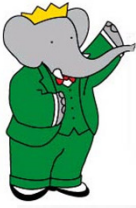


Some Recent Results from *BABAR*

Abi Soffer

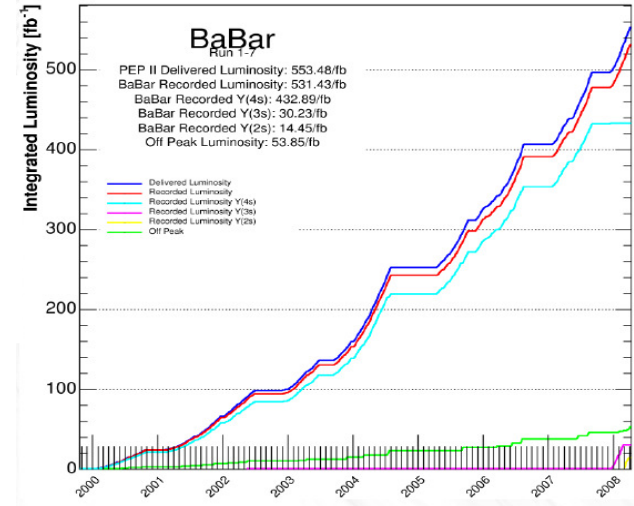
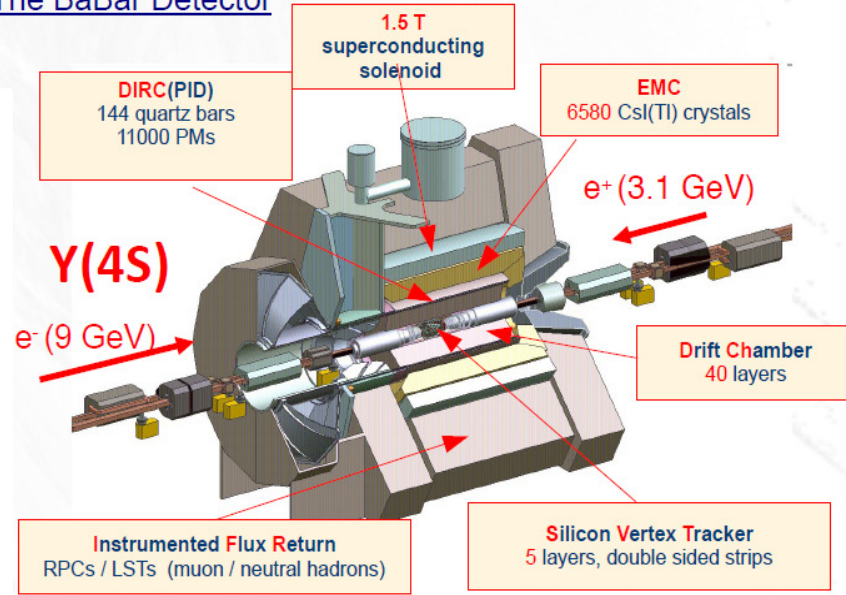
Tel Aviv Univ., SLAC

SLAC seminar, Sep 6, 2012



BABAR overview

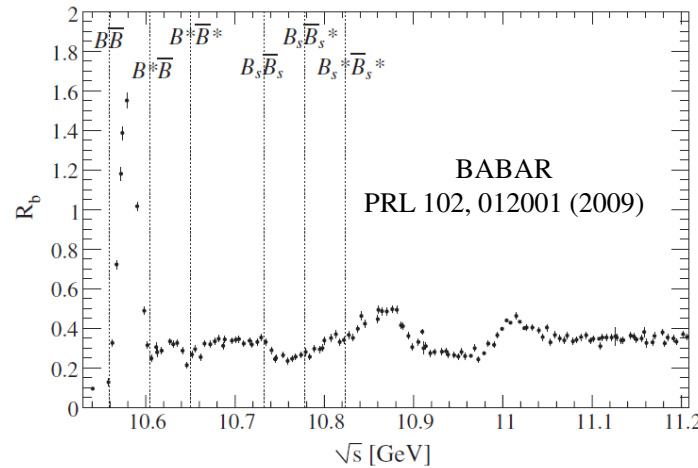
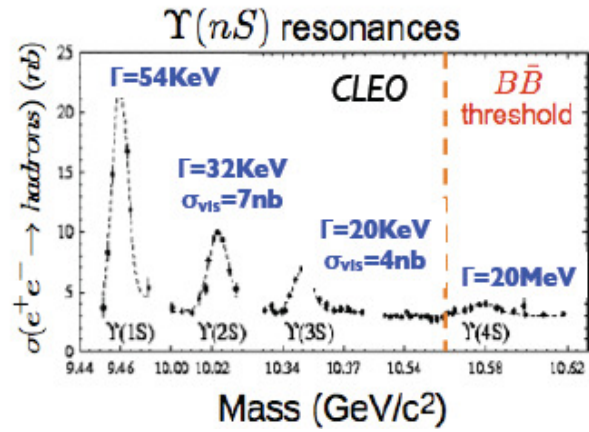
The BaBar Detector

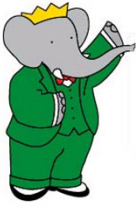


$$L(4S) = 424 \text{ fb}^{-1} \quad N(4S) = 471 \text{ M}$$

$$L(3S) = 28 \text{ fb}^{-1} \quad N(3S) = 121 \text{ M}$$

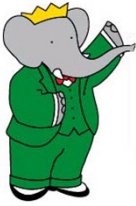
$$L(2S) = 14 \text{ fb}^{-1} \quad N(2S) = 99 \text{ M}$$





Publications statistics

- 491 papers published or accepted (mostly PRL and PRD, 1 NIM)
- Additional 15 recently submitted
- In 2012:
 - 20 published
 - 23 submitted
 - 6–10 on track for submission this year
 - Compare: 26 submitted in 2011 and 38 in 2010.
 - So far over 130 conference talks
 - 15 @ ICHEP (similar to LHCb & large ATLAS/CMS groups)
- Projection for the future:
 - 70 analyses are on-track for submission in coming years
 - Of these 12 started in 2012, almost all are new ideas

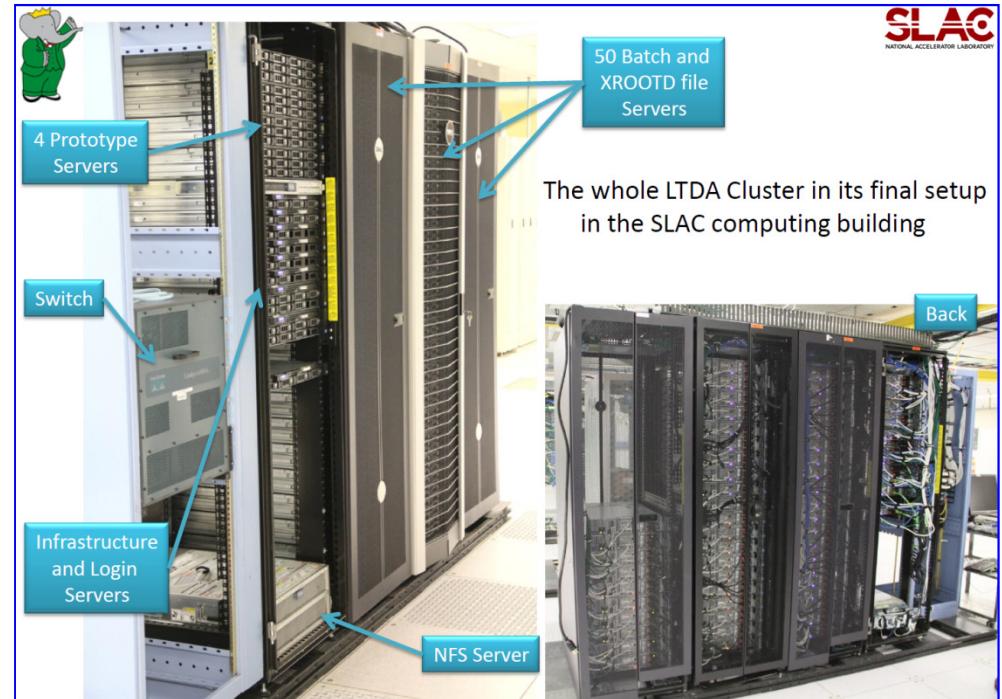


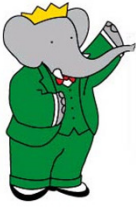
Supporting future analyses

Long-Term Data Access system

- Supports computing needs until at least 2018
- Frozen software release and operating system, isolated from the environment for security
- Ability to create virtual machines with older releases/OS
- In operation since March
- Most advanced of HEP “data preservation” projects

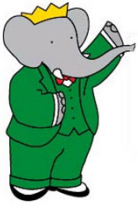
Renewed documentation



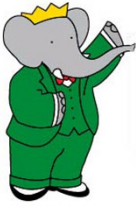


Results covered here

- Direct observation of time-reversal violation
 - [arXiv:1207.5832](#) submitted to PRL
- Search for light Higgs
 - [PRL107, 221803 \(2011\)](#)
 - 2 preliminary results presented @ ICHEP, soon submitted to PRD-RC
- Search for dark Higgs and dark photon
 - [PRL 108, 211801 \(2012\)](#)
- Search for $B \rightarrow \text{invisible}$
 - [arXiv:1206.2543](#) submitted to PRD-RC
- Won't cover $B \rightarrow D^{(*)} \tau \nu$
 - Seminar by Manuel Franco Sevilla
 - Now accepted by PRL, [arXiv:1205.5442](#)

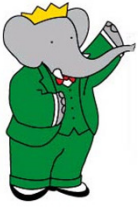


Direct observation of T violation



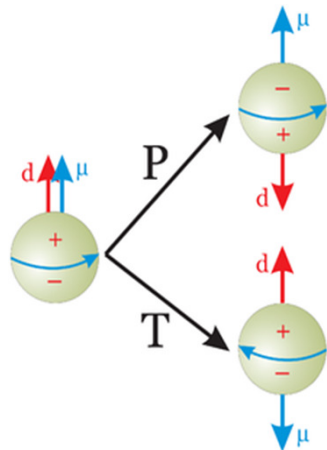
T, CP, and CPT

- CP violation has been well established
- The CPT theorem:
 - A QFT with local Lorentz invariance and a Hermitian Hamiltonian conserves CPT
 - “Where there’s CP violation there’s T violation”
 - Stringent experimental constraints on CPT violation
- But can TV be directly observed, independently of CPV?

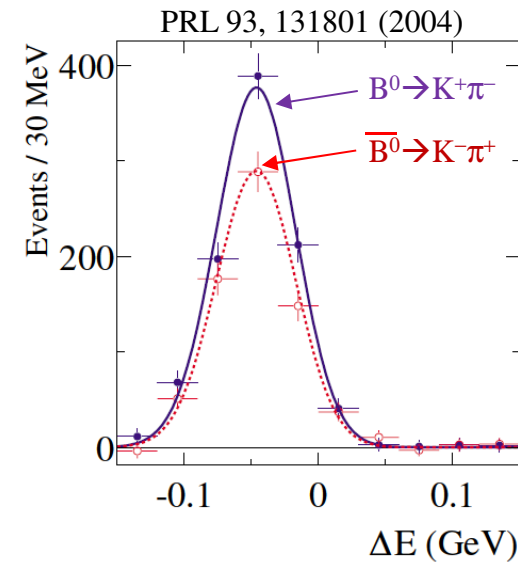


Ways to measure TV

Electric dipole moment
(tight EDM limits exist)



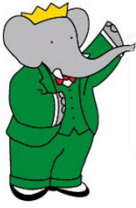
BABAR & Belle see CPV in $B \rightarrow K\pi$:



Can we observe $K\pi \rightarrow B$?

No: $\sigma(K\pi \rightarrow \text{hadrons}) \gg \sigma(K\pi \rightarrow B)$

Essentially all other measurements use observables that are not only T violating but also CP violating, so the measurement is not CP- & CPT-independent.



Results in PDG

e electric dipole moment

μ electric dipole moment

μ decay parameters

transverse e^+ polarization normal to plane of μ spin, e^+ momentum

α'/A

β'/A

$\text{Re}(d_\tau = \tau$ electric dipole moment)

P_T in $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$

P_T in $K^+ \rightarrow \mu^+ \nu_\mu \gamma$

$\text{Im}(\xi)$ in $K^+ \rightarrow \pi^0 \mu^+ \nu_\mu$ decay (from transverse μ pol.)

asymmetry A_T in $K^0\text{-}\bar{K}^0$ mixing

$\text{Im}(\xi)$ in $K_{\mu 3}^0$ decay (from transverse μ pol.)

$A_T(D^\pm \rightarrow K_S^0 K^\pm \pi^+ \pi^-)$

$A_T(D^0 \rightarrow K^+ K^- \pi^+ \pi^-)$

$A_T(D_S^\pm \rightarrow K_S^0 K^\pm \pi^+ \pi^-)$

p electric dipole moment

n electric dipole moment

$n \rightarrow p e^- \bar{\nu}_e$ decay parameters

ϕ_{AV} , phase of g_A relative to g_V

triple correlation coefficient D

triple correlation coefficient R

Λ electric dipole moment

triple correlation coefficient D for $\Sigma^- \rightarrow n e^- \bar{\nu}_e$

$<10.5 \times 10^{-28}$ ecm, CL = 90%

$(-0.1 \pm 0.9) \times 10^{-19}$ ecm

$(-2 \pm 8) \times 10^{-3}$

$(-10 \pm 20) \times 10^{-3}$

$(2 \pm 7) \times 10^{-3}$

-0.220 to 0.45×10^{-16} ecm, CL = 95%

$(-1.7 \pm 2.5) \times 10^{-3}$

$(-0.6 \pm 1.9) \times 10^{-2}$

-0.006 ± 0.008

$(6.6 \pm 1.6) \times 10^{-3}$

-0.007 ± 0.026

[b] $(-12 \pm 11) \times 10^{-3}$

[b] $(1 \pm 7) \times 10^{-3}$

[b] $(-14 \pm 8) \times 10^{-3}$

$<0.54 \times 10^{-23}$ ecm

$<0.29 \times 10^{-25}$ ecm, CL = 90%

[c] $(180.018 \pm 0.026)^\circ$

[d] $(-1.2 \pm 2.0) \times 10^{-4}$

[d] 0.008 ± 0.016

$<1.5 \times 10^{-16}$ ecm, CL = 95%

0.11 ± 0.10

CPLEAR: PLB 444, 43 (1998)

Compares $K^0 \rightarrow \bar{K}^0$ with $\bar{K}^0 \rightarrow K^0$

Mixing rate.

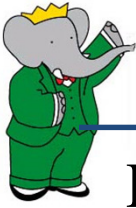
- Related by T and CP.
- Not time-dependent.
- Various criticisms.

