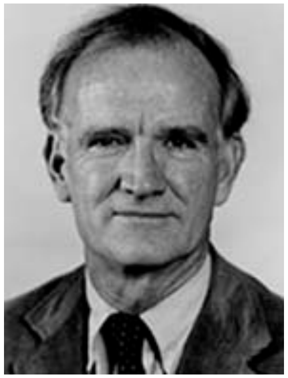


Symposium and Memorial Concert
for Val Fitch (1923-2015)

CP Violation in 21st Century

CP violation Beyond Kaons
CP Violation vs Standard Model
CP Violation & New Physics Searches

Hassan Jawahery
University of Maryland
May 15, 2015

CP Violation Beyond Kaons

Status

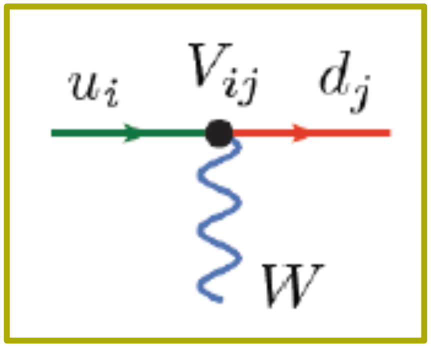
- CP Violation in the B meson system:
  - CPV measured in many channels, and beyond Mixing
    - Indirect CPV in interference of decay and mixing
    - Direct CPV in the decay amplitude
  - Time-Reversal (T) violation observed in the B system
    - In balance with observed CPV in B, supporting CPT invariance.
  - K and B mesons are sole sources of CPV & T-Violation
    - No evidence for CPV in the charm system, or in any baryons
    - No evidence for EDM
    - Plans underway to measure CPV in the lepton sector

CP Violation vs Standard Model

Kobayashi-Maskawa Mechanism (1973)

CP violation originates from the scalar sector of Standard Model

Interactions of quarks with Higgs & with gauge bosons



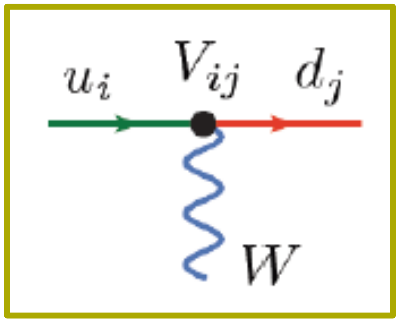
$$\hat{V}_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

A complex matrix, in general

For 3 generations of quarks, parametrised by

3 angles and a single complex phase as the sole source of CPV in SM

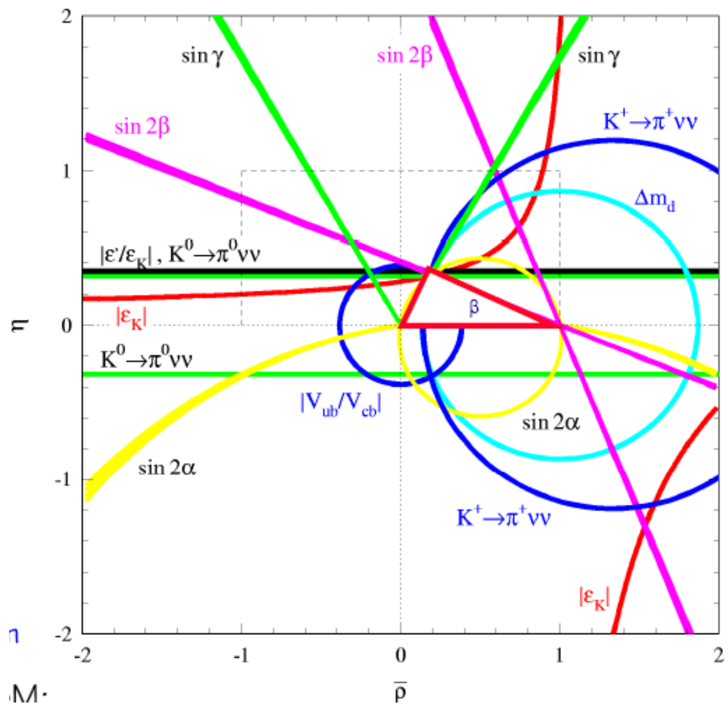
CP Violation vs Standard Model



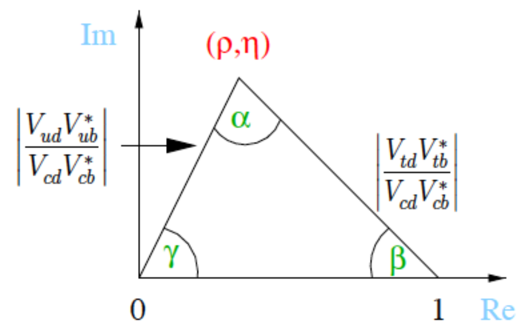
L. Wolfenstein Parameterization of CKM matrix (1983)

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

All CPV effects governed by η

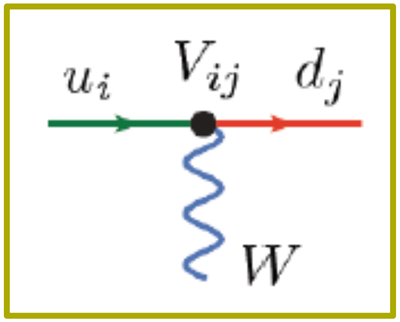


Unitarity of the CKM matrix



CP Violation vs Standard Model

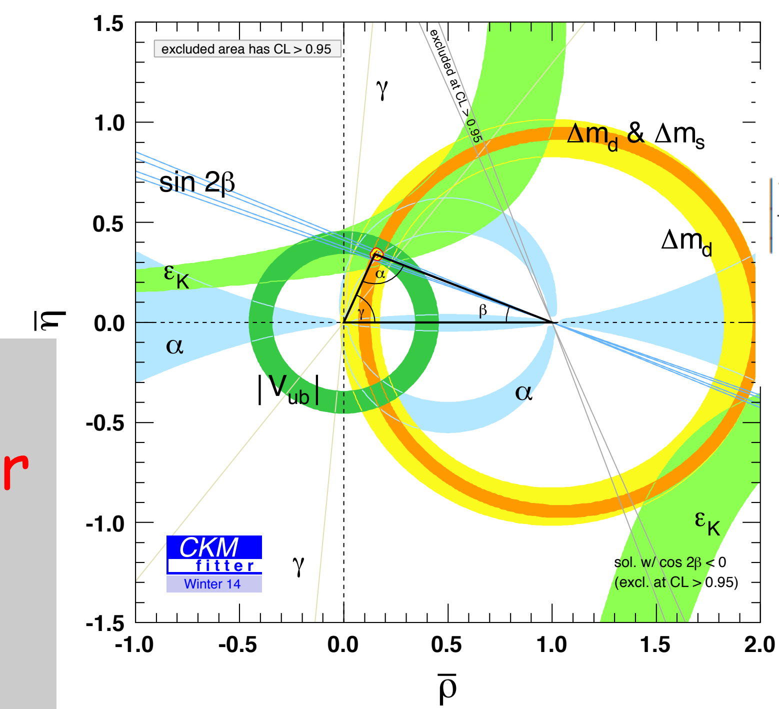
Status



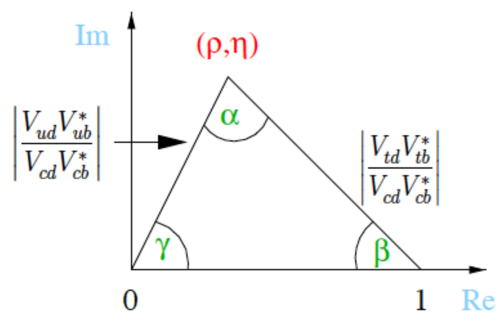
$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\,\eta) & -A\lambda^2 & 1 \end{pmatrix} +O(\lambda^4)$$

All CPV effects governed by η

The CKM picture able to account for all observed CPV effects & flavor interactions



Unitarity of the CKM matrix

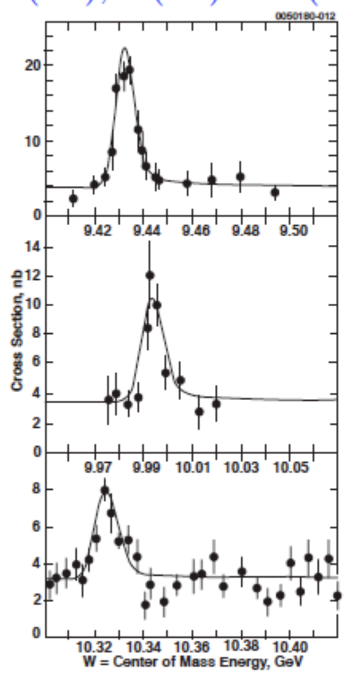


A very brief historical detour starting at 1981

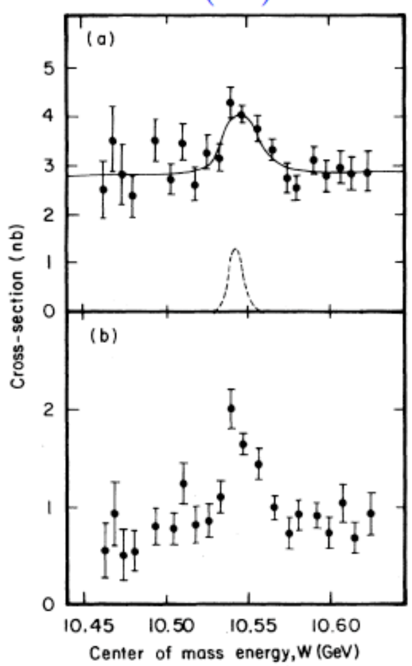
- Existence of the narrow Υ resonances established at FNAL, DORIS and CESR
- CLEO had observed $\Upsilon(4S)$ – 22 MeV above the $B\bar{B}$ threshed. PRL 45, 219 (1981)
- CLEO observed enhanced e & μ rates at the 4S- PRL 46, 84(1981)
    - Evidence for weakly decaying B meson: $B(B \rightarrow Xe\nu) = 13 \pm 3 \pm 3\%$

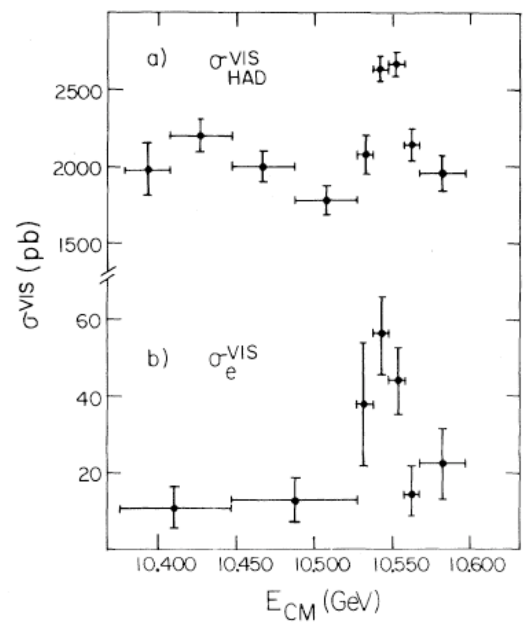
Program of B Physics was launched

$\Upsilon(1S)$, $\Upsilon(2S)$ & $\Upsilon(3S)$



$\Upsilon(4S)$





NOTES ON THE OBSERVABILITY OF *CP* VIOLATIONS IN B DECAYS

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Received 16 June 1981

We describe a general method of exposing *CP* violations in on-shell transitions of B mesons. Such *CP* asymmetries can reach values of the order of up to 10% within the Kobayashi–Maskawa model for plausible values of the model parameters. Our discussion focuses on those (mainly non-leptonic) decay modes which carry the promise of exhibiting clean and relatively large *CP* asymmetries at the expense of a reduction in counting rates. Accordingly we address the complexities encountered when performing *CP* tests with a high statistics B meson factory like the Z^0 (and a toponium) resonance.

