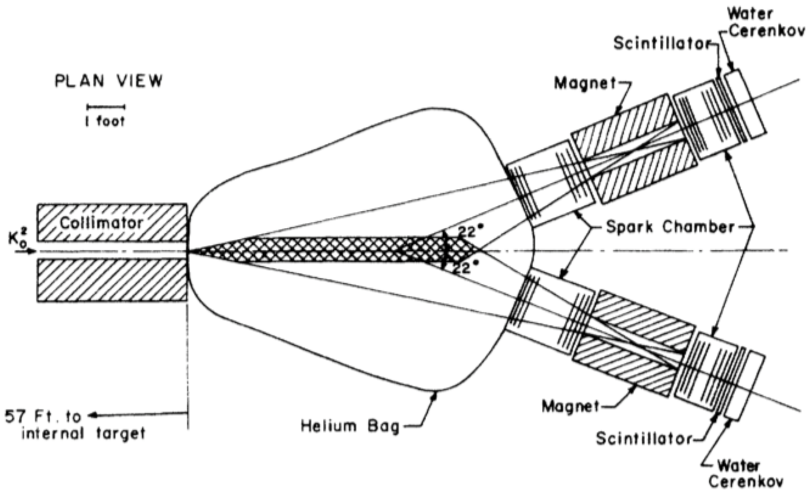
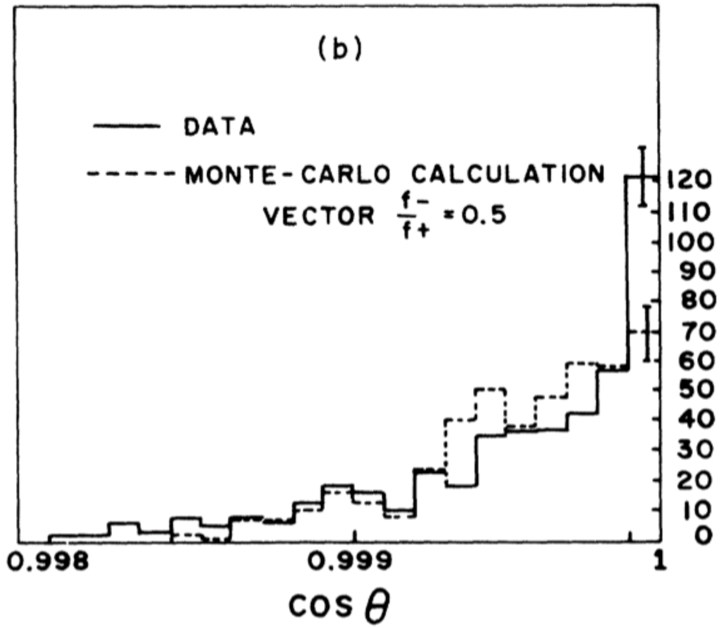
CP violation: review and perspectives

Tagir Aushev (ITEP)

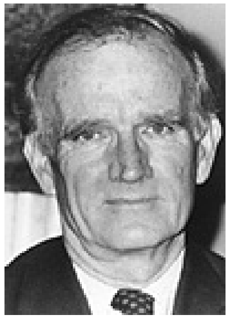
50 years of CP violation

- This year, 50th anniversary of CP violation:
  - In 1964 J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay discovered CPV in the neutral long-lived kaon system: $K_L \rightarrow \pi^+\pi^-$





J. Cronin



V. Fitch

1980

Kobayashi-Maskawa model

- In 1973 to explain CPV in kaons M.Kobayashi and T.Maskawa proposed a model with:
  - existence of the third generation of quarks
    - remarkable that only u, d & s quarks were known at that time
  - presence of complex phase in the quarks transitions
- Cabibbo matrix was extended to 3x3 CKM matrix:

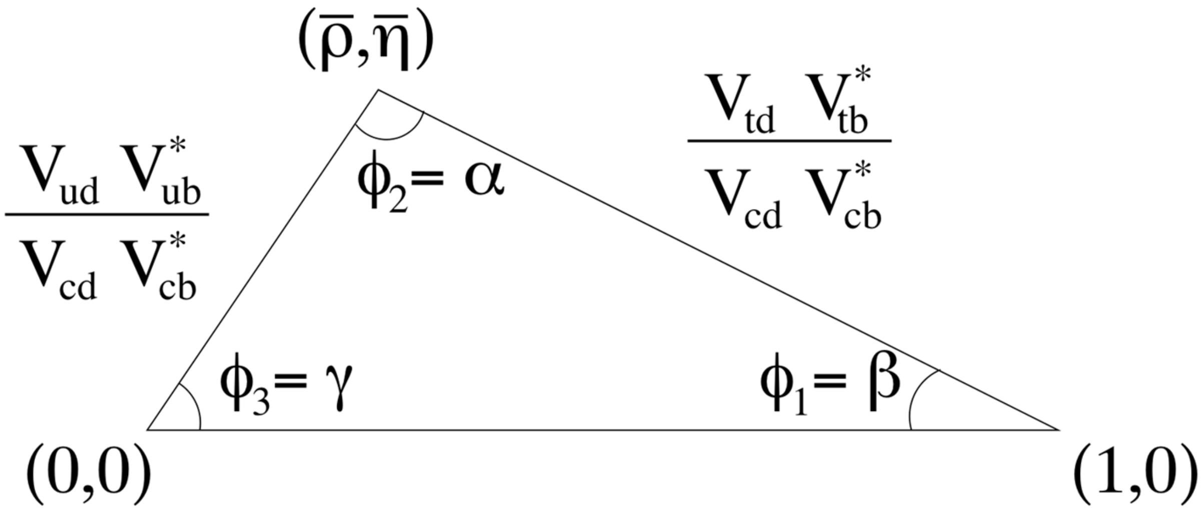
$$V_{KM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

Unitarity triangle

- Unitarity of the CKM matrix leads to one of equations:

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

- Involves matrix elements corresponding to B meson decays and mixing
- Can be presented on the complex plane as a triangle



$$\phi_1 \equiv \beta = \arg\left[-\frac{V_{cd}V_{cb}^{*}}{V_{td}V_{tb}^{*}}\right]$$

$$\phi_2 \equiv \alpha = \arg\left[-\frac{V_{td}V_{tb}^{*}}{V_{ud}V_{ub}^{*}}\right]$$

$$\phi_3 \equiv \gamma = \arg\left[-\frac{V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}}\right]$$

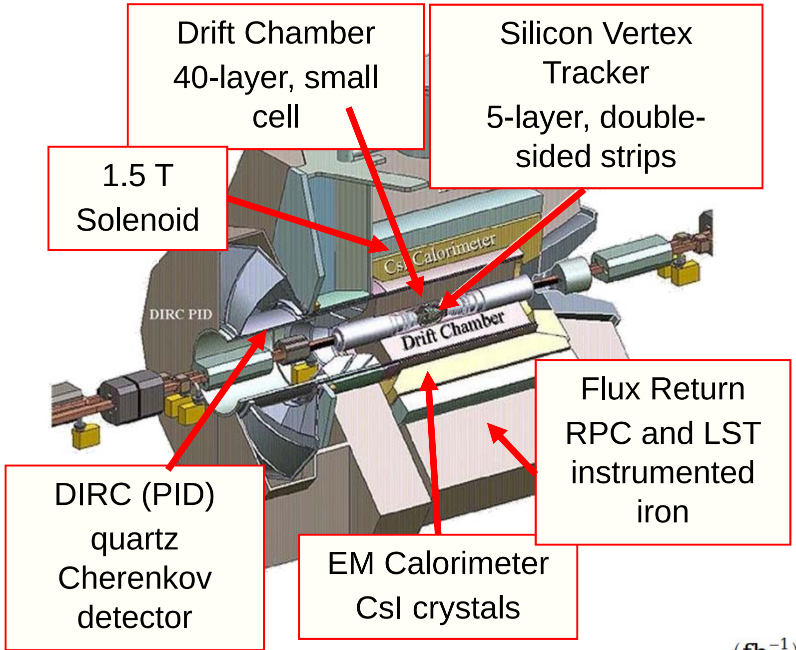
$$\phi_s = \arg\left[-\frac{V_{ts}V_{tb}^{*}}{V_{cs}V_{cb}^{*}}\right]$$

