Searches for Low-mass New Physics

XinChou Lou

The University of Texas at Dallas

and

The Institute of High Energy Physics, Beijing

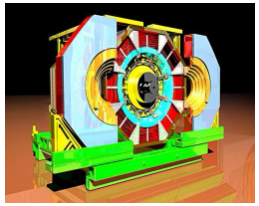
Representing BES-III, BELLE, BABAR Experiments

FPCP Hefei May 24 2012

Outline

- Overview of Searches for Low Mass, New Physics
- The Experiments, Data Samples

BES-III *BELLE* *BABAR*



- Results
- Summary

Overview

Many direct searches for new physics below the Υ mass at e^+e^- colliders

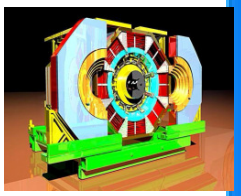
Search for Dark Matter candidates:

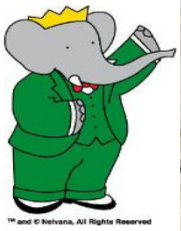
- Dark Bosons, Dark Photons, Dark Higgs
- $\Upsilon(2S,3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ **invisible** $(+\gamma)$

Search for Light CP-odd Higgs A^0:

- $\Upsilon(2S,3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$, $\tau^+\tau^-$, hadrons
- $\psi' \rightarrow \pi^+\pi^- J/\psi$, $J/\psi \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

Search for new physics



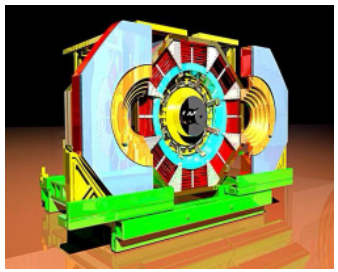


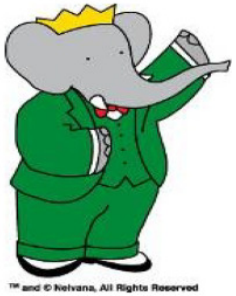
Search for new physics

at charm and beauty facilities

branching fractions
predicted to be small

Experiments and Data Samples





The BES-III, BELLE, BABAR Detectors

- Fine tracking (Si vertex detector For BELLE, BABAR)
- Excellent γ, π^0 detection with CsI Calorimeters
- Excellent PID for charged hadrons
- Good muon ID

Experiments and Data Samples

BABAR

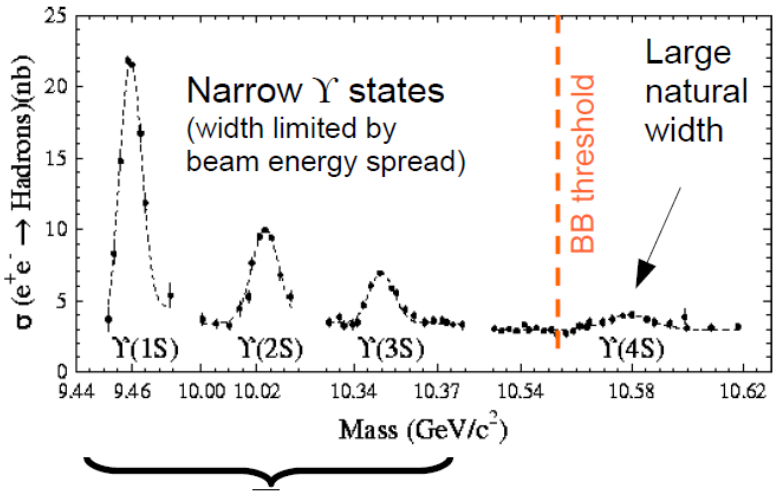
- 531.4 fb^{-1} at $\Upsilon(4S)$
  465M BB pairs
- **30 fb^{-1} at $\Upsilon(3S)$**
  121M $\Upsilon(3S)$ decays
- **98M $\Upsilon(2S)$ decays**
  ~18M $\Upsilon(1S)$ from
  $\Upsilon(2S) \rightarrow \pi\pi\ \Upsilon(1S)$ tags

BELLE

- 121 fb^{-1} at $\Upsilon(5S)$
- 711 fb^{-1} at $\Upsilon(4S)$
- **3 fb^{-1} at $\Upsilon(3S)$**
- **25 fb^{-1} at $\Upsilon(2S)$**
- **6 fb^{-1} at $\Upsilon(1S)$**
- 100 fb^{-1} continuum

BES-III

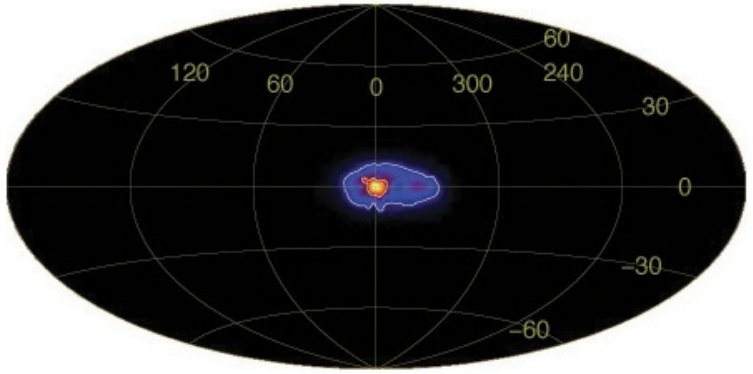
- 470 pb^{-1} 4.01 GeV
- 2.7 fb^{-1} $\psi(3770)$
- **520M $\psi(2S)$**
- 225M J/ψ



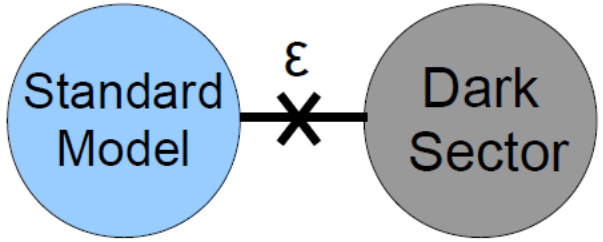
$\Upsilon(1S,2S,3S)$ are narrow, significantly better sensitivity to production of light degrees of freedom

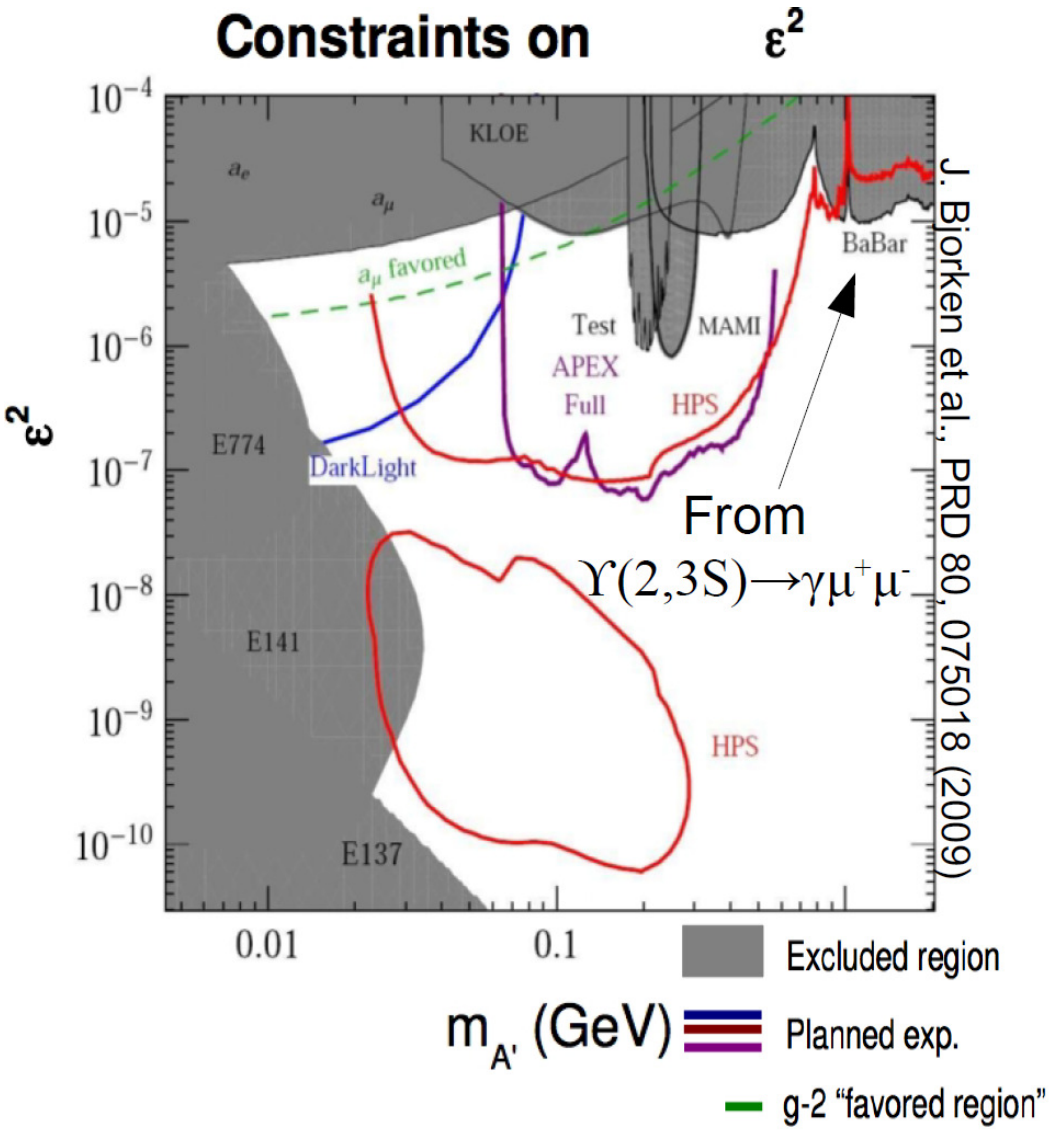
Dark Forces

- Overwhelming astrophysical evidence of dark matter
- New models introduce new "dark forces" with light hidden sectors to explain observations such as the 511 keV gamma ray excess from galatic center reported by INTEGRAL, positron excess in cosmic rays by PAMELA, annual modulation data by DAMA, etc.
  - ➢ Dark matter self-interaction mediated by dark gauge boson with mass in ~GeV range
  - ➢ Dark boson (i.e. dark photon A') could couple to the SM particles through a small kinetic mixing term (with mixing strength ε)
  - ➢ Various model possibilities exist:
    Dark Higgs h' (in Abelian and some non-Abelian),
    Dark Boson W' (in some non-Abelian), etc....
    ESA/Integral/MPE (G. Weidenspointner et al.)
    N. Arkani-Hamed, et al, PRD79, 015014(2009);
    B. Batell, et al, PRD79, 115008(2009);
    D. McKeen, PRD80 015007(2009)



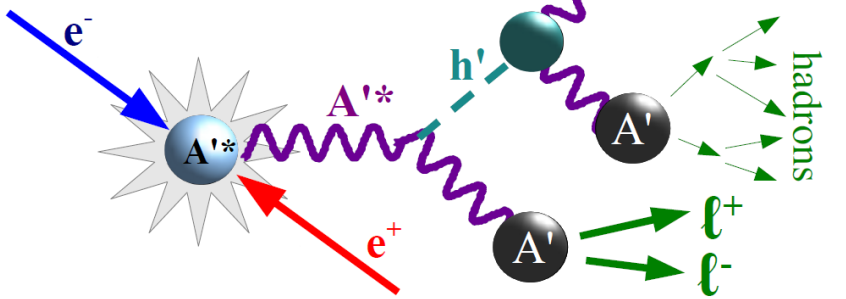
ESA/Integral/MPE (G. Weidenspointner et al.)

