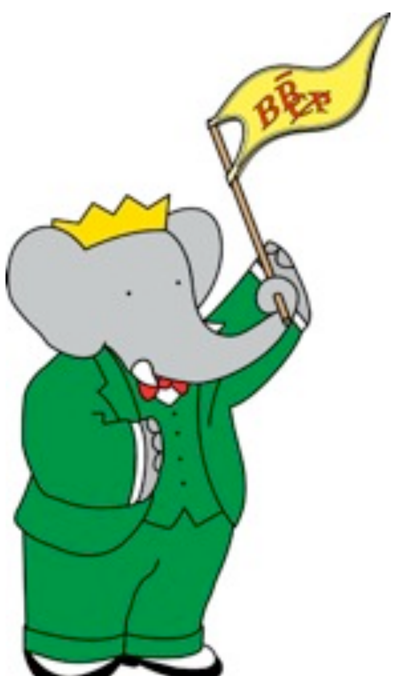
Direct searches for light new physics with BaBar



Neus Lopez March
IFIC (Universitat de Valencia - CSIC)
for the BABAR collaboration

Kruger National Park , Dec 2010

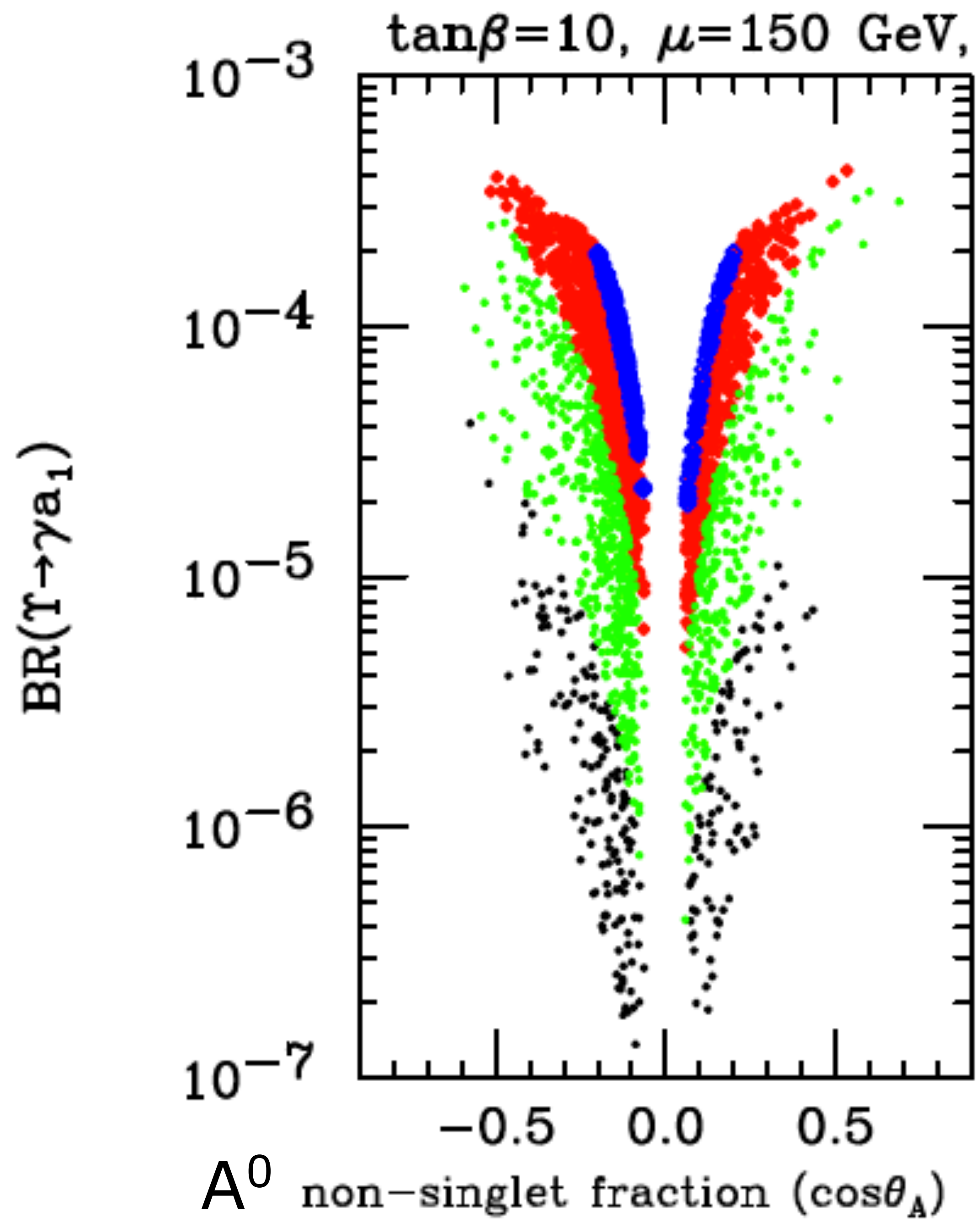
IFIC
INSTITUT DE FÍSICA CORPUSCULAR

Motivation

- NMSSM proposed to reduce the amount of fine tuning of the MSSM
- NMSSM adds a singlet Higgs field to MSSM which results in an additional CP-odd Higgs that mixes with MSSM CP-odd Higgs: $A^0 = \cos(\theta_A) a_{MSSM} + \sin(\theta_A) a_{singlet}$,
  - For $m_{A0} < 2m_b$ the lightest CP-even Higgs (h^0) can evade LEP bound by $h \to A^0A^0$ (BF>0.7)
  - Large BF for $\Upsilon \to \gamma A^0$ possible
- Generic dark matter models predict a light component of the dark matter spectrum
  - $BR(\Upsilon \to \gamma A) \sim 10^{-6}$-$10^{-5}$ with $m_A \sim$ 400-800 MeV

Nomura, Thaler, PRD79, 075008 (2009) and other

- HyperCP resonance-like structure in $\Sigma \to p\mu\mu$ decays, could be a light CP-odd Higgs (0.2GeV) Phys. Rev. Lett. 94, 021801 (2005)

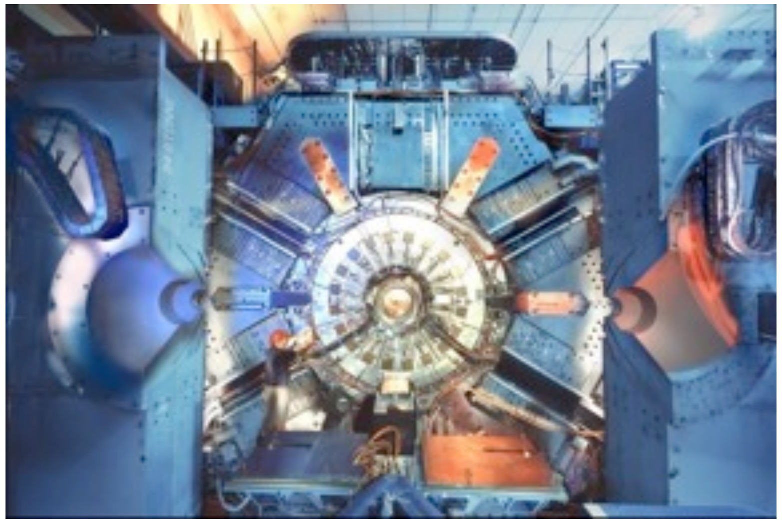


$m(A^0) < 2M(\tau)$
$2M(\tau) < M(A^0) < 7.5$GeV
$7.5 < M(A^0) < 8.8$ GeV
$8.8 < M(A^0) < 9.2$ GeV

PRD76,051105(2007)

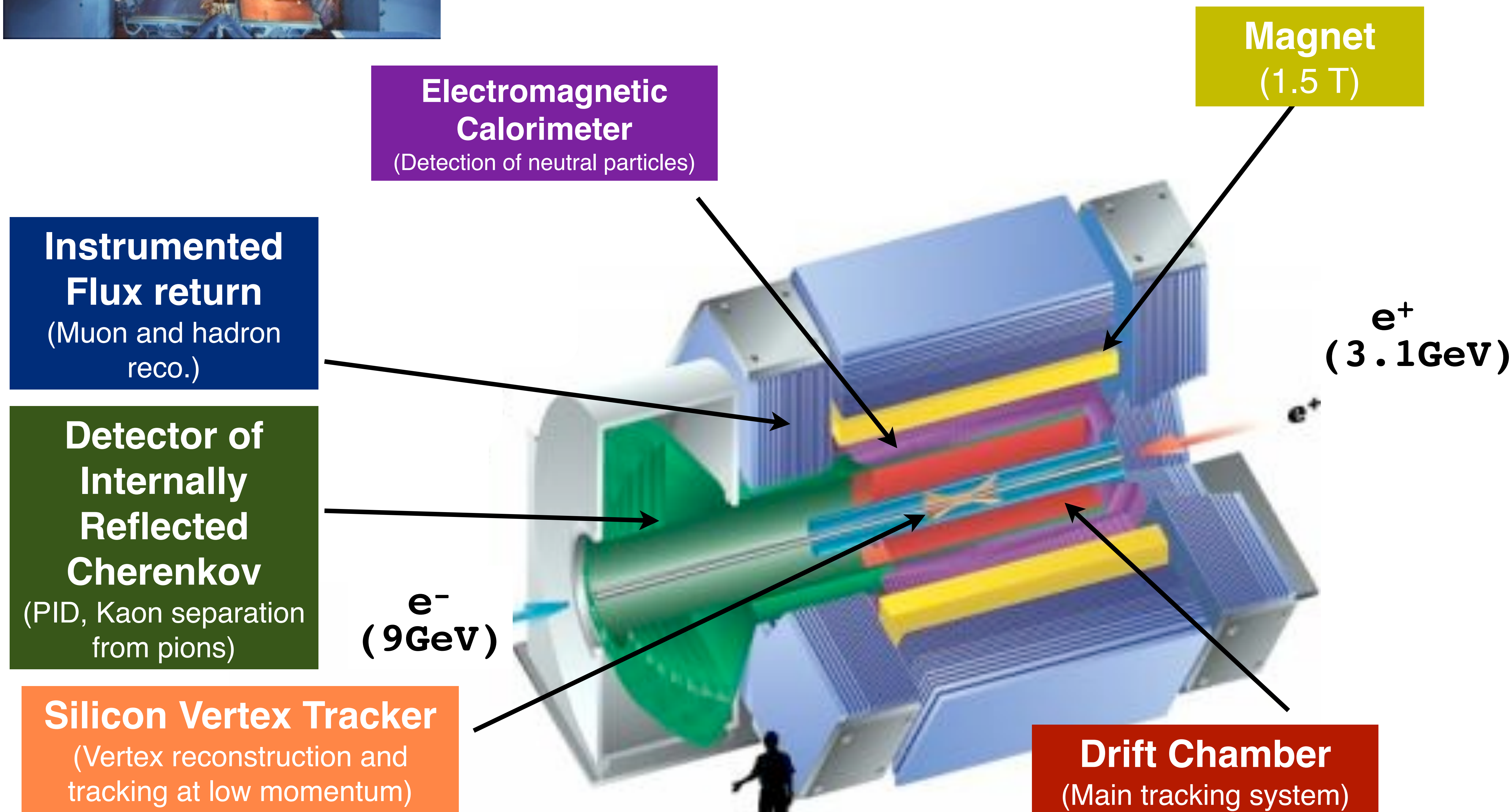
In this talk...

- Searches for light-Higgs/ dark matter candidates:
  - $\Upsilon(3,2S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$
  - $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$
  - $\Upsilon(3S) \rightarrow \Upsilon(1S)\,\pi\pi$, $\Upsilon(1S) \rightarrow$ Invisible
  - $\Upsilon(2S) \rightarrow \Upsilon(1S)\,\pi\pi$, $\Upsilon(1S) \rightarrow \gamma$ Invisible
- Indirect search for light higgs through a lepton universality test
- Direct search for Dark sector



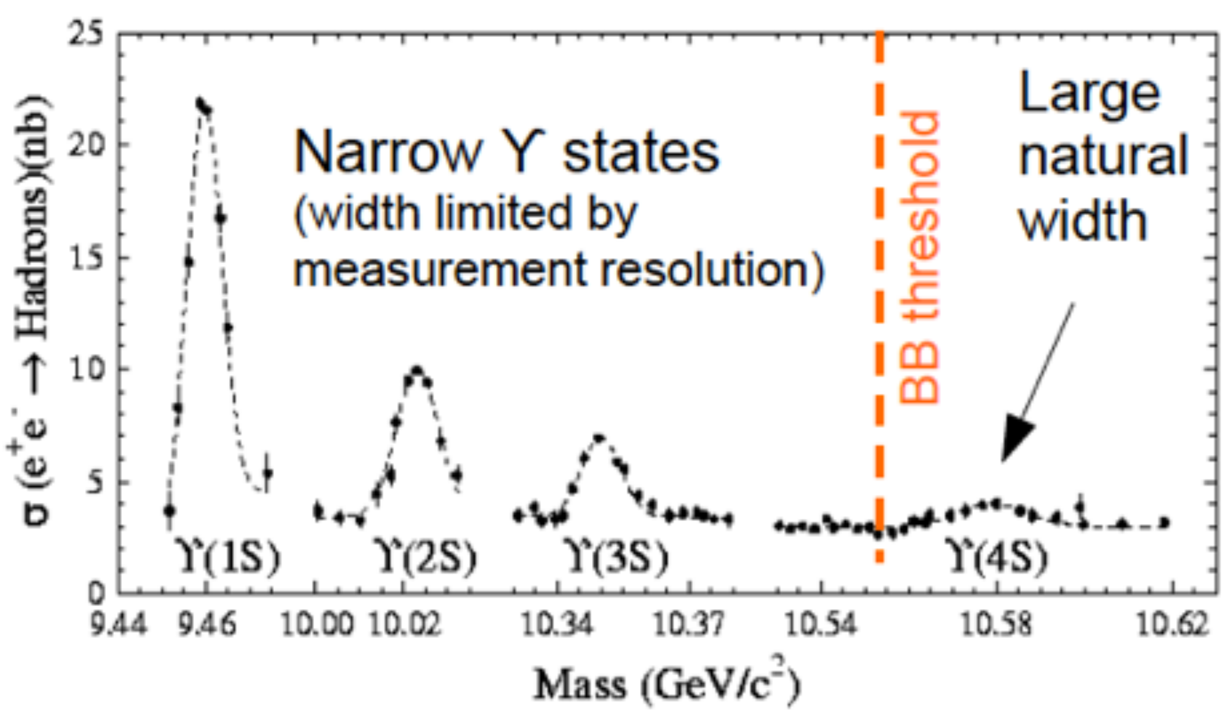
BaBar detector

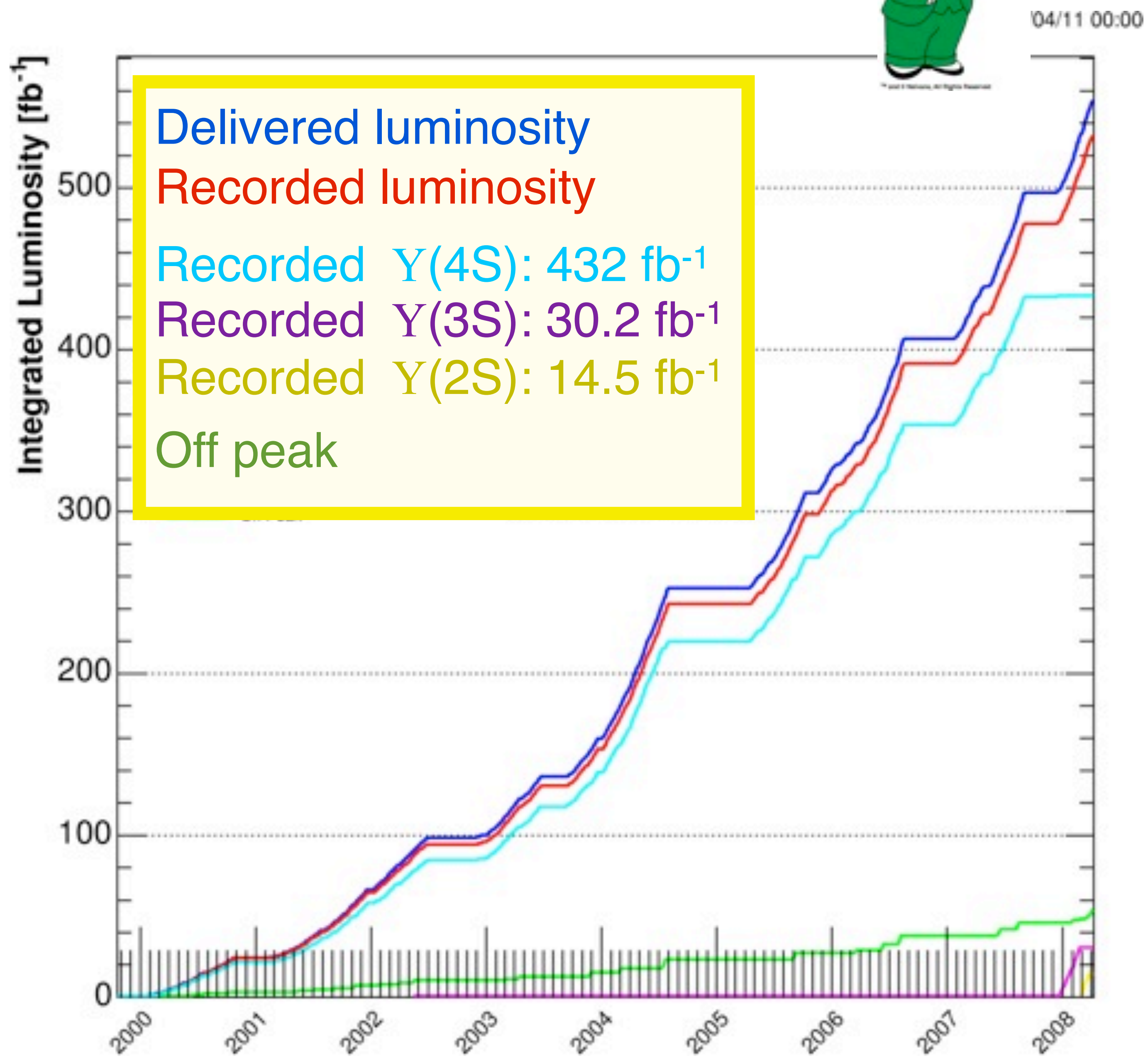
Located at the single IP of the e^+e^- assymetric collider at SLAC National Accelerator Laboratory



