The Unitarity Triangle

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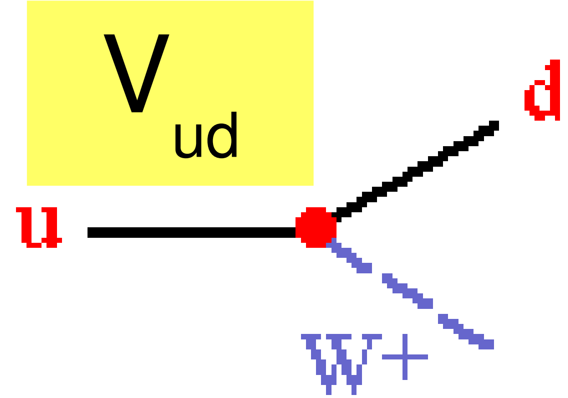
University of Warwick

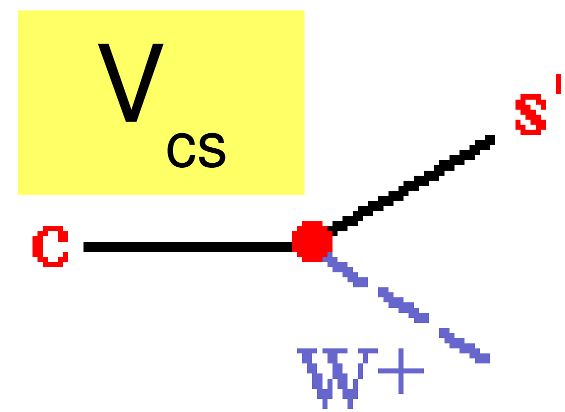
Seminar in Universität Gießen
17th January 2008

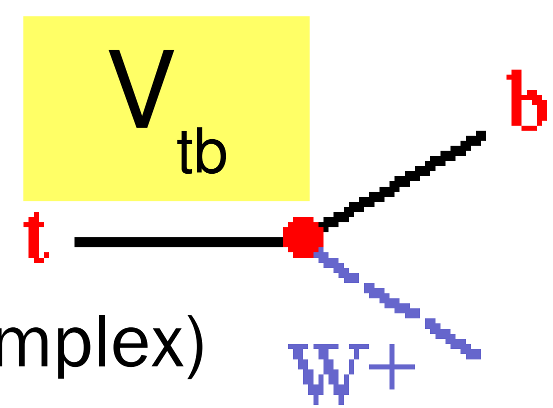
Partially based on “A Triangle That Matters”, Physics World, April 2007

CKM Matrix / KM mechanism

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$







- 3x3 matrix of complex numbers
  - $\Rightarrow$ 18 parameters
- Unitary
  - $\Rightarrow$ 9 parameters
- Quark fields absorb unobservable phases
  - $\Rightarrow$ 4 parameters
  - $\Rightarrow$ 3 mixing angles and 1 phase (V_{CKM} complex)

CP-Violation in the Renormalizable Theory of Weak Interaction

Progress of Theoretical Physics, Vol. 49 No. 2 pp. 652-657

Makoto Kobayashi and Toshihide Maskawa
Department of Physics, Kyoto University, Kyoto

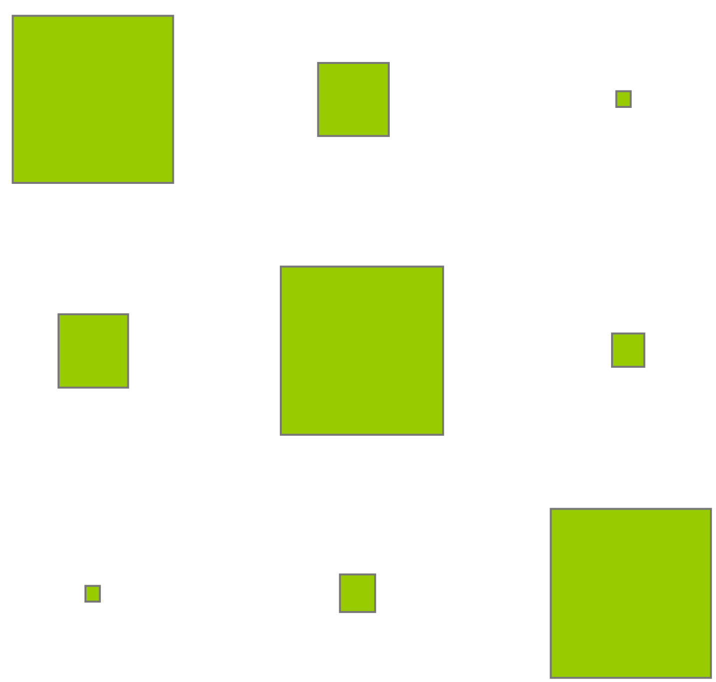
(Received September 1, 1972)

In a framework of the renormalizable theory of weak interaction, problems of CP-violation are studied. It is concluded that no realistic models of CP-violation exist in the quartet scheme without introducing any other new fields. Some possible models of CP-violation are also discussed.

Hierarchy in quark mixing

Wolfenstein parameterization – expansion in $\lambda = \sin\theta_C \sim 0.22$

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}\left(\lambda^4\right)$$



Unitarity

$$V^\dagger V = 1$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \qquad V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

$$|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2 = 1 \qquad V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

$$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1 \qquad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

$$|V_{ud}|^2 + |V_{cd}|^2 + |V_{td}|^2 = 1 \qquad V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

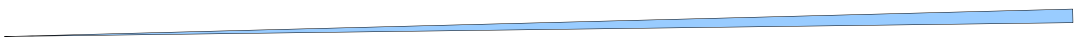
$$|V_{us}|^2 + |V_{cs}|^2 + |V_{ts}|^2 = 1 \qquad V_{ud}V_{td}^* + V_{us}V_{ts}^* + V_{ub}V_{tb}^* = 0$$

$$|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1 \qquad V_{cd}V_{td}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$$

Unitarity triangles

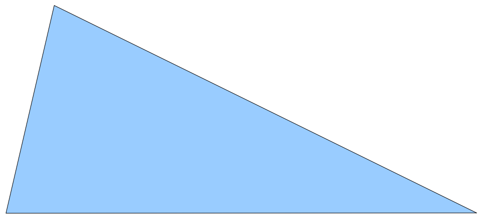
$$V_{ud}V_{us}^* + V_{cd}V_{cs}^* + V_{td}V_{ts}^* = 0$$

λ λ λ^5



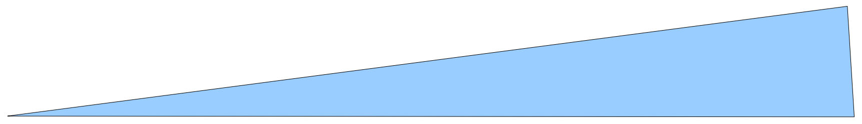
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

λ^3 λ^3 λ^3



$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

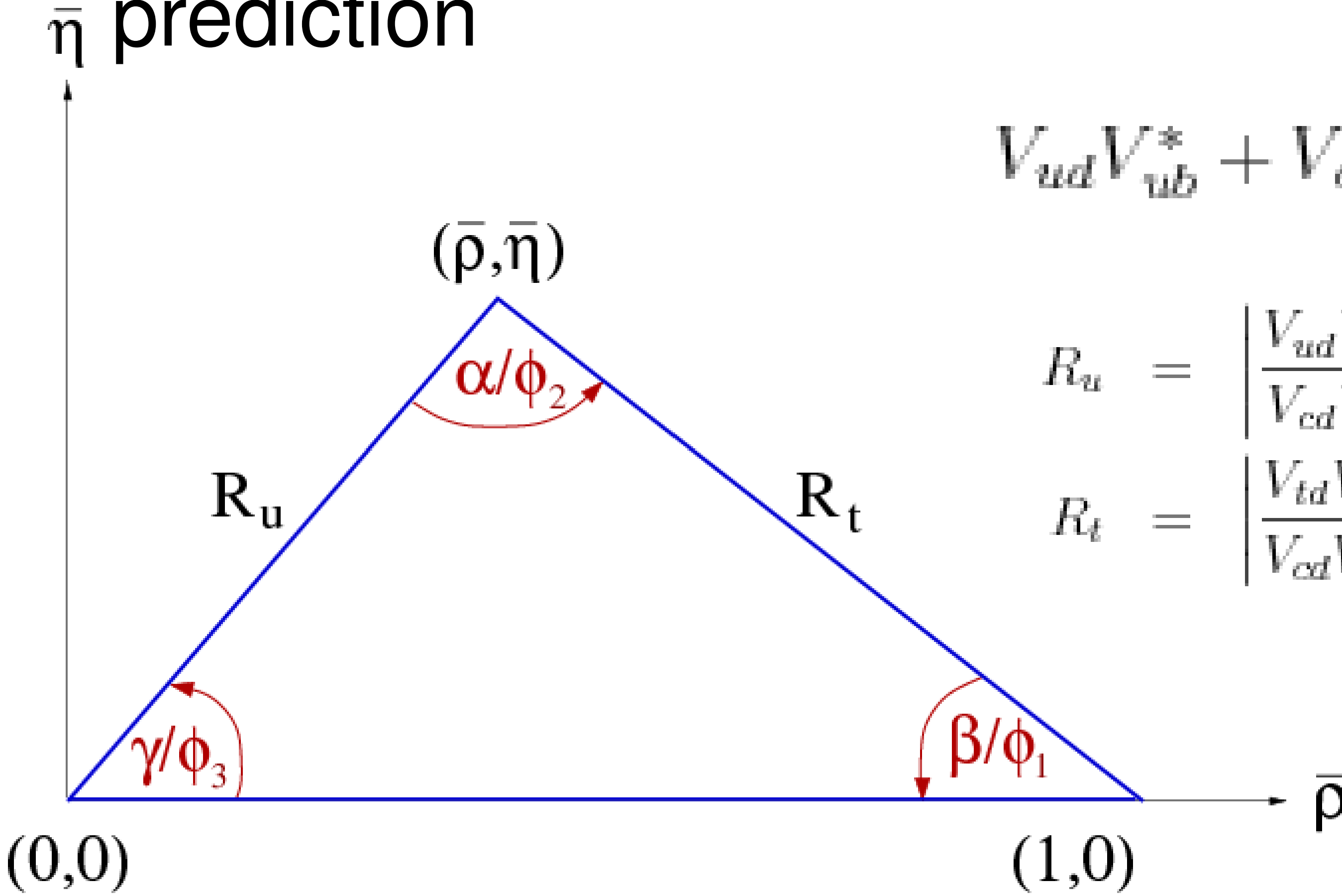
λ^4 λ^2 λ^2



DISCLAIMER : THESE ARE NOT TO SCALE!

The Unitarity Triangle

- Convenient method to illustrate (dis-)agreement of observables with CKM prediction



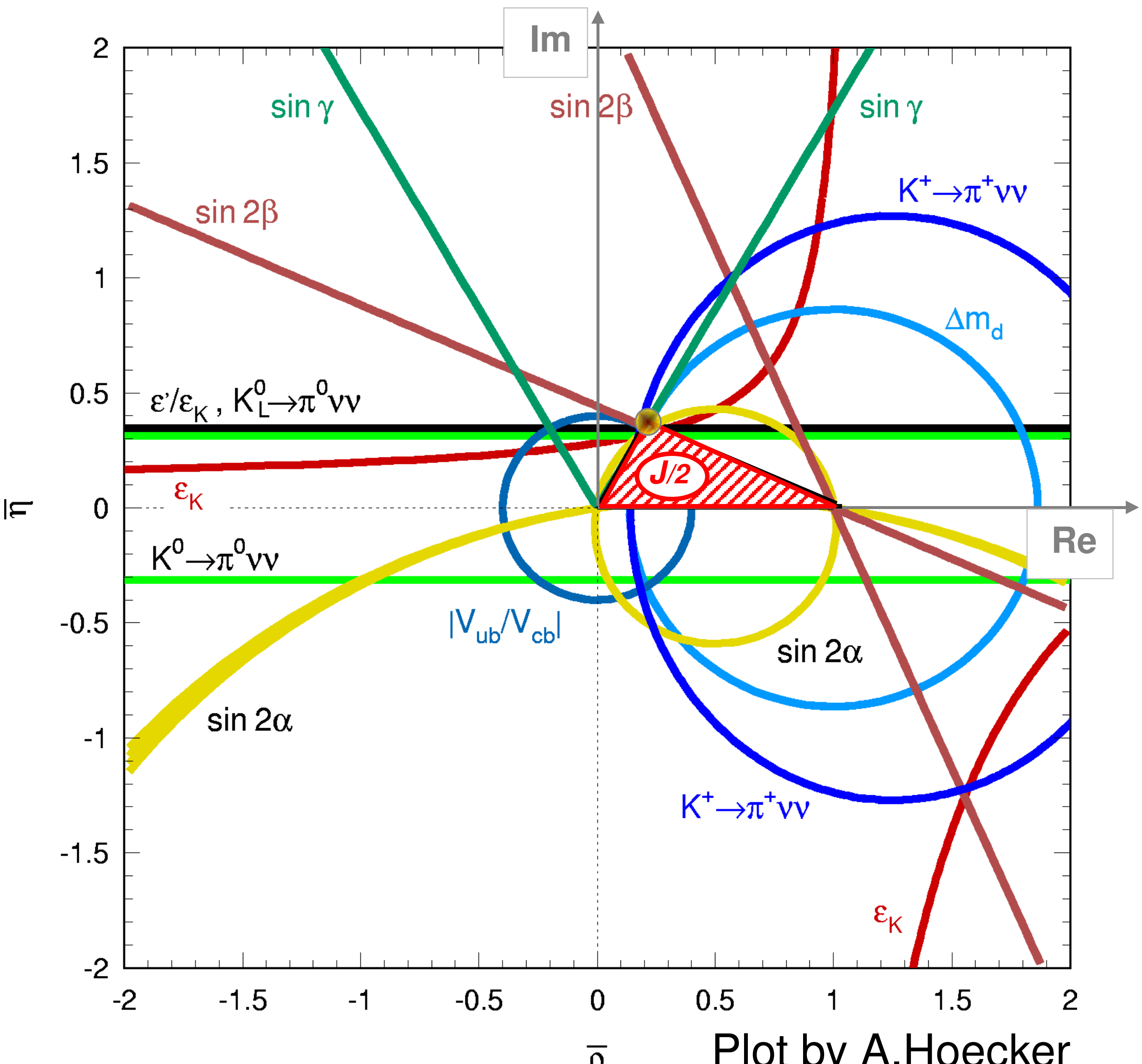
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0,$$

$$R_u = \left|\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right| = \sqrt{\bar{\rho}^2 + \bar{\eta}^2},$$

$$R_t = \left|\frac{V_{td}V_{tb}^*}{V_{cd}V_{cb}^*}\right| = \sqrt{(1-\bar{\rho})^2 + \bar{\eta}^2}.$$

Predictive nature of KM mechanism

All measurements must agree



Plot by A.Hoecker

A brief history of B physics

- 1977 – discovery of the Y
- 1980 – discovery of the Y(4S)
- 1981 – discovery of B mesons
  - [PRL 46, 84 (1981); PRL 46, 88 (1981)]
- 1983 – lifetime of the B meson measured
  - [PRL 51, 1022 (1983); PRL 51, 1316 (1983)]
- 1987 – observation of B0 mixing
  - [PLB 192, 245 (1987)]

Discovery of bottomonium (Υ)
Fermilab National Accelerator Laboratory
$p + \{Cu,Pt\} \rightarrow \mu^+\mu^- X$

Observation of a Dimuon Resonance at 9.5 GeV in 400-GeV Proton-Nucleus Collisions

S. W. Herb, D. C. Hom, L. M. Lederman, J. C. Sens,[a] H. D. Snyder, and J. K. Yoh
Columbia University, New York, New York 10027

and

J. A. Appel, B. C. Brown, C. N. Brown, W. R. Innes, K. Ueno, and T. Yamanouchi
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974

(Received 1 July 1977)

Accepted without review at the request of Edwin L. Goldwasser under policy announced 26 April 1976

Dimuon production is studied in 400-GeV proton-nucleus collisions. A strong enhancement is observed at 9.5 GeV mass in a sample of 9000 dimuon events with a mass $m_{\mu^+\mu^-} > 5$ GeV.

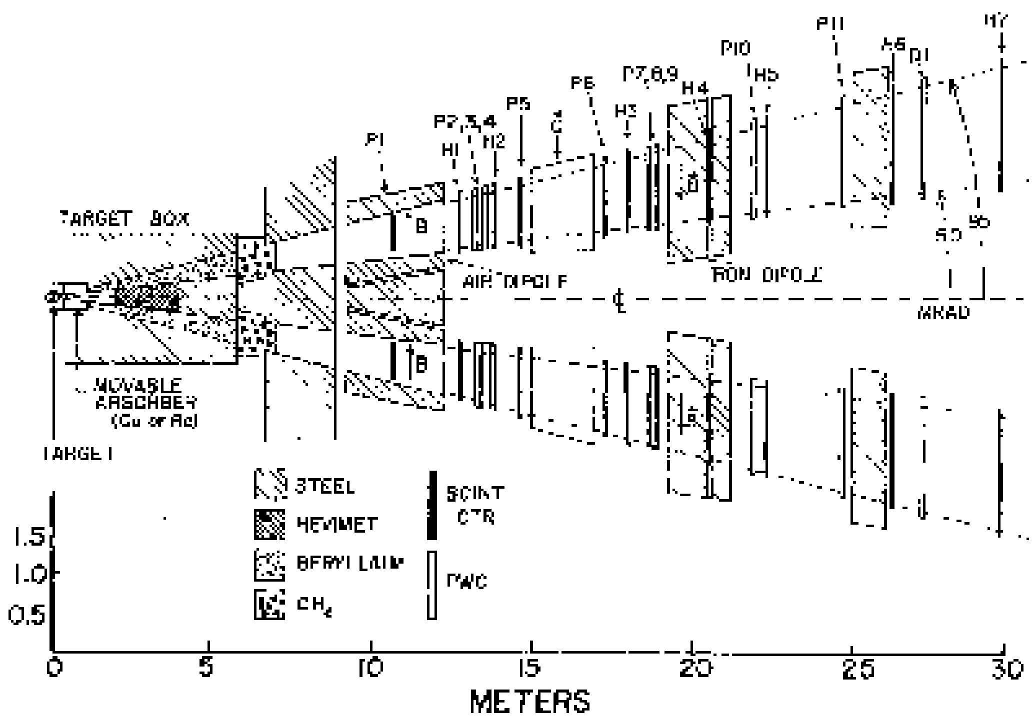


FIG. 1. Plan view of the apparatus. Each spectrometer arm includes eleven PWC's P1–P11, seven scintillation counter hodoscopes H1–H7, a drift chamber D1 and a gas-filled threshold Čerenkov counter Č. Each arm is up/down symmetric and hence accepts both positive and negative muons.

Discovery of bottomonium (Υ)

Fermilab National Accelerator Laboratory

$p + \{Cu,Pt\} \rightarrow \mu^+\mu^- X$

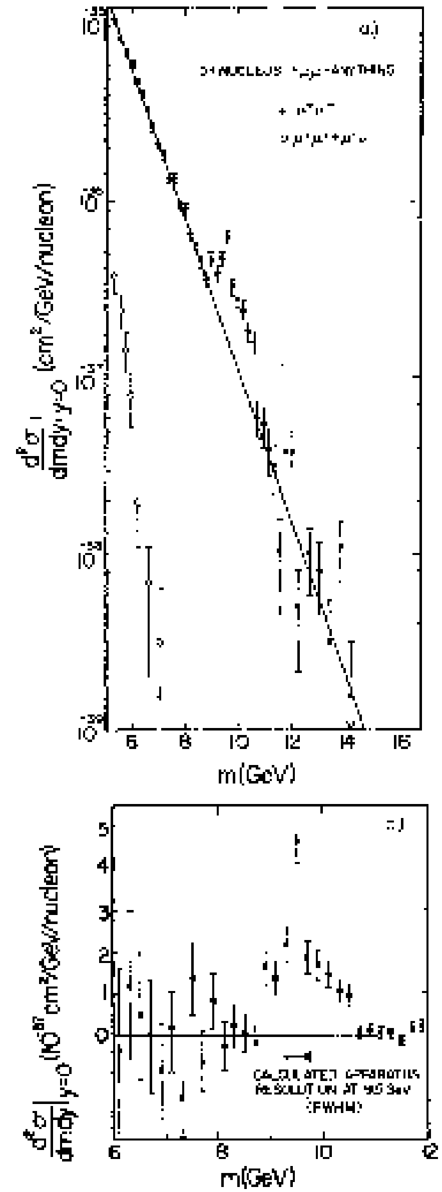


FIG. 3. (a) Measured dimuon production cross sections as a function of the invariant mass of the muon pair. The solid line is the continuum fit outlined in the text. The equal-sign–dimuon cross section is also shown. (b) The same cross sections as in (a) with the smooth exponential continuum fit subtracted in order to reveal the 8–10-GeV region in more detail.

Discovery of Υ(4S)
Cornell University
e^+e^- collisions

Observation of a Fourth Upsilon State in e^+e^- Annihilations

D. Andrews, K. Berkelman, R. Cabenda, D. G. Cassel, J. W. DeWire, R. Ehrlich, T. Ferguson, T. Gentile, M. G. D. Gilchriese, B. Gittelman, D. L. Hartill, D. Herrup, M. Herzlinger, D. L. Kreinick, N. B. Mistry, E. Nordberg, R. Perchonok, R. Plunkett, K. A. Shinsky, R. H. Siemann, A. Silverman, P. C. Stein, S. Stone, R. Talman, H. G. Thonemann, and D. Weber
Cornell University, Ithaca, New York 14853

and

C. Bebek, J. Haggerty, J. M. Izen, W. A. Loomis, F. M. Pipkin, J. Rohlf, W. Tanenbaum, and Richard Wilson
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and

A. J. Sadoff
Ithaca College, Ithaca, New York 14850

and

D. L. Bridges
Le Moyne College, Syracuse, New York 13214, and Syracuse University, Syracuse, New York 13210

and

K. Chadwick, P. Ganci, H. Kagan, R. Kass, F. Lobkowicz, A. Melissinos, S. L. Olsen, R. Poling, C. Rosenfeld, G. Rucinski, E. H. Thorndike, and G. Warren
University of Rochester, Rochester, New York 14627

and

D. Bechis, J. J. Mueller, D. Potter, F. Sannes, P. Skubic, and R. Stone
Rutgers University, New Brunswick, New Jersey 08854

and

A. Brody, A. Chen, M. Goldberg, N. Horwitz, J. Kandaswamy, H. Kooy, P. Lariccia,[a] and G. C. Moneti
Syracuse University, Syracuse, New York 13210

and

M. S. Alam, S. E. Csorna, R. S. Panvini, and J. S. Poucher
Vanderbilt University, Nashville, Tennessee 37235
(Received 18 April 1980)

A fourth state in the upsilon energy region has been seen in e^+e^- collisions at the Cornell Electron Storage Ring. A resonance is observed with a mass 1112±5 MeV above the lowest upsilon state. The 9.6-MeV rms width is greater than the 4.6-MeV energy resolution of the e^+e^- beams. The observed characteristics of the new state make it a likely candidate for the 4S state of the $b\bar{b}$ system, lying above the threshold for the production of B mesons.

