CP Violation in B Decays

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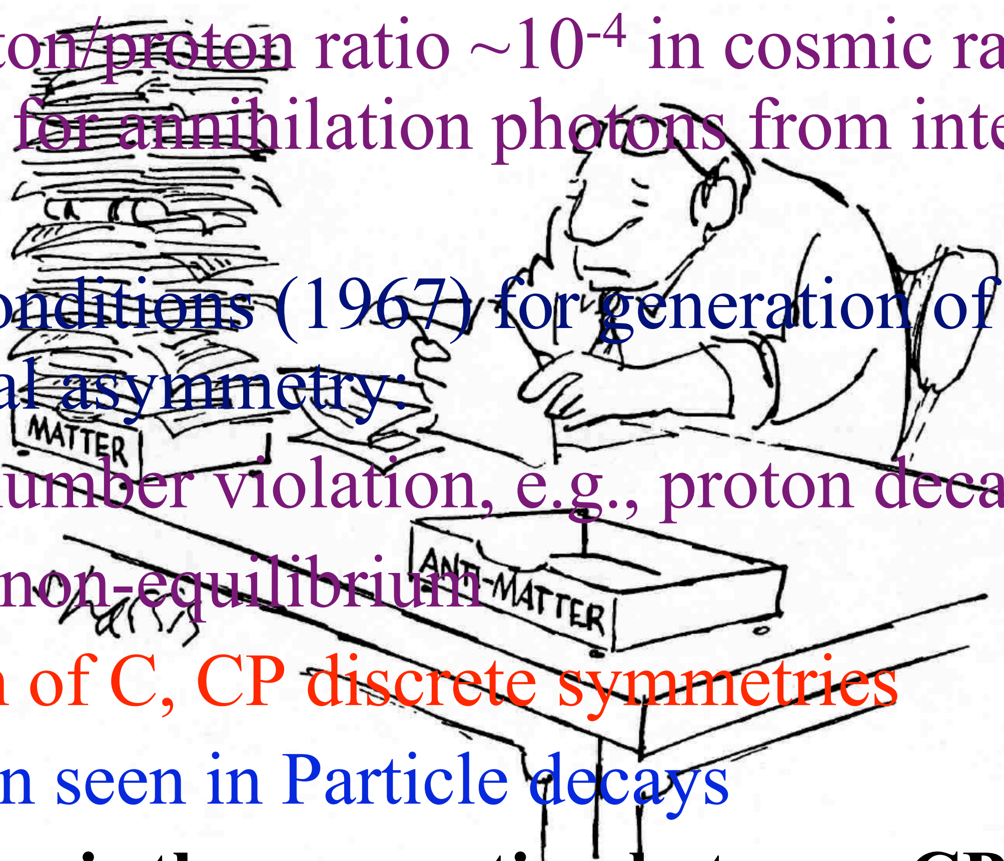
From Cosmos To Quarks !

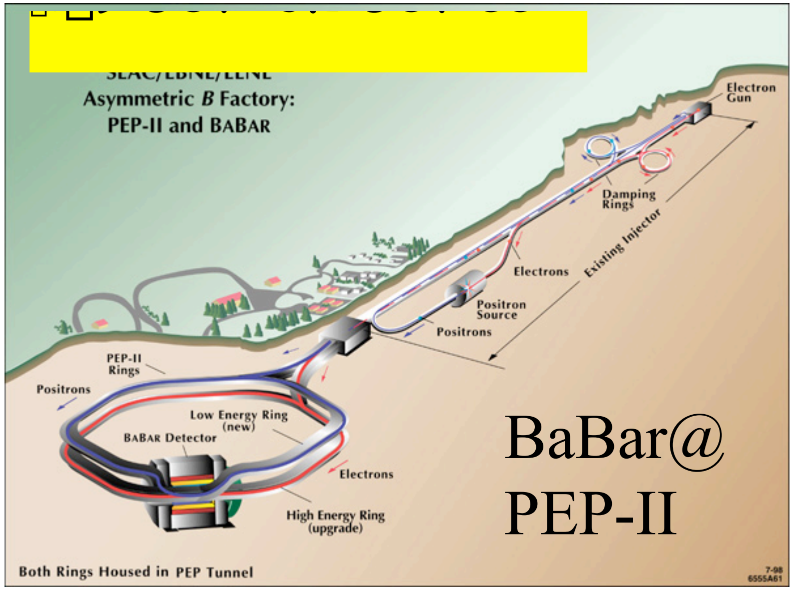
- The universe is now matter dominated: where has all the primordial anti-matter gone?
  - Anti-proton/proton ratio ~10^{-4} in cosmic rays; no evidence for annihilation photons from intergalactic clouds
- Sakharov conditions (1967) for generation of cosmological asymmetry:
  - Baryon number violation, e.g., proton decay
  - Thermal non-equilibrium
  - Violation of C, CP discrete symmetries
- CP Violation seen in Particle decays
- **What, if any, is the connection between CP violation in the cosmos and the CPV in subatomic systems ?**



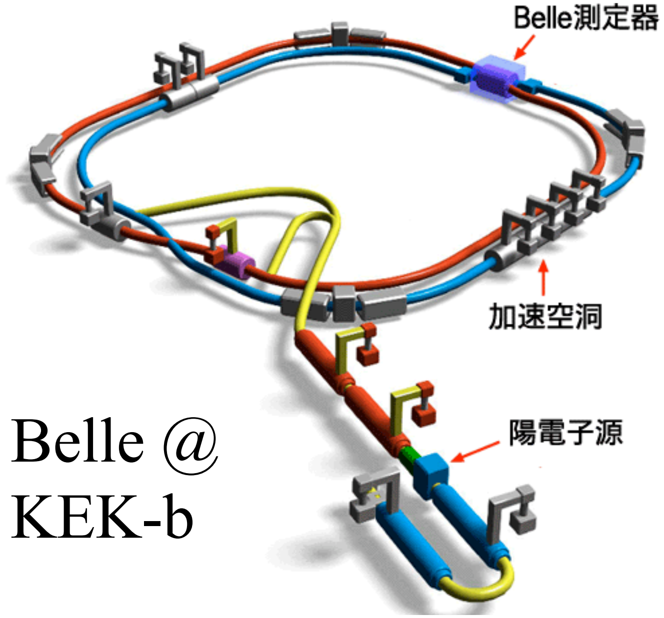
CP Violation In Subatomic Systems

- CP Violation first discovered in the Kaon system
- Kaon system has been the playground of CPV model-building and model-killing) since discovery (1964)
- Kobayashi & Maskawa's proposition (1973) of CPV in the context of the complex weak couplings of 3 generations of quarks consistent with observed CPV in the Kaon system (postdiction!)
- But hadronic uncertainties in the Kaon system makes clean interpretation of CPV in terms of SM or New Physics difficult
- B mesons are the "new" & theoretically clean laboratory for investigation of CP Violation within SM & Beyond Standard Model
- Two dedicated experimental efforts:
  - PEP-II Collider & BaBar detector in California
  - KEK-B Collider & Belle detector in Japan

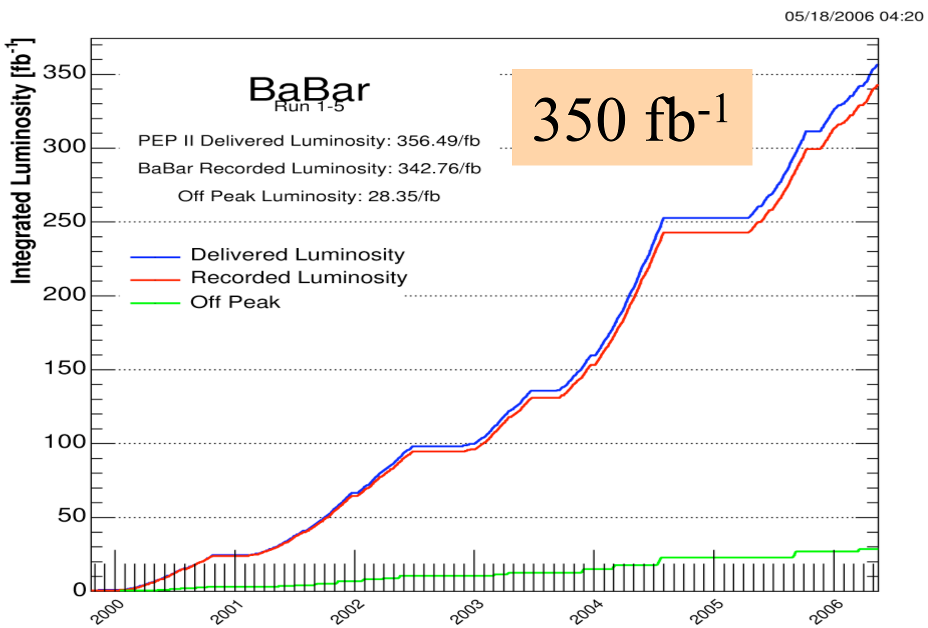
Asymmetric Energy $e^+ e^-$ Colliders: B Factories



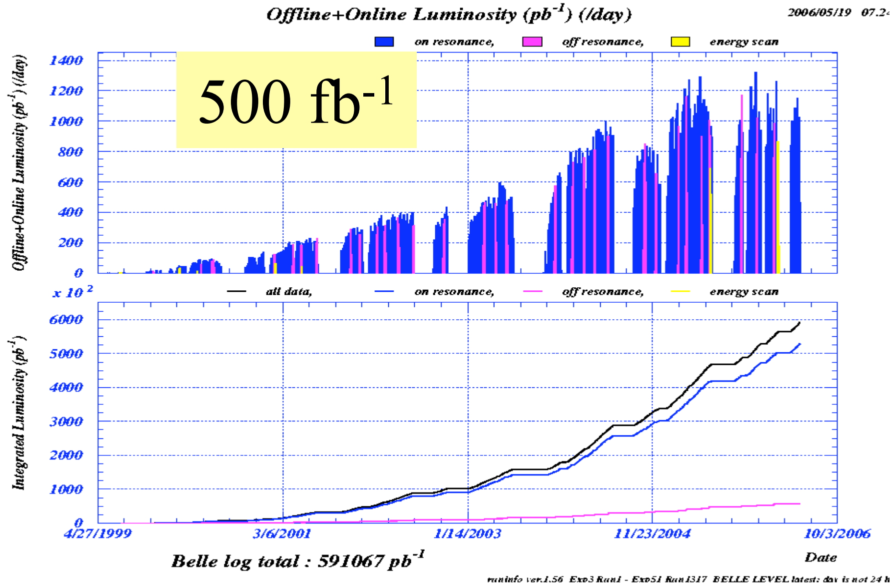
BaBar@
PEP-II



Belle @
KEK-b

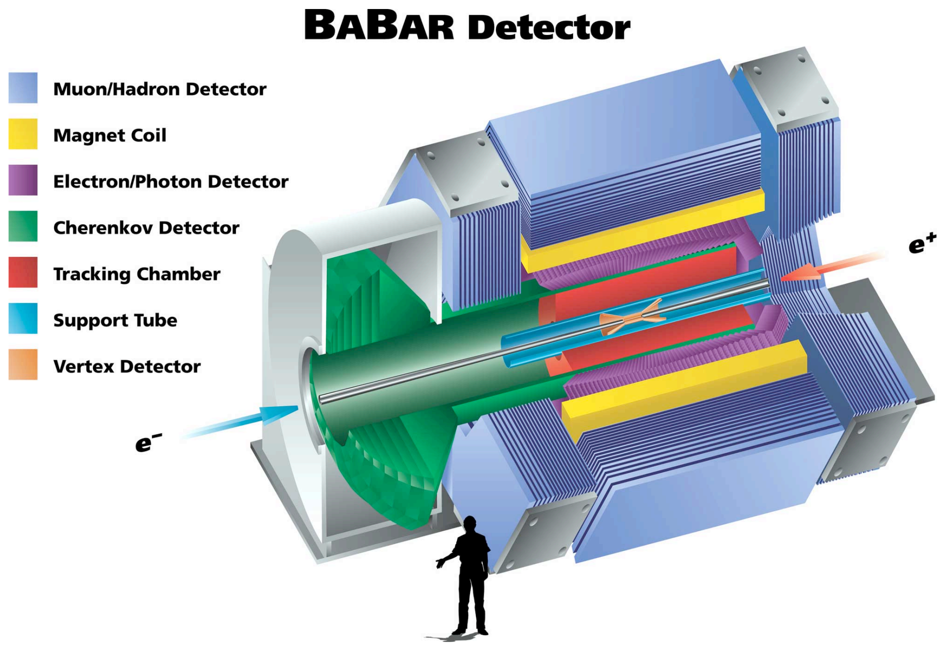


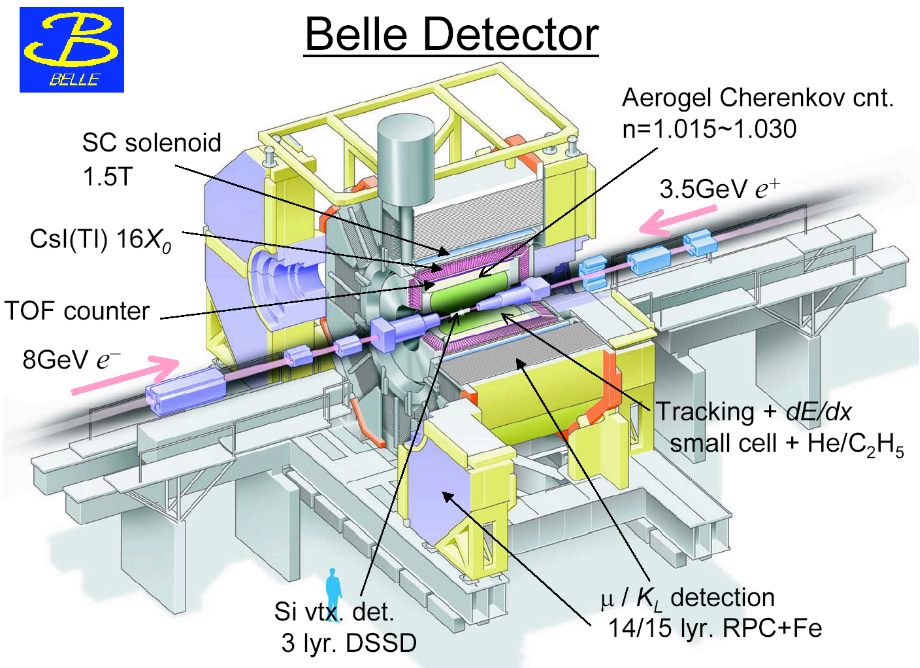
350 fb^{-1}

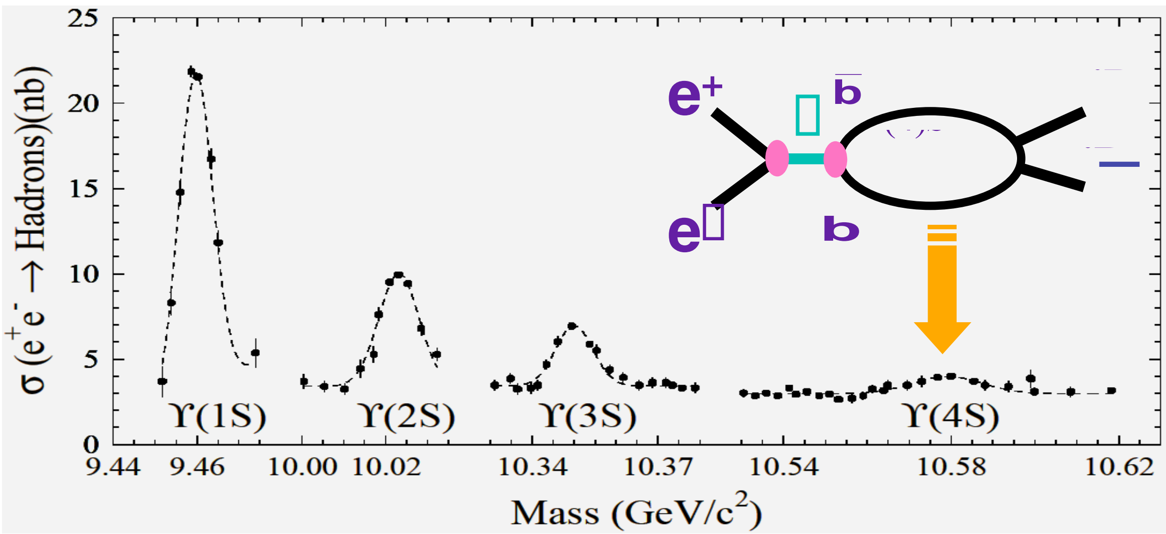


500 fb^{-1}

Belle and Babar Detectors







Enough energy to barely produce 2 B mesons, nothing else!

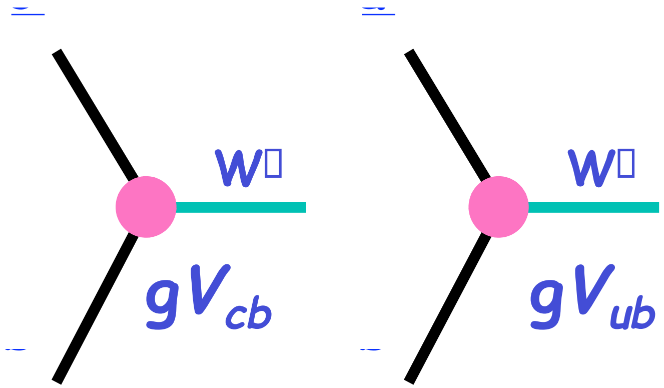
B mesons are entangled

Need for Asymm energy collisions

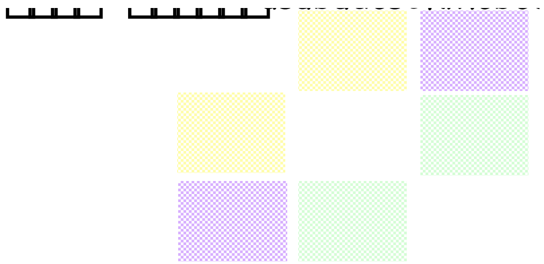
CP Violation Studies at Asymmetric Energy Colliders

Inter Quark Couplings: CKM Matrix

Flavor changes through mixed couplings to quarks



Cabibbo-Kobayashi-Maskawa (CKM) Matrix



Unitary matrix described for 3 generations of quarks by 3 rotation angles and 1 non-trivial phase

KM Conjecture: The phase of CKM matrix is source of CPV

CKM Matrix: Phenomenology

ckm phase

Wolfenstein parameterization:

Observed experimental hierarchy

3x3 matrix: 3 quark generations

2x2 submatrix: u,d,s,c quarks only

$\lambda \sim 0.22$

$\sin\theta_C$

Cabibbo angle

$2 \leftrightarrow 1$

$3 \leftrightarrow 1$

$\sim\lambda^3$

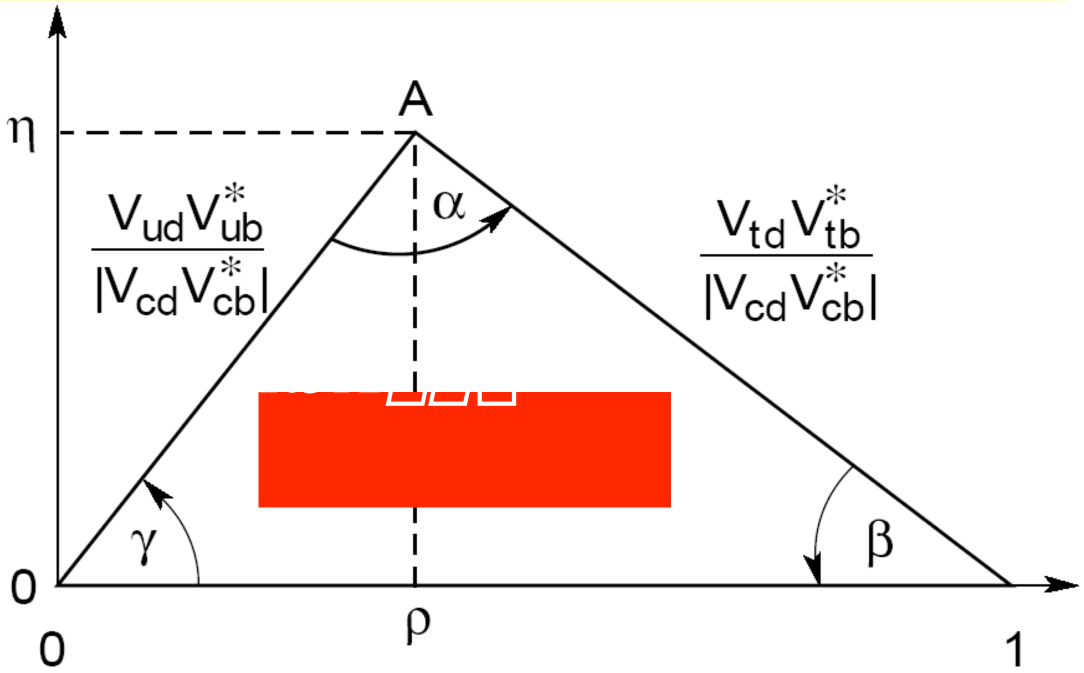
$3 \leftrightarrow 2$

$\sim\lambda^2$

CKM Phase: changes sign under CP

The Unitarity Triangle For B System

Angles of Unitarity Triangle



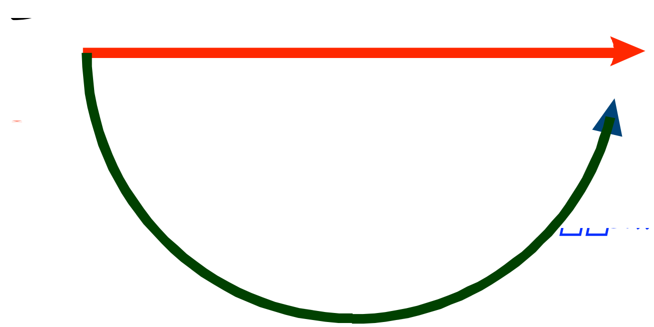
Specific forms of CP Violation in B decay provide **clean** information about the **angles** of the UT triangle

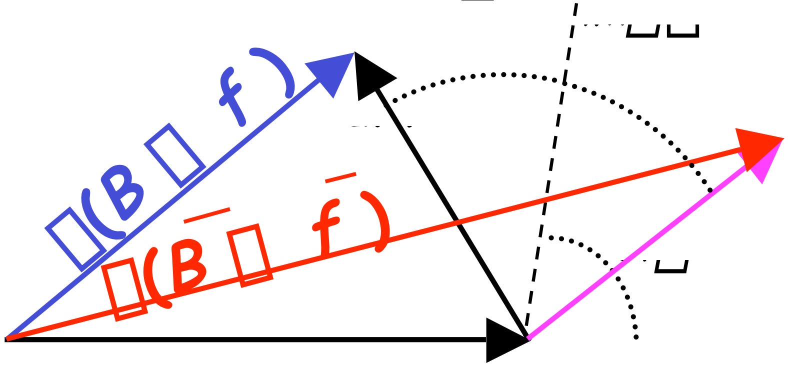
Same triangle also defined by length of its sides (from CP conserving B decay processes such as b→ u l nu) ⇒ Overconstrained triangle

CP Violation As Quantum Interference

Analogous to a two-slit quantum interference experiment!

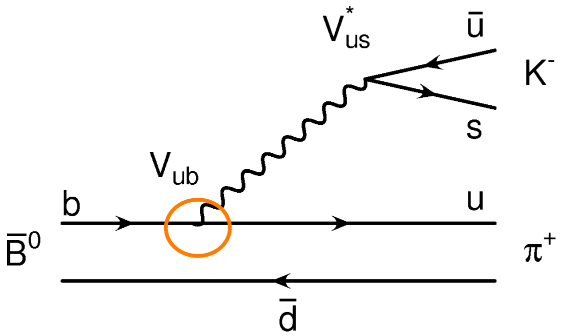
- CPV due to interference of meson decay amplitudes

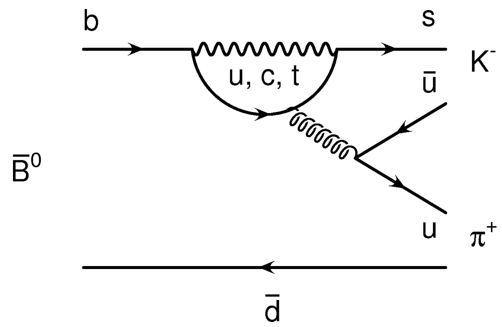




Direct CP Violation in $B^0 \to K \pi$

T





P

Classic example of Quantum Interference

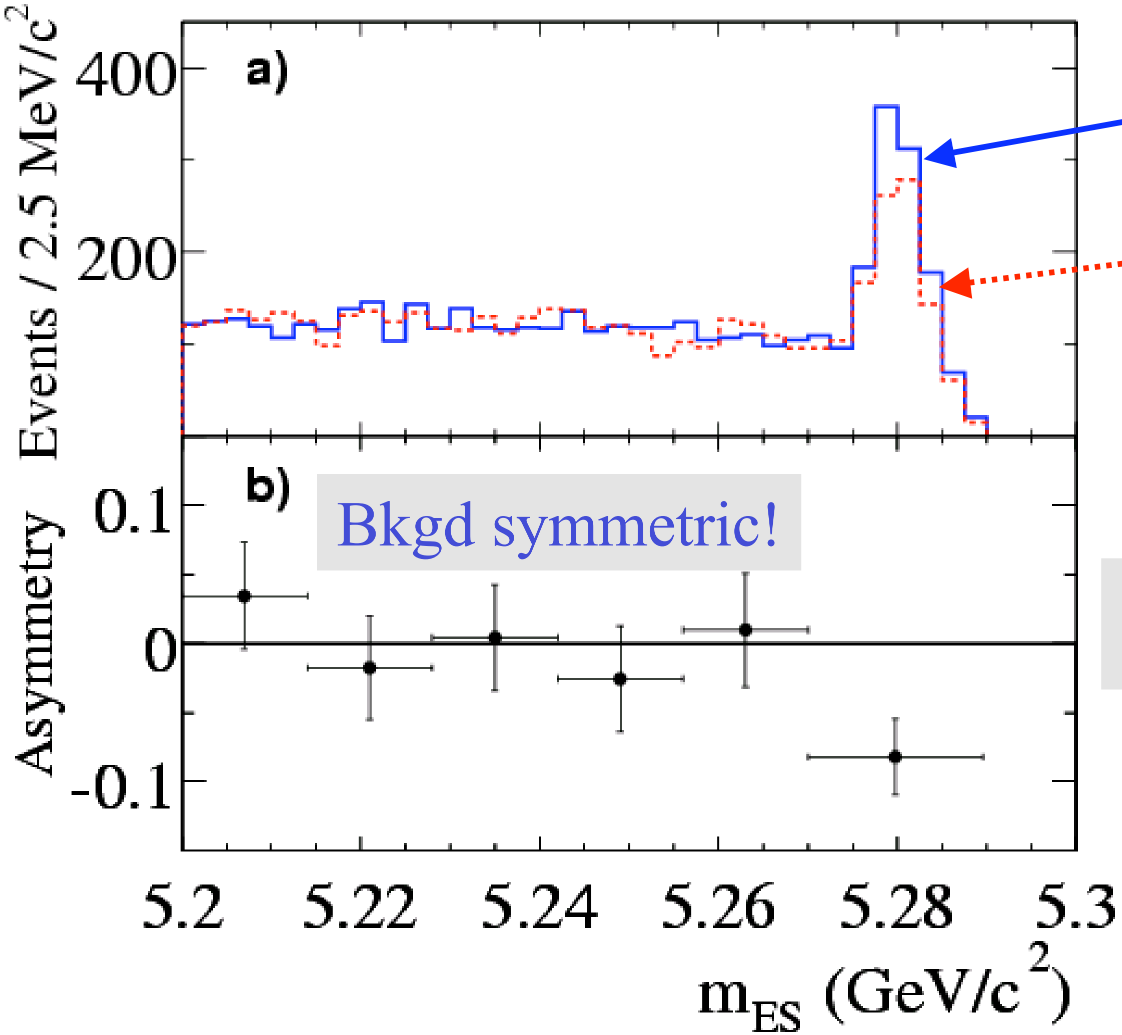
•Loop diagrams from New Physics (e.g. SUSY) can modify SM asymmetry contributing to the Penguin (P) amplitude

• Measurement is a simple "Counting Experiment"

Direct CP Violation in $B^0 \rightarrow K^+$□□

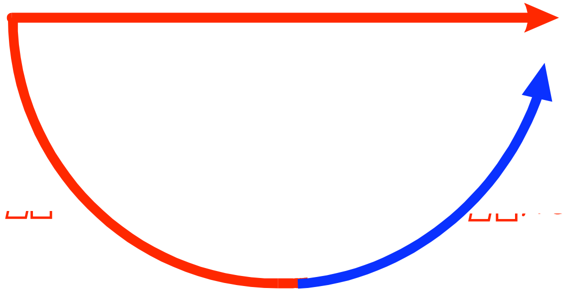
BaBar

4.2□, syst. included



"Indirect" CP Violation

➢ CPV through interference between mixing and decay amplitudes

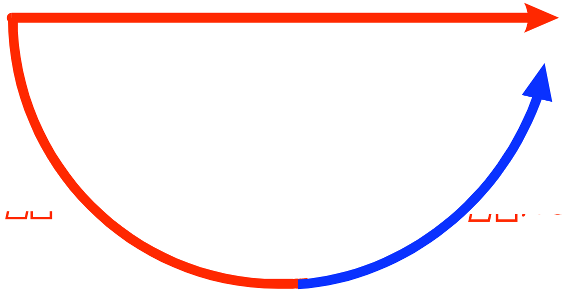


Time-dependent asymmetry

Case Of Single Decay Amplitude

- **CPV through interference between mixing and decay amplitudes**

Directly related to CKM angles for single decay amplitude

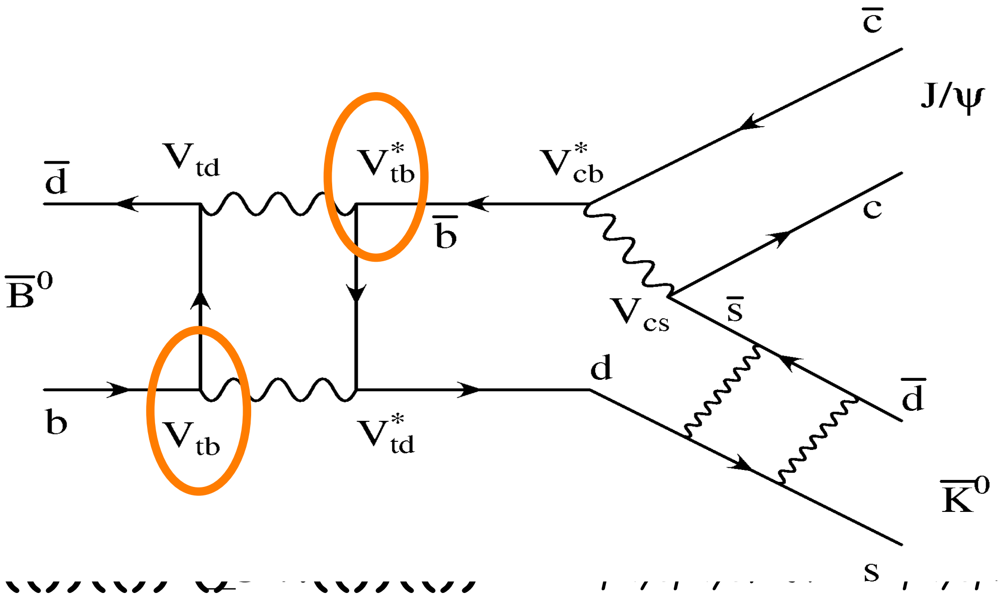


Time-dependent asymmetry

For the simple case shown with single decay mechanism

SM Predicts Large CPV in B Decays

Golden Channel



CP Eigenstate:

η_{CP} = -1: K_s

η_{CP} = -1: K_L

Amplitude of *CP* asymmetry

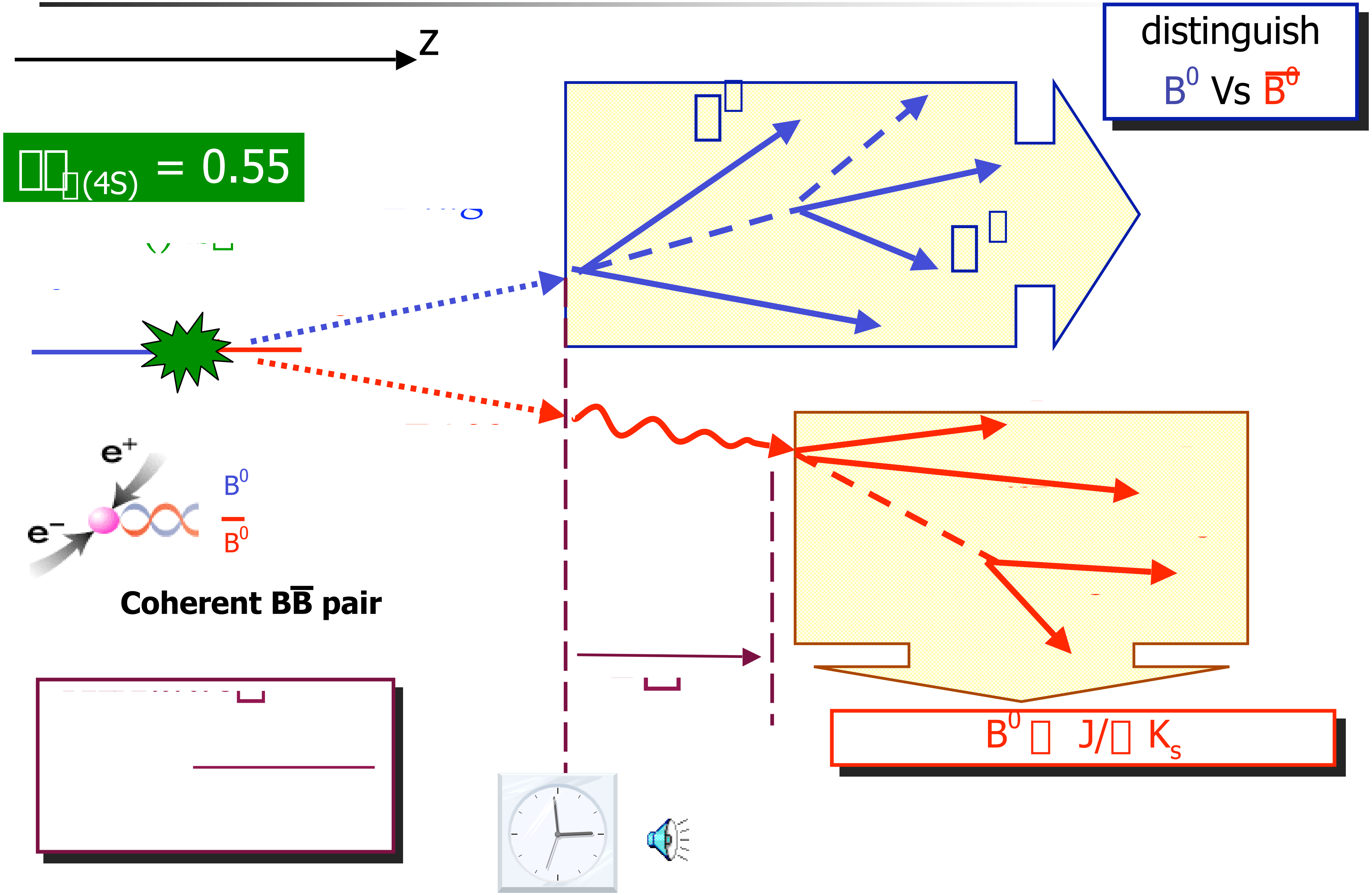
Quark subprocess

B^0 mixing

K^0 mixing

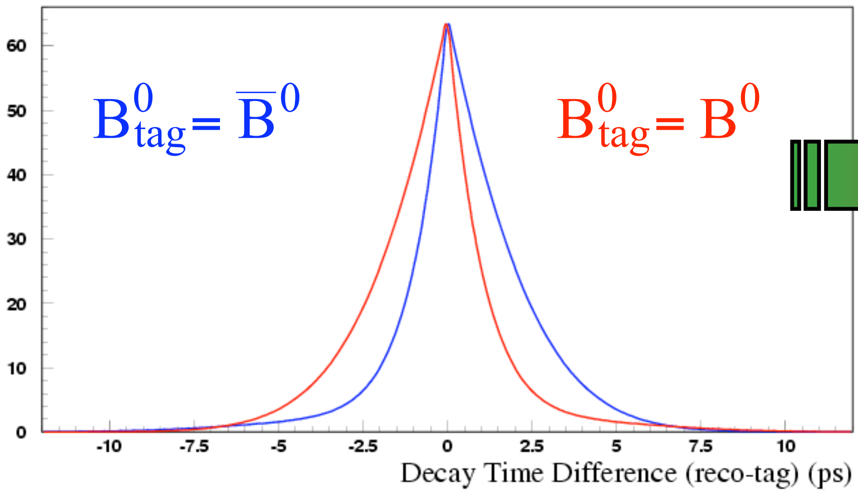
~0.7 instead of 2×10^{-3} in Kaons!

