Recent Results of Dark Sector Searches with the BABAR Experiment

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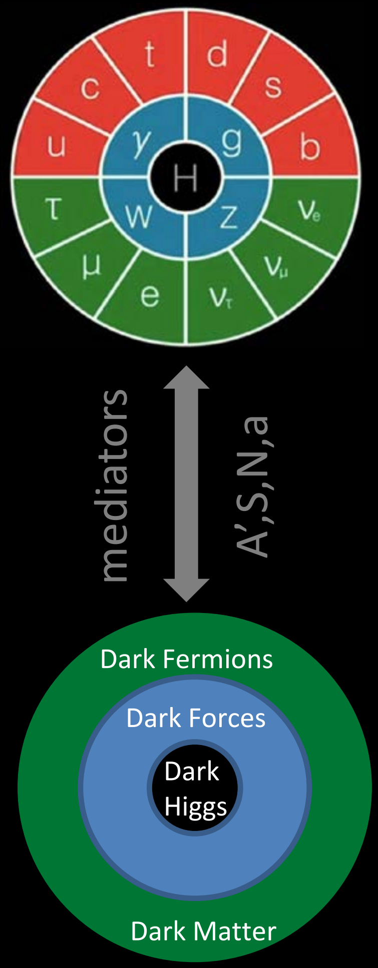
on behalf of the BABAR collaboration

ICPPA 2020 – virtual space

Dark sectors in a nutshell

What are dark sectors / hidden sectors

- New particle(s) that don't couple directly to the SM
- Theoretically motivated: many BSM scenarios (e.g. EWSB) and string theory include dark sectors
- Could have rich structure (SM structure is non-trivial)
- Dark matter could reside inside dark sector (lot of recent activity around light hidden sector dark matter)



Interaction with the SM through "portals"

Lowest order portals:

- Vector – $\varepsilon B^{\mu\nu} A'_{\mu\nu}$
- Scalar – $H^2 (\mu S + \lambda S^2)$
- Neutrino – $yHLN$
- Axion – $1/f_a(c_1 \mathrm{tr}(G\tilde{G}) + c_2 F\tilde{F} + c_3 \partial_\mu j^\mu)\, a$ (dim 5)

Motivates broad exploration of dark sector.
Low energy e^+e^- colliders offer an ideal environment to study them.

Wide program at BABAR

Prel. studies | **Published**

Extensive "dark sector" program conducted at BABAR over the last decade

Search for dark photon

$e^+e^- \to \gamma A'$, $A' \to e^+e^-, \mu^+\mu^-$
$e^+e^- \to \gamma A'$, $A' \to$ invisible
$\pi^0 \to \gamma\, l^+l^-, \eta \to \gamma\, l^+l^-, \phi \to \eta\, l^+l^-, \ldots$

Search for dark Higgs boson

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

Search for dark boson(s)

$e^+e^- \to \gamma A' \to W' W''$

Search for dark hadrons

$e^+e^- \to \pi_D + X, \quad \pi_D \to e^+e^-, \mu^+\mu^-$

Search for "muonic dark force"

$e^+e^- \to \mu^+\mu^- Z'$, $Z' \to \mu^+\mu^-$

Search for leptophilic dark scalar

$e^+e^- \to \tau^+\tau^- h'$, $h' \to \mu^+\mu^-$

Search for axion

$B \to Ka, a \to \gamma\gamma$

Search for self-interacting DM

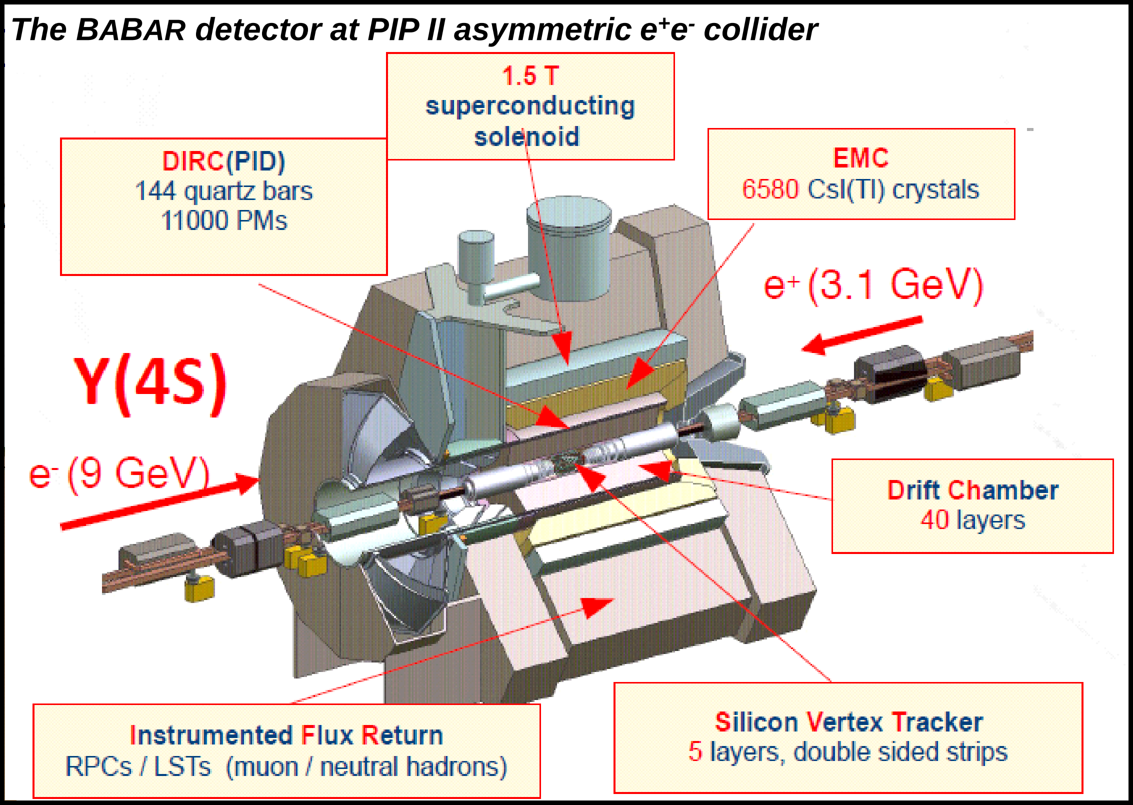
$e^+e^- \to Y_D \to A'A'A' \to 3X^+X^-$ $(X=l,\pi)$