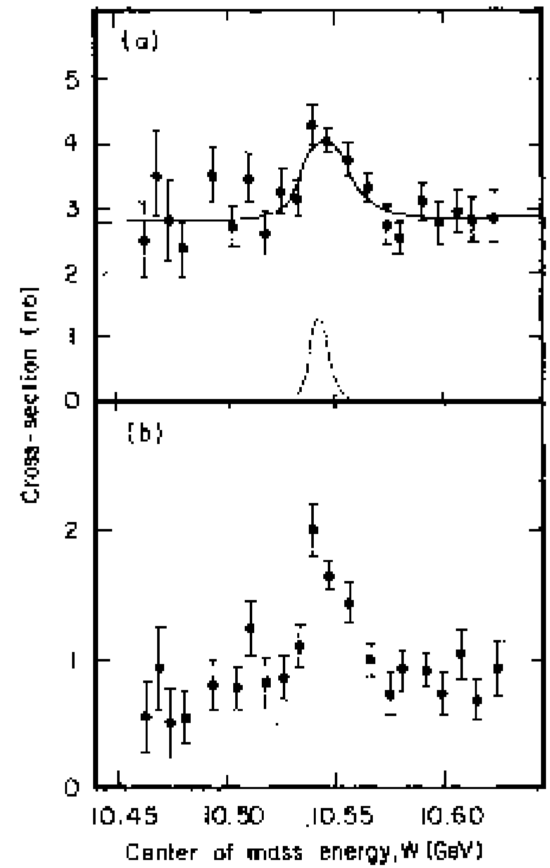


FIG. 1. Hadronic cross sections corrected for acceptance, as a function of center-of-mass energy, W. There is an additional overall systematic error of ±15%, arising mainly from the uncertainty in the detector acceptance. (a) Total hadronic cross section. The curve is a radiatively corrected Gaussian fit to the resonance above a smooth continuum varying as W^{-2}. The dashed curve indicates the beam energy resolution. (b) Partial cross section for events with $R_2 < 0.3$. (See text.)

First B meson lifetime measurement

Long lifetime – $|V_{cb}|$ is small ($|V_{ub}|$ too)

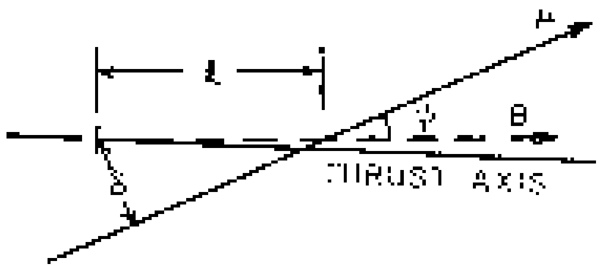


FIG. 1. Direction vectors and production and decay points relevant to heavy-hadron leptonic decay.

1023

$\tau(B) = (1.8 \pm 0.6 \pm 0.4)$ ps

PDG 2006 : (1.530 ± 0.009) ps

(previous best UL: $\tau(B) < 1.4$ ps)

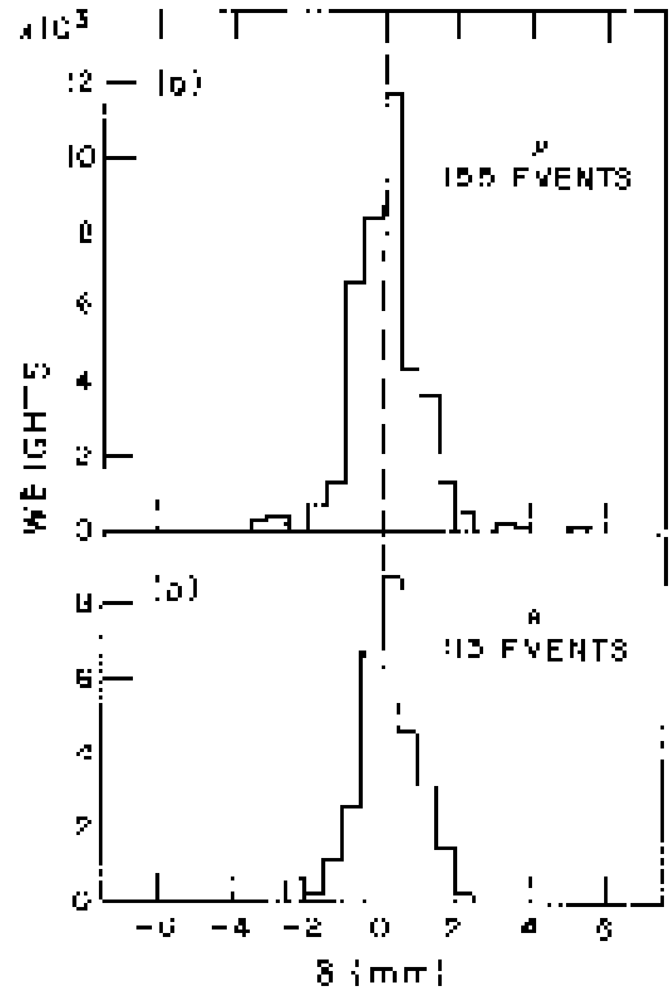
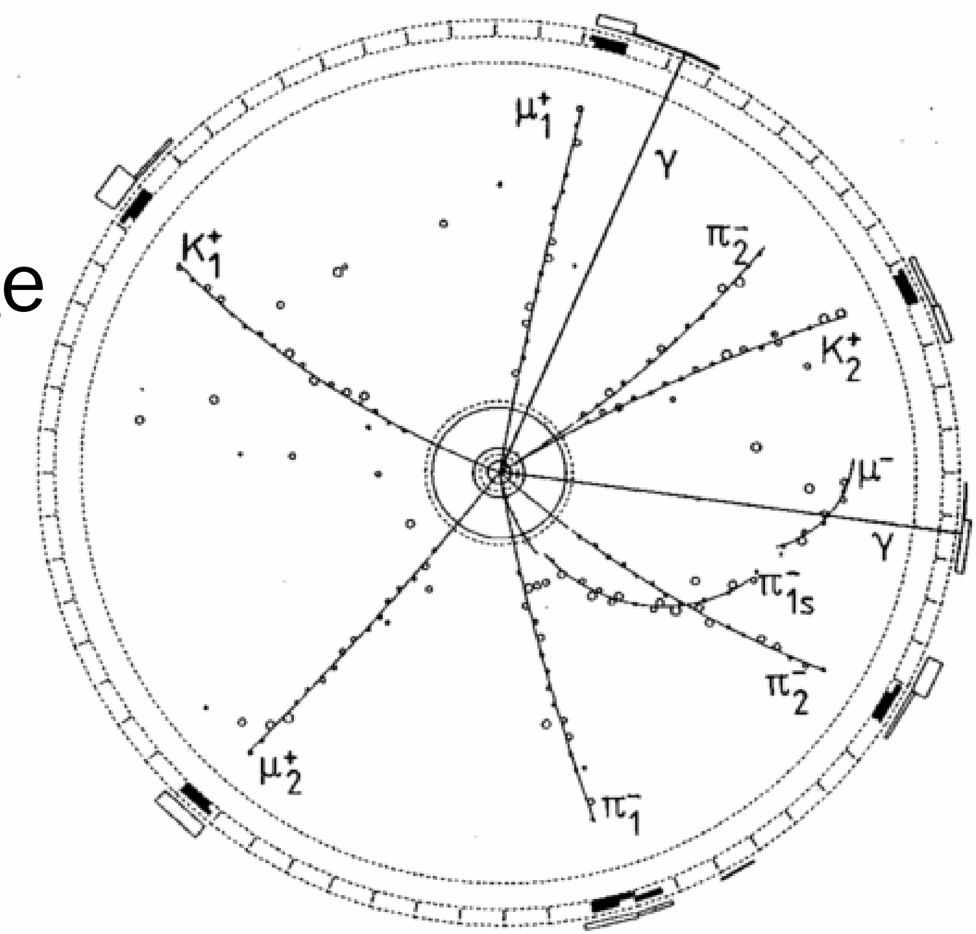


FIG. 3. Distribution of δ for (a) muons and (b) electrons.

MAC experiment (1983)

Observation of B^0-$\underline{B}^0$ mixing

- Same sign leptons
  - ⇒ same flavour B mesons
- Mixing probability is large
  - ⇒ top quark is heavy
- Mixing probability
  - $r = 0.21 \pm 0.08$
- PDG 2006:
  - "r" $(\chi_d) = 0.188 \pm 0.003$
- From 103/pb of data



ARGUS experiment (1987)

B mixing with current data sets

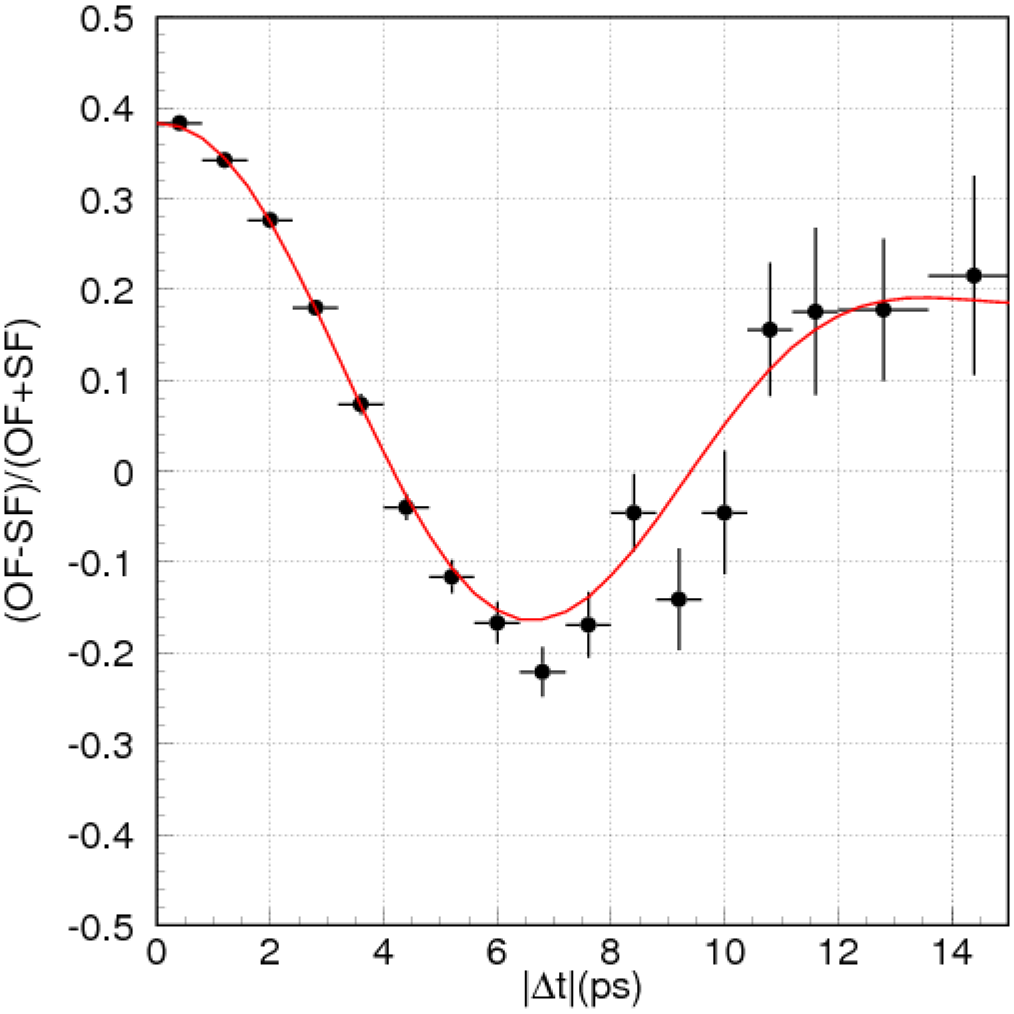
$$P(\Delta t) = (1 \pm \cos(\Delta m \Delta t)) e^{-|\Delta t|} / 2\tau$$

- Belle experiment

  PRD 71, 072003 (2005)

  $\Delta m = (0.511 \pm 0.005 \pm 0.006)\ \mathrm{ps}^{-1}$

- From 140/fb of data

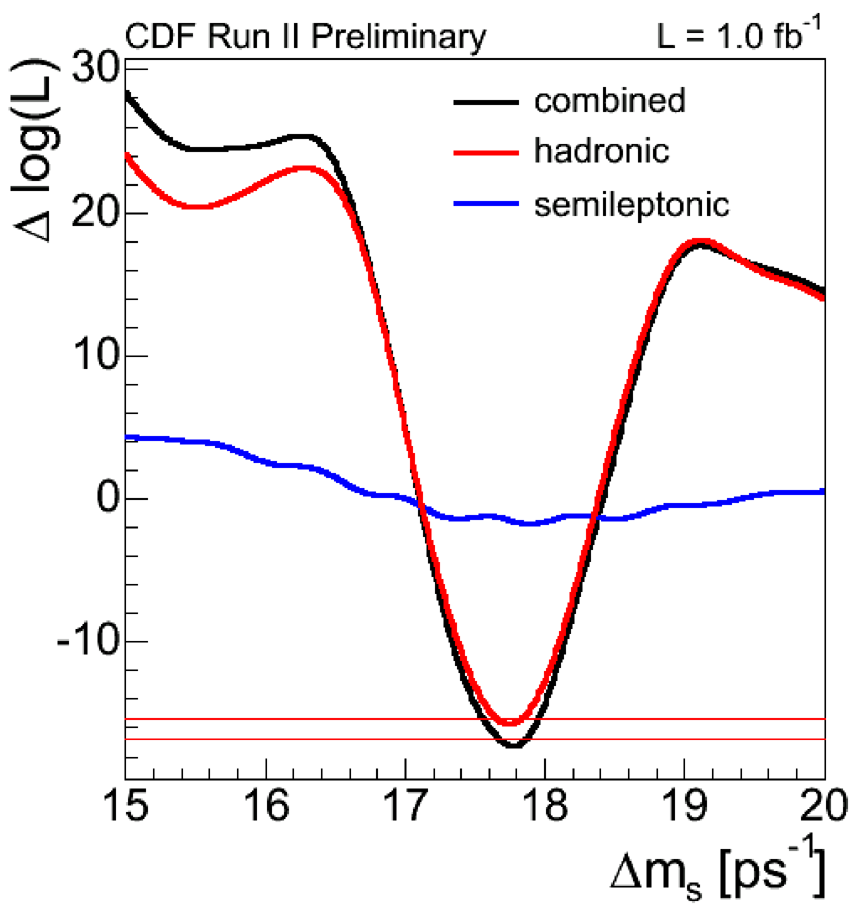


B_s mixing

- Mixing in the B_s system is large
  - PDG 2004
    - $\Delta m_s > 14.5\ ps^{-1}$
    - χ_s ("r") > 0.49884
- October 2006:
  - B_s mixing measured

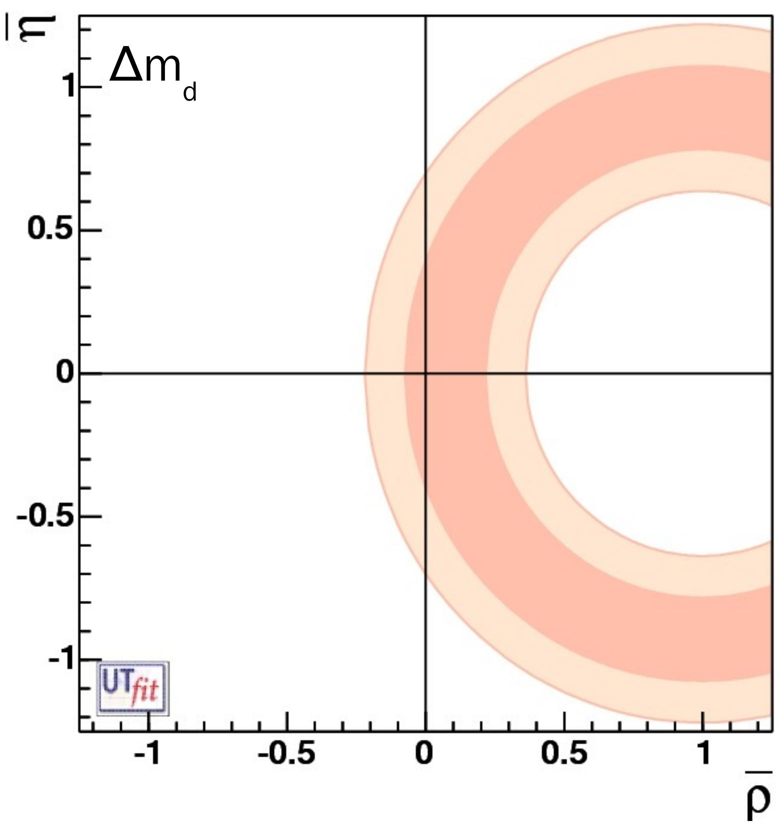
CDF – PRL 97, 242003 (2006)

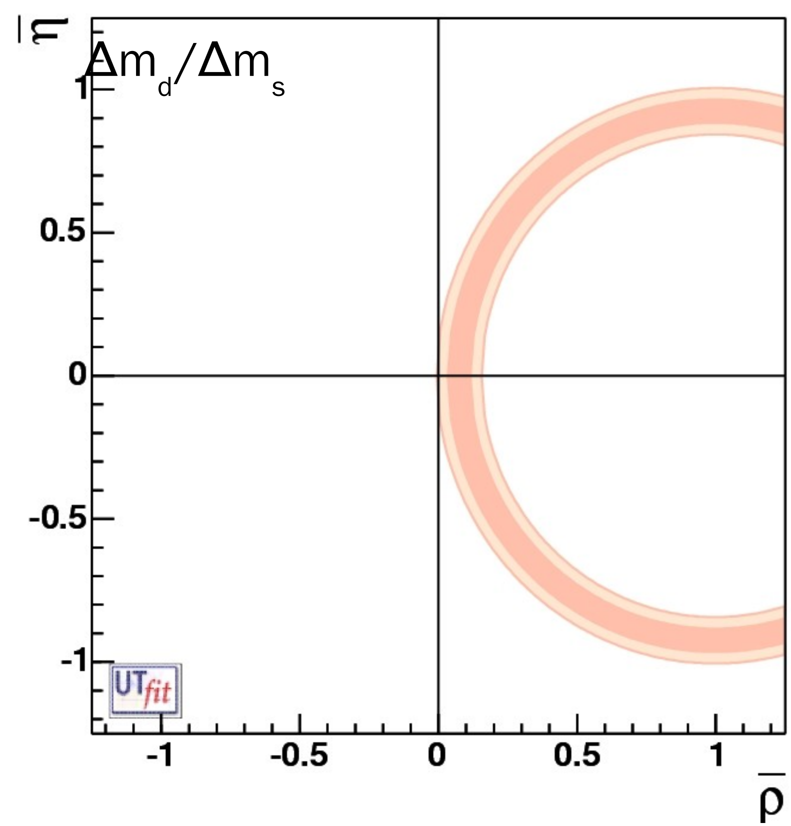
$\Delta m_s = (17.77 \pm 0.10 \pm 0.07)\ ps^{-1}$



UT Constraints from Mixing

- Δm_d contains information on $|V_{td}|$
- $\Delta m_d/\Delta m_s$ preferred since theoretically cleaner





Constraints from mixing

$$\Delta m_d = \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{tb}|^2 |V_{td}|^2 =$$

$$= \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{cb}|^2 \lambda^2 ((1-\bar{\rho})^2 + \bar{\eta}^2)$$

many theoretical uncertainties cancel

$$\frac{\Delta m_d}{\Delta m_s} = \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \frac{|V_{td}|^2}{|V_{ts}|^2} =$$

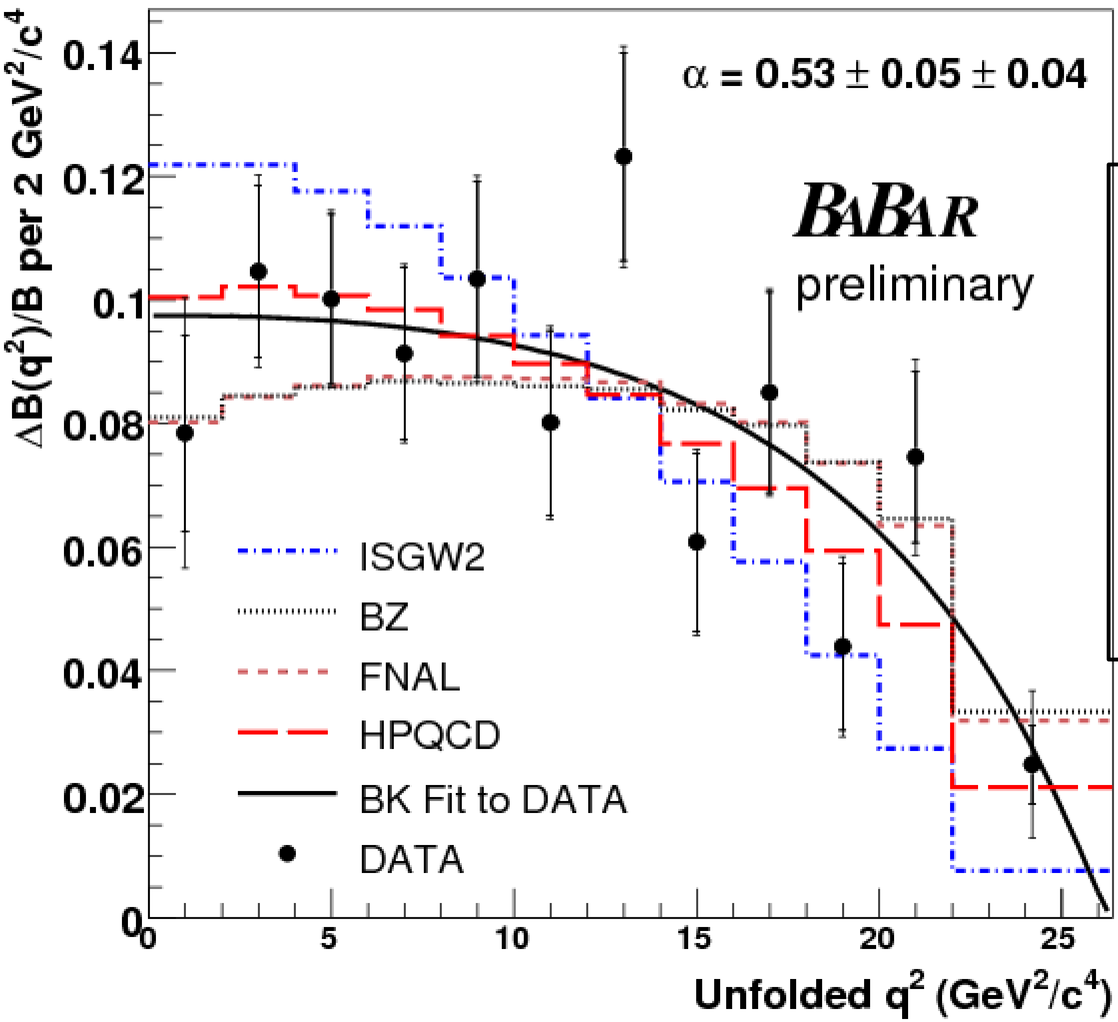
$$= \frac{m_{B_d} f_{B_d}^2 \hat{B}_{B_d}}{m_{B_s} f_{B_s}^2 \hat{B}_{B_s}} \left(\frac{\lambda}{1-\lambda^2/2}\right)^2 \frac{((1-\bar{\rho})^2 + \bar{\eta}^2)}{\left(1 + \frac{\lambda^2}{1-\lambda^2/2}\bar{\rho}\right)^2 + \lambda^4 \bar{\eta}^2}$$