Steps in Time-Dependent CPV Measurement

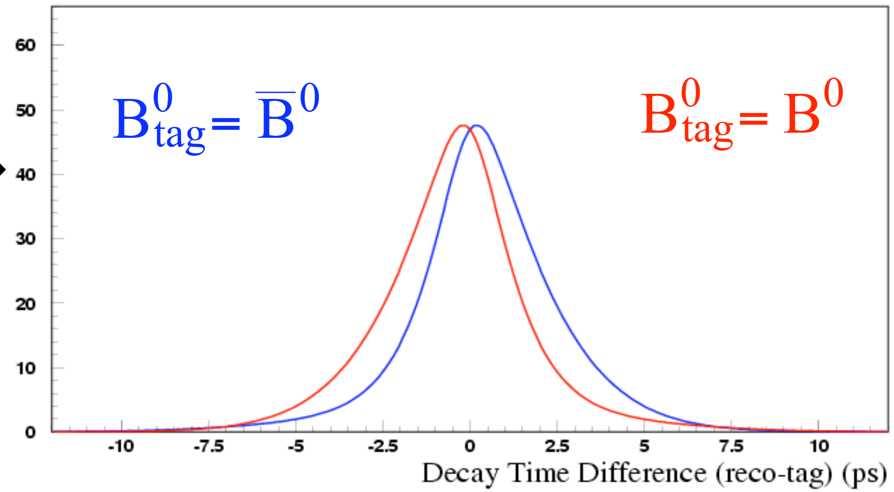


Effect of Mis-measurements On □t Distribution

perfect
flavor tagging & time resolution

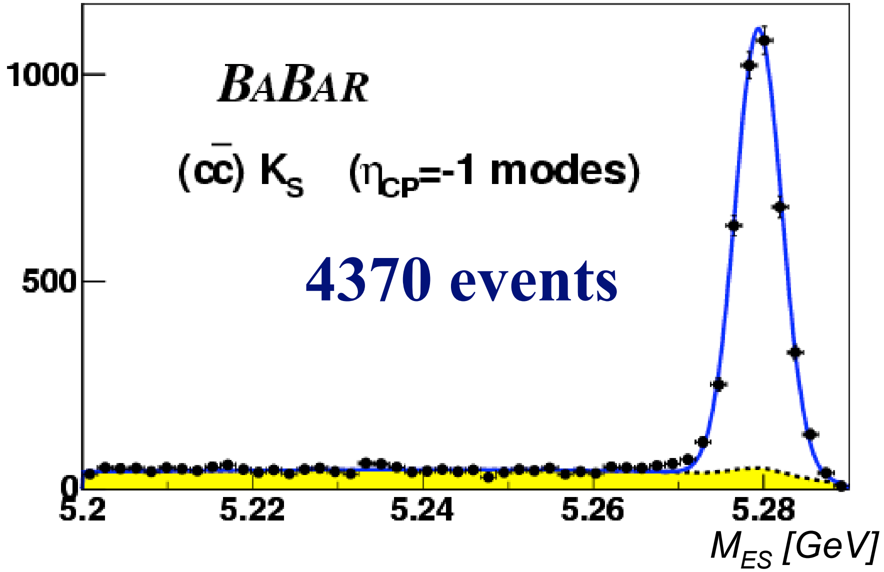


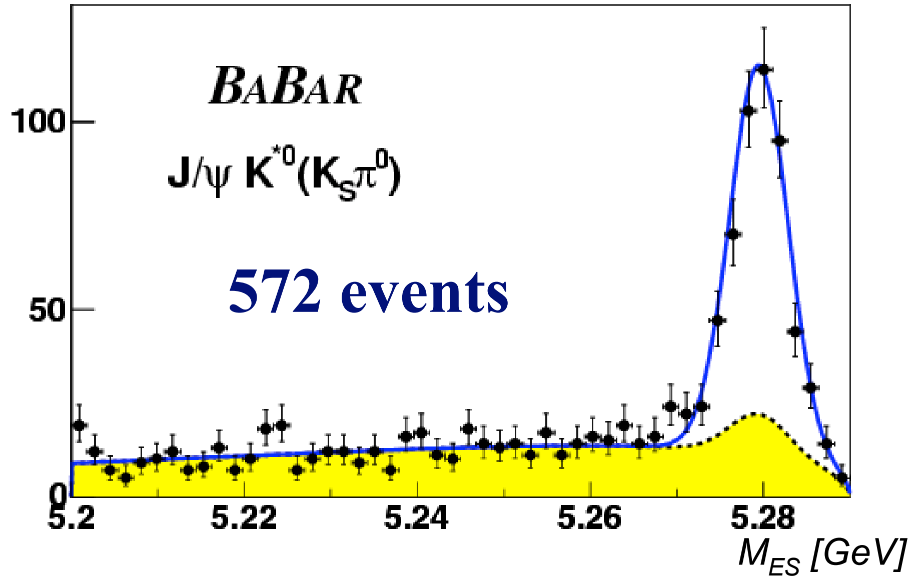
realistic
mis-tagging & finite time resolution

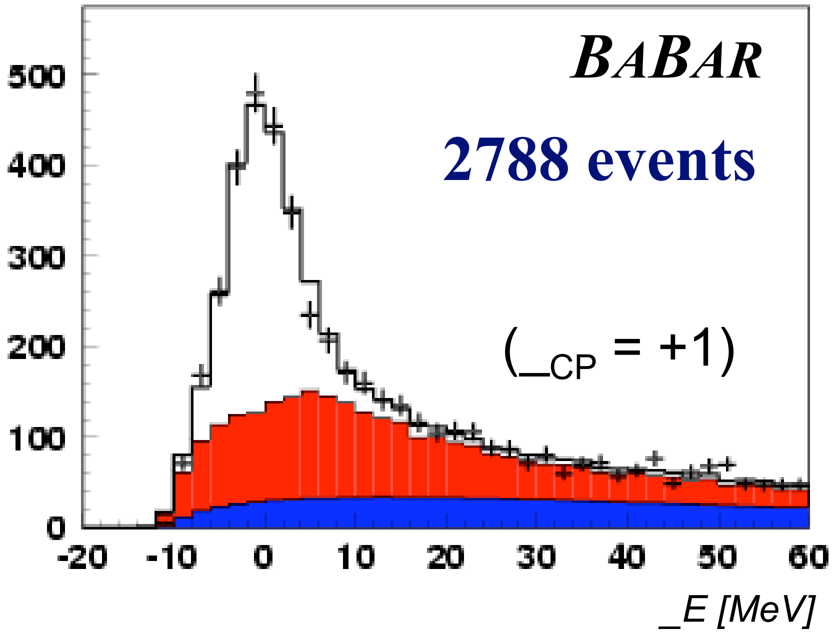


CP PDF

B→ Charmonium Data Samples



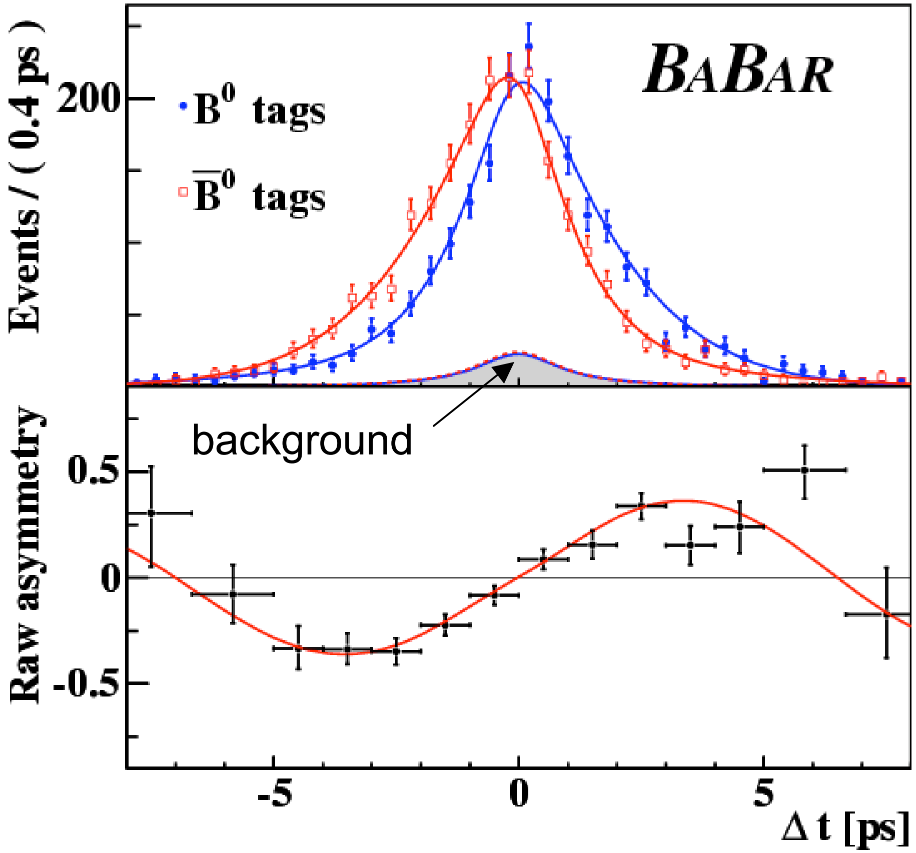




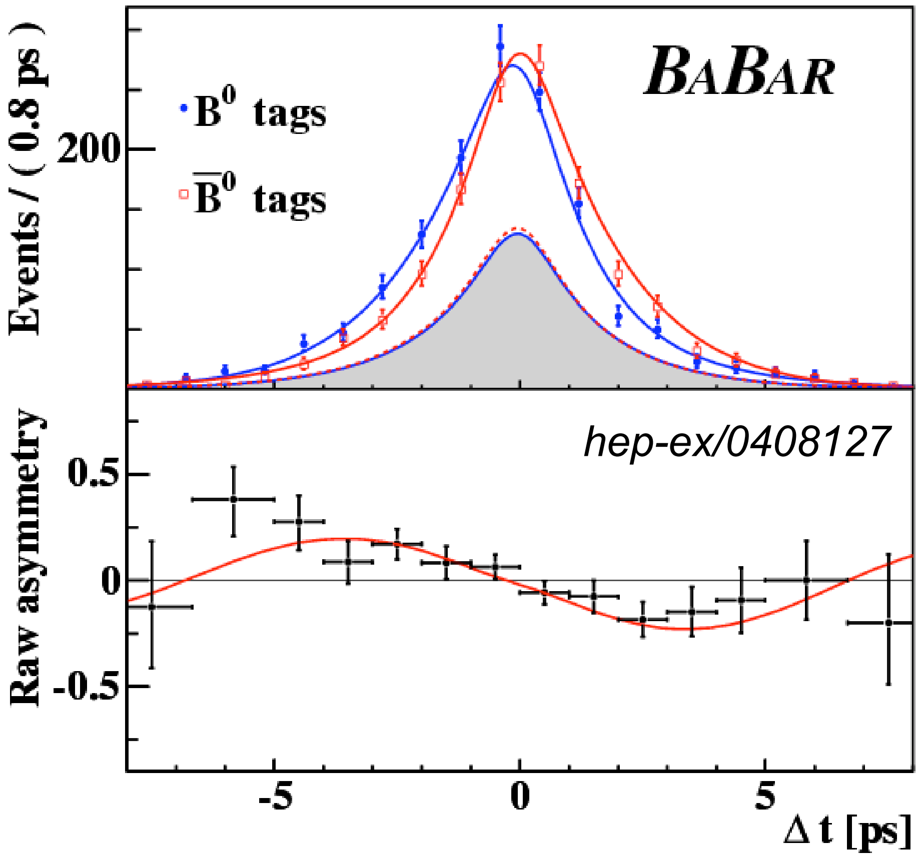
CP sample	N_{TAG}	purity	$\_{CP}$
J/_ K_S (K_S_$\pi^+\pi^-$)	2751	96%	□1
J/_ K_S (K_S_$\pi^0\pi^0$)	653	88%	□1
_(2S) K_S (K_S_$\pi^+\pi^-$)	485	87%	□1
$\_{c1}$ K_S (K_S_$\pi^+\pi^-$)	194	85%	□1
$\_{c}$ K_S (K_S_$\pi^+\pi^-$)	287	74%	□1
Total for $\_{CP}$=-1	**4370**	92%	□1
J/_ K^{*0}(K^{*0}_ $K_S\pi^0$)	572	77%	+0.51
J/_ K_L	2788	56%	+1
Total	**7730**	78%	

Sin(2□) Result From B→ Charmonium K^0 Modes (2004)

$(c\bar{c})\ K_S$ modes (CP = □1)



J/_ K_L mode (CP = +1)



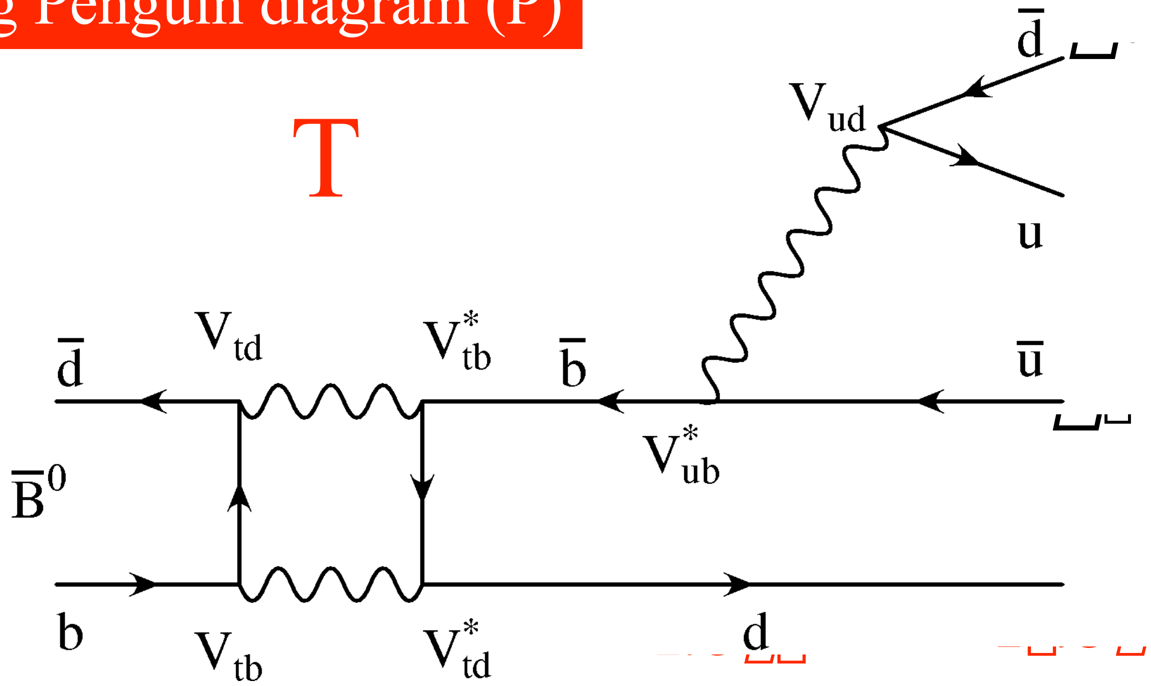
sin2_ = 0.722 ± 0.040 (stat) ± 0.023 (syst)

(PRL 89, 201802 (2002): sin(2_) = 0.741 ± 0.067 ± 0.034)

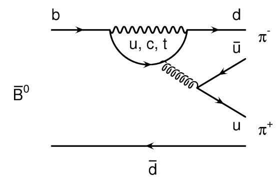
Angle □ From B^0 □ □$^+$□$^-$

Neglecting Penguin diagram (P)

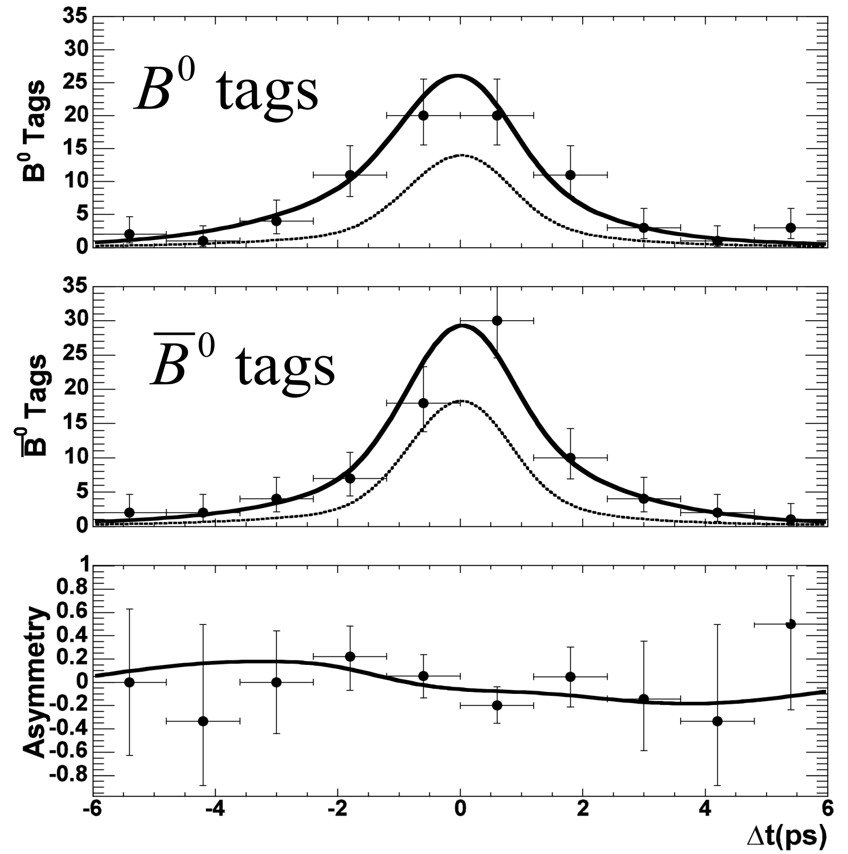
T

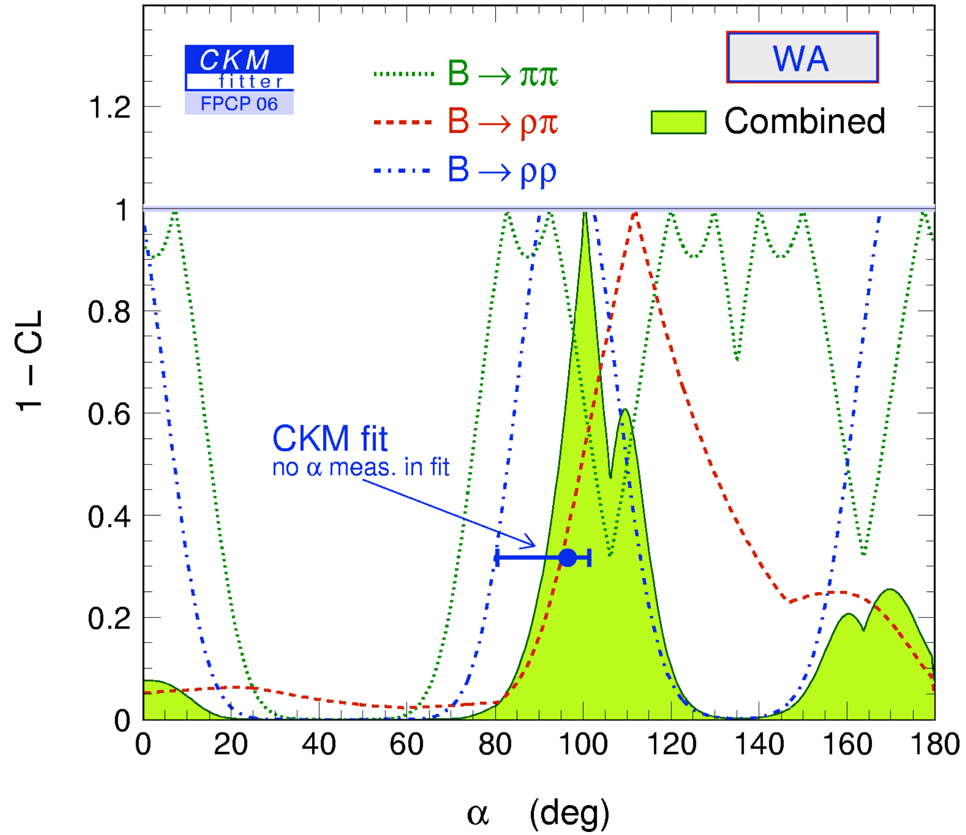


P



Angle α From $B^0 \to \pi^+\pi^-$



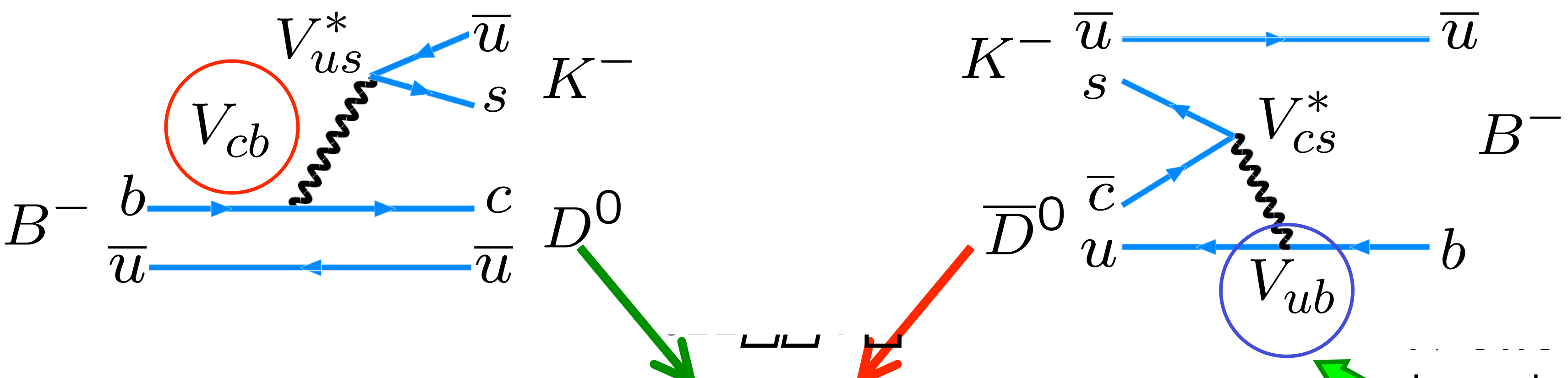


$$S_{\pi\pi} = -0.33 \pm 0.024^{+0.008}_{-0.014}$$

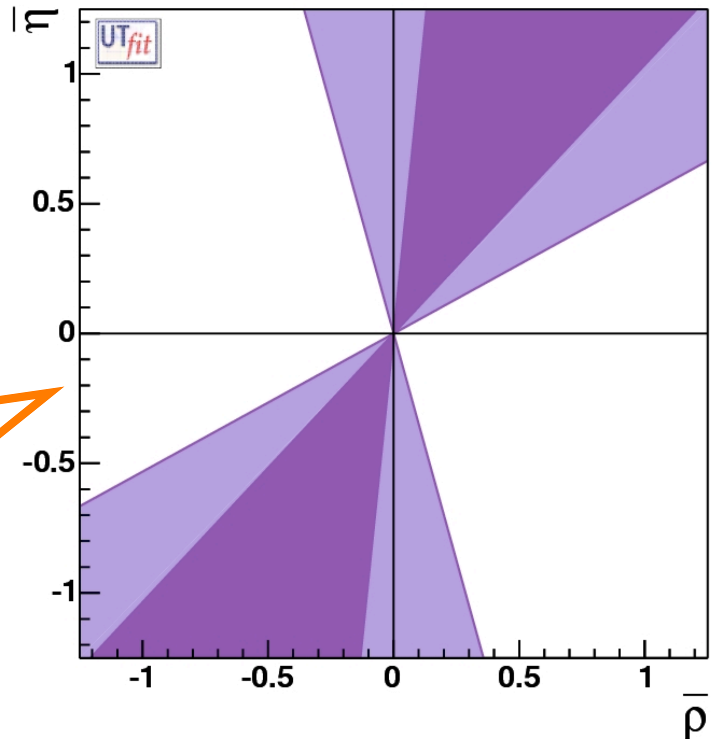
$$C_{\pi\pi} = -0.03 \pm 0.18 \pm 0.09$$