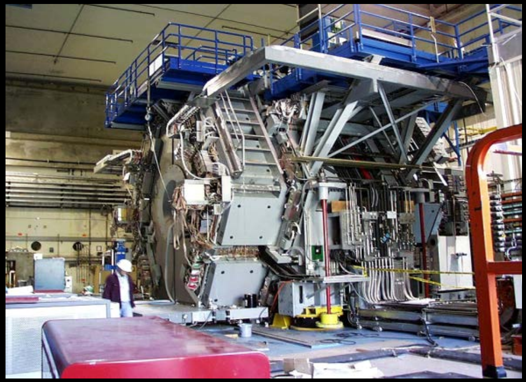
+ other DM searches

This talk will discuss recent results on leptophilic dark scalar and preliminary results on axion

The BABAR experiment

BABAR collected ~500 fb^{-1} around the $\Upsilon(4S)$, $\Upsilon(3S)$ and $\Upsilon(2S)$ resonance between 1999 - 2008





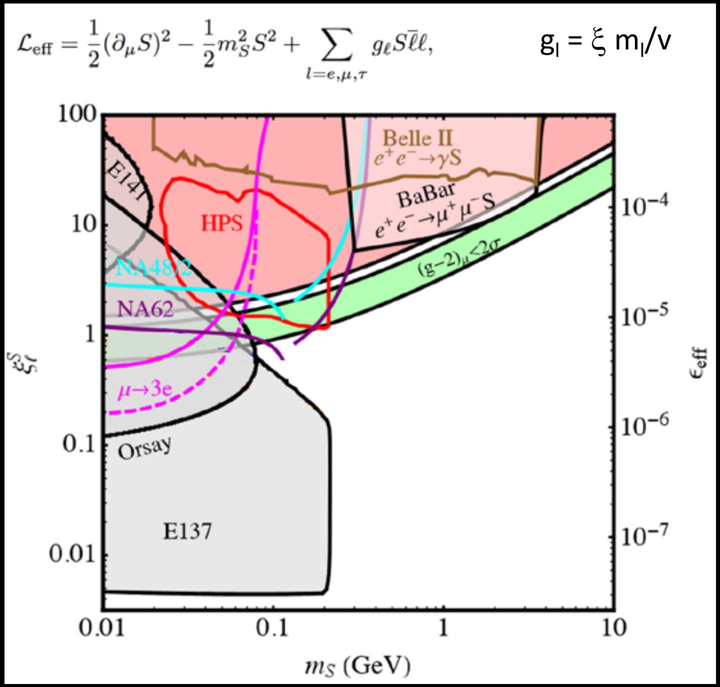
Collaboration is still active more than 10 years after data taking ended !!!

Leptophilic dark scalar

Many BSM models predict the existence of an extended Higgs sector with new light gauge singlets that can mix with the Higgs boson. Strong experimental constraints on this scenario.

If the new scalar interacts predominantly with leptons rather than quarks, experimental constraints are significantly weakened due to the reduced coupling to electrons

A leptophilic scalar could explain the g-2 anomaly (1606.04943, 1605.04612) and the more recent KOTO excess (2001.06522)



Battell et al., arxiv:1606.04943

A few features

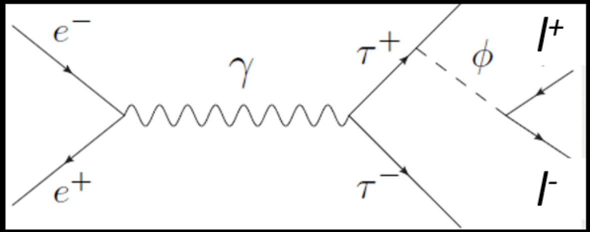
- Mass proportional coupling → produced preferentially via its coupling to τ
- Decays preferentially to the most massive lepton-pair kinematically accessible
- Long-lived particle for sufficiently low values of coupling constant → search for both prompt and displaced decays

Leptophilic dark scalar

Accepted by PRL

Search for dielectron and dimuon decay of a leptophilic dark scalar (ϕ_L) radiated off a tau lepton:

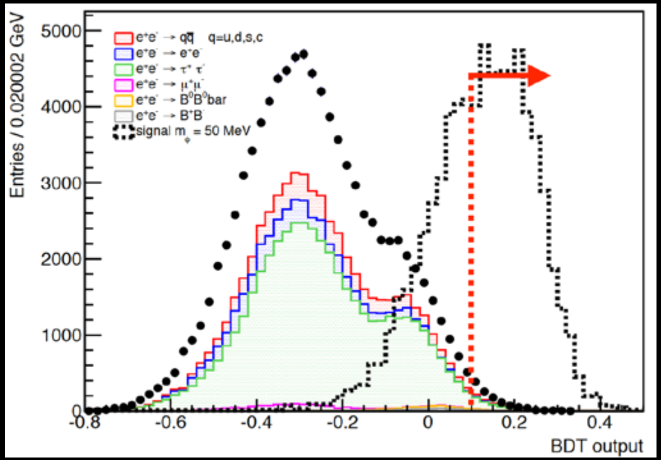
$$e^+e^- \to \tau^+\tau^- \phi_L,\ \phi_L \to l^+l^-\ (l=e,\mu)$$



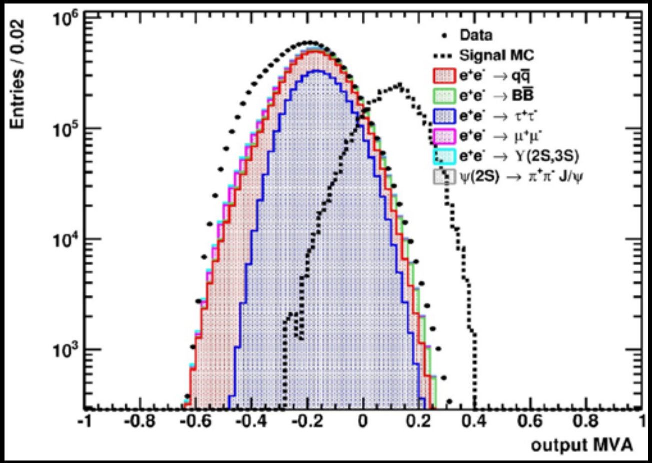
Analysis strategy – see 2005.01885 for details

- Consider all 1-prong decays of the tau
- Train BDT to increase signal purity (see backup slide)
- Optimize analysis for each final state and prompt or long-lived ϕ_L

Dielectron BDT (prompt)



