Searches for Dark Forces and Low-Mass Higgs in BABAR

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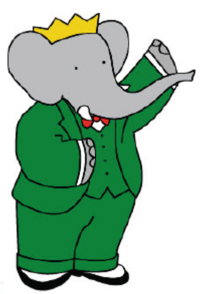
Symposium on Prospects in the Physics of Discrete Symmetries (DISCRETE 2010)

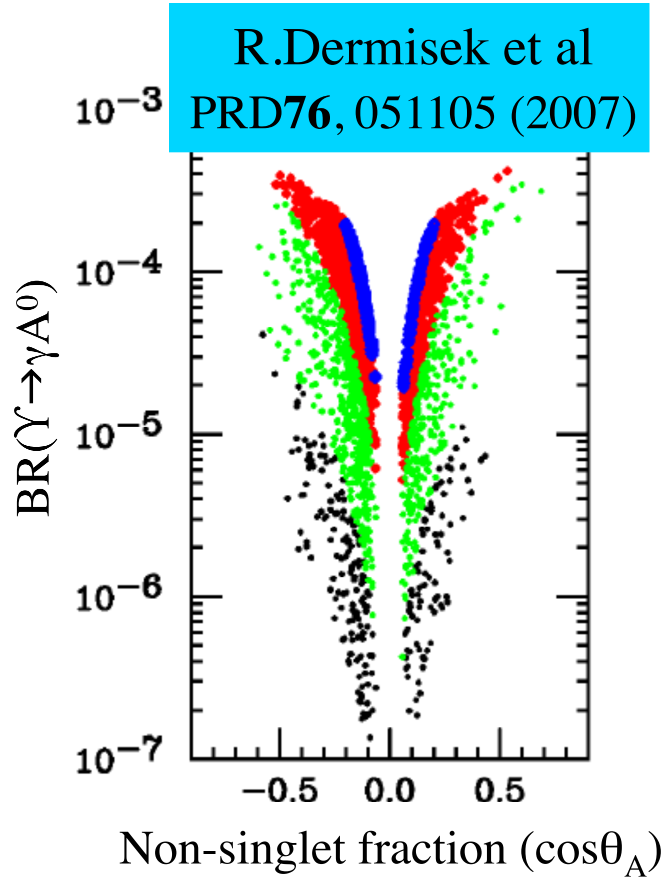
December 7, 2010, Rome, Italy

- ✔ Low-Mass Higgs Searches
- ✔ Light dark matter in $\Upsilon(1S)\to$invisible
- ✔ Multi-Leptonic Final States



Motivation

- A number of BSM models predict light weakly-interacting degrees of freedom
  - ❑ Motivated my astrophysical observations, theoretical prejudice
- E.g. NMSSM models with light CP-odd Higgs
  - ❑ Solve fine-tuning problems in MSSM
  - ❑ CP-odd Higgs, A^0, below $2m_b$ is not constrained by LEP
    - ☞ Large BR for $\Upsilon \to \gamma A^0$ possible
- Also models with low-mass dark matter and/or gauge bosons
  - ☞ E.g. "Dark Sector"
- Accessible at B-Factories in e^+e^- annihilation or bottomonium decays



$m_{A0} < 2m_\tau$

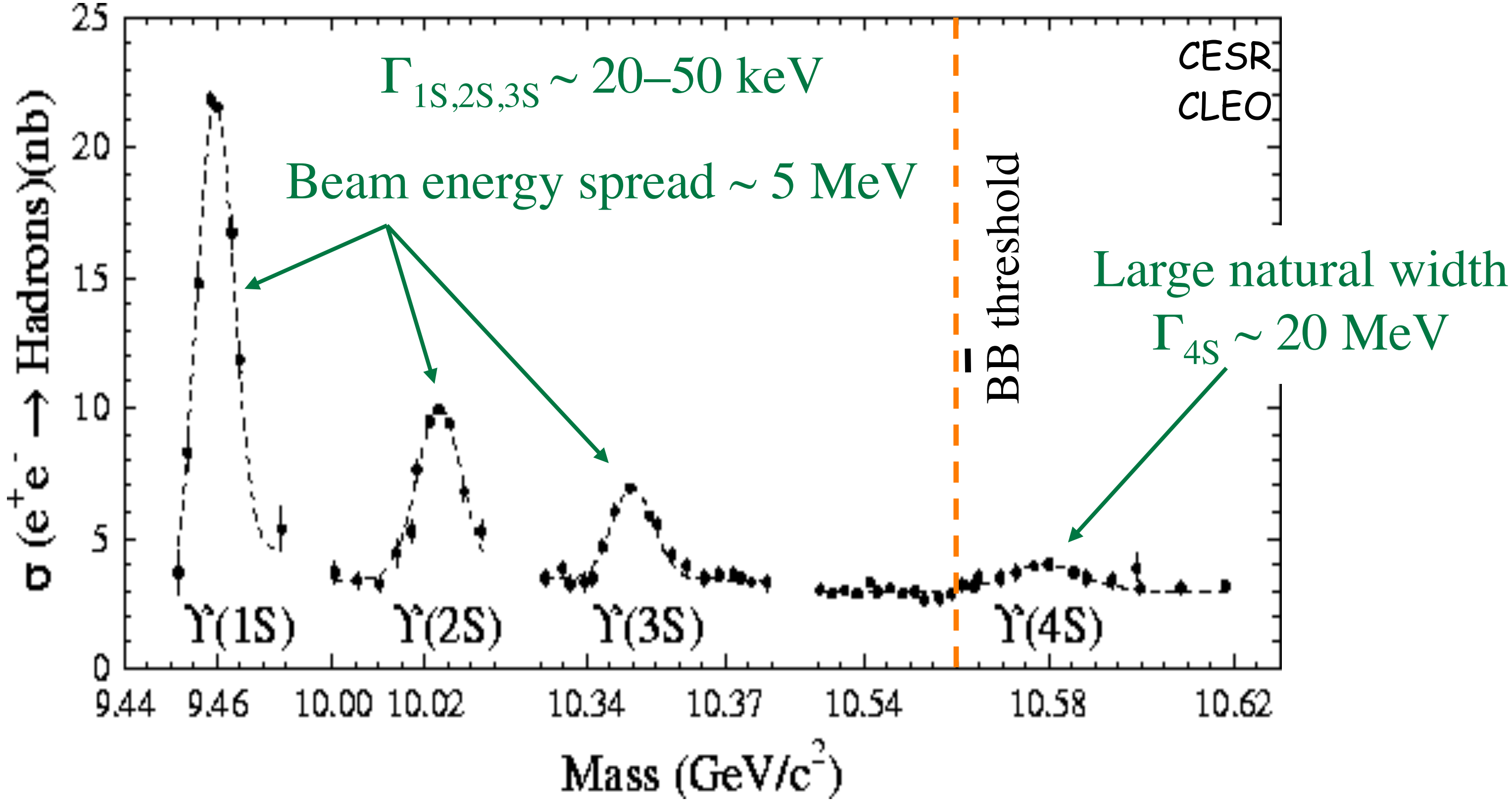
$2m_\tau < m_{A0} < 7.5$ GeV

7.5 GeV $< m_{A0} < 8.8$ GeV

8.8 GeV $< m_{A0} < 9.2$ GeV

Upsilon Resonances

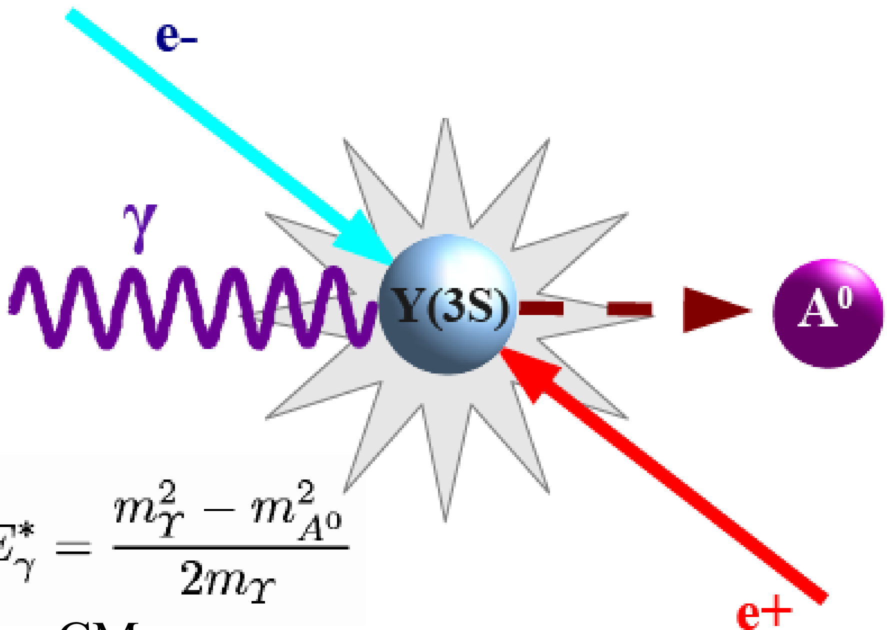
- Electron-Positron collider: $e^+e^- \to \gamma^* \to \Upsilon(nS)$



For any bottomonium process $BF_{nS}=\Gamma_{nS}/\Gamma_{tot} >> BF_{4S}$, n=1,2,3

Significantly better sensitivity to new physics @ narrow resonances

Searches for a Light Higgs in BaBar



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

CM energy

Key experimental signature: monochromatic photon in the Center-of-Mass (CM) frame

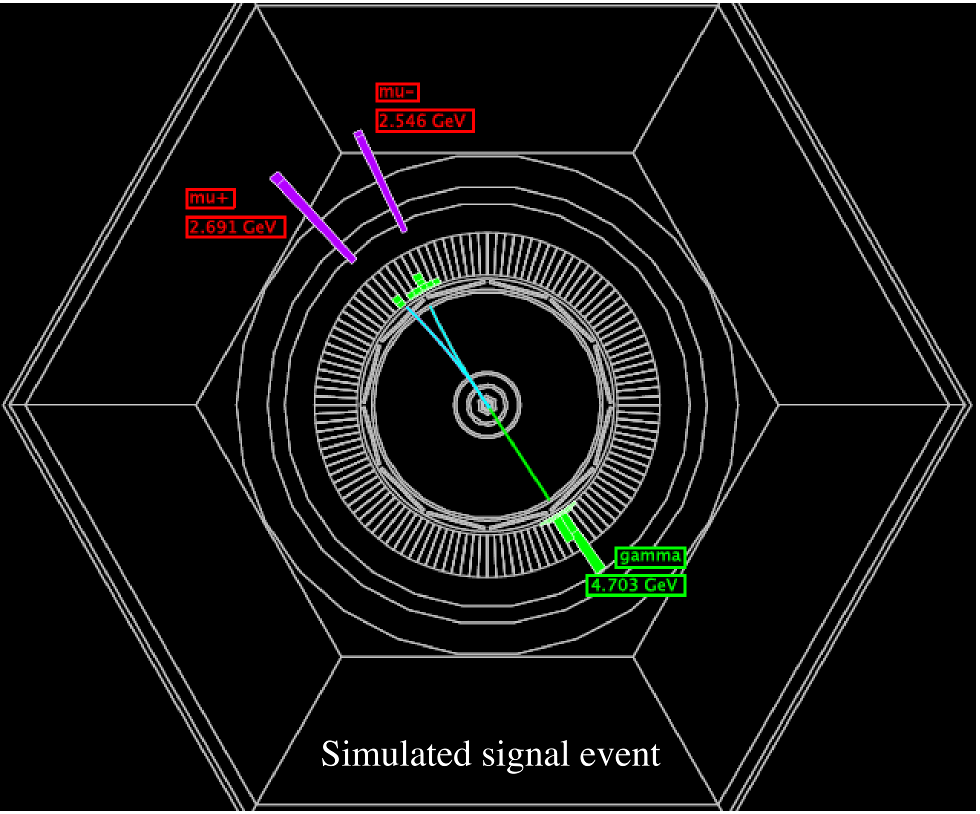
Well-understood initial state (narrow Υ(2S) or Υ(3S) resonance)

Fully or partially reconstructed final state, depending on the decay pattern of A^0

This talk:

- ✔ $A^0 \to \mu^+\mu^-$, PRL**103**, 081803 (2009)
- ✔ $A^0 \to \tau^+\tau^-$, PRL**103**, 181801 (2009)
- ✔ $A^0 \to$ invisible (light dark matter), arXiv:1007.4646, submitted to PRL

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

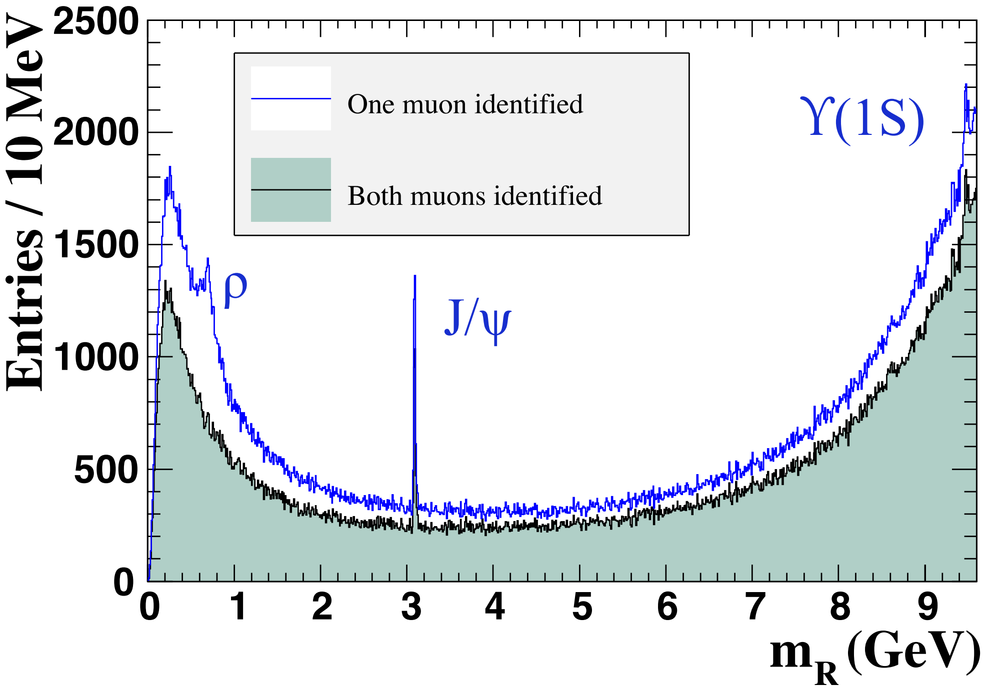


- Fully-reconstructed final state: 2 charged tracks, 1 photon
  - ☞ 1 or 2 muons identified
  - ☞ $E^*_\gamma > 0.2$ GeV
  - ☞ Loose kinematic selection requires consistency with CMS energy and momentum