World Average:

Direct CPV In B□ DK Decay □ Angle □



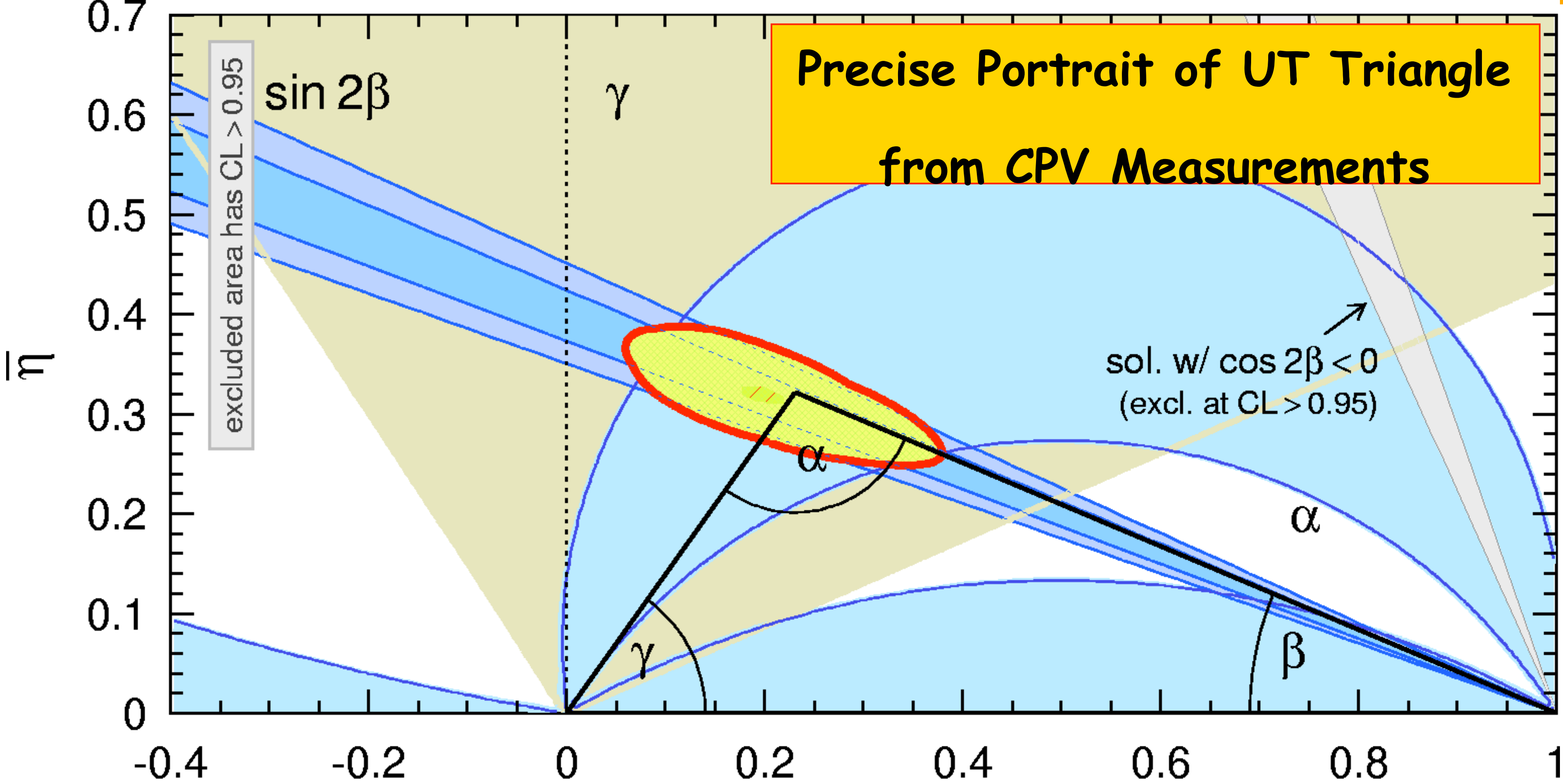
Constraint on □ in the □,□ plane



$\square_{WA} = 59^\circ \pm 19^\circ$

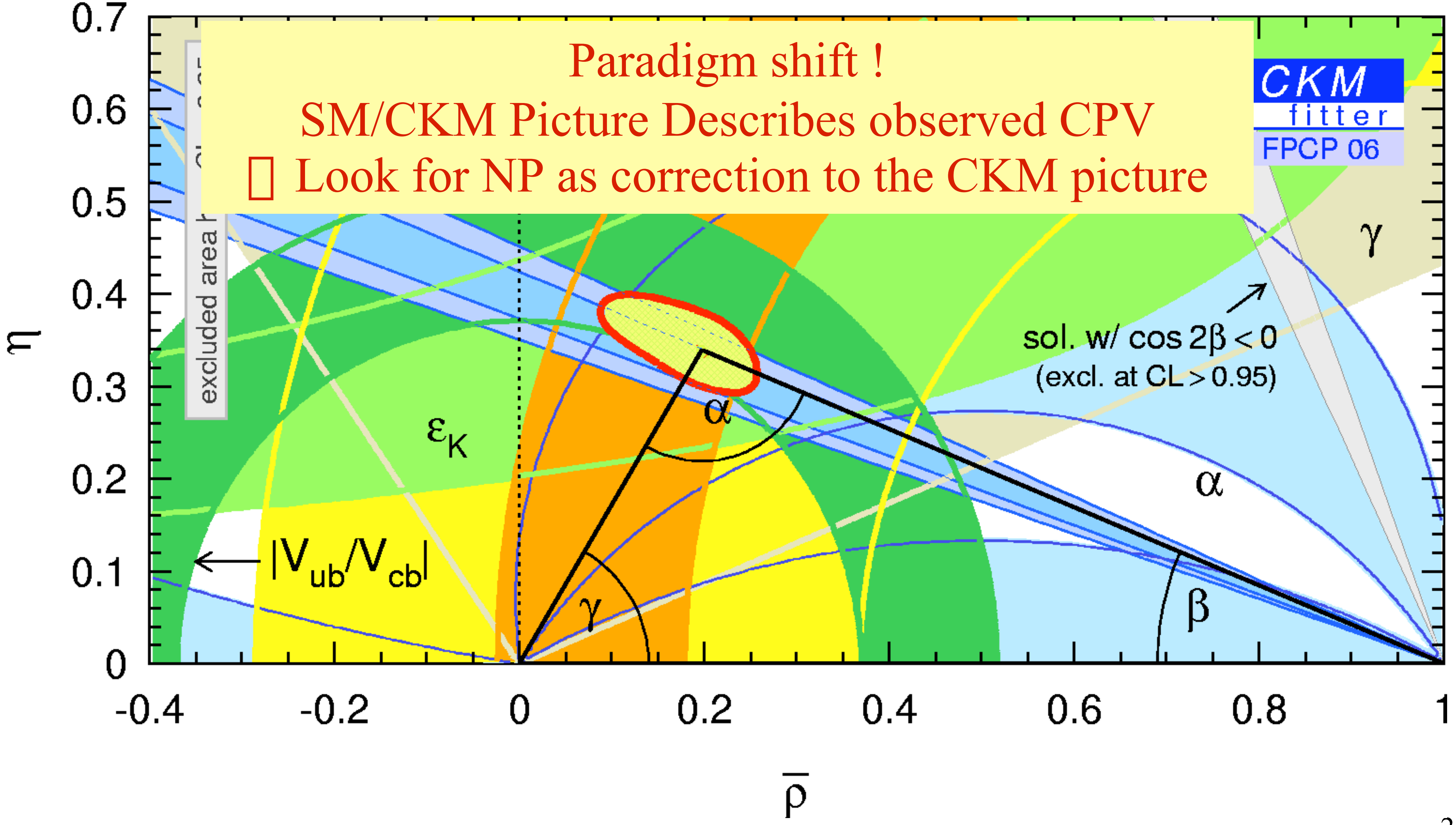
measurements data limited (~ 2.4□)

The Unitarity Triangle Defined By CPV Measurements

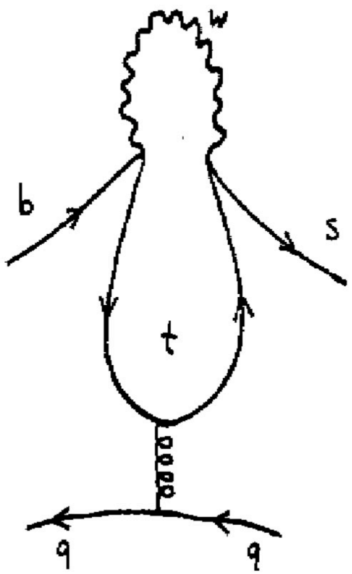


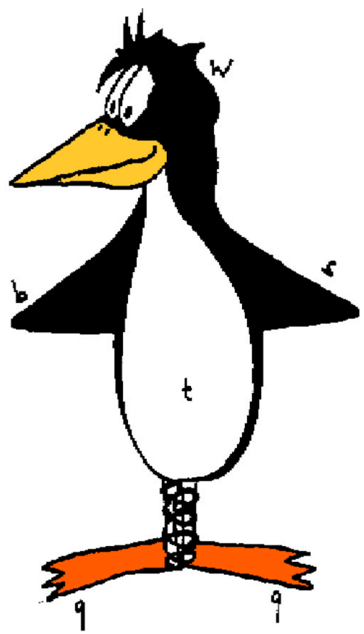
UT With CPV & CP Conserving Measurements

Incredible consistency between measurements !

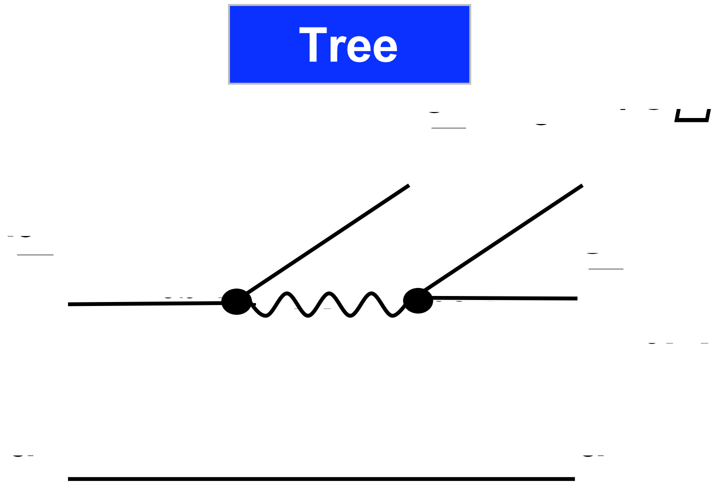


Searching For New Physics by Comparing **Pattern** of CP Violation in Penguin Decays of B Mesons

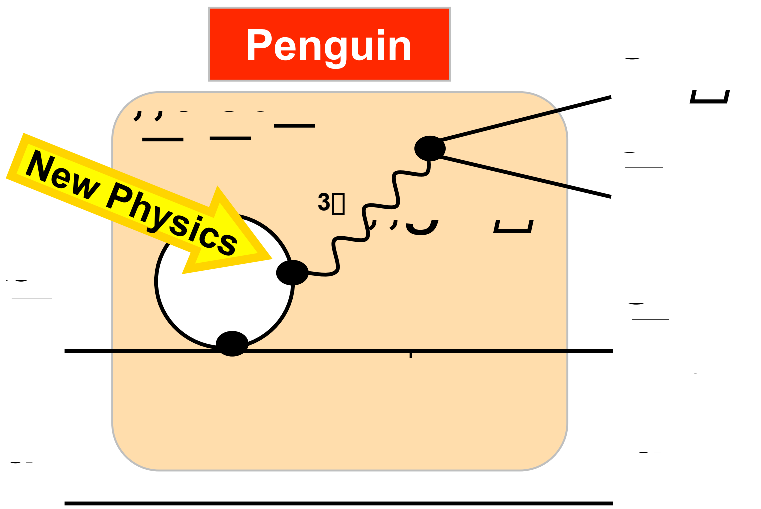




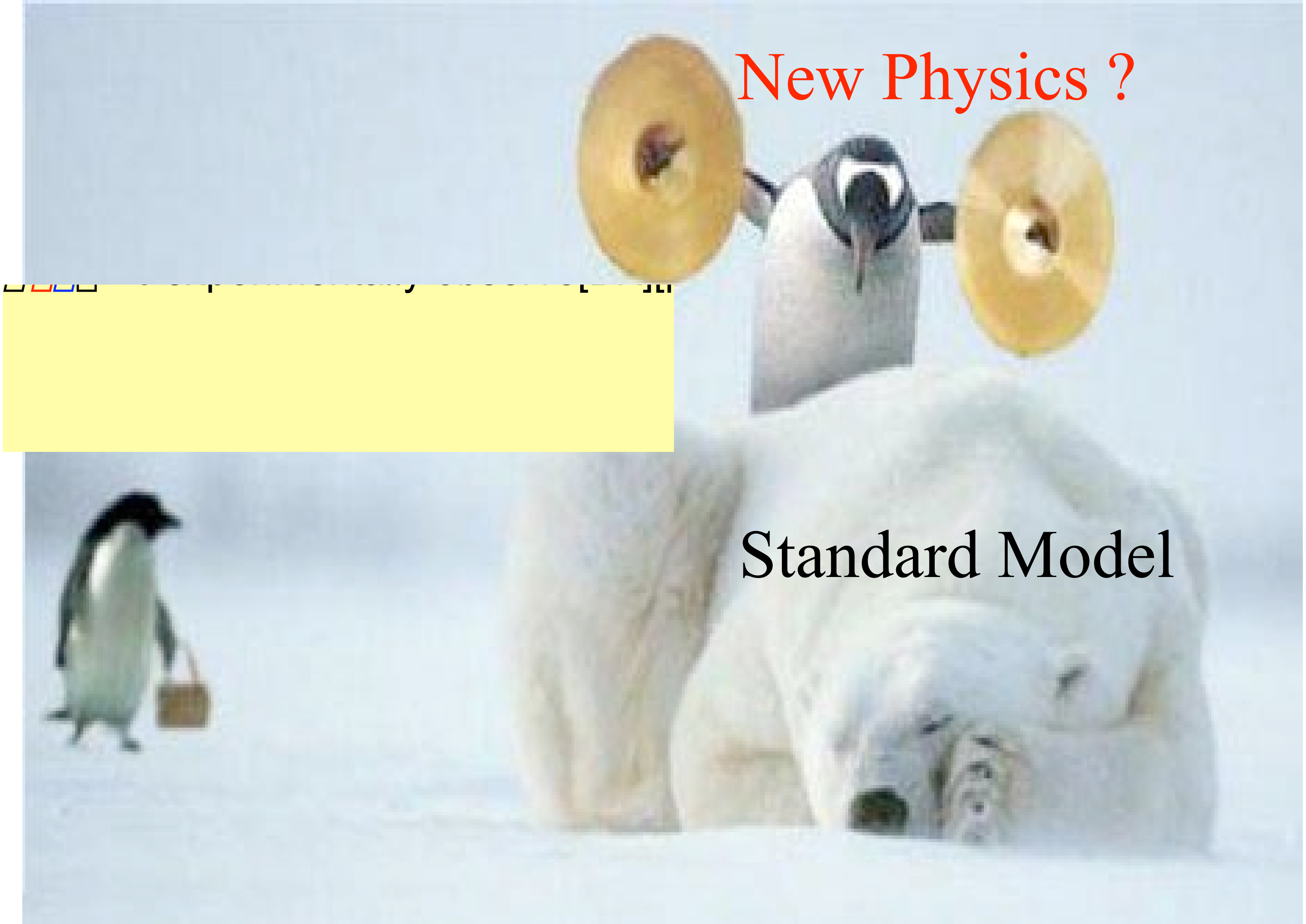
Comparing CP Asymmetries : Penguins Vs Tree



In SM both decays dominated by a single amplitude with no additional weak phase



New physics coupling to Penguin decays can add additional amplitudes with different CPV phases

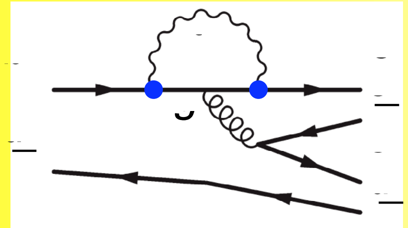


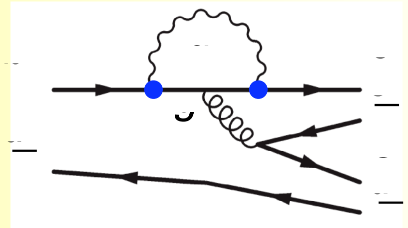
New Physics ?
Standard Model

Naïve Ranking Of Penguin Modes by SM "pollution"

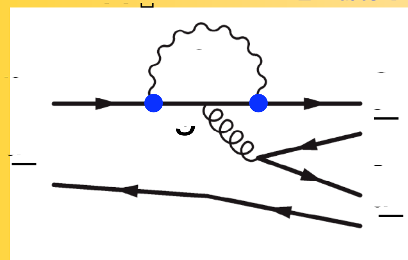
Decay amplitude of interest | **SM Pollution** | Naive (dimensional) uncertainties on sin2

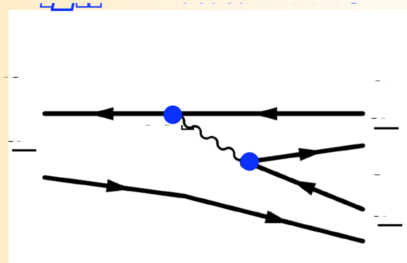
SuperGold



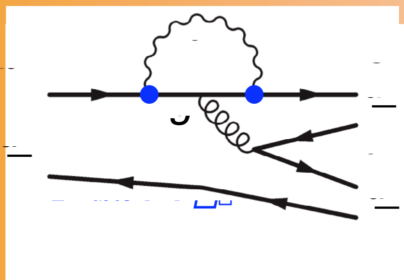


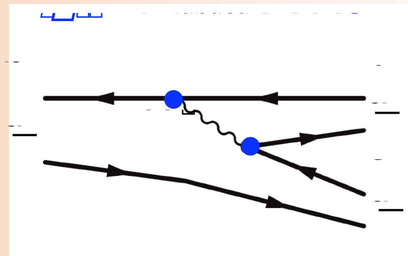
Gold





Bronze



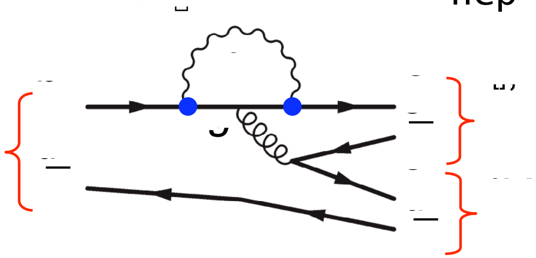


Note that within QCD Factorization these uncertainties turn out to be much smaller !

