The 22nd International Conference on Supersymmetry and Unification of Fundamental Interactions
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Direct searches for New Physics at *BABAR*

Elisa Guido

Università degli Studi di Genova & INFN

(on behalf of the BABAR Collaboration)

Outline

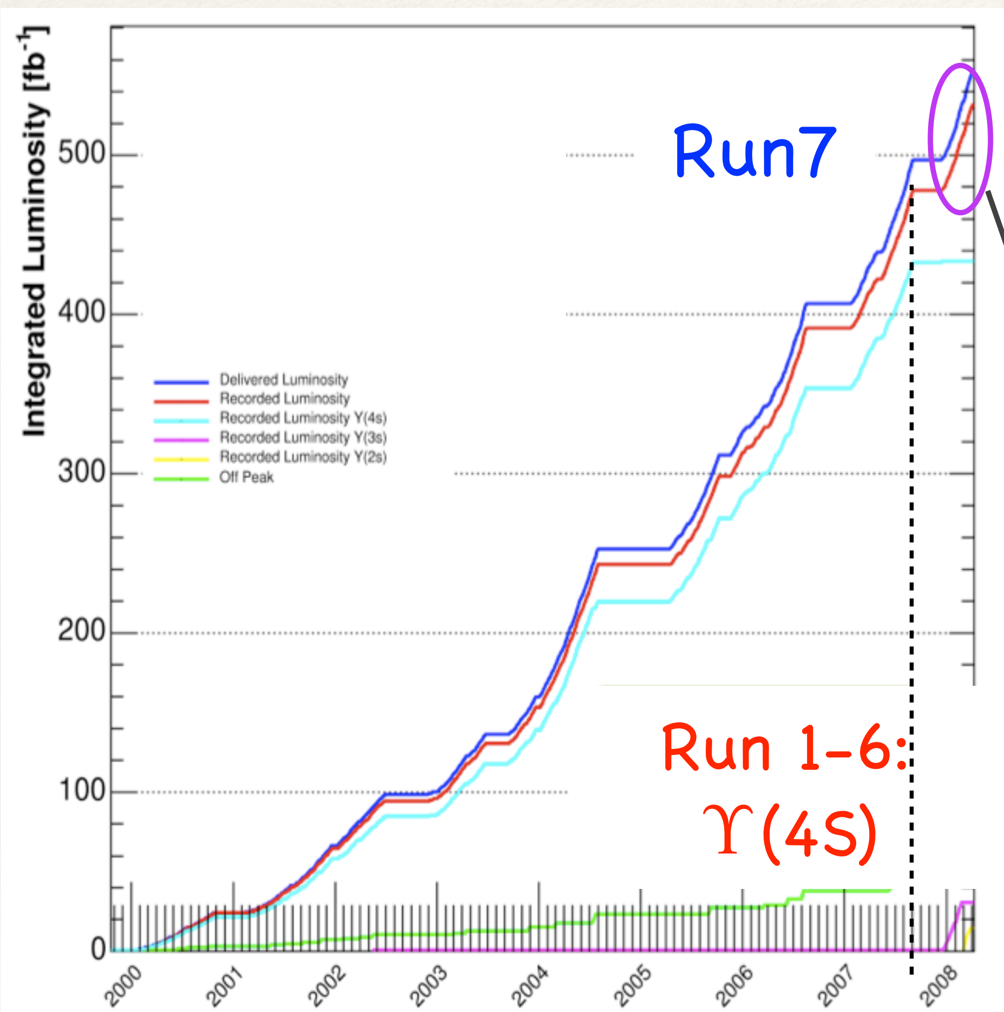
New!

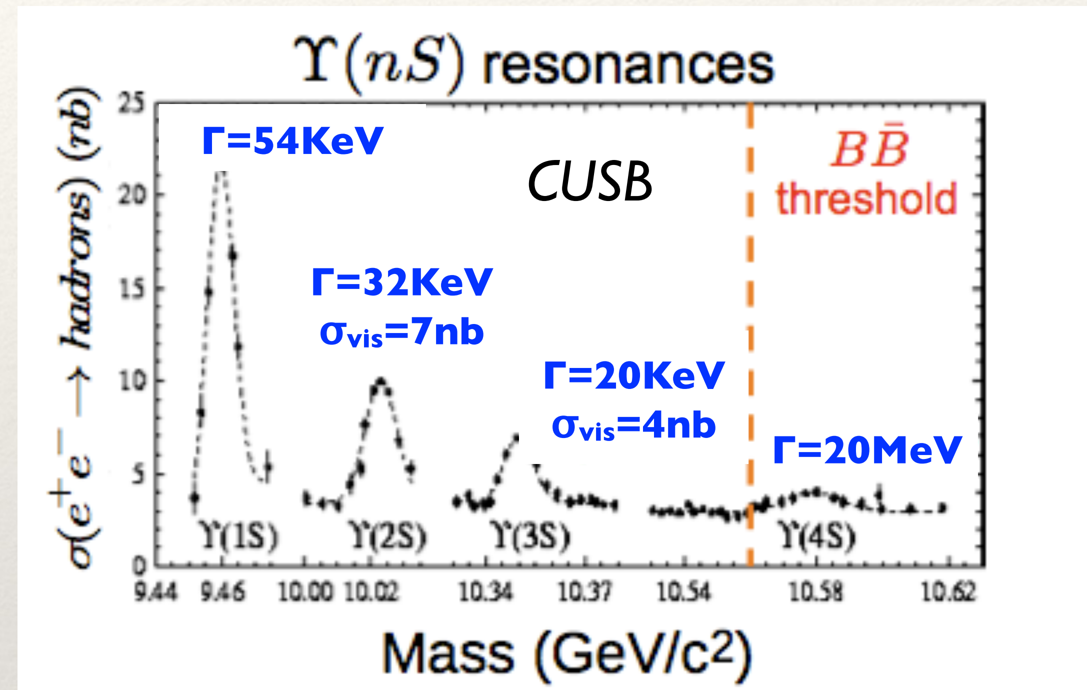
Highlights of recent *BABAR* searches:

- **Searches for a light CP-odd Higgs boson decaying to:**
  - $\mu^+\mu^-$ PRD 88, 031701 (2013)
  - $\tau^+\tau^-$ PRD 87, 031102 (2013)
  - $s\bar{s}$, gg PRD 88, 071102 (2013)
- **Search for a dark photon** arXiv:1406.2980 [hep-ex] (submitted to PRL)

BaBar data samples

- ✓ PEP-II asymmetric energy e^+e^--collider operating at the Υ resonances
- ✓ *BaBar* recorded luminosity:





- 433 fb^{-1} of data at $\Upsilon(4S)$ –> ~$470 \cdot 10^6$ $\Upsilon(4S)$
- 28.5 fb^{-1} of data at $\Upsilon(3S)$ –> ~$122 \cdot 10^6$ $\Upsilon(3S)$
- 14.4 fb^{-1} of data at $\Upsilon(2S)$ –> ~$99 \cdot 10^6$ $\Upsilon(2S)$

└–> ~$23 \cdot 10^6$ $\Upsilon(2S,3S)$—>$\pi^+\pi^-\Upsilon(1S)$

Light CP-odd Higgs boson searches

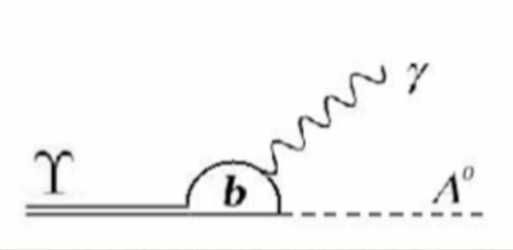
Theory

- An enlarged Higgs sector is predicted by many Standard Model (SM) extensions
- Next to Minimal Super-symmetric SM (**NMSSM**) includes the possibility of a light pseudoscalar Higgs boson

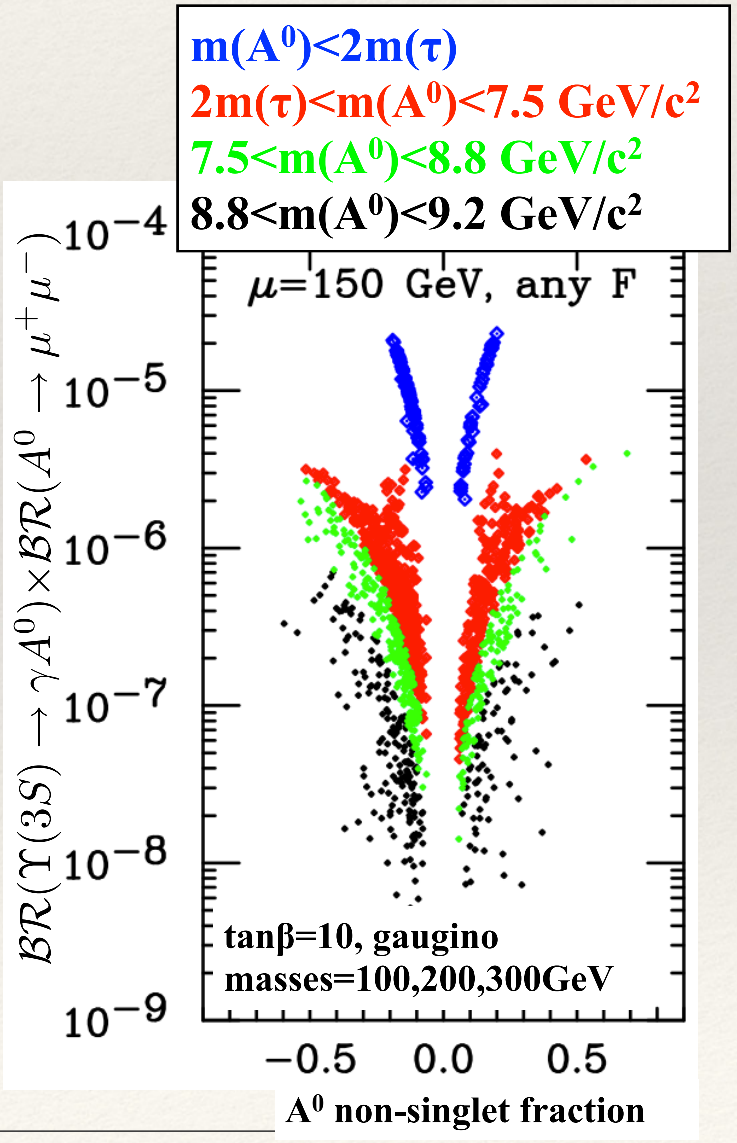
$$A^0 = \cos(\theta_A) a_{MSSM} + \sin(\theta_A) a_{singlet}$$

  - Not excluded by LEP limits
  - Light —> accessible to B-factories
- Radiative decays of narrow Υ resonances are an ideal environment for the search for A^0