BABAR:

PRD(RC)81, 111103 (2010)

PRD(RC) 84, 031103 (2011)

Triple products



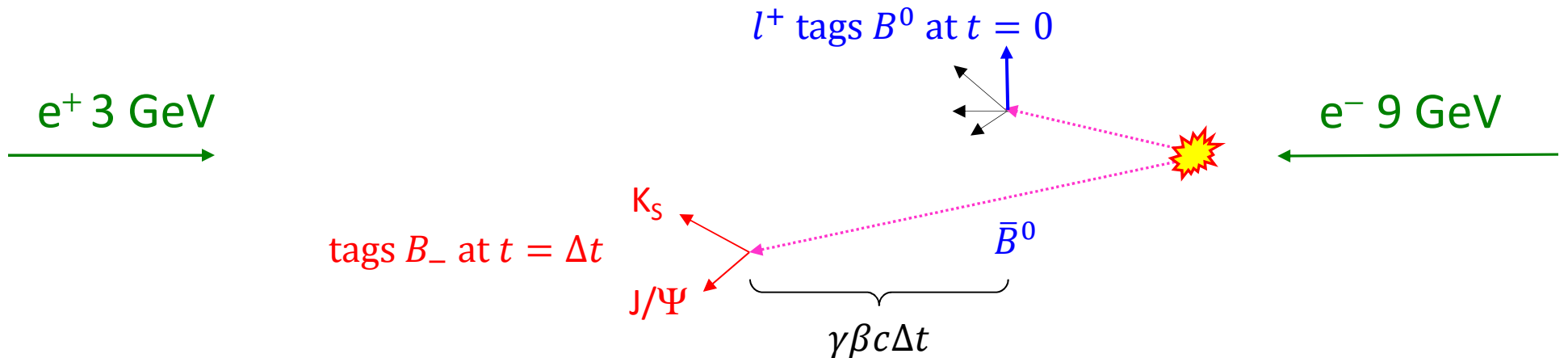
Foundations of the analysis

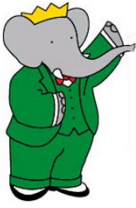
EPR entanglement produced by the decay of the $\Upsilon(4S)$:

$$\begin{aligned}
 |i\rangle &= 1/\sqrt{2}[B^0\bar{B}^0 - \bar{B}^0B^0] \\
 &= 1/\sqrt{2}[B_+B_- - B_-B_+]
 \end{aligned}$$

Flavor states: $\left. \begin{matrix} B^0 \\ \bar{B}^0 \end{matrix} \right\}$ projected by $\left\{ \begin{matrix} l^+ \\ l^- \end{matrix} \right.$

CP eigenstates: $\left. \begin{matrix} B_+ \\ B_- \end{matrix} \right\}$ projected by $\left\{ \begin{matrix} J/\psi K_L \\ J/\psi K_S \end{matrix} \right.$

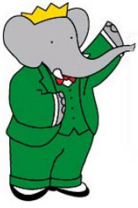




Process undergone by the B that decays second

<i>Transition</i> (decay 1, decay 2)	<i>T-Transformed</i> (decay 1, decay 2)
$B^0 \rightarrow B_+$ (l^- , $J/\psi K_L$)	$B_+ \rightarrow B^0$ ($J/\psi K_S$, l^+)
$B^0 \rightarrow B_-$ (l^- , $J/\psi K_S$)	$B_- \rightarrow B^0$ ($J/\psi K_L$, l^+)
$\bar{B}^0 \rightarrow B_+$ (l^+ , $J/\psi K_L$)	$B_+ \rightarrow \bar{B}^0$ ($J/\psi K_S$, l^-)
$\bar{B}^0 \rightarrow B_-$ (l^+ , $J/\psi K_S$)	$B_- \rightarrow \bar{B}^0$ ($J/\psi K_L$, l^-)

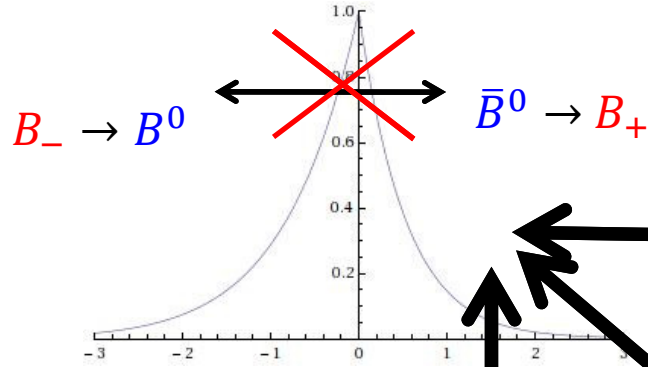
From this, one can construct 4 T-violating asymmetries
that don't depend directly on CP violation



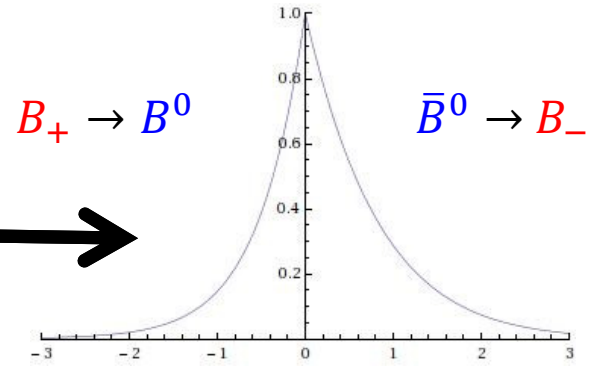
Expected intensities as function of Δt

l^+

$J/\psi K_L$



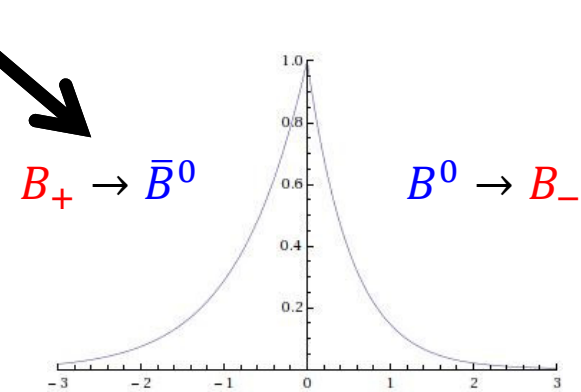
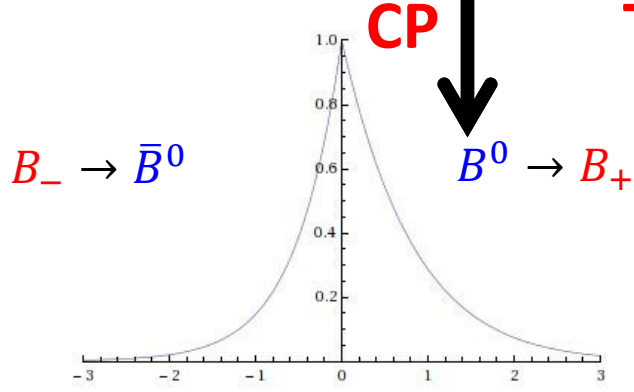
$J/\psi K_S$



CPT

l^-

CP **T**

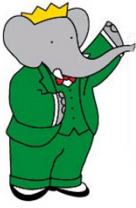


In total we can build:

- 4 Independent **T** comparisons.
- 4 Independent **CP** comparisons.
- 4 Independent **CPT** comparisons.

TV measurement implies comparison of:

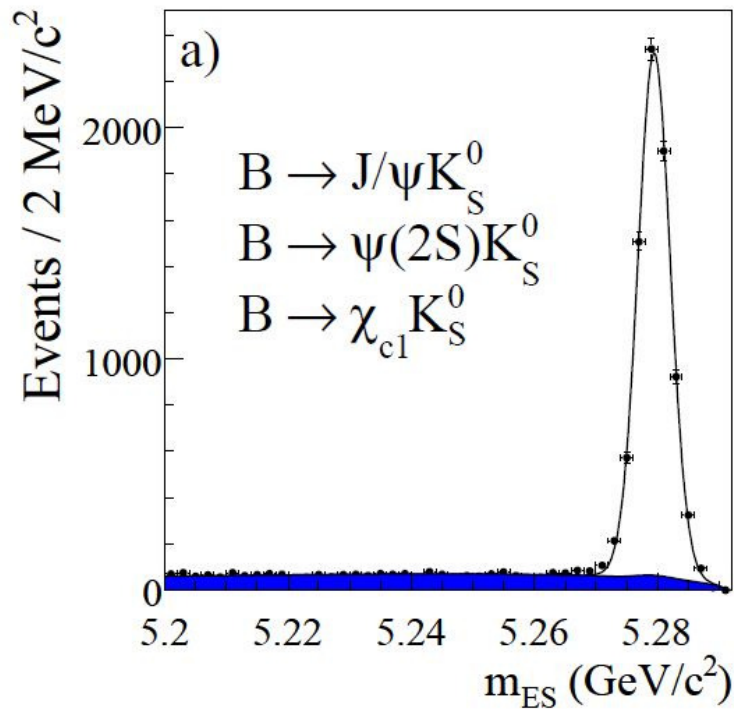
- 1) Opposite Δt sign (which decay is first)
- 2) Opposite CP states ($J/\psi K_S$ vs. $J/\psi K_L$)
- 3) Opposite flavor states (B^0 vs \bar{B}^0)



Reconstructed events

Employ standard B reconstruction techniques (event shape for $q\bar{q}$ suppression, etc.)

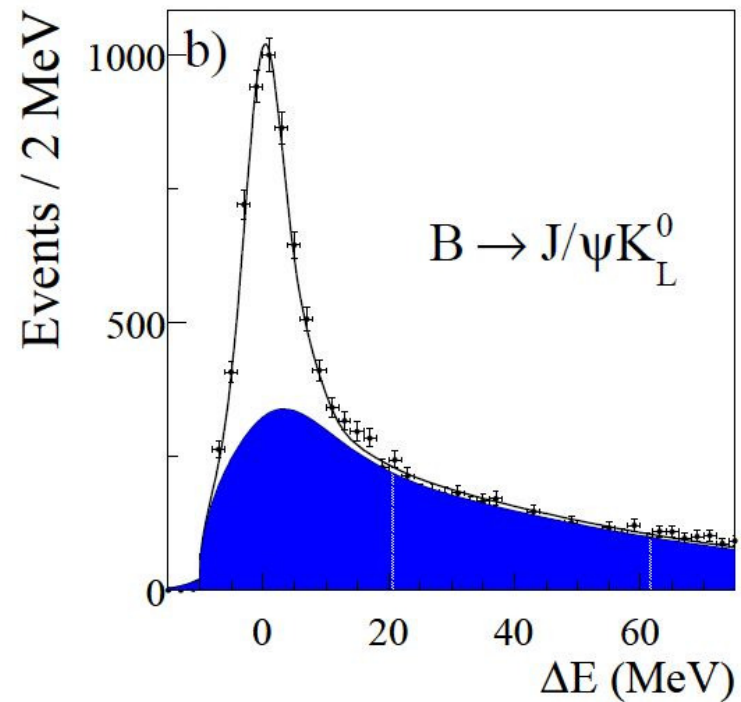
$c\bar{c}K_S$ sample



$$m_{ES} = \sqrt{E_{\text{beam}}^2 - p_B^{*2}}$$

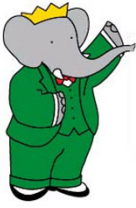
7796 events
Purity: 87% to 96%

$J/\psi K_S$ sample



$$\Delta E = E_B^* - E_{\text{beam}}$$

5813 events
Purity: ~56%



Probability density function

8 combinations

l^+, l^- K_L, K_S Step function

Resolution function, from “Bflav” sample:
 $B^0 \rightarrow D^* \pi^- (\rho^-, a_1^-), B^0 \rightarrow J/\psi K^{*0}$

$$H_{\alpha,\beta}(\Delta t) \propto g_{\alpha,\beta}^+(\Delta t_{\text{true}}) \times \mathbf{H}(\Delta t_{\text{true}}) \otimes \mathcal{R}(\delta t; \sigma_{\Delta t}) + g_{\alpha,\beta}^-(\Delta t_{\text{true}}) \times \mathbf{H}(-\Delta t_{\text{true}}) \otimes \mathcal{R}(\delta t; \sigma_{\Delta t})$$

$\Delta t - \Delta t_{\text{true}}$

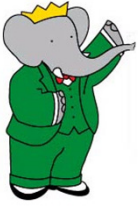
$$g_{\alpha,\beta}^{\pm} = e^{-\Gamma \Delta t_{\text{true}}} \left\{ 1 + S_{\alpha,\beta}^{\pm} \sin(\Delta m \Delta t_{\text{true}}) + C_{\alpha,\beta}^{\pm} \cos(\Delta m \Delta t_{\text{true}}) \right\}$$

$\Delta m = m_{B_{\text{heavy}}} - m_{B_{\text{light}}}$

Probes Decay-mixing interference

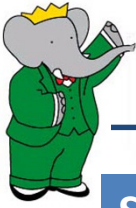
Probes decay

- Flavor-mistag rates, (not shown in PDF) also obtained from Bflav sample
- Floating in the fit: 8 pairs of S and C parameters, 11 background CPV parameters
- The 16 S and C parameters are combined into 12 CP-, T-, and CPT-violating observables



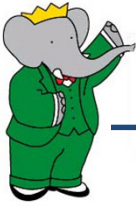
Results

	Parameter	Result	Expected value (given CPV)
TV	$\Delta S_T^+ = S_{\ell^-, K_L^0}^- - S_{\ell^+, K_S^0}^+$	$-1.37 \pm 0.14 \pm 0.06$	-1.4
	$\Delta S_T^- = S_{\ell^-, K_L^0}^+ - S_{\ell^+, K_S^0}^-$	$1.17 \pm 0.18 \pm 0.11$	1.4
	$\Delta C_T^+ = C_{\ell^-, K_L^0}^- - C_{\ell^+, K_S^0}^+$	$0.10 \pm 0.14 \pm 0.08$	0.0
	$\Delta C_T^- = C_{\ell^-, K_L^0}^+ - C_{\ell^+, K_S^0}^-$	$0.04 \pm 0.14 \pm 0.08$	0.0
CPV	$\Delta S_{CP}^+ = S_{\ell^-, K_S^0}^+ - S_{\ell^+, K_S^0}^+$	$-1.30 \pm 0.11 \pm 0.07$	-1.4
	$\Delta S_{CP}^- = S_{\ell^-, K_S^0}^- - S_{\ell^+, K_S^0}^-$	$1.33 \pm 0.12 \pm 0.06$	1.4
	$\Delta C_{CP}^+ = C_{\ell^-, K_S^0}^+ - C_{\ell^+, K_S^0}^+$	$0.07 \pm 0.09 \pm 0.03$	0.0
	$\Delta C_{CP}^- = C_{\ell^-, K_S^0}^- - C_{\ell^+, K_S^0}^-$	$0.08 \pm 0.10 \pm 0.04$	0.0
CPTV	$\Delta S_{CPT}^+ = S_{\ell^+, K_L^0}^- - S_{\ell^+, K_S^0}^+$	$0.16 \pm 0.21 \pm 0.09$	0.0
	$\Delta S_{CPT}^- = S_{\ell^+, K_L^0}^+ - S_{\ell^+, K_S^0}^-$	$-0.03 \pm 0.13 \pm 0.06$	0.0
	$\Delta C_{CPT}^+ = C_{\ell^+, K_L^0}^- - C_{\ell^+, K_S^0}^+$	$0.14 \pm 0.15 \pm 0.07$	0.0
	$\Delta C_{CPT}^- = C_{\ell^+, K_L^0}^+ - C_{\ell^+, K_S^0}^-$	$0.03 \pm 0.12 \pm 0.08$	0.0
Reference	$S_{\ell^+, K_S^0}^+$	$0.55 \pm 0.09 \pm 0.06$	0.7
	$S_{\ell^+, K_S^0}^-$	$-0.66 \pm 0.06 \pm 0.04$	-0.7
	$C_{\ell^+, K_S^0}^+$	$0.01 \pm 0.07 \pm 0.05$	0.0
	$C_{\ell^+, K_S^0}^-$	$-0.05 \pm 0.06 \pm 0.03$	0.0



