# Search for light Higgs and Dark Gauge Bosons at $e^+e^-$ colliders

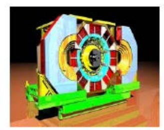
Sven E. Vahsen, University of Hawaii

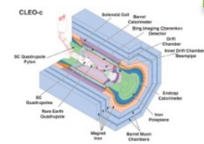
2013 Conference on Flavor Physics and CP Violation

Buzios, Rio de Janeiro, Brazil

# Outline

- Physics Motivation
- Experiments / Data Samples



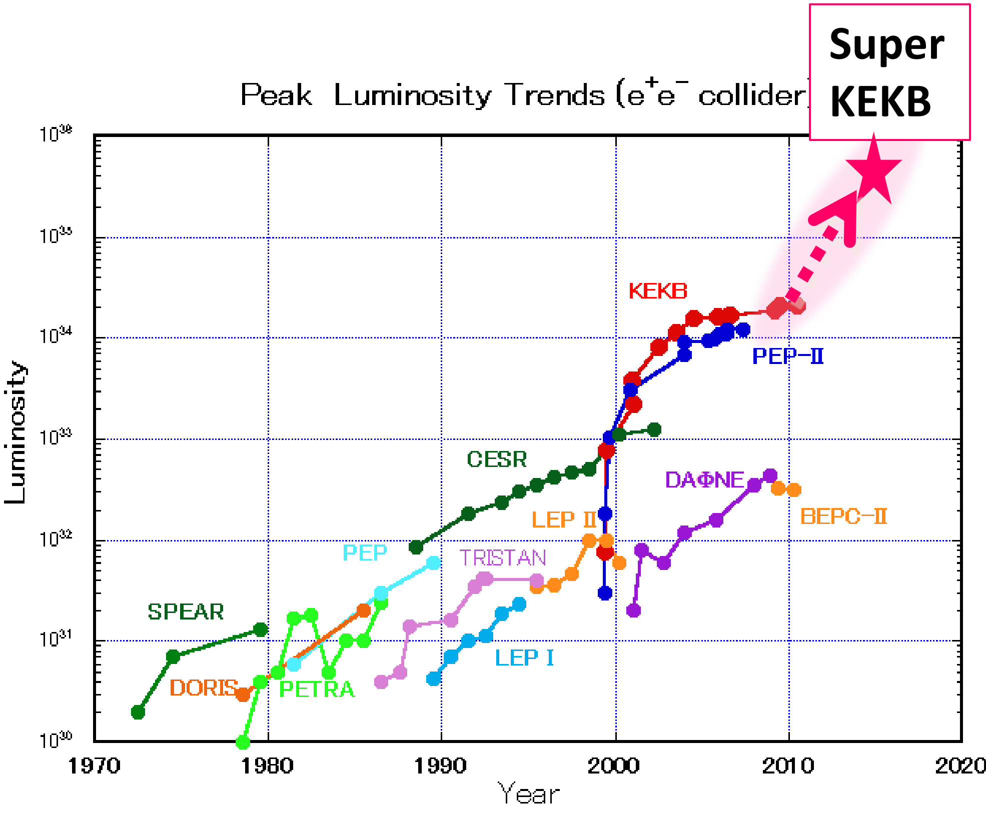


Belle BaBar BES CLEO

- Results of searches for
  - Light Higgs
  - Dark Gauge Bosons
- Prospects for the future

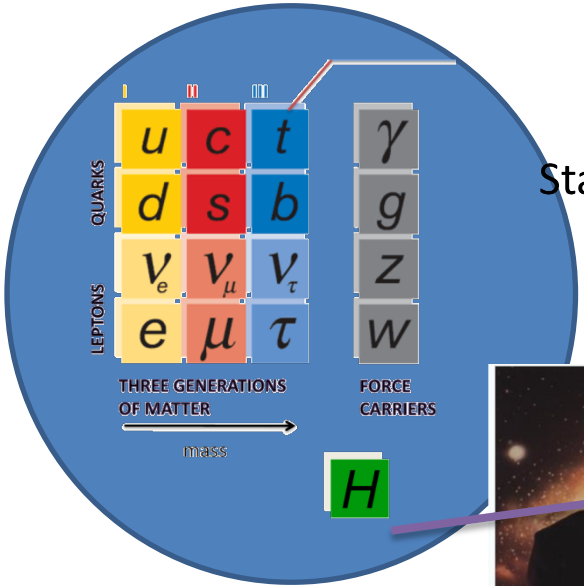
# Introduction and Motivation

- LHC: is energy-frontier tool for exploring TeV-scale physics
- But, many models of physics beyond the standard model feature new **low-mass** particles (MeV-GeV)
- The machines most suitable to search for those particles tend to be **low energy, high-luminosity $e^+e^-$ colliders**
- Examples in this talk
  - Light CP-odd Higgs: $A^0$
  - Dark Photon: A' (a.k.a. U)
  - Dark Higgs: h'



# *Another* Higgs Boson?

- Didn't the LHC already discover the "God Particle"? So the SM is complete, and we are done with the Higgs, right?
- No – we ***want* to go beyond** the SM. We dream of
  - unifying all forces in nature
  - explaining flavor structure
  - solving hierarchy problem
- And we ***have* to go beyond** the SM – to explain *observations* not accommodated by it
  - neutrino masses
  - dark energy
  - dark matter




Standard Model (SM)


Physicists Find Elusive Particle Seen as Key to Universe

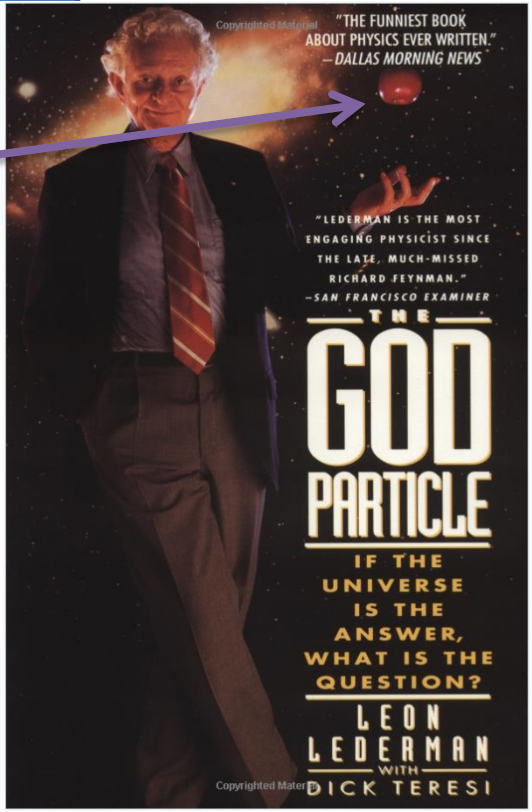
Pool photo by Denis Balibouse

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

By DENNIS OVERBYE
Published: July 4, 2012 | 122 Comments

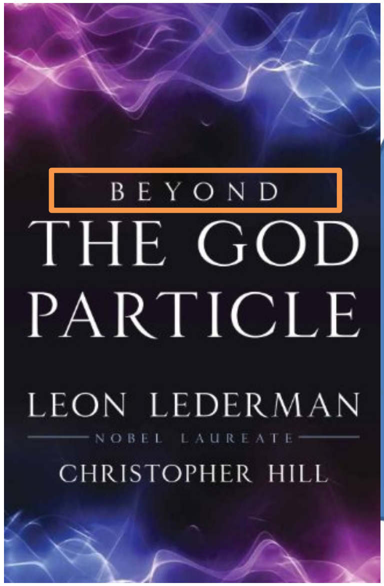
ASPEN, Colo. — Signaling a likely end to one of the longest, most expensive searches in the history of science, physicists said Wednesday that they had discovered a new subatomic particle that looks for all the world like the Higgs boson, a key to understanding why there is diversity and life in the universe.

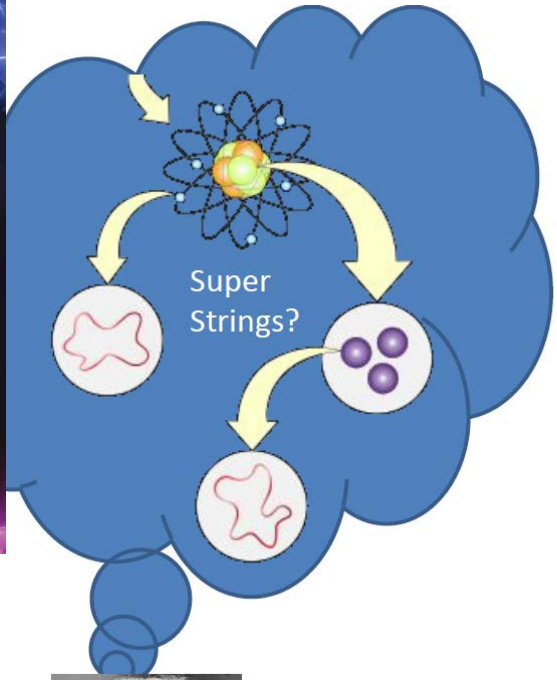
FACEBOOK
TWITTER
GOOGLE+
E-MAIL

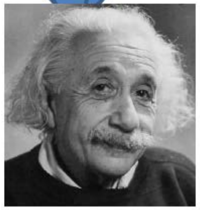



→ We both want to and must go beyond the Standard Model

# Beyond the Standard Model



- Beyond the SM, there might be SUSY, and there tend to be additional Higgs Bosons
- Example: Next-to-Minimal Supersymmetric Standard Model (nMSSM)
  - charged: $H^+, H^-$
  - neutral: $H_0^1, H_0^2, H_0^3$ (CP-even)
  - neutral: $A_0^1, A_0^2$ (CP-odd)

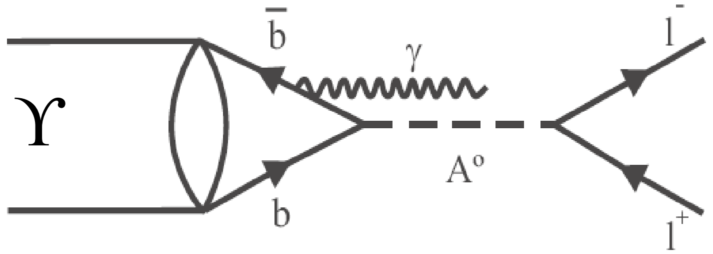
$A^0$ can be light. If $m_{A0} < 2m_b$, could have evaded previous searches, yet be accessible at B-factories. Constraints on low-mass nMSSM Higgs sector may be important for understanding LHC discovery.

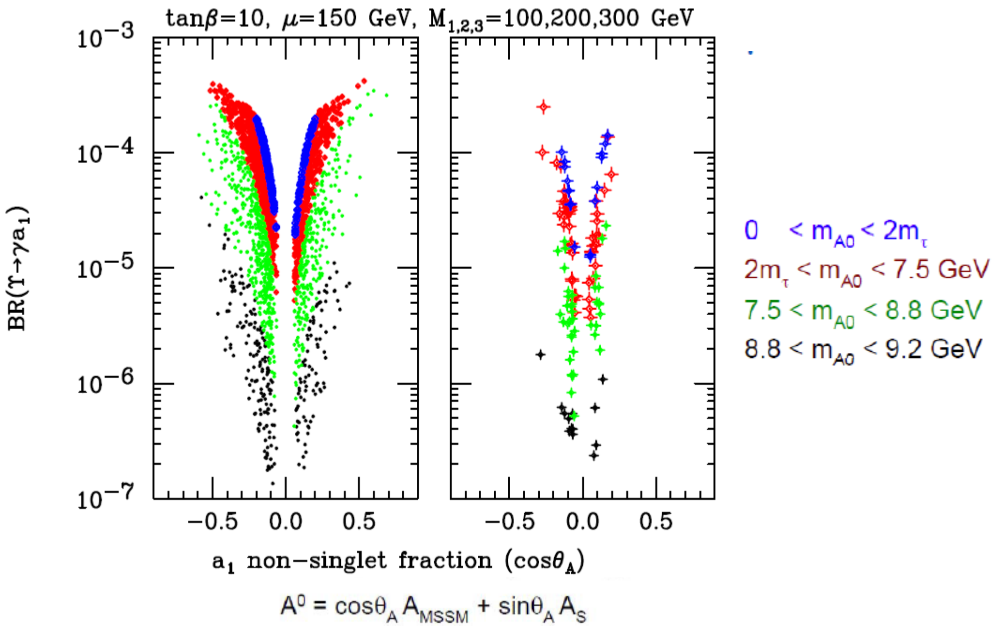
# Searching for a CP-odd light Higgs

- Search for $A^0$ in $\Upsilon$ (bottomonium) decays proposed by Dermíšek, Gunion, & McElrath in 2007
- At e+e- colliders, can produce
  - Directly

    $$e^+e^- \to \Upsilon[1s] \to \gamma A^0$$
  - in cascades

    $$e^+e^- \to \Upsilon[2s] \to \Upsilon[1s]\pi^+\pi^-$$
    with $\Upsilon[1s] \to \gamma A^0$
- BR($\Upsilon \to \gamma A^0$ ) in nMSSM can be large – up to $10^{-4}$
- $\Upsilon[ns]$ samples at B-factories: ~$10^8$



