Status and Prospects of CP Violation Experiments

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- Recent quests for CP violation
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- Where are the still interesting signals
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Introduction

- Significance of Symmetries in particle physics:
  - Symmetry is a fundamental concept for constructing laws of physics:
    e.g. spatial translation → momentum conservation

Introduction

- Significance of Symmetries in particle physics:
  - Symmetry is a fundamental concept for constructing laws of physics:
    e.g. spatial translation → momentum conservation
  - Symmetry breaking can reveal dynamics:
    e.g. parity violation → Lorentz structure of the weak interactions

Introduction

- CP violation: experimental discovery came first

1964, J.H. Christenson et al., $Br(K^0_L \to \pi^+\pi^-) \neq 0$

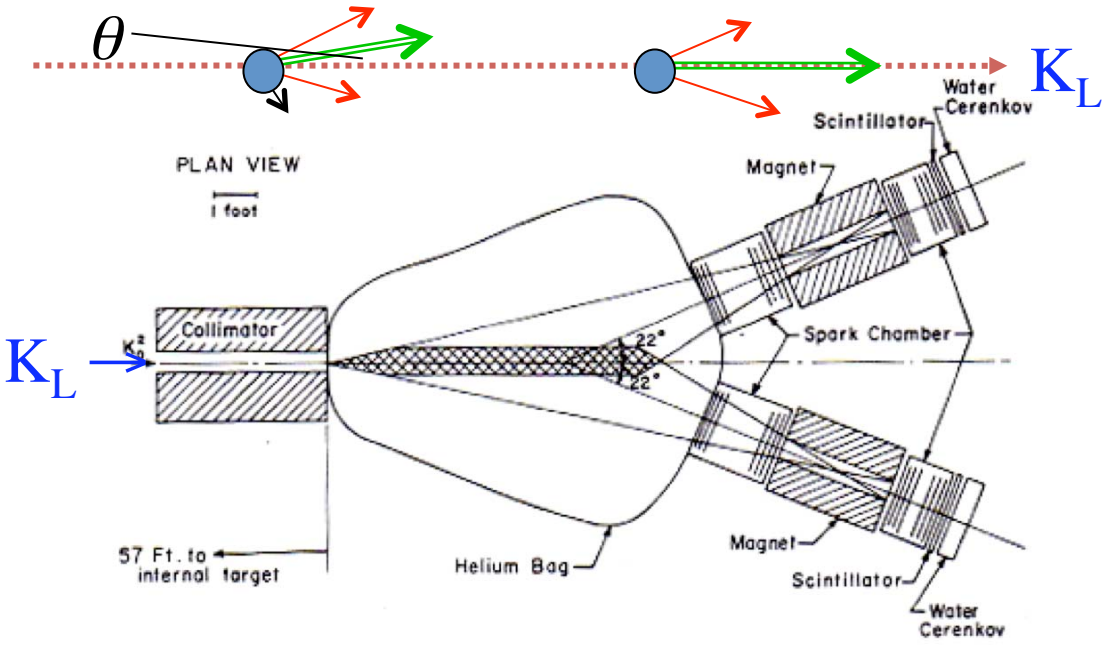
$K_L \to \pi^+\pi^- X^0$

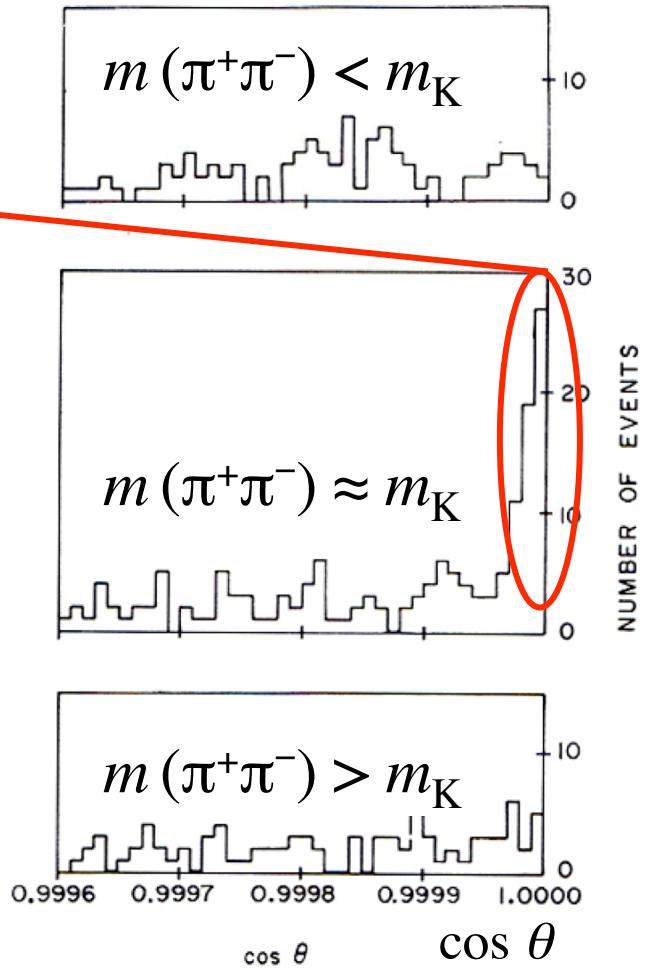
$p_{+-} = p_{\pi^+} + p_{\pi^-}$

θ = angle between p_{K_L} and p_{+-}

If $X^0 = 0$, $p_{+-} = p_{K_L}$: cos $\theta = 1$

If $X^0 \neq 0$, $p_{+-} \neq p_{K_L}$: cos $\theta \leq 1$





Introduction

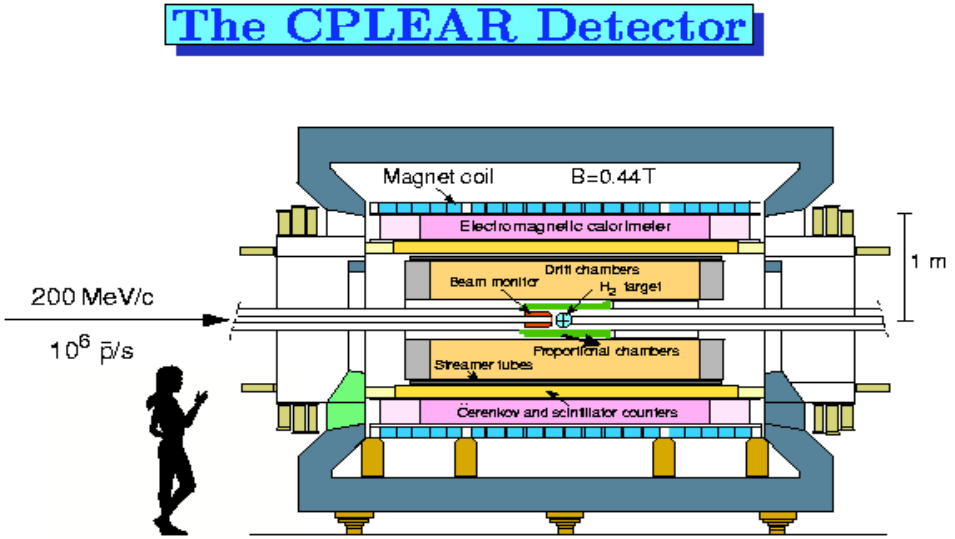
- Event by event tagged K^0 and $\overline{K}^0$
  - CPLEAR experiment

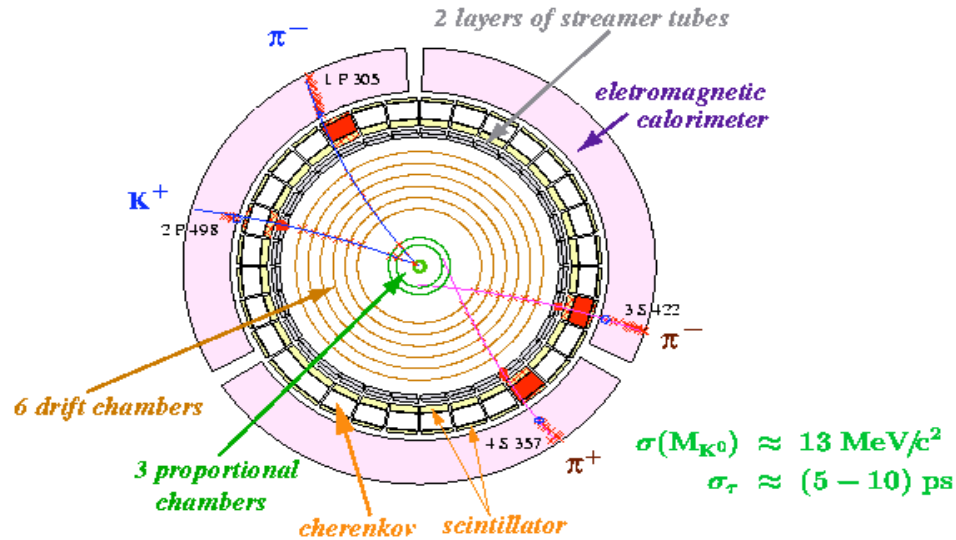
$$p\bar{p} \begin{cases} \nearrow K^-\pi^+K^0 \\ \searrow K^+\pi^-\overline{K}^0 \end{cases}$$

