Searches for a Low-Mass Higgs in Upsilon Decays in BaBar

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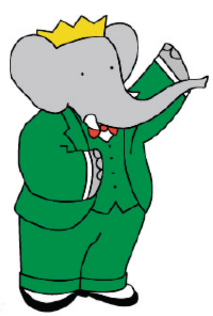
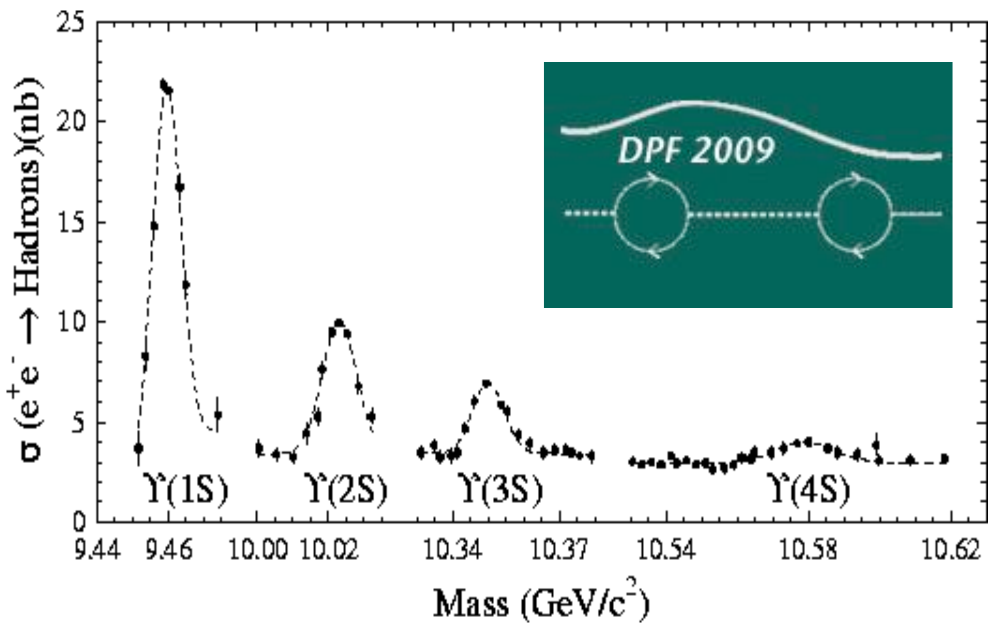
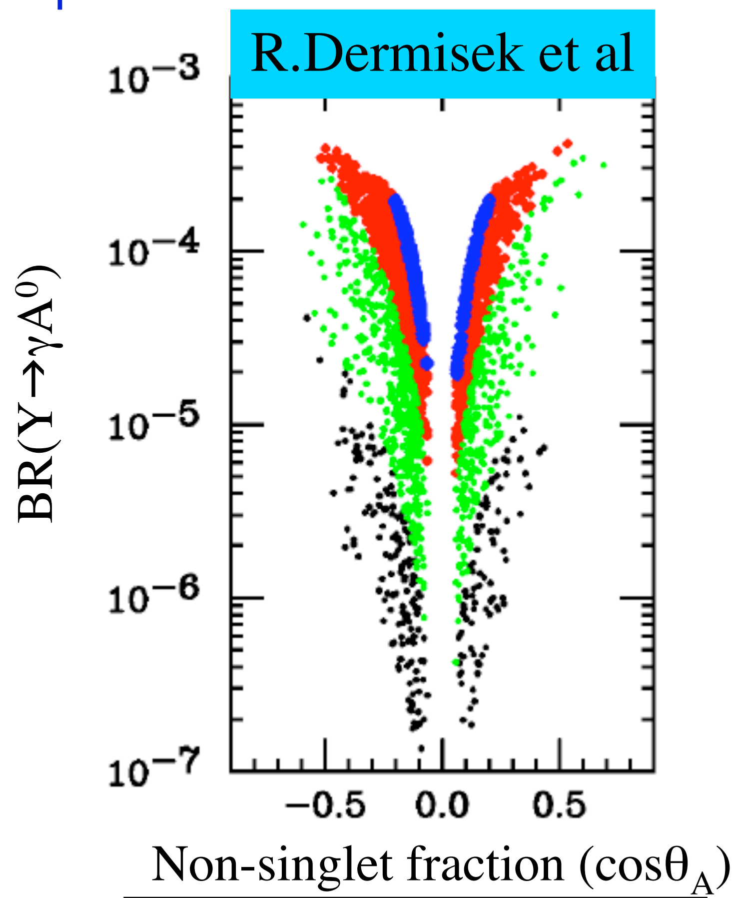




Motivation



$m_{A0}<2m_\tau$

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

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

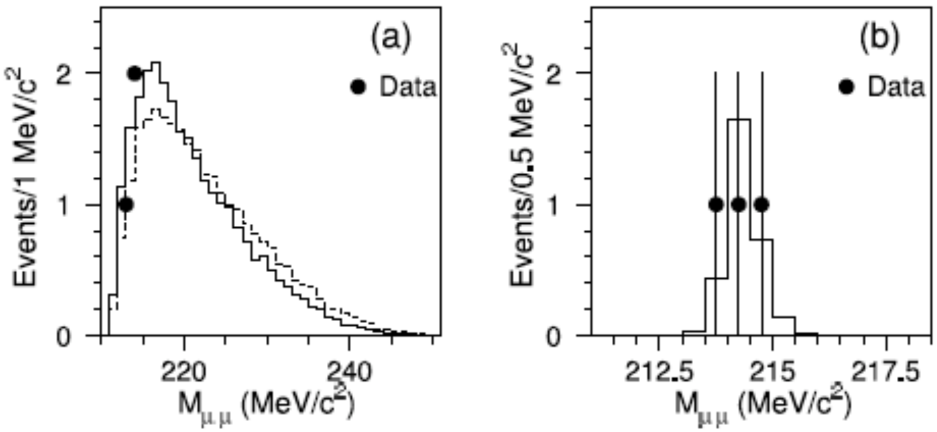
8.8 GeV $<m_{A0}<$ 9.2 GeV

PRD**76**, 051105 (2007)

- 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
- Dark matter axion portal
  - Nomura, Thaler, PRD**79**, 075008 (2009) and others
    - ☞ Predict $BR(\Upsilon \to \gamma A) \sim 10^{-6}-10^{-5}$ with $m_A \sim 400$-800 MeV
- Also interesting to look in η_b region
  - Leptonic BR is expected to be small if η_b is a meson

Experimental Constraints

HyperCP anomaly



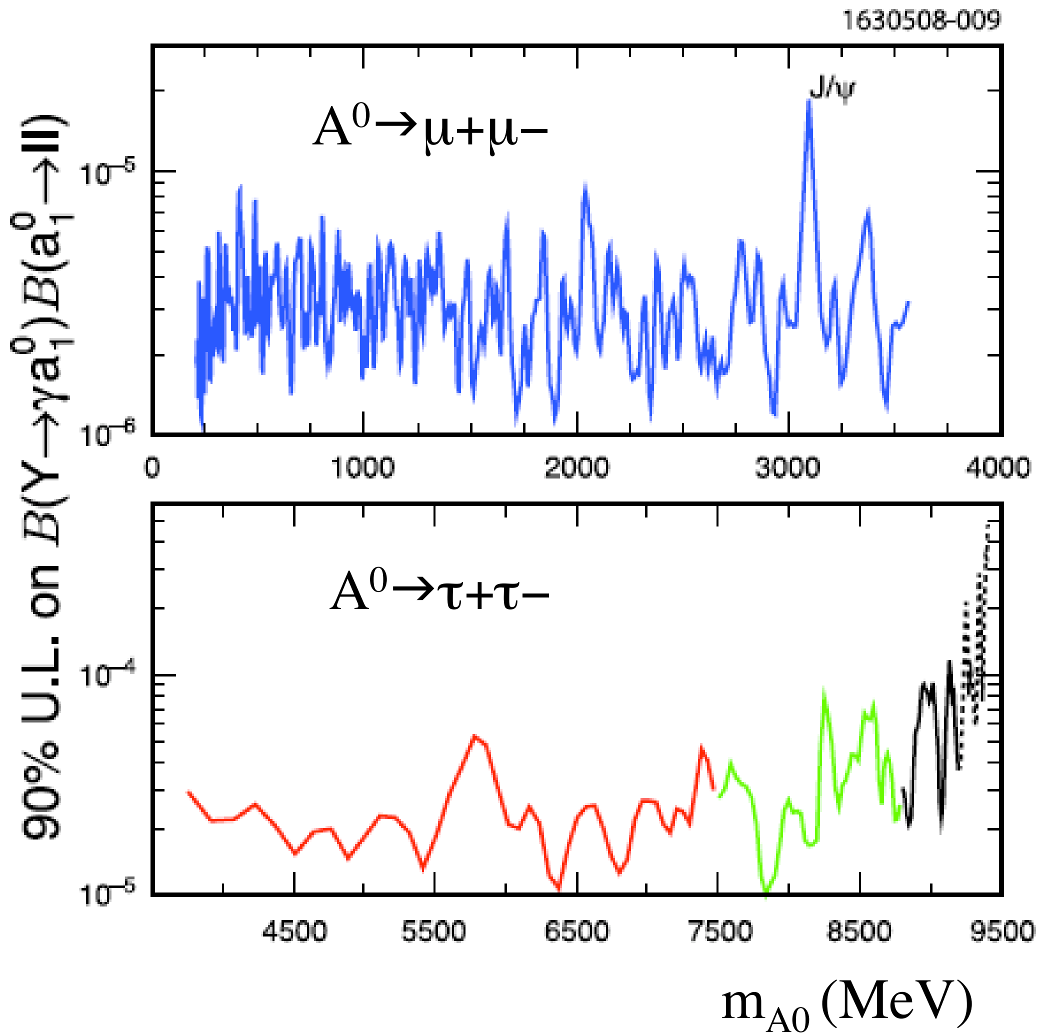
H. Park et al., PRL**94**, 021801 (2005)

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

Small width (Γ<1 MeV)

