Recent BaBar Searches for New Physics

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Representing the BaBar Collaboration

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Overview: 4 New Results

1) Search for lepton flavour violation: $B^{\pm} \to h^{\pm}\tau\ell$

arXiv:1204.2852, submitted to PRD

2) Search for a low-mass "dark" Higgs boson: $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

arXiv:1202.1313, accepted by PRL

3) Updated search for **invisible** decays of the B^0

about to be submitted to PRD

4) **Evidence** (!) for an excess of $B \to D^{(*)}\tau\nu$

arXiv:1205.5442, submitted to PRL

1) Search for lepton flavour violation: $B^{\pm} \to h^{\pm}\tau\ell$

arXiv:1204.2852,
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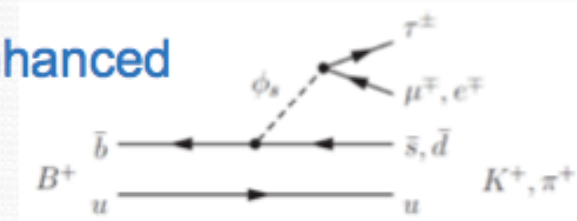
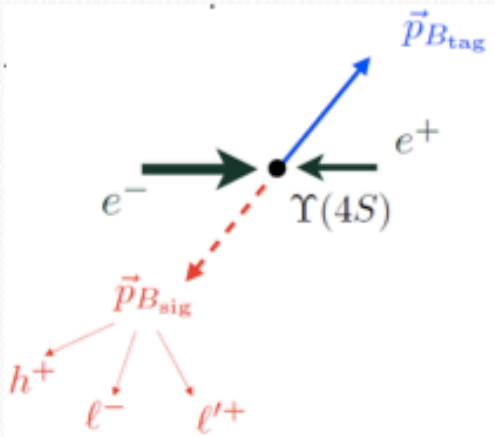
Search for lepton flavour violation: $B^{\pm} \to h^{\pm}\tau\ell$

472 x 10^6 *B* pairs

- FCNC and charged lepton flavor violation (LFV) forbidden in SM at tree level
- In many extensions of the SM, FCNC and/or LFV enhanced
  - Especially for **second** and **third** generations
    Phys. Rev. D44, 1461 (1991)



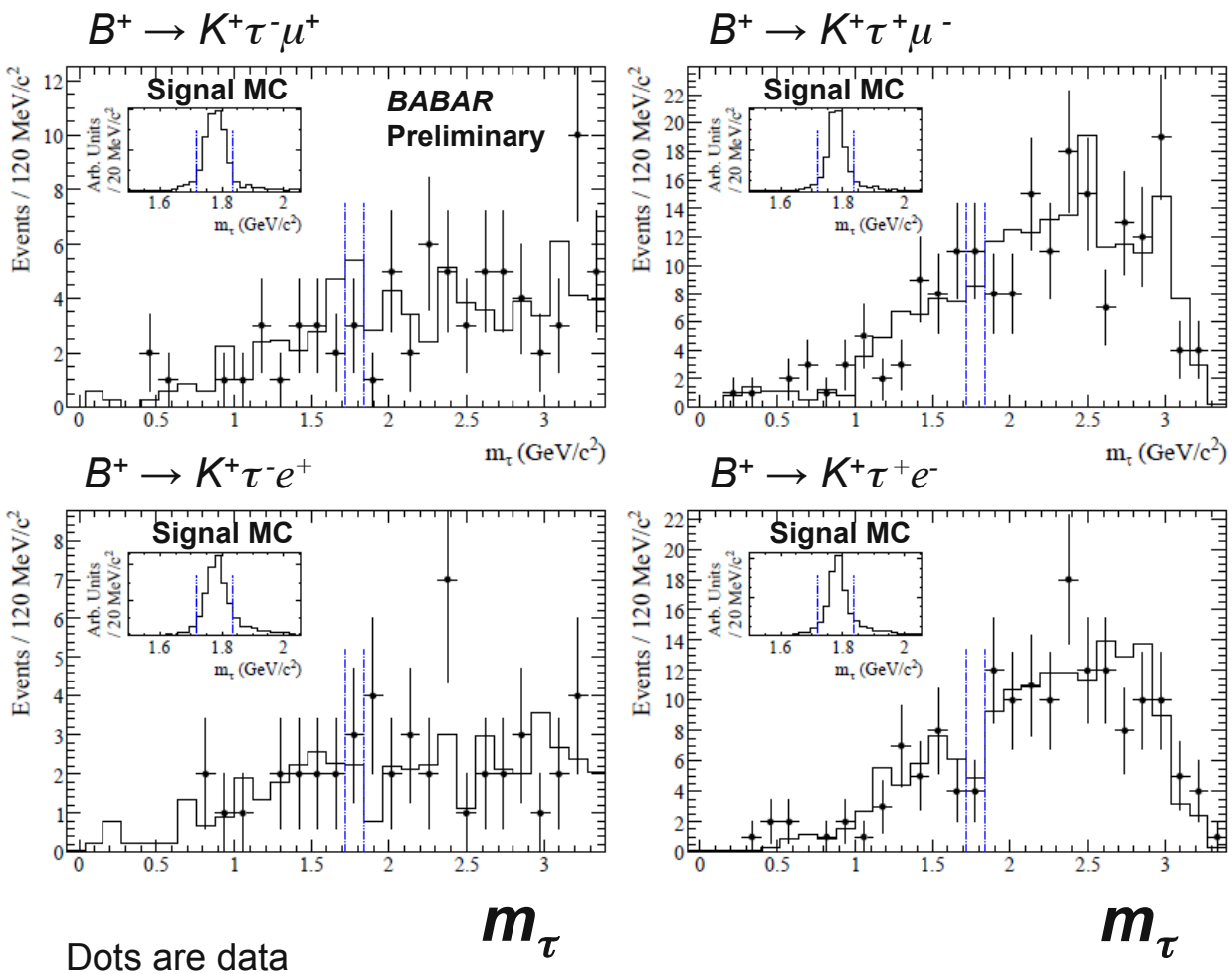
- 8 final states
  - $h = K, \pi \quad l = e, \mu$
  - $B^+ \to K^+\tau e$, $B^+ \to \pi^+\tau\mu$, $B^+ \to \pi^+\tau e$ **never done** before
- Indirect reconstruction of the tau
  - **Fully reconstructed** hadronic *B* on one side (**tag *B***)
    - $B^- \to D^{(*)0}X^-$, X^- composed of $\pi^{\pm}, K^{\pm}, K^0_S, \pi^0$
  - This determines the three-momentum of the other B (**signal B**) and thus the **tau**
    - $p_\tau = p_B - p_h - p_l$
    - $E_\tau = E_{beam} - p_h - p_l$



- Single-prong tau decays
  - $\tau \to e\nu\bar{\nu}$
  - $\tau \to \mu\nu\bar{\nu}$
  - $\tau \to \pi^+ (\geq 0\pi^0)\, \nu$

Search for lepton flavour violation: $B^{\pm} \to h^{\pm}\tau\ell$: Kaon modes

472 x 10^6 *B* pairs



Dots are data
Histograms are MC

- Signal region:
  $m_\tau \pm 60$ MeV
- No evidence for signal
- Combined limits:

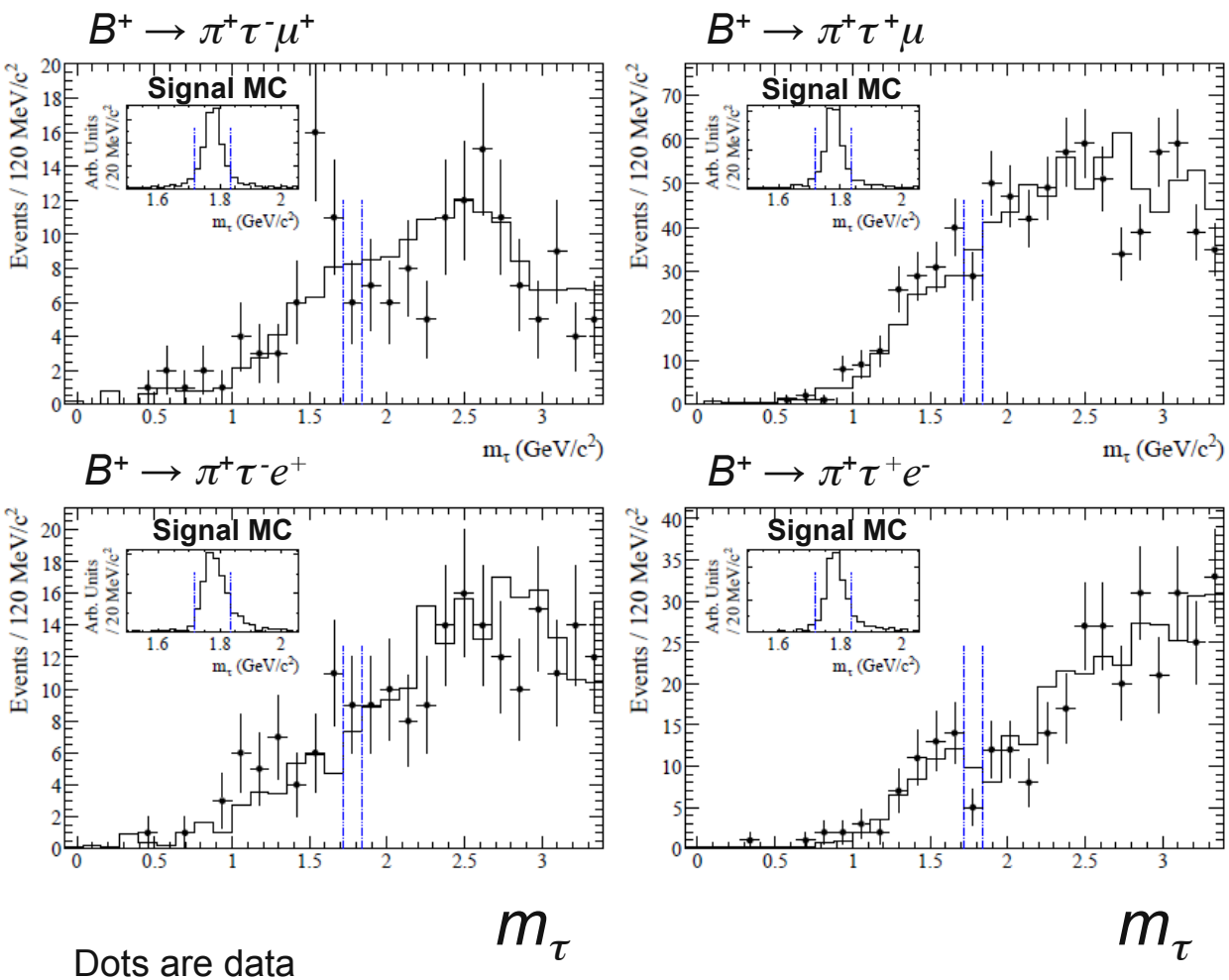
Mode	90% CL Upper Limit (10^{-5})
$B^+ \to K^+\tau\mu$	4.8
$B^+ \to K^+\tau e$	3.0