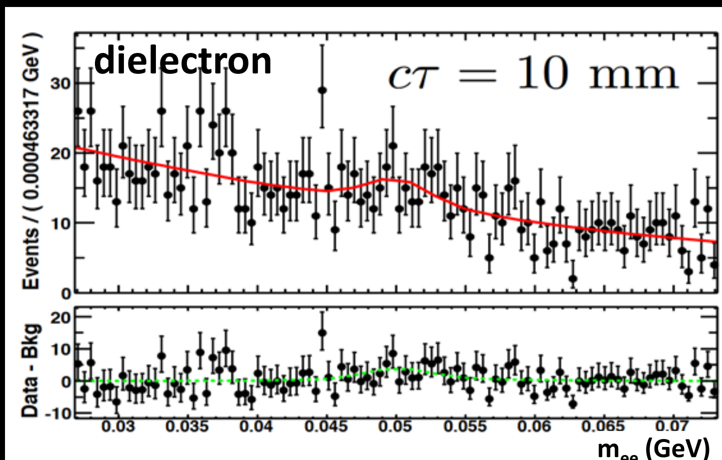
Dimuon BDT (prompt)

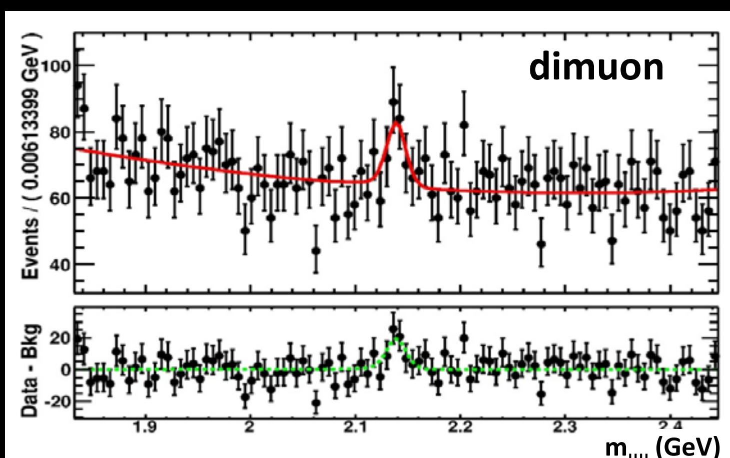


Data/MC discrepancy due to non-modelled MC components (two-photon, ISR, high-multiplicity QED,...) but this discrepancy has very limited impact on the results

Leptophilic dark scalar

Extract signal as a function of dark scalar mass with fits over sliding intervals (background MC independent)





Fit 966 mass hypotheses, step size taken as signal resolution (1-50 MeV depending on m_ϕ)

Fit includes signal, peaking and continuum background components:

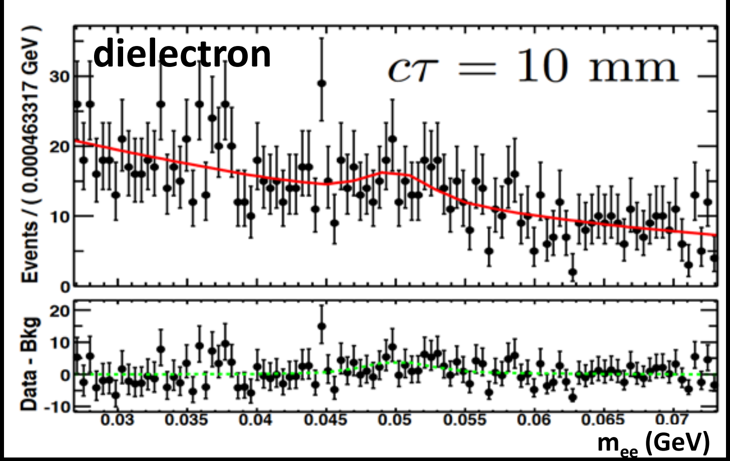
- Signal modeled from signal MC and interpolated between simulated mass points
- Continuum background modelled by second or third order polynomials
- Peaking background (π^0, J/ψ, $\psi(2S)$) modelled from bkg MC

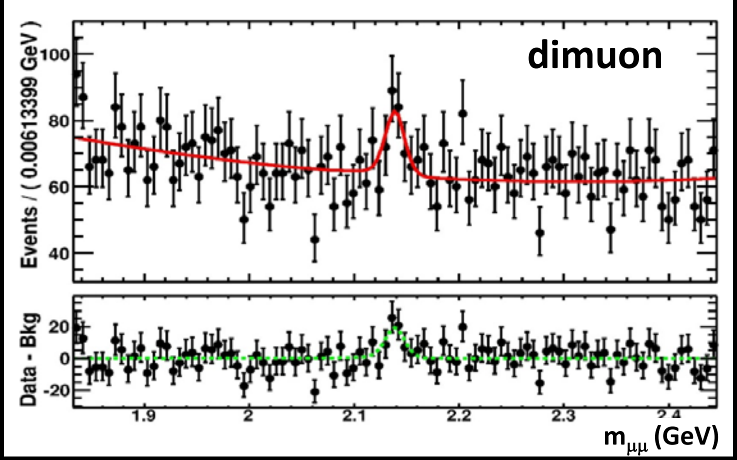
Signal efficiency validated by data/MC comparison of sideband regions. Derive correction factors (2-7%) applied to MC

Exclude regions around J/ψ and $\psi(2S)$ masses.

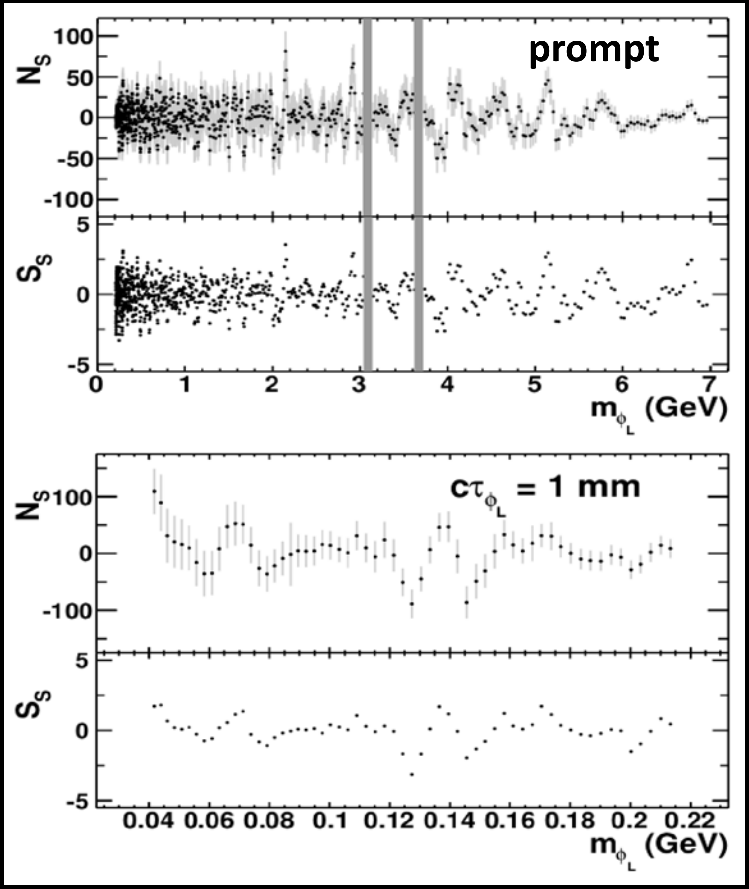
Leptophilic dark scalar

Extract signal as a function of dark scalar mass with fits over sliding intervals
(background MC independent)