Systematic uncertainties

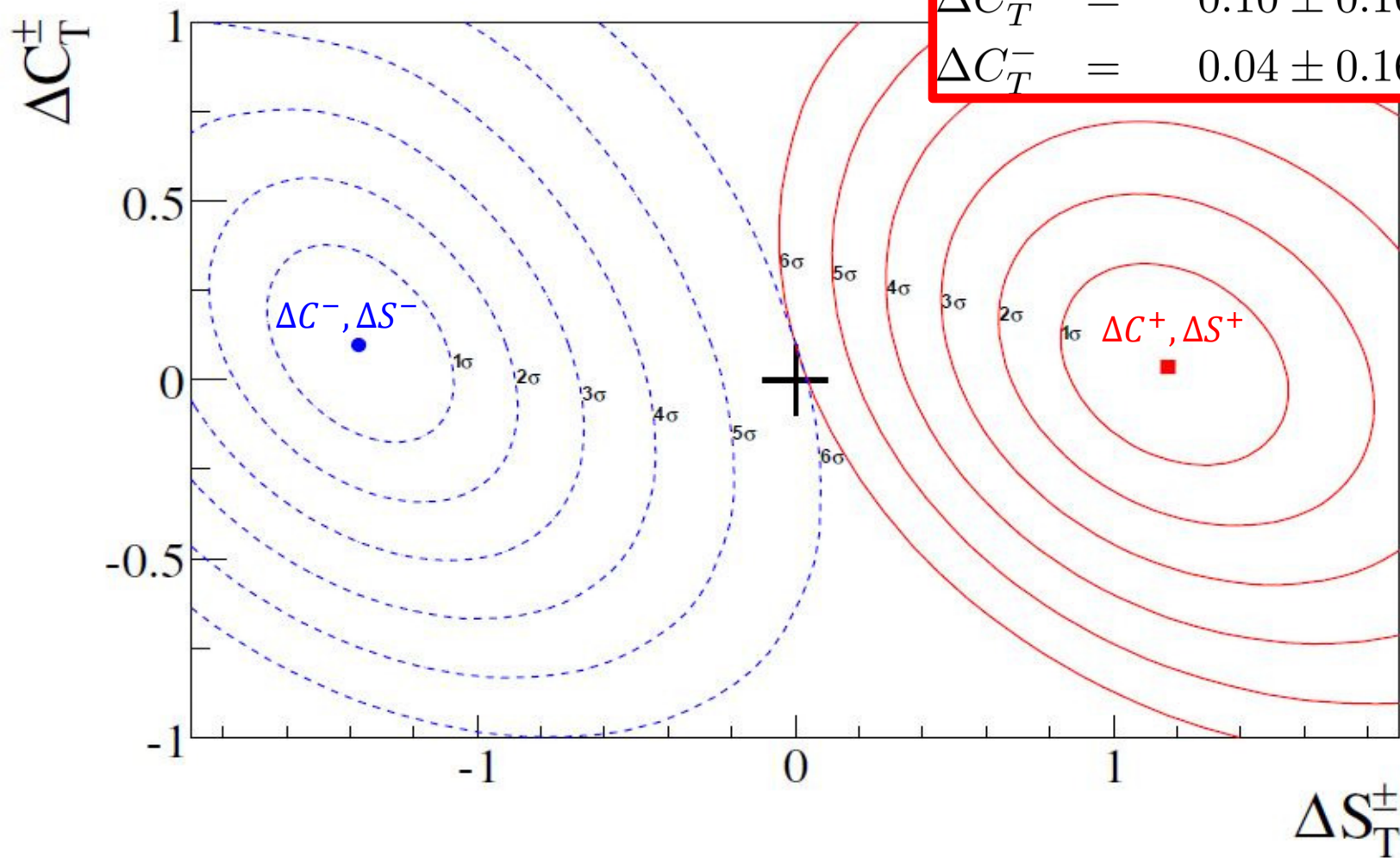
Systematic source	ΔS_T^+	ΔS_T^-
misID flavour	0.019	0.019
Δt resolution function	0.02	0.05
Outlier's scale factor	0.012	-0.013
m_{ES} parameters	0.012	0.0018
ΔE parameters	0.017	0.017
K_L systematics	0.03	0.03
Differences between B_{CP} and B_{flav}	0.02	0.02
Background effects	0.03	0.04
Uncertainty on fit bias from MC	0.010	0.08
Detector and vertexing effects.	0.011	0.04
$\Delta\Gamma \neq 0$ effects	0.004	0.003
External physics parameters	0.005	0.006
Normalization effects	0.012	0.009
Total Systematics	0.06	0.11

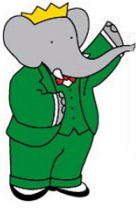


Interpretation of the results

14 σ using Gaussian likelihood,
accounting for systematics

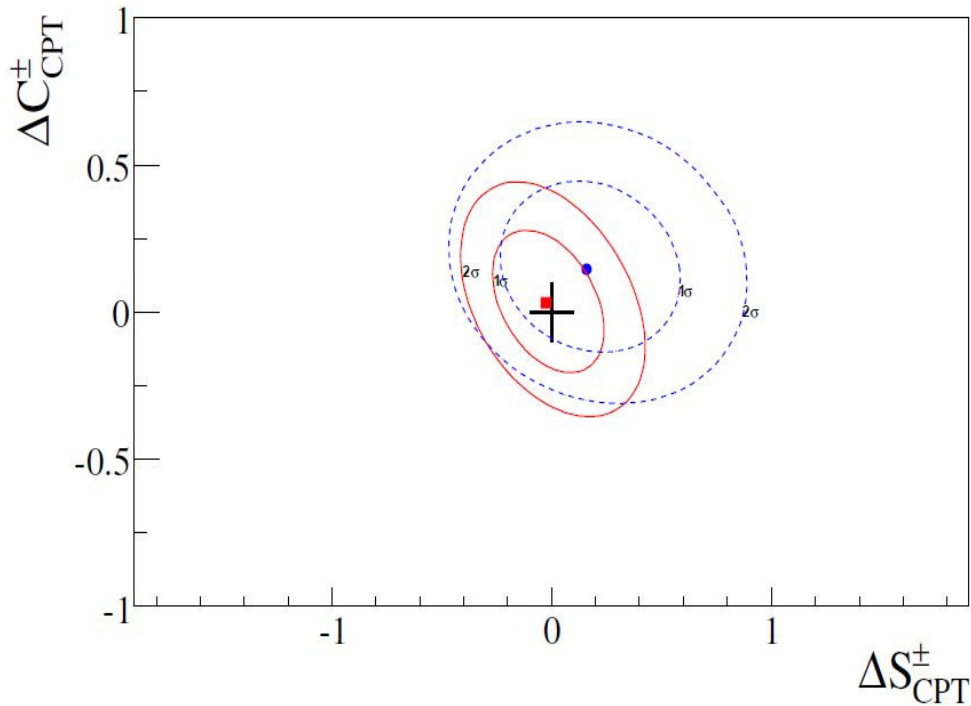
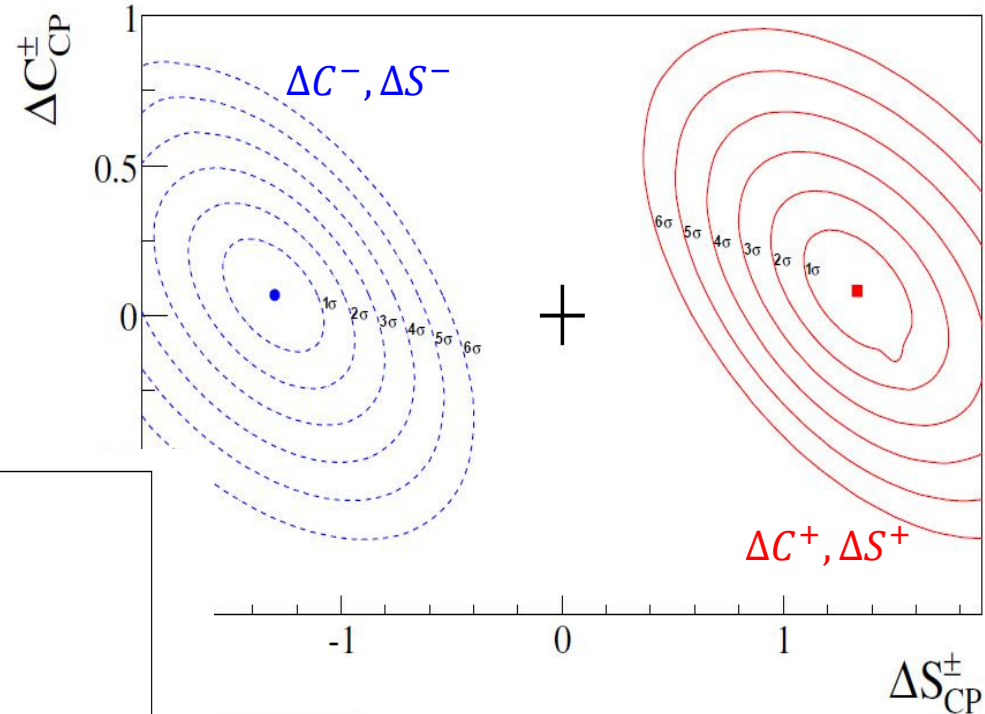
ΔS_T^+	=	$-1.37 \pm 0.14 \pm 0.06$
ΔS_T^-	=	$1.17 \pm 0.18 \pm 0.11$
ΔC_T^+	=	$0.10 \pm 0.16 \pm 0.08$
ΔC_T^-	=	$0.04 \pm 0.16 \pm 0.08$



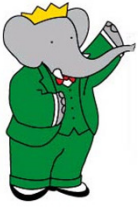


Interpretation of the results

$$\begin{aligned}\Delta S_{CP}^+ &= -1.30 \pm 0.10 \pm 0.07 \\ \Delta S_{CP}^- &= 1.33 \pm 0.12 \pm 0.06 \\ \Delta C_{CP}^+ &= 0.07 \pm 0.10 \pm 0.03 \\ \Delta C_{CP}^- &= 0.08 \pm 0.09 \pm 0.04\end{aligned}$$



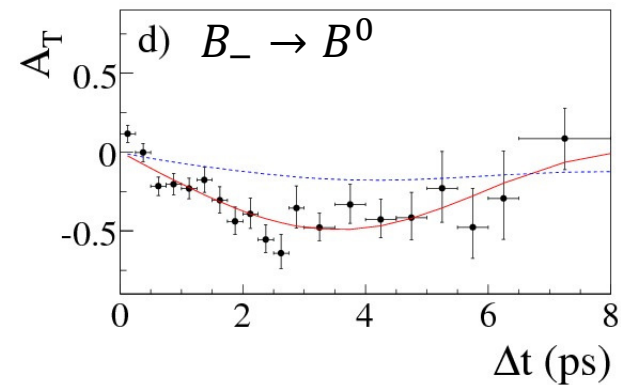
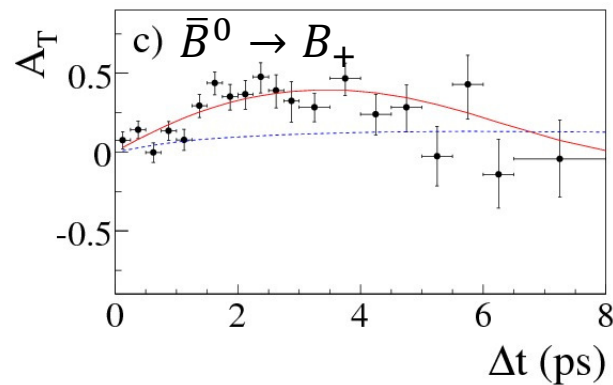
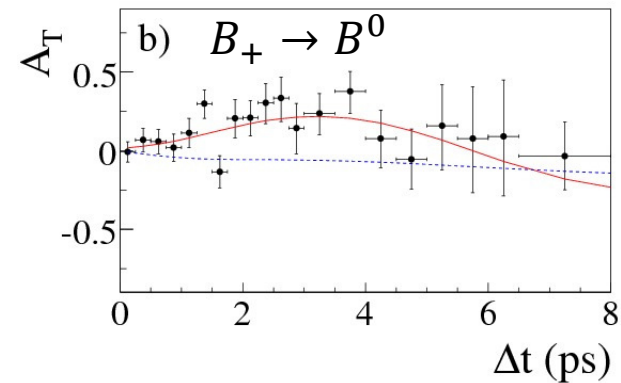
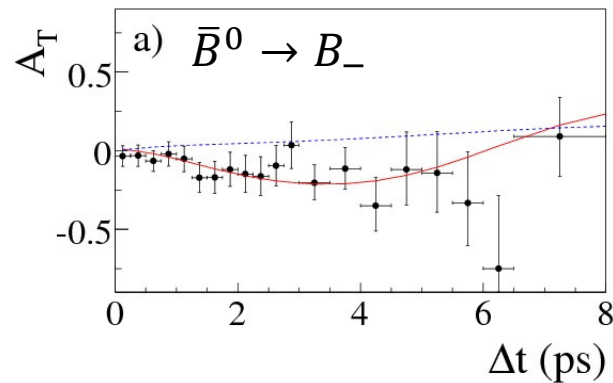
$$\begin{aligned}\Delta S_{CPT}^+ &= 0.16 \pm 0.20 \pm 0.09 \\ \Delta S_{CPT}^- &= -0.03 \pm 0.13 \pm 0.06 \\ \Delta C_{CPT}^+ &= 0.15 \pm 0.17 \pm 0.07 \\ \Delta C_{CPT}^- &= 0.03 \pm 0.14 \pm 0.08\end{aligned}$$

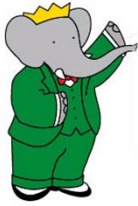


Visualizing asymmetries

$$A_T(\Delta t) \equiv \frac{H_{\Gamma, K_L}^-(\Delta t) - H_{K_S, l^+}^+(\Delta t)}{H_{\Gamma, K_L}^-(\Delta t) + H_{K_S, l^+}^+(\Delta t)} \approx \frac{\Delta C_T^+}{2} \cos \Delta m \Delta t + \frac{\Delta S_T^+}{2} \sin \Delta m \Delta t$$

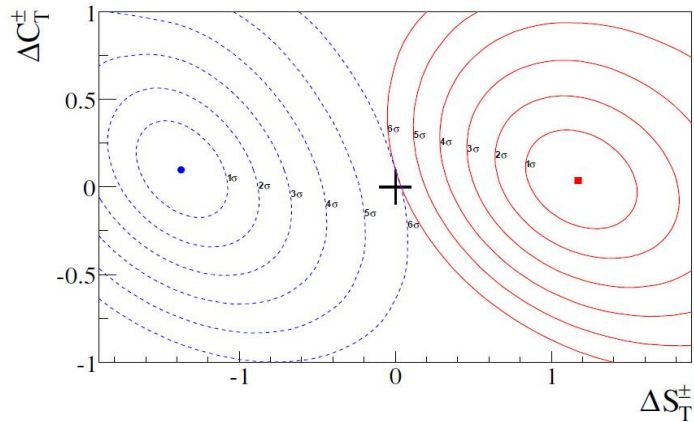
→ Neglecting experimental effects





T-violation summary

- T violation observed for the first time, very high significance



- Added bonus: article in the Economist:

Economist Conferences The Economist OCTOBER 29TH 2012, **STRENGTHENING HEALTH SYSTEMS, CHANGING BEHAVIOUR** [LEARN MORE](#)

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The arrow of time

Backward ran sentences...

