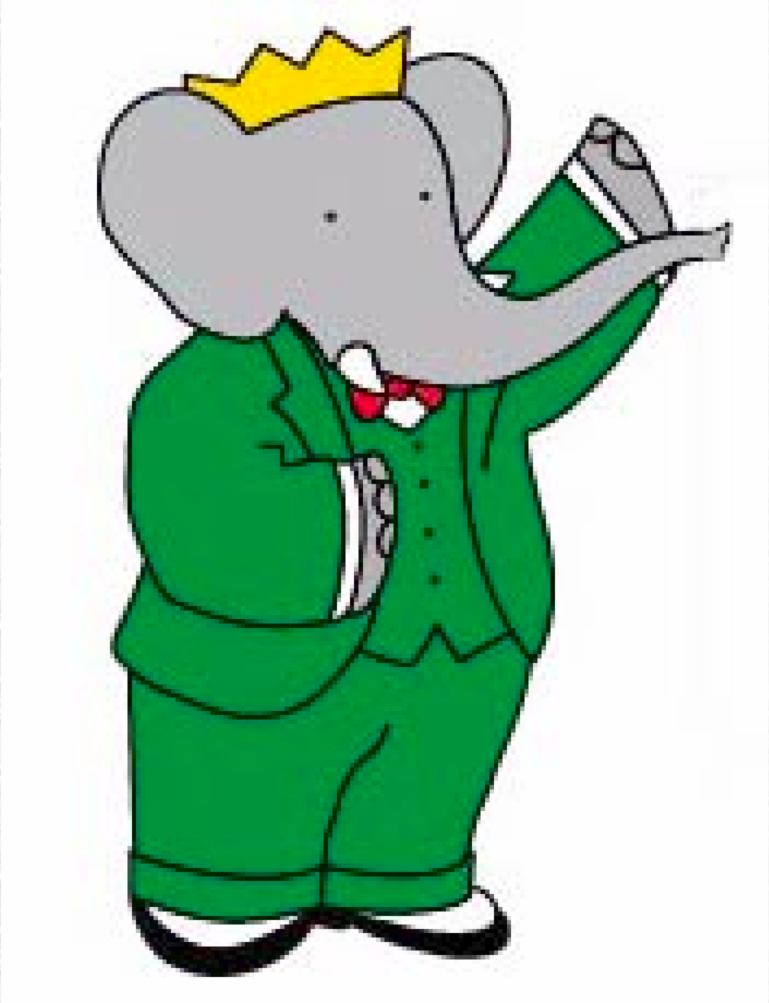
Recent BaBar results on BSM Higgs



Dana Lindemann
On Behalf of the
BaBar Collaboration

Higgs Quo Vadis
Aspen
March 11, 2013

SLAC
NATIONAL ACCELERATOR LABORATORY

Outline

- Searches for Charged Higgs
  - $B \to \tau\nu$ — submitted to PRD-RC, arXiv:1207.0698
  - $B \to D^{(*)}\tau\nu$ — PRL 109, 101802 (2012) and
    New preliminary extra studies submitted to PRD, arXiv:1303.0571
- Searches for Low-mass Higgs
  - $\Upsilon(1S) \to A^0\gamma;\ A^0 \to \tau^+\tau^-,\ \mu^+\mu^-$ — PRD 87, 031102 (2013) and
    submitted to PRD-RC, arXiv:1210.5669
- Searches for Dark Higgs — PRL 108, 21180 (2012)

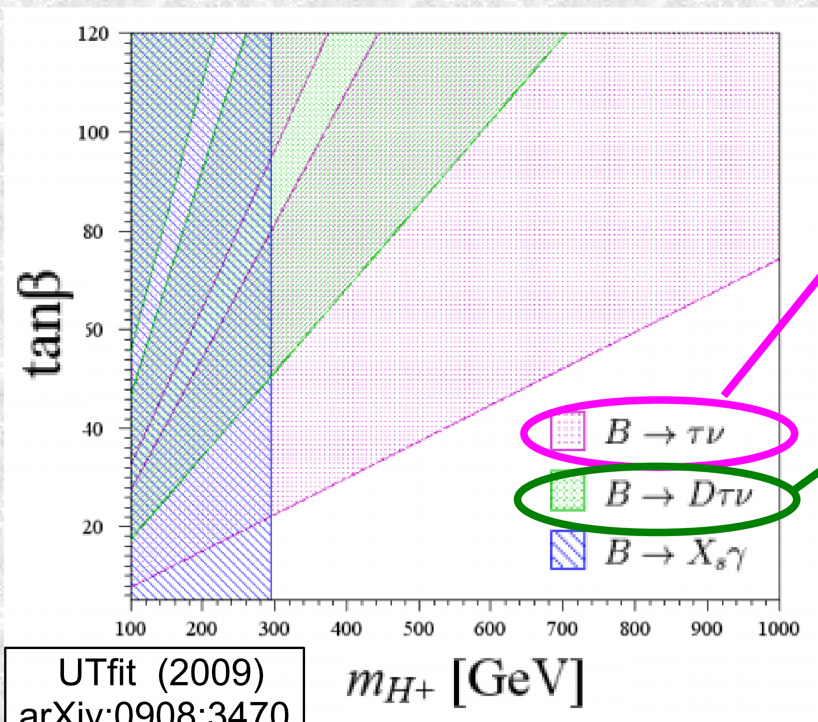
Preliminary New Results

The use of charge conjugate modes are implied throughout talk

Charged Higgs Searches

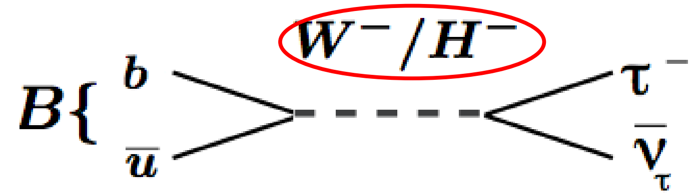
$B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$ Motivation

- H^+ predicted by many New Physics scenarios
  - *e.g.* Type-II Two-Higgs Doublet Model (2HDM) of MSSM
- H^+-ℓ coupling $\propto m_\ell$



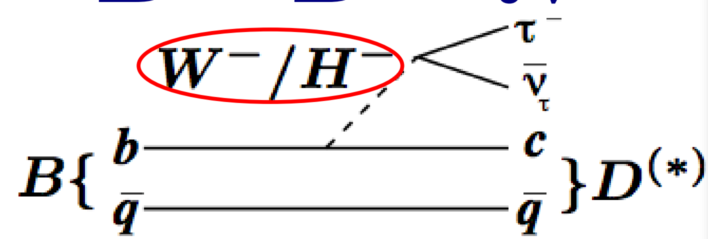
UTfit (2009)
arXiv:0908:3470

$B \to \tau\nu$



- H^+ enters at tree-level
- Theor. uncertainty: ~25% (Vub, f_B)
- BF ≈ 0.01%
  - Helicity suppressed

$B \to D^{(*)}\tau\nu$



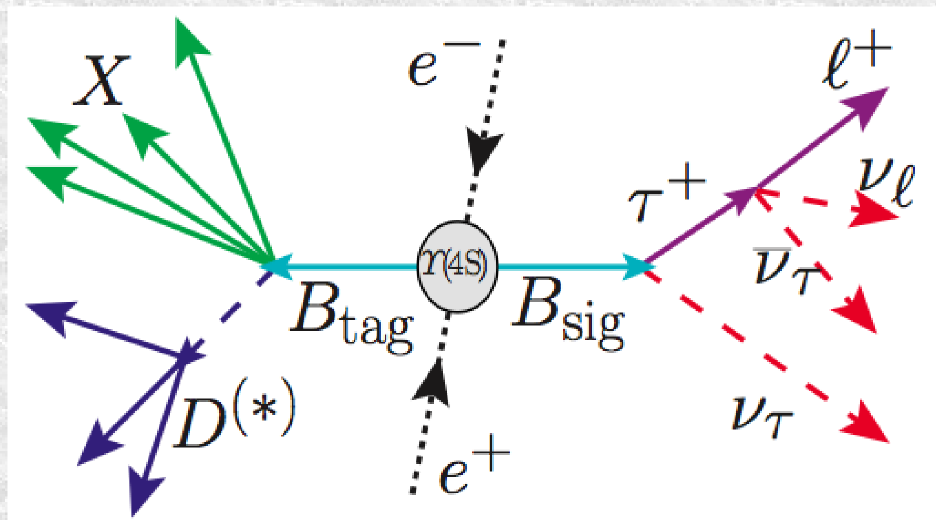
- H^+ enters at tree-level
- Theor. uncertainty ~5% (FFs, Vcb)
- BF ≈ 2%
- 3-body decays: additional constraints/observables

$B \to \tau\nu$ and $B \to D^{(*)}\tau\nu$
Common Methodology

- Hermetic BaBar detector : neutrino “detection” via p_{miss}
- Exploit $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ production by reconstructing both B's

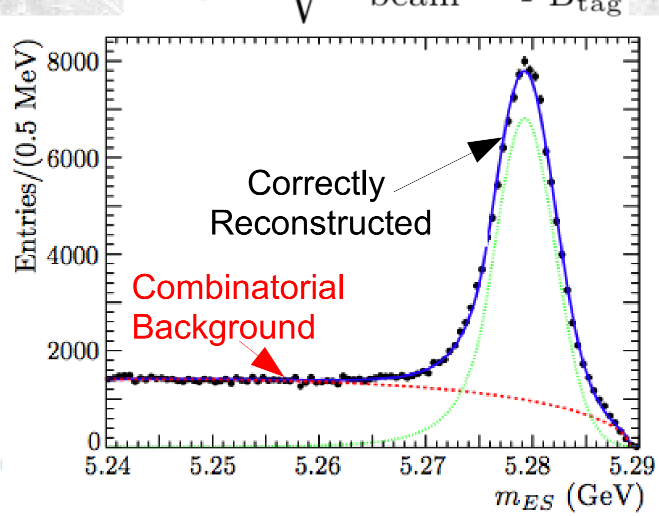
① **Hadronic tag reconstruction:**

Fully reconstruct B_{tag} in hadronic modes



② Look for **signal decay** in rest of the event (+ p_{miss})

$$m_{ES} \equiv \sqrt{E_{beam}^2 - \vec{p}_{B_{tag}}^{\,2}}$$



- B_{tag} reco → High purity B samples, Low reco efficiency (but ~2x efficiency over past algorithms)
- Full data samples: ~470 x 10^6 $B\bar{B}$ (429 fb^{-1})

$B^+ \to \tau^+ \nu$ Search

arXiv:1207.0698
Submitted to PRD

Clean test of SM predictions without uncertainties from hadronic (QCD) final-states

$$\mathcal{B}(B \to \ell\nu) = \frac{G_F^2 m_B}{8\pi} m_l^2 (1 - \frac{m_l^2}{m_b^2})^2 f_B^2 |V_{ub}|^2 \tau_B$$

$|V_{ub}|$ and f_B dominate SM uncertainty

f_B = B decay constant (lattice QCD)