Initial K^0 and $\overline{K}^0$

$\rightarrow 2\pi$, 3π, $l^\pm\pi^\mp\nu_l$ at t

CP and T violation measurements





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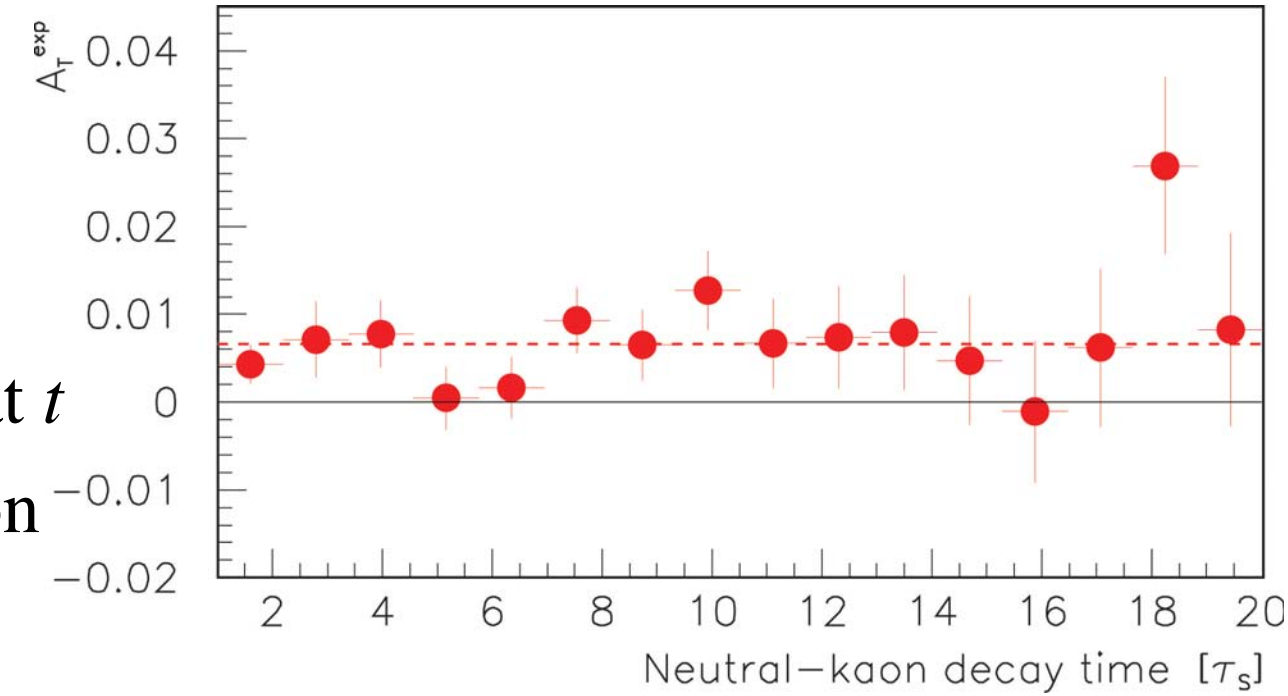
$$A_T(t) = \frac{\overline{K}^0{}_{t=0} \to e^+\pi^-\nu(t) - K^0{}_{t=0} \to e^-\pi^+\nu(t)}{\overline{K}^0{}_{t=0} \to e^+\pi^-\nu(t) + K^0{}_{t=0} \to e^-\pi^+\nu(t)}$$

$$p\bar{p} \begin{cases} \nearrow K^-\pi^+K^0 \\ \searrow K^+\pi^-\overline{K}^0 \end{cases}$$

Initial K^0 and K^0

$\to 2\pi$, 3π, $l^\pm\pi^\mp\nu_l$ at t

CP and T violation measurements



$$A_T = (6.6 \pm 1.6) \times 10^{-3}$$

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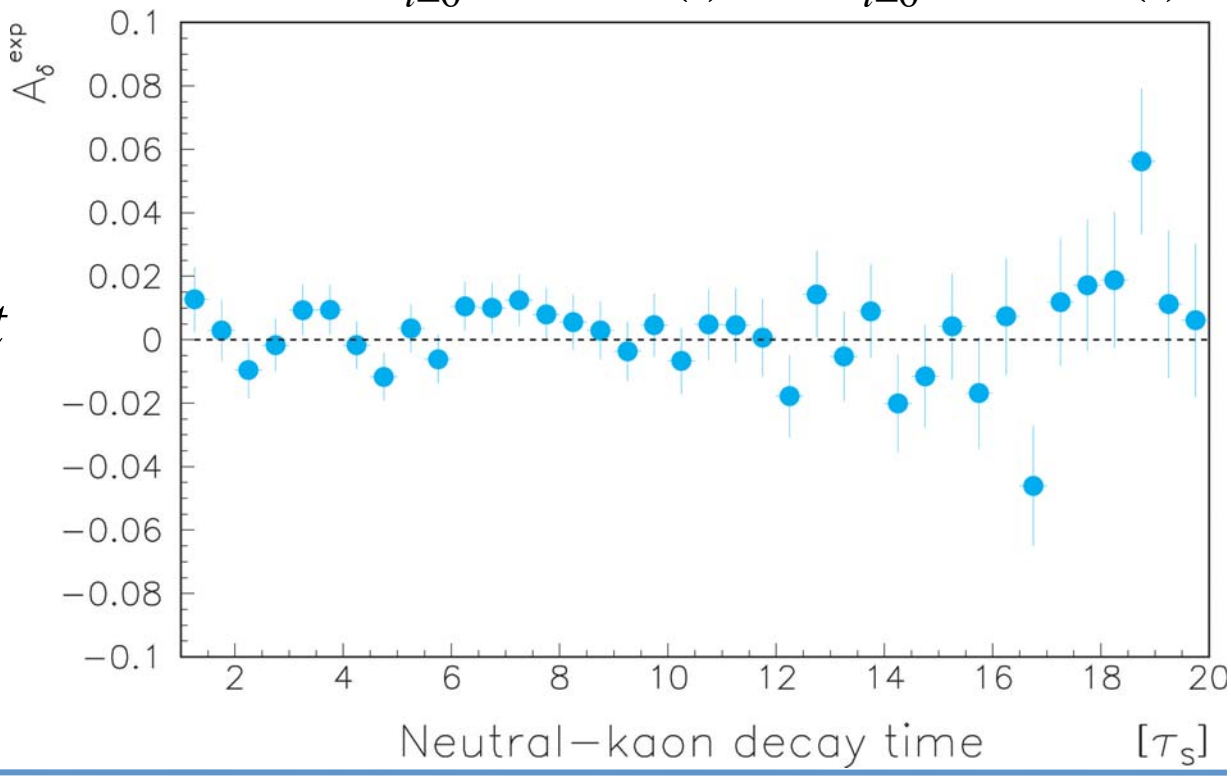
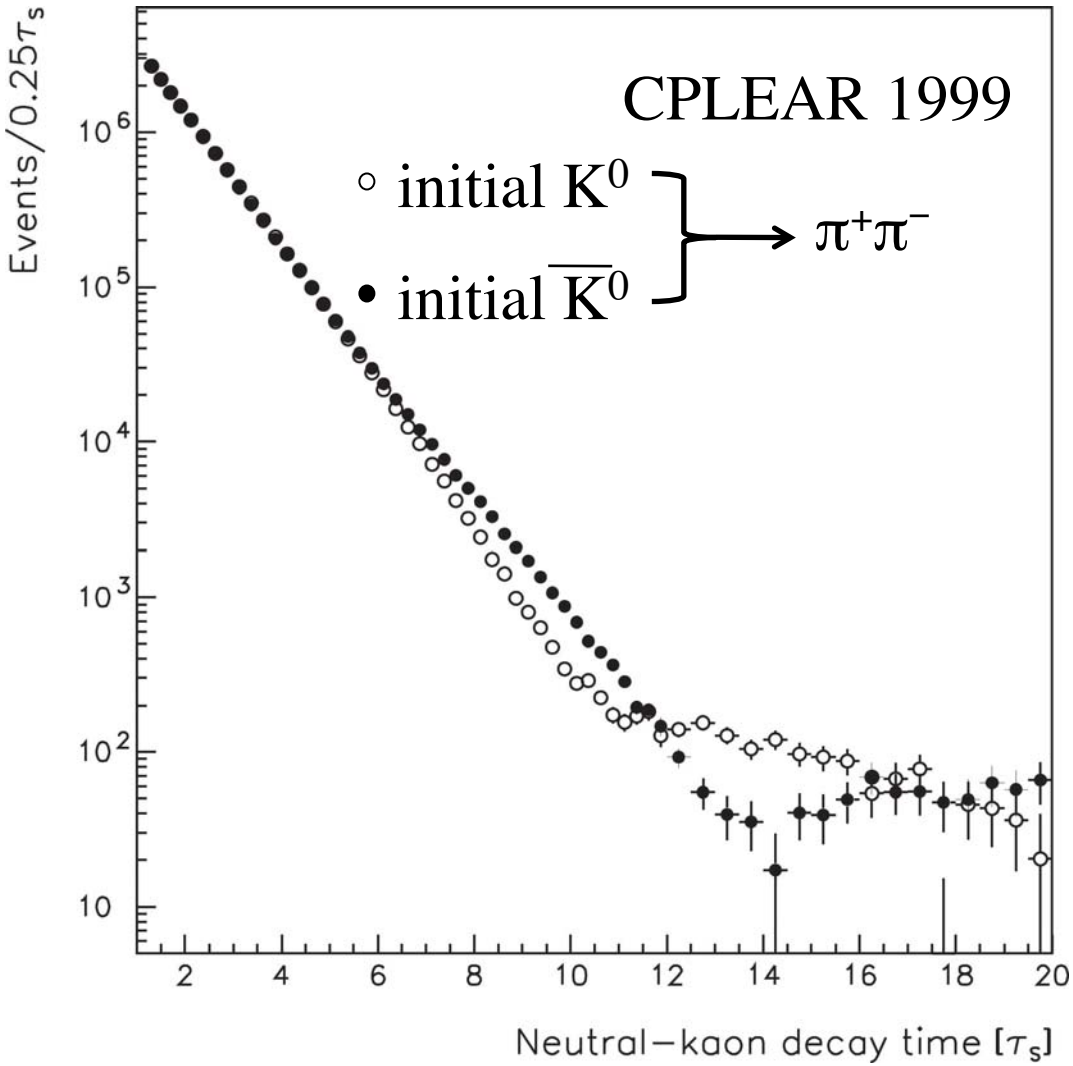
CP and T violation measurements and CPT study

$$A_{CPT}(t) \approx \frac{\overline{K}^0{}_{t=0} \rightarrow e^-\pi^+\nu(t) - K^0{}_{t=0} \rightarrow e^+\pi^-\nu(t)}{\overline{K}^0{}_{t=0} \rightarrow e^-\pi^+\nu(t) + K^0{}_{t=0} \rightarrow e^+\pi^-\nu(t)}$$



Introduction

- $K_S \to \pi^+\pi^-$(CP)-$K_L \to \pi^+\pi^-$ (~~CP~~) interference:
  - K^0 and $\overline{K}^0$ are K_S-K_L coherent sum with opposite phases



Recent quests for CP violation

- Mechanism of generating CP violation:
  - new $\Delta S = 2$ interactions with complex coupling: e.g. Superweak model Wolfenstein in 1964
  - or within the SM weak interactions via KM mechanism Kobayashi-Maskawa 1973?

