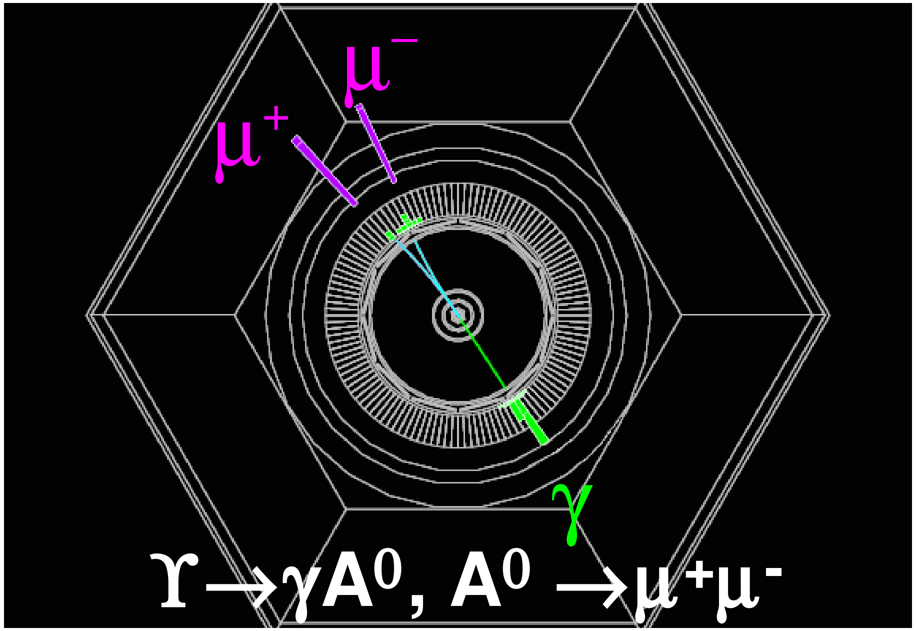


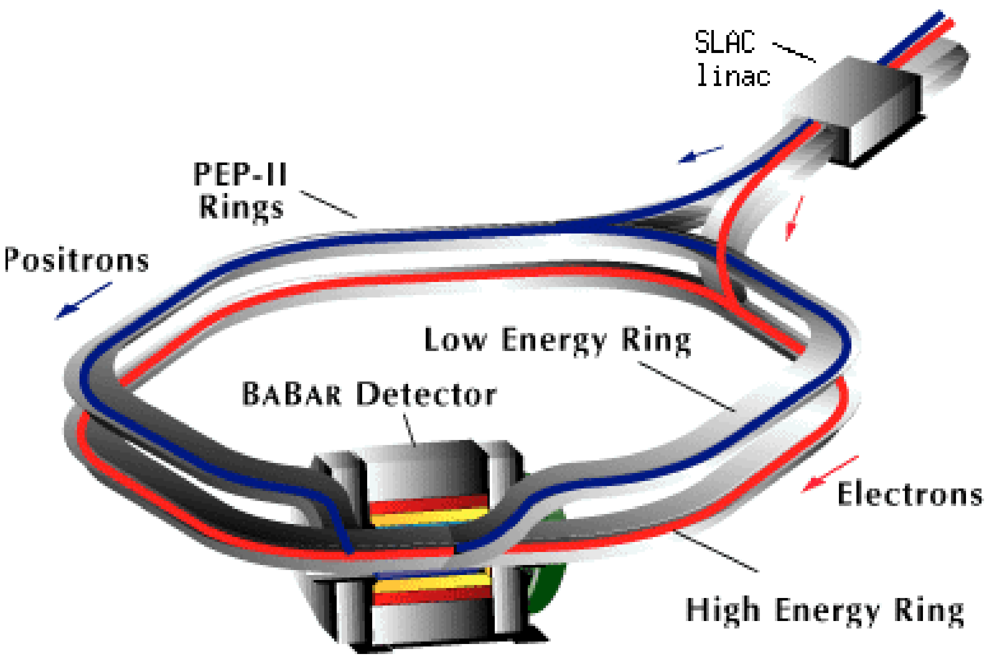
Searches for New Physics in Narrow Upsilon Decays at BaBar

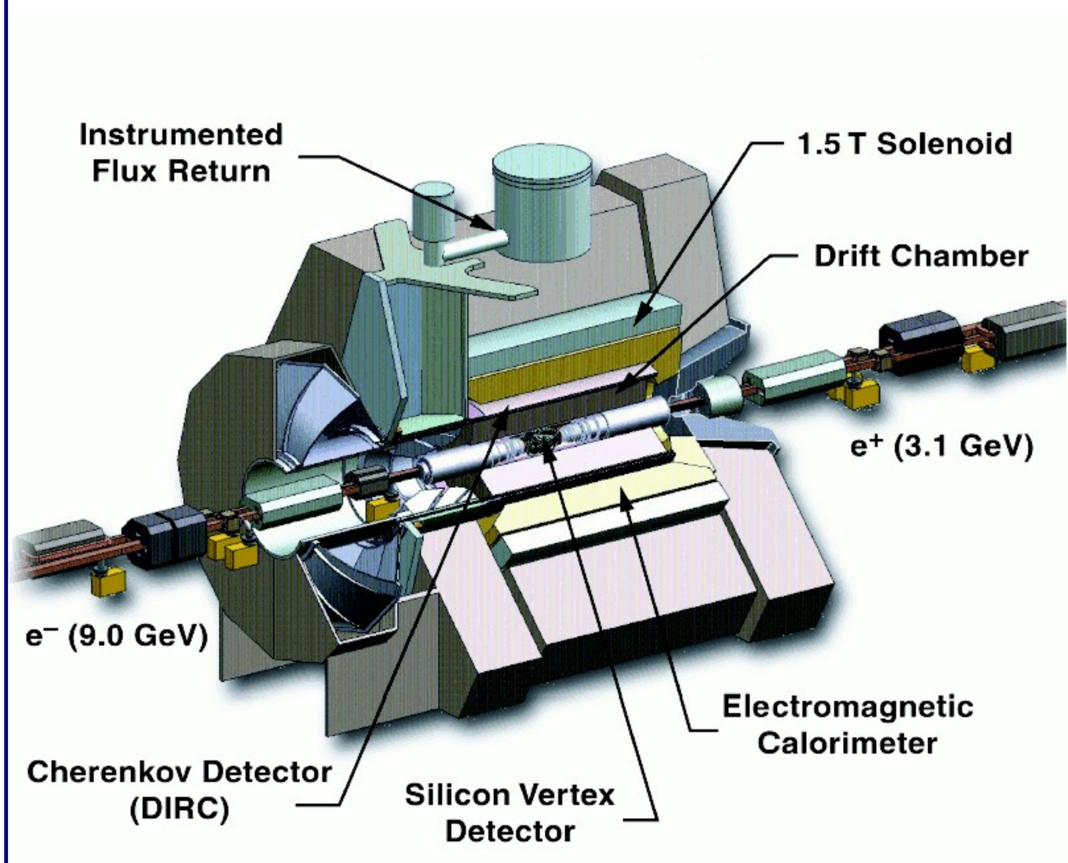
Ben Hooberman, on behalf of the BaBar collaboration

Outline

- **Introduction**
- Search for Light Higgs
  - $A^0 \to \mu^+\mu^-$
  - $A^0 \to \tau^+\tau^-$
  - $A^0 \to$ invisible
- Search for Light Dark Matter
- Search for Lepton Flavor Violation
- Test of Lepton Universality

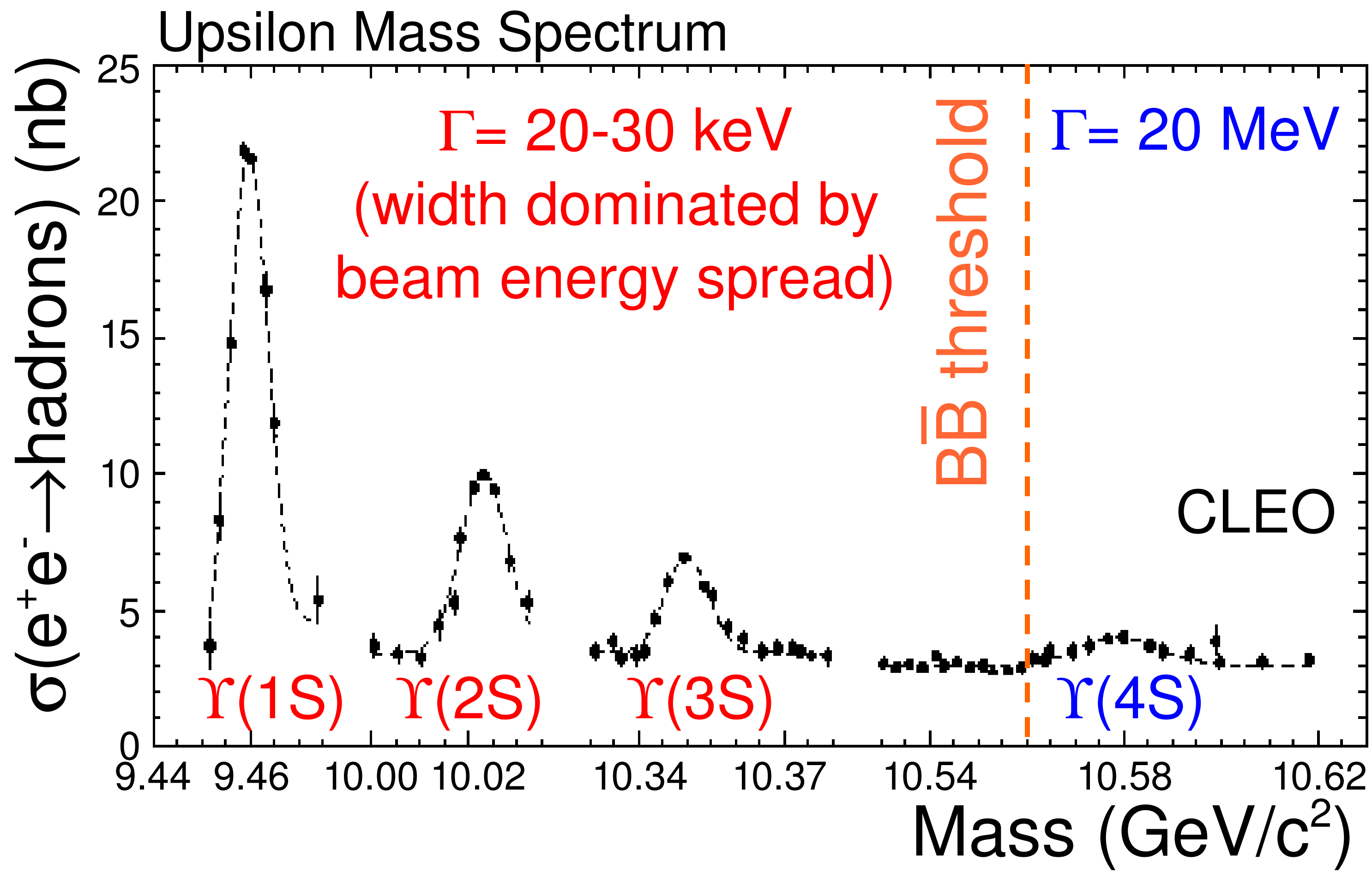
The PEPII Collider and BABAR Detector





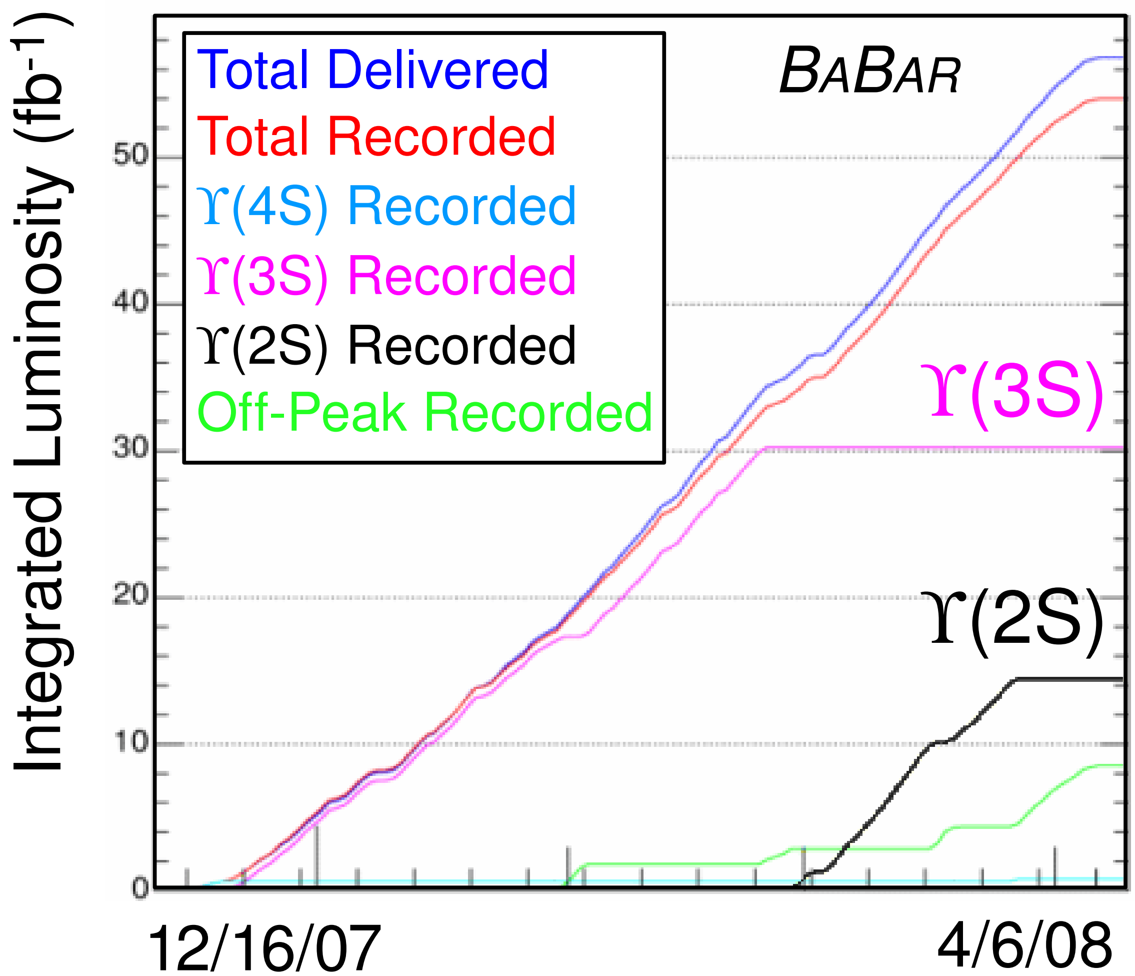
- Asymmetric energy e^+e^- collider
- Nominal $\sqrt{s} = M(\Upsilon(4S))$

Narrow Upsilon Motivation



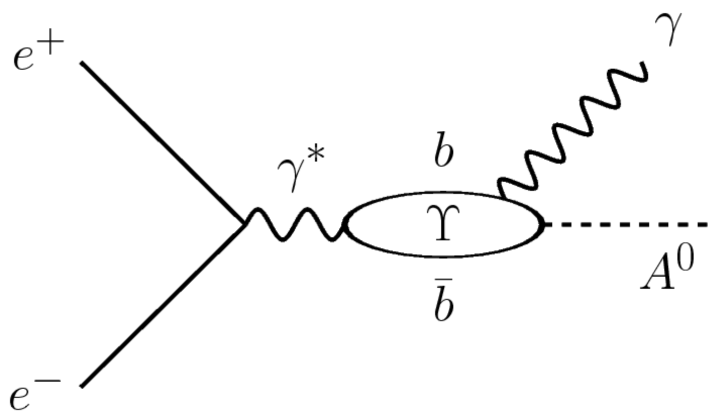
- Most BaBar data collected at $\Upsilon(4S)$ (decays to $B\bar{B}$ dominate) to search for CP violation in B meson decays
- Rare BFs at $\Upsilon(nS)$ n=1,2,3 enhanced by $\Gamma(\Upsilon(4S))$ / $\Gamma(\Upsilon(nS))$ = $O(10^3)$