And Carter & Sanda

Indirect CPV due to the interference of decay and mixing amplitudes in modes common to B^0 and $\bar{B}^0$

$$\begin{array}{l} B_d^0 \searrow \\ \qquad \psi K_S + X,\ D\bar{D}[F^+F^-]K_S + X\,, \\ \bar{B}_d^0 \nearrow \end{array}$$

Rare processes

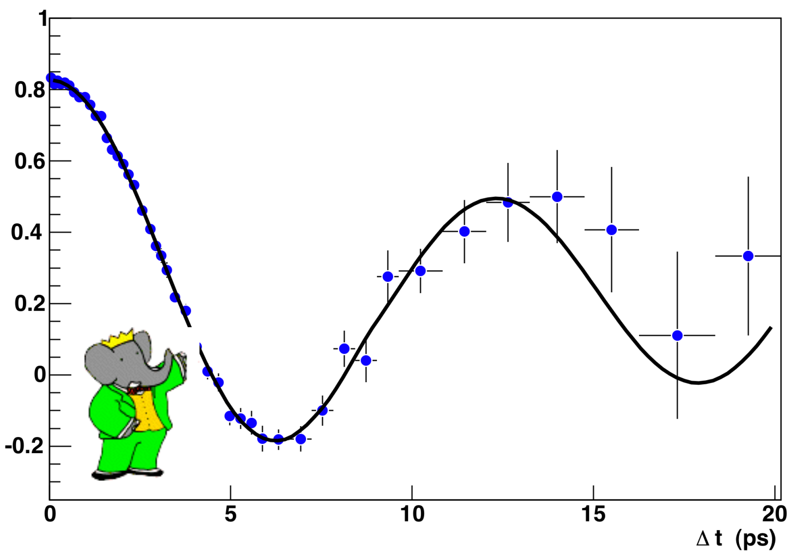
<u>The required elements of a program for CPV study:</u>

- •Long B lifetime [i.e. suppressed $|V_{cb}|$] (MARK-II & MAC at PEP 1983).
- •Large $B^0 \Leftrightarrow \bar{B}^0$ oscillation rate [UA1,ARGUS (1987), CLEO (1988)]
- •A B factory: Large number of B mesons; Preferably boosted for time-dependent measurements.

$B^0 \Leftrightarrow \bar{B}^0$ oscillation Today

Time evolution of a state prepared as B^0

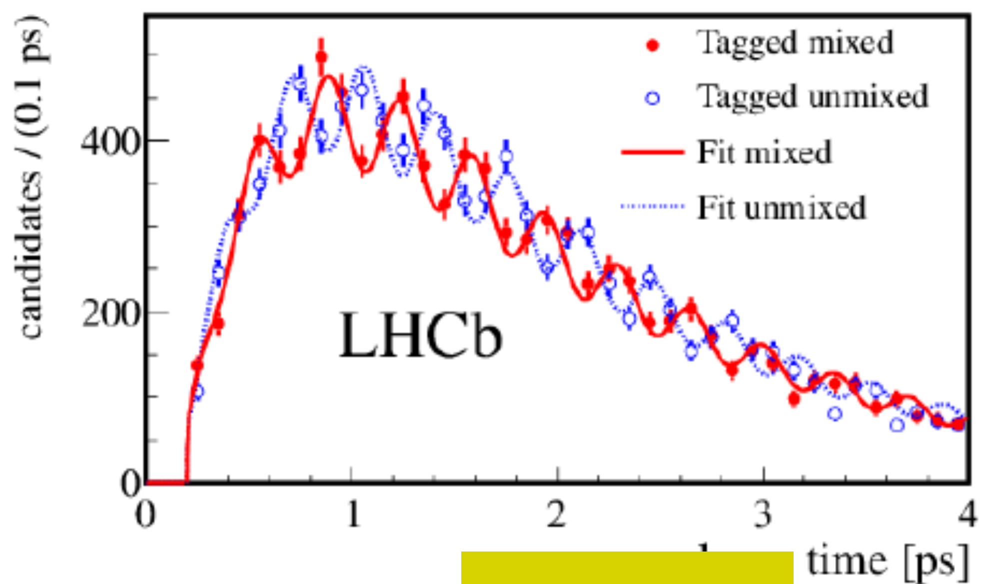
$B_d^0(\bar{b}d) \Leftrightarrow \bar{B}_d^0(b\bar{d})$



~81 GHz

$\propto m_t^2 \,|V_{tb}^* V_{td}|^2$

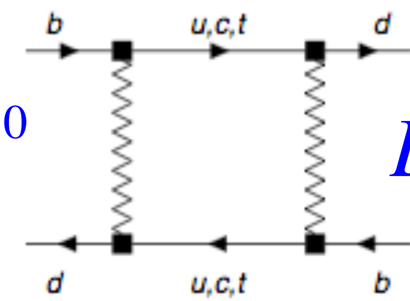
$B_s^0(\bar{b}s) \Leftrightarrow \bar{B}_s^0(b\bar{s})$



~2.82 THz

$\propto m_t^2 \,|V_{tb}^* V_{ts}|^2$

$\bar{B}^0$



B^0

Experimental Landscape in 1990's

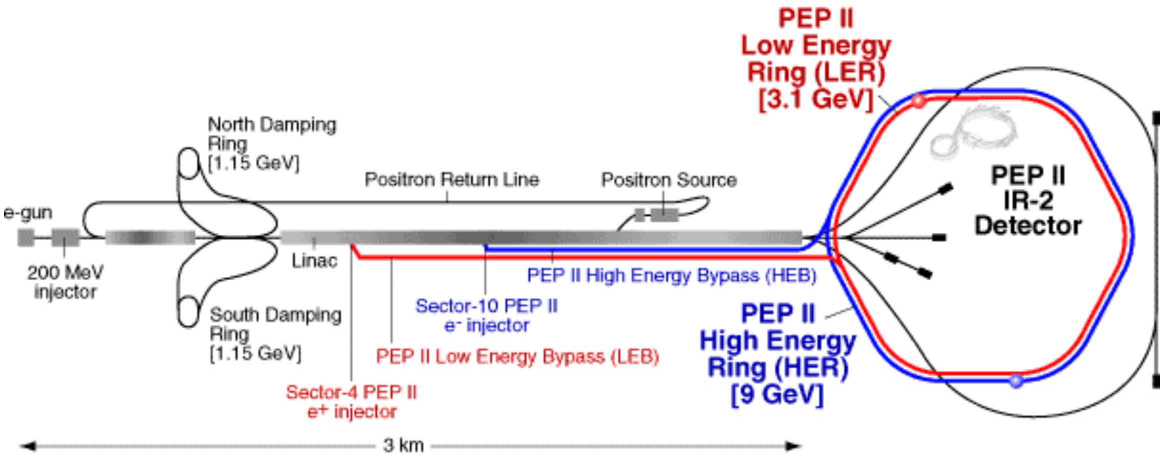
- 1993:
  - End of hope for SSC
  - Approval of high luminosity asymmetric energy electron-positron B factories at SLAC & at KEK
  - CLEO continuing to run with symmetric machine

- 1999: Both B Factories begin operation
  - CPV in B decays observed in 2001

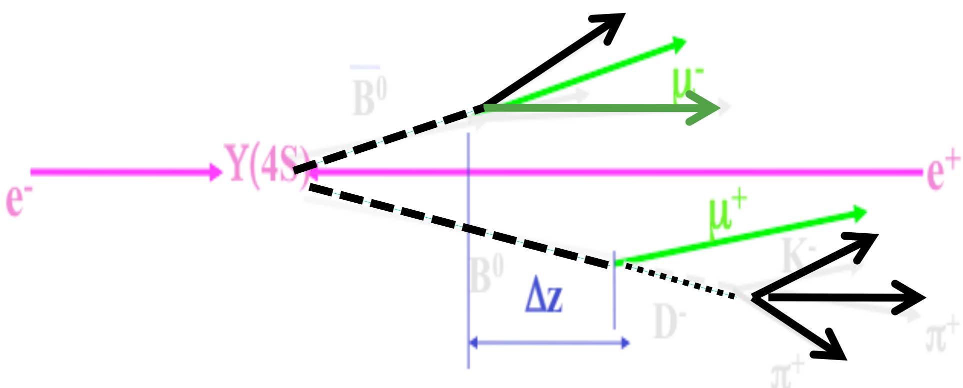
"After 37 years of searching for further examples of CP violation, physicists now know that there are at least two kinds of subatomic particles that exhibit this puzzling phenomenon, thought to be responsible for the great preponderance of matter in the Universe," said Princeton University physicist Stewart Smith, spokesman of the collaboration.