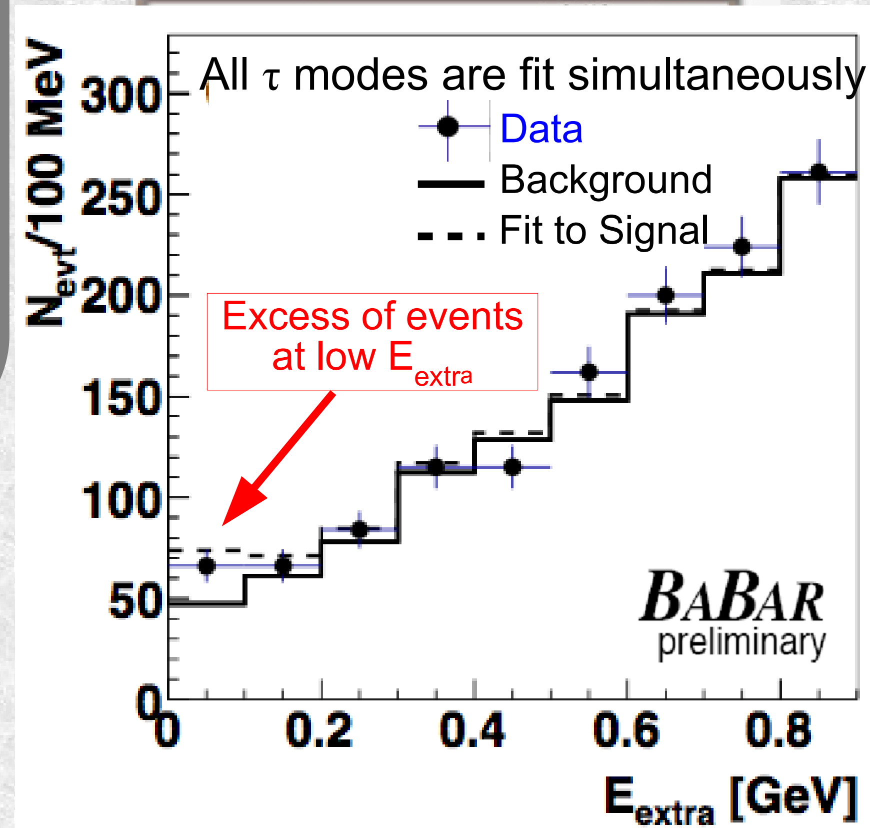
$B(B \to \tau\nu)_{SM}$ is $O(10^{-4})$

Charged Higgs can enhance or suppress SM rate:

$$\mathcal{B}(B \to \tau\nu)_{2HDM} = \mathcal{B}_{SM} \times (1 - \tan^2\beta \frac{m_B^2}{m_H^2})^2$$

Decay Mode	$\mathcal{B}(\times 10^{-4})$
$\tau^+ \to e^+ \nu \bar{\nu}$	$0.35^{+0.84}_{-0.73}$
$\tau^+ \to \mu^+ \nu \bar{\nu}$	$1.12^{+0.90}_{-0.78}$
$\tau^+ \to \pi^+ \nu$	$3.69^{+1.42}_{-1.22}$
$\tau^+ \to \rho^+ \nu$	$3.78^{+1.65}_{-1.45}$

stat errors only



Event Selection:

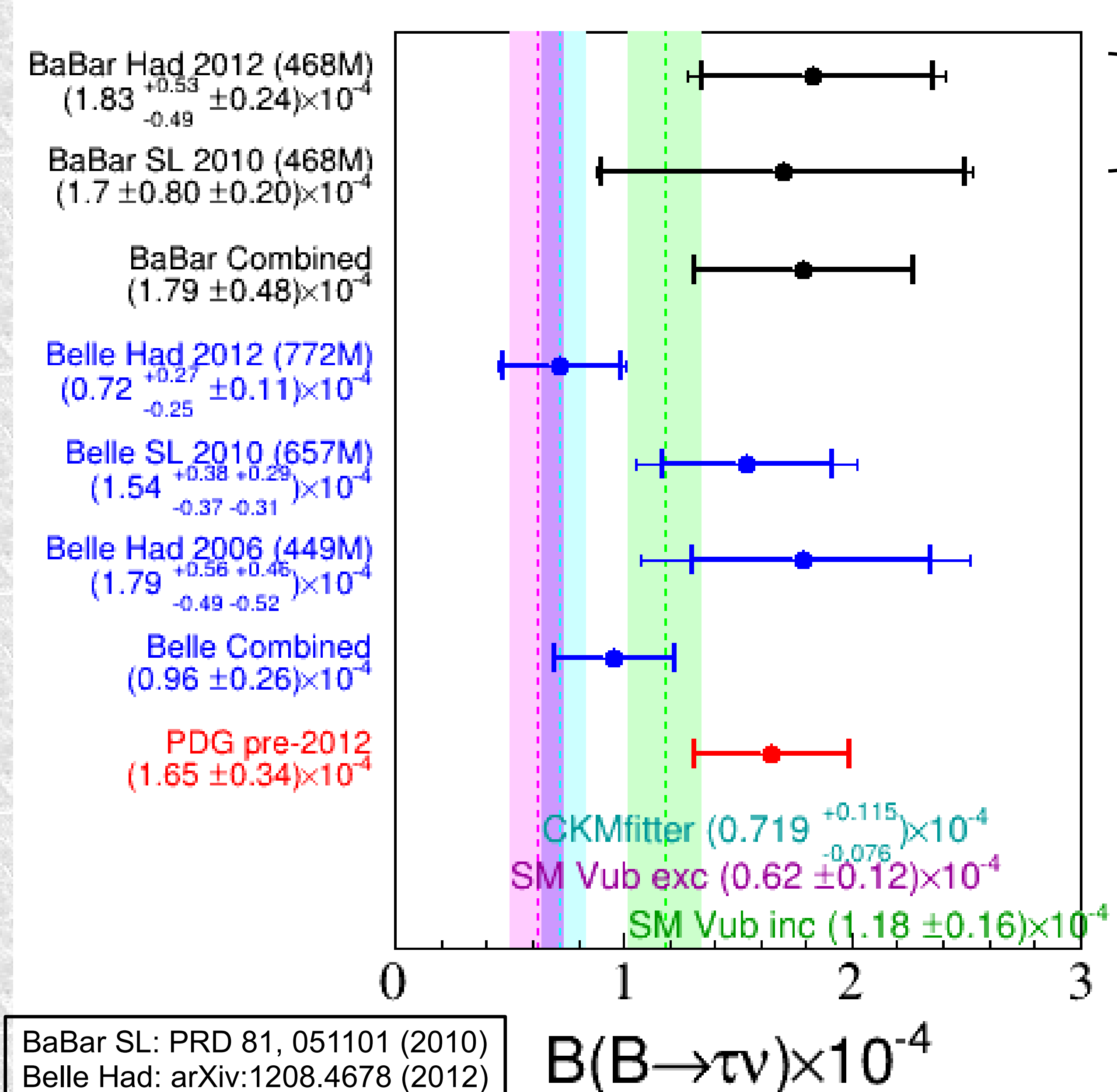
- Reconstruct 1-prong τ decay modes:
  $e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$, $\pi\nu$, and $\rho\nu \to \pi^+\pi^0\nu$
- 2- and 4-variable LHR for $\pi\nu$ and $\rho\nu$
- Unbinned Maximum LH fit to
  E_{extra} = sum of neutral energy
  not associated with B_{sig} or B_{tag}

$$\mathcal{B}(B \to \tau\nu) = (1.83^{+0.53}_{-0.49} \pm 0.24) \times 10^{-4}$$

Exclusion of null hypothesis at 3.8 σ (incl. syst.)

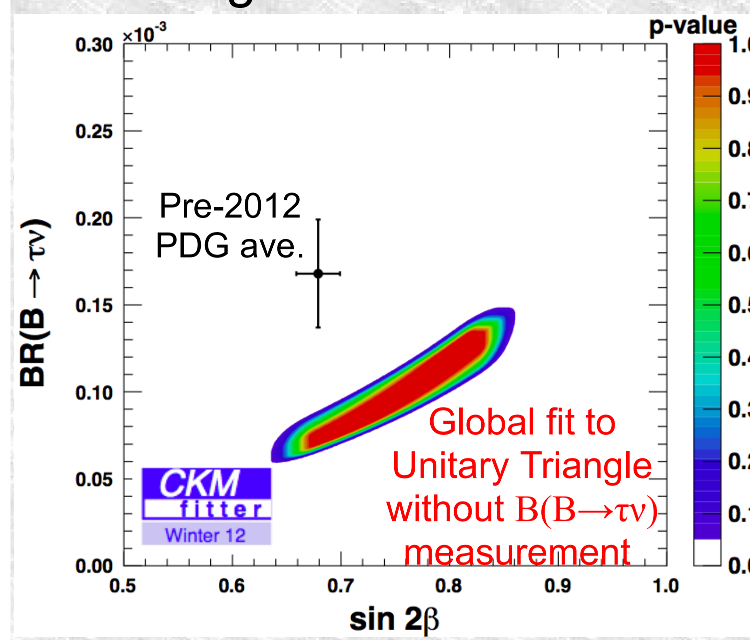
$B^+ \to \tau^+ \nu$ Results in Context

arXiv:1207.0698
Submitted to PRD



These hadronic tag results are combined with BaBar 2010 SL tag results

Results are in excess of SM values and with other Unitarity Triangle measurements



Answers from Belle II?

BaBar SL: PRD 81, 051101 (2010)
Belle Had: arXiv:1208.4678 (2012)
Belle SL: PRD 82, 071101 (2010)
Belle Had: PRL 97, 251802 (2006)

$B \to D^{(*)} \tau \nu$ Search

PRL 109, 101802 (2012)

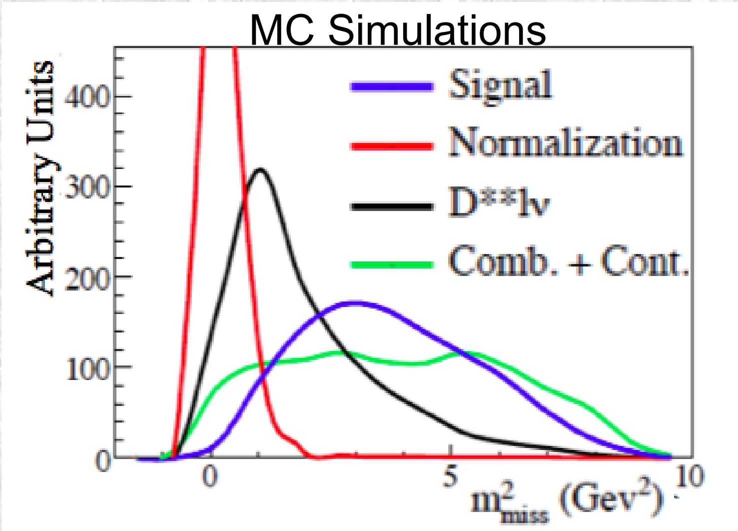
Sensitivity to New Physics through $R(D^{(*)})$

signal

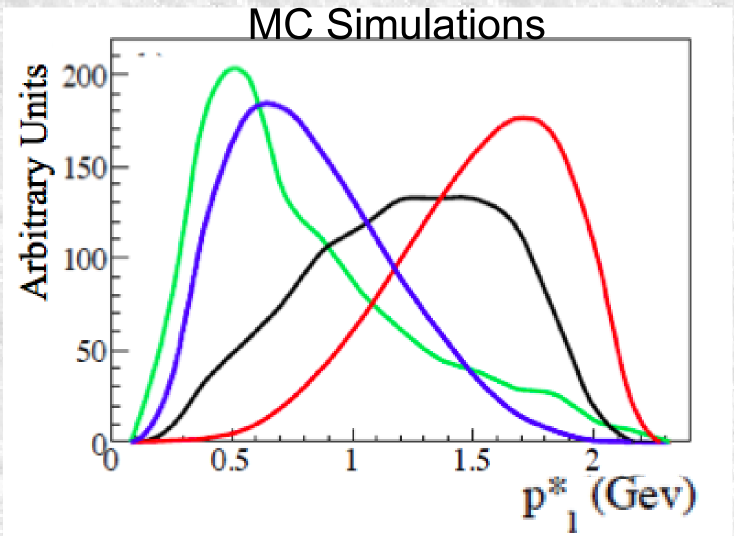
$$R(D^{(*)}) = \frac{\Gamma(B \to D^{(*)} \tau \nu_\tau)}{\Gamma(B \to D^{(*)} \ell \nu_\ell)_{\ell = e, \mu}}$$

normalization

- Several uncertainties cancel in ratios: theoretical and experimental
  - theoretical: |Vcb|, Form factors
  - experimental: Leptonic τ decay modes have same final event topology as normalization decays
- Spin-0 Higgs doesn't couple to all helicity states: affects D and D* differently



$$m^2_{miss} = \left(p_{e^+e^-} - p_{B_{tag}} - p_{D^{(*)}} - p_\ell\right)^2$$



Event Selection:

- Reconstruct $D^{(*)}$ candidate
- Exactly one extra leptonic track ($\tau \to e\nu\bar{\nu}$, $\mu\nu\bar{\nu}$)
- Multiple variables in Boosted Decision Trees
- Key variables to discriminate signal/norm decays: m^2_{miss} and p^*_ℓ in B_{sig} rest frame

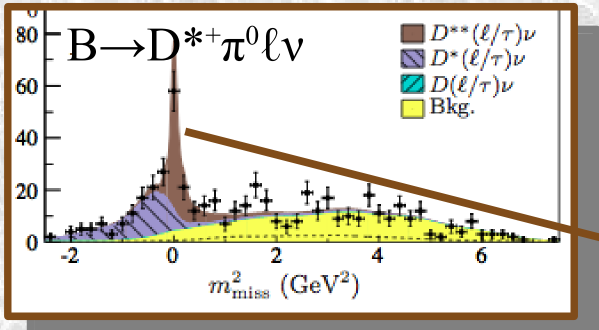
$B \to D^{(*)}\tau\nu$ Results

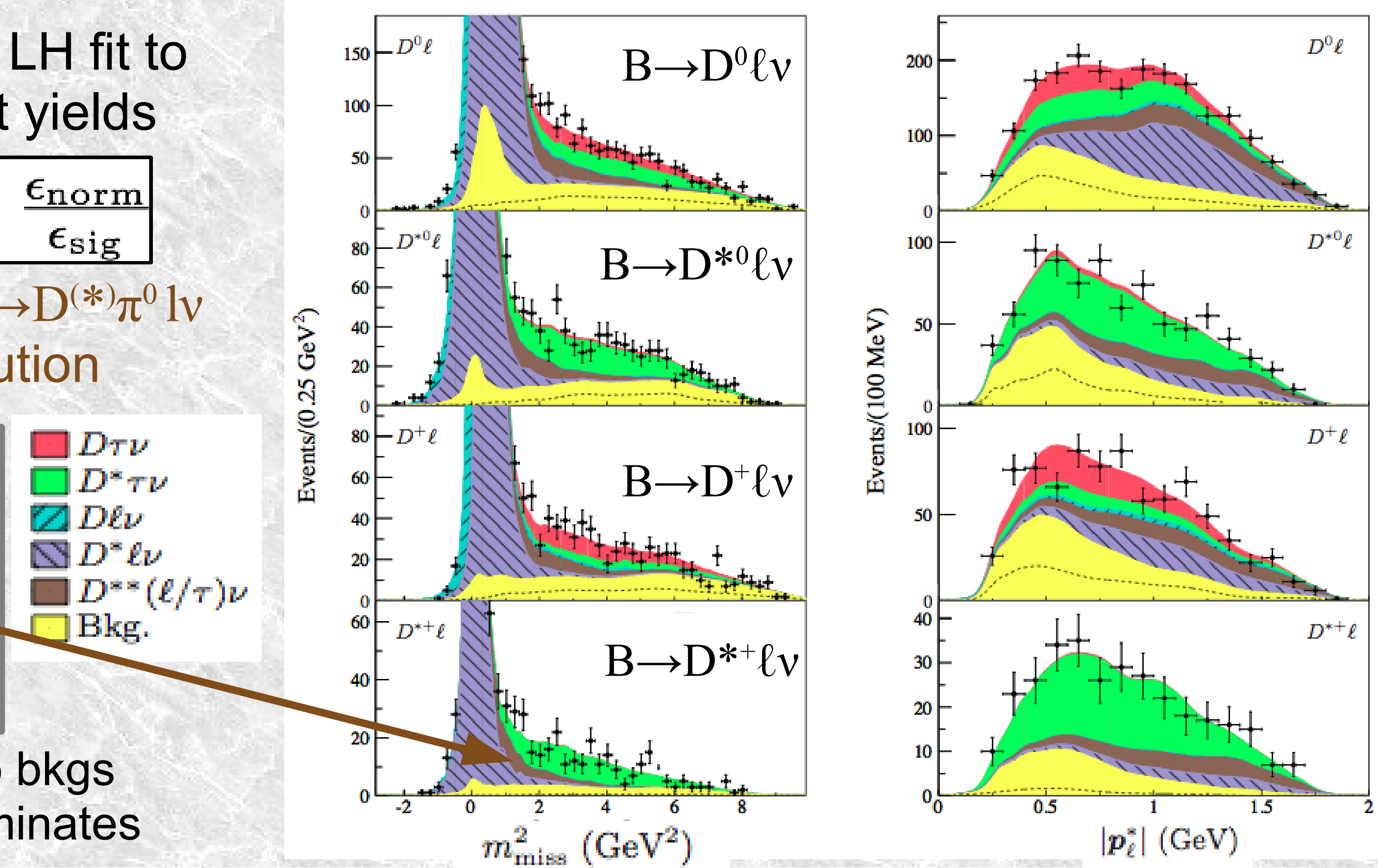
PRL 109, 101802 (2012)

- 2D Extended Maximum LH fit to m^2_{miss} and p^*_ℓ to extract yields

$$R(D^{(*)}) = \frac{N_{sig}}{N_{norm}} \times \frac{\epsilon_{norm}}{\epsilon_{sig}}$$

- Simultaneous fit with $B \to D^{(*)}\pi^0 l\nu$ to estimate D^{**} contribution





- Largest systematic due to bkgs
- Statistical uncertainty dominates

Decay	N_{sig}	$\mathcal{R}(D^{(*)})$	$\mathcal{B}(B \to D^{(*)}\tau\nu)$ (%)	Σ_{stat}
$B^- \to D^0\tau^-\overline{\nu}_\tau$	314 ± 60	$0.429 \pm 0.082 \pm 0.052$	$0.99 \pm 0.19 \pm 0.12 \pm 0.04$	5.5
$B^- \to D^{*0}\tau^-\overline{\nu}_\tau$	639 ± 62	$0.322 \pm 0.032 \pm 0.022$	$1.71 \pm 0.17 \pm 0.11 \pm 0.06$	11.3
$\overline{B}^0 \to D^+\tau^-\overline{\nu}_\tau$	177 ± 31	$0.469 \pm 0.084 \pm 0.053$	$1.01 \pm 0.18 \pm 0.11 \pm 0.04$	6.1
$\overline{B}^0 \to D^{*+}\tau^-\overline{\nu}_\tau$	245 ± 27	$0.355 \pm 0.039 \pm 0.021$	$1.74 \pm 0.19 \pm 0.10 \pm 0.06$	11.6
$\overline{B} \to D\tau^-\overline{\nu}_\tau$	489 ± 63	$0.440 \pm 0.058 \pm 0.042$	$1.02 \pm 0.13 \pm 0.10 \pm 0.04$	8.4
$\overline{B} \to D^*\tau^-\overline{\nu}_\tau$	888 ± 63	$0.332 \pm 0.024 \pm 0.018$	$1.76 \pm 0.13 \pm 0.10 \pm 0.06$	16.4

Isospin constrained

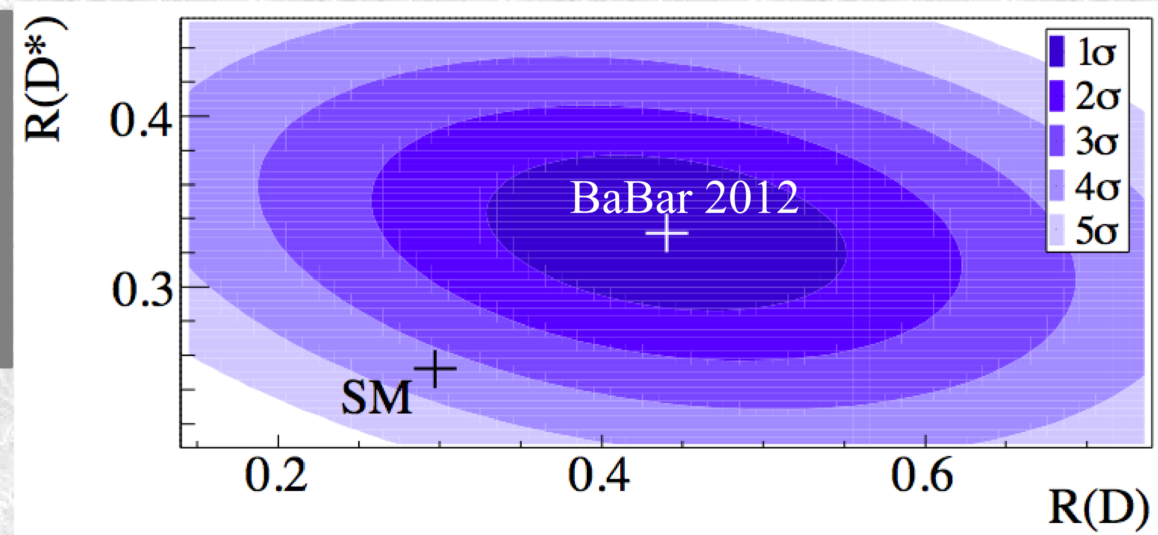
First observation!!

$B \to D^{(*)}\tau\nu$ Results II

PRL 109, 101802 (2012)

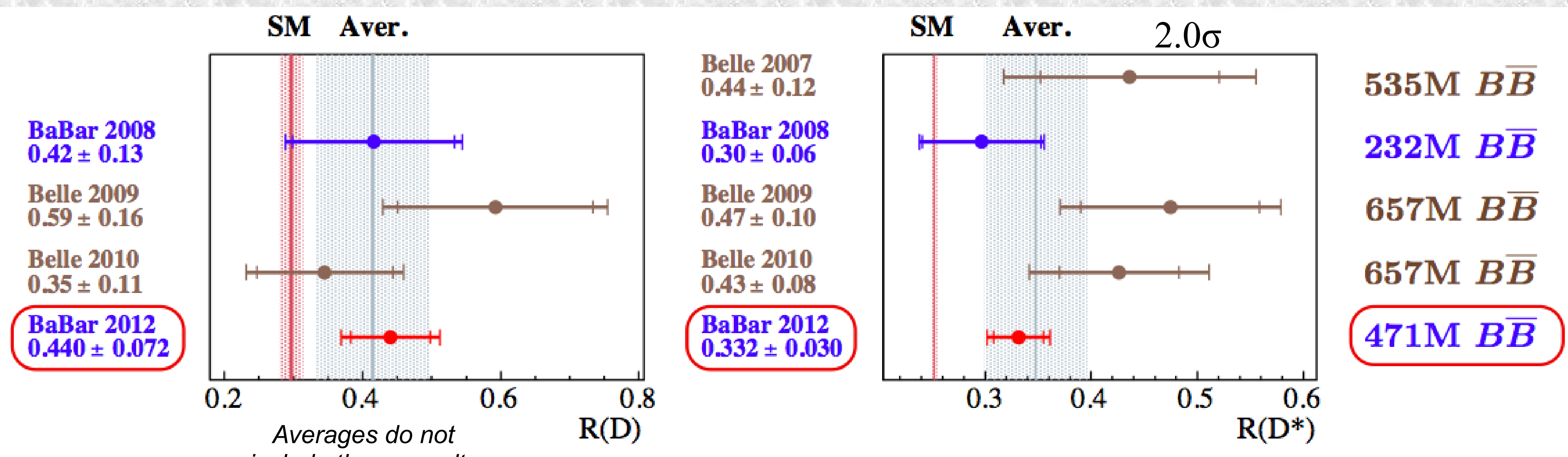
$$R(D) = \left\{ \begin{array}{ll} 0.440 \pm 0.072 & \text{BaBar} \\ 0.297 \pm 0.017 & \text{SM} \end{array} \right\} 2.0\sigma$$

$$R(D^*) = \left\{ \begin{array}{ll} 0.332 \pm 0.030 & \text{BaBar} \\ 0.252 \pm 0.003 & \text{SM} \end{array} \right\} 2.7\sigma$$