$$\Upsilon(nS) \rightarrow \gamma A^0, n=1,2,3$$

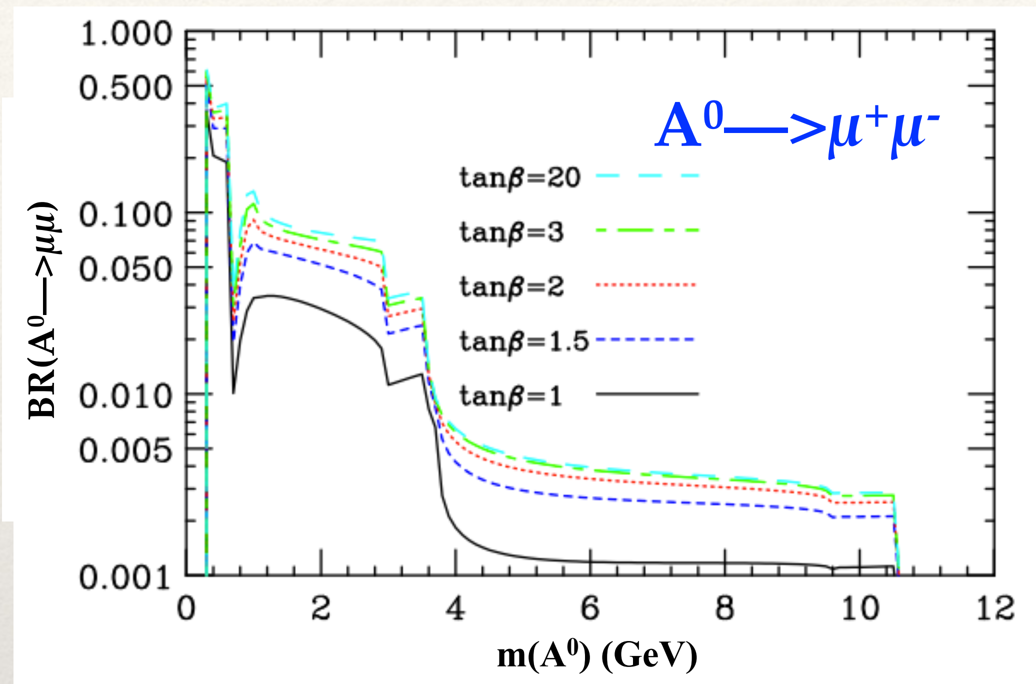


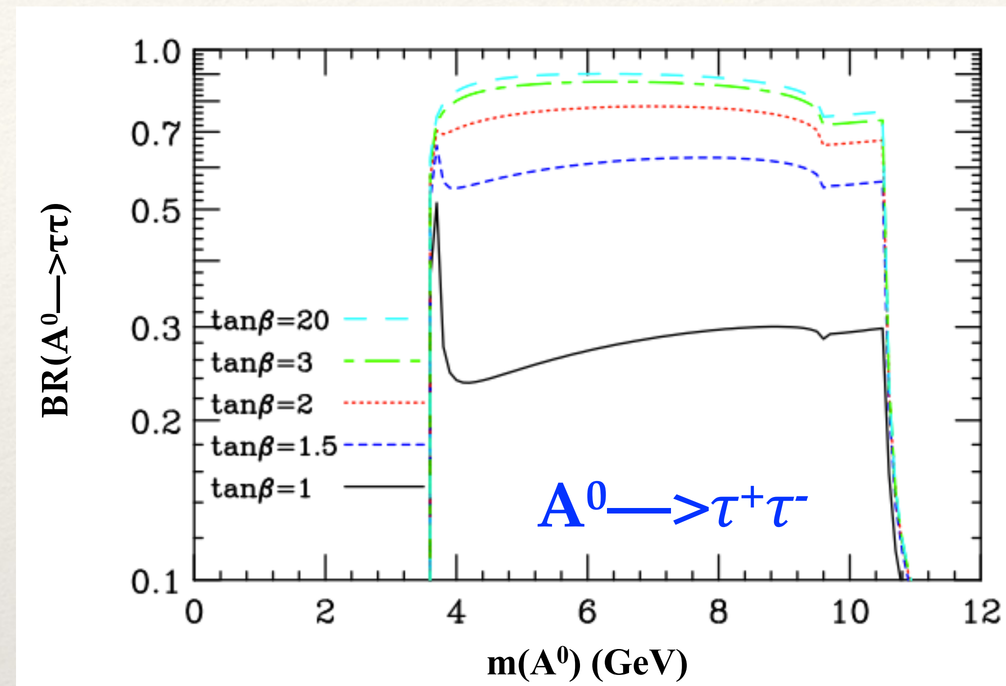
- They have predicted branching ratios (BRs) up to ~O(10^{-5})



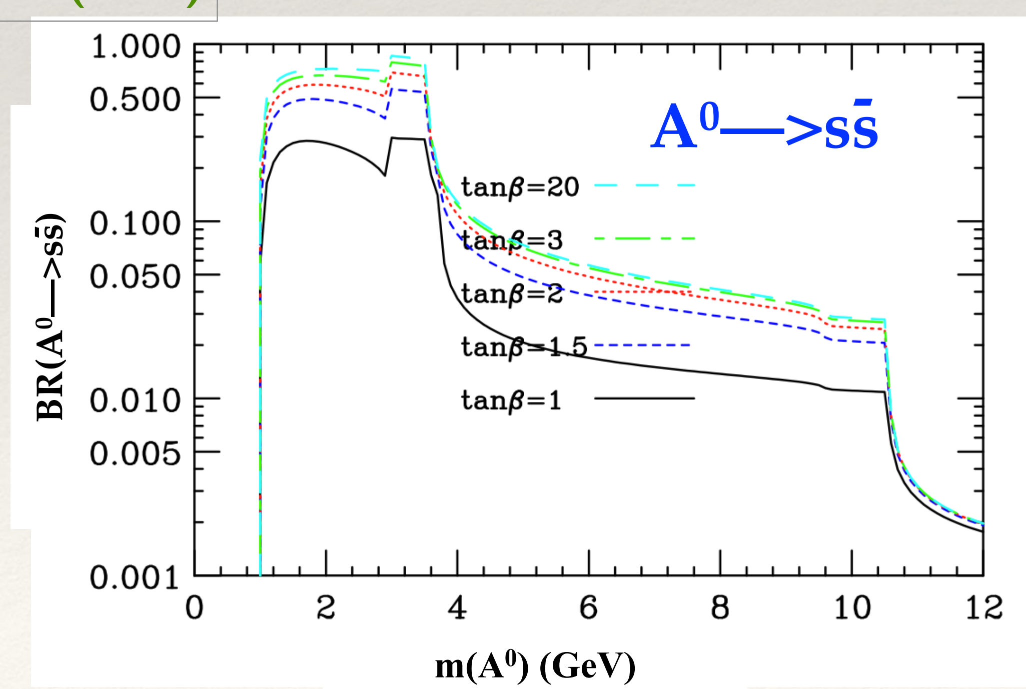
PRD 81, 075003 (2010)

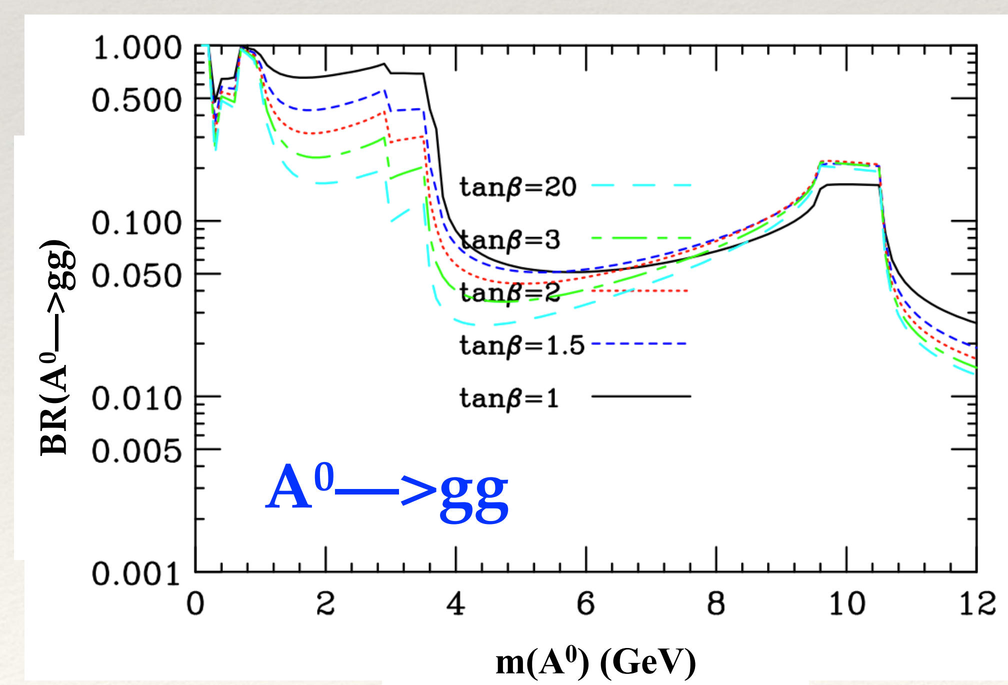
- The subsequent different A^0 decays are dominant for different mass regions and according to the choice of the model parameters





PRD 81, 075003 (2010)





A^0 at *BABAR*

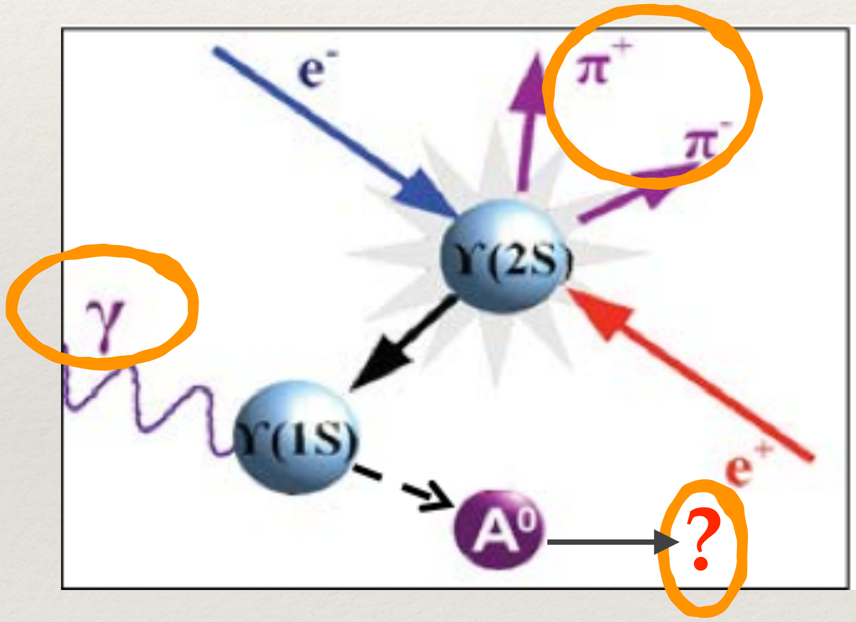
- Using the Υ(3S,2S) datasets, or tagging the Υ(1S) through dipion transitions from higher-mass resonances
  - ✓ Y(2S,3S)—>γA^0, A^0—>$\mu^+\mu^-$ Phys. Rev. Lett. 103 (2009) 081803
  - ✓ Y(2S,3S)—>γA^0, A^0—>$\tau^+\tau^-$ Phys. Rev. Lett. 103 (2009) 181801
  - ✓ Test of lepton universality in Y decays Phys. Rev. Lett. 104 (2010) 191801
  - ✓ Y(2S,3S)—>γA^0, A^0—>hadrons Phys. Rev. Lett. 107 (2011) 221803
  - ✓ Y(1S)—>γA^0, A^0—>invisible Phys. Rev. Lett. 107 (2011) 021804
  - ✓ Y(2S,3S)—>γA^0, A^0—>hadrons Phys. Rev. Lett. 107 (2011) 221803
  - ✓ Y(1S)—>γA^0, A^0—>$\mu^+\mu^-$ Phys. Rev. D 87 (2013) 031102
  - ✓ Y(1S)—>γA^0, A^0—>$\tau^+\tau^-$ Phys. Rev. D 88 (2013) 071102
  - ✓ Y(1S)—>γA^0, A^0—>gg, $s\bar{s}$ Phys. Rev. D 88 (2013) 031701
  - ✓ Y(2S,3S)—>γA^0, A^0—>invisible arXiv:0808.0017

✓ **radiative Y(2S,3S) decays**
✓ **radiative Y(1S) decays tagged through Y(2S,3S) dipion transitions to Y(1S)**

In this talk

General experimental strategy

- **Υ(3S,2S) data** samples + off-resonance samples for continuum background studies
- Υ(1S) is tagged from **Υ(3S,2S) —> $\pi^+\pi^-$Υ(1S): the pions provide 2 charged tracks in the final state**
- **Υ(1S)—>γA^0 —> an energetic photon in the final state**



- Subsequent different A^0 decays are reconstructed by the different analyses
- All of them are looking for events containing 2 charged tracks ($\pi^\pm$), 1 photon + A^0 decay products

PRD 87, 031102 (2013)

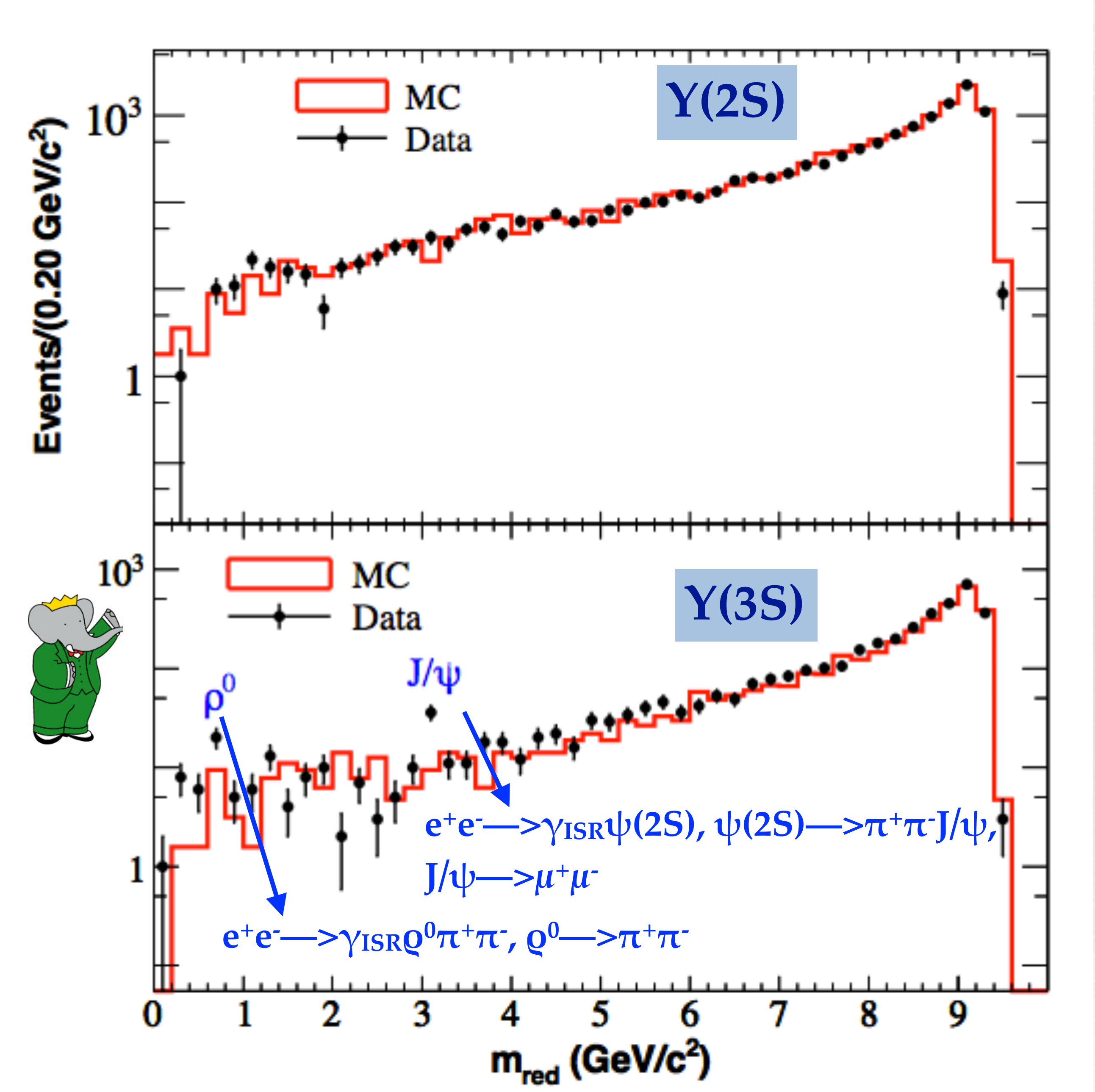
Search for Υ(1S)—>γA^0,A^0—>$\mu^+\mu^-$

