Search for Low-mass New Physics States At BABAR

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Outline

The Standard Model and its extensions

The BABAR experiment and data sample

Low-mass new physics states –

Searches

Results

Discussion and prospects

Introduction – the Standard Model and Issues

The Standard Model has been very successful tested by experiments

However it is not a complete theory

facing serious tensions:

naturalness and stability, g-2, W mass, R_K, R_D, R_{D^*} , . . .

can not explain:

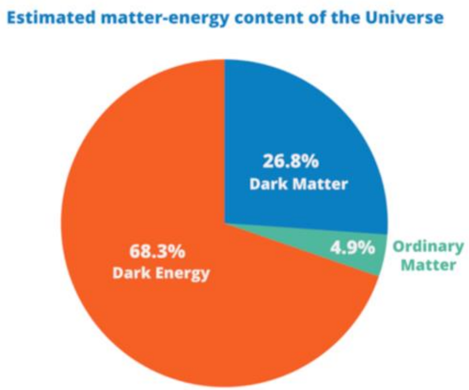
existence & mechanism of dark matter and dark energy,
baryon asymmetry of the Universe,
neutrino masses and oscillations, hierarchy

Real opportunities for discovering new physics beyond the SM

Planck 2022

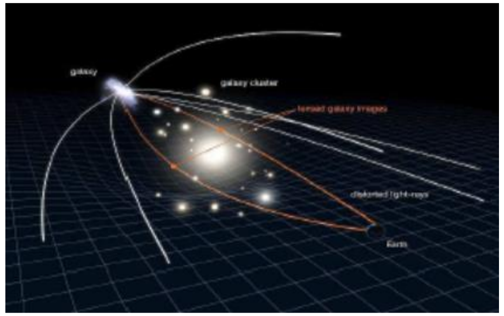
Extensions to the Standard Model

Observations of galactic dynamics and Cosmic Microwave Background (CMB) showed that the SM particles are not abundant enough to account for all matter in the universe. Thus the existence and the mechanism of dark matter

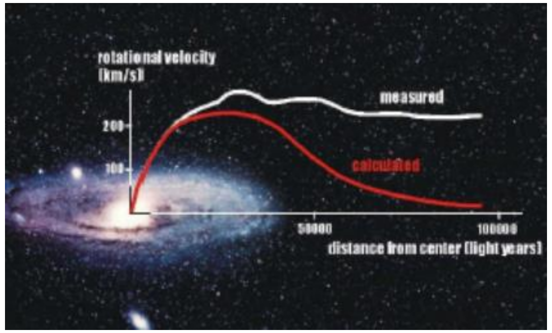


Percentage of ordinary matter, dark matter, dark energy (Image: CERN/ESA)

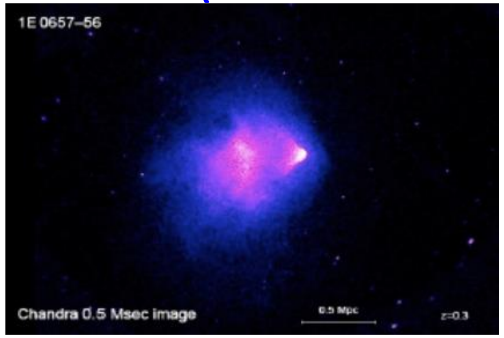
Gravitational lensing



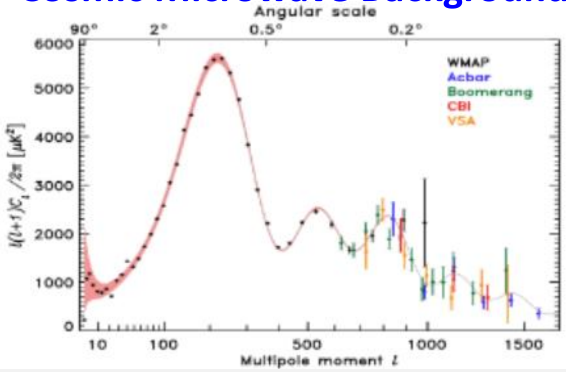
Galactic rotation curve



Bullet cluster (DM collision in GM)



Cosmic Microwave Background



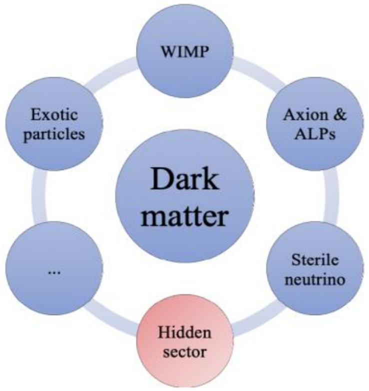
Dark Matter –

- does not interact with strong, weak, or EM forces
- making it extremely hard to spot
- inferred from gravitational effect on visible matter
- outweigh visible matter (~6 to 1)
- Ordinary matter, makes up all stars and galaxies, only accounts for ~5% of content of the universe!

Clear astrophysical and cosmological evidence for dark matter

Dark Matter not seen in particle physics experiments

SM can not explain DM ⇒ Extending the SM to include DM



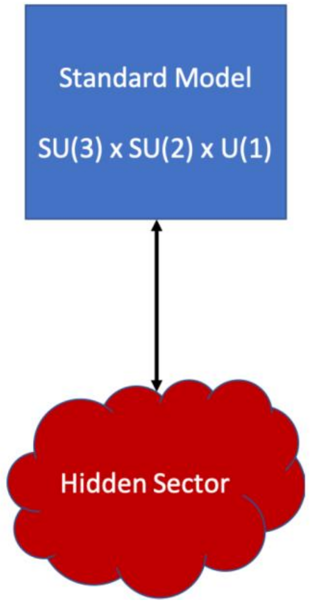
$$\mathcal{L} \supset \begin{cases} -\dfrac{\varepsilon}{2\cos\theta_W} B_{\mu\nu} F'^{\mu\nu}\,, & \text{vector portal} \\ (\mu\phi + \lambda\phi^2) H^\dagger H\,, & \text{Higgs portal} \\ y_n LHN, & \text{neutrino portal} \\ \dfrac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, & \text{axion portal} \end{cases}$$

A' kinetic mixing with γ, Z

Dark Higgs (mixes with SM Higgs)

Sterile neutrino

Axion, coupling to DM



Low-mass New Physics States – Searches

Is there New Physics at low mass?

A group of models

- suggests that DM might be light (up to a few GeV); these models are unconstrained by WIMP , in which light DM couples to SM through a portal with a light mediator
  vector portal - dark photon A'
- non-minimal DM models allow for different couplings to the 2nd/3rd generation
  Z' coupling to muons could contribute to $(g-2)_\mu$ anomaly, sterile neutrino abundance
- tightly bound stable hexaquark (uuddss) could be DM candidate
  Search for missing momentum recoiling against two strange antibaryons
- Axion-like particles (ALPs) – masses can be well below the electroweak scale. With couplings to electroweak bosons, they could be emitted in flavor-changing B meson decays.
  Search for axion-like particles in B meson decays
- Dark matter bound states (darkonium) could arise if a dark photon A' is light enough to generate an attractive force between 2 dark fermions.
  Search for dark matter bound states
- A heavy neutral lepton (HNL), capable of mixing with the SM τ neutrino with a mixing strength of $|U_{\tau 4}|^2$, **Search for Heavy Neutral Leptons Using τ Decays**

Benjamin W. Lee and Steven Weinberg. Phys. Rev. Lett. 39, 165 (1977) ,...