R_u side

- $R_u = |V_{ub}^* V_{ud}| / |V_{cb}^* V_{cd}|$
  - need precise measurement of $|V_{ub}|/|V_{cb}|$
  - Obtain both $|V_{ub}|$ and $|V_{cb}|$ from semileptonic decays
    - exclusive semileptonic B decays
      - eg. $B^0 \to \pi^- e^+ \nu$ for $|V_{ub}|$; $B^0 \to D^{*-} e^+ \nu$ for $|V_{cb}|$
      - moderate theoretical (hadronic) uncertainties
    - inclusive semileptonic B decays
      - ie. $B^0 \to X_u e^+ \nu$ for $|V_{ub}|$; $B^0 \to X_c e^+ \nu$ for $|V_{cb}|$
      - experimentally challenging
    - rare leptonic B decays, eg. $B^+ \to \tau^+ \nu$, also probe $|V_{ub}|$
      - experimentally challeging

$|V_{ub}|$ - exclusive semileptonic decays

- Current best measurement: PRL 98, 091801 (2007)



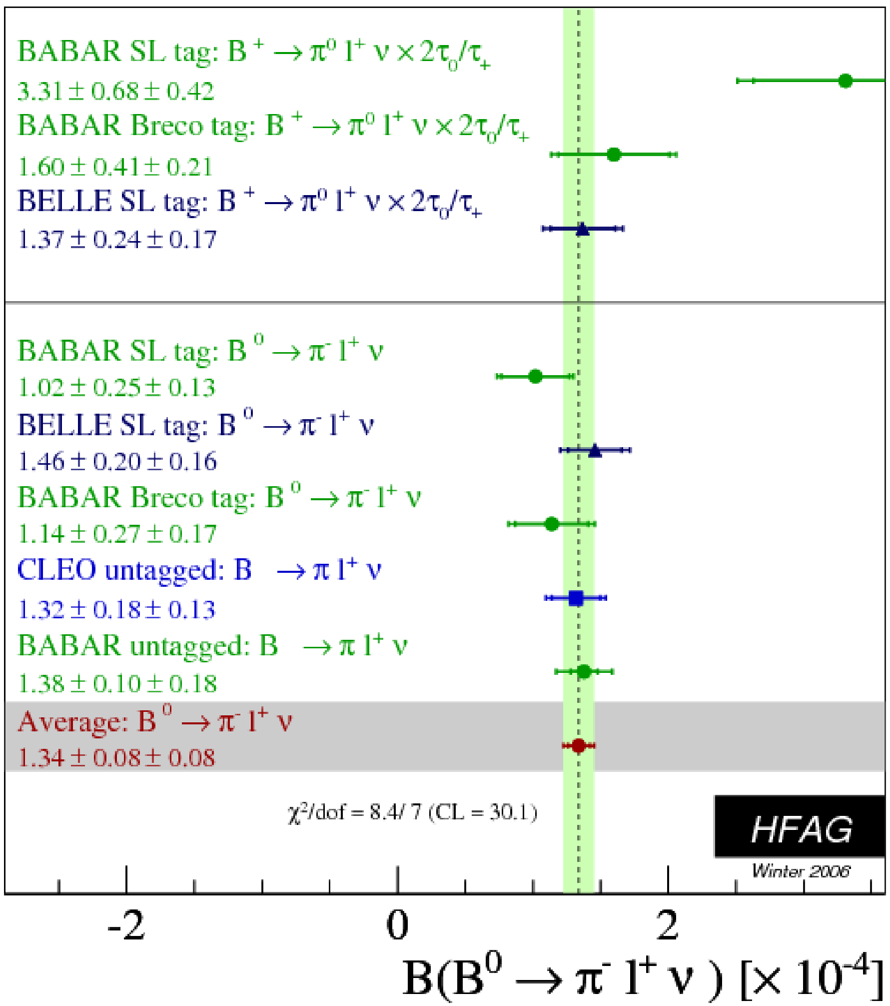
$B^0 \rightarrow \pi^- l^+ \nu$

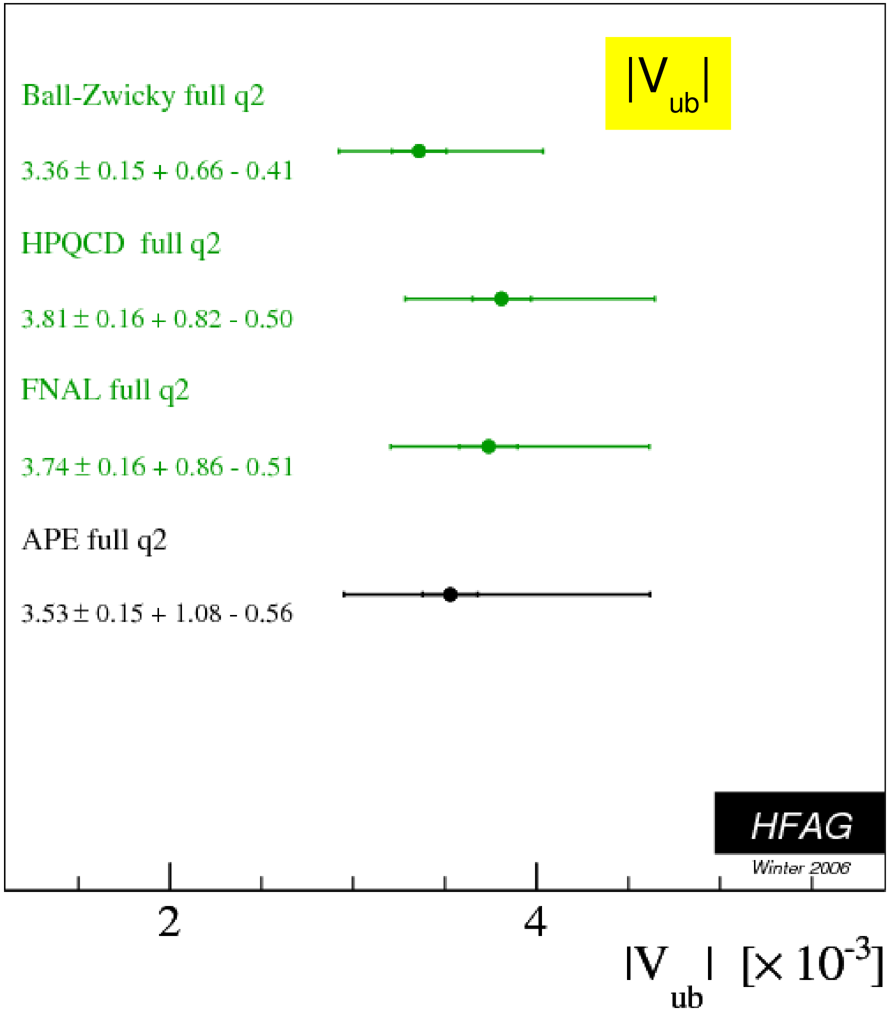
$BF(B^0 \rightarrow \pi^- l^+ \nu) = (1.46 \pm 0.07 \pm 0.08) \times 10^{-4}$

$|V_{ub}| = (4.1 \pm 0.2 \pm 0.2\ ^{+0.6}_{-0.4}) \times 10^{-3}$

$|V_{ub}|$ - exclusive semileptonic decays

- Compilation of results by HFAG





Different theoretical approaches

$|V_{ub}|$ - inclusive semileptonic decays

- Main difficulty to measure inclusive $B^0 \rightarrow X_u l^+ \nu$
  - background from $B^0 \rightarrow X_c l^+ \nu$
- Approaches
  - cut on E_l (lepton endpoint)
  - cut on $M(X_u)$
  - other combinations of cuts on $M(X_u)$ and q^2
- Cuts $\Rightarrow$ theoretical uncertainty
- Ability to perform inclusive analysis depends on detector *hermiticity*

$|V_{ub}|$ inclusive - M_X analysis

- Best current measurement PRL 95, 241801 (2005)

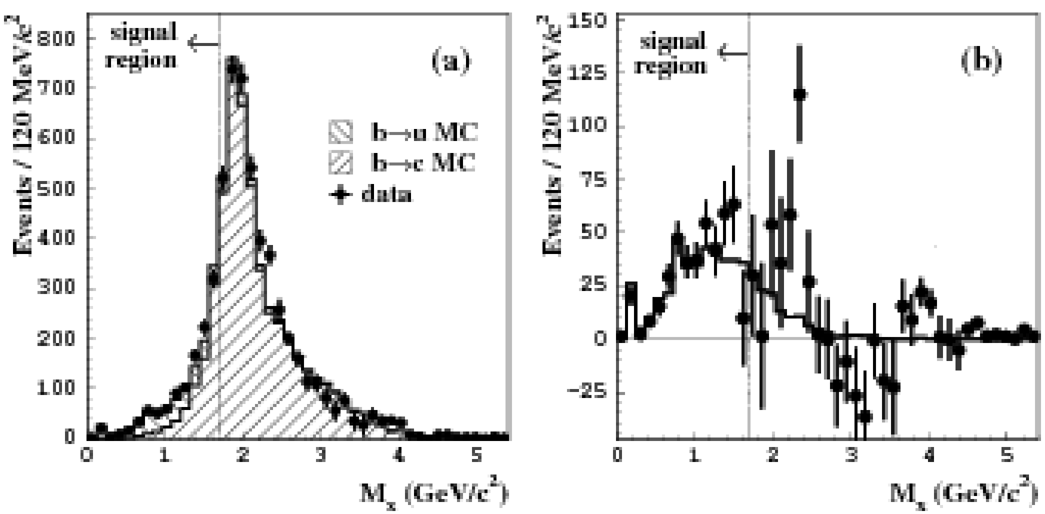
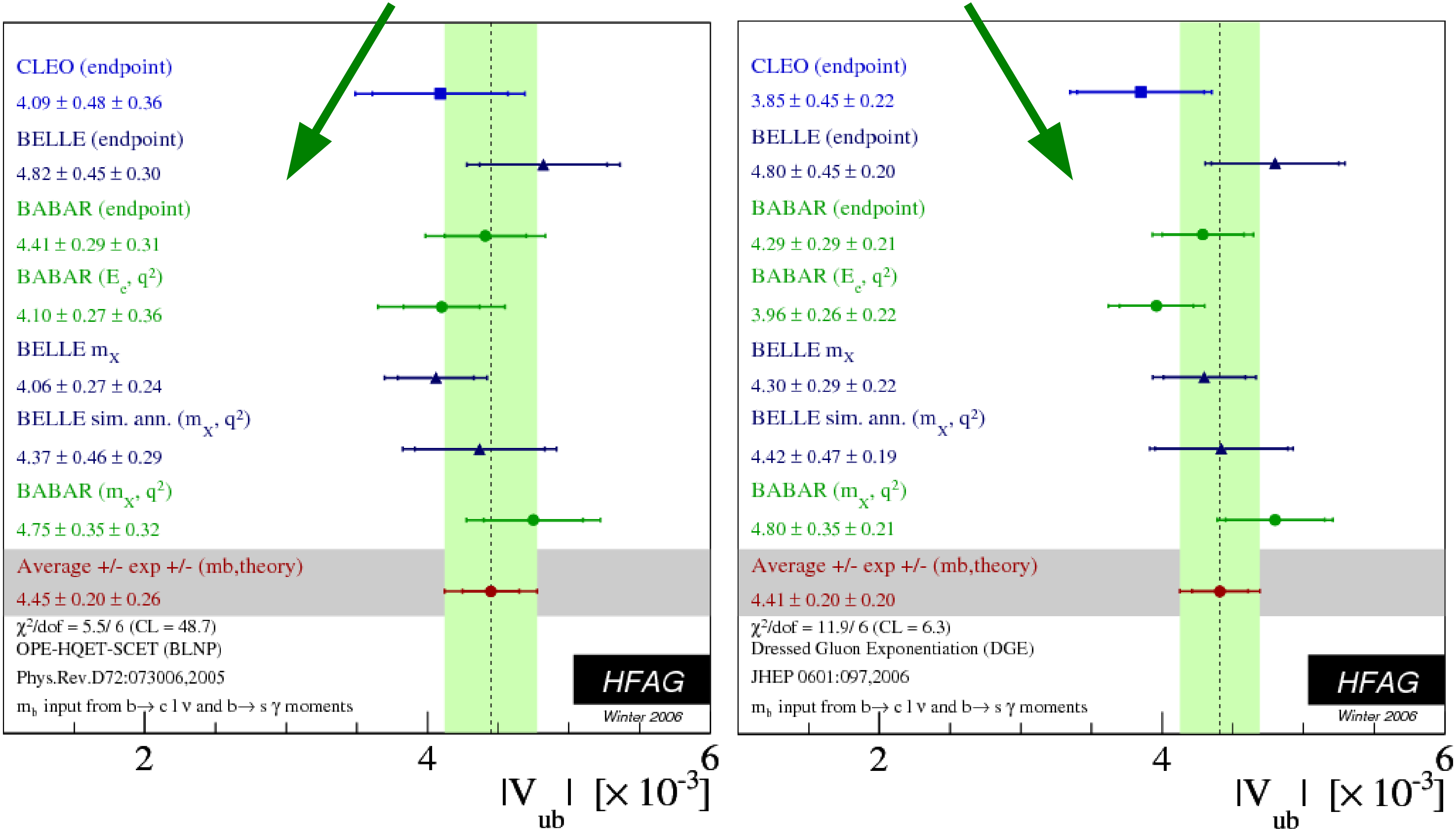


FIG. 3: M_X distribution (no q^2 requirement) with fitted contributions from $X_c\ell\nu$ and $X_u\ell\nu$: (a) before and (b) after subtracting the $X_c\ell\nu$ contribution (symbols with error bars), shown with the prediction for $X_u\ell\nu$ (MC, histogram).

$$|V_{ub}| = (4.09 \pm 0.19 \pm 0.20 \pm 0.15 \pm 0.18) \times 10^{-3}$$

$|V_{ub}|$ inclusive - compilation

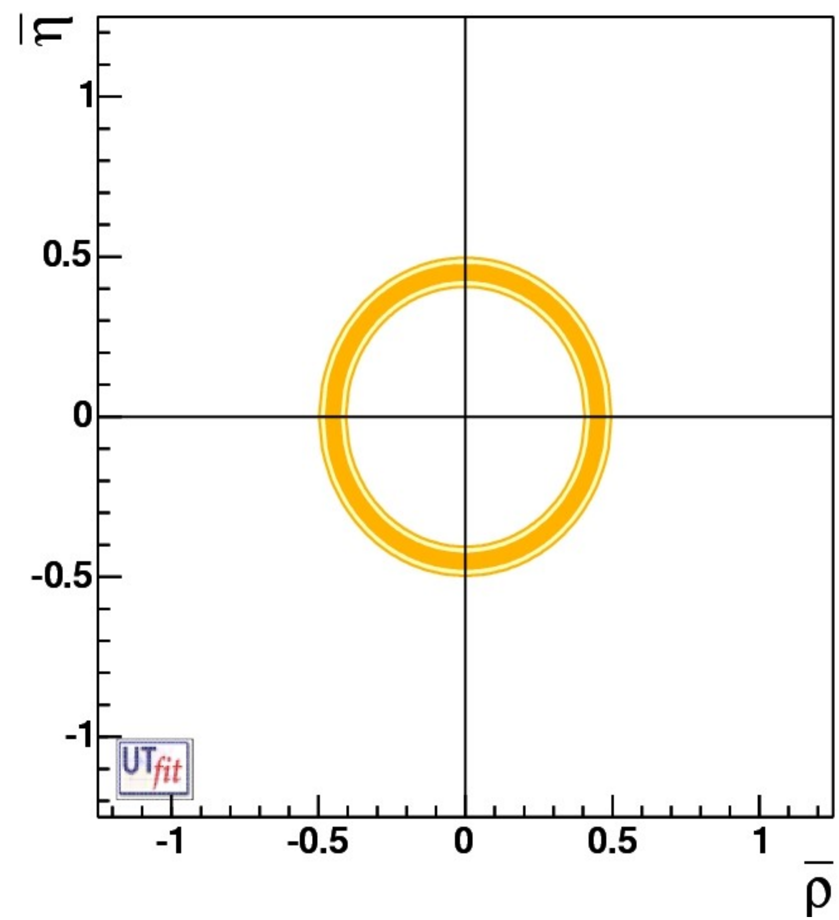
Different theoretical approaches



$|V_{ub}|$ average

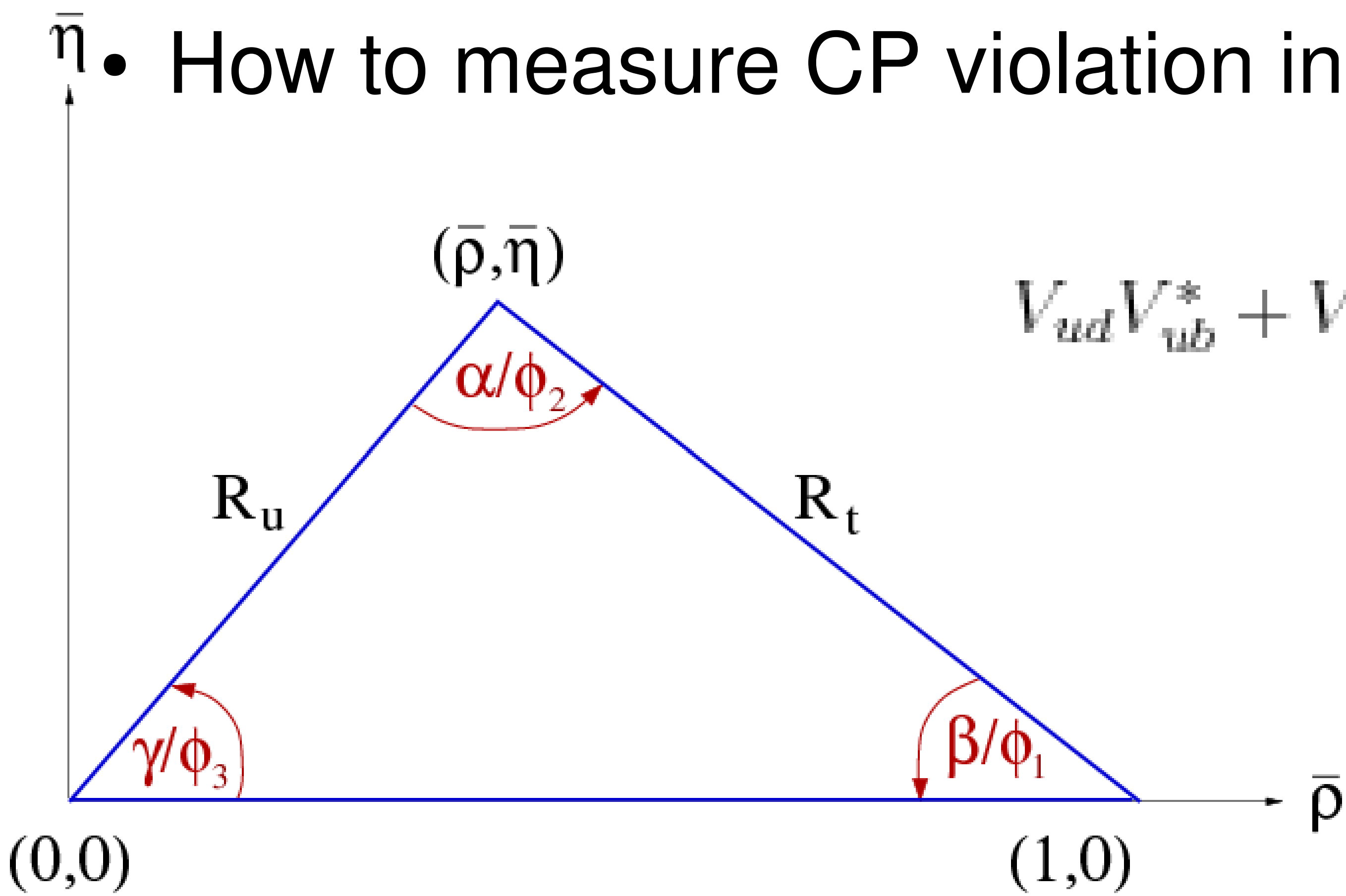
Very hard to make an average!

PDG2006 gives: $|V_{ub}| = (4.31 \pm 0.30) \times 10^{-3}$



How to measure the angles?

- How to measure CP violation in the B system?