BaBar Dataset

- BaBar datasets from Dec 2007 to April 2008:
  - 122 x 10^6 Υ(3S) decays
  - 99 x 10^6 Υ(2S) decays
  - "offpeak" $1.4 fb^{-1}$ ~30MeV below Υ(2S)
  - "offpeak" $2.4 fb^{-1}$ ~30MeV below Υ(3S)





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

PRL 103 , 081803 (2009)

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

PRL 103, 181801 (2009)

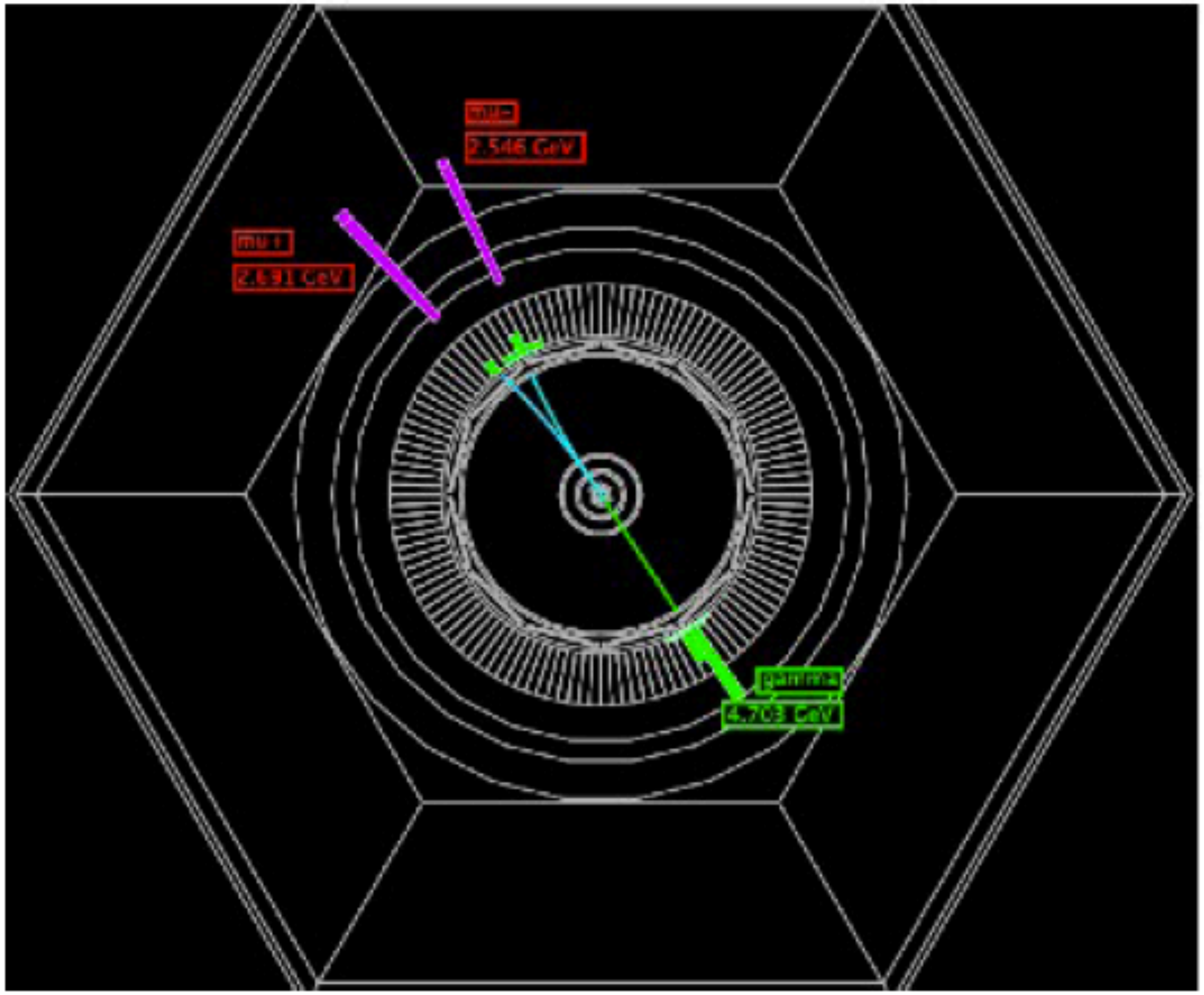
$A^0 \rightarrow \mu\mu$

122 x 10^6 Υ(3S) decays
99 x 10^6 Υ(2S) decays

Analysis

- Search for Υ(3,2S) → γA^0 , $A^0 \rightarrow \mu^+\mu^-$
- Select one energetic (E*>0.2GeV) photon and two tracks kinematically compatible with the CM energy
- Search for a narrow peak in the reduced mass distribution:

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



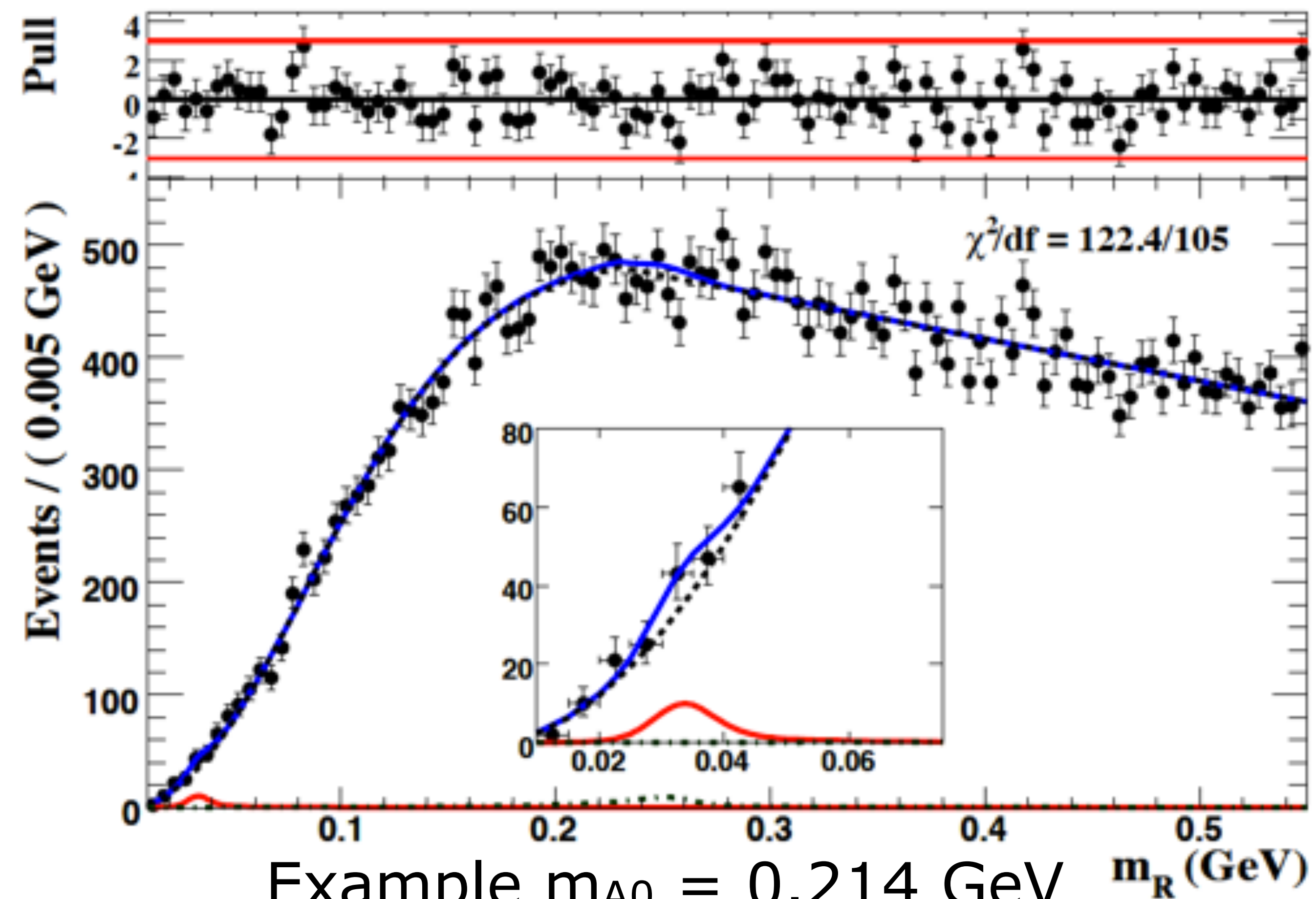
Main background comes from:

- $e^+e^- \rightarrow \gamma\mu^+\mu^-$
- ISR production of ρ(770), φ(1020), J/ψ, Υ(1S)

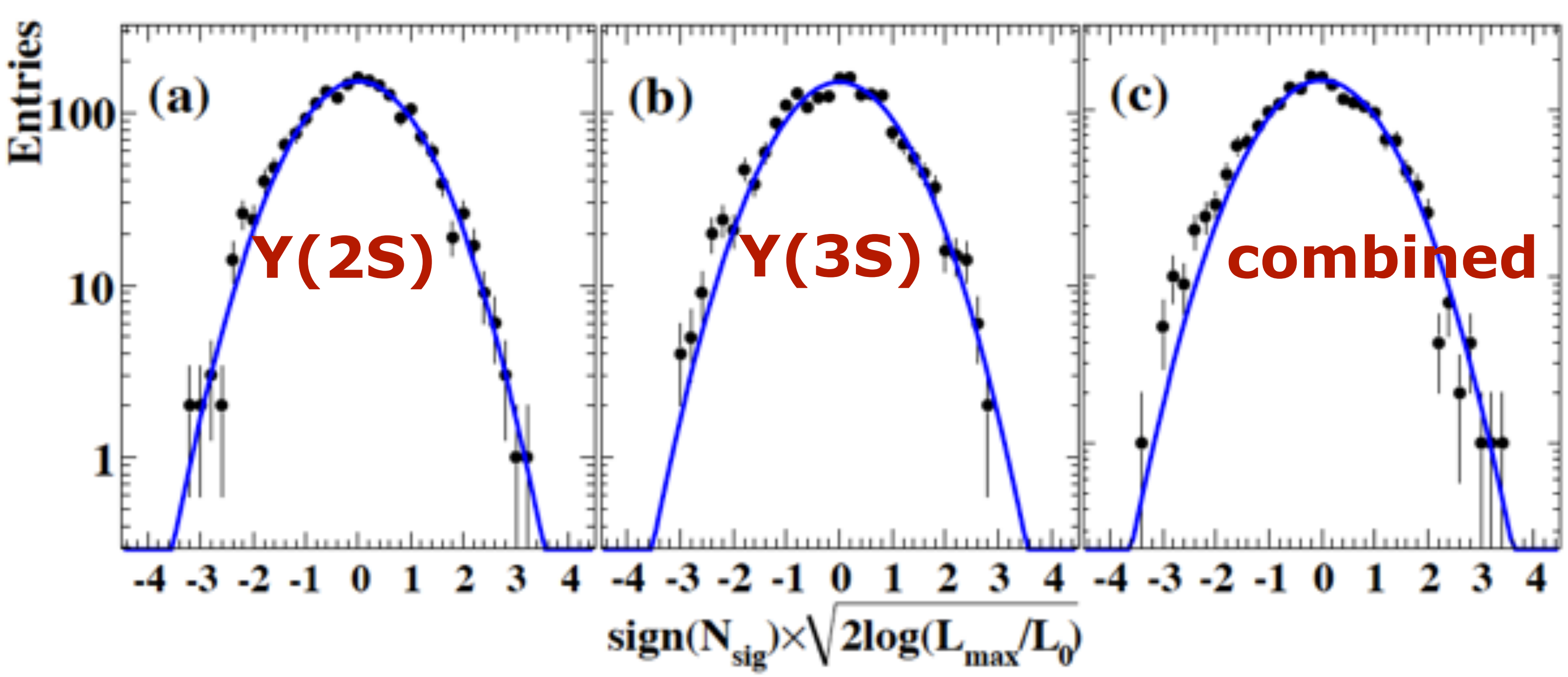
$A^0 \rightarrow \mu\mu$

Fit

- Scan on the mass range: $0.212 < m_{A0} < 9.3$GeV
- 1955 scan points at 2-5 MeV steps in the Υ(2S) and Υ(3S) datasets



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

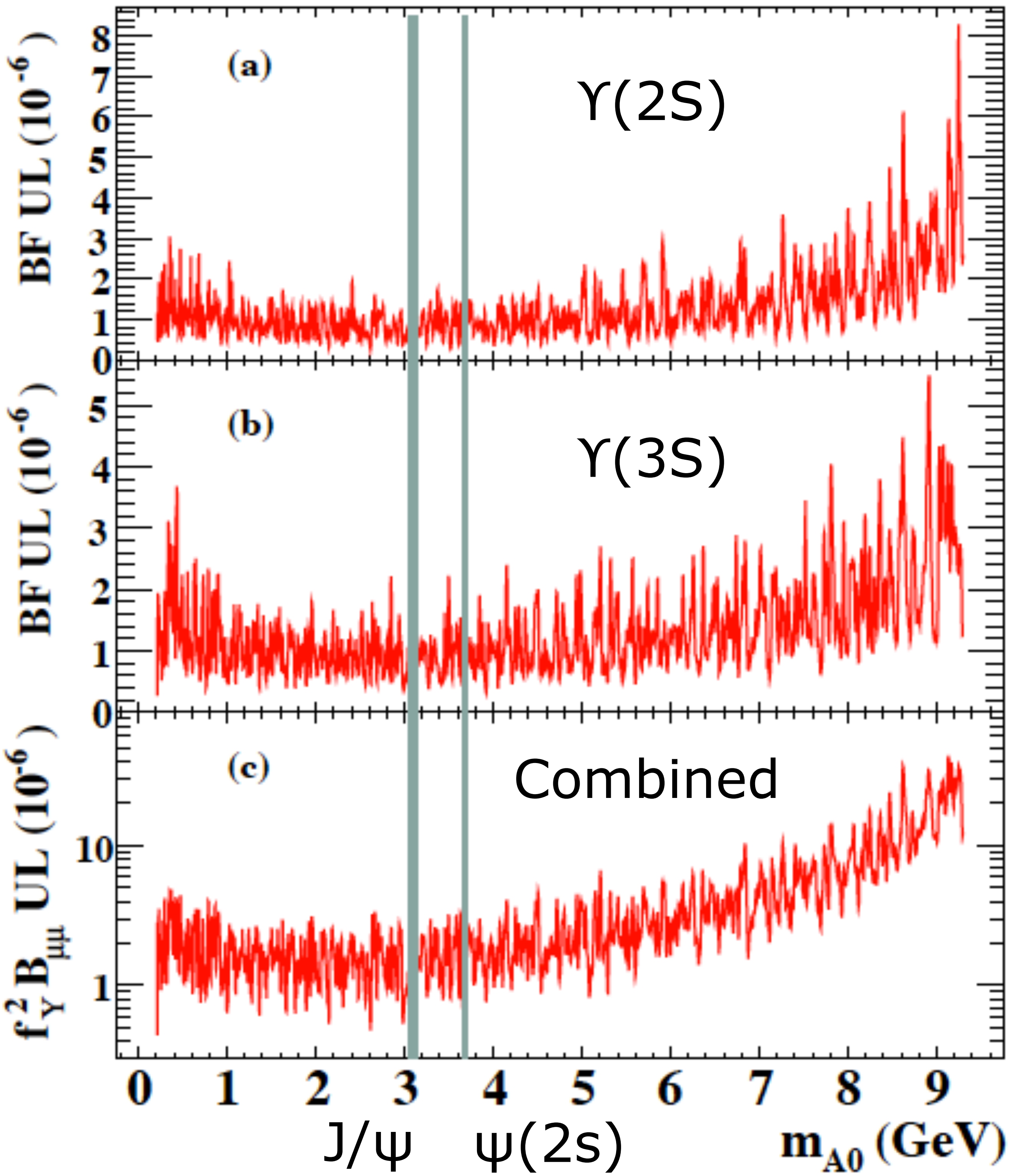


Distributions of significances for the scan points:

no deviations from normal distributions

$A^0 \to \mu\mu$

Result



- Set UL for both datasets
- Extract $f^2_{\Upsilon} B_{\mu\mu}$ where f^2_{Υ} is the effective Yukawa coupling of the bound b-quark to the A^0

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

f^2_{Υ} (m_{A0}=0.214GeV) $<1.6\times10^{-6}$ at 90% CL

Significantly smaller to be able to explain the HyperCP events as light Higgs production

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

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

PRL 103, 181801 (2009)

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

PRL 103, 181801 (2009)

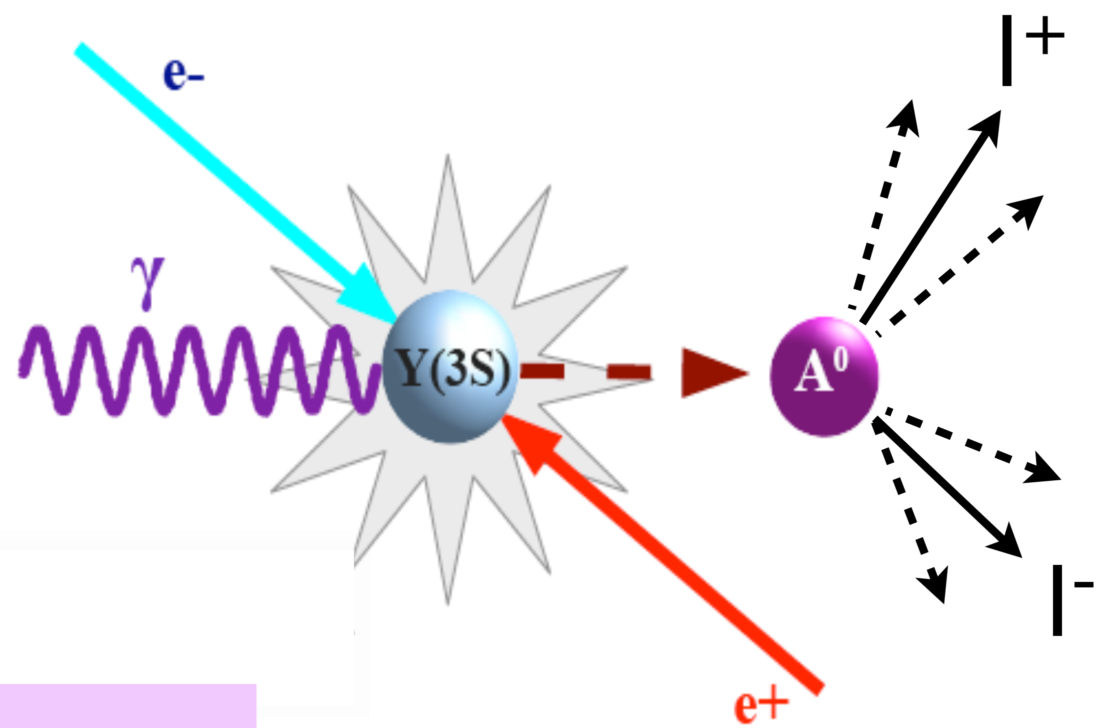
$A^0 \to \tau\tau$

122 x 10^6 Υ(3S) decays

Analysis

- Search for $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau\tau$
- 3 final states: $\tau\tau \to ee, \mu\mu, e\mu$ $(+4\nu)$
- Search for a narrow peak in the photon energy distribution
  range: $4.03 < m_{A0} < 10.10$ GeV/c^2
- Select events with 1 energetic photon ($E_\gamma > 100$ MeV), two identified leptons and a large missing energy and mass