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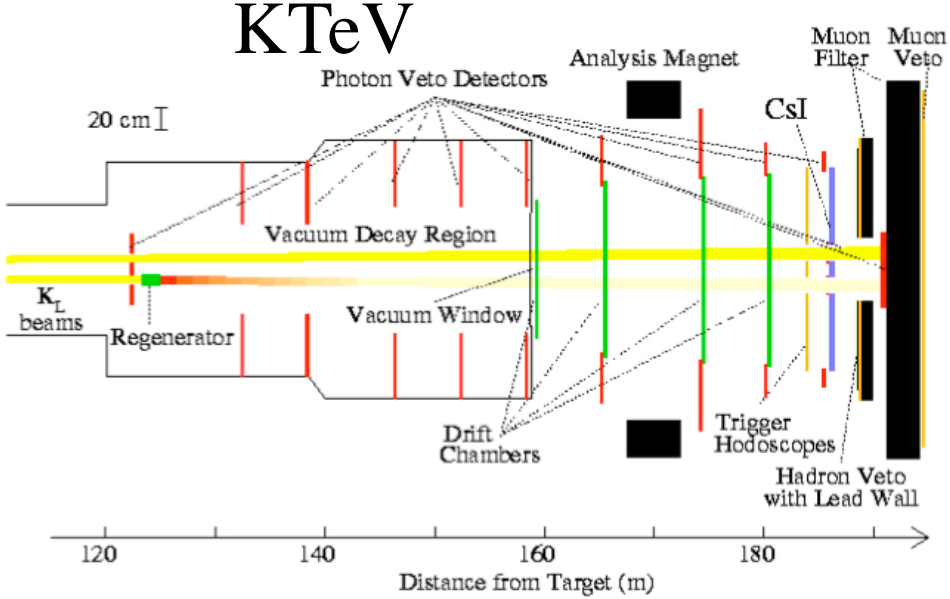
- Mechanism of generating CP violation:
  - new $\Delta S = 2$ interactions with complex coupling: e.g. Superweak model Wolfenstein in 1964
  - or within the SM weak interactions via KM mechanism Kobayashi-Maskawa 1973?
- Superweak model does not generate CP violation in the decay amplitudes: i.e. $\mathrm{Re}(\varepsilon') = 0$.
- Early SM theoretical estimates for

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = \frac{1}{3}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|\right) \approx 0.01 \text{ (Gilman\&Wise 1979)}$$

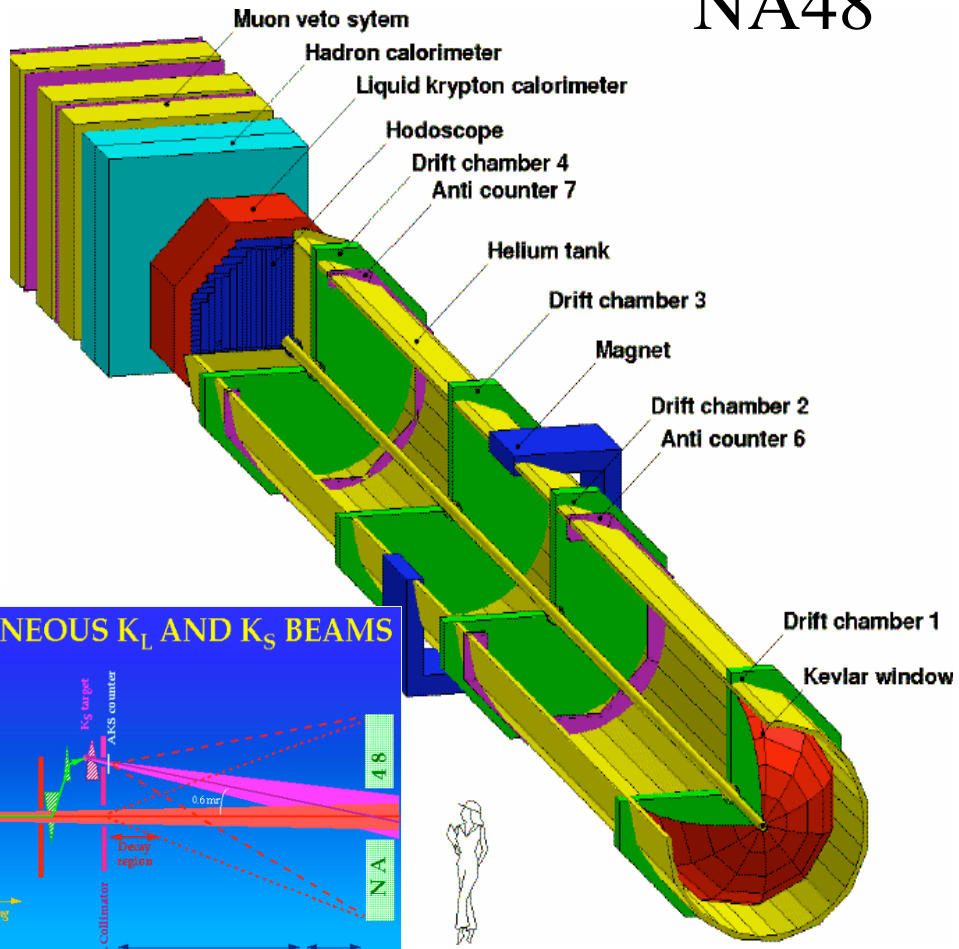
Recent quests for CP violation

- Experimental effort to measure Re (ε'/ε) continued

KTeV



NA48



K_S-K_L double beam
Simultaneous $\pi^+\pi^-$ and $\pi^0\pi^0$ detections

Recent quests for CP violation

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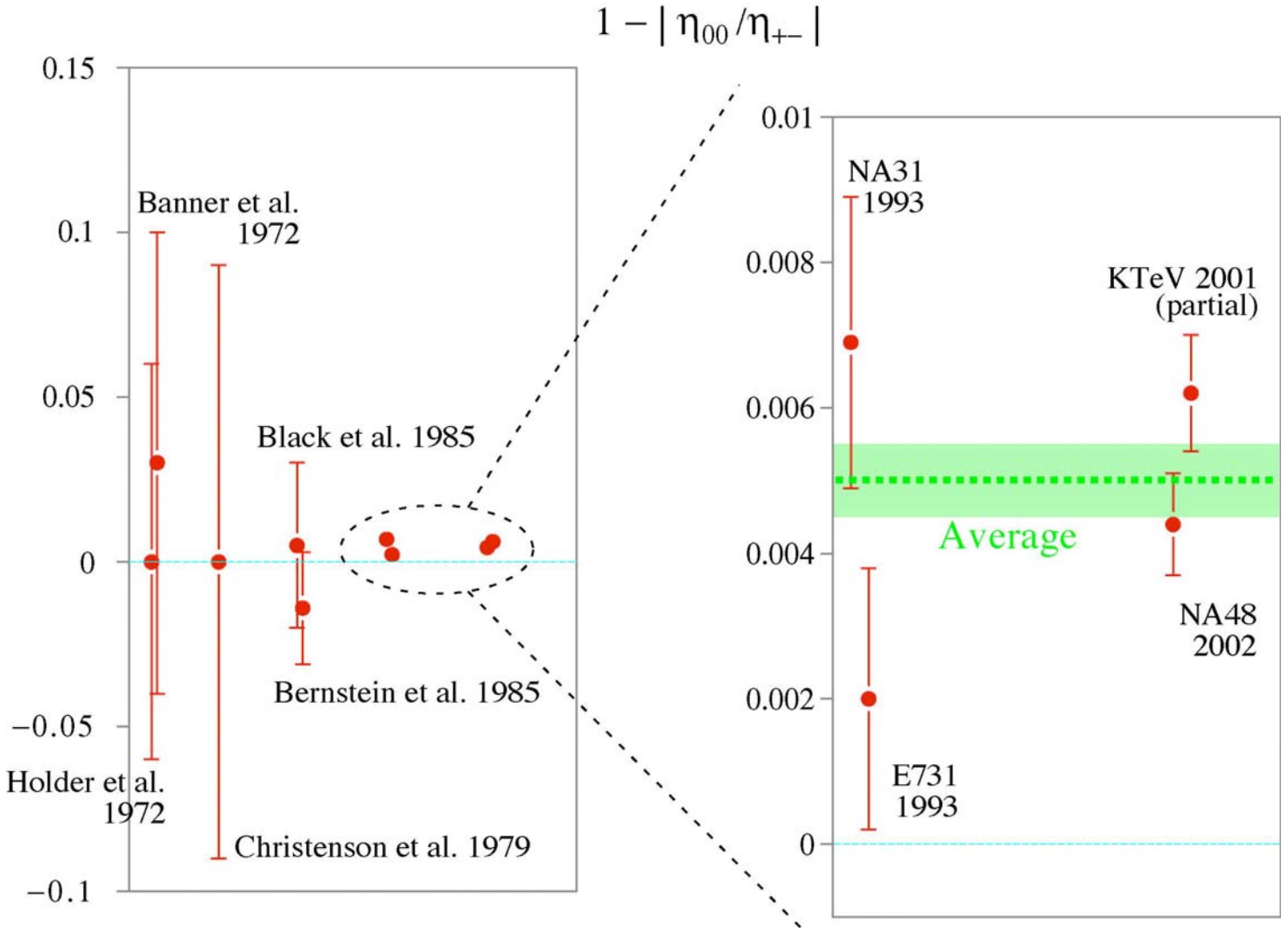

Recent quests for CP violation

- Current measurements
  $\mathrm{Re}\,(\varepsilon'/\varepsilon) = (1.65 \pm 0.26)\times 10^{-3}$ (PDG 2008)
- Since 1979, theoretical values has decreased; large m_t, EW penguins, etc. (some even negative now!)
  And with still large hadronic uncertainties.
  On going effort in the lattice calculations.
  No experimental effort to reduce the current errors is foreseen.

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  And with still large hadronic uncertainties.
  On going effort in the lattice calculations.
  No experimental effort to reduce the current errors is foreseen.
- CP violation in the decay amplitudes is present: Superweak excluded, and compatible with the SM (qualitative agreement).

