BABAR Experiment

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& McGill University

CAP Congress
Laurentian University
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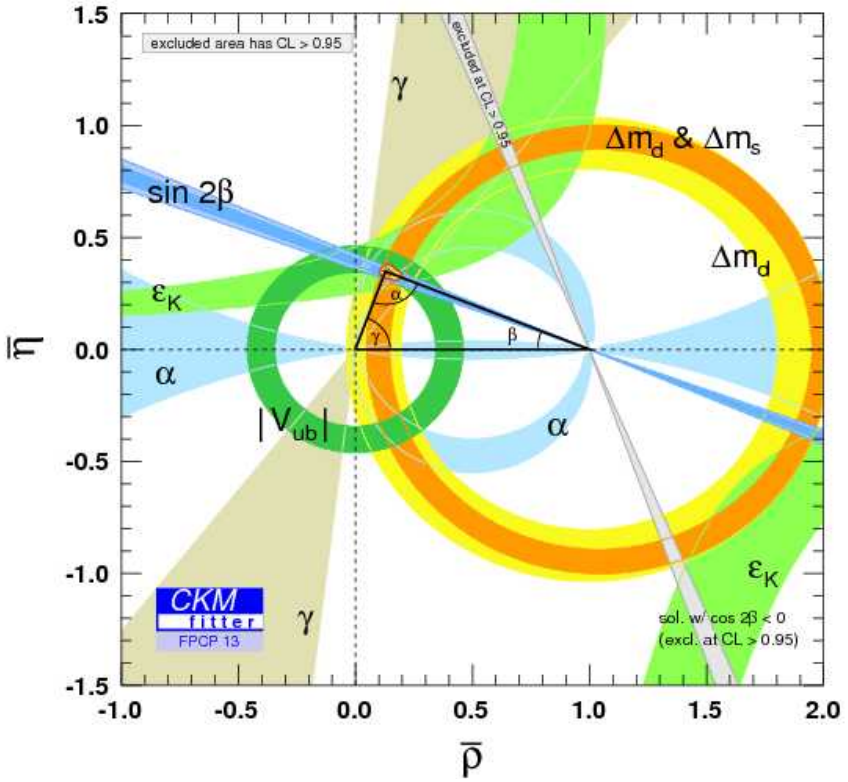
Outline

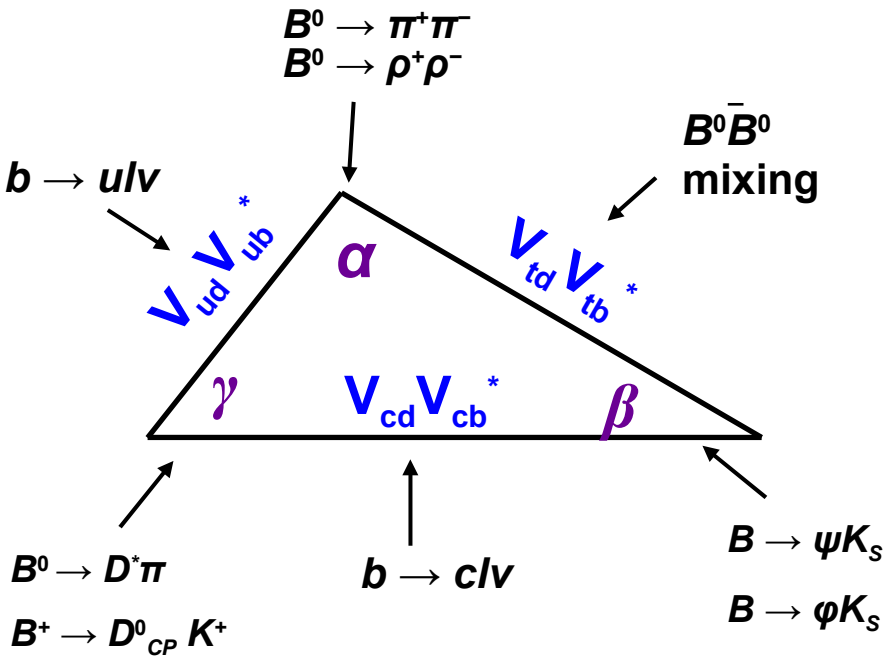
- Overview: motivation, data samples and physics program
- Milestones and recent projects
- Physics highlights

Physics overview

Heavy flavour provides an ideal testing ground for precision probes of physics beyond the Standard Model

- Precision measurements across a large variety of independent decay channels provide stringent tests of the underlying physics, e.g. BABAR/Belle constraints on the CKM “unitarity triangle”:





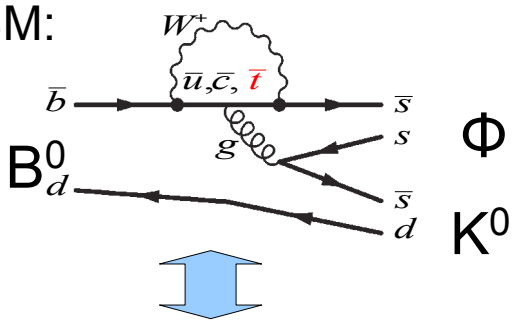
Physics overview (2)

In addition to “bread-and-butter” CP violation and CKM program, BABAR supports a very diverse physics program:

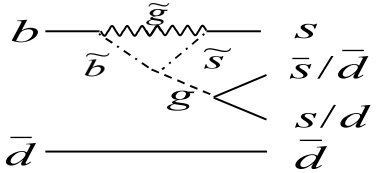
- New physics sensitivity across a broad range of searches and precision measurements in B, charm and tau decays,
- Wide variety of “exotic” searches for Higgs, dark matter (and force) candidates,
- quarkonium and new states
- $e^+e^- \rightarrow$ hadrons (muon g-2)

Hadronic decays:

SM:

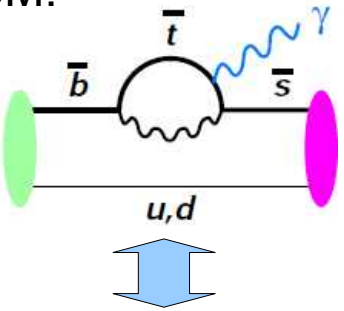


SUSY:

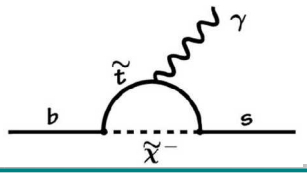


Electroweak FCNCs:

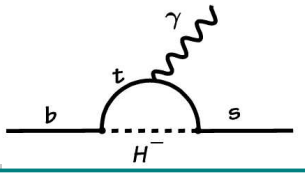
SM:



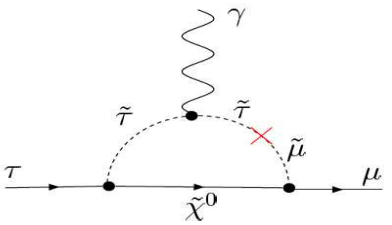
SUSY:



Charged Higgs:



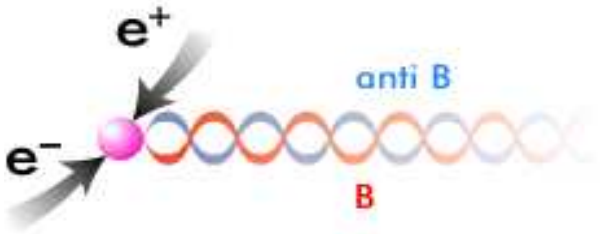
Rare/forbidden decays:



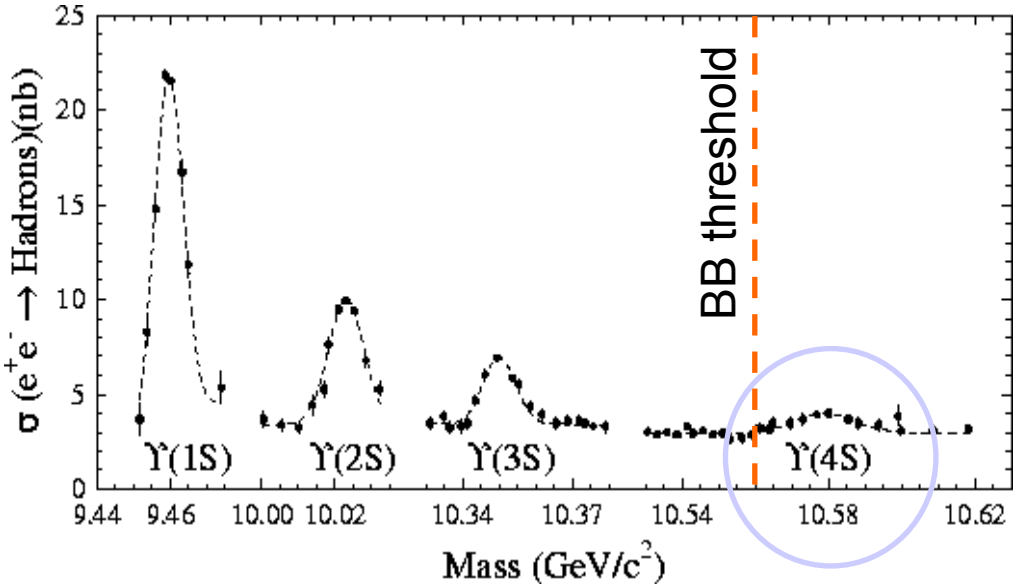
Asymmetric B Factories

Υ(4S) resonance lies just above the mass threshold for production of $B\bar{B}$ meson pairs

$B^0\bar{B}^0$ pair is produced in a coherent L=1 state



The two B mesons evolve in phase until one decays (EPR situation)



Process	Cross section (nb)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
light quark $q\bar{q}$	~2.1
$\tau\tau$	0.9
ee	~40

Boost from asymmetric beam energies permits separation of (nearly at rest in CM frame) B meson decay vertices