- Model-independent bounds on the energy scale of new physics in flavor-changing operators
  - $\Lambda_{bs} > 15$ TeV (90% CL)
    - (was 2.6 TeV)

*Phys. Rev. D**66**, 053002 (2002)*

Search for lepton flavour violation: $B^{\pm} \to h^{\pm}\tau\ell$: Pion modes

472 x 10^6 *B* pairs



Dots are data
Histograms are MC

- No evidence for signal
- Combined limits:

Mode	90% CL Upper Limit (10^{-5})
$B^+ \to \pi^+\tau\mu$	7.2
$B^+ \to \pi^+\tau e$	7.5

- Model-independent bounds on the energy scale of new physics in flavor-changing operators
  - Λ_{bd} > 11 TeV (90% CL)
    - (was 2.2 TeV)

*Phys. Rev. D**66**, 053002 (2002)*

2) Search for a low-mass "dark" Higgs boson:

$A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

arXiv:1202.1313,
accepted by PRL

Search for a low-mass "dark" Higgs boson: $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

- New dark sector with a $U(1)_D$ gauge group.
- New gauge boson: **dark photon A' with O(GeV) mass.**
- Interaction with the SM is via **kinetic mixing**

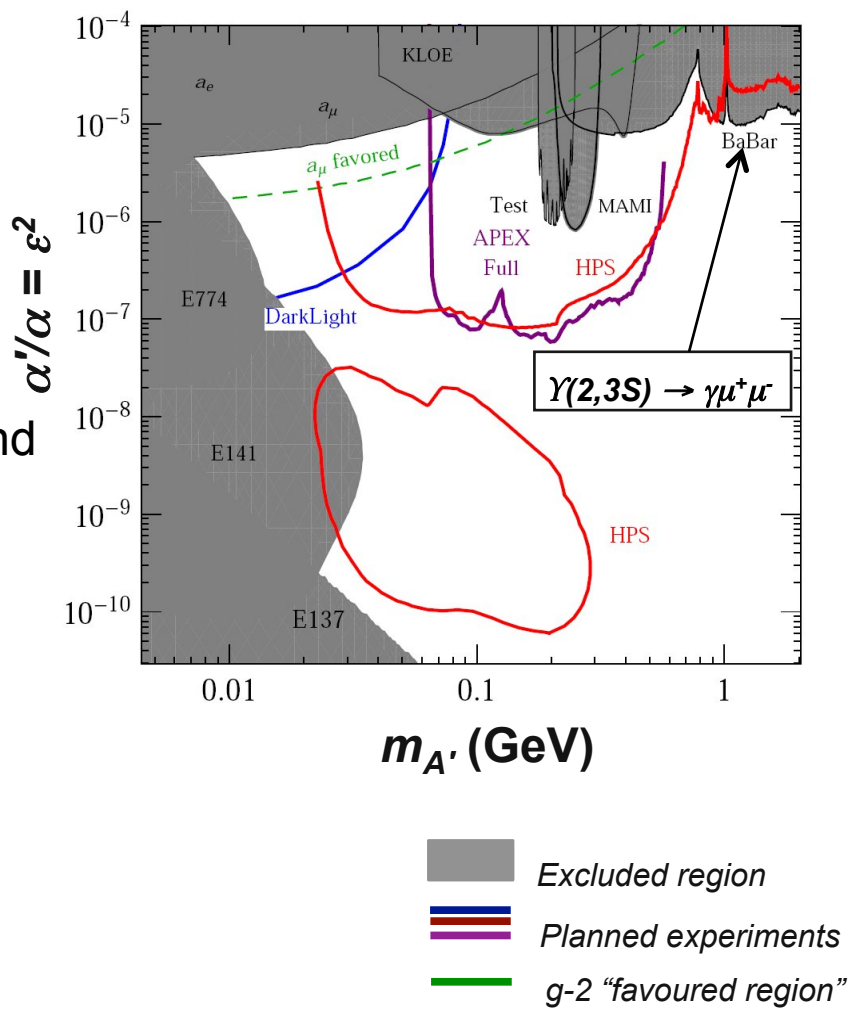
  $$e\, F^{mn} B_{mn}$$

  with a **mixing strength ε.**
- The dark photon acquires a charge εe, and the **coupling of the dark photon to SM fermions** is characterized by $\alpha' = \alpha\, \varepsilon^2$
- A dark photon can be readily produced in

  $$e^+e^- \rightarrow \gamma A', A' \rightarrow f \bar{f}$$
- The limits on $e^+e^- \rightarrow \Upsilon(2S,3S) \rightarrow \gamma\mu^+\mu^-$ can be reinterpreted as limits on dark photon production.

J.D. Bjorken et al., PRD 80 (2009) 075018

Constraints on $\alpha'/\alpha = \varepsilon^2$



Search for a low-mass "dark" Higgs boson: $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

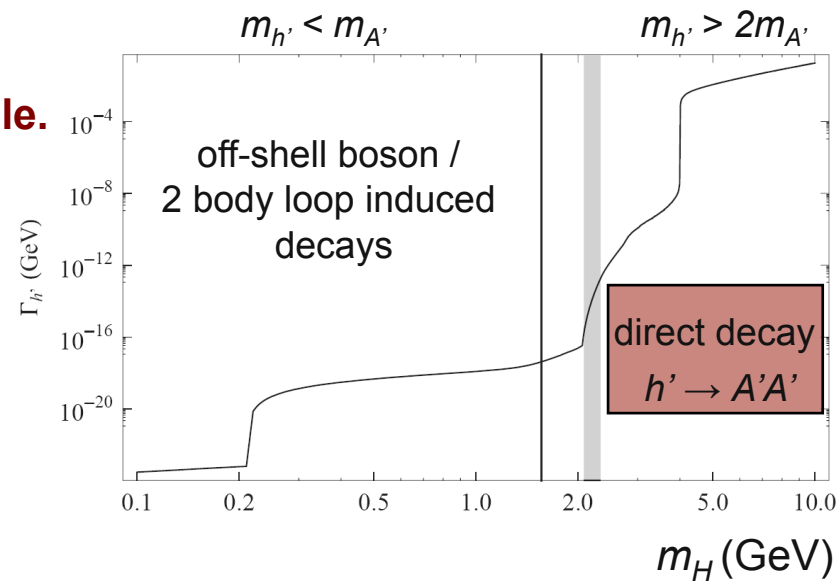
- Dark boson mass is generated via the Higgs mechanism, **adding a dark Higgs boson (*h*') to the theory.**
- A **minimal scenario** has a **single dark photon and a single dark Higgs boson**.
- The **dark Higgs mass** could be at **the GeV scale.**
- The **Higgs'-strahlung process**

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

  is very interesting, as it is **only suppressed by ε^2** and is expected to have a **very small background.**

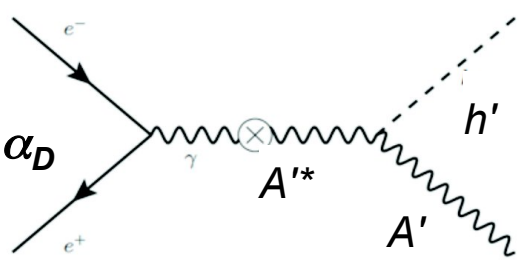
B. Batell et al., PRD 79 (2009) 115008
R. Essig et al., PRD 80 (2009) 015003

Higgs decay kinematics



displaced / invisible decay prompt decay

$\sigma \sim \varepsilon^2 \alpha_D$



$\alpha_D = g_D^2 / 4\pi$

g_D is the dark sector gauge coupling

Search for a low-mass "dark" Higgs boson: $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

Fully reconstructed	*Partially reconstructed*
$e^+e^- \rightarrow h' A' \rightarrow A' A' A'$ with $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$	$e^+e^- \rightarrow h' A_1', h' \rightarrow A_2' A_3'$ $A'_{1,2} \rightarrow e^+e^-, \mu^+\mu^-$, $A'_3 \rightarrow X$ + perm.