Signal yields and significances

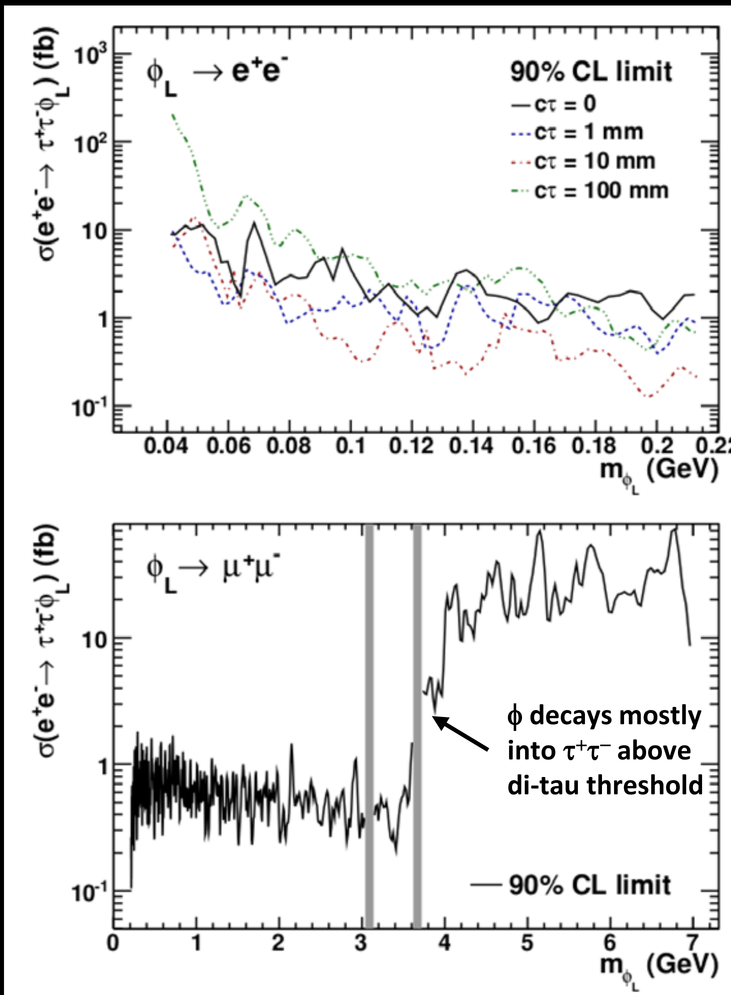


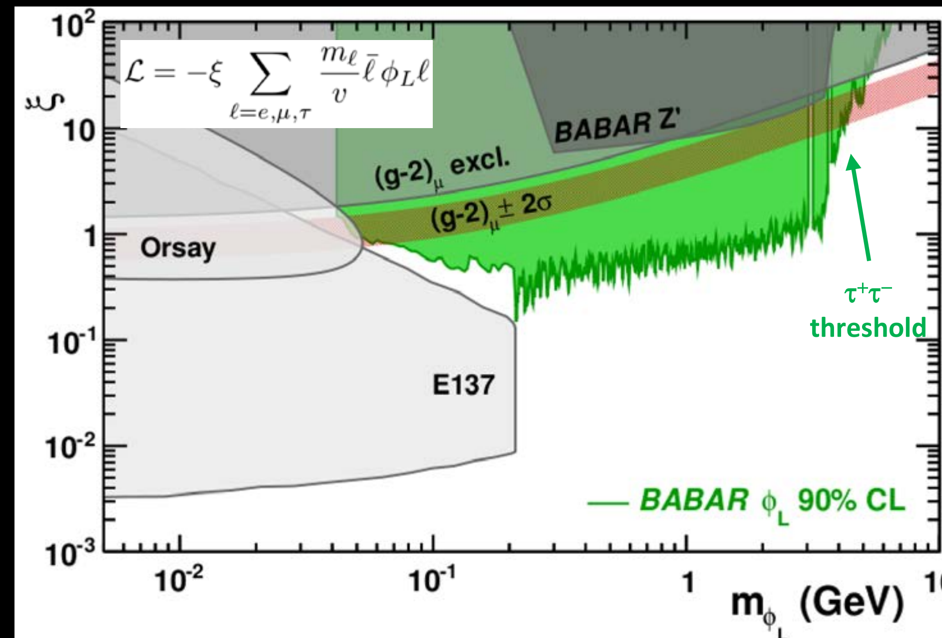
No significant signal, consistent with null hypothesis

Leptophilic dark scalar

Accepted by PRL, arxiv: 2005.01885

Extract limit on the production cross-section and the coupling parameter ξ





Probe ϕ_L lifetime $c\tau$ ~10 cm below dimuon mass

Significant improvement over previous bounds

The g-2 region is clearly excluded for almost all masses below the ditau threshold!

Belle II should be able to further improve

Axion like particle (ALP)

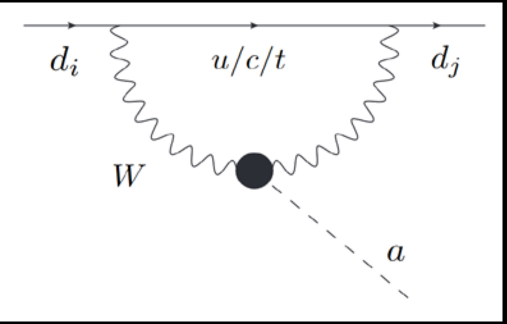
What are axion like particles

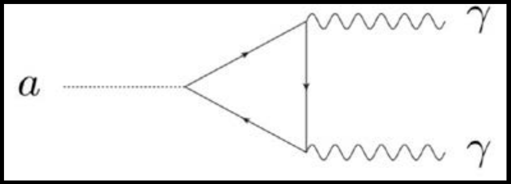
- Pseudo-goldstone bosons ubiquitous in BSM physics, coupling predominantly to pair of bosons with non-renormalizable coupling constant $f_a \sim 1/m_a$
- Low-mass ALP can mediate dark sector – standard model interactions
- Most searches focus on photon or gluon couplings at low energies as effects from $W^\pm$ coupling are suppressed by G_F^2

$$\mathcal{L} = (\partial_\mu a)^2 - \frac{1}{2}M_a^2 a^2 - \frac{g_{aW}}{4}\, a\, W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$