Narrow Upsilon Dataset

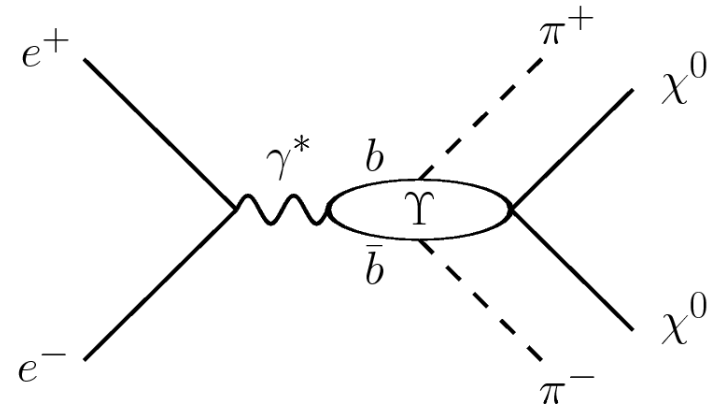


At end of PEPII operations, collected 122×10^{6} $\Upsilon(3S)$ decays (28.5 fb^{-1}) and 99×10^{6} $\Upsilon(2S)$ decays (14.4 fb^{-1}) to search for exotic processes

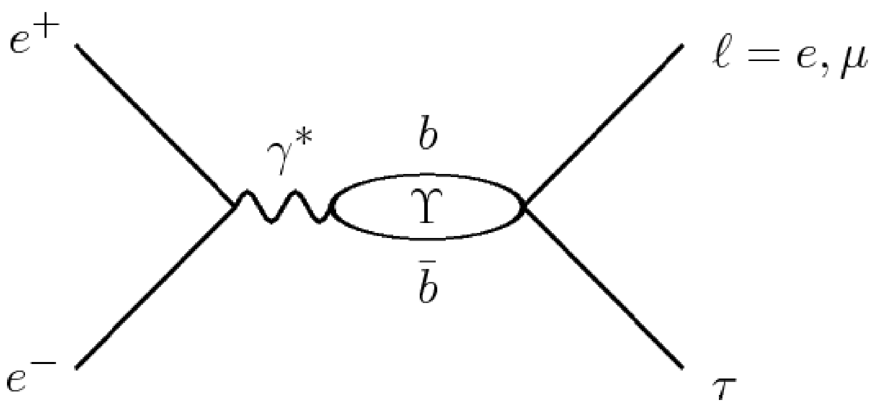
New Physics Signatures in Υ Decays



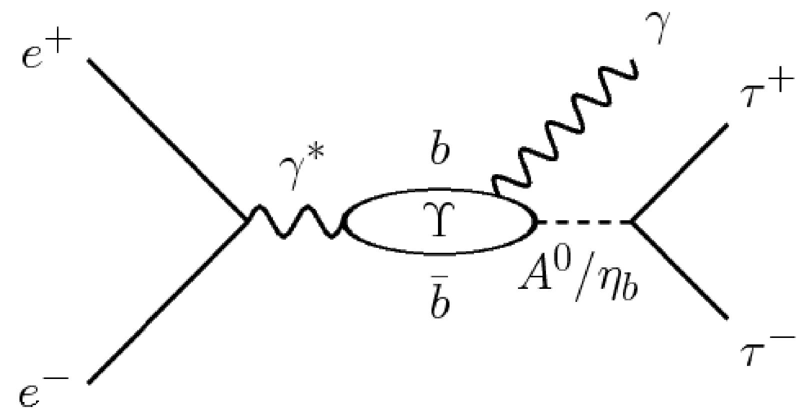
Light Higgs Production



Light Dark Matter Production



Lepton Flavor Violation



Violation of Lepton Universality

- Wide variety of new physics signatures
- BABAR: precise knowledge of E_{CM} + clean environment + largest narrow Υ sample $\rightarrow$ precise measurements **complementary to direct searches at TeVatron/LHC**

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Motivation for Light Higgs(-like) State

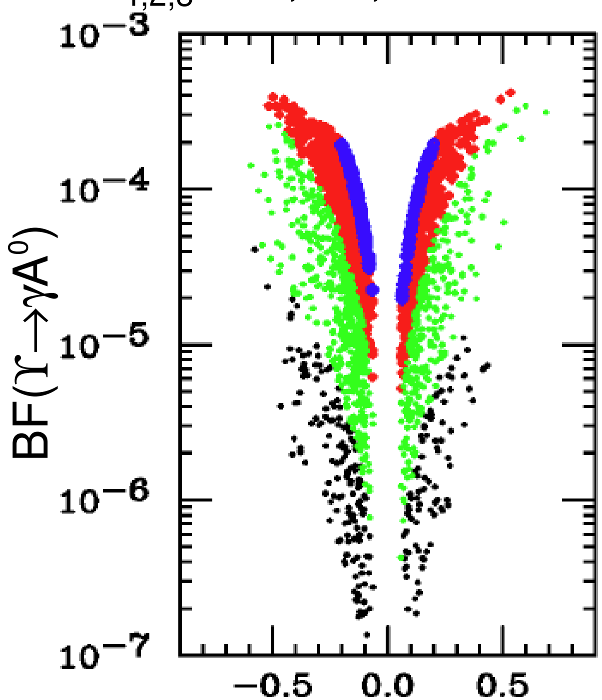
- NMSSM introduces singlet CP-odd light Higgs state (PRD 73, 111701(R) 2006)
  - $A^0 \equiv a1 = \cos(\theta_A) a_{MSSM} + \sin(\theta_A) a_{singlet}$
  - $BF(\Upsilon \rightarrow \gamma A^0)$ up to 10^{-4}
  - For $M(A^0) < 2m_b$, lightest CP-even Higgs h^0 evades LEP constraints by $h^0 \rightarrow A^0A^0 \rightarrow \tau^+\tau^-\tau^+\tau^-$
  - Coupling to heavy particles enhanced

search for A^0 In Υ decays

- Recent axion model introduces scalar with Higgs-like couplings (PRD 79, 075008 2009)
  - $BF(\Upsilon \rightarrow \gamma a) \sim 10^{-5}$-$10^{-6}$
- $O(10^8)$ $\Upsilon(2S/3S)$ decays $\rightarrow$ BABAR achieves sensitivity to BFs of order 10^{-7} - 10^{-5}

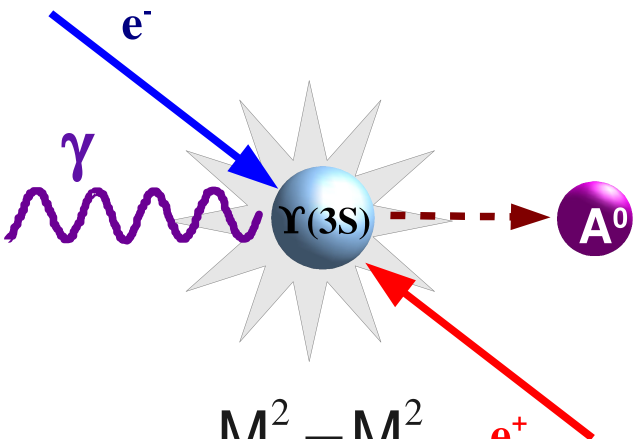
$M(A^0)<2M(\tau)$
$2M(\tau)<M(A^0)<7.5$ GeV
7.5 GeV$<M(A^0)<$8.8 GeV
8.8 GeV$<M(A^0)<$9.2 GeV

NMSSM $\tan\beta=10$, $\mu=150$ GeV, $M_{1,2,3}=100,200,300$ GeV



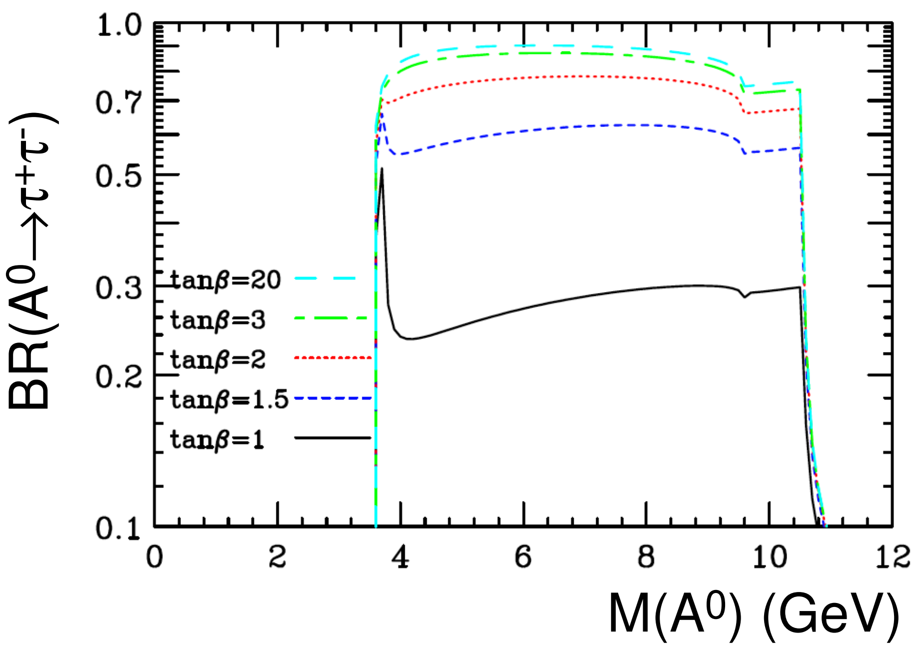
A^0 non-singlet fraction ($\cos\theta_A$)

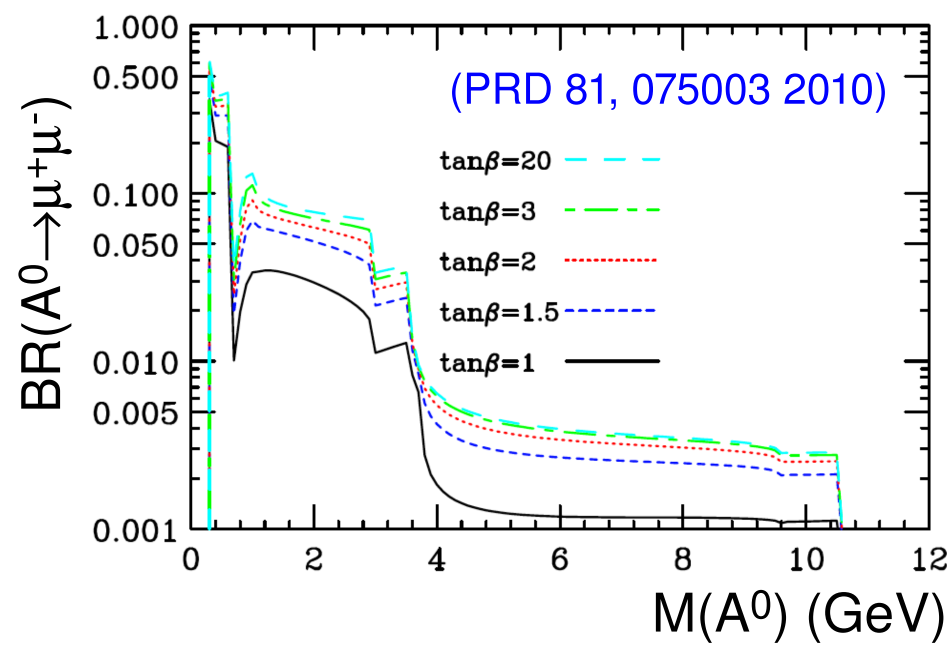
A^0 Production & Decay Modes



$$E_\gamma^* = \frac{M_\Upsilon^2 - M_{A^0}^2}{2M_\Upsilon}$$

- $A^0 \to \mu^+\mu^-$ significant for $M(A^0) < 2m_\tau$
- $A^0 \to \tau^+\tau^-$ dominant for $M(A^0) > 2m_\tau$
- $A^0 \to$ invisible (ie. $\chi\chi$) enhanced in NMSSM with light χ LSP





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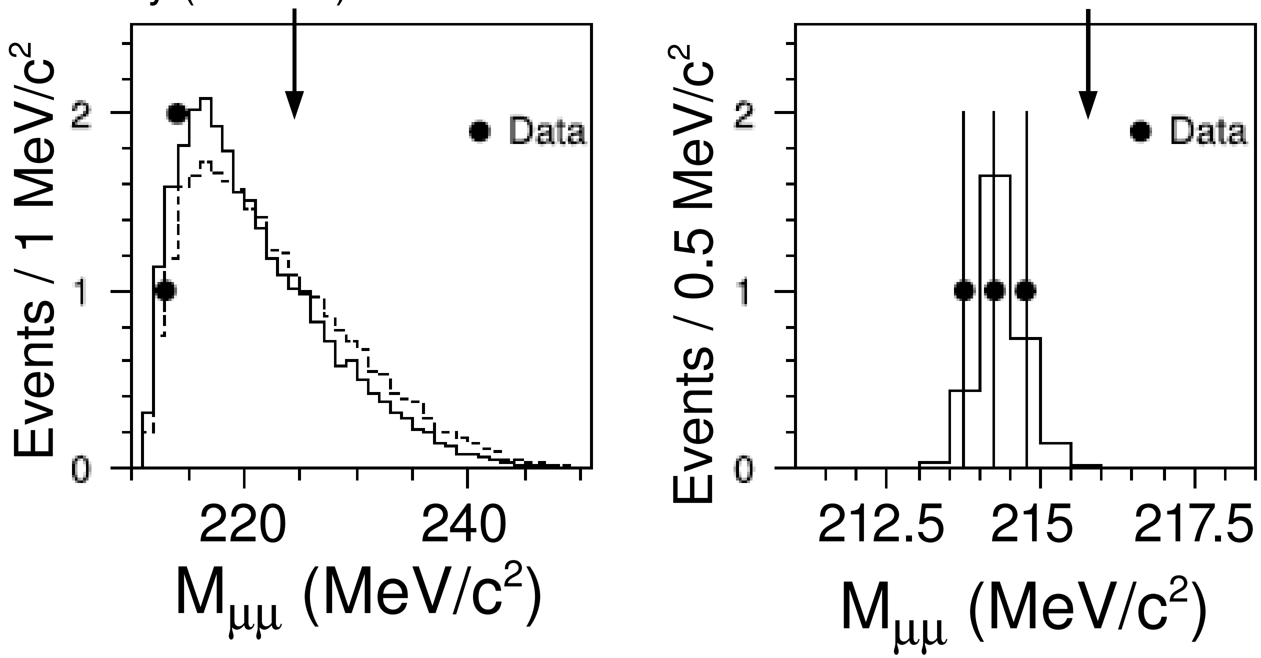
Motivation: HyperCP Anomaly & η_b

Form-factor decay (solid)
Uniform phase-space decay (dashed)

(HyperCP PRL 94, 021801 2005)

