Direct Searches of New Physics Particles with BABAR

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On behalf of the BABAR Collaboration

25th International Workshop on Weak Interactions and Neutrinos (WIN2015)
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Outline

- Search for a dark photon PRL113, 201801 (2014)
- Search for long lived particles PRL114, 171801 (2015)
- Search for a low mass Higgs boson PRD 91, 071102 (2015)

with BABAR 

Motivation

With the ~125 GeV/c^2 Higgs scalar, the Standard Model (SM) particle contents might be complete.

However, big Beyond Standard Model (BSM) questions remain :

***Dark matter**, Neutrino masses,*

Baryon Asymmetry in the Universe, Inflation, Dark Energy

There are intriguing cosmic observations: *Pamela, Fermi, AMS2…*

Could there be a hidden sector at low energy?

A flurry of models include: Portals/new effective scales:

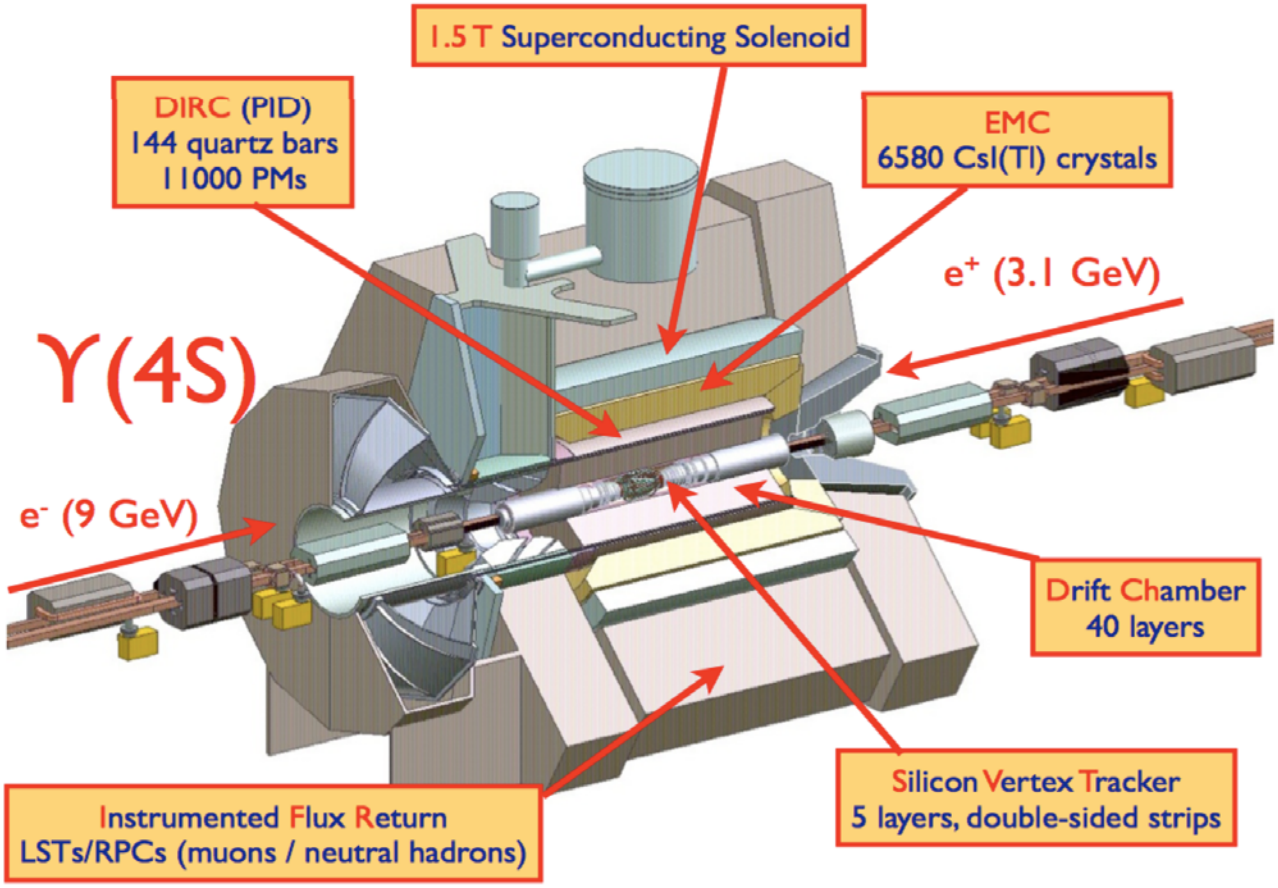
Vector, Scalar, Neutrino, axion-like…

An emerging experimental field at accelerators (colliders, beam dumps)

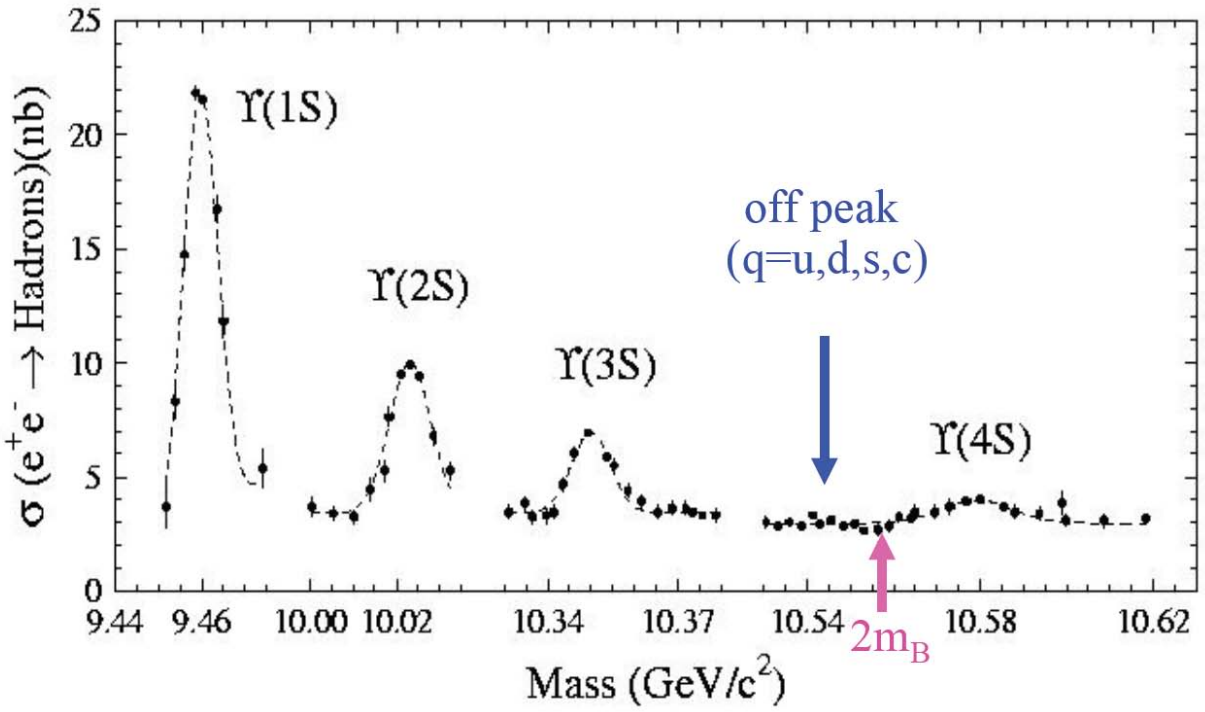
- Today: recent results from BABAR at PEP-II

Nucl.Instrum.Meth. A479 (2002)
Nucl.Instrum.Meth.A729 615 (2013)

The *BABAR* Experiment



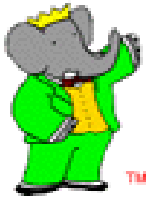
Datasets



- A' and L searches on full data sample

514 fb^{-1} (of 531.34 fb^{-1})

- A^0 search on the narrow resonances
  - ➢ inclusive
  - ➢ tagged



18 M ← 99 M ← 122 M 471 M events

+ 5 M

$\pi\pi$ transitions

Dark photon A′ (or U boson)

PRL113, 201801 (2014)

L=514 fb^{-1}

Dark Sector

- Gauge boson of new U(1)' the A', with MeV-GeV mass

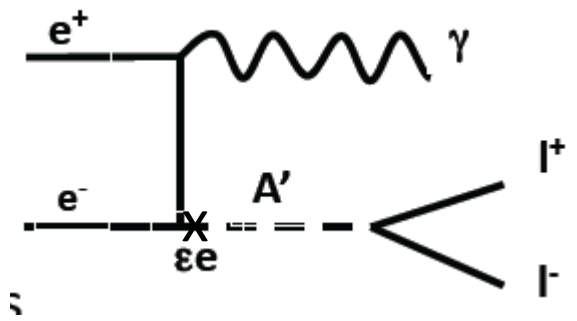
  P. Fayet PLB 95, 285(1980)

- Kinetic mixing with γ, A' couples to electric charge with strength εe
- A' couples to **dark sector particles**
- *Unexplained cosmic ray observations*
- *Impacts g-2 puzzle*
- Dark higgs h' expected

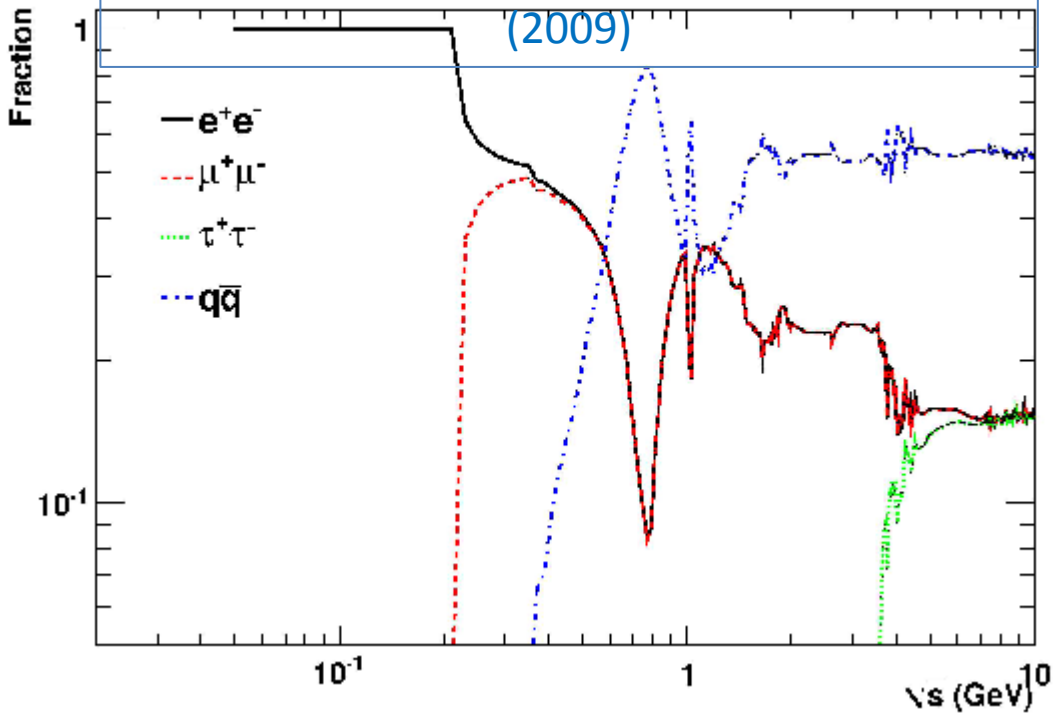
Recent review with references: R. Essig et al. arXiv: 1311.0029 [hep-ph]

Dark photon

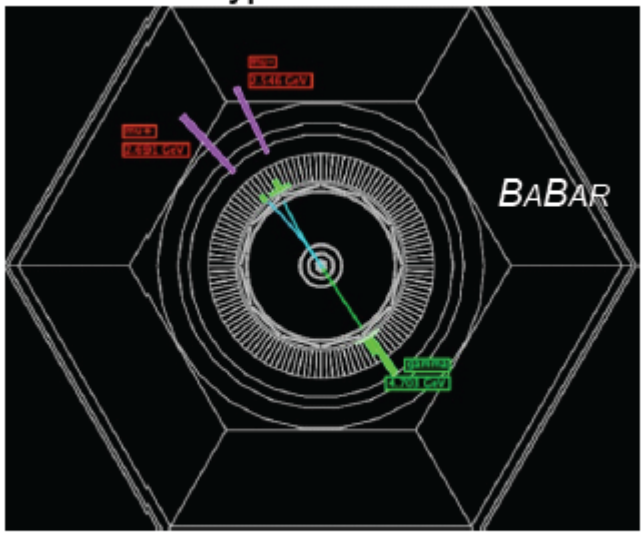
- photon → A'; $\alpha \rightarrow \varepsilon^2\alpha$. A' narrow
- look for narrow resonance produced in e^+e^-, decaying to 2 leptons $A' \rightarrow e^+e^-, \mu^+\mu^-$