~1.1 million BB pairs per fb^{-1}

BABAR Detector

1.5T
Solenoid

EMC
6580 CsI(Tl) crystals

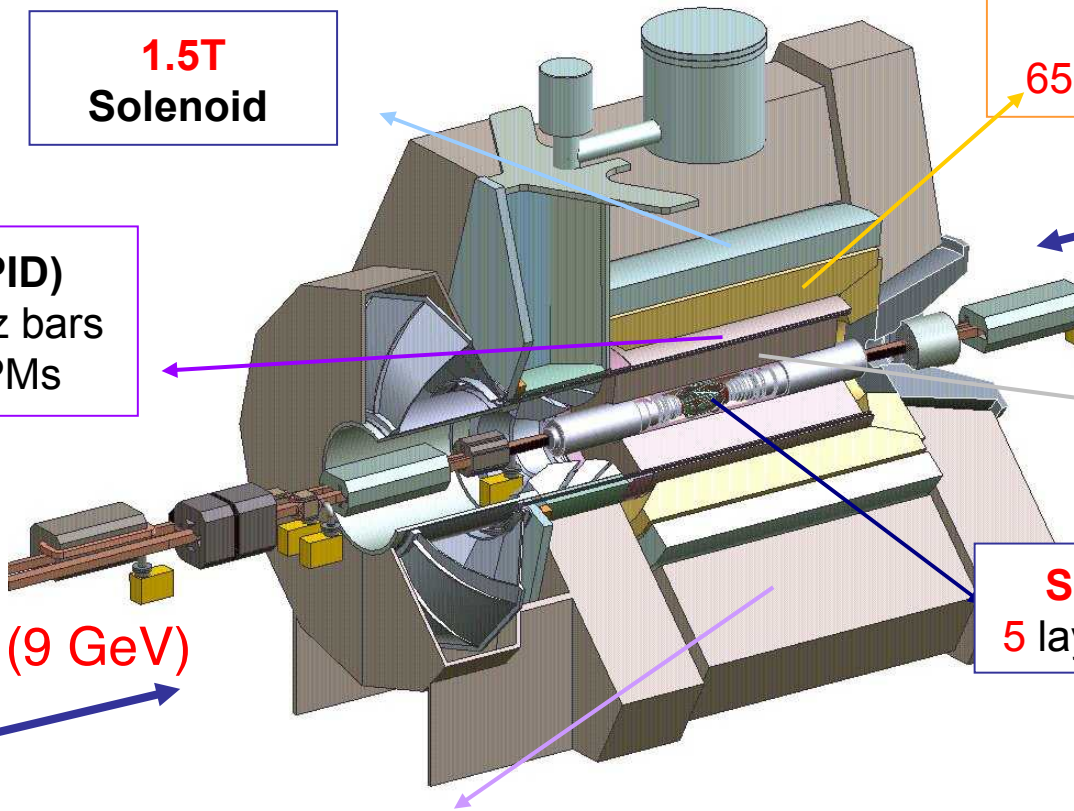
e (3.1GeV)

DIRC (PID)
144 quartz bars
11000 PMs

Drift Chamber
40 layers

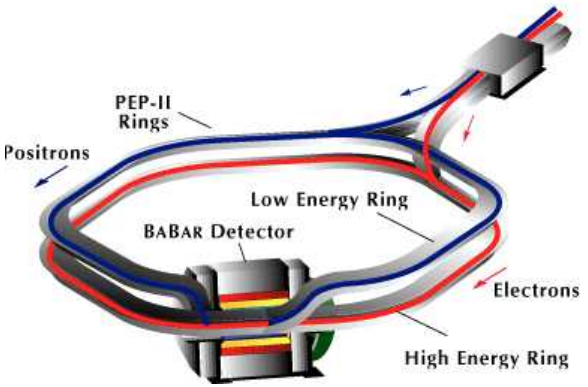
Silicon Vertex Tracker
5 layers, double sided strips

e (9 GeV)



Instrumented Flux Return
iron / RPCs (muon / neutral hadrons)

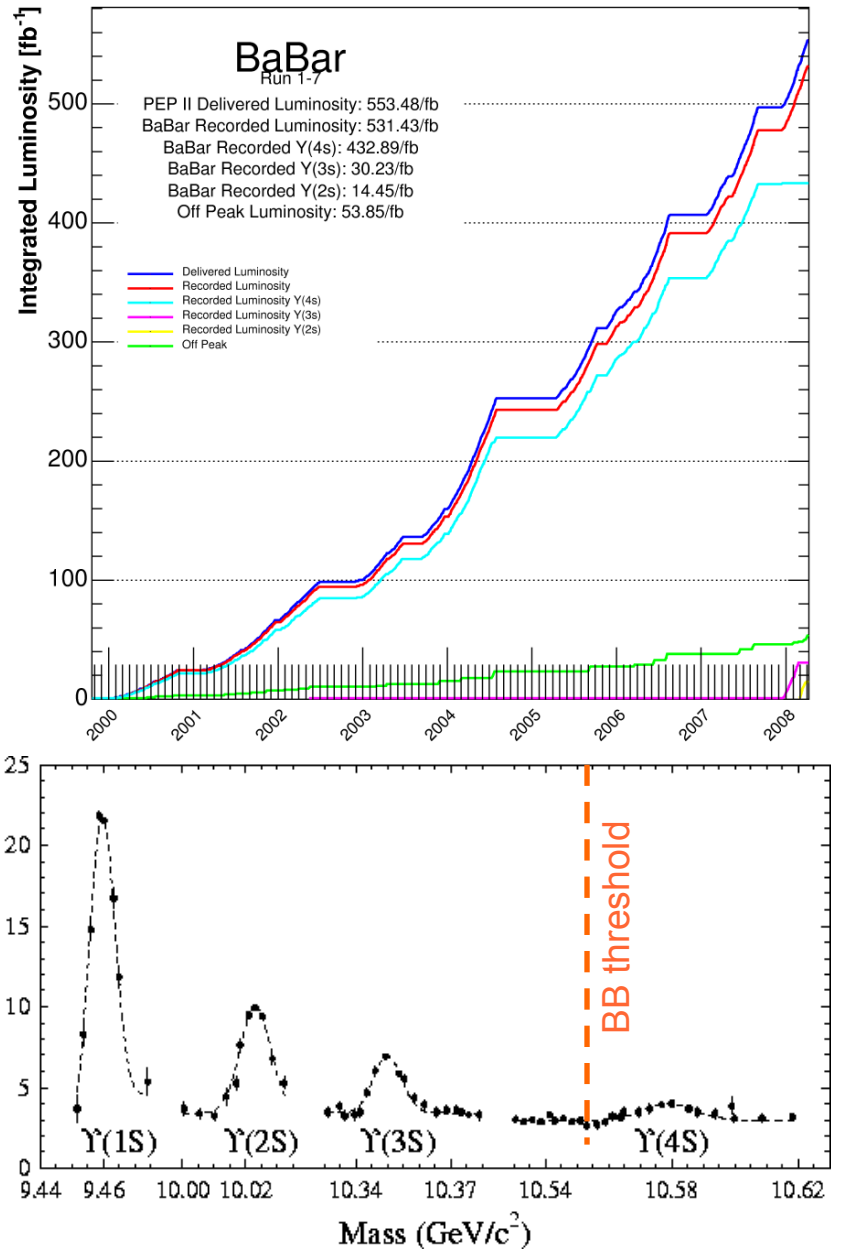
13 Countries
~72 Institutions
~280 Physicists



Data sets

BABAR collected data from 1999-2008

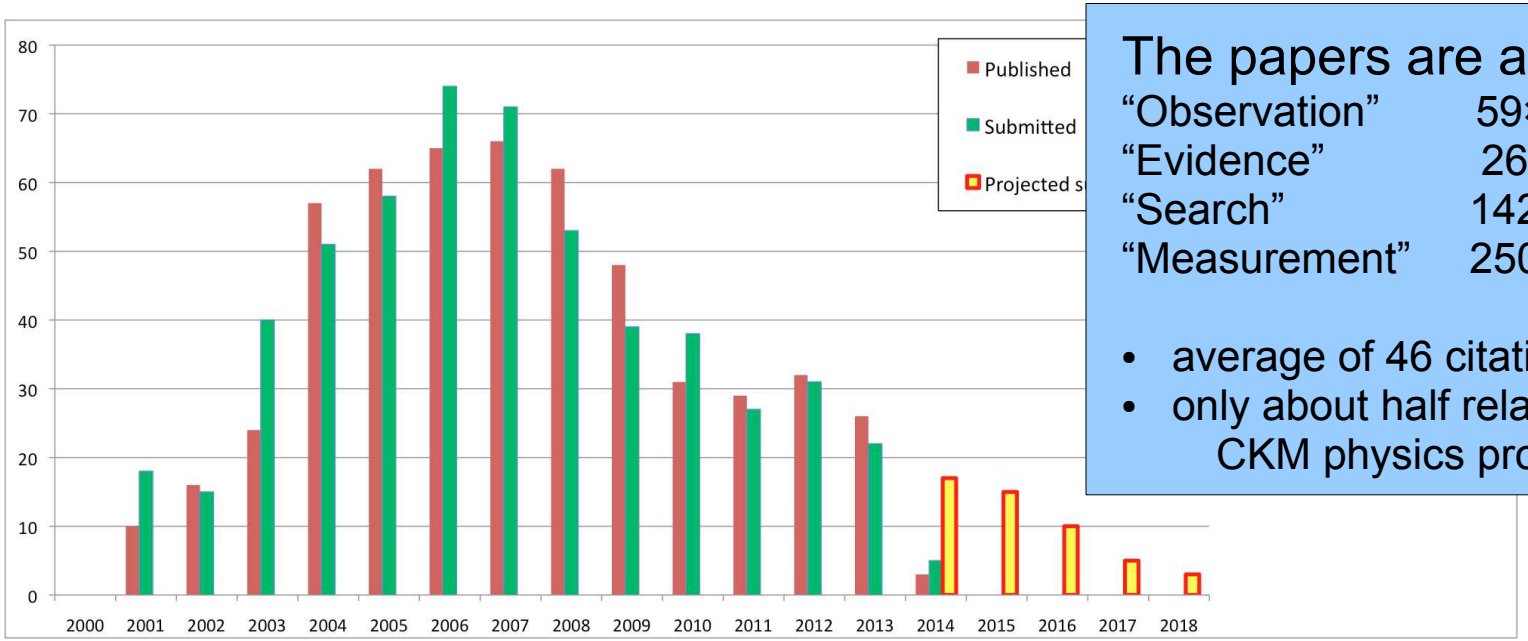
- 432 fb^{-1} $\Upsilon(4S)$ "onpeak"
  (~470 x 10^6 BB pairs)
- 53 fb^{-1} "offpeak"
  - collected ~40MeV below $\Upsilon(4S)$ peak
- Samples of "narrow Υ" events collected during last few months of running:
  - 122 x 10^6 $\Upsilon(3S)$ decays
  - 99 x 10^6 $\Upsilon(2S)$ decays



