Searches for Exotics in Upsilon Decays at BaBar

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Dark Force Workshop

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Outline

- Motivation
- Present four recent exotics searches at BaBar:

  Higgs searches
  - $\Upsilon(3S,2S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ — *PRL 103, 081803 (2009)*
  - $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$ — *Submitted to PRL* *arXiv:0906.2219*
  - $\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ invisible — *Preliminary* *arXiv:0808.0017*

  Dark Matter search
  - $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \to$ invisible — *Submitted to PRL* *arXiv:0908.2840*

- Summary

Motivation

Light exotic particle can be discovered at BaBar!

Exotic particles:

- Light CP-odd Higgs
- Axion-like Pseudoscalar particle
- Dark Matter (DM) candidate

Motivation for Higgs searches

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

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

Motivation for Higgs Searches

Next-to-Minimal Supersymmetric SM

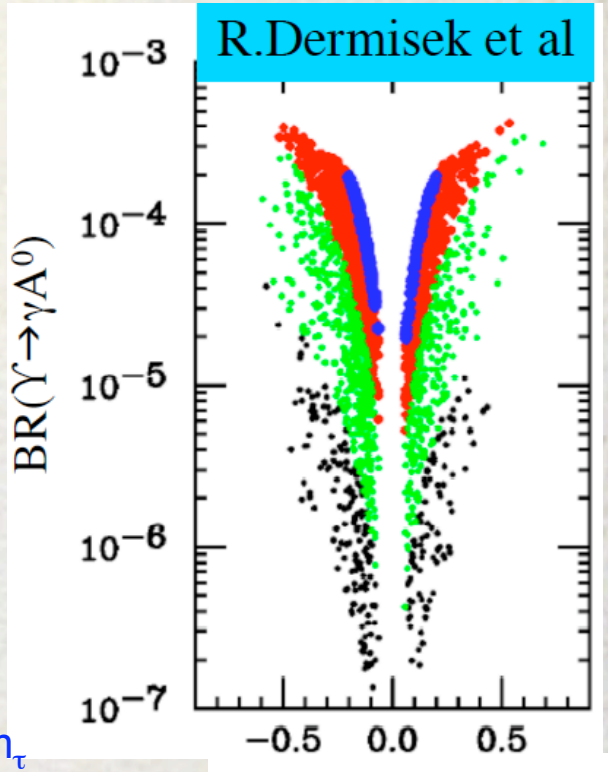
- It solves hierarchy problem by extending Higgs sector
- It leads to a CP-odd Higgs A^0
  - Its mass can be less than $2m_b$
  - Large BF for $\Upsilon \rightarrow \gamma A^0$ is expected

R. Dermisek et al., PRD 76, 051105 (2007)

Look for η_b mass region

- Recently discovered at BaBar
  - Confirmed by CLEO

BEAUTY 2009, K. Seth's talk



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

Motivation for $A^0 \rightarrow \mu^+\mu^-$

Axion-like Pseudoscalar particle

- TeV-scale DM that annihilates into them
- Predicts BF($Y \rightarrow \gamma A^0$) to be 10^{-6}~10^{-5} at m_{A0} around 400~800 MeV
- A^0 dominantly decays into $\mu^+\mu^-$

Nomura, Thaler, PRD 79, 075008 (2009)

HyperCP experiment

- Observed resonance-like feature at ~214 MeV decaying into $\mu^+\mu^-$

Mangano, Nason, Mod. Phys. Lett. A 22, 1373 (2007)

Motivation for DM search

$\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ invisible

Motivation for DM Search

Light scalar DM couple to SM thru new Gauge boson U

McElrath, PRD 72, 103508 (2005)

- This theory can explain
  - INTEGRAL's detection of 511 keV gamma rays from the galactic center. If it's from DM annihilation into e^+e^-, DM's mass: 1~100MeV

    Phys.Rev.Lett. 92, 101301 (2004)
- Estimated Branching Fraction:
  - BF(Y(1S)$\rightarrow\nu\nu$) ~ 9.9×10^{-6}
  - BF(Y(1S)$\rightarrow\chi\chi$) ~ 4.2×10^{-4} (s-wave)
  - BF(Y(1S)$\rightarrow\chi\chi$) ~ 1.8×10^{-3} (p-wave)

Searches for Higgs

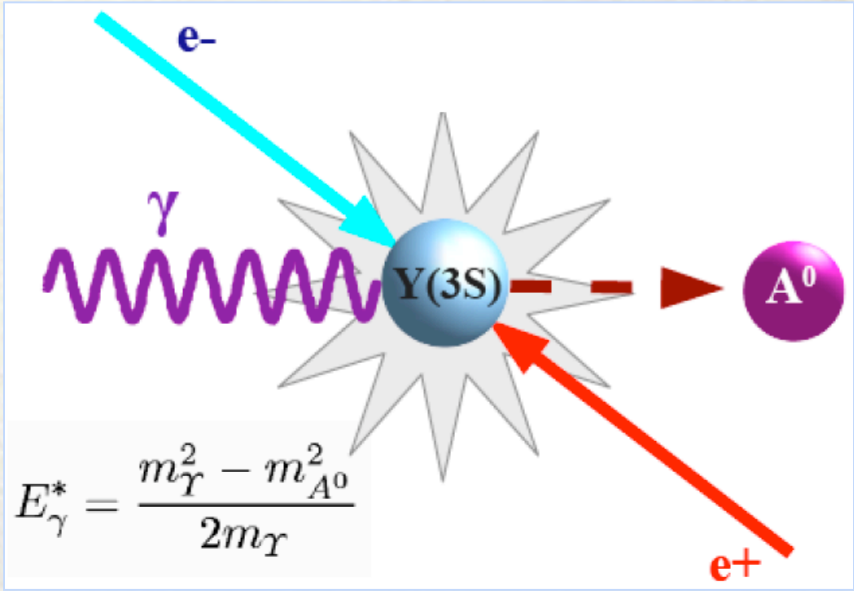
$\Upsilon(3S,2S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

Searches for Higgs from Upsilon decays

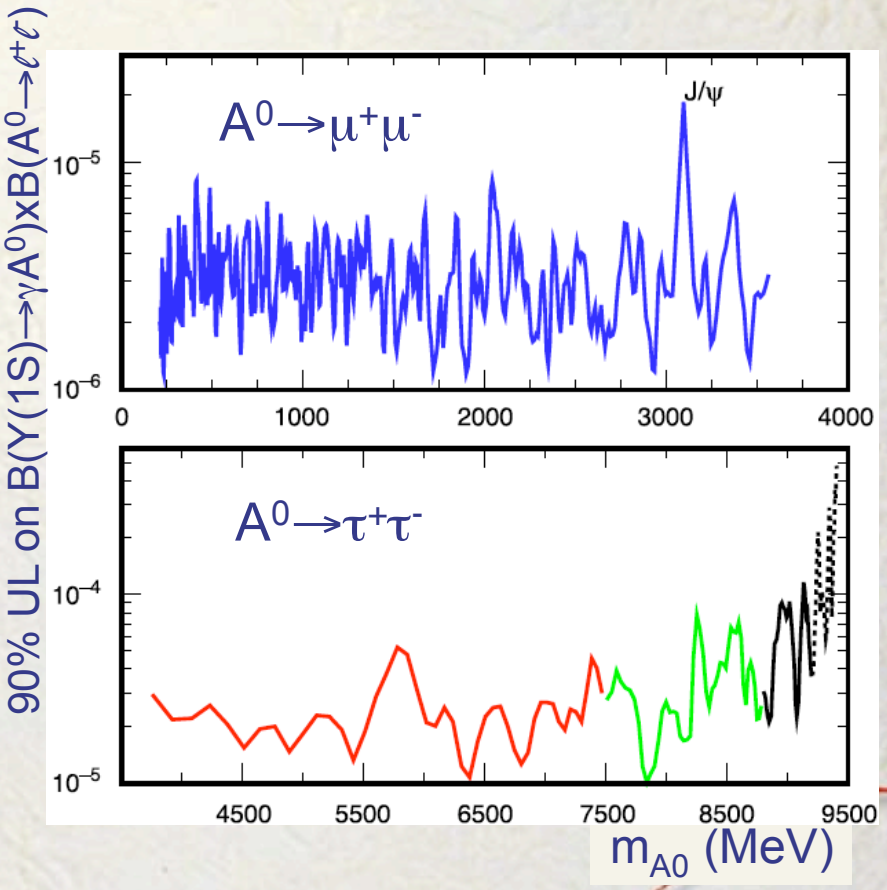
- Wilczek proposed to look at $\Upsilon \rightarrow \gamma A^0$ *PRL 39, 1304 (1977)*
- Key feature: two body decay
  - Photon energy is related to the Higgs (recoil) mass
- Scan for bumps
- BaBar data sample contains 122x10^6 Y(3S), 99x10^6 Y(2S) events



Previous Searches

- CLEO has limit on BF(Y(1S)→γA^0)
  - A^0→μ$^+$μ$^-$
    - UL @ 10^{-6}~10^{-5}
    - m_{A0} range:
      0.201~3.565 GeV
  - A^0→τ$^+$τ$^-$
    - UL @ 10^{-5}~10^{-4}
    - m_{A0} range:
      4.03~9.5 GeV

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



Searches for Higgs

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

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

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

Event Selection

- Fully-reconstructed final state: exactly 2 oppositely-charged tracks, 1 photon with E*>0.2 GeV
- At least one track should satisfy μ particle ID
- Y candidate is energy and beam spot constrained
- Muon pair & photon are back-to-back in CM
- Signal eff: 24~55%

