Searches for Exotics in Upsilon Decays in BaBar

Yury Kolomensky
UC Berkeley/LBNL
For the BaBar Collaboration

14th Lomonosov Conference on Elementary Particle Physics
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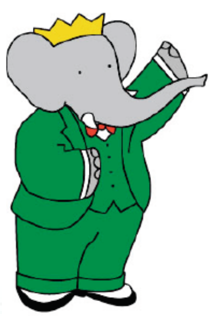
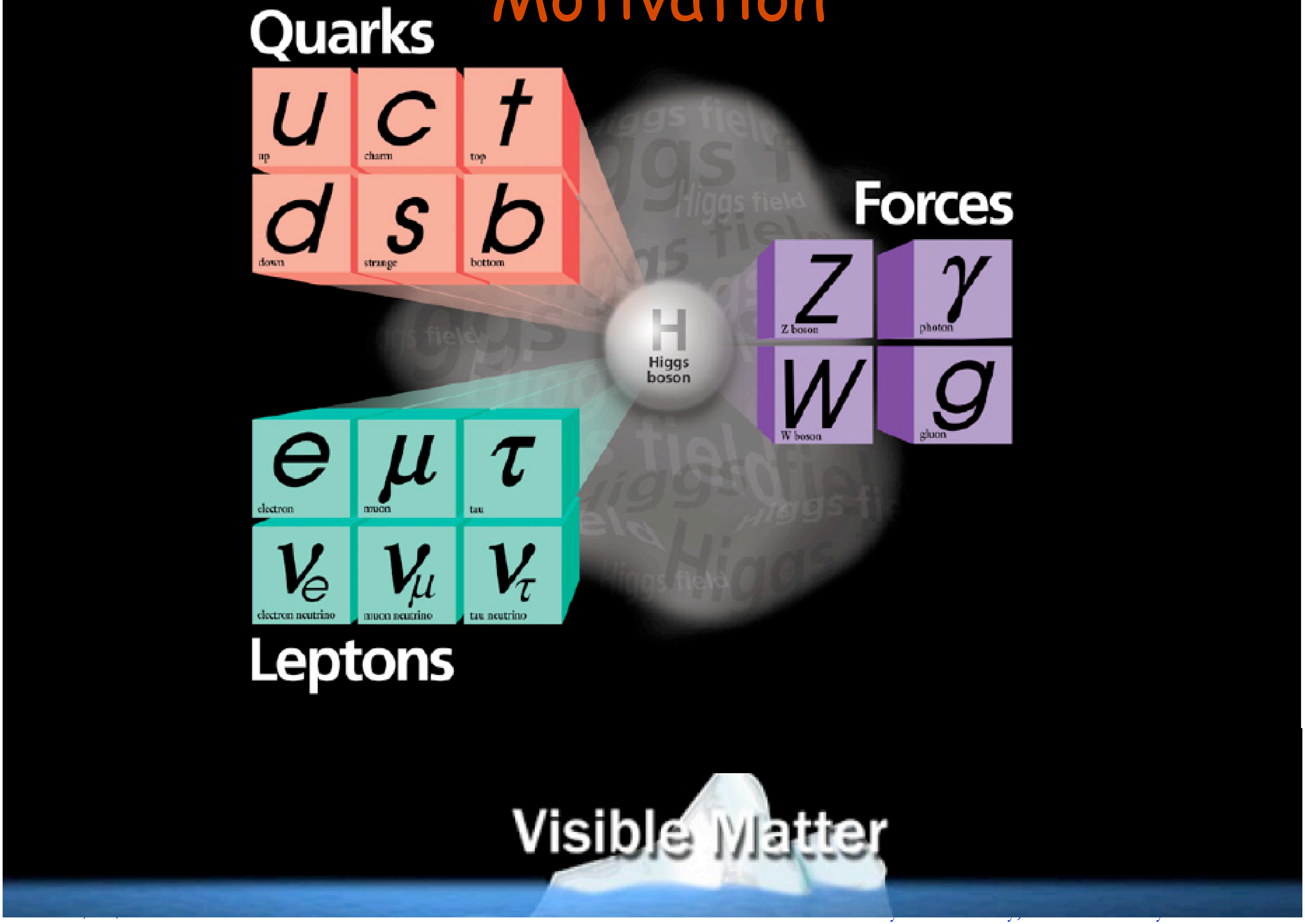
- ✔ Light Higgs Searches
- ✔ Light dark matter in $\Upsilon(1S)\rightarrow$invisible
- ✔ Lepton-Flavor Violating Υ decays



Motivation


Quarks
u
up
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gluon
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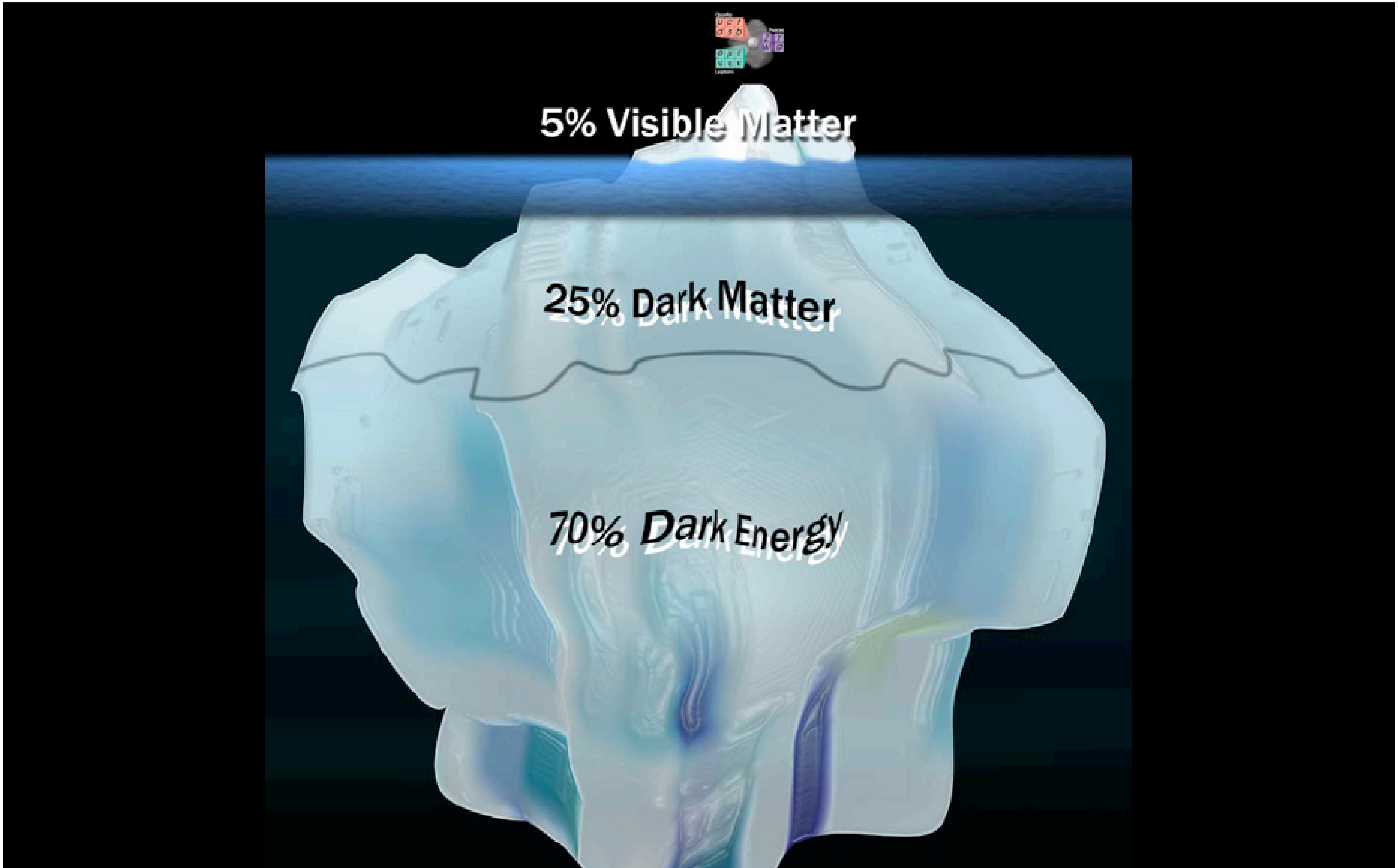
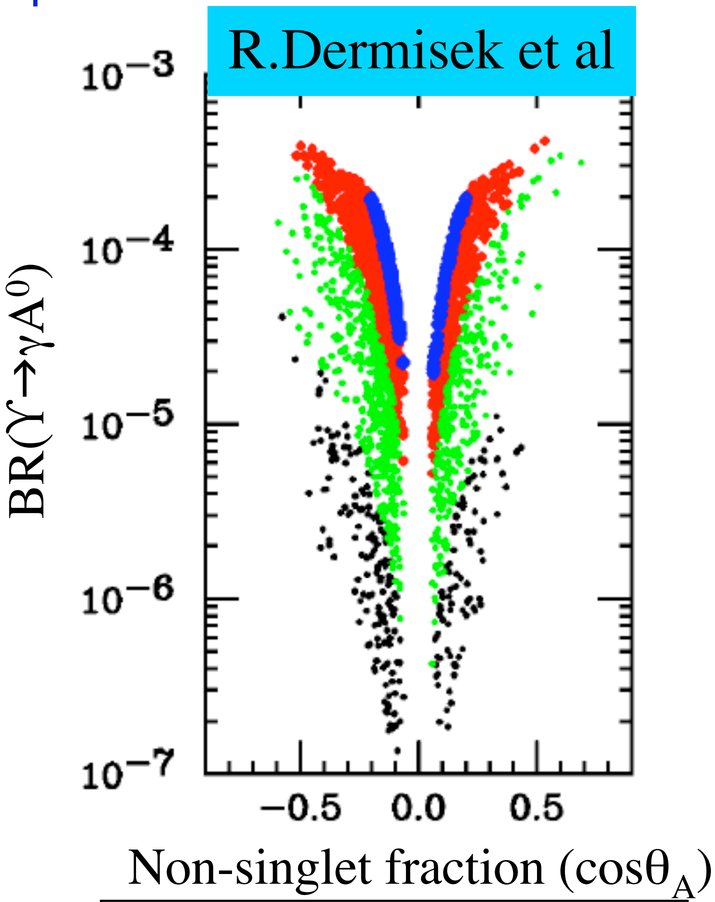
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons
Visible Matter



What is the Energy Scale of New Physics ?
What is the spectrum of the Dark Sector ?
Are there any low-energy observables ?

Theory Examples



$m_{A0}<2m_\tau$

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

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

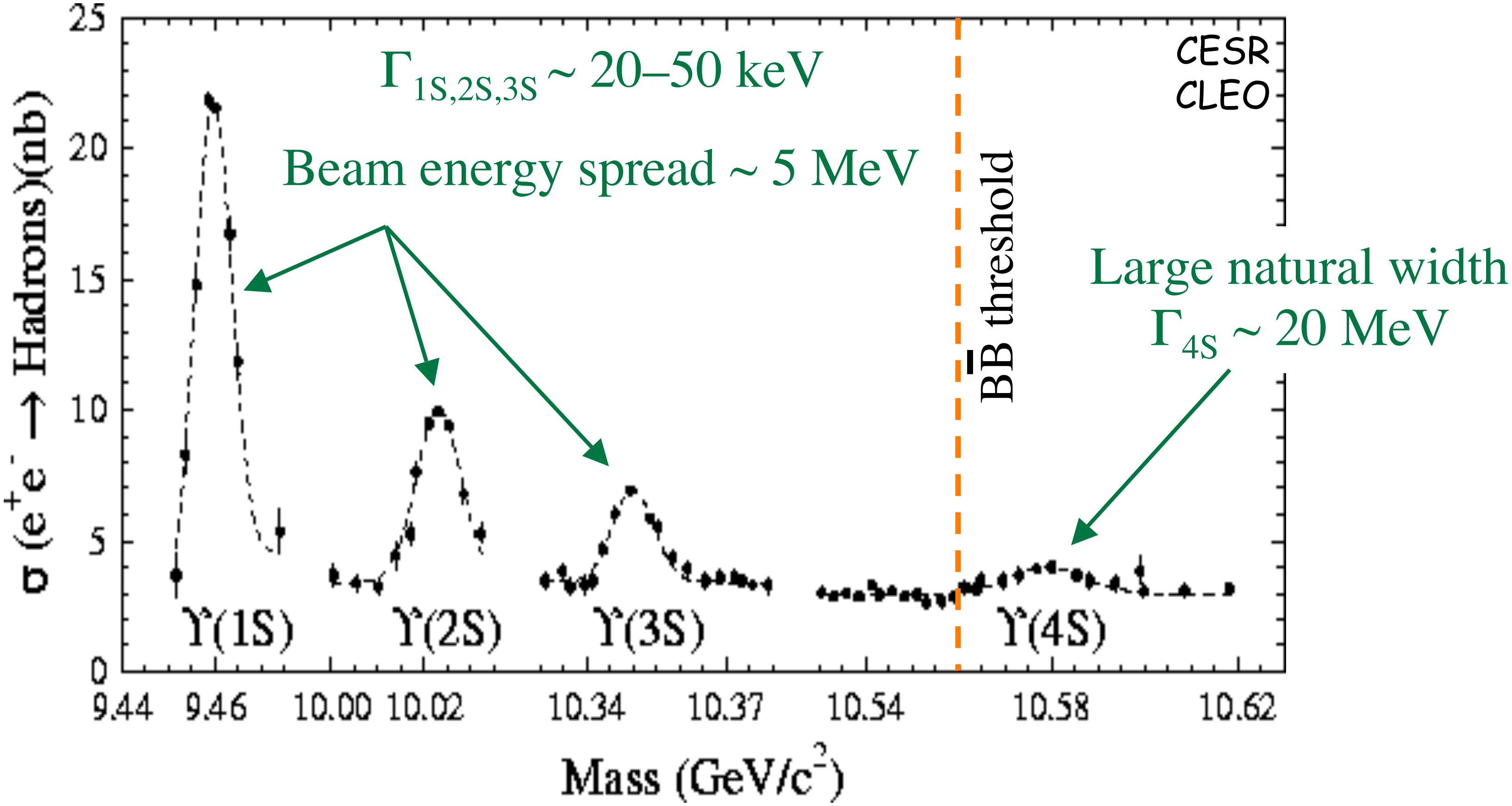
8.8 GeV$<m_{A0}<$9.2 GeV

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($\Upsilon\to\gamma A$)~10^{-6}–10^{-5} with m_A~400-800 MeV
- Also interesting to look in η_b region
  - Recently discovered state (BaBar, 2008)
  - Leptonic BR is expected to be small if η_b is a meson