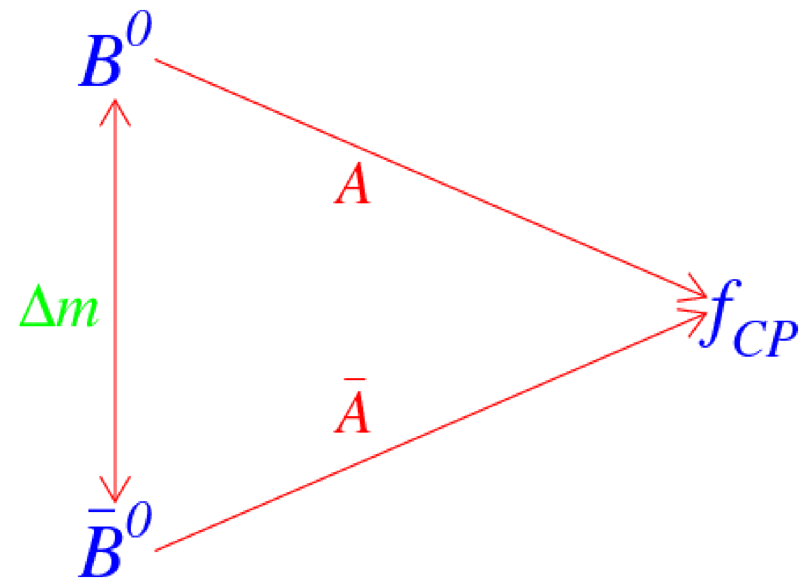


$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0,$$

$$\alpha \equiv \phi_2 = \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right], \quad \beta \equiv \phi_1 = \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right], \quad \gamma \equiv \phi_3 = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

Categories of CP violation

- Consider decay of neutral particle to a CP eigenstate



$$\lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

$$\left|\frac{q}{p}\right| \neq 1$$

CP violation in mixing

$$\left|\frac{\overline{A}}{A}\right| \neq 1$$

CP violation in decay (direct CPV)

$$\Im\left(\frac{q}{p}\frac{\overline{A}}{A}\right) \neq 0$$

CP violation in interference between mixing and decay

Evolution with time

- Consider a B meson which is known to be B^0 at time t=0
- At later time t:

$B^0_{(phys)}(\Delta t)$ =

$$e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m\Delta t/2)\ B^0 + i\ (q/p)\ e^{-iMt}e^{-\Gamma t/2}\sin(\Delta m\Delta t/2)\ \underline{B}^0$$

amplitudes

CP violating mixing parameter

- Similarly

$\underline{B}^0_{(phys)}(\Delta t)$ =

$$(p/q)\ i\ e^{-iMt}e^{-\Gamma t/2}\sin(\Delta m\Delta t/2)\ B^0 + e^{-iMt}e^{-\Gamma t/2}\cos(\Delta m\Delta t/2)\ B^0$$

Evolution with time

- Include decays to CP eigenstate

$\Gamma[B^0_{(phys)} \to f](\Delta t) \sim e^{-\Gamma t}\{1 - (C\cos(\Delta m \Delta t) - S\sin(\Delta m \Delta t))\}$

$\Gamma[\underline{B}^0_{(phys)} \to f](\Delta t) \sim e^{-\Gamma t}\{1 + (C\cos(\Delta m \Delta t) - S\sin(\Delta m \Delta t))\}$

- where
  - $C = (1 - |\lambda_{CP}|^2)/(1 + |\lambda_{CP}|^2)$
  - $S = 2\,\mathrm{Im}(\lambda_{CP})/(1 + |\lambda_{CP}|^2)$

$$\lambda_{CP} = \frac{q}{p}\frac{\overline{A}}{A}$$

- Standard Model (usual phase convention)
  - $q/p \sim e^{-2\beta}$

The golden mode – $B^0 \to J/\psi\ K_S$

- Dominated by $b \to c\underline{c}s$ tree diagram
  - subleading $b \to sc\underline{c}$ penguin has the same weak phase
- $|\underline{A}| = |A| \Rightarrow$ no direct CP violation
- $C = 0$ & $S = -\eta_{CP} \sin(2\beta)$
- Reasonable branching fraction & experimentally clean signature

Problem

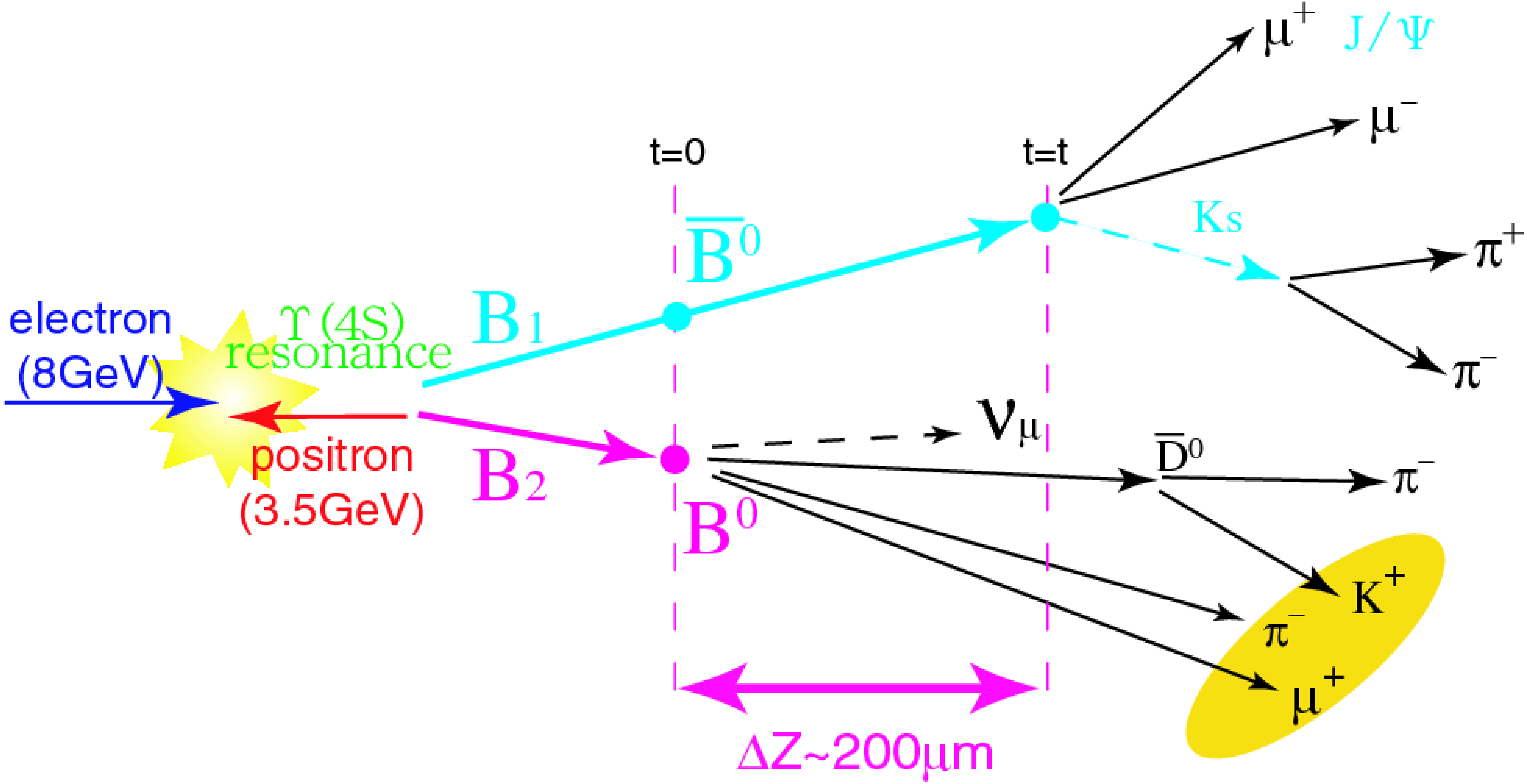
- How can we measure decay time in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\underline{B}^0$?

- The answer: (P.Oddone)

  <u>asymmetric-energy</u> B factory

- Key points
  - $\Upsilon(4S) \rightarrow B^0\underline{B}^0$? produces coherent pairs
  - B mesons are moving in lab frame

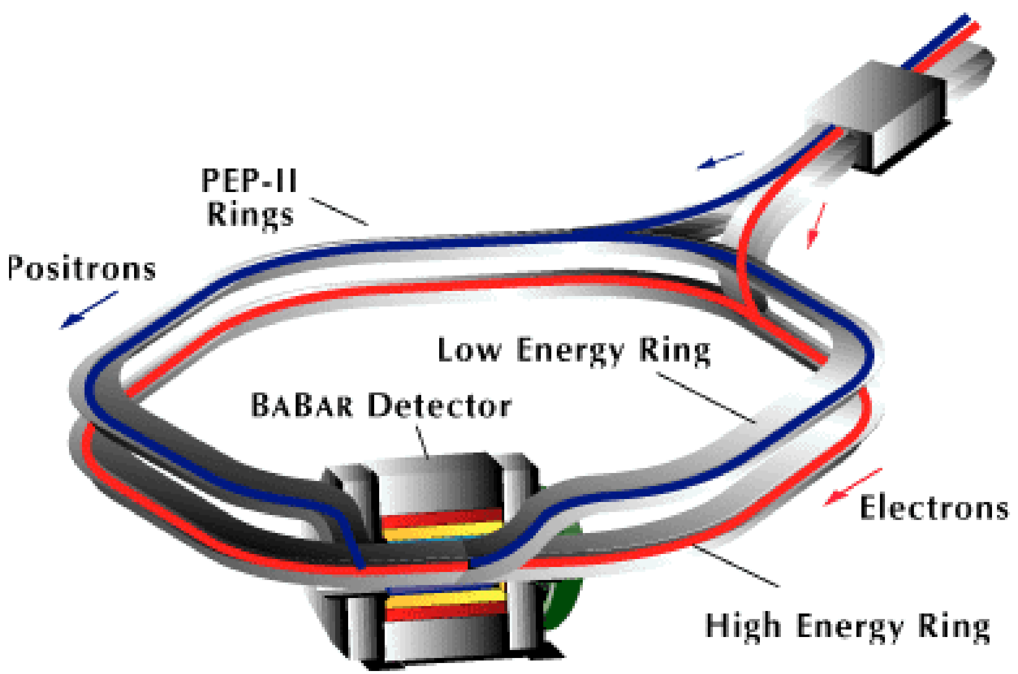
Asymmetric B factory principle

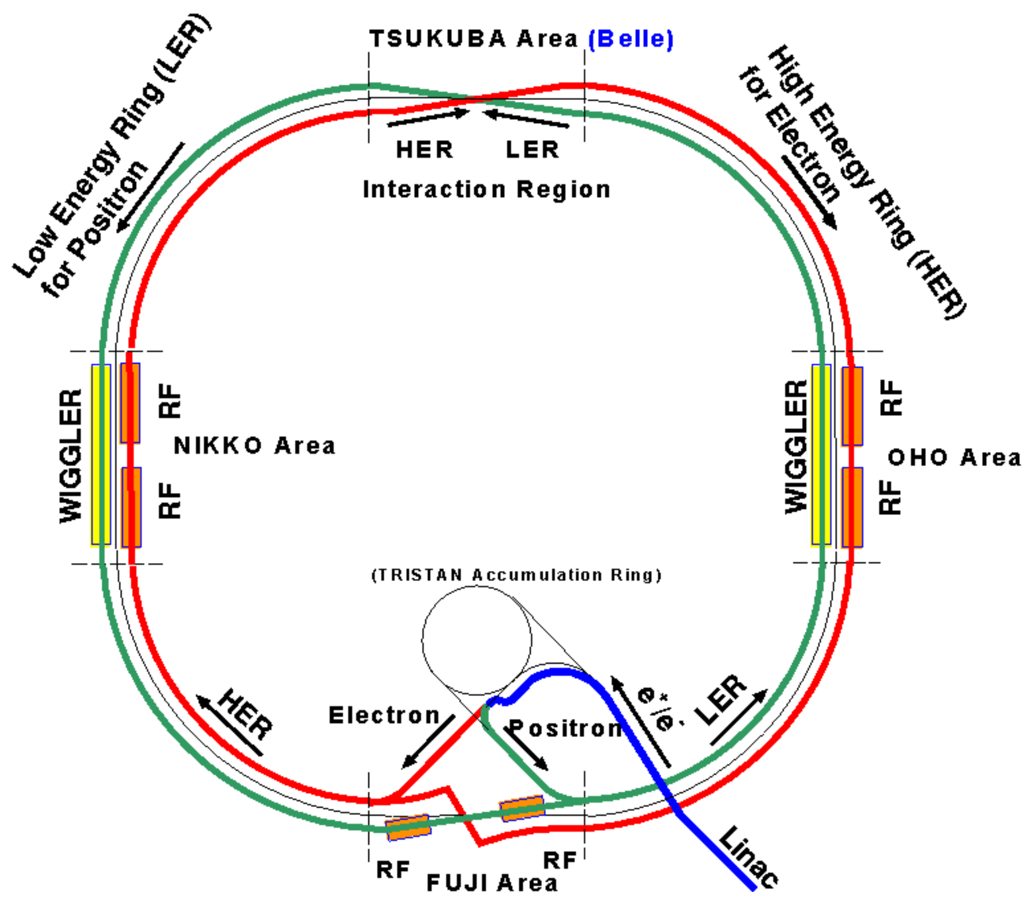


Asymmetric B Factories

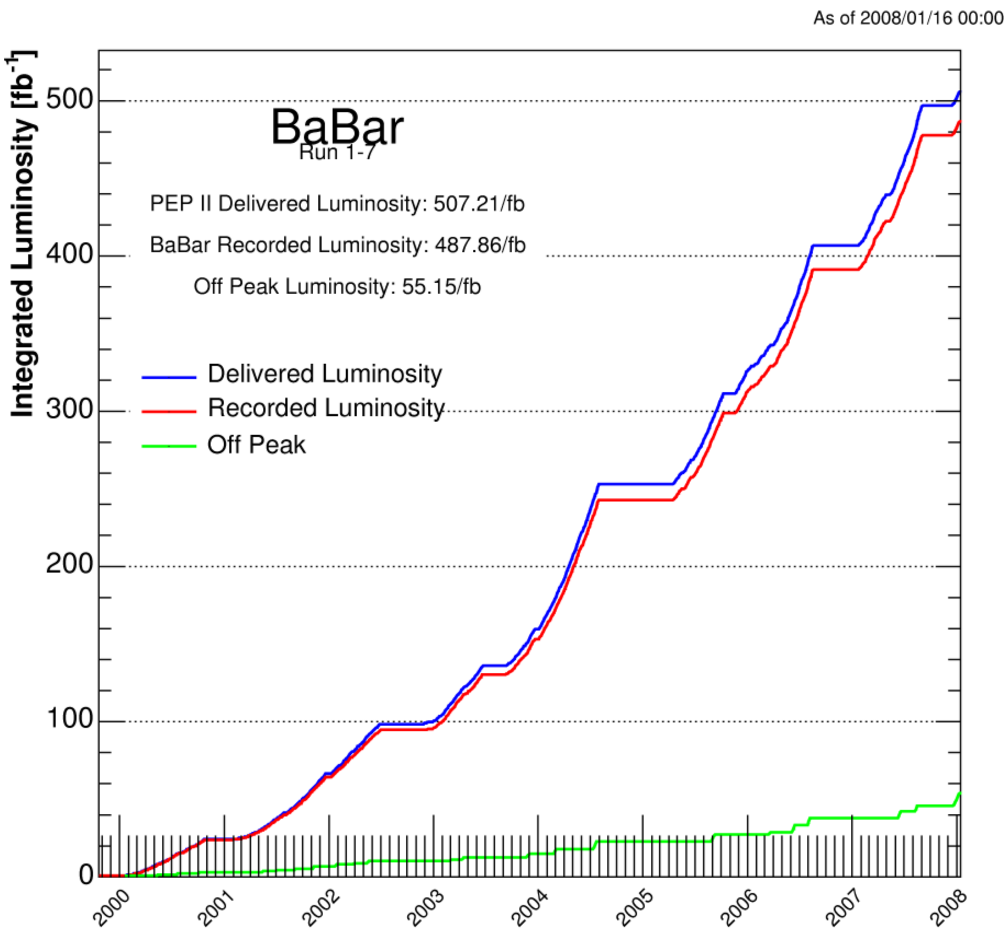
PEPII at SLAC
9.0 GeV e^- on 3.1 GeV e^+

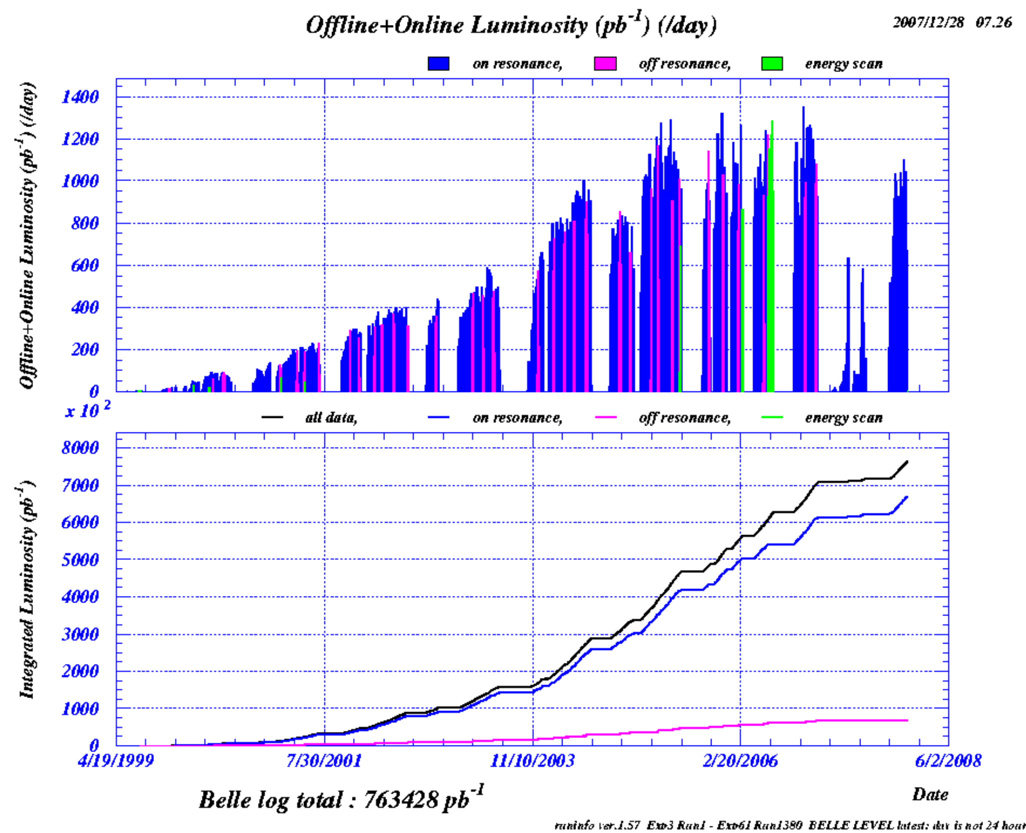
KEKB at KEK
8.0 GeV e^- on 3.5 GeV e^+





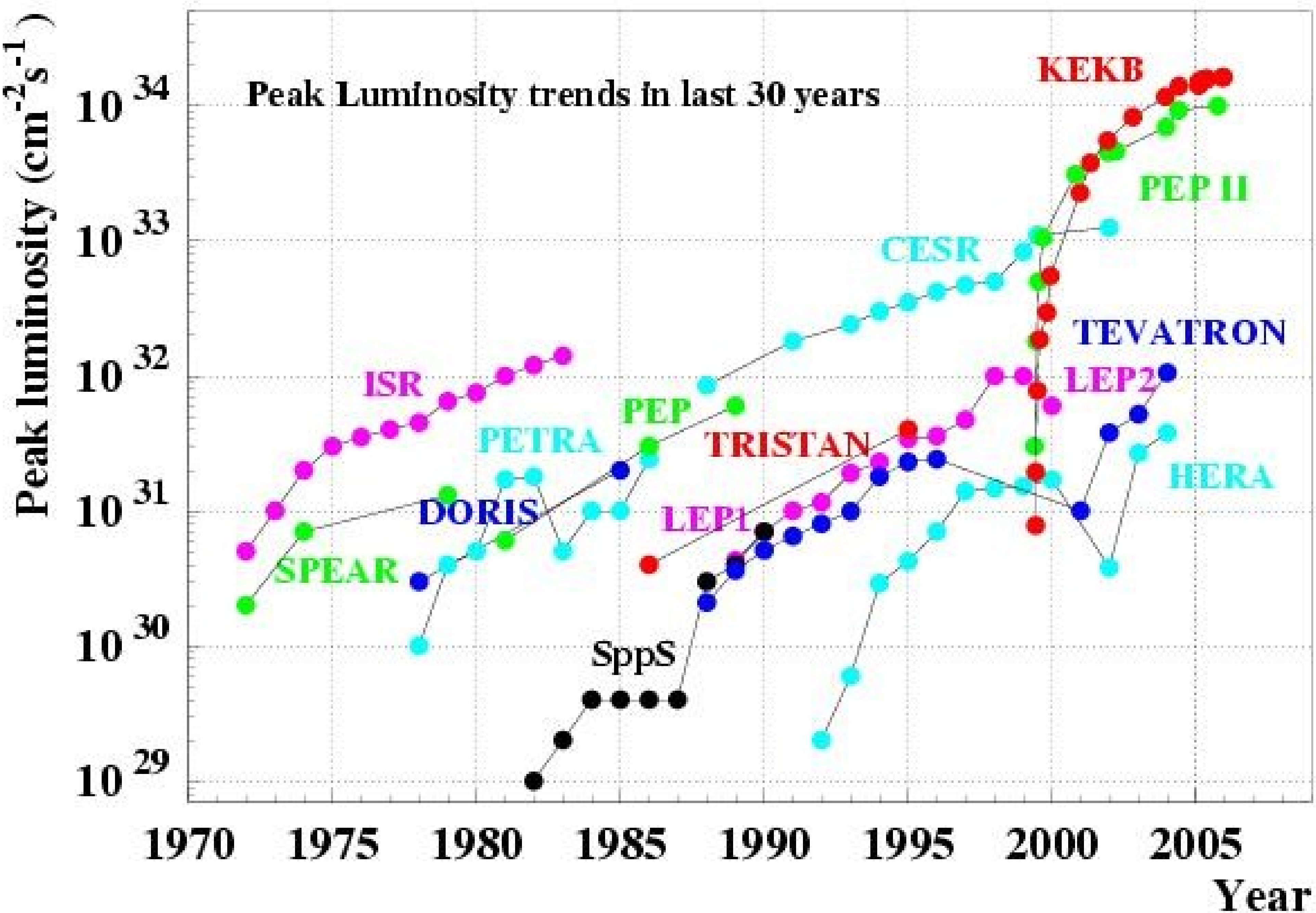
B Factories – World Record Luminosities





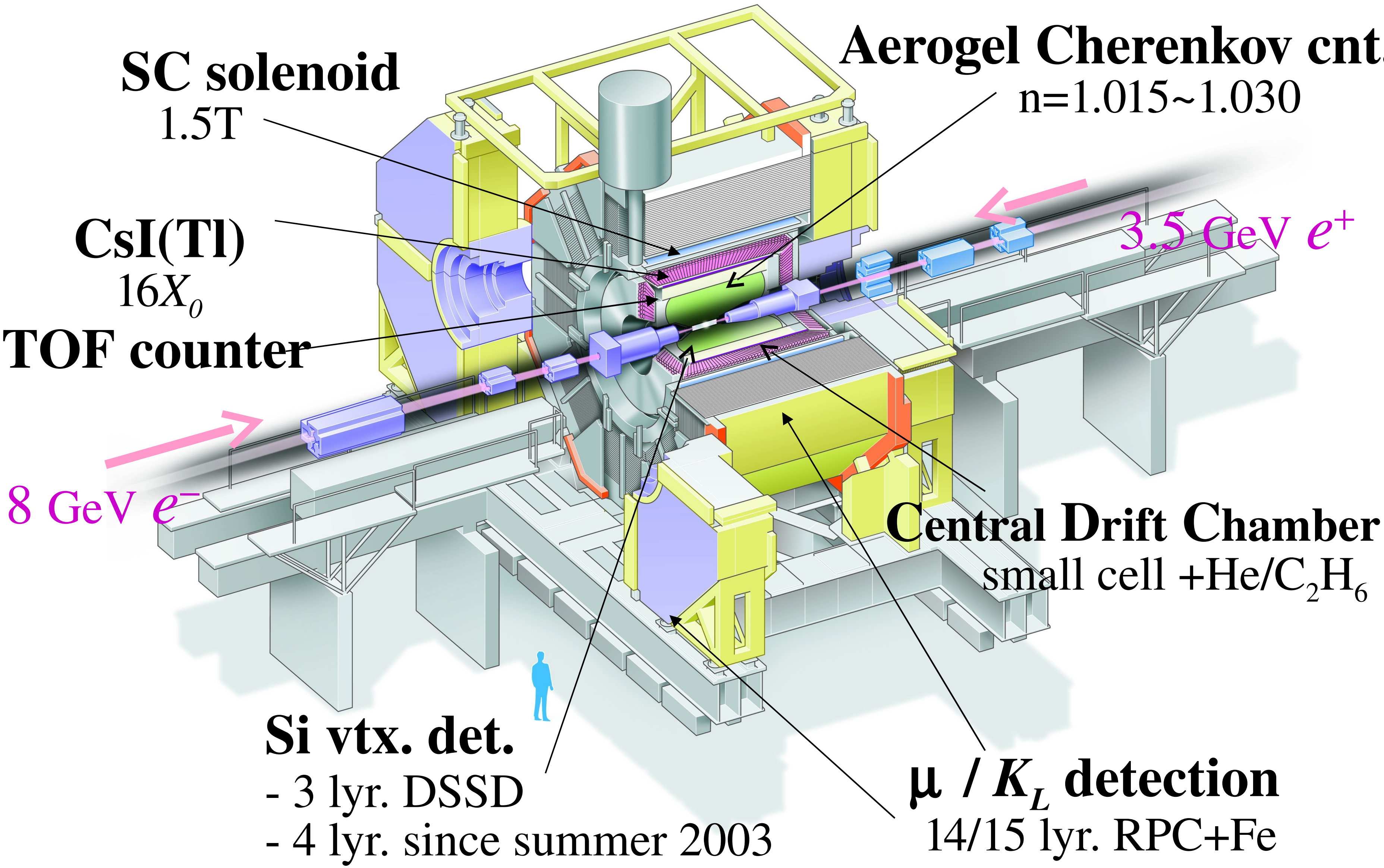
~ 430/fb on Υ(4S)