Recent quests for CP violation

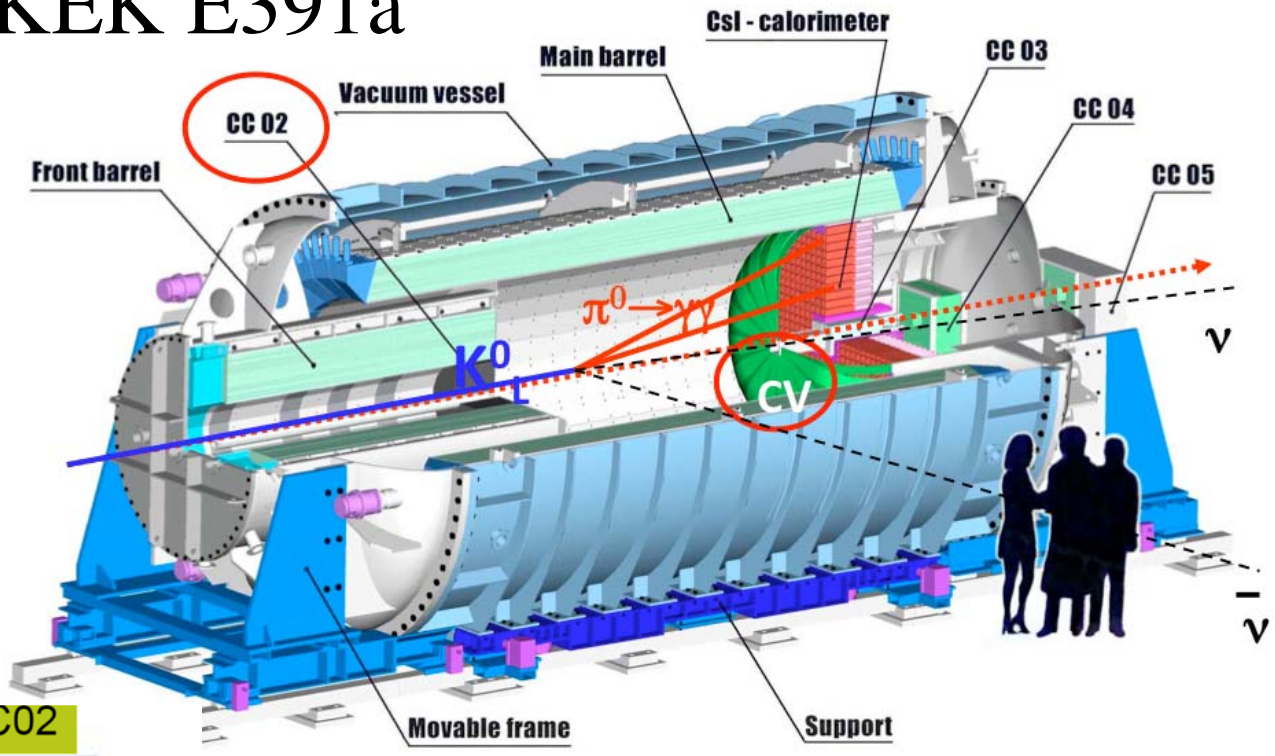
- Theoretically clean measurement is $K_L \to \pi^0 \nu\bar{\nu}$: CP violating decay generated by the interference between the decay and oscillations:
  - the phase difference is totally dominated by the V_{td}
  - other hadronic matrix elements taken from the semileptonic decays.

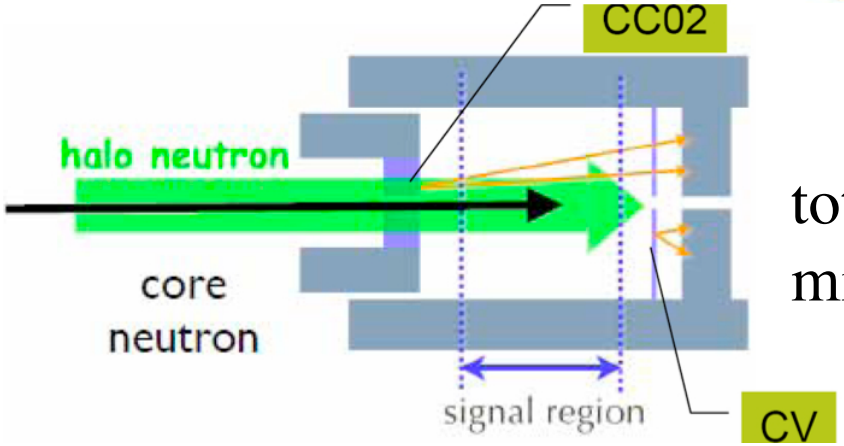
$\Rightarrow$Uncertainties in the theoretical prediction dominated by the CKM parameters.
but very small Br~3×10^{-11}.

A tough experiment: nothing decays to nothing

Recent quests for CP violation

- State of the art: KEK E391a





totally surrounded by the veto counters
minimising the neutron interactions

Recent quests for CP violation

- KEK E391a 2008

Background Source	Estimated # BG
$K^0_L \rightarrow \pi^0 \pi^0$	0.11 ± 0.09
CC02	0.16 ± 0.05
CV	0.08 ± 0.04
CV-h	0.06 ± 0.02
Total	**0.41 ± 0.11**

Recent quests for CP violation

- KEK E391a 2008
  $BR(K^0_L \rightarrow \pi^0 \nu\nu) < 6.7 \times 10^{-8}$ 90% CL

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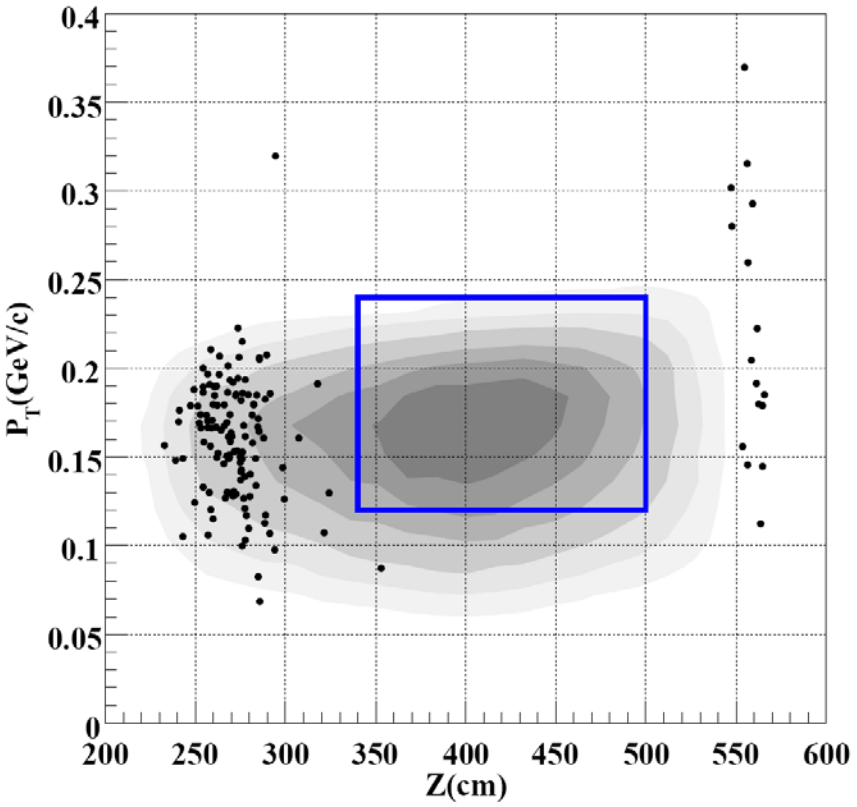

Recent quests for CP violation

- Real quantitative tests are done with the B_d mesons
  Amplitude of time dependent CP asymmetries,
  a term proportional to sin $\Delta m \cdot t \rightarrow$ theoretically clean
  depends only on the CKM parameters: "sin 2β"
- Before 1990, with the B_d-$\overline{B}_d$ oscillation frequency Δm (ARGUS 1987) and Re(ε), "sin 2β" was predicted as ~0.4 (**NB**: in 1983, $f_B \approx 110$ MeV), with little m_t dependence, i.e. large CP violation in $B \rightarrow J/\psi K_S$.

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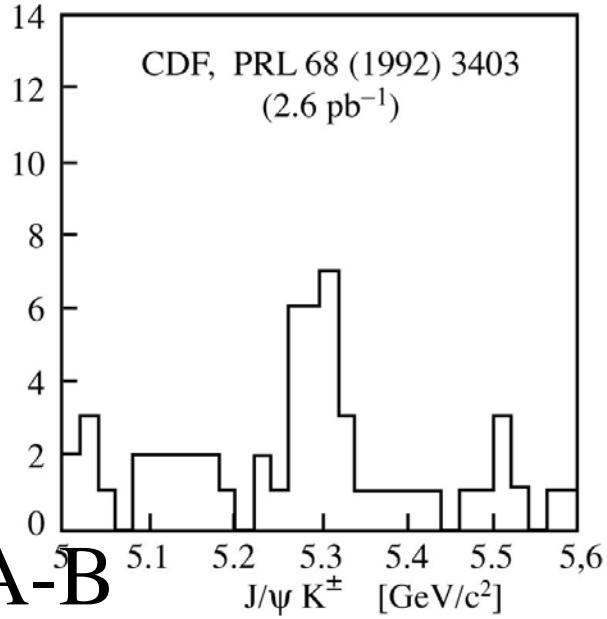
⇒ Clear benchmark luminosity for a B factory: i.e.
a few years of data taking with $L \approx 10^{33}$ cm^{-1}s^{-1}
for 5σ observation of $\not{CP}$ in $B \to J/\psi K_S$ if SM.

Recent quests for CP violation

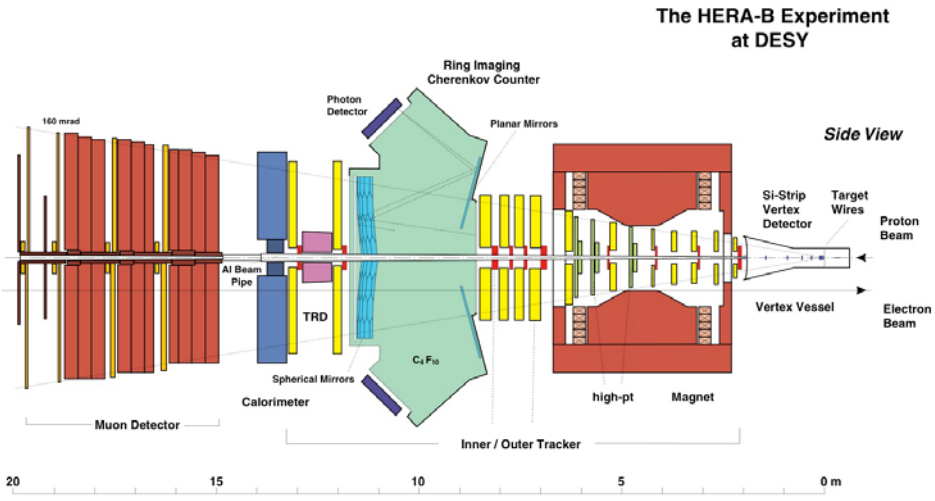
- Many attempts to construct e^+e^- B factories in Europe (CH, DE, IT, RU and CERN), Japan (KEK) and US (Cornell, SLAC, UCLA) in 1985~1990, mostly asymmetric designs with $L > 10^{33}$ cm^{-2}s^{-1}.
- KEKB (10^{34} with finite crossing angle) and PEP-II (3×10^{33} with head-on collision) approved in 1993, having the first collisions in 1998~1999.
- "Hadronic" B factory started to be interesting, but was not yet there…

