Hot Topics From BABAR Experiment

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University of South Alabama, USA

QUARKS-2010 International Seminar
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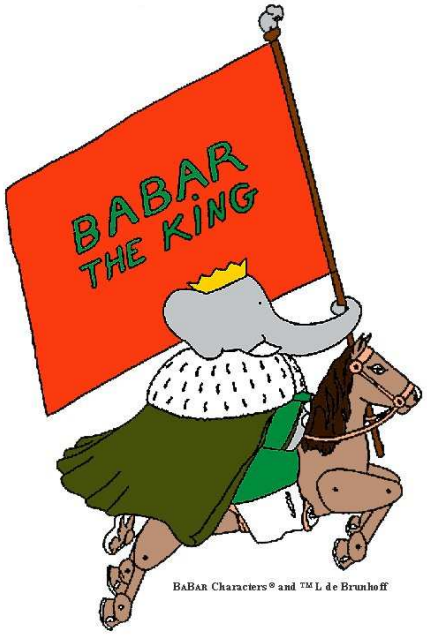
The BABAR Collaboration

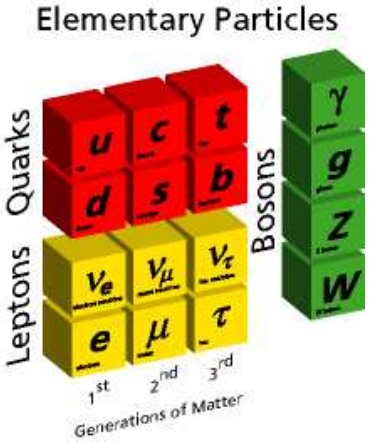


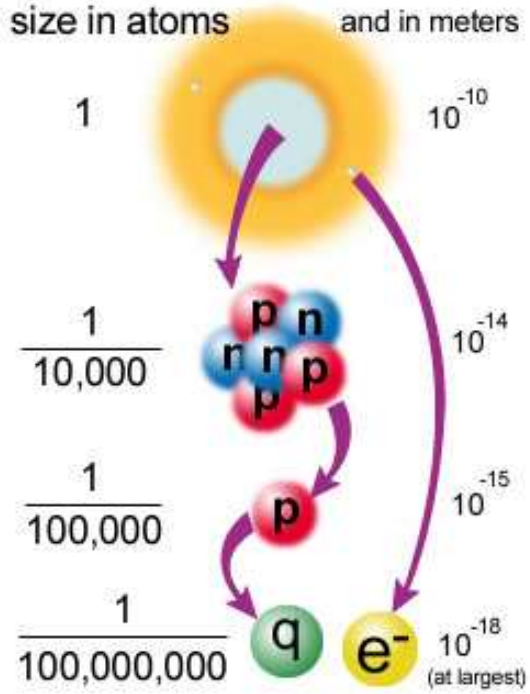
What is the World Made of ?

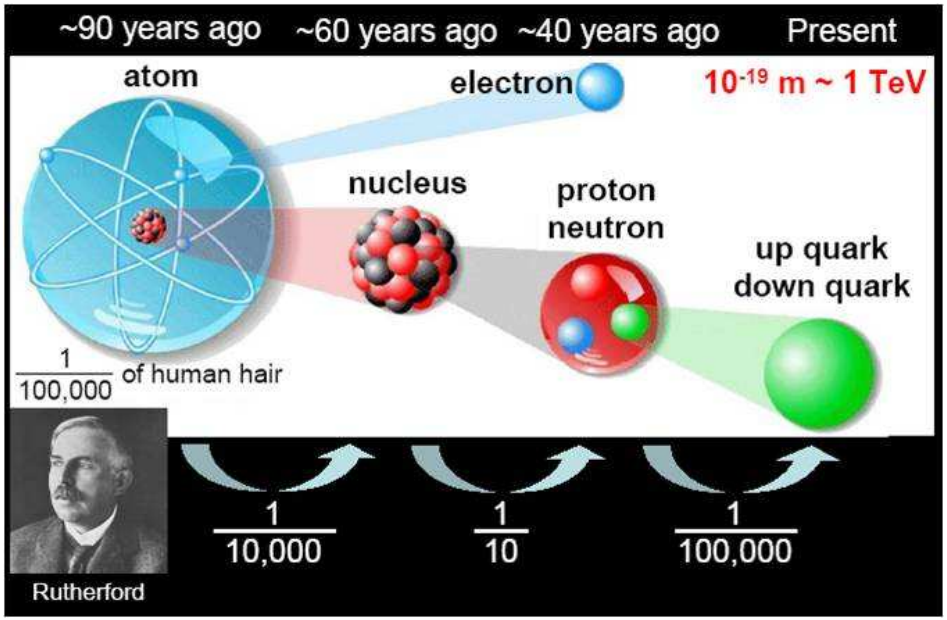
☐ **Scientists originally thought the nucleus was a fundamental particle but**

→ **nucleus is made of protons and neutrons**

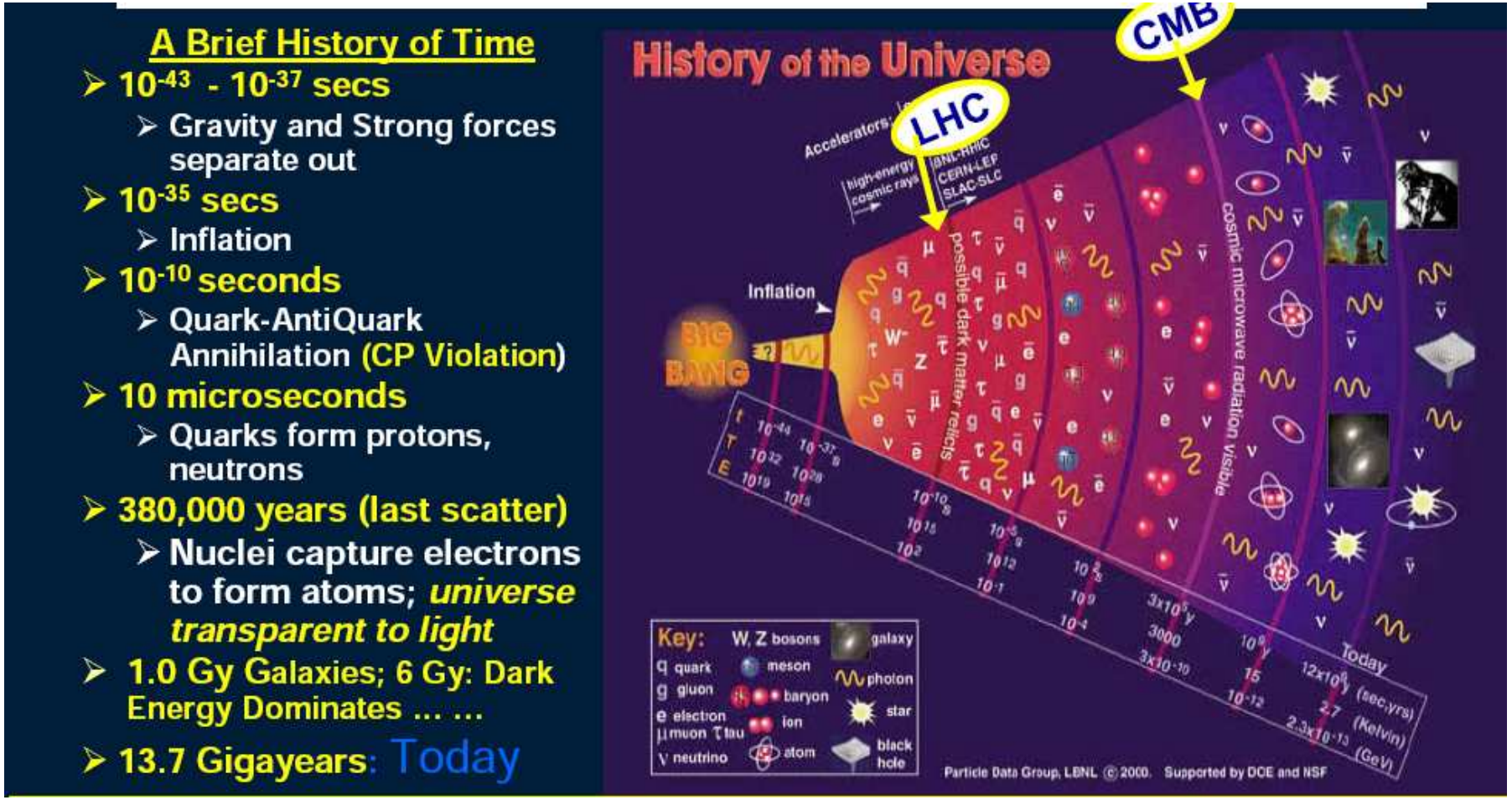
→ **protons and neutrons are made of quarks**







The Birth of the Universe (13.7 Billion Years Ago)



- After the Big Bang exploded with enormous energy, the universe began to cool-down that has lasted until our own time

- CP Violation process occurred 10^{-10} seconds after the explosion.

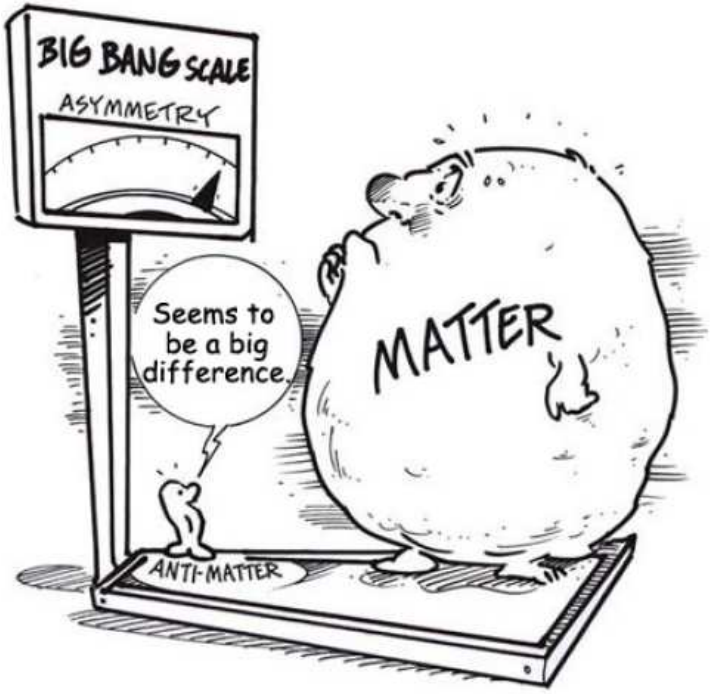
What Happened to the Antimatter

Why is the Universe Exclusively Made of Matter ?

