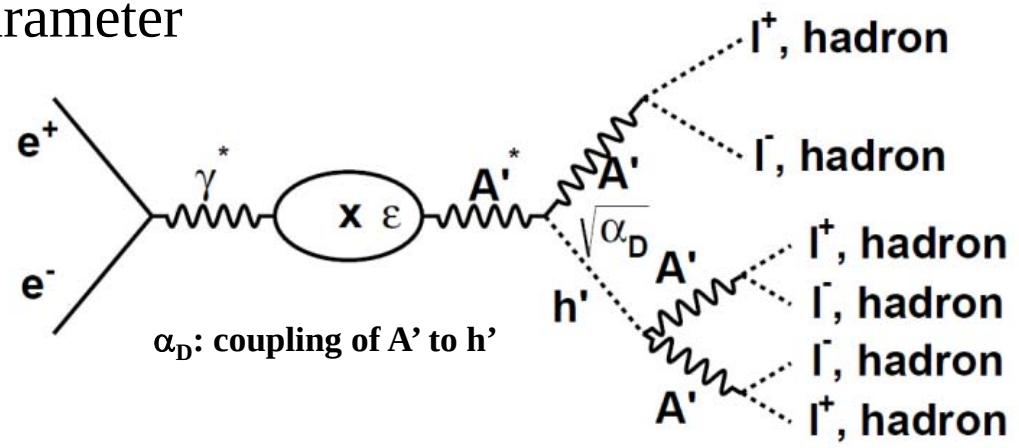
- Improved low-multiplicity trigger required

Courtesy
C. Hearty

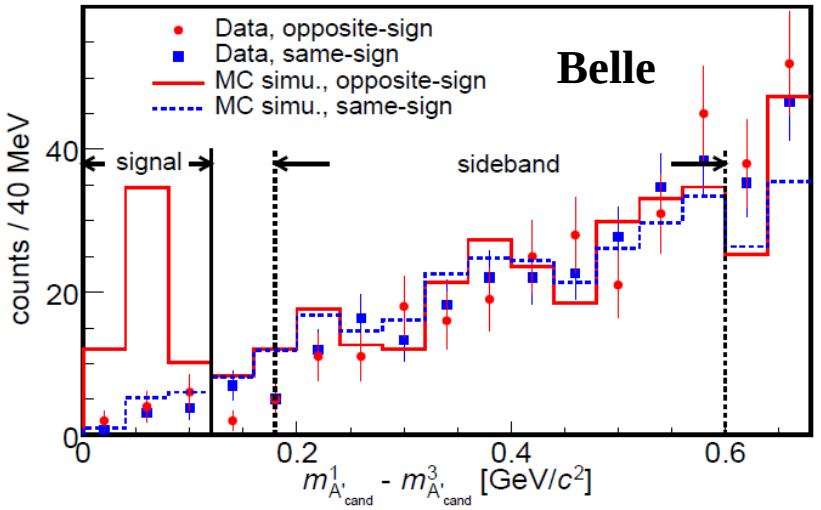


Dark photon and dark Higgs boson search at Belle

- Prompt decays for A' (dark photon) and h' (dark Higgs boson)
  - Tracks selected with small impact parameter
- $m_{h'} > 2\, m_{A'}$ ($h' \rightarrow A'A'$)
- Scanned parameter space
  - $0.1 < m_{A'} < 3.5$ GeV
  - $0.2 < m_{h'} < 10.5$ GeV

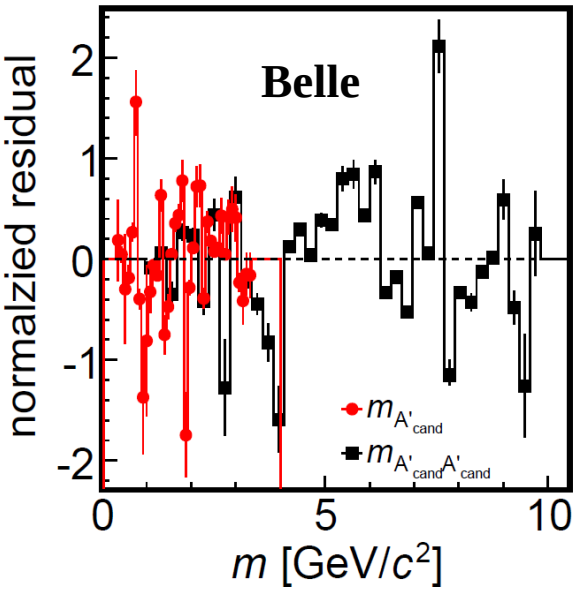


- Analysis channels
  - 10 exclusive: $3(l^+l^-)$, $2(l^+l^-)(\pi^+\pi^-)$, $2(\pi^+\pi^-)(l^+l^-)$ and $3(\pi^+\pi^-)$ with l=e or μ
  - 3 inclusive: $2(l^+l^-)X$, X being a dark photon detected via its missing mass
- Keep combinations with the 3 « A' » masses close
- Signal simulated with MADGRAPH
- Background extracted from data using « same sign » events: $2(l^+l^-)(l^-l^-)$
  - Sideband method to estimate contribution in signal region
- Full Belle dataset: 977 fb^{-1}

