Searches for light Higgs / Axions at *BABAR*

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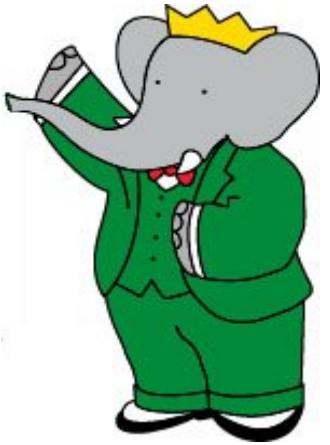
Representing
the *BABAR* Collaboration



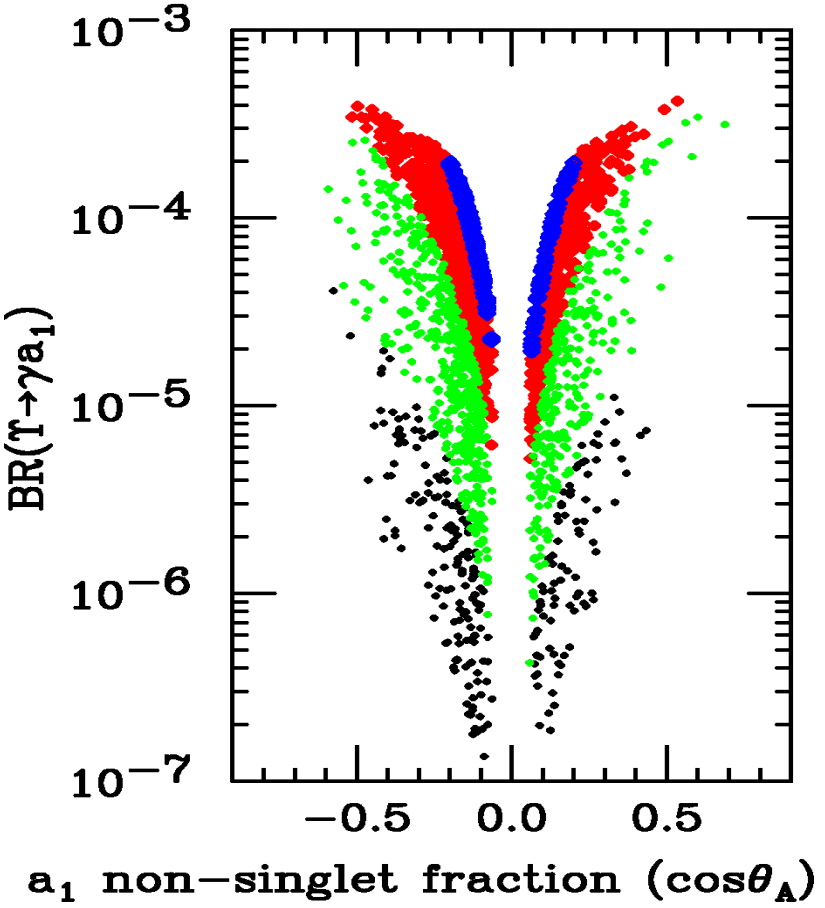
5th Patras Workshop on Axions, WIMPs and WISPs
Durham (UK), 13-17 July 2009

Outline

- Motivations;
- The PEP-II Collider and the BaBar detector;
- Searches for light-Higgs / Axions decaying to:
  - invisible;
  - $\tau^+ \tau^-$;
  - $\mu^+ \mu^-$;
- Tests of Lepton Universality;
- Prospects at a future Super Flavor Factory;
- Summary.

Motivations (1)

- NMSSM proposed to reduce the amount of fine tuning in the MSSM;
- A light CP-odd Higgs A^0, with mass lower than $2m_b$ not constrained by LEP;
- Could also explain the excess of $b\bar{b}$ events seen by LEP at ~100 GeV, if $h \rightarrow A^0A^0$ is dominant;
- It can be seen at $\Upsilon(nS) \rightarrow \gamma A^0$;
- Particularly interesting the region of the η_b (~9.39 GeV).



$m_{A0} < 2m_\tau$

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

$7.5 < m_{A0} < 8.8$ GeV

$8.8 < m_{A0} < 9.2$ GeV

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

Motivations (2)

Y. Nomura, J. Thaler PRD**79**, 075008 (2009)

- Motivated by positron excess seen by PAMELA;
- TeV-scale particle dominantly annihilating into a pseudoscalar axion *a* ;
- Several phenomenological constraints to be taken into account, first of all the absence of an anti-proton excess;
- Also necessary to constrain the decay of a to γ's (and π^0's);
- Model prediction: $m_K - m_\pi < m_a < \sim 800\,\mathrm{MeV}$

with $a \to \mu^+\mu^-$ dominant and

$$\mathrm{BF}(\Upsilon \to \gamma a) \simeq 3 \times 10^{-6} \sin^4\beta (1\,\mathrm{TeV}/f_a)^2$$

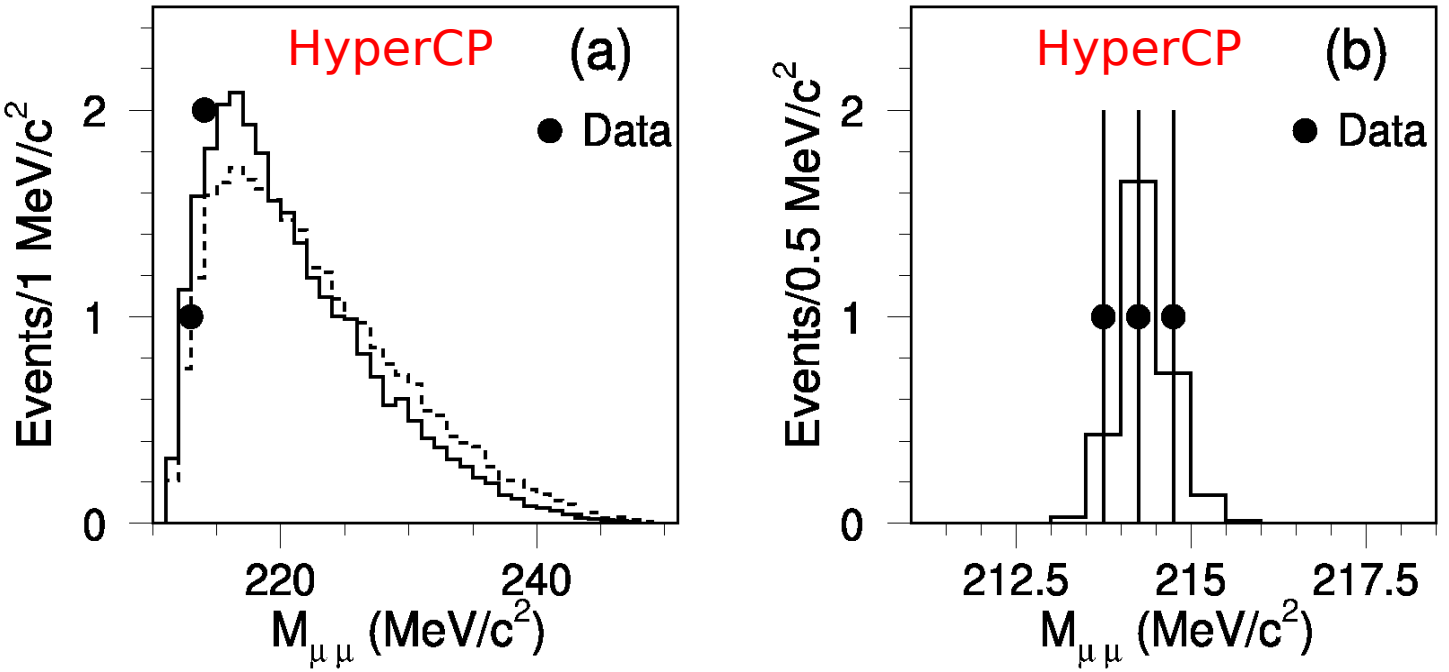
f_a : axion decay constant

Experimental Motivations

- HyperCP experiment at FNAL: evidence for the decay $\Sigma^+ \to p\,\mu^+\mu^-$;
- Found three signal candidates:

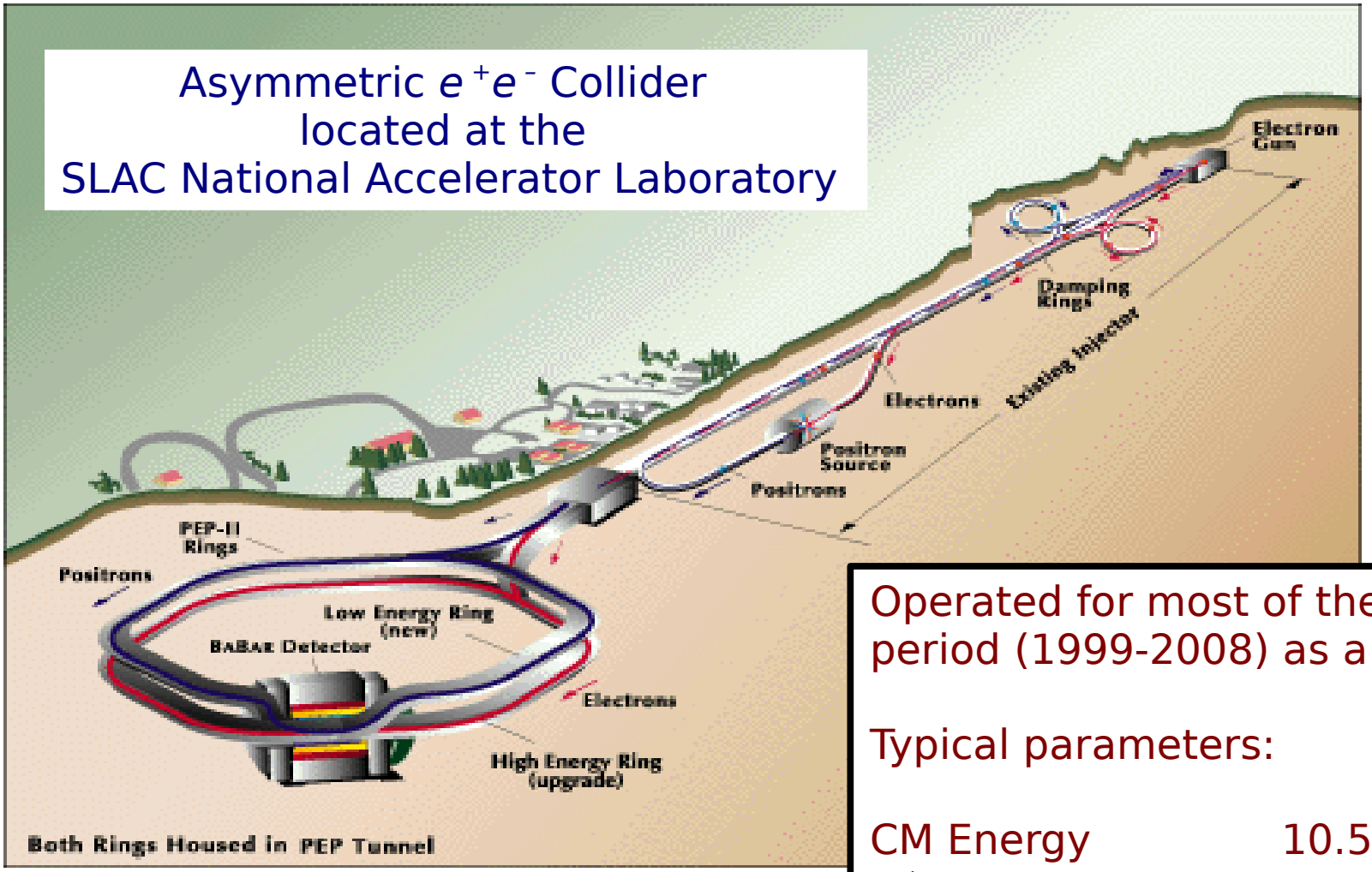
The invariant masses of the muon pairs cluster around 214 MeV

Probability of getting this for a pure phase-space distribution < 1%



- Explained with the existence of a P^0 of mass 214.3 ± 0.5 MeV decaying into muon pairs;

The PEP-II Collider



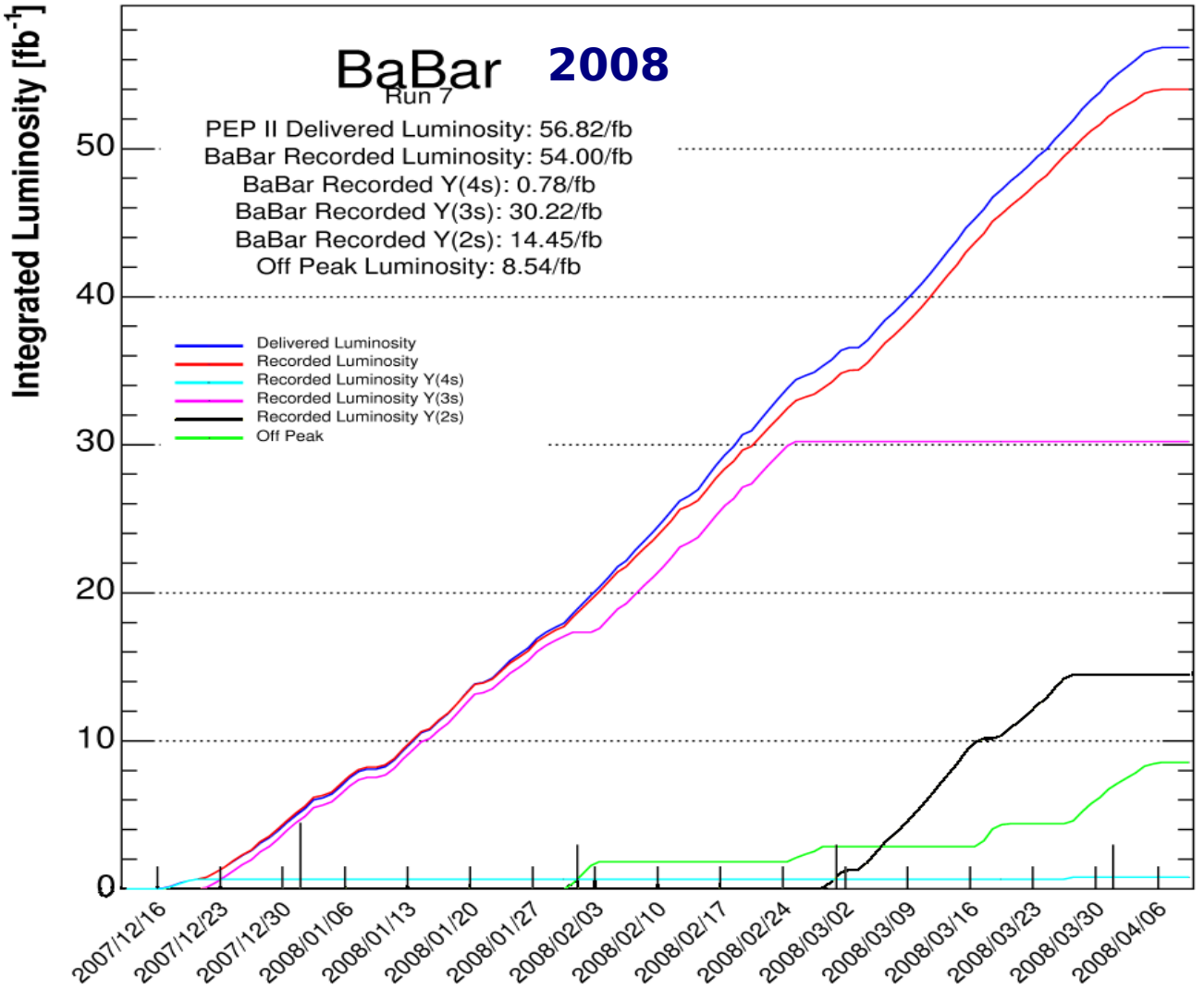
Operated for most of the data-taking period (1999-2008) as a B-factory.

Typical parameters:

CM Energy	10.58 GeV
e^+ Energy	3.1 GeV
e^- Energy	9.0 GeV
Max Luminosity	1.2×10^{34} cm^{-2}s^{-1}

'Special' Datasets

Moved CM Energy to Y(3S), Y(2S) and scan over Y(4S) during the last months of data-taking