- Non-zero square of the Unitarity triangle
  → existence of CP violation

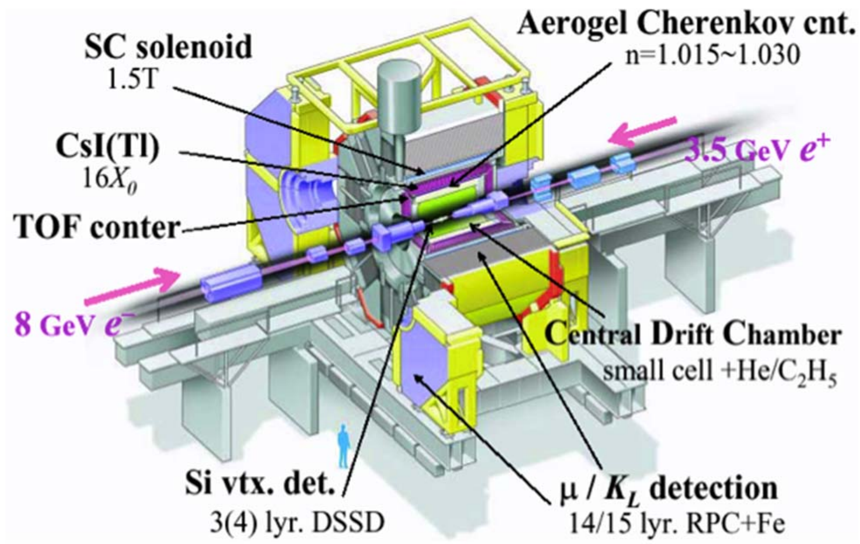
CPV in B^0 system

- For almost 40 years K^0-K^0bar system was the only one, where CPV was observed
- Observation of large B^0-B^0bar mixing by ARGUS was a crucial discovery for further CPV studies:
  - it led to the proposal of a construction of the asymmetric energy B-factories to study CPV in B decays
- CP violating effects in the B sector are O(1) rather than $O(10^{-3})$ as in the kaon system
- In 1999 two experiments, BaBar at SLAC, USA and Belle in KEK, Japan, started the data collection

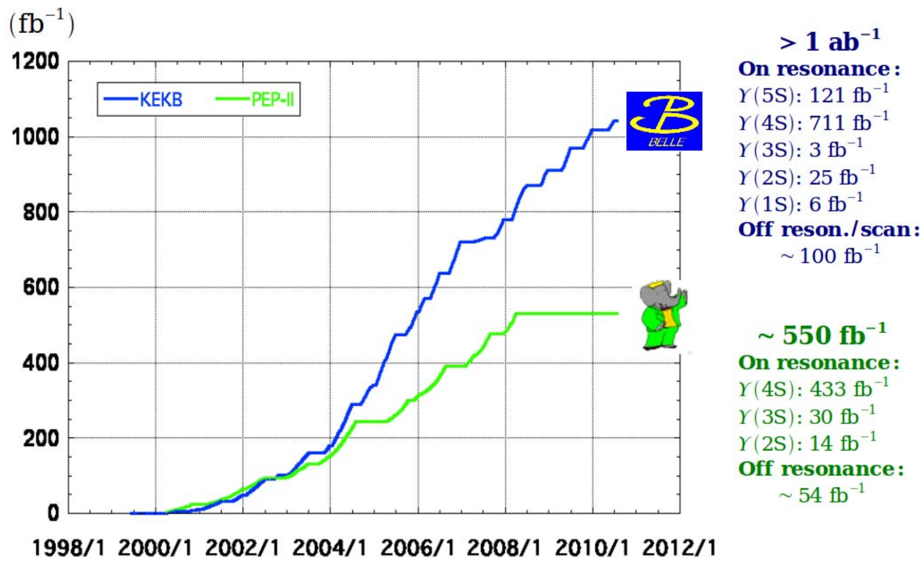
Decade of Belle & BaBar B-factories



TM & © Nelvana



Integrated luminosity of B factories



Main principles of CPV measurements

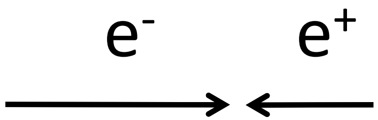
- CPV is observed in the interference of direct decay and via mixing:

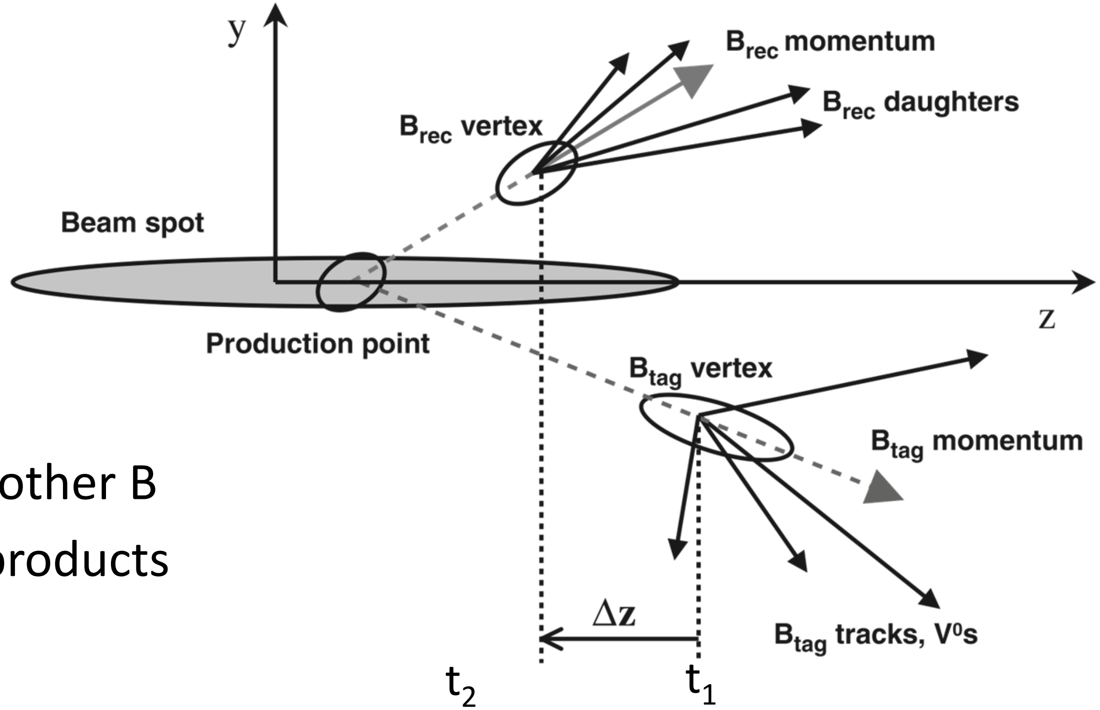
$$B^0 \to f \leftarrow \bar{B}^0 \leftarrow B^0$$

$$P(\Delta t, q) = \frac{e^{-|\Delta t|/\tau}}{4\tau}\{1 + q[S\cdot \sin(\Delta m \Delta t) + C\cdot \cos(\Delta m \Delta t)]\}$$

- The “golden mode” is $B^0 \to J/\psi\ K^0$
- Due to the asymmetric beam energies of B-factories, B mesons fly in the same direction