Recent quests for CP violation

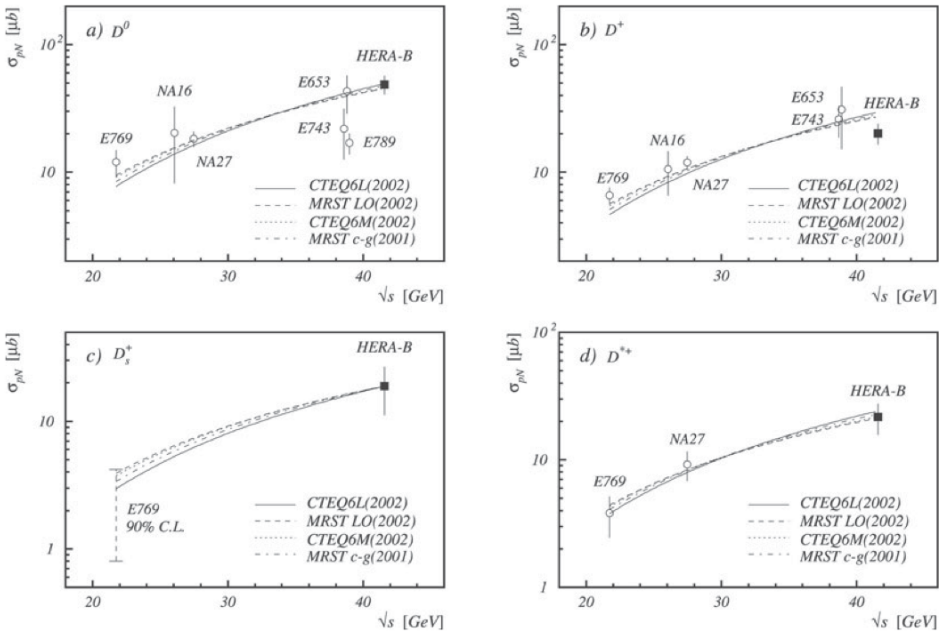
- CDF



- HERA-B

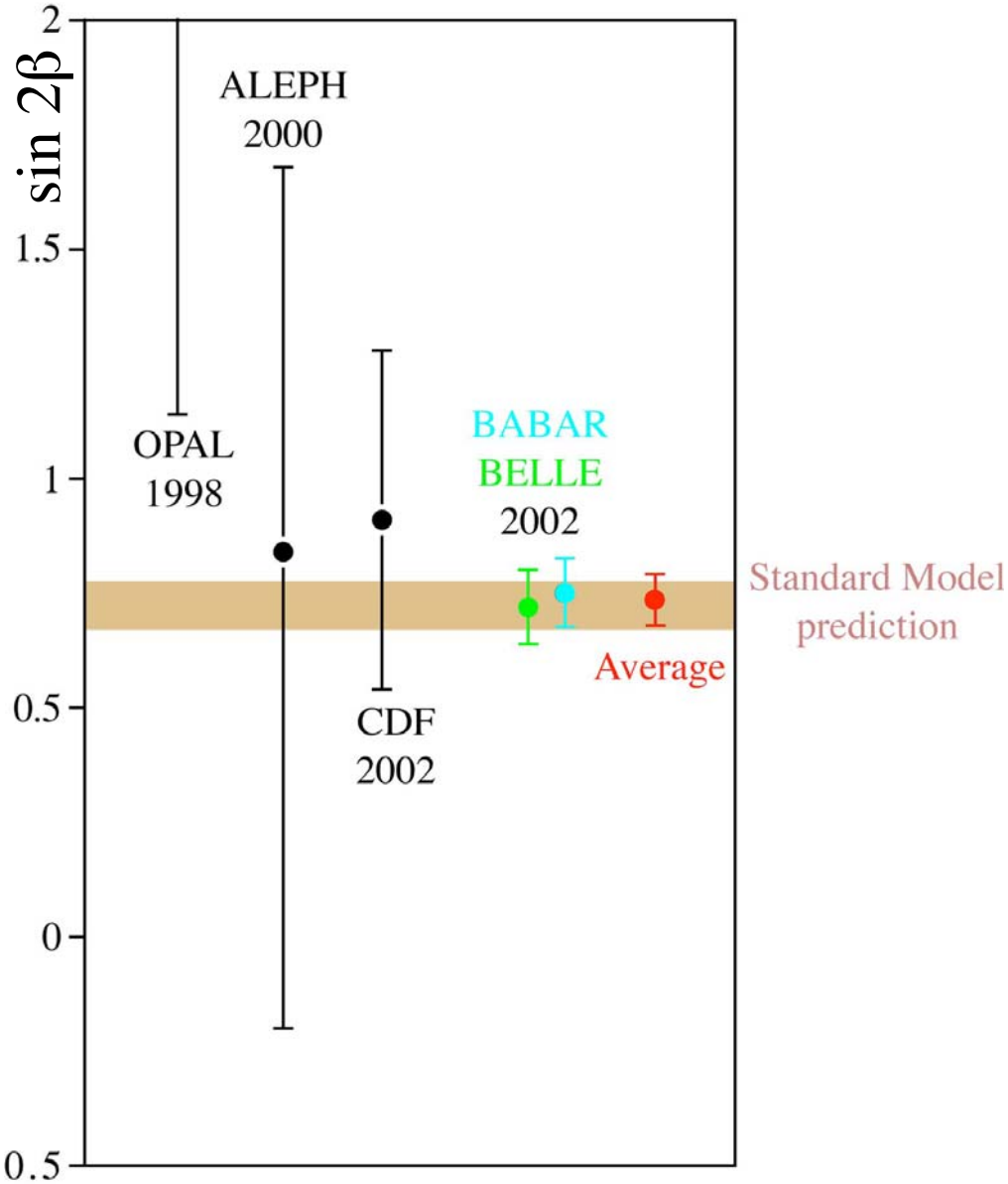


HERA-B EPJ C (2007)



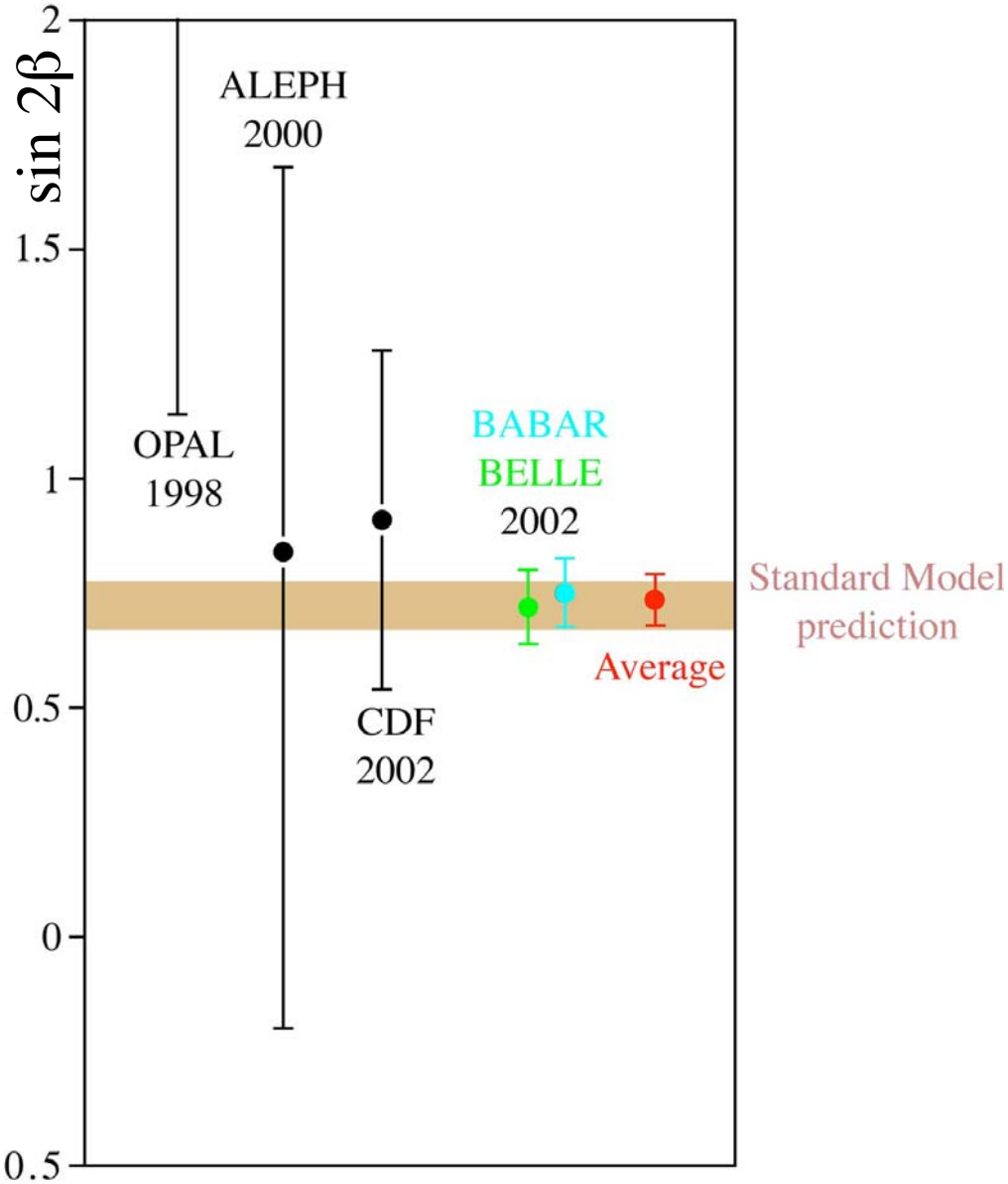
Recent quests for CP violation

- BABAR and Belle achievement in 2002
  Quantitative test of SM.