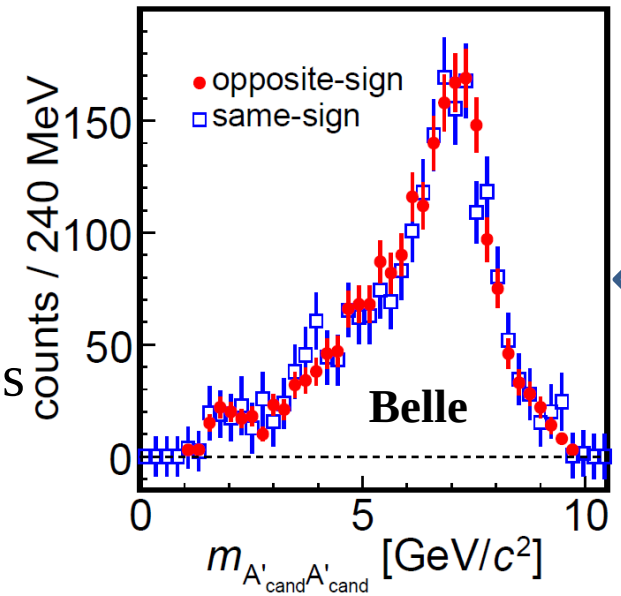


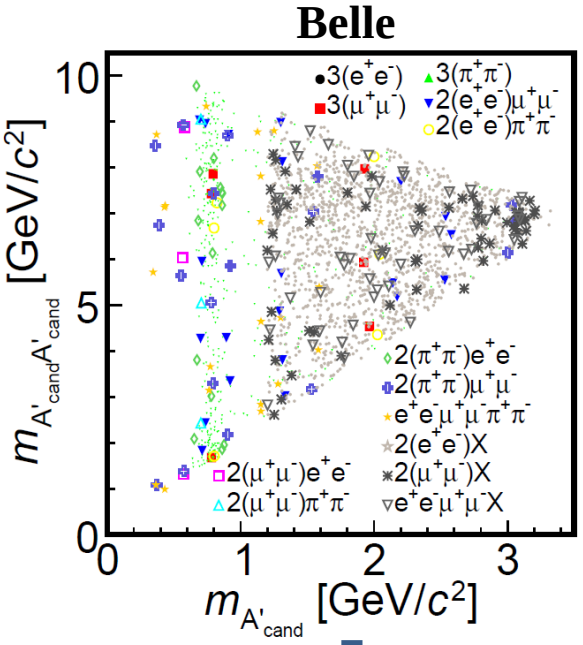
Observed events

- Selected events in the m_h, vs $m_{A'}$ plane
- Corresponding projections on both axis
- Red dots: signal candidates
- Blue squares: background prediction
- Normalized residuals



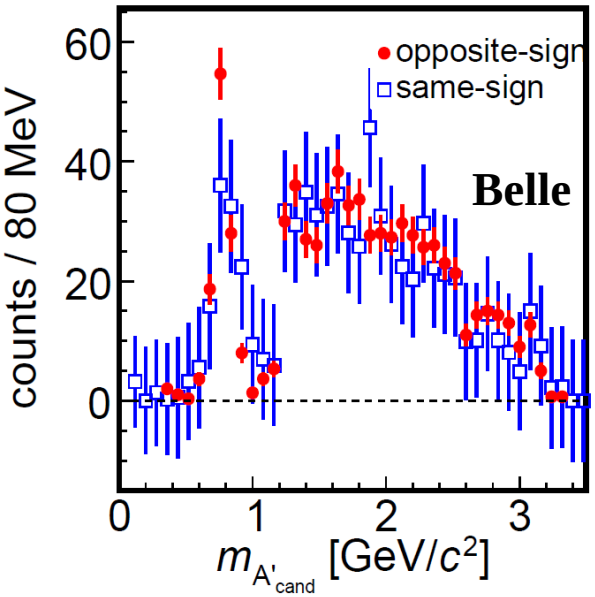
$(N_{obs} - N_{bkg})/\sqrt{\sigma^2_{obs} + \sigma^2_{bkg}}$.





- Number of observed events per channel

Final-state	Events	Final-state	Events
$3(e^-e^+)$	1	$2(\mu^+\mu^-)(e^+e^-)$	1
$3(\mu^+\mu^-)$	2	$2(\mu^+\mu^-)(\pi^+\pi^-)$	1
$3(\pi^+\pi^-)$	147	$2(\pi^+\pi^-)(e^+e^-)$	5
$2(e^+e^-)(\mu^+\mu^-)$	7	$2(\pi^+\pi^-)(\mu^+\mu^-)$	6
$2(e^+e^-)(\pi^+\pi^-)$	2	$(e^+e^-)(\mu^+\mu^-)(\pi^+\pi^-)$	7
$2(e^+e^-)X$	572	$(e^+e^-)(\mu^+\mu^-)X$	30
$2(\mu^+\mu^-)X$	20		

