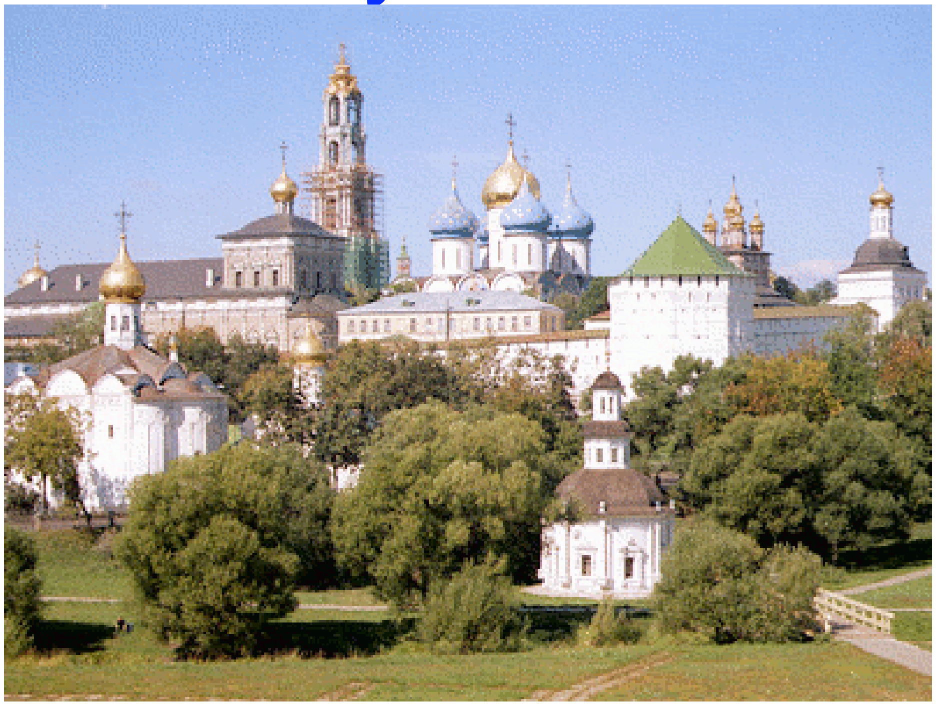
Quarks 2008

Highlights from Heavy Quark and CP Physics from BABAR (and Belle)



Janis McKenna
University of British Columbia
Representing the BABAR Collaboration

Standard Model

Matter/ Antimatter

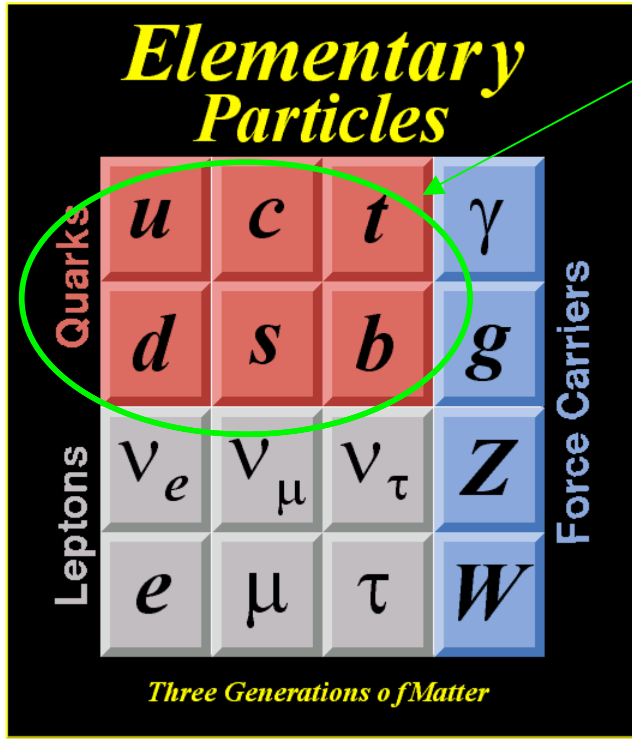
Forces: Electromagnetic

Strong

Weak

Matter: Quarks

Leptons



We ended the 20th century with triumphant successes of the Standard Model

We are now trying to find where it breaks down or extends.

A handful of free parameters: **Extremely simple and predictive**

-Thousands of predicted quantities have been experimentally tested & verified

-At B Factories, we have performed many redundant tests and many precise tests

- so far, no “big holes” in Standard Model.

BaBar: 15 year Experimental Program in Heavy Quarks & CP violation

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 K)

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

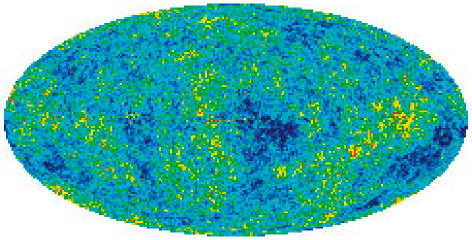
2007: First observation of D^0 -$\overline{D}^0$ mixing

2008: Babar's Final Run ended April 7, 2008
Final datasets: just starting to be analysed

B Factories - Precision Tests of Standard Model: CP violation, CKM mixing mechanism, Search for new physics

•Perform MANY precision tests in the weak sector of the Standard Model, constrain and test for consistency.

WMAP has measured the baryon asymmetry of the universe:



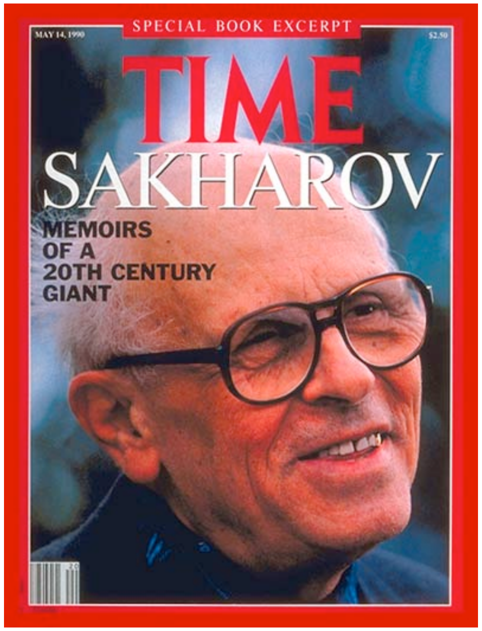
$$BAU = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx (4.7 - 6.5) \times 10^{-10} \ @95\% \mathrm{CL}$$

We'd like to understand whether this large baryon asymmetry shares its origin with the tiny matter-antimatter asymmetry in the electroweak sector of the Standard Model - or elsewhere within the Standard Model

Study CP violation in EW sector of Standard Model using a B Factory

Sakharov’s conditions

It is possible to start with a baryonic symmetric universe, and make an asymmetrical universe.



1967: Сахаров

Сформулировал 3 условия:

1 нарушение барионного заряда

2 отсутствие термодинамического равновесия

3 нарушение CP

А. Д. Сахаров, *Письма в ЖЭТФ*, **5**, № 1, 32-35, 1 января 1967

A.D. Sakharov, JETP, 5, No. 1, 32-35, 1, 1967.

All exist in Standard Model of Particle Physics

- Big Bang cool-down and expansion: non-equilibrium
- Even minimal Standard Model has baryon number violation (B-L is conserved)
- CP-violation observed in K and B systems

Matter and Antimatter

CPT Particles and Antiparticles must have:

Same mass **Same lifetime**

~~CP~~ can have different partial rates to selected final states

i.e. $\Gamma(X \rightarrow YZ) \neq \Gamma(\bar{X} \rightarrow \bar{Y}\bar{Z})$ (at least for Lorentz invariant local field theories)

- CP violation observed in K system in 1964. It was a surprise!
  CP parameters in K system - measured to impressive precision
- BUT: Cosmological Matter-Antimatter asymmetry is orders of magnitude greater than tiny asymmetry seen in K system
- Can huge matter-antimatter asymmetry possibly be accommodated by one small parameter in the Standard Model?
- Do we require sources of CP violation beyond our Standard Model??

Looks like both manifestations of Matter Antimatter asymmetry (K & BAU) can't be rooted in same phenomenon in the Standard Model

Weak Interactions & CKM mixing matrix

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

Weak Eigenstates — CKM matrix — Strong/Mass Eigenstates

Cabibbo-Kobayashi-Maskawa mixing matrix.
Introduced as origin of CP-violation in SM,

Elements:
Couplings between up-type & down-type quarks

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

A~.82,
λ~.224
(sine of Cabibbo angle)

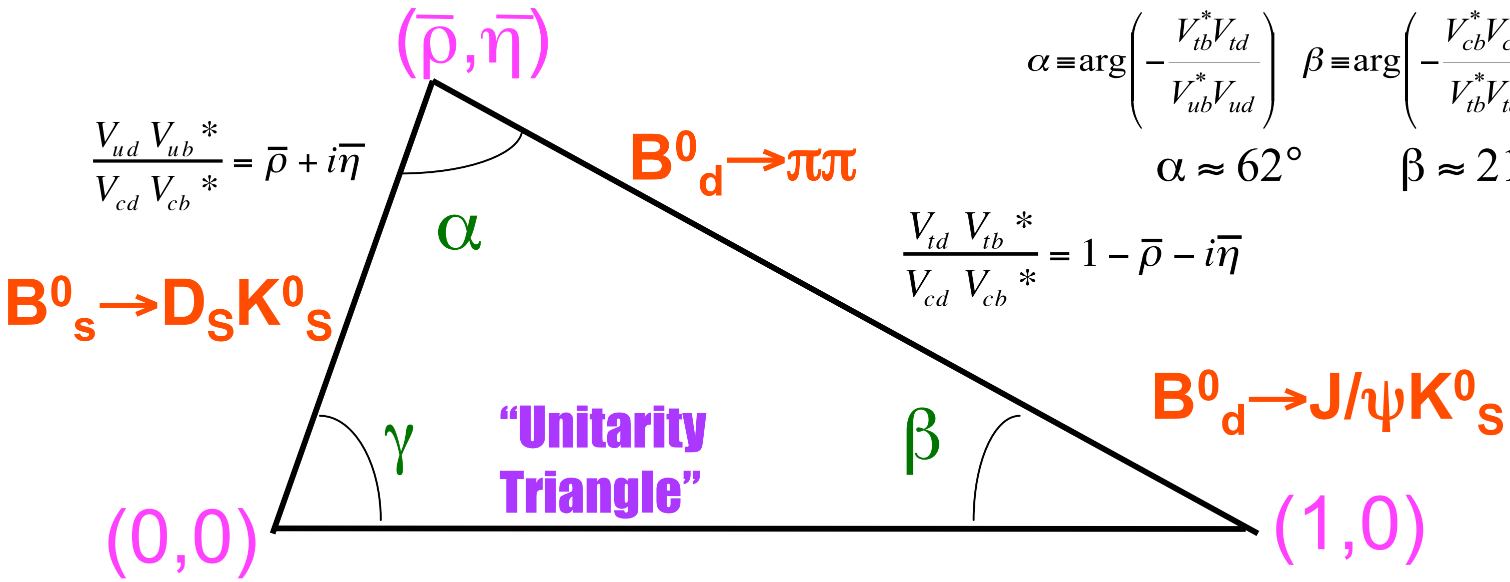
$$\bar{\rho} \equiv \rho\left(1-\lambda^2/2\right) \qquad \bar{\eta} \equiv \eta\left(1-\lambda^2/2\right)$$

In Standard Model with 3 quark generations, 4 free parameters: A, λ, ρ, η completely specify quark mixing in electroweak sector. $i\eta$ can accommodate CP Violation (in K & B systems). → Test it experimentally.

Is the η in CKM matrix indeed the origin of CPV and BAU?

We measure ρ, η

CKM mixing & CP Violation in Standard Model



$$\alpha \equiv \arg\left(-\frac{V_{tb}^* V_{td}}{V_{ub}^* V_{ud}}\right) \quad \beta \equiv \arg\left(-\frac{V_{cb}^* V_{cd}}{V_{tb}^* V_{td}}\right) \quad \gamma \equiv \arg\left(-\frac{V_{ub}^* V_{ud}}{V_{cb}^* V_{cd}}\right)$$

$\alpha \approx 62°$ $\beta \approx 21°$ $\gamma \approx 87°$

$\alpha = \pi - \beta - \gamma$

3 generations + unitarity of CKM matrix lead to "unitarity triangle" constraints:

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

Measure α, β, γ and hence $\bar{\rho}$ & $\bar{\eta}$ via asymmetries in B decays.

If $\bar{\eta}=0$ then CKM phase is not the source of CP Violation

Test the Standard Model via its redundancy & constraints.

Measure angles α, β, γ and the triangle sides independently using several different techniques: **Test for consistency.**

First, measure β

There are several "Easy" Decay Modes used to measure β:

$b \rightarrow c\bar{c}s$

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

"Easy" to interpret theoretically
and to perform experimentally

• Because ϒ(4s) is coherent quantum state:
For decays in which we look for "indirect" CP violation in (interference in decays with/without mixing), the integrated (or time averaged) asymmetry in B and $\overline{\text{B}}$ decay is zero.

∴In this case → must perform **time dependent asymmetry measurement**

Time Dependent Asymmetry

Time dependent asymmetry A_{CP} :

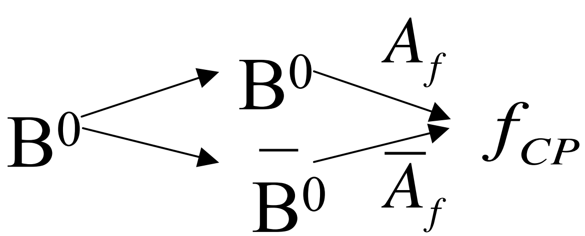
$$A_{CP}(t) = \frac{(\Gamma(\overline{B}^0(t) \to f_{CP}) - (\Gamma(B^0(t) \to f_{CP})}{(\Gamma(\overline{B}^0(t) \to f_{CP}) + (\Gamma(B^0(t) \to f_{CP})}$$

Time dependent decay rates:

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

Fit

Extract sin2β, sin2α



$$|B_{L,H}\rangle = p|B^0\rangle \pm q|\overline{B}^0\rangle$$

$$\lambda_f = \frac{q\,\overline{A}_f}{p\,A_f} \qquad C_f = \frac{1-|\lambda_f|^2}{1+|\lambda_f|^2} \qquad S_f = \frac{2\,\mathrm{Im}\,\lambda_f}{1+|\lambda_f|^2}$$

Technique to measure ~~CP~~ in B system

1. Make **lots** of B's: $\Upsilon(4S) \rightarrow \overline{B}B$

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 time (Δt) between 2 B decays

5. Fit and extract CP parameters

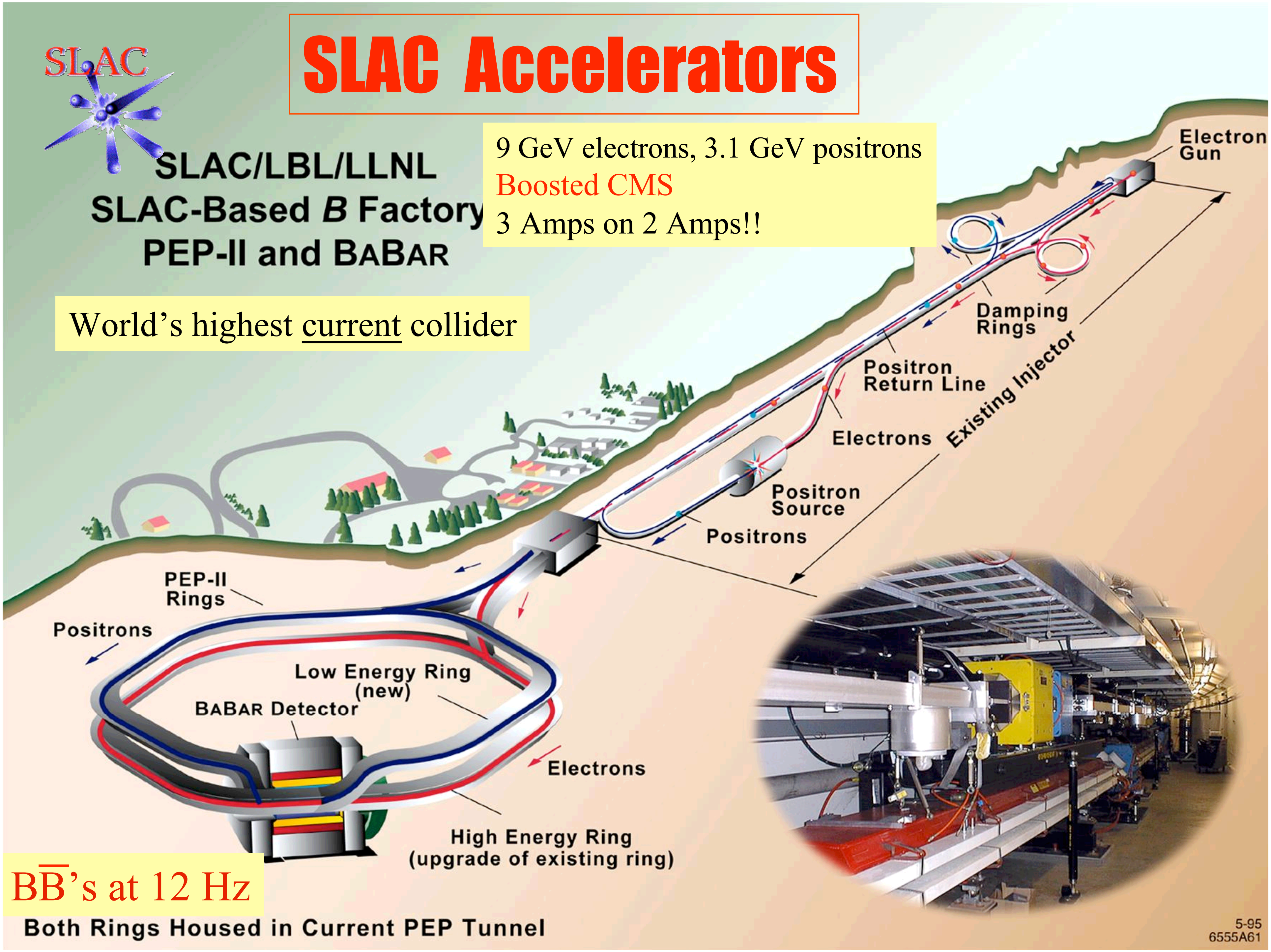
And since the dataset is so large, can also look for rare processes in addition to CP violation

SLAC Accelerators

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

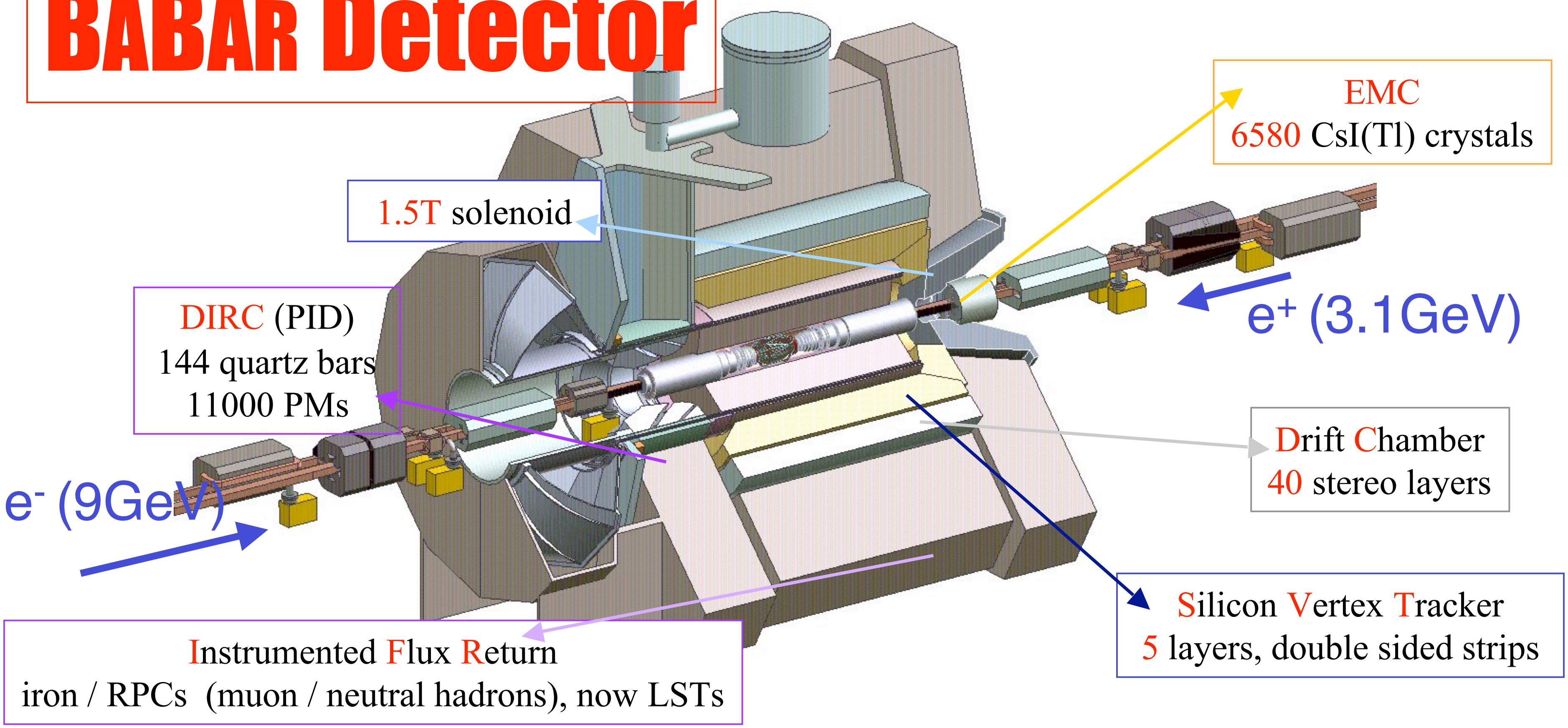
World's highest current collider

$B\overline{B}$'s at 12 Hz



SLAC Accelerators

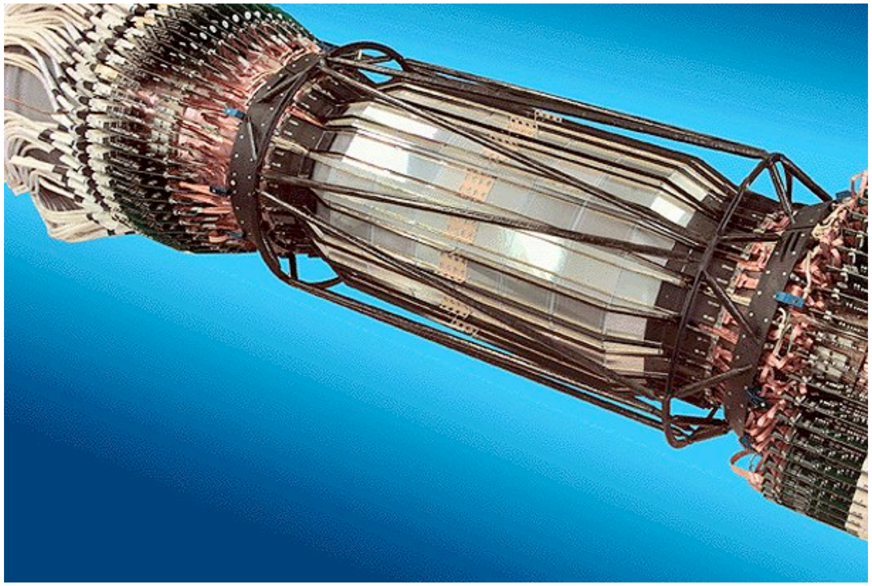
BaBar Detector



- Silicon Detector:, 97% efficiency, 15μ z-hit resolution (inner layers)
- Tracking Drift Chamber : $\sigma(p_T)/p_T = 0.13\% \times p_T \oplus 0.45\%$ (1.5T B field)
- EMC: CsI crystal calorimeter $\sigma_E/E = 2.3\% \cdot E^{-1/4} \oplus 1.9\%$
- DIRC : K-π separation >3.4σ for p<3.5GeV/c particle identification
- IFR and LSTs: Muon detector and K_L identification

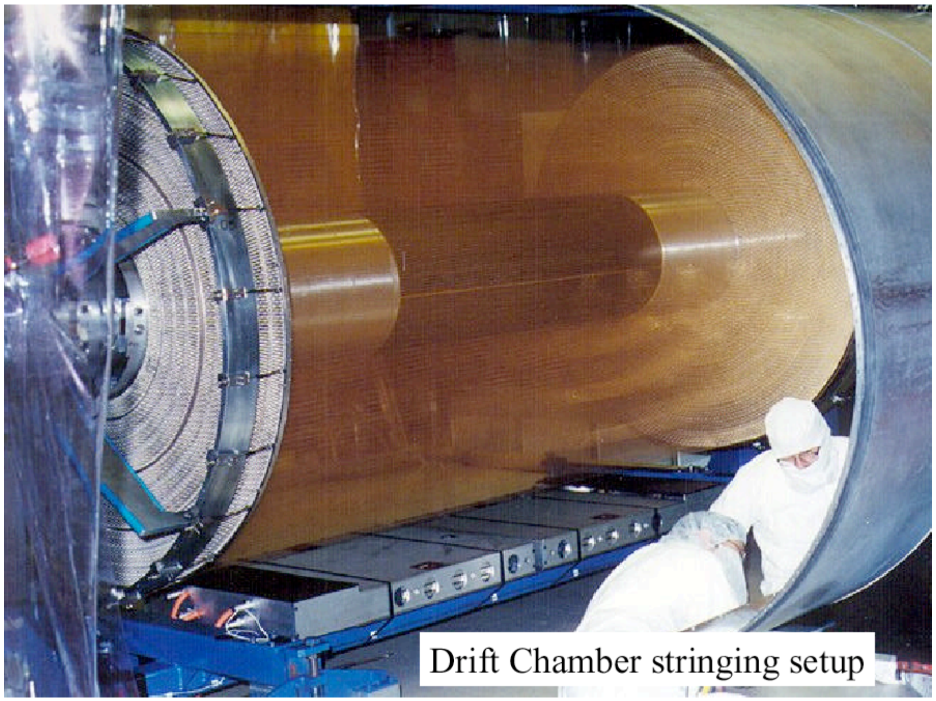
BABAR Silicon Microvertex Detector

150,000 channels



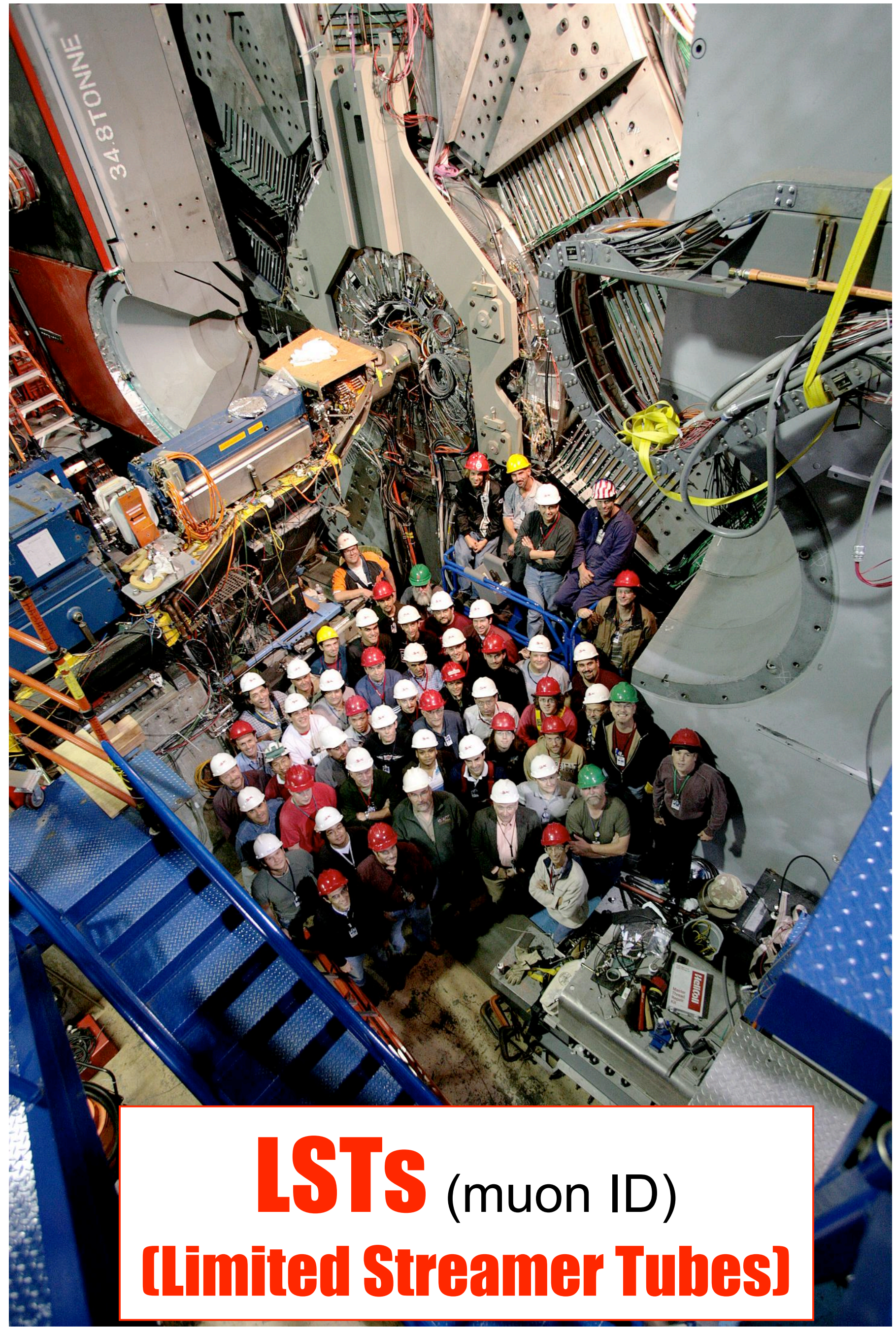
5 layers, ~15μm hit resolution

BABAR Drift Chamber



Drift Chamber stringing setup

40 layers, ~35,000 wires



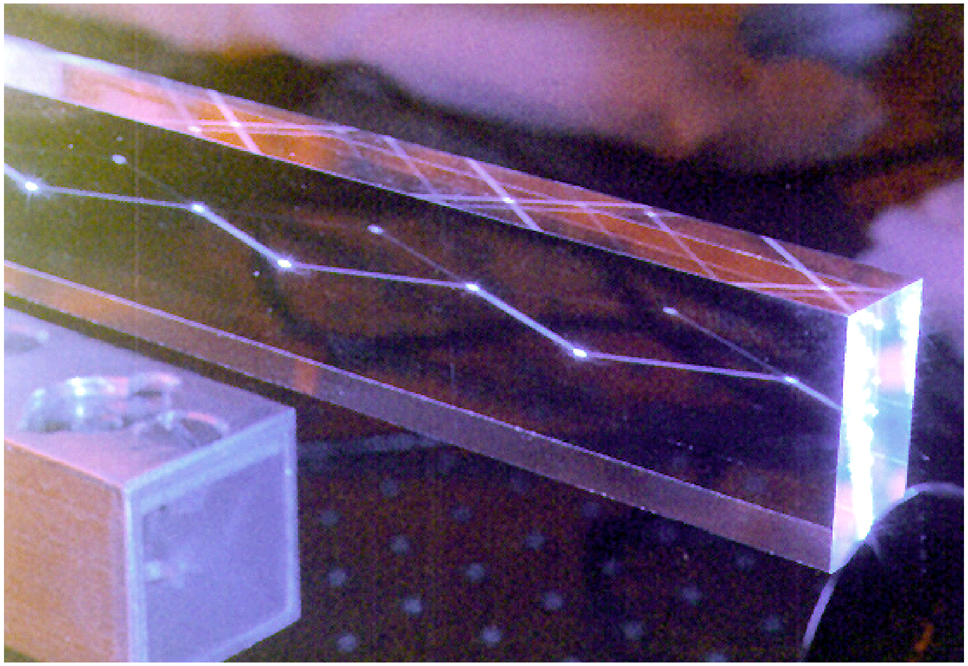
LSTs (muon ID)

(Limited Streamer Tubes)

BaBar Detector

Electromagnetic Calorimeter

(~6580 Cs I crystals)



DIRC Detector
(Quartz Bar)

(excellent K π separation)

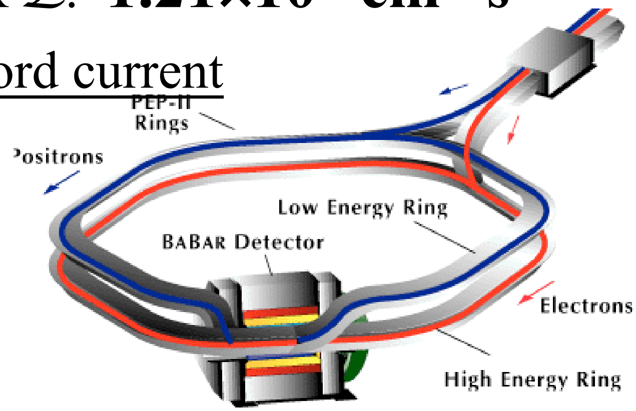
Two B Factories

PEP-II at SLAC (USA)

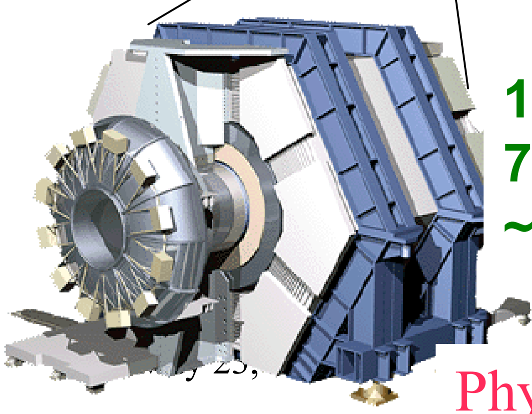
9GeV (e^-) × 3.1GeV (e^+)

Peak $\mathcal{L}$: **1.21×10^{34}cm^{-2}s^{-1}**

Record current

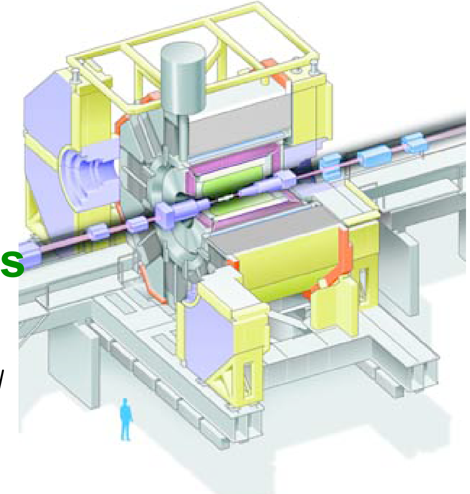


BaBar

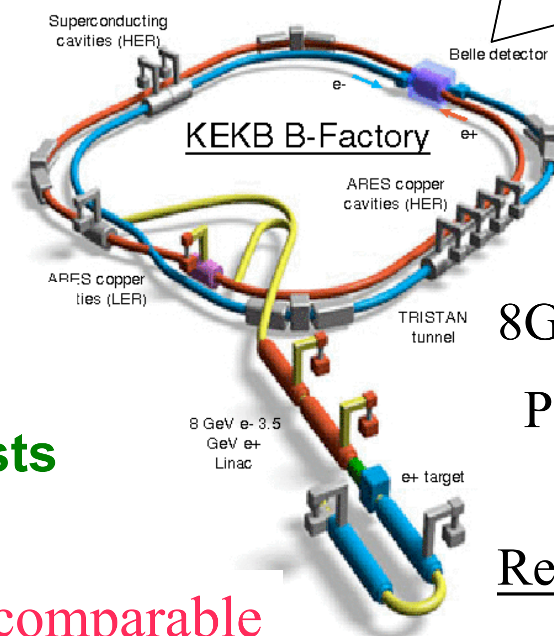


10 countries,
77 institutes,
~520 physicists

13 countries,
51 institutes,
~380 physicists



Belle



KEKB (Japan)

8GeV (e^-) × 3.5GeV (e^+)

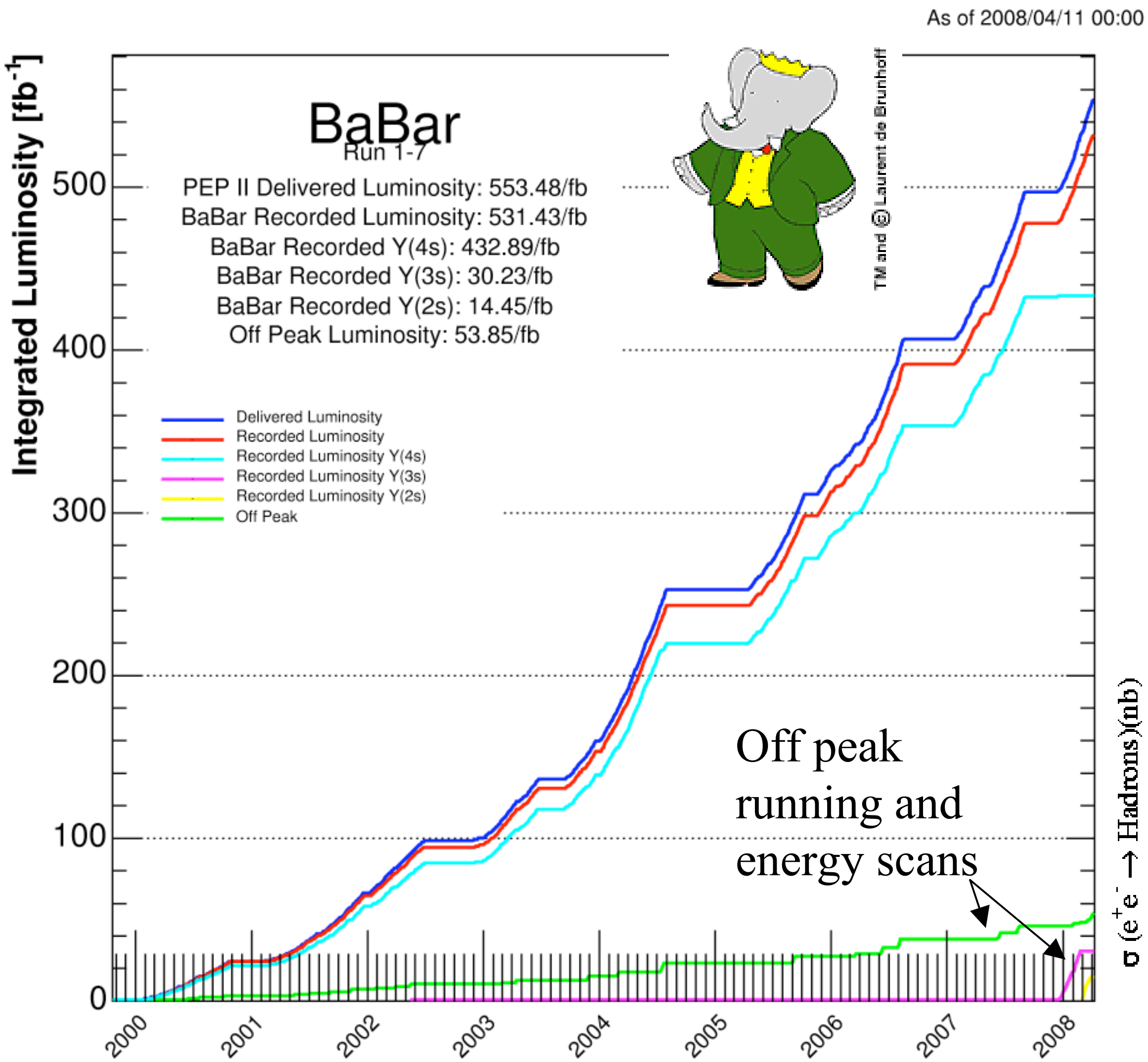
Peak $\mathcal{L}$:

1.71×10^{34}cm^{-2}s^{-1}

Record Luminosity

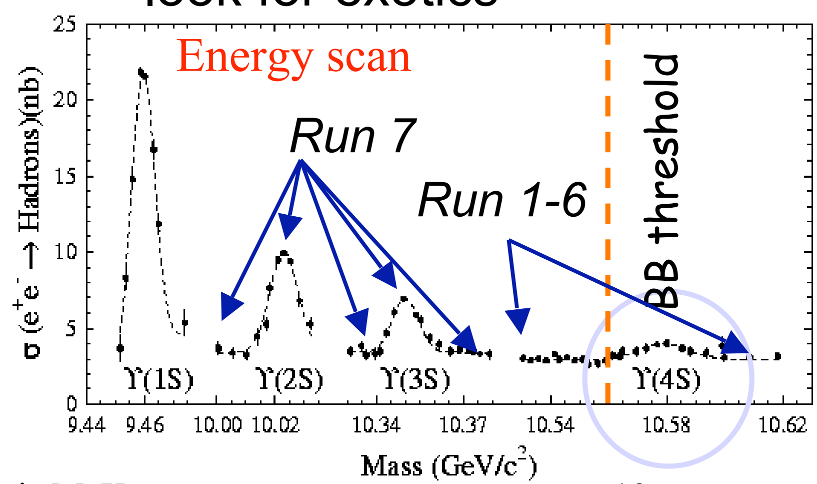
Physics output: comparable

PEP- II & BaBar : lots of B's

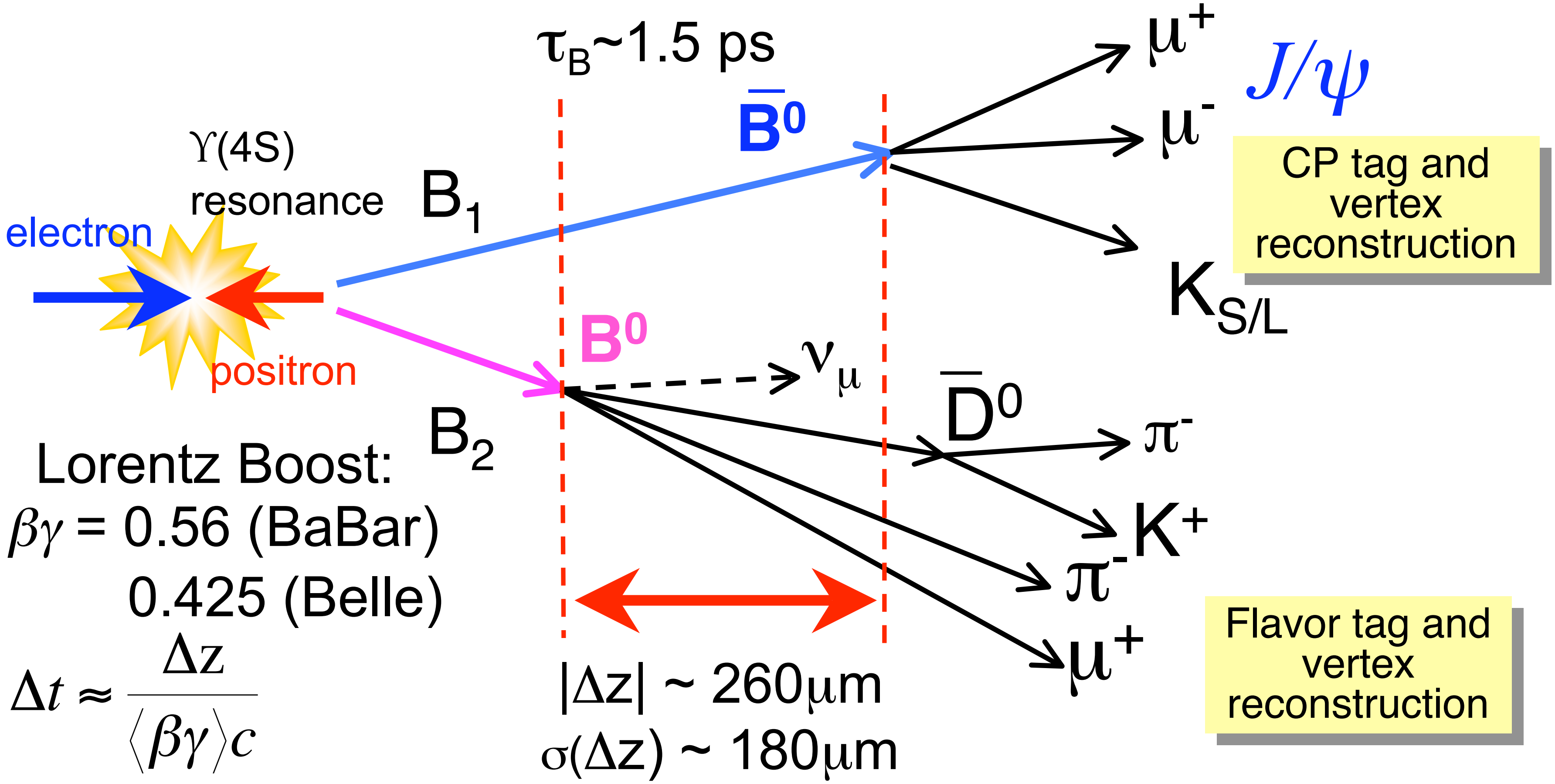


7 Physics Runs 2000 - 2008:
BaBar recorded 531 fb^{-1}
over 500 Million $B\bar{B}$ pairs
(Petabytes of data)

Ended Babar's running with energy scan;
 ϒ(2S) + above ϒ(4S): 14/fb
 ϒ(3S): 30/fb
(close to no B's in run 7)
- look for exotics



Measuring Δz (and hence Δt)



Lorentz Boost:

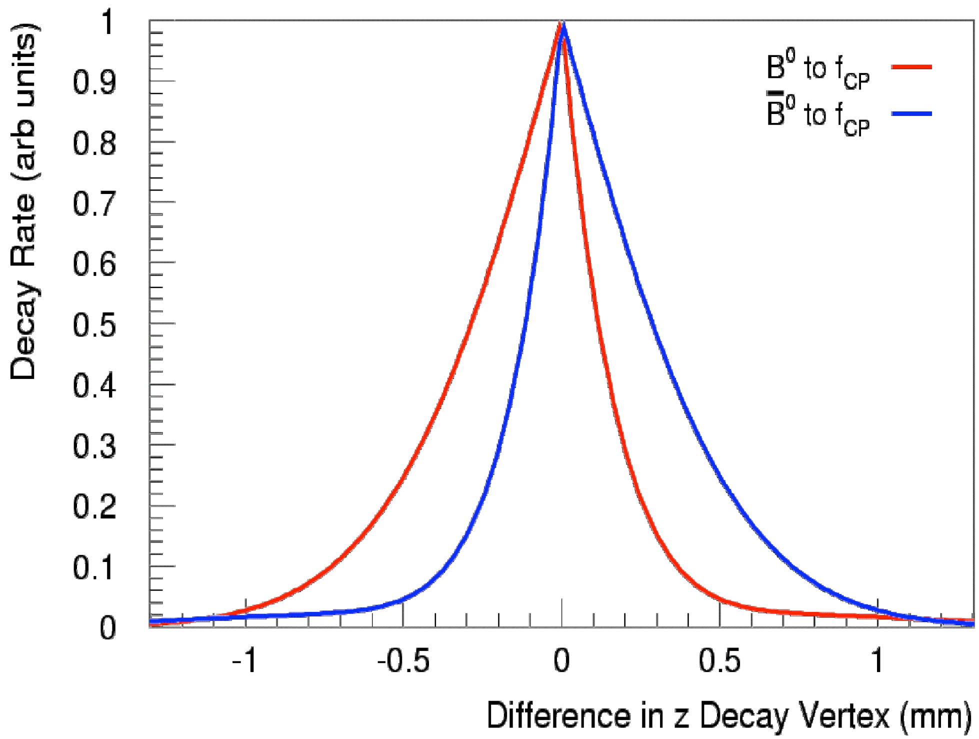
$\beta\gamma$ = 0.56 (BaBar)

0.425 (Belle)

$$\Delta t \approx \frac{\Delta z}{\langle \beta\gamma \rangle c}$$

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)

B Decay time distribution



B decay time distributions shifted due to CP violation

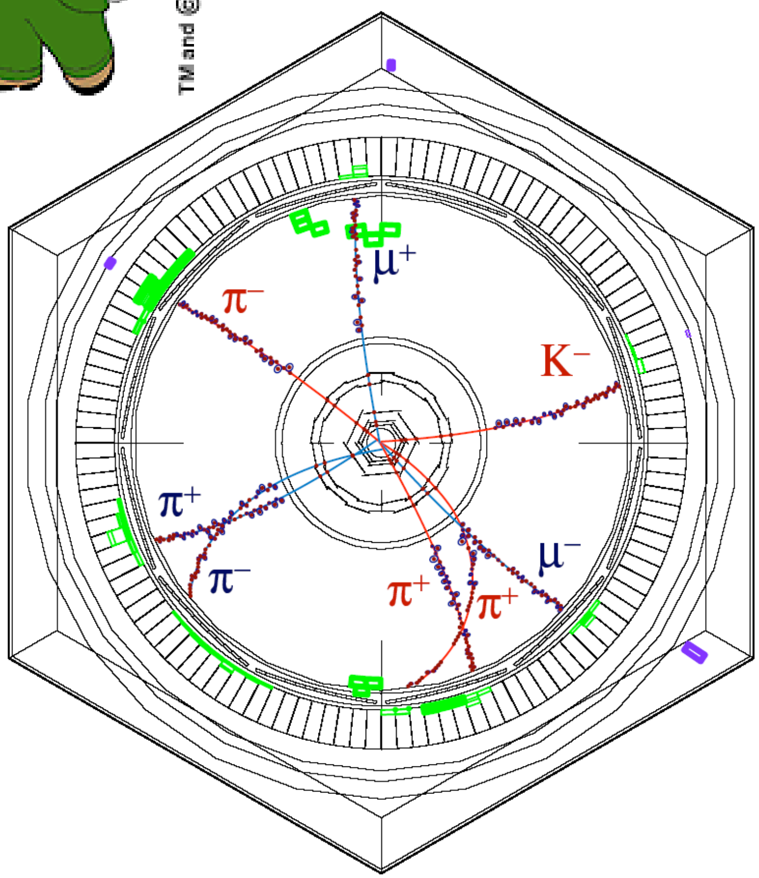
Time dependent decay asymmetry appears as a shift in Δt (time difference) and hence the Δz (vertex position) distribution for events tagged as B^0 and those tagged as $\overline{B^0}$

$\Rightarrow$ **Indirect CP Violation**

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

Fully Reconstructed Event

$\Upsilon(4S) \to B^0 \bar{B}^0$



Candidate Event:

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

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

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

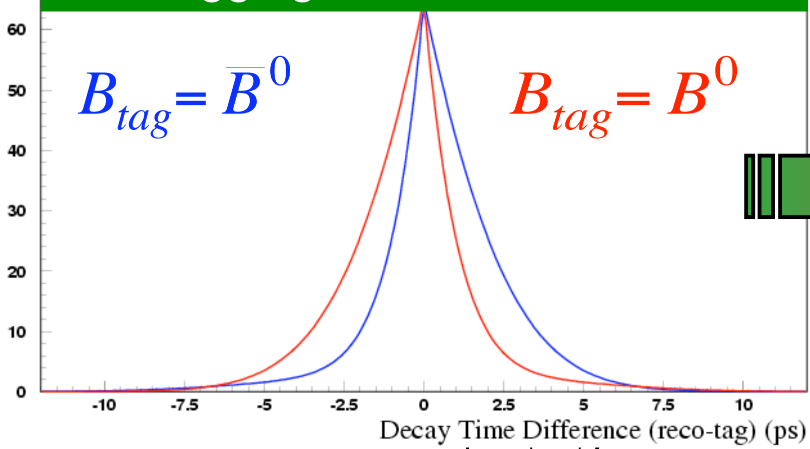
$\bar{B}^0 \to D^{*+} \pi^-_f$

$D^{*+} \to D^0 \pi^+_s$

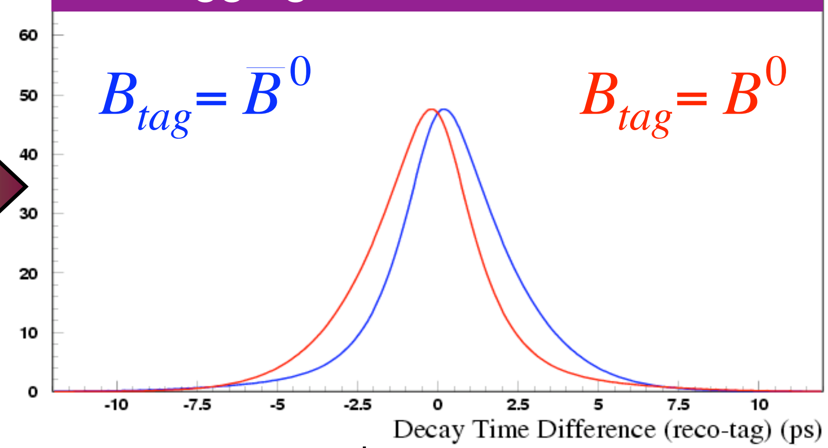
$D^0 \to K^-\pi^+$

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

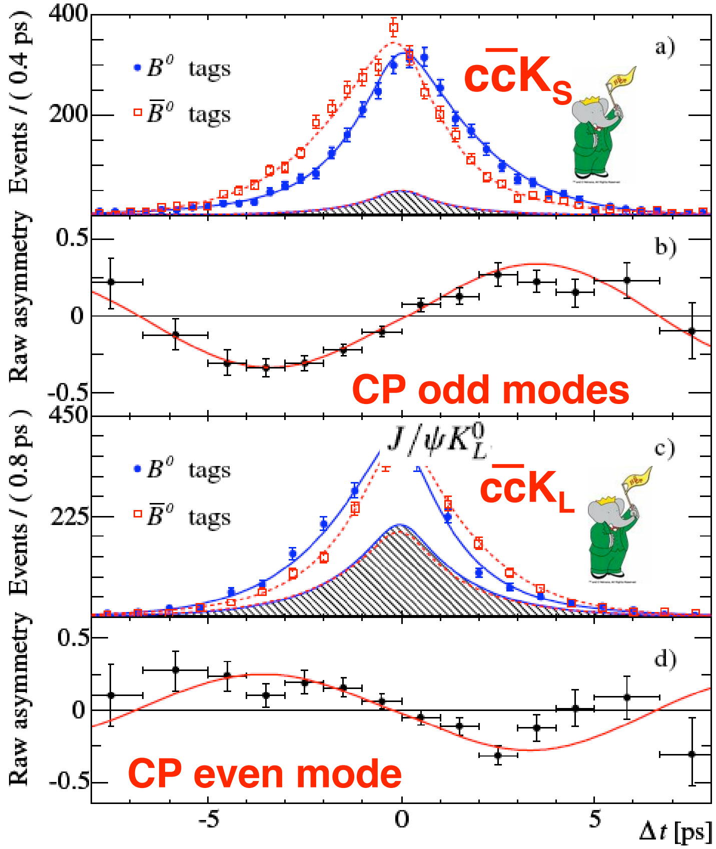
Self-tag(fully reconstructed) → measure resolution, vertex separation, mistag rate

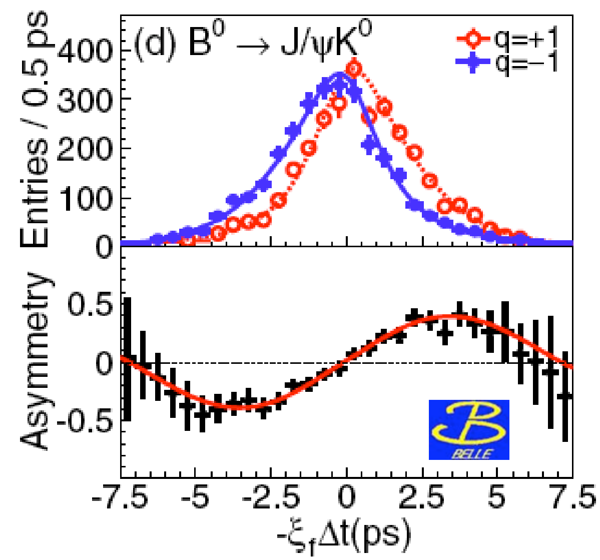
USING DATA

Sin 2β: B → Charmonium + K systems

with >400 million BB decays: ⇒ Still statistics limited!

$(J/\psi K^0_S,\ \psi(2S)K^0_S,\ \chi_{c1}K^0_S,\ \text{and}\ \eta_c K^0_S)$

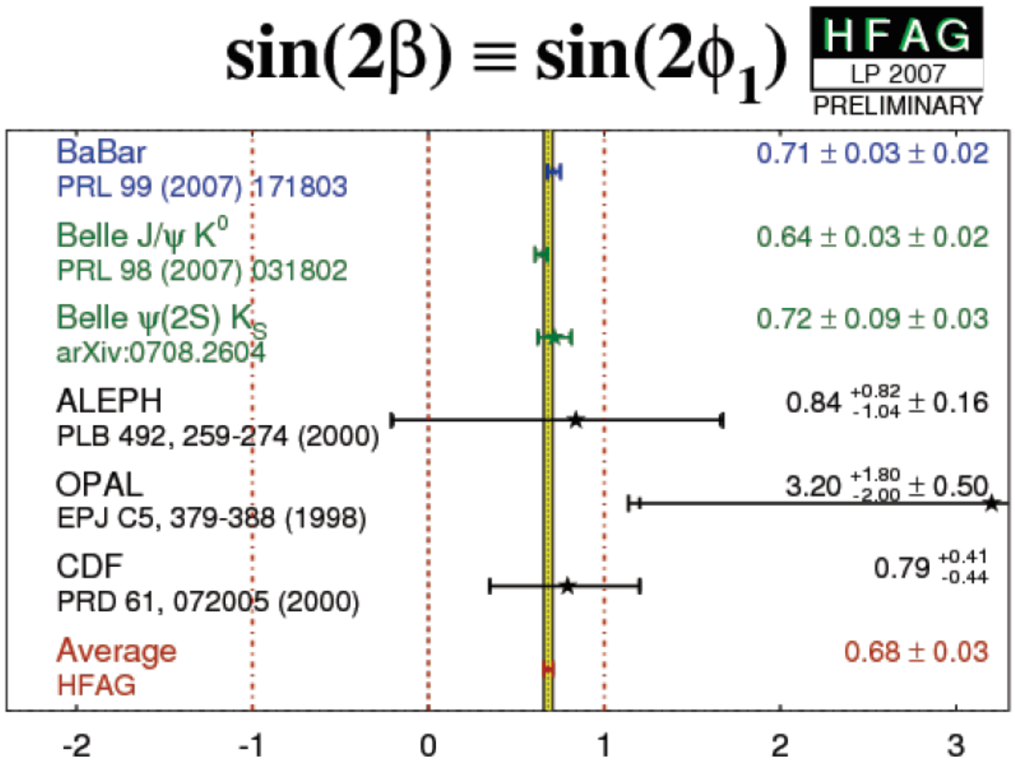


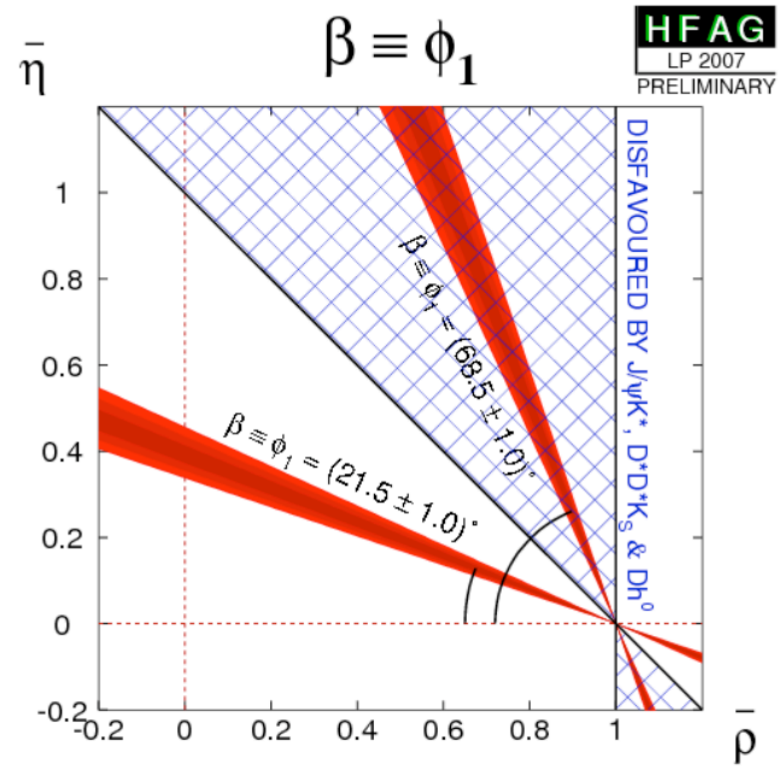


	BaBar (PRL 99 (2007) 171803)	Belle (PRL 98 (2007) 031802)
J/ψ KS (η CP=−1)	0.686 ± 0.039 ± 0.015	0.643 ± 0.038stat
J/ψ KL (η CP=+1)	0.735 ± 0.074 ± 0.067	0.641 ± 0.057stat

Sin 2β: Combined measurements

Charmonium modes





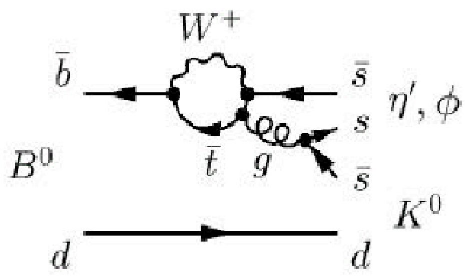
Resolve 2-fold ambiguity in angle β

(use S- and P- wave components in $B^0 \to D^0 \pi^0$, $D^0 \to K^0_S \pi^+ \pi^-$)

β=21.5° or β=68.5°

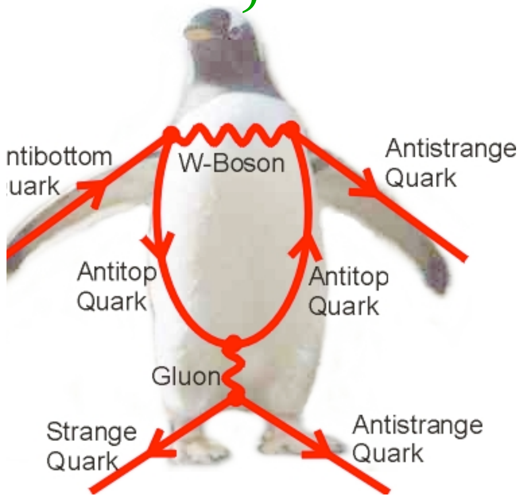
(21.5° favoured at 87% CL, cos 2β > 0 at 98% CL)

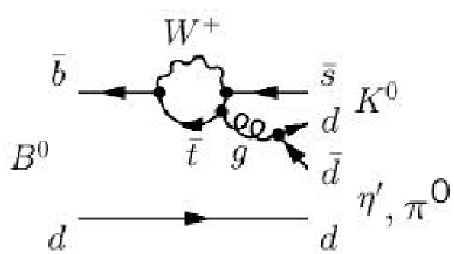
$\sin 2\beta_{eff}$ via Penguin Decay Modes

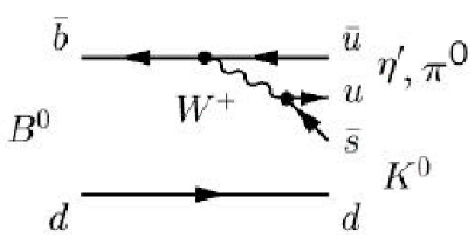


Look at sin 2β in other B decay modes:

$b \to s\bar{s}s$, $b \to s\bar{u}u$ Consistent??



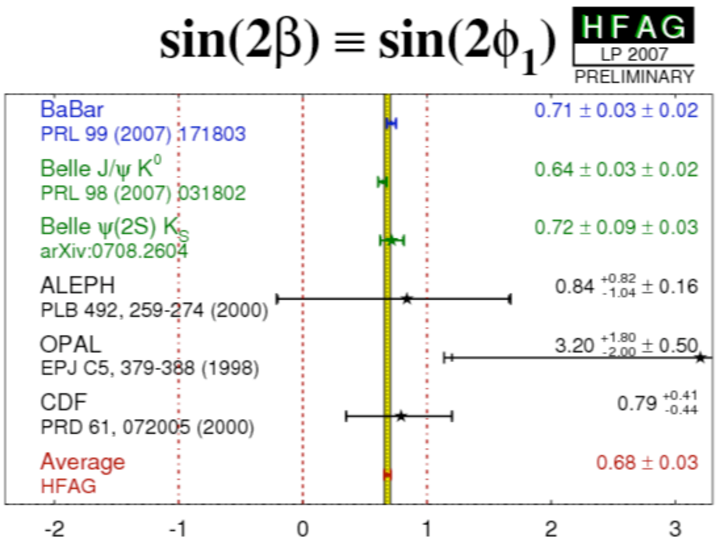


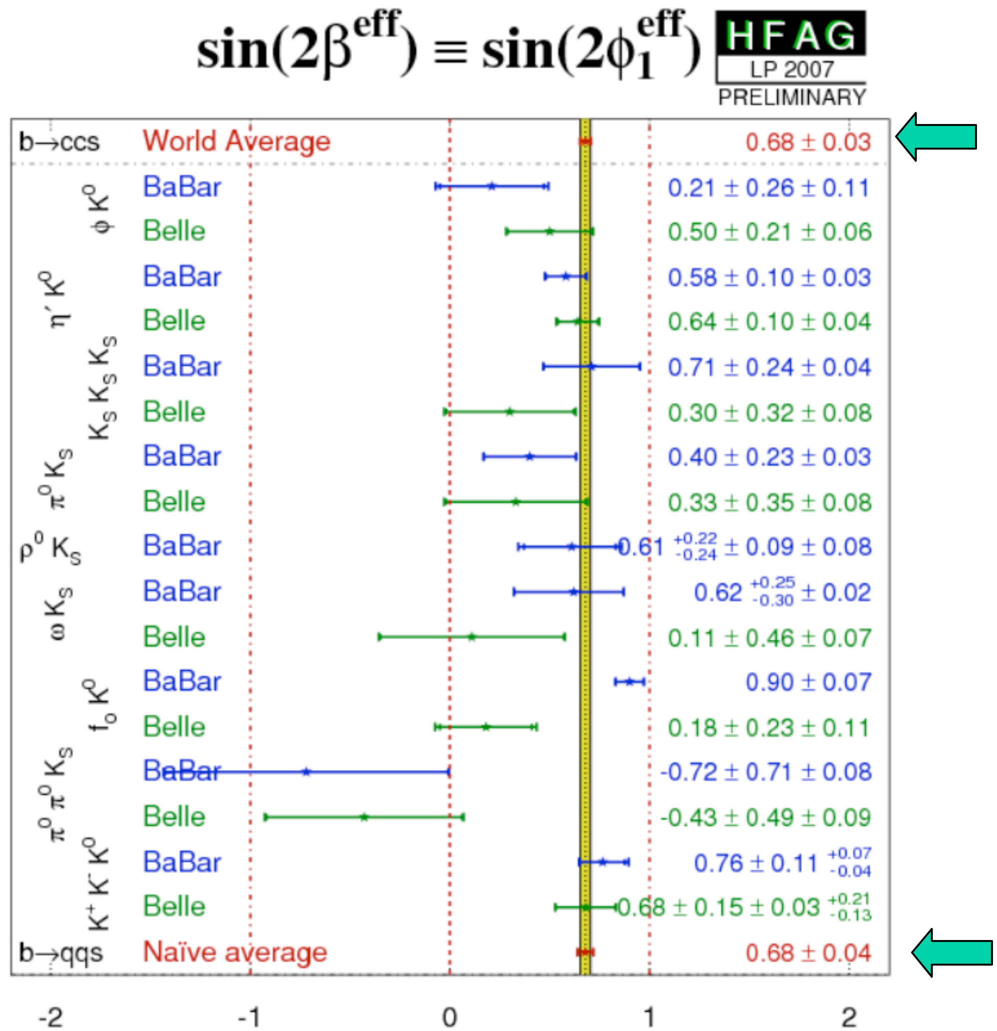


New physics can enter via virtual non-Standard Model particles in penguin loop or other loop diagrams. If new particle contributes to weak phase, we'll measure a different effective "sin2β"

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

Sin 2β





$\sin 2\beta$: charmonium modes

$\sin 2\beta_{eff}$ penguin modes

2.5σ difference in tree and penguin modes from 2004 has diminished with more data.

Caution: HFAG Penguin averages assume Gaussian errors - not justified for all measurements. (χ^2 very high.)

3 body Dalitz/ quasi 2-body

Measure angle α

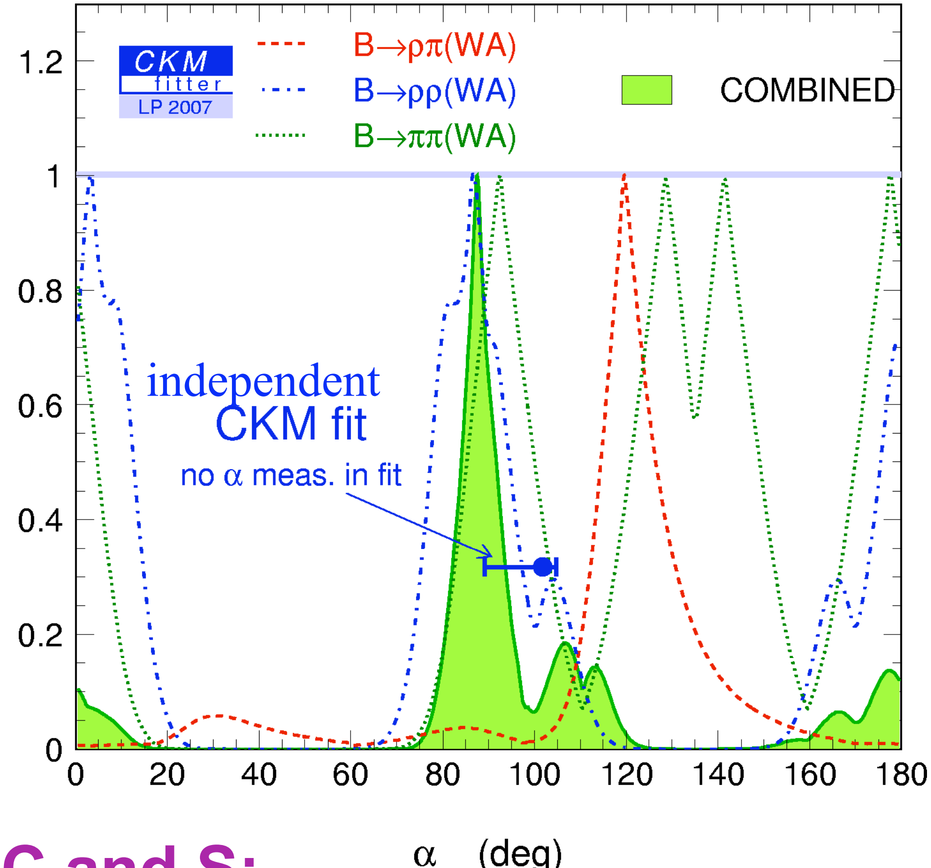
Channels **B→ππ B→ρρ B→ρπ**

Technical Complications:

Tree and penguin amplitudes contribute with different phases.
Time dependent asymmetry would give sin2α **if** penguin amplitude were negligible (but it's not!)
Tree amplitude, color-suppressed tree amplitude & charmless penguin amplitude all contribute to the decay process.

Measure effective α_{eff}, then extract α using isospin analysis

Gronau & London: Phys.Rev.Lett.65:3381 ,1990.



Fit for 2 quantities, C and S:

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

Constraint on α:

$$\alpha = 87.5^{\circ}{}^{+6.2^{\circ}}_{-5.3^{\circ}}$$

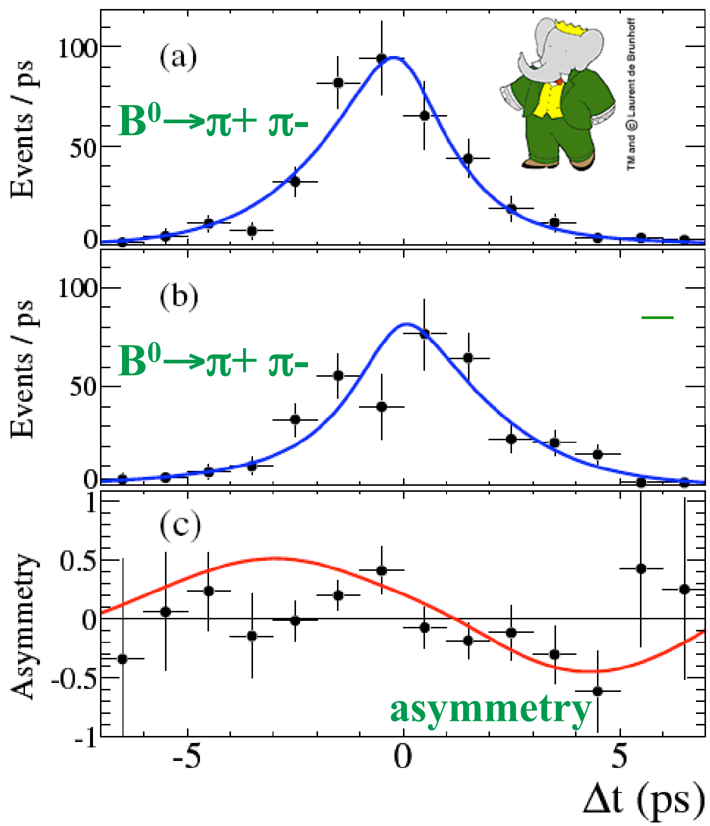
α measured 2 ways: consistent

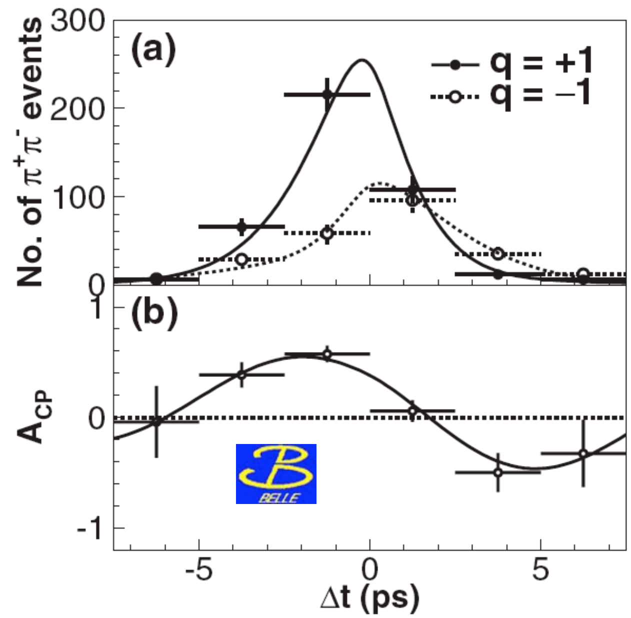
Charmless B→π+π- CP Violation

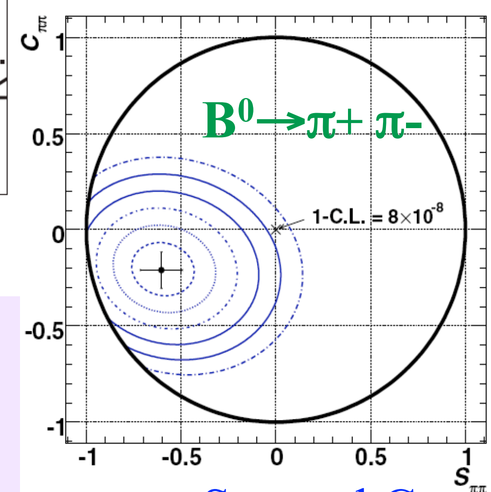
π+ π- CP Violation:

Both types of CPV observed:

1. Direct 2. Via mixing







$S_{\pi\pi}$ and $C_{\pi\pi}$

3 amplitudes contribute:

1. Tree
2. Colour-suppressed tree
3. Gluonic penguin

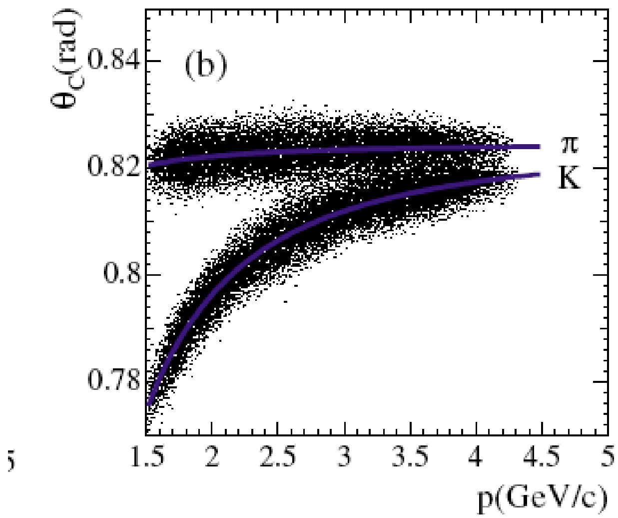
BELLE: PRL 98, 211801 (2007)

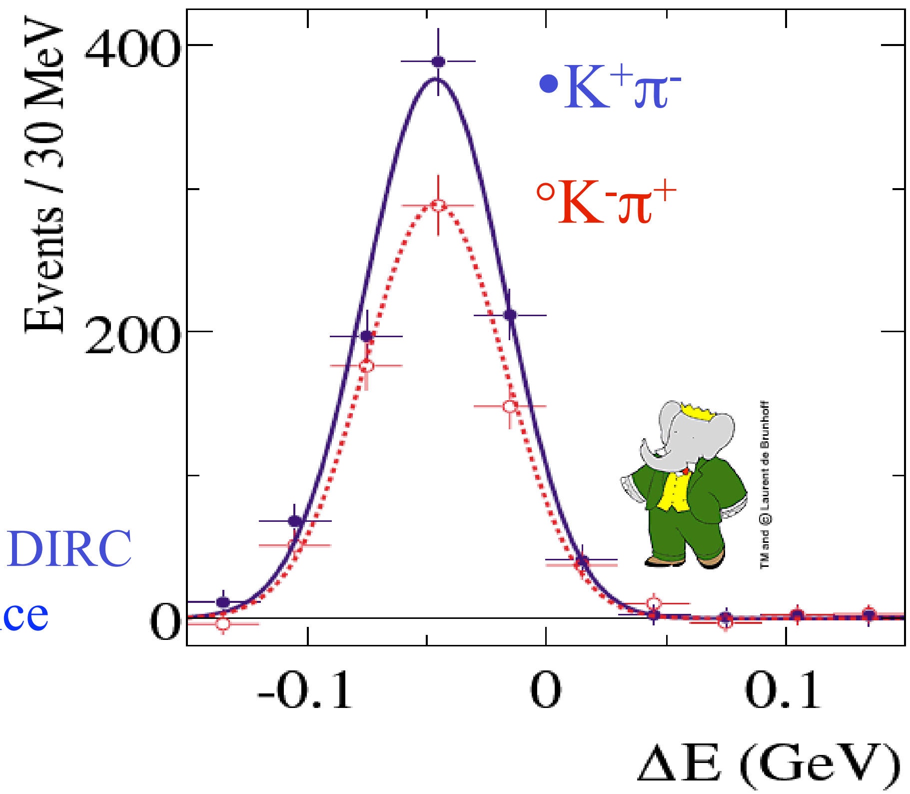
BABAR: PRL 99, 021603 (2007)

Direct CP Violation

B→K+π-

Direct CP Violation: doesn't involve oscillations/mixing
Asymmetry in yields between a decay and its CP conjugate
(different weak and strong phases)





Excellent charged K / π separation with DIRC

Direct CP Violation: 5.5 σ significance

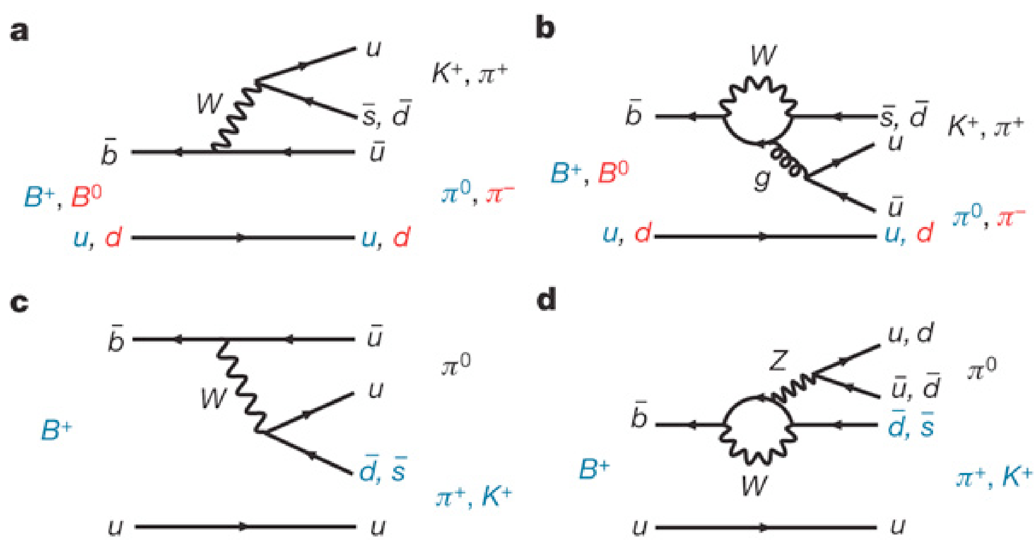
BABAR: PRL, 93, 131801 (2004)

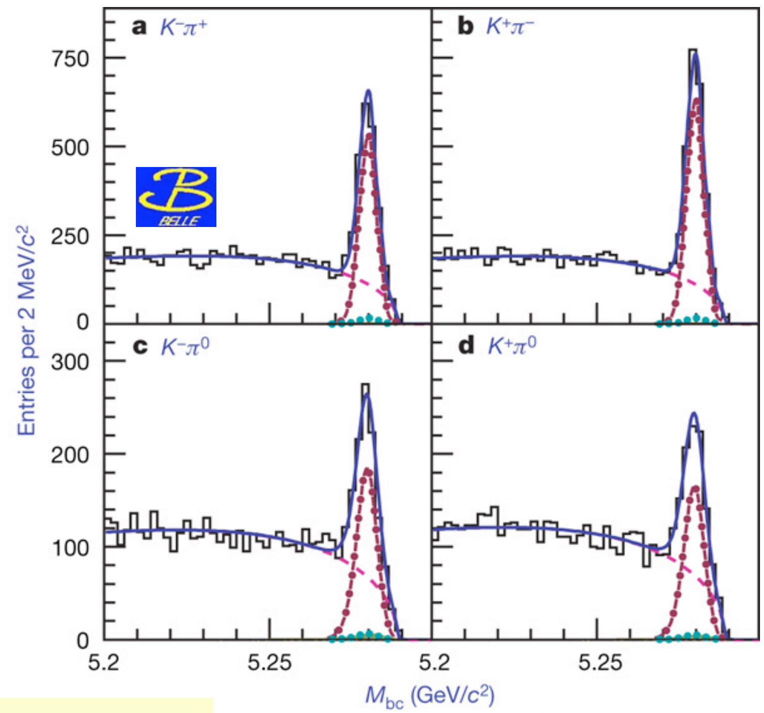
BABAR: PRL 99, 021603 (2007)

BELLE: PRL 98, 211801 (2007) & BELLE-CONF-0802 - **Direct** CPV in ππ and DK modes

Direct CPV in Charged & Neutral B→ Kπ

B→Kπ decays: tree & penguin contributions:





Belle measures 4.4σ difference in direct CP violation in charged and neutral B decays to Kπ final states:

$B^0 \rightarrow K^+\pi^-$ $B^+ \rightarrow K^+\pi^0$ (and CCs)

	$A_{cp}(K^+\pi^-)$	$A_{cp}(K^+\pi^0)$
Belle (585M)	-0.09±0.02 ±0.01	0.07±0.03 ±0.01
BaBar (385M)	-0.11±0.02 ±0.01	0.03±0.04 ±0.01
Average	-0.097 ±0.012	0.050 ±0.025

New Physics?? - or final state interactions?

or colour suppression not understood in neutral tree diagram?

BELLE: Nature 452, 332-335 (20 March 2008)

BABAR: PRL 99, 021603 (2007) & PRD 76, 091102 (2007)

Unitarity angle γ

γ is the most difficult of the three angles to measure directly at KEKB and PEP-II, (we don't produce B^0_S)

Strategies:

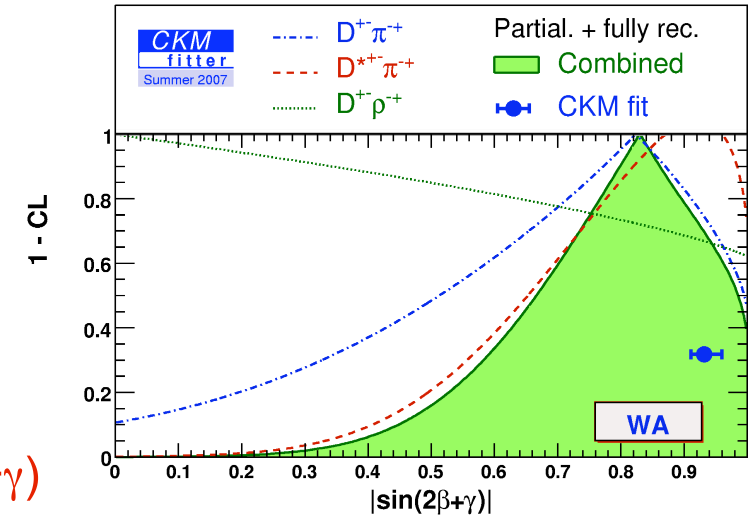
- Time dependence in interference in b→u and b →c with mixing gives $\sin(2\beta+\gamma)$

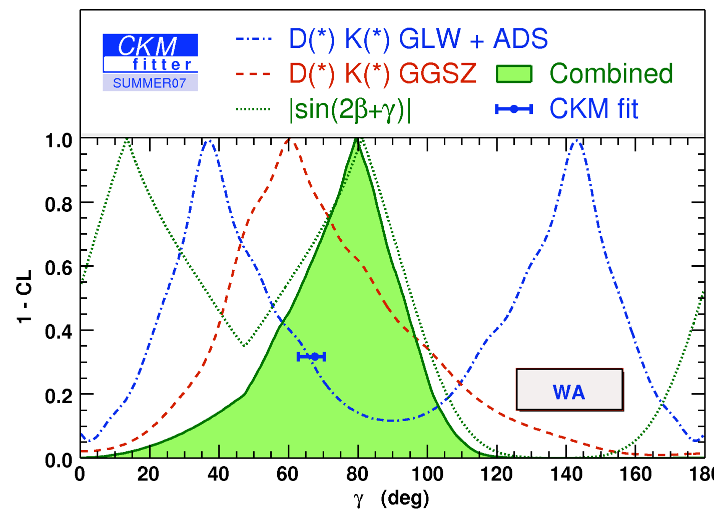
- time independent interference in b→u and b →c.

(Gronau, London, Wyler
Atwood, Dunietz, Soni)

$$B^0 \to D^{\mp}\pi^{\pm} \quad B^0 \to D^{*\mp}\pi^{\pm} \quad B^0 \to D^{\mp}\rho^{\pm} \quad B^0 \to D^{*\mp}\rho^{\pm}$$

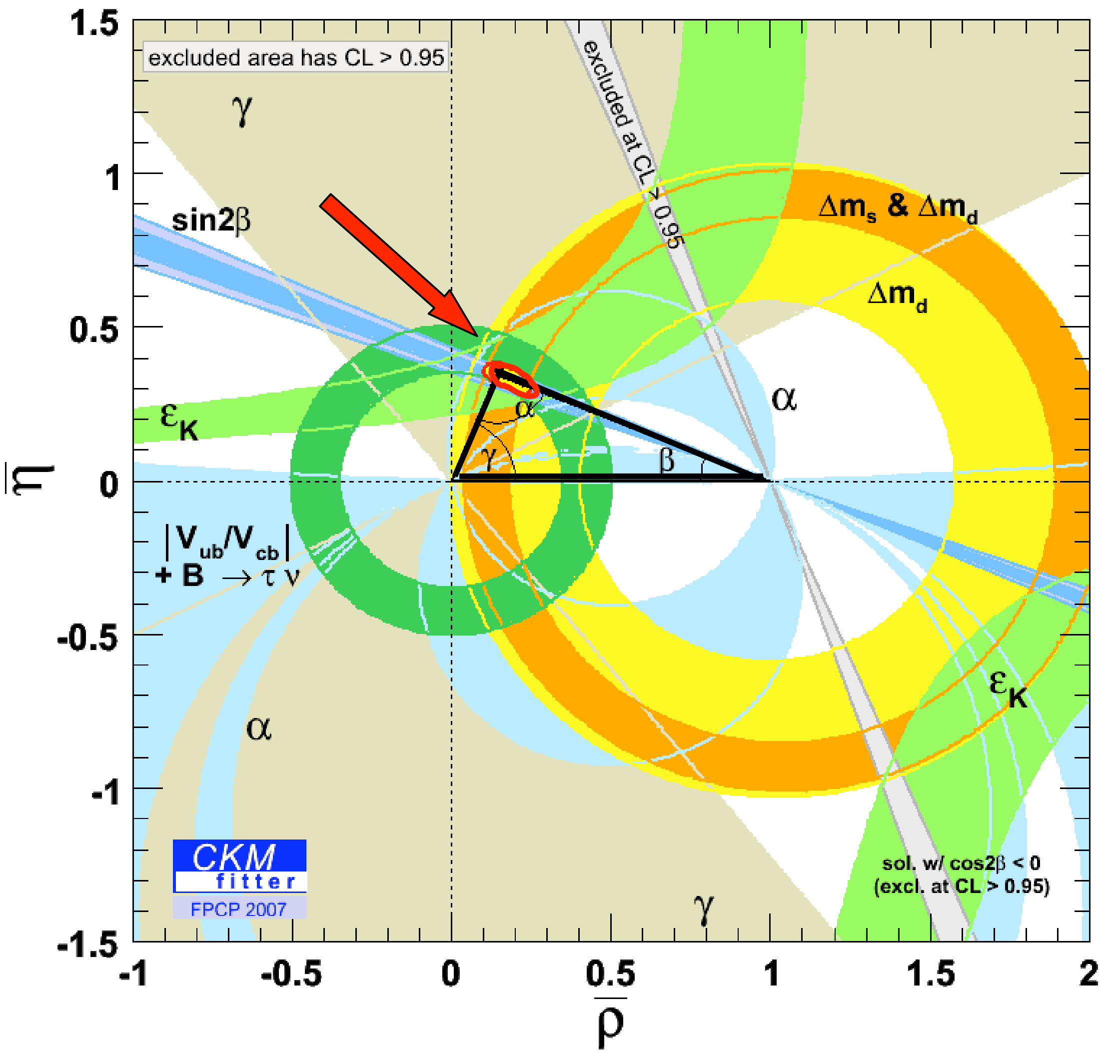
Plots show this direct measurement in green area
blue bars come from combined contraints in CKM fitter





Result: $\gamma = \left(80^{+18}_{-26}\right)^{\circ}$

Combine all Experimental Results



<u>We've measured all 3 unitary triangle angles and 2 sides</u>

Fit includes constraints from B factories as well as other experiments:

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

One solution (in red) in amazing agreement !

(CKM in indeed source of CP violation in SM)

Amazing (but least interesting) result!

<u>All</u> consistent: success of SM!

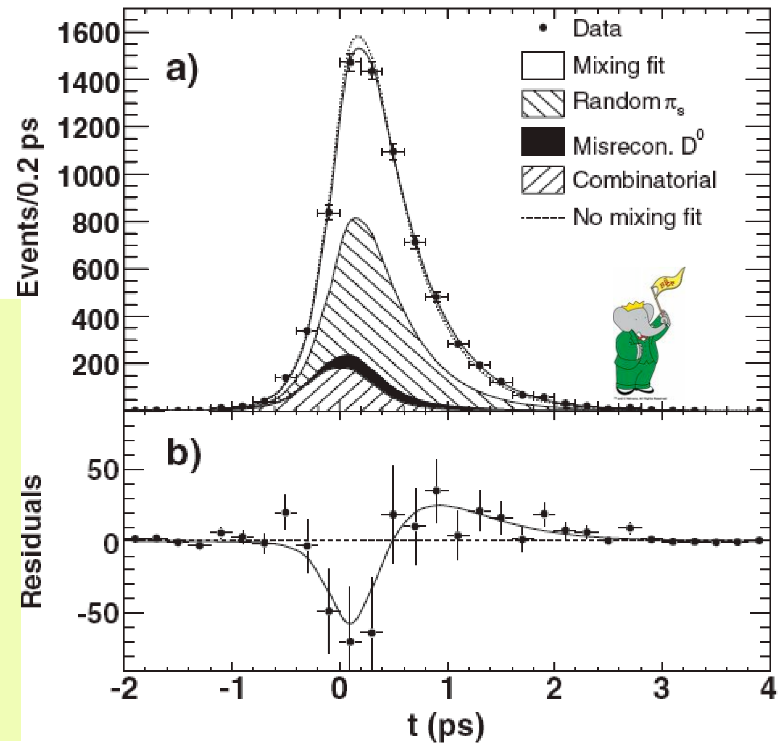
First Observation of Mixing in the charm sector

Mixing has long been predicted to occur in charm sector:
very small rate.

Strategy: look for "right sign" and "wrong sign" D decays in the channel and "tag" them using slow pion in D* decay: $D^{*+} \to \pi_s^{\ +} D^0$

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

wrong sign D decays



BABAR: PRL 98, 211802, 2007

DD mixing has been observed at 3.9σ level at Babar, (>1M "right sign" and 4K "wrong sign" events) and at several other experiments: Belle, CDF.

Babar: $x'^2 = (-0.22 \pm 0.30(stat) \pm 0.21(syst)) \times 10^{-3}$

$y'^2 = (9.7 \pm 4.4(stat) \pm 3.1(syst)) \times 10^{-3}$

No evidence for CP violation in charm sector: expected small in SM

Outlook

15 year PEP-II/BaBar program is in final phase.

Many analyses will benefit from increased statistics of final Babar Runs.

Most CP and Unitarity Triangle parameters are **still** statistically limited!

LHC: will make progress on β and γ measurements (eventually), but won't make rapid progress on α. Babar and Belle will continue in this area for several years.

- We've measured all three unitarity triangle angles.
  (α & γ are much more challenging than β)
- We're improving statistics and precision in CKM and SM parameters
- Along with CP violation physics, we're studying/measuring rare B decays, D mixing, charm.

-BaBar & Belle have collected more than a billion $B\overline{B}$ pairs - (not all analysed yet)!

-Now performing precision SM tests - (loop contributions in rare decays)

-Didn't have time to talk about: B^+ B^0 masses, lifetime measurements, semileptonic decays, V_{ub}, V_{cb}, spectroscopy, tau physics, new charmonium states, radiative penguins, & more.

Then SUPER B or KEK B

Hoping for Failure - a breakdown in the Standard Model → new physics

Summary

Standard Model is amazingly self-consistent

Eyes are open for signs of new physics (rare decays, exotics) with increased statistics in final runs. Hints in penguin sector.

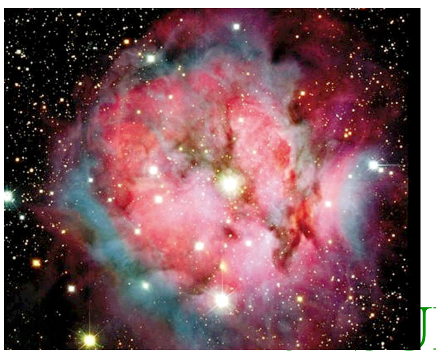
B Factories will continue to be prime place to look for New Physics.

There must be more CP violation in new physics (neutrino sector?) because phase in CKM can't accommodate BAU.

INTERESTING to confirm everything we know about Standard Model.

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

⇒Next 2 years: continue mining our data, look for new Physics!

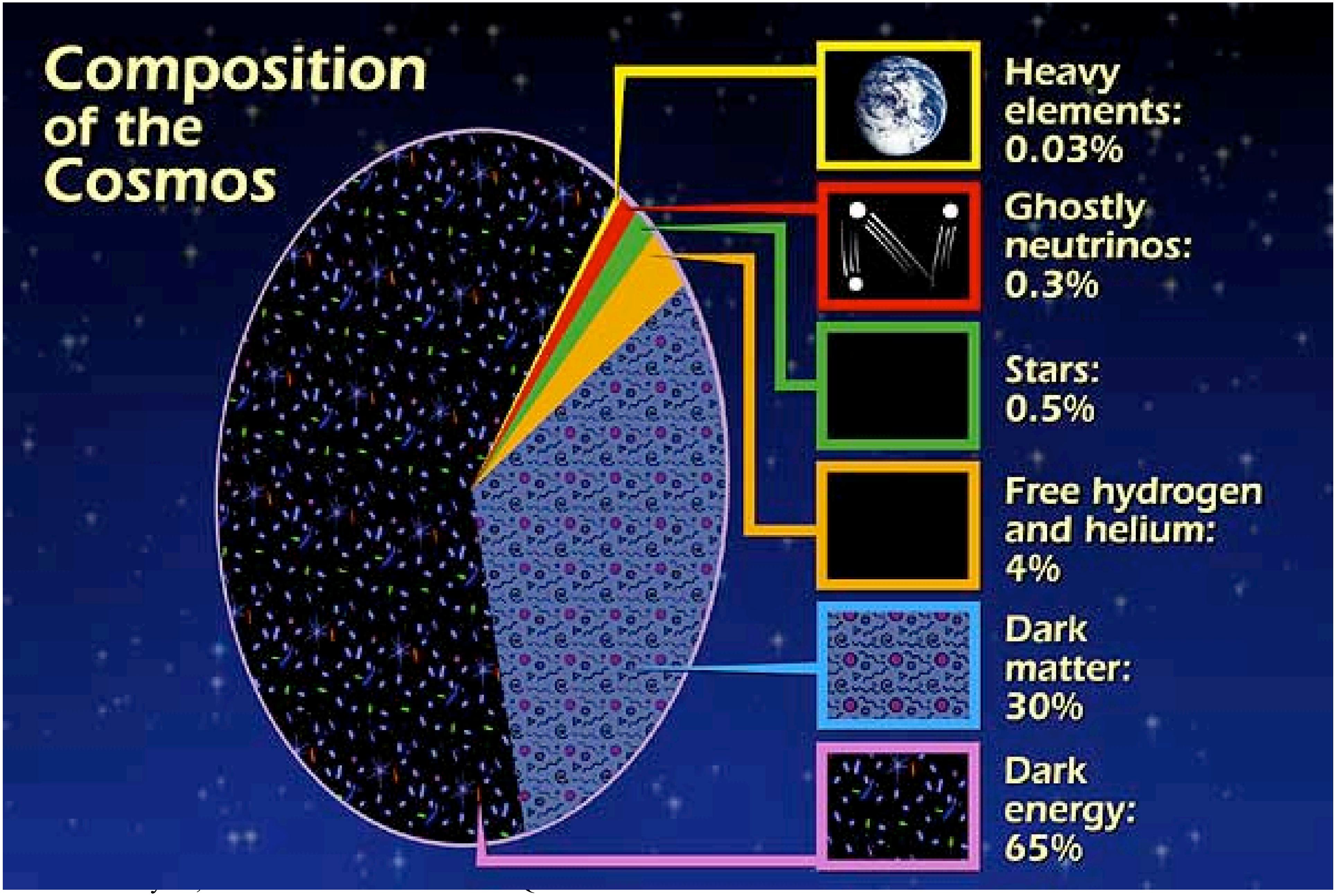


- ♥We've been looking for inconsistencies in SM
- ♥ Measure angles and sides of UT - all 3 for constraint
- ♥ Search for new physics

Direct CP violation   Rare B decays

…PERB - 3rd generation B Factory

HOPING FOR FAILURE in Standard Model


Composition of the Cosmos
Heavy elements: 0.03%
Ghostly neutrinos: 0.3%
Stars: 0.5%
Free hydrogen and helium: 4%
Dark matter: 30%
Dark energy: 65%

Control Samples

Control samples: no asymmetry (charged final states)