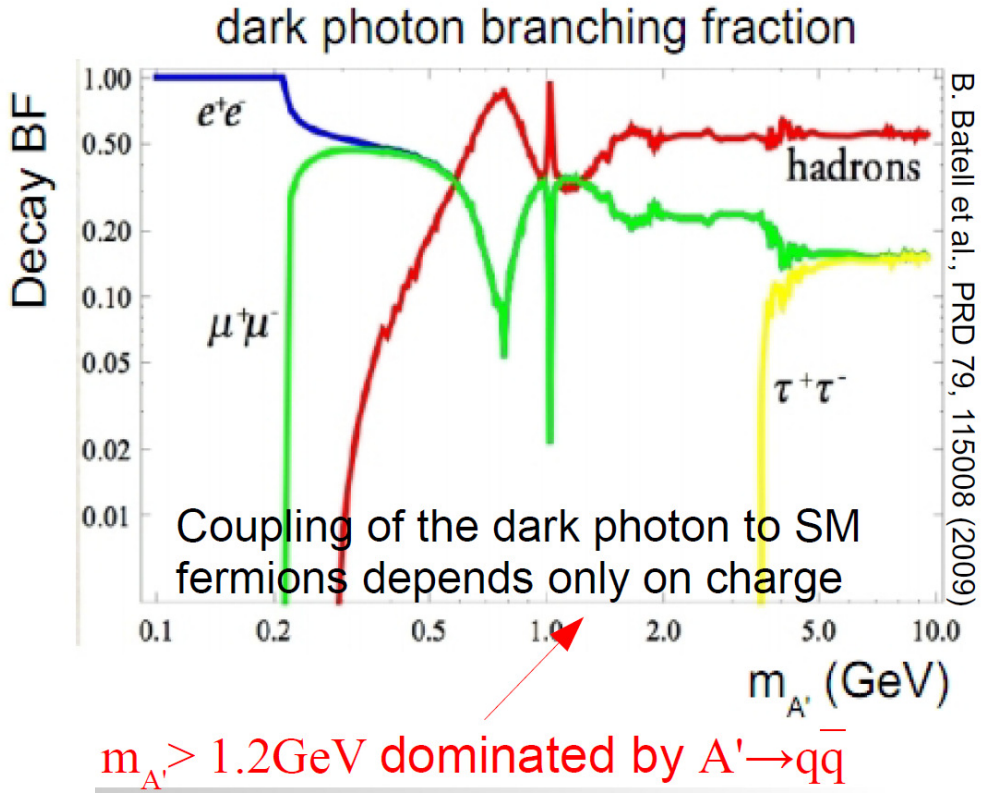



Constraints on ε^2
ε^2
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
KLOE
a_e
a_μ
a_μ favored
BaBar
Test
MAMI
APEX
Full
HPS
E774
DarkLight
From
$\Upsilon(2,3S)\rightarrow\gamma\mu^+\mu^-$
E141
HPS
E137
0.01
0.1
$m_{A'}$ (GeV)
Excluded region
Planned exp.
g-2 "favored region"
J. Bjorken et al., PRD 80, 075018 (2009)

Search for a Dark Higgs h'

Higgs-strahlung process $e^+e^- \rightarrow A'^* \rightarrow h'A'$, $h' \rightarrow A'A'$
only suppressed by factor of ε^2

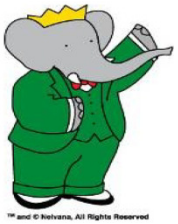




$m_{A'} > 1.2$GeV dominated by $A' \rightarrow q\bar{q}$

Search for a Dark Higgs h'

arXiv:1202.1313,
Submitted to PRL



Event Selection (Two ways):

1. Fully reconstruct all 3 dark photons: $A' \to e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$

   6 tracks with an invariant mass $m_{tot} > 0.95\ \sqrt{s}$

2. Partial reconstruction: 2 A' decaying to leptons and 1 A' to $q\bar{q}$:

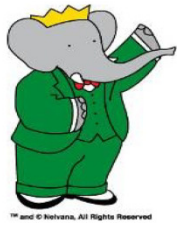
   $A'_1 \to e^+e^-$, $\mu^+\mu^-$; $A'_2 \to \mu^+\mu^-$; $A'_3 \to X$ ($X \neq \ell^+\ell^-$ or $\pi^+\pi^-$)
   4 or more tracks
   Reconstruct four-momentum $\mathbf{p_3 = p_{ee} - p_1 - p_2}$

plus

- PID for $A' \to \ell^+\ell^-$, $\pi^+\pi^-$
- cos of helicity angle of $A' \to e^+e^- < 0.9$
- 3 A' candidates have similar masses
- full BABAR dataset (Υ(4,3,2S)~516 fb^{-1})
- Search for dark higgs (h'): $m_{h'} > 2m_{A'}$, $0.8 < m_{h'} < 10$ GeV, $0.1 < m_{A'} < 0.3$ GeV

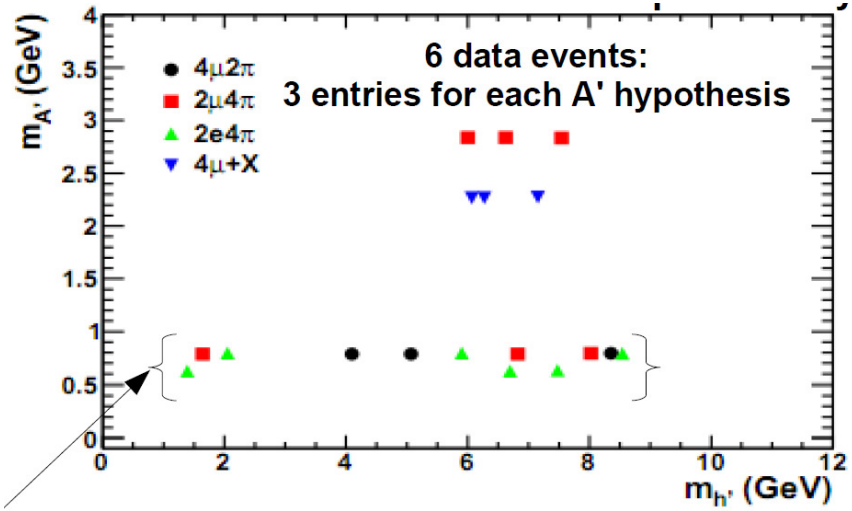
Search for a Dark Higgs h'

arXiv:1202.1313
Submitted to PRL

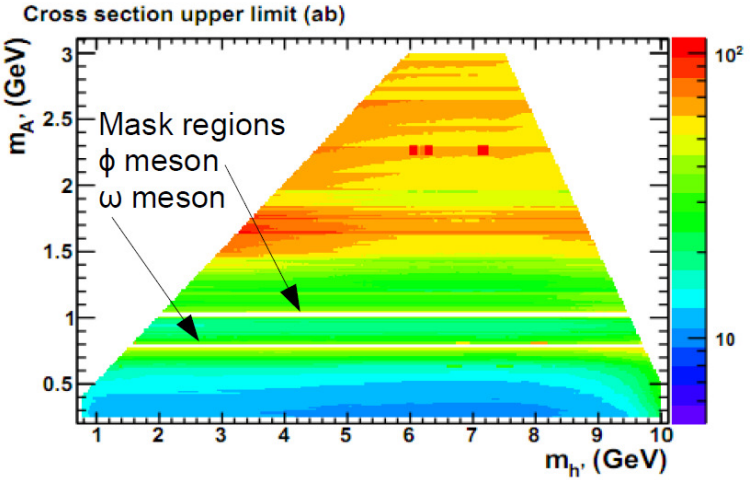


Results:

- No signal observed in 6 lepton search
- 6 data events observed in partial reconstruction search
- Consistent with the background hypothesis from same-sign control samples ($(e^+e^-)(\mu^+\mu^-)(\mu^+\mu^-)$, etc.)



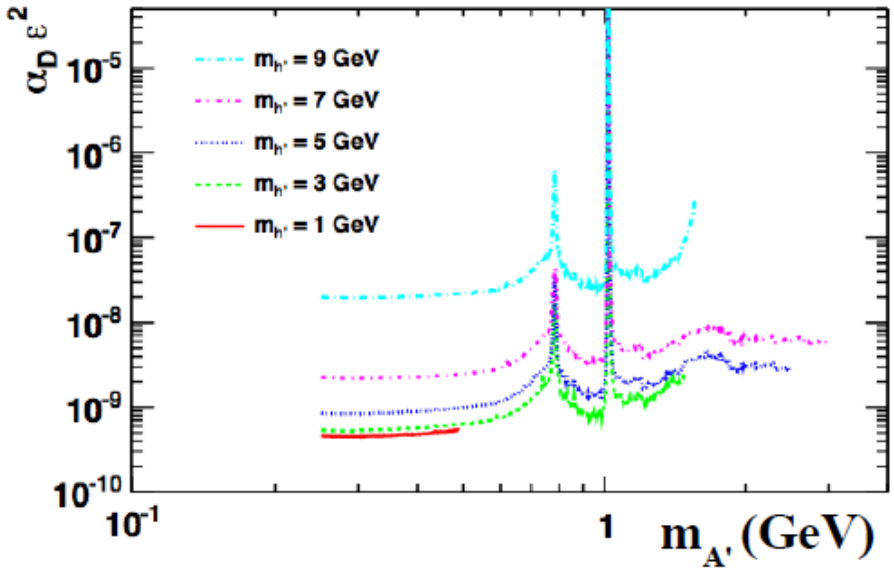
Most likely from $e^+e^- \to (e^+e^-)\rho\rho$, $(e^+e^-)\omega\omega$, or 6π final states

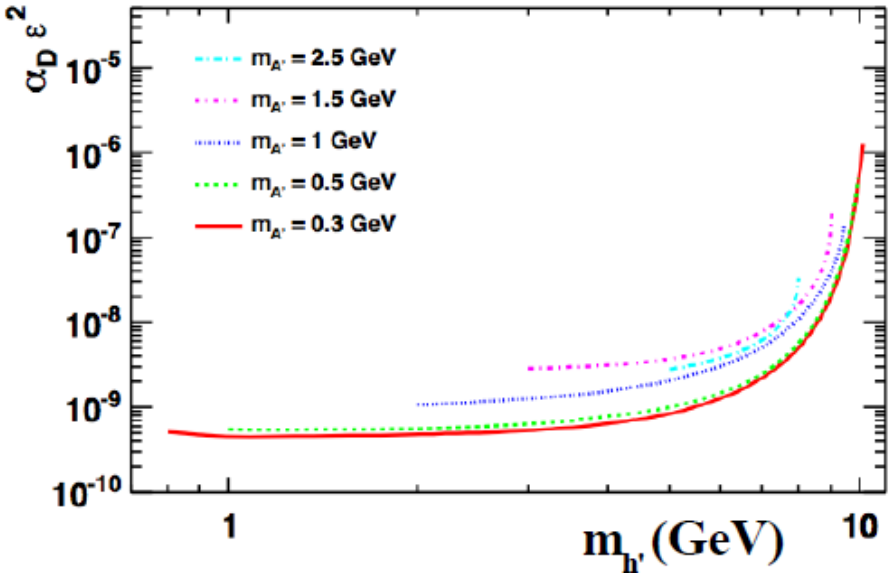


$\sigma(e^+e^- \to h'A', h' \to A'A') < 10\text{-}100$ ab at 90% CL

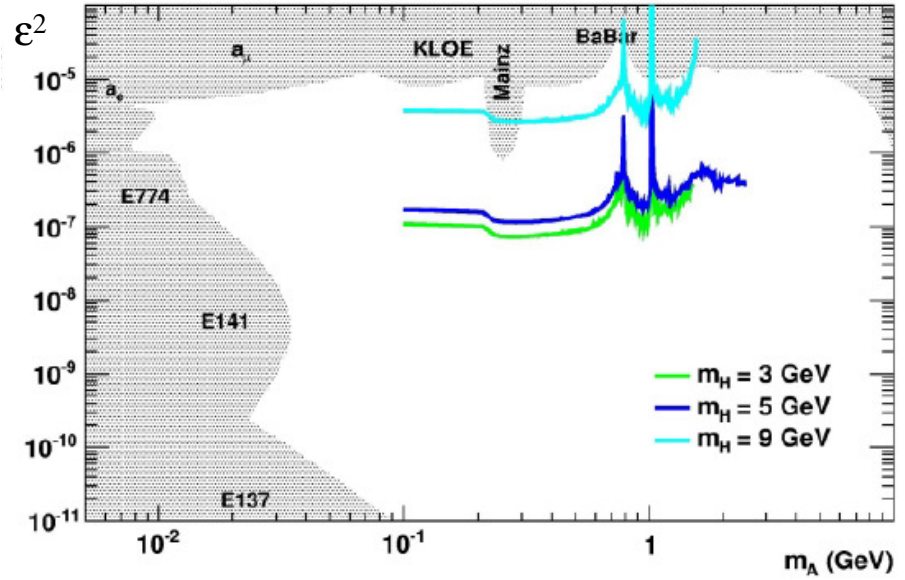
Search for a Dark Higgs h'

arXiv:1202.1313
Submitted to PRL





Limit on ε^2 assuming $\alpha_D = \alpha_{em}$



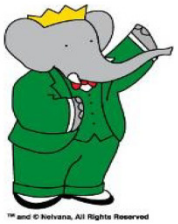
$\alpha_D \varepsilon^2 <$ few x10^{-10} at 90% CL