- R(D) and R(D*) are not independent: -27% correlation

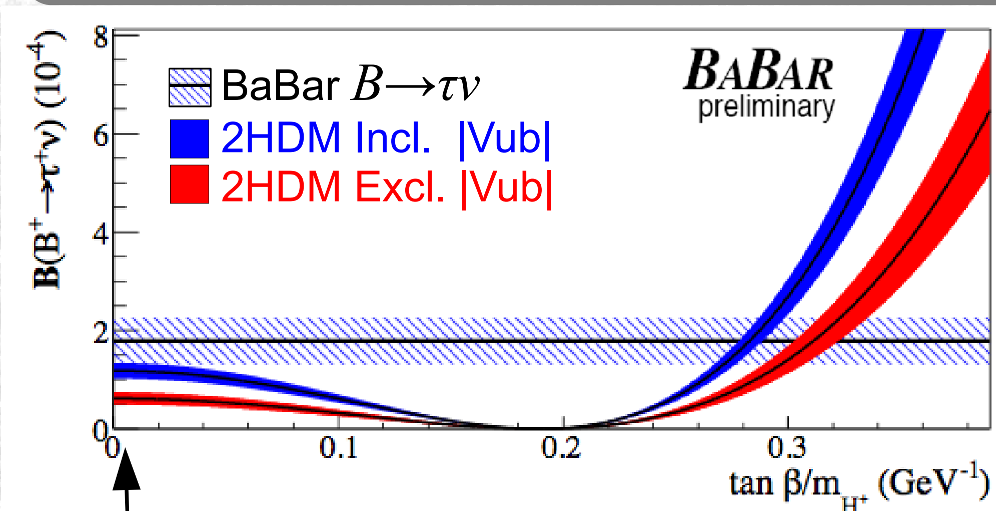
Combined deviation from SM: **$R(D^{(*)}) = 3.4\sigma$**



Type-II 2HDM

arXiv:1207.0698
and
PRL 109, 101802 (2012)

$$\mathcal{B}(B \to \tau\nu)_{\rm 2HDM} = \mathcal{B}_{\rm SM} \times \left(1 - \tan^2\beta \frac{m_B^2}{m_H^2}\right)^2$$



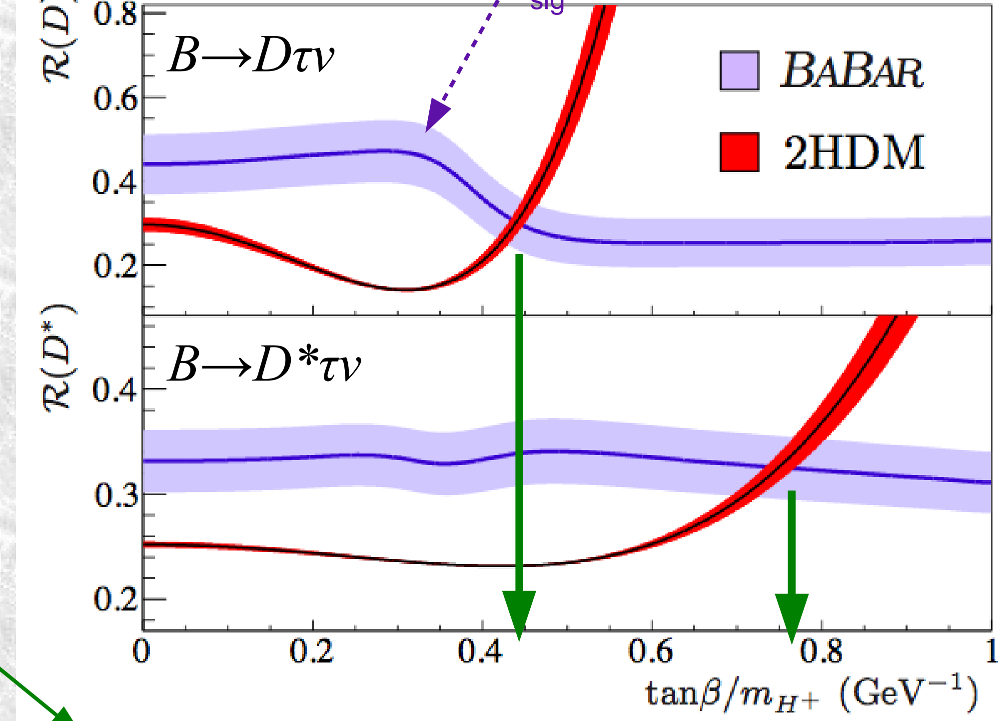
Standard Model at 0

Scalar Helicity Angle:

$$H_{0t}^{\rm 2HDM} \approx H_{0t}^{\rm SM} \times \left(1 - \frac{\tan^2\beta}{m_{H+}^2} \frac{q^2}{1 \mp m_c/m_b}\right)$$

+ for B→D*τν, - for B→Dτν

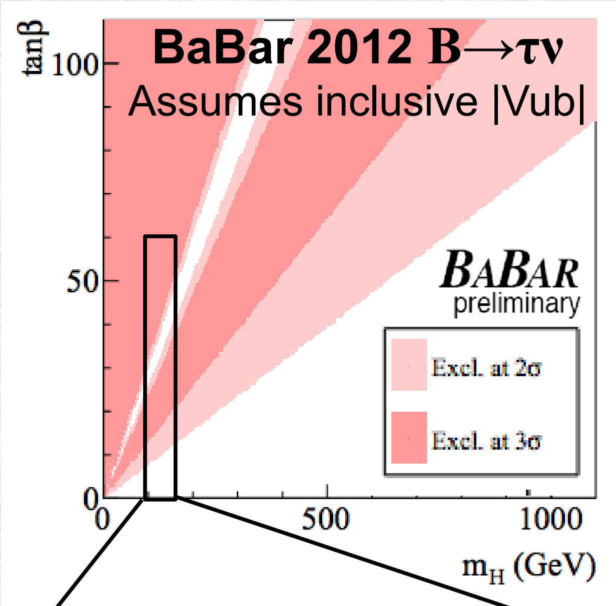
2HDM affects B→D$^{(*)}$τν fit variables, and hence ε_{sig} and PDFs

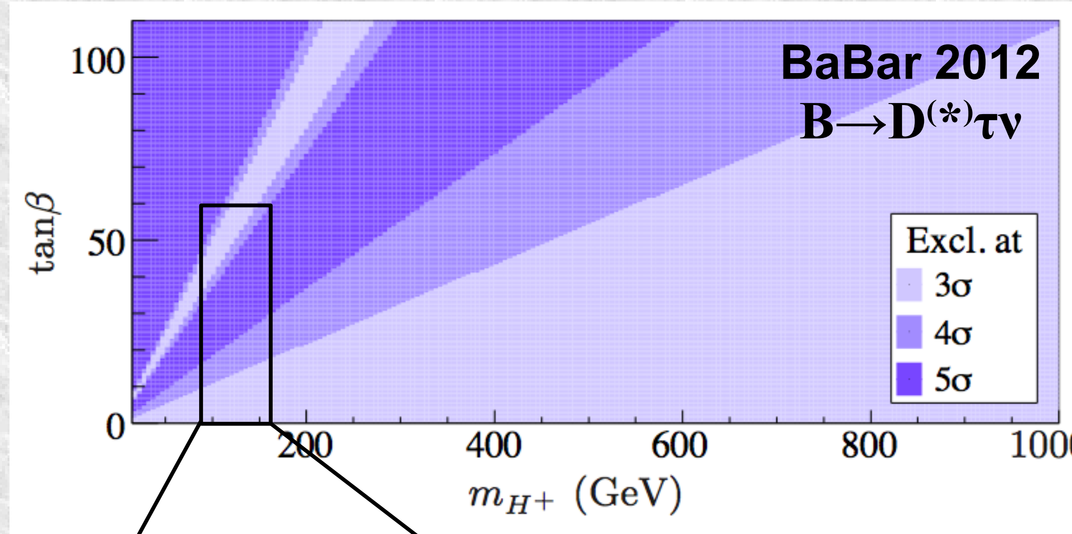


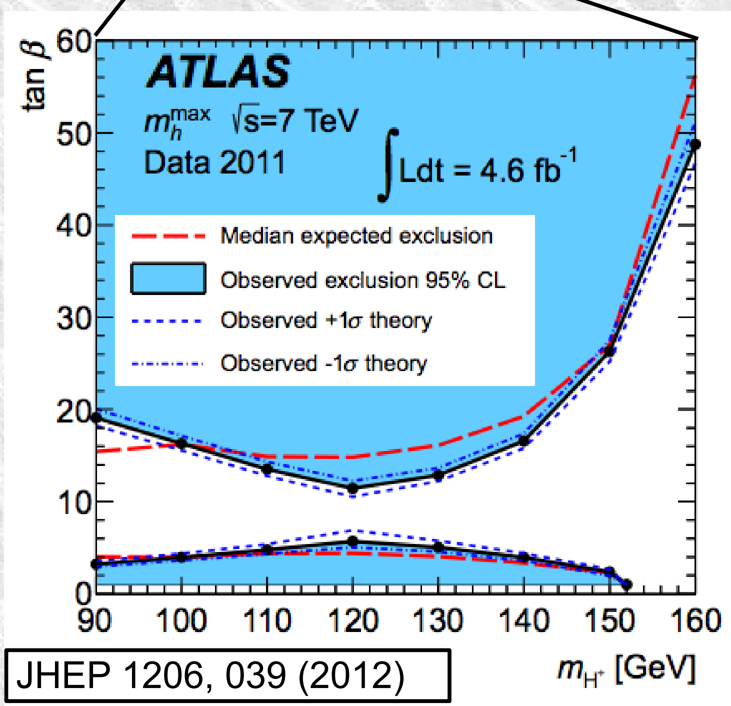
Combination of R(D) and R(D*)
excludes Type-II 2HDM
in full $\tan\beta$-m_H parameter space
with probability of >99.8% (~3.1σ)
(with m_{H+} >15 GeV,
but $m_{H+} \lesssim$ 300GeV already excluded by B→Xsγ)

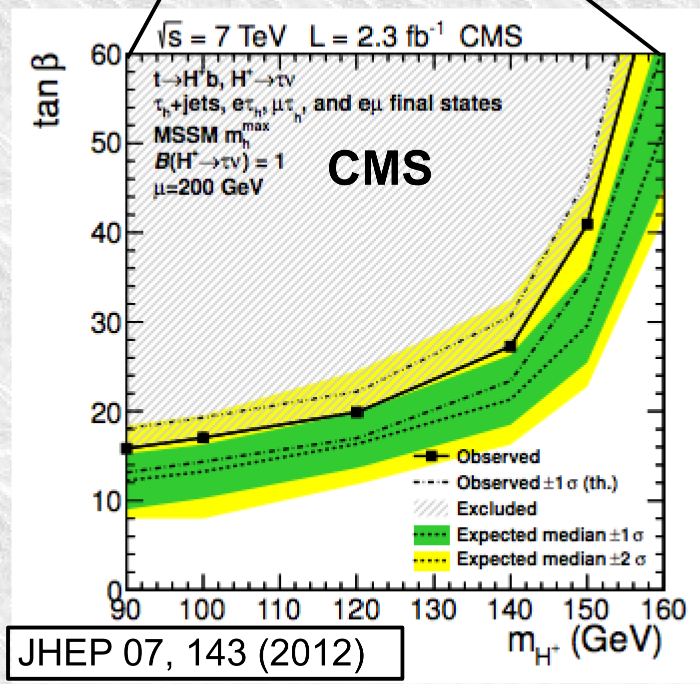
$$\mathcal{R}(D) \Longrightarrow \tan\beta/m_H = 0.44 \pm 0.02$$
$$\mathcal{R}(D^*) \Longrightarrow \tan\beta/m_H = 0.75 \pm 0.04$$