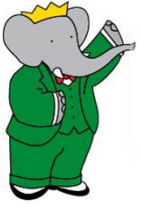
To the relief of physicists, time really does have a preferred direction

Sep 1st 2012 | from the print edition [Like](#) 132 [Tweet](#) 37

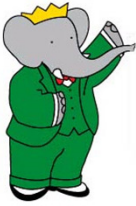
TIME seems to flow inexorably in one direction. Superficially, that is because things deteriorate with age—and this, in turn, is because there are innumerable fewer ways to arrange particles in an orderly fashion than in a jumbled mess. Any change in an existing arrangement is therefore likely to increase its disorder.

Dig a little deeper, though, and time's arrow becomes mysterious. A particle cannot, by itself, become disordered, so when you examine its behaviour in isolation the past and the future are hard to distinguish. If you film its movement and then give the film to someone else, he will not be able to work out just from the particle's behaviour which way to run the film through the projector. Essentially, the two ways of doing so are symmetrical. Or so physicists used to think until hints to the contrary emerged in the

[Next](#) [Previous](#) [Highlight all](#) Match case

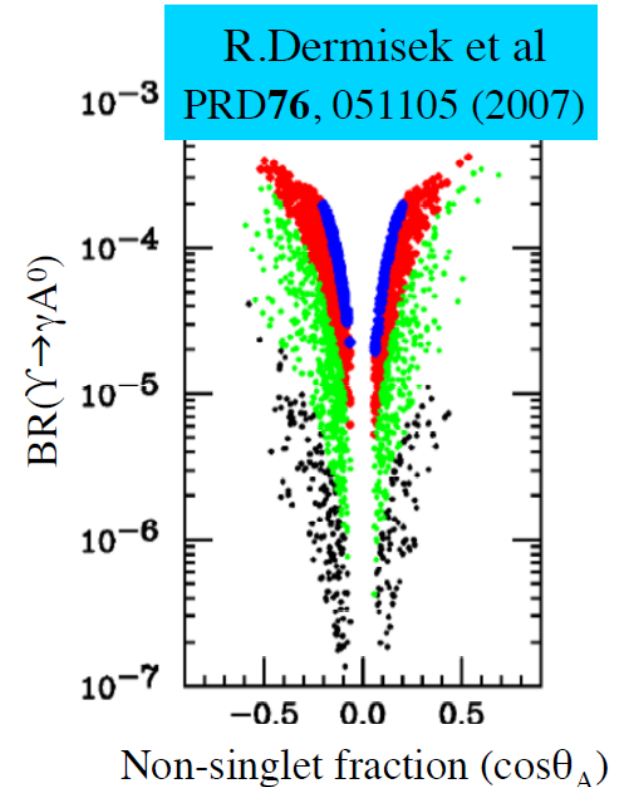
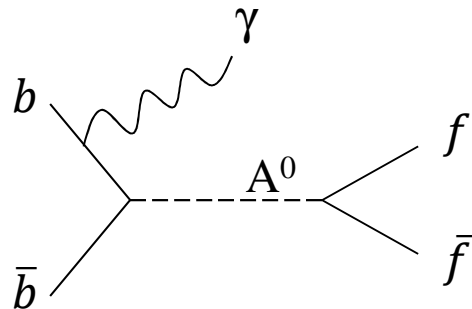


NMSSM Higgs searches



Which Higgs did LHC see?

- SM? MSSM? Beyond...?
- Next-to-minimal SSM (NMSSM):
 - Addresses MSSM μ and little hierarchy problems
 - Has a light CP-odd Higgs, A^0
 - For $m_{A^0} < 2m_b$, not constrained by LEP searches
 - Produced in radiative decays of narrow bottomonium states:



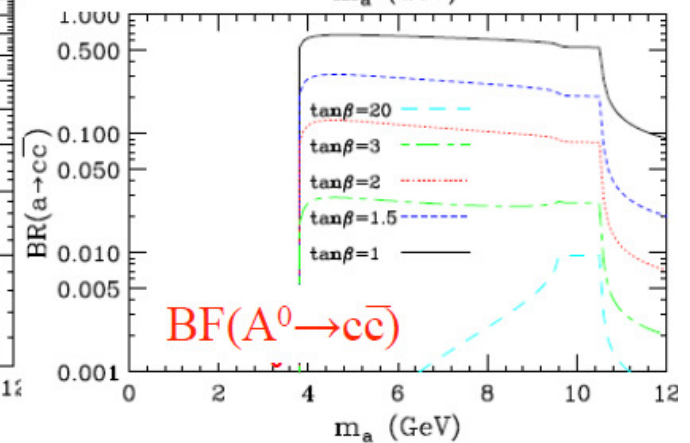
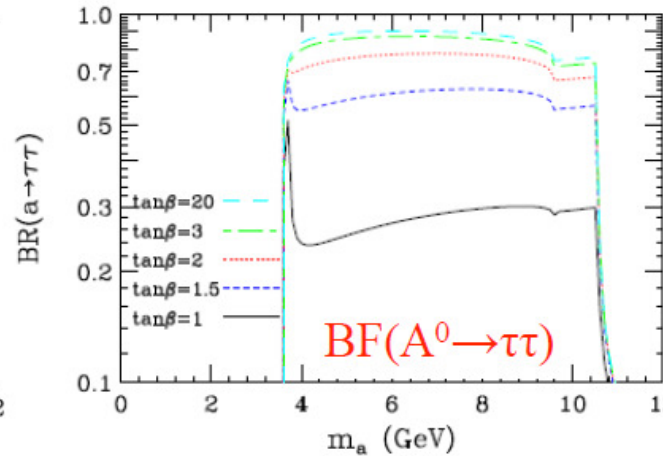
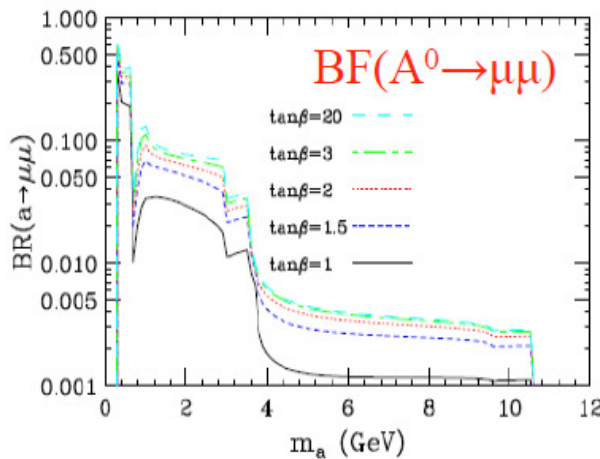
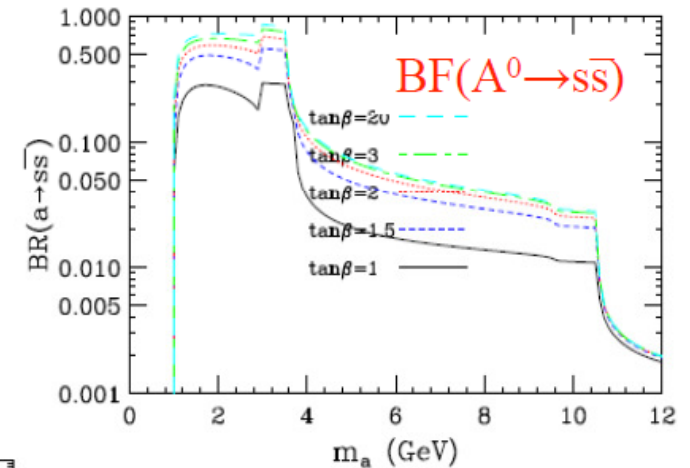
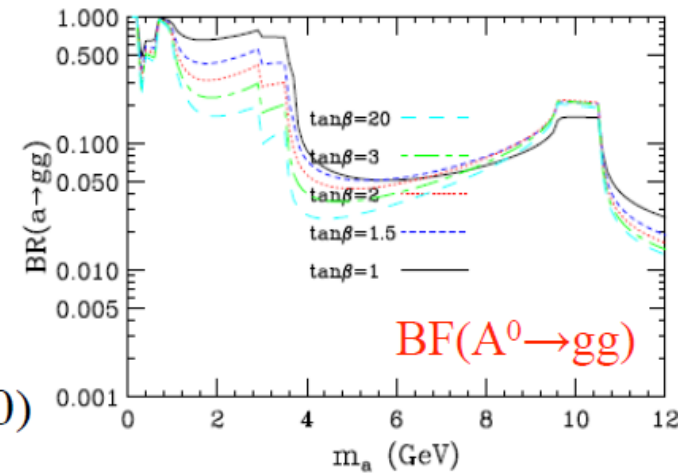
$m_{A^0} < 2m_\tau$
 $2m_\tau < m_{A^0} < 7.5 \text{ GeV}$
 $7.5 \text{ GeV} < m_{A^0} < 8.8 \text{ GeV}$
 $8.8 \text{ GeV} < m_{A^0} < 9.2 \text{ GeV}$

Low-Mass Higgs Decays

- Pattern of decays depends on A^0 mass and couplings ($\tan\beta$)

☞ Dermisek & Gunion, PRD 81, 075003 (2010)

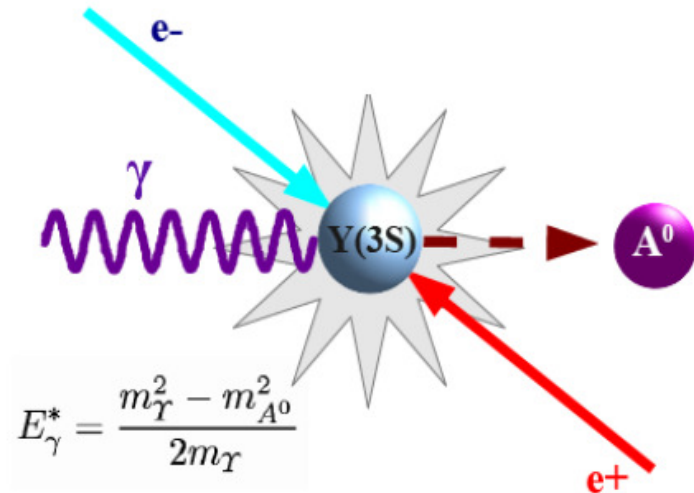
- Comprehensive search in a variety of final states
 - Leptonic and hadronic



Searches for a Light Higgs in BABAR

Radiative Decays of $\Upsilon(nS)$

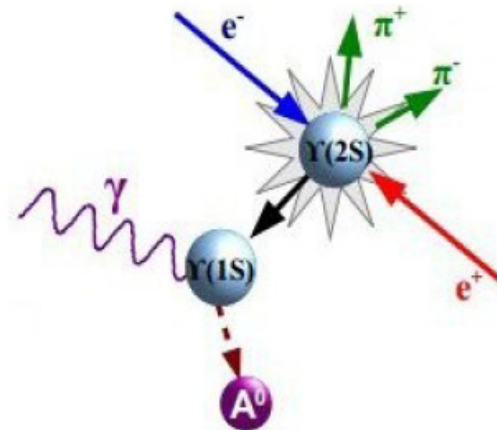
Signature: monochromatic photon



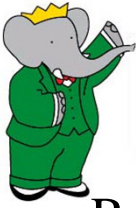
- ✓ $A^0 \rightarrow \mu^+ \mu^-$, PRL103, 081803 (2009)
- ✓ $A^0 \rightarrow \tau^+ \tau^-$, PRL103, 181801 (2009)
- ✓ $A^0 \rightarrow \text{hadrons}$, PRL107, 221803 (2011)
(this talk)

Additional constraints: $\Upsilon(1S)$ from $\Upsilon(2S,3S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$ transitions


Signature: two low-momentum pions, recoiling against $\Upsilon(1S)$

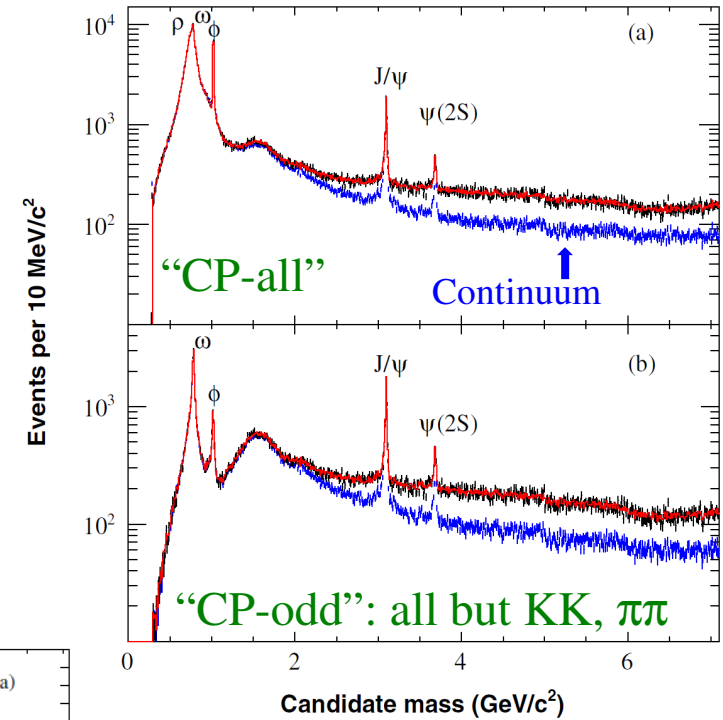



- ✓ $A^0 \rightarrow \mu^+ \mu^-$, NEW ! this talk
- ✓ $A^0 \rightarrow \tau^+ \tau^-$, NEW ! this talk
- ✓ $A^0 \rightarrow \text{invisible}$ (light dark matter), PRL107, 021804 (2011)

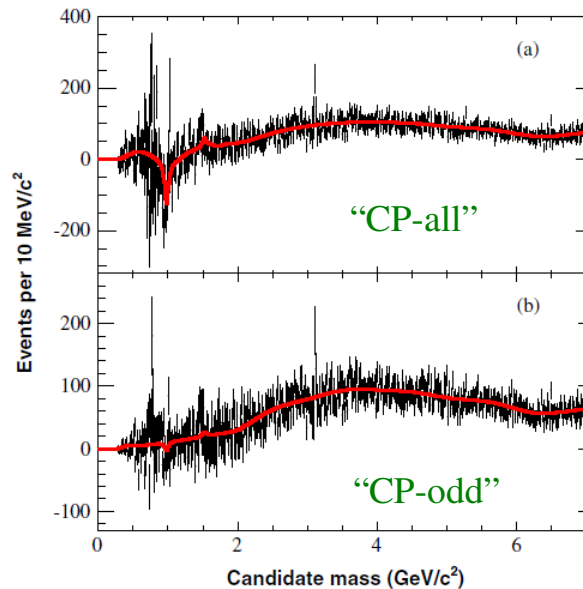


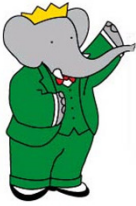
$A^0 \rightarrow$ hadrons from $Y(2S, 3S)$

- Reconstruct everything in the event:
 - Photon with 2.5 (2.2) GeV in 3S (2S) data, π^0 veto
 - At least 2 charged tracks in A^0 candidate decay
- Reject Bhabha & dimuon with PID
- Beam-energy constraint improved m_{A^0} resolution
- Fit m_{A^0} spectrum to sum of 3 components: 
 - Continuum (from off-resonance data)
 - Nonresonant Y decays (spline)
 - Resonant Y decays (5–16 resonances)