$\alpha_D \equiv g_D^2/4\pi$

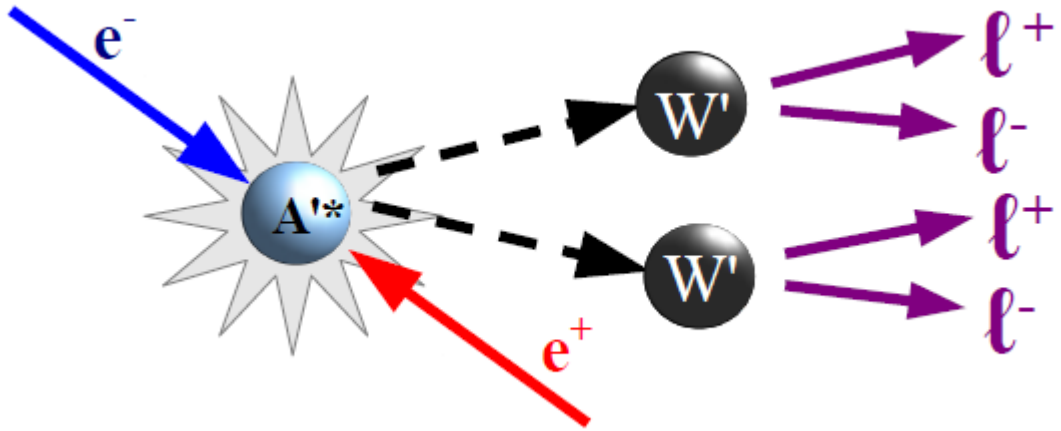
g_D = dark sector coupling constant

Search for Dark Boson W'

arXiv:0908.2821
BABAR Preliminary



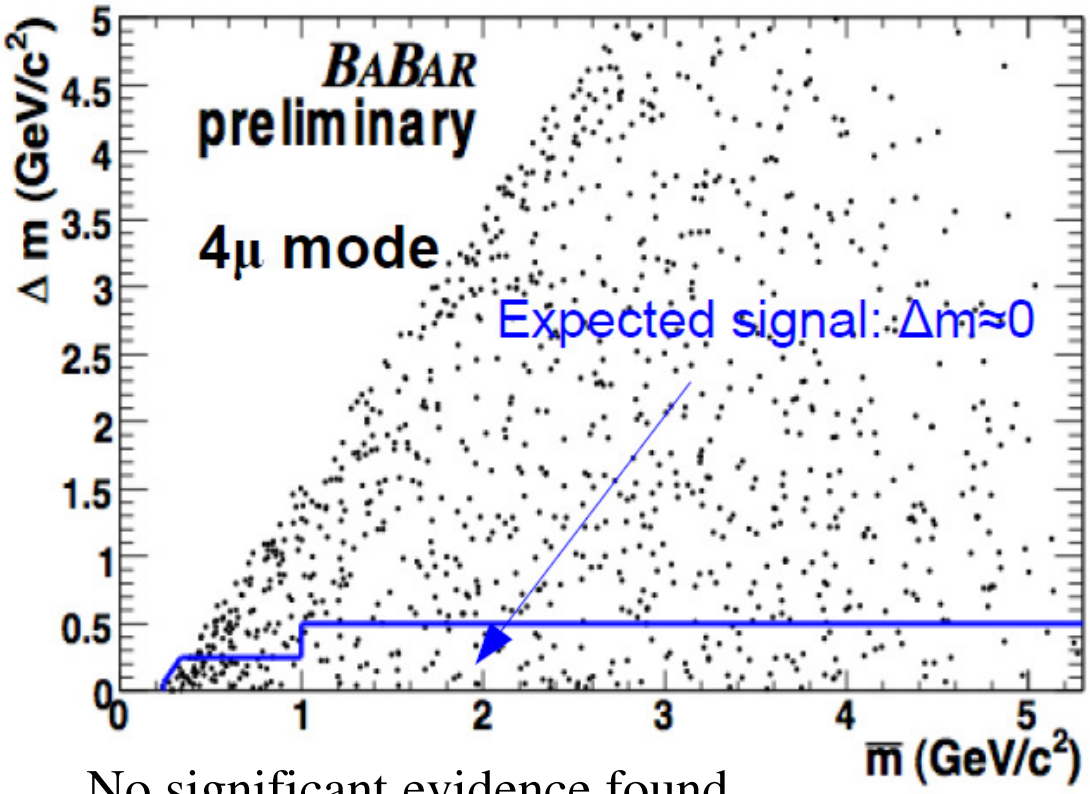
$e^+e^- \rightarrow W'W' \rightarrow (\ell^+\ell^-)(\ell^+\ell^-)$



- 4 leptons of zero total charge, carrying the full beam energy and momentum
- 2 di-lepton resonances have similar masses
- Used full BABAR dataset
- Cut-and-count using: $m = (m_1+m_2)/2$, $\Delta m=|m_1-m_2|$
  m_i is the mass of $(\ell^+\ell^-)$ pair;
  Δm is the mass difference between the $(\ell^+\ell^-)$ pairs

Search for Dark Boson W'

arXiv:0908.2821
BABAR Preliminary



No significant evidence found

$\sigma\,(e^+e^- \to W'W' \to (\ell^+\ell^-)(\ell^+\ell^-)) < 25\text{-}60$ ab

$g_D\varepsilon^2 < 10^{-9} - 10^{-7}$

at 90% CL

Assumes $B(W' \to e^+e^-) = B(W' \to \mu^+\mu^-)$

Search for Light Higgs

Motivations

- Light CP-odd Higgs arise in several beyond SM scenarios
- NMSSM: adds singlet Higgs field to MSSM
  Solves "μ" problem (fine-tuning at EW scale)
  Results in an additional CP-odd Higgs that mixes with MSSM CP-odd Higgs, and adds a light neutralino (χ^0)
- Light CP-odd Higgs (A^0) and/or low mass Dark Matter candidates (χ) can be directly produced in decays of heavy quarkonium states:
  J. Gunion et al., PRD 73, 015011 (2006)
  $\Upsilon \rightarrow \chi\chi$ via a new gauge boson or scalar
  $\Upsilon \rightarrow \mathbf{A^0}\,\gamma$ where $\mathbf{A^0} \rightarrow$ **SM particles** and/or $\chi^0\chi^0$ **(i.e. invisible)**
- Models can evade existing Higgs & SUSY LSP limits from e.g. LEP, while predicting quite large branching fractions
- HyperCP observation of 3 anomalous $\Sigma^+ \rightarrow p\mu^+\mu^-$ events with $M(\mu^+\mu^-)$~214.3 MeV/c^2
  H. K. Park et al. PRL 94, 021801 (2005)

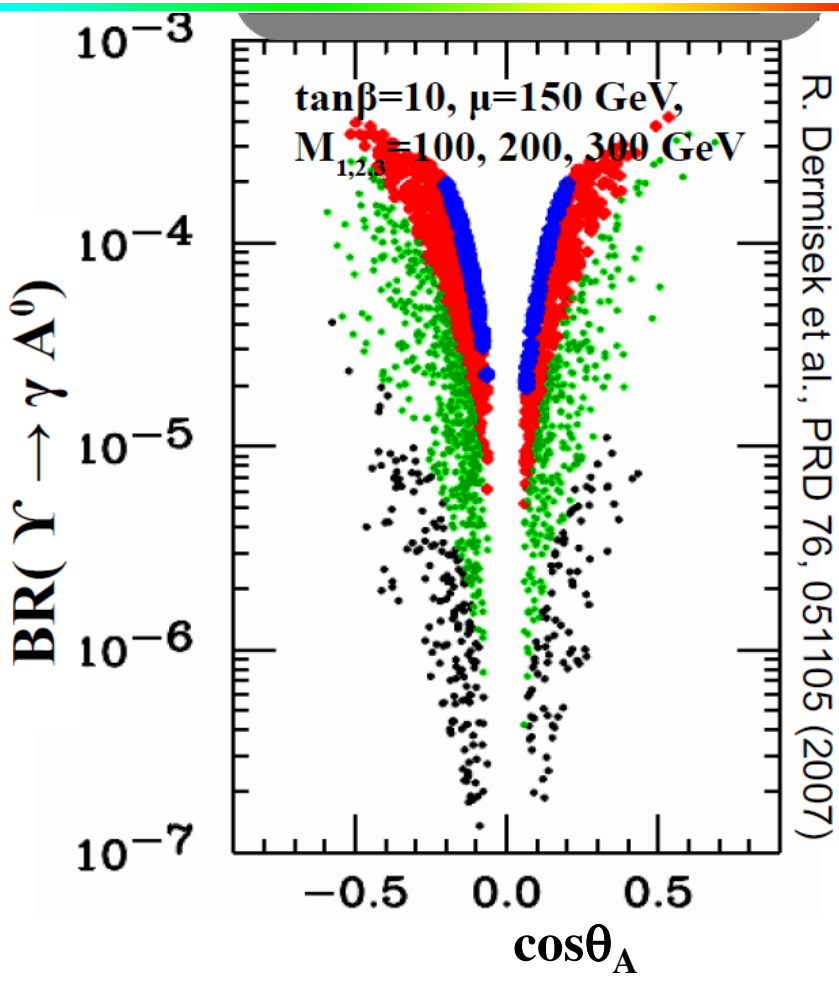
Search for Light Higgs

$m_{A^0} < 2m_\tau$

$2m_\tau < m_{A^0} < 7.5$ GeV

7.5 GeV $< m_{A^0} < 8.8$ GeV

8.8 GeV $< m_{A^0} < 9.2$ GeV



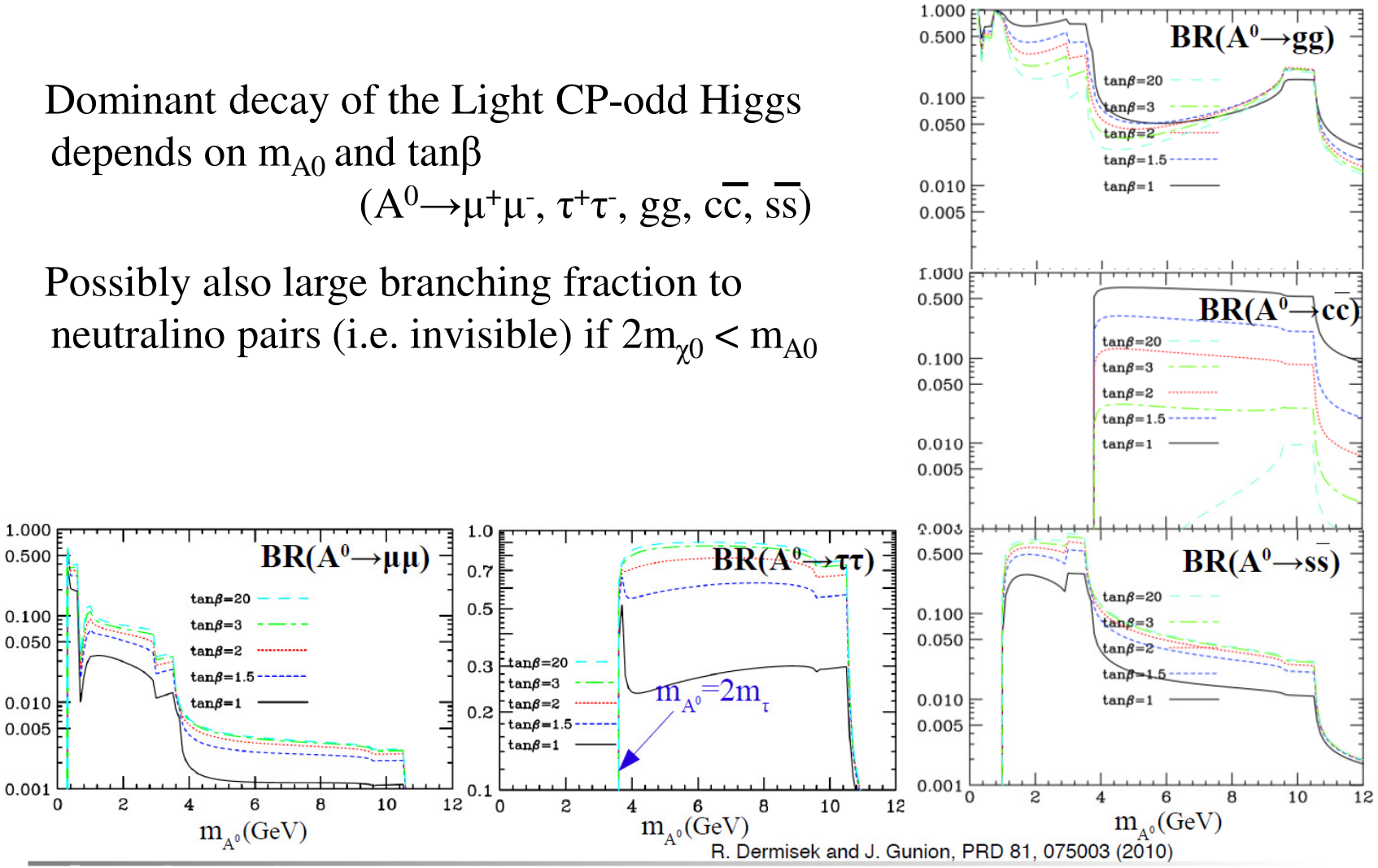
$A^0 = \cos\theta_A A_{MSSM} + \sin\theta_A A_{singlet}$

