Searches for dark photons at BABAR

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(on behalf of BABAR Collaboration)

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Outline

- ✓ Introduction to the Dark sector
- ✓ ***BABAR*** potentiality
- ✓ Analyses which can be reinterpreted in terms of dark photon searches:
  - ✓ $\Upsilon(3S,2S) \to \gamma$ + hadrons — **PRL 107 (2011) 221803 [arXiv:1108.3549]**
  - ✓ $\Upsilon(3S) \to \gamma + \mu^+\mu^-$ — **PRL 103 (2009) 081803 [arXiv:0905.4539]**
  - ✓ $\Upsilon(3S) \to \gamma + \tau^+\tau^-$ — **PRL 103 (2009) 181801 [arXiv:0906.2219]**
  - ✓ $\Upsilon(3S) \to \gamma$ + invisible — **arXiv:0808.0017**
- ✓ Future perspectives

Dark sector (I)

✓ Additional U(1) model (aka several names, among which dark force)

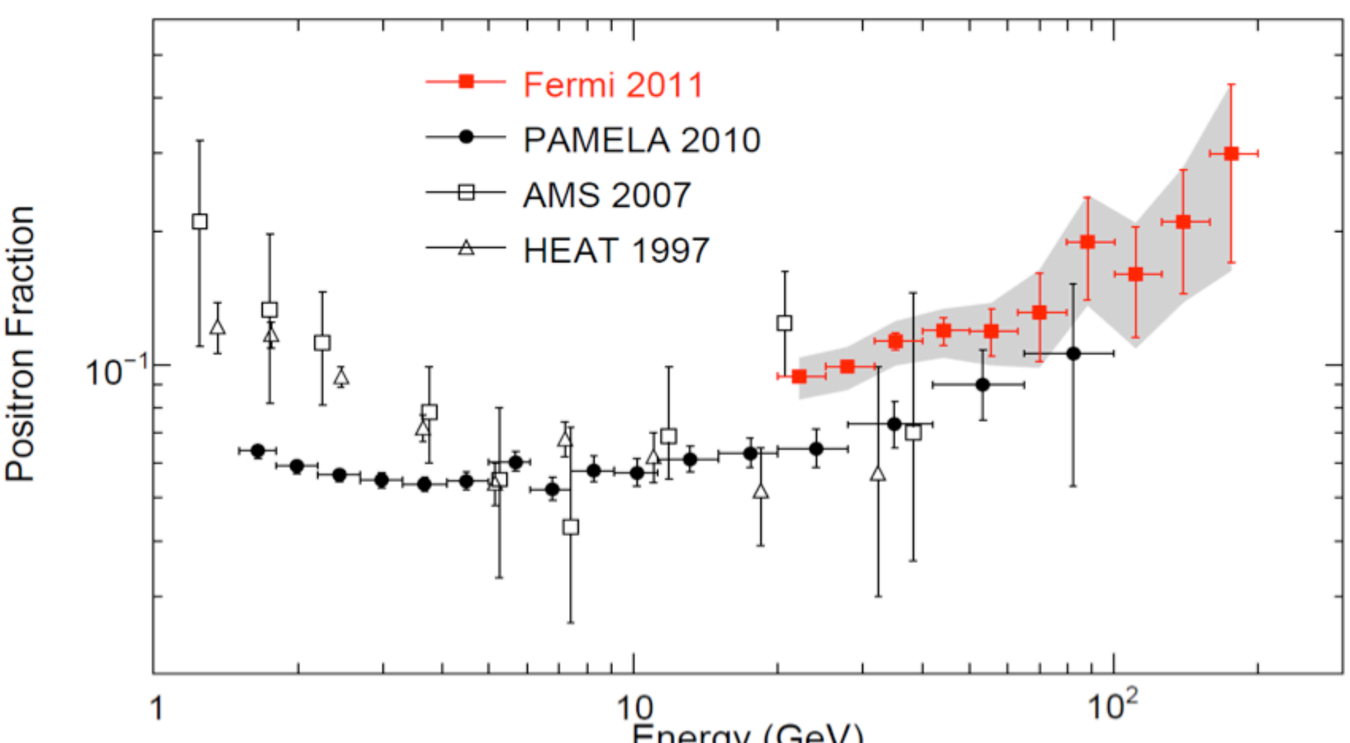
✓ a dark massive photon-like vector and a new light Higgs-like boson. Masses are O(GeV). Couplings to SM are small.

✓ introduced in order to explain several experimental observations (PAMELA, FERMI, DAMA/LIBRA, CREST...)

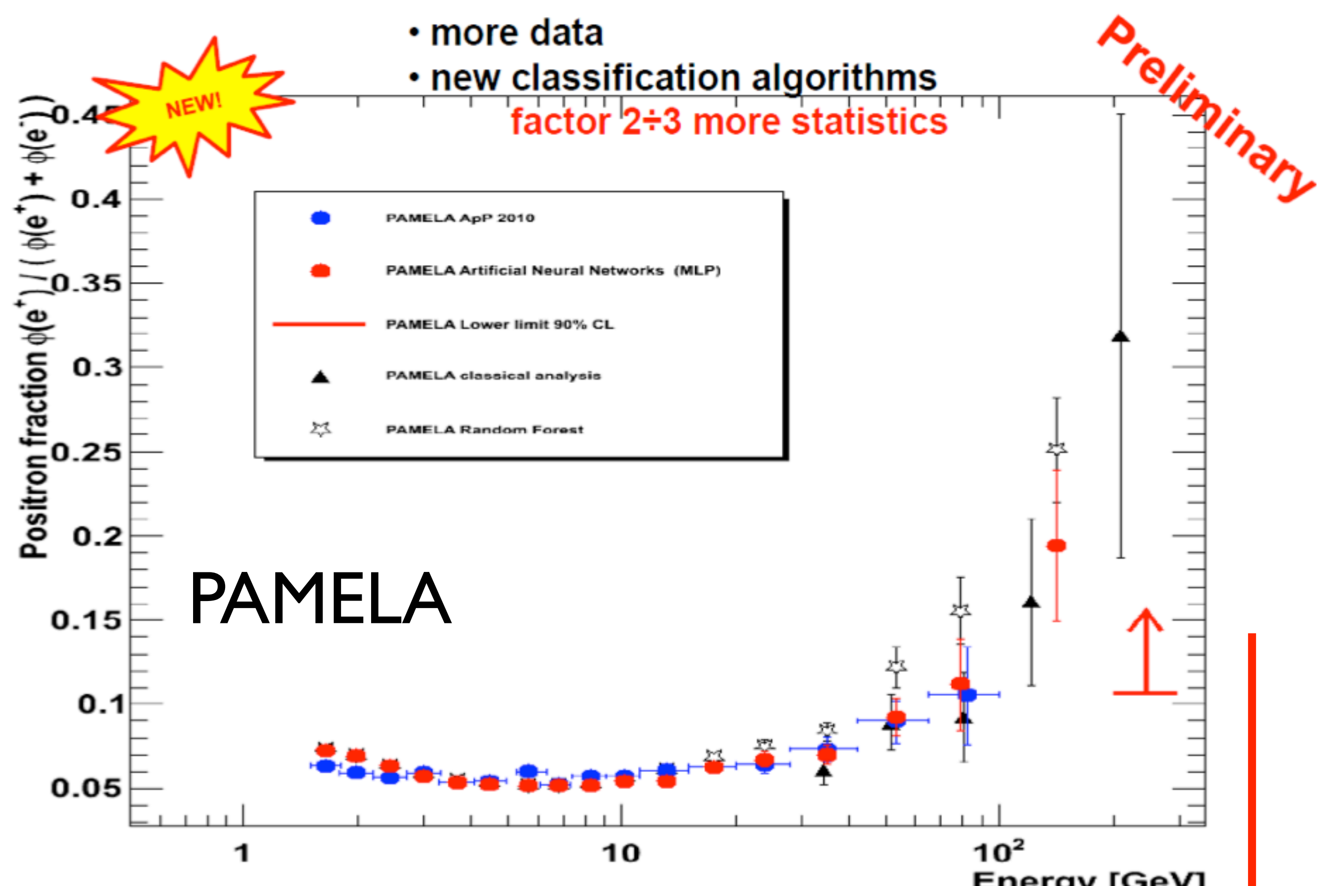
✓ Positron fraction can be explained in terms of secluded WIMPs (TeV scale): annihilation into pairs of dark bosons, subsequently decaying into lepton pairs

✓ Poorly constrained and worth exploring; e^+-e^- colliders offer a good environment in the search for new O(GeV) particles

FERMI



PRL 108 (2012) 011103 [arXiv:1109.0521]