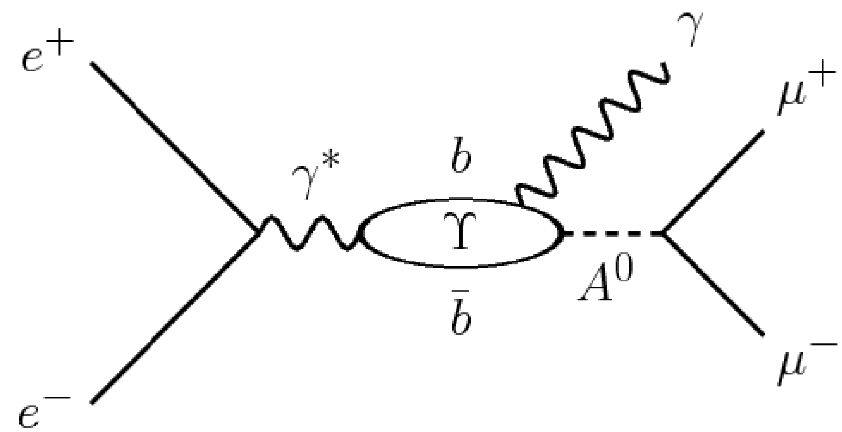
Resonant decay



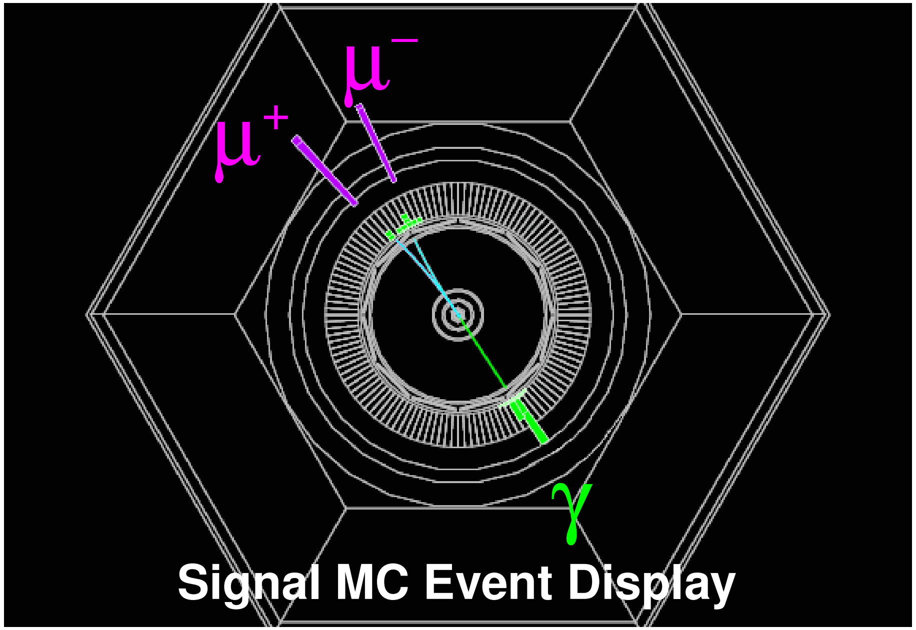
- HyperCP experiment observed resonance structure in $\Sigma \to p\mu^+\mu^-$ scattering. Light scalar decaying to $\mu^+\mu^-$?
- η_b recently discovered $b\bar{b}$ ground state (BABAR PRL 101, 071801 2008)
  - Check $M(\eta_b)$=9.38 GeV/c^2, don't expect $BF(\eta_b \to \mu^+\mu^-)$ to be sizable

Signal Signature and Selection

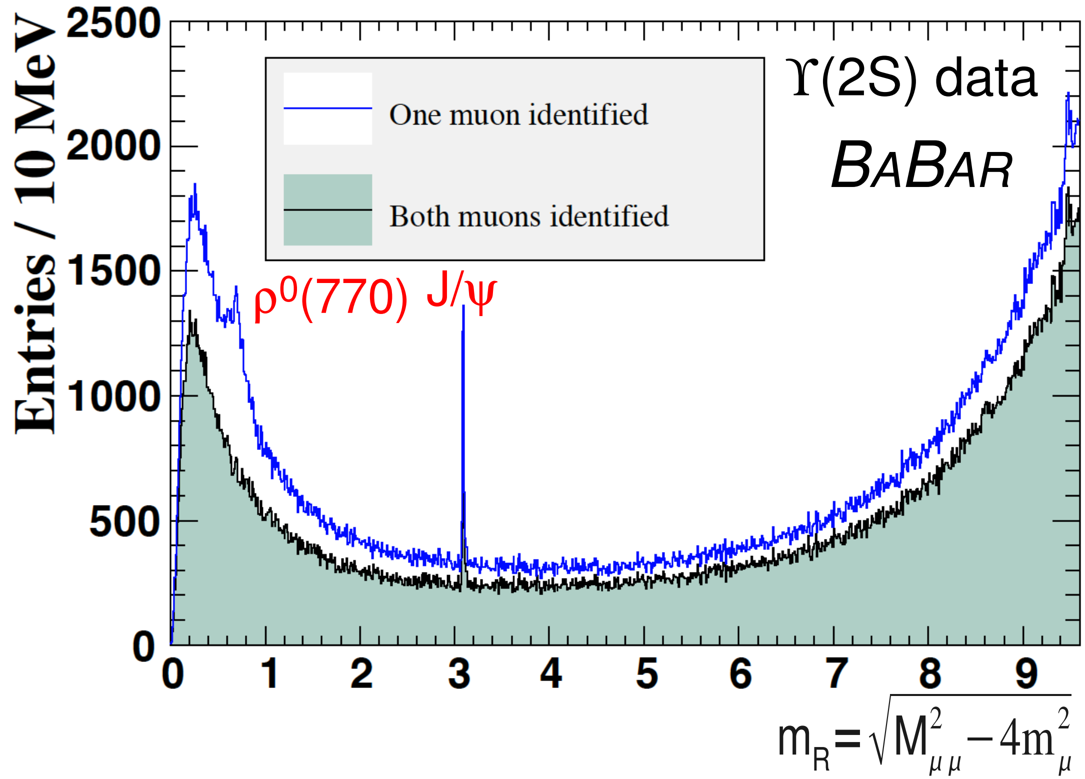
- Fully reconstructed $\mu^+\mu^-\gamma$ final state
- $\mu^+\mu^-$ system back-to-back with γ in CM system
  - 2 oppositely-charged tracks
  - Exactly 1 γ with $E_\gamma > 0.2$ GeV
- Total energy consistent with E_{CM}
- Perform kinematic fit of $\mu^+\mu^-\gamma$ system using beam energy & vertex constraints



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



Signal Extraction



$M_{A^0} < 1.05$ GeV/c^2: require 2 identified muons

$M_{A^0} > 1.05$ GeV/c^2: require ≥1 identified muons

- Scan "reduced mass" m_R distribution for evidence of signal peak
- Sliding window ~300 MeV/c^2 in m_R , perform ~2000 ML fits from $0.212 < M_{A^0} < 9.3$ GeV/c^2 in 2-5 MeV steps ($< \sigma(M_{A^0})$)
  - Known resonances included in background parameterization
  - Take signal shape from MC, width varying as a function of M_{A^0}

Results

- Observed yields consistent with zero signal given # of independent trials

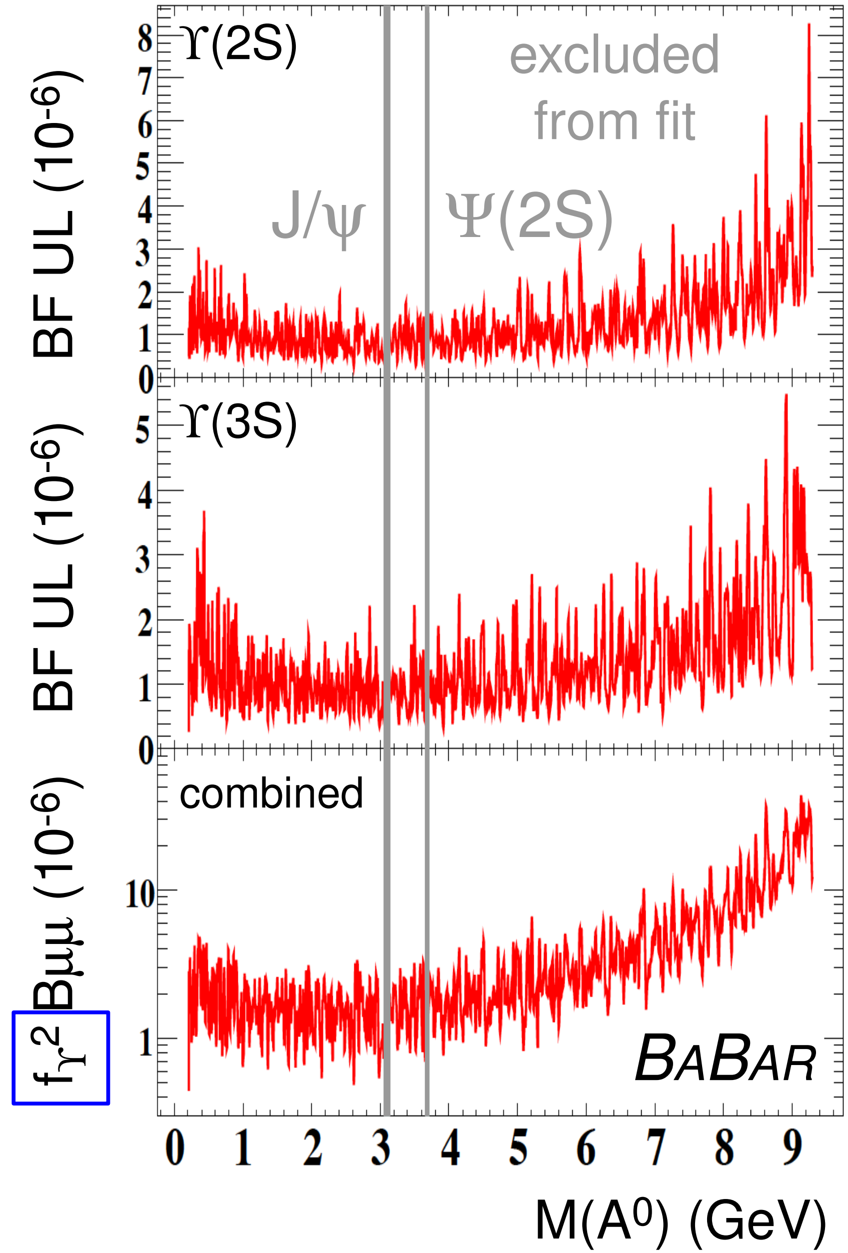
- **No signal at 214 MeV (HyperCP)**
- **$BF(\eta_b \to \mu^+\mu^-) < 0.9\%$ @ 90% CL**

- Set 90% CL upper limits on $BF_{TOT} \equiv BF(\Upsilon(2S/3S) \to \gamma A^0) \times BF(A^0 \to \mu^+\mu^-)$
  - **$BF_{TOT}(\Upsilon(2S)) < (0.26\text{-}8.3)\times 10^{-6}$**
  - **$BF_{TOT}(\Upsilon(3S)) < (0.27\text{-}5.5)\times 10^{-6}$**

Effective Yukawa coupling of A^0 to bound-state b-quark

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

BABAR PRL 103, 081803 2009



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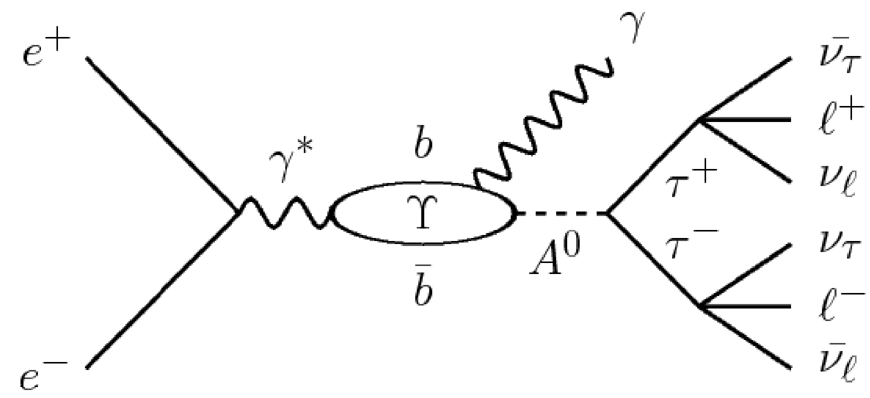
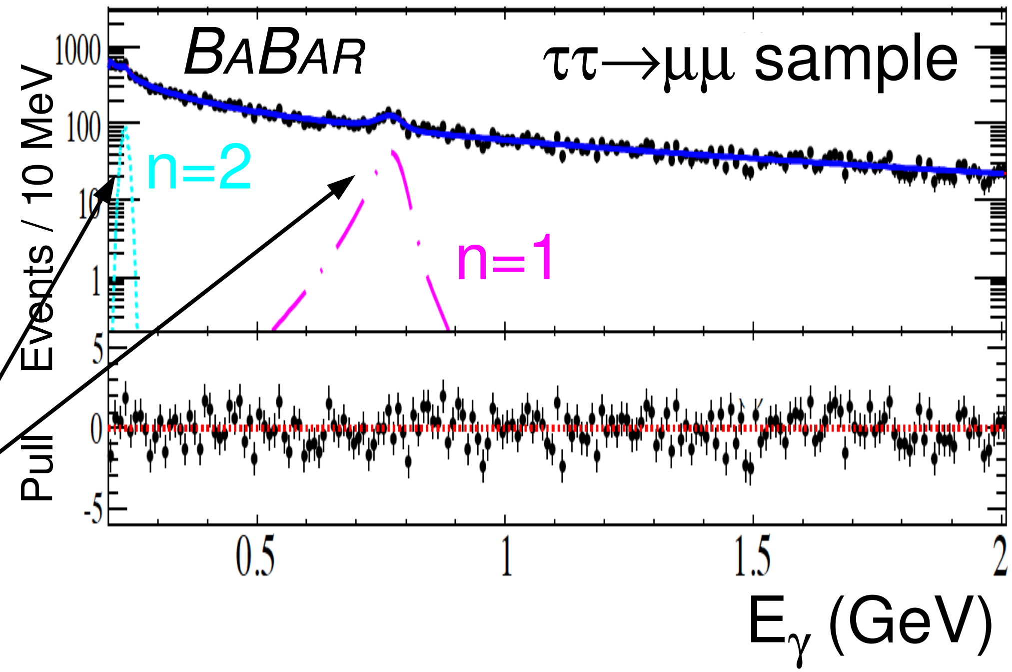
Signal Signature and Selection

- Search for $\Upsilon(3S)\rightarrow\gamma A^0$, $A^0\rightarrow\tau^+\tau^-$ with $\tau\rightarrow e\nu\nu$ / $\tau\rightarrow\mu\nu\nu$
    - ee, μμ, eμ samples
- 2 oppositely-charged tracks identified as leptons + exactly 1 γ with $E_\gamma > 0.1$ GeV



- Final state not fully reconstructed: look at mass recoiling against γ
  $$M^2_{\tau\tau} = M^2_{\Upsilon(3S)} - 2M_{\Upsilon(3S)}E_\gamma$$
- Primary bkg: QED $e^+e^-\rightarrow\tau^+\tau^-\gamma$ + 2-photon processes
- Peaking bkg: $\Upsilon(3S)\rightarrow\gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P)\rightarrow\gamma\Upsilon(nS)$ (n=1,2 J=0,1,2)