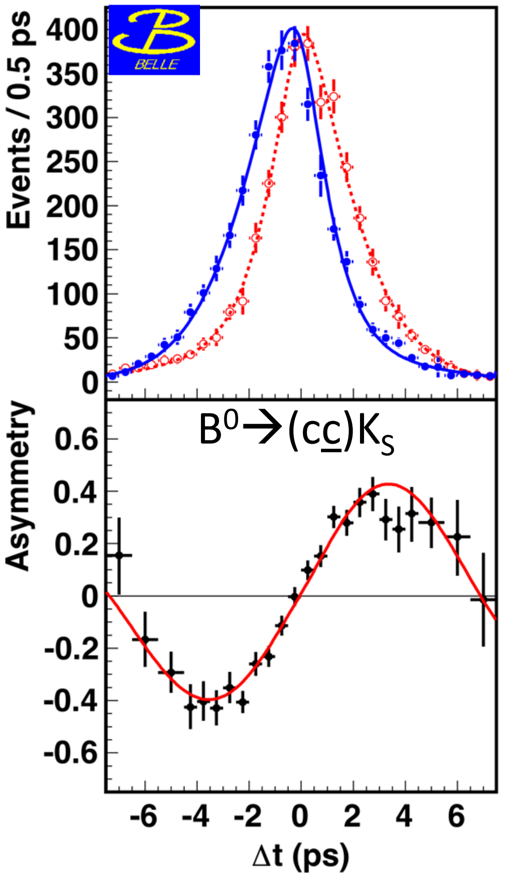
  → allows to measure Δt

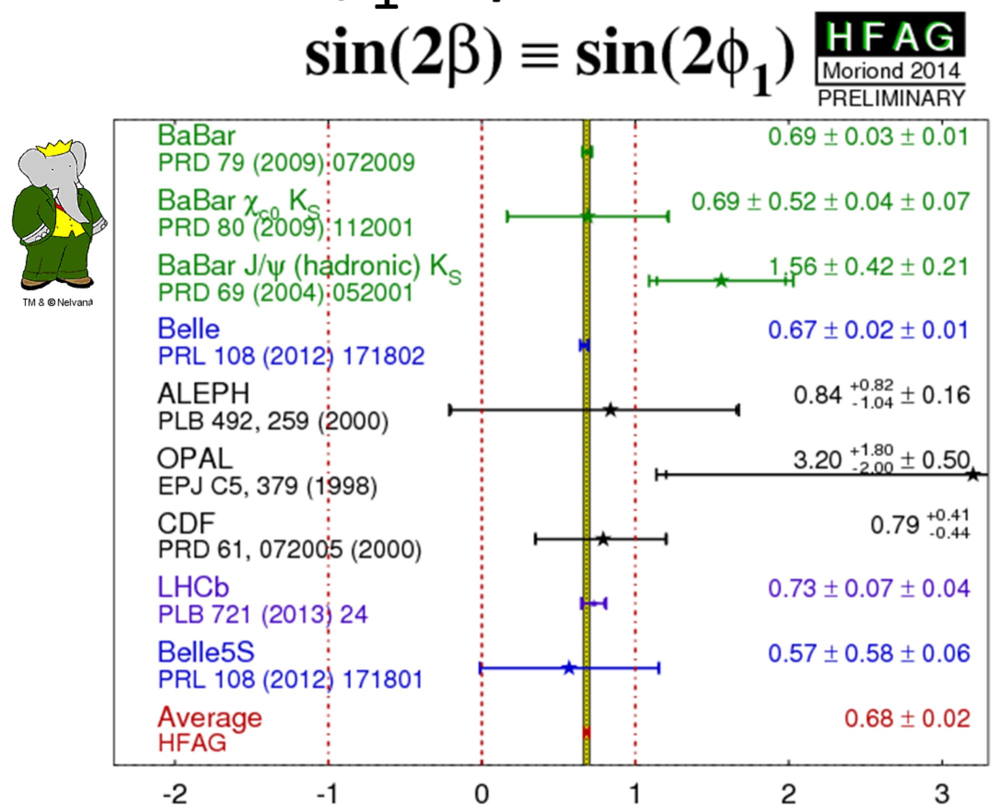




- Flavor and decay vertex of another B are determined by its decay products

Results for $\phi_1 = \beta$





$\sin 2\varphi_1$ (WA) = 0.682 ± 0.019


M. Kobayashi


T. Maskawa


2008

- 2001 first evidence
- 2002 first observation
- 2005 precise measurement
- 2008 Nobel prize
- 2012 final result

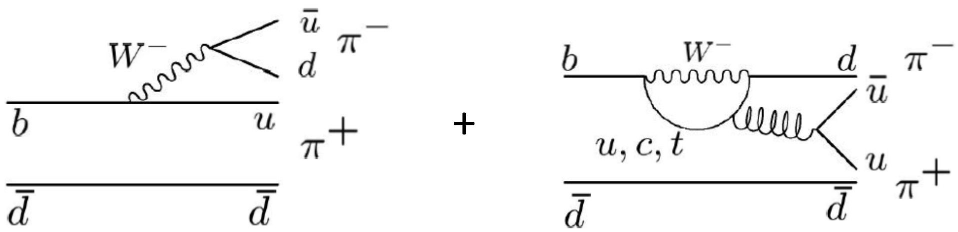
Unitarity triangle self-consistence

- Build theory
- Confirm theory
- Disprove theory

- SM – done by Kobayashi & Maskawa
- Large CPV in B system found by Belle & BaBar
- One of the way – check whether all parameters of Unitarity triangle are consistent

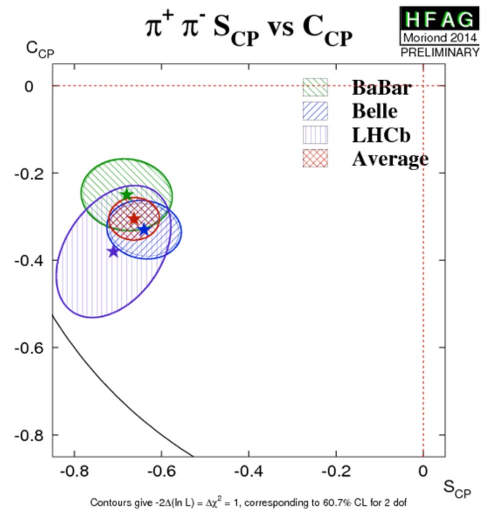
$\phi_2 = \alpha$

- Similar to φ_1, $\sin(2\varphi_2)$ thought to be measured in $B^0 \rightarrow \pi^+\pi^-$ time-dependent analysis
- Assumed to be easy to do, but finally it turned to be the most complicated one
- First results shown that penguin pollutions, which have different weak phase, are too large

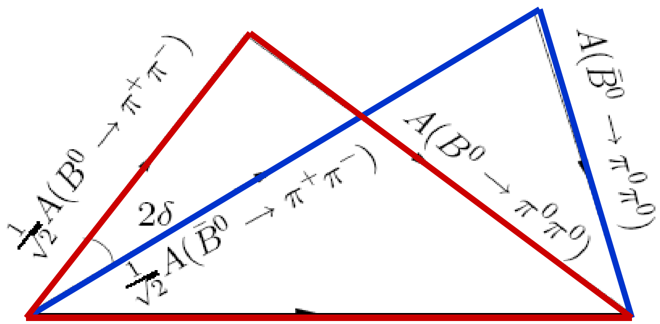


$$\underbrace{e^{+i2\beta}}_{\text{mixing}}\underbrace{e^{+i2\gamma}}_{\text{decay}} = e^{-2i\alpha}$$