Dominant Background

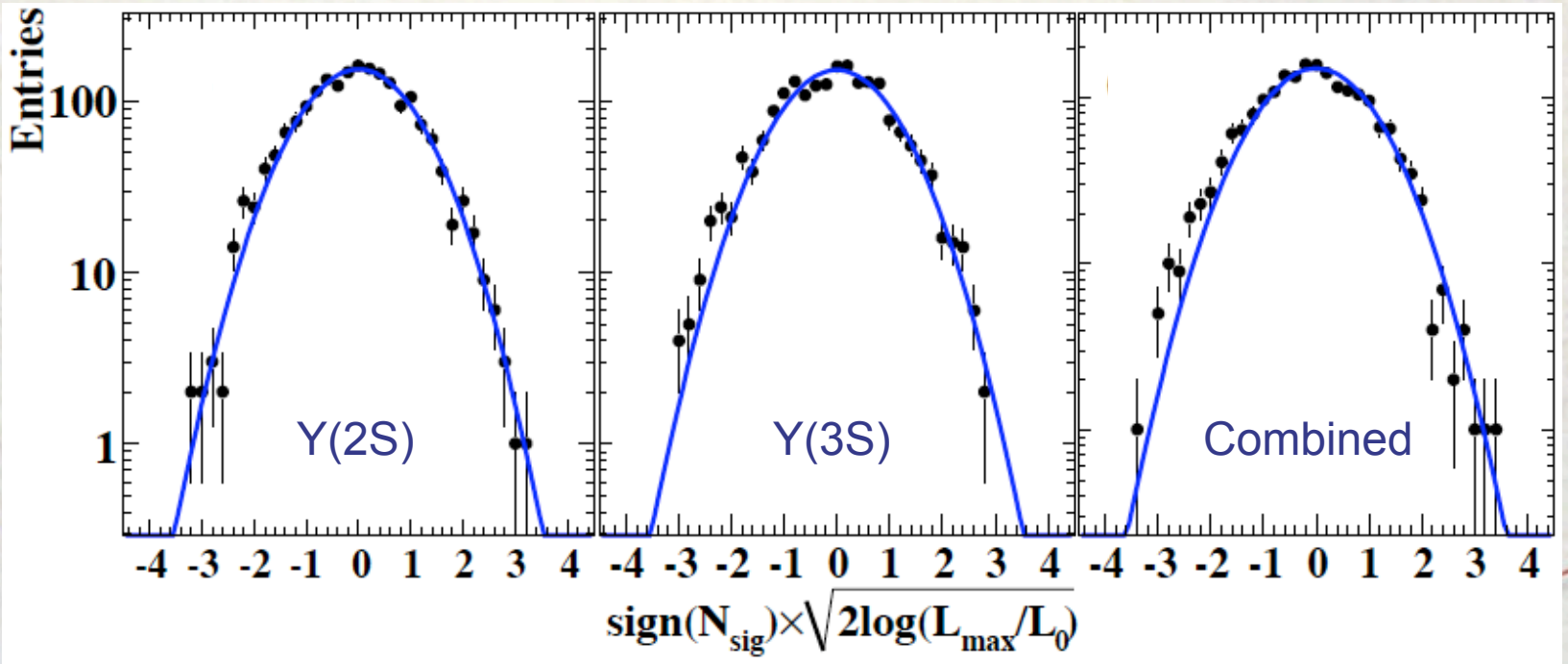
- QED continuum events $e^+e^- \to \gamma\mu^+\mu^-$
- ISR production of ρ^0
  - Require both tracks to satisfy muon PID in $0.5<m_{A0}<1.05$ GeV
- ISR production of Y(1S)
  - $\Upsilon(2S) \to \gamma_2\chi_b(1P), \chi_b(1P) \to \gamma_1\Upsilon(1S)$
  - $\Upsilon(3S) \to \gamma_2\chi_b(2P), \chi_b(2P) \to \gamma_1\Upsilon(1S)$
  - Require no secondary photon(γ_2) with E*>0.1(2S), 0.08(3S) GeV

Scan strategy

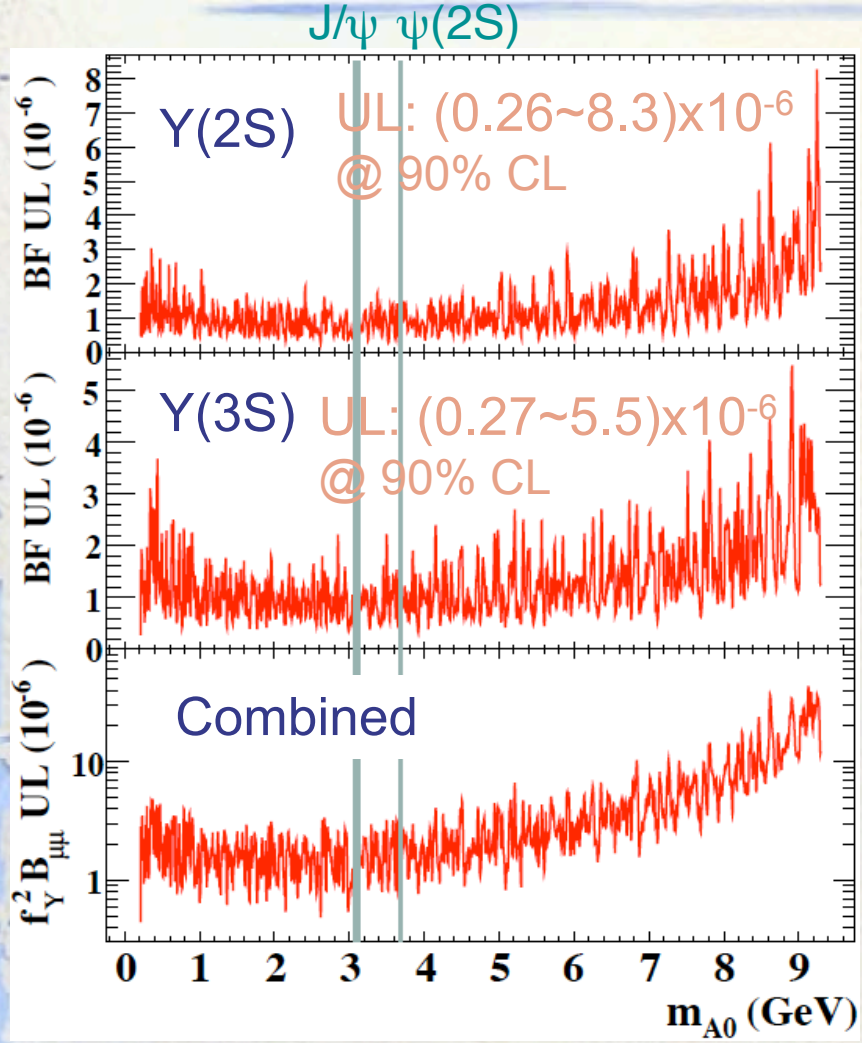
- Extended unbinned ML fit in 1951 scan points
  - Mass range: m_{A0}=0.212~9.3 GeV
  - Step size: 2-5 MeV steps,
- Fit to "reduced mass" $m_R = \sqrt{m^2_{A^0} - 4m^2_\mu} = 2|p^{A^0}_\mu|$
- Probability Density Functions:
  - Signal: Sum of two Crystal Ball functions
  - Peaking bkg: ϕ, J/ψ, ψ(2S), Y(1S)
    - PDF (same as signal), included in fit
    - J/ψ, ψ(2S) veto (exclude ~40(25) MeV near J/ψ(ψ(2S)) mass)
  - Continuum bkg: tanh function for low mass (m_{A0}<0.23) and Chebychev polynomial

Scan Result

- Sign(N_{sig})xsqrt(2log(L_{max}/L_0)) distribution
- Agrees with standard normal distribution for null hypothesis. => No significant outliers



Results



- Rule out Higgs interpretation of HyperCP events
- Limit on BF($\eta_b \to \mu^+\mu^-$)<0.9% at 90% CL
- Combined result is related to the effective Yukawa coupling f_Y

$$\frac{\mathcal{B}(\Upsilon(nS) \to \gamma A^0)}{\mathcal{B}(\Upsilon(nS) \to l^+l^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right)$$

- For m_{A0}<1GeV, $f_Y < 0.12 f_Y^{SM}$

PRL 103, 081803 (2009)

Searches for Higgs

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

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

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

Event Selection

- Both τ decay leptonically (ee, eμ, $\mu\mu$ modes)
- Partially-reconstructed final states: 1 photon with E_γ>100MeV, exactly two charged tracks
- Signal eff:10~14%(ee), 22~26%(eμ), 12~20%($\mu\mu$)
- E_γ resolution: 8~55MeV grows with E_γ

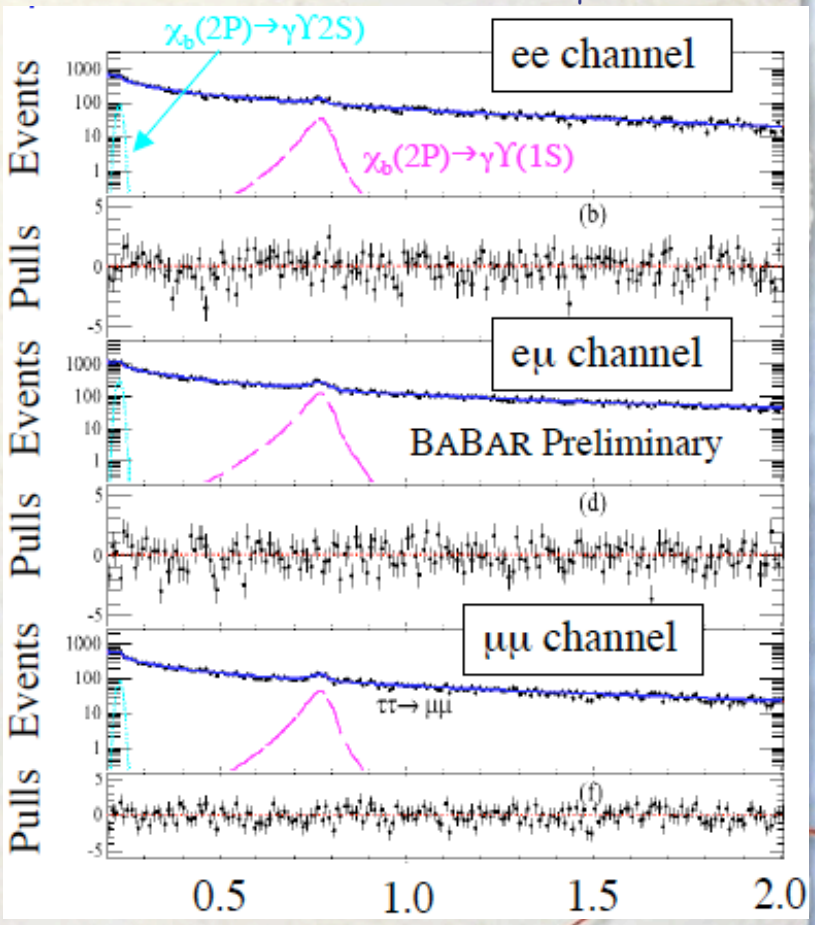
Dominant Background

- QED continuum events $e^+e^- \to \gamma\tau^+\tau^-$
- Higher order QED events such as $e^+e^- \to e^+e^-e^+e^-$, $e^+e^- \to e^+e^-\mu^+\mu^-$
- Constrain on missing mass/angle, angle btw photon and plane of leptons, total energy, …
- Optimize in 5 E_γ ranges