☐ Andrei Sakharov (JETP, 5, No 1, 1967)

1. Baryon violating interactions
2. Thermal non-equilibrium situation
3. CP Violation

Nobel Peace Prize in 1975 →



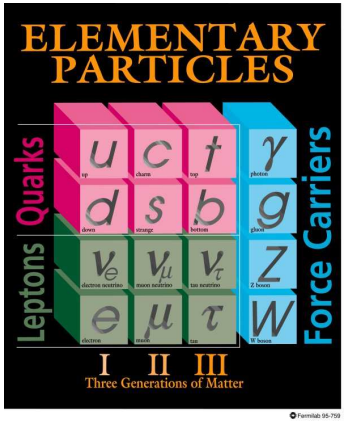
☐ Testing the Sakharov's criteria:

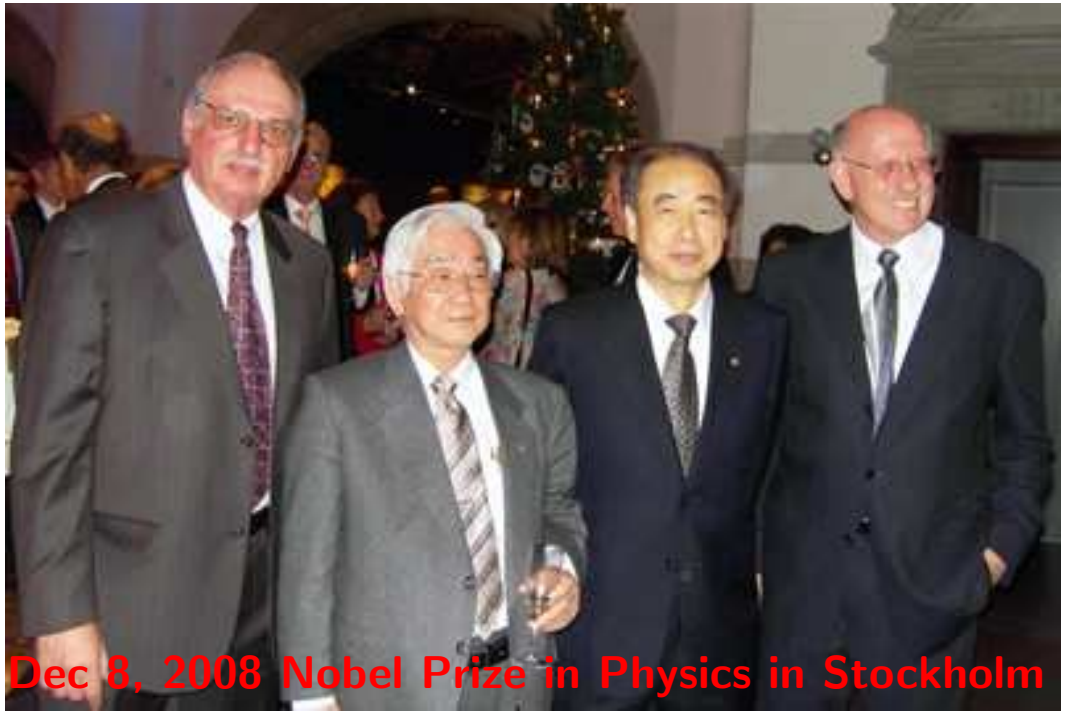
1. No evidence that baryon number is violated
2. In thermal equilibrium particles are identical → No asymmetry

CP violation is necessary to understand matter-antimatter imbalance

Nobel Price in Physics 2008

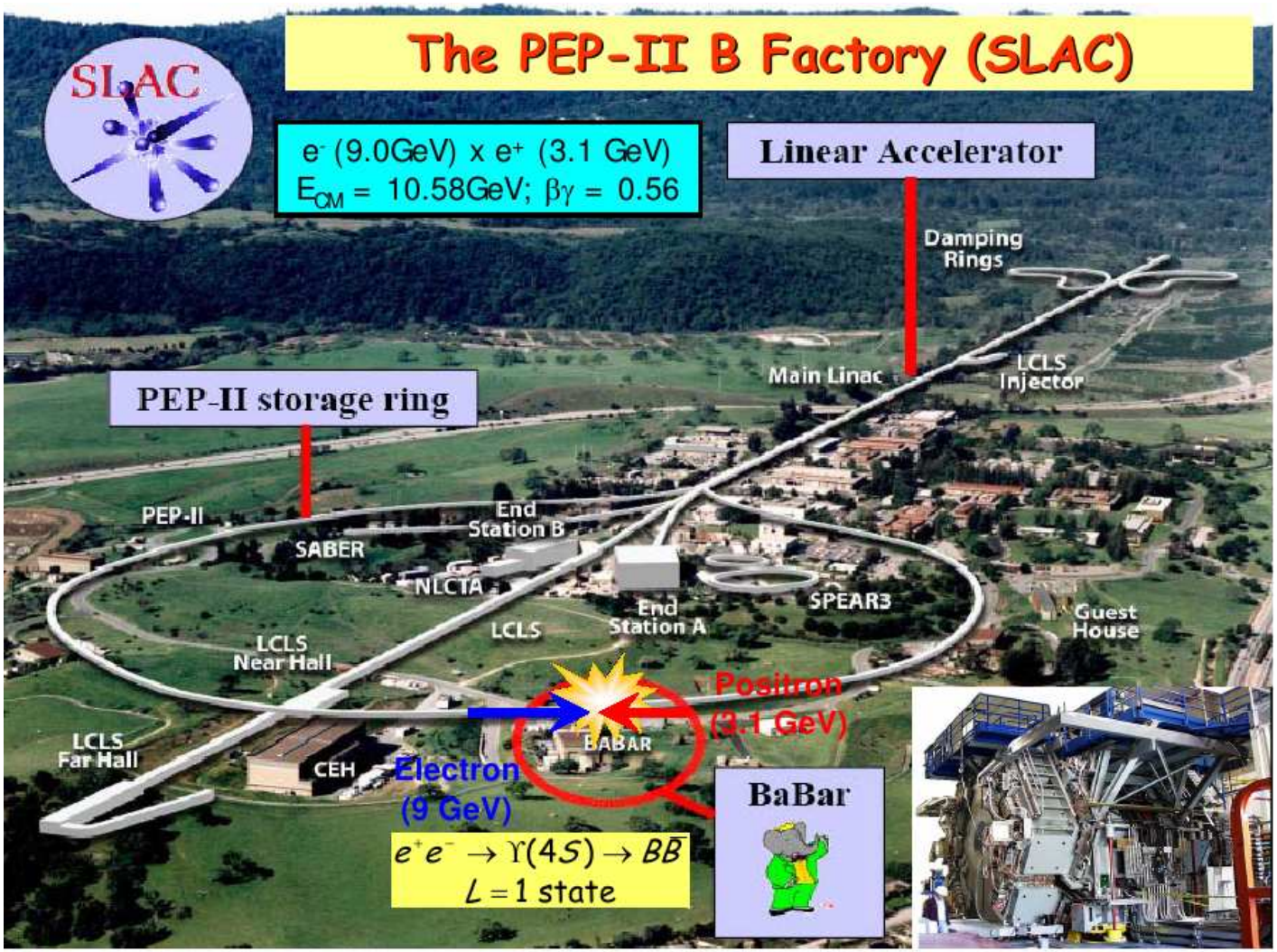
- In 2001 BABAR and Belle discovered direct CP violation in B mesons





