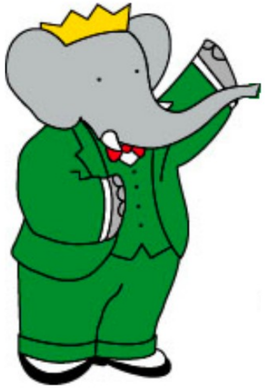
Search for low-mass new physics states at BaBar

19th International Conference on B-Physics at Frontier Machines

21-24 September 2020 – IPMU, Tokyo – Virtual conference



Laura Zani*

On behalf of the BaBar collaboration

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

erc

*zani@cppm.in2p3.fr - Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France

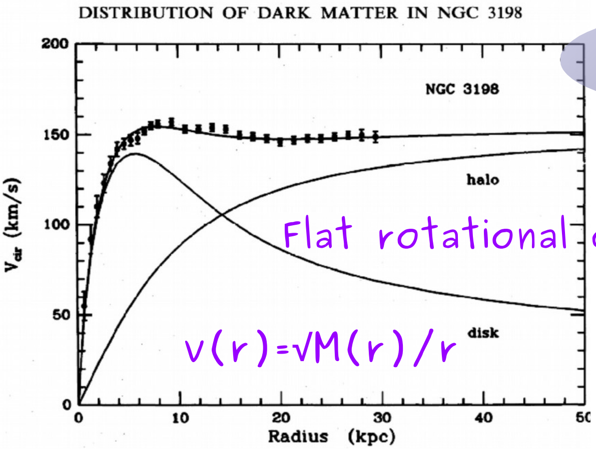
Outline

- Dark Matter puzzle
- Experimental context: B-factories and BaBar
- Dark sector searches at electron-positron colliders
  - Axion-Like Particles in meson decays
  - Dark tauonic force *arxiv:2005.01885*
- Results

Dark matter puzzle

- ***Dark Matter (DM)*** is one of the most compelling reason for New Physics (NP) searches

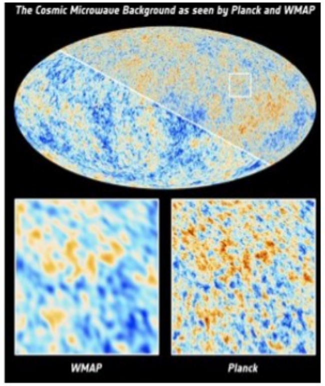
It exists...



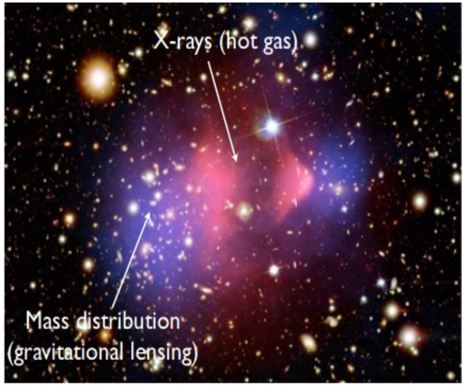
Flat rotational curves

$v(r)=\sqrt{M(r)/r}$

CMB fluctuations

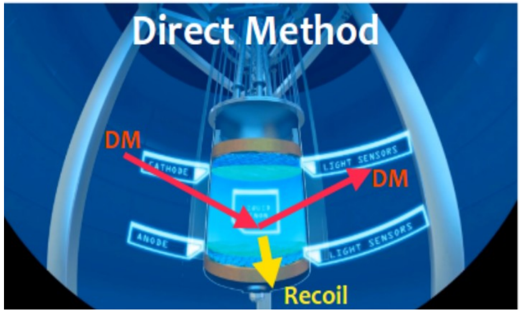


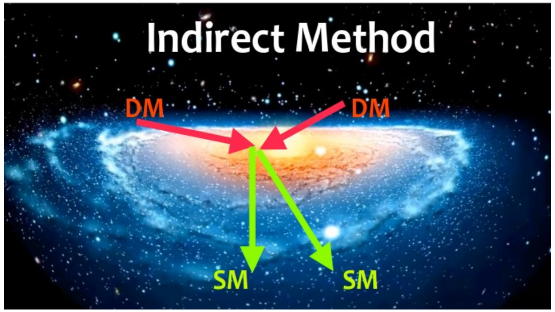
Gravitational lensing



...how to search for it?

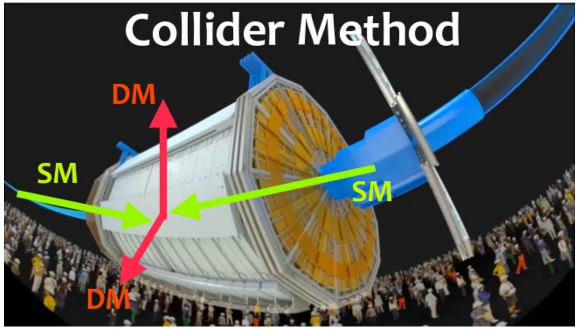
1) Detect the energy of *nuclear(electron) recoil*





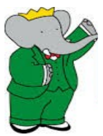
2) Detect the *flux of visible particles* produced by *DM annihilation* and decay

3) DM weakly couples to SM particles and it can be produced in *SM-particles annihilation* at ***accelerators***



→ **This presentation will focus on DM searches at B-factories**

BaBar experiment



BaBar belongs to the first generation of **B-factories**: dedicated experiments at *e^+e^- asymmetric-energy colliders* for the production of quantum coherent $B\bar{B}$ pairs $\rightarrow$ **CP violation studies**.

$$e^+e^- \rightarrow \Upsilon(4S)\ [10.58\ \text{GeV}] \rightarrow B\bar{B}$$

$\sigma(b\bar{b}) = 1.1$ nb, $\sigma(\tau^+\tau^-) = 0.91$ nb

(1999-2008)

SVT: 5 layers double-sided Si. Crucial for measuring Δt.

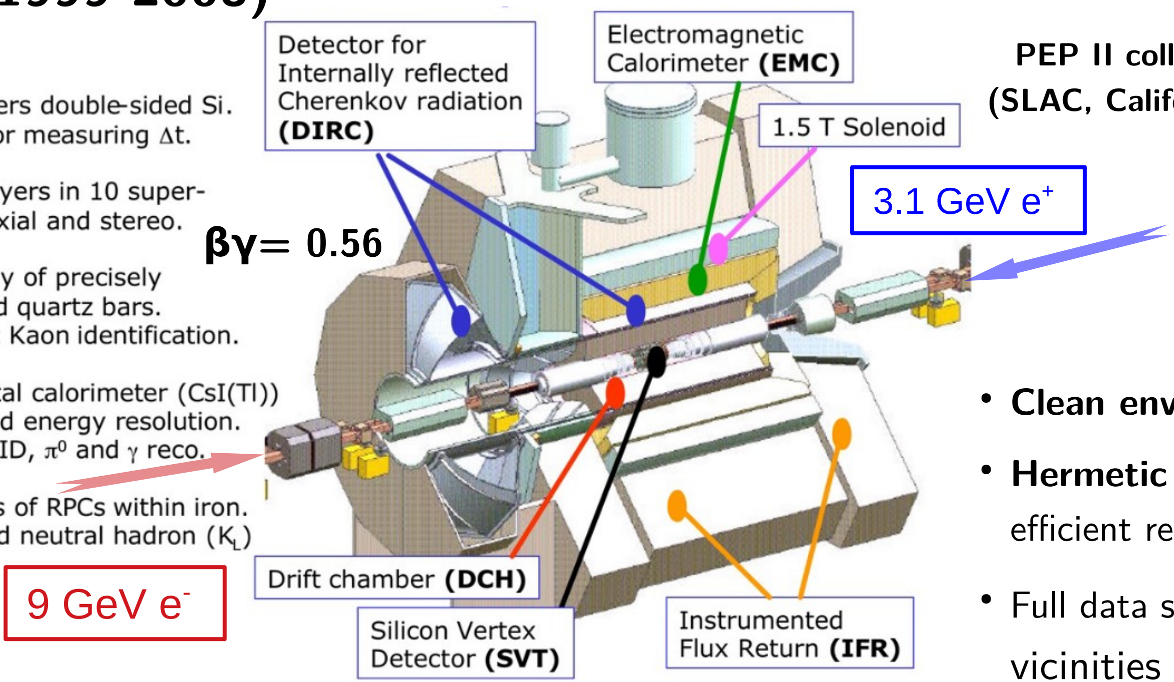
DCH: 40 layers in 10 super-layers, axial and stereo.