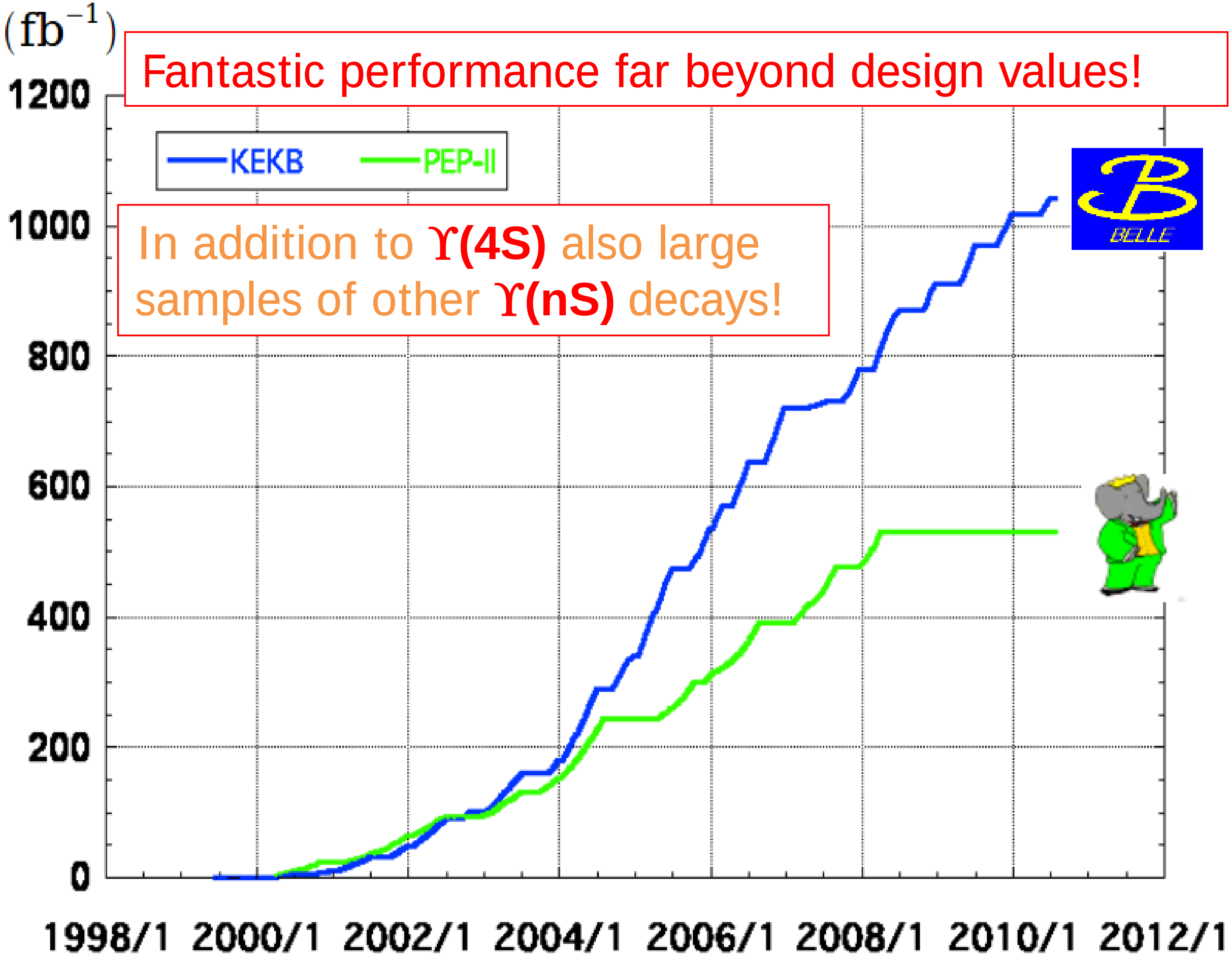




Phys.Rev.D76:051105,2007
arXiv:hep-ph/0612031

# Experiments & Data Samples

Fantastic performance far beyond design values!

In addition to $\Upsilon$**(4S)** also large samples of other $\Upsilon$**(nS)** decays!




**> 1 $ab^{-1}$**

**On resonance:**

$\Upsilon(5S)$: 121 $fb^{-1}$

$\Upsilon(4S)$: 711 $fb^{-1}$

$\Upsilon(3S)$: 3 $fb^{-1}$

$\Upsilon(2S)$: 25 $fb^{-1}$

$\Upsilon(1S)$: 6 $fb^{-1}$

**Off reson./scan:**

~ 100 $fb^{-1}$

**~ 550 $fb^{-1}$**

**On resonance:**

$\Upsilon(4S)$: 433 $fb^{-1}$

$\Upsilon(3S)$: 30 $fb^{-1}$

$\Upsilon(2S)$: 14 $fb^{-1}$

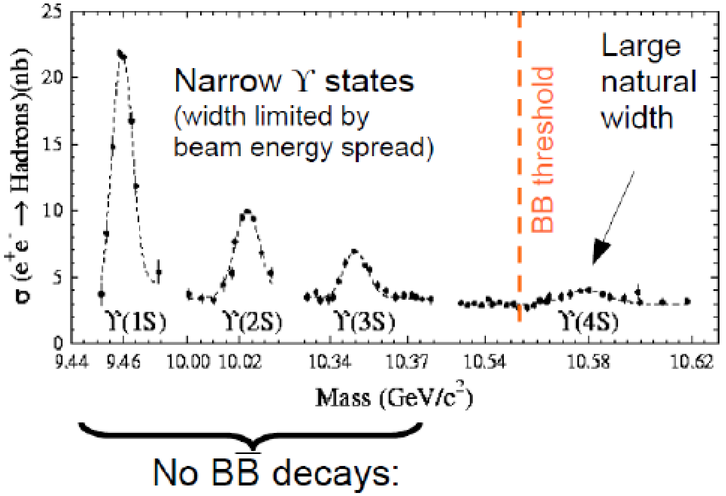
**Off resonance:**

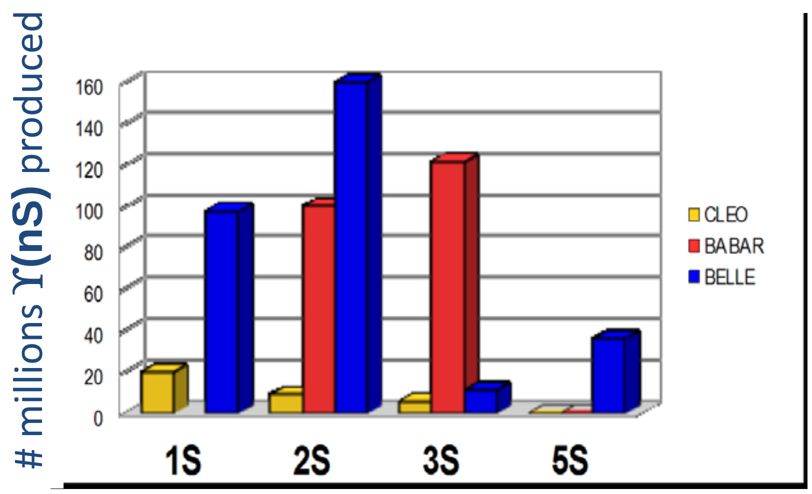
~ 54 $fb^{-1}$

**CLEO**

**$\Upsilon$(1S): 1.1 $fb^{-1}$**

# Upsilon 1S, 2S, 3S samples



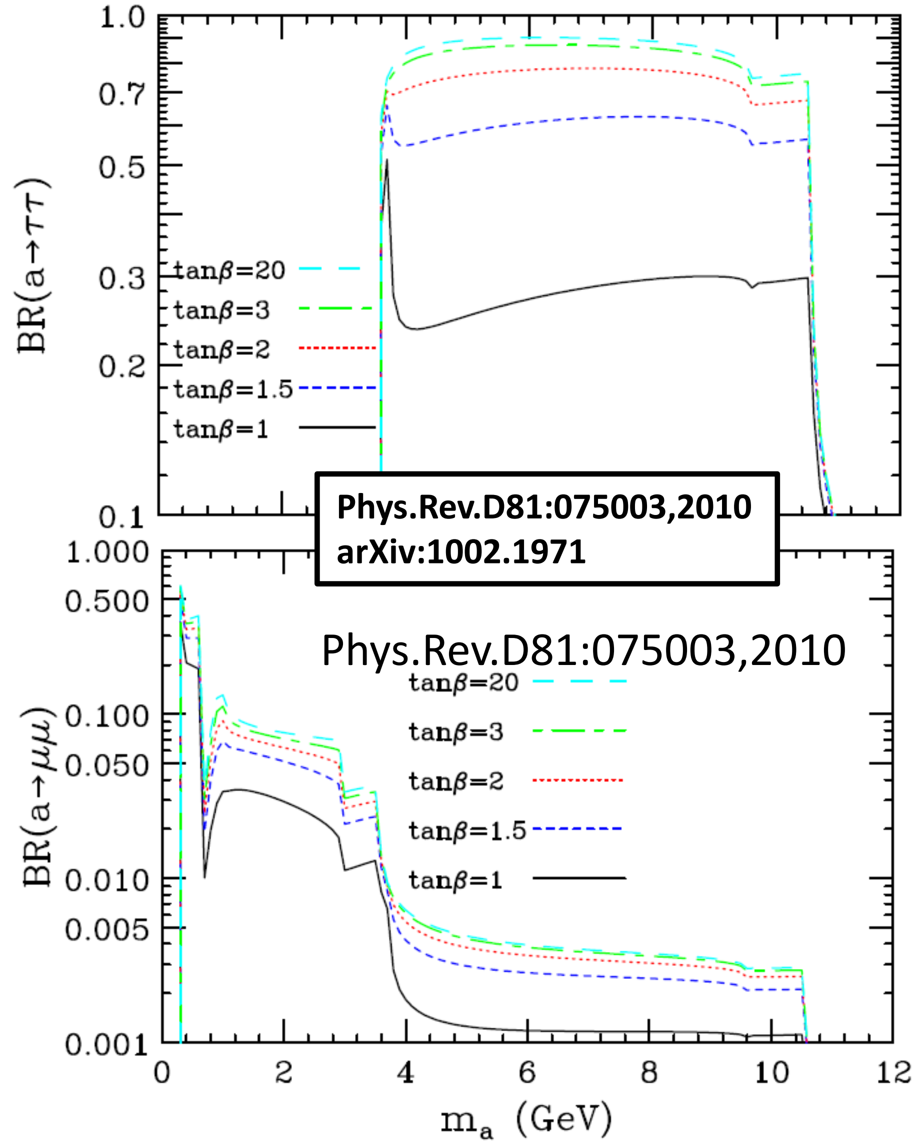

- Upsilon(1S,2S,3S) narrow
- Don't decay to BB

→ cleaner event samples, more suitable for background-limited searches for new low-mass states

- Belle, BaBar, CLEO samples complementary

# Expected $A^0$ Decays in NMSSM

- Preferred decays depend on $A^0$ mass & model parameters
- If sufficiently light neutralinos ($\chi^0$) exist, $A^0 \rightarrow \chi^0\chi^0$(=missing energy) may dominate
- Otherwise
  - For $M_{A^\circ} > 2M_\tau$; ττ and hadronic
  - For lower $M_{A^\circ}$; μμ and hadronic



# Light CP-odd Higgs: Belle and BaBar Searches

- BaBar carried out large number of searches
- No significant signals observed → limits set
- Shown at FPCP 2012. Also summarized in **arXiv:1209.1143 (B. Echenard)**

| Mode | Mass range (GeV) | BF upper limit (90% CL) |
|---|---|---|
| $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$ | $0.21 < m_A < 9.3$ | $(0.3 - 8.3) \times 10^{-6}$ |
| $\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$ | $4.0 < m_A < 10.1$ | $(1.5 - 16) \times 10^{-5}$ |
| $\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ hadrons | $0.3 < m_A < 7.0$ | $(0.1 - 8) \times 10^{-5}$ |
| $\Upsilon(1S) \to \gamma A^0, A^0 \to \chi\bar{\chi}$ | $m_\chi < 4.5$ GeV | $(0.5 - 24) \times 10^{-5}$ |
| $\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible | $m_A < 9.2$ GeV | $(1.9 - 37) \times 10^{-6}$ |
| $\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible | $m_A < 9.2$ GeV | $(0.7 - 31) \times 10^{-6}$ |

New searches since then

- $e^+e^- \to \Upsilon[1s] \to \gamma A^0(\to \tau^+\tau^-)$
- $e^+e^- \to \Upsilon[2s] \to \gamma A^0(\to \tau^+\tau^-,\ \mu^+\mu^-)$
- $e^+e^- \to \Upsilon[2s] \to \Upsilon[1s]\pi^+\pi^-;\ \Upsilon[1s] \to \gamma A^0(\to \tau^+\tau^-,\ \mu^+\mu^-)$
- $e^+e^- \to \Upsilon[2s] \to \Upsilon[1s]\pi^+\pi^-;\ \Upsilon[1s] \to \gamma A^0(\to \tau^+\tau^-)$
- $e^+e^- \to \Upsilon[2s,3s] \to \Upsilon[1s]\pi^+\pi^-;\ \Upsilon[1s] \to \gamma A^0(\to \mu^+\mu^-)$

Belle Preliminary (first three); BaBar (last two)

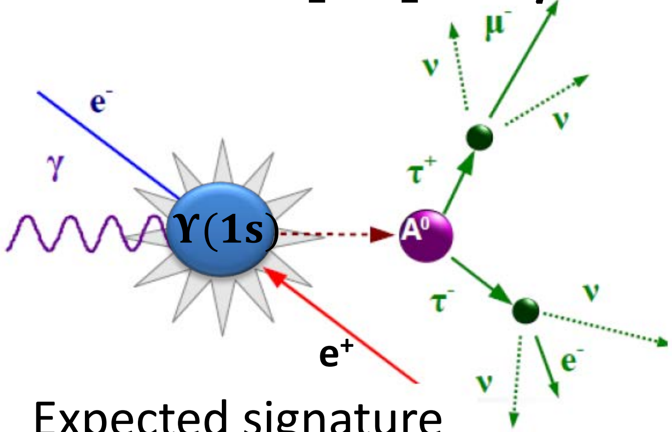
Much activity last year. Most low-hanging fruit picked. Increased emphasis on cascade decays.