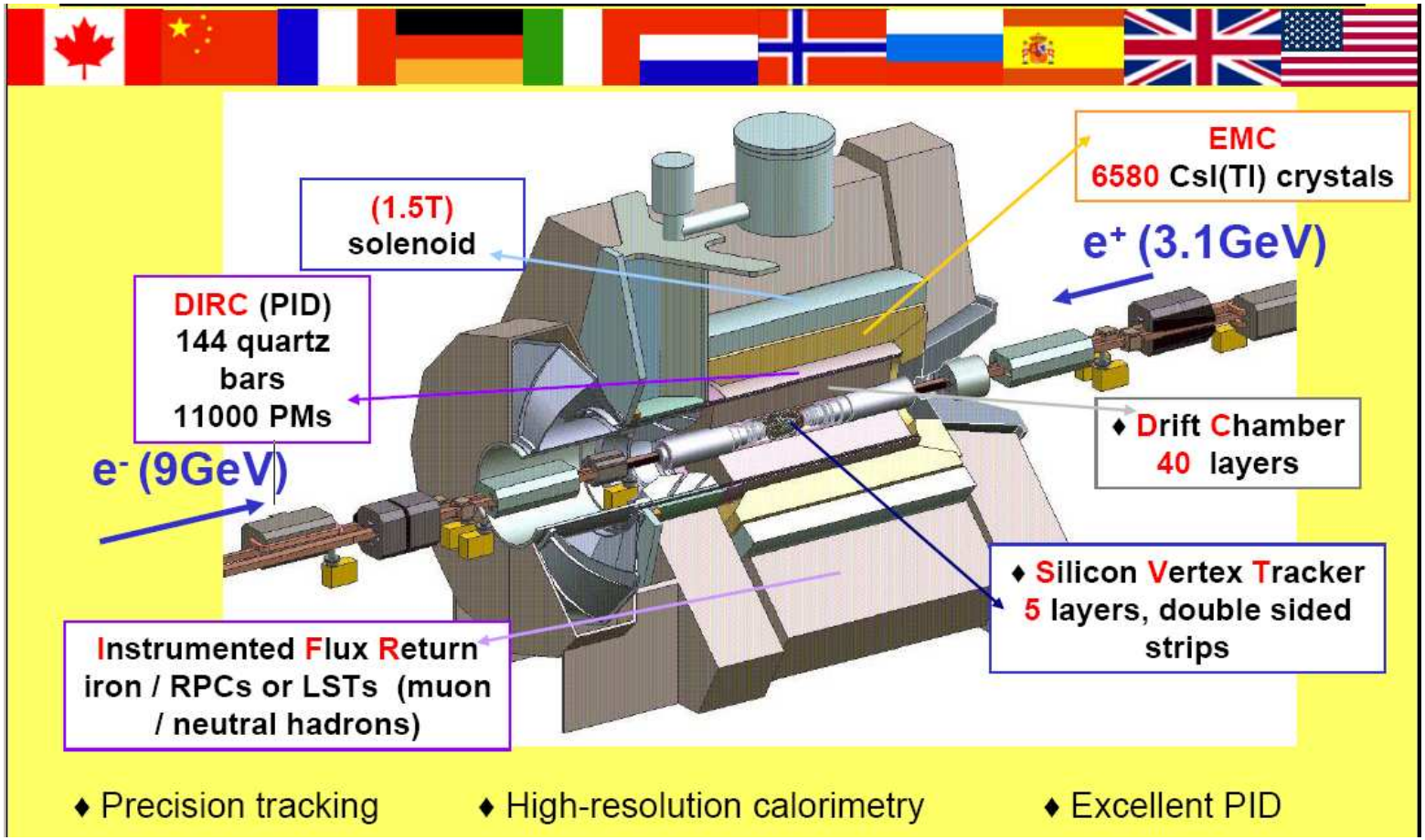
B Meson Factories

- BABAR at SLAC National Accelerator Laboratory, California, USA



- Another B-factory machine is at KEKB (Tsukuba) in Japan

BABAR Detector



- Collides (9 GeV) $e^- \bowtie e^+$ (3.1 GeV) $\hookrightarrow \Upsilon(4S)$ with $E_{CM} = 10.58$ GeV
- Peak luminosity : $\sim 1.21 \times 10^{34}\ cm^{-2}s^{-1}$, $B^0\overline{B}^0$ production $\sim$ 12 Hz
- Boost $\beta\gamma = 0.56$ allows to measure B decay times

BABAR Collaboration

The *BABAR* Collaboration
10 Countries
77 Institutions
522 Physicists

USA [34/256]
California Institute of Technology
UC, Irvine
UC, Los Angeles
UC, Riverside
UC, San Diego
UC, Santa Barbara
UC, Santa Cruz
U of Cincinnati
U of Colorado
Colorado State
Harvard U
U of Iowa
Iowa State U
Johns Hopkins U
LBNL
LLNL
U of Louisville
U of Maryland
U of Massachusetts, Amherst
MIT
U of Mississippi
SUNY, Albany
U of Notre Dame
Ohio State U
U of Oregon
Princeton U
SLAC
U of South Carolina
Stanford U
U of Tennessee
U of Texas at Austin
U of Texas at Dallas
U of Wisconsin
Yale

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University of British Columbia
McGill University
University de Montréal
University of Victoria

France [5/40]
LAPP, Annecy
LAL Orsay
LPNHE des Universités Paris VI et VII
Ecole Polytechnique, Laboratoire Leprince-Ringuet
CEA, DAPNIA, CE-Saclay

Germany [6/31]
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Universitaet Dortmund
Technische Univeritaet Dresden
Universitaet Heidelberg
Universitaet Rostock
Universitaet Karlsruhe

Italy [12/90]
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INFN, Ferrara
Lab. Nazionali di Frascati dell' INFN
INFN, Genova & Univ
INFN, Milano & Univ
INFN, Napoli & Univ
INFN, Padova & Univ
INFN, Pisa & Univ & Scuola Normale Superiore
INFN, Perugia & Univ
INFN, Roma & Univ "La Sapienza"
INFN, Torino & Univ
INFN, Trieste & Univ

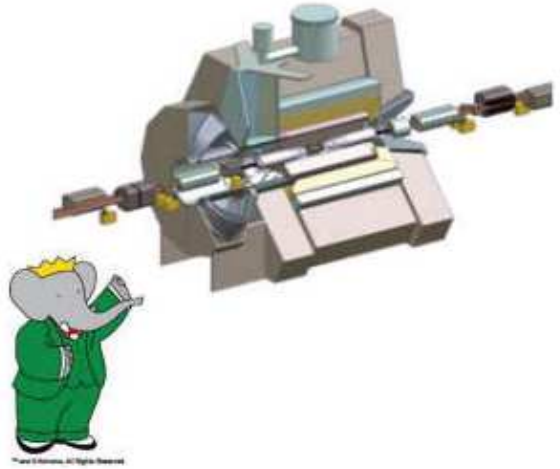
The Netherlands [1/3]
NIKHEF, Amsterdam

Norway [1/4]
U of Bergen

Russia [1/10]
Budker Institute, Novosibirsk

Spain [2/7]
IFAE-Barcelona
IFIC-Valencia

United Kingdom [11/58]
U of Birmingham
U of Bristol
Brunel U
U of Edinburgh
U of Liverpool
Imperial College
Queen Mary , U of London
U of London, Royal Holloway
U of Manchester
Rutherford Appleton Laboratory
U of Warwick



October 17, 2006

BABAR Collaboration

University of South Alabama & University of Mississippi: R. Godang

Mobile, Alabama

University of South Alabama

Student Recreation Center

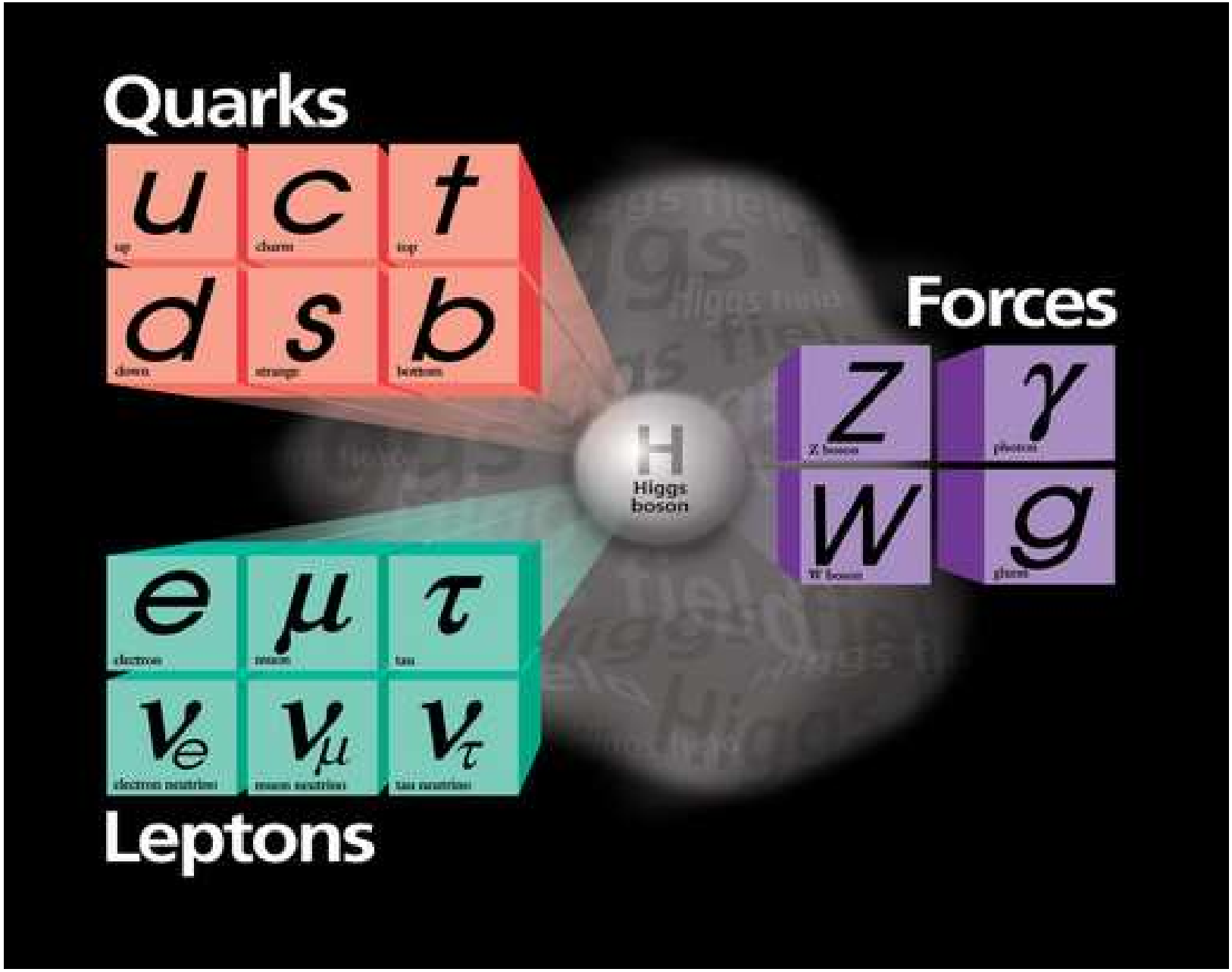
USA Main Campus

Students Enrolled: 14,757

http://www.southalabama.edu

Established in 1964

Search for Higgs Bosons and New Physics



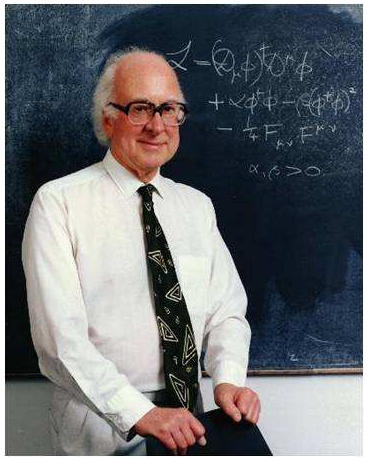
Search for SM Higgs (CP-Even Scalar)

How the Elementary Particles Get Their Mass ?