R. Batell, M. Pospelov, A. Ritz, PRD 79 115008 (2009)



Typical event



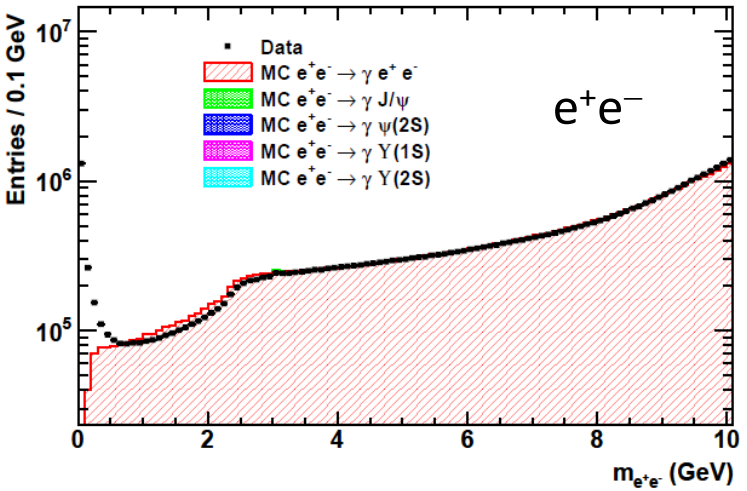
Tracks
Photon
Signal in muon/hadron detector

A′ → e^+e^-, $\mu^+\mu^-$

PRL113, 201801 (2014)

Event selection

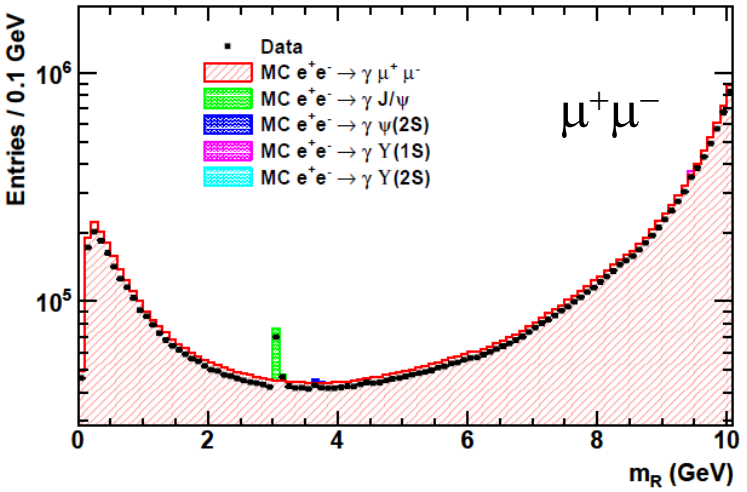
- 2 tracks + 1 photon with E_{cm}>200 MeV
- 1 (e) or 2 (e,μ) track(s) positively identified
- Kinematic+ geometric fit
- MVA to remove conversions (e)



Measurement (blind analysis)

- Final sample with radiative Bhabha's + μμγ + narrow resonances
  - Correction to model the remaining conversions
- Extract cross section with fits over sliding windows covering

0.02 (e), 0.212 (μ) < $m_{A'}$ < 10.2 GeV

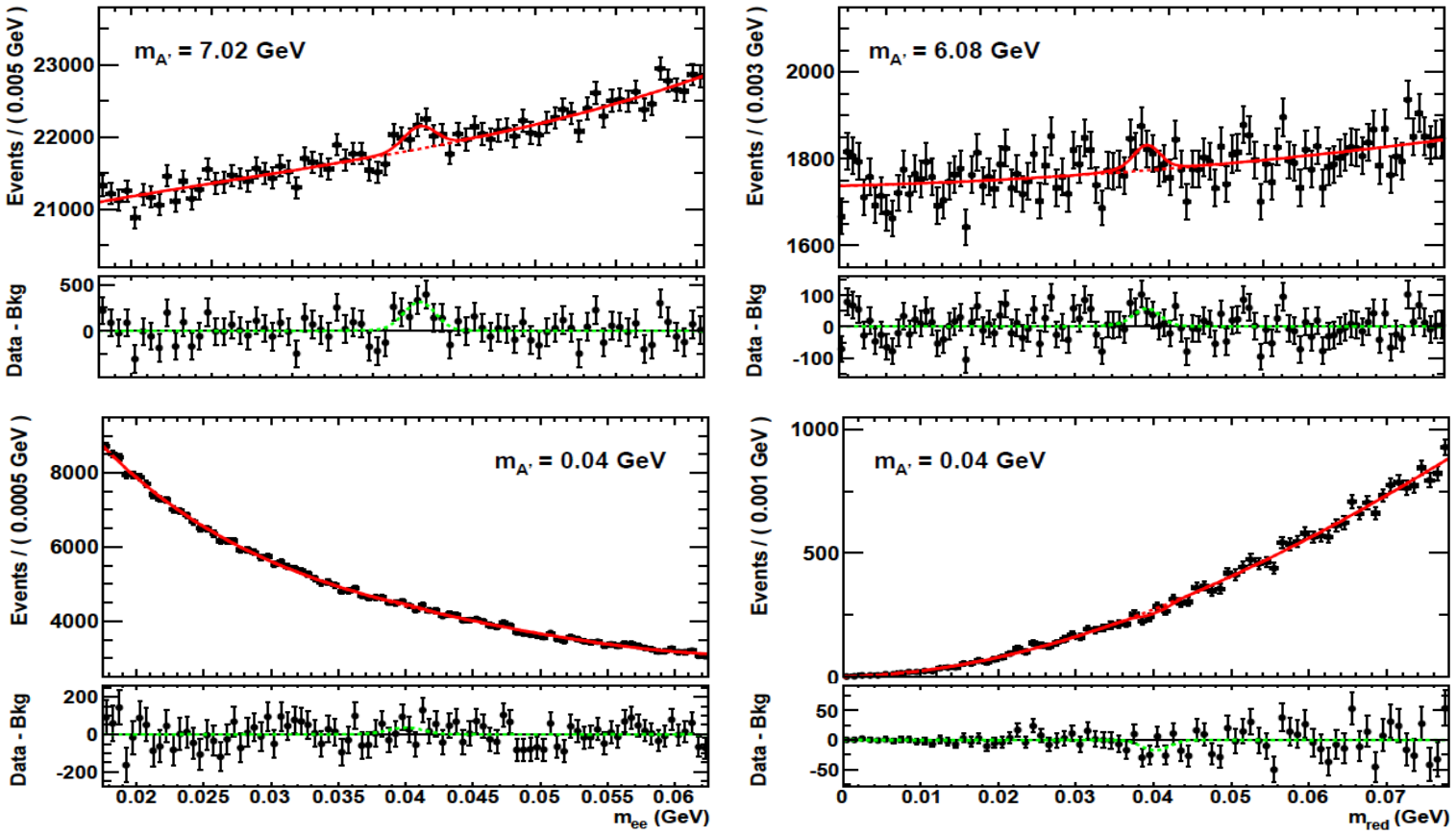


$A' \rightarrow e^+e^-, \mu^+\mu^-$

PRL113, 201801 (2014)

Fit window size >> signal width, << total mass range. Hence, we can use a polynomial$^+$ background shape to obtain an optimal signal to background ratio.

A few scan points:



$A' \rightarrow e^+e^-, \mu^+\mu^-$

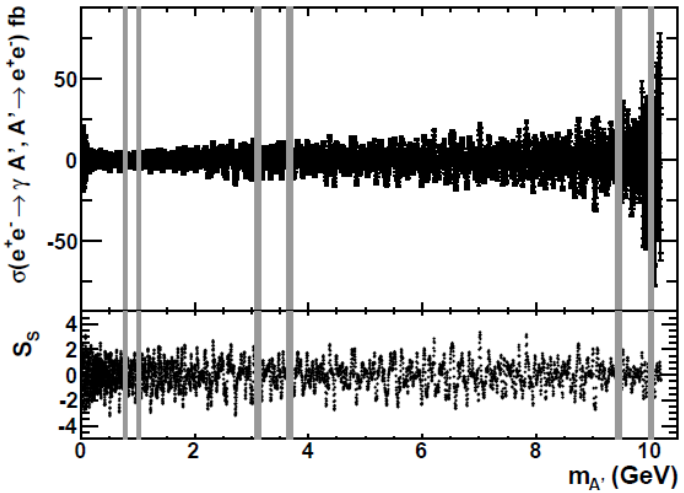
PRL113, 201801 (2014)

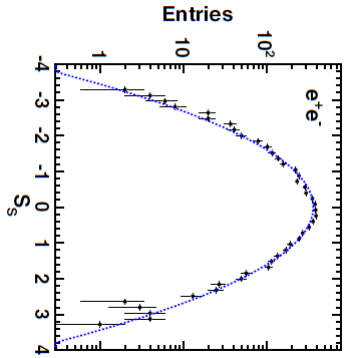
- Highest fluctuations

  - 3.4 σ (e) M=7.02 GeV
  - 2.9 σ (μ) M=6.09 GeV
    p-values=0.57, 0.94
    including trial factors.

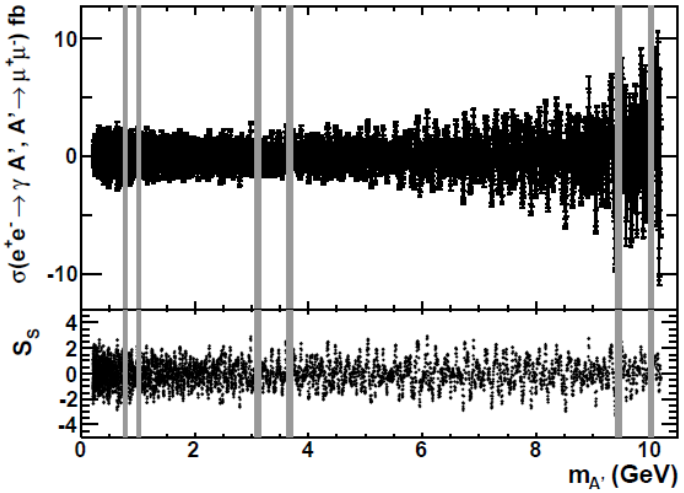
- Bayesian 90% C.L. upper limits ~ 1 to 10 fb

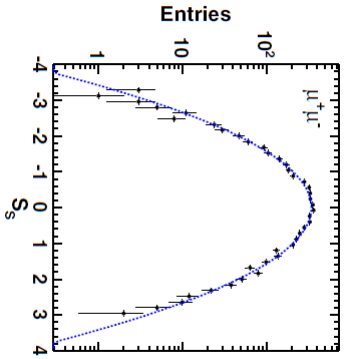
- used to derive 90% u.l. on ε.