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



Main background comes from:

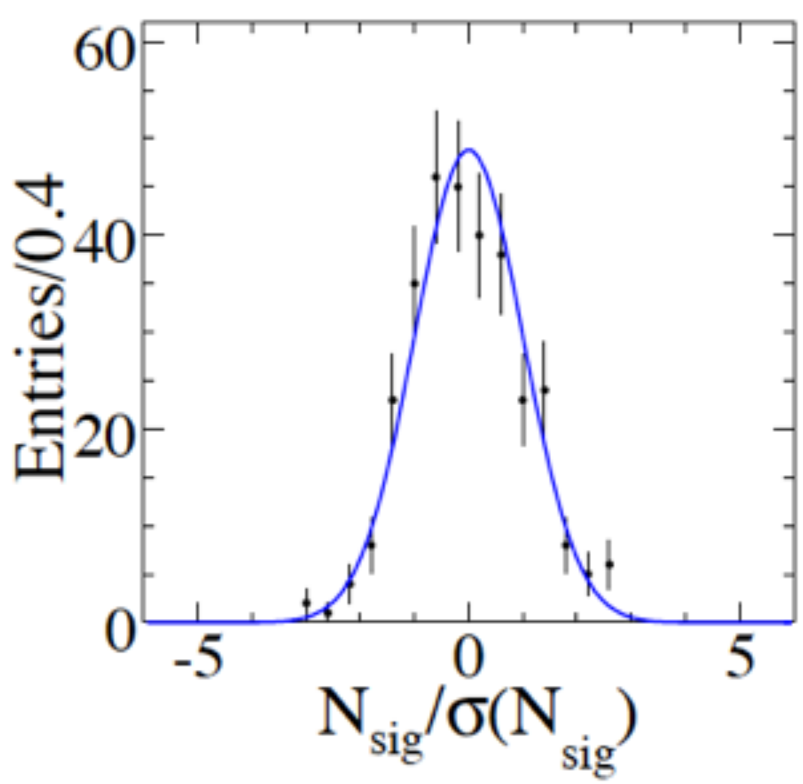
- **QED events** ($e^+e^- \to \gamma\tau^+\tau^-$, and higher-order processes)
- **Peaking events**: $\Upsilon(3S) \to \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \to \gamma\Upsilon(nS)$, with J=0,1,2 and n=1,2

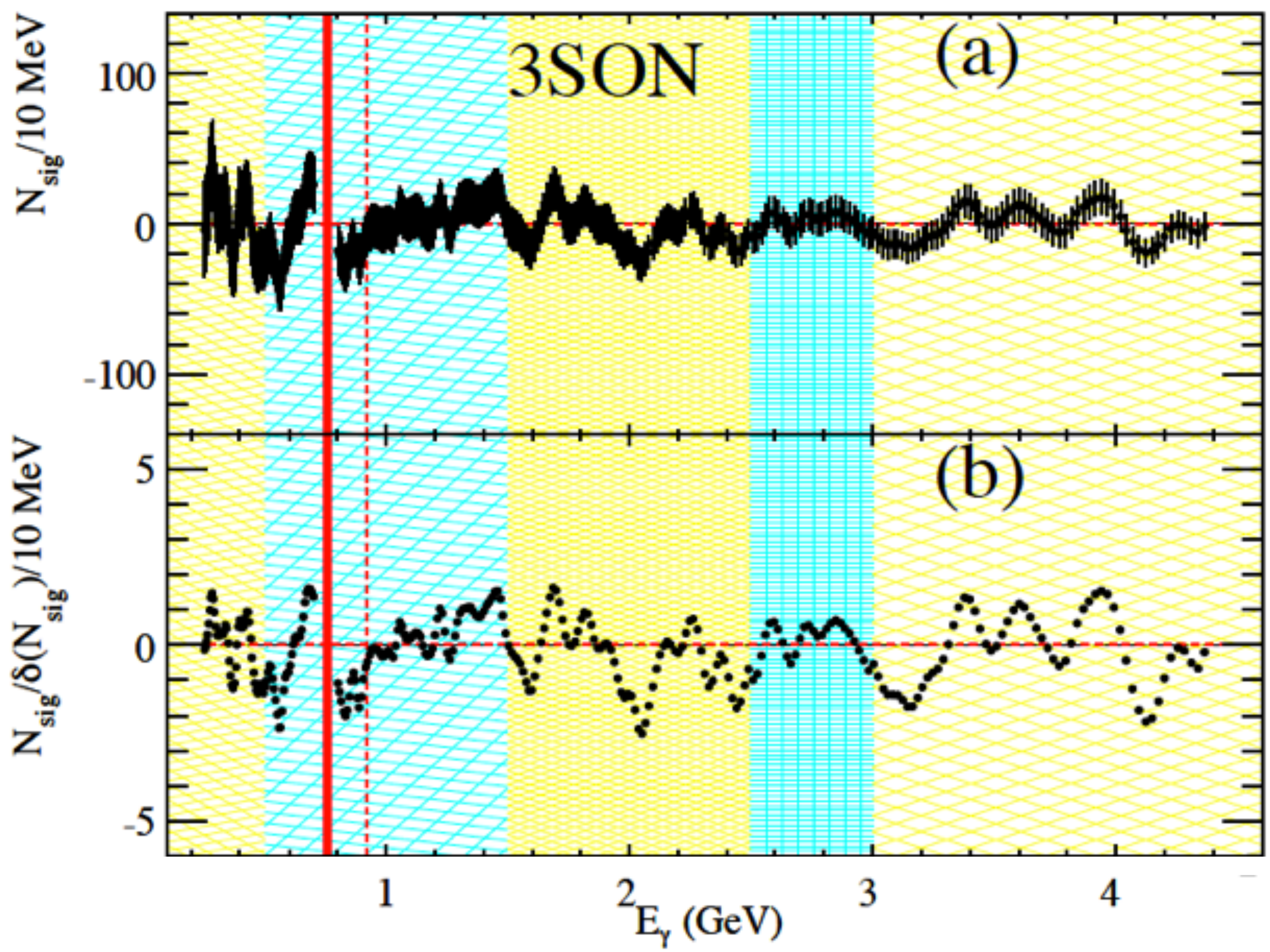
$A^0 \to \tau\tau$

Fit

Scan for peaks in the Eγ distribution in steps of half the resolution (307 scans in total)

In a range corresponding to $4.03 < M(A_0) < 10.10$GeV





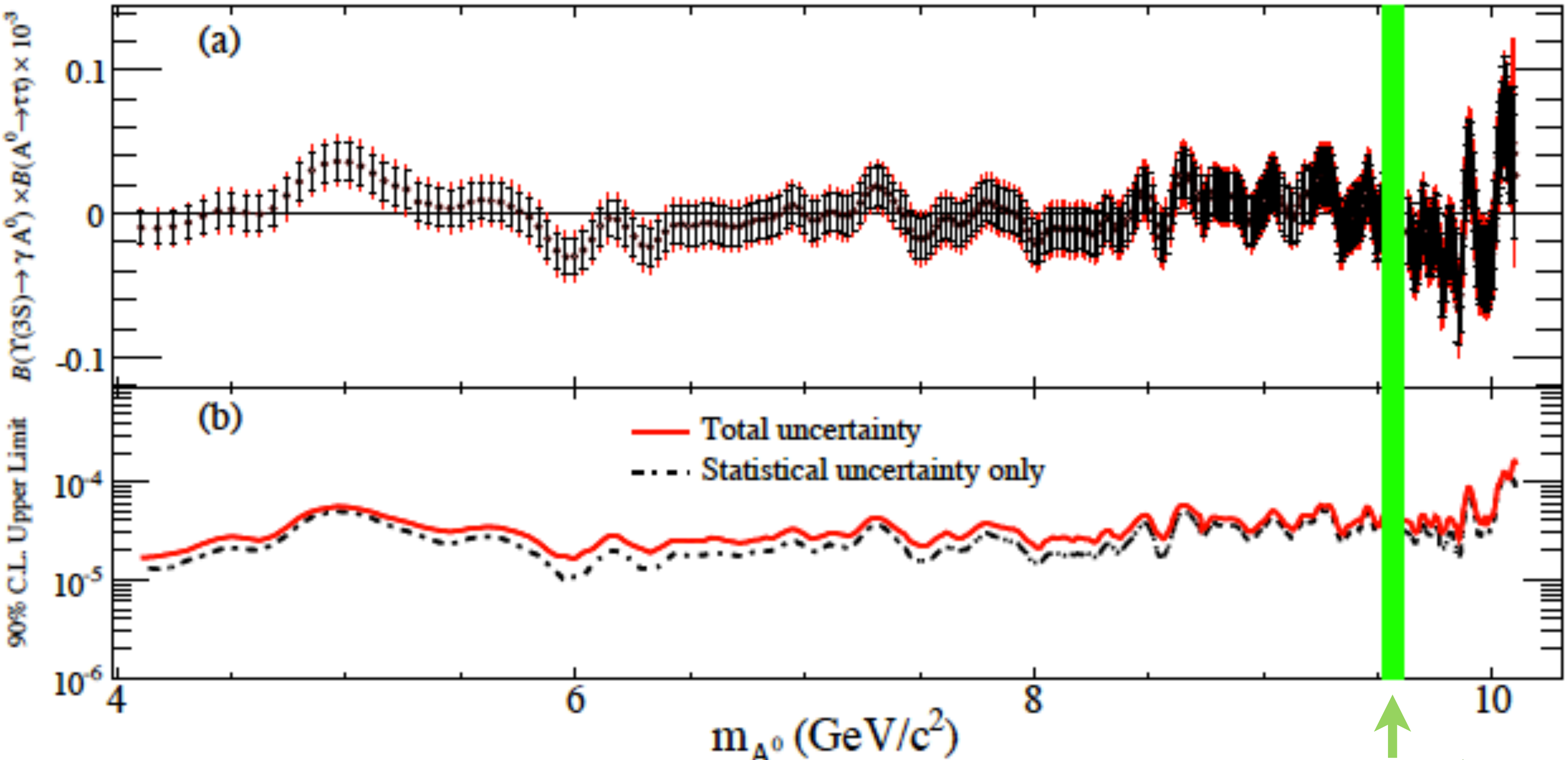
Most of the scanning points give a yield between 2-3 σ

No peaking structure is observed

$A^0 \rightarrow \tau\tau$

Result

- No statistically significant yield -> Set 90% CL UL
- $BR(Y(3S) \rightarrow \gamma A_0) \cdot BR(A_0 \rightarrow \tau\tau) < (1.5\text{-}16) \cdot 10^{-5}$



Excluded region: $\chi_{bJ}(2P) \rightarrow \gamma \Upsilon(1S)$

[$9.52 < M(A_0) < 9.61$ GeV/c^2]

$\Upsilon(2S) \rightarrow \Upsilon(1S)\ \pi\pi$, $\Upsilon(1S) \rightarrow \gamma$Invisible

arxiv:1007.4646[hep-ex]

$\Upsilon(3S) \rightarrow \Upsilon(1S)\ \pi\pi$, $\Upsilon(1S) \rightarrow$Invisible

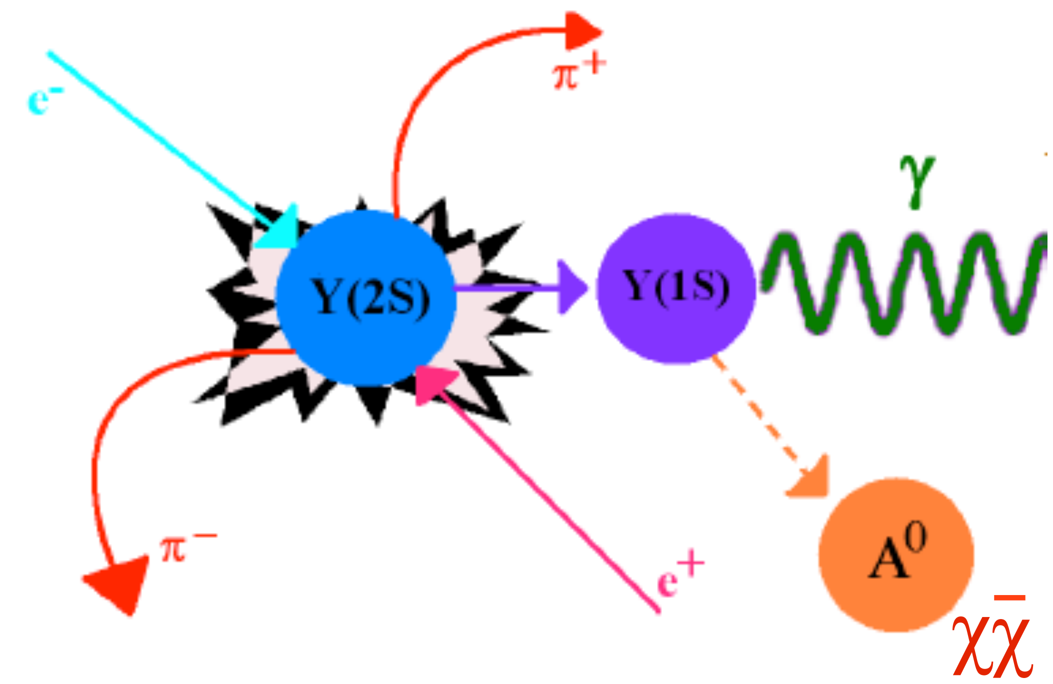
PRL 103, 251801 (2009)

$\Upsilon(1S) \to \gamma$ invisible

Analysis

- Search for $\Upsilon(1S) \to \gamma$ + invisible in $\Upsilon(2S) \to \Upsilon(1S)\,\pi\pi$ decays
- Resonant $\Upsilon(1S) \to \gamma + A^0$ ($\to$invisible, BF~10^{-4}) [1] or $\Upsilon(1S) \to \gamma\,\chi\bar{\chi}$ (BF~10^{-5} - 10^{-4}) [2]
- $A^0 \to \chi^0\chi^0$ can be dominant decay in some NMSSM scenarios with a light neutralino (LSP)
- Signature: single energetic photon (>1.1GeV) and large amount of missing energy and momentum + two pions
- Used a Neural Network discriminant to suppress the main background, trained in MC and Off-peak data

99 x 10^6 $\Upsilon(2S)$ decays



[1] PRD76,051105(2007)

[2] PRD 80,115019(2009), arXiv: 0712.0016[hep-ph] (2007)

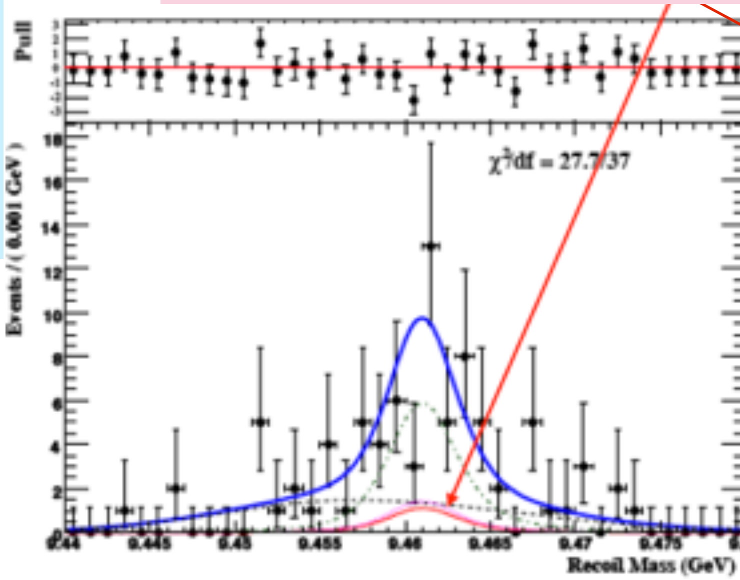
Main background comes from:

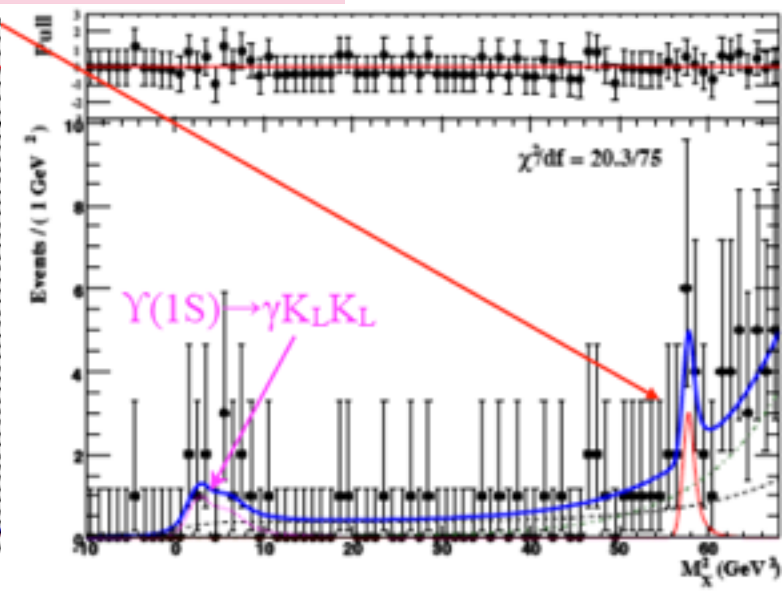
- $e^+e^- \to \gamma\,\pi^+\pi^-$, $\Upsilon(1S) \to \gamma l^+l^-$ (continuum)
- peaking background: $\Upsilon(1S) \to \gamma\, K^0_L\, K^0_L$ and $\Upsilon(1S) \to \gamma n\bar{n}$