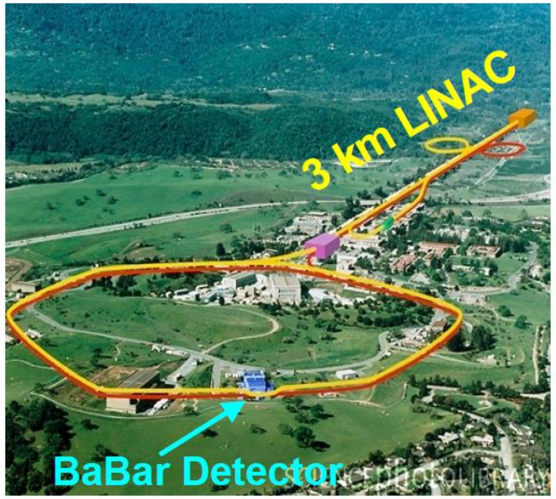
The BABAR Experiment and the Data Sample

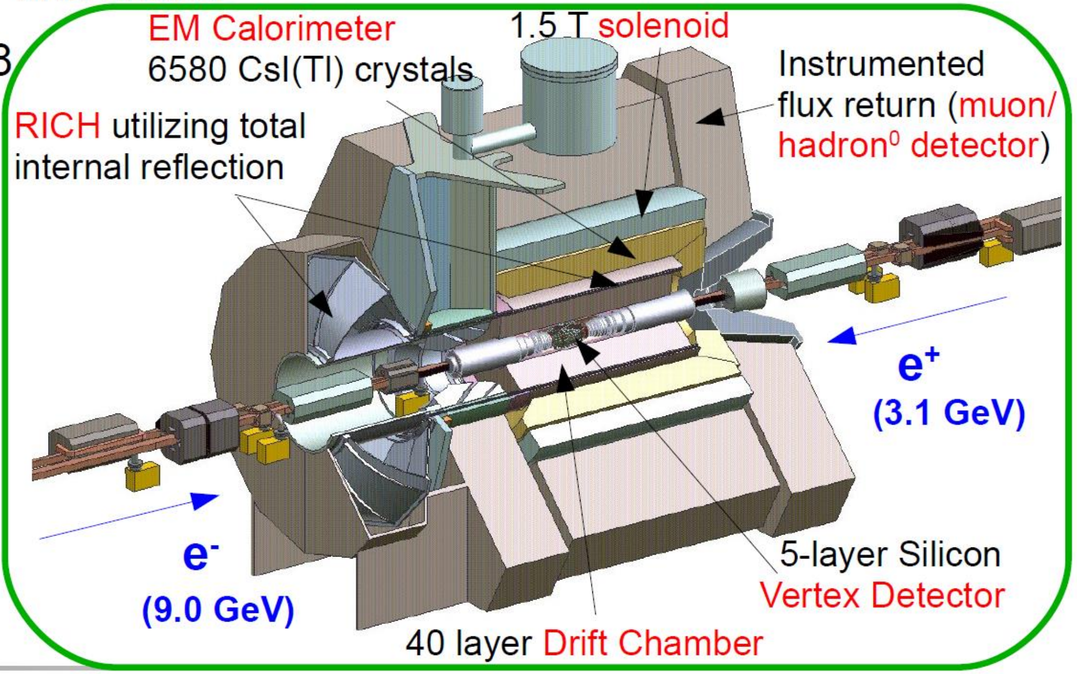
- B-Factory at the PEP-II aymmetric e^+e^- collider located at SLAC
- Collected **424 fb^{-1}** at the CM energy 10.58 GeV for $\Upsilon(4S)\to B\overline{B}$

  4.72×10^8 $B\overline{B}$ pairs **$4X10^8$ τ pairs**

  - Substantial samples of $\tau^+\tau^-$ and charm
- Data-taking from 1998 to 2008

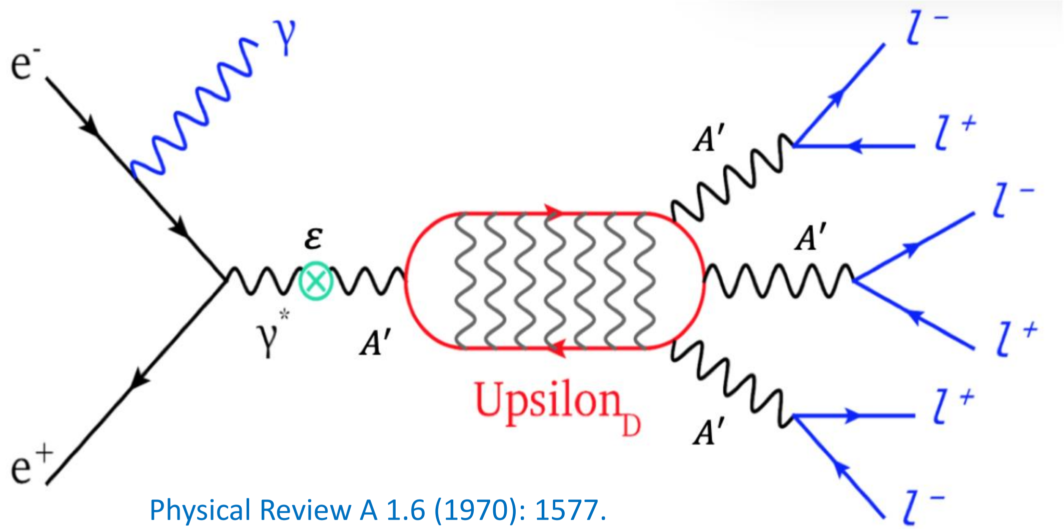
Design luminosity: 3.0 x 10^{33} cm^{-2} s^{-1}
Record luminosity: 12.07 x 10^{33} cm^{-2} s^{-1}





Productions and decays – dark matter bound states

- A minimal dark sector model contains a single Dirac fermion (χ) charged under a new U(1) gauge group with a coupling constant g_D.
- Sufficiently strong values of g_D could result in the formation of bound states $\chi\bar{\chi}$ (darkonium).
- The existence of stable bound states requires $1.68 m_A \leq \alpha_D m_\chi$
- One lowest bound state Upsilon$_D$ ($J^{PC} = 1^{--}$) predicts the process



Physical Review A 1.6 (1970): 1577.
Physical Review Letters 116.15 (2016): 151801.

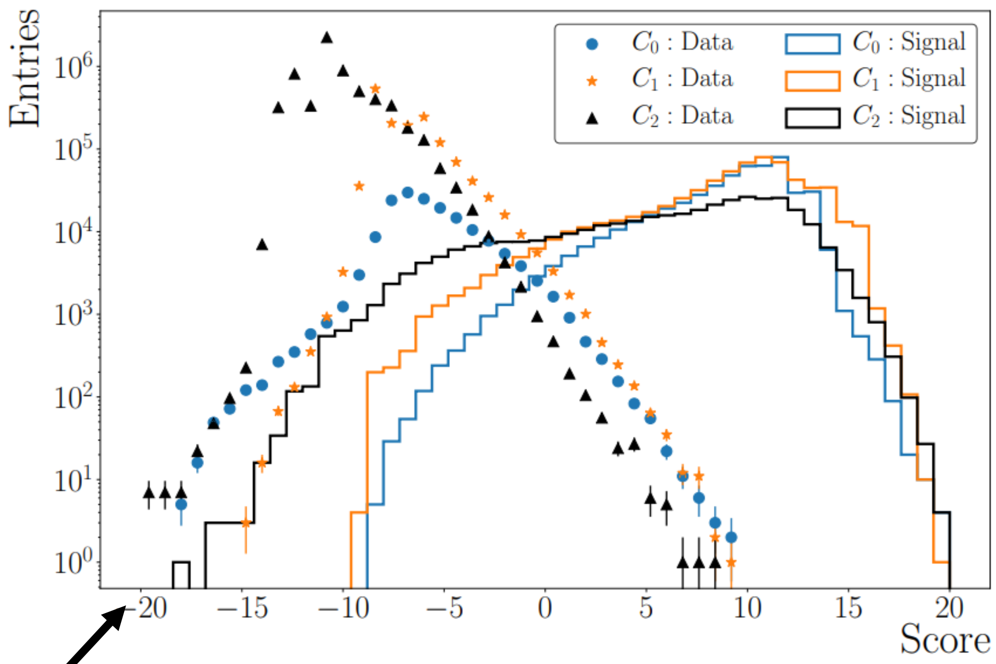
We search for the reaction $e^+e^- \rightarrow \gamma\Upsilon_D$, $\Upsilon_D \rightarrow A'A'A'$, $A' \rightarrow X^+X^-$ ($X = e, \mu, \pi$)