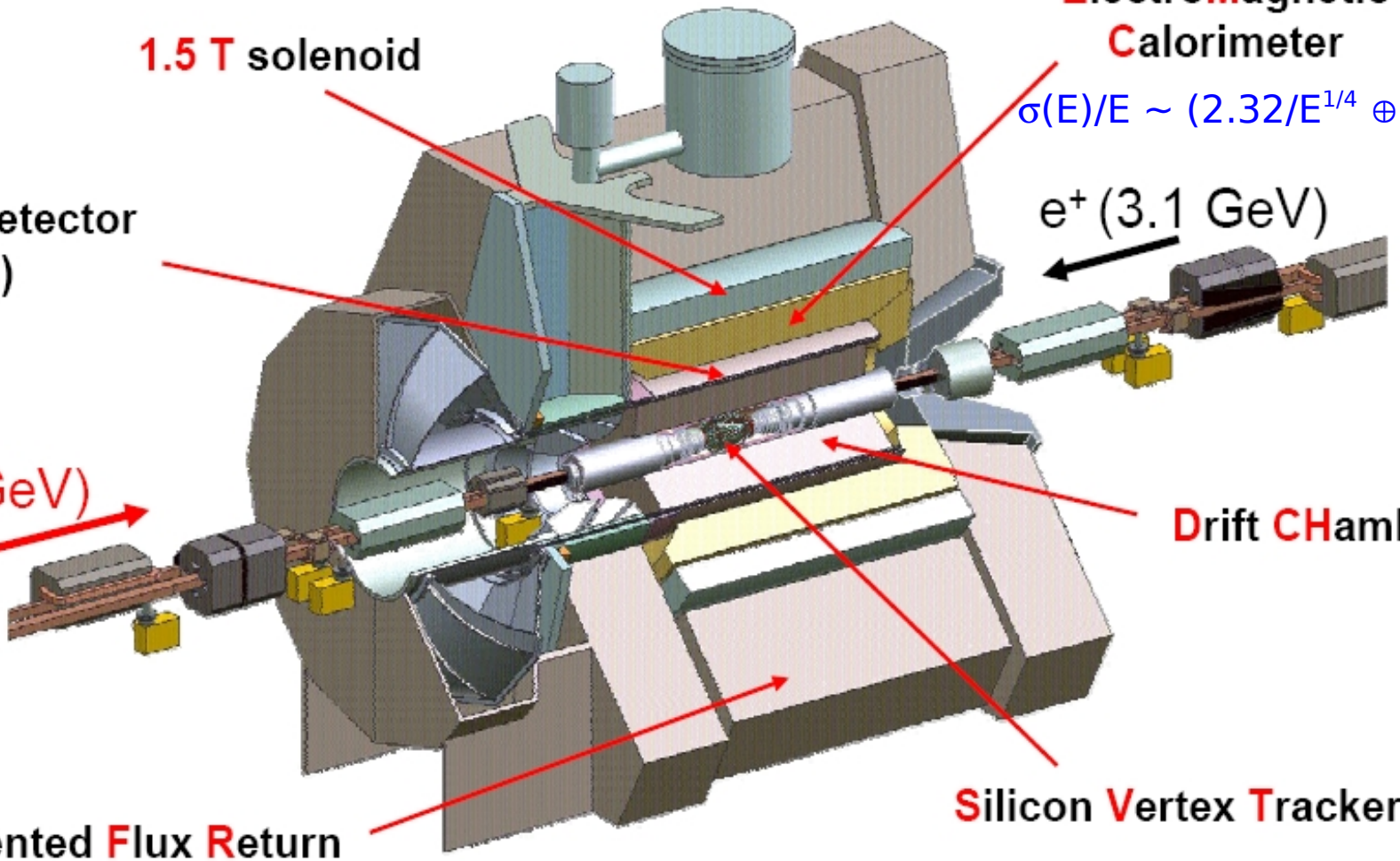


122M Y(3S) decays

99M Y(2S) decays

'Continuum' background studied moving the collision energy away from the resonances

The *BABAR* detector



A^0 to invisible

arXiv:0808.0017 [hep-ex]
presented at ICHEP08

A^0 to invisible - introduction

- Dedicated single-photon trigger for the last period of data-taking;
- Y(3S) sample to search for events:

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

- Scan for peaks in the photon energy (in the CM frame):
- Analysis optimized in two E^*_γ regions:

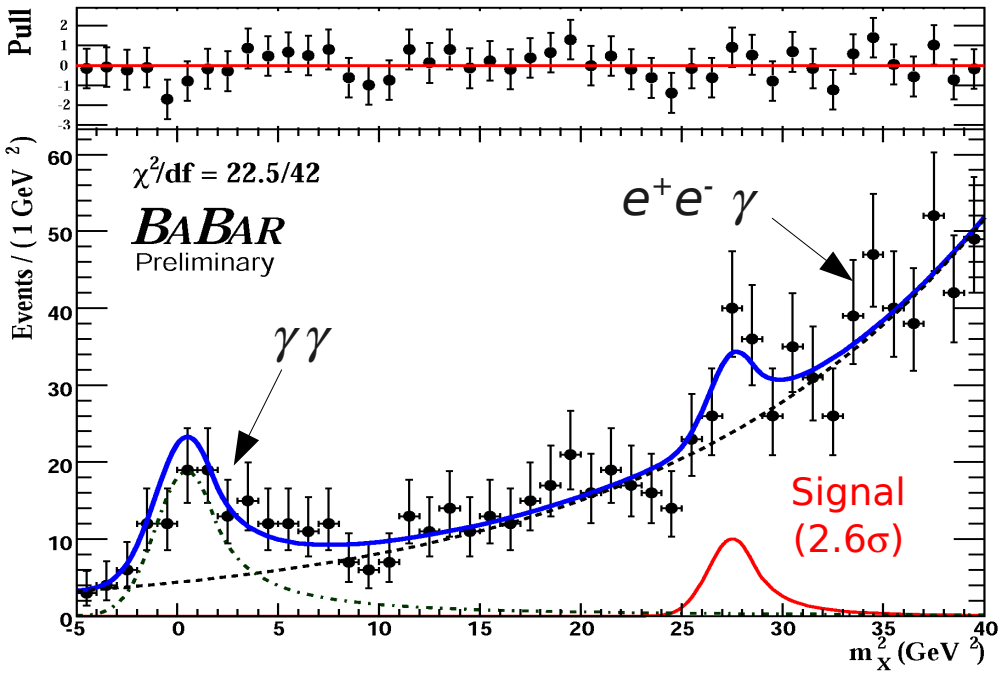
$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$

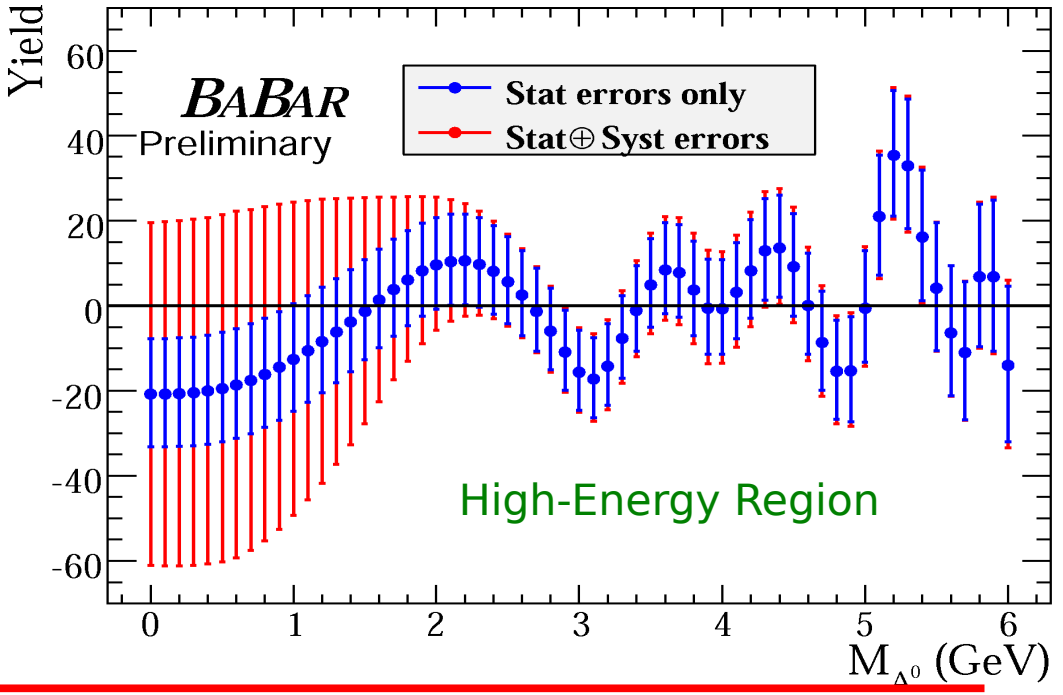
High-Energy Region:
$3.2 < E^*_\gamma < 5.5$ GeV ($0 < m_{A0} < 6$ GeV)
dominant background: $e^+e^- \rightarrow \gamma\gamma$

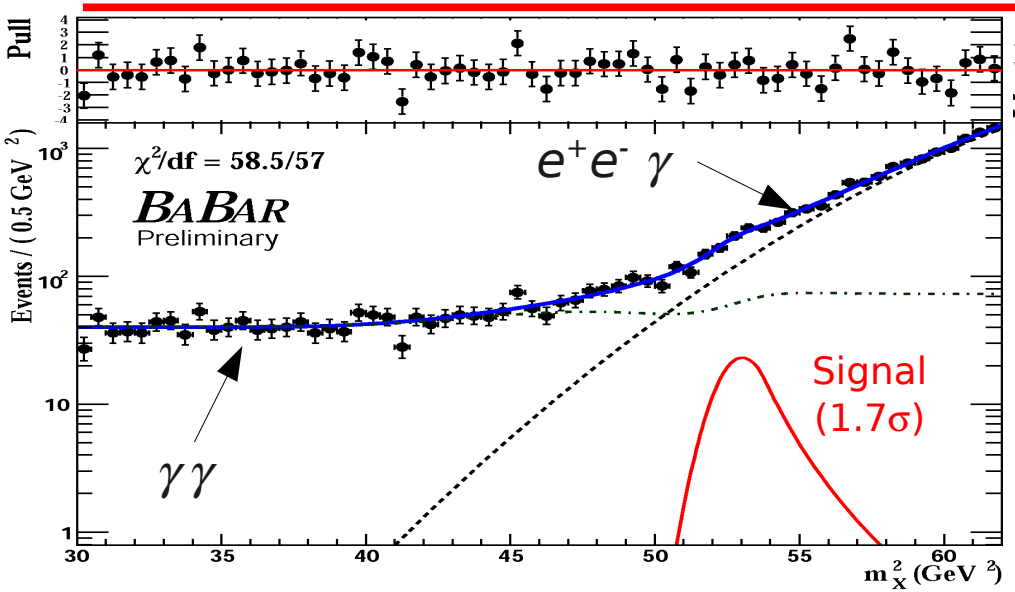
Low-Energy Region:
$2.2 < E^*_\gamma < 3.7$ GeV ($6 < m_{A0} < 7.8$ GeV)
dominant background: $e^+e^- \rightarrow e^+e^-\gamma$