- CDF and D0, having found the top, with their innovative Silicon vertex trackers produce first hint of CPV in B, and later B^0_s oscillations

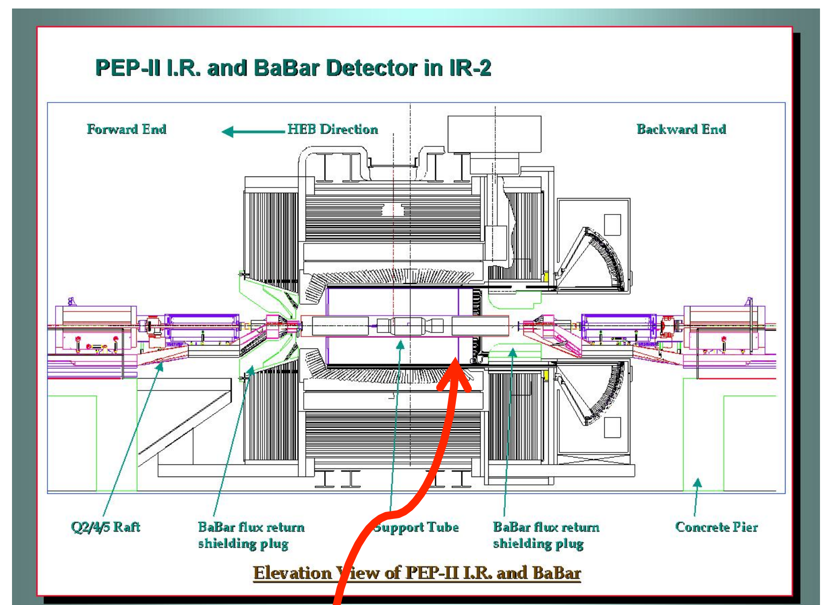
B^0_d Mesons at the e+e- B Factories (SLAC, KEK)



$\Upsilon(4S) \rightarrow B^0 \overline{B}^0$
in $J^{cp} = 1^-$
The B meson pair in an entangled state

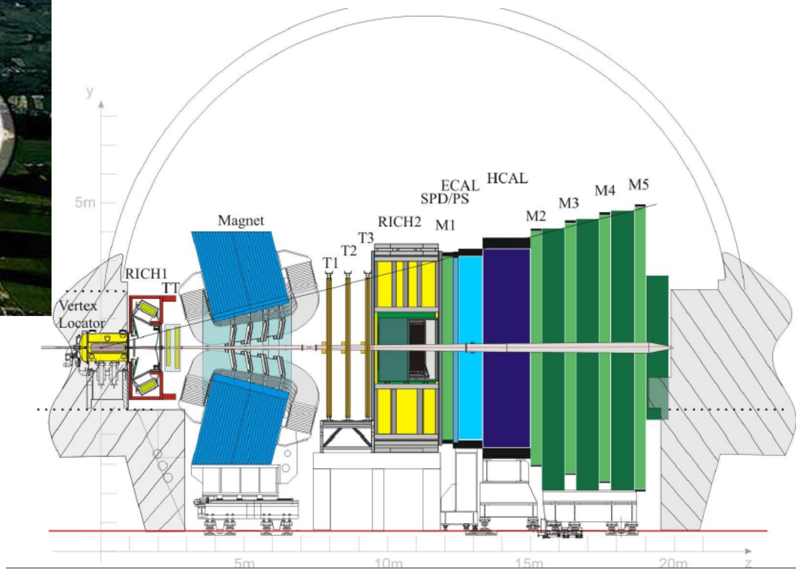


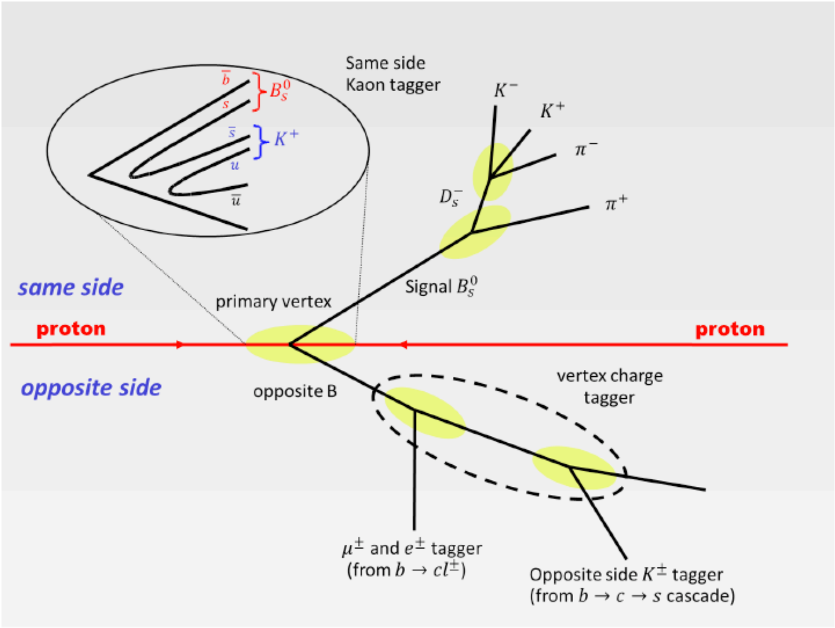
~250 μm

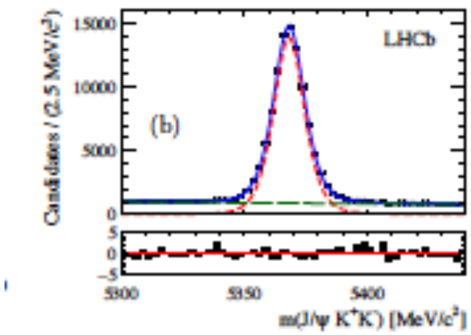


DIRC invented by Ratcliff
The ultimate Fitch counter

B^0_s Meson at Hadron Colliders (Tevatron, LHC)

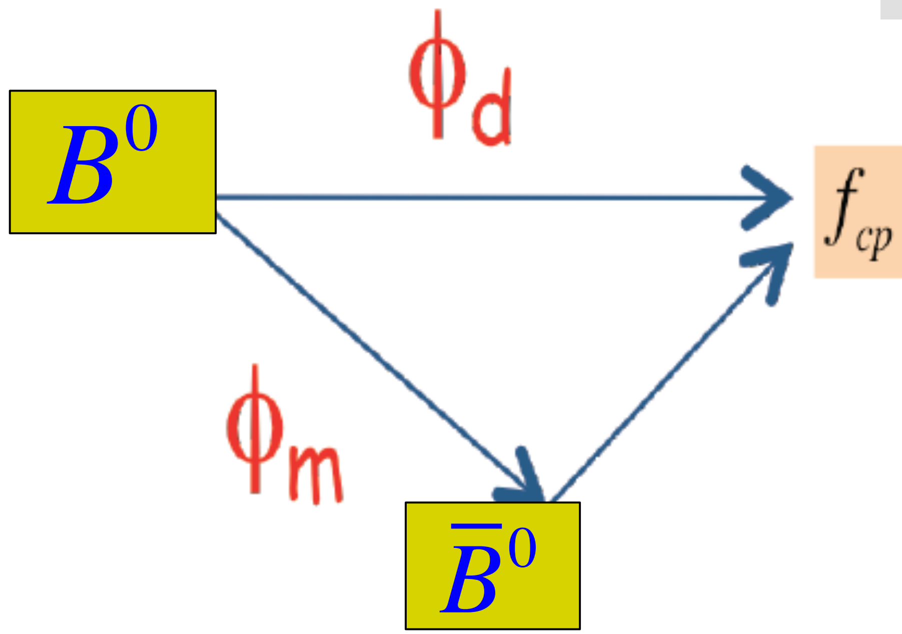






Indirect CPV in B decays
Measuring the CKM phase via interferometry

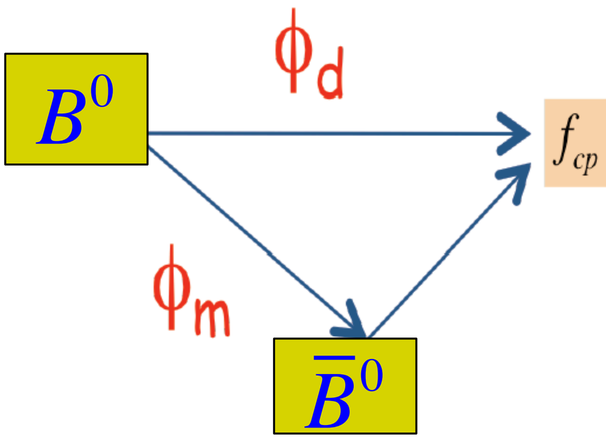
Bigi, Sanda & Carter (81)

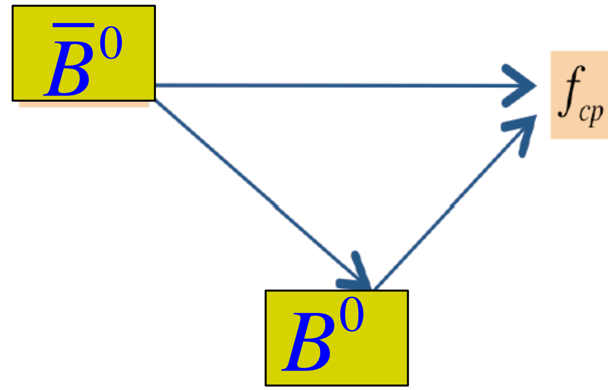


With careful set up of both initial and final states

$$|\langle f_{cp} | H | B^0 \rangle|^2 \propto | A_{f_{cp}} |^2 e^{-\Gamma t} [1 - \sin 2(\phi_m - \varphi_d) \sin \Delta m t]$$

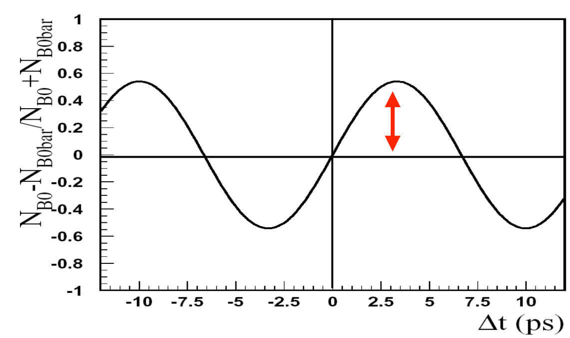
Indirect CPV in B decays
Measuring the CKM phase via interferometry



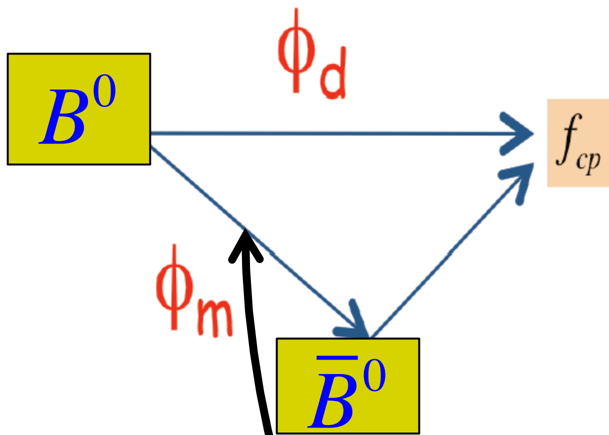


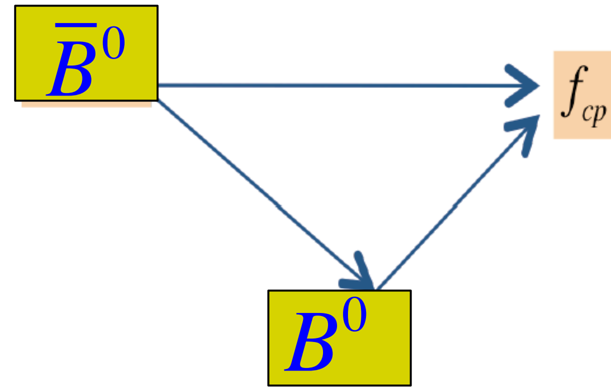
$$A_{cp}(t)=\frac{\Gamma(B^0(t)\to f_{cp})-\Gamma(\bar{B}^0(t)\to f_{cp})}{\Gamma(B^0(t)\to f_{cp})+\Gamma(\bar{B}^0(t)\to f_{cp})}=\sin 2(\varphi_m-\varphi_D)\sin\Delta mt$$