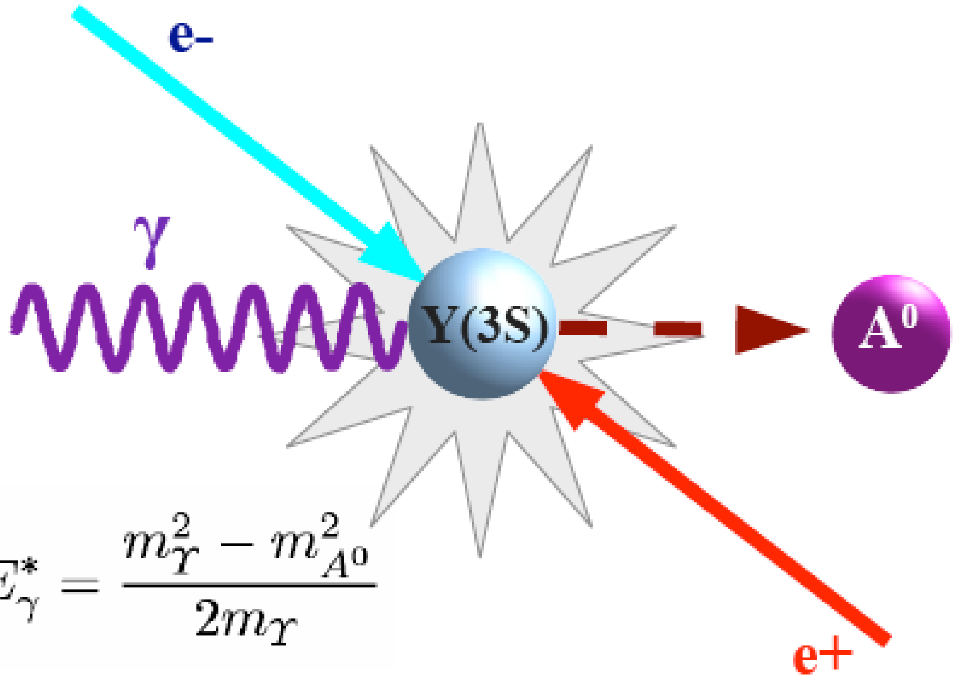
Upsilon Resonances

- 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



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

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

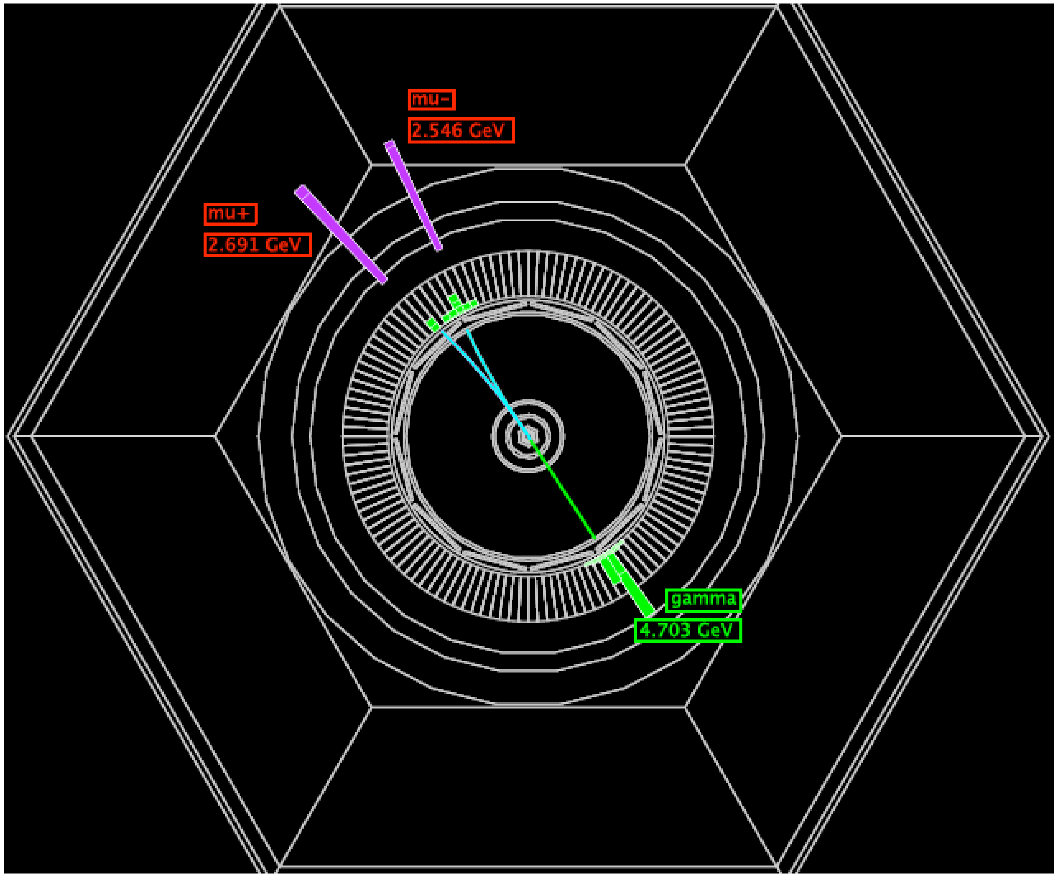
Fully or partially reconstructed final state, depending on the decay pattern of A^0

This talk:

- ✔ $A^0 \rightarrow \mu^+\mu^-$, PRL**103**, 081803 (2009)
- ✔ $A^0 \rightarrow \tau^+\tau^-$, arXiv:0906.2219, submitted to PRL
- ✔ $A^0 \rightarrow$invisible (light dark matter), arXiv:0808.0017, preliminary

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

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

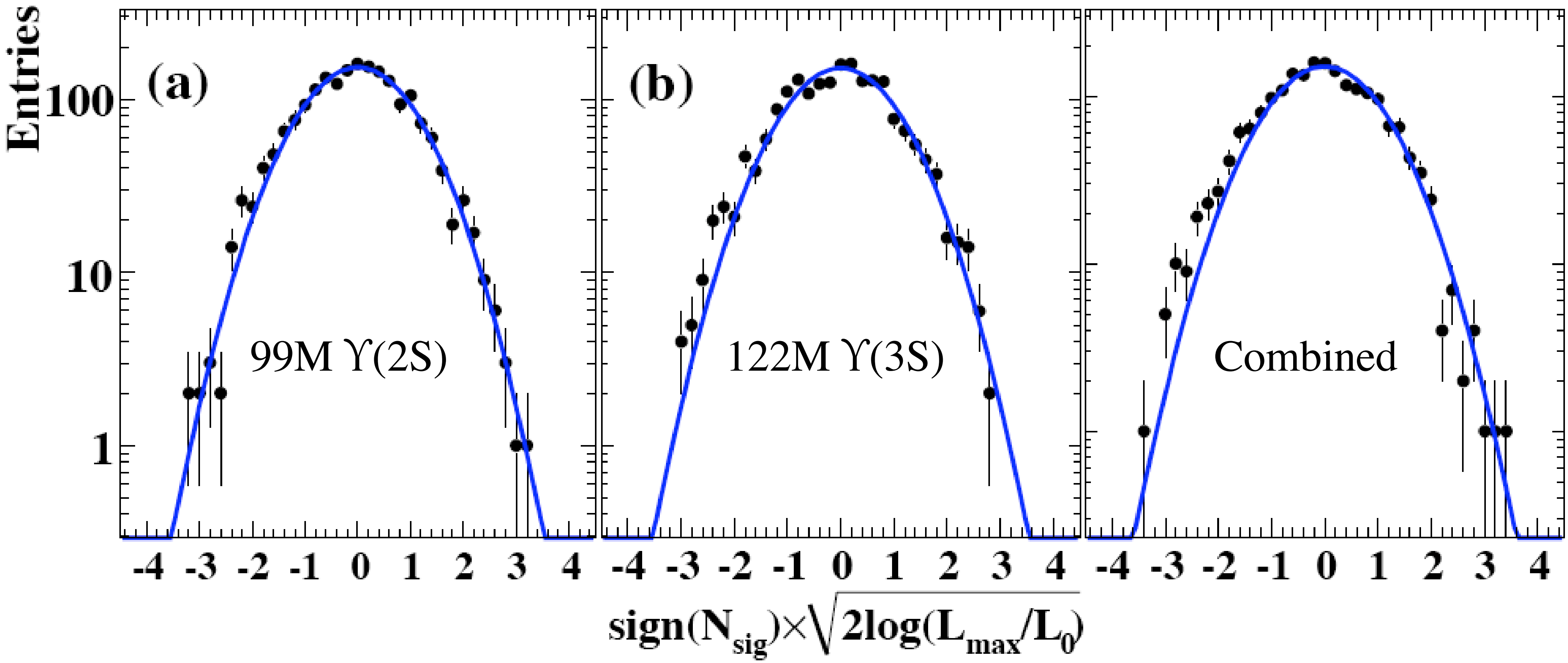


- Fully-reconstructed final state: 2 charged tracks, 1 photon
  - ☞ 1 or 2 muons identified
  - ☞ $E^*_\gamma > 0.2$ GeV
  - ☞ Loose kinematic selection requires consistency with CMS energy and momentum

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

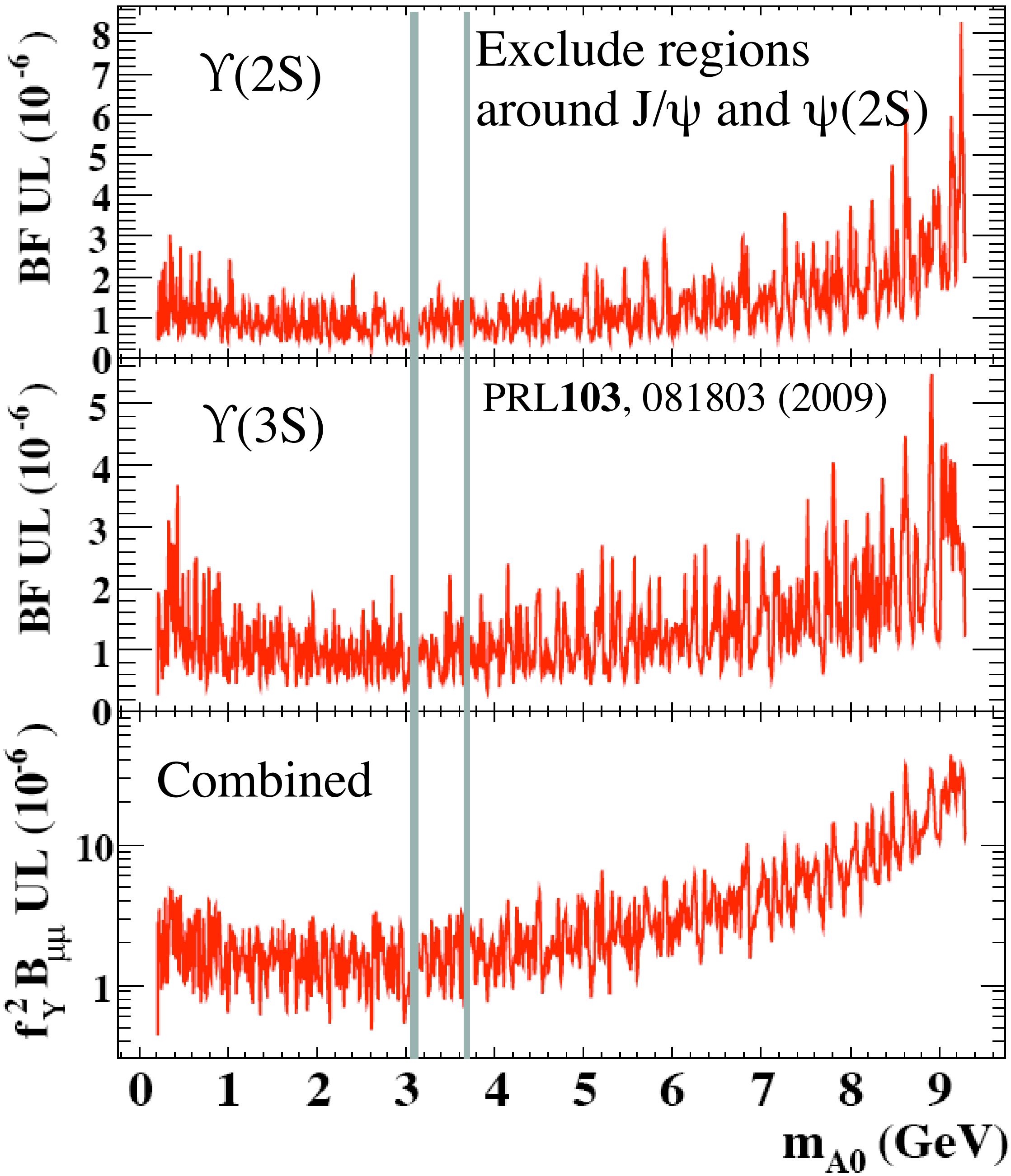
Identify A^0 decays by a narrow peak in $\mu^+\mu^-$ invariant mass (resolution 2-10 MeV)

Results: Υ(2S,3S)→γA^0, A^0→$\mu^+\mu^-$



Expect standard normal distribution for 1955 scan points under null hypothesis
Observe no significant outliers.

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



Bayesian 90% C.L upper limits

Significant constraints on theoretical models

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

Also limit

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

at 90% C.L.

Combined results for effective Yukawa coupling f_Υ

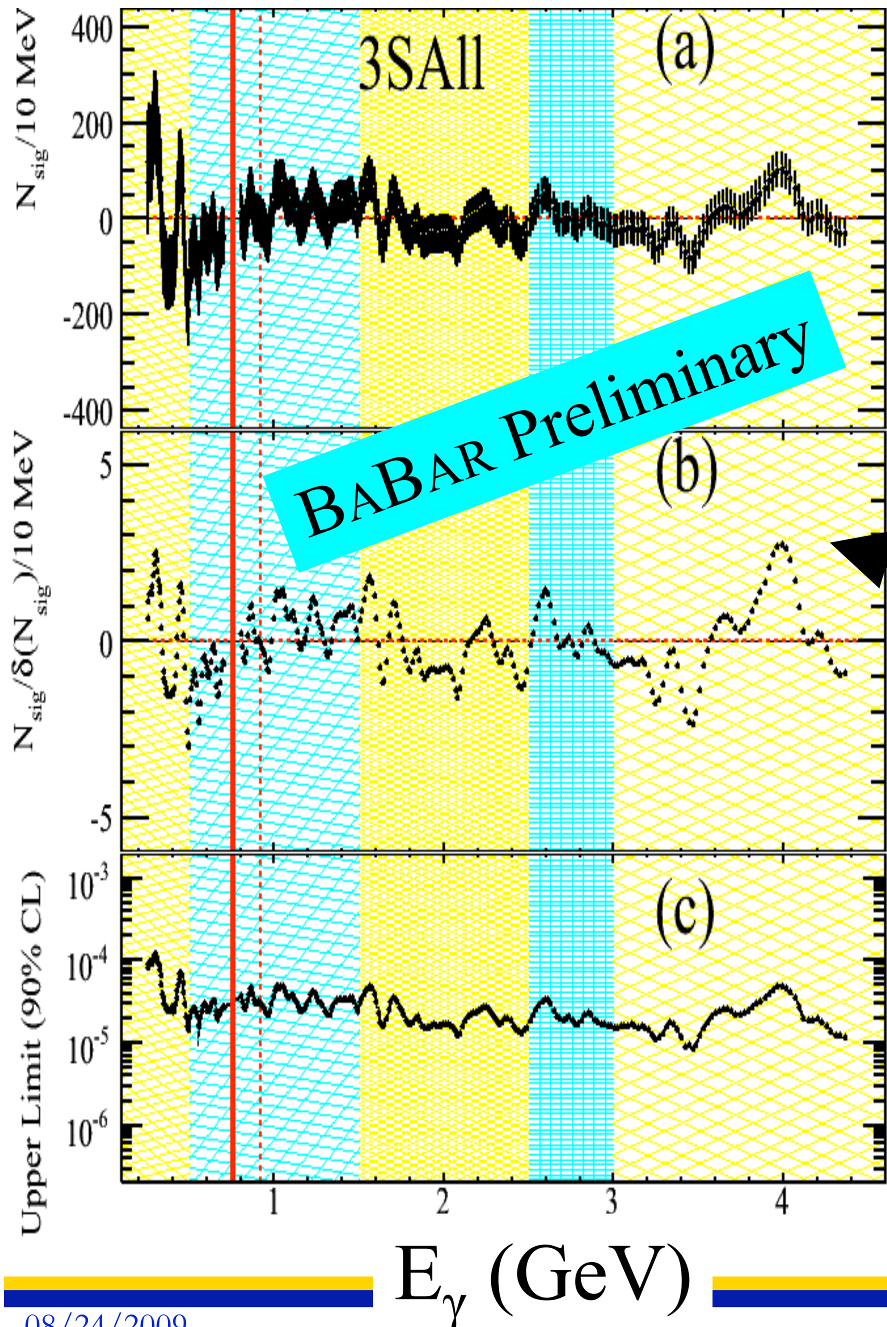
$$\frac{\mathcal{B}(\Upsilon(nS)\rightarrow\gamma A^0)}{\mathcal{B}(\Upsilon(nS)\rightarrow l^+l^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right)$$