Υ(3S,2S) data

- Final states containing **4 tracks**, with at least 1 identified as a ***μ***
- $\gamma\mu\mu$ system required to be compatible with a Υ(1S), kinematic constraints to improve resolution
- A^0 would appear as **a narrow peak in the reduced mass spectrum**

$$m_{red} = \sqrt{m(A^0)^2 - 4m(\mu)^2}$$

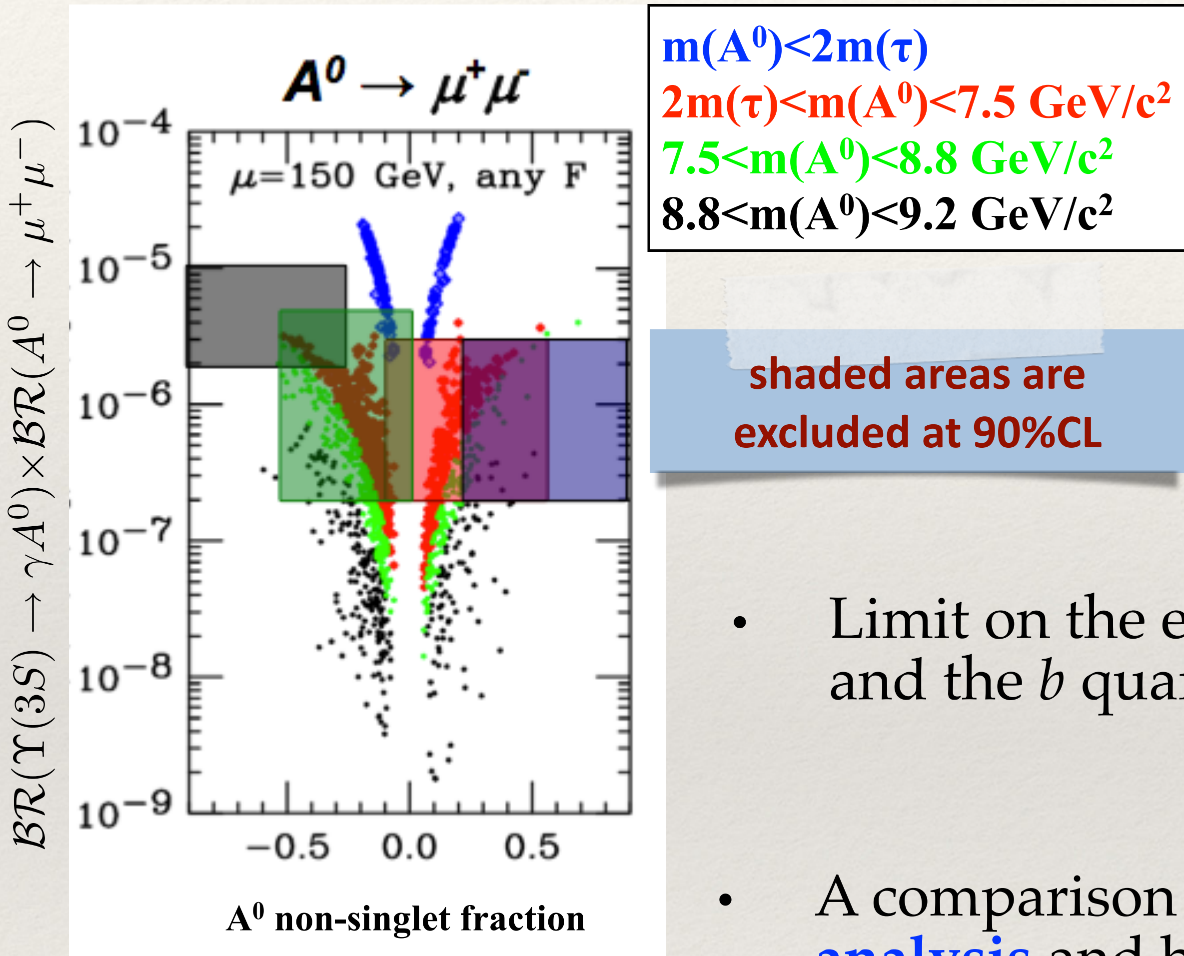
- A scan of the reduced mass distribution in the range $0.212 \leq m(A^0) \leq 9.20$ GeV/c^2
- **No significant signal** through the entire mass region

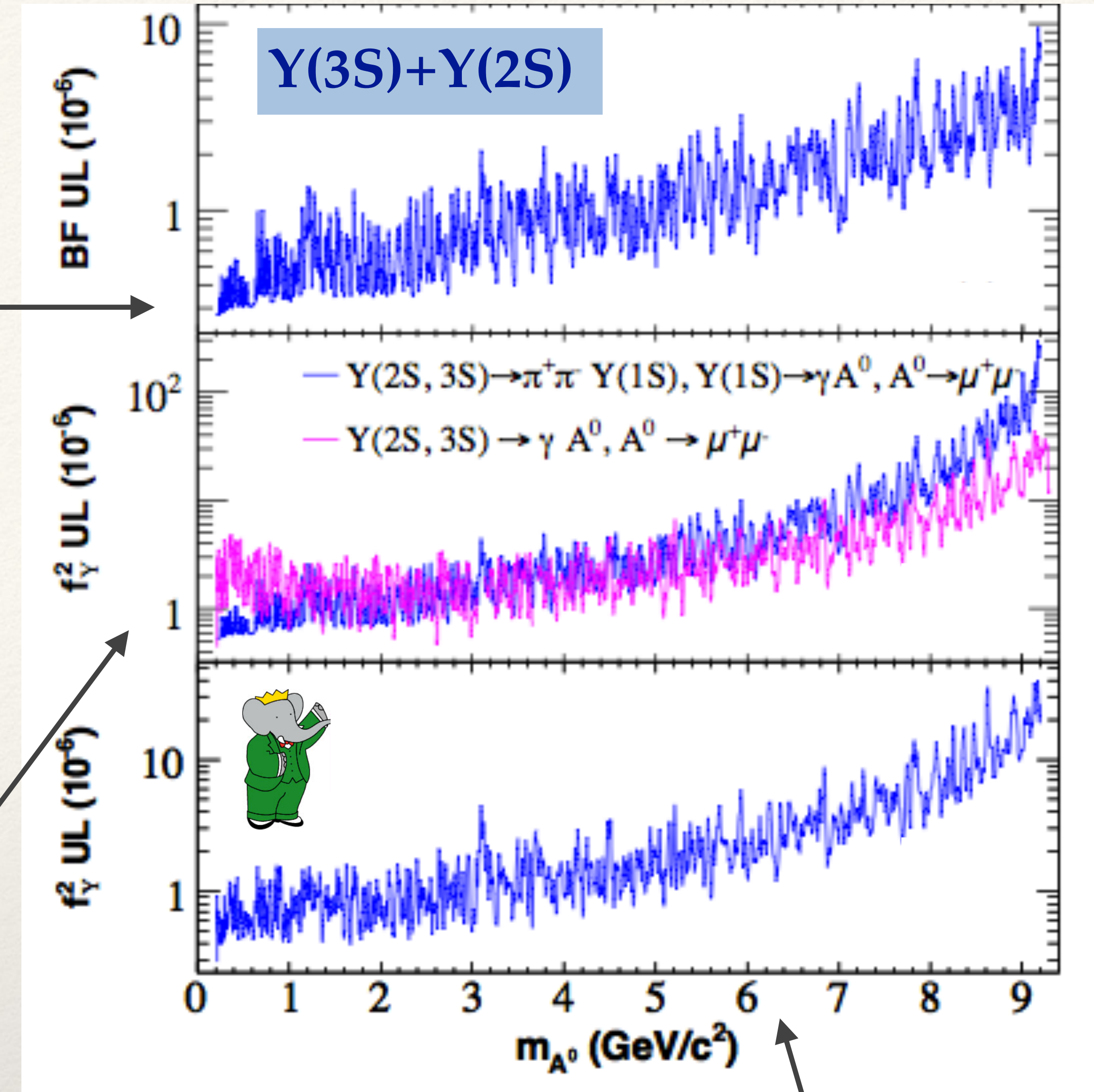


- Bayesian upper limits at 90% CL are set on the product of braching fractions

$BR(\Upsilon(1S) \rightarrow \gamma A^0) \times BR(A^0 \rightarrow \mu^+\mu^-) < (0.1 - 9.7) \times 10^{-6}$

- <u>Deeply excluding the available parameter space of the theory</u>





- Limit on the effective Yukawa coupling (**f_Υ**) between A^0 and the *b* quarks

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

- A comparison can be made between limits obtained by **this analysis** and by **Y(2S,3S) decays**: PRL 103, 081803 (2009)

- Limits of the 2 analyses are comparables, with advantages of one with respect to the other in different mass regions

- Combining the results of both analyses, we obtain an <u>improved limit on f_Υ^2</u>

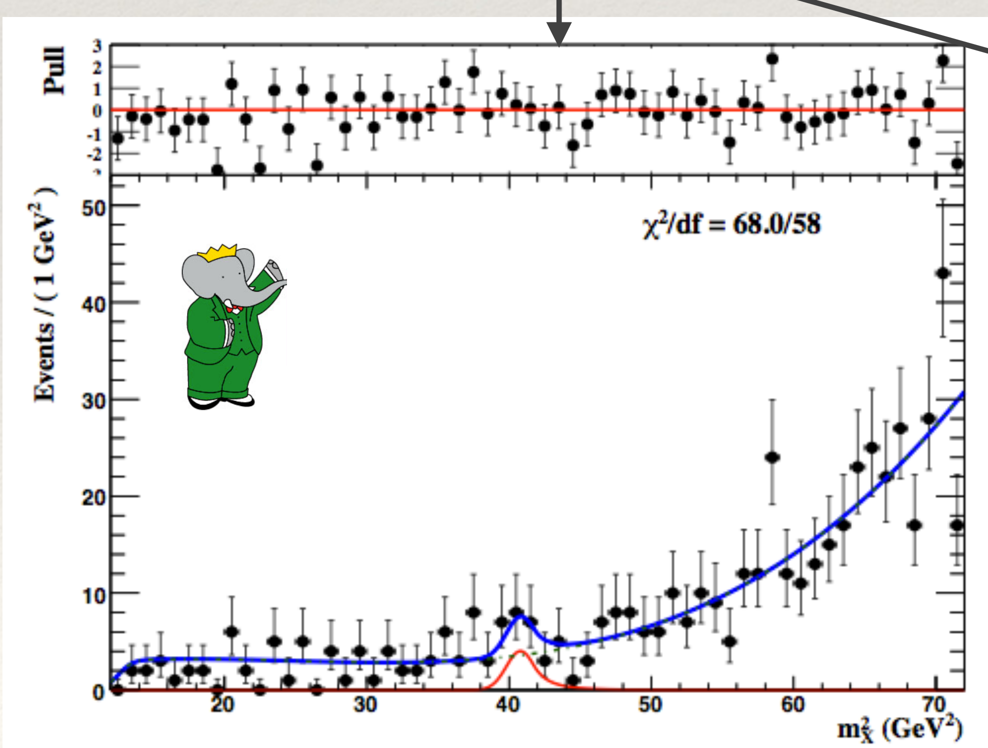
$f_\Upsilon^2 \times BR(A^0 \rightarrow \mu^+\mu^-) < (0.3 - 40) \times 10^{-6}$ @ 90%CL