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

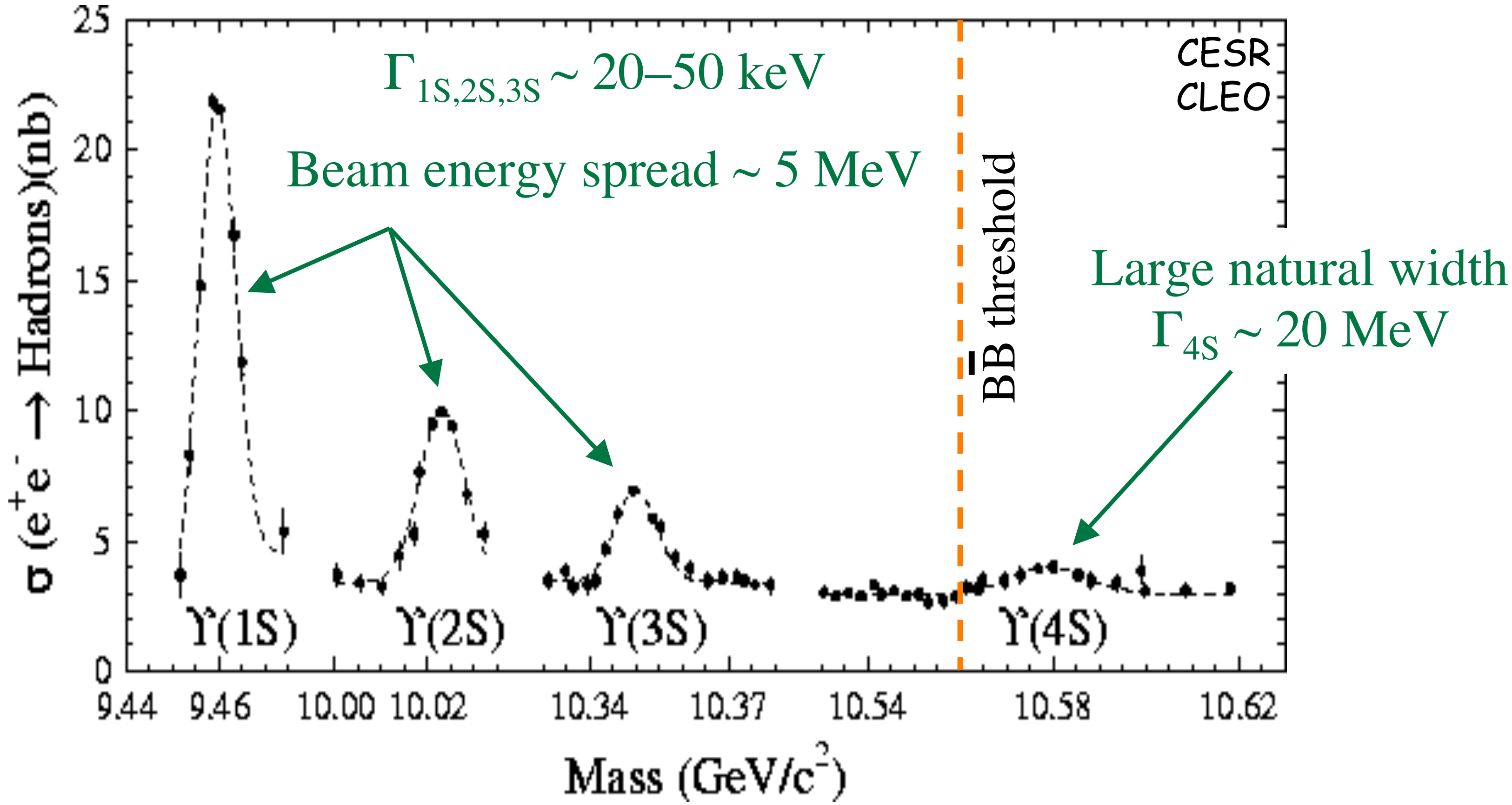
CLEO limits on $\Upsilon(1S) \to \gamma A^0$



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

Upsilon Resonances

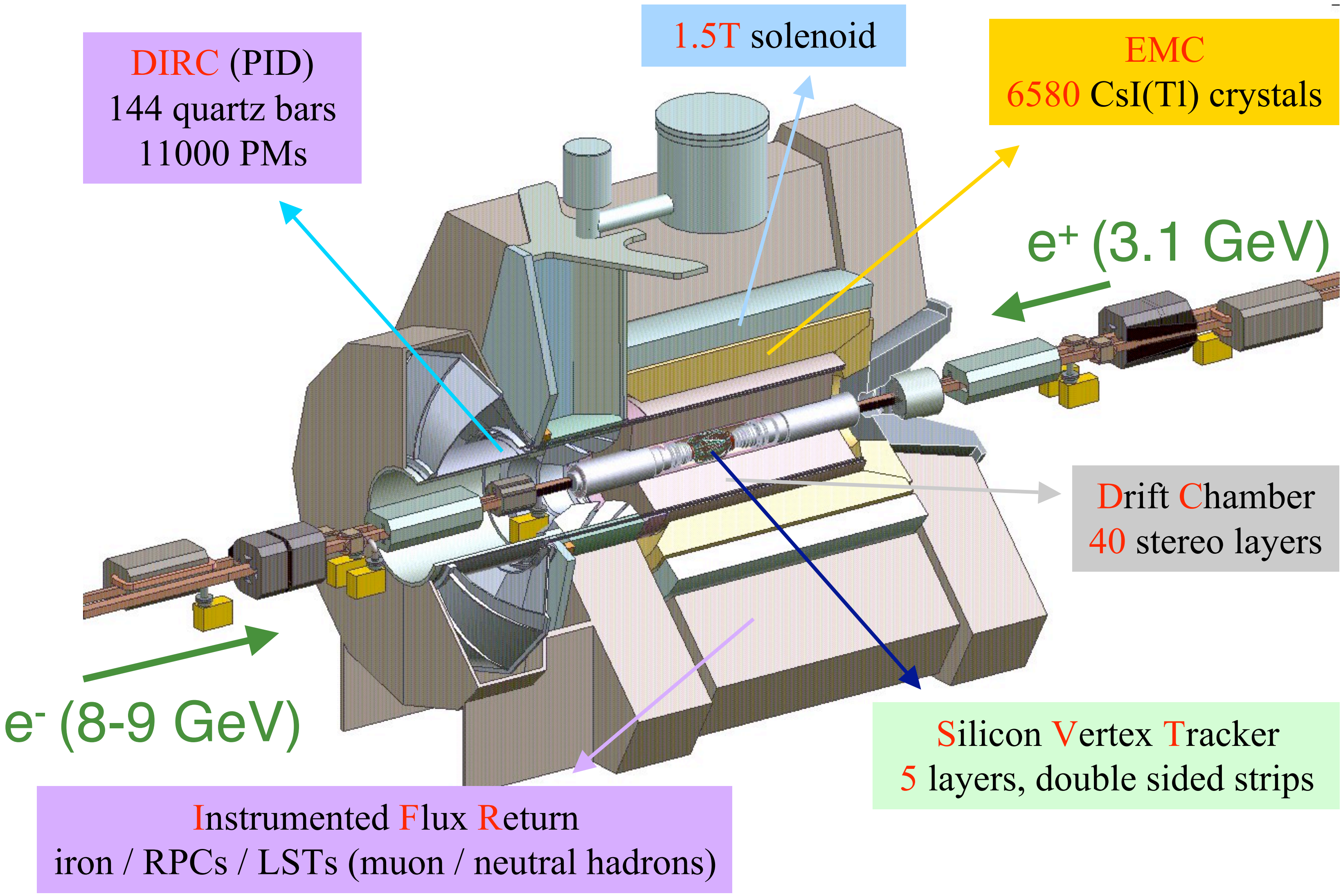
- Electron-Positron collider: $e^+e^- \rightarrow \gamma^* \rightarrow \Upsilon(nS)$



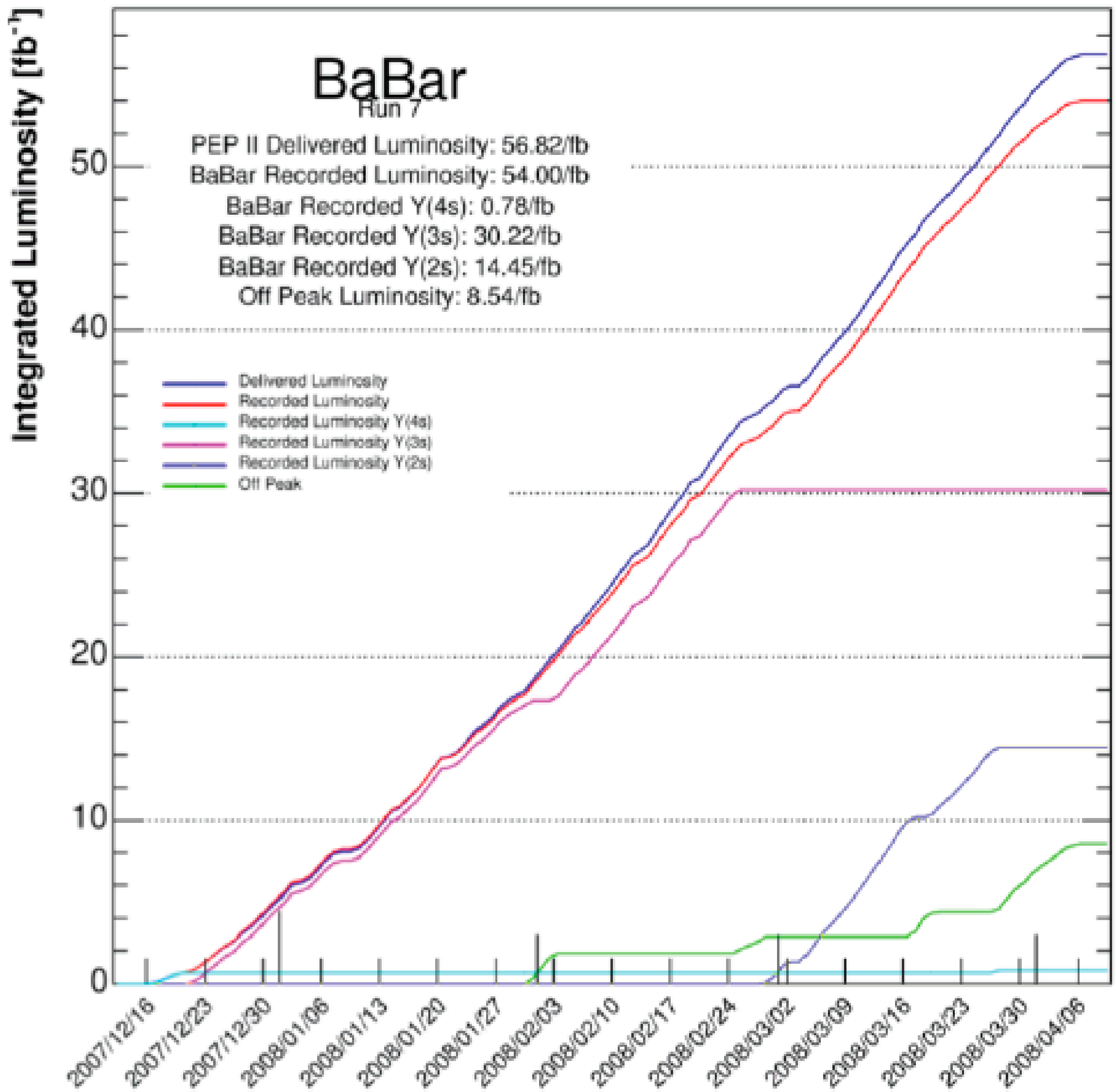
For any bottomonium process $BF_{nS}=\Gamma_{nS}/\Gamma_{tot} \gg BF_{4S}$, n=1,2,3

