Review on CP Violation

1st International Conference on New Frontiers in Physics
10-16 June 2012, Kolymbari, Crete, Greece

T. Nakada

EPFL-LPHE
Lausanne, Switzerland

History of Flavour

- Theory

- Experiments
  - Discovery of strange particles,

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)

- Experiments
  - Discovery of strange particles,

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)

- Experiments
  - Discovery of strange particles,
  - Discovery of tau-theta puzzle ($K^+ \to \pi^+\pi^0$ and $\pi^+\pi^+\pi^-$)

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)
  - Parity violation, Lee&Yang (1956)

- Experiments
  - Discovery of strange particles,
  - Discovery of tau-theta puzzle

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)
  - Parity violation, Lee&Yang (1956)

- Experiments
  - Discovery of strange particles,
  - Discovery of tau-theta puzzle
    ⇒ parity violating nucleon β decays and μ decay

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)
  - Parity violation, Lee&Yang (1956)

- Experiments
  - Discovery of strange particles, **their decay properties**
  - Discovery of tau-theta puzzle
    ⇒ parity violating nucleon β decays and μ decay

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)
  - Parity violation, Lee&Yang (1956)
  - Flavour mixing, Cabibbo (1963)
  - GIM mechanism, Glashow, Iliopoulos, and Maiani (1970)

- Experiments
  - Discovery of strange particles, **their decay properties**
  - Discovery of tau-theta puzzle
    ⇒ parity violating nucleon β decays and μ decay

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)
  - Parity violation, Lee&Yang (1956)
  - Flavour mixing, Cabibbo (1963)
  - GIM mechanism, Glashow, Iliopoulos, and Maiani (1970)

- Experiments
  - Discovery of strange particles, **their decay properties**
    ⇒ discovery of c, b and t and studies of their decays
  - Discovery of tau-theta puzzle
    ⇒ parity violating nucleon β decays and μ decay

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)
  - Parity violation, Lee&Yang (1956)
  - Flavour mixing, Cabibbo (1963)
  - GIM mechanism, Glashow, Iliopoulos, and Maiani (1970)

- Experiments
  - Discovery of strange particles, **their decay properties**
    ⇒ discovery of c, b and t and studies of their decays
  - Discovery of tau-theta puzzle
    ⇒ parity violating nucleon β decays and μ decay
  - Discovery of CP violation in the kaon system (1964)

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)
  - Parity violation, Lee&Yang (1956)
  - Flavour mixing, Cabibbo (1963)
  - GIM mechanism, Glashow, Iliopoulos, and Maiani (1970)
  - Three family flavours and CP violation, Kobayashi and Maskawa (1973)

- Experiments
  - Discovery of strange particles, **their decay properties**
    ⇒ discovery of c, b and t and studies of their decays
  - Discovery of tau-theta puzzle
    ⇒ parity violating nucleon β decays and μ decay
  - Discovery of CP violation in the kaon system (1964)

History of Flavour

- Theory
  - Introduction of "strangeness" quantum number
    Gelmann, Nishijima, and others (1955)
  - Parity violation, Lee&Yang (1956)
  - Flavour mixing, Cabibbo (1963)
  - GIM mechanism, Glashow, Iliopoulos, and Maiani (1970)
  - Three family flavours and CP violation, Kobayashi and Maskawa (1973)
  - ???
- Experiments
  - Discovery of strange particles, **their decay properties**
    ⇒ discovery of c, b and t and studies of their decays
  - Discovery of tau-theta puzzle
    ⇒ parity violating nucleon β decays and μ decay
  - Discovery of CP violation in the kaon system (1964)
    ⇒ further investigations in the K, D and B systems