Fully reconstructed signal

- Three dark photons fully reconstructed

Modes included

- $e^+e^- \rightarrow (l^+l^-)\ (l^+l^-)\ (l^+l^-)$ $l=e,\mu$
- $e^+e^- \rightarrow (l^+l^-)\ (l^+l^-)\ (\pi^+\pi^-)$
- $e^+e^- \rightarrow (l^+l^-)\ (\pi^+\pi^-)\ (\pi^+\pi^-)$

Selection

- 6 tracks with an invariant mass $m_{tot} > 0.95\ \sqrt{s}$
- apply particle identification
- cosine helicity angle of $A' \rightarrow e^+e^-$ candidates < 0.9
- three dark photon candidates have similar mass

Partially reconstructed signal

- In the high mass region (m_A > 1.2 GeV), the decay of the dark photon is dominated by $A' \rightarrow q\bar{q}$
- Measure 2 A' decaying to leptons and 1 A' to $q\bar{q}$
- Reconstruct four-momentum $P_3 = P_{ee} - P_1 - P_2$

Modes included

- $e^+e^- \rightarrow (l^+l^-)\ (\mu^+\mu^-) + X$ where X is not l^+l^- / $\pi^+\pi^-$

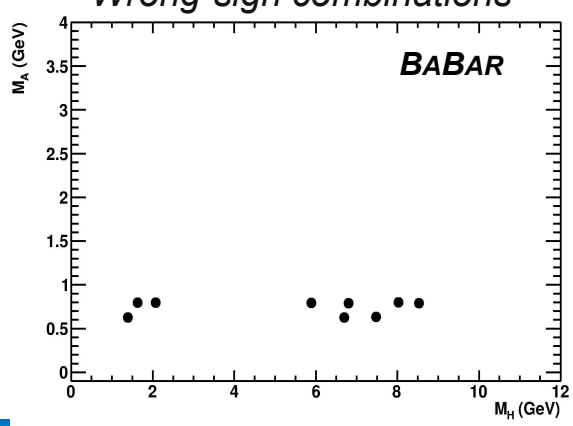
Selection

- 4 or more tracks
- apply particle identification for $A' \rightarrow l^+l^-$ decays
- cosine helicity angle of $A' \rightarrow e^+e^-$ candidates < 0.9
- three dark photon candidates have similar mass

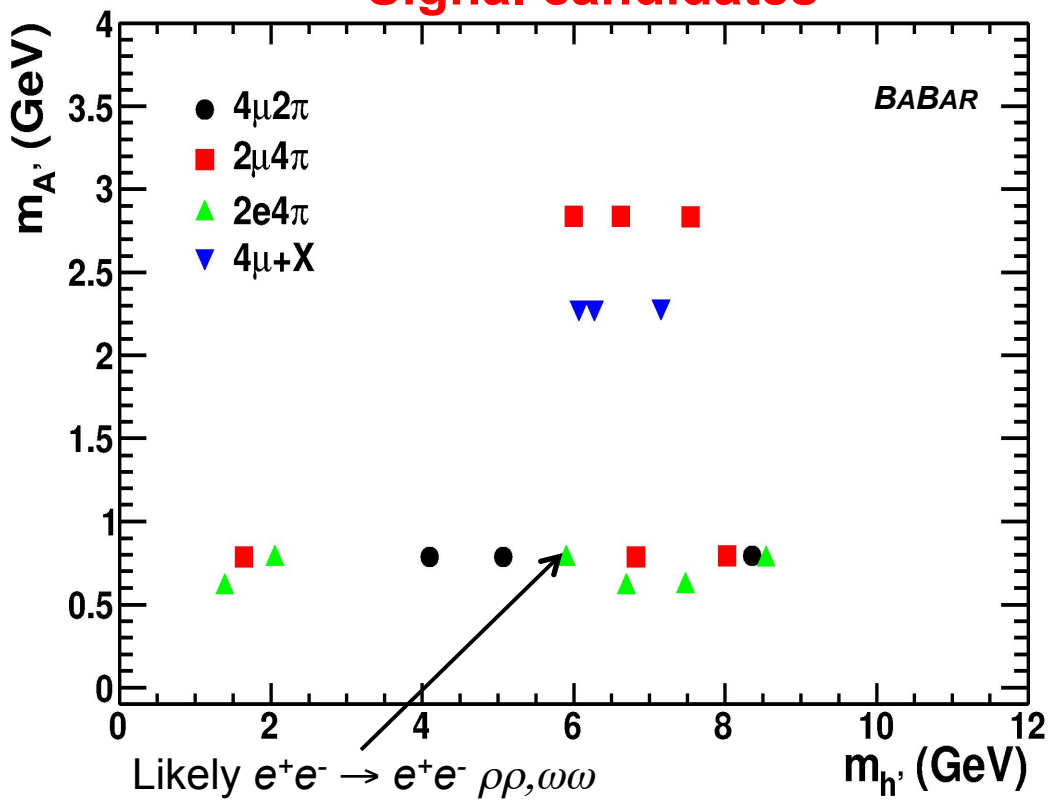
Search for a low-mass "dark" Higgs boson: $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

- *Six* events are selected from the full BABAR dataset (517 fb^{-1})
- Three entries for each event corresponding to the three possible assignments of the $h' \rightarrow A'A'$ decay
- Estimate background from wrong-sign combinations, *e.g.*
  $e^+e^- \rightarrow (e^+e^+)\ (e^-e^-)\ (\mu^+\mu^-)$
  - sidebands from final sample
  - rate for 6 leptons ~ 100x rate for $4\pi+2l$ *above 1.5 GeV*

Wrong-sign combinations



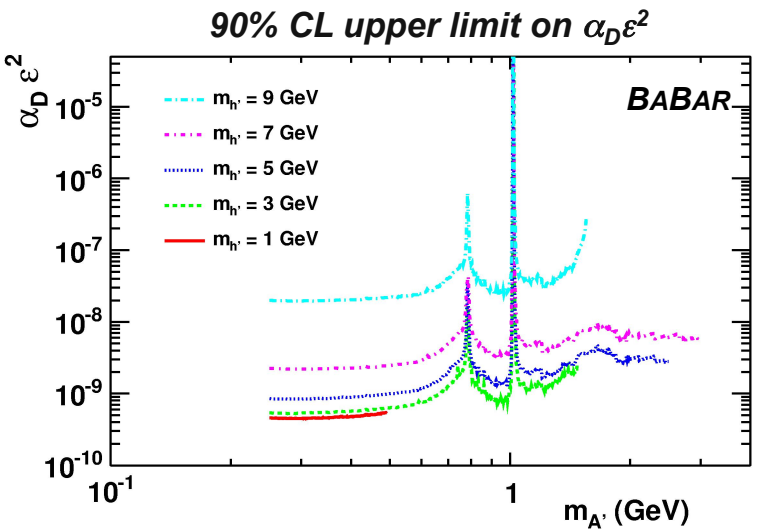
Signal candidates

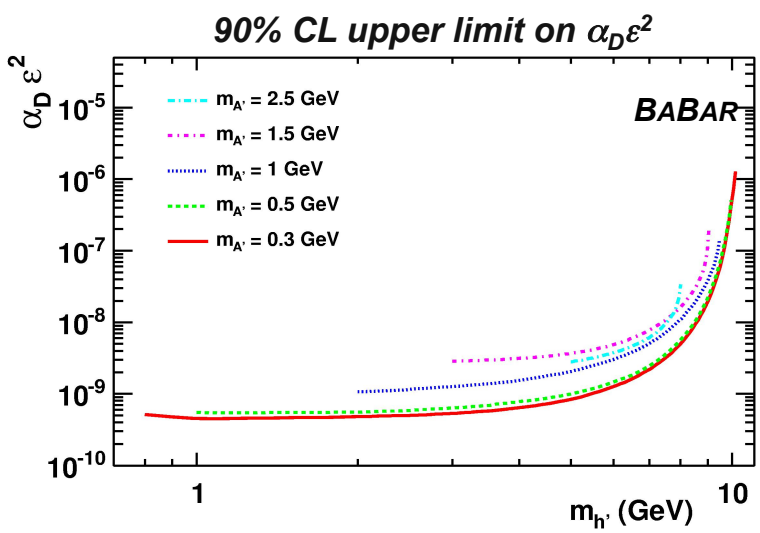


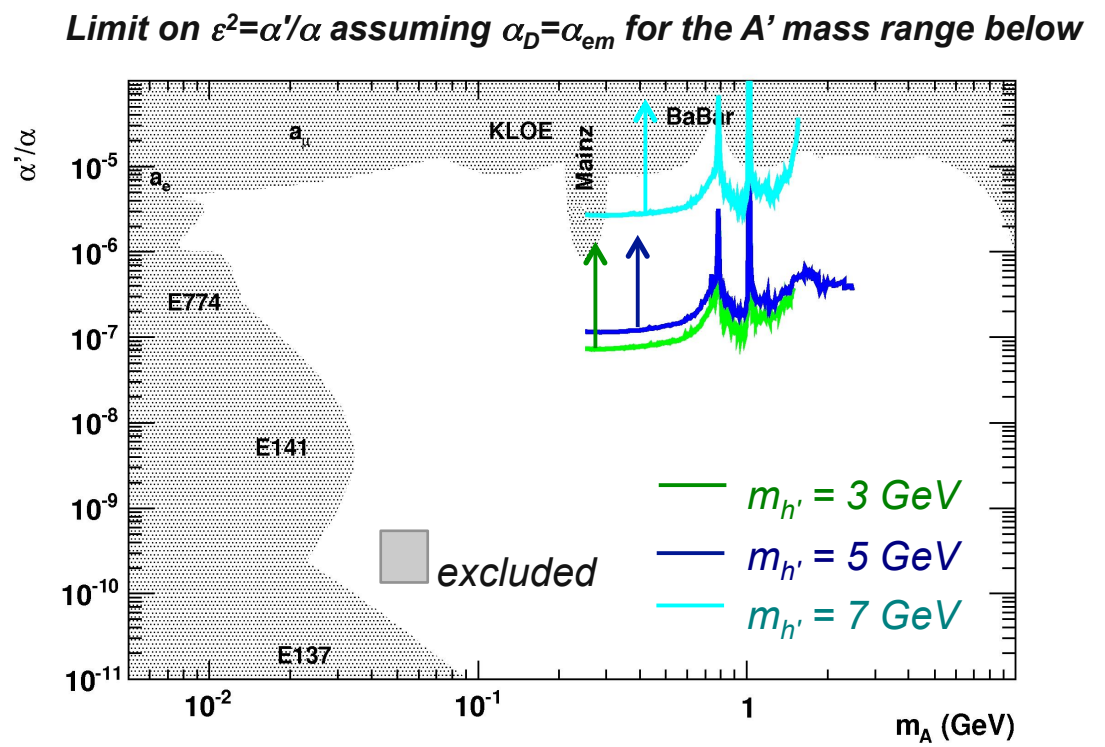
Likely $e^+e^- \rightarrow e^+e^-\ \rho\rho,\omega\omega$
or $e^+e^- \rightarrow 6\pi$