Low mass Dark Matter predictions

- $B(\Upsilon(1S)\to\nu\bar{\nu})_{SM} \sim 10^{-6}$
- $B(\Upsilon(1S)\to\chi\bar{\chi})_{SM} \sim (4\text{-}18)10^{-4}$ B. McElrath, PRD 72, 103508(2005)
- $B(\Upsilon(1S)\to\gamma\chi\bar{\chi})_{SM} \sim 10^{-5}\text{-}10^{-4}$ G. Yeghiyan, PRD 80, 103508(2009)

Light CP-odd Higgs (A^0)

- Dominant decay of the Light CP-odd Higgs depends on m_{A0} and tanβ
  ($A^0 \rightarrow \mu^+\mu^-, \tau^+\tau^-, gg, c\bar{c}, s\bar{s}$)
- Possibly also large branching fraction to neutralino pairs (i.e. invisible) if $2m_{\chi 0} < m_{A0}$



R. Dermisek and J. Gunion, PRD 81, 075003 (2010)

A^0 Event Tagging

- 2-body radiative decays of well-understood narrow Υ states, $\Upsilon(nS)\to\gamma A^0$ (n=1,2,3), offer a clean search environment for the light Higgs

  Key experimental signature: monochromatic photon in the CM frame

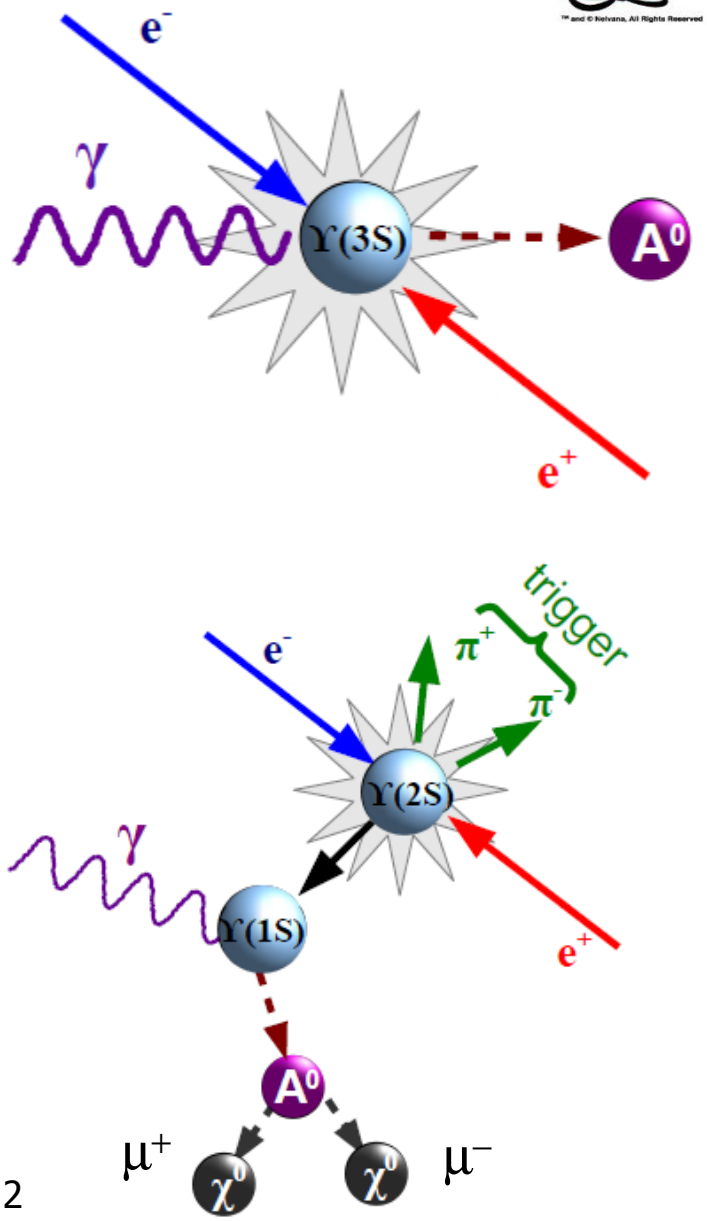
$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$

$\Upsilon(2,3S)\to\gamma A^0,\ A^0\to\mu^+\mu^-$	PRL 103, 081803 (2009)
$\Upsilon(2,3S)\to\gamma A^0,\ A^0\to\tau^+\tau^-$	PRL 103, 181801 (2009)
$\Upsilon(2,3S)\to\gamma A^0,\ A^0\to$hadrons	PRL 107, 221803 (2011)

- $\Upsilon(nS)\to\pi^+\pi^-\Upsilon(1S)$ transitions provide a di-pion trigger for $\Upsilon(1S)\to$invisible $(+\gamma)$ reconstruction

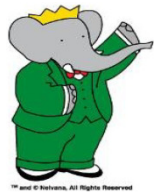
  Key experimental signatures:
  Exactly 2 tracks,
  forming vertex and identified as $\pi^\pm$;
  $\pi\pi$ Recoil Mass = $\sqrt{}\approx M\Upsilon(1S)$

$\Upsilon(1S)\to$invisible $+\gamma$	PRL 107, 021804 (2011)
$\Upsilon(1S)\to$invisible	PRL 103, 251801 (2009)



$\Upsilon(1S) \rightarrow$ invisible (+γ)

PRL 107, 021804 (2011)
PRL 103, 251801 (2009)

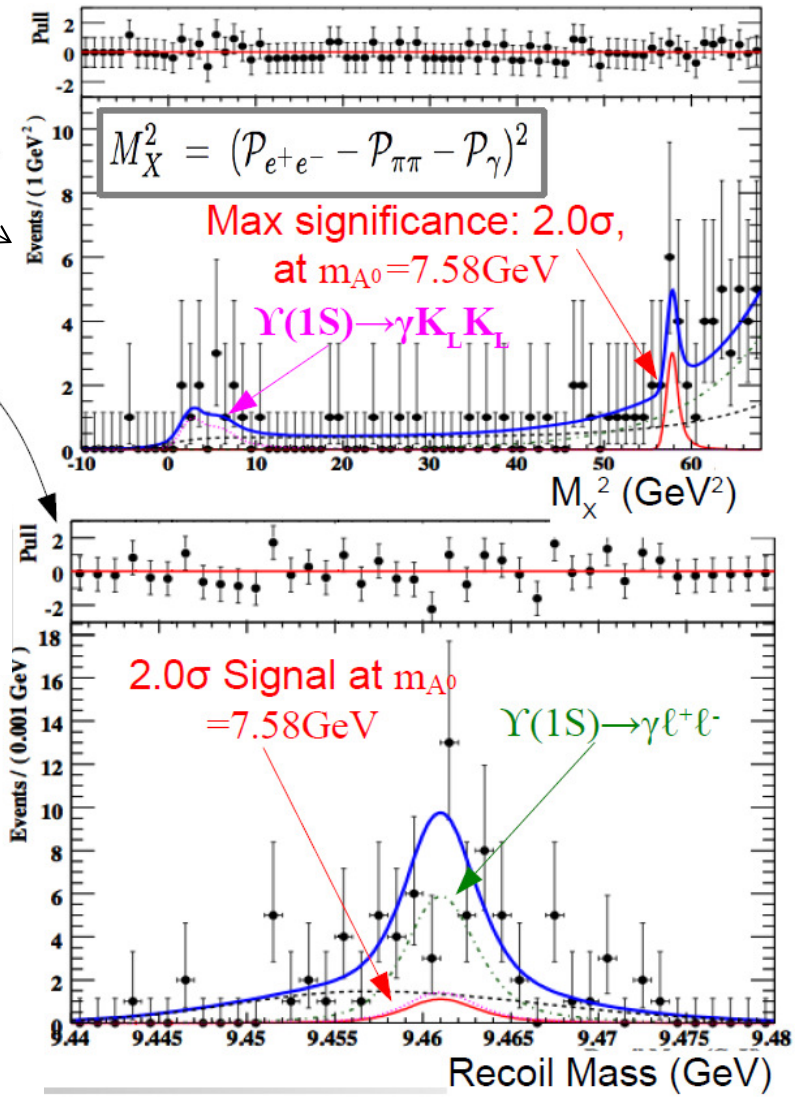


- **$\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ invisible + γ**
  1 photon with Eγ >0.15 GeV
  2D fit to $\pi\pi$ Recoil Mass & Missing Mass^2
  No significant signal observed for:
  $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible
  $\Upsilon(1S) \rightarrow \gamma\, \chi\chi$

$B(\Upsilon(1S) \rightarrow \gamma A^0, A^0 \rightarrow \text{invisible}) < (1.9\text{-}37) \times 10^{-6}$
$B(\Upsilon(1S) \rightarrow \gamma\, \chi\chi) < (0.5\text{-}24) \times 10^{-5}$
at 90% CL

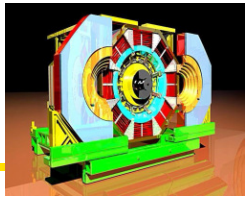
- **$\Upsilon(3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ invisible**
  No extra activity in event
  Fit to $\pi\pi$ Recoil Mass
  No evidence of dark matter contribution

$B(\Upsilon(1S) \rightarrow \text{invisible}) < 3.0 \times 10^{-4}$ at 90% CL



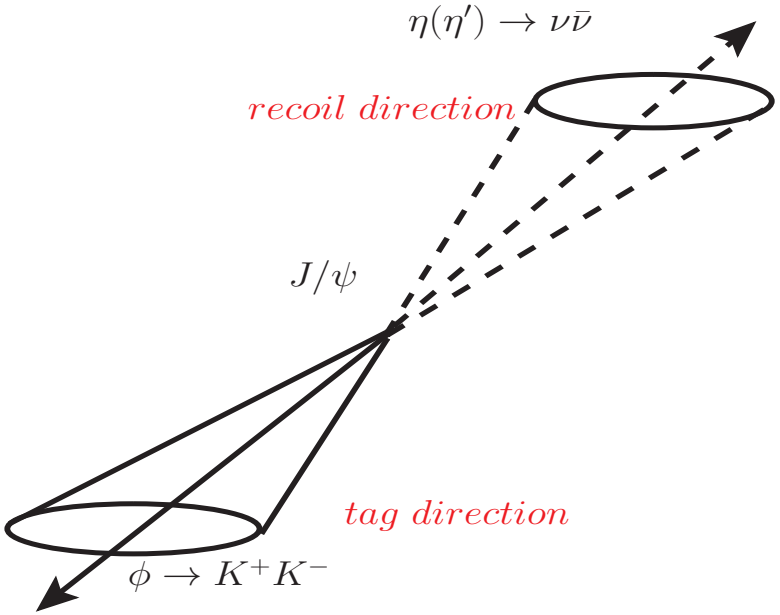
η,η′→invisible

PRL 97, 202002 (2006)
+ current update

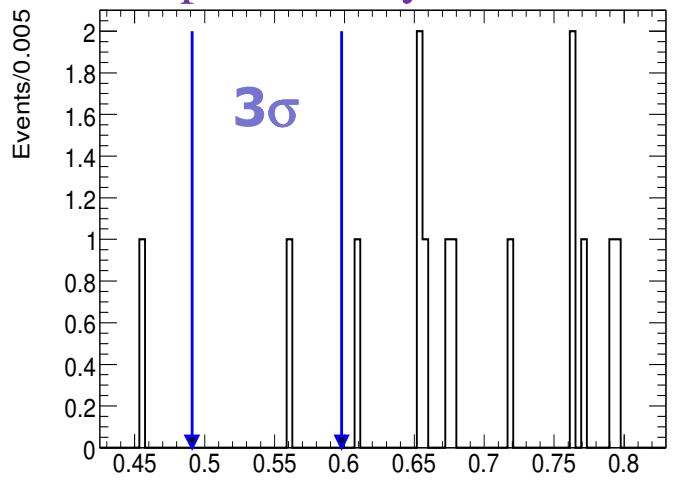


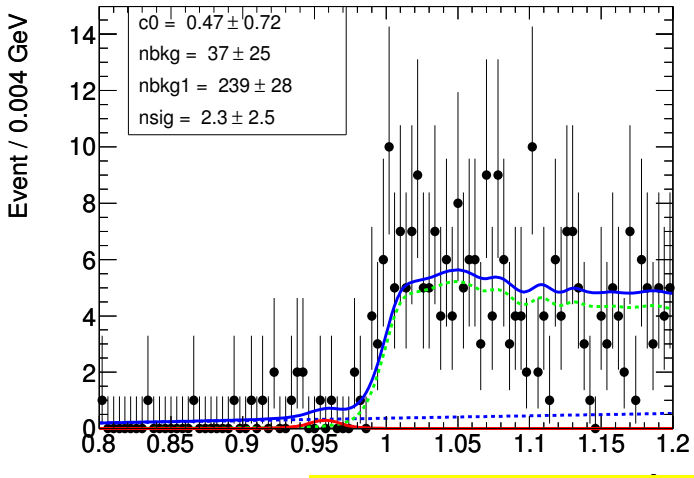
BES-III

- **J/ψ→ϕ (η,η′), (η,η′)→invisible**
  only two charged tracks in event,
  tracks identified as kaons
  photon veto inside 1 rad cone around η,η′
  $|\cos(\theta_{recoil})|<0.70$
  ϕ mass window $1.01<M(K^+K^-)<1.03$ GeV/c^2



preliminary

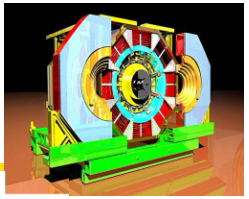




M(recoiling ϕ)(GeV

$\eta,\eta' \to$ invisible

PRL 97, 202002 (2006)
+ current update



BES-III

Looking for $\eta/\eta' \to$ Invisible in $J/\psi \to \phi\eta/\eta'$

BESIII Preliminary Result

$$\frac{Br(\eta/\eta' \to \text{invisible})}{Br(\eta/\eta' \to \gamma\gamma)} < \frac{n^{up} \cdot \epsilon_{\gamma\gamma}}{n_{\gamma\gamma} \cdot \epsilon_{\text{invisible}}} \cdot \frac{1}{1-\sigma_{\eta/\eta'}}$$

