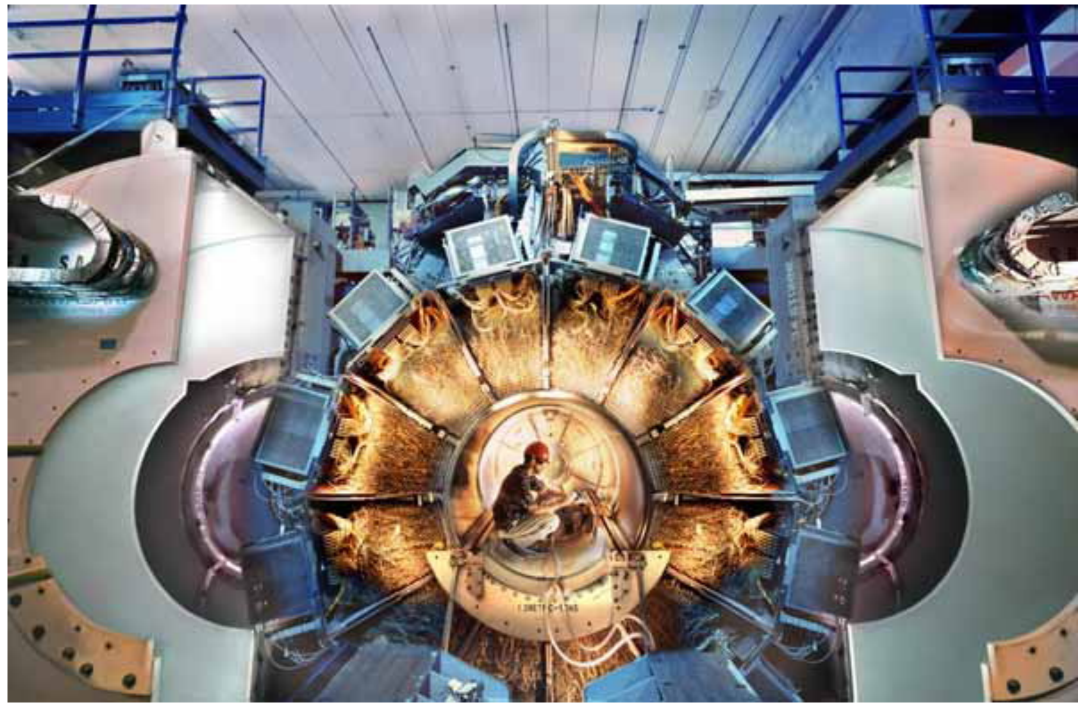
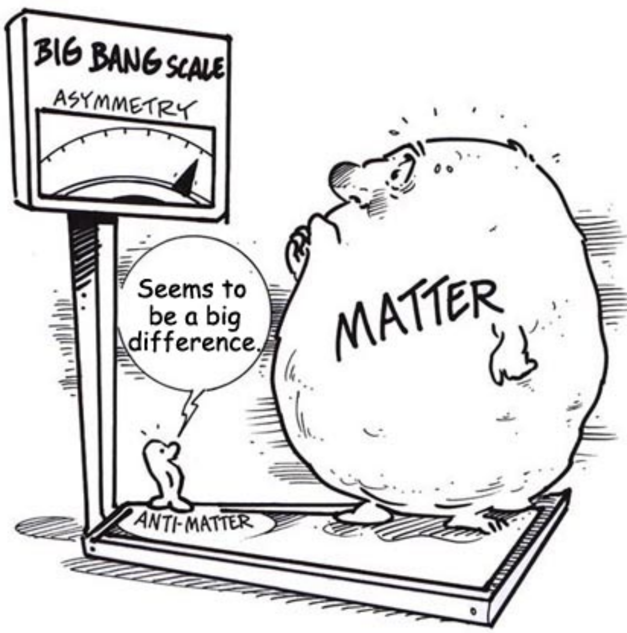
Something's the Matter with Anti-Matter: CP Violation and the Babar Experiment





Janis McKenna
University of British Columbia

Particles, Antiparticles & Symmetries of Nature

- Matter-Antimatter
  - Matter-Antimatter Asymmetry of Universe
  - CP Violation in the Standard Model of Particle Physics
  - Measuring Matter-Antimatter Asymmetry in B meson system
  - Looking for new Physics (beyond the Standard Model)
- Hardware to examine the problem:
  - The PEP-II Accelerator
  - The BABAR Experiment (Finishing running an 18 yr experimental program)
- CP Violation: What have we learned?

We often wonder what the world is made of, how it was made, and what holds it all

Composed by Jayanne English (CGPS/U. of Manitoba) with support by A. R. Taylor (CGPS/U. of Calgary) for The Canadian Galactic Plane Survey.

Does our universe have a beginning and an end?

Where did the stuff in it come from?

Are there other universes out there?

Is it all matter? Where's the antimatter?

What's the Matter? Where's the Antimatter?

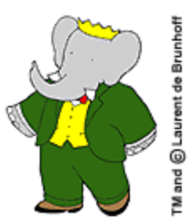
- Universe created in hot Big Bang
- Matter created in Matter anti-Matter particle pairs
- 50-50 matter-antimatter, or pure energy

SURPRISING- universe is not equal parts matter/antimatter

SLAC Linear Accelerator

At
Stanford U

Detector
named
"Babar"



April 18, 2012

BaBar: 18 year Experimental Program in Quarks & Matter-Antimatter

New CP violation, new particles, precision measurements: Excitement, press releases & surprises

1993: Construction starts on PEP-II, design & prototypes for BaBar Detector

1994-9: BaBar Detector Construction

1999: PEP-II & BaBar complete**, take data!**

2000: PEP-II runs at design luminosity

2001: First observation of CP Violation in B system (27 yrs after CPV seen in K's)

2003: New charmed particle $D_S(2317)$

2004: Direct CP violation observed in B system

2004: PEP-II at 3 × design luminosity

2005: new charmonium-like particles observed

2006: Precision & consistency in electroweak sector of Standard Model

2007: First observation of D^0 -$\overline{D}^0$ mixing

2008: Babar's Final Run ended April 7, 2008

2008: New Charm Resonances

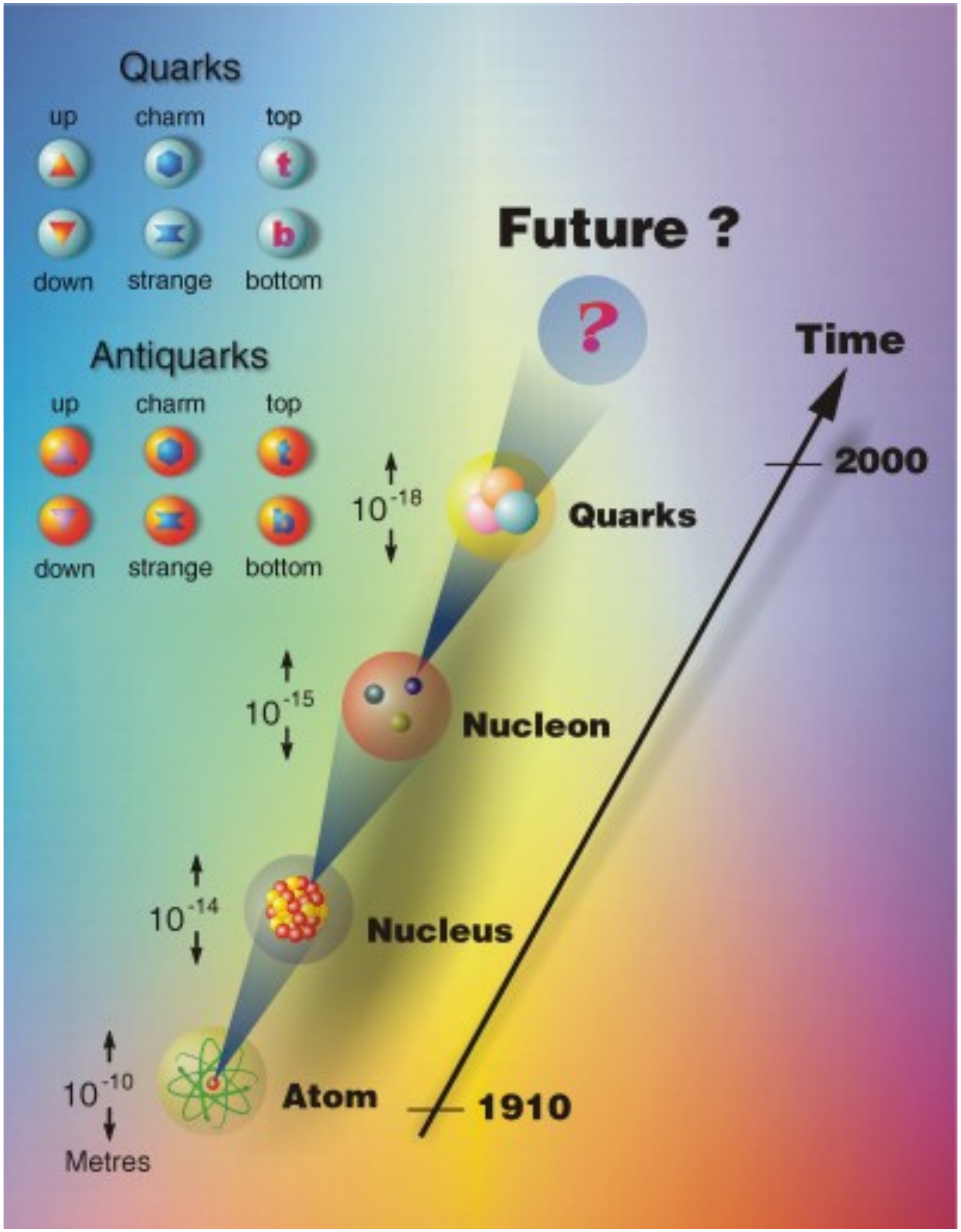
2008: Nobel Prize to Kobayashi & Maskawa
(theory of broken symmetries -which we validated)

2009-13: Final analyses; write final papers

What’s the world made of?

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr



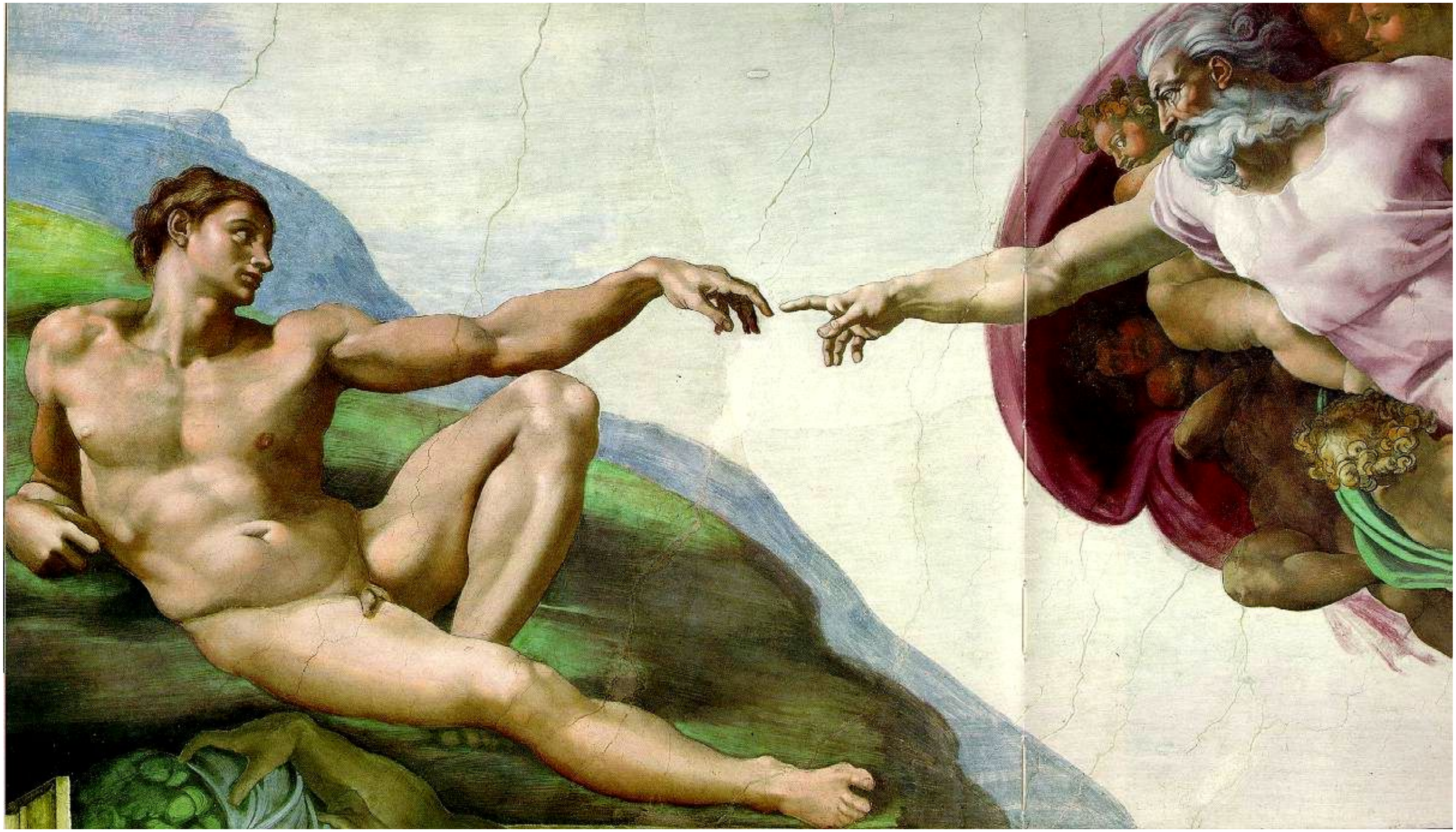
Quarks
up
charm
top
down
strange
bottom
Antiquarks
up
charm
top
down
strange
bottom
Future ?
?
Time
2000
1910
10^{-18}
Quarks
10^{-15}
Nucleon
10^{-14}
Nucleus
10^{-10}
Atom
Metres

Matter Dominated Universe

Moon
- not antimatter

Solar system- no antimatter
Milky Way - no antimatter
Larger scales - no antimatter

As far as we can see, universe looks like it's made up of only matter



Michaelangelo → God is not antimatter!