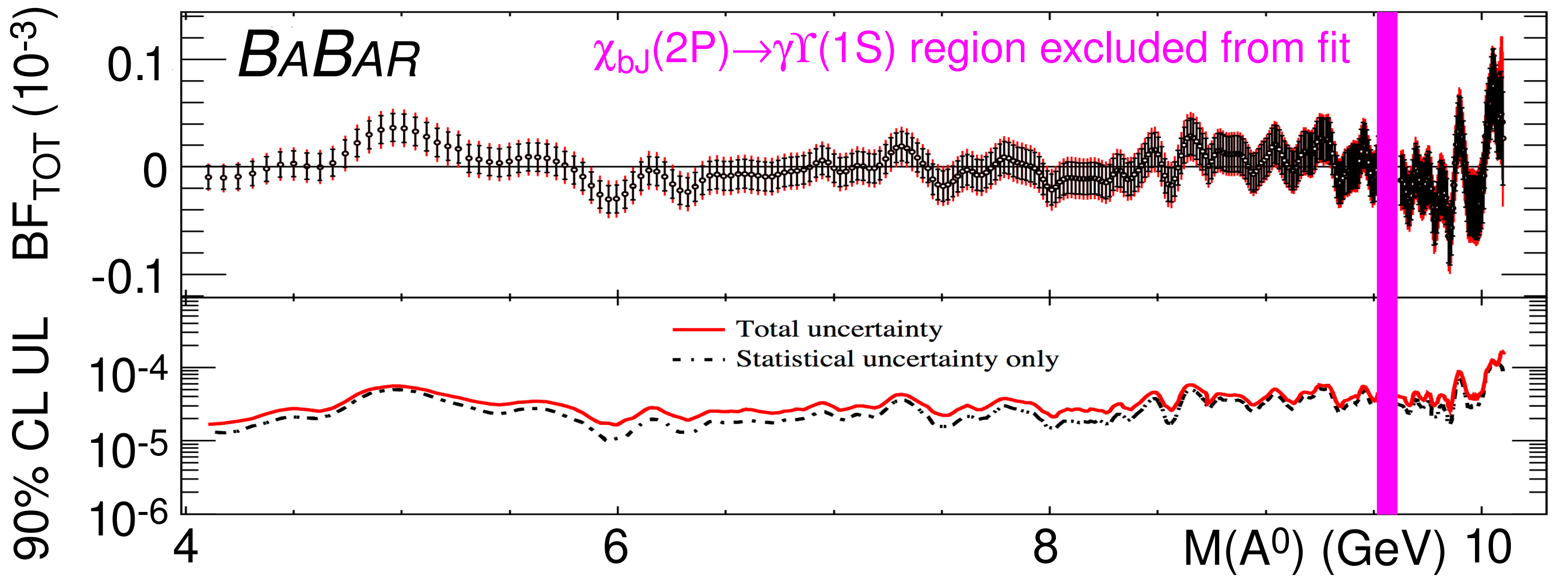


Signal Extraction & Results

- Scan for peaks in E_γ distribution (~300 fits) across range corresponding to $4.03<M(A^0)<10.10$ GeV
  - Signal represented by peaking PDF with width varying w/ E_γ
  - Perform simultaneous fit to $\gamma ee, \gamma\mu\mu, \gamma e\mu$ samples
- No stat significant signal yield → set 90% CL upper limits

$BF_{TOT} = BF(\Upsilon(3S)\to\gamma A^0) \times BF(A^0 \to\tau^+\tau^-) < (1.5\text{-}16) \times 10^{-5}$

BaBar PRL 103, 181801 2009



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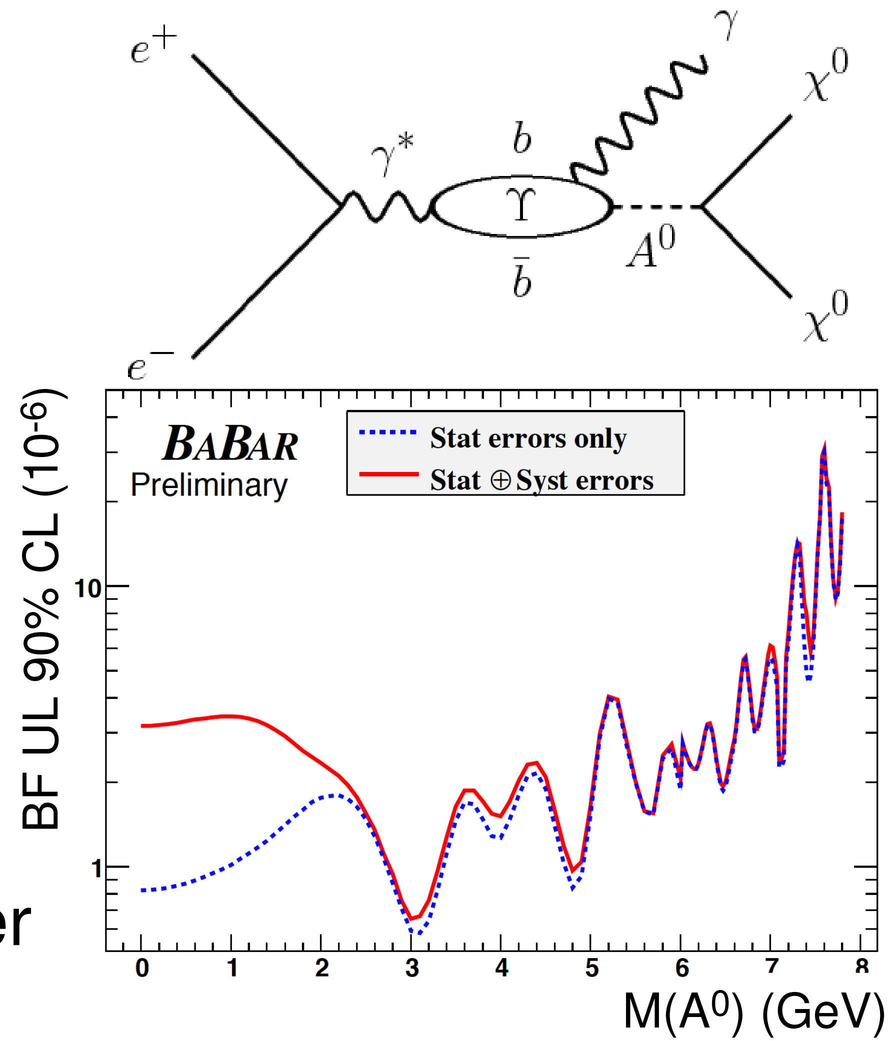
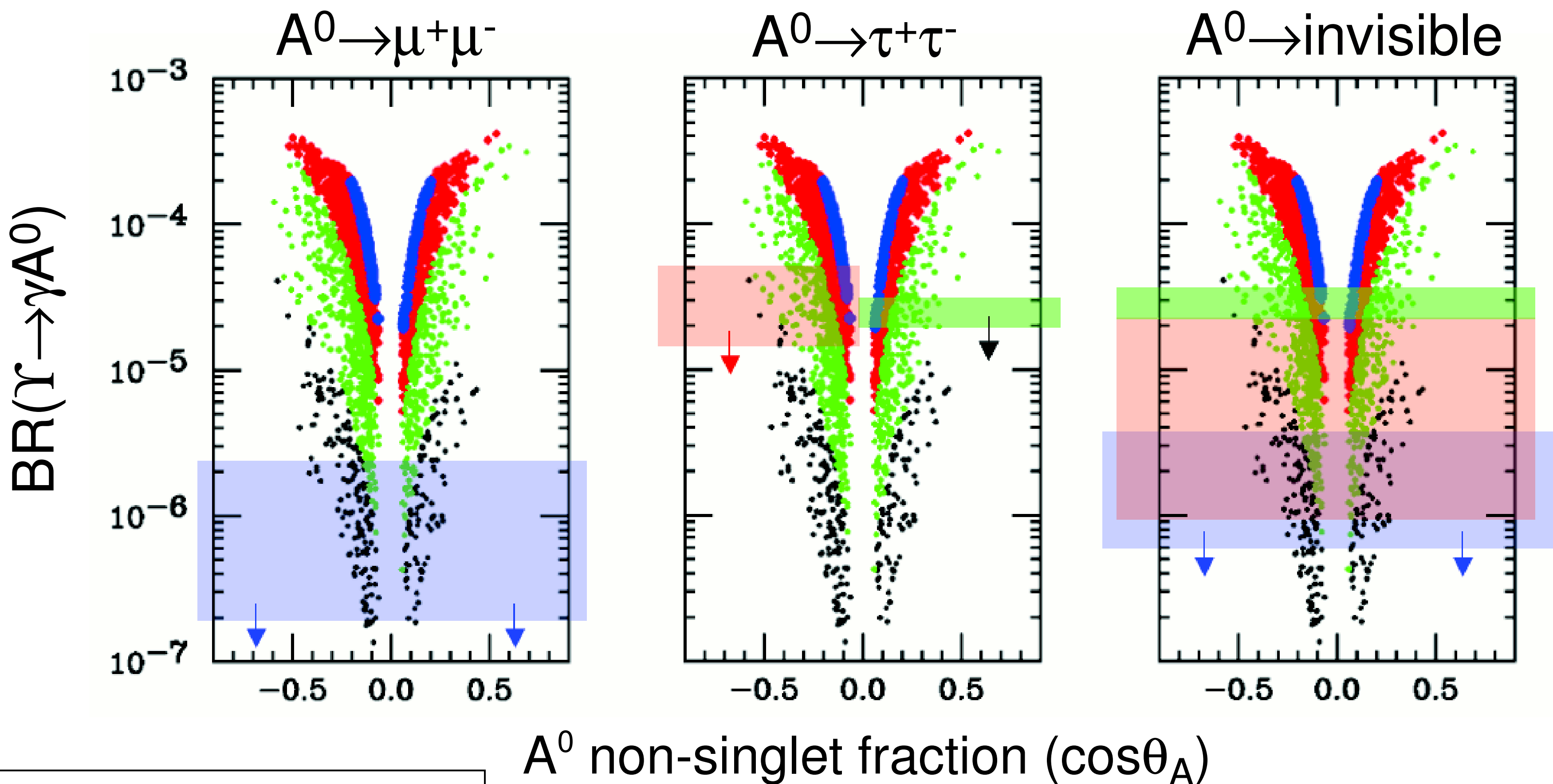
$A^0 \to$ invisible

- $A^0 \to \chi\chi$ dominant in some NMSSM scenarios with light χ LSP
- Signature: single photon recoiling against invisibly decaying particle $\to$ search for peak in E_γ distibution, compute mass recoiling against γ
- No statistically significant signal observed $\to$ set 90% CL UL
- Preliminary results available, finalized results coming this summer



$BF_{TOT} = BF(\Upsilon(3S) \to \gamma A^0) \times BF(A^0 \to \text{invisible}) < (0.7\text{-}31) \times 10^{-6}$
(for $M(A^0)$<7.8 GeV) BaBar arXiv:0808.0017 [hep-ex]

NMSSM Predictions 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

(dots = NMSSM predictions with $\tan\beta=10$, $\mu=150$ GeV, $M_{1,2,3}=100,200,300$ GeV)

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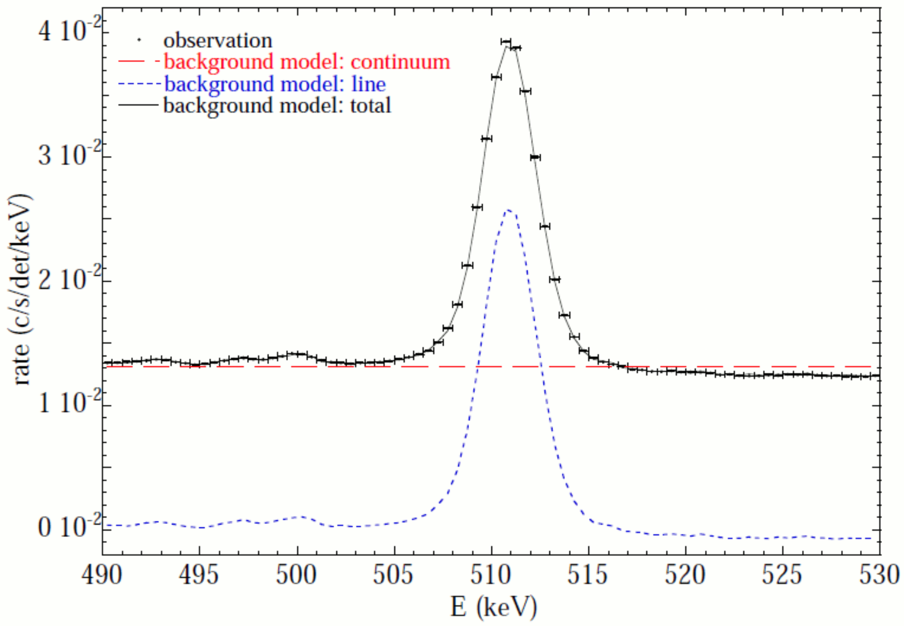
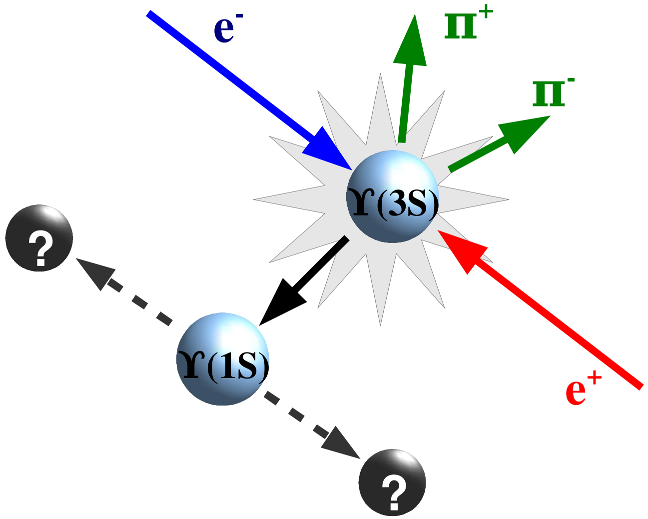
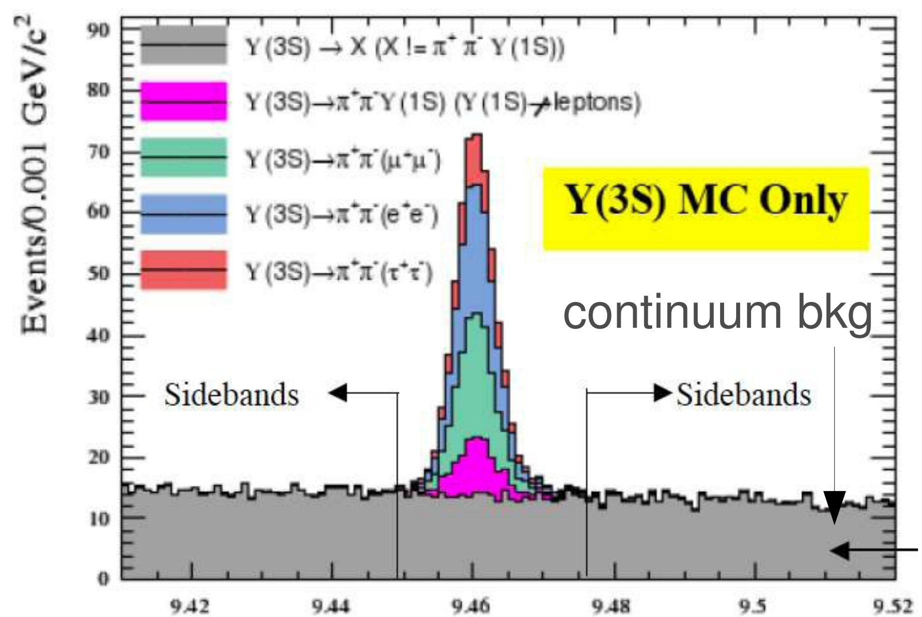
Motivation for Low-Mass DM

- DM may consist of several components
  - Low-mass component not ruled out
  - Difficult/impossible to detect at LHC or direct detection experiments → probe of low-mass regime at B-factory critical for comprehensive DM program
- INTEGRAL anomaly: observe excess of 511 keV photons from galactic center → positrons annihilating at rest
- Positrons may be produced by low-mass DM annihilation (PRL 92, 101301 2004)
- May be observed in Υ decays with BF($\Upsilon(1S)\rightarrow\chi\chi$) up to (4-18)$\times10^{-6}$ (arXiv:0712.0016v2 [hep-ph])