~ 660/fb on Υ(4S)

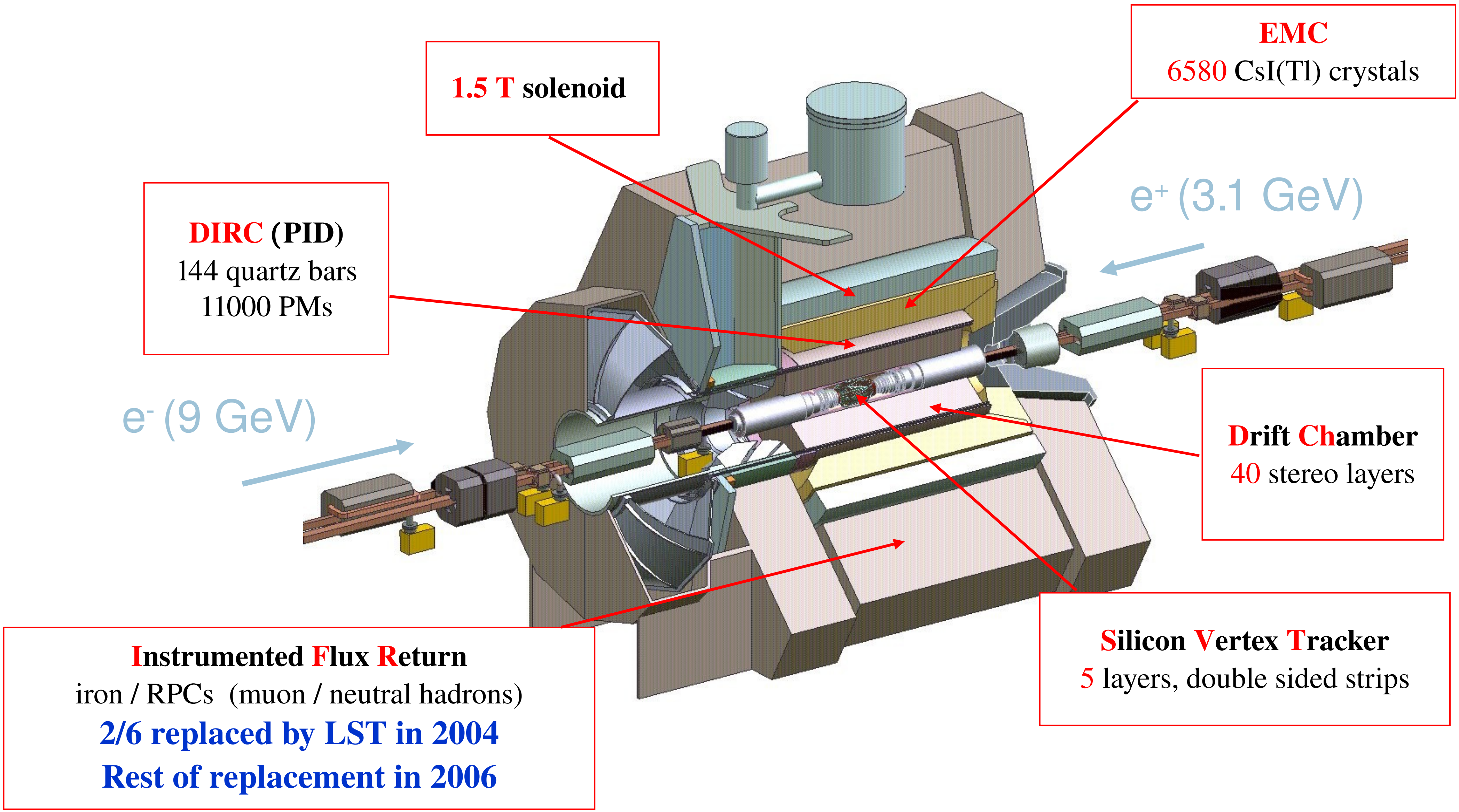


Peak Luminosity trends in last 30 years
Peak luminosity ($cm^{-2}s^{-1}$)
10^{34}
10^{33}
10^{32}
10^{31}
10^{30}
10^{29}
KEKB
PEP II
CESR
TEVATRON
ISR
LEP2
PEP
PETRA
TRISTAN
HERA
DORIS
LEP1
SPEAR
SppS
1970
1975
1980
1985
1990
1995
2000
2005
Year

Belle Detector



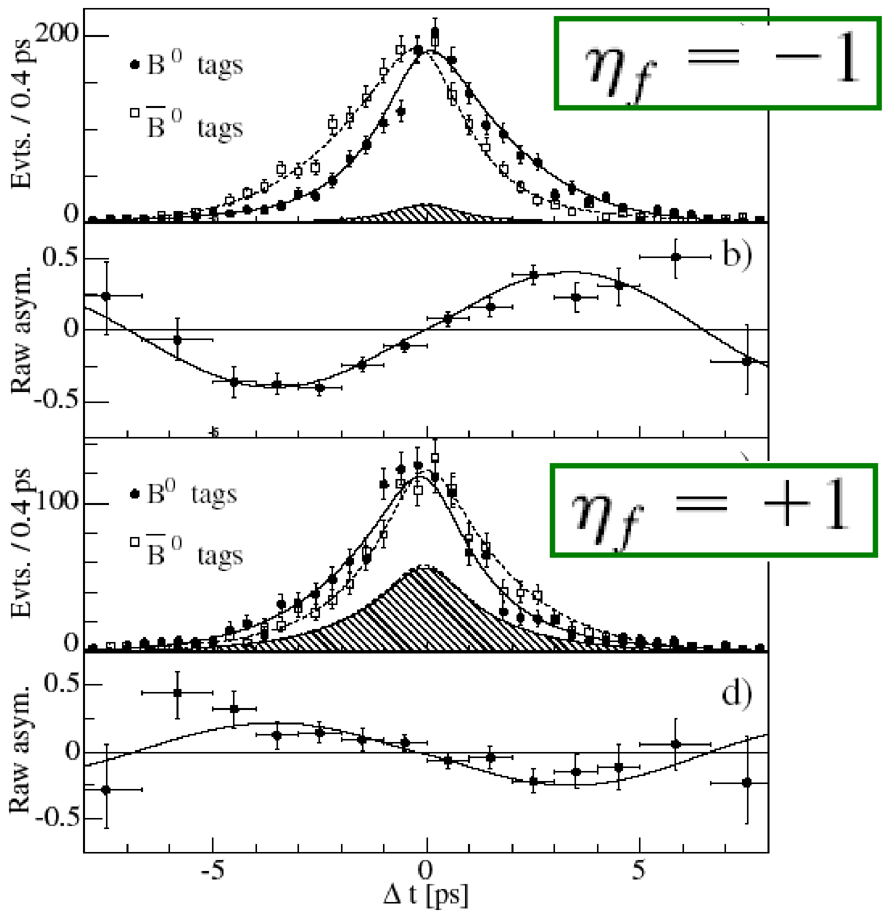
BaBar Detector



Results for the golden mode

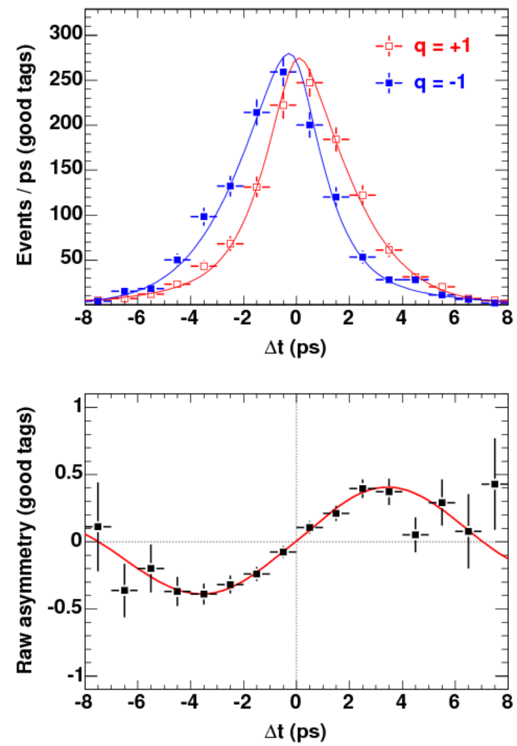
$B^0 \to J/\psi K^0$

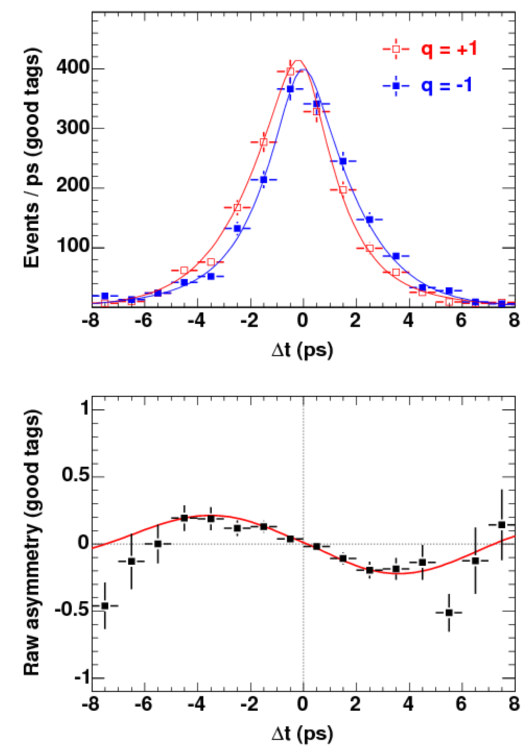
BABAR



PRL **94,** 161803 (2005)

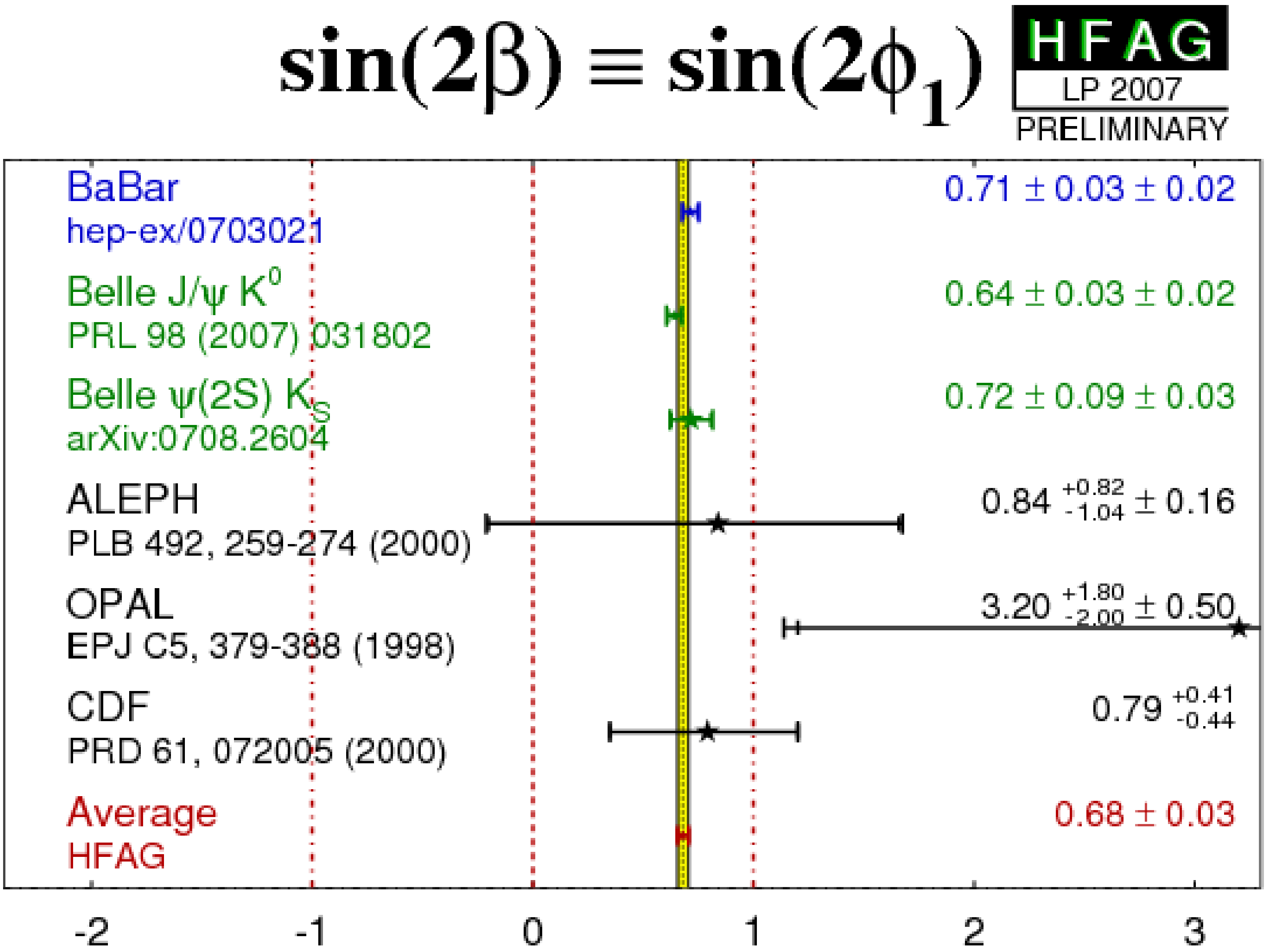
BELLE



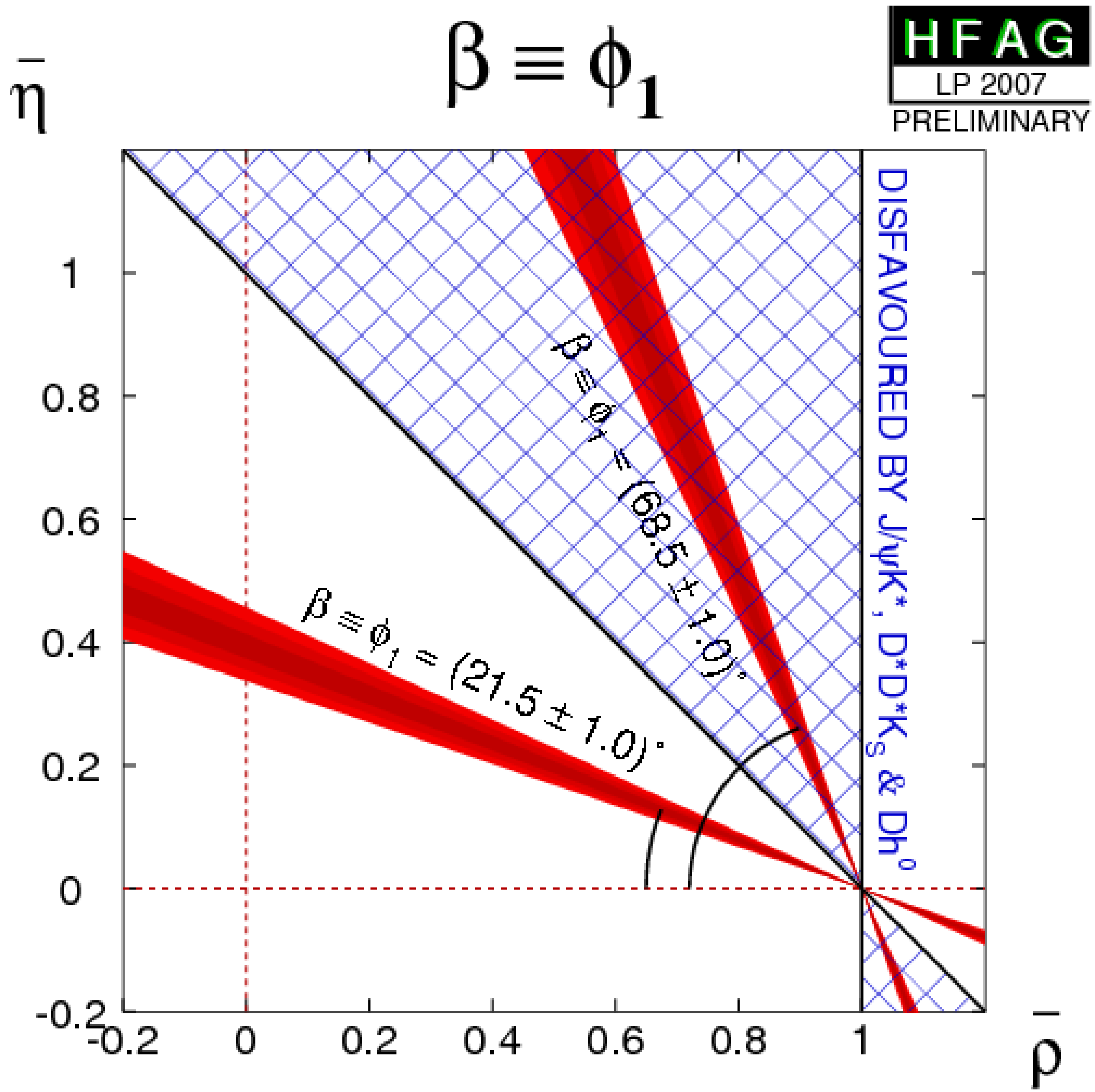


PRL 98, 031802 (2007)