Physics program

Over 530 BABAR physics papers published since 1999, almost 200 of which were after the end of data taking in 2008

- Anticipate ~20 publications in 2014, with about 50 analyses still (genuinely) active within the collaboration
- Canadian leadership in many key research areas, including semileptonic B decays, rare decay searches, tau and quarkonium physics and dark matter / light Higgs boson searches



The papers are about (from INSPIRE):

"Observation"	59× (31 PRL, 28 PRD)
"Evidence"	26× (16 PRL, 10 PRD)
"Search"	142× (54 PRL, 88 PRD)
"Measurement"	250× (98 PRL, 152 PRD)

- average of 46 citations per paper
- only about half relate to "core" BABAR CKM physics program

Canadian participation

Substantial Canadian participation and leadership in BABAR over the years, and continued high level of activity

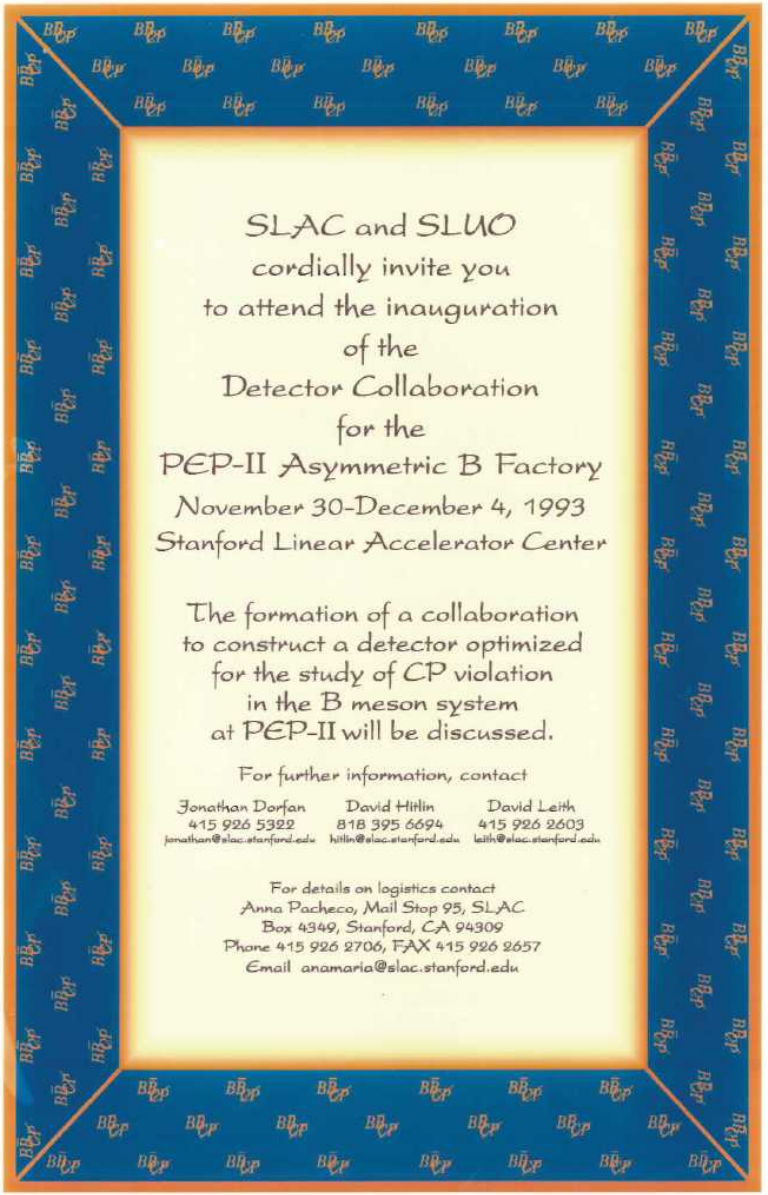
- Canadian responsibility for BABAR drift chamber construction and operation
- M. Roney is collaboration spokesperson
- Three former Physics Coordinators, several Run Coordinators, Speakers Bureau Chairs and Publications Board Chairs
- Leadership of Analysis Working Groups and in several areas of physics research, with ~35 publications having Canadians as primary analysts/authors

Signatories of current NSERC project grant:

UBC: C. Hearty, J. McKenna, T. Mattison
UVic: J. Albert, B. Kowalewski, M. Roney
McGill: S. Robertson
(UdeM group left the collaboration in 2013)

- Currently 7 Canadian graduate students and postdocs
- 14 BABAR conference talks in by Canadian group members in 2013

20 Years of BABAR


SLAC and SLUO
cordially invite you
to attend the inauguration
of the
Detector Collaboration
for the
PEP-II Asymmetric B Factory
November 30-December 4, 1993
Stanford Linear Accelerator Center

The formation of a collaboration
to construct a detector optimized
for the study of CP violation
in the B meson system
at PEP-II will be discussed.

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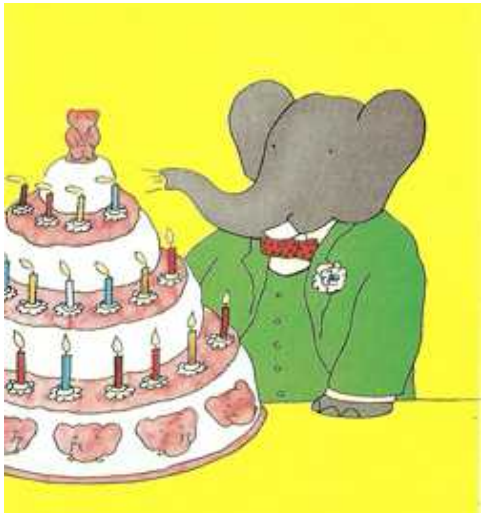
Phone 415 926 2706, FAX 415 926 2657
Email anamaria@slac.stanford.edu

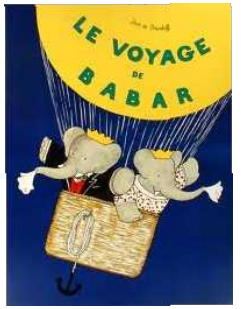
BABAR experiment collaboration celebrated its 20th birthday at the end of 2013

- Collaboration celebrated this significant milestone during a recent collaboration meeting in Frascati, Italy



Historical reflection on development of the B factories and the achievements of BABAR

BABAR Prehistory



- In early 1980's Bigi and Sanda showed that a measurement of CP violation in B decays could be cleanly interpreted in a CKM context
- Measurements of B meson lifetime (Mark II and MAC), combined with substantial Bd mixing (ARGUS and UA1) in the late 80's indicated that CP violation measurements might be possible

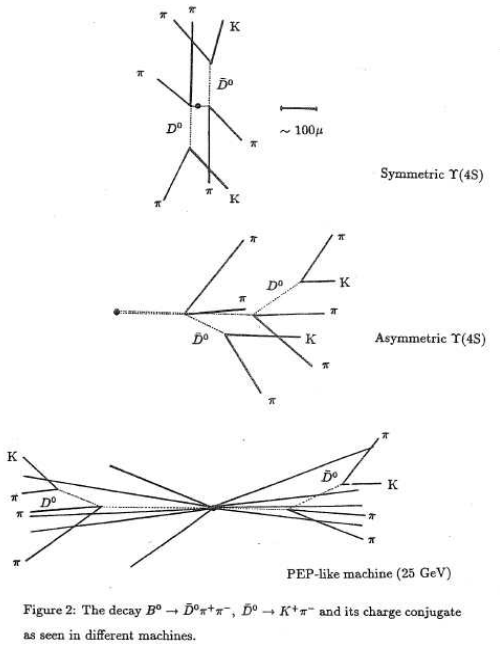


Figure 2: The decay $B^0 \to \bar{D}^0\pi^+\pi^-$, $\bar{D}^0 \to K^+\pi^-$ and its charge conjugate as seen in different machines.

P. Oddone

Proceedings of the UCLA Workshop

LINEAR-COLLIDER BB̄ FACTORY CONCEPTUAL DESIGN

26-30 January 1987

E_{CM} GeV	Class	$E_1 \times E_2$ GeV × GeV	$\sigma_{b\bar{b}}$	Peak L proposed $cm^{-2}sec^{-1}$		
Υ(4S)	CM RING	5 × 5		5×10^{32}		
	CM LINEAR	5 × 5		10^{33}		
	BOOSTED LINEAR	2 × 12.5	1 nb	5×10^{32}	$5 \cdot 10^6$	*Sessler & Wurtele*[3]
	BOOSTED RING	2 × 12.5		5×10^{32}	$5 \cdot 10^6$	*Oddone*[4]
Continum 20 GeV	RING		0.1 nb	5×10^{33}	$5 \cdot 10^6$	*Bloom*[5]
	LINEAR			10^{34}	10^7	*Amaldi & Coignet*[2]
Z^0	LINEAR SLC	45 × 45	5 nb	5×10^{30}	$2.5 \cdot 10^5$	*SLC Study*[6]
	LEP	45 × 45		2×10^{31}	$8 \cdot 10^5$	*LEP Study*[7]
	RING IMAGINARY	45 × 45		5×10^{33}	$2.5 \cdot 10^8$	