- **Spontaneous symmetry-breaking: the Higgs generates mass by self-interaction**

  ★ **It implies the existence new particle so called "Higgs boson"**

- **Higgs particle is named after Peter Higgs**



Peter Higgs

- **Leon Lederman (Nobel 1988) called it "God Particle"**
- **Challenge: The Higgs mass is a free parameter in the SM**

  ↪ **What is the Higgs mass?**

- **LEP ($e^+ - e^-$) at CERN (2002) searched for the SM Higgs (CP-even scalar)**

  ↪ **Yield a lower limit: $M_H > 114.4$ GeV (95% C.L.)**

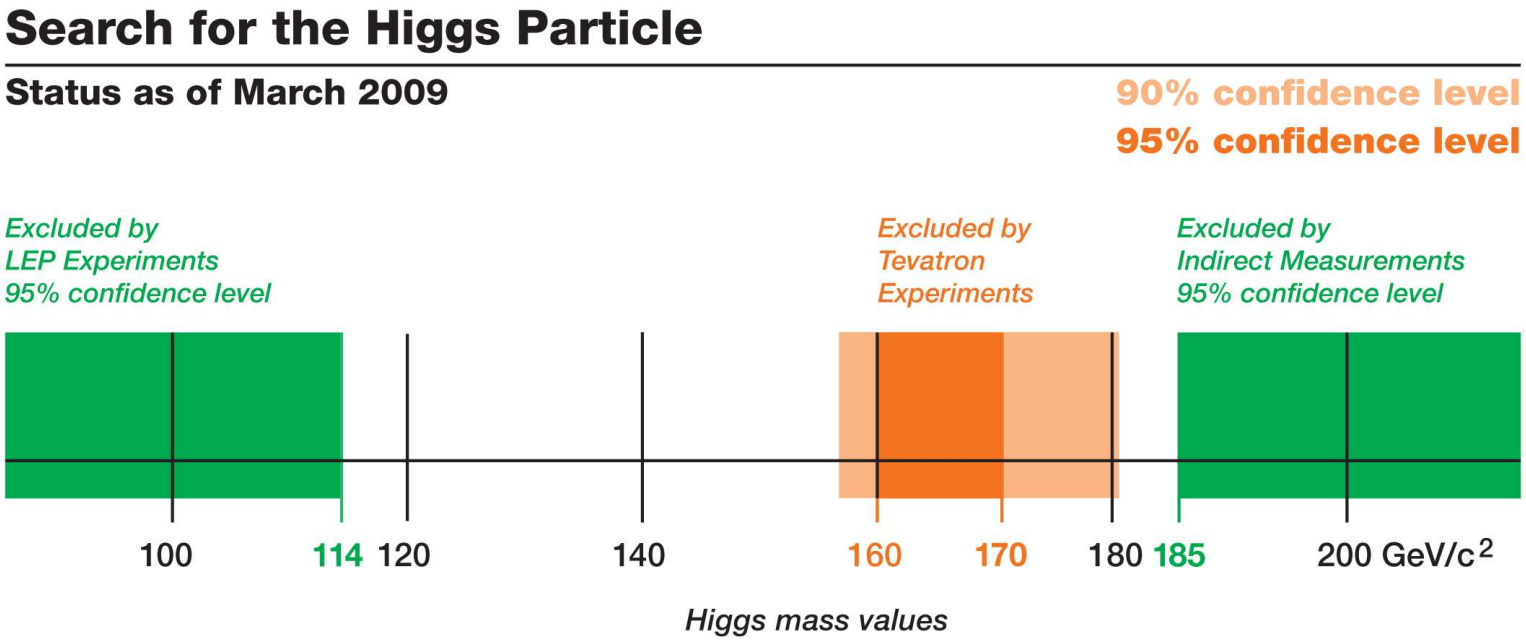
Search for SM Higgs at Tevatron

- March, 2009 : D0 measured the mass of W

$$M_W = 80.401 \pm 0.044 \text{ GeV}/c^2 \text{ (a precision of 0.05\%)}$$

- March, 2009 : CDF and D0 Experiments

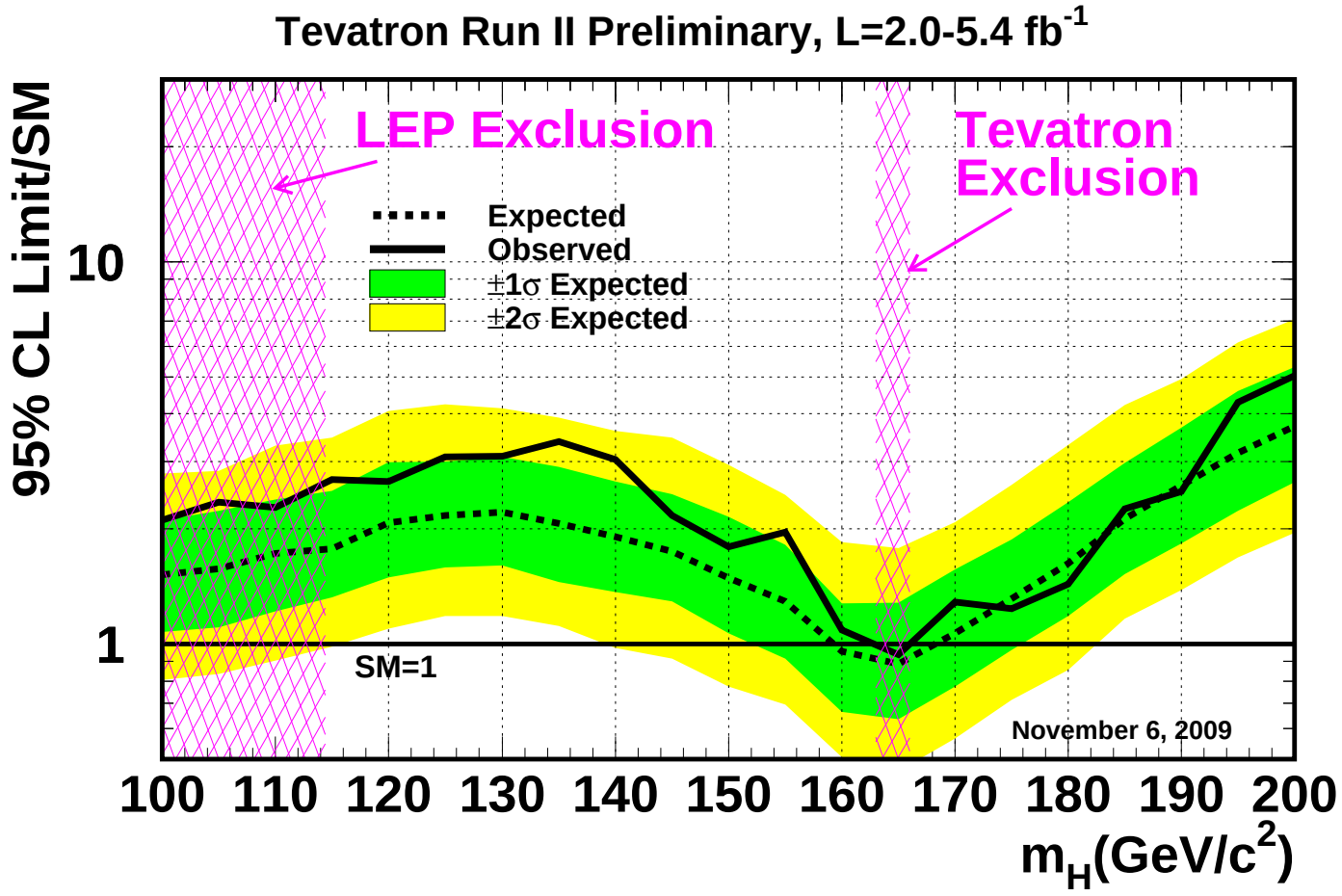
Excluded $160 < M_H < 170$ GeV/c^2



Search for SM Higgs (CP-Even Scalar)

☐ **November, 2009 : Update from CDF and D0 arXiv:0911.3930**

Excluded $163 < M_H < 166$ GeV/c^2 (95% C.L. Limit)



NMSSM Higgs PRD 76, 051105, 2007: Dermisek, Gunion, McElrath

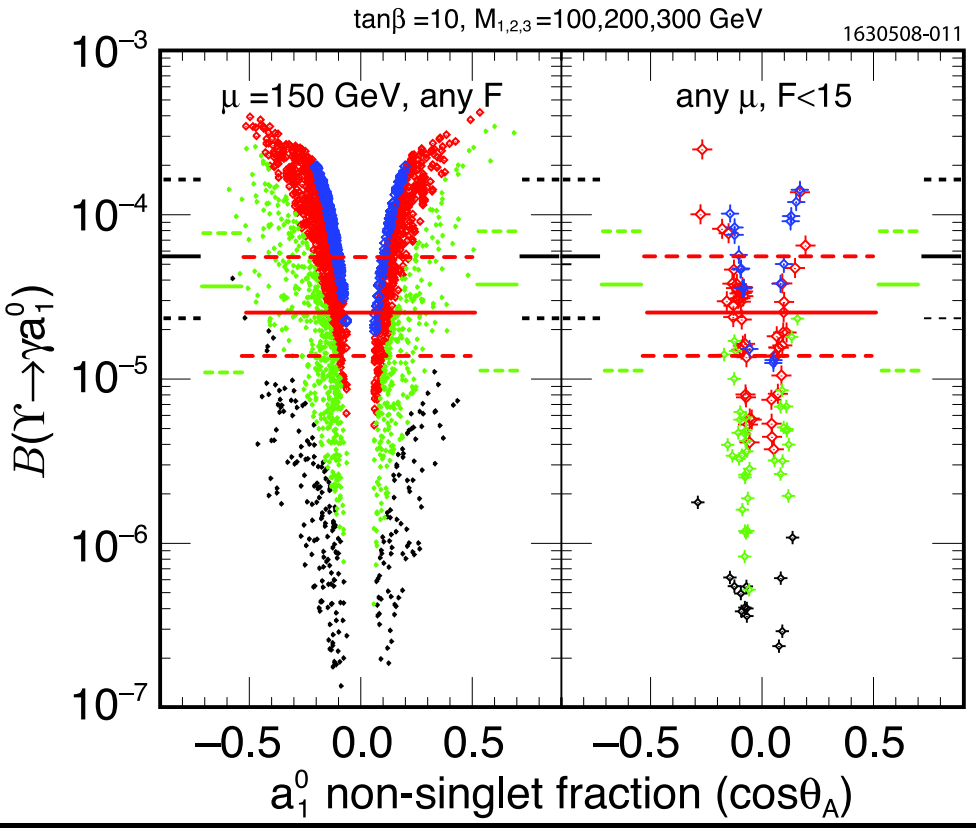
- Next-to-Minimal Supersymmetric Standard Model (NMSSM)