Exclusion reach of Type-II 2HDM









B→τν and B→D(*)τν searches are complementary to $t \to bH^+$ └→τν searches at LHC

Type-III 2HDM

New Results!
arXiv:1303.0571
submitted to PRD

Type-III 2HDM: More general charged Higgs model

$$\mathcal{H}_{\rm eff} = \frac{4G_F V_{cb}}{\sqrt{2}}\left[(\bar{c}\gamma_\mu P_L b)\,(\bar{\tau}\gamma^\mu P_L \nu_\tau) + S_R(\bar{c}P_R b)\,(\bar{\tau}P_L\nu_\tau)\right] + S_L(\bar{c}P_L b)\,(\bar{\tau}P_L\nu_\tau)$$

Crivellin, Greub, & Kokulu, arXiv:1206.2634 (2012); Datta et al, PRD 86, 034027 (2012)

R(D) and R(D*) depend on 2 independent NP parameters ($S_R \pm S_L$)

$$\mathcal{R}(D) = \mathcal{R}(D)_{\rm SM} + A'_D{\rm Re}(S_R + S_L) + B'_D|S_R + S_L|^2$$

$$\mathcal{R}(D^*) = \mathcal{R}(D^*)_{\rm SM} + A'_{D^*}{\rm Re}(S_R - S_L) + B'_{D^*}|S_R - S_L|^2$$

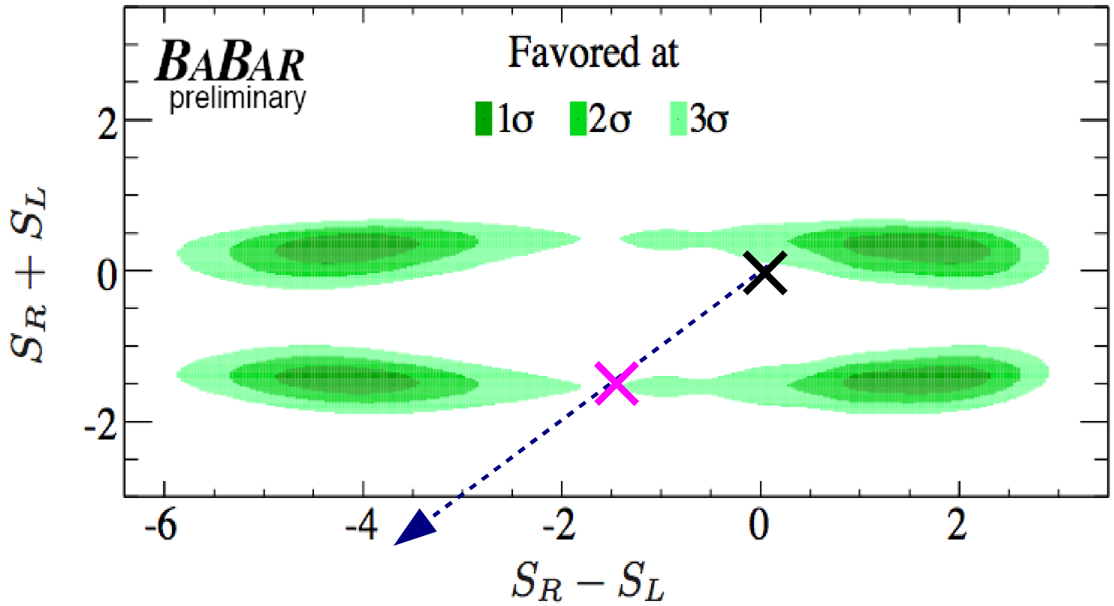
Type-II 2HDM: one Higgs doublet couples to **up** quarks, one to **down** & **leptons**.

Subset of Type-III

$S_L = 0$

$$S_R = -m_b m_\tau \frac{\tan\beta^2}{m_H^2}$$

- Type-II has no solution for both R(D) and R(D*)
- Type-III has 4 solutions for real $S_R \pm S_L$ (more for complex values)



- - Type-II: $S_R + S_L = S_R - S_L$

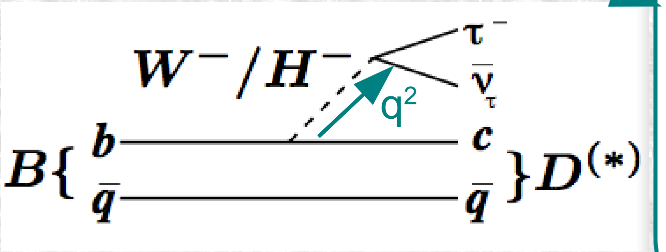
× SM value

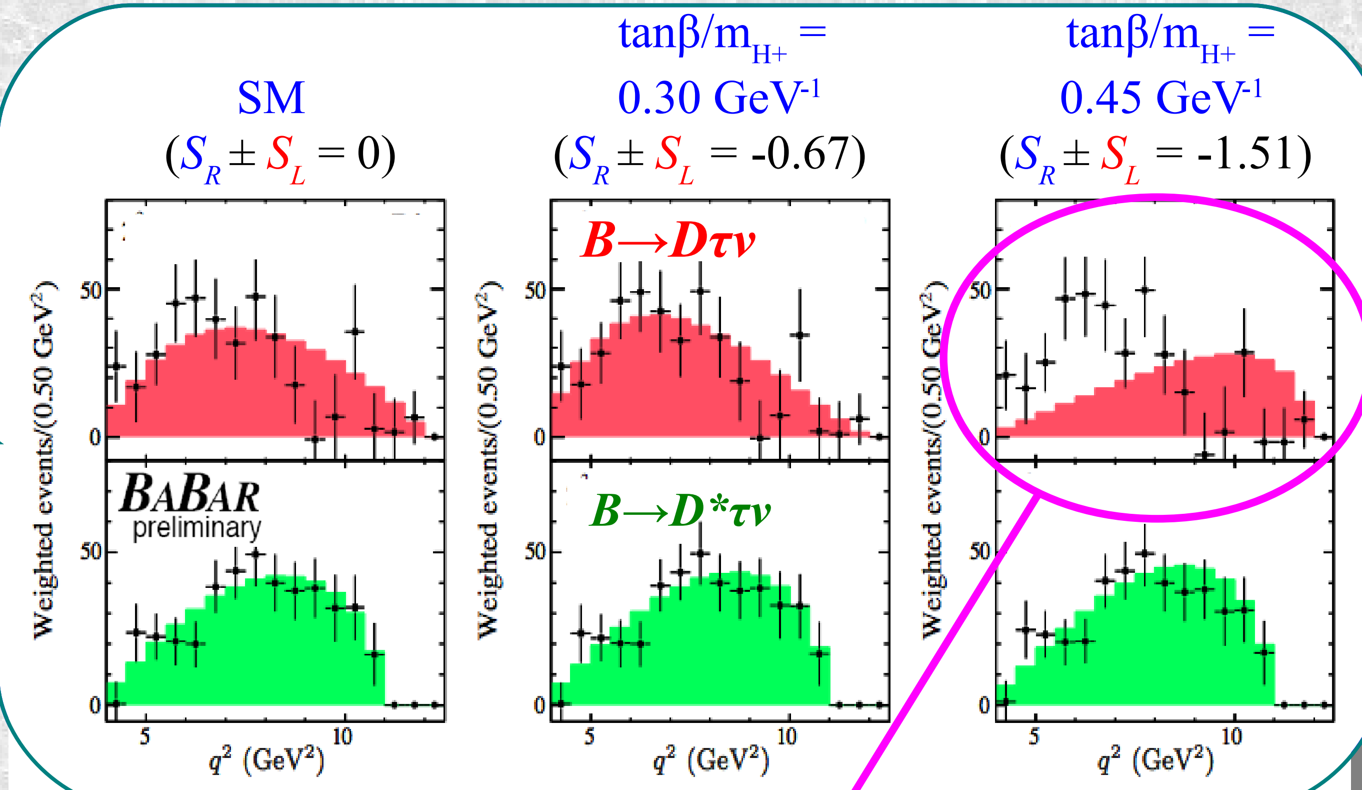
× Measured value for R(D) in Type-II: $S_R \pm S_L = -1.51$

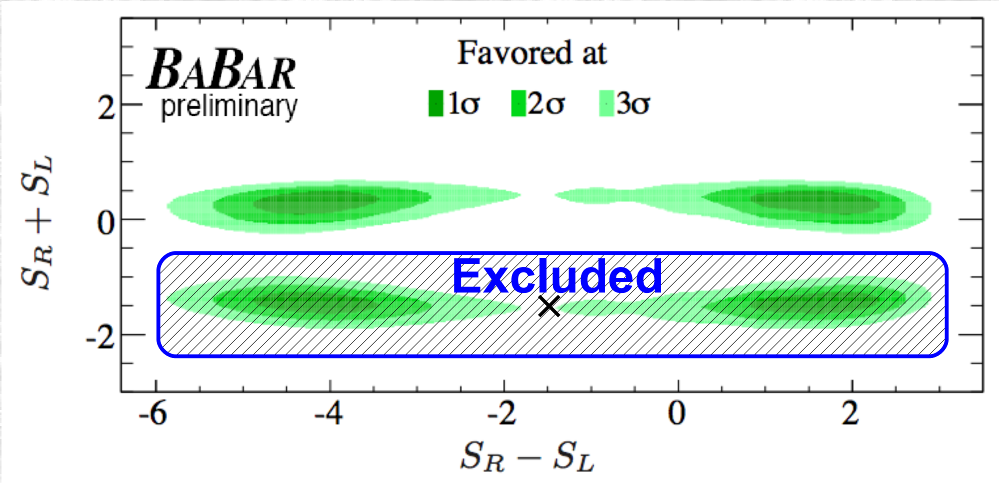
Type-III 2HDM Exclusions

New Results!
arXiv:1303.0571
submitted to PRD

$\tan\beta/m_{H+}$ affects
(bkg-subtracted)
signal q^2 distributions







- p-value is 0.4% (with syst.), excluding solutions around $S_R \pm S_L \approx -1.5$ with >2.9σ

- Other more general H^+ models, or NP contributions with spin-1 (favored!), are also compatible with measurements

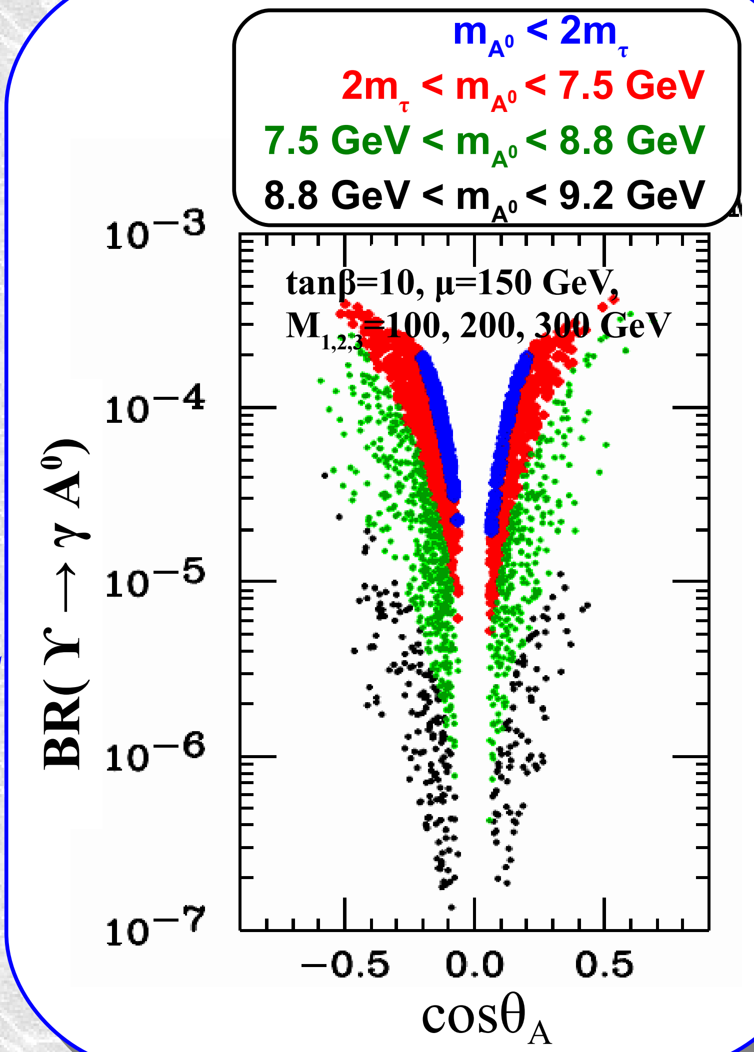
Light Higgs Searches

Light Higgs Motivation

- Low-mass Higgs arise in several BSM scenarios
- NMSSM: proposed to solve EW scale fine-tuning by adding a singlet Higgs field to MSSM
  - Adds an additional CP-odd Higgs (A^0) that mixes with MSSM CP-odd Higgs