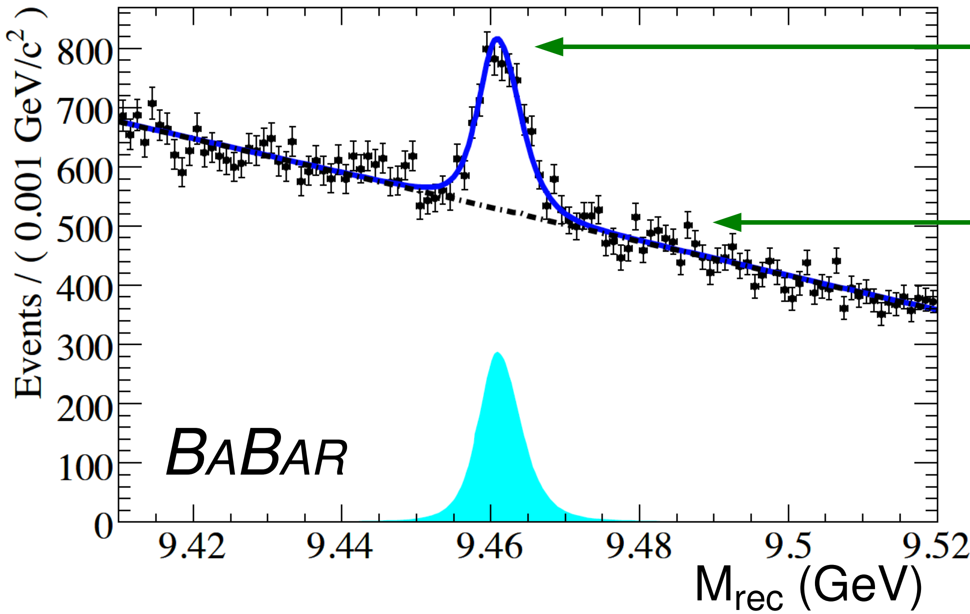




$M^2_{rec} = s + M^2_{\pi\pi} - 2\sqrt{s}\,E^*_{\pi\pi}$ (GeV/c²)

- Search for $\Upsilon(3S)\rightarrow\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(1S)\rightarrow\chi\chi$
- Identify $\Upsilon(3S)\rightarrow\Upsilon(1S)$ transition by requiring $\pi^+\pi^-$ recoil mass ~ $M(\Upsilon(1S))$
- SM BF($\Upsilon(1S)\rightarrow\nu\bar{\nu}$)~$10^{-5}$, BF($\Upsilon(1S)\rightarrow\chi\chi$) up to 10^{-4}-10^{-3}
- Require no significant additional activity in detector
- Continuum + peaking bkg ($\Upsilon(1S)$ decays to particles outside detector acceptance)

Signal Extraction and Results



signal/peaking bkg PDF from "visible" $\Upsilon(1S)$ sample

combinatorial bkg PDF from sideband data

Fit yield: 2326 $\pm$ 105
Bkg pred: 2444 $\pm$ 123
Signal: -118 $\pm$ 105 $\pm$ 24

- Use multivariate classifier to reduce non-peaking background (train on sideband data and signal MC)
- Perform maximum likelihood fit to recoil mass distribution
- Predict peaking background from MC, use data control samples ($\pi^+\pi^-$ + 1 track, $\pi^+\pi^-$ + 2 tracks) to validate/correct prediction
- Observed yield consistent with expected peaking background

BF($\Upsilon(1S)\rightarrow$invisible) = (-1.6$\pm$1.4(stat)$\pm$1.6(syst)) $\times 10^{-4} < 3.0 \times 10^{-4}$ at 90% CL
BaBar PRL 103, 251801 (2009) ~10$\times$ improvement over prior UL

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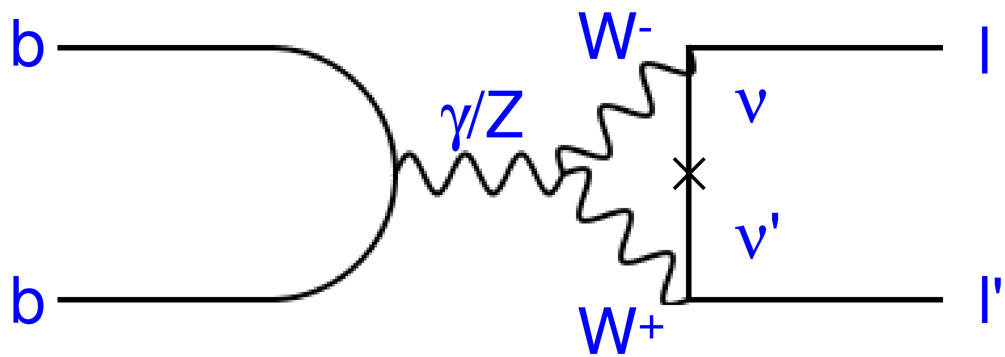
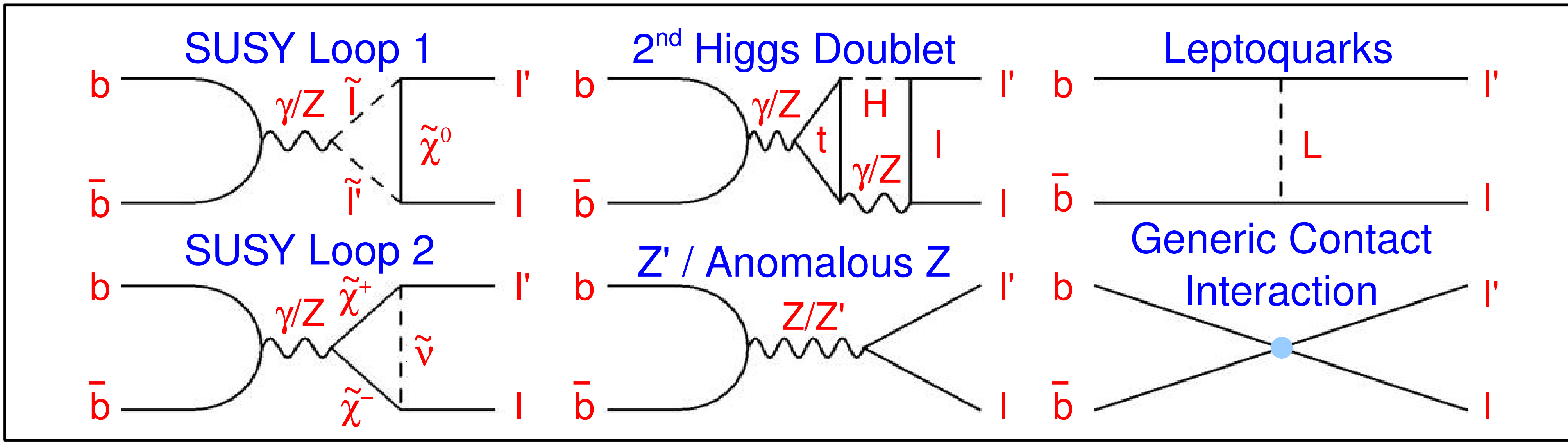
Introduction to Lepton Flavor Violation



$BF(\Upsilon \to ll') \sim ((\Delta m_\nu)^2/M_W^2)^2 < O(10^{-48})$

- Lepton flavor is conserved in SM with massless neutrinos
- $m_\nu \neq 0 \to$ neutrinos oscillate between flavors $\to$ neutral LFV
- Even with neutrino masses added to SM, charged LFV (CLFV) processes are suppressed by $((\Delta m_\nu)^2/M_W^2)^2 \to$ unobservable
- **Observation of CLFV$\to$ unambiguous signal of new physics**

CLFV in BSM Scenarios

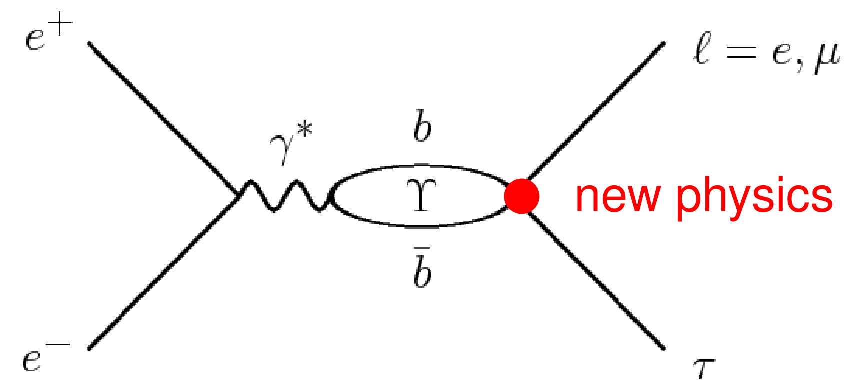


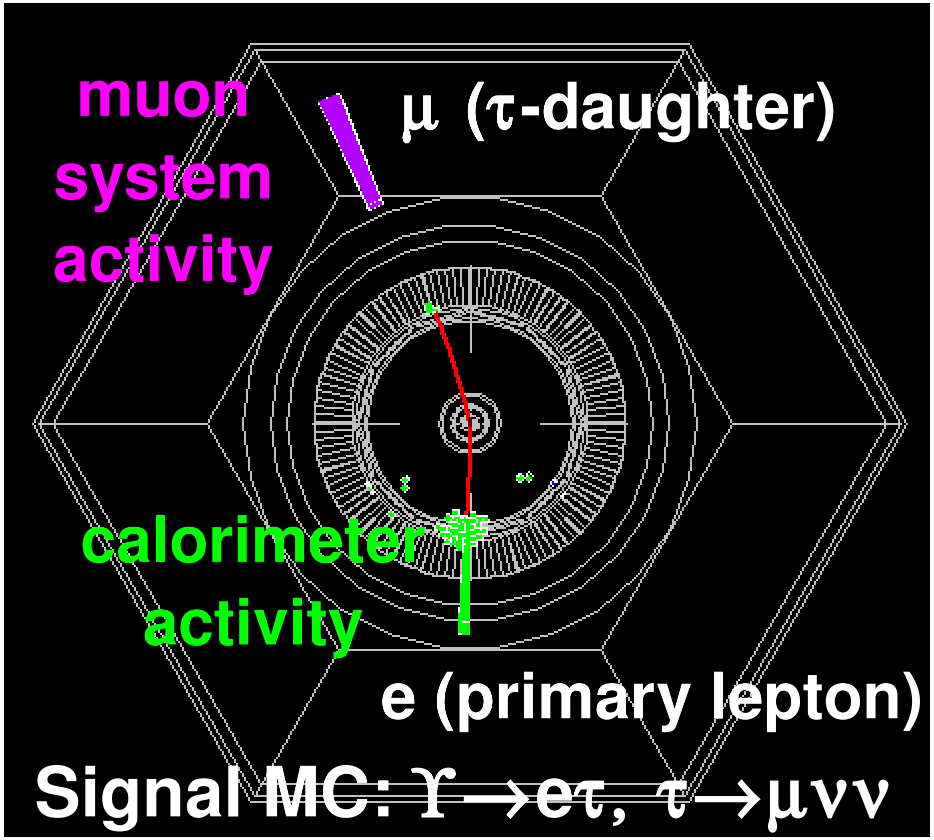
- Many BSM mechanisms for LFV ϒ decays
- Process probes TeV-scale physics at $E_{CM} = O(10\ \text{GeV})$
- Large dataset $O(10^8)$ ϒ(2S), ϒ(3S) decays decays offer significant improvement w.r.t. prior ULs: BF(ϒ(2S/3S)→μτ) = $O(10^{-5})$ (CLEO PRL 101, 201601 2008)
- Results 1000 more sensitive than indirect constraints from CLFV τ-decays (see slide 47)

Signal Signatures and Channels

- **Signal: $e^+e^- \rightarrow \Upsilon(2S/3S) \rightarrow e\tau/\mu\tau$**
- Signature:
  - Primary lepton (e or μ) with close to full beam energy + τ decay in other hemisphere
  - τ required to decay to single charged particle ($e,\mu,\pi^{\pm}$) + possible additional π^0's
  - Define 4 signal channels:

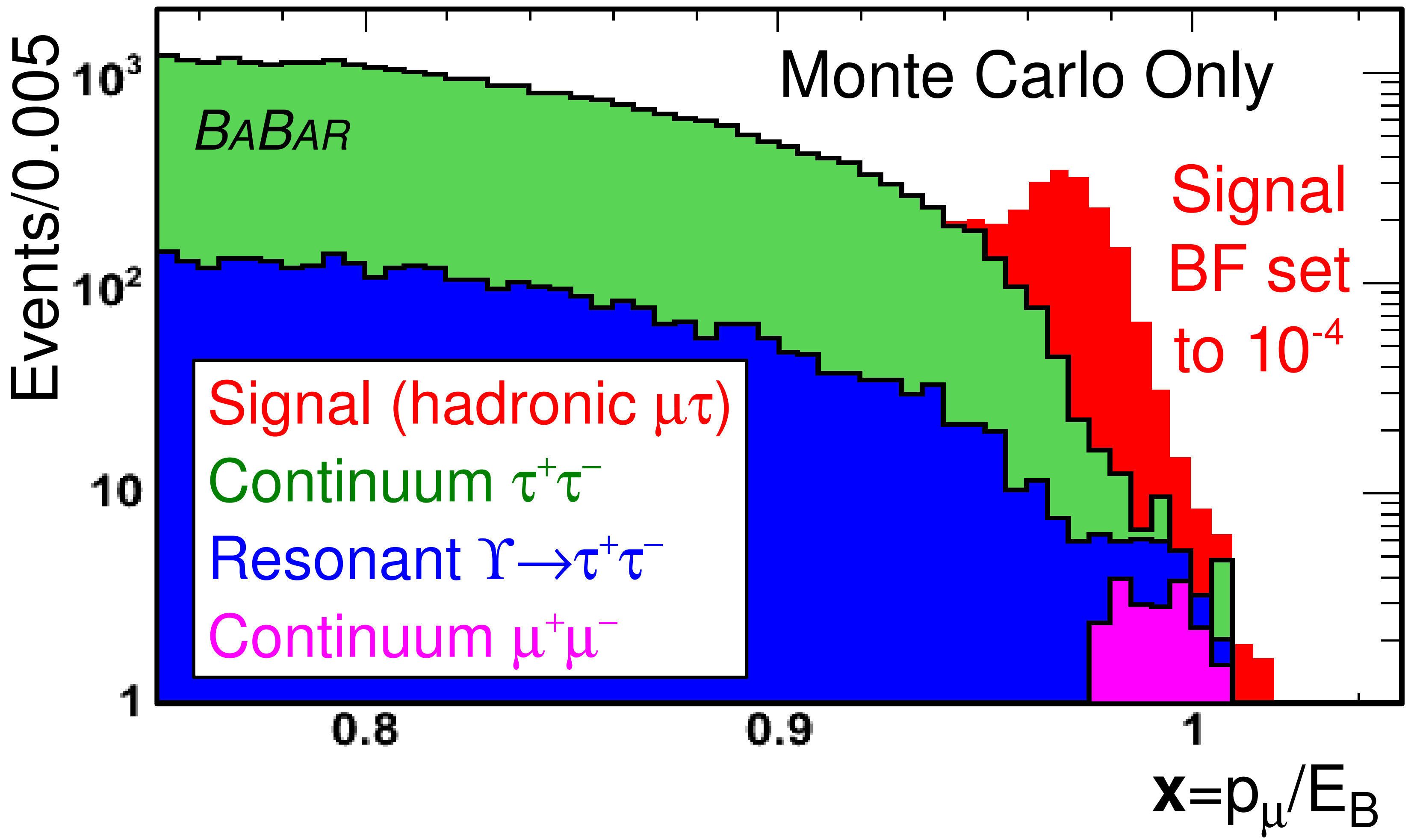
Process	τ Decay	Channel
$\Upsilon(3S)\rightarrow e\tau$	$\tau\rightarrow\mu\nu\nu$	leptonic $e\tau$
$\Upsilon(3S)\rightarrow e\tau$	$\tau\rightarrow\pi^{\pm}\pi^0\nu/\pi^{\pm}\pi^0\pi^0\nu$	hadronic $e\tau$
$\Upsilon(3S)\rightarrow \mu\tau$	$\tau\rightarrow e\nu\nu$	leptonic $\mu\tau$
$\Upsilon(3S)\rightarrow \mu\tau$	$\tau\rightarrow\pi^{\pm}\pi^0\nu/\pi^{\pm}\pi^0\pi^0\nu$	hadronic $\mu\tau$