  → Light CP-Odd Pseudoscalar:

$$A^0 \equiv a_1^0 \equiv a_1 = cos\ \theta_A\ a_{MSSM} + sin\ \theta\ a_S$$

- For $m_{a_1} < 2m_b$, the lightest CP-even Higgs (h^0)

$h^0 \rightarrow a_1 a_1$ can avoid LEP limits



F = Electroweak Symmetry Breaking (EWSB) fine tuning

$tan\ \beta$ = ratio of the vacuum expectation values

$m_{a_1} < 2m_\tau$

$2m_\tau < m_{a_1} < 7.5$ GeV

7.5 GeV $< m_{a_1} <$ 8.8 GeV

8.8 GeV $< m_{a_1} <$ 9.2 GeV

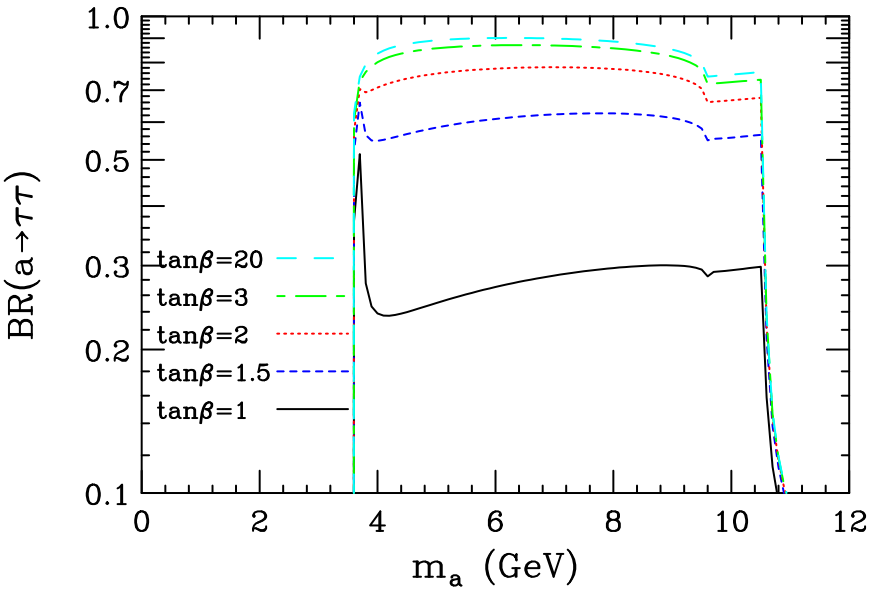
Prediction Higgs A^0: PRD 81, 075003 (2010): Dermisek, Gunion

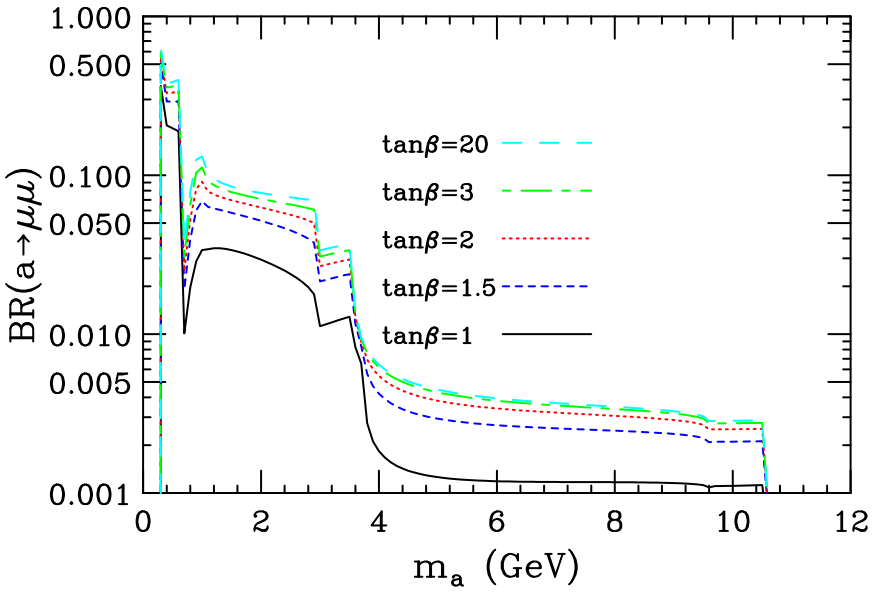
- At tree-level, $\mathcal{B}(a)$ apply equally to $\mathcal{B}(A^0)$

  independent of $cos\ \theta_A$ due to the absence of tree-level a

- $\mathcal{B}(a \to \tau^+\tau^-)$ and $\mathcal{B}(a \to \mu^+\mu^-)$ as a function of $tan\ \beta$

  $tan\ \beta = h_u/h_d$ = ratio of the vacuum expectation value





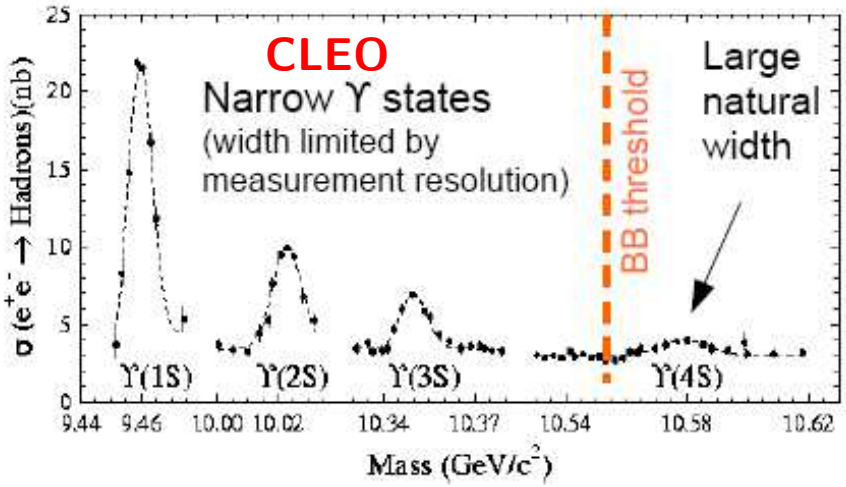
- At $tan\ \beta > 2$, $\mathcal{B}(a \to \tau^+\tau^-)$ and $\mathcal{B}(a \to \mu^+\mu^-)$

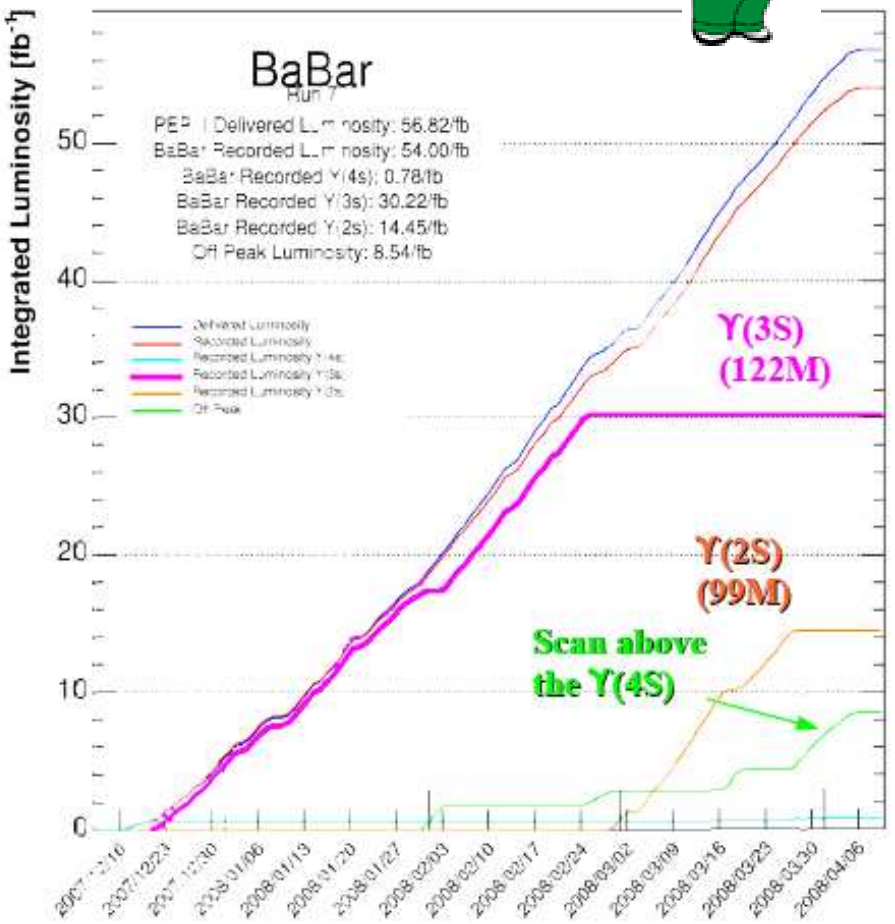
  change very little with increasing $tan\ \beta$ at any given m_a

BABAR Data: $\Upsilon(nS)$

Final BABAR Data

- BaBar data sets:
  - 122 x 10^6 $\Upsilon(3S)$ decays
  - 99 x 10^6 $\Upsilon(2S)$ decays
  - "offpeak" samples of 1.4fb^{-1} and 2.4fb^{-1} collected ~30 MeV below the $\Upsilon(2S)$ and $\Upsilon(3S)$
  - 79 fb^{-1} "continuum background" samples of $\Upsilon(4S)$ with similar detector conditions