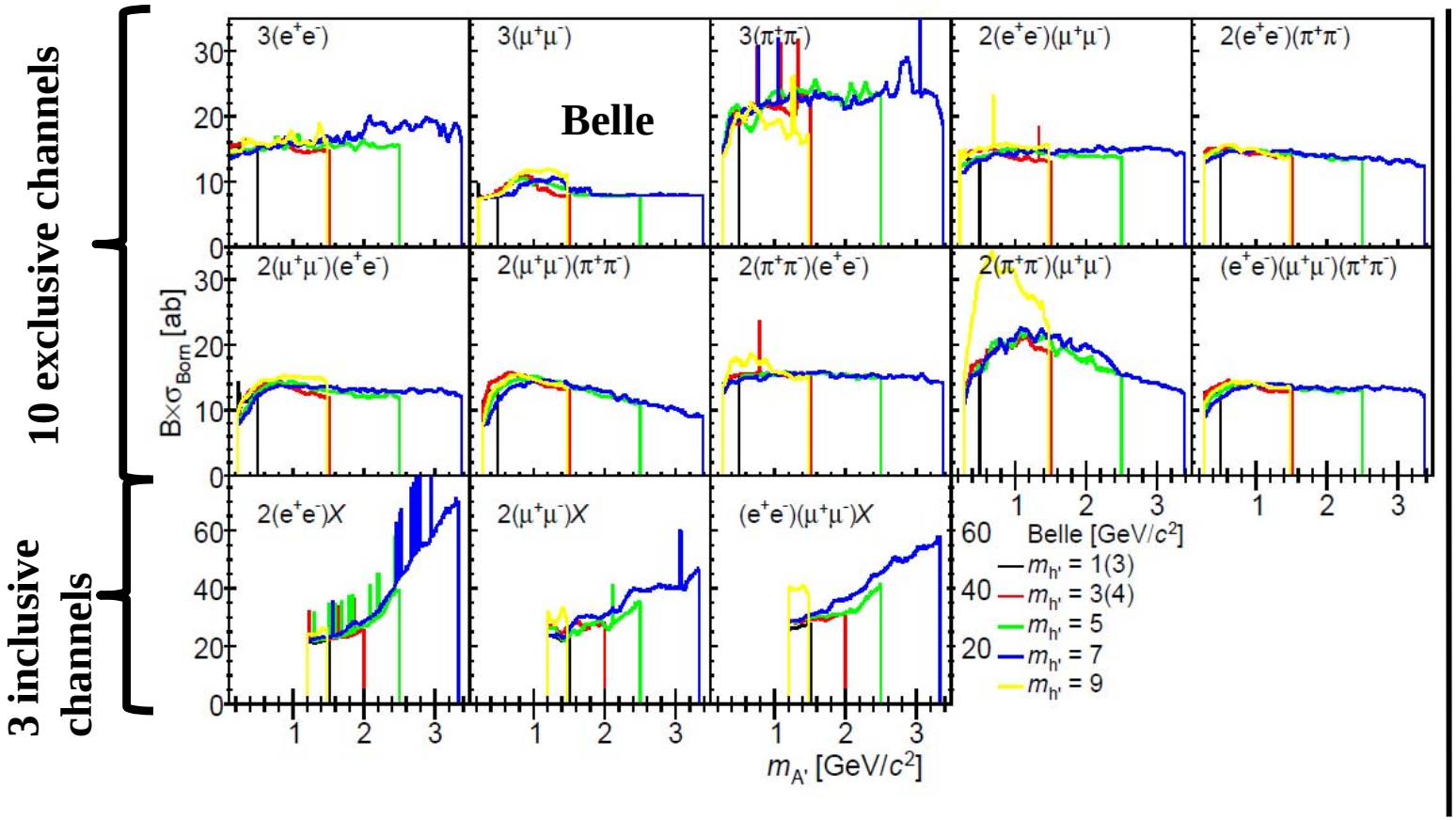


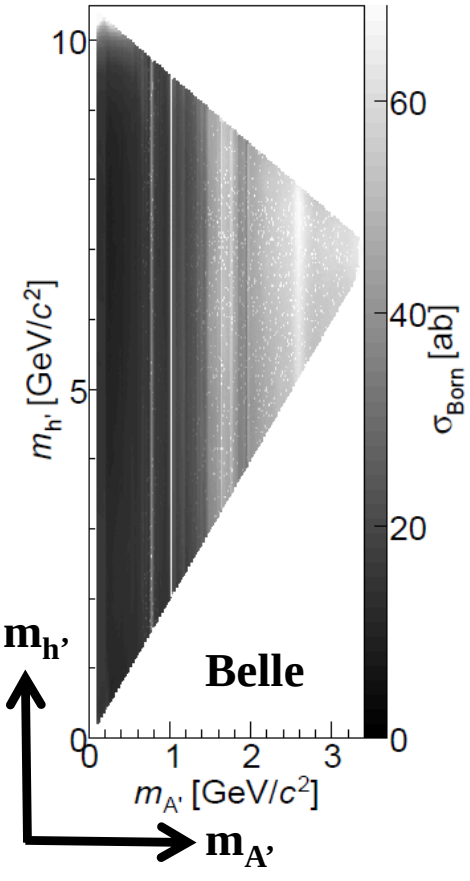
Results

- All numbers of observed events consistent with background estimates
  - 90% C.L. upper limits on the product (branching fraction) × (Born cross section)

- Upper limits for the 13 final states (10 exclusive, 3 inclusive) and different h' masses