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

Fit & Results

m_{A0}=7.58 GeV, 2.0σ significance

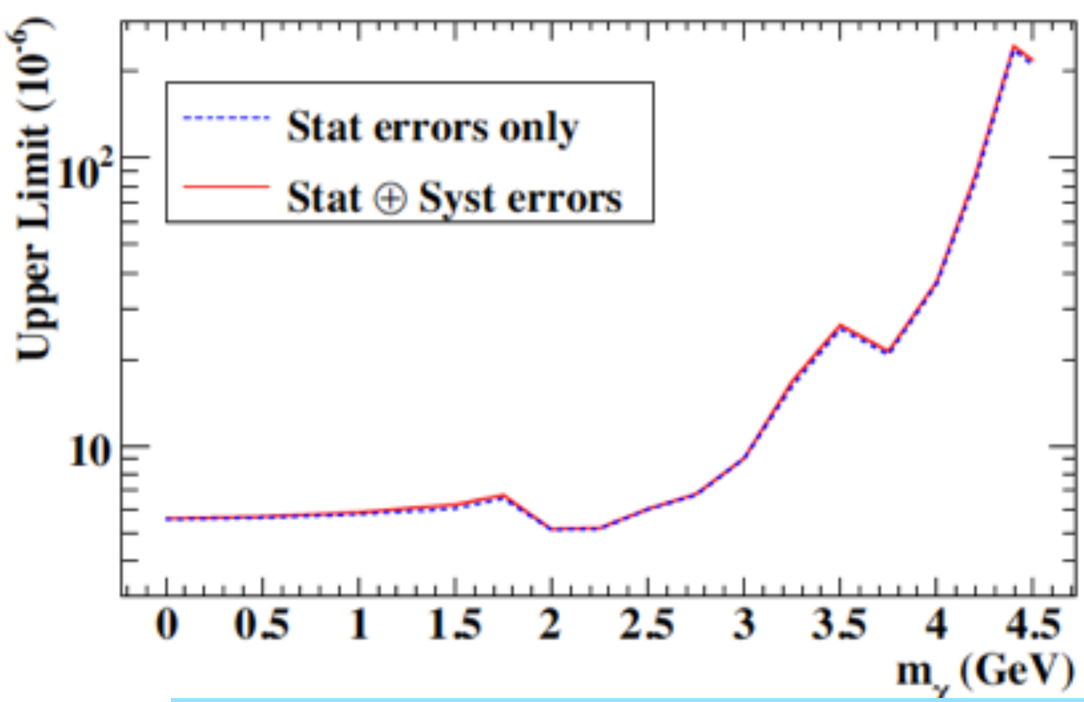


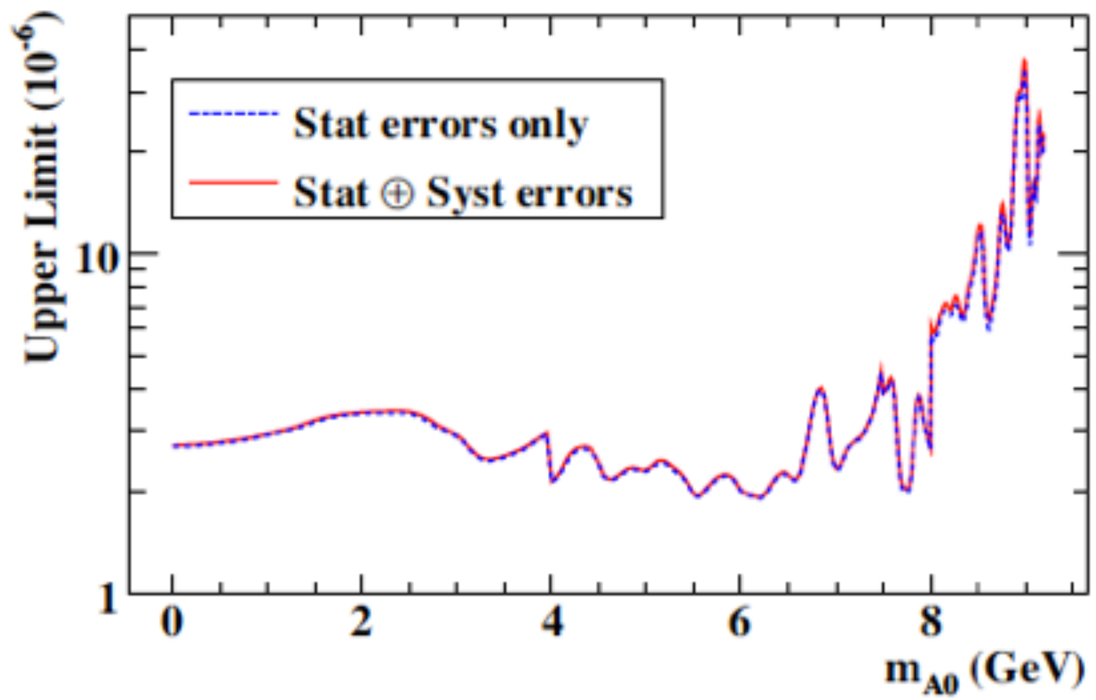


- Extract signal yield as function of m_{A0} ($0 \le m_{A0} \le 8$ GeV,196 steps) ($7.5 \le m_{A0} \le 9.2$ GeV,146 steps) and m_χ ($0 \le m_\chi \le 4.5$ GeV,17steps) performing 2D fit to:

$$M^2_{\rm recoil} = M^2_{\Upsilon(2S)} + m^2_{\pi\pi} - 2M_{\Upsilon(2S)}E^*_{\pi\pi}$$

$$M^2_X = (\mathcal{P}_{e^+e^-} - \mathcal{P}_{\pi\pi} - \mathcal{P}_\gamma)^2$$



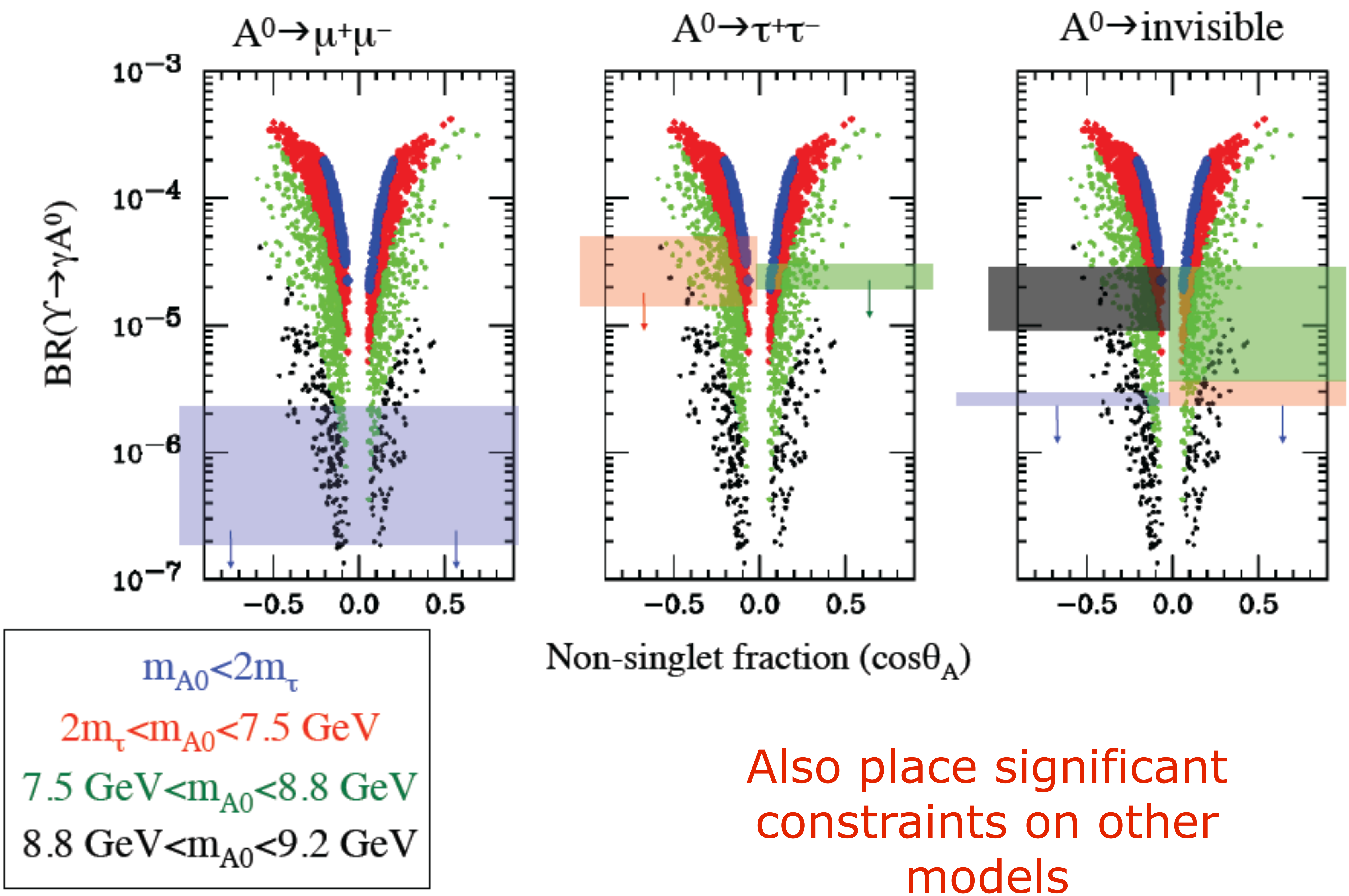


$B(\Upsilon(1S) \rightarrow \gamma\chi\chi < (0.5\text{-}24) \times 10^{-5}$ at 90% C.L

$B(\Upsilon(1S) \rightarrow \gamma(A^0 \rightarrow \text{invisible}) < (1.9\text{-}37) \times 10^{-6}$ at 90% C.L

Previous limits: $B(\Upsilon(1S) \rightarrow \gamma\chi\chi \sim 10^{-3}$ (CLEO), $B(\Upsilon(1S) \rightarrow \gamma(X \rightarrow \text{invisible}) < 3 \times 10^{-5}$ ($m_X \sim < 7.2$GeV) at 90% C.L

NMSSM predictions vs BaBar limits



Also place significant constraints on other models

$\Upsilon(2S) \to \Upsilon(1S)\,\pi\pi$, $\Upsilon(1S) \to \gamma$Invisible

arxiv:1007.4646[hep-ex]

$\Upsilon(3S) \to \Upsilon(1S)\,\pi\pi$, $\Upsilon(1S) \to$ Invisible

PRL 103, 251801 (2009)

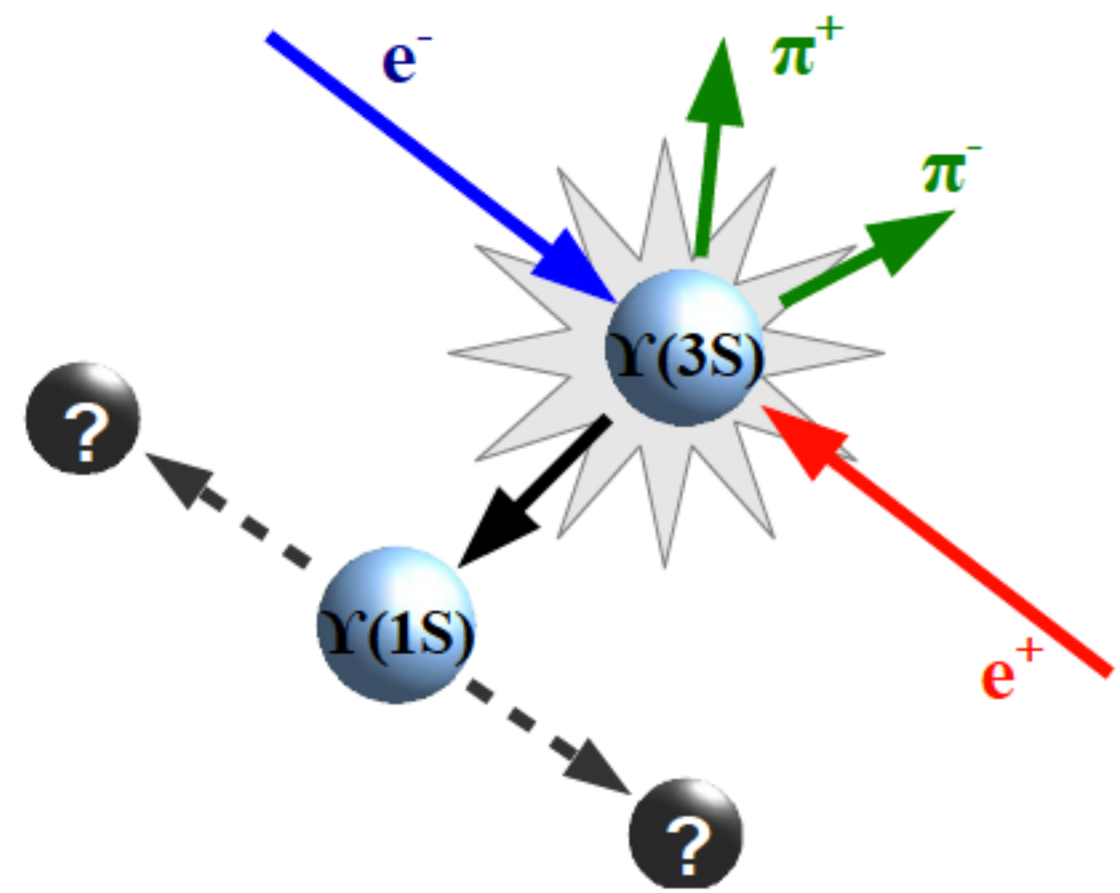
Υ(1S)→invisible

Analysis

- Observation of SM particles coupling to undetectable final states might provide information on candidate dark matter constituents
- Identify the Υ(1S) from the Υ(3S) → Υ(1S) ππ with recoil dipion mass consistent with Υ(1S)

$$M^2_{\rm rec} = s + M^2_{\pi\pi} - 2\sqrt{s}E^*_{\pi\pi}$$

- Select two soft pions and absence of significant additional activity in the detector ("invisible" sample)



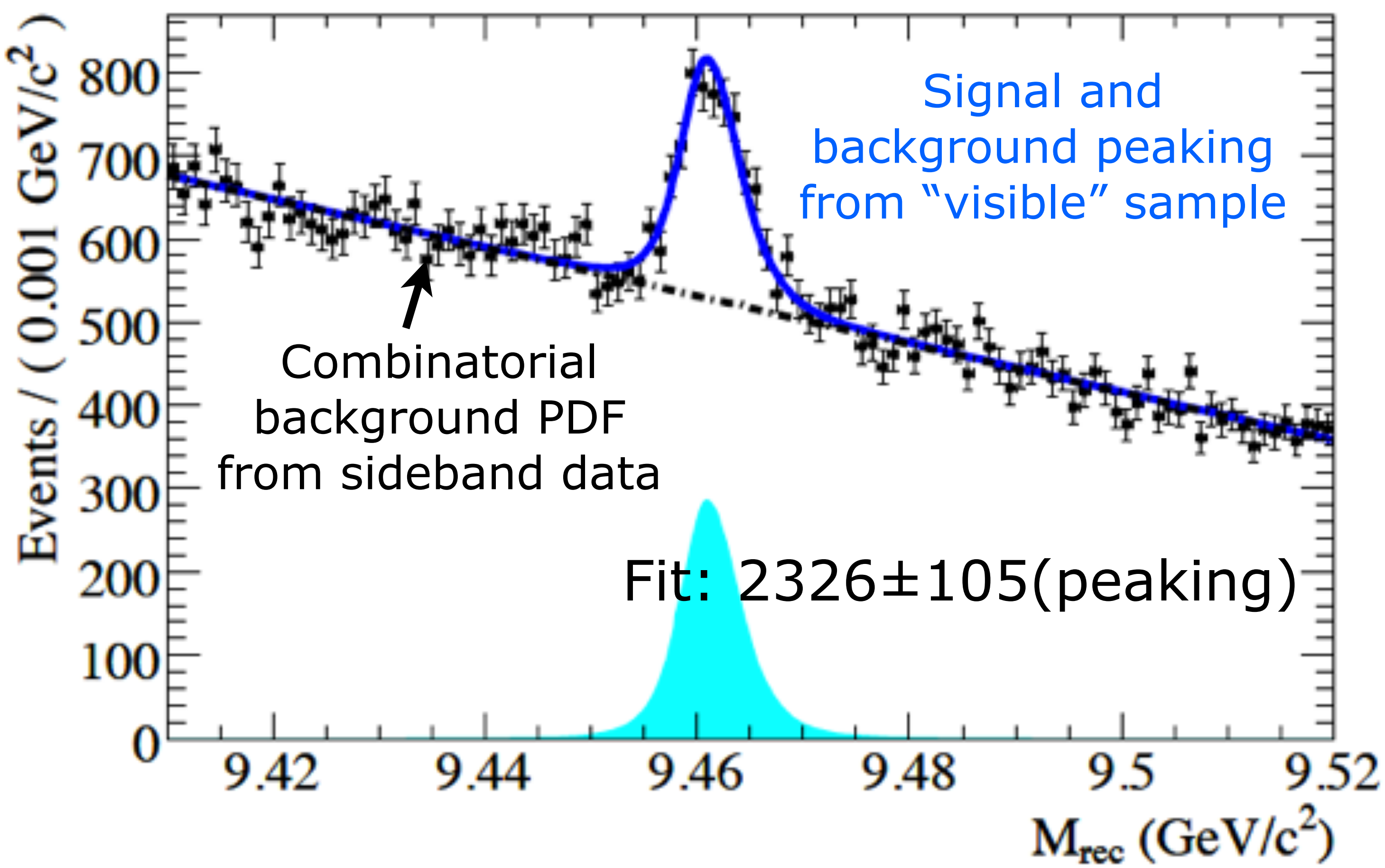
Main background comes from:

- Peaking background: Υ(1S) final state undetected
- non-peaking bckg: two pairs of low-momentum pions

$\Upsilon(1S)\rightarrow$*invisible*

Fit & Results

- Used MVA to suppress non-peaking background (trained on sideband data and signal MC, optimized to minimize background statistical error)
- Used "visible" data sample ($\Upsilon(1S) \rightarrow$ 1or 2 tracks) to check and correct MC predictions for the peaking background



Estimated yield and corrected (from MC): 2444±123 (peaking)
Signal yield: -118±105(stat.)±124(syst.)