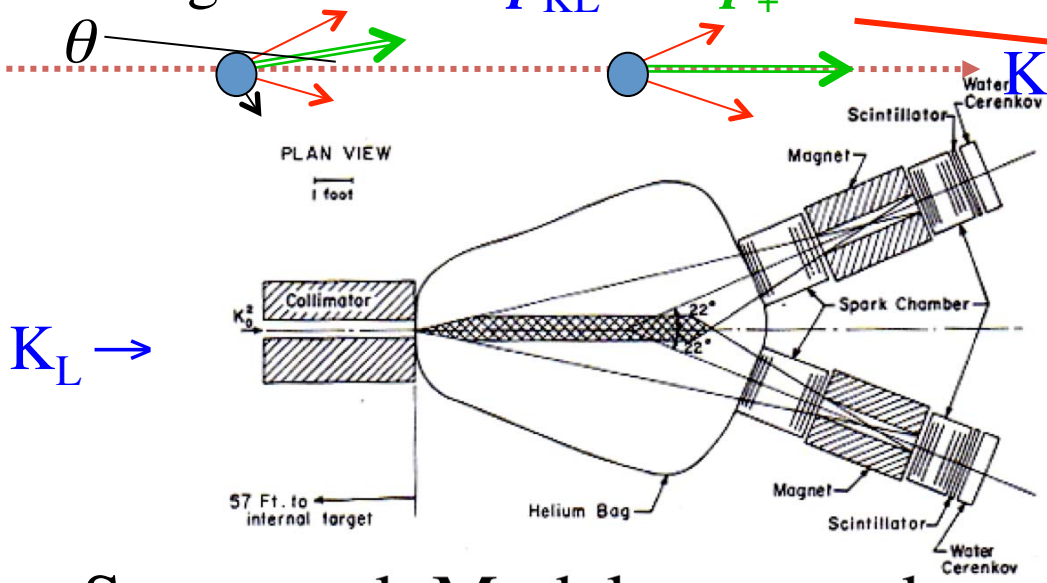
History of Flavour

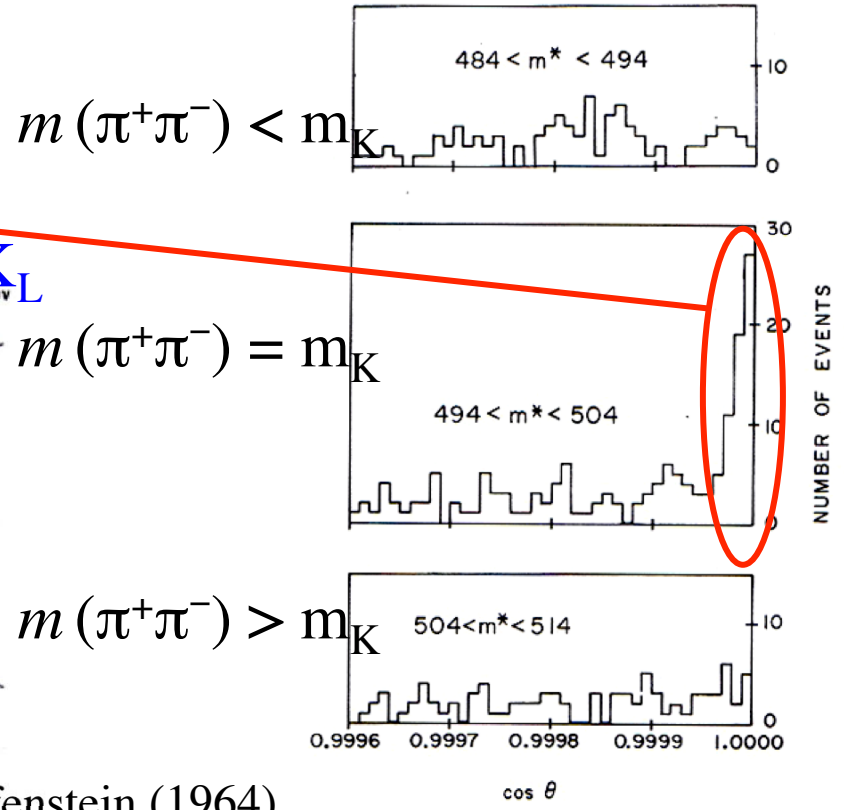
- Right after the discovery of CP violating $K^0_L \to \pi^+\pi^-$ decay

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

θ = angle between p_{KL} and p_{+-}

1964, J.H. Christenson et al.



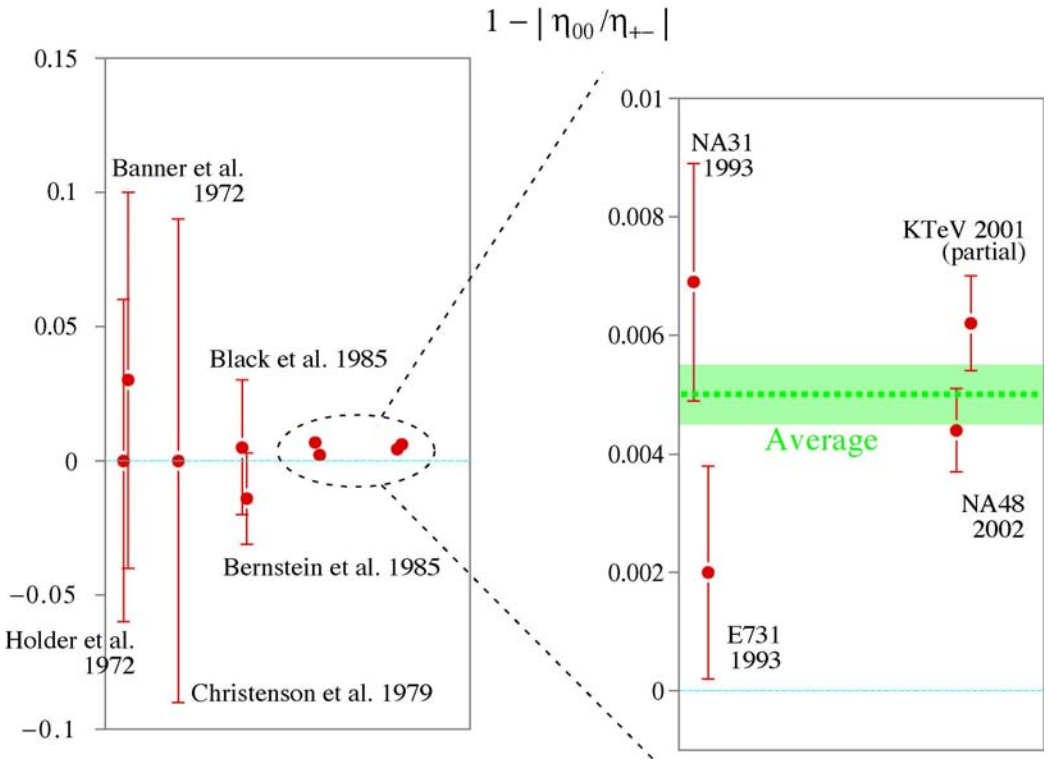


- Superweak Model proposed Wolfenstein (1964)
  CPV is due to the interference of Weak⊗Superweak

$$K^0 \xrightarrow{\text{“}\pi\pi\text{”}\ \text{“}\pi\pi\pi\text{”}} \bar{K}^0 \quad + \quad K^0 \xrightarrow{\text{Super weak}} \bar{K}^0$$