Compilation of results



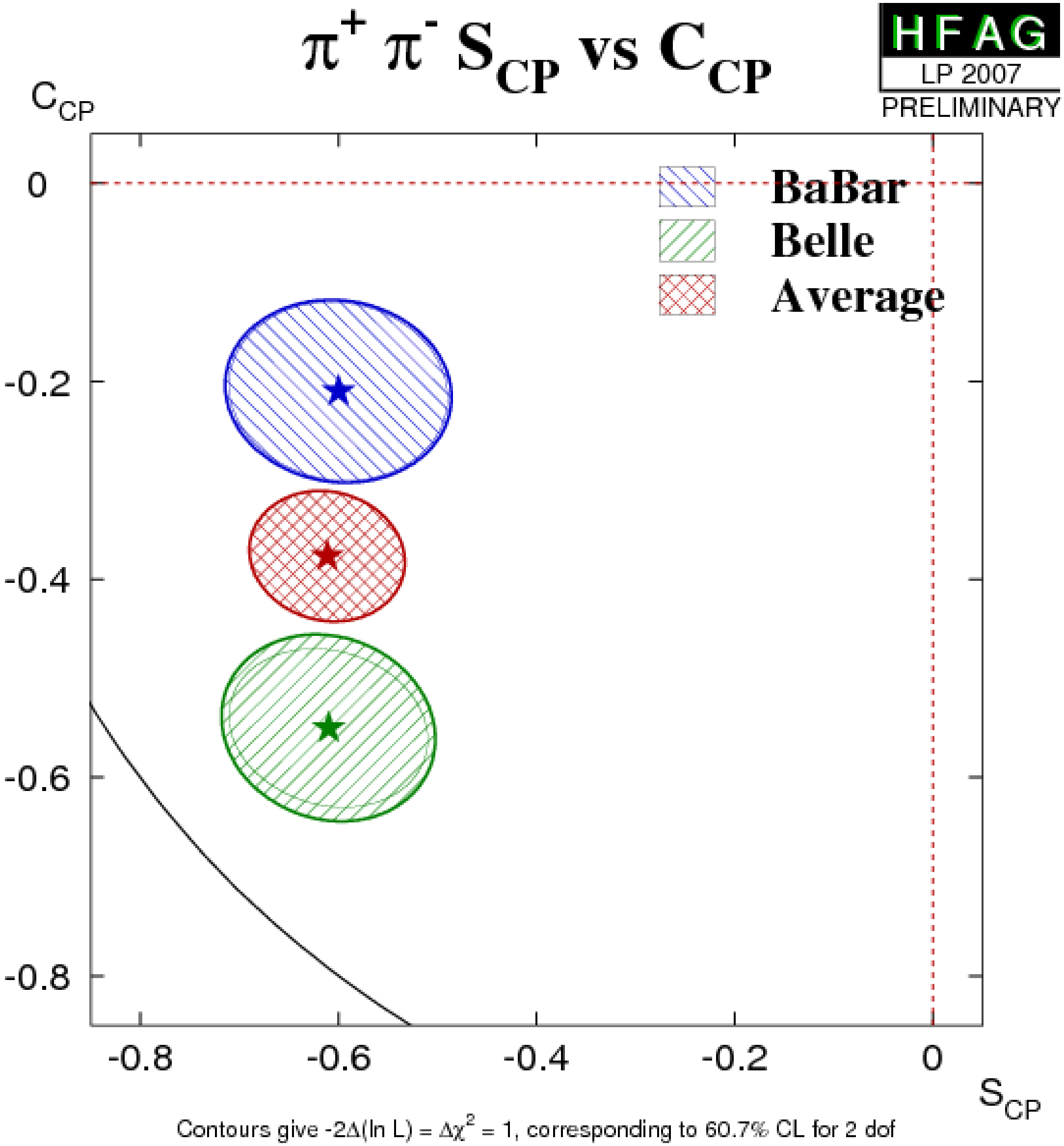
Constraint from β measurement

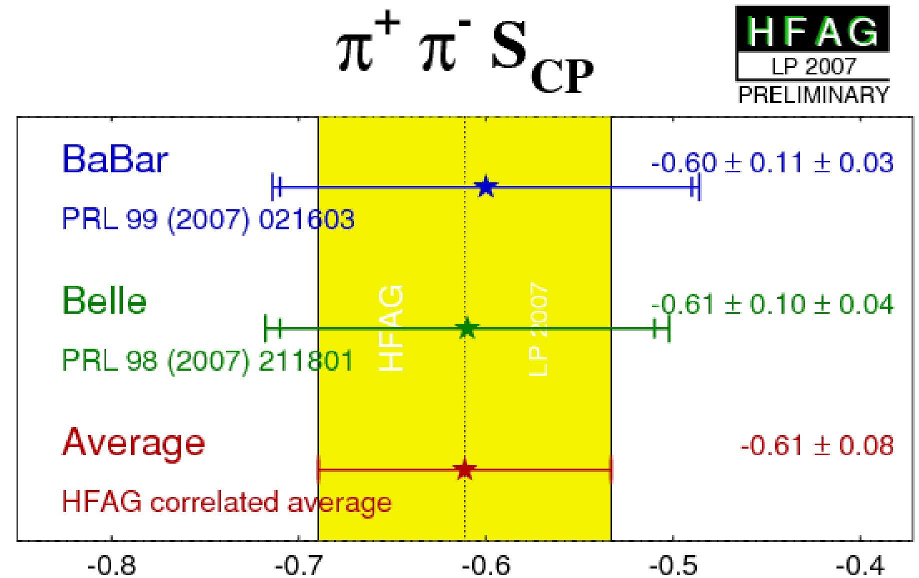


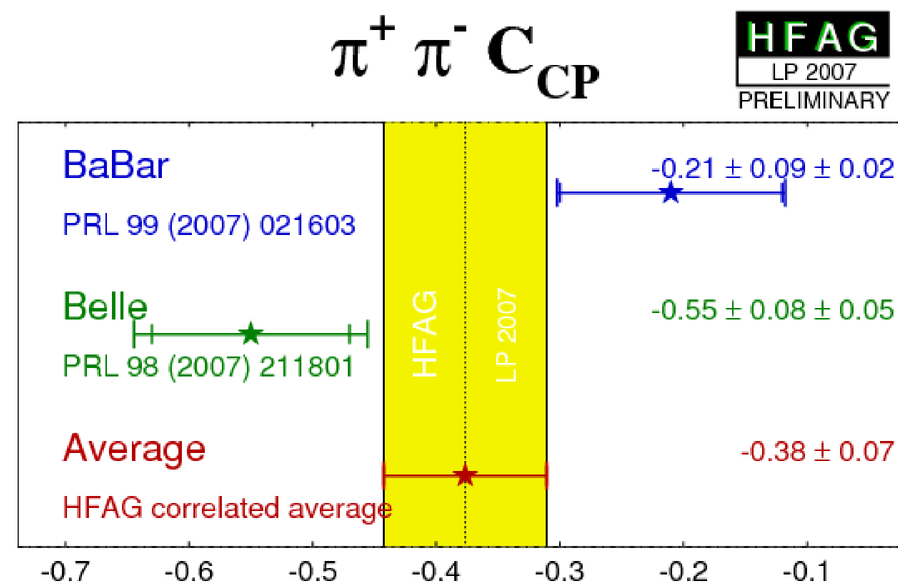
Measurement of α

- Time-dependent CP violation in modes dominated by $b \rightarrow u\underline{u}d$ tree diagrams probes α (or π–(β+γ))
  - $C = 0$ & $S = +\eta_{CP} \sin(2\alpha)$
- $b \rightarrow du\underline{u}$ penguin transitions contribute to same final states ⇒ "penguin pollution"
  - $C \neq 0 \Leftrightarrow$ direct CP violation can occur
  - $S \neq +\eta_{CP} \sin(2\alpha)$
- Two approaches (optimal approach combines both)
  - try to use modes with small penguin contribution
  - correct for penguin effect (isospin analysis)

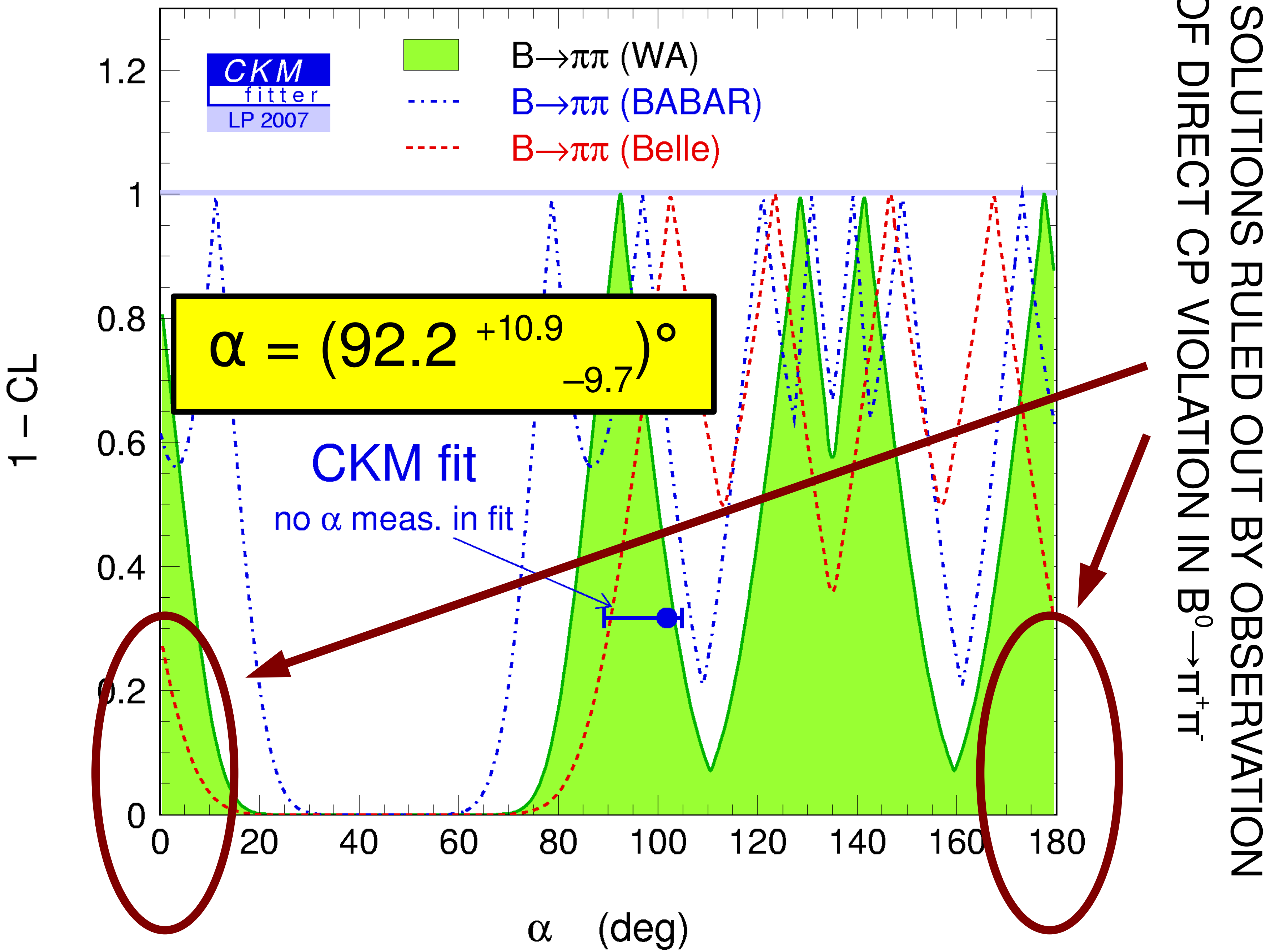
$B^0 \rightarrow \pi^+\pi^-$ – Experimental Situation







Measurement of α



Measurement of γ

- Charmless B decays, eg. $B^0 \rightarrow K^+\pi^-$
  - contributions from
    - P : $b \rightarrow s\underline{u}u$ penguin
    - T : $b \rightarrow us\underline{u}$ tree
  - relative weak (CP violating) phase is γ
  - relative strong (CP conserving) phase δ

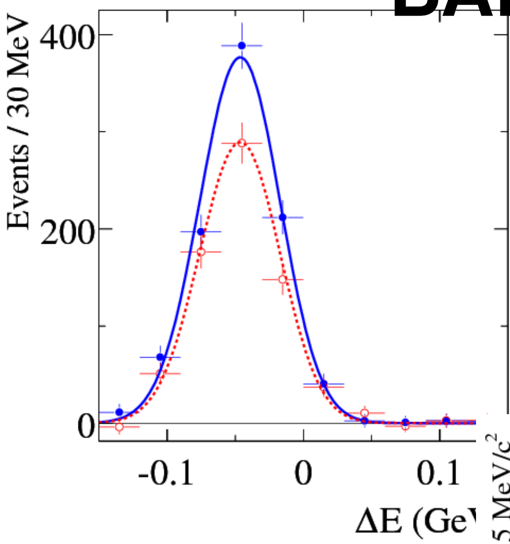
$$A_{CP} = 2|P||T|\sin(\gamma)\sin(\delta)/\{|P|^2+|T|^2+2|P||T|\cos(\gamma)\cos(\delta)\}$$

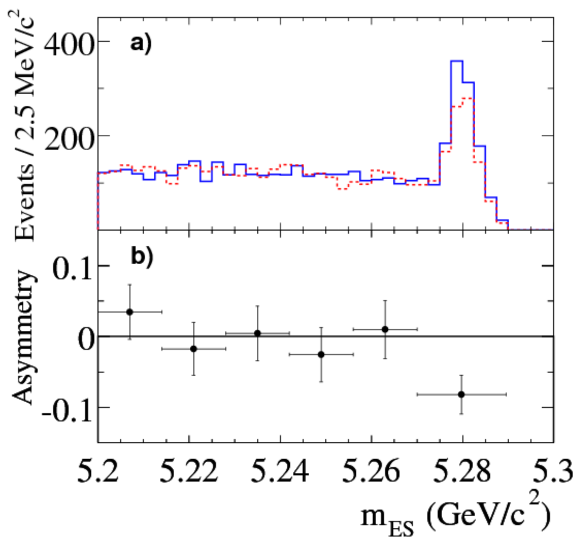
- Hadronic uncertainties:
  - even if we observe $A_{CP} \neq 0$, cannot easily extract γ
  - other processes also contribute

Direct CP violation in the B system

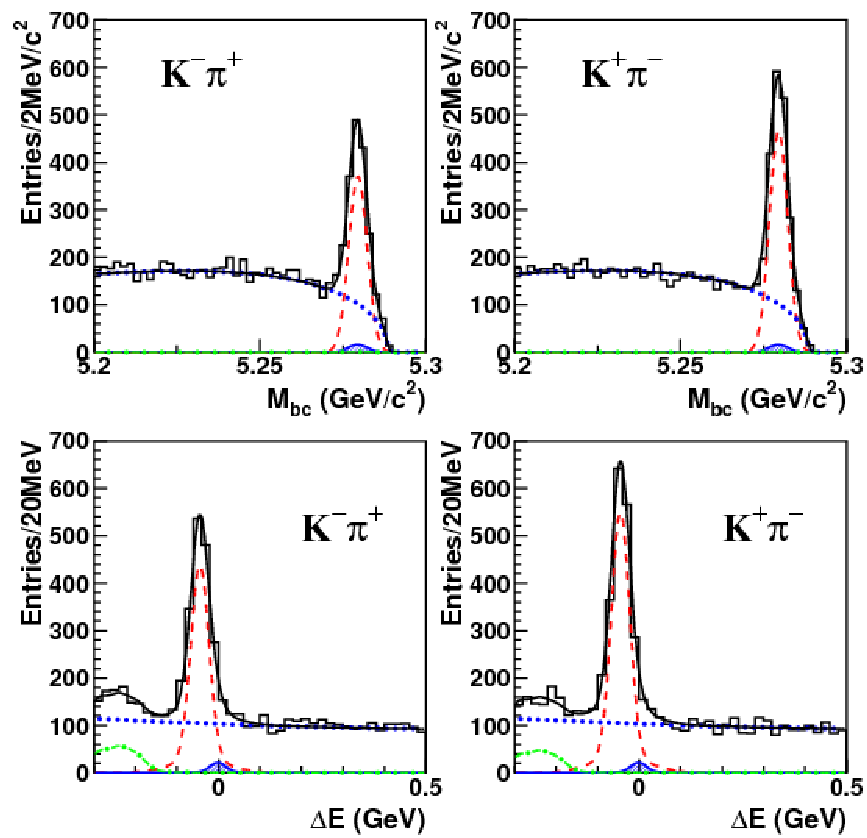
$$B^0 \rightarrow K^+\pi^-$$

BABAR





BELLE



PRL 93 (2004) 131801

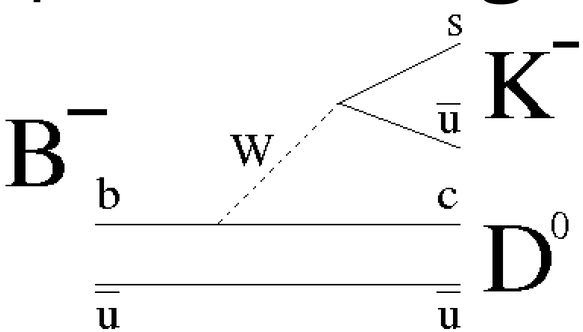
BELLE-CONF-0523

Clean measurement of γ

- A theoretically clean measurement of γ can be made using $B \to DK$ decays
- Reconstruct D mesons in states accessible to both D^0 and $\underline{D}^0$
  - interference between $b \to c\underline{u}s$ and $b \to u\underline{c}s$
  - relative weak phase is γ
  - various different D decays utilized
  - large statistical errors at present

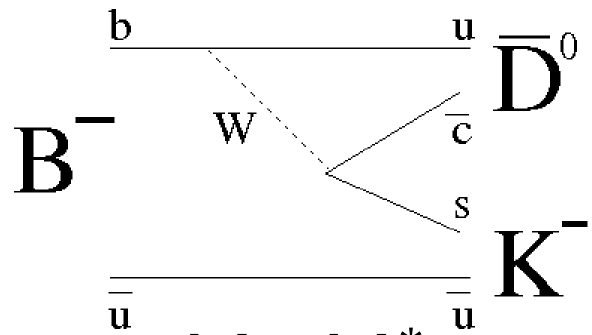
The Idea

- Two possible diagrams for $B^- \to DK^-$



$\propto V_{cb} V_{us}^{*}$

- colour allowed
- final state contains D^0



$\propto V_{ub} V_{cs}^{*}$

- colour suppressed
- final state contains $\overline{D}^{0}$

Relative magnitude of suppressed amplitude is r_B

Relative weak phase is $-\gamma$, relative strong phase is δ_B

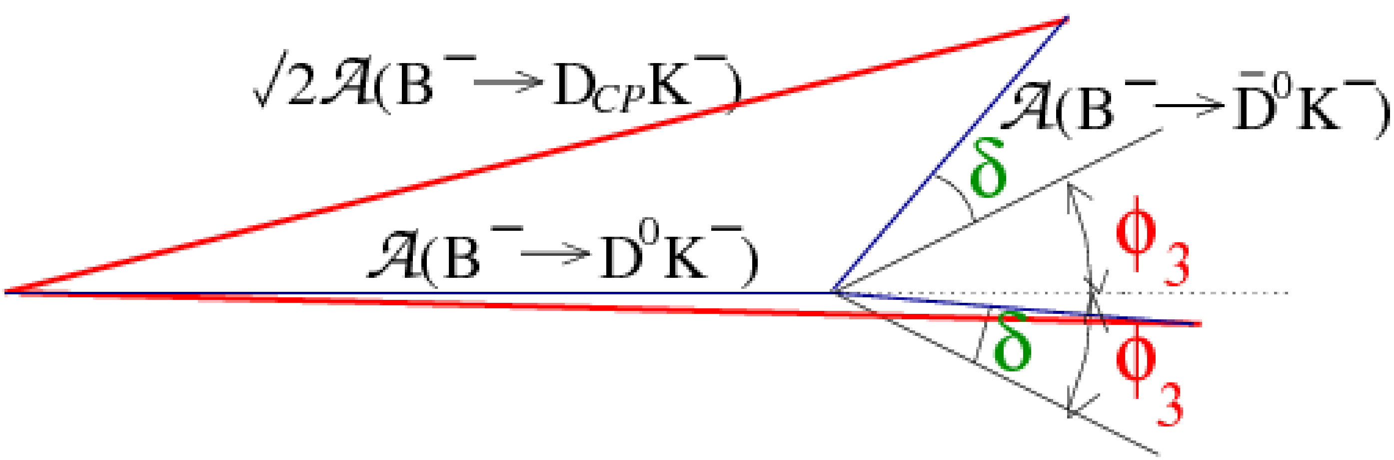
Need D^0 and $\overline{D}^{0}$ to decay to common final state

D→CP eigenstates

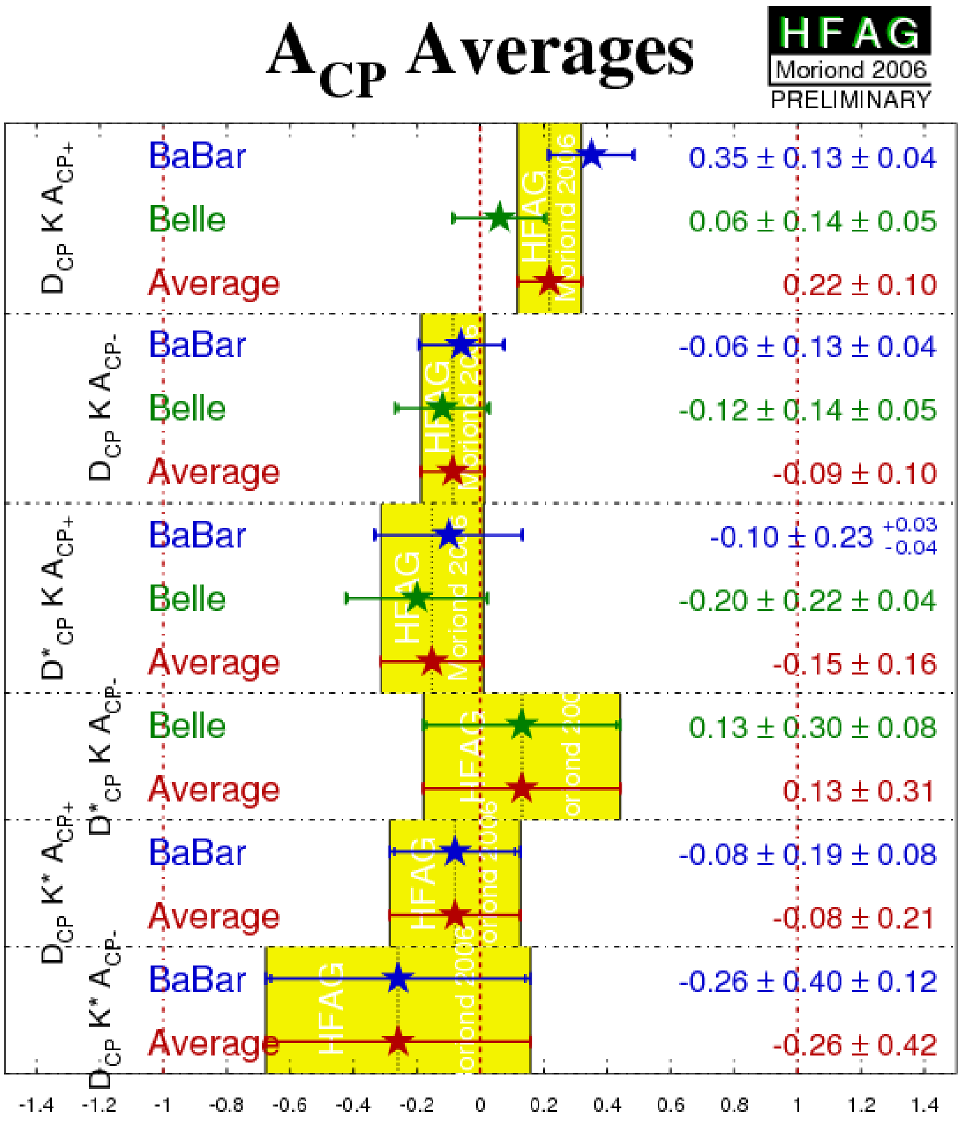
- Neglecting CP violation in charm decay

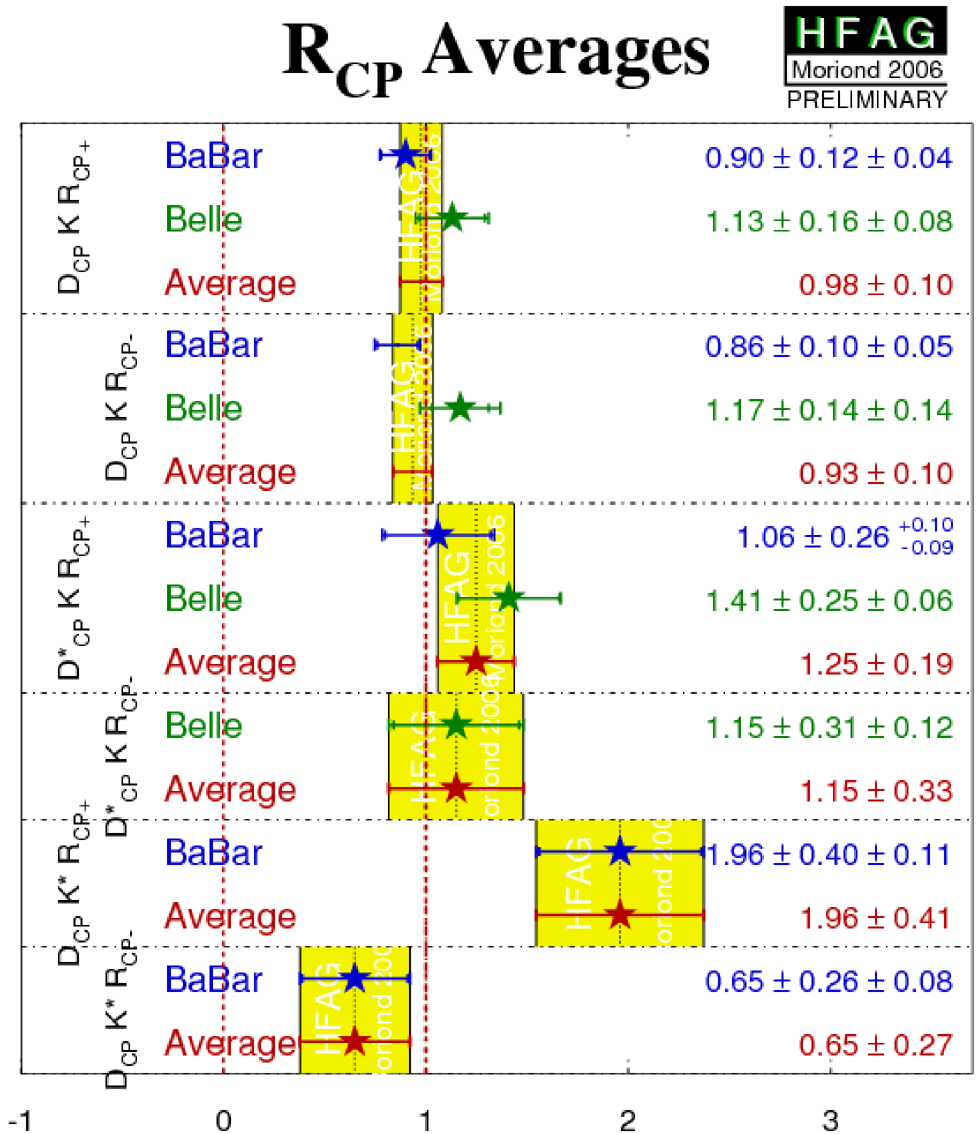
$$A(D^0 \to CP) = A(\overline{D}^0 \to CP)$$