DIRC: Array of precisely machined quartz bars. Excellent Kaon identification.

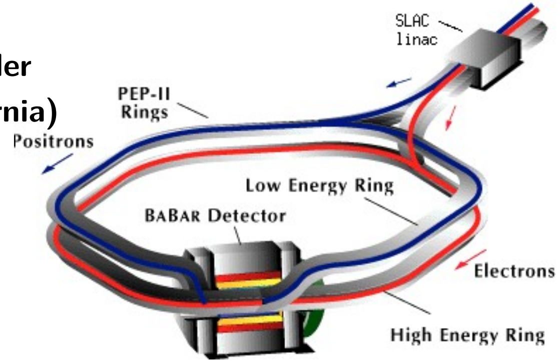
EMC: Crystal calorimeter (CsI(Tl)) Very good energy resolution. Electron ID, π^0 and γ reco.

IFR: Layers of RPCs within iron. Muon and neutral hadron (K_L)

$\beta\gamma = 0.56$



PEP II collider (SLAC, California)

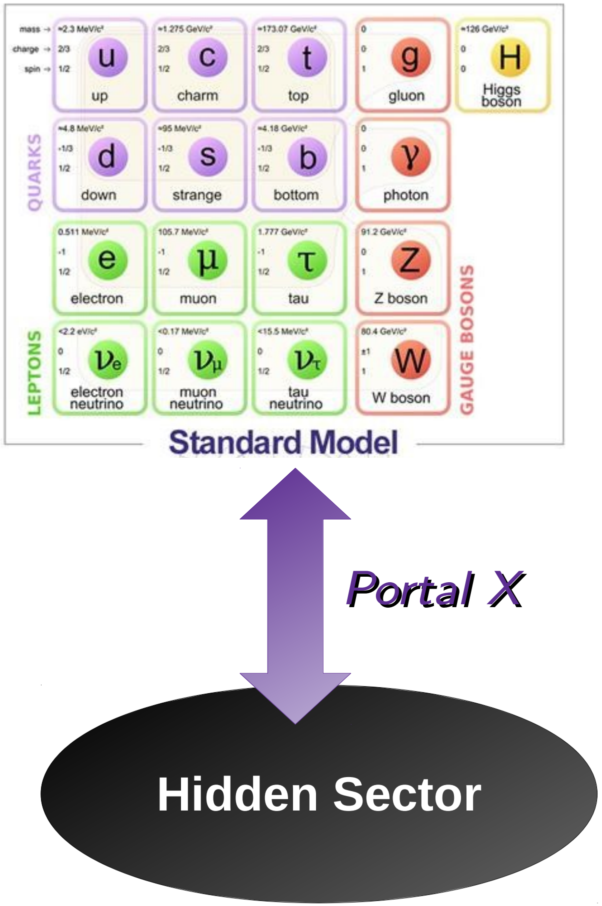


- **Clean environment** $\rightarrow$ lower background, high resolution
- **Hermetic detector** with excellent PID capability $\rightarrow$ efficient reconstruction of ***neutrals*** (π^0, η, …)
- Full data set **at Υ(4S), Υ(3S), Υ(2S)** and their vicinities (*off-resonance* scans)*: **514 fb^{-1}**

**Luminosity paper: https://arxiv.org/pdf/1301.2703.pdf*

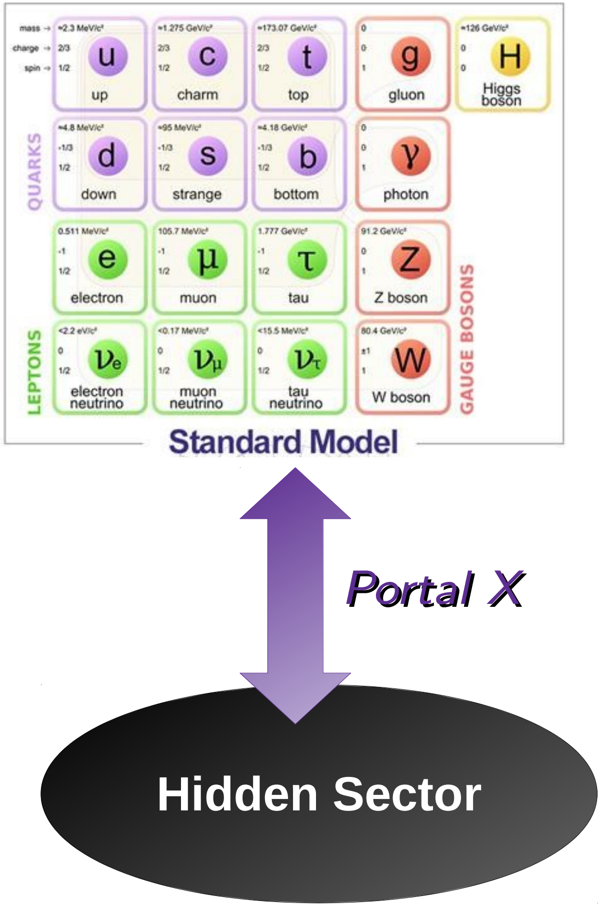
Dark Sector at B-Factories

- Possible sub-GeV scale scenario: light dark sector weakly coupled to SM through a light ***mediator X***
  - Scalar portal → Dark Higgs/Scalars
  - Vector portal → Dark Photon A'
  - Neutrino portal → Sterile Neutrinos
  - *Pseudo-scalar portal → Axion Like Particles (ALPs)*



Dark Sector at B-Factories

- Possible sub-GeV scale scenario: light dark sector weakly coupled to SM through a light ***mediator X***
  - **Scalar portal → Dark Higgs/Scalars**
  - Vector portal → Dark Photon A'
  - Neutrino portal → Sterile Neutrinos
  - ***Pseudo-scalar portal → Axion Like Particles (ALPs)***



Preliminary, finalizing submission

- Search for ALPs in B-meson decays: $B^{\pm} \to K^{\pm}a,\ a \to \gamma\gamma$
- Search for dark leptophilic scalars in τ-pair events: $e^+e^- \to \tau^+\tau^-\varphi_L,\ \varphi_L \to \ell^+\ell^-\ (\ell = e, \mu)$

Submitted to PRL, arxiv:2005.01885

ALPs in meson decays

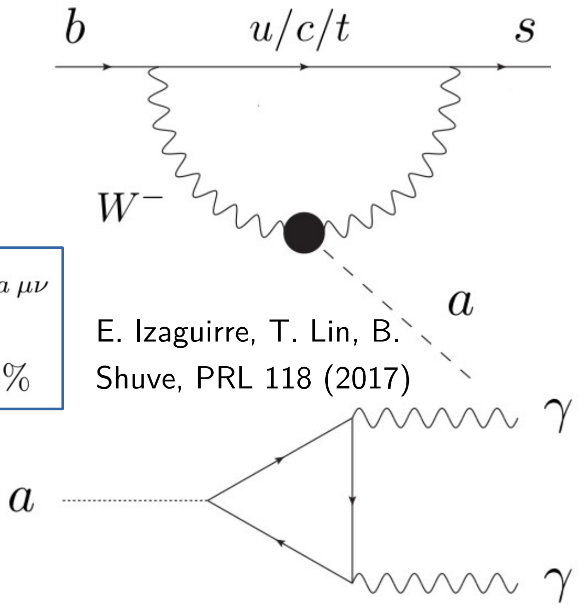
- ALPs are pseudo-scalars mainly coupling to pairs of gauge bosons, with non-renormalizable coupling constant $[g_{aV}] \sim 1/M$
- Most of ALPs searches target ***gluons or photons coupling*** at E ~ MeV-GeV
- $W^{\pm}$ coupling is usually suppressed at low energy for $E << M_W$