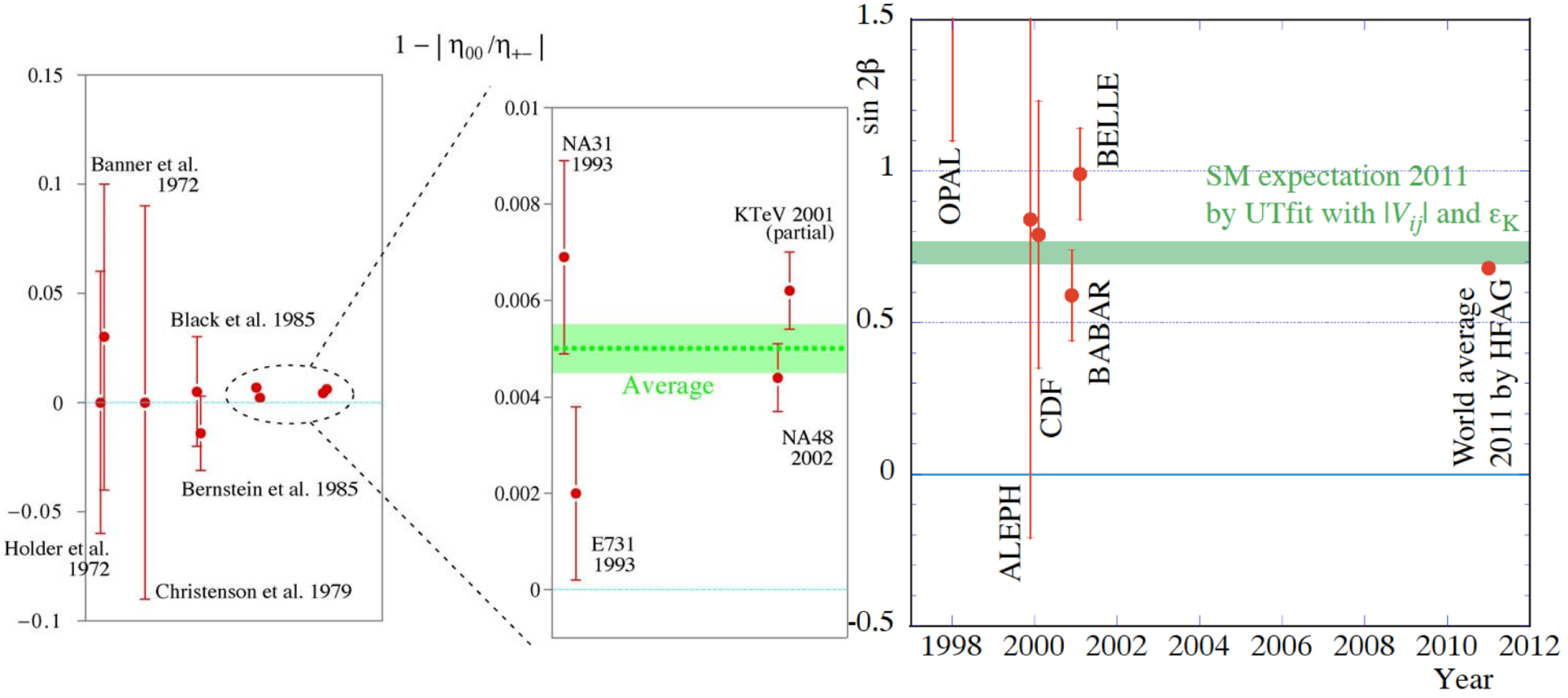
History of CP Violation

- Took till 2001 to rule out the Superweak Model (Re $\varepsilon' \neq 0$), i.e. CPV in $K_L \to \pi^+\pi^- \neq K_L \to \pi^0\pi^0$



History of CP Violation

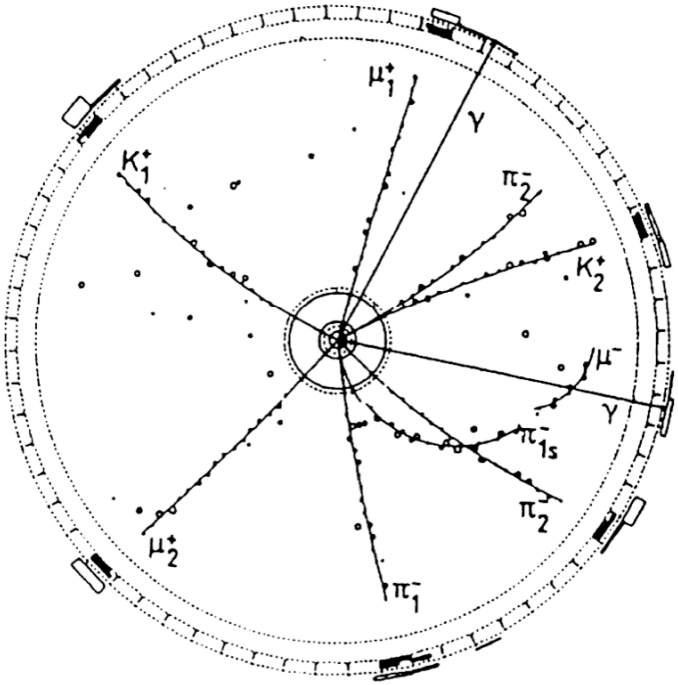
- Took till 2001 to rule out the Superweak Model (Re $\varepsilon' \neq 0$) and to confirm the Standard Model being the major source of CP violation (CPV in $B \rightarrow J/\psi K_S$ in good agreement with the SM)

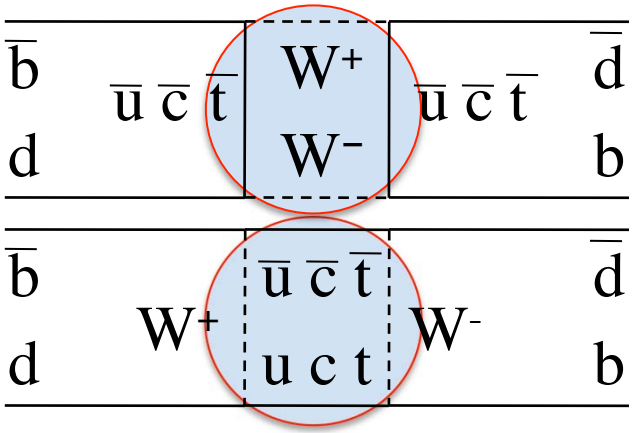


Example of Indirect Measurement

- Kaon had opened the wealth of flavour physics, and B meson brought the full glory through "loop" effect, e.g. B-$\overline{\text{B}}$ oscillation frequency measurement, Δm_d, and m_{top}

ARGUS 1987 $m_{\text{top}} > 50$ GeV/c^2





$\Upsilon(4S) \rightarrow B_d^0 \overline{B}_d^0$

$\rightarrow B_d^0 B_d^0$ or $\overline{B}_d^0 \overline{B}_d^0$

$\rightarrow \ell^+\ell^+$ or $\ell^-\ell^-$

$24.8 \pm 7.6 \pm 3.8$

$\Delta m(B_d) \sim 100 \times \Delta m(K^0)$

Example of Indirect Measurement

- Kaon had opened the wealth of flavour physics, and B meson brought the full glory through "loop" effect, e.g. B-$\overline{\text{B}}$ oscillation frequency measurement, Δm_d, and m_{top}

ARGUS 1987 $m_{\text{top}} > 50$ GeV/c^2

NB: UA1 result in 1984

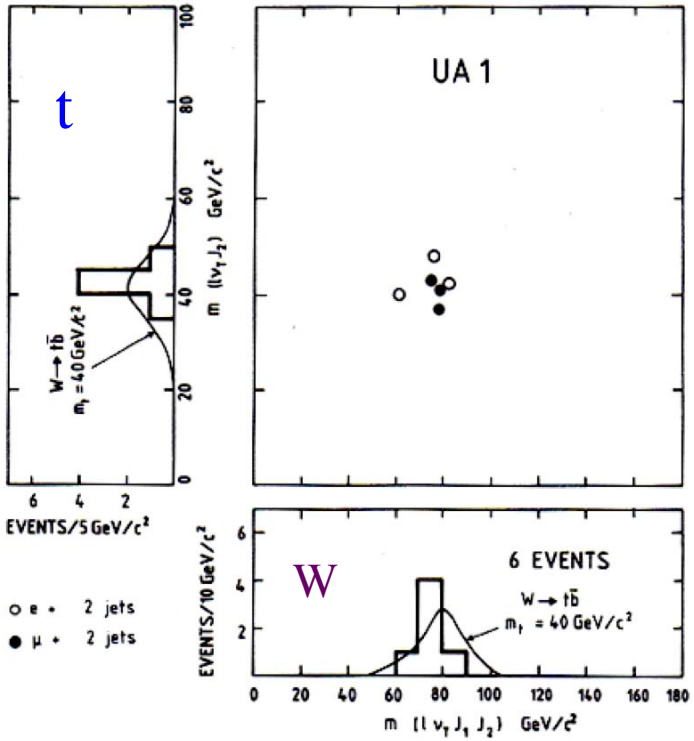
$p\bar{p} \rightarrow W^+ + X$

↳ $t\,\bar{b}$ → jet

↳ $bl\nu$

↳ jet

$m_t = 30\sim50$ GeV/c^2



Example of Indirect Measurement

- Kaon had opened the wealth of flavour physics, and B meson brought the full glory through "loop" effect, e.g. B-$\overline{\text{B}}$ oscillation frequency measurement, Δm_d, and m_{top}