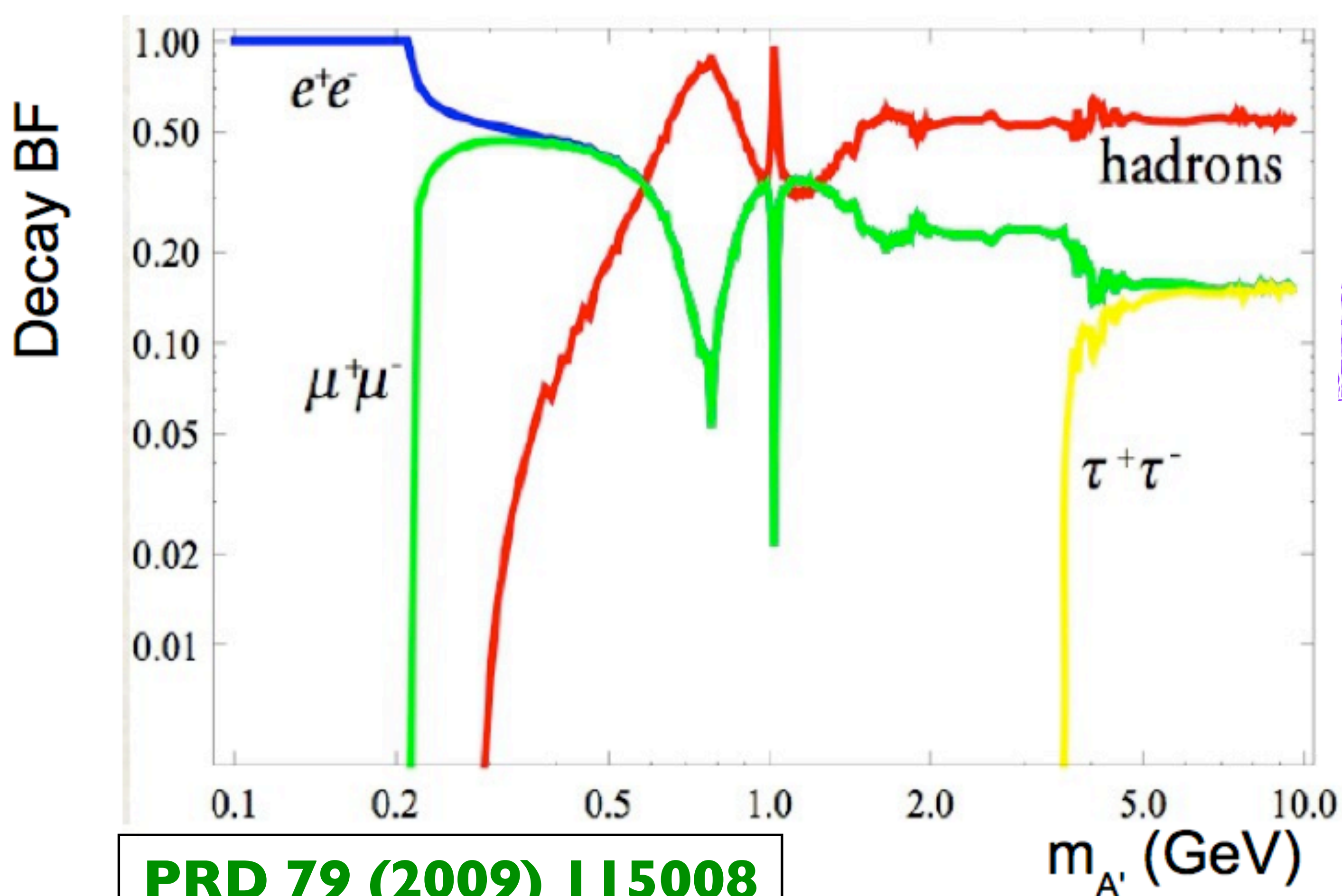


E.Mocchiutti, International workshop on positrons in Astrophysics 2012

Dark sector (II)

- ✓ New U(1) model attached to SM via a vector "portal", i.e. through kinetic mixing: $\Delta\mathcal{L}_{mix} = \varepsilon F^{\mu\nu}B_{\mu\nu}$
  - ✓ ε mixing angle controlling the coupling to SM
  - ✓ naturalness arguments seem to favor $\varepsilon \sim 10^{-4} - 10^{-2}$
  - ✓ ε being small ⟶ light - i.e. O(GeV) - new gauge bosons
- ✓ Dark photon (A') acquires a charge eε

dark photon branching fraction



PRD 79 (2009) 115008

- ✓ Assumption: no light dark fermions. A' has to decay back to SM particles. The coupling of A' to SM fermions is described by $\alpha' = \alpha\varepsilon^2$
- ✓ A' lifetime usually small (prompt decay)

$$\mathcal{B}(A' \to \text{hadrons})/\mathcal{B}(A' \to \mu^+\mu^-) = R(s = m_{A'}^2)$$

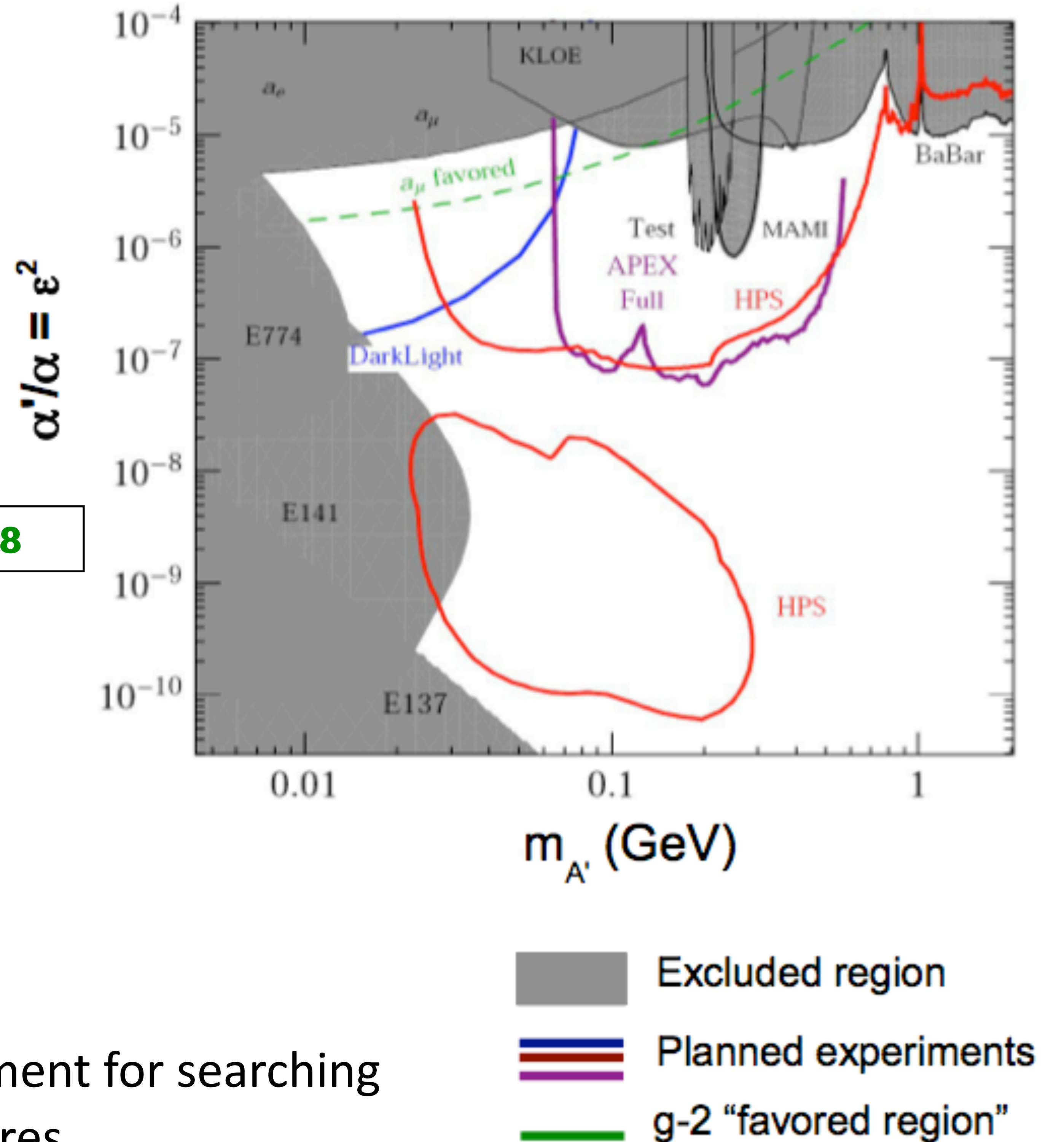
- ✓ Above 1.2 GeV, hadronic decays are dominant, but leptonic modes are still important

Dark sector (III)

✓ Current limits on the mixing strength ε^2 as a function of A' mass:

✓ Different experiments (some of them planned)

PRD 80 (2009) 075018



✓ In particular, e^+e^- colliders:

✓ **low-energy**

✓ **high-luminosity**

→ they offer a low-background environment for searching for MeV/GeV-scale hidden sector signatures