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

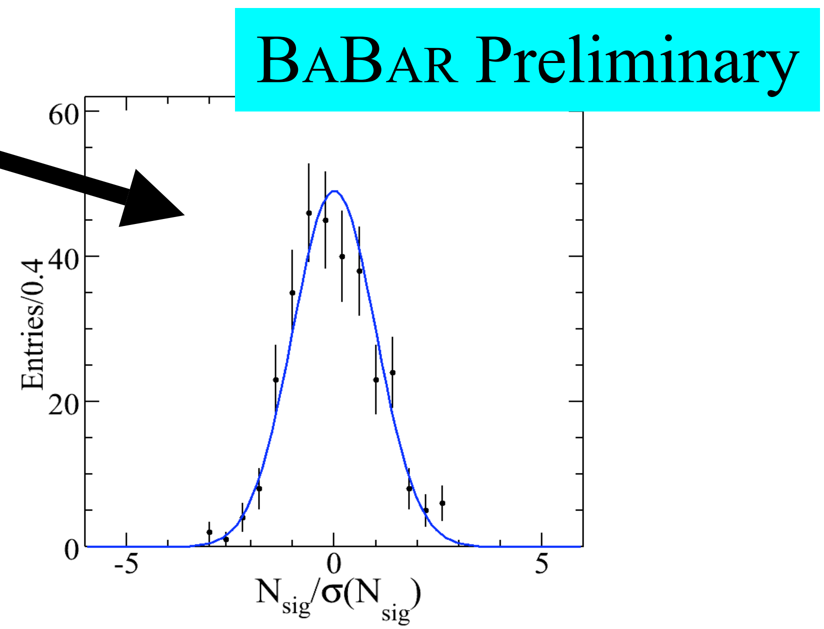
$\Upsilon(3S)\to\gamma A^0$, $A^0\to\tau^+\tau^-$

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

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

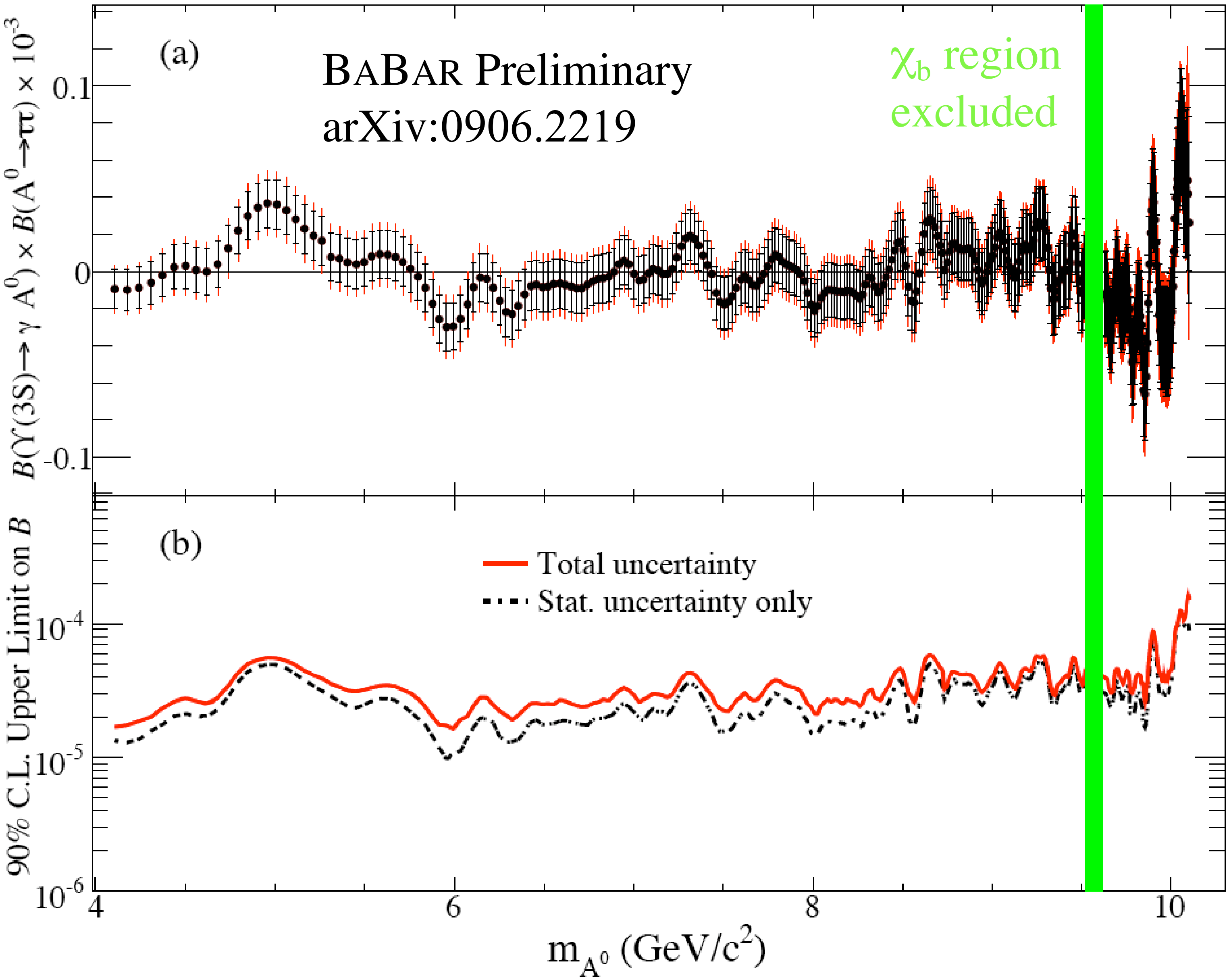


- Scan E_γ distribution in steps of half resolution (307 scan points in total)
- Simultaneous fits (binned ML) to the different ττ-decay modes



No evidence for a peaking structure

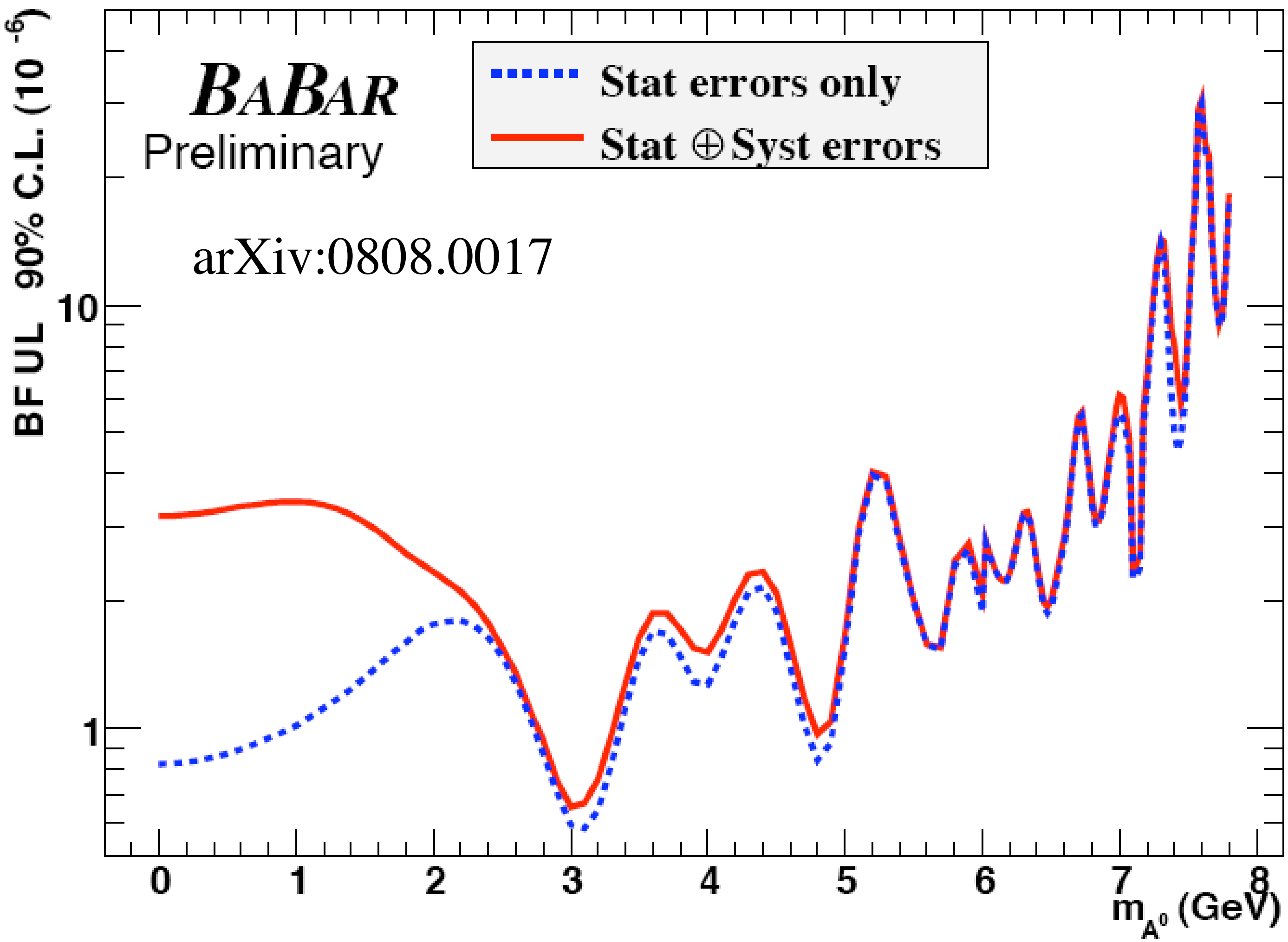
$\Upsilon(3S)\to\gamma A^0$, $A^0\to\tau^+\tau^-$ Results



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.

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

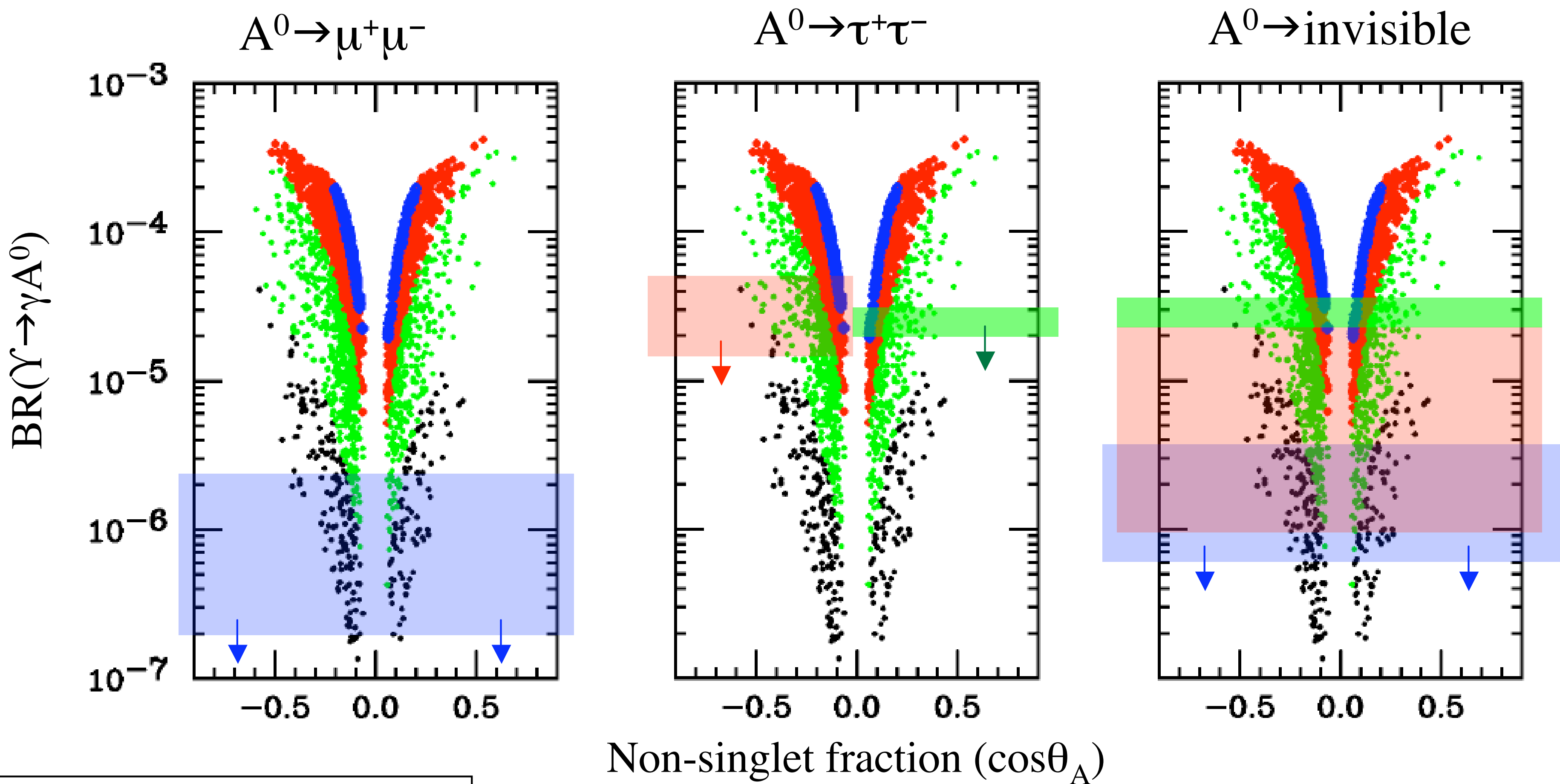


Select events with a single energetic photon and *nothing else* in the detector

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

No significant signal; limits on BF constrain NMSSM parameter space

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

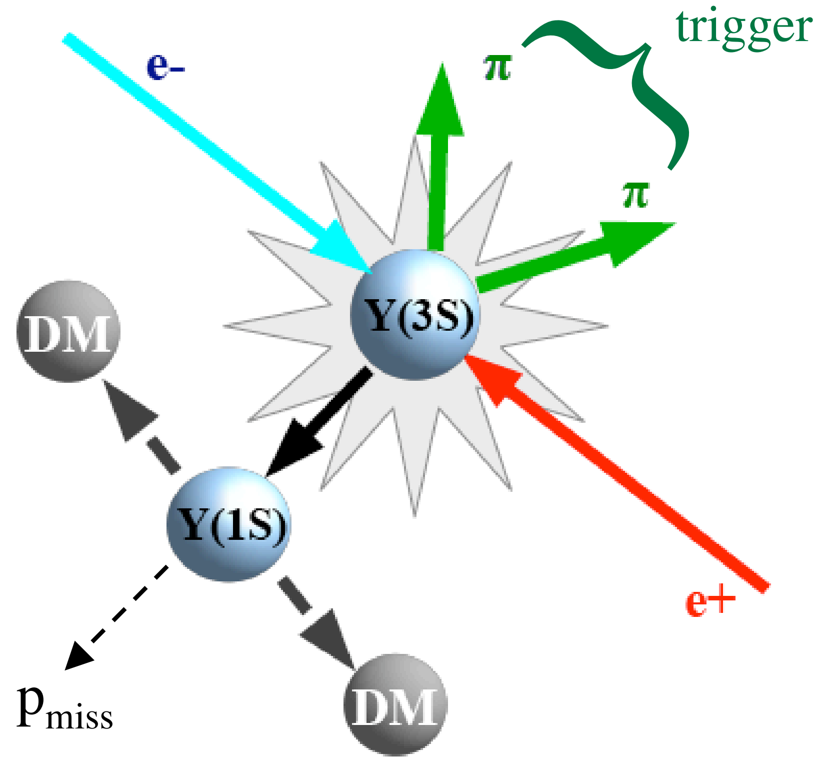


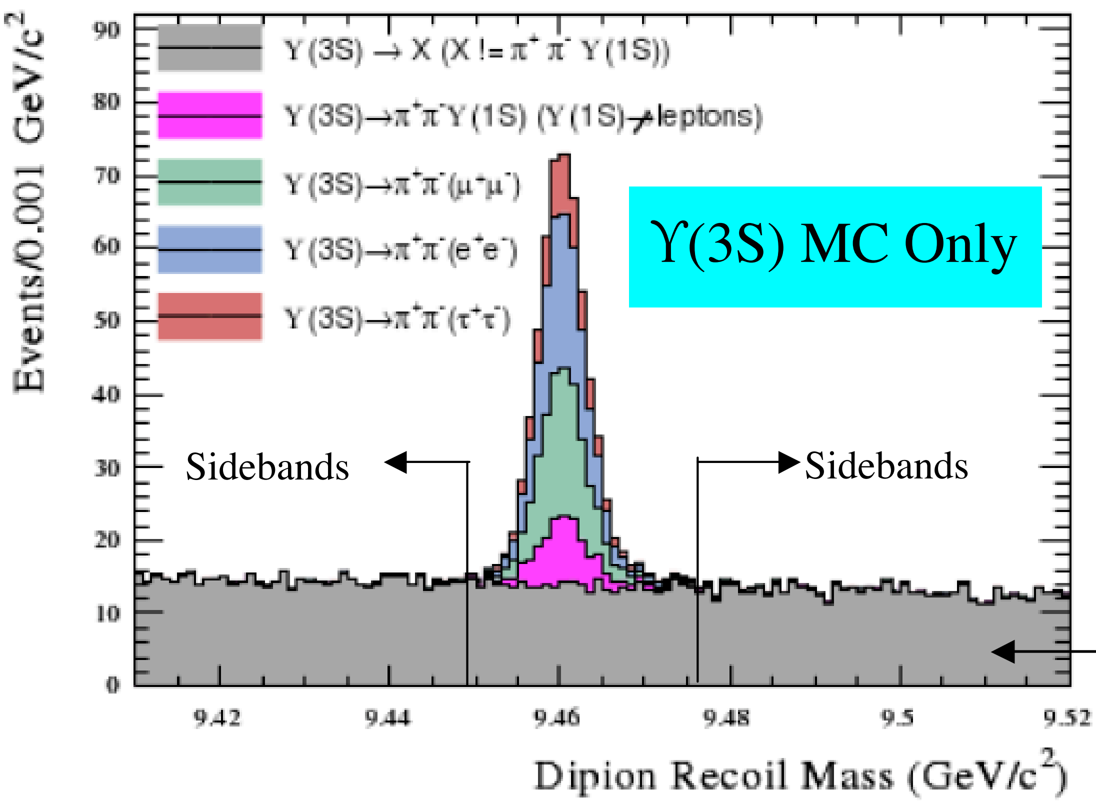
$m_{A0} < 2m_\tau$
$2m_\tau < m_{A0} < 7.5$ GeV
7.5 GeV $< m_{A0} < 8.8$ GeV
8.8 GeV $< m_{A0} < 9.2$ GeV