Search for ALP in $B \to Ka$, $a \to \gamma\gamma$ decays

- FCNC are also extremely suppressed in the SM, and they are a perfect testbed to search for ALP emission by $W^\pm$ boson
- Search for ALP in $B \to Ka$ decays, exploiting $b \to s$ transition
- Axion lifetime becomes important at low masses and couplings ($\tau \sim 1/m_a^3 g_{aW}^2$) $\to$ long-lived axion





E. Izaguirre et al., PRL 118 (2017) 111802

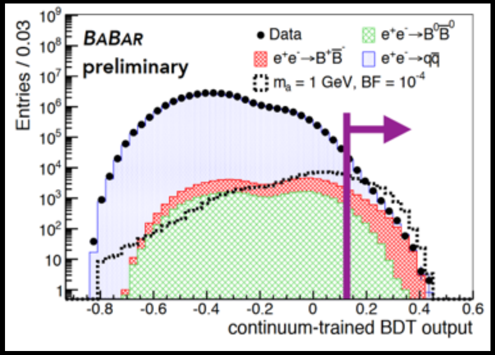
Axion like particle (ALP)

Search for prompt diphoton decay of an axion (a) produced in B decays: **$B \to Ka$, $a \to \gamma\gamma$**

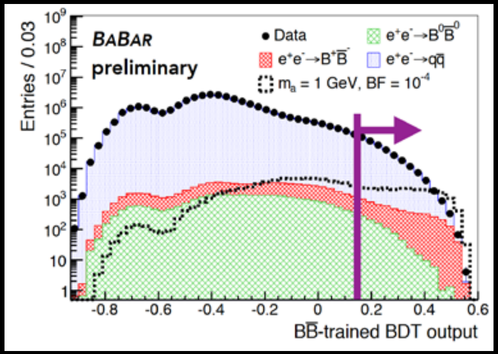
Analysis strategy

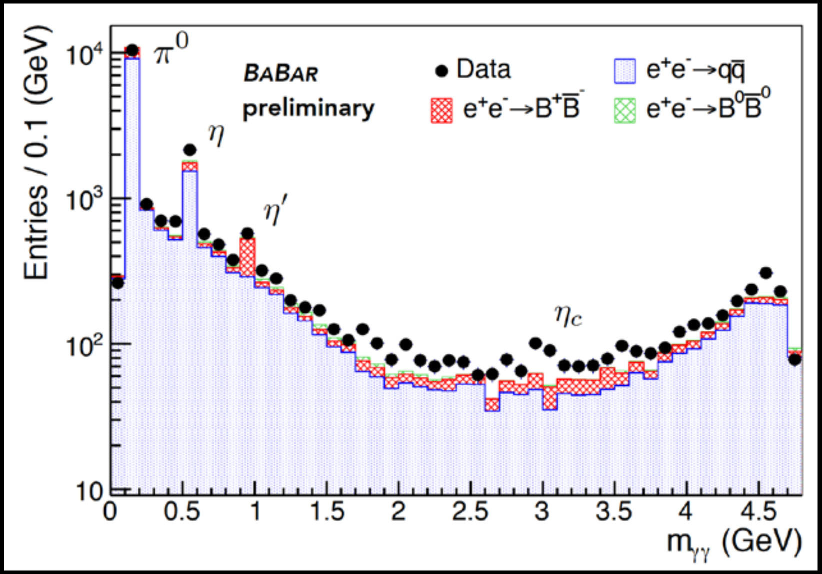
- Combine well-identified K with two photons to form B candidate
- Apply kinematic fit to improve axion mass resolution
- Train 2 BDTs to separate signal from $e^+e^- \to q\bar{q}$ (q=u,d,s,c) and $e^+e^- \to B\bar{B}$ backgounds
- Analysis optimized for prompt decays – discuss displaced case later

Continuum BDT



B-Bbar BDT

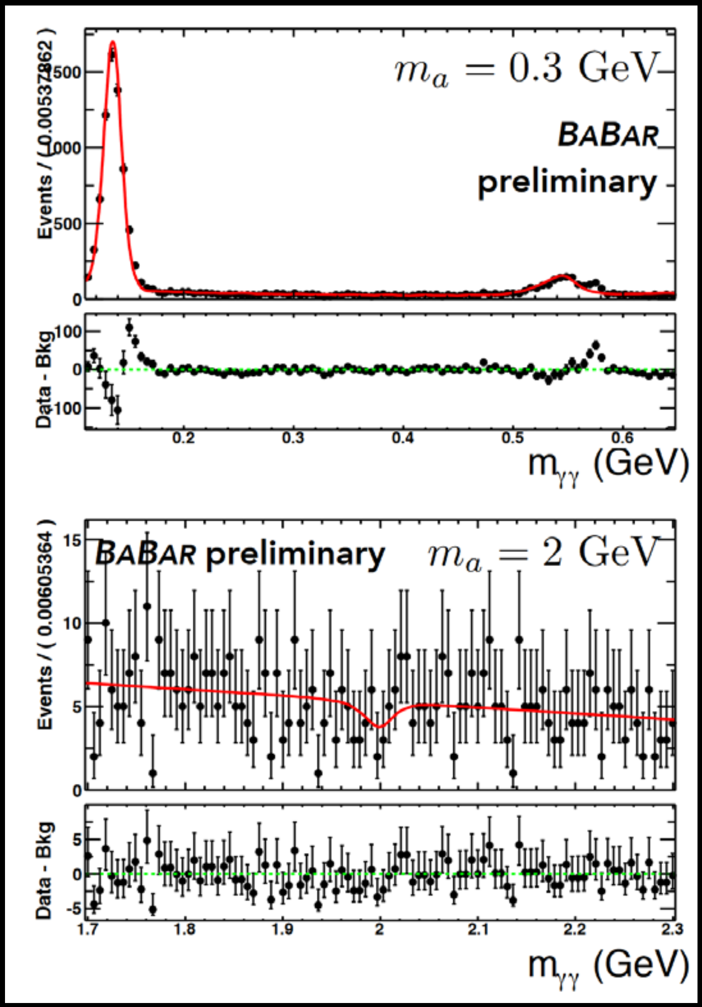




Peaking background at π^0,η,η' masses,
broad excess near η_c, background + $B \to K\eta_c(\to \gamma\gamma)$

Axion like particle (ALP)

Extract signal as a function of axion mass with fits over sliding intervals (prompt decays, background MC independent)



Fit 476 mass hypotheses, step size taken as signal resolution (8-14 MeV)

Fit includes signal, peaking and continuum background components:

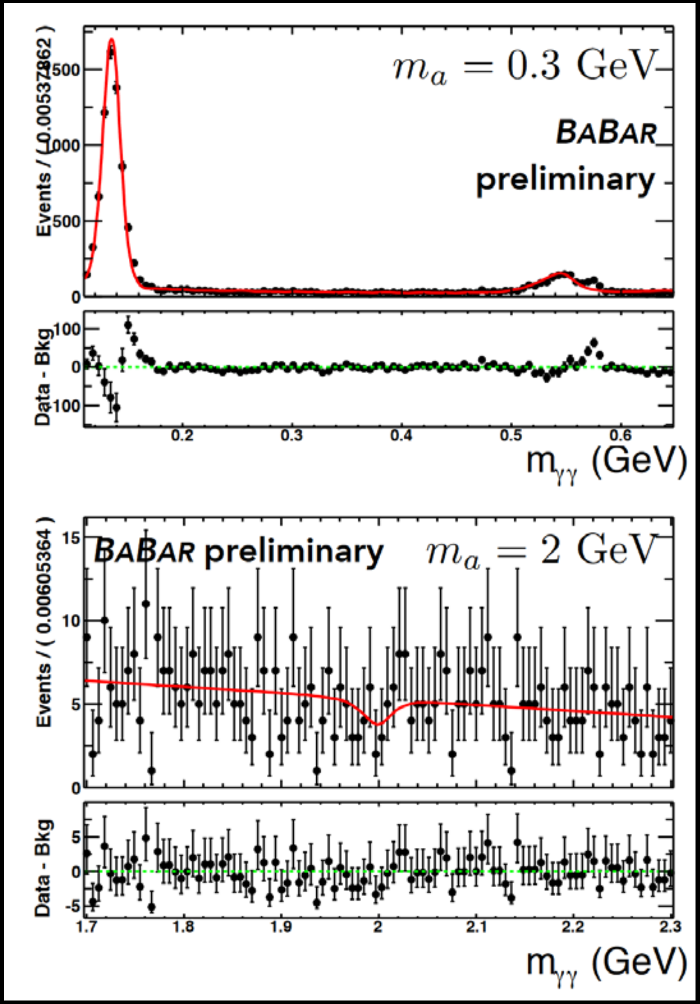
- Signal modeled from signal MC and interpolated between simulated mass points
- Continuum background modelled by first or second order polynomials
- Peaking background modelled from bkg MC

Signal MC resolution validated by data/MC comparisons of $B \to K\pi^0$ and $B \to K\eta$, found to be consistent within 3%

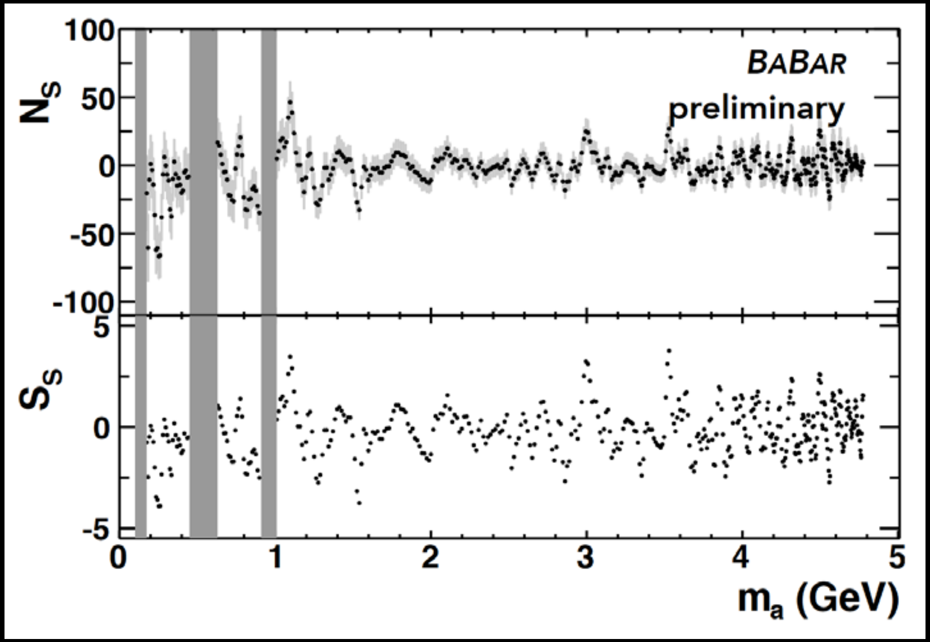
Exclude regions around π^0, η, η' masses.

Axion like particle (ALP)

Extract signal as a function of axion mass with fits over sliding intervals
(prompt decays, background MC independent)



Signal yields and local significances



Global significances <1σ with trial factor, consistent with background only hypothesis

No significant signal is observed

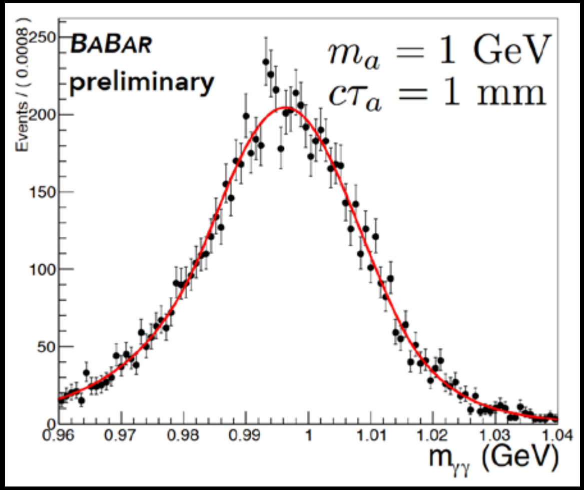
Axion like particle (ALP)

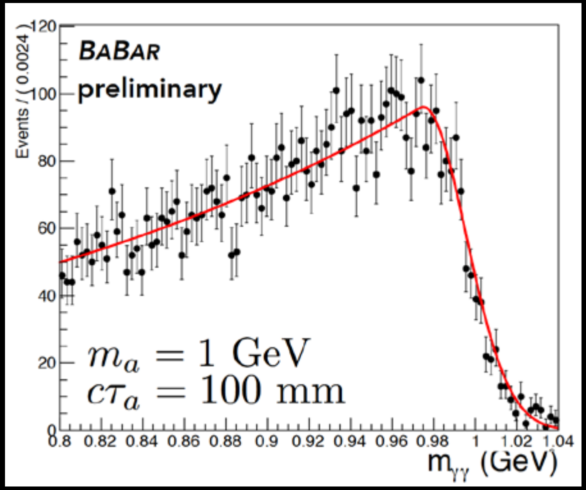
Analysis sufficiently sensitive in the low mass region to probe couplings for which the ALP lifetime becomes non-negligible

The search is optimized for prompt ALP decays, and it is applied without re-optimization to assess the sensitivity to long lived ALPs

Apply same reconstruction / selection for $c\tau_a$ = 1,10,100 mm for m_a < 2.5 GeV

Signal becomes distorted for longer lifetimes $\rightarrow$ signal extraction is more difficult and systematic uncertainties larger.