Golden Penguin Mode : B^0 □ □K^0

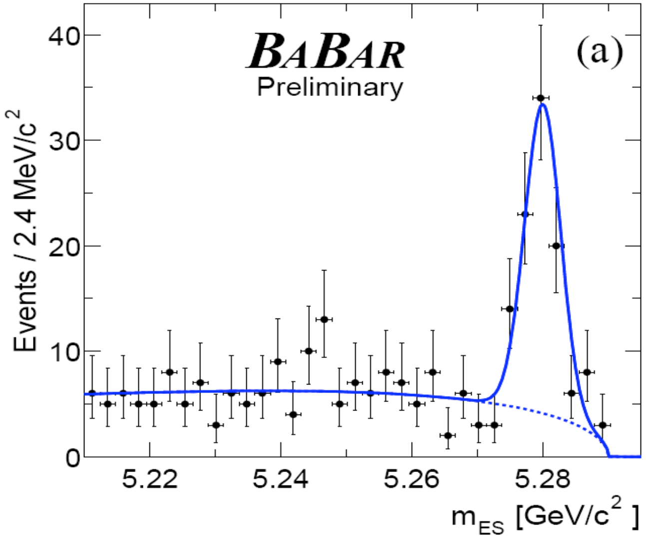
BaBar: 222M BB

hep-ex/0502019

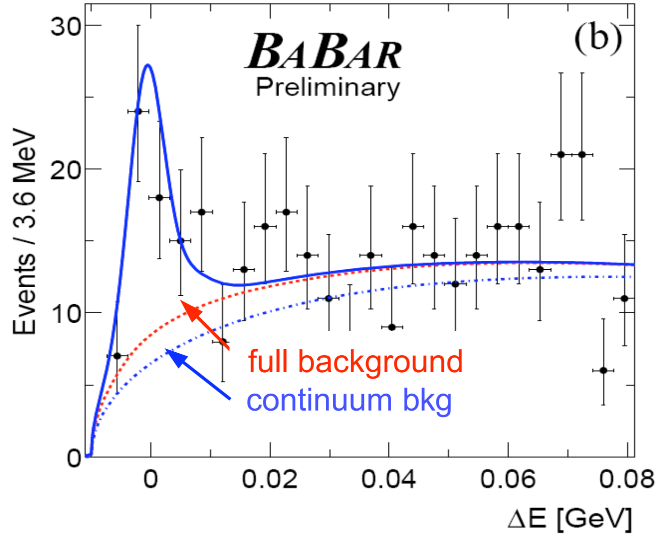


- Modes with K_S and K_L are both reconstructed

(Opposite CP)



114 ± 12 signal events

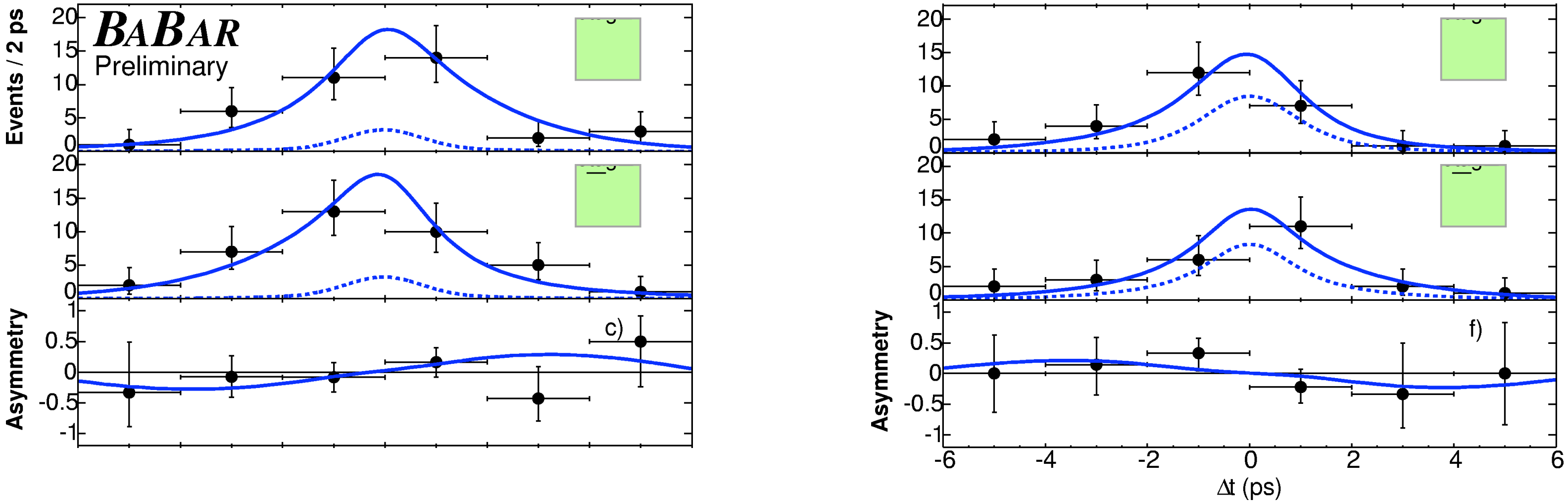


98 ± 18 signal events

CP analysis of 'golden penguin mode' B^0 □ □K^0

BaBar

(Opposite CP)



S(□K$_S$) = +0.29 ± 0.31(stat)

S(□K$_L$) = -1.05 ± 0.51(stat)

Combined fit result

□$_{□K0}$□

0.8□

Standard Model Prediction

S(□K^0) = sin2□ = 0.69 ± 0.03

C(□K^0) = 1-|□| = 0

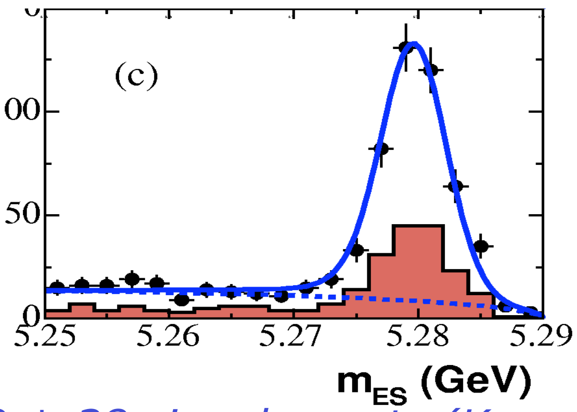
Golden penguin mode: $B^0 \rightarrow$ □'K^0

hep-ex/0502017,0507087

$B^0 \rightarrow$ □'K_S

- Large statistics mode

- Reconstruct many modes
  - □' □ □□$^+$□$^-$, □^{0} □
  - □□ □□, □$^+$□$^-$□^{0}



819 ± 38 signal events (K_s mode)

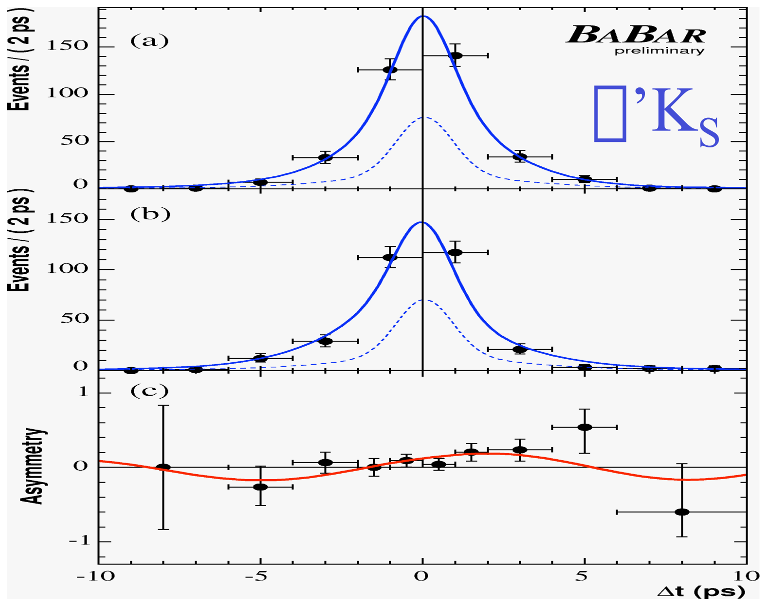
440 ± 54 signal events (K_L mode)

BaBar

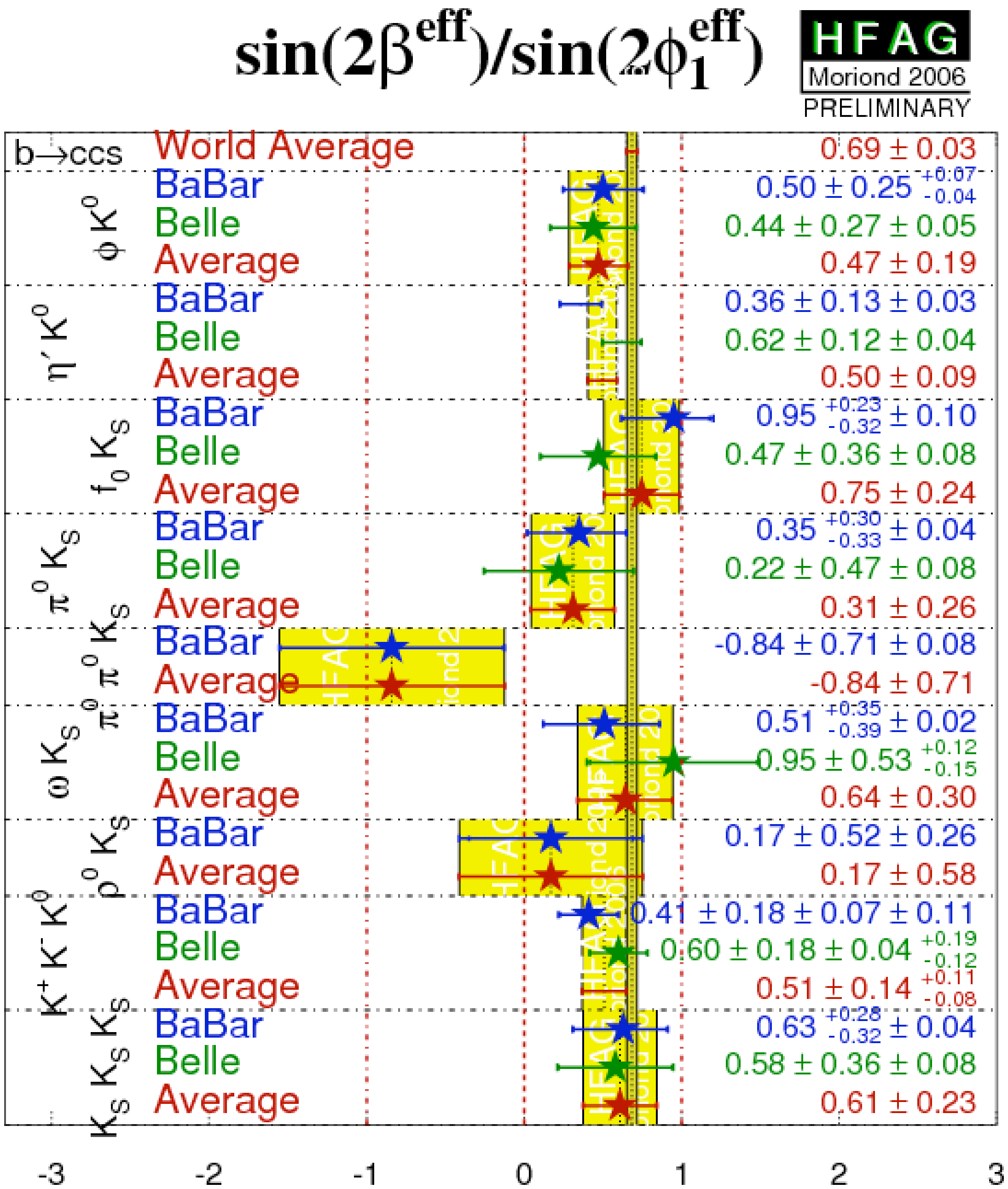
$B^0 \rightarrow$ □'K^0

□$_{□K0}$□

≠ sin2□ [cc] @ 2.7□



Bottom line



Taken individually, each decay mode in reasonable agreement with SM

but (almost) all measurements are lower than sin2□ from cCs

Naïve b □ s penguin average

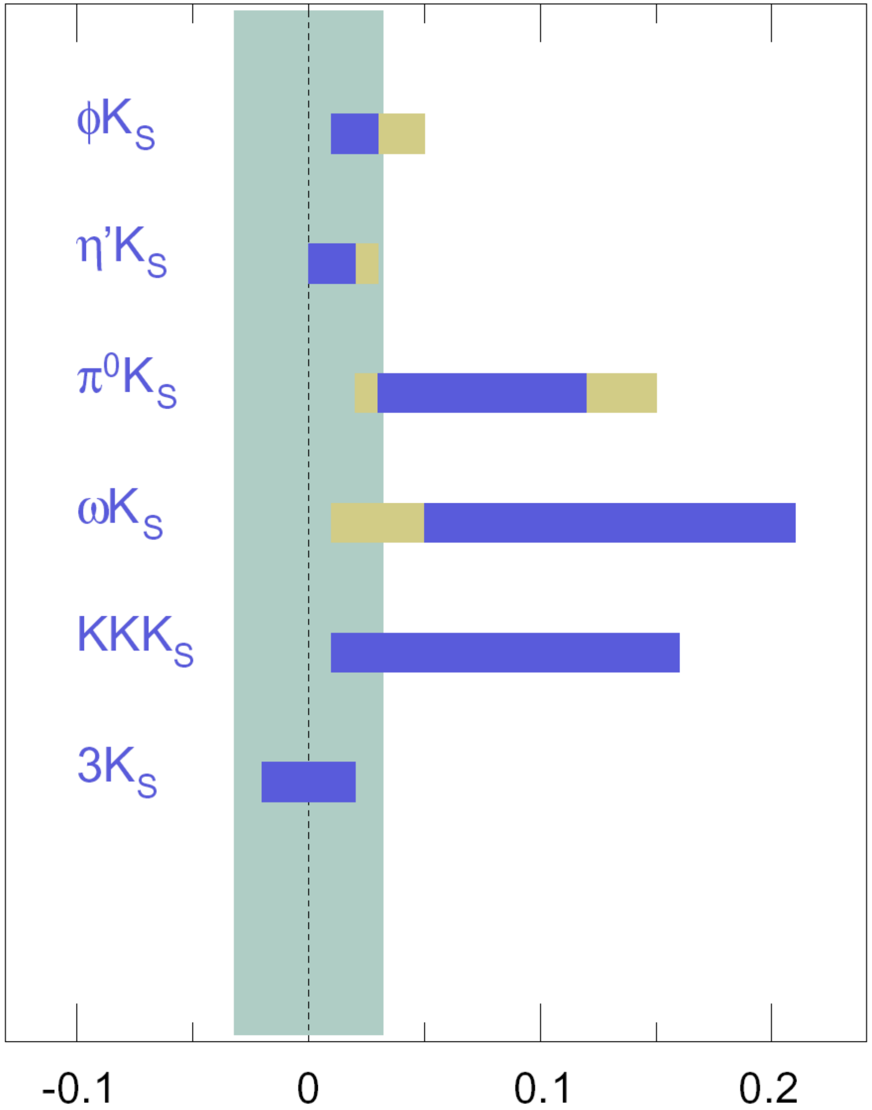
$\sin 2\square_{eff} = 0.50 \pm 0.06$

Compared to Tree:

$\sin 2\square eff = 0.69 \pm 0.03$

Theory models predict SM pollution to **increase** $\sin 2\square_{eff}$!!

Theory Predictions, Accounting For subdominant SM Amplitudes



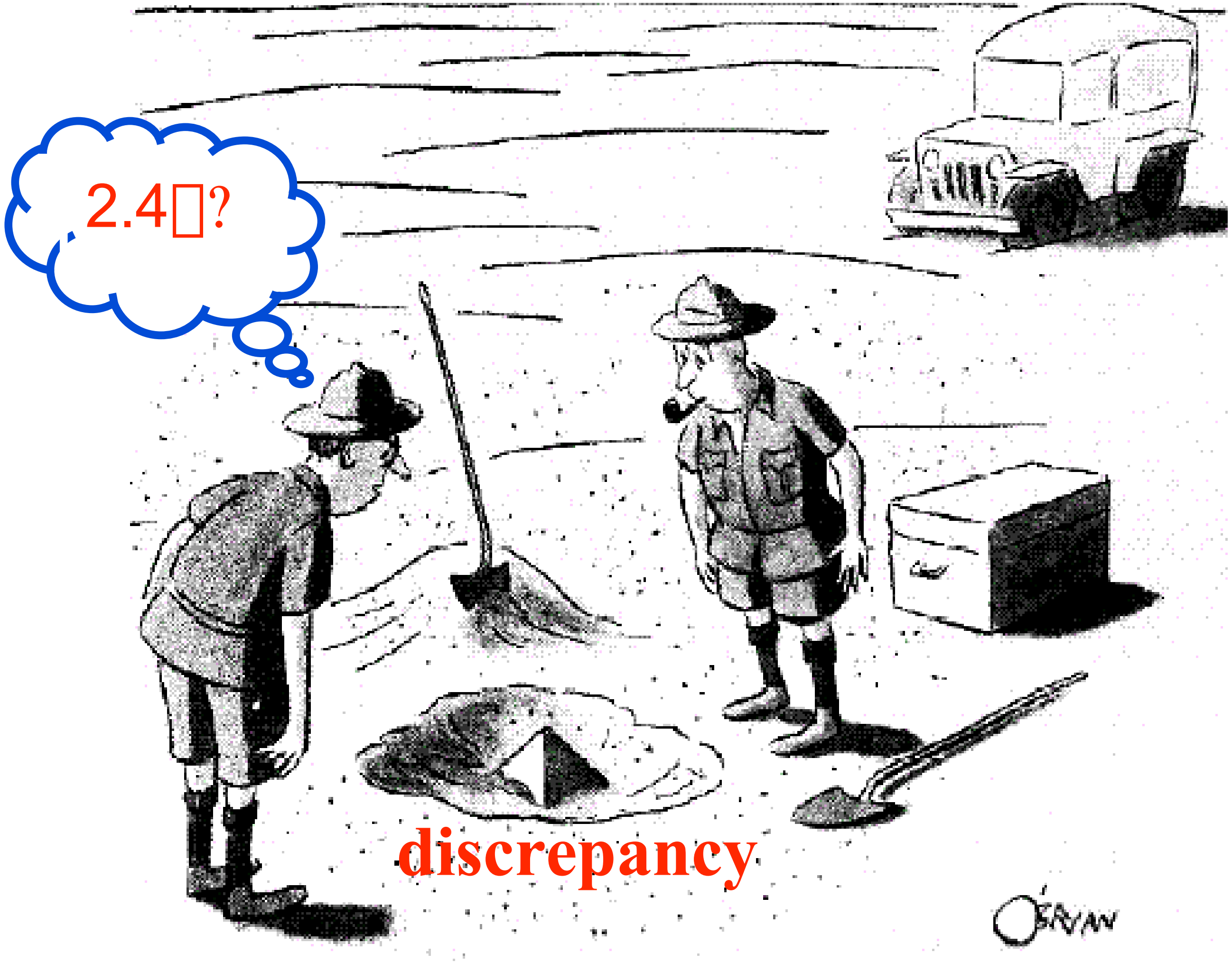
2-body:
Beneke, PLB 620 (2005) 143

Calculations within framework of QCD factorization

3-body:
Cheng, Chua & Soni, hep-ph/0506268

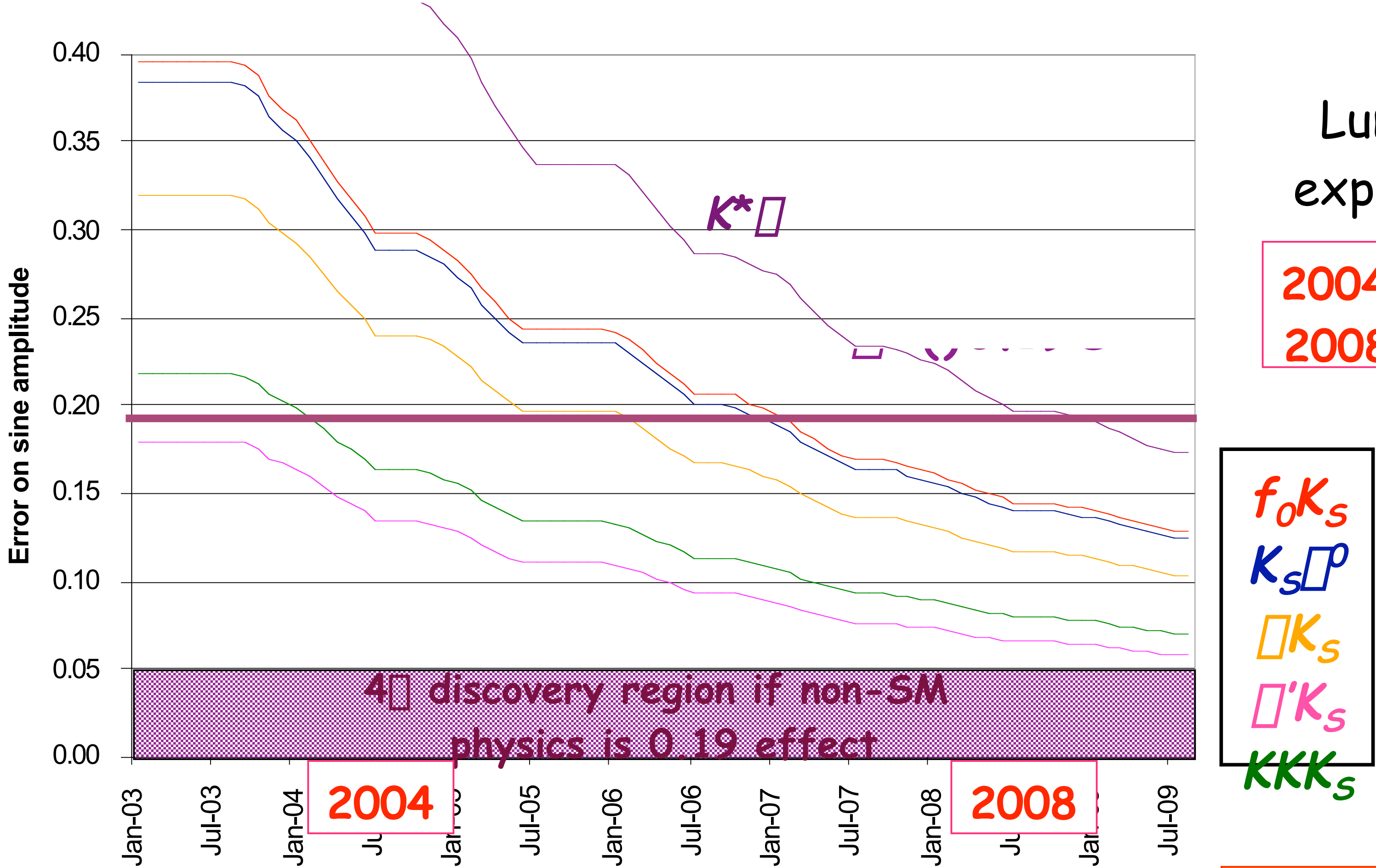
□ sin2□$_{eff}$ > 0.69
□ larger discrepency !