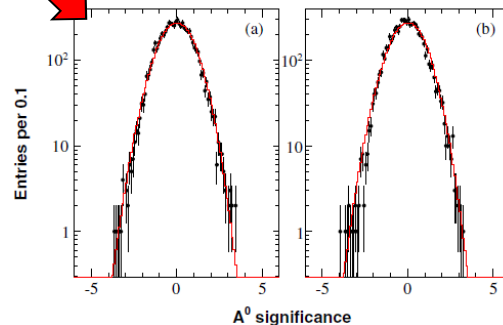
- Continuum-subtracted spectrum: 
 - A_0 would show up as a peak



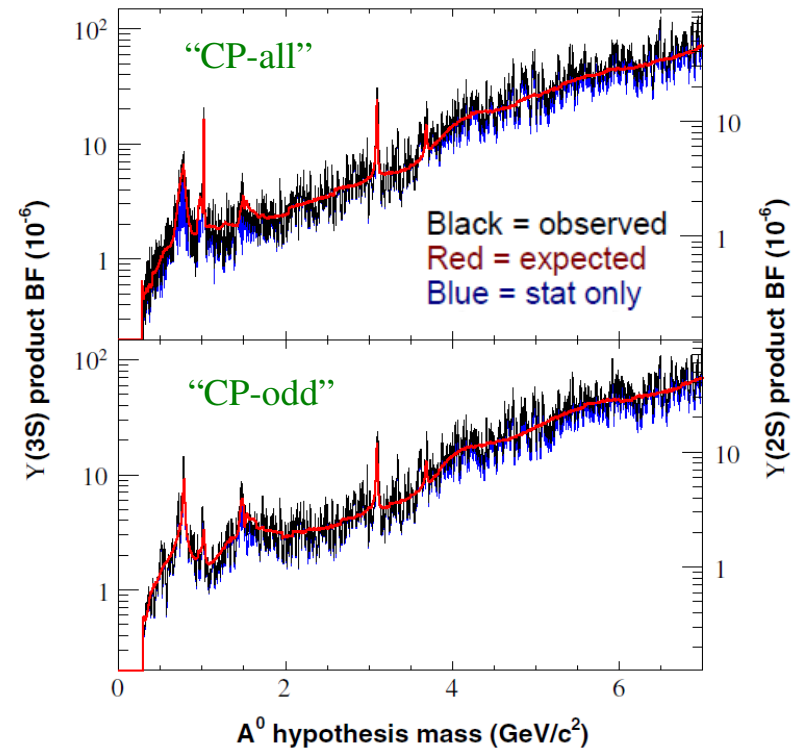
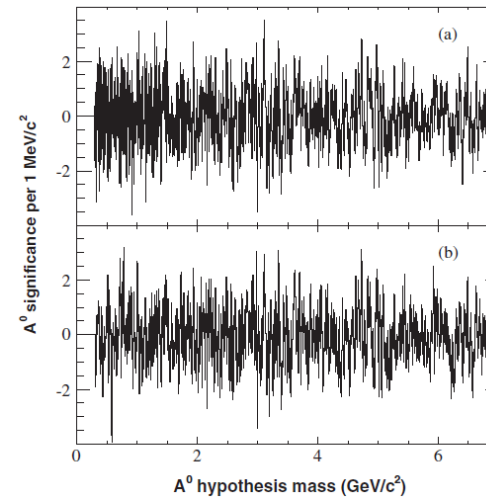


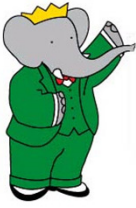
Limits

- Add narrow signal function to fit, moved along spectrum with 1 MeV steps
- Plot signal significance @ each step: 
- Significance distribution is parabolic: 



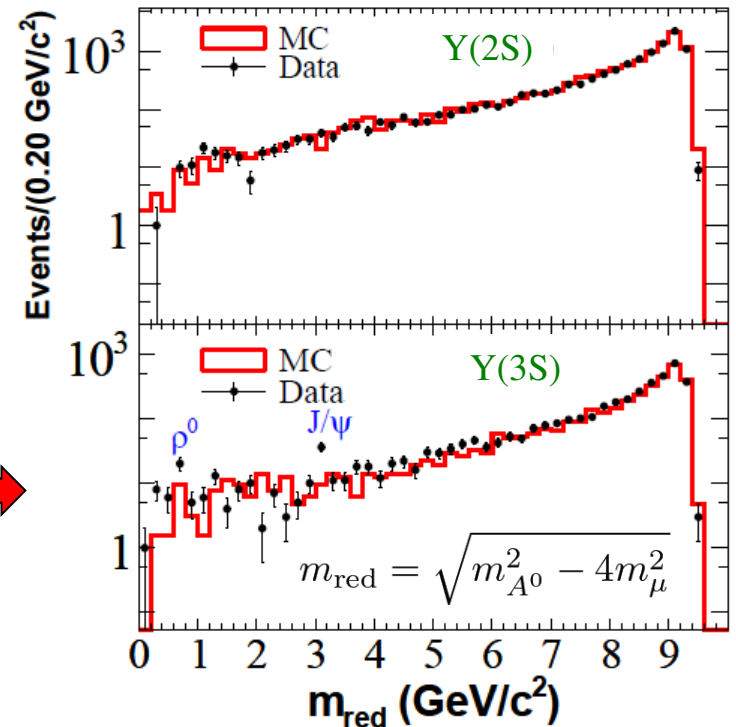
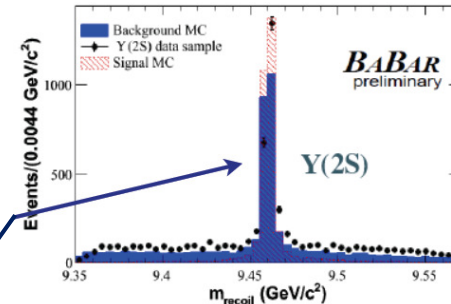
- Calculate 90% CL Upper limits on $BF(Y \rightarrow \gamma A^0) \times BF(A^0 \rightarrow \text{hadrons})$ assuming
 - Gaussian likelihoods with uniform prior for $BR > 0$
 - Same couplings for $Y(3S)$, $Y(2S)$

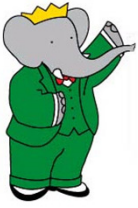




$A^0 \rightarrow \alpha^+ \alpha^-$ from $Y(1S)$

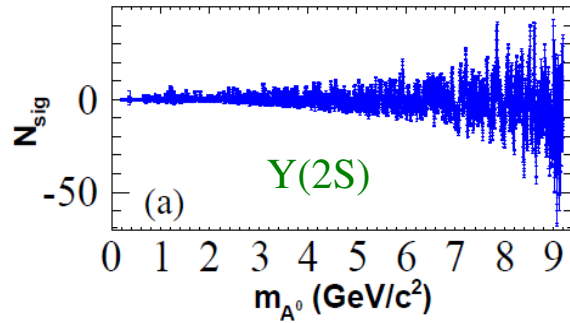
- The 2009 $A^0 \rightarrow \alpha^+ \alpha^-$ analysis had the same idea as the $A^0 \rightarrow$ hadrons analysis:
 - Search for $e^+e^- \rightarrow Y(2S,3S) \rightarrow \gamma A^0$; $A^0 \rightarrow \alpha^+ \alpha^-$
- A new analysis takes advantage of clean Y tagging via $Y(2S,3S) \rightarrow \pi^+ \pi^- Y(1S)$
- Tag using $Y(1S)$ mass recoiling against $\pi^+ \pi^-$:
- $BF(\pi^+ \pi^- Y(1S)) = 2.2 - 2.3\%$ only
- But tagging greatly reduced the background
- Search for $Y(1S) \rightarrow \gamma A^0$; $A^0 \rightarrow \alpha^+ \alpha^-$
 - Require $\gamma \alpha^+ \alpha^-$ with $E_\gamma < 0.2$ GeV
 - Beam-energy & Y mass constraints
 - Look for peaks in reduced-mass spectrum
 - Background analytical function obtained from MC and off-resonance data



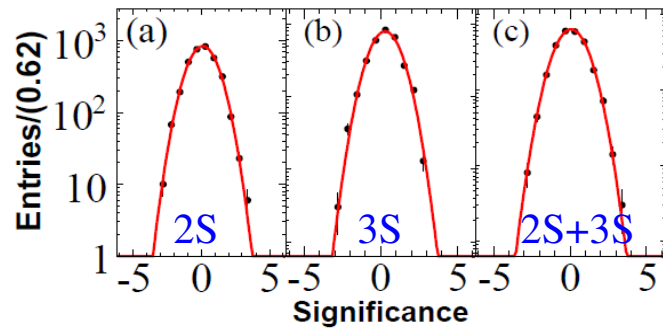


Limits

Signal yield:

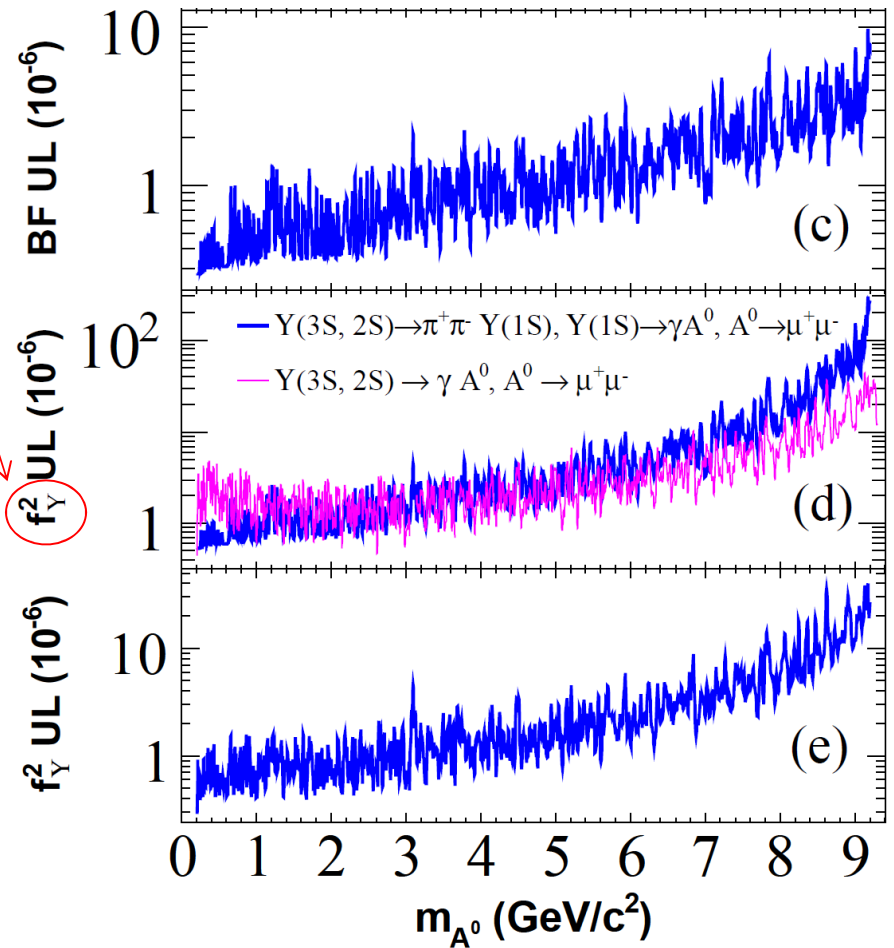


Signal significance distributions:

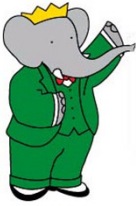


Upper limits (2S+3S combined):

Effective Yukawa coupling

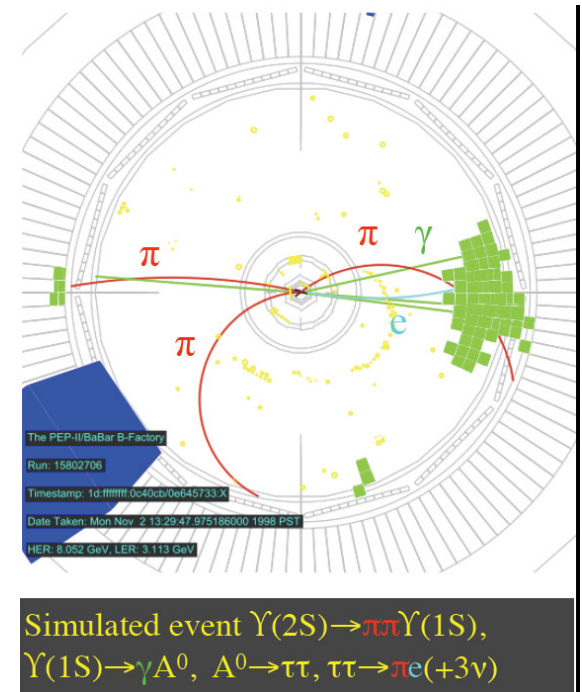


$f_Y^2\ UL\ (10^{-6})$

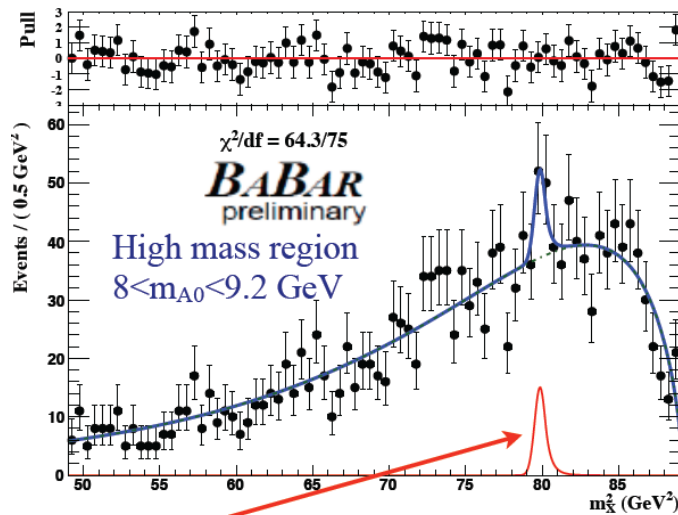


$A^0 \rightarrow \tau^+ \tau^-$ from $Y(1S)$

- As in $A^0 \rightarrow \rho^+ \rho^-$, 2009 analysis used direct $Y(2S, 3S)$ decays, now adding $Y(1S)$ decays.
- Tag $Y(2S, 3S) \rightarrow \pi^+ \pi^- Y(1S)$
- γ + two 1-prong τ decays in $ee, e\rho, \rho\rho, e\pi, \rho\pi$
- m_{A^0} from mass recoiling against the $\gamma\pi\pi$ system, fit for signal peak:

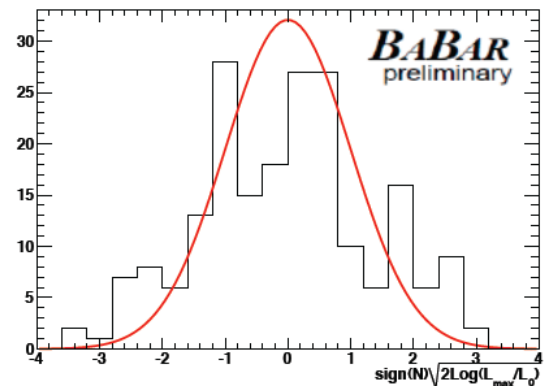


Most significant peak:



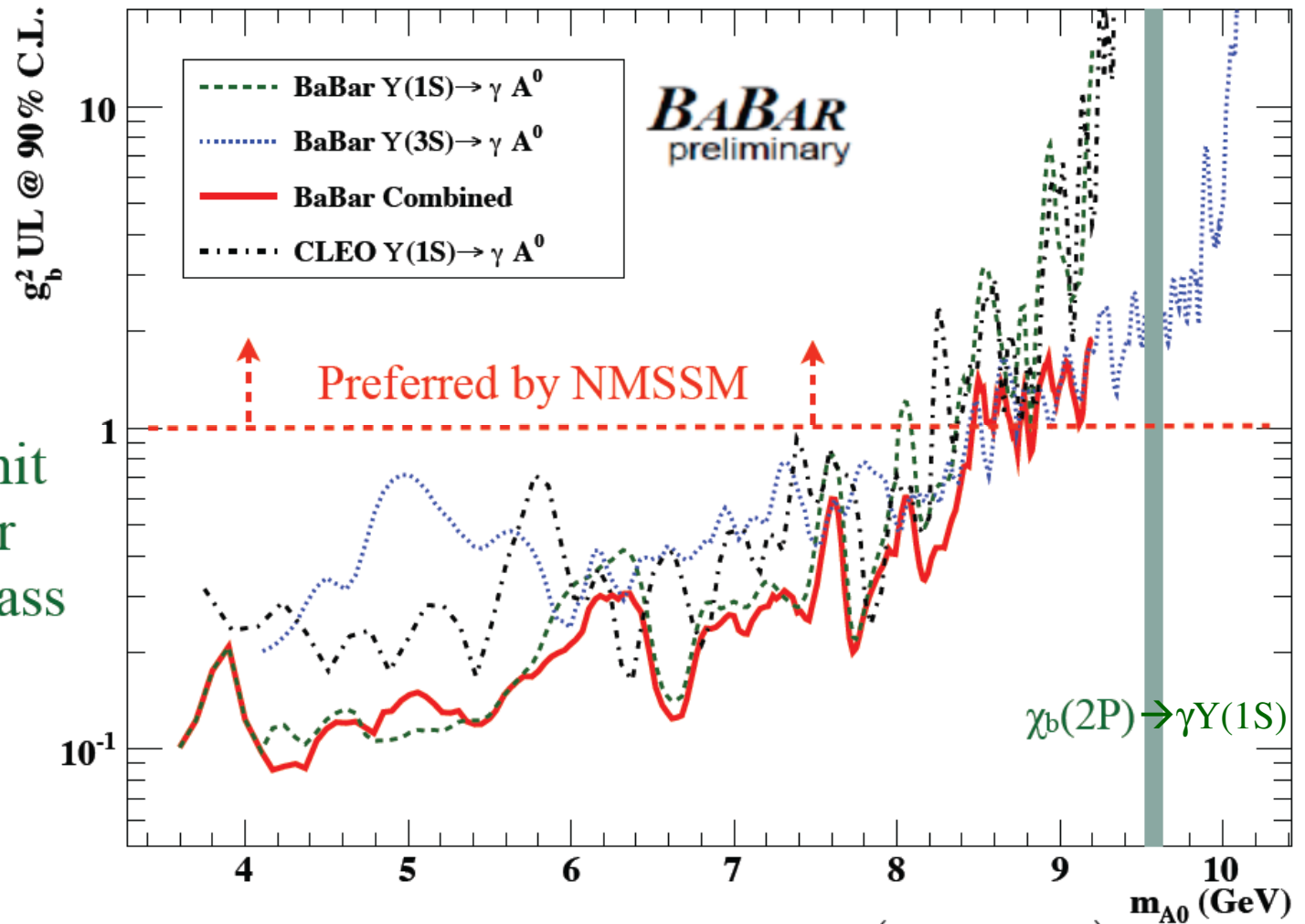
$m_{A^0} = 8.93 \text{ GeV}$, Local significance = 3.0σ
Global significance = 1.4σ

Local significance distribution:

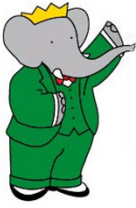


$\Upsilon(nS) \rightarrow \gamma A^0, A^0 \rightarrow \tau^+\tau^-$: Summary

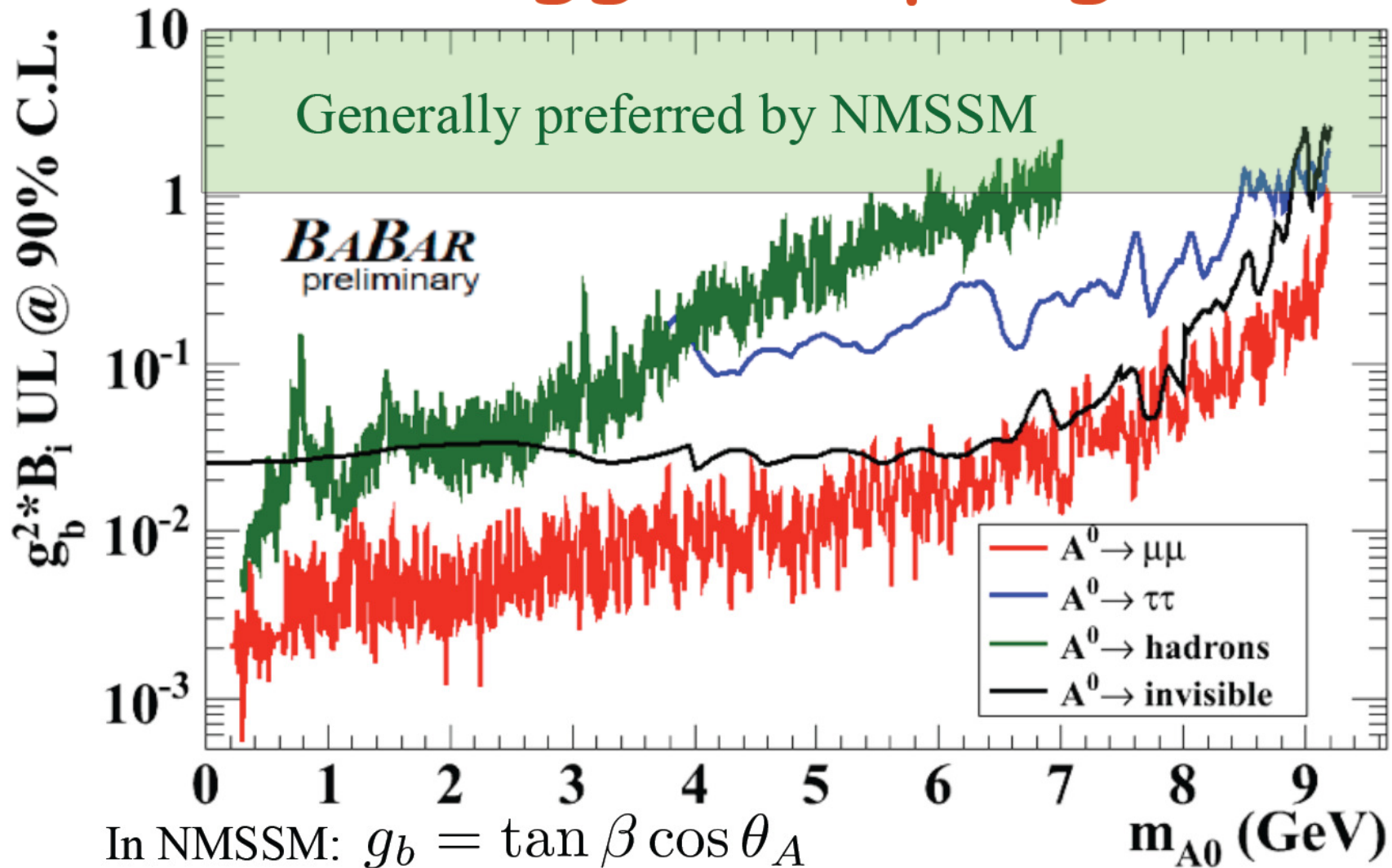
Combine results with previous BaBar search, limit A^0 couplings over broad range of mass



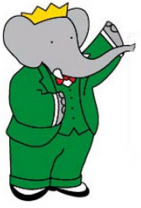
$$\frac{B(\Upsilon(nS) \rightarrow \gamma A^0)}{B(\Upsilon(nS) \rightarrow l^+l^-)} = \frac{g_b^2 G_F m_b^2}{\sqrt{2}\pi\alpha} \mathcal{F}_{QCD} \left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2} \right)$$



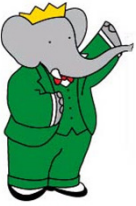
BABAR Higgs Coupling Limits



Comprehensive limits on low-mass (NMSSM etc.) Higgs

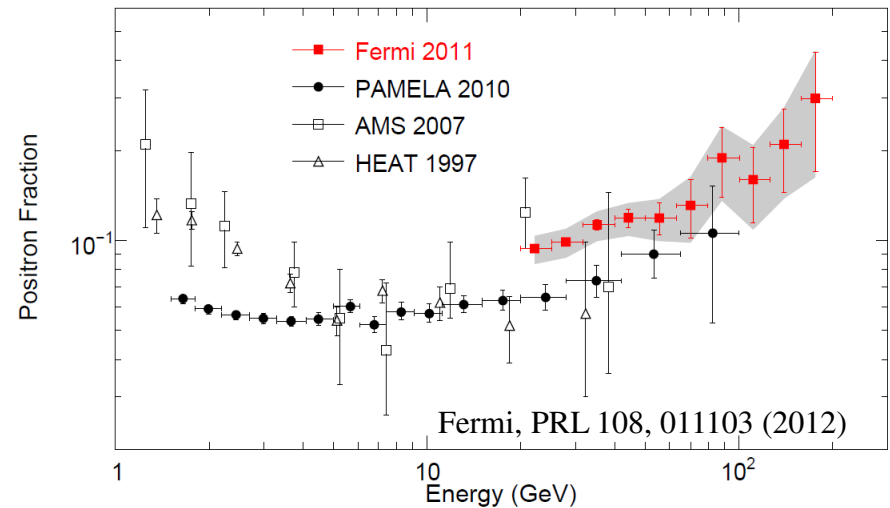


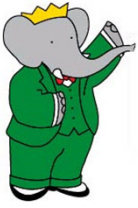
Dark Higgs and dark photon



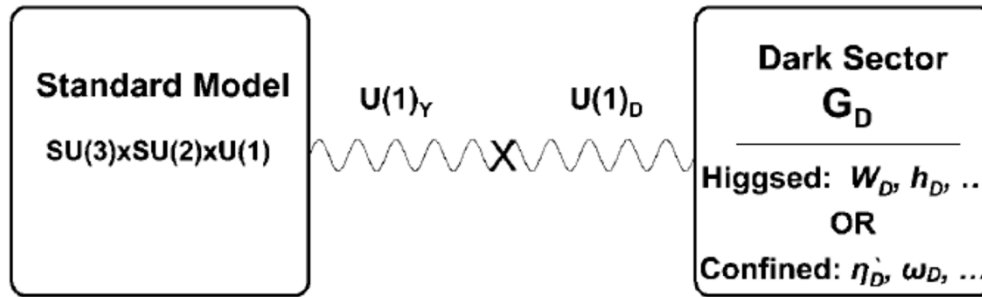
Motivation

- Astronomical anomalies
 - E.g., Increasing positron fraction in cosmic rays:
- May have astrophysical origins
- But raised interest in low-mass dark-sector (or otherwise hidden) states
- E.g., Arkani-Hamed et al, PRD 79, 015014
 - Posits U(1) gauge symmetry in dark sector
 - “Dark photon” A' mediates interactions among TeV dark fermions.
 - $m_{A'} < \sim 2 \text{ GeV}$ (since no antiproton excess seen)
 - A' mixes with SM photon via $\mathcal{L}_{\text{mix}} = \frac{1}{2} \epsilon b_{\mu\nu} F^{\mu\nu}$