Significantly better sensitivity to new physics @ narrow resonances

BaBar Detector



BaBar 2008 Dataset



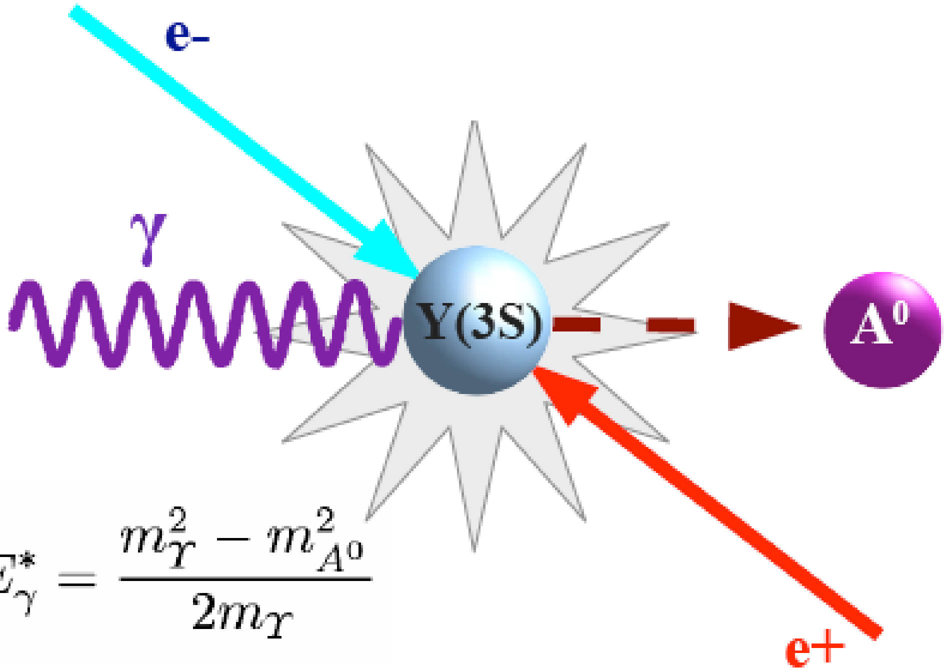
Dec. 2007 - Apr. 2008

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

122M Υ(3S) decays

99M Υ(2S) decays

Searches for a Light Higgs in BaBar



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

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

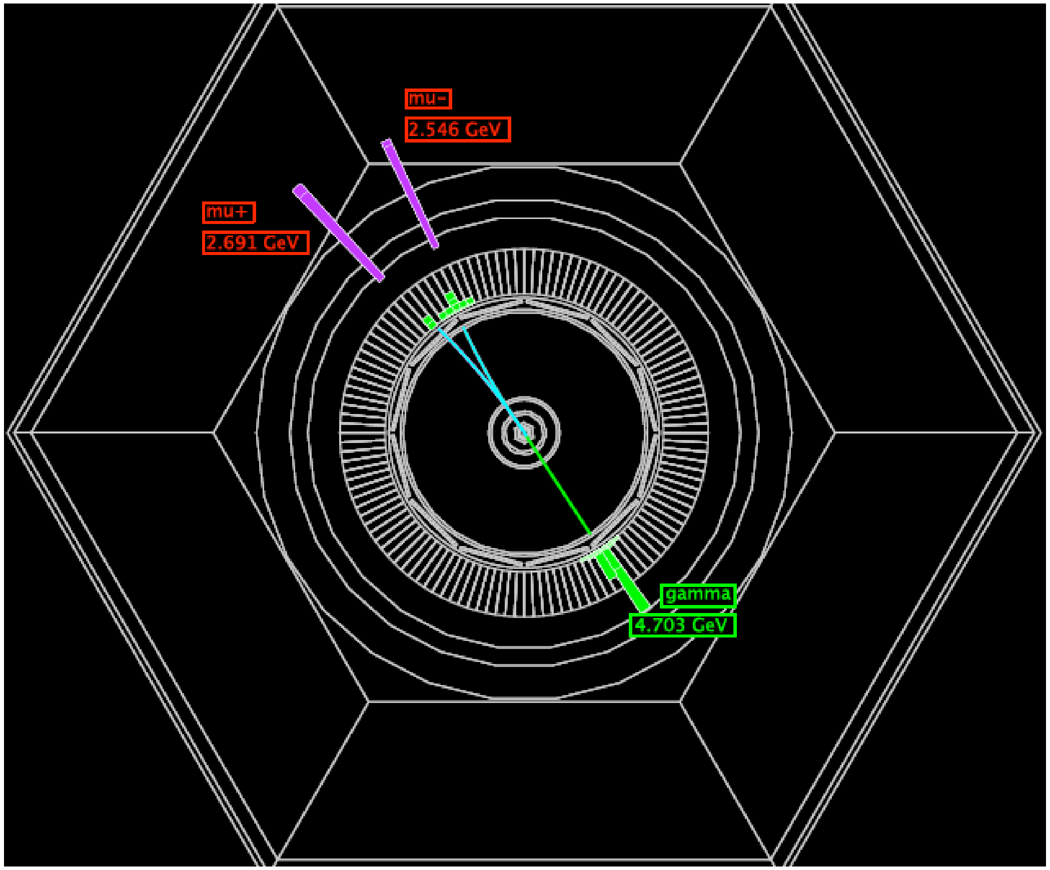
Well-understood initial state (narrow Υ(2S) or Υ(3S) resonance)

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

This talk:

- ✔ $A^0 \rightarrow \mu^+\mu^-$, arXiv:0905.4539, accepted to PRL
- ✔ $A^0 \rightarrow \tau^+\tau^-$, arXiv:0906.2219, submitted to PRL
- ✔ $A^0 \rightarrow$ invisible (light dark matter), arXiv:0808.0017, preliminary

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



- 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

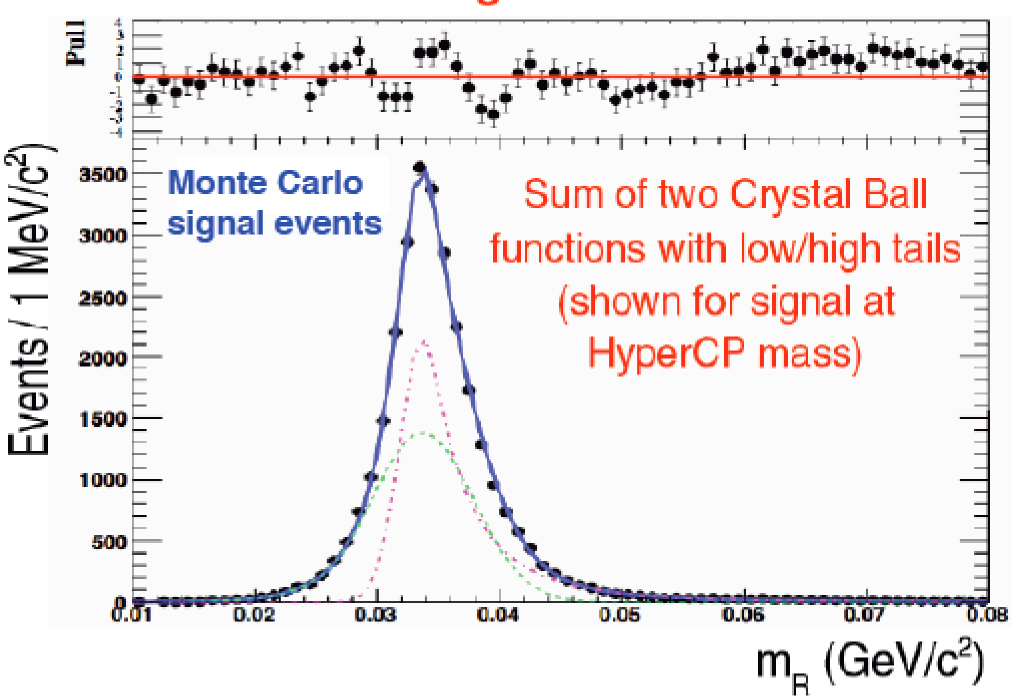
Backgrounds dominated by (irreducible) $e^+e^-\rightarrow\gamma\mu^+\mu^-$ and two-body decays of ISR-produced of $\phi(1020)$, $\rho(770)$, J/ψ, $\Upsilon(1S)$