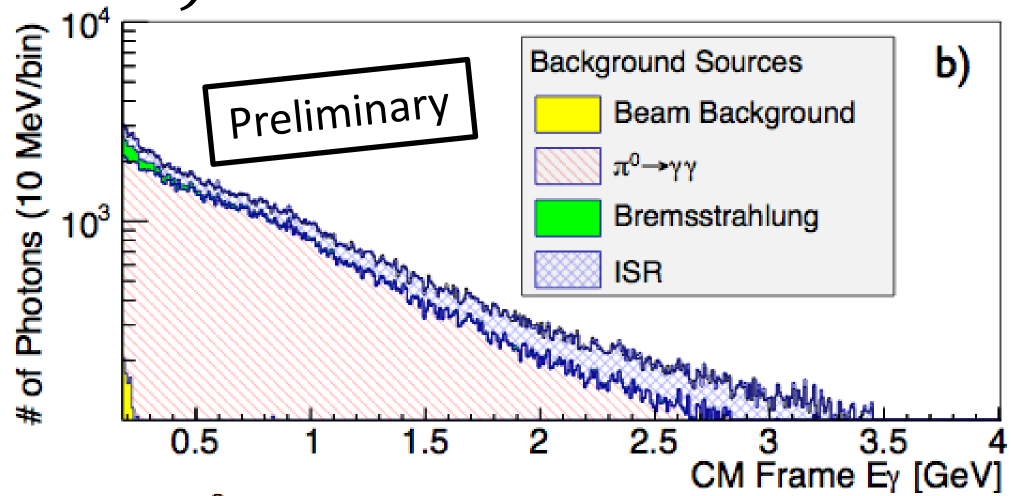
NEW

# Recent $A^0$ Searches

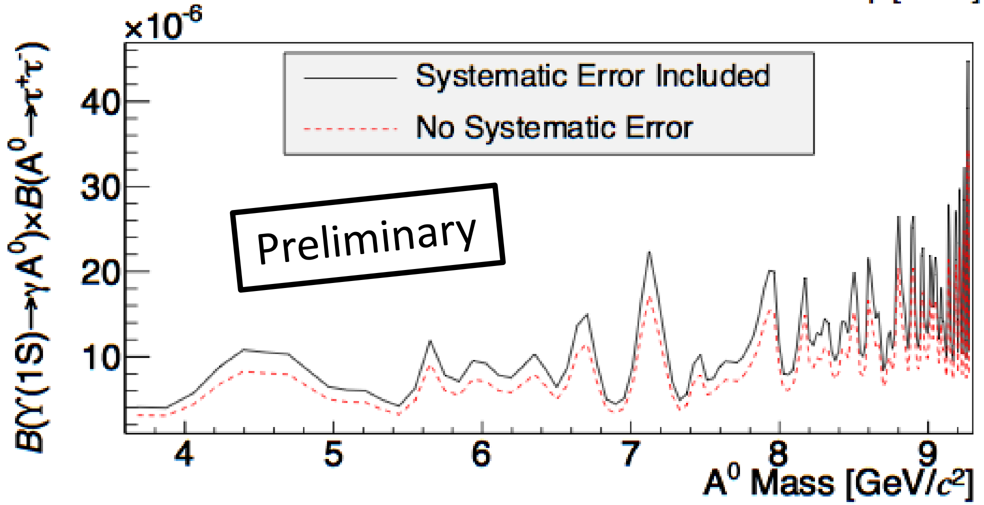
Preliminary

$$e^+e^- \rightarrow \Upsilon[1s] \rightarrow \gamma A^0(\rightarrow \tau^+\tau^-)$$



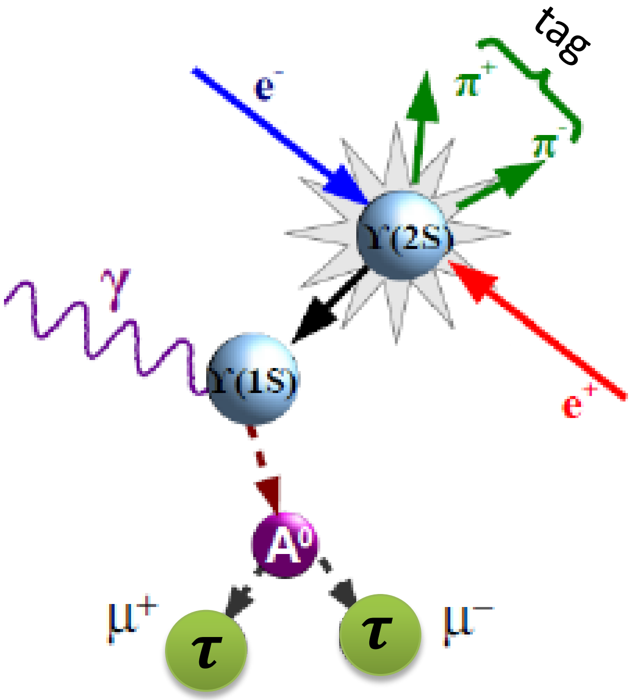

- Expected signature
  - mono-energetic photon line
  - products of two Tau decays
- Event selection
  - two charged tracks only, at least one with positive μ or e ID
  - Missing energy
  - veto Bremsstrahlung and $\pi^0$
- Fit for peak in $E_\gamma$spectrum
- None observed → set limit




- Factor ~2 improvement over previous $\Upsilon(1S)\rightarrow \gamma A^0(\rightarrow \tau^+\tau^-)$ world limit by CLEO
- Sensitivity scales with 1/sqrt(L), due to large BG. Also see BaBar results p. 14,15.

# $\pi\pi$–Tagging of Cascades

- If background could be greatly reduced, limits might scale like 1/L instead..
- One promising approach is to utilize cascade decays w/ pion tags




$$\Upsilon[ns] \rightarrow \Upsilon[1s]\pi^+\pi^-;\ \Upsilon[1s] \rightarrow \gamma A^0$$

# Recent $A^0$ Searches (II)

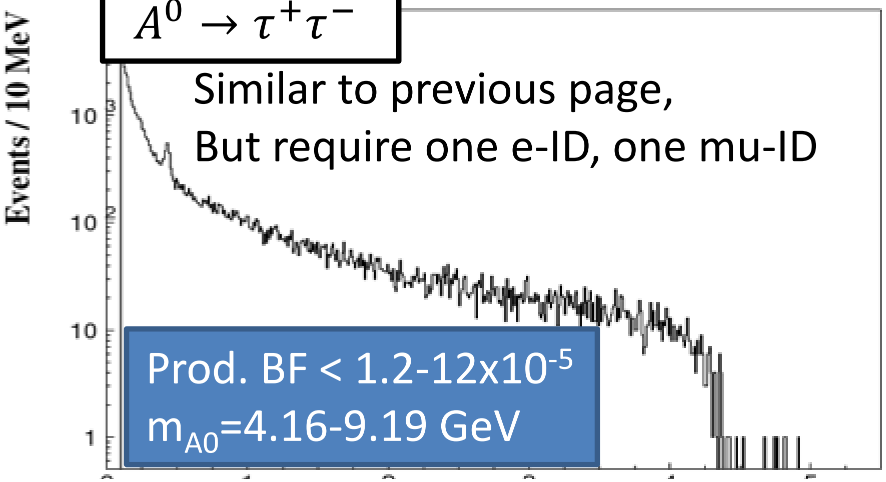
NEW

Preliminary

## $\Upsilon[2s] \rightarrow \gamma A^0$ (direct)

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

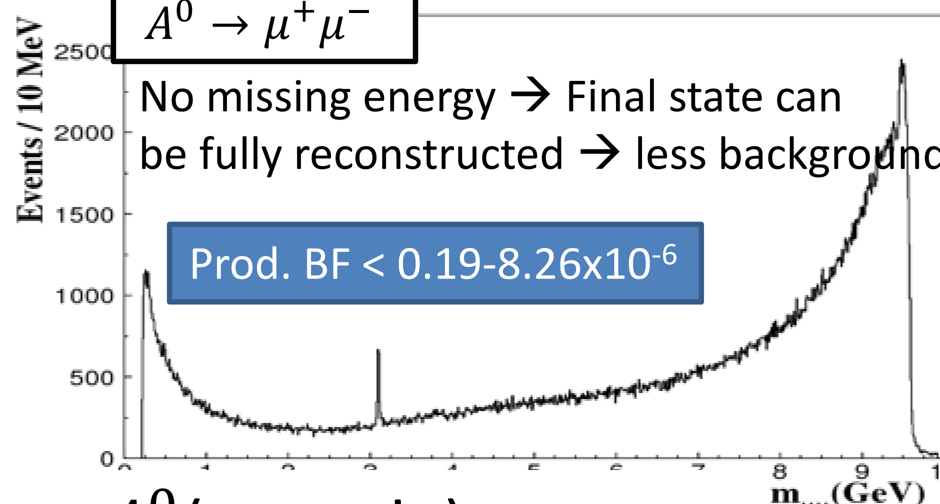
Similar to previous page,
But require one e-ID, one mu-ID




Prod. BF < 1.2-12x10$^{-5}$
$m_{A0}$=4.16-9.19 GeV

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

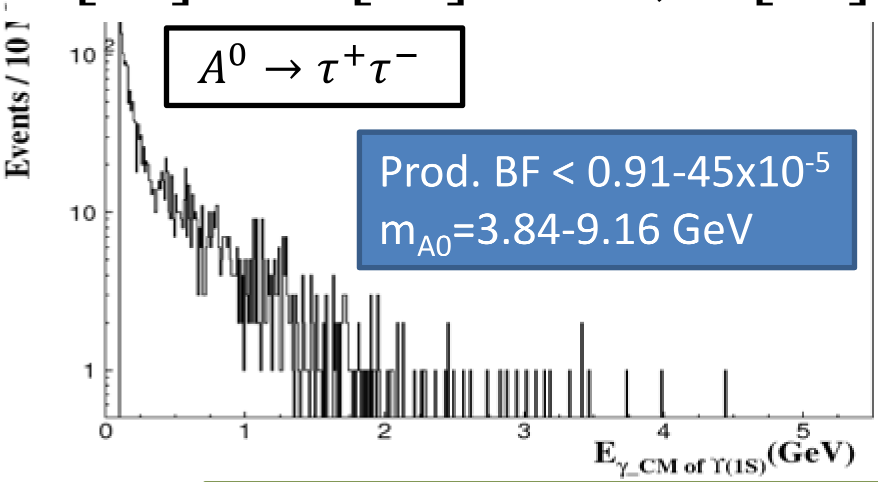
No missing energy → Final state can be fully reconstructed → less background