Scan Stragety

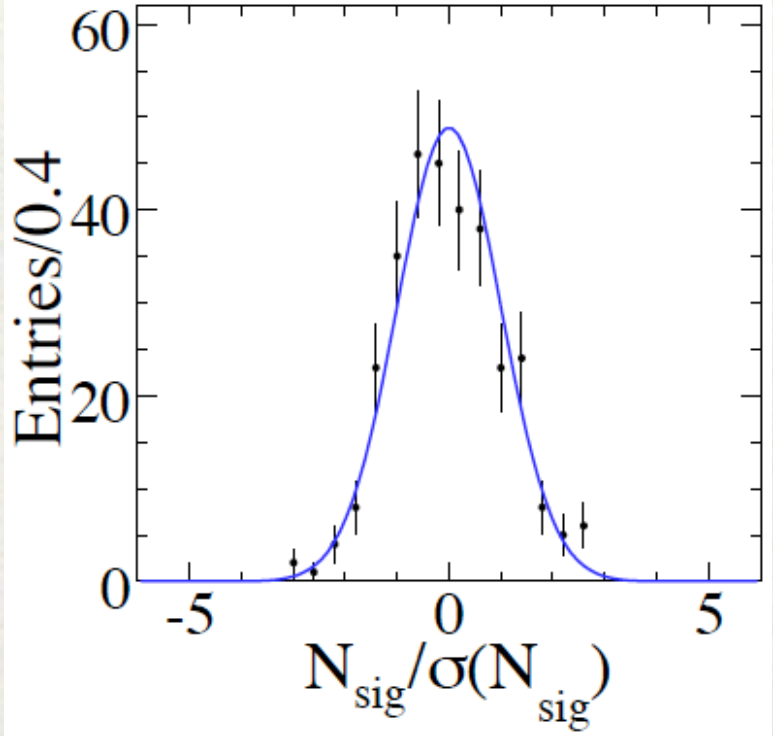
- Binned ML fit in 307 scan points, simultaneously to all modes in E_γ distribution (step size= $0.5 \times \sigma(E_\gamma)$)
- Signal PDF: Crystal Ball function
- Peaking bkg:
  - $\Upsilon(3S) \to \gamma\chi_b$, $\chi_b \to \gamma\Upsilon(1S,2S)$ $\Upsilon(1S,2S) \to \tau^+\tau^-$
  - Crystal Ball functions

Bkg distribution for E_γ<2GeV

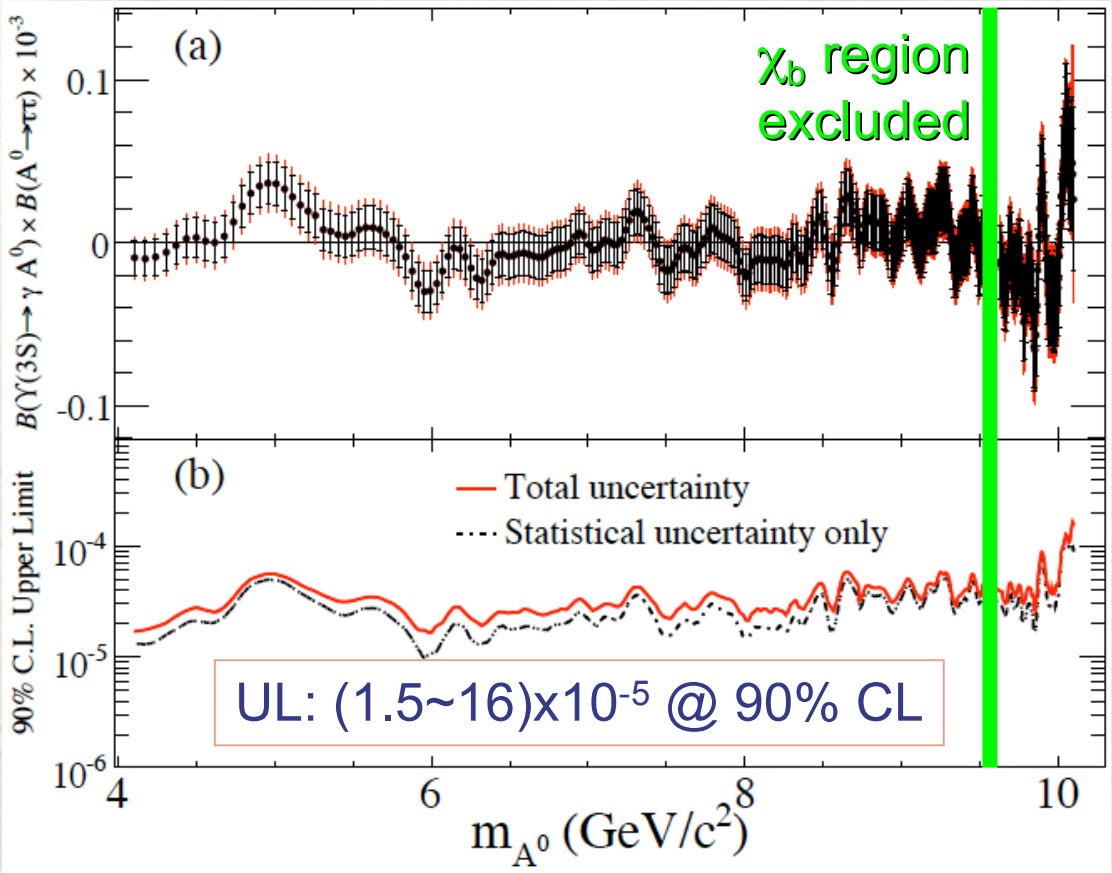


Scan Result

- $N_{sig}/\sigma(N_{sig})$ distribution
- Agrees with standard normal distribution for null hypothesis. => No significant outliers



Results



Submitted to PRL
arXiv:0906.2219

- Set a limit on BF($\eta_b \to \tau^+\tau^-$)<8% at 90% CL

Searches for Higgs

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

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

$\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow$ invisible

- Require a single photon with $E^*_\gamma > 2.2$ GeV, no charged tracks
- Little activities in the detector is required
- Resolution for signal event: 1.5~0.7GeV, shrinks as m_{A0} increases
- Signal eff: 10~11%($E^*_\gamma > 3$GeV), ~20%($E^*_\gamma < 3$GeV)

Dominant Background

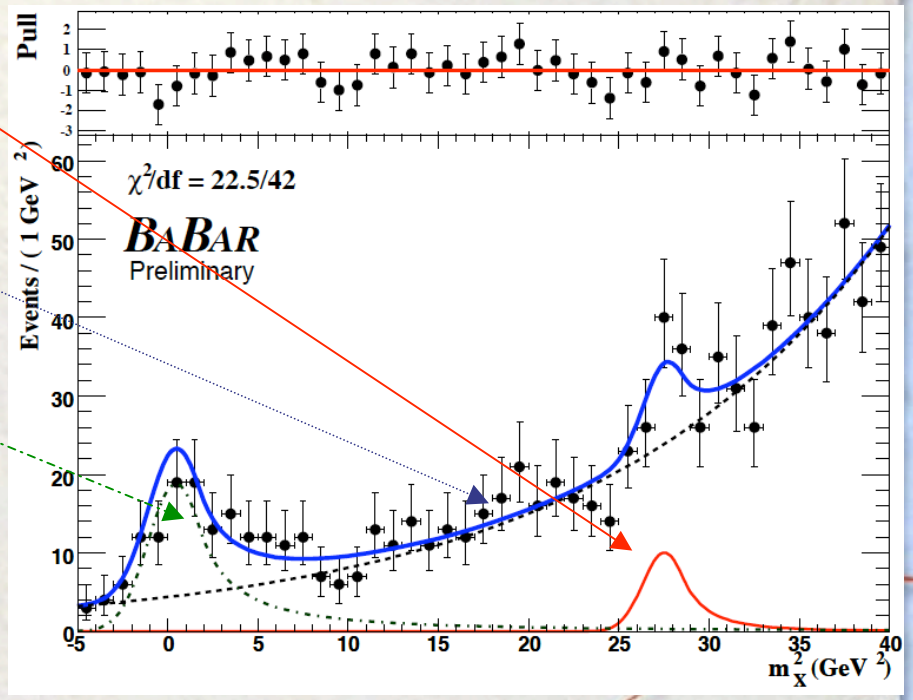
- QED process $e^+e^- \rightarrow \gamma\gamma$
  - Peaking bkg, include in fit
- Radiative Bhabha event $e^+e^- \rightarrow \gamma e^+e^-$, two photon fusion event
  - Non peaking, include in fit
- Previous searches by CLEO
  - UL @ 10^{-5}~10^{-3} (@90% CL)

Balest et al., PRD 51, 2053 (1995)

Scan Strategy

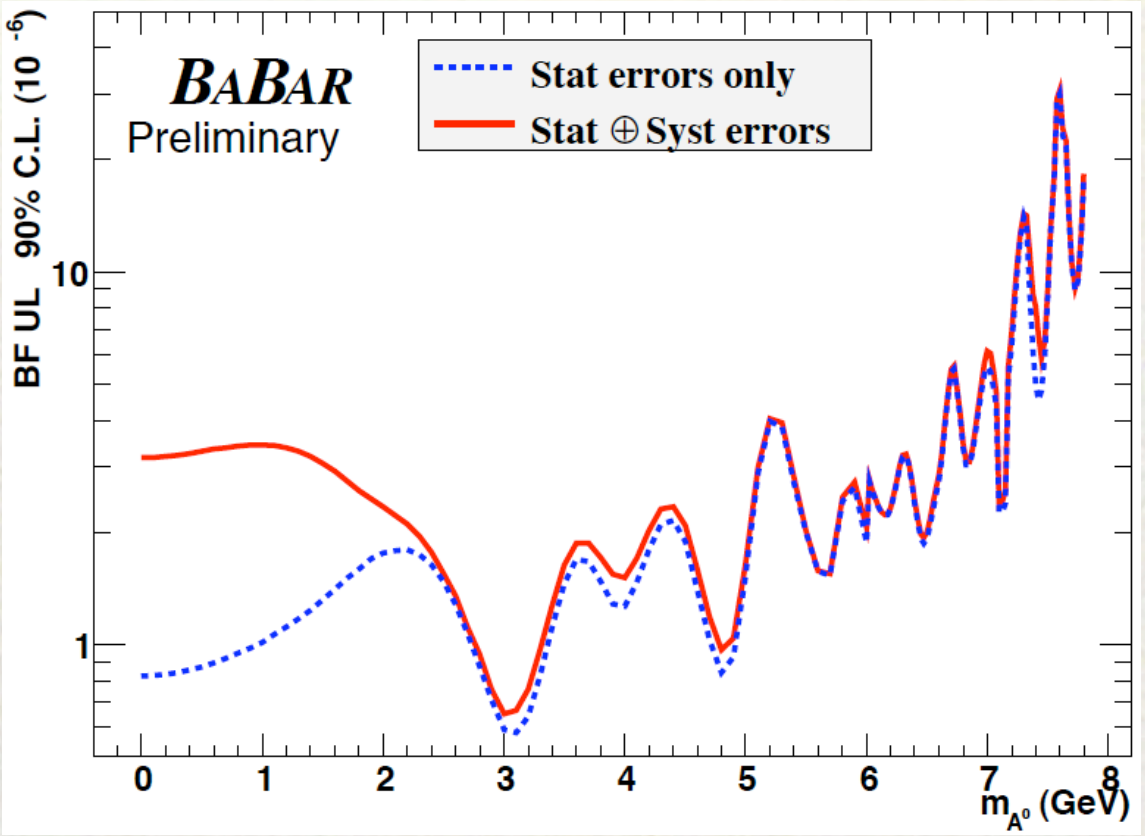
- Unbinned extended ML fit to distribution of missing mass squared $m_X^2 \equiv m_{\Upsilon(3S)}^2 - 2E_\gamma^* m_{\Upsilon(3S)}$
  - In steps of 100 MeV (E^*_γ>3GeV), 25 MeV(E^*_γ<3GeV)
- Signal PDF: Crystal Ball
- Continuum PDF:

  Exponential function
- Peaking Bkg:
  - From $e^+e^- \rightarrow \gamma\gamma$
  - Fixed in fit



Result

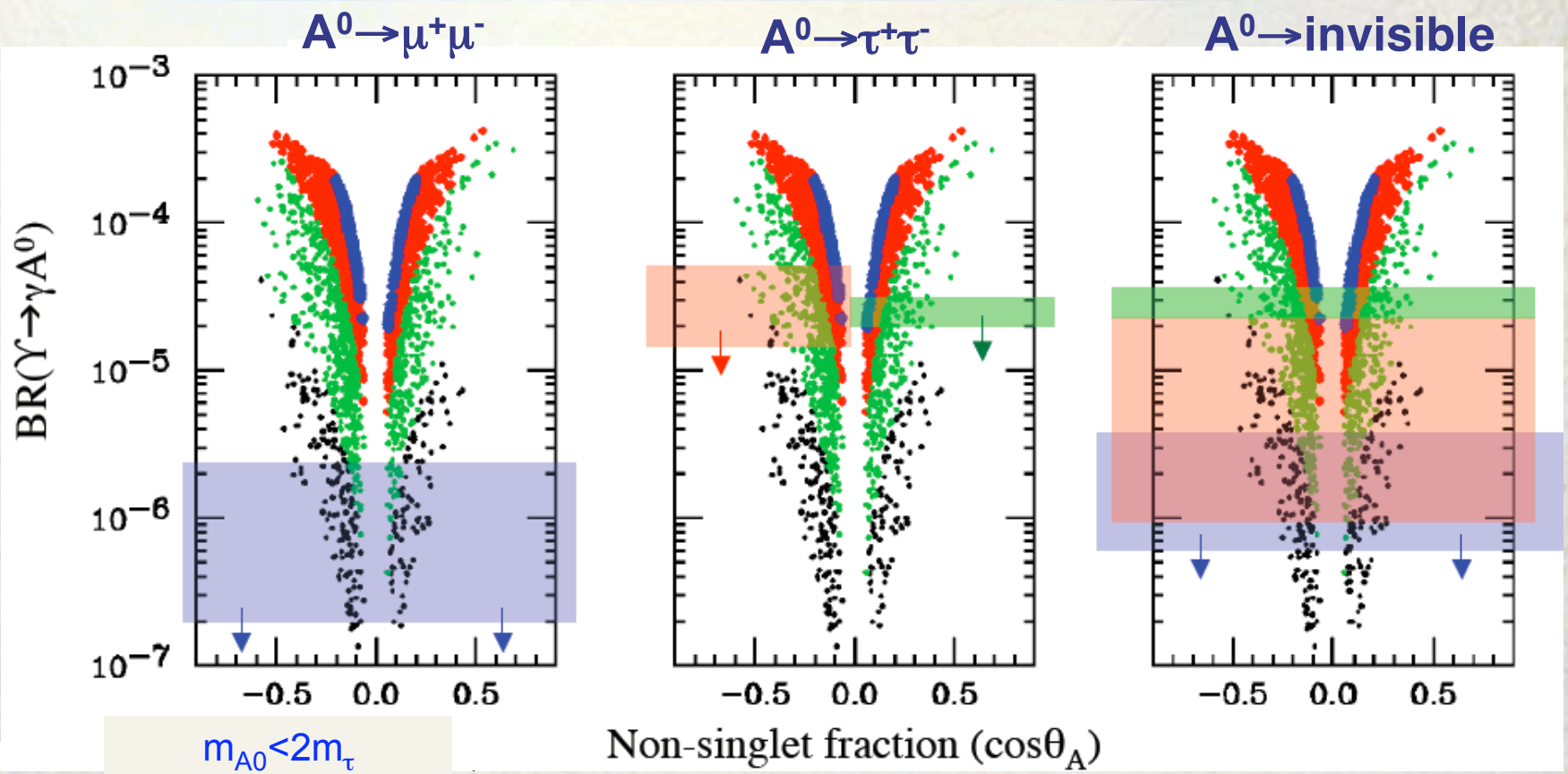
- 90% CL Bayesian UL: $(0.7 \sim 31) \times 10^{-6}$