- Possible states
  - CP even: (D_1) K^+K^-, $\pi^+\pi^-$, $K_s\pi^0\pi^0$
  - CP odd: (D_2) $K_s\pi^0$, $K_s\eta$, $K_s\eta'$, $K_s\rho^0$, $K_s\omega$, $K_s\varphi$



Experimental Summary

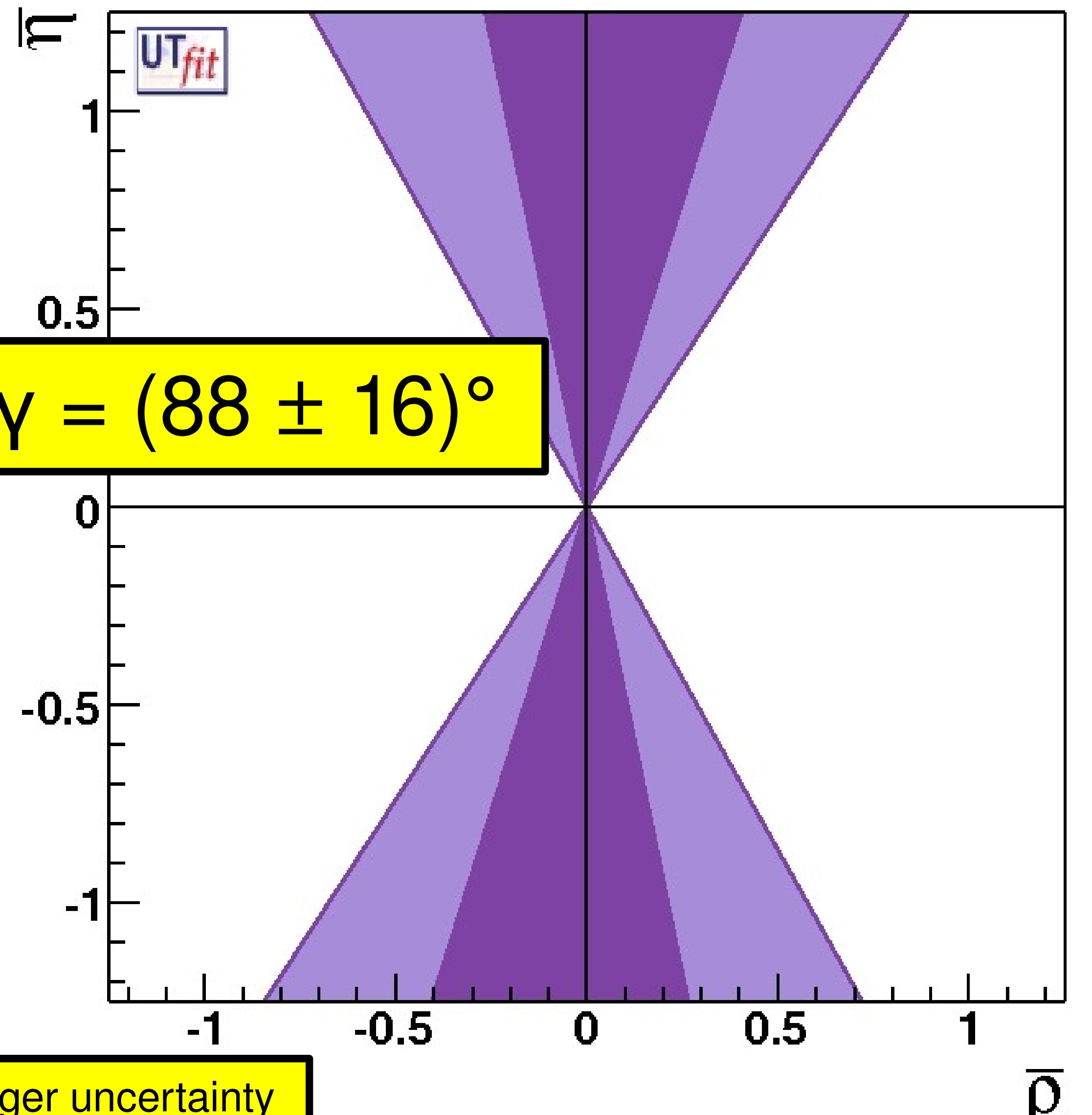




Constraint from γ

Best constraint from combining all available results

- $B \to DK$, $B \to D^{(*)}K$, $B \to DK^{(*)}$
- Different D decays
  - $D \to CP$ eigenstates
  - $D \to$ suppressed states
    - (eg. $K\pi$)
  - $D \to$ multibody states
    - (eg. $K_S\pi^+\pi^-$)

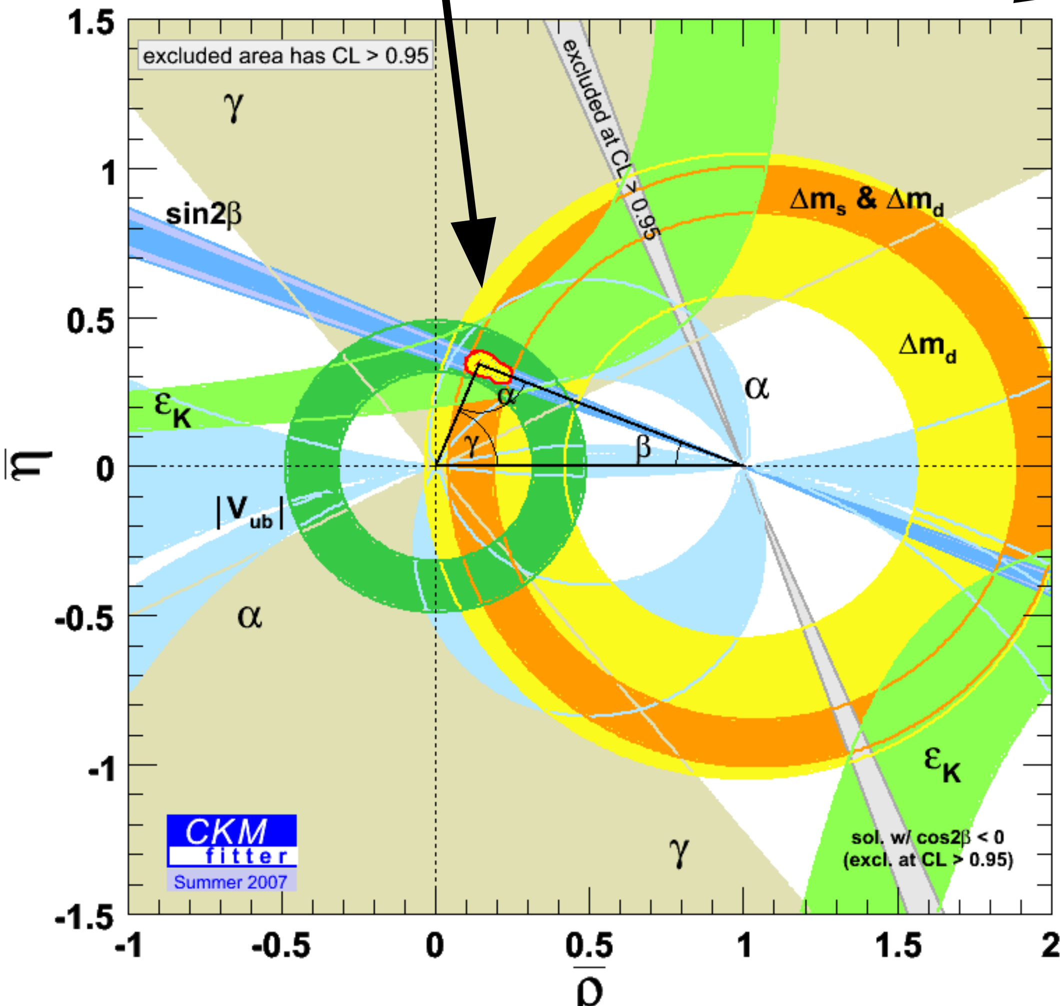


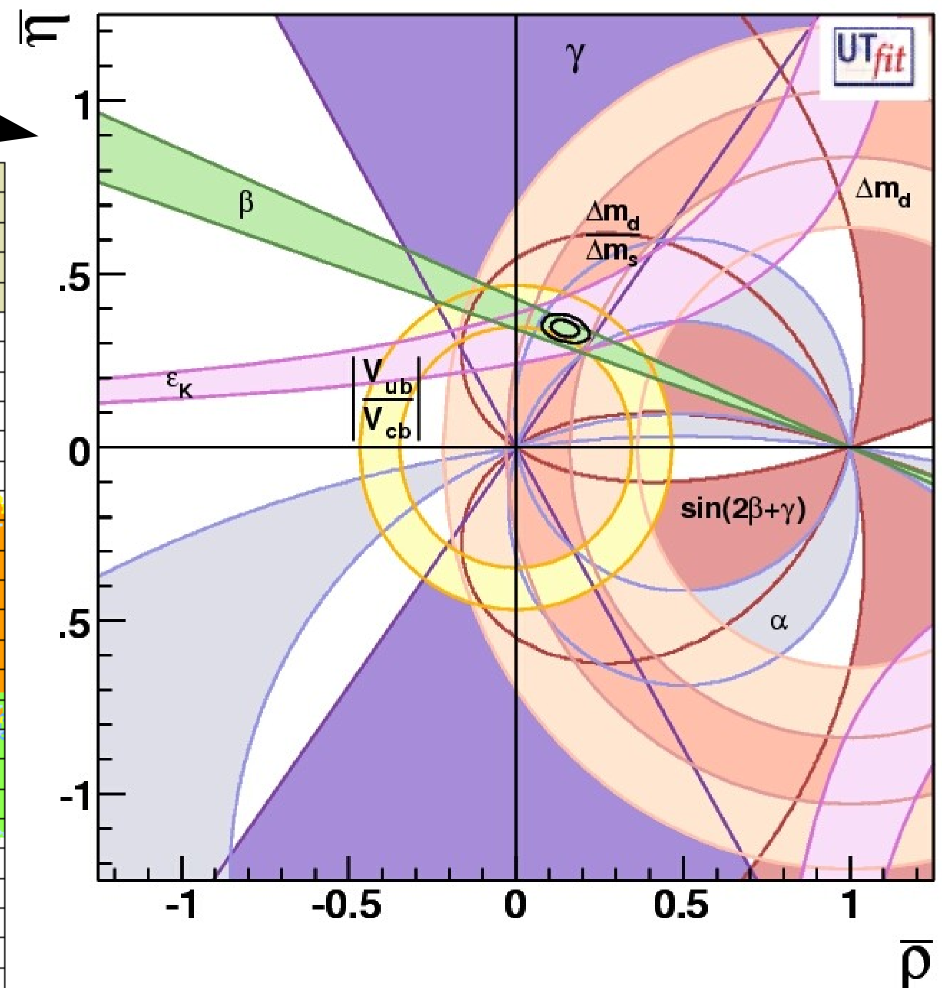
$\gamma = (88 \pm 16)°$

NB. Other statistical approaches give much larger uncertainty

Consistency of measurements with the KM mechanism

Different statistical approaches





... same answer

Dual Goals of CKM Metrology

- Unitarity Triangle parameters are fundamental in the Standard Model
  - We should measure them as well as possible
- Flavour provides an excellent arena to search for New Physics effects
  - History: Effects from higher scales seen
  - Most NP models predict inconsistencies with CKM Unitarity Triangle
- Certainly need to reduce current errors (~10%)

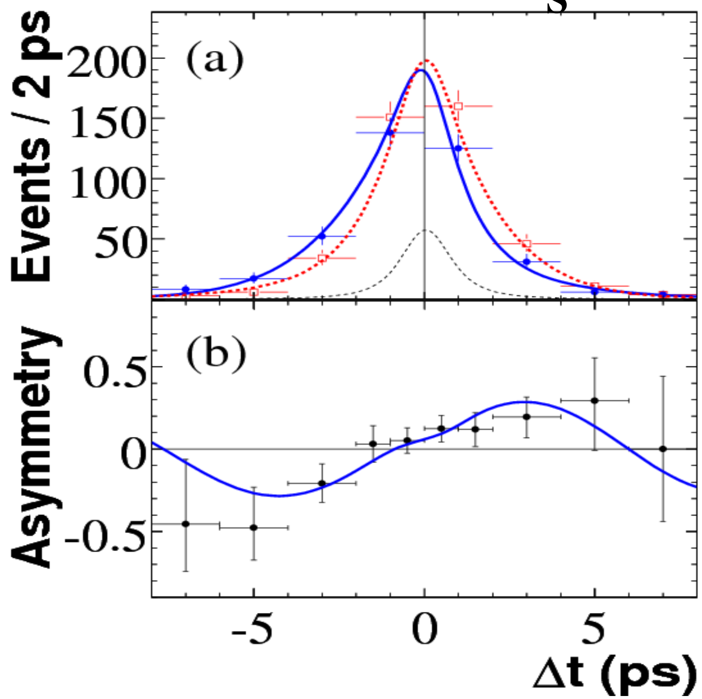
Searches for New Physics

- Massive, beyond SM, particles may contribute to B decay processes in loop diagrams
  - same true for kaon, charm & charged lepton physics
  - strong constraints in NP model building (flavour problem)
- Particularly interesting (not yet well tested) are $b \to s$
  - B_s mixing
  - $b \to sg$ (eg. time-dependence in $B^0 \to \phi K_S$, etc.)
  - $b \to s\gamma$ (eg. rates and moments, TDCPV in $B^0 \to K_S\pi^0\gamma$)
  - $b \to sll$ (eg. FB asymmetry in $B \to K^*ll$)
  - $b \to s\nu\nu$ (also $s \to d\nu\nu$)

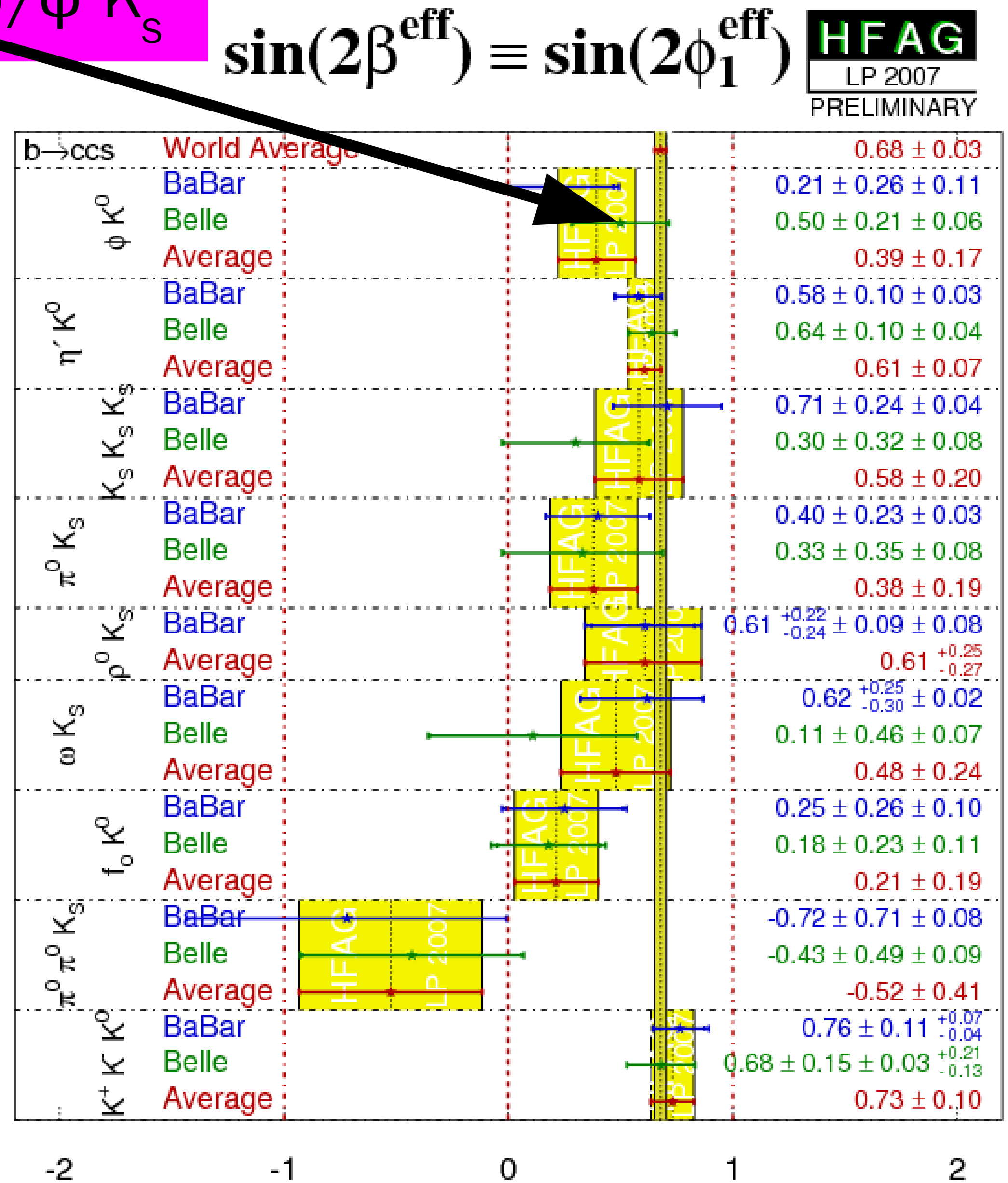
Discrepancies in hadronic b→s TDCPV

SM expectation : same as $B^0 \to J/\psi\, K_S$

BABAR - $B^0 \to \eta' K_S$



PRL 98 031801 (2007)



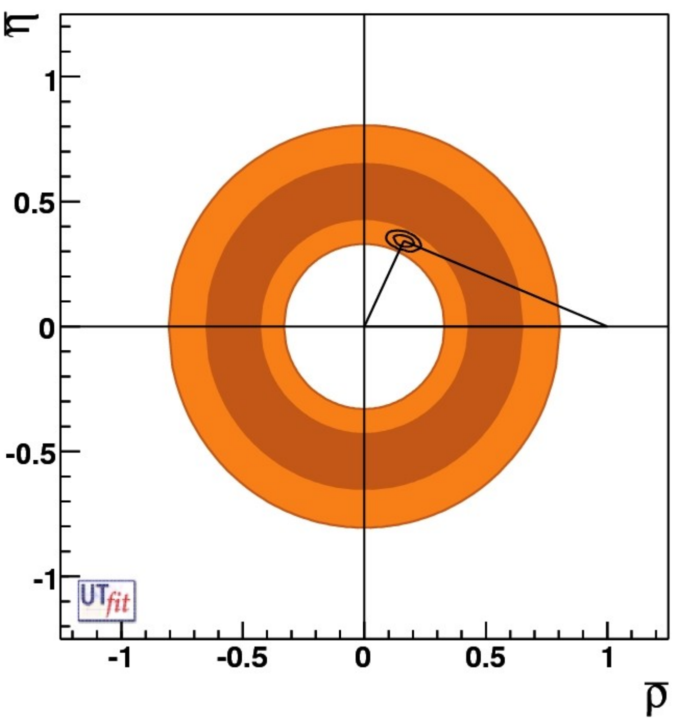
Improved & additional measurements essential

Discrepancies in leptonic B decays

- Interesting alternative approach to $|V_{ub}|$

$$\mathcal{B}(B^- \to \ell^- \overline{\nu}) = \frac{G_F^2 m_B m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 f_B^2 |V_{ub}|^2 \tau_B$$

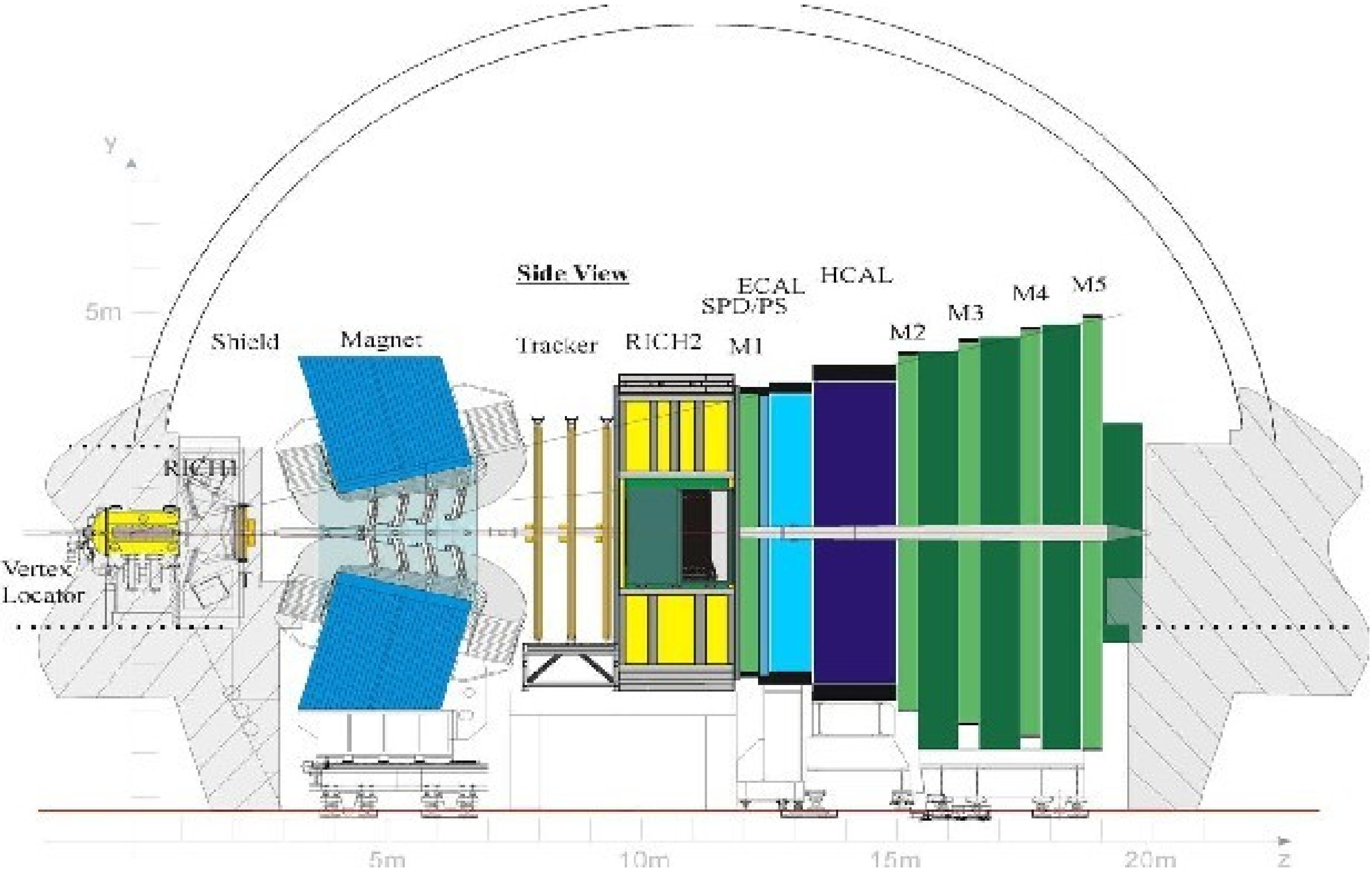
- Sensitive to corrections from new physics (charged Higgs)
- First evidence for this decay:
  - $B(B^- \to \tau^- \nu) = (1.8 \pm 0.5 \pm 0.5) \times 10^{-4}$
  - BELLE – PRL 97 (2006) 251802