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

  - Also adds a neutralino and a CP-even Higgs
- If $m_{A^0} < 2m_b$, models are not excluded by LEP constraints
- Light CP-odd Higgs can be directly produced in radiative decays of heavy quarkonium states like $\Upsilon(nS)$
  - Can have large branching fractions

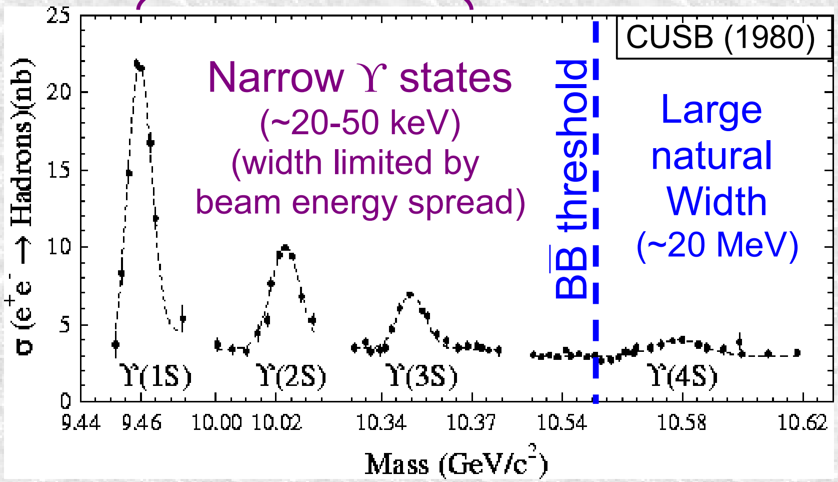


Dermisek et al., PRD 76, 051105 (2007)
Dermisek and Gunion, PRD 81, 075003 (2010)

BaBar Light Higgs Searches

No $B\bar{B}$ decays

Clean environment for New Physics (A^0) searches using 2-body radiative decays

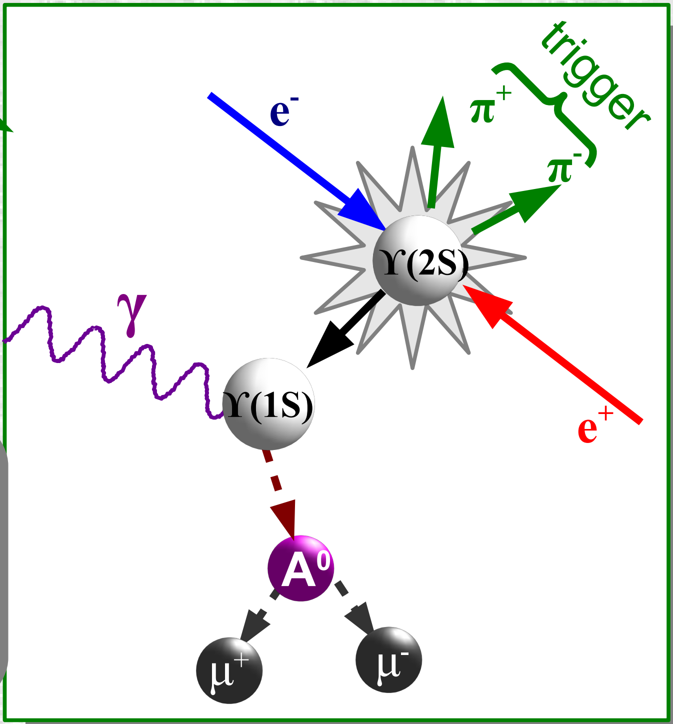


BaBar data samples:

- **121 x 10^6 ϒ(3S)** (x10 Belle)
- **98 x 10^6 ϒ(2S)** (x10 CLEO)

$\Upsilon(2S, 3S)\to\gamma A^0,\ A^0\to\mu^+\mu^-$	PRL 103, 081803 (2009)
$\Upsilon(2S, 3S)\to\gamma A^0,\ A^0\to\tau^+\tau^-$	PRL 103, 181801 (2009)
$\Upsilon(2S, 3S)\to\gamma A^0,\ A^0\to$hadrons	PRL 107, 221803 (2011)

- $\Upsilon(3S, 2S)\to\pi\pi\Upsilon(1S)$ provides clean di-pion trigger
  - ~18 x 10^6 $\Upsilon(2S)\to\pi\pi\Upsilon(1S)$
  - $\pi\pi$ recoil mass ≈ mass of ϒ(1S)
  - Monochromatic photon in ϒ(1S) rest frame



$\Upsilon(1S)\to\gamma A^0,\ A^0\to\mu^+\mu^-$	arXiv:1210.0287	New Results!
$\Upsilon(1S)\to\gamma A^0,\ A^0\to\tau^+\tau^-$	PRD 87, 031102 (2013)	
$\Upsilon(1S)\to$invisible + γ	PRL 107, 021804 (2011)	
$\Upsilon(1S)\to$invisible	PRL 103, 251801 (2009)	

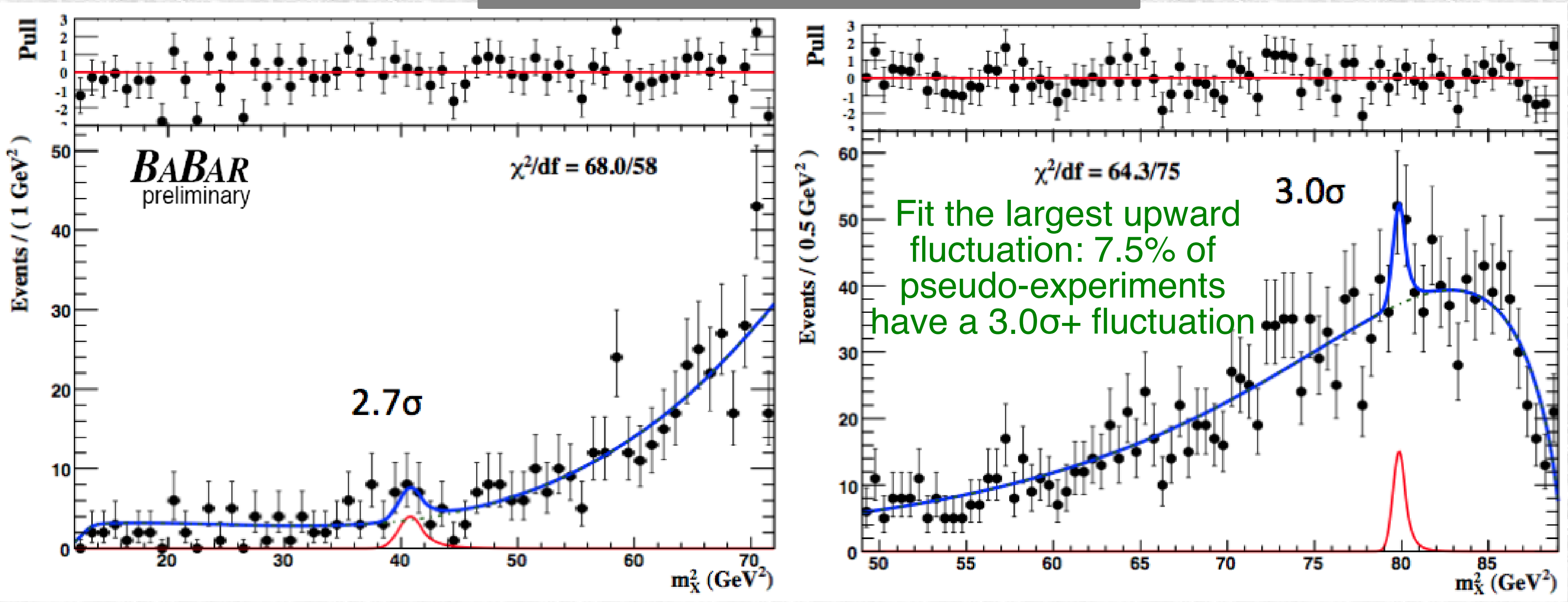
$\Upsilon(2S) \rightarrow \pi\pi\Upsilon(1S)$, $\Upsilon(1S) \rightarrow \gamma A^0$, $A^0 \rightarrow \tau^+\tau^-$

arXiv:1210.5669
Submitted to PRD-RC

Event Selection:

- Require 4 tracks: $\pi\pi$ tag + ee, $e\mu$, $e\pi$, $\mu\mu$, or $\mu\pi$ for tau pair
- Two neural nets ($N_{\pi\pi}$ and $N_{\tau\tau}$) to discriminate background from signal
- Search for narrow peak in photon energy spectrum by scanning mass of A^0:

$$m_X^2 = (P_{e^+e^-} - P_{\pi\pi} - P_\gamma)^2$$



- Observed deviations are consistent with background fluctuations

arXiv:1210.5669
Submitted to PRD-RC

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

Results from this search:

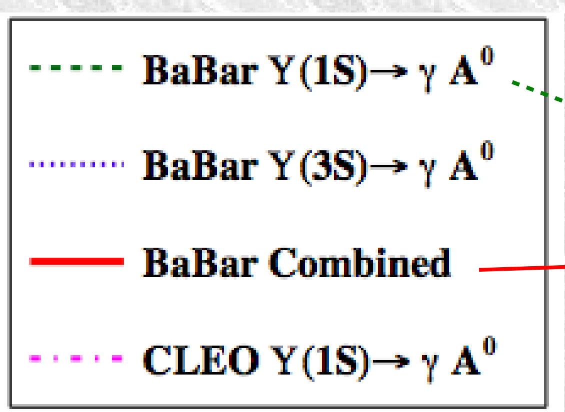
$$\mathcal{B}(\Upsilon(1S)\to\gamma A^0) \times \mathcal{B}(A^0\to\tau^+\tau^-) < (0.9 - 13)\times 10^{-5} \quad \text{for} \quad 3.6 < m_{A0} < 9.2\ \text{GeV}$$