No events with 6 leptons, consistent with the pure background hypothesis

Search for a low-mass "dark" Higgs boson: $A' \rightarrow e^+e^-, \mu^+\mu^-, \pi^+\pi^-$







Substantial improvement over existing limits for $m_{A'}$ < 5 - 7 GeV if low-mass dark Higgs boson exists

3) Updated search for invisible decays of the B^0

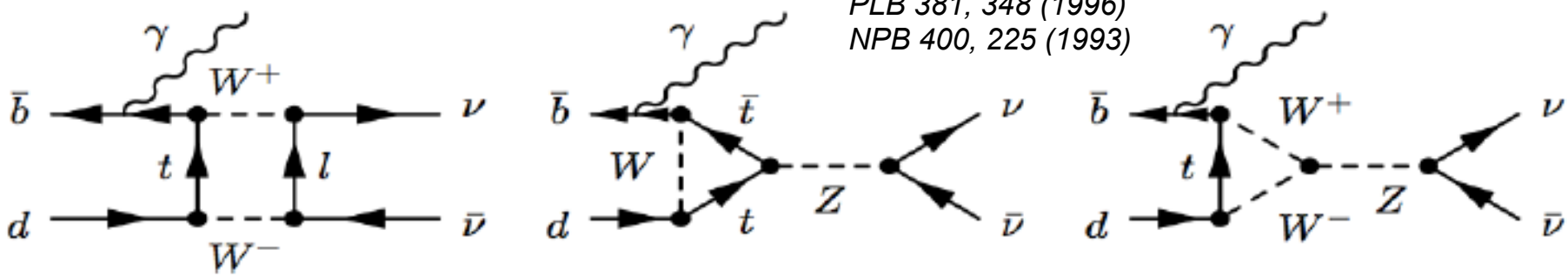
to be submitted to PRD

Updated search for invisible decays of the B^0

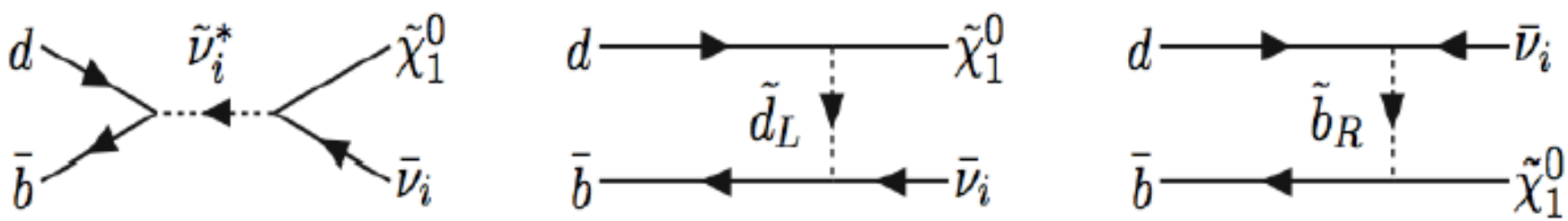
- Invisible decay products include neutrinos as well as exotic particles

- The SM $B^0 \to \nu\nu$ decay is suppressed by a factor $(m_\nu/m_B)^2$ while the BF($B^0 \to \nu\nu\gamma$) is of the order of 10^{-9}

A. Badin and A. Petrov, PRD 82, 034005 (2010)
PLB 381, 348 (1996)
NPB 400, 225 (1993)



- In SUSY model **BR($B^0 \to$ Invisible)** is enhanced up to **10^{-7}-10^{-6}** due to neutrino+neutralino production in the final state



A. Dedes, H. Dreiner, and P. Richardson, hep-ph/0106199, Phys. Rev.D65, 015001 (2001)

Updated search for invisible decays of the B^0

- Update of a Recoil analysis performed on Runs 1+2 with Semileptonic Tag (~88.5fb^{-1})

$$\mathcal{B}(B^0 \to \text{invisible}) < 22 \times 10^{-5}$$

$$\mathcal{B}(B^0 \to \nu\bar{\nu}\gamma) < 4.7 \times 10^{-5}$$

B. Aubert et al., Phys.Rev.Lett.93:091802,2004

- Semileptonic Tag:
  - reconstruct events in which a B^0 decays to $D^{(*)-}l^+\nu$ ("tag side"), then look for consistency with an invisible(+γ) decay of the other neutral B ("signal side")

$B^0 \to D^- l\nu$

$D^- \to K^+\pi^-\pi^-$

$D^- \to K_S\pi^-$

$B^0 \to D^{*-} l\nu$

$D^{*-} \to D^0\pi^-, D^-\pi^0$

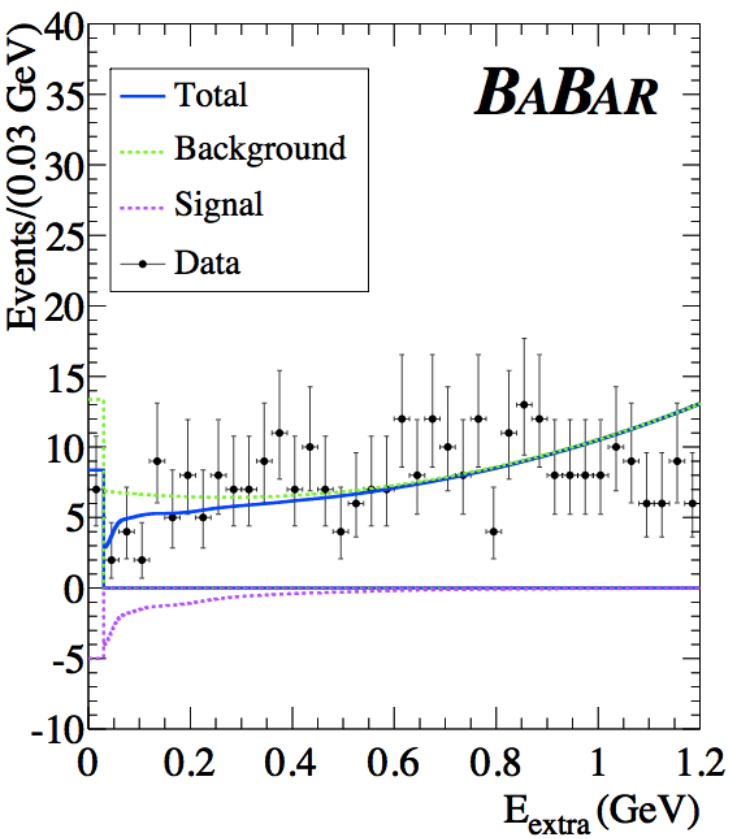
$D^0 \to K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$

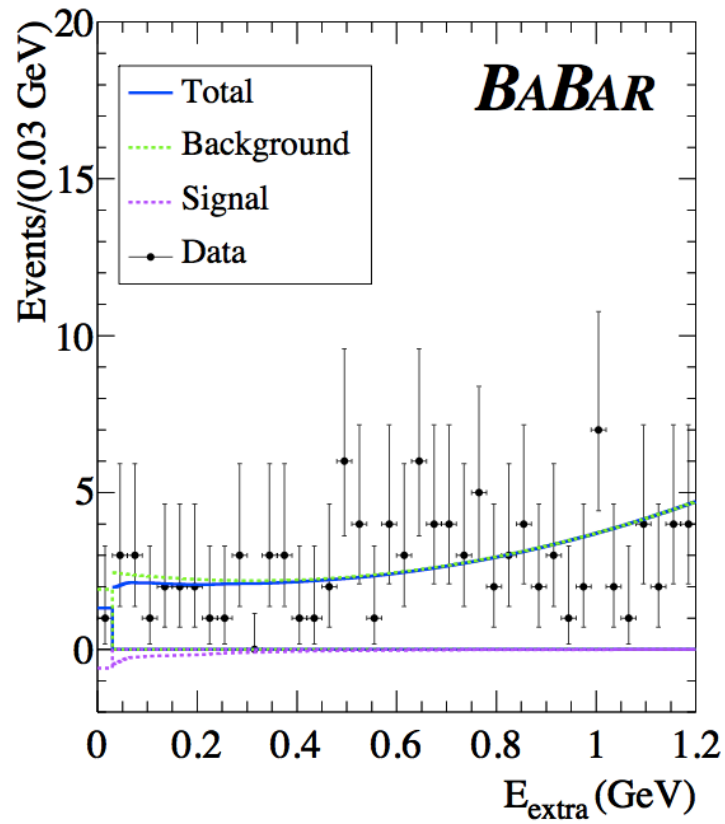
Updated search for invisible decays of the B^0

472 x 10^6 B^0

- **90% CL upper limits on branching fractions:**

$B^0 \rightarrow$ invisible: 2.4×10^{-5} $B^0 \rightarrow$ invisible + γ : 1.7×10^{-5}





to be submitted to PRD

4) Evidence (!) for an unexplained excess of

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

arXiv:1205.5442,
submitted to PRL

Evidence for an excess of $B \to D^{(*)}\tau\nu$

- S.L. decays involving a τ have an additional helicity amplitude (for $D^*\tau\nu$):

$$\frac{d\Gamma_\tau}{dq^2} = \frac{G_F^2|V_{cb}|^2|\mathbf{p}|q^2}{96\pi^3 m_B^2}\left(1-\frac{m_\tau^2}{q^2}\right)^2\left[\left(|H_{++}|^2+|H_{--}|^2+|H_{00}|^2\right)\left(1+\frac{m_\tau^2}{2q^2}\right)+\frac{3}{2}\frac{m_\tau^2}{q^2}|H_{0t}|^2\right]$$

For $D\tau\nu$, only H_{00} and H_t contribute!