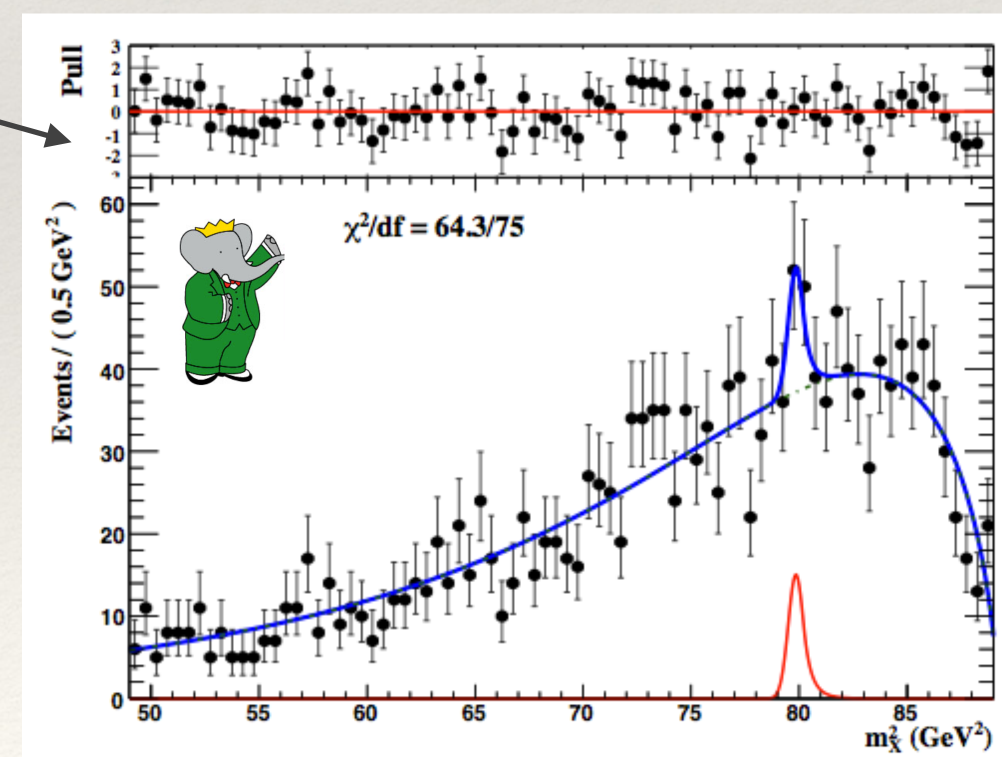
PRD 88, 071102 (2013)

Search for Y(1S)–>ɣA^0, A^0–>$\tau^+\tau^-$

Y(2S) data

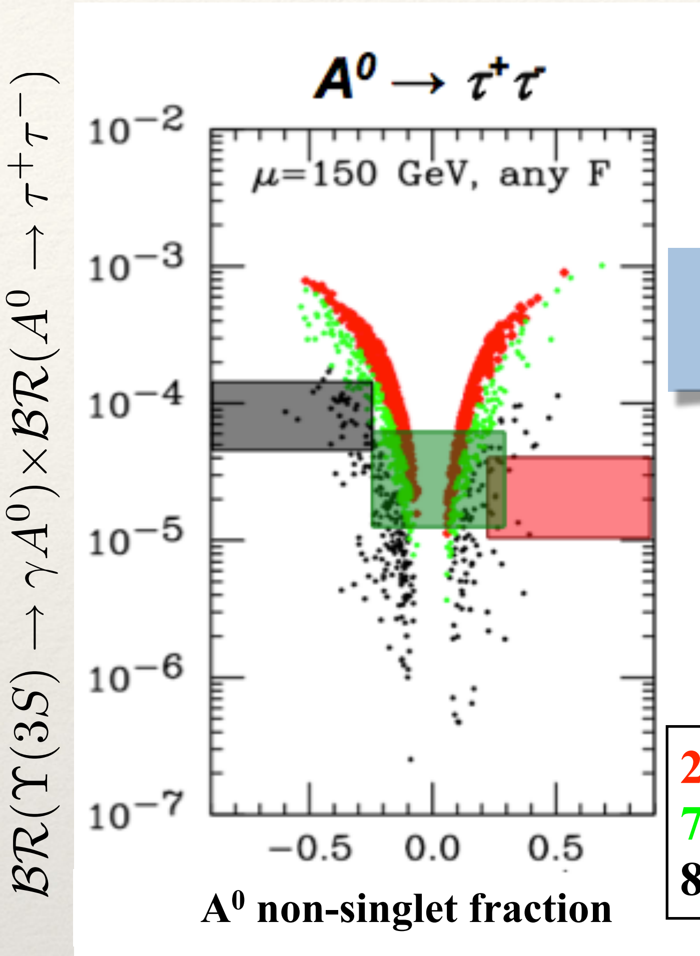
- Reconstruct **1-prong decay of τ** ($\tau \rightarrow \mu\nu\nu$, $\tau \rightarrow e\nu\nu$, $\tau \rightarrow \pi\nu\nu$)
- Require at least 1 τ decaying leptonically
- Optimized in low ($3.6 < m(A^0) < 8.0$ GeV/c^2) and high mass ($8.0 < m(A^0) < 9.2$ GeV/c^2) regions separately
- Scanning for a narrow peak in the photon recoil mass in the Y(1S) system $m_X^2 = (P_{e^+e^-} - P_{\pi\pi} - P_\gamma)^2$
- Examples of fit in the low and high mass region, for the largest upward fluctuations (significance ≤3σ)





- **No significant signal** through the entire mass region analyzed: $3.6 \le m(A^0) \le 9.20\ GeV/c^2$
- Bayesian upper limits at 90% CL are set on the product of braching fractions

$BR(\Upsilon(1S) \to \gamma A^0) \times BR(A^0 \to \tau^+\tau^-) < (0.9 - 13) \times 10^{-5}$



shaded areas are excluded at 90%CL

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

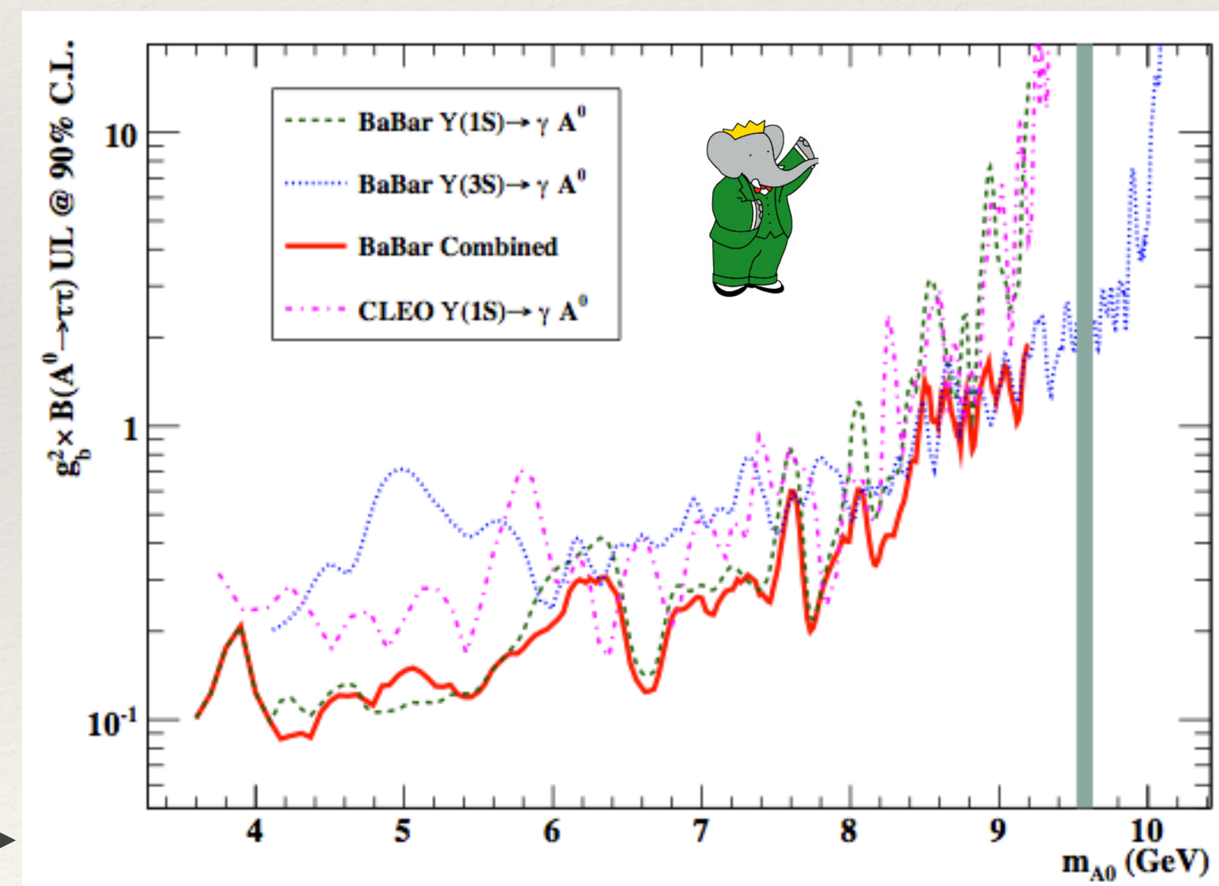
- Excluding part of the available parameter space of the theory
- Limits 2-3 times better with respect to those obtained **from $\Upsilon(3S)$ decays** in the low-mass region

PRL 103, 181801 (2009)

- Combination with the results from $\Upsilon(3S)$ decays —> limit on the effective Yukawa coupling (g_b) between A^0 and the *b* quarks

$$\frac{B(\Upsilon(nS) \to \gamma A^0)}{B(\Upsilon(nS) \to \ell^+\ell^-)} = \frac{g_b^2 G_F m_b^2}{\sqrt{2}\pi\alpha} \mathcal{F}_{QCD} \left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(ns)}^2}\right)$$

$g_b^2 \times BR(A^0 \to \tau^+\tau^-) < 0.1 - 1.9$ @ 90%CL →



PRD 88, 031701 (2013)

Search for Υ(1S)—>γA⁰, A⁰—>ss̄,gg

Υ(2S) data

- **A^0 fully reconstructed into a hadronic system** : exclusive reco in 26/14 final states for A^0—>gg / A^0—>ss̄.
- 2-body decays excluded (A^0 is CP-odd and cannot decay into 2 pseudoscalar mesons)

#	Channel	#	Channel
1	$\pi^+\pi^-\pi^0$	14	$K^+K^-\pi^+\pi^-$
2	$\pi^+\pi^-2\pi^0$	15	$K^+K^-\pi^+\pi^-\pi^0$
3	$2\pi^+2\pi^-$	16	$K^\pm K^0_S\pi^\mp\pi^+\pi^-$
4	$2\pi^+2\pi^-\pi^0$	17	$K^+K^-\eta$
5	$\pi^+\pi^-\eta$	18	$K^+K^-2\pi^+2\pi^-$
6	$2\pi^+2\pi^-2\pi^0$	19	$K^\pm K^0_S\pi^\mp\pi^+\pi^-2\pi^0$
7	$3\pi^+3\pi^-$	20	$K^+K^-2\pi^+2\pi^-\pi^0$
8	$2\pi^+2\pi^-\eta$	21	$K^+K^-2\pi^+2\pi^-2\pi^0$
9	$3\pi^+3\pi^-2\pi^0$	22	$K^\pm K^0_S\pi^\mp2\pi^+2\pi^-\pi^0$
10	$4\pi^+4\pi^-$	23	$K^+K^-3\pi^+3\pi^-$
11	$K^+K^-\pi^0$	24	$2K^+2K^-$
12	$K^\pm K^0_S\pi^\mp$	25	$p\bar{p}\pi^0$
13	$K^+K^-2\pi^0$	26	$p\bar{p}\pi^+\pi^-$