With careful set up of both initial and final states



Indirect CPV in B decays
Measuring the CKM phase via interferometry



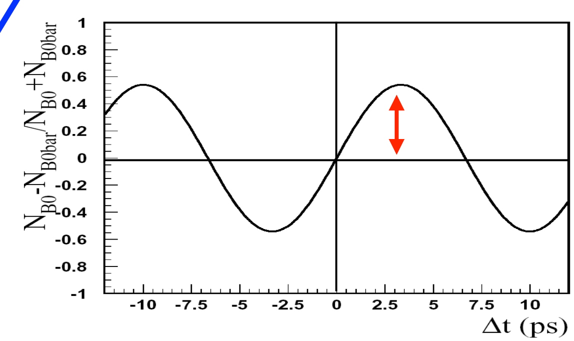


$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\,\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\,\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

With careful set up of both initial and final states

$B_d \rightarrow J/\psi\, K^0_s$ :: $\sim \arg(V^*_{td}) \sim 25^o$

$B_s \rightarrow J/\psi\, \phi$ :: $\sim \arg(V^*_{ts}) \sim 1^o$

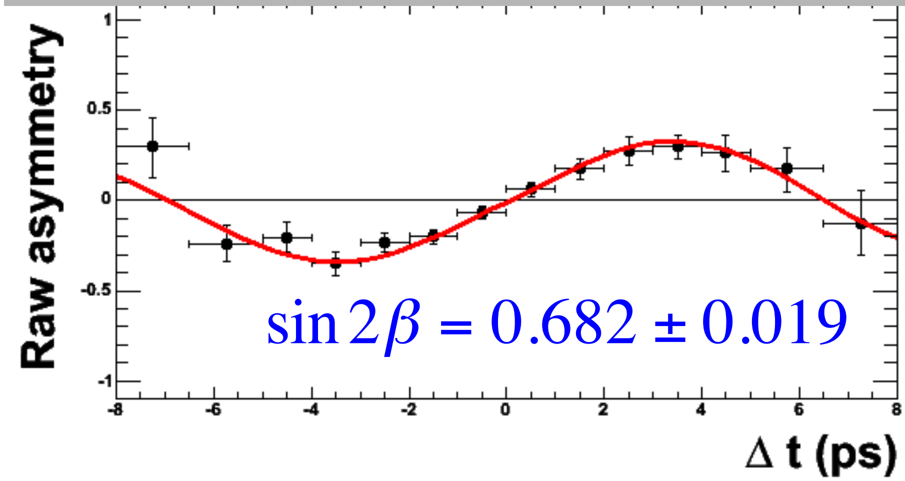


$$A_{CP}(t) = \sin\Phi \sin(\Delta m t)$$

$B_d \rightarrow J/\psi\ K^0_s$

$$\Phi_d = 2\beta \sim 2\arg(V^*_{td})$$

$\beta=(21.5\ ^{+0.8}_{-0.7})^O$

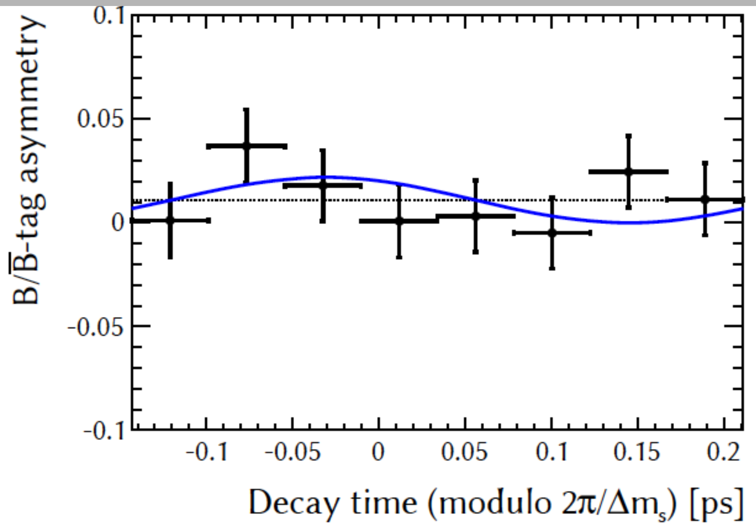


$$\beta \approx 25^O (SM)$$

$B_s \rightarrow J/\psi\ \phi$

$$\Phi_s = 2\beta_s \sim 2\arg(V^*_{ts})$$

$\beta_s=(-0.43\pm1)^O$

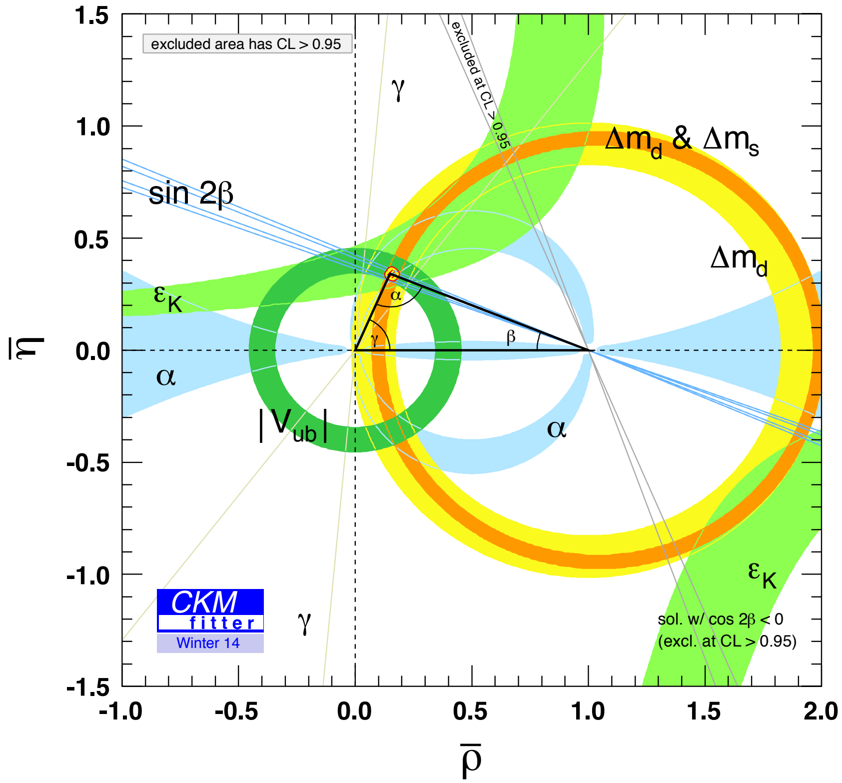


$$\beta_s \approx 1^O (SM)$$

Status of CKM (2015)

All is well with the CKM picture at O(10%) level:

$$\alpha + \beta + \gamma = (175.2 \pm 9.3)^o$$

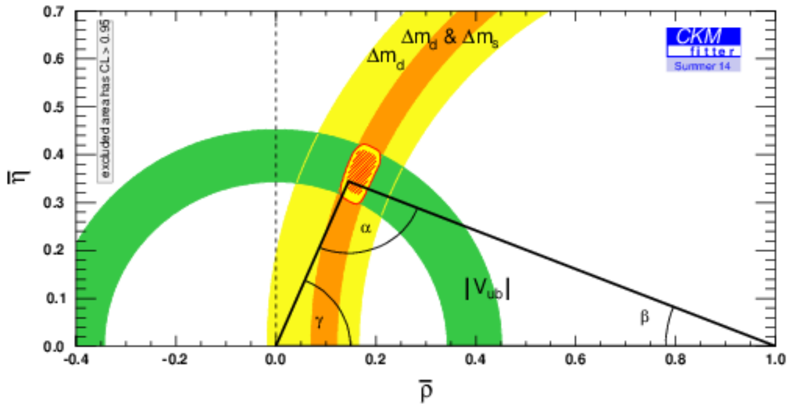


	Direct	CKM fit
α	$= \left(88.8^{+4.5}_{-4.3}\right)^o$	$\left(93.6^{+3.2}_{-2.9}\right)^o$
β	$= \left(21.5^{+0.8}_{-0.7}\right)^o$	$\left(25.38^{+0.80}_{-1.57}\right)^o$
γ	$= \left(70^{+7.7}_{-9.0}\right)^o$	$\left(66.4^{+1.2}_{-3.3}\right)^o$
$-2\beta_s$	$= +0.00 \pm 0.07$	$-0.0363^{+0.0014}_{-0.0012}$

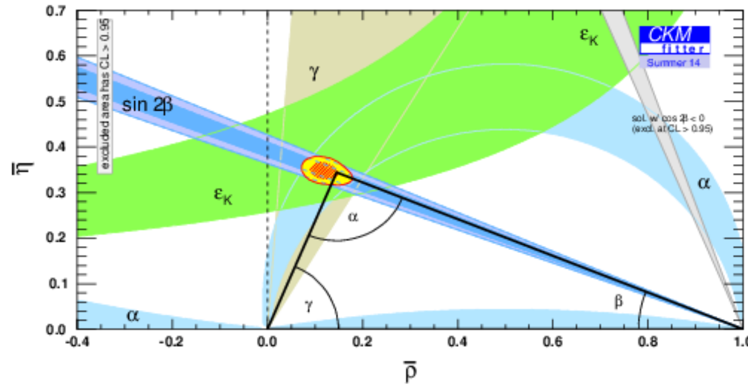
Sin2β tension (driven by B→τν) eased

$\sin 2\beta = 0.682 \pm 0.019(meas)$ $\quad 0.774^{+0.017}_{-0.036}(fit) \quad (< 2.3\sigma)$