$\rightarrow$ *Flavor Changing Neutral Current* processes are a perfect testbed to search for low mass ALP emitted by a $W^{\pm}$ (exploit $b \rightarrow s$ transitions)

- $B \rightarrow K\gamma\gamma$ is extremely rare in the SM and hence uniquely sensitive to very small **ALP-W coupling** $\mathbf{g_{aW}}$
- $\tau \sim 1/m_a^3 g^2_{a\gamma\gamma}$: displaced vertex, long-lived particle constraints

$$\mathcal{L} = -\frac{g_{aV}}{4}\, a\, W^a_{\mu\nu} \tilde{W}^{a\,\mu\nu}$$

$$BF(a \to \gamma\gamma) = 100\%$$



E. Izaguirre, T. Lin, B. Shuve, PRL 118 (2017)

Search for the process $B^{\pm} \rightarrow K^{\pm}a,\ a \rightarrow \gamma\gamma$ by looking at narrow peaks in the **diphoton invariant mass** spectrum $\rightarrow$ *signature searched for the **first time**!*

$B^\pm \to K^\pm a$: event selection

- Reconstruct an event with a *good $K^\pm$ candidate* and *2 photons*, constrained by a **kinematic fit** to come from the *beam spot*
- Constrain the reconstructed **B-meson kinematic variables** (mass, energy) to the beam energy:

$$m_{\rm ES} = \sqrt{\frac{(s/2 + \vec{p}_i \cdot \vec{p}_B)^2}{E_i^2} - p_B^2} > 5.0\ \text{GeV}$$

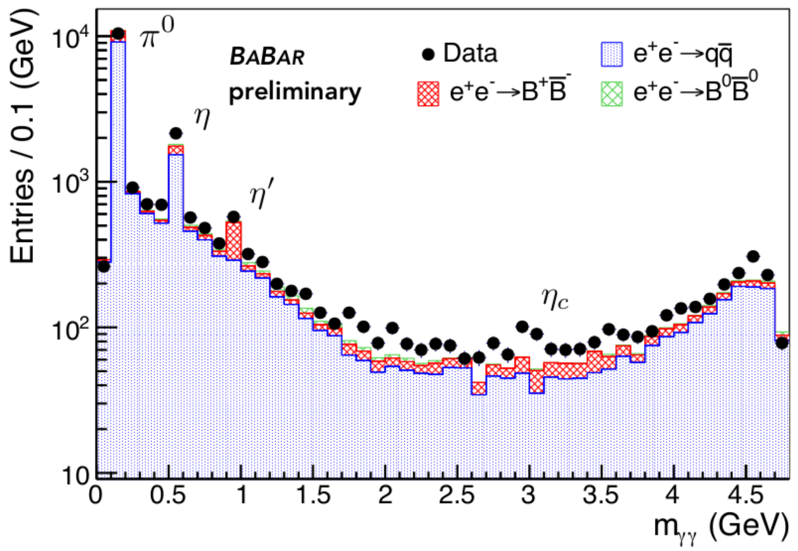
$$|\Delta E| = |\sqrt{s}/2 - E_B^{\rm CM}| < 0.3\ \text{GeV}$$

(E_i, p_i) = four momentum of CM system in lab frame

- **2 Boosted Decision Trees** trained separately on the two main background contributions: continuum from $e^+e^- \to q\bar{q}$ processes and generic $B\bar{B}$ decays

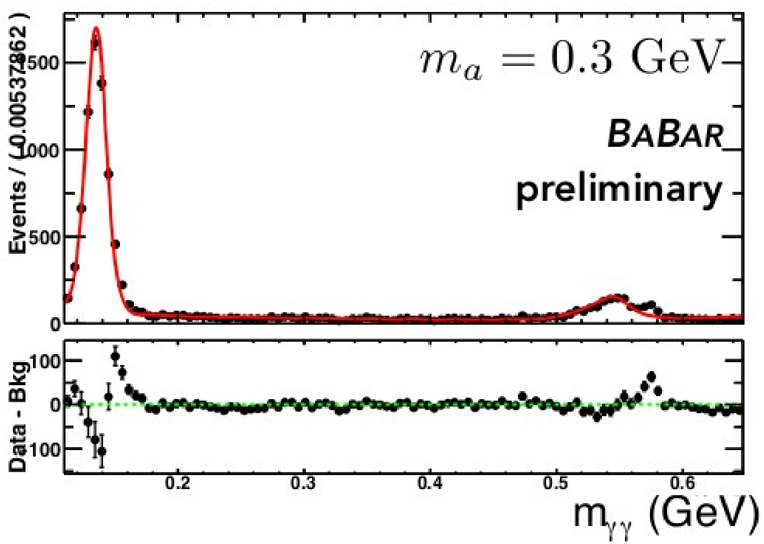
  → Final BDT output selections Punzi FOM optimized

Total data set: 424/fb at $\Upsilon(4S)$, corresponding to 240 million B^+B^- pairs
Blind analysis: optimize selections on 8% of data then discard it.



$B^{\pm} \to K^{\pm}a$: fit strategy and signal extraction

- Scan diphoton spectrum: **476 unbinned maximum likelihood fits** for each mass hypothesis (excluding scan in the vicinity of peaking background contamination from π^0, η, η')
- Fit windows vary from 30-70σ, with **σ the signal resolution** (8-14 MeV) $\to$ extracted from fits to signal simulations by using double-side Crystal Ball function and interpolated for intermediate values



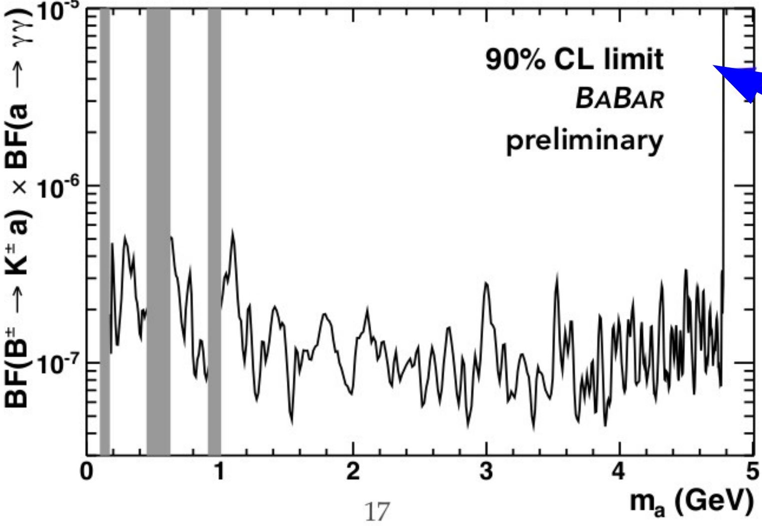
- **Signal PDF**: double-side Crystal Ball function; shape parameters fixed to results from fits to simulations
- **Background PDF**:
  - *Combinatoric from continuum* $\to$ 2nd-order polynomial for $m_a <$ 1.35 GeV, 1st-order polynomial for higher masses;
  - *Peaking* $\to$ SM diphoton resonance templates (from simulation) + resolution Gaussian function.