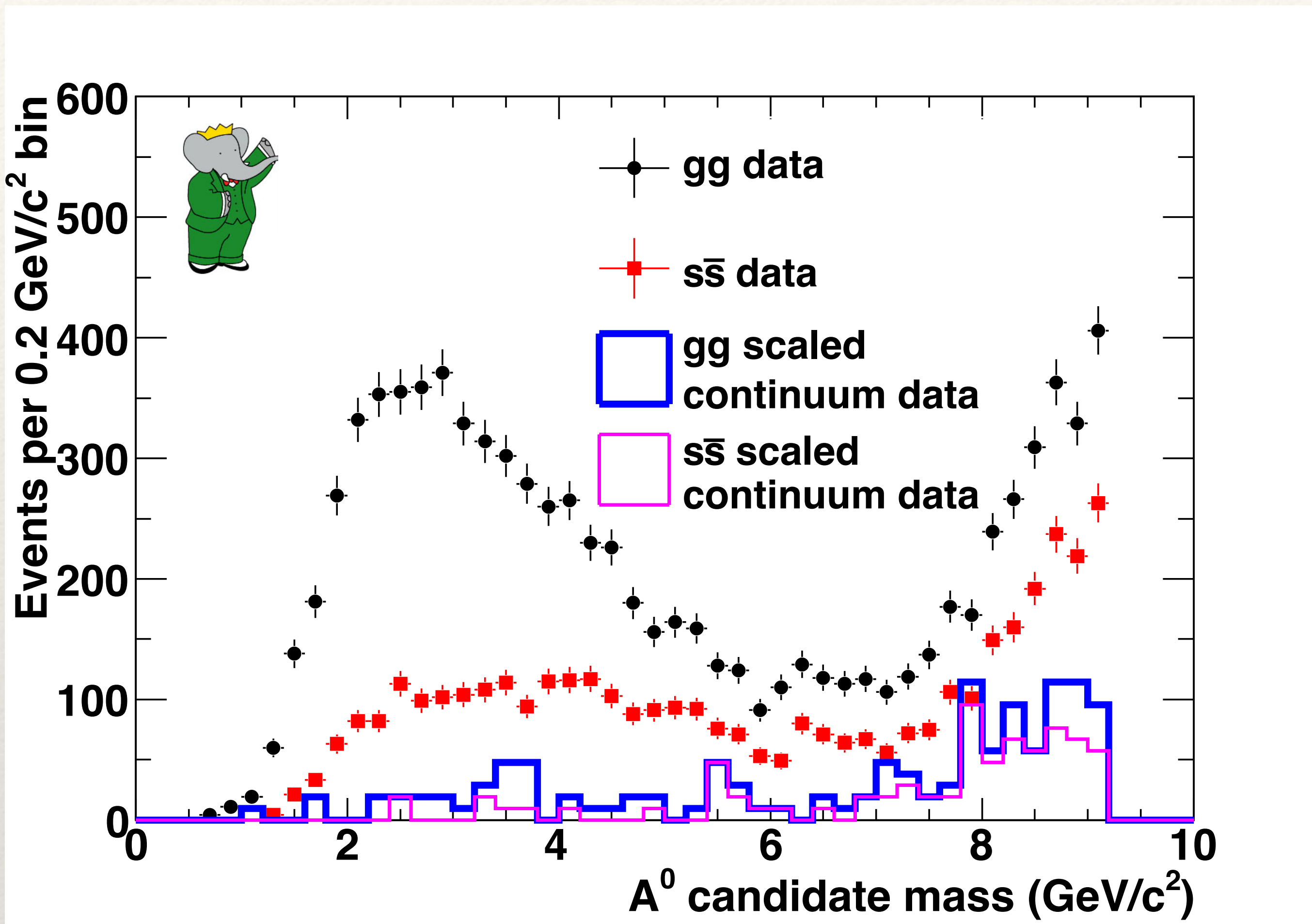
A^0—>gg (channels 1–26); A^0—>gg and A^0—>ss̄ (channels 11–13 and 15–24)

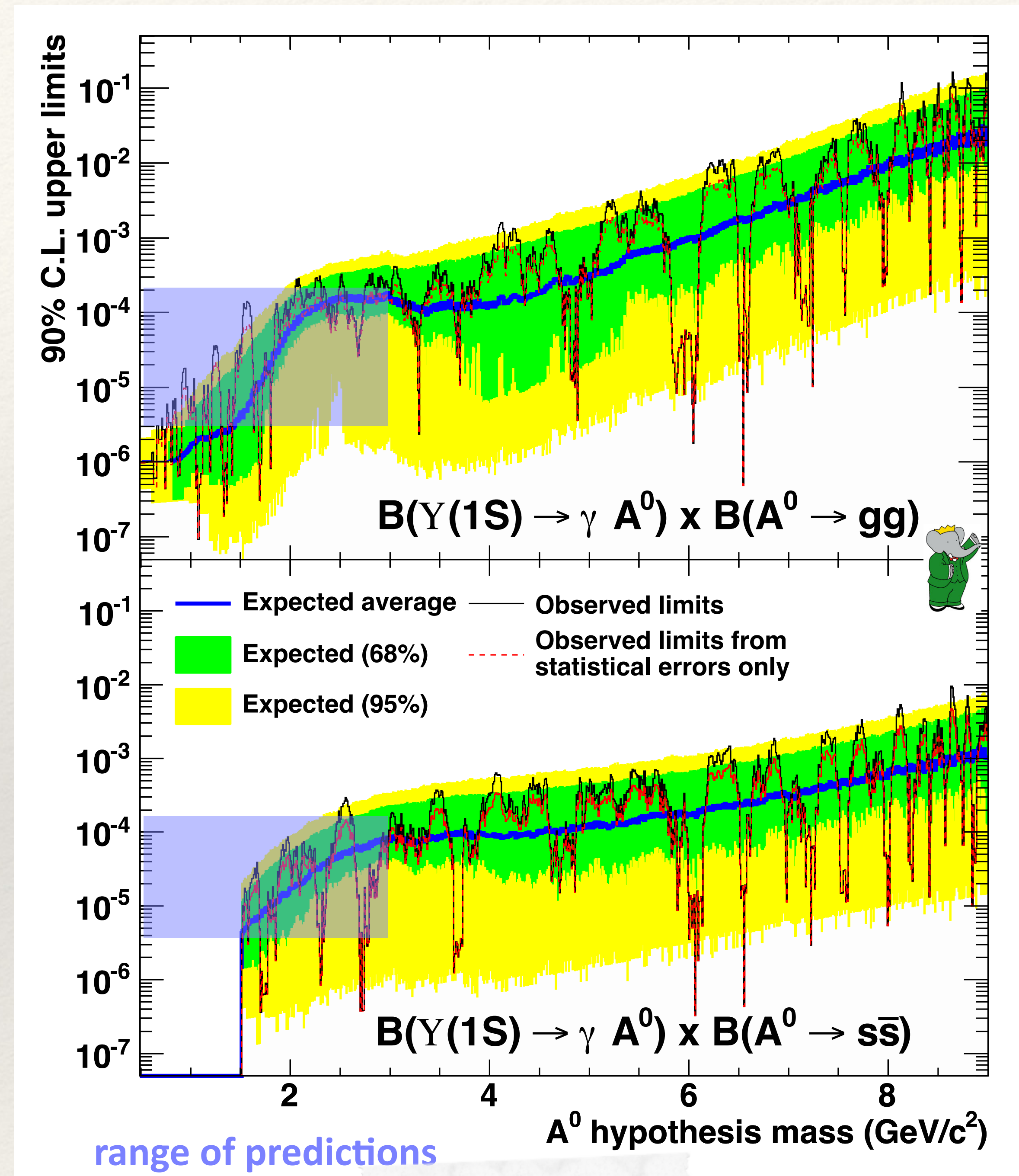
- Main backgrounds:
  - **Υ(1S)—>γgg** with gluons hadronizing to more than one daughter (2<m(A^0)<4 GeV/c^2)
  - **Υ(1S)—>ggg** with a π^0 mistaken as a γ (7<m(A^0)<9 GeV/c^2)
- Crucial importance of the **hadronization modeling** in simulations in order to determine the signal efficiency: data and MC are compared using Υ(1S)—>γgg events
  - Corrections are obtained in terms of scaling factors applied to the efficiencies, and a global **systematic uncertainty of 50%**

- A^0 would appear as **a narrow peak in the candidate mass spectrum**
- Scan of the mass spectrum in 10 MeV / c² steps, **from 0.5 to 9.0 GeV/c**

$BR(\Upsilon(1S) \rightarrow \gamma A^0) \times BR(A^0 \rightarrow gg) < 10^{-6} - 10^{-2}$

$BR(\Upsilon(1S) \rightarrow \gamma A^0) \times BR(A^0 \rightarrow s\bar{s}) < 10^{-5} - 10^{-3}$

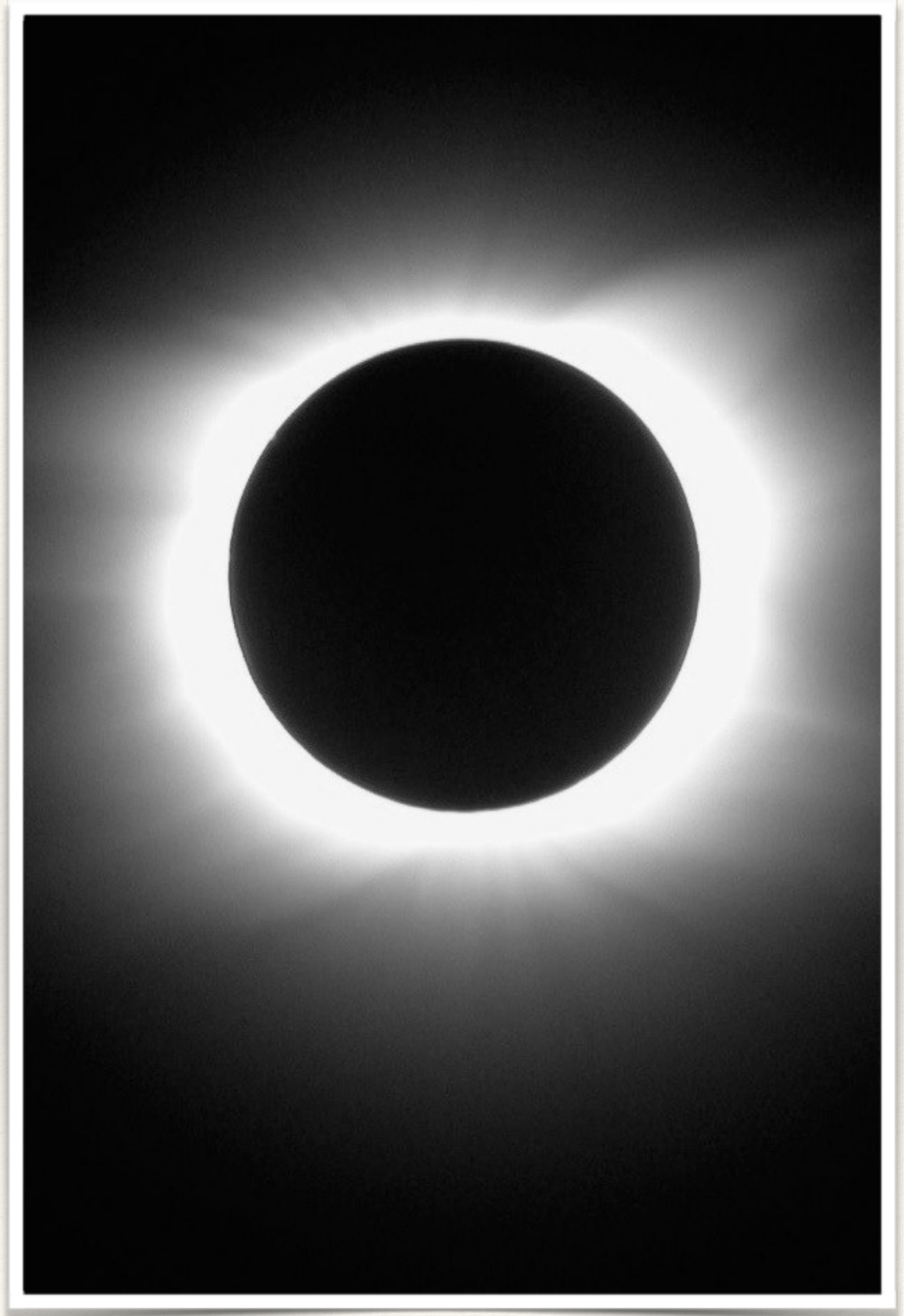




- **No significant signal through the entire mass region analyzed**
- Bayesian upper limits at 90% CL are set on the product of braching fractions

No evidence either for the signal or for any narrow hadronic resonance
Low-mass region excluded

Dark sector

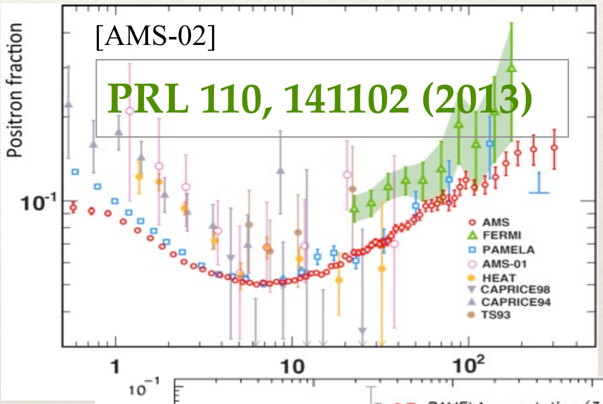


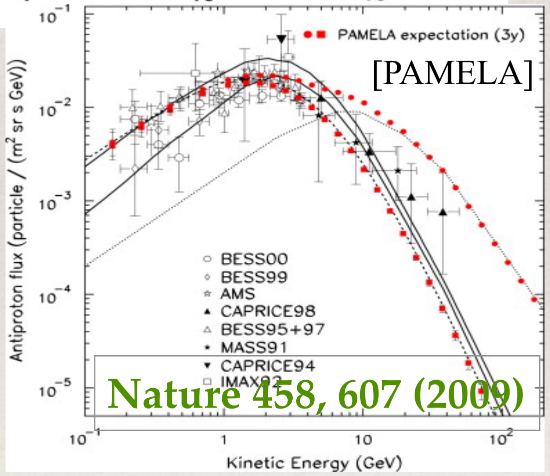
Motivations

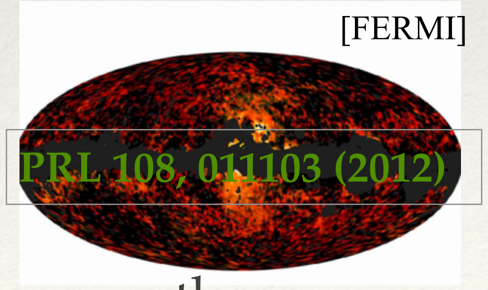
- In the context of dark matter models, new particles interacting feebly with ordinary matter, easily escaped from detection so far

