Quark flavour physics

Michal Kreps

Physics Department

- Plan
  - Kaon physics and SM construction (bit of history)
  - Establishing SM experimentally
  - Looking for breakdown of SM
- Hard to cover everything in details in three lectures, some details are offloaded to exercises

Outline – lecture 2

- Discovery of charm and bottom quark
- Basic requirements for CP violation
- Classification of CP violation
- How CKM matrix is experimentally determined
- If time permits, few more words about CP violation in kaon system

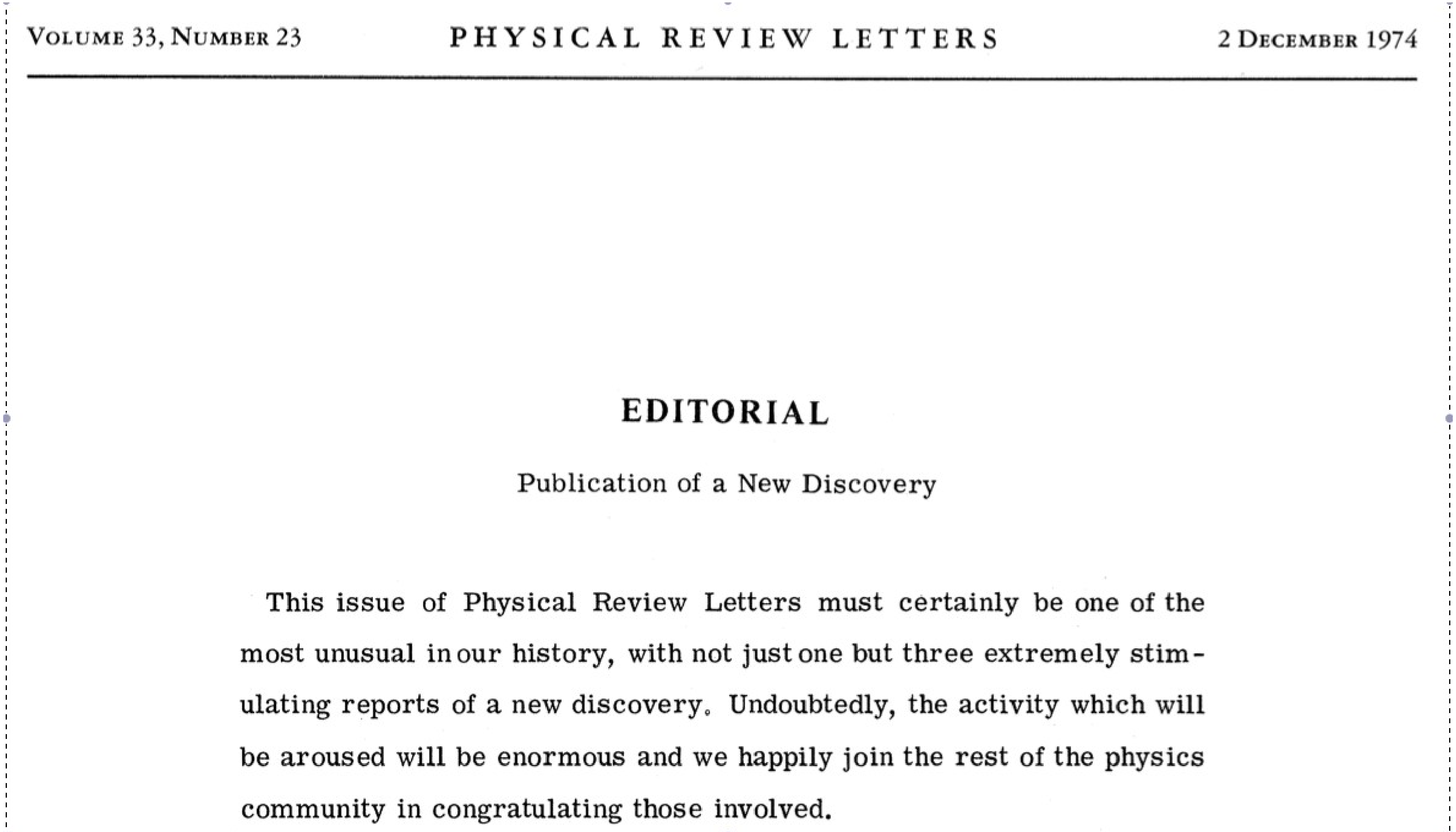
Some questions for thinking

- What are implications of observation of CP violation?
- What you would do to confirm Kobayashi-Maskawa mechanism
- If you have answers in terms of experiment, what capabilities experiment has to have?
- How would you determine CKM matrix elements?

Discovery of charm quark

- GIM requires charm quark to work
- Big change, known also as November revolution came in 1974
- Two experiments, one at Brookhaven and other at SLAC announced their discoveries
- Brookhaven experiment led by S. Ting measured cross section for production of e^+e^- pairs in p-Be interactions
- SLAC experiment led by B. Richter studied annihilation of e^+e^-
- This was rather unusual moment of discovery by two independent experiments and another confirmation in single edition of journal

What PRL said



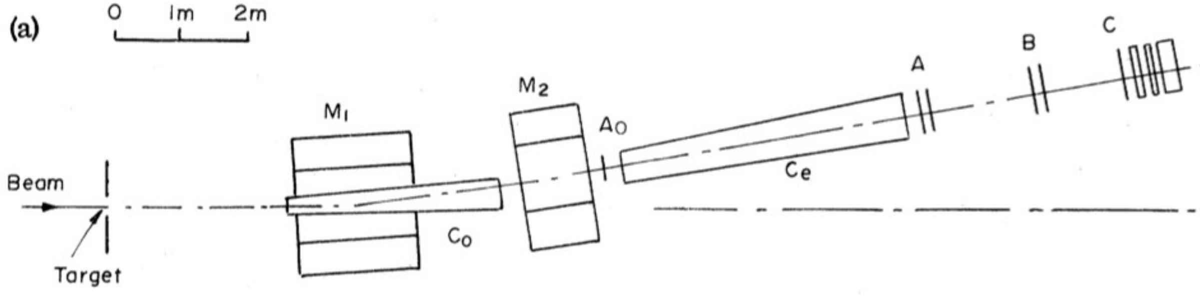
VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

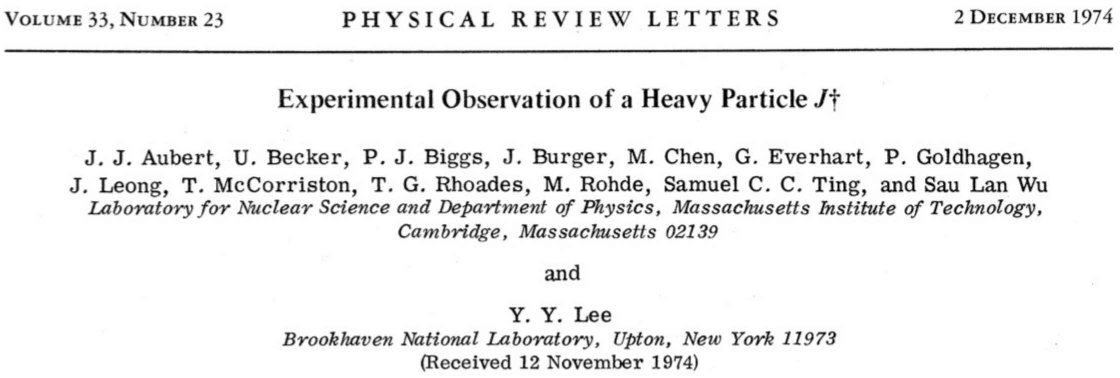
EDITORIAL

Publication of a New Discovery

This issue of Physical Review Letters must certainly be one of the most unusual in our history, with not just one but three extremely stimulating reports of a new discovery. Undoubtedly, the activity which will be aroused will be enormous and we happily join the rest of the physics community in congratulating those involved.

J part (S. Ting)




VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle *J*†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen,
J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

and

Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
(Received 12 November 1974)

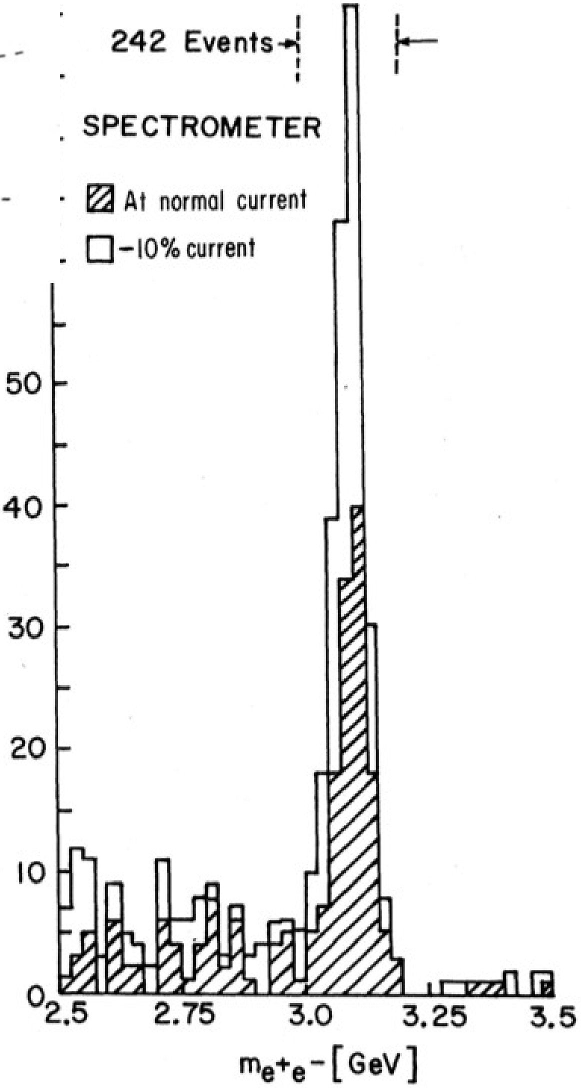
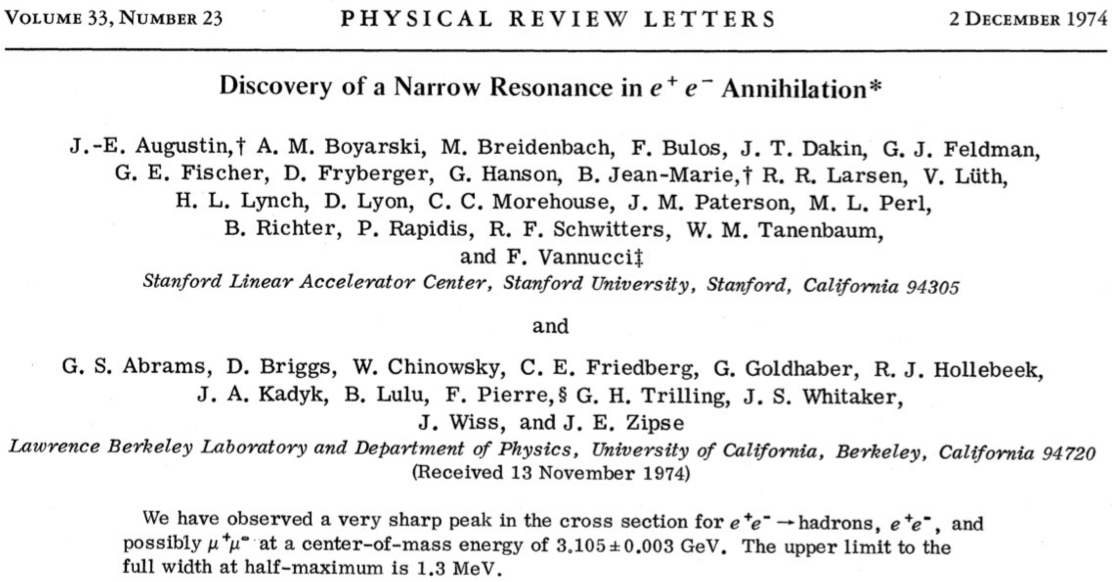


FIG. 2. Mass spectrum showing the existence of *J*. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

ψ part (B. Richter)



VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman,
G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth,
H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl,
B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum,
and F. Vannucci‡
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