Orders of magnitude improvement from CLEO result

Preliminary
arXiv:0808.0017

BaBar constraints on NMSSM Predictions for $\Upsilon \to \gamma A^0$



$m_{A0} < 2m_\tau$

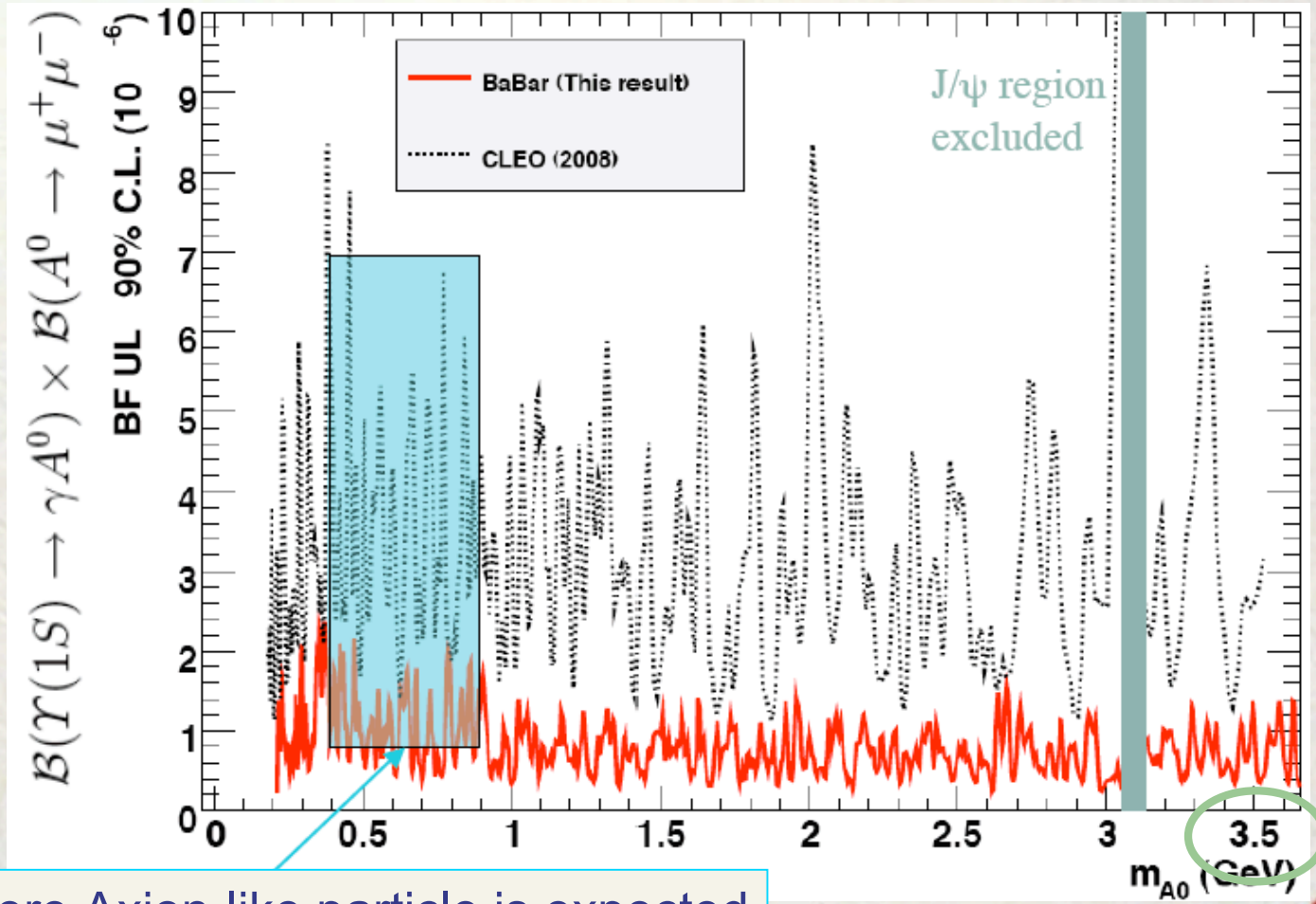
$2m_\tau < m_{A0} < 7.5$ GeV

$7.5 < m_{A0} < 8.8$ GeV

$8.8 < m_{A0} < 9.2$ GeV

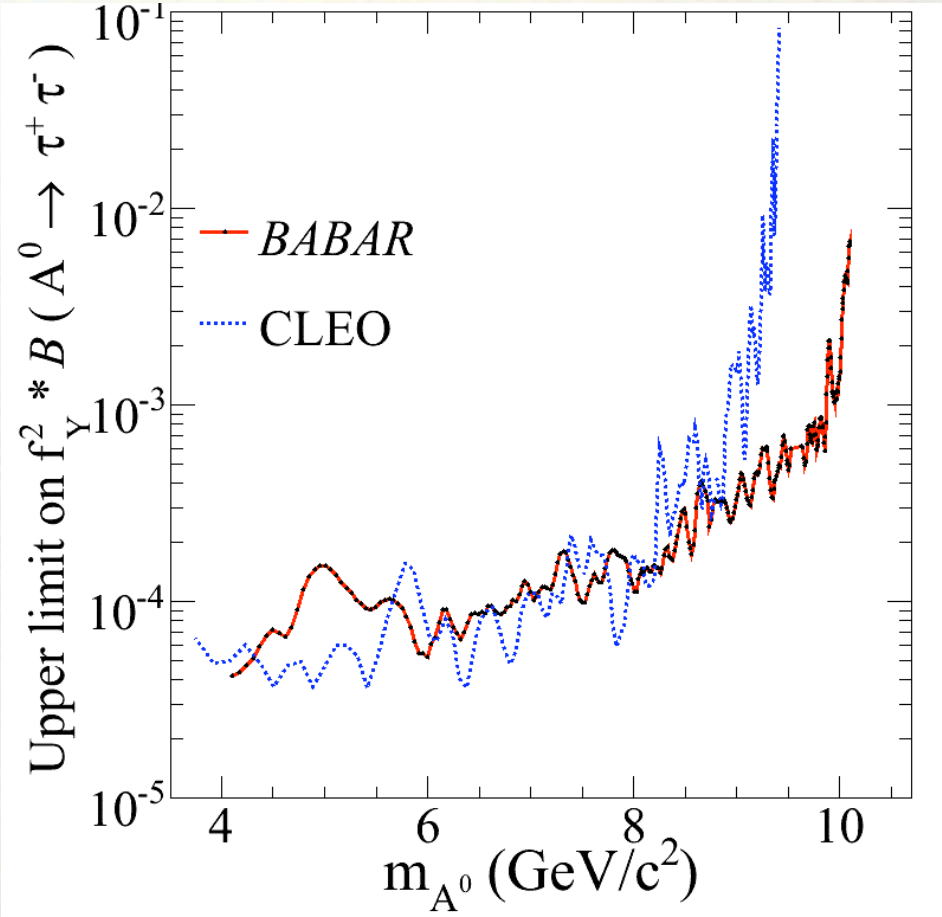
$A^0 \rightarrow \mu^+\mu^-$

CLEO-BaBar comparison



Where Axion-like particle is expected

CLEO-BaBar Comparison

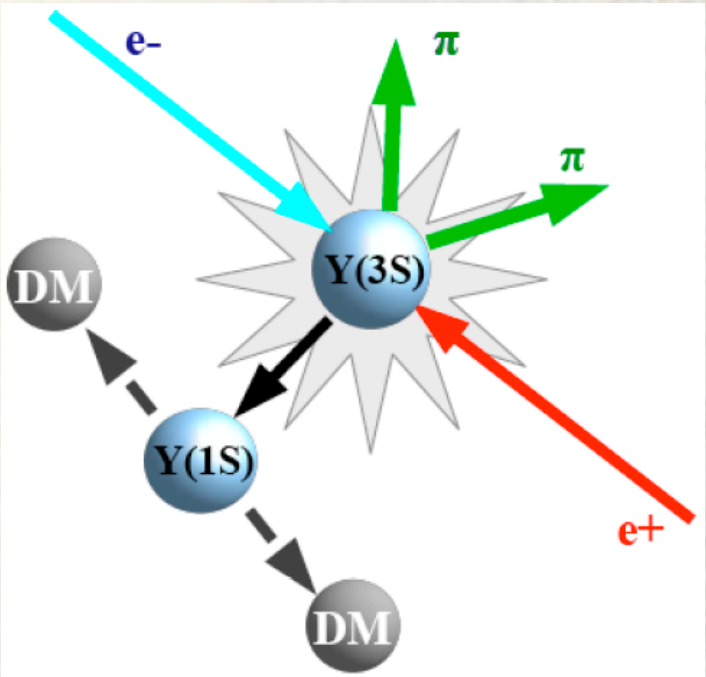


Search for DM

$\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ invisible

$Y(3S)\to\pi^+\pi^- Y(1S)$, $Y(1S)\to$invisible

- Estimated Branching Fraction:
  - BF($Y(1S)\to\nu\nu$) ~ 9.9×10^{-6}
  - BF($Y(1S)\to\chi\chi$) ~ 4.2×10^{-4} (s-wave)
  - BF($Y(1S)\to\chi\chi$) ~ 1.8×10^{-3} (p-wave)
- To ensure Y(1S) in the event with suppressed bkg: $Y(3S)\to\pi^+\pi^- Y(1S)$
- Previous searches by
  - CLEO, BF($Y(1S)\to$invisible)$<3.9\times10^{-3}$ @ 90%CL
    PRD 75, 031104 (2007)
  - Belle, BF($Y(3S)\to\pi^+\pi^- Y(1S)$, $Y(1S)\to$invisible)$<2.5\times10^{-3}$ @90%CL
    PRL 98, 132001 (2007)



$\Upsilon(3S) \to \pi^+\pi^- \Upsilon(1S)$, $\Upsilon(1S) \to$ invisible

Event Selection

- Exactly two low-momentum oppositely charged tracks & little activity in the detector
- Cuts optimized using multivariate method
  - $\pi^+\pi^-$ vertex is from IP
  - Angle and p_T of $\pi^+\pi^-$
  - π pass e, K, μ PID or not
- Signal efficiency ~ 18%

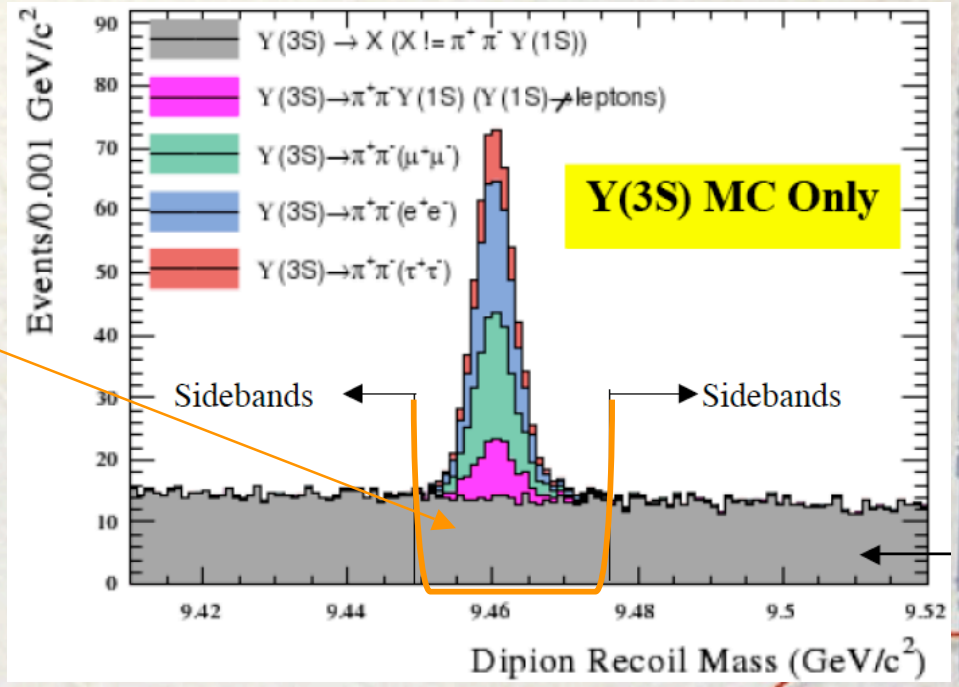
Background

- Non-peaking background is suppressed by more than a factor of 1000
- Peaking backgrounds
  - where $\Upsilon(3S)$ decays into leptons/hadrons
- Use $\Upsilon(1S) \to \ell^+\ell^-$ sample with 1 or 2 leptons reconstructed for calibration, cross-checks

Strategy

Y(1S) mass is known!

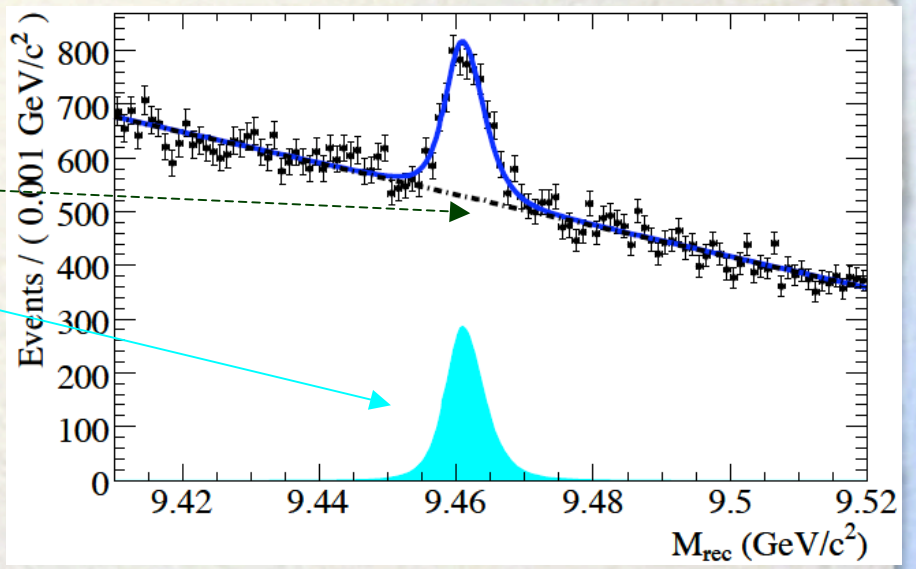
- Look at recoil mass $M^2_{\rm rec} = s + M^2_{\pi\pi} - 2\sqrt{s}E^*_{\pi\pi}$
  - Sqrt(s)=10.3552 GeV/c^2
  - M_{rec} should be Y(1S) mass
- Do not look at data in Signal Region
  - Optimize cuts using signal MC and sidebands
  - From MC 2444 ± 123 peaking background events are expected



Result

Extended unbinned ML fit to recoil mass distribution on data

- Non-peaking bkg:
  - 1st order polynomial
- Peaking PDF (Crystal Ball)
  - Includes signal and peaking background
  - Yield: 2326 ± 105 evts
- Bayesian UL at 90% CL: BF(Y(1S)→invis.)<3.0x10^{-4}
- 91.4x10^{6} Y(3S) events used for BF/UL calculation