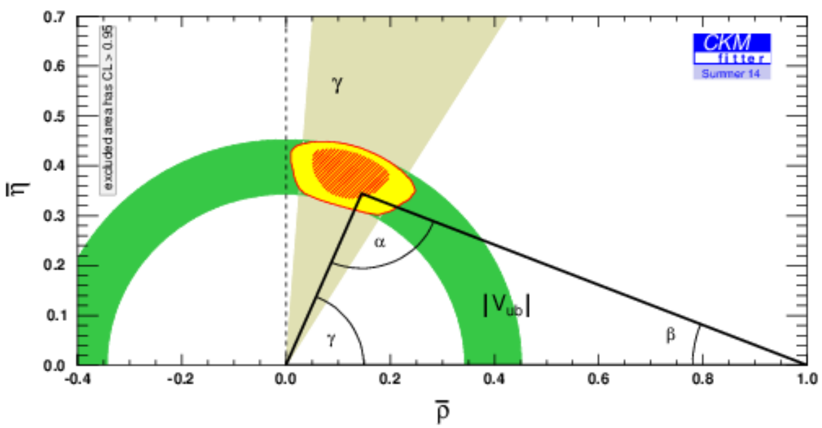
CPV conserving measurements



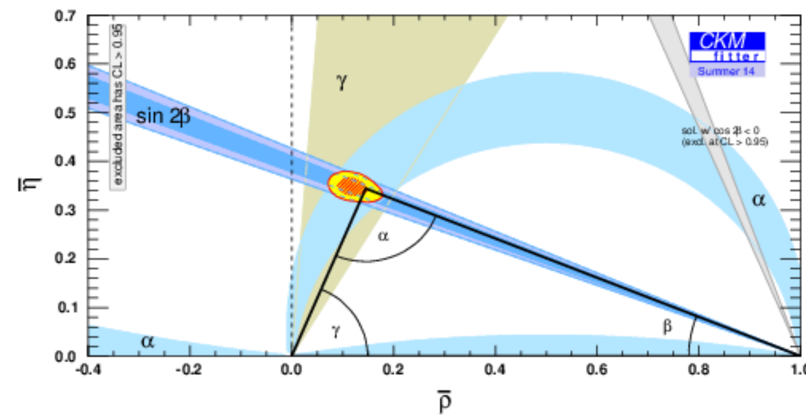
CPV Violating measurements



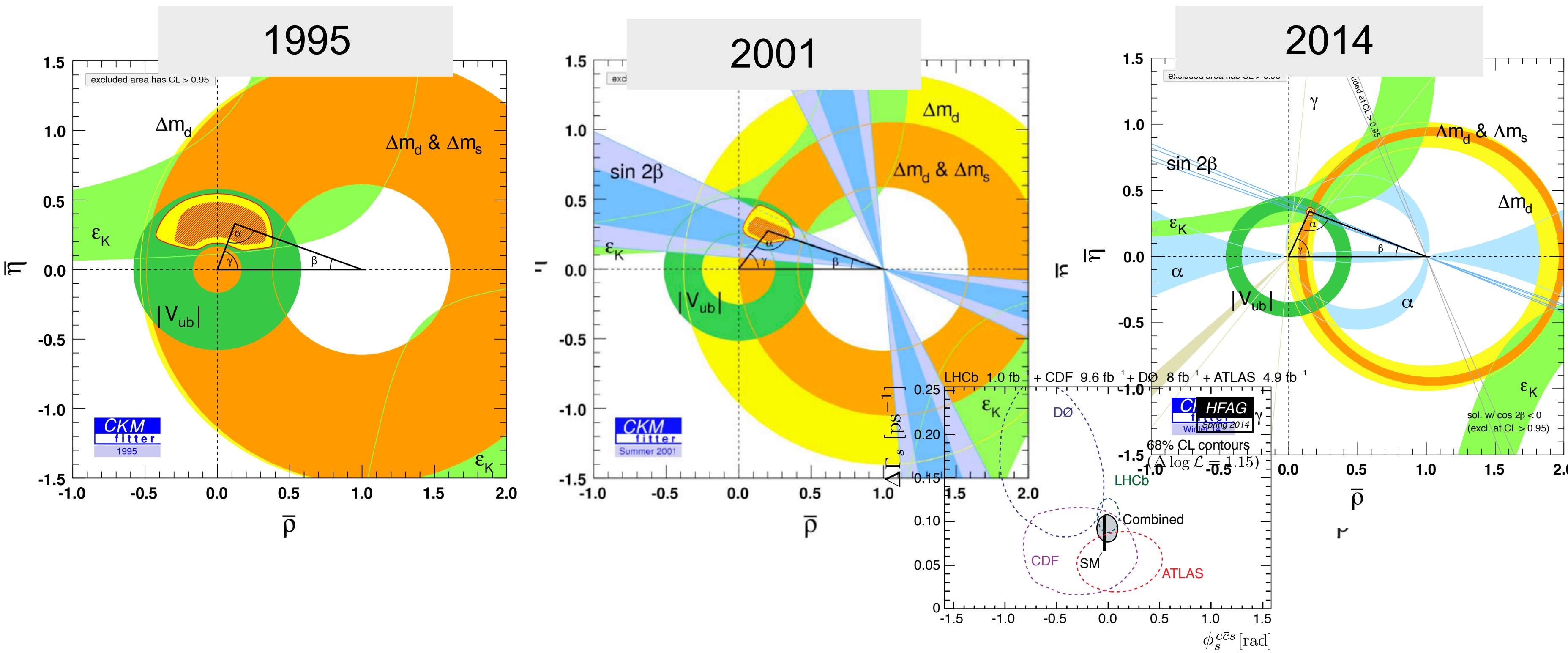
"Tree" level measurements



CKM angles measurements

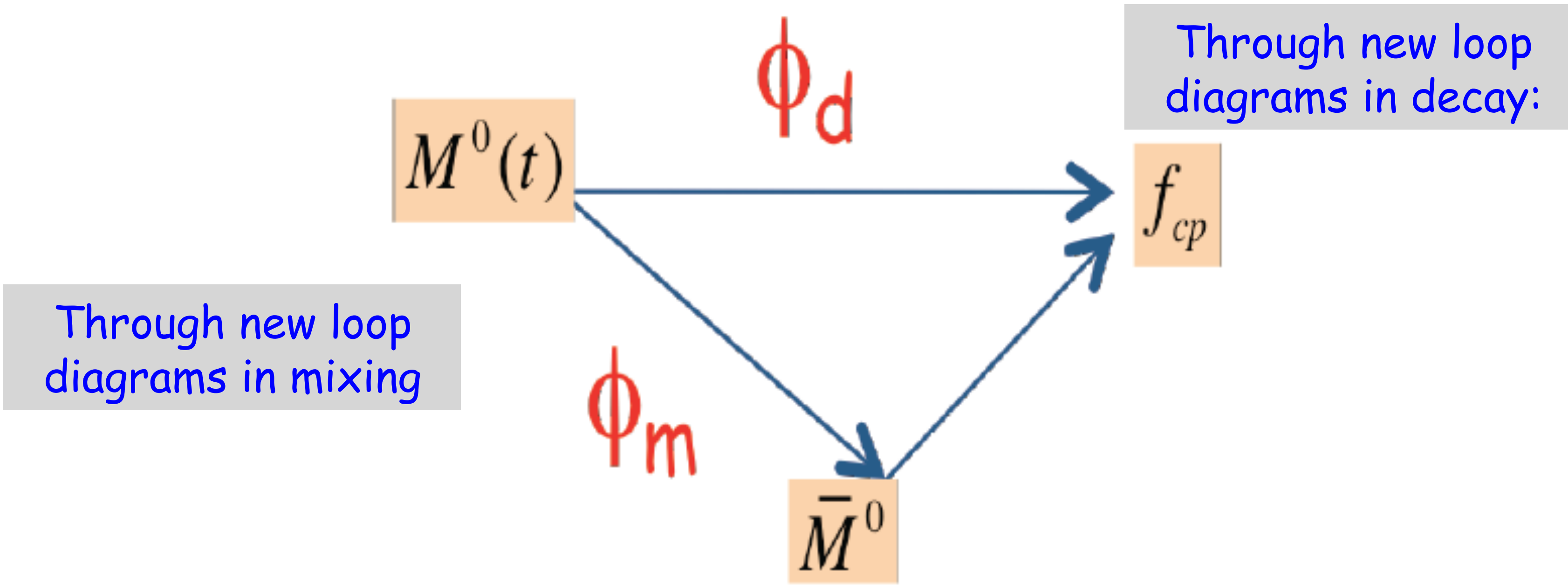


The CKM-project has been extremely successful
Thanks to the B factories, Tevatron , LHC, theory insights & LQCD



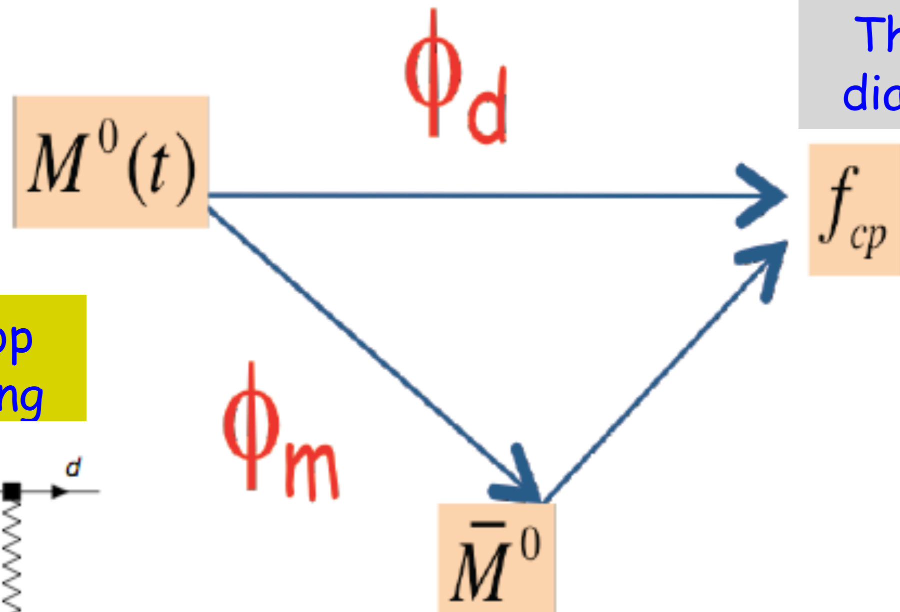
- The CKM picture of CPV in SM seems to be correct (Nobel 2008);
- Flavor remains the only source of observed CP & T-violations

Is there room for CPV sources beyond SM?

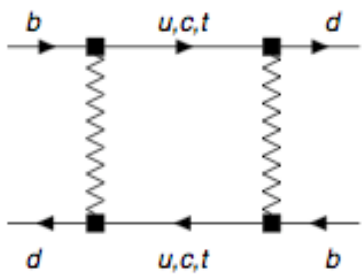


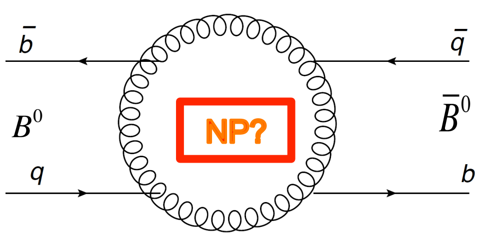
Is there room for CPV sources beyond SM?

Through new loop diagrams in decay:



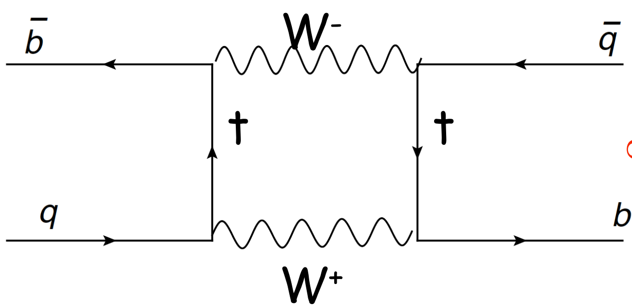
Through new loop diagrams in mixing



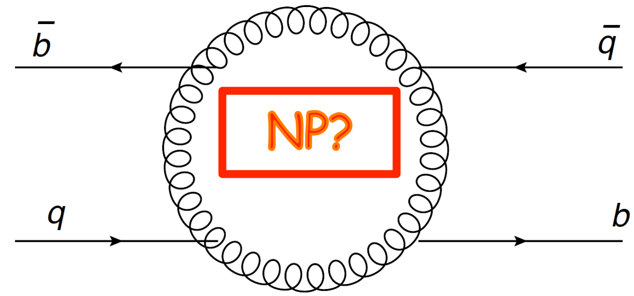


How much NP is allowed?