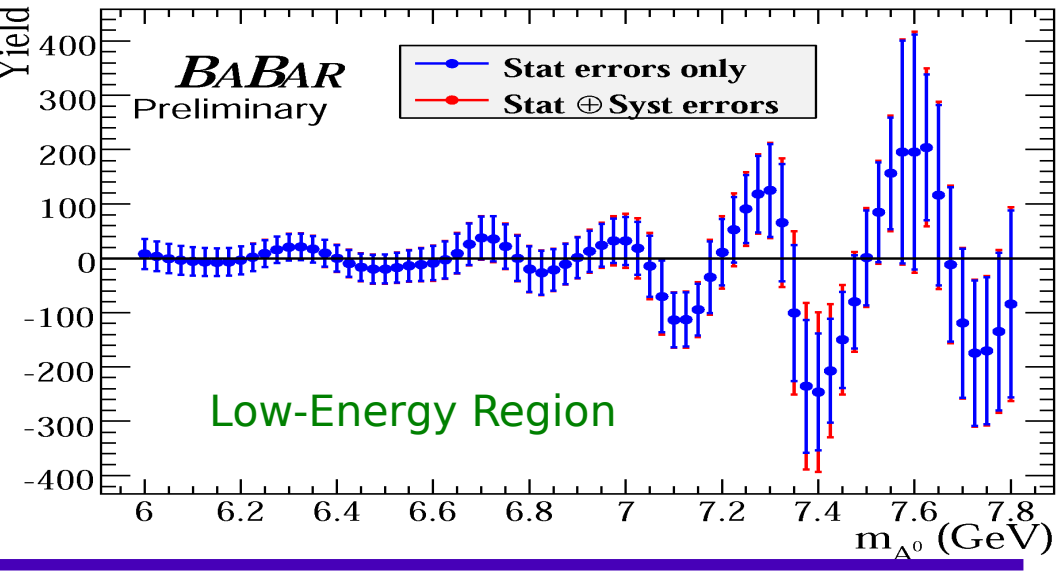
Backgrounds reduced by refining selection of the photon candidate.

A^0 to invisible - fit

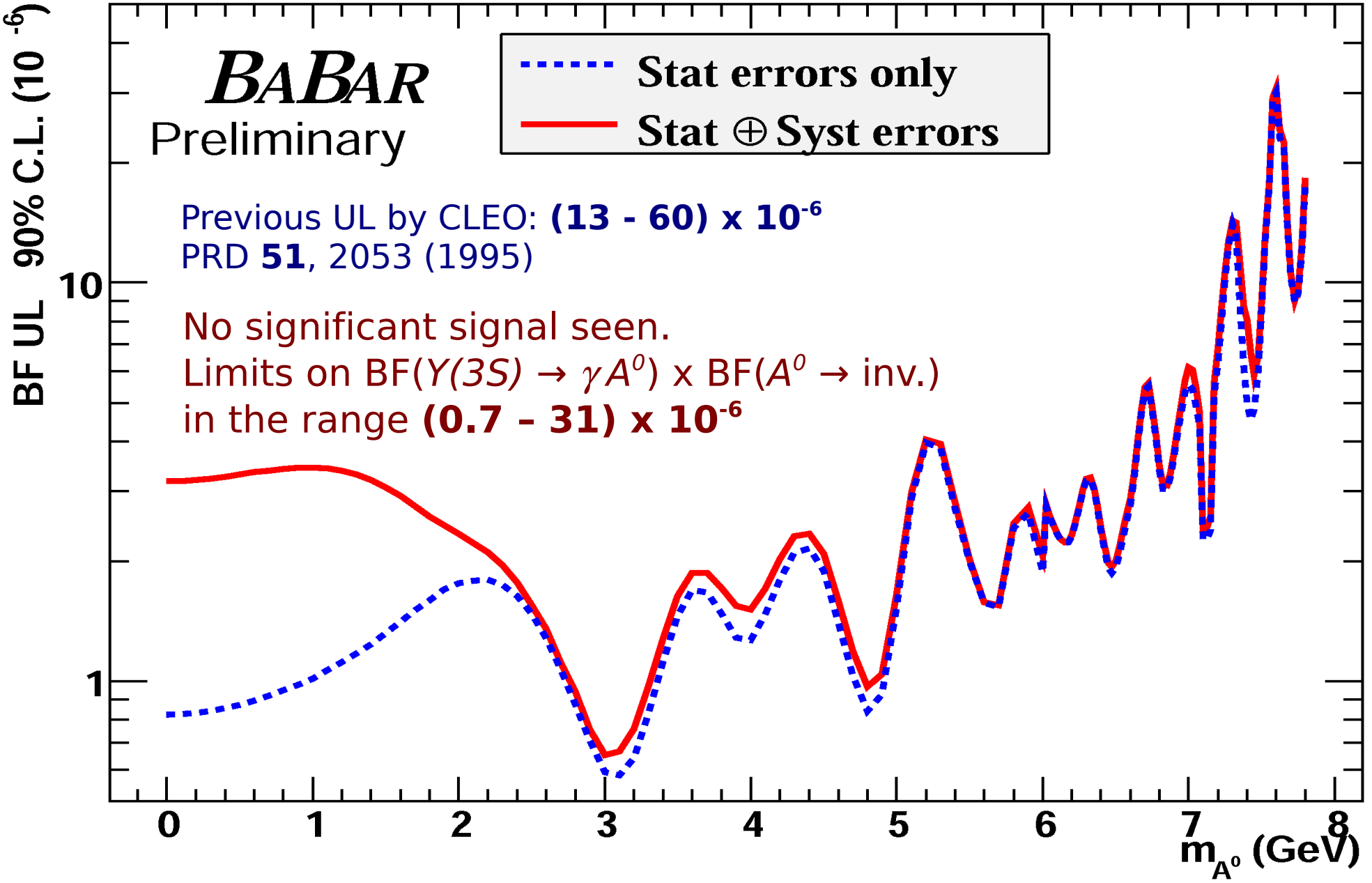








A^0 to invisible - results



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

arXiv:0906.2219 [hep-ex]
submitted to PRL

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

- If $m_{A0} > 2m_\tau$, dominant decay expected to be:

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

- Request τ to decay either to $e\,\nu\,\bar{\nu}$ or $\mu\,\nu\,\bar{\nu}$;
- Partial reconstruction due to the presence of neutrinos: request an energetic photon, exactly two identified leptons in the event, missing energy consistent with τ decays;
- Selection optimized in 5 regions of the whole E^*_γ spectrum (from 0.2 to 5.0 GeV). Signal efficiency in the range 10-26%;
- Scan for a peak in the E^*_γ spectrum, fitting simultaneously all 3 final states ($e^\pm e^\mp$, $e^\pm \mu^\mp$, $\mu^\pm \mu^\mp$).