N^{up}: #observed signal @ 90% C.L.
$N_{\gamma\gamma}$: #observed $\eta/\eta' \to \gamma\gamma$
$\varepsilon_{invi.}$: Efficiency of signal mode
$\varepsilon_{\gamma\gamma}$: Efficiency of $\eta/\eta' \to \gamma\gamma$
$\sigma_{\eta/\eta'}$: 1 sigma uncertainty

$\frac{BR(\eta \to invisible)}{BR(\eta \to \gamma\gamma)} < 3.37 \times 10^{-4}$ @ 90% C.L.

$\frac{BR(\eta' \to invisible)}{BR(\eta' \to \gamma\gamma)} < 2.39 \times 10^{-2}$ @ 90% C.L.

Many uncertainty related to tag side and Detector noise cancelled in the ratio.

preliminary

$BR(\eta \to \text{invisible}) < 1.32 \times 10^{-4}$ @ 90% C.L.
$BR(\eta' \to \text{invisible}) < 5.31 \times 10^{-4}$ @ 90% C.L.

Theory:
B. McElrath PRD 72, 103508(2005)

$BR(\eta \to \chi\chi) \sim 7.4 \times 10^{-5}$
$BR(\eta' \to \chi\chi) \sim 8.1 \times 10^{-7}$

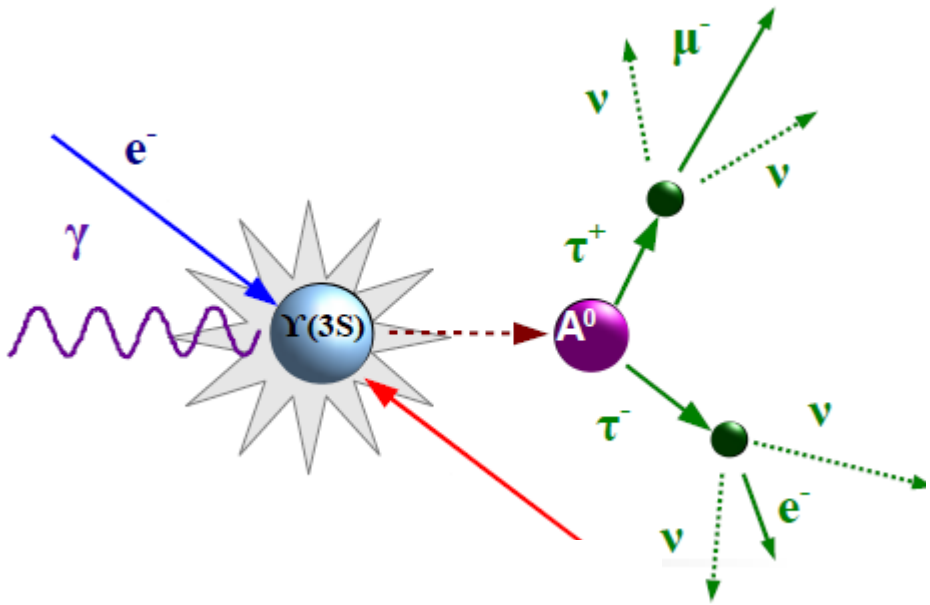
$BR(\eta \to \text{invisible}) < 6.0 \times 10^{-4}$ @ 90% C.L.
$BR(\eta' \to \text{invisible}) < 1.4 \times 10^{-3}$ @ 90% C.L.

BESII result:
PRL 97, 202002 (2006)

$\Upsilon(2, 3S) \to \gamma A^0, A^0 \to \mu^+\mu^-, \tau^+\tau^-$

- **$\Upsilon(2, 3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$**
  2 tracks, forming vertex & muon PID
  Photon with $E_\gamma > 200$ MeV
  Fit and scan $\mu^+\mu^-$ invariant mass
  No significant signal observed

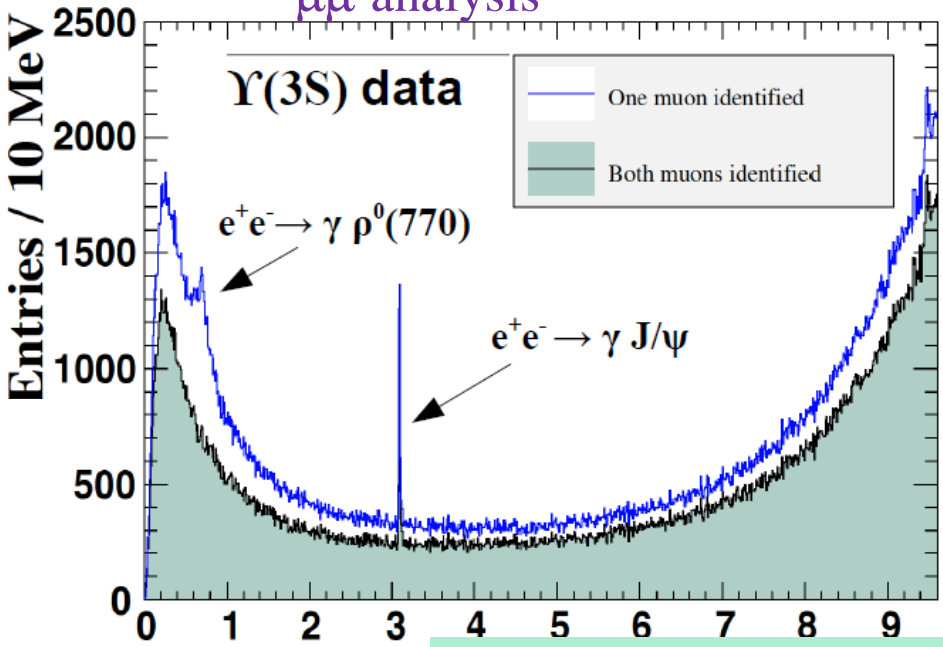
- **$\Upsilon(2, 3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$**
  Consider both $\tau^+ \to e^+ \nu\bar{\nu}$,$\tau^+ \to \mu^+\nu\bar{\nu}$
  $E_\gamma > 100$ MeV and 2 tracks
  identified as leptons
  Fit and scan E_γ
  No significant signal observed



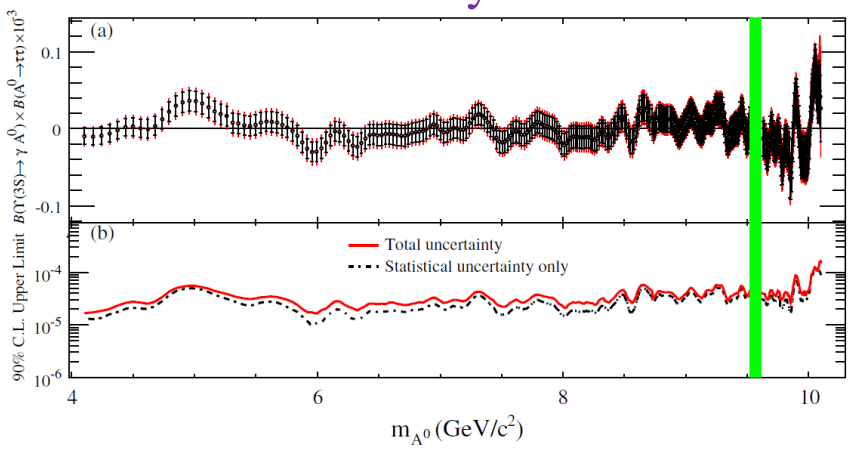
$\Upsilon(2, 3S) \to \gamma A^0,\ A^0 \to \mu^+\mu^-,\ \tau^+\tau^-$

PRL 103, 081803 (2009)
PRL 103, 181801 (2009)

μμ analysis



ττ analysis



$B(\Upsilon(2S) \to \gamma A^0,\ A^0 \to \mu^+\mu^-) < (0.26 - 8.3) \times 10^{-6}$
$B(\Upsilon(3S) \to \gamma A^0,\ A^0 \to \mu^+\mu^-) < (0.27 - 5.5) \times 10^{-6}$
at 90% CL

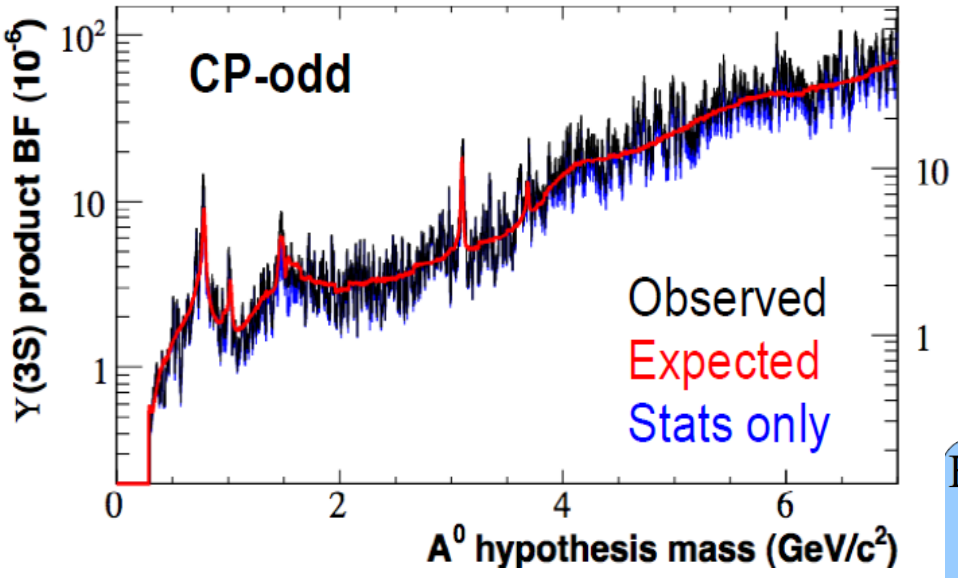
$B(\Upsilon(2,3S) \to \gamma A^0,\ A^0 \to \tau^+\tau^-) < (1.5 - 16) \times 10^{-5}$ at 90% CL

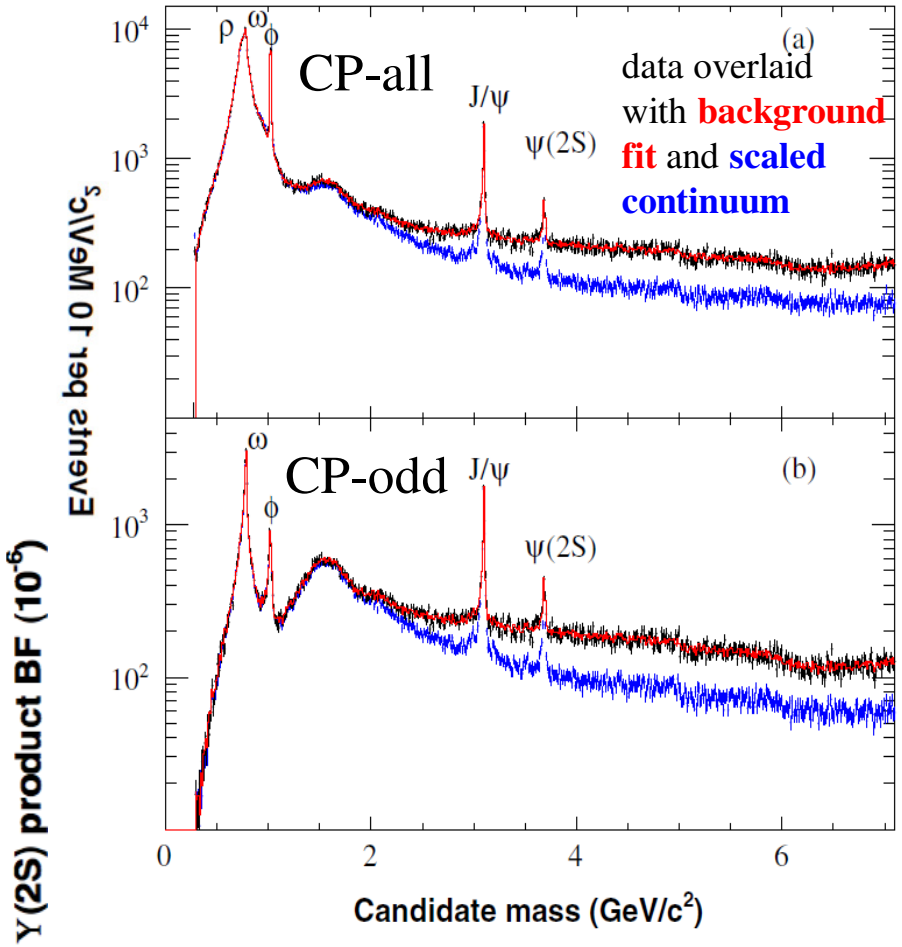
$\Upsilon(2, 3S) \to \gamma A^0, A^0 \to$ hadrons