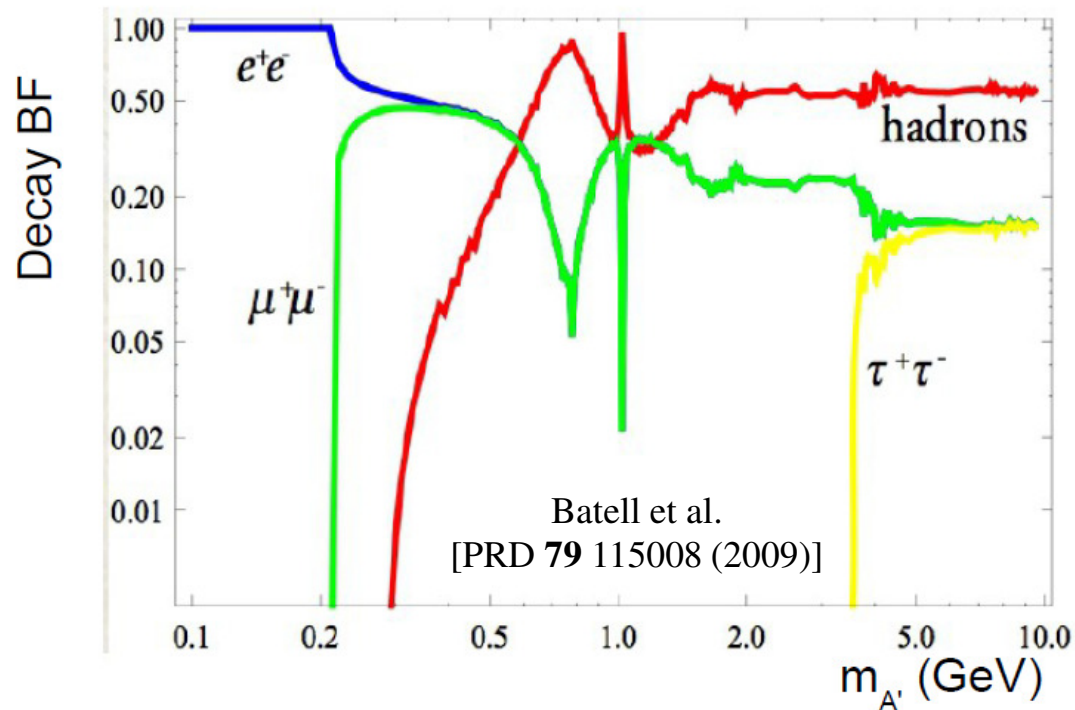


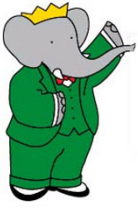


Dark photon coupling and decay

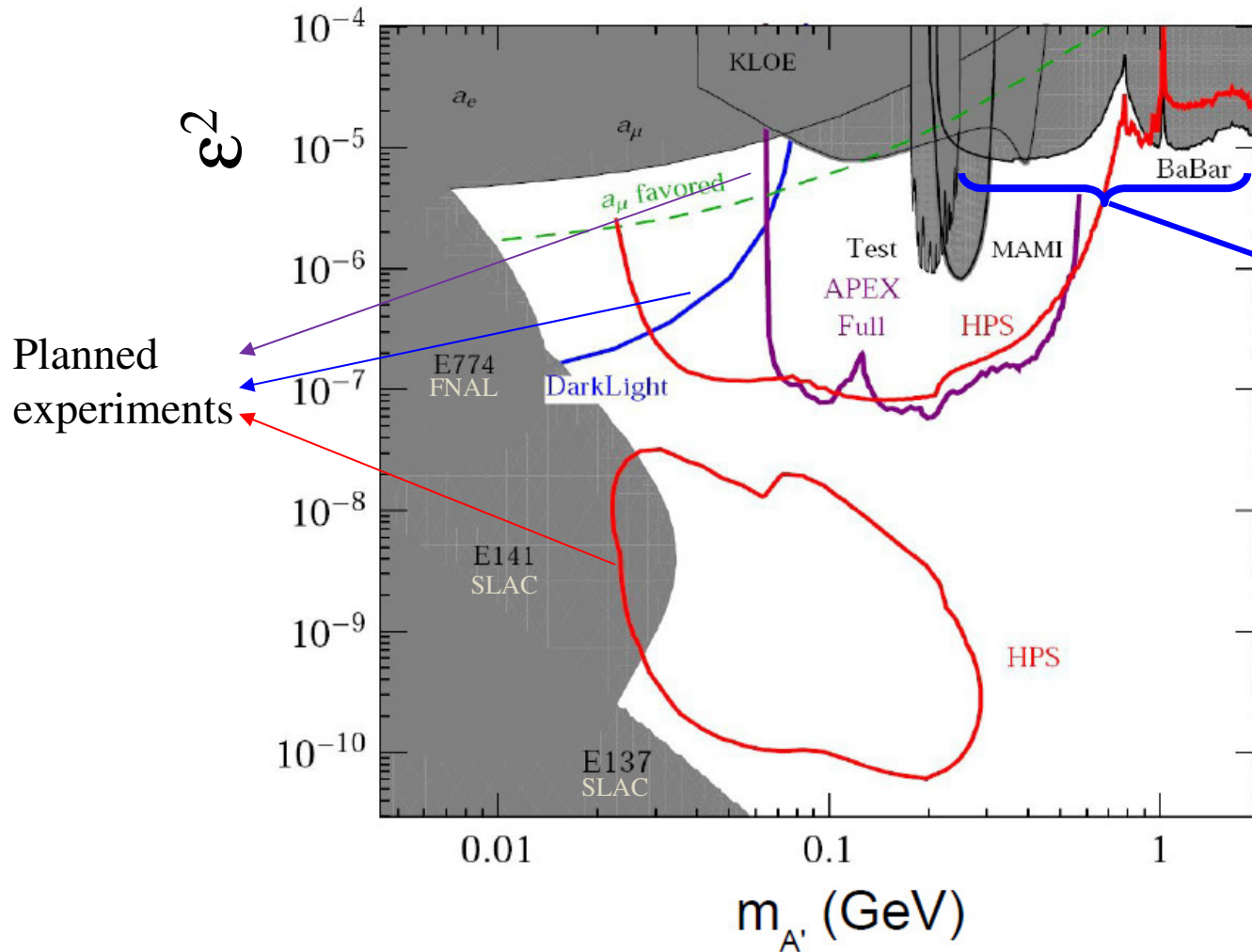


e.g. R. Essig et al.
[PRD **80** 015003 (2009)]





Direct-search constraints

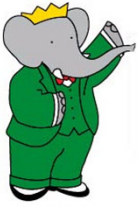


Reinterpretation
of BABAR's 2009
Higgs $\rightarrow \infty$ search.

Potential for:

- $\times 15$ luminosity
- More modes
- Broader range

Following Bjorken et al
PRD 80, 075018 (2009)



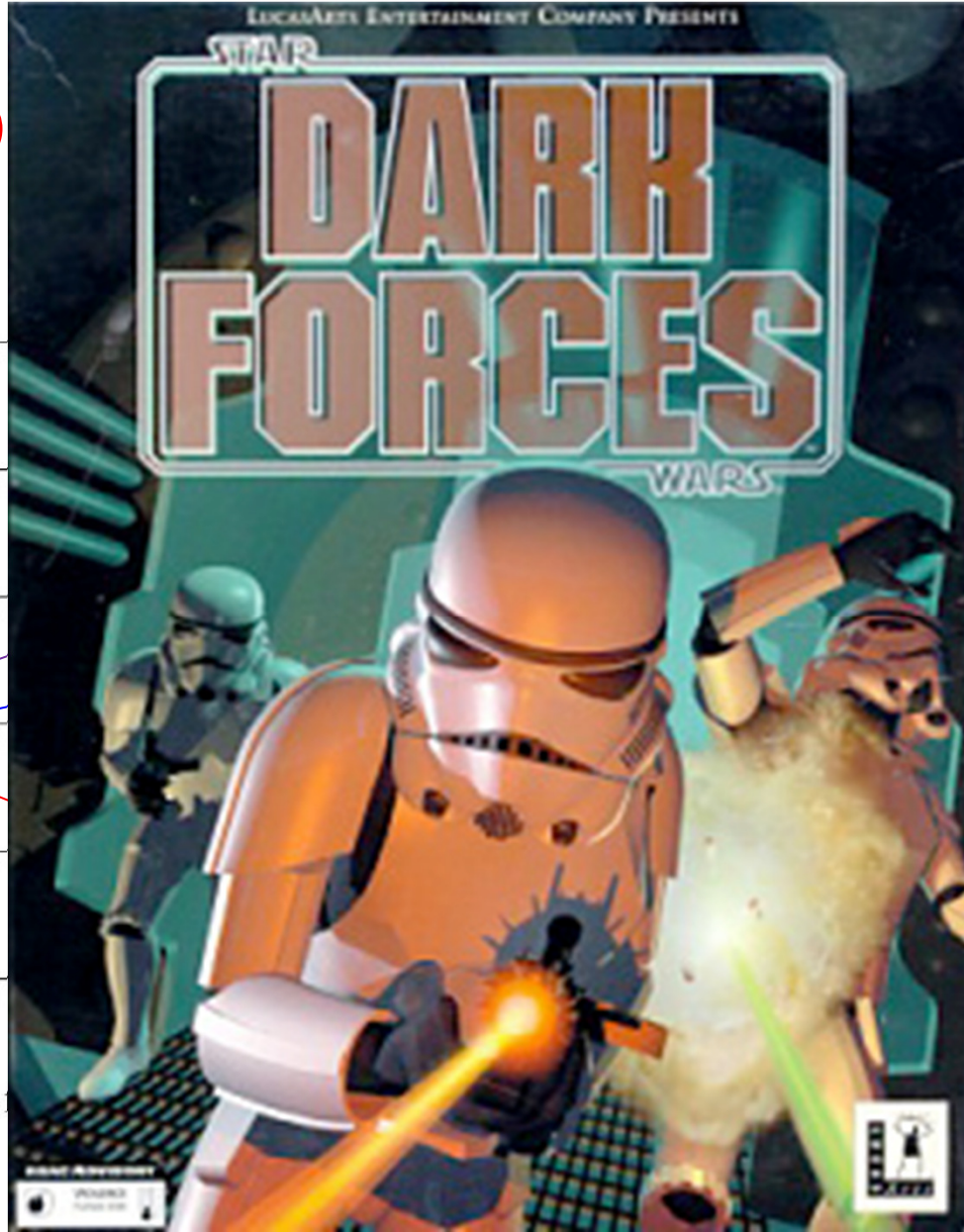
D

nts

Planned experiments

ϵ^2

10⁻¹
10⁻²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶



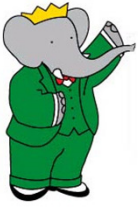
Reinterpretation of BABAR's 2009 Higgs $\rightarrow \infty$ search.

Potential for:

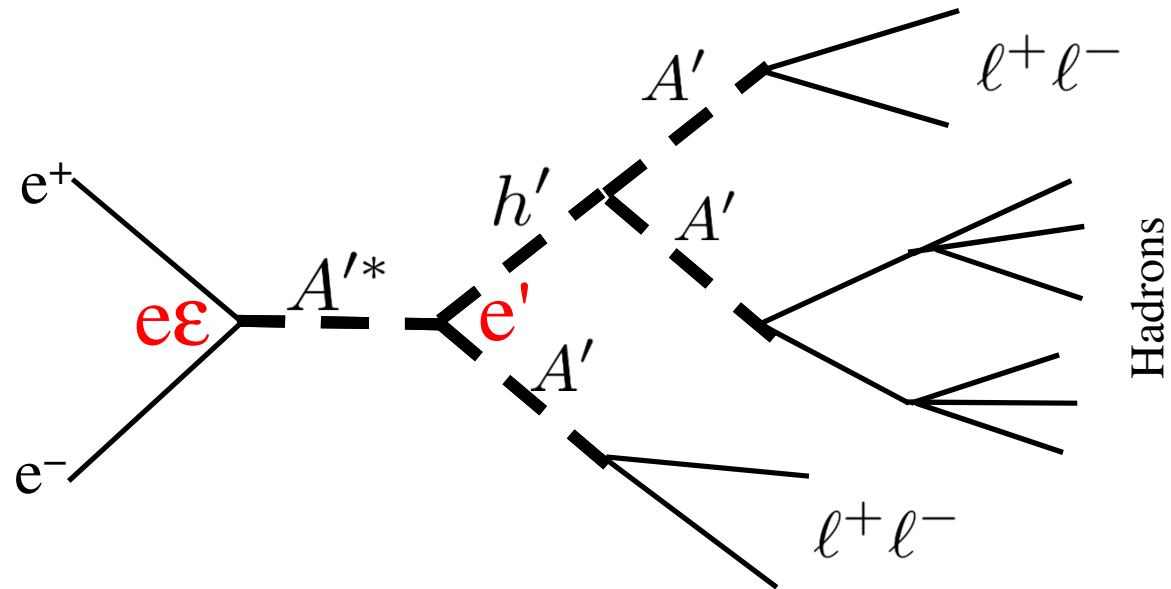
- $\times 15$ luminosity
- More modes
- Broader range

$m_{A'}$ (GeV)

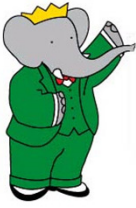
Following Bjorken et al PRD 80, 075018 (2009)



Dark Higgsstrahlung signature



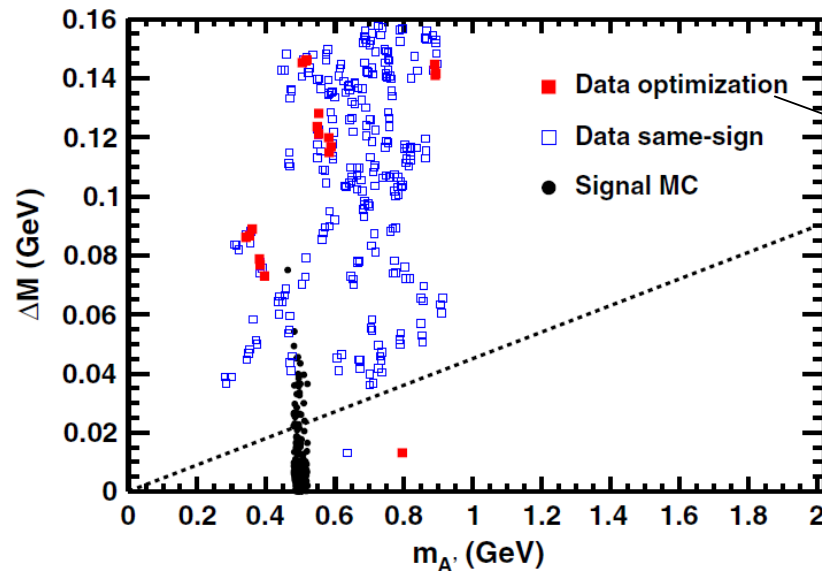
Very little background due to 3 on-shell dark photons



Main event selection criteria

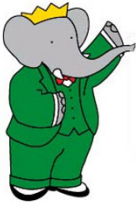
- Exclusive final states: $A' \rightarrow e^+ e^-, \mu^+ \mu^-, \pi^+ \pi^-$
 - 6 tracks with at least one pair of oppositely charged leptons.
 - $3A'$ candidates must contain 95% of CM energy.
 - A' masses must be within 10-240 MeV/ c^2 of each other (depending on mode and mass)

Largest mass diff:



10% of data used for optimization

- For $m_{A'} > 1.2$ GeV, also search for inclusive final states:
 - $4\mu + X$ or $2\mu 2e + X$
 - Recoil mass of the X similar to di-lepton masses.



Results

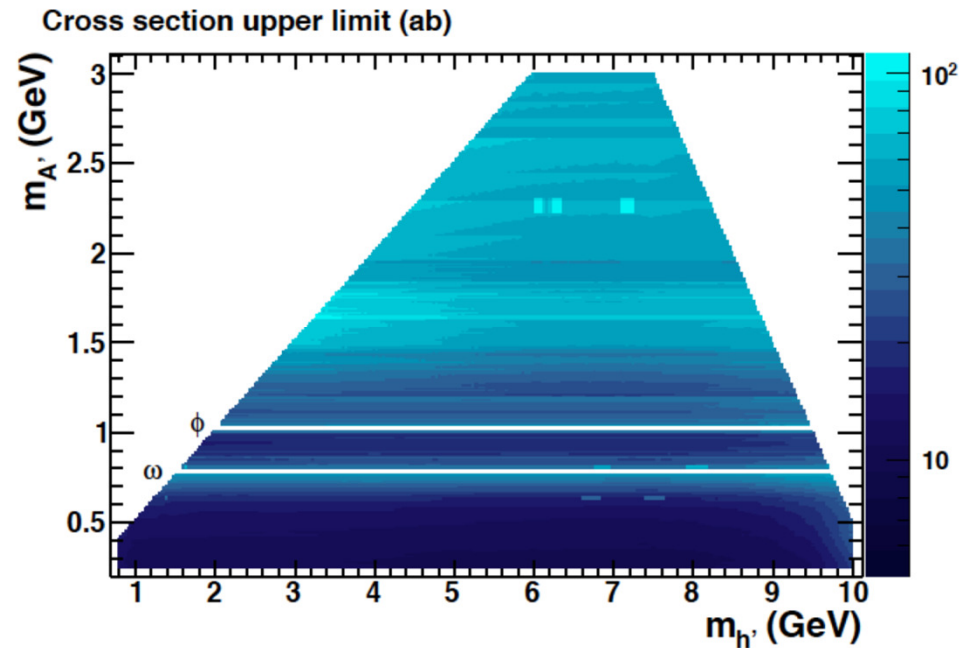
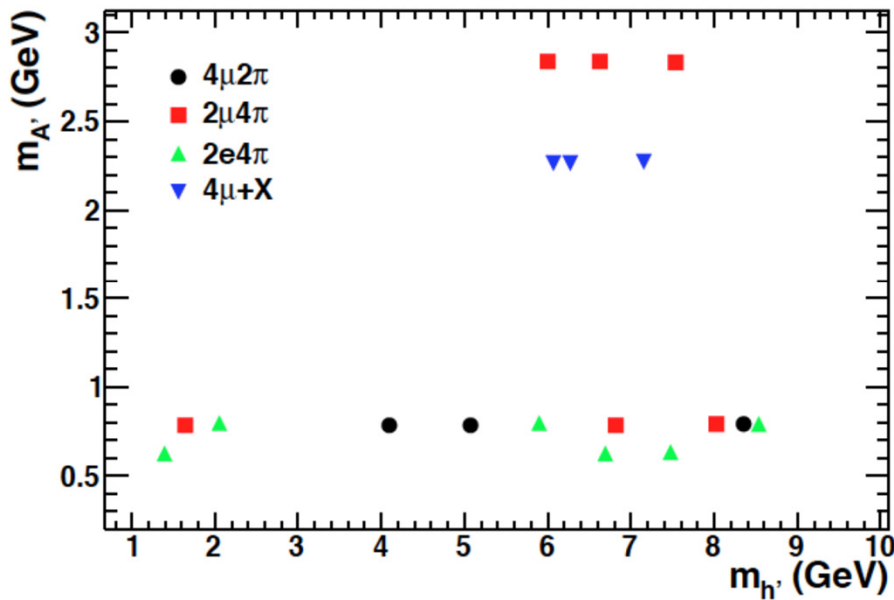
- After applying ϕ and ω vetoes, find 6 candidates in 4 channels:
- Consistent with bgd from same-sign A' candidates