- Example: The Neutral Meson Oscillation



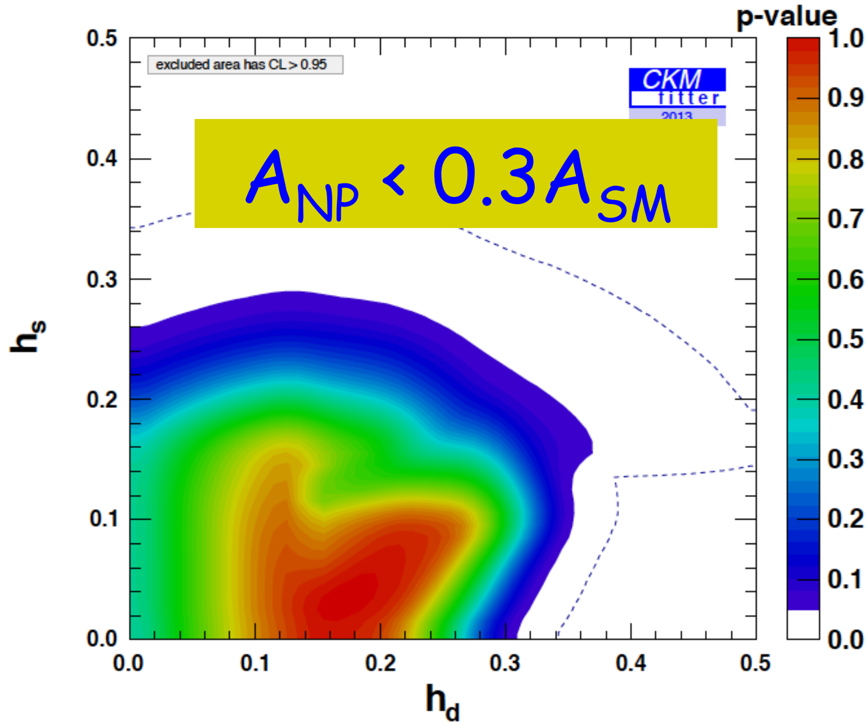
$$\propto \frac{|V_{tq}|^2\, m_t^2}{M_W^4}$$



$$\propto \frac{|C|^2}{\Lambda_{NP}^2}$$

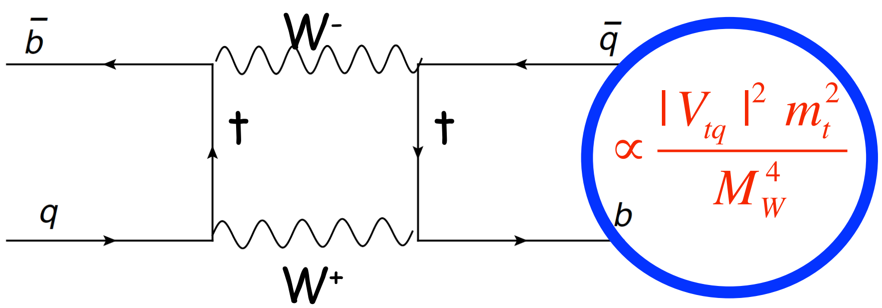
Charles et al (arXiv: 1309.2293)
Fit the data allowing NP amplitude

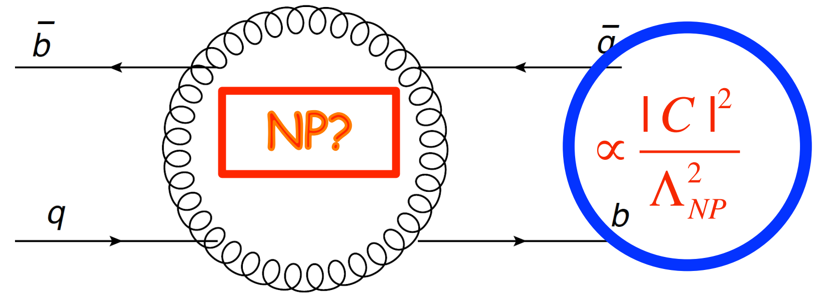
$$M_{12} = M_{12}^{\mathrm{SM}} \times \left(1 + h\, e^{2i\sigma}\right)$$



How much NP is allowed?

- Example: The Neutral Meson Oscillation



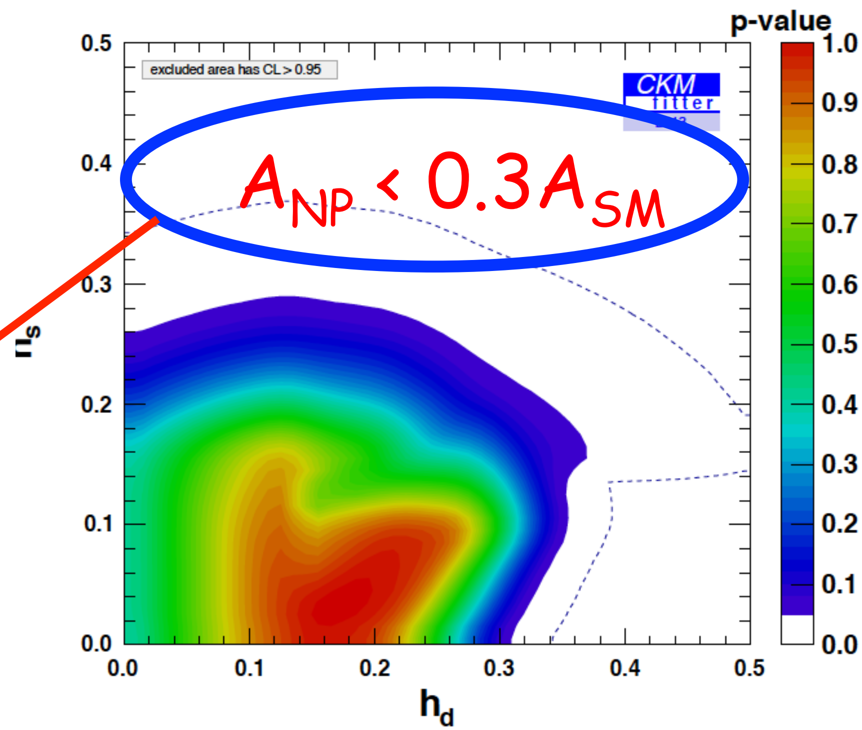


Charles et al (arXiv: 1309.2293)
Fit the data allowing NP amplitude

$$M_{12} = M_{12}^{\rm SM} \times \left(1 + h\, e^{2i\sigma}\right)$$

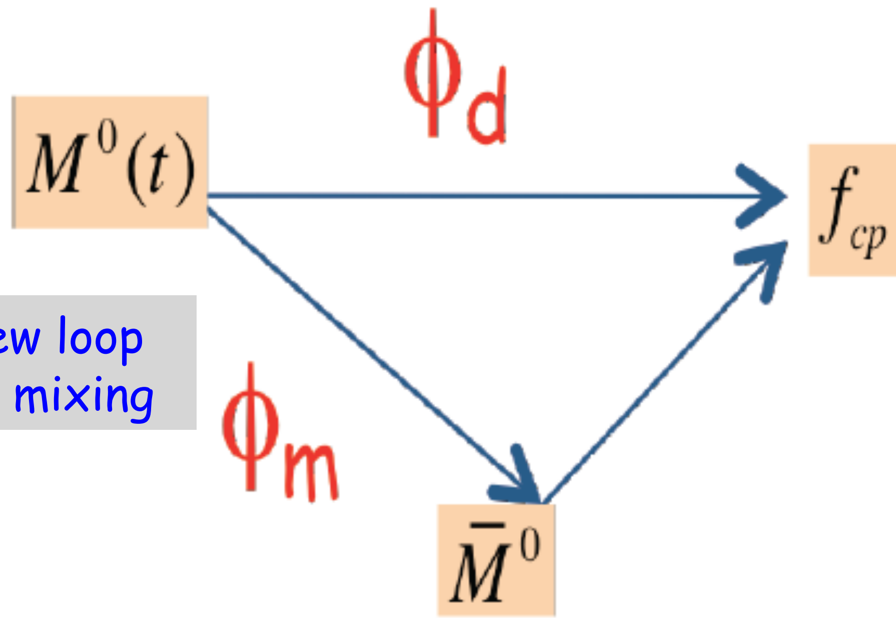
For C=1

$$\Lambda_{NP} \gg 10^3 TeV$$



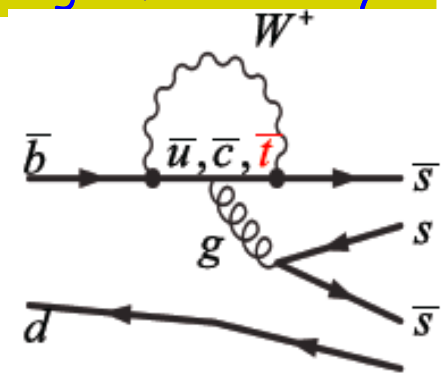
If NP is at ~1 TeV,
New flavor violations
must be highly suppressed

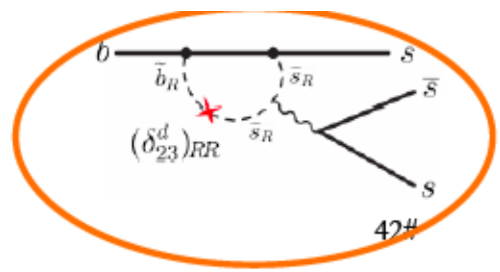
Is there room for CPV sources beyond SM?