PRL 107, 221803 (2011)

Selections

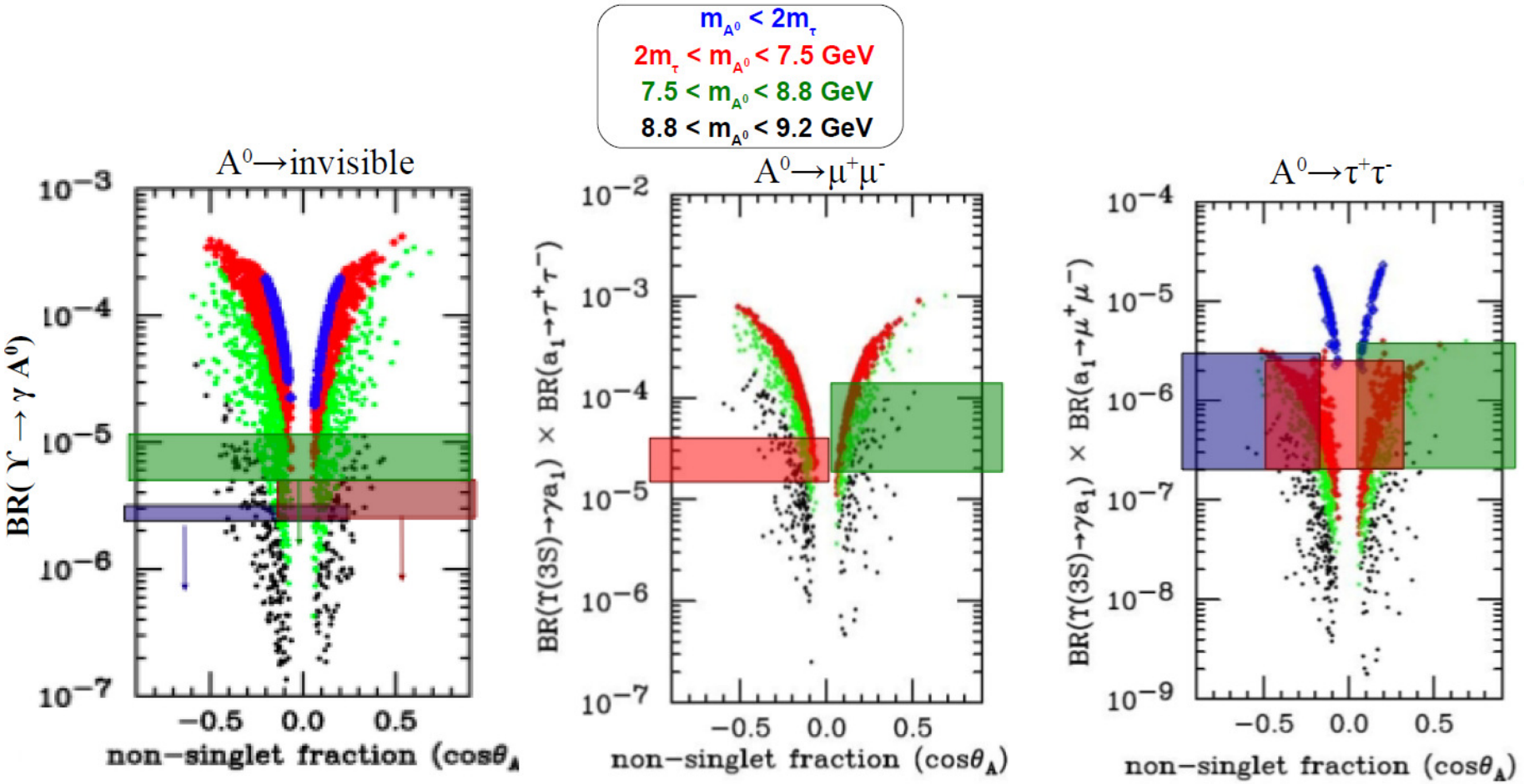
- E_γ > ~2 GeV and at least 2 tracks
- Reconstruct A^0 using rest of event
- Consider both "CP all" and CP-odd (no K^+K^- or $\pi^+\pi^-$) hypotheses
- Fit and scan A^0 mass
- No significant signal observed





B(Υ(nS)$\to \gamma A^0, A^0 \to$ hadrons) < (0.1- 8) x10^{-5} at 90% CL
(assumes both decays have same matrix elements)

A^0 Upper Limits

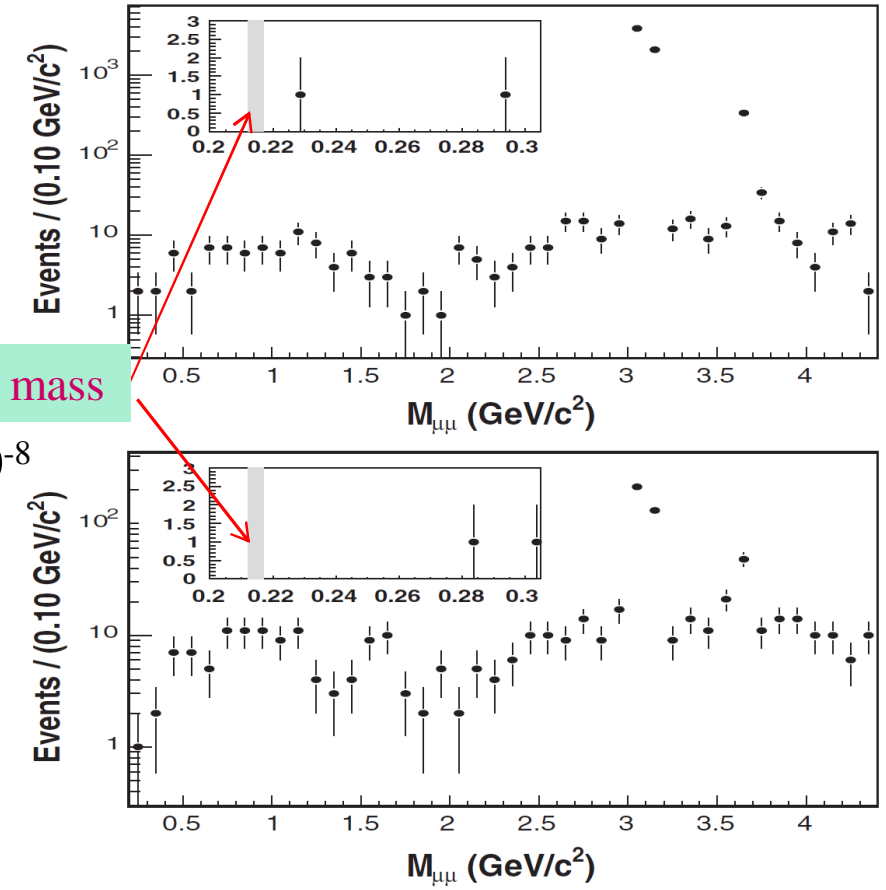


$B^0 \to (K^{*0}, \rho^0) A^0$, $A^0 \to \mu^+\mu^-$

PRL 105, 091801 (2010)

657M $B\bar{B}$ events

standard B selection with M_{bc}, ΔE



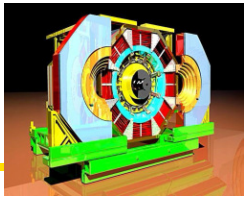
- $B(B0 \to K^{*0}A^0) \times B(A^0 \to \mu^+\mu^-) < 2.26(7) \times 10^{-8}$
- $B(B0 \to \rho^0 A^0) \times B(A^0 \to \mu^+\mu^-) < 1.73 \times 10^{-8}$ at 90%C.L.
- No evidence for signal between 212 – 300 MeV/c^2

CLEO saw no evidence for a Higgs state ~214 MeV/c^2

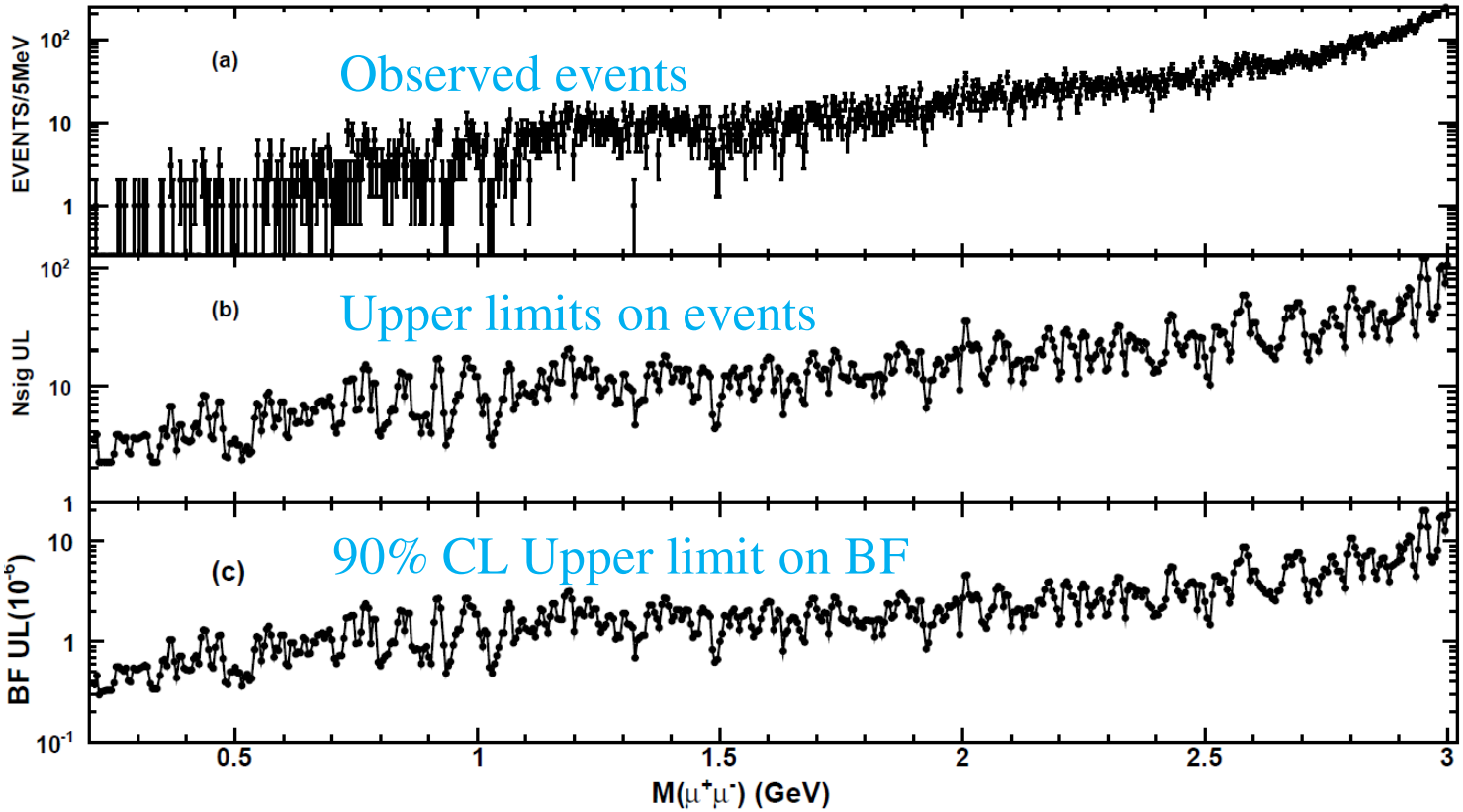
W. Love et. al., PRL 101 151802 (2008)

$A^0 \to \mu^+\mu^-$, through $\psi' \to \pi^+\pi^- J/\psi$, $\psi \to \gamma(\mu^+\mu^-)$

BES-III Collab.
arXiv:1111.2112v1



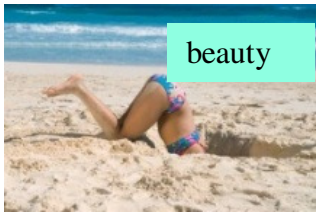
BES-III



- 105M ψ' events
- J/ψ selected via $\psi' \to \pi^+\pi^- J/\psi$ and the $(\pi^+\pi^-)$ tag
- Mass range to 3 GeV/c^2

- Limits $\mathbf{4 \times 10^{-6}}$ **- 2.1** $\times 10^{-5}$ in the mass range searched
- No confirmation of HyperCP around 214.3 MeV/c^2, observes 1 $\mu^+\mu^-$ event below 255 MeV/c^2, limit set at $\mathbf{5 \times 10^{-7}}$

We might just need more powerful tool
to "dig out" the Dark Matter, Higgs & New Physics



Dr. Super or
Dr. Large

Summary

- Searches have been performed by BESIII, BELLE, BABAR for

  CP-odd light Higgs in Charmonium and Bottomonium decays

  Dark sector candidates

- No significant signal for the light Higgs and Dark Matter

  improved limits

  exclude a large portion of the parameter space

- More analyses forthcoming
- Full exploration with LHC, KEKB2, SuperB, Super Charm tau ….