- To test the SM prediction, we measure

$$R(D) = \frac{Y(\overline{B} \to D\tau\nu)}{Y(\overline{B} \to D\ell\nu)} \qquad R(D^*) = \frac{Y(\overline{B} \to D^*\tau\nu)}{Y(\overline{B} \to D^*\ell\nu)}$$

Only leptonic τ decays used

Several experimental and theoretical uncertainties cancel in the ratio!

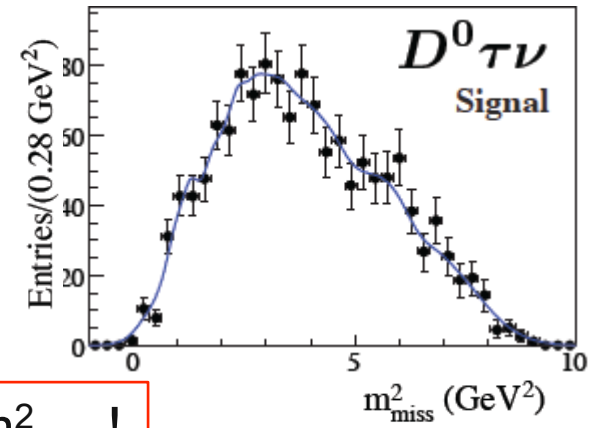
- $B\overline{B}$ events are fully reconstructed:
  - hadronic B tag (tagging efficiency improved 2x)
  - reconstruction of $D^{(*)}$ and e or μ (extended to lower momenta)
  - no additional charged particles
  - kinematic selections: $q^2 > 4$ GeV^2

  Background suppression by BDT (combinatorial and $D^{**}l\nu$)

- Full BABAR data sample, MC correction based on data control samples

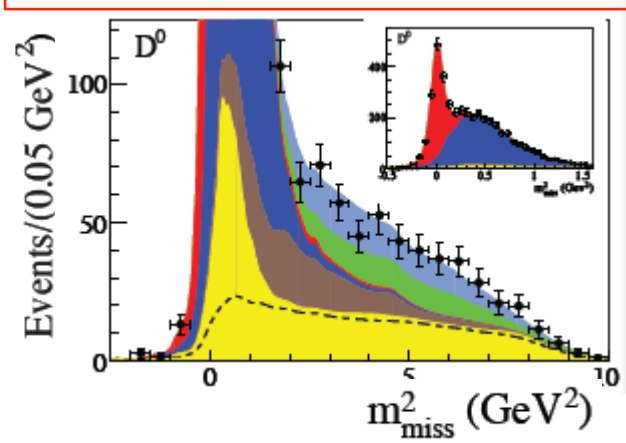
Evidence for an excess of $B \to D^{(*)}\tau\nu$

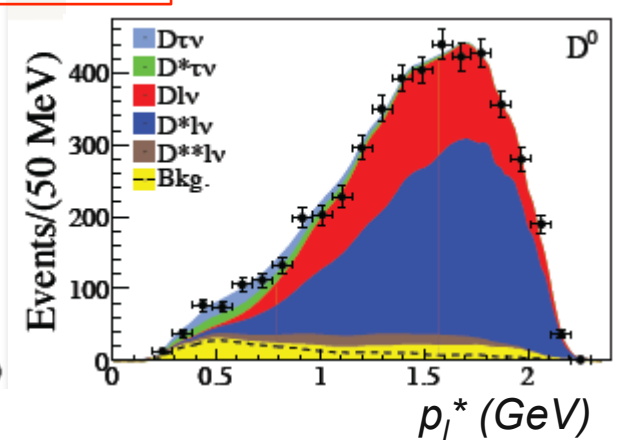
- Unbinned M.L. fit
  - 2-distributions: $m^2_{miss} = (P_{ee} - P_{Btag} - P_{D(*)} - P_\ell)^2$ Missing mass squared; p^*_ℓ (≡ lepton momentum in B rest frame)
- 4 signal samples: D^0l, $D^{*0}l$, D^+l, $D^{*+}l$, ($l=e^\pm$ or $\mu^\pm$)
- $4D^{(*)}\pi^0 l\nu$ control samples



- PDFs from MC (approximated by KEYS prob. dist.)
- Fitted Yields
  - 4 $D^{(*)}\tau\nu$ Signal
  - 4 $D^{(*)}l\nu$ Normalization
  - 4 $D^{**}l\nu$ Background
- Fixed Backgrounds
  - B^0–B^+ cross feed
  - $B\bar{B}$ combinatorial Bg
  - Continuum $e^+e^- \to ff(\gamma)$

$D^{(*)}\tau\nu$ signal is at larger m^2_{miss}!





(MC simulation)

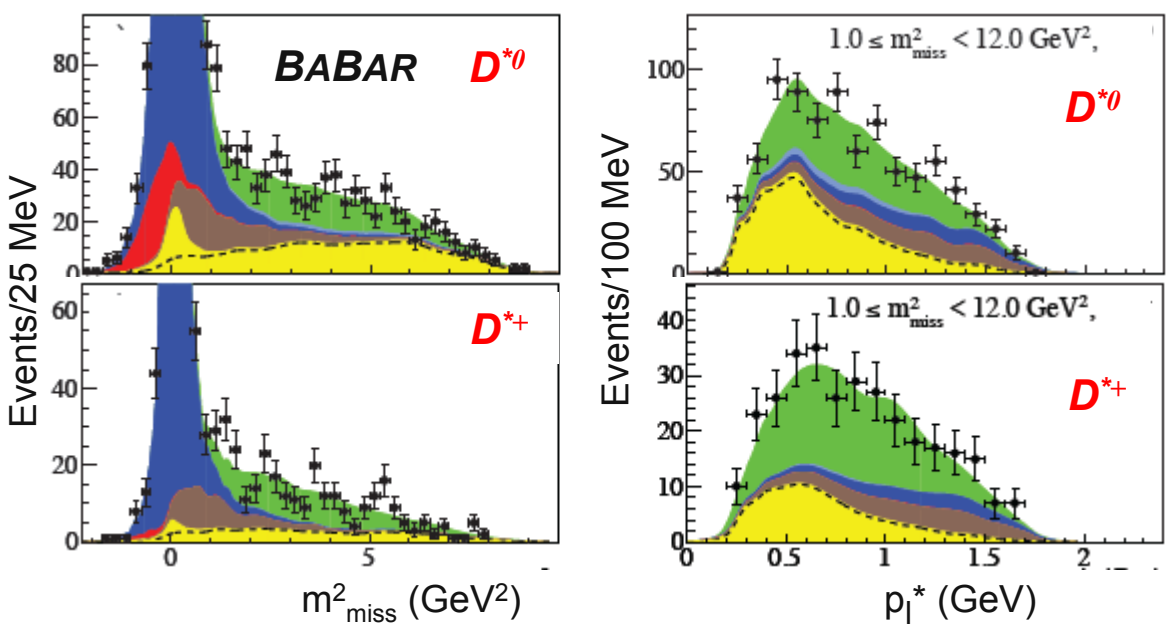
Evidence for an excess of $B \to D^{(*)}\tau\nu$

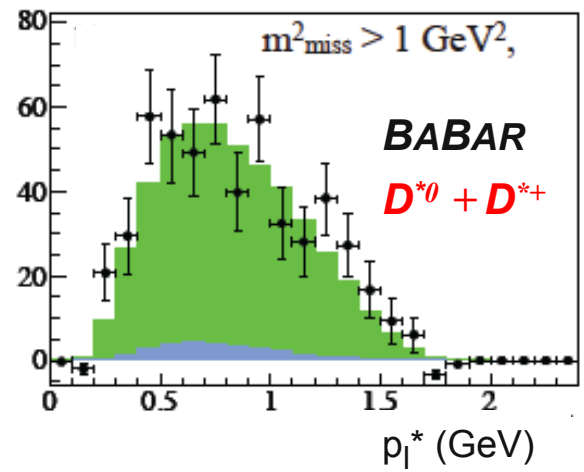
BABAR arXiv:1205.5442, submitted to PRL

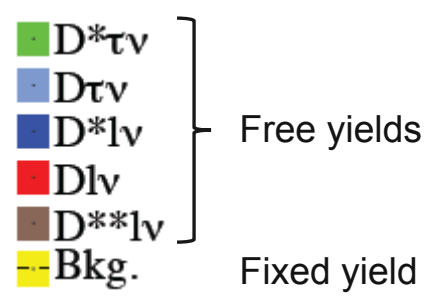
	$D^{*0}\tau\nu$	$D^{*+}\tau\nu$	$D^{*}\tau\nu$
$N_{\rm sig}$	639 ± 62	245 ± 27	888 ± 63
Significance (σ)	11.3	11.6	16.4
$R(D^*)$	0.322 ± 0.032	0.355 ± 0.039	0.332 ± 0.024