The *BABAR* detector

Cherenkov Detector

Particle identification (PID)
K-π separation >3.4σ for p<3.5GeV/c

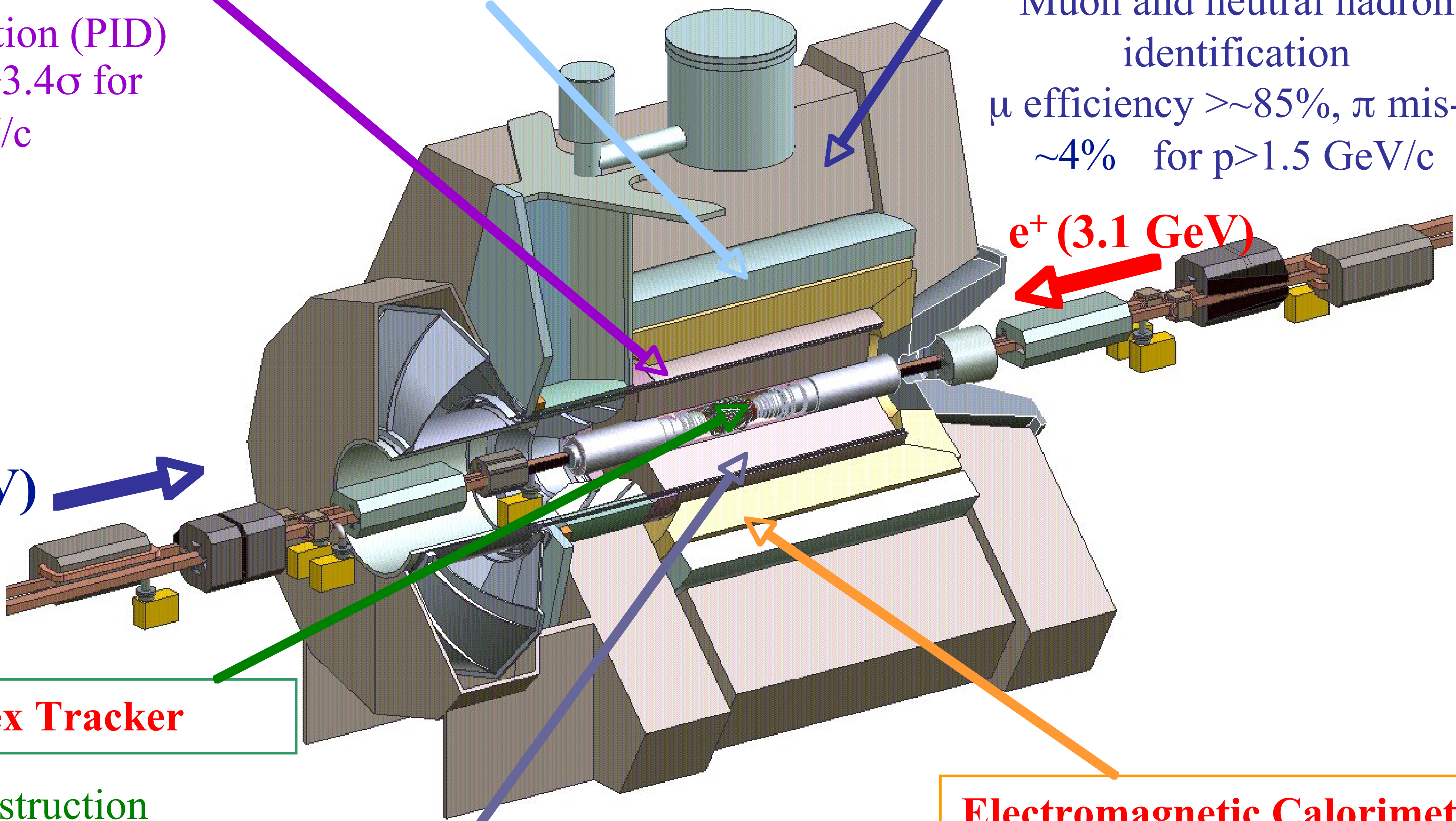
Solenoid 1.5T

Instrumented Flux Return

Muon and neutral hadron identification
μ efficiency >~85%, π mis-id ~4% for p>1.5 GeV/c

e⁺ (3.1 GeV)

e⁻ (≤ 9 GeV)



Silicon Vertex Tracker

Vertex reconstruction and tracking + dE/dx.
Efficiency ~ 97%

Drift Chamber

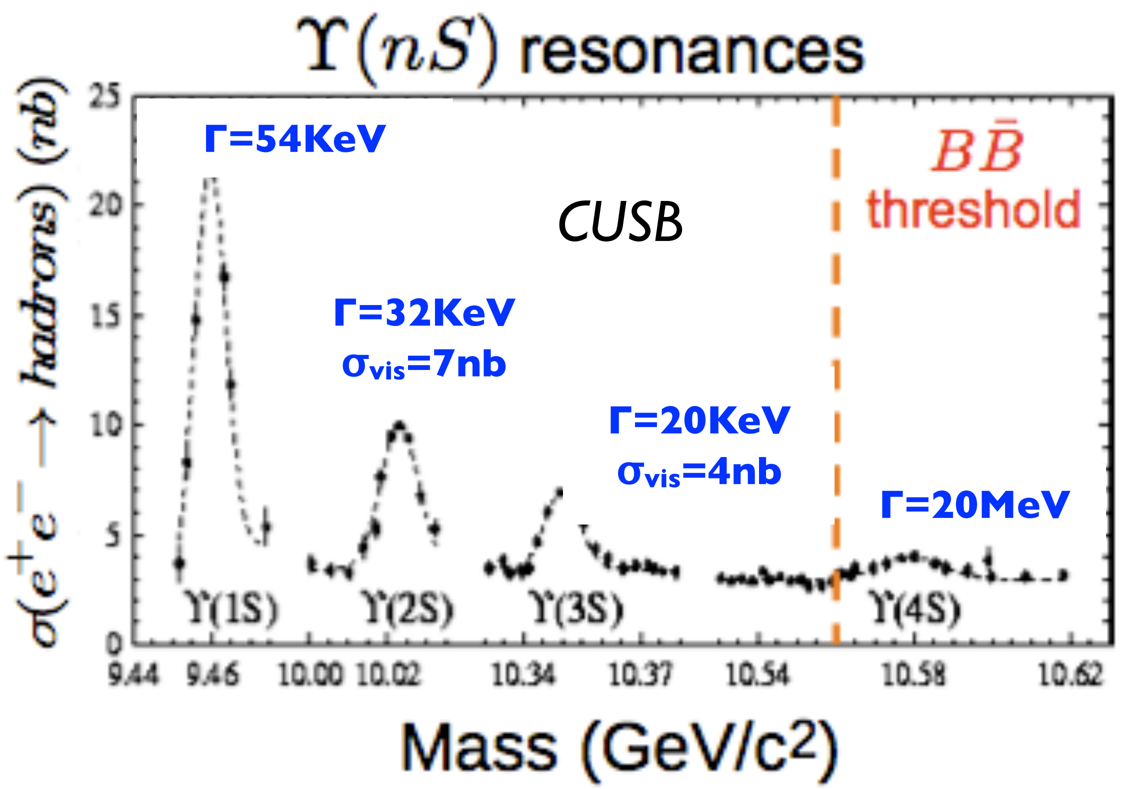
Momentum measurement for charged particles + dE/dx.
$\sigma(p_T)/p_T = 0.13\% p_T \oplus 0.45\%$

Electromagnetic Calorimeter

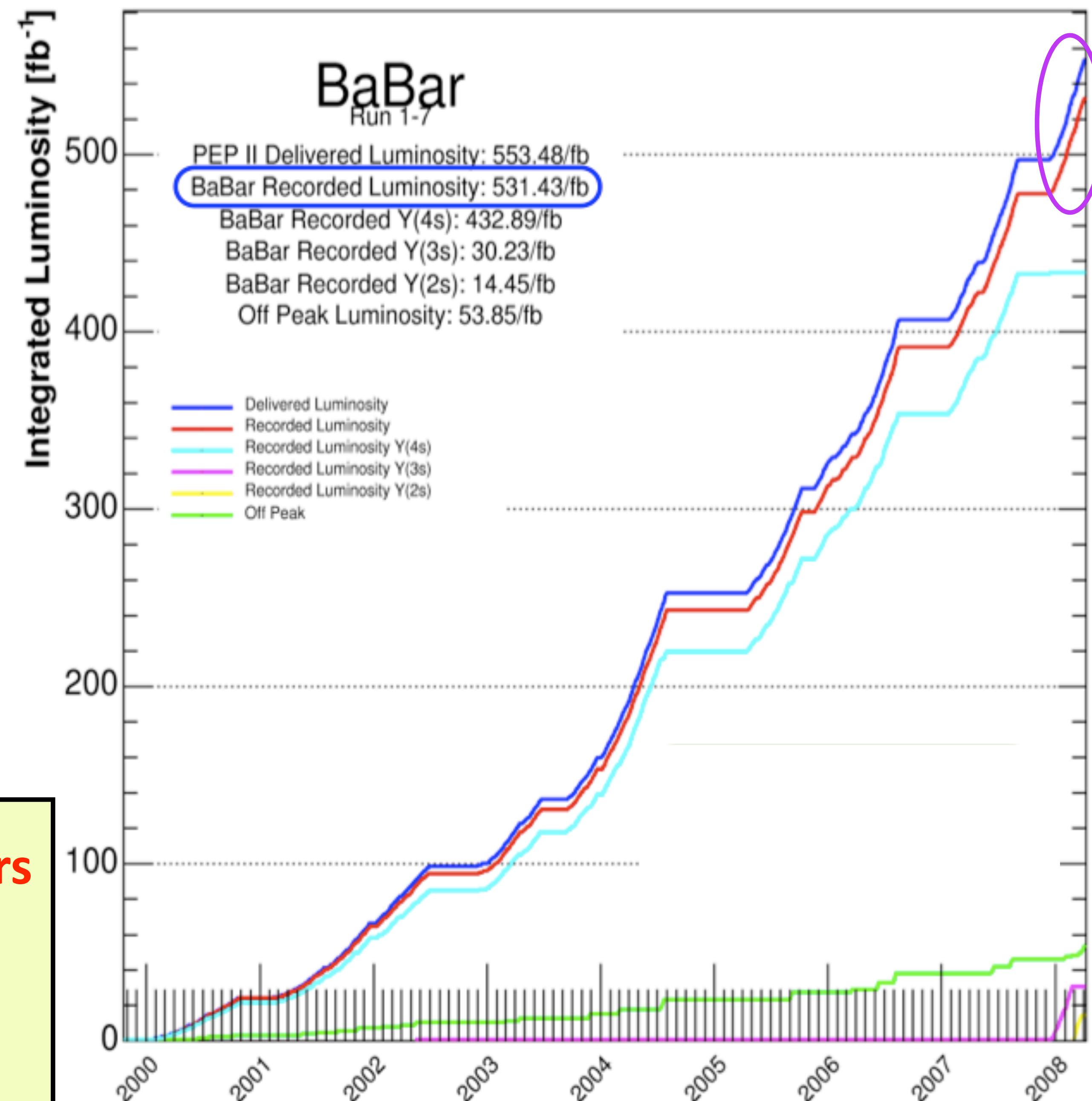
Electron and photon energy measurement. $\sigma(E)/E = 1.33\% E^{-1/4} \oplus 2.1\%$

BaBar data samples

- ✓ PEP-II asymmetric energy e^+e^--collider operating at the ϒ resonances



- ✓ ***BaBar*** recorded luminosity



- ✓ 425.6 fb^{-1} of data at ϒ(4S) ⟶ **~467·10⁶ $B\bar{B}$ pairs**
- ✓ 28.0 fb^{-1} of data at ϒ(3S) ⟶ **~122·10⁶ ϒ(3S)**
- ✓ 13.6 fb^{-1} of data at ϒ(2S) ⟶ **~99·10⁶ ϒ(2S)**
- ✓ 3.9 fb^{-1} scan above ϒ(4S)

Possible searches at *BABAR*

- **Search for dark photon**

  $e^+e^-\to\gamma A'$, $A'\to e^+e^-,\mu^+\mu^-,\pi^+\pi^-$

- **Search for "invisible" dark photon**

  $e^+e^-\to\gamma A'$, $A'\to$invisible

this talk

- **Search for dark bosons**

  $e^+e^-\to A'^*\to W'W'$ **arXiv:0908.2821**

  $e^+e^-\to\gamma A'\to W'W''$

- **Search for dark Higgs boson**

  $e^+e^-\to h'A'$, $h'\to A'A'$

A.Gaz's talk

- **Search for dark hadrons**

  $e^+e^-\to\pi_D X$, $\pi_D\to e^+e^-,\mu^+\mu^-$

- **Search for dark photon in meson decay**

  $\pi^0\to\gamma l^+l^-$, $\eta\to\gamma l^+l^-$, $\phi\to\eta l^+l^-$, ...