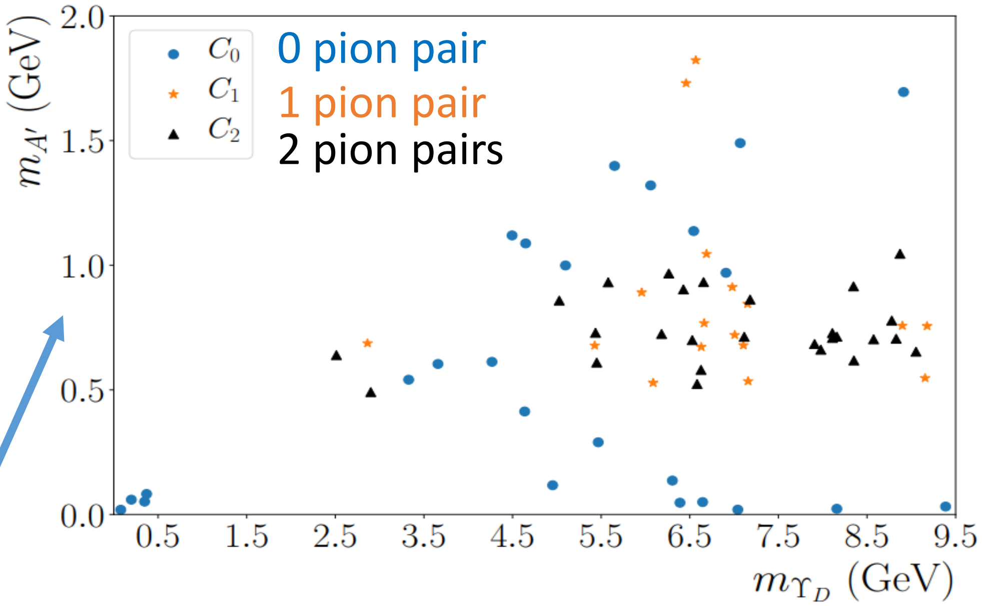
- Final states consist of three pairs of leptons or pions, with two or more electron or muon candidates.
- Dark photons should have same masses.
- Recoil mass against Υ_D should be compatible with the photon hypothesis
- Extra neutral energy should be small.

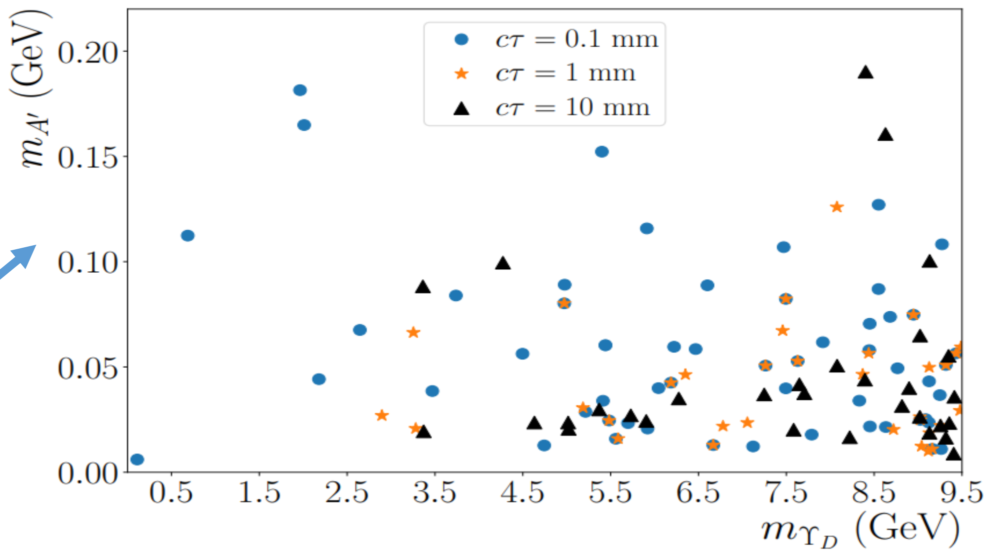
Dark photon is small in mass and could be short or long-lived depending on the dark photon mass, momentum and mixing strength, decay can either be prompt or displaced.