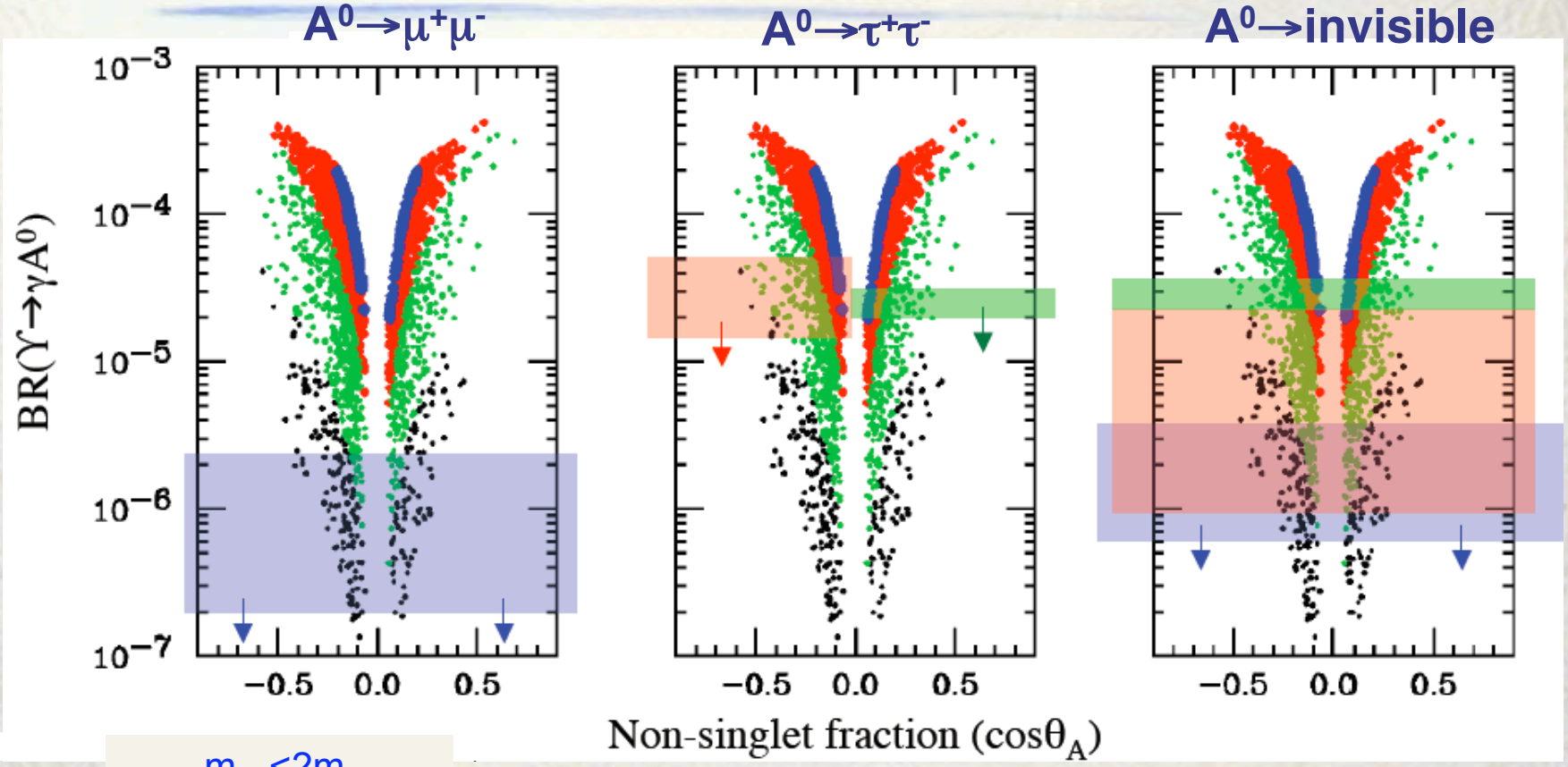
- Order of magnitude improvement from Belle result

Submitted to PRL
arXiv:0908.2840

Summary

- No observed signal of CP-odd Higgs in radiative Y(2S,3S) decays in $\mu^+\mu^-$, $\tau^+\tau^-$, invisible final states
  - Set upper limits that rule out much of available parameter space
  - Rule out Higgs interpretation of HyperCP anomaly
  - Set the first limits on BF of exclusive η_b decays
    - $BF(\eta_b \to \mu^+\mu^-) < 0.9\%$, $BF(\eta_b \to \tau^+\tau^-) < 8\%$ (@90% CL)
- No observed signal of DM in invisible decays of Y(1S)
  - Set the most stringent UL: $BF(Y(1S) \to \text{invis.}) < 3.0 \times 10^{-4}$
  - Significant constraints on the models of light DM

Summary

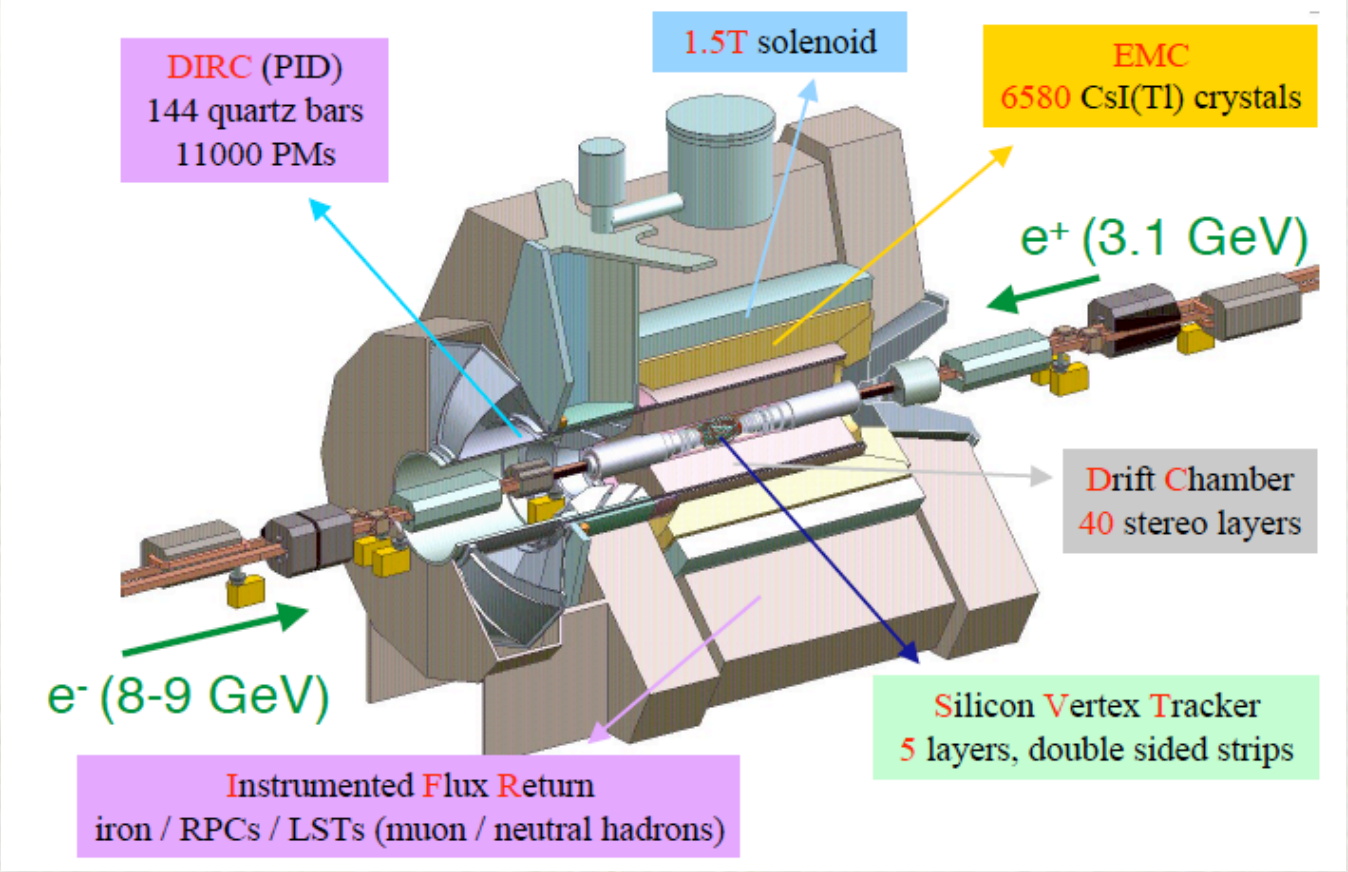


$m_{A0}<2m_\tau$
$2m_\tau<m_{A0}<7.5$ GeV
$7.5<m_{A0}<8.8$ GeV
$8.8<m_{A0}<9.2$ GeV

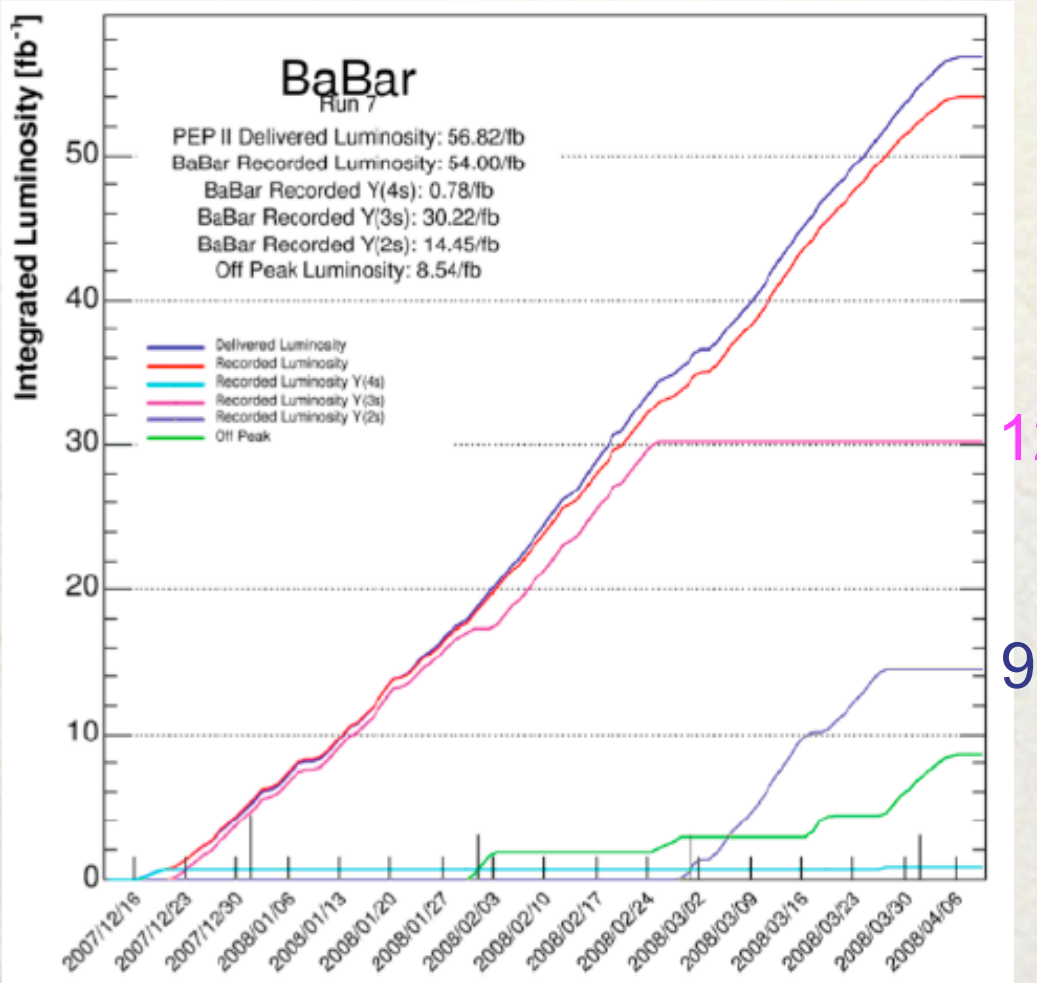
BF(Y(1S)→invis.)<3.0×10^{-4}
CLEO, Belle's UL ~ 10^{-3}
Theory prediction: 10^{-4}~10^{-3}