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

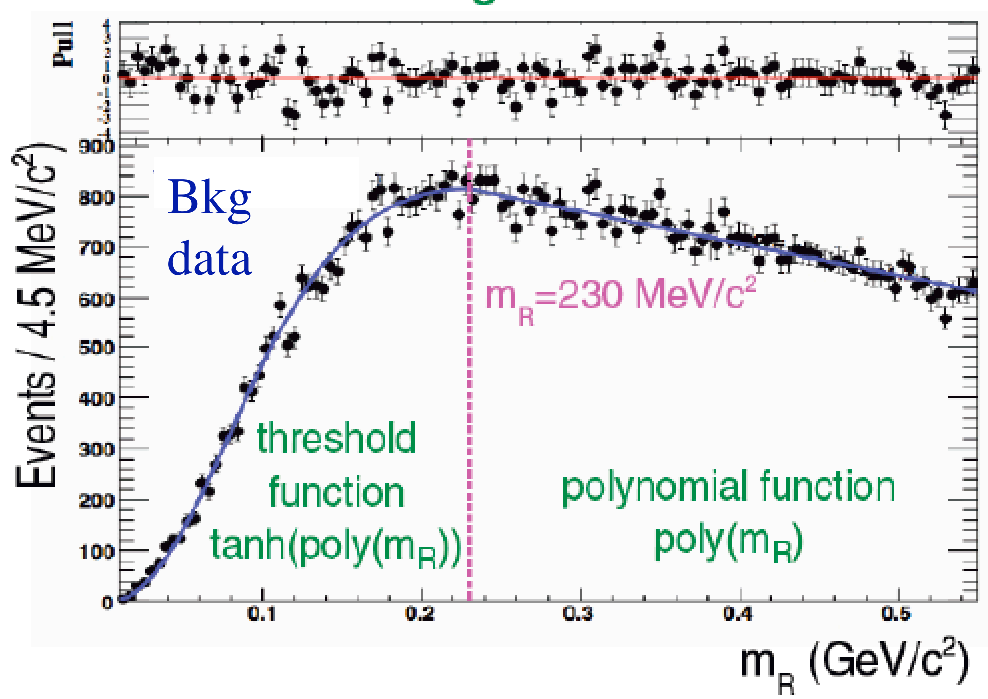
Strategy for $A^0 \to \mu^+\mu^-$

- 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}

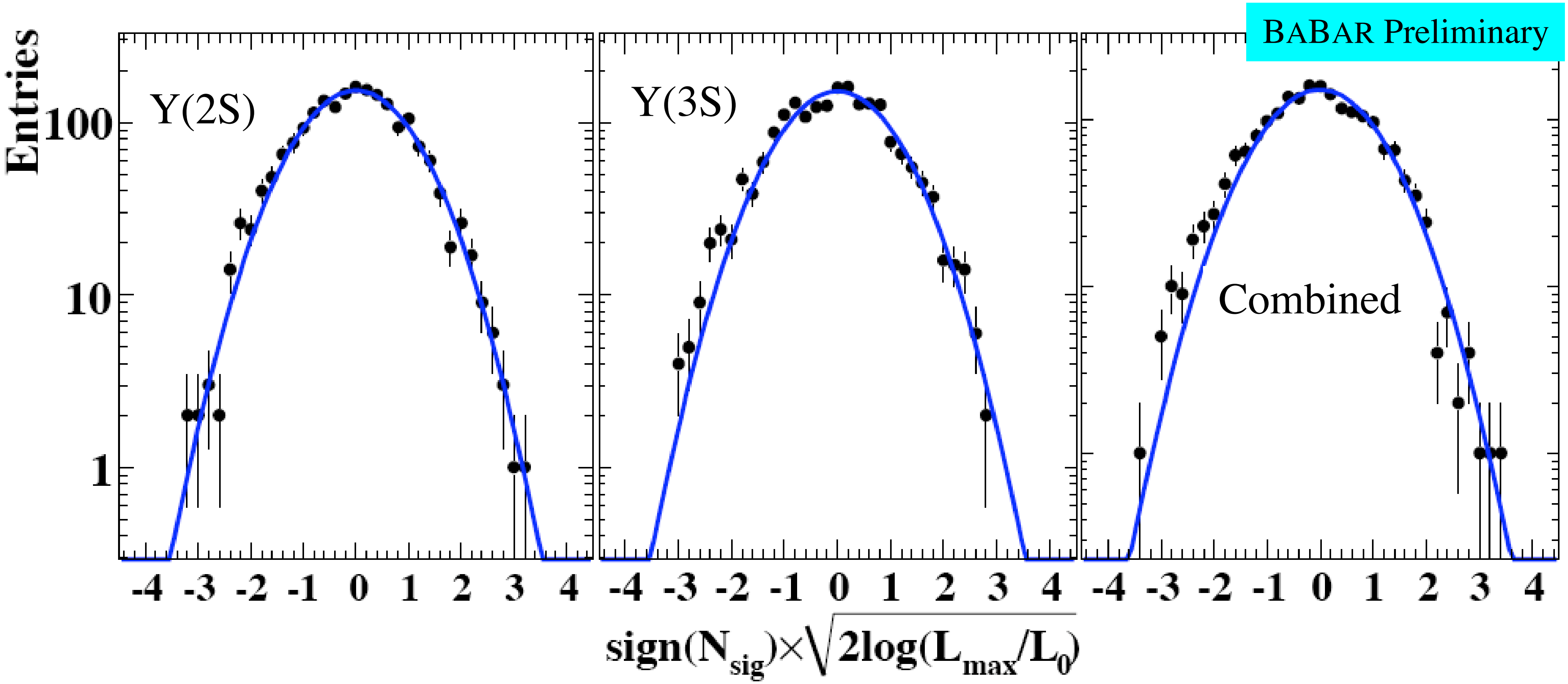
Signal PDF



Background PDF

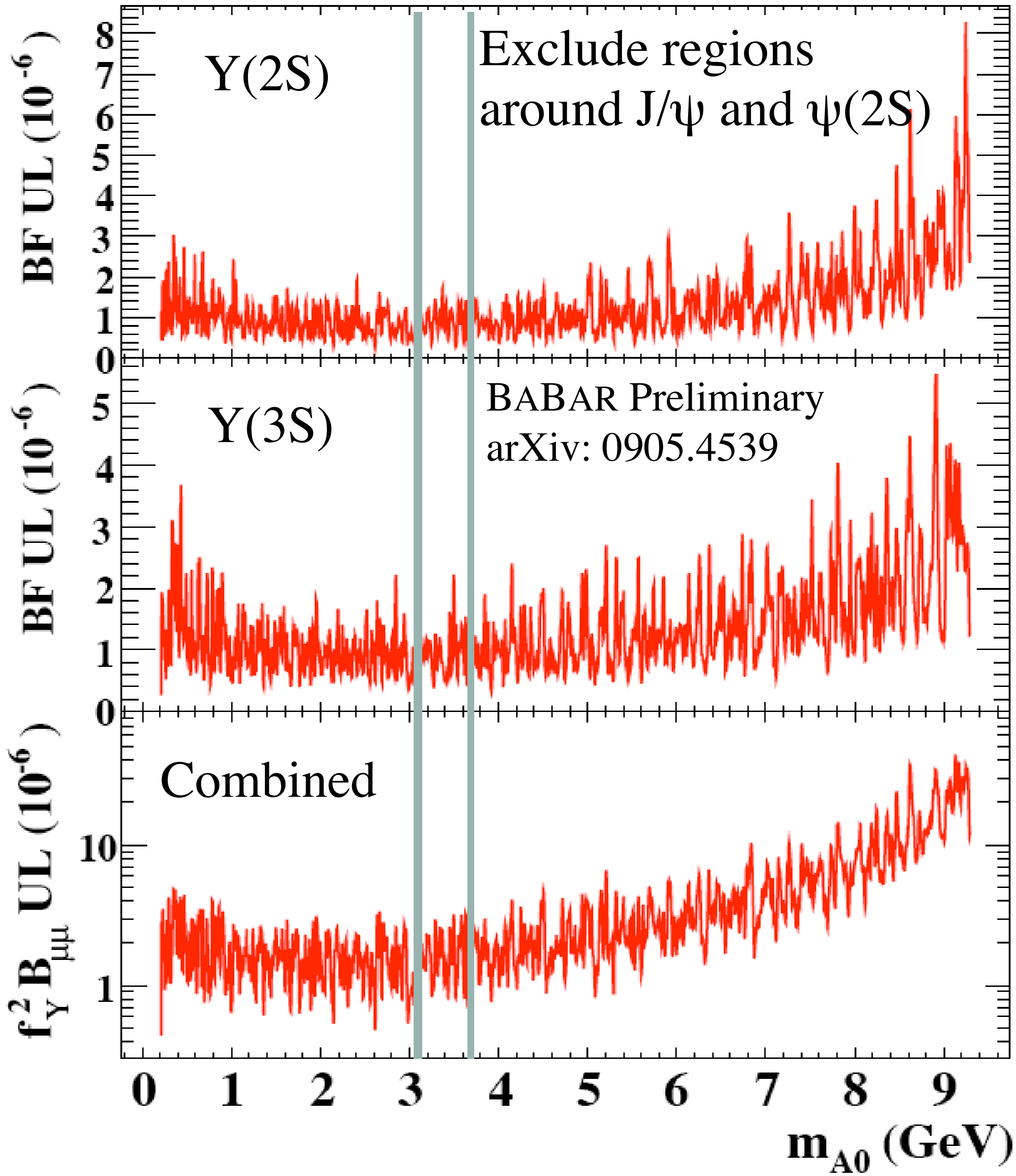


Results: $\Upsilon(2S,3S)\to\gamma A^0$, $A^0\to\mu^+\mu^-$



Expect standard normal distribution for 1955 scan points 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

Also limit

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

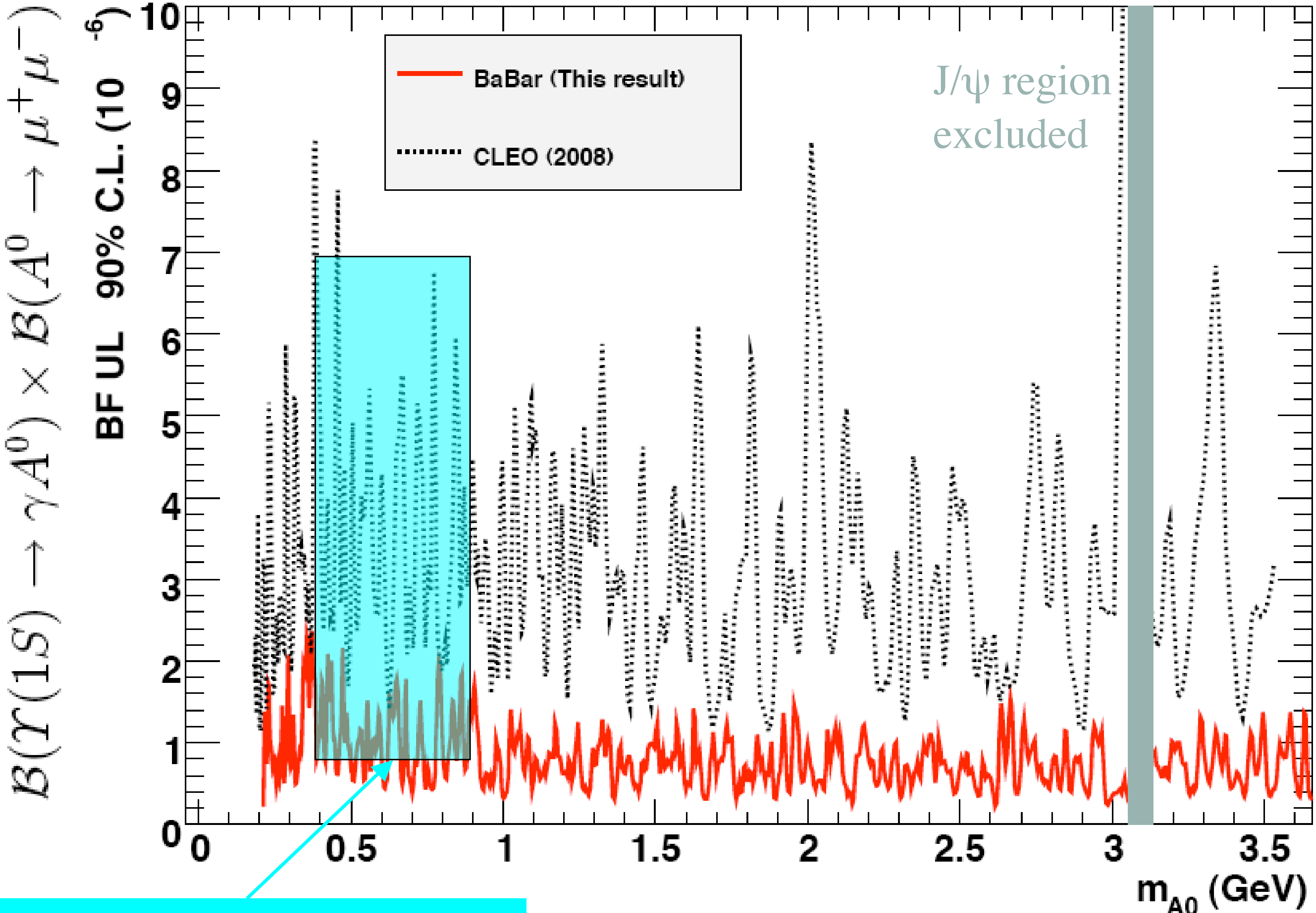
at 90% C.L.

Combined results for 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}<1 GeV, this corresponds to $f_Y < 0.12\, f_{\text{Standard Model}}$

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

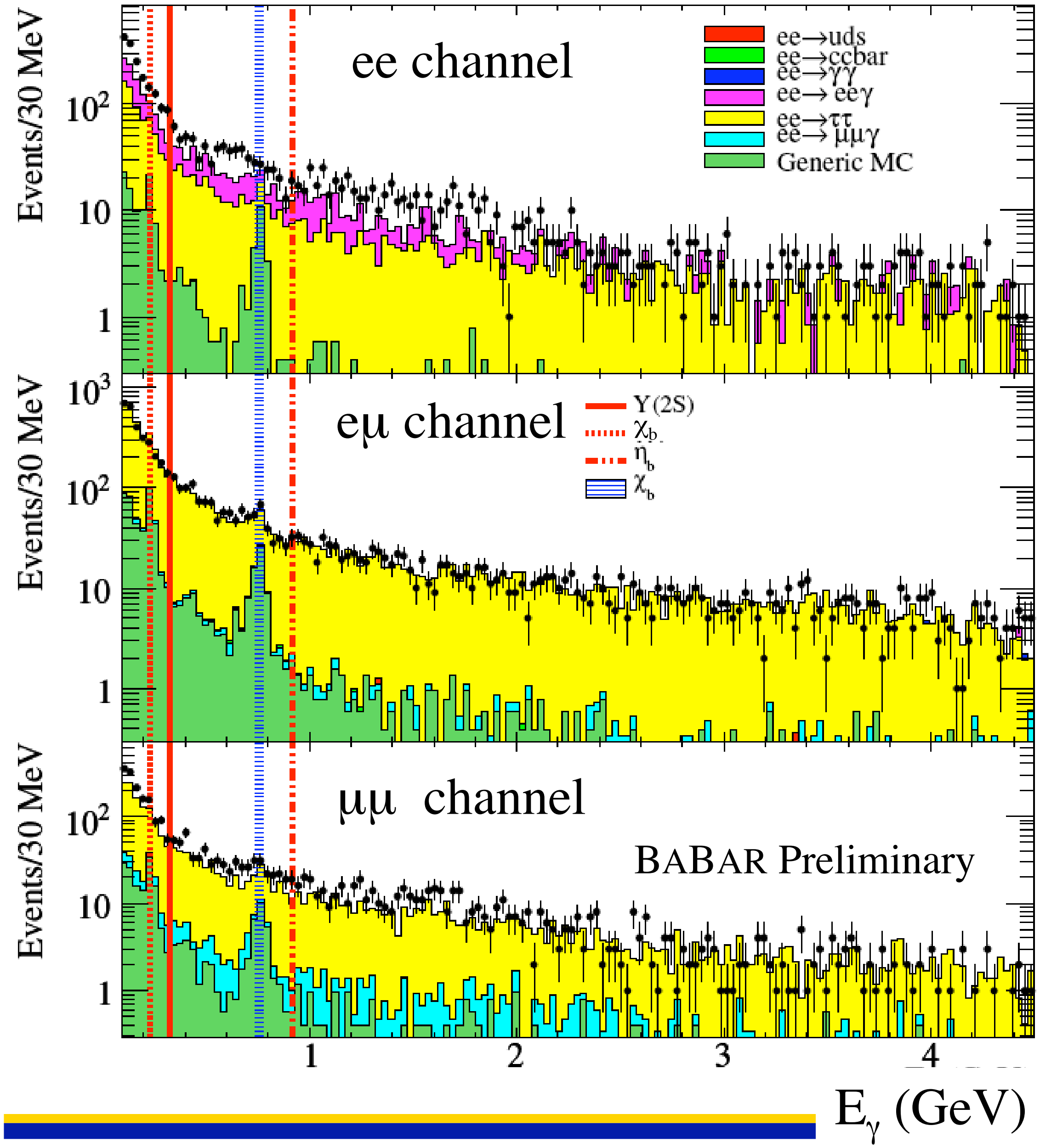


Range predicted by
Axion model (Nomura,Thaler)