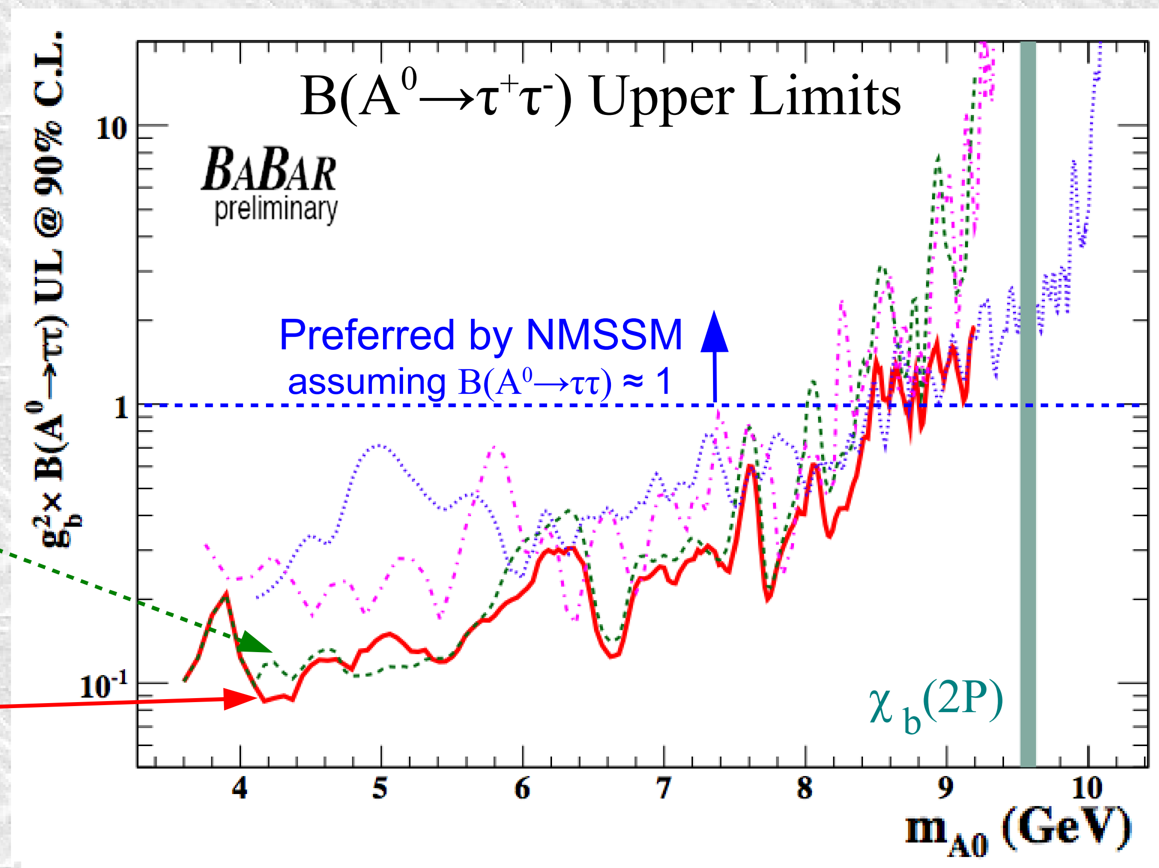
Combine with previous $\mathcal{B}(A^0\to\tau^+\tau^-)$ results using:

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

g_b = Yukawa coupling of b-quark to A^0
= $\cos\theta_A \tan\beta$ in NMSSM

Dermisek and Gunion,
PRD 81, 075003 (2010)

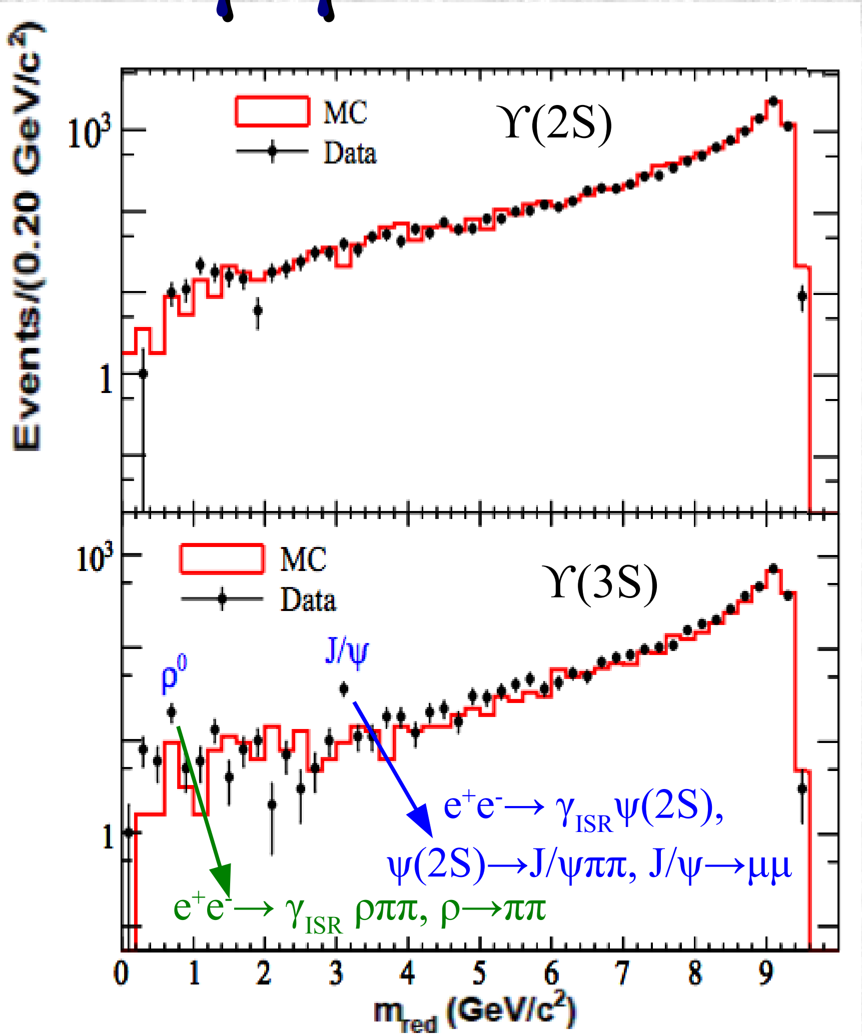




$\Upsilon(2S,3S)\to\pi\pi\Upsilon(1S)$, $\Upsilon(1S)\to\gamma A^0$, $A^0\to\mu^+\mu^-$

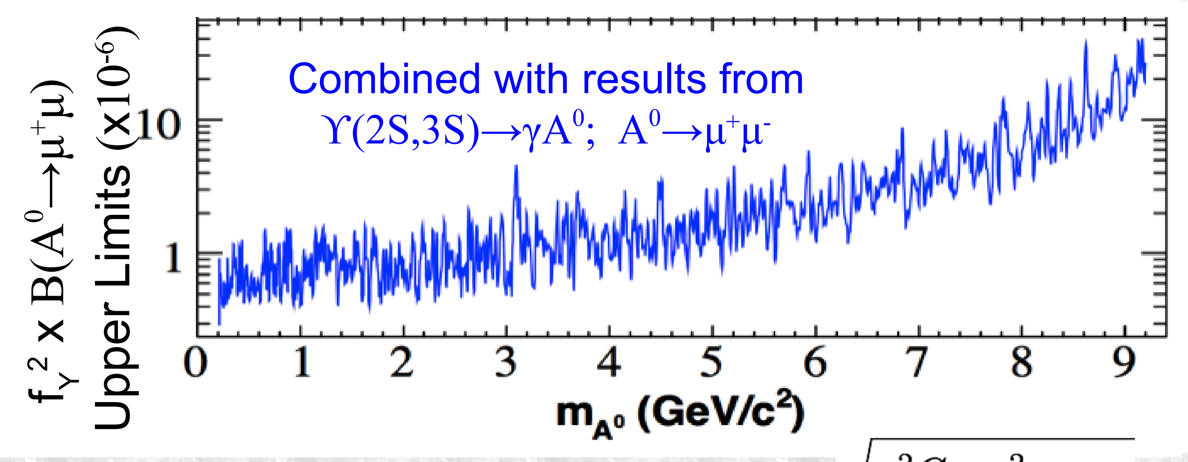
PRD 87, 031102 (2013)

- Select 4 track events ($\pi\pi$ tag plus $\mu\mu$) plus 1 energetic photon (>0.2GeV)
- Random Forest Classifier to reduce bkg
- Scan reduced dimuon mass spectrum
- Observed deviations are consistent with background fluctuations



$B(\Upsilon(1S)\to\gamma A^0) \times B(A^0\to\mu^+\mu^-) < (0.28\text{-}9.7) \times 10^{-6}$ for $m_{A0} < 9.2$ GeV

- Improve current limits by 2-3x for m_{A0} <1.2 GeV

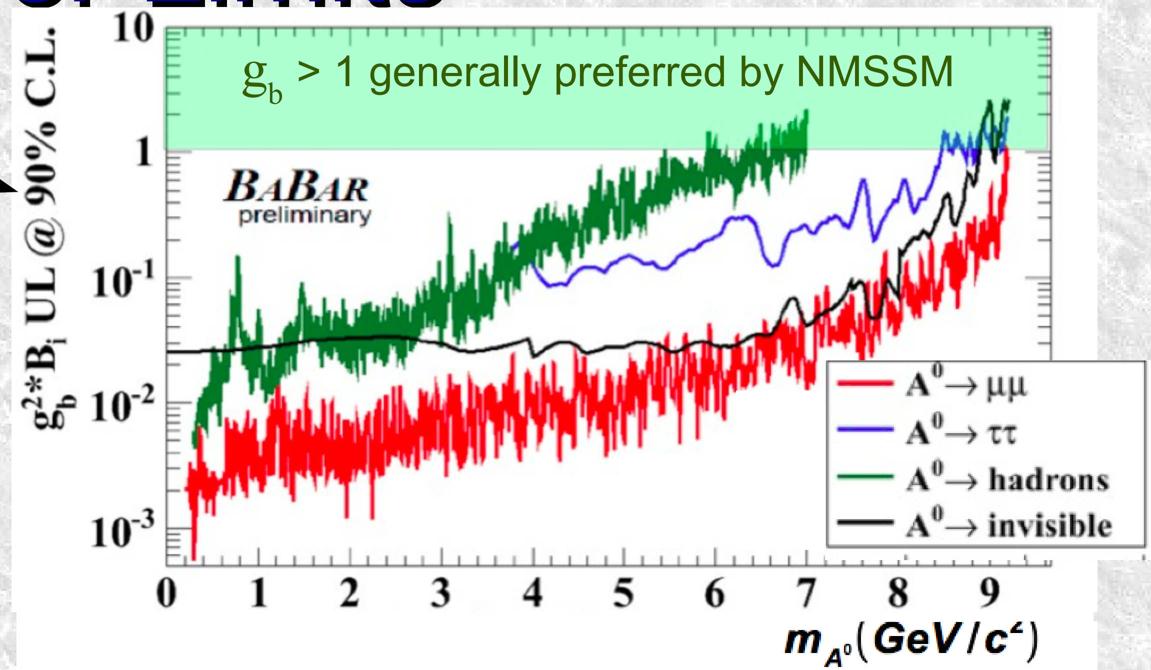


$$m_{\rm red} = \sqrt{m^2_{\mu^+\mu^-} - 4m^2_\mu}$$
$= 2\vec{p}_\mu$ in A^0 rest frame

where f_Υ = effective Yukawa coupling = $\sqrt{\frac{g_b^2 G_F m_b^2}{\sqrt{2}}\mathcal{F}_{\rm QCD}}$