$$S_{\pi\pi} \propto \sin 2\alpha_{eff} = \sin 2(\alpha + \delta)$$



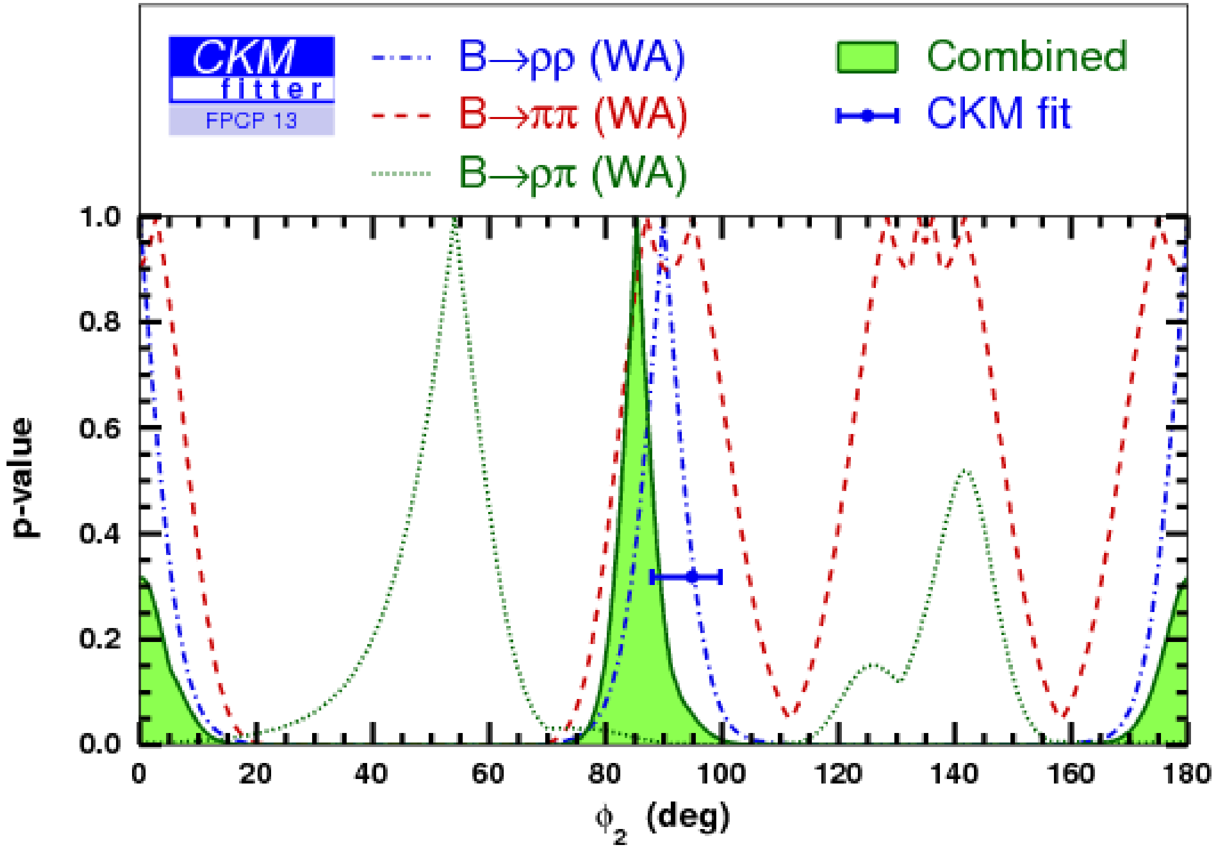
- Possible to determine δ using isospin analysis (Gronau & London, PRL 65, 3381, 1990), but with 8-fold ambiguities because all BR of $B \rightarrow \pi\pi$ have the same order



$$|A(B^- \to \pi^-\pi^0)| = |A(B^+ \to \pi^+\pi^0)|$$

sin(2ϕ_2) using B → ρρ

- Not the case for B→ρρ: $\Gamma_{\rho+\rho-} \sim \Gamma_{\rho+\rho0} >> \Gamma_{\rho0\rho0}$
  - only two fold ambiguity
- Penguin contribution in B→ρρ is small
- Longitudinal polarization is ~100%



Methods of $\phi_3 = \gamma$ measurement

- Based on B^0 decays (measurement of $2\phi_1+\phi_3$)
  - $B^0 \rightarrow D^{(*)-}\pi^+$, $D\rho$
- Based on $B \rightarrow D^{(*)}K$ decay with D^0-$\bar{D}^0$ interference:
  - GLW (CP eigenstates: $D^0 \rightarrow \pi\pi$, KK, $K_S\phi$, $K_S\omega$)

    Gronau & London, PLB 253, 483 (1991);
    Gronau & Wyler, PLB 265, 172 (1991)

  - ADS (CF and DCS states: $D^0 \rightarrow K\pi$, $K\pi\pi^0$)

    Atwood, Dunietz, & Soni, PRL 78, 3257 (1997),
    Atwood, Dunietz, & Soni, PRD 63, 036005 (2001)

- Dalitz (multibody states: $D^0 \rightarrow K_S\pi\pi$, K_SKK, $\pi\pi\pi^0$)

  Giri, Grossman, Soffer, & Zupan, PRD 68, 054018 (2003)

  Bondar, PRD 70, 072003 (2004)

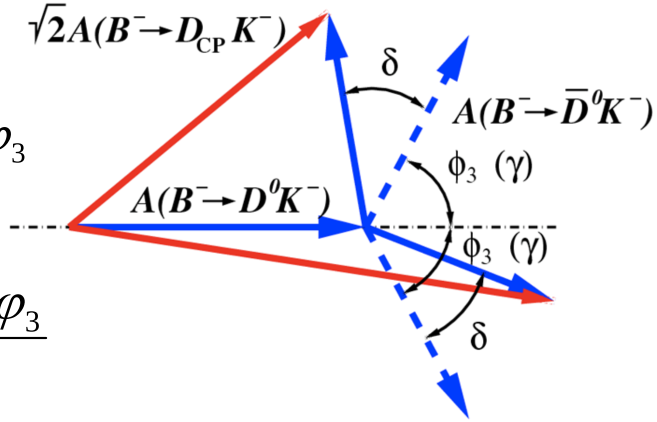
GLW method

M. Gronau, D. London, D. Wyler, **PLB 253, 483 (1991); PLB 265, 172 (1991)**

CP eigenstate of D-meson is used (D_{CP})
CP-even: $D_1 \rightarrow K^+K^-$, $\pi^+\pi^-$, CP-odd: $D_2 \rightarrow K_S\pi^0$, $K_S\omega$, $K_S\phi$, $K_S\eta$, …

$$R_{1,2} = \frac{Br(B \to D_{1,2}K)/Br(B \to D_{1,2}\pi)}{Br(B \to D^0 K)/Br(B \to D^0\pi)} = 1 + r_B^2 + 2r_B \cos\delta' \cos\varphi_3$$

$$A_{1,2} = \frac{Br(B^+ \to D_{1,2}K^+) - Br(B^- \to D_{1,2}K^-)}{Br(B^+ \to D_{1,2}K^+) + Br(B^- \to D_{1,2}K^-)} = \frac{2r_B \sin\delta' \sin\varphi_3}{R_{1,2}}$$



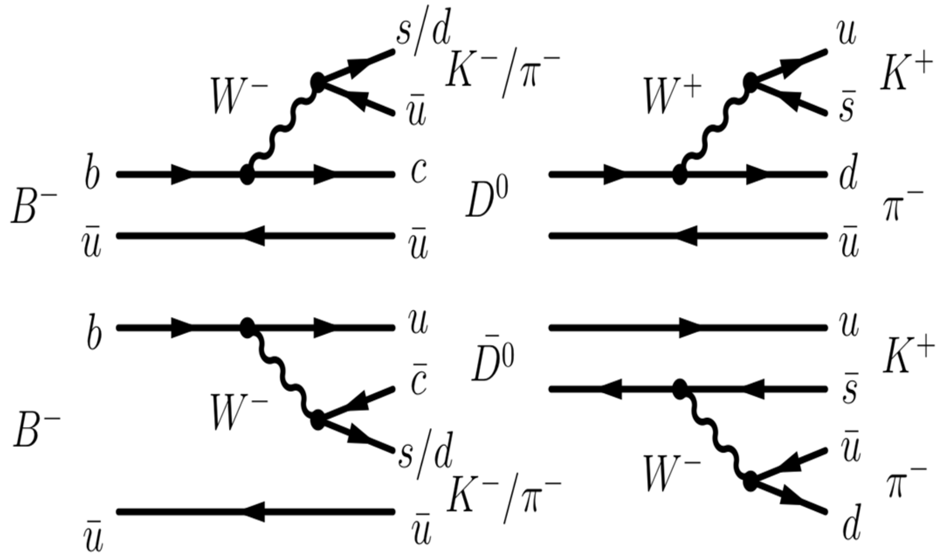
Sensitivity depends on hadronic parameters r_B and δ'

Alternative set of variables: $x_{\pm} = r_B \cos(\delta \pm \varphi_3) = \frac{R_1(1 \mp A_1) - R_2(1 \mp A_2)}{4}$ $\quad r_B^2 = \frac{R_1 + R_2 - 2}{2}$

Does not provide direct measurement of ϕ_3/γ, but helps in combination with other methods
Sensitivity depends on strong phase (δ=0 or 180 give no sensitivity)