- A new dark sector with a new gauge group ***U(1)′*** can be introduced
- The corresponding gauge boson is the **dark photon A′** PLB 166, 196 (1986)
  - couples to SM hypercharge via kinetic mixing with a **mixing strentgh ε**. Effective interaction: $\varepsilon e A'_\mu J^\mu_{EM}$
  - dark photon-SM fermion coupling **α′ = ε²α**
  - typically ε ~ O(10^{-5} - 10^{-2}) or smaller
  - <u>recent anomalies observed in cosmic rays:</u> may be accommodated by a dark photon with **m(A′) ~ O(MeV-GeV)** arXiv:1311.0029 (for instance)

—> <u>low-energy e⁺e⁻-colliders an ideal environment to probe low-mass dark sector</u>

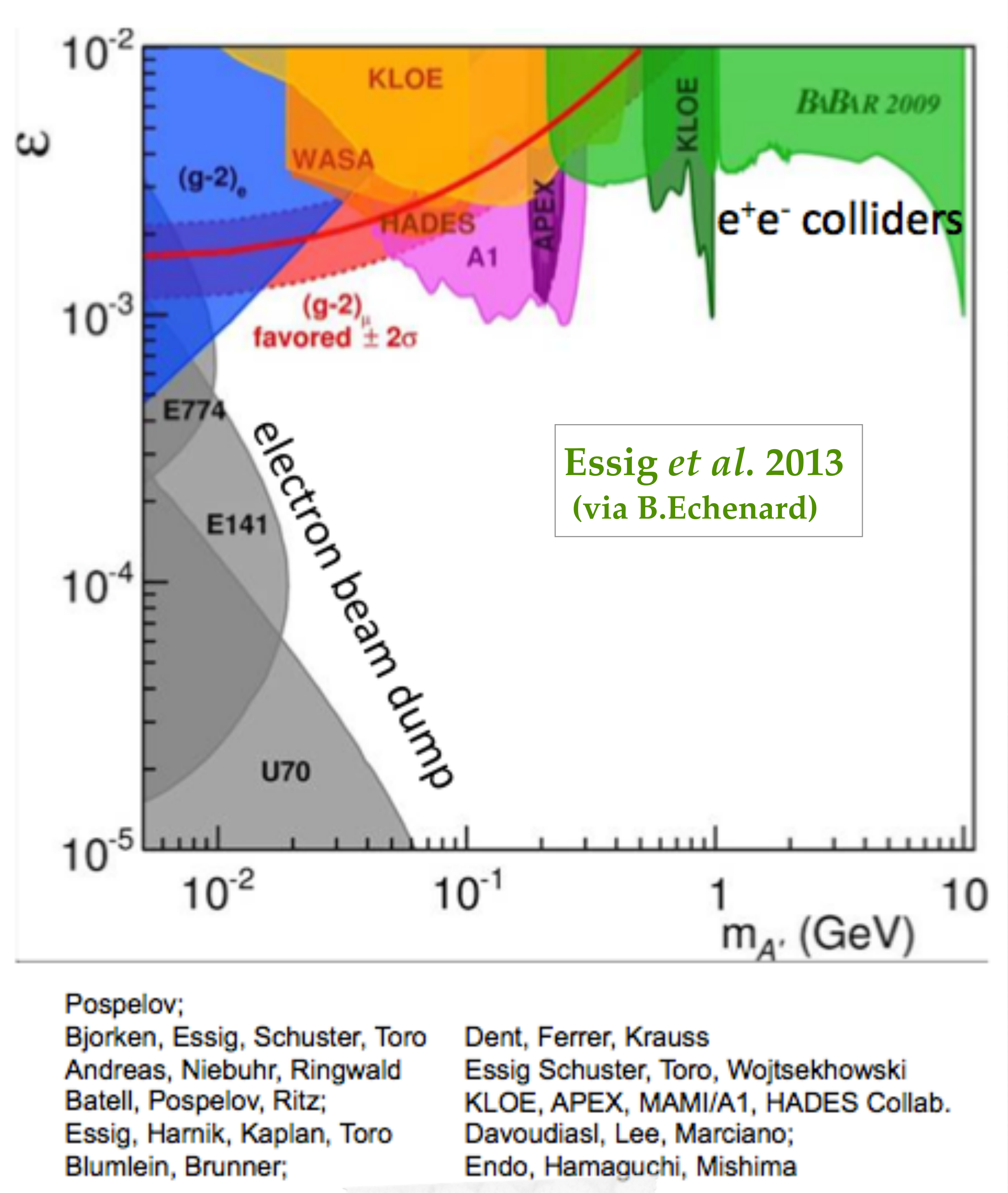






… and many others

- Constraints on mass and mixing from fixed target and e^+e^- colliders, and region favored by the muonic g-2 measurement

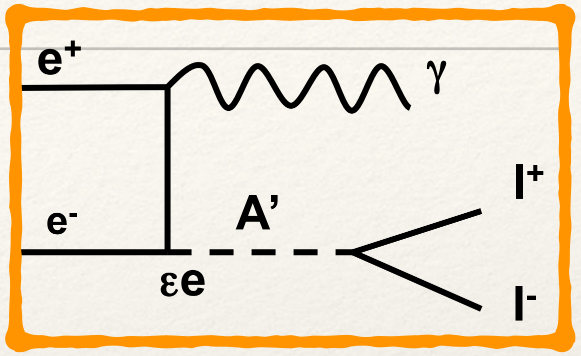


The *BaBar* constraint shown comes from re-interpretation of light CP-odd Higgs boson searches

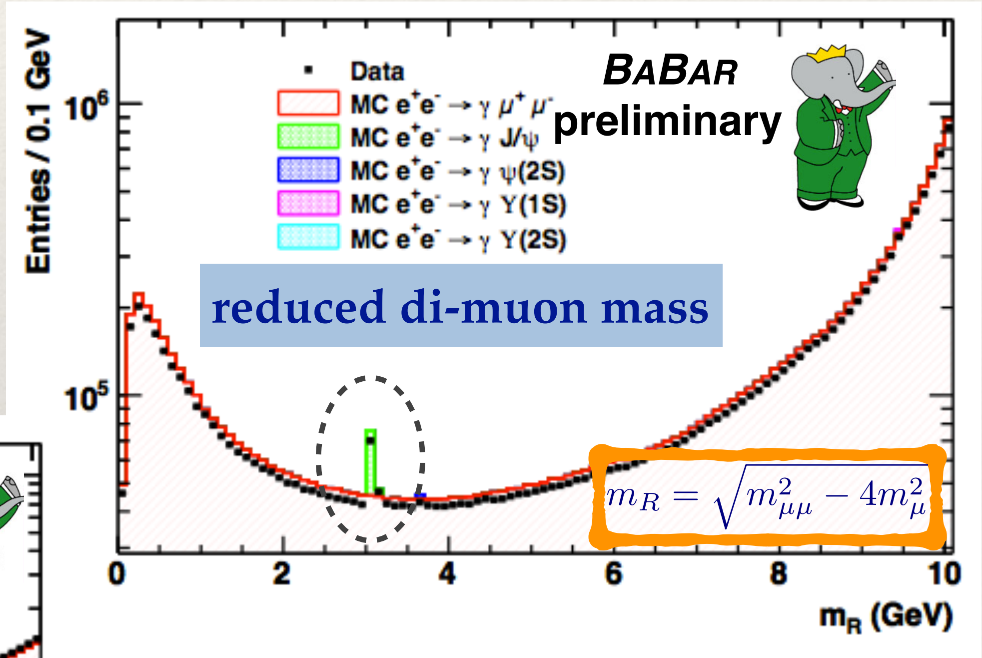
New!

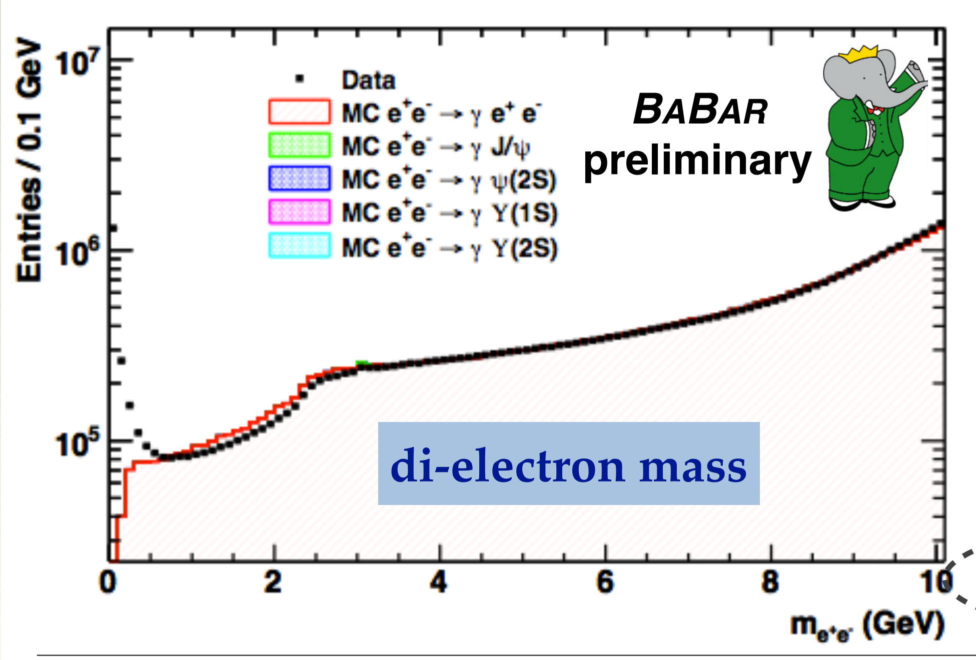
Search for dark photons at *BABAR*

arXiv:1406.2980



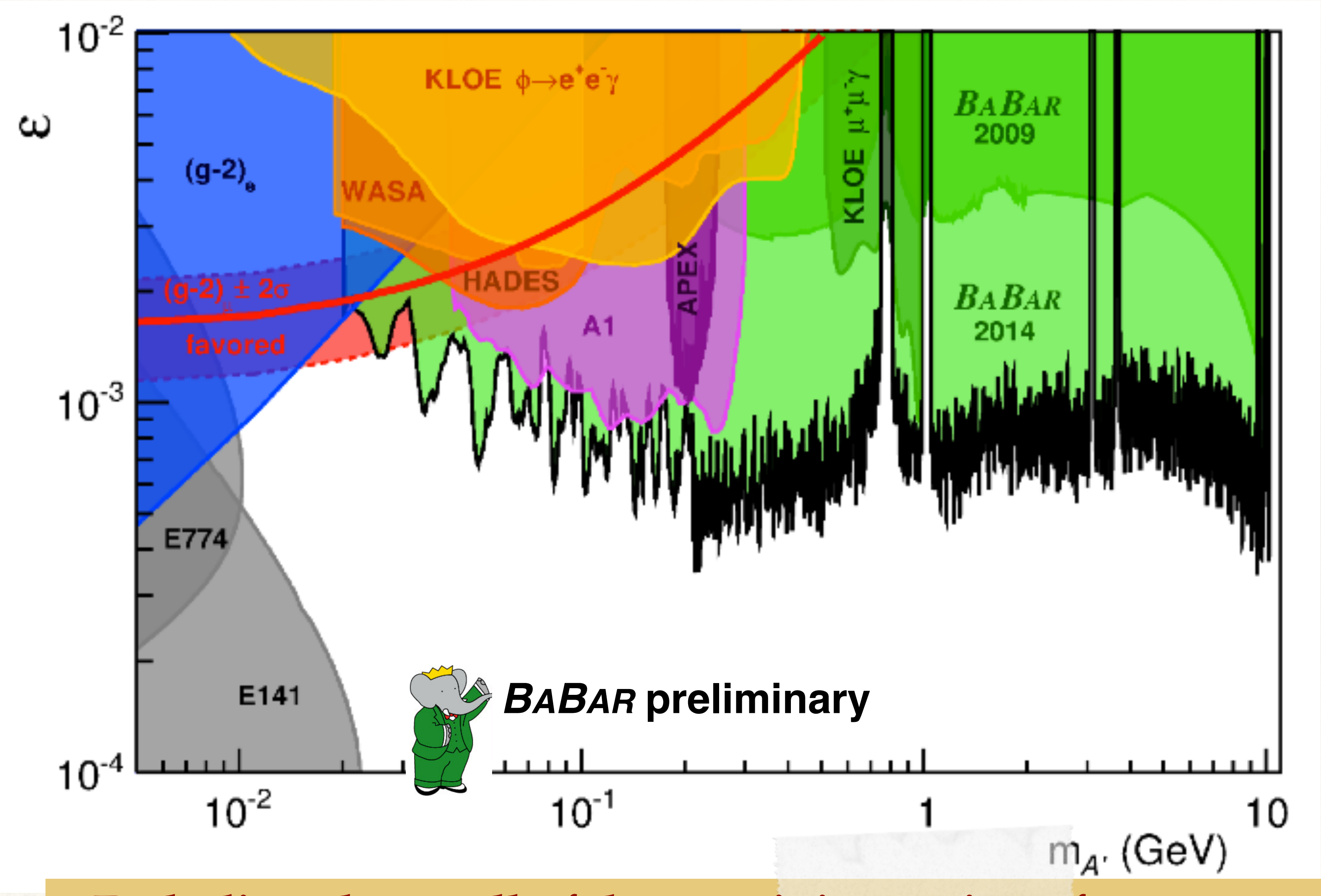
- A′ can be produced in association with a photon in e^+e^- collisions
- Decay back to SM fermions (in the assumption that there are no light dark fermions)
- Width suppressed by a factor ε^2 well below experimental resolution —> narrow resonances in radiative e^+e^- —> γl^+l^- events
- Search for A′ in **e^+e^- —> γA′, A′—>l^+l^- (l=e,μ)** events using the **full *BABAR* dataset** (on-peak + off) **~514 fb^{-1}**
- Selected events with two oppositely charged tracks (at least one electron, or both muons) + a single energetic photon (E_{CM}>0.2 GeV)
- Additional low-energy photons allowed
- Explored mass ranges 0.02 - 10.2 GeV / c² (ee) and 0.212 - 10.2 GeV / c² ($\mu\mu$)