What Are s-Penguins Telling Us ?



This could be one of the greatest discoveries of the century, depending, of course, on how far down it goes…

Need More Data To Understand The Puzzle



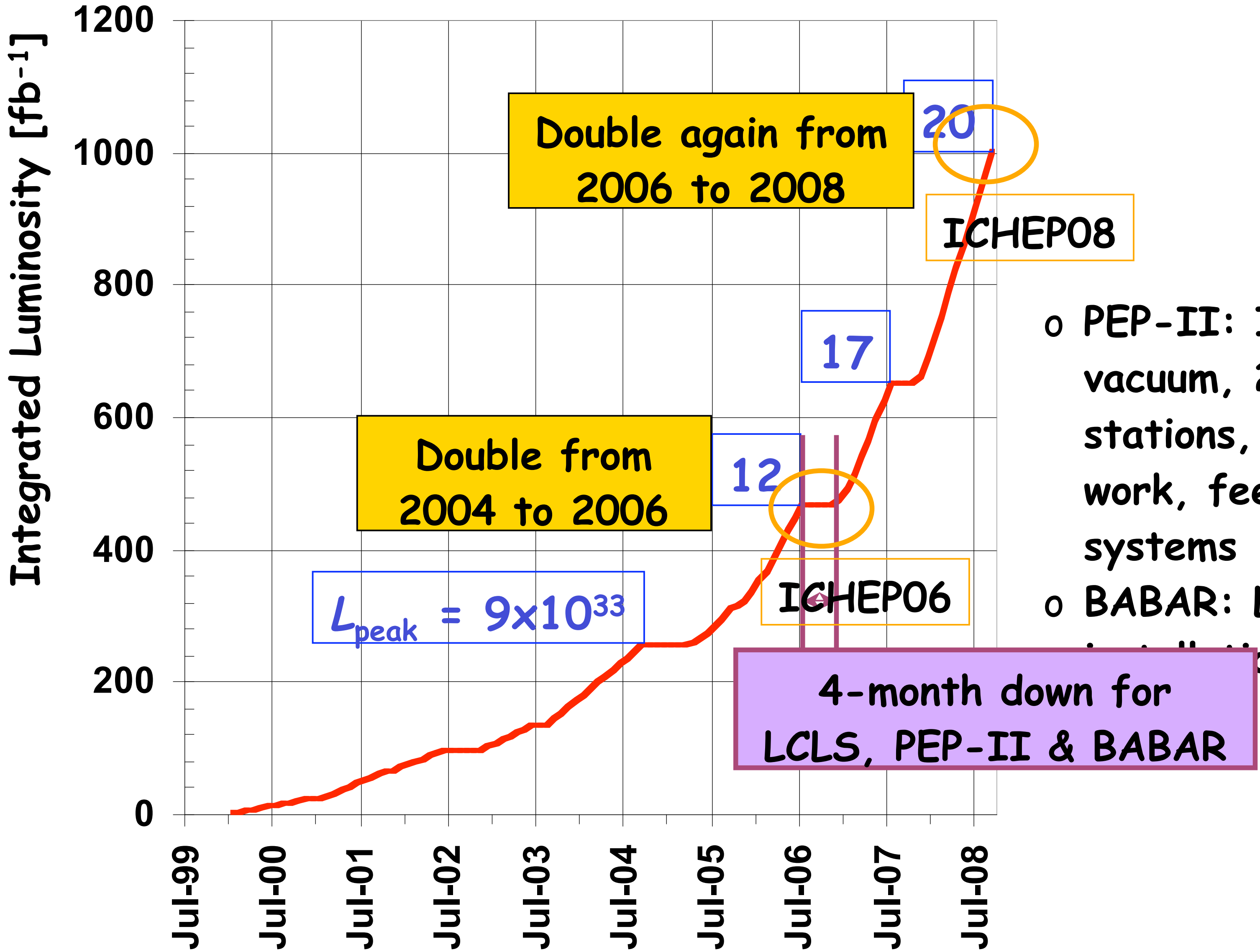
Luminosity expectations:

2004=240 fb^{-1}
2008=1.0 ab^{-1}

Projections are statistical errors only; but systematic errors at few percent level

Individual modes reach 4-5 sigma level

Projected Data Sample Growth



- PEP-II: IR-2 vacuum, 2xrf stations, BPM work, feedback systems
- BABAR: LST installation

Expect each experiment to accumulate 1000 fb^{-1} by 2008

Summary & Prospects

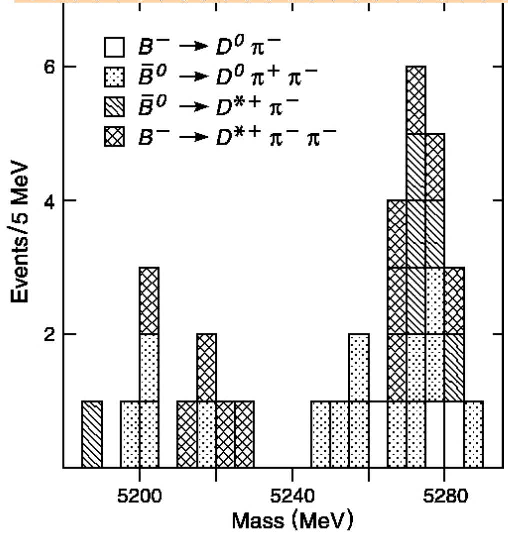
- CP Violation in B decays systematically studied at BaBar & Belle. A Comprehensive profile emerging
- Standard Model picture (3 generation CKM matrix) of CP Violation consistent will all observations
  - SM CPV too weak to explain cosmic CPV
- New Physics (in loops) can still contribute to observed CPV but is unlikely to be the dominant source
- CPV violation in the (rare) Penguin Decays appears lower than SM predictions ($> 2.4\sigma$)
  - more data needed to reveal true nature of discrepancy
  - B-factories expect to triple data sets by 2008
- Super B-factories after then…

Backup Slides

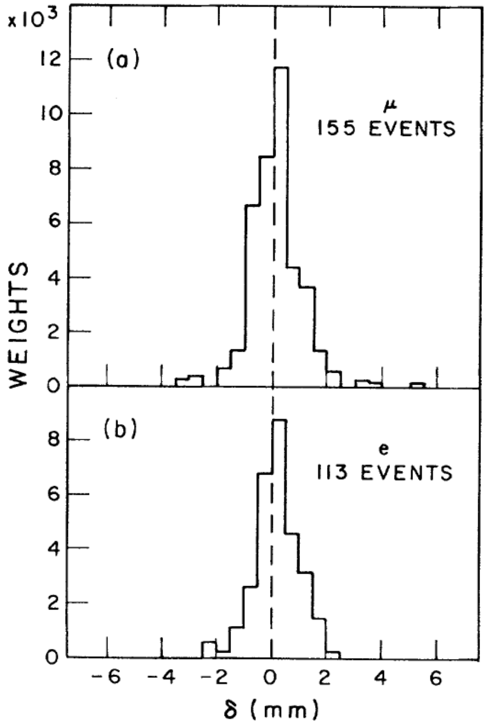
B Meson: Special Laboratory for CPV Investigations

- Large Mass : M_B=5.279 GeV/c^2
- "Large" lifetime:
- Large mixing
- Large rate for penguin decays

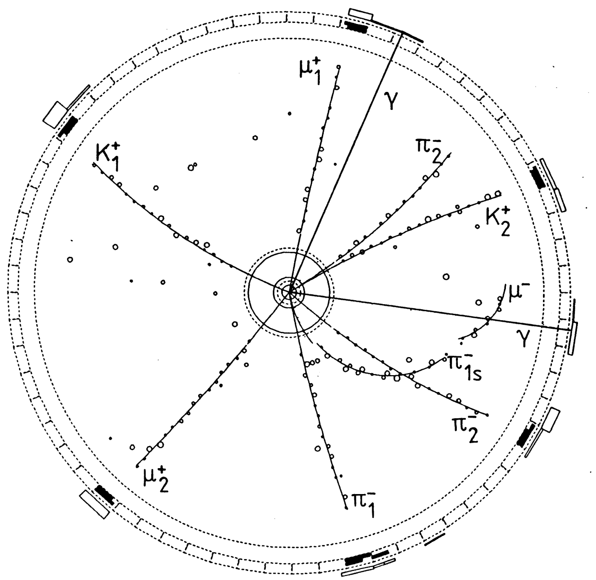
Exclusive *B* decays



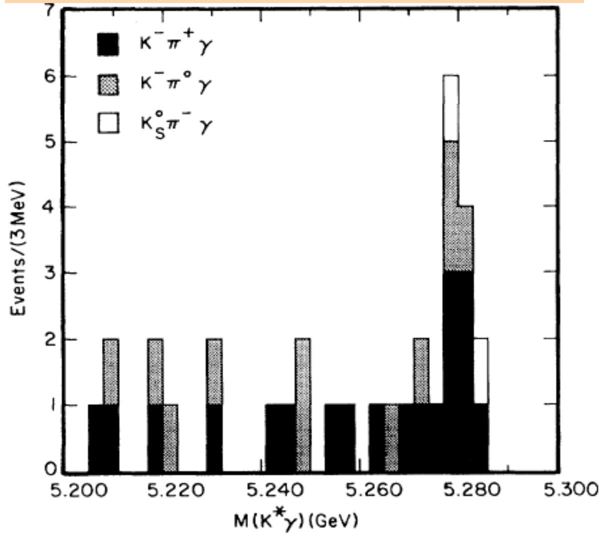
Long *B* lifetime



B^0 B^0 oscillations

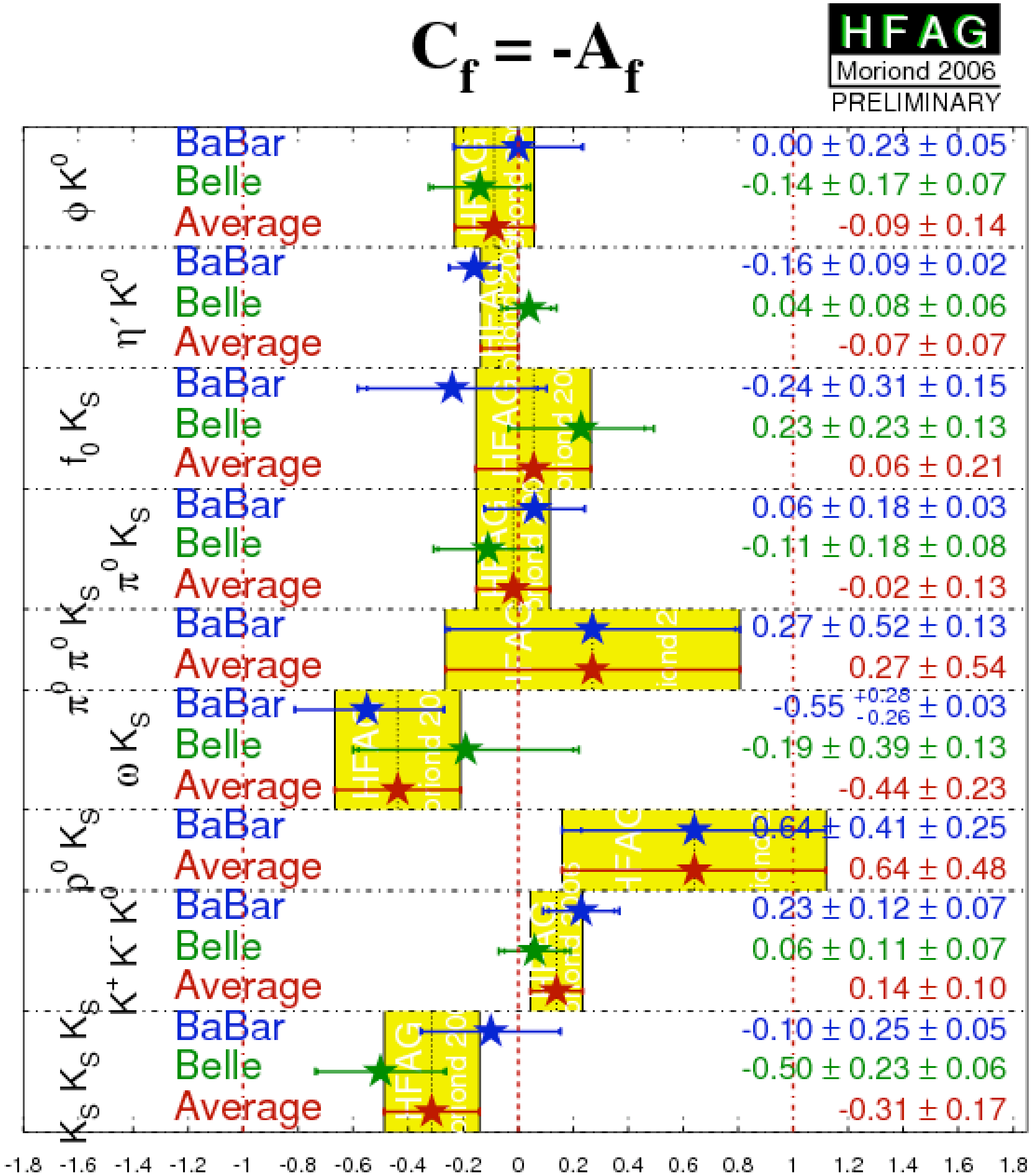


Observation of *B*→*K **



Direct CPV in s-Penguins ?

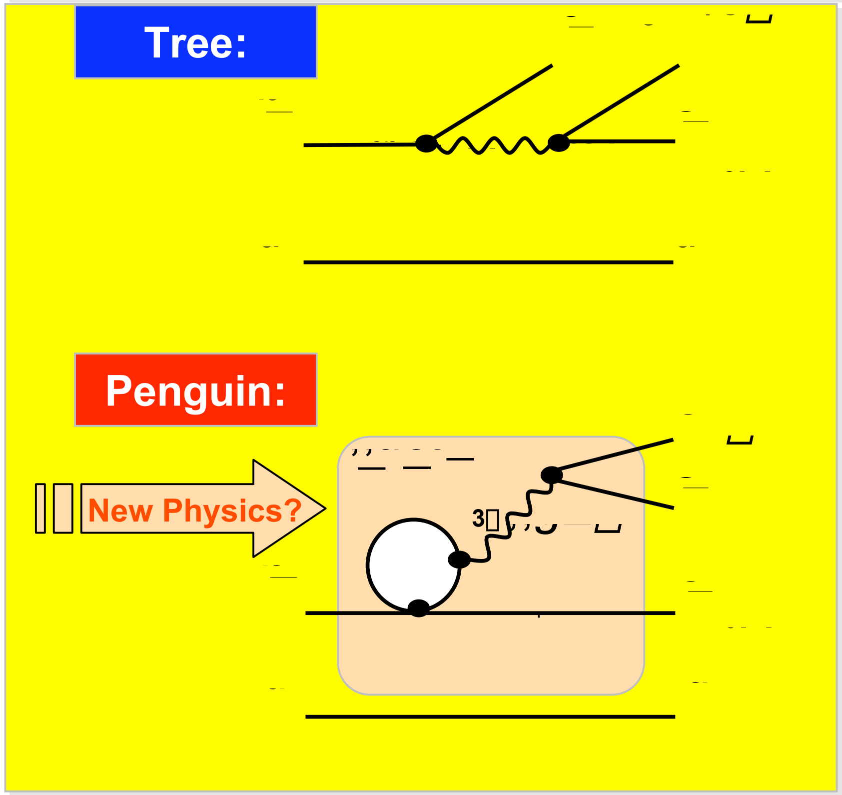
$$C_f = -A_f$$



No sign of direct CPV !

Compare sin2 *with* “sin2” from CPV in Penguin decays of B^0

Both decays dominated by single weak phase

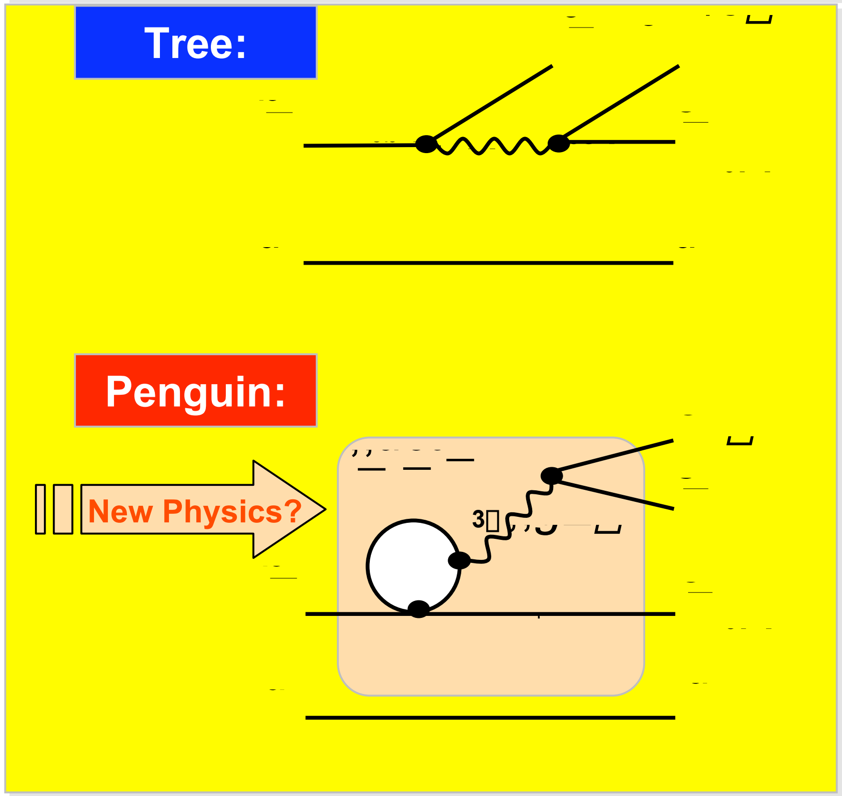


?