A^0 Upper Limits

Upper limits on light Higgs coupling from several BaBar measurements



g_b = Yukawa coupling of b-quark to A^0

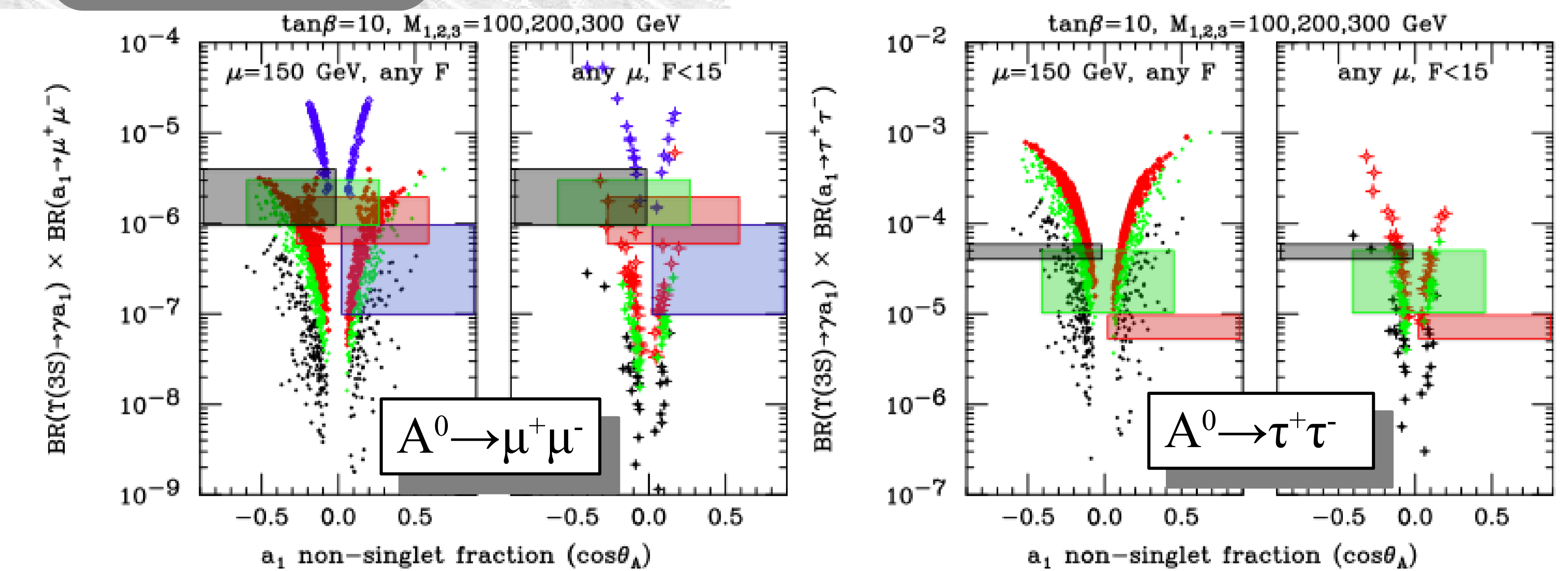
= $\cos\theta_A \tan\beta$ in NMSSM

$m_{A^0} < 2m_\tau$

$2m_\tau < m_{A^0} < 7.5$ GeV

$7.5 < m_{A^0} < 8.8$ GeV

$8.8 < m_{A^0} < 9.2$ GeV



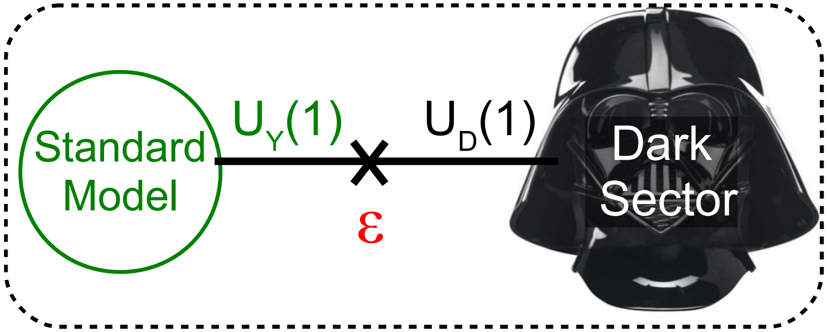
Dark Higgs Searches

Dark Forces

- Overwhelming evidence of Dark Matter + Recent astronomical observations
  - 511 keV γ-ray excess (INTEGRAL), $e^{\pm}$ excess (PAMELA, ATIC, FERMI, HESS), etc.

New models introduce new hidden dark sector with $U(1)_{DARK}$ gauge group

- TeV-scale dark matter → GeV-scale dark photon pair → SM fermions
- Dark photon (A') could couple to SM particles through a small kinetic mixing term ($\varepsilon F^{\mu\nu} B_{\mu\nu}$)
- Dark photon coupling to SM fermions: $\alpha' = \varepsilon^2 \alpha_D$

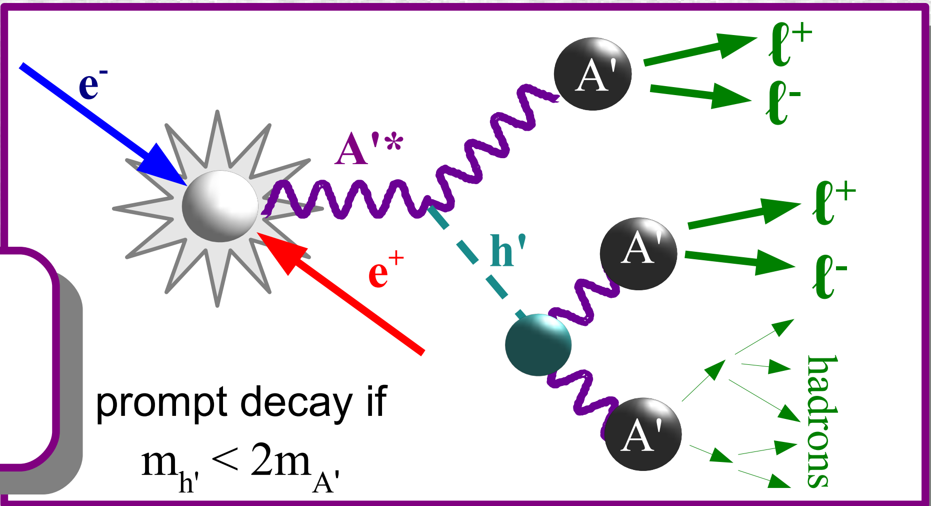


- Some models include a dark Higgs (h') (gives mass to dark photon)

Arkani-Hamed et al, PRD 79, 015014 (2009);
Batell et al, PRD 79, 115008 (2009); Essig et al, PRD 80, 015003 (2009);

GeV-range dark photons
could be produced at B-factories!

Higgs-strahlung process
$e^+e^- \rightarrow A'^* \rightarrow h'A'$, $h' \rightarrow A'A'$
only suppressed by factor of ε



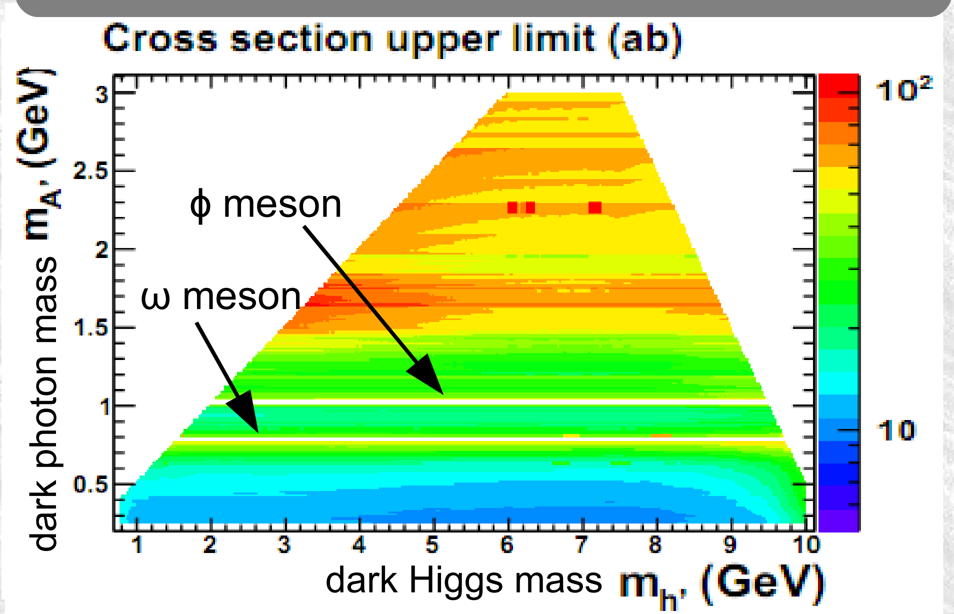
Also, $A^0 \rightarrow \ell\ell$ searches can be reinterpreted as $A' \rightarrow \ell\ell$

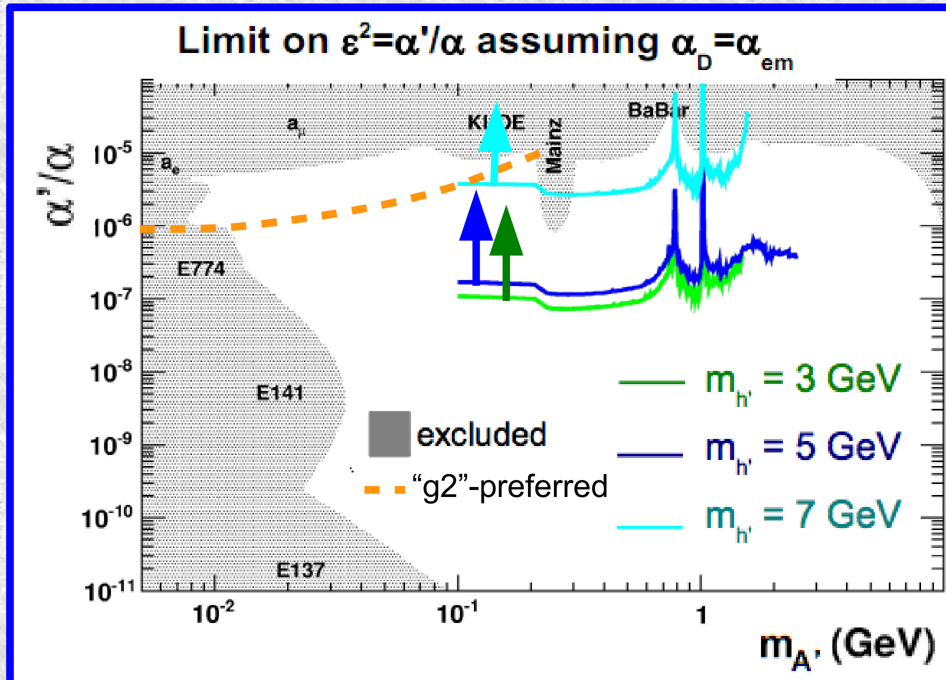
Search for a Dark Higgs h'

PRL 108, 211801 (2012)

- Event Selection on full BaBar dataset $\Upsilon(4S,3S,2S)$
  - (a) Exclusive: Fully reconstruct 3 dark photons: $A' \to e^+e^-$, $\mu^+\mu^-$, $\pi^+\pi^-$
  - (b) Inclusive/partial reconstruction: 2 A' decaying to leptons and 1 A' to $q\bar{q}$
    - Four momentum $p_3 = p_{ee} - p_1 - p_2$
  - 3 A' candidates have similar masses
- 6 events observed (none with 6 leptons), consistent with bkg from control samples

$\sigma\ (e^+e^- \to h'A',\ h' \to A'A') <$ 10-100 ab
at 90% CL





$\alpha_D\varepsilon^2 <$ few x 10^{-10} at 90% CL

~ order of mag. improvement, assuming $\alpha_D=\alpha_{EM}$

$\alpha'=\varepsilon^2\alpha_D$: dark photon - SM fermion coupling

$\alpha_D \equiv g_D^2/4\pi$, g_D = dark sector coupling constant

Summary

- The B-factory environment of BaBar provides access to missing-energy decays and to high-energy regions not accessible to hadron machines
- BaBar has searched for evidence of several types of BSM Higgs:
  - Charged Higgs
    - $\mathcal{B}(B \to D^{(*)}\tau\nu)$ and $\mathcal{B}(B \to \tau\nu)$ measured in excess of SM predictions
    - $B \to D^{(*)}\tau\nu$ has excluded MSSM Type-II 2HDM at 99.8% CL
  - Light Higgs favored by NMSSM
    - Comprehensive searches using a variety of channels, including new $\Upsilon(1S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$ and $\tau^+\tau^-$ results, significantly constrain NMSSM parameter space
  - Dark Higgs suggested by dark sector models
    - Constraints on the coupling parameters of dark-sector models
- Ongoing searches in progress!
  - *e.g.* Additional $B \to D^{(*)}\tau\nu$, $\Upsilon(nS) \to \gamma A^0$, and $A' \to \ell^+\ell^-$ analyses