5704 trials

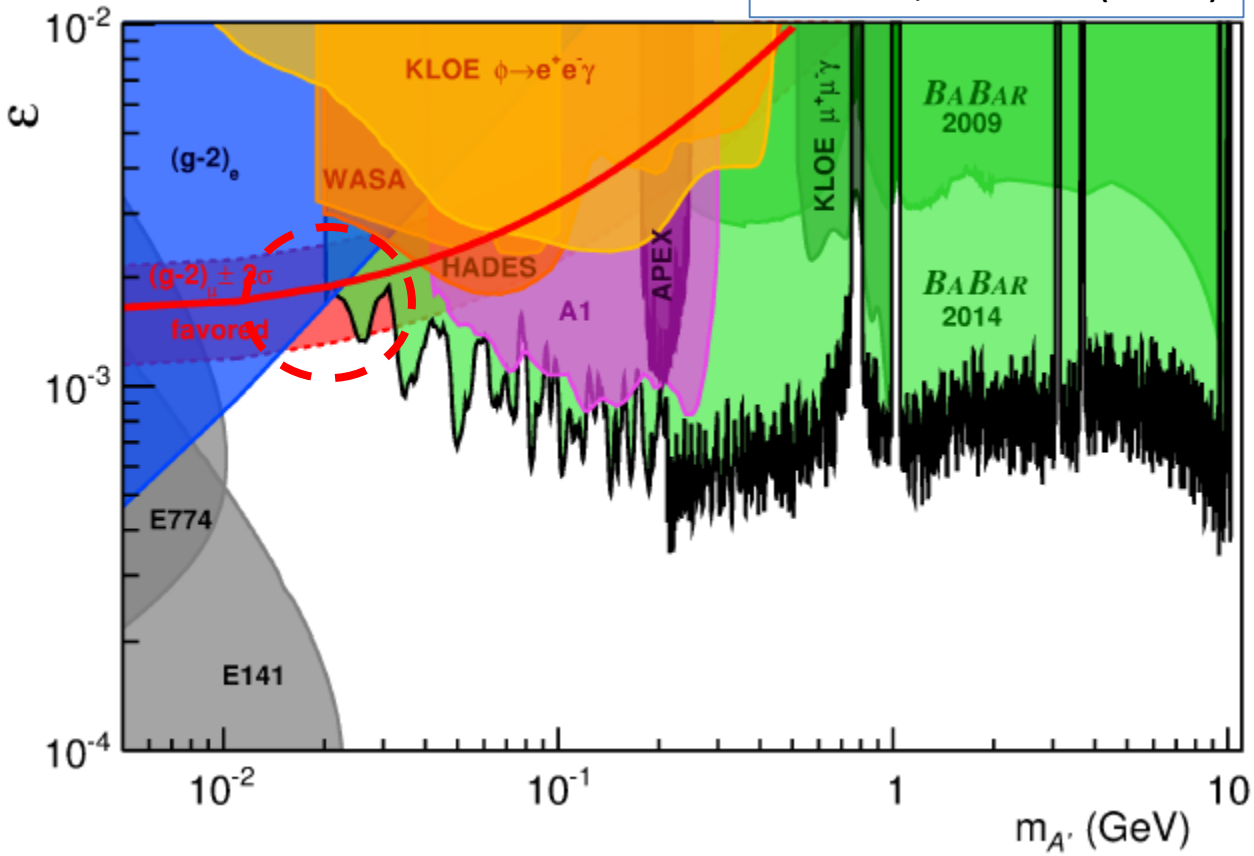




5370 trials

Dark photon Impact

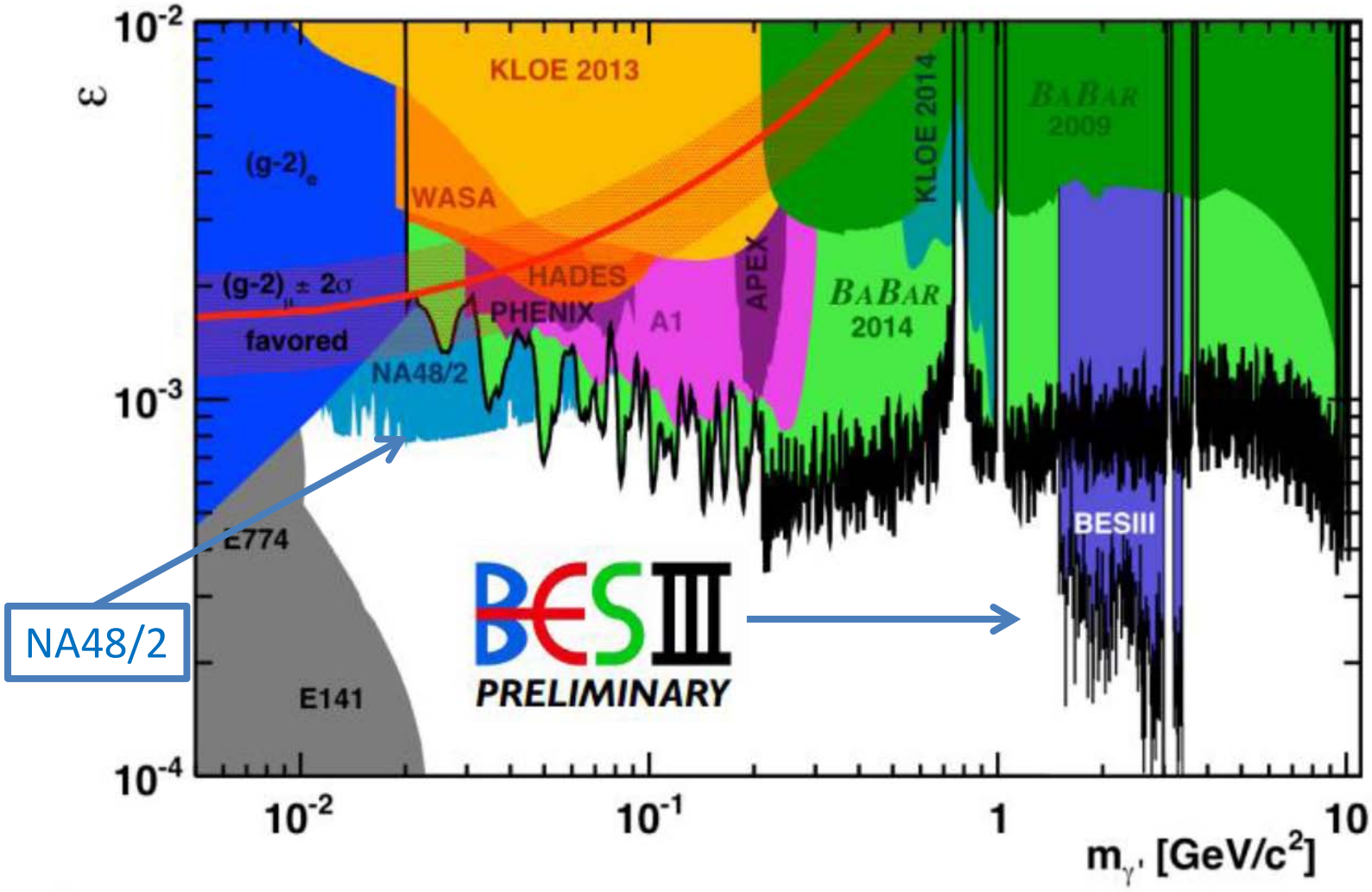
PRL113, 201801 (2014)



- BABAR all inclusive search in $e^+e^- \to \gamma$ A' has improved the constraints by an order of magnitude in the relevant mass range $0.2 < m_{A'} < 10$ GeV/c^2.
- Parameter space for A' causing g-2 effect is now restricted to $15 < m_{A'} < 35$ MeV

Dark photon Impact:

update at CHARM2015/FPCP (courtesy B. Echenard)



Search for long lived particles

PRL114, 171801 (2015)

L(4S) = 404 fb^{-1} N(4S) = 448 $\times 10^6$ events
(below) 44 fb^{-1}
[+ (4S) 20 fb^{-1} validation]

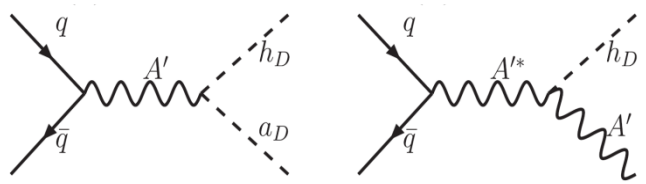
L(3S) = 28 fb^{-1} N(3S) = 121 $\times 10^6$
L(2S) = 14 fb^{-1} N(2S) = 98 $\times 10^6$

Motivation

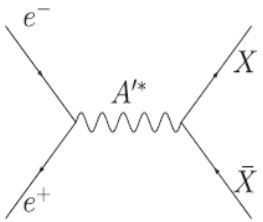
At the B factories LLP could come via

- **Vector portal**

  Dark photon couples to light dark sector (pseudo) scalar/vector which could be long lived



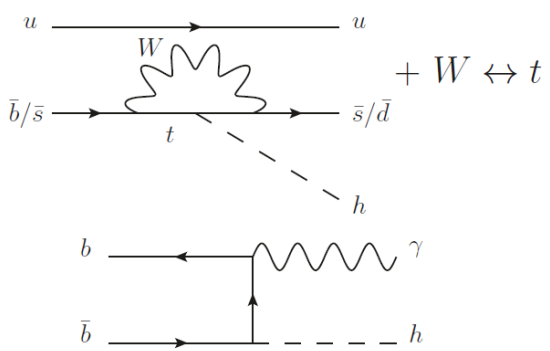
P. Schuster, N. Toro, I. Yavin, PRD 81, 016002 (2010)

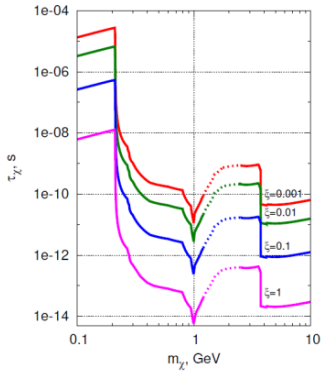


R. Essig, P. Schuster, N. Toro, PRD 80, 015003 (2009)

- **Scalar portal**

  $h_{(D)}$ mixing with H





J.D. Clarke, R. Foot, R. Volkas, PRD 80, 015003 (2009)
F. Bezrukov, D. Gorbunov JHEP 1307 (2013) 140

Inflaton

Method

- Search in e+e- collisions for **L**
  - Long lived
  - Neutral
  - with 2-body charged decays **L** $\rightarrow$ f, f=

    e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$, $\pi^+\pi^-$, K^+K^-, $\pi^\pm K^\mp$

- Presented in 2 ways
  - (MI) Model independent
  - (MD) B $\rightarrow X_s$ **L**

➢ Displaced vertex

➢ Peaks in V invariant mass

Upper limits vs m of

➢ $\sigma(e+e \rightarrow \mathbf{L}) \times BF(\mathbf{L} \rightarrow f) \times \varepsilon(f)$

at or near Y(4S), at Y(2S,3S)

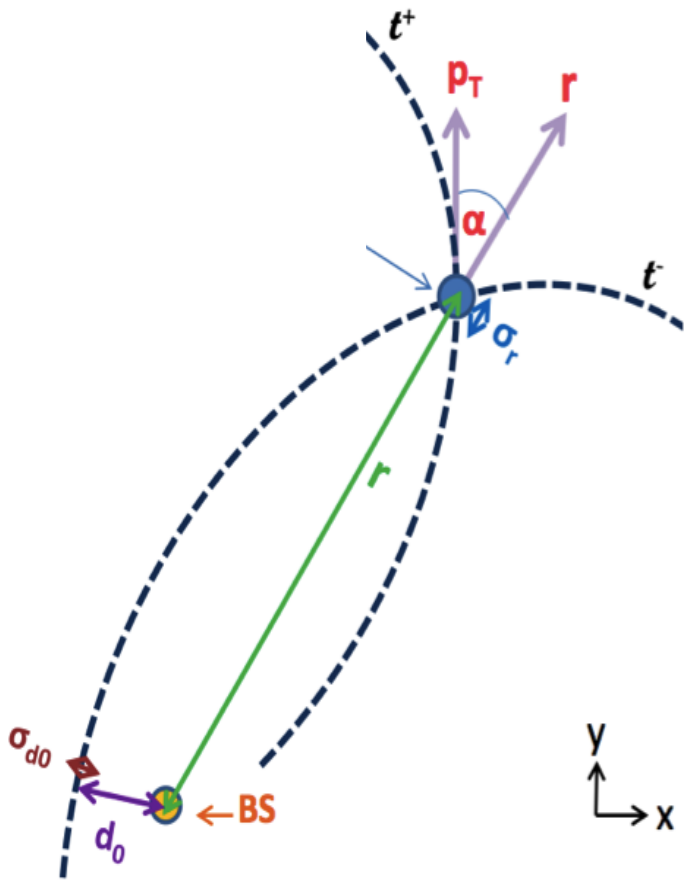
giving tables of $\varepsilon(m, p_t, c\tau)$

➢ $BF(B \rightarrow X_s \mathbf{L}) \times BF(\mathbf{L} \rightarrow f)$

Supplement to PRL114, 171801 (2015)

Selection

- Select x^+x^- pair
  - *Loose* particle identification , allowing reuse
- $d_0 > 3\ \sigma(d_0)$
- Vertex at *r* from beamspot
  - $\chi^2<10$
  - $1<r<50$ cm, $\sigma_r<2$cm
  - away from material
  - $\alpha< 0.01$ rad
  - $\sigma_m<0.2$ GeV/c^2
- No upstream hit on tracks
- Remove Λ, K_S candidates (mass)



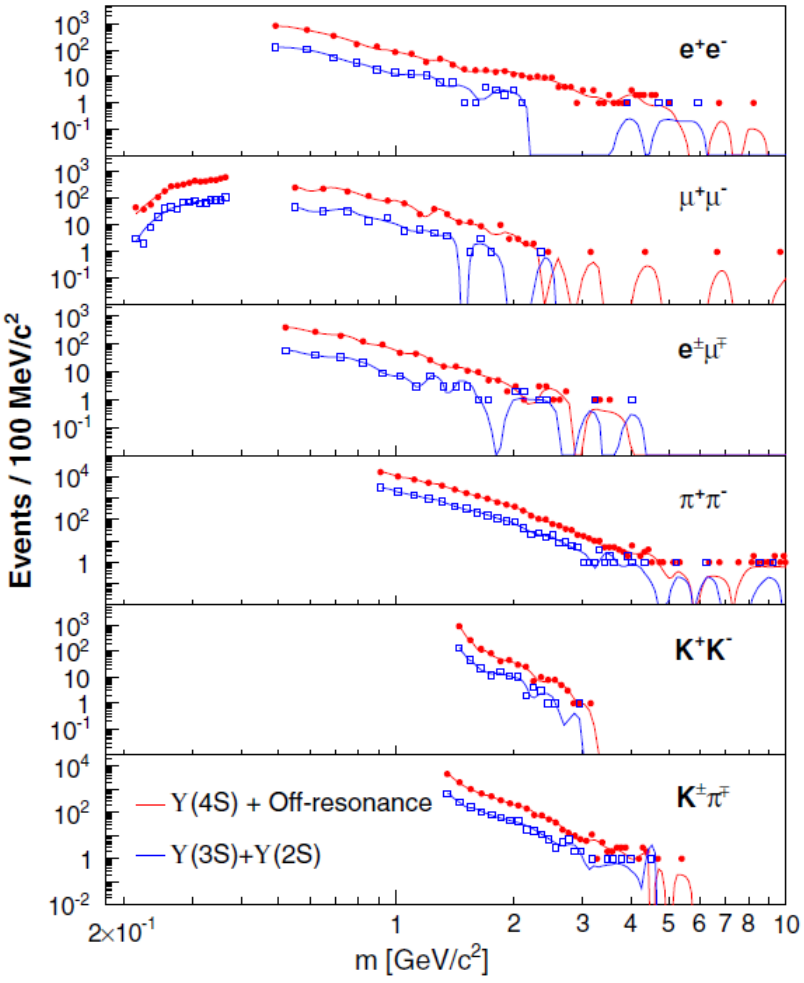
- ε_{max}=52% for f=$\pi\pi$ with m=2GeV/c^2, cτ=6cm and p_t>4GeV/c
- main background: random pairs of high d_0 tracks from Λ, K_S and K/π decays in flight

Signal extraction

PRL114, 171801 (2015)

For each mode & each data sample, perform unbinned likelihood fits, scanning the mass range in 2 MeV/c^2 steps.