- Upper limit on the combined Born cross section

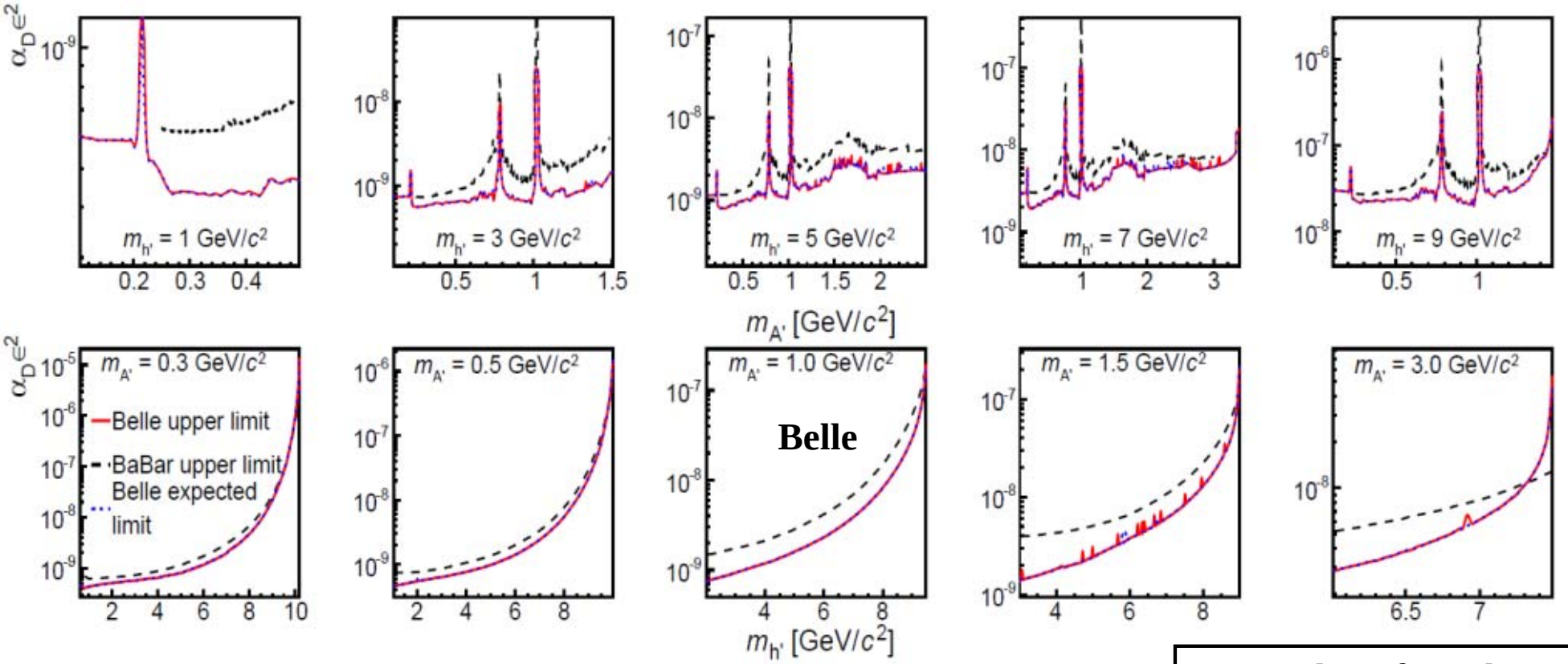




Constraints on dark sector models

- Examples of upper limits on $\alpha_D \times \varepsilon^2$ for various h' and A' masses
  - Black: BaBar constraints on the visible cross section – PRL 108 211801 (2012)
  - Red: Belle constraints on the Born cross section – this analysis

  → ISR effects not negligible, to be taken into account for comparison

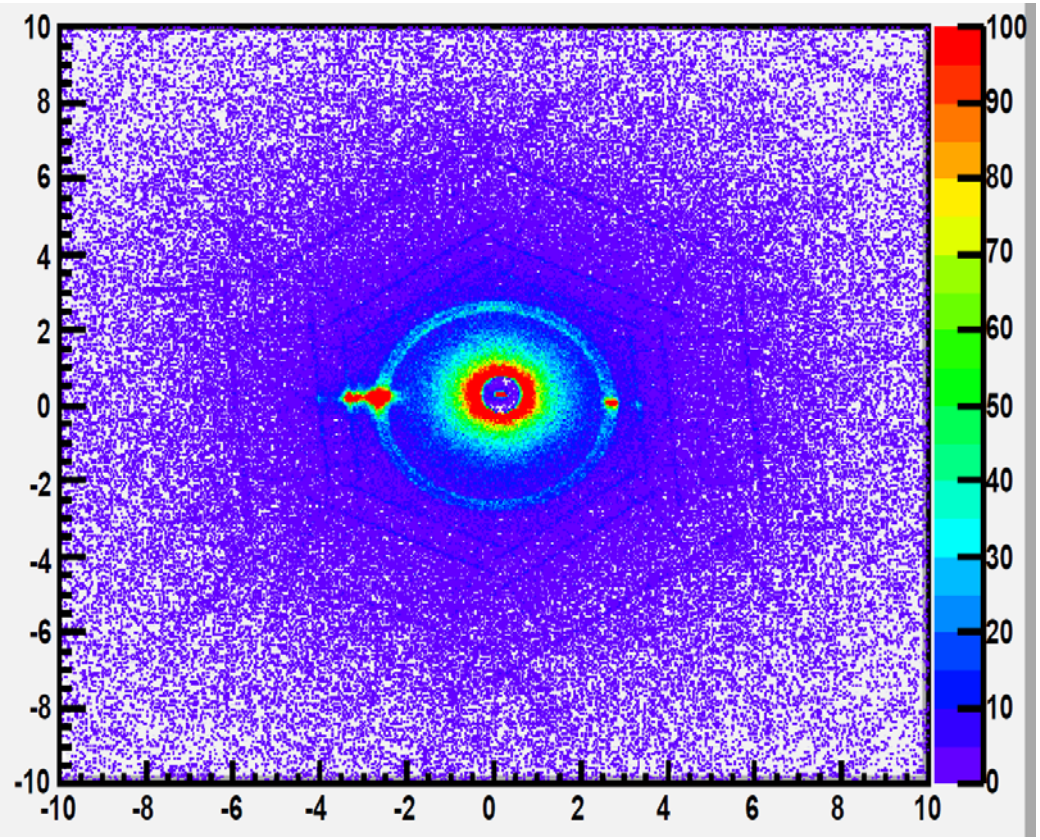


α_D: coupling of A' to h'
ε: A' kinetic mixing with γ

- Results scale nearly linearly with integrated luminosity

  → Promising for Belle-2

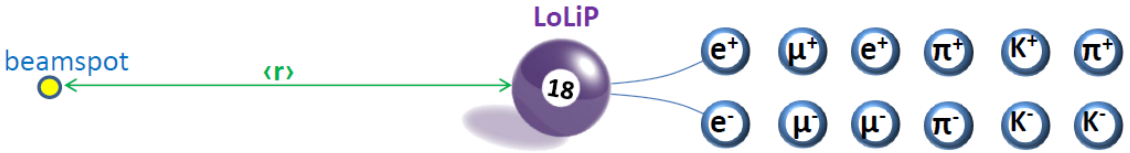
Search for long-lived particles



Radiography of the BaBar inner detector based on $\pi^+\pi^-$ conversion pairs passing generic cuts

Search for long-lived neutral particles at BaBar

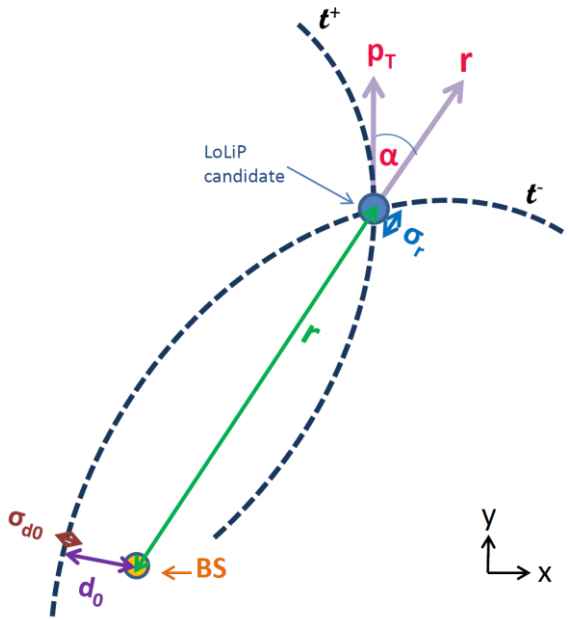
- B-factories suitable for searches in the GeV mass range
  - Various sub-GeV (NuTeV) and multi-GeV (Tevatron, LHC) searches
- Six exclusive final states (two particles of opposite charges) for the long-lived neutral spin-0 particle (« LoLiP ») L