$B(\Upsilon(1S) \rightarrow \text{invisible}) = -1.6 \pm 1.4(\text{stat}) \pm 1.6(\text{syst}) \times 10^{-4}$
$< 3.0 \times 10^{-4}$ at 90% C.L

Previous limits: $<3.9\times10^{-3}$ (CLEO), $< 2.5\times10^{-3}$ (Belle) at 90% C.L

Lepton Universality test in:

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

PRL 104,191801(2010)

LU test

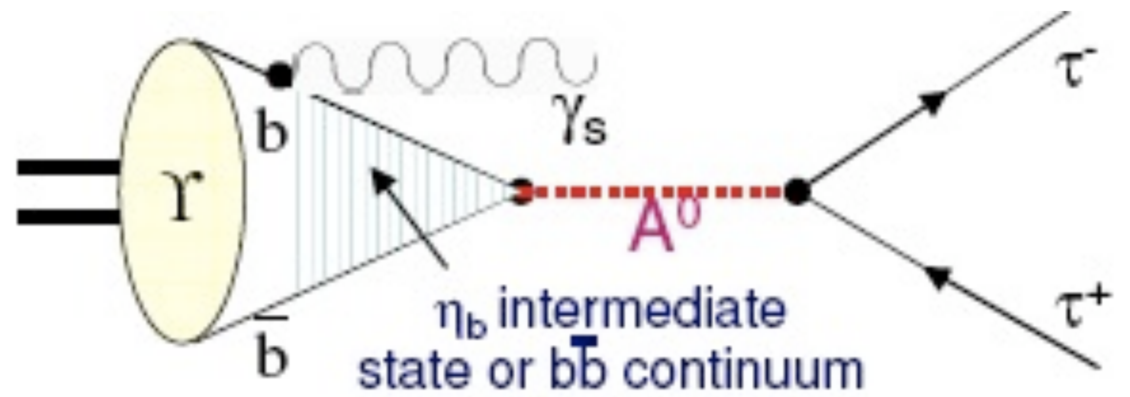
Theory

- In the SM couplings of gauge bosons to leptons are independent of the lepton flavor
- SM expectation for $\mathbf{R_{ll'}=BF(\Upsilon(nS)\rightarrow l^+l^-)/BF(\Upsilon(nS)\rightarrow l'^+l'^-)\sim 1}$

  (except for small lepton-mass effects, $R_{\tau\mu}\sim 0.992$)

- In NMSSM deviations from $\mathbf{R_{ll'}}$ may appear due to the existence of a light pseudo-scalar Higgs boson $\mathbf{A^0}$ mediating the decay

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

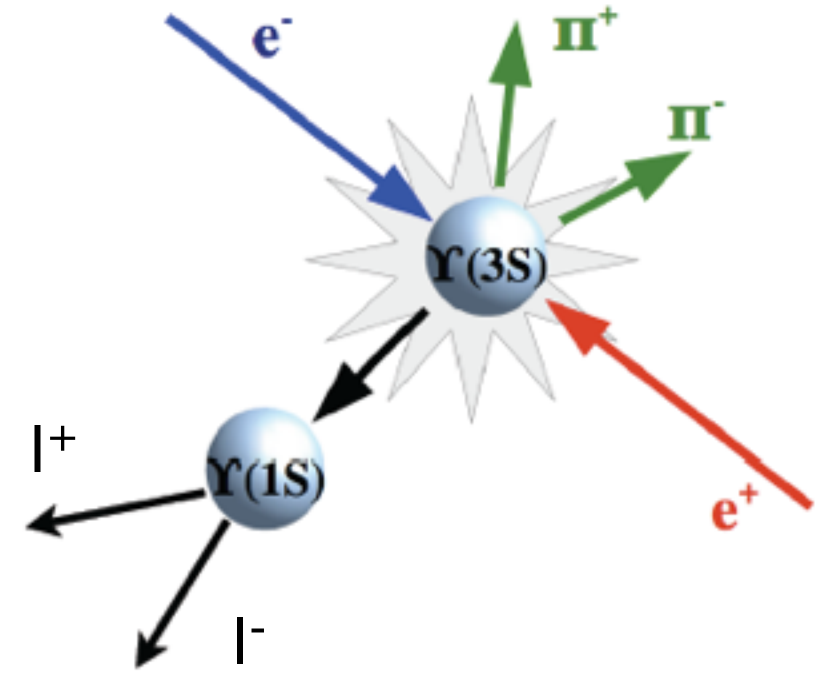


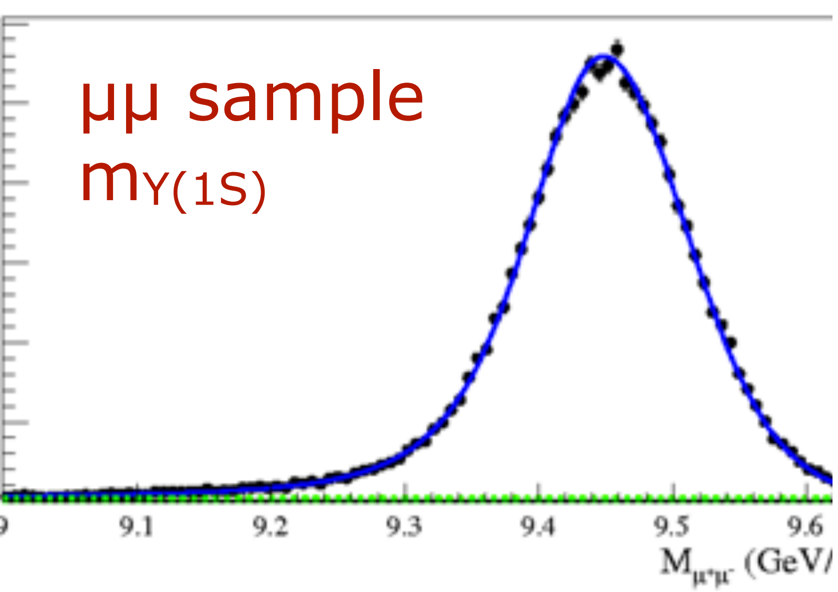
- A deviation from $\mathbf{R_{ll'}\sim 1}$ will be observed due to the proportionality of the coupling of the Higgs to the lepton mass

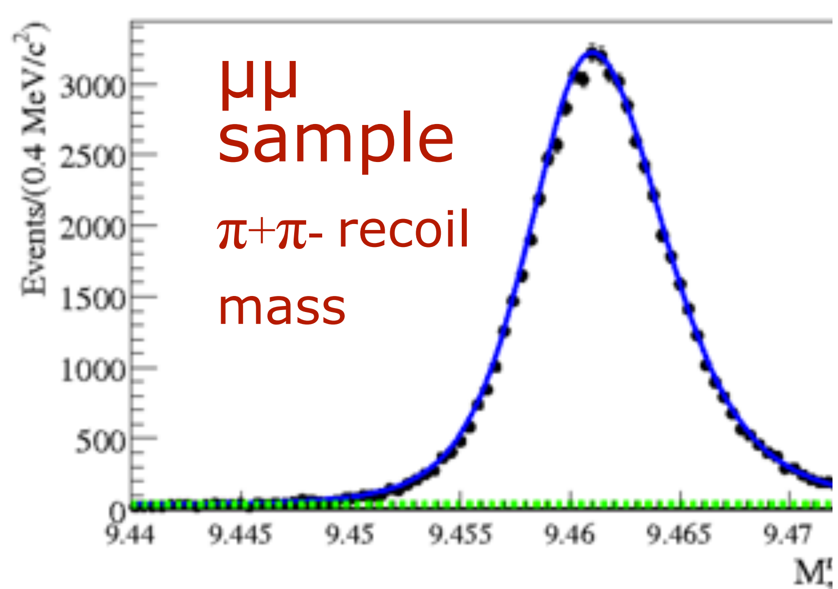
LU test

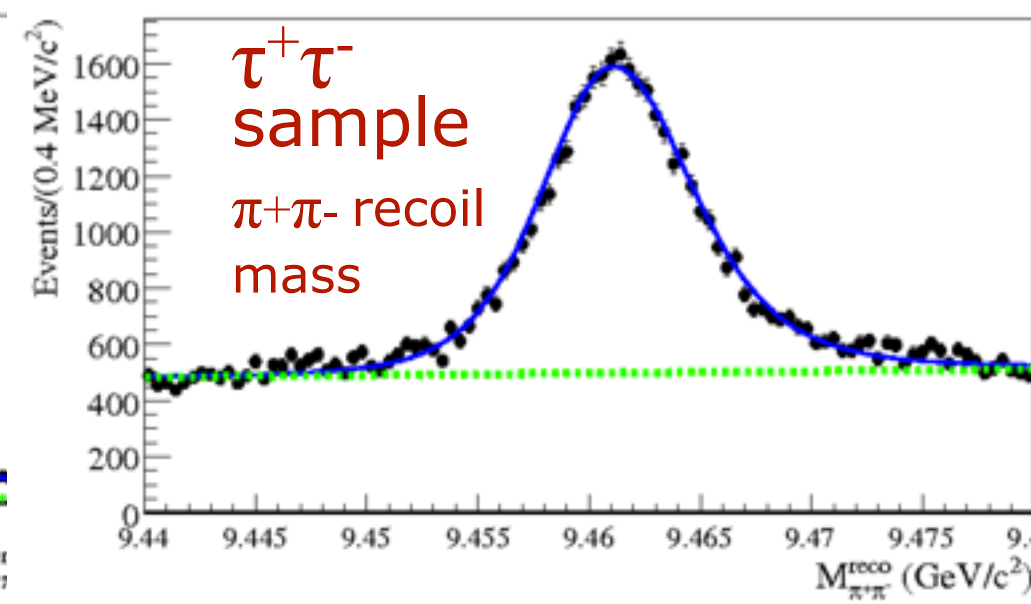
Result

- Used the dedicated Υ(3S) sample, ~122M Υ(3S) events
- Tag Υ(1S)exploiting $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ (BF ~ 5%),$\Upsilon(1S) \to \tau^+\tau^-$ and $\mu^+\mu^-$
- Difficulty of the analysis is the $\tau^+\tau^-$ channel:
  - -separate selection for $\tau^+\tau^-$ and $\mu^+\mu^-$
  - -for $\tau^+\tau^-$ mode a multivariate analysis needed to handle the background









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

Improved respect to CLEO:
$R_{\tau\mu}(\Upsilon(1S))$: 1.02 ± 0.02 (stat.) ± 0.05 (syst.)]

PRL98, 052002 (2007)

Direct search for Dark sector

arXiv: 0908.2821 [hep-ex]

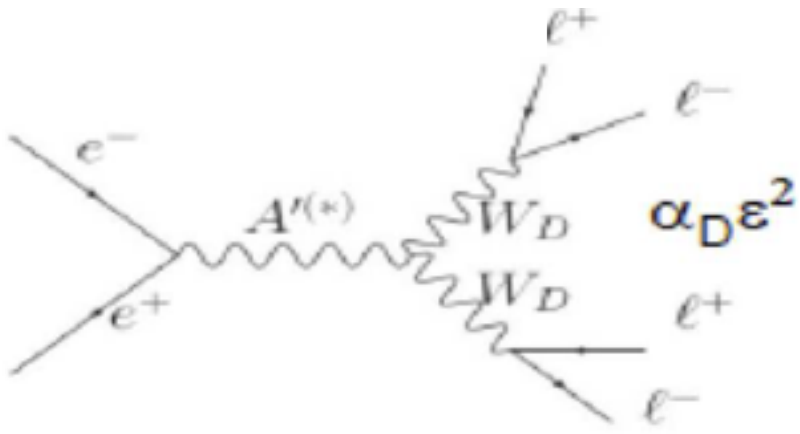
Direct search for Dark sector

Full BaBar dataset 536fb^{-1}

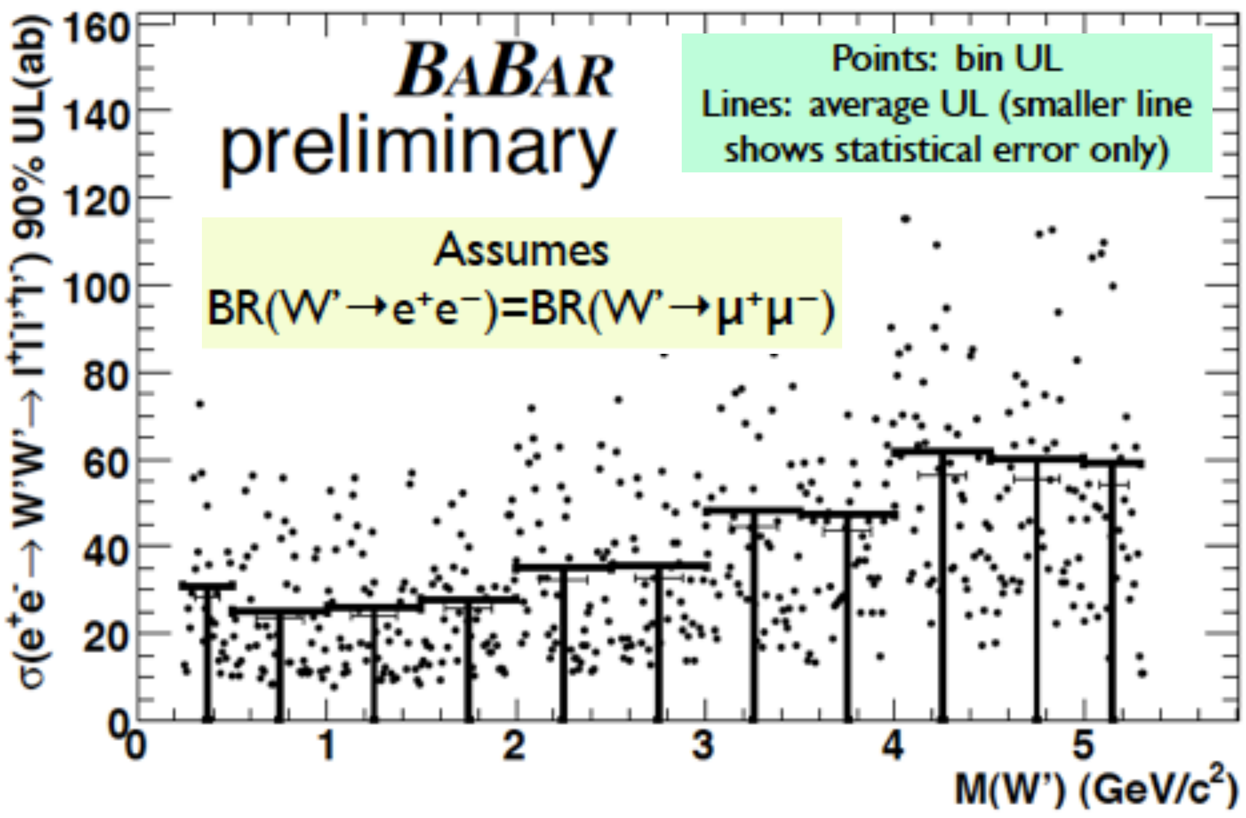
Fit & Results

N. Arkani-Hamed et al.
PRD 79, 015014 (2009)

- New "dark force" with gauge boson W'~ GeV while the dark matter particle is ~TeV scale



- Signature: 4 leptons (4e,2e+2μ,4μ) with zero total charge carrying the full beam momentum where the two dilepton invariant masses are equal (bkg from 4-lepton QED processes)
- Look for a narrow peak in the mass distribution of W' in the mass range from 0.24 and 5.3 GeV
- Signal extraction by a cut-and-count analysis in bins of m_W (10MeV step)



No significant signal observed-->Set UL (90%CL)

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

Conclusions

- No significant signal of a light scalar particle (e.g. CP-odd Higgs) in radiative decays of $\Upsilon(3,2S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$ and $\Upsilon(3S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$, on dipion transitions of $\Upsilon(2S) \rightarrow \Upsilon(1S)\,\pi\pi$, $\Upsilon(1S) \rightarrow \gamma$ Invisible, and on indirect searches through a test of lepton universality
    - Set upper Limits that rule out some parameters space of New physics Models
- No evidence $\Upsilon(3S) \rightarrow \Upsilon(1S)\,\pi\pi$, $\Upsilon(1S) \rightarrow (\gamma)$ Invisible
    - Constrains models with light dark matter
- No evidence for the process $e^+e^- \rightarrow W'W' \rightarrow l^+\, l^-\, l'^+\, l'^-$
    - No evidence for "dark forces"
- New BaBar results are expected so stay tuned!

THANK YOU!