- Fit background on data assuming no peak.
- Signal PDF has the MC mass resolution shape, scaled to the measured rms.
- σ_m from 6 to 180 MeV/c^2 across the range.
- Significance: $S = \mathrm{sgn}(n_s)\sqrt{2Ln\frac{L(s+b)}{L(b)}}$ <3 except for 2 scan points in Y(4S) sample
  - One consistent with γ conversion,
  - The other is not significant, when accounting for the *look elsewhere effect*.

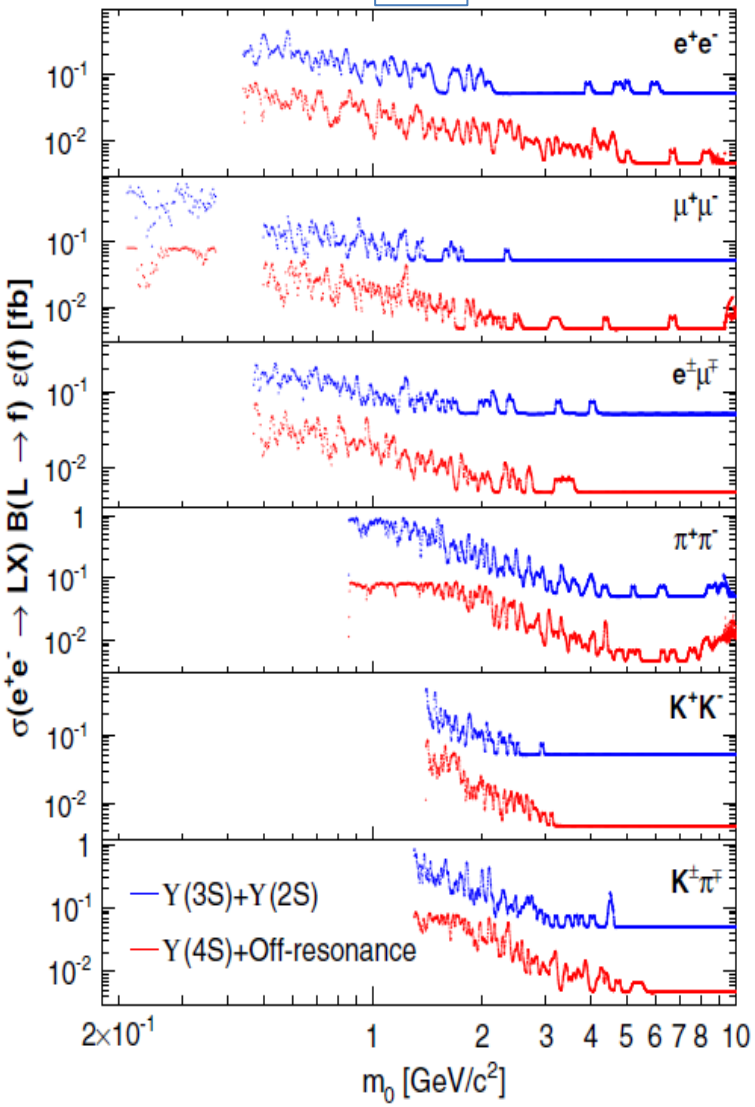


90% c.l. Bayesian U.L. including systematics (mainly background PDF)

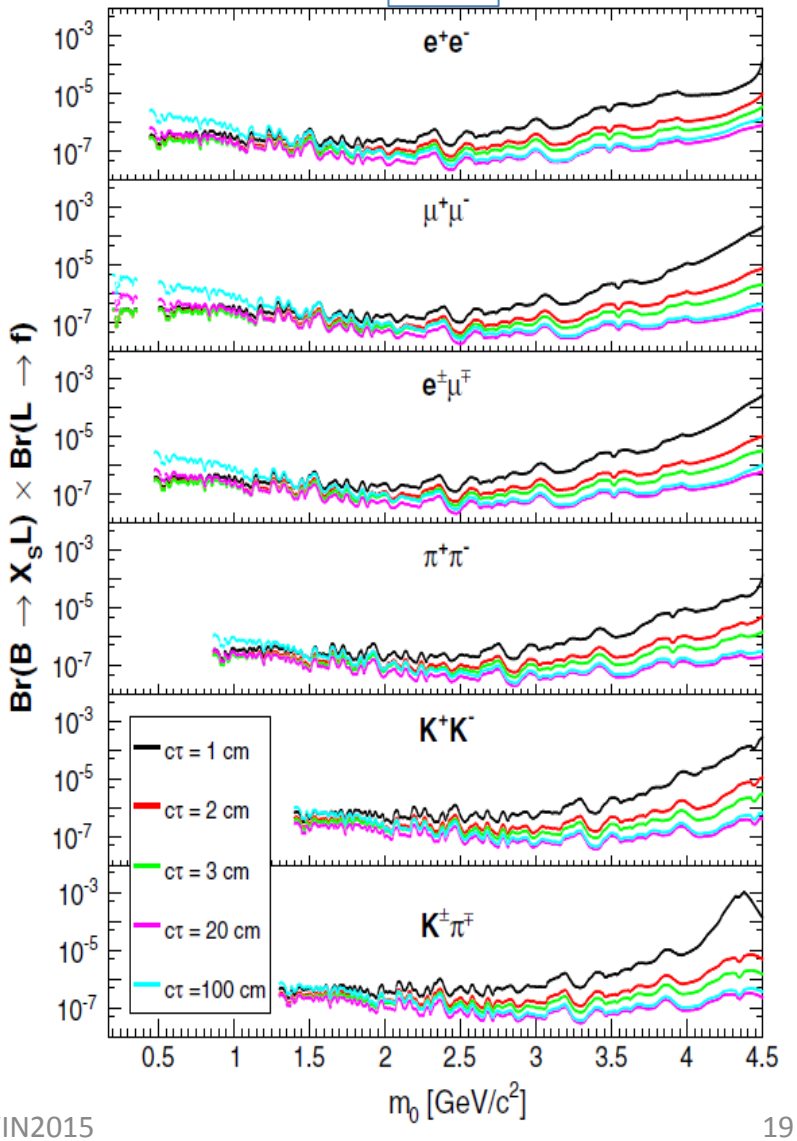
Results

PRL114, 171801 (2015)

MI



MD



Search for light Higgs particles

PRD 91, 071102 (2015)

L(2S) = 14 fb^{-1}

L(below) = 1.4 fb^{-1}.

N(2S) =98 $\times$ 10^6 events,

N(2S$\rightarrow\pi^+\pi^-$1S) =18 $\times$ 10^6 events.

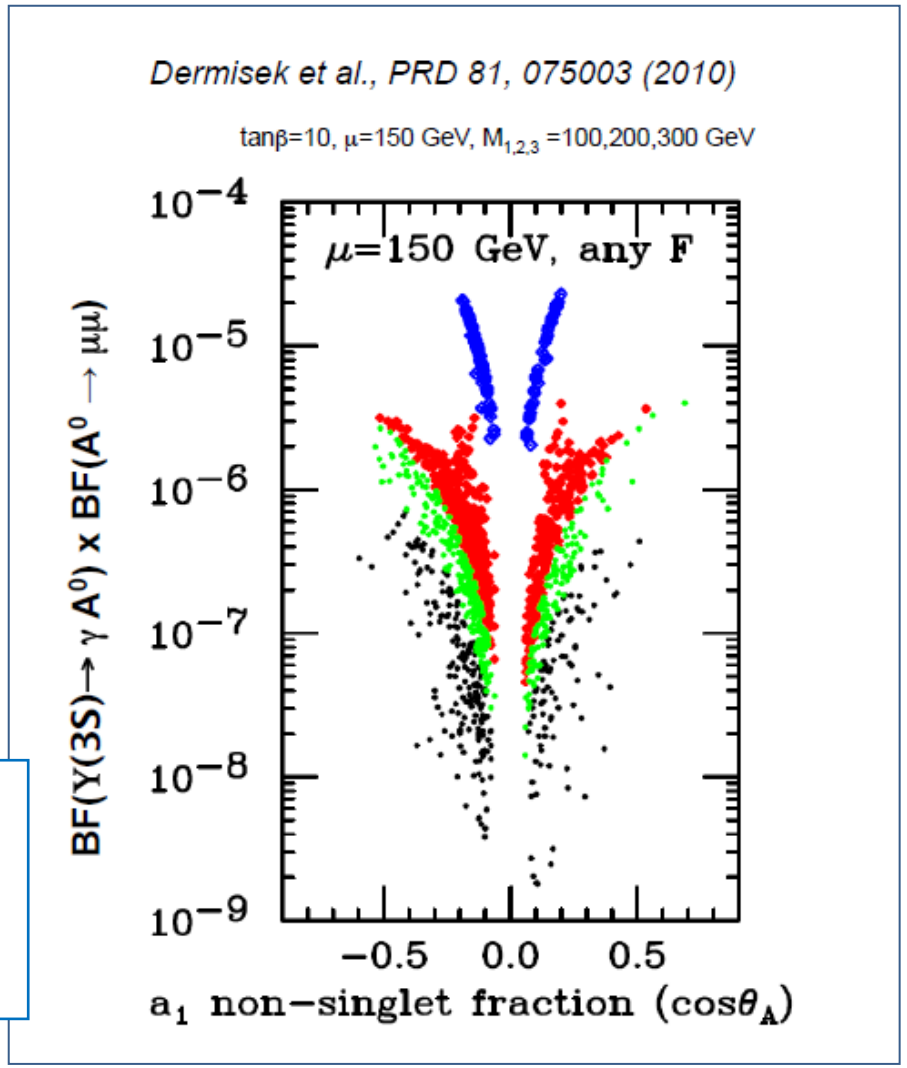
CP-odd Higgs in NMSSM

- $\Upsilon \rightarrow \gamma A^0$, $A^0 \rightarrow \bar{f}f$, gg
- $A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_{singlet}$
- Predicted BF depend on

  $\cos\theta_A$, $\tan\beta$, m_{A0}

  ➢ Scans of e.g.