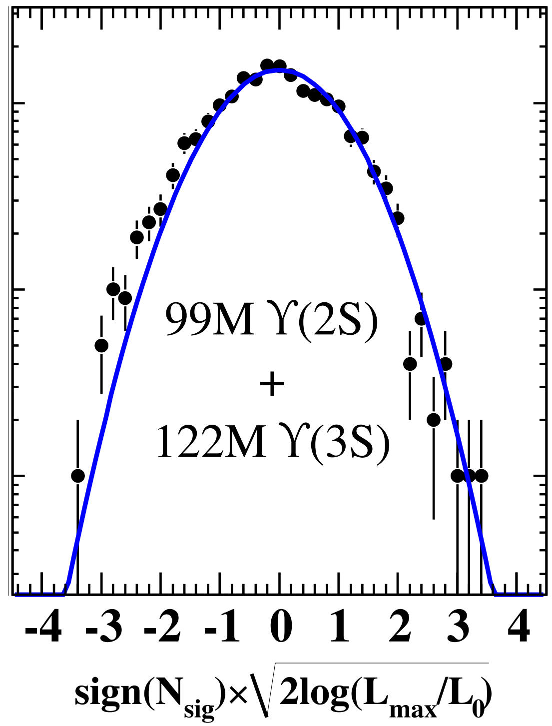
Backgrounds dominated by (irreducible) $e^+e^- \to \gamma\mu^+\mu^-$ and two-body decays of ISR-produced of $\phi(1020)$, $\rho(770)$, J/ψ, $\Upsilon(1S)$

Identify A^0 decays by a narrow peak in $\mu^+\mu^-$ invariant mass (resolution 2-10 MeV)

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



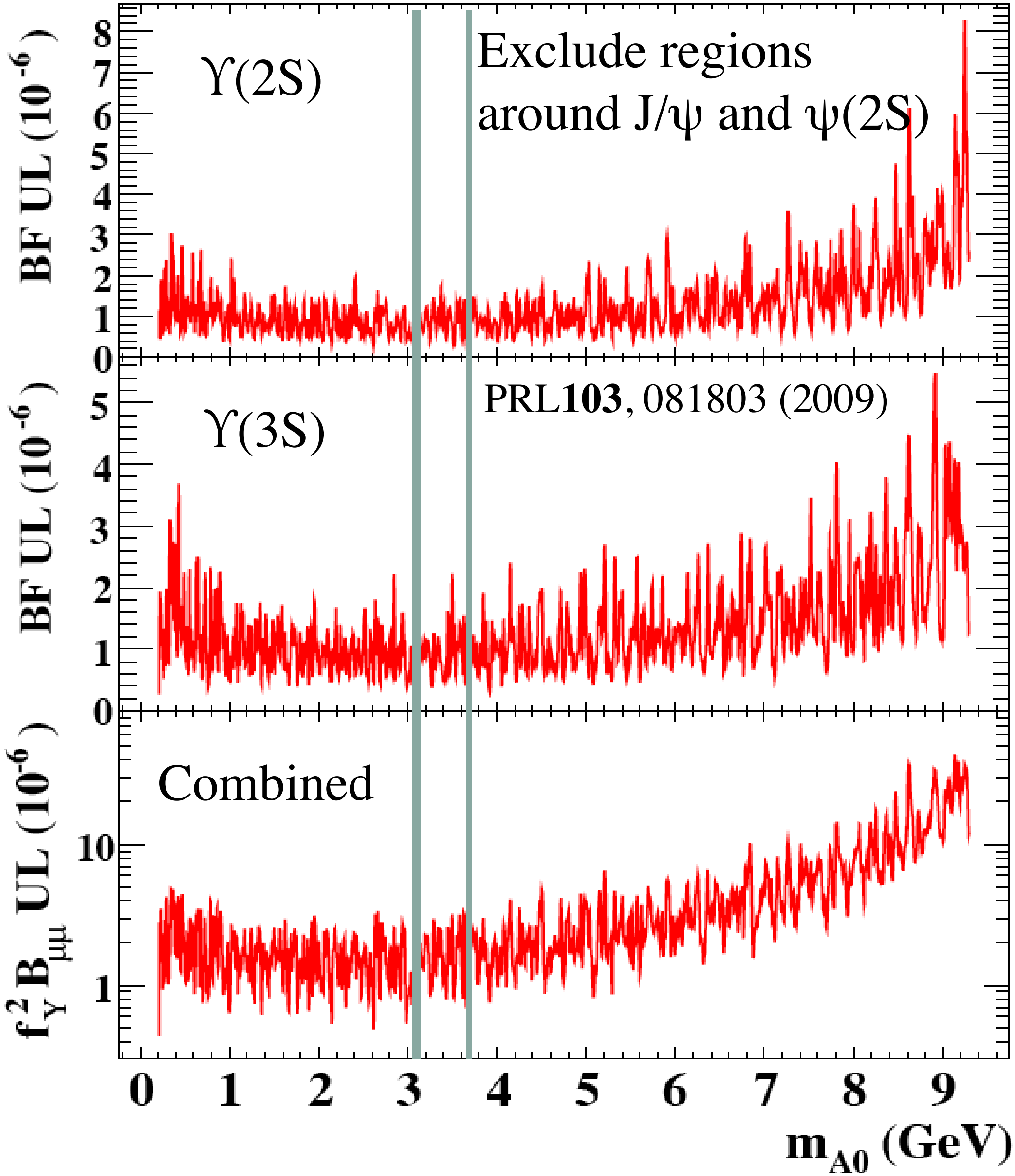
1955 fits vs m_{A0}



(stat significance)

Expect standard normal distribution for signal significance (or pull) under null hypothesis
Observe no significant outliers.

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



Bayesian 90% C.L upper limits

Significant constraints on theoretical models

Rule out Higgs interpretation of HyperCP events (m_{A0}=214 MeV)

Also limit

$$\mathcal{B}(\eta_b \to \mu^+\mu^-) < 0.9\%$$

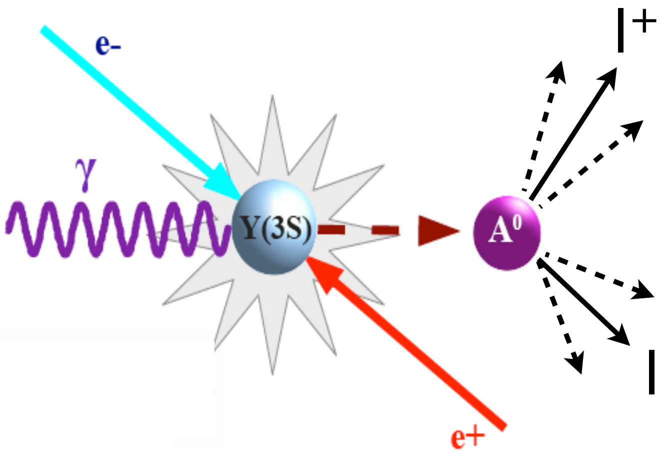
at 90% C.L.

Combined results for effective Yukawa coupling f_Υ

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

For m_{A0}<1 GeV, this corresponds to f_Υ<0.12 $f_{\text{Standard Model}}$

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



Select events with 2 identified leptons, one energetic photon, and large missing energy and mass consistent with tau decays

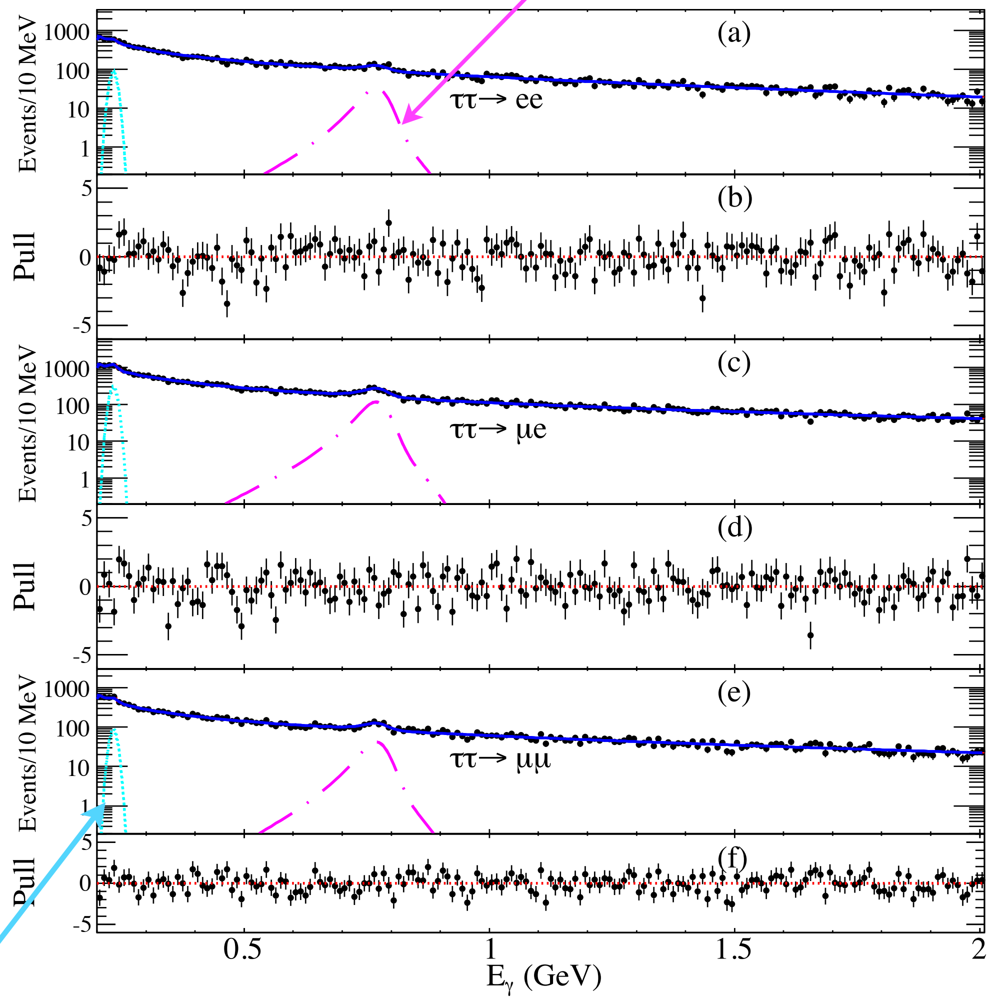
10-26% efficiency depending on E_γ and final state

Sample of 122M $\Upsilon(3S)$ decays

- Expect tau decays of A^0 to be dominant above the $\tau\tau$ threshold
- Strategy:
  - ❑ Look for a narrow peak in the photon energy spectrum above E^*_γ>0.1 GeV
    - ☞ 3 final states: ee, μμ, ττ
    - ☞ Scan E_γ distributions in steps of half-resolution (307 points)
    - ☞ Simultaneous binned ML fit to 3 decay modes

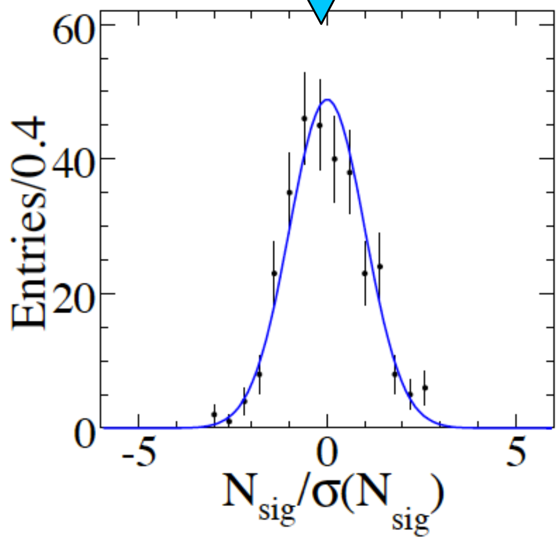
$\Upsilon(3S)\rightarrow\gamma A^0$, $A^0\rightarrow\tau^+\tau^-$ Fit

$\Upsilon(3S)\rightarrow\gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P)\rightarrow\gamma\Upsilon(1S)$



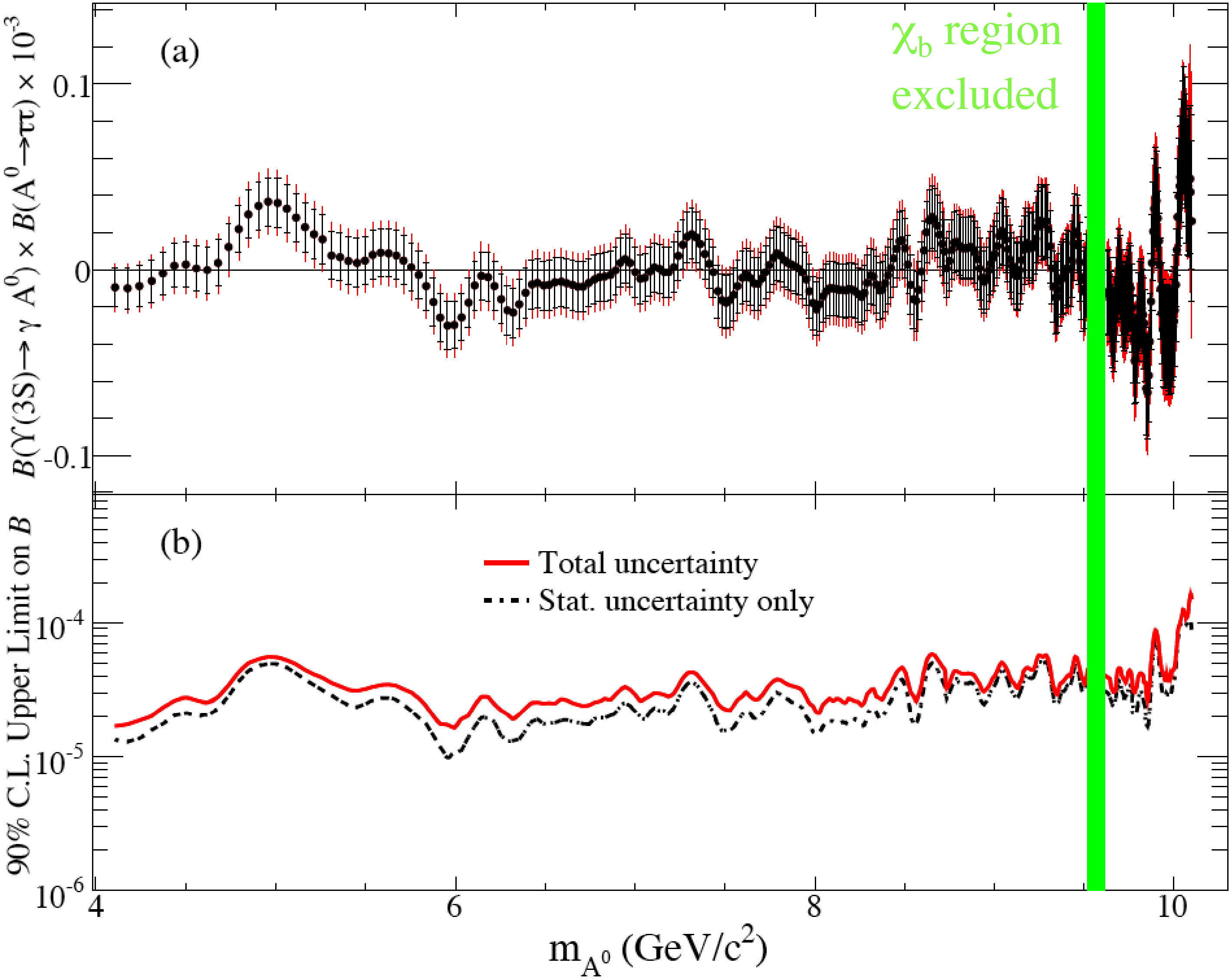
$\Upsilon(3S)\rightarrow\gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P)\rightarrow\gamma\Upsilon(1S)$