Signal vs. Backgrounds

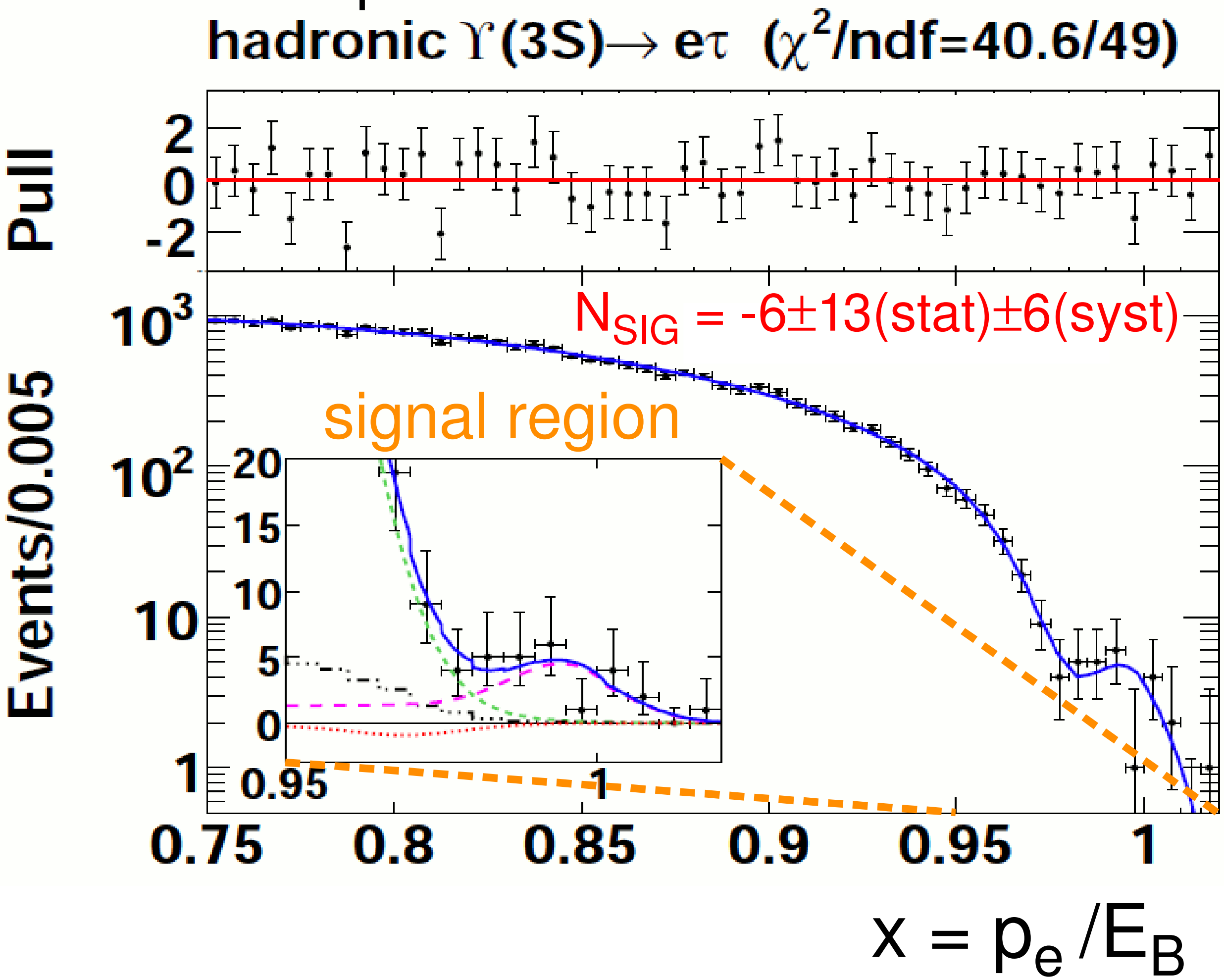
Discriminant variable **x** = primary lepton CM momentum / beam energy



Perform maximum likelihood fit to x distribution for 4 signal channels

Maximum Likelihood Fit Strategy

example fit:



Global PDF

Signal: Gaussian core + non-Gaussian tails

τ-pair Bkg: poly ⊕ Gaussian detector resolution function

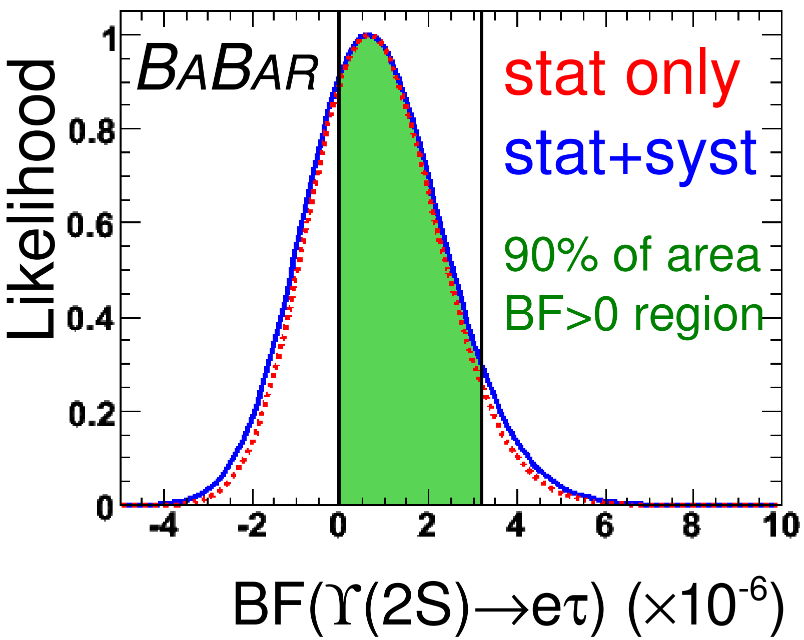
Bhabha/μ-pair Bkg: Gaussian + threshold function

π-hadron Bkg

Results

- All channels: signal yields consistent with zero within 1.8σ
- Perform Bayesian likelihood technique to extract 90% CL upper limits O(10^{-6}) on CLFV Υ decay BFs

Example Likelihood Scan



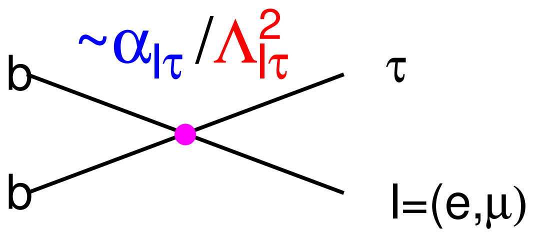
improvement factor over prior UL

	$\mathcal{B}\ (10^{-6})$	UL (10^{-6})	
$\mathcal{B}(\Upsilon(2S) \to e^{\pm}\tau^{\mp})$	$0.6^{+1.5+0.5}_{-1.4-0.6}$	< 3.2	First!
$\mathcal{B}(\Upsilon(2S) \to \mu^{\pm}\tau^{\mp})$	$0.2^{+1.5+1.0}_{-1.3-1.2}$	< 3.3	3.7
$\mathcal{B}(\Upsilon(3S) \to e^{\pm}\tau^{\mp})$	$1.8^{+1.7+0.8}_{-1.4-0.7}$	< 4.2	First!
$\mathcal{B}(\Upsilon(3S) \to \mu^{\pm}\tau^{\mp})$	$-0.8^{+1.5+1.4}_{-1.5-1.3}$	< 3.1	5.5

BaBar PRL 104, 151802 2010

Constraints on New Physics

CLFV Υ decays: bblτ contact interaction with NP coupling constant and mass scale

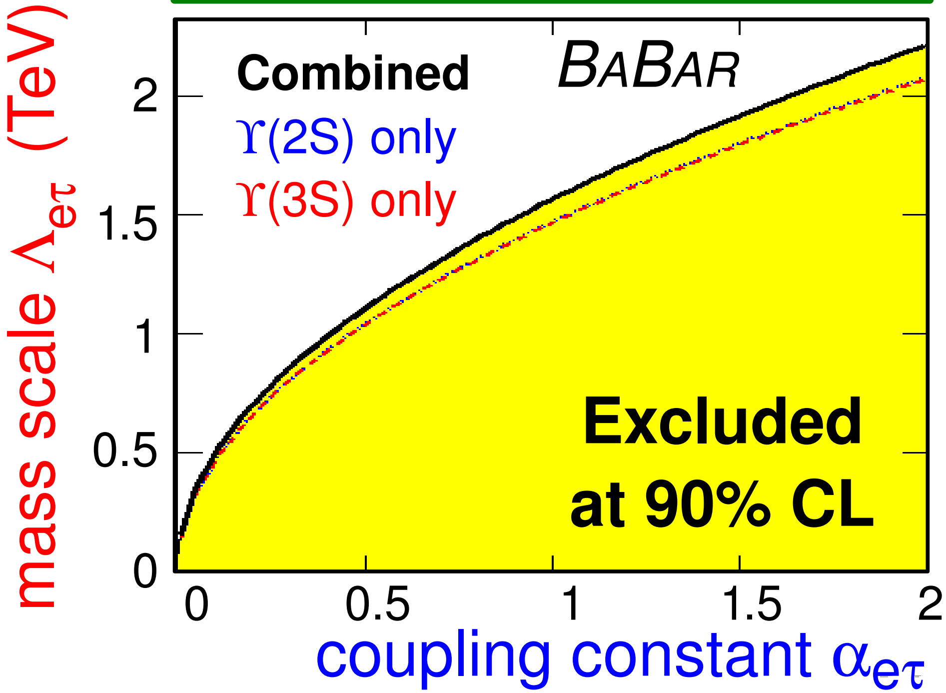


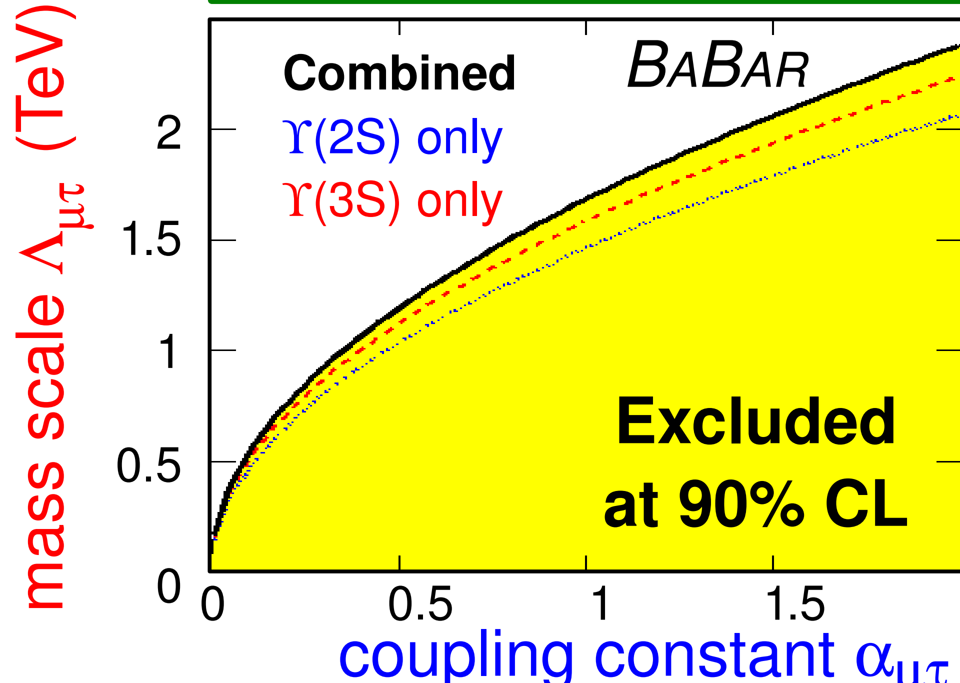
$$\frac{\alpha_{l\tau}^2}{\Lambda_{l\tau}^4} = \frac{BF(\Upsilon(3S)\to l\tau)}{BF(\Upsilon(3S)\to ll)} \frac{2q_b\alpha^2}{(M_{\Upsilon(nS)})^4} \qquad l = (e,\mu)$$

Silagadze Phys. Scripta 64.128 & Black et al. PRD 66.053002

$\alpha_{e\tau} = 1 \to \Lambda_{e\tau} > 1.6$ TeV

$\alpha_{\mu\tau} = 1 \to \Lambda_{\mu\tau} > 1.7$ TeV



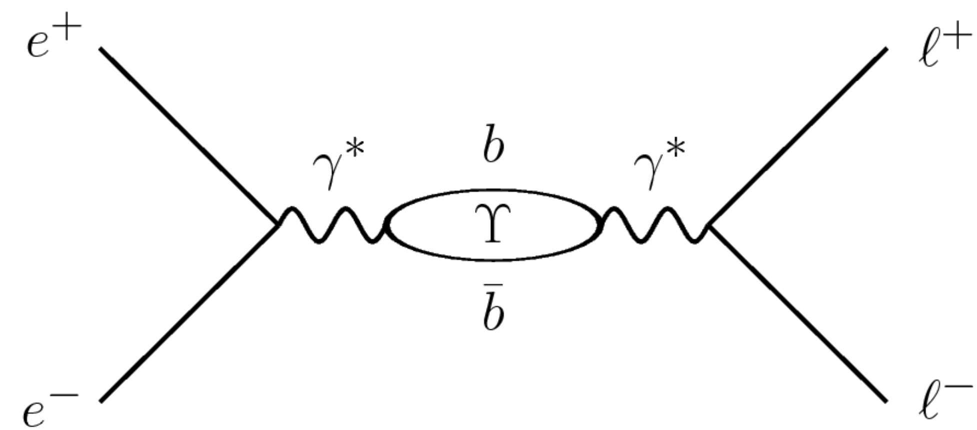


Outline

- Introduction
- Search for Light Higgs
  - $A^0 \to \mu^+\mu^-$
  - $A^0 \to \tau^+\tau^-$
  - $A^0 \to$invisible
- Search for Light Dark Matter
- Search for Lepton Flavor Violation
- **Test of Lepton Universality**

Introduction to Lepton Universality

- SM couplings of gauge bosons to leptons independent of lepton flavor $\rightarrow$ check by comparing BF(Υ(1S)$\rightarrow\tau^+\tau^-$) vs. BF(Υ(1S)$\rightarrow\mu^+\mu^-$)

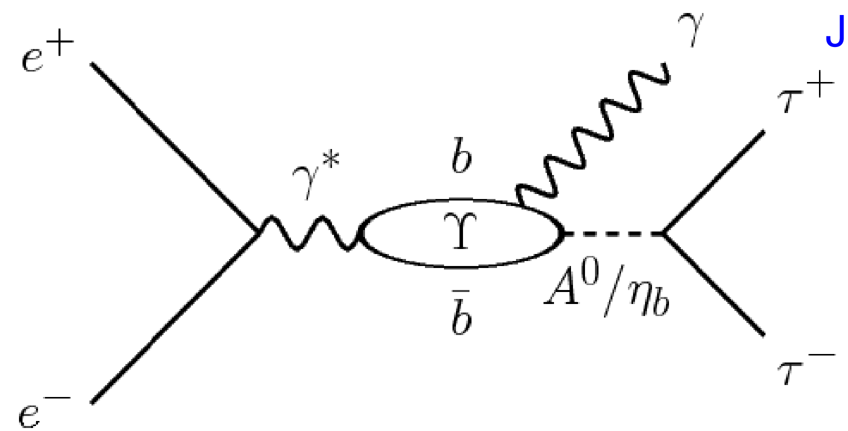


$$\Gamma(\Upsilon \rightarrow l\,l) = 4\,\alpha_{EM}^2 Q_b^2 \frac{|R_n(0)|^2}{M_\Upsilon^2}\left(1+2\frac{M_l^2}{M_\Upsilon^2}\right)\sqrt{1-4\frac{M_l^2}{M_\Upsilon^2}}$$