ARGUS 1987 $m_{\text{top}} > 50$ GeV/c^2

NB: UA1 result in 1984

$p\bar{p} \rightarrow W^+ + X$

↳ $t\,\bar{b}$ → jet

↳ $bl\nu$

↳ jet

$m_t = 30\sim50$ GeV/c^2

LEP electroweak fit: 150~210 GeV/c^2

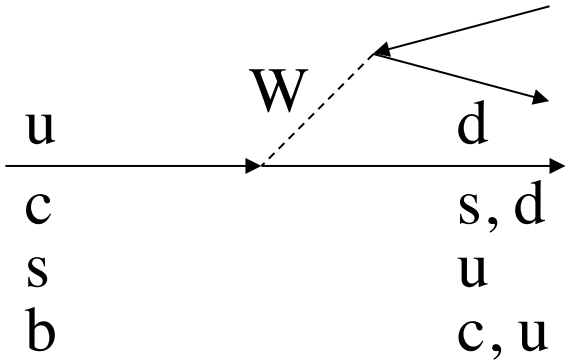
1995 CDF: $175\pm8\pm10$ GeV/c^2

D0: $199^{+19}_{-21}\pm22$ GeV/c^2

Recent Progress

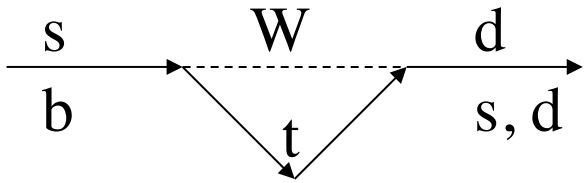
- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{\text{K}}$ and B-$\overline{\text{B}}$ oscillations

Tree level decays



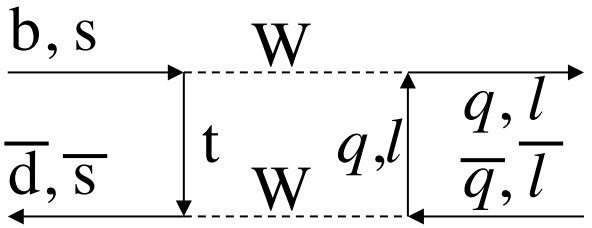
$|V_{ud}|, |V_{cs}|, |V_{cd}|$
$|V_{us}|, |V_{cb}|, |V_{ub}|$

Penguin level decays



$|V_{ts}|, |V_{td}|, |V_{tb}|$

Box level decays



$|V_{ts}|, |V_{td}|, |V_{tb}|$

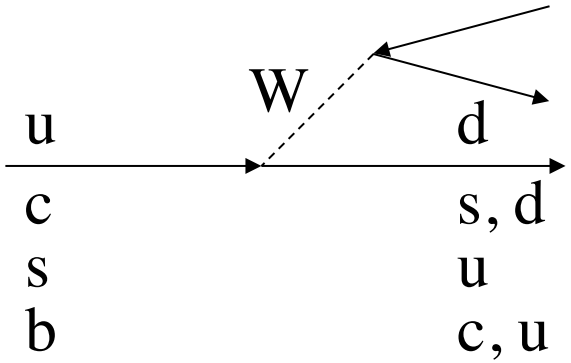
dominant contributions

virtual processes!!!

Recent Progress

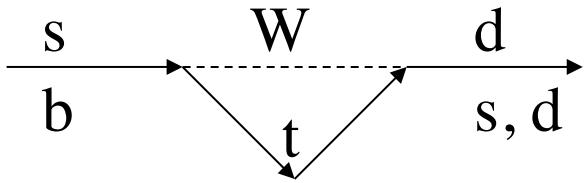
- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{\text{K}}$ and B-$\overline{\text{B}}$ oscillations

Tree level decays



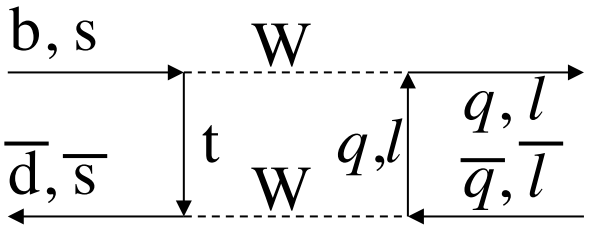
$|V_{ud}|, |V_{cs}|, |V_{cd}|$
$|V_{us}|, |V_{cb}|, |V_{ub}|$

Penguin level decays



$|V_{ts}|, |V_{td}|, |V_{tb}|$

Box level decays



$|V_{ts}|, |V_{td}|, |V_{tb}|$

dominant contributions

virtual processes!!!

Plus some other diagrams but less relevant for "flavour" physics
BABAR, Belle, CDF, and D0 measurements allow very accurate measurements of the CKM matrix elements.

Recent Progress

- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{K}$ and B-$\overline{B}$ oscillations
- CP violation in K and B

  For the kaon system CPV is established in

  i) Oscillations: $\mathrm{Re}\eta_{+-}$, $\mathrm{Re}\eta_{00}$ ($\mathrm{Re}\varepsilon$) $\neq 0$

  ii) Interplay decay-oscillations: $\mathrm{Im}\eta_{+-}$, $\mathrm{Im}\eta_{00} \neq 0$

  iii) Decay amplitudes: $|\eta_{+-}| - |\eta_{00}| \neq 0$

  have been well experimentally established

  measured with ~5‰ accuracy for i) and ii)