Results

dark matter bound states – analysis



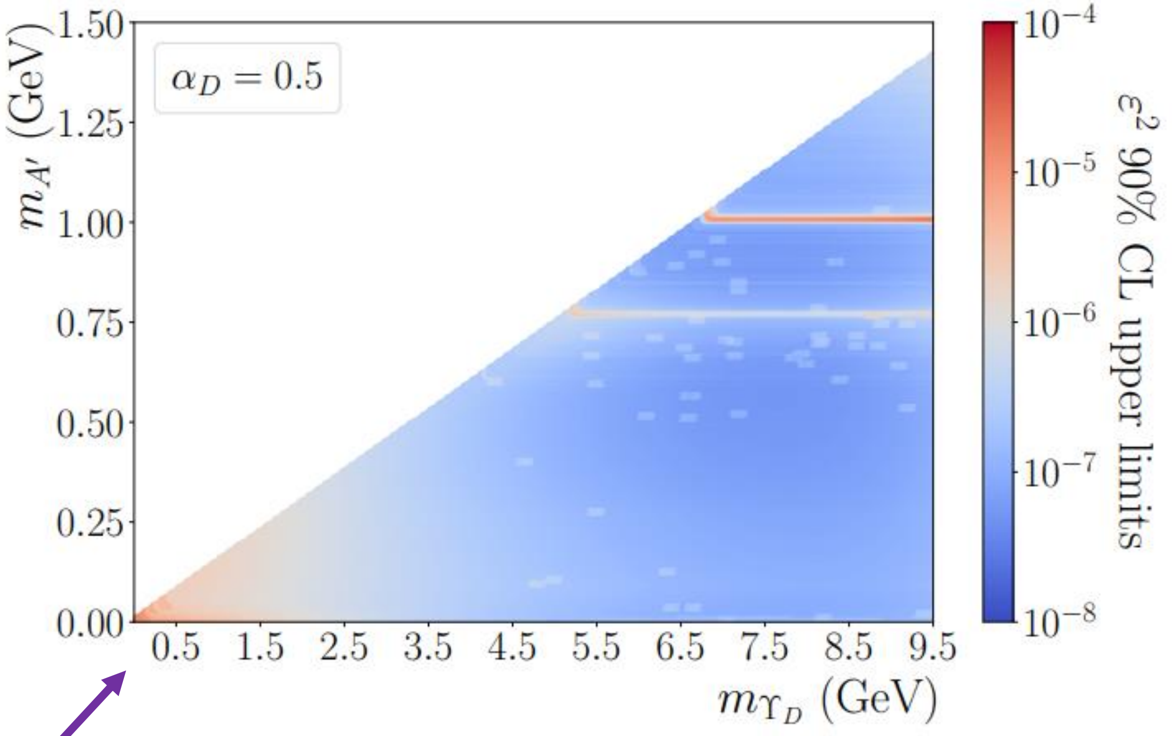


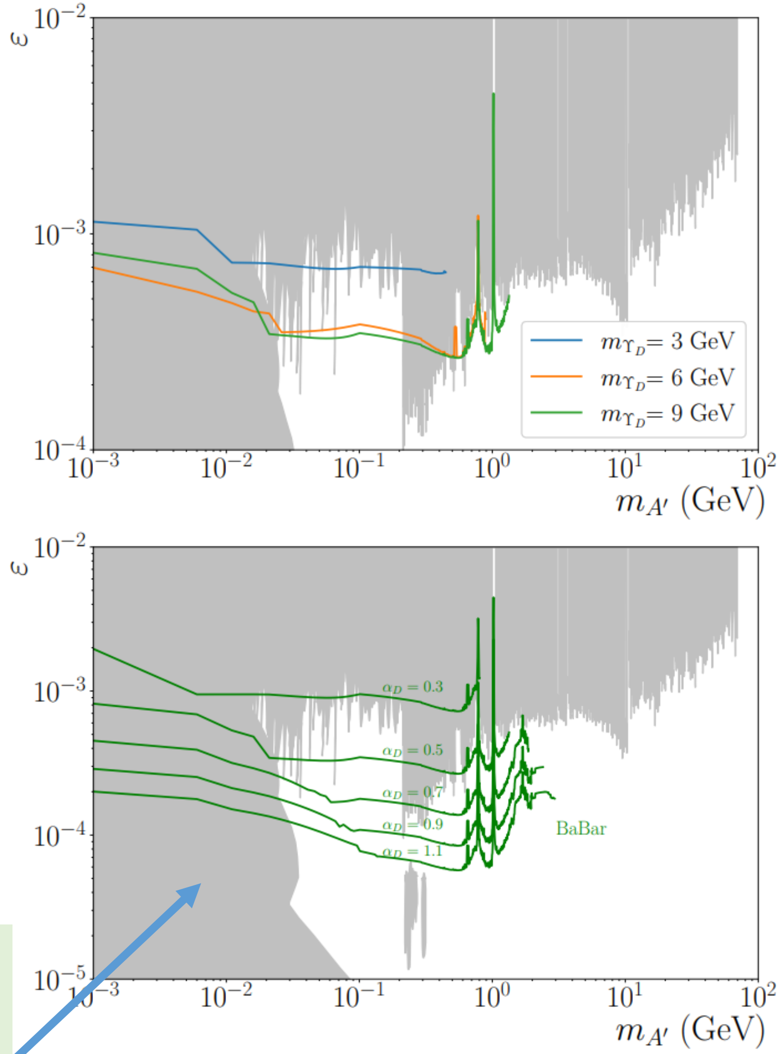


- Data compared with signal MC events for 0,1,2 pion pairs.
- events passing all selection criteria for prompt dark photon decays.
- event candidates passing all selection criteria for the datasets optimized for each dark photon lifetime.

Results

dark matter bound states



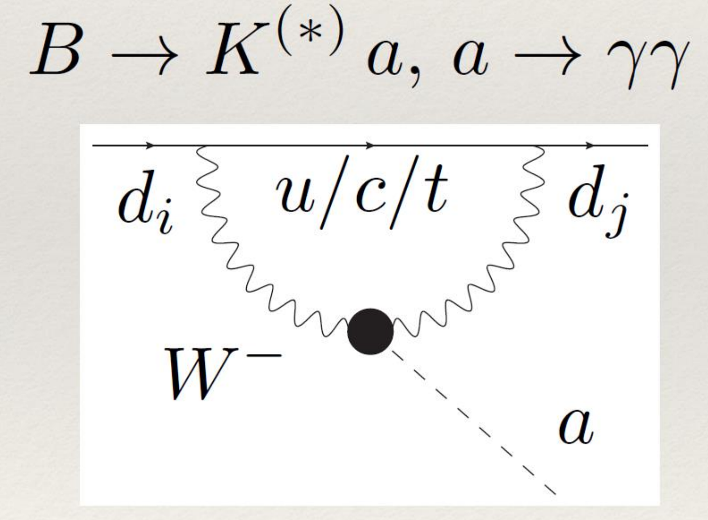


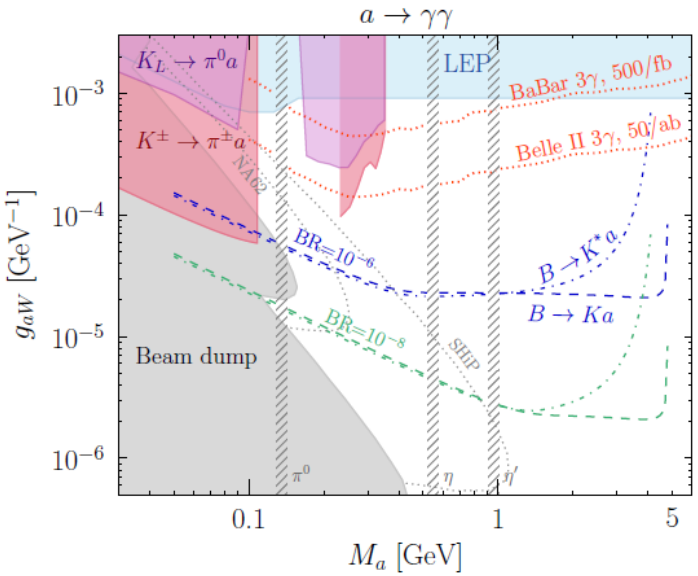
- ✓ Bounds on the kinetic mixing ε^2 down to $10^{-9} - 10^{-6}$ are excluded for a large fraction of the parameter space.
- ✓ Constraints for different values of α_D, $m_{A'}$ and $m_{\Upsilon D}$ are also shown.

Low-mass New Physics States – Searches

Axion-like particles in B decays

- New light pseudoscalar, couples predominantly to gauge bosons
- In presence of coupling SU(2) gauge bosons, get large FCNC production rate
- At small mass/coupling, lifetime becomes appreciable (mm-10s of cm)





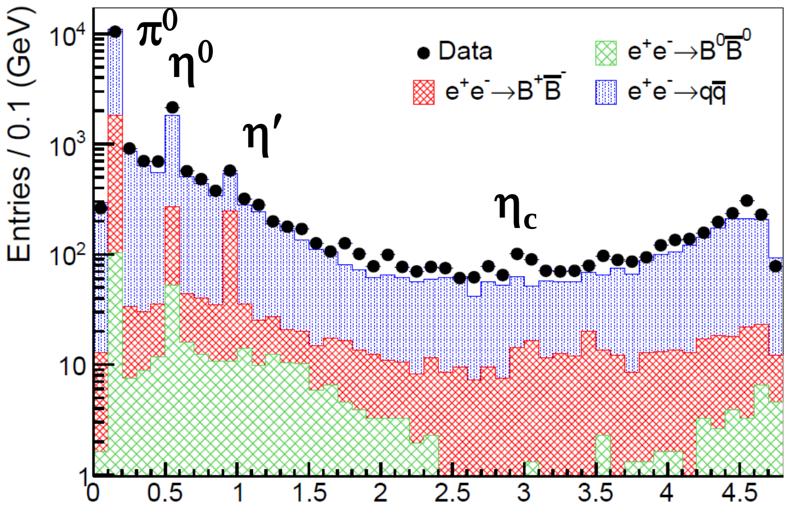
Physical Review Letters (2017, arXiv1611.09355)

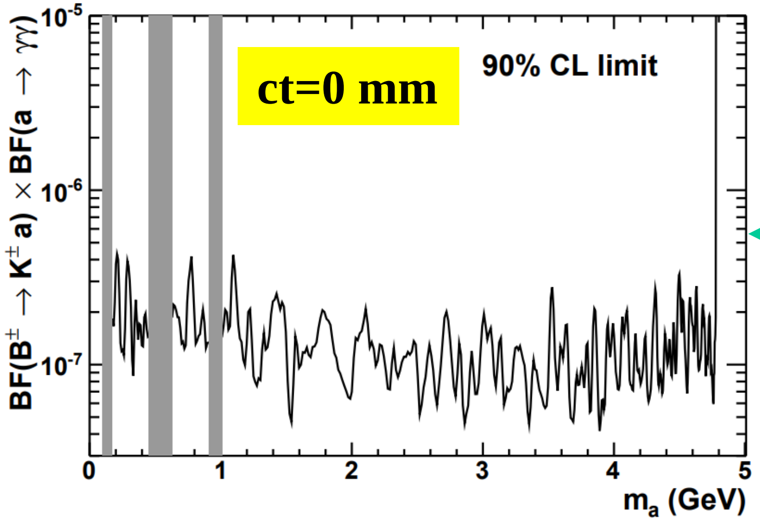
We fully reconstruct $B^\pm \to K^\pm\gamma\gamma$