  $BF(\Upsilon \rightarrow A^0)\, BF(A^0 \rightarrow \mu^+\mu^-)$
- Rate accessible to BABAR

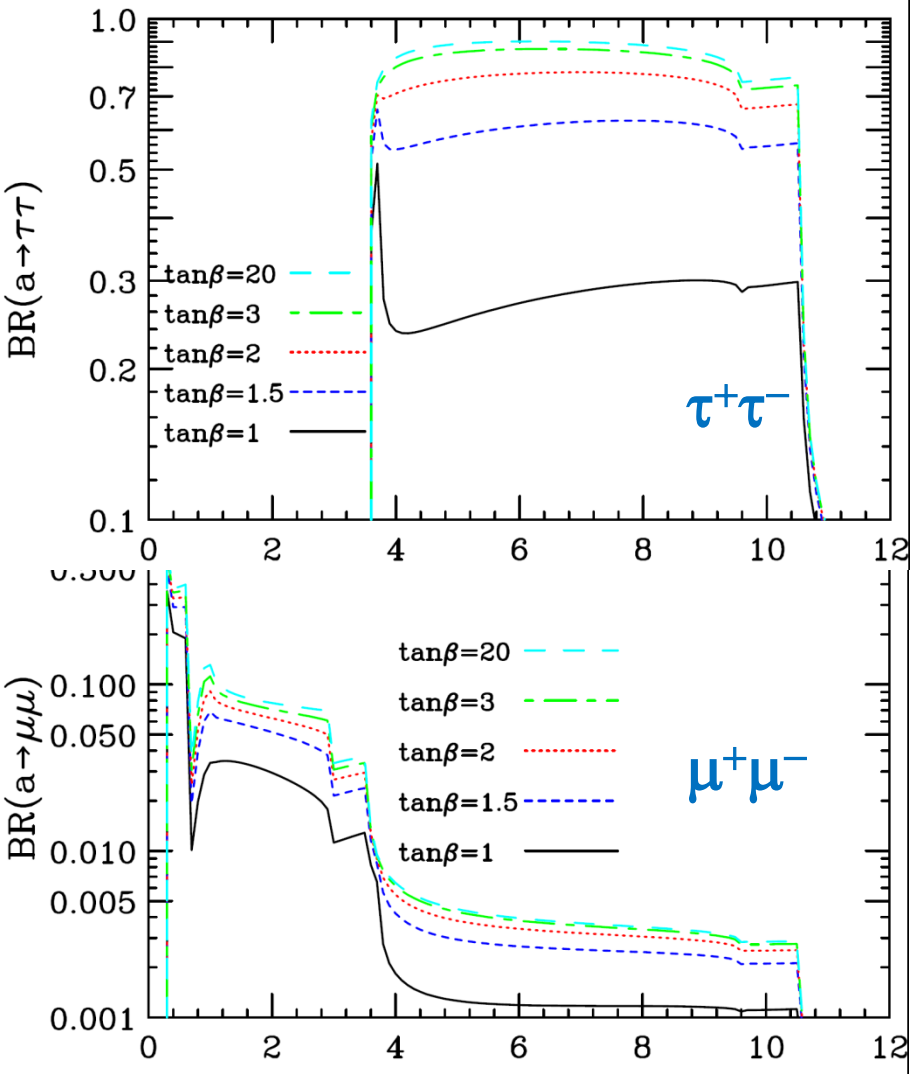


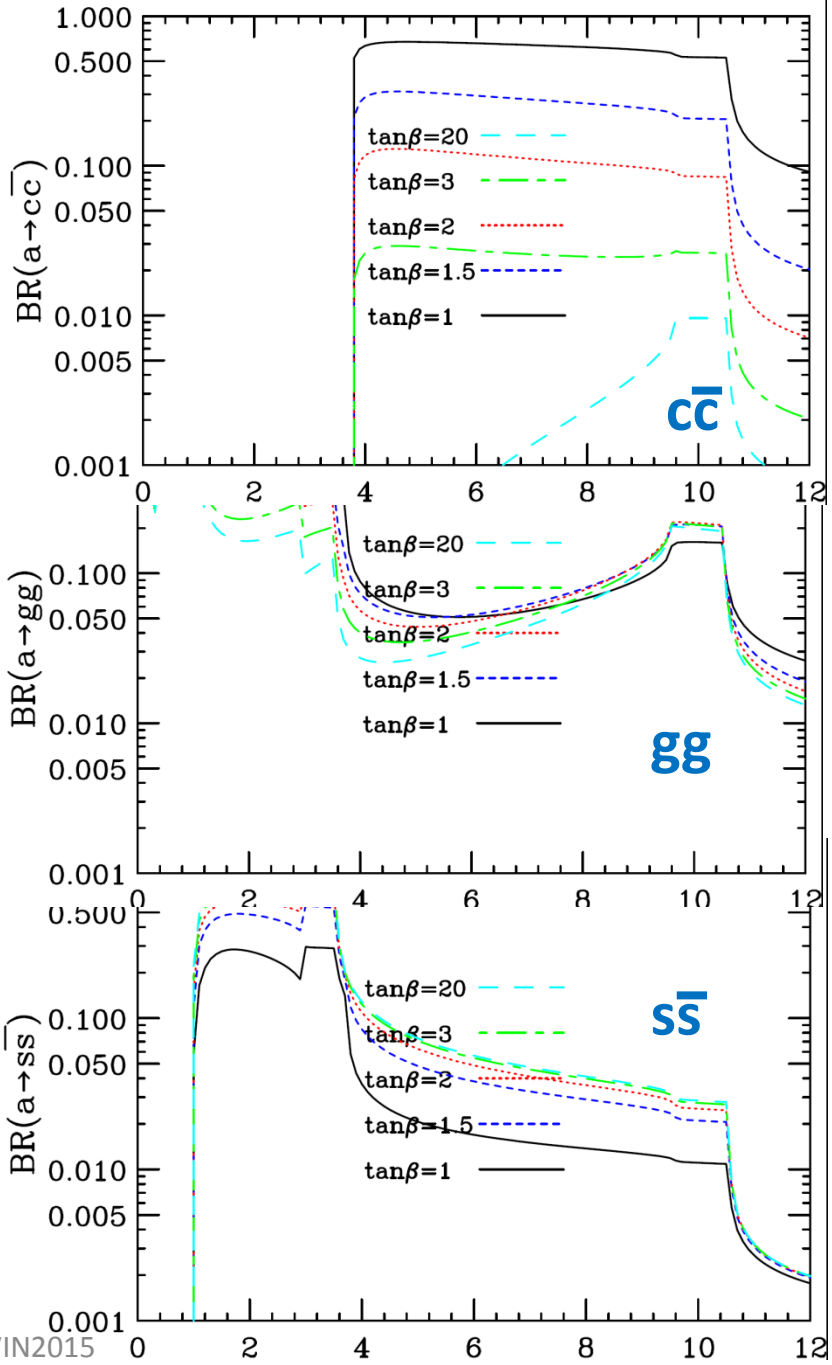
$0 < m_{A0} < 2m_\tau$
$2m_\tau < m_{A0} < 7.5$ GeV
$7.5 < m_{A0} < 8.8$ GeV
$8.8 < m_{A0} < 9.2$ GeV

A^0 branching fractions

sensitive to m_A, tanβ, fermion masses

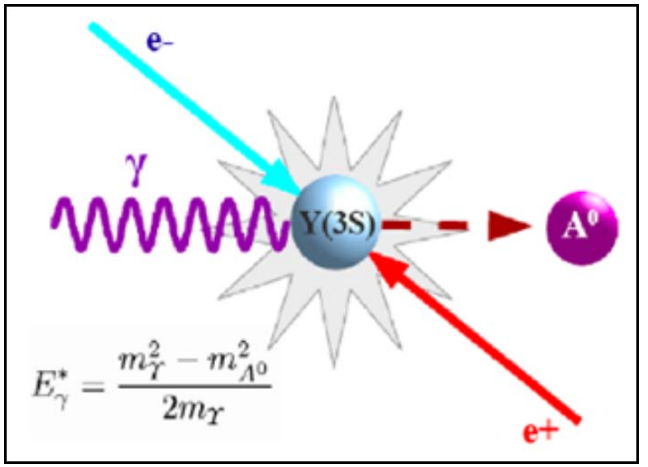
Dermisek et al., PRD81, 075003 (2010) Γ_{inv}=0 assumed

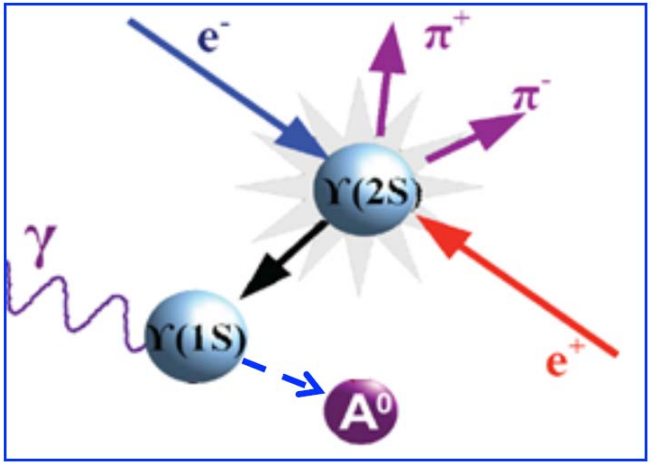




Searches at BABAR

Y(3S) → γ A^0, A^0 → invisible	arXiv:0808.0017 [hep-ex]
Y(3S) → γ A^0, A^0 → $\tau^+\tau^-$	PRL 103, 181801 (2009)
Y(2S, 3S) → γ A^0, A^0 → $\mu^+\mu^-$	PRL 103, 081801 (2009)
Y(2S, 3S) → γ A^0, A^0 → hadrons	PRL 107, 221801 (2011)
Y(1S) → γ A^0, A^0 → invisible	PRL 107, 021804 (2011)
Y(1S) → γ A^0, A^0 → $\mu^+\mu^-$	PRD 87, 031102 (2013)
Y(1S) → γ A^0, A^0 → $\tau^+\tau^-$	PRD 88, 031102 (2013)
Y(1S) → γ A^0, A^0 → gg,ss	PRD 88, 031701 (2013)
Y(1S) → γ A^0, A^0 → cc	**PRD 91, 071102 (2015)**



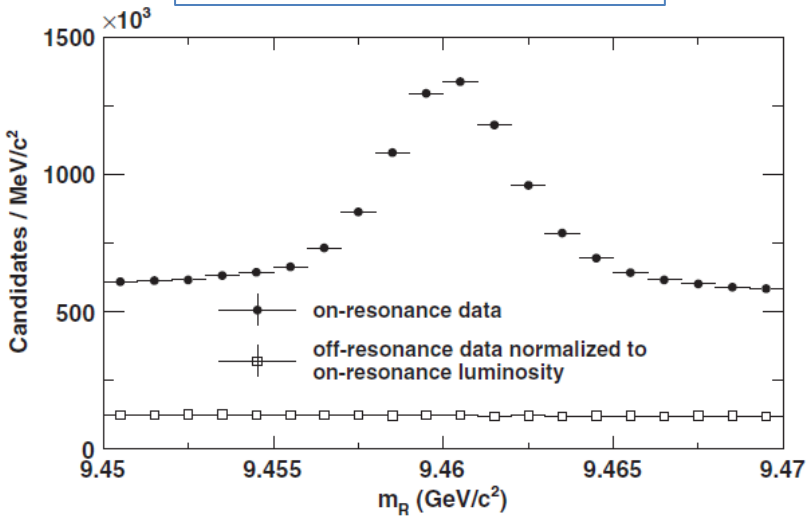


$\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow c\bar{c}$

PRD 91, 071102 (2015)

- Event selection

- 2 tracks (dipion), 1 photon, hadronic system (cc->D+X)
- Missing mass consistent with Y(1S)
- 5 (charm) × 2 (m) BDT to discriminate signal from background



Charm tag:

1. $D^0 \rightarrow K^- \pi^+$
2. $D^0 \rightarrow K^- \pi^+\pi^+\pi^-$
3. $D^0 \rightarrow K_S \pi^+\pi^-$
4. $D^+ \rightarrow K^- \pi^+\pi^+$
5. $D^{*+} \rightarrow \pi^+ D^0$, $D^0 \rightarrow K^- \pi^+ \pi^0$

Backgrounds:

- 1S → γgg
- 1S → X
- 2S → X
- qq continuum

- photon with E_{cm}>30 MeV
- Scan m_X

$$m_X^2 = (P_{e^+e^-} - P_{\pi^+\pi^-} - P_\gamma)^2$$

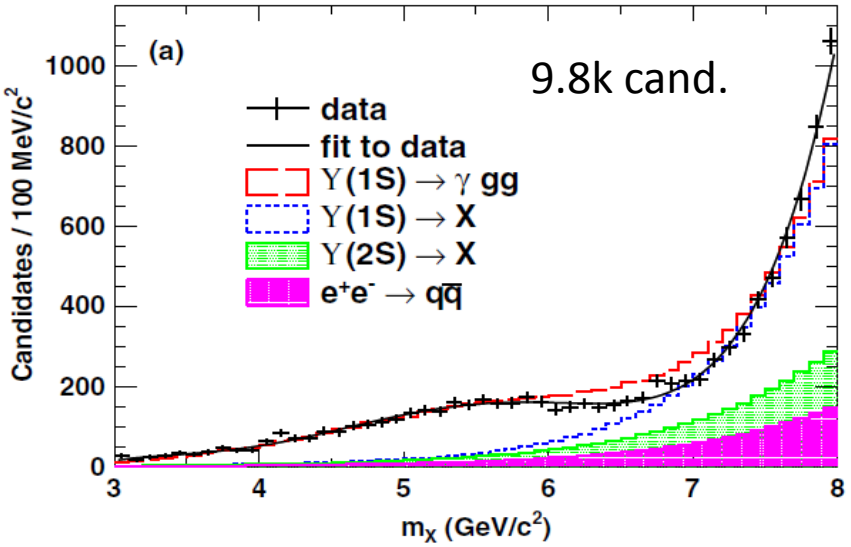
  - High mass [7.50 – 9.25] GeV/c2
  - Low mass [4.99 – 8.00]
- Exclude [8.95 – 9.10] to avoid $(2S \rightarrow \chi_b \rightarrow 1S)$ cascade