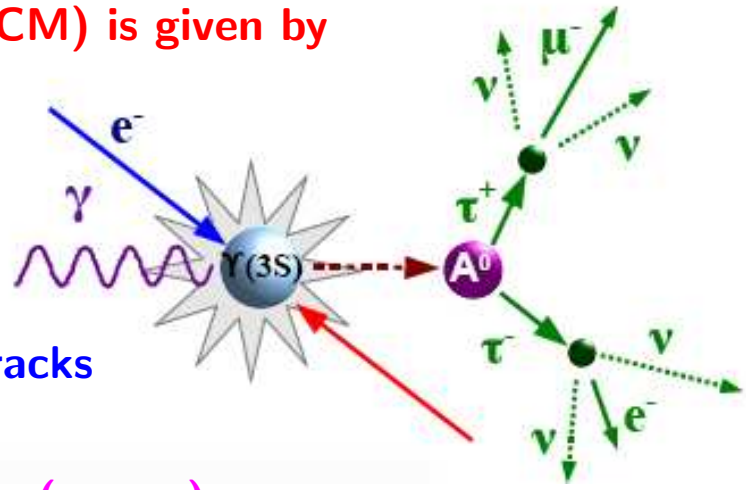


- Trigger requirements modified for narrow Υ data taking

♢ Search for $\Upsilon(3S) \to \gamma A^0,\ A^0 \to \tau^+\tau^-$, PRL 103, 181801 (2009)

☐ The photon energy in the Center-of-Mass (CM) is given by

$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$



☐ $E_\gamma > 100$ MeV, and exactly two charged tracks

☐ Both charged tracks are identified as leptons (e or μ)

☐ Backgrounds

- $e^+e^- \to \gamma\tau^+\tau^-$ (mostly)
- QED process including two photons i.e:
  - ▷ $e^+e^- \to e^+e^-e^+e^-$
  - ▷ $e^+e^- \to e^+e^-\mu^+\mu^-$
- $e^+e^- \to q\bar{q}$ $(q = u, d, s, c) \to$ small

$\Upsilon(3S) \to \gamma A^0,\ A^0 \to \tau^+\tau^-$ PRL 103, 181801 (2009) BABAR

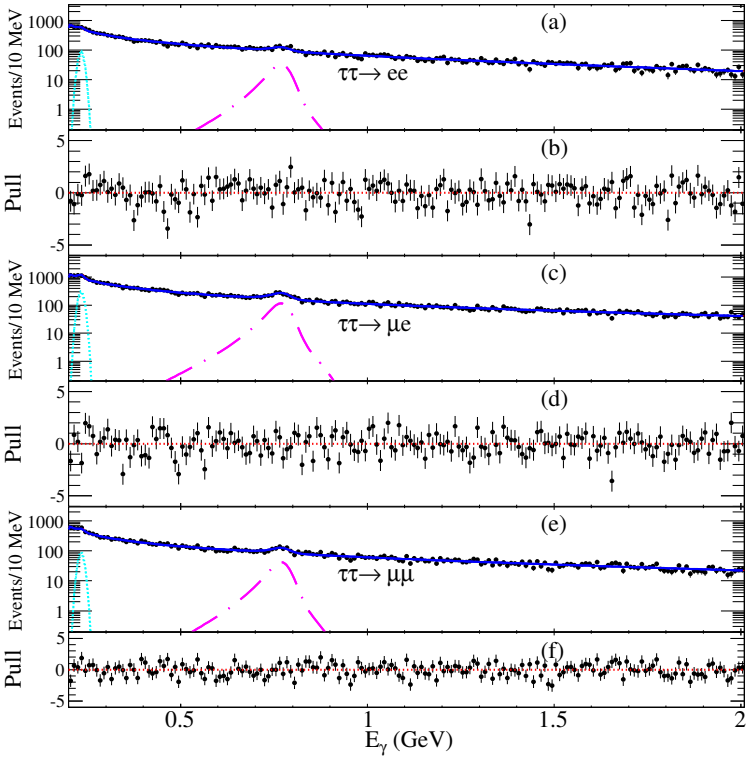
- The residual background is exploited by 8 kinematic and angular variables

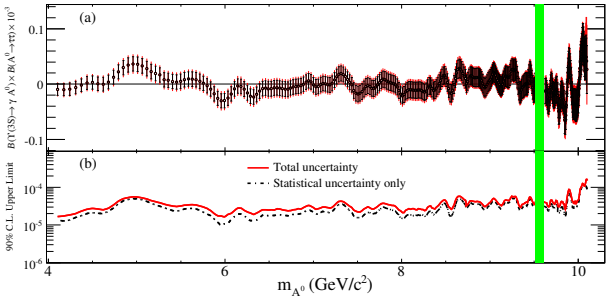
- Peaking contributions

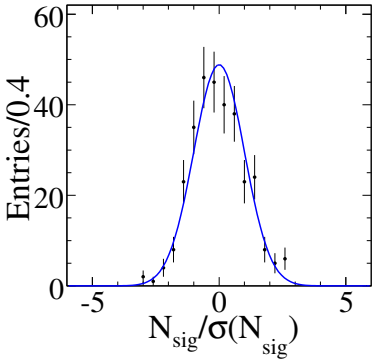
  - $\Upsilon(3S) \to \gamma\ \chi_{bJ}(2P)(J = 0, 1, 2)$

    $\hookrightarrow \chi_{bJ}(2P) \to \gamma\Upsilon(nS)(n = 1, 2)$

    $\hookrightarrow \Upsilon(nS) \to \tau^+\tau^-$







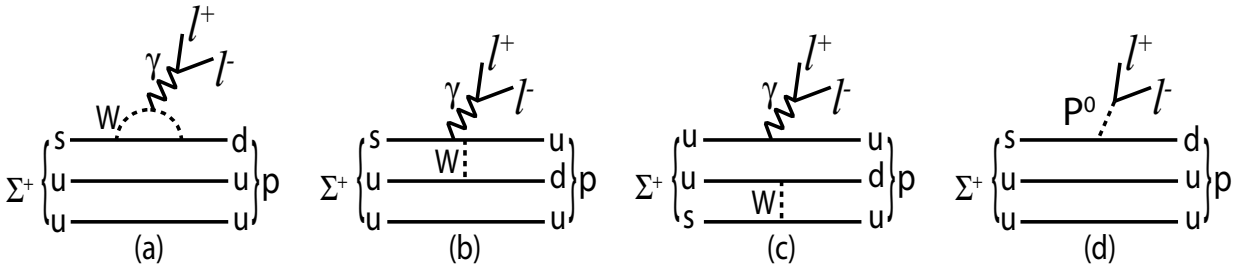
- Search A^0 in E_γ spectrum at $4.03 < m_{A^0} < 10.10$ GeV/c^2

$$\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \times \mathcal{B}(A^0 \to \tau^+\tau^-) < (1.5 - 16) \times 10^{-5} \quad \textbf{90\% C.L.}$$

$$\mathcal{B}(\eta_b \to \tau^+\tau^-) < 9\% \text{ at } 90\% \text{ C.L.}$$

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

☐ **HyperCP: Evidence $\Sigma^+ \to p\mu^+\mu^-$, PRL, 94, 021801 (2005)**



(a-c) $\Sigma^+_{p\ell\ell}$ in SM

(d) $\Sigma^+_{p\ell\ell}$ in NP

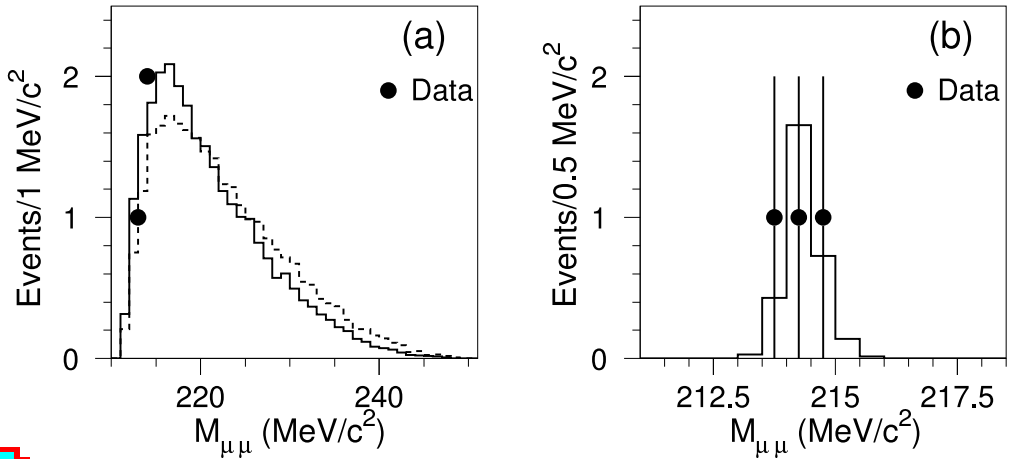
(a) Data and MC: form factor (solid)

and phase space (dashed)

$\Sigma^+ \to p\mu^+\mu^-$ (SM)

(b) Data and normalized MC

$\Sigma^+ \to pP^0,\ P^0 \to \mu^+\mu^-$ (3 events)



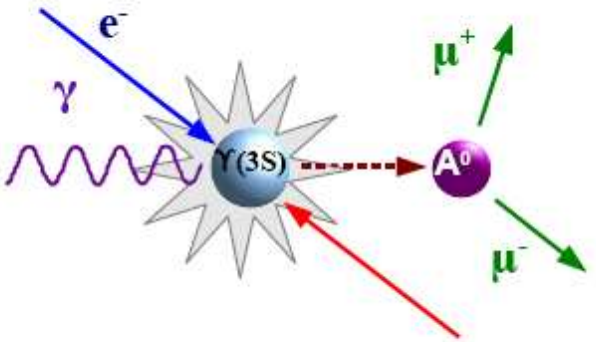
$\mathcal{B}(\Sigma^+ \to p\mu^+\mu^-) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$