- **Search for dark scalar/pseudoscalar**

  $B\to K^{(*)}s_D\to K^{(*)}l^+l^-$ and $B\to K^{(*)}a_D\to K^{(*)}l^+l^-$

  $B\to s_Ds_D\to 2(l^+l^-)$

  $B\to K\ 2(l^+l^-)$

  $B\to 4(l^+l^-)$

searches on-going...

Status of searches for dark photons

- ✓ ***BABAR*** has a number of analyses performed as searches for **A^0**, a light CP-odd Higgs (foreseen in several extensions of the SM, for instance NMSSM) which can be reinterpreted as results for dark photon searches

PRD 76, 051105 (2007)

  - ✓ based on Υ(3S,2S) datasets
  - ✓ different possible final states (dimuon, $\tau^+\tau^-$, hadrons, invisible), pattern of decays depending on A^0 mass
  - ✓ obtained limits on A^0 mass

$e^+e^- \rightarrow \gamma A^0$, $A^0 \rightarrow l^+l^-, q\bar{q}$, invisible

↓

$e^+e^- \rightarrow \gamma A'$, $A' \rightarrow l^+l^-, q\bar{q}$, invisible

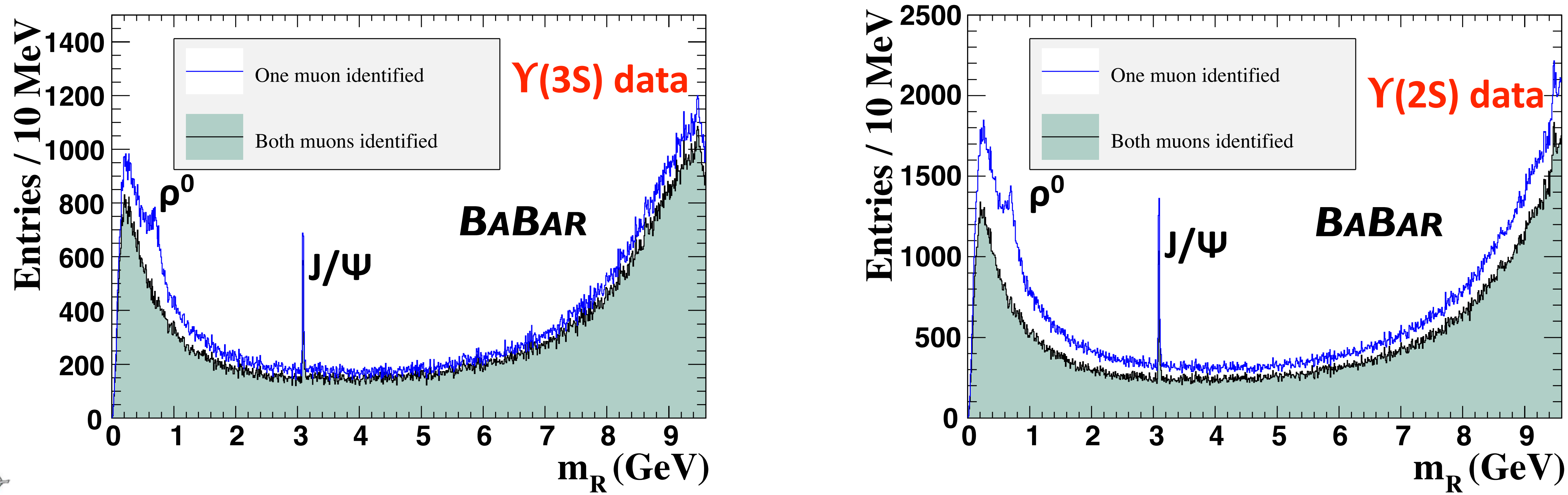
Caveat: **A'** is a vector → limits should be reinterpreted taking into account a variation in the efficiency (not estimated yet)

- ✓ Nevertheless, a good estimate for the order of magnitude of the limit
- ✓ Already re-interpreted: $\Upsilon(3S,2S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$

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

PRL 103 (2009) 081803 [arXiv:0905.4539]

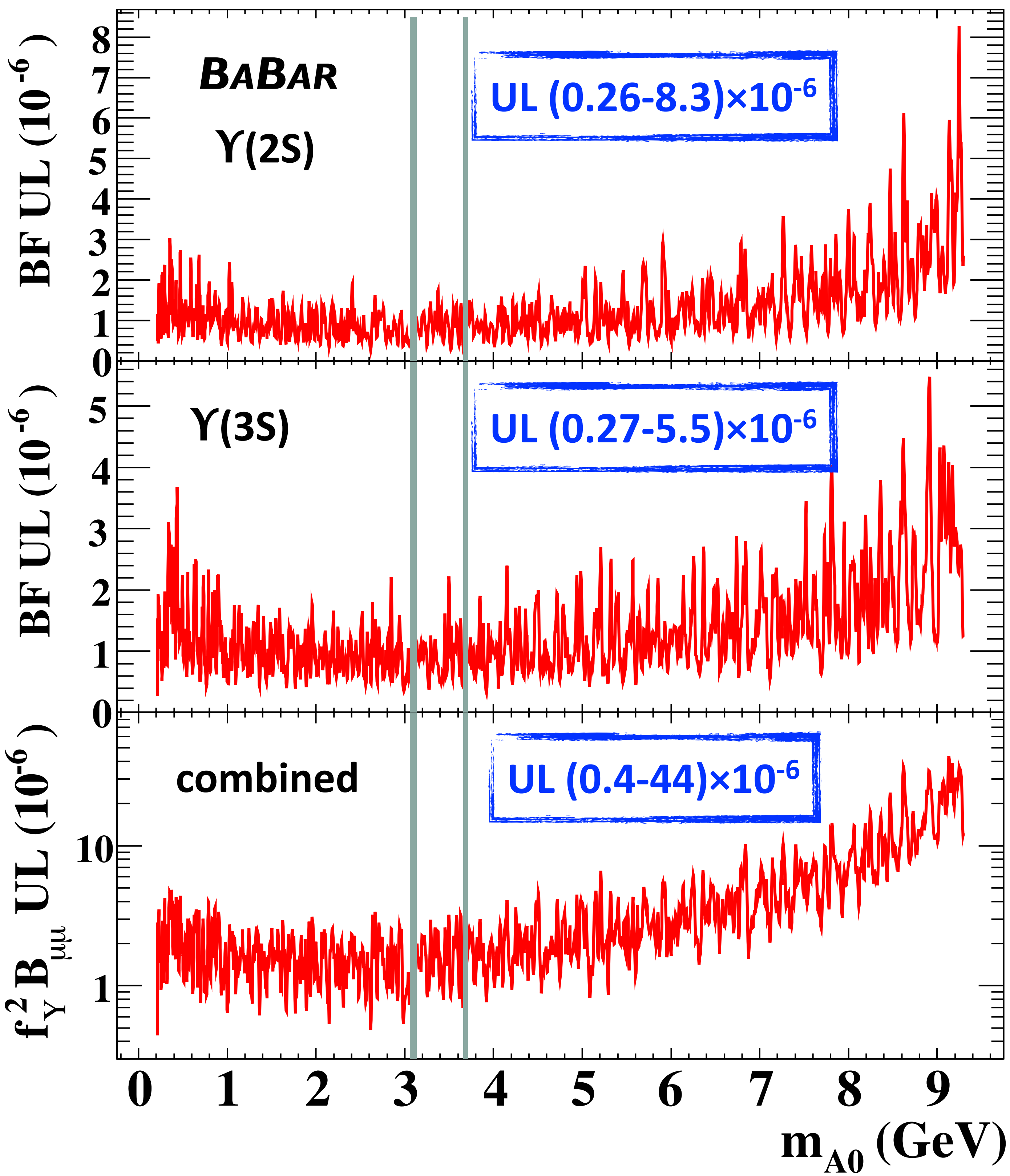
- ✓ Events with exactly 2 oppositely-charged tracks and a single energetic photon ($E_\gamma^* \geq 200$ MeV)
  - ✓ at least one track identified as a μ
  - ✓ dimuon candidate and γ are back-to-back in the center of mass frame
- ✓ Backgrounds dominated by QED processes:
  1. "continuum" $e^+e^-\to\gamma\mu^+\mu^-$
  2. ISR production of ρ^0, ϕ, J/Ψ, Ψ(2S) and ϒ(1S)
- ✓ Signal yield as a function of A^0 mass in the interval $0.212 < m(A^0) < 9.3$ GeV: unbinned maximum likelihood fits to the reduced mass distribution $m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$