Prod. BF < 0.19-8.26x10$^{-6}$

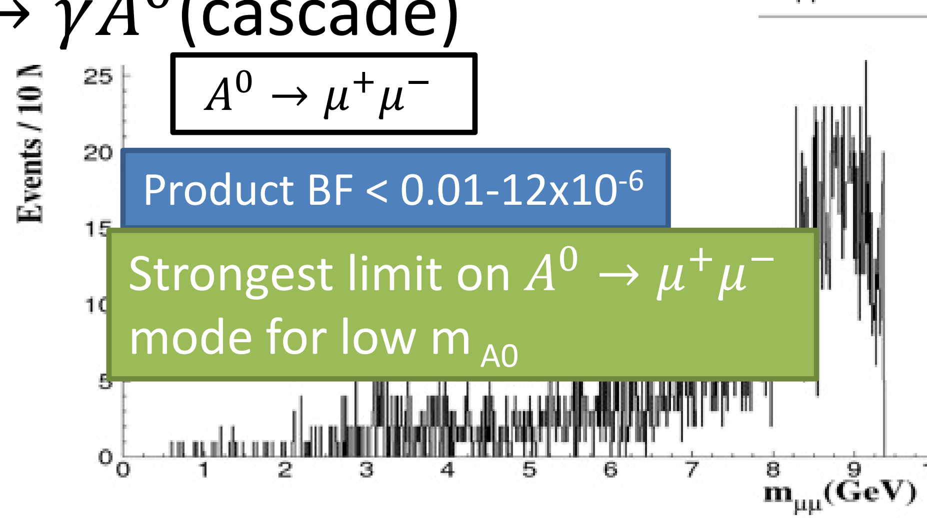
## $\Upsilon[2s] \rightarrow \Upsilon[1s]\pi^+\pi^-$; $\Upsilon[1s] \rightarrow \gamma A^0$(cascade)

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




Prod. BF < 0.91-45x10$^{-5}$
$m_{A0}$=3.84-9.16 GeV

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




Product BF < 0.01-12x10$^{-6}$

Strongest limit on $A^0 \rightarrow \mu^+\mu^-$ mode for low $m_{A0}$

- Modes with the π+π- tag have lower BG, but also lower statistics…
- Don't always improve limit, but may scale better with luminosity

NEW

# Recent $A^0$ Searches (III)

$$\Upsilon[2s] \rightarrow \Upsilon[1s]\pi^+\pi^-; \Upsilon[1s] \rightarrow \gamma A^0(\rightarrow \tau^+\tau^-)$$

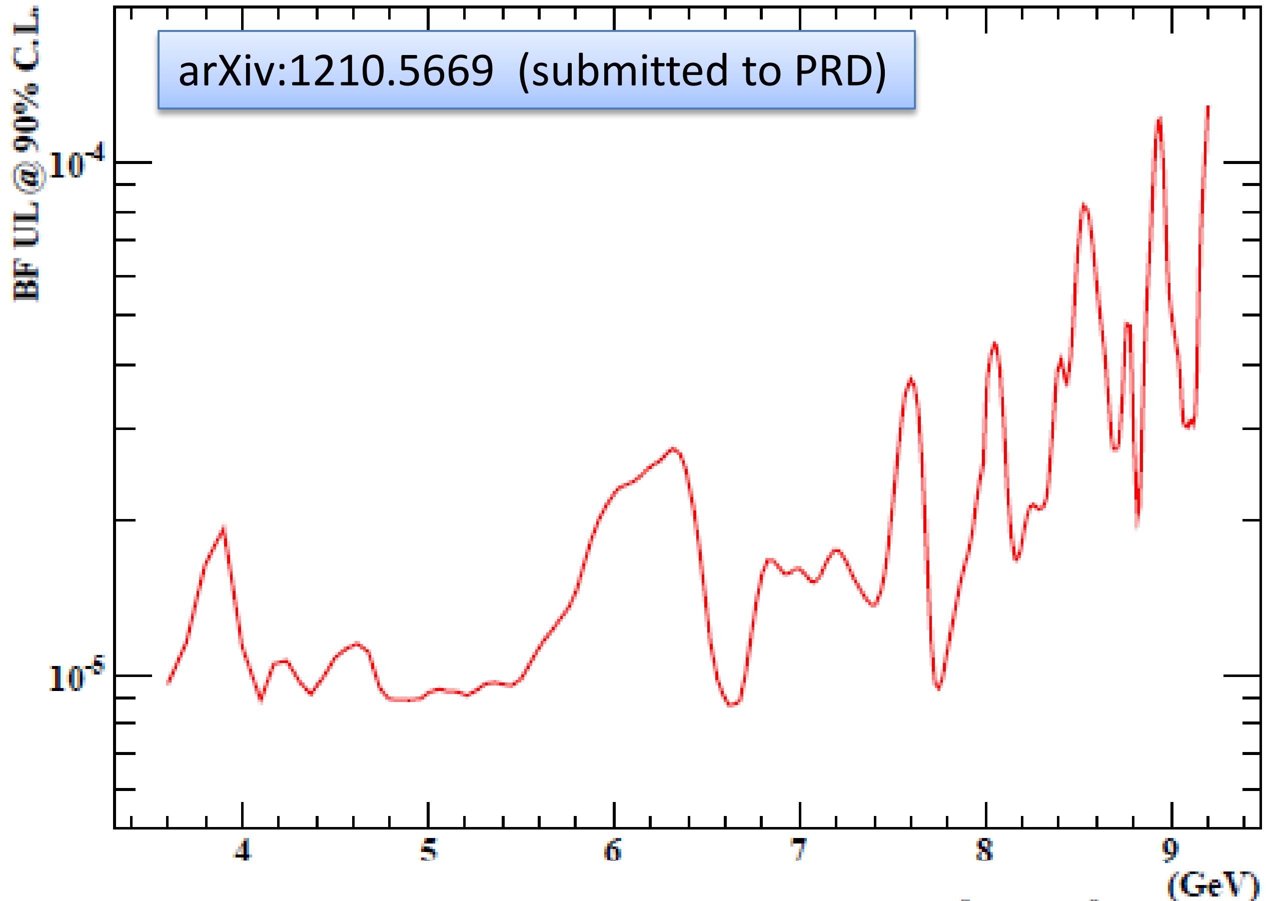


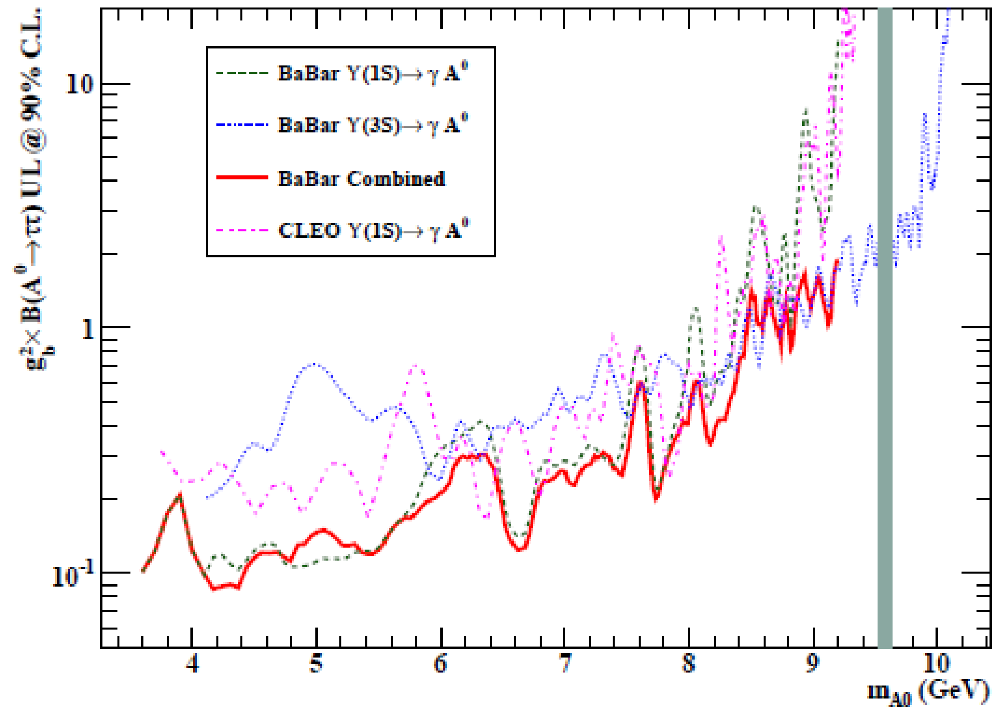

FIG. 3: 90% C.L. upper limits for $\mathcal{B}(\Upsilon(1S) \rightarrow \gamma A^0) \times \mathcal{B}(A^0 \rightarrow \tau^+\tau^-)$.

BaBar limit already published. Belle (preliminary) limit just slightly stronger.

# Recent $A^0$ Searches (III)

$$\Upsilon[2s] \to \Upsilon[1s]\pi^+\pi^-; \Upsilon[1s] \to \gamma A^0(\to \tau^+\tau^-)$$

- New from Babar: combine limits from different Υ resonances by plotting limit on Yukawa coupling x BF
- The Upsilon(3s) analysis helps extend the limit to higher A0 masses



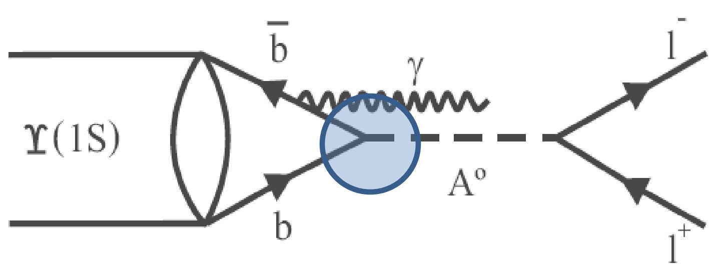




FIG. 4: 90% C.L. upper limits for Yukawa coupling $g_b^2 \times \mathcal{B}(A^0 \to \tau^+\tau^-)$. Shown are combined *BABAR* results (red solid line), results from this analysis only (dashed green line), the previous *BABAR* measurement [9] (dotted blue line), and results from the CLEO experiment [12] (dot-dashed black line). The shaded vertical bar shows the region around $\chi_b(2P)$ mass excluded from Ref. [9].

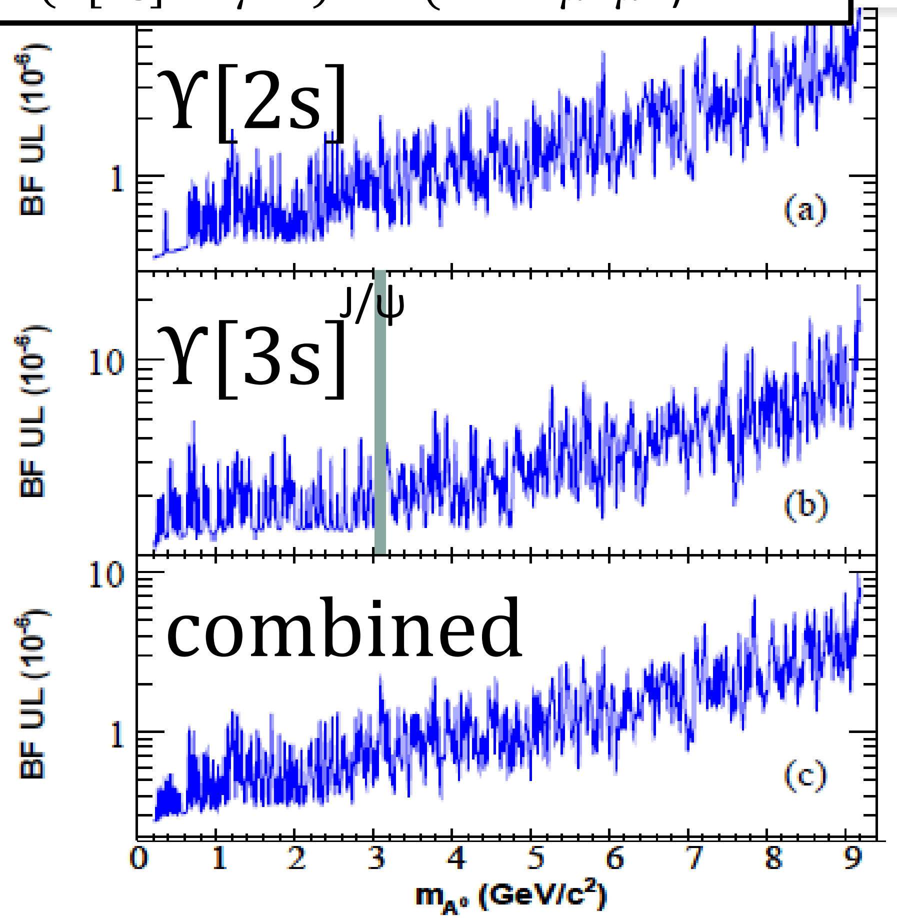
# Recent $A^0$ Searches (III)