☐ **These events have been interpreted as a light Higgs boson (A^0)**

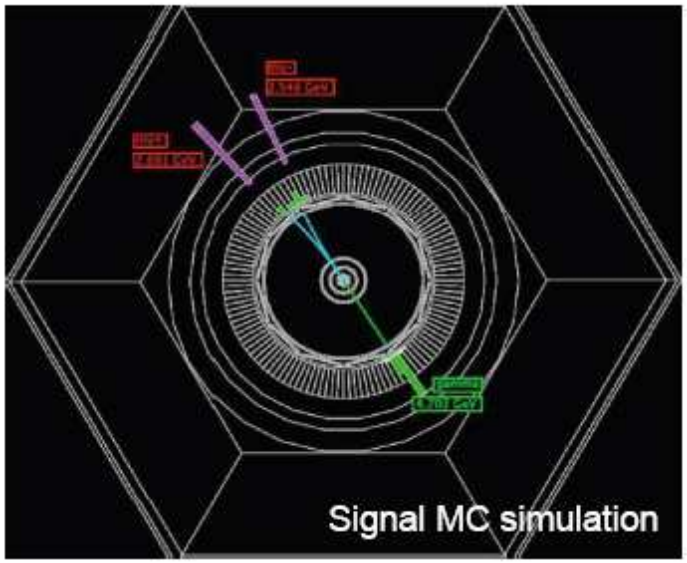
with mass of 214.3 MeV, PRL 98, 081802 (2007): X-G He, Tandean, Valencia

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

- Search for A^0 scalar boson in the radiative decays of $\Upsilon(2S)$ and $\Upsilon(3S)$



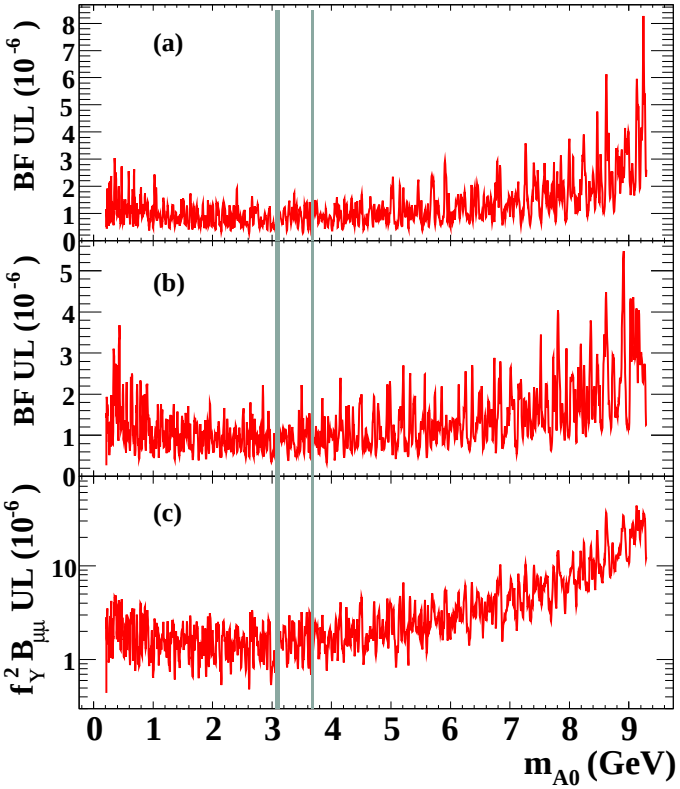
- If A^0 exists its decays depends on its mass
- Assuming no invisible (neutralino) decays $\mathcal{B}(A^0 \to \mu^+\mu^-) \approx$ sizable at low $m_{A^0} < 2m_\tau$



- Require 2 oppositely charged tracks and one γ at least one of which is identified as a muon
- $E_\gamma > 200$ MeV (COM), while allowing additional γ with energy lower than 200 MeV
- Use kinematic fit of $\gamma\mu^+\mu^-$ system, including the beam energy and decay vertex constraints

$\Upsilon(2S,3S) \to \gamma A^0$, $A^0 \to \mu^+\mu^-$, PRL 103, 081803 (2009) BABAR

- Search for A^0 as a function of mass m_{A^0}



Scan range $0.212 < m_{A^0} < 9.3$ GeV

(a) $\mathcal{B}(\Upsilon(2S) \to \gamma A^0) \times \mathcal{B}_{\mu\mu}$

(b) $\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \times \mathcal{B}_{\mu\mu}$

(c) $f_\Upsilon^2 \times \mathcal{B}_{\mu\mu}$

$\mathcal{B}(\Upsilon(nS) \to \gamma A^0)$ are related to the effective Yukawa coupling f_Υ of bound b quark to A^0

$$\frac{\mathcal{B}(\Upsilon(nS)\to\gamma A^0)}{\mathcal{B}(\Upsilon(nS)\to\ell^+\ell^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right)$$

- Shaded area is excluded from the search around the J/ψ and $\psi(2S)$ resonances
- No signal observed at $m_{A^0} \sim 214$ MeV

Significant positive fluctuation of $\Upsilon(3S) \sim 2.8\sigma$ and $\Upsilon(2S) \sim 3.1\sigma$

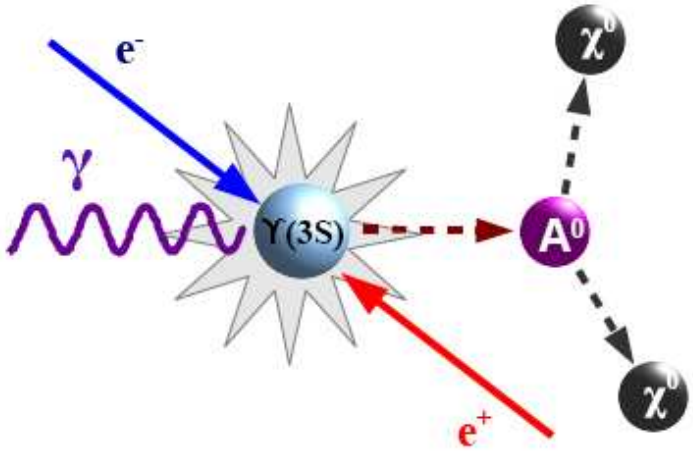
$\mathcal{B}(\eta_b \to \mu^+\mu^-) < 0.9\%$ at 90% C.L.

$\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ Invisible BABAR

- NMSSM scenario: If $m_{A^0} < 2m_\tau$

  $\Longrightarrow$ the dominant decay is $A^0 \to$ invisible

$$\Upsilon(3S) \to \gamma A^0, \quad A^0 \to \chi^0\chi^0$$



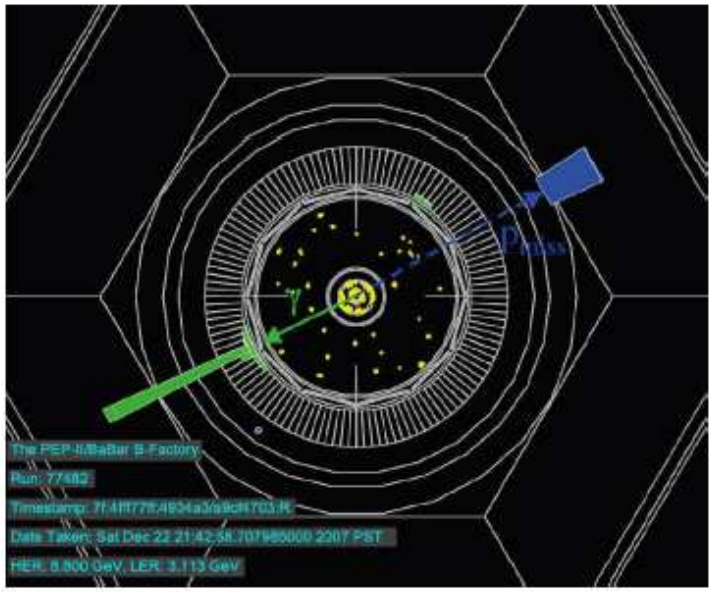
- χ^0 is the LSP Neutralino

  (Light Supersymmetric Particle)

- Experimental signatures: monochromatic γ

  from $\Upsilon(3S) \to \gamma A^0$, accompanied by

  significant missing energy and momentum



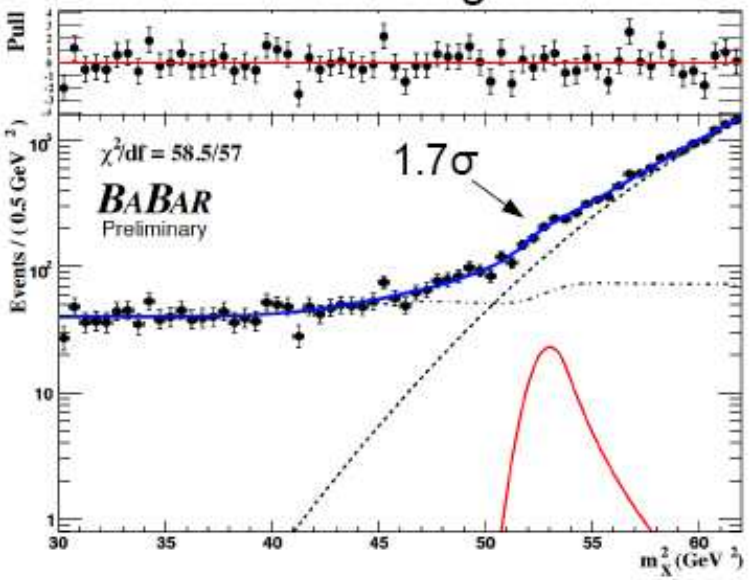
- The photon energy in CM system

$$E^*_\gamma = \frac{m^2_\Upsilon - m^2_{A^0}}{2m_\Upsilon}$$

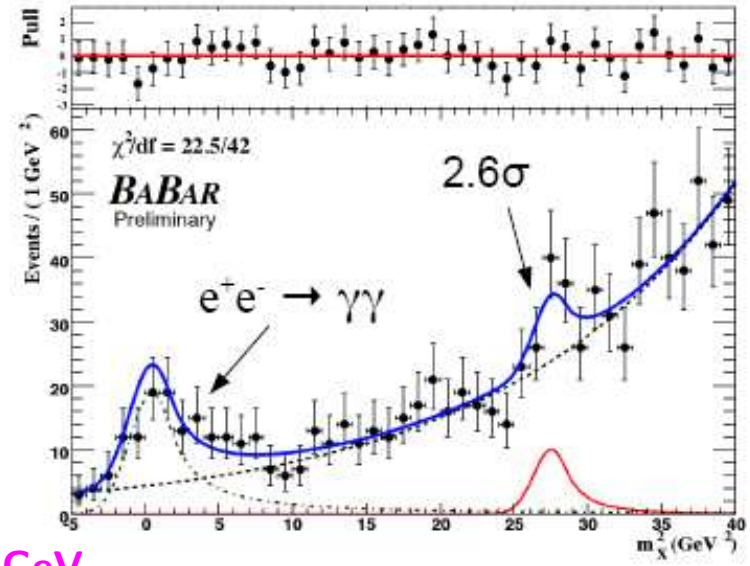
$\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ Invisible. hepex/0808.0017, Preliminary BABAR

- There are two photon energy regions:
  - High-energy region $3.2 < E^*_\gamma < 5.5$ GeV
  - Low-energy region $2.2 < E^*_\gamma < 3.7$ GeV
- The missing mass squared: $m^2_X \equiv m^2_{\Upsilon(3S)} - 2E^*_\gamma\, m_{\Upsilon(3S)}$

Low mass region



High mass region



$m_{A^0} < 7.8$ GeV

$\mathcal{B}(\Upsilon(3S) \to \gamma A^0) \times \mathcal{B}(A^0 \to$ invisible) at (0.7-31) $\times 10^{-6}$ at 90% C.L.