The Future of Flavour Physics

- B sector
  - LHC will produce copious amounts of B mesons (and also D mesons, B&D baryons, τ leptons, ...)
  - LHCb is dedicated B physics experiment
  - Difficulties
    - triggering interesting events
    - maintaining manageable trigger rate
    - reconstructing neutral particles

LHCb detector

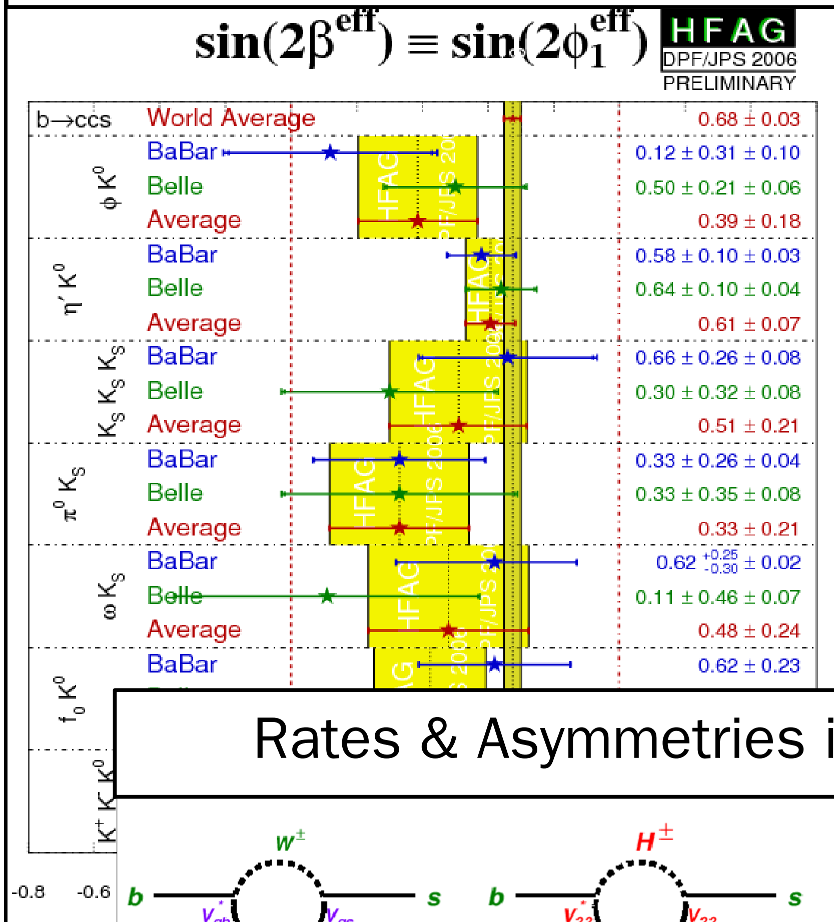


LHCb & Super Flavour Factory

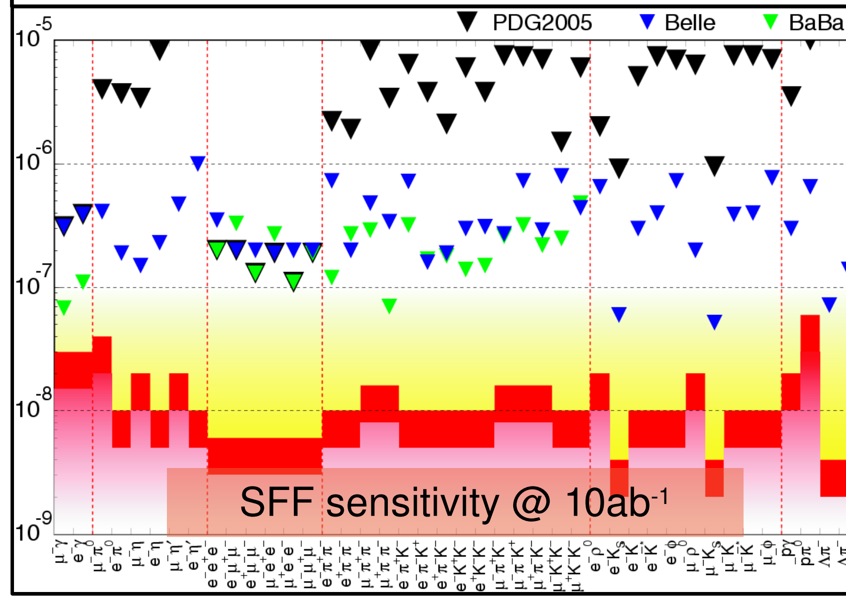
- LHCb will provide essential information on numerous important modes that cannot be studied elsewhere
  - eg. $B_s \rightarrow J/\psi\varphi$, $B_s \rightarrow D_s^+D_s^-$, $B_s \rightarrow K^+K^-$, $B_s \rightarrow D_s^+K^-$, etc.
  - ATLAS and CMS can also contribute for, eg. $B_{s,d} \rightarrow \mu^+\mu^-$
- However, there are certain channels that are impossible for LHCb
  - modes with neutrals/neutrinos/hard trigger topologies
  - need a “Super Flavour Factory”

Super Flavour Factory
Key Measurements

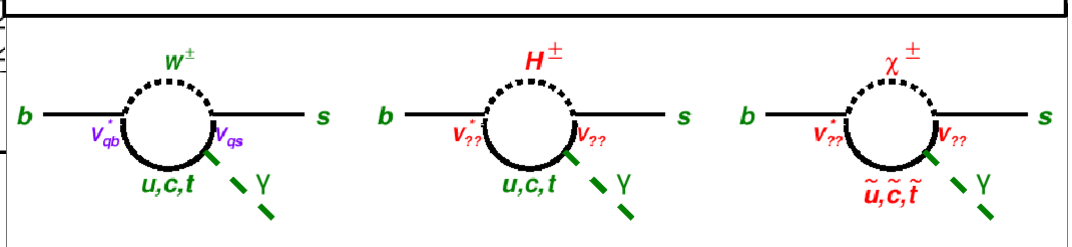
CP Violation in Hadronic b→s



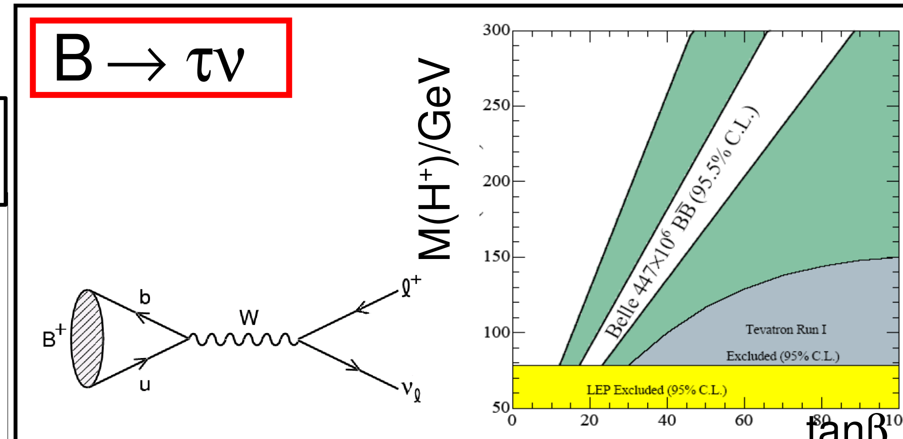
Lepton Flavour Violation in τ Decay



Rates & Asymmetries in b→sγ

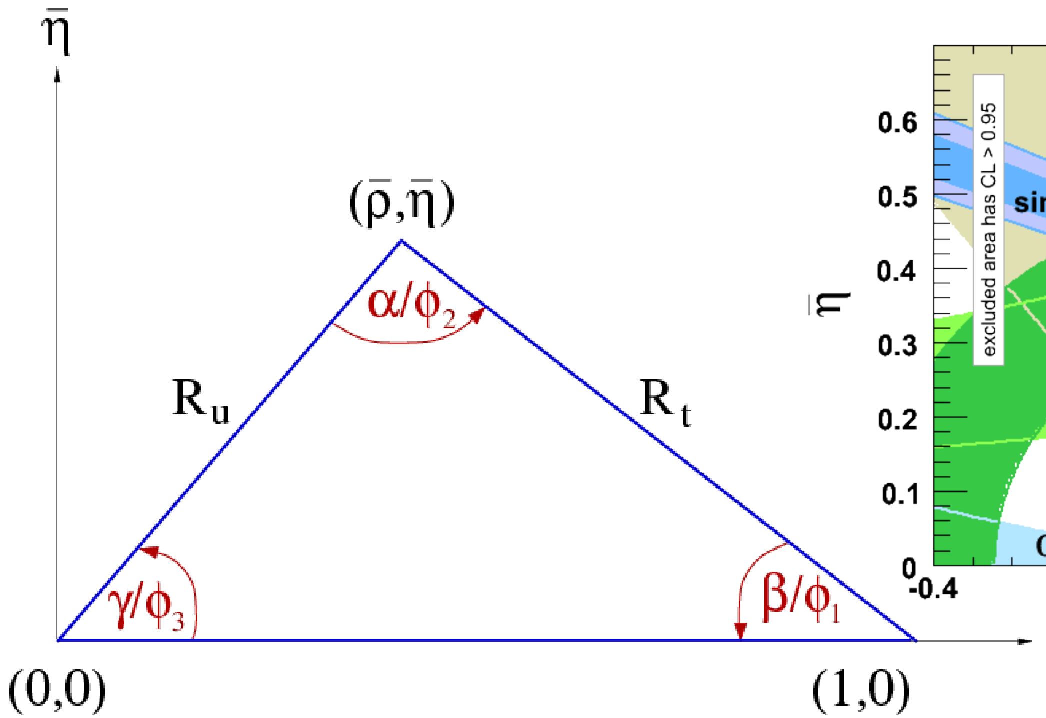


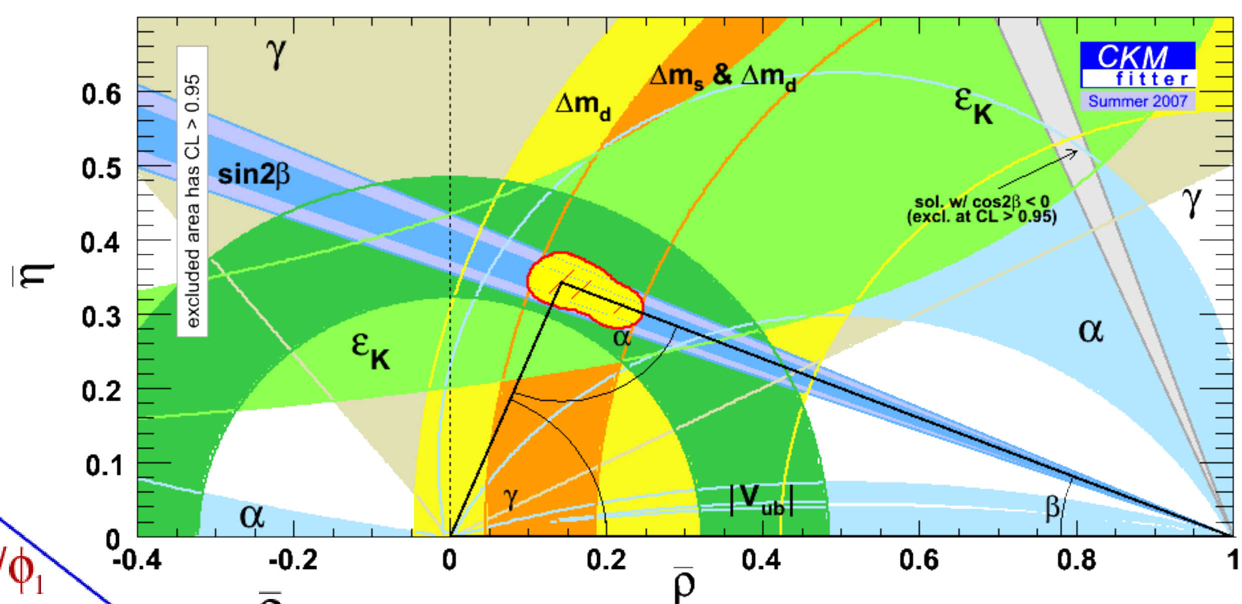
B → τν



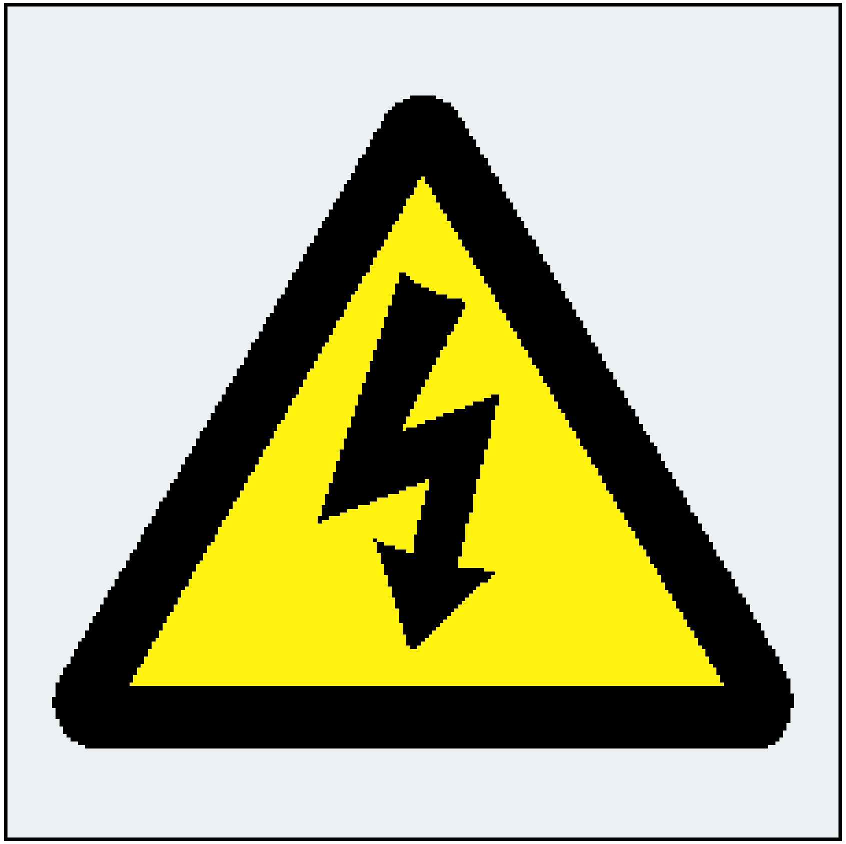
Summary

- Enormous progress by B factories to measure Unitarity Triangle and constrain flavour sector
- Still at the beginning of the programme ...
  - LHCb, KEKB upgrade, Super*B*, LHCb upgrade, ...





Back Up



Jarlskog

- All unitarity triangles have the same area
  - $A = J/2$
  - J is the Jarlskog invariant
  - $J = c_{12}\, c_{23}\, c_{13}^2\, s_{12}\, s_{23}\, s_{13} \sin\delta \sim 4\ 10^{-5}$
    - invariant measure of CP violation in the quark sector
  - $|J| = \mathrm{Im}(V_{ij}\, V_{kl}\, V_{kj}^*\, V_{il}^*)$, for any choice of ijkl ($i \neq k$; $j \neq l$)
  - J related to commutator of mass matrices
    - $[M,M'] = iC \quad \det(C) = -2\, F\, F'\, J$
    - $F = (m_t - m_c)(m_t - m_u)(m_c - m_u)$
    - $F' = (m_b - m_s)(m_b - m_d)(m_s - m_d)$

Some theory papers

- Ellis, Gaillard, Nanopoulos & Rudaz, NPB 131, 285 (1977)
- Bander, Silverman & Soni, PRL 43, 242 (1979)
  - CP violation may be large in the B system
- Carter & Sanda, PRD 23, 1567 (1981)
  - time-dependence in $e^+e^- \rightarrow \Upsilon(4S) \rightarrow B^0\underline{B}^0$
- Bigi & Sanda, NPB 193, 85 (1981)
  - $B^0 \rightarrow J/\psi\ K_S$ and other possible decay modes

Comment on theoretical tools

- Most significant theoretical uncertainties in quark flavour physics arise due to *hadronization*
  - strong interaction effects – not calculable peturbatively
  - precision will be improved with lattice QCD calculations
  - alternative: QCD sum rules (parton-hadron duality)
- Operator product expansion
  - match physics to relevant *scales*
- For kaon physics, utilize approximate chiral symmetry of low energy QCD
  - chiral perturbation theory

Neutral B mixing parameters

- Recall: $q/p = -(\Delta m - \tfrac{1}{2}i\Delta\Gamma)/2(M_{12} - \tfrac{1}{2}i\Gamma_{12})$

  $(\Delta m)^2 - \tfrac{1}{4}(\Delta\Gamma)^2 = 4(|M_{12}|^2 + \tfrac{1}{4}|\Gamma_{12}|^2)$ $\Delta m\Delta\Gamma = 4\mathrm{Re}(M_{12}\Gamma_{12}^*)$

- In the neutral B system $\Delta m \gg \Delta\Gamma$

  $\Delta m \sim 2|M_{12}|$ $\Delta\Gamma \sim 2\mathrm{Re}(M_{12}\Gamma_{12}^*)/|M_{12}|$ $q/p \sim -|M_{12}|/M_{12}$

- $|M_{12}|$ from mixing diagram

  $\Rightarrow$ $q/p \sim e^{-2i\beta}$ (in the usual phase convention)

Comment on theoretical tools (2)

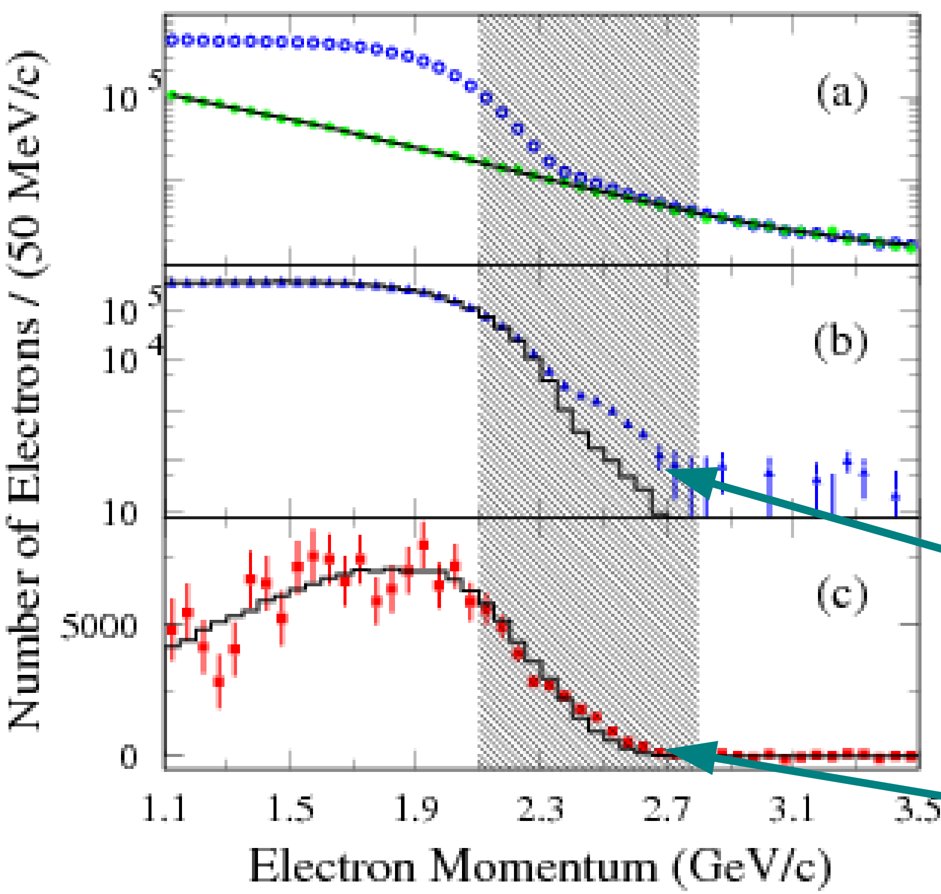
- In B physics, can exploit the fact that $m_b >> \Lambda_{QCD}$
  - heavy quark expansion & heavy quark efffective theory
  - factorization
    - QCD factorization
    - soft collinear effective theory (SCET)
- Phenomenological treatments also very useful
  - SU(3)
  - isospin
  - U-spin

Measurement of $|V_{cb}|$

- Possible methods to measure $|V_{cb}|$ very similar to those for $|V_{ub}|$
- Current best method uses
  - inclusive semileptonic decay rates for $B \rightarrow X_c l\nu$
  - moments of decay distributions in $m(X_c)$ & q^2
    - fit to extract theoretical parameters from data
  - moments of E_γ in $B \rightarrow X_s\gamma$ decays also used
- PDG 2006 gives $|V_{cb}| = (41.4 \pm 0.6) \times 10^{-3}$

$|V_{ub}|$ inclusive - endpoint analysis

- Best current measurement PRD 73, 012006 (2006)



$$\ldots_u e\nu) = \qquad (9)$$

$$.26_{exp}\ {}^{+0.33}_{-0.28}\ {}_{SF} \pm 0.17_{theory}) \times 10^{-3},$$

$$(10)$$

$$.25_{exp}\ {}^{+0.42}_{-0.38}\ {}_{SF} \pm 0.22_{theory}) \times 10^{-3}.$$

non BB background subtracted

$X_c\ l^+\ \nu$ background subtracted