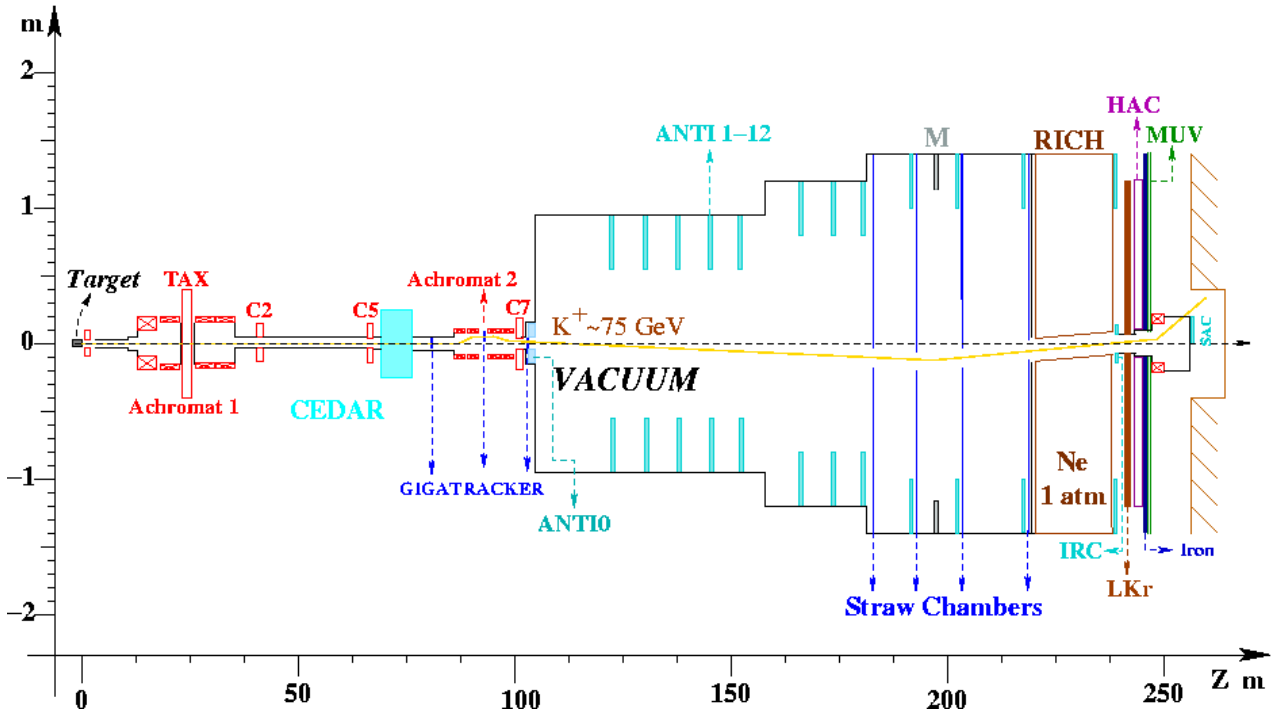
  ~16% for iii)

  large theoretical uncertainties to extract the CKM parameters

  Future: $K \to \pi\nu\overline{\nu}$ at CERN(K^+) and JPARC(K_L)

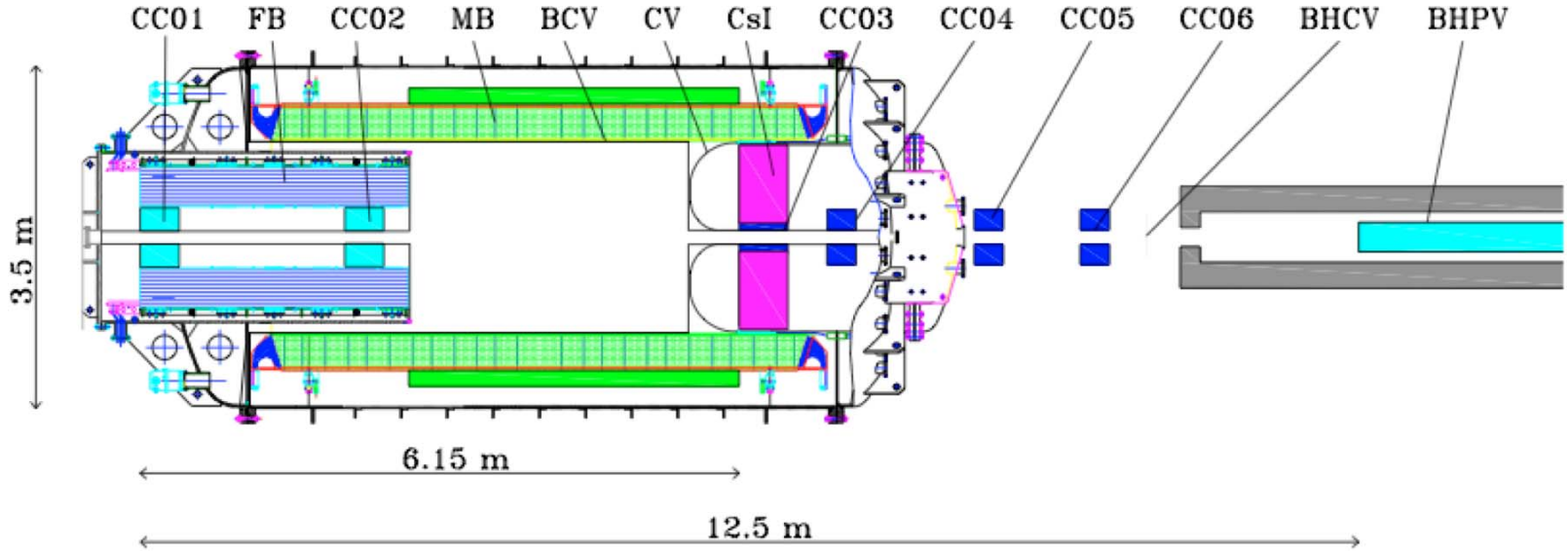
Recent Progress

- NA62@CERN: ~100 $K^+ \to \pi^+ \nu\bar{\nu}$
  a clean determination of $|V_{ts}{}^* V_{td}|$
  detector construction in progress
  technical run with the partial detector in November
  physics run in 2014 when SPS is back for operation



Recent Progress

- KOTO@JPARC: few $K^0 \to \pi^0 \nu\bar{\nu}$
  a clean determination of $\mathrm{Im}(V_{ts}^* V_{td})$
  test run in Feb 2012 for CsI calorimeter wall
  various calibration runs including $K_L \to 3\pi^0$
  complete detector by the end of 2012
  physics run in Spring 2013



Recent Progress

- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{K}$ and B-$\overline{B}$ oscillations
- CP violation in K and B
  - BABAR (N. Arnaud) and Belle, show that CP violation in B_d sector is dominated by the Standard Model, in agreement with the CKM paradigm, with a little "tension", e.g. $|V_{ub}|$ v.s. β v.s. ε_K, but could be due to poor understanding in strong interactions.