ADS method: $B^- \to DK^-$ with $D \to K^+\pi^-$

D. Atwood, I. Dunietz and A. Soni, PRL **78, 3357 (1997)**
Enhance magnitude of CP violation by using Doubly Cabibbo-suppressed *D* decays



$$R_{ADS} = \frac{Br(B \to D_{\text{sup}}K)}{Br(B \to D_{fav}K)} = r_B^2 + r_D^2 + 2r_B r_D \cos\delta \cos\varphi_3$$

$$\delta = \delta_B + \delta_D, r_D = \left|\frac{A(D^0 \to K^-\pi^+)}{A(D^0 \to K^+\pi^-)}\right| = 0.0578 \pm 0.0008$$

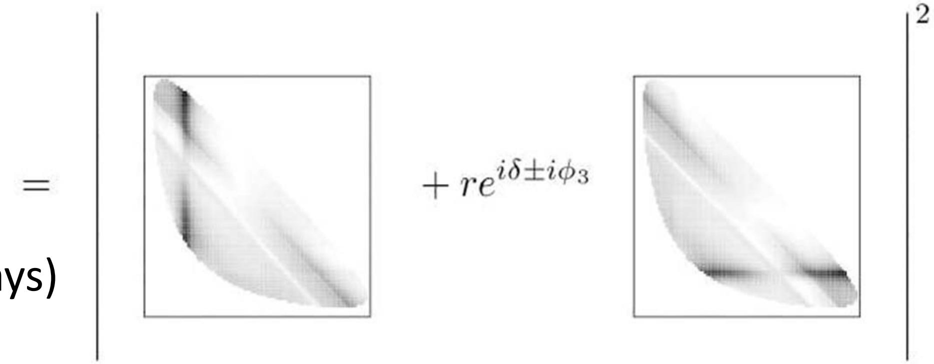
Dalitz analysis: three-body decays

A.Giri, Yu.Grossman, A.Soffer, J.Zupan, PRD 68, 054018 (2003)
A.Bondar, Proc. of Belle Dalitz analisis meeting, 24-26 Sep 2002

$\left|D^0\right\rangle + re^{i\theta}\left|\overline{D}^0\right\rangle$ Using 3-body final state, identical for D^0 and anti-D^0: $K_S\pi^+\pi^-$

Dalitz distribution density: $$dp(m^2_{K_S\pi^+}, m^2_{K_S\pi^-}) \sim \left|f_D\right|^2 dm^2_{K_S\pi^+} dm^2_{K_S\pi^-}$$

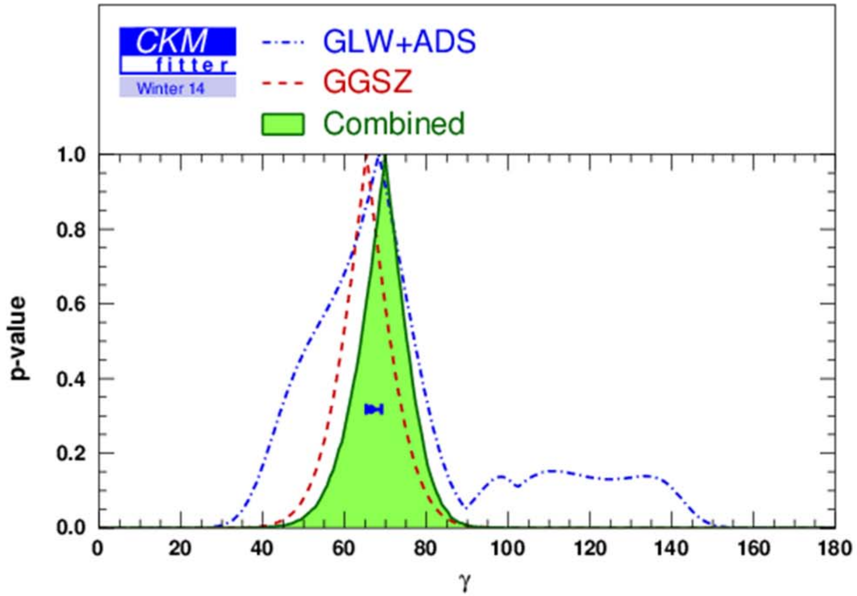
$$\left|f_B(m^2_{K_S\pi^+}, m^2_{K_S\pi^-})\right|^2 =$$

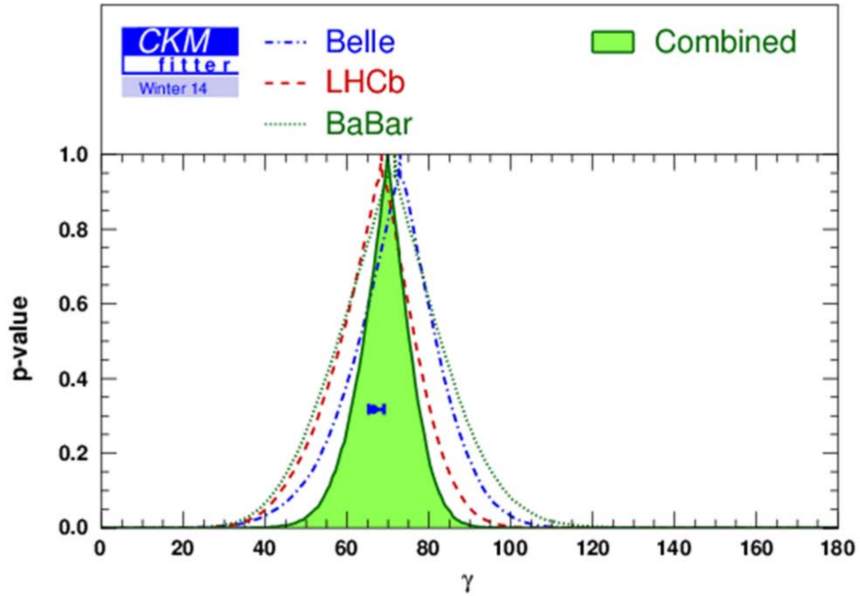


(Assuming CP-conservation in D^0 decays)

If $f_B(m^2_{K_S\pi^+}, m^2_{K_S\pi^-})$ is known, parameters ($\phi_3/\gamma, r_B, \delta$) are obtained from the fit to Dalitz distributions of $D \rightarrow K_S\pi^+\pi^-$ from $B^\pm \rightarrow DK^\pm$ decays.
Need to know a complex form of the D^0 decay amplitude, but only $|f_D|^2$ is obtained from $D^* \rightarrow D\pi$: Need to use model description, model uncertainty as a result.

$\phi_3 = \gamma$ results





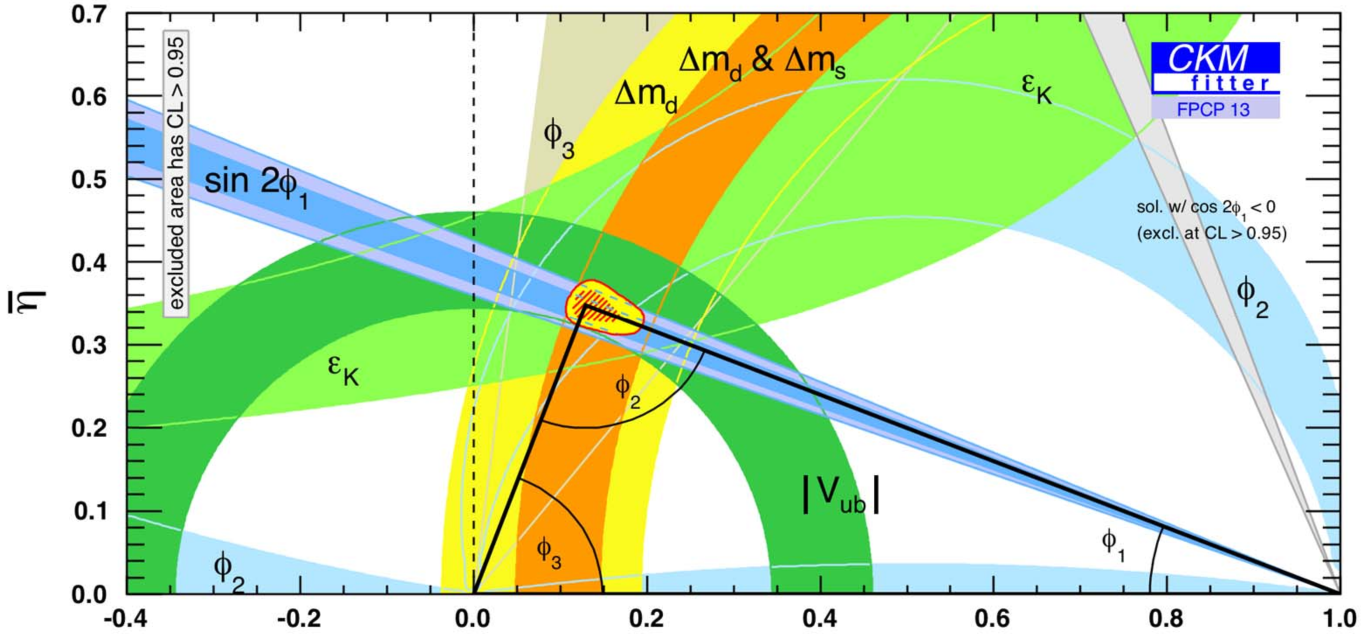
LHCb entered to the game with the best measurement