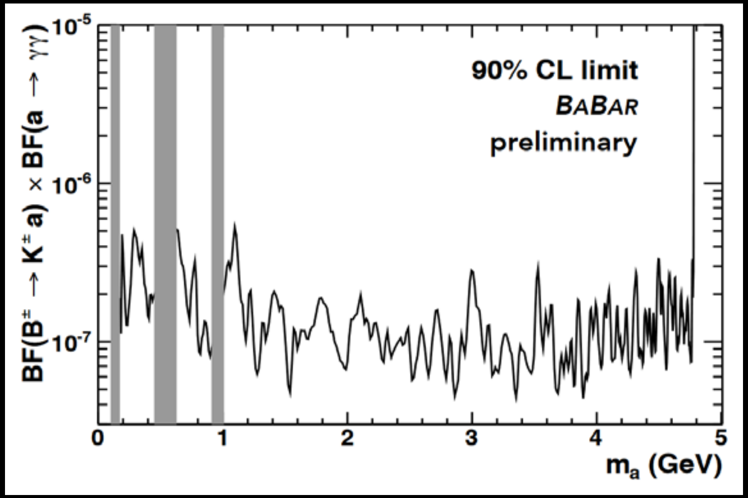




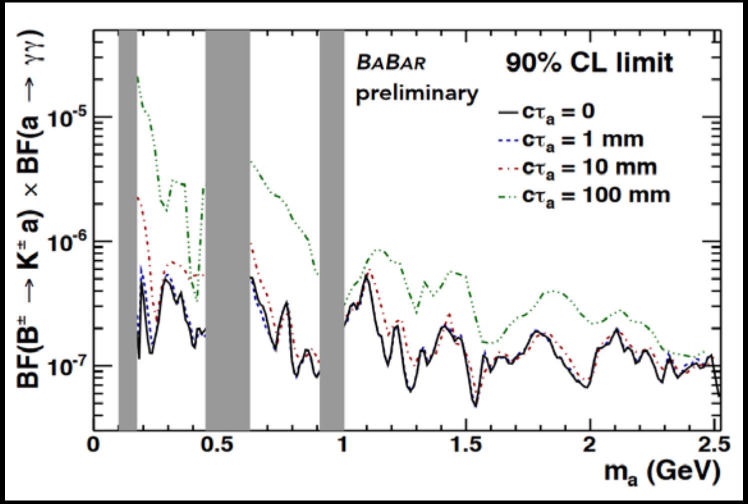
Axion like particle (ALP)

Extract limit on the production cross-section and the coupling parameter g_{aW}

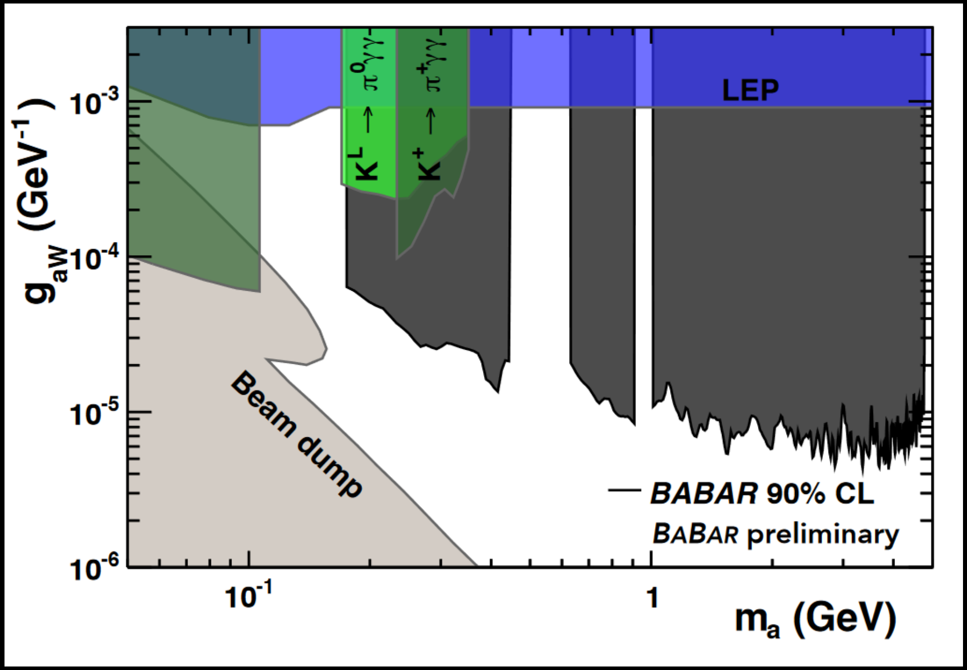
Prompt decays



Displaced decays



90% CL upper limits on coupling g_{aW}

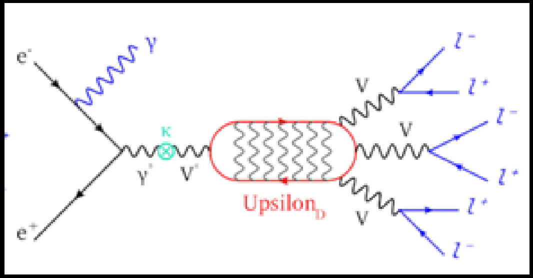


Improvement up to two orders of magnitude over a large mass range

More to come

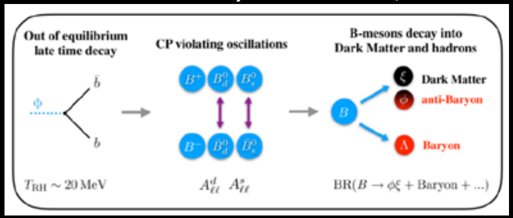
On-going searches for dark sector / dark matter at B*ABAR*

PRL 116 (2016) 151801



Self-interacting dark matter: if the dark-sector coupling is strong, dark sector bound states (darkonium) could be formed. Such states would leave a striking multi-muon final signature at *BABAR*.

Phys. Rev. D 99, 035031



Dark matter and baryogenesis: Search for signature of a new mechanism of baryogenesis and dark matter production in which both the dark matter relic abundance and the baryon asymmetry arise from neutral B meson oscillations and decays.

We're far from being done….

Summary

Dark sectors have emerged as a intriguing possibility to explain dark matter, and more generally to search for light new physics

Low-energy, high-intensity colliders offer an ideal environment to comprehensively probe dark sectors

B*A*B*AR* has conducted an extensive program to search for dark sector signatures, and set stringent limits on their existence

Recently set world leading constraints on leptophilic dark scalar and axion couplings. And more results are on their way!