Highest global significance $<1\sigma$ after including trial factors

$B^{\pm} \to K^{\pm}a$: branching fraction limits

- No significant signal observed, set **Bayesian 90% CL upper limits** on the BF($B^{\pm} \to K^{\pm}a$, $a \to \gamma\gamma$):
  - Flat positive priors and integrate over nuisance parameters (***marginalization***)$\to$ *systematic uncertainty* modeled with a Gaussian distribution with width equal to the size of the estimated effect
- Systematic effect due to background modeling expected to be improved in final revision
- Same selection and fit procedures as optimized for **prompt ALPs** applied to *long-lived ALPs*, for $m_a < 2.5$ GeV

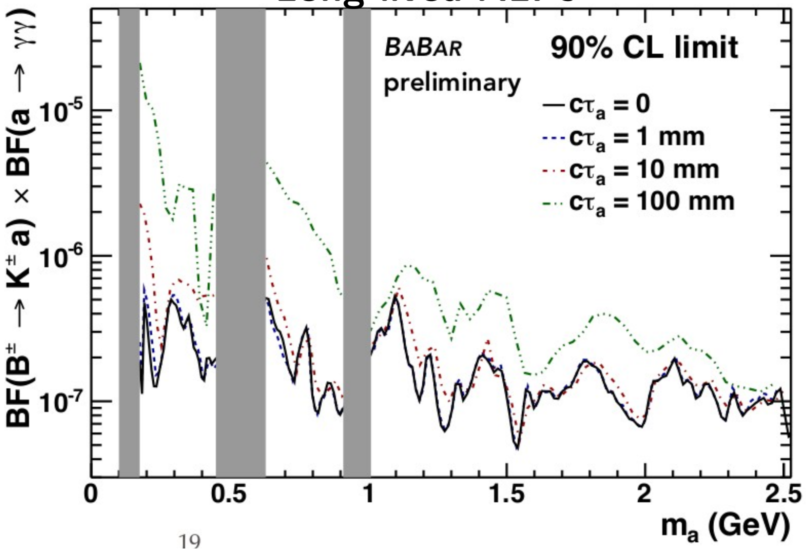
Prompt decaying ALPs



kinematic limit

$m_a > m_B - m_K$

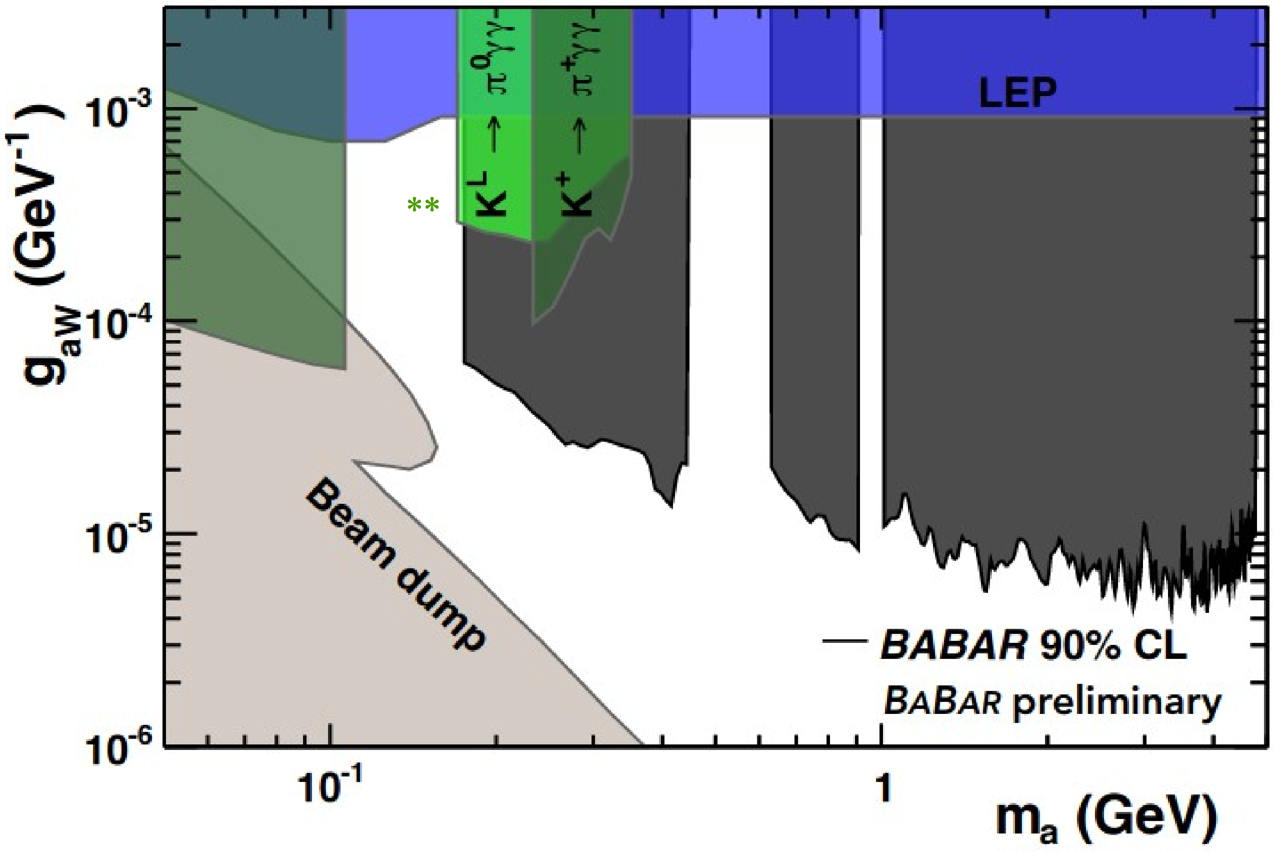
Long-lived ALPs



$B^\pm \to K^\pm a$: limits on ALP coupling

- From measured upper limits on BF as a function of the lifetime derive limits on g_{aW} coupling
- Improvement of 2 orders of magnitude on all the mass spectrum for $m_a < 5$ GeV

** Limits from kaons decays are extracted from existing measurements, according to the study presented here: Phys.Rev.Lett. 118 (2017) 11, 111802



Dark tauonic force

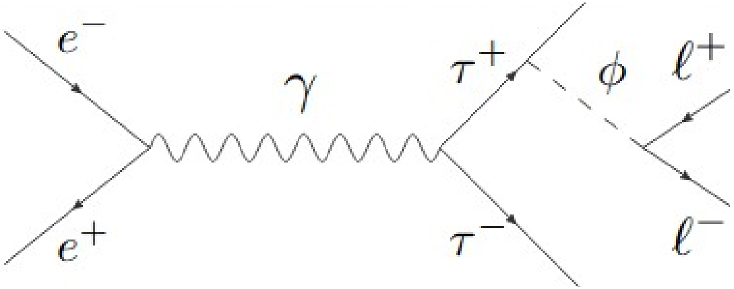
- New light dark scalar with mass-proportional coupling to leptons
- Could explain the g-2 muon anomaly (only weakly constrained by previous searches for *muonic dark force**)

  → Leptophilic scalar radiatively emitted by τ pairs may be enhanced due to larger masses!