Scan for narrow peaks
Under null hypothesis, normalized residuals are gaussian-distributed



No evidence of narrow structures

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



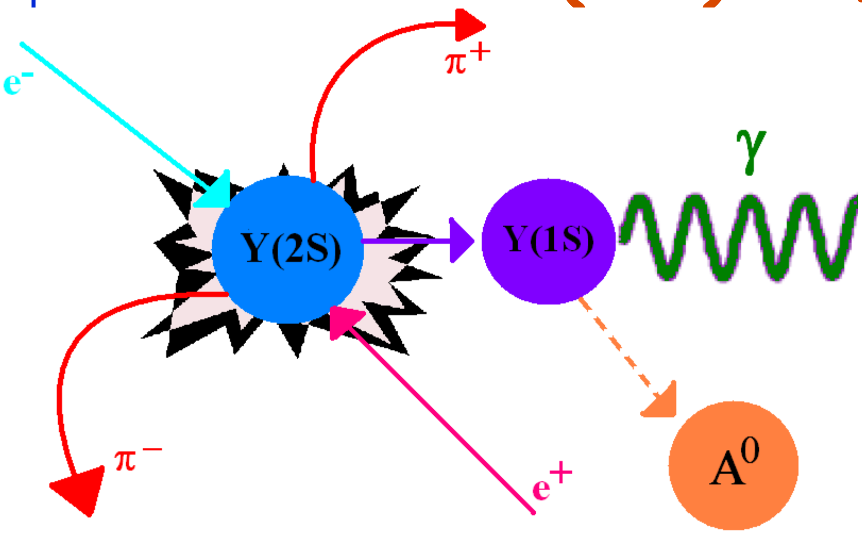
Bayesian 90% C.L. upper limits: significant constraints on NMSSM parameter space

Also set a limit

$$\mathcal{B}(\eta_b \rightarrow \tau^+\tau^-) < 8\%$$

at 90% C.L.

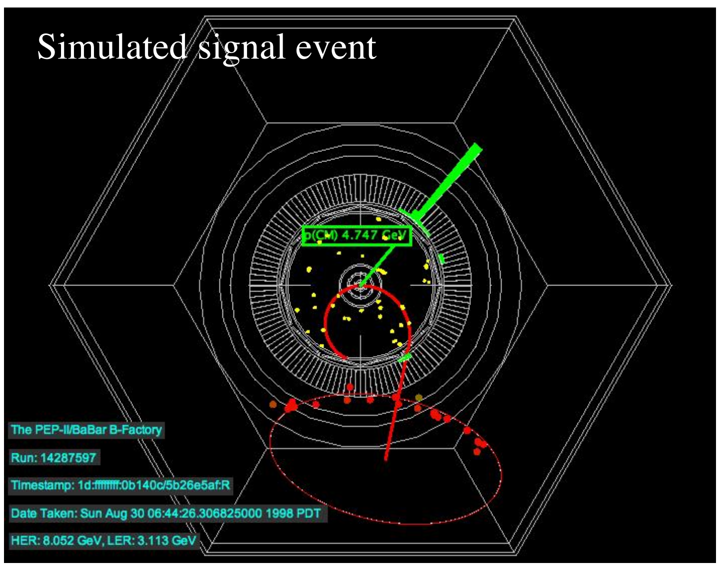
$\Upsilon(1S) \rightarrow \gamma$ +invisible



Search for decay chain $\Upsilon(2S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma$+invisible

Resonant (invisible=Higgs) or non-resonant (invisible=$\chi\chi$, e.g. light dark matter)

Identify the event by two low-momentum pions from $\Upsilon(1S) \rightarrow \pi^+\pi^-$ transition, a single energetic photon, and large missing energy



Two key kinematic variables: missing mass M_X^2, and dipion recoil mass

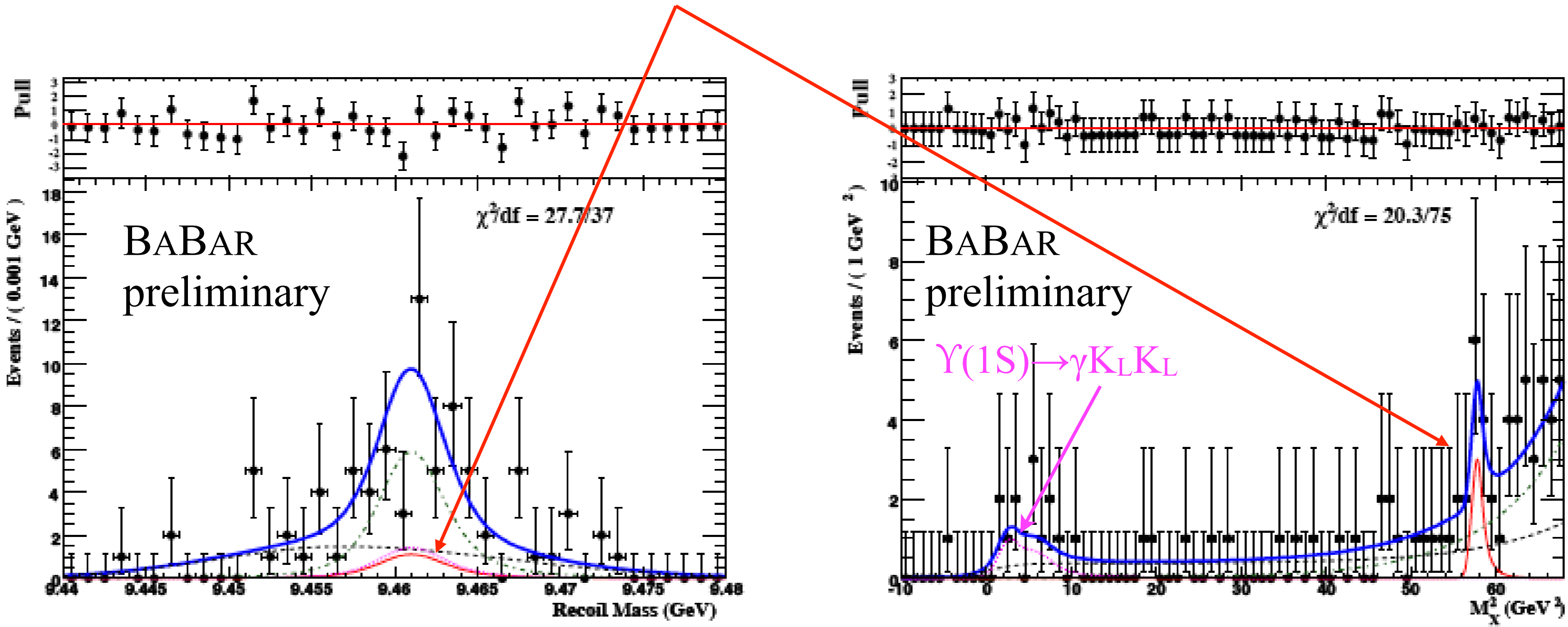
$$E^*_\gamma = \frac{M^2_{\Upsilon(1S)} - M^2_X}{2M_{\Upsilon(1S)}}$$

$$m^2_{recoil} = s + m^2_{\pi\pi} - 2\sqrt{s}E_{\pi\pi}$$

Search for excess of events over background as a function of missing mass

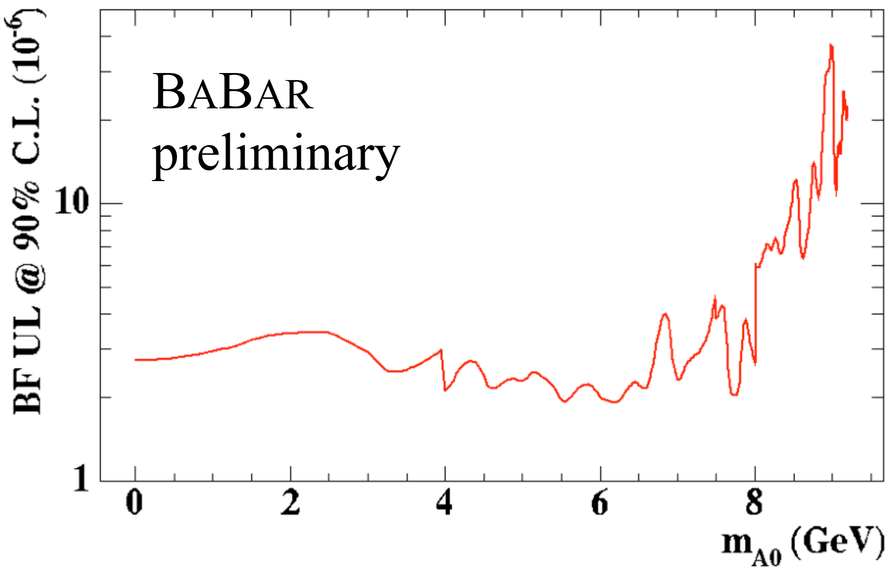
Most Significant Signal Peak

m_{A0}=7.58 GeV, 2.0σ significance

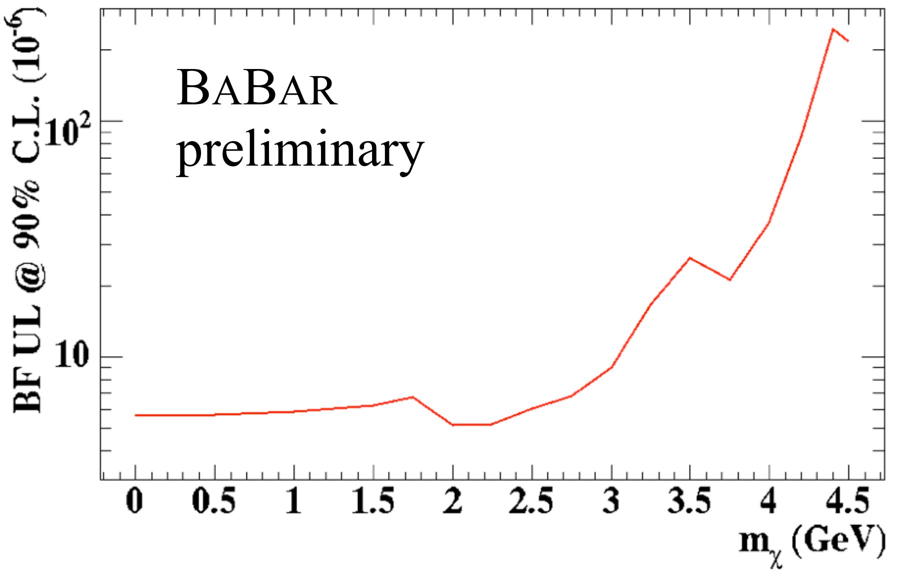


>30% probability to observe a peak of this significance *anywhere* in m_{A0}<9.2 GeV range

$\Upsilon(1S)\rightarrow \gamma$ +invisible Limits



Resonant $\Upsilon(1S)\rightarrow\gamma A^0$ search

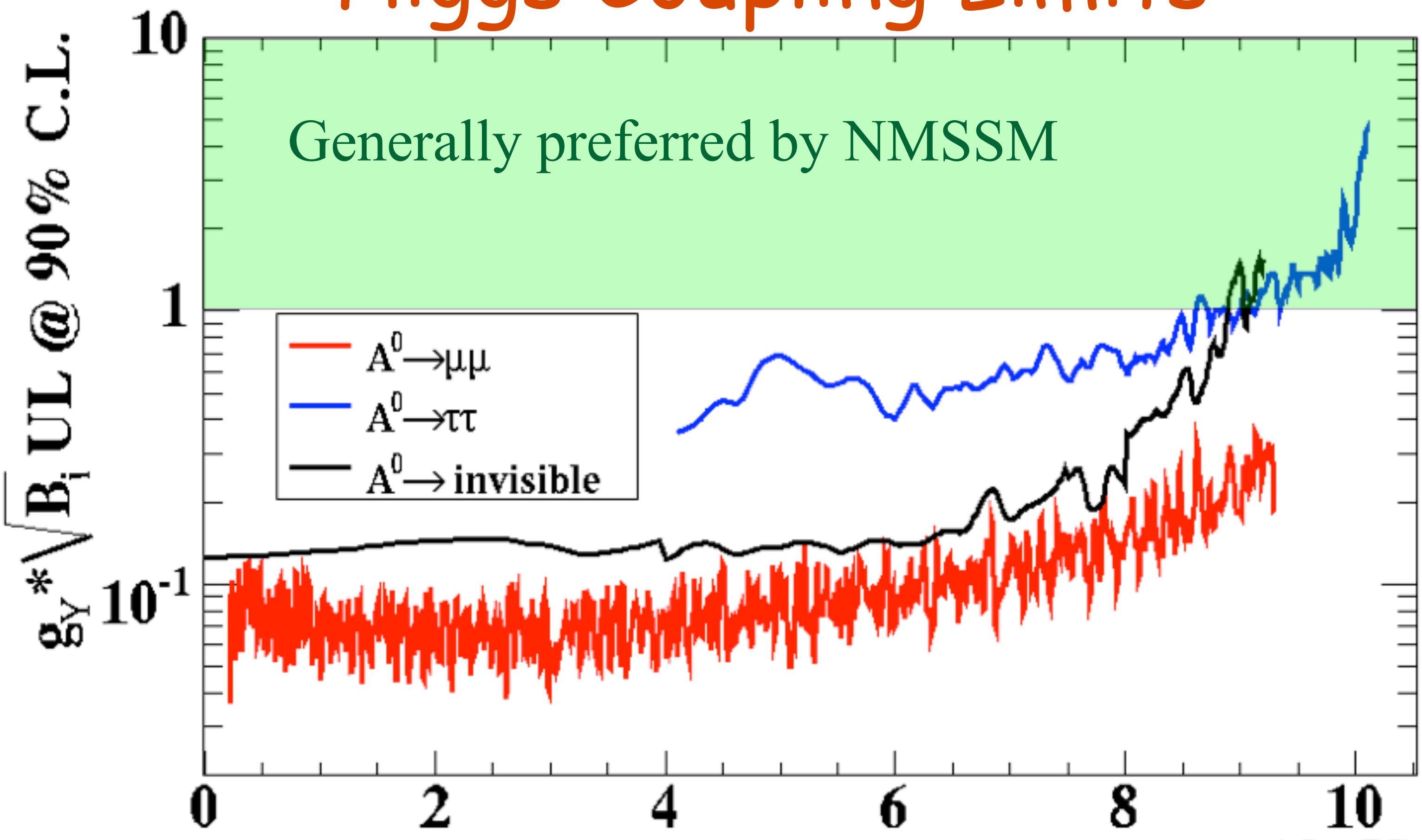


Non-resonant $\Upsilon(1S)\rightarrow\gamma\chi\chi$ search

Best limits on radiative decays of $\Upsilon(1S)$ to invisible final states

arXiv:1007:4646 (submitted to PRL)