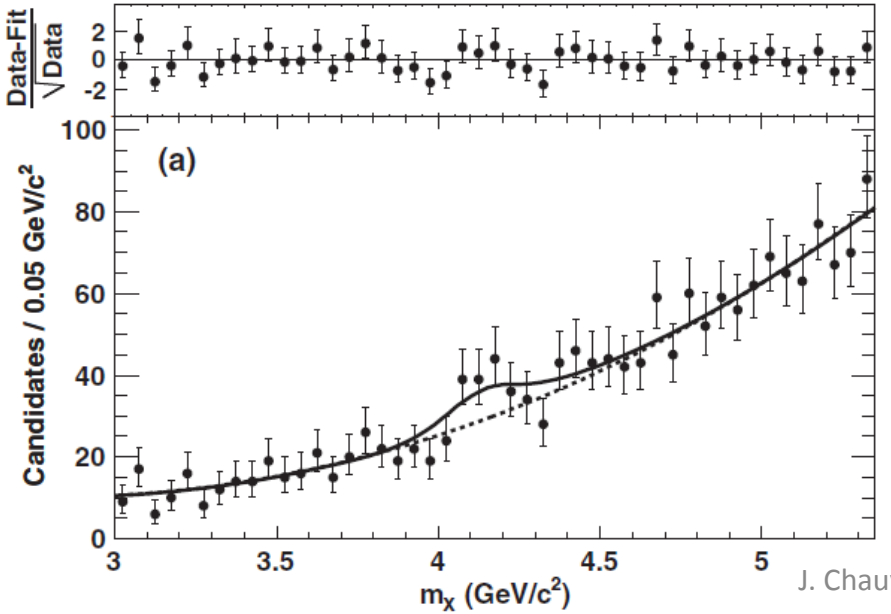
$\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow c\bar{c}$

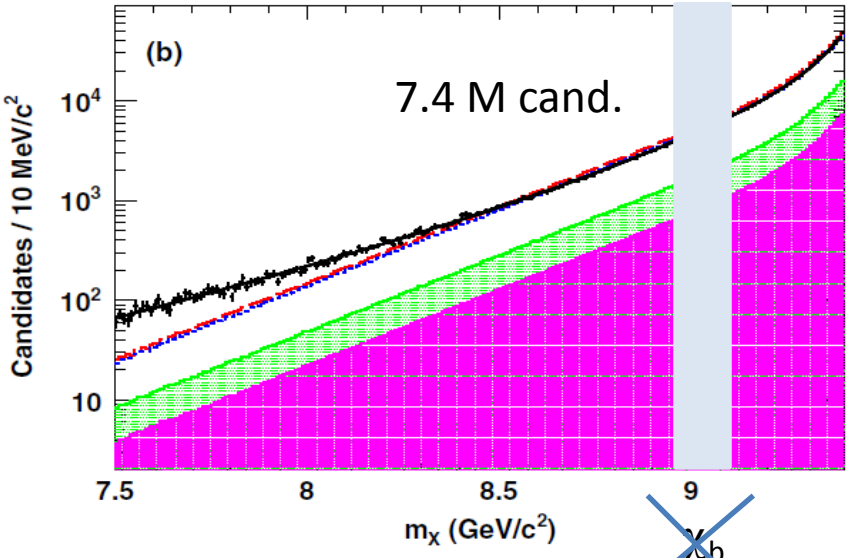
PRD 91, 071102 (2015)

Measurements

- background from global fits
- efficiency from 0.04 to 0.026 with ~10% systematics ($c\bar{c}$ hadronization dominant)
- resolution from 120 MeV to 8 MeV
- Local fits in ±10 resolution ranges
- steps < 0.3 resolution
  - signal PDF with fixed local parameters
  - background PDF 2nd order polynomial



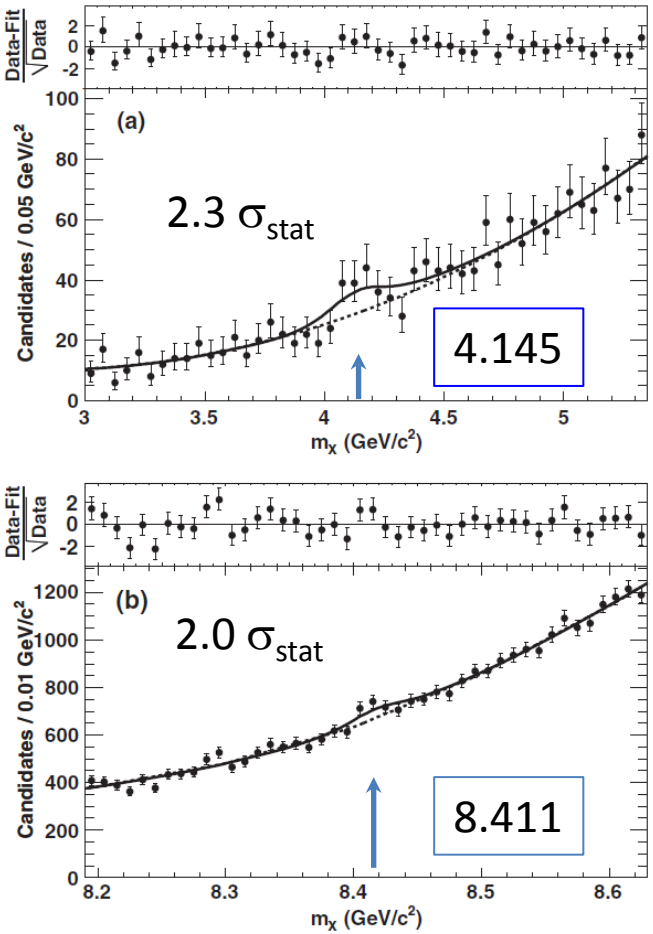


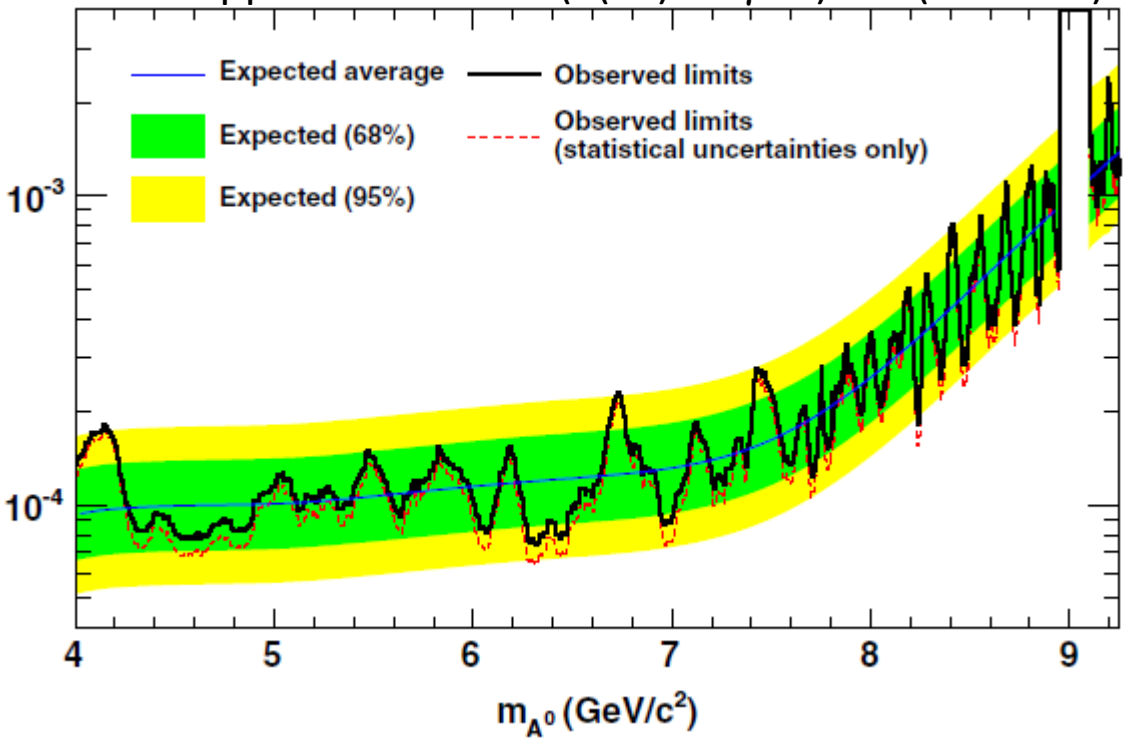


$\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow c\bar{c}$

PRD 91, 071102 (2015)

Biggest peaks are not significant . Derive 90% Upper Limits on BF($\Upsilon(1S) \rightarrow \gamma A^0$) $\times$BF($A^0 \rightarrow c\bar{c}$)





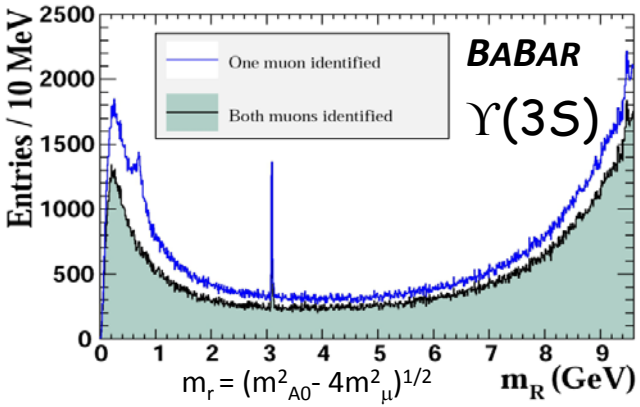
BF($\Upsilon(1S) \rightarrow \gamma A^0$) $\times$BF($A^0 \rightarrow c\bar{c}$) < [$7.4 \times 10^{-5} - 2.4 \times 10^{-3}$] at 90% c.l.

Summary and outlook

- **BABAR has made significant contributions to the emerging research on light hidden sector particles**
  - Pushing down limits on A' with ISR technique.
  - Ruling out a wide parameter space region for an NMSSM-like A^0 boson, exploring all accessible final states (most recently the $A^0 \to c\bar{c}$ channel).
  - Exploring generically the production of long lived neutral particles in e^+e^- collisions and B decays.
- **Further progress is expected from Intensity Frontier experiments**
  - e^+e^- machines: recently BES III, especially Belle-II.
  - Beam dump experiments: at electron (e.g. HPS) and proton (SHiP project).

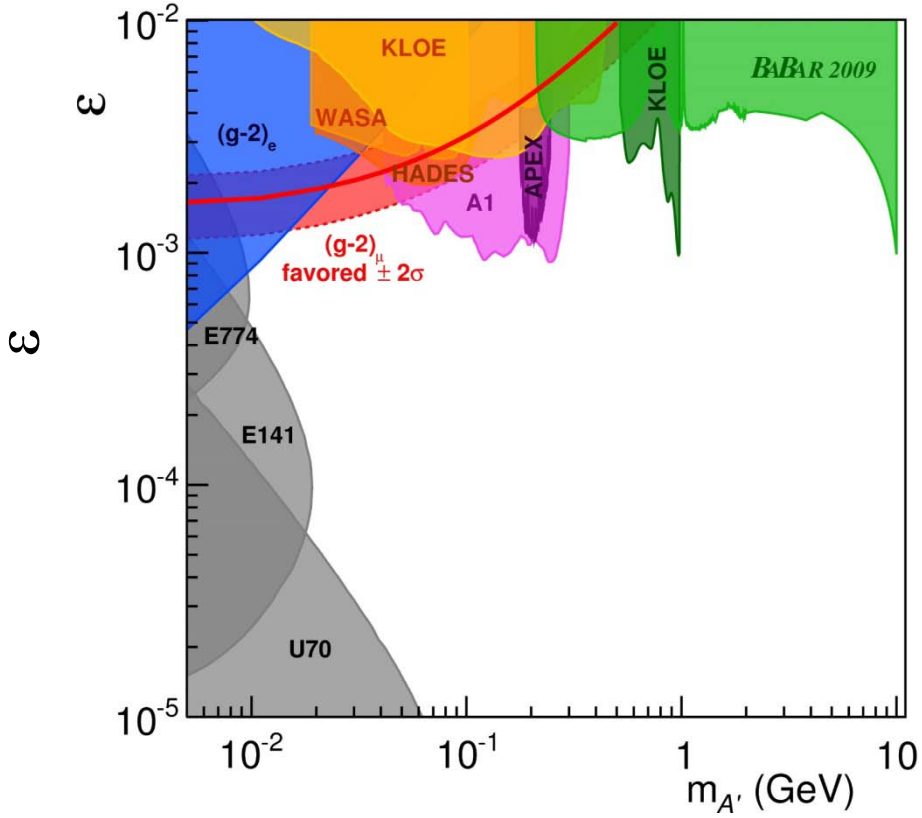
Backup

Dark photon (2)