- Look for the process: $\mathbf{e^+e^- \to \tau^+\tau^- \varphi_L,\ \varphi_L \to \ell^+\ell^-\ (\ell = e, \mu)}$
- Search for a narrow resonance in **dilepton spectrum** for $0.04\ \text{GeV} < m_{\varphi L} < 7.0\ \text{GeV}$:
  - $m_{\varphi L} < 2m_\mu$ search separately for lifetimes $c\tau_{\varphi L} = 0, 1, 10, 100$ mm;
  - above dimuon threshold, only prompt decays.

$$\mathcal{L} = -\xi \sum_{\ell = e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell} \phi_L \ell$$

arXiv:1606.04943



Total BaBar data set at $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$ and their vicinities: **514 fb^{-1}**

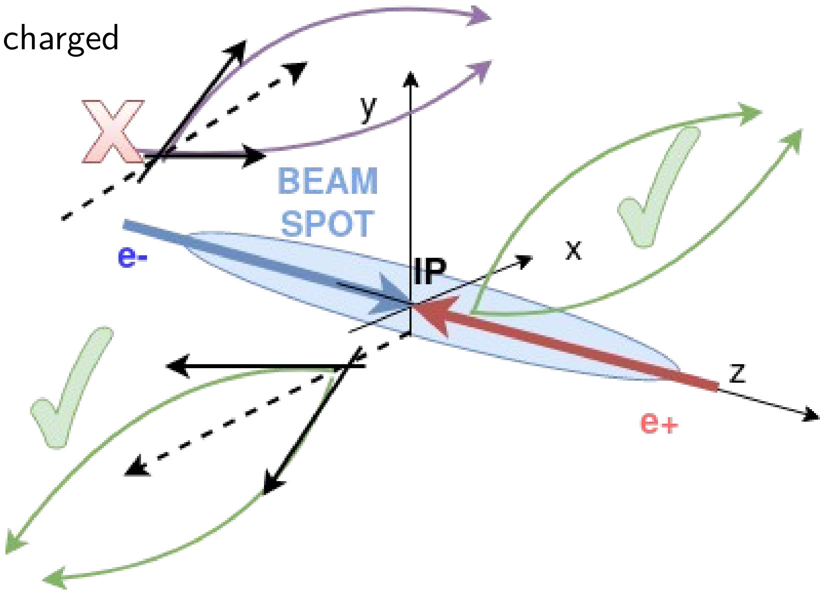
- 5% used for analysis optimization and discarded → **BLIND ANALYSIS**

* Phys. Rev. D 94,011102 (2016)

Dark leptophilic scalar: event selection

- Only 4 tracks + missing energy/momentum due to τ neutrinos
- Apply Lepton Identification and reconstruct φ_L candidates as two oppositely charged leptons, kinematically fitted to the **same vertex**:
  - Constrain to beam spot region for dimuon resonance (prompt only)
  - Resulting momentum points back to Interaction Point for e^+e^-

    $\rightarrow$ ***allow for displaced vertex signatures***
- Reject radiative dilepton + pair conversions contamination:
  - Visible mass lower than 9 GeV
  - Angular isolation from nearby tracks for reconstructed φ_L candidate
  - Missing momentum of the event > 300 MeV
- **Boosted Decision Tree** optimized for best signal sensitivity as function of the φ_L mass



- Remaining **peaking background** from J/ψ and $\Upsilon(2S)$ contamination $\rightarrow$ corresponding mass not scanned in the signal search
- ***$\pi^0 \rightarrow$*** *$\gamma\gamma$, with* ***$\gamma \rightarrow e^+e^-$ conversions*** observed for $c\tau_{\varphi L} = 1$mm $\rightarrow$ broader feature than signal resonances, included in the scan and model as background component

Dark leptophilic scalar: signal yield extraction

- **Scan** the dilepton mass spectra with *unbinned maximum likelihood fits* for each mass hypothesis as a function of the lifetimes, in step of **signal resolution, σ**
- For dimuon final states, fit *dimuon reduced mass* for more precise background description:

$$\rightarrow m_R = (m^2_{\mu\mu} - 4m^2_{\mu})^{1/2}$$

- Fit windows on **dielectron** (*dimuon*) spectrum of **20-50σ** (*fixed to 60σ*)

Resolutions, σ:

1 MeV ($m_{\varphi L}$ = 40 MeV, $c\tau_{\varphi L}$ = 100 mm) – 50 MeV ($m_{\varphi L}$= 5 GeV, prompt decays)

→ extracted from fits to signal simulations by using double-side Crystal Ball function

Fit Properties

- **Signal PDF**: non-parametric kernel density function, modeled from signal samples and interpolated among simulated mass points

- **Background PDF**:
  - *Combinatoric from continuum* → ***dielectron:*** 2nd-order polynomial + exponential (except for $c\tau_{\varphi L}$= 100 mm, polynomial only); ***dimuon:*** 3rd-order polynomial and 2nd-order polynomial for higher masses.
  - *Peaking from π^0 conversions* (for $c\tau_{\varphi L}$= 1mm)→ resolution Gaussian function modeled from ***sideband data***
  - *Peaking from* J/ψ and $\Upsilon(2S)$ → shape fixed to results from fits to simulated samples, floating yields (fitted directly on ***data***)

→ Highest significance, including trial factor, is 1.4 σ at ~ 2.14 GeV mass

Dark leptophilic scalar: results

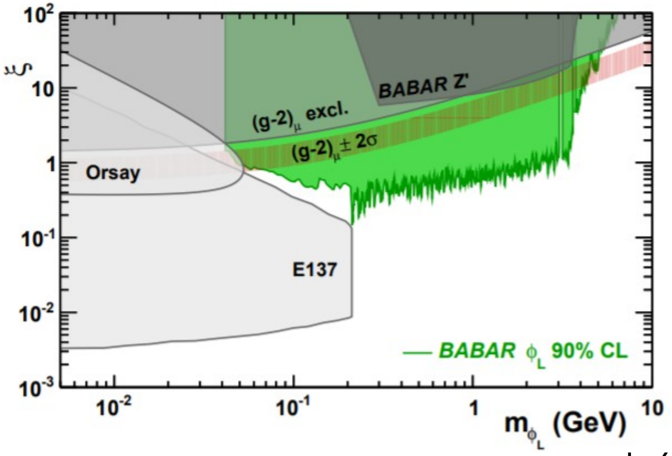
- From the fitted signal yields compute the cross section for $e^+e^- \to \tau^+\tau^-\varphi_L$, $\varphi_L \to \ell^+\ell^-$ (ℓ=e,μ) for different {lifetime, final state} as a function of the beam energy

$$\sigma_{4S} = \frac{N_{sig}}{\sum_{i=2S,3S,4S} \left(\frac{\sigma_{th,i}}{\sigma_{th,4S}}\epsilon_i \mathcal{L}_i\right) BF(\phi_L \to \ell^+\ell^-)}$$

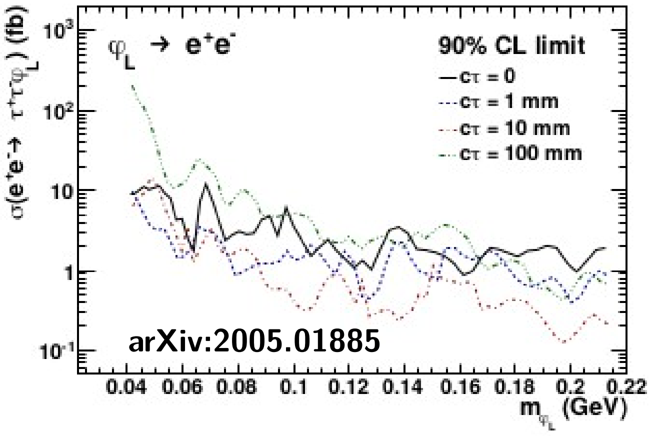
- Extract 90% CL Bayesian upper limits

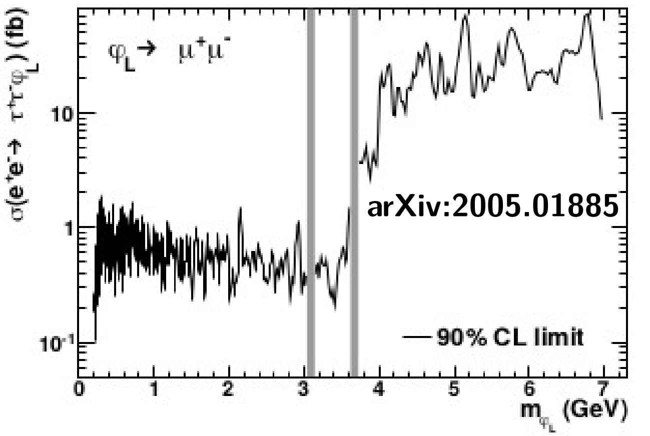
  → flat positive priors and Gaussian-distributed systematic uncertainty ***included by marginalizing***