- SM prediction: $R_{\tau\mu}$(Υ(1S)) = Γ(Υ(1S)$\rightarrow\tau^+\tau^-$) / Γ(Υ(1S)$\rightarrow\mu^+\mu^-$) $\approx$ 1
  - $R_{\tau\mu}$ (Υ(1S))= 0.992 due to lepton mass effects

Introduction to Lepton Universality

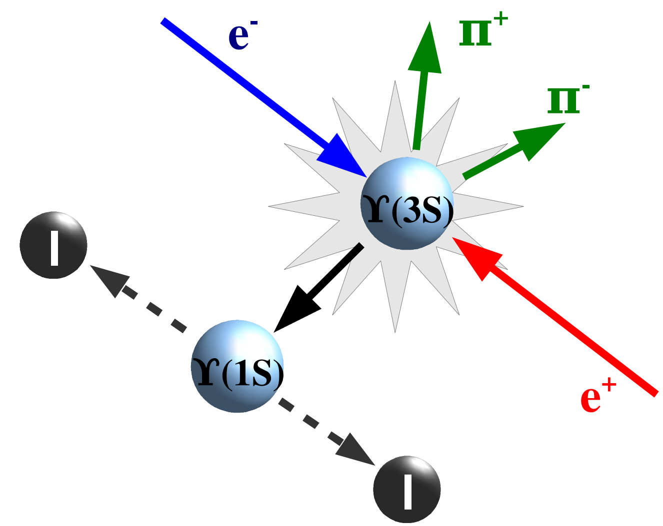
JHEP 0901, 061 (2009)
PL B653, 67 (2007)



$\Upsilon(1S)\rightarrow\gamma A^0$, $A^0\rightarrow l^+l^-$ OR $\Upsilon(1S)\rightarrow\eta_b(1S)\gamma$, $\eta_b(1S)\rightarrow A^0\rightarrow l^+l^-$

- NMSSM introduces CP-odd Higgs A^0, contributes to $\Upsilon\rightarrow l^+l^-$ (especially to $\Upsilon \rightarrow \tau^+\tau^-$ due to enhanced Higgs coupling)
- γ energetic enough to be detected $\rightarrow$ search for peak in E_γ distribution (as previously discussed)
- γ undetected $\rightarrow$ apparent violation of lepton universality. Effect larger for decays to τ-pairs (up to ~4%) (Int.J.Mod.Phys. A19, 2183 2004)
- Previous result: $R_{\tau\mu}(\Upsilon(1S))$ = 1.02±0.02(stat)±0.05(syst) (CLEO PRL 98, 052002 2007)

Signal Signature

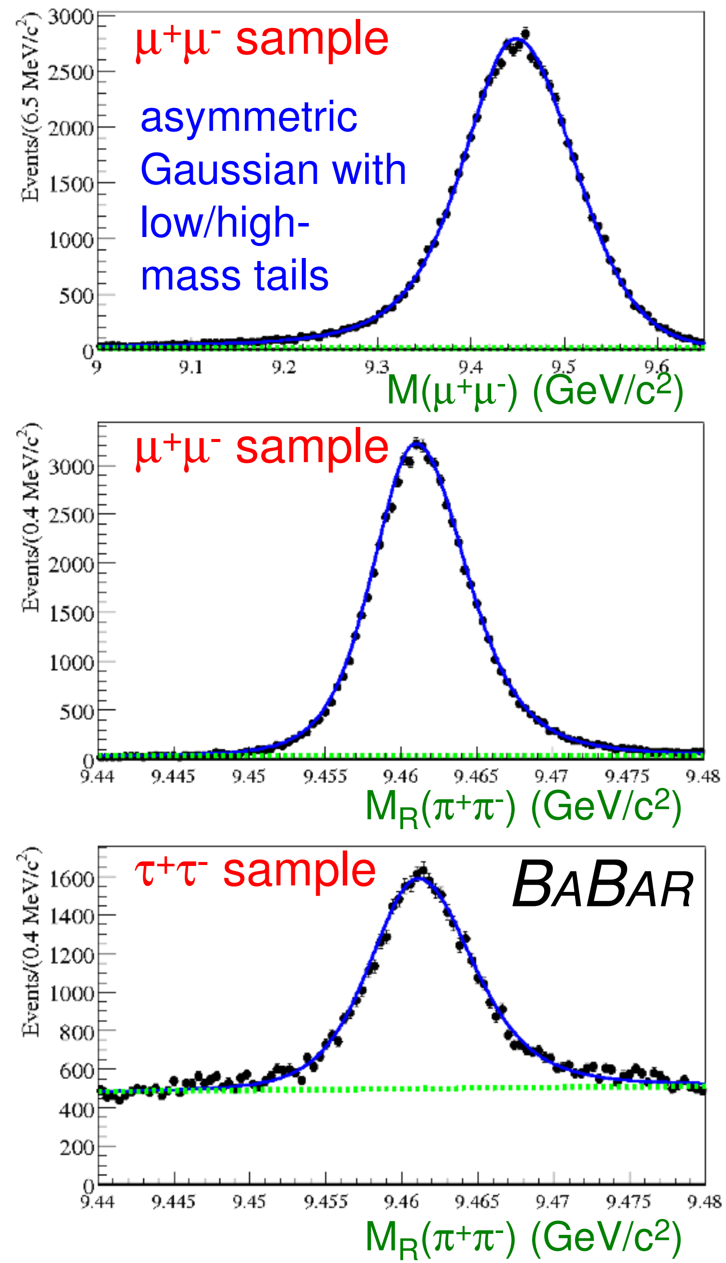


$\Upsilon(3S)\rightarrow\Upsilon(1S)\pi^{+}\pi^{-}$, $\Upsilon(1S)\rightarrow l^{+}l^{-}$ ($l = \mu,\tau$)

- Tag $\Upsilon(3S)\rightarrow\Upsilon(1S)$ dipion transition (BF=5%) to reduce bkg
- Select 1-prong τ decays $\rightarrow$ 4 tracks + any number of photons
- Separate selections for $\mu^{+}\mu^{-}$ vs. $\tau^{+}\tau^{-}$ to reduce bkg ($e^{+}e^{-}\rightarrow\tau^{+}\tau^{-}$ and generic $\Upsilon(1S)$ decays)
  - Tighter selection for $\tau^{+}\tau^{-}$ to reduce additional bkg, including boosted decision tree ($e_{\mu\mu}$=45% vs $e_{\tau\tau}$=17%)

Signal Extraction

- Unbinned, extended ML fit using:
  - $M(\mu^+\mu^-)$ = dimuon invariant mass
  - $M_R(\pi^+\pi^-)$ = mass recoiling against dipion system
- $\mu^+\mu^-$: 2-dimensional likelihood based on $M(\mu^+\mu^-)$, $M_R(\pi^+\pi^-)$
- $\tau^+\tau^-$: 1-dimensional likelihood based on $M_R(\pi^+\pi^-)$
- Perform simultaneous fit to 2 samples to extract $R_{\tau\mu}$



Results

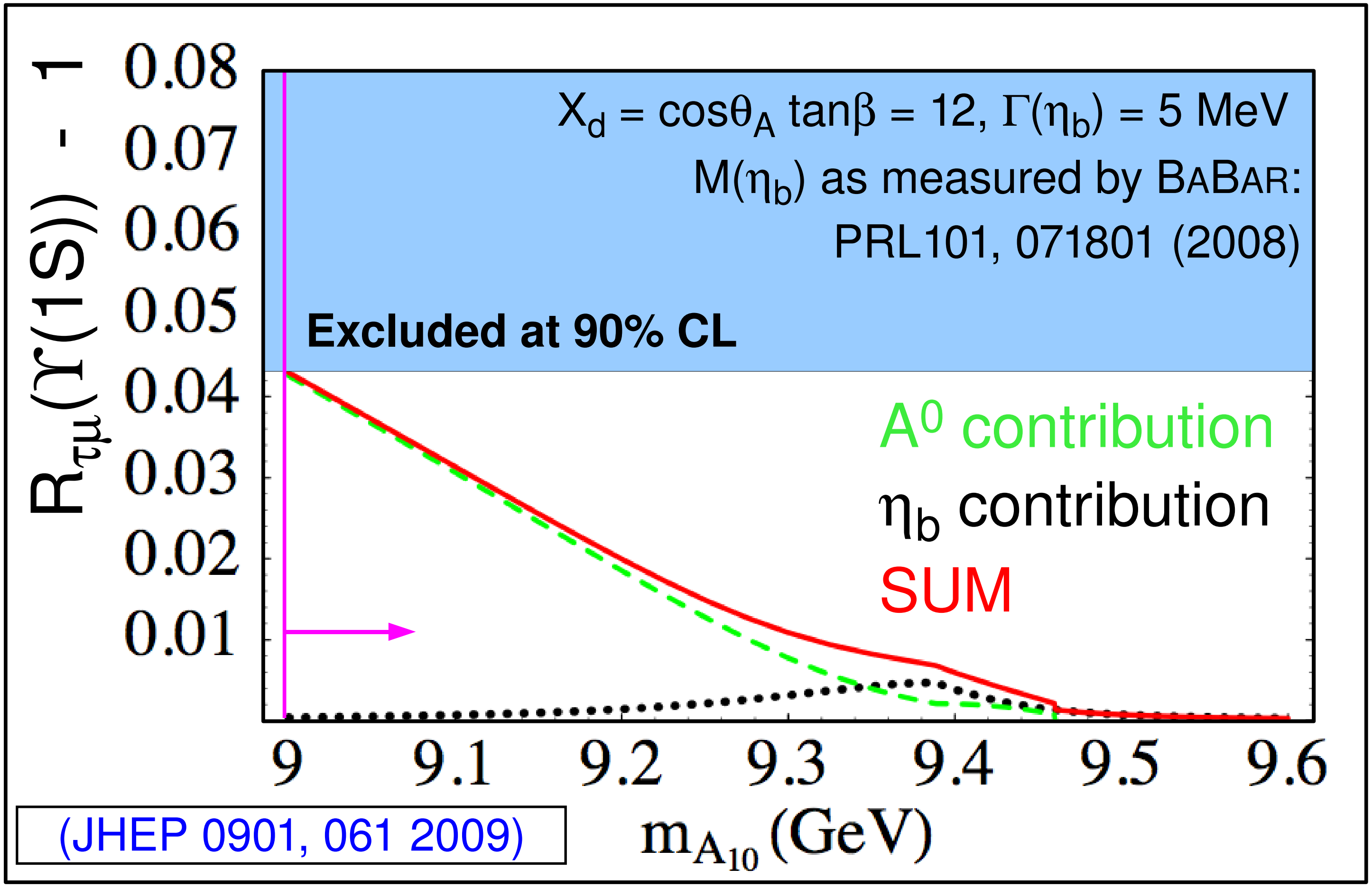
- Systematic uncertainties:
  - Event selection efficiency
  - μ identification efficiency
  - Trigger efficiency
  - Signal & background PDF shapes
  - Peaking background yield from generic $\Upsilon(1S)$ decays

$$R_{\tau\mu}(\Upsilon(1S)) = 1.005 \pm 0.013(\text{stat}) \pm 0.022(\text{syst})$$

(arXiv:1002.4358 [hep-ex] accepted by PRL)

- No deviation w.r.t. to SM ($R_{\tau\mu}$=0.992) observed
- $\times$2 improvement in precision w.r.t. previous result

Constraints on New Physics



Exclude $M(A^0) < 9$ GeV at 90% CL

Conclusions

- $\Upsilon(2S)$ & $\Upsilon(3S)$ data collected by BaBar has yielded many constraints on NP which are complementary to direct searches at higher energy (LHC/TeVatron)
- Light Higgs searches
  - Tightest constraints on decay BF's to date probe region predicted by NMSSM
- Light Dark Matter searches
  - $10\times$ improvement on BF($\Upsilon(1S)\to$invisible)
- Constraints on Lepton Flavor Violation
  - BF upper limits $O(10^{-6})$ probe TeV-scale NP
- Precise Tests of Lepton Universality
  - $2\times$ improvement in precision provides stringent test of SM and improves constraints on A^0 mass

Additional Slides

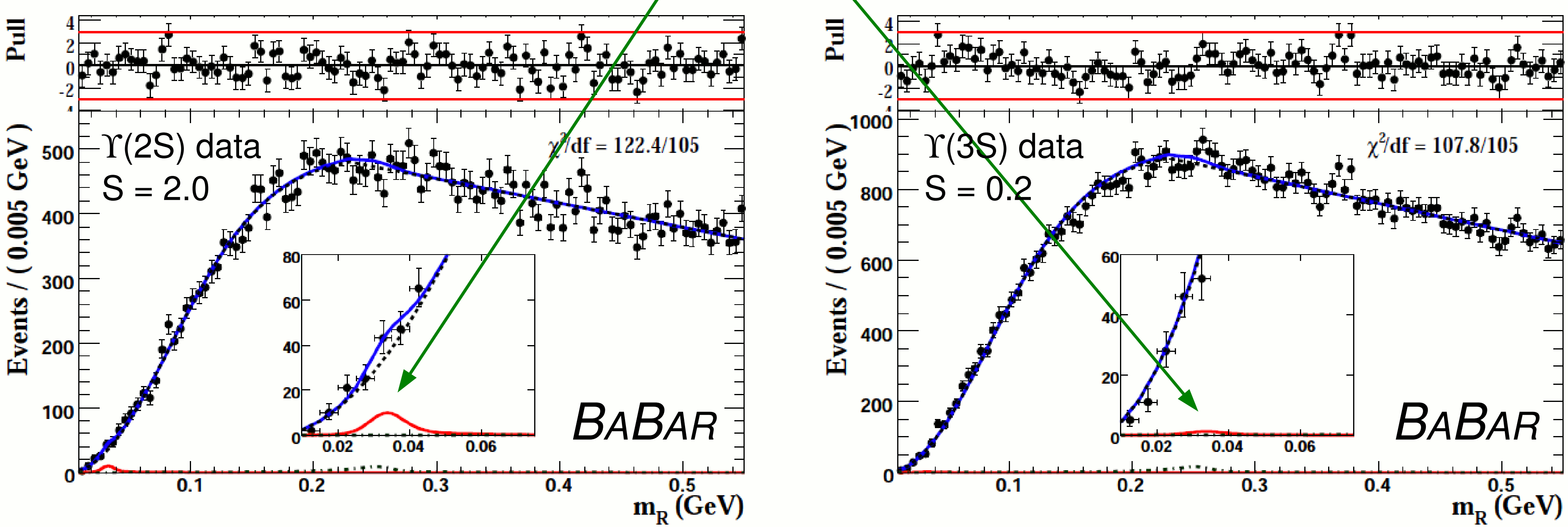
New Physics at BABAR References

- [1] “Search for Dimuon Decays of a Light Scalar Boson in Radiative Transitions $\Upsilon \to \gamma A^0$”
  - Phys. Rev. Lett. 103, 081803 (2009)
- [2] “Search for a Low-Mass Higgs Boson in $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$ at BABAR”
  - Phys. Rev. Lett. 103, 181801 (2009)
- [3] “Search for Invisible Decays of a Light Scalar in Radiative Transitions $\Upsilon(3S) \to A^0$”
  - BABAR-CONF-08/019, SLAC-PUB-13328, arXiv:0808.0017v1 [hep-ex],
- [4] “Search for Invisible Decays of the $\Upsilon(1S)$”
  - Phys. Rev. Lett. 103, 251801 (2009)
- [5] “Search for Charged Lepton Flavor Violation in Narrow Υ Decays”
  - Phys. Rev. Lett. 104:151802 (2010)
- [6] “Test of lepton universality in $\Upsilon(1S)$ decays at BABAR”
  - BABAR-PUB-09/038, SLAC-PUB-14008 arXiv:1002.4358v2 [hep-ex]