There are still amazing possibilities at the GeV-scale, and dedicated programs are underway to explore them.

ADDITIONAL MATERIAL

Leptophilic dark scalar

BDT input variables

TABLE I: List of variables used as input to the dimuon boosted decision trees.

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.

TABLE II: List of variables used as input to the dielectron boosted decision trees.

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.
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.

Axion like particle (ALP)

BDT input variables

m_{ES}	0.231
Cosine of sphericity angle	0.110
Maximum K PID selector	0.102
Legendre moment of order 2	0.0996
Helicity angle of a daughter photon with highest energy	0.0889
Difference to π^0 mass	0.0882
ΔE (energy difference between E^*_B and E^*_{beam})	0.0721
Maximum of a daughter energies	0.0653
Invariant mass of all tracks and neutral clusters except $B^\pm \to K^\pm a$ candidate	0.0430
Number of neutral clusters in event	0.0420
Kaon helicity angle	0.0416
Difference to η mass	0.0095
Difference to η' mass	0.0076

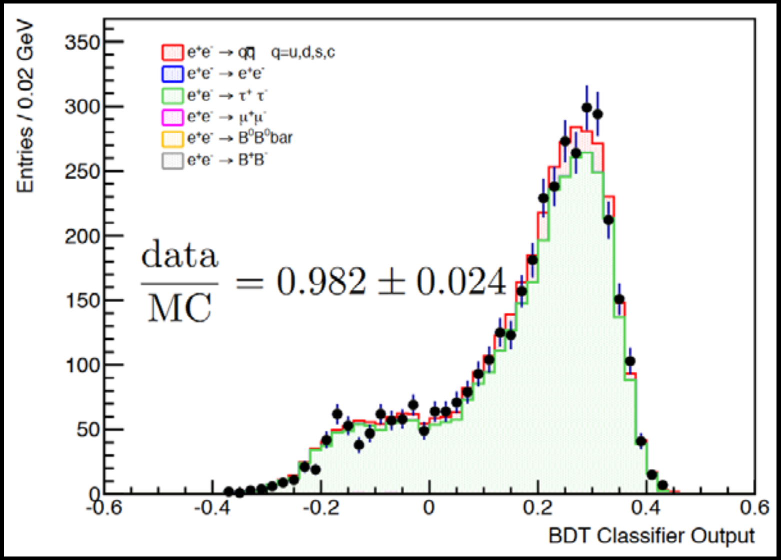
Table 3: Variables used in training the BDT, along with the relative importance when trained with uds backgrounds.

Leptophilic dark scalar

Validate efficiency with control samples and derive corresponding corrections

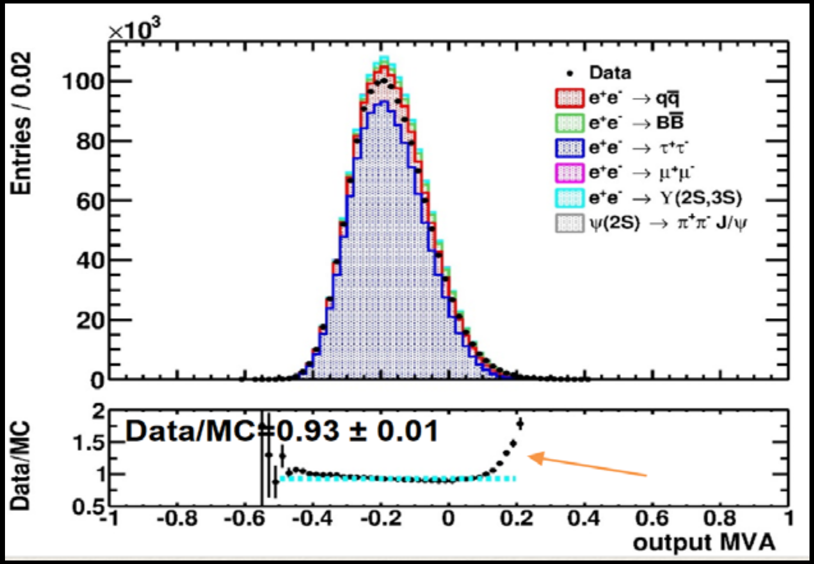
Dielectron

Sample of $K_s \rightarrow \pi^+\pi^-$ in τ decays obtained with a similar selection procedure



Dimuon

BDT response for data with recoil p_T > 2 GeV to suppress non-modelled components

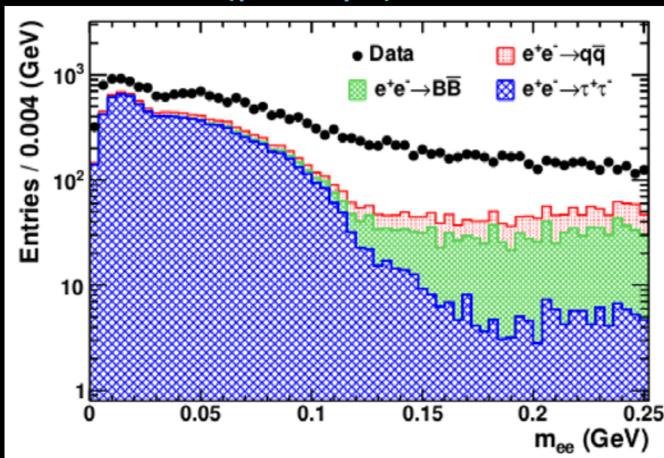


Data globally well reproduced by MC predictions, corrections between 2-7%

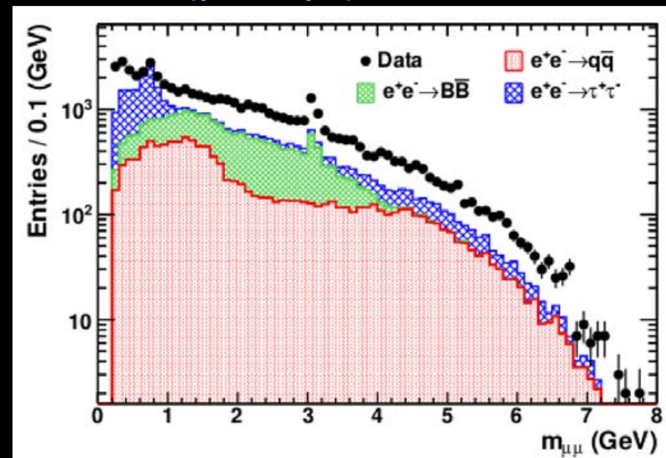
Leptophilic dark scalar

Final mass spectra for each final state and lifetime

Dielectron (prompt)



Dimuon (prompt)



Dielectron (displaced)