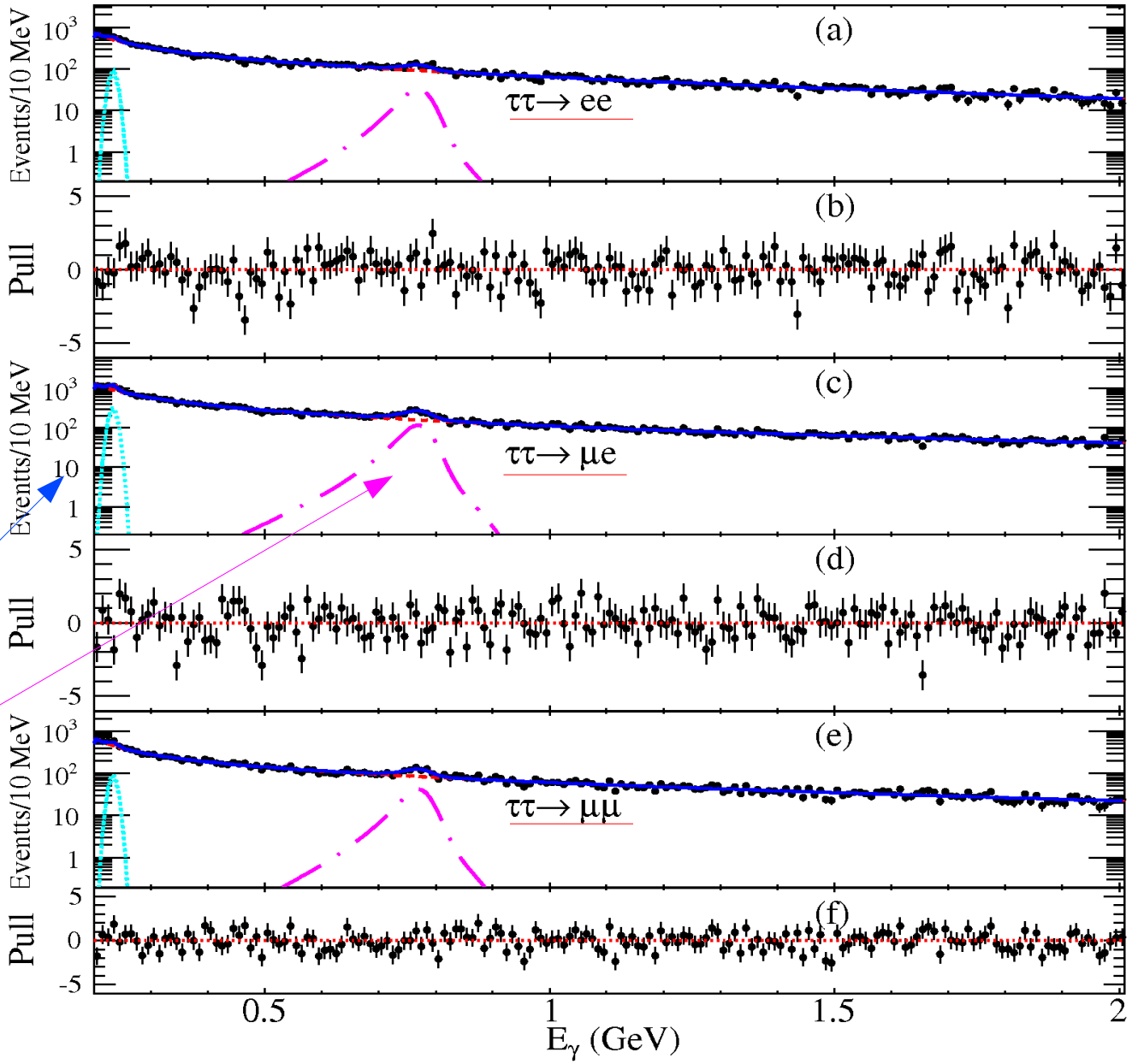
$A^0 \rightarrow \tau^+\tau^-$ - fit

Dominant backgrounds: irreducible $e^+e^- \rightarrow \tau^+\tau^-$, higher order QED processes, ...
Fit with a smooth function.

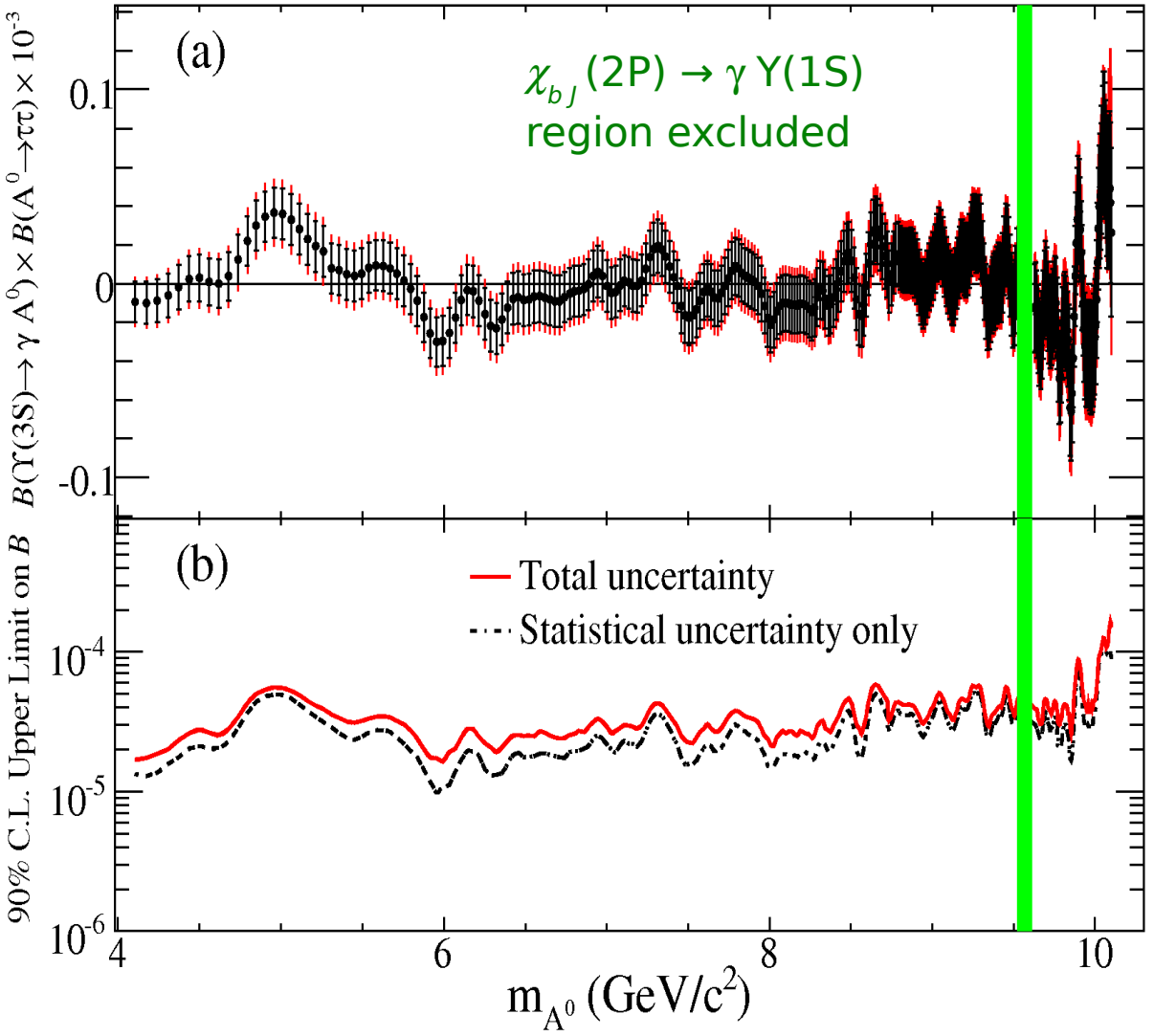
Peaking backgrounds also included:

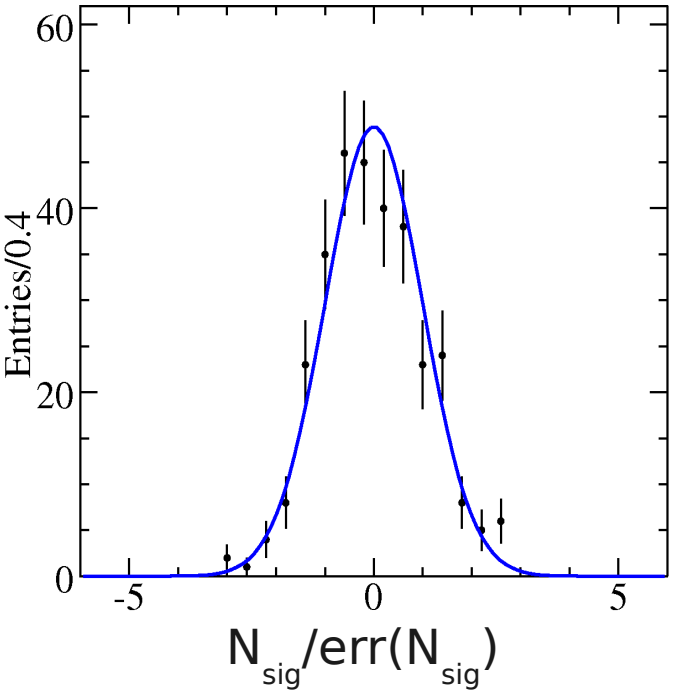
$\chi_{bJ}(2P) \rightarrow \gamma Y(2S)$

$\chi_{bJ}(2P) \rightarrow \gamma Y(1S)$



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





Signal significance of the **307** scan points: no evidence of a signal

Previous UL by CLEO on Y(1S): **(1.0 - 48) x 10^{-5}**
PRL **101**, 151802 (2008)

Upper limits on the product BF in the range **(1.5 – 16) x 10^{-5}**

Also BF($\eta_b \to \tau^+\tau^-$) < 8 %

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

arXiv:0905.4539 [hep-ex]
submitted to PRL

$A^0 \to \mu^+\mu^-$ - introduction

- Search for:

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

- Request one energetic photon and two charged tracks kinematically compatible with CM energy;
- One track identified as μ . In the ρ (770) region, request both tracks to be identified as μ ;
- Fully reconstruct the A^0 candidate, search for a narrow peak in the 'reduced mass' distribution:

$$m_R = \sqrt{m^2_{A^0} - 4m^2_\mu}$$

Smooth behavior at threshold

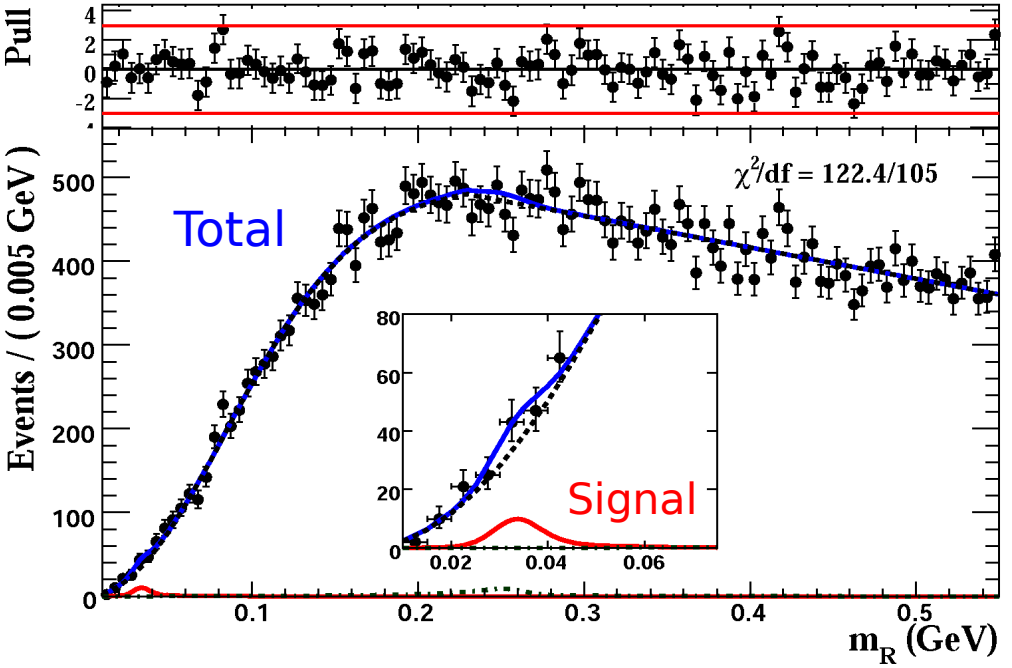
- Dominant backgrounds: $e^+e^- \to \mu^+\mu^-\gamma$ and ISR production of ρ (770), ϕ (1020), J/Ψ, Y(1S).

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

- Scan on the mass range $0.212 < m_{A0} < 9.3$ GeV;
- 1955 (~1500 independent) scan points at 2-5 MeV steps in the Y(2S) and Y(3S) datasets;
- For each dataset we extract $f_\Upsilon \mathcal{B}_{\mu\mu}$, where f_Υ is the effective Yukawa coupling of the bound b quarks to the A^0:

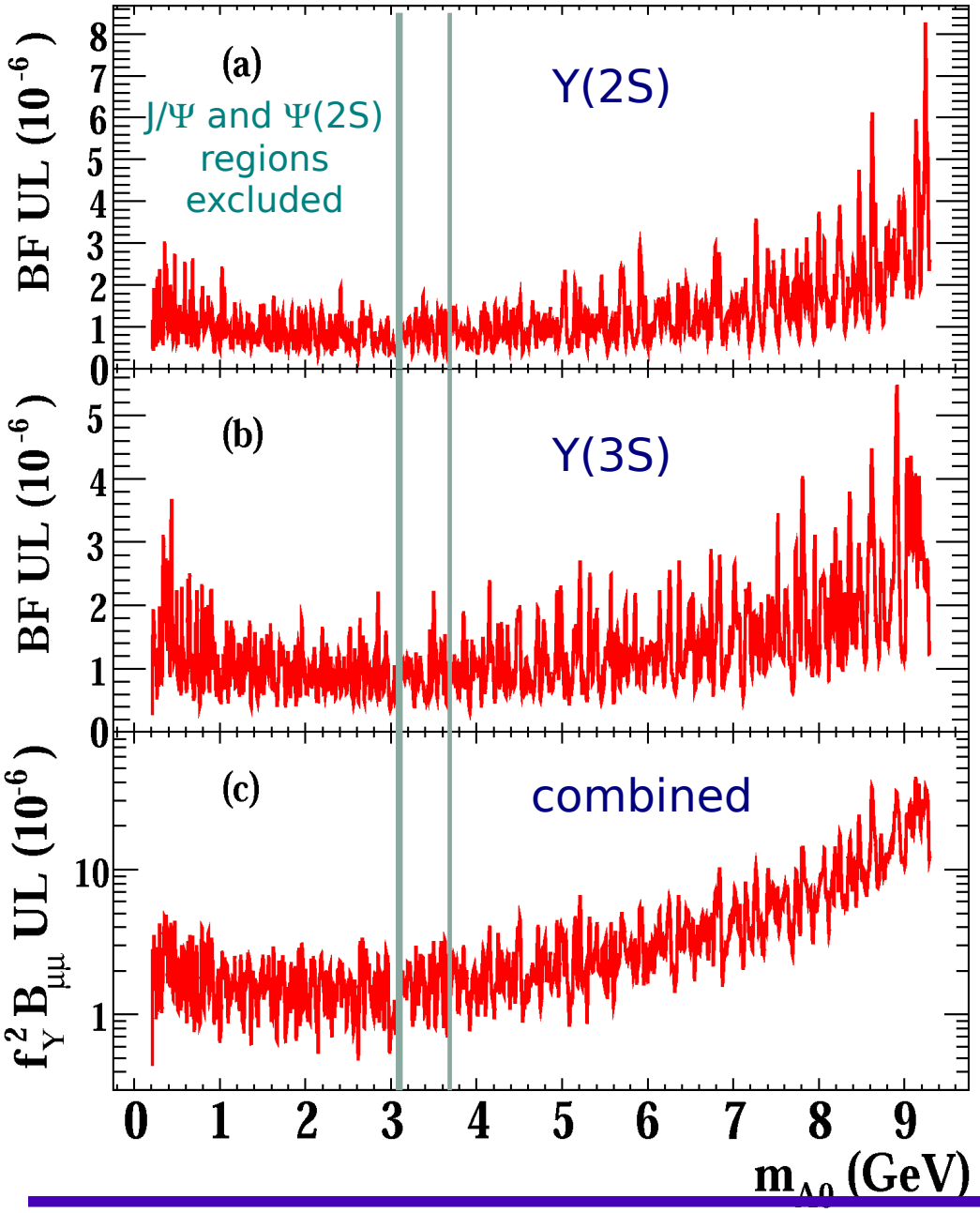
$$\frac{\mathcal{B}(\Upsilon(nS) \rightarrow \gamma A^0)}{\mathcal{B}(\Upsilon(nS) \rightarrow l^+l^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right)$$

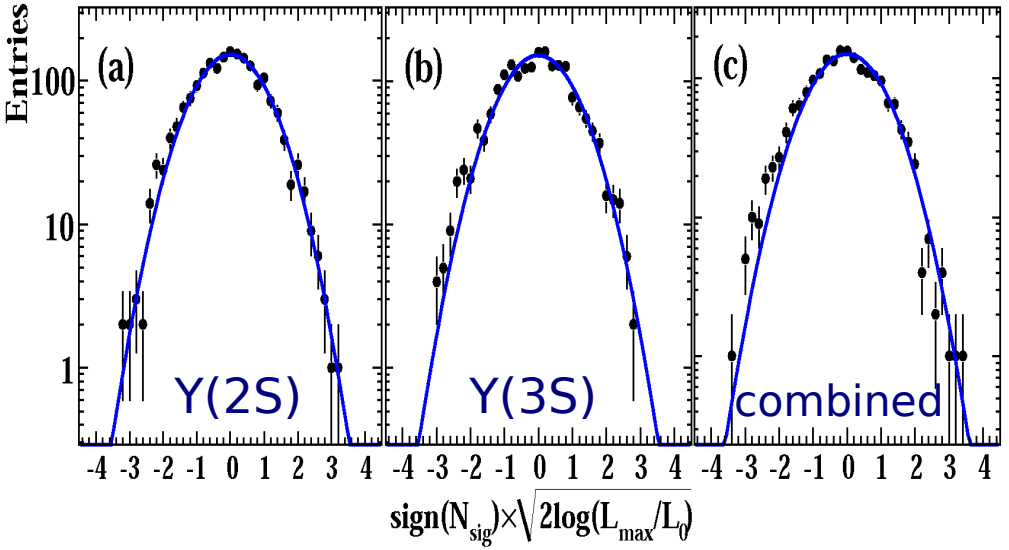
and combine the results;