Adapted from D. Hitlin

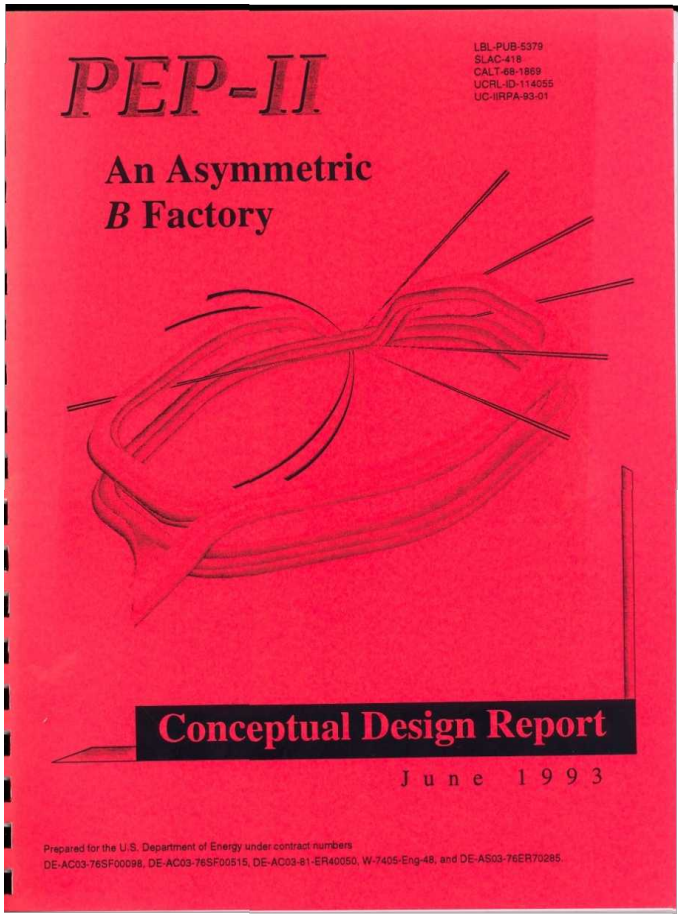
Over 20 distinct concepts and proposals for e+e- B factories, as well as several hadronic machines

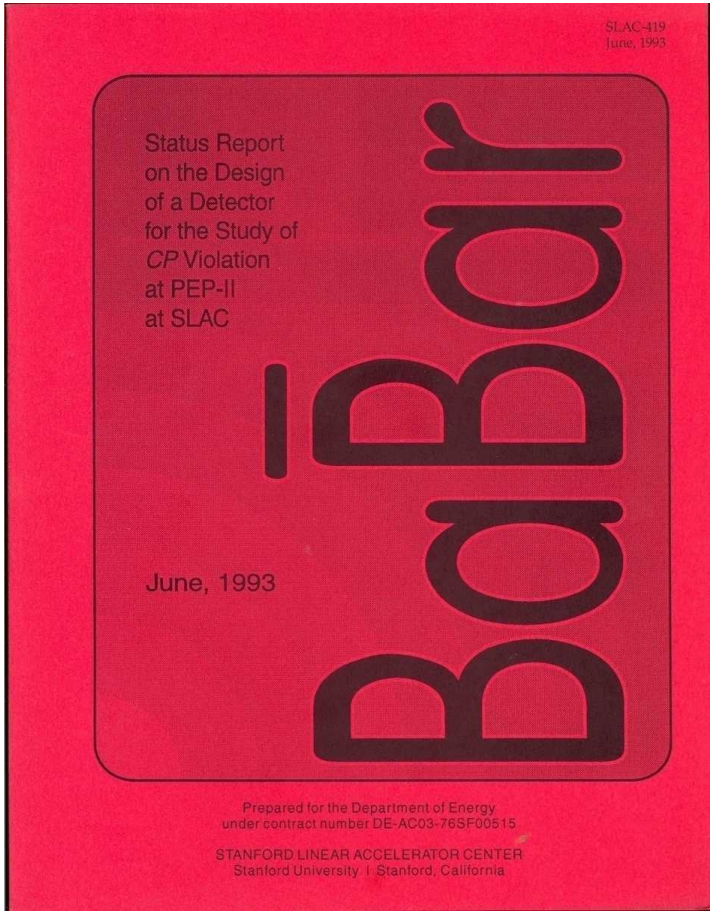
BABAR Prehistory

"It is SLAC's goal to be ready to propose an intermediate energy linear collider (0.5 to 1.5 TeV) by the early 1990s."

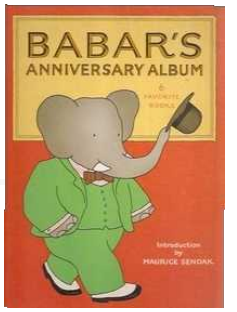
Gary Feldman, Physics in Collision, 1986