BACKUP

BaBar Detector



BaBar 2008 Dataset

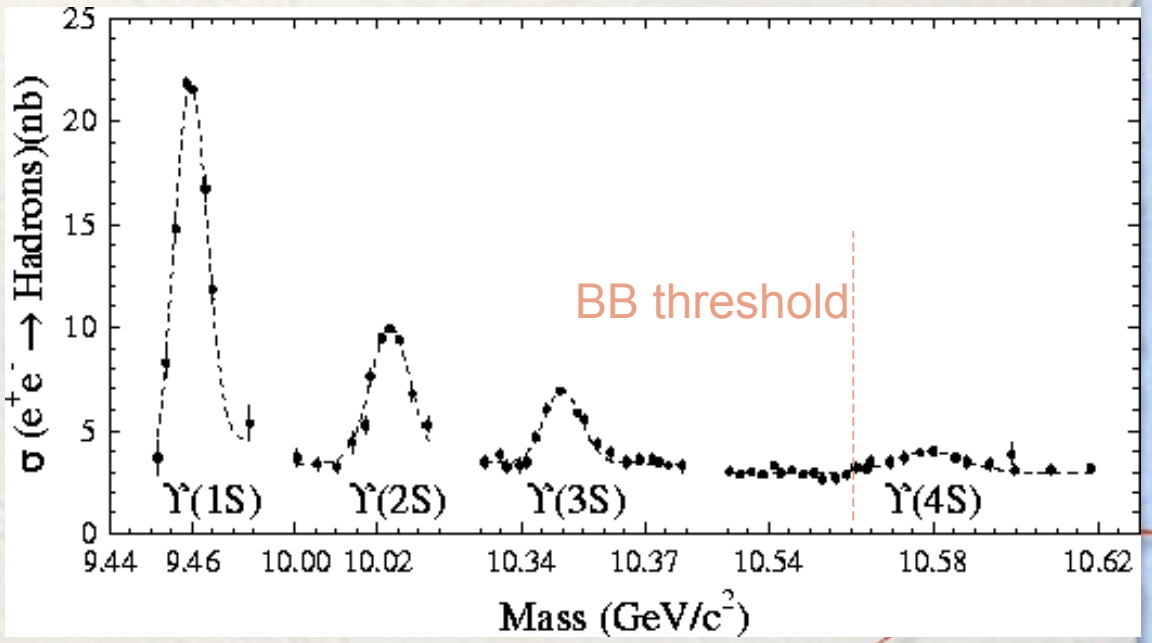


122 Million Y(3S)

99 Million Y(2S)

Searches for Higgs from Upsilon decays

- Y(1~3S) has better sensitivity to new physics than Y(4S) due to narrow width.
  - Γ1~3S : 20~50 keV
  - Γ4S : ~20 MeV

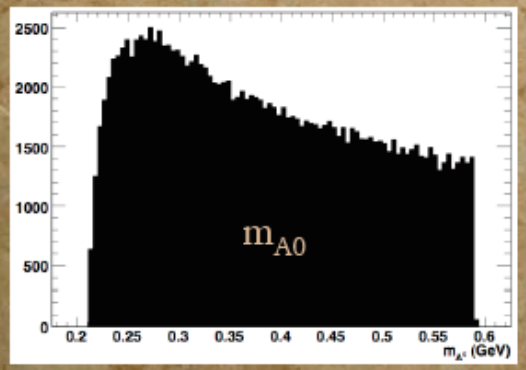


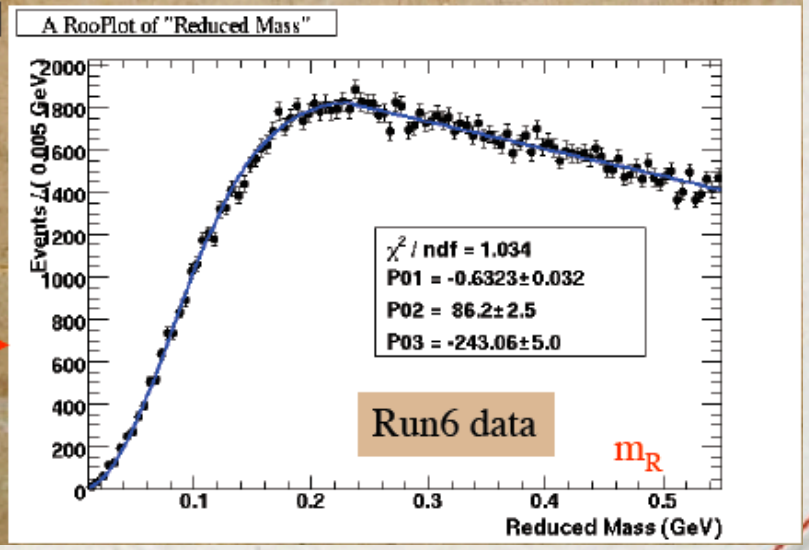
Reduced Mass

- Signal extraction: ML fit in slices of invariant mass
  - Variable of choice is "reduced mass"