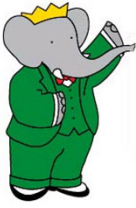
$1 \times 4\mu 2\pi$
$2 \times 2\mu 4\pi$
$2 \times 2e 4\pi$
$1 \times 4\mu X$

- Largest systematic (1% – 8%) due to signal-efficiency interpolation between simulated points

Each of the 6 event plotted 3 times for the 3 $h' \rightarrow A'A'$ assignments:

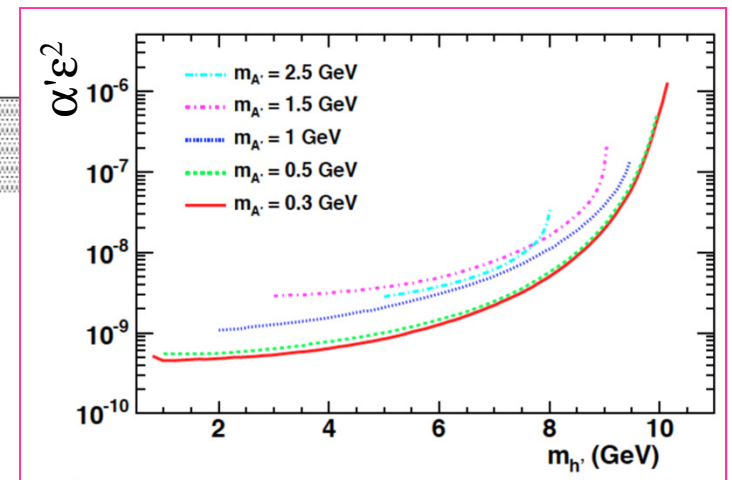
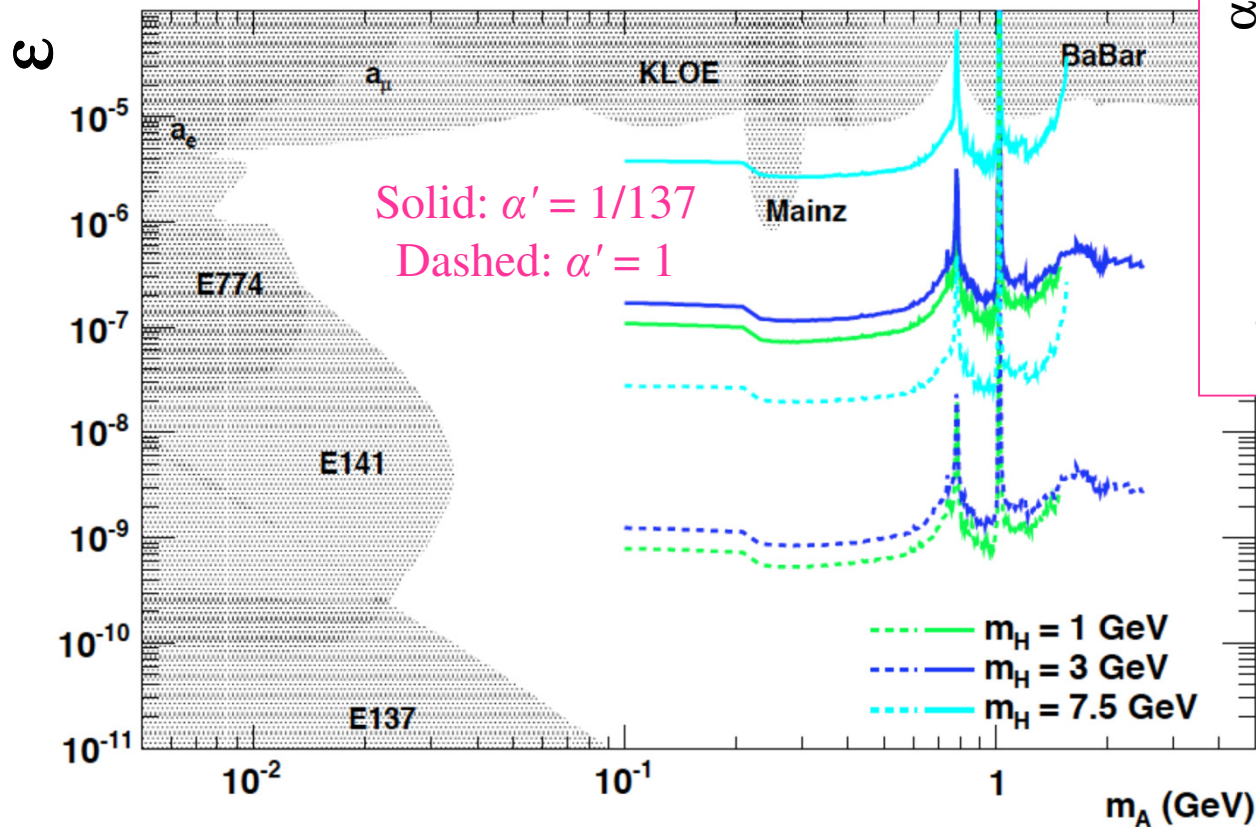
90% CL Bayesian upper limit on x-section, computed with a uniform prior:

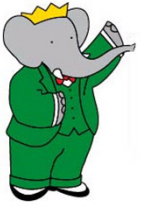




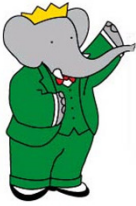
Parameter limits

- This model has a 4-parameter space: ϵ , $m_{A'}$, $m_{h'}$, α' .
- But here is a convenient representation for comparison with previous limits (which, keep in mind, depend only on ϵ , $m_{A'}$):





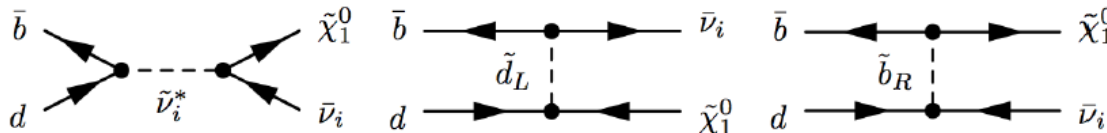
B → invisible



Motivation

- In SM $\text{BF}(B^0 \rightarrow \nu\nu) \sim (m_\nu/m_B)^2$ helicity suppressed
- $\text{BF}(B^0 \rightarrow \nu\nu\gamma) \sim 10^{-9}$, still unobservable
- In some NP models, $\text{BF}(B^0 \rightarrow \text{invisible})$ can be up to 10^{-6} :
 - Light neutralino contributions to $B^0 \rightarrow \text{invisible}$:

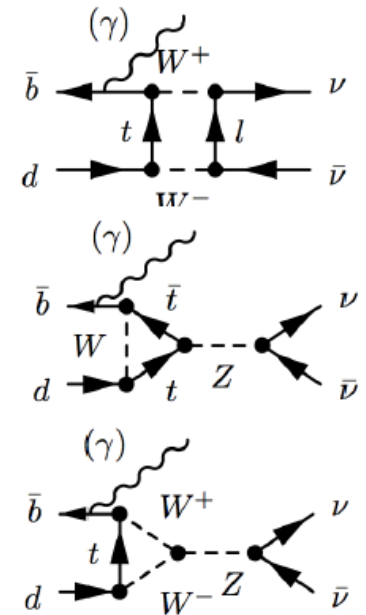
$$B_d^0 \rightarrow \bar{\nu}_i \tilde{\chi}_1^0$$

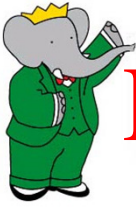


A. Dedes, H. Dreiner, and P. Richardson,
Phys. Rev. D65, 015001 (2002).

- Only existing limits are from BABAR (PRL 93, 091802 (2004)):
 - $\text{BF}(B^0 \rightarrow \text{invisible}) < 22 \times 10^{-5}$
 - $\text{BF}(B^0 \rightarrow \nu\nu\gamma) < 4.7 \times 10^{-5}$
- We now have
 - 5 times more data
 - Improved reconstruction, calibration, data reprocessing

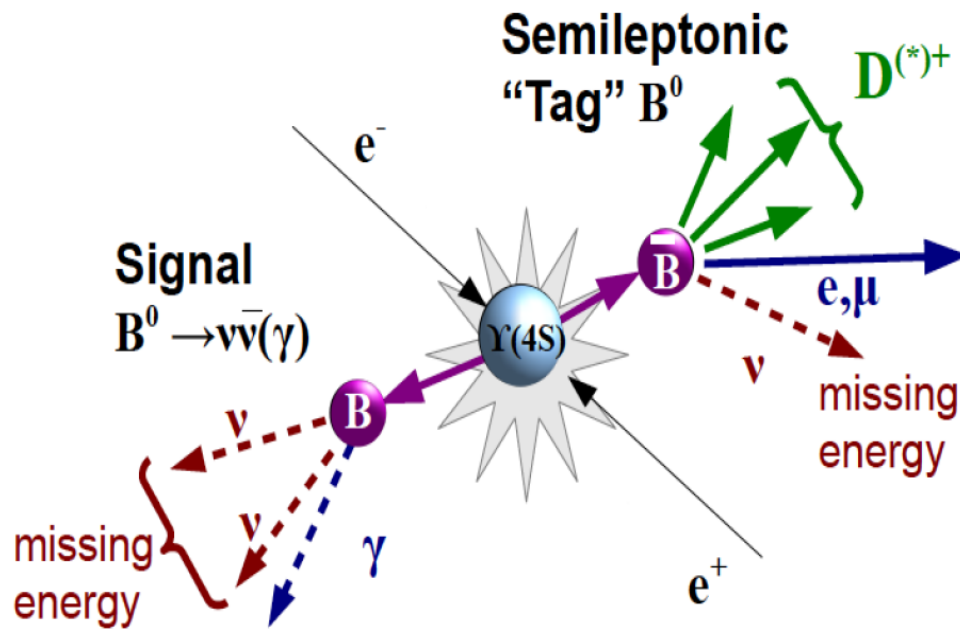
SM contributions:



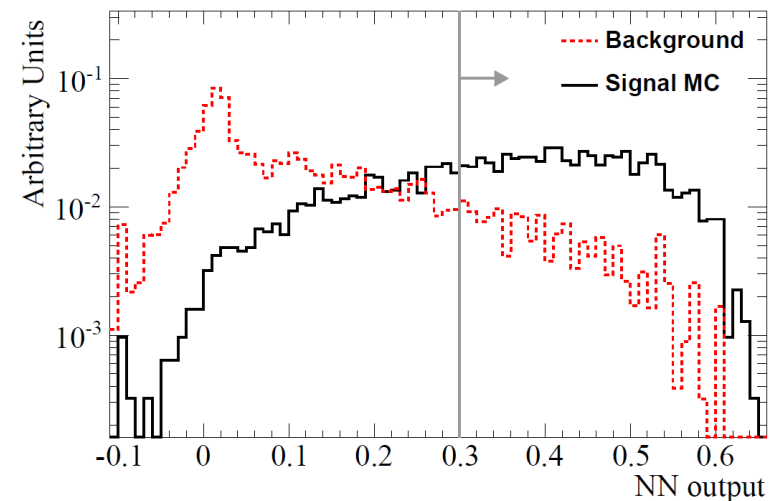


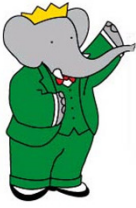
Exploiting the clean e^+e^- environment

Use semileptonic B tagging,
reconstructing only the D^{*l-} (and the optional γ):



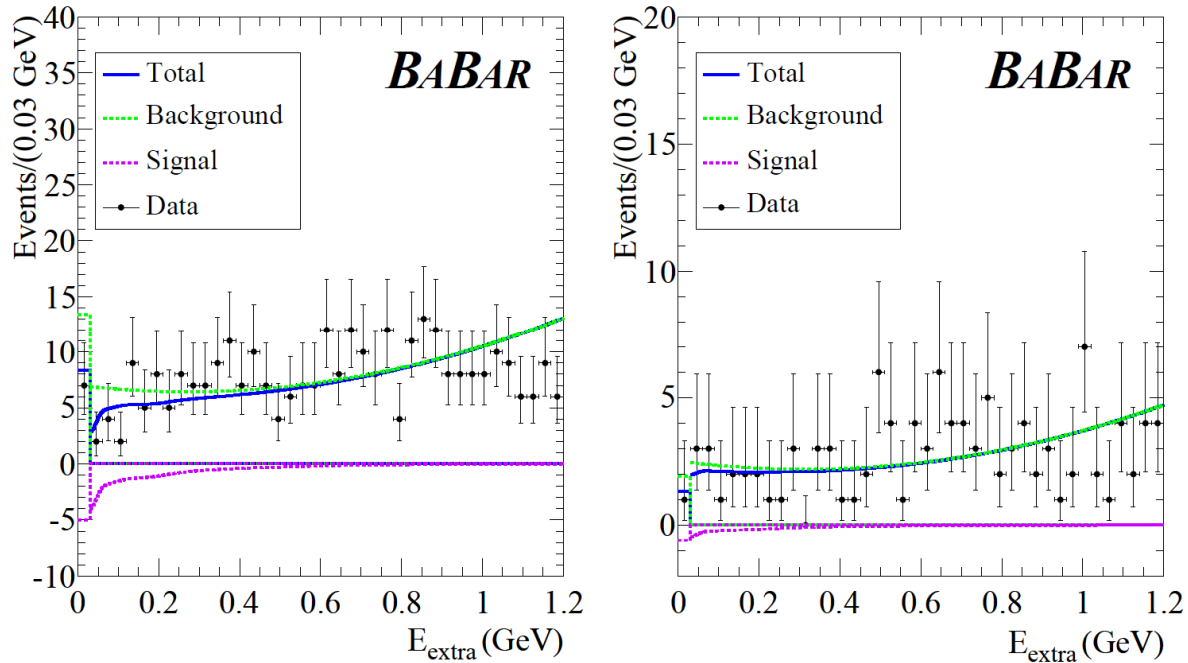
Combine 3-6 variables into a
neural network:





Results

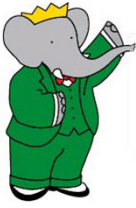
Fit the distribution of the extra energy in the calorimeter:



- Fit functions from MC
- Systematic on background shape from data-MC comparison in D sideband

Extract Bayesian upper limits @ 90% CL:

$$\mathcal{B}(B^0 \rightarrow \text{invisible}) < 2.4 \times 10^{-5}$$
$$\mathcal{B}(B^0 \rightarrow \text{invisible} + \gamma) < 1.7 \times 10^{-5}$$



Summary

- BABAR is very productive 4.5 years after end of data taking
- Recent and still-to-come results taking advantage of
 - Clean e^+e^- environment
 - Experience and interest of a large number of active analysts
 - New ideas (both theoretical and experimental)
- ~70 more papers to publish – stay tuned.