  – dominant systematic effect coming from data/MC comparison → assign 3.8% (4%) systematic uncertainty in the dielectron (dimuon) signal efficiency



Limits on the *leptophilic scalar coupling* as a function of the searched mass are derived within MadGraph5 (iterative procedure)

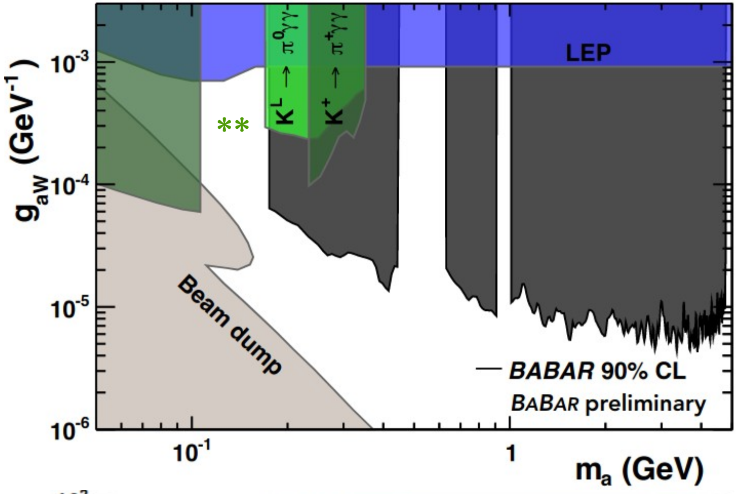


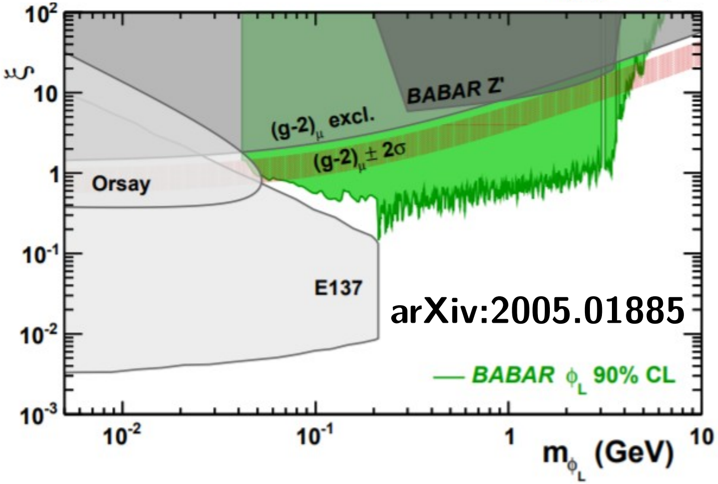


Summary

- **The full BaBar data set dominates constraints on some low mass New Physics states.**

- **Shown today:**
  - ***First ALPs search in flavor changing B-meson decays ($B^{\pm} \to K^{\pm}a$, $a \to \gamma\gamma$)***
    - improve the existing limits on the ALP and W-boson **coupling g_{aW}** of 2 orders of magnitude below 5 GeV
  - ***First search for a new dark leptophilic scalar produced in τ-pair events***
    - limits on the leptophilic **scalar coupling ξ** improved by one order of magnitude → favored g-2 muon anomaly band ruled out completely up to 4 GeV.





arXiv:2005.01885

Thanks for your attention!

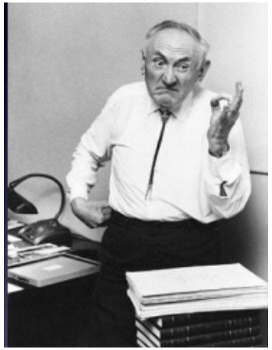
** Limits derived in Phys.Rev.Lett. 118 (2017) 11, 111802

backup

Introduction to dark matter

- Dark Matter (DM) is one of the most compelling issue for physics beyond the Standard Model. Many **astrophysics** and **cosmological observations** provide evidences for its existence:

F.Zwicky, 1933

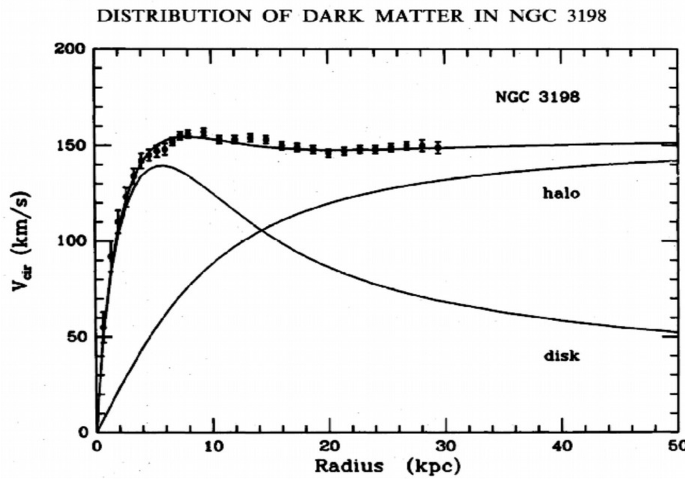


Virial Theorem:

$2E_{kine} = - U$

$\langle v(r)^2 \rangle = GM(r)/r$

V.Rubin, 1970s

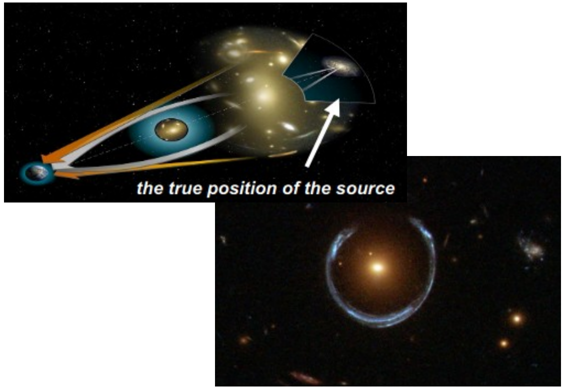


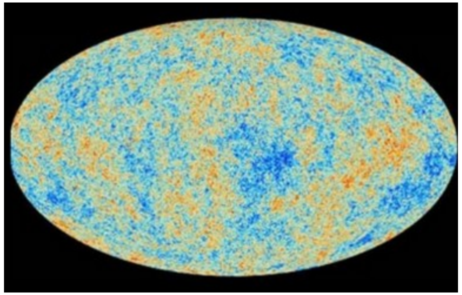
Flat rotational curves: $v(r)$ = const

→ mass distribution linearly growing with r (assuming $\rho(r)=1/r^2$)

A large amount of not-luminous matter must populate galaxy bulks.

Gravitational Lensing





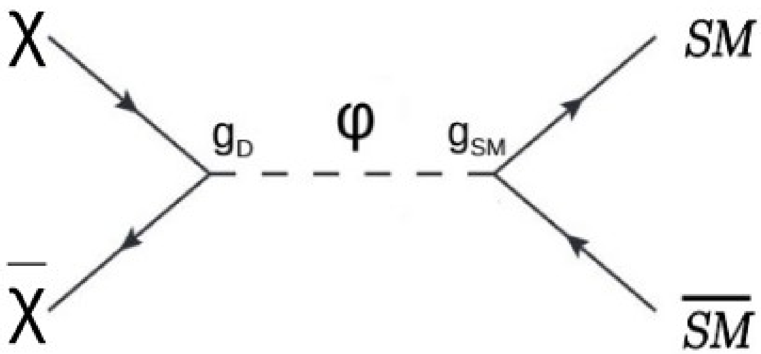
CMB Fluctuations

Light dark sectors

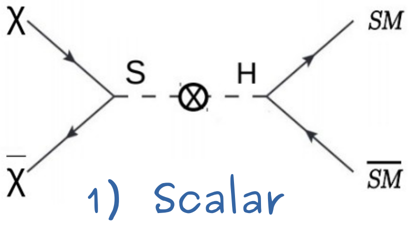
- Possibility of *light dark sectors* motivates the search for a ***DM mediator (φ):***