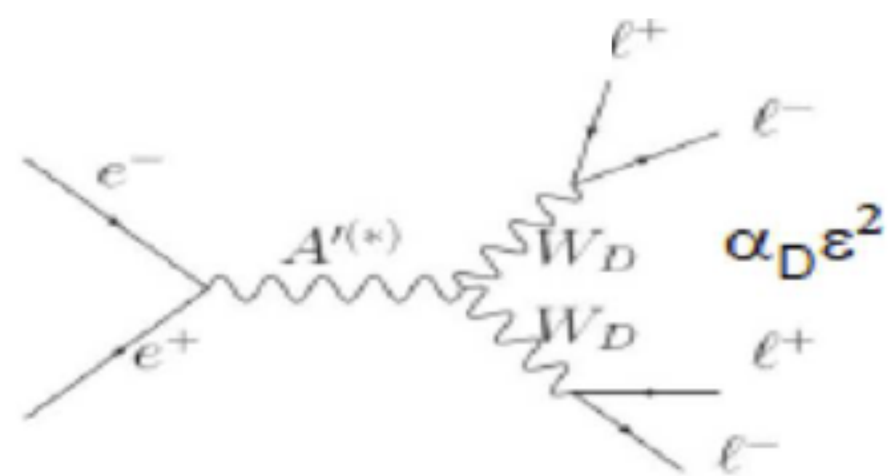
Neus Lopez March, Kruger National Park , Dec 2010

Direct search for Dark sector

Theory

- Models motivated by the galactic γ ray and positron emission from the galactic center (INTEGRAL, PAMELA, ATIC, etc...)
- New "dark force" with gauge boson W_D~ GeV while the dark matter particle is ~TeV scale
- Coupling to leptons due to small mixing SM and Dark sector
- Decays to lepton pairs (e^+e^-, $\mu^+\mu^-$) but not pp because W_D is bellow pp threshold (2GeV)

Generic dark boson
Non-abelian structure



Look for the exclusive pair production of a narrow resonance at B-factories

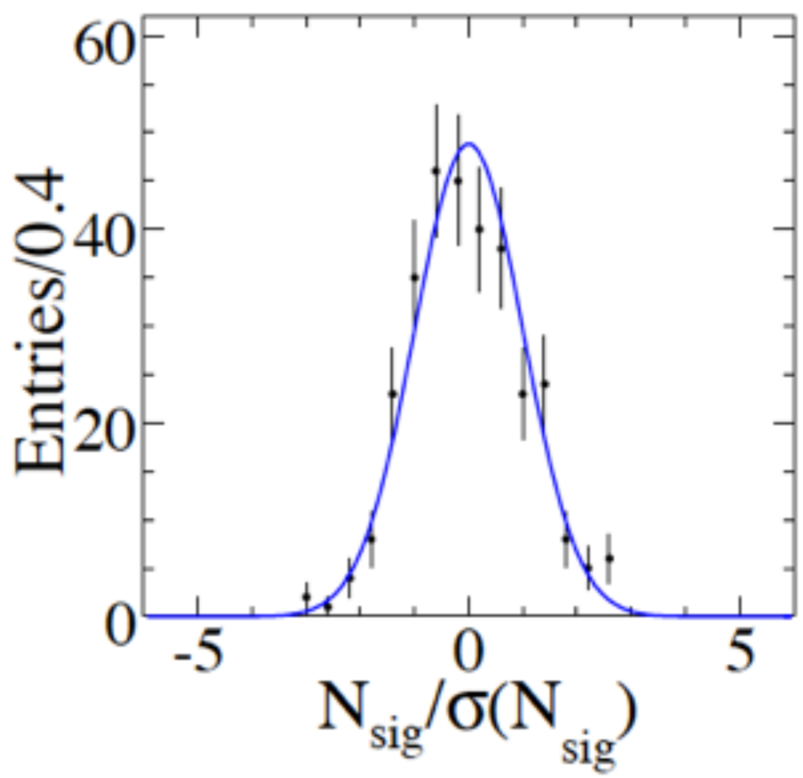
N. Arkani-Hamed et al.
PRD 79, 015014 (2009)

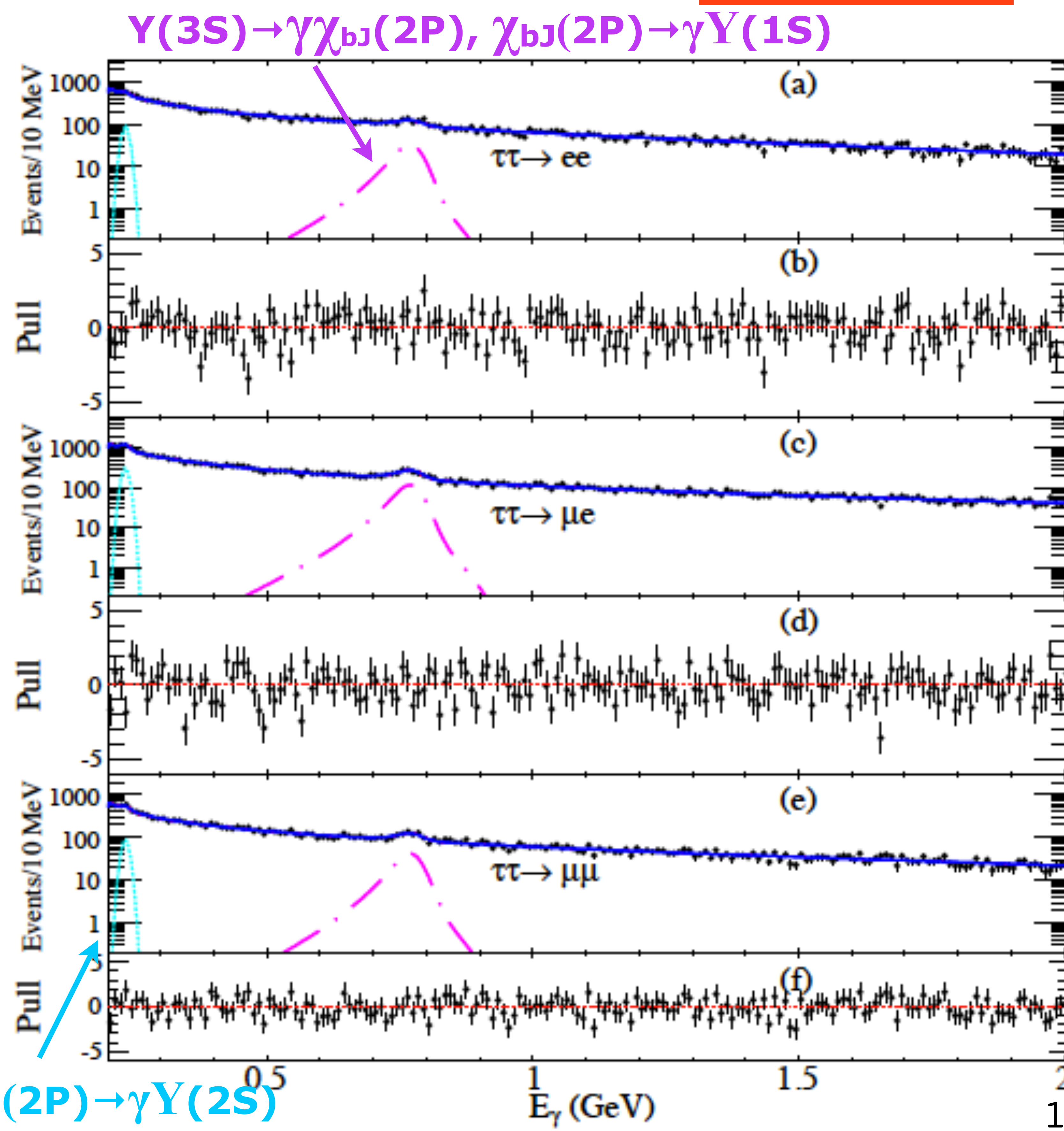
$A^0 \to \tau\tau$

Fit

Scan for peaks in the E_γ distribution in steps of half the resolution (307 scans in total)

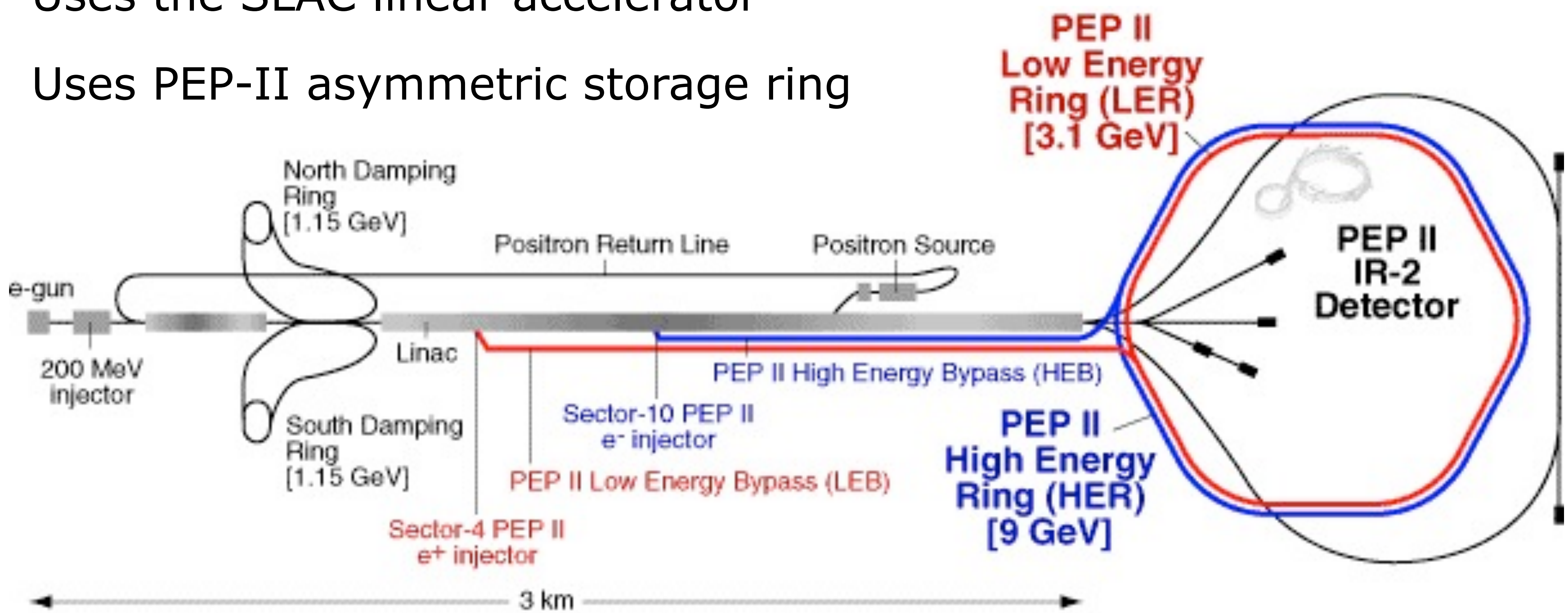
In a range corresponding to $4.03 < M(A_0) < 10.10$GeV





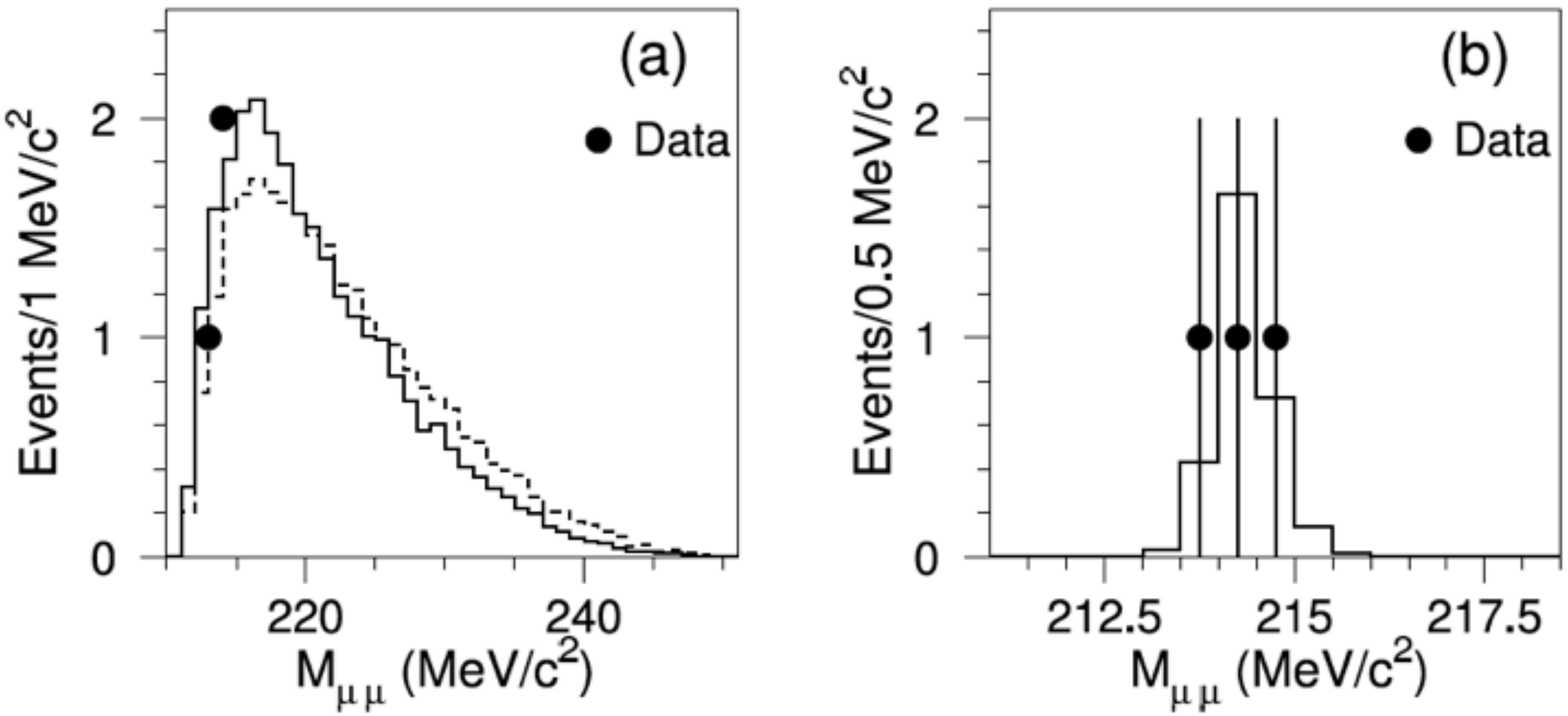
BABAR experiment

- e^+e^- machine located at SLAC (IR2)
- Operates at the Υ(4S) resonance (10.58GeV)
- Uses the SLAC linear accelerator
- Uses PEP-II asymmetric storage ring



- Use asymmetric beams, Υ(4S) is boosted in the lab frame ($\gamma\beta$~0.56) to separate B decay vertices along the z axis

Motivation

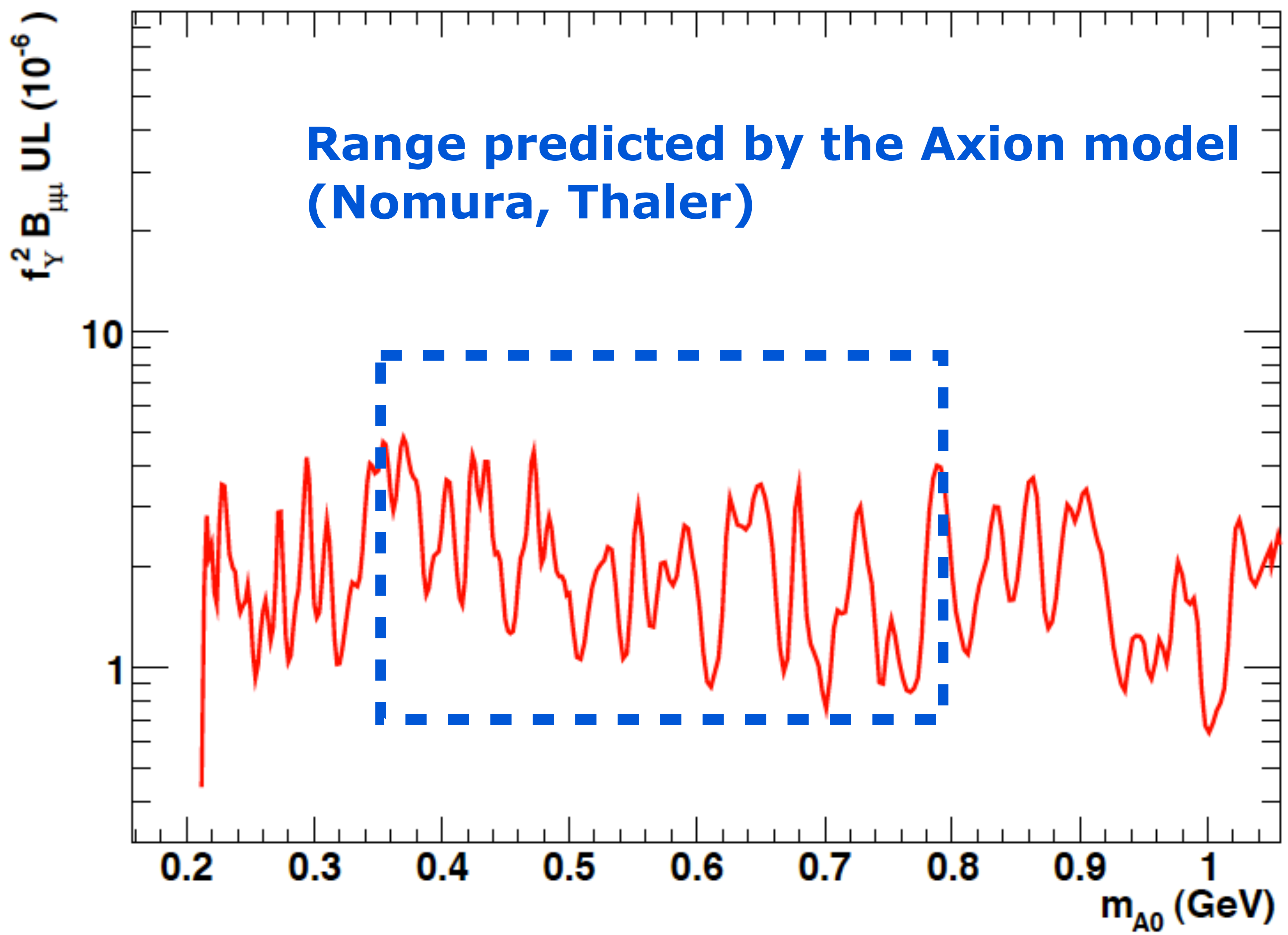


(a)
Data
Events/1 MeV/c^2
0
1
2
220
240
$M_{\mu\mu}$ (MeV/c^2)
(b)
Data
Events/0.5 MeV/c^2
0
1
2
212.5
215
217.5
$M_{\mu\mu}$ (MeV/c^2)