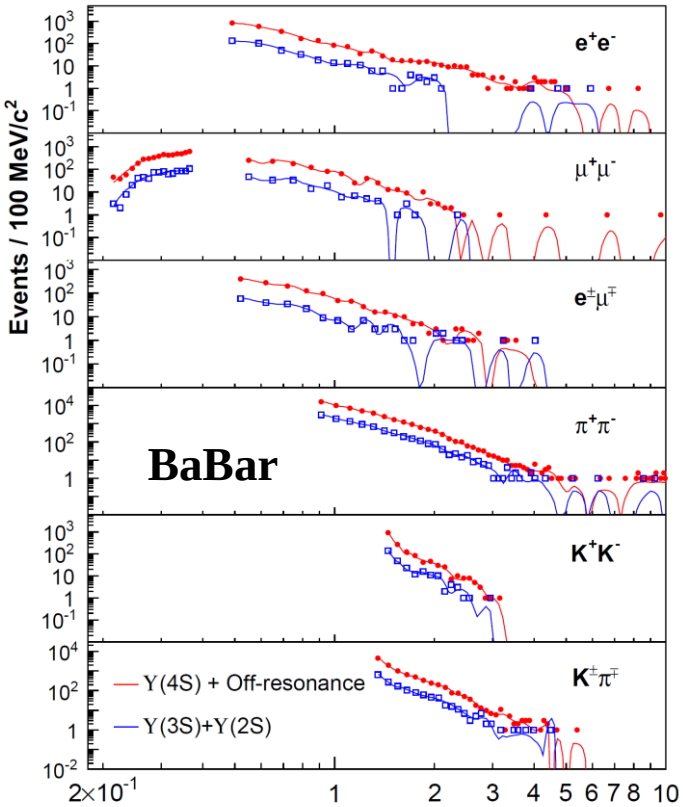


- BaBar $\Upsilon(2S)$, $\Upsilon(3S)$ & $\Upsilon(4S)$ datasets used: 489 fb^{-1}
  - 5% data used to validate the analysis procedure – not used in the final sample
- Twofold analysis
  - Model-independent results
    → Product of the inclusive production cross section $\sigma(e^+e^- \to LX)$
    × the branching fraction $B(L \to \text{final state})$ × the efficiency $\varepsilon(\text{final state})$
    → Efficiency tables $\varepsilon(m_L, p_T, c\tau_L)$ provided to compare data with any model
  - Model-dependent results: Higgs portal-type model (inflaton mixing with SM H)
    → Set limits on the branching fraction $B(B \to X_s L)$,
    X_s hadronic system with strangeness -1

Analysis method

- Look at displaced vertices:
  - $1 < r < 50$ cm in the transverse plane XY
- 2-track invariant mass cuts dependent on the final state
  - Reject background from K_S and Λ
- Dominant background: random combination of tracks in high-multiplicity hadronic events and/or interactions with detector material
- Unbinned extended maximum likelihood fit
  - Signal PDF $\propto$ mass resolution from signal MC
  - Background PDF: second-order polynomial spline obtained from data
  - Scan mass ranges in 2 MeV steps
- Statistical significance extracted from the ratio of likelihood values with and without signal