1993

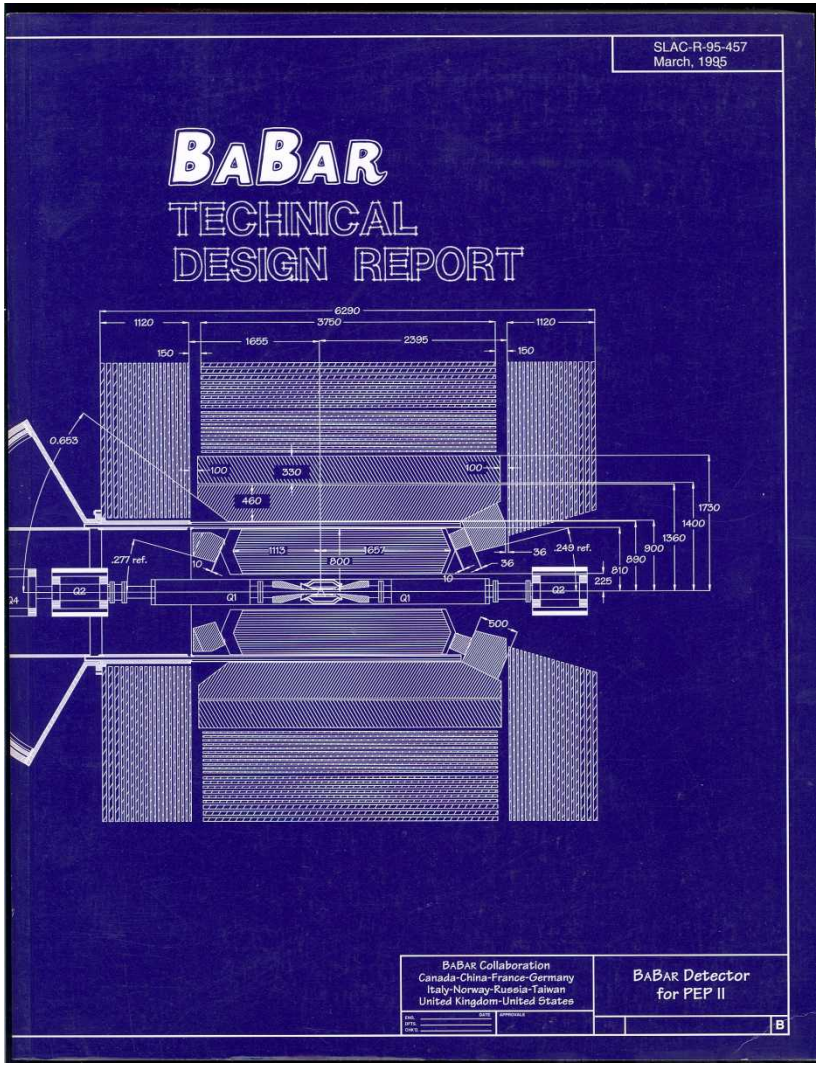




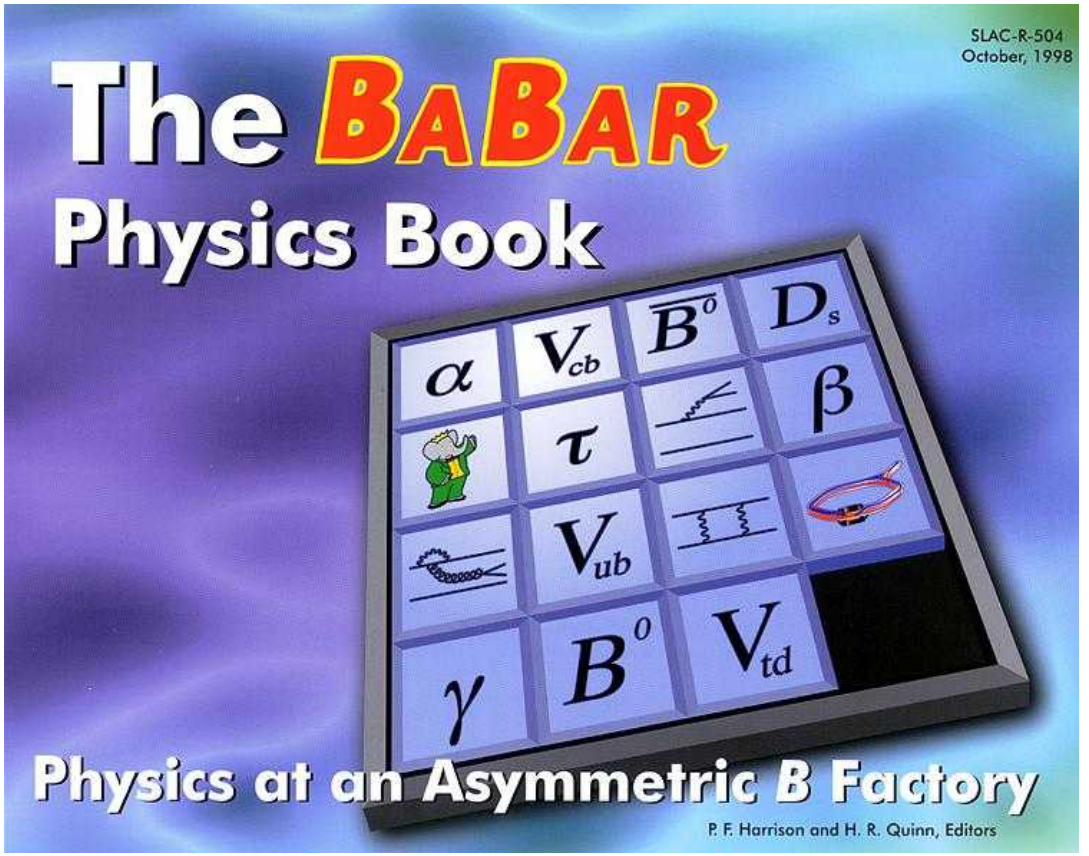
BABAR / PEP-II



March 1995

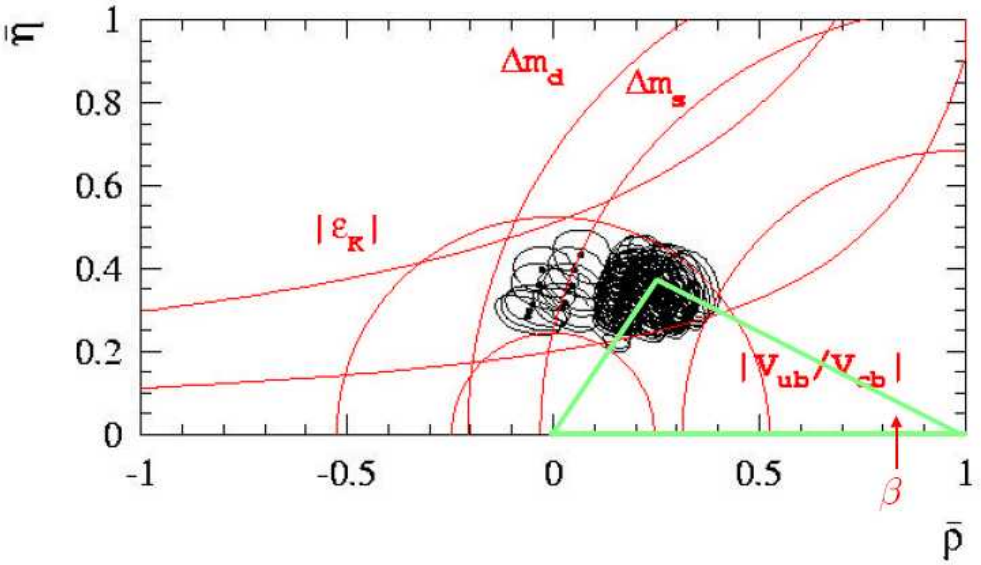


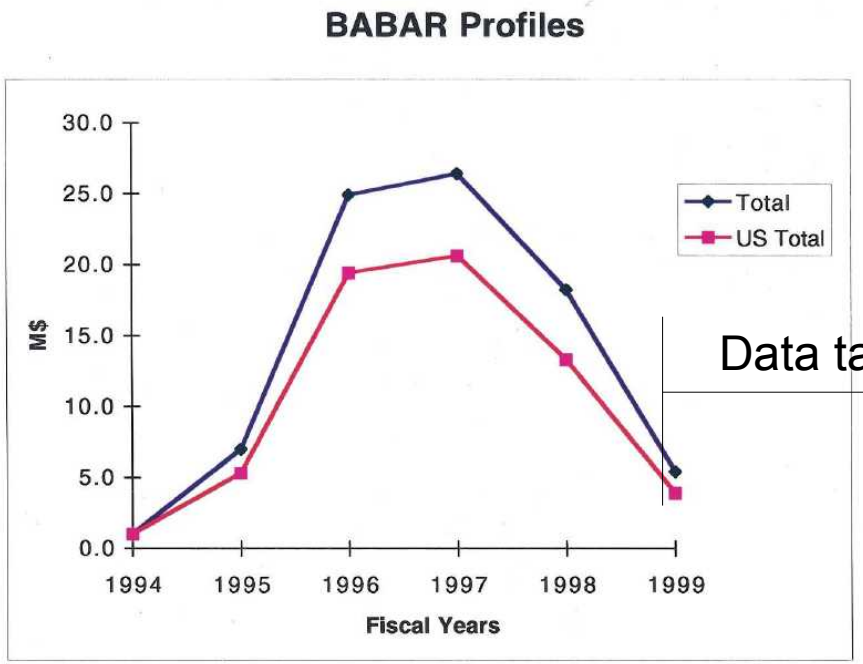
Oct 1998



Start of data taking (98-99)

- Very short construction and commissioning phase, and rapid transition to data taking





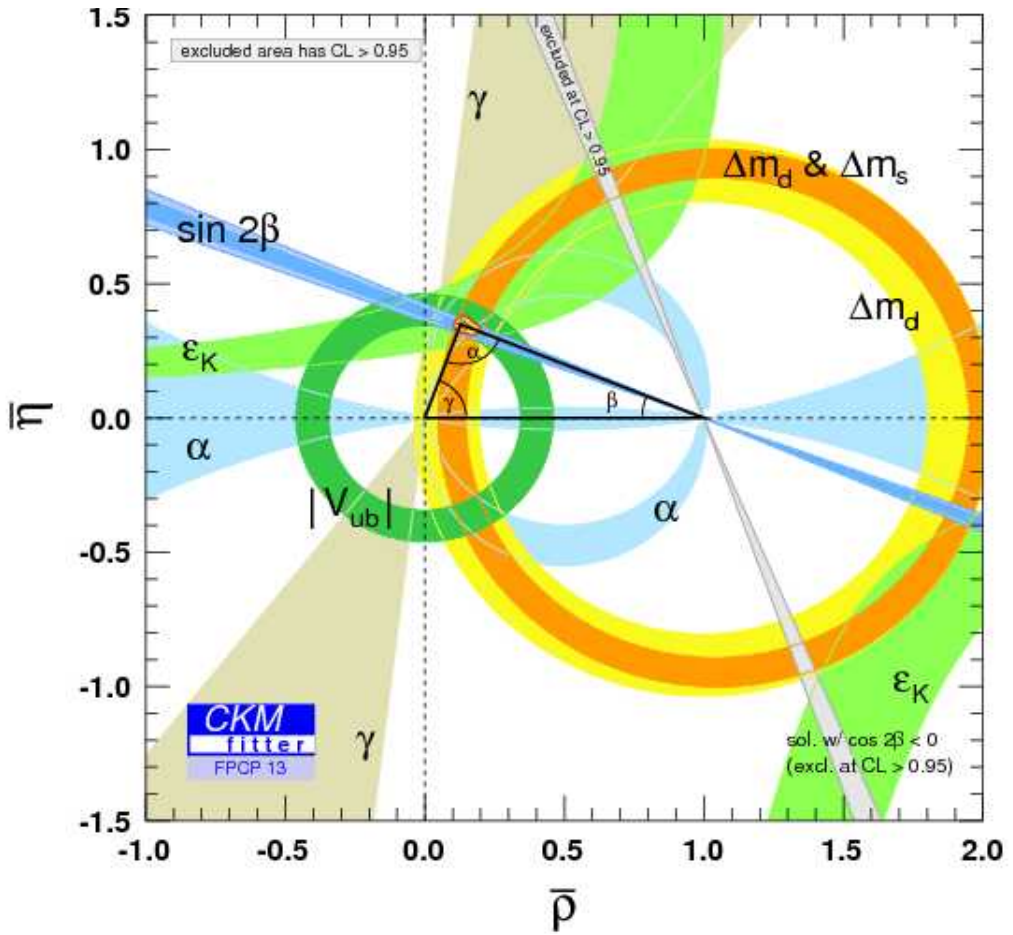
	1994	1995	1996	1997	1998	1999	Sum
Total	1.0	7	24.9	26.4	18.2	5.4	82.9
US Total	1.0	5.3	19.4	20.6	13.3	3.9	63.5

Data taking →

1998:
Unitarity Triangle sides were poorly determined and no angles had been measured

- First CP violation measurements published in Feb 2001

Results



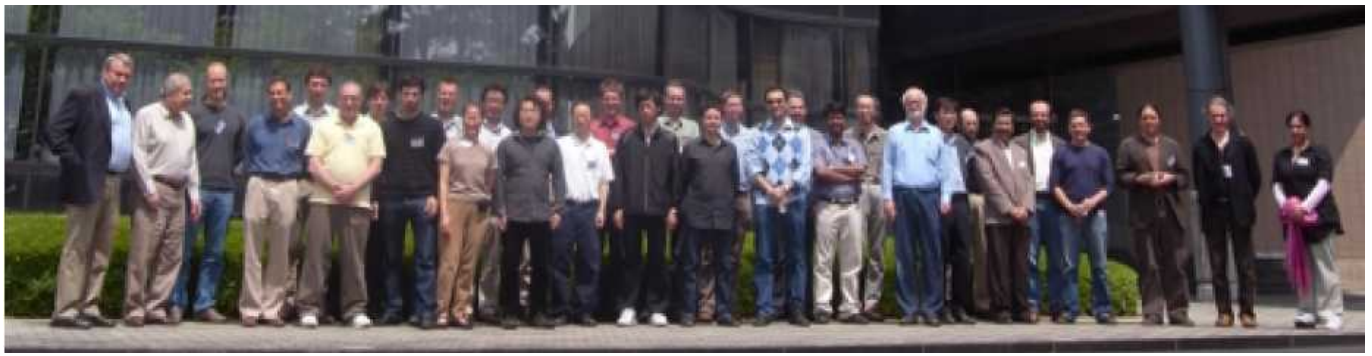
2008 Nobel citation:

"As late as 2001, the two particle detectors BaBar at Stanford, USA andBelle at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as Kobayashi and Maskawa had predicted almost three decades earlier."

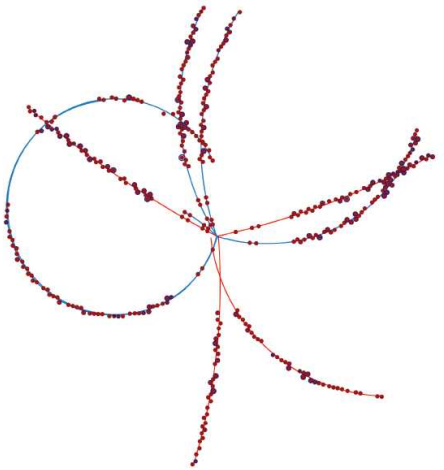
Physics of the B Factories

"Physics of the B Factories" book

- Collaborative project with Belle to document the physics program of the asymmetric B factories
  - Pedagogic presentation aimed at new generation of flavour physics students
  - 937 pages of text covering 25 chapters, to be published as a stand-alone volume
- Multi-year effort with substantial contributions by ~100 BABAR/Belle co-editors and contributors including several Canadian group members
- Currently undergoing final editing; submission to publishers within next few weeks!