Higgs Coupling Limits

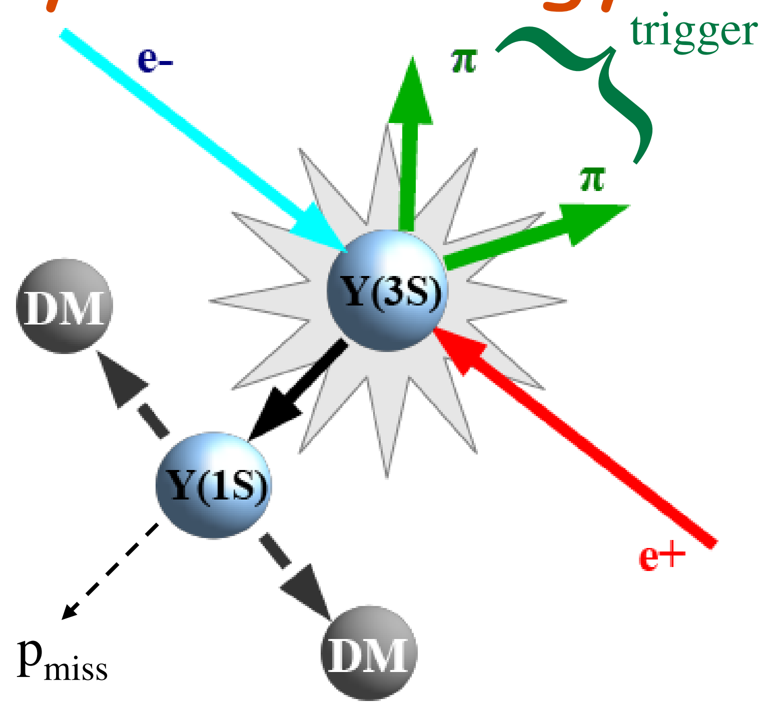


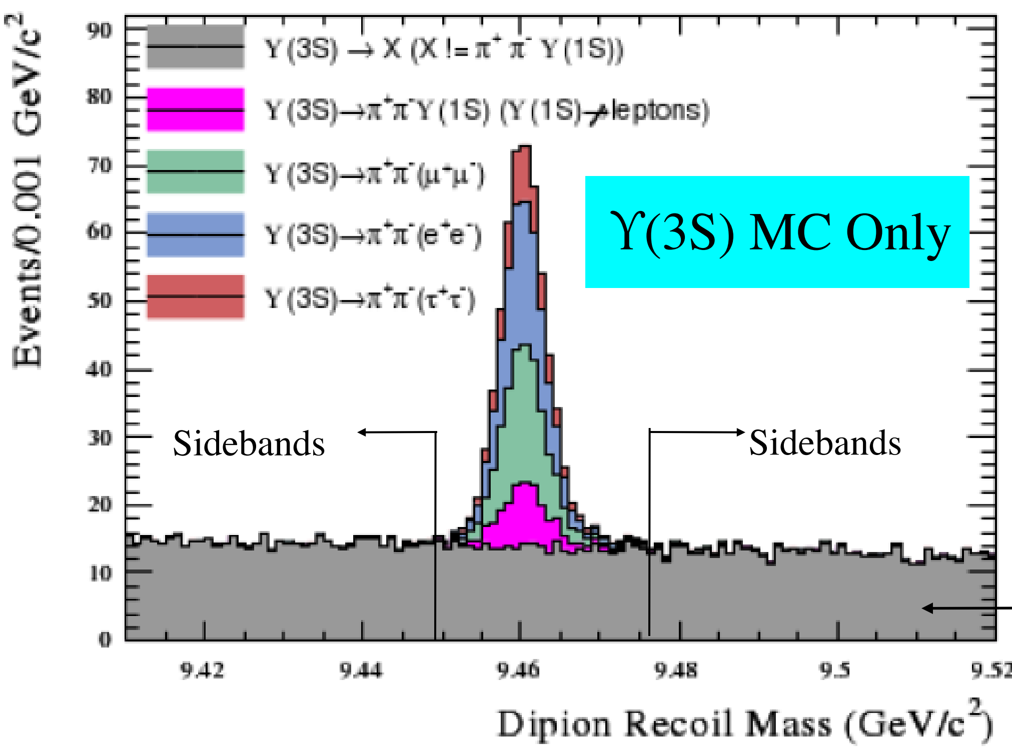
In NMSSM: $g_\Upsilon = \tan\beta \cos\theta \times \sqrt{\mathcal{C}_{\text{binding}}}$

Also place significant constraints on other models, e.g. axion-like states, dark photons (from $e^+e^- \to \gamma\phi$)

Υ(1S)→invisible: Analysis Strategy

Leverage the charged dipion transition to the Υ(1S) (4.48%) to suppress background





$$m^2_{recoil} = s + m^2_{\pi\pi} - 2E_{\pi\pi}\sqrt{s}$$

Additional non-peaking backgrounds from $e^+e^- \to \gamma^*\gamma^* \to e^+e^-\pi^+\pi^-$ not included

Υ(1S)→invisible: Signal Extraction

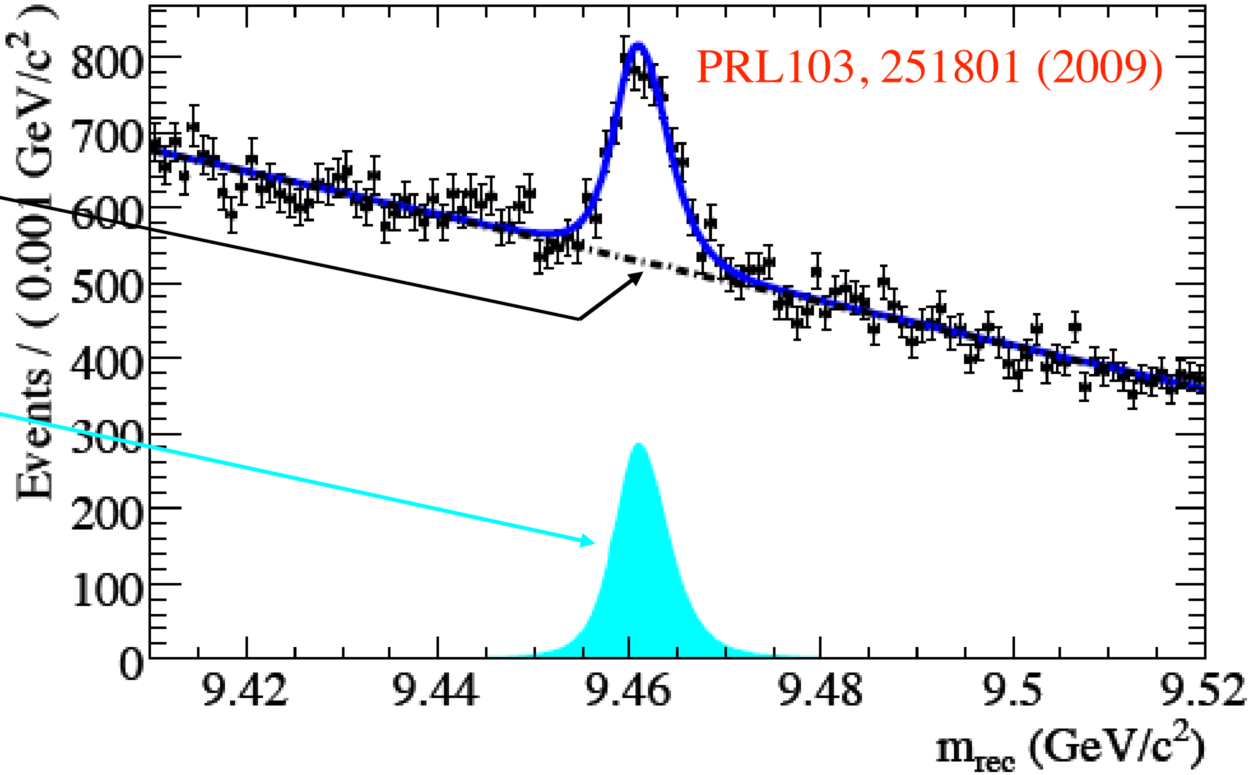
Maximum likelihood fit to 2-track "invisible" sample

Non-peaking background:

- ✔ Float all parameters and yield

Peaking Component:

- ✔ Fix shape, float yield
  Contains peaking background and signal



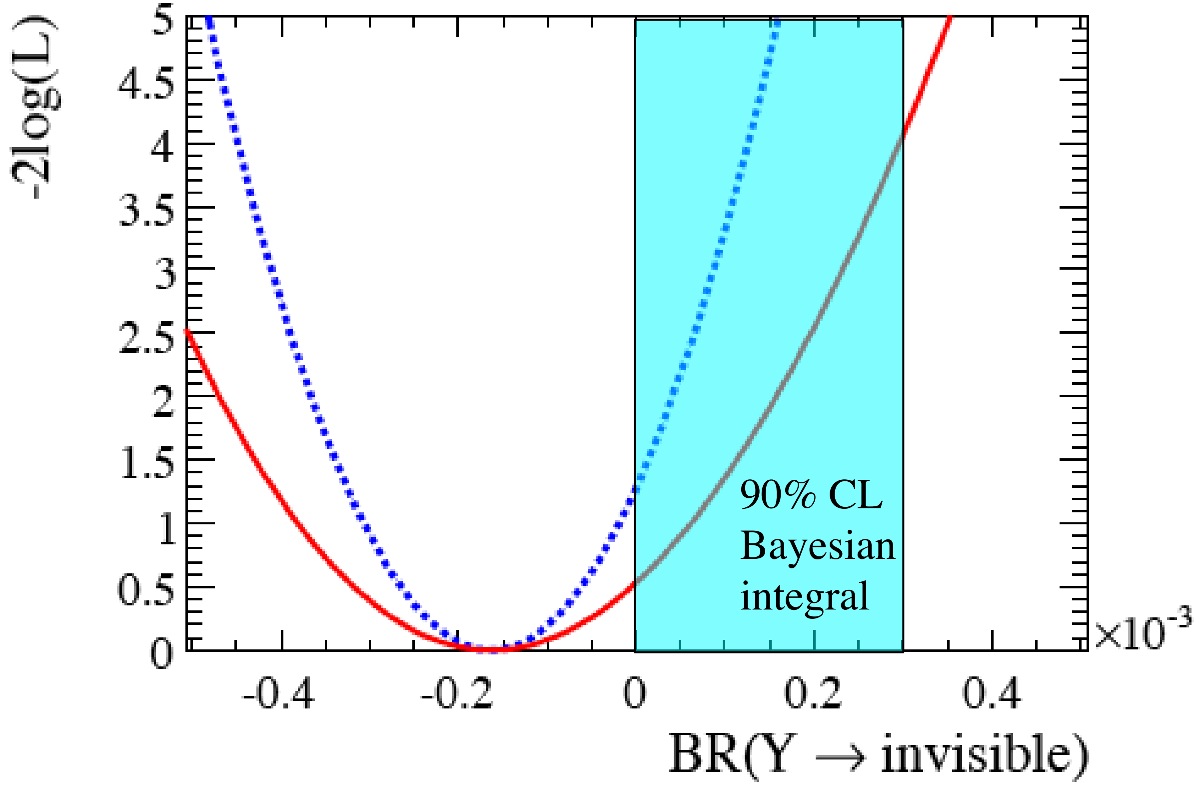
Fit Results: N_{peak} = 2326 ± 105 (stat.) events

Peaking background estimate, calibrated against control sample data:

N_{bkg} = 2444 ± 123 (syst.) events

Y(1S)→invisible yield: –118 ± 105 (stat.) ± 124 (syst.)

Υ(1S)→invisible: Final Results



$BR(\Upsilon(1S)\rightarrow invisible) = [\,-1.6 \pm 1.4\ (stat.) \pm 1.6\ (syst.)\,]\times 10^{-4}$

$BR(\Upsilon(1S)\rightarrow invisible) < 3.0\times 10^{-4}$ @ 90% C.L.