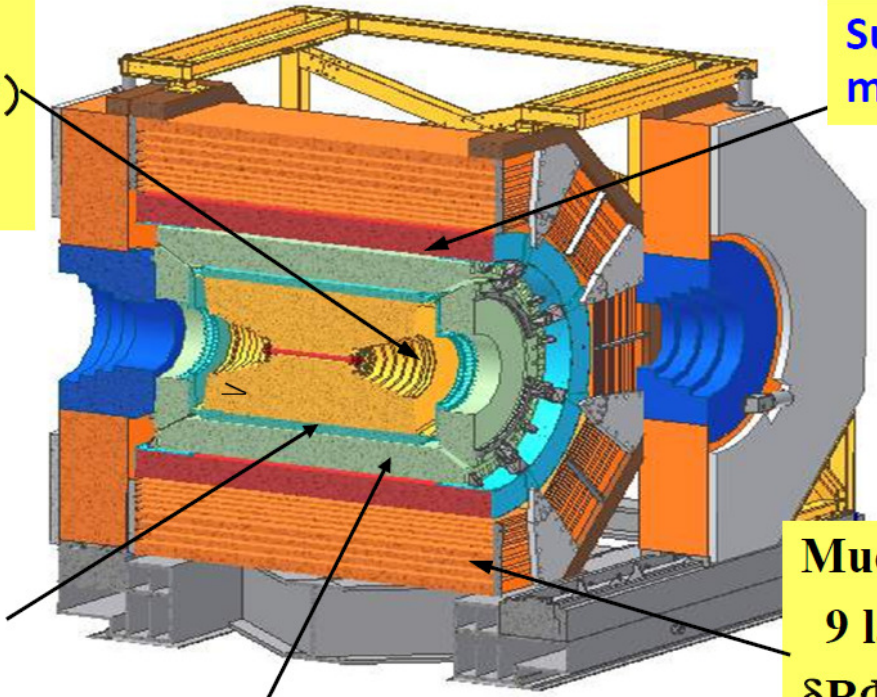
Backup slides

Backup slides

The BESIII Detector

NIM A614 (2010)

Drift Chamber (MDC)
$\sigma P/P\ (^0/_0) = 0.5\%(1GeV)$
$\sigma_{dE/dx}\ (^0/_0) = 6\%$



Super-conducting magnet (1.0 Tesla)

Time Of Flight (TOF)
σ_T : 90 ps Barrel
110 ps endcap

Muon Counter
9 layers RPC
$\delta R\Phi$=1.4 cm~1.7 cm

EMC: $\sigma E/\sqrt{E}(^0/_0) = 2.5\ \%\ (1\ GeV)$
(CsI) $\sigma_{z,\phi}(cm) = 0.5 - 0.7\ cm/\sqrt{E}$

http://bes3.ihep.ac.cn

BESIII commissioning

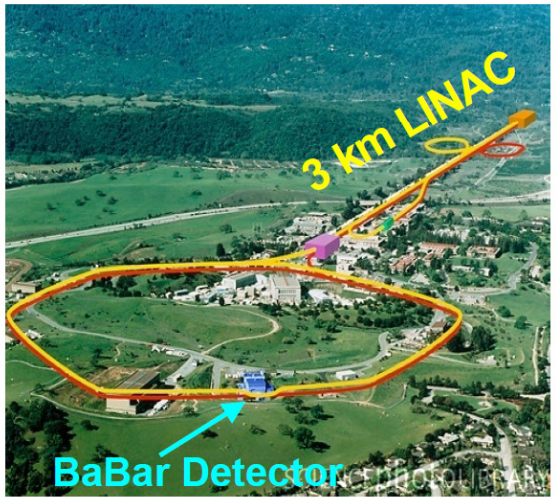
- July 19, 2008: first e^+e^- collision event in BESIII
- Nov. 2008: ~ 14M $\psi(2S)$ events for detector calibration
- 2009: 106M $\psi(2S)$ 4*CLEOc
  225M J/ψ 4*BESII
- 2010: 900 pb^{-1} $\psi(3770)$
- 2011: 1800 pb^{-1} $\psi(3770)$ 3.5*CLEOc
  470 pb^{-1} @ 4.01 GeV
- 2012: $\psi(2S)$: ~0.4 billion,
- @J/ψ since April 5, ~0.7 billion (peak lum. $2.7X10^{32}$)

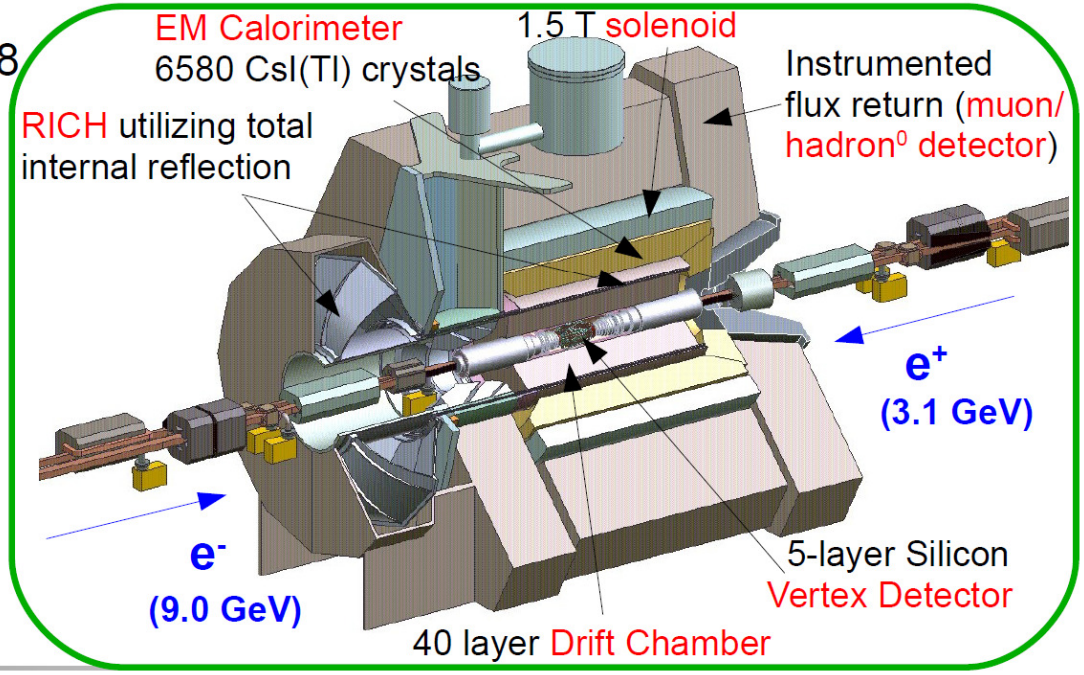
Peak luminosity reached 6.5 X 10^{32} @3770 MeV

The BaBar Experiment

- B-Factory at the PEP-II aymmetric e^+e^- collider located at SLAC National Accelerator Laboratories, California
- Collected 531.43 fb^{-1} at the CM energy 10.58 GeV for $\Upsilon(4S) \rightarrow B\overline{B}$
  - 465 x 10^6 $B\overline{B}$ 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}



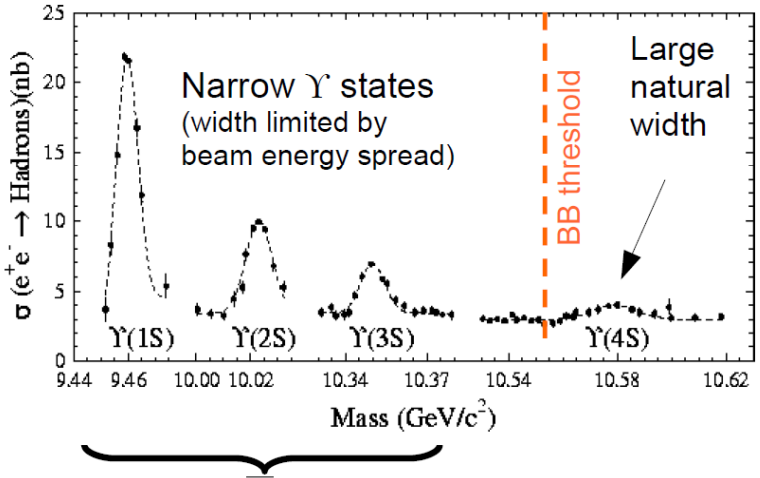


BaBaR Data Samples

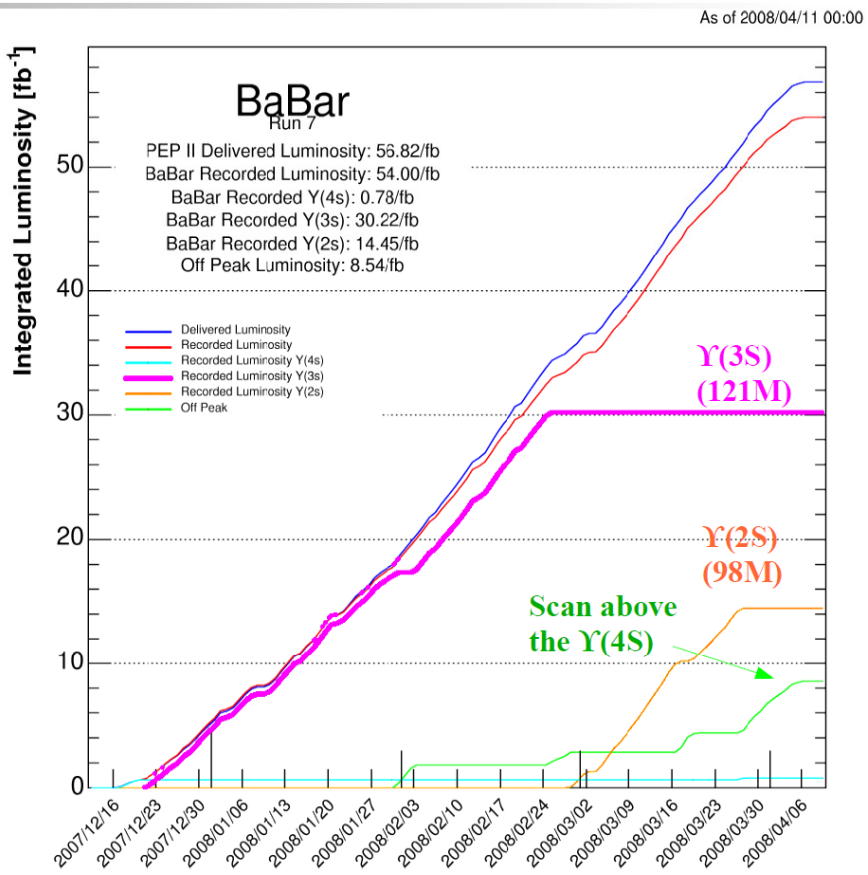
- In final year, also collected:

Today's Talk

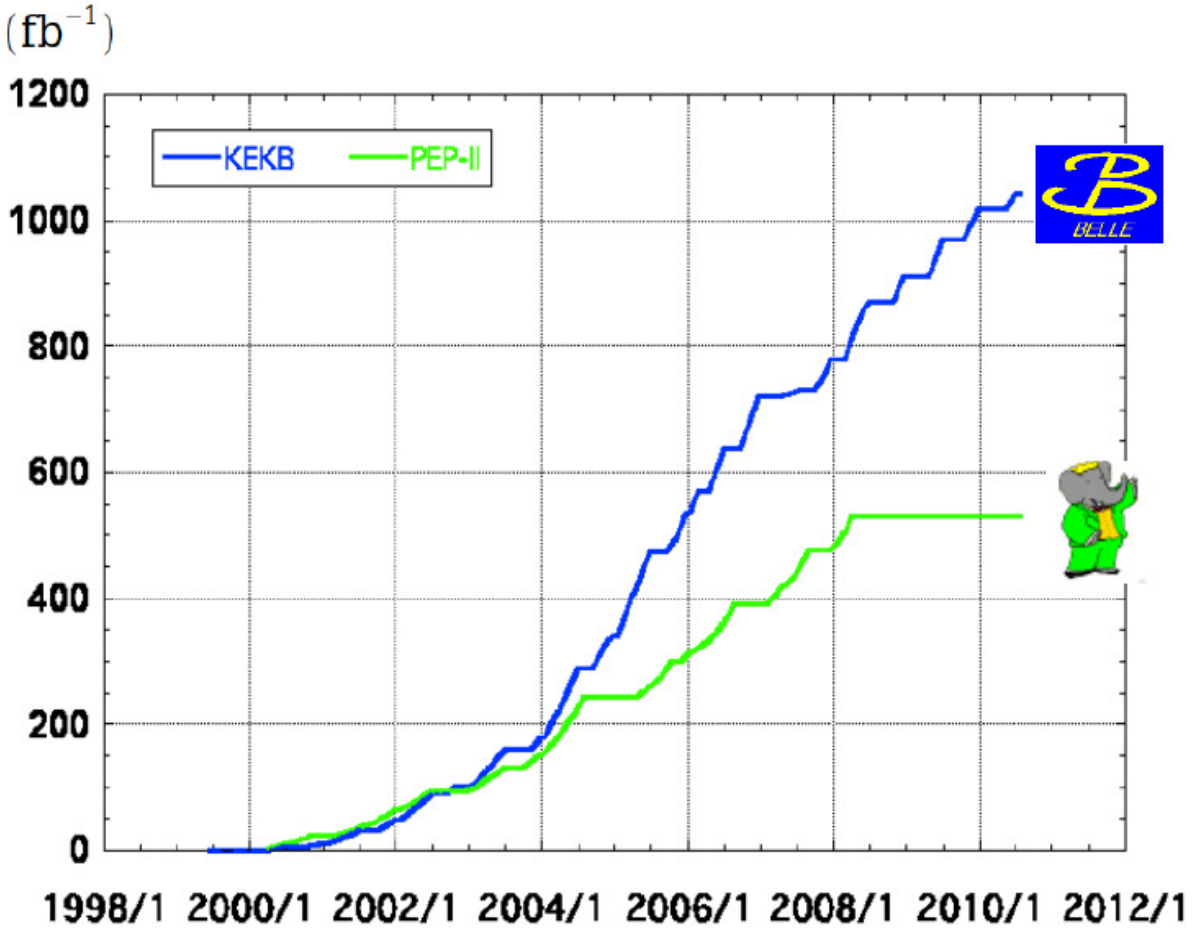
- 121 x 10^6 $\Upsilon(3S)$ decays
- 98 x 10^6 $\Upsilon(2S)$ decays
- ~18 x 10^6 $\Upsilon(1S)$ from $\Upsilon(2S) \rightarrow \pi\pi\Upsilon(1S)$ decays
- Above $\Upsilon(4S)$ scan



No $B\bar{B}$ decays:
Clean environment for New Physics searches



Integrated luminosity of B factories



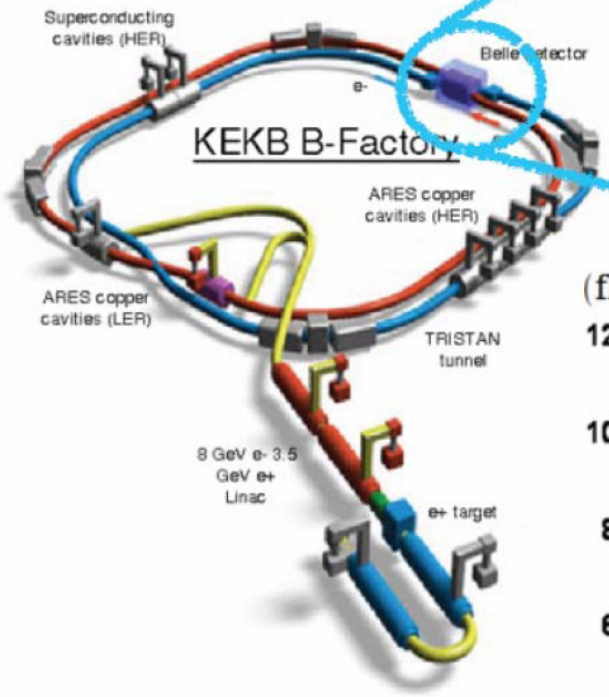
> 1 ab^{-1}
On resonance:
Υ(5S): 121 fb^{-1}
Υ(4S): 711 fb^{-1}
Υ(3S): 3 fb^{-1}
Υ(2S): 25 fb^{-1}
Υ(1S): 6 fb^{-1}
Off reson./scan:
~ 100 fb^{-1}

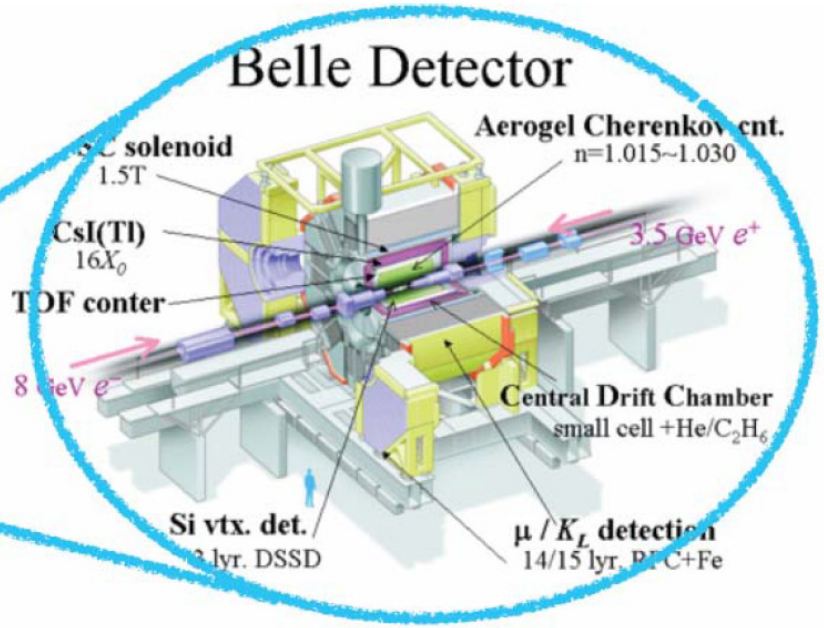
~ 550 fb^{-1}
On resonance:
Υ(4S): 433 fb^{-1}
Υ(3S): 30 fb^{-1}
Υ(2S): 14 fb^{-1}
Off resonance:
~ 54 fb^{-1}

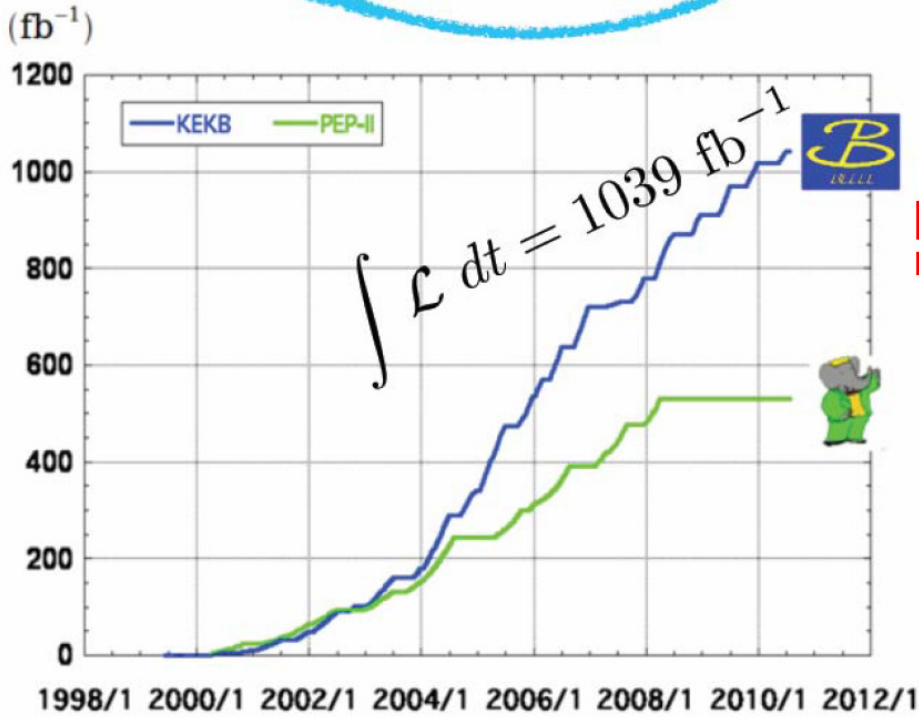
1020 fb^{-1} of data collected

13 countries
65 institues
~400 members

$\mathcal{L}_{\rm peak} = 21.1\ {\rm nb}^{-1}{\rm s}^{-1}$







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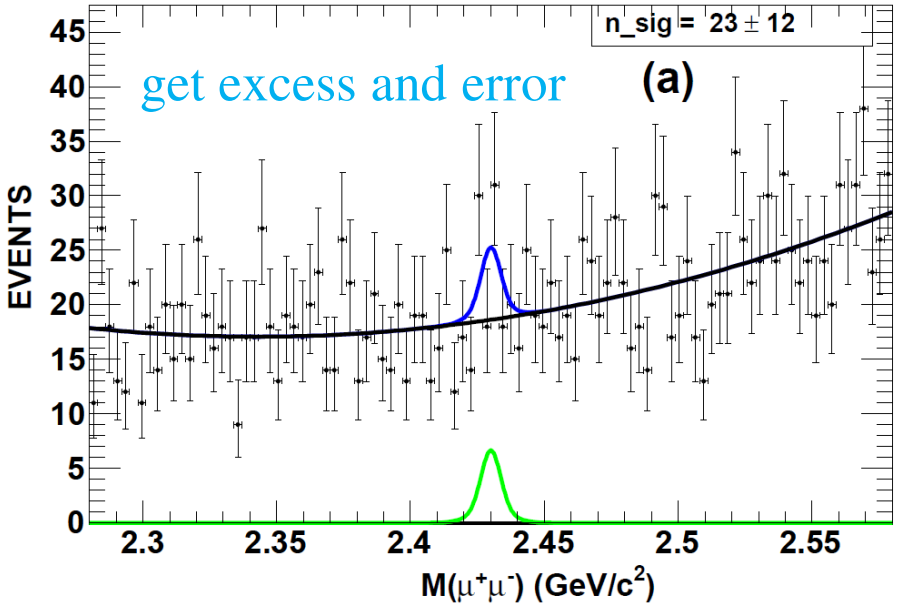
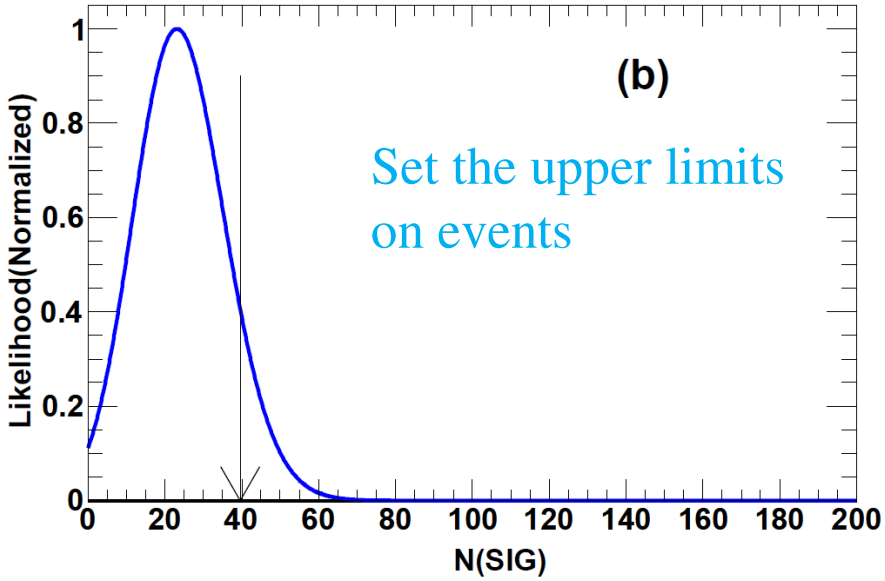
arXiv:1111.2112v1





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