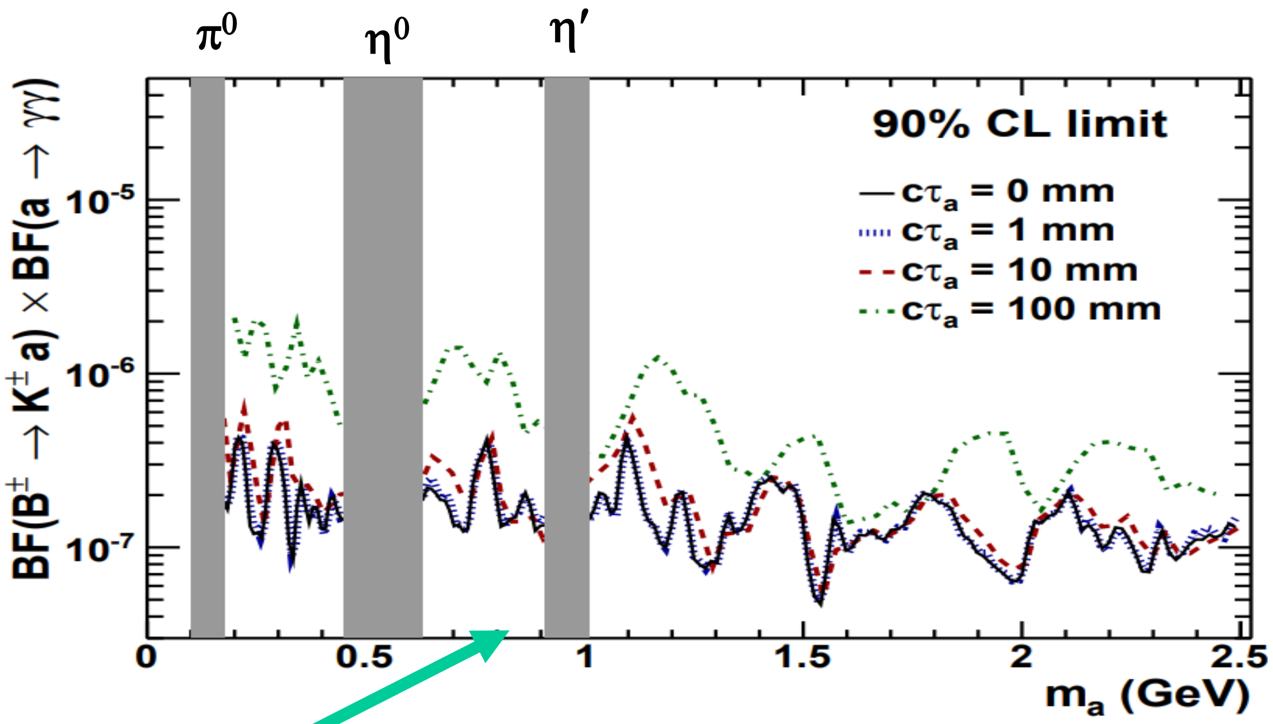
- K and 2γ candidates forming the B.
- Kinematic fit including beam, energy, and mass constraints.
- Loose pre-selection for candidates: m_{ES} > 5 GeV, |E| < 0.3 GeV
- 13 BDT training observables.

Results

Axion-like particles in B decays







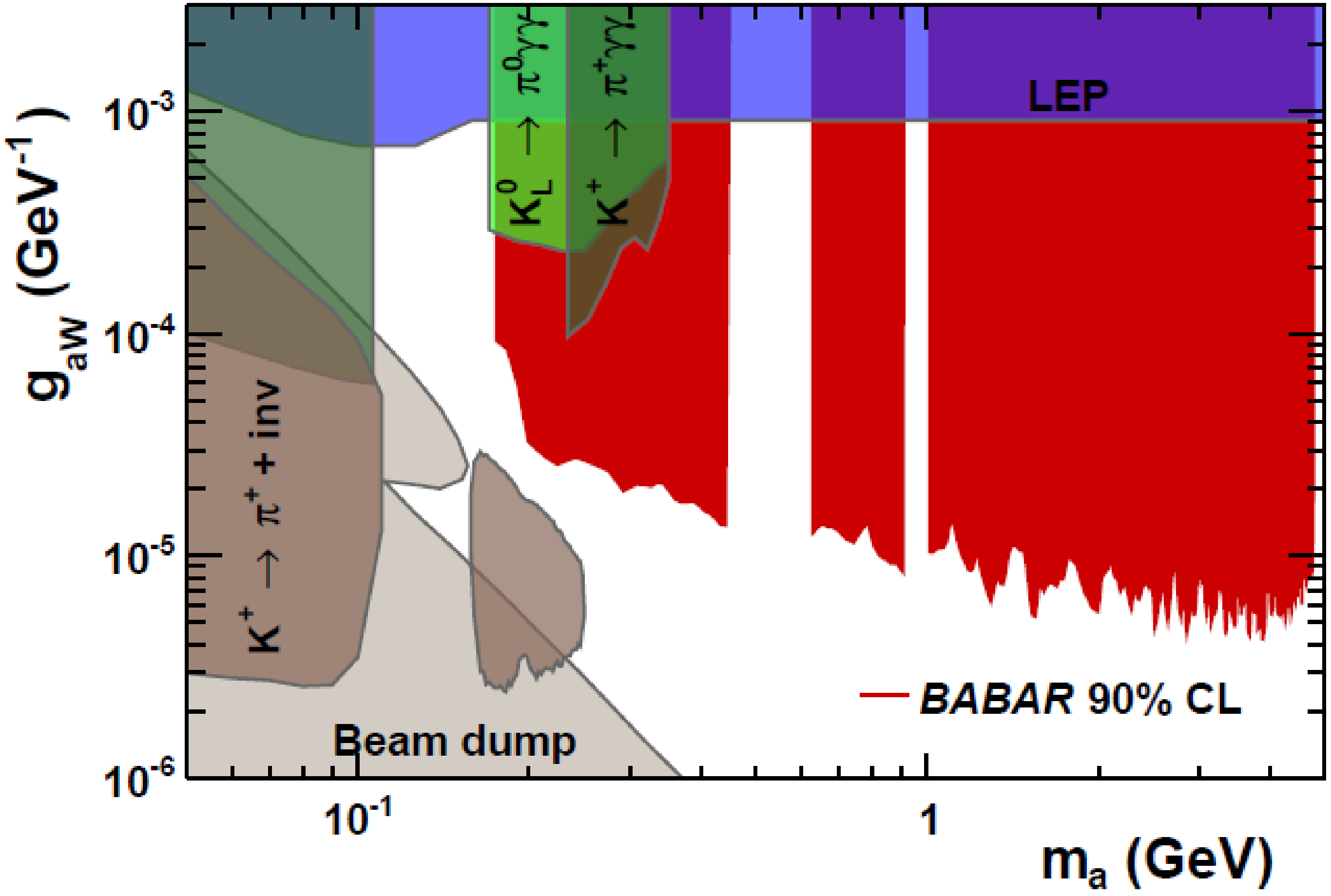
The 90% CL upper limits on the $B^\pm \to K^\pm a$ branching fraction

- for m_a < 2.5 GeV and $c\tau_a$ between 0 and 100mm.
- all m_a and $c\tau_a = 0$.

The vertical gray bands indicate the regions excluded from the search in the vicinity of the π^0, η, and η' masses.