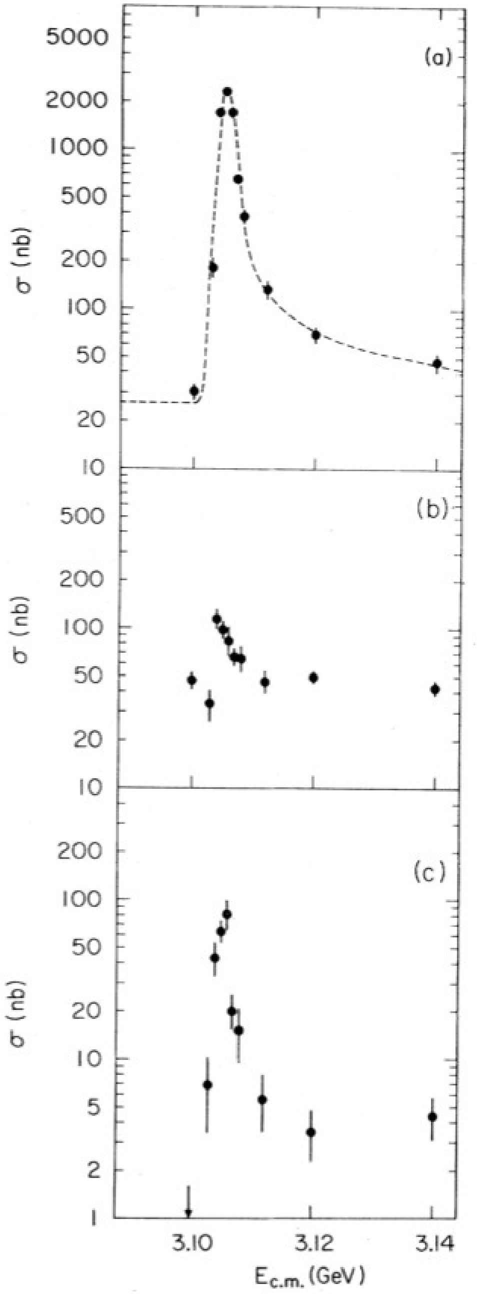
and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek,
J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker,
J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

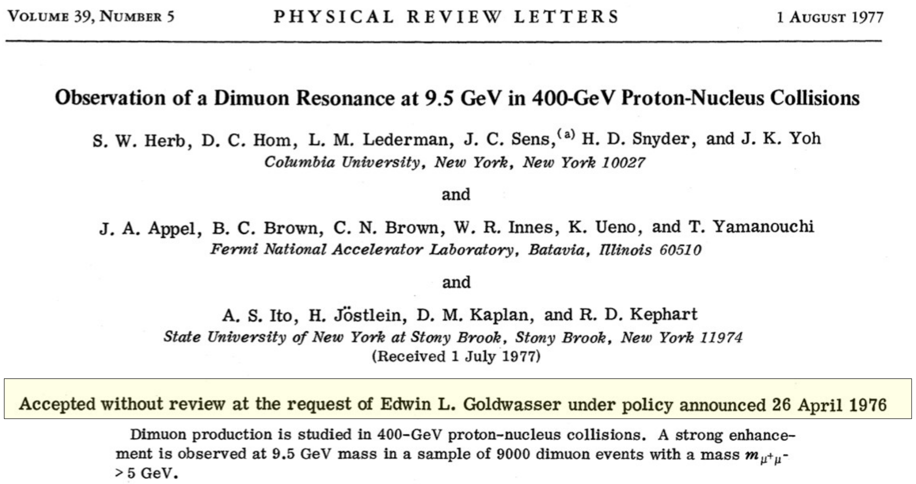
(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^- \rightarrow$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

- What they discovered is now known as J/ψ
- Particle consisting of $c\bar{c}$
- It still took some work and few other discoveries to decide it is indeed discovery of charm
- I should not omit Giorgio Belletini for his push to confirm this at Frascati



Two way second shot by L. Lederman



VOLUME 39, NUMBER 5 PHYSICAL REVIEW LETTERS 1 AUGUST 1977

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

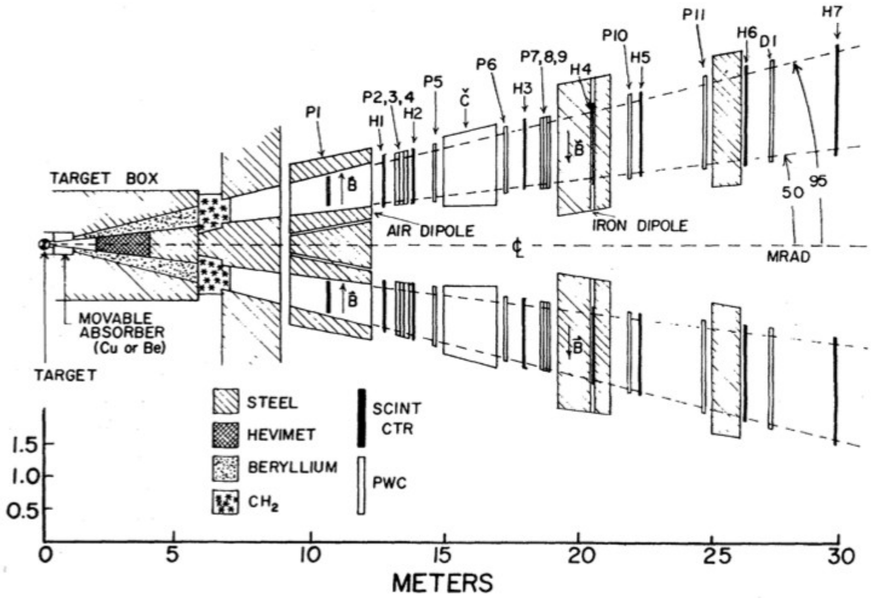
and

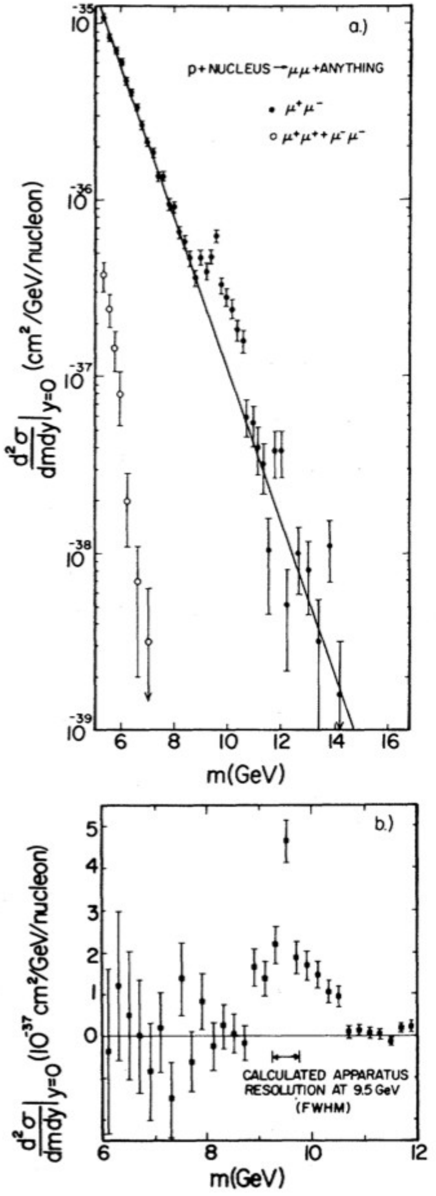
A. S. Ito, H. Jöstlein, D. M. Kaplan, and R. D. Kephart
State University of New York at Stony Brook, Stony Brook, New York 11974

(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.





Final word on quarks discoveries

- It took almost 20 years to finish quest for all quarks
- Top quark was discovered at 1995 at Fermilab's Tevatron collider by CDF and D0 experiments
    - As side note, it remained only place to produce top quarks until 2011
- Next we turn back to CP violation to arrive to final conclusion that KM mechanism proposed to explain CPV in K^0 is right one

CPV formalism

- First, definitions of decay amplitudes (valid for any hadron)

$$A_f = \langle f|H|M\rangle \quad \overline{A}_f = \langle f|H|\overline{M}\rangle$$

$$A_{\overline{f}} = \langle \overline{f}|H|M\rangle \quad \overline{A}_{\overline{f}} = \langle \overline{f}|H|\overline{M}\rangle$$

- For neutral mesons we need in addition

$$i\frac{d}{dt}\left(\begin{array}{c}|B(t)\rangle\\ |\overline{B}(t)\rangle\end{array}\right) = \left(\hat{M} - \frac{i}{2}\hat{\Gamma}\right)\left(\begin{array}{c}|B(t)\rangle\\ |\overline{B}(t)\rangle\end{array}\right),$$

$$|B_H\rangle = p\,|B\rangle + q\,|\overline{B}\rangle \quad |B_L\rangle = p\,|B\rangle - q\,|\overline{B}\rangle$$

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - (i/2)\Gamma_{12}^*}{M_{12} - (i/2)\Gamma_{12}}$$

- With those definitions, we can start to investigate CP violation

CP violating observables

- In quantum physics we cannot observe directly phases, only phase differences
- In order to have observable CP violation, we need interference of at least two amplitudes
  - If only one amplitude enters (or strongly dominates) no CP violation can be observed
- All CP violation can be described in terms of phase invariant variables:
  - $|\overline{A}_{\bar{f}} / A_f|$ for all hadrons
  - $|q/p|$ and $\lambda_f=(q/p)(\overline{A}_f / A_f)$ in addition for neutral mesons

Types of CP violation

- CP violation in decay (also called direct CPV)
  - $|\overline{A}_{\bar{f}} \,/\, A_f| \neq 1$
  - Only possible CPV for charged mesons and baryons
  - Measured as

$$A = \frac{\Gamma(M^- \to f^-) - \Gamma(M^+ \to f^+)}{\Gamma(M^- \to f^-) + \Gamma(M^+ \to f^+)} = \frac{|\overline{A}_{f^-}/A_{f^+}|^2 - 1}{|\overline{A}_{f^-}/A_{f^+}|^2 + 1}$$

- CP violation in mixing
  - $|q/p| \neq 1$
  - It is difference in rate $M \to \overline{M}$ and $\overline{M} \to M$
  - Original CPV discovery in 1964 is of this kind

$$A = \frac{d\Gamma/dt[\overline{M} \to f^+] - d\Gamma/dt[M \to f^-]}{d\Gamma/dt[\overline{M} \to f^+] + d\Gamma/dt[M \to f^-]} = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

Types of CP violation

- CP violation in interference of decays with and without mixing
    - $\mathrm{Im}(\lambda_f) \neq 0$
    - Practically does not exist in kaon system
    - Well visible in B^0

$$A = \frac{d\Gamma/dt[\overline{M} \to f_{CP}] - d\Gamma/dt[M \to f_{CP}]}{d\Gamma/dt[\overline{M} \to f_{CP}] + d\Gamma/dt[M \to f_{CP}]}$$

    - In case of $\Delta\Gamma=0$ and $|q/p|=1$ it has simple form of

$$A(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

$$S_f = \frac{2Im(\Lambda_f)}{1+|\lambda_f|^2} \quad C_f = \frac{1-|\lambda_f|^2}{1+\lambda_f|^2}$$

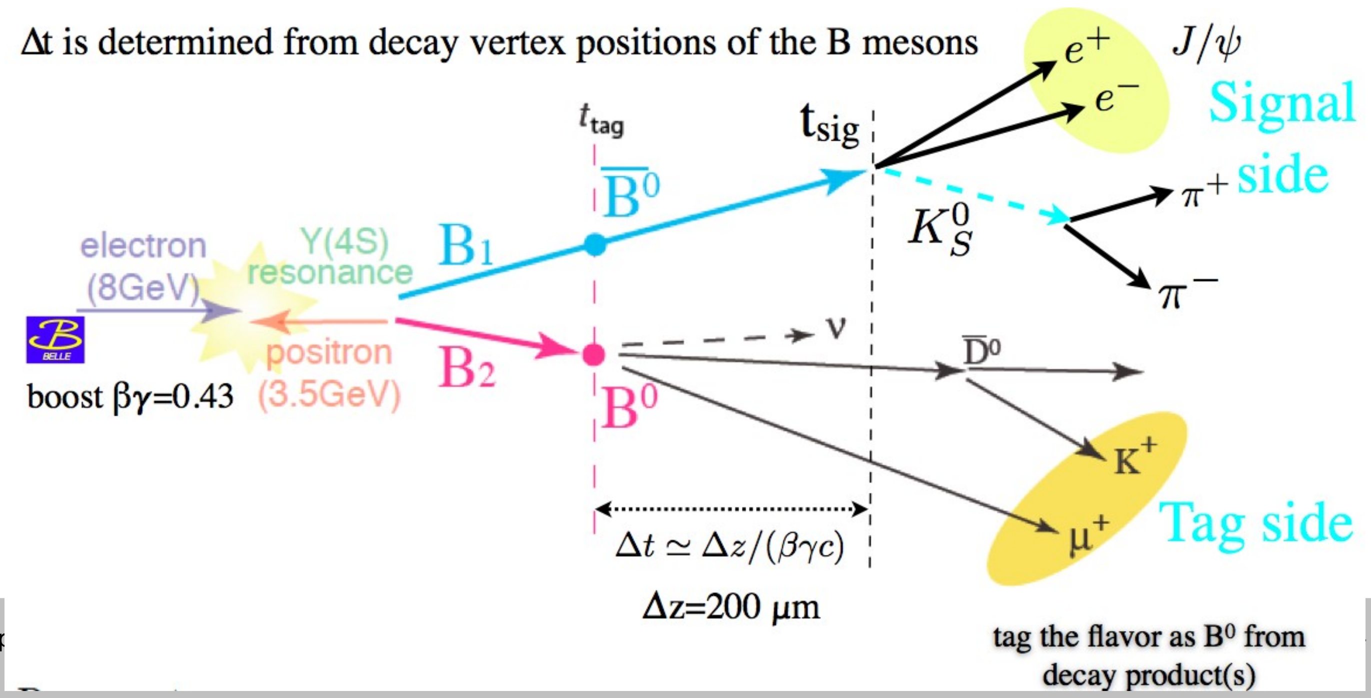
- Skipping details, KM mechanism explaining small CPV in K^0 implies large S_f in B^0