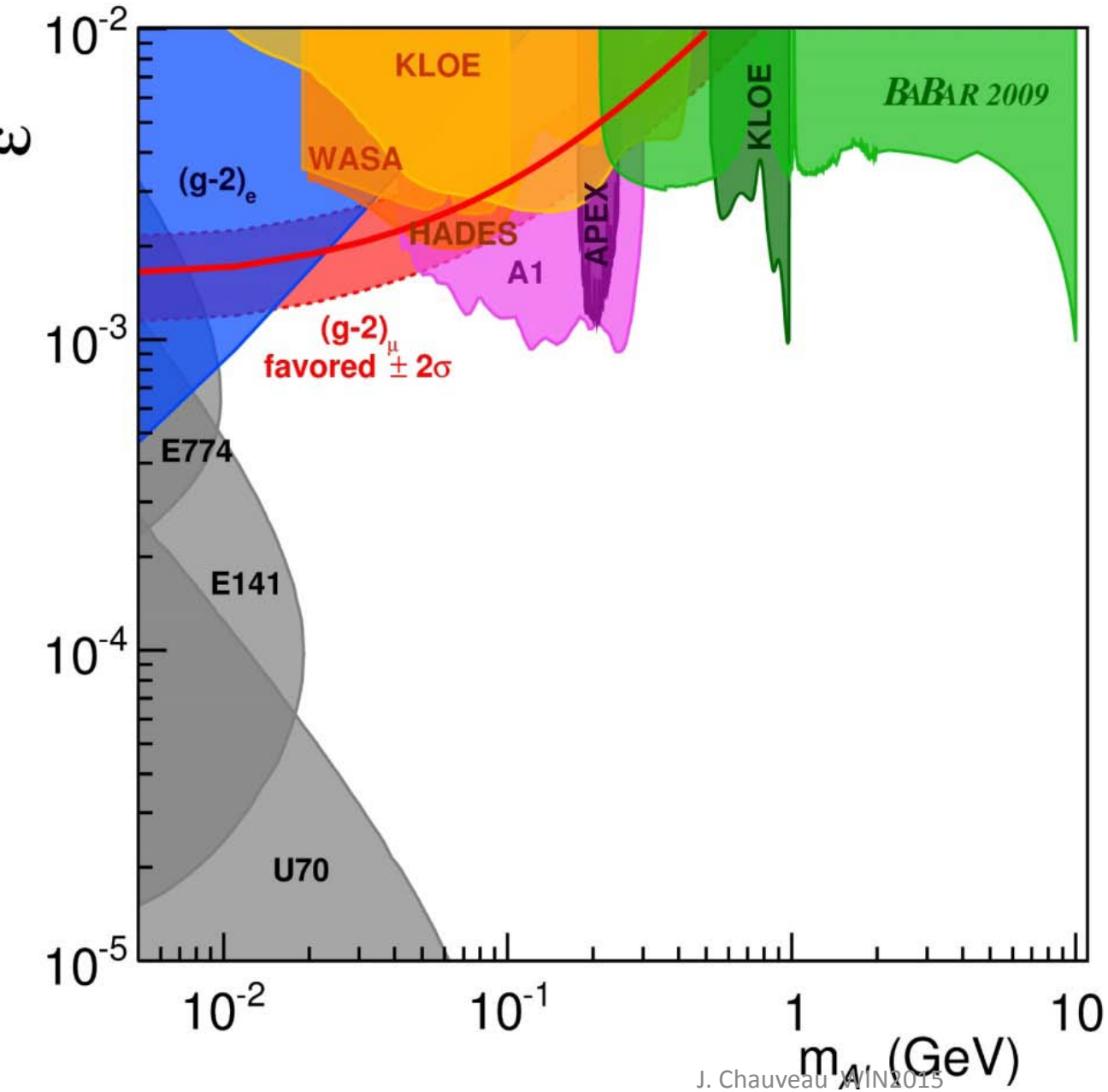


Early measurement: $A^0 - \mu\mu$ spinoff
No significant signal.

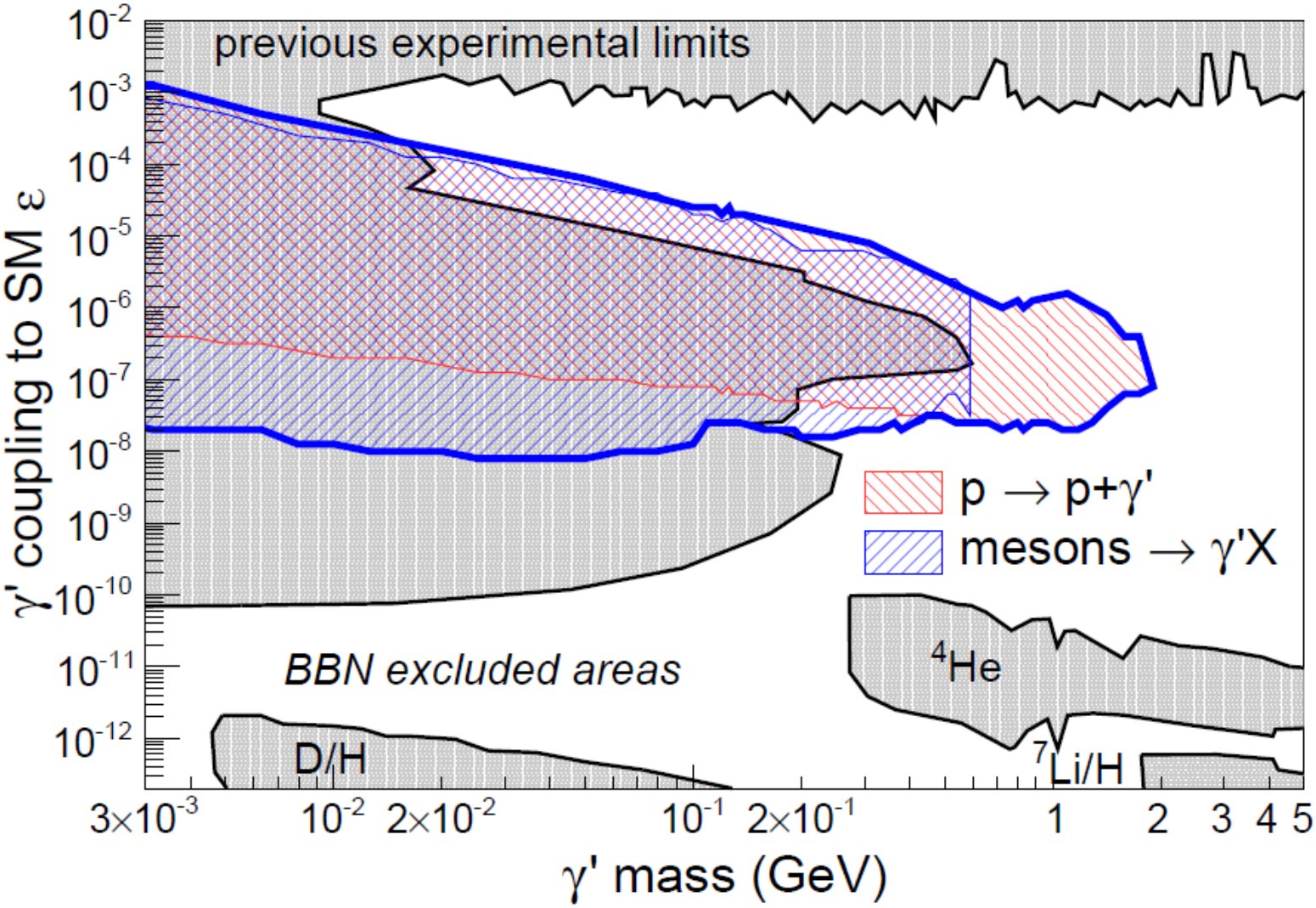
Constraints on ε vs. $m_{A'}$



Dark photon (5) Impact



SHiP


previous experimental limits
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
γ' coupling to SM ε
p → p+γ'
mesons → γ'X
BBN excluded areas
^{4}He
^{7}Li/H
D/H
3×10^{-3}
10^{-2}
2×10^{-2}
10^{-1}
2×10^{-1}
1
2
3
4
5
γ' mass (GeV)

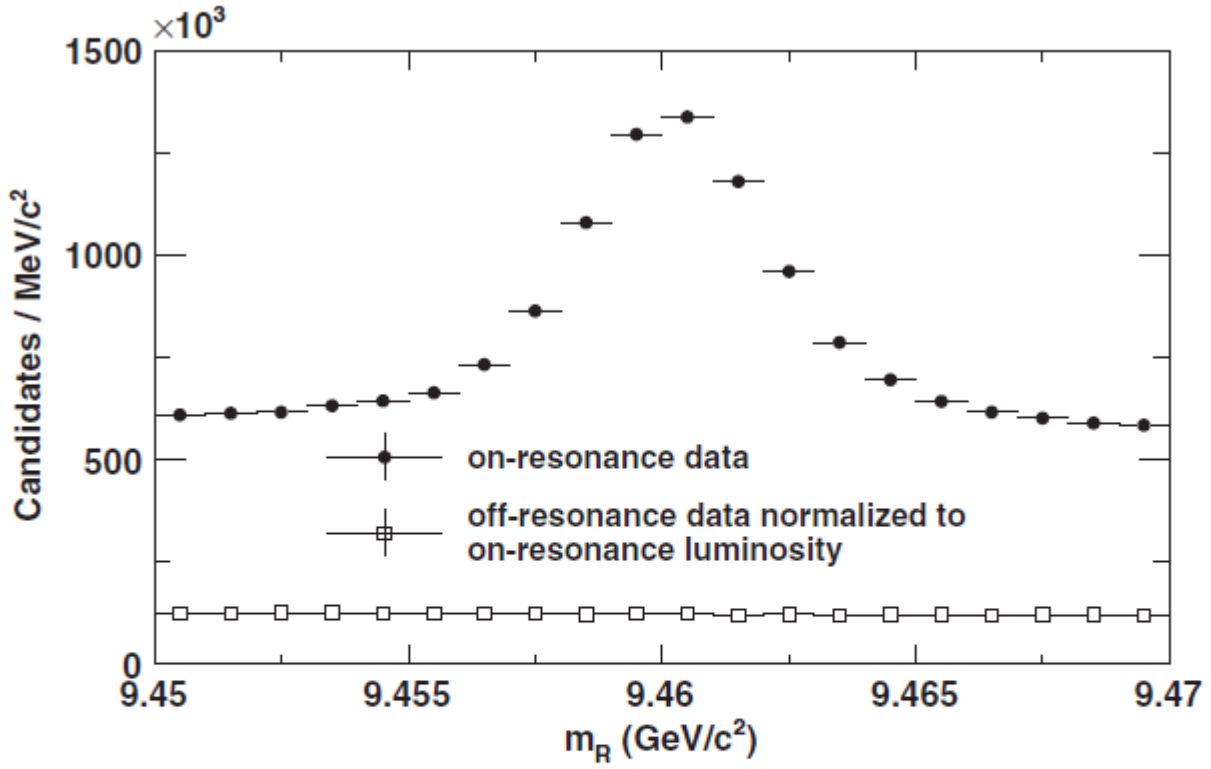


FIG. 1. The m_R distribution of events with a dipion, charm, and photon tag before application of selection criteria based on the BDT output (see text). The solid circles indicate the on-resonance data. The open squares indicate the off-resonance data normalized to the on-resonance luminosity.