- ✓ Mass steps of 2-5 MeV, for a total of 1951 mass values
- ✓ Excluding regions in the vicinity of J/Ψ and Ψ(2S)
- ✓ Signal has a typical resolution of 2-10 MeV, increasing with mass
- ✓ No significant excess of events above the background in the entire range
- ✓ 90% CL Bayesian ULs on the product of branching fractions of the decays

$$\mathcal{B}(\Upsilon(nS) \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-)$$

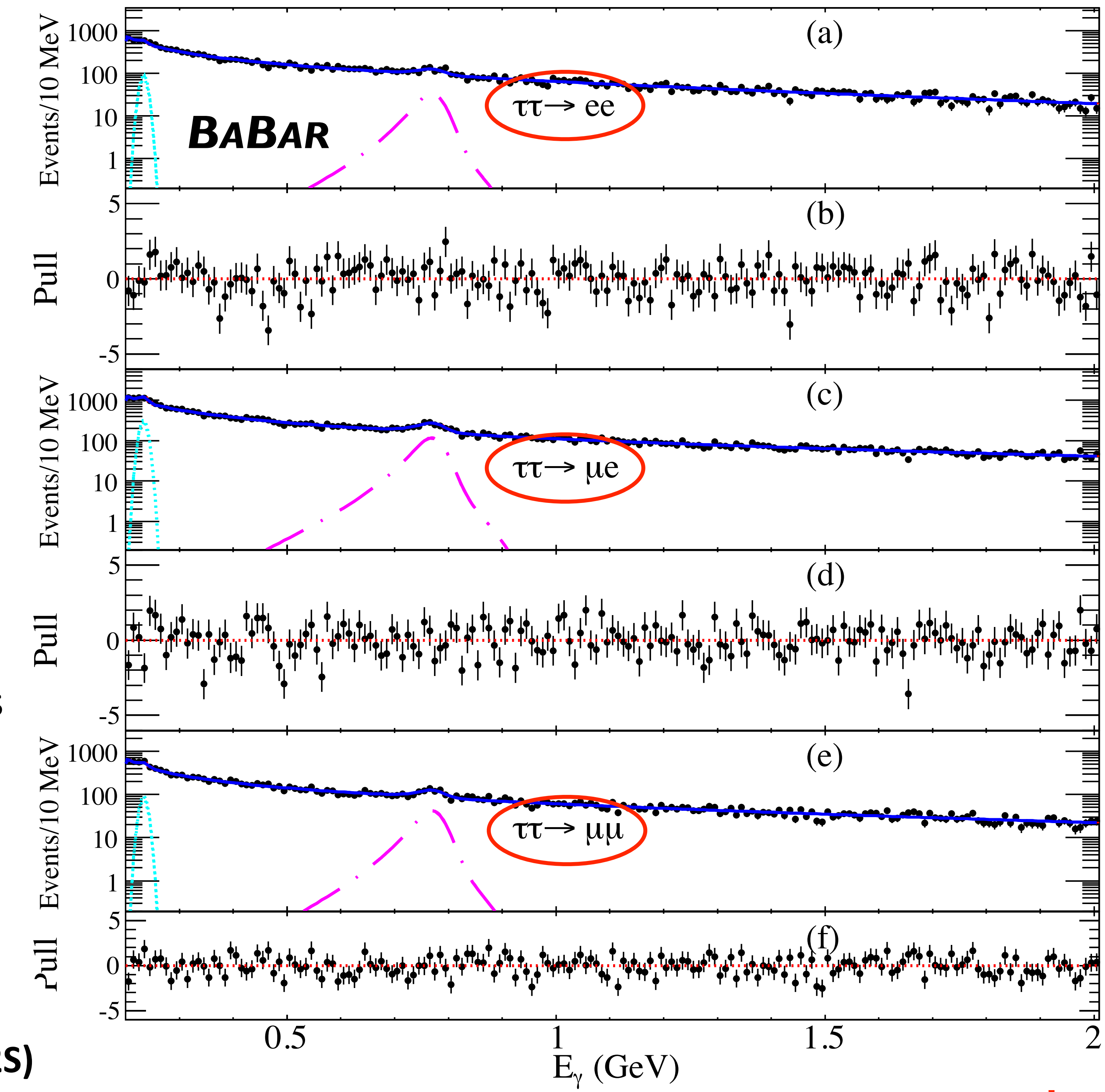
- ✓ Combined UL on the quantity $f^2_\Upsilon B_{\mu\mu}$, with f_Υ the effective coupling



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

PRL 103 (2009) 181801 [arXiv:0906.2219]

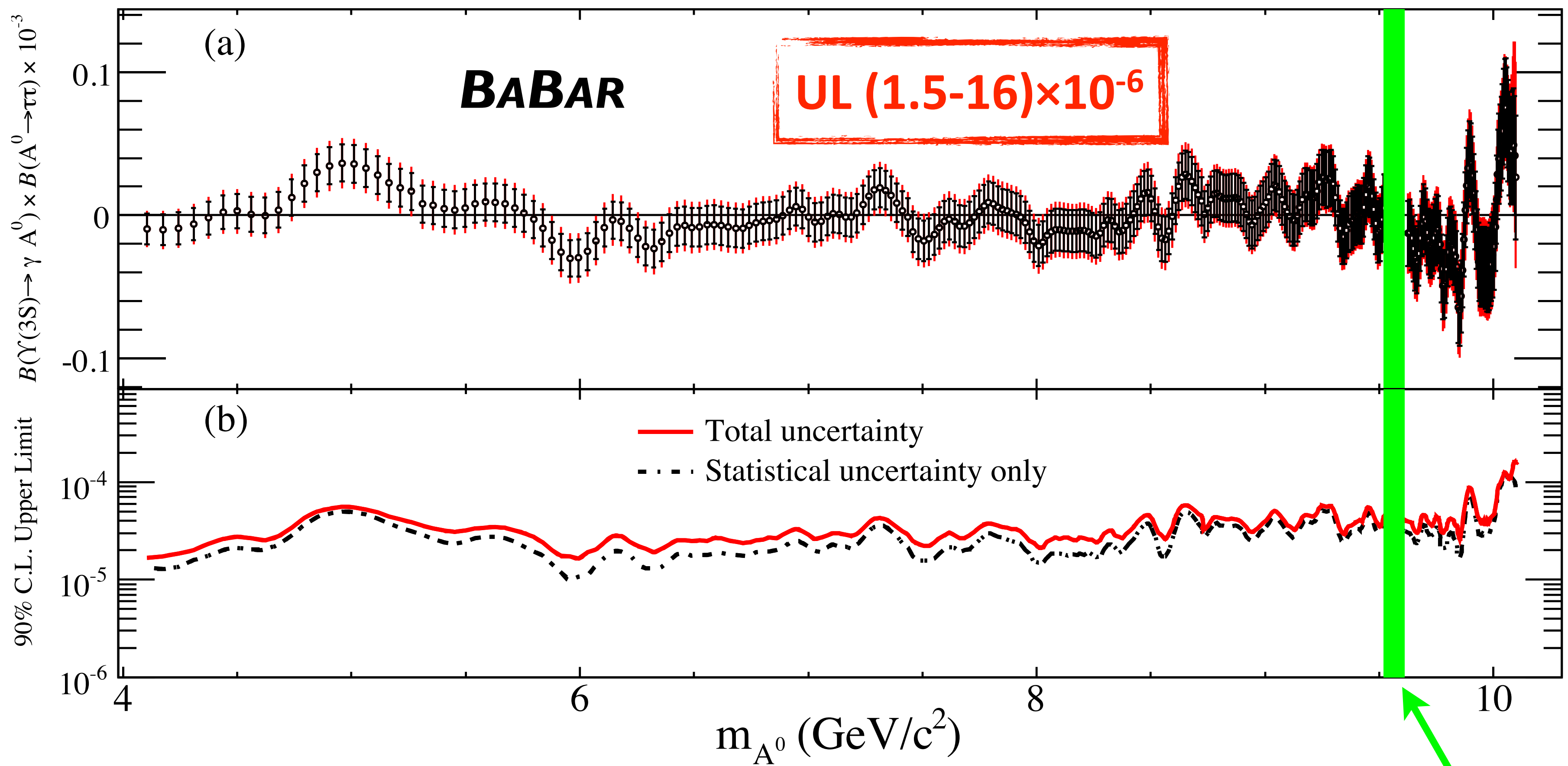
- ✓ Events with exactly 2 oppositely-charged tracks and a single energetic photon ($E_\gamma^* \geq 100$ MeV)
  - ✓ both τ decay leptonically (either $\tau \rightarrow e\nu_e\bar{\nu}_\tau$ or $\tau \rightarrow \mu\nu_\mu\bar{\nu}_\tau$)
- ✓ Backgrounds dominated by:
  1. $e^+e^- \rightarrow \gamma\tau^+\tau^-$ (dominant) and higher-order QED processes
  2. other $\Upsilon(3S)$ decays and $e^+e^- \rightarrow q\bar{q}$ (smaller contributions)
- ✓ Any peak in the recoil mass ($m_{\tau\tau}$) translates to a peak in the photon energy distribution
- ✓ Search for an excess in a narrow region of the E_γ spectrum



■ - data
■ - $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(2S)$
■ - $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$
■ - background

- ✓ Scan of the photon energy spectrum
- ✓ Range analyzed 4.03 < $m_{\tau\tau}$ < 10.10 GeV, excluding the region of the decays $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \rightarrow \gamma\Upsilon(1S)$, where J=0,1,2, due to irreducible photon backgrounds
- ✓ No evidence for a narrow resonance in all the mass range
- ✓ 90% CL Bayesian ULs on the product of branching fractions of the decay

$$\mathcal{B}(\Upsilon(3S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \tau^+\tau^-)$$