Also place significant constraints on other models

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 $e^+e^- \rightarrow \gamma^*\gamma^* \rightarrow e^+e^-\pi^+\pi^-$ not included

$\Upsilon(1S)\rightarrow$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 $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$ 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: $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S)\rightarrow l^+l^-$
    - Check selection, calibrate acceptance, detection efficiency and BR for $\Upsilon(3S)\rightarrow\pi^+\pi^-\Upsilon(1S)$
    - Calibrate di-pion mass resolution
    - Affects both signal and peaking background from $\Upsilon(1S)\rightarrow l^+l^-$ events with missing particles
  - 3-track sample
    - Check acceptance

Υ(1S)→invisible: Signal Extraction

Maximum likelihood fit to 2-track "invisible" sample

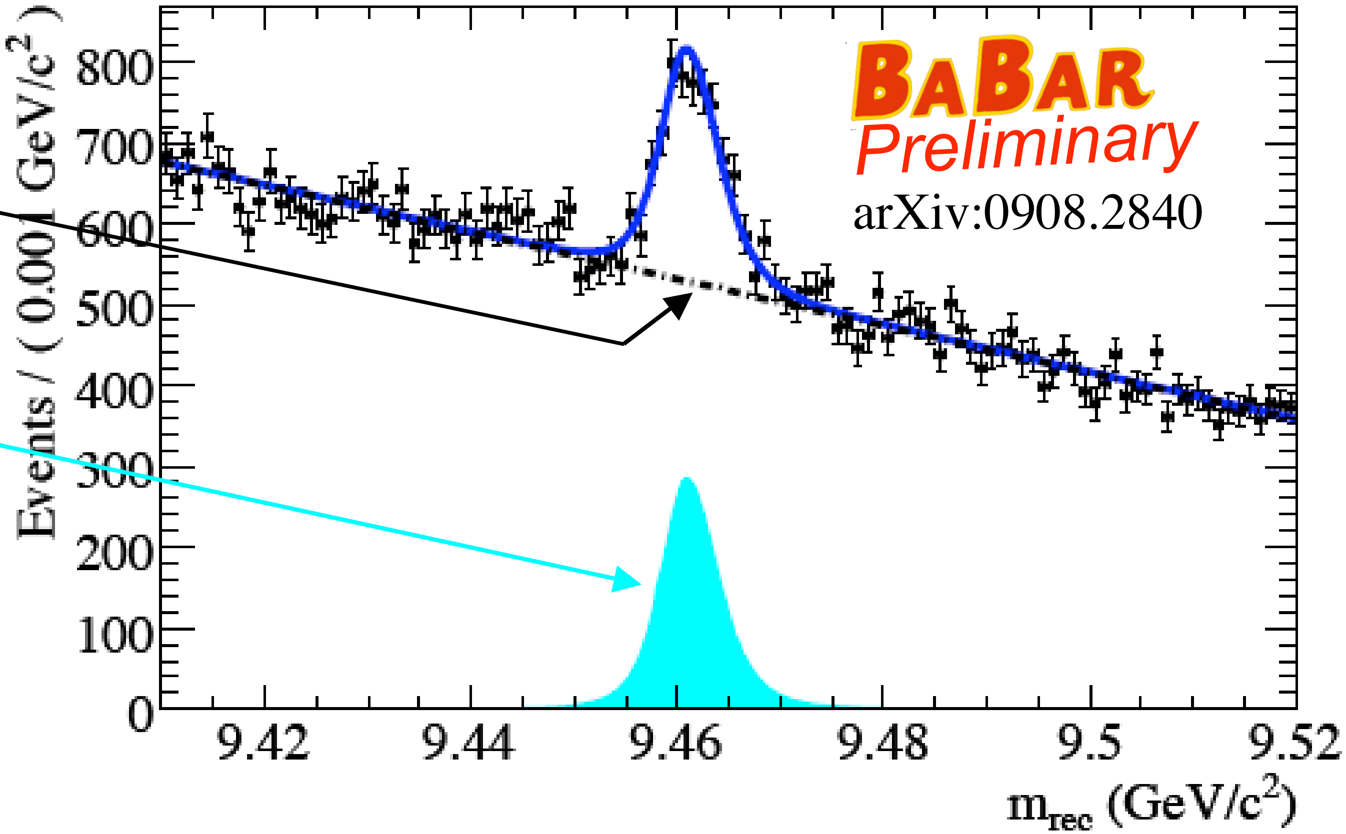
Non-peaking background:

- ✔ Float all parameters and yield

Peaking Component:

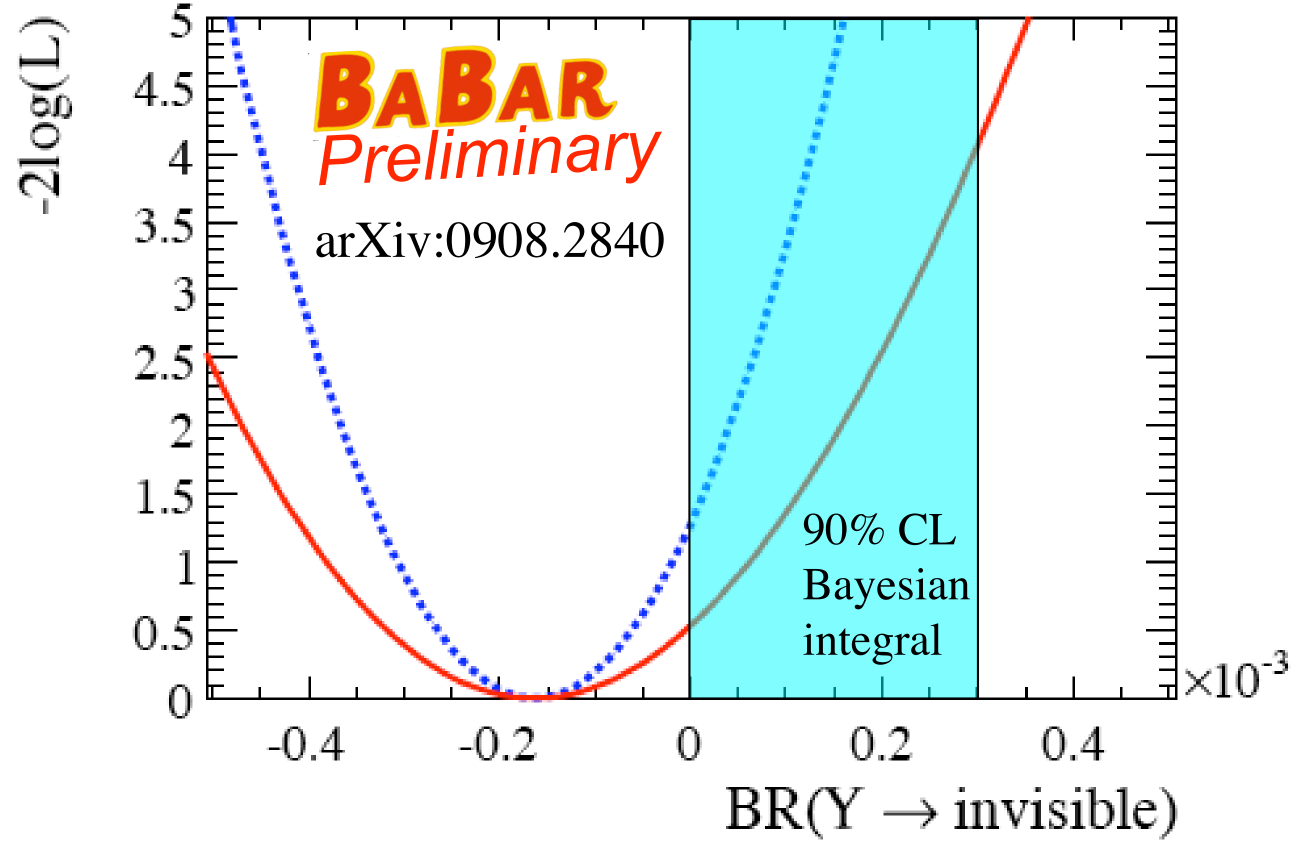
- ✔ Fix shape, float yield

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

Υ(1S)→invisible: Final Results



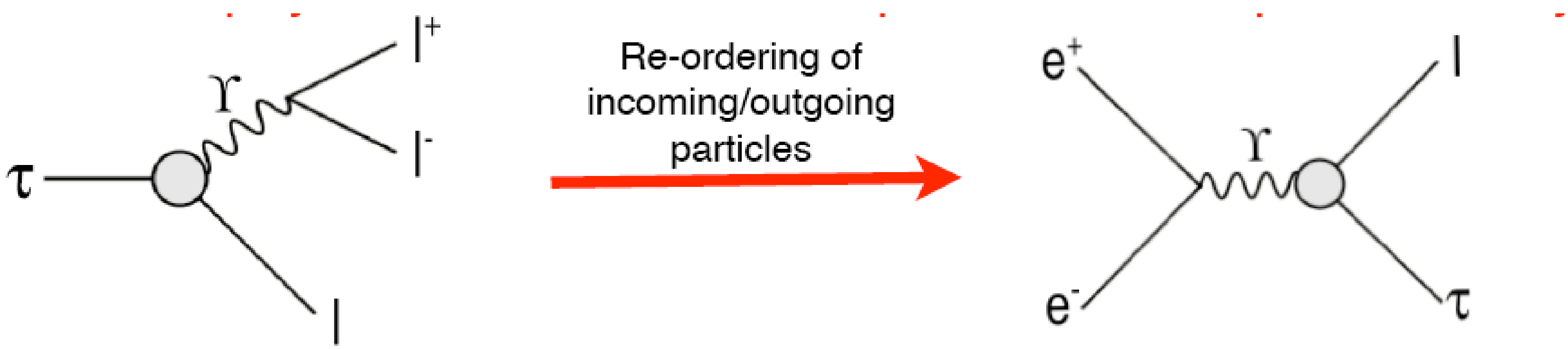
$BR(\Upsilon(1S) \rightarrow invisible) = [-1.6 \pm 1.4\ (stat.) \pm 1.6\ (syst.)] \times 10^{-4}$

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

Brand-new result: arXiv:0908.2840 [hep-ex], submitted to PRL

Lepton Flavor Violation in ϒ Decays

- CLFV: an unambiguous signature of new physics
  - ☞ Unobservably small in the Standard Model
  - ☞ Sensitivity to multi-TeV mass scales far beyond the reach of direct searches
  - ☞ Complementary to the LHC
- Relation to LFV tau decays
  - ☞ See M. Giorgi's talk next



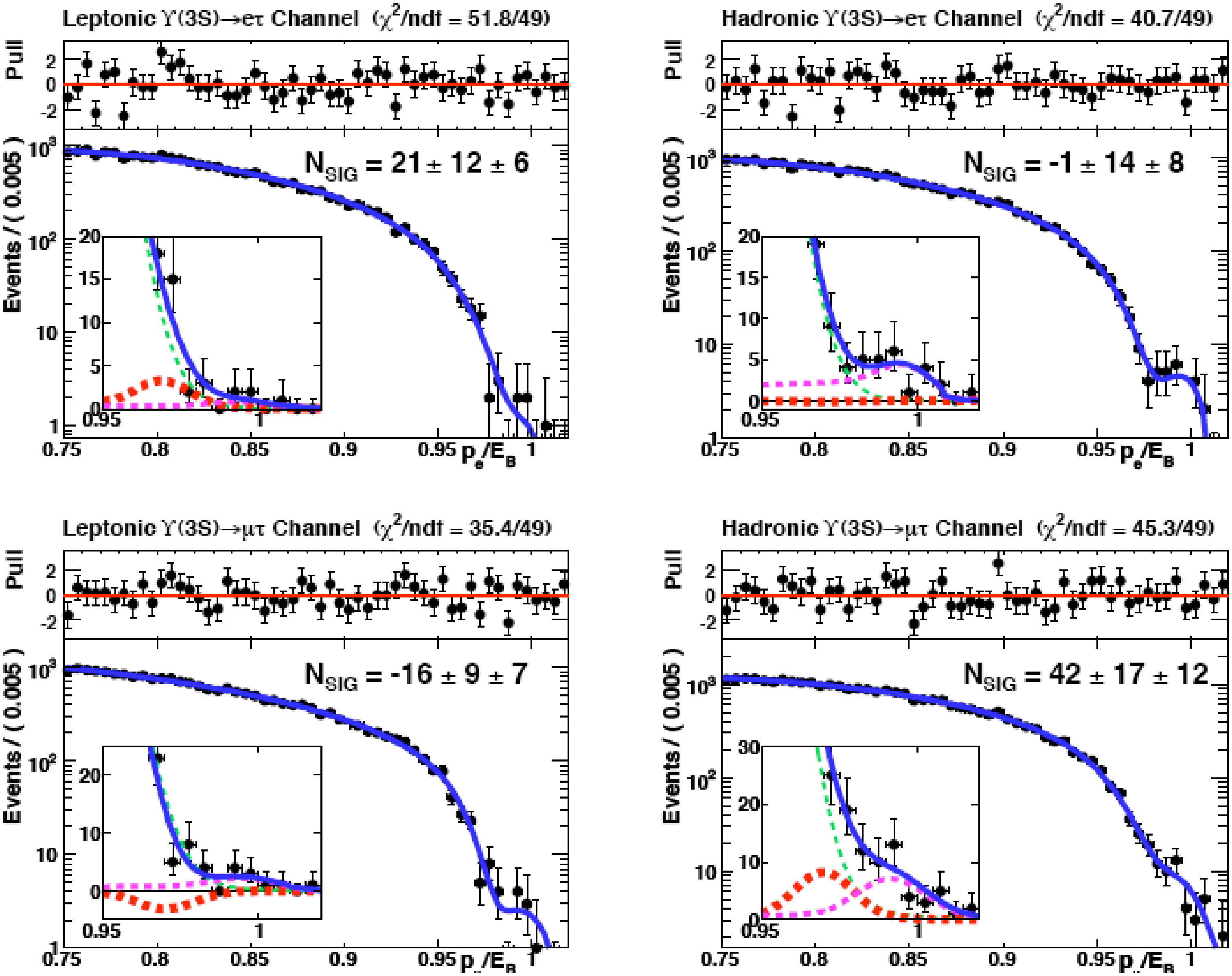
$$\mathcal{B}(\Upsilon \to \ell\tau) \sim \frac{\mathcal{B}(\tau \to \ell\ell\ell)}{\mathcal{B}(\tau \to \ell\nu\overline{\nu})} \frac{\Gamma(W \to \ell\nu)^2}{\Gamma(\Upsilon)\Gamma(\Upsilon \to \ell\ell)} (M_\Upsilon / M_W)^6$$