Example: m_{A0} = 0.214 GeV (HyperCP region), Y(2S) dataset

$A^0 \to \mu^+\mu^-$ - results



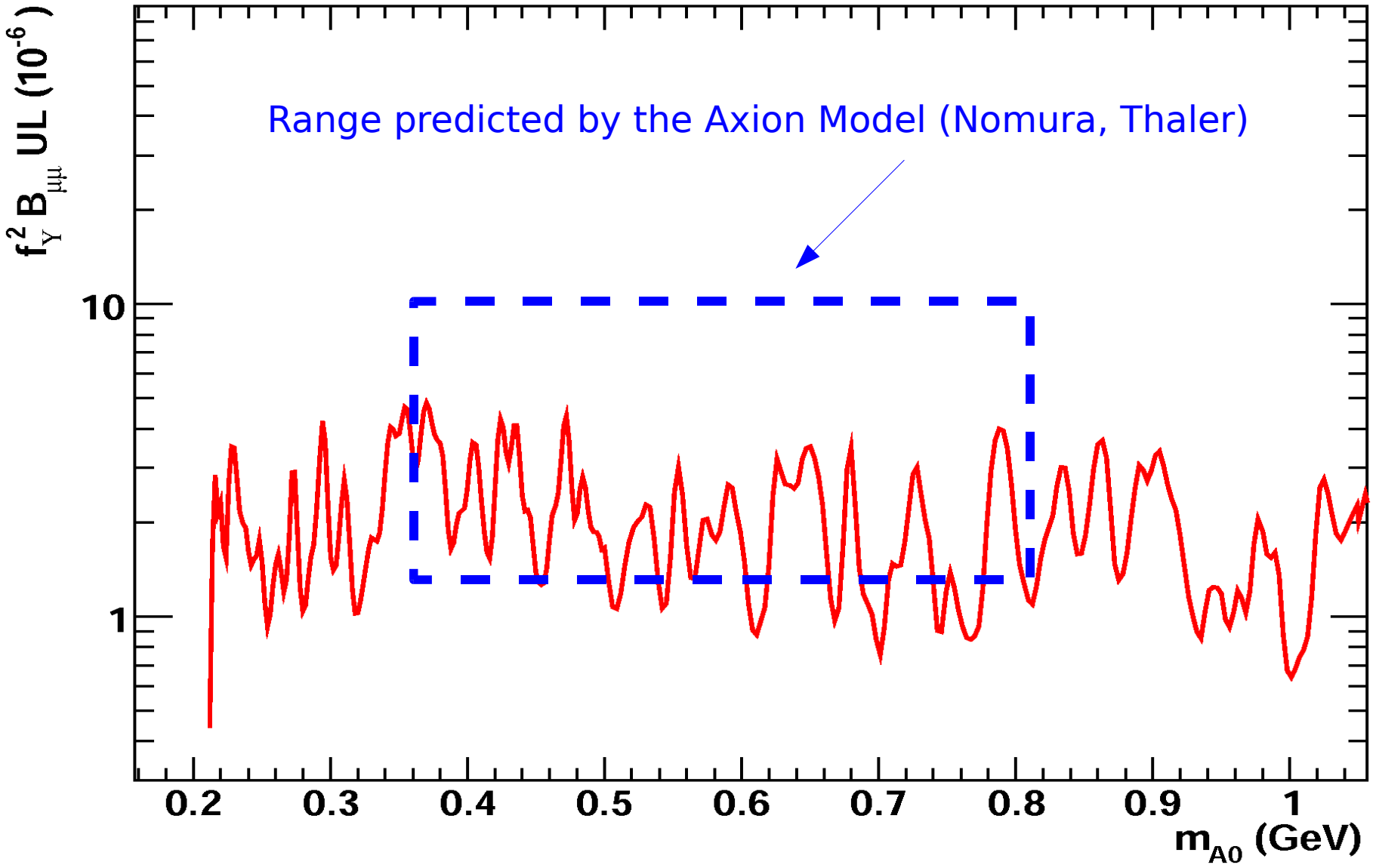


Distributions of significances for the scan points: no deviations from normal distribution

Previous UL by CLEO on Υ(1S):
(1 - 10) x 10^{-6}
PRL **101**, 151802 (2008)

BF upper limits and combined effective coupling

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



Tests of Lepton Universality

Presented at FPCP09
see talk by Gerard Bonneaud

Tests of LU - introduction

- In the Standard Model, the coupling of leptons to gauge bosons is independent of lepton flavor (Lepton Universality);

- Decay width of Y(nS) to l^+l^-:

$$\Gamma^{(em)}_{\Upsilon(nS)\to ll} = 4\alpha^2 Q_b^2 \frac{|R_n(0)|^2}{m_\Upsilon^2}\left(1+2\frac{m_l^2}{m_\Upsilon^2}\right)\sqrt{1-4\frac{m_l^2}{m_\Upsilon^2}}$$

$R_n(0)$: non-relativistic radial wave function of the $b\bar{b}$ state

- The presence of exotic particles can modify the Branching Fractions of Y(nS) to leptons;

- We search for:

$$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S) \longrightarrow \Upsilon(1S) \to \tau^+\tau^-,\ \mu^+\mu^-$$

- And compute:

$$R_{\tau\mu} = \frac{\Gamma^{(em)}_{\Upsilon(1S)\to\tau^+\tau^-}}{\Gamma^{(em)}_{\Upsilon(1S)\to\mu^+\mu^-}}$$

Tests of LU - strategy

$$\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S) \longrightarrow \Upsilon(1S) \to \tau^+\tau^-,\ \mu^+\mu^-$$

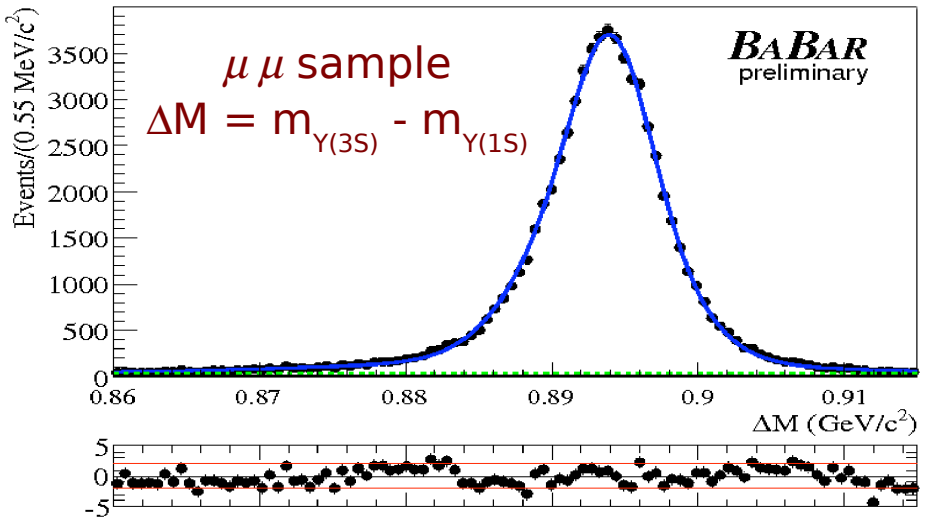
- Strategy: simultaneous fit to $\tau\tau$ and $\mu\mu$ samples and extraction of $R_{\tau\mu}$;
- $\mu\mu$ sample: fully reconstruct the decay chain, exploiting knowledge of the initial energy. Discriminating variables used in the fit: M($\mu^+\mu^-$) and ΔM = M($\pi^+\pi^-\mu^+\mu^-$) - M($\mu^+\mu^-$);
- $\tau\tau$ sample: cannot fully reconstruct the decay, select *1-prong* τ decays and request the visible energy of the event to be 5 GeV smaller than the total energy. Discriminating variable: mass of the recoil $M_{\pi\pi}$

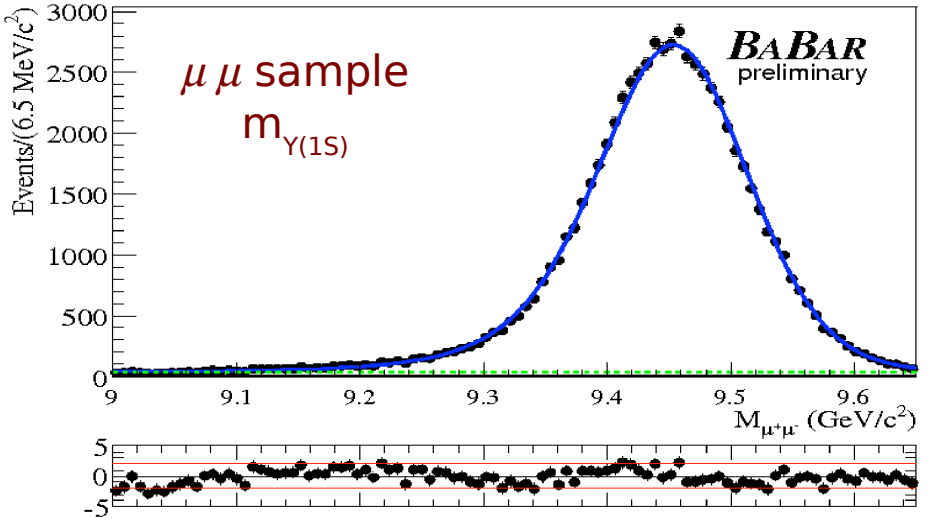
$$M^{reco}_{\pi^+\pi^-} = \sqrt{s + M^2_{\pi^+\pi^-} - 2\cdot\sqrt{s}\cdot\sqrt{M^2_{\pi^+\pi^-} + p^2_{\pi^+\pi^- CM}}}$$

s: initial energy squared

- Probability Density Functions taken from a sub-sample of the dataset (1/10 of the statistics, discarded from the nominal fit);