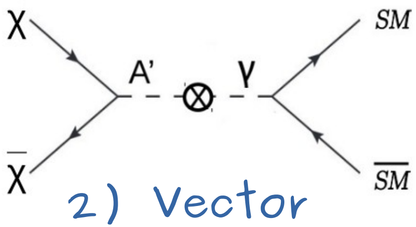
$$\langle \sigma v \rangle_{relic} \sim \frac{g_D g_{SM} m_\chi^2}{m_\phi^4}$$

$$m_\phi^4 \leq \frac{m_\chi^2}{< \sigma v >} \text{ since g} < O(1)$$



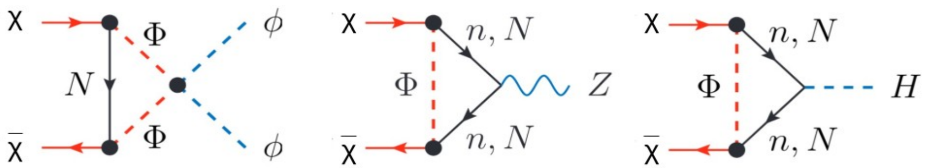
→ According to the spin and parity of new mediator, 3 renormalizable portals with dimensionless couplings are allowed by SM symmetries:





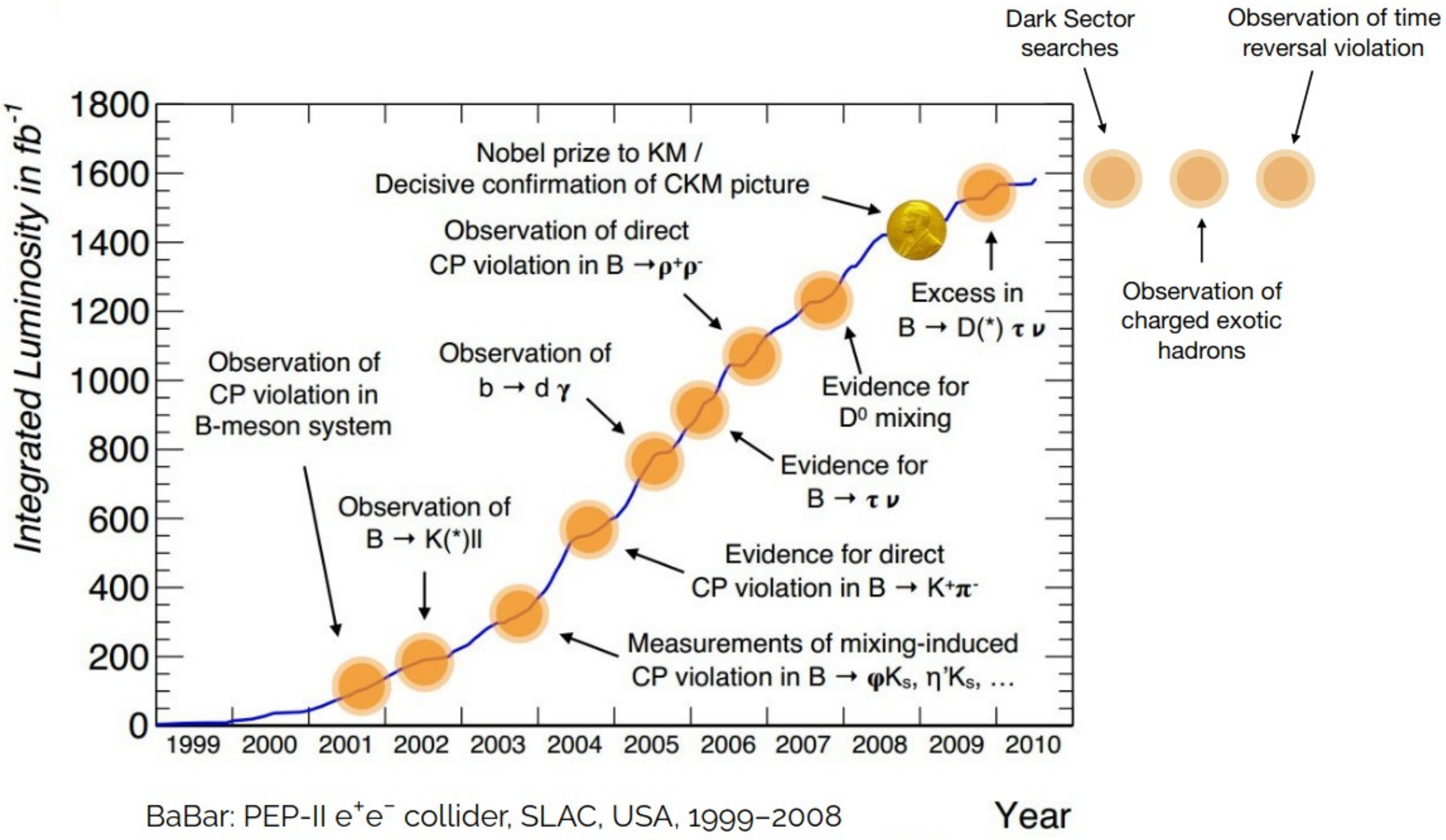
Naturally included in the context of light *dark sectors* → *much more generic*

3) Neutrino portal



+ a not-renormalizable pseudo−scalar portal assuming Axion-Like Particles (ALPs) as mediators: $\mathscr{L}_a = \frac{1}{f_a} a F^{\mu\nu} \tilde{F}_{\mu\nu}$

Physics at B-factories



BaBar: PEP-II e^+e^- collider, SLAC, USA, 1999–2008
Belle: KEKB e+e– collider, KEK, Tsukuba, Japan, 1999–2010

$B^{\pm} \to K^{\pm}a$: analysis strategy

- Search for the process **$B^{\pm} \to K^{\pm}a$, $a \to \gamma\gamma$** by looking at narrow peaks in the **diphoton invariant mass** spectrum $\to$ *Promising signature searched for the **first time**!*
- Extract from unbinned maximum likelihood fits the signal yields and measure the branching fraction $BF(B^{\pm} \to K^{\pm}a,\ a \to \gamma\gamma)$ for $0.1\ \text{GeV} < m_a < 4.78\ \text{GeV}$
- Exclude mass intervals in vicinity of peaking π^0, η, η' backgrounds: 0.1-0.175 GeV, 0.45-0.63 GeV, 0.91-1.01 GeV
- For $m_a < 2.5$ GeV, ALPs can be long lived $\to$ determine signal BFs for $c\tau_a = 1, 10, 100$ mm

Monte Carlo Simulation

Signal (EvtGen): promptly decaying samples for 24 ALP mass points (0.1-4.78 GeV), long-lived samples for 16 ALP mass points (0.1-2.5 GeV)