Large CPV in B^0

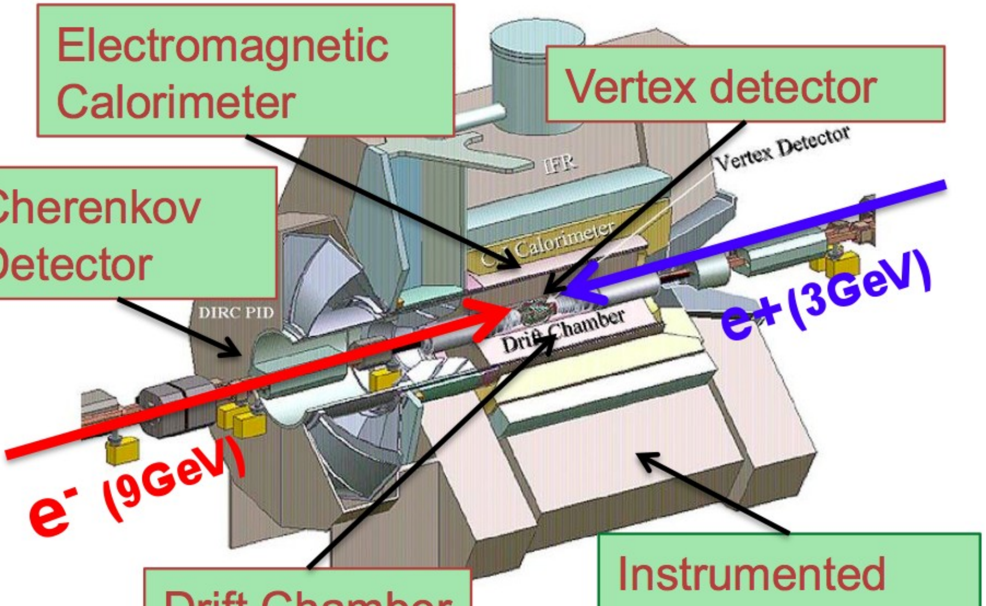
$$A = \frac{d\Gamma/dt[\overline{M} \to f_{CP}] - d\Gamma/dt[M \to f_{CP}]}{d\Gamma/dt[\overline{M} \to f_{CP}] + d\Gamma/dt[M \to f_{CP}]}$$

$$A(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

- We need two main non-trivial ingrediences
  - Resolve time dependence
  - Find out whether meson was produced as B or $\overline{\text{B}}$



Large CPV in B^0



Electromagnetic Calorimeter

Vertex detector

Cherenkov Detector

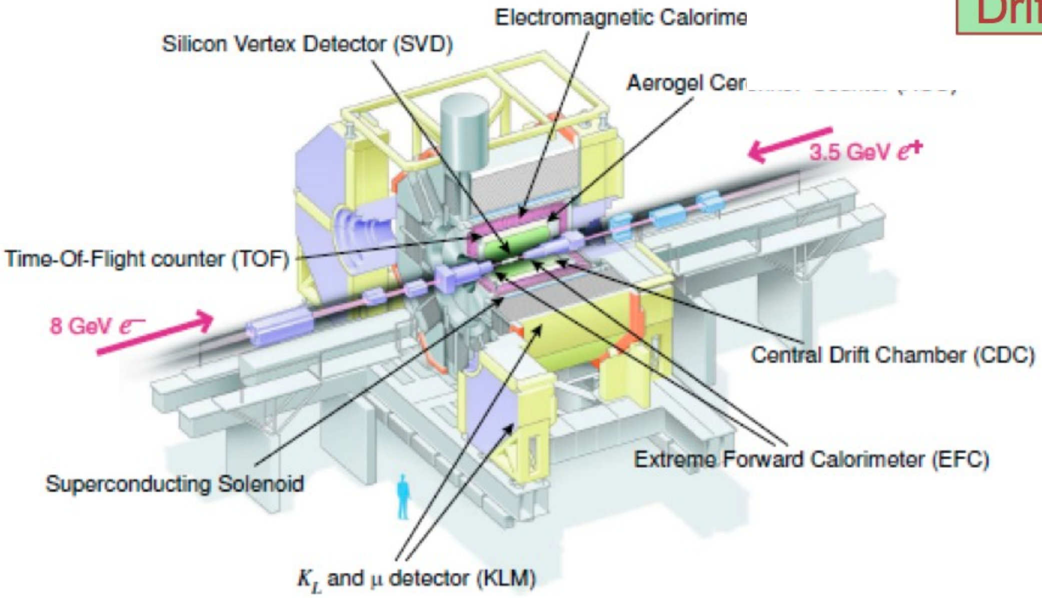
e^- (9GeV)

$e+$(3GeV)