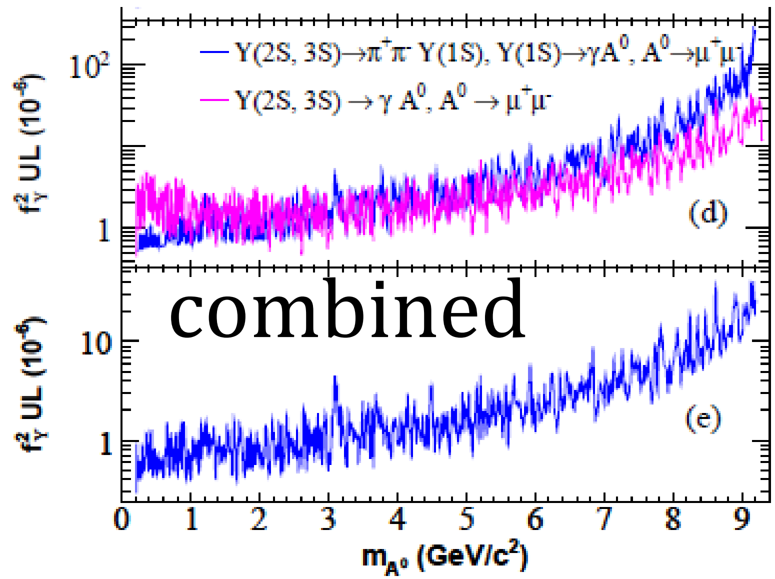
NEW

$$\Upsilon[2s,3s] \to \Upsilon[1s]\pi^+\pi^-;\ \Upsilon[1s] \to \gamma A^0(\to \mu^+\mu^-)$$

90% C.L. UL on product branching fraction
$B(\Upsilon[1s] \to \gamma A^0) \times B(A^0 \to \mu^+\mu^-)$

PRD-RC 87,031102,2013



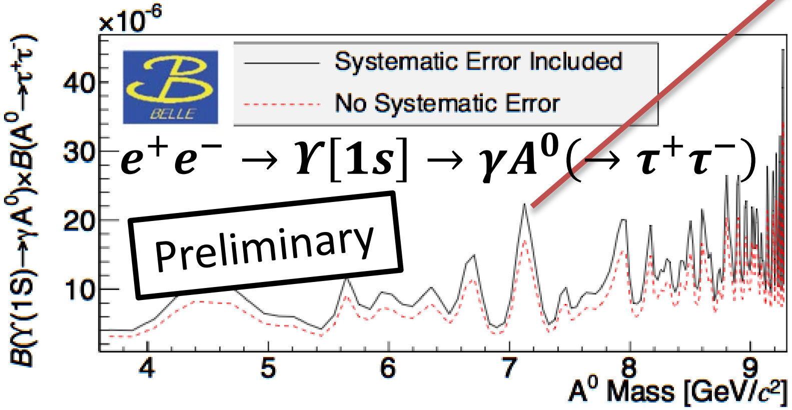

New: 90% C.L. Upper Limit on
"Effective Yukawa coupling" $f_T^2 \times B(A^0 \to \mu^+\mu^-)$
(see backup slides)

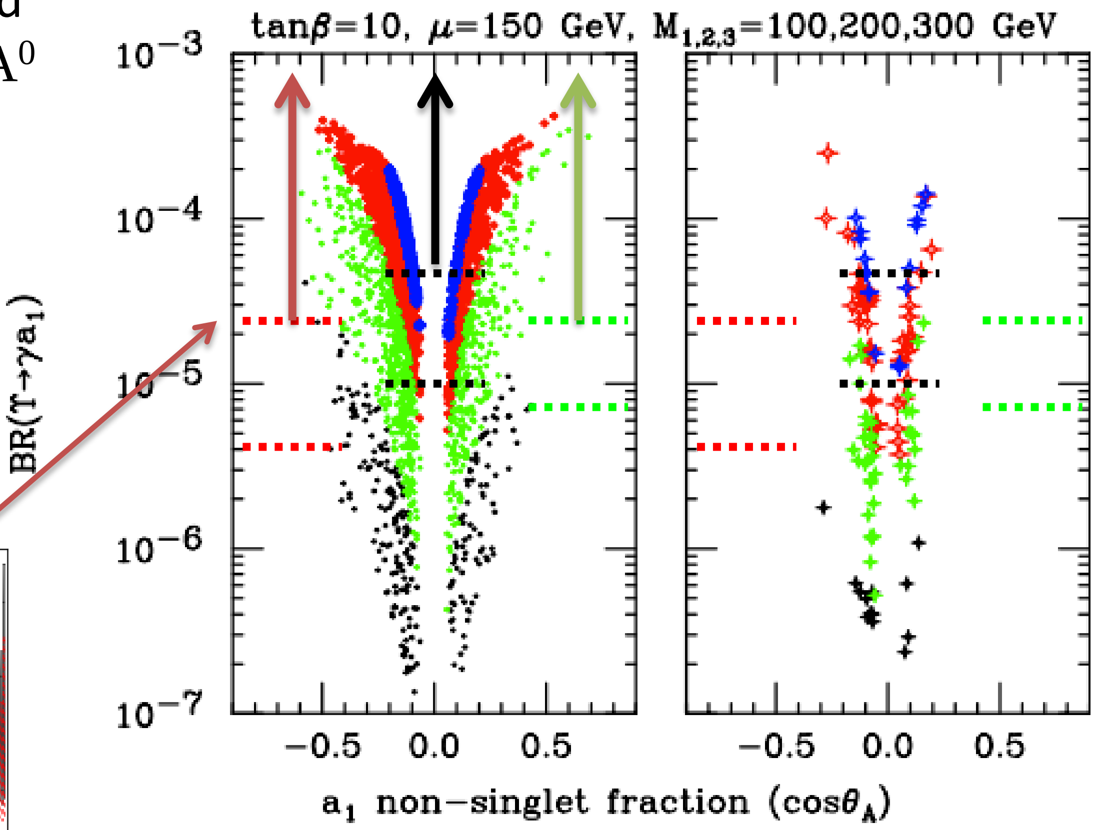
Strongest limit on $A^0 \to \mu^+\mu^-$ mode for large m $_{A0}$

# CP-odd Light Higgs limits versus nMSSM

- Assume $BR(A^0 \to \tau^+\tau^-)=1$
- Dashed lines to show highest and lowest upper limits in different $A^0$ mass regions

$A^0<2M_\tau$
$2M_\tau<A^0<7.5$ GeV/c²
7.5 GeV/c² $<A^0<$ 8.8 GeV/c²
8.8 GeV/c² $<A^0<$ 9.2 GeV/c²



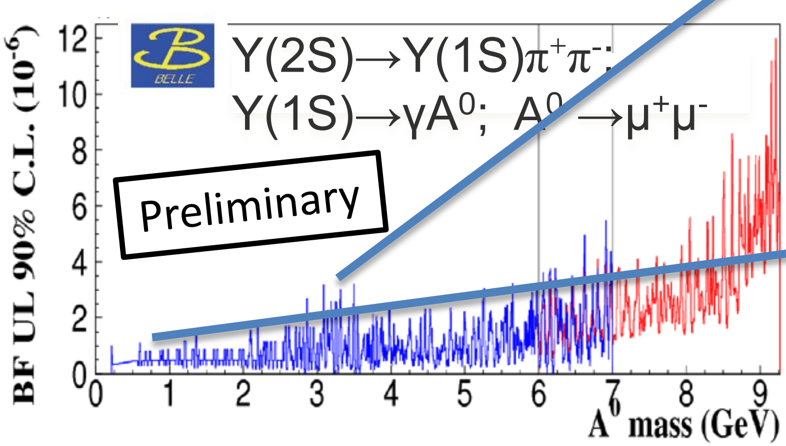



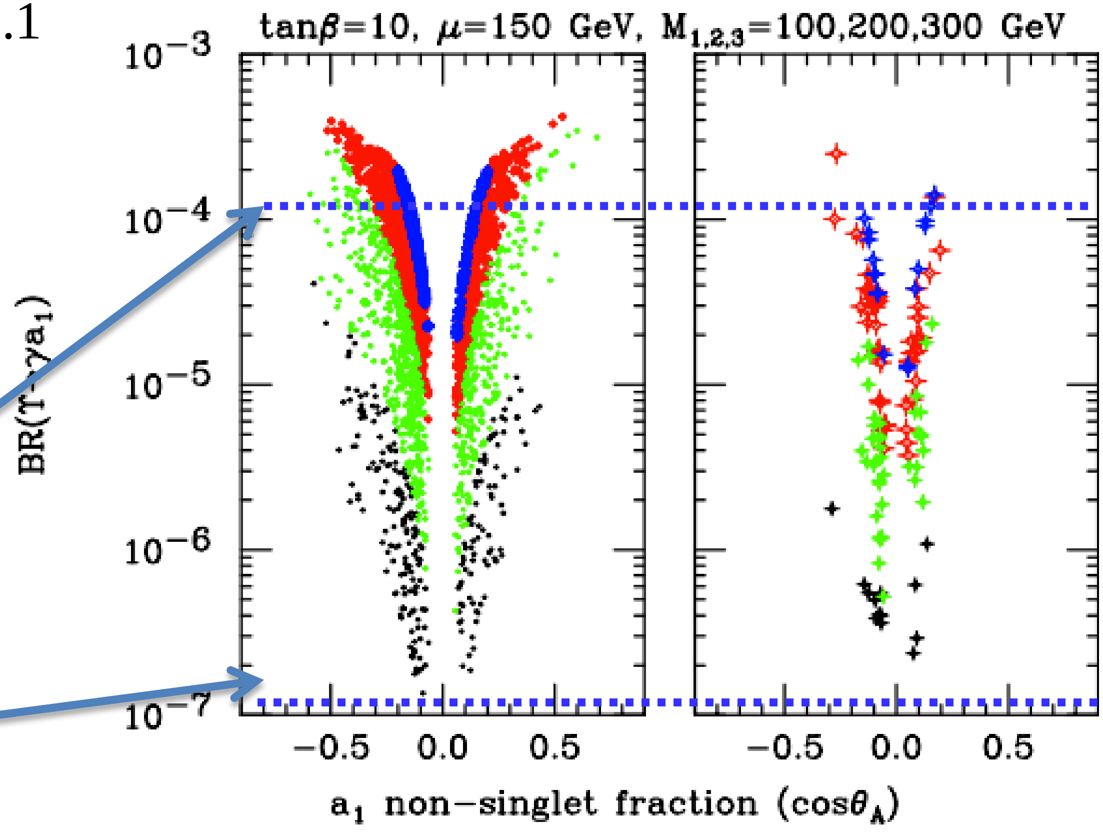

Significant constraints on nMSSM, many models already ruled out

# CP-odd Light Higgs limits versus nMSSM II

- Repeat for muon final state
- Assume $BR(A^0 \rightarrow \mu^+\mu^-)=0.025\text{-}0.1$

$A^0<2M_\tau$
$2M_\tau<A^0<7.5$ GeV/c$^2$
7.5 GeV/c$^2$$<A^0<$8.8 GeV/c$^2$
8.8 GeV/c$^2$$<A^0<$9.2 GeV/c$^2$




*PRD **76** 051105(R) (2007)

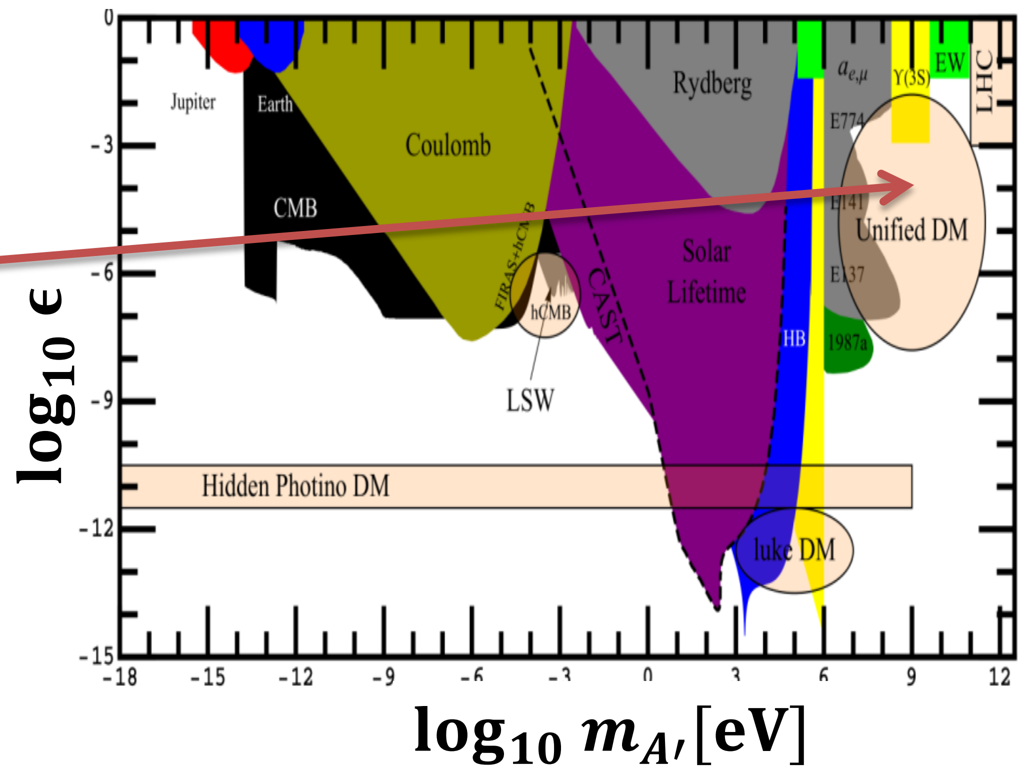
**Q: how many of these models satisfy recent LHC Higgs discovery and latest LHC SUSY limits?**

Might be interesting to combine all limits & scan models compatible with LHC results.