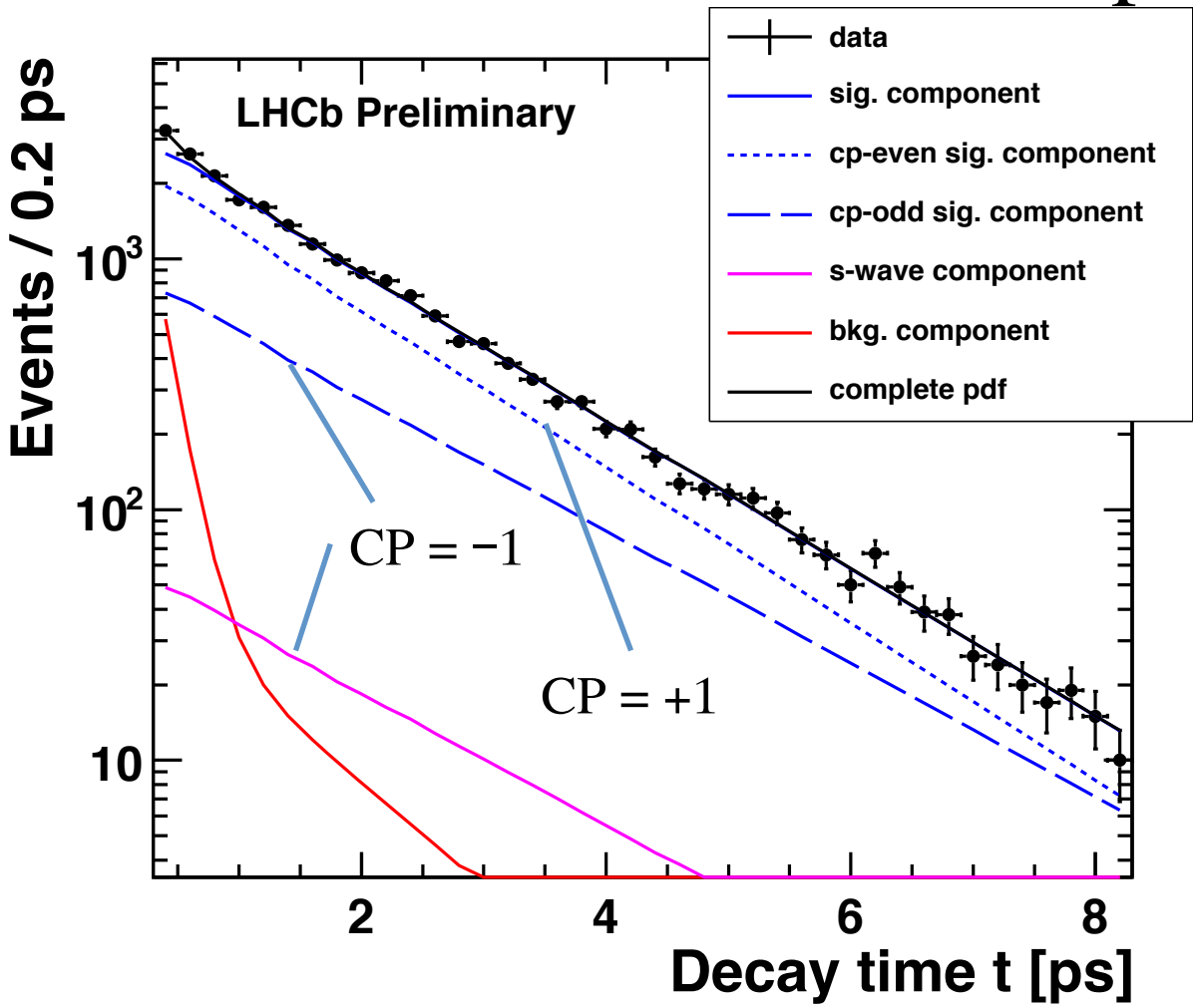
Recent Progress

- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{\text{K}}$ and B-$\overline{\text{B}}$ oscillations
- CP violation in K and B
  - BABAR (N. Arnaud) and Belle, show that CP violation in B_d sector is dominated by the Standard Model, in agreement with the CKM paradigm (with a little "tension", e.g. $|V_{ub}|$ v.s. β v.s. ε_K).
  - CDF and D0, explored B_s sector, largely in an agreement with the Standard Model, with some intriguing indications…
    - somewhat larger CPV in $B_s \to J/\psi\phi$ than the SM prediction
    - much larger CPV in B-$\overline{\text{B}}$ oscillations (A_{SL}) than the SM predictions

Recent Progress

- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{K}$ and B-$\overline{B}$ oscillations
- CP violation in K and B
  - BABAR (N. Arnaud) and Belle, show that CP violation in B_d sector is dominated by the Standard Model, in agreement with the CKM paradigm (with a little "tension", e.g. $|V_{ub}|$ v.s. β v.s. ε_K).
  - CDF and D0, explored B_s sector, largely in an agreement with the Standard Model, with some intriguing indications…
    - somewhat larger CPV in $B_s \to J/\psi\phi$ than the SM prediction
    - much larger CPV in B-$\overline{B}$ oscillations (A_{SL}) than the SM predictions
  - LHC(b) has entered the game (U. Egede)
    - CPV in $B_s \to J/\psi\phi$ in agreement with SM
    - B_s is a bit like K^0, i.e. the heavy state lives longer and almost CP = −1