Statistical errors only

Isospin constrained





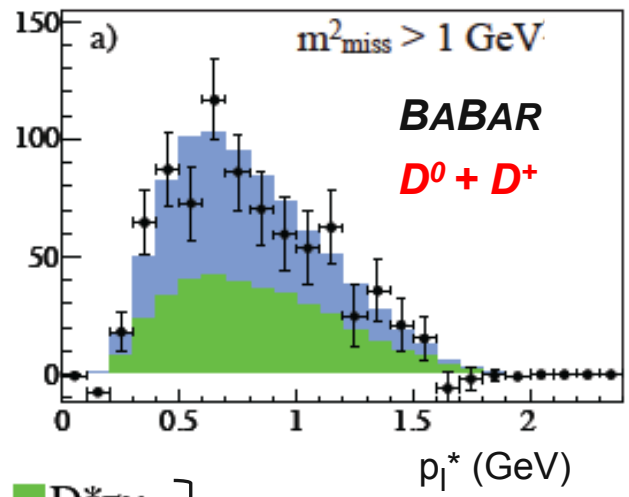


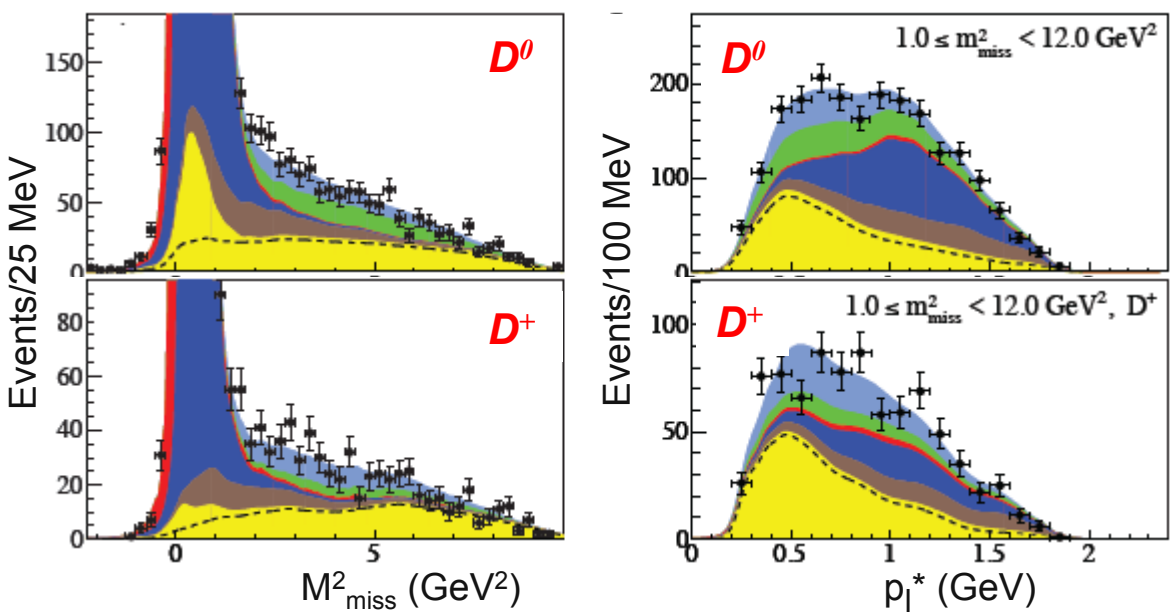
Evidence for an excess of $B \to D^{(*)}\tau\nu$

BABAR arXiv:1205.5442, submitted to PRL

	$D^0\tau\nu$	$D^+\tau\nu$	$D\tau\nu$
$N_{\rm sig}$	314 ± 60	177 ± 31	489 ± 63
Significance (σ)	5.5	6.1	8.4
$R(D)$	0.429 ± 0.082	0.469 ± 0.084	0.440 ± 0.058

Statistical errors only





$D^*\tau\nu$
$D\tau\nu$
$D^*l\nu$
$Dl\nu$
$D^{**}l\nu$
Bkg.

Free yields

Fixed yield

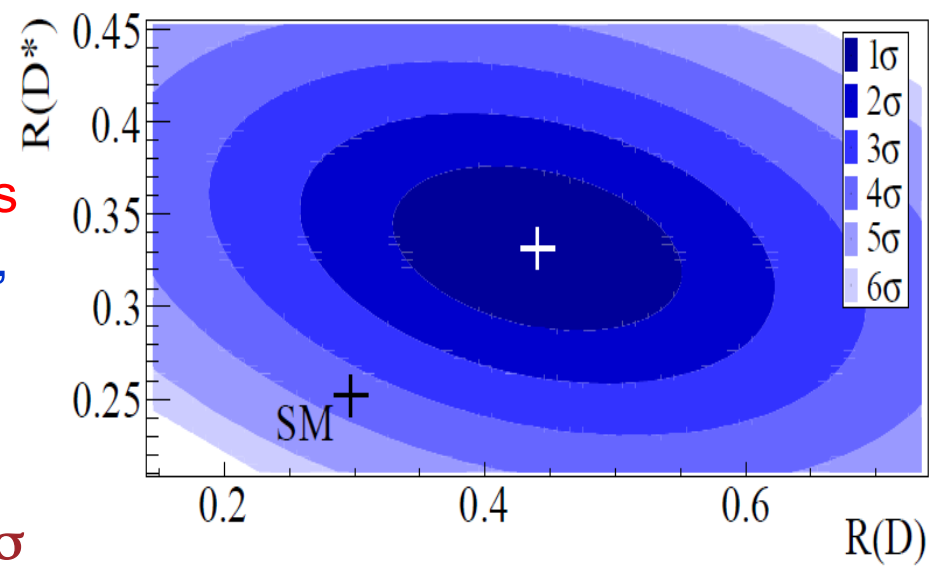
Evidence for an excess of $B \to D^{(*)}\tau\nu$

Comparison with SM calculation::

	R(D)	R(D*)
BABAR	0.440 +/- 0.071	0.332 +/- 0.029
SM	0.293 +/- 0.017	0.252 +/- 0.003
Difference	**2.0 σ**	**2.7 σ**

SM calculations in:
Z. Phys. C46, 93 (1990)
PRD 78, 0156006 (2008)
PRD 85, 094025 (2012)
and recent updates

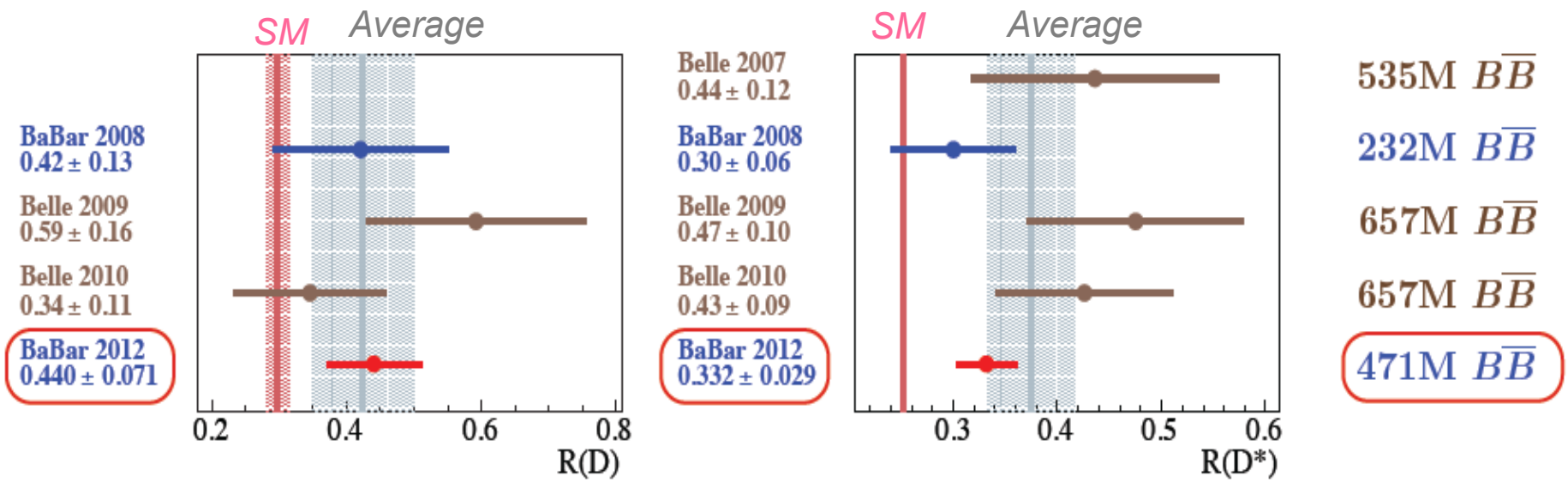
The combination of the two measurements (-0.27 correlation) yields χ^2/NDF = 14.6/2, i.e. prob. = 6.9 x 10^{-4} !!



Thus SM prediction is excluded at 3.4 σ

arXiv:1205.5442, submitted to PRL

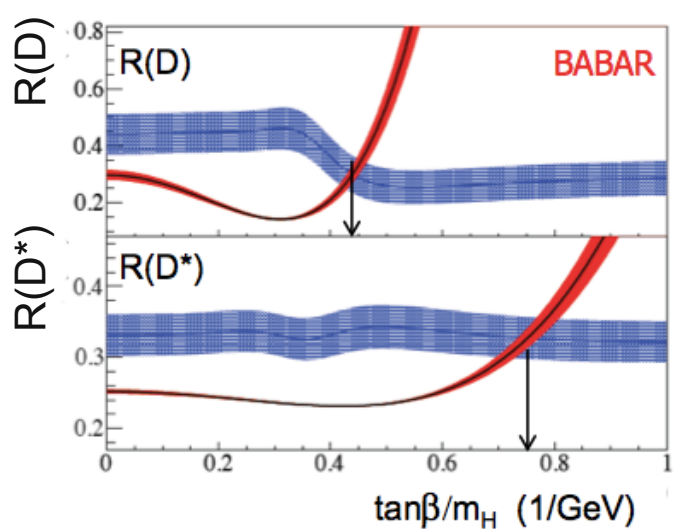
Evidence for an excess of $B \to D^{(*)}\tau\nu$



The new measurements are fully compatible with earlier results

NB: The average above does not include this measurement.

… and also exclude a type-II 2HDM.