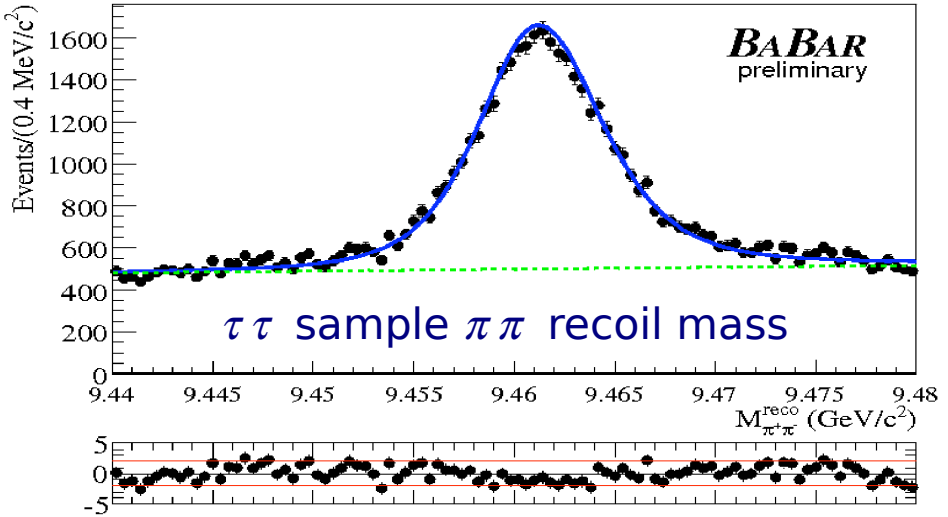
Tests of LU - fit





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

$$\Upsilon(1S) \to \tau^+\tau^-,\ \mu^+\mu^-$$



$$R_{\tau\mu} = 1.009 \pm 0.010(stat.) \pm 0.024(syst.)$$

Previous CLEO result:
$R_{\tau\mu} = 1.02 \pm 0.02 \pm 0.05$
PRL **101**, 151802 (2008)

Prospects at a Super-Flavor Factory

- Most of the measurements I presented today are limited by the statistics: still room for improvement;
- Two proposals for building (in Italy & Japan) a very high-luminosity (a factor ~100 the current ones) "Flavor-Factory";
- Physics case:
  - rare *B*-meson decays, CP violation, tests of CKM;
  - charm physics, *D* mixing;
  - Lepton Flavor Violation from τ decays;
  - ...
- Very promising case also for the search of light Higgs/Axions and Lepton Universality violation.

Prospects at a Super-Flavor Factory

F. Domingo et al. arXiv:0907.0348 [hep-ph]

- Interesting case when $9.4 < m_{A0} < 10.5$ GeV: mixing with the η_b states can occur;
- Disagreement at 2σ level with QCD predictions in the hyperfine splitting $E_{hfs} = m_{Y(1S)} - m_{\eta b(1S)}$:

$$\mathcal{M}^2 = \begin{pmatrix} m^2_{\eta_b^0(1S)} & 0 & 0 & \delta m_1^2 \\ 0 & m^2_{\eta_b^0(2S)} & 0 & \delta m_2^2 \\ 0 & 0 & m^2_{\eta_b^0(3S)} & \delta m_3^2 \\ \delta m_1^2 & \delta m_2^2 & \delta m_3^2 & m_A^2 \end{pmatrix}$$

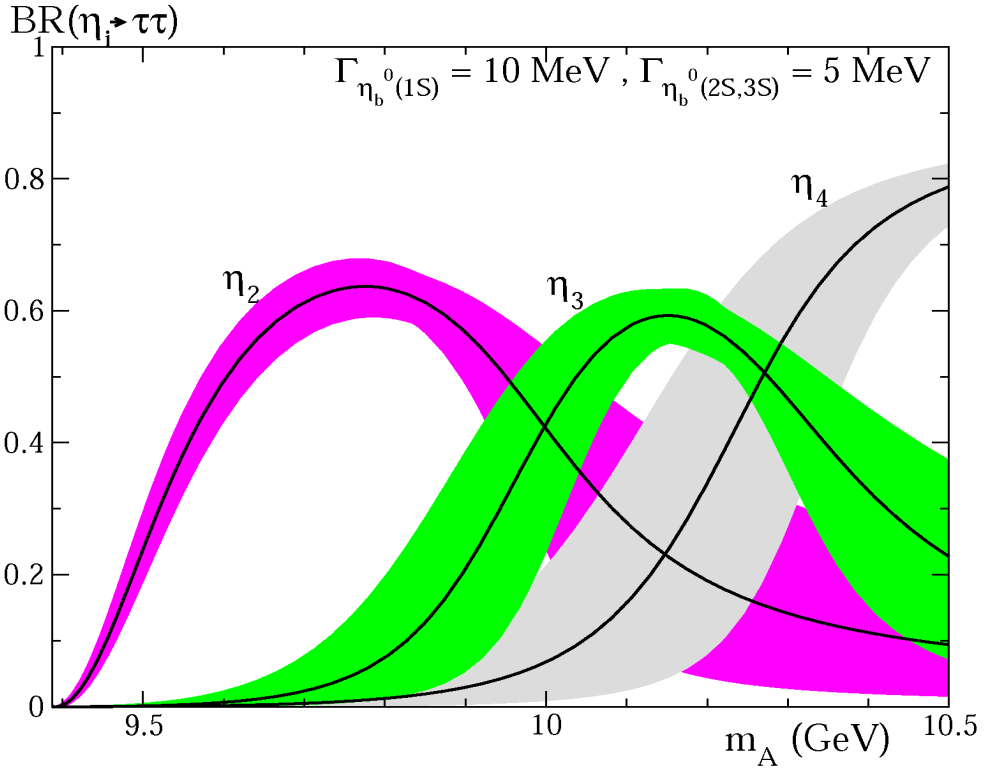
$$E_{hfs}^{exp} = 69.9 \pm 3.1 \text{ MeV}$$

$$E_{hfs}^{pQCD} = 42 \pm 13 \text{ MeV}$$

- Very interesting to look at the mass spectrum of the other η_b states, as well as their branching fraction to $\tau^+\tau^-$.

Prospects at a Super-Flavor Factory

$\Upsilon(nS) \rightarrow \gamma A^0,\ A^0 \rightarrow l^+ l^-$
$\Upsilon(nS) \rightarrow \gamma \eta_b,\ \eta_b \rightarrow A^0 \rightarrow l^+ l^-$



- Potentially very large branching fraction of $\eta_b(nS)$ states to $\tau^+\tau^-$;
- Predicted BF($\eta_b(1S) \rightarrow \tau^+\tau^-$) ~ a few %, compatible with BaBar UL ;
- Due to background, most prominent experimental signature would be violation of Lepton Universality.

Conclusions

- BaBar searched for light Higgs/Axions in *Y(nS)* decays and found no significant signal. Sizable improvement over previous upper limits set by CLEO;
- Excluded a large fraction of parameters space for some New Physics models;
- Improved precision on test of Lepton Universality on *Y(1S)* decays;
- Even more progress expected from the next generation of experiments at e^+e^- colliders.

Backup Slides

A^0 to invisible - selection

Variable	$3.2 < E^*_\gamma < 5.5$ GeV	$2.2 < E^*_\gamma < 3.7$ GeV
Number of crystals in EMC cluster	$20 < N_{\rm crys} < 48$	$12 < N_{\rm crys} < 36$
LAT shower shape	$0.24 < LAT < 0.51$	$0.15 < LAT < 0.49$
a_{42} shower shape	$a_{42} < 0.07$	$a_{42} < 0.07$
Polar angle acceptance	$-0.31 < \cos\theta^*_\gamma < 0.6$	$-0.46 < \cos\theta^*_\gamma < 0.46$
2nd highest cluster energy (CMS)	$E^*_2 < 0.2$ GeV	$E^*_2 < 0.14$ GeV
Extra photon correlation	$\cos(\phi^*_2 - \phi^*_1) > -0.95$	$\cos(\phi^*_2 - \phi^*_1) > -0.95$
Extra EMC energy (Lab)	$E_{\rm extra} < 0.1$ GeV	$E_{\rm extra} < 0.22$ GeV
IFR veto	$\cos(\Delta\phi^*_{\rm NH}) > -0.9$	$\cos(\Delta\phi^*_{\rm NH}) > -0.95$
IFR fiducial	$\cos(6\phi^*_\gamma) < 0.96$	...

Prospects at a Super-Flavor Factory

F. Domingo et al. arXiv:0907.0348 [hep-ph]