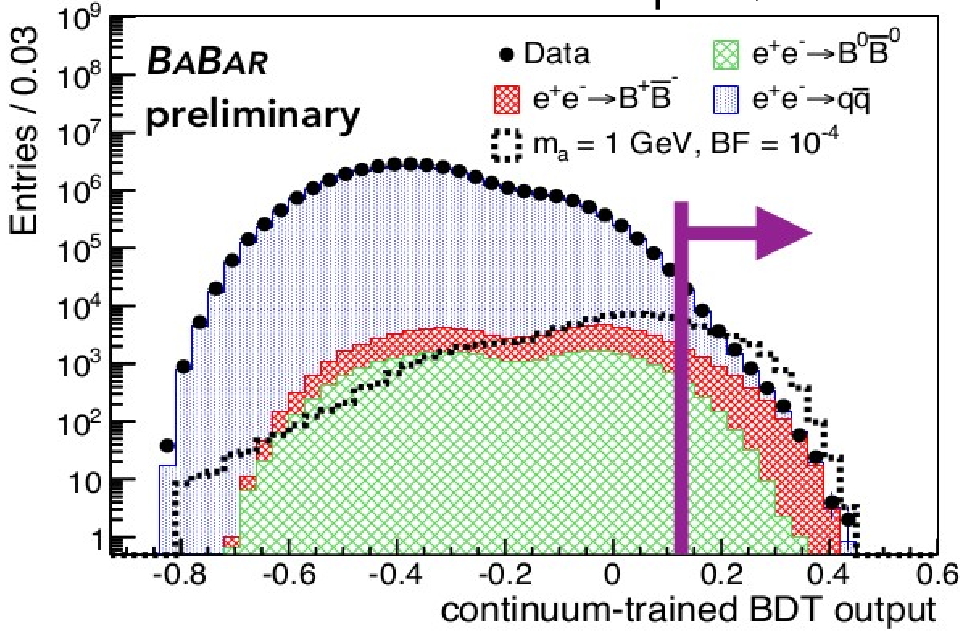
Background (weighted to data luminosity): $e^+e^- \to q\bar{q}$ (JetSet), $e^+e^- \to B\bar{B}$ (EvtGen)+ two-lepton final states (KKMC + Tauola)

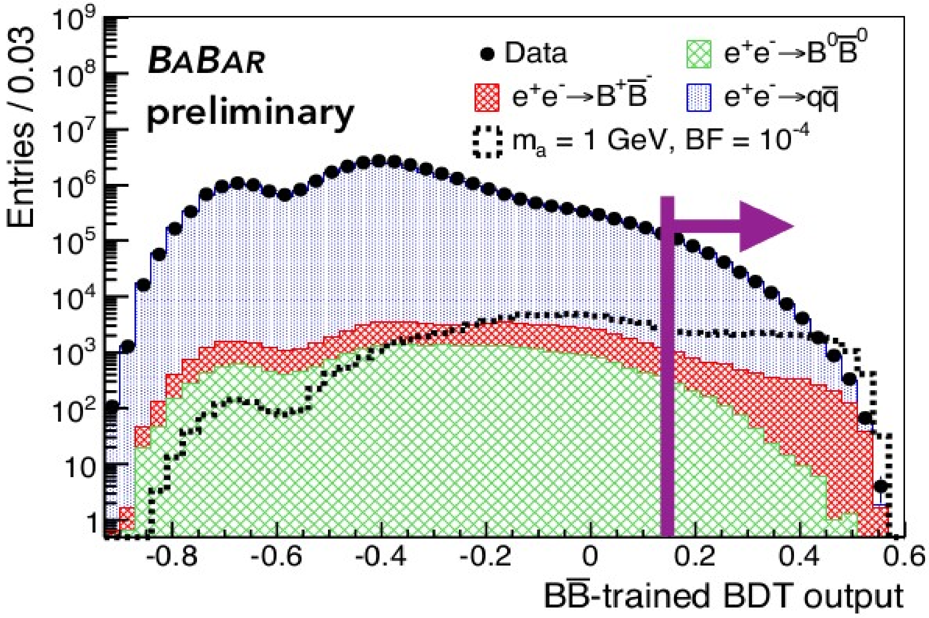
$B^{\pm} \to K^{\pm}a$: selection variables

- 13 BDT training observables:
  - m_{ES}
  - ΔE
  - cosine of angle between sphericity axes of $B^{\pm}$ candidate and rest of event (ROE)
  - PID info for kaon candidate
  - 2nd Legendre moment of ROE, calculated relative to $B^{\pm}$ thrust axis
  - helicity angle of most energetic photon, and of kaon
  - energy of most energetic photon in a candidate
  - invariant mass of ROE
  - multiplicity of neutral clusters
  - invariant mass of diphoton pair, with 1 photon in $B^{\pm}$ candidate and 1 photon in ROE, closest to each of π^0, η, η'

$B^{\pm} \to K^{\pm}a$: final selections

- Optimized BDT output selections with Punzi FOM:
  - Continuum-trained BDT output > 0.13
  - BB trained BDT output > 0.15





$B^{\pm} \to K^{\pm}a$: systematic uncertainties

- Assess uncertainty on signal yield from fit by varying order of polynomial for continuum background (3rd-order for $m_a < 1.35$ GeV, constant at higher mass), varying shape of peaking background within uncertainties, and using next-nearest neighbor for interpolating signal shape
  - Dominates total uncertainty for some masses in vicinity of π^0/η
- Systematic uncertainty on signal yield from varying signal shape width within uncertainty is on average 3% of statistical uncertainty
- 6% systematic uncertainty on signal efficiency, derived from data/MC ratio in vicinity of η'
- Other systematic effects negligible by comparison, including on limited signal MC statistics, luminosity

Dark leptophilic scalar: simulation details

- **Signal** (MadGraph): 36 mass points of promptly decaying φ_L samples + long-lived samples up to $c\tau_{\varphi L} = 300$ mm
- **Background (weighted to data luminosity)**: $e^+e^- \rightarrow q\bar{q}$ (JetSet), $e^+e^- \rightarrow (B\bar{B}, \Upsilon(2S, 3S))$ (EvtGen)+ radiative dilepton final states (BHWIDE, KKMC + Tauola)

Dark leptophilic scalar: BDT training variables

Input distributions used in dimuon BDT:

- Ratio of second to zeroth Fox-Wolfram moment of all tracks and neutrals.
- Invariant mass of the four track system, assuming the pion (muon) mass for the tracks originating from the tau (φ_L) decays.
- Invariant mass and transverse momentum of all tracks and neutrals.
- Invariant mass squared of the system recoiling against all tracks and neutrals.
- Transverse momentum of the system recoiling against all tracks and neutrals.
- Number of neutral candidates with an energy greater than 50 MeV.
- Invariant masses of the three track systems formed by the φ_L and the remaining positively or negatively charged tracks.
- Momentum of each track from φ_L decays.
- Angle between the two tracks produced by the tau decay.
- Variable indicating if a track has been identified as a muon or an electron by PID algorithm for each track.

Dark leptophilic scalar: BDT training variables

Input distributions used in dielectron BDT:

- Transverse momentum of the system recoiling against all tracks and neutrals.
- Energy of the system recoiling against all tracks and neutrals.
- Number of tracks identified as electron candidates by a PID algorithm applied to each track.
- Angle between φ_L candidate momentum and closest track produced in tau decay.
- Angle between φ_L candidate momentum and farthest track produced in tau decay.
- Angle of φ_L candidate relative to the beam in the center-of-mass frame.
- Angle between the two tracks produced by the tau decay.
- Angle between φ_L candidate and nearest neutral candidate with $E > 50$ MeV.
- Energy of nearest neutral candidate (with $E > 50$ MeV) to φ_L candidate.
- Total energy in neutral candidates, each of which has an energy greater than 50 MeV.
- Distance between beamspot and φ_L candidate vertex.
- Uncertainty in the distance between beamspot and φ_L candidate decay vertex.
- φ_L candidate vertex significance, defined by the beamspot-vertex distance divided by its uncertainty.
- φ_L candidate vertex significance, defined by the beamspot-vertex distance divided by its uncertainty.
- Angle between the φ_L candidate momentum, and line from beamspot to φ_L decay vertex.
- Distance of closest approach to beamspot of $e-$ in φ_L candidate.
- Distance of closest approach to beamspot of $e+$ in φ_L candidate.
- Transverse distance between φ_L decay vertex and best-fit common origin of τ candidates and φ_L candidate.
- χ 2 of the kinematic fit to the φ_L and τ candidates constraining their origin to the same production point.
- χ 2 of the kinematic fit of the φ_L candidate with the constraint that the $e+e-$ pair is produced from a photon
- conversion in detector material.
- Dielectron mass for φ_L candidate when re-fit with the photon conversion constraint.8