# The Dark Photon (a.k.a. A' or U Boson)

- New "Dark" U(1) Gauge Boson: A'
  - Interaction with the SM is via kinetic mixing with strength ε
  - acquires a charge εe, and the coupling to SM fermions is characterized by $\alpha' = \alpha\varepsilon^2$
- Recently, strong renewed interest in MeV – GeV mass region
- Invoked to explain e.g.
  - DAMA/LIBRA
  - Positron excess in cosmic rays
  - g-2
- Not a WIMP, but a force carrier in the dark sector
- Many models - often also contain a Dark Higgs

**Existing Limits**




J. Jaeckel and A. Ringwald - arXiv:1002.0329v1

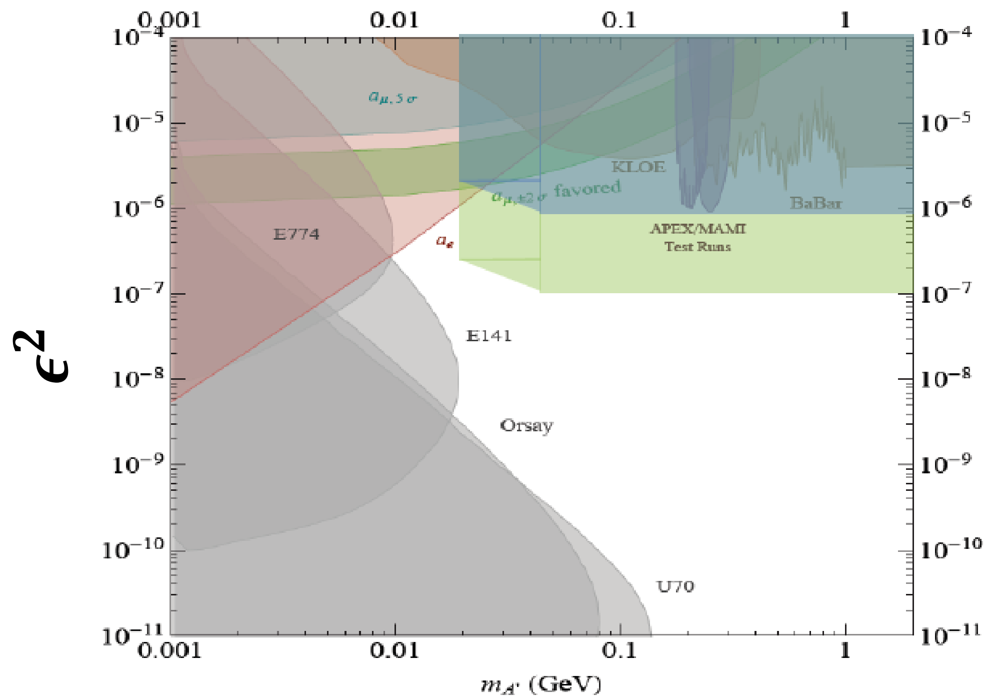
# The Dark Photon (a.k.a. A’ or U Boson)

$$e^+e^- \to \gamma A'(\to e^+e^-, \mu^+\mu^-, \pi^+\pi^-) \text{ etc}$$

- Note: same final states as light Higgs
- Hence light Higgs search results can be re-interpreted as limits on dark photon
- Update in progress at BaBar with full dataset, should cover interesting part of parameter space
- Drawback is large amount of irreducible background

  →limit scales as $1/\sqrt{\int L\, dt}$

courtesy: Bertrand Echenard



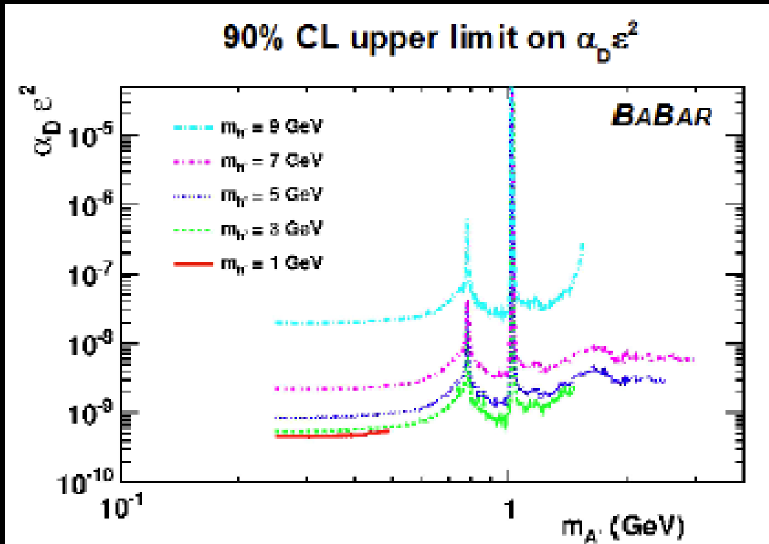

BABAR 40 $fb^{-1}$
BABAR 500 $fb^{-1}$
Belle II 50 $ab^{-1}$

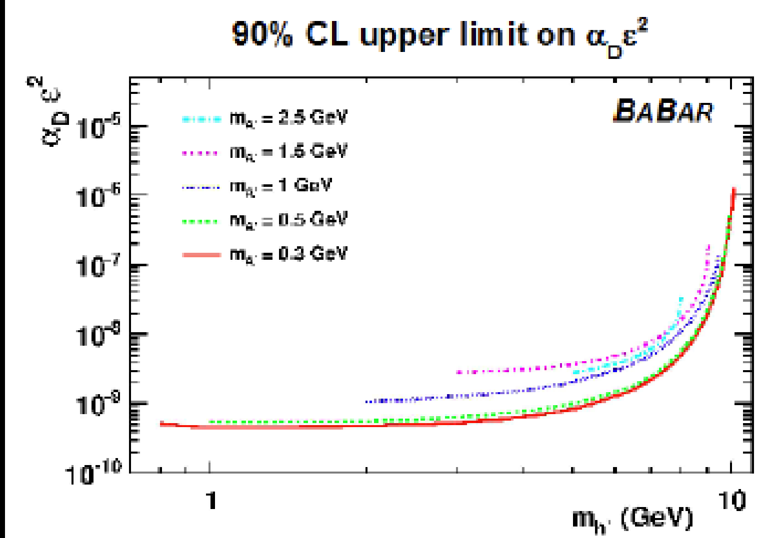
# Dark Photon and Dark Higgs

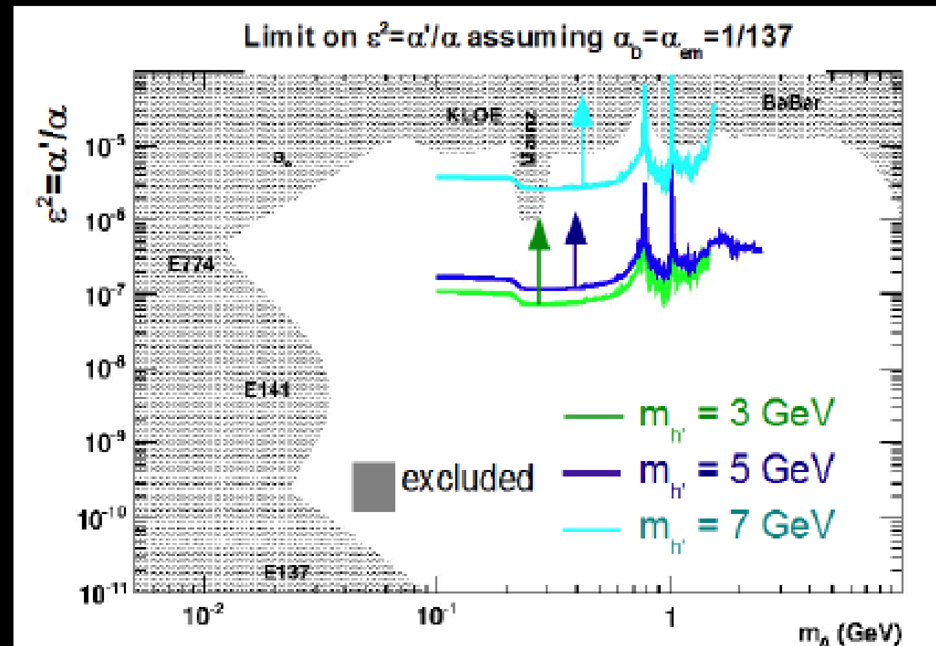
521 $fb^{-1}$

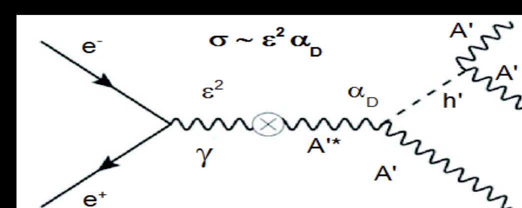
- Higgs-strahlung channel – close to BG free !