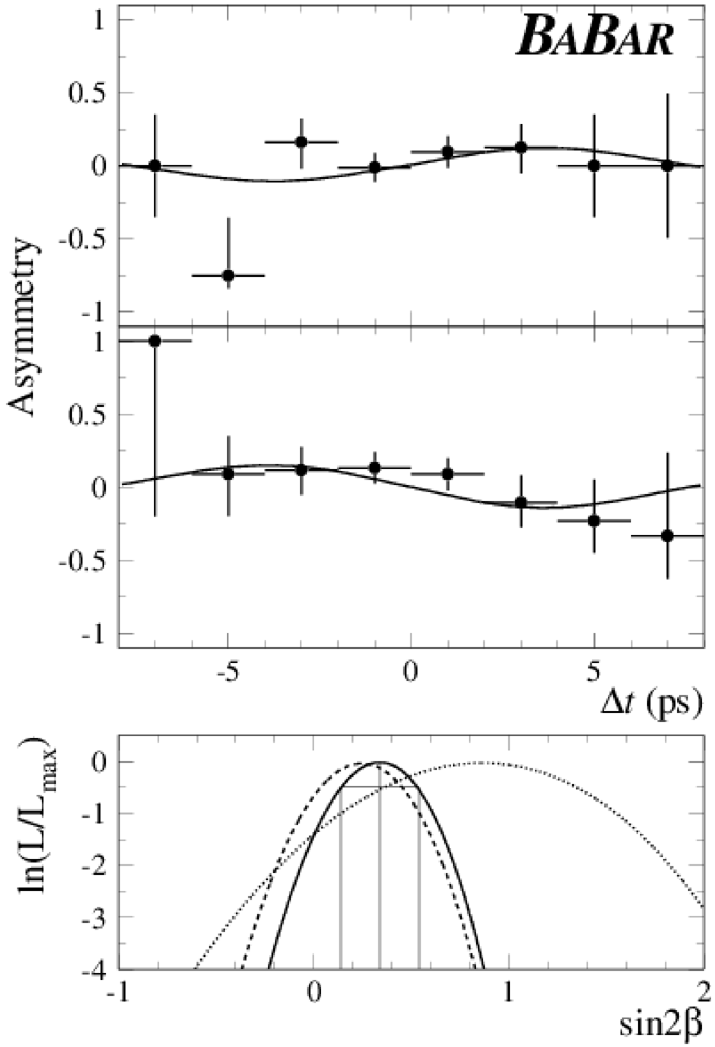
Drift Chamber

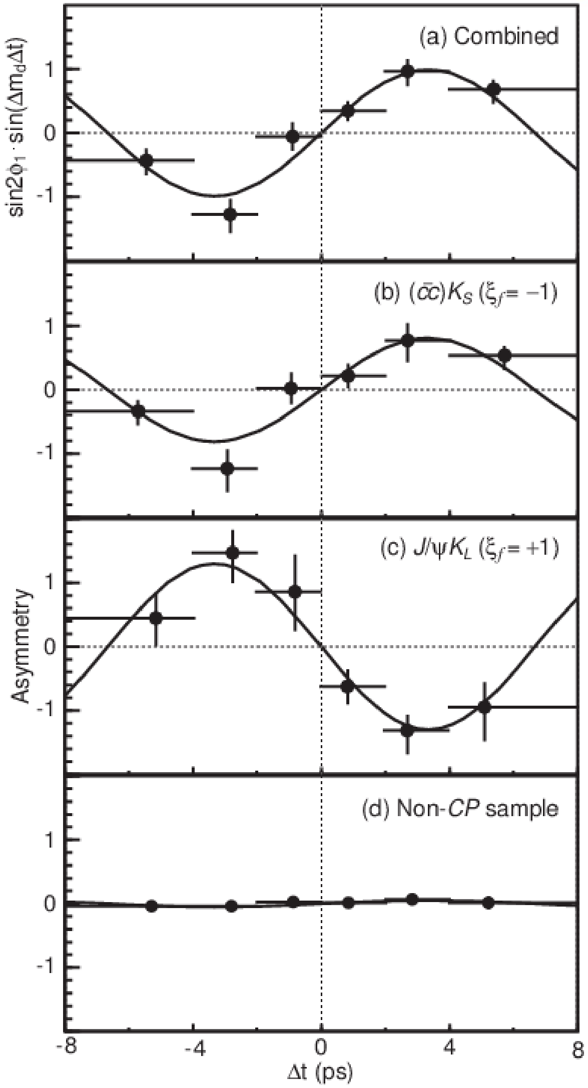
Instrumented Flux Return

Belle Detector



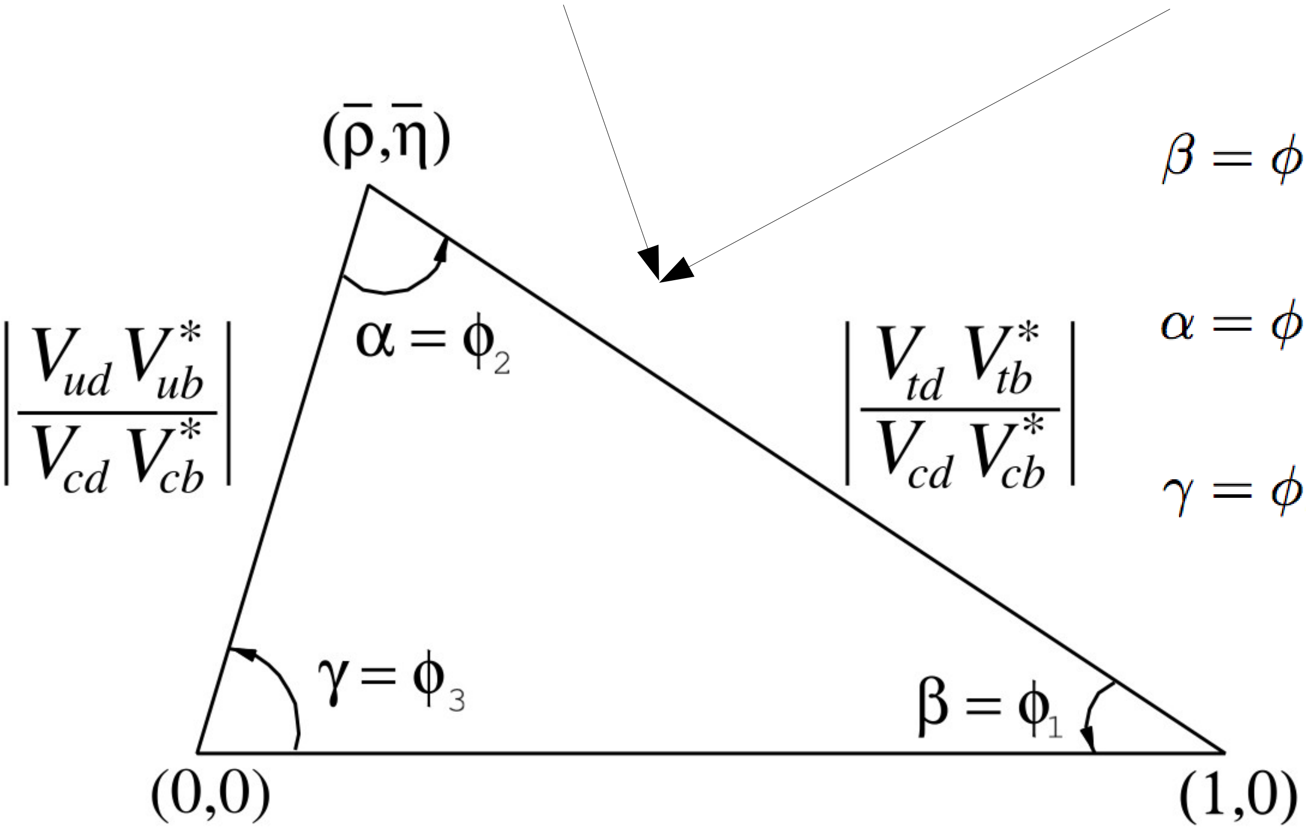
B^0 CPV measurement





Unitarity triangle

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



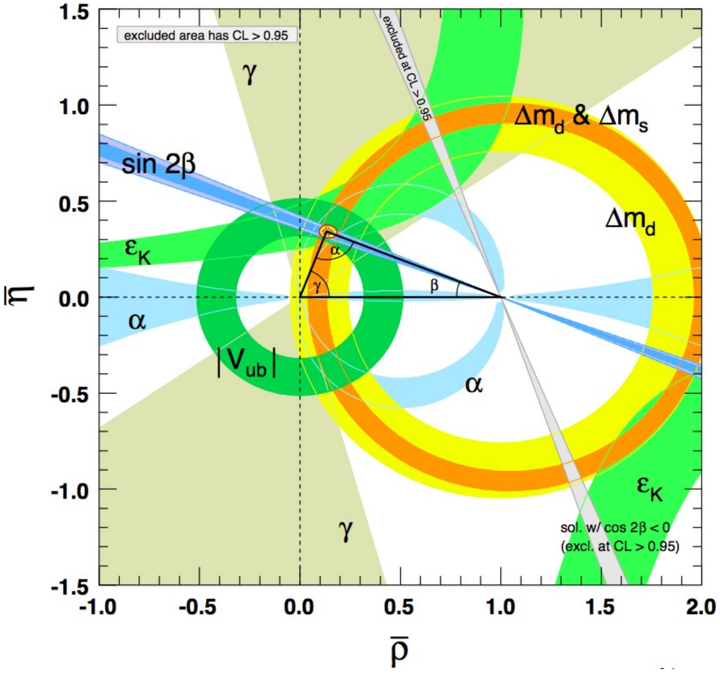
$$\beta = \phi_1 = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

$$\alpha = \phi_2 = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$

$$\gamma = \phi_3 = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$$

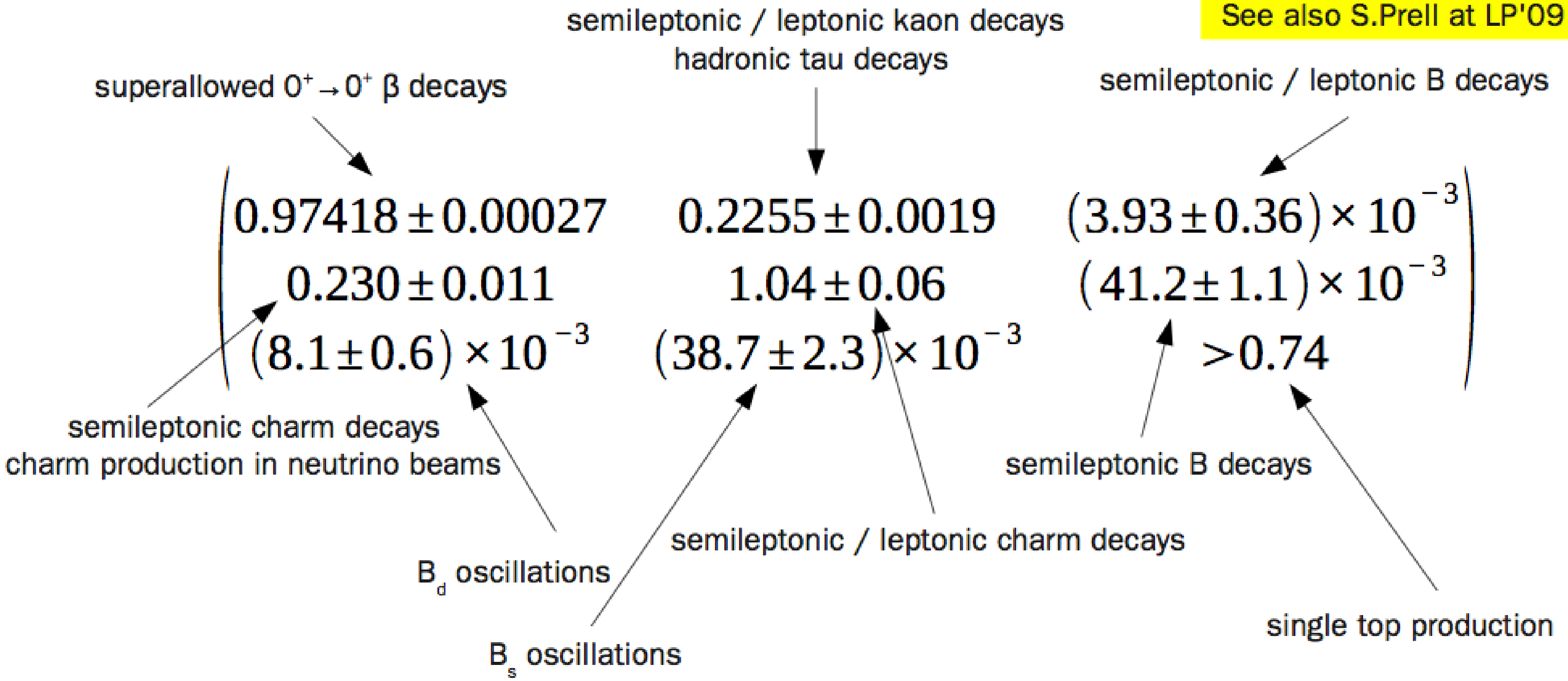
Colourful plot

- Game is to overconstrain unitarity triangle
- If SM is right, everything should be consistent
- If SM is not right, consistency is hopefully broken at some place
- Three widely known fits exist
  - CKMFitter (shown)
  - UTFit
  - Soni and Lungi
- They differ mainly in way how they treat theory uncertainties and frequentist vs. Bayesian interpretation



CKM matrix magnitudes

PDG 2008
See also S.Prell at LP'09



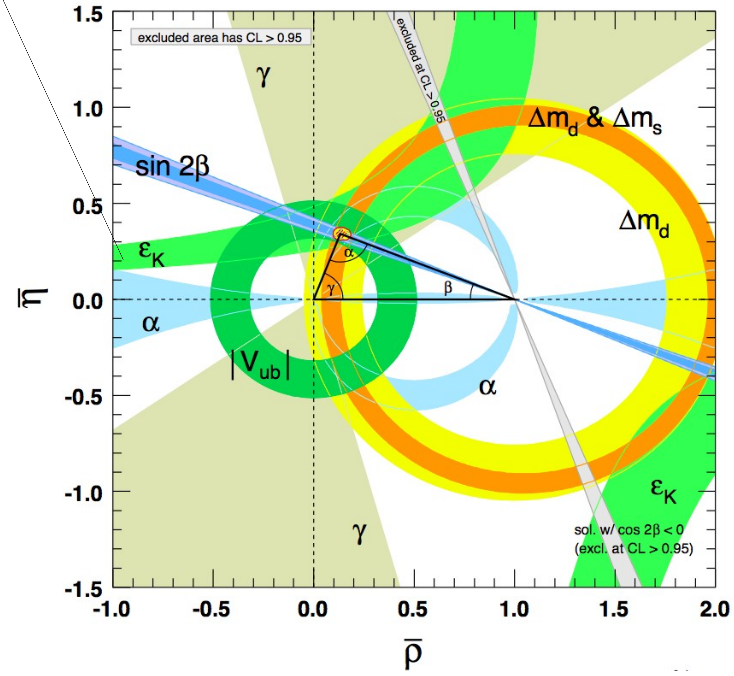
$$\begin{pmatrix} 0.97418 \pm 0.00027 & 0.2255 \pm 0.0019 & (3.93 \pm 0.36) \times 10^{-3} \\ 0.230 \pm 0.011 & 1.04 \pm 0.06 & (41.2 \pm 1.1) \times 10^{-3} \\ (8.1 \pm 0.6) \times 10^{-3} & (38.7 \pm 2.3) \times 10^{-3} & > 0.74 \end{pmatrix}$$

theory inputs (eg., lattice calculations) required

$|\varepsilon_K|$

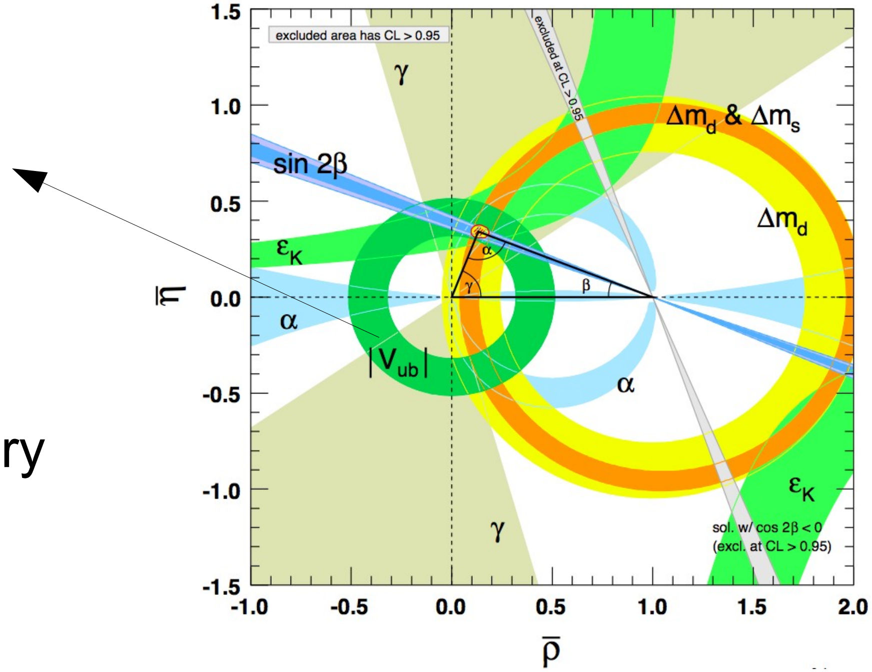
$$|\varepsilon_K| = C_\varepsilon B_K A^2\lambda^6\bar{\eta}\{-\eta_1 S_0(x_c)(1-\lambda^2/2)+\eta_3 S_0(x_c,x_t)+\eta_2 S_0(x_t)A^2\lambda^4(1-\bar{\rho})\}$$

- Experimentally comes from rate of $K_L\to 2\pi$
- Main theoretical uncertainty comes from hadronic physics (B_K)
    - Calculated with lattice QCD
- It is loop process (mixing)



$|V_{ub}|$

- Measured in semileptonic $B \rightarrow X_u l \bar{\nu}$
- Inclusive approach
  - Cleaner theory
  - Very difficult experimentally
- Exclusive approach
  - Rather easy for experiment
  - Quite some difficulties for theory
- Other option is to use decays $B^+ \rightarrow \tau\nu$
  - Sensitive to new physics, so no good for determination of SM

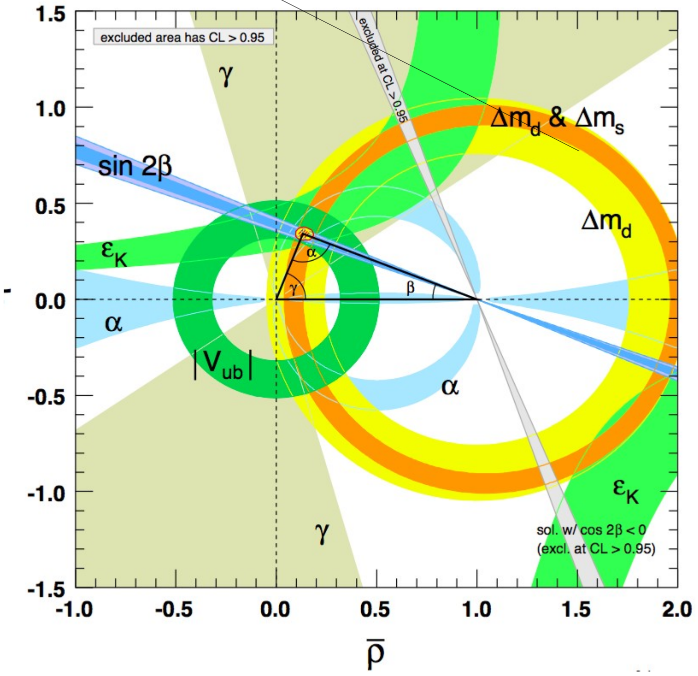


$B^0_{(s)}$ mixing

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

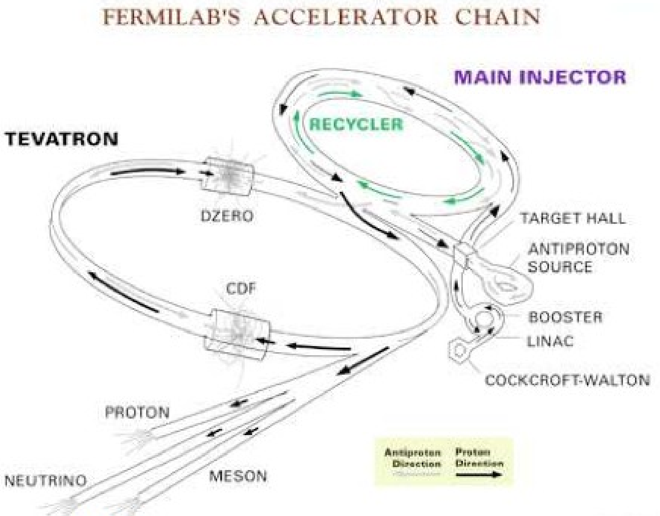
$$= \frac{G_F^2}{6\pi^2} m_W^2 \eta_b S(x_t) m_{B_d} f_{B_d}^2 \hat{B}_{B_d} |V_{cb}|^2 \lambda^2 ((1-\bar{\rho})^2 + \bar{\eta}^2)$$