- Radiative Bhabha for ee (dimuon for $\mu\mu$) production dominant
- Smaller peaking contributions from ISR production of J / ψ, ψ(2S), Υ(1S,2S)

- A scan of the mass distributions for each beam energy
- Steps = half of the dark photon resolution
- No significant signal has been observed
- Bayesian upper limits at 90% CL are set on the e^+e^- **—> γA′ cross-section**, typically **O(1-10) fb**
    - translated into **limits on the mixing strength as a function of A′ mass**



- Significant improvement wrt previous constraints!
- Dominant in the range 30 MeV - 10 GeV!

Excluding almost all of the remaining region of parameter space favored by $(g\text{-}2)_\mu$

Conclusions

- *BABAR* physics program has been succesfully extended to New Physics
- *BABAR* extensively searched for a **light Higgs boson**, significantly restricting the available parameter space for New Physics models (like NMSSM)
- *BABAR* provides the best limits on the search for a **dark photon** in the range of mass between 30 MeV and 10 GeV
- Still more results to come!

Backup

The BABAR detector

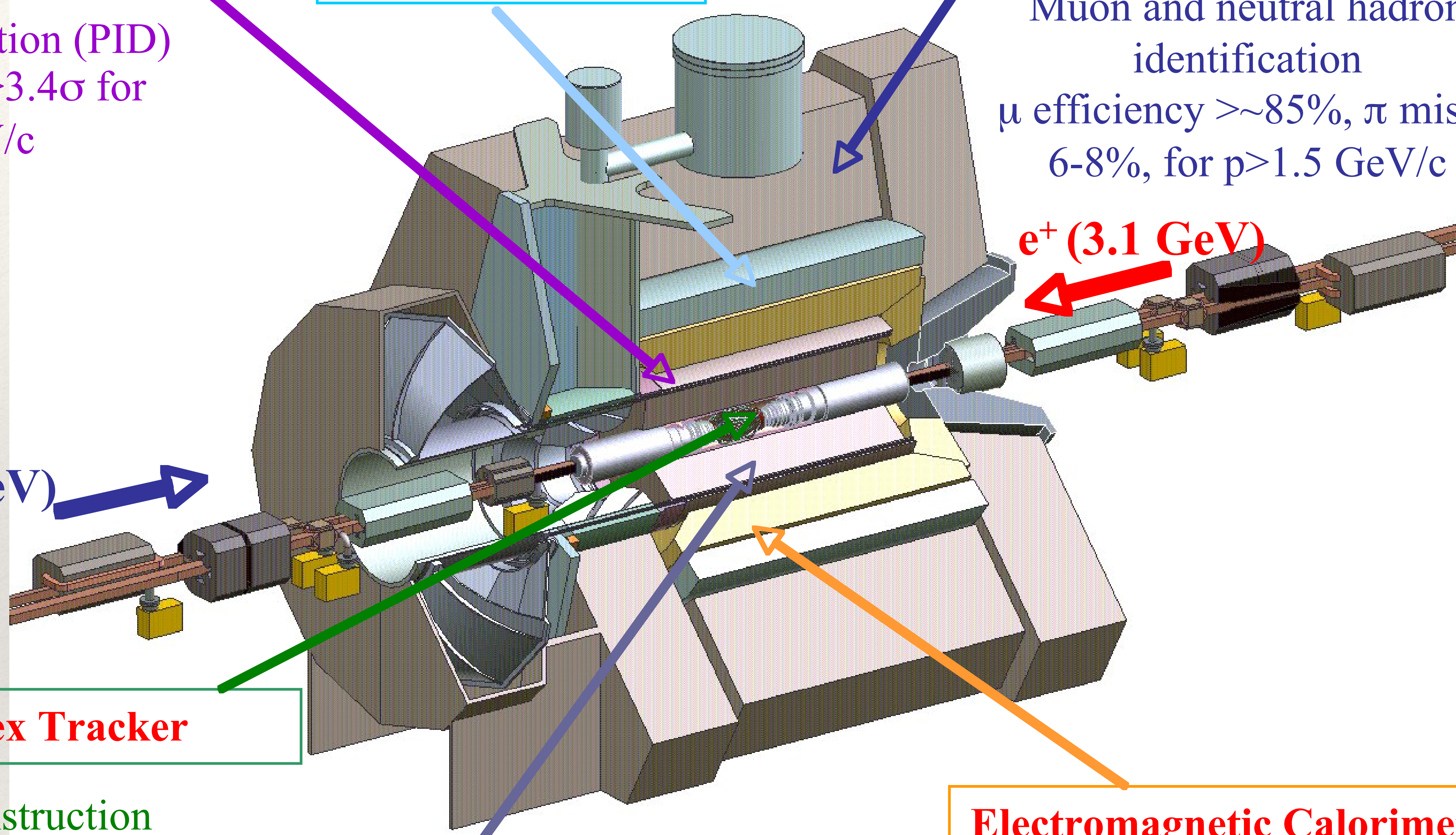
Cherenkov Detector

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

Solenoid 1.5T

Instrumented Flux Return

Muon and neutral hadron identification
μ efficiency >~85%, π mis-id 6-8%, for $p>1.5$ GeV/c



Silicon Vertex Tracker

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

Drift Chamber

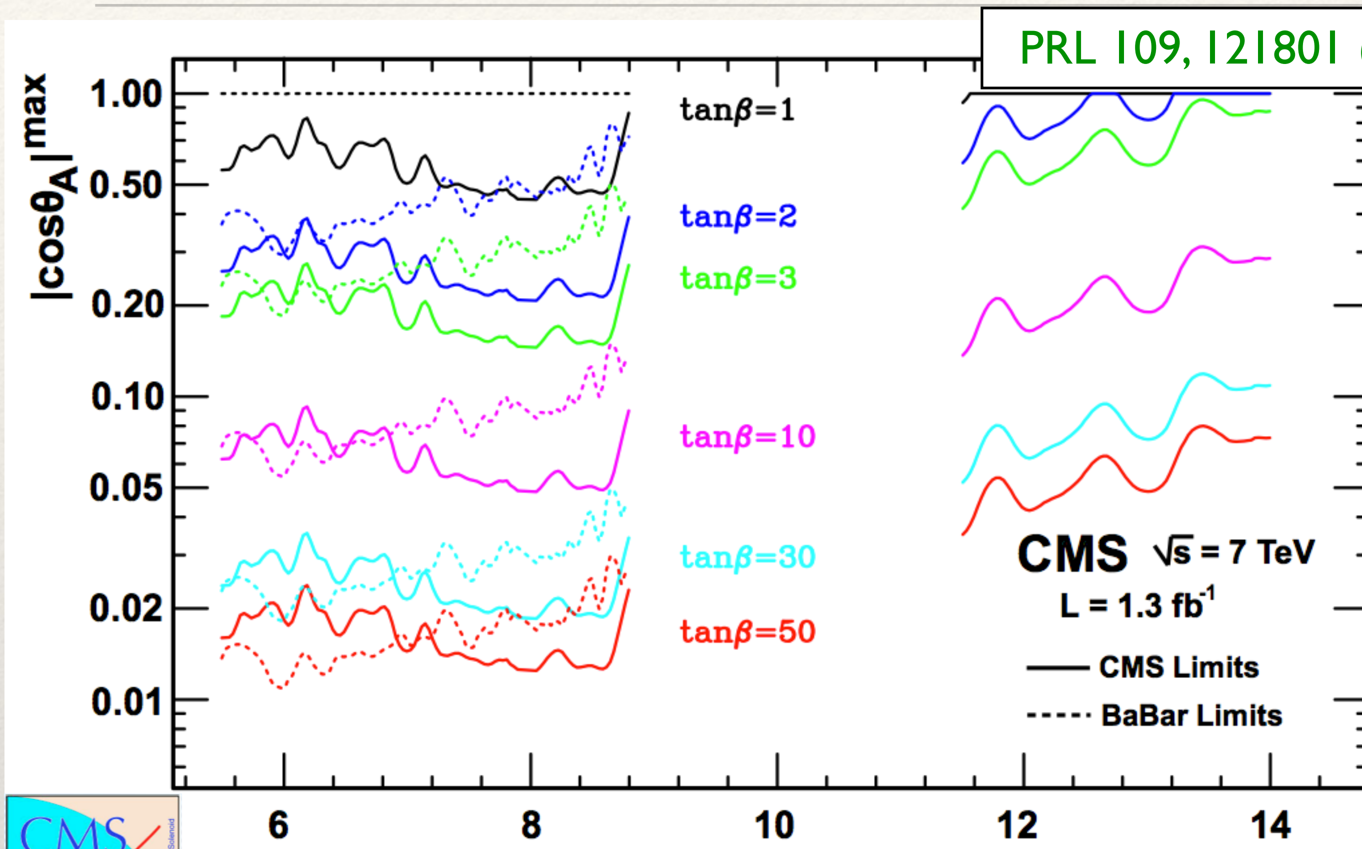
Momentum measurement for charged particles + dE/dx.
$\sigma(p_T)/p_T = 0.13\% p_T \oplus 0.45\%$