PRL 108 (2012) 211801



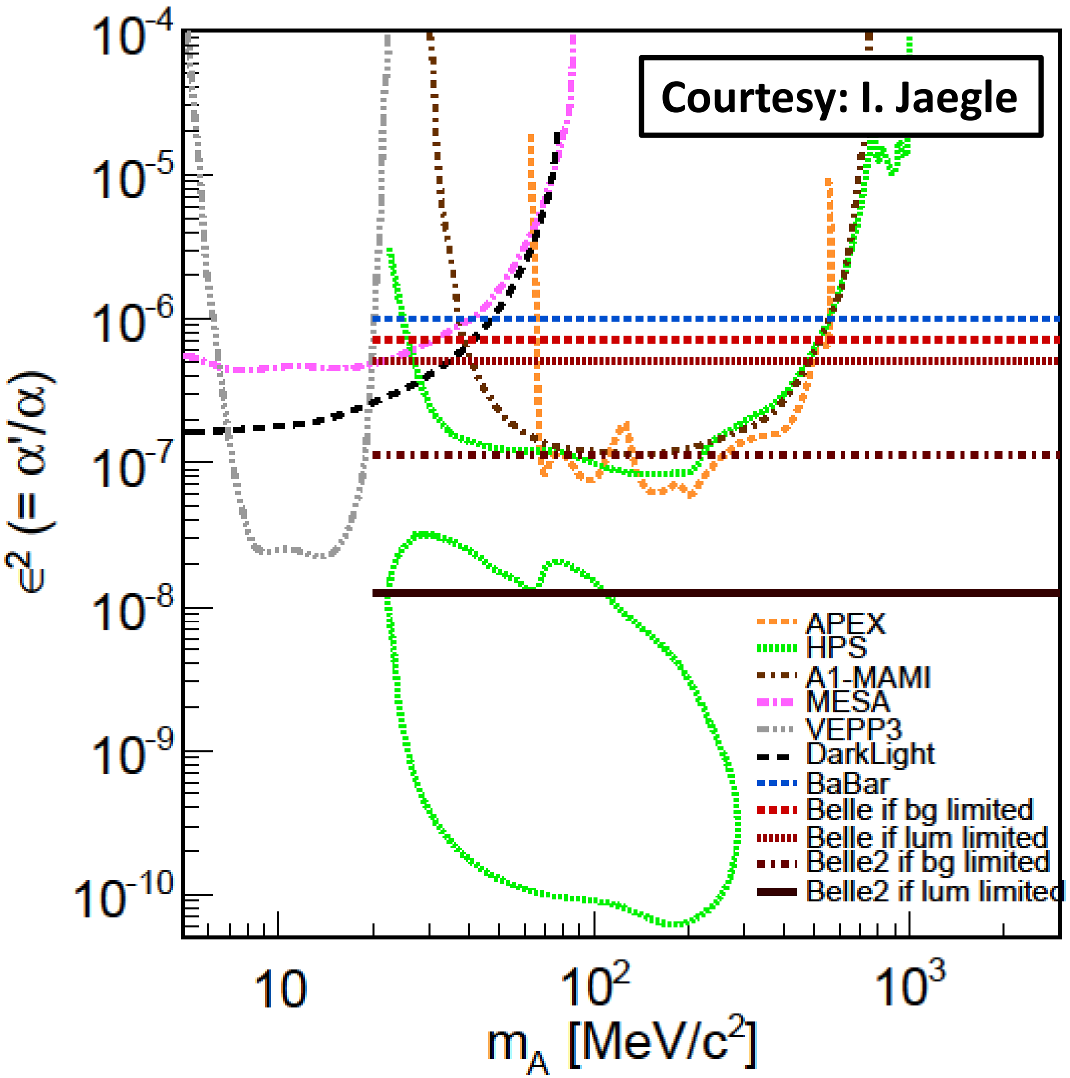




$$e^+e^- \rightarrow A'h'(\rightarrow A'A')$$

# Projected Belle II Reach

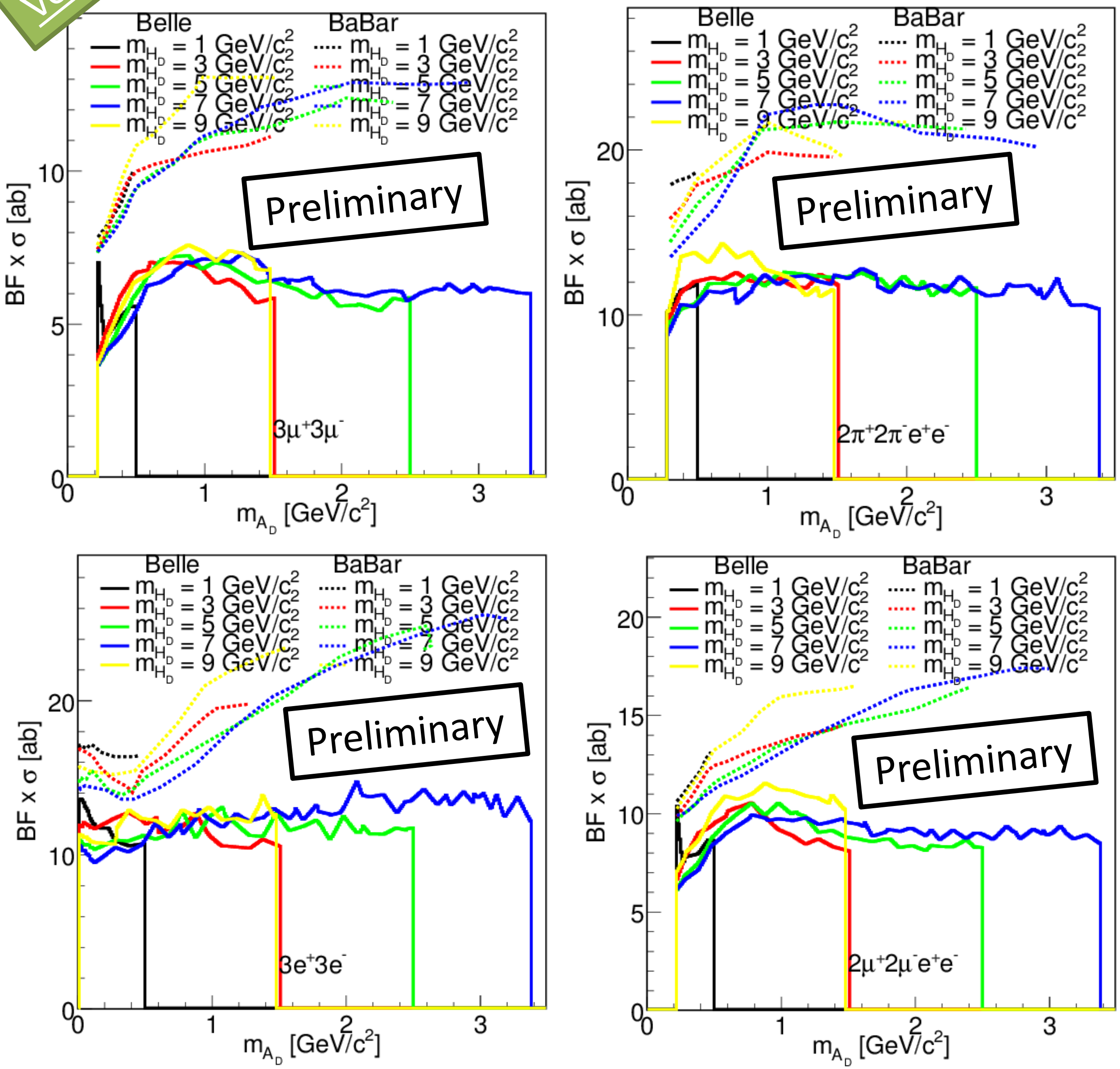
- Belle II could improve limit on $\epsilon^2$ by factor 10-100, depending on BG level
- The fixed target experiments only need to run for ~weeks
- However, Belle II searh would have unique mass reach, and low incremental cost



Very New

# Dark Photon and Dark Higgs (II)

923 fb$^{-1}$




- Analysis ongoing at Belle – box opening for first channels last week
- Event count consistent w/ BG expectation
- ~ factor 1.5-2 improvement in limit over BaBar as expected from luminosity scaling

# Conclusion

- Much activity, but nothing found to date…
- Light-CP odd Higgs
  - most, but not all, BaBar/Belle samples exploited
  - Since BG limited, further progress at Belle II may be slow. Pion-tagging the way forward?
- Dark Photon and Dark Higgs searches
  - a number of BaBar/Belle results still expected
  - In the next years, expect more sensitive dark photon searches at fixed-target experiments and Belle II to probe very interesting parts of parameter space

# Or to say it like last year's speaker…

Either light higgses, dark gauge bosons, etc don't really exist…

**BaBar & Belle,**
**digging for light particles**

…Or we just need to dig deeper to find 'em

**SuperKEKB ?**

# BACKUP SLIDES

# Acknowledgements

- Material received/taken from
  - Igal Jaegle
  - Jamal Rorie
  - Bertrand Echenard
  - XinChou Lou
  - Peter Krizan
  - Tom Browder
  - G. Calderini
- →Thank you!

Jamal Rorie

# SELECTION CRITERIA

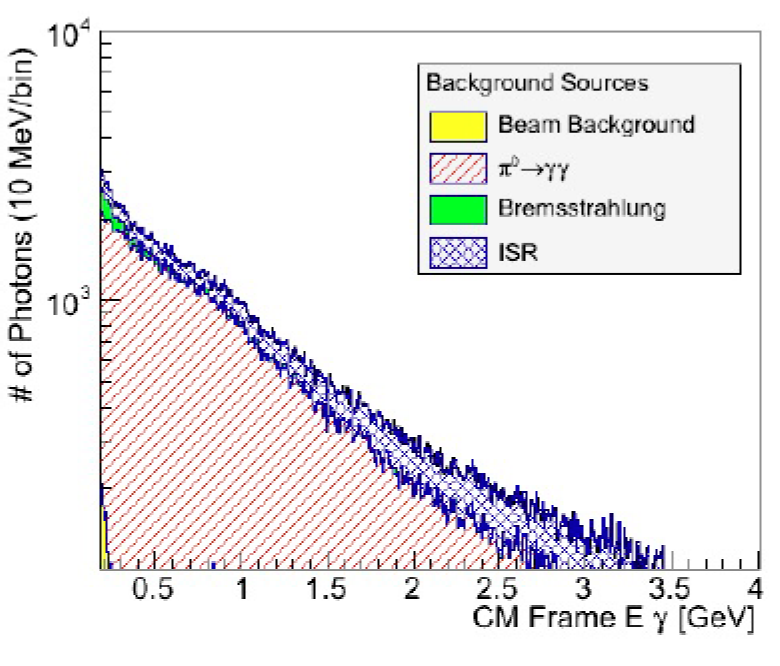
$\Upsilon(1S) \to \gamma A^0;\ A^0 \to \tau^+\tau^-$

$\tau^- \to$ "1prong" $\to e^-\bar{\nu}_e\nu_\tau$ *or* $\mu^-\bar{\nu}_\mu\nu_\tau$ *or* $\pi^-\nu_\tau$ *or* $\rho\nu_\tau$ *or* $a_1\nu_\tau$

$\tau^+ \to$ "lepton" $\to e^+\nu_e\bar{\nu}_\tau$ *or* $\mu^+\nu_\mu\bar{\nu}_\tau$

} and charge conjugates

| Selection | Description |
|---|---|
| Charge | 2 charged tracks<br>Charge sum is zero |
| Particle Identification | One charged track is either an electron OR a muon; other charged track can be unidentified.<br>• Event is rejected if both charged tracks are identified as electrons |
| Missing Energy | 1.5GeV < M(miss,CM) < 7.5GeV |
| Cos Missing Angle | -0.95< CosTheta(miss,CM) <0.90 |
| Location | -0.82<CosTheta(CM)<0.65 for candidate γ |
| Bremsstrahlung | Photons rejected if their tracks lie in a cone of 0.2 radians around either charged track |
| $\pi^0$ Cut | Candidate photon CANNOT combine with any other photon in the event with 110MeV <$M_{\gamma\gamma}$<160 MeV |




6

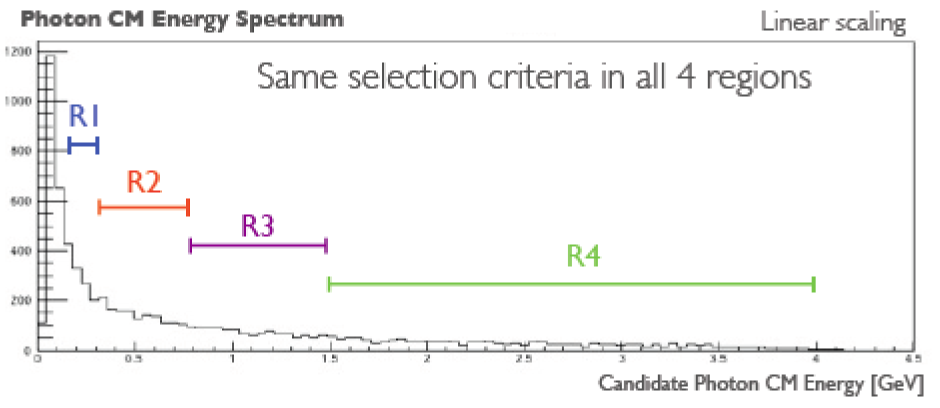
Thursday, February 21, 13

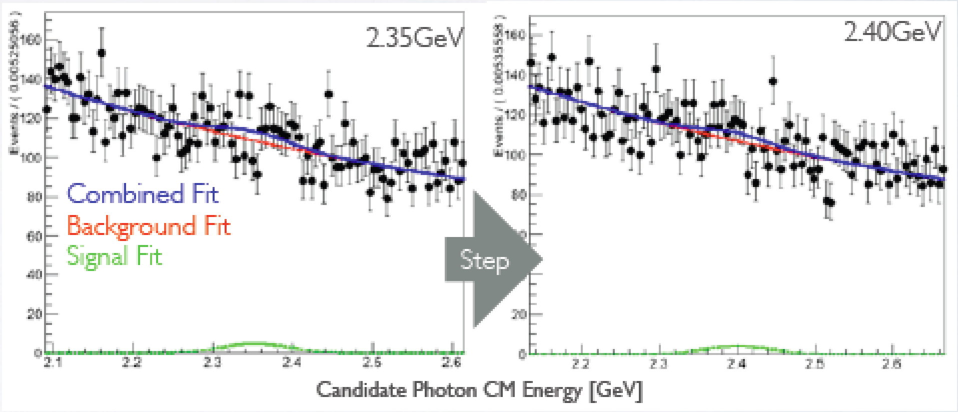
Jamal Rorie

# FITTING TECHNIQUE

We have a data sample, now we search the photon spectrum for a monochromatic peak against the background

- Background PDF
  - Background can't be fit with single simple analytic function
  - Fit each region independently with 3rd order polynomials
- Signal PDF
  - Monochromatic photon signal can be fit with a Gaussian
  - $\sigma$ determined from interpolation of signal MC fits
- Combined PDF
  - Extended Maximum Likelihood Fit
  - Fit window is $\pm 6\sigma$ about central value of peak
  - All fit parameters are fixed EXCEPT FOR YIELDS



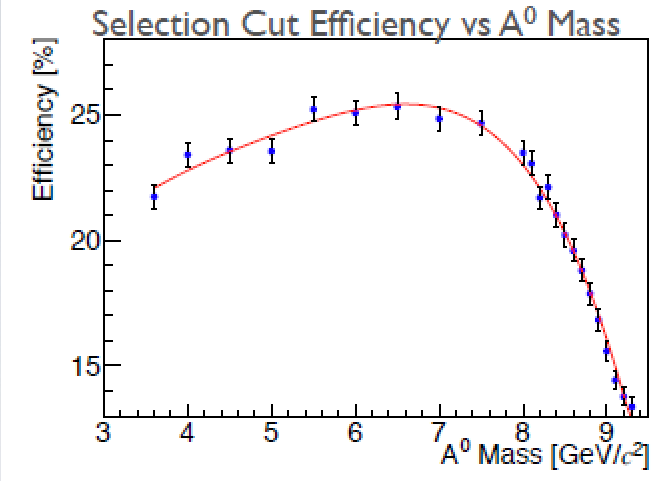

- Fit combined PDF from 0.15 GeV to 4.0 GeV
- Step sizes are dependent upon detector resolution