PBF Book workshop, KEK 2010



Performance papers

Companion paper on BABAR detector performance published in NIM in 2013 (~100 pages)

- Also final performance papers on tracking and luminosity

The *BABAR* detector: Upgrades, operation and performance

B. Aubert[a], R. Barate[a], D. Boutigny[a], F. Couderc[a], P. del Amo Sanchez[a], J.-M. Gaillard[a], A. Hicheur[a], Y. Karyotakis[a], J.P. Lees[a], V. Poireau[a], X. Prudent[a], P. Robbe[a], V. Tisserand[a], A. Zghiche[a], E. Grauges[b], J. Garra Tico[b], L. Lopez[c, d], M. Martinelli[c, d], A. Palano[c, d], M. Pappagallo[c, d], A. Pompili[c, d], G.P. Chen[e], J.C. Chen[e], N.D. Qi[e], G. Rong[e], P. Wang[e], Y.S. Zhu[e], G. Eigen[f], B. Stugu[f], L. Sun[f], G.S. Abrams[g], M. Battaglia[g], A.W. Borgland[g], A.B. Breon[g], D.N. Brown[g], J. Button-Shafer[g], R.N. Cahn[g], E. Charles[g], A.R. Clark[g], C.T. Day[g], M. Furman[g],

Time-integrated luminosity recorded by the BABAR detector at the PEP-II e^+e^- collider

J.P. Lees[a], V. Poireau[a], V. Tisserand[a], E. Grauges[b], A. Palano[ab, c], G. Eigen[d], B. Stugu[d], D.N. Brown[e], L.T. Kerth[e], Yu.G. Kolomensky[e], G. Lynch[e], H. Koch[f], T. Schroeder[f], D.J. Asgeirsson[g], C. Hearty[g], T.S. Mattison[g], J.A. McKenna[g], R.Y. So[g], A. Khan[h], V.E. Blinov[i], A.R. Buzykaev[i], V.P. Druzhinin[i], V.B. Golubev[i], E.A. Kravchenko[i], A.P. Onuchin[i], S.I. Serednyakov[i], Yu.I. Skovpen[i], E.P. Solodov[i], K.Yu. Todyshev[i], A.N. Yushkov[i], D. Kirkby[j], A.J. Lankford[j], M. Mandelkern[j], B. Dey[k], J.W. Gary[k], O. Long[k], G.M. Vitug[k], C. Campagnari[l], M. Franco Sevilla[l], T.M. Hong[l], D. Kovalskyi[l],

Track finding efficiency in *BABAR*

T. Allmendinger[a], B. Bhuyan[b], D.N. Brown[c], H. Choi[d], S. Christ[e], R. Covarelli[f], M. Davier[g], A.G. Denig[h], M. Fritsch[h], A. Hafner[h], R. Kowalewski[d], O. Long[i], A.M. Lutz[g], M. Martinelli[ij], D.R. Muller[k], I.M. Nugent[d], D. Lopes Pegna[i], M.V. Purohit[m], E. Prencipe[h], J.M. Roney[d], G. Simi[n], E.P. Solodov[o], A.V. Telnov[i], E. Varnes[i], R. Waldi[e], W.F. Wang[p], R.M. White[m]

Canadian contributions to all three papers

Planning for the future

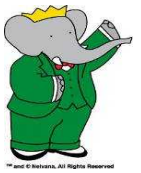
BABAR anticipates SLAC-supported analysis activities through 2018, but long-term planning is in progress

- Recent changes to collaboration governance and publications rules to ensure the possibility of publishing BABAR papers indefinitely

Long Term Data Analysis (LTDA) system

- Provides stable computing access in “archival” system to full suite of data and software tools (simulation, reconstruction, analysis etc.), databases, and documentation through at least 2018
- First instance of a fully-deployed “archival data system” for HEP by a large experimental collaboration
- Now the primary analysis platform for all ongoing BABAR analysis (~500000 batch jobs in April 2014)

Planning for the future (2)



Analysis documentation

- Overhaul of the analysis software and tools documentation to ensure that it is usable for future data analysis, in the absence of accessible “experts”

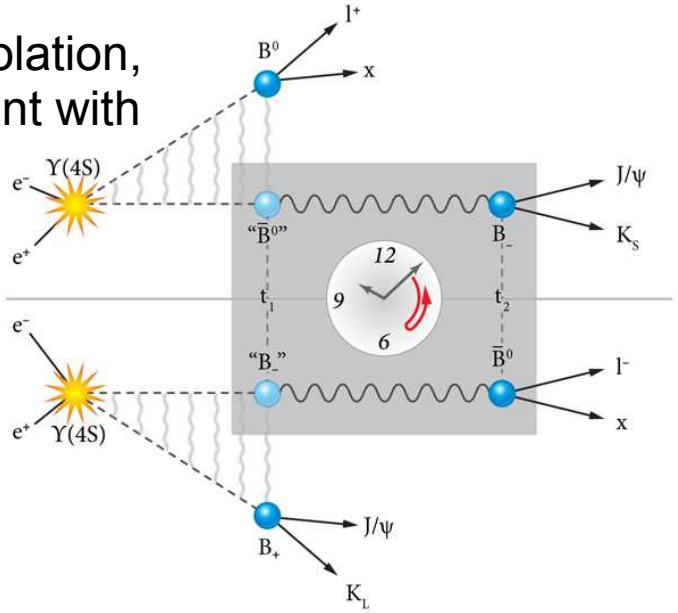
BABAR-On-The-Go

- Porting of entire suite of software tools, databases, code etc to “decentralized” computing platforms (i.e your laptop), to ensure capability to analyze BABAR data into the indefinite future

Recent highlights: T violation

First unequivocal measurement of T (time reversal) violation independent of CP (or CPT)

- compare time-order reversed decays of entangled $B\overline{B}$ pairs into CP and flavour-tagged states
- ~14σ significance T-violation, (reassuringly) consistent with CPT conservation



Physics
spotlighting exceptional research

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Viewpoint: Particle Decays Point to an Arrow of Time

Michael Zeller, *Department of Physics, Yale University, New Haven, CT 06520, USA*

Published November 19, 2012 | *Physics* 5, 129 (2012) | DOI: 10.1103/Physics.5.129

An experiment studying *B* meson decays makes a direct observation of time-reversal violation without relying on assumed relationships with other fundamental symmetries.

http://physics.aps.org/articles/v5/129

The Economist

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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 444 Tweet 63

http://www.economist.com/node/21561111

Observation of Time-Reversal Violation in the B^0 Meson System

J. P. Lees et al. (The BABAR Collaboration)

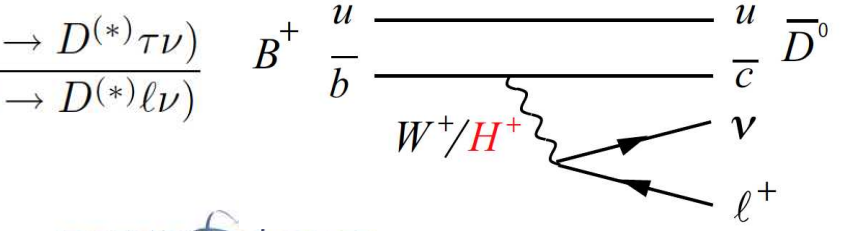
Phys. Rev. Lett. **109**, 211801 – Published 19 November 2012

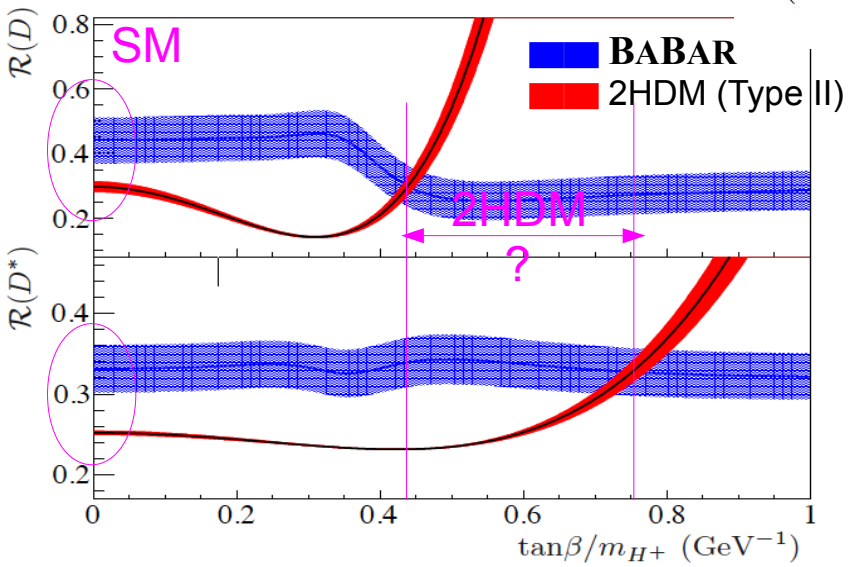
$B \to D^{(*)}\tau\nu$

Intriguing inconsistency with SM predictions in $B \to D^*\tau\nu$ and $B \to D\tau\nu$

- tree-level SM process with potential sensitivity to charged Higgs in Type-II 2HDM
- simultaneous measurement of ratio of BFs expected to be theoretically and experimentally clean:

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





Evidence for an Excess of $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$ Decays

J. P. Lees et al. (BABAR Collaboration)

Phys. Rev. Lett. **109**, 101802 – Published 6 September 2012

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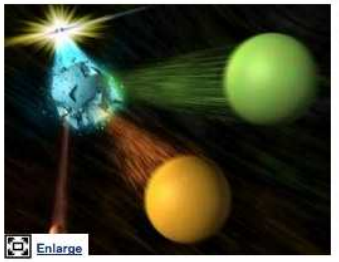
BaBar experiment data hint at cracks in the Standard Model

June 18, 2012



The latest results from the BaBar experiment may suggest a surplus over Standard Model predictions of a type of particle decay called "B to D-star-tau-nu." In this conceptual art, an electron and positron collide, resulting in a B meson (not shown) and an antimatter B-bar meson, which then decays into a D meson and a tau lepton as well as a smaller antineutrino. Credit: Image by Greg Stewart, SLAC National Accelerator Laboratory

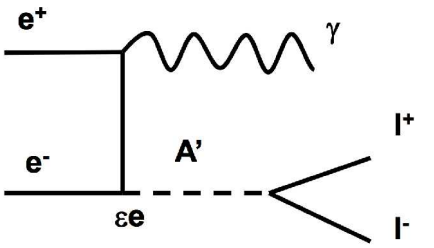
(Phys.org) -- Recently analyzed data from the BaBar experiment may suggest possible flaws in the Standard Model of particle physics, the reigning description of how the universe works on subatomic scales. The data from BaBar, a high-energy physics experiment based at the U.S. Department of Energy's (DOE) SLAC National Accelerator Laboratory, show that a particular type of particle decay called "B to D-star-tau-nu" happens more often than the Standard Model says it should.