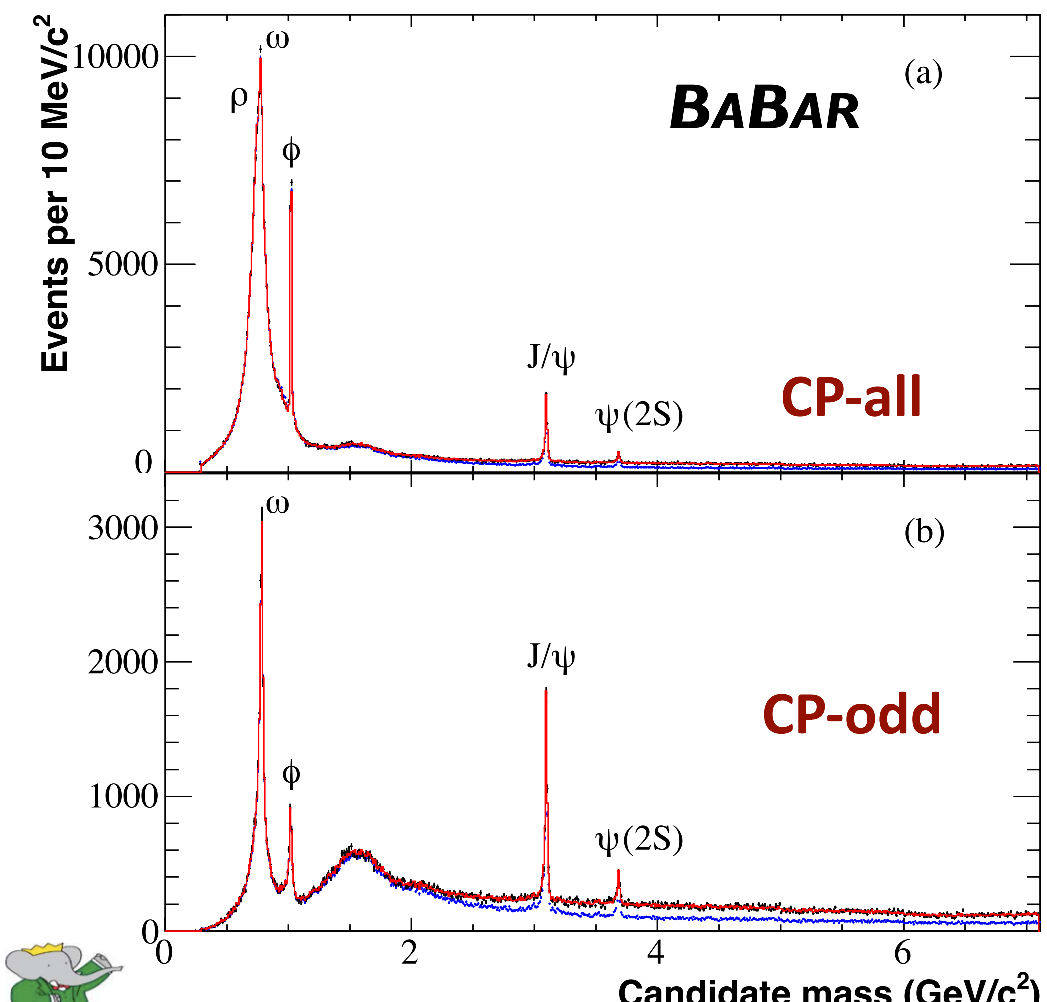


excluded mass region corresponding to $\Upsilon(3S) \rightarrow \gamma\chi_{bJ}(2P)$, $\chi_{bJ}(2P) \rightarrow \gamma\, \Upsilon(1S)$ decays

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

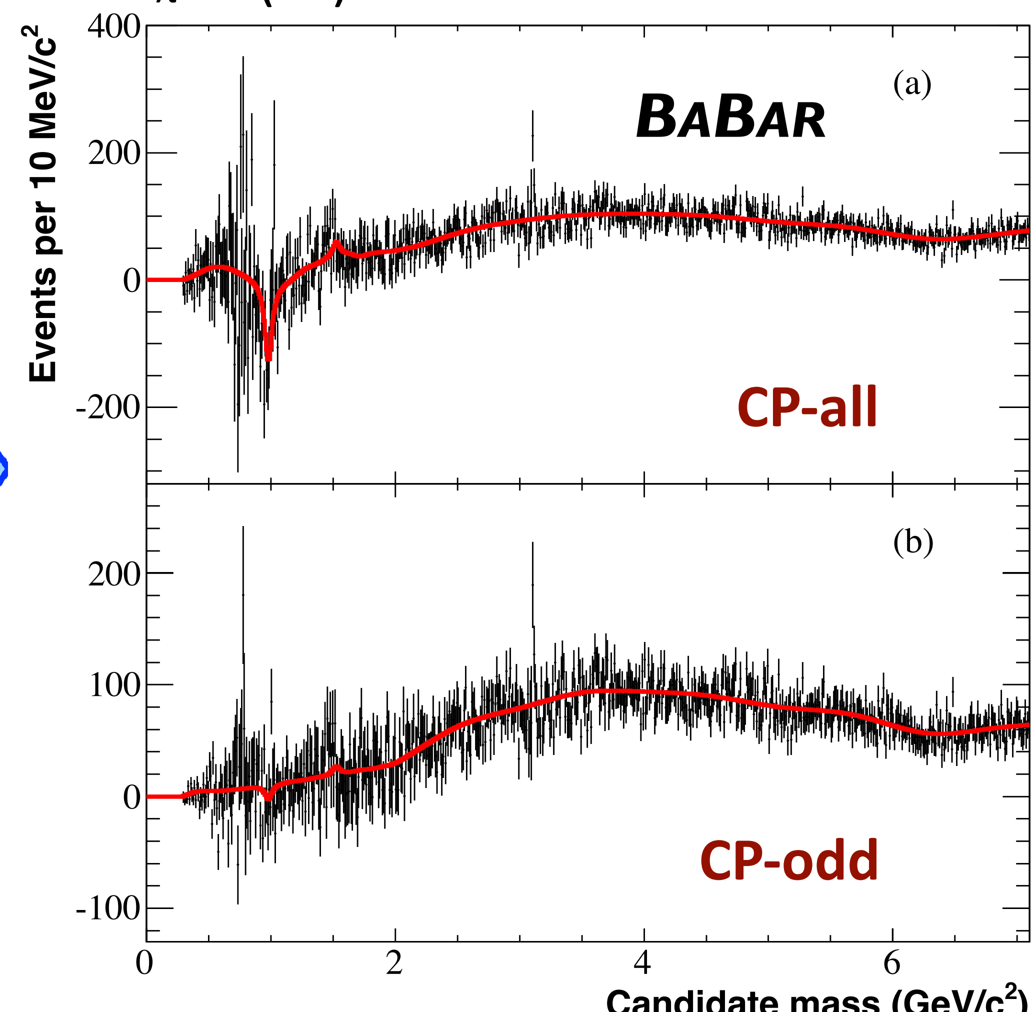
PRL 107 (2011) 221803
[arXiv:1108.3549]

- ✓ Hadronic events with full event energy reconstructed, with $E_\gamma^* \geq 2.5(2.2)$ GeV for the radiative photon from the $\Upsilon(3S)$ ($\Upsilon(2S)$) decay, and at least 2 charged tracks
- ✓ Backgrounds:
  1. radiative Bhabha events ($e^+e^-\rightarrow \gamma e^+e^-$) or radiative μ pairs ($e^+e^-\rightarrow \gamma\mu^+\mu^-$)
  2. continuum (dominant): initial state radiation production of a light vector meson or a non-resonant hadrons
  3. $\Upsilon(nS)$ radiative decays either to a light vector meson or to a non-resonant hadron
- ✓ A^0 signal = a narrow peak in the candidate mass spectrum: $2m_\pi<m(A^0)<7$ GeV