S.Nussinov, et. al. PRD 63, 016003 (2001)

$$\mathcal{B}(\tau \to \ell\ell\ell) < 2-4 \times 10^{-8} \quad \Rightarrow \quad \mathcal{B}(\Upsilon \to \ell\tau) < 3-6 \times 10^{-3}$$

BaBar PRL 99, 251803 (2007), Belle PLB 660,154 (2008)

Search for Υ→τl Decays



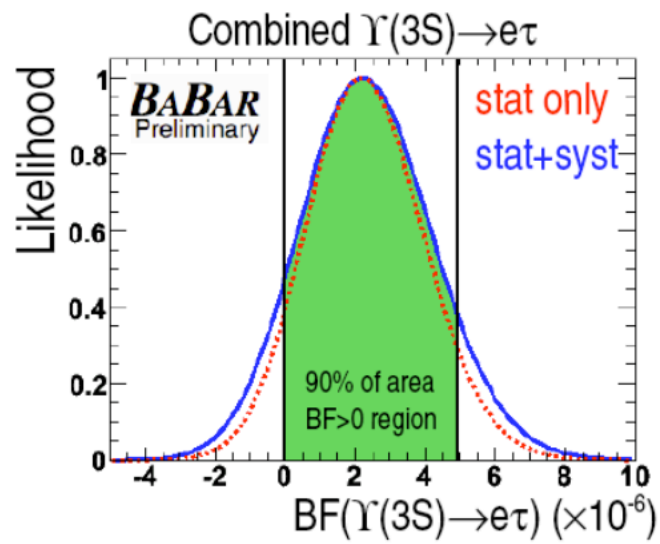
p/E p/E

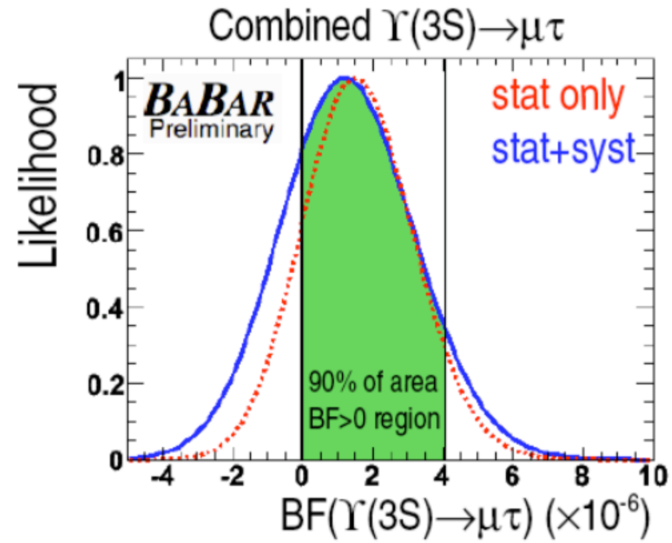
Search for events with an energetic lepton (e or μ), a second charged particle of different flavor, and missing energy

BaBar preliminary: arXiv:0812.1021

No signal found: Set limits

$\Upsilon \rightarrow e\tau$ and $\Upsilon \rightarrow \mu\tau$ Limits





Best limit for $\Upsilon \rightarrow \tau\mu$

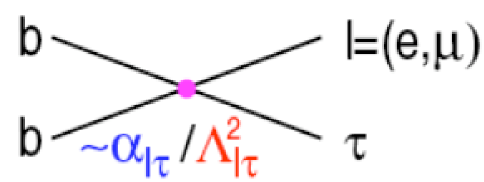
First limit for $\Upsilon \rightarrow e\tau$

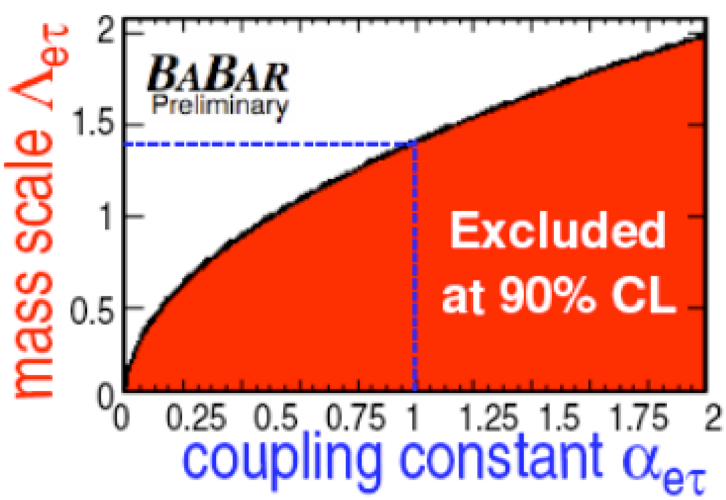
arXiv:0812.1021 (preliminary)

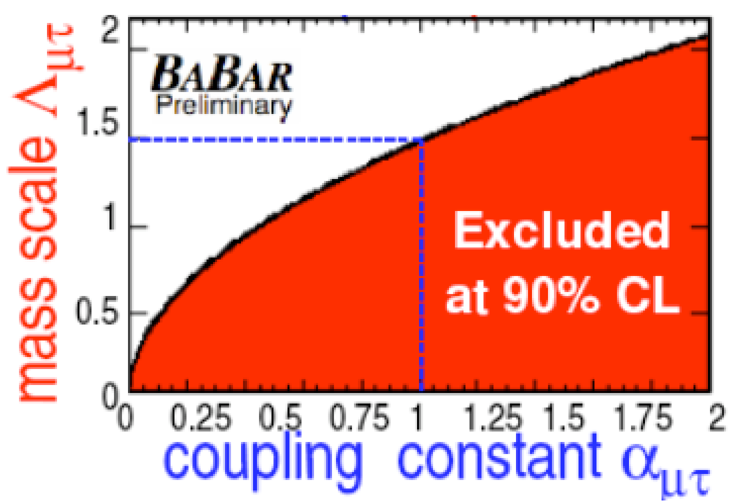
$BF(\Upsilon(3S) \rightarrow e\tau) < 5.0 \times 10^{-6}$

$BF(\Upsilon(3S) \rightarrow \mu\tau) < 4.1 \times 10^{-6}$

Fermi contact interaction scale O(TeV):







Assume strong coupling $\alpha_{e\tau} = \alpha_{\mu\tau} = 1$:

$\Lambda_{e\tau} > 1.4$ TeV

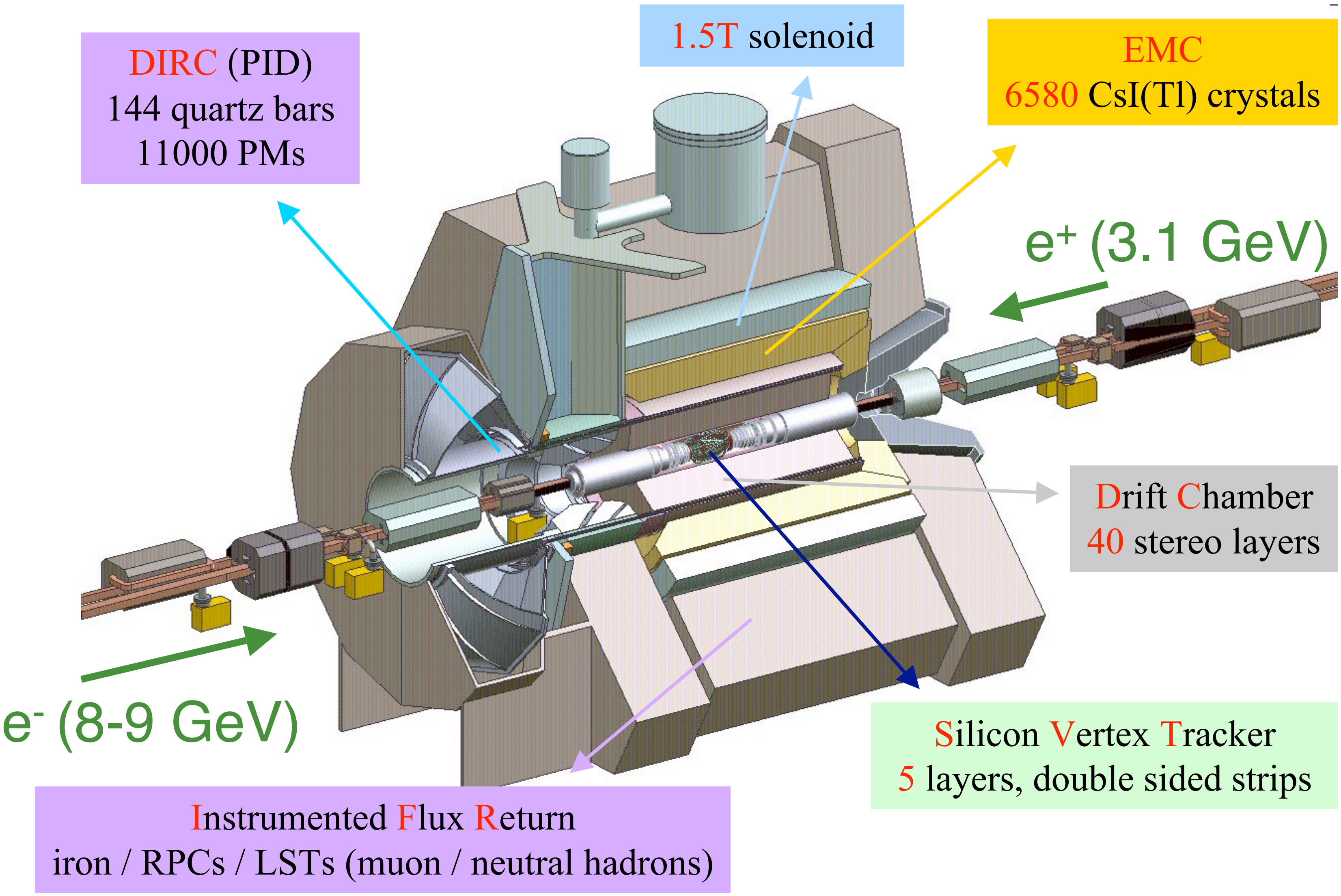
$\Lambda_{\mu\tau} > 1.5$ TeV

Summary

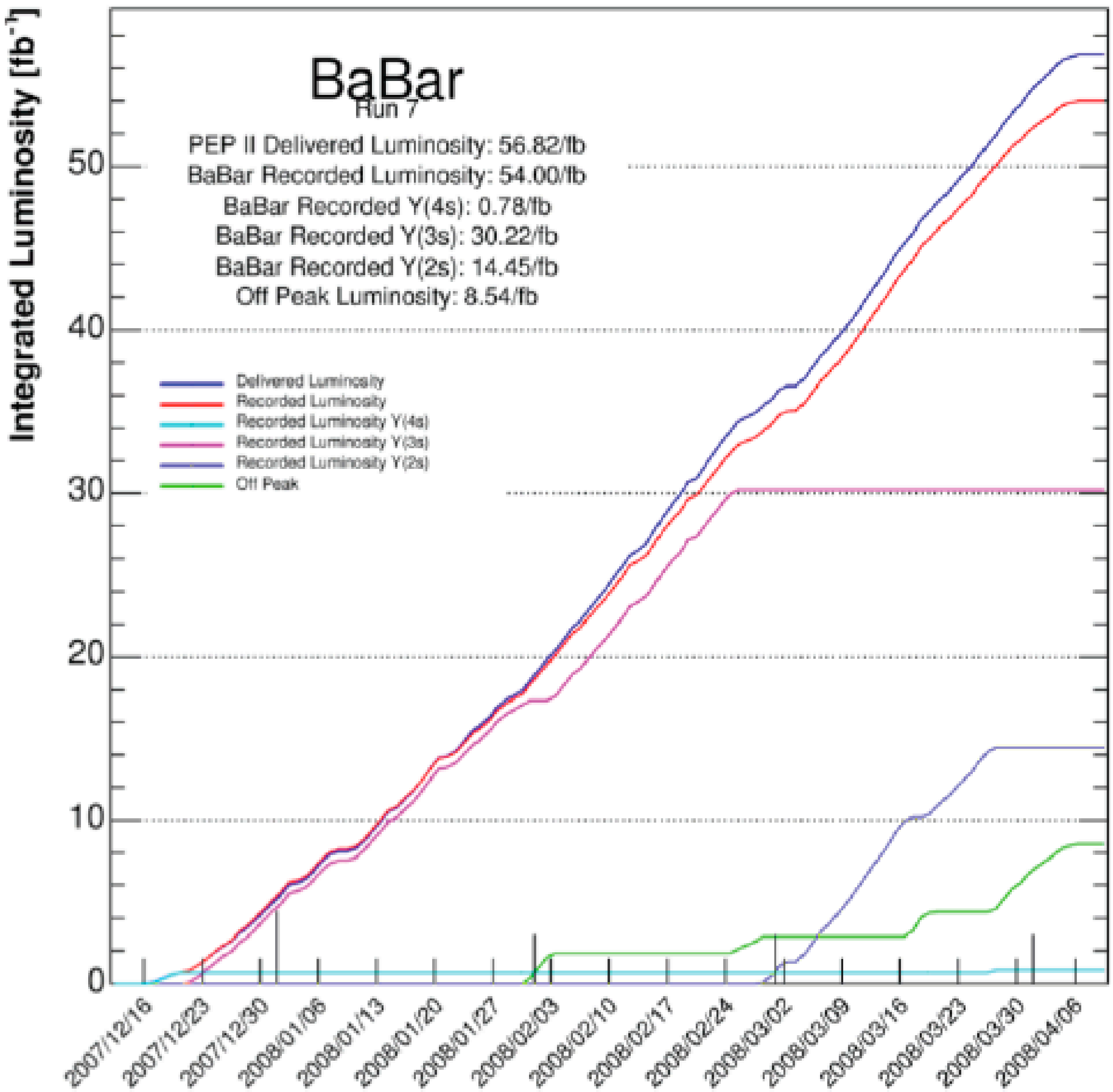
- Unique sensitivity to new physics in bottomonium decays
- No signal of a light scalar particle (e.g. CP-odd Higgs) in radiative decays of $\Upsilon(2S)$ and $\Upsilon(3S)$ in $\mu^+\mu^-$, $\tau^+\tau^-$, or invisible final states
  - Set upper limits that rule out much of available parameter space; most stringent constraints to date
  - Also set a limit on dimuon and $\tau^+\tau^-$ BF of η_b
    - ☞ Consistent with mesonic interpretation
    - ☞ First ever measurements of the exclusive η_b decays
- No evidence for invisible decays of $\Upsilon(1S)$
  - Constrain models with light dark matter
- No evidence for LFV in $\Upsilon(3S)$ decays
- Publications
    - ☞ PRL **103**, 081803 (2009) ($A^0 \to \mu^+\mu^-$)
    - ☞ arXiv:0906.2219 ($A^0 \to \tau^+\tau^-$), preliminary, submitted to PRL
    - ☞ arXiv:0808.0017 ($A^0 \to$ invisible), preliminary
    - ☞ arXiv:0908.2840 ($\Upsilon(1S) \to$ invisible), preliminary, submitted to PRL
    - ☞ arXiv:0812.1021 ($\Upsilon(3S) \to \tau l$), preliminary
- Additional datasets available in BaBar and Belle: stay tuned !