Inflaton

F. Bezrukov, D. Gorbunov JHEP 1307 (2013) 140

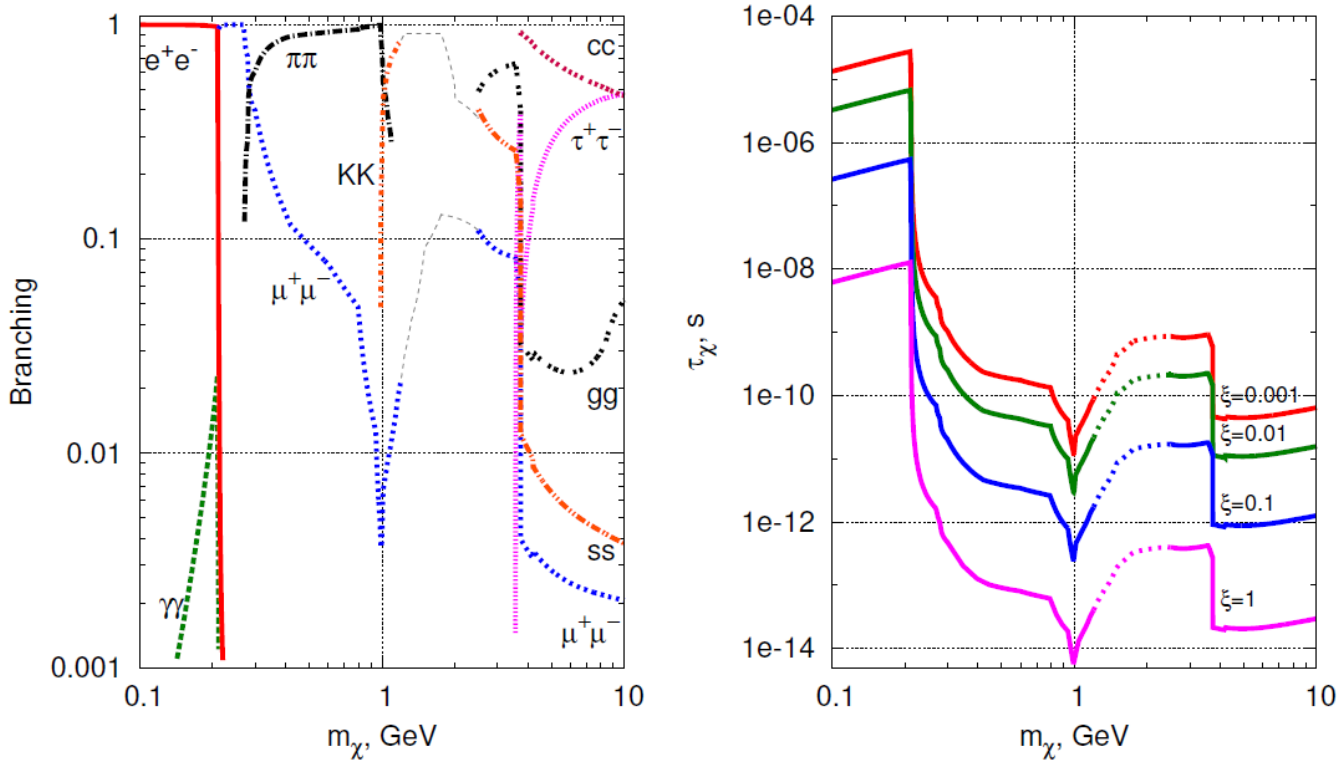


Figure 3: Inflaton decay branching ratios (*left plot*) and inflaton lifetime (*right plot*); theoretical predictions for $m_\chi \simeq 1 - 2\,\mathrm{GeV}$ (thin dashed lines on the *left plot* and dotted lines on the *right plot*) suffer from significant QCD-uncertainties.

Light CP-odd Higgs

- *Explore extended Higgs sector*
- NMSSM and other models come with light Higgs bosons
- Large BF predicted for radiative decays Y(nS) → γ A^0
- A^0 decays to ll, qq and gg
- And also A^0→ invisible (ν or **DM** or ??)

$Y(2S) \rightarrow \pi^+\pi^- Y(1S) \rightarrow \gamma A^0, A^0 \rightarrow ss, gg$

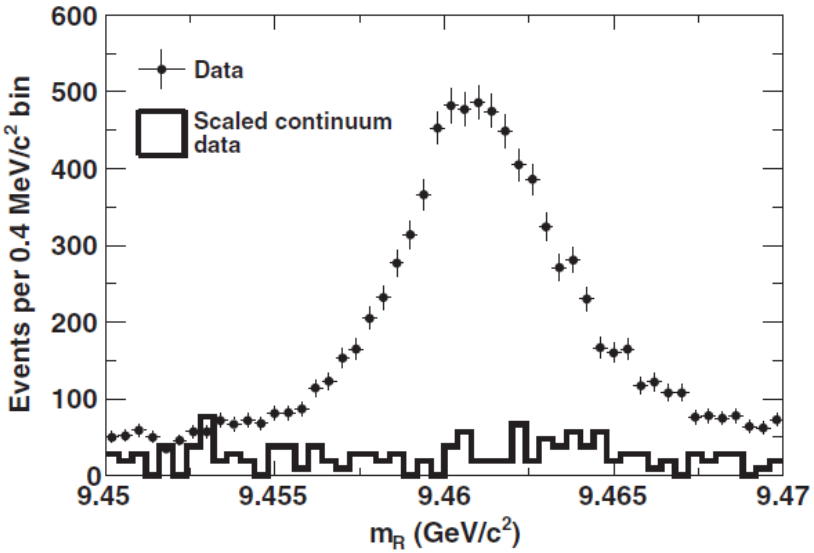
Event selection

PRD 88, 031701(R) (2013)

- 2 tracks (dipion), 1 photon, hadronic system (not 2-body, gg and/or ss)
- Missing mass consistent with Y(1S)
- MLP against Y hadronic background

TABLE I. Decay modes for candidate $A^0 \rightarrow gg$ and $s\bar{s}$ decays, sorted by the total mass of the decay products.

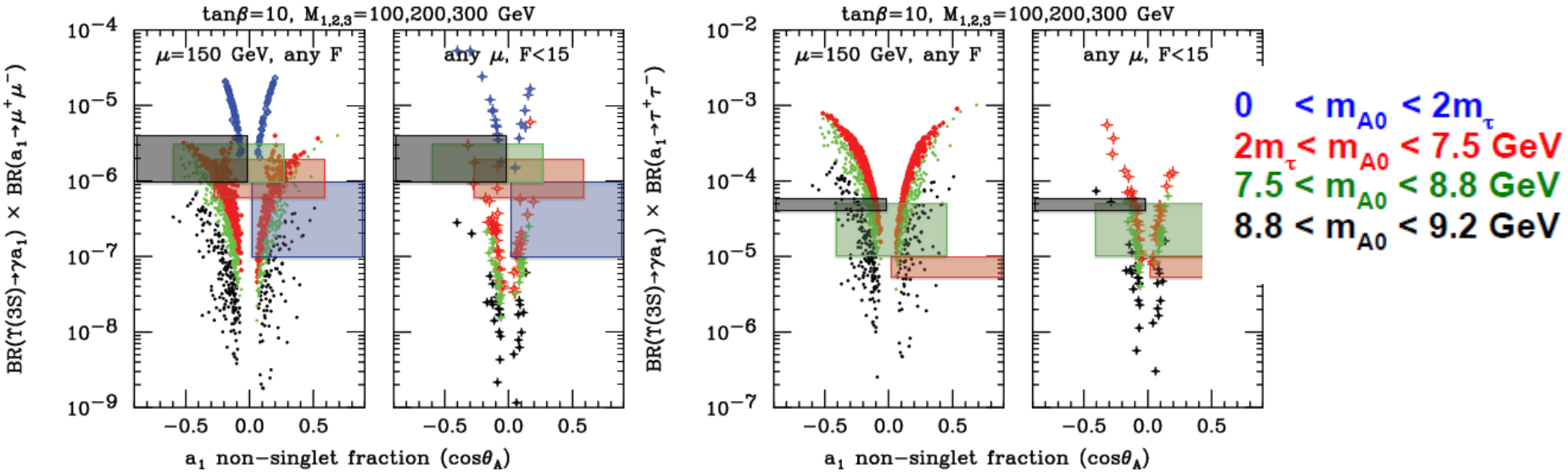
Number	Channel	Number	Channel
1	$\pi^+\pi^-\pi^0$	14	$K^+K^-\pi^+\pi^-$
2	$\pi^+\pi^-2\pi^0$	15	$K^+K^-\pi^+\pi^-\pi^0$
3	$2\pi^+2\pi^-$	16	$K^\pm K_S^0\pi^\mp\pi^+\pi^-$
4	$2\pi^+2\pi^-\pi^0$	17	$K^+K^-\eta$
5	$\pi^+\pi^-\eta$	18	$K^+K^-2\pi^+2\pi^-$
6	$2\pi^+2\pi^-2\pi^0$	19	$K^\pm K_S^0\pi^\mp\pi^+\pi^-2\pi^0$
7	$3\pi^+3\pi^-$	20	$K^+K^-2\pi^+2\pi^-\pi^0$
8	$2\pi^+2\pi^-\eta$	21	$K^+K^-2\pi^+2\pi^-2\pi^0$
9	$3\pi^+3\pi^-2\pi^0$	22	$K^\pm K_S^0\pi^\mp2\pi^+2\pi^-\pi^0$
10	$4\pi^+4\pi^-$	23	$K^+K^-3\pi^+3\pi^-$
11	$K^+K^-\pi^0$	24	$2K^+2K^-$
12	$K^\pm K_S^0\pi^\mp$	25	$p\bar{p}\pi^0$
13	$K^+K^-2\pi^0$	26	$p\bar{p}\pi^+\pi^-$



- photon with E_{cm}>200 MeV
- Fit constraining A^0 and γ candidates to Y(1S) mass and beam spot. Hence $\sigma(m_A)$~100MeV/c^2.
- π^0 vetos

CP-odd Higgs (older results)

$\mu^+\mu^-$ PRD 81, 075003 (2010) $\tau^+\tau^-$

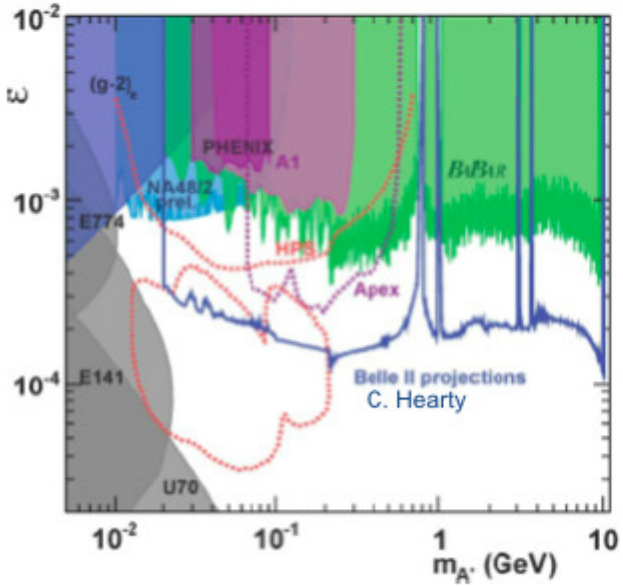


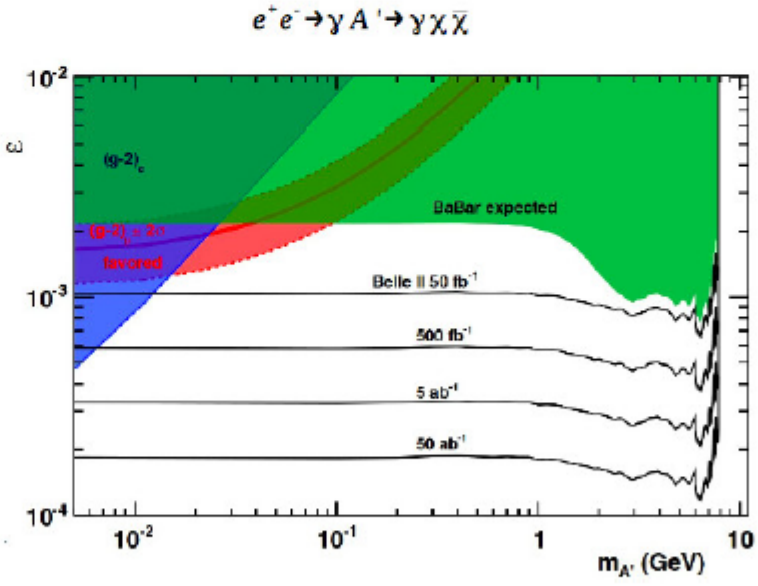
Mode	Mass range (GeV)	BF upper limit (90% CL)
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	$0.21 < m_A < 9.3$	$(0.3 - 8.3) \times 10^{-6}$
$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	$4.0 < m_A < 10.1$	$(1.5 - 16) \times 10^{-5}$
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ hadrons	$0.3 < m_A < 7.0$	$(0.1 - 8) \times 10^{-5}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to \chi\bar{\chi}$	$m_\chi < 4.5$ GeV	$(0.5 - 24) \times 10^{-5}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible	$m_A < 9.2$ GeV	$(1.9 - 37) \times 10^{-6}$
$\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible	$m_A < 9.2$ GeV	$(0.7 - 31) \times 10^{-6}$

arXiv: 1209.1143 (B. Echenard)

Outlook

Belle2 at SuperKEKb will take 40x more statistics
Shut down for upgrade 2010.
Belle-II due to roll in mid 2015, followed by commissioning.
First physics data due 2017.





DM searches, including Higgsstrahlung analysis, will continue

ε Limits

A. Soffer
At FPCP2015