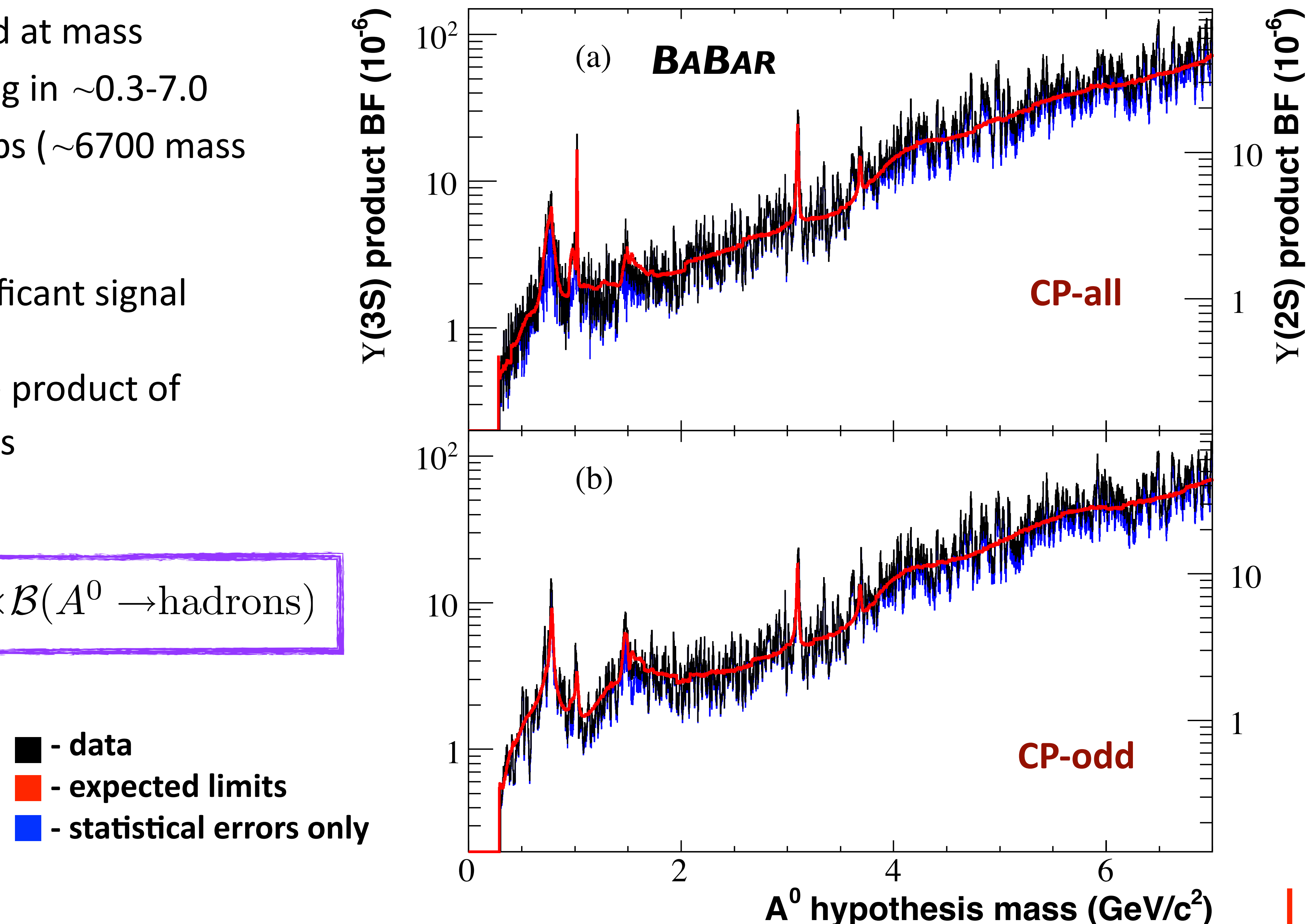
after continuum subtraction

- data
- bkg fit
- continuum data



- ✓ A^0 signal evaluated at mass hypotheses ranging in ~0.3-7.0 GeV, in 1 MeV steps (~6700 mass hypotheses)
- ✓ Absence of a significant signal
- ✓ 90% CL ULs on the product of branching fractions

$$\mathcal{B}(\Upsilon(nS) \to \gamma A^0) \times \mathcal{B}(A^0 \to \text{hadrons})$$



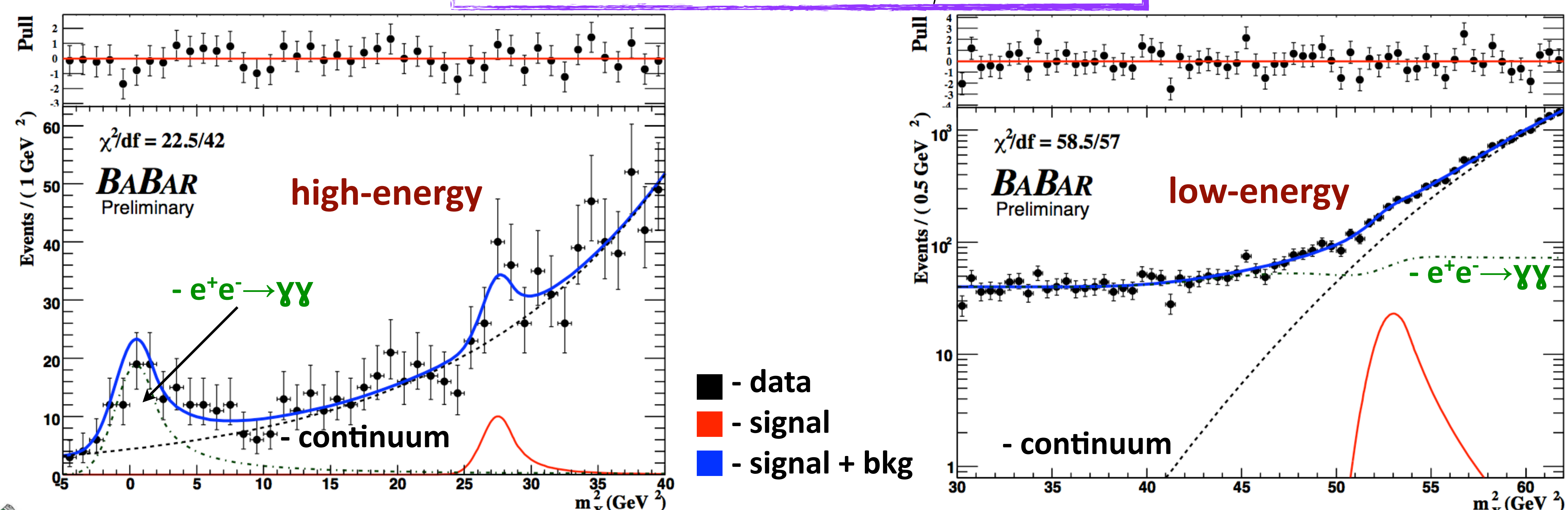
UL (1-80)×10⁻⁶

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

arXiv:0808.0017

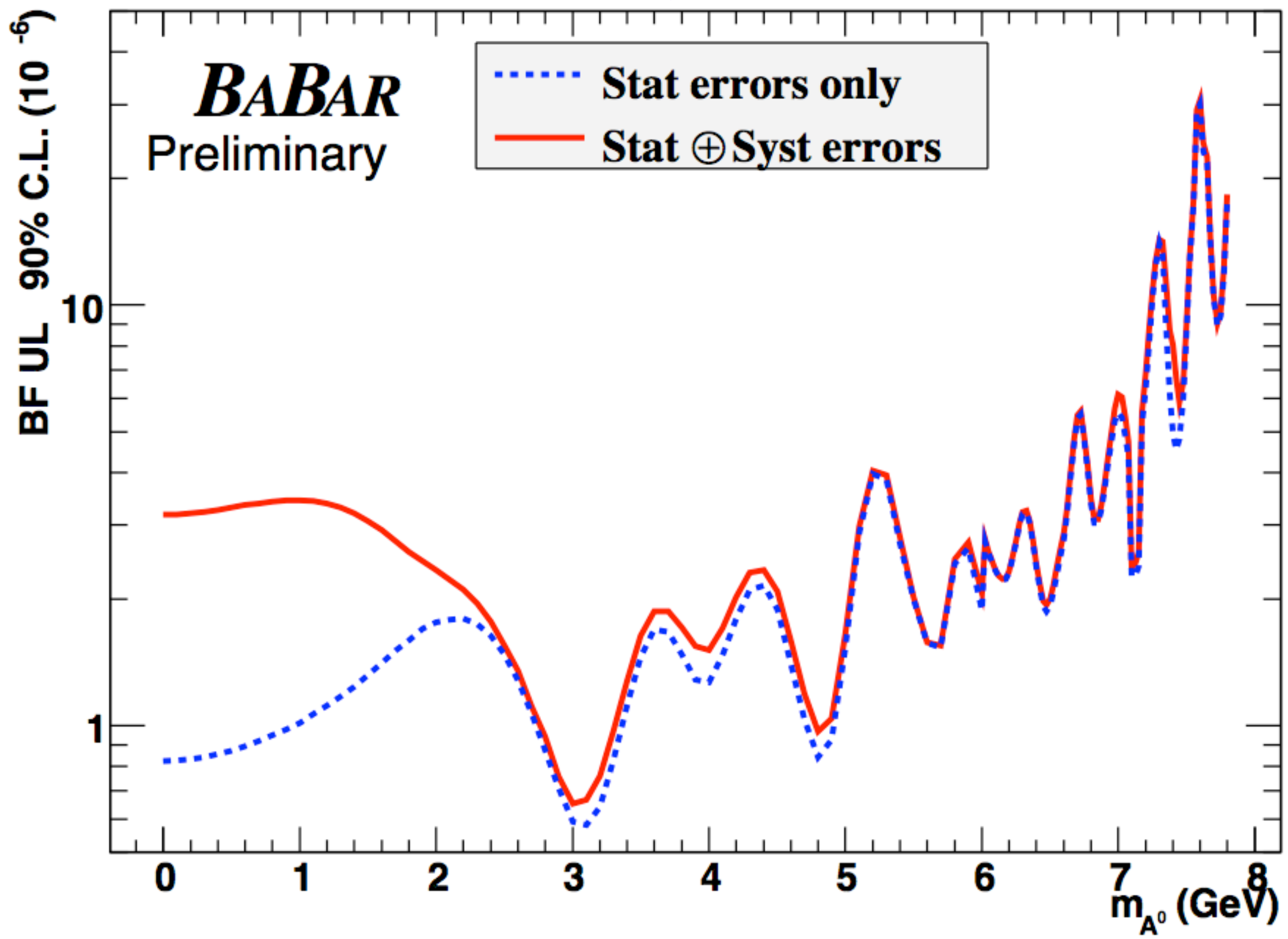
- ✓ A^0 could have an invisible decay: $A^0 \rightarrow \chi^0 \bar{\chi}^0$ decay (χ^0 is the LSP) in the case of $m(\chi^0) > m(\tau)$ or $m(A^0) < 2m(\tau)$
- ✓ Events with a single energetic photon ($E_\gamma^* \geq 3.0$ (1.5) GeV in the high (low) energy region) and no tracks originating from the e^+e^- interaction region
  - ✓ high-energy region: $3.2 < E_\gamma^* < 5.5$ GeV $\rightarrow$ dominant background: QED process $e^+e^- \rightarrow \gamma\gamma$
  - ✓ low-energy region: $2.2 < E_\gamma^* < 3.7$ GeV $\rightarrow$ dominant background: radiative Bhabha $e^+e^- \rightarrow \gamma\, e^+e^-$
- ✓ Search for a monochromatic peak in the squared missing mass distribution

$$m_X^2 = m(\Upsilon(3S))^2 - 2E_\gamma^* m(\Upsilon(3S))$$



- ✓ Set of maximum likelihood fits to the mass distribution
- ✓ No significant excess of events observed above the background in the range $0 < m(A^0) \leq 7.8$ GeV
- ✓ 90% CL Bayesian ULs on the product of branching fractions of the decay

$$\mathcal{B}(\Upsilon(3S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \text{invisible})$$