Backup

BaBar Detector



BaBar 2008 Dataset



Dec. 2007 - Apr. 2008

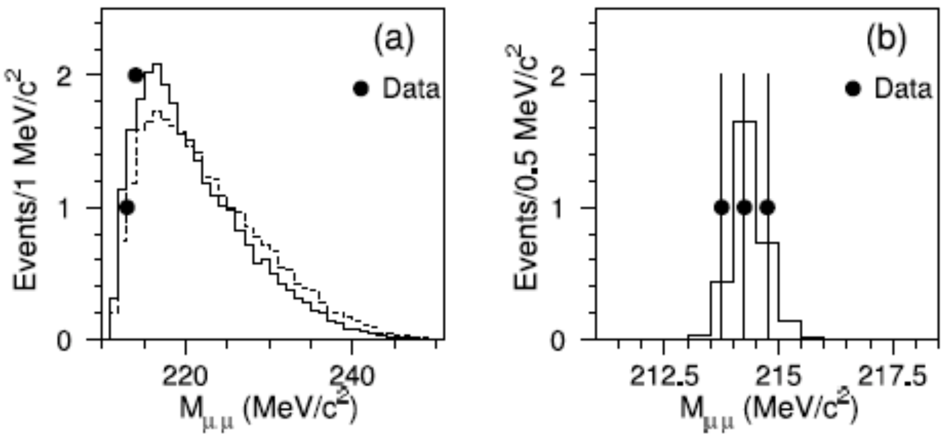
Dedicated run on Υ(3S) and Υ(2S), cross section scan above Υ(4S)

122M Υ(3S) decays

99M Υ(2S) decays

Existing Constraints

HyperCP anomaly



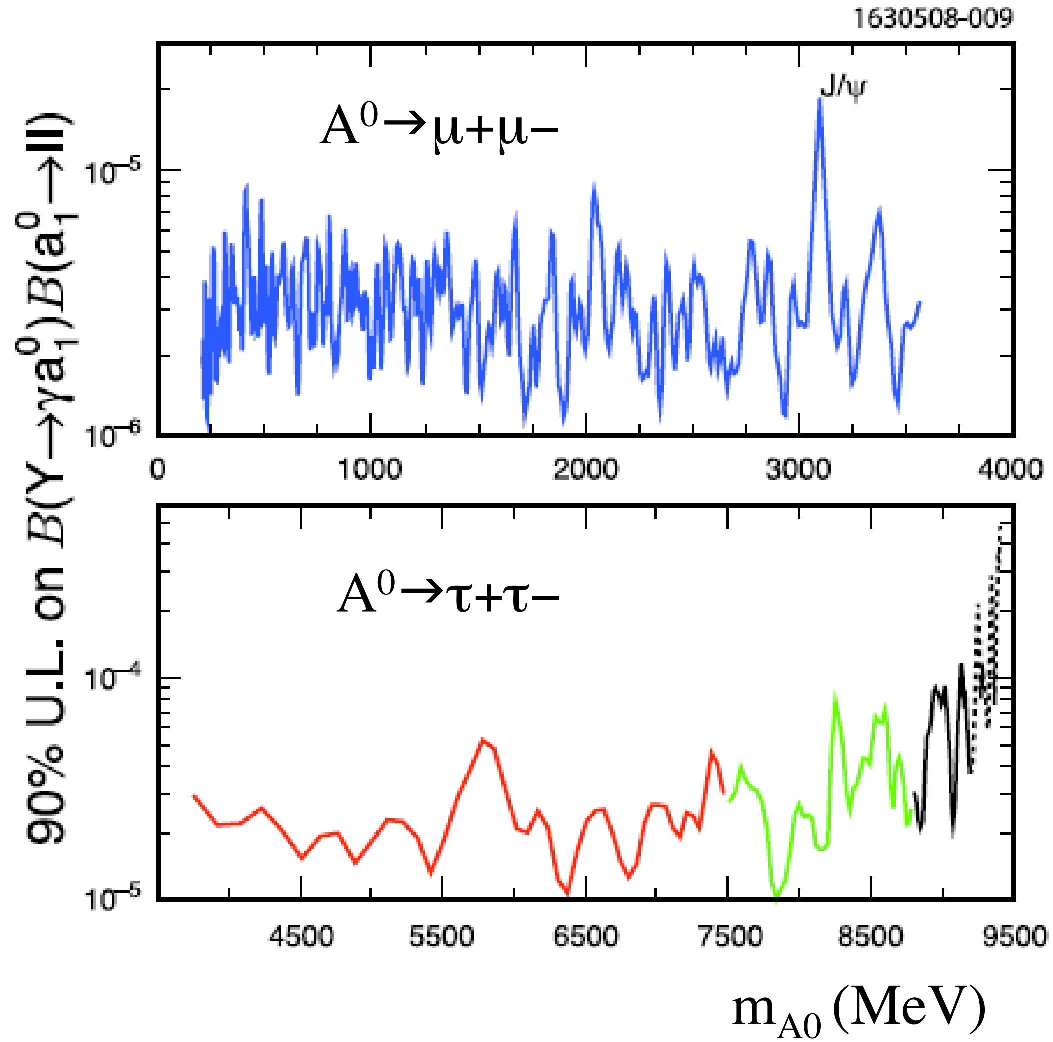
H. Park et al., PRL**94**, 021801 (2005)

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

Small width (Γ<1 MeV)

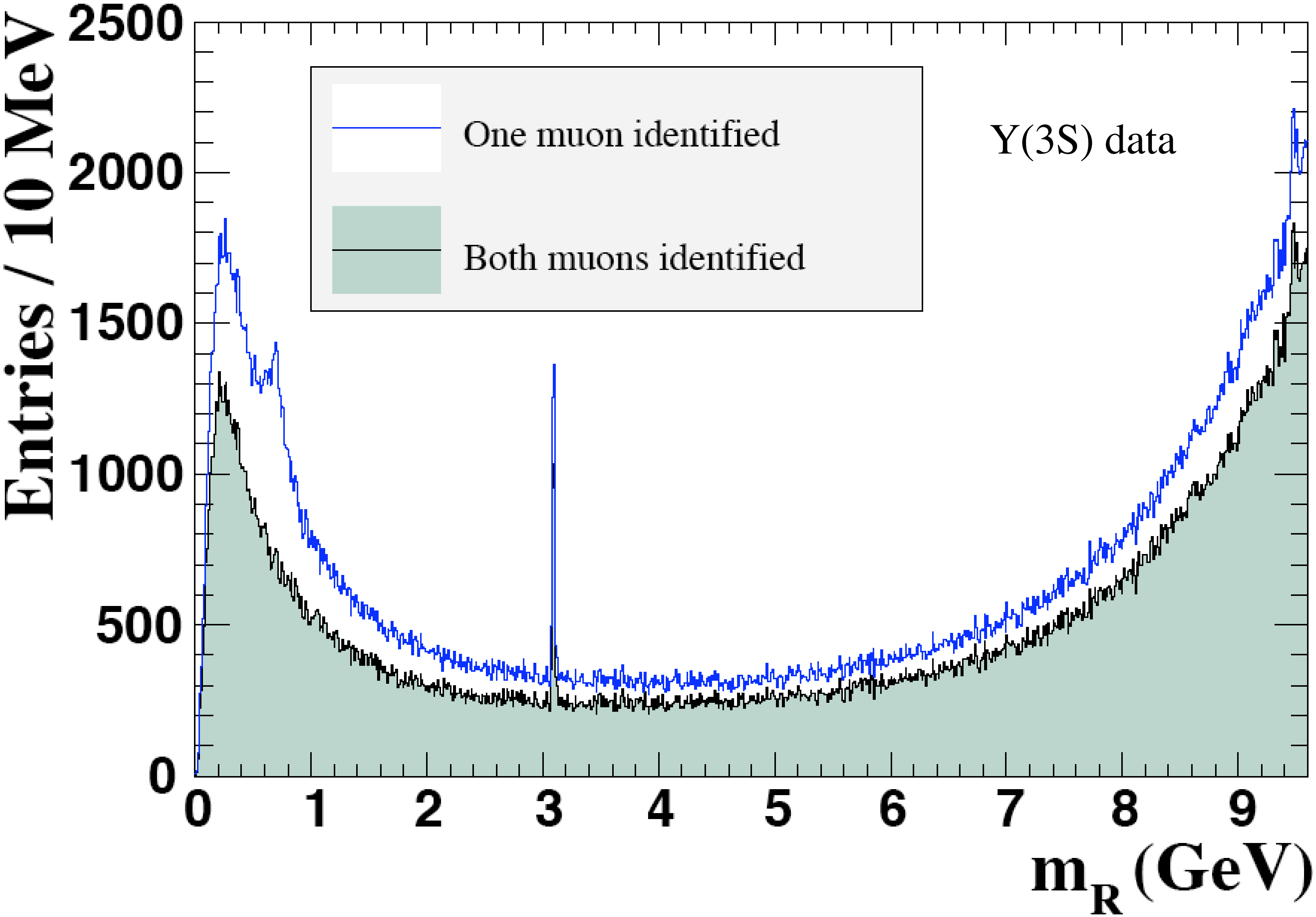
If light CP-odd Higgs, could be produced in $\Upsilon \rightarrow \gamma X(214)$.

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



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

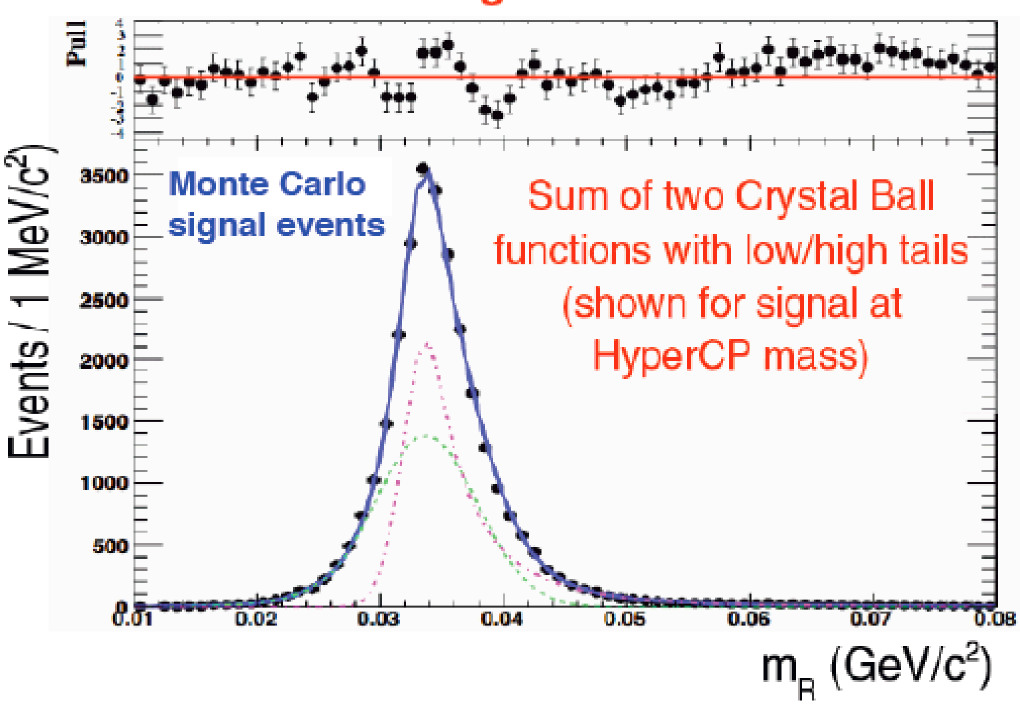
$A^0 \to \mu^+\mu^-$ Mass Spectrum



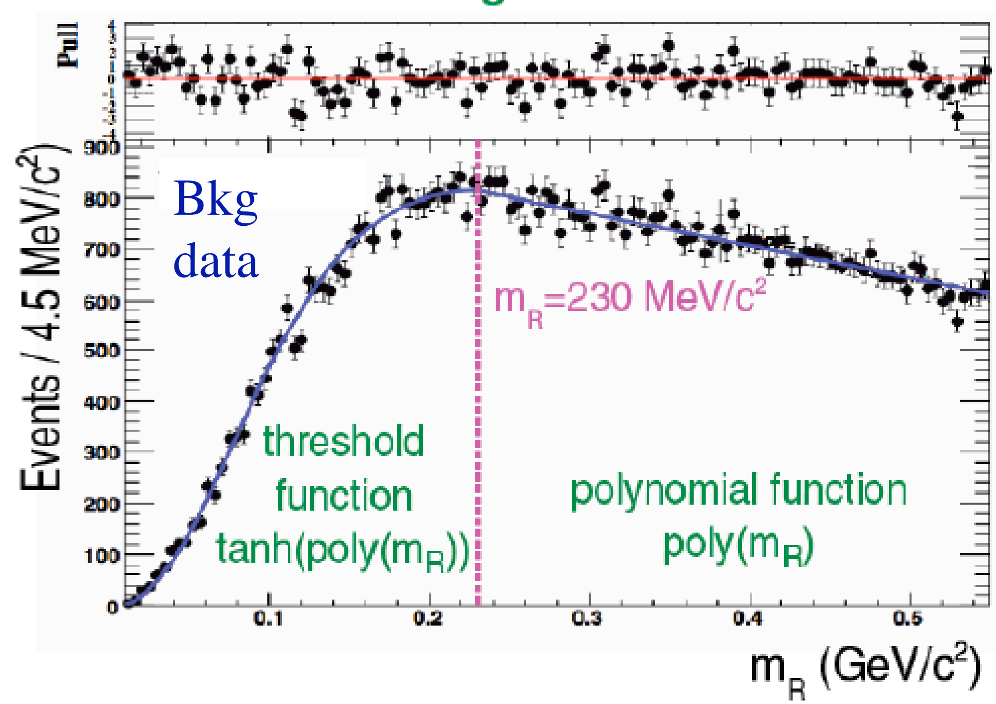
Strategy for $A^0 \to \mu^+\mu^-$

- Signal extraction: ML fit in slices of invariant mass
  - 1955 distinct slices from $0.212 \leq m_{A0} \leq 9.3$ 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