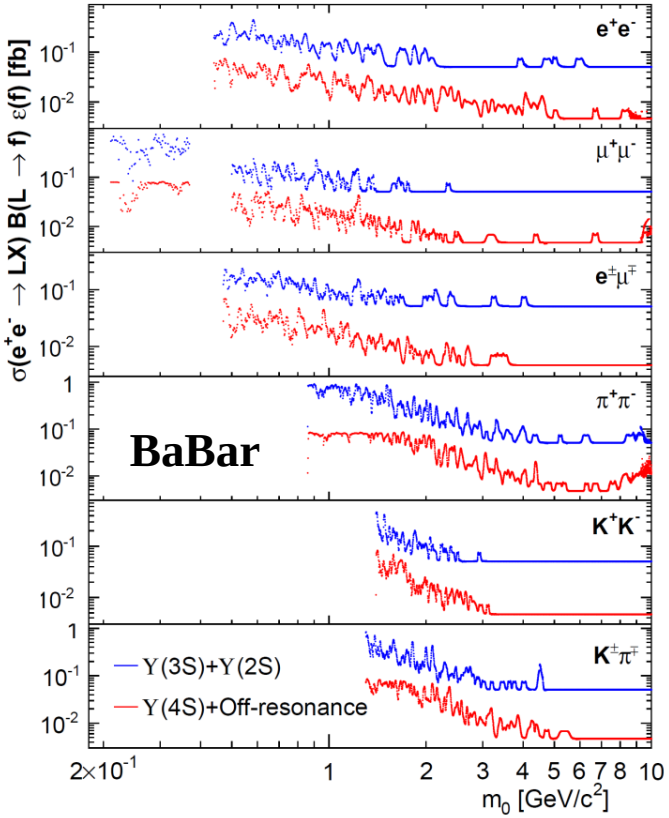




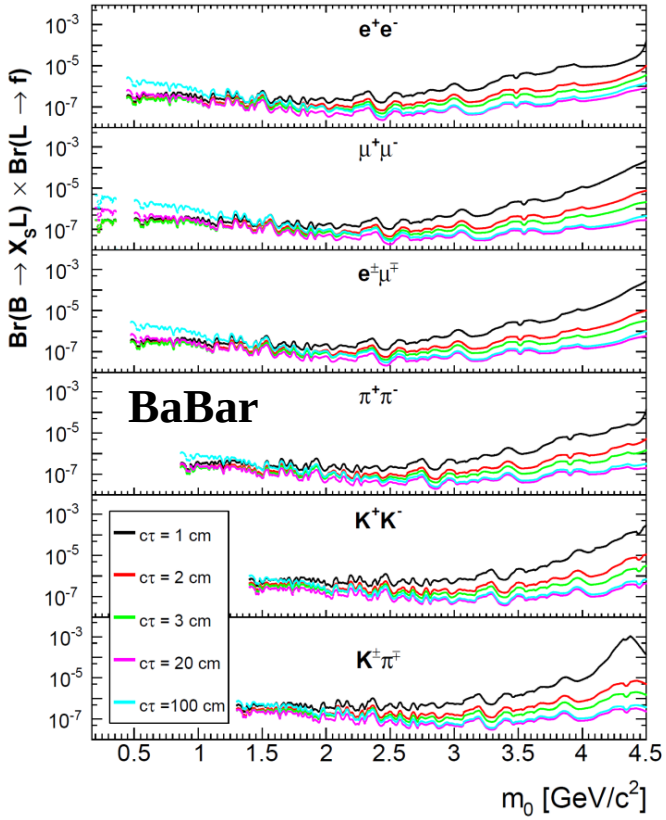
Results

- No significant signal found
  - → 90% C.L. upper limits set
    - Two points have significance larger than 3
      - → Fluctuations expected when including the « look elsewhere » effect
      - → Several events are likely misidentified photon conversions

- Model-independent upper limits

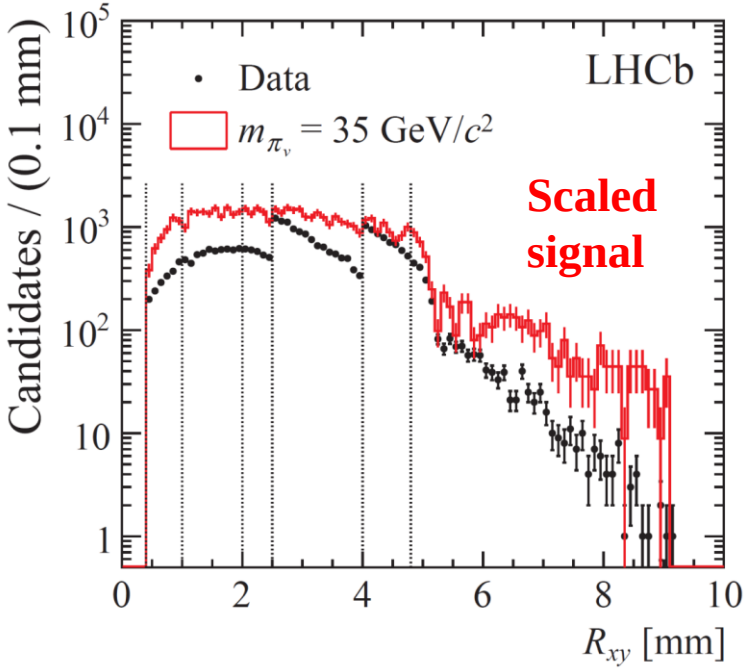


- Higgs portal-type upper limits



Search for long-lived particles decaying to jet pairs at LHCb

- Parameter space scanned
  - 25 < mass < 50 GeV
    → Lower bound coming from jet identification
    → Upper bound from LHCb acceptance
  - 1 < lifetime < 200 ps

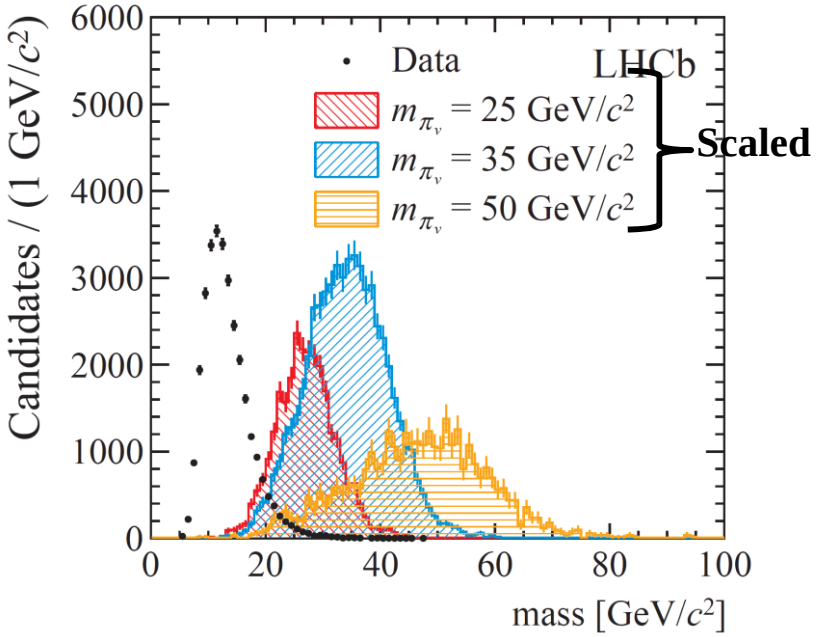


- Decay chain: $H \to \pi_v\pi_v$, $\pi_v \to b\bar{b}$ (also: $c\bar{c}$ and $s\bar{s}$)
  - H: 120 GeV SM-like Higgs boson
  - π_v: long-lived massive particle
- Two hadronic jets originating from a displaced vertex
  - 0.4 mm < R_{xy} < 4.8 mm
  → Reject background from heavy flavor decays
  → Select vertices inside the beampipe, avoid background generated by beampipe wall
- Dataset: 0.62 fb^{-1} recorded at 7 TeV
  - Dedicated trigger implemented during the second half of 2011
- Simulated samples
  - Lifetimes of 10 ps and 100 ps
    → Reweighting to study other lifetimes
  - Masses: 25, 35, 43, 50 GeV