BaBar: $\gamma = (69\ ^{+17}_{-16})^\circ$

Belle: $\phi_3=(68\ ^{+15}_{-14})^\circ$

LHCb: $\gamma = (67\ ^{+12}_{-12})^\circ$

Result of 15 years of Belle, BaBar, LHCb operations



$$\beta \equiv \phi_1 = (21.5^{+0.8}_{-0.7})^\circ$$

$$\alpha \equiv \phi_2 = (85.4^{+4.0}_{-3.8})^\circ$$

$$\gamma \equiv \phi_3 = (68.0^{+8.0}_{-8.5})^\circ$$

All triangle parameters are well self-consistent ☹

Don’t give up: we still have a chance to see NP in CKM with x50 more data from Belle II and upgraded LHCb

Is it really an end of the story?

- In 1967, soon after CPV discovery A.Sakharov shown:
  - existence of CPV is one of the requirement for the matter-antimatter asymmetry, which we see in the Universe

Из эффекта С. Окубо
при большой температуре
для Вселенной сшита шуба
по ее кривой фигуре

**НАРУШЕНИЕ CP-ИНВАРИАНТНОСТИ, C-АСИММЕТРИЯ
И БАРИОННАЯ АСИММЕТРИЯ ВСЕЛЕННОЙ**

А.Д.Сахаров

Теория расширяющейся Вселенной, предполагающая сверхплотное начальное состояние вещества, по-видимому, исключает возможность макроскопического разделения вещества и антивещества; поэтому следует

Federer and Nadal are warming up before the game

- If Federer serves faster (more often) than Nadal, sooner or later all balls will be on Nadal's half
  - Q: How much faster Federer should serve to create the existing baryon asymmetry in the Universe?
- A: Much faster than the current mechanism of CPV

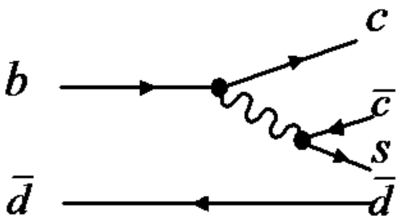
Where is a new source of CPV?

- Currently known mechanism of CPV is ~10 orders smaller than necessary to explain a large baryon asymmetry in the Universe
- Hardly there is a source of this asymmetry other than CPV
- There must be other sources of CPV
- Q: Where is it ?!
- The answer is unknown, but we can look for/in:
  - new particles in the penguin loops
  - direct CPV in B and D decays
  - leptonic sector
  - strong interaction

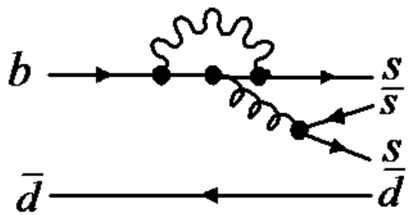
New Physics in the penguin loop

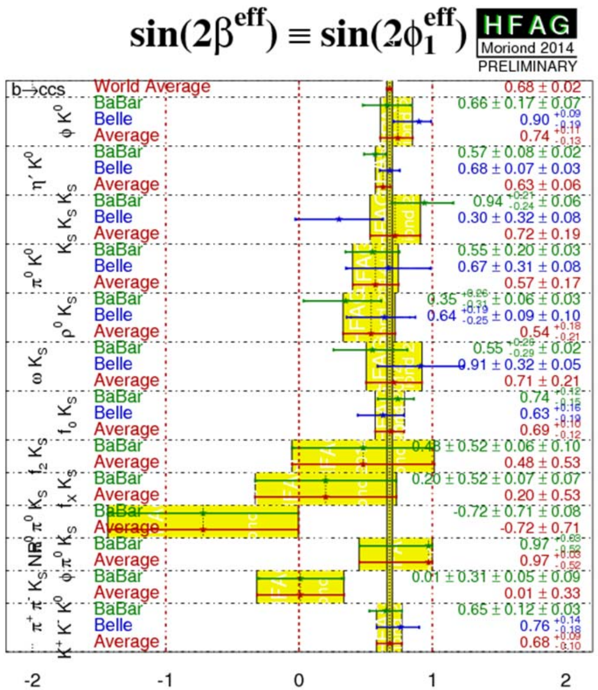
- CPV in SM in decays $b \to c\bar{c}s,\ b \to c\bar{c}d,\ b \to s\bar{s}s,\ b \to d\bar{d}s$ is proportional to sin(2ϕ_1), e.g.

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



$B^0 \to \phi K_S^0$





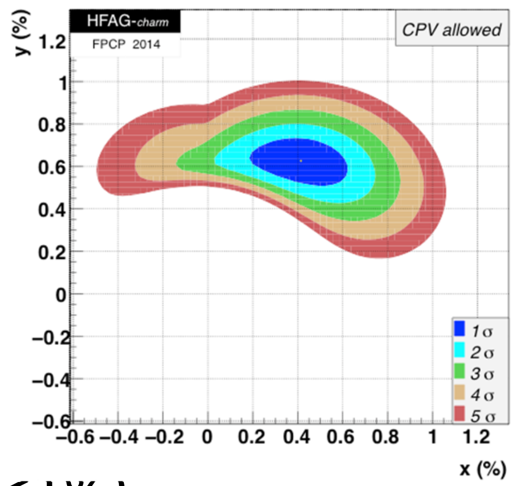
– Presence of new particles in the penguin loops can change CP asym.

– No signs of NP observed yet

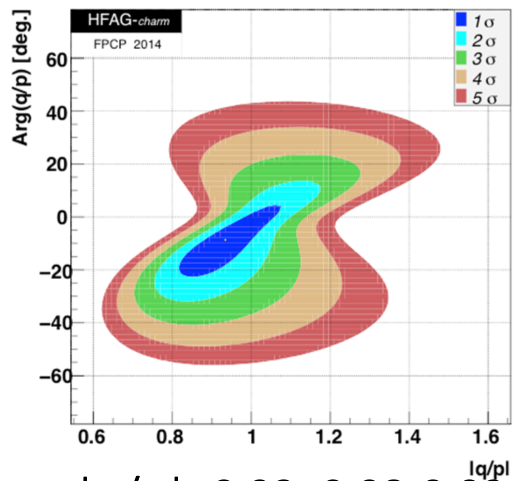
– Due to small BR's of penguin decays, much larger statistics is necessary

→ looking forward for Belle II and upgraded LHCb results

CPV in charm



- Only two generations are involved
  - --> CPV is predicted in SM to be small
    - direct CPV a few 0.1%
    - indirect CPV in order of 0.01%
    - any larger evidence of CPV in charm sector indicates NP
- D^0-Mixing is well established, however it is small (<1%)
  - high statistics is needed to study mixing-induced effects
- Current LHCb, BaBar & Belle precisions are at ~0.1% level
  - no clear evidence for CPV
- Future Belle II & LHCb will reach 0.01% level
  - again, all hopes on that



|q/p|=0.93+0.08-0.09

phi=8.7+9.1-8.8

CP violation in B_s system

$$\phi_s = \arg\left[-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right]$$ → no CPV is expected in SM

Observation of CPV in B_s system would be a clear sign of NP

B_s mixing is well measured by CDF & LHCb:

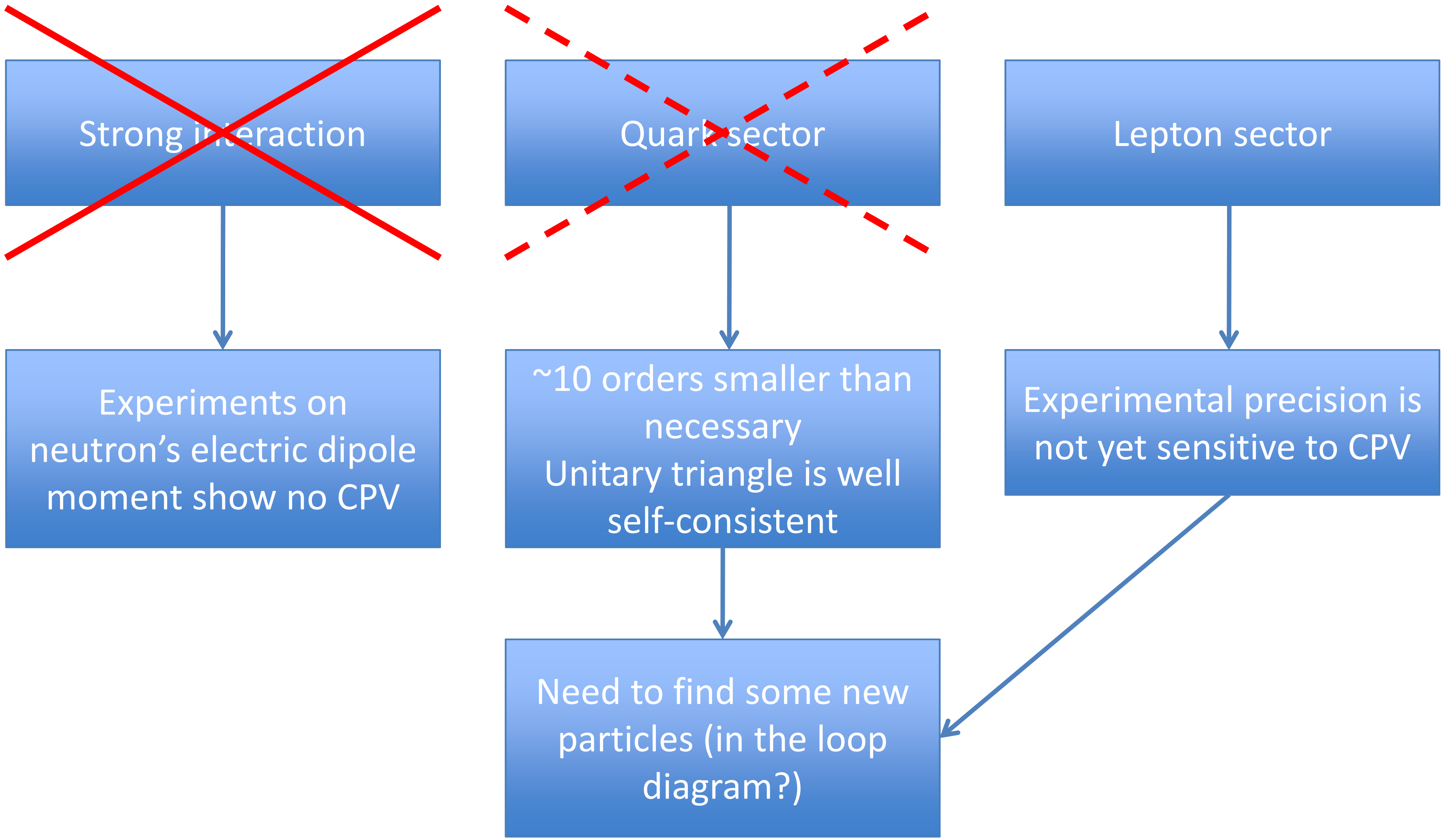
$$\Delta m_s = 17.69 \pm 0.08$$

Main hope for LHCb and ATLAS for the CPV studies in B_s decays, however, it seems, statistics is still not enough to find it:

$$\phi_s = (1 \pm 6)^\circ$$

Lets wait for upgraded LHCb

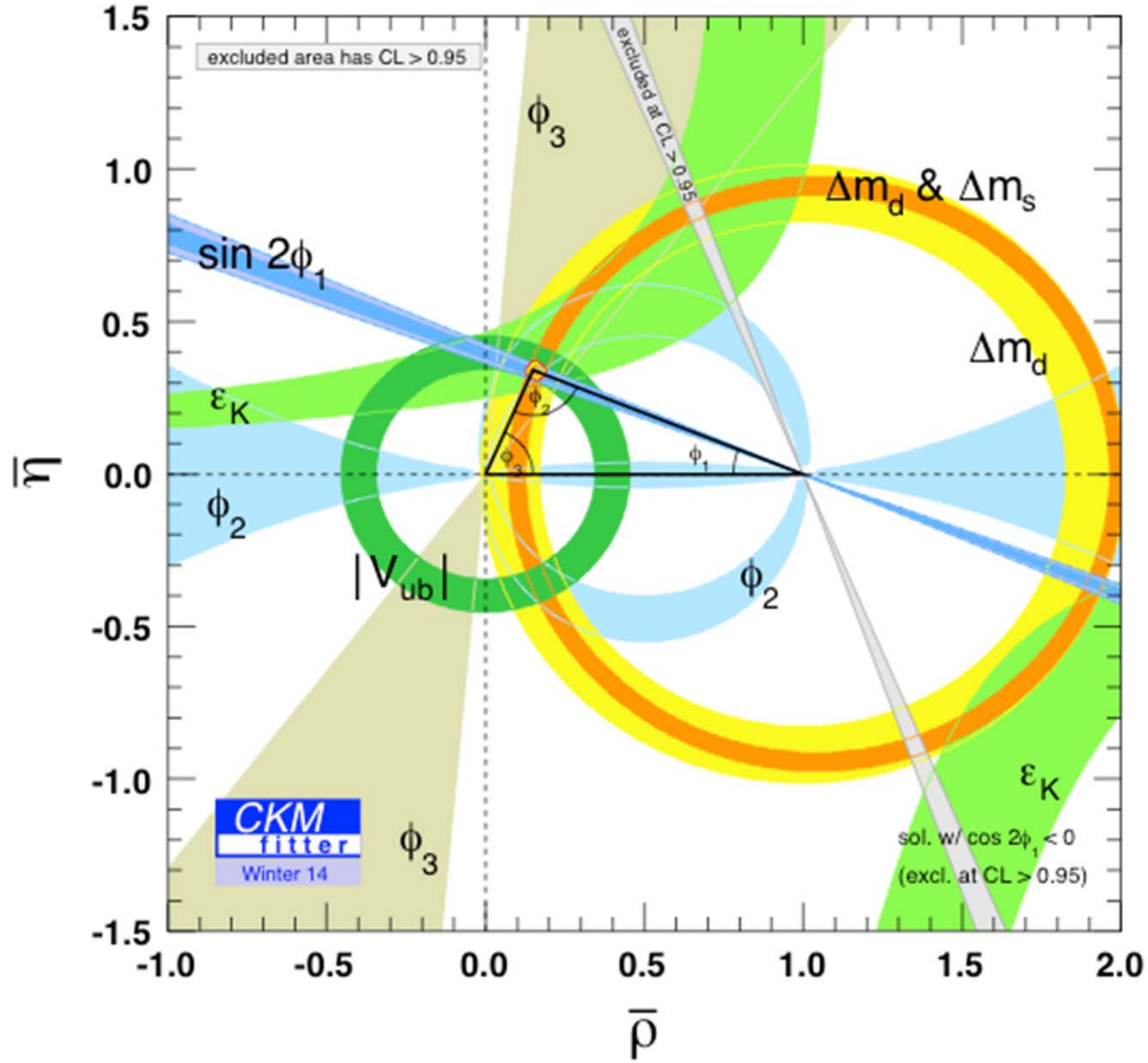
Sources of CP violation



Conclusion

- KM model works good… even too good
- Unitarity triangle is well self-consistent
  - not much space for NP or new source of CP violation
- No signs of new particles are found in the penguin loops
  - SuperB-factories data are necessary
- CP violation in D^0 and B_s are not found yet
  - no NP here as well
  - SuperB-factories may help
- Missing source of the CPV could be found in the leptonic sector
  - new experiments are needed

CKM change from 1995 to 2014



Thank you!