Results

Axion-like particles in B decays



The 90% CL upper limits on the coupling g_aW as a function of the ALP mass (red), together with existing constraints (blue, green, brown, and grey)

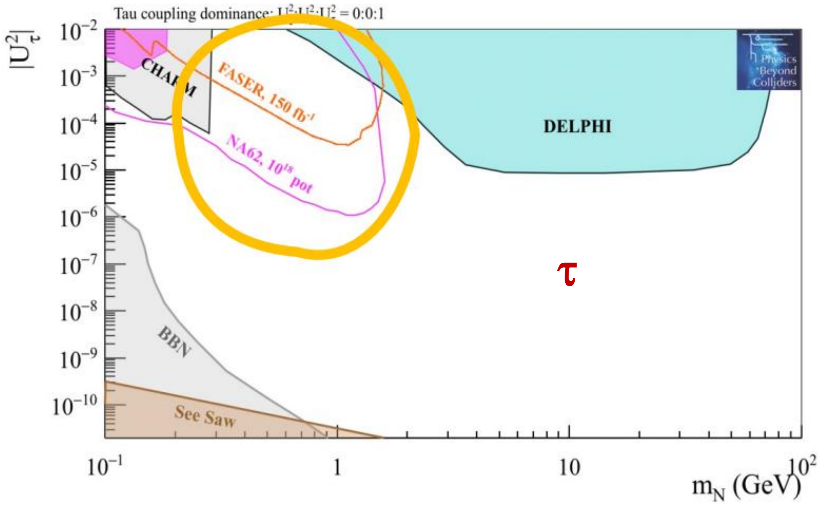
Searching for Heavy Neutral Leptons Using τ Decays

Several phenomena could be related to existence of Heavy Neutral Leptons (HNL), including:

1. Flavor violation in neutrino experiments,
2. the cosmological origin of the baryonic matter in the universe,
3. the composition and origin of dark matter.

Very different scales depending on model:

- Those with masses 100 MeV - GeV can be produced in muon and tau decays giving rise to deviations from SM expectations.
- Very heavy states in GeV - TeV range: open the door to explaining the BAU via low-scale scenarios of leptogenesis without conflict with other cosmological observations



Searching for Heavy Neutral Leptons Using τ Decays

Literature suggests BABAR could place stringent limits on the probability of N (HNL) interacting with tau neutrinos ($|U_{\tau N}|$)

arXiv: 1412.4785 , 2007.08239, 1908.09719, 1502.06541,

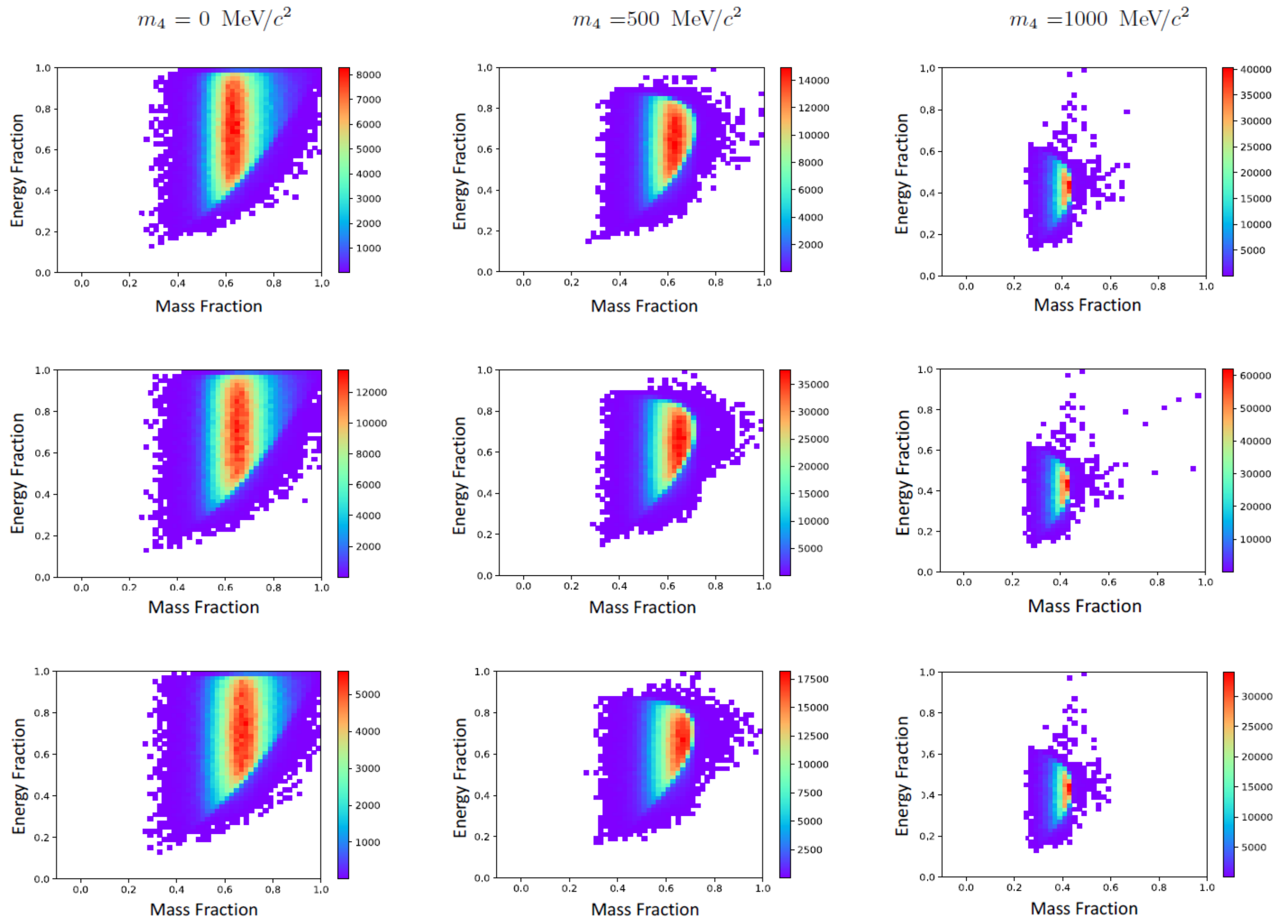
Method

- Model 3-pronged decay as if it were 2-body with HNL and hadronic system as outgoing particles.
- Define E_h as energy and m_H as the invariant mass of the hadronic products.
- $E_\tau = E_{cms}/2$ is the limit of no ISR. The value of m_H can exist, in principle, in the range $3m_{\pi\pm} < m_H < m_\tau - m_{HNL}$. The range of E_h is
- Templates for each mass in the form of 2D plots of E_h v. m_h . Curvature in this plot due to massive neutrino if present

$$\tau^- \to h^-(E_h, \vec{p}_h) + \nu(E_\nu, \vec{p}_\nu),$$

$$E_h^{\max} = E_\tau - \sqrt{m_\nu^2 + q_+^2},$$
$$E_h^{\min} = E_\tau - \sqrt{m_\nu^2 + q_-^2},$$

Searching for Heavy Neutral Leptons Using τ Decays – analysis



Examples of reconstructed outgoing hadronic invariant mass and energy (mh, Eh) (as fraction of incoming τ mass and energy) for HNL masses of