Interestingly, $B \to \tau\nu$ shows a similar excess, but also inconsistent with 2HDM interpretation

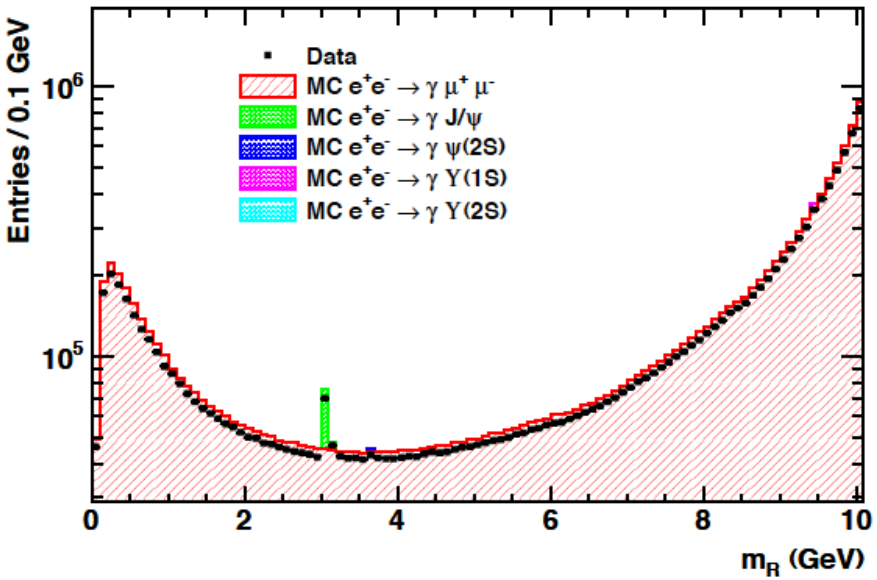
“Dark Forces”

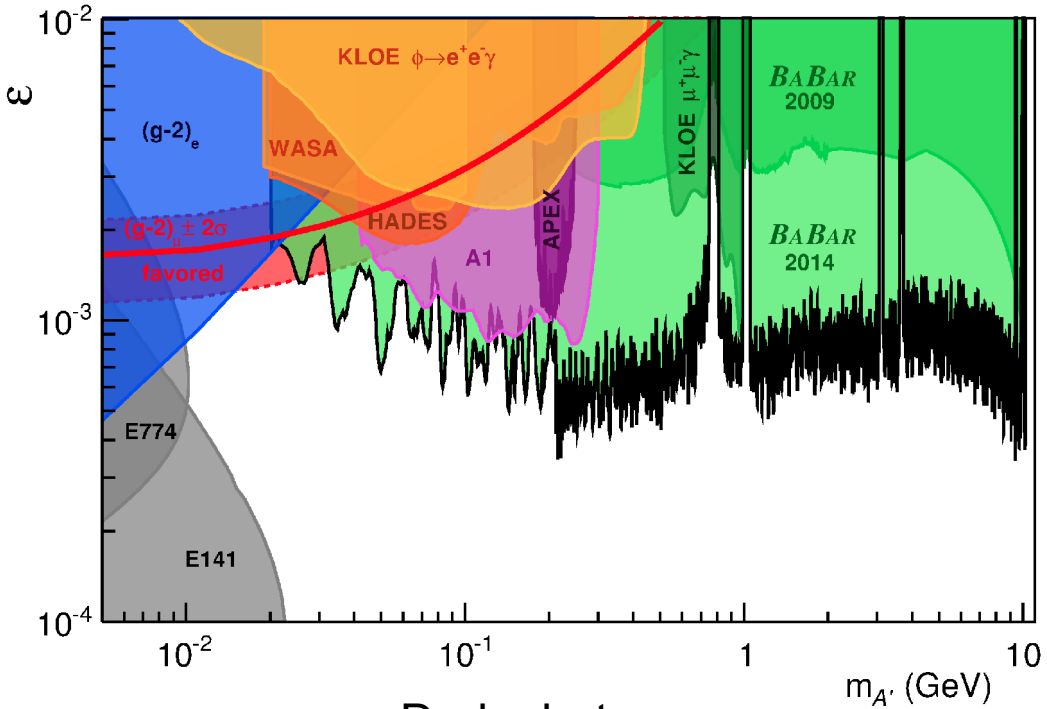
“Dark sector” models explain dark matter by introducing new particles which interact via their own gauge (and Higgs) sector

arXiv:1406.2980 [hep-ex]



- massive Abelian gauge boson (A') can interact with SM particles via kinetic mixing, parametrized by coupling ε
- search for mass peaks in di-lepton invariant mass spectrum





Dark photon mass

Light Higgs

NMSSM solves the "μ problem" of the MSSM by adding a singlet chiral superfield

- two additional Higgs bosons, the lightest of which (A^0) can be ~1 GeV (too light to decay to bb)
- decays characterized by m_{A0}, tanβ and the mixing between the singlet and non-singlet CP-odd Higgses

Non singlet fraction $\mathrm{Cos}\theta_A$

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

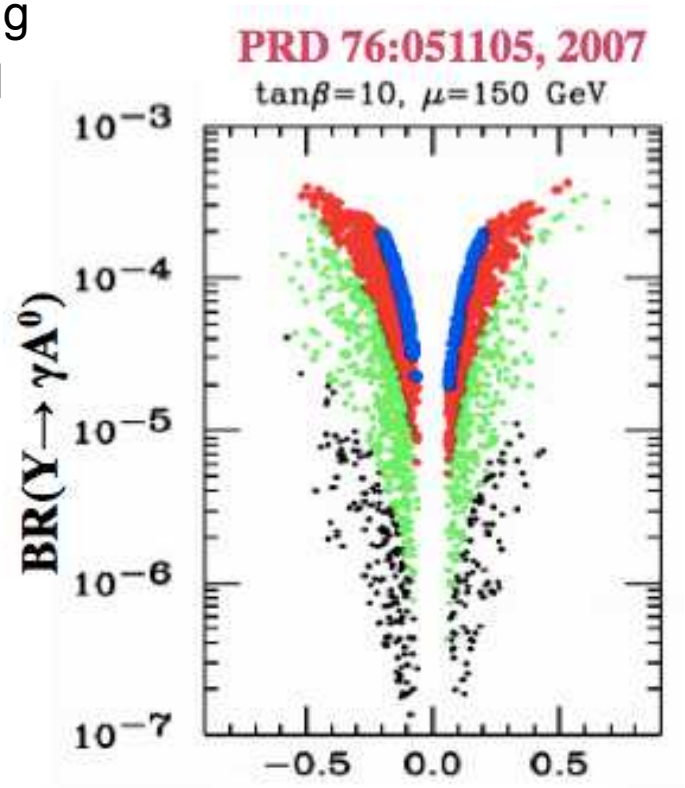
$2m_\tau < m_{A^0} < 7.5$ GeV/c²

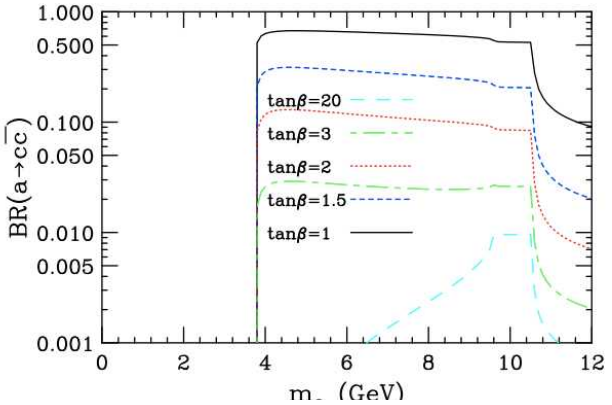
7.5 GeV < m_{A^0} < 8.8 GeV/c²

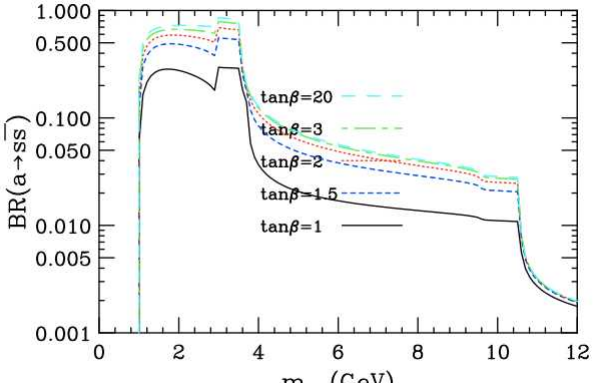
8.8 GeV/c² < m_{A^0} < 9.2 GeV/c²

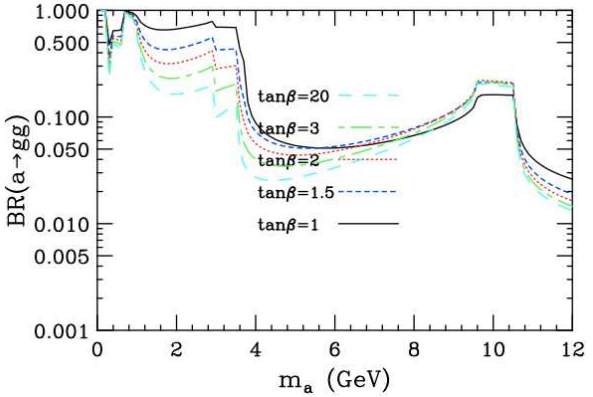
$A^0 = \mathrm{Cos}\Theta_A A_{MSSM} + \mathrm{Sin}\Theta_A A_S$