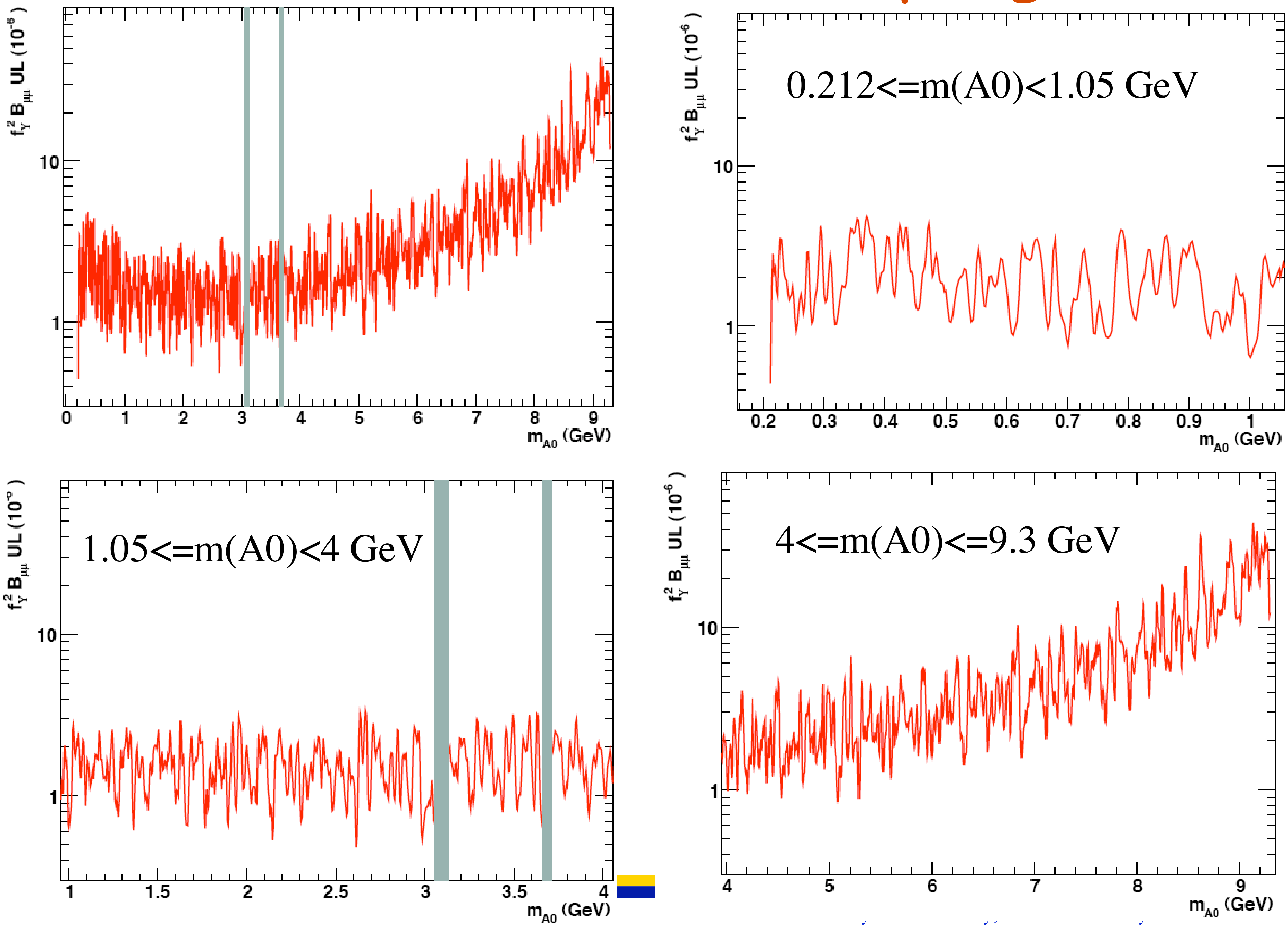


Background PDF

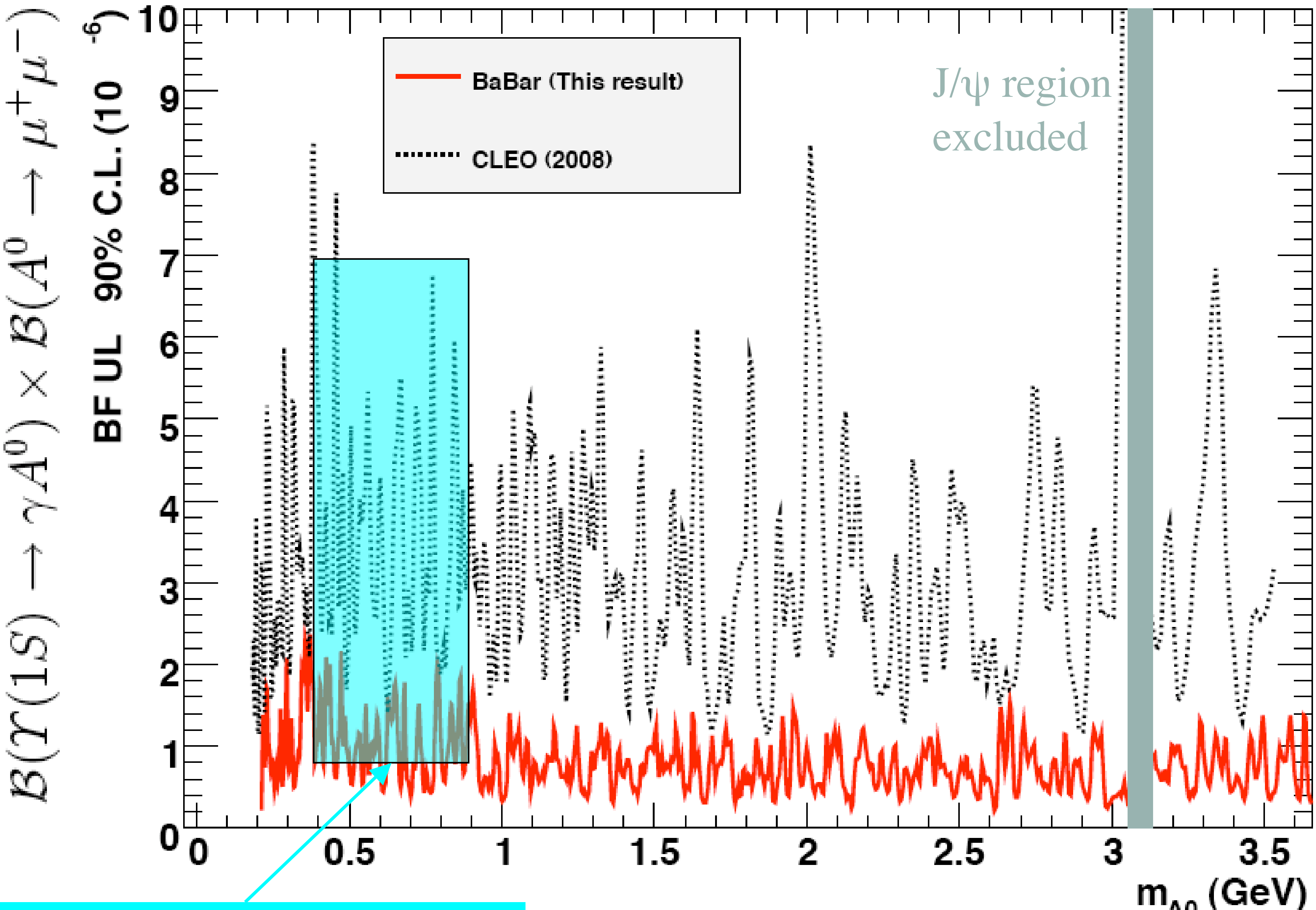


$A^0 \to \mu^+\mu^-$: Yukawa Coupling

90% CL UL on Yukawa coupling $f_{\Upsilon}^2 \times \mathcal{B}_{\mu\mu}$

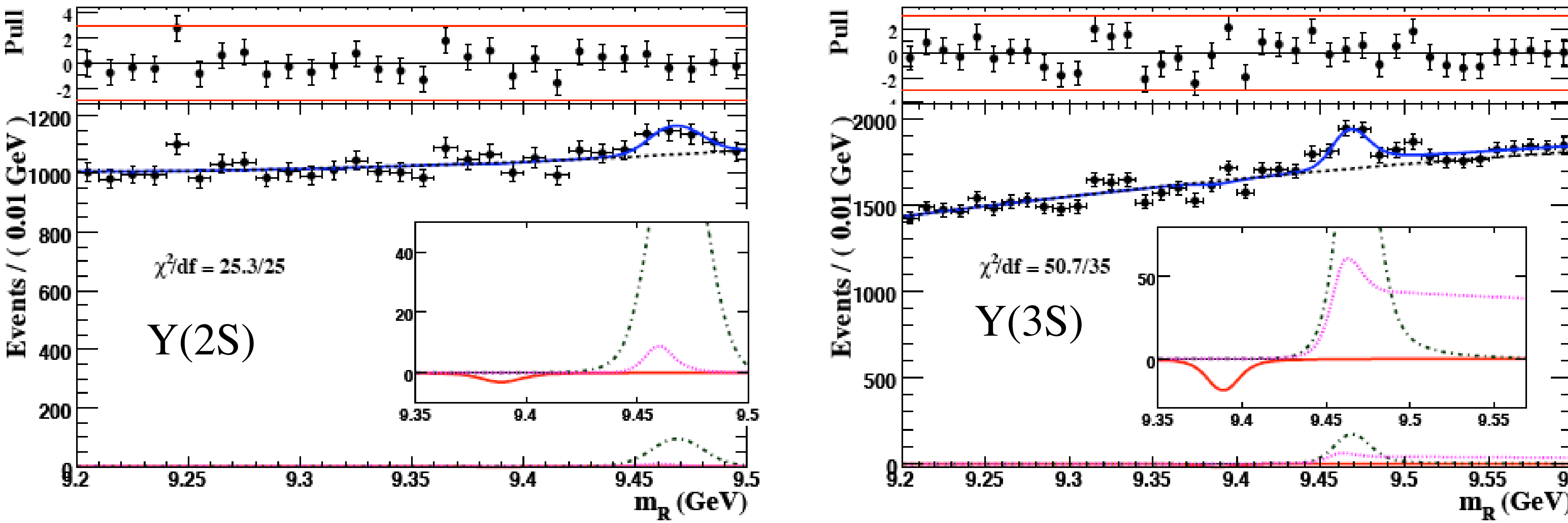


Results at Low Mass: $A^0 \to \mu^+\mu^-$



Range predicted by
Axion model (Nomura,Thaler)

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



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

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

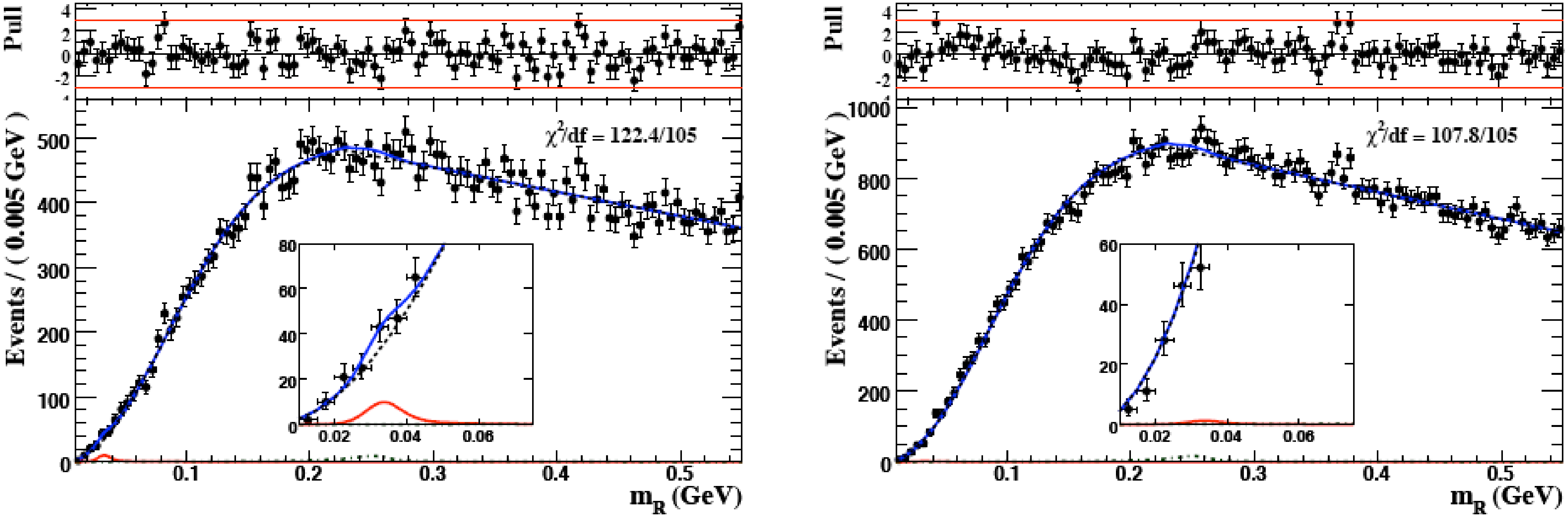
$$\mathcal{B}(\eta_b \to \mu^+\mu^-) = (-0.10 \pm 0.93 \pm 0.33)\% \ (\Upsilon(2S) \text{ dataset})$$

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

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

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

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



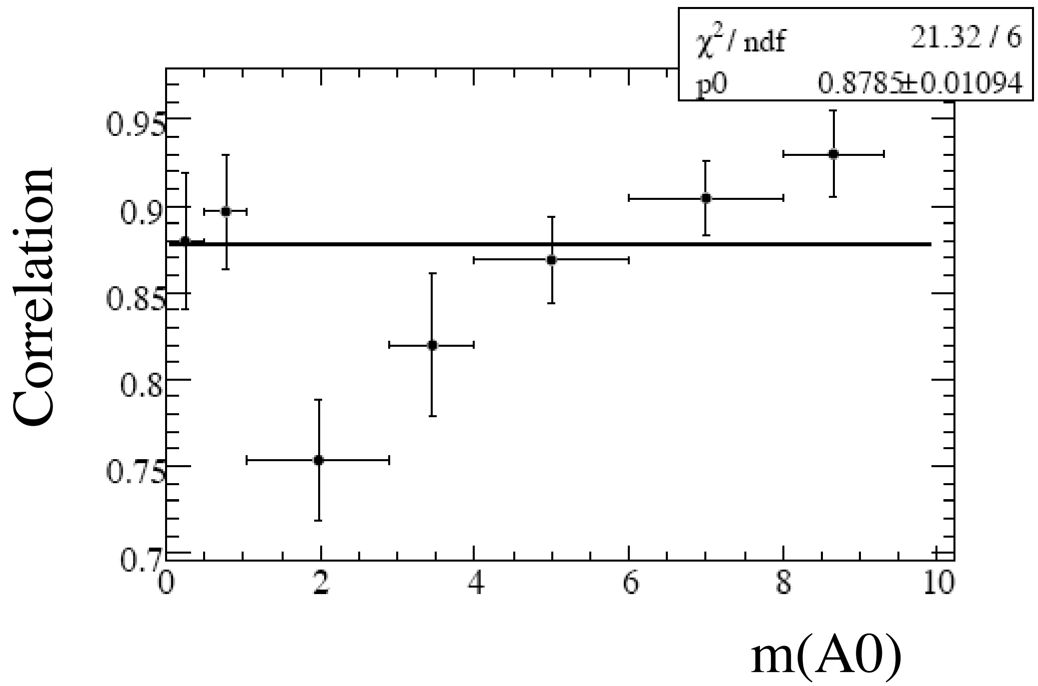
No significant peak at m(A0)=0.214 GeV

Set a stringent upper limit:

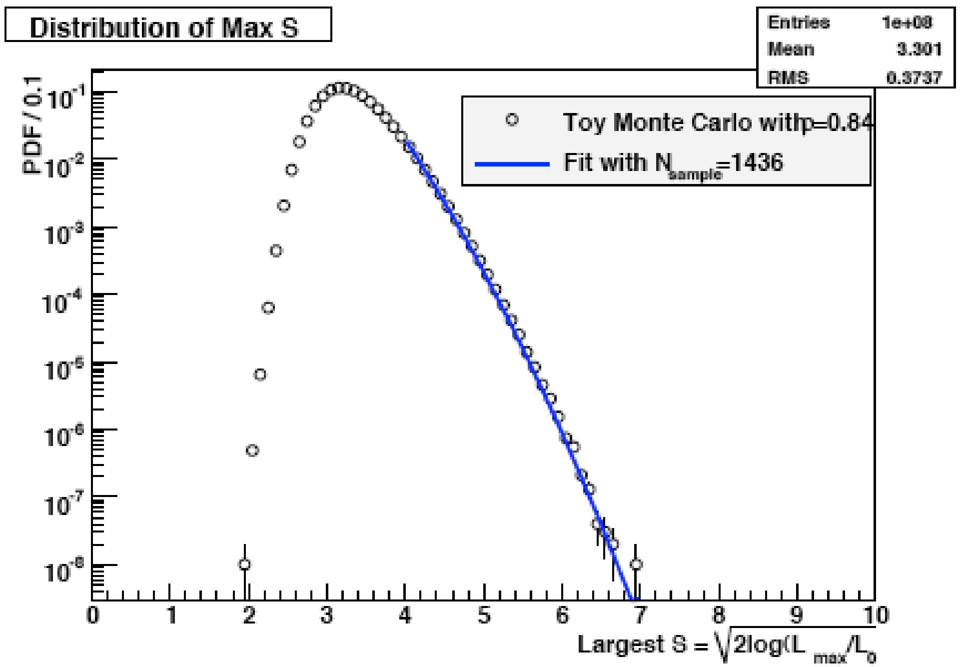
$$f^2_{\Upsilon}(m_{A^0} = 0.214\,\mathrm{GeV}) < 1.6 \times 10^{-6} \text{ at } 90\% \text{ C.L}$$