What's the Matter? Where's the Antimatter?

- Universe created in hot Big Bang
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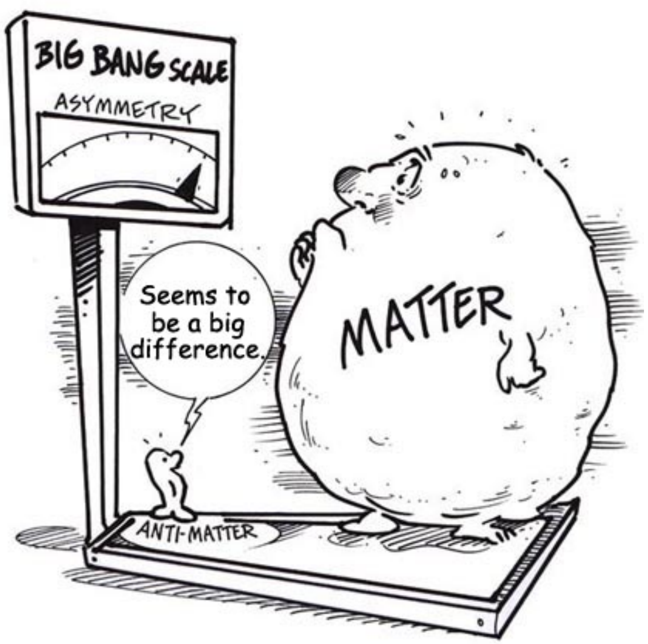
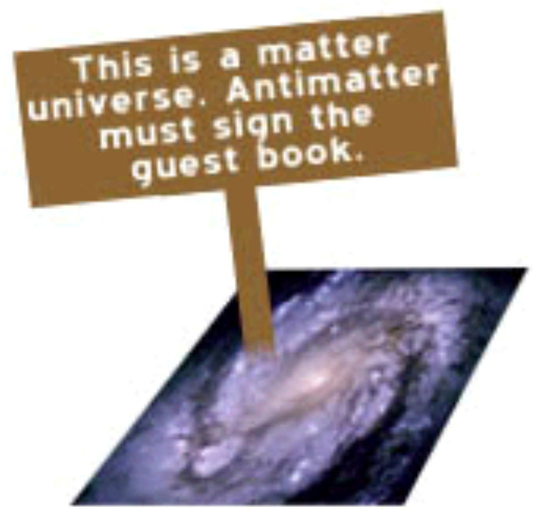
- 50-50 matter-antimatter, or pure energy

SURPRISING- universe is not equal parts matter/antimatter





What happened to all the AntiMatter??

A scenario:
Initial conditions of universe matter-antimatter symmetric

•Hot Big Bang- equal parts matter and antimatter.

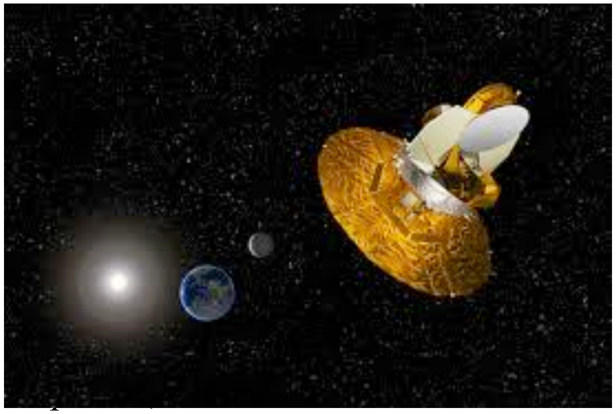
•Matter and antimatter annihilate, making energy (photons).

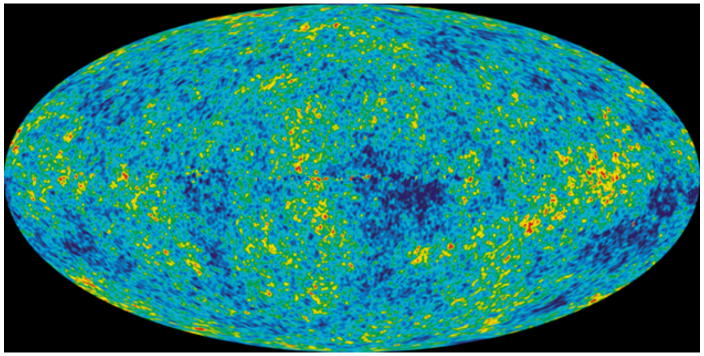
•(Somewhere along way) some processes have very slightly different rates for matter/antimatter

•A tiny bit of extra matter is leftover, plus lots of energy + ~ no antimatter

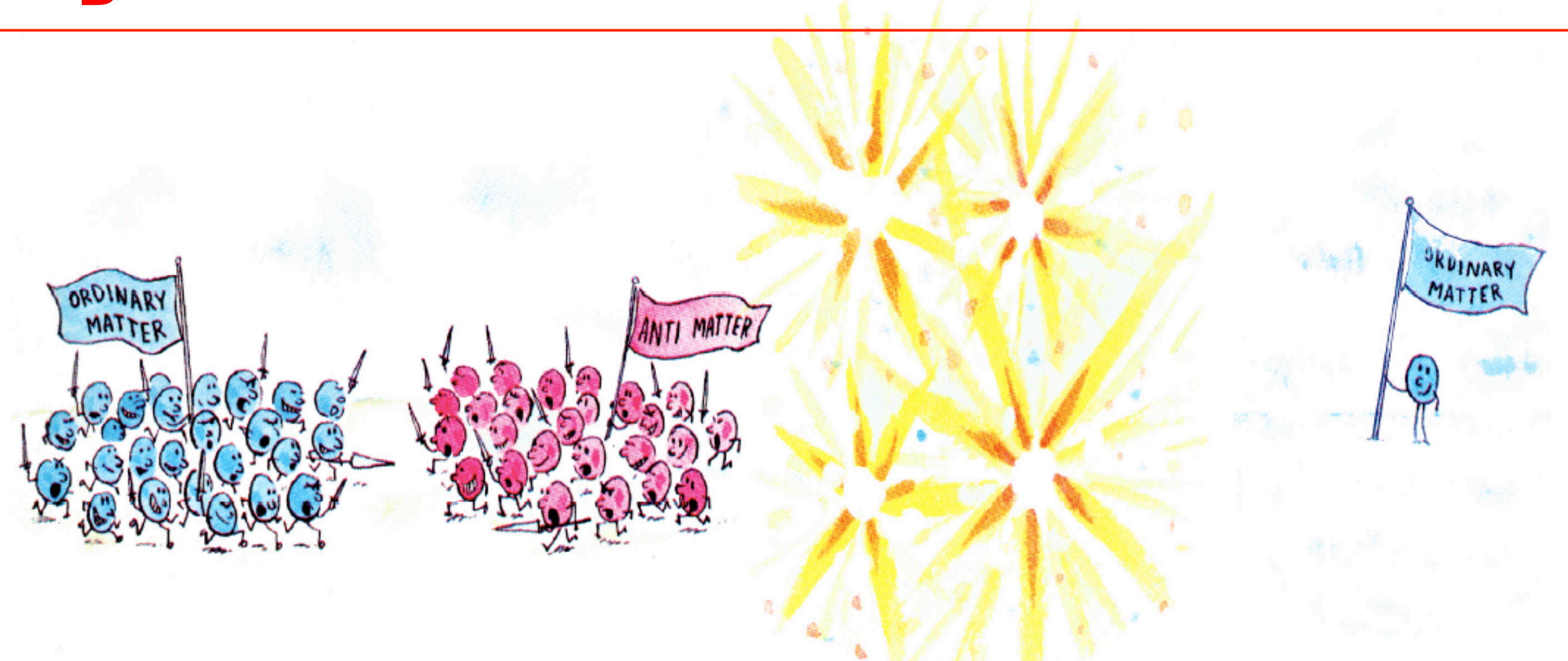
•Cosmologists have measured the matter (baryon) to photon ratio

(WMAP Cosmic Microwave Background Satellite)





Tiny excess of matter over AntiMatter??



Antimatter annihilated with matter in first millisecond after Big Bang.

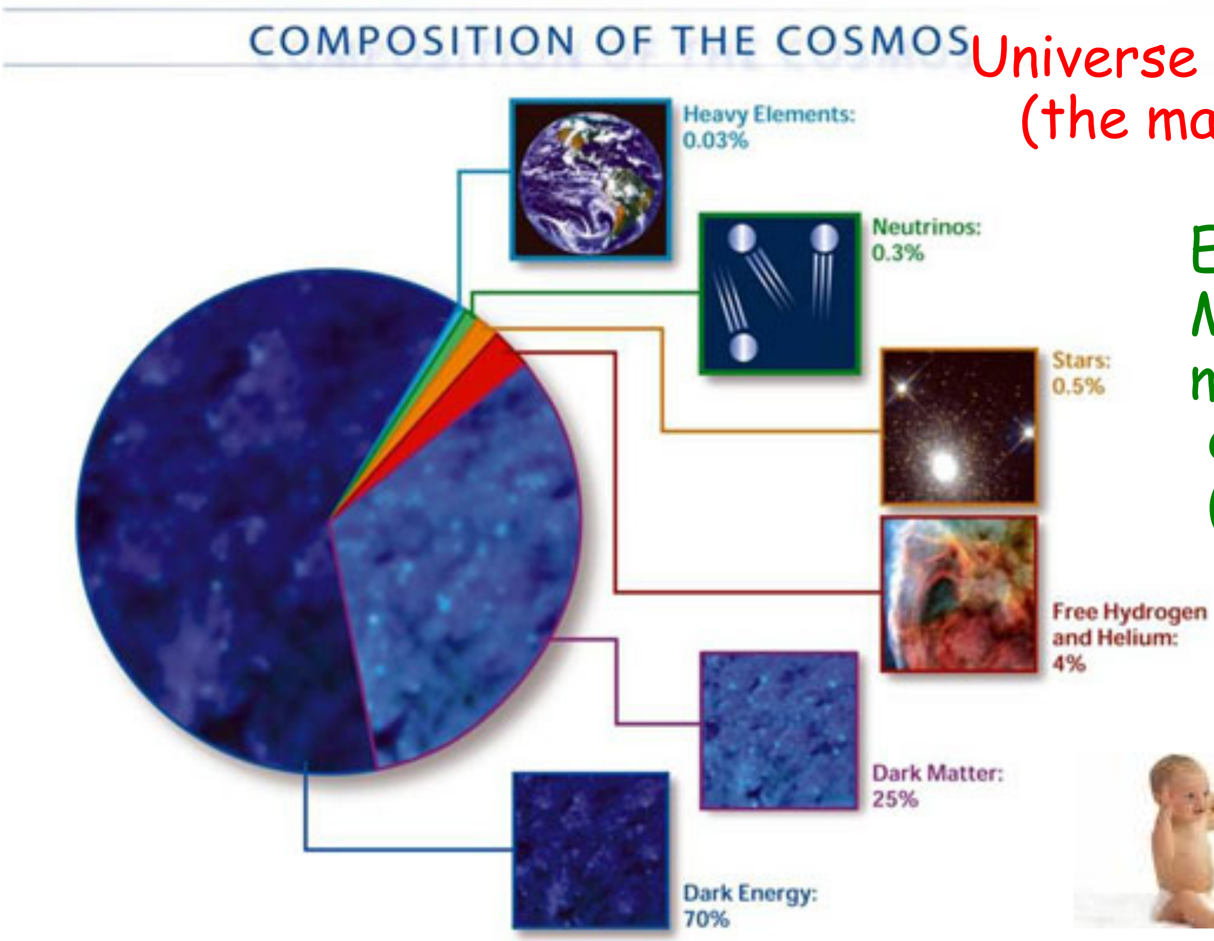
Matter: 10 billion and 1 particles   Antiatter: 10 billion antiparticles

Annihilate to 20 billion photons! Plus one particle leftover

Given results of recent cosmology experiments (WMAP), abundances of elements in universe can be predicted.

This tiny excess of matter became everything in our universe!

Hey, where's the antimatter??