Electromagnetic Calorimeter

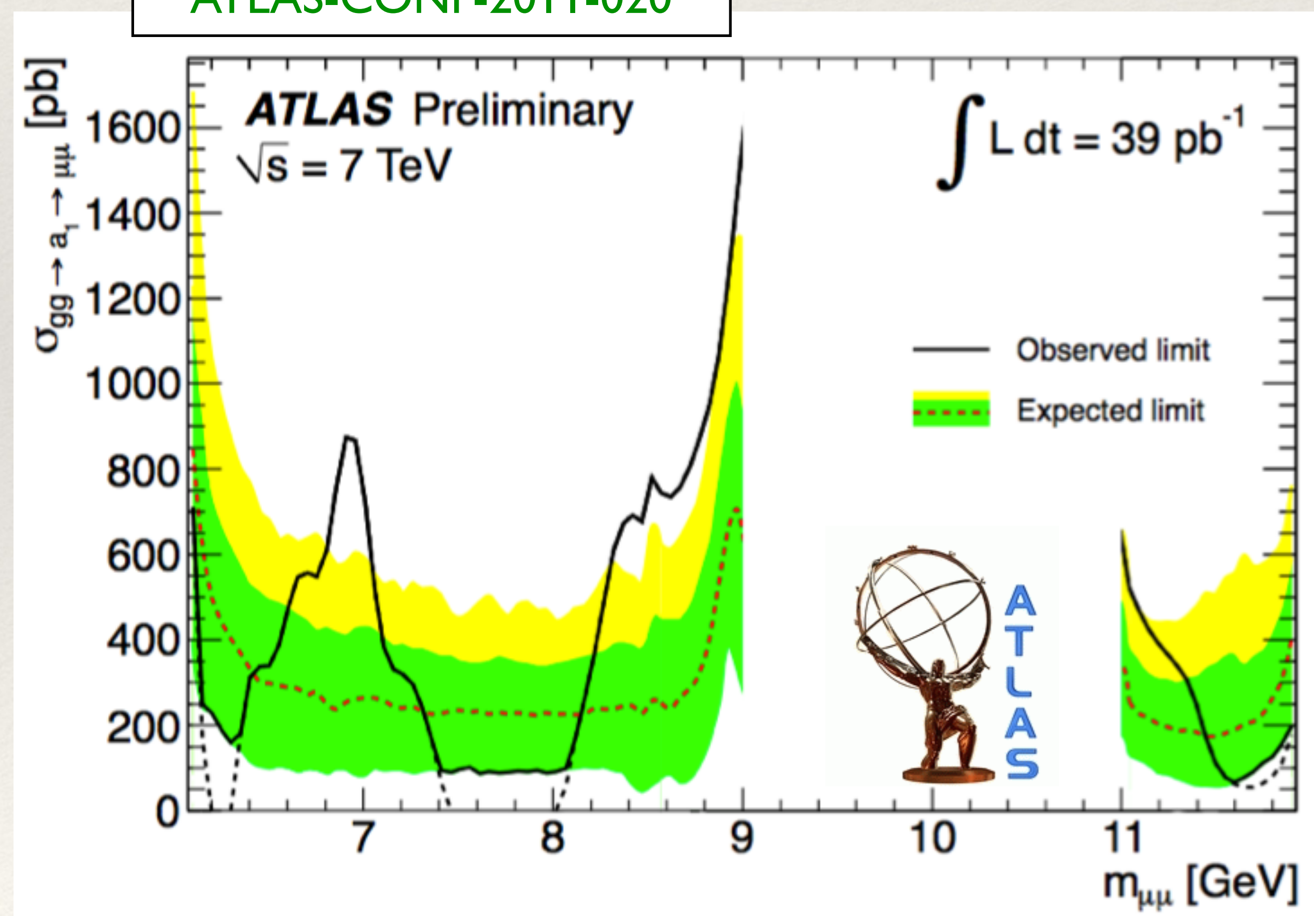
Electron and photon energy measurement. $\sigma(E)/E = 1.33\% E^{-1/4} \oplus 2.1\%$

A^0 searches at the LHC

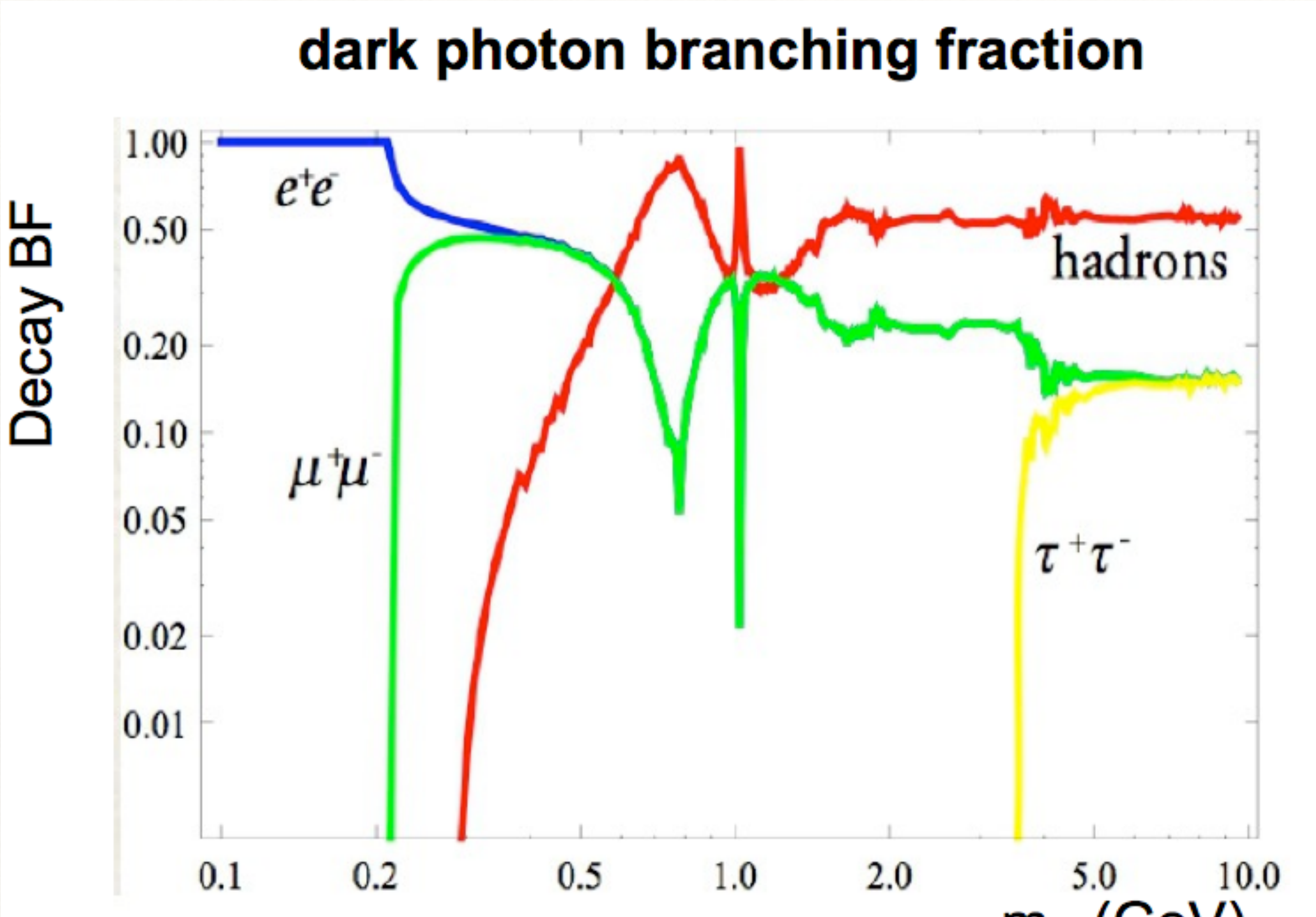
PRL 109, 121801 (2012)



ATLAS-CONF-2011-020



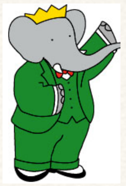
A' decays



PRD 79 (2009) 115008

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

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

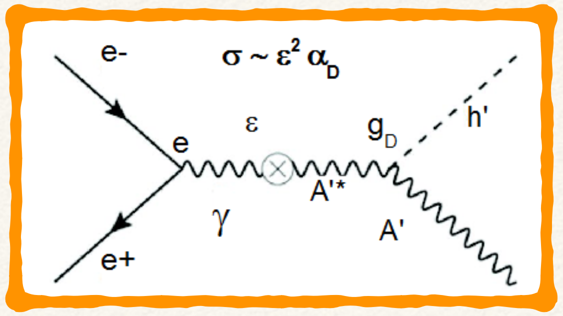


Re-interpretation of A^0 analyses as A' searches

- ***BaBar*** has a number of analyses performed as searches for **A^0**, a light CP-odd Higgs which can be reinterpreted as results for dark photon searches
  - 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 $e^+e^- \to \gamma A^0$, $A^0 \to l^+l^-, q\bar{q}$, invisible → $e^+e^- \to \gamma A'$, $A' \to l^+l^-, q\bar{q}$, invisible

Caveat: **A'** is a vector → limits should be reinterpreted taking into account a variation in the efficiency

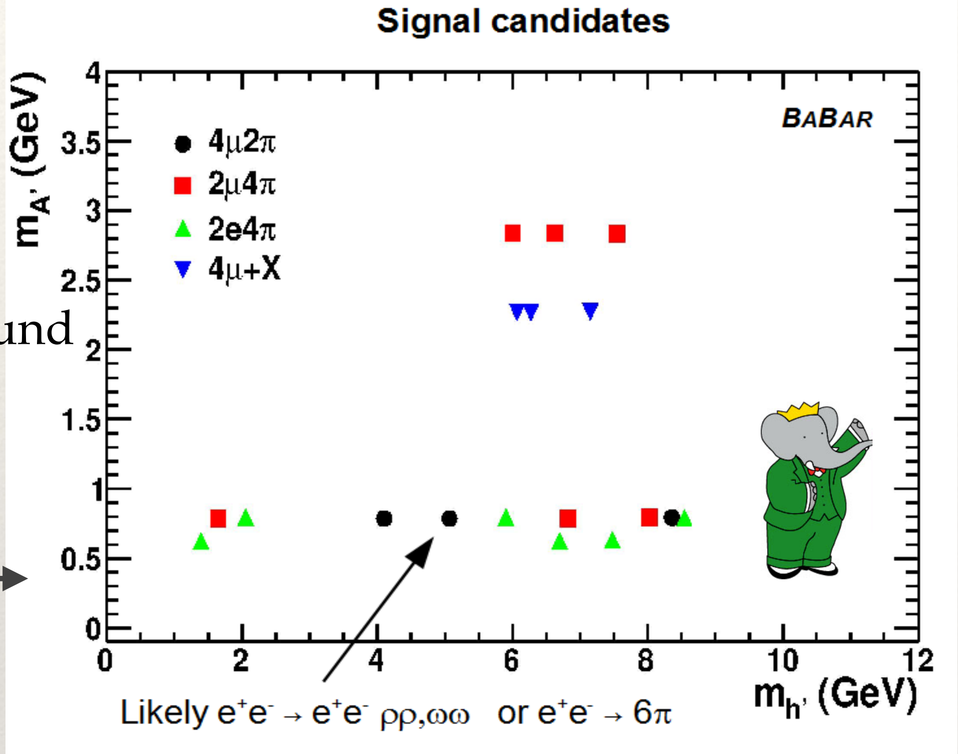
- Nevertheless, a good estimate for the order of magnitude of the limit

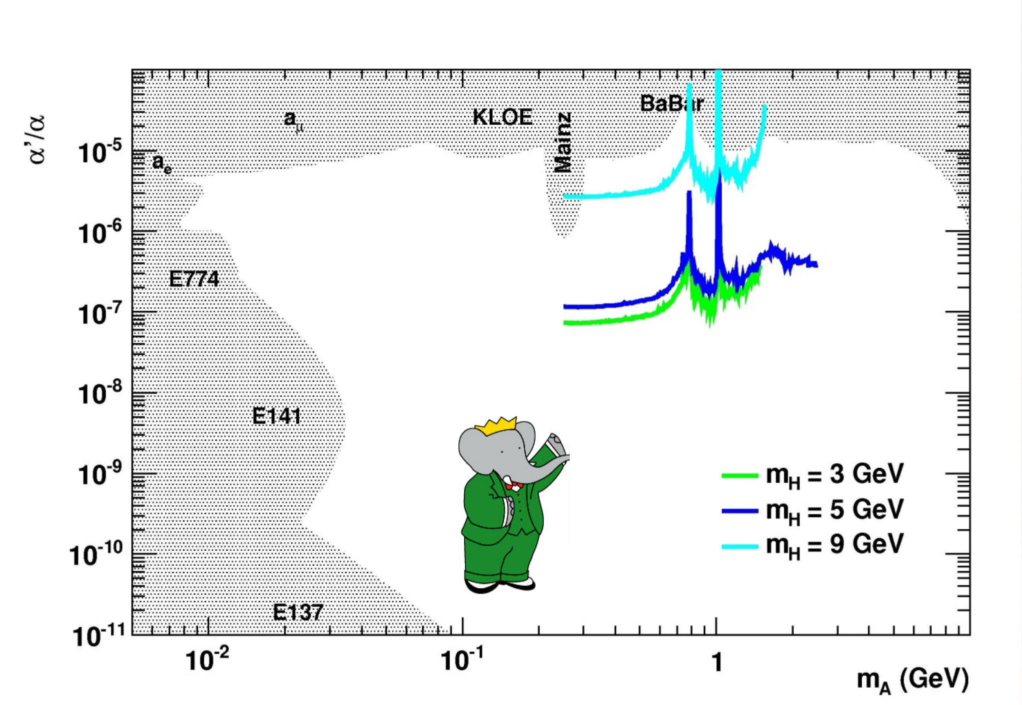


PRL 108, 211801 (2012)

Dark Higgs

- ✓ Dark photon mass generated via the Higgs mechanism, adding a dark Higgs boson (**h′**)
- ✓ 1 dark photon and 1 dark Higgs in a minimal scenario
- ✓ Dark Higgs mass O(MeV-GeV)
- ✓ The Higgsstrahlung process is only suppressed by ε^2 and has low background
- ✓ Search for prompt h′ decays: $\mathbf{e^+e^- \longrightarrow A'^* \longrightarrow h'A', h' \longrightarrow A'A', A' \longrightarrow l^+l^-, \pi^+\pi^-}$
- ✓ Using the full *BABAR* dataset: 6 candidates selected





- ✓ three entries for each event (corresponding to the possible assignments of h′—>A′A′)
- ✓ no events with 6 leptons, consistent with the pure background hypothesis
- ✓ **substantial improvement over existing limits for m(h′)< 5-7 GeV**