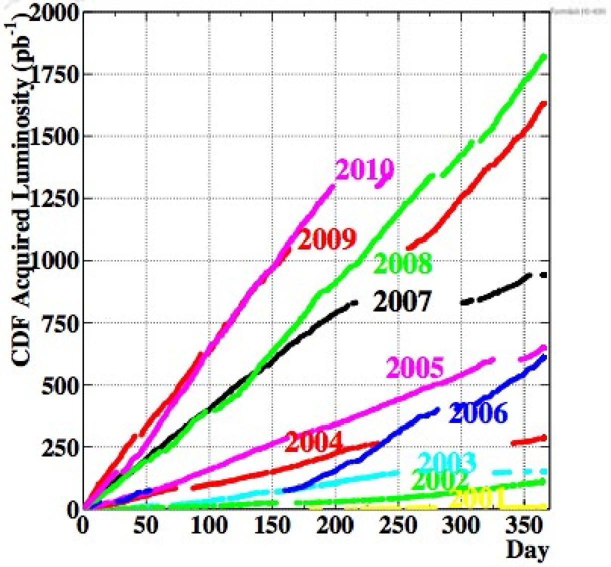
- Sensitive to V_{tq} in mixing box diagram
- Usually for constraint we use $\Delta m_d/\Delta m_s$
    - This assumes unitarity
    - Many theory uncertainties cancel out
    - Very precise experimentally, main limitation in theory at this moment

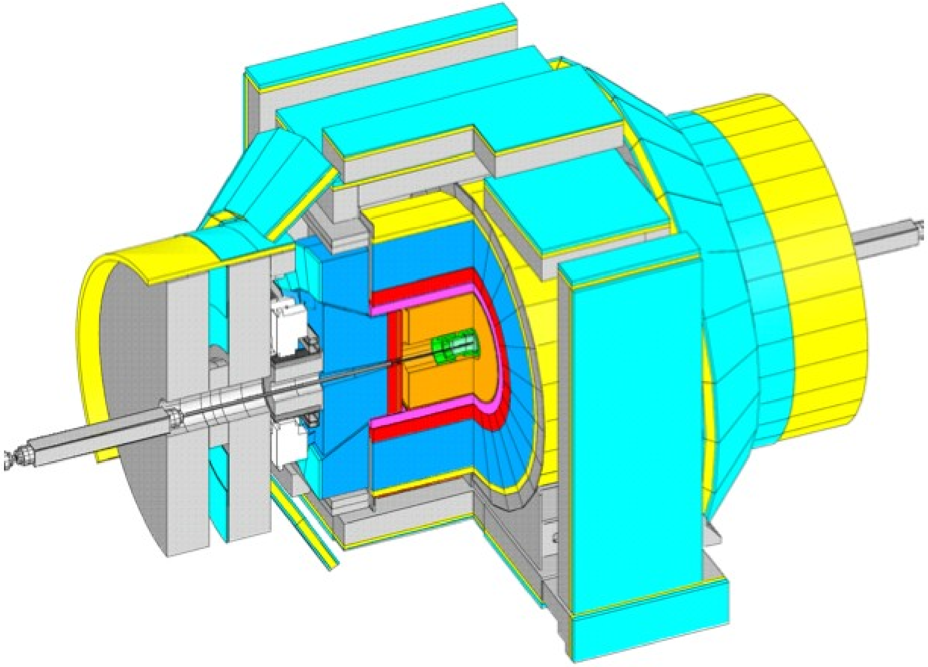


Tevatron and CDF

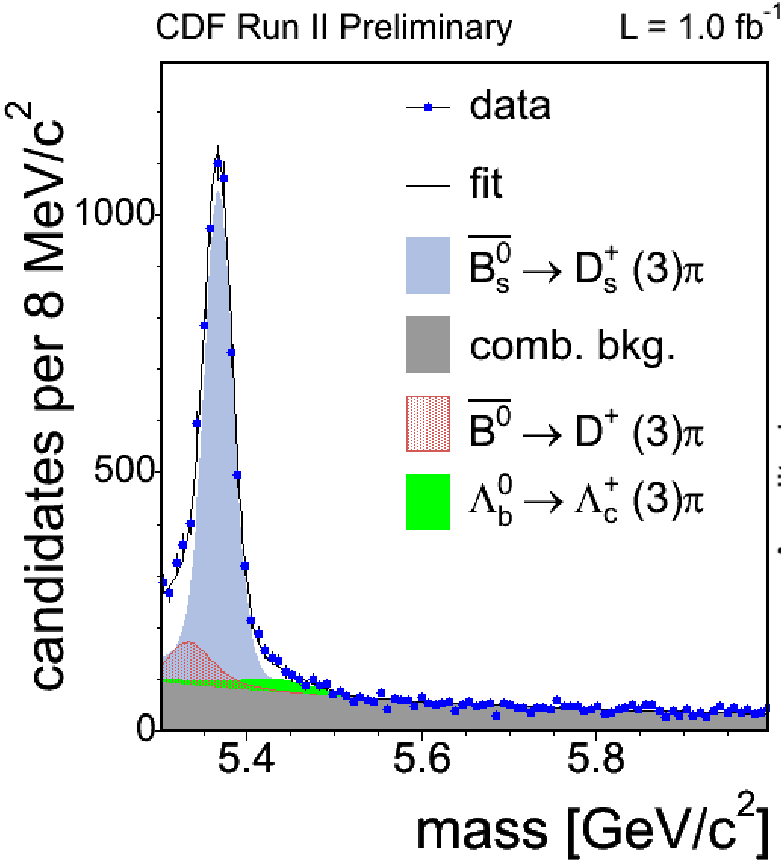
- $p\bar{p}$ collisions at $\sqrt{s} = 1.96\,\mathrm{TeV}$
- Peak luminosity $\approx$ $3.5 - 3.8 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Collected about $\approx 7\mathrm{fb}^{-1}$