PRL**103**, 251801 (2009)

Gauge Bosons in the "Dark Sector"

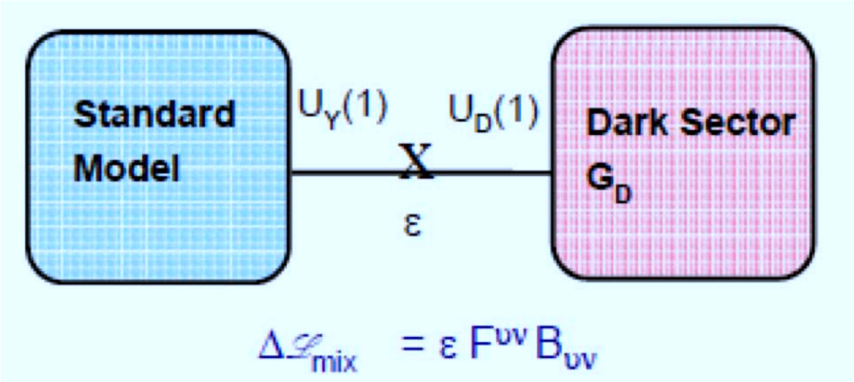
Models motivated by γ-ray and positron emission from the galactic center (INTEGRAL, PAMELA, ATIC, etc)

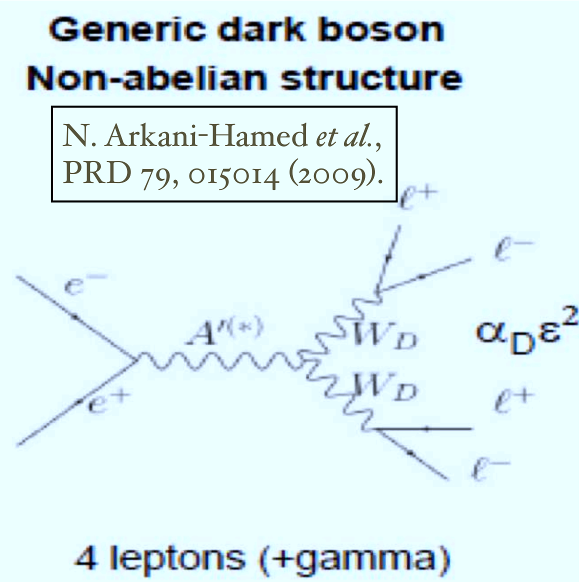
Dark matter particles in ~TeV range, but new gauge bosons in ~GeV range

Coupling to leptons due to small mixing between SM and DS

New gauge bosons decay to lepton pairs, anti-proton production forbidden by kinematics or suppressed → explains PAMELA/ATIC features

Search for low-mass states in e^+e^- annihilation @ B-Factories

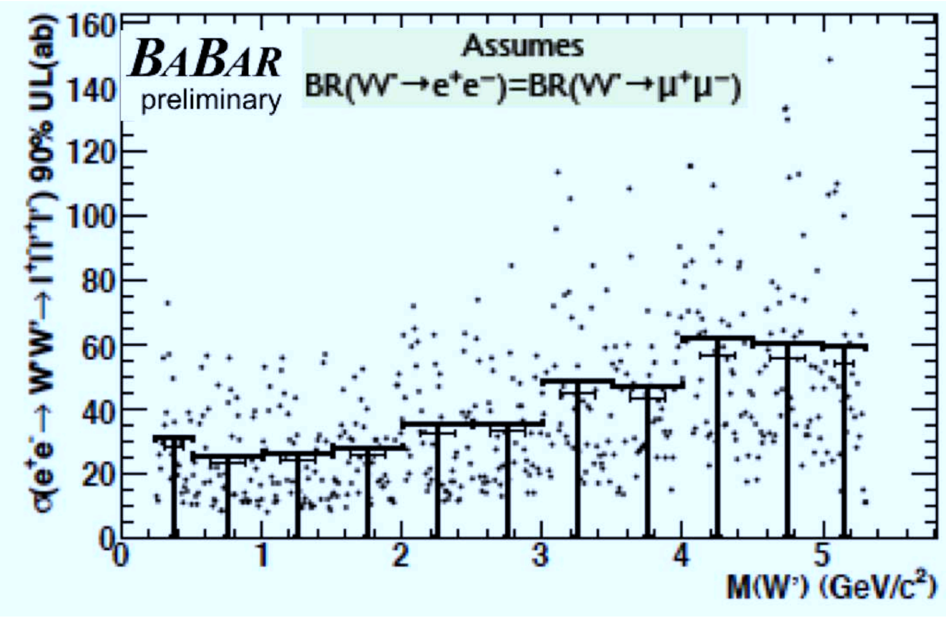


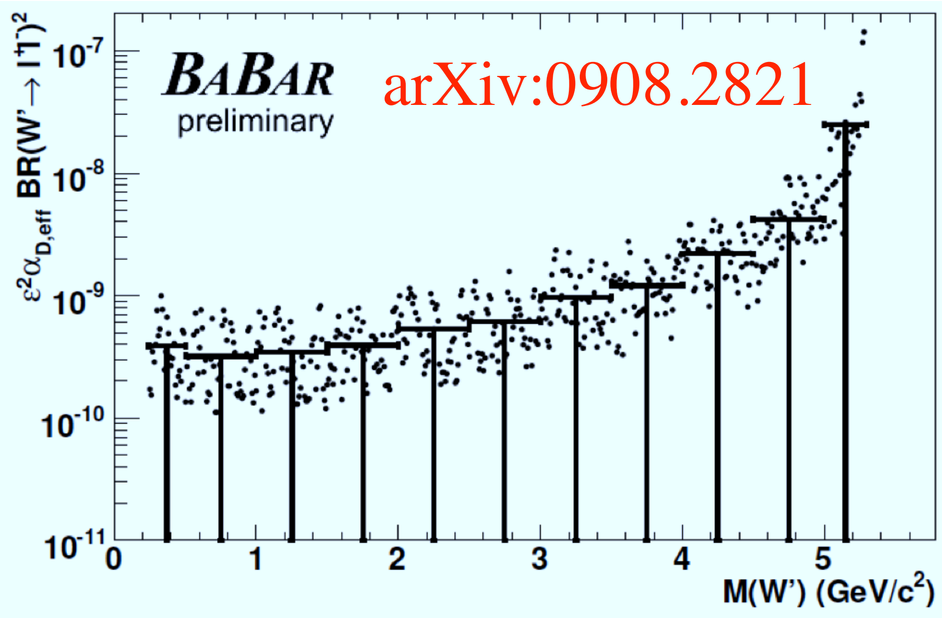


Direct Search for Dark Sector

Look for $e^+e^- \to l^+l^-l^+l^-$ final states (4e, 2e,2μ,4μ) as a function of two-lepton mass

Full BaBar dataset (~540 fb^{-1})





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

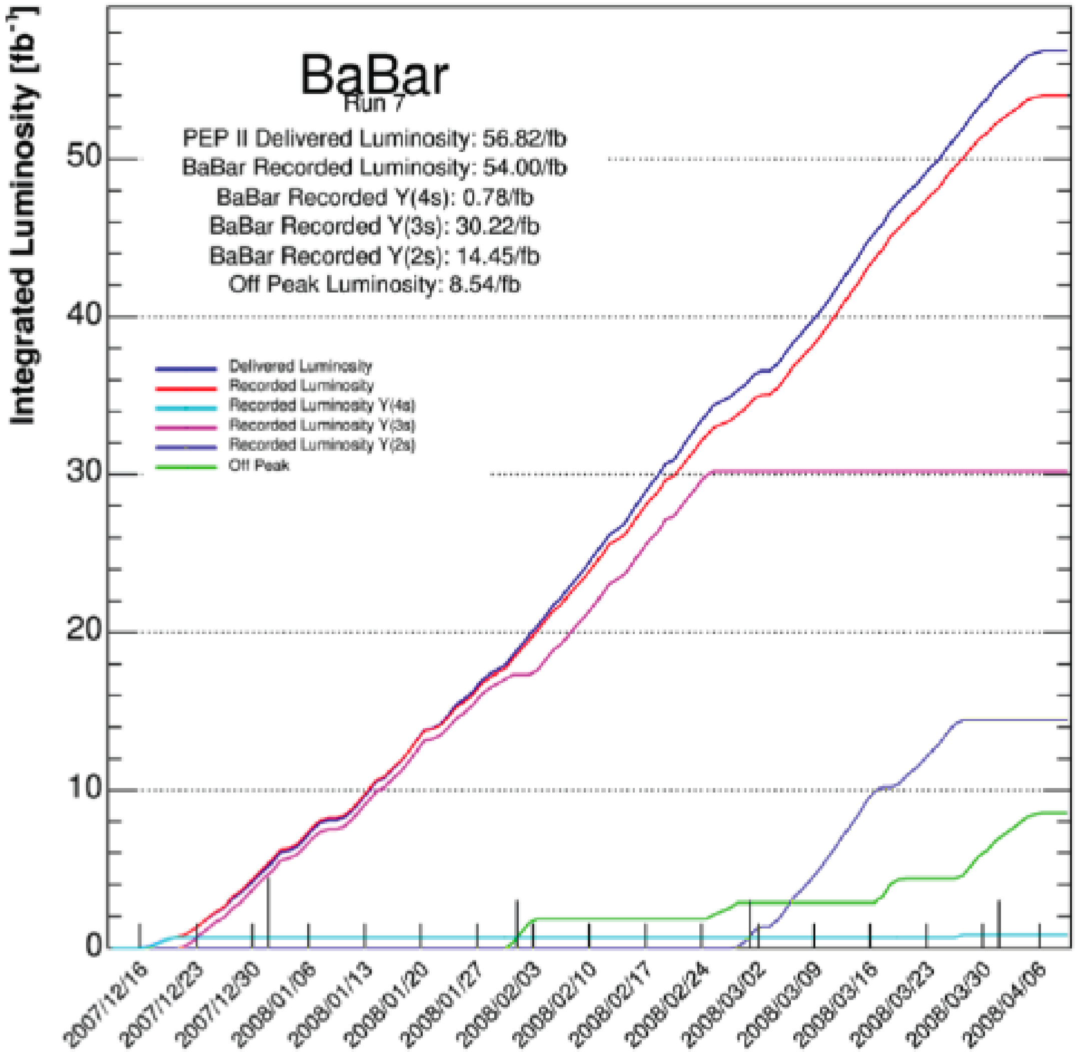
Some of the smallest cross section ULs measured @ B-Factories

Summary

- Unique sensitivity to low-mass new physics in high-statistics datasets
- No signal of a light scalar particle (e.g. CP-odd Higgs) in radiative decays of $\Upsilon(2S)$ and $\Upsilon(3S)$ in $\mu^+\mu^-$, $\tau^+\tau^-$, or invisible final states
  - Set upper limits that rule out much of available parameter space; most stringent constraints to date
    - ☞ See also E.Guido's talk in C/P/T session (LFV, universality)
- No evidence for invisible decays of $\Upsilon(1S)$
  - Constrain models with light dark matter
- No evidence for "dark forces"
- Publications
  - ☞ PRL**103**, 081803 (2009): $A^0 \to \mu^+\mu^-$
  - ☞ PRL**103**, 181801 (2009): ($A^0 \to \tau^+\tau^-$
  - ☞ arXiv:1007.4646: $\Upsilon(1S) \to \gamma$+invisible, submitted to PRL
  - ☞ PRL**103**, 251801 (2009): $\Upsilon(1S) \to$invisible
  - ☞ arXiv:0908.2821: $e^+e^- \to l^+l^-l^+l^-$, preliminary
- Additional datasets available in BaBar and Belle: stay tuned !

Backup

BaBar 2008 Dataset



Dec. 2007 - Apr. 2008

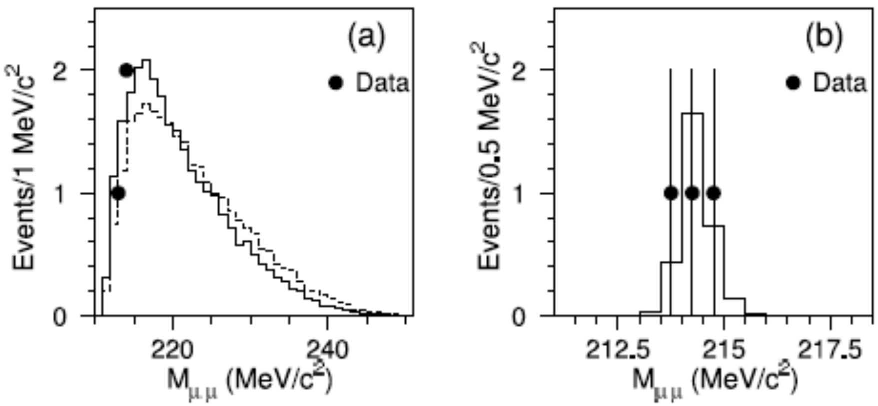
Dedicated run on Υ(3S) and Υ(2S), cross section scan above Υ(4S)

122M Υ(3S) decays

99M Υ(2S) decays

Previous Constraints

HyperCP anomaly



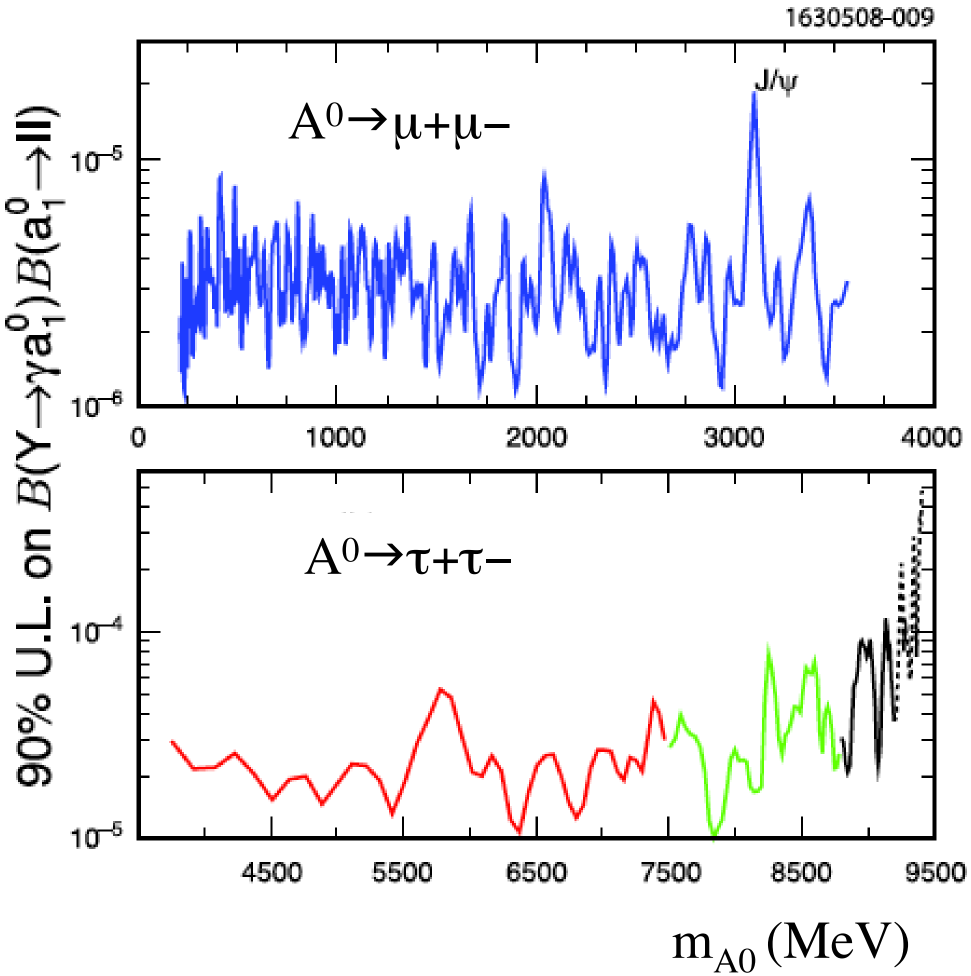
H. Park et al., PRL**94**, 021801 (2005)

Resonance-like structure in $\Sigma \rightarrow p\mu^+\mu^-$ near threshold ($m_{\mu\mu}$=214 MeV)

Small width (Γ<1 MeV)

If light CP-odd Higgs, could be produced in $\Upsilon \rightarrow \gamma X(214)$.