$A^0 \to \mu\mu$

Result

ZOOM

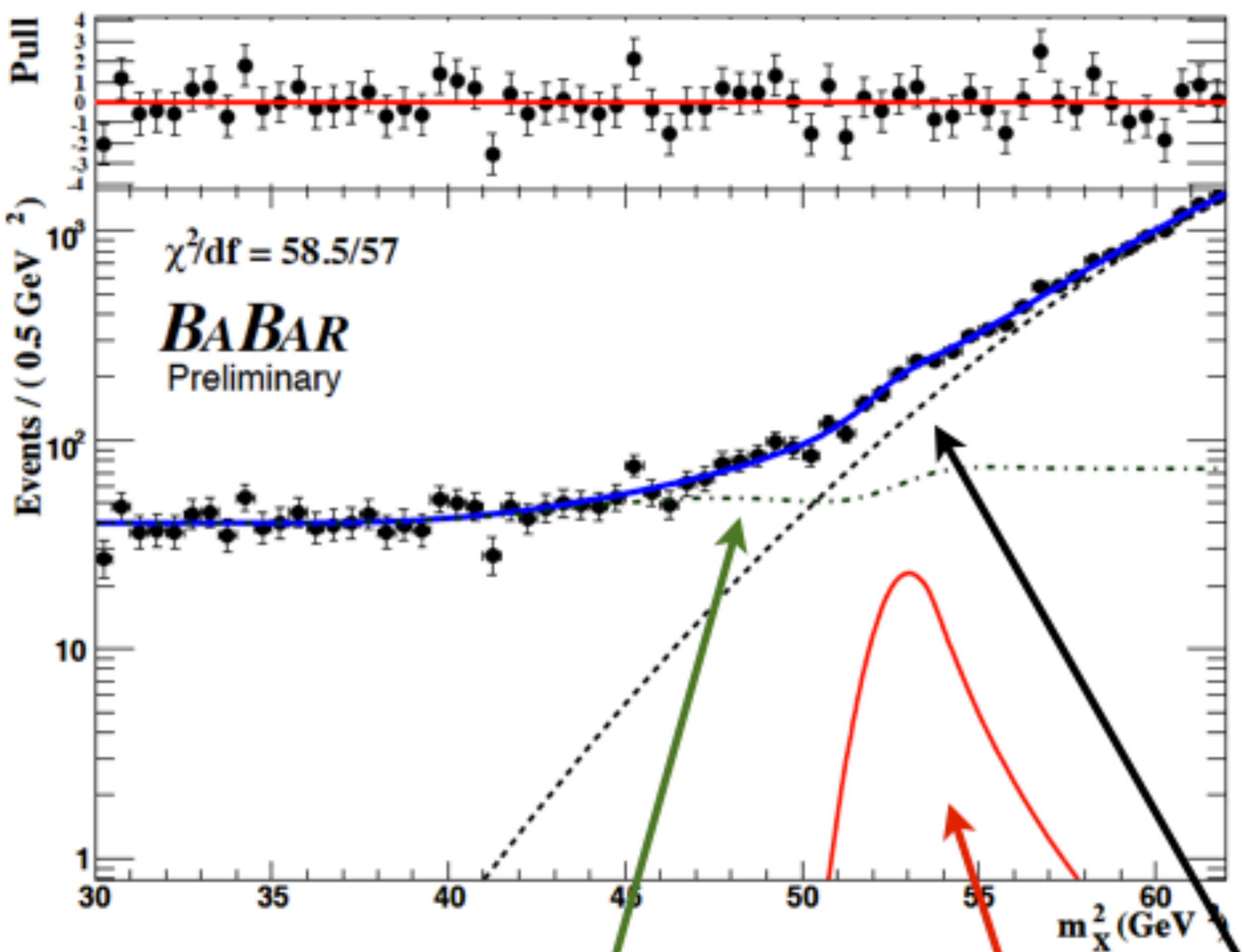


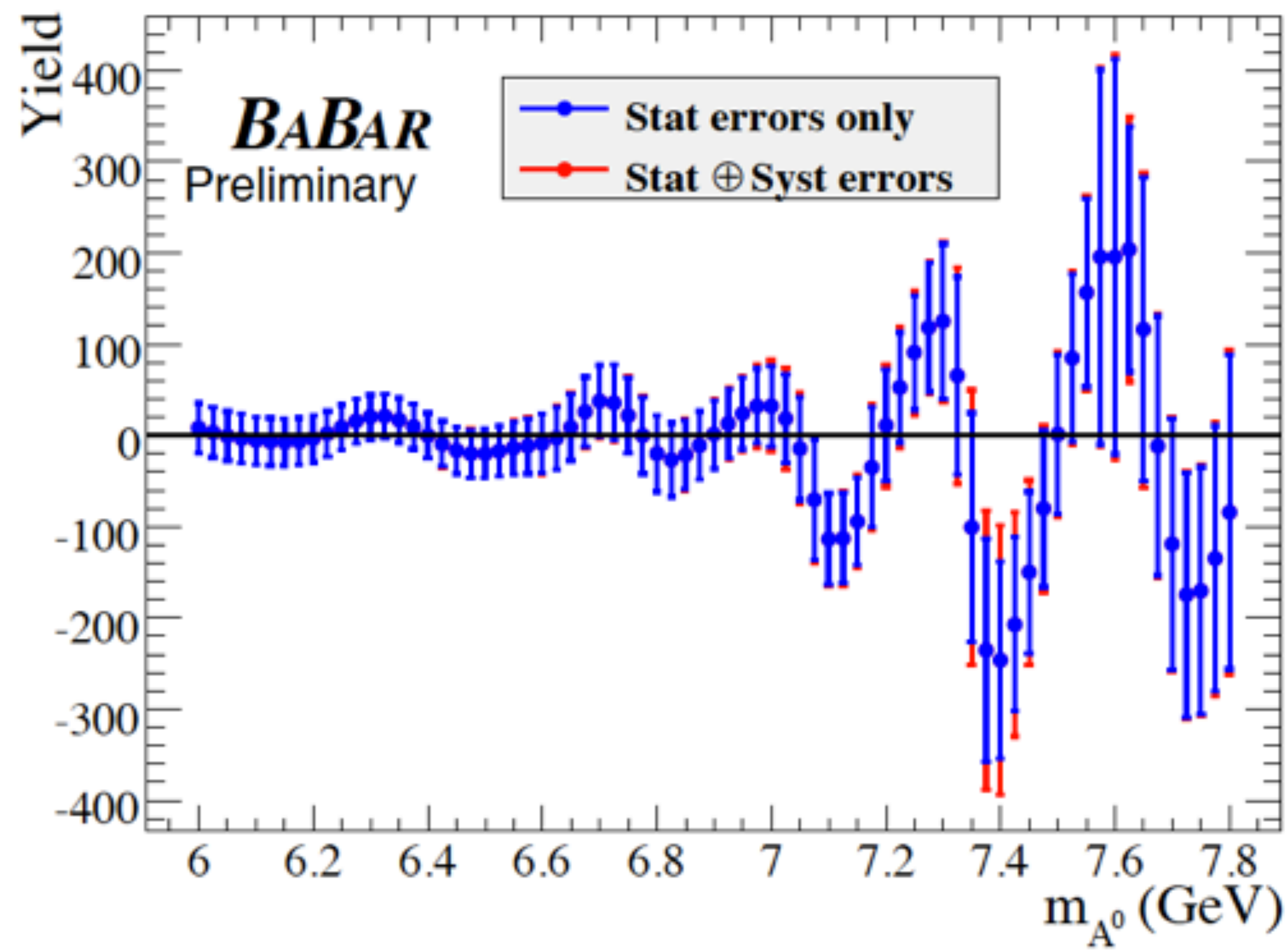
$A^0 \rightarrow$ Invisible

LowE Fit

83M Υ(3S)

Fit for m_{A0}=7.3 GeV:
N_{signal}=119±71 events,
1.7σ significance (stat only)





γγ contribution
(110±46 events, fixed)

Signal

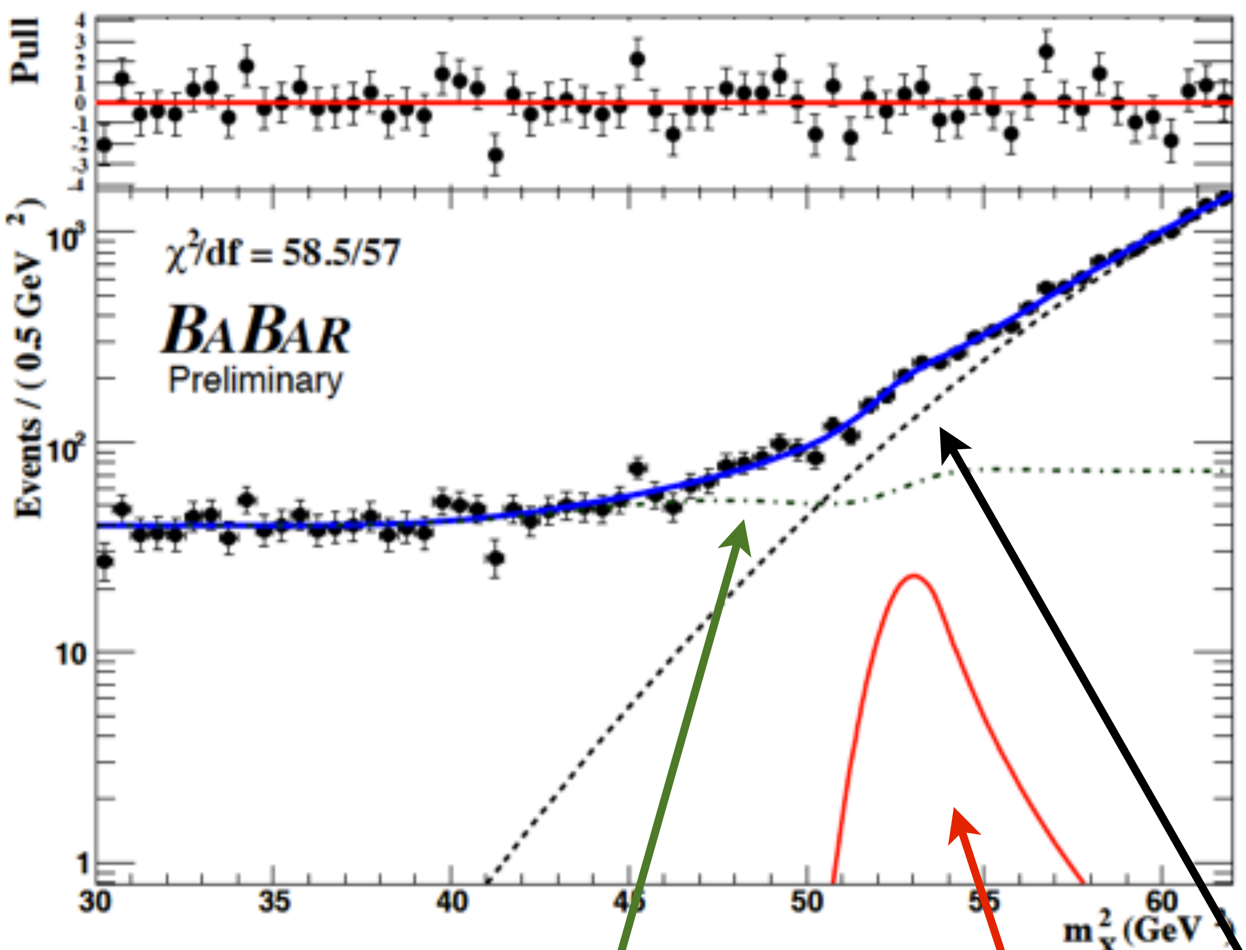
Bhabha contribution
(yield and shape float.)

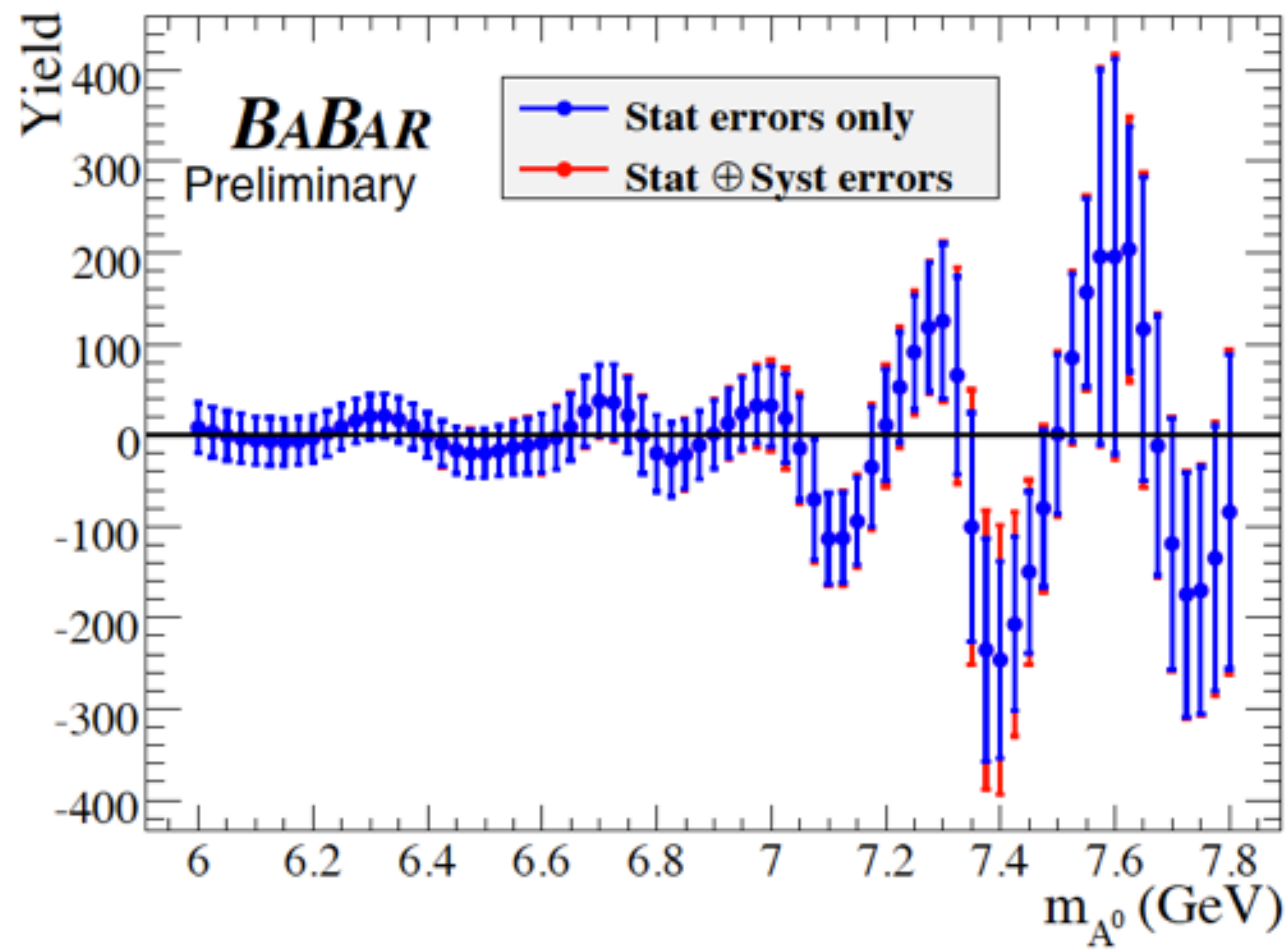
$A^0 \rightarrow$ *Invisible*

LowE Fit

83M Υ(3S)

Fit for m_{A0}=7.3 GeV:
N_{signal}=119±71 events,
1.7σ significance (stat only)



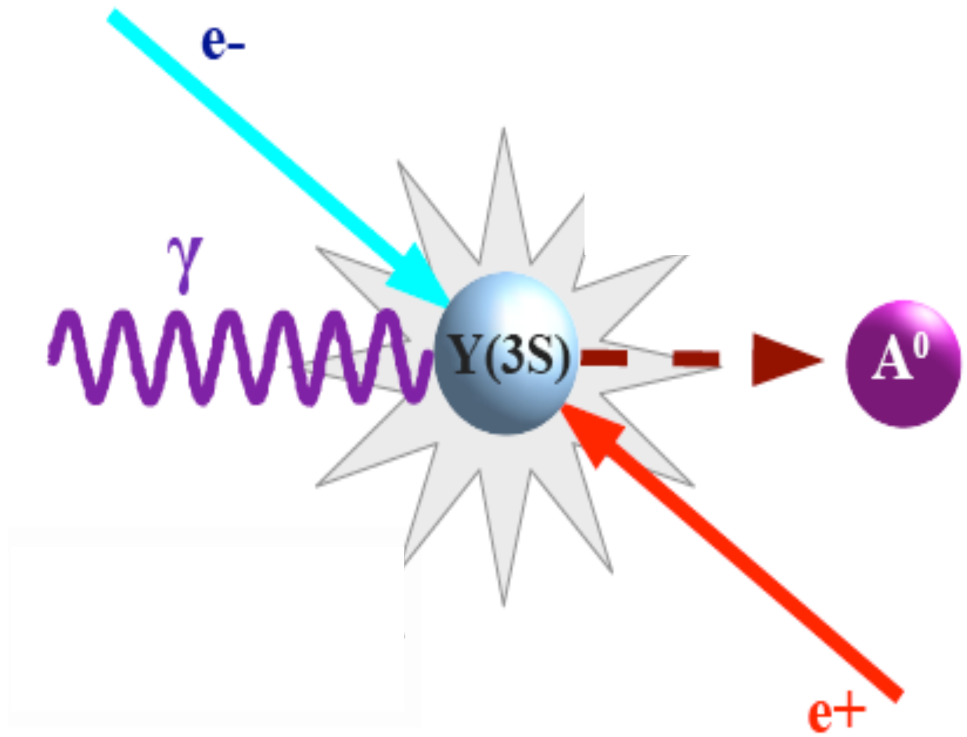


$\gamma\gamma$ contribution
(110±46 events, fixed)

Signal

Bhabha contribution
(yield and shape float.)