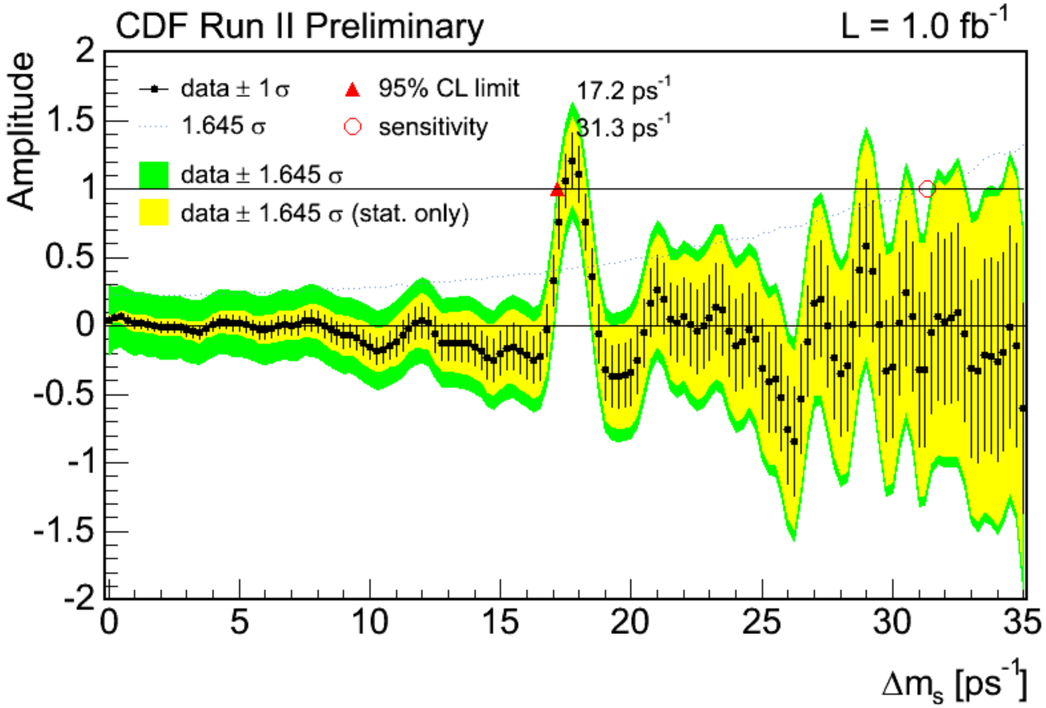




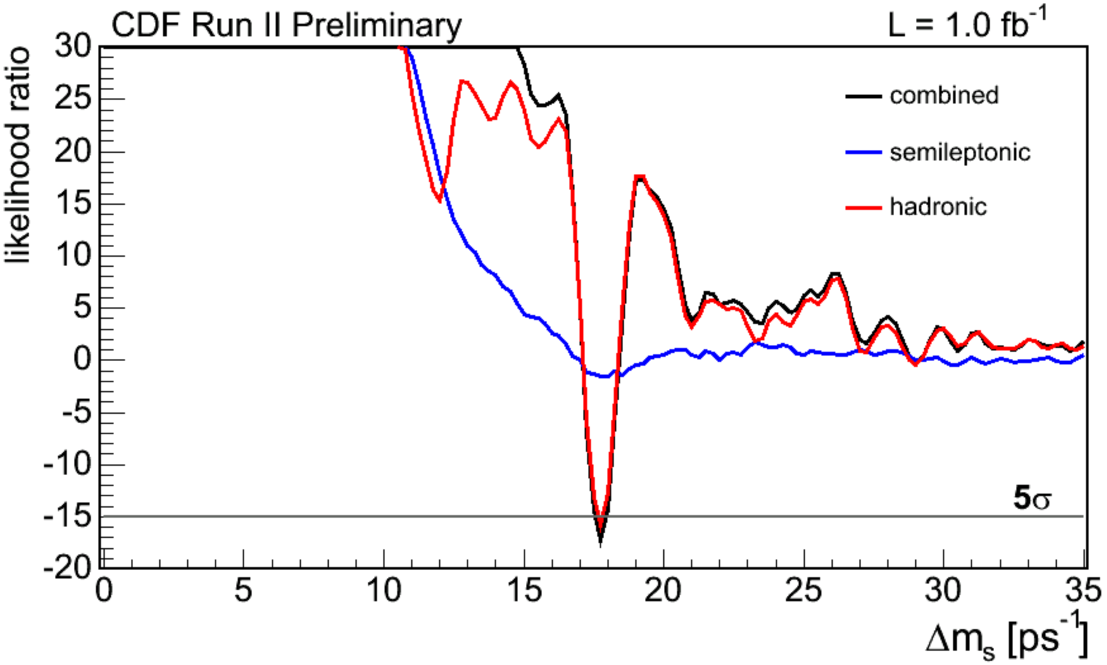


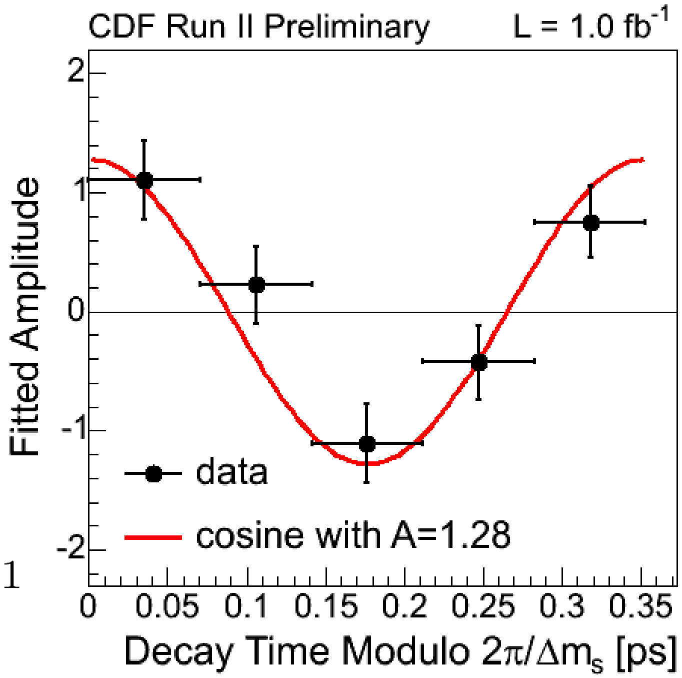
B_s mixing @ CDF





B_s mixing @ CDF





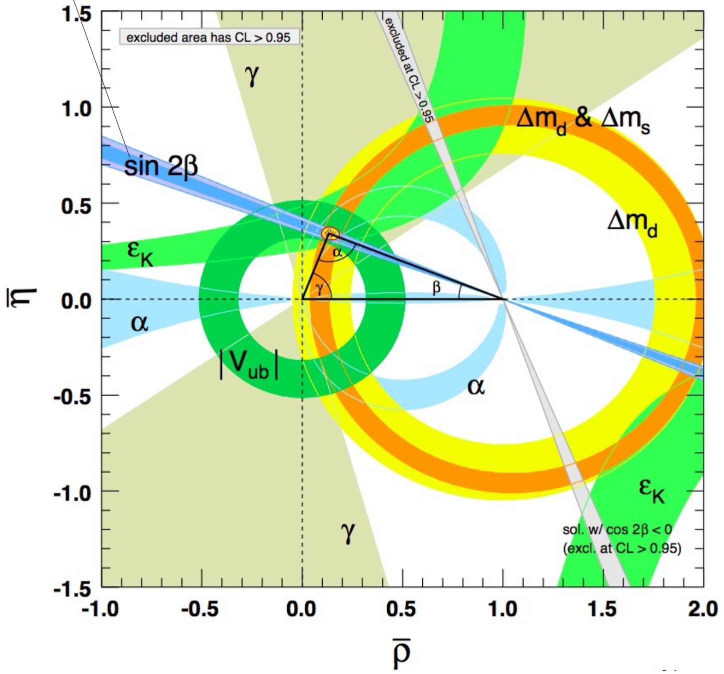
$$\Delta m_s = 17.77 \pm 0.10(stat) \pm 0.07(syst) ps^{-1}$$

Angle β

- S_f is in fact sin(2β)
- Two-fold ambiguity exists in measurement
- One way to resolve it is to use decays $B^0 \rightarrow J/\psi K\pi$ with interference between K^* and s-wave Kπ
- Can exclude one of the two solutions at reasonable confidence

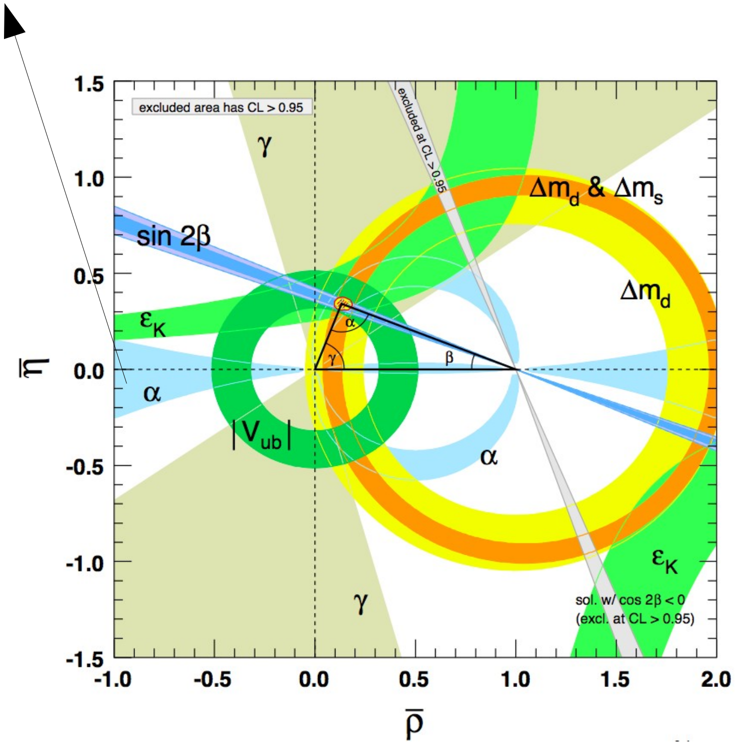
$$A(t) = S_f \sin(\Delta m t) - C_f \cos(\Delta m t)$$

$$S_f = \frac{2Im(\Lambda_f)}{1+|\lambda_f|^2} \quad C_f = \frac{1-|\lambda_f|^2}{1+\lambda_f|^2}$$



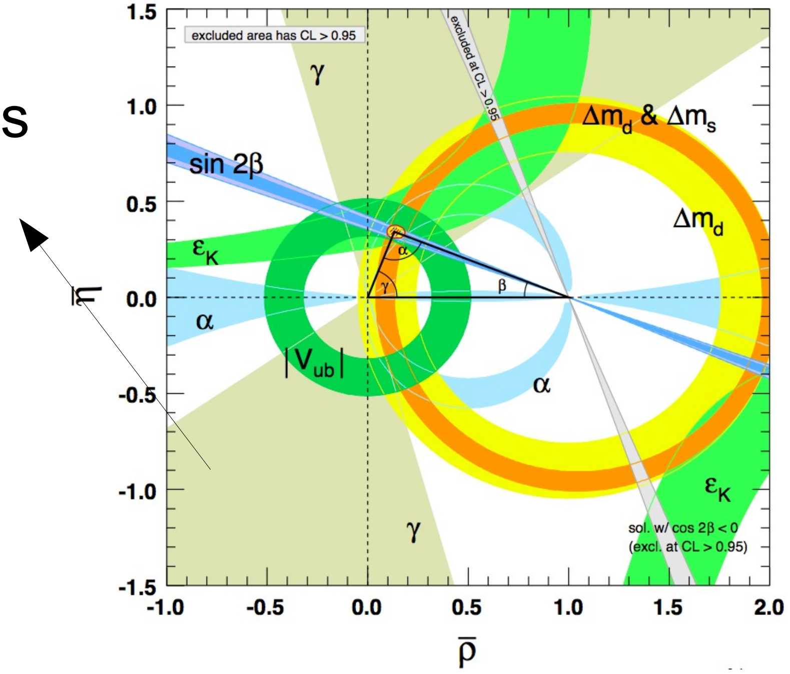
Angle α

- α is phase between $V_{tb}^*V_{td}$ and $V_{ub}^*V_{ud}$
- Extracted from $b\to u\bar{u}d$ transitions using mixing induced CPV
  - $B^0\to\pi\pi, \rho\rho, \pi\rho$
  - As those decays are suppressed, penguin contributions play also role
  - Isospin analysis used to correct for penguin contributions
- Current (2010) value is 89±4.4°



Angle γ

- Interference of $B^- \to D^0 K^-$ (V_{cb}) and $B^- \to \overline{D}^0 K^-$ (V_{ub}) when using common final state for D^0 and $\overline{D}^0$
- Plays special role as it is extracted from tree level decays
- Provides CKM phase without being significantly affected by new physics
- Three different D final states used
  - GLW: Cabbibo suppressed CP-eigenstates (KK, ππ)
  - ADS: Doubly Cabbibo suppressed $D^0 \to K^+\pi^-$
  - Dalitz plot: $K_s\pi\pi$



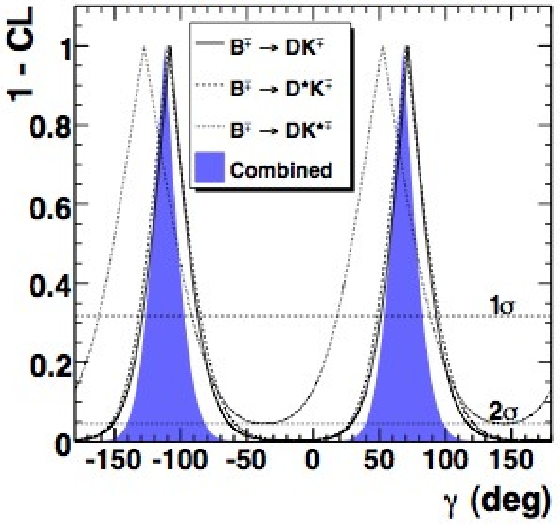
Angle γ

- B^- decays are challenging for γ measurement as
  - CP asymmetry is large, but rate is very small (ADS)
  - Rate is reasonable, but CP asymmetry is small (GLW)
  - Only in about last year experiments start to see significant signals
- Other promising decay is $B_s \rightarrow D_s K$
  - But this requires to resolve fast B_s oscillation
  - No experiment capable of measurement up to now

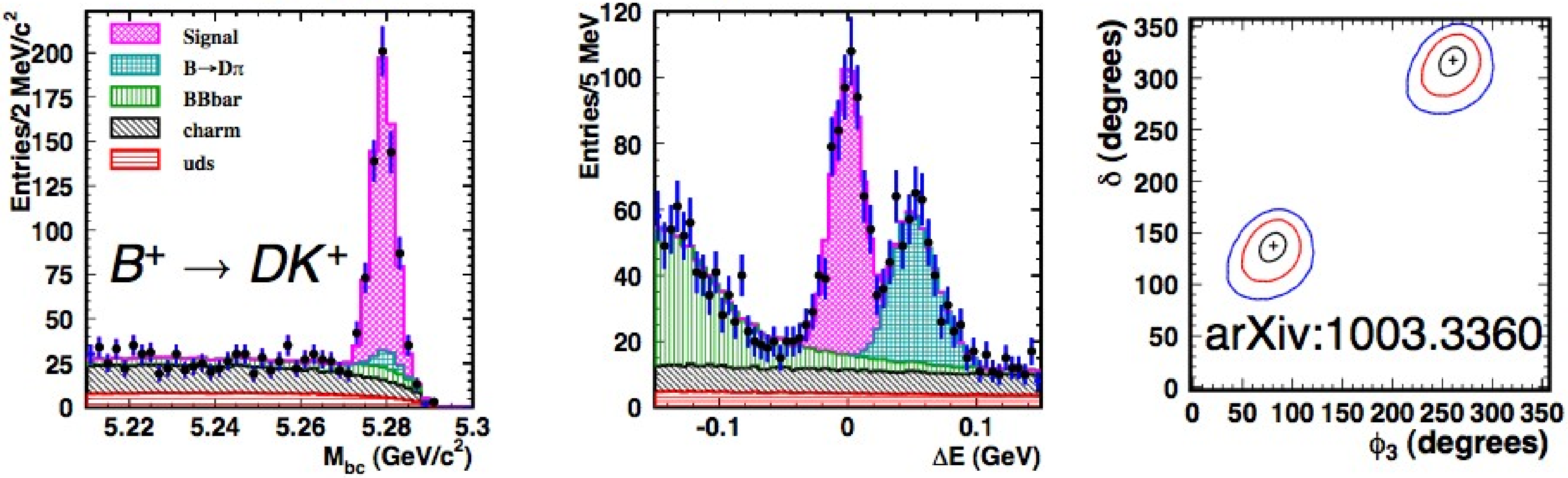
Angle γ

- Most sensitive is GGSZ method with $D^0 \to K_s\pi^+\pi^-$
- Belle and Babar made recent updates
- Both experiments see 3.5σ evidence for CPV
- Belle: $\gamma = (78^{+11}_{-12} \pm 4 \pm 9)^\circ$
- Babar: $\gamma = (68 \pm 14 \pm 4 \pm 3)^\circ$

arXiv:1005.1096



Babar



arXiv:1003.3360

Belle

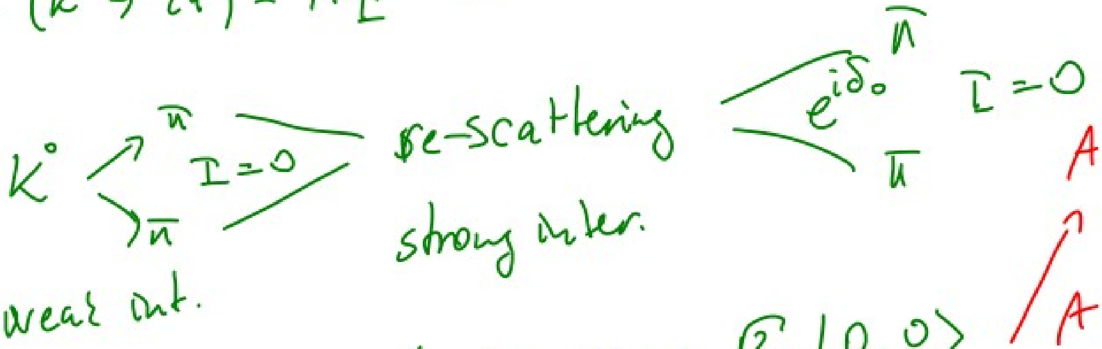
K Direct CPV

$A(K^0\to\pi\pi) = A(\bar{K}^0\to 2\pi)$ assumed up to now

what happens if we don't make assumption?