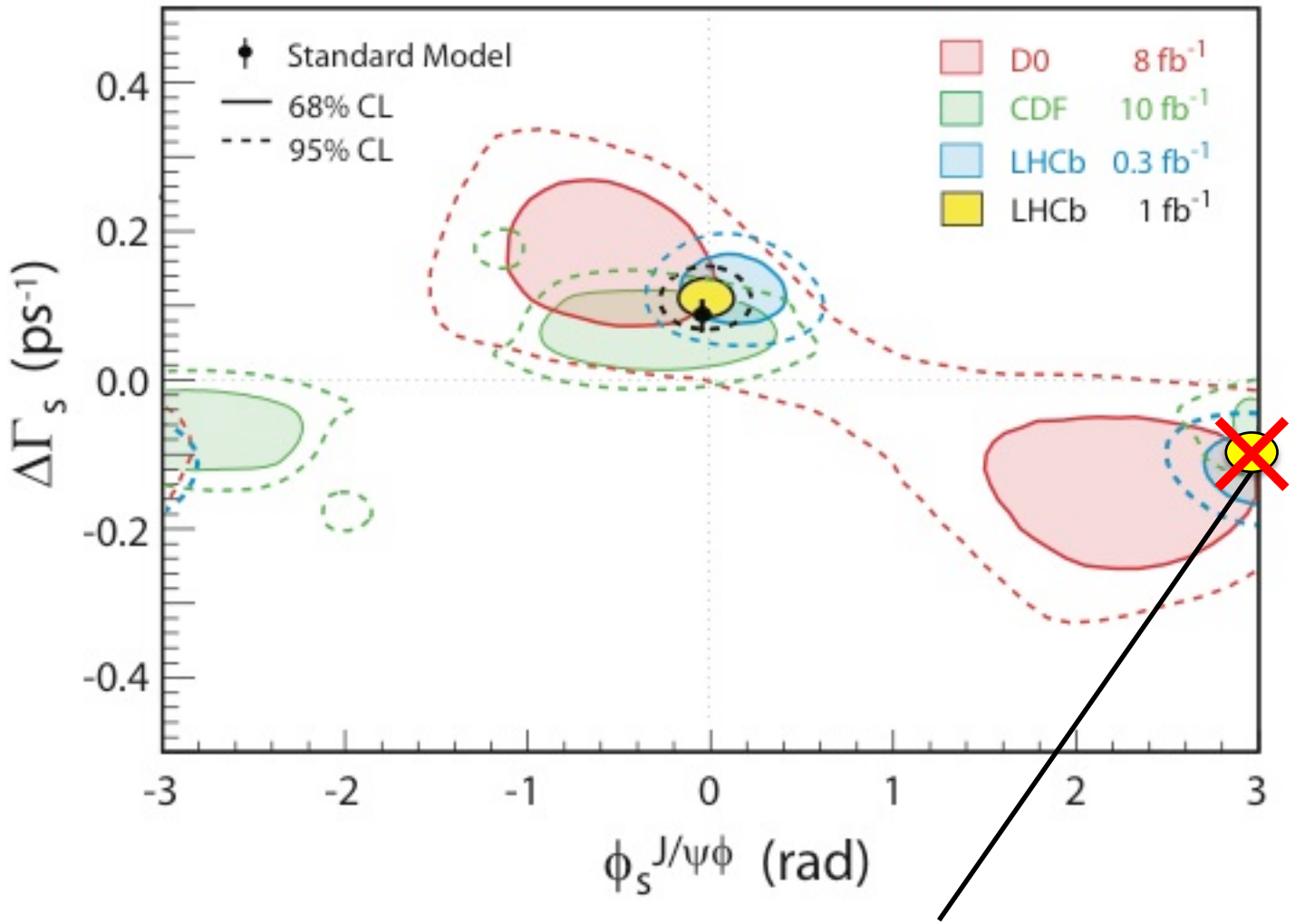
LHCb example



$B_s^0 + \overline{B}_s^0 \rightarrow J/\psi\,(K^+K^-)_\phi$

Decays into CP=+1 final state is steeper!

LHCb example



LHCb excludes this solution from the strong phase shift analysis

Recent Progress

- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{\text{K}}$ and B-$\overline{\text{B}}$ oscillations
- CP violation in K and B
  - BABAR (N. Arnaud) and Belle, show that CP violation in B_d sector is dominated by the Standard Model, in agreement with the CKM paradigm (with a little "tension", e.g. $|V_{ub}|$ v.s. β v.s. ε_K).
  - CDF and D0, explored B_s sector, largely in an agreement with the Standard Model, with some intriguing indications…
    - somewhat larger CPV in $B_s \to J/\psi\phi$ than the SM prediction
    - much larger CPV in B-$\overline{\text{B}}$ oscillations (A_{SL}) than the SM predictions
  - LHC(b) has entered the game (U. Egede)
    - CPV in $B_s \to J/\psi\phi$ in agreement with SM
    - B_s is a bit like K^0, i.e. the heavy state lives longer and almost CP = −1
    - With measured Δm_s (CDF, D0, LHCb), $\Delta\Gamma_s$(LHCb), a large A_{SL} is difficult to accommodate. (looking forward to the LHCb A_{SL} measurement)

Recent Progress

- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{K}$ and B-$\overline{B}$ oscillations
- CP violation in K and B
  - In general in a good agreement with the Standard Model expectations. No real smoking gun.

Recent Progress

- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{K}$ and B-$\overline{B}$ oscillations
- CP violation in K and B
  - In general in a good agreement with the Standard Model expectations. No real smoking gun.
  - Together with the rare decays, such as $B_{d,s} \rightarrow \mu^+\mu^-$, start to constrain seriously the parameter space for new physics, in particular the MSSM type of the model. CKM-fit will soon be replace by "SUSY"-fit?