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

- Expect tau decays of A^0 to be dominant above the tau threshold
- Strategy:
  - ☞ Look for A^0 decays as a narrow peak in the photon energy spectrum above $E^*_\gamma>0.2$ GeV
  - ☞ Select leptonic decays $\tau\to(e,\mu)\nu\nu$
  - ☞ 3 final states: ee, μμ, eμ
  - ☞ Select events with exactly 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

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



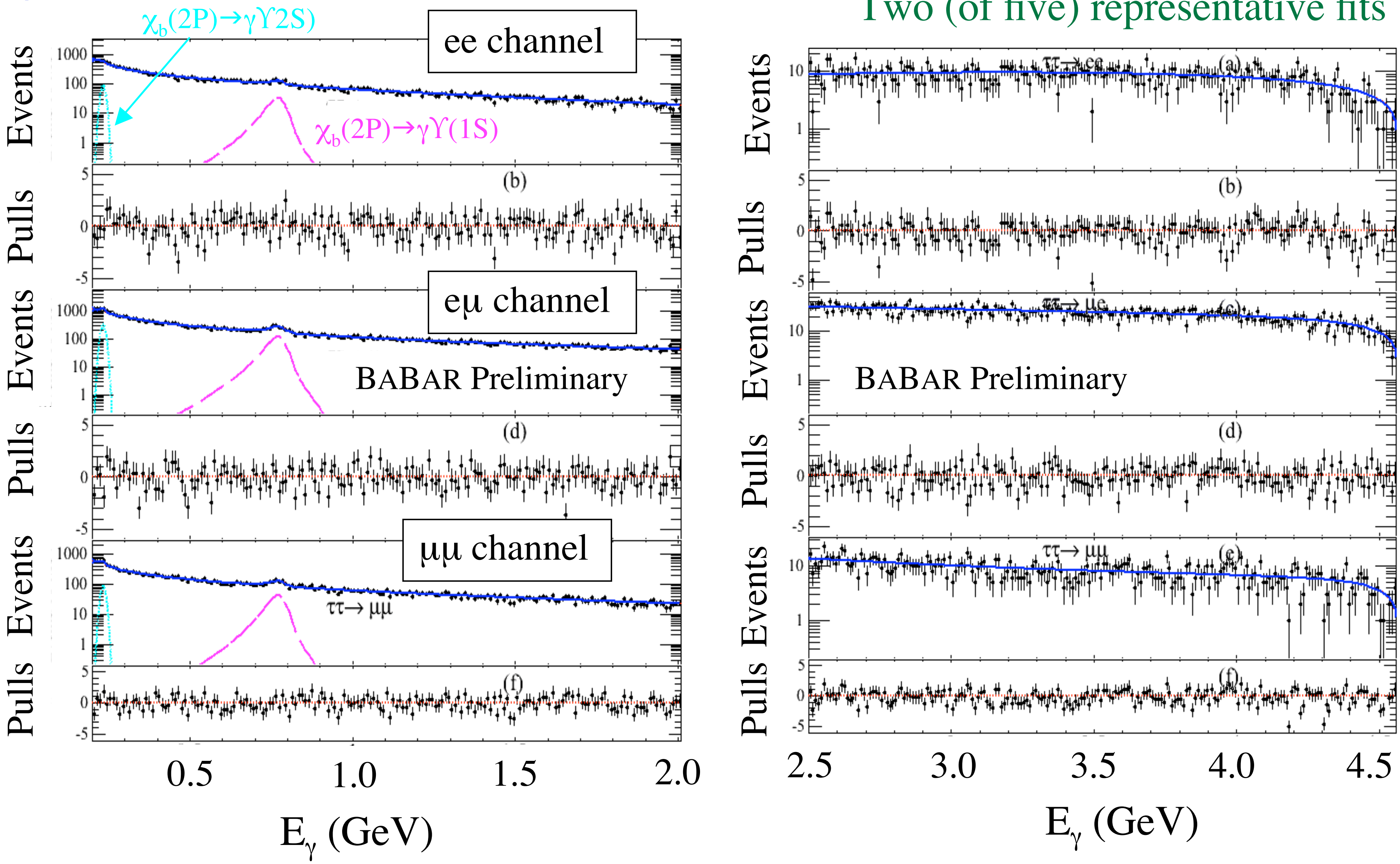
Selection optimized in five large energy regions. Background dominated by irreducible $e^+e^-\rightarrow\tau^+\tau^-$

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

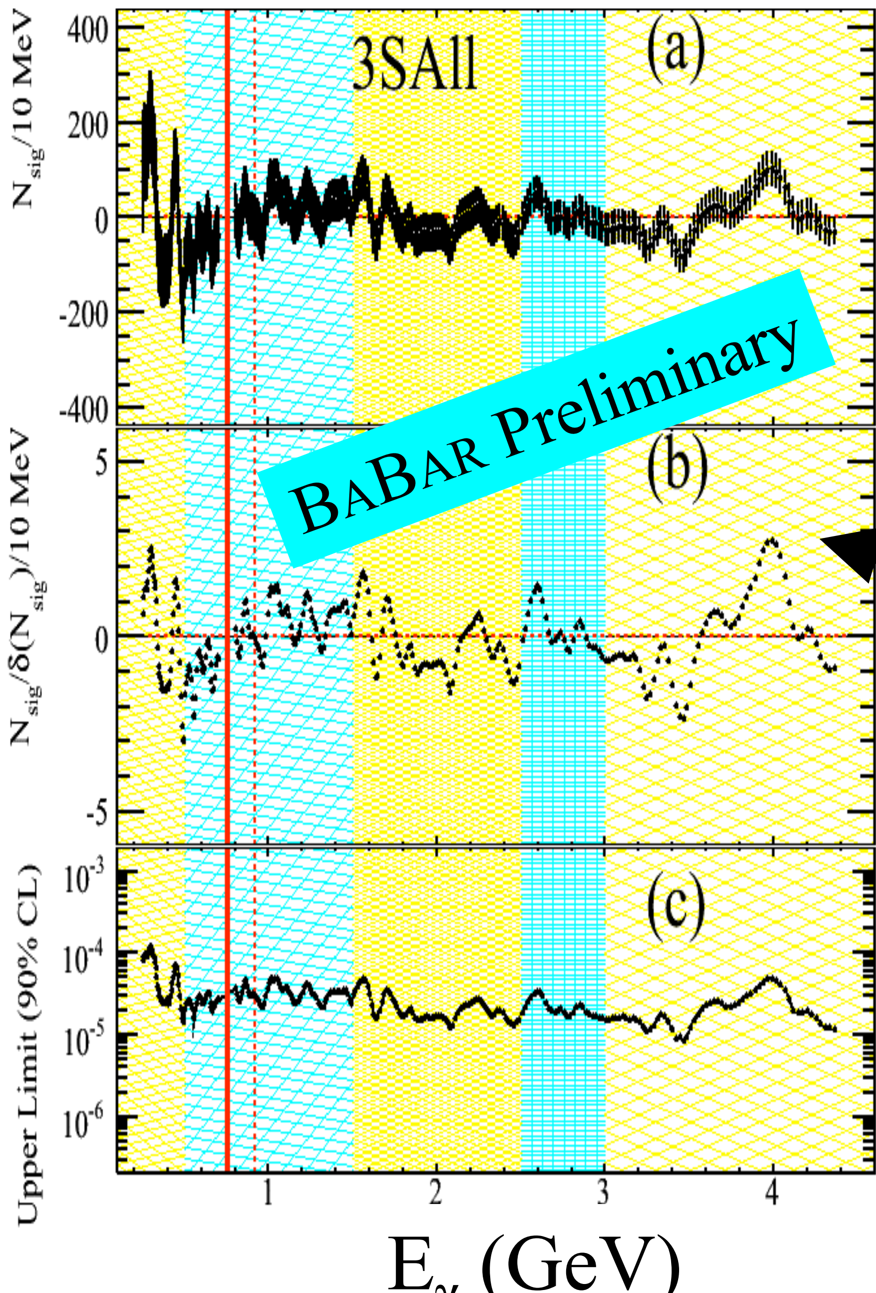
Signal distribution: Crystal Ball PDF with low-energy tail, resolution 10-55 MeV grows with E_γ