Backup’s

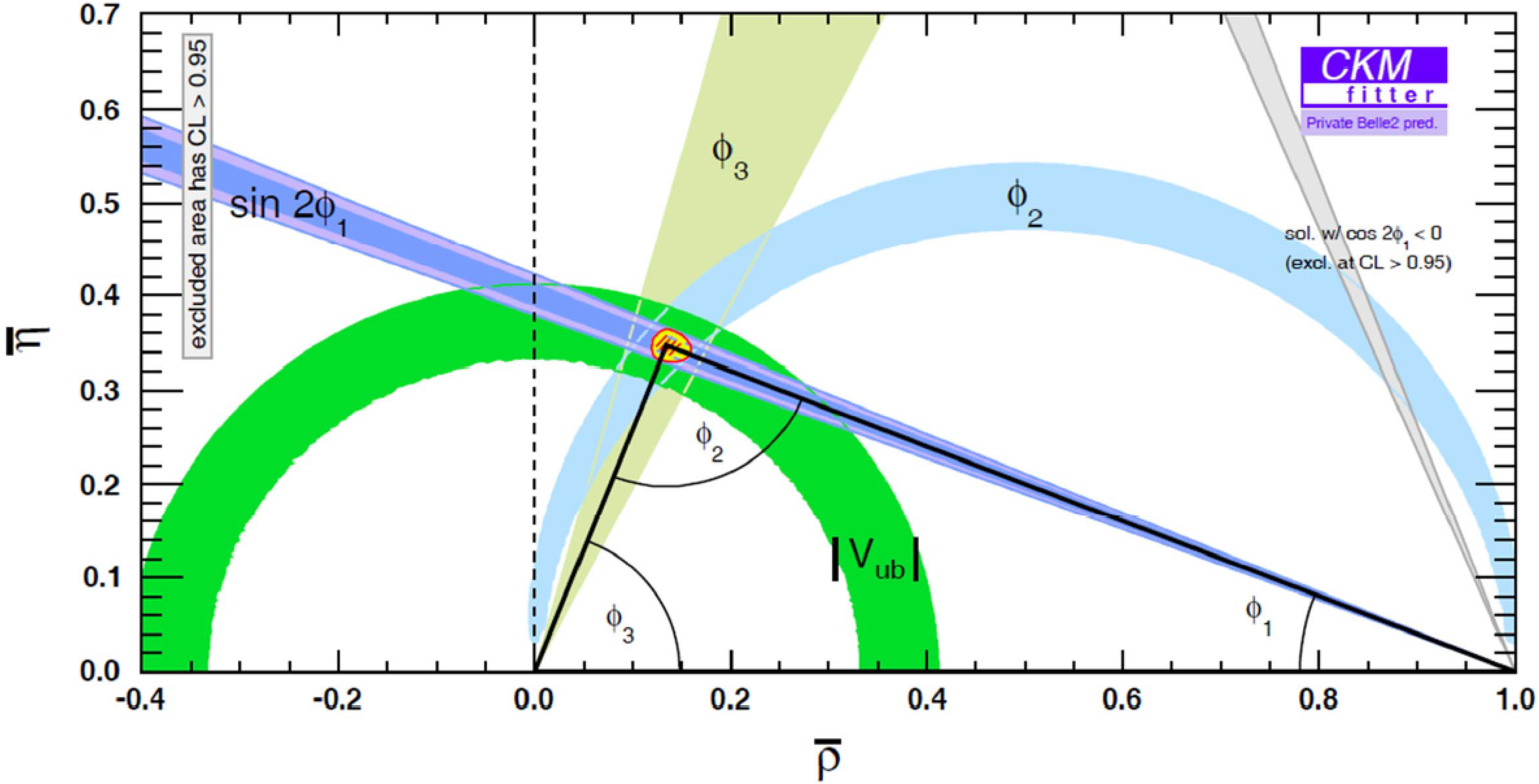
CPV in neutrinos

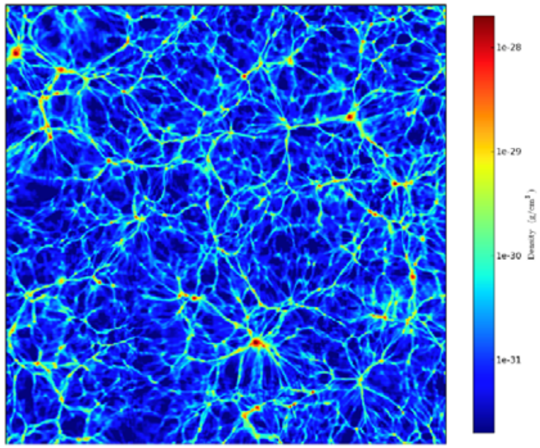
- Neutrinos have very small masses, but non-zero as postulated in SM → oscillate
- Mixing angles diff from quark's

$$V_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.1 & 1 \end{pmatrix} \qquad V_{PMNS} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

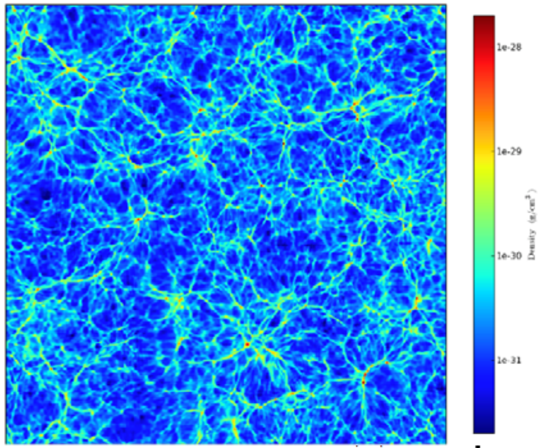
- Can be searched by NOvA, LAGUNA-LBNO, LBNE, Hyper-Kamiokande,…

$$\int \mathcal{L} dt = 50 \text{ ab}^{-1}$$

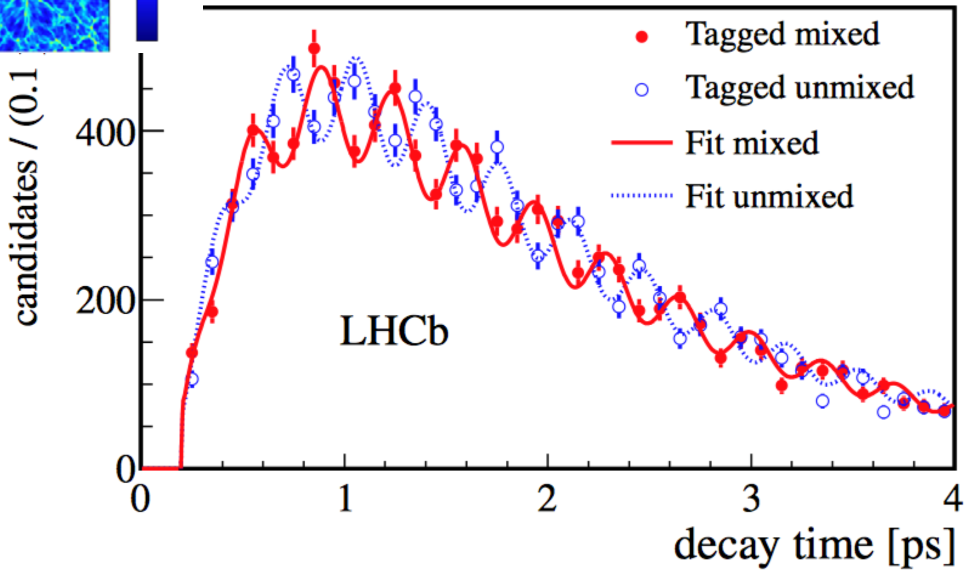




1e-28
1e-29
1e-30
1e-31



1e-28
1e-29
1e-30
1e-31



Tagged mixed
Tagged unmixed
Fit mixed
Fit unmixed
LHCb
candidates / (0.1
0
200
400
0
1
2
3
4
decay time [ps]