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

$M_{A^0} = 214$ MeV/c^2

$m_R = 34$ MeV/c^2



- **No signal observed at M_{A^0}=214 MeV/c^2**
- **$f_\Upsilon^2(M_{A^0}=214\ \text{MeV}/c^2) < 1.6 \times 10^{-6}$ @ 90% CL (assuming $BF(A^0 \to \mu^+\mu^-) = 1$)**

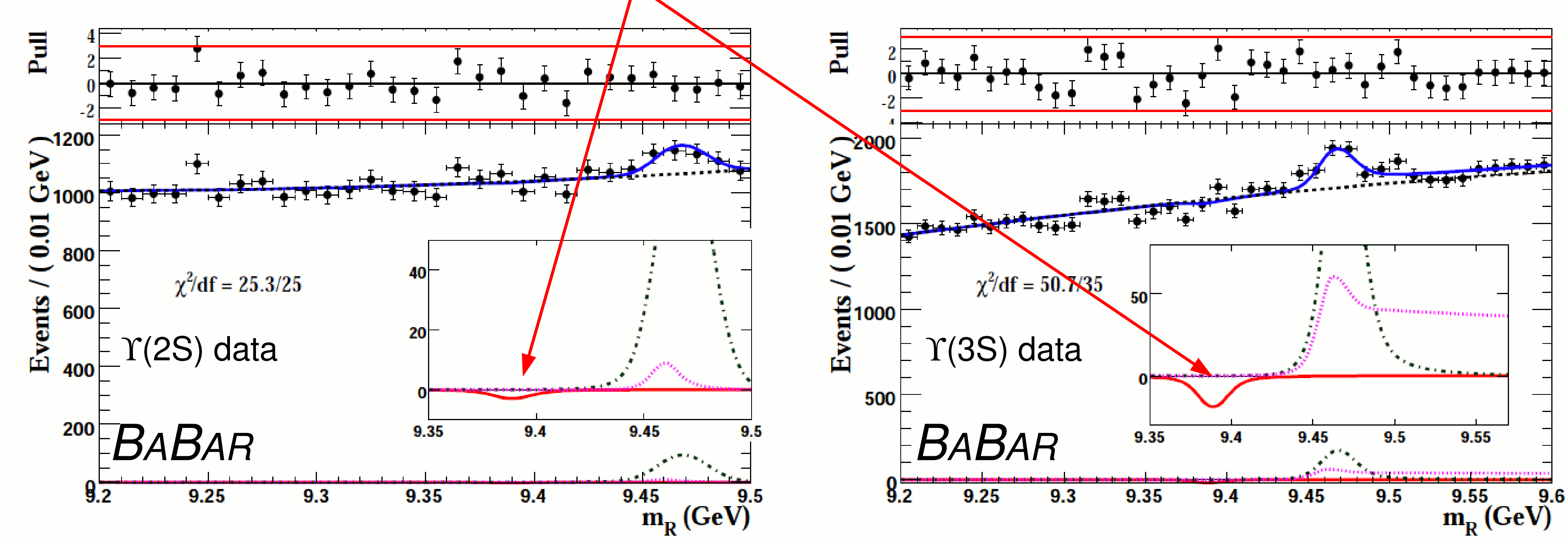
BABAR PRL 103, 081803 2009

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

$e^+e^- \to \gamma_{ISR}\Upsilon(1S)$

$\Upsilon(3S) \to \gamma\chi_b(2P)$, $\chi_b(2P) \to \gamma\Upsilon(1S)$

signal at η_b mass

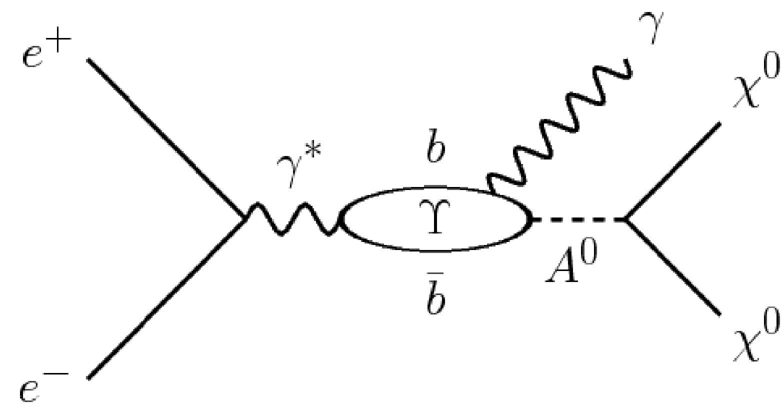


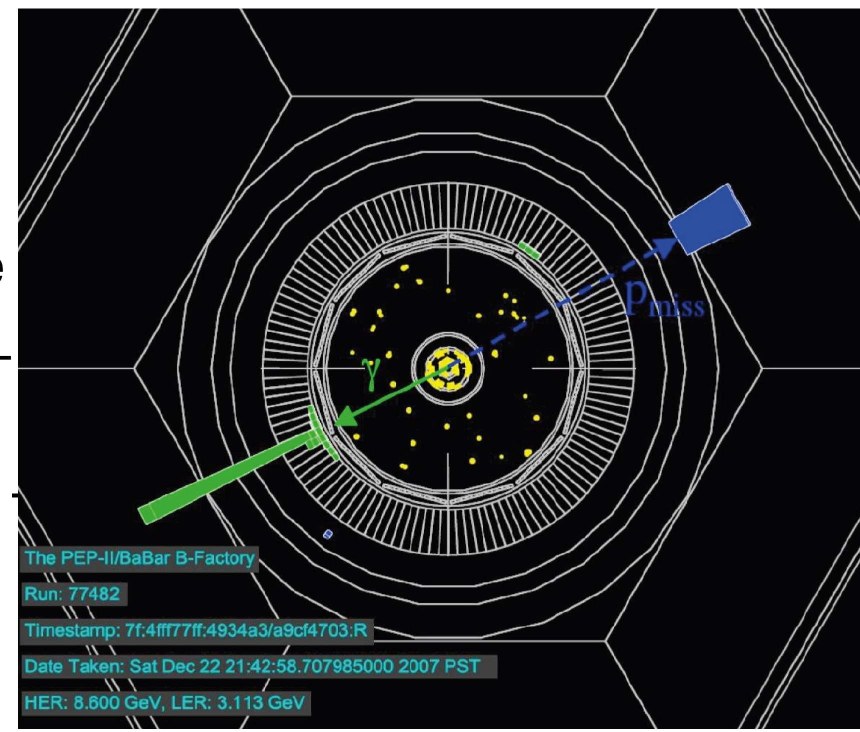
- **No signal observed at $M_{A^0}=M(\eta_b)$**
- **$BF(\eta_b \to \mu^+\mu^-)= (-0.25\pm0.51\pm0.33)\% < 0.9\%$ (at 90% CL)**

BABAR PRL 103, 081803 2009

$A^0 \to$invisible: Signal Signature & Selection

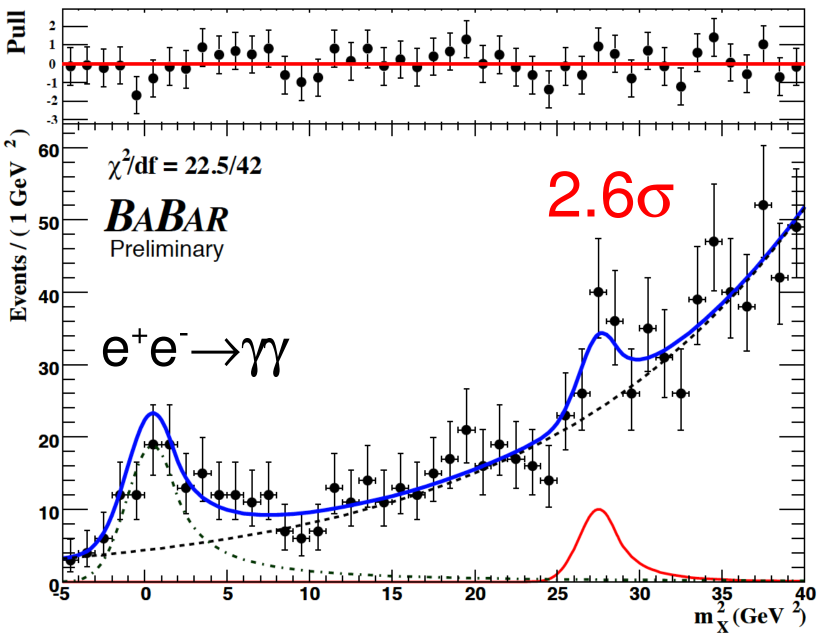
- $A^0 \to \chi\chi$ dominant in some NMSSM scenarios with light χ LSP
- Signal signature: single photon recoiling against invisibly decaying particle
- Search for peak in E_γ distibution, compute mass recoiling against γ
- Selection
  - Photon EMC shower shape, fiducial volume
  - No tracking system / muon system activity + no additional energetic photons
- Backgrounds
  - $e^+e^- \to \gamma\gamma$ (dominant in low $M(A^0)$ region)
  - $e^+e^- \to e^+e^-\gamma$ (dominant in high $M(A^0)$ region)



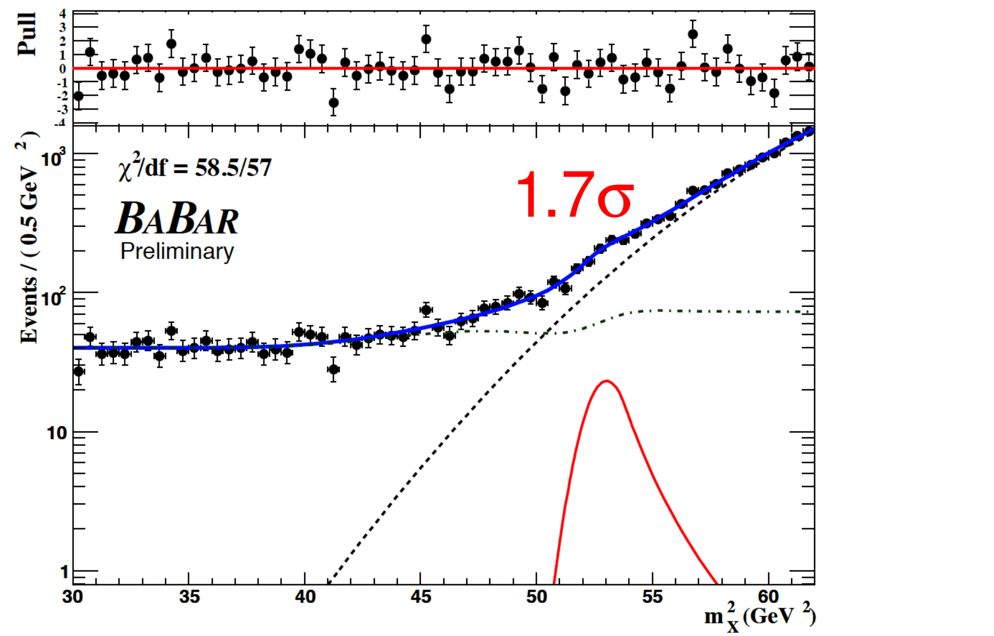


$A^0 \to$invisible Signal Extraction

Low Mass region (sample fit with highest signal significance)

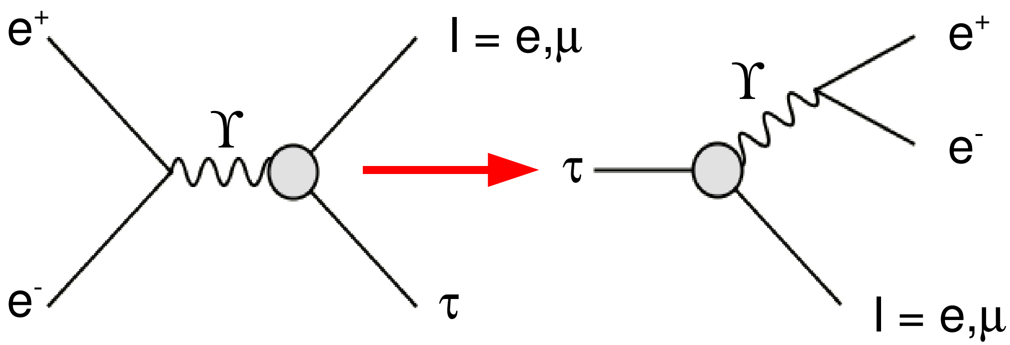


High Mass region (sample fit with highest signal significance)



- Perform ML fits to $m_X^2 = m_{\Upsilon(3S)}^2 - 2E_\gamma^* m_{\Upsilon(3S)}$ dist in steps of $\Delta m_X = 0.1$ GeV
- Signal PDF: Gaussian core with low/high-mass tails
- Smooth backgrounds from $e^+e^- \to e^+e^-\gamma$ and two-pthoton fusion processes

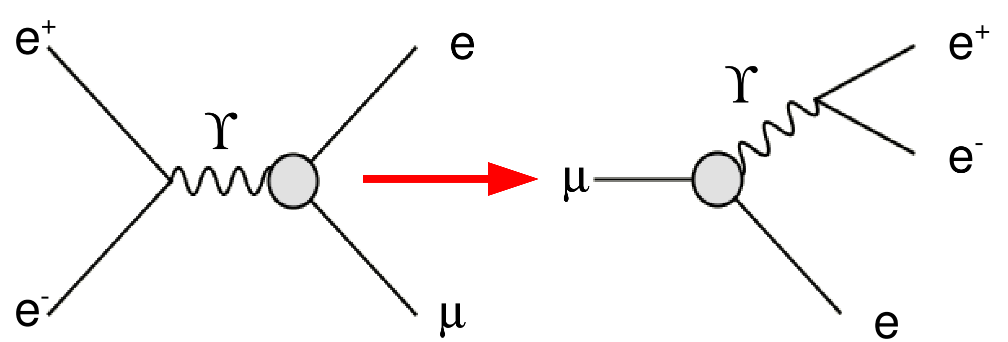
$\Upsilon \to l\tau$ related to $\tau \to lll$ via re-ordering of input/output lines



$$BF(\Upsilon \to l\tau) \le \frac{BF(\tau \to lll)}{BF(\tau \to l\nu\nu)} \left(\frac{\Gamma(W \to l\nu)}{\Gamma(\Upsilon)\Gamma(\Upsilon \to l^+l^-)}\right)^2 (M_\Upsilon / M_W)^6$$

$BF(\tau \to lll) < 4\text{-}8 \times 10^{-8} \to$ **$BF(\Upsilon(3S) \to l\tau) < 3\text{-}6 \times 10^{-3}$**

$\Upsilon \to e\mu$ related to $\mu \to eee$ via re-ordering of input/output lines



$$BF(\Upsilon \to e\mu) \le BF(\mu \to eee) \left(\frac{\Gamma(W \to l\nu)}{\Gamma(\Upsilon)\Gamma(\Upsilon \to l^+l^-)}\right)^2 (M_\Upsilon / M_W)^6$$

$BF(\mu \to eee) < 10^{-12} \to$ **$BF(\Upsilon(3S) \to e\mu) < 10^{-8}$**

Nussinov et al. hep-ph/0004153