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

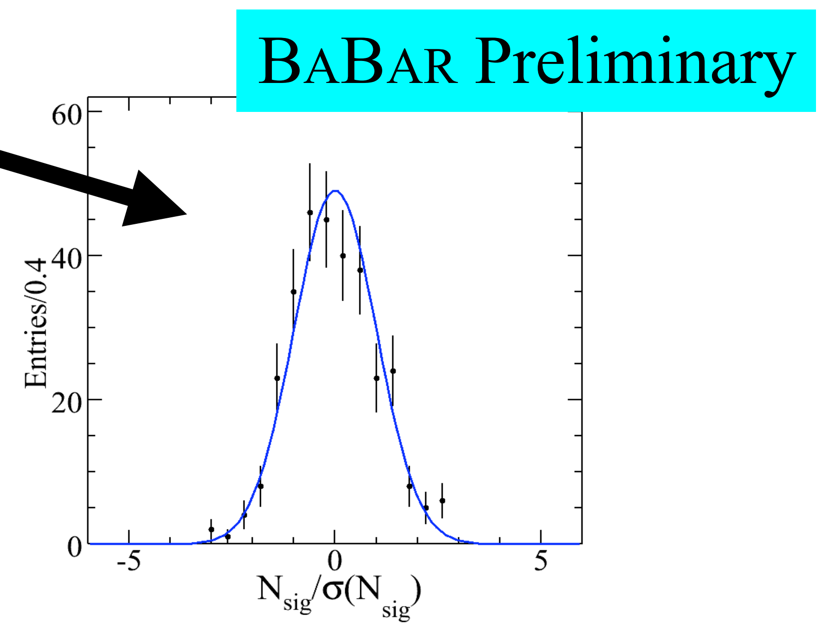
Two (of five) representative fits



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

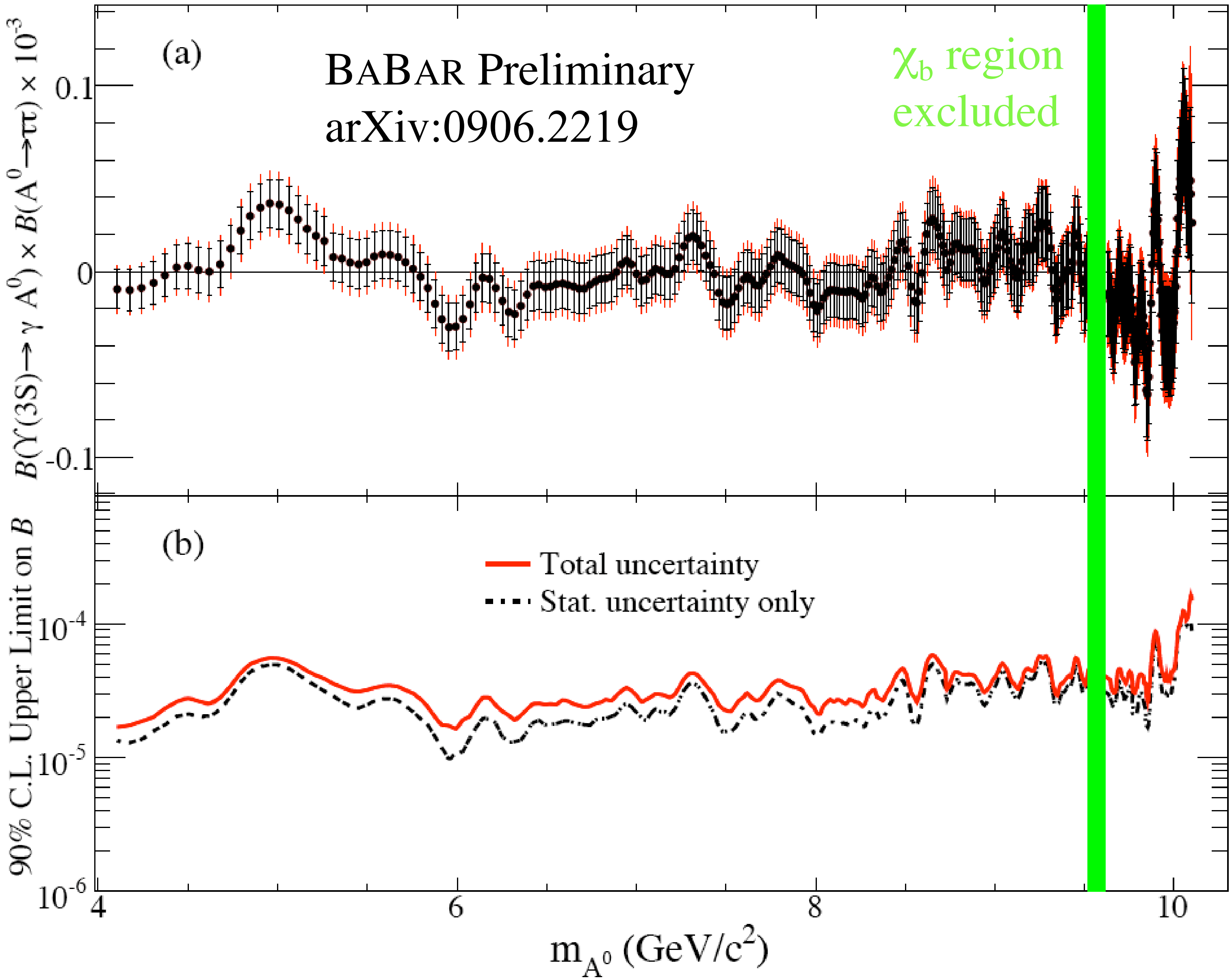


- Scan E_γ distribution in steps of half resolution (307 scan points in total)
- Simultaneous fits (binned ML) to the different ττ-decay modes



No evidence for a peaking structure

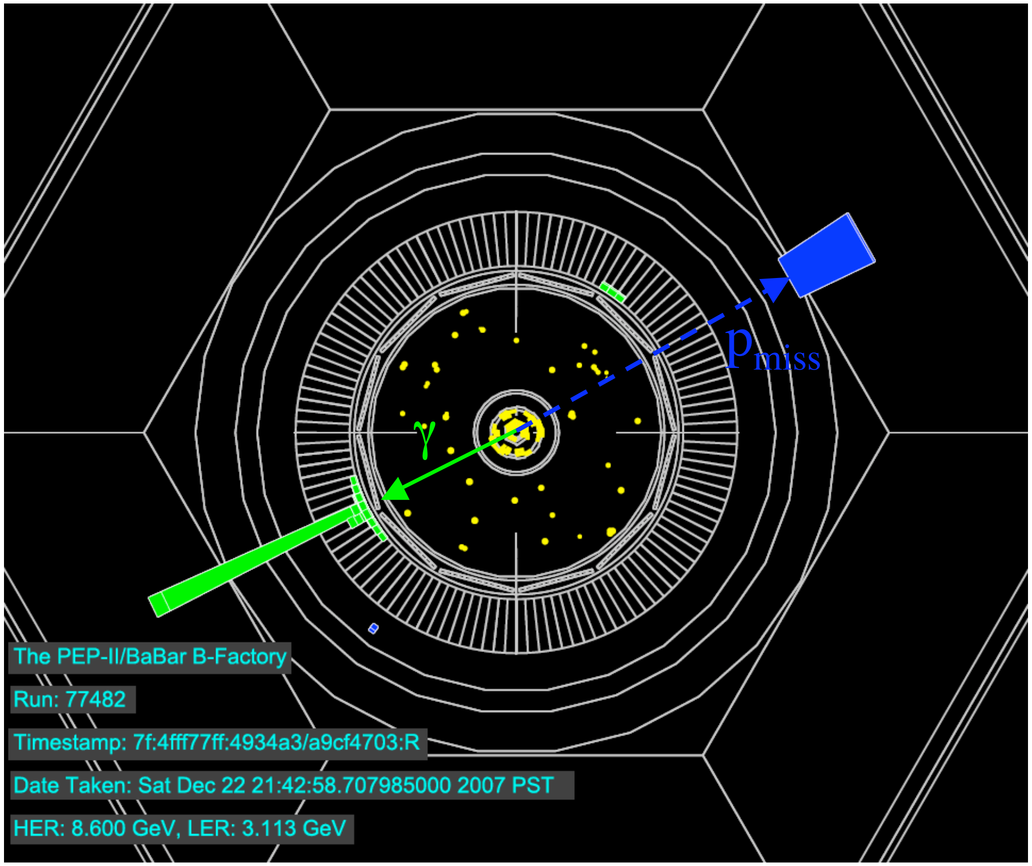
$\Upsilon(3S)\to\gamma A^0$, $A^0\to\tau^+\tau^-$ Results



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

Also set a limit $\mathcal{B}(\eta_b \to \tau^+\tau^-) < 8\%$ at 90% C.L.

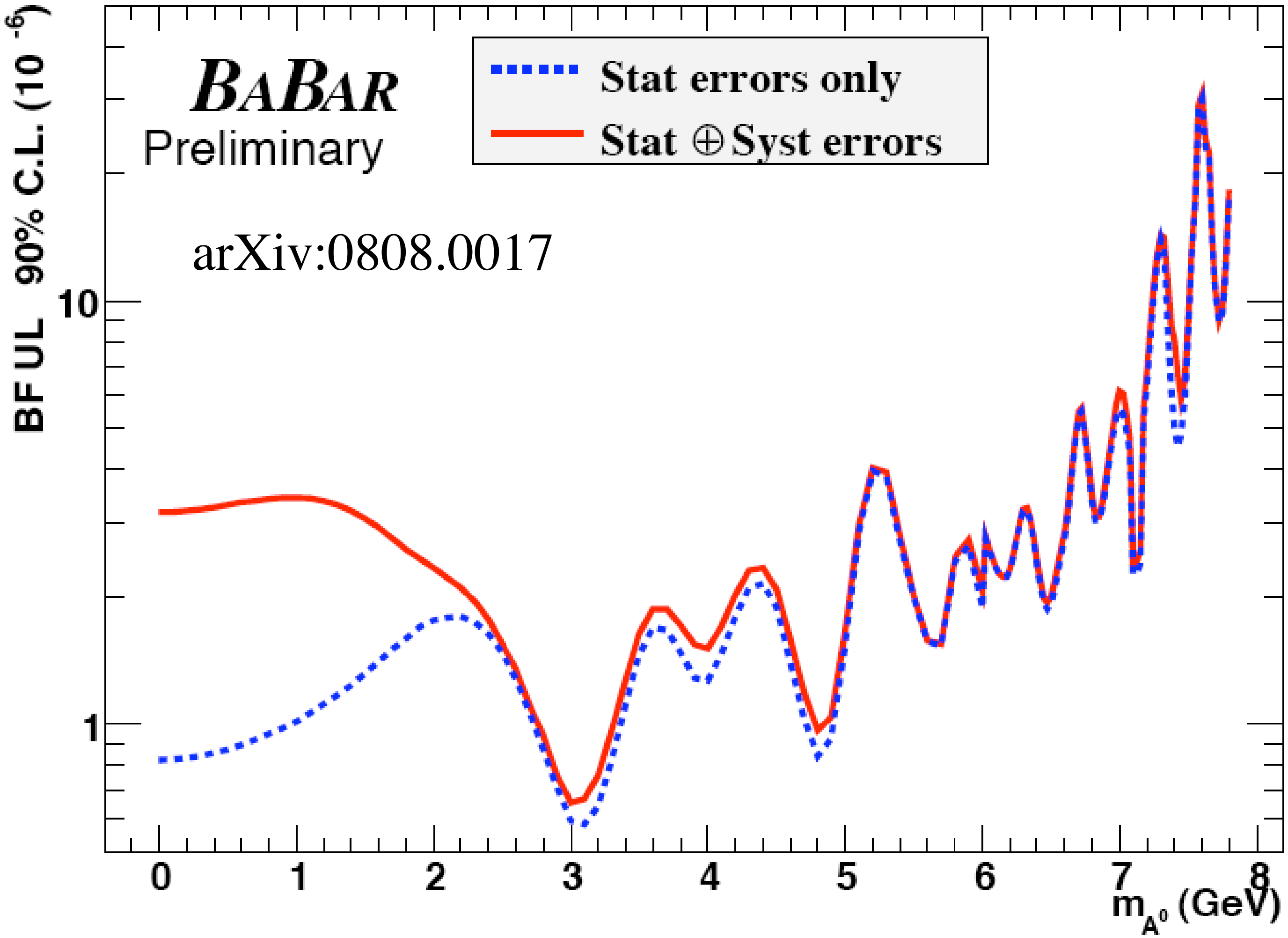
$\Upsilon(3S)\to\gamma A^0$, $A^0\to$invisible



Dominant background from $e^+e^-\to\gamma\gamma$, with one of the photons missing the EM calorimeter. Veto such events by detecting activity in the muon detector (IFR).

- Require a single photon with $E^*_\gamma>2.2$ GeV
- No charged tracks
- No additional energy in EMC above 100 MeV
- Missing momentum points to EMC
- No activity in IFR aligning with missing momentum
- Selection efficiency: 10-11% ($E^*_\gamma>3$ GeV), ~20% ($E^*_\gamma<3$ GeV)