CLEO limits on $\Upsilon(1S) \rightarrow \gamma A^0$

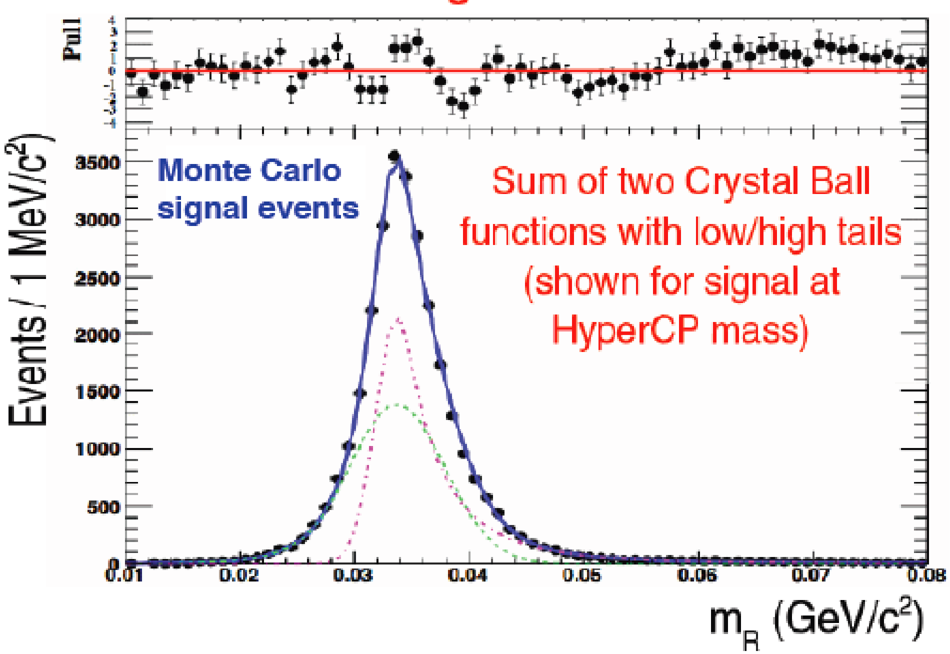


W. Love et al., PRL**101**, 151802 (2008)

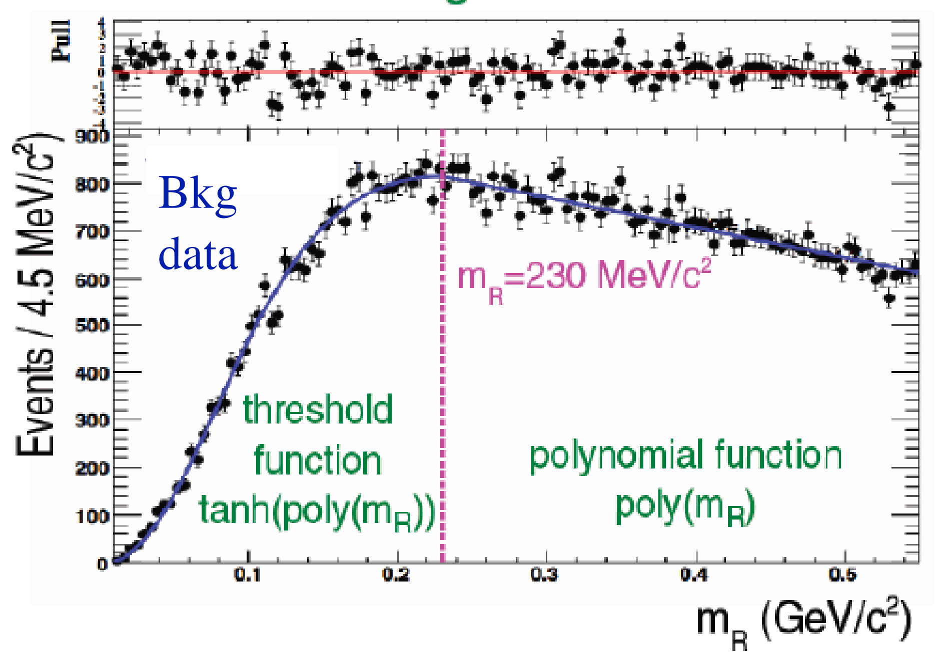
Strategy for $A^0 \to \mu^+\mu^-$

- Signal extraction: ML fit in slices of invariant mass
  - ☞ 1955 distinct slices from $0.212 \le m_{A0} \le 9.3$ GeV, in 2-5 MeV steps
  - ☞ Fit to “reduced mass” $m_R = \sqrt{m_{A^0}^2 - 4m_\mu^2} = 2|p_\mu^{A^0}|$
  - ☞ Smooth threshold behavior, slightly shifted from m_{A0}

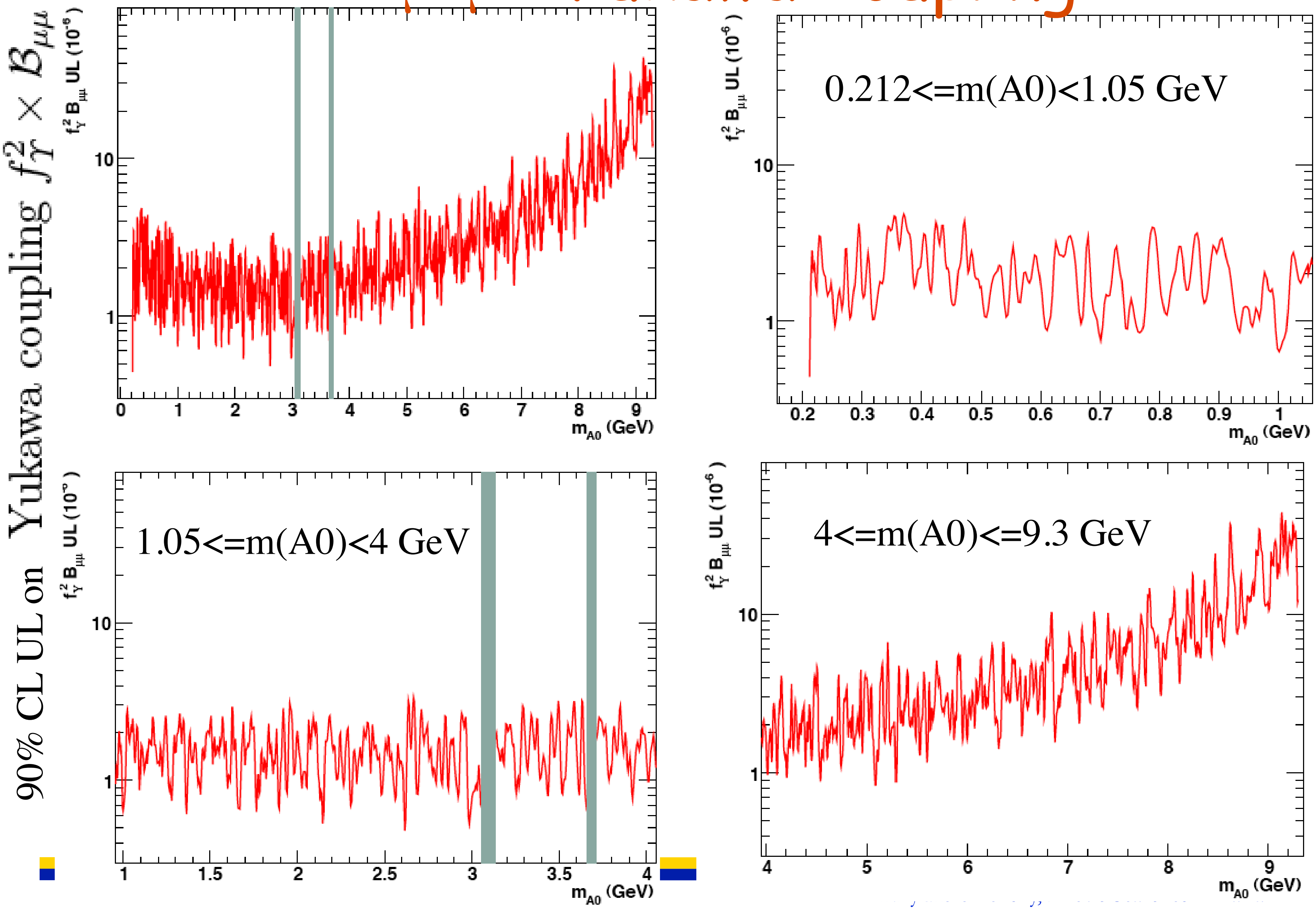
Signal PDF



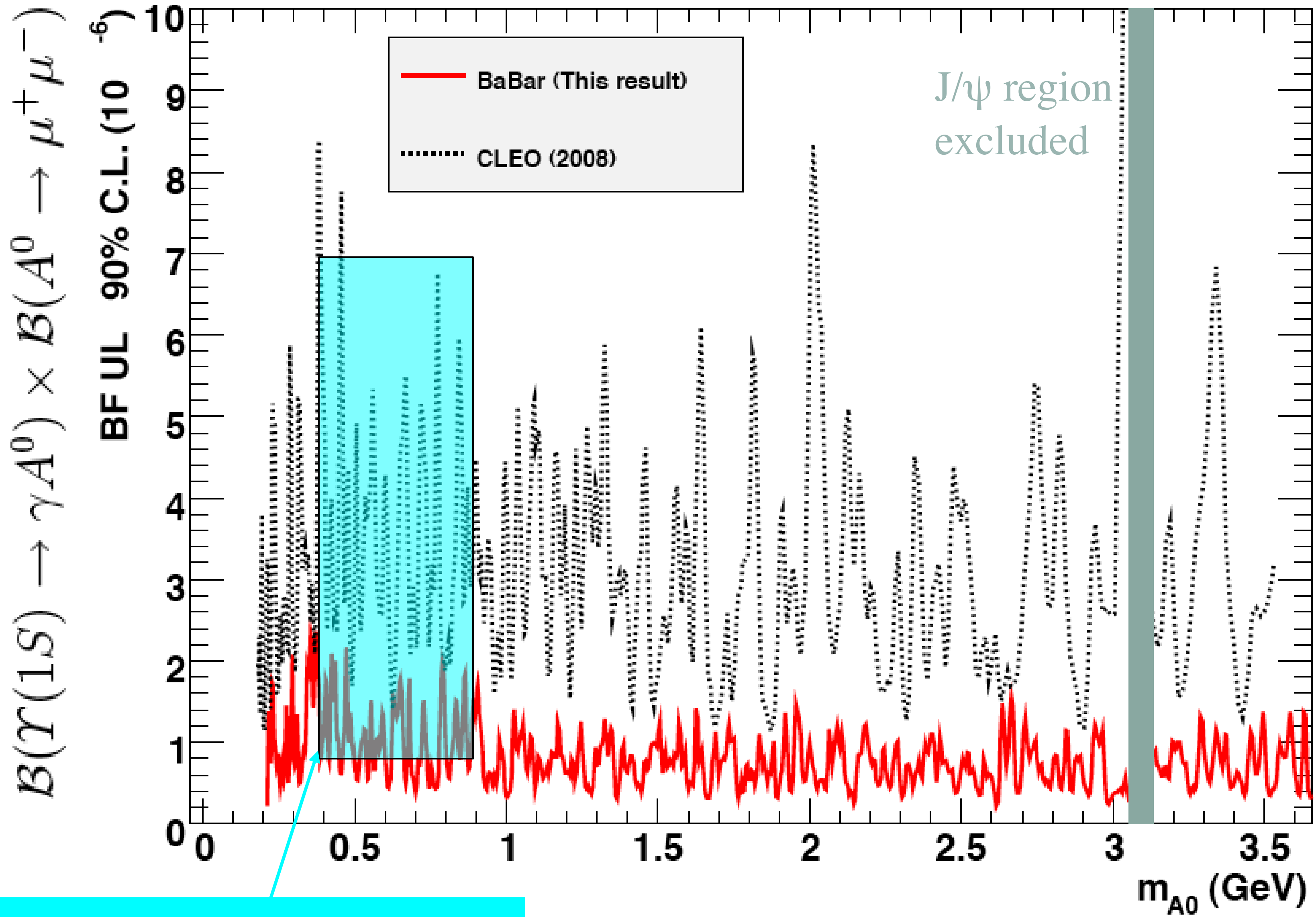
Background PDF



$A^0 \to \mu^+\mu^-$: Yukawa Coupling

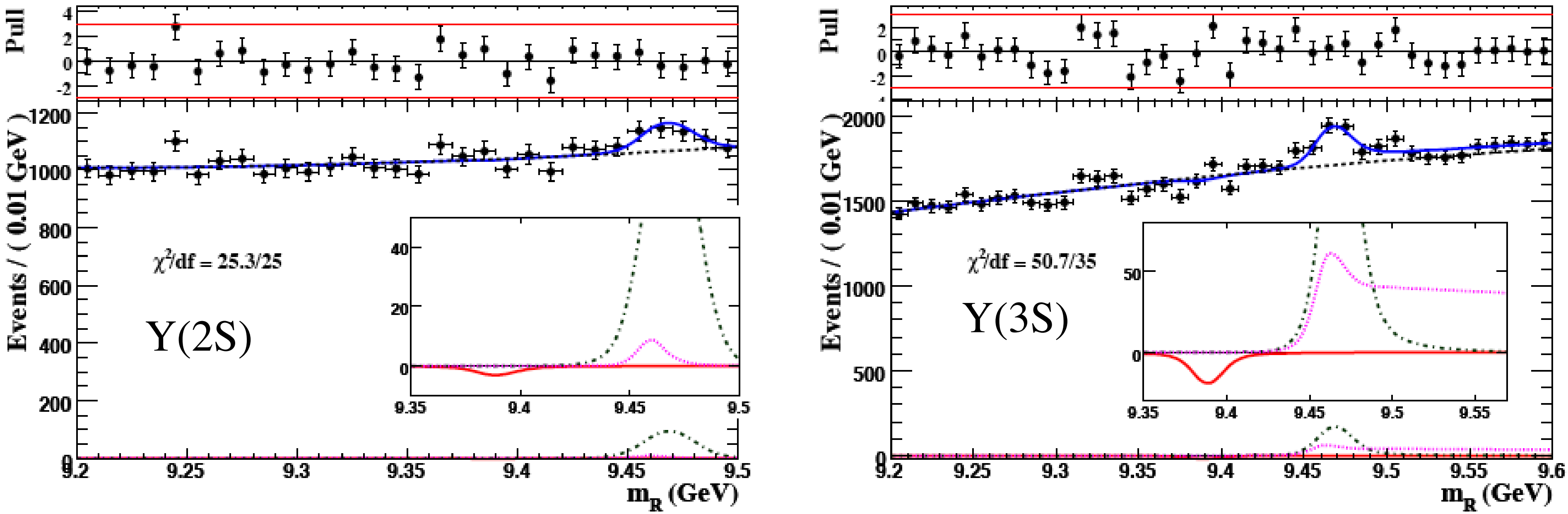


Results at Low Mass: $A^0 \to \mu^+\mu^-$



Range predicted by
Axion model (Nomura,Thaler)