$A(K^0\to 2\pi) = A_I \cdot e^{i\delta_I}$ A_I isospin amplitude

$A(\bar{K}^0\to 2\pi) = A_I^* \cdot e^{i\delta_I}$ δ_I strong phase



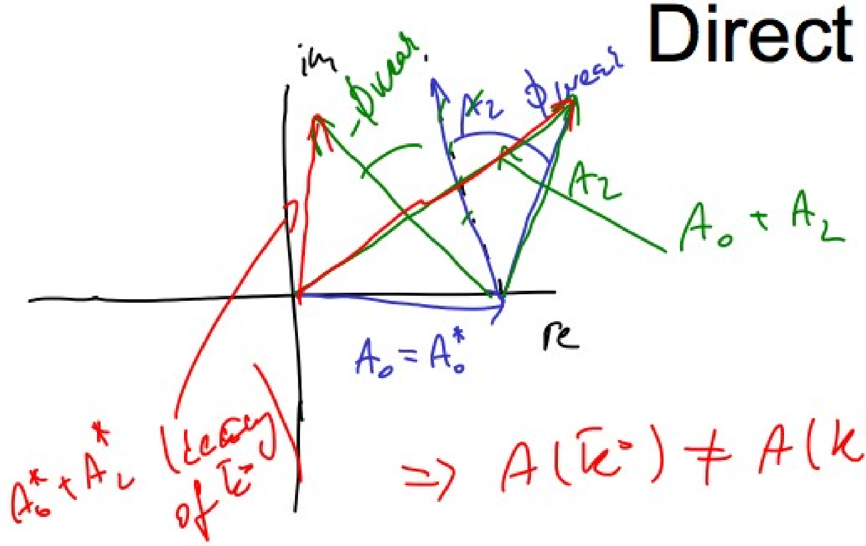
$A(K^0\to 2\pi) = \sqrt{\frac{2}{3}}\,A_0 e^{i\delta_0} + \sqrt{\frac{1}{3}}\,A_2 e^{i\delta_2}$

$A(\bar{K}^0\to 2\pi) = \sqrt{\frac{2}{3}}\,A_0^* e^{i\delta_0} + \sqrt{\frac{1}{3}}\,A_2^* e^{i\delta_2}$

$|\pi^+\pi^-\rangle = \frac{1}{\sqrt{3}}|2,0\rangle + \sqrt{\frac{2}{3}}|0,0\rangle$

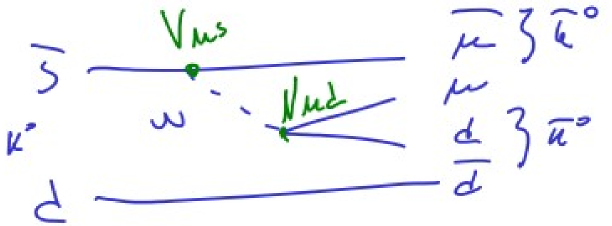
$|\pi^0\pi^0\rangle = \sqrt{\frac{2}{3}}|2,0\rangle - \sqrt{\frac{1}{3}}|0,0\rangle$

Direct CPV

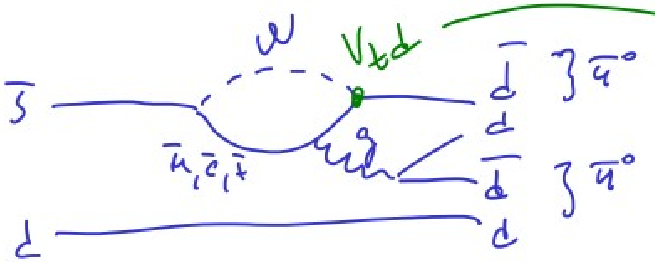


$\Rightarrow$ weak phase between amplit.
strong phase between ampl.

$\Rightarrow A(\bar{K}^0) \neq A(K^0)$



no weak phase
contr. to A_0, A_2



gives weak phase (complex)
contributes only to A_0 ($I=0$)

A_0 with compl. phase ; A_2 without compl. phase

Kaon direct CPV

$$\eta_{+-} = \frac{A(K_L \to \pi^+\pi^-)^{\;\swarrow \text{ CPV}}}{A(K_S \to \pi^+\pi^-)^{\;\nwarrow \text{ CP cons.}}} =$$

$$= \frac{\langle \pi^+\pi^- | K_L \rangle}{\langle \pi^+\pi^- | K_S \rangle} = \frac{\langle \pi^+\pi^- | (1+\varepsilon)K^0 - (1-\varepsilon)\bar{K}^0 \rangle}{\langle \pi^+\pi^- | (1+\varepsilon)K^0 + (1-\varepsilon)\bar{K}^0 \rangle} =$$

$$= \underbrace{\varepsilon}_{\nearrow \text{ ind. CPV}} + \underbrace{\frac{\langle \pi^+\pi^- | K_2 \rangle}{\langle \pi^+\pi^- | K_1 \rangle}}_{\Downarrow\ \varepsilon' \ \nwarrow \text{ direct CPV}} \qquad \eta_{+-} = \varepsilon + \varepsilon'$$

$$\eta_{00} = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon'$$

Kaon direct CPV

$A_0 = |A_0| e^{i\delta_0} e^{i\phi_w}$ assume $\delta_0 = -\phi_w$

$\mathrm{Im}(A_0) = 0$

$$A(K^0 \to \pi^+\pi^-) = \sqrt{\tfrac{2}{3}}\, A_0 e^{i\delta_0} + \sqrt{\tfrac{1}{3}}\, A_2 e^{i\delta_2}$$

$$A(\bar{K}^0 \to \pi^+\pi^-) = \sqrt{\tfrac{2}{3}}\, A_0^* e^{i\delta_0} + \sqrt{\tfrac{1}{3}}\, A_2^* e^{i\delta_2}$$

$$\varepsilon' = \frac{\cancel{\sqrt{\tfrac{2}{3}} A_0} e^{i\delta_0} + \sqrt{\tfrac{1}{3}}\, e^{i\delta_2} - \cancel{\sqrt{\tfrac{2}{3}} A_0^*} e^{i\delta_0} - \sqrt{\tfrac{1}{3}}\, A_2^* e^{i\delta_2}}{\sqrt{\tfrac{2}{3}}\, A_0 e^{i\delta_0} + \sqrt{\tfrac{1}{3}}\, e^{i\delta_2} + \sqrt{\tfrac{2}{3}}\, A_0^* e^{i\delta_0} + \sqrt{\tfrac{1}{3}}\, A_2^* e^{i\delta_2}} =$$

$$= \frac{e^{i\delta_2}(A_2 - A_2^*)}{\sqrt{2}\, 2 A_0 e^{i\delta_0} + e^{i\delta_2}(A_2 + A_2^*)}$$

$\left|\frac{A_2}{A_0}\right| \sim 5\%$

$$\varepsilon' \approx \frac{i}{\sqrt{2}}\, e^{i(\delta_2 - \delta_0)} \frac{\mathrm{Im}(A_2)}{A_0}$$

Experimental observables

$$\eta_{+-} = \varepsilon + \varepsilon' = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)}$$

$$\eta_{00} = \varepsilon - 2\varepsilon' = \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)}$$

$$\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 = \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} \cdot \frac{A(K_S \to \pi^0\pi^0)}{A(K_L \to \pi^0\pi^0)} \cdot \frac{A^*(K_L \to \pi^+\pi^-)}{A^*(K_S \to \pi^+\pi^-)} \cdot \frac{A^*(K_S \to \pi^0\pi^0)}{A^*(K_L \to \pi^0\pi^0)} =$$

$$= \frac{\Gamma(K_L \to \pi^+\pi^-)}{\Gamma(K_S \to \pi^+\pi^-)} \cdot \frac{\Gamma(K_S \to \pi^0\pi^0)}{\Gamma(K_L \to \pi^0\pi^0)} = \text{ratio of branching fractions}$$

ε'/ε is small number

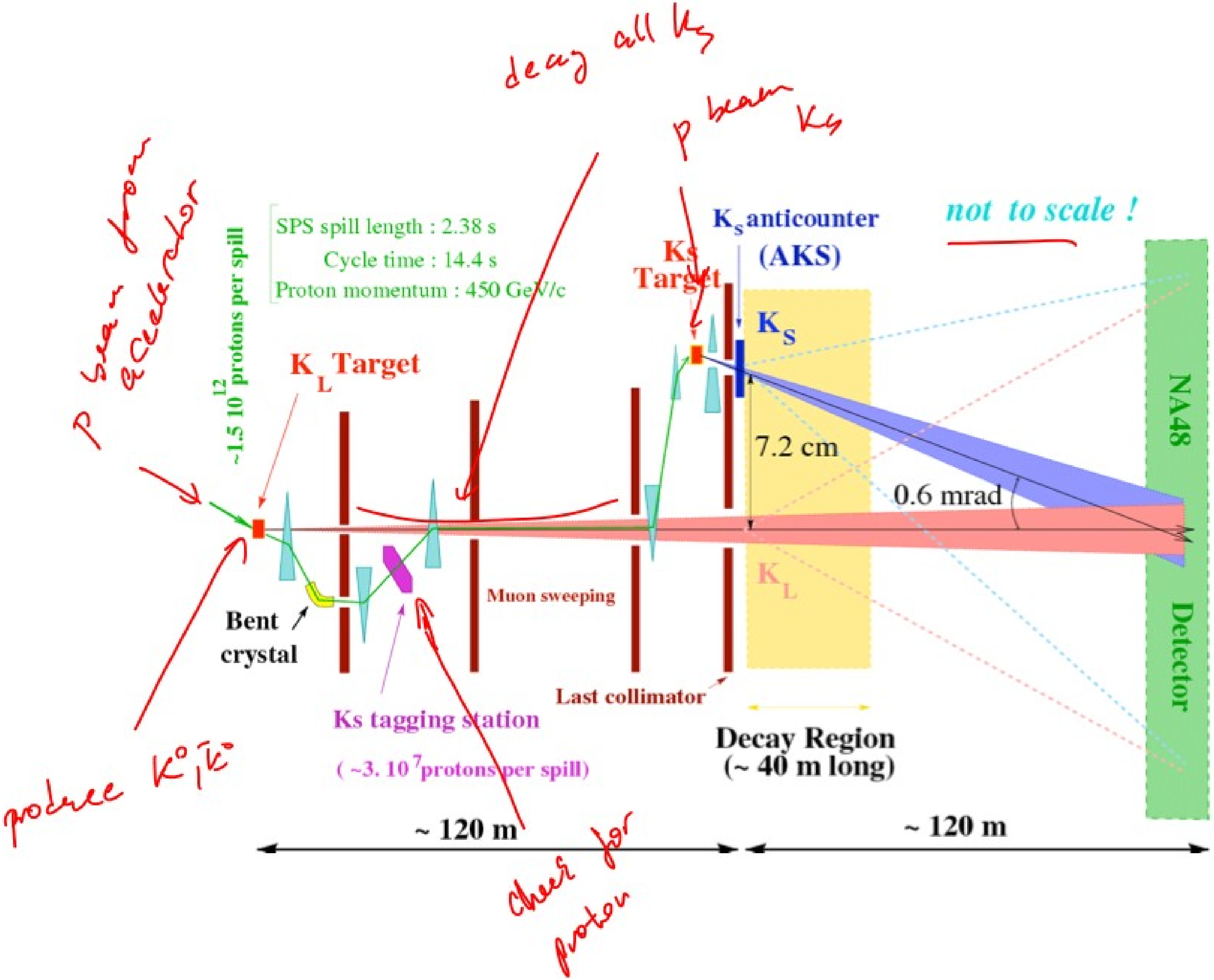
$$\frac{N(K_L \to \pi^+\pi^-)}{N(K_S \to \pi^+\pi^-)} \Big/ \frac{N(K_L \to \pi^0\pi^0)}{N(K_S \to \pi^0\pi^0)}$$