Through new loop diagrams in mixing

Through new loop diagrams in decay:





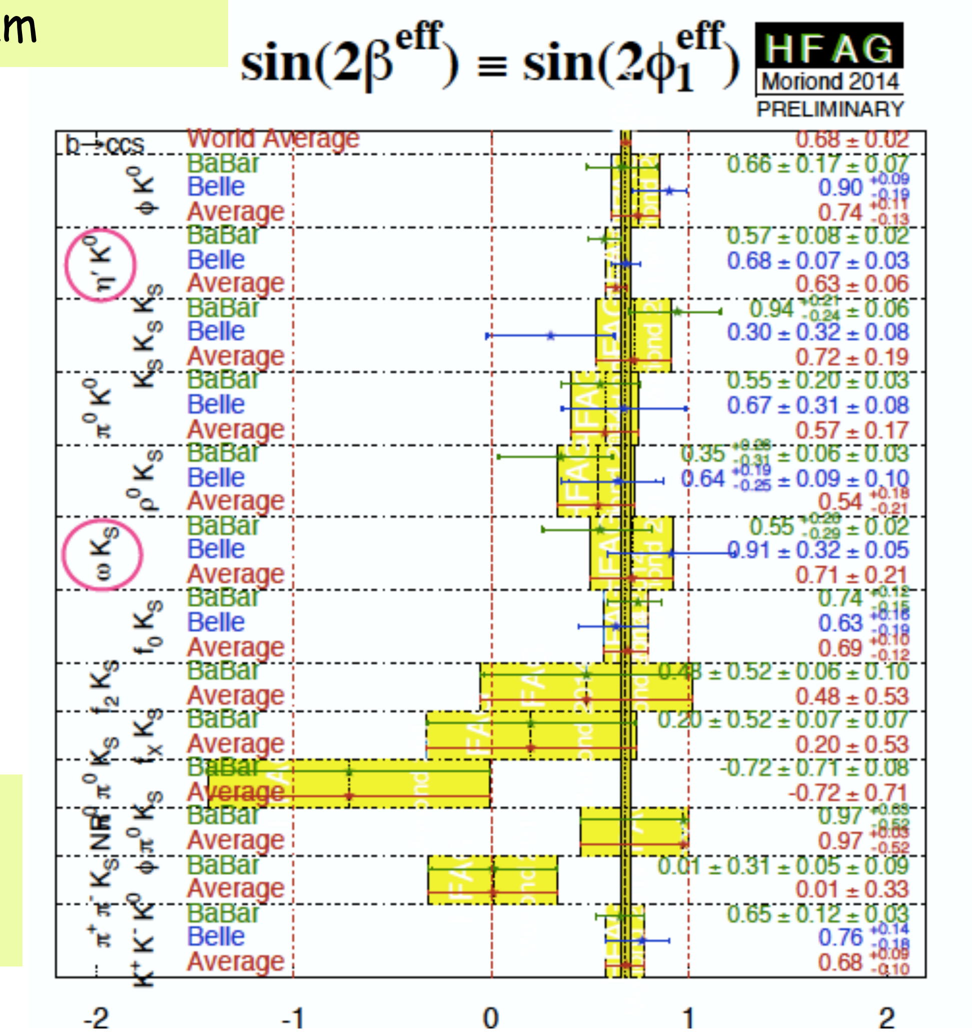
New Physics loops can lead to deviation of CPV from sin2β

Penguin dominated B^0 decays measurements of "sin2β", "ϕ_s"

New B^0_s addition to this program

ϕ_s from a $B_s \to \phi\phi$ (penguin dominated process)-Analog of $B^0 \to \phi K_s$

ϕ_s=-0.17±0.19 ±0.03 (rad)
λ=1.04±0.15±0.03
Consistent with no CPV
& SM ϕ_s



current results are consistent with SM. But theoretical uncertainties are unknown (range of 0.02→0.1)

Broader program of search for NP signature in flavor processes

Example of theorist vision: *"DNA of flavor physics effects"*

by W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi D.M. Straub,

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

★★★ large effects
★★ visible but small effects
★ unobservable effects

Broader program of search for NP signature in flavor processes

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by W. Altmannshofer, A.J. Buras, S. Gori, P. Paradisi D.M. Straub,

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0-\bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{\rm CP}(B\to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B\to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B\to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B\to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s\to\mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+\to\pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L\to\pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu\to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau\to\mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu+N\to e+N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

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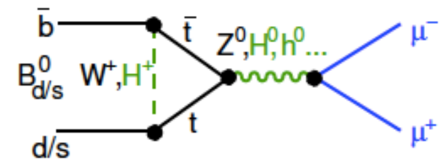
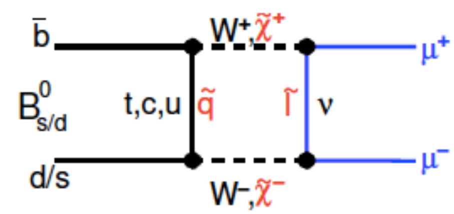
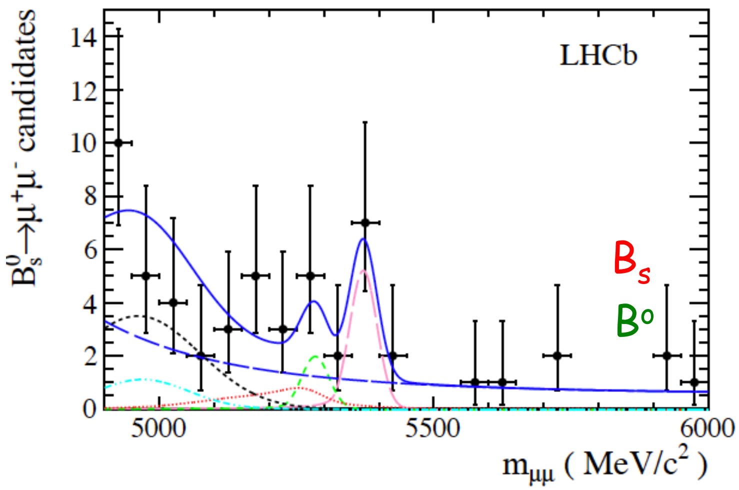
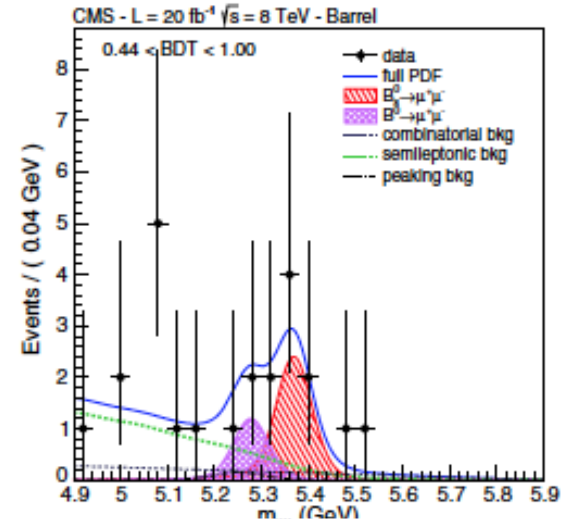


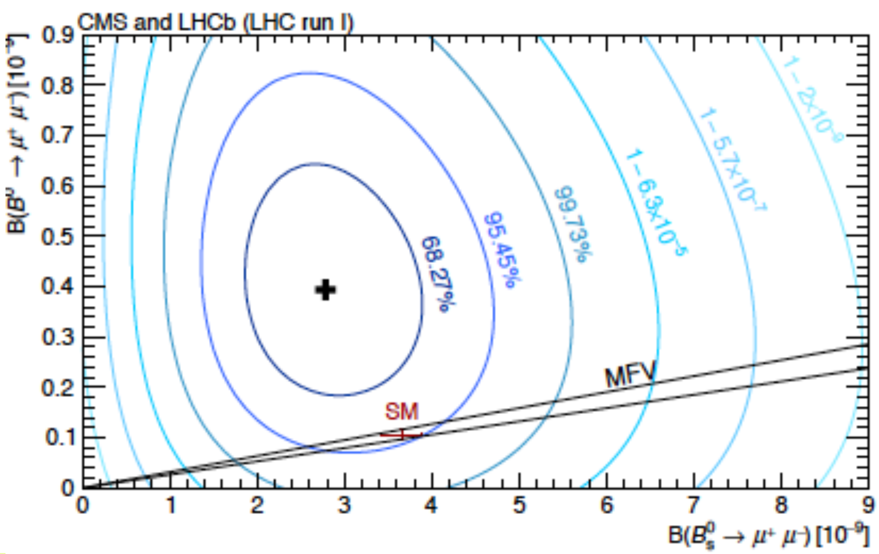


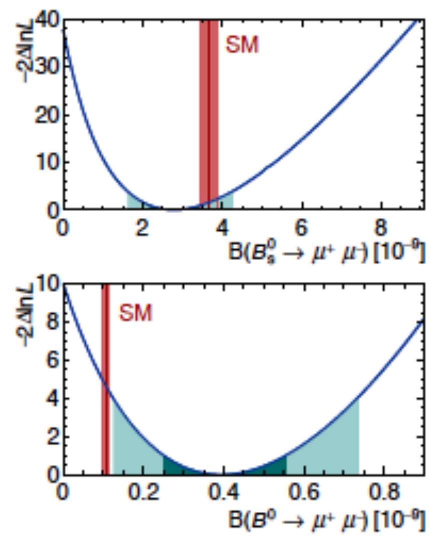
$$Br(B_s^0\to\mu^+\mu^-) = (3.66\pm0.23)\times10^{-9}$$

$B^0_s \to \mu^+\mu^-$:finally seen







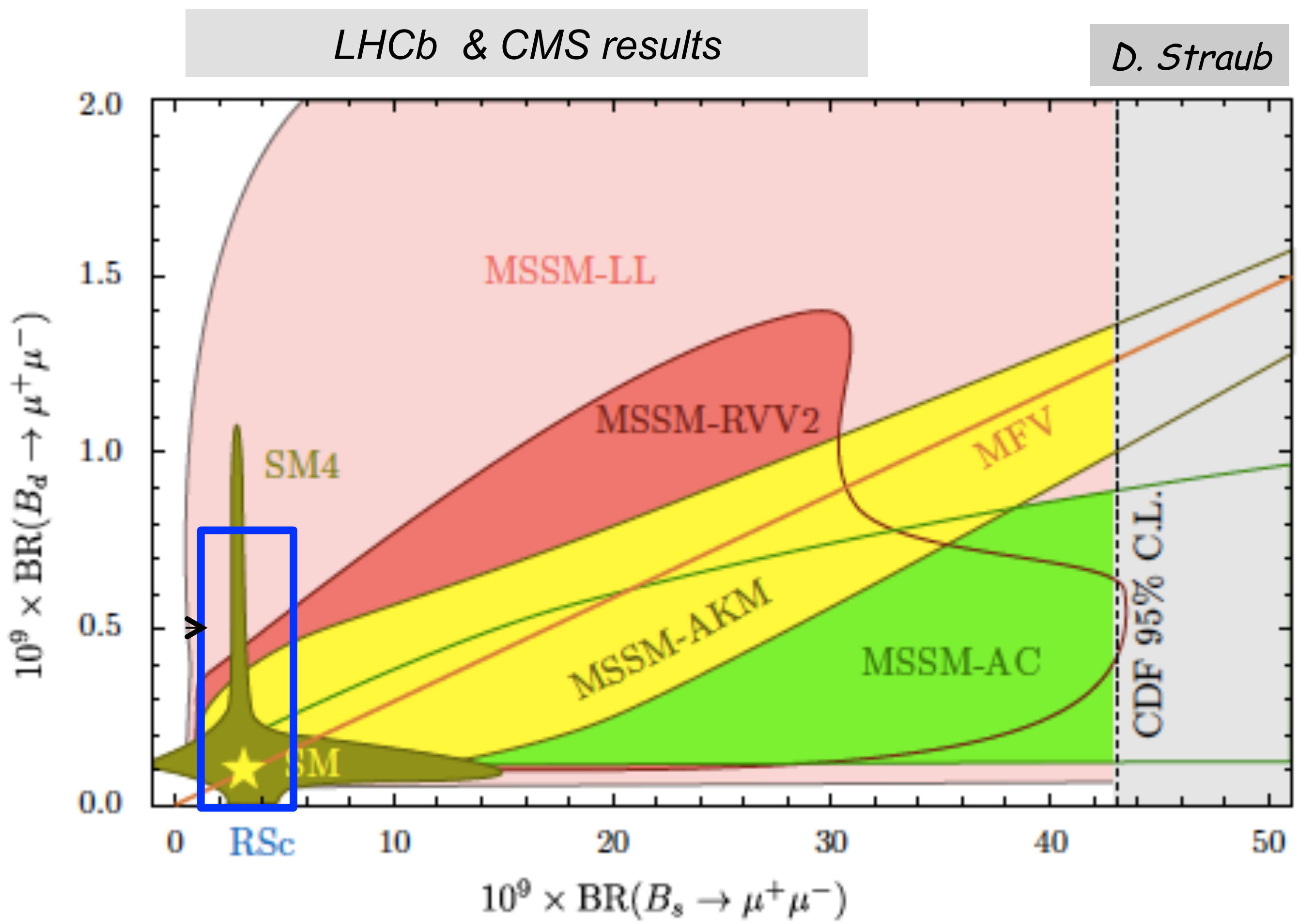


- SM is triumphant

Major impact on SUSY parameter space

Most constraining at large tanβ

$$B(B_{s,d} \to \mu^+\mu^-) \propto m_\mu^2 \tan^6 \beta$$



There are some areas of tension with SM- and slowly growing; all in need of plausible SM explanations ..or (NP?)