BABAR arXiv:1205.5442, submitted to PRL

Summary

1) Search for lepton flavour violation:
$B^{\pm} \to h^{\pm}\tau\ell$

O(10^{-5}) upper limits on BFs

5x improvement on bounds for the energy scale of new flavor-changing physics

arXiv:1204.2852, submitted to PRD

2) Search for a low-mass "dark" Higgs boson: $A' \to e^+e^-, \mu^+\mu^-, \pi^+\pi^-$

arXiv:1202.1313, accepted by PRL

Exclusion of a large fraction of the phase-space for such theories

3) Updated search for **invisible** decays of the B^0

An order of magnitude improvement on upper limits

about to be submitted to PRD

4) **Evidence** (!) for an excess of $B \to D^{(*)}\tau\nu$

3.4 σ excess above SM expectation!!!

arXiv:1205.5442, submitted to PRL

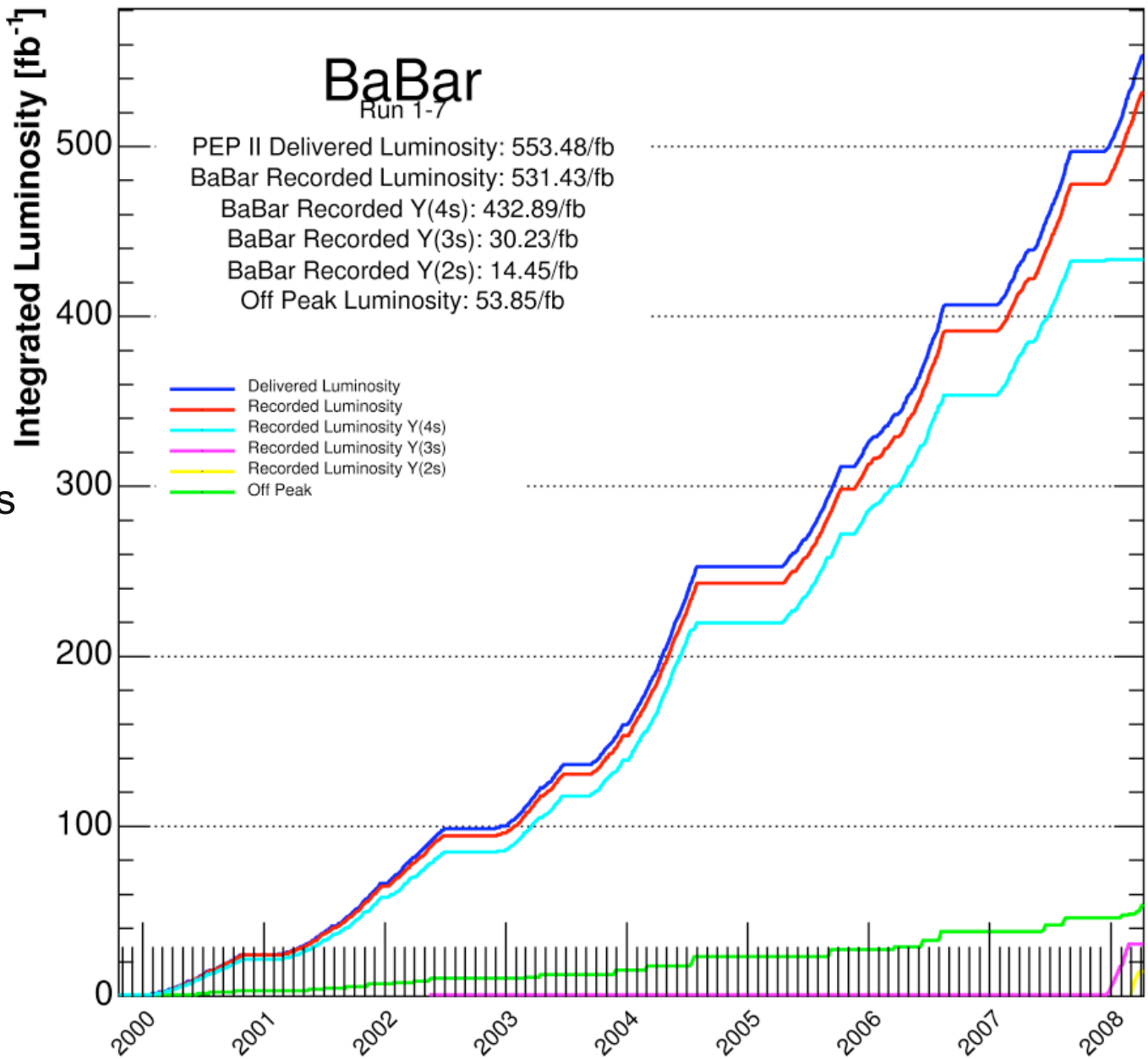
Backup Slides

The BaBar Dataset

sample	fb^{-1}
$\Upsilon(4S)$	430
$\Upsilon(3S)$	30.2
$\Upsilon(2S)$	14.5
Off-$\Upsilon(nS)$	54

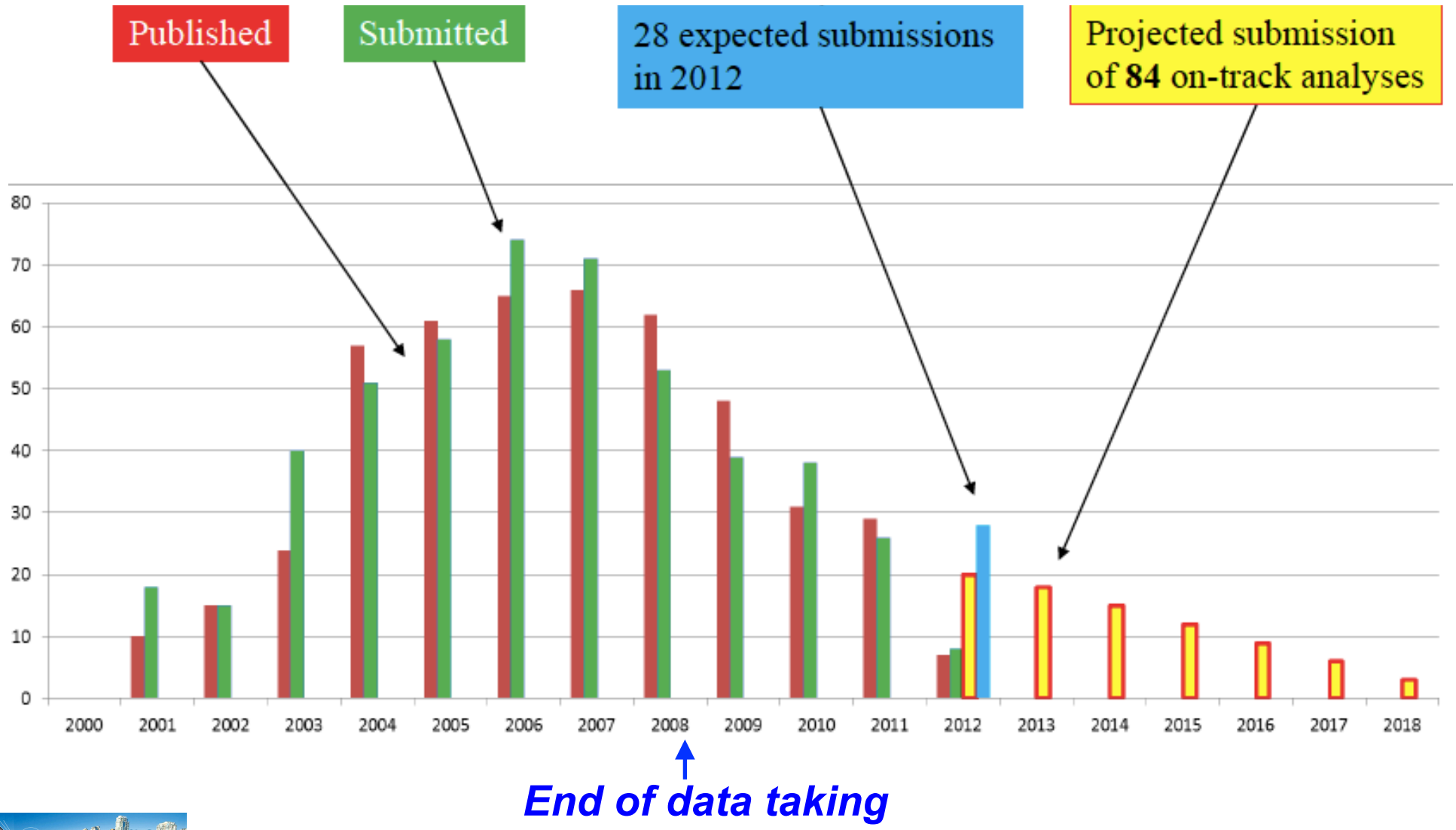
- **472** million neutral *B*
- **472** million charged *B*
- **690** million *c* anti-*c* pairs
- **500** million $\tau^+\tau^-$ pairs
- **117** million Υ(3S)
- **93** million Υ(2S)

➢ ***Data taking ended 4 years ago…***



The BaBar Science Output

- ***… but the physics sure hasn't ended!***



3) Search for a low-mass *CP*-odd Higgs boson:

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

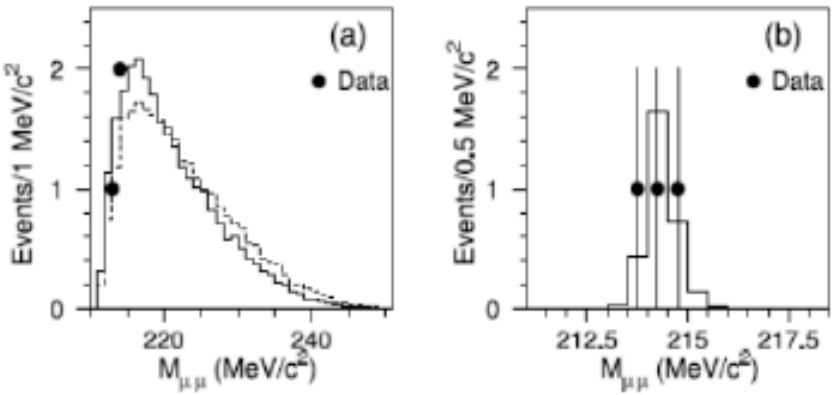
Preliminary !