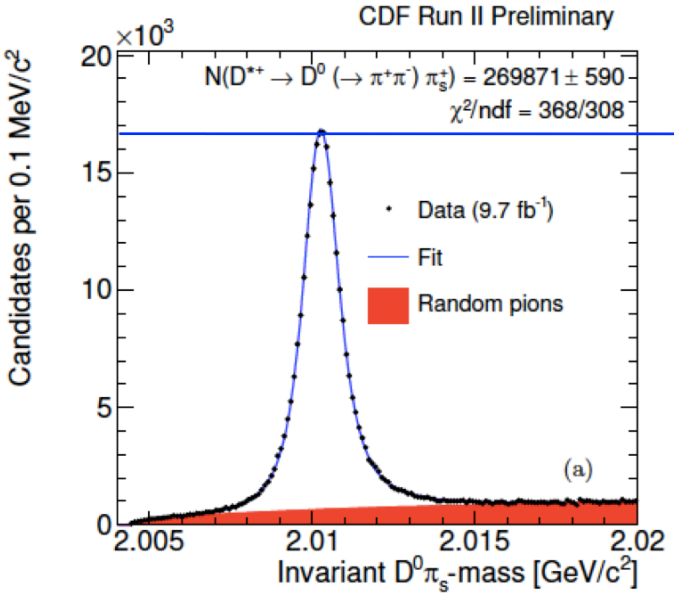
Recent Progress

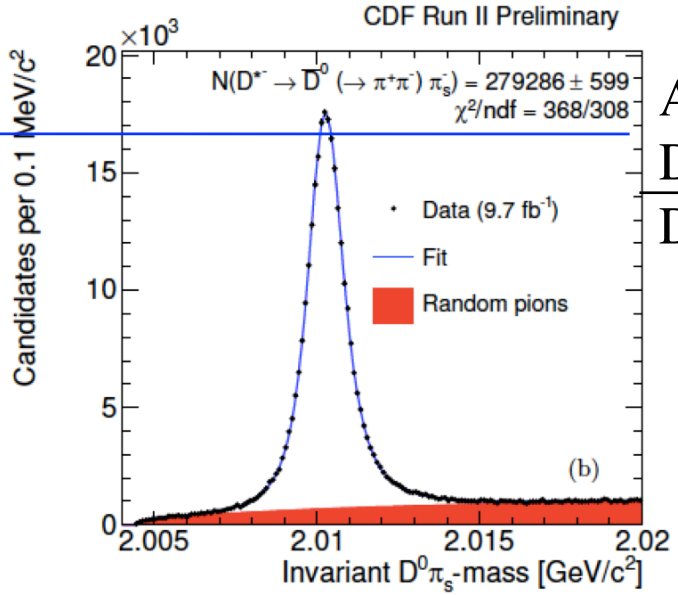
- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{K}$ and B-$\overline{B}$ oscillations
- CP violation in K and B
  - In general in a good agreement with the Standard Model expectations. No real smoking gun.
  - Together with the rare decays, such as $B_{d,s} \rightarrow \mu^+\mu^-$, start to constrain seriously the parameter space for new physics, in particular the MSSM type of the model. CKM-fit will soon be replace by "SUSY"-fit?
  - Analysis addressing the Lorentz structure of b→s penguin diagrams are emerging:
    $B_{d(s)} \rightarrow K^{*0}(\phi)\mu^+\mu^-$, $\rightarrow K^{*0}(\phi)\mu^+\mu^-$, $\rightarrow K^{*0}(\phi)\gamma$
    sensitive to new physics even for the MFV case

Recent Progress

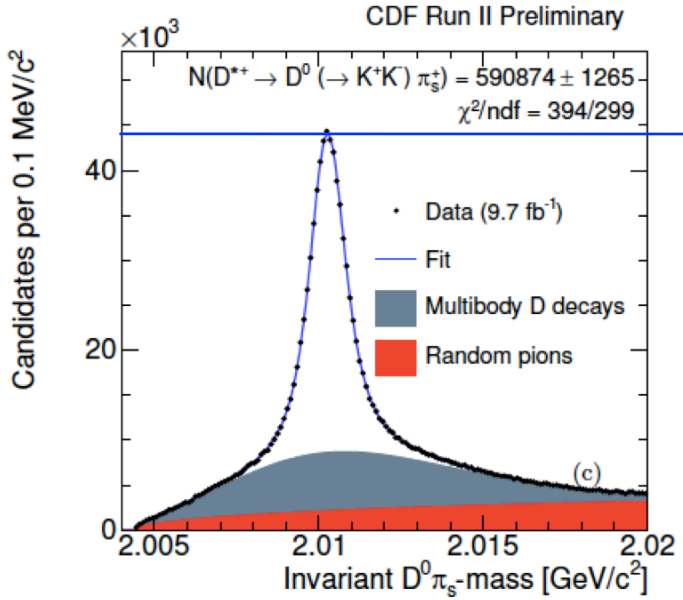
- Precise branching fraction measurements on the decays of u, c, s, and b hadrons and K-$\overline{K}$ and B-$\overline{B}$ oscillations
- CP violation in K and B
  - In general in a good agreement with the Standard Model expectations. No real smoking gun.
  - Together with the rare decays, such as $B_{d,s} \to \mu^+\mu^-$, start to constrain seriously the parameter space for new physics, in particular the MSSM type of the model. CKM-fit will soon be replace by "SUSY"-fit?
  - Analysis addressing the Lorentz structure of b→s penguin diagrams are emerging:
    $B_{d(s)} \to K^{*0}(\phi)\mu^+\mu^-$, $\to K^{*0}(\phi)\mu^+\mu^-$, $\to K^{*0}(\phi)\gamma$
    sensitive to new physics even for the MFV case
  - Interesting evidence for CP violation in D decays (LHCb, CDF), larger than naïve Standard Model expectations, could be due to strong interactions…

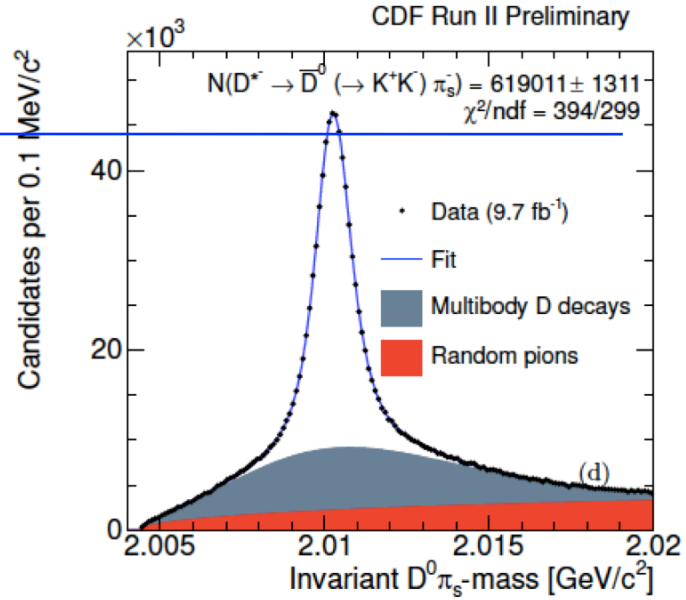
CDF example





$$A_{CP}^{\pi} = \frac{D^0 \to \pi^+\pi^- - D^0 \to \pi^+\pi^-}{D^0 \to \pi^+\pi^- - D^0 \to \pi^+\pi^-}$$





$$A_{CP}^{K} = \frac{D^0 \to K^+K^- - D^0 \to K^+K^-}{D^0 \to K^+K^- - D^0 \to K^+K^-}$$

$\Delta A_{CP}^{K} = A_{CP}^{K} - A_{CP}^{\pi}$
$= -(0.62 \pm 0.21 \pm 0.10)\%$

$= -(0.82 \pm 0.21 \pm 0.11)\%$
LHCb

Conclusions

- CP violation and flavour physics have excellent track records in detecting "energy threshold" beyond the direct reach by the energy of accelerators.
- Flavour structure of the quark system is now well measured and in a good agreement with the CKM description.
- No clear evidence of New Physics has been seen and parameter space for "simple" SUSY models is shrinking.
- Therefore, physics must be searched at many fronts:
  at high energies, direct search
  with high precision measurements, indirect search
  in the universe, somewhat mixed
  and neutrinos…

Conclusions

- CP violation and flavour physics have excellent track records in detecting "energy threshold" beyond the direct reach by the energy of accelerators.
- Flavour structure of the quark system is now well measured and in a good agreement with the CKM description.
- No clear evidence of New Physics has been seen and parameter space for "simple" SUSY models is shrinking.
- Therefore, physics must be searched at many fronts:
  at high energies, direct search
  with high precision measurements, indirect search
  in the universe, somewhat mixed
  and neutrinos…
- CP violation and rare decay are clearly at the front!