$\eta_b \rightarrow \mu^+\mu^-$ Results



$$\mathcal{B}(\Upsilon(2S) \rightarrow \gamma\eta_b) \times \mathcal{B}(\eta_b \rightarrow \mu^+\mu^-) = (-0.4 \pm 3.9 \pm 1.4) \times 10^{-6}$$

$$\mathcal{B}(\Upsilon(3S) \rightarrow \gamma\eta_b) \times \mathcal{B}(\eta_b \rightarrow \mu^+\mu^-) = (-1.5 \pm 2.9 \pm 1.6) \times 10^{-6}$$

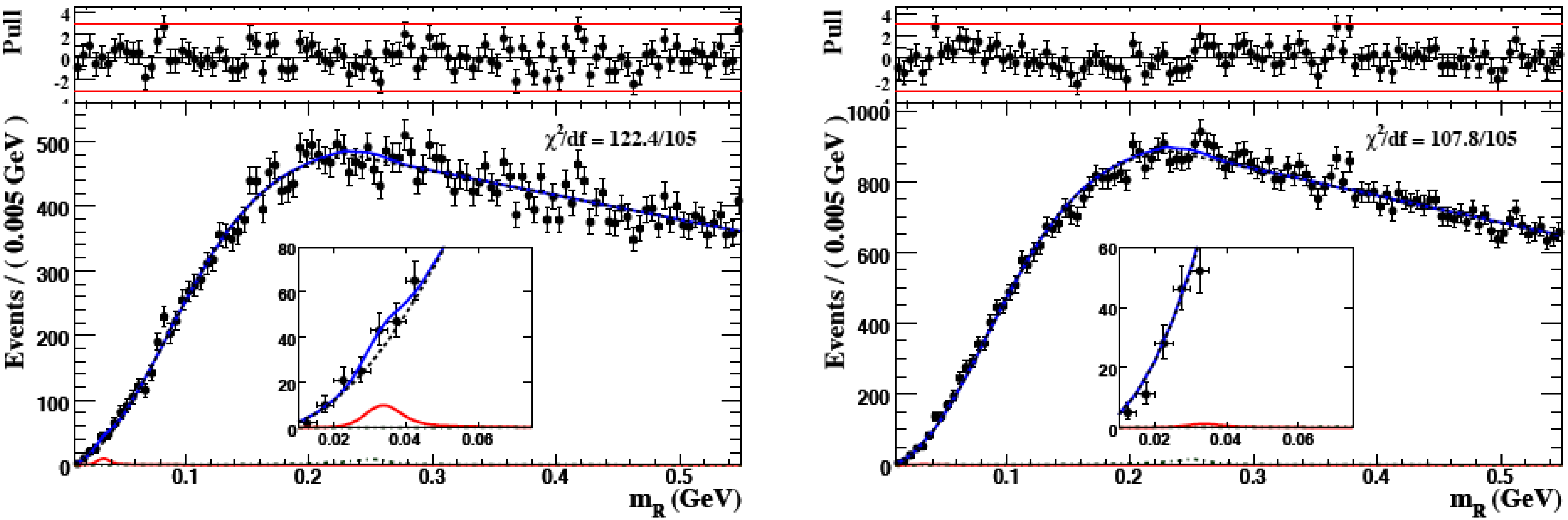
$$\mathcal{B}(\eta_b \rightarrow \mu^+\mu^-) = (-0.10 \pm 0.93 \pm 0.33)\% \ (\Upsilon(2S) \text{ dataset})$$

$$\mathcal{B}(\eta_b \rightarrow \mu^+\mu^-) = (-0.31 \pm 0.61 \pm 0.32)\% \ (\Upsilon(3S) \text{ dataset})$$

$$\mathcal{B}(\eta_b \rightarrow \mu^+\mu^-) = (-0.25 \pm 0.51 \pm 0.33)\% \ (\text{average}) \ .$$

90% CL Upper Limit: $\mathcal{B}(\eta_b \rightarrow \mu^+\mu^-) < 0.9\%$

$A^0 \to \mu^+\mu^-$ HyperCP Point



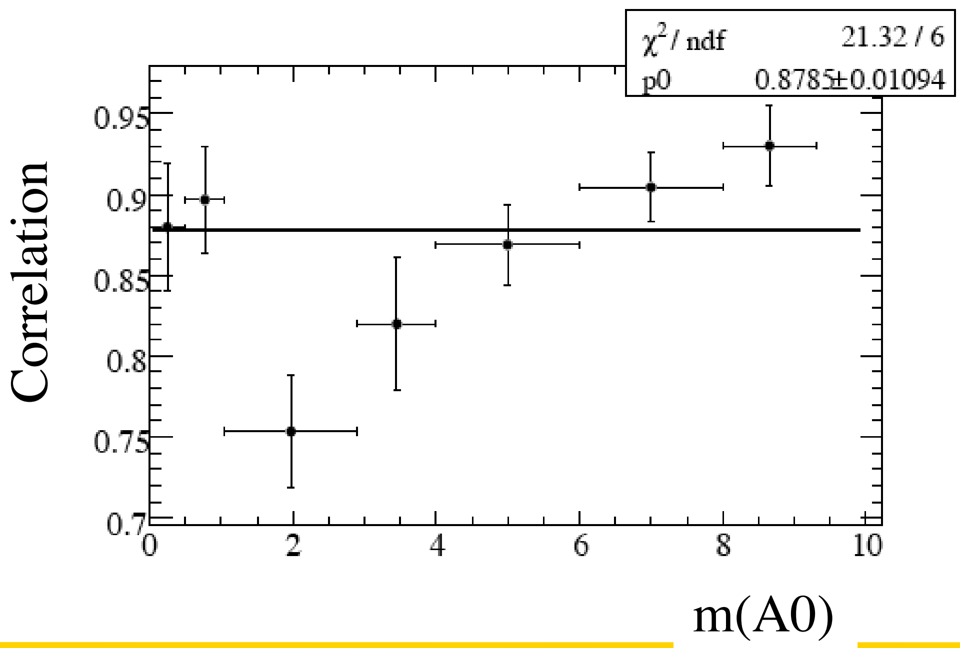
No significant peak at m(A0)=0.214 GeV

Set a stringent upper limit:

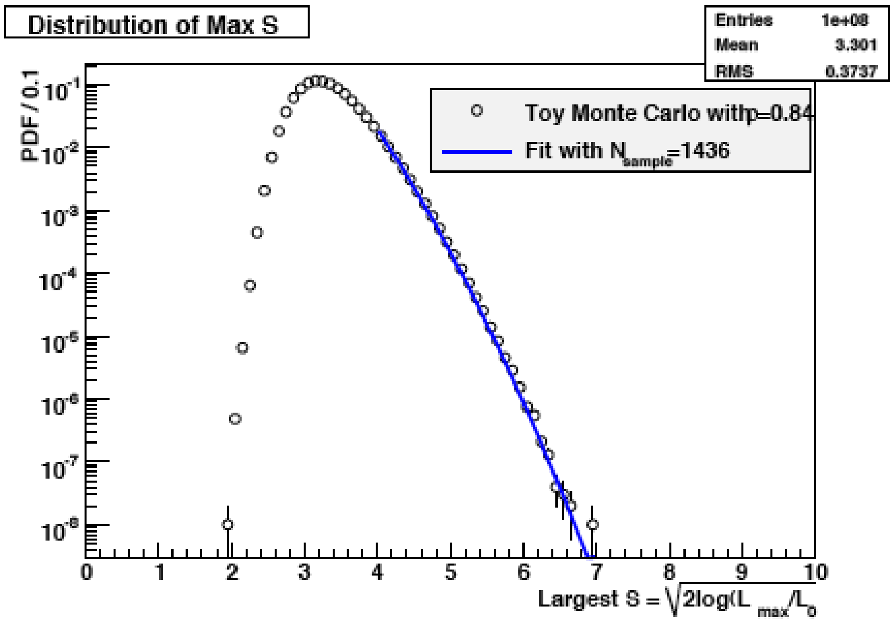
$$f^2_{\Upsilon}(m_{A^0} \;=\; 0.214\,\mathrm{GeV}) \;<\; 1.6 \times 10^{-6} \;\; \mathrm{at} \;\; 90\% \;\; \mathrm{C.L}$$

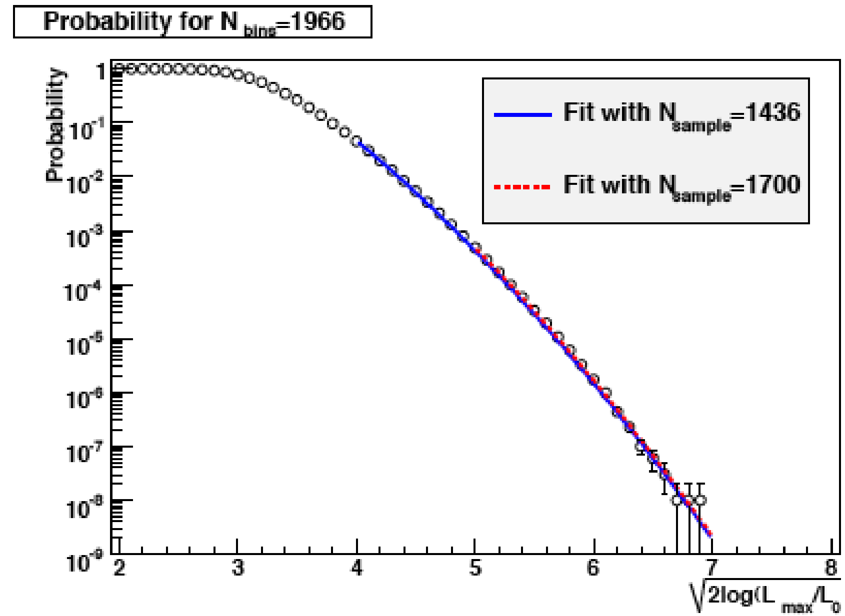
Significance Calculation

- Need to take into account the "number of samples"
  - ☞ Generally, $P_{Nsample}(\chi^2) \approx N_{sample} P_1(\chi^2)$
- ❑ Need to determine the number of independent samples
  - ☞ Look at correlation between adjacent scan points



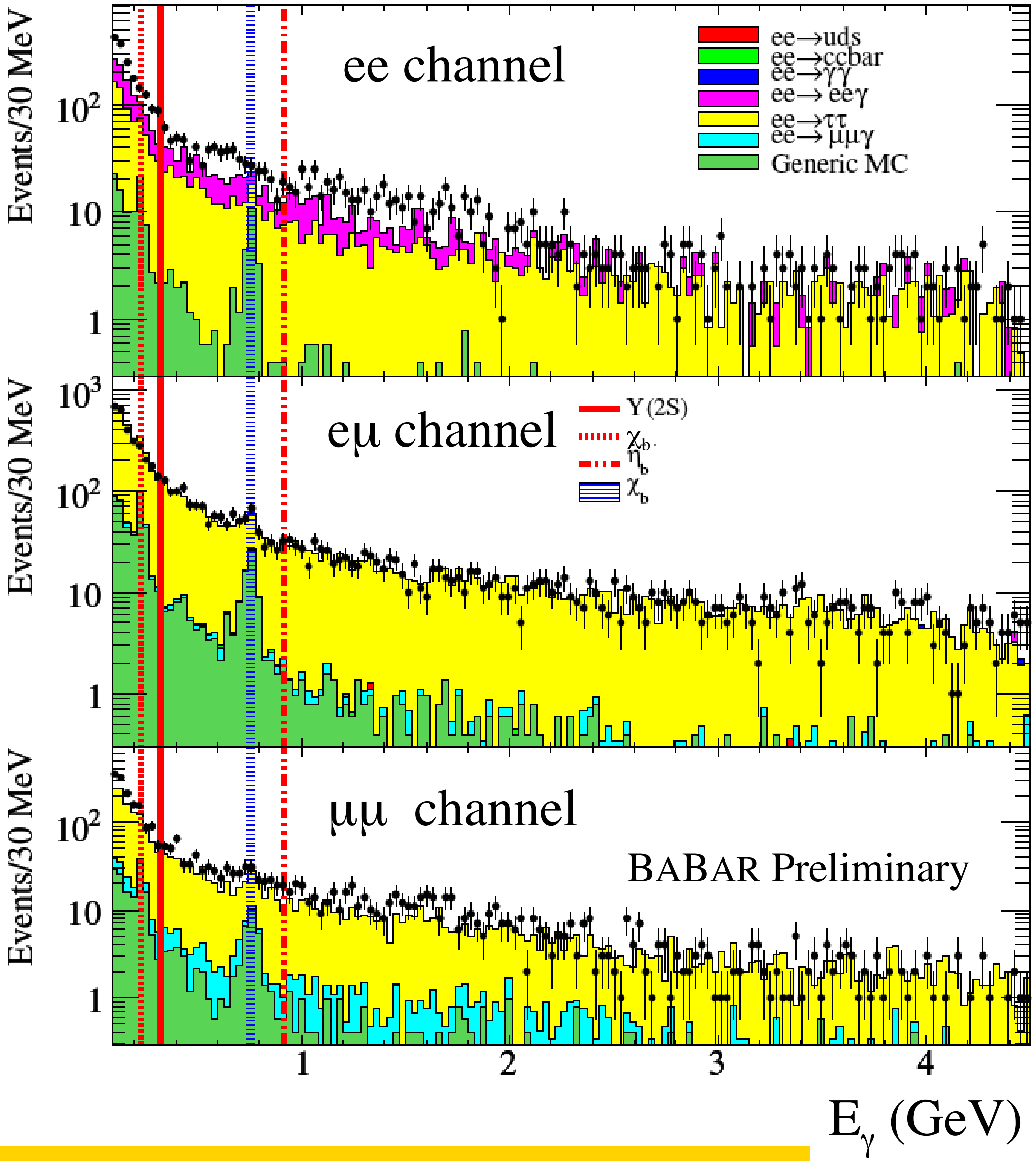
Toy Distribution of Maximum S





Generate 10^8 toy experiments with 1966 bins:
normal distribution for each bin, adjacent bins correlated by 88%
Typical trial factor ~1500