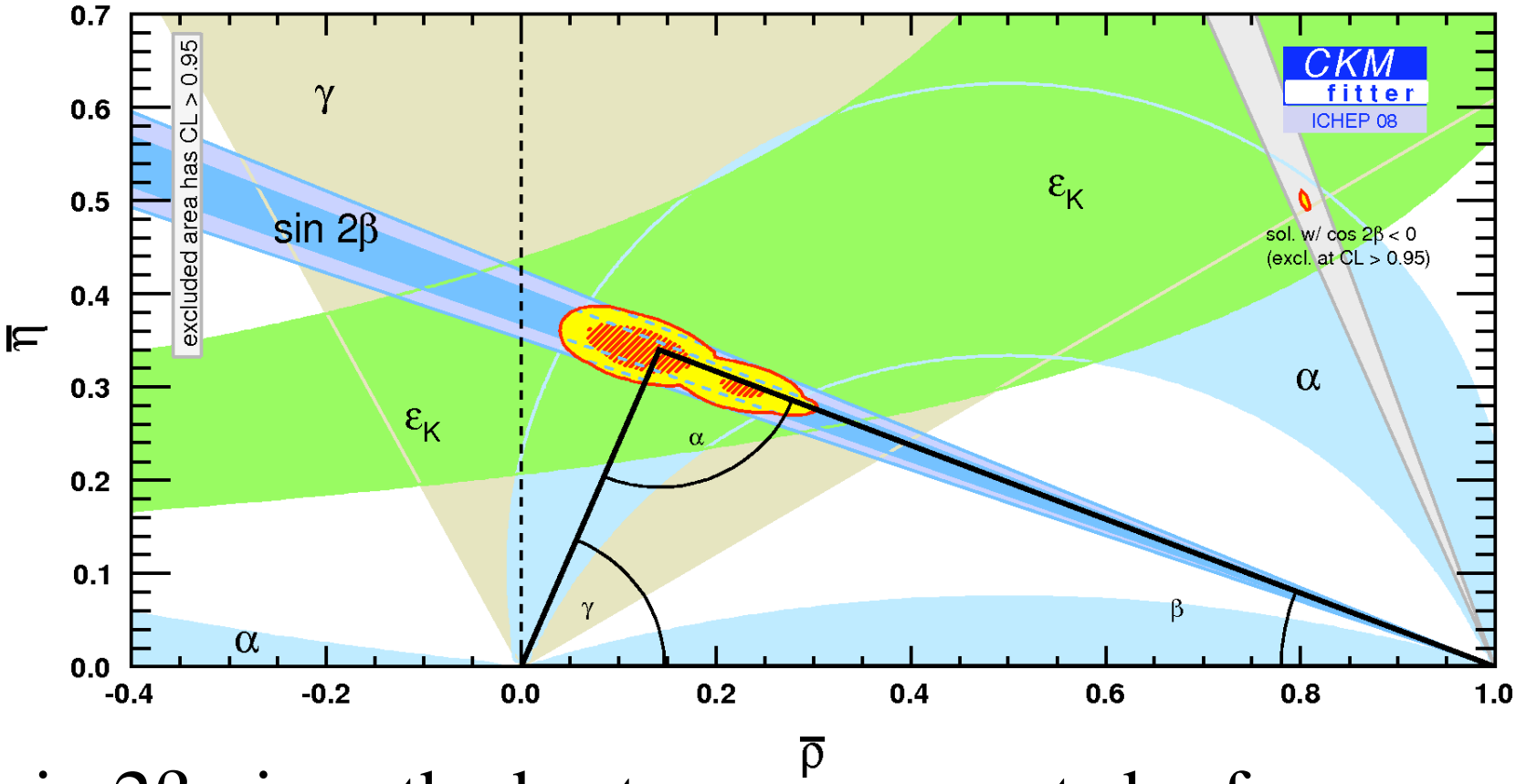
Recent quests for CP violation

- BABAR and Belle achievement in 2002
  Quantitative test of SM.
- Evidence for CP violation in the decay amplitudes $B \to K^{\pm}\pi^{\mp}$
  already in 2004 by BABAR and Belle.
  (cf how long it took for K)



Recent quests for CP violation

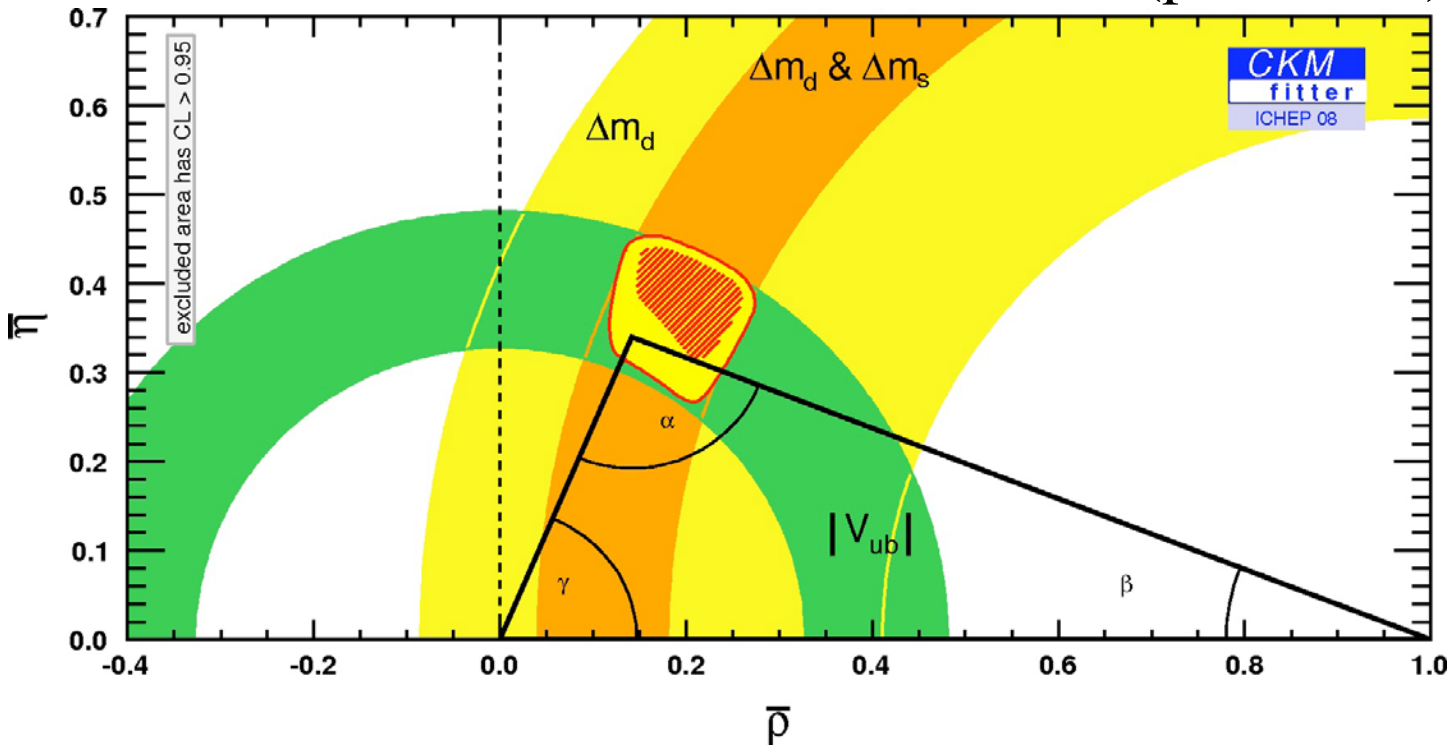
- K and B CP violation measurements now are perfectly consistent with the Standard Model.



sin 2β gives the best measurements by far…

Recent quests for CP violation

- It is even more remarkable that they agree well with the non CP violation measurements. (para. talks)



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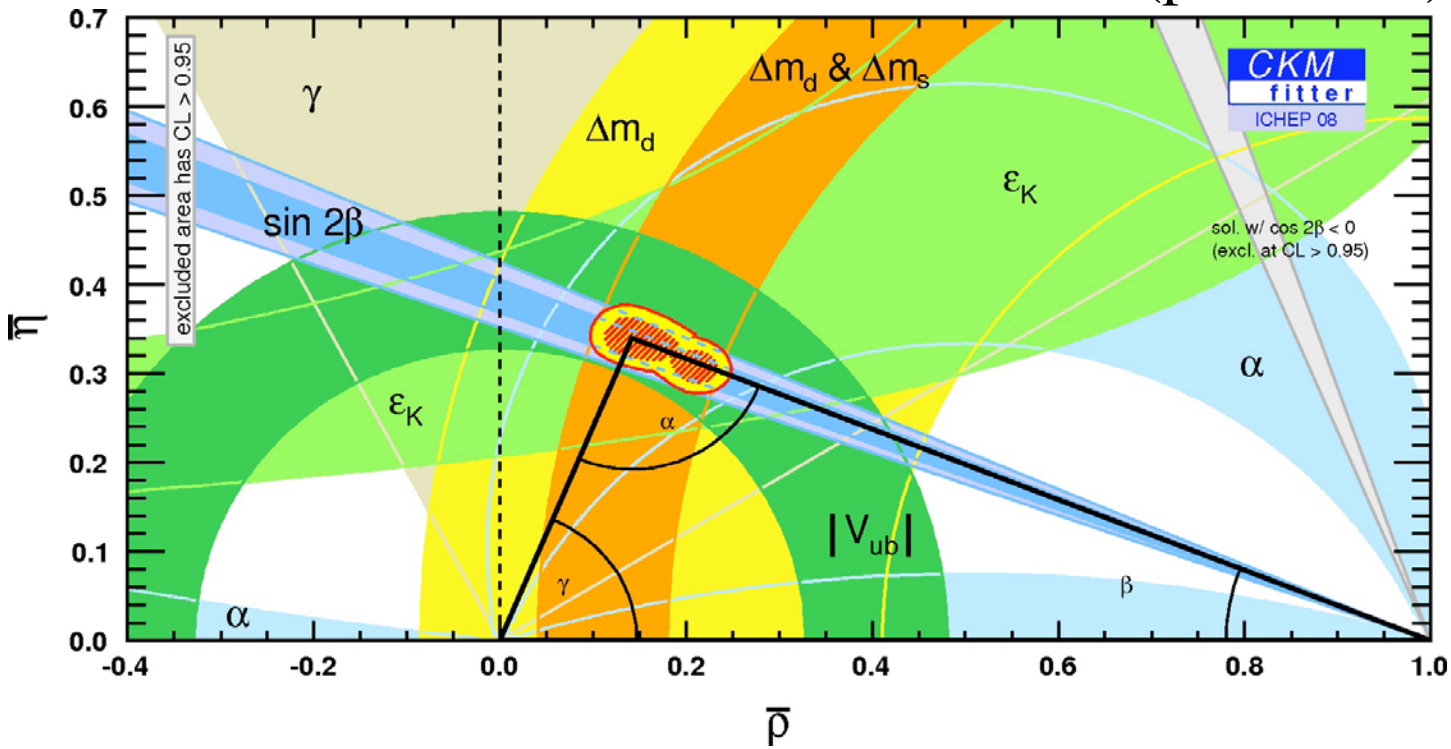

New physics has either a "special" flavour structure or is at higher energy than anticipated.

Recent quests for CP violation

- Hadron machine experiments, CDF and D0, start contributing in this field, e.g. (para. talk)
  $A_{CP}(B \to K^{\pm}\pi^{\mp}) = -0.086 \pm 0.023 \pm 0.009$ CDF2008
  as well as
  Δm_s measurements
  $B_s \to \mu^+\mu^-$ limit
  etc.