Search for a low-mass *CP*-odd Higgs boson: $A^0 \rightarrow \mu^+\mu^-$

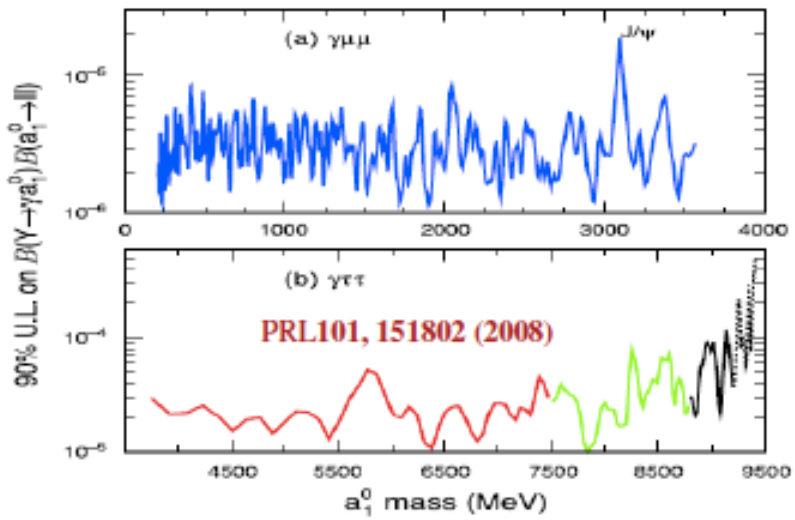
❖ Experimental constraints

➢ HyperCP Anomaly

- Observed three anomalous events in $\Sigma \rightarrow p\mu^+\mu^-$ the near threshold ($m_{\mu\mu}$ = 214 MeV). [PRL94, 021801 (2005)]
- Interpreted as CP-odd light Higgs boson.

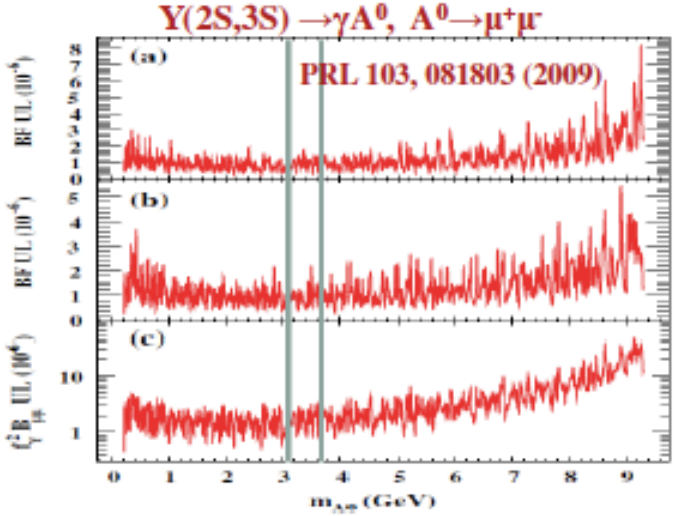


➢ CLEO collaboration



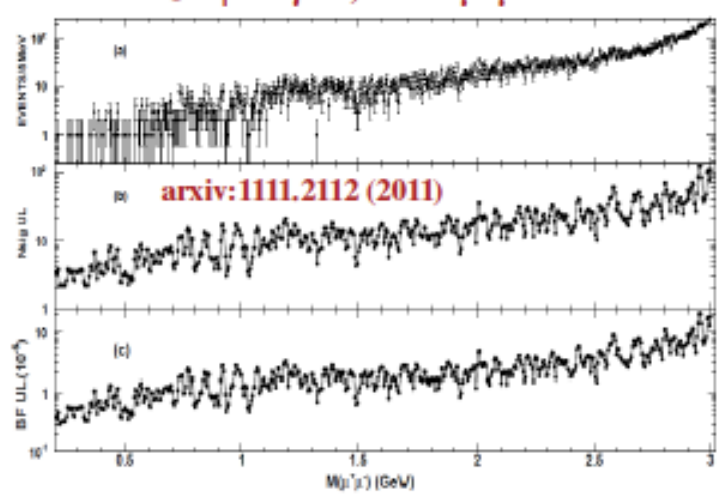
➢ BaBar collaboration

Υ(2S,3S) →γA⁰, A⁰→μ⁺μ⁻

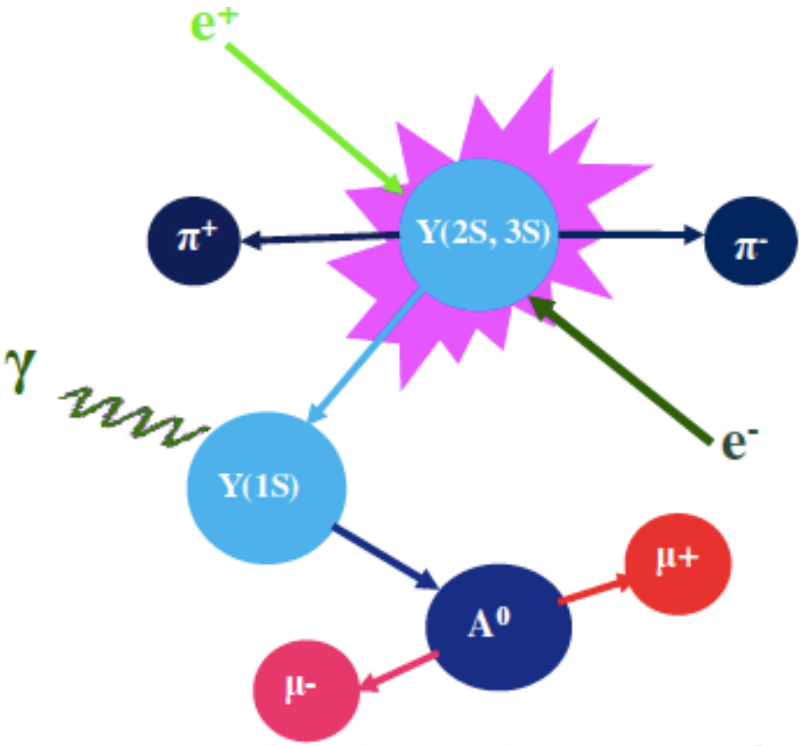


➢ BESIII collaboration

J/ ψ →γA⁰, A⁰→μ⁺μ⁻

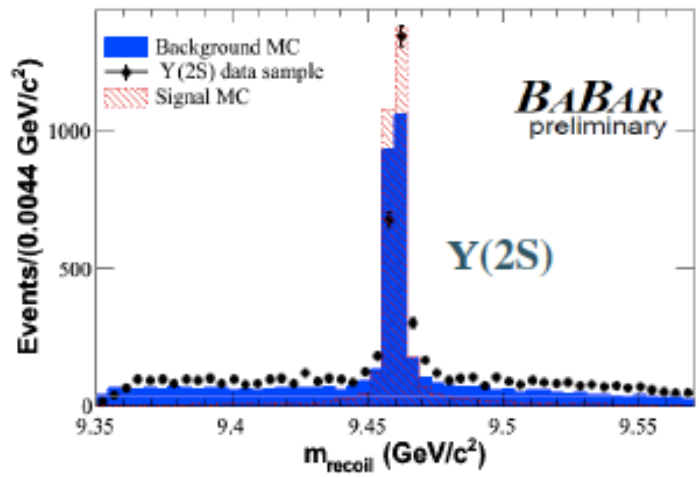


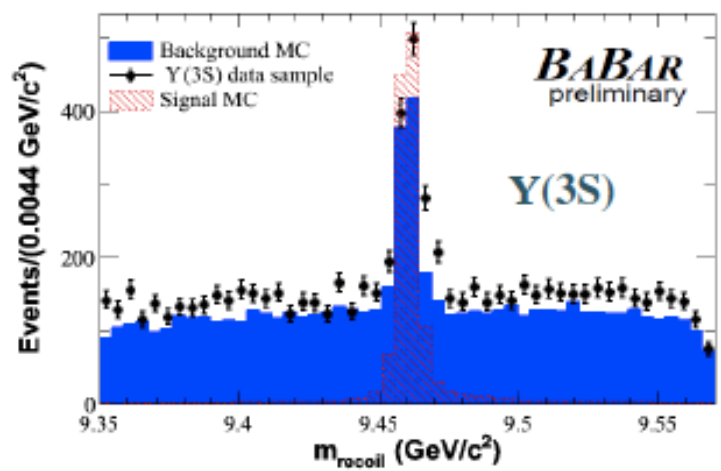
Search for a low-mass *CP*-odd Higgs boson: $A^0 \rightarrow \mu^+\mu^-$: Event Reconstruction



Di-pion recoil mass:

$$m^2_{recoil} = S + m^2_{\pi^+\pi^-} - 2\sqrt{S}E_{\pi^+\pi^-}$$





- Reconstruct the decay chain using four charged tracks and a photon with minimum center of mass energy of 0.2 GeV , while allowing photons with CM energy below this threshold to be present.
- We also require trigger and Filter in the decay channel
- Use 5% of Υ(2S,3S) onpeak data-sets to check the agreement between data and MC at skim level.

Search for a low-mass *CP*-odd Higgs boson: $A^0 \to \mu^+\mu^-$

- Set a 90% C.L. upper limit on the branching ratio (B.R.) of $\mathcal{B}(\Upsilon(1S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \mu^+\mu^-))$ in the mass range of $0.212 \le m_{A^0} \le 9.20$ GeV/c^2 using Bayesian approach.