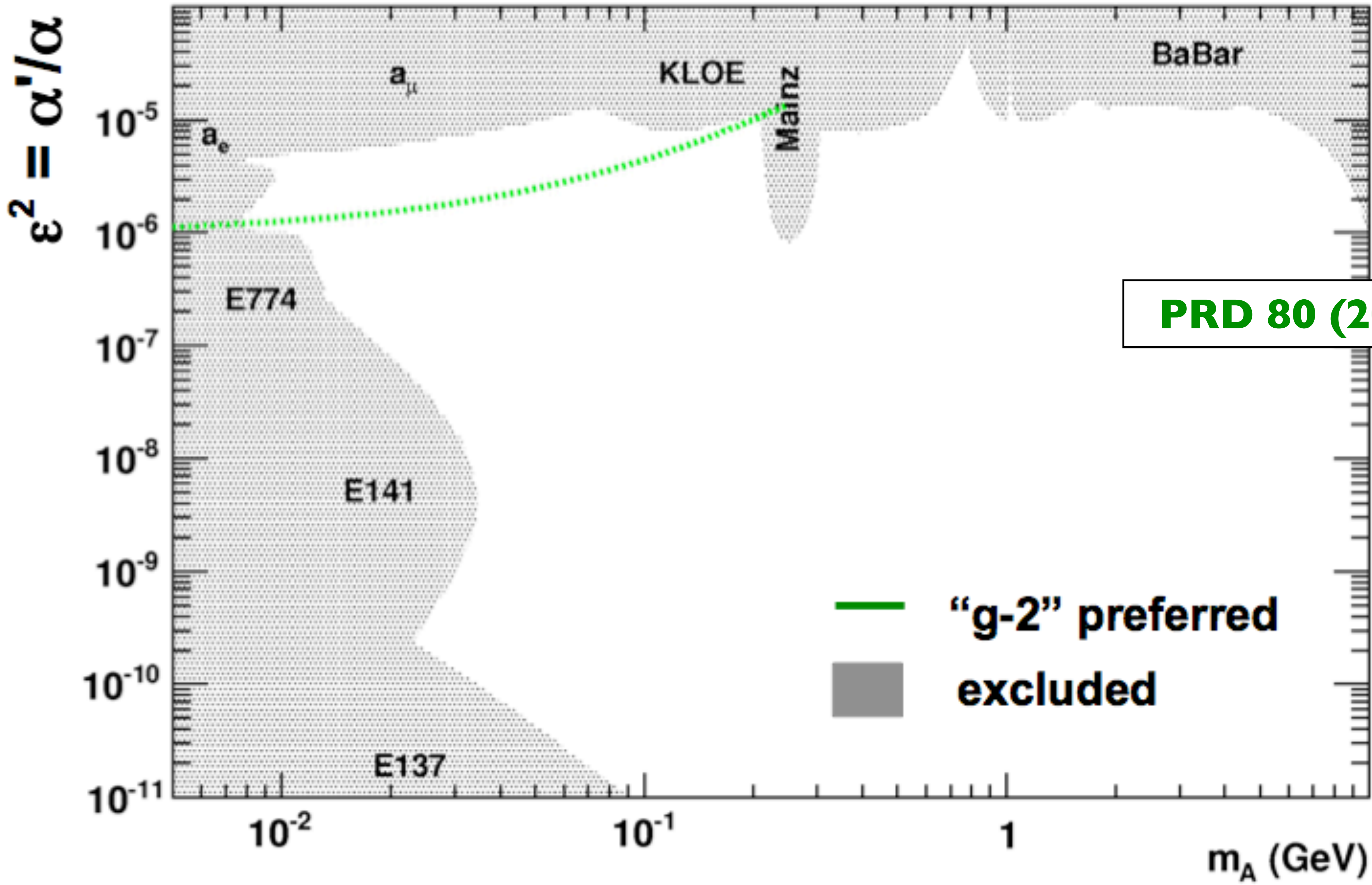


UL $(0.7\text{-}31)\times10^{-6}$

- ✓ Also a dark photon can decay to invisible particles in several scenarios (light dark matter, for instance) **arXiv:1108.1391**
- ✓ Dark photon or similar particles may be long-lived and escape detection

Reinterpretation for dark photons

✓ Limits obtained by reinterpreting the $\Upsilon(3S,2S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ measurements

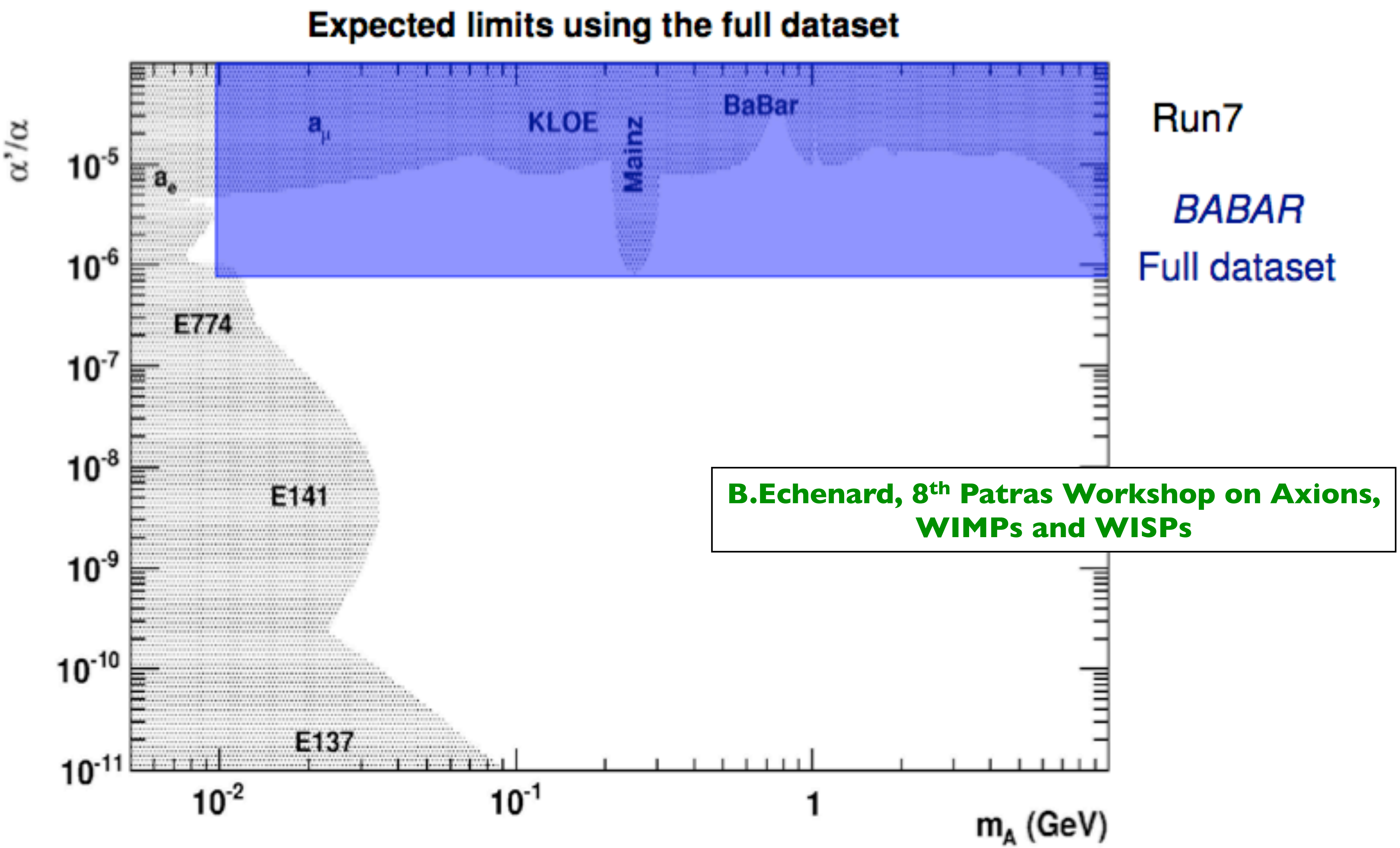


PRD 80 (2009) 075018

✓ Measurement done on $\Upsilon(3S)$ and $\Upsilon(2S)$ data samples only. Extending to all ***BaBar*** dataset - and to all final states - will lead to tighter limits (excluding deeply the "g-2" preferred region)

Reinterpretation for dark photons

✓



✓ Even more powerful exclusion within the reach of a Super Flavour Factory ($O(50ab^{-1})$)

Conclusions

- ✓ A summary of ***BaBar*** analyses searching for a light Higgs boson, decaying into different final states ($\mu^+\mu^-$, $\tau^+\tau^-$, hadrons, or invisible)

- ✓ These analyses can be reinterpreted in terms of search for a dark photon

- ✓ It has been actually done for $\Upsilon(3S,2S) \rightarrow \gamma A^0$, $A^0 \rightarrow \mu^+\mu^-$ measurement
  $\rightarrow$ a good estimate of the limits we can achieve

- ✓ Possibility of extending to all the available measurements, and to the complete dataset

- ✓ Many different searches for dark sector are on-going: stay tuned!