Outlook

- Search for New Physics by combining CP and $\not{CP}$.
  - Measurements related to the b→s or →d loop amplitudes
    Change in phase, absolute value, or Lorentz structure
    CP conserved: Δm, rare decay Br's, angular distributions
    CP violating: sin 2β, sin $2\beta_s$, α
  - Measurements related to the b→c or →u tree amplitudes
    Pure Standard Model measurements
    CP conserved: $|V_{ub}/V_{cb}|$
    CP violating: γ

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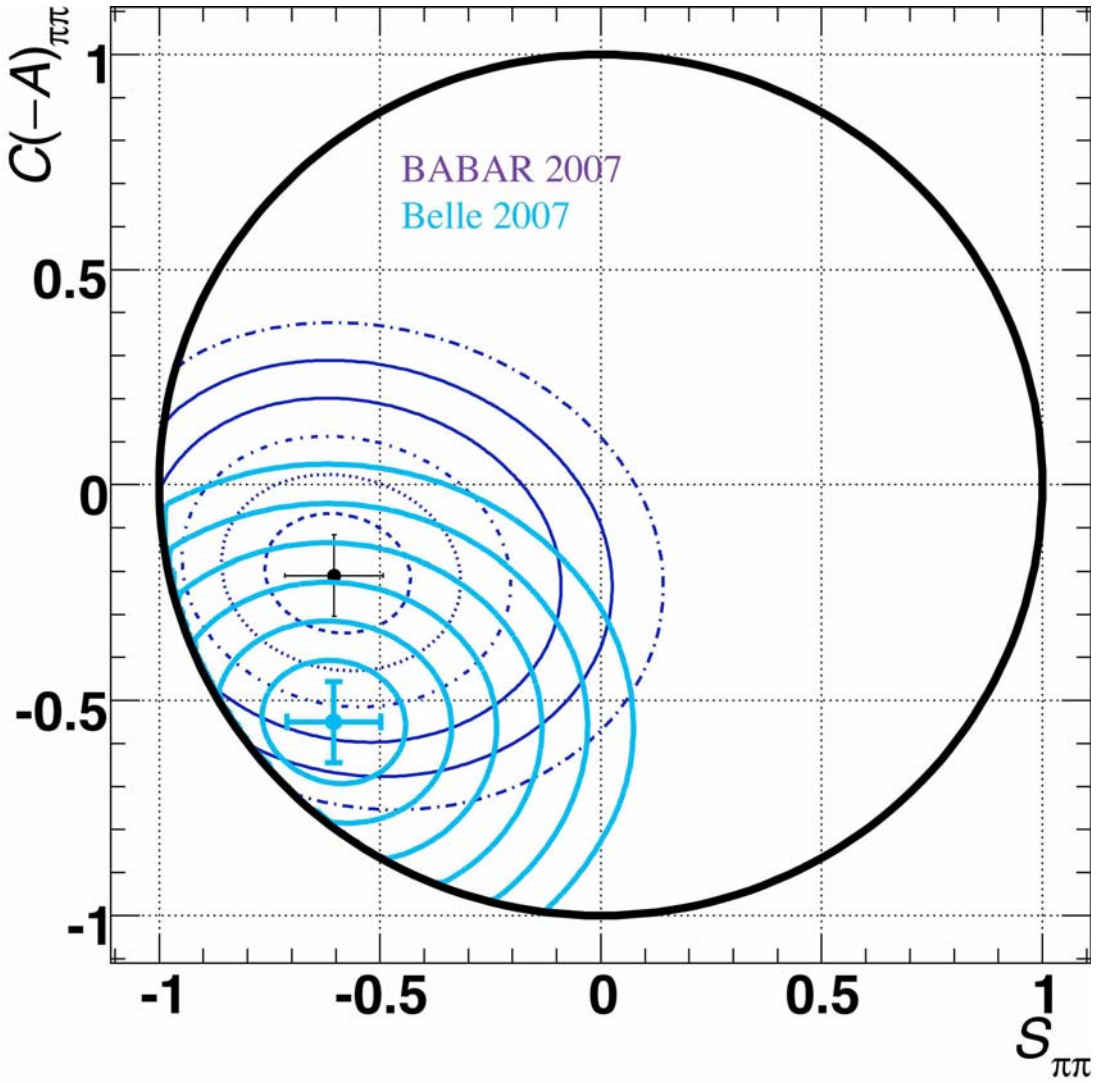
  - Measurements related to the b→c or →u tree amplitude:
    Pure Standard Model measurements
    CP conserved: $|V_{ub}/V_{cb}|$
    CP violating: γ
- An unique way to use ~~CP~~: $B_s \to \phi\gamma$, $B_d \to K^*(K_S\pi^0)\gamma$
  ~~CP~~ possible only through wrong chirality, very small in the Standard Model, probing Lorentz structure.

Where are the still interesting signals?

- Is there CP violation in the decay amplitudes for $B_d \to \pi^+\pi^-$?

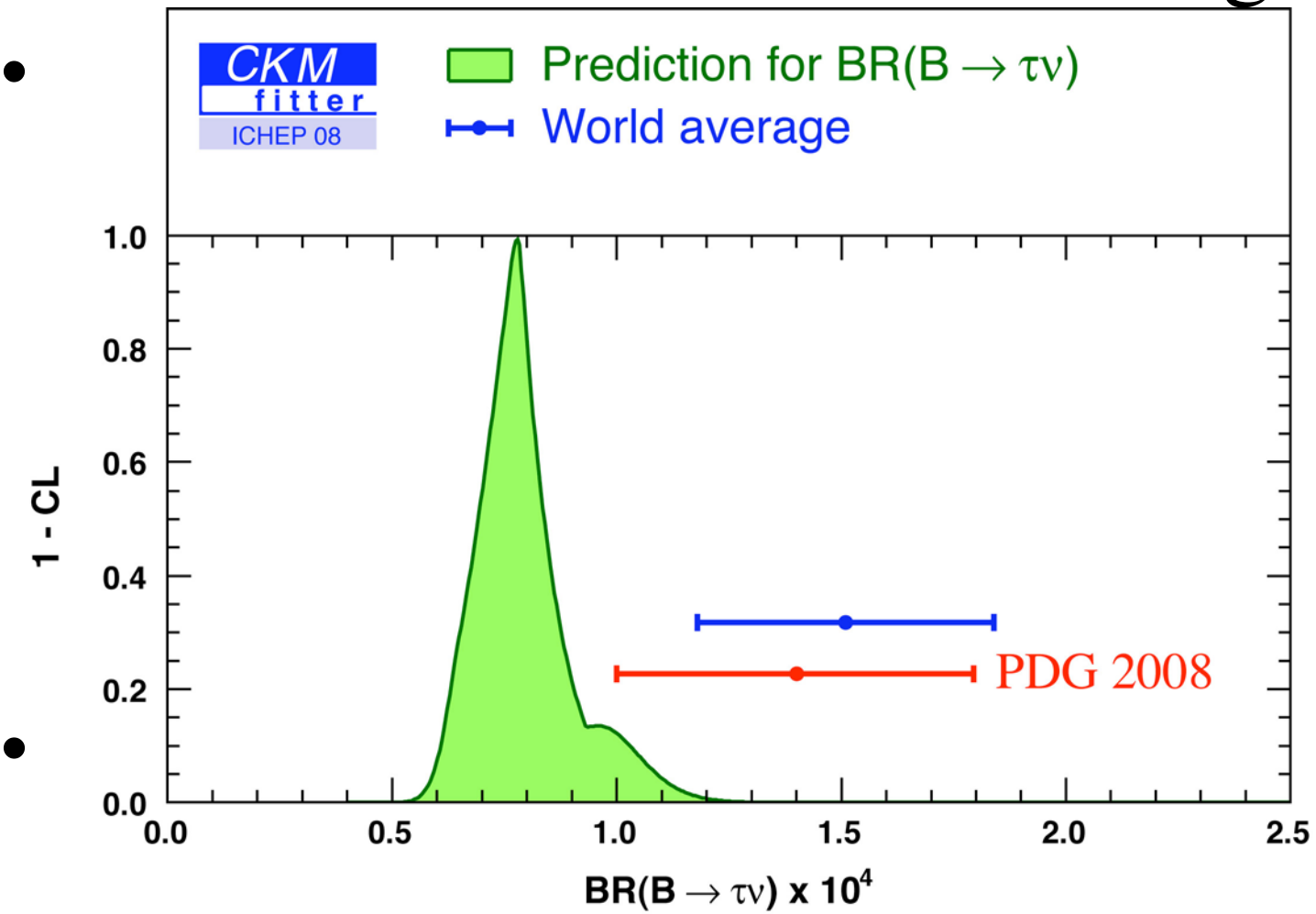
  Most probably will not be resolved by BABAR and Belle.



Where are the still interesting signals?

- Difference in CP asymmetries between
  charged-B→Kπ; 0.027±0.032
  neutral-B→Kπ; −0.101±0.015 (BABAR+BELLE+CDF; PDG08)
  CP violation in the decay amplitudes.
  Naive SM expectation; they are equal, but…
  more likely to be hadron physics issues, rather than due to new physics…
- Time dependent CP asymmetries for b→s$\bar{c}$c (tree) and b→s$\bar{s}$s (loop), no longer show real discrepancies

Where are the still interesting signals?

- 

.E+CDF; PDG08)

t…

ather than

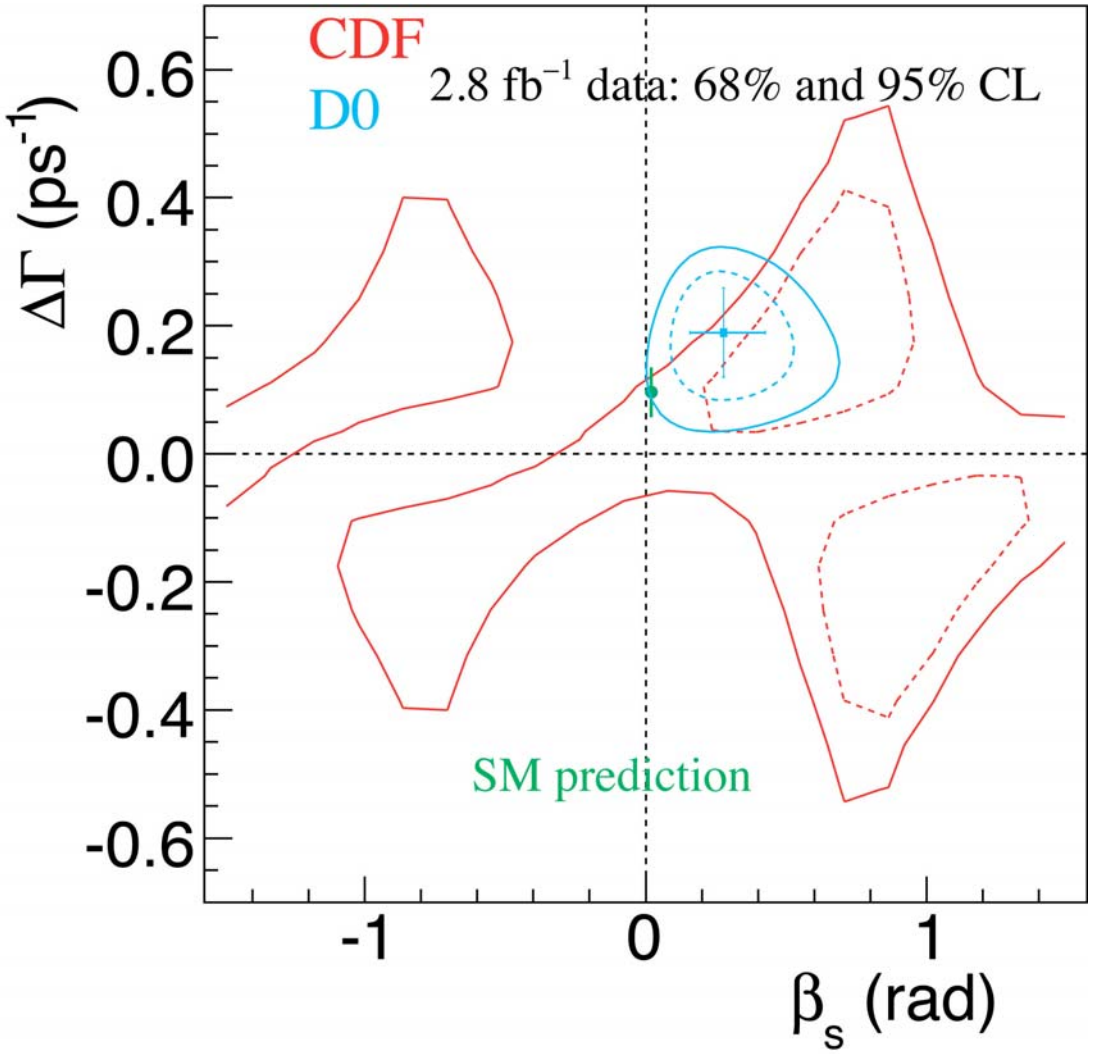
- sc̄c (tree)