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



Search for A^0 signal as a peak in E_γ spectrum

No significant signal; limits on BF constrain NMSSM parameter space

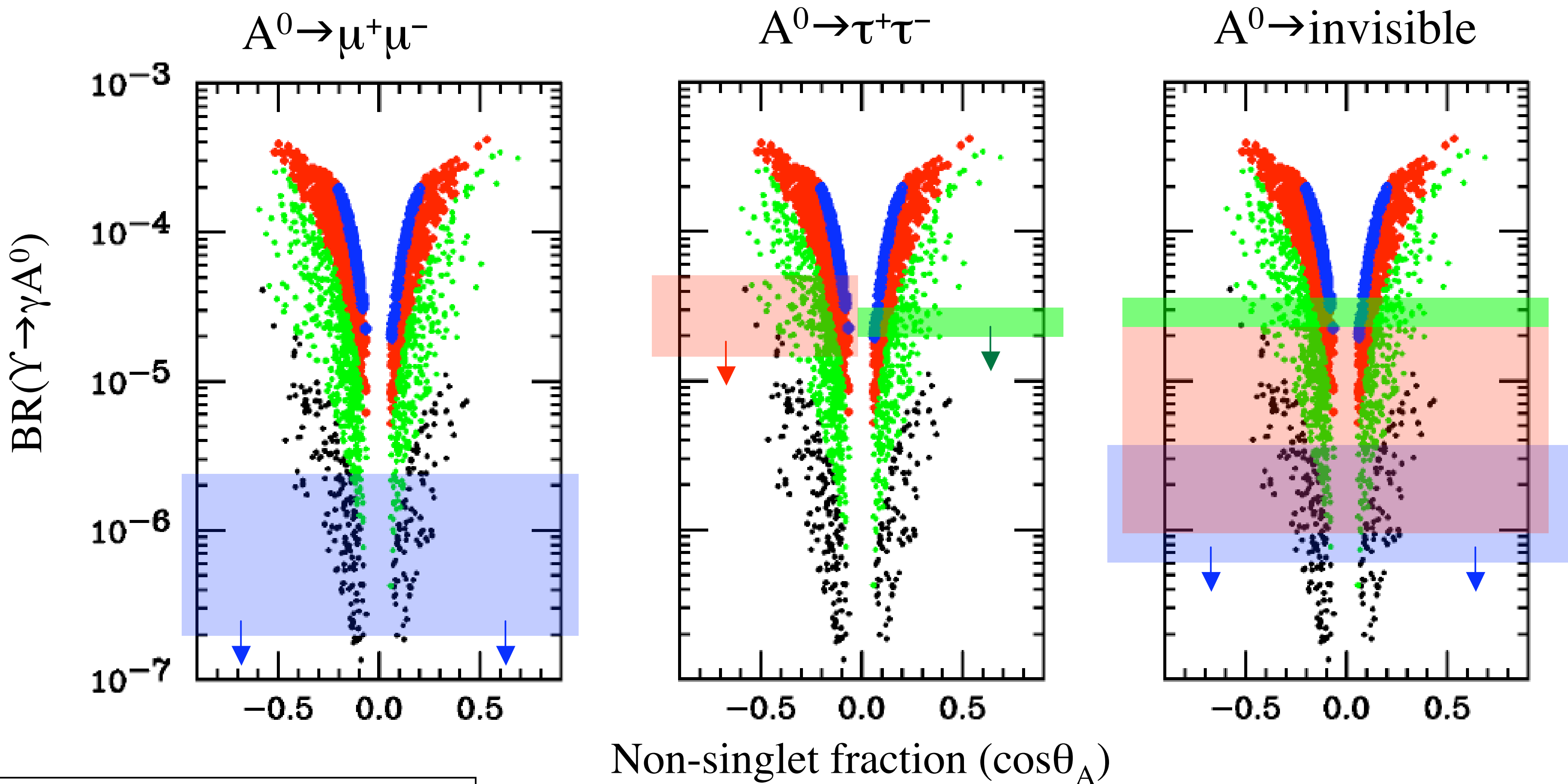
Summary

- 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
    - Rule out CP-odd Higgs interpretation of HyperCP anomaly
  - Also set a limit on dimuon and $\tau^+\tau^-$ BF of η_b

$$\left.\begin{array}{l}\mathcal{B}(\eta_b \to \mu^+\mu^-) < 0.9\% \\ \mathcal{B}(\eta_b \to \tau^+\tau^-) < 8\%\end{array}\right\} \text{@ 90 C.L.}$$

    - Consistent with mesonic interpretation
    - First ever measurements of the exclusive η_b decays
- Publications
    - arXiv:0905.4539 ($A^0 \to \mu^+\mu^-$), preliminary, accepted to PRL
    - arXiv:0906.2219 ($A^0 \to \tau^+\tau^-$), preliminary, submitted to PRL
    - arXiv:0808.0017 ($A^0 \to$invisible), preliminary

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



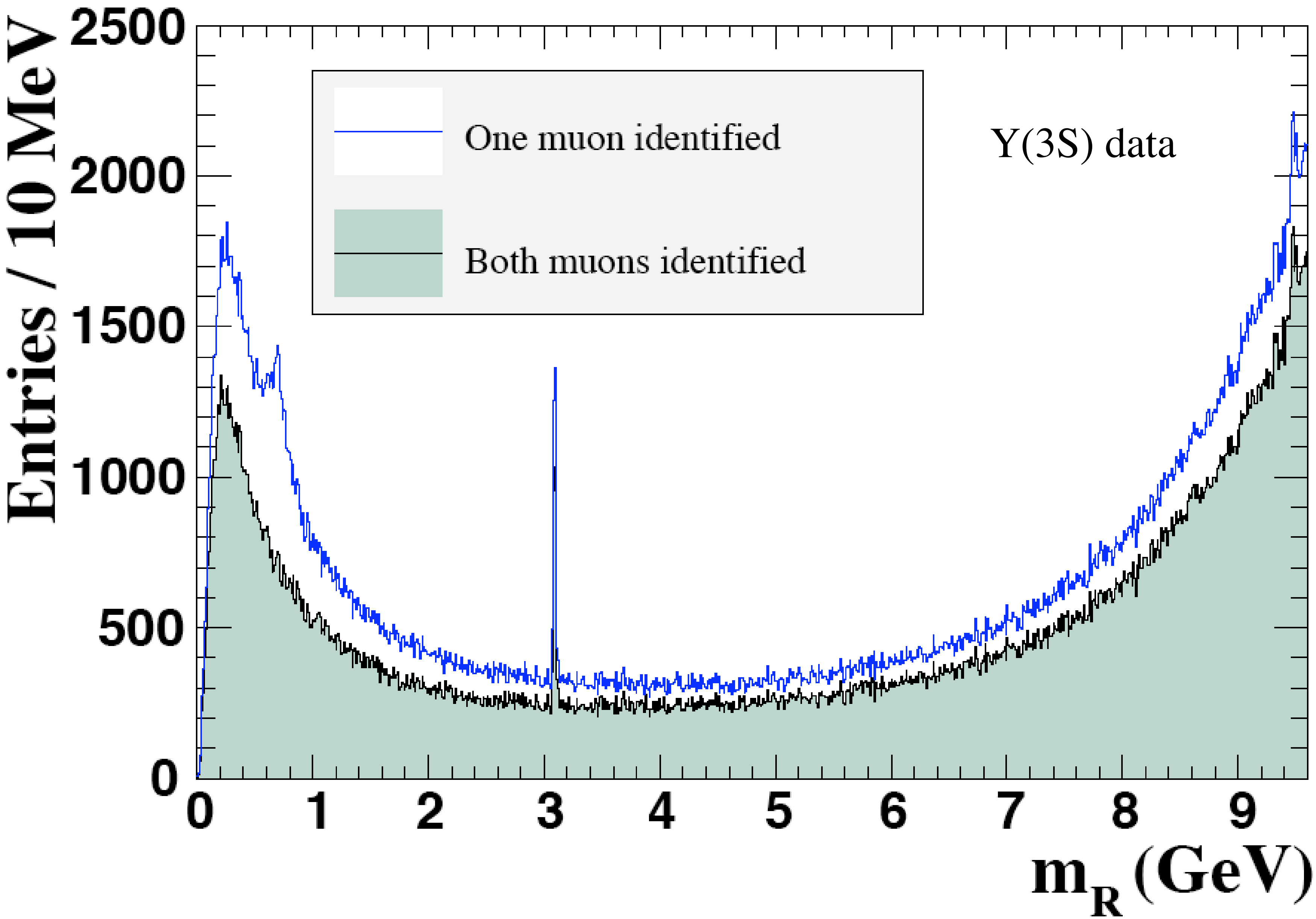
$m_{A0} < 2m_\tau$
$2m_\tau < m_{A0} < 7.5$ GeV
7.5 GeV $< m_{A0} < 8.8$ GeV
8.8 GeV $< m_{A0} < 9.2$ GeV

Related Talks at DPF2009

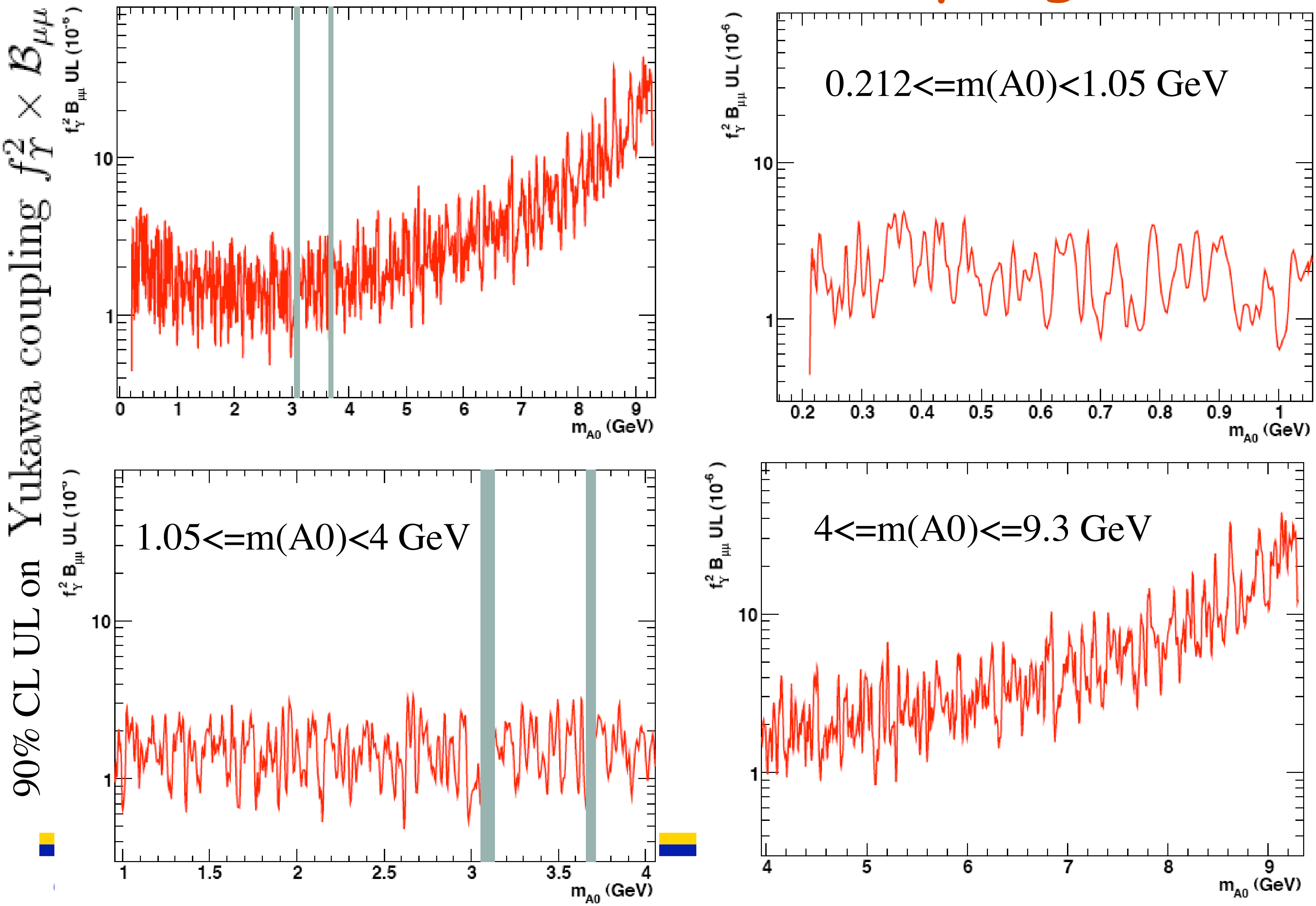
- Search for Υ→invisible Decays
  - ☞ YGK, LE-BSM Session (Thu, 7/30)
- Lepton Universality in Upsilon Decays
  - ☞ Elisa Guido, LE-BSM Session (Thu, 7/30)
- Lepton Flavor Violation Searches in Tau and Upsilon Decays
  - ☞ Swagato Banerjee, LE-BSM Session (Fri. 7/31)