- Inclusive vs exclusive V_{ub} and V_{cb}
- Sin2β tension (direct vs CKM fit)
- Di-muon Asymmetry
- Lepton universality tests (e.g. $B \to D^{(*)}\tau\nu$,..)
- Tensions in radiative decays
- $K\pi$-puzzle
- large direct CPV in B
- ...

Ultimately the Data itself may set the direction of the field, if some of the current tensions survive:

Future

Aiming for ~x10 better precision

Need at least x100 statistical power; much higher intensity accelerator/experiments

Equally large leap in precision of theoretical inputs

The past decade saw major advances in possibilities for future flavor experiments

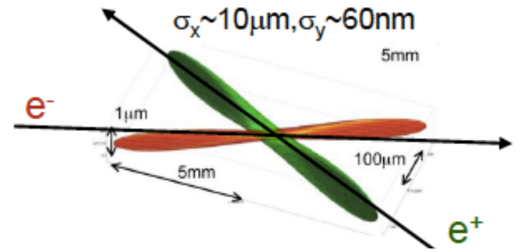
- A new novel accelerator concept emerged for realization of an e+e- Super Flavor factory at ~X100 intensity of SLAC and KEK B factories

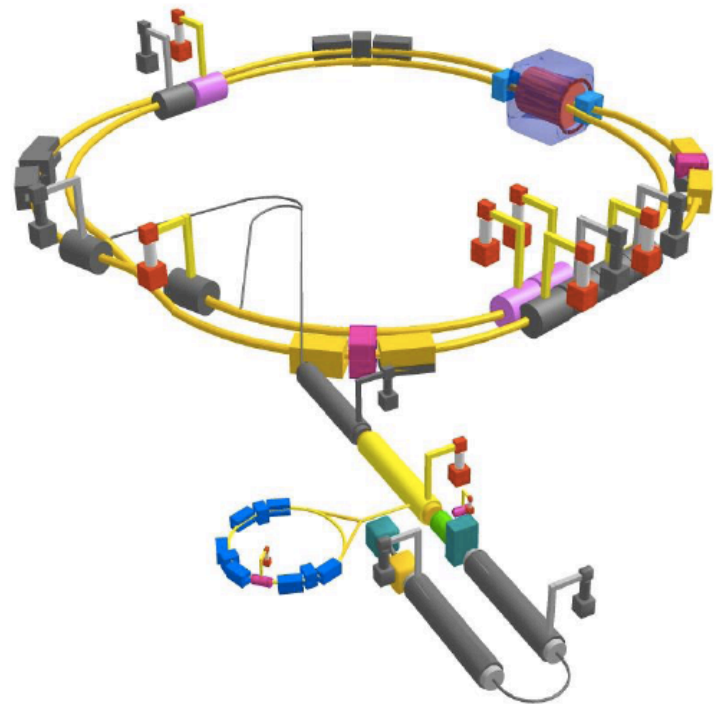
- Heavy flavor physics at hadron colliders successfully demonstrated by Tevatron & LHC experiments. LHCb detector & trigger concepts proved very successful with spectacular results.

Belle-II at SuperKEKB

Asymmetric Energy e+e- collider at goal peak Luminosity 8×10^{35} /cm^2/s aiming for 50 ab^{-1}

Design based on Nano-beam scheme proposed by P. Raimondi (Frascati), tight focusing, larger crossing angle & higher I_b





Accelerator Upgrade

- low emittance electron injector
- New positron damping ring
- New vacuum chambers
- New HER and LER lattice and long dipoles for low emittance
- New IR for low β*
- Modified and additional RF for higher currents

The LHCb upgrade

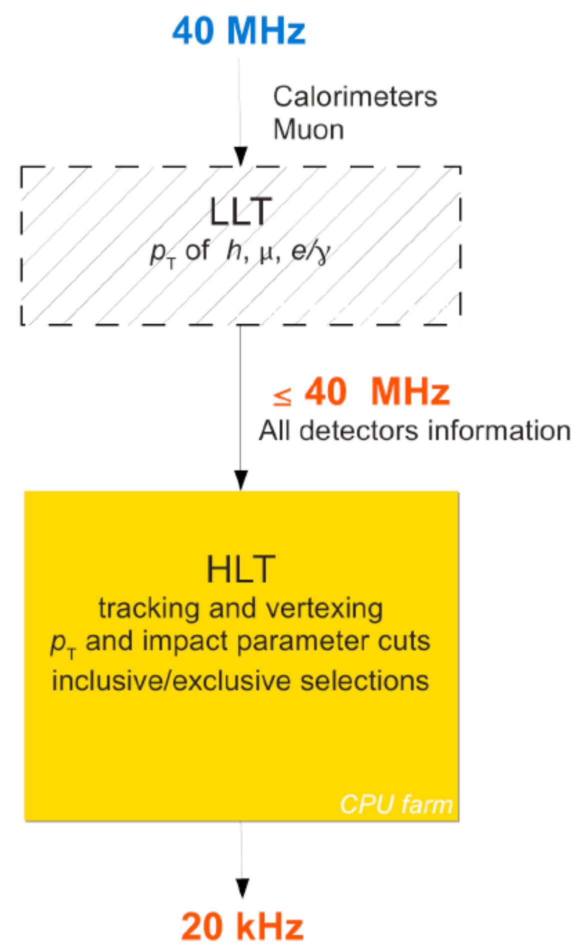
The upgrade is designed to run at luminosity of (1-2)x10^{33} $cm^{-2}s^{-1}$; Aiming for 50 fb^{-1}

- Requires new approach to the LHCb trigger scheme to overcome L0 (1MHz) limitation.

➔ New Trigger Apporach:

- Remove L0 (hardware) trigger
- Readout the detector at the 40 MHz LHC clock rate
- Move to a fully flexible software trigger

=>>Major upgrade of LHCb detector required : to cope with increase occupancy, data rate and radiation dose, & to preserve efficiency and low ghost rate: Replace all readout electronics, entire tracking system (Vertex locator, upstream & downstream tracking detectors) & upgrade Particle ID system



Benchmark for future NP sensitivity

- Example: NP constraints from Meson Mixing

Charles et al (arXiv: 1309.2293).

$$M_{12} = M_{12}^{\mathrm{SM}} \times \left(1 + h\, e^{2i\sigma}\right)$$

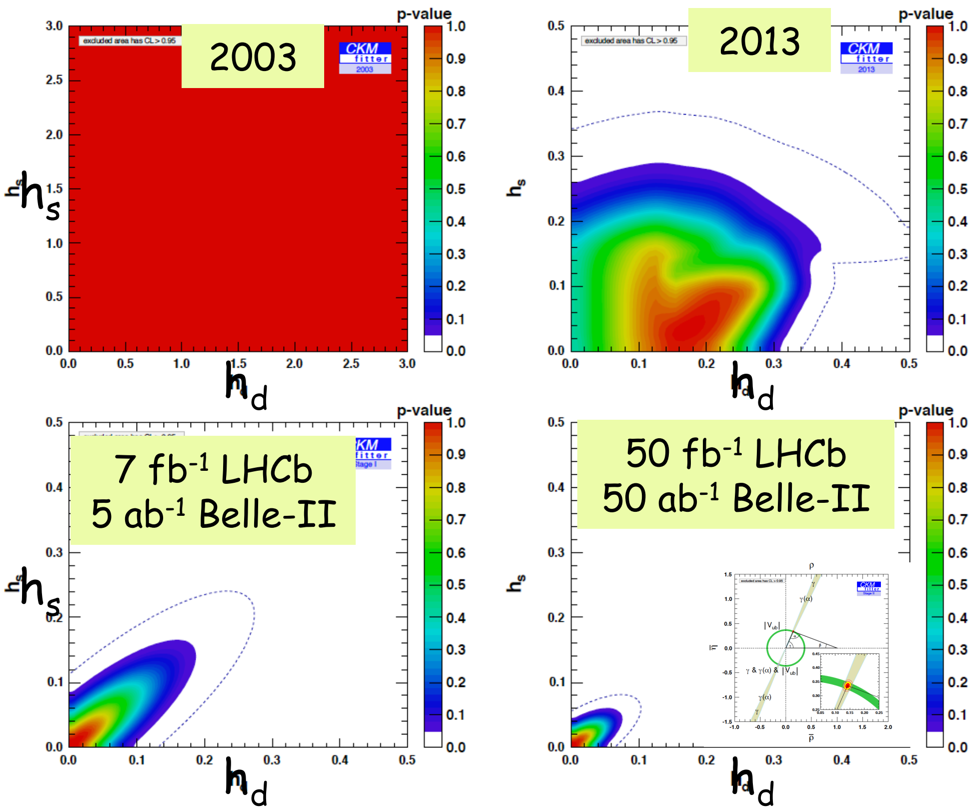
➢Current data:

◆B_s is now on equal ground as B_d system (Thanks to LHCb results).

◆Data allows NP at 20-30% SM

➢Future:

If consistency with SM persists- LHCb and Belle-II measurements- combined with improved LQCD errors- will constrain the magnitude of NP contribution to ~5% of SM



Outlook:

- Fitch and Cronin's path continues: the search for the origins of CP violation in the quark sector remains one of the primary drivers of the search for physics beyond SM.
  - The current data is consistent with the Standard Model, setting severe constrains on scenarios of new physics, but many stones remain unturned.
    - There are some areas of tensions with SM, waiting for more precise measurements and theoretical calculations. Stay tuned.
  - The planned experimental program for the next decade or more, together with advances on the theory front will challenge the SM with tremendous precision.
- Great plans are underway for the new frontier: CP violation in the lepton sector.