Non singlet — Singlet









Light Higgs

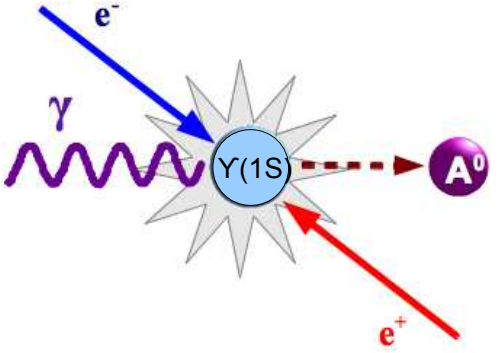
PRD-RC 88, 031701 (2013)

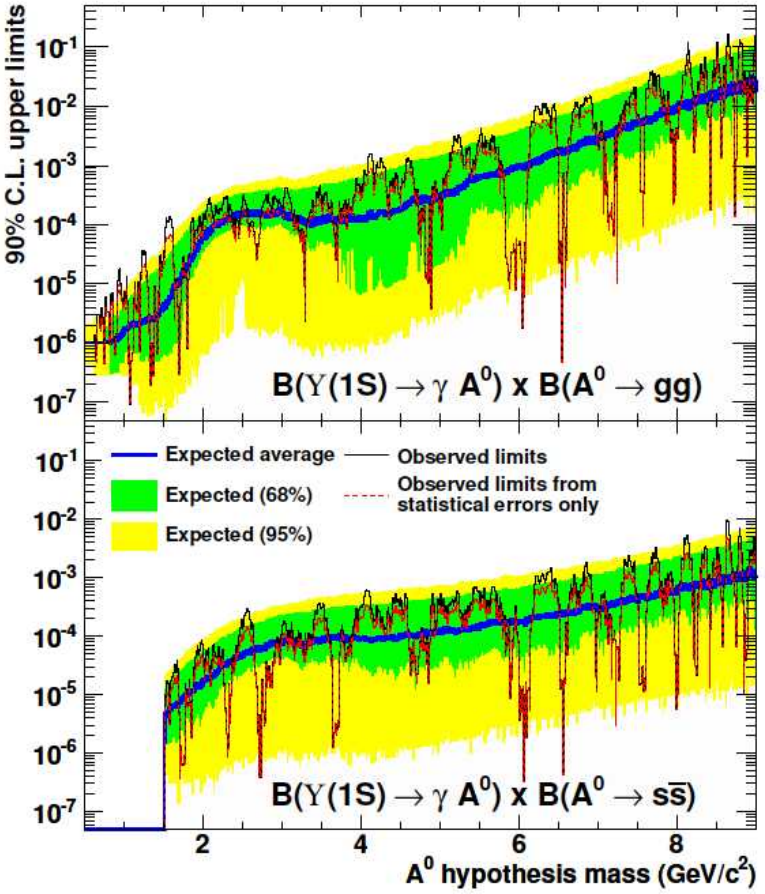
Use dipion tagging in $\Upsilon(2S)$ sample to select very clean $\Upsilon(1S)$ sample

- 18 x 10^6 events selected

Search for A^0 in various hadronic final states:

$$\Upsilon(2S) \rightarrow \pi^+\pi^- \Upsilon(1S)$$
$$\Upsilon(1S) \rightarrow \gamma A^0$$
$$A^0 \rightarrow gg,\ s\bar{s},\ c\bar{c}$$





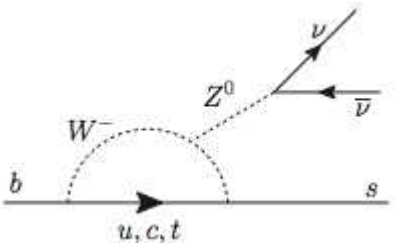
- Fully reconstruct A^0 using remaining π, K and p
- Charm search still in progress (Rocky So, Chris Hearty)

$B \to K^{(*)}\nu\bar{\nu}$

PRD 87, 112005 (2013)

Search for flavour changing neutral current process with missing energy in the final state

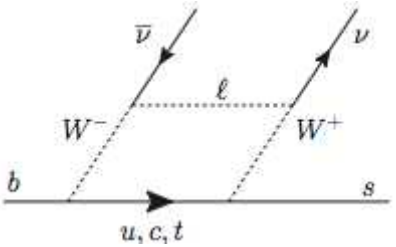
- related to $B \to K l^+ l^-$ and $b \to s\gamma$ but with different sensitivity to Wilson coefficients and new physics



Utilize "hadronic tag reconstruction" to identify decay products of non-signal B in $\Upsilon(4S) \to B\bar{B}$

- associate all remaining detector activity (including missing energy) with signal candidate

(see talks by Robert Seddon and Racha Cheaib in this session)



$B^+ \to K^+\nu\bar{\nu}$	$B^0 \to K^0\nu\bar{\nu}$	$B^+ \to K^{*+}\nu\bar{\nu}$	$B^0 \to K^{*0}\nu\bar{\nu}$
$(<3.7\times10^{-5})$	$(<8.1\times10^{-5})$	$(<11.6\times10^{-5})$	$(<9.3\times10^{-5})$
$(>0.2, <3.2)\times10^{-5}$		$(<7.9)\times10^{-5}$	

Dana Lindemann & Racha Cheaib

$B \to K^{(*)}\nu\bar{\nu}$

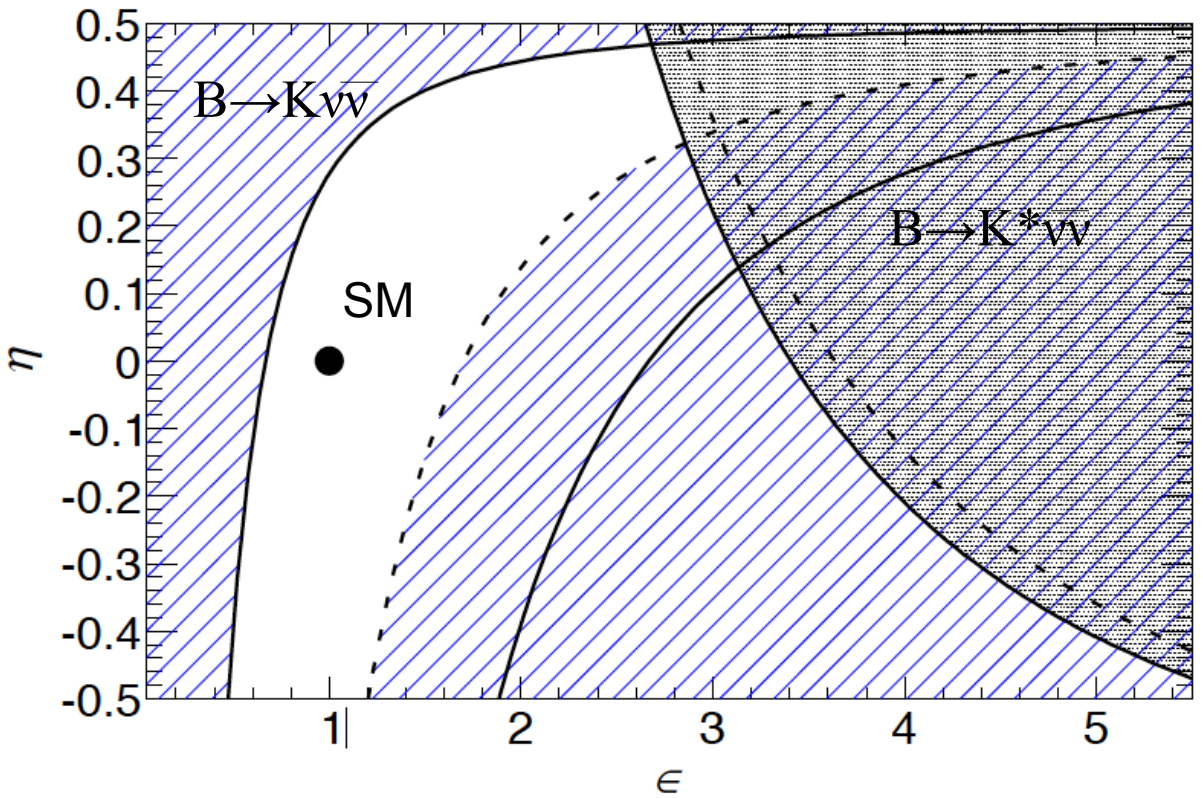
Branching fraction limits provide bounds on Wilson coefficients $|C^{\nu}_{L,R}|$:

PRD 87, 112005 (2013)

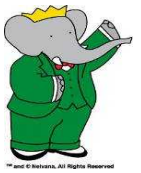
$$\varepsilon \equiv \frac{\sqrt{|C_L^{\nu}|^2 + |C_R^{\nu}|^2}}{|C_{L,SM}^{\nu}|}$$

$$\eta \equiv \frac{-\mathrm{Re}(C_L^{\nu} C_R^{\nu *})}{|C_L^{\nu}|^2 + |C_R^{\nu}|^2}$$

Altmannshofer, Buras, Straub, Wick
JHEP 0904:022 (2009)



Conclusion



More than six years after the end of data taking, the BABAR experiment remains highly productive

- current publication rate 0.4x ATLAS
- still substantial Canadian contributions to leadership and to the scientific program

Several major projects recently completed, or close to completion

- publication of detector performance NIMs and B factory book

Strong focus on completion of physics program:

- publish, publish publish...
- planning to ensure continued access to data and analysis resources to enable analysis activities into the indefinite future

2014 is the last year of Canadian BABAR funding, with 7 students/postdocs still involved in the project and 7 papers still to go