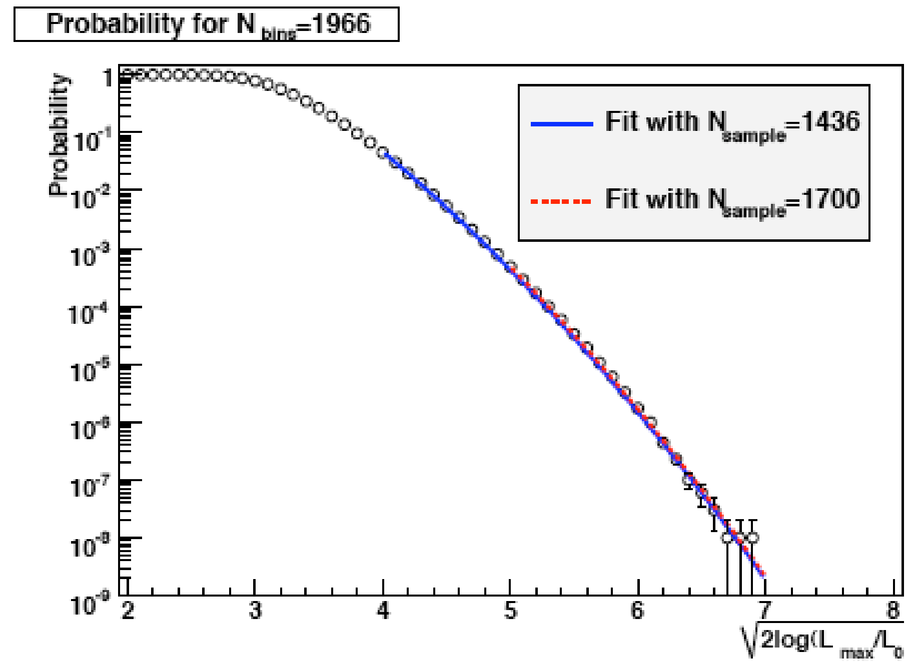
Significance Calculation

- 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



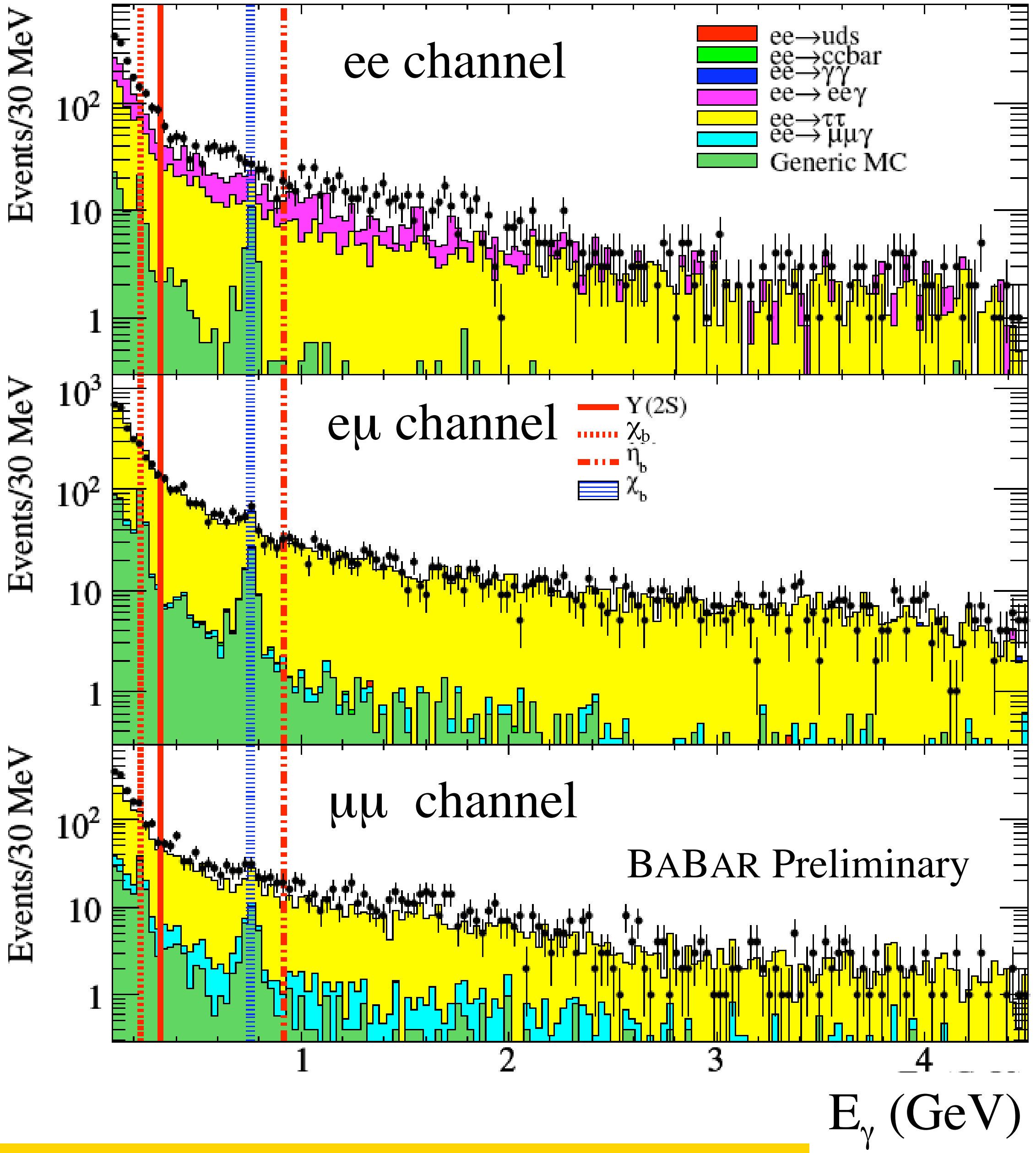


Generate 10^8 toy experiments with 1966 bins:

normal distribution for each bin, adjacent bins correlated by 88%

Typical trial factor ~1500

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



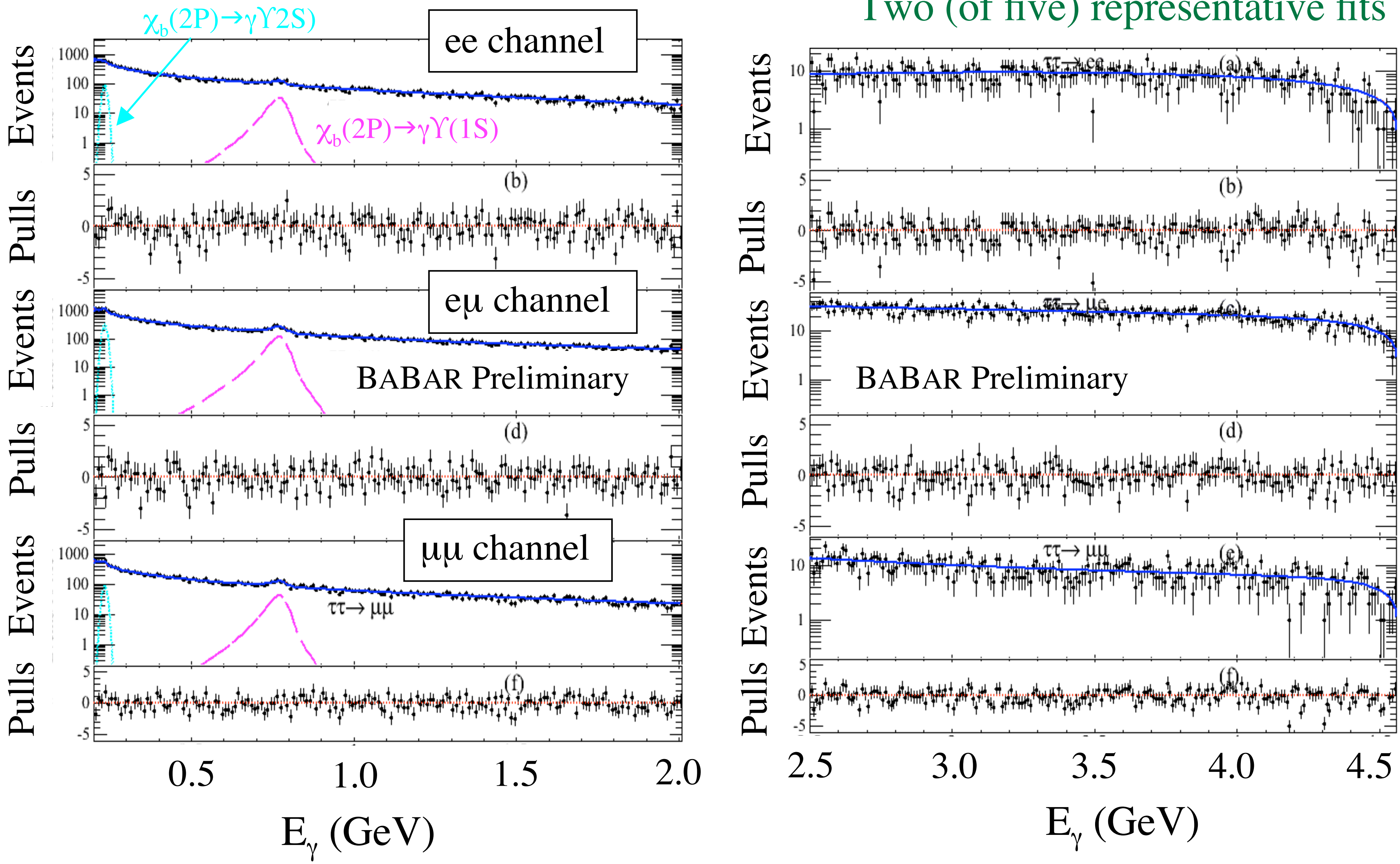
Selection optimized in five large energy regions. Background dominated by irreducible $e^+e^-\to\tau^+\tau^-$

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

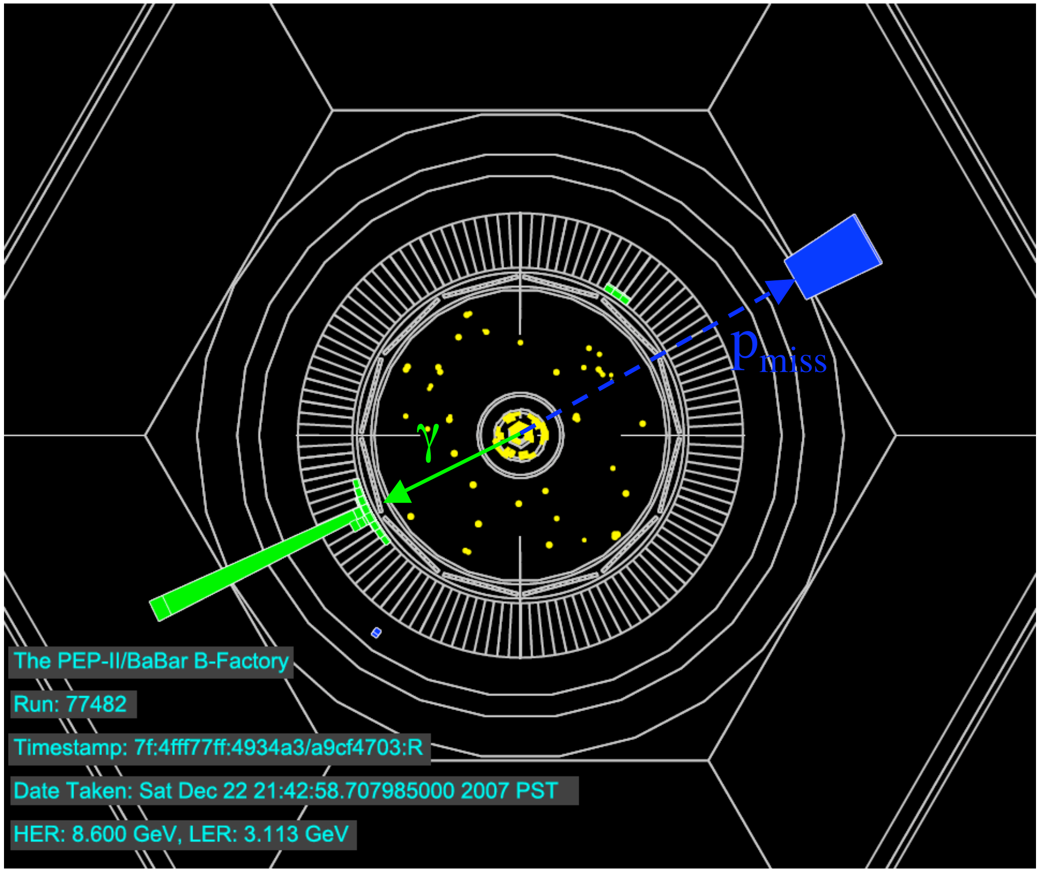
Signal distribution: Crystal Ball PDF with low-energy tail, resolution 10-55 MeV grows with E_γ

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

Two (of five) representative fits



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



- Require a single photon with E^*_γ>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^*_γ>3 GeV), ~20% (E^*_γ<3 GeV)

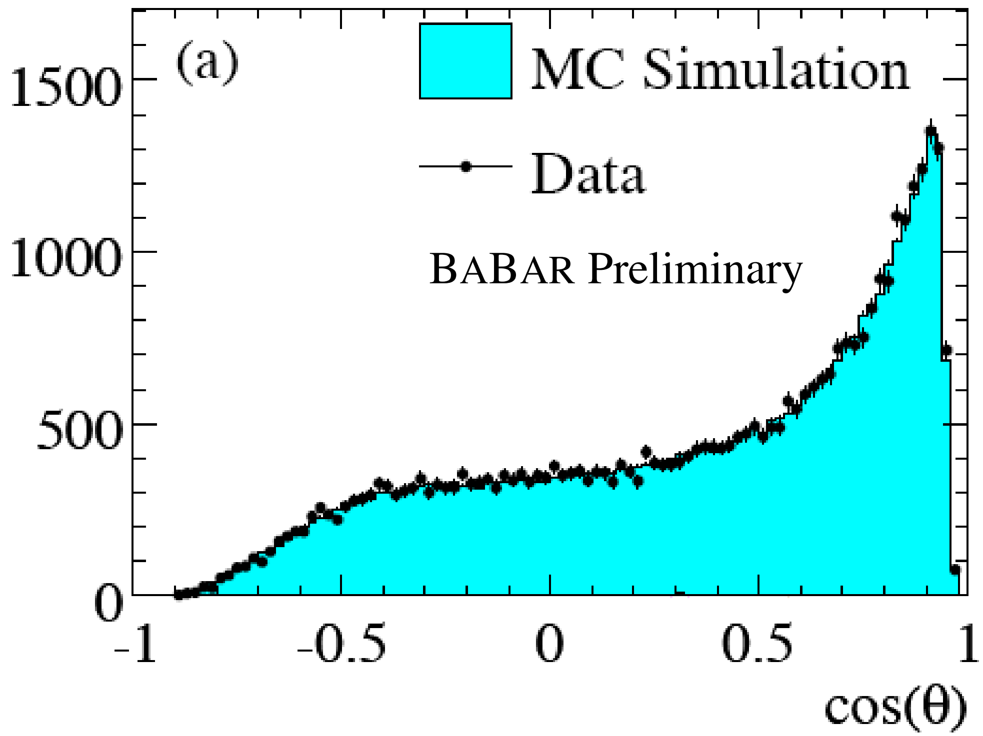
Dominant background from $e^+e^-\to\gamma\gamma$, with one of the photons missing the EM calorimeter. Veto such events by detecting activity in the muon detector (IFR).

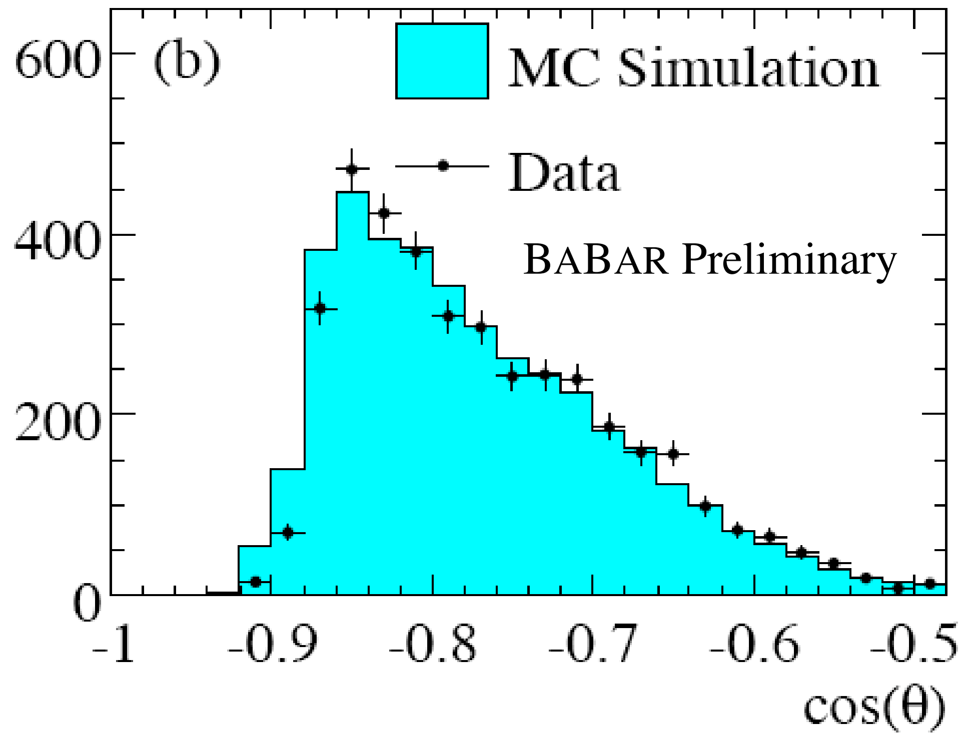
Corrections and Systematics

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