Channels used



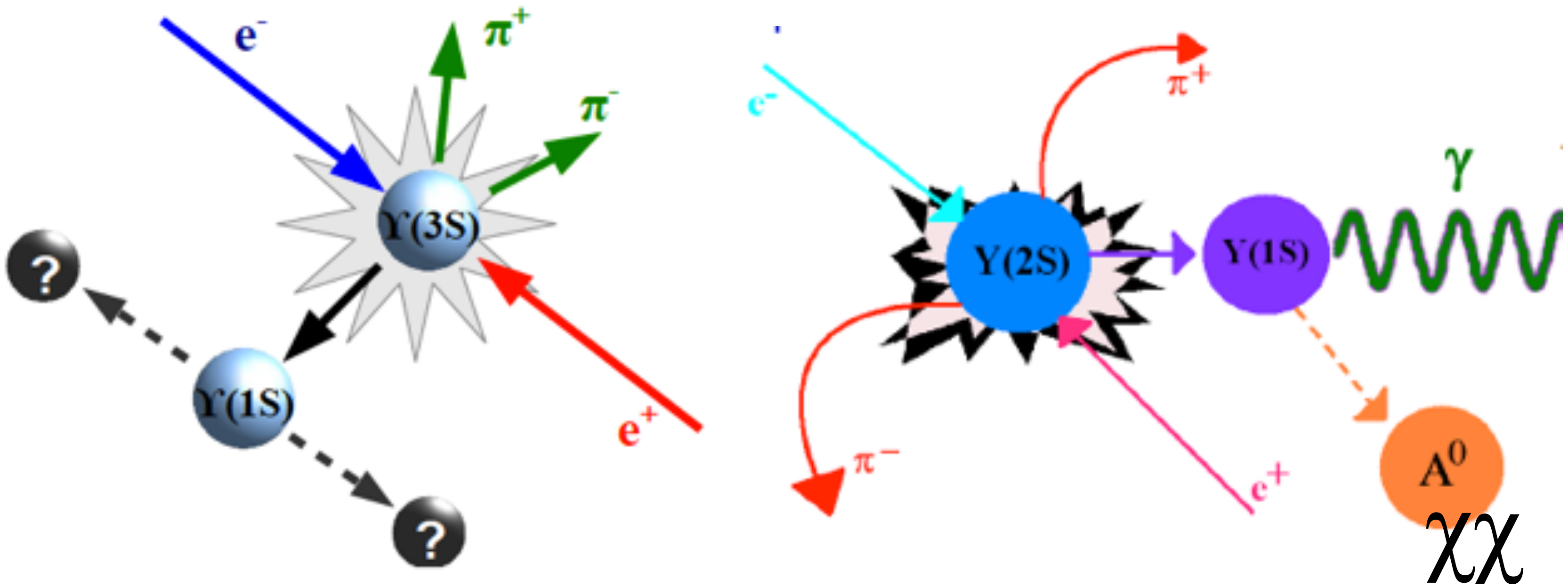
Look for a peak in m(l+l−)spectrum

$A^0 \rightarrow \mu\mu$

$A^0 \rightarrow \tau\tau$

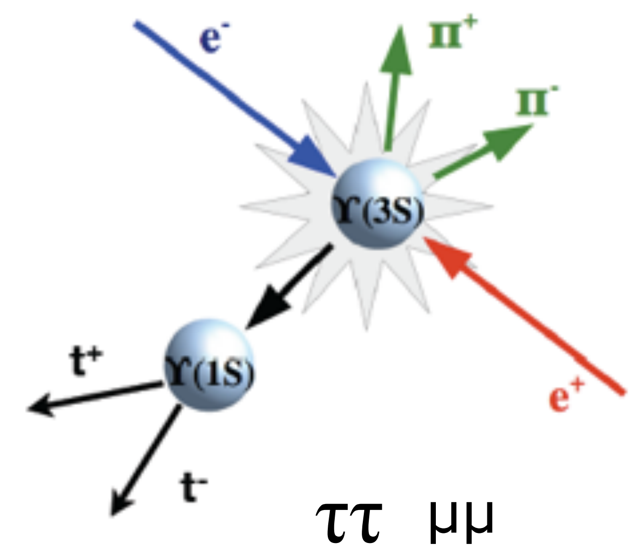
Look for peak in the “missing mass”

$A^0 \rightarrow$invisible



Missing mass + recoil mass

$A^0 \rightarrow$invisible



Lepton Universality test

$A^0 \rightarrow$ *Invisible*

Analysis

- Two single trigger lines were used for this analysis -> the analysis was performed in two regions:

Low Energy region	High Energy region
$2.2 < E^*\gamma < 3.7$	$3.2 < E^*\gamma < 5.5$

- Use a limited number of variables (very low-multiplicity events): photon quality, fiducial selection of primary photons, veto extra particles in the event (no charged particles, cuts on the E of a second photon,...), IFR veto (detects missing photons on the EMC)

Bkg: $e^+e^- \rightarrow e^+e^- \gamma$

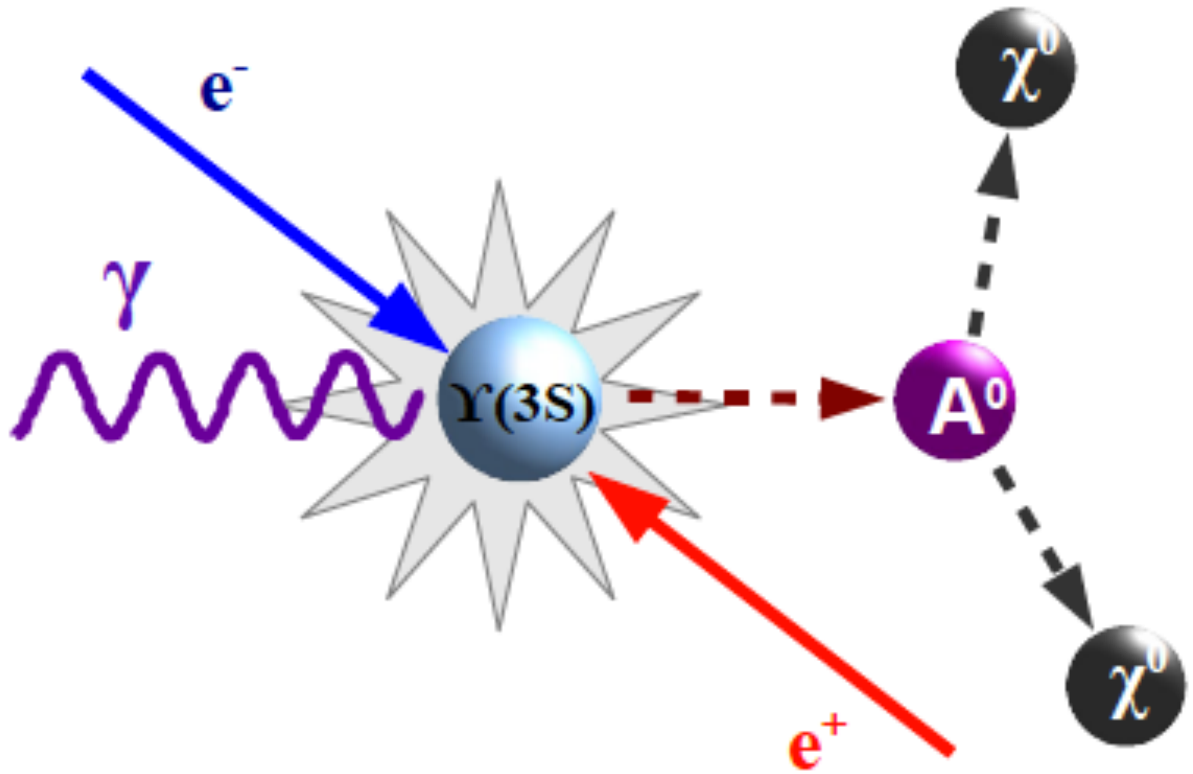
Bkg: $e^+e^- \rightarrow \gamma\gamma$

$A^0 \rightarrow$ *Invisible*

Analysis

122 x 10^6 Υ(3S) decays

- $A^0 \rightarrow \chi^0\chi^0$ can be dominant decay in some NMSSM scenarios with a light neutralino (LSP)
- Search for one energetic photon in the final state: $\Upsilon(3S) \rightarrow \gamma A^0$ and look for a bump in E^*_γ or missing mass
- Selection based on photon quality and fiducial requirements and the presence of additional detector activity in the event
- Two different single-photon trigger lines used, naturally split low and high E_γ regions



Main background comes from:

- $e^+e^- \rightarrow \gamma\gamma$ (High energy region)
- $e^+e^- \rightarrow e^+e^-\gamma$ (Low energy region)

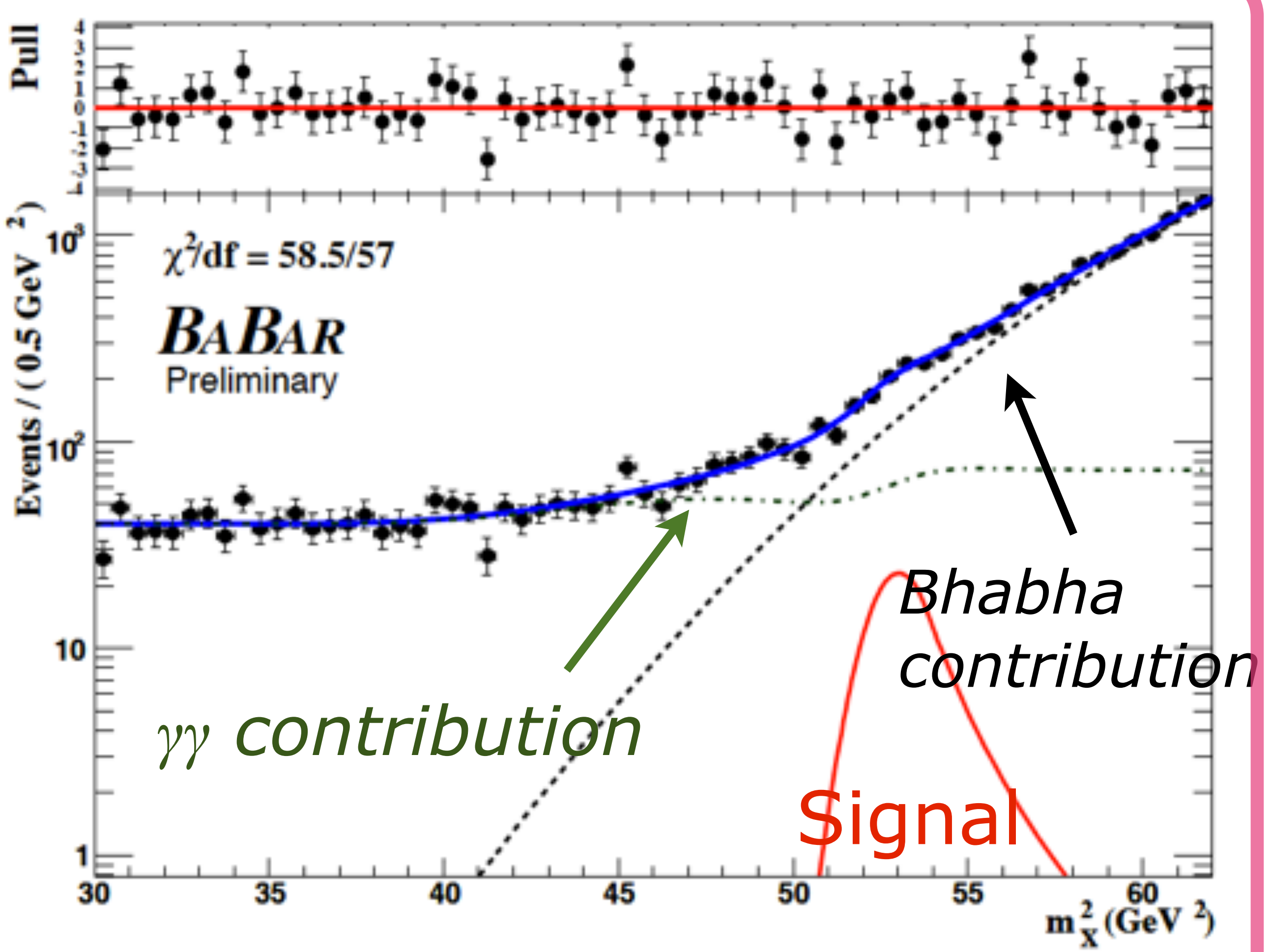
$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$

$A^0 \rightarrow$ *Invisible*

Fit

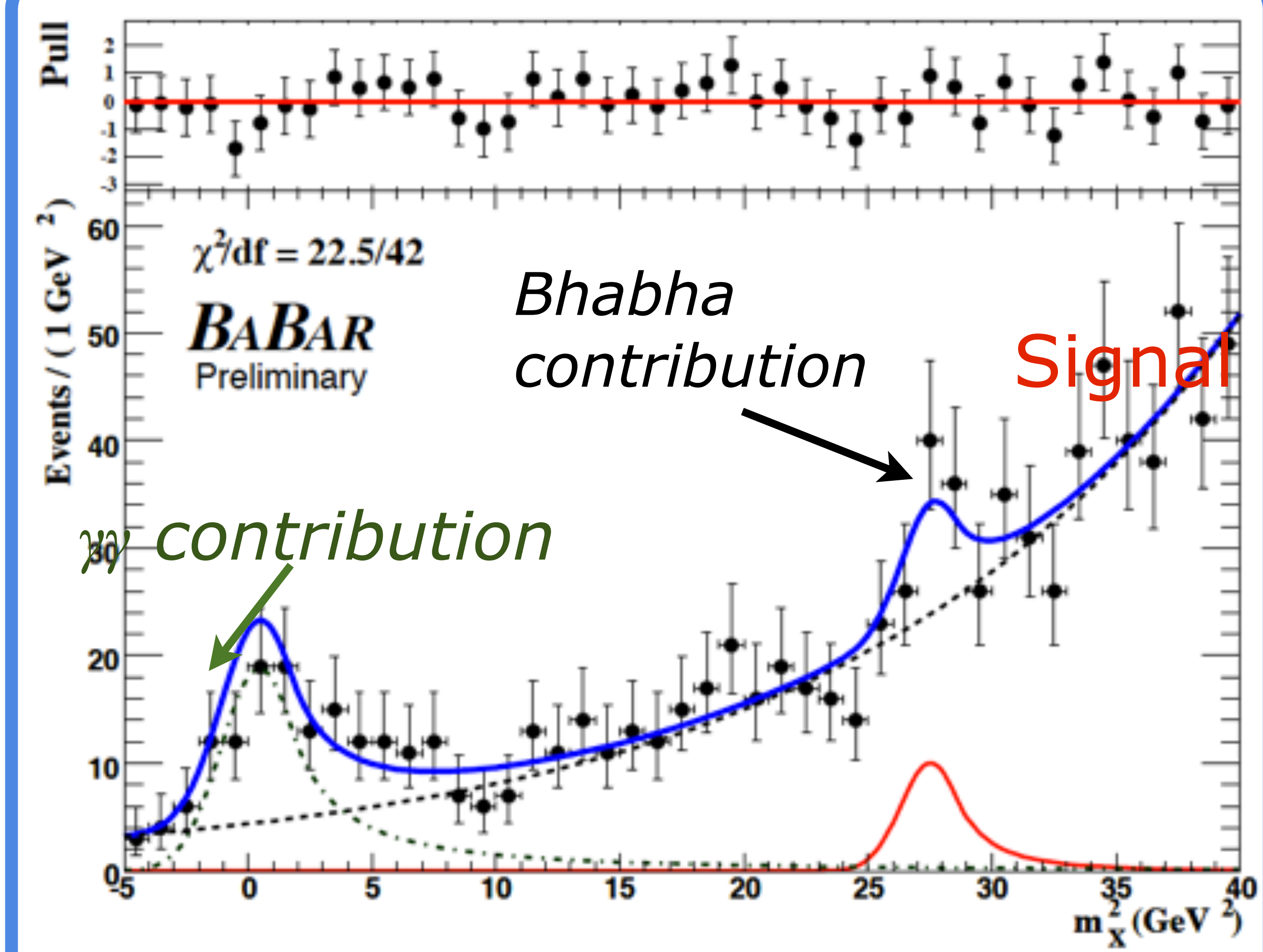
- Fit to the missing mass squared: $m^2_X = m^2_{\Upsilon(3S)} - 2E^*_\gamma\, m_{\Upsilon(3S)}$ (steps 0.1GeV)
- Extract signal yields as a function of m_A, in the mass range $m_A < 7.8$GeV

Low energy region $2.2 < E^*\gamma < 3.7$



- Fit for m_{A0}=7.3 GeV:
  N_{signal}=119±71 events,
  1.7σ significance (stat only)

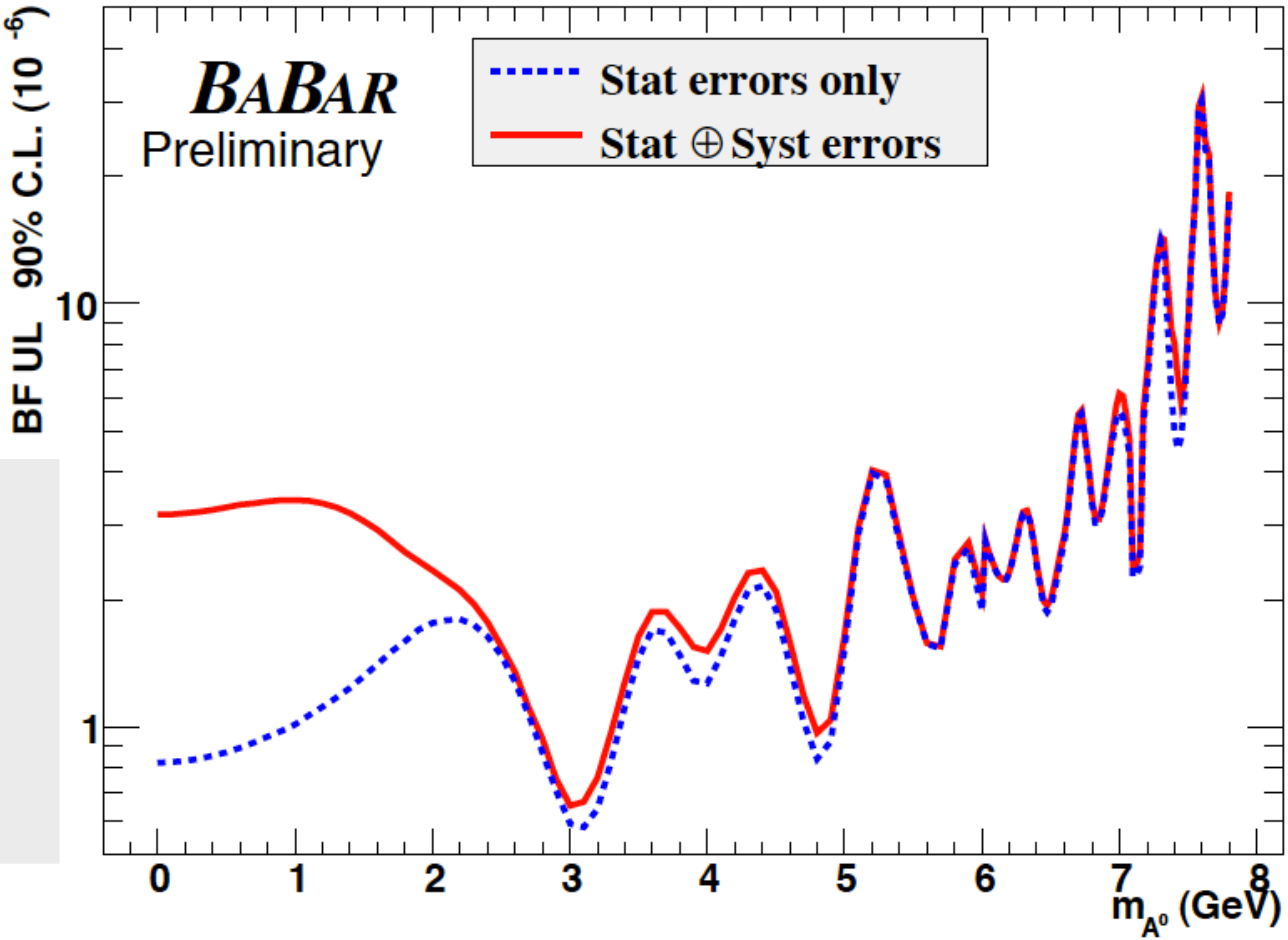
High energy region $3.2 < E^*\gamma < 5.5$



- Fit for mA0=5.2 GeV:
  N_{signal}=37±15 events
  2.6σ significance (stat. only)

$A^0 \rightarrow$ Invisible

Results



No significant signal, limits BR and constrains NMSSM parameters.