7

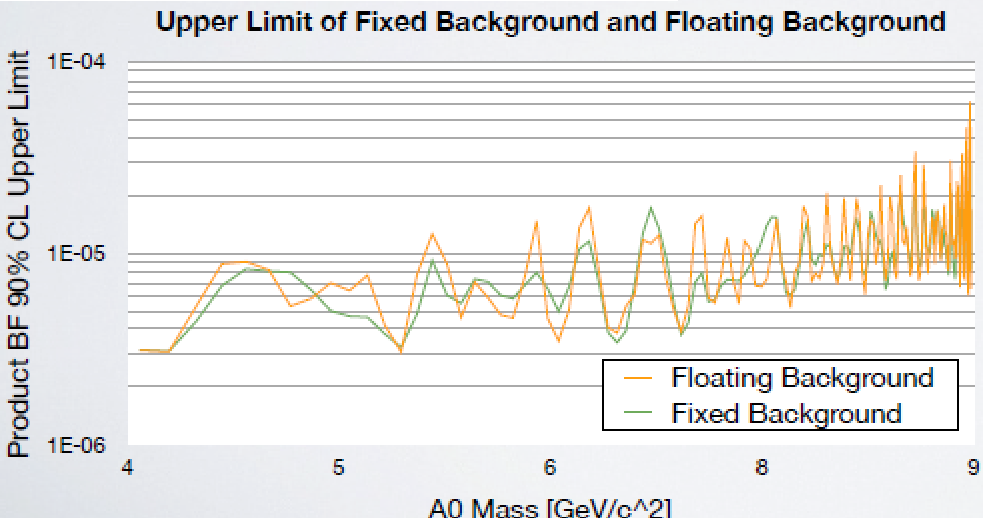
Thursday, February 21, 13

Jamal Rorie

# CORRECTIONS & SYSTEMATICS




- Need a scale factor, $\epsilon_{cuts}$, to correct for selection cut efficiency
- Generated signal MC for a range of $A^0$ masses
- Applied selection criteria.
- Find events left, fit with 4th order polynomial




| Systematics [%] | |
|---|---|
| Background Modeling | 25 |
| Signal Modeling | 11 |
| Fit Window Width | 8 |
| Efficiency Interpolation | 4.5 |
| Other Sources | 6.5 |
| **Overall Systematics** | **30** |

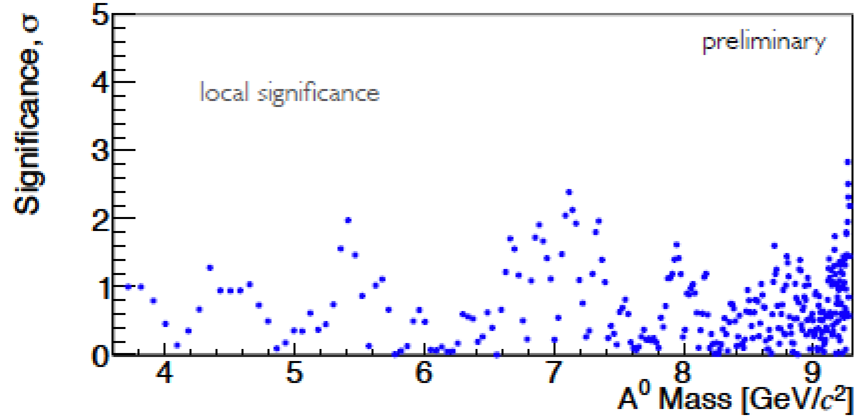
8

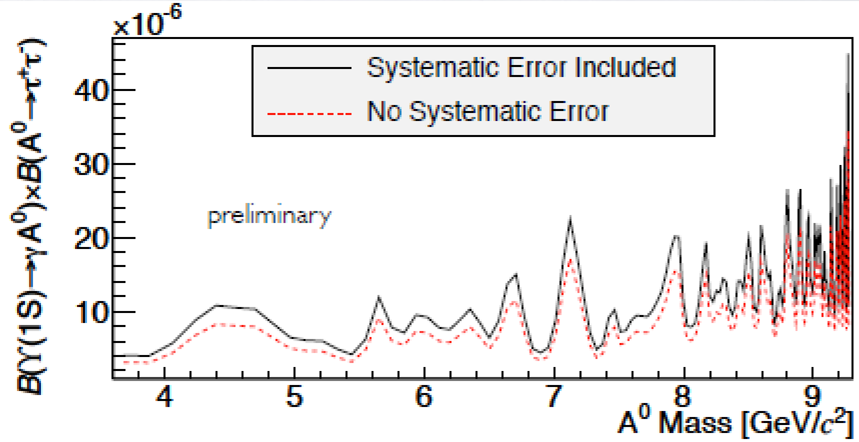
Thursday, February 21, 13

Jamal Rorie

# RESULTS

- Signal detection
  - Sought points with $\sigma_{significance}>3$
  - Step size less than detector resolution, signal should produce several consecutive points with high significance
  - No such signal found
  - Set upper limit
- BF 90% CL UL
  - $4.0\times10^{-6}$ to $4.5\times10^{-5}$
- $A^0$ Mass Range
  - 3.6GeV to 9.3GeV



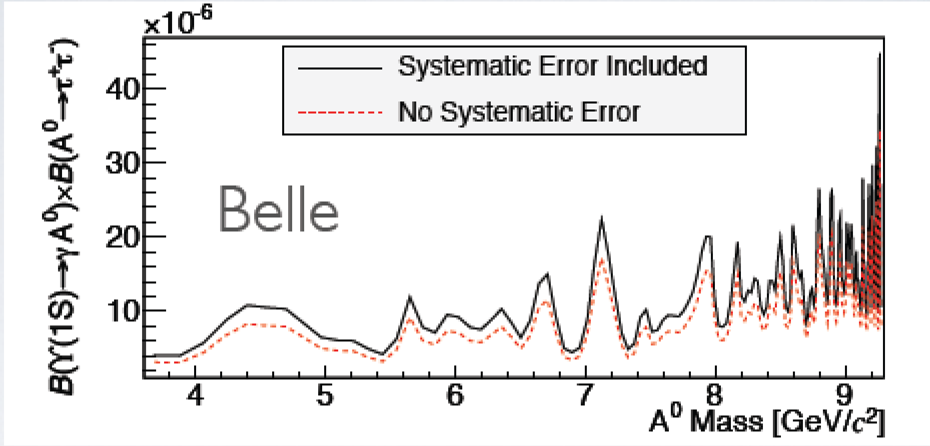

Using $B_{\Upsilon(1S)\to\gamma A^0} \times B_{A^0\to\tau\tau} = \frac{nsig}{\epsilon_{cuts} N_{\Upsilon(1S)} B_{\tau\to l\nu_l\nu_\tau} B_{\tau\to 1prong}}$

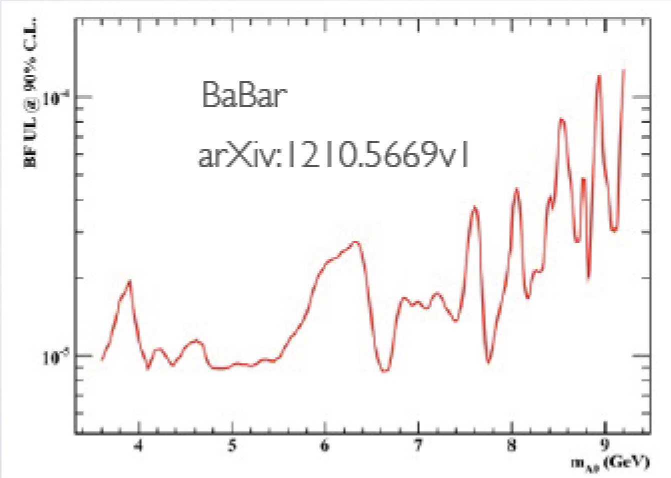
9

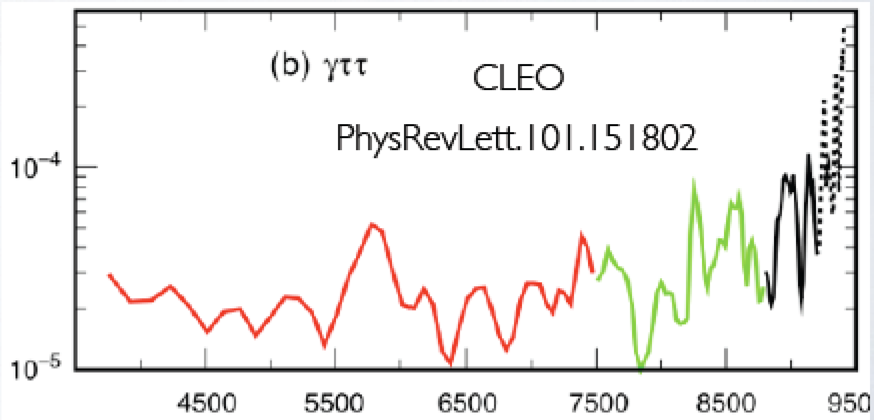
Thursday, February 21, 13

Jamal Rorie

# Y(1S) UPPER LIMIT PLOTS




24

Thursday, February 21, 13

Jamal Rorie

# Introduction and Event Selection

Search for light Higgs ($A^0$) in the following modes:

1. $\Upsilon(2S) \to \gamma A^0$; $A^0 \to \mu^+ \mu^-$
2. $\Upsilon(2S) \to \gamma A^0$; $A^0 \to \tau^+ \tau^-$ ($\tau\tau \to e\mu$)
3. $\Upsilon(2S) \to \Upsilon(1S) \pi^+ \pi^-$; $\Upsilon(1S) \to \gamma A^0$; $A^0 \to \mu^+ \mu^-$
4. $\Upsilon(2S) \to \Upsilon(1S) \pi^+ \pi^-$; $\Upsilon(1S) \to \gamma A^0$; $A^0 \to \tau^+ \tau^-$ ($\tau\tau \to e\mu$)

---

- **The decay modes would be denoted by their final state in the following.**
- **Expect the modes with $\pi\pi$ tag could give stronger upper limit.**
- **Will check cos(γ,lep). Might be included into event selection.**

| Terms | $\gamma\mu^+\mu^-$ | $\gamma\tau^+\tau^-$ ($\tau\tau \to e\mu$) | $\pi^+\pi^-\gamma\mu^+\mu^-$ | $\pi^+\pi^-\gamma\tau^+\tau^-$ ($\tau\tau \to e\mu$) |
|---|---|---|---|---|
| TauPair skim | applied | | | |
| $\mid dr \mid$ | $< 0.5$ cm | | | |
| $\mid dz \mid$ | $< 3.0$ cm | | | |
| Prob(K;$\pi$) for $\pi$ | $< 0.4$ | | | |
| eid | $> 0.8$ | | | |
| $\mu$id | $> 0.8$ | | | |
| $E_\gamma$ in $\Upsilon(2S)$'s CM | $> 0.1$ GeV | $> 0.1$ GeV | ✗ | ✗ |
| $E_\gamma$ in $\Upsilon(1S)$'s CM | ✗ | ✗ | $> 0.1$ GeV | $> 0.1$ GeV |
| number of $\mu^+ = 1$, $\mu^- = 1$ | applied | ✗ | applied | ✗ |
| number of $e^+\mu^-$ pair $= 1$ or $e^-\mu^+$ pair $= 1$ | ✗ | applied | ✗ | applied |
| number of charged track | =2 | =2 | ✗ | ✗ |
| total charge | $= 0$ | $=0$ | ✗ | ✗ |
| $\cos(\gamma, \mu^+\mu^-)$ | $< -0.95$ | ✗ | ✗ | ✗ |
| missing energy (GeV) | ✗ | $> 2.0$ | ✗ | $> 2.0$ |
| missing polar angle in CM (degree) | ✗ | $30 \sim 150$ | ✗ | $30 \sim 150$ |
| $m(\mu\mu\gamma)$ (GeV) | $9.4 \sim 10.4$ | ✗ | ✗ | |
| $m(\pi\pi\mu\mu\gamma)$ (GeV) | ✗ | ✗ | $9.6 \sim 10.4$ | ✗ |
| $\Delta m = m(\pi\pi\mu\mu\gamma) - m(\mu\mu\gamma)$ (GeV) | ✗ | ✗ | $0.55 \sim 0.57$ | ✗ |
| recoil mass of $\pi^+\pi^-$ (GeV) | ✗ | ✗ | ✗ | $9.32 \sim 9.60$ |

Thursday, February 21, 13