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



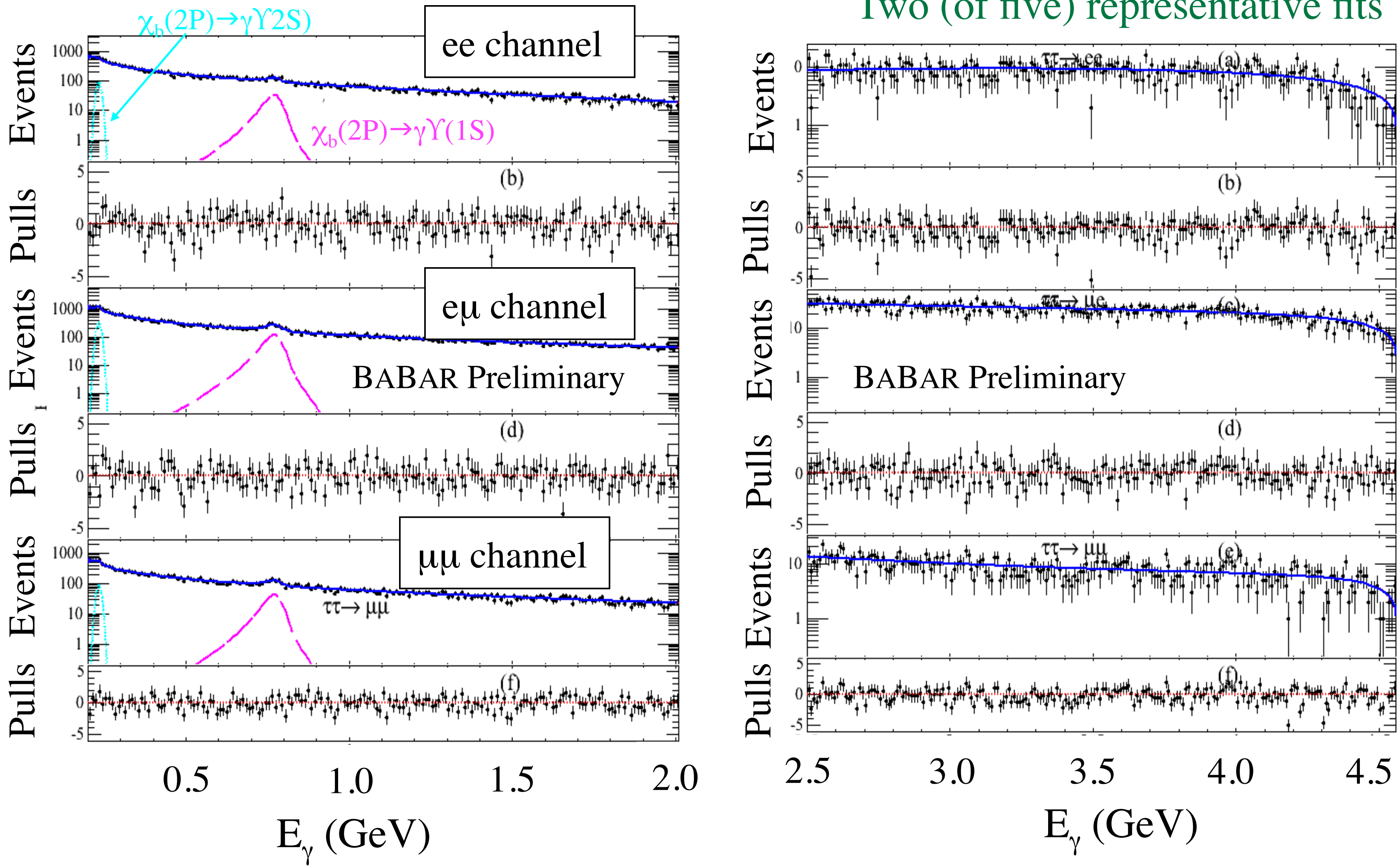
Selection optimized in five large energy regions. Background dominated by irreducible $e^+e^-\rightarrow\tau^+\tau^-$

Describe background by a smooth distribution, include peaking contributions for $\chi_b(2P)\rightarrow\gamma\Upsilon(1S,2S)$

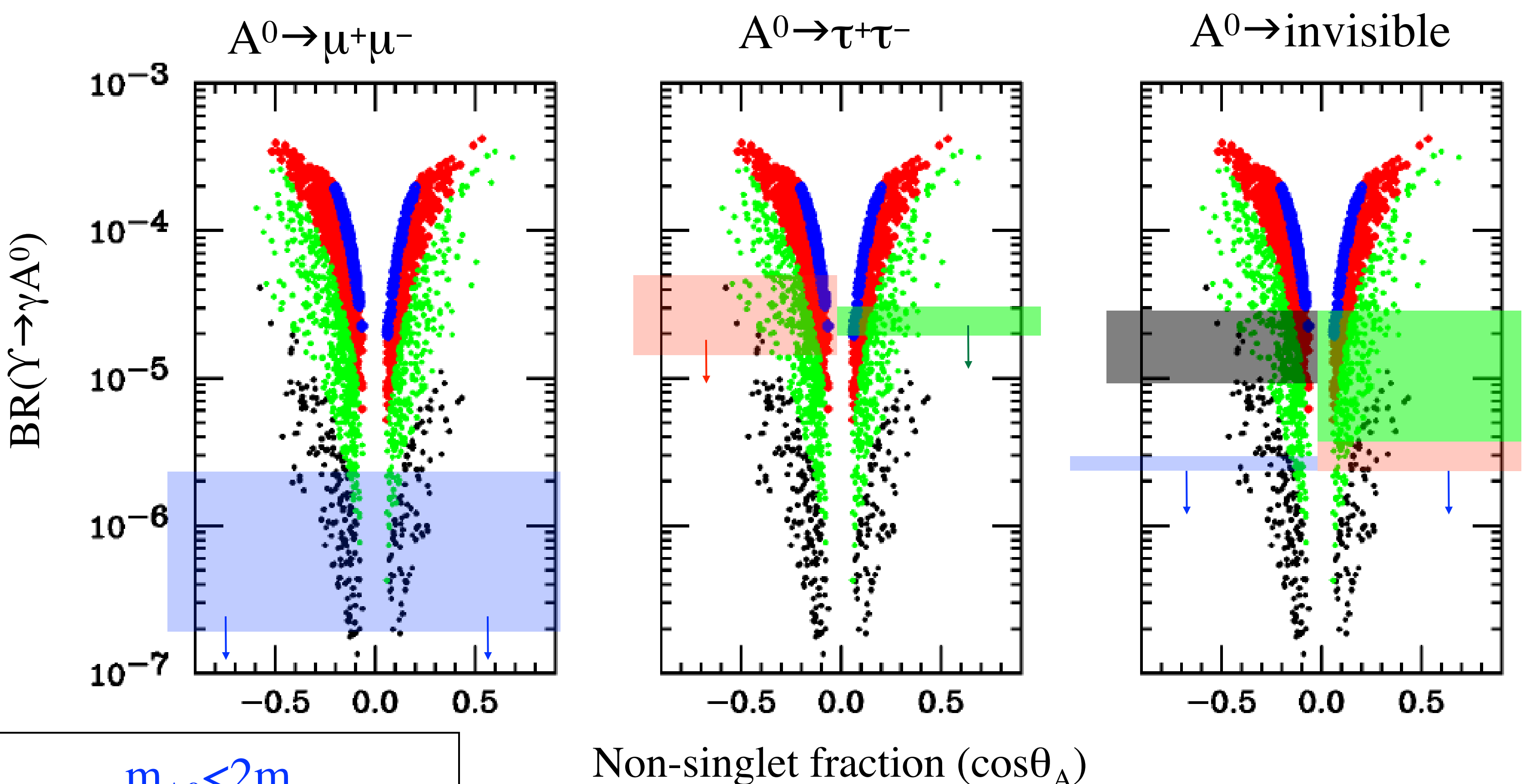
Signal distribution: Crystal Ball PDF with low-energy tail, resolution 10-55 MeV grows with E_γ

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

Two (of five) representative fits



NMSSM Predictions for $\Upsilon \to \gamma A^0$ vs BaBar Limits



$m_{A0} < 2m_\tau$

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

7.5 GeV $< m_{A0} <$ 8.8 GeV

8.8 GeV $< m_{A0} <$ 9.2 GeV

Also place significant constraints on other models

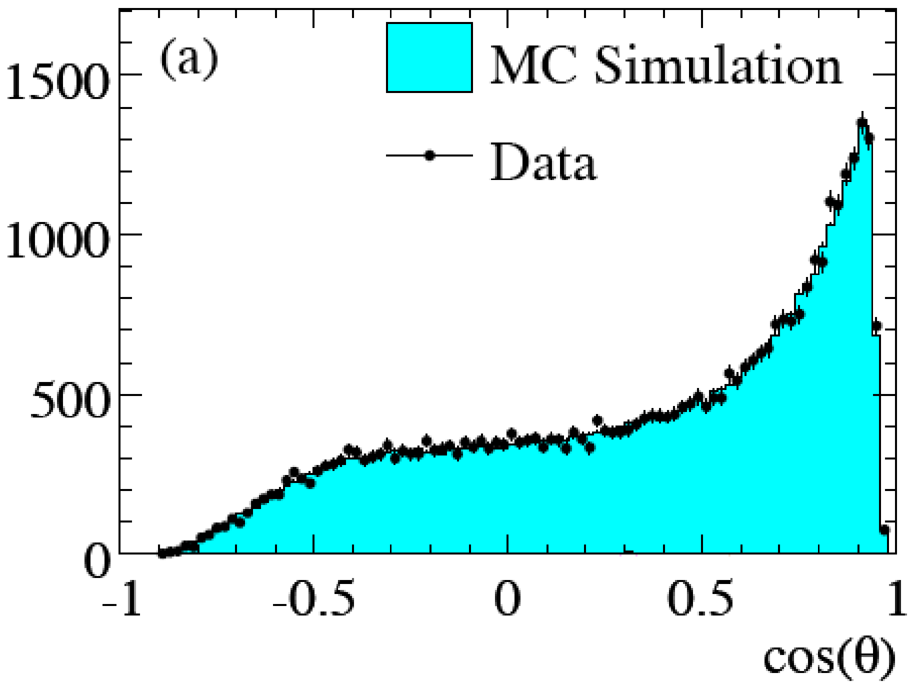
$\Upsilon(1S)\to$invisible: Event Selection

- "Invisible sample":
  - Select events with two low-momentum charged tracks and little additional activity in the detector
    - Di-pion kinematics specific to $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$ transition (C.C.D. Cronin-Hennessy et al., PRD**76**, 072001 (2007))
    - Signal efficiency: 18%
    - Multi-variate selection (BDT)
- "Visible sample"
  - 4-track fully-reconstructed sample: $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\to l^+l^-$
    - Check selection, calibrate acceptance, detection efficiency and BR for $\Upsilon(3S)\to\pi^+\pi^-\Upsilon(1S)$
    - Calibrate dipion mass resolution
    - Affects both signal and peaking background from $\Upsilon(1S)\to l^+l^-$ events with missing particles
  - 3-track sample
    - Check acceptance

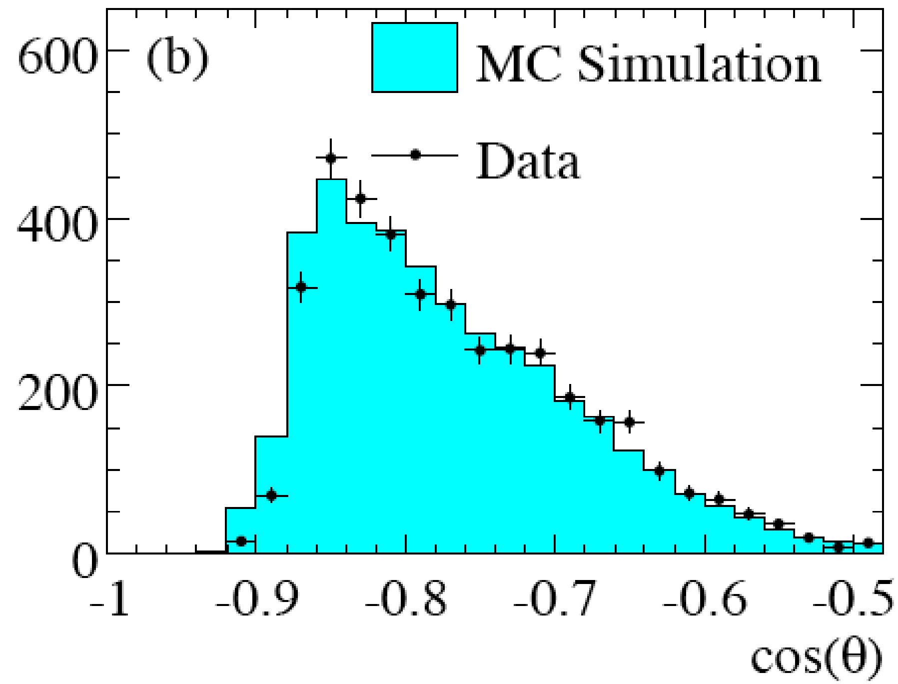
Υ(1S)→invisible: Corrections and Systematics

Geometric acceptance and efficiency for visible events

4-track sample



3-track sample: one track missing in forward direction



Use data distributions in the polar angle to re-weight the simulated events, recompute efficiency. Plots shown after re-weighting. Correction of 1.088±0.012 (applies to the product of efficiency and BR($\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$))