$\frac{\eta_{+-}}{\eta_{00}} \to$ Taylor expansion to first order

$$\left|\frac{\eta_{+-}}{\eta_{00}}\right|^2 \approx 1 + 6\,\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right)$$

phase of ε, ε' is almost same

NA48 @ CERN



p beam from accelerator

produce $K^0/\bar{K}^0$

decay all K_S

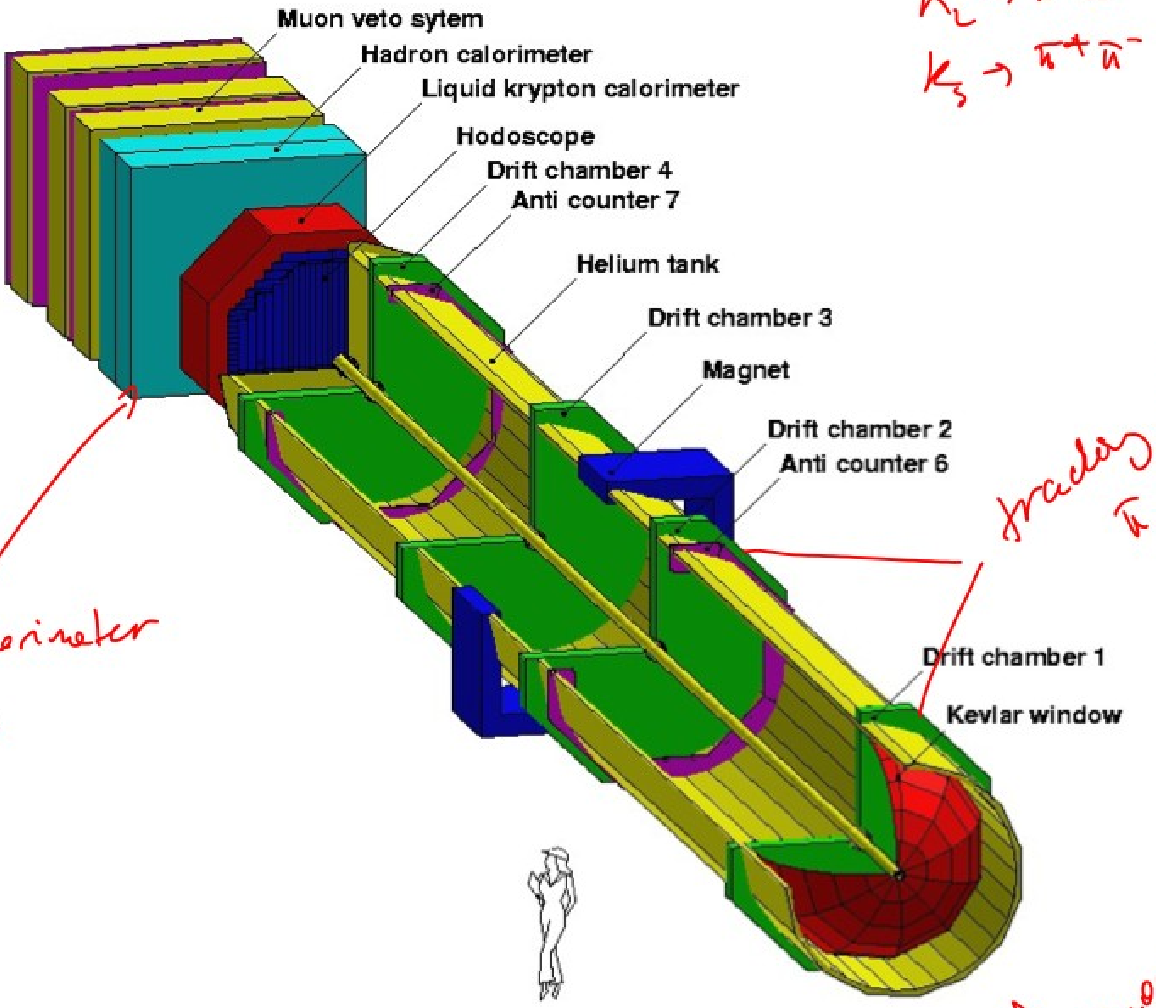
p beam K_S

check for proton

NA48 @ CERN

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

$K_S \to \pi^+\pi^-, \pi^0\pi^0$



em calorimeter

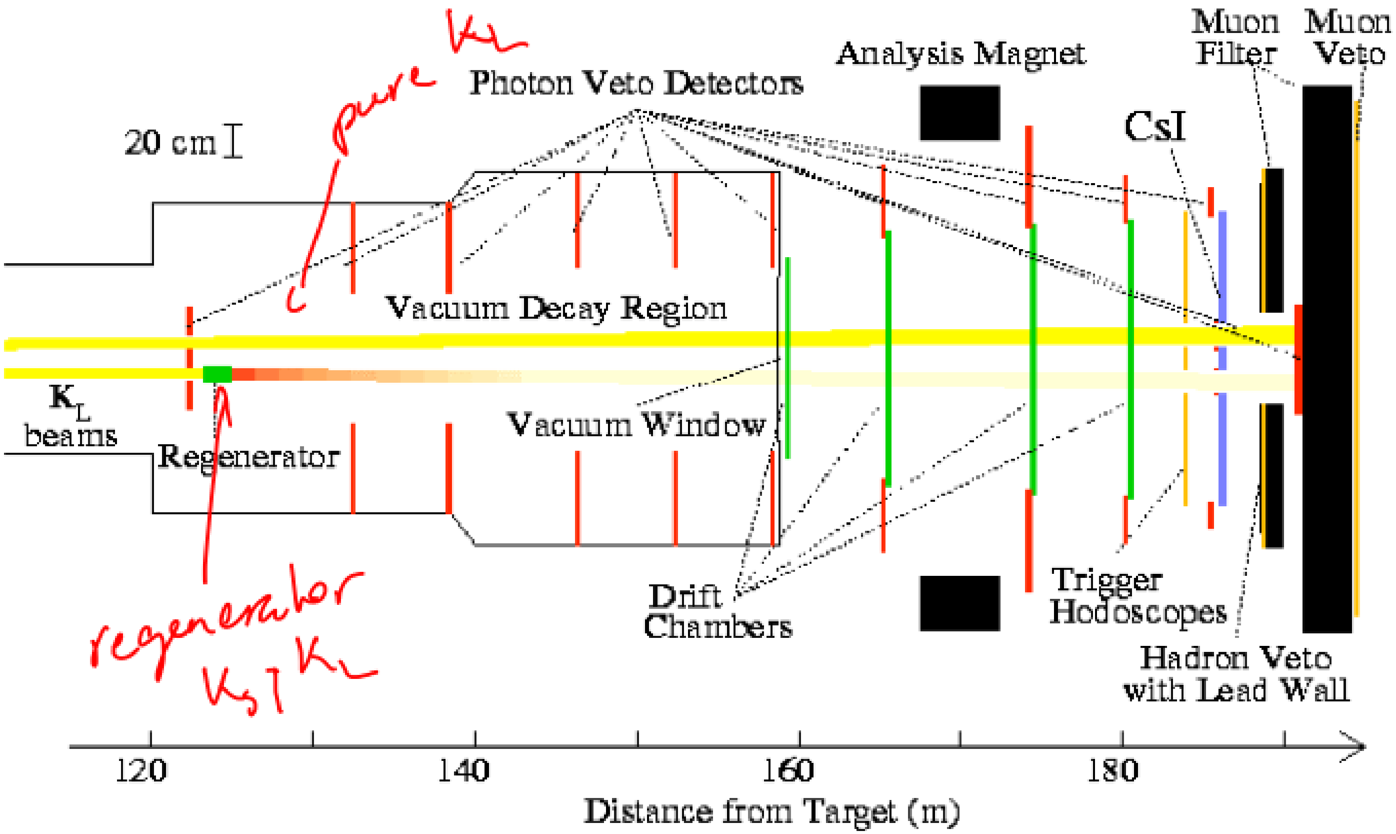
$\pi^0 \to 2\gamma$

tracking of charged π

↑ kaons → 2π

KTeV @ FNAL

beam of protons producing $K^0, \bar{K}^0$

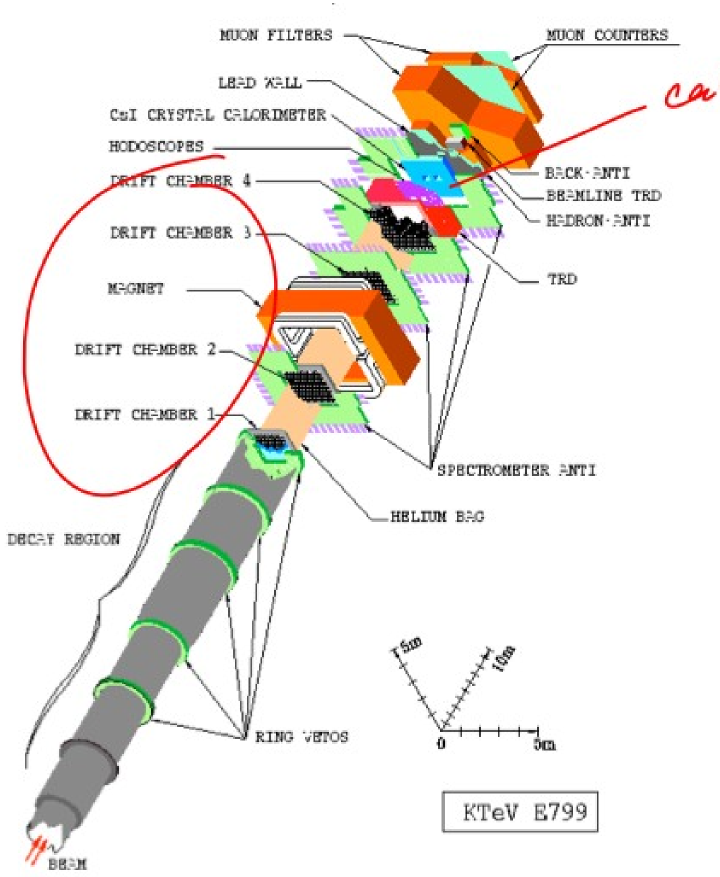


pure K_L

double K_L

regenerator K_S, K_L

KTeV @ FNAL



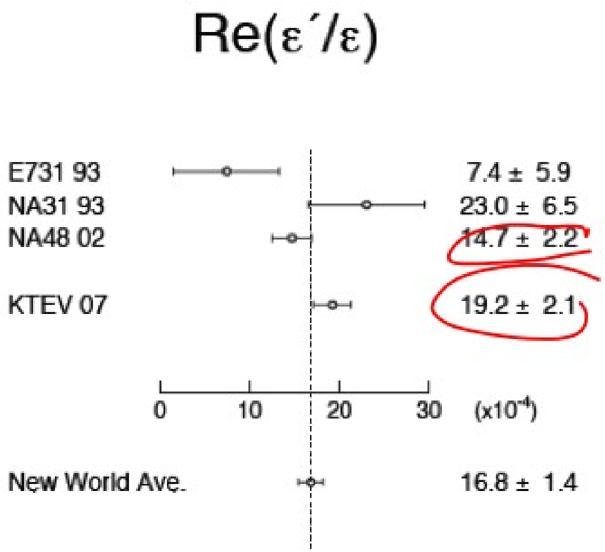
tracking for $\pi^+ \pi^-$

calorimeter CsI

$\pi^0 \to 2\gamma$

K beam

Experiment vs Theory



NA48

KTeV

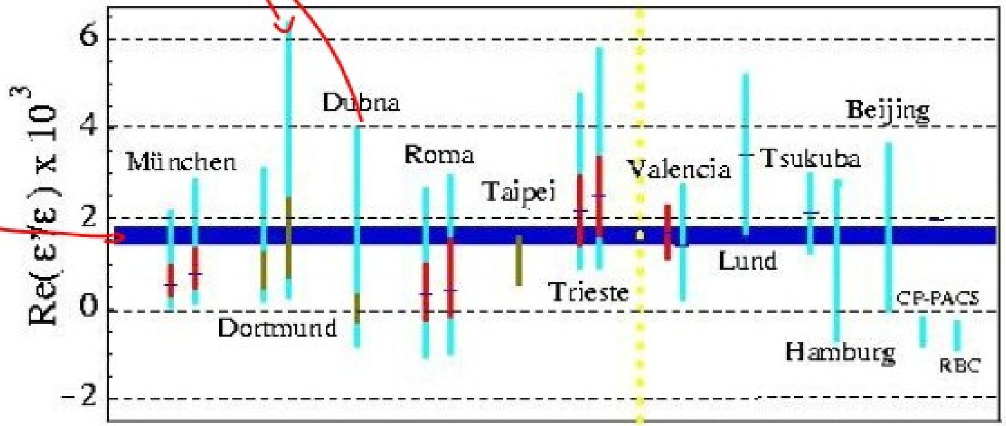
$Re\left(\frac{\varepsilon'}{\varepsilon}\right) = (16.8 \pm 1.4) \times 10^{-4}$

indirect CPV $\varepsilon \approx 2 \times 10^{-3}$

direct CPV $\varepsilon' \approx 2 \times 10^{-3}\,\varepsilon$

$\varepsilon' \approx 4 \times 10^{-6}$

Theory predictions



Theory has to work to improve calculations

experiment