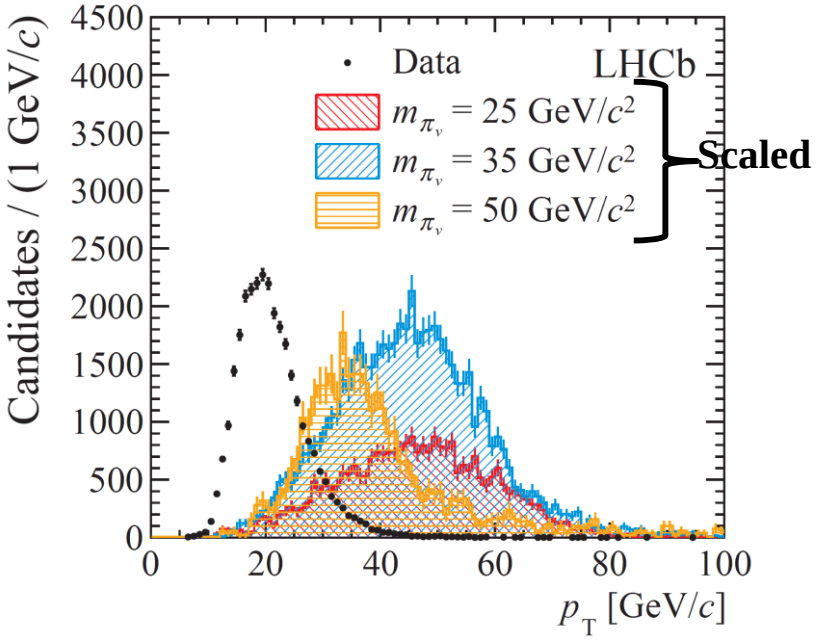
Analysis

- 5-10% trigger efficiency
  - Jets are triggering the event
- Secondary vertex reconstruction
- Jet reconstruction
  - Particle flow method
  - Anti-k_T jet clustering algorithm
  - Jet energy correction

    → Account for multiple interactions and underlying event
- The dijet invariant mass is the discriminating variable
- Additional « jet quality » requirements to enhance signal purity
  - Dijet candidate pointing back to the primary vertex
  - Jets not back-to-back (background)



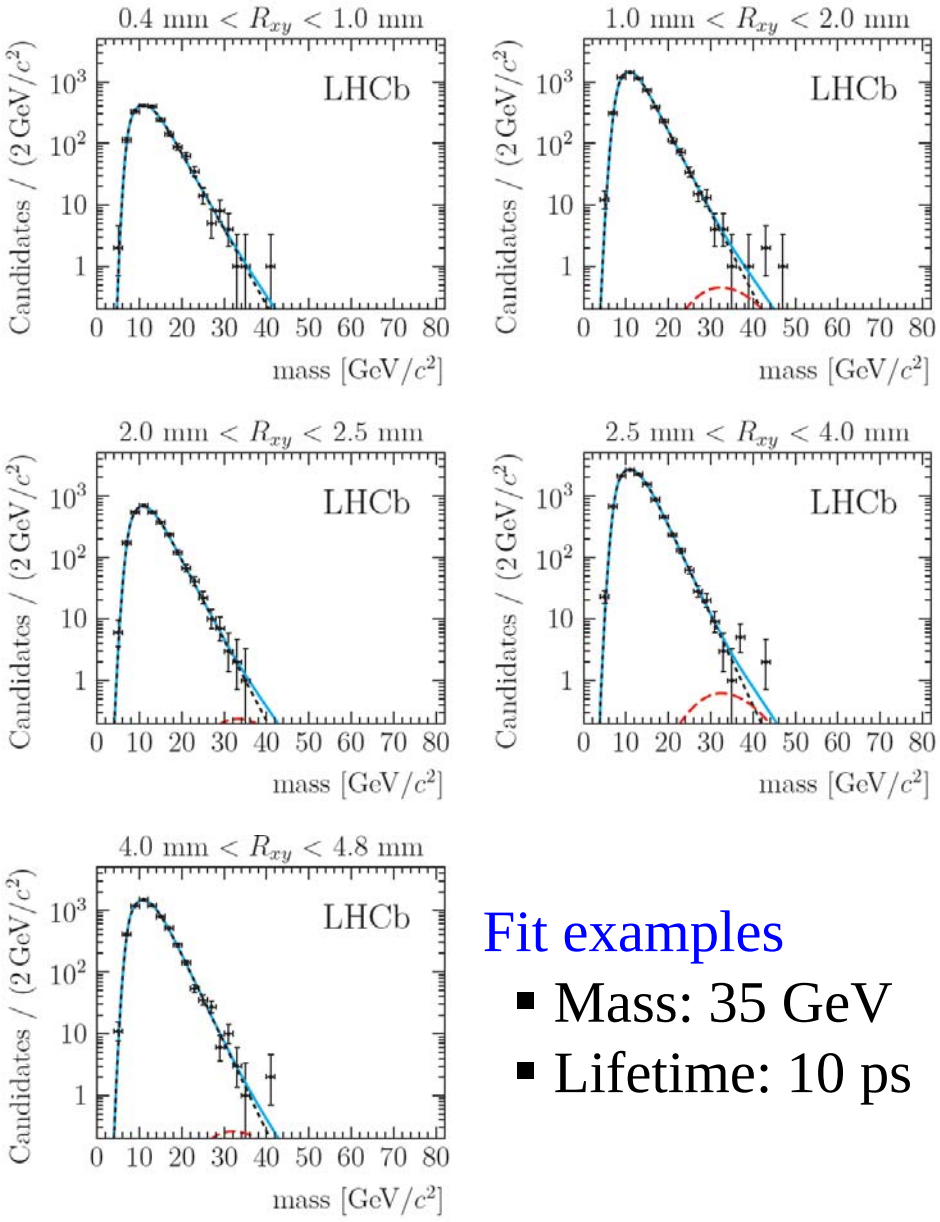
10 ps lifetime



Fit

- Maximum likelihood fit to the invariant mass distribution
  - Assuming smooth background shape
  → Simultaneous fit in five R_{xy} bins
- Signal PDF parameters fixed in MC
- Background parameters free in the fit
- Systematics
  - Vertex finding
  - Track finding
  - Displaced tracks
  - Jet selection
  - Jet energy scale
  - « Jet quality »
  - Trigger

  } ~13% relative uncertainty
- Alternative models tested
  - Nominal one gives the most conservative limits
  → No additional systematics