$$m_R = \sqrt{m_{A^0}^2 - 4m_\mu^2} = 2|p_\mu^{A^0}|$$

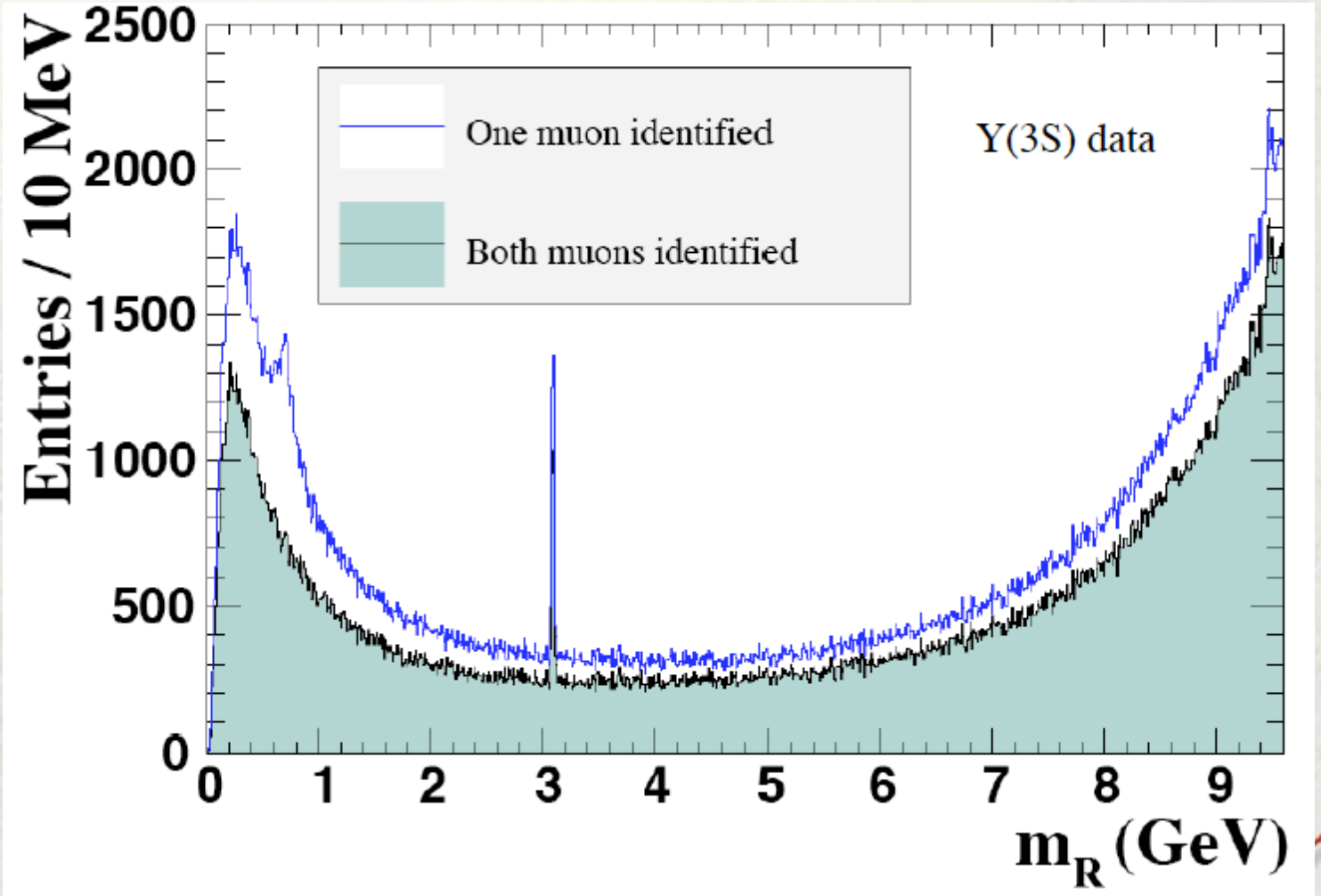
  - Smooth threshold behavior





$A^0 \rightarrow \mu^+\mu^-$

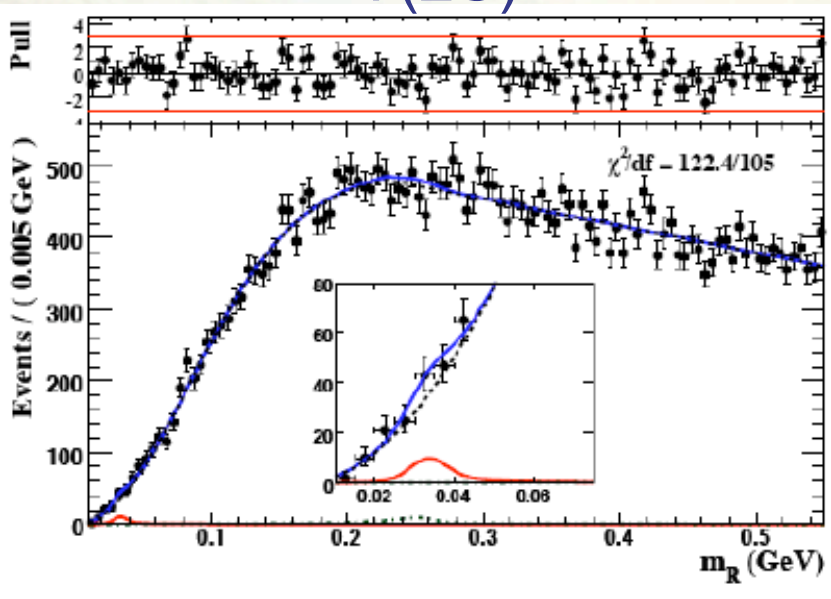
Reduced Mass distribution



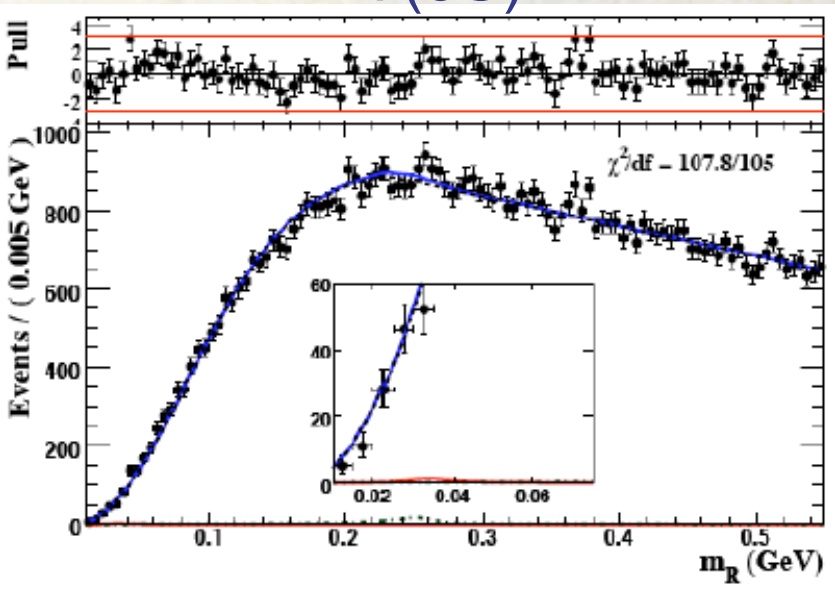
$A^0 \rightarrow \mu^+\mu^-$

HyperCP Mass (m_{A0}=214MeV)

Y(2S)



Y(3S)



$$f_\Upsilon^2(m_{A^0} = 0.214\,\mathrm{GeV}) < 1.6 \times 10^{-6} \text{ at } 90\% \text{ C.L}$$

m_{A0}=0.214GeV ~ m_R=0.034GeV

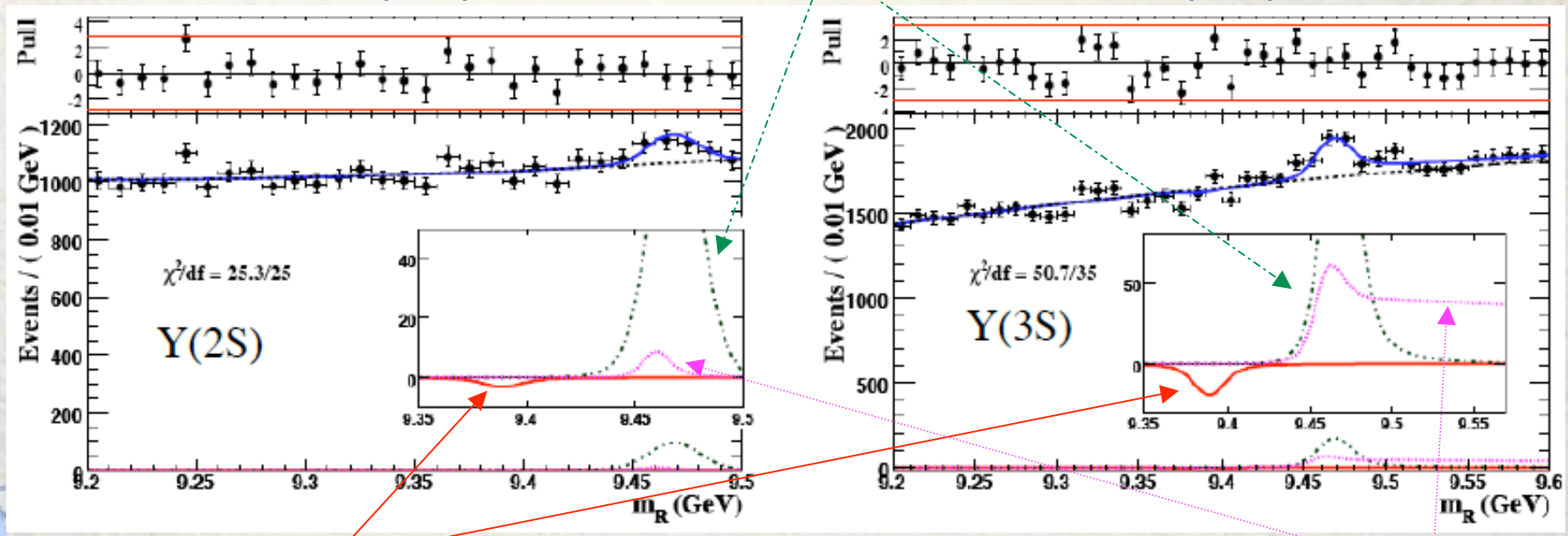
$A^0 \rightarrow \mu^+\mu^-$

η_b region

$e^+e^- \rightarrow \gamma Y(1S)$

Y(2S)

Y(3S)



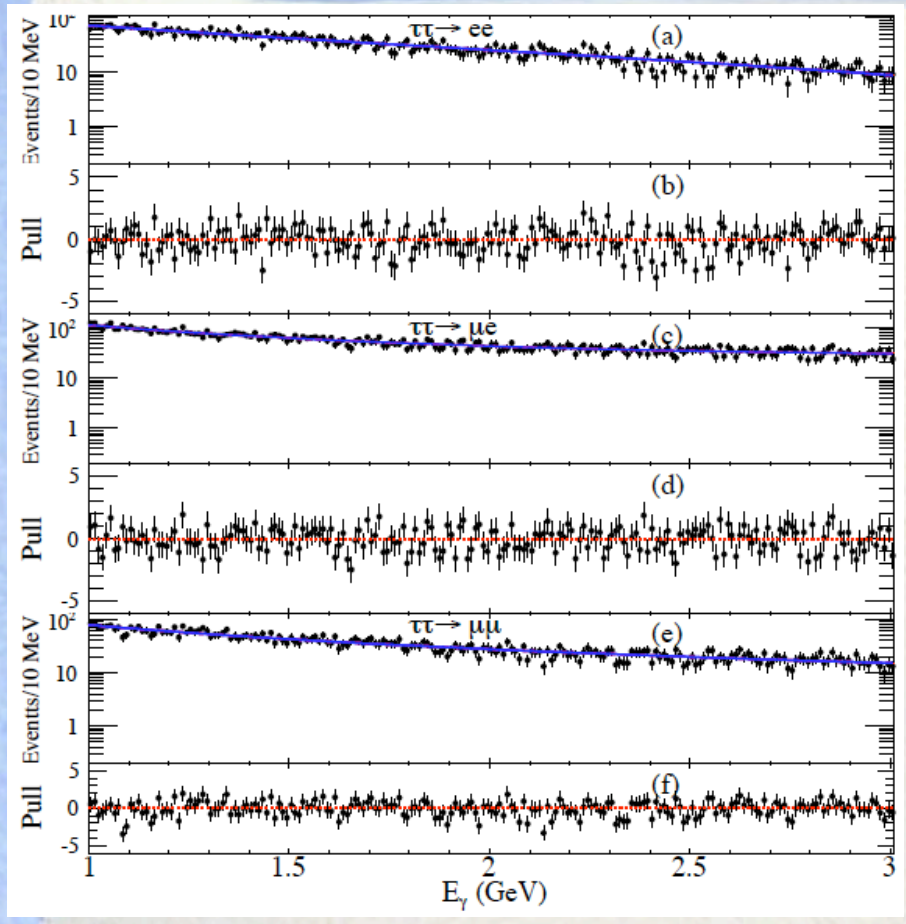
signal

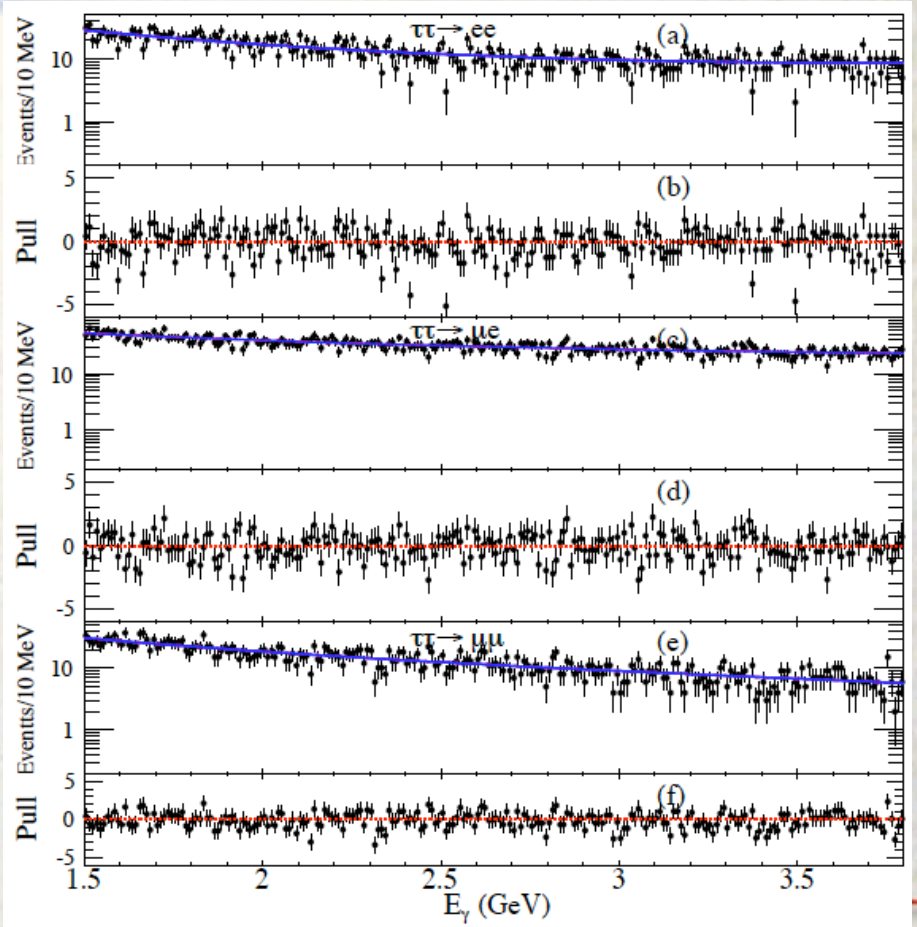
$Y(3S) \rightarrow \gamma\chi b(2P), \chi b(2P) \rightarrow \gamma Y(1S)$

m_{A0}=9.389GeV ~ m_R=9.387GeV

$A^0 \to \tau^+\tau^-$

Background distributions





2nd and 3rd out of 5 photon energy regions

$A^0 \rightarrow \tau^+\tau^-$

Scan Result