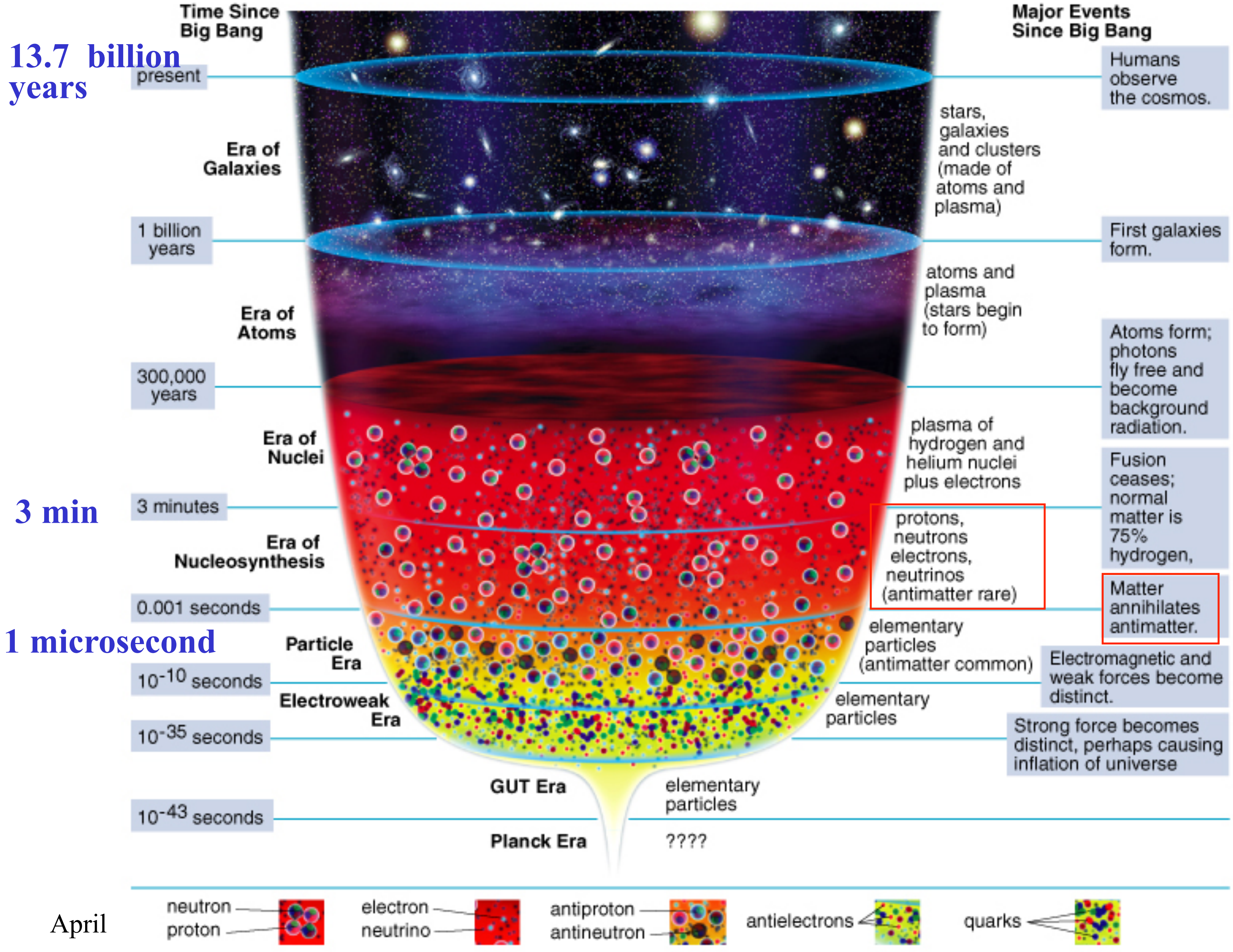


Universe is ~4.5% baryonic matter (the matter we know about)

Embarrassing:
Most of the universe is made up of "stuff" we don't even know about !!
(➔ new physics)

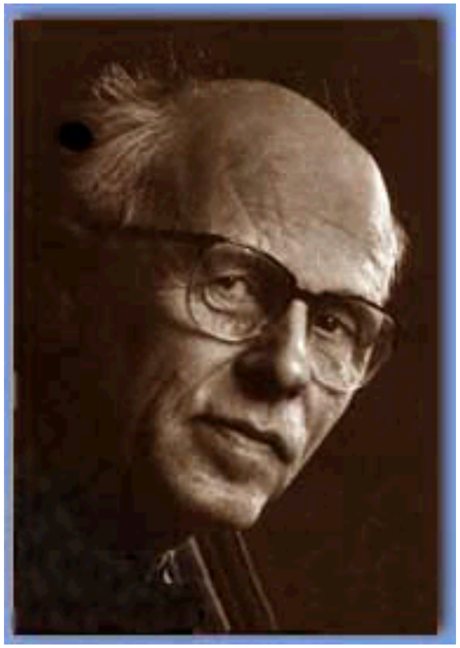
Big Bang Nucleosynthesis: Key in determining abundances of light elements

Big Bang: pure energy → subatomic particles → atoms → galaxies → the cosmos



Andrei Sakharov

→ possible to start with a matter and antimatter symmetric universe, and make an asymmetrical one.



Sakharov: conditions for cosmological formation of matter-antimatter asymmetry:

- **Absence of thermal equilibrium**
- **Baryon number violation**
- **Some processes must exist which violate matter -antimatter symmetry**

No problem for Standard Model of Particle Physics

(All known physics)

Matter - Antimatter Asymmetry

CPT SYMMETRY Particles and Antiparticles must have:

Same mass   Same lifetime

~~CP~~ Particles can have different <u>partial</u> rates to selected final states

- Matter/Antimatter asymmetry

- CP parameters well measured

- Matter-Antimatter asymmetry in Kaon system: tiny.
- Cosmological Matter-Antimatter asymmetry: huge

Are both manifestations of matter- antimatter asymmetry rooted in same phenomenon?

Broken Symmetries

CP violation: discovered in 1964, not explained by Standard Model

Kobayashi & Maskawa, 1973, postulated a mechanism by which CP- violation / matter-antimatter asymmetry could be explained.

It was a very "far out" theory at the time:

Predicted 3 generations of quarks, explains how matter-antimatter asymmetry could originate via interactions of quarks.

But it agreed with experimental results.

Our goal:

Find an inconsistency in their theory: a place where it breaks down - by doing precise rigourous experiments in matter-antimatter asymmetry.

Standard Model of Particle Physics

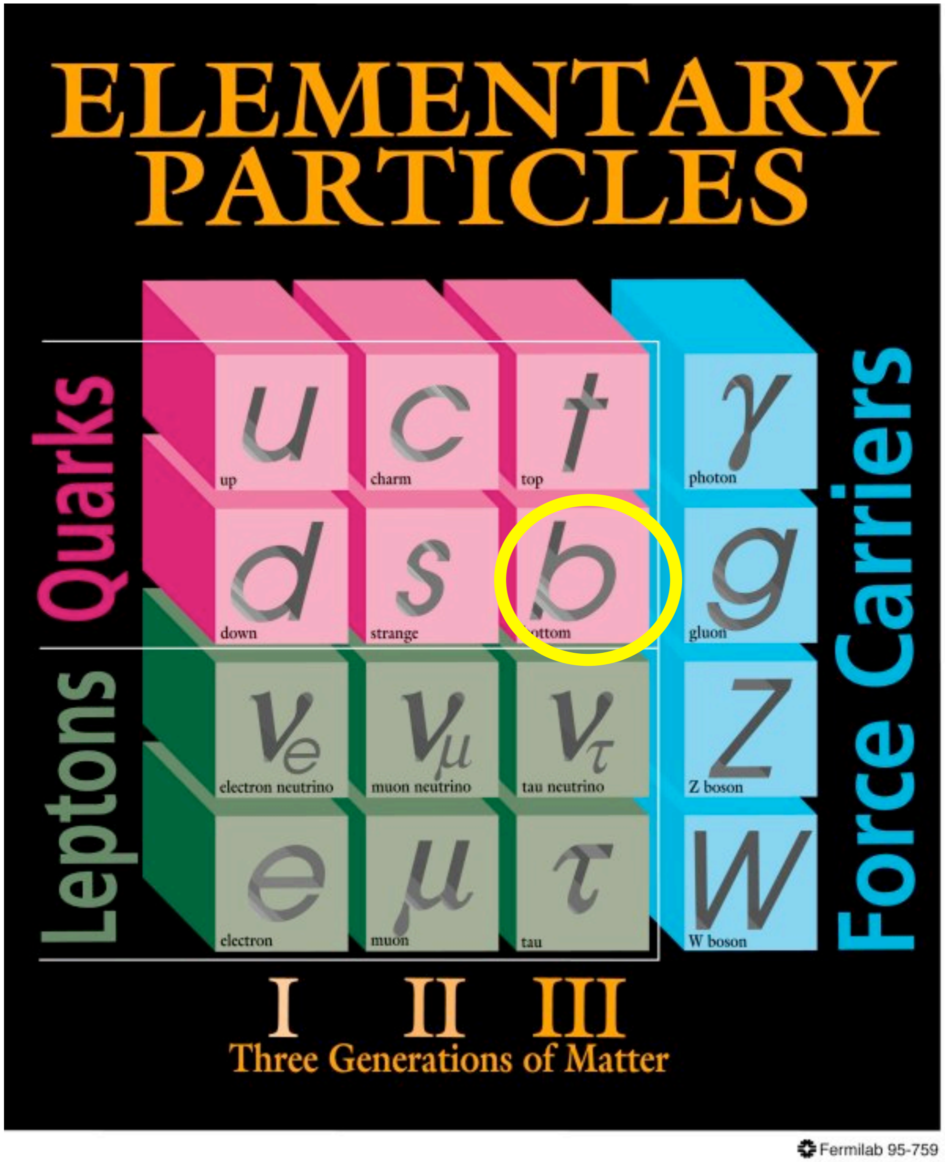
Forces: Electromagnetic

Strong

Weak

Matter: Quarks

Leptons



Higgs Boson ?

Weak Interactions & KM mixing matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix

Weak Eigenstates	CKM matrix	Strong/Mass Eigenstates

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \approx \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\bar{\rho}-i\bar{\eta}) & -A\lambda^2 & 1 \end{pmatrix} + \vartheta(\lambda^4)$$

$$\bar{\rho} \equiv \rho\left(1-\lambda^2/2\right) \qquad \bar{\eta} \equiv \eta\left(1-\lambda^2/2\right)$$

A~.82, λ~.224

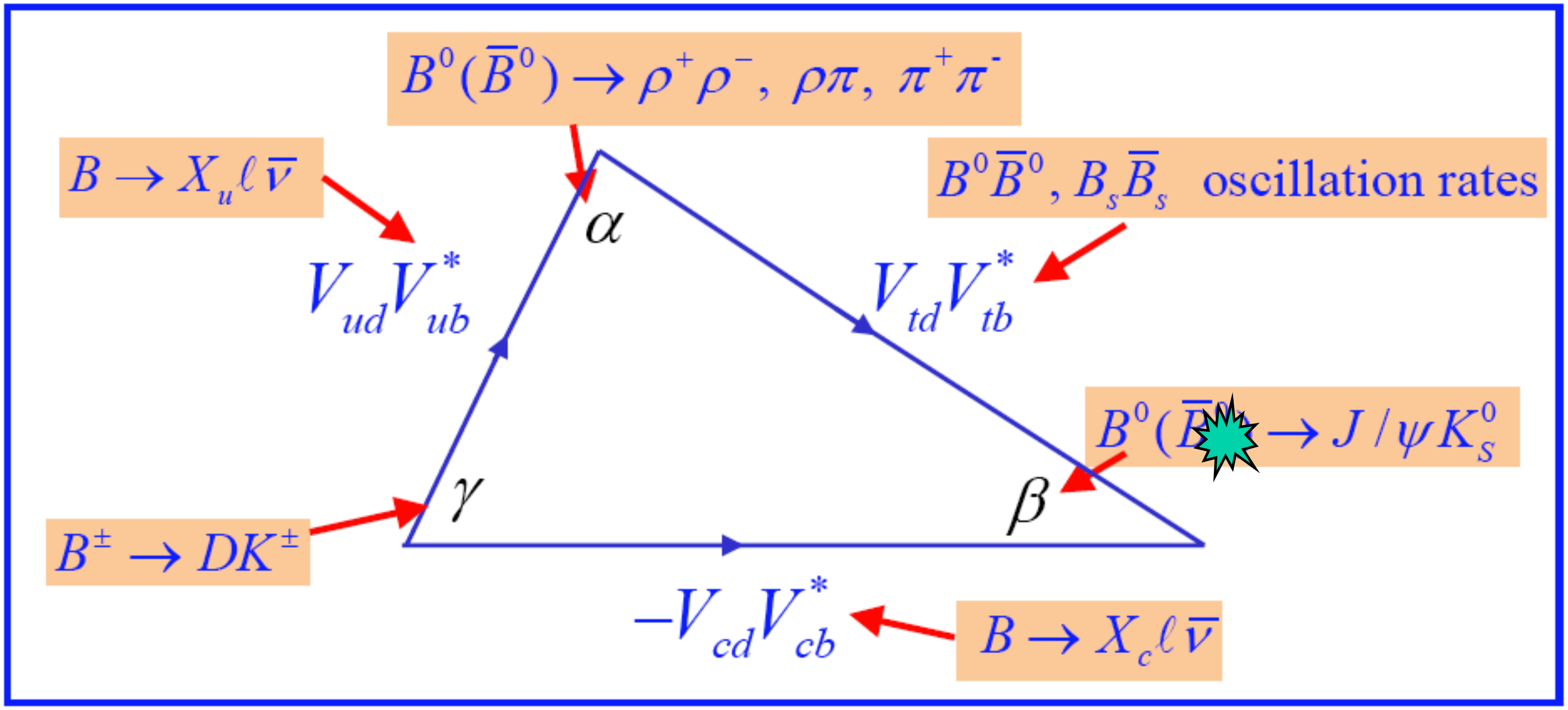
In Standard Model with 3 quark generations, - one free parameter can accommodate CP Violation (in in K & B systems)

We measure η, λ

But is the complex η in CKM matrix indeed the origin of BAU?

"Unitarity Triangle"

SM prediction: ALL measurements of *W*-mediated quark processes must be consistent with the CKM framework.



- **Angles** of triangle: measure from CP **asymmetries** in B decay
- **Sides** of triangle: measure **rates** for b→ulν, $B^0\overline{B}^0$ mixing
- **Other constraints** in ρ,η plane from CP violation in K decay

How to Measure matter-antimatter asymmetry in B system

1. Make **lots** of B's (>900 million $B\bar{B}$ pairs collected)

2. Reconstruct one B^0 ($\overline{B^0}$) decay to a CP eigenstate final state
3. Tag the other B^0 ($\overline{B^0}$) -- i.e. determine whether it is a B^0 or $\overline{B^0}$
4. Reconstruct the decay vertices of the B's
   - and hence determine Δt between their decays
5. Fit and extract parameters in theory of Kobayashi and Maskawa to test theory

B Decays & Matter Antimatter Asymmetry

Quantum Mechanics: Examine particle decays

a "double slit" type experiment

$$
\begin{tikzcd}
 & B^0 \arrow[dr] & \\
B^0 \arrow[ur] \arrow[dr] & & f_{CP} = J/\psi K_S \\
 & \bar{B}^0 \arrow[ur] &
\end{tikzcd}
$$

B system great place to study matter-antimatter asymmetry due to 2 strokes of luck:

1. B lifetime is extremely long; 1.5 picoseconds -

2. Neutral B mesons have large mixing - thanks to heavy top quark mass.

To access complex critical parameter η in theory of Kobayashi and Maskawa, measure interference between direct & mixed B decays to same final state.

Measuring ~~CP~~ in B system

"Easy" Decay Mode:

$$B \to J/\psi\, K_S^0 \qquad J/\psi \to e^+e^-(\mu^+\mu^-) \qquad K_S^0 \to \pi^+\pi^-$$

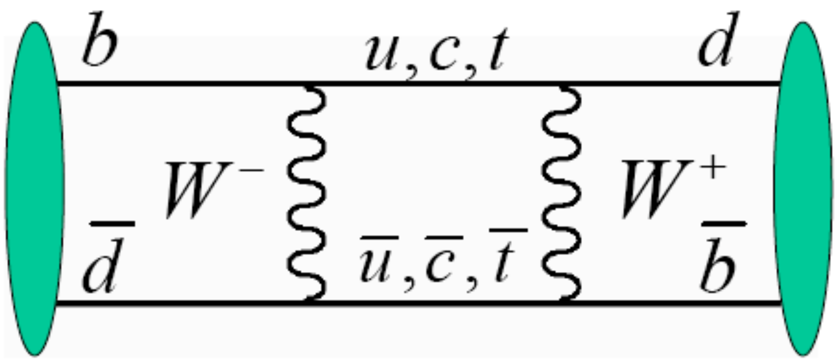
"Easy" both to interpret theoretically
and to perform experimentally

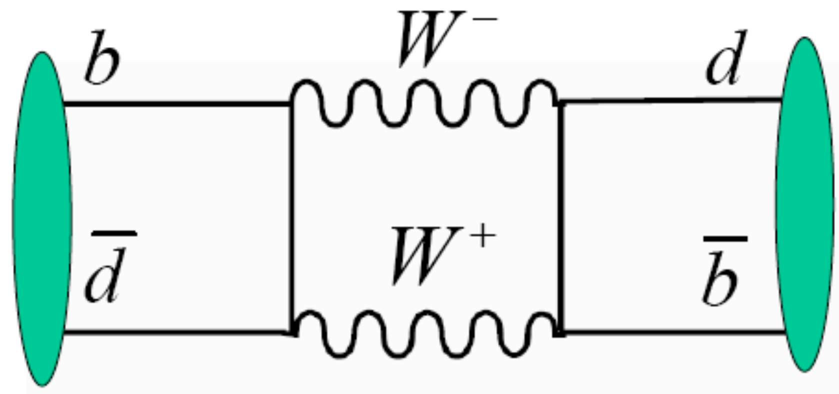
Problems:

- Can't tell a B^0 from a $\overline{B}^0$ when they decay to CP eigenstates
- Υ(4s) is coherent quantum state: time averaged asymmetry is zero.

∴ Perform **<u>time dependent measurement</u>** to observe asymmetry

Weak transitions underlying $B^0\, \overline{B}^0$ oscillations





$$\left|B^0(t)\right\rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt}\left(\cos\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle + i\alpha\cdot\sin\frac{\Delta M\cdot t}{2}\left|\overline{B}^0\right\rangle\right)$$

$$\left|\overline{B}^0(t)\right\rangle = e^{-\frac{\Gamma}{2}t} e^{-iMt}\left(\frac{i}{\alpha}\sin\frac{\Delta M\cdot t}{2}\left|B^0\right\rangle + \cos\frac{\Delta M\cdot t}{2}\left|\overline{B}^0\right\rangle\right)$$

B^0 and $\overline{B}^0$ spontaneously evolve into each other. More precisely, a particle that is initially a B^0 evolves into a superposition of B^0 and $\overline{B}^0$.

Time Dependent Asymmetry

Time dependent asymmetry defined:

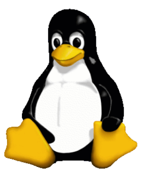
$$A_{CP}(t) = \frac{(\Gamma(\overline{B}^0(t) \to f_{CP}) - (\Gamma(B^0(t) \to f_{CP})}{(\Gamma(\overline{B}^0(t) \to f_{CP}) + (\Gamma(B^0(t) \to f_{CP})}$$

Time dependant decay rates:

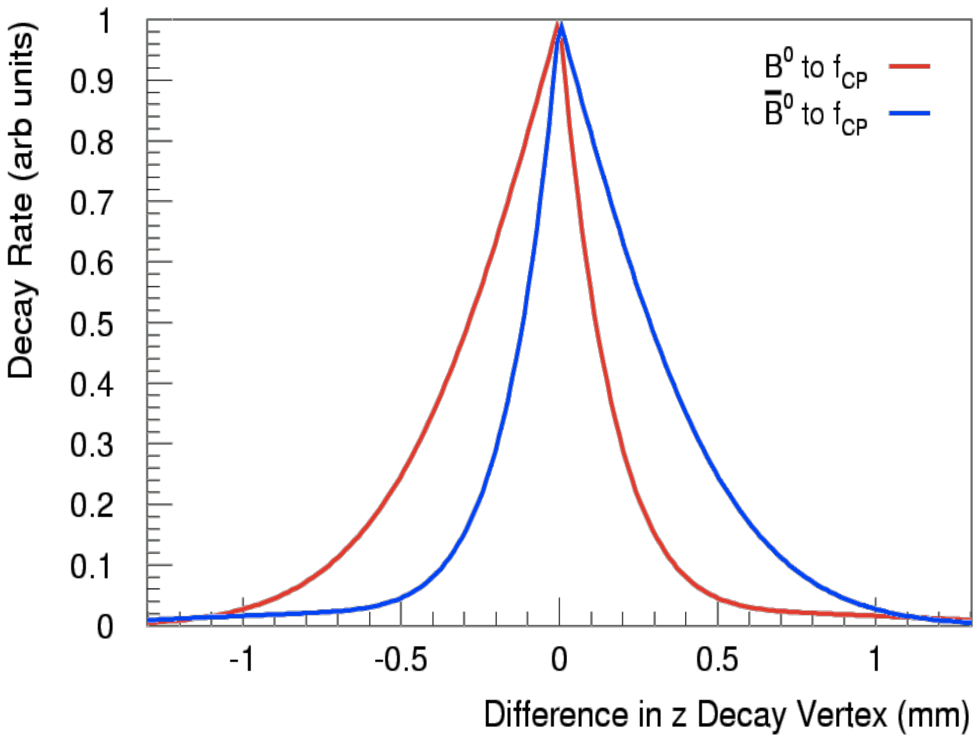
$$\left\{ \begin{matrix} \Gamma(B^0(t) \to f_{CP}) \\ \Gamma(\overline{B}^0(t) \to f_{CP}) \end{matrix} \right\} \sim e^{-\Gamma t}(1 \mp A_{CP} \cos \Delta m t \pm S_{CP} \sin \Delta m t)$$

$B \to J/\psi\ K_S$, $B \to \pi^+\pi^-$

Many decay channels give us access to quantities to test & validate theory of K&M



B Decay time distribution



Distributions shifted due to matter-antimatter asymmetry.

Time dependent asymmetry appears as a shift in the Δt and hence Δz distribution between events tagged as B^0 and events tagged as $\overline{B}^0$

Indirect CP Violation

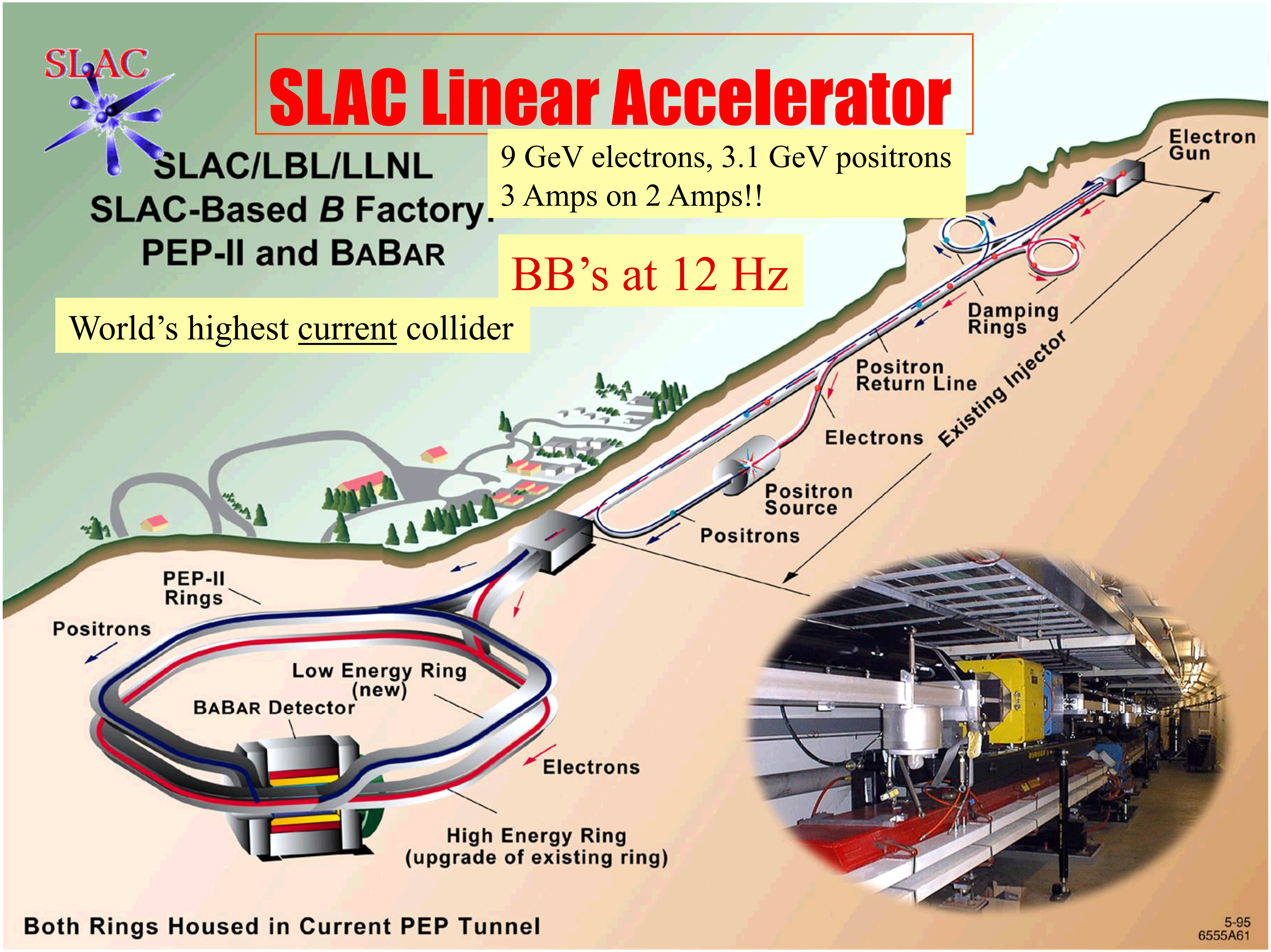
Direct CP violation would show up as time-independent difference in area under the 2 curves

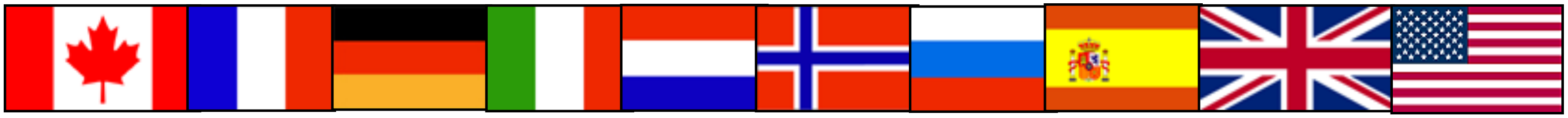
SLAC Linear Accelerator

9 GeV electrons, 3.1 GeV positrons
3 Amps on 2 Amps!!

BB's at 12 Hz

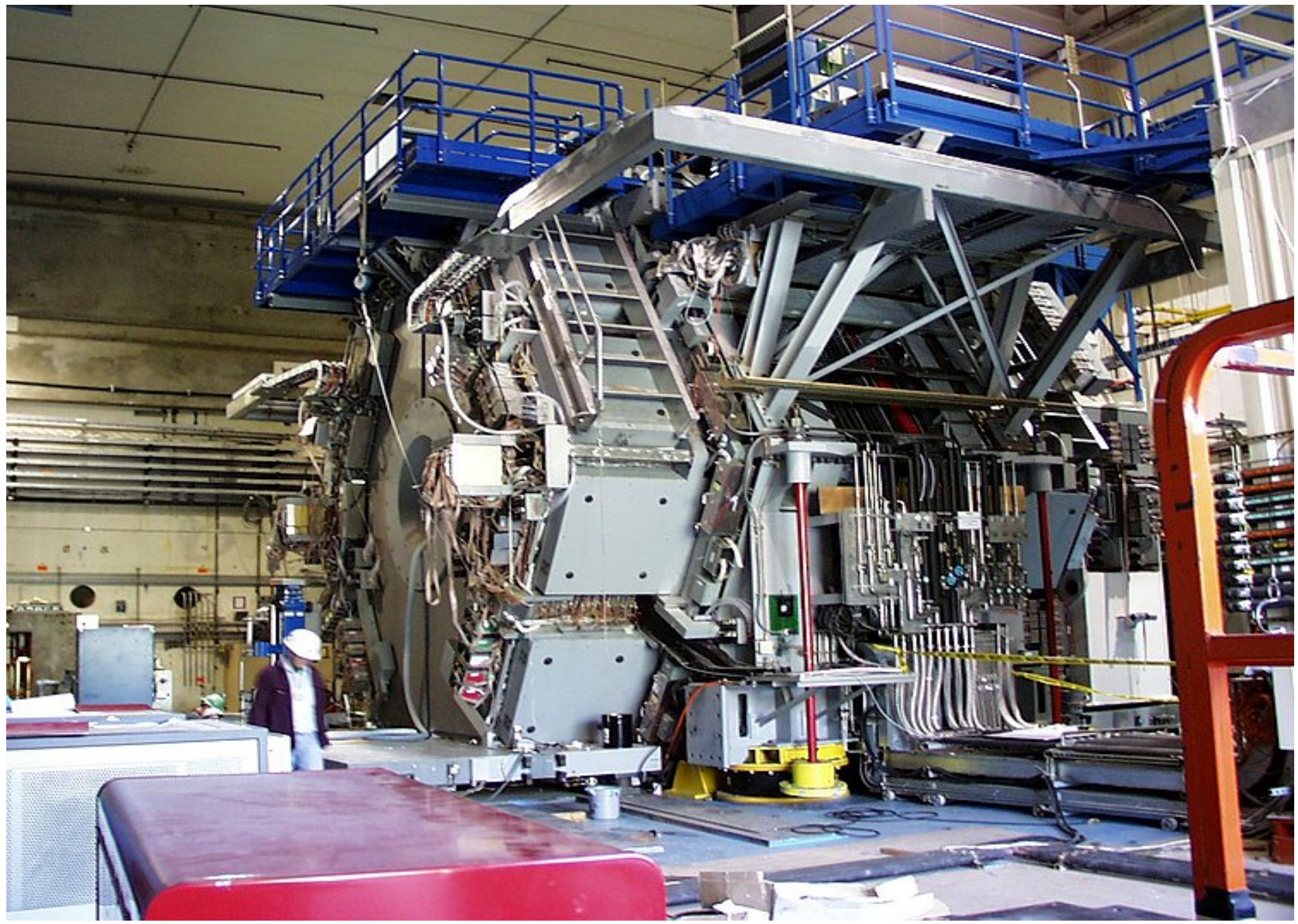
World's highest <u>current</u> collider





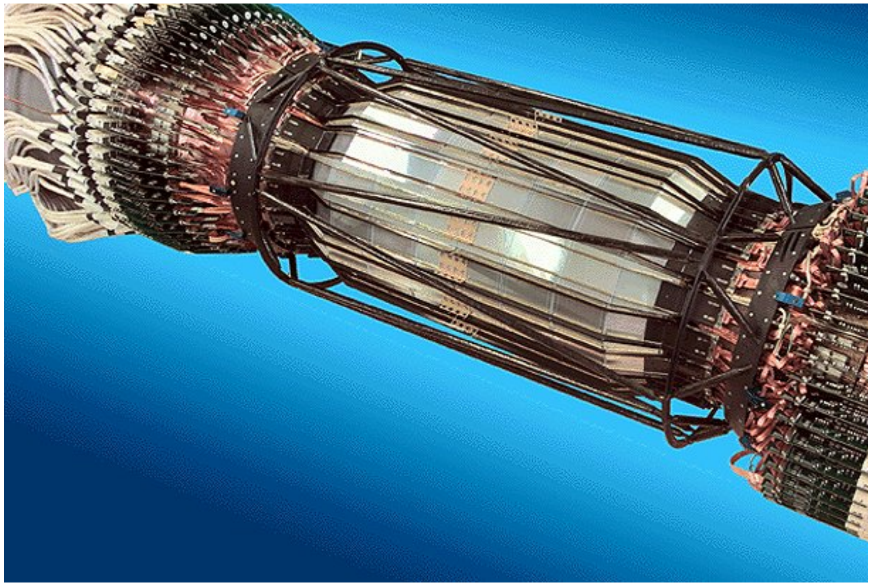
10 countries, 522 physicists, 77 institutes, (31 Canadians)

BaBar Detector



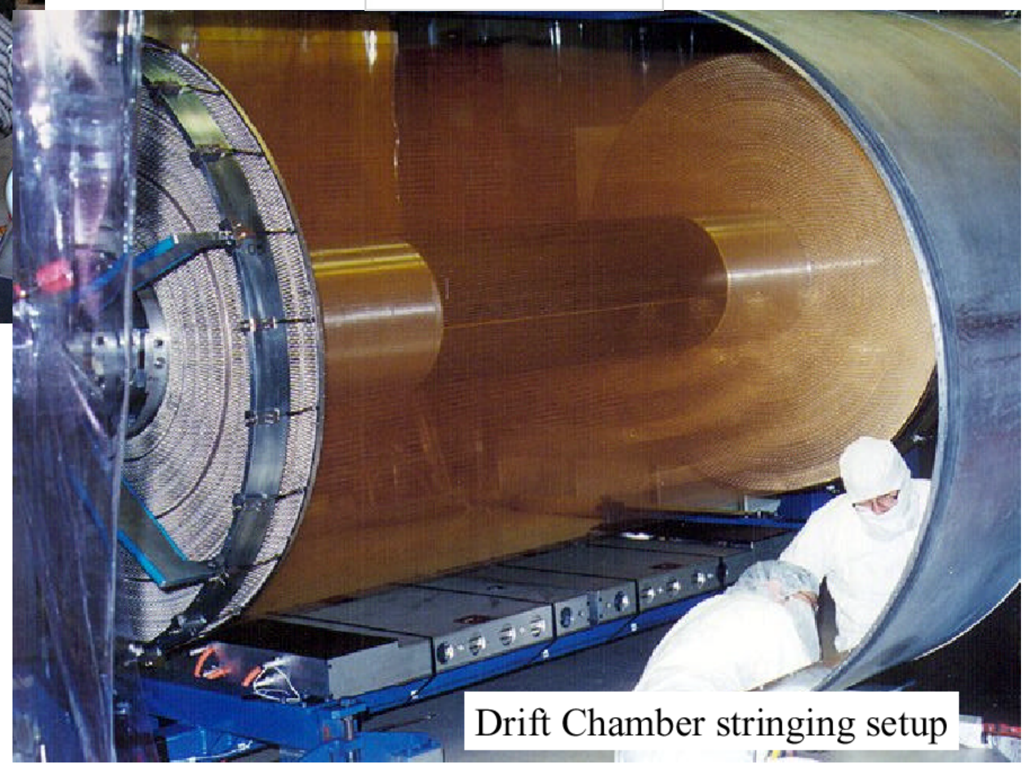
BABAR Silicon Microvertex Detector

150,000 channels



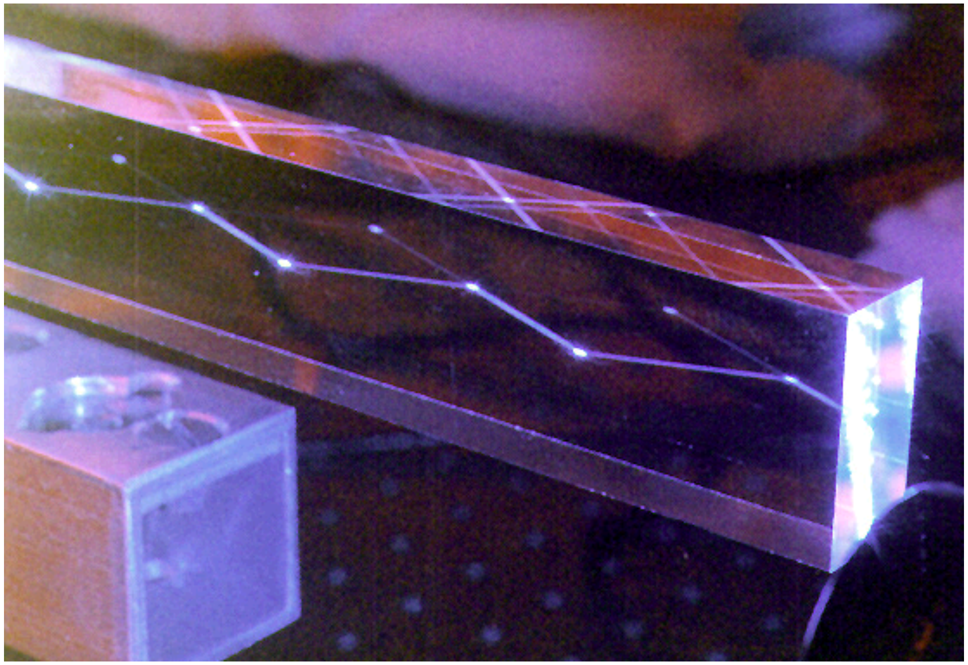
BaBar Drift Chamber

MADE IN CANADA
FABRIQUÉ AU CANADA



Drift Chamber stringing setup

BaBar Detector

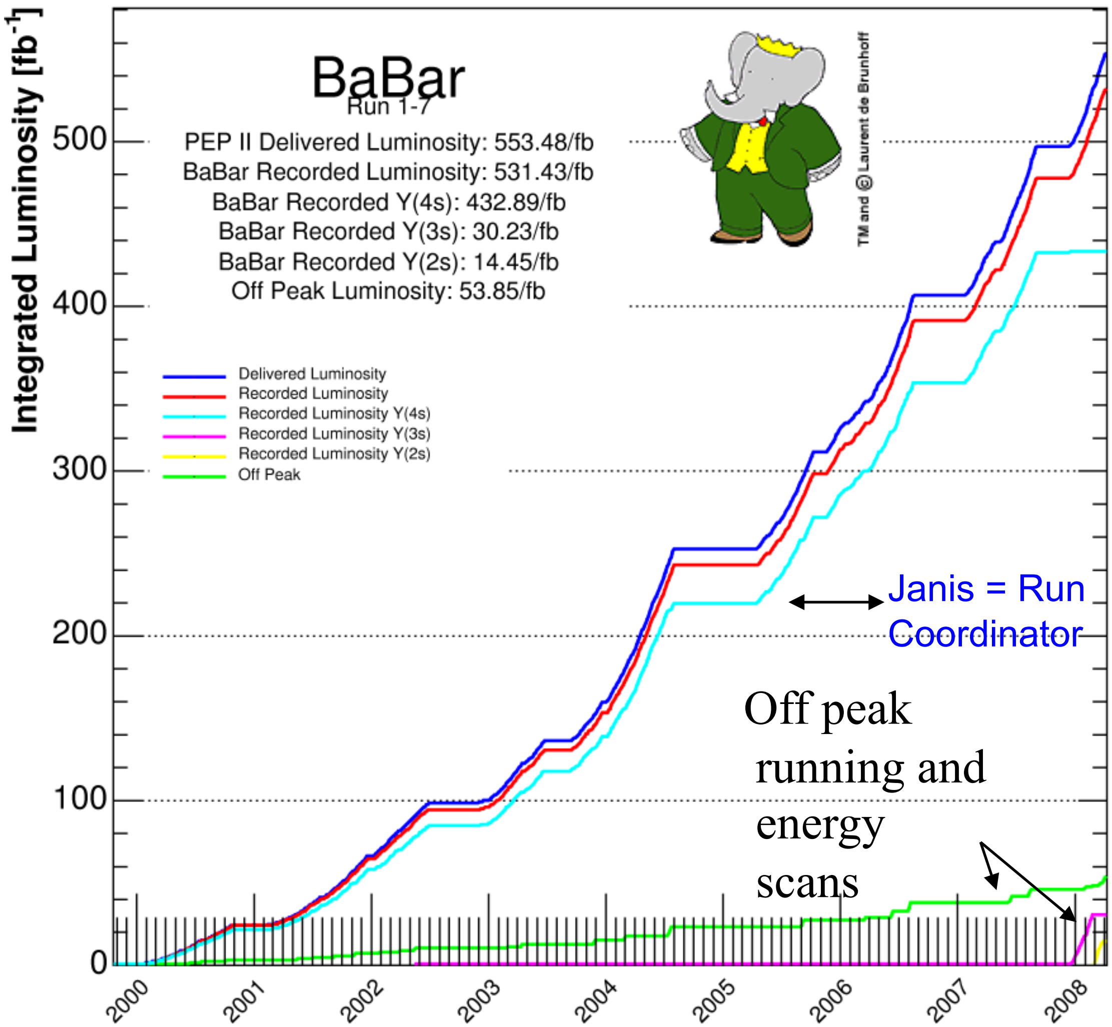


DIRC Detector
(Quartz Bar)

Electromagnetic
Calorimeter

(~6580 crystals)

PEP- II Accelerator



Physics Runs 2000-08

BaBar recorded

> 900 Million $B\overline{B}$ pairs

"interesting interactions in over 22 billion electron-positron annihilations"

-over 4 Petabytes of data!

Also generate simulated data (at the level of electronic signals) to study physics, test our methods, check biases, deduce efficiencies..)

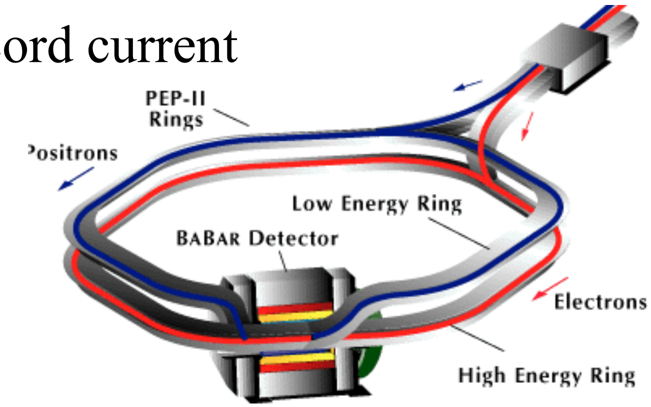
Two B Factories

PEP-II at SLAC (USA)

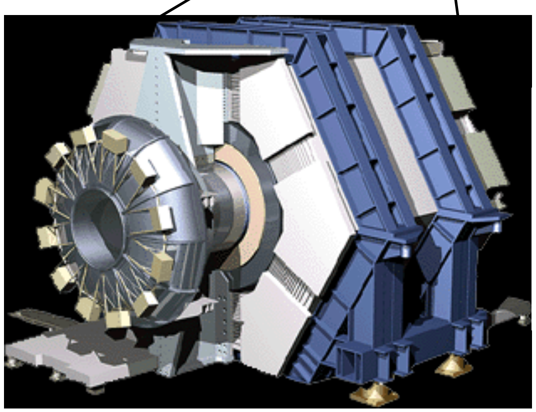
9GeV (e^-) $\rightarrow$ 3.1GeV (e^+)

Peak L: **$1.21\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$**

Record current

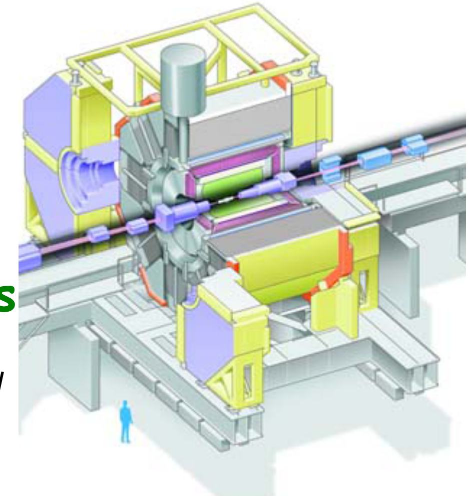


BaBar

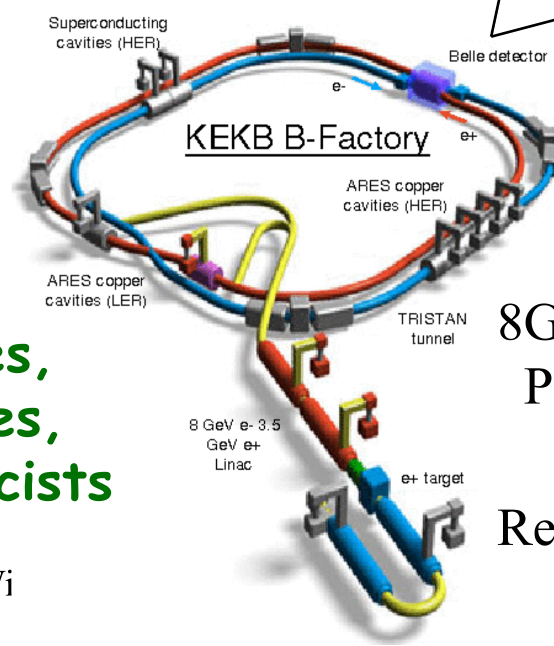


10 countries,
77 institutes,
~520 physicists

13 countries,
57 institutes,
~400 physicists



Belle



KEKB (Japan)

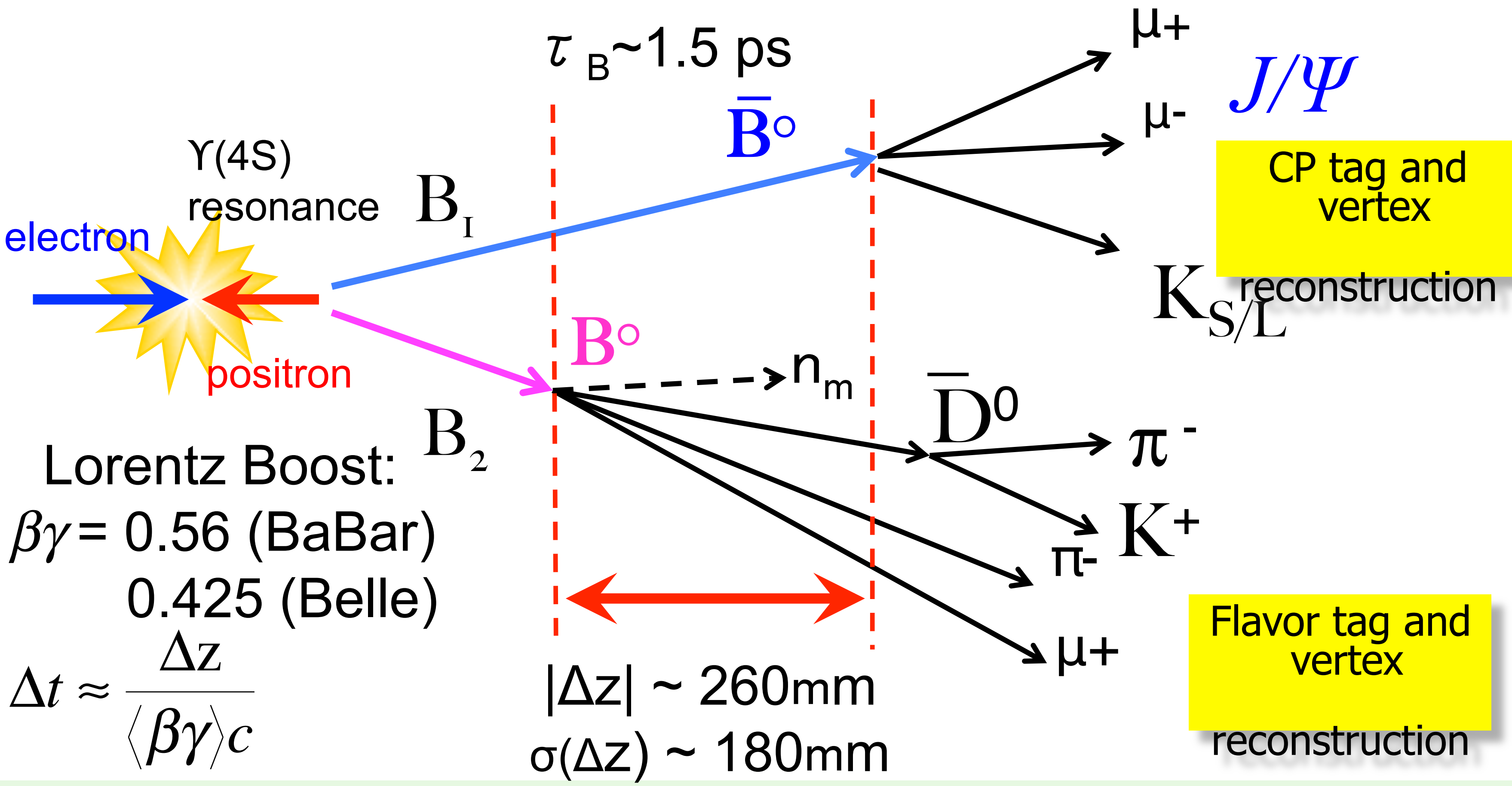
8GeV (e^-) $\rightarrow$ 3.5GeV (e^+)

Peak L:

$1.71\times10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

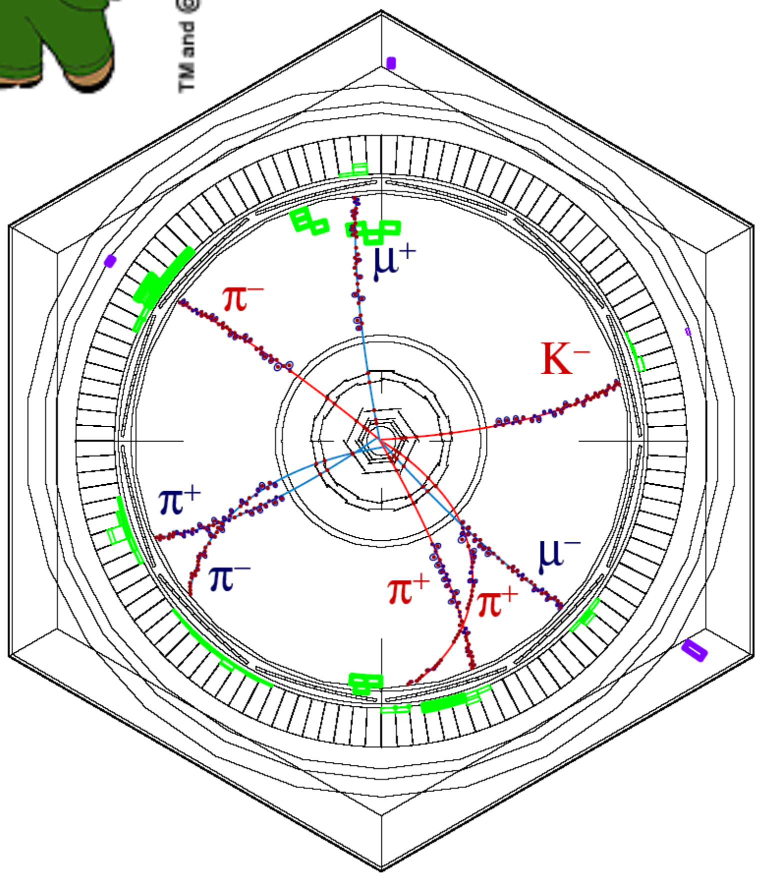
Record Luminosity

Measuring Δz (and hence Δt)



1. Fully reconstruct one B-meson which decays to CP eigenstate
2. Tag other B to determine its flavor
3. Proper time (Δt) is measured from decay-vertex difference (Δz)

Fully Reconstructed Event



Candidate Event:

$$B^0_{CP} \rightarrow \psi(2S)\, K^0_S, \quad K^0_S \rightarrow \pi^+\pi^-$$

$$\psi(2S) \rightarrow \mu^+\mu^-$$

The second B meson is **fully reconstructed:**

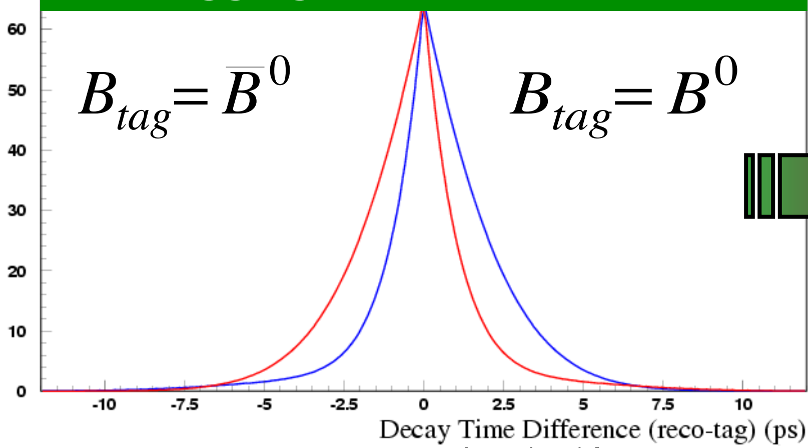
$$\overline{B}^0 \rightarrow D^{*+}\pi_f^-$$

$$D^{*+} \rightarrow D^0 \pi_s^+$$

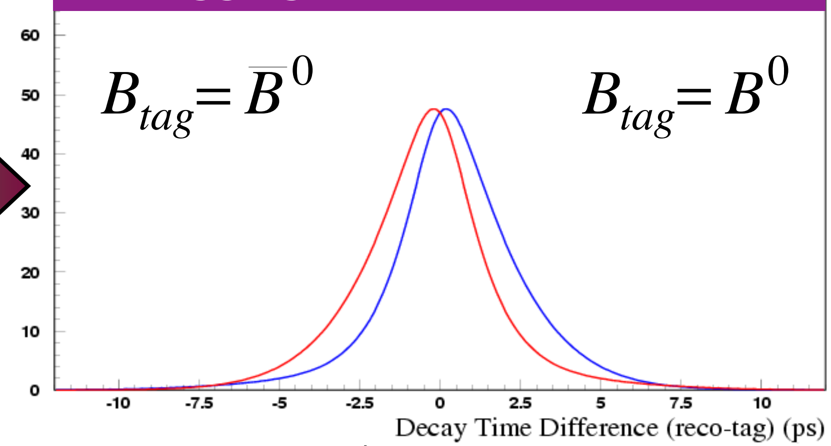
$$D^0 \rightarrow K^-\pi^+$$

Δt Resolution & Mis-tag Dilution

perfect
tagging & time resolution



typical
mistagging & finite time resolution



$$f(\Delta t) = \left\{ \frac{e^{-|\Delta t|/\tau_B}}{4\tau_B} \left[1 \mp \eta_f \sin 2\beta (1-2w) \sin(\Delta m_d \Delta t) \right] \right\} \otimes R(\Delta t)$$

Mistag fraction w

resolution R

Get w and R(Δt) from DATA: $\overline{B^0}$-B^0 mixing event analysis

Self-tag(fully reconstructed) → measure resolution, vertex separation, mistag rate

USING DATA Fit for parameters in Kobayashi- Maskawa theory.

Fit for Triangle Parameters & sin 2β

- β parameter is the angle in unitarity triangle
- If β is non-zero then we have CP violation in B meson system

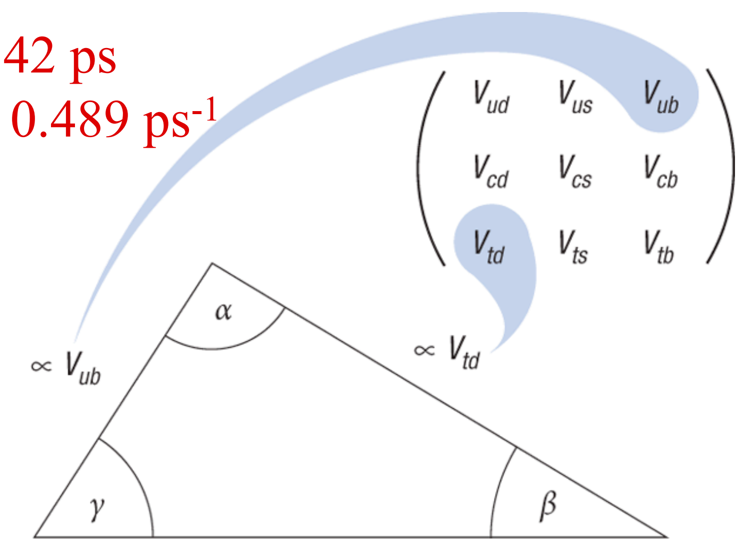
Maximum likelihood fit to the Δt distributions for CP and oscillation (B mixing) samples

34 fit parameters:

Sin 2 β	**1**
Mistag fractions *w*	8
Signal Δt resolution	8
Background time dependence	6
Background Δt resolution	3
Mistag fractions	8

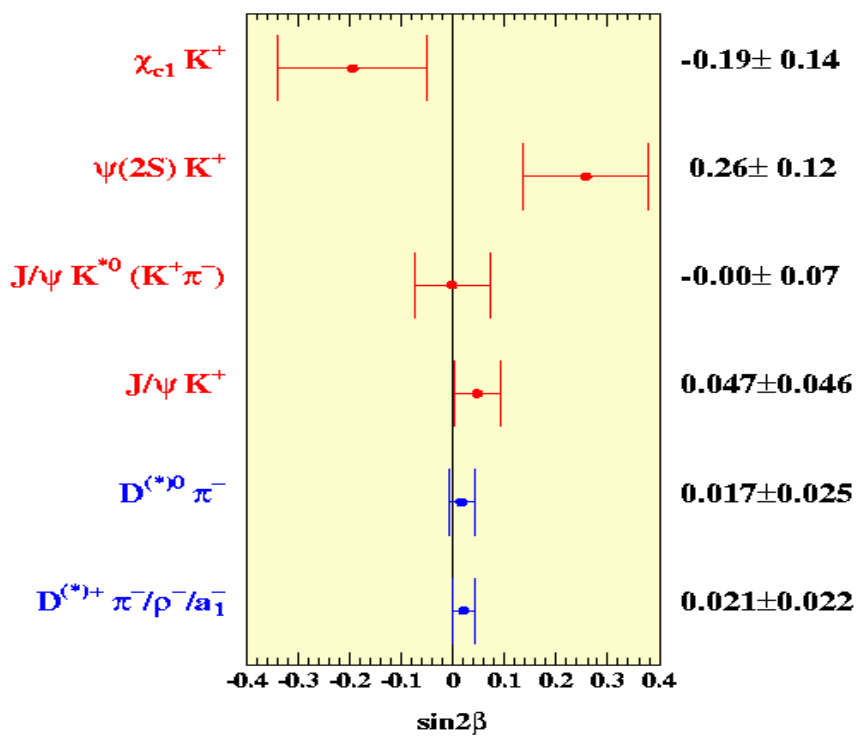
τ_B=1.542 ps

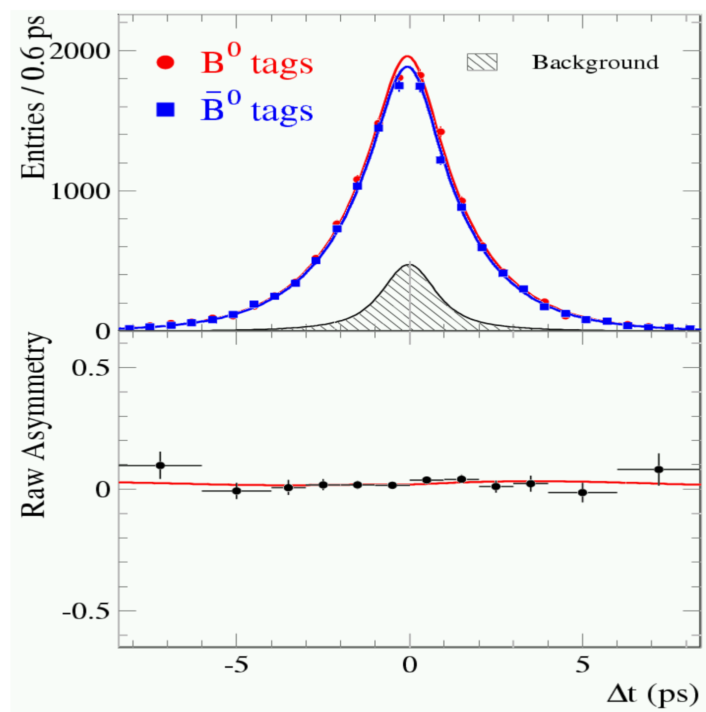
Δm_d = 0.489 ps^{-1}

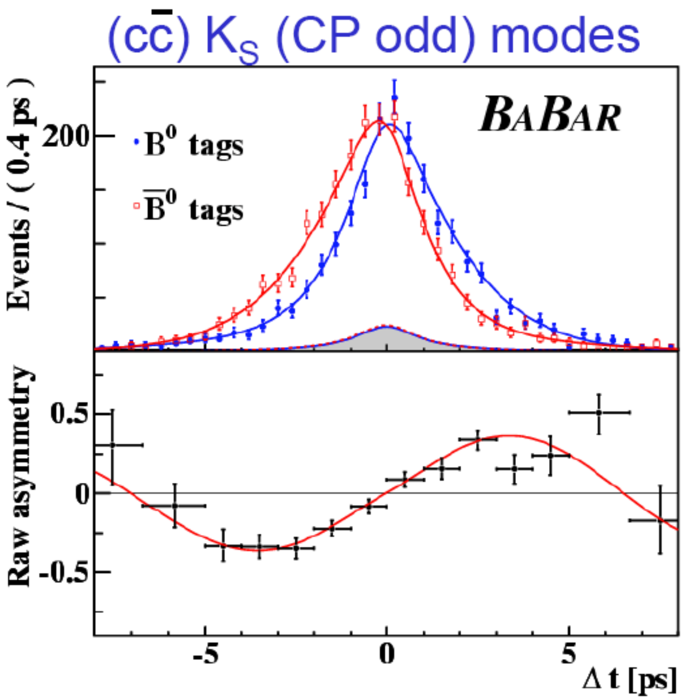


Control Samples

Control samples: no asymmetry (charged final states)





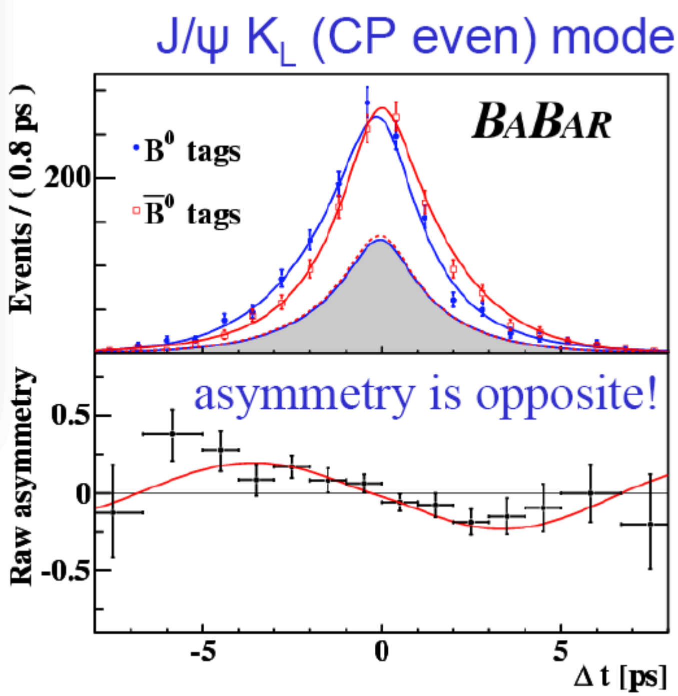


sin 2β Fit Results
(charmonium K modes)

Typical: ~80% purity

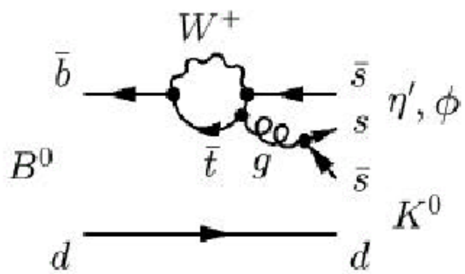
tagging efficiency: ~28%

statistics limited!



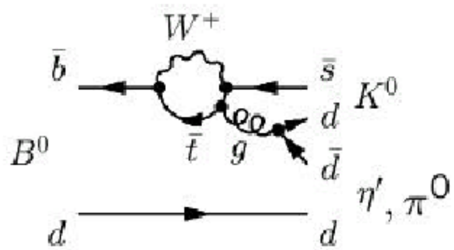
$\sin 2\beta = 0.710 \pm 0.034\ (\text{stat}) \pm 0.019\ (\text{sys})$
$|\lambda| = 0.932 \pm 0.026\ (\text{stat}) \pm 0.017\ (\text{sys})$

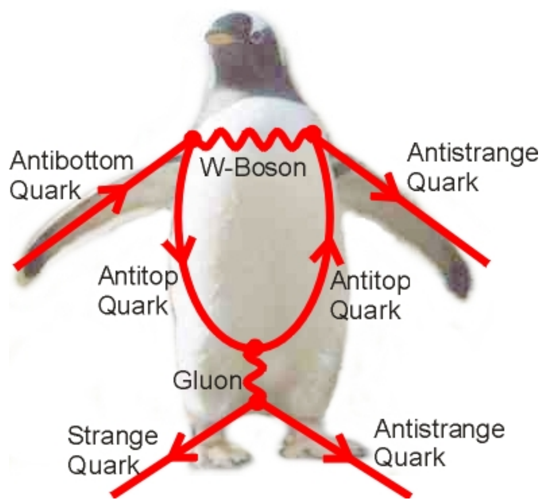
sin 2β via Penguin Decay Modes

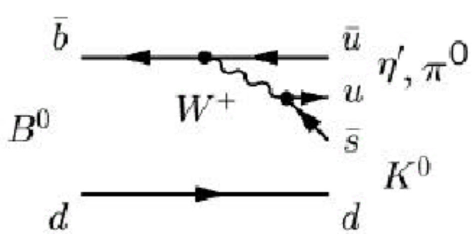


Look at sin 2β in other B decay modes:

$b \to \bar{s}ss$, $b \to \bar{s}uu$ Consistent??





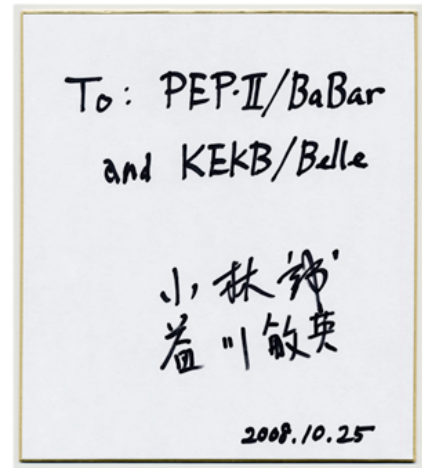


New physics can enter via virtual non-Standard Model particles in penguin loop and other loop diagrams, comparable in amplitude

$B \to \Phi K^0_S$, $B \to \eta' K^0_S$, $B \to \pi^0 K^0_S$

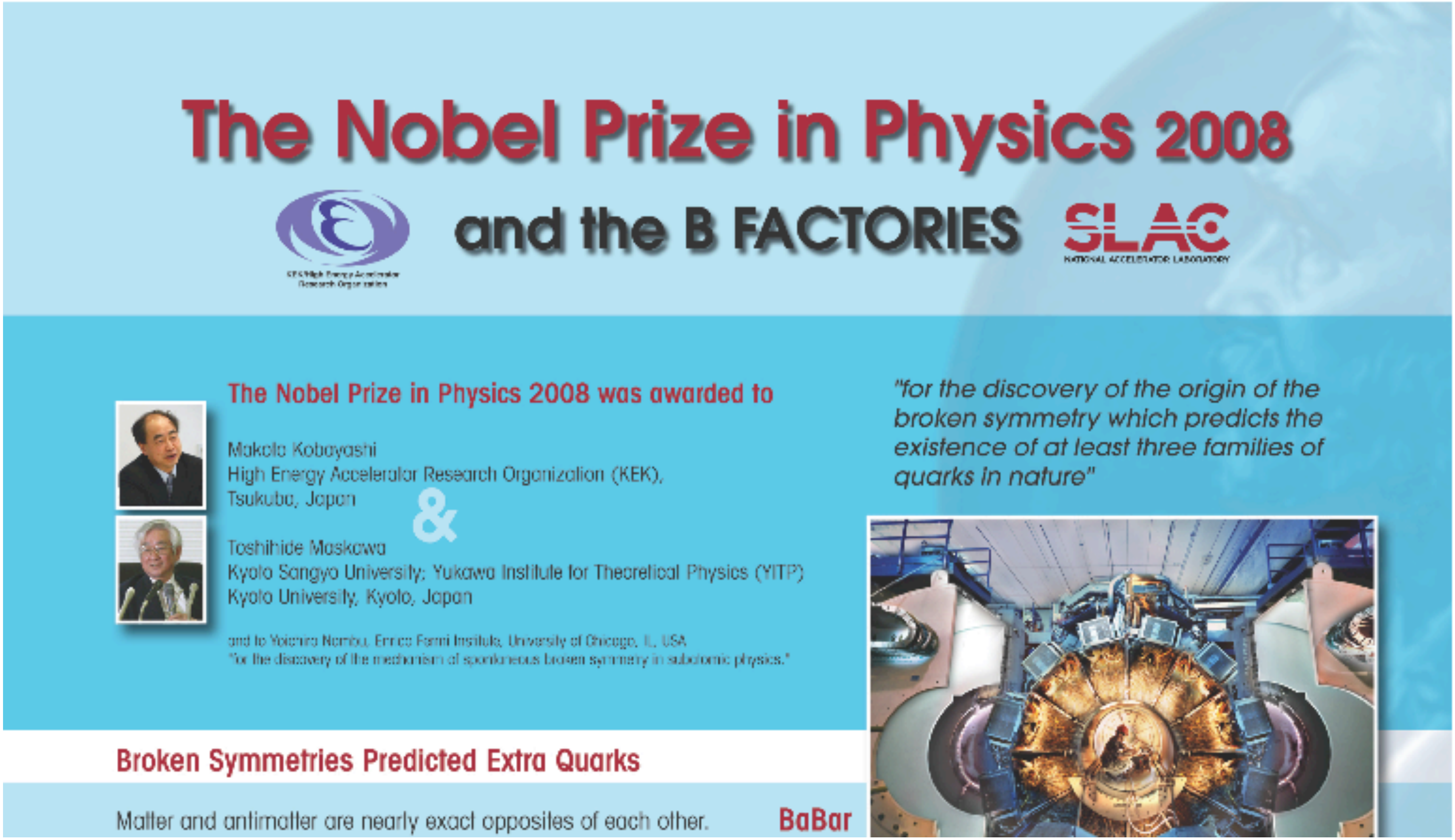
Symmetry and Broken Symmetry: 2008 Nobel Prize in Physics

Nambu Kobayashi Maskawa



"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"

"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"



The Nobel Prize in Physics 2008
and the B FACTORIES
SLAC
NATIONAL ACCELERATOR LABORATORY
The Nobel Prize in Physics 2008 was awarded to
Makoto Kobayashi
High Energy Accelerator Research Organization (KEK),
Tsukuba, Japan
&
Toshihide Maskawa
Kyoto Sangyo University; Yukawa Institute for Theoretical Physics (YITP)
Kyoto University, Kyoto, Japan
and to Yoichiro Nambu, Enrico Fermi Institute, University of Chicago, IL, USA
"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics."
"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"
Broken Symmetries Predicted Extra Quarks
Matter and antimatter are nearly exact opposites of each other.
BaBar

The Nobel Prize in Physics 2008 Press Release

KUNGL. VETENSKAPSAKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

Passion for Symmetry

The fact that our world does not behave perfectly symmetrically is due to deviations from symmetry at the microscopic level.

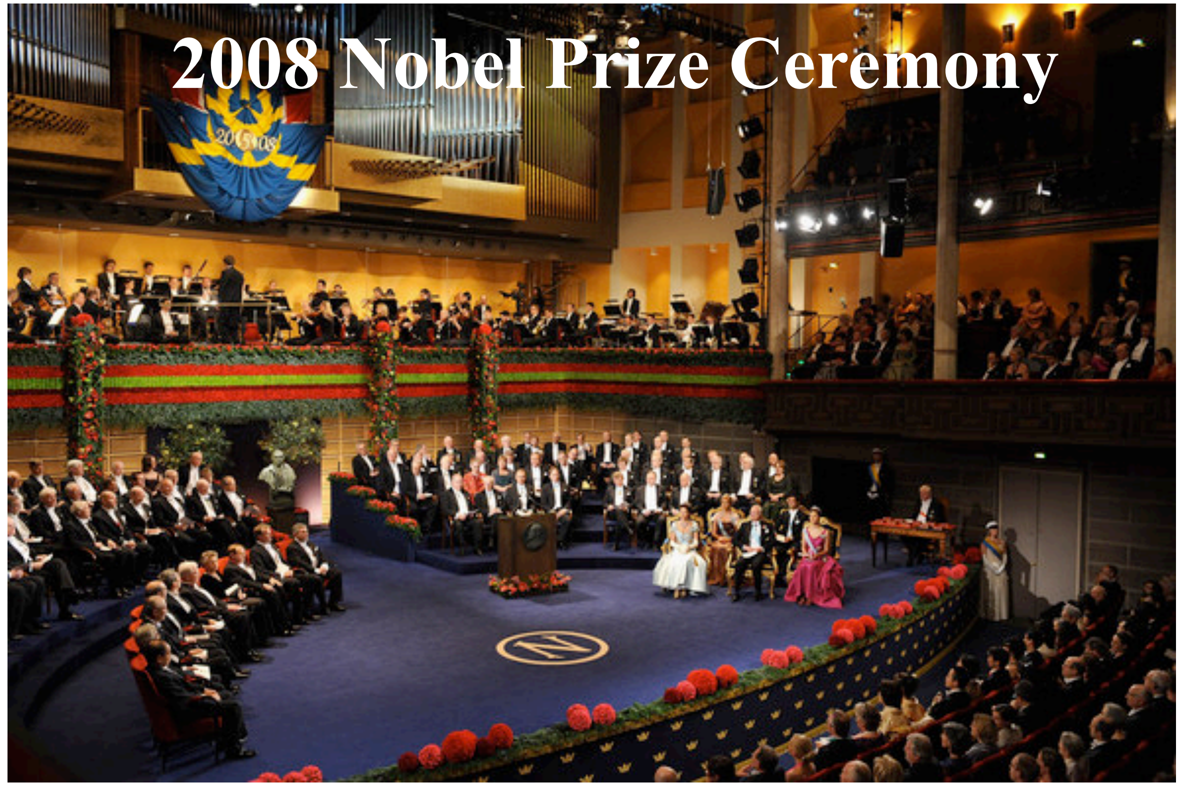
As early as 1960, Yoichiro Nambu formulated his mathematical description of spontaneous broken symmetry in elementary particle physics. Spontaneous broken symmetry conceals nature's order under an apparently jumbled surface. It has proved to be extremely useful, and Nambu's theories permeate the Standard Model of elementary particle physics. The Model unifies the smallest building blocks of all matter and three of nature's four forces in one single theory.

The spontaneous broken symmetries that Nambu studied, differ from the broken symmetries described by Makoto Kobayashi and Toshihide Maskawa. These spontaneous occurrences seem to have existed in nature since the very beginning of the universe and came as a complete surprise when they first appeared in particle experiments in 1964. It is only in recent years that scientists have come to fully confirm the explanations that Kobayashi and Maskawa made in 1972. It is for this work that they are now awarded the Nobel Prize in Physics. They explained broken symmetry within the framework of the Standard Model, but required that the Model be extended to three families of quarks.

These predicted, hypothetical new quarks have recently appeared in physics experiments. As late as 2001, the two particle detectors **BaBar at Stanford, USA** and Belle 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.

A hitherto unexplained broken symmetry of the same kind lies behind the very origin of the cosmos in the Big Bang some 14 billion years ago. If equal amounts of matter and antimatter were created, they ought to have annihilated each other. But this did not happen, there was a tiny deviation of one extra particle of matter for every 10 billion antimatter particles. It is this broken symmetry that seems to have caused our cosmos to survive. The question of how this exactly happened still remains unanswered. Perhaps the new particle accelerator LHC at CERN in Geneva will unravel some of the mysteries that continue to puzzle us.

2008 Nobel Prize Ceremony

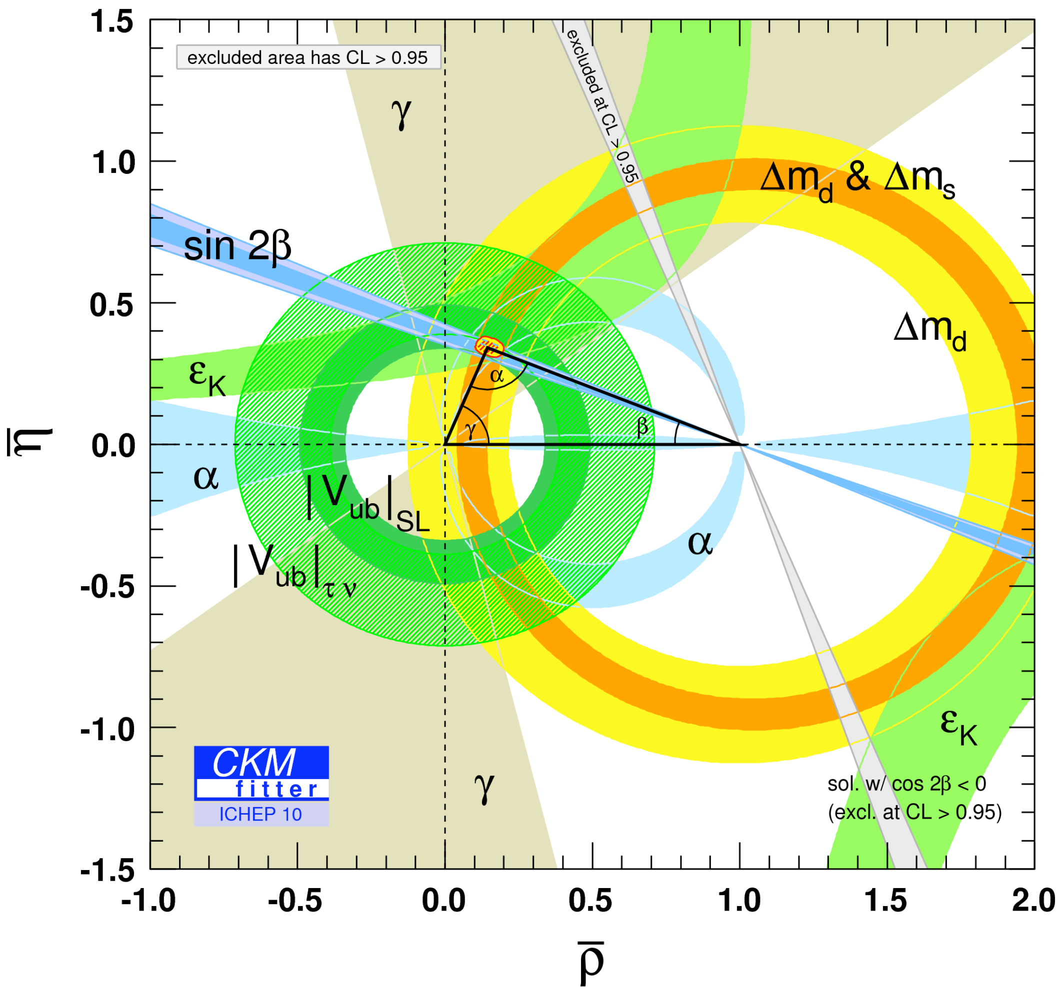


"Please accept our deepest respect and gratitude for the B factory achievements. In particular, the high-precision measurement of CP violation and the determination of the mixing parameters are great accomplishments, without which we would not have been able to earn the Prize."

小林誠 (Makoto Kobayashi)

益川敏英 (Toshihide Maskawa)

Combine BaBar with other (indirect) Results



We've measured parameters in theory

Plus other experiments:

- K system,
- B-mixing rate
- charmless B decays

One solution in amazing agreement !

(either no new physics seen, or here it conspires to cancel)

or Darn It! All consistent & nothing outside SM!

Summary

Standard Model is amazingly self-consistent

Verified KM model of Matter-antimatter asymmetr

Searched for signs of new physics (rare decays, exotics)

Factories will continue to be prime place to look for New Phy

There must be more CP violation in new physics (neutrino sector?)

because phase in CKM theory can't accommodate cosmological asymmetry.

INTERESTING to confirm everything we know about Standard Model.

EVEN MORE INTERESTING to find a place where it breaks down!

finishing mining our Petabyes of data

♥ We've been looking for inconsistencies in SM

♥ Measure angles and sides of UT - all 3 for constraint

♥ Search for new physics

Direct CP violation   Rare B decays

Testing Standard Model