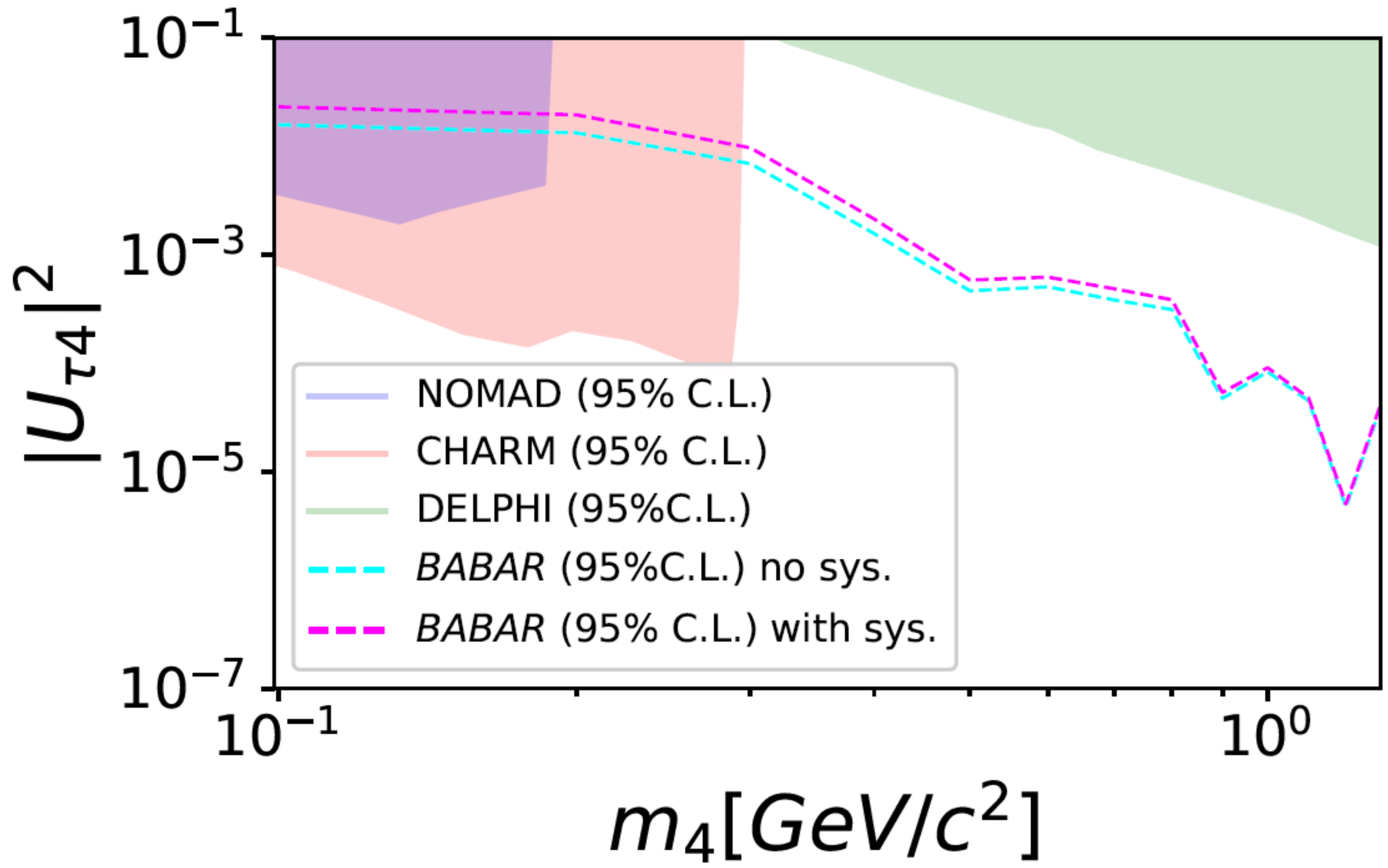
m4 = 0 MeV/c2 (left column),
500 MeV/c2 (middle column), and
1000 MeV/c2 (right column)

for three ma1 possibilities:
1190 MeV/c2 (top row),
1230 MeV/c2 (middle row), and
1270 MeV/c2 (bottom row).

These samples are used to re-weight the 2D template histograms and the shift in the derived value of $|U_{\tau 4}|$.

Results

Searching for Heavy Neutral Leptons Using τ Decays



- The upper limit at the 95 % confidence level provided by this analysis using the binned likelihood technique described.
- The magenta line represents the upper limit when all systematic uncertainties are considered.

Discussion and Prospects

Dark matter bound states

- This is the first search for a dark sector bound state decaying into three dark photons in the range 0.001 GeV < $m_{A'}$ < 3.16 GeV and 0.05 GeV < $m_{\Upsilon D}$ < 9.5 GeV.
- No significant signal is seen, and we derive limits on the γ–A' kinetic mixing ε^2 at the level of $10^{-9} - 10^{-4}$, depending on the values of the model parameters.
- These measurements improve upon existing constraints over a significant fraction of dark photon masses below 1 GeV for large values of the dark sector coupling constant

Discussion and Prospects

Axion-like particles in B decays

- First search for axion-like particles in the process $B^{\pm} \to K^{\pm}a$, $a \to \gamma\gamma$.
- The results strongly constrain ALP couplings to electroweak gauge bosons, improving upon current bounds by several orders of magnitude, except in the vicinity of the π0, η, and η' resonances.
- Our results demonstrate the sensitivity of flavor-changing neutral current probes of ALP production, which complement existing searches for the ALP coupling to photons below the B meson mass

Discussion and Prospects

Heavy Neutral Leptons Using τ Decays

- Limits derived for the lower mass hypotheses are within the already excluded region, as expected since with this kinematic method the higher mass signals would produce the most signal/background discrimination, and, therefore, better limits (in this case).
- It should also be noted that the limits provided here are competitive with the current projections for experiments in the 10 year time frame in this mass range including those from FASER and NA62.
- Looking further ahead, significant improvements are expected from the proposed facilities: the CEPC, FCC-ee & the ILC.

Special Acknowledgement

Frank Porter, Brian Shuve, Steve Robertson, Gerard Bonneaud, Abner Soffer, …

All of my BABAR colleagues

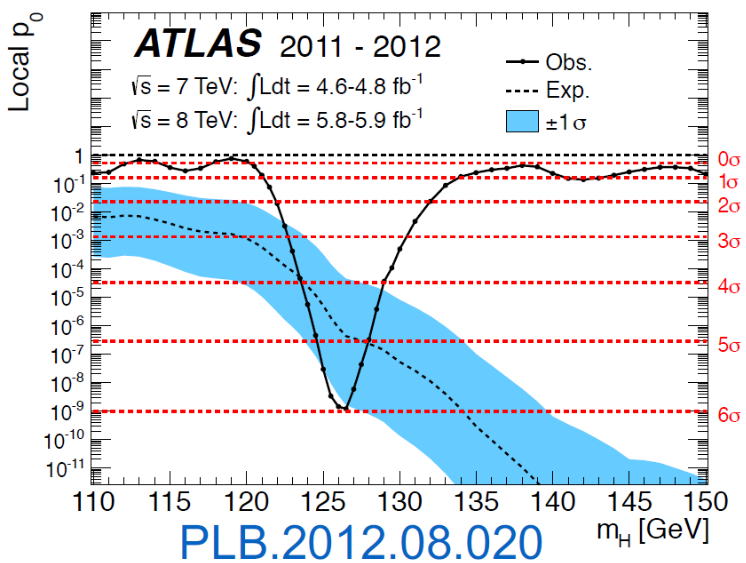
Backup Slides

Introduction – the Standard Model and Issues

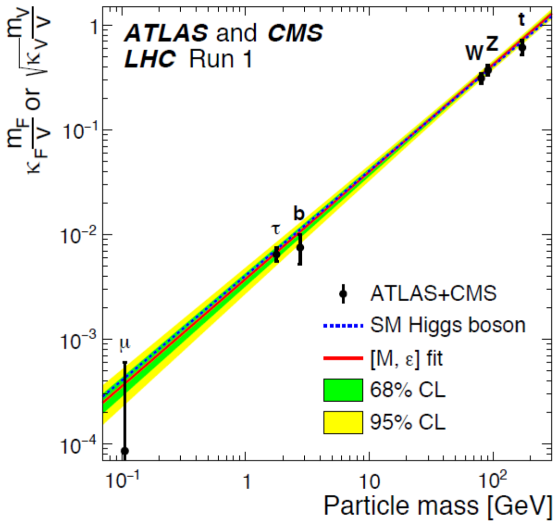
The Standard Model of Elementary Particle Physics

has been very successful in describing data

is further supported by the discovery of the Higgs boson in 2012
& the Higgs behavior seen at the LHC



PLB.2012.08.020



JHEP08(2016)045

SM provides consistent description of Nature's fundamental constituents and their interactions

- It's predictions tested and confirmed by numerous experiments.
- Large Hadron Collider (LHC) runs culminated in the discovery of Higgs boson particle with mass of 125 GeV – the last critical SM component.
- In principle, all particles needed to explain results of previous accelerator experiments have been found.
- At the same time, no significant deviations from SM were found in direct or in indirect searches for New Physics (NP).