Must be if one amplitude dominates

Compare sin2□ *with* "sin2□" from CPV in Penguin decays of B^0

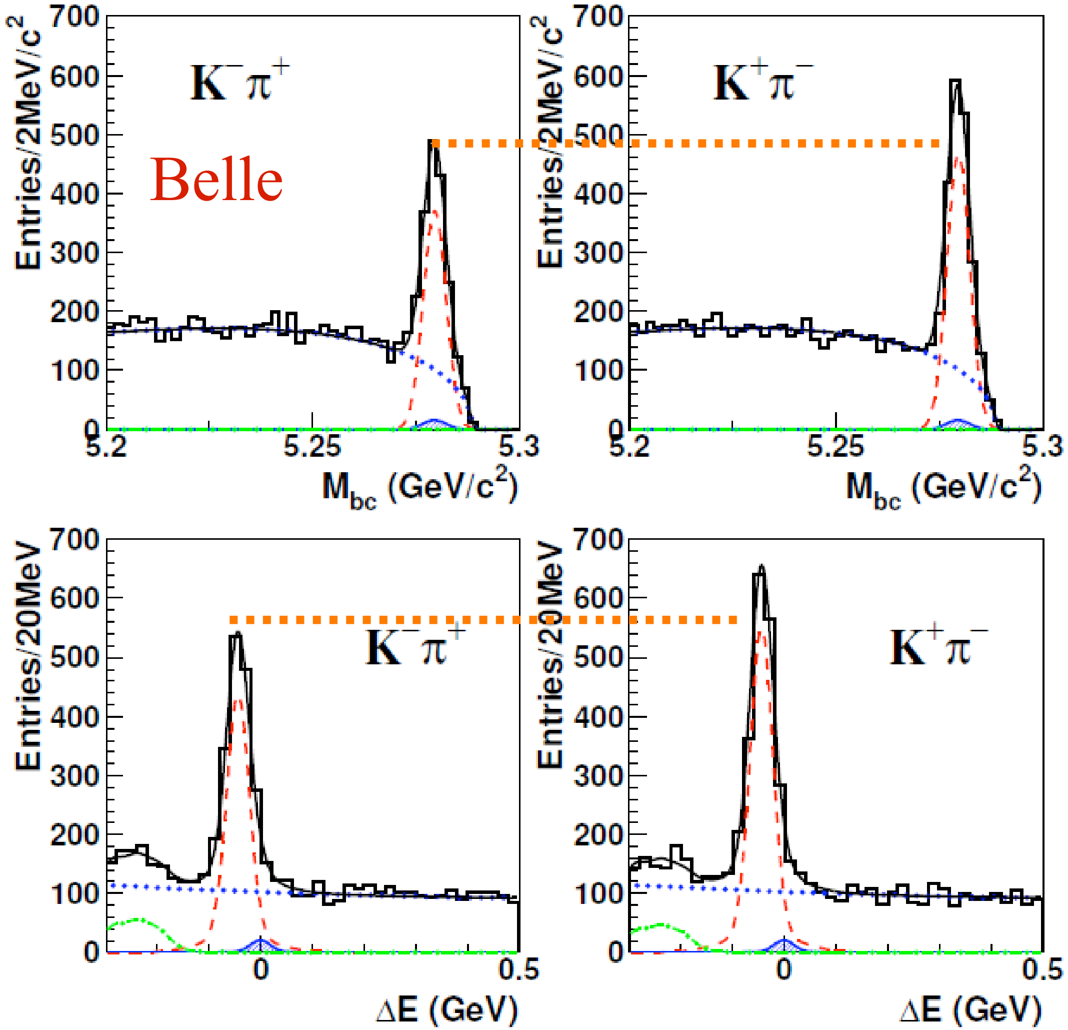
Both decays dominated by single weak phase



?

Must be if one amplitude dominates

Direct CP Violation in $B^0 \to K\pi$: Belle (386M BB)



Combined significance >> 6σ

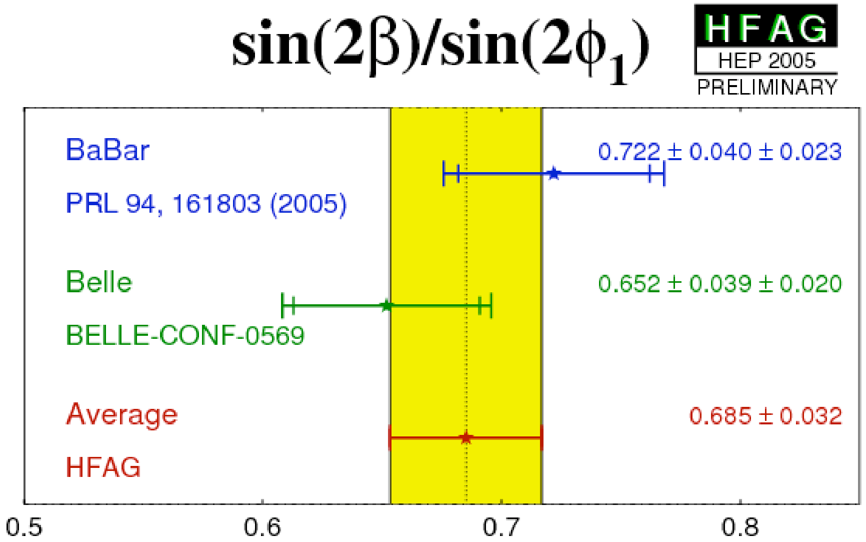
Rules out Superweak model

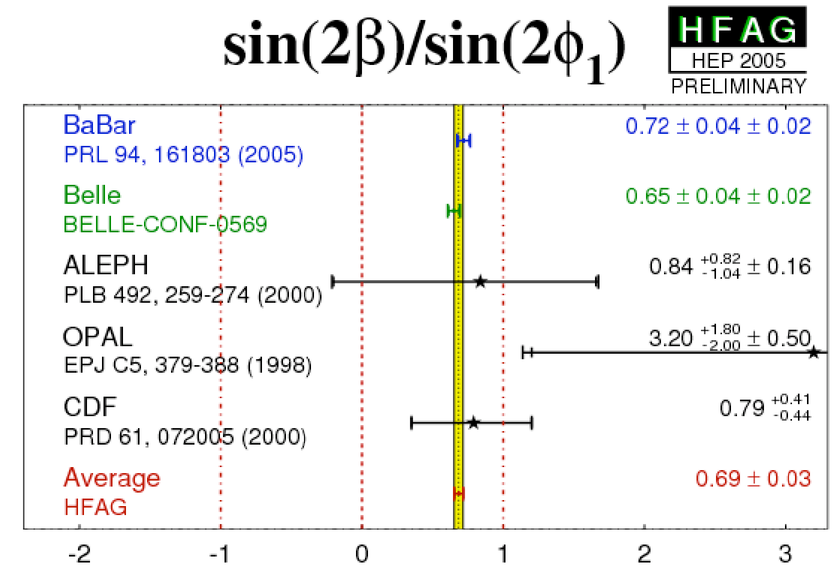
Establishes CPV not just due to phase of B Mixing

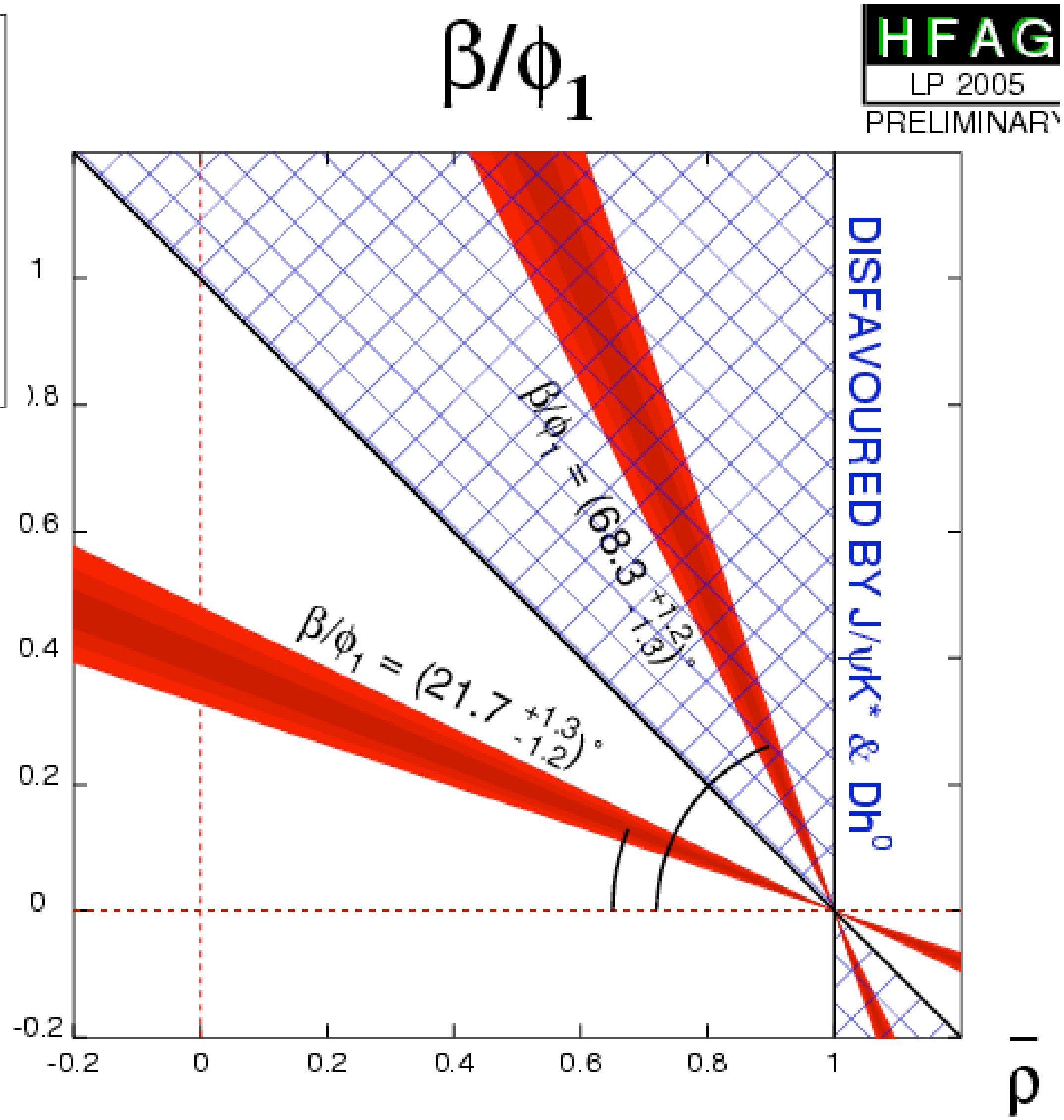
But hadronic uncertainties preclude determination of CKM angle [illegible]

$\to$ challenge to theory

$$A_{CP}(K^+\pi^-) = -0.113 \pm 0.022 \pm 0.008$$

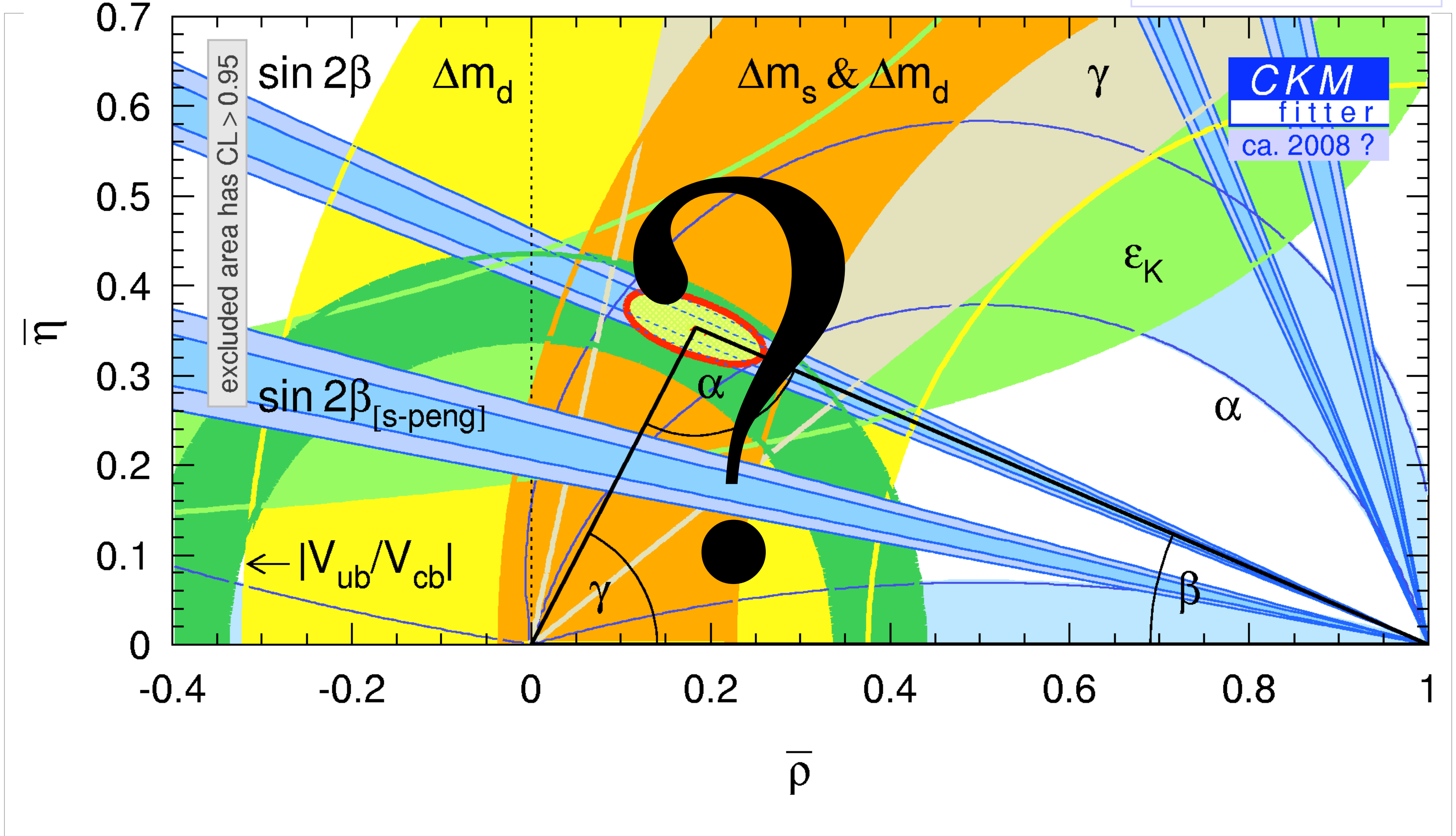

sin(2β)/sin(2φ1)
HFAG
HEP 2005
PRELIMINARY
BaBar
PRL 94, 161803 (2005)
0.722 ± 0.040 ± 0.023
Belle
BELLE-CONF-0569
0.652 ± 0.039 ± 0.020
Average
HFAG
0.685 ± 0.032
0.5
0.6
0.7
0.8


sin(2β)/sin(2φ1)
HFAG
HEP 2005
PRELIMINARY
BaBar
PRL 94, 161803 (2005)
0.72 ± 0.04 ± 0.02
Belle
BELLE-CONF-0569
0.65 ± 0.04 ± 0.02
ALEPH
PLB 492, 259-274 (2000)
0.84 +0.82 -1.04 ± 0.16
OPAL
EPJ C5, 379-388 (1998)
3.20 +1.80 -2.00 ± 0.50
CDF
PRD 61, 072005 (2000)
0.79 +0.41 -0.44
Average
HFAG
0.69 ± 0.03
-2
-1
0
1
2
3


β/φ1
HFAG
LP 2005
PRELIMINARY
DISFAVOURED BY J/ψK* & Dh0
β/φ1 = (68.3 +1.2 -1.3)°
β/φ1 = (21.7 +1.3 -1.2)°
1
0.8
0.6
0.4
0.2
0
-0.2
-0.2
0
0.2
0.4
0.6
0.8
1
ρ̄

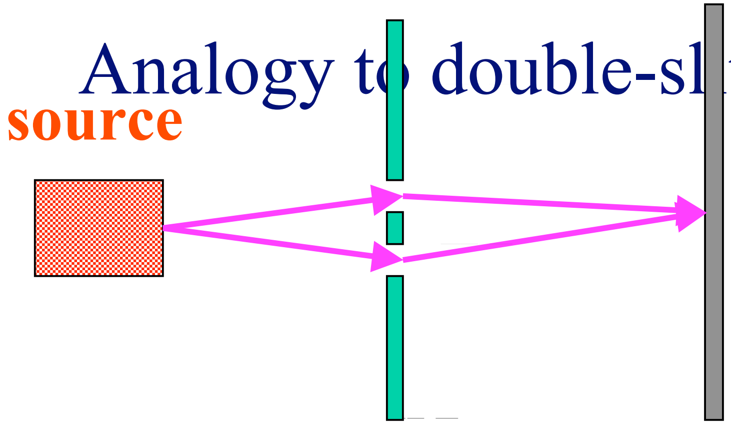
An Optimist's Global CKM fit ? : 2008 (1 fb^{-1} each)

95% contours

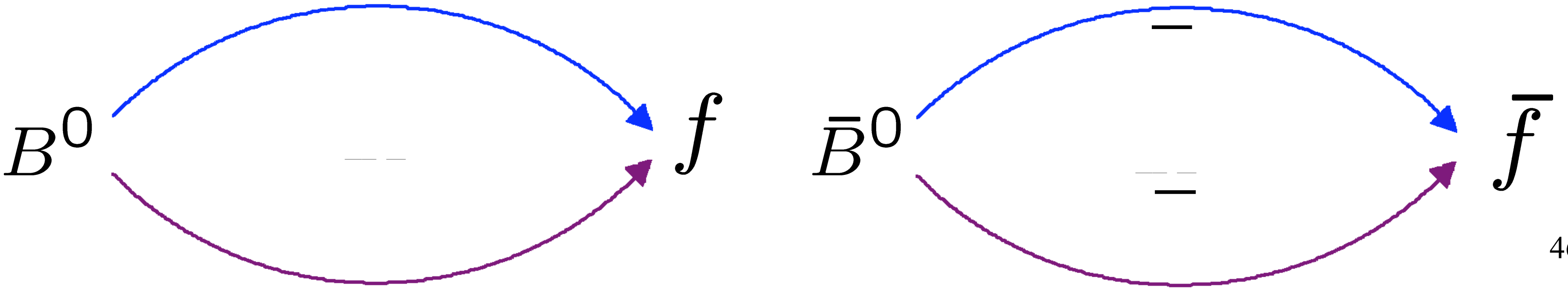


CP Violation

- CP violation can be observed by comparing decay rates of particles and antiparticles
- The difference in decay rates arises from a different interference term for the matter vs. antimatter process. Analogy to double-slit experiment:



Classical double-slit experiment:
Relative phase variation due to different path lengths: interference pattern in space



CP Violation Is a Quantum Phenomenon

- CPV is due to Quantum interference between > two amplitudes
- Phases of QM amplitudes is the key
- Need to consider two types of phases
  - *CP-conserving phases*: don’t change sign under CP (**Sometimes called *strong phases* since they can arise from strong, final-state interactions**)
  - *CP-violating phases*: these do change sign under CP transformation

(originate in the Weak interaction

Definition of CP Asymmetry

To extract the CP-violating phase from an observed CP asymmetry, we need to know the value of the CP-conserving phase difference

***B* system: extraordinary laboratory for quantum interference experiments: many final states, multiple "paths"→ Lots of channels for CP Violation**