Backup

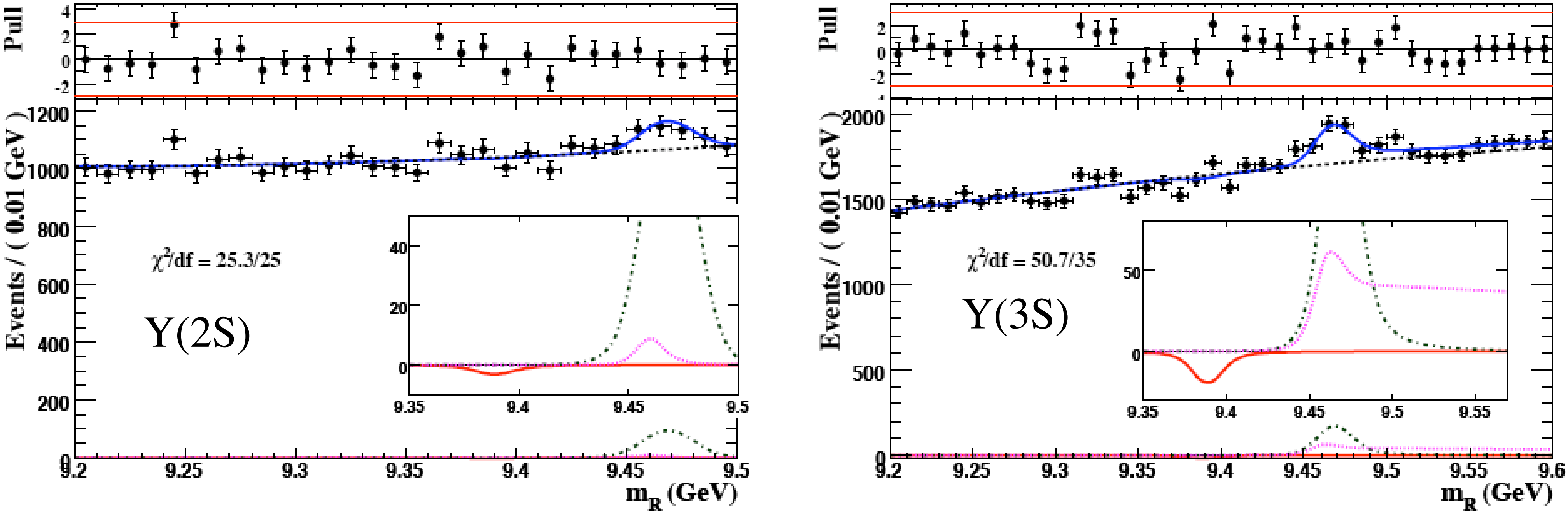
$A^0 \to \mu^+\mu^-$ Mass Spectrum



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



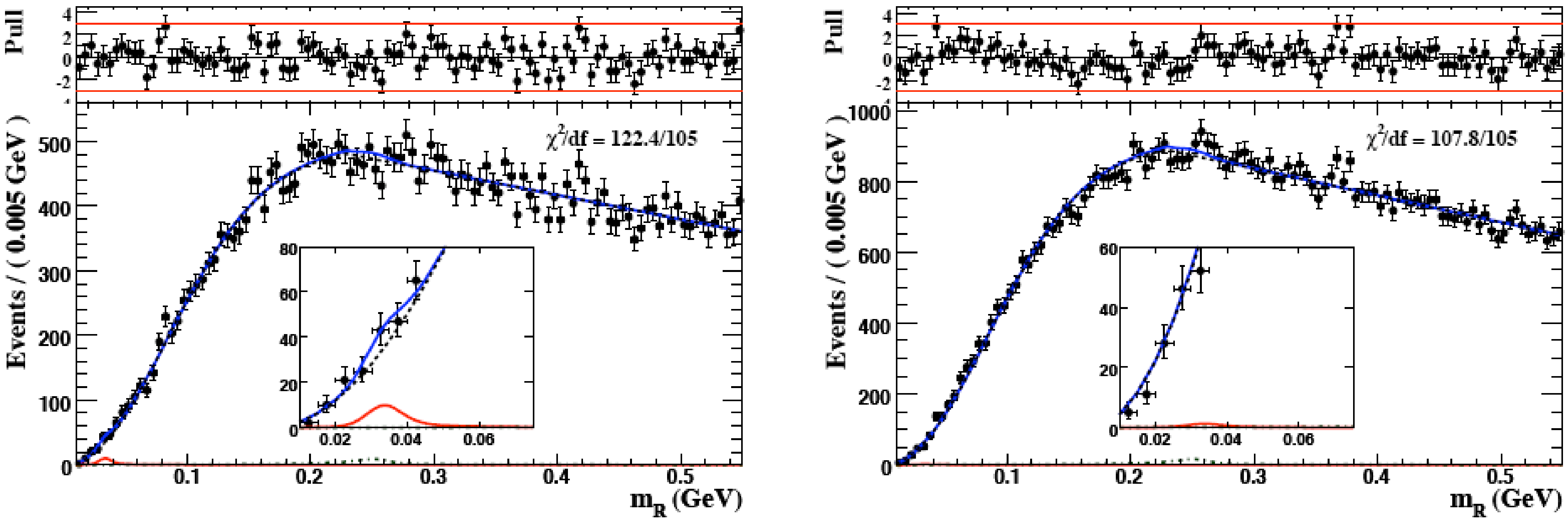
$\eta_b \to \mu^+\mu^-$ Results



$$\mathcal{B}(\Upsilon(2S) \to \gamma\eta_b) \times \mathcal{B}(\eta_b \to \mu^+\mu^-) = (-0.4 \pm 3.9 \pm 1.4) \times 10^{-6}$$
$$\mathcal{B}(\Upsilon(3S) \to \gamma\eta_b) \times \mathcal{B}(\eta_b \to \mu^+\mu^-) = (-1.5 \pm 2.9 \pm 1.6) \times 10^{-6}$$
$$\mathcal{B}(\eta_b \to \mu^+\mu^-) = (-0.10 \pm 0.93 \pm 0.33)\% \ (\Upsilon(2S) \text{ dataset})$$
$$\mathcal{B}(\eta_b \to \mu^+\mu^-) = (-0.31 \pm 0.61 \pm 0.32)\% \ (\Upsilon(3S) \text{ dataset})$$
$$\mathcal{B}(\eta_b \to \mu^+\mu^-) = (-0.25 \pm 0.51 \pm 0.33)\% \ (\text{average}) .$$

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

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



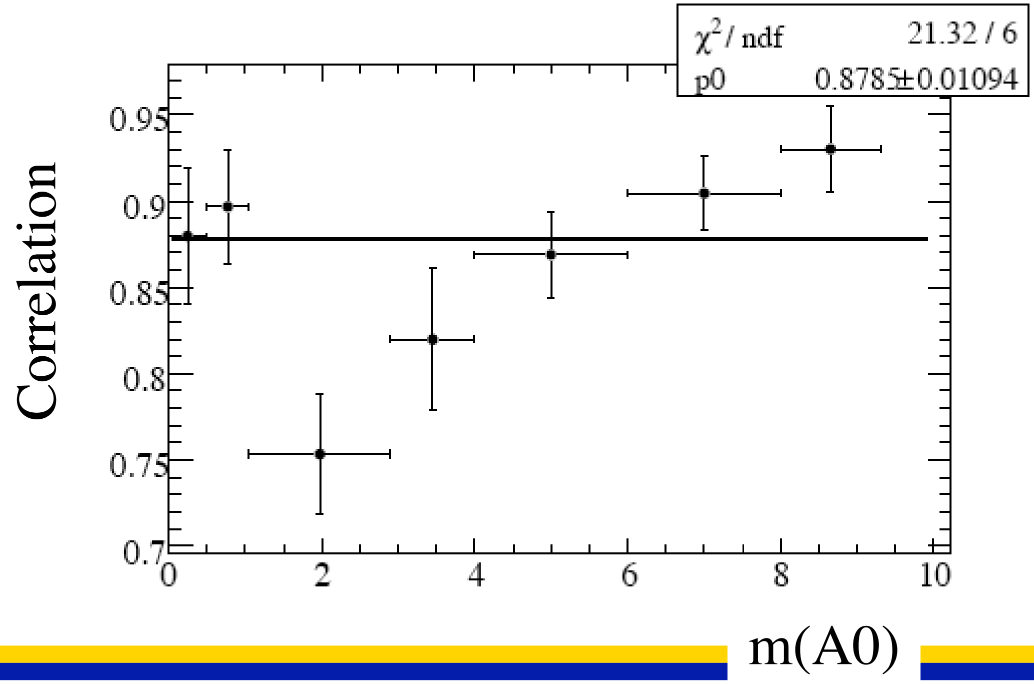
No significant peak at m(A0)=0.214 GeV

Set a stringent upper limit:

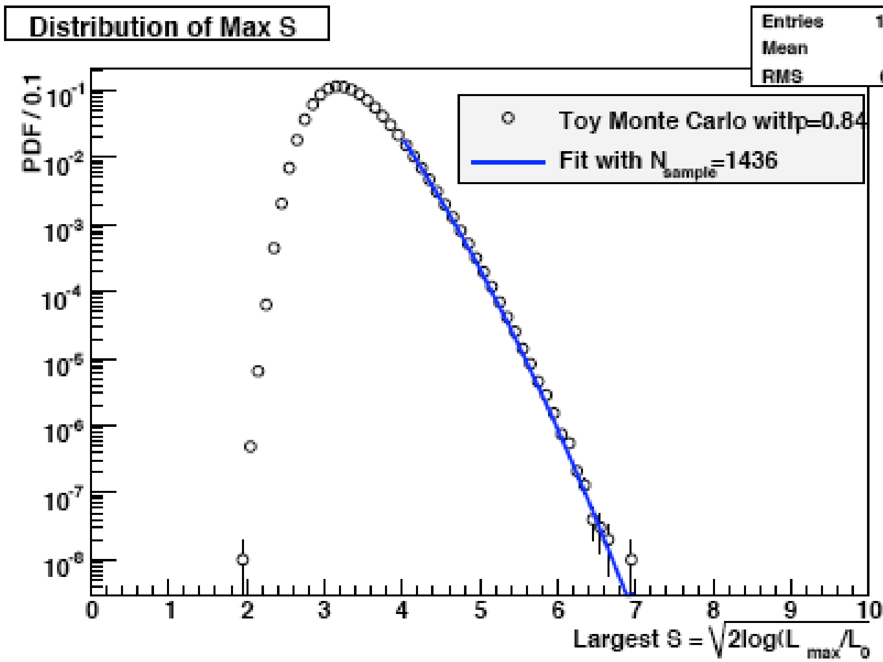
$$f_{\Upsilon}^2(m_{A^0} = 0.214\,\text{GeV}) < 1.6 \times 10^{-6} \text{ at } 90\% \text{ C.L}$$

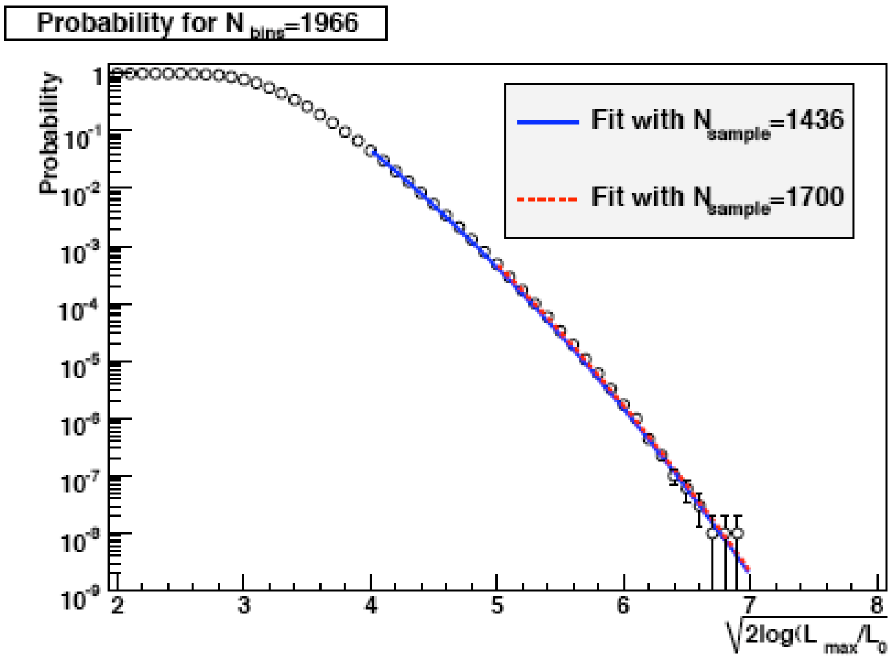
Significance Calculation

- 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