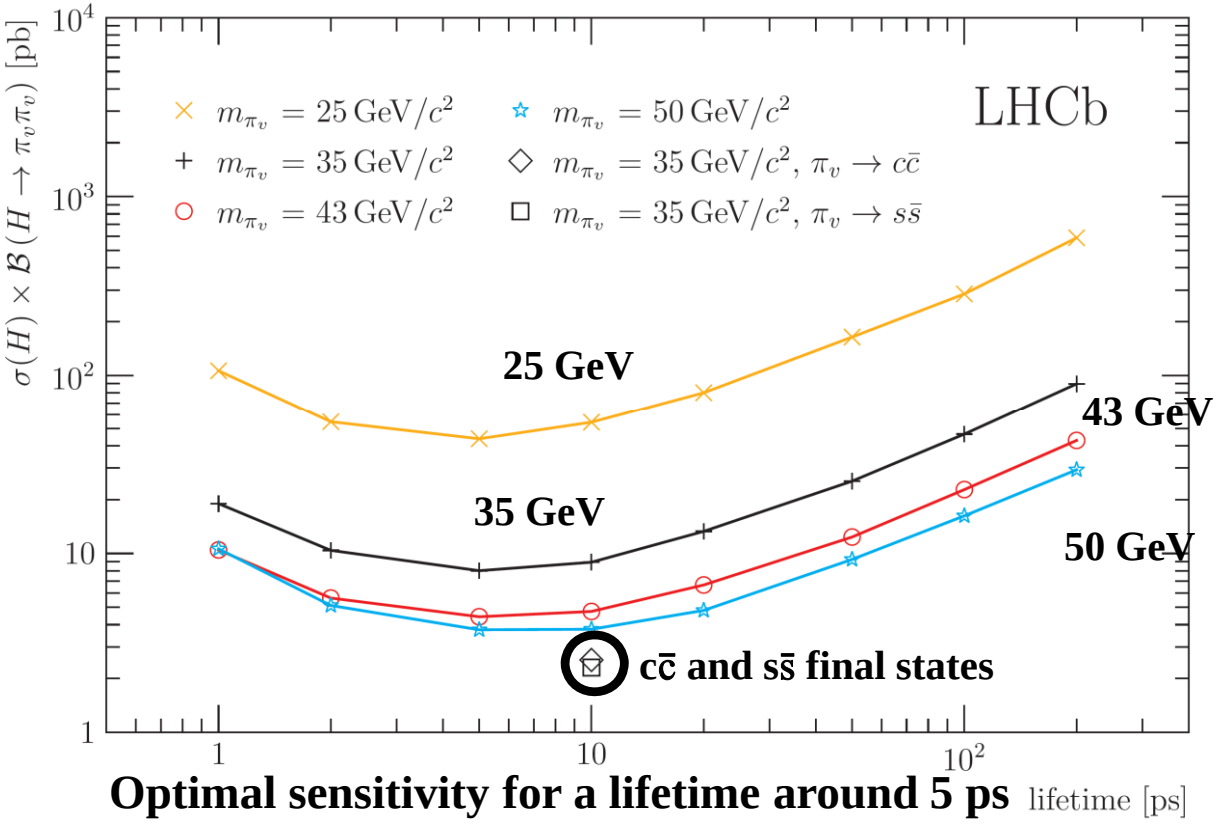
Fit examples
- Mass: 35 GeV
- Lifetime: 10 ps

Results

- No significant signal observed
  → 95% C.L. upper limits set

- Stronger limits with increasing mass
  - Background decreases

- Assumption: 100% decay $\pi_v \rightarrow q\bar{q}$
  - Limits scale like $1/(\mathcal{B}_{q\bar{q}}(2-\mathcal{B}_{q\bar{q}}))$ with $B_{q\bar{q}}$ being the branching fraction $\pi_v \rightarrow q\bar{q}$

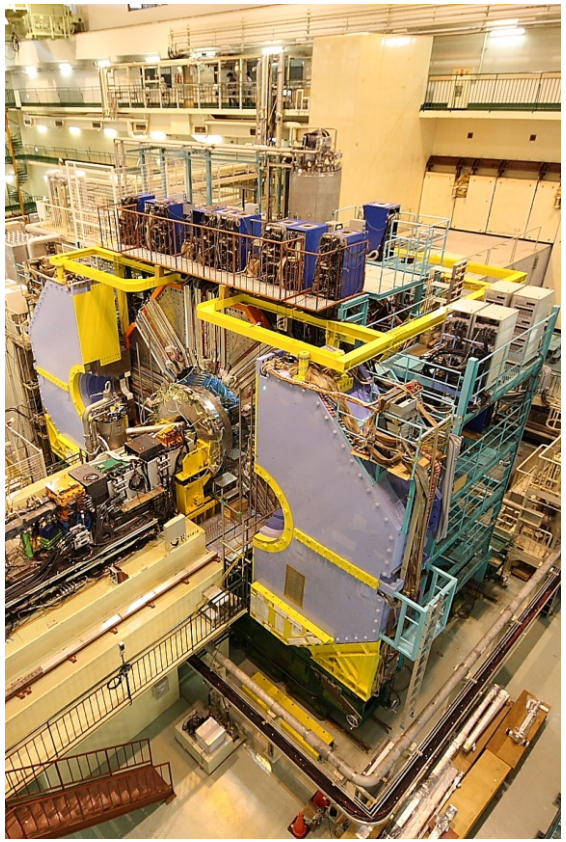


- Most sensitive measurement limits the branching fraction $H \rightarrow \pi_v\,\pi_v$ to 25%
  - Assuming a SM Higgs boson cross section of ~17 pb @ 7 TeV

- Parameter space region unexplored at the LHC so far

- Upper limits improved w.r.t. to those coming from the Tevatron experiments

Outlook



- Several searches for new particles
  (dark sector, long lived neutral particles)
  performed at BaBar, Belle and LHCb

- No significant signal found in any mode
  → Upper limits set, which constraint theoretical models

- Improvements expected from future experiments
  - Belle-2, LHC Run 2