Introduction – the Standard Model and Issues

However, the Standard Model is not a complete theory

It is facing serious tensions: naturalness and stability, g-2, W mass, R_K, R_D, R_{D^*}, …

It can not explain: existence & mechanism of dark matter and dark energy,
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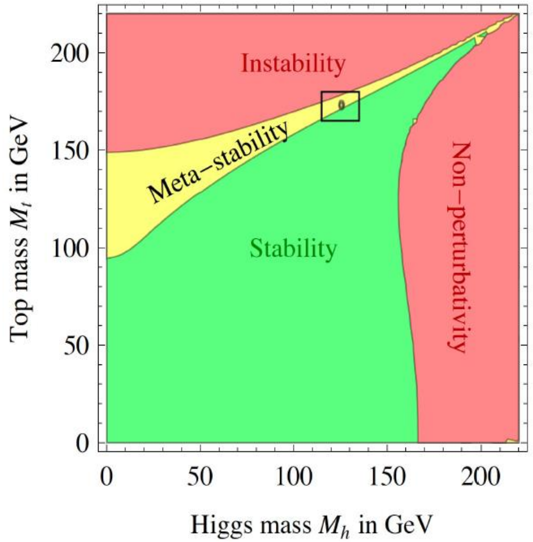
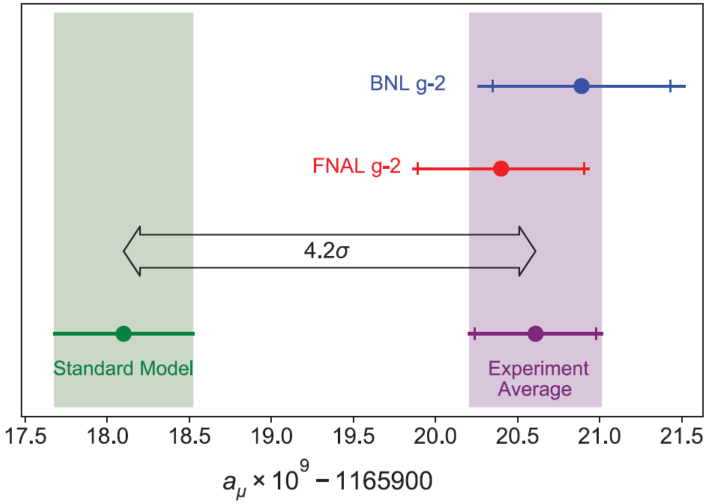
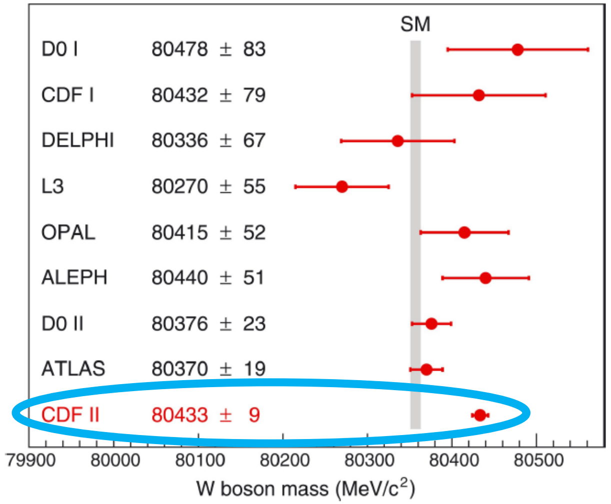


JHEP08(2012)098



Phys. Rev. Lett. 126.141801



Science.abk1781

Real opportunities for discovering new physics beyond the SM

Low-mass New Physics States – Searches

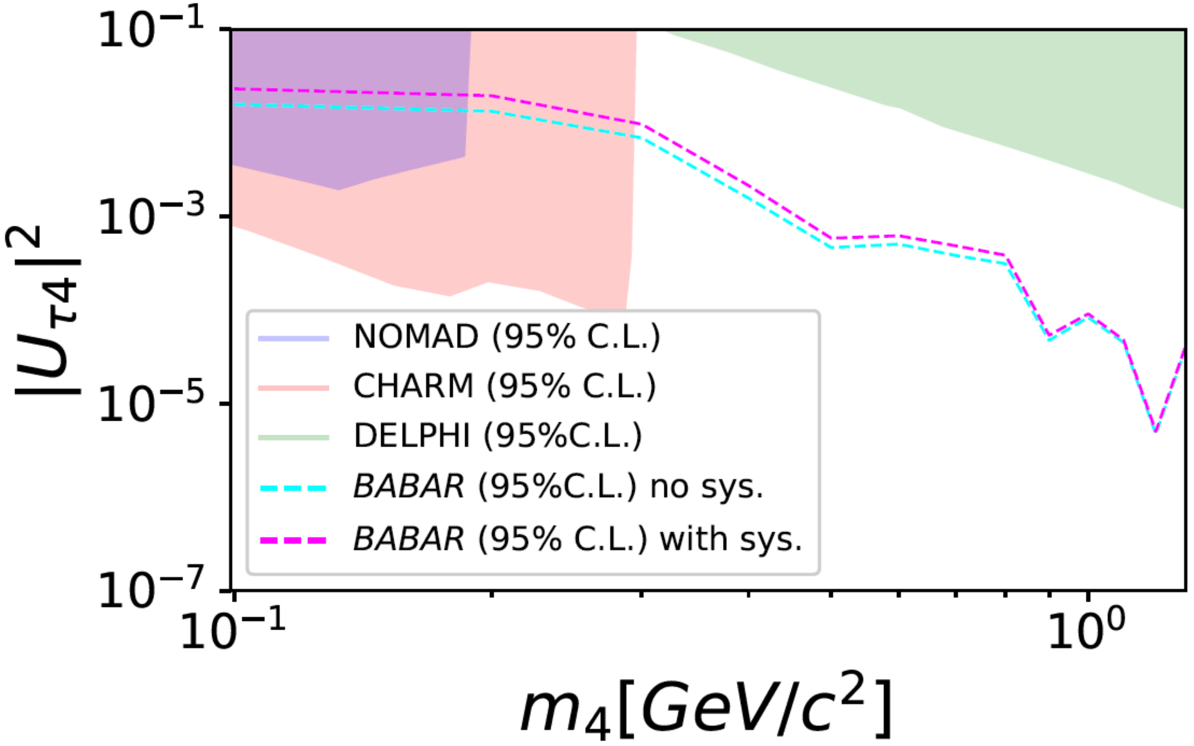
ÉCOLE POLYTECHNIQUE ParisTech

BABAR is pursuing actively the following areas:

- Dark-matter bound state, darkonium
- Axion-like particles
- Prompt and long-lived particles
- Hidden scalars (dark Higgs) decaying leptonically
- Heavy neutral leptons (100 MeV – 1.3 GeV) in tau decays

Results

Searching for Heavy Neutral Leptons Using τ Decays



Mass [MeV/c^2]	No Sys.	With Sys.
100	1.58×10^{-2}	2.31×10^{-2}
200	1.33×10^{-2}	1.95×10^{-2}
300	6.91×10^{-3}	9.67×10^{-3}
400	1.57×10^{-3}	2.14×10^{-3}
500	4.65×10^{-4}	5.85×10^{-4}
600	5.06×10^{-4}	6.22×10^{-4}
700	3.82×10^{-4}	4.85×10^{-4}
800	3.12×10^{-4}	3.85×10^{-4}
900	4.70×10^{-5}	5.38×10^{-5}
1000	8.34×10^{-5}	9.11×10^{-5}
1100	4.49×10^{-5}	4.78×10^{-5}
1200	4.70×10^{-6}	5.04×10^{-6}
1300	3.85×10^{-5}	4.09×10^{-5}

- **The upper limit at the 95 % confidence level provided by this analysis using the binned likelihood technique described.**
- The magenta line represents the upper limit when all systematic uncertainties are considered.