screpancies

- $Br(B \rightarrow \tau\nu_\tau) = 1.4 \pm 0.4$ (BABAR+BELLE; PDG08)
  $\lesssim 2\sigma$ discrepancy

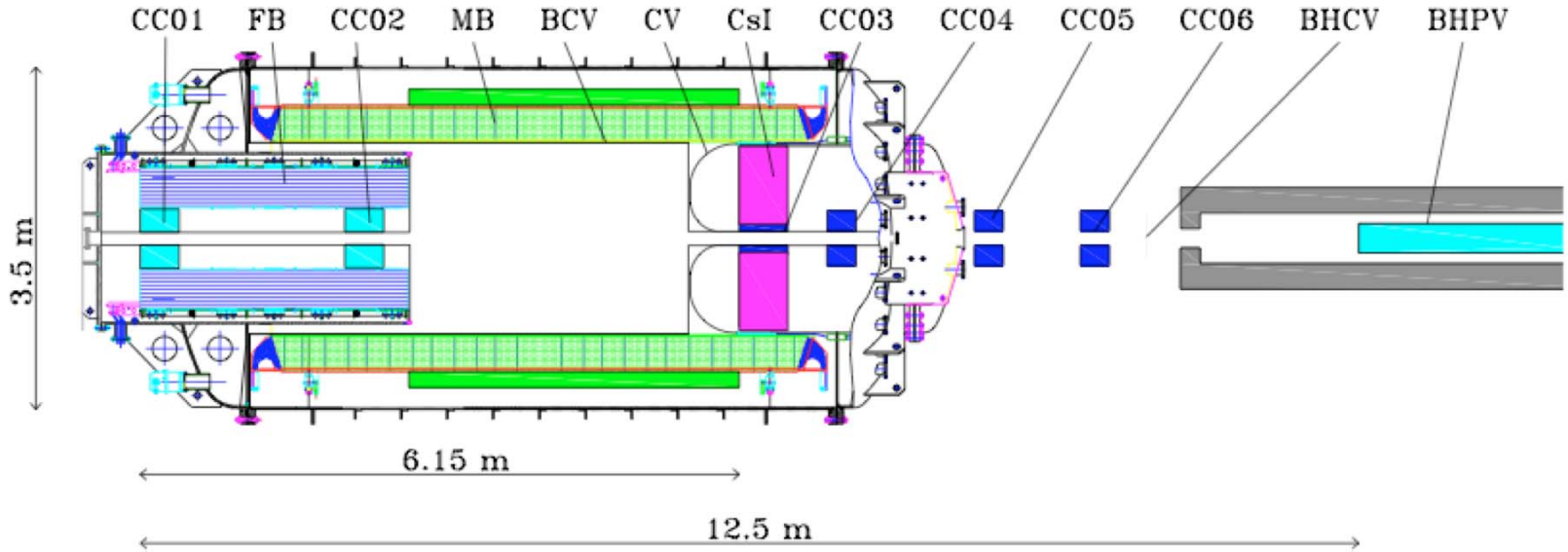
Where are the still interesting signals?

- CP violation in $B_s \rightarrow J/\psi\phi$, counter pert of $B_d \rightarrow J/\psi K_S$
  - a mixture of CP = +1 and −1 final states.
  - Need to be at hadron machines
  - Tevatron experiments still large statistical errors



Near future

- Further push on $K_L \rightarrow \pi^0 \nu\bar{\nu}$
  J-PARC E14: upgrade of E391



CsI calorimeter with a finer granularity
New photon veto in the beam
Waveform digitization for higher rates

3 years data taking
2.7 signal with ~2 background

- And NA62 for $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ (para. talk) (KLOE-2?)

Near future

- LHCb experiments from 2009

  (para. talks)

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- Below 1 fb^{-1}, less than one year data taking excluding large new physics contribution still allowed:
  e.g. CP violation in $B_s \rightarrow J/\psi\phi$, $B_s \rightarrow \mu^+\mu^-$

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- From 2 fb^{-1}, catching up and superseding the B factory results for $B_d \to \pi^+\pi^-$, $B_d \to K^{*0}\mu^+\mu^-$, etc.

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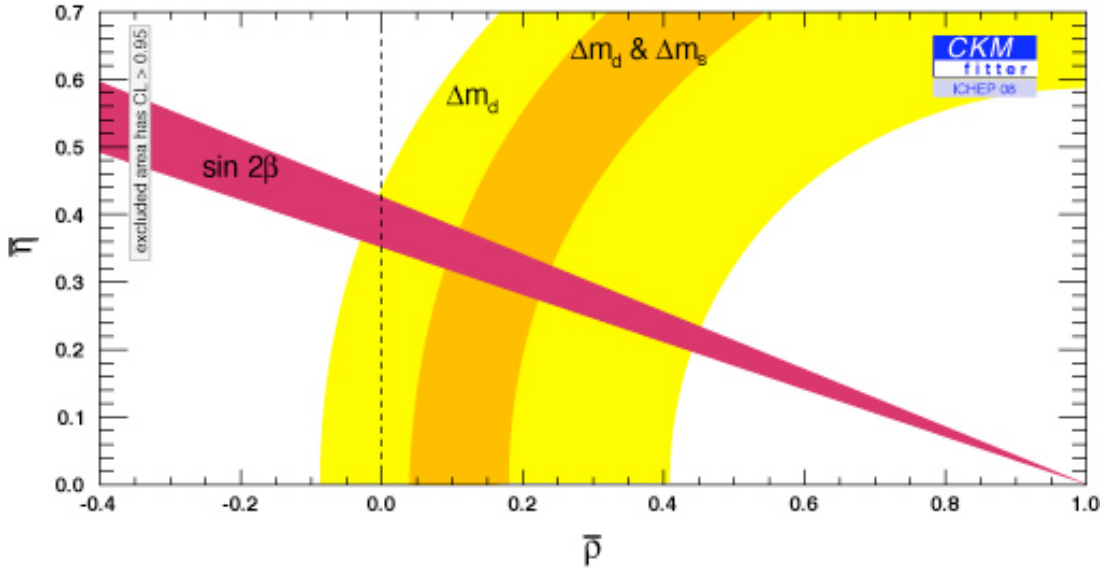
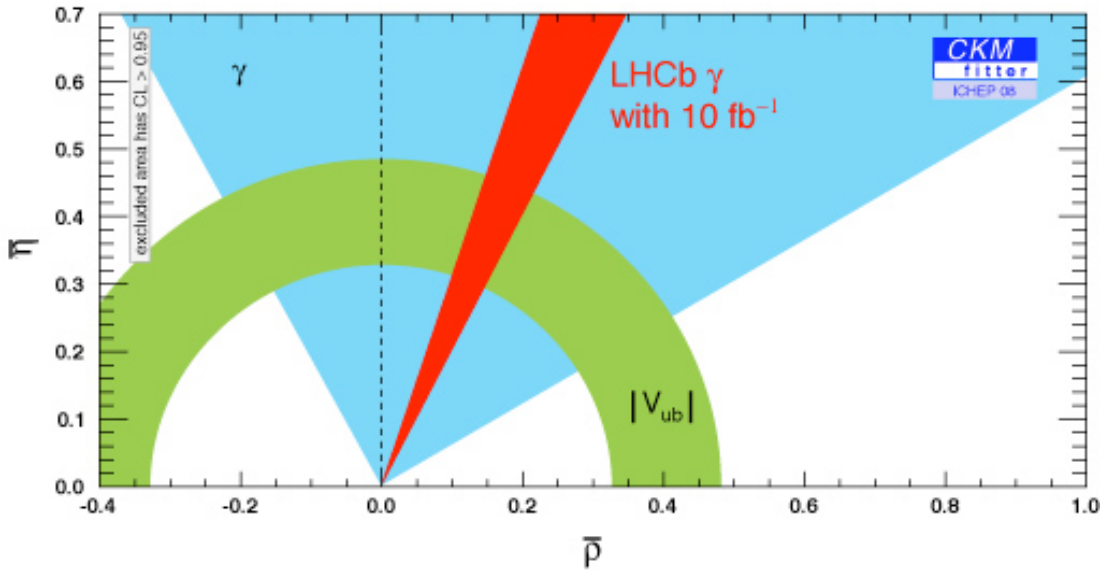
- From 2 fb^{-1}, catching up and superseding the B factory results for $B_d \to \pi^+\pi^-$, $B_d \to K^{*0}\mu^+\mu^-$, etc.
- With 10 fb^{-1} by 2015, γ measurements from the tree b decays with $\sigma_\gamma = 2\sim3°$, CP asymmetry in $B_s \to \phi\gamma$, or CP asymmetry in D^0 decays to a level of 10^{-3}.

Near future

- In ~2015, CKM parameters obtained through the loop processes and through tree processes will have a similar accuracies.





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- After the completion of BABAR, Belle, CDF and D0, LHCb will continue this road with b and c quarks. A few Kaon experiments will be carried out as well.
- Joined by S-B factory (talks later), S-LHCb, S-τCharm…?