Romulus Godang
University of South Alabama, USA

$\Upsilon(1S) \rightarrow$ Invisible BABAR

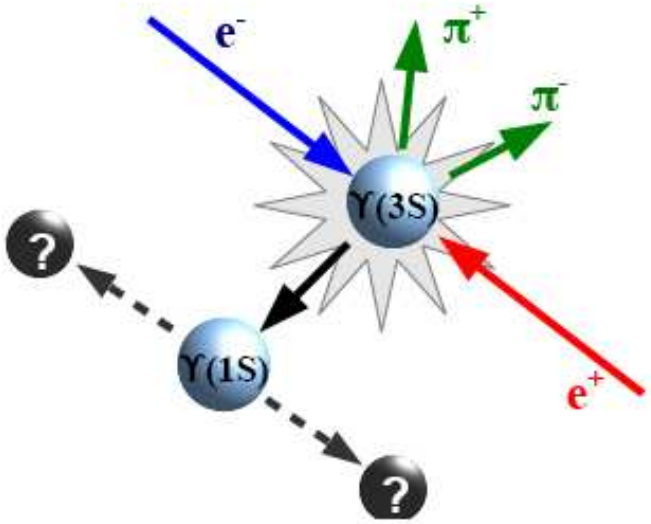
- SM predicted $\mathcal{B}(\Upsilon(1S) \rightarrow \text{invisible}) \approx 10^{-5}$

  It is below the current experimental sensitivity

- However, low-mass dark matter candidates

  could couple weakly to SM particles to enhance

$$\mathcal{B}(\Upsilon(1S) \rightarrow \text{invisible}) \approx 10^{-4} - 10^{-3}$$



- In $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, we search for evidence of undetected

  $\Upsilon(1S)$ decays recoiling against the dipion system

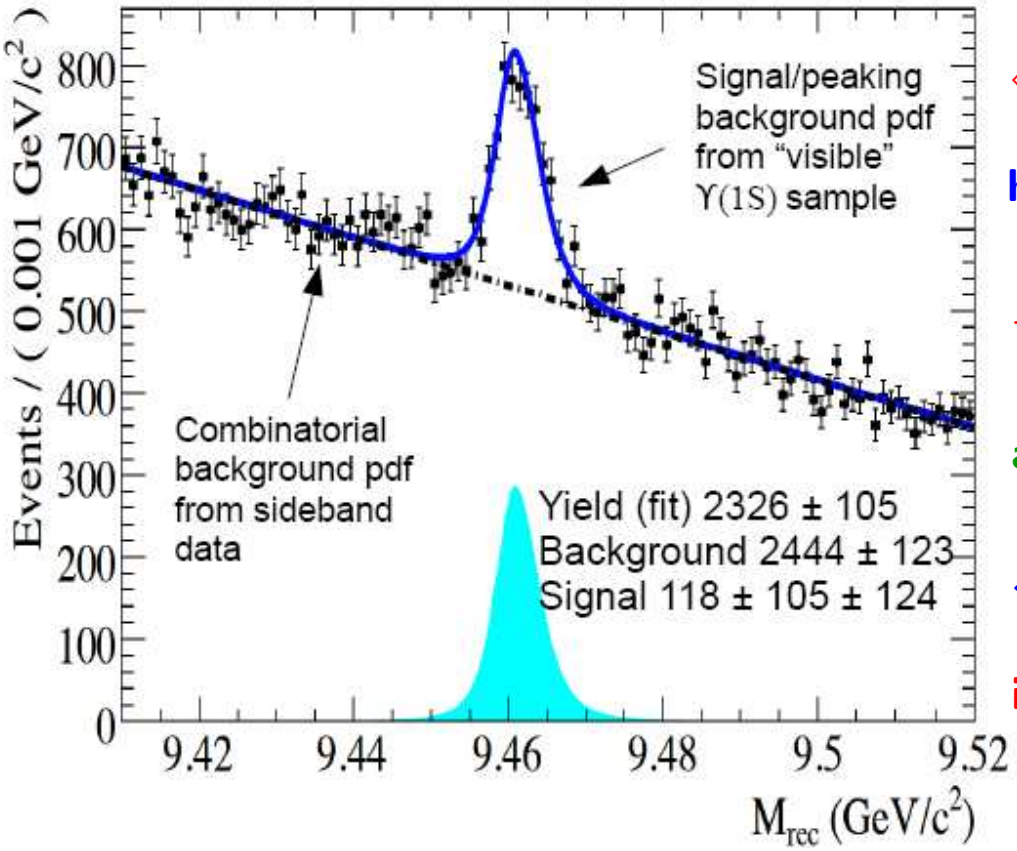
- The dipion recoil mass $\quad M^2_{rec} = s + M^2_{\pi\pi} - 2\sqrt{s}\, E^*_{\pi\pi}$

  $\sqrt{s} = m_{\Upsilon(3S)} = 10.3552$ GeV/c^2 $\quad E^*_{\pi\pi}$ = CM of $\pi^+\pi^-$ system

- The M^2_{rec} should peak around $\Upsilon(1S)$ mass $\Longrightarrow$ 9.4603 GeV/c^2

$\Upsilon(1S) \rightarrow$ Invisible. PRL 103, 251801 (2009)

☐ M_{rec} distribution in $\Upsilon(3S) \rightarrow \pi^+\pi^-\Upsilon(1S)$, $\Upsilon(1S) \rightarrow$ invisible



♢ Signal and peaking bkg

have the same shape in M_{rec}

$\rightarrow \Upsilon(1S)$ final SM particles

are undetected (peak bkg)

♢ Non-peak bkg (low P_π)

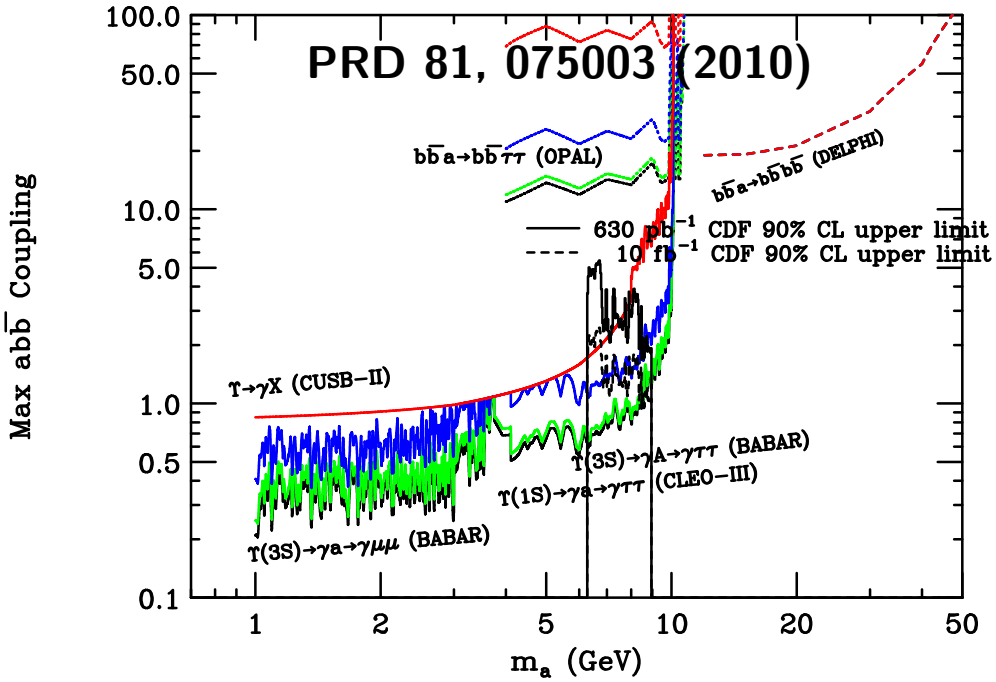
is estimated using SB data

$$\mathcal{B}(\Upsilon(1S) \rightarrow \text{invisible}) = (-1.6 \pm 1.4 \pm 1.6) \times 10^{-4}$$

$$\mathcal{B}(\Upsilon(1S) \rightarrow \text{invisible}) = < 3.0 \times 10^{-4} \quad 90\% \text{ C.L.}$$

Summary

- BABAR results provide increased constraints on light CP-Odd Higgs boson



Based on experimental results

- $\Upsilon(3S) \to \gamma A^0$, $A^0 \to \tau^+\tau^-$

  PRL 103, 181801 (2009)

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

  PRL 103, 081803 (2009)

- $\Upsilon(3S) \to \gamma A^0$, $A^0 \to$ Invisible

  hepex/0808.0017 (Preliminary)

- $\Upsilon(1S) \to$ Invisible

  PRL 103, 251801 (2009)

- These measurements are important input to rule out much of the parameter space allowed by the light Higgs and other models

- $\Upsilon(1S) \to$ Invisible might provide information on dark matter


THANK YOU!