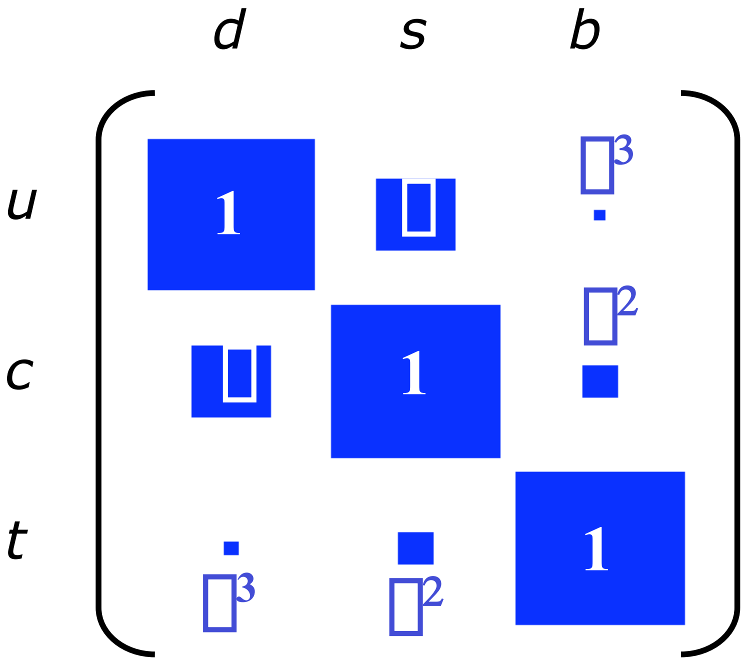
The CKM matrix & its mysterious pattern

(Wolfenstein parametrization)

- The SM offers no explanation for this numerical pattern.
- But SM framework is highly predictive:
  - ❑ Unitarity triangle: (Col 1)(Col 3)* =0 etc.
  - ❑ Only 4 independent parameters: A, □, □, □
  - ❑ **One independent *CP*-violating phase parameter**

Impressionist's View of The CKM matrix

Magnitudes of CKM elements

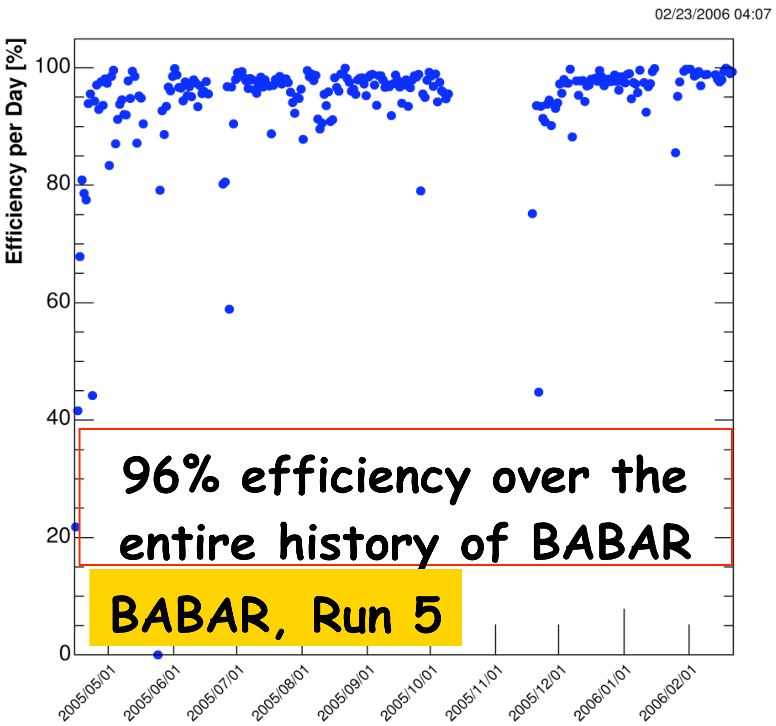


Largest phases in the Wolfenstein parametrization

Note: all terms in the inner product between columns 1 and 3 are of order $\square^3$. This produces a unitarity triangle of roughly equal sides.

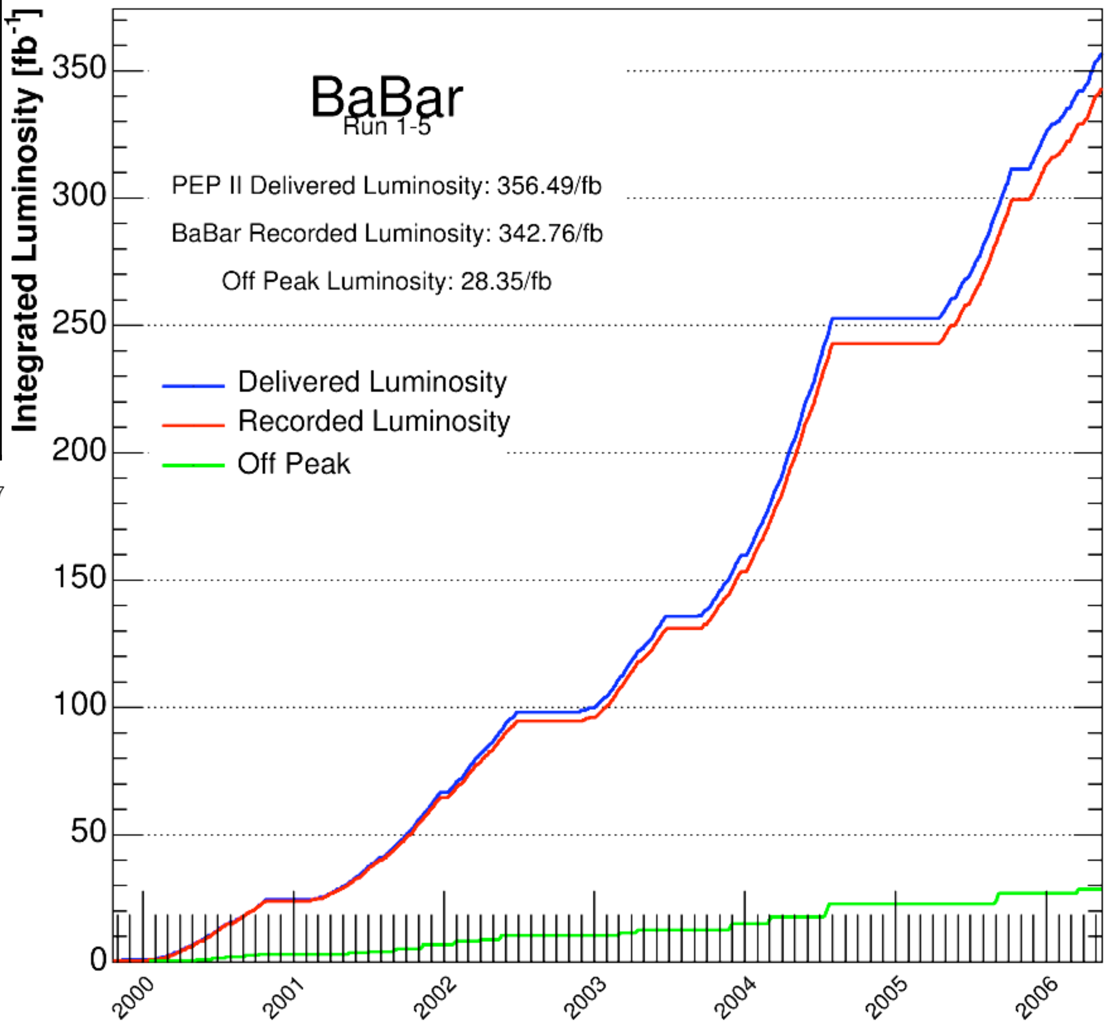
Machine Performance Exceeds Design (x3)

Peak luminosity ($cm^{-2}s^{-1}$)	1.0025×10^{34}
Best shift	247.2 pb^{-1}
Best day	710.5 pb^{-1}
Best week	4.464 fb^{-1}
Best month	17.036 fb^{-1}
BABAR logged	343 fb^{-1}



96% efficiency over the entire history of BABAR

BABAR, Run 5

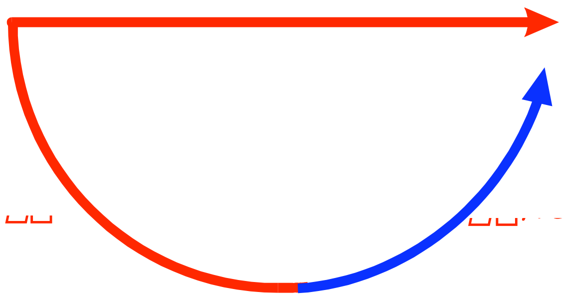


KEK-B operation even more spectacular !

CP violation in the B system

- CPV through interference between mixing and decay amplitudes

Directly related to CKM angles for single decay amplitude

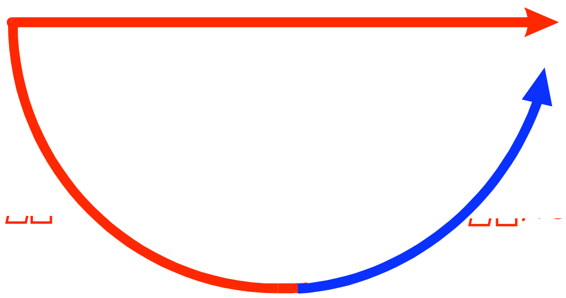


Time-dependent asymmetry

CP violation in the B system

- CPV through interference between mixing and decay amplitudes

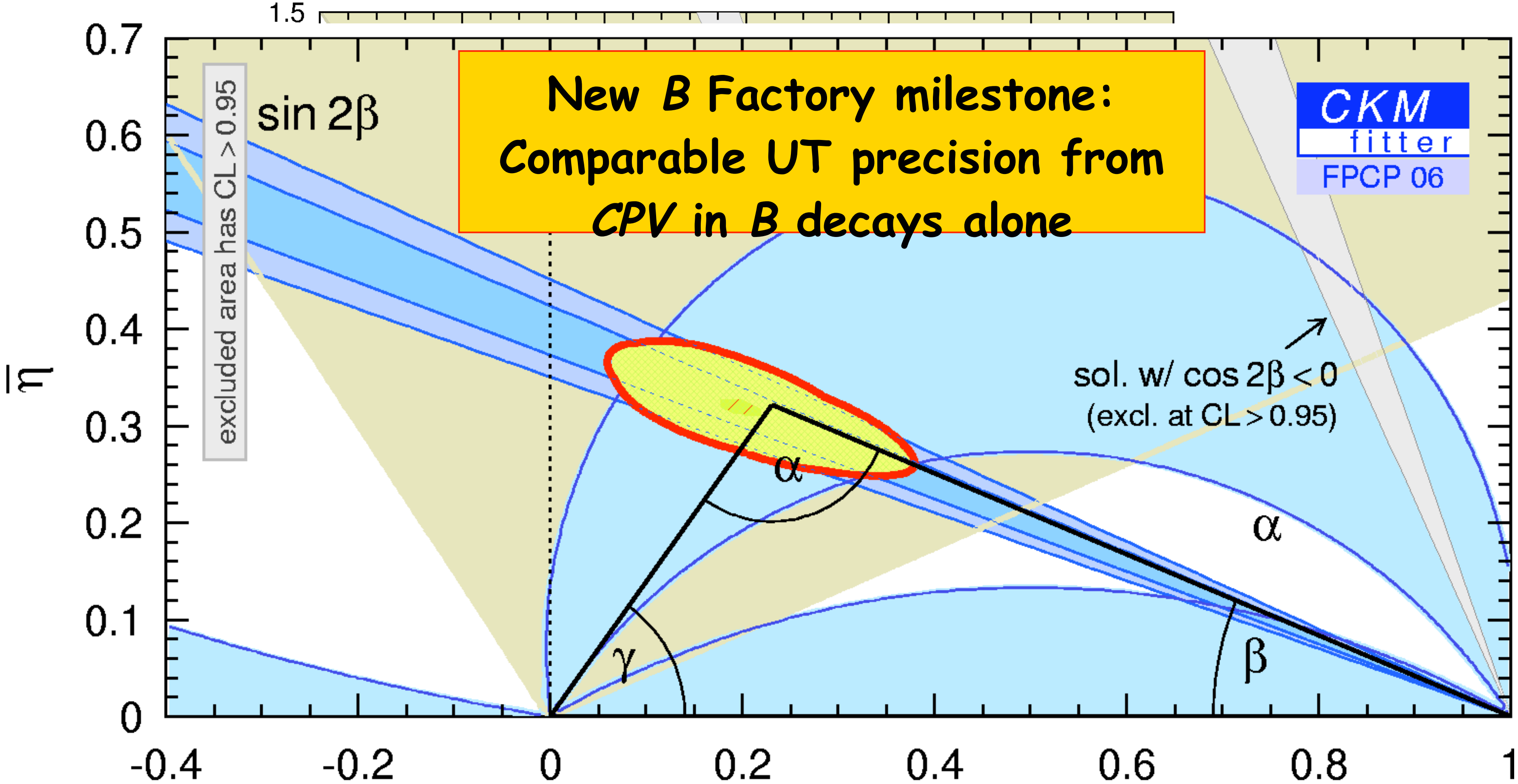
Directly related to CKM angles for single decay amplitude



Time-dependent asymmetry

For simple case shown with single decay mechanism

The Unitarity Triangle Defined By CPV Measurements

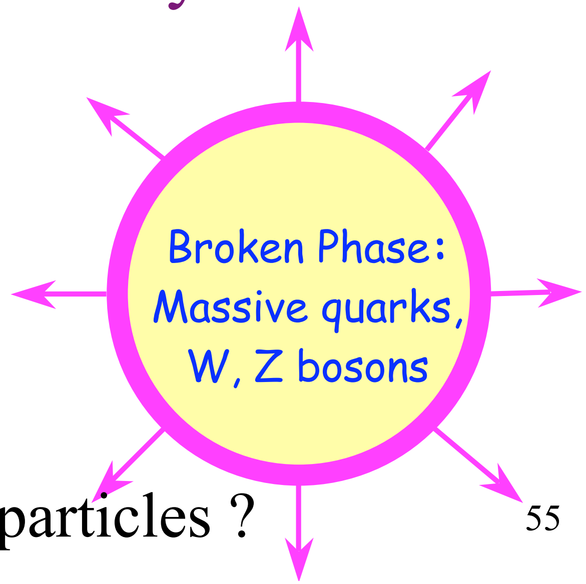


A fundamental cosmological question

- The universe is now matter dominated: where has all the anti-matter gone?
  - Anti-proton/proton ratio ~10^{-4} in cosmic rays; no evidence for annihilation photons from intergalactic clouds
- Cosmological generation of asymmetry: Sakharov conditions (1967)
  - Baryon number violation, e.g., proton decay
  - Thermal non-equilibrium
  - Violation of CP discrete symmetry

Transition to broken electroweak symmetry provides these conditions

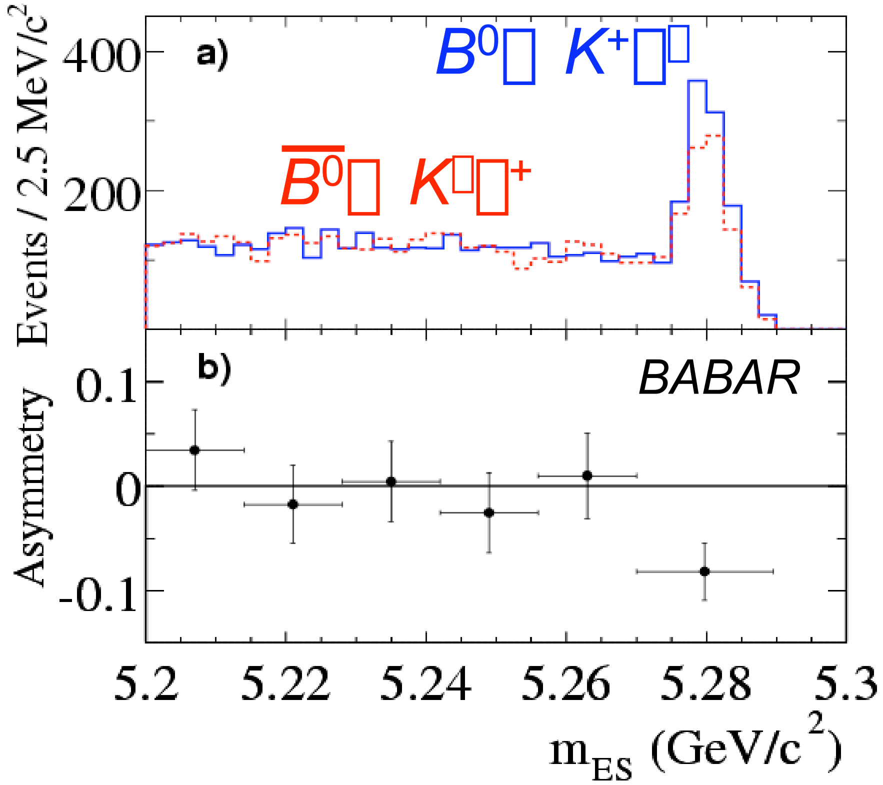
Unbroken Phase:
Massless quarks



Connection between CPV in cosmos & subatomic particles ?

Direct CP Violation in $B^0 \to K\pi$: BaBar

$$A_{K^-\pi^+} \equiv \frac{\Gamma(\overline{B} \to K^-\pi^+) - \Gamma(B \to K^+\pi^-)}{\Gamma(\overline{B} \to K^-\pi^+) + \Gamma(B \to K^+\pi^-)}$$

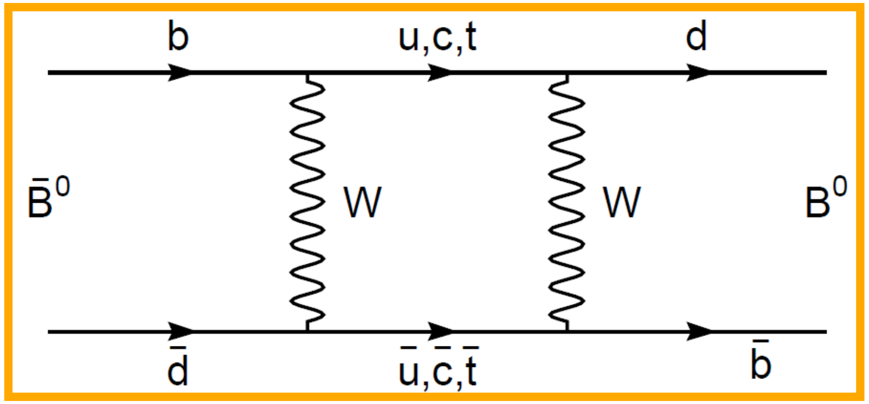


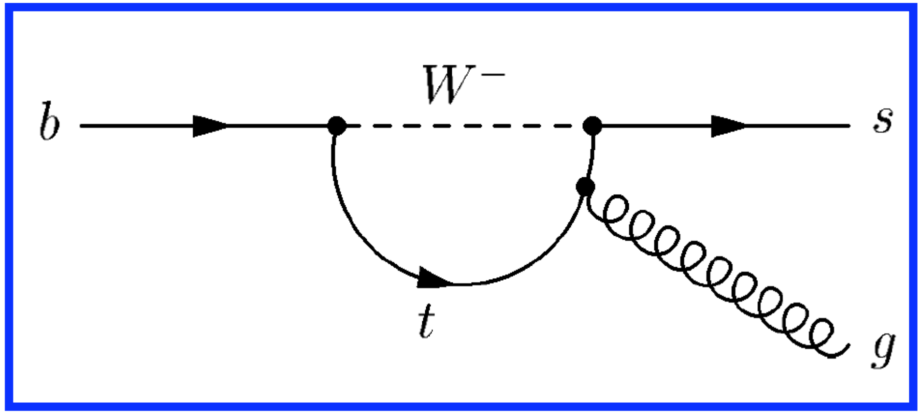
4.2σ effect (syst. included)

similar results from Belle

CP Violation & Sensitivity To New Physics

- New physics at the electroweak scale generically introduces many new large flavor-violating or CP-violating couplings to quarks
- Quantum loop diagrams can attract couplings to heavy new particles of BSM